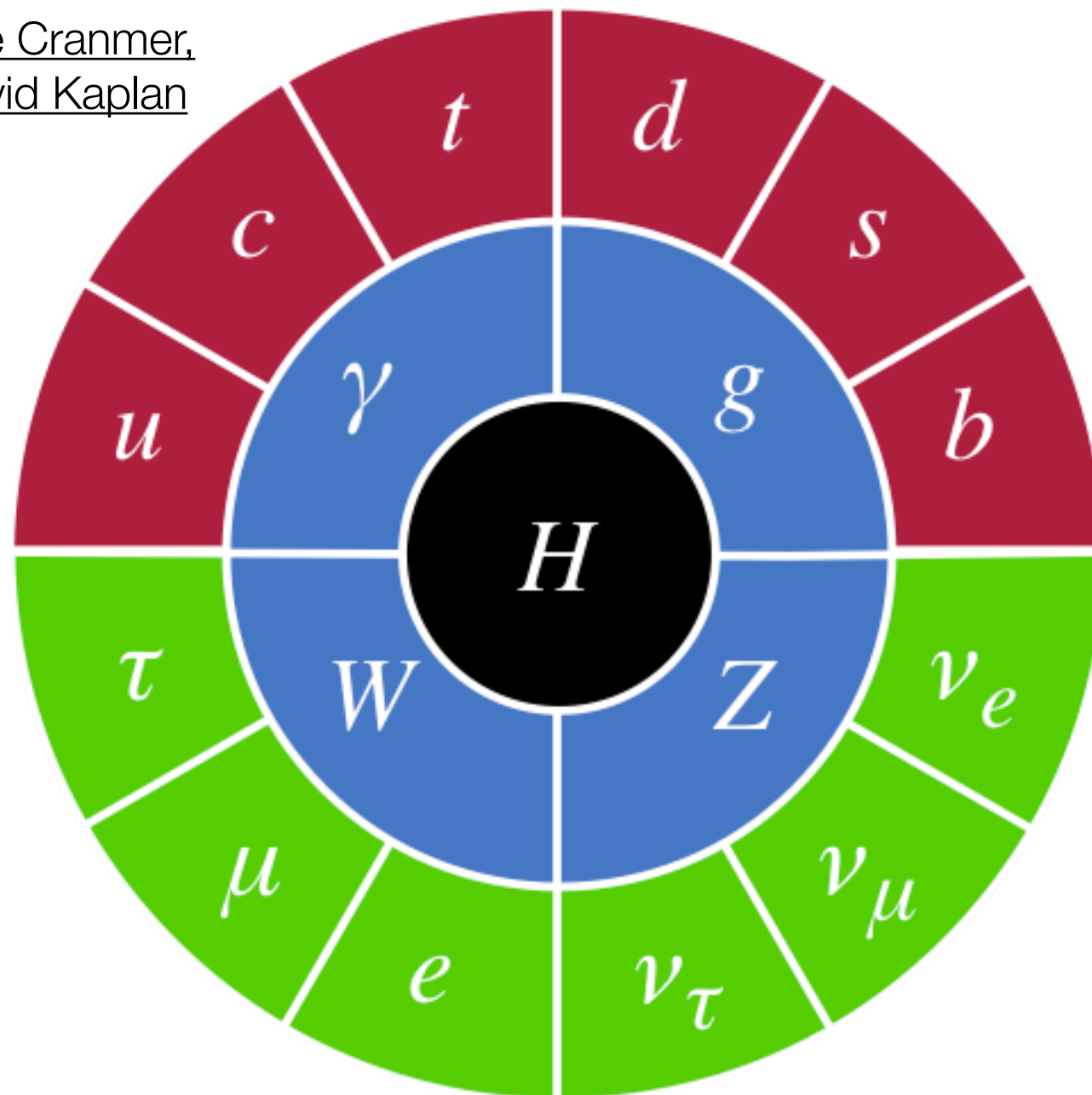# Hunting for new physics using long-lived particles

Kate Pachal
Duke University

What we know about particle physics

Kyle Cranmer, David Kaplan

Quarks
Strong and electroweak interactions

Leptons
Electroweak interactions

Bosons
Force carriers

Higgs boson
Electroweak symmetry breaking

Higgs was the last puzzle piece!

What we know about particle physics

Kyle Cranmer, David Kaplan

Is this picture complete?

Quarks
Strong and electroweak interactions

Leptons
Electroweak interactions

Bosons
Force carriers

Higgs boson
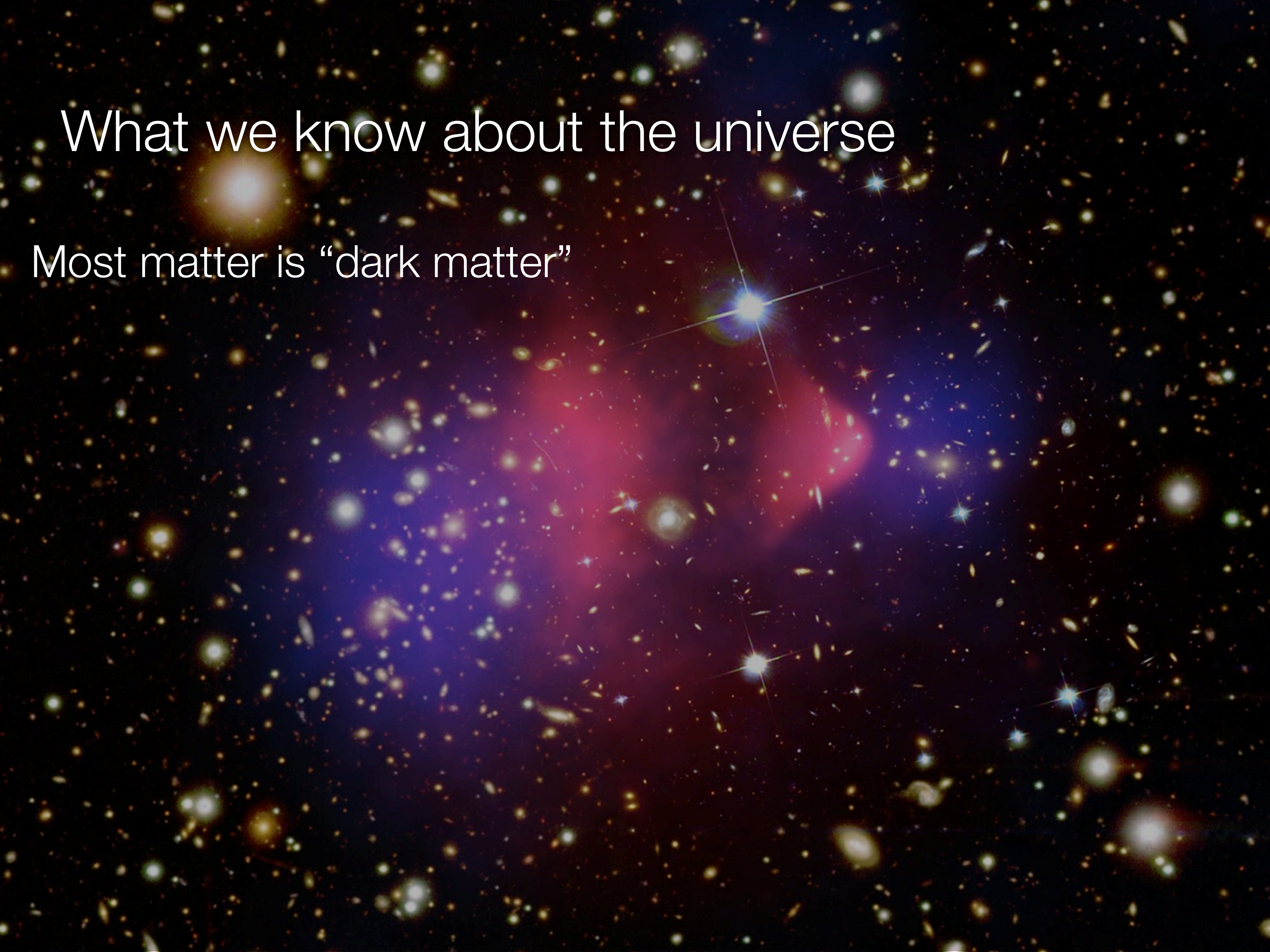Electroweak symmetry breaking
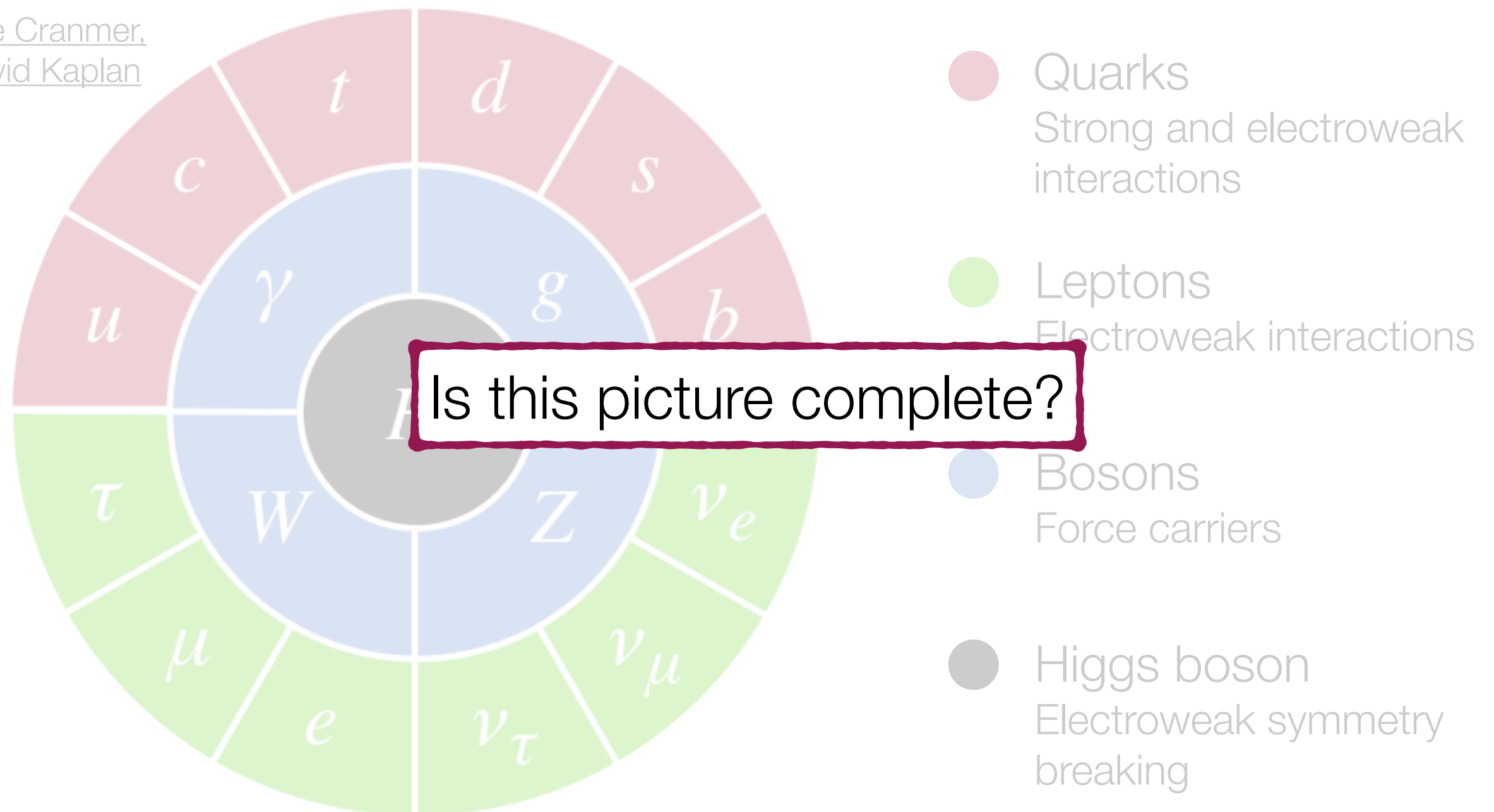
Higgs was the last puzzle piece!

What we know about the universe

What we know about the universe
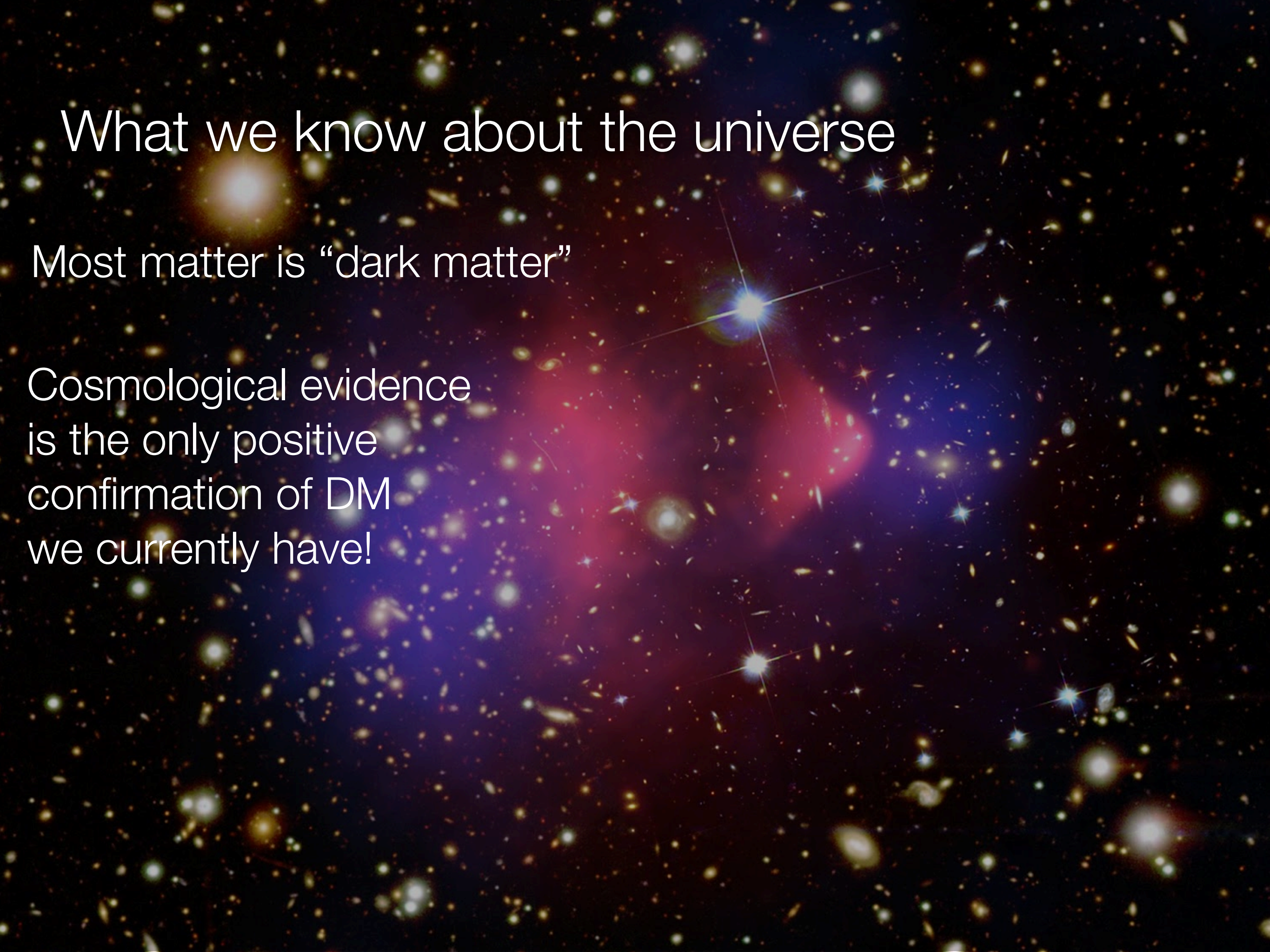
Most matter is "dark matter"

What we know about the universe

Most matter is "dark matter"

Cosmological evidence
is the only positive
confirmation of DM
we currently have!

What we know about the universe

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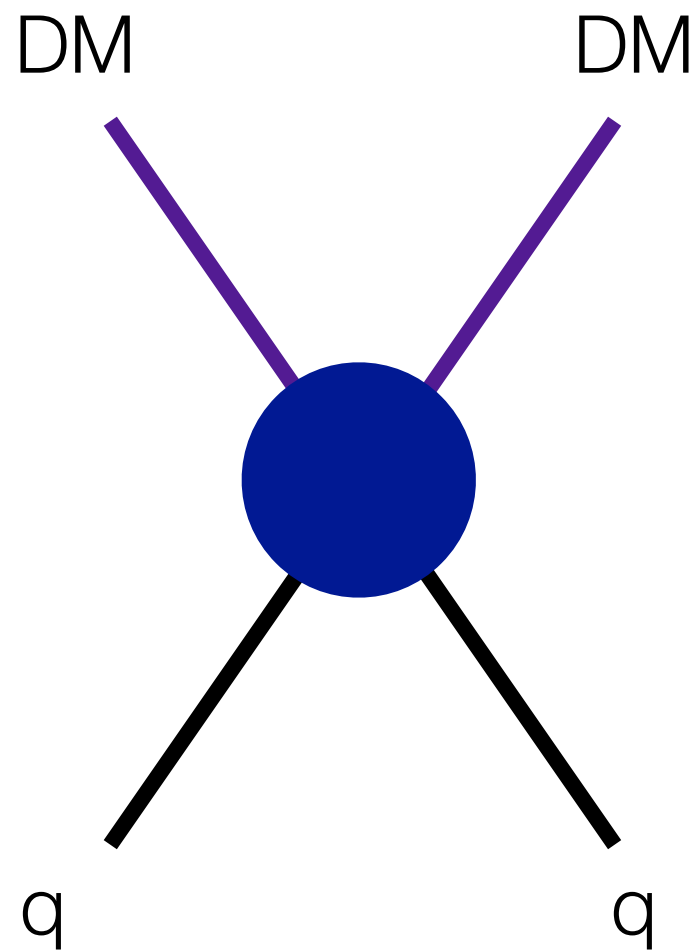we currently have!

What we know about
dark matter:
- Long lifetime
- No EM charge
- Specific relic density

What we don't know:
- Mass
- How it connects to
the Standard Model
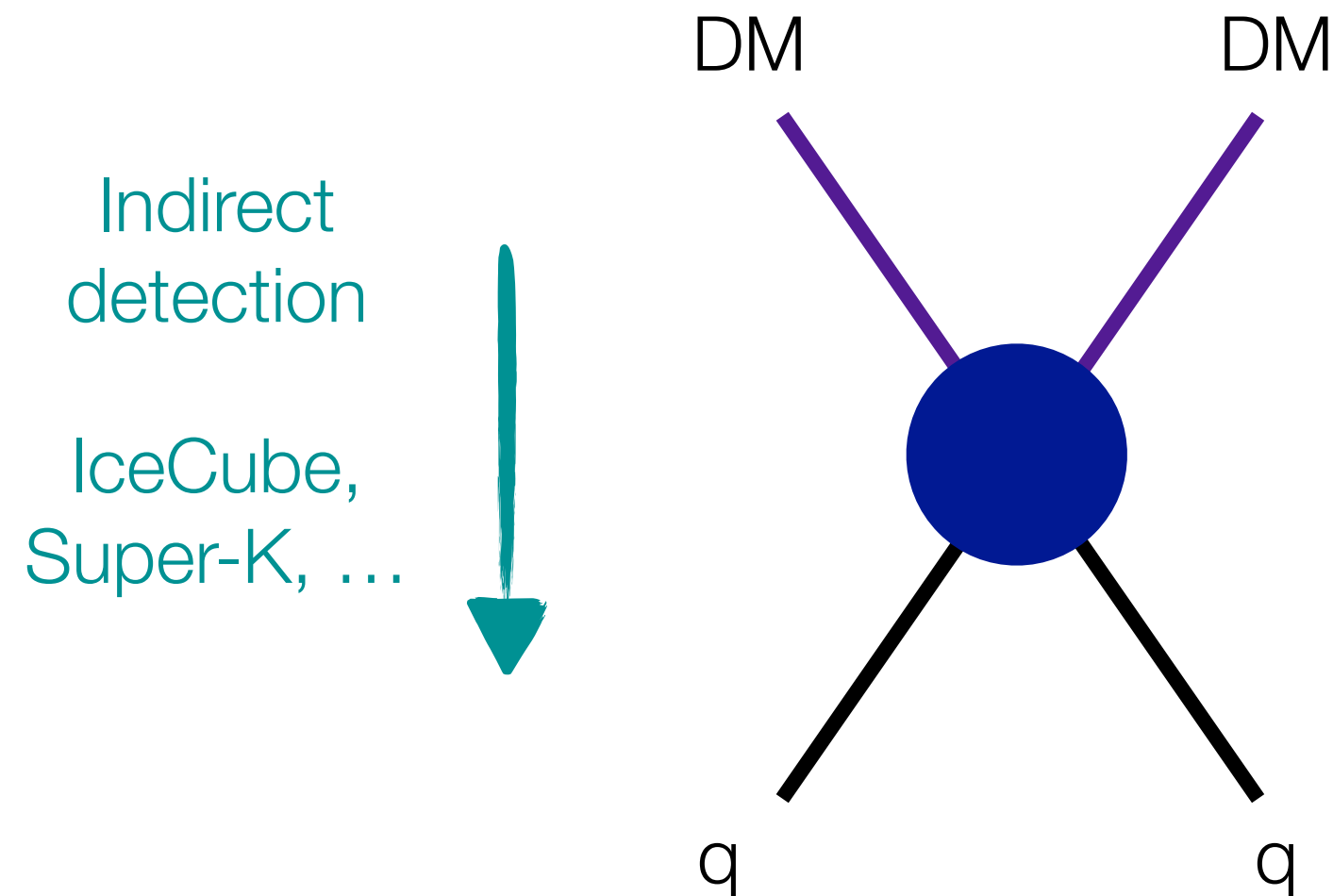
Looking for dark matter with experiments

Looking for dark matter with experiments

Indirect detection

IceCube, Super-K, …

DM   DM

q   q

Looking for dark matter with experiments

Looking for dark matter with experiments

DM   DM

Indirect
detection

IceCube,
Super-K, …

Colliders

ATLAS
& CMS

q   q

Direct detection: LUX, XENON, …
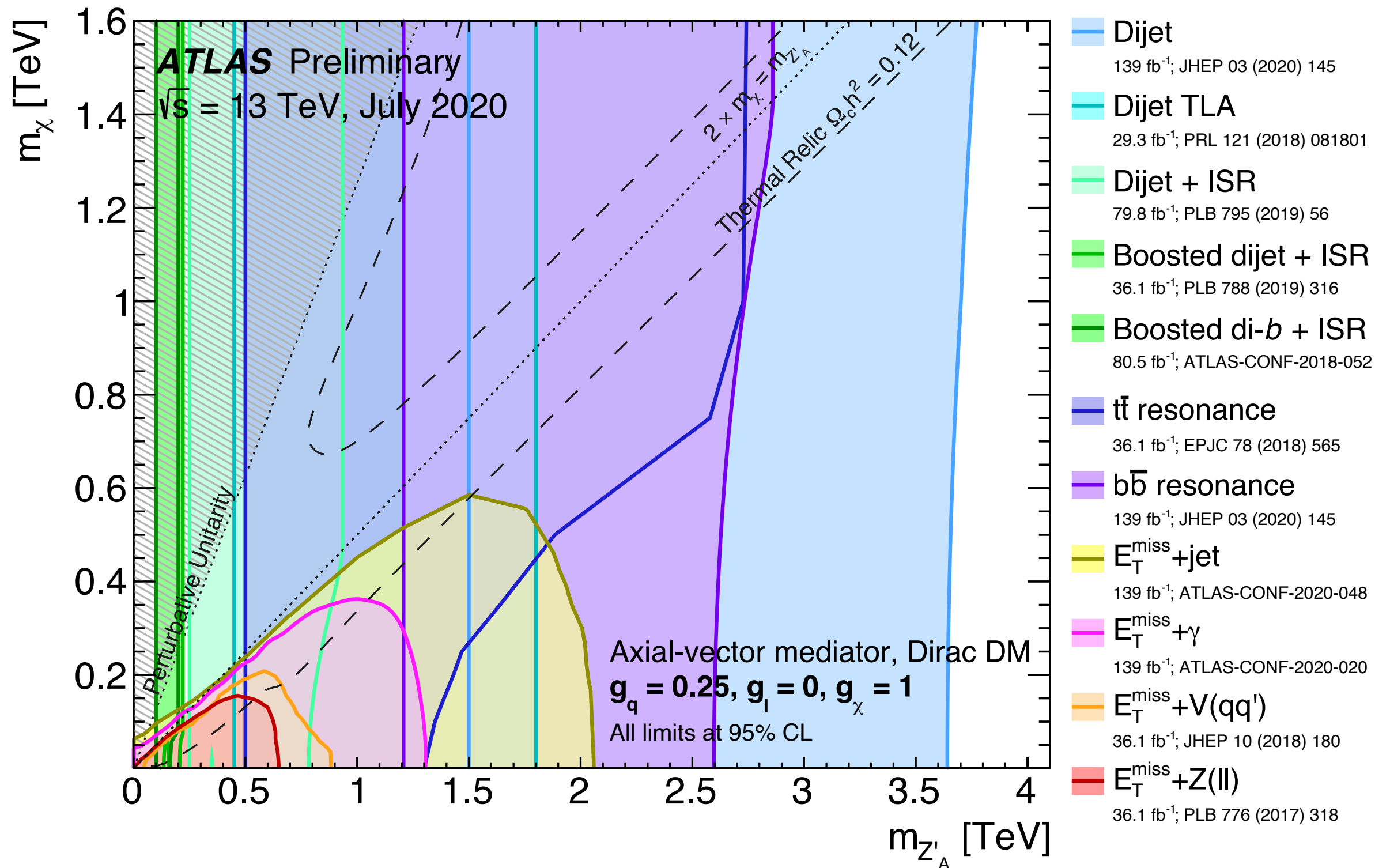
4
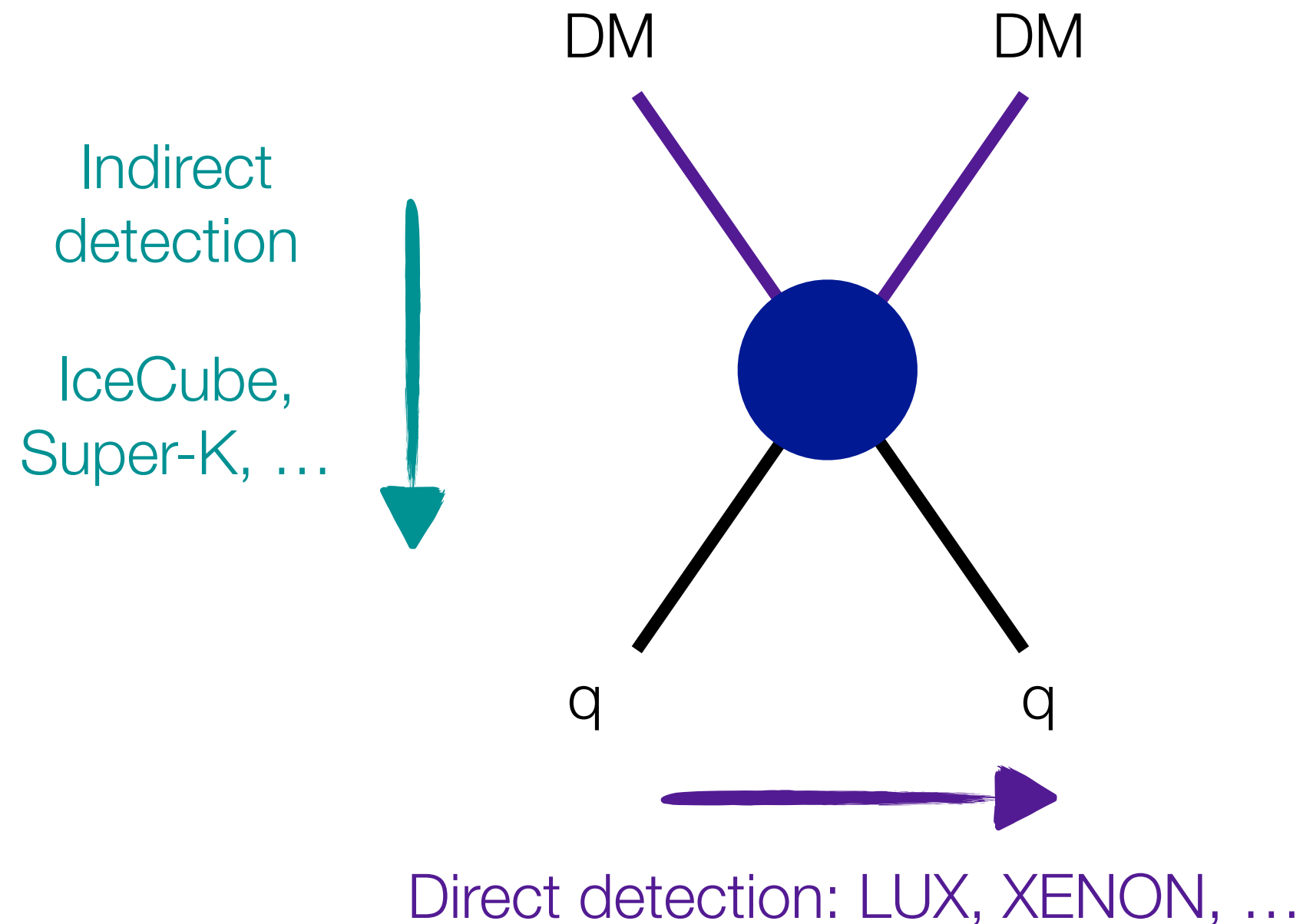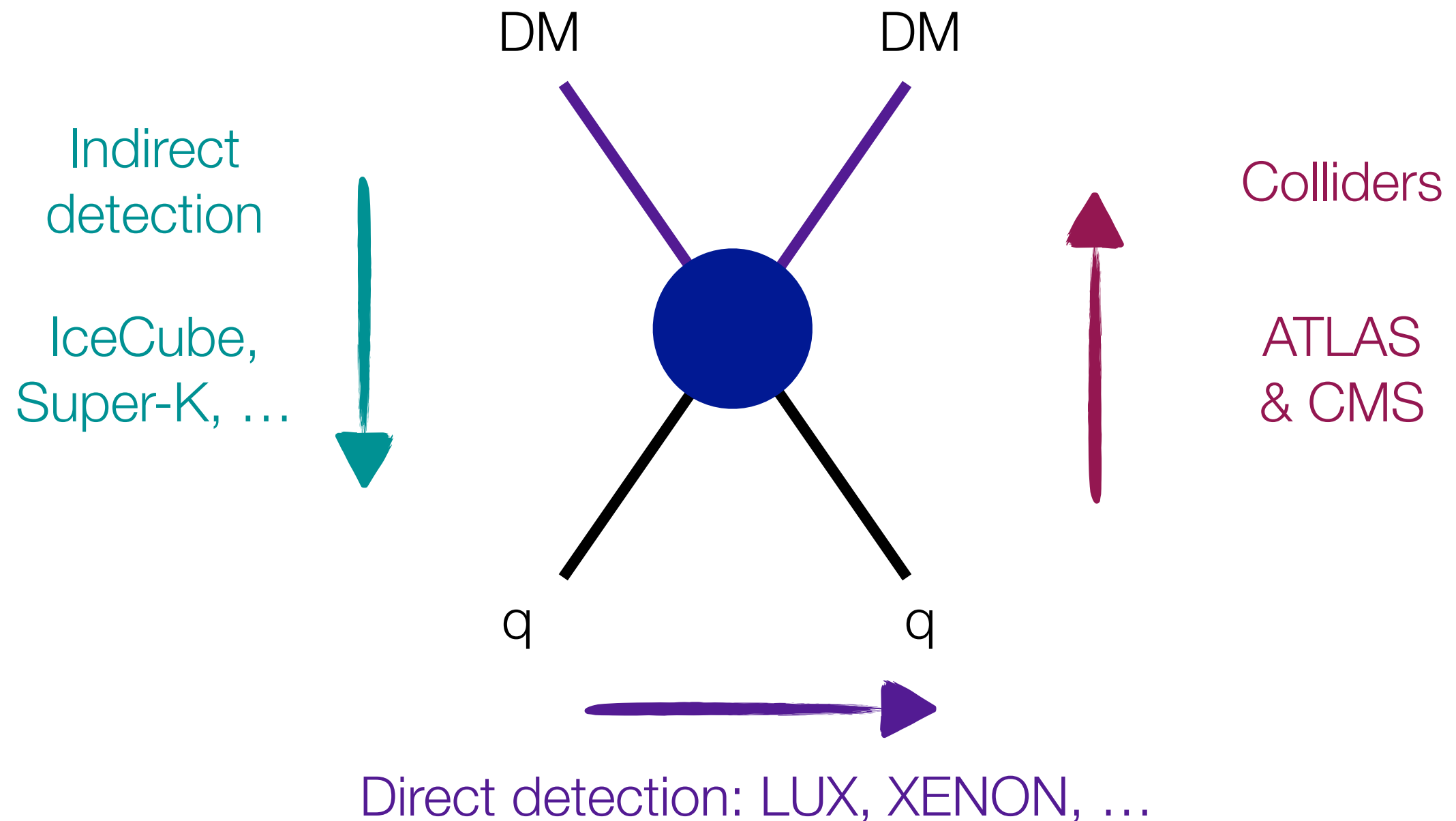
Looking for dark matter with experiments
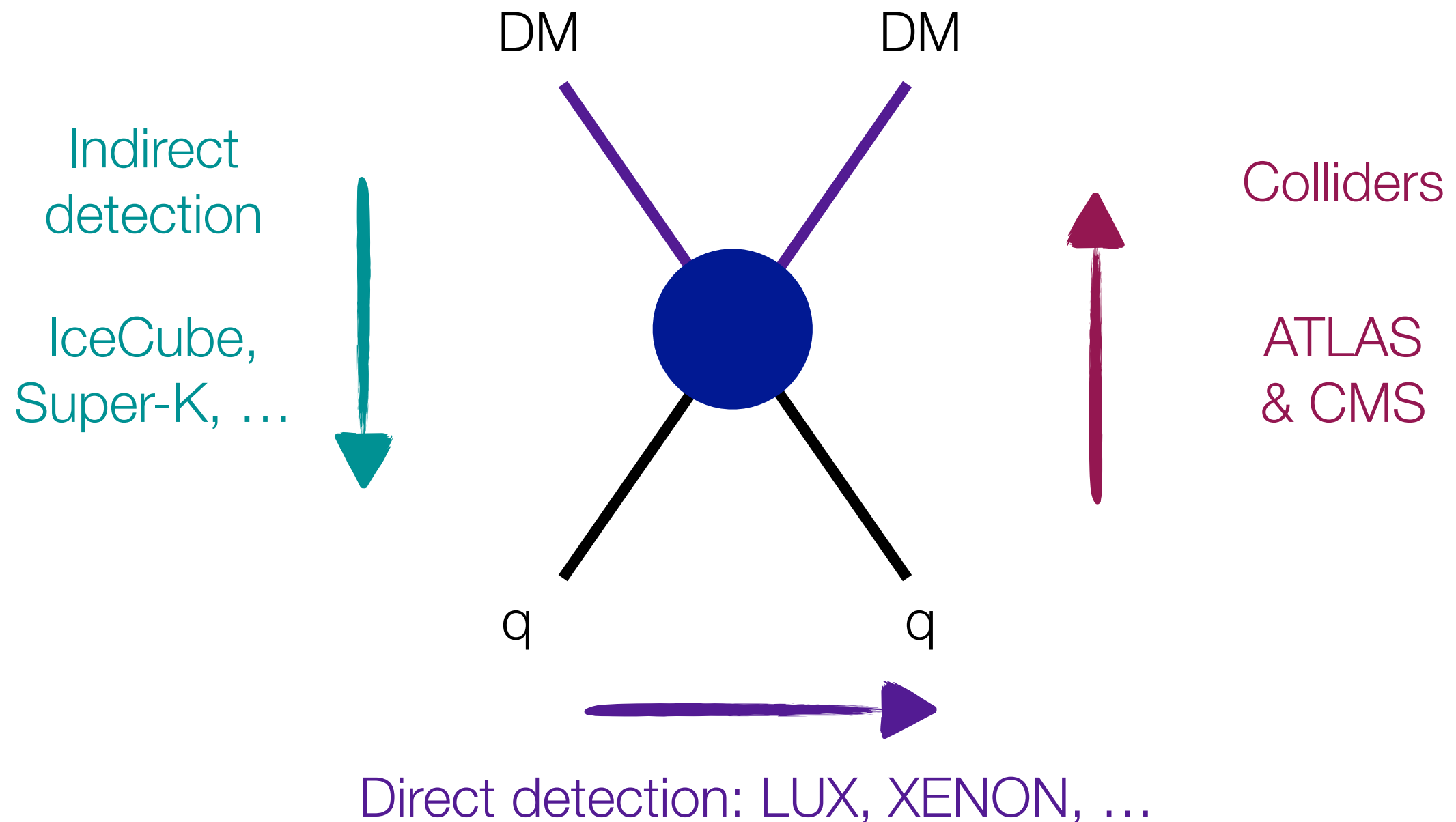
If there is some interaction with the Standard Model, at a moderate energy scale, → then we should be able to produce DM at the LHC!

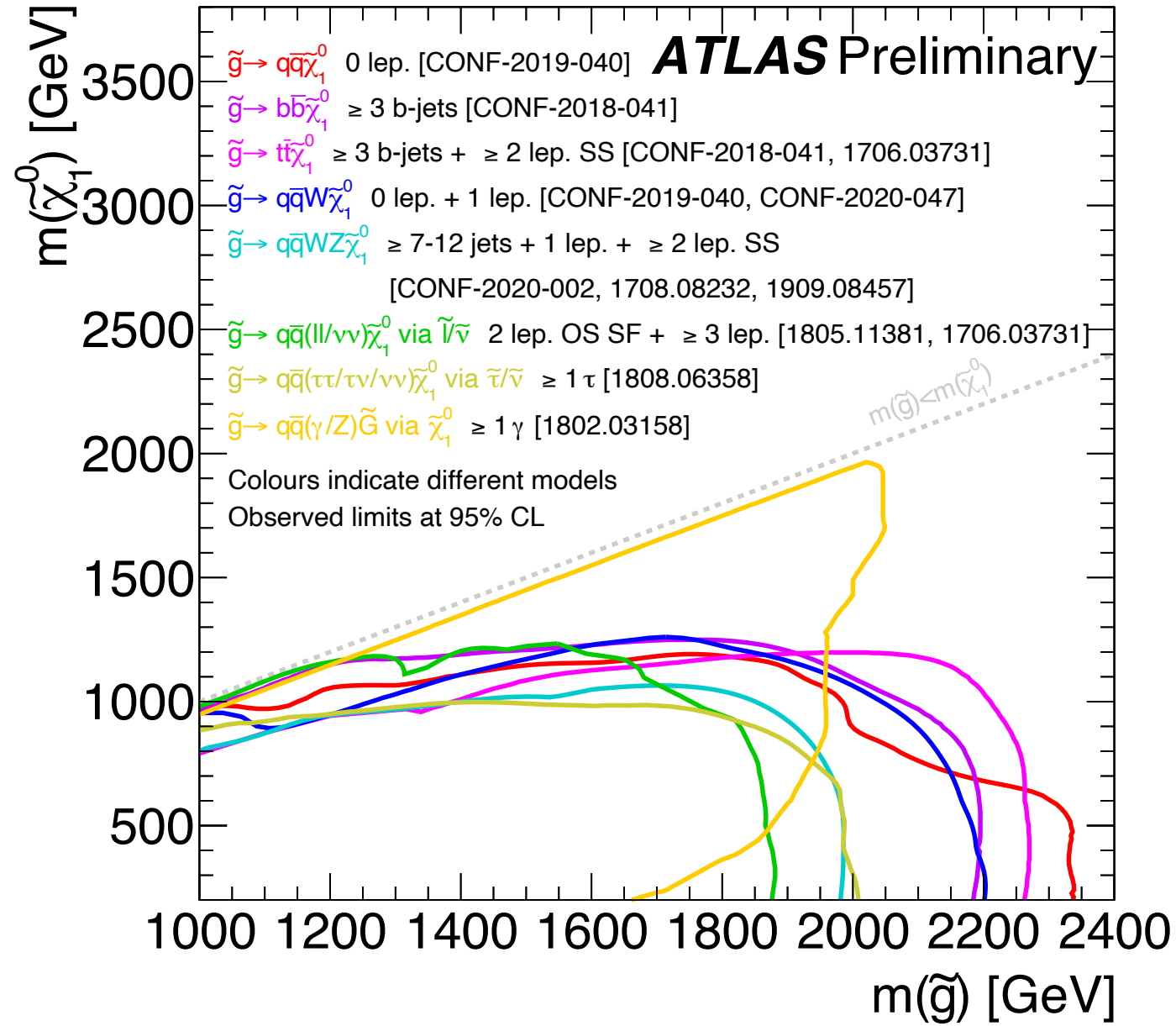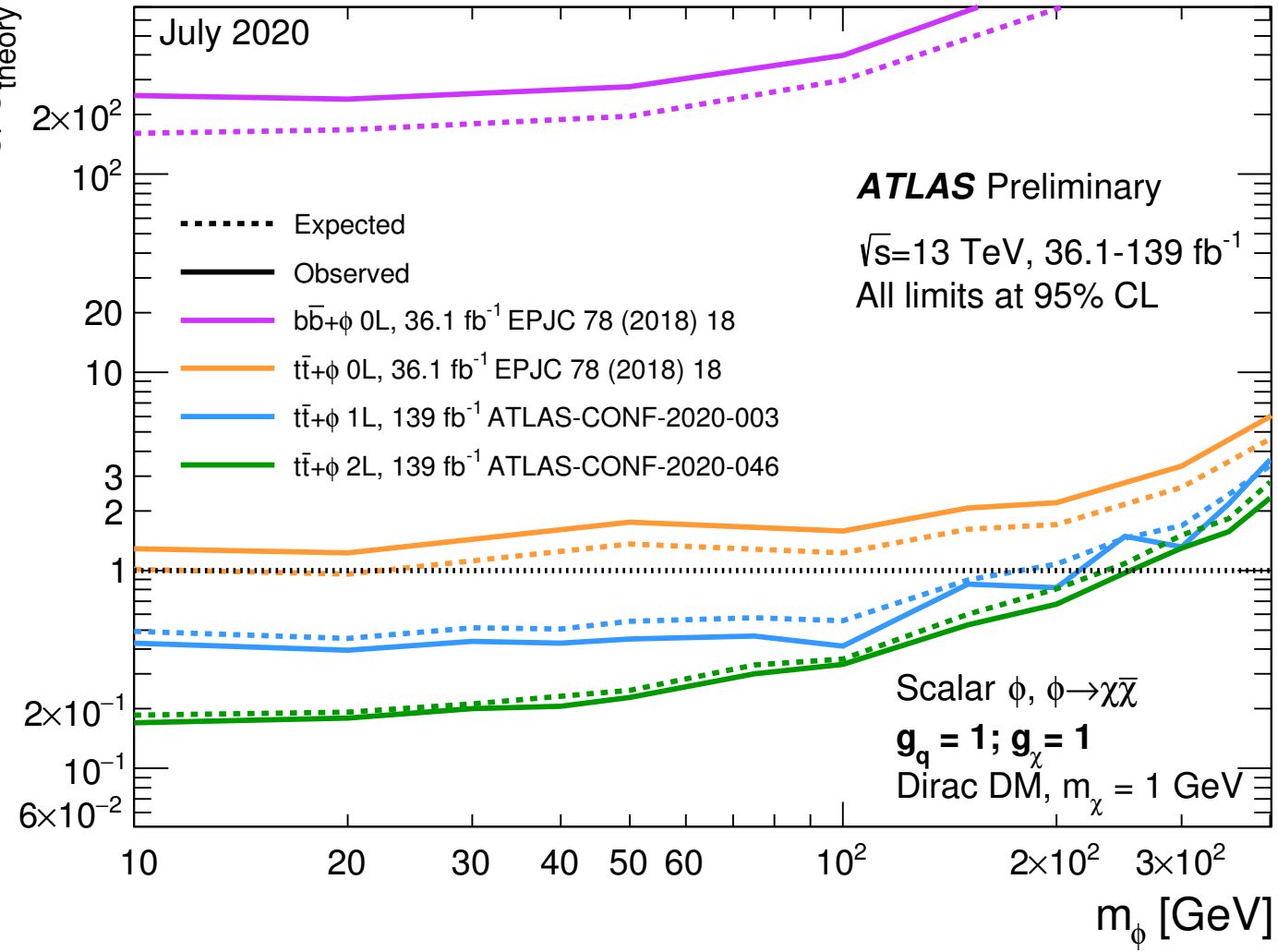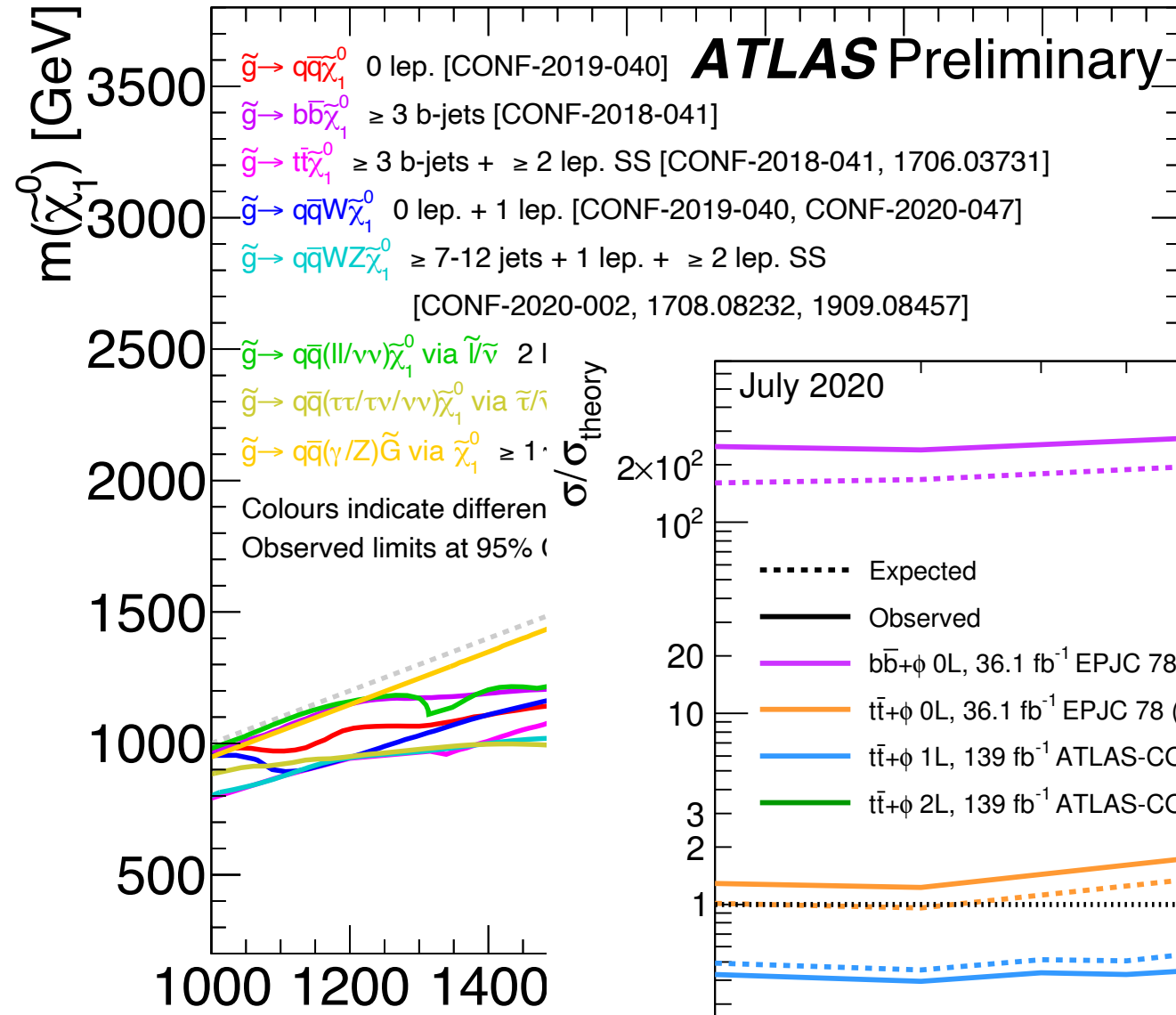4

LHC dark matter limits today

√s=13 TeV, 36.1 - 139 fb^{-1} July 2020

$\tilde{g} \to q\bar{q}\tilde{\chi}_1^0$ 0 lep. [CONF-2019-040]   **ATLAS** Preliminary

$\tilde{g} \to b\bar{b}\tilde{\chi}_1^0$ ≥ 3 b-jets [CONF-2018-041]

$\tilde{g} \to t\bar{t}\tilde{\chi}_1^0$ ≥ 3 b-jets + ≥ 2 lep. SS [CONF-2018-041, 1706.03731]

$\tilde{g} \to q\bar{q}W\tilde{\chi}_1^0$ 0 lep. + 1 lep. [CONF-2019-040, CONF-2020-047]

$\tilde{g} \to q\bar{q}WZ\tilde{\chi}_1^0$ ≥ 7-12 jets + 1 lep. + ≥ 2 lep. SS

[CONF-2020-002, 1708.08232, 1909.08457]

$\tilde{g} \to q\bar{q}(ll/\nu\nu)\tilde{\chi}_1^0$ via $\tilde{l}/\tilde{\nu}$ 2 lep. OS SF + ≥ 3 lep. [1805.11381, 1706.03731]

$\tilde{g} \to q\bar{q}(\tau\tau/\tau\nu/\nu\nu)\tilde{\chi}_1^0$ via $\tilde{\tau}/\tilde{\nu}$ ≥ 1 τ [1808.06358]

$\tilde{g} \to q\bar{q}(\gamma/Z)\tilde{G}$ via $\tilde{\chi}_1^0$ ≥ 1 γ [1802.03158]

Colours indicate different models
Observed limits at 95% CL

$m(\tilde{g}) < m(\tilde{\chi}_1^0)$

√s=13 TeV, 36.1 - 139 fb⁻¹ — July 2020

ATLAS Preliminary

$\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$ 0 lep. [CONF-2019-040]

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[CONF-2020-002, 1708.08232, 1909.08457]

$\tilde{g} \rightarrow q\bar{q}(ll/\nu\nu)\tilde{\chi}_1^0$ via $\tilde{l}/\tilde{\nu}$ 2 l

$\tilde{g} \rightarrow q\bar{q}(\tau\tau/\tau\nu/\nu\nu)\tilde{\chi}_1^0$ via $\tilde{\tau}/\tilde{\nu}$

$\tilde{g} \rightarrow q\bar{q}(\gamma/Z)\tilde{G}$ via $\tilde{\chi}_1^0$ ≥ 1

Colours indicate differen

Observed limits at 95%

July 2020

ATLAS Preliminary

√s=13 TeV, 36.1-139 fb⁻¹
All limits at 95% CL

- - - - Expected

——— Observed

——— $b\bar{b}+\phi$ 0L, 36.1 fb⁻¹ EPJC 78 (2018) 18

——— $t\bar{t}+\phi$ 0L, 36.1 fb⁻¹ EPJC 78 (2018) 18

——— $t\bar{t}+\phi$ 1L, 139 fb⁻¹ ATLAS-CONF-2020-003

——— $t\bar{t}+\phi$ 2L, 139 fb⁻¹ ATLAS-CONF-2020-046

Scalar ϕ, $\phi \rightarrow \chi\bar{\chi}$

g_q = 1; g_χ = 1

Dirac DM, m_χ = 1 GeV

√s=13 TeV, 36.1 - 139 fb^{-1} July 2020

$m(\tilde{\chi}_1^0)$ [GeV]

ATLAS Preliminary

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[CONF-2020-002, 1708.08232, 1909.08457]

$\tilde{g} \to q\bar{q}(ll/\nu\nu)\tilde{\chi}_1^0$ via $\tilde{l}/\tilde{\nu}$ 2 l

$\tilde{g} \to q\bar{q}(\tau\tau/\tau\nu/\nu\nu)\tilde{\chi}_1^0$ via $\tilde{\tau}/\tilde{l}$

$\tilde{g} \to q\bar{q}(\gamma/Z)\tilde{G}$ via $\tilde{\chi}_1^0$ ≥ 1

Colours indicate differen

Observed limits at 95% C

σ/σ_{theory}

July 2020

ATLAS Preliminary

√s=13 TeV, 36.1-139 fb^{-1}
All limits at 95% CL

········ Expected

——— Observed

——— $b\bar{b}+\phi$ 0L, 36.1 fb^{-1} EPJC 78 (2018) 18

——— $t\bar{t}+\phi$ 0L, 36.1 fb^{-1} EPJC 78 (2018) 18

——— $t\bar{t}+\phi$ 1L, 139 fb^{-1} ATLAS-CONF-2020-003

$\sigma_{WIMP-nucleon}$ [cm^2]

ATLAS Preliminary

$B_{inv} < 0.11$

√s = 13 TeV, 139 fb^{-1}

All limits at 90% CL

Higgs Portal   Other experiments

Scalar WIMP   DarkSide-50

Majorana WIMP   LUX

                     PandaX-II

Xenon1T

m_{WIMP} [GeV]

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: May 2020

$\int \mathcal{L}\, dt = (3.2 - 139)\ \text{fb}^{-1}$ $\sqrt{s} = 8, 13$ TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt[\text{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	$0\ e, \mu$	$1 - 4$ j	Yes	36.1	M_D 7.7 TeV	$n = 2$	1711.03301
	ADD non-resonant $\gamma\gamma$	$2\ \gamma$	–	–	36.7	M_S 8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	37.0	M_{th} 8.9 TeV	$n = 6$	1703.09127
	ADD BH high $\sum p_T$	$\geq 1\ e, \mu$	≥ 2 j	–	3.2	M_{th} 8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	$2\ \gamma$	–	–	36.7	G_{KK} mass 4.1 TeV	$k/\overline{M}_{Pl} = 0.1$	1707.04147
	Bulk RS $G_{KK} \to WW/ZZ$	multi-channel			36.1	G_{KK} mass 2.3 TeV	$k/\overline{M}_{Pl} = 1.0$	1808.02380
	Bulk RS $G_{KK} \to WV \to \ell\nu qq$	$1\ e, \mu$	2 j / 1 J	Yes	139	G_{KK} mass 2.0 TeV	$k/\overline{M}_{Pl} = 1.0$	2004.14636
	Bulk RS $g_{KK} \to tt$	$1\ e, \mu$	≥ 1 b, ≥ 1J/2j	Yes	36.1	g_{KK} mass 3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	$1\ e, \mu$	≥ 2 b, ≥ 3 j	Yes	36.1	KK mass 1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	1803.09678
Gauge bosons	SSM $Z' \to \ell\ell$	$2\ e, \mu$	–	–	139	Z' mass 5.1 TeV		1903.06248
	SSM $Z' \to \tau\tau$	$2\ \tau$	–	–	36.1	Z' mass 2.42 TeV		1709.07242
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	Z' mass 2.1 TeV		1805.09299
	Leptophobic $Z' \to tt$	$0\ e, \mu$	≥ 1 b, ≥ 2 J	Yes	139	Z' mass 4.1 TeV	$\Gamma/m = 1.2\%$	2005.05138
	SSM $W' \to \ell\nu$	$1\ e, \mu$	–	Yes	139	W' mass 6.0 TeV		1906.05609
	SSM $W' \to \tau\nu$	$1\ \tau$	–	Yes	36.1	W' mass 3.7 TeV		1801.06992
	HVT $W' \to WZ \to \ell\nu qq$ model B	$1\ e, \mu$	2 j / 1 J	Yes	139	W' mass 4.3 TeV	$g_V = 3$	2004.14636
	HVT $V' \to WV \to qqqq$ model B	$0\ e, \mu$	2 J	–	139	V' mass 3.8 TeV	$g_V = 3$	1906.08589
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	V' mass 2.93 TeV	$g_V = 3$	1712.06518
	HVT $W' \to WH$ model B	$0\ e, \mu$	≥ 1 b, ≥ 2 J		139	W' mass 3.2 TeV	$g_V = 3$	CERN-EP-2020-073
	LRSM $W_R \to tb$	multi-channel			36.1	W_R mass 3.25 TeV		1807.10473
	LRSM $W_R \to \mu N_R$	$2\ \mu$	1 J	–	80	W_R mass 5.0 TeV	$m(N_R) = 0.5$ TeV, $g_L = g_R$	1904.12679
CI	CI $qqqq$	–	2 j	–	37.0	Λ 21.8 TeV η_{LL}^-		1703.09127
	CI $\ell\ell qq$	$2\ e, \mu$	–	–	139	Λ 35.8 TeV η_{LL}^-		CERN-EP-2020-066
	CI $tttt$	$\geq 1\ e, \mu$	≥ 1 b, ≥ 1 j	Yes	36.1	Λ 2.57 TeV	$|C_{4t}| = 4\pi$	1811.02305
DM	Axial-vector mediator (Dirac DM)	$0\ e, \mu$	$1 - 4$ j	Yes	36.1	m_{med} 1.55 TeV	g_q=0.25, g_χ=1.0, $m(\chi)$ = 1 GeV	1711.03301
	Colored scalar mediator (Dirac DM)	$0\ e, \mu$	$1 - 4$ j	Yes	36.1	m_{med} 1.67 TeV	g=1.0, $m(\chi)$ = 1 GeV	1711.03301
	$VV\chi\chi$ EFT (Dirac DM)	$0\ e, \mu$	1 J, ≤ 1 j	Yes	3.2	M_* 700 GeV	$m(\chi) < 150$ GeV	1608.02372
	Scalar reson. $\phi \to t\chi$ (Dirac DM)	$0\text{-}1\ e, \mu$	1 b, 0-1 J	Yes	36.1	m_ϕ 3.4 TeV	$y = 0.4$, $\lambda = 0.2$, $m(\chi) = 10$ GeV	1812.09743
LQ	Scalar LQ 1st gen	1,2 e	≥ 2 j	Yes	36.1	LQ mass 1.4 TeV	$\beta = 1$	1902.00377
	Scalar LQ 2nd gen	$1,2\ \mu$	≥ 2 j	Yes	36.1	LQ mass 1.56 TeV	$\beta = 1$	1902.00377
	Scalar LQ 3rd gen	$2\ \tau$	2 b	–	36.1	LQ_3^u mass 1.03 TeV	$\mathcal{B}(LQ_3^u \to b\tau) = 1$	1902.08103
	Scalar LQ 3rd gen	$0\text{-}1\ e, \mu$	2 b	Yes	36.1	LQ_3^d mass 970 GeV	$\mathcal{B}(LQ_3^d \to t\tau) = 0$	1902.08103
Heavy quarks	VLQ $TT \to Ht/Zt/Wb + X$	multi-channel			36.1	T mass 1.37 TeV	SU(2) doublet	1808.02343
	VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	B mass 1.34 TeV	SU(2) doublet	1808.02343
	VLQ $T_{5/3} T_{5/3} | T_{5/3} \to Wt + X$	2(SS)/$\geq$3 e, μ	≥ 1 b, ≥ 1 j	Yes	36.1	$T_{5/3}$ mass 1.64 TeV	$\mathcal{B}(T_{5/3} \to Wt) = 1$, $c(T_{5/3} Wt) = 1$	1807.11883
	VLQ $Y \to Wb + X$	$1\ e, \mu$	≥ 1 b, ≥ 1j	Yes	36.1	Y mass 1.85 TeV	$\mathcal{B}(Y \to Wb)= 1$, $c_R(Wb) = 1$	1812.07343
	VLQ $B \to Hb + X$	$0\ e, \mu, 2\ \gamma$	≥ 1 b, ≥ 1j	Yes	79.8	B mass 1.21 TeV	$\kappa_B = 0.5$	ATLAS-CONF-2018-024
	VLQ $QQ \to WqWq$	$1\ e, \mu$	≥ 4 j	Yes	20.3	Q mass 690 GeV		1509.04261
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	139	q^* mass 6.7 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1910.08447
	Excited quark $q^* \to q\gamma$	$1\ \gamma$	1 j	–	36.7	q^* mass 5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	36.1	b^* mass 2.6 TeV		1805.09299
	Excited lepton ℓ^*	$3\ e, \mu$	–	–	20.3	ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	$3\ e, \mu, \tau$	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	Type III Seesaw	$1\ e, \mu$	≥ 2 j	Yes	79.8	N^0 mass 560 GeV		ATLAS-CONF-2018-020
	LRSM Majorana ν	$2\ \mu$	2 j	–	36.1	N_R mass 3.2 TeV	$m(W_R) = 4.1$ TeV, $g_L = g_R$	1809.11105
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	36.1	$H^{\pm\pm}$ mass 870 GeV	DY production	1710.09748
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	$3\ e, \mu, \tau$	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$	1411.2921
	Multi-charged particles	–	–	–	36.1	multi-charged particle mass 1.22 TeV	DY production, $|q| = 5e$	1812.03673
	Magnetic monopoles	–	–	–	34.4	monopole mass 2.37 TeV	DY production, $|g| = 1g_D$, spin 1/2	1905.10130

$\sqrt{s} = 8$ TeV $\sqrt{s} = 13$ TeV partial data $\sqrt{s} = 13$ TeV full data

Mass scale [TeV] 10^{-1} 1   10

7

*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

Where is the new physics?

- We **know** it's out there

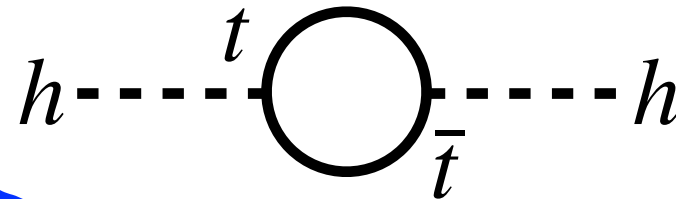# Where is the new physics?

- We **know** it's out there

Dark matter?

Where is the new physics?

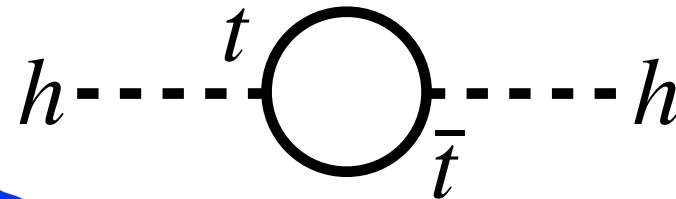- We **know** it's out there

Dark matter?

Higgs mass too light?

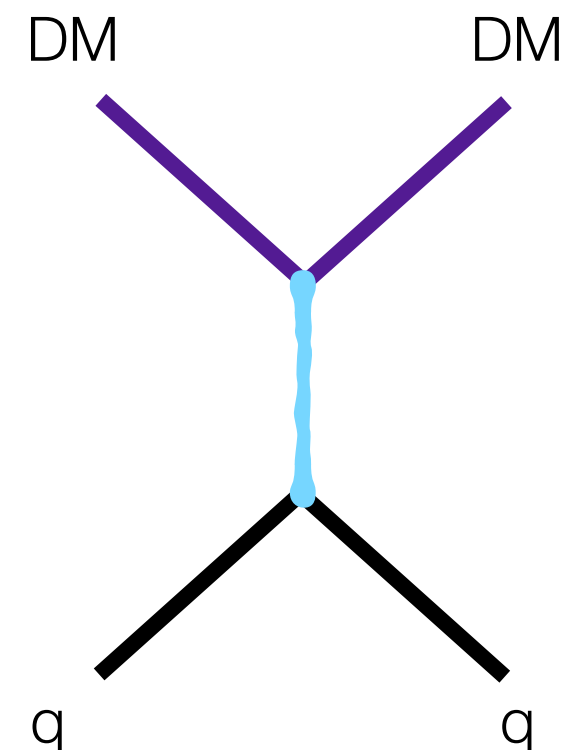$$h \; \text{---} \; \overset{t}{\underset{\bar{t}}{\bigcirc}} \; \text{---} \; h$$

Where is the new physics?

- We **know** it's out there

Dark matter?

Higgs mass too light?

$$h \text{-----} t \bigcirc \bar{t} \text{-----} h$$

Where is all the antimatter?

Where is the new physics?
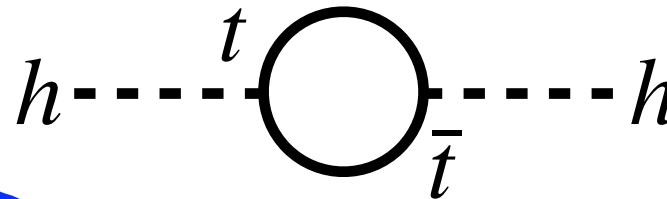
- We **know** it's out there

Dark matter?

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$h \, \text{-} \, \text{-} \, \text{-} \, \text{-} \, \overset{t}{\bigcirc}_{\bar{t}} \, \text{-} \, \text{-} \, \text{-} \, \text{-} \, h$

Where is all the antimatter?

- So why haven't we seen it yet? A couple possible reasons:

  1. It is above the scale accessible by the LHC

  2. It isn't where we have been looking

Where is the new physics?
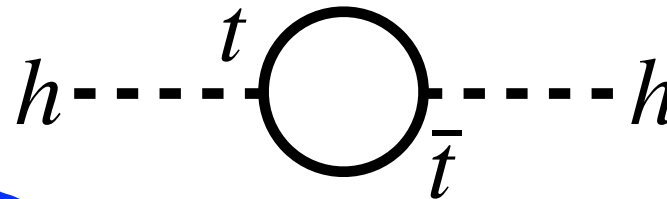
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$$h\text{-----}\overset{t}{\underset{\bar{t}}{\bigcirc}}\text{-----}h$$

Where is all the antimatter?

- So why haven't we seen it yet? A couple possible reasons:

    1. It is above the scale accessible by the LHC

    2. It isn't where we have been looking

- In case 1, not much we can do about it. But we have all the power in case 2! Need to understand where else to look.

How we should read our limits

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

ATLAS Preliminary

Status: May 2020

$\int \mathcal{L}\, dt = (3.2 - 139)\ \text{fb}^{-1}$ $\sqrt{s}$ = 8, 13 TeV

Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt\,[\text{fb}^{-1}]$	Limit		Reference
Axial-vector mediator (Dirac DM)	0 e, μ	1 − 4 j	Yes	36.1	m_{med}	1.55 TeV	g_q=0.25, g_χ=1.0, $m(\chi)$ = 1 GeV	1711.03301
Colored scalar mediator (Dirac DM)	0 e, μ	1 − 4 j	Yes	36.1	m_{med}	1.67 TeV	g=1.0, $m(\chi)$ = 1 GeV	1711.03301
$VV\chi\chi$ EFT (Dirac DM)	0 e, μ	1 J, ≤ 1 j	Yes	3.2	M_* 700 GeV		$m(\chi) < 150$ GeV	1608.02372
Scalar reson. $\phi \to t\chi$ (Dirac DM)	0-1 e, μ	1 b, 0-1 J	Yes	36.1	m_ϕ	3.4 TeV	y = 0.4, λ = 0.2, $m(\chi)$ = 10 GeV	1812.09743

- Remember: we use really simple models and scenarios for these plots

9

How we should read our limits

ATLAS
$\sqrt{s} = 13$ TeV, 36.1 fb^{-1}
Axial-Vector Mediator
Dirac Fermion DM
$g_q = 0.25$, $g_\chi = 1.0$
95% CL limits

- Expected limit ± 2 σ_{exp}
- Expected limit (± 1σ_{exp})
- Observed limit (± 1$\sigma_{theory}^{PDF, scale}$)
- Perturbativity Limit
- Relic Density (MadDM)
- ATLAS $\sqrt{s} = 13$ TeV, 3.2 fb^{-1}

$m_{Z_A} = 2\, m_\chi$

axes: m_χ [GeV], m_{Z_A} [GeV]

- Remember: we use really simple models and scenarios for these plots

  - Basic t-channel simplified model

DM   DM

q   q

9

How we should read our limits

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: May 2020

ATLAS Preliminary

$\int \mathcal{L}\, dt = (3.2 - 139)\ \text{fb}^{-1}$ $\sqrt{s}$ = 8, 13 TeV

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- Remember: we use really simple models and scenarios for these plots

  - Basic t-channel simplified model

  - Only relevant couplings active

9

How we should read our limits

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

ATLAS Preliminary

Status: May 2020

$\int \mathcal{L} \, dt = (3.2 - 139) \, fb^{-1}$ $\sqrt{s} = 8, 13$ TeV

Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L} \, dt[fb^{-1}]$	Limit		Reference
Axial-vector mediator (Dirac DM)	0 e, μ	1 − 4 j	Yes	36.1	m_{med}	1.55 TeV	g_q=0.25, g_χ=1.0, $m(\chi)$ = 1 GeV	1711.03301
Colored scalar mediator (Dirac DM)	0 e, μ	1 − 4 j	Yes	36.1	m_{med}	1.67 TeV	g=1.0, $m(\chi)$ = 1 GeV	1711.03301
$VV\chi\chi$ EFT (Dirac DM)	0 e, μ	1 J, ≤ 1 j	Yes	3.2	M_* 700 GeV		$m(\chi)$ = 150 GeV	1608.02372
Scalar reson. $\phi \to t\chi$ (Dirac DM)	0-1 e, μ	1 b, 0-1 J	Yes	36.1	m_ϕ	3.4 TeV	y = 0.4, λ = 0.2, $m(\chi)$ = 10 GeV	1812.09743

- Remember: we use really simple models and scenarios for these plots
  - Basic t-channel simplified model
  - Only relevant couplings active
  - Best limit at any mass reported

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DM

- Remember: we use really simple models and scenarios for these plots

  - Basic t-channel simplified model

  - Only relevant couplings active

  - Best limit at any mass reported

- There is still lots of room for dark matter, just in more complicated scenarios!

9

What if we've been thinking too simplistically?

How to get the right amount of dark matter in the universe

SM ⬅➡ Some mediator ⬅➡ DM

Freeze-out scenarios:
lots of DM in the early
universe, decouples once
temperature drops
enough

What if we've been thinking too simplistically?

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SM ⬅➡ Some mediator ⬅➡ DM

Freeze-in scenarios: no DM in early universe, mediator and SM in equilibrium. DM sector slowly populated via **very small coupling** to mediator.

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Freeze-in scenarios: no DM in early universe, mediator and SM in equilibrium. DM sector slowly populated via **very small coupling** to mediator.

Still gets you the right relic density

Suppressed decays in dark matter models

q

DM

$\lambda << 1$

[Warning - still super basic/oversimplified]

q

DM

Suppressed decays in dark matter models

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Only decay for Y is to qχ

11
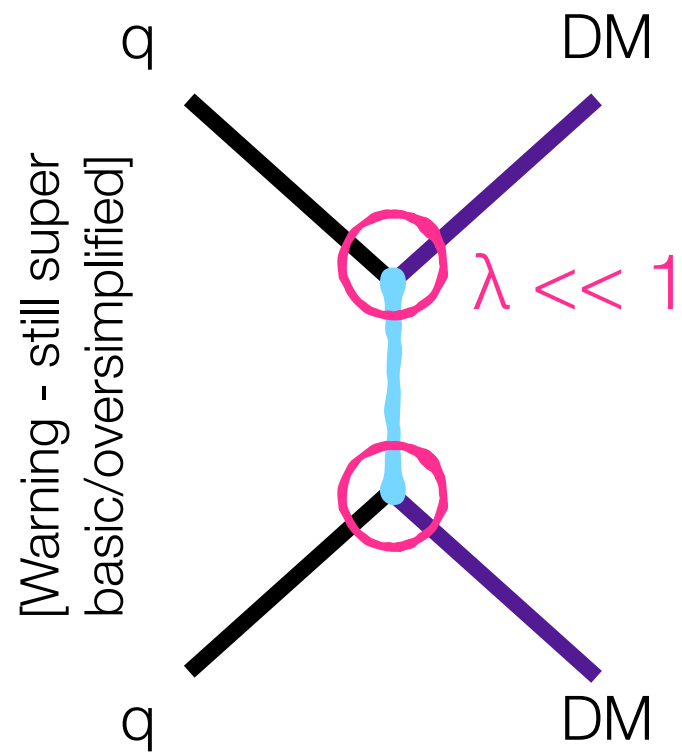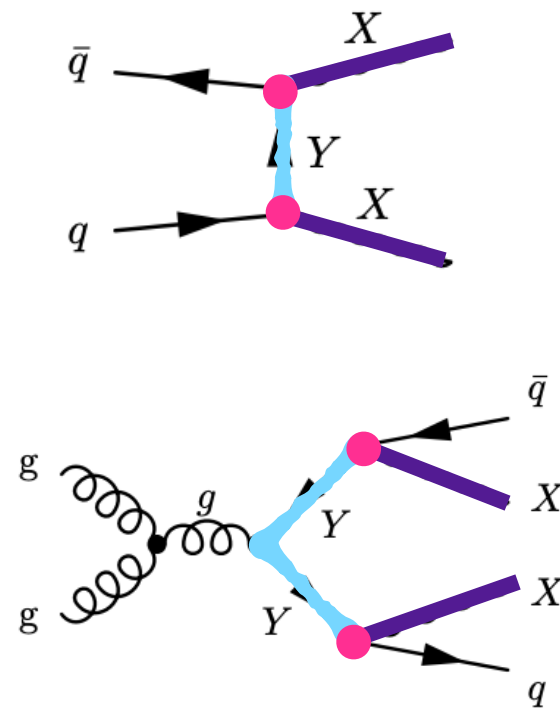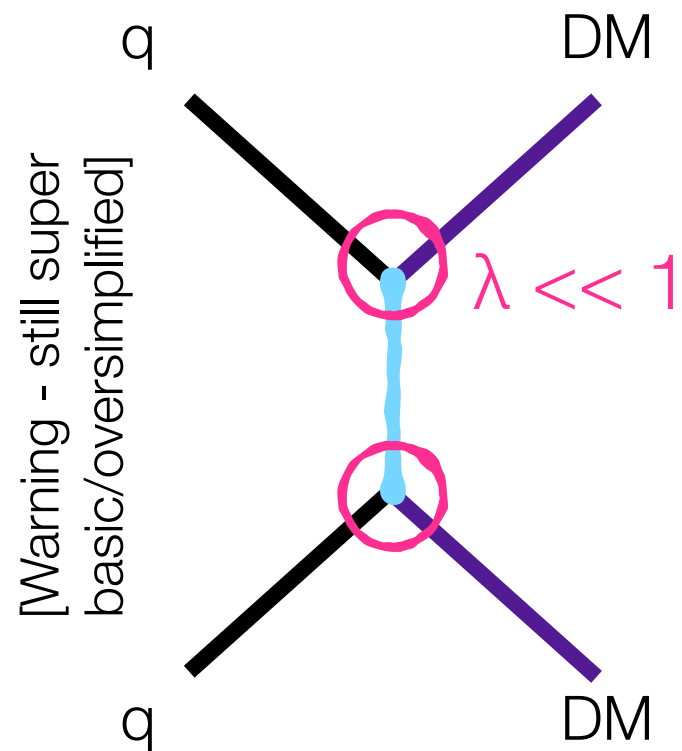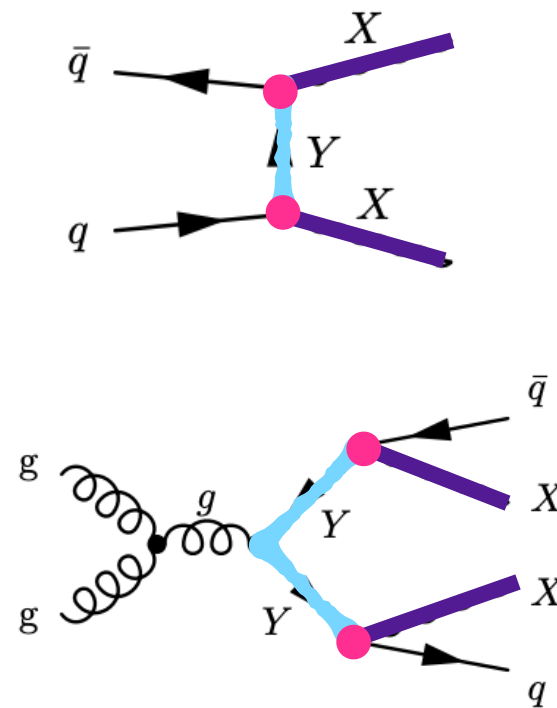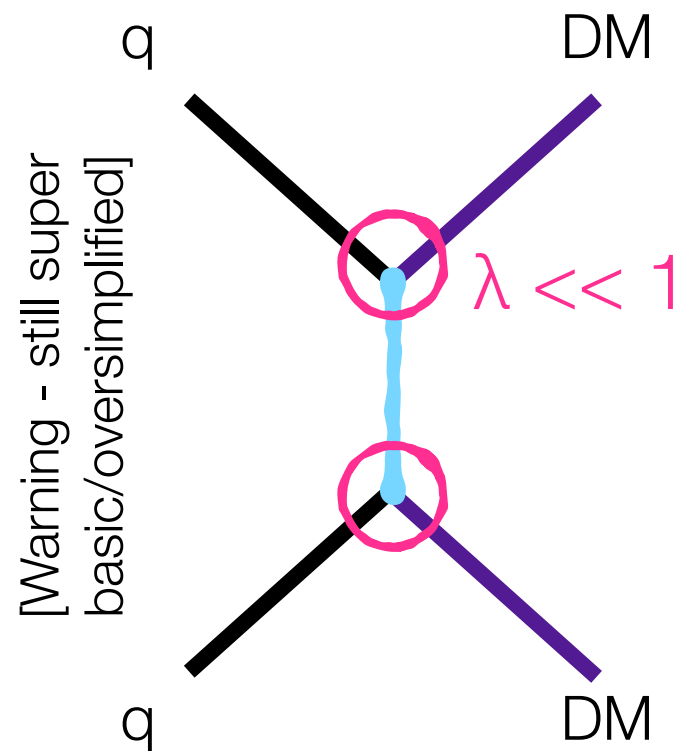
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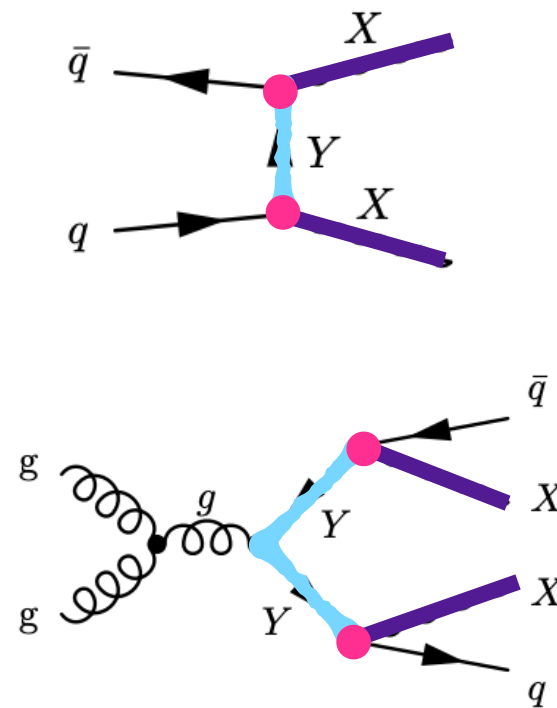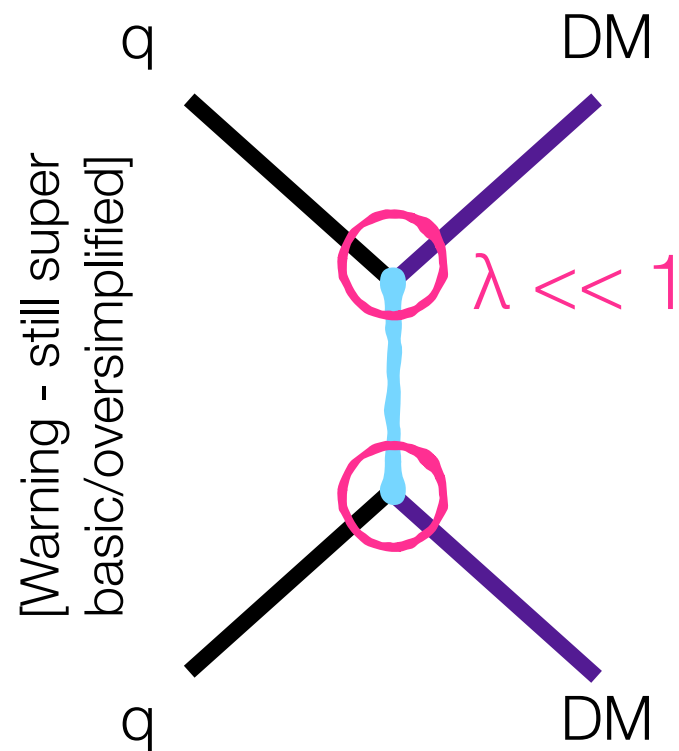
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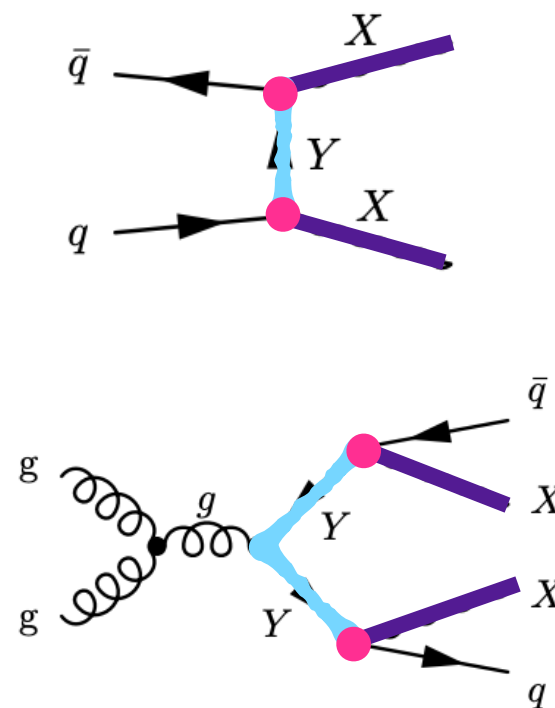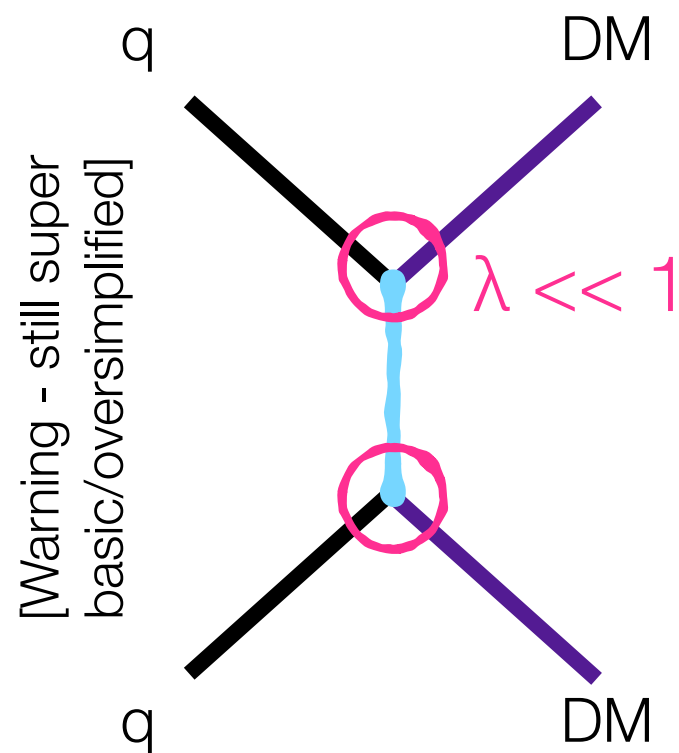
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DM

$\lambda << 1$

q

DM

$\bar{q}$

X

Y

q

X

g

g

g

Y

Y

$\bar{q}$

X

X

q

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Small couplings → small total width → **long lifetimes!**

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λ

0   1

Freeze-in   Conversion-driven freeze-out   Co-annihiliation   Vanilla WIMPs

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λ

0 ————————————————————————————— 1

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11

Long lifetimes and where to find them

Small couplings

e.g. SM lepton flavour violation

tiny

μ → eγ BR < 1e-13

Long lifetimes and where to find them

Small couplings

e.g. SM lepton flavour violation

Limited phase space
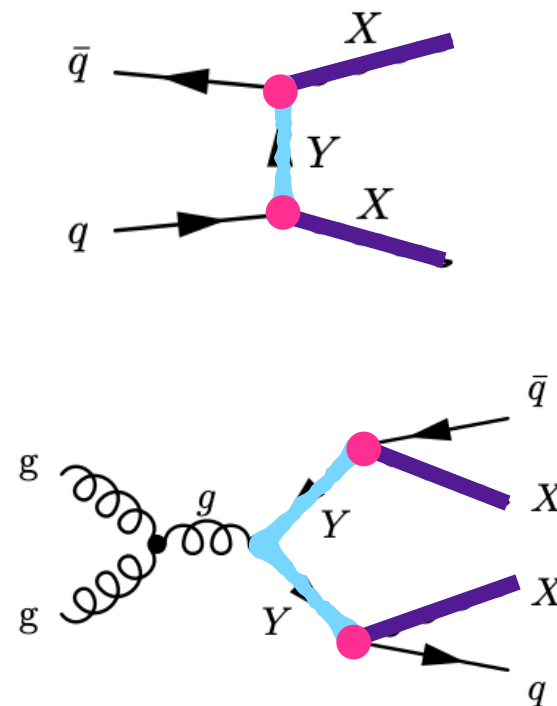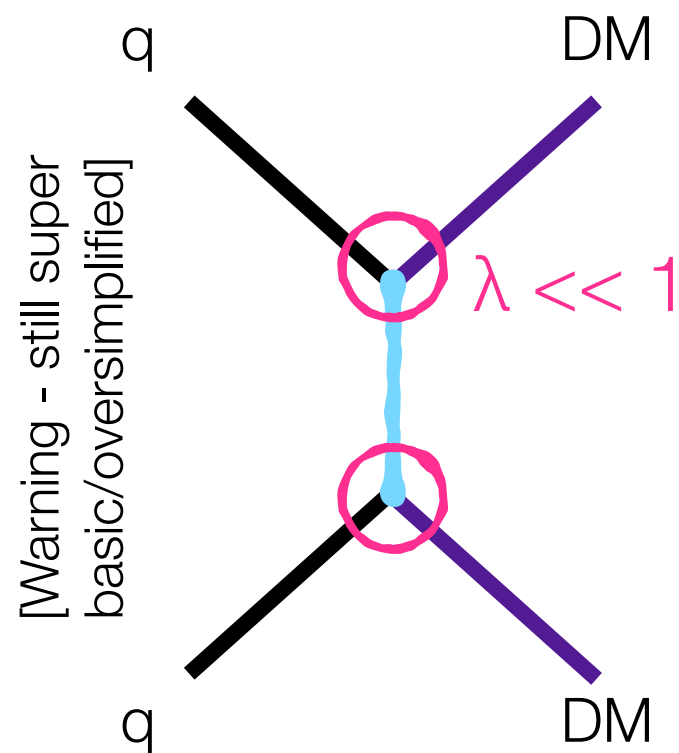
e.g. K_{short} vs K_{long} lifetimes

$K^0_S \rightarrow \pi\pi$

$K^0_L \rightarrow \pi\pi\pi$

Mass of K^0 just a bit larger than mass of three pions

Lifetime 9e-11 s versus 5e-8 s

Long lifetimes and where to find them

Small couplings

e.g. SM lepton flavour violation

Limited phase space

e.g. K_{short} vs K_{long} lifetimes

Decays via heavy particle
e.g. μ to e via off-shell W
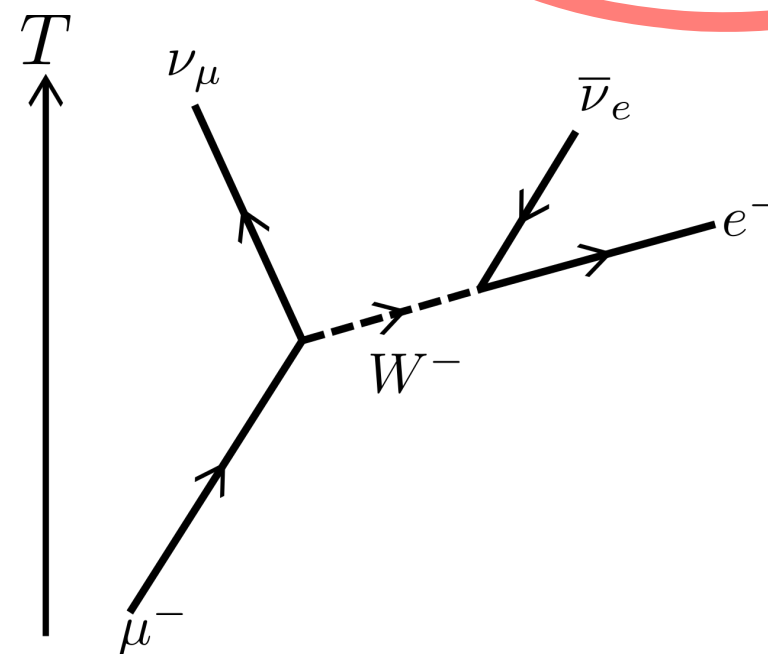
Long lifetimes and where to find them

Small couplings
e.g. our DM
simplified model
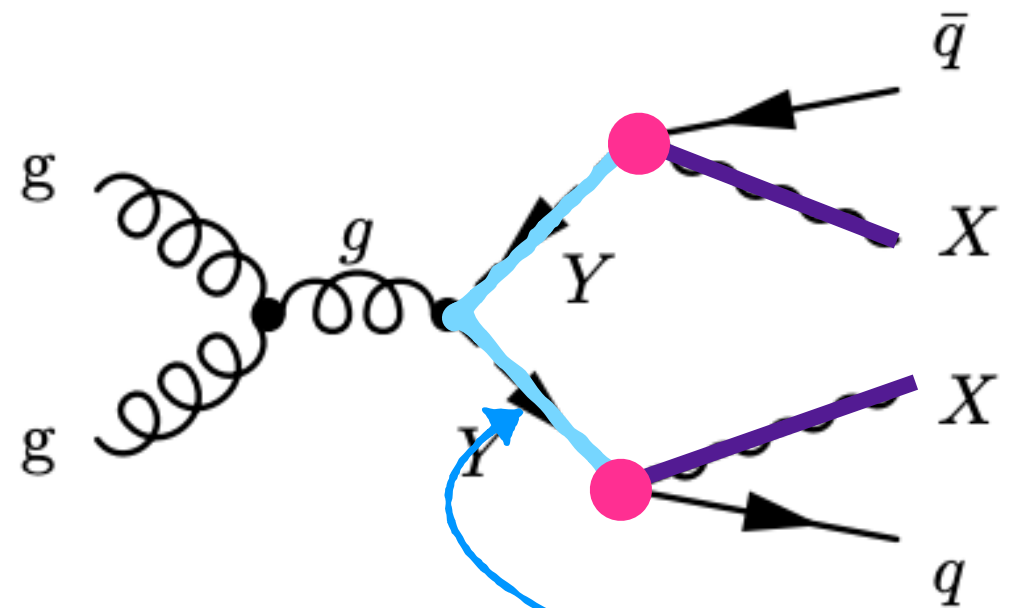
Becomes long-lived
when λ'' is very small

Long lifetimes and where to find them

Small couplings
e.g. our DM simplified model

Limited phase space
e.g. AMSB-style pure Wino LSP

$$m_{\tilde{\chi}_1^\pm} \sim m_{\tilde{\chi}_1^0}$$

p

p

j

$\tilde{\chi}_1^0$

$\tilde{\chi}_1^\pm$

$\tilde{\chi}_1^0$

$\pi^\pm$

arXiv:1712.02118
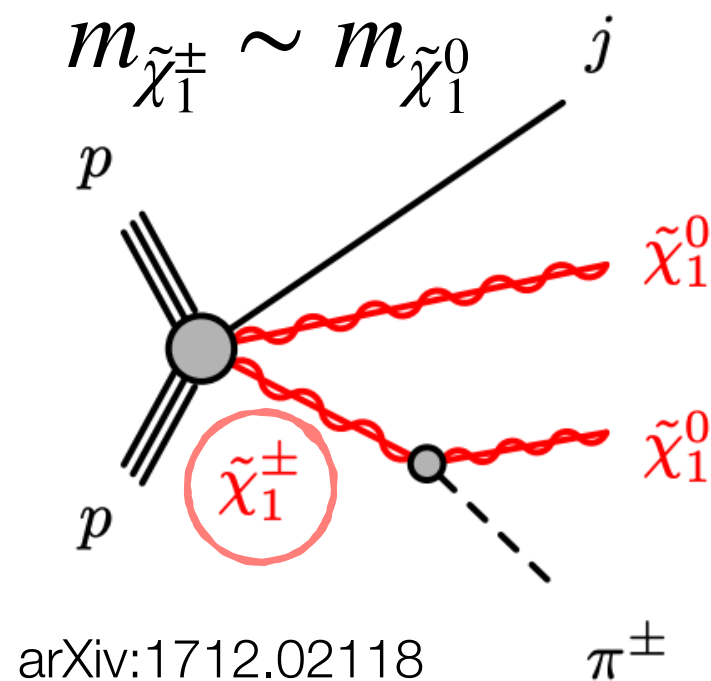
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e.g. heavy neutrinos
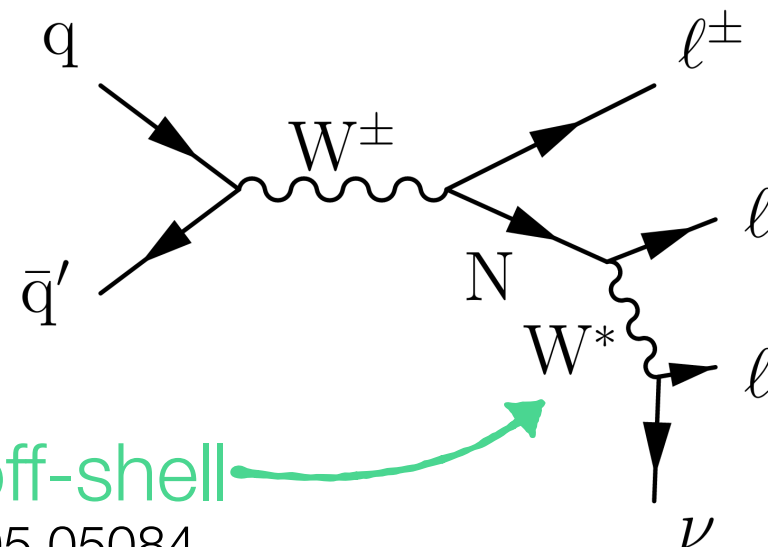
super off-shell

arXiv:1805.05084

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BSM with long lived particles

- **Any model** with small couplings, small mass splittings, or decays via off-shell particles can result in long lived particles (LLPs)

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Hidden sector portals!

Example: scalar *s* mixes with higgs
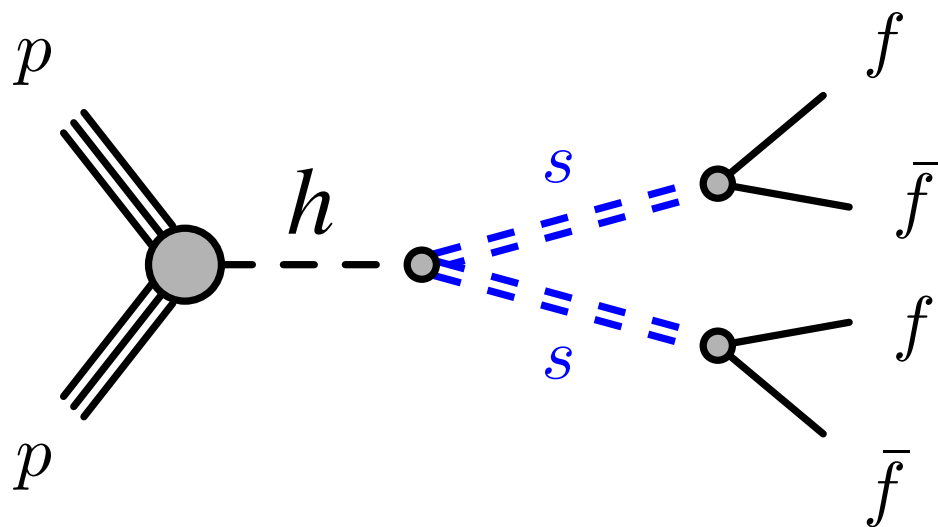
EXOT-2018-61

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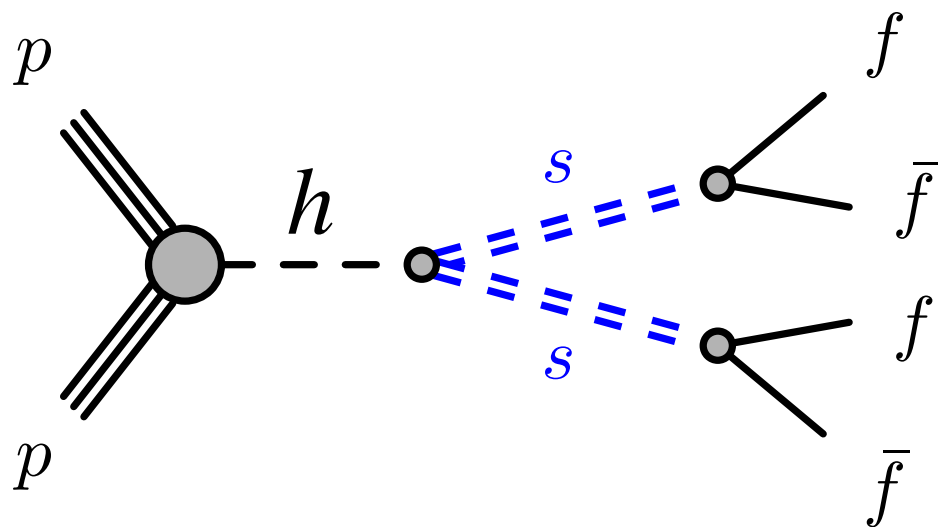
EXOT-2018-61

SUSY!

Example: R-parity violation

(Parts of) the LLP world

R-parity violating SUSY

Portals + broader dark sector (HNLs, axions, Z_d, …)

Dark matter: Asymmetric, freeze-in, co-annihilation, …

Split SUSY, GMSB, compressed EW, …

Long lived particles

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ATLAS Experiment

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ATLAS Experiment

Measuring particles in the ATLAS detector

Muon spectrometer

HCAL

ECAL

Tracker

17
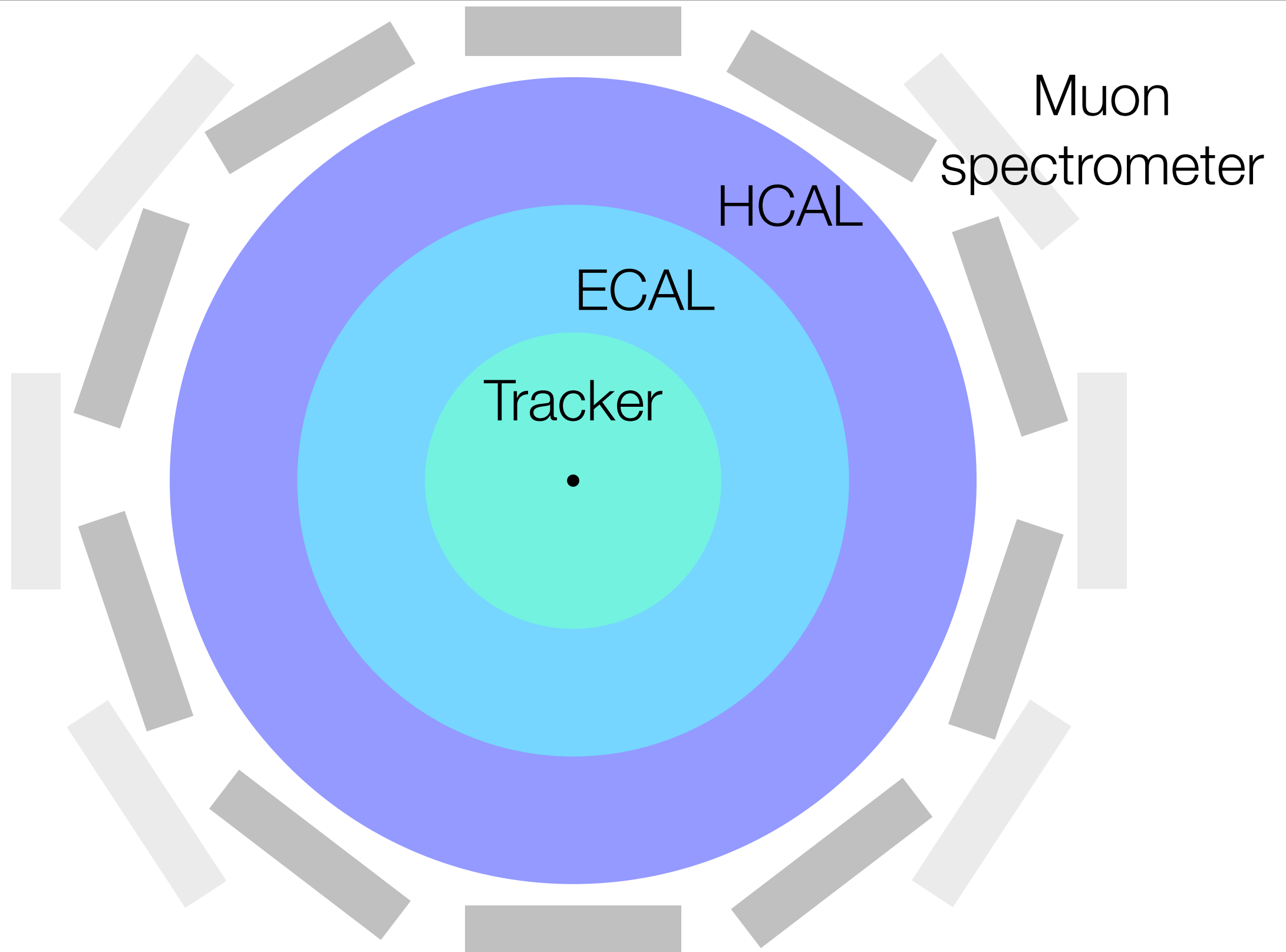
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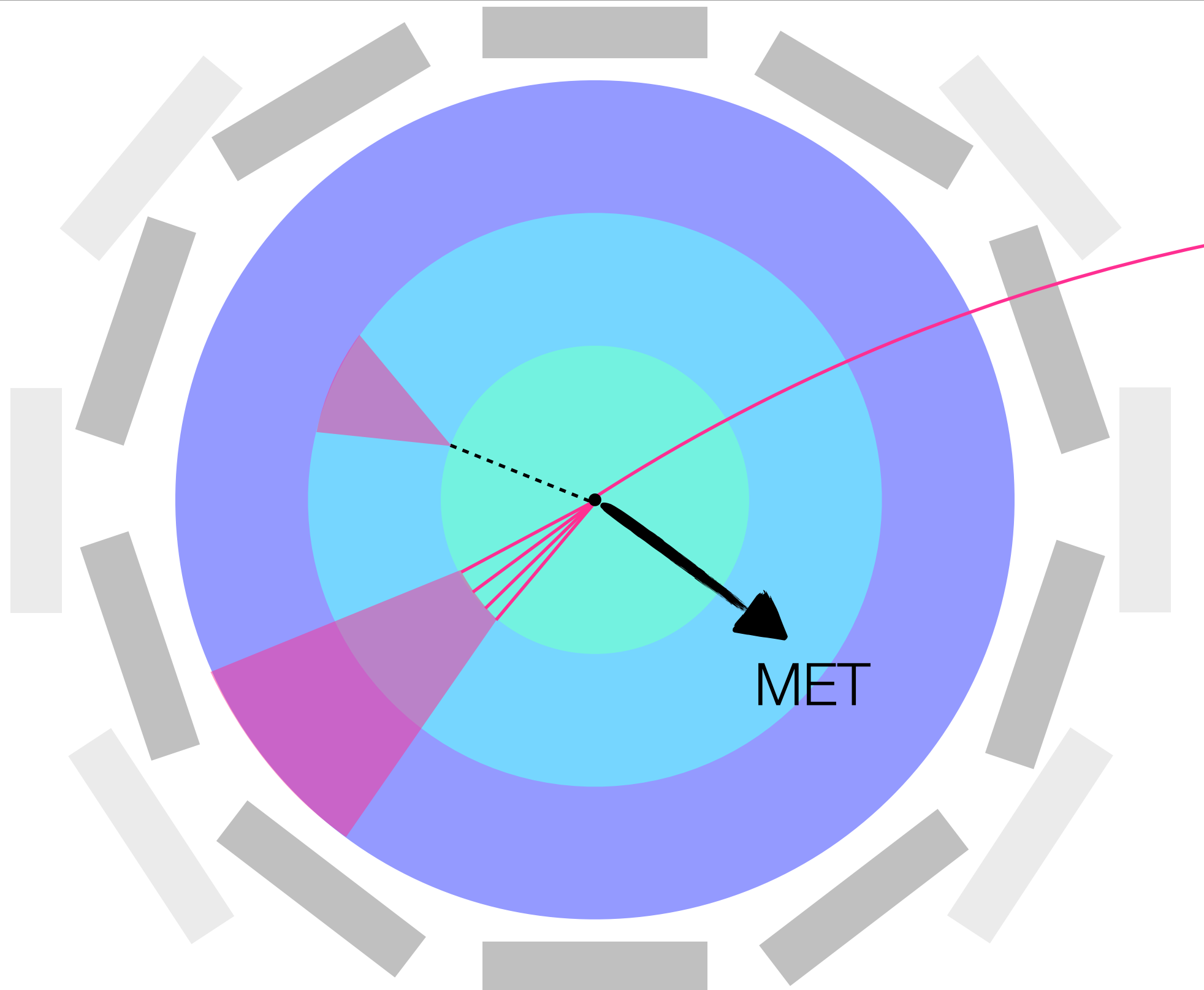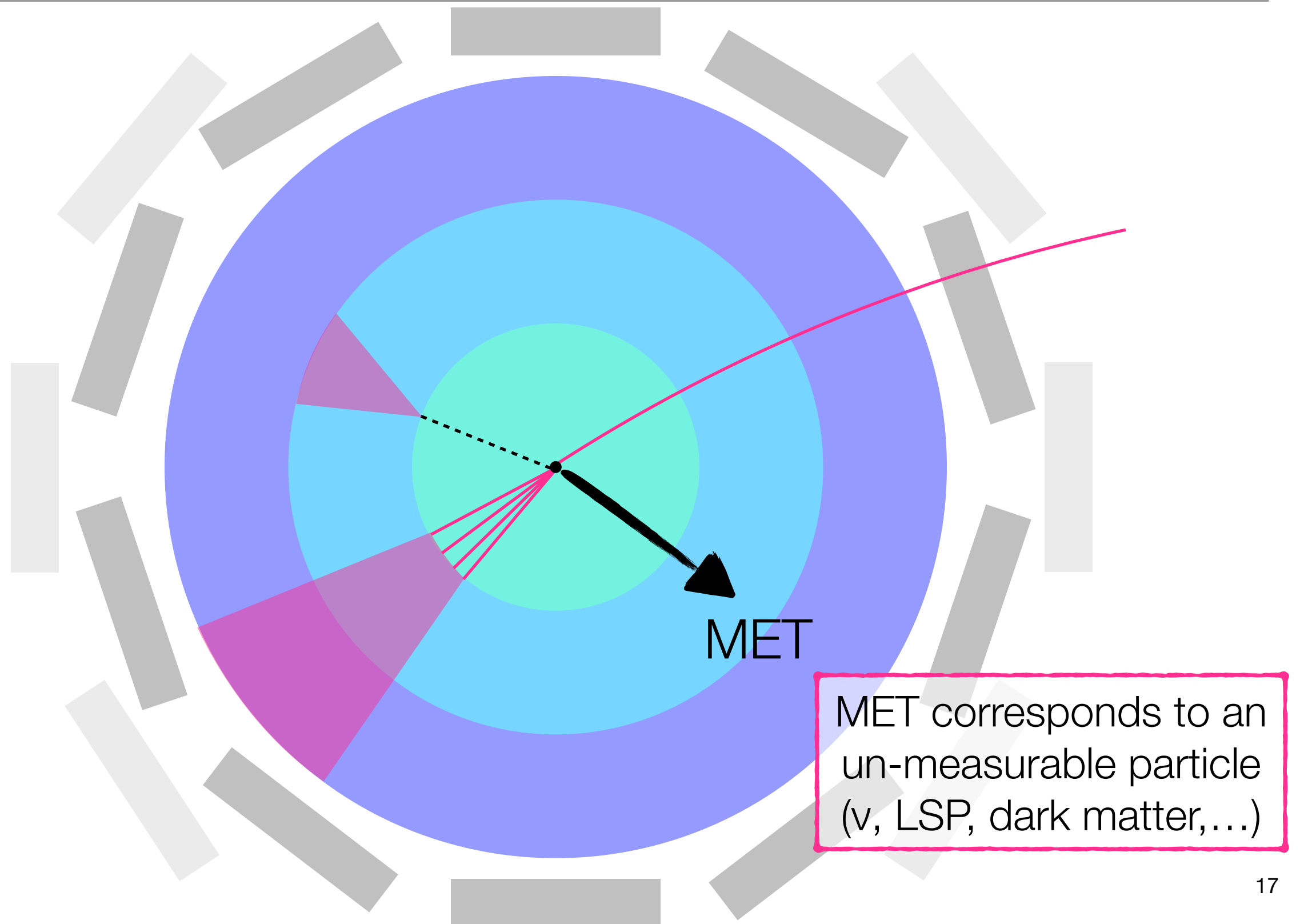
MET

Measuring particles in the ATLAS detector

MET

MET corresponds to an un-measurable particle (ν, LSP, dark matter,…)

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Connecting lifetime to location

Mean distance travelled = $\beta\gamma c\tau$

- $c\tau$ = simple distance metric. Order 30cm for τ = 1 nanosecond

- Lorentz boost $\beta\gamma = p/M$. Ranges from ~ 0.8 or 0.9 for really heavy particles to ~30 for really light ones.

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Values of $\tau \sim 10^{-13}$ to 10^{-7} seconds are "long-lived particles"

Where should we look for particle decays?
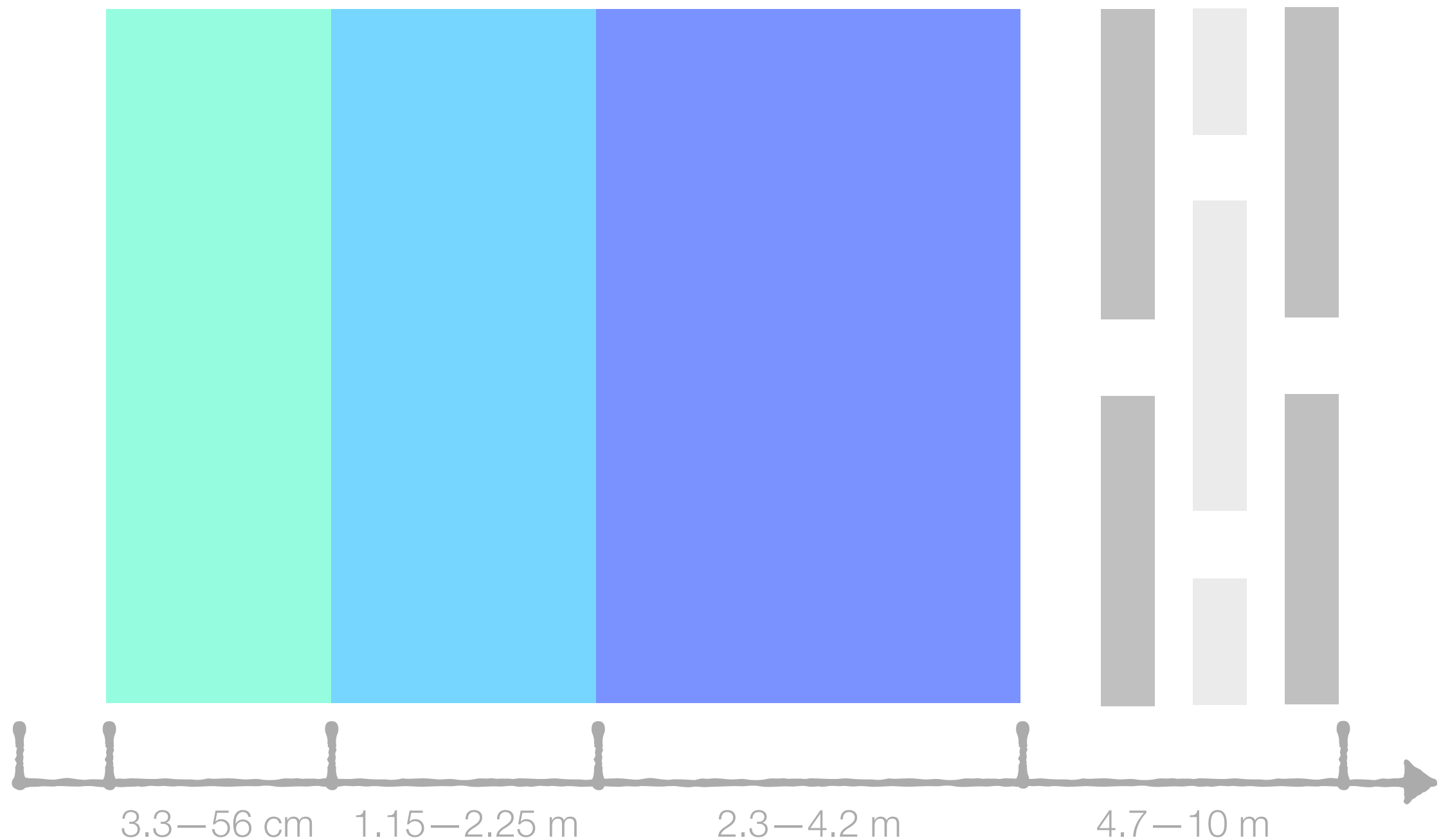
Mean distance travelled = $\beta\gamma c\tau$

3.3—56 cm   1.15—2.25 m   2.3—4.2 m   4.7—10 m

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What if decay
rate looks like
this?

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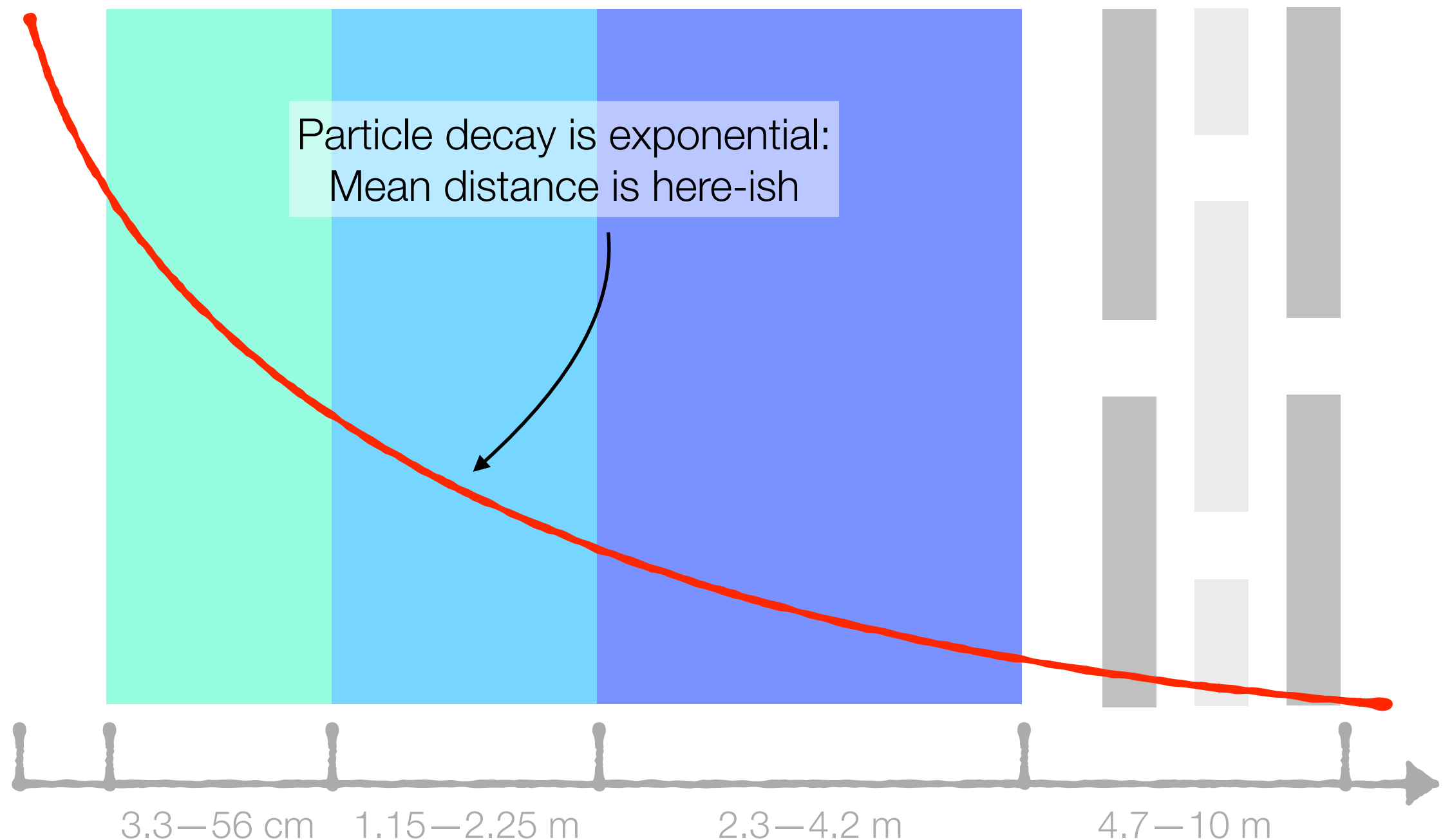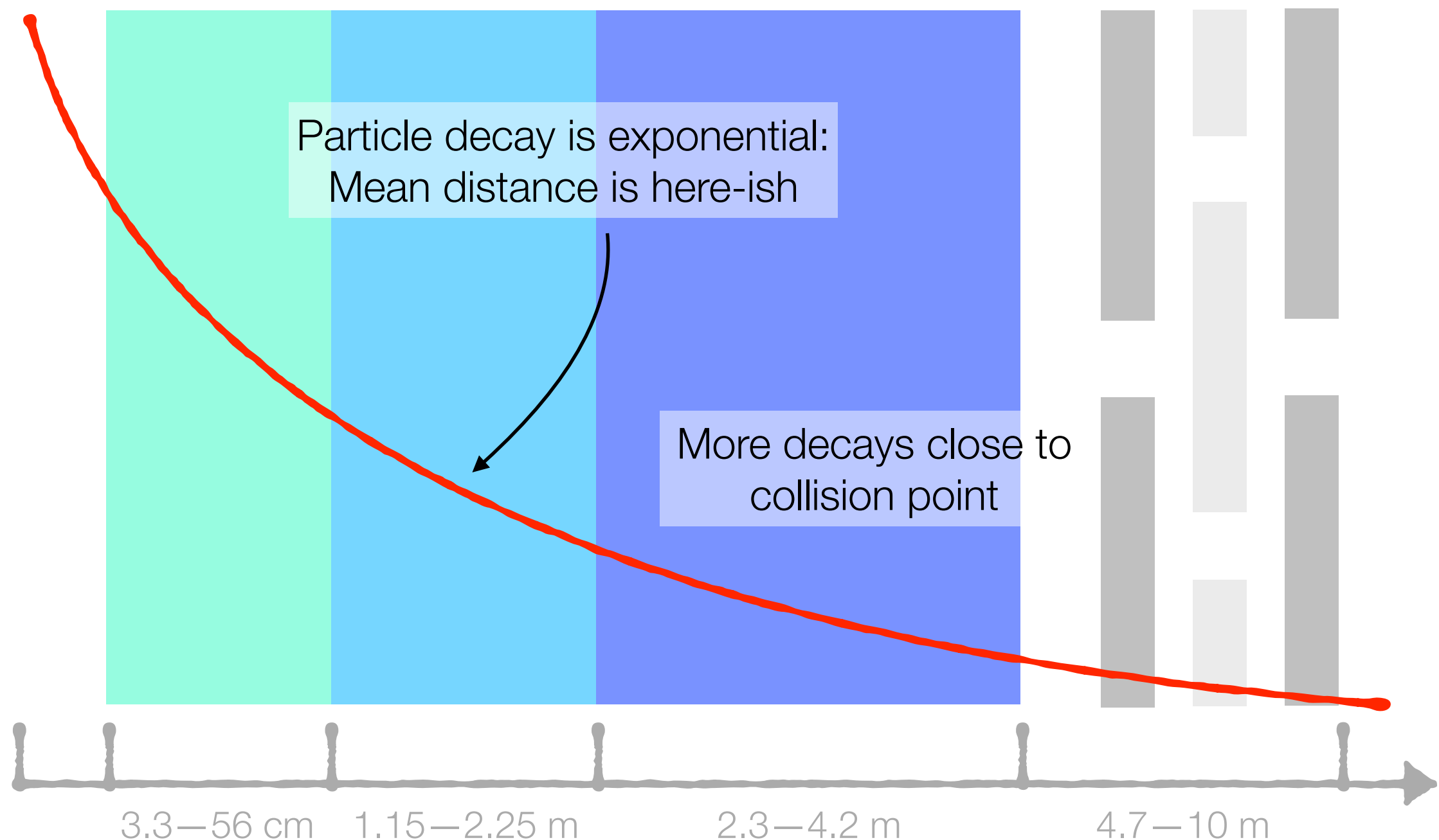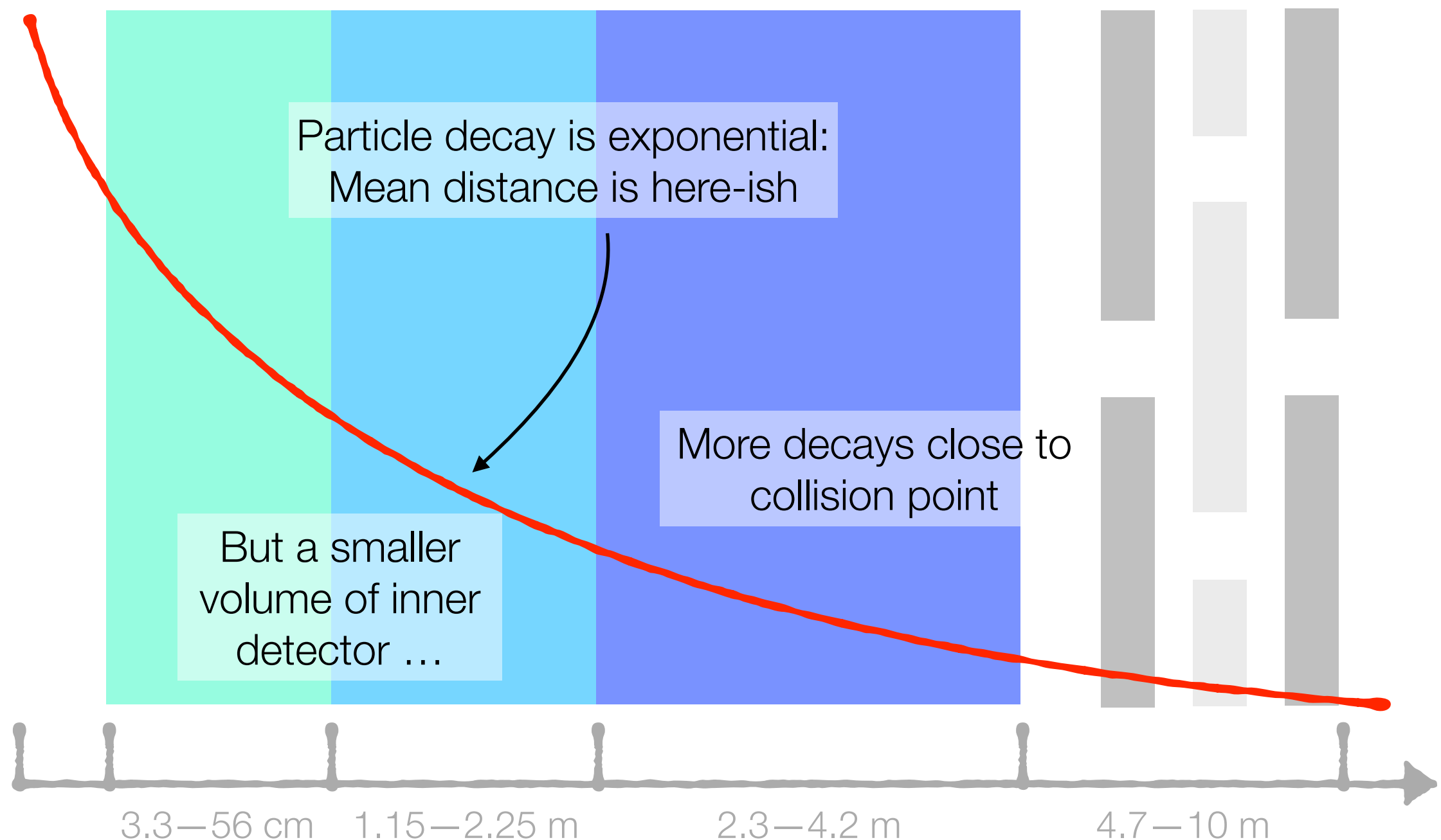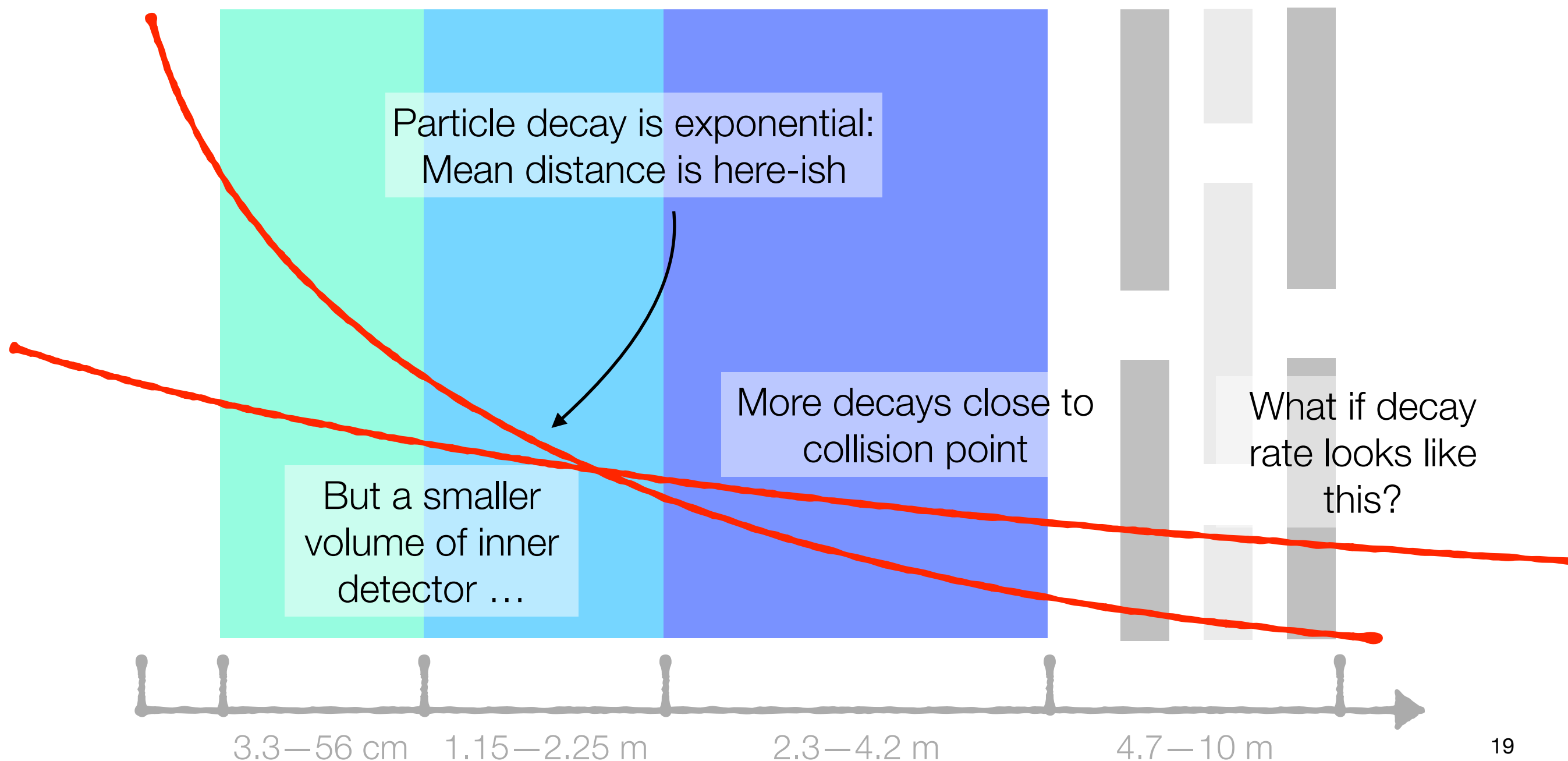
Different detector systems for different targets
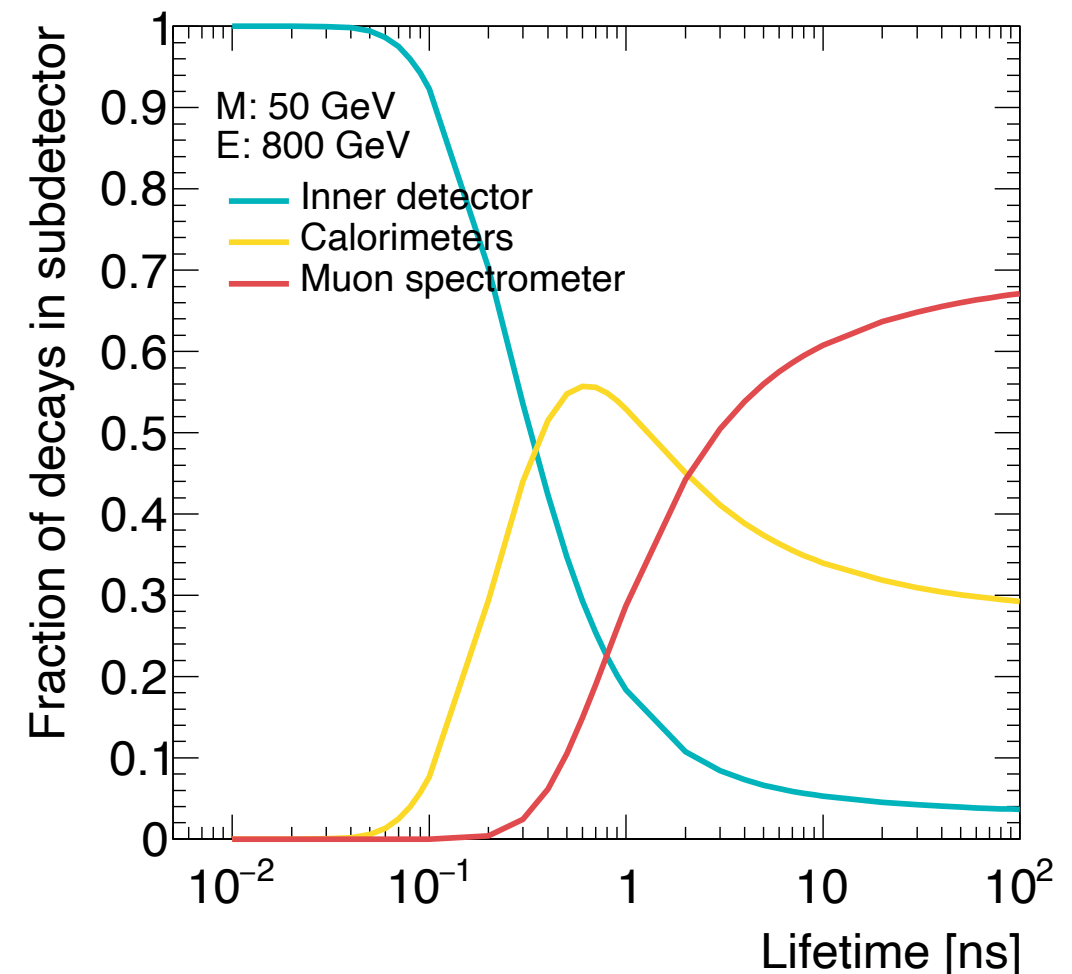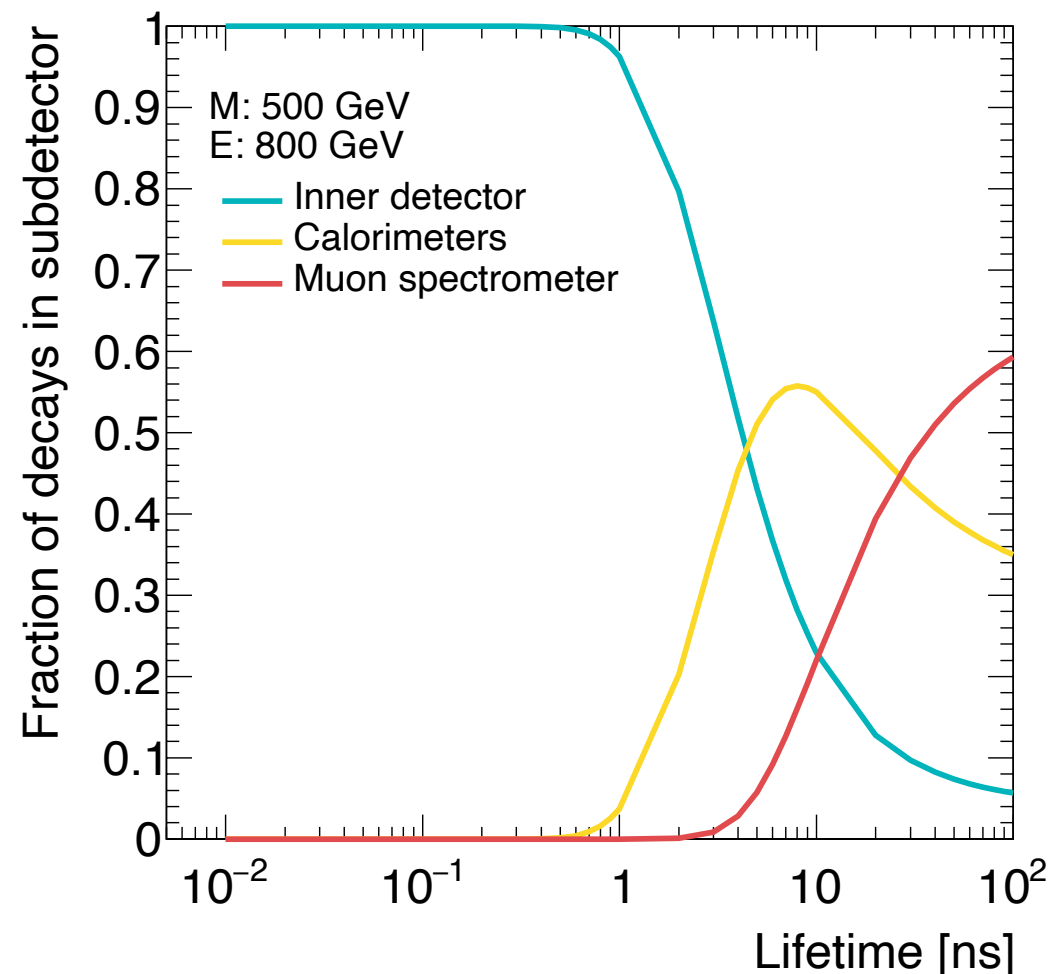
- Lighter particles have higher βγ and so travel farther for the same lifetime

- Muon spectrometer becomes useful for Higgs-portal-style signatures

- For target masses > order 100 GeV (i.e. EW SUSY), **inner detector is critical**

How do we use our detectors for these searches?

Tracking

EM showers

Hadronic showers

Stable charged particles (muons)

Collision point

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Direct detection: charged LLP

Observable track

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For heavy LLPs, can use timing as well

What would new long-lived physics look like?

Muon spectrometer

HCAL

ECAL

Tracker

What would new long-lived physics look like?

stopped particles

displaced leptons

(meta-)stable charged particles

displaced vertex in association with MET, jets, …

disappearing tracks

Higgs-mediated DM

Inspired by Heather Russell

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What makes LLPs so hard?

What makes LLPs so hard?

Triggering

Electrons?? Trigger unsure
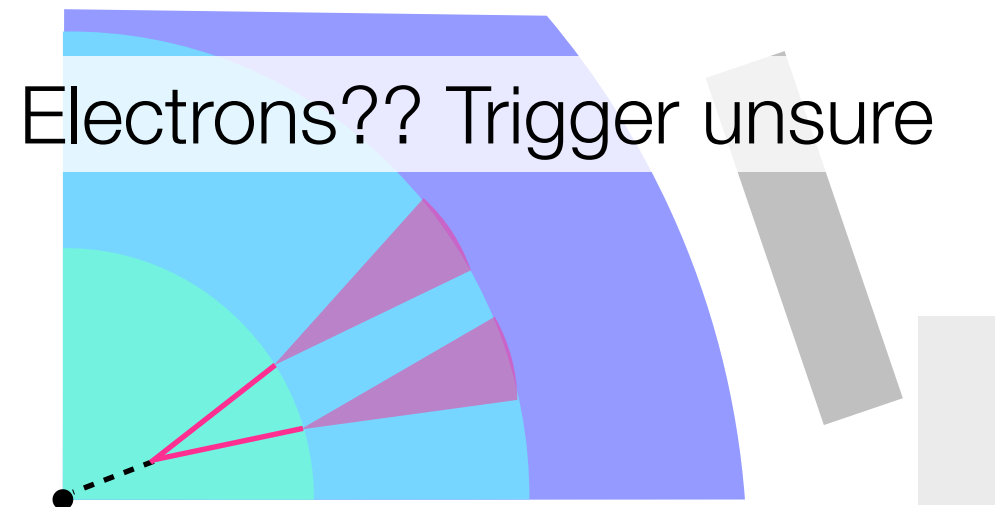
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Large-radius tracking

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Standard tracking will miss it, LRT is slow and bulky

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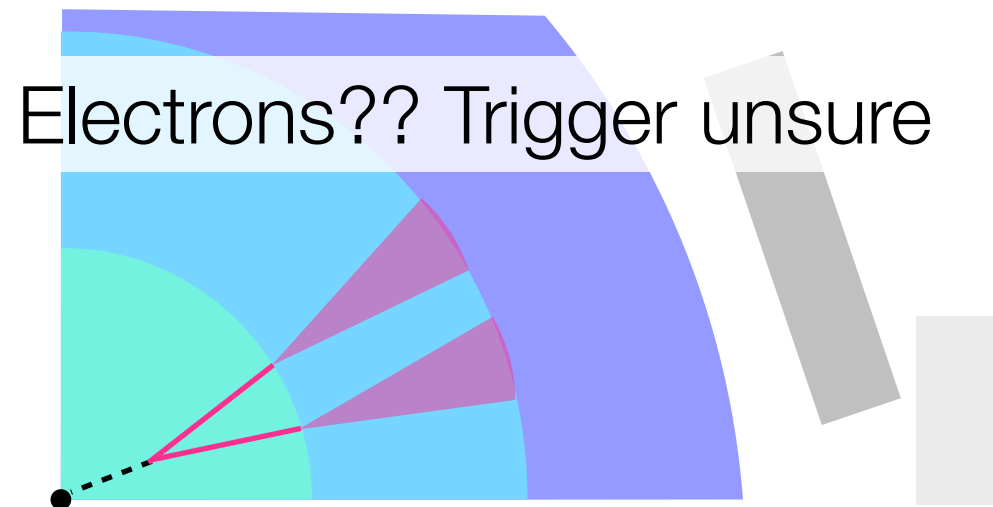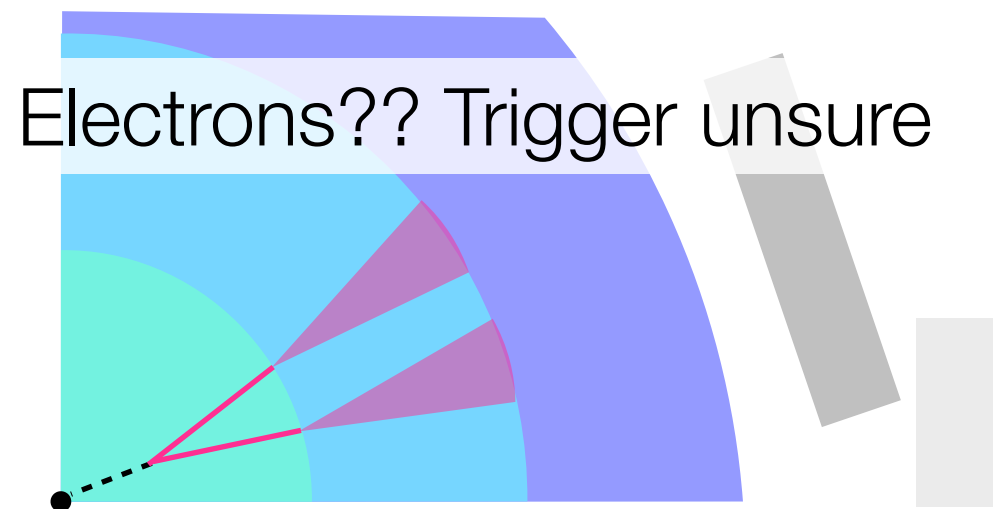
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Data flow

RAW → Standard → Analysis

Event filtering

RAW → LLP reconstruction → Analysis
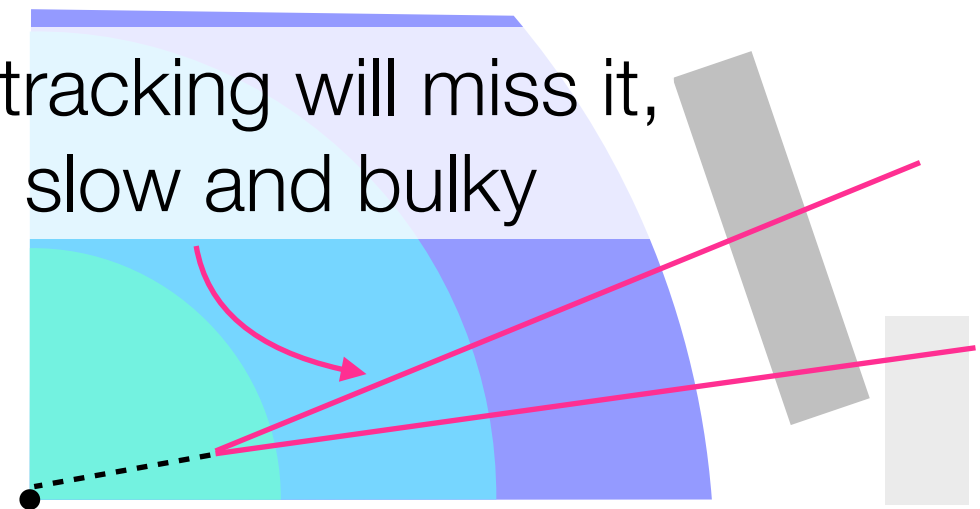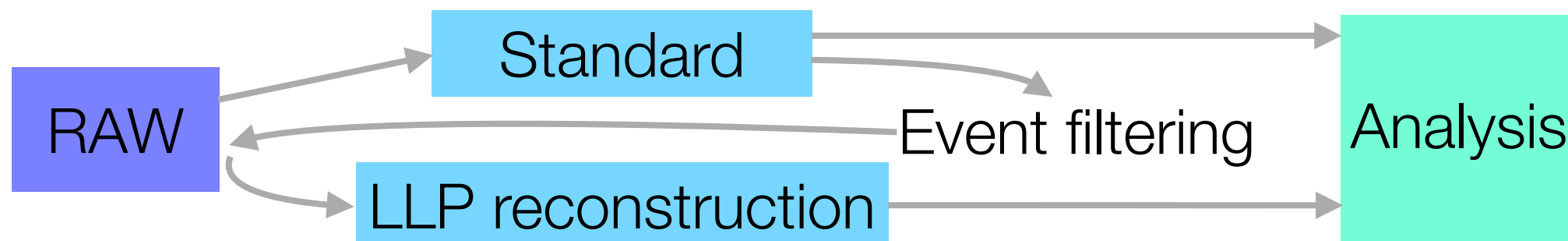
Triggering and long-lived particles

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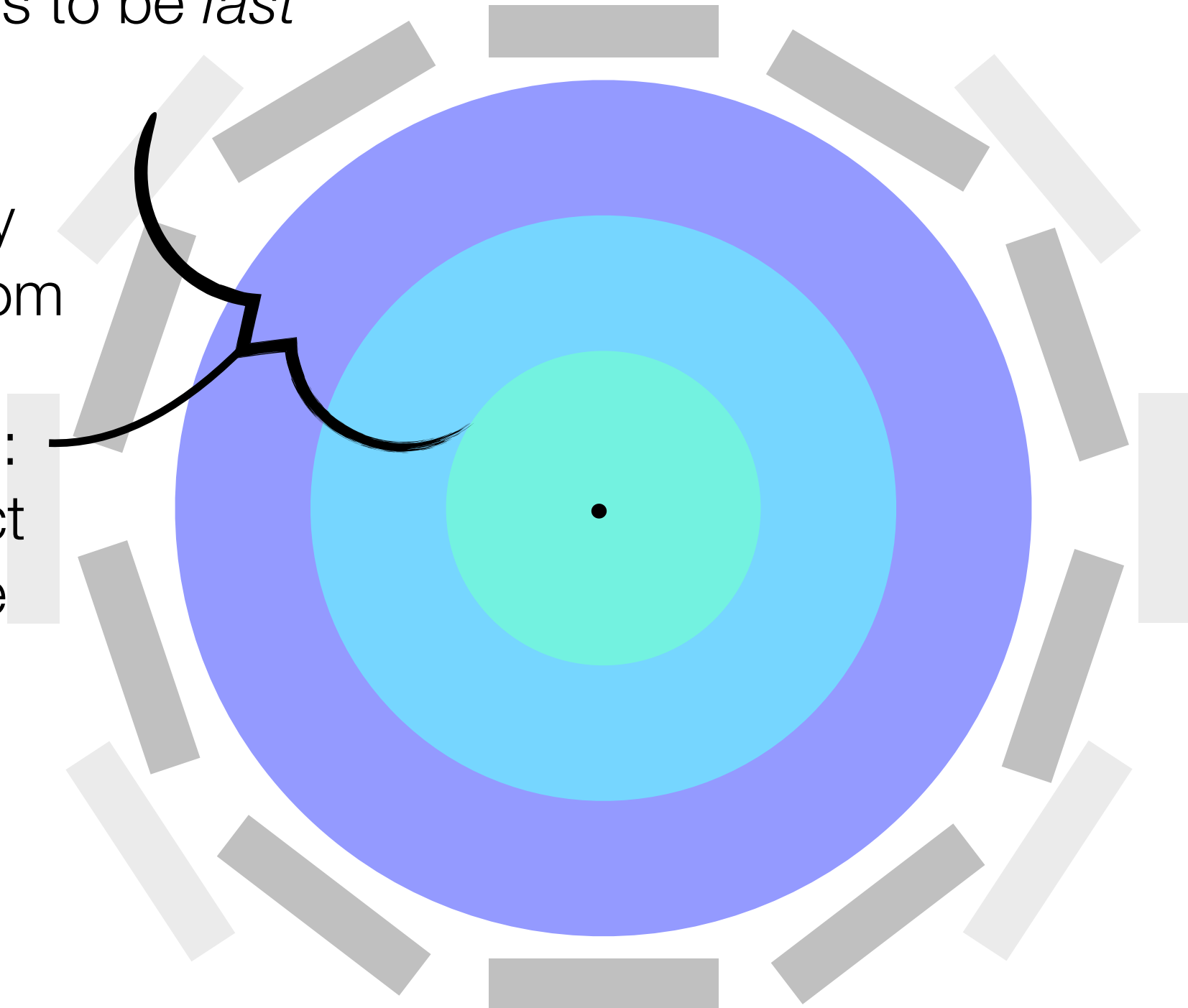
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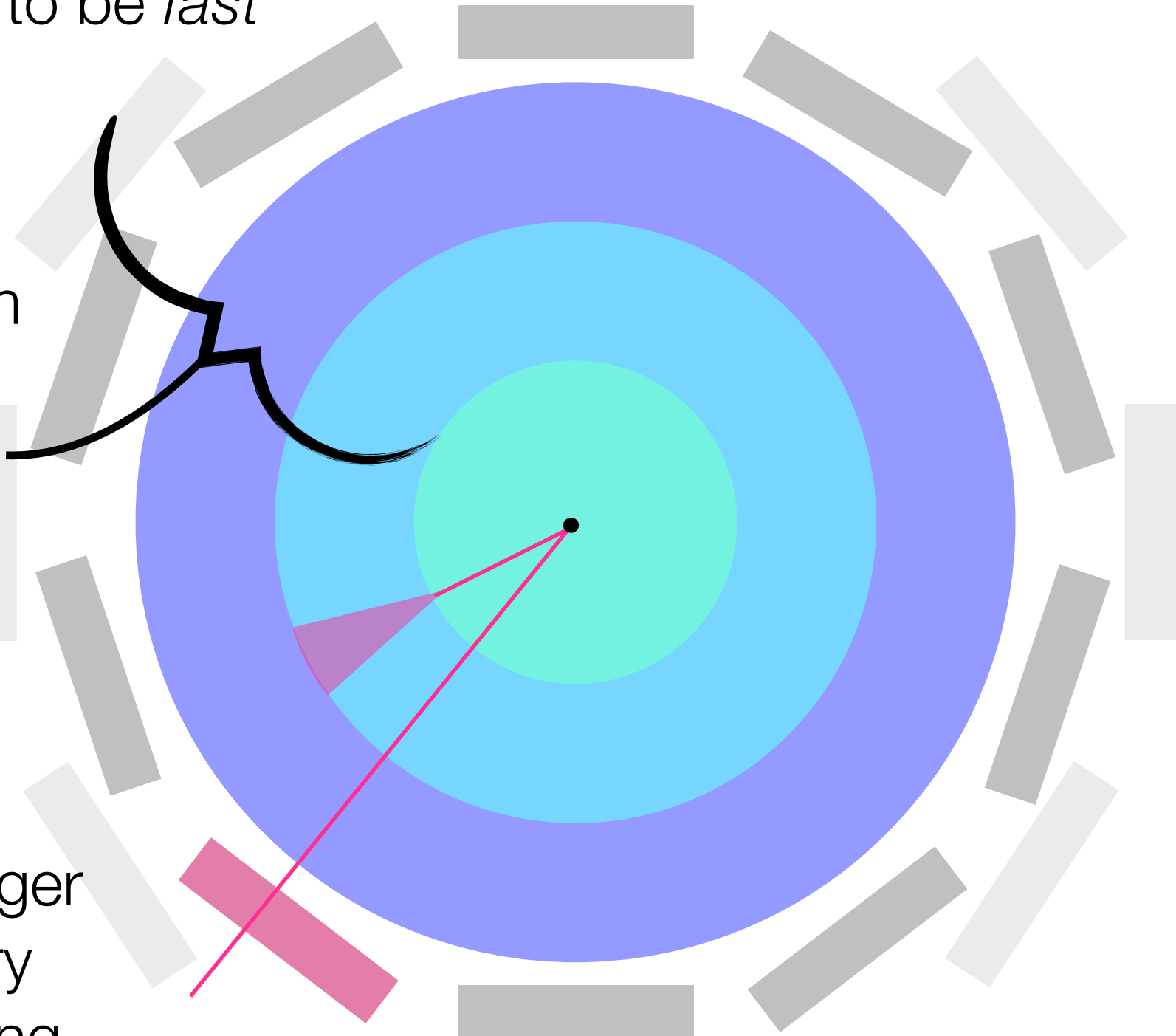
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Easiest to use:
- loose trigger
- something else in event
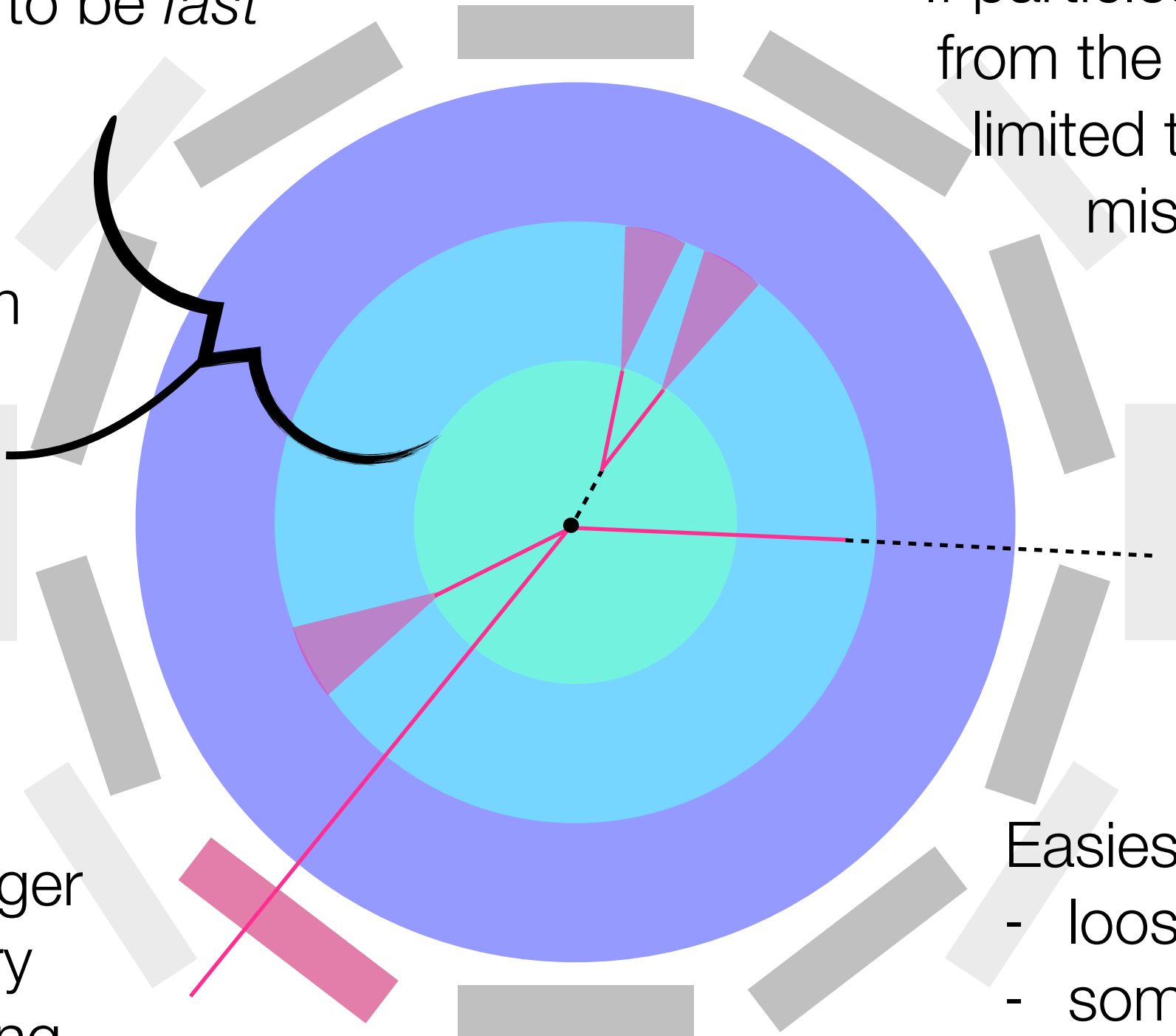
24

Understanding backgrounds

- Long-lived particle searches often have small and/or unusual backgrounds due to ~no simple Standard Model processes imitating signatures

- Sources of remaining backgrounds LLP searches include:

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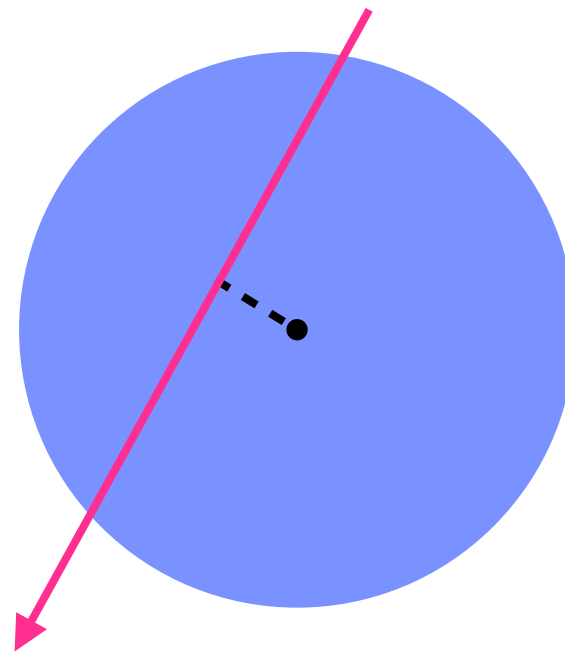
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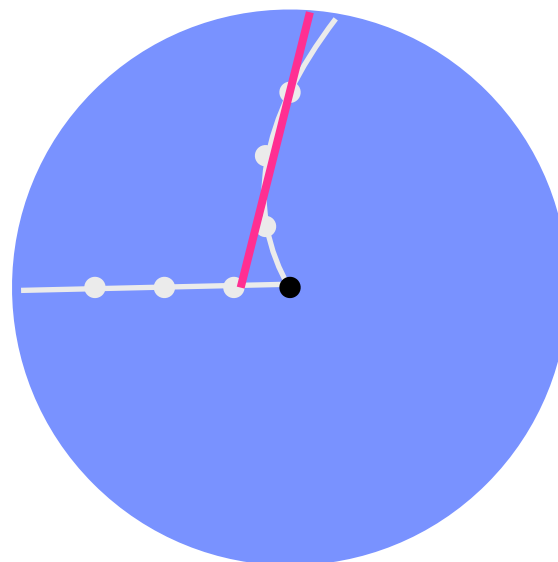
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- For almost all background contributions, no possibility of simulating them well

- So you will see fully data-driven background estimates for ~all LLP searches!

A direct detection example: pixel dEdx analysis
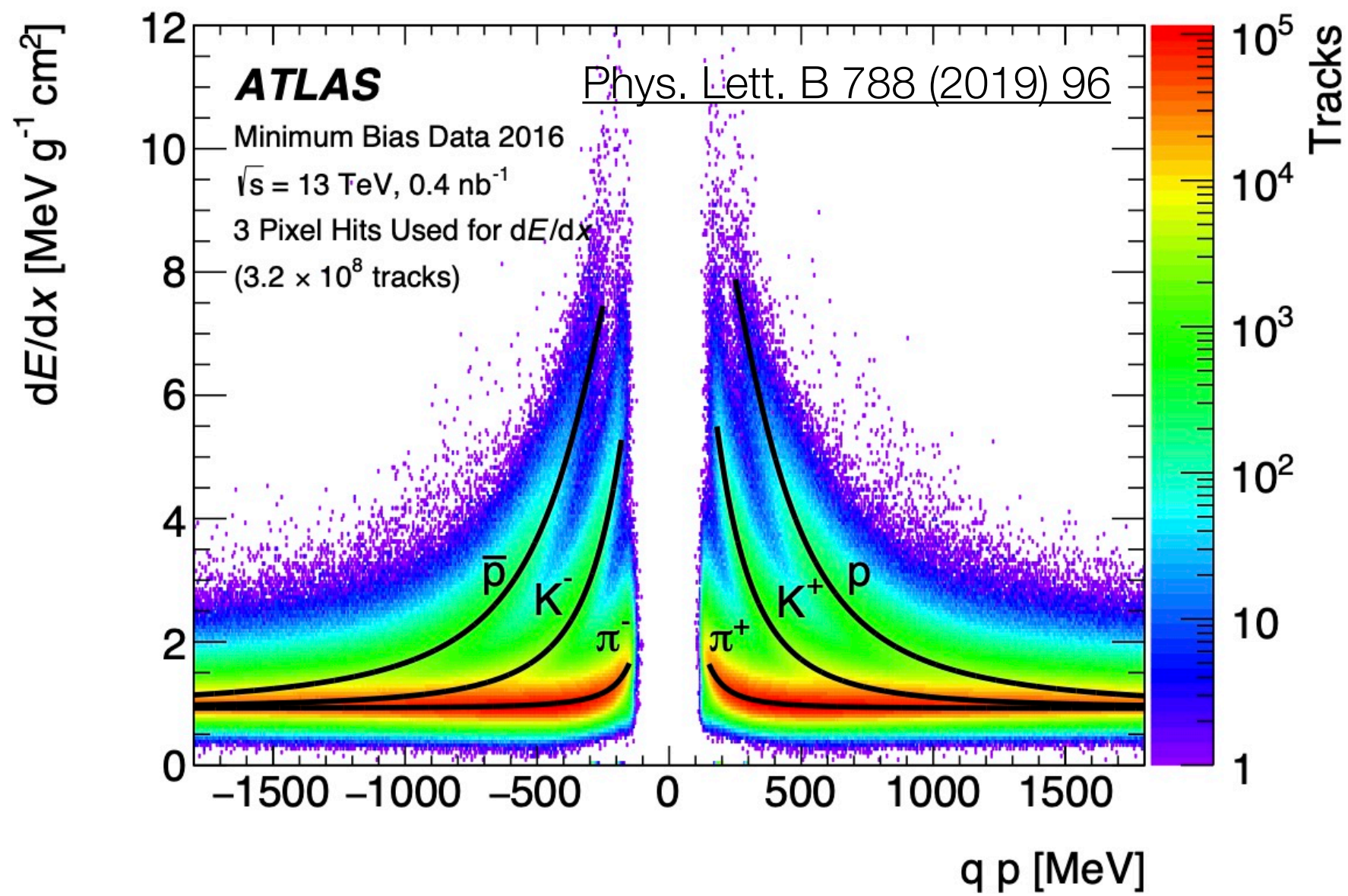
For a relativistic particle, $\beta = v/c$, $\gamma = E/m$, $\beta\gamma = p/M$

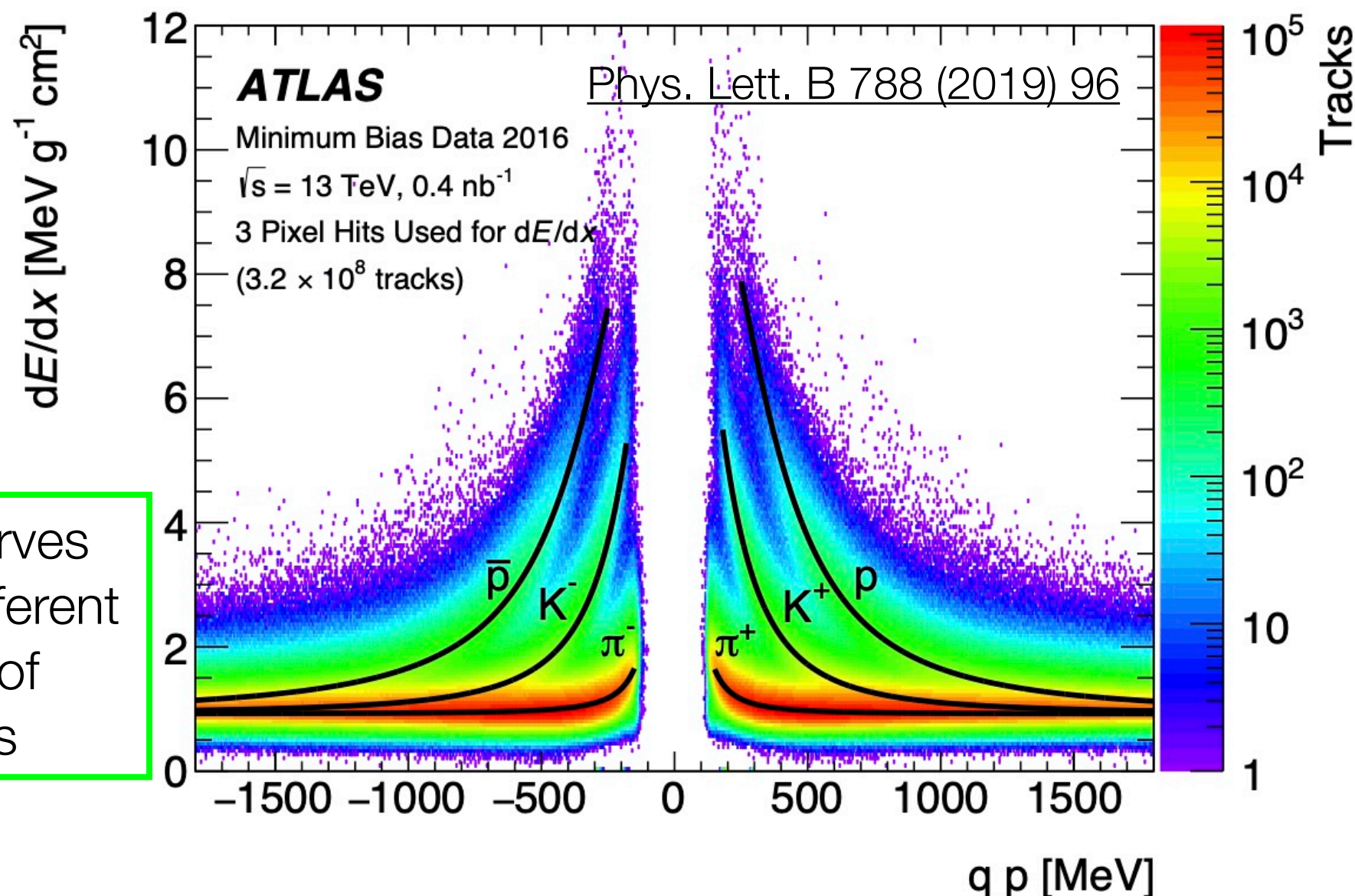# A direct detection example: pixel dEdx analysis

For a relativistic particle, $\beta = v/c$, $\gamma = E/m$, $\beta\gamma = p/M$

Energy deposited via ionisation = $dE/dx \propto ln(\beta^2\gamma^2)/\beta^2$ (Bethe Bloch)
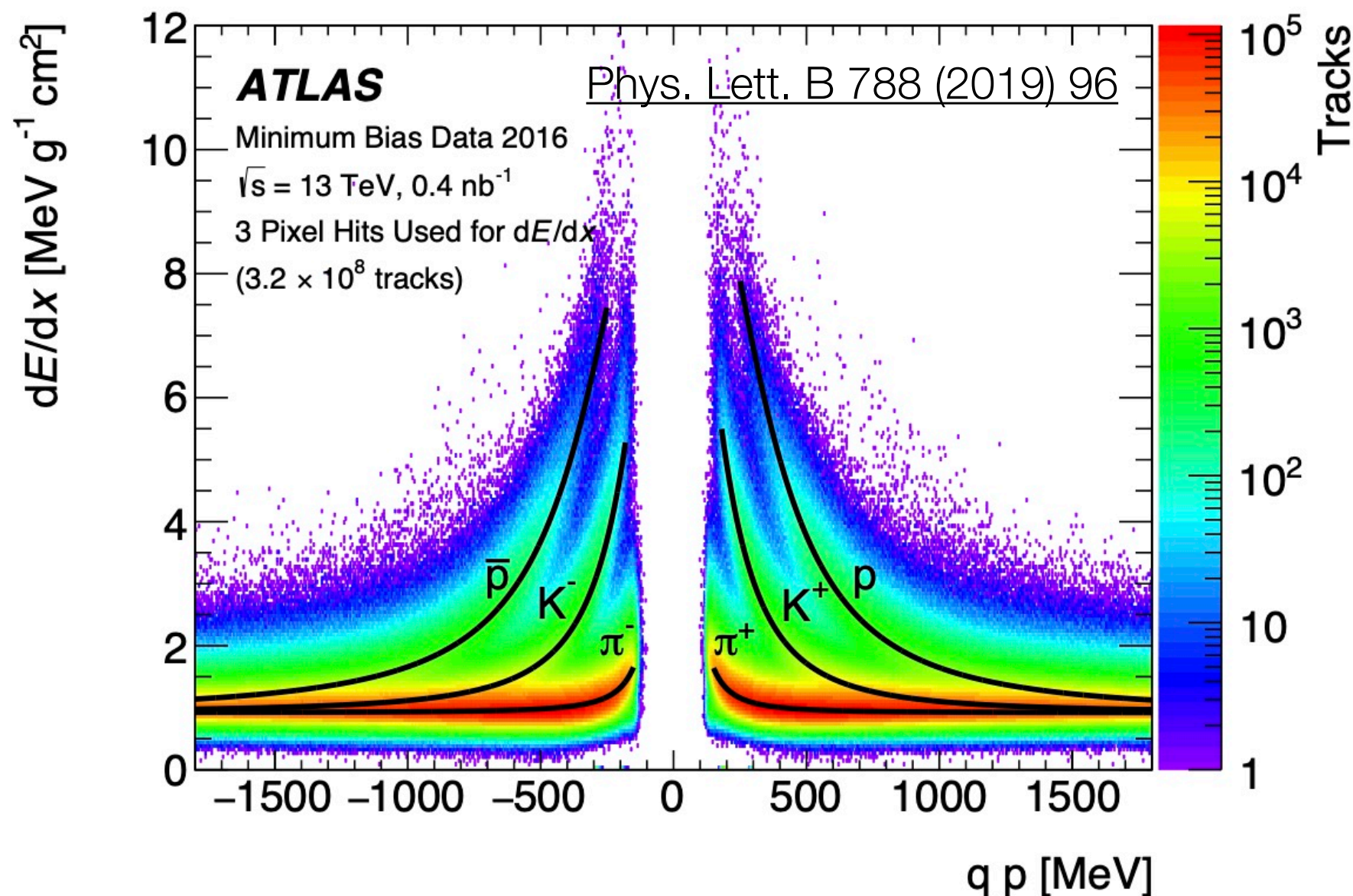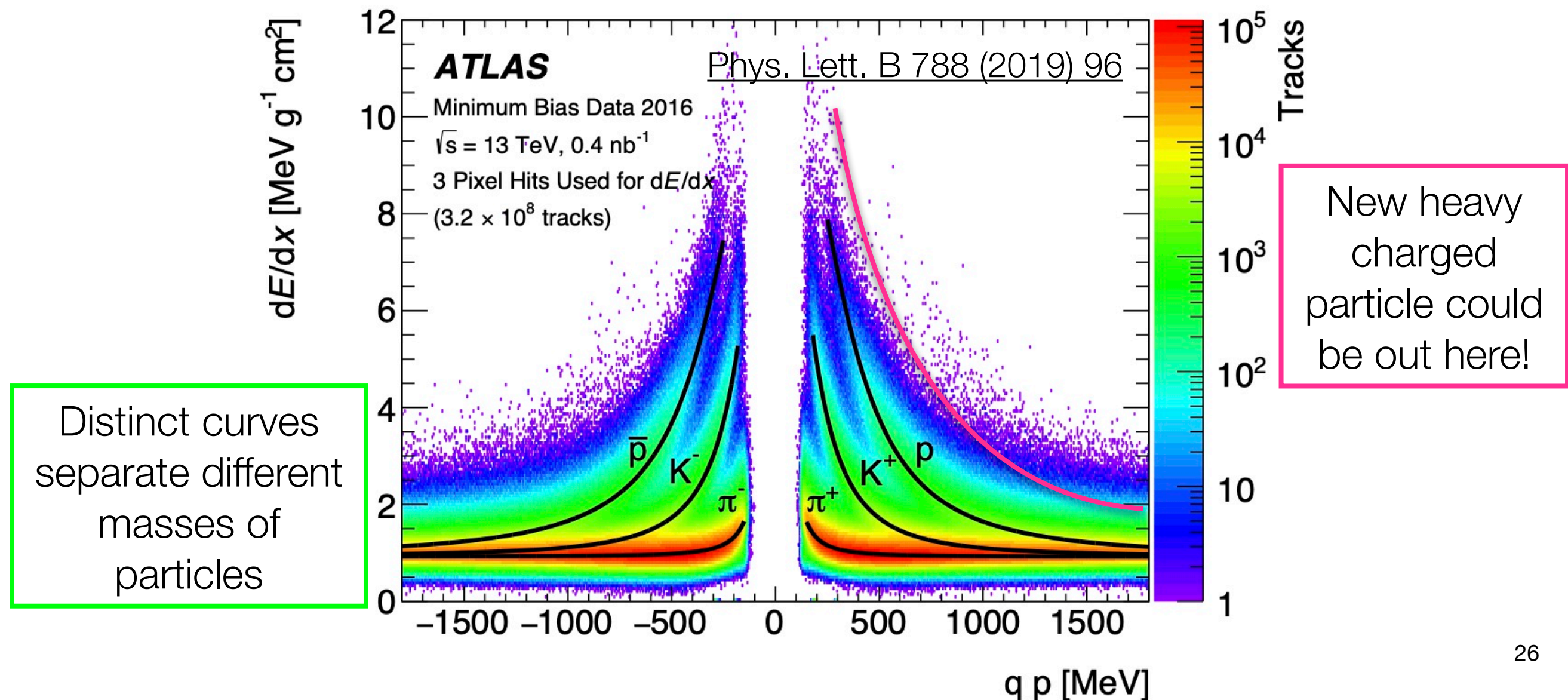
A direct detection example: pixel dEdx analysis

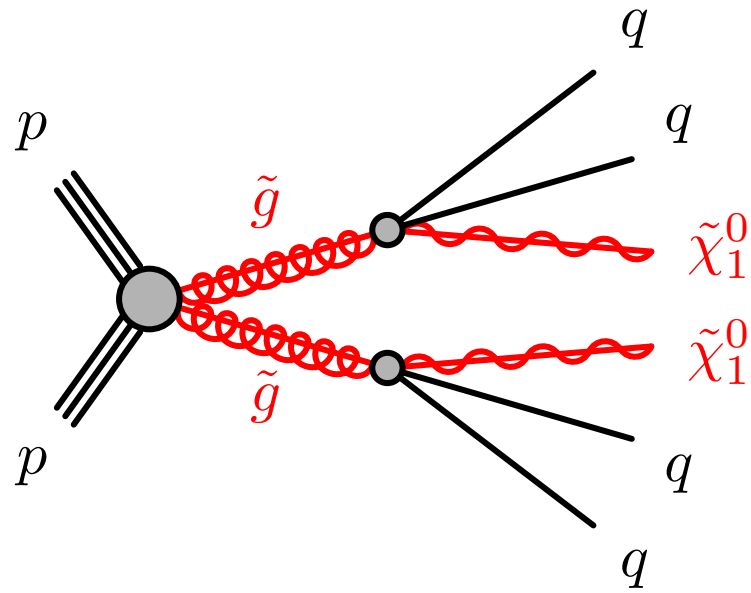For a relativistic particle, $\beta = v/c$, $\gamma = E/m$, $\beta\gamma = p/M$

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→ Ionisation energy connects momentum to mass

A direct detection example: pixel dEdx analysis

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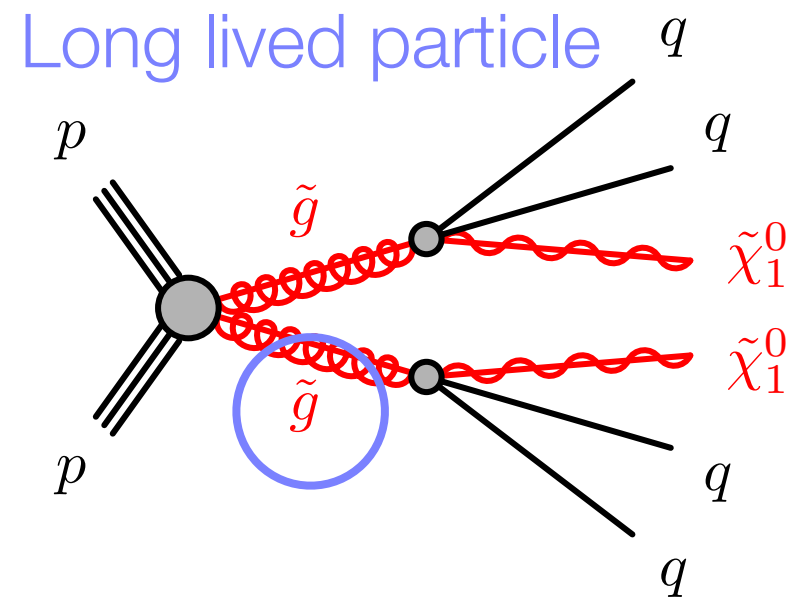
→ Ionisation energy connects momentum to mass

Distinct curves separate different masses of particles

Phys. Lett. B 788 (2019) 96

ATLAS
Minimum Bias Data 2016
$\sqrt{s}$ = 13 TeV, 0.4 nb^{-1}
3 Pixel Hits Used for dE/dx
$(3.2 \times 10^8$ tracks)

A direct detection example: pixel dEdx analysis

For a relativistic particle, $\beta = v/c$, $\gamma = E/m$, $\beta\gamma = p/M$

Energy deposited via ionisation = $dE/dx \propto ln(\beta^2\gamma^2)/\beta^2$ (Bethe Bloch)

→ Ionisation energy connects momentum to mass

Distinct curves separate different masses of particles

New heavy charged particle could be out here!

Event selection in the dEdx analysis

Event selection in the dEdx analysis

Event selection in the dEdx analysis

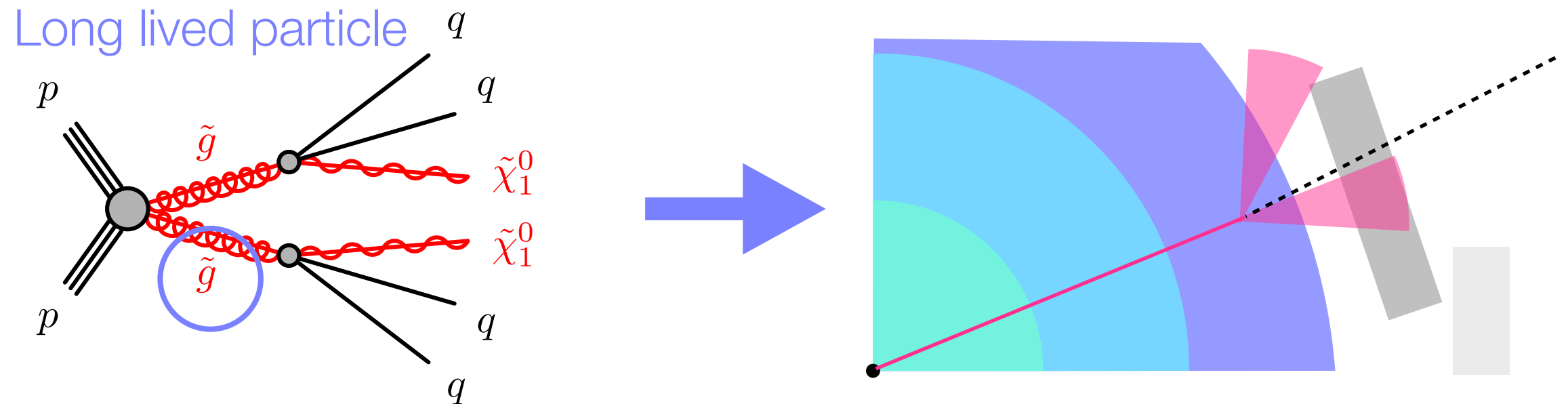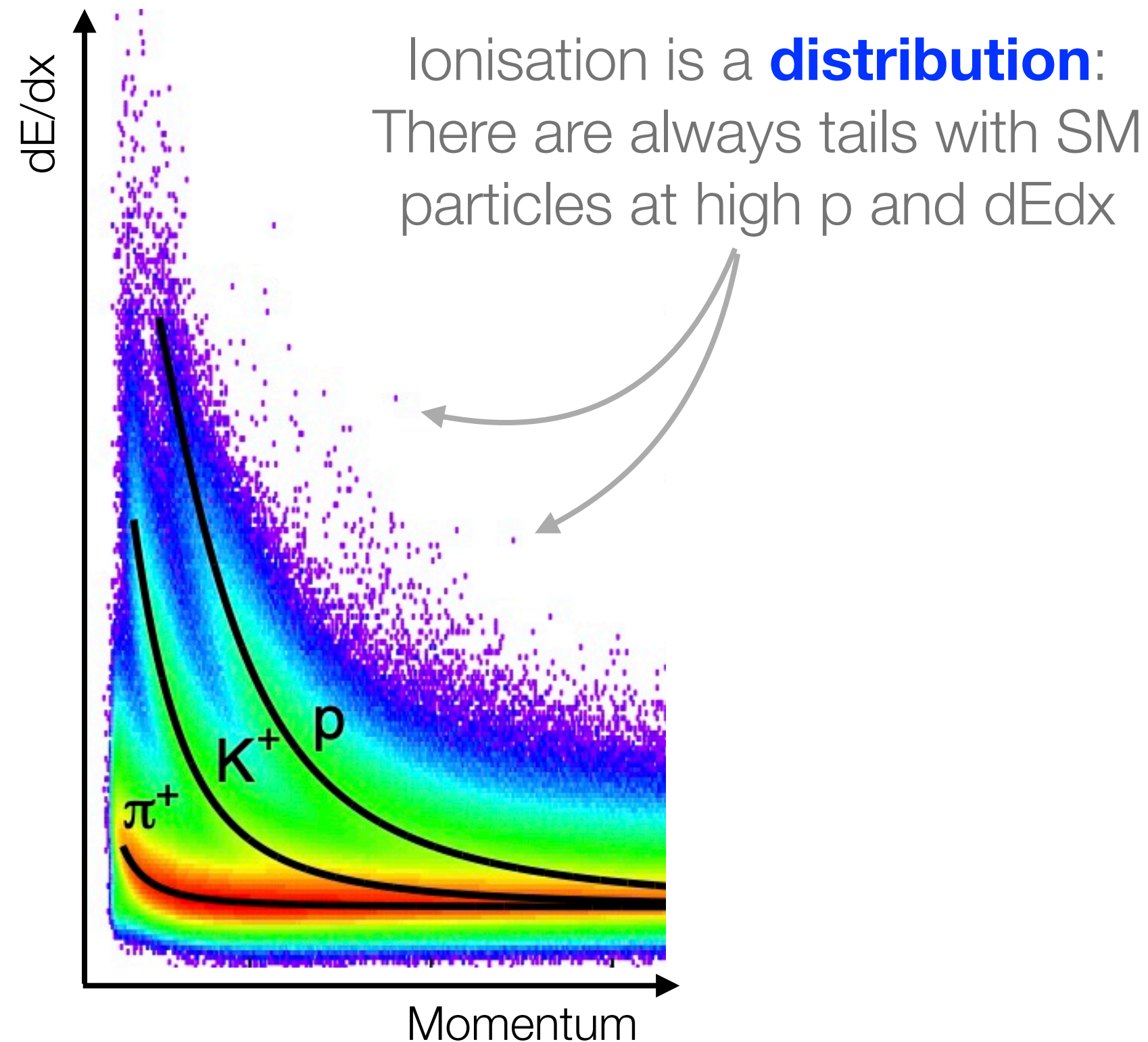# Event selection in the dEdx analysis

- LLP is heavy: moves slowly and leaves **more ionisation energy**

- **High momentum** compared to SM backgrounds
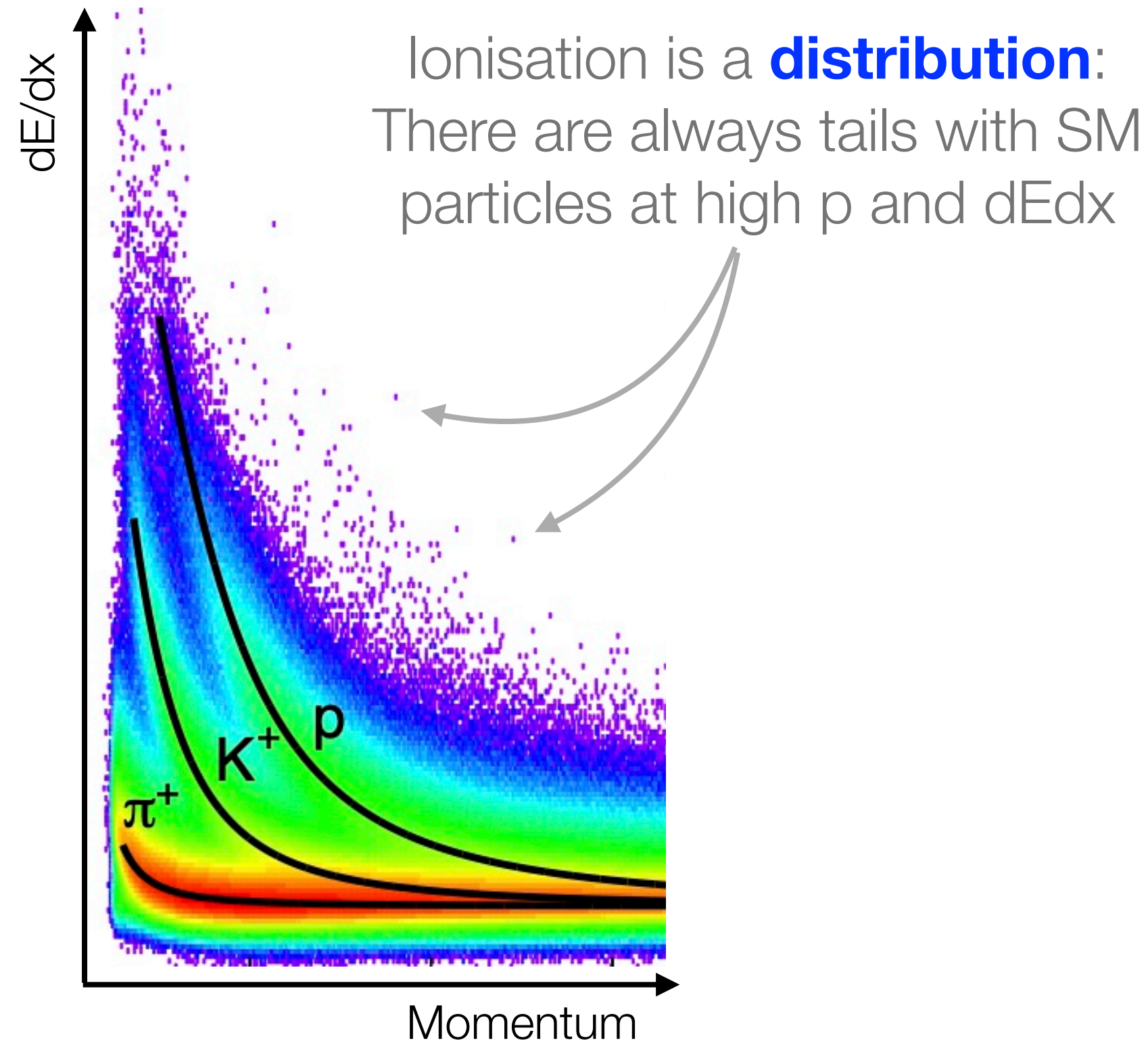
Event selection in the dEdx analysis
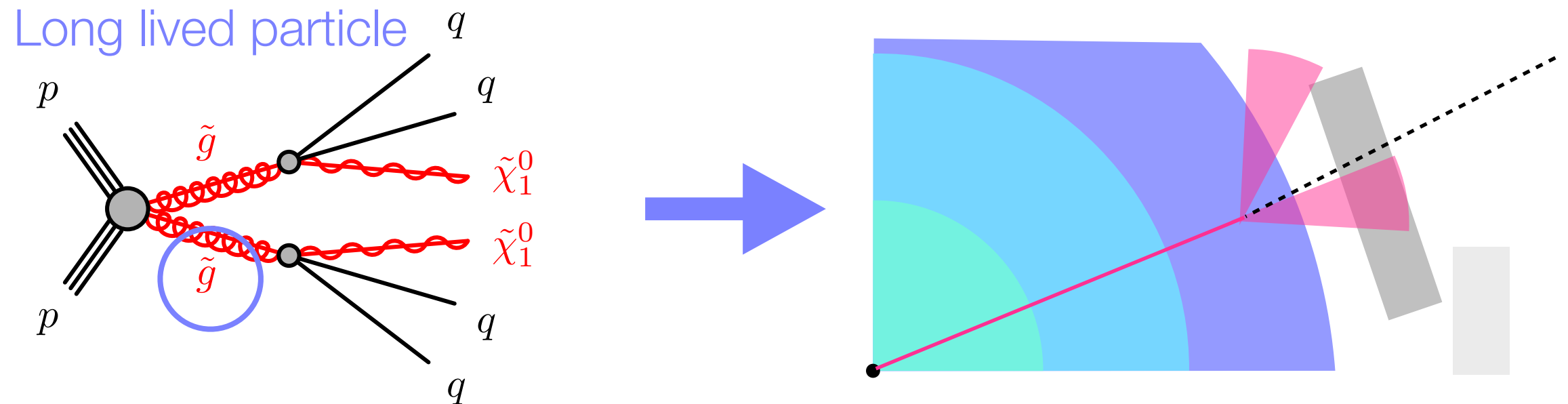
- LLP is heavy: moves slowly and leaves **more ionisation energy**

- **High momentum** compared to SM backgrounds

- What to **trigger** on? Likely to miss track, no reliable objects

- Use **missing momentum** to trigger

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Event selection in the dEdx analysis

- LLP is heavy: moves slowly and leaves **more ionisation energy**

- **High momentum** compared to SM backgrounds

- What to **trigger** on? Likely to miss track, no reliable objects

- Use **missing momentum** to trigger

Selection: missing momentum in event, high momentum track with large dE/dx
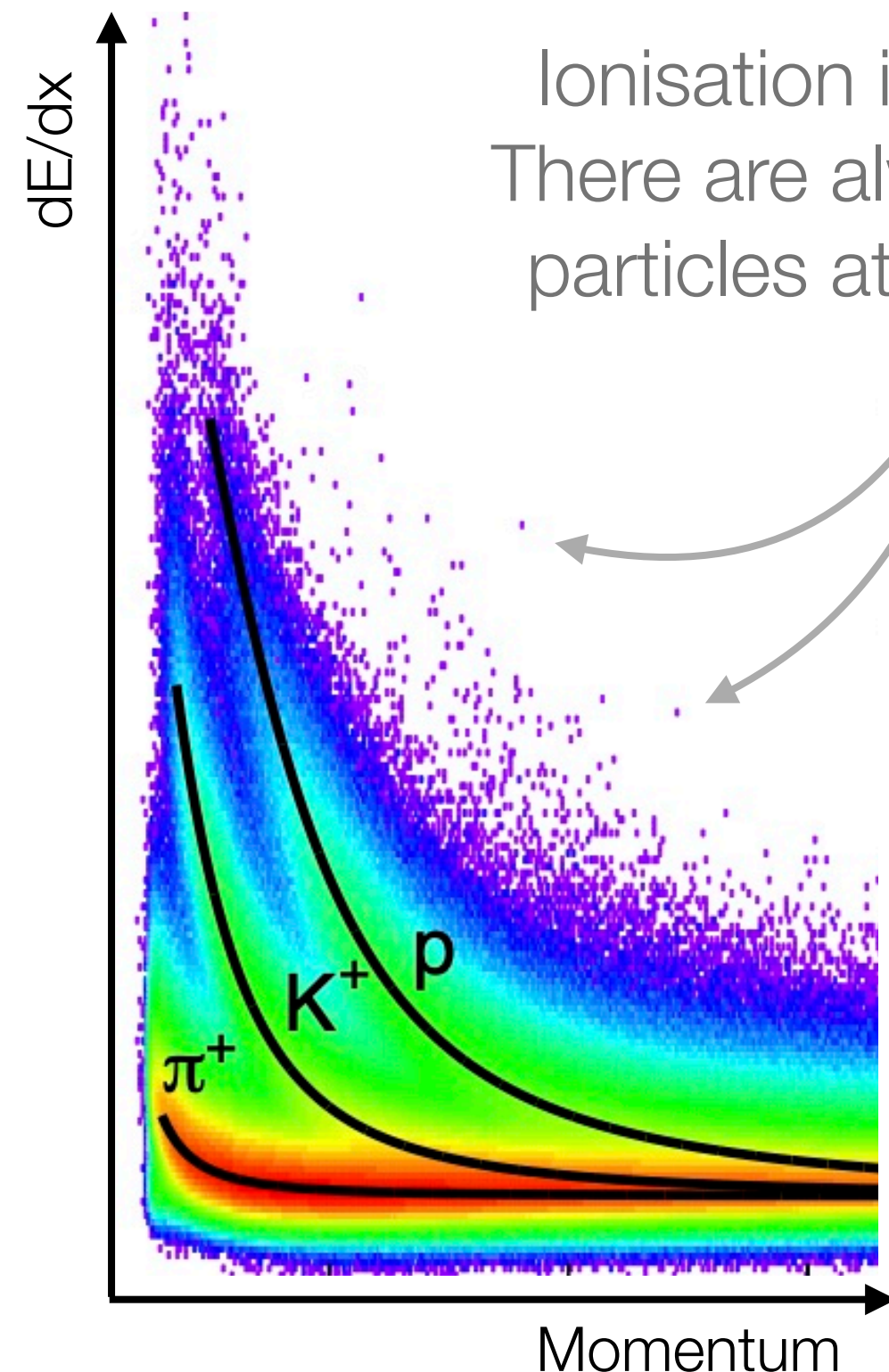
Backgrounds in the dEdx search

Ionisation is a **distribution**:
There are always tails with SM
particles at high p and dEdx

dE/dx

Momentum

π^+ K^+ p

Backgrounds in the dEdx search

Ionisation is a **distribution**:
There are always tails with SM
particles at high p and dEdx

**How do we
predict tails?**

dE/dx

π^+

K^+

p

Momentum

Backgrounds in the dEdx search

Ionisation is a **distribution**:
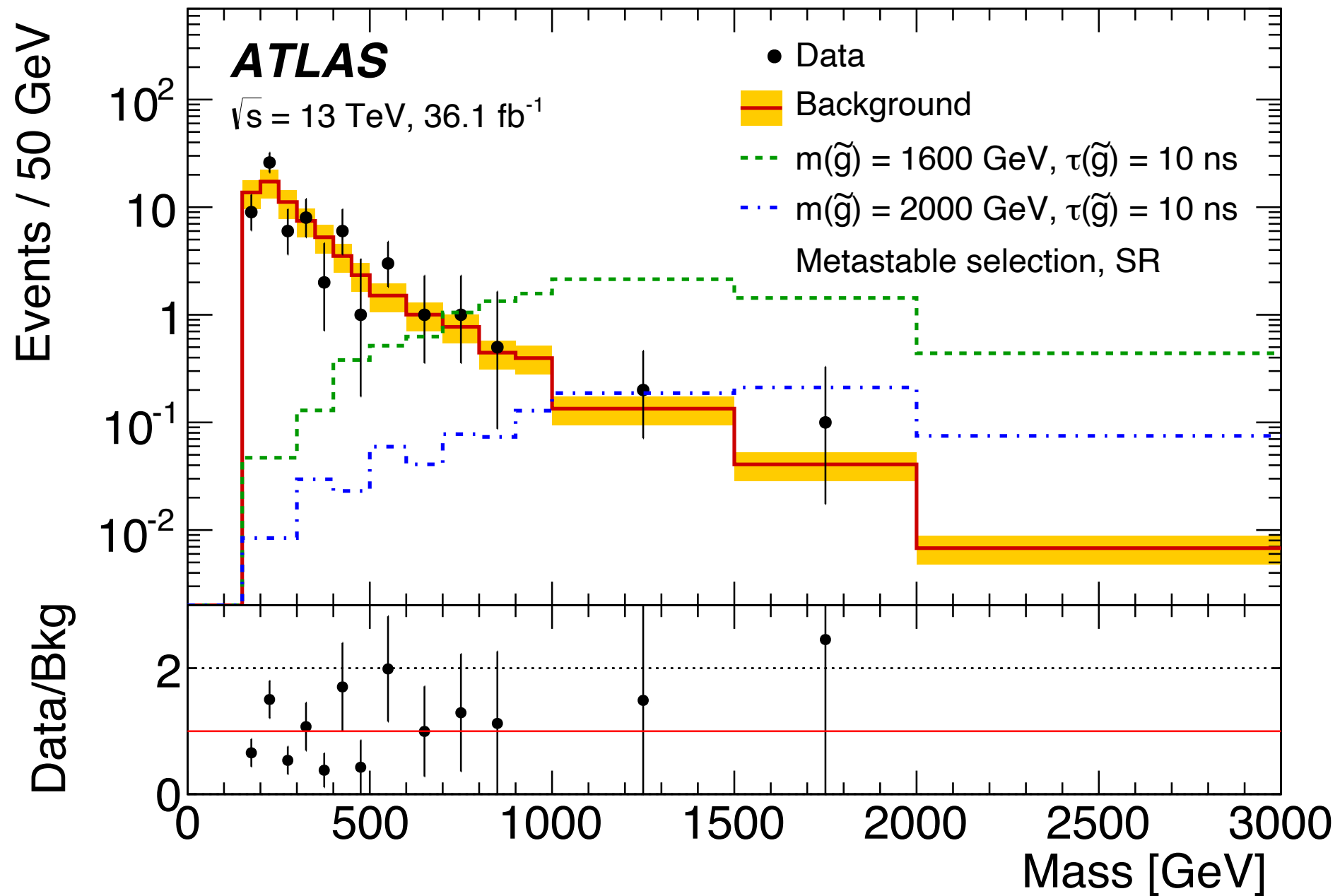There are always tails with SM
particles at high p and dEdx

**How do we
predict tails?**

- Missing momentum is **independent** of track dEdx

- Use **control regions** with low missing momentum to predict SM backgrounds

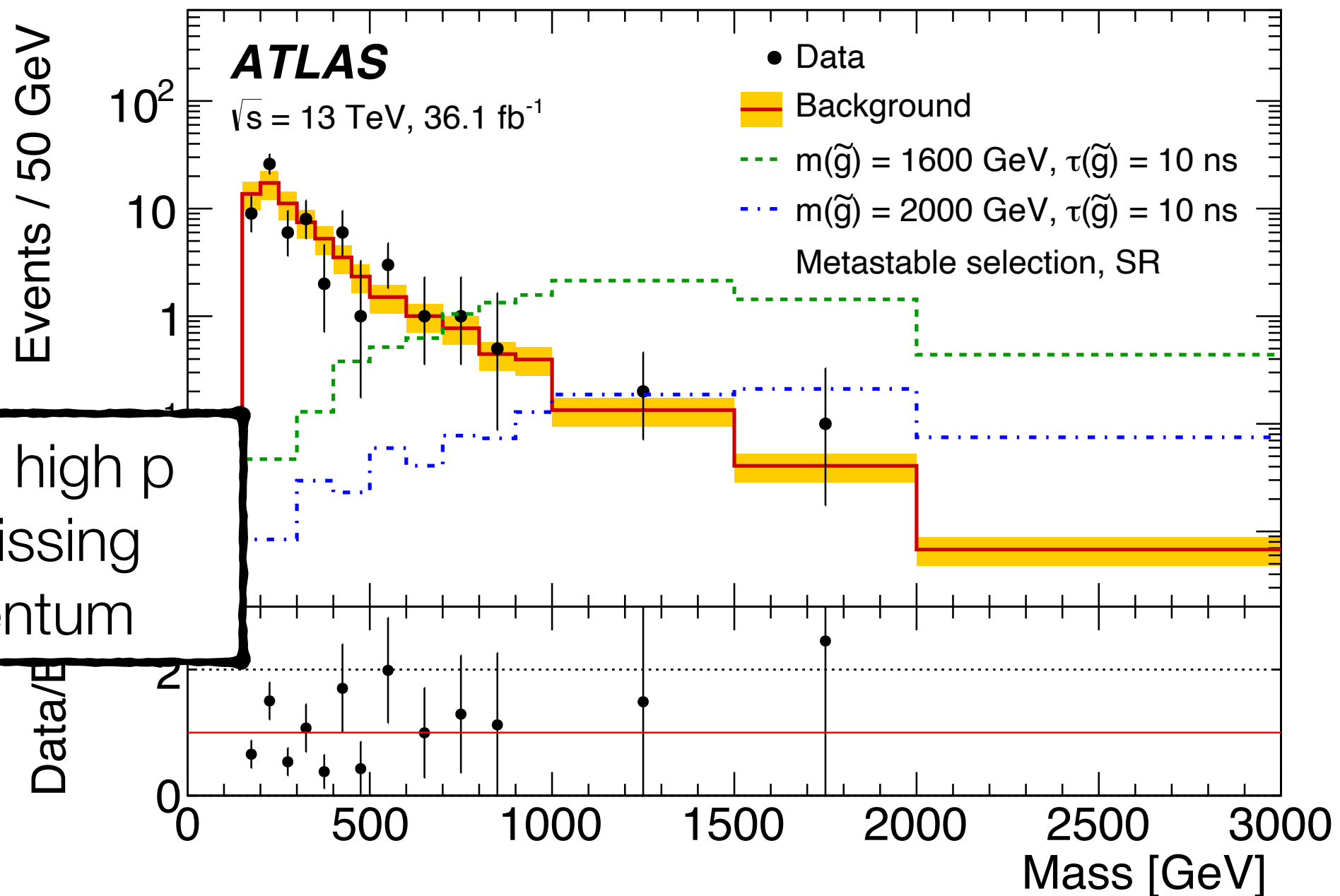- Convert prediction from p and dEdx to most likely particle mass

dEdx latest results and current status
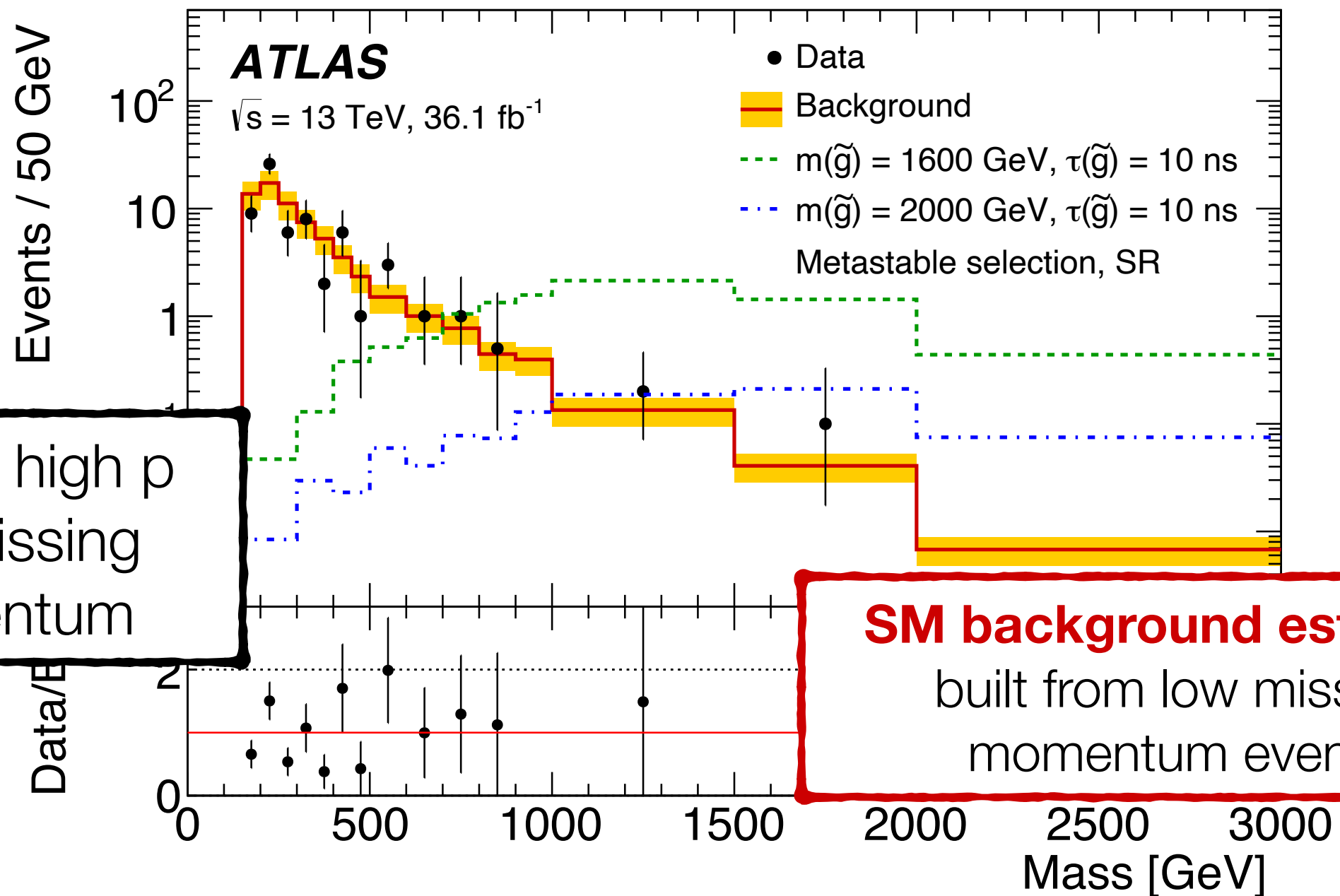

Optimised for lower lifetimes

ATLAS

$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}

- Data
- Background
- m($\tilde{g}$) = 1600 GeV, $\tau(\tilde{g})$ = 10 ns
- m($\tilde{g}$) = 2000 GeV, $\tau(\tilde{g})$ = 10 ns

Metastable selection, SR

Events / 50 GeV

Data/Bkg

Mass [GeV]

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dEdx latest results and current status

Optimised for lower lifetimes

Data at high p and missing momentum

29

dEdx latest results and current status

Optimised for lower lifetimes

Data at high p and missing momentum

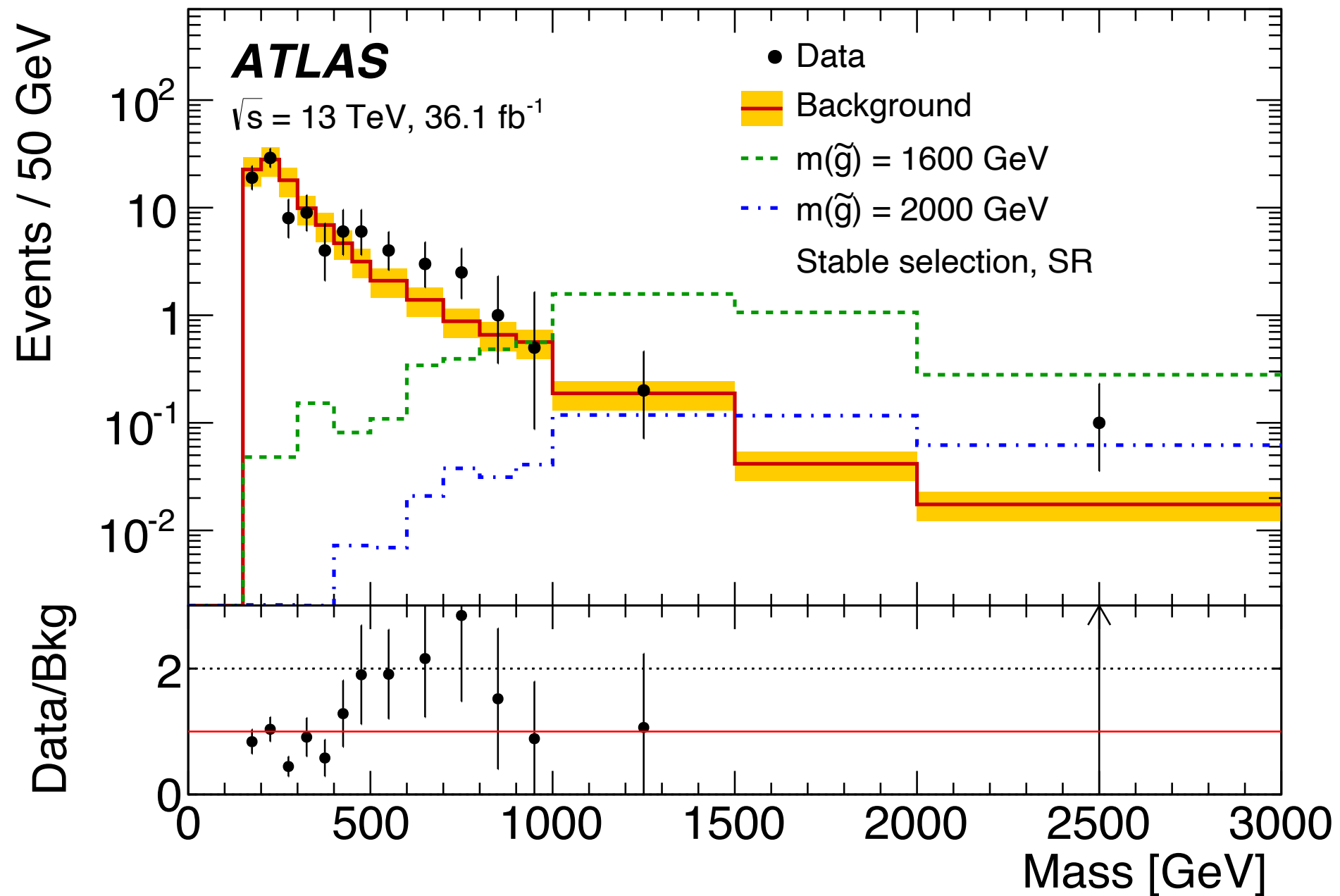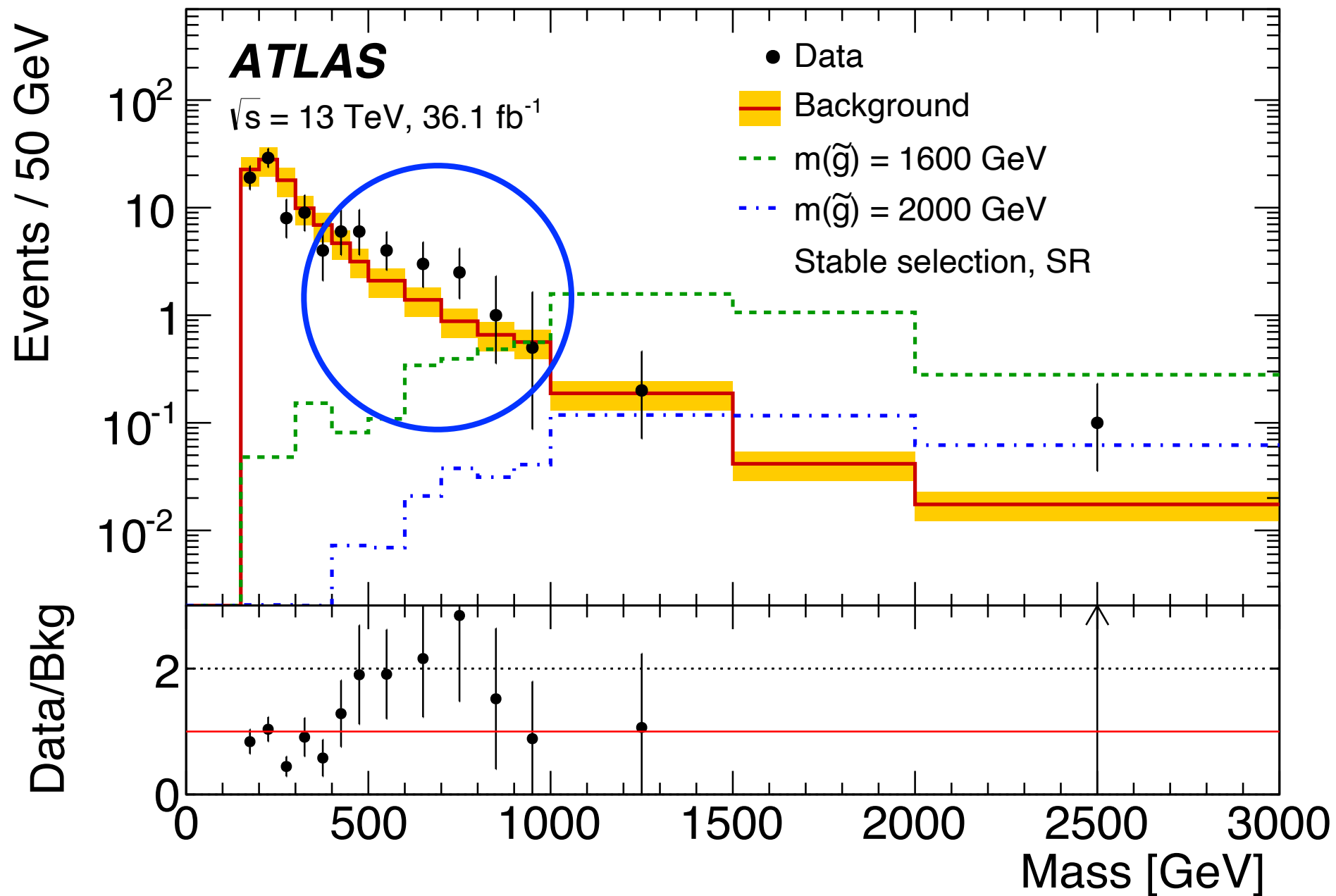**SM background estimate** built from low missing momentum events

dEdx latest results and current status

Optimised for higher lifetimes

dEdx latest results and current status

Optimised for higher lifetimes

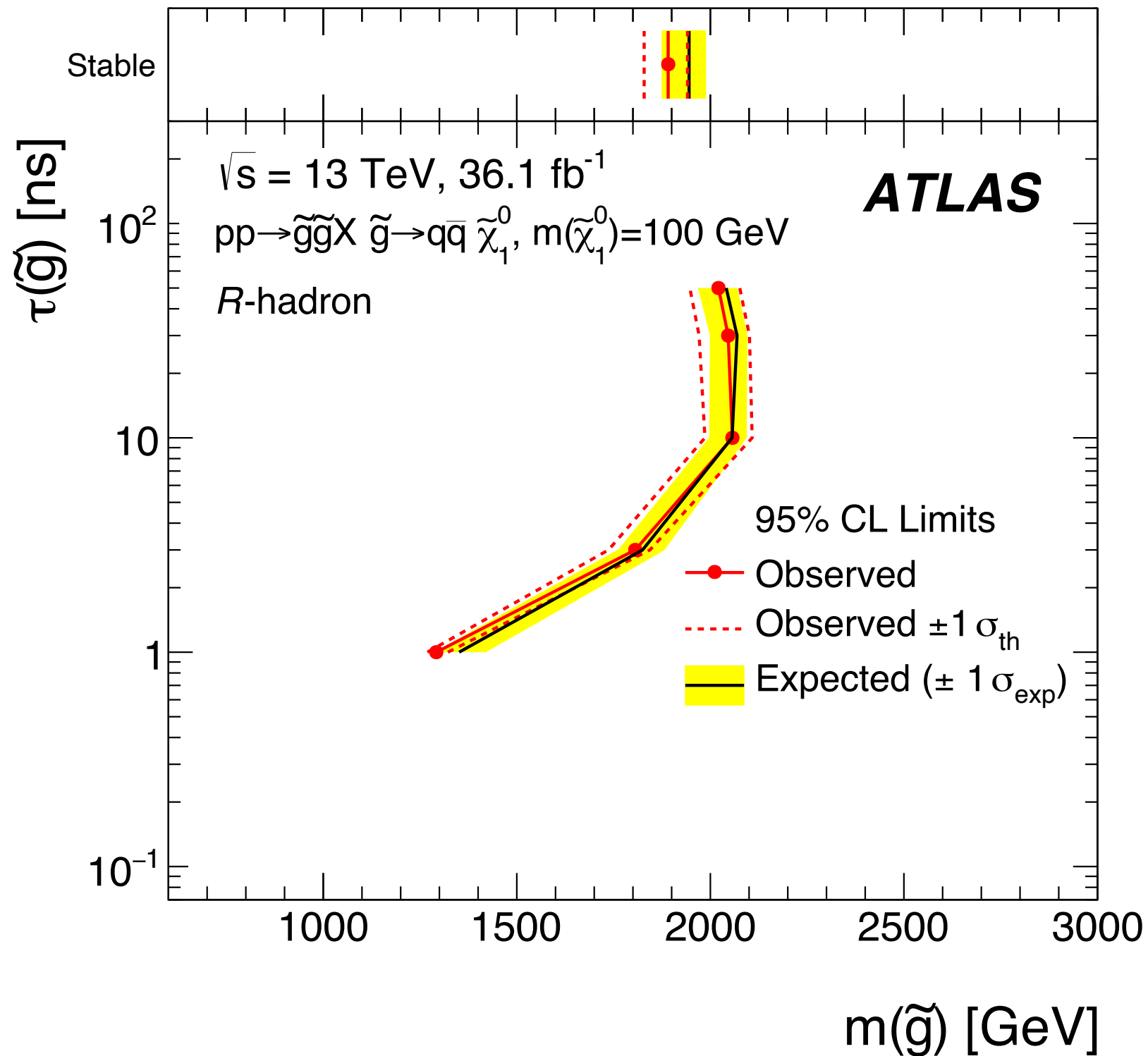# dEdx latest results and current status
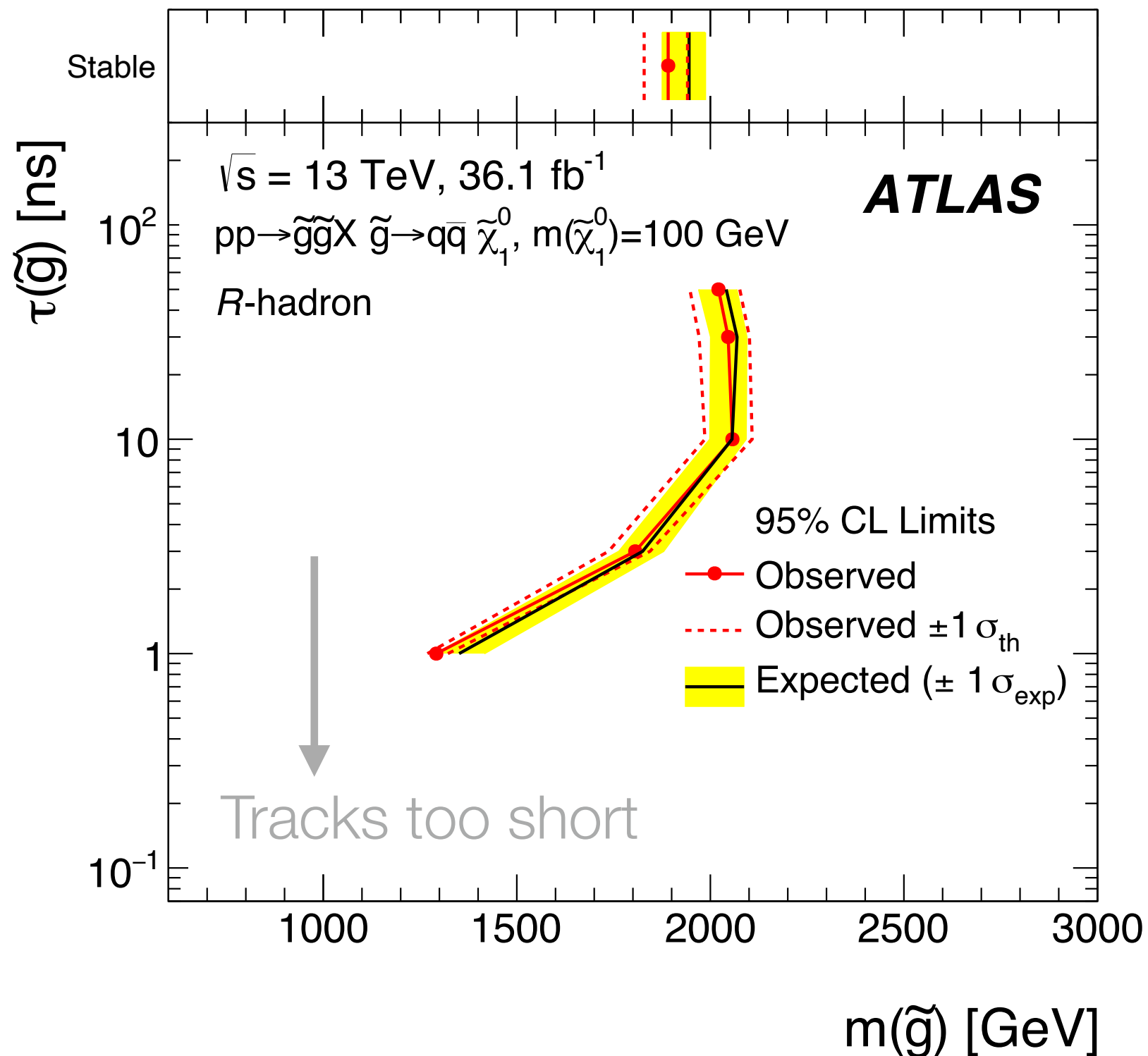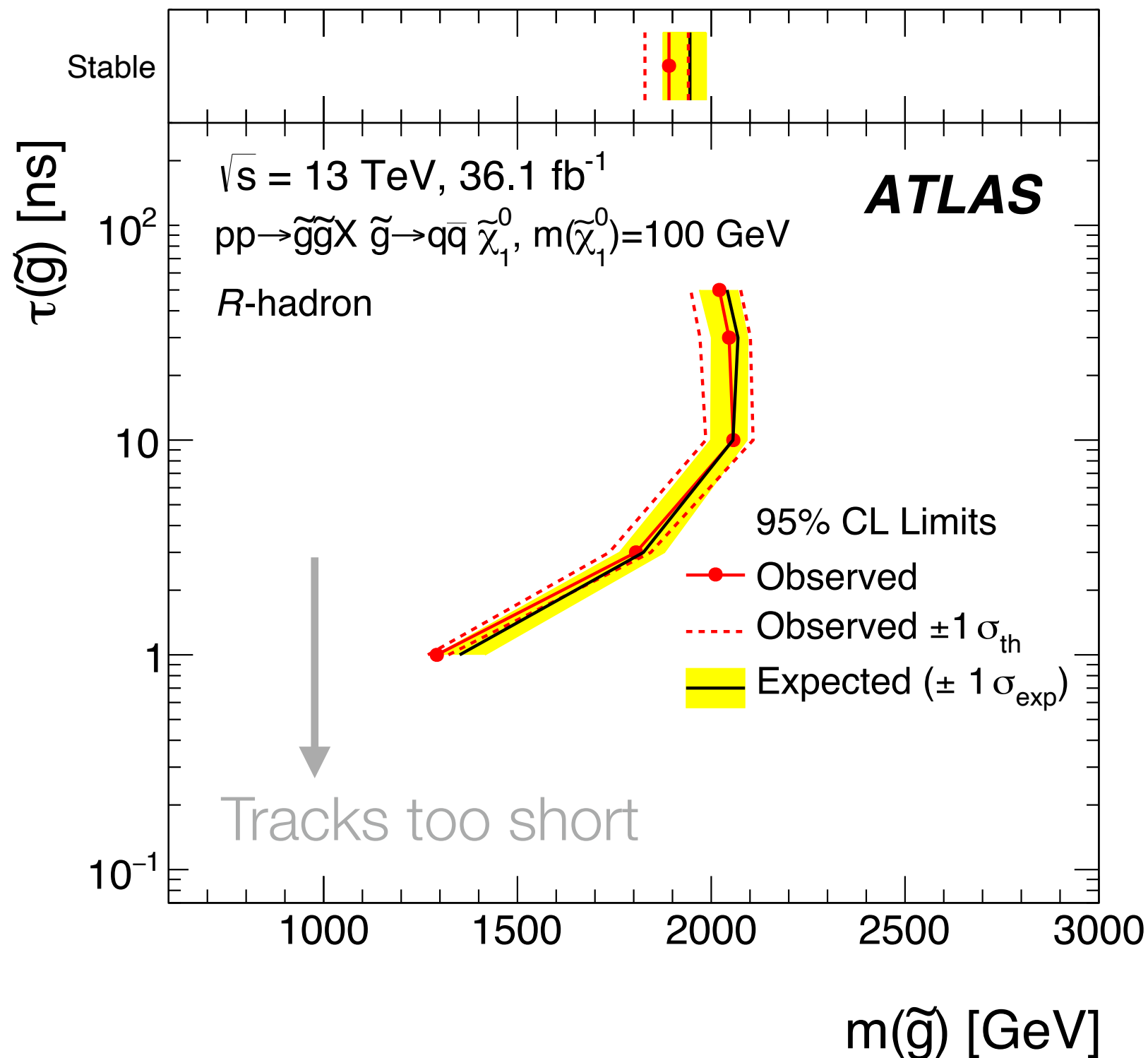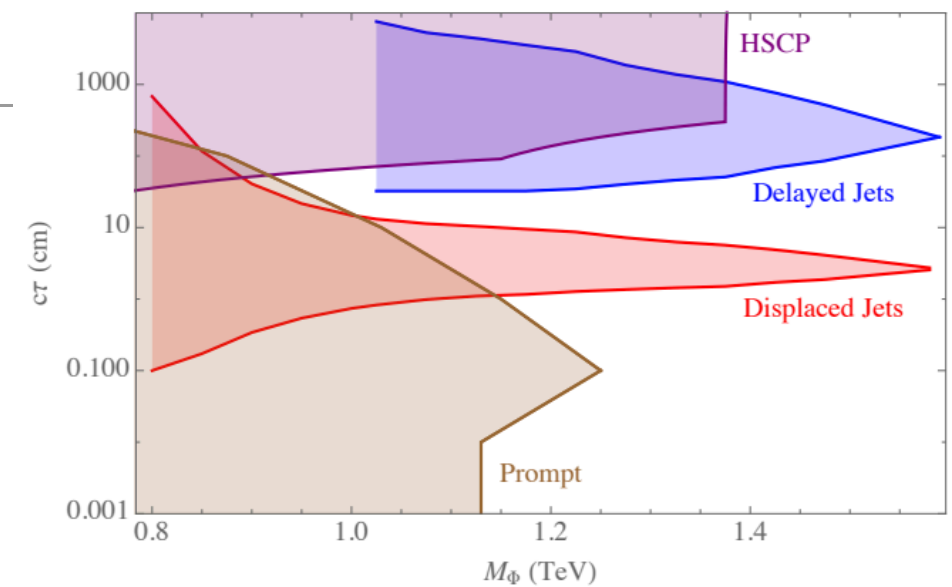

Optimised for higher lifetimes

ATLAS
√s = 13 TeV, 36.1 fb⁻¹

Data
Background
m($\tilde{g}$) = 1600 GeV

Full Run 2 analysis will have updated selections, more sophisticated background estimation, and improved tracking — **stay tuned**!

Data/Bkg

2

0

0   500   1000   1500   2000   2500   3000
Mass [GeV]

Limits from dEdx

Limits from dEdx

Limits from dEdx

$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}

pp→$\tilde{g}\tilde{g}$X $\tilde{g}$→q$\bar{q}$ $\tilde{\chi}_1^0$, m($\tilde{\chi}_1^0$)=100 GeV

ATLAS

R-hadron

95% CL Limits

● Observed

--- Observed ±1 σ_{th}

Expected (± 1 σ_{exp})
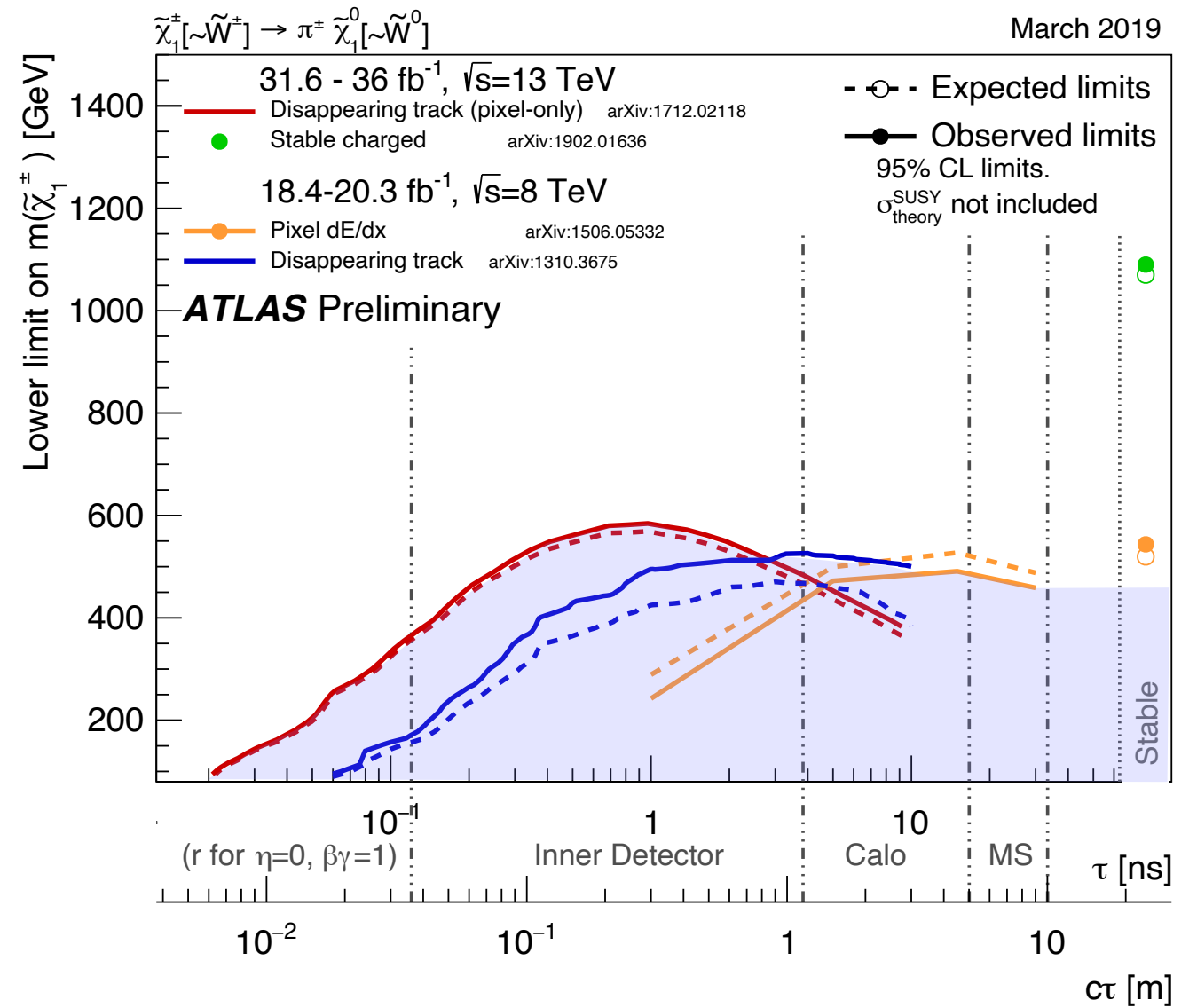
Tracks too short

Stable

$\tau(\tilde{g})$ [ns]

m($\tilde{g}$) [GeV]

dEdx constrains dark matter models! Above, recent reinterpretation

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Disappearing tracks

Disappearing tracks

Disappearing tracks

Disappearing tracks
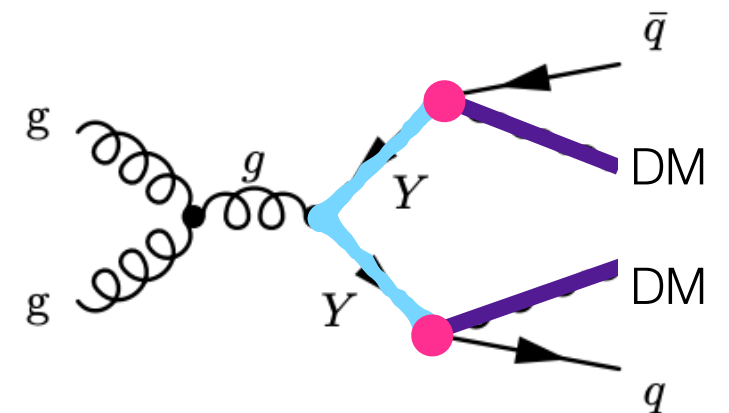
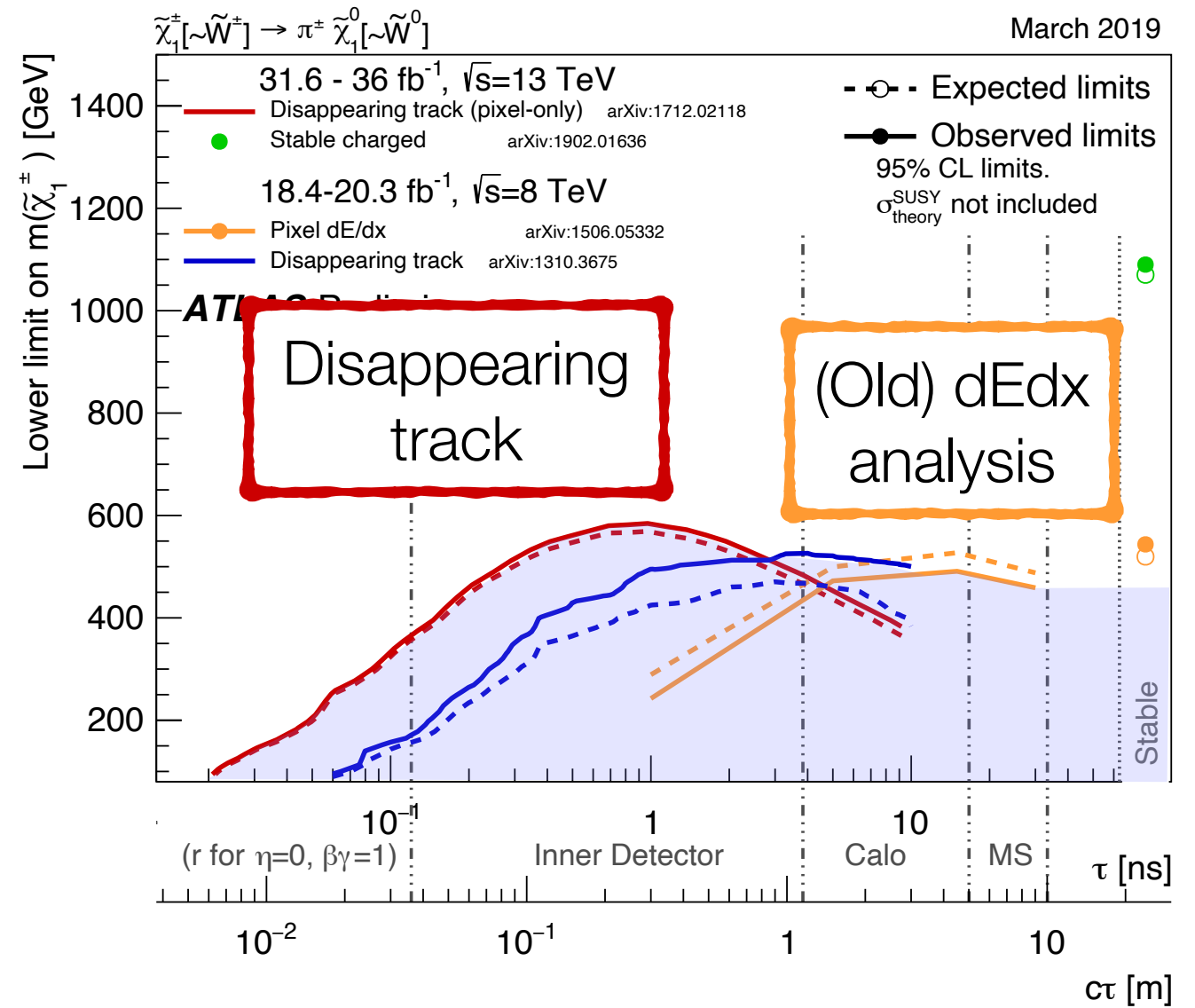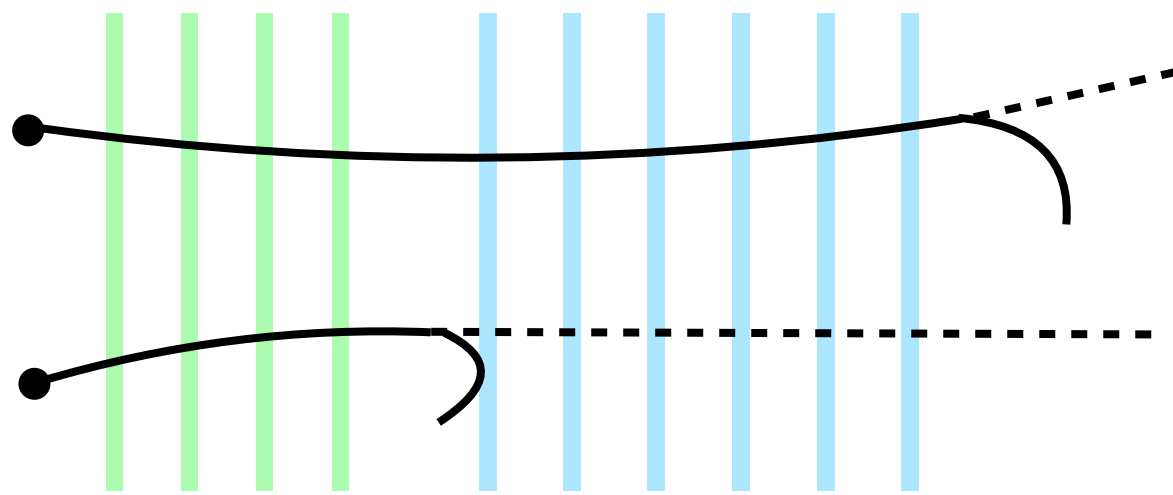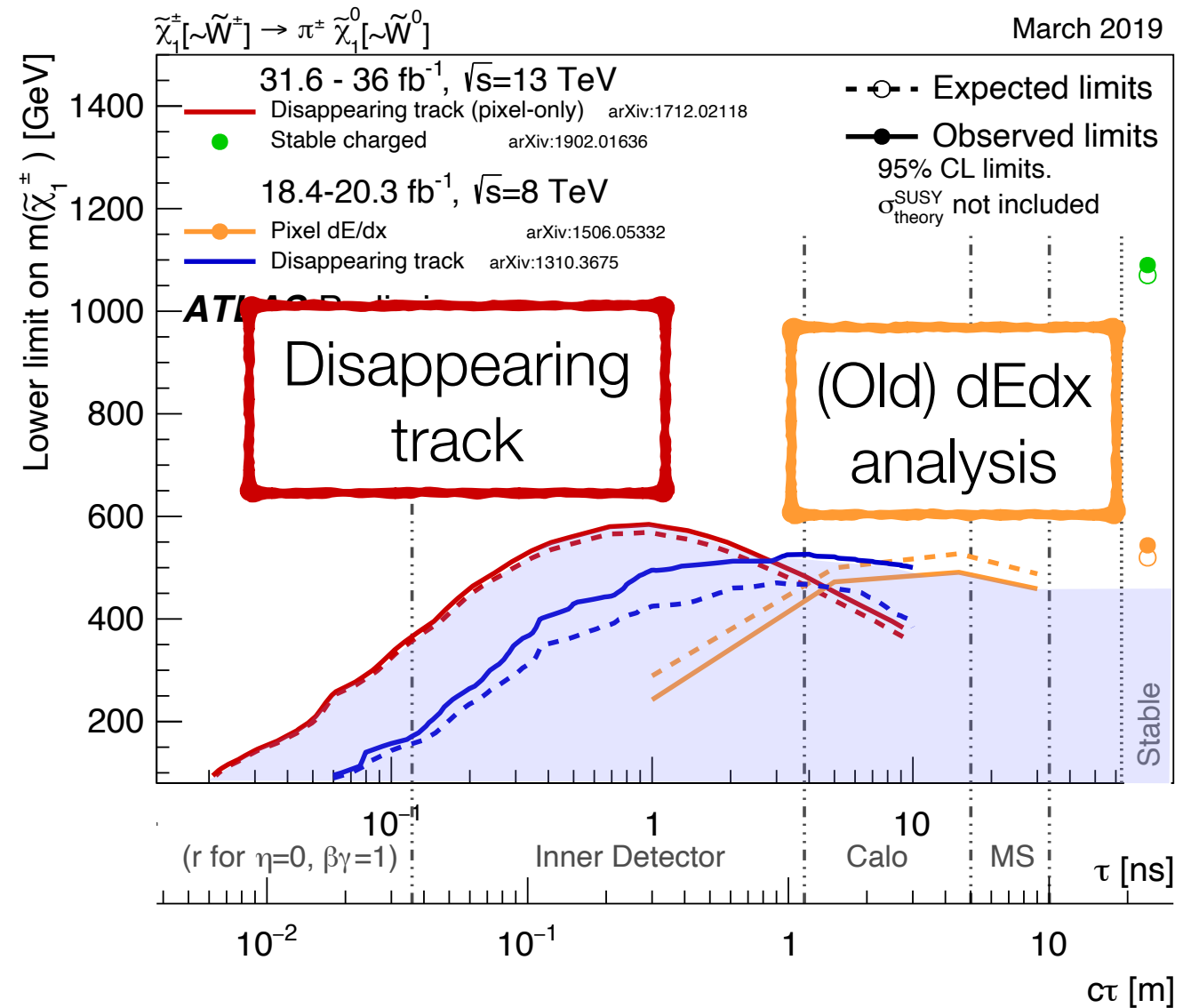# Disappearing tracks

arXiv:1712.02118

dEdx analysis
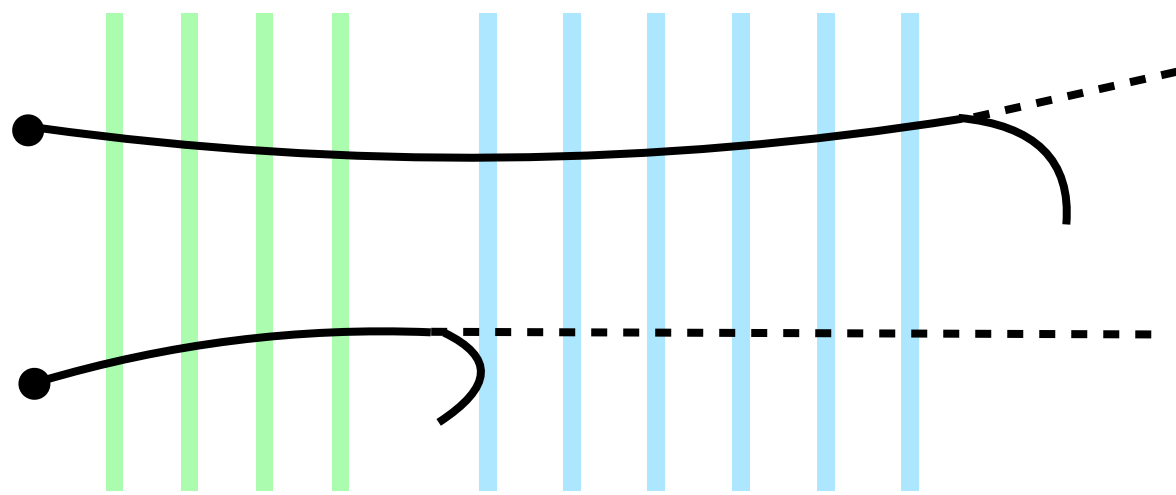
Disappearing track analysis

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Disappearing tracks
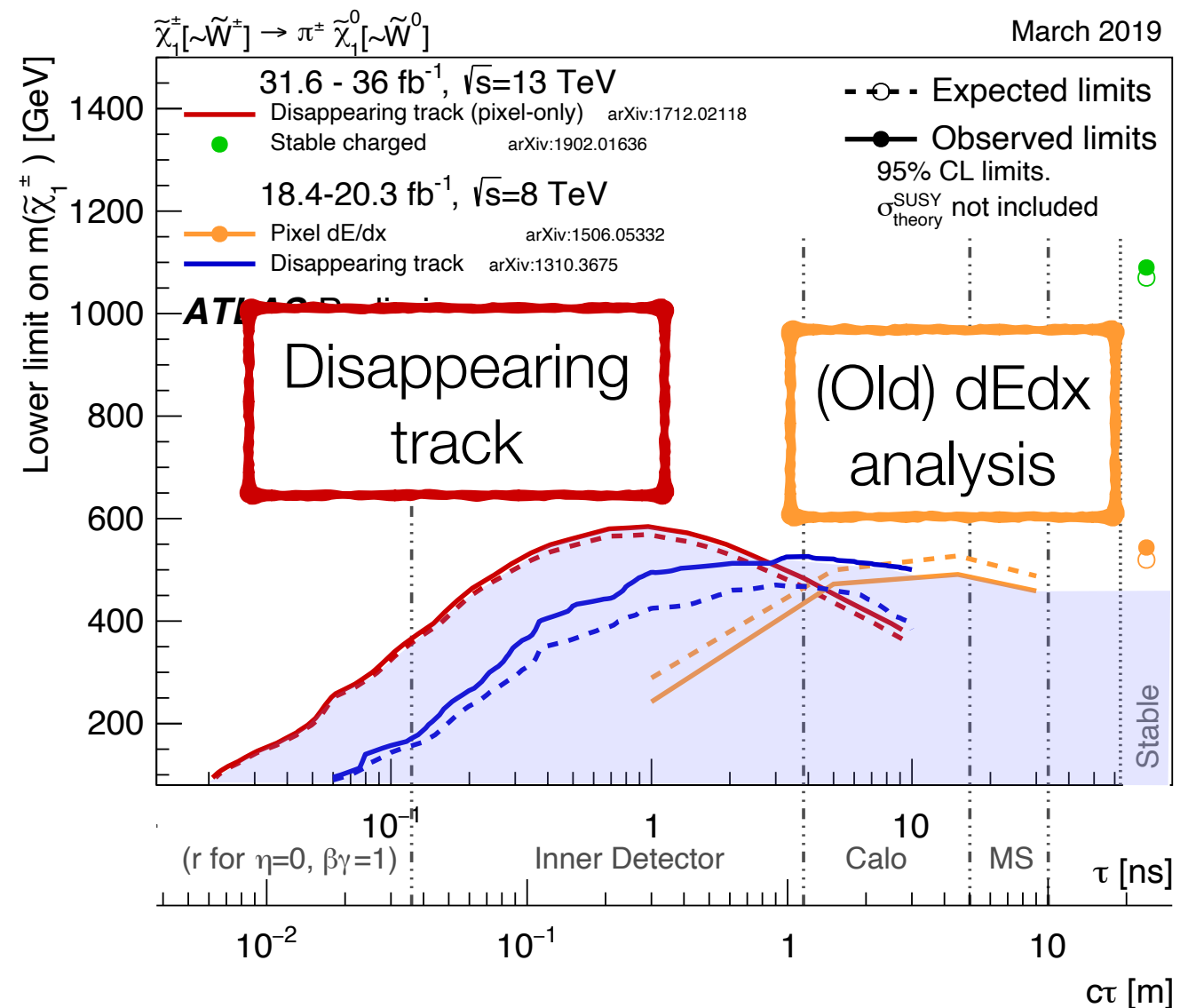
- Pure wino LSP scenarios naturally predicts a $\widetilde{\chi}_1^{\pm}$ lifetime around 0.2 ns

- Signature: track that vanishes midway through inner detector

- Similar to dEdx, commonly reinterpreted (including covering key range in pure-Higgsino LSP)

Disappearing tracks

- Trigger: missing energy

- Backgrounds:

  - Real hadrons & leptons that dramatically change direction (bremsstrahlung, material interactions, multiple scattering)

  - Fake tracklets made from mis-associated hits

- Extract templates in control regions and perform fit in signal regions to get normalisations

Disappearing tracks

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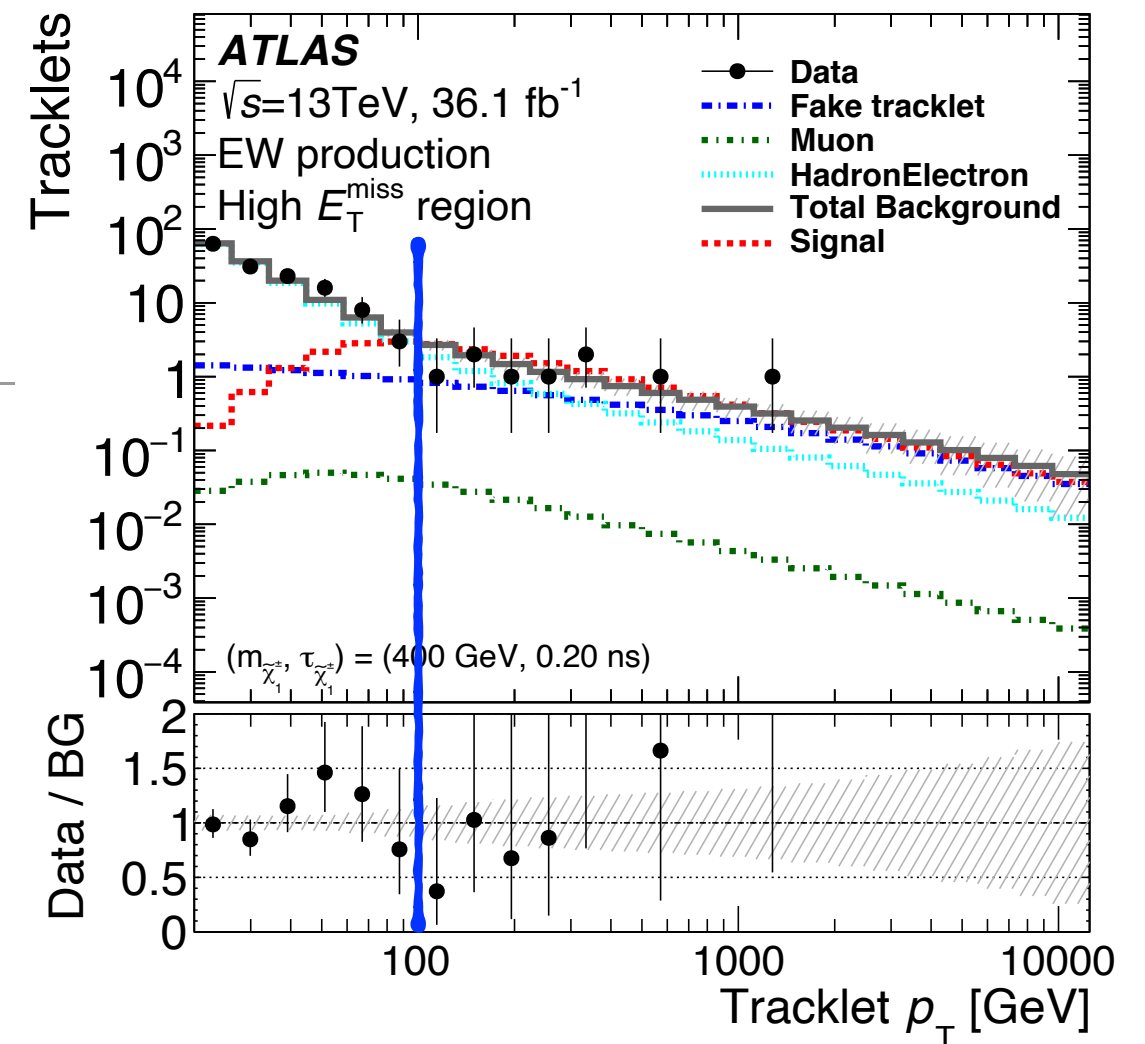
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ATLAS $\sqrt{s}$=13TeV, 36.1 fb^{-1}
EW production
High E_T^{miss} region

$(m_{\tilde{\chi}_1^\pm}, \tau_{\tilde{\chi}_1^\pm}) = (400 \text{ GeV}, 0.20 \text{ ns})$

- Data
- Fake tracklet
- Muon
- HadronElectron
- Total Background
- Signal

Tracklets

Data / BG

Tracklet p_T [GeV]

$\tilde{\chi}_1^\pm \tilde{\chi}_1^0, \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ production

$\tan\beta = 5, \mu > 0$

$\tau_{\tilde{\chi}_1^\pm}$ [ns]

ATLAS
$\sqrt{s}$=13TeV, 36.1 fb^{-1}

Observed 95% CL limit ($\pm 1 \sigma_{theory}$)
Expected 95% CL limit ($\pm 1 \sigma_{exp}$)
ATLAS (8 TeV, 20.3 fb^{-1}, EW prod. Obs.)
Theory (Phys. Lett. B721 (2013) 252)
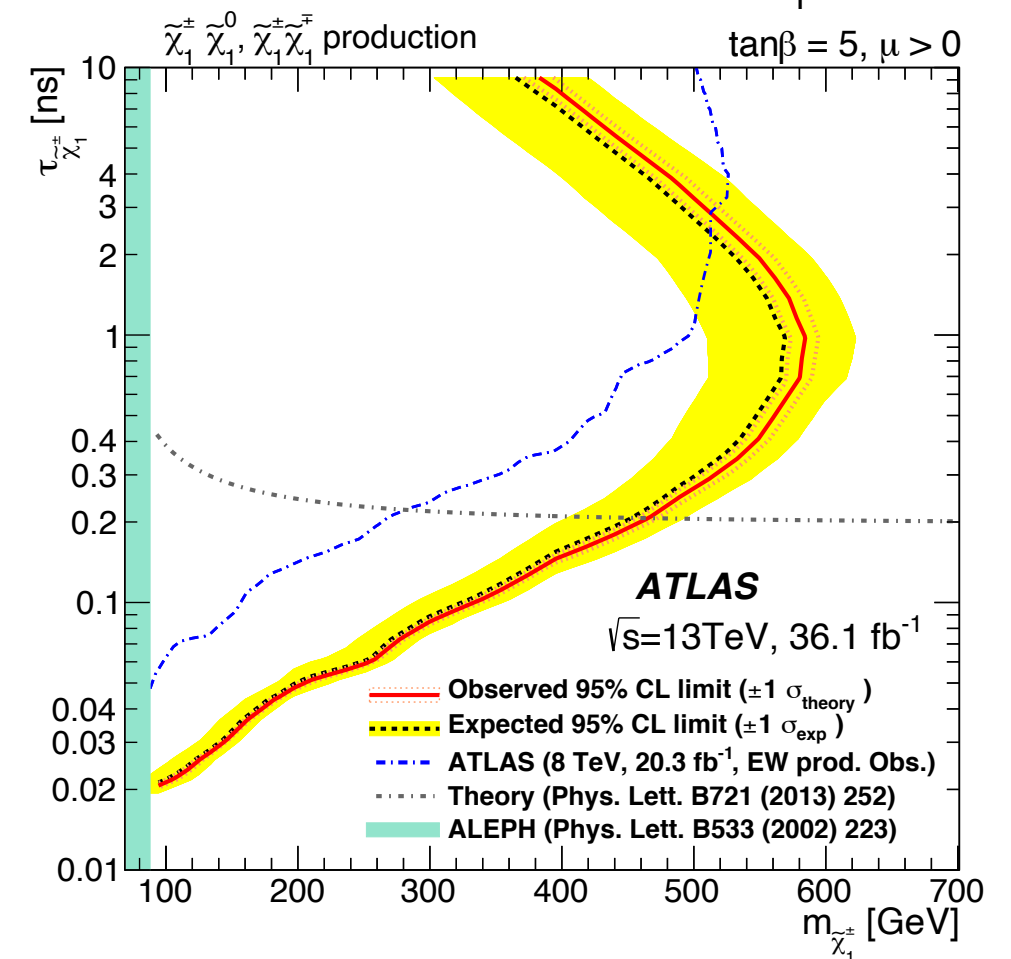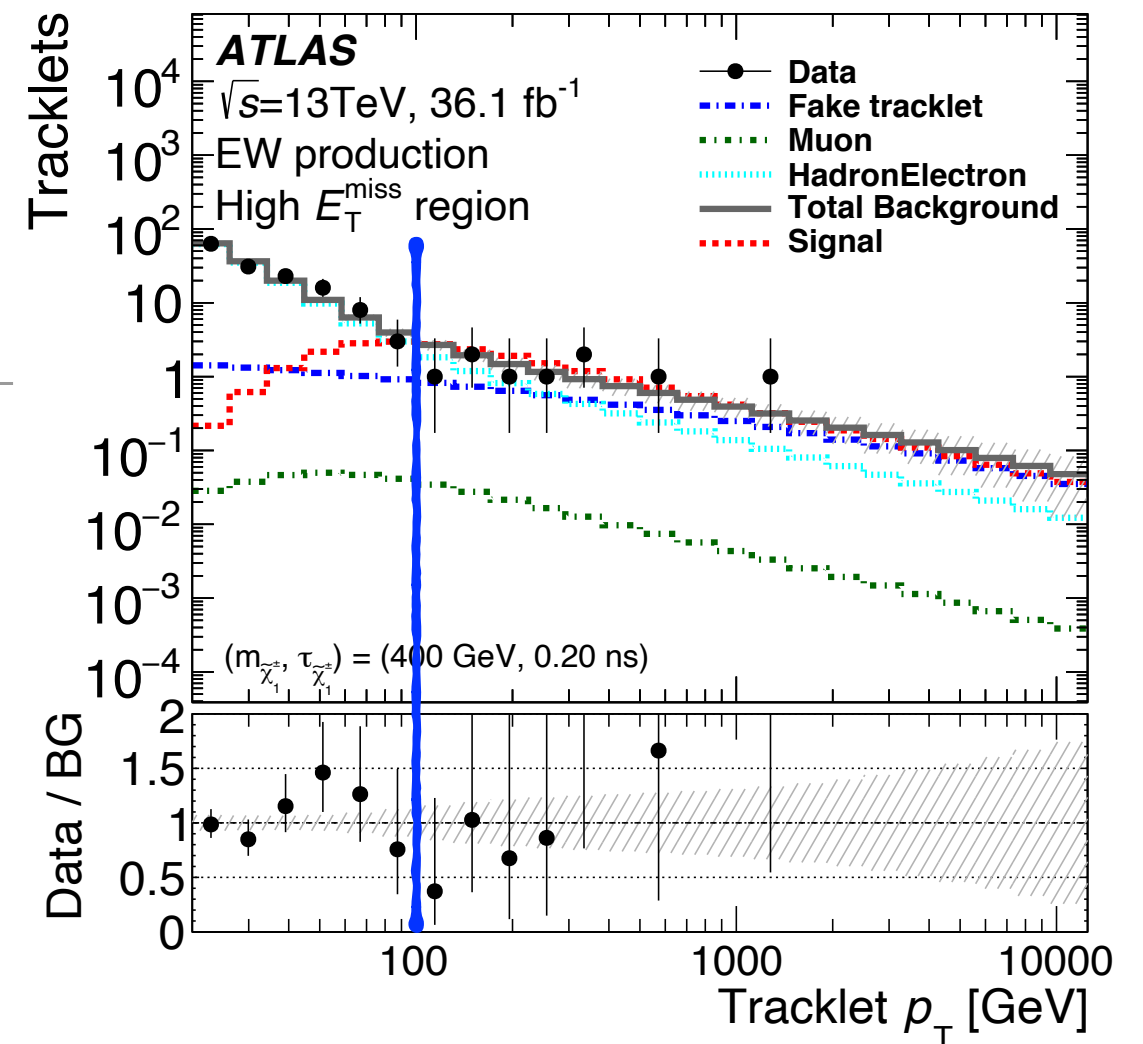ALEPH (Phys. Lett. B533 (2002) 223)
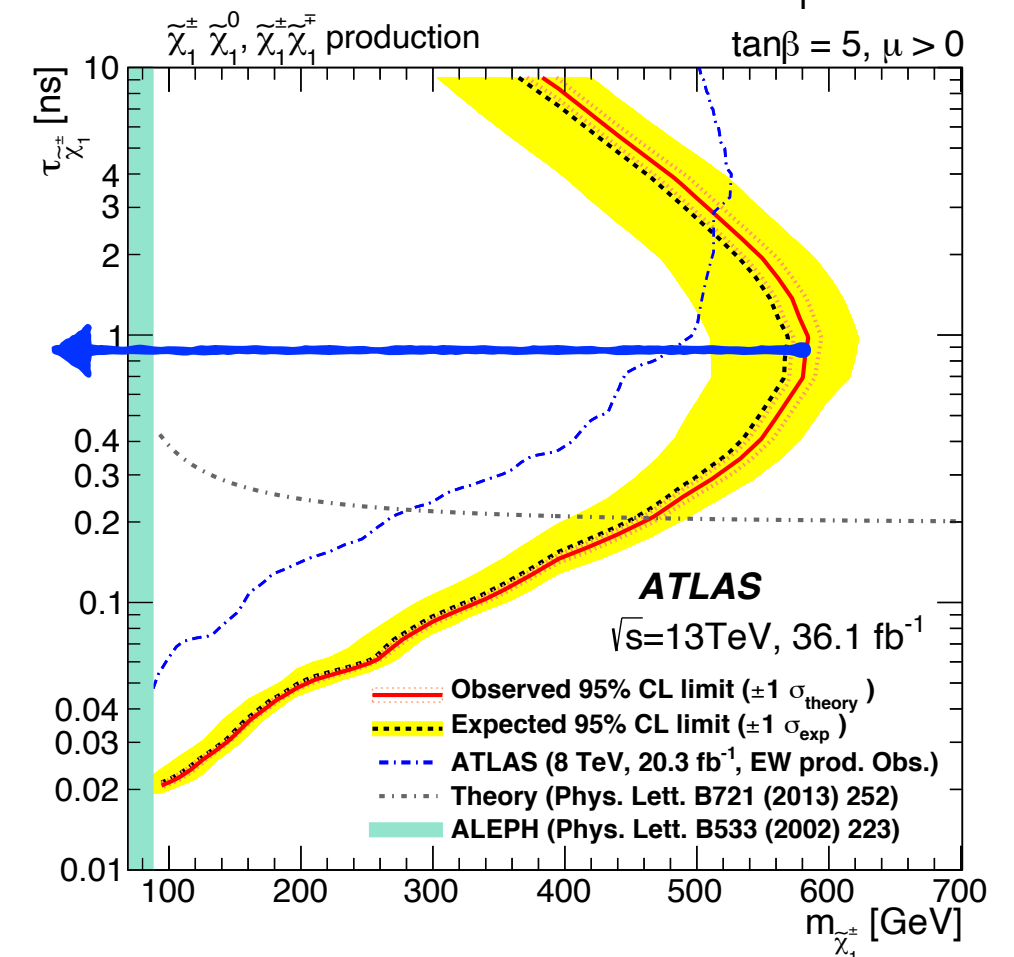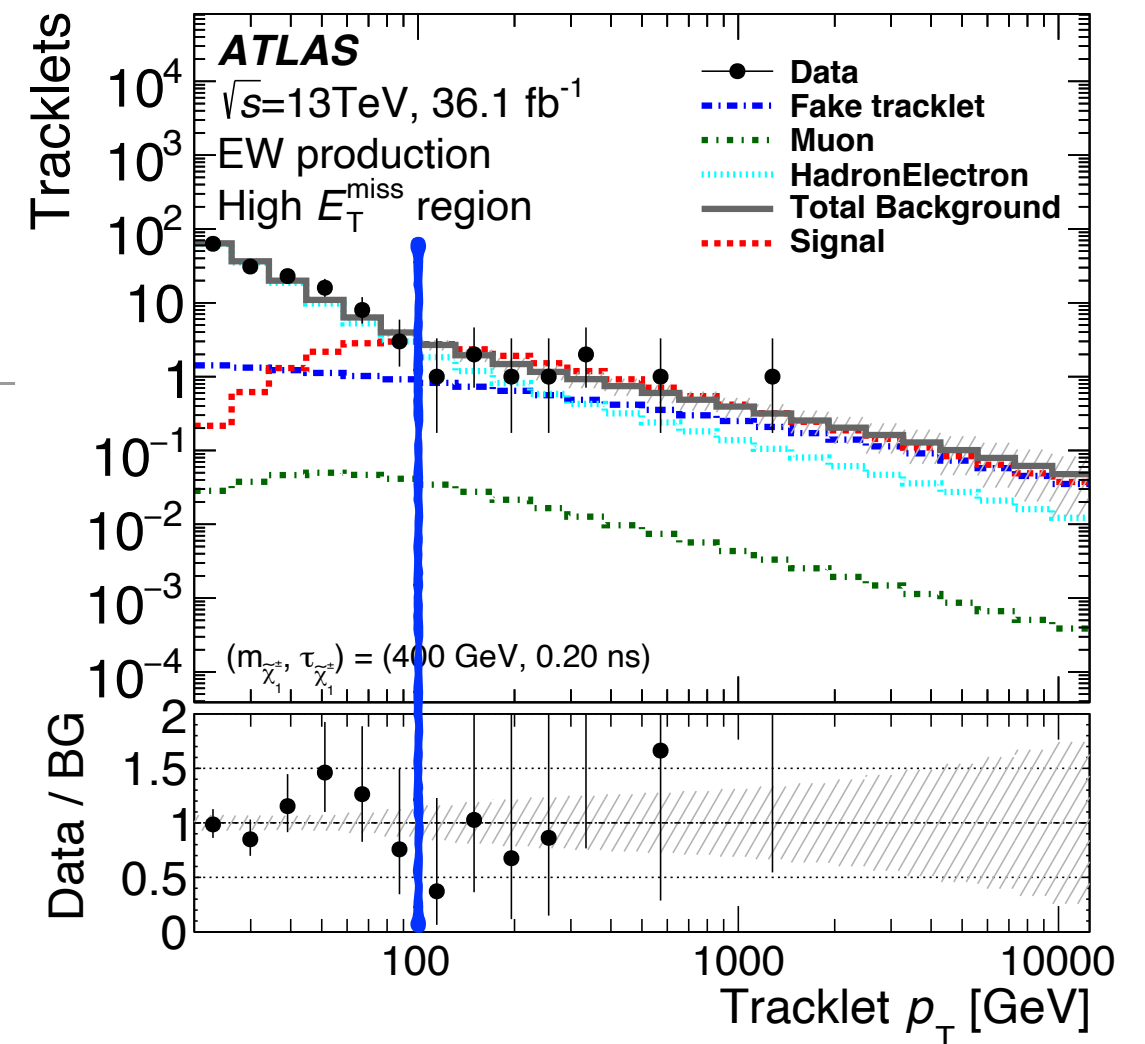
$m_{\tilde{\chi}_1^\pm}$ [GeV]

Disappearing tracks

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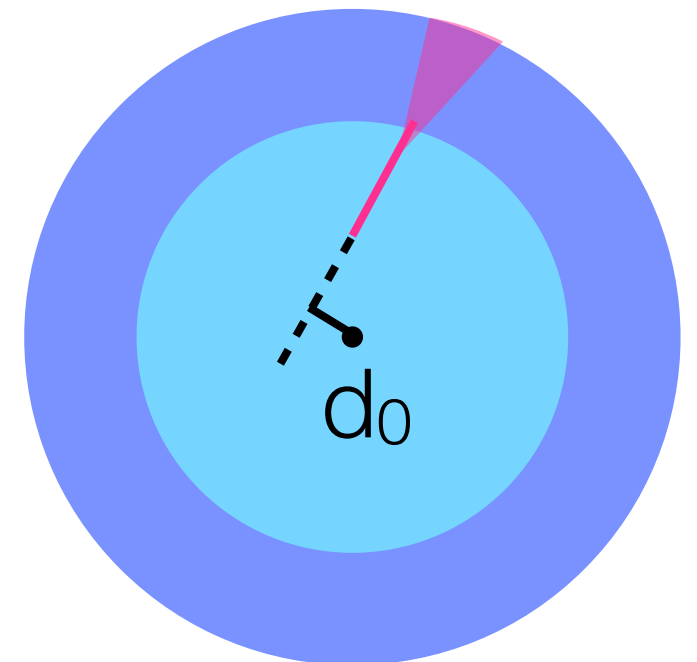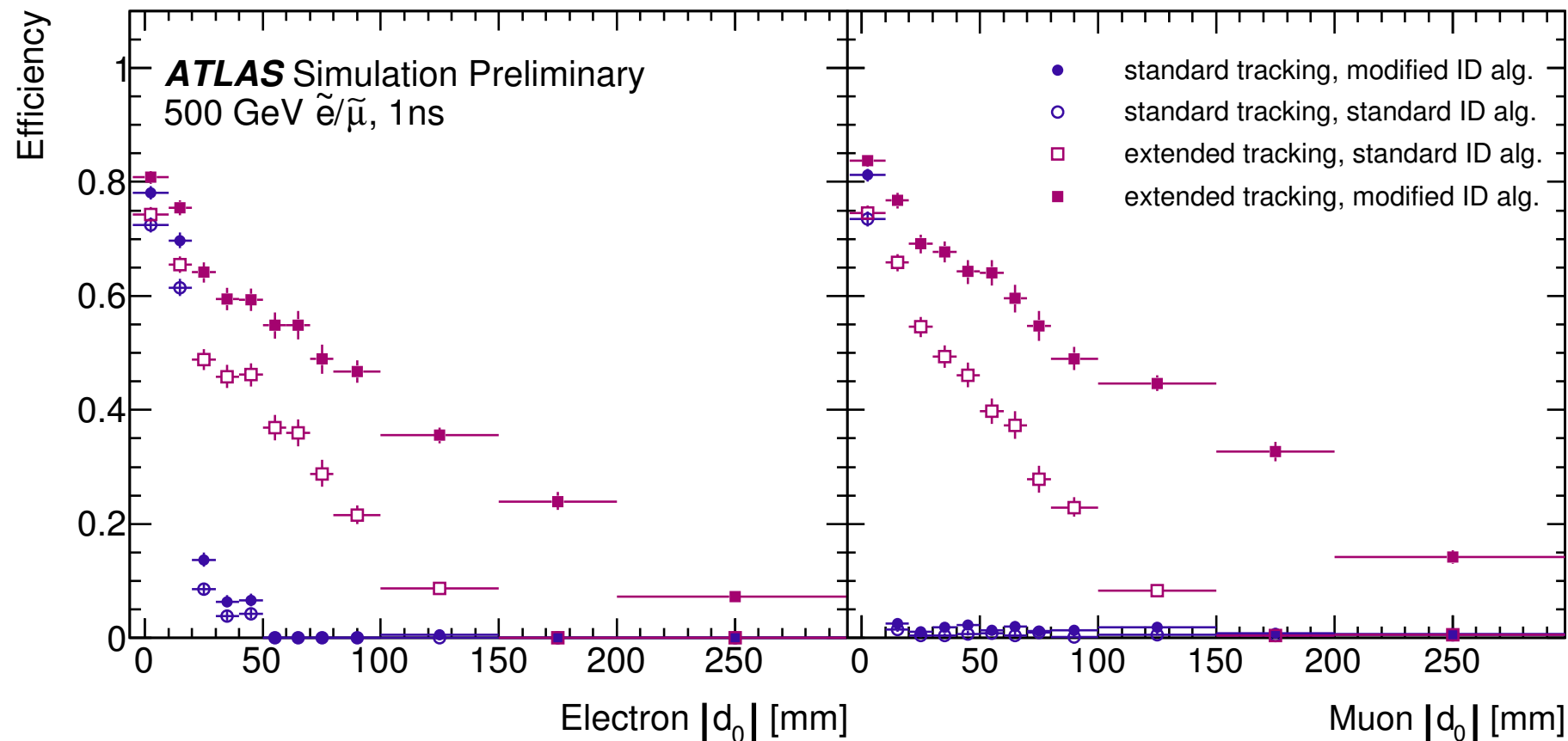

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Data / BG

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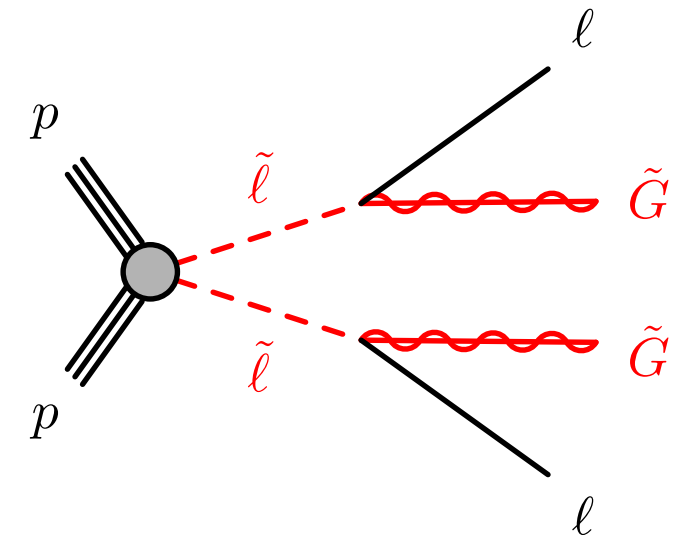- ALEPH (Phys. Lett. B533 (2002) 223)

$m_{\tilde{\chi}_1^\pm}$ [GeV]

Indirect detection example: displaced leptons

- Search for two light leptons (3 SRs: ee, μμ, eμ) not originating from the collision point

- Requires special "large radius" tracking for displaced objects, customised electron and muon identification
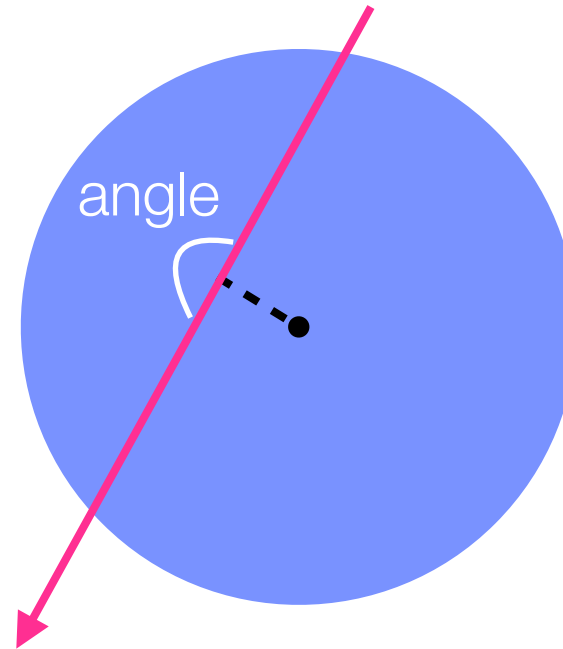

ATLAS Simulation Preliminary
500 GeV $\tilde{e}/\tilde{\mu}$, 1ns

- standard tracking, modified ID alg.
- standard tracking, standard ID alg.
- extended tracking, standard ID alg.
- extended tracking, modified ID alg.

Efficiency

Electron $|d_0|$ [mm]

Muon $|d_0|$ [mm]

d_0

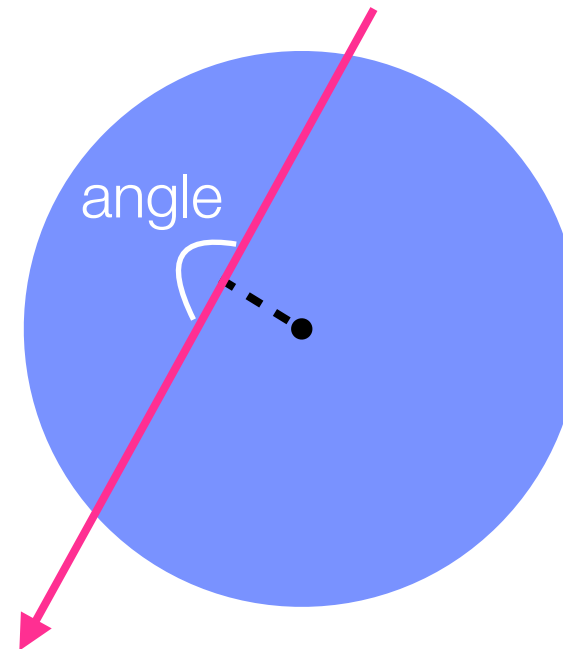# Backgrounds to displaced leptons

- Cosmic ray muons

angle

1) Remove:

Any muon back-to-back with another muon/muon spectrometer hits

Backgrounds to displaced leptons
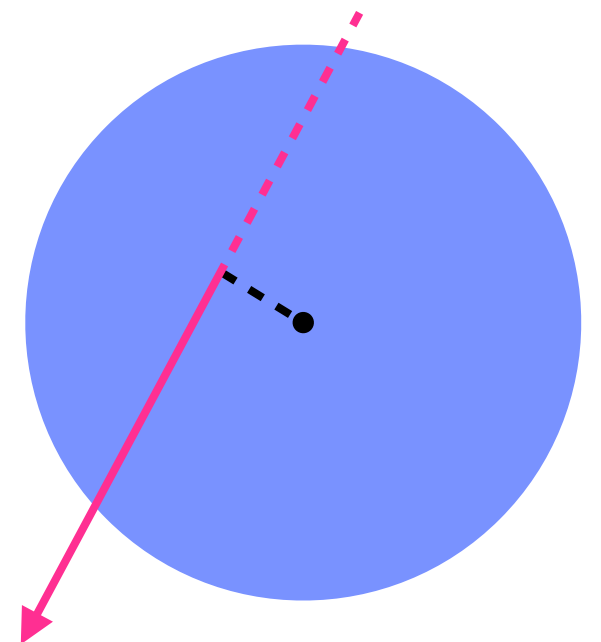
Main backgrounds

- Cosmic ray muons

Background estimation

- μμ: extrapolate from cases where cosmic muons correctly tagged

angle

1) Remove:

Any muon back-to-back with another muon/muon spectrometer hits

Measure probability of tagging each half of cosmic muon

Apply to 1-tagged control sample to estimate SR events

Backgrounds to displaced leptons

- Cosmic ray muons

- "Fake" electrons: track mis-associated to calorimeter energy deposit

- Heavy-flavour decays

- μμ: extrapolate from cases where cosmic muons correctly tagged

1) Remove:

All leptons must be isolated and of good quality (track/calo agreement, good track, …)
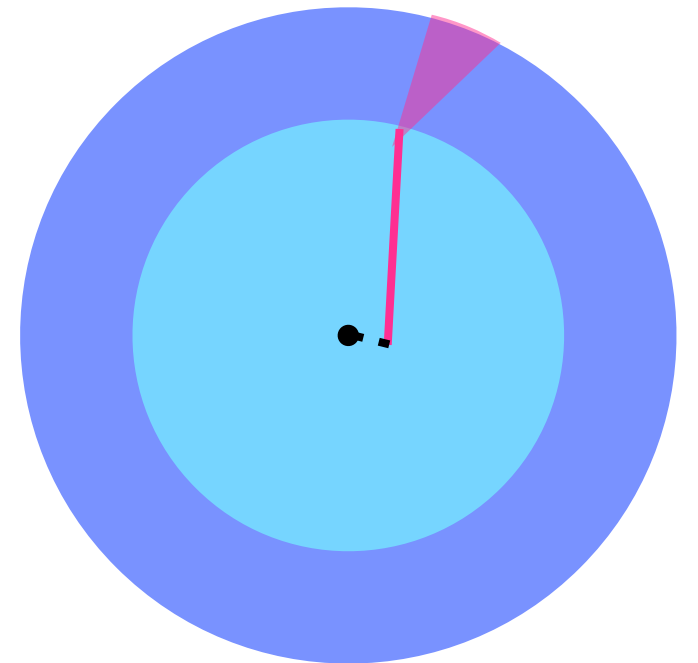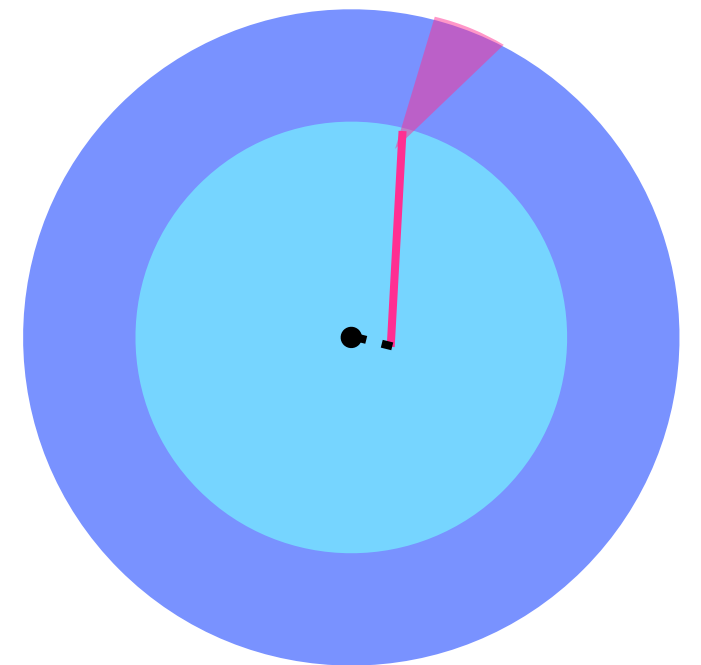
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Quality of two leptons independent.
$N_{sig} = N_B * N_C / N_D$

Backgrounds to displaced leptons

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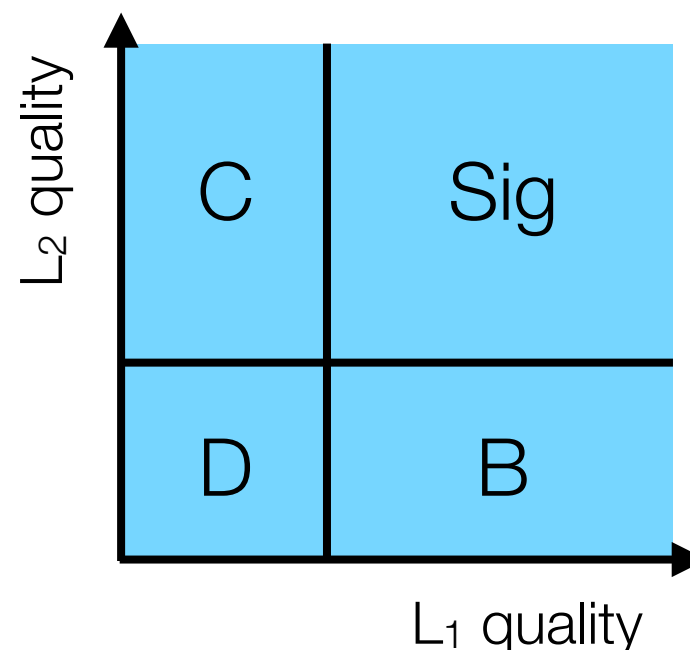
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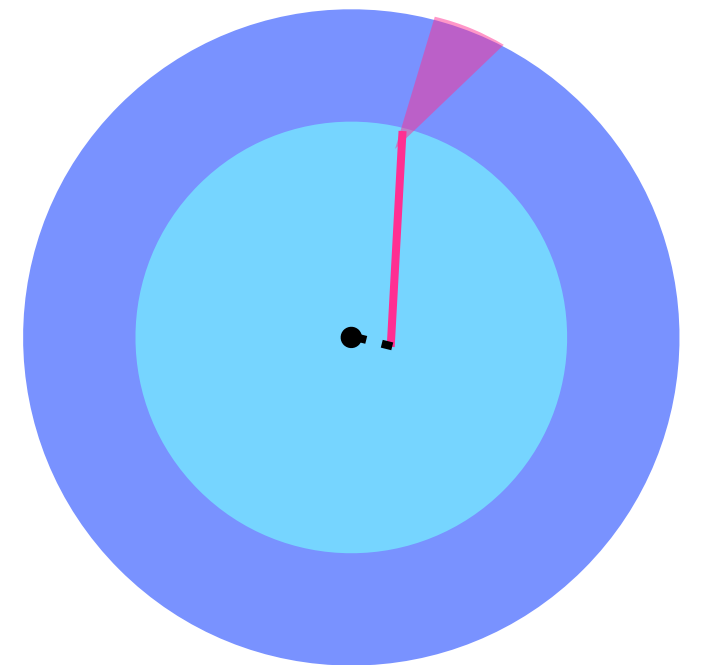
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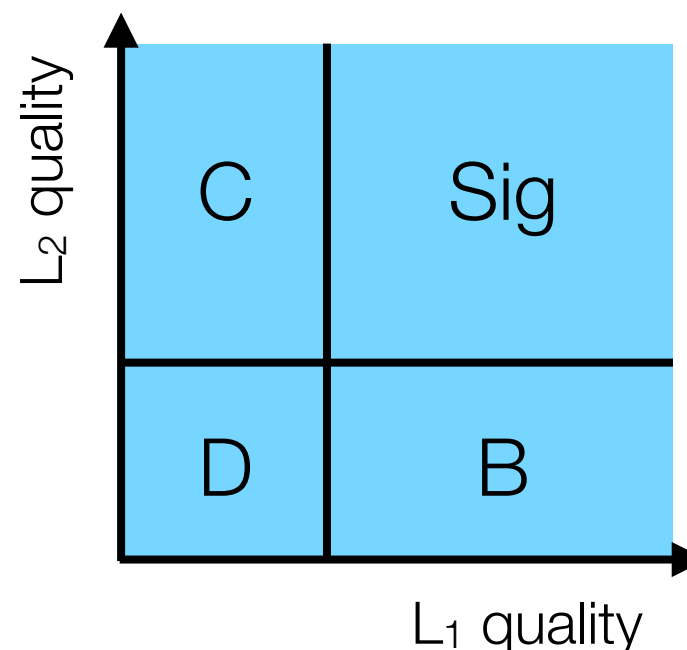$N_{sig} = N_B * N_C / N_D$

Results from displaced lepton search

Region	SR-ee	SR-$\mu\mu$	SR-$e\mu$
Fake + Heavy-Flavor	0.46 ± 0.10	–	$0.007^{+0.019}_{-0.007}$
Cosmics	–	$0.11^{+0.20}_{-0.11}$	–
Expected Background	0.46 ± 0.10	$0.11^{+0.20}_{-0.11}$	$0.007^{+0.019}_{-0.007}$
Observed events	0	0	0

Model-independent upper
limits: ~3 events

Model-dependent limits:
staus and co-NLSP
sleptons

LEP limits (previous best)
are up to ~ 65-90 GeV

Results from displaced lepton search

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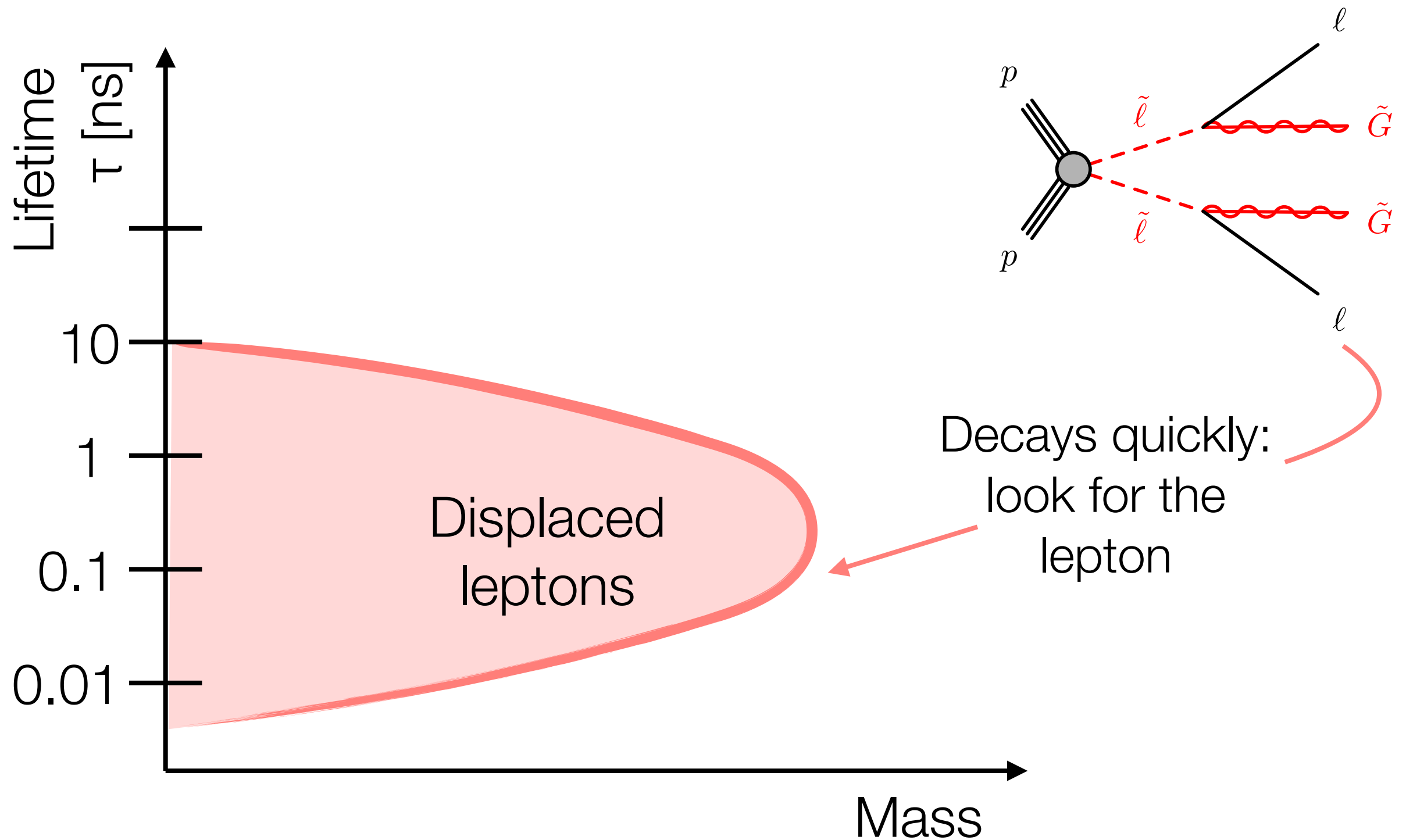
LEP limits (previous best) are up to ~ 65-90 GeV

All new at the LHC!

35
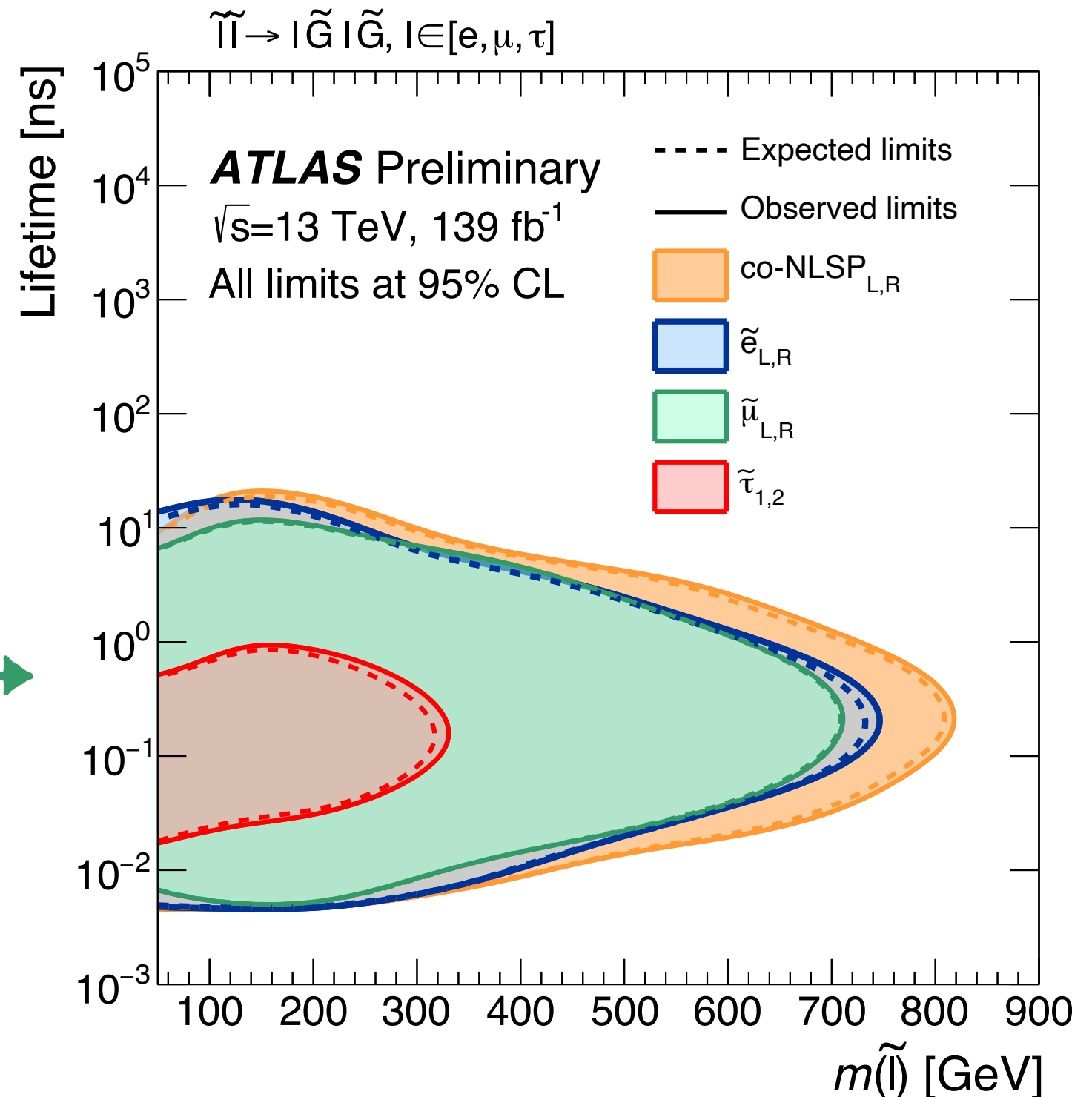
LLP searches complement each other

LLP searches complement each other
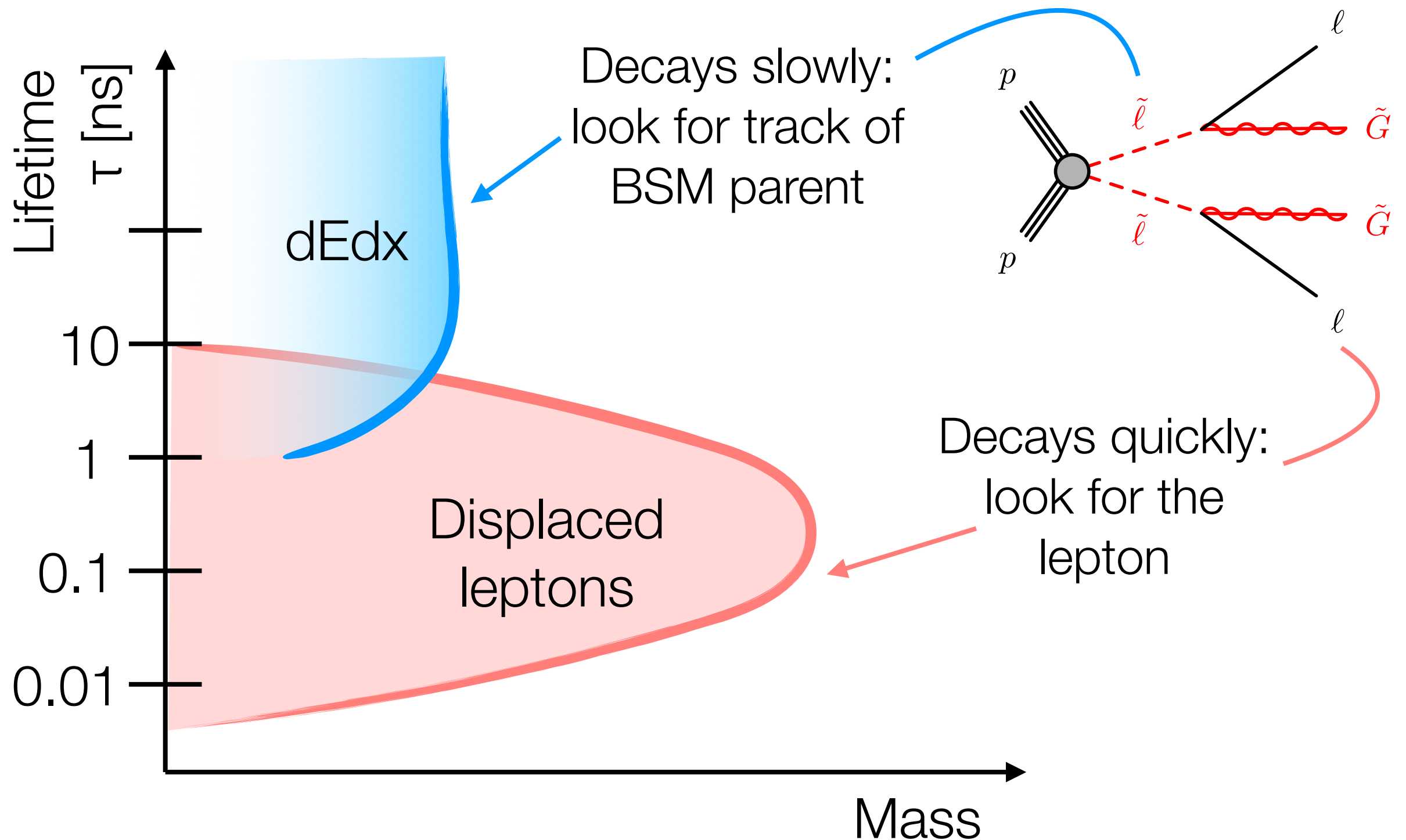
Why LLP searches are the right target for Run 3

- When we decide to do any search, must consider a couple factors:

- We should look **somewhere important**

  - **Motivated by theory**: we already know LLPs are strongly motivated in many BSM models

- We should look **somewhere effective**

  - Look for targets which will benefit most from **increasing datasets**

  - Find **opportunities** where the LHC dataset and our technical abilities give us the most power, so work invested will yield better results

  - Prioritise "**discovery potential**"!

  - LLPs are a great candidate for effectiveness as well

LLPs and increasing datasets

Rule of thumb: with **high backgrounds**, sensitivity $\mathcal{S} \approx s/\sqrt{b}$

$$s, b \propto \mathcal{L} \text{, therefore } \mathcal{S} \propto \sqrt{\mathcal{L}}$$

Need 4x the data to double the analysis reach!

LLPs and increasing datasets

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For LLP analyses, cuts can always be tuned to keep **~zero background events** while keeping some signal acceptance

LLPs and increasing datasets

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Need 4x the data to double the analysis reach!

For LLP analyses, cuts can always be tuned to keep **~zero background events** while keeping some signal acceptance

Upper limit on 0 events is ~3

Cross section limit is ~$3/\mathscr{L}$, therefore $\mathscr{S} \propto \mathscr{L}$

LLPs and increasing datasets

Rule of thumb: w ...ensitivity $\mathscr{S} \approx s/\sqrt{b}$

s $\overline{\mathscr{L}}$

Need 4x t ...ysis reach!

For LLP analyse ...d to keep **~zero background ev** ...signal acceptance
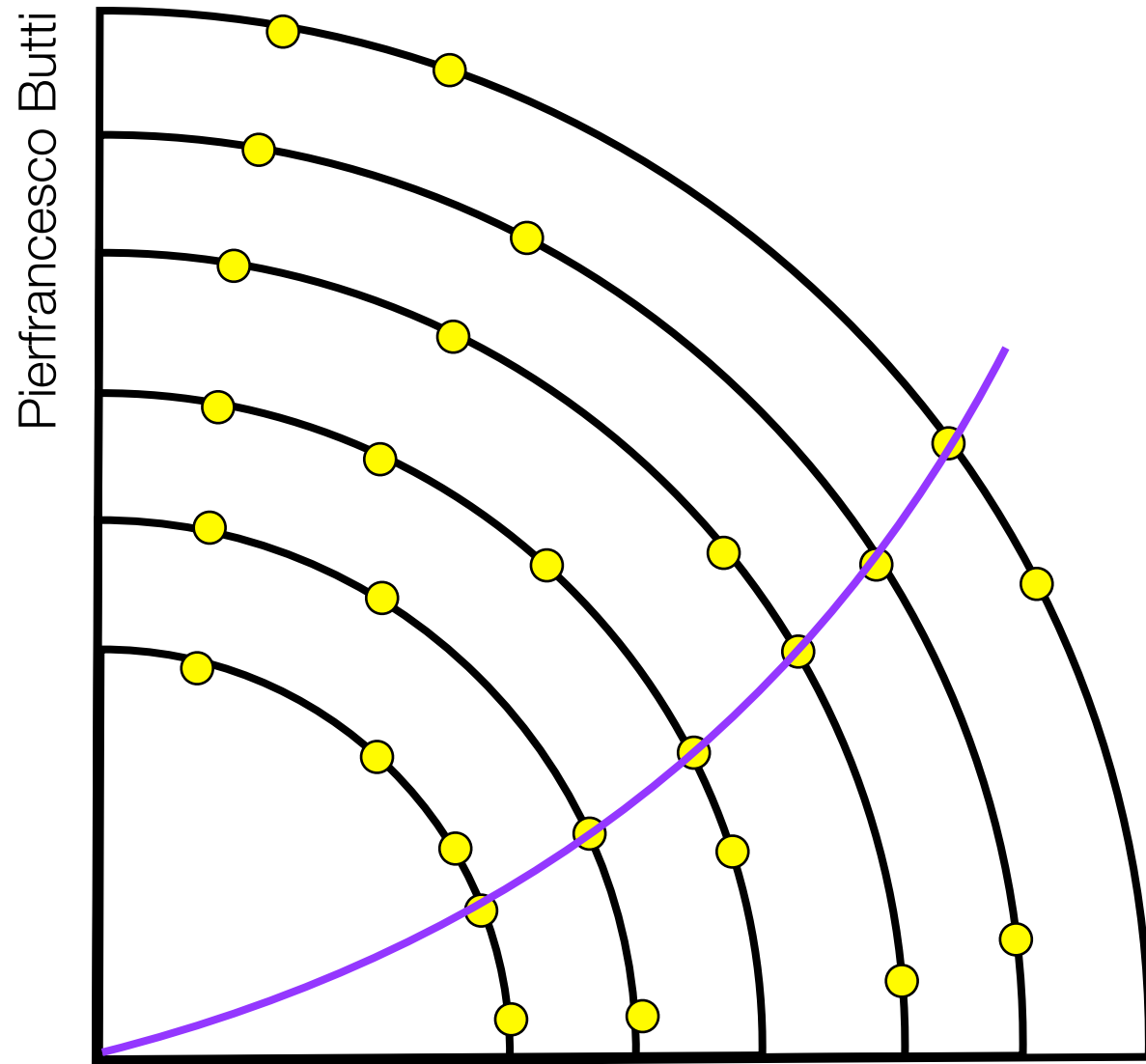
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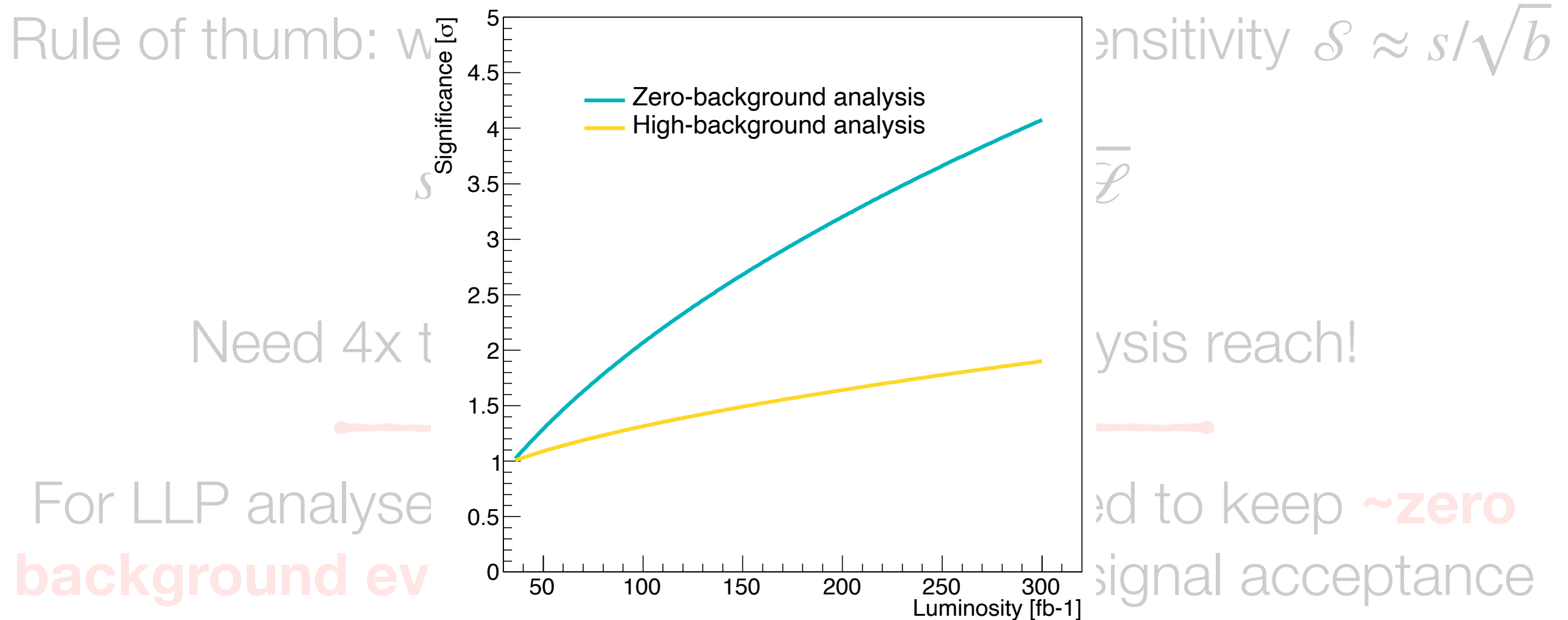
LLP analyses **benefit most** from larger datasets!

Cross section limit is ~3/$\mathscr{L}$, therefore $\mathscr{S} \propto \mathscr{L}$

Improving track reconstruction

Pierfrancesco Butti

Step 1: tracks from origin
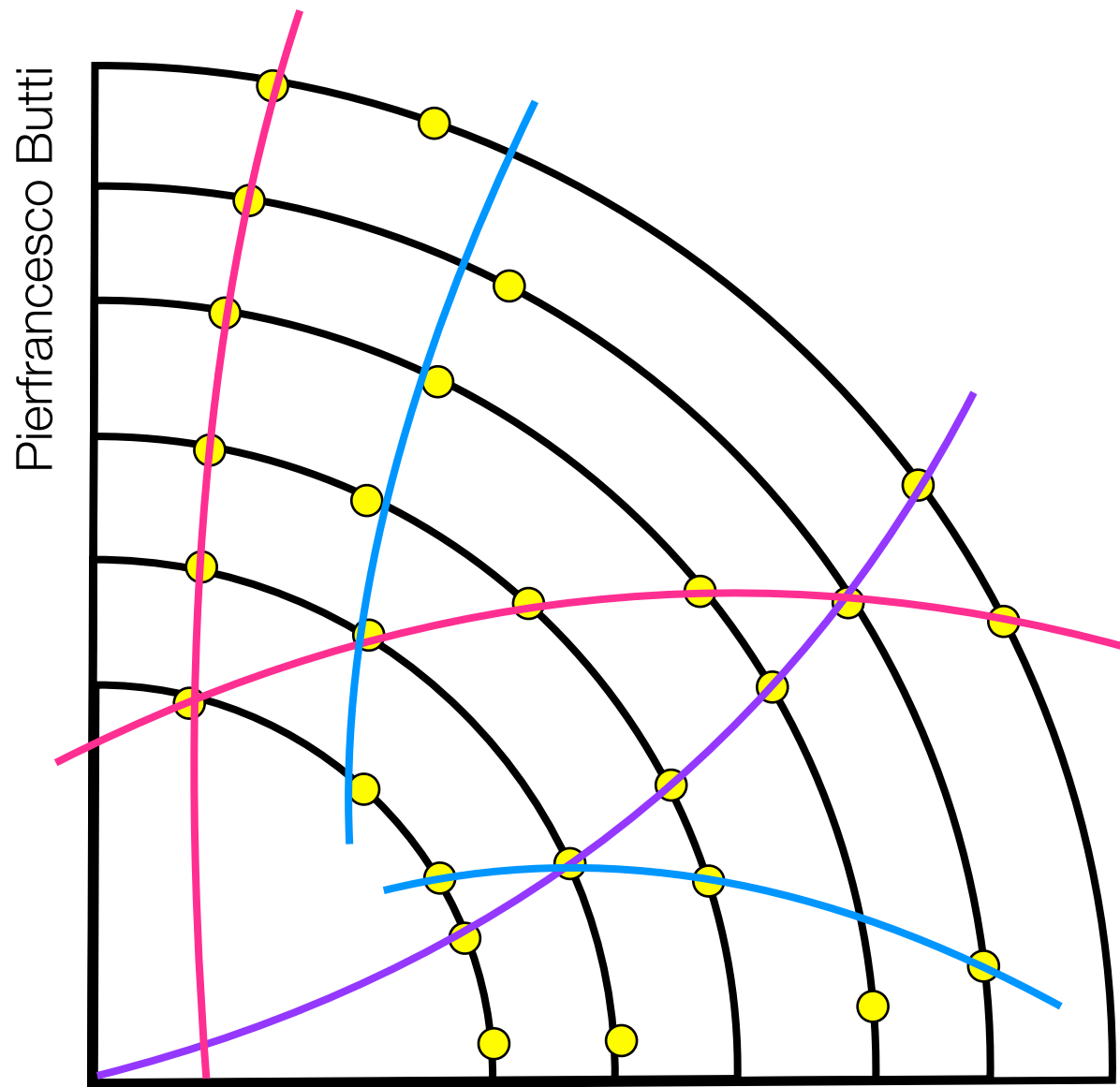
Improving track reconstruction
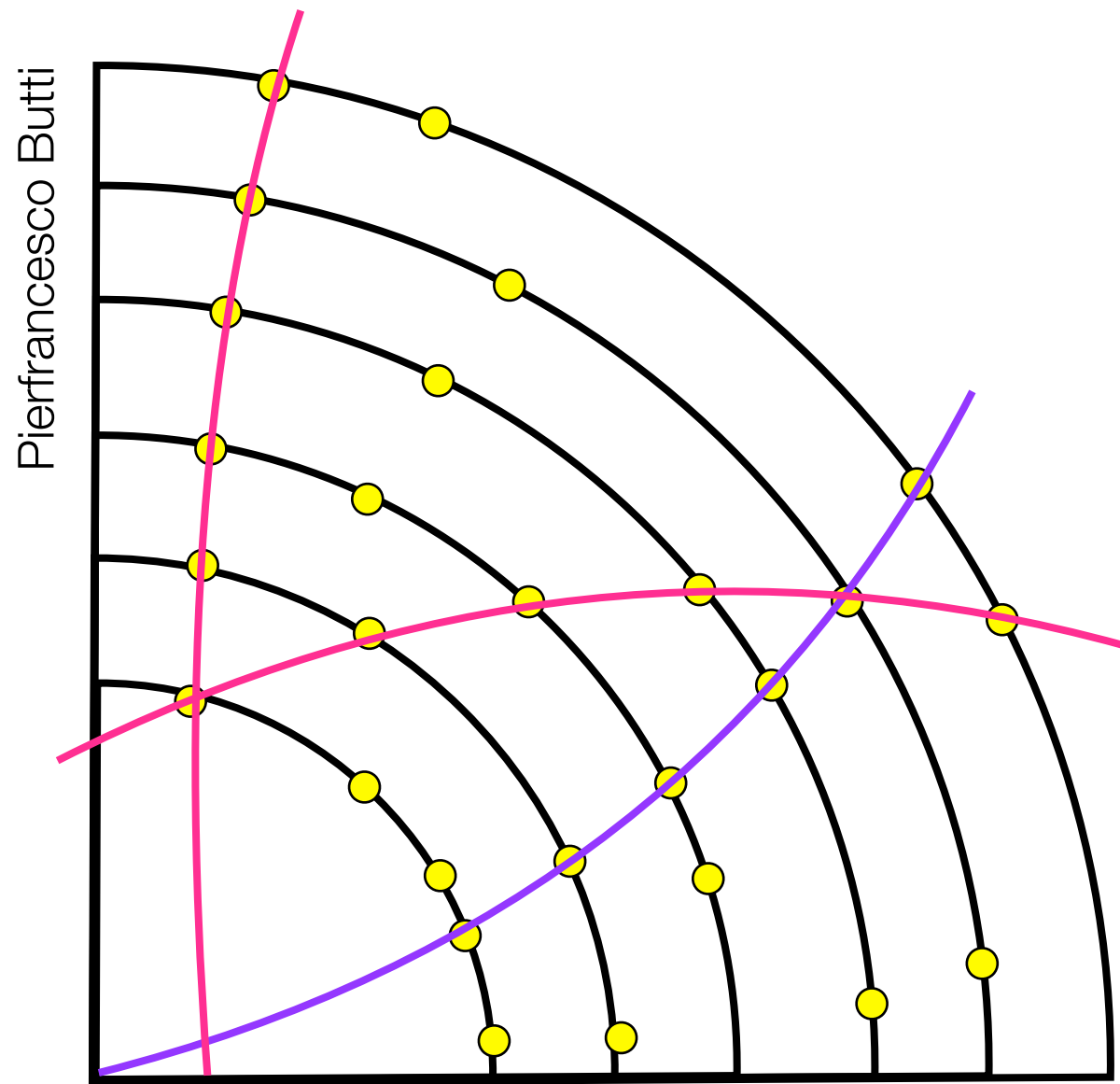
Step 1: tracks from origin

Step 2: large-radius tracks

Improving track reconstruction

Pierfrancesco Butti

Step 1: tracks from origin

Step 2: large-radius tracks

Today

- Large-radius tracking (LRT) is slow and produces many "**fake**" tracks

- Can only run it on pre-selected subset of events - missing some

39

Improving track reconstruction

Step 1: tracks from origin

Step 2: large-radius tracks

Pierfrancesco Butti

Today

- Large-radius tracking (LRT) is slow and produces many "**fake**" tracks

- Can only run it on pre-selected subset of events - missing some

LHC Run 3

- Thanks to recent updates, LRT faster and produces fewer fakes

- Improvements offline & online

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Better data flow

Run 2

Data flow
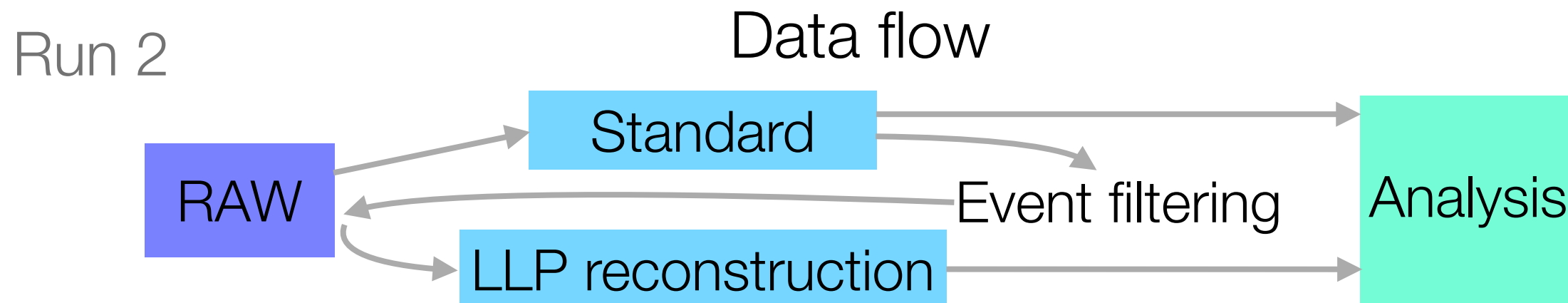
- Due to size of large-radius tracking output, was impossible to run on all events

- Filtering step used information in standard reconstruction to pick events which would be processed with LRT - essentially acts as a second trigger with signal efficiency < 1

- Removing fakes reduced LRT output size so that no filters needed in Run 3

- Result: **increased acceptance for every analysis** using large-radius tracking; corresponding sensitivity increase

New triggers to extend ATLAS LLP search reach

Run 2
- Tracking at high-level trigger only for "standard" tracks and in regions of interest

Run 3
- Extending HLT tracking to full event in all jet and MET signatures

- Introducing large-radius tracking in specific regions of interest (in progress)
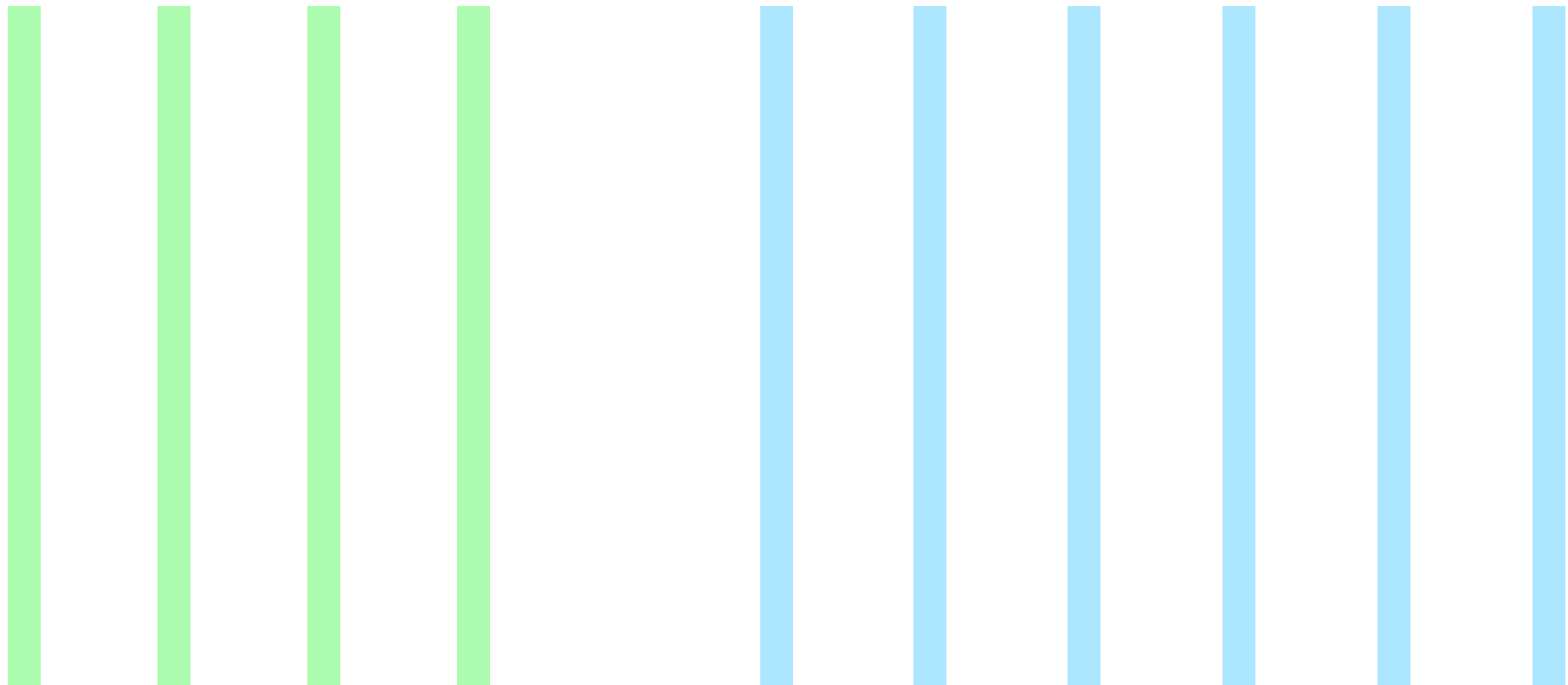
New triggers to extend ATLAS LLP search reach

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With standard tracking in full event:

New triggers to extend ATLAS LLP search reach

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Run 3 · Extending HLT tracking to full event in all jet and MET signatures

· Introducing large-radius tracking in specific regions of interest (in progress)

With standard tracking in full event:

Trigger on an isolated high-momentum track (dEdx)

New triggers to extend ATLAS LLP search reach

Run 2
- Tracking at high-level trigger only for "standard" tracks and in regions of interest

Run 3
- Extending HLT tracking to full event in all jet and MET signatures

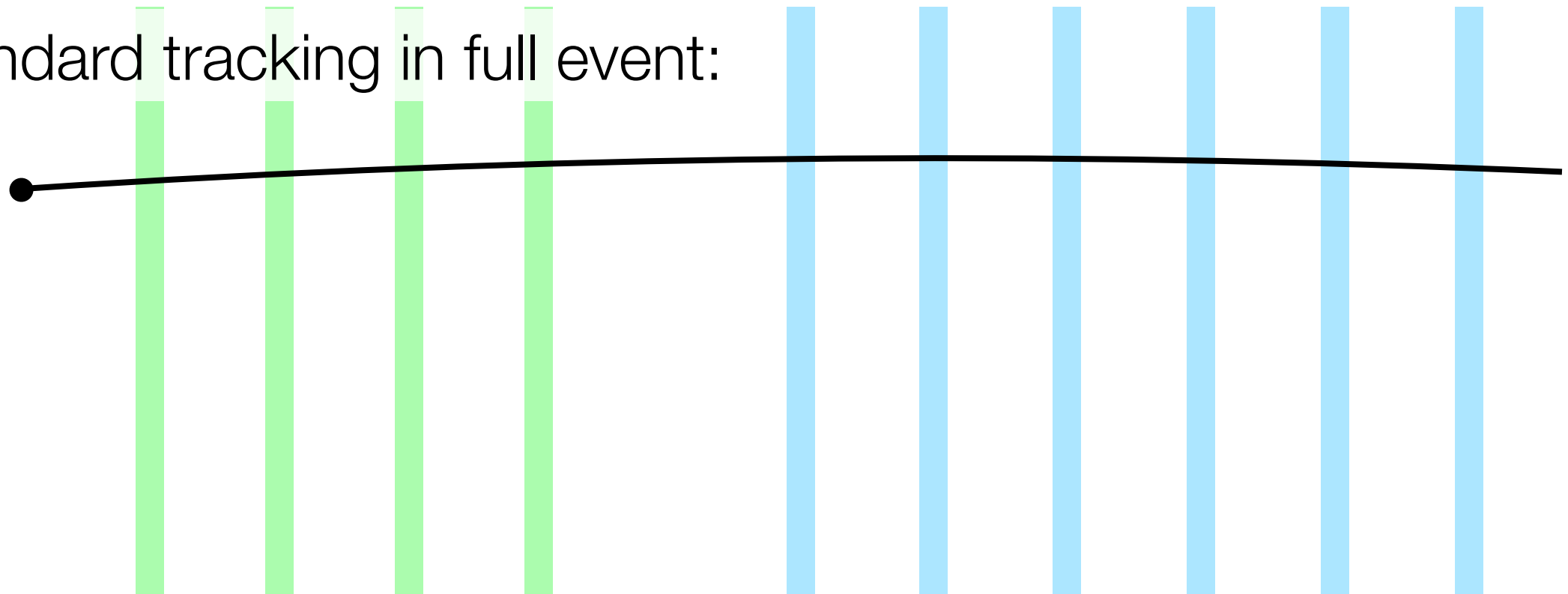- Introducing large-radius tracking in specific regions of interest (in progress)

With standard tracking in full event:

With large-radius tracking:

New triggers to extend ATLAS LLP search reach

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- Extending HLT tracking to full event in all jet and MET signatures

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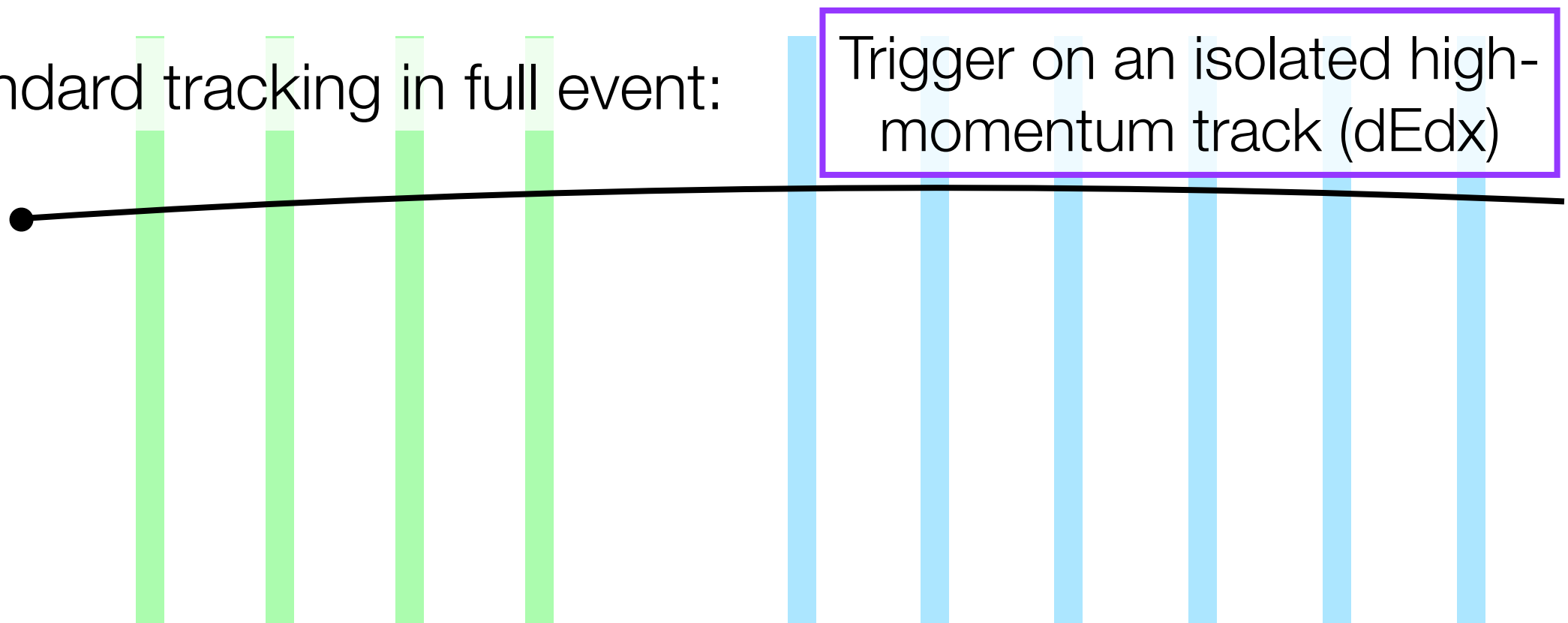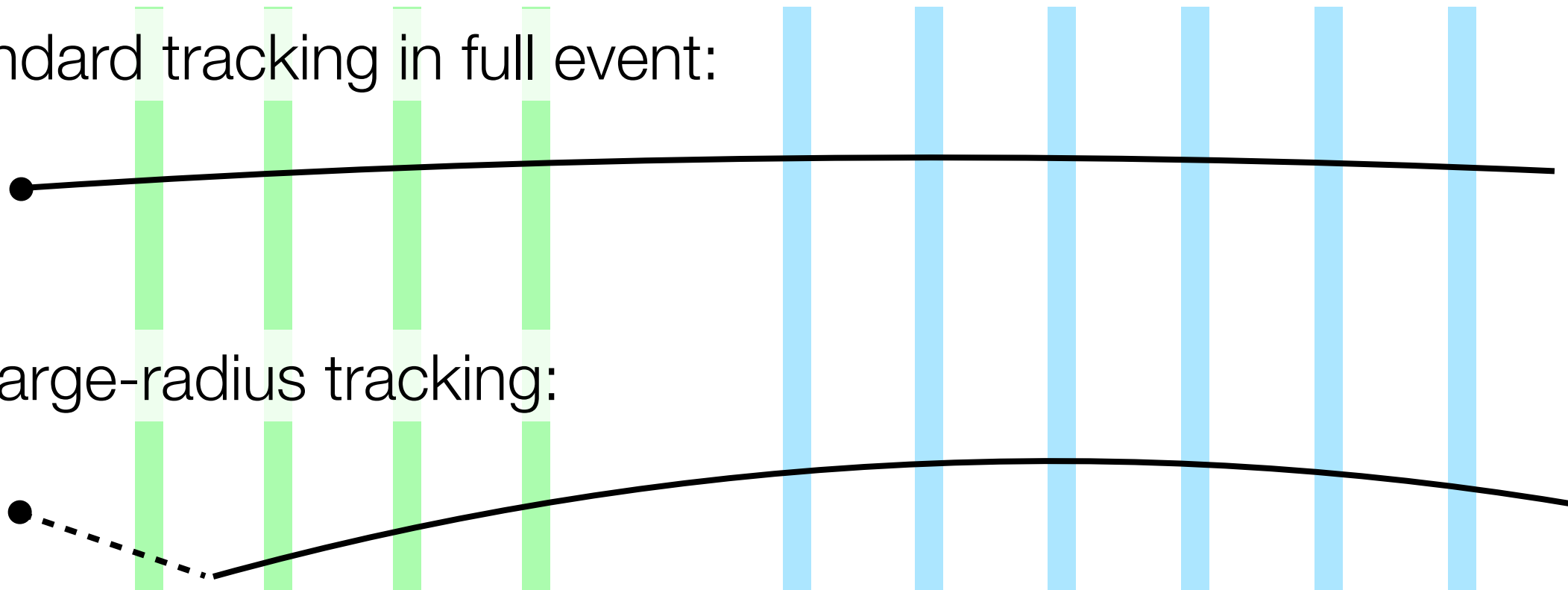
With standard tracking in full event:
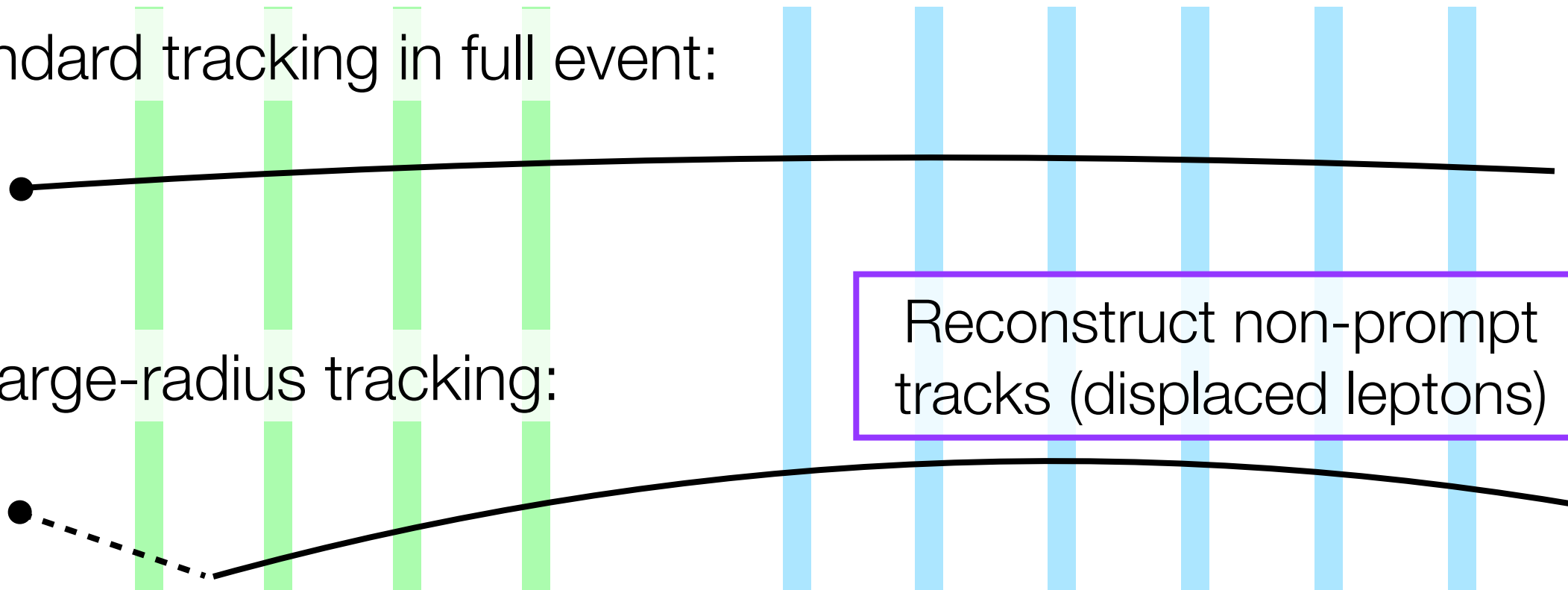
With large-radius tracking:

Reconstruct non-prompt tracks (displaced leptons)

Reinterpretations
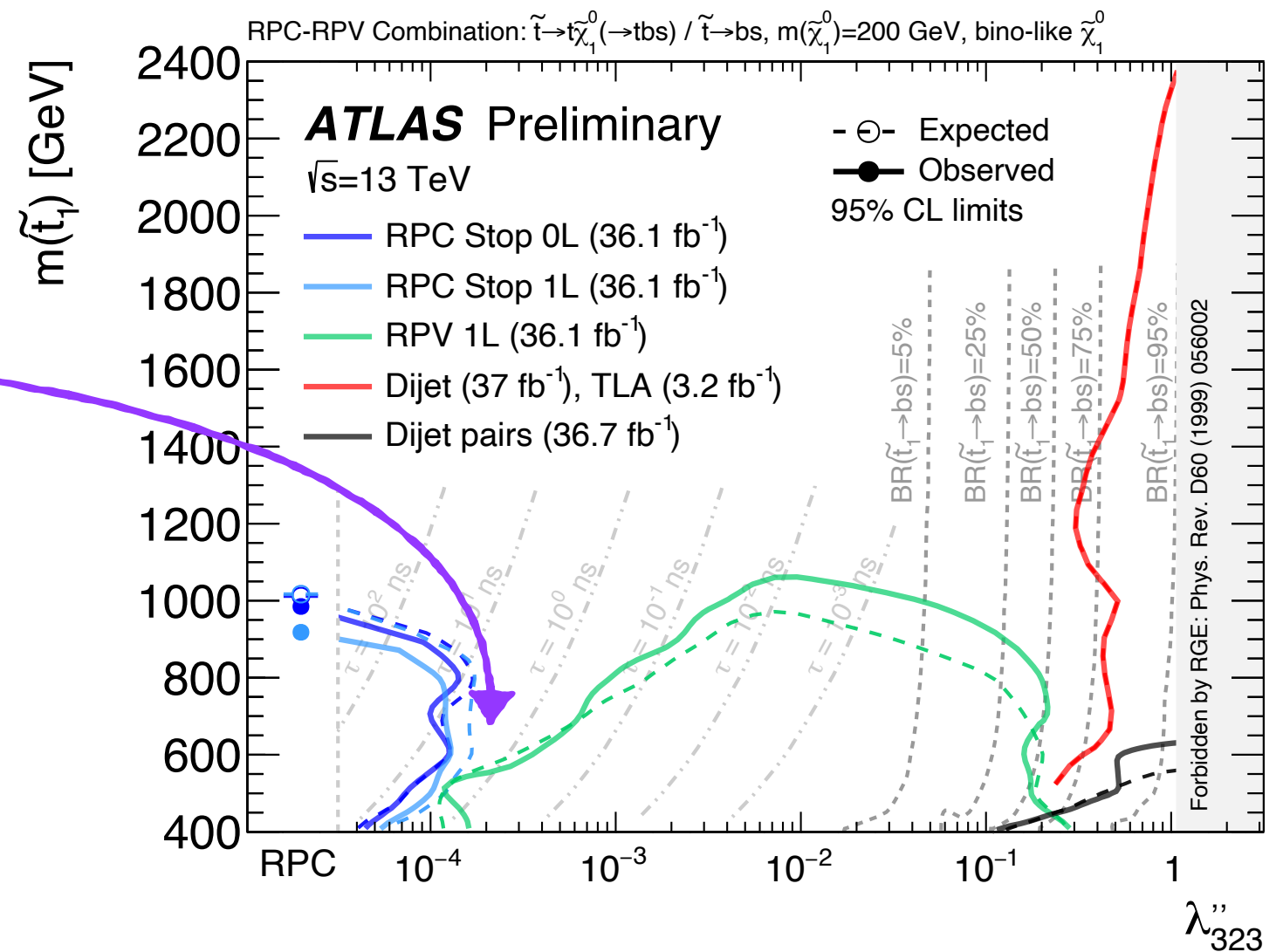
This should be covered by displaced vertex+jets analysis

RPC-RPV Combination: $\tilde{t} \to t\tilde{\chi}_1^0(\to tbs)$ / $\tilde{t} \to bs$, $m(\tilde{\chi}_1^0)$=200 GeV, bino-like $\tilde{\chi}_1^0$

ATLAS Preliminary

$\sqrt{s}$=13 TeV

95% CL limits

- $-\ominus-$ Expected
- $-\bullet-$ Observed

RPC Stop 0L (36.1 fb^{-1})
RPC Stop 1L (36.1 fb^{-1})
RPV 1L (36.1 fb^{-1})
Dijet (37 fb^{-1}), TLA (3.2 fb^{-1})
Dijet pairs (36.7 fb^{-1})

$m(\tilde{t}_1)$ [GeV]

λ''_{323}

BR($\tilde{t}_1 \to bs$)=5%
BR($\tilde{t}_1 \to bs$)=25%
BR($\tilde{t}_1 \to bs$)=50%
BR($\tilde{t}_1 \to bs$)=75%
BR($\tilde{t}_1 \to bs$)=95%

Forbidden by RGE: Phys. Rev. D60 (1999) 056002

Reinterpretations

This should be covered by displaced vertex+jets analysis

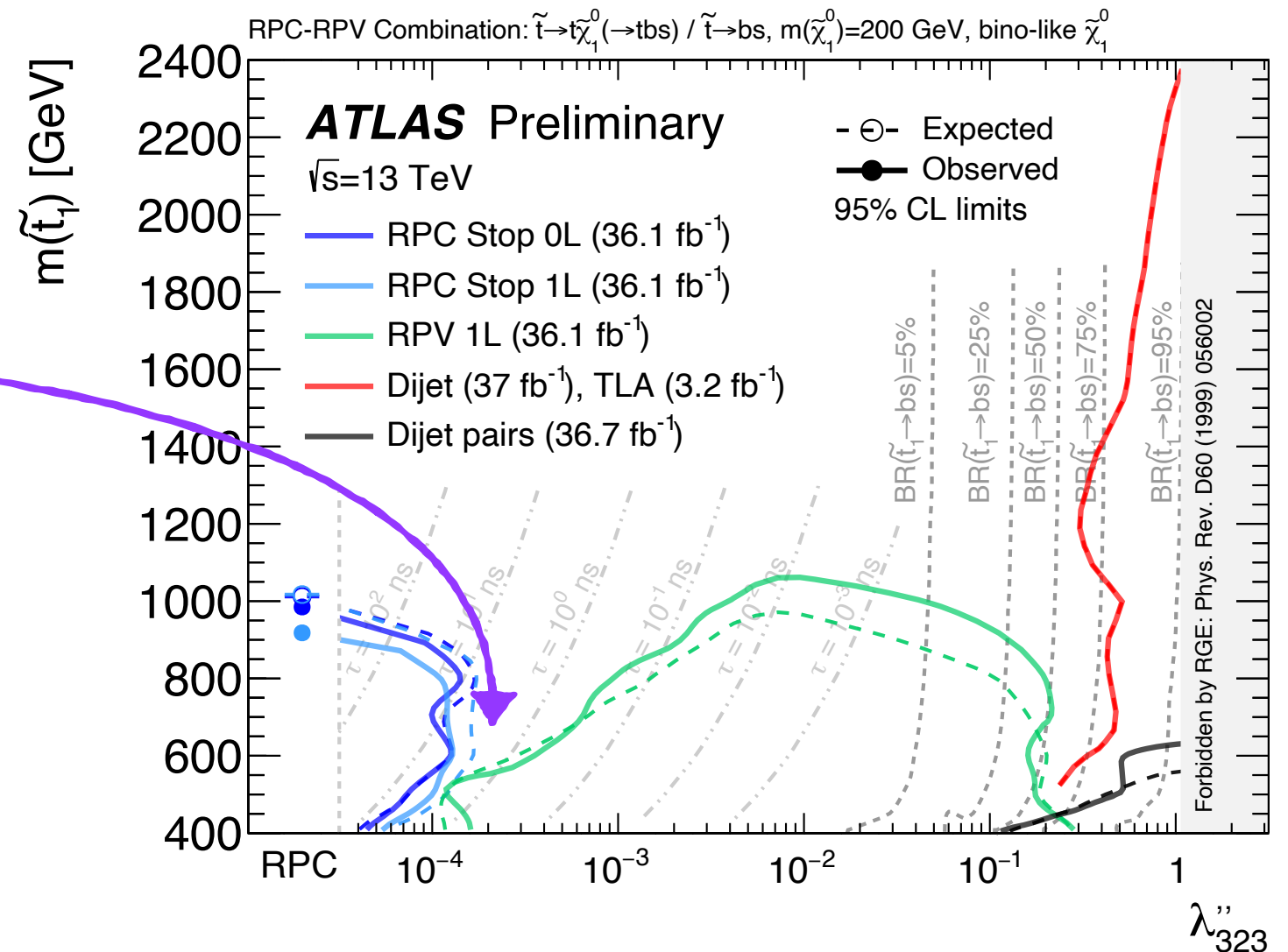So why is there no line in the plot?

Reinterpretations

This should be covered by displaced vertex+jets analysis

So why is there no line in the plot?

RPC-RPV Combination: $\tilde{t}\to t\tilde{\chi}^0_1(\to tbs)$ / $\tilde{t}\to bs$, $m(\tilde{\chi}^0_1)$=200 GeV, bino-like $\tilde{\chi}^0_1$

ATLAS Preliminary
$\sqrt{s}$=13 TeV

- RPC Stop 0L (36.1 fb^{-1})
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- ⊝ - Expected
- ● - Observed
95% CL limits

$m(\tilde{t}_1)$ [GeV]

λ''_{323}

Forbidden by RGE: Phys. Rev. D60 (1999) 056002

BR($\tilde{t}_1\to bs$)=5%, BR($\tilde{t}_1\to bs$)=25%, BR($\tilde{t}_1\to bs$)=50%, BR($\tilde{t}_1\to bs$)=75%, BR($\tilde{t}_1\to bs$)=95%

- Testing new interpretations for LLP searches can be tricky after the fact!

- This is one of our **key points for improvement**. Internally, new framework for code preservation allowing easy re-running within the collaboration

- What about for **external users**? Continually looking for improved ways to make our results useful - let us know any suggestions!

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Long lived particles …

Long lived particles …

→ belong naturally in tons of BSM models

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→ can help explain where dark matter is

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→ improve ~linearly with data collected

→ give us new opportunities for discovery

Stay tuned (or join in) for exciting results!

Backup

Further trigger info for displaced leptons

- Triggers for electrons: HLT_g140_loose, HLT_2g50_loose, HLT_2g50_loose_L12EM20VH

  - L1 requirements: pT 2x20 with no isolation or 1x24 with isolation ending at 50 GeV

  - "Loose" at HLT: defined based on shower shape variables, leakage into HCal, energy distribution [ref.]

- Triggers for muons: HLT_mu60_0eta105_msonly

  - L1 requirements: no isolation on candidate, 20 GeV pT. Some built-in pointing requirements which start to harm efficiency at high d0 (200ish)

  - HLT requirements: central ($|\eta| < 1.05$) track in muon spectrometer, pT > 60, no requirement for an associated inner detector track

dEdx measurements in the ATLAS tracker

- Pixel: up to 5 hits (depending on layer overlap), use a truncated mean to define the dEdx used in the analysis

- SCT: outputs essentially binary information. Some preliminary studies in 2015 demonstrate it's potentially possible to extract dEdx equivalent information though with much worse resolution than we have in pixels. At present no plans to use this.

- TRT: does provide dEdx measurements, but have not been calibrated or explored by the analysis team. This has been used by other ATLAS analyses though.

  - Constraints for use in analysis: would require new dedicated calibration, and could only be used for stable particle exclusions
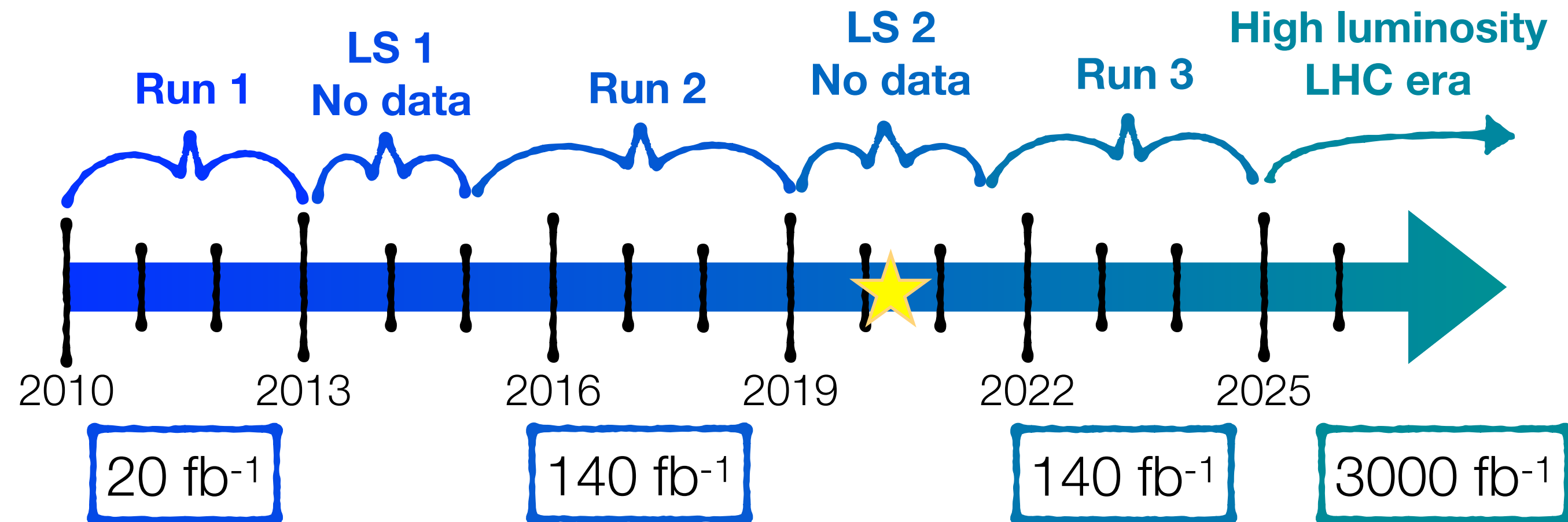
LHC: energies and datasets

Two **key factors**: amount of data collected
and collision centre of mass energy
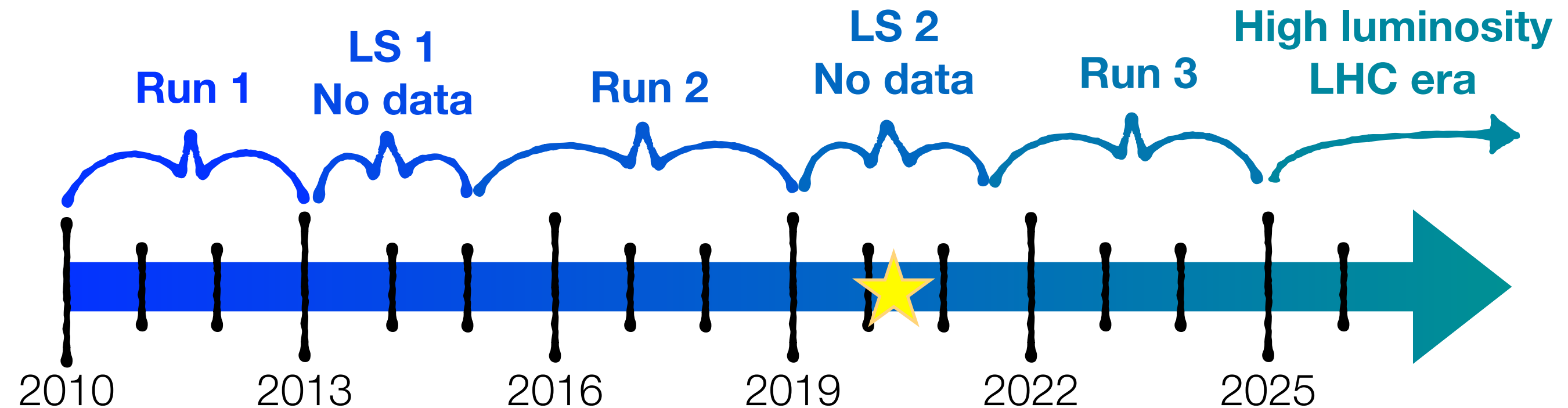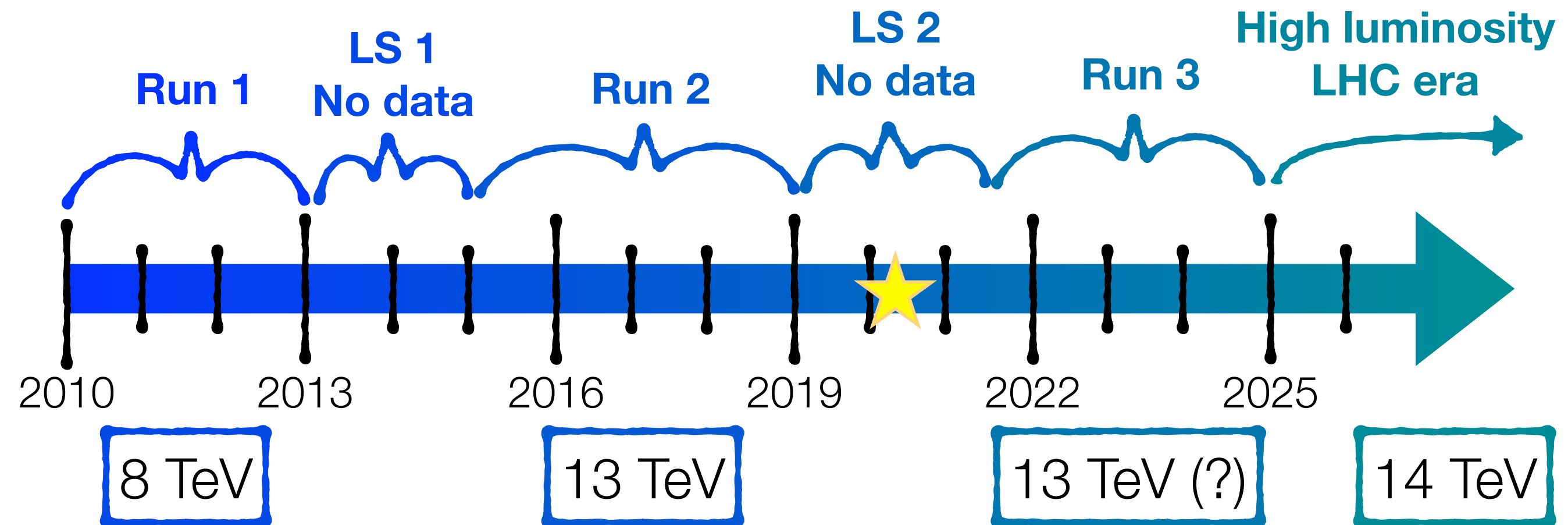
LHC: energies and datasets

Two **key factors**: amount of data collected
and collision centre of mass energy

- Amount of data collected: "luminosity"

- Measure in "inverse femtobarns": more fb^{-1} = more data

LHC: energies and datasets

Two **key factors**: amount of data collected
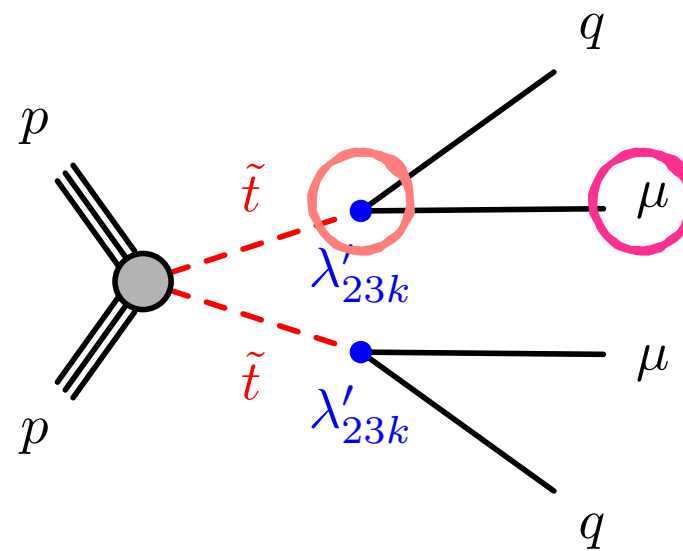and collision centre of mass energy

- Center of mass energy: "TeV"

- Higher energy = higher rate of interesting processes

Indirect detection example: Displaced vertices + a muon
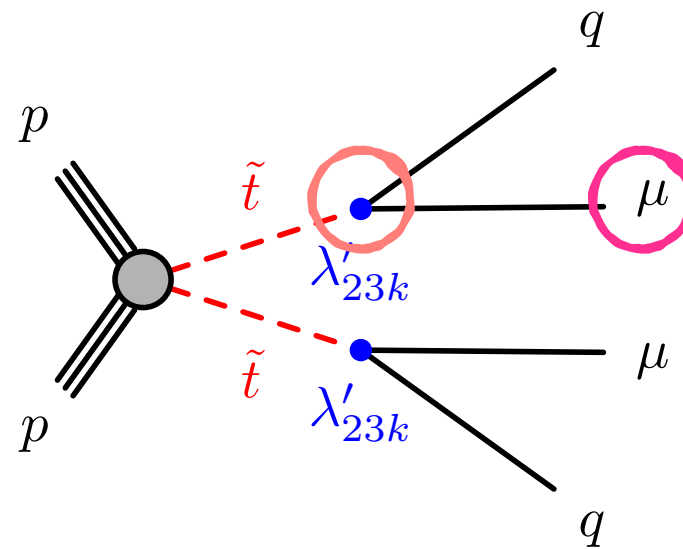
Vertex far away from collision point

High p_T muon and MET used for triggering

μ not required to come from DV, but must not point to collision

Indirect detection example:
Displaced vertices + a muon

Vertex far away from collision point

High-mass vertex excludes K$_{long}$

High p$_T$ muon and MET used for triggering

μ not required to come from DV, but must not point to collision

Indirect detection example: Displaced vertices + a muon

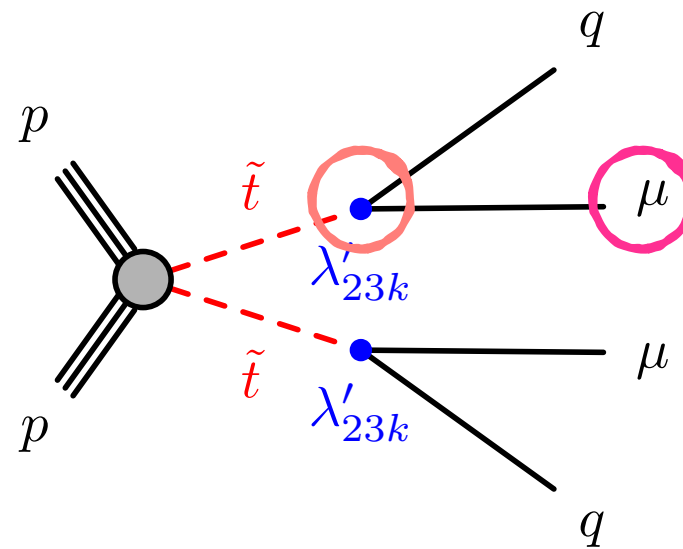Vertex far away from collision point

High-mass vertex excludes K_{long}

High p_T muon and MET used for triggering

μ not required to come from DV, but must not point to collision

- Analysis requires special "large radius" tracking for muons and tracks in DV

- **Cosmic muon** background reduced by rejecting events where MS activity is opposite muon

Indirect detection example: Displaced vertices + a muon

Vertex far away from collision point

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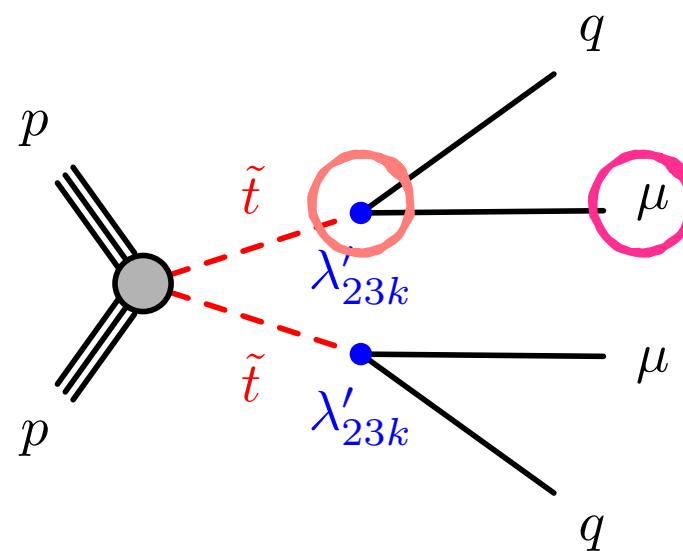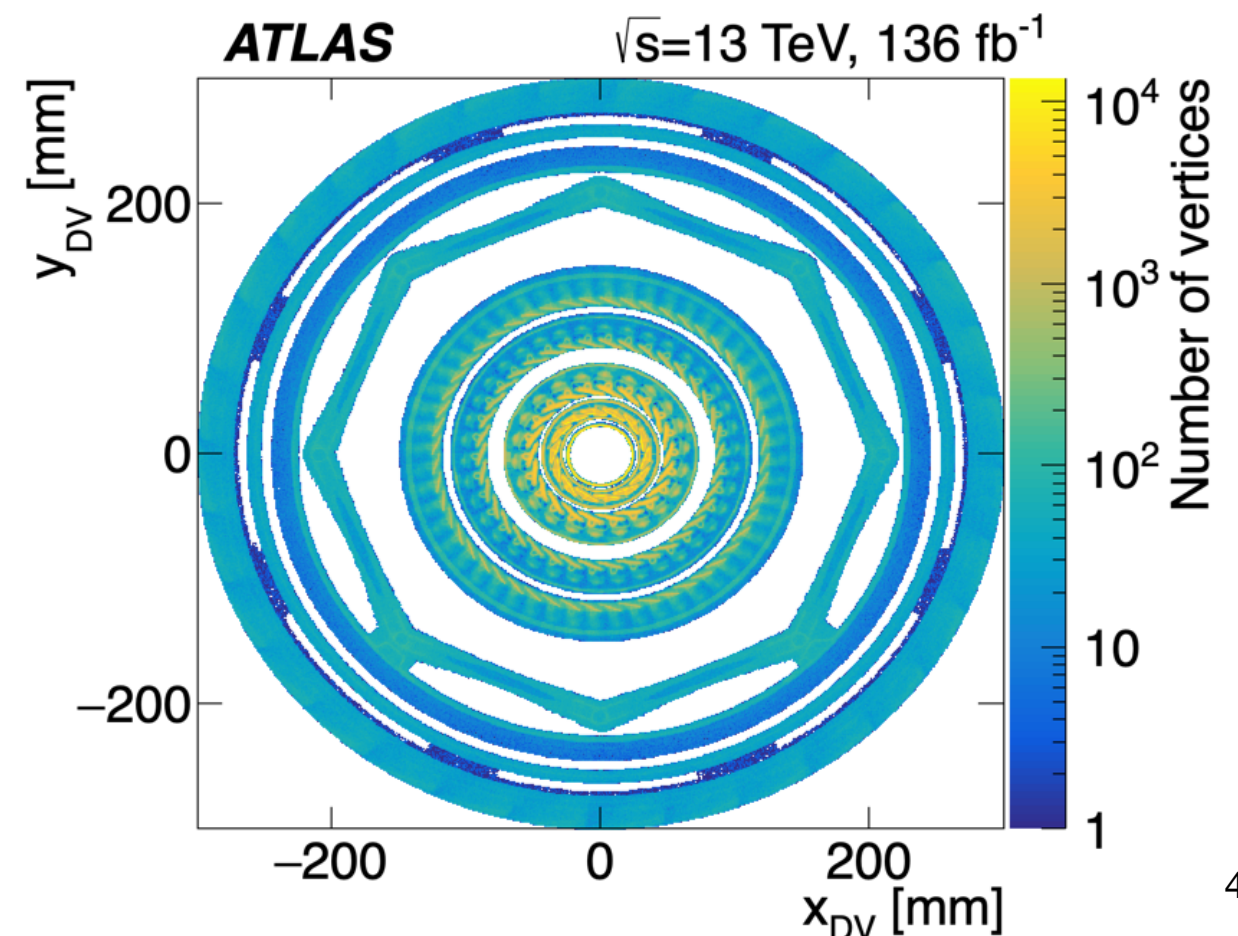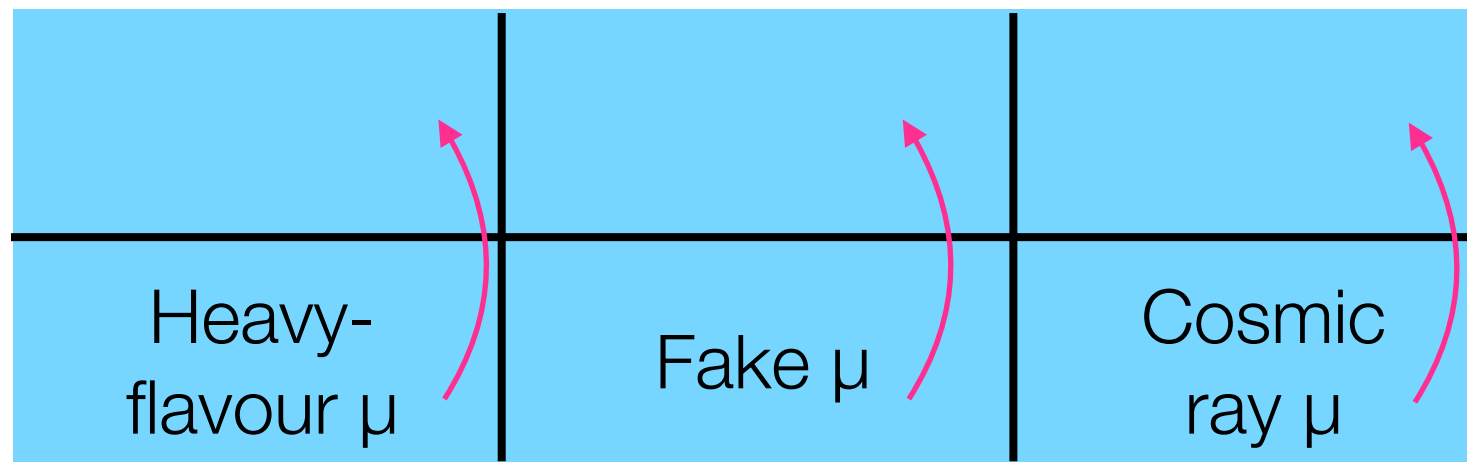
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ATLAS $\sqrt{s}$=13 TeV, 136 fb^{-1}
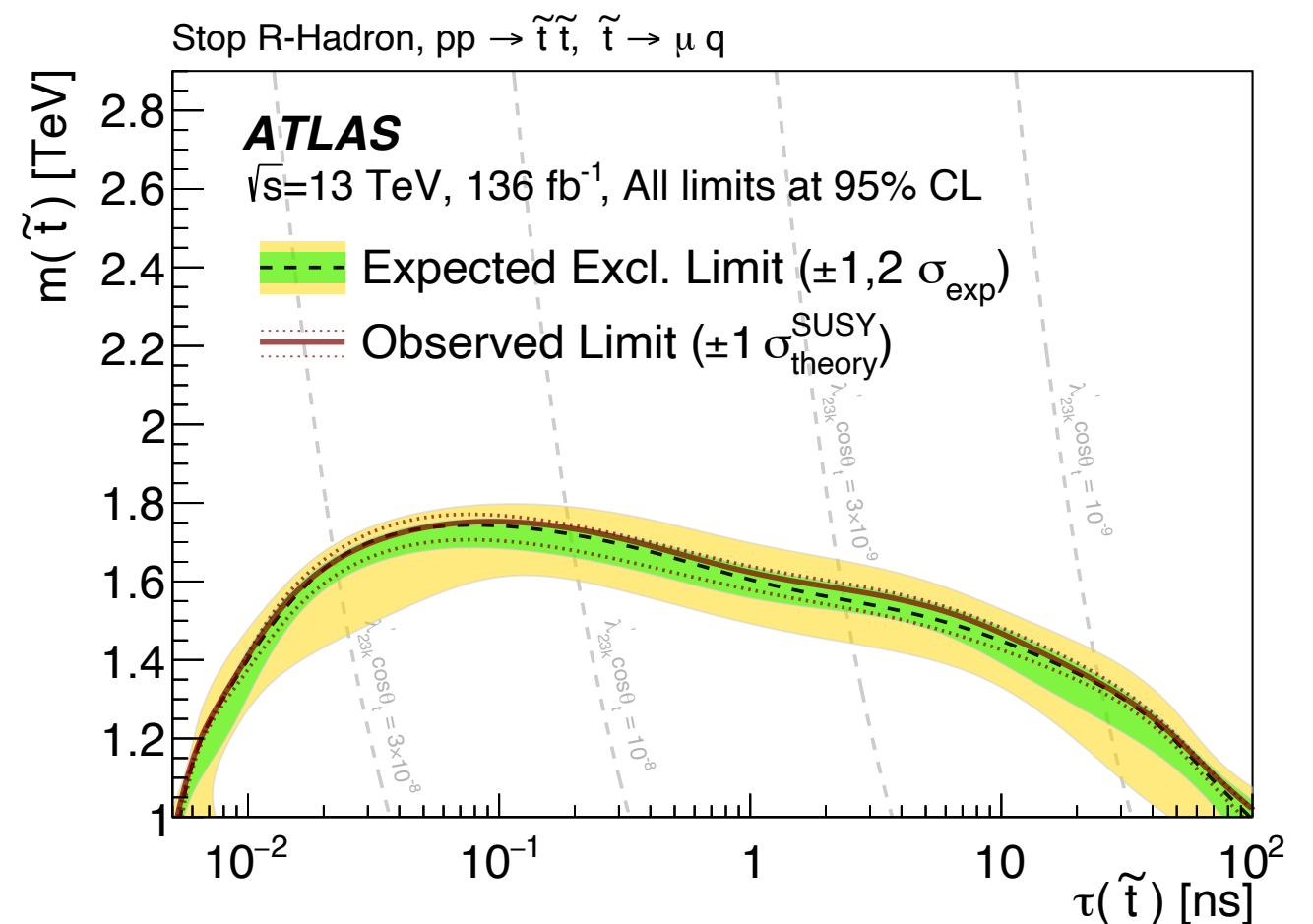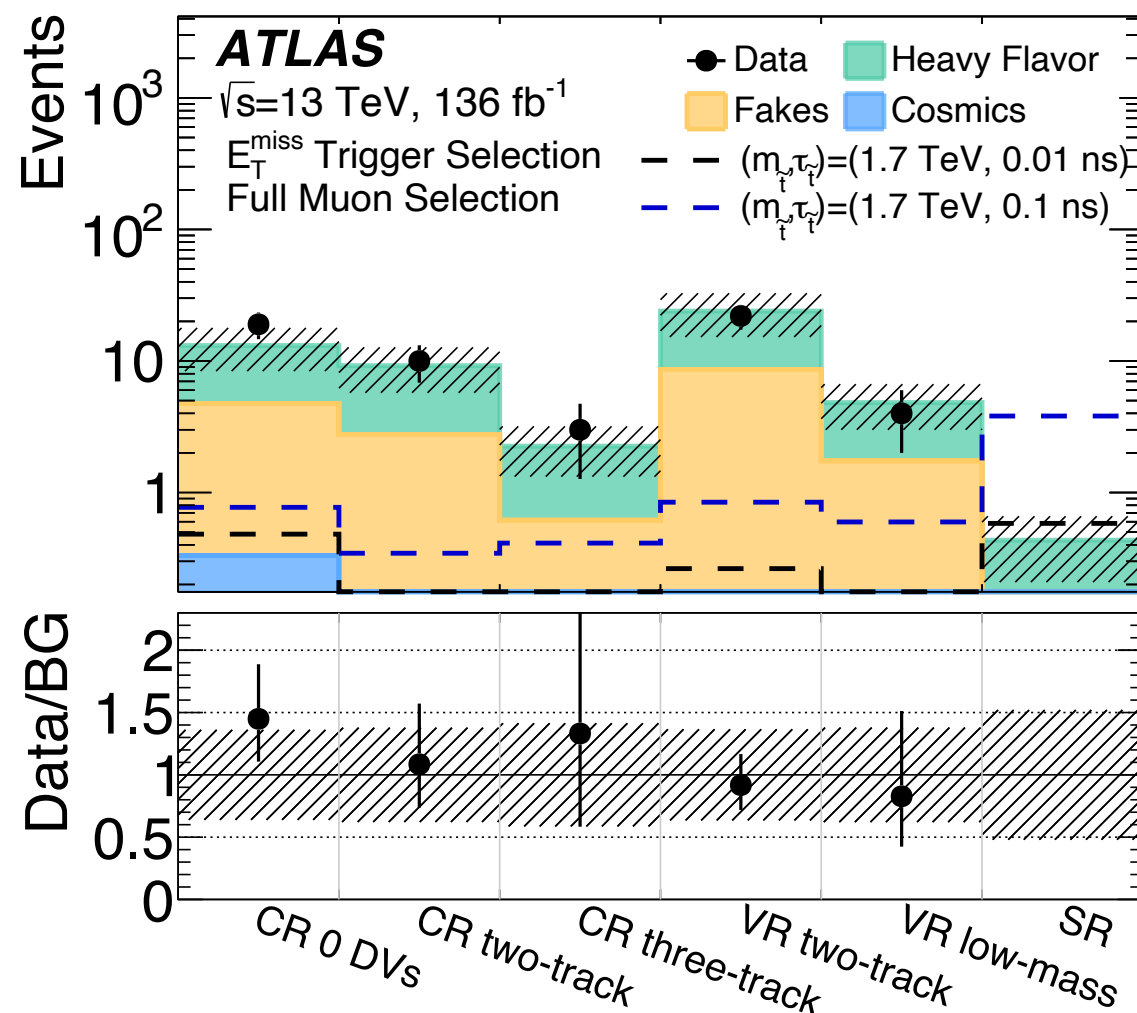
y_{DV} [mm]

Number of vertices

x_{DV} [mm]

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Results of DV + muon

Control region with background-like DVs

Heavy-flavour μ

Fake μ

Cosmic ray μ

Derive transfer factors from ratios

ATLAS
√s=13 TeV, 136 fb⁻¹
E_T^{miss} Trigger Selection
Full Muon Selection

Data   Heavy Flavor
Fakes   Cosmics
($m_{\tilde{t}}, \tau_{\tilde{t}}$)=(1.7 TeV, 0.01 ns)
($m_{\tilde{t}}, \tau_{\tilde{t}}$)=(1.7 TeV, 0.1 ns)

CR 0 DVs   CR two-track   CR three-track   VR two-track   VR low-mass   SR

Stop R-Hadron, pp → $\tilde{t}\tilde{t}$, $\tilde{t} \to \mu q$

ATLAS
√s=13 TeV, 136 fb⁻¹, All limits at 95% CL

Expected Excl. Limit (±1,2 σ_{exp})
Observed Limit (±1 σ_{theory}^{SUSY})

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Results of DV + muon

Apply transfer factors in regions with signal like DVs
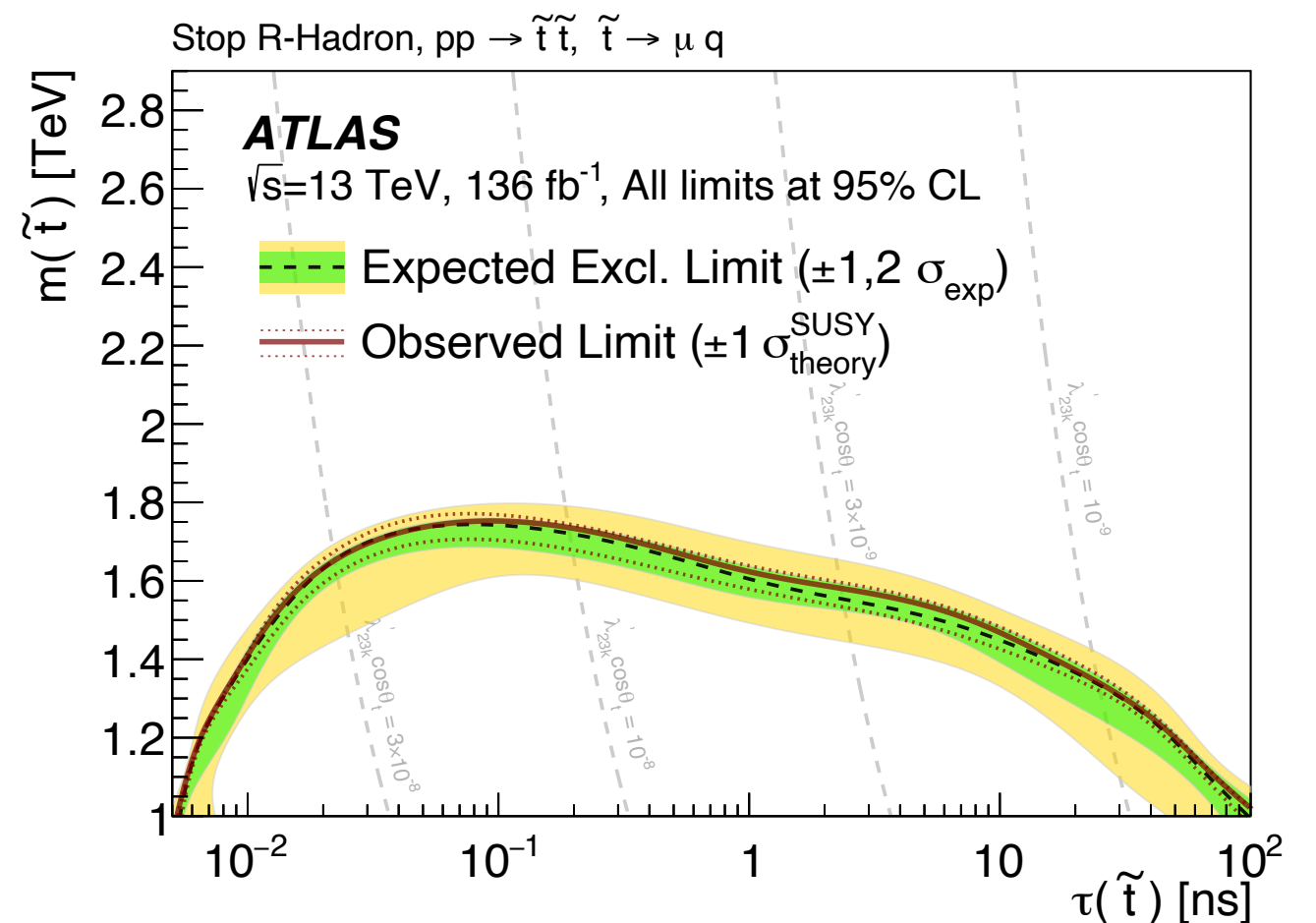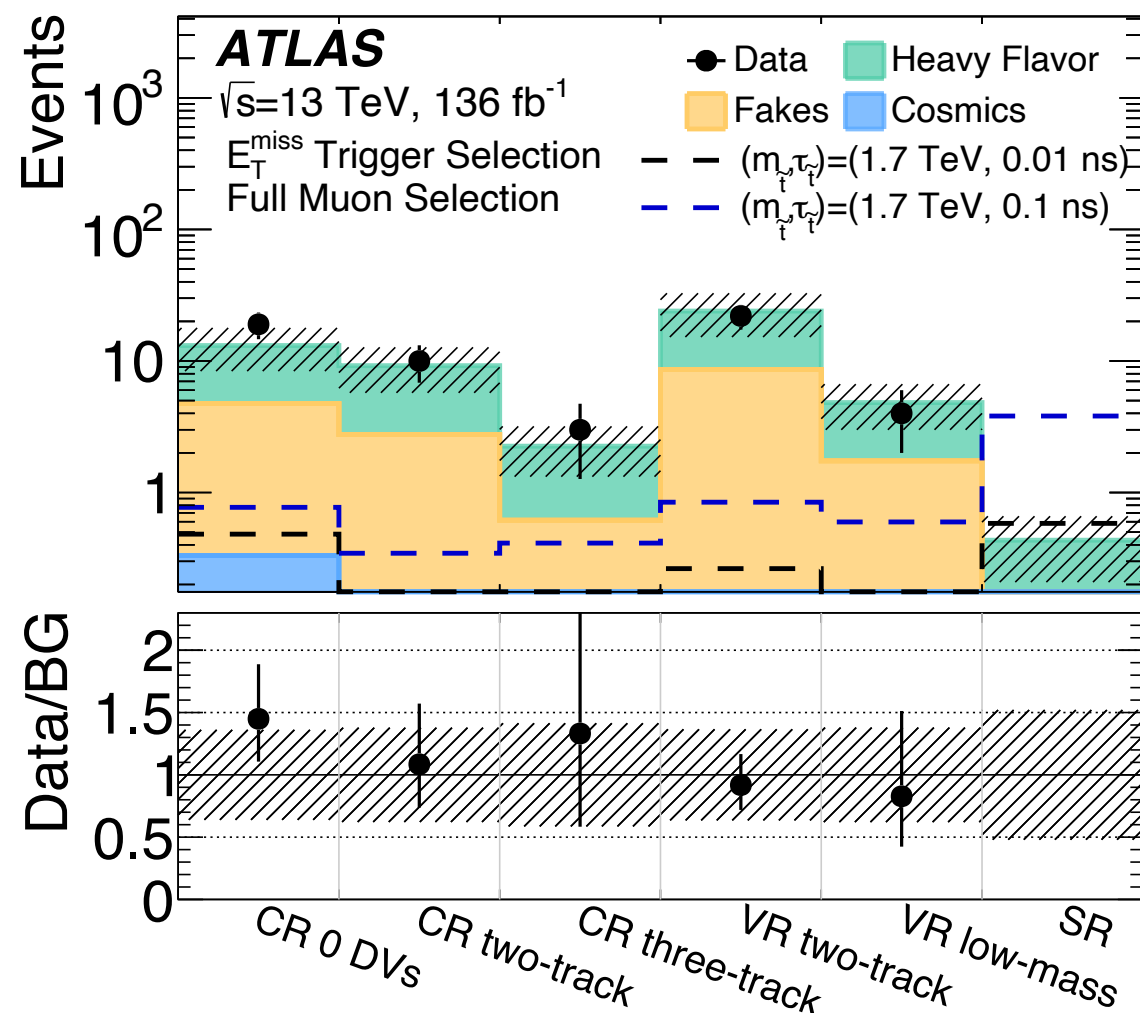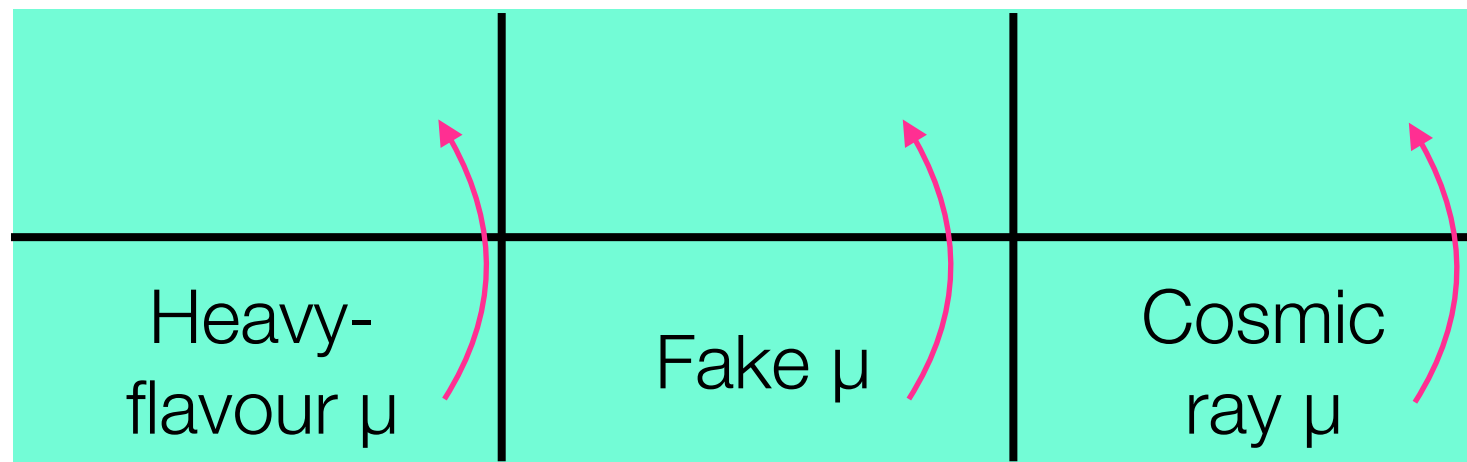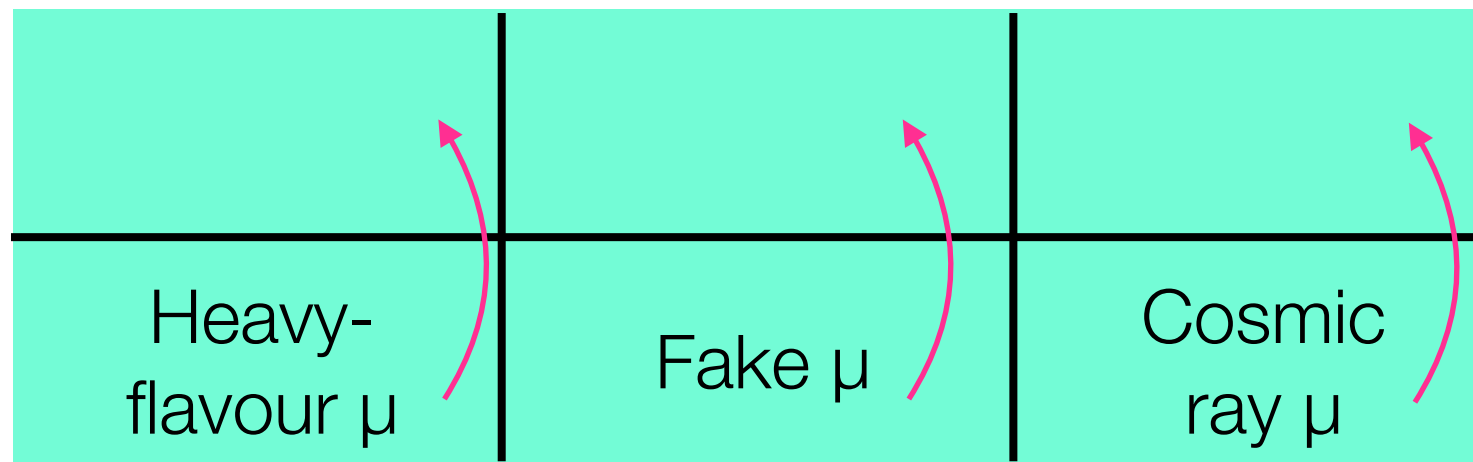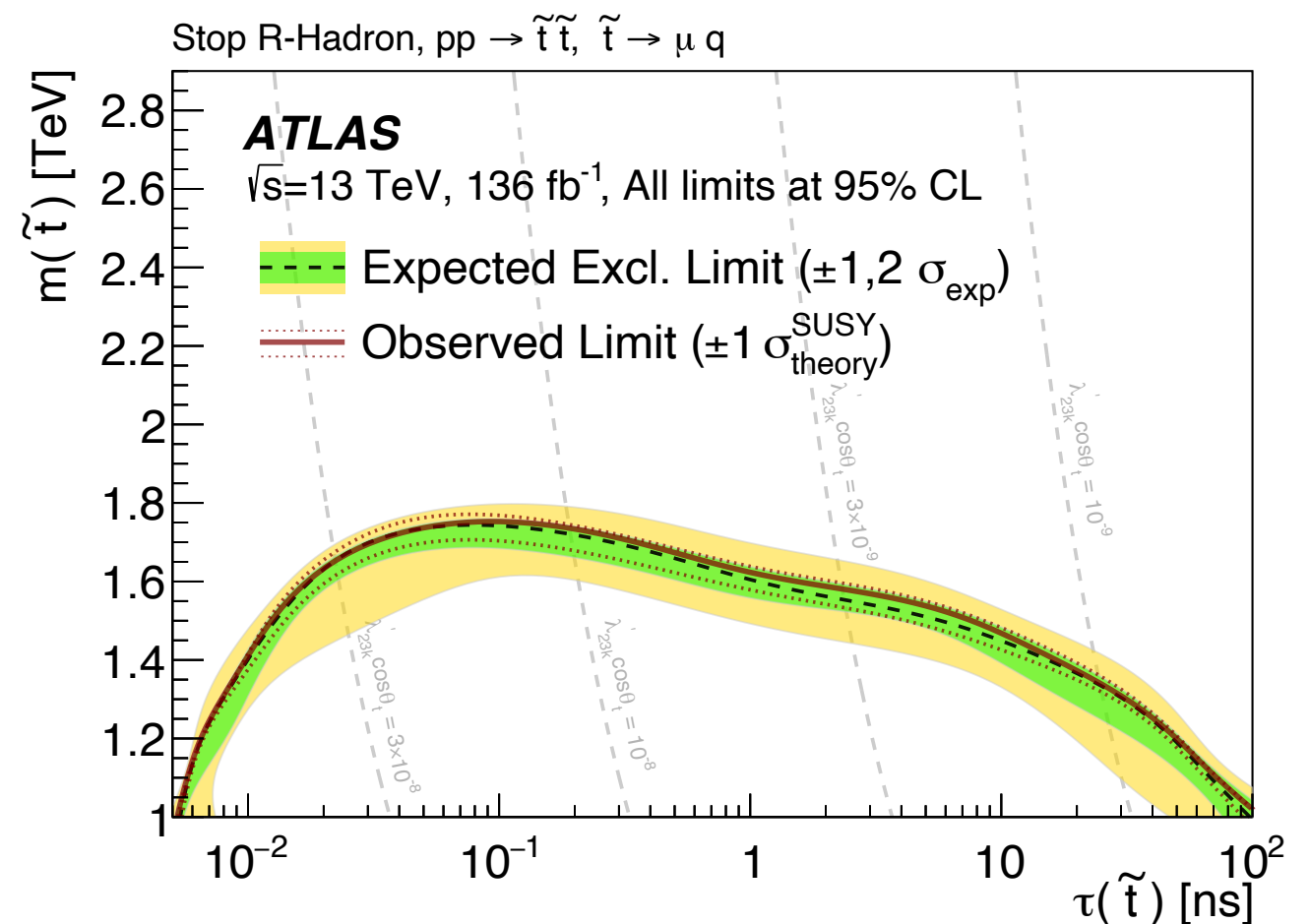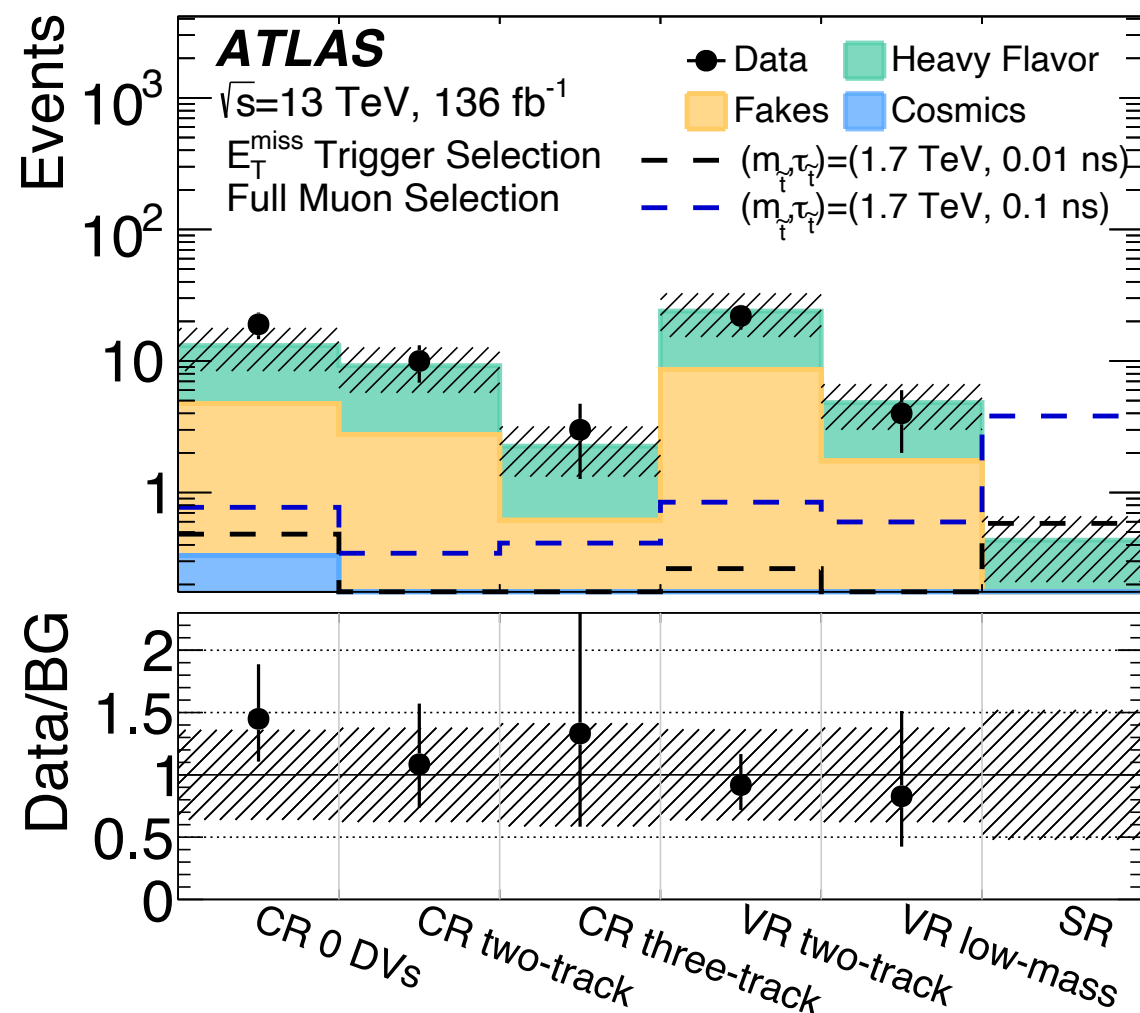
Results of DV + muon

Apply transfer factors in regions with signal like DVs

Background estimate!

Improving analysis targeting

- LLP analyses fairly simple at this point and target signals not necessarily most important for Run 3

- **dEdx**: optimise for lighter signals; add two-track signal region to improve targeting of SUSY-specific models

- **Disappearing track**: attempting to target even shorter lifetimes

- **Displaced leptons**: optimise directly for staus, focusing on lowering lepton p_T threshold, add 1 displaced lepton + 1 tau SR

- **In general**: move away from long-lived squarks/gluinos and target direct EWK production instead

L-violating bilinear coupling

$$\mu'^i L_i H_u$$

- Representative interactions between Higgsinos/leptons and Higgses/sleptons

  - $\tilde{\chi}^0 \to \ell^\pm W^\mp, \nu Z$

  - $\tilde{\chi}^\pm \to \ell^\pm Z, W^\pm \nu$

- Get neutrino masses automatically

- Can convert terms between bilinear and trilinear depending on basis, so other analyses have implications here and vice-versa
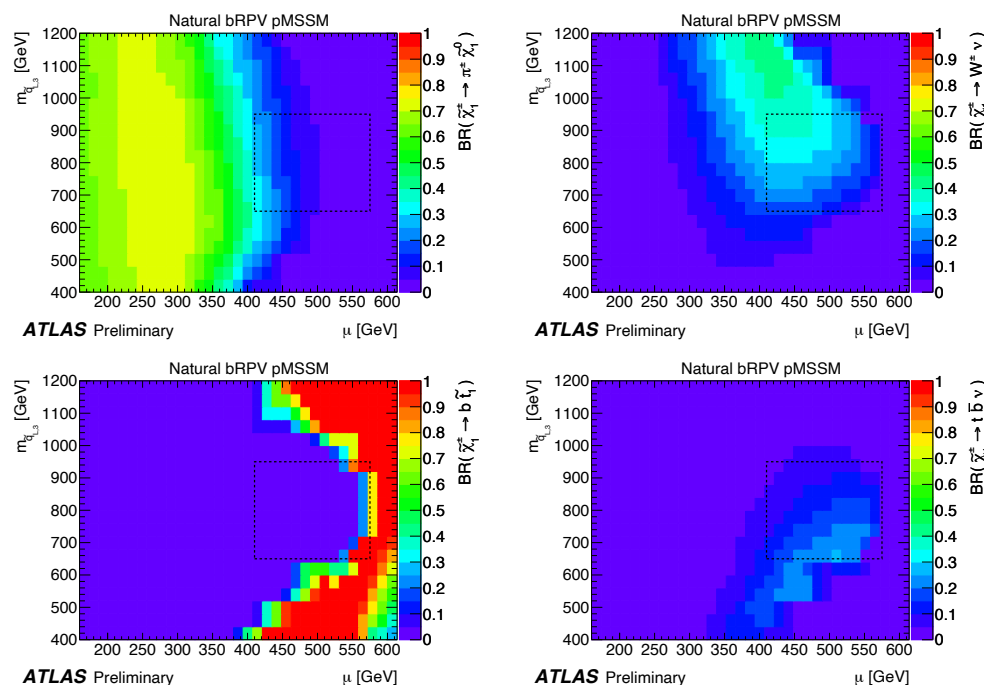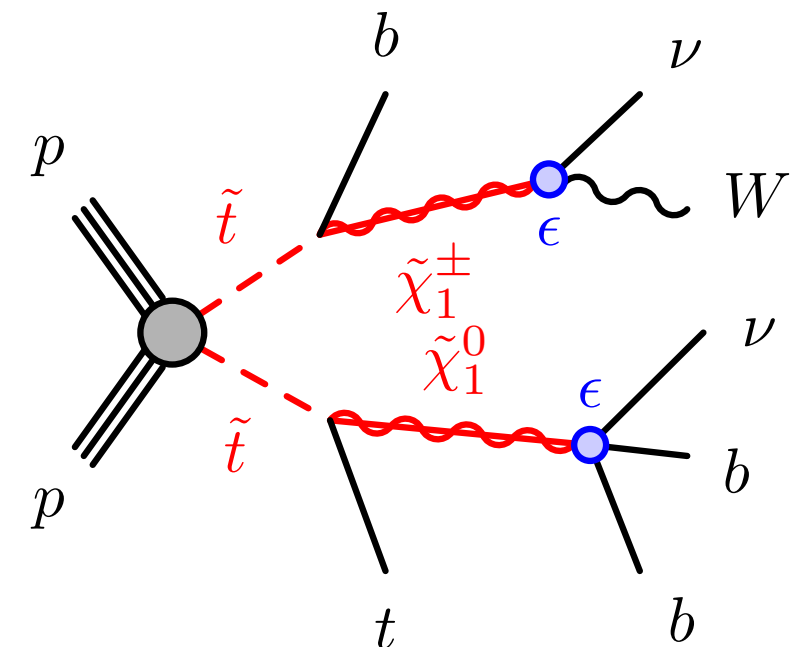
Run 1 summary: huge variations in final states and kinematics with small changes in model parameters!
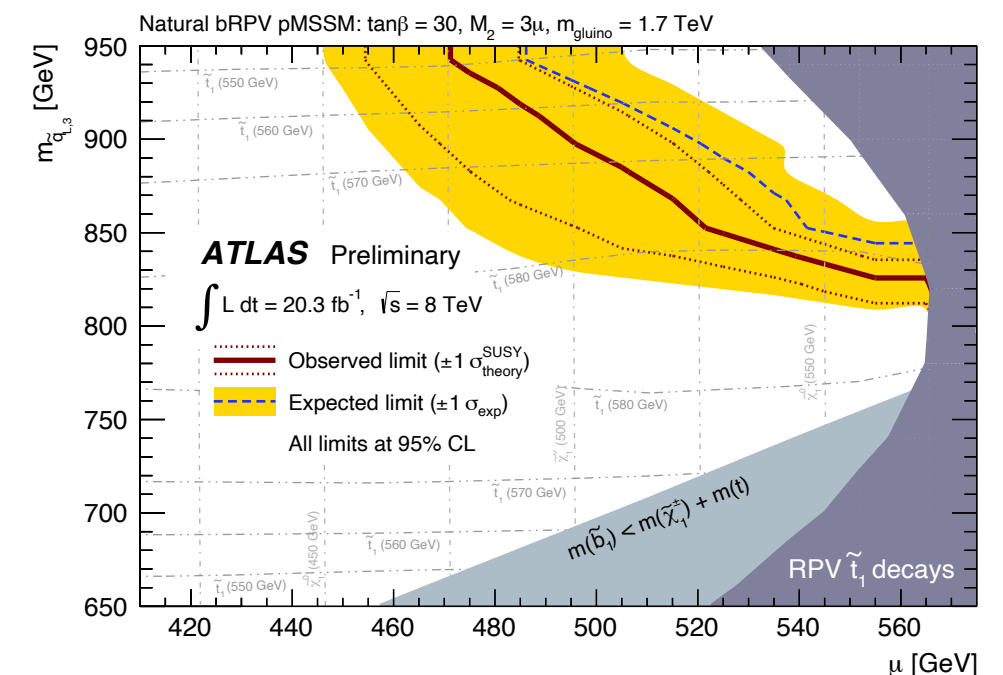
Lepton coupling, L-violating LLE: λ

Primes indicate flavour indices: determine different combinations of leptons

- LSP decays to leptons via sneutrino/slepton

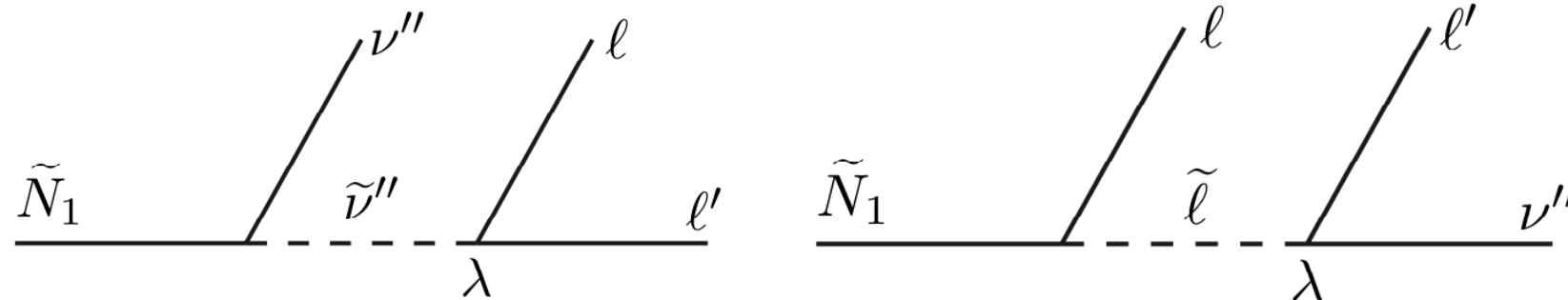- Very small λ: get nonzero lifetime for intermediate particle and we'll see displaced lepton pairs (covered by dilepton DV) or one displaced, one prompt (should be some coverage from exotics HNL? Displaced leptons?)

- Medium λ: lots of prompt leptons in the final state. Constraints from electroweak 3L and 4L analyses

taus = weaker limits

$pp \to \tilde{g}\tilde{g} \to qq\tilde{\chi}_1^0 qq\tilde{\chi}_1^0$ $\tilde{\chi}_1^0 \to l^+ l^- \nu$ $\sqrt{s} = 8$ TeV, 20.3 fb^{-1}
All limits at 95% CL $m(\tilde{\chi}_1^0) / m(\tilde{g}) = 0.5$

LLE Gluino
Run 1

light leptons = stronger limits
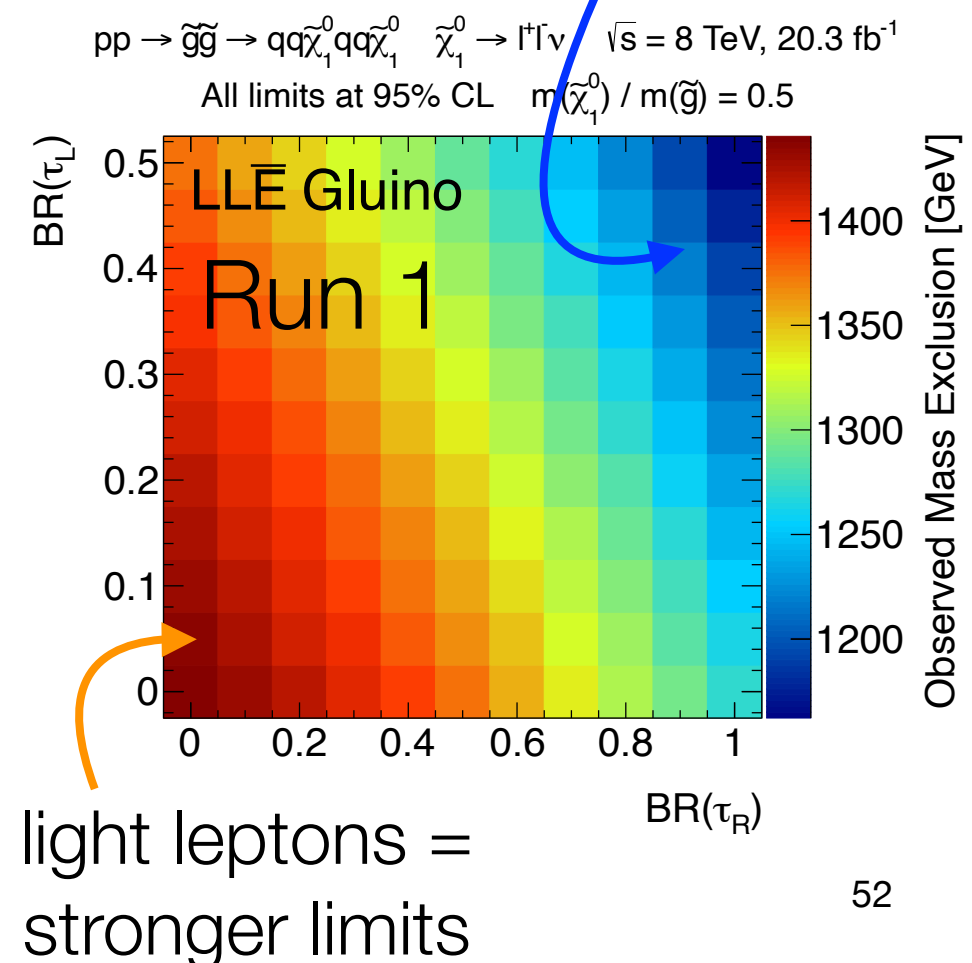
Leptons and jets, L-violating LQD: λ'
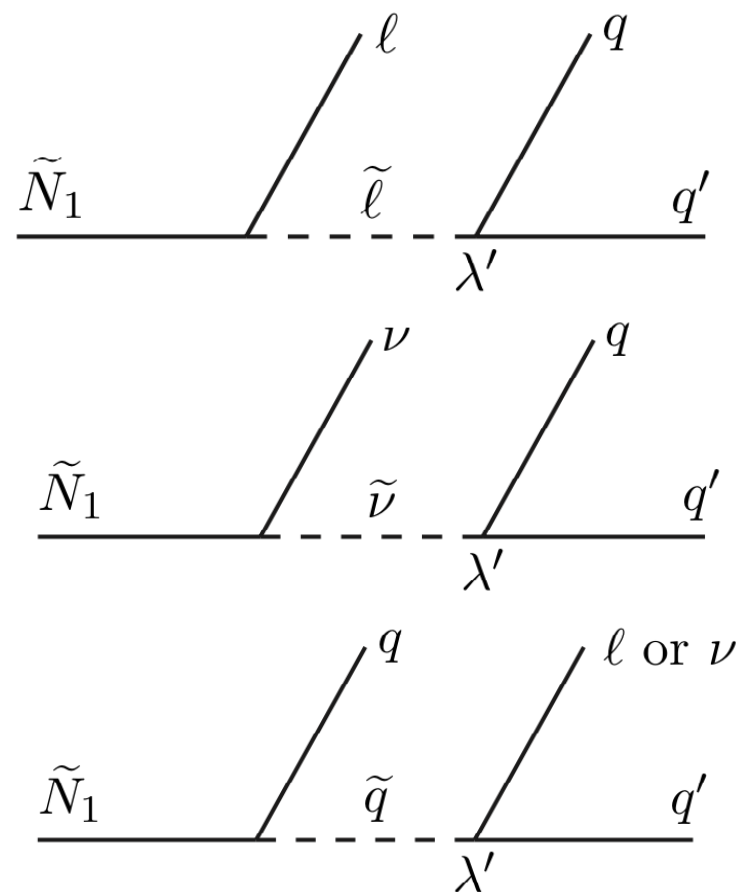
Analysis reach varies with final state flavours…

… and mass splittings: no Run 1 exclusions for largest splittings

pp → $\widetilde{q}\widetilde{q}$ → $q\widetilde{\chi}_1^0 q\widetilde{\chi}_1^0$ $\widetilde{\chi}_1^0$ → l/ν qq   √s = 8 TeV, 20.3 fb⁻¹
All limits at 95% CL   m($\widetilde{\chi}_1^0$) / m($\widetilde{q}$) = 0.9

LQD̄ Squark

Run 1

ATLAS Preliminary

BR(b)

BR(τ)

Expected Mass Exclusion [GeV]
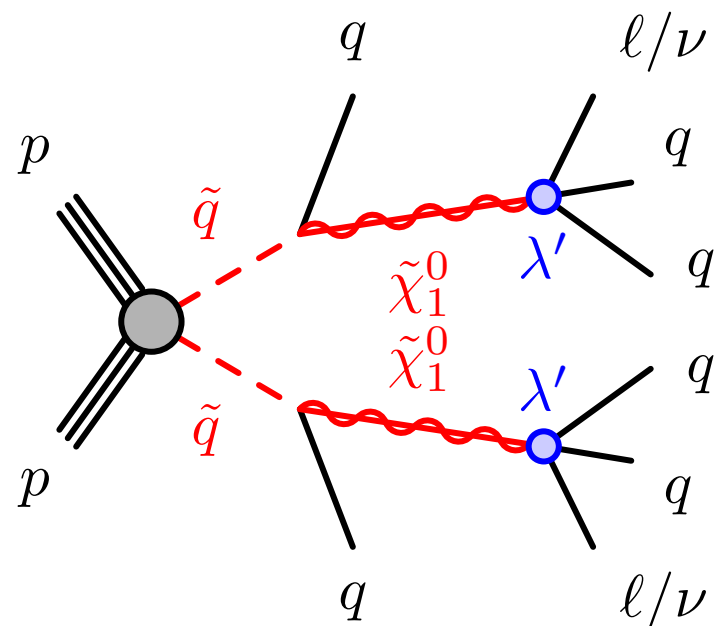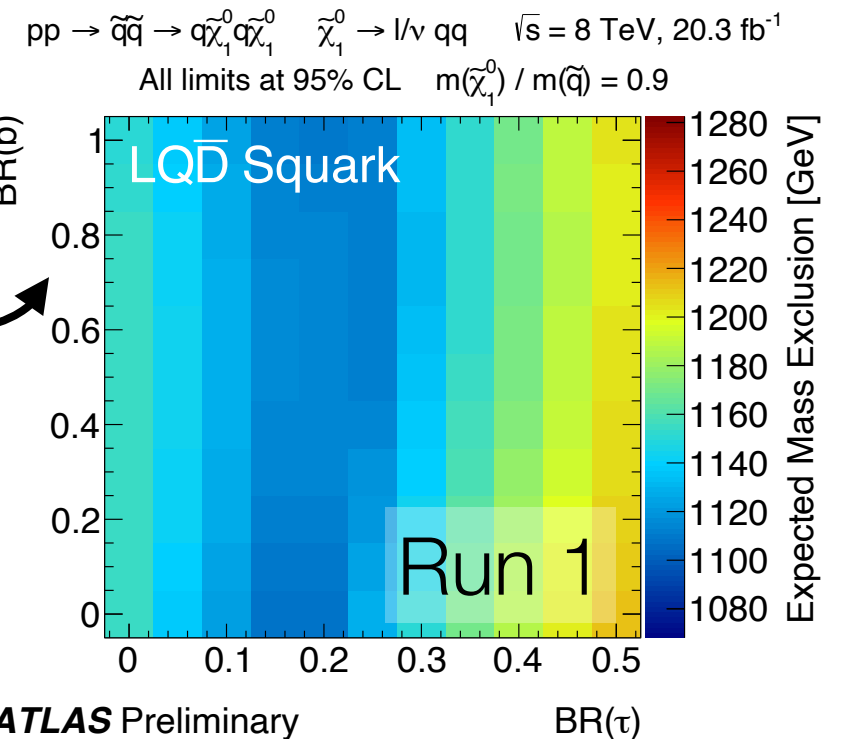
- Couple quarks to leptons and neutrinos: get LSP decay to jets and l/ν

- Small λ': long-lived N1 leads to displaced jets; coverage from DV analyses

- Medium λ': multijets and lepton or significant MET. Constraints from multijet 0L, EW 3L (not shown today), stop B-L (discussed already), multijet 1L (see next section) at present
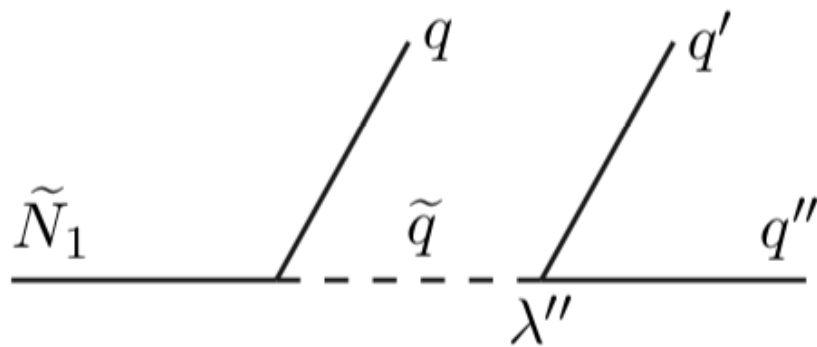
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B-violation with tons of quarks, UDD: λ"

Note different indices will result in different quark flavours!
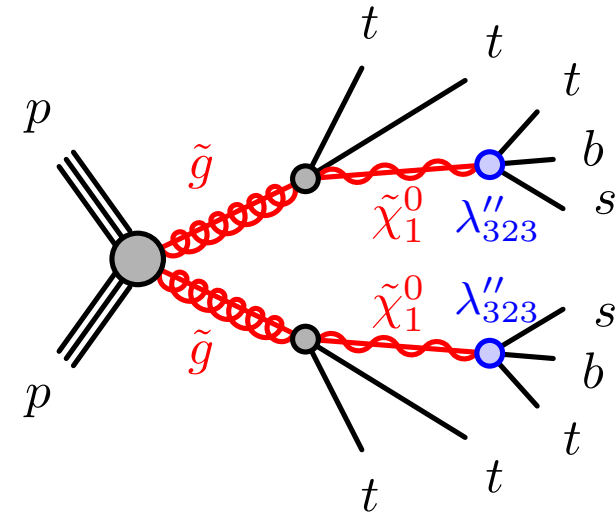
Jet-filled final states, but with t's present you can have lepton(s) and MET as well

B-violation with tons of quarks, UDD: λ"

Note different indices will result in different quark flavours!

Jet-filled final states, but with t's present you can have lepton(s) and MET as well

RPC-RPV Combination: $\tilde{g} \to t\bar{t}\tilde{\chi}_1^0(\to tbs)$ / $\tilde{g} \to tbs$, m($\tilde{\chi}_1^0$)=200 GeV, bino-like $\tilde{\chi}_1^0$

ATLAS Preliminary
$\sqrt{s}$=13 TeV, 36.1 fb^{-1}

- ⊖ - Expected
- ● - Observed
95% CL limits
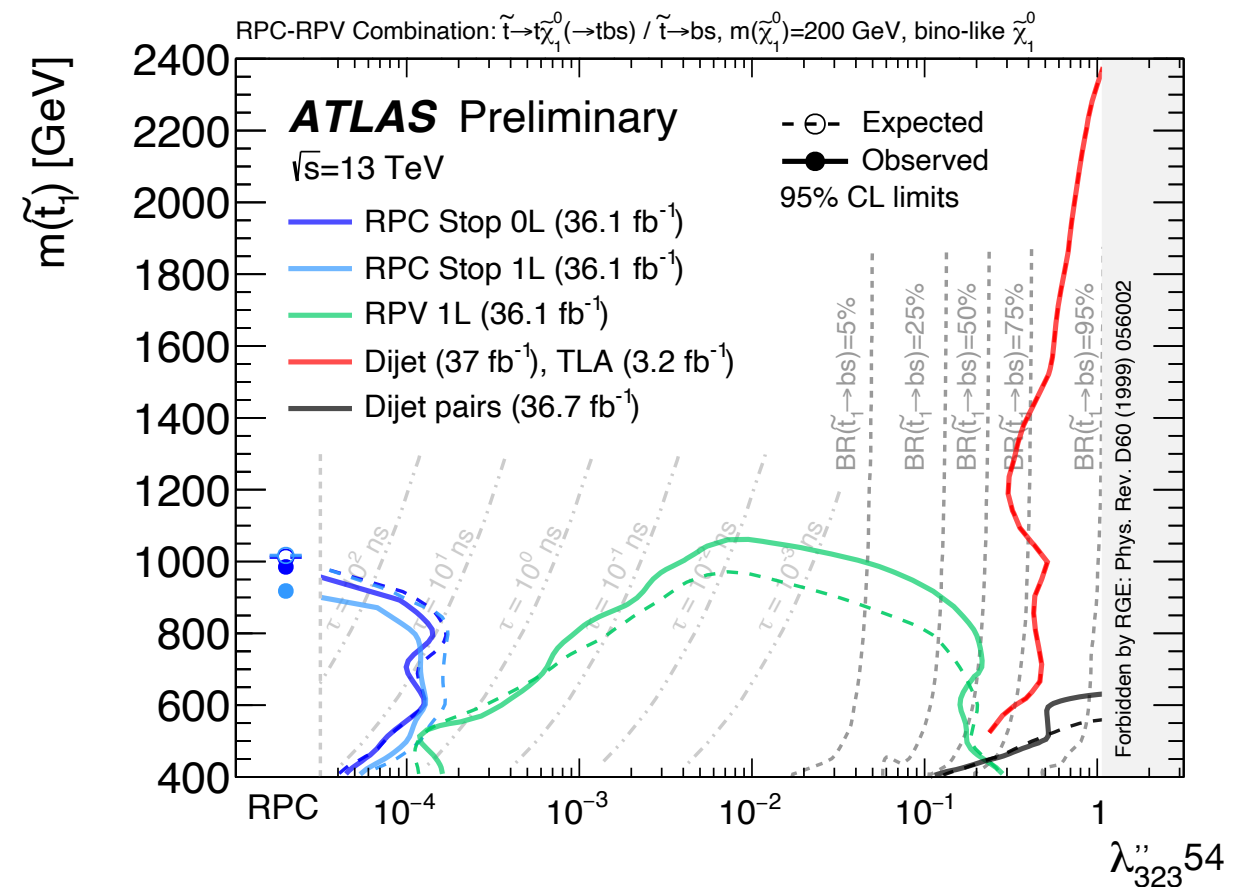
- RPC ≥ 3 b-jets
- RPC 0L 7-11j
- RPV 1L
- RPC-RPV SS/3L

Forbidden by RGE: Phys. Rev. D60 (1999) 0
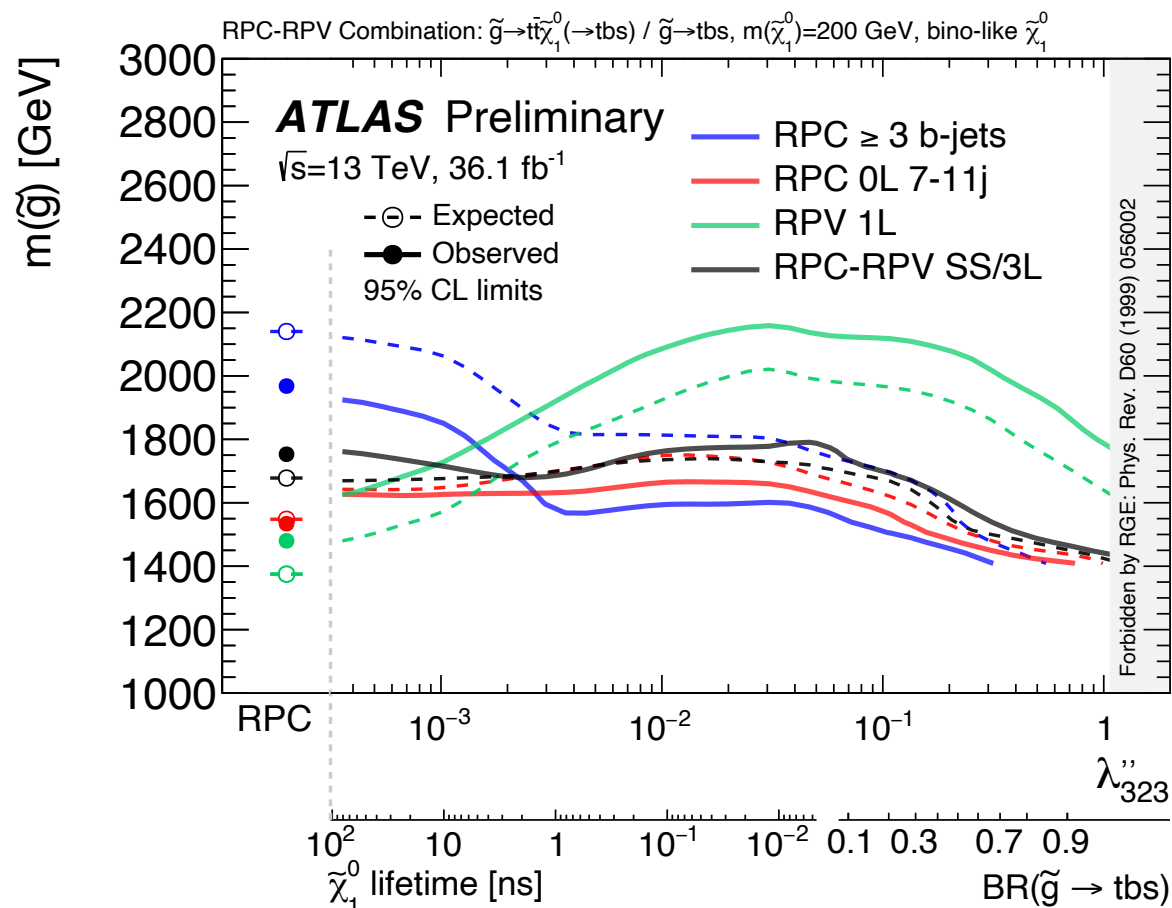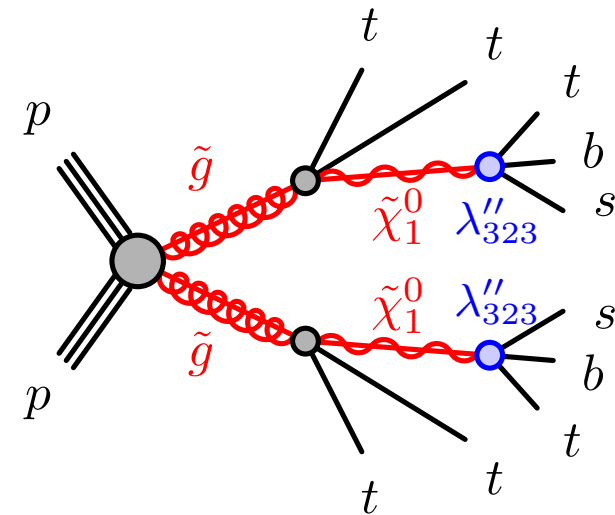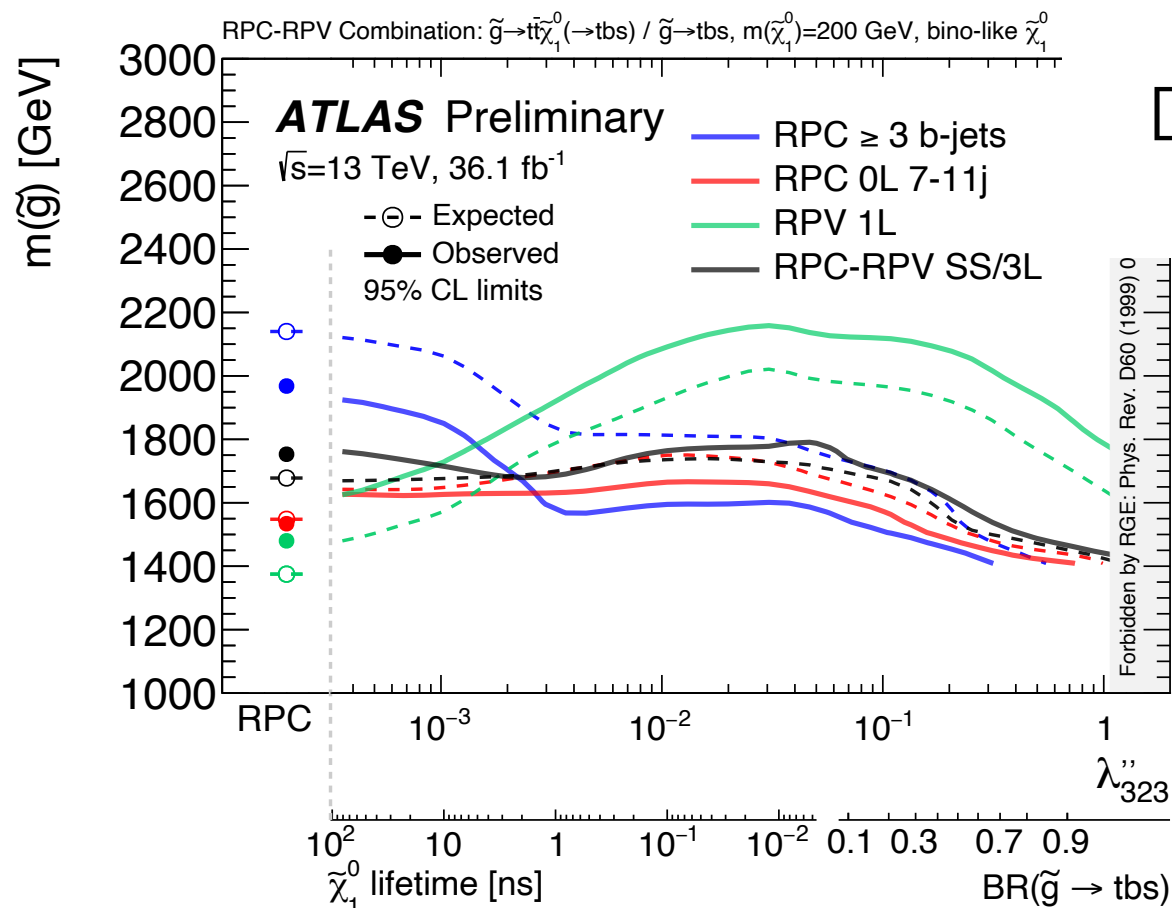
Different models = different degrees of sensitivity from RPC analyses

RPC-RPV Combination: $\tilde{t} \to t\tilde{\chi}_1^0(\to tbs)$ / $\tilde{t} \to bs$, m($\tilde{\chi}_1^0$)=200 GeV, bino-like $\tilde{\chi}_1^0$

- RPC Stop 1L (36.1 fb^{-1})
- RPV 1L (36.1 fb^{-1})
- Dijet (37 fb^{-1}), TLA (3.2 fb^{-1})
- Dijet pairs (36.7 fb^{-1})

Forbidden by RGE: Phys. Rev. D60 (1999) 056002

54
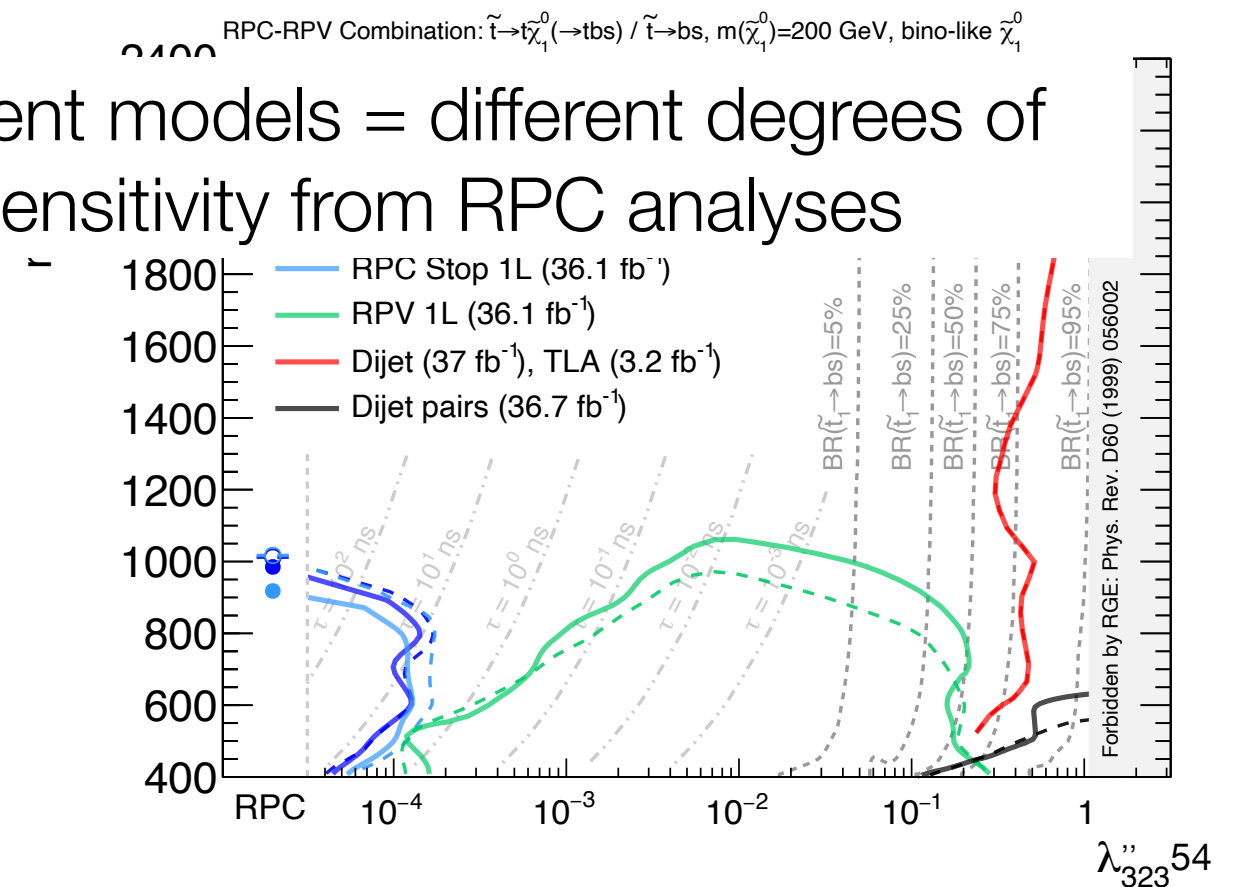
What about dark matter in RPV?

- Gravitino takes over as most likely dark matter candidate

- RPV would allow its decay, but proportionally to gravitational coupling, and thus the lifetime is really really long

LLP searches and the Higgsino mass gap

ATLAS Preliminary

$\sqrt{s}$ = 13 TeV

$pp \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^\pm, \tilde{\chi}_2^0 \tilde{\chi}_1^0, \tilde{\chi}_1^+ \tilde{\chi}_1^-, \tilde{\chi}_1^\pm \tilde{\chi}_1^0$ (Higgsino)

All limits at 95% CL

Observed limits

Expected limits

Soft 2ℓ, 139 fb^{-1}, arXiv:1911.12606, $m(\tilde{\chi}_2^0) = m(\tilde{\chi}_1^0) + 2\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$

Disappearing track, 36.1 fb^{-1}, PHYS-PUB-2017-019, $m(\tilde{\chi}_2^0) = m(\tilde{\chi}_1^0)$

LEP2 $\tilde{\chi}_1^\pm$ excluded

Theoretical prediction for pure Higgsino

May 2020

$\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ [GeV]

$m(\tilde{\chi}_1^\pm)$ [GeV]

LLP searches and the Higgsino mass gap

ATLAS Preliminary
$\sqrt{s}$ = 13 TeV
$pp \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^\pm, \tilde{\chi}_2^0 \tilde{\chi}_1^0, \tilde{\chi}_1^+ \tilde{\chi}_1^-, \tilde{\chi}^\mp \tilde{\chi}_1^0 \ldots$

May 2020

All limits at 95% CL
Observed limits
Expected limits

Compressed region: decay via off-shell W, identify very soft leptons

VERY compressed: chargino becomes long-lived, search via disappearing track:

Soft 2ℓ, 139 fb^{-1}, arXiv:1911.12606, $m(\tilde{\chi}_2^0) = m(\tilde{\chi}_1^0) - 2\Delta m(\tilde{\chi}_1, \tilde{\chi}_1)$
Disappearing track, 36.1 fb^{-1}, PHYS-PUB-2017-019, $m(\tilde{\chi}_2^0) = m(\tilde{\chi}_1^0)$
LEP2 $\tilde{\chi}_1^\pm$ excluded
Theoretical prediction for pure Higgsino

$\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ [GeV]

$m(\tilde{\chi}_1^\pm)$ [GeV]
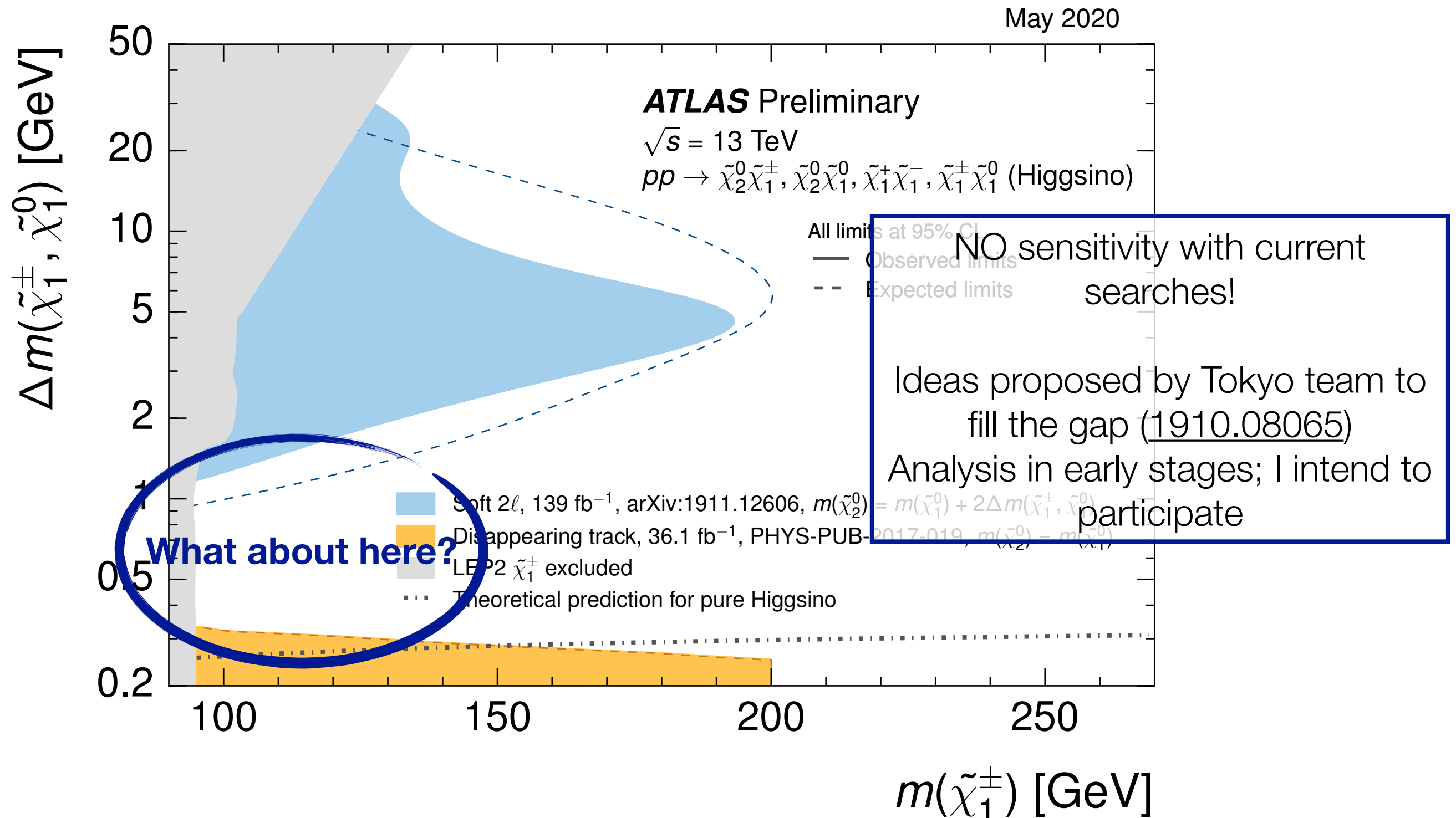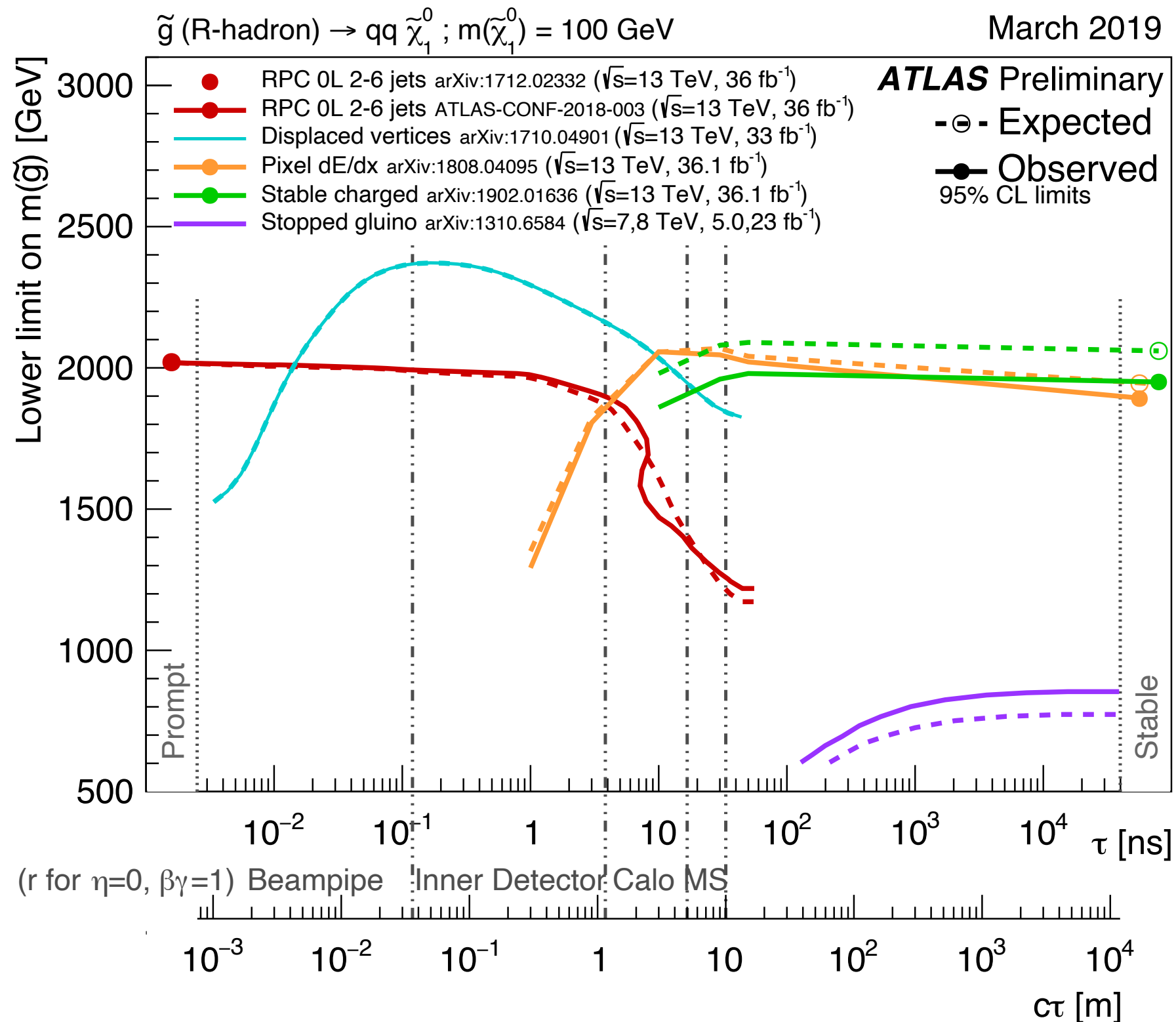
LLP searches
and the Higgsino mass gap
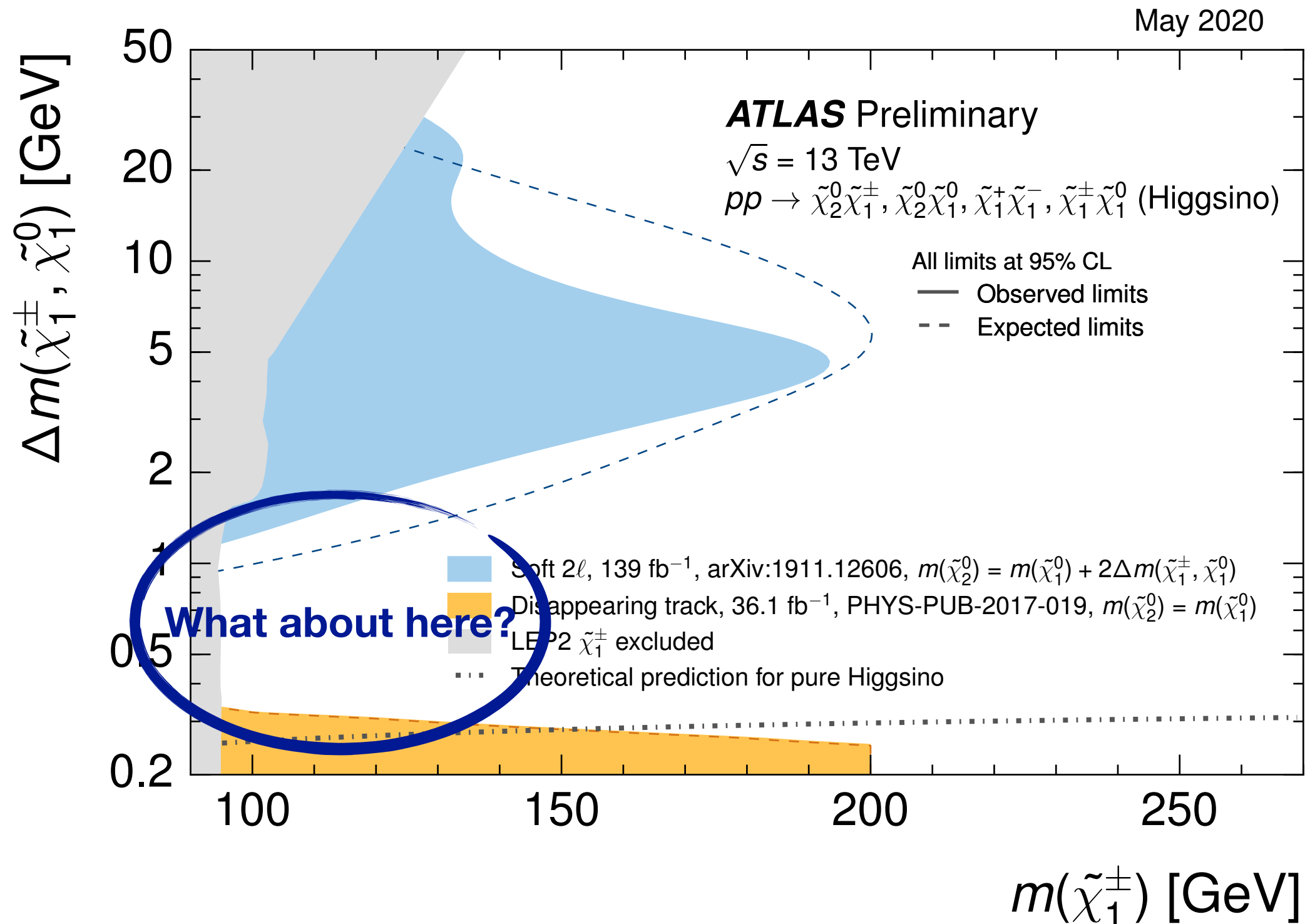
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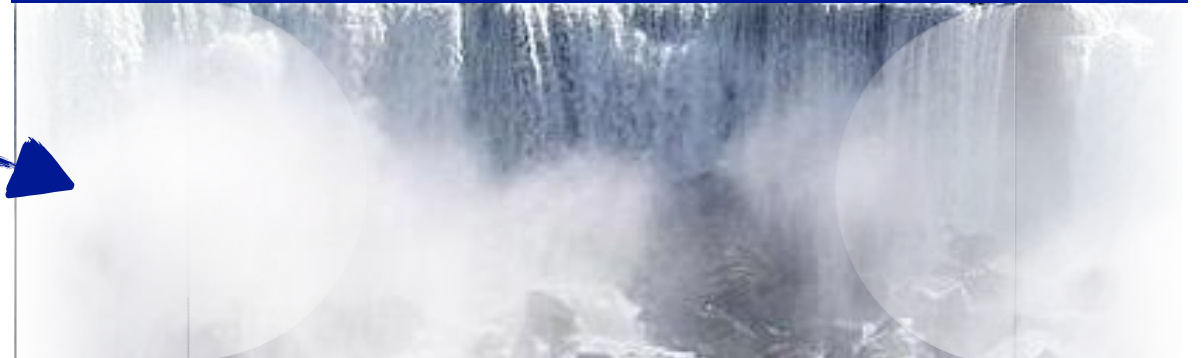# Why standard searches don't suffice

What is a trigger?

Data leaves detector at 40 MHz: way more than we can process and store!
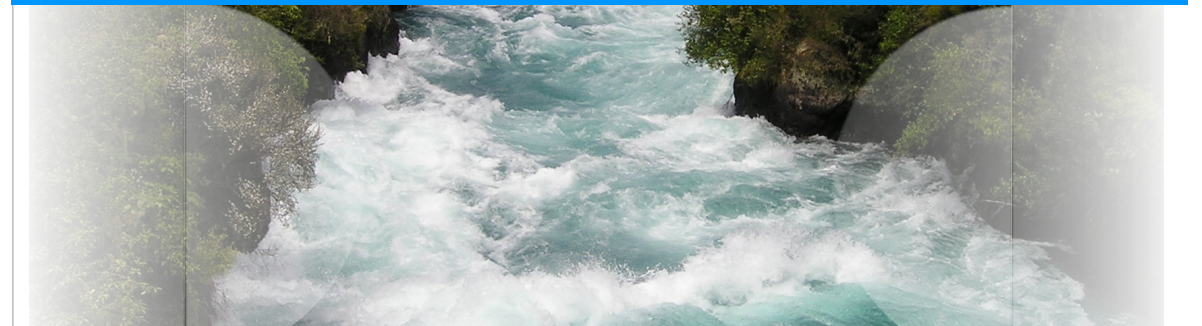
ATLAS Detector

L1 Trigger

Hardware L1 trigger reduces flow to 100 kHz
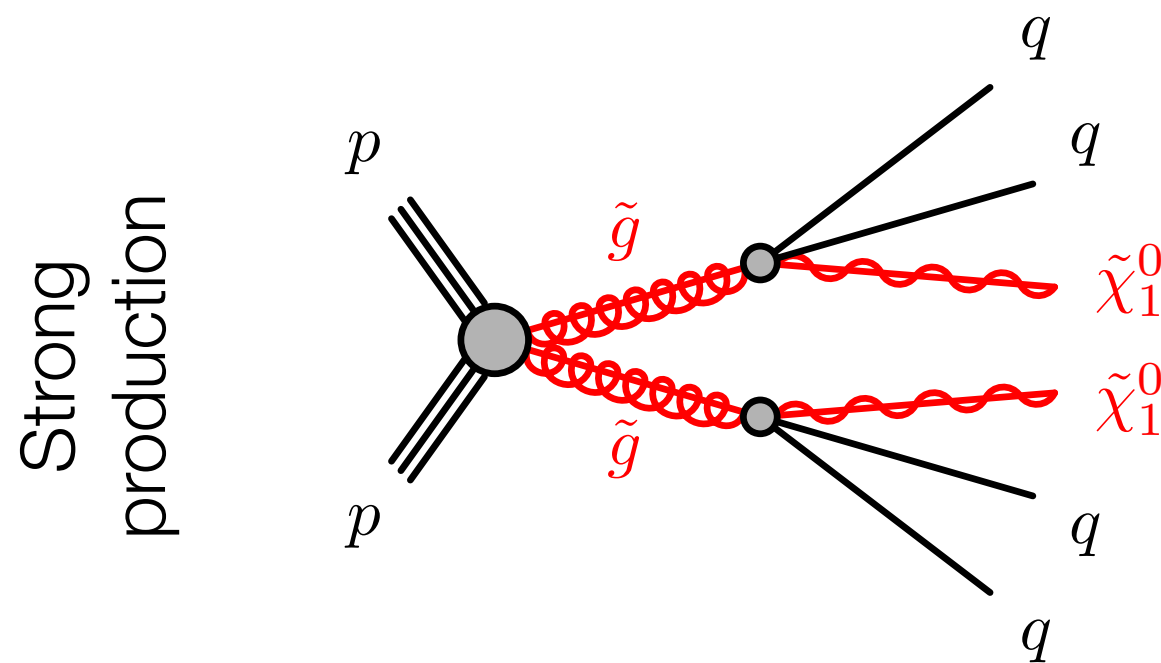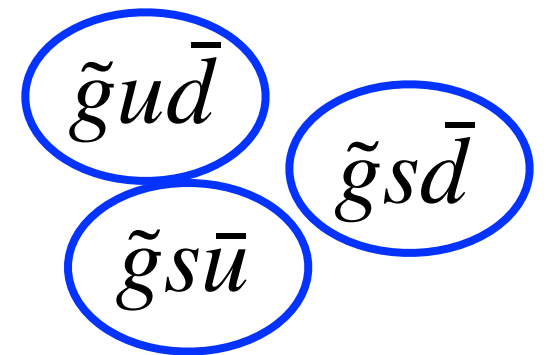
Software HLT passes ~1 kHz: 40,000 x less

High level trigger

A perfect drop of physics!

More dEdx: R-hadrons

p

Strong production

$\tilde{g}$

$\tilde{g}$

q

q

$\tilde{\chi}_1^0$

$\tilde{\chi}_1^0$

q

q

p

~20% of these hadrons are charged

$\tilde{g}u\bar{d}$

$\tilde{g}s\bar{d}$

$\tilde{g}s\bar{u}$

- Long lived squark or gluino results in R-hadron. Charged fraction hypothesized ~20%

- R-hadron interacts minimally with calorimeter (think very high pT pion) - missing energy signature

- Case where stable charged particle not necessarily going to do better at long lifetimes: charge flipping can occur as R-hadron collects & deposits quarks in calorimeter. Can have ID track and nothing in the MS

More dEdx: R-hadrons

p

q
q

Strong production

$\tilde{g}$

$\tilde{\chi}_1^0$

$\tilde{g}$

$\tilde{\chi}_1^0$

p

q

q

Our gluino isn't charged… but all strongly charged particles must hadronise

~20% of these hadrons are charged

$\tilde{g}u\bar{d}$

$\tilde{g}s\bar{d}$

$\tilde{g}s\bar{u}$
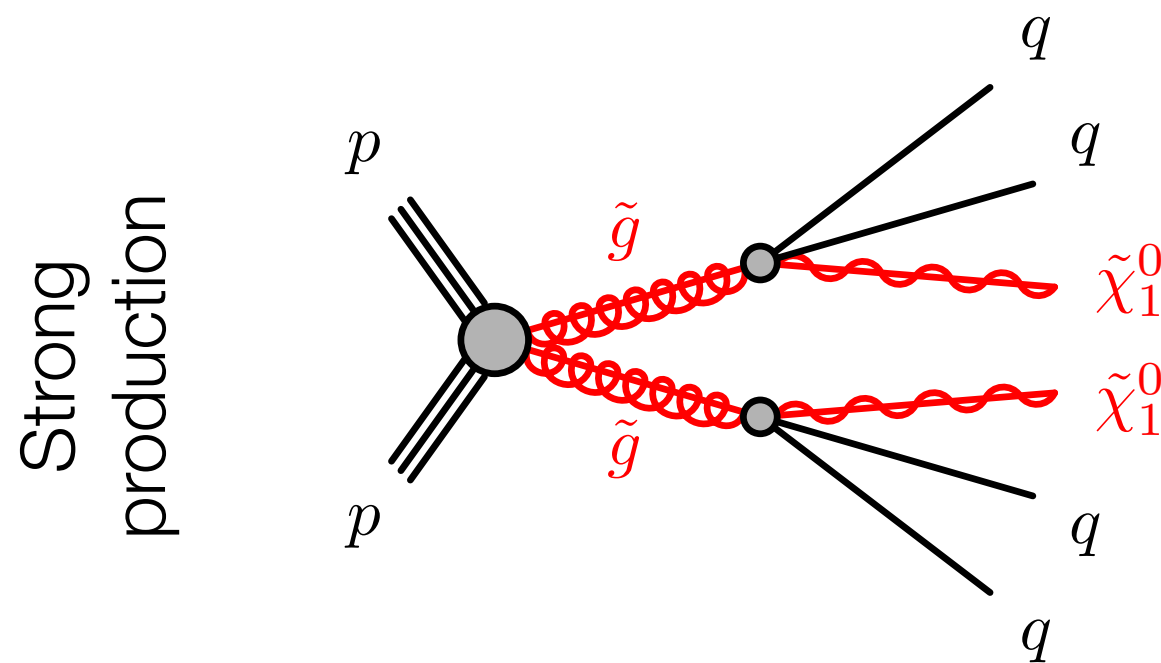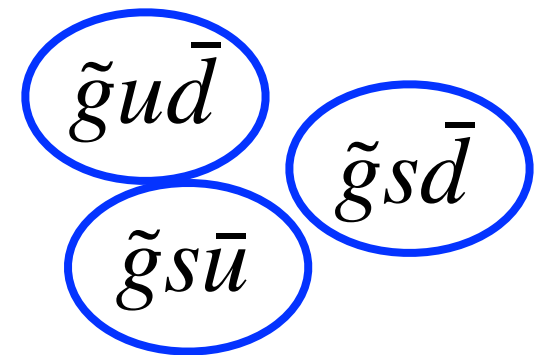
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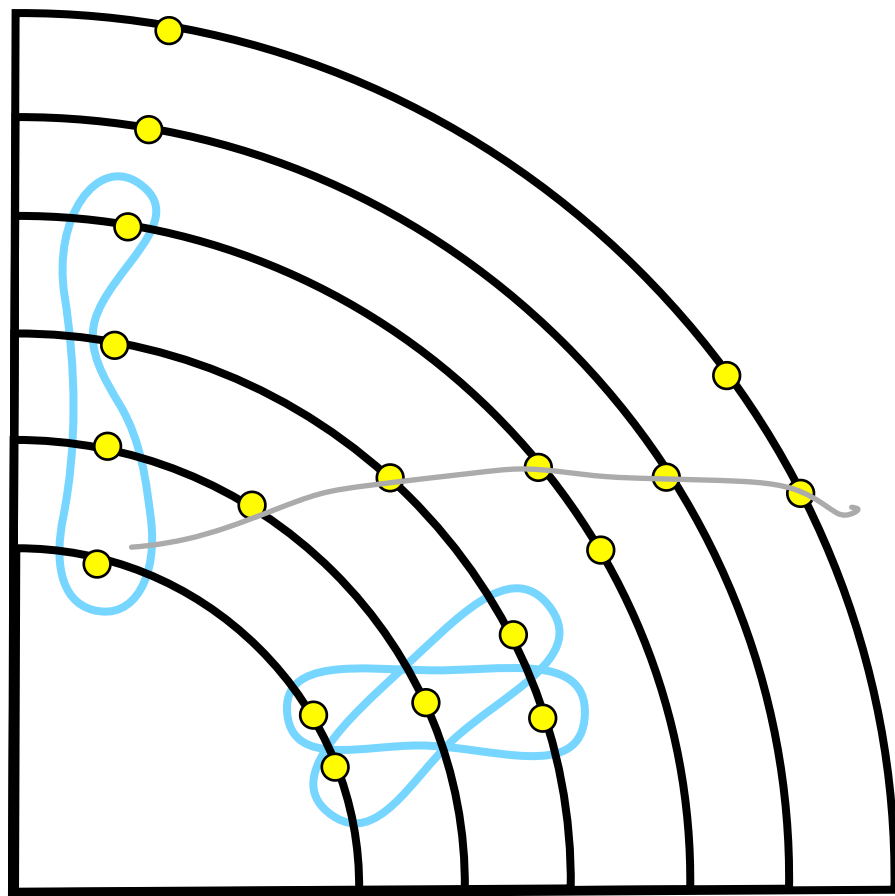
Cosmic ray vetos

- ~70% of cosmic events in ATLAS reconstructed as two muons. Remainder are missing top half (timing identified as backward-going).

- In these cases, use muon spectrometer hits to check opposite a reconstructed muon

  - Use direction from spectrometer hits to do matching, rather than η/ϕ w.r.t. origin

- Additional veto for cases where incoming muon would have passed through non-instrumented slice at $\eta=0$

- Efficiency for eliminating cosmics = 99.7% as tested in cosmic run

How does track reconstruction work? ATLAS

Pierfrancesco Butti

Next: outside-in starts from TRT seeds and extrapolates backwards. Both restrict candidates to near PV.

- Inside-out tracking (ATLAS primary)

  - Find **seeds** (pixel detector only) using 3-hit groups.

  - **Extend** seeds to strips detector layers with combinatorial Kalman filter

  - Assess track candidates: χ2, number of holes, number of shared hits, etc. Throw away suboptimal ones

- **Extend to TRT**

- **Refit with all points** to get best track parameters
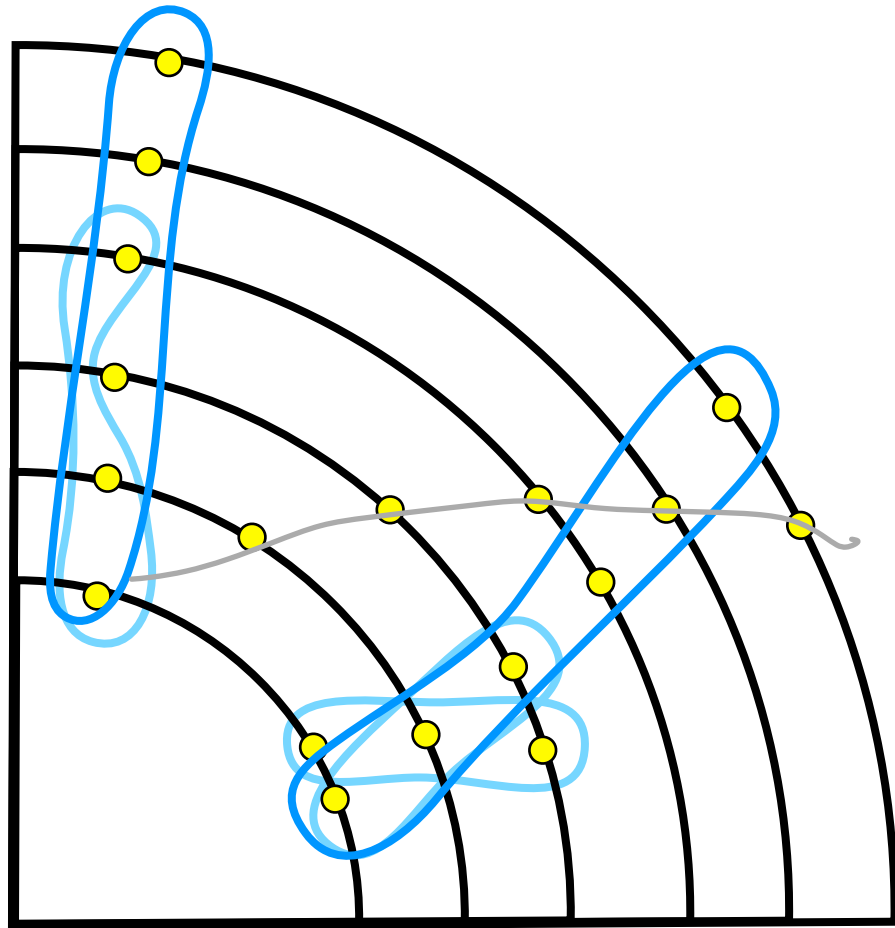
How does track reconstruction work? ATLAS

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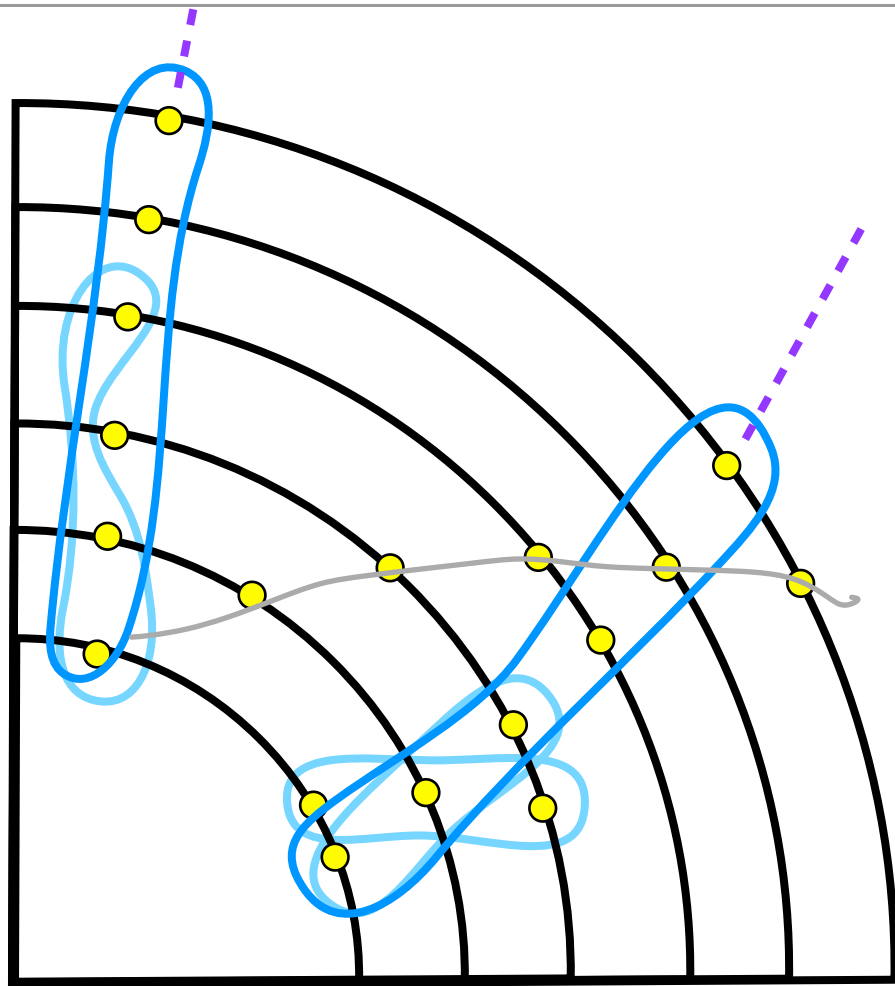# How does track reconstruction work? ATLAS

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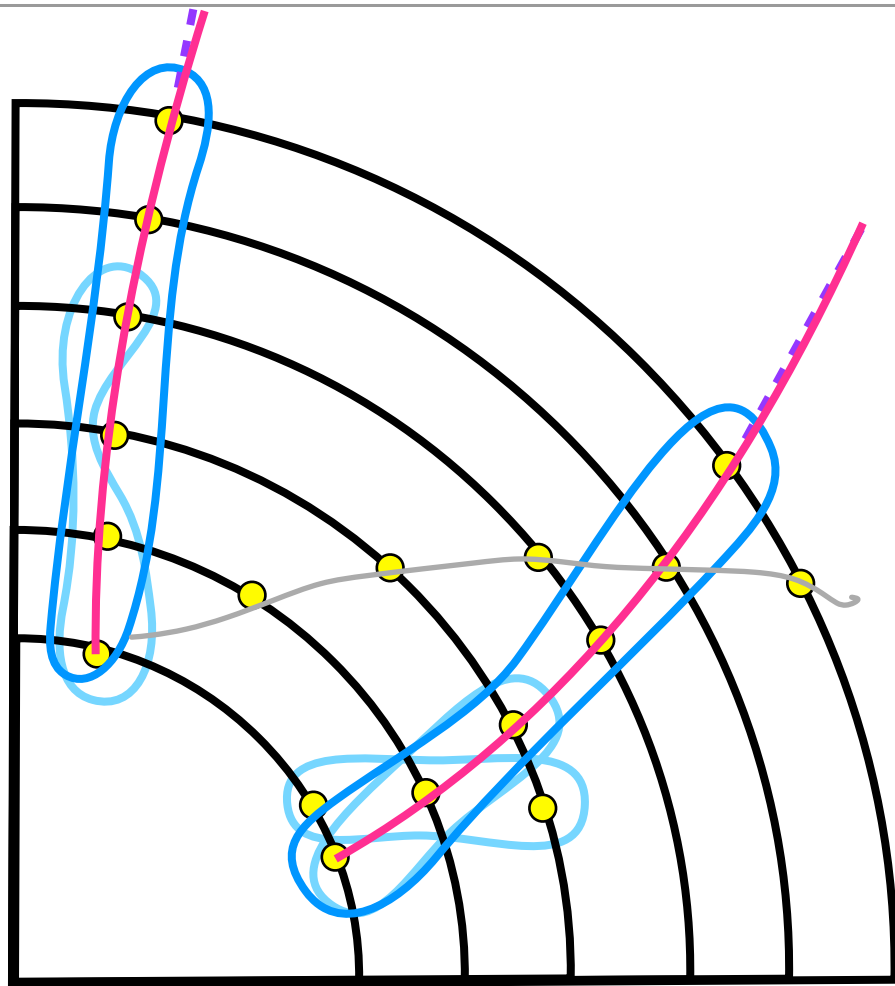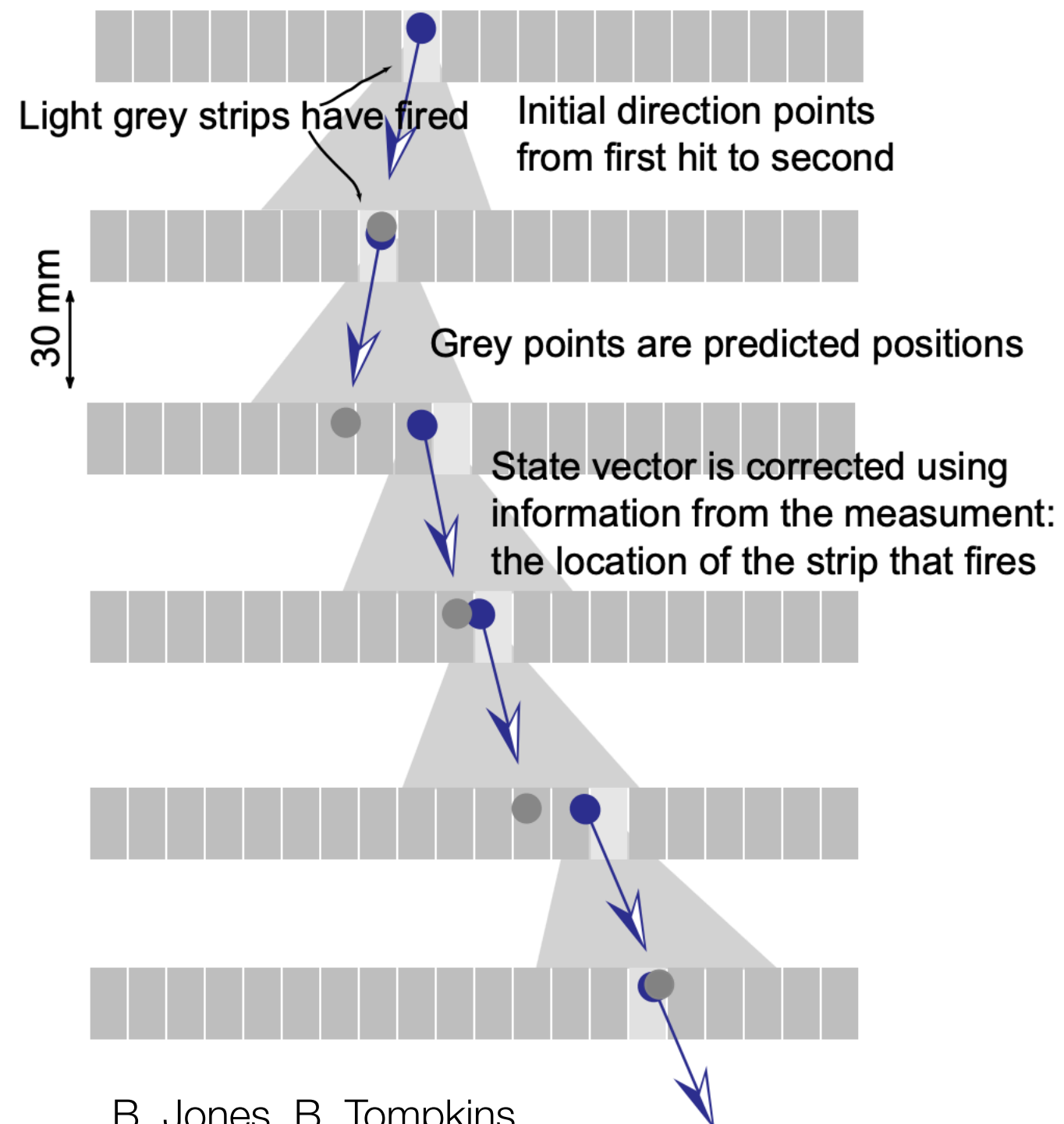
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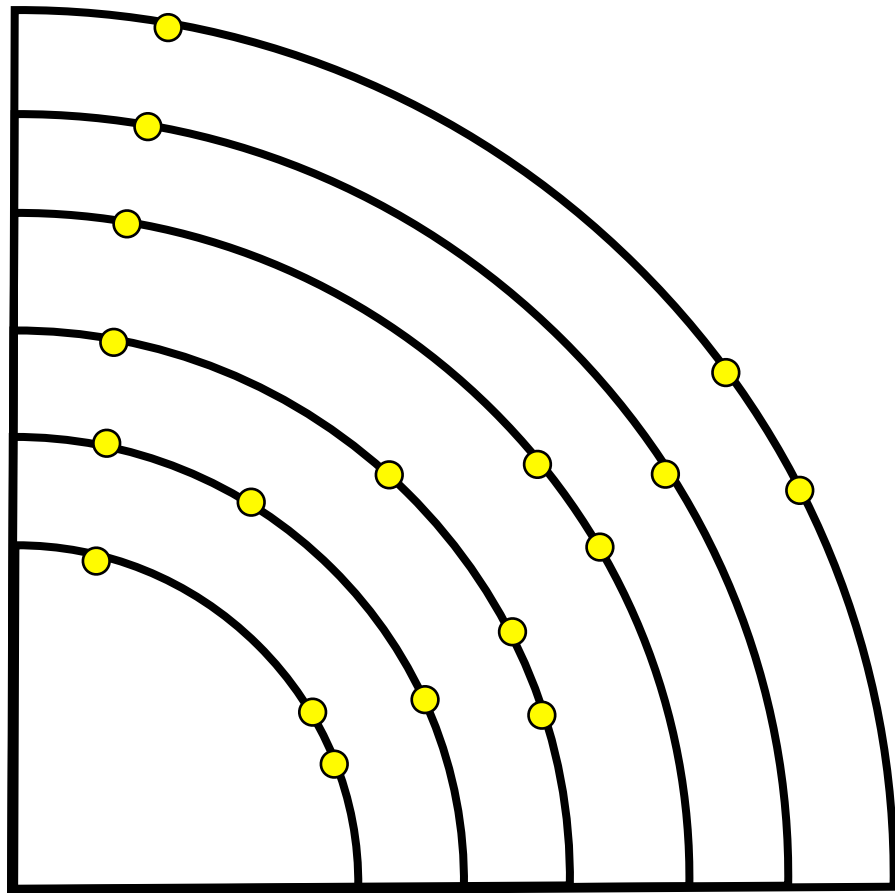 - **Refit with all points** to get best track parameters

What's a Kalman filter?

- "Linear quadratic estimation". Algorithm which uses set of points to predict next point in the set using joint probability distribution of those already observed.

- Prediction step, then once next point is added, taken into account and probability distribution adjusted.

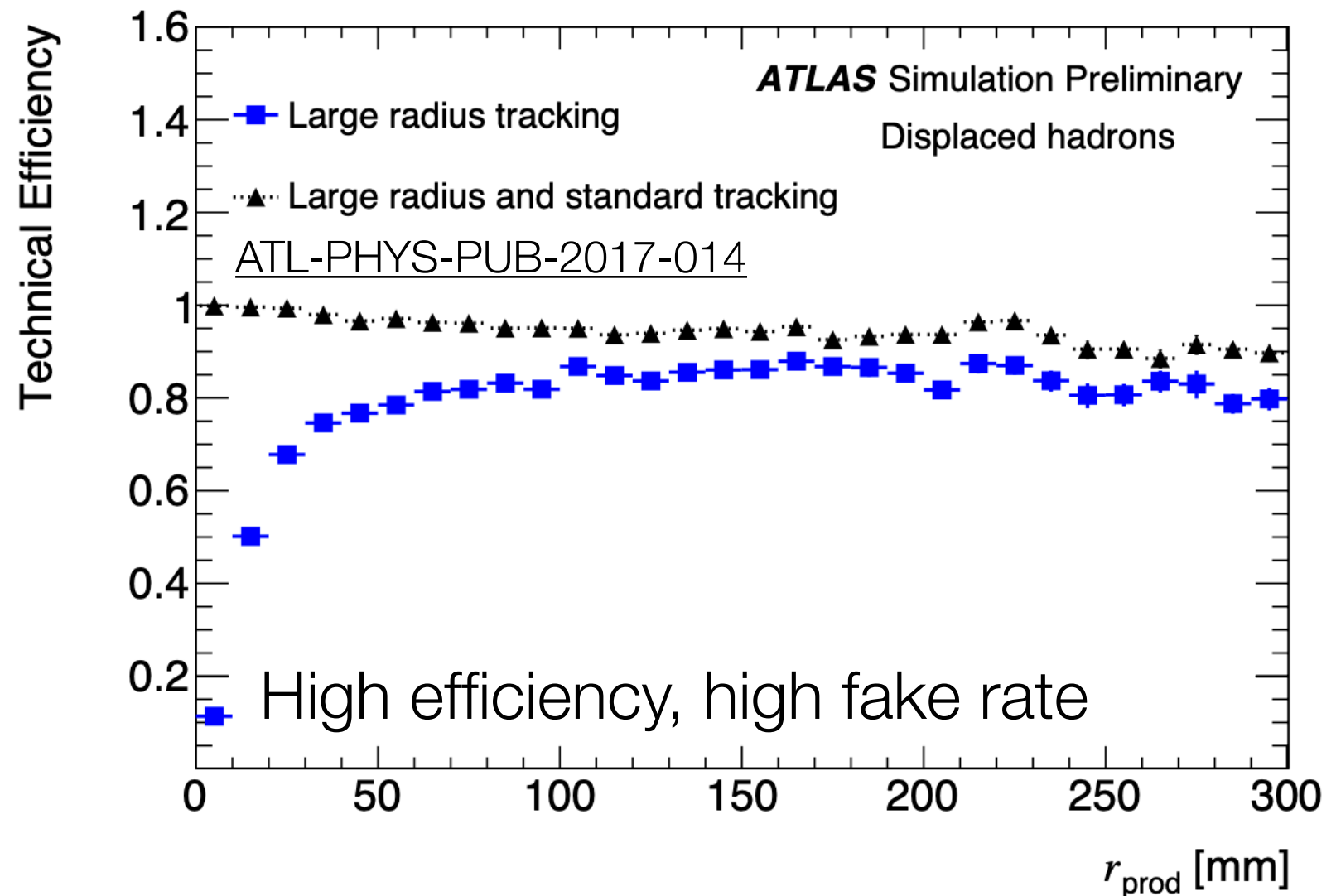Light grey strips have fired

Initial direction points from first hit to second

30 mm

Grey points are predicted positions

State vector is corrected using information from the measument: the location of the strip that fires

B. Jones, B. Tompkins

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Large-radius tracking in ATLAS

ATLAS Simulation Preliminary
Displaced hadrons

- Large radius tracking
- Large radius and standard tracking

ATL-PHYS-PUB-2017-014

High efficiency, high fake rate

Technical Efficiency

r_{prod} [mm]

- After inside-out and outside-in standard tracking, leftover points can now be used for second-pass tracking

- Sequential Kalman filter. Otherwise much the same as standard tracking but with loosened z0 and d0 requirements

63

Large-radius tracking in ATLAS

ATL-PHYS-PUB-2017-014

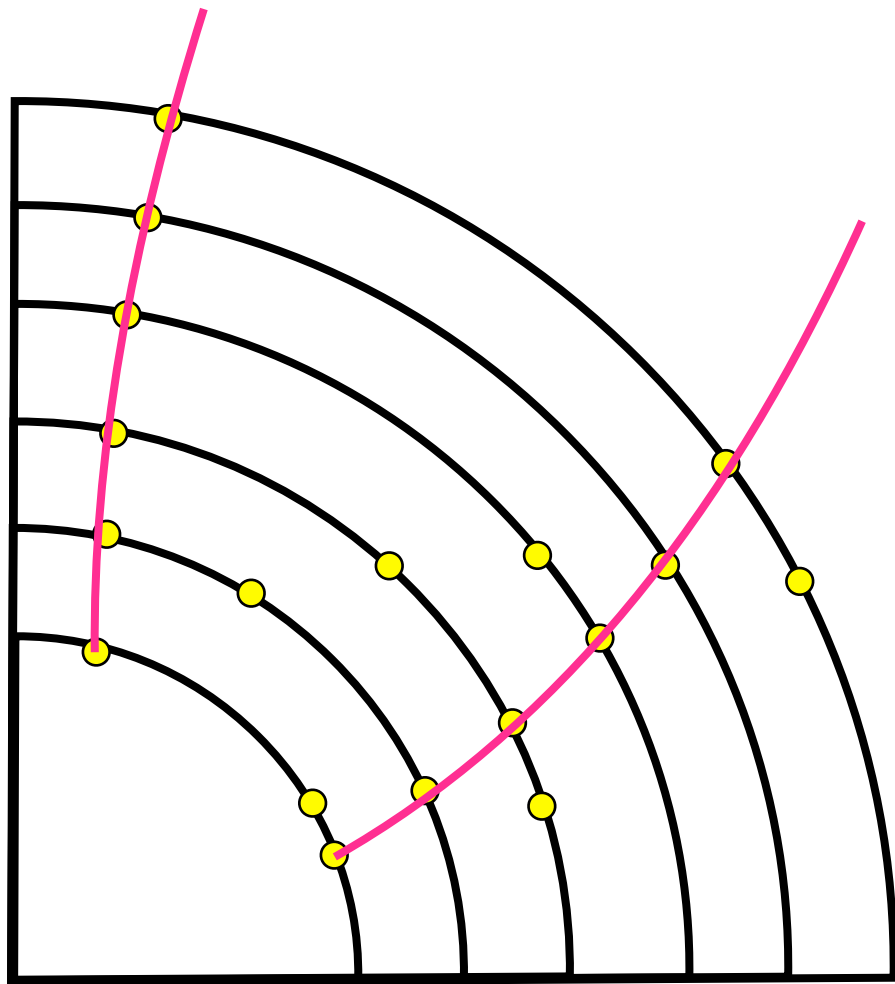High efficiency, high fake rate

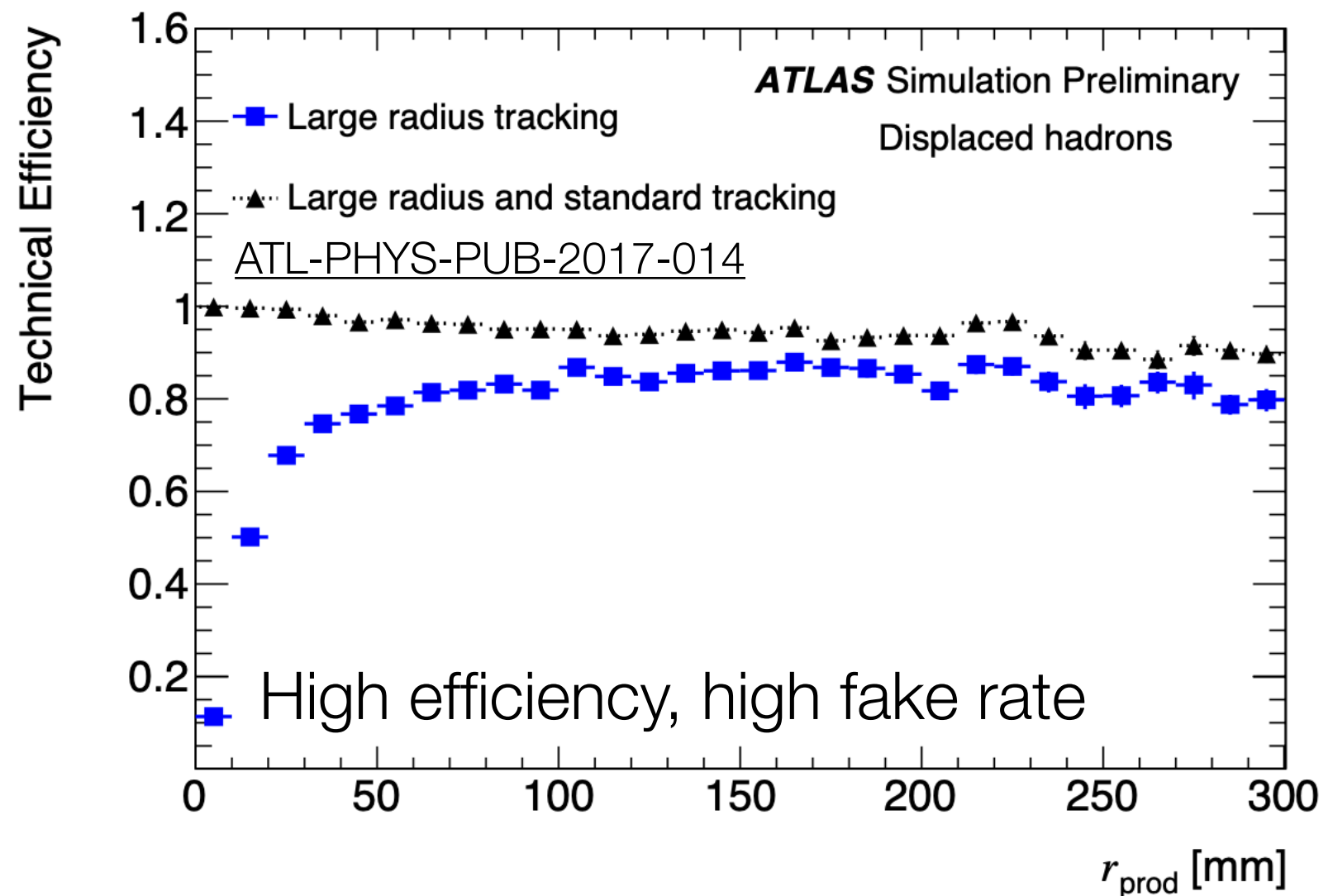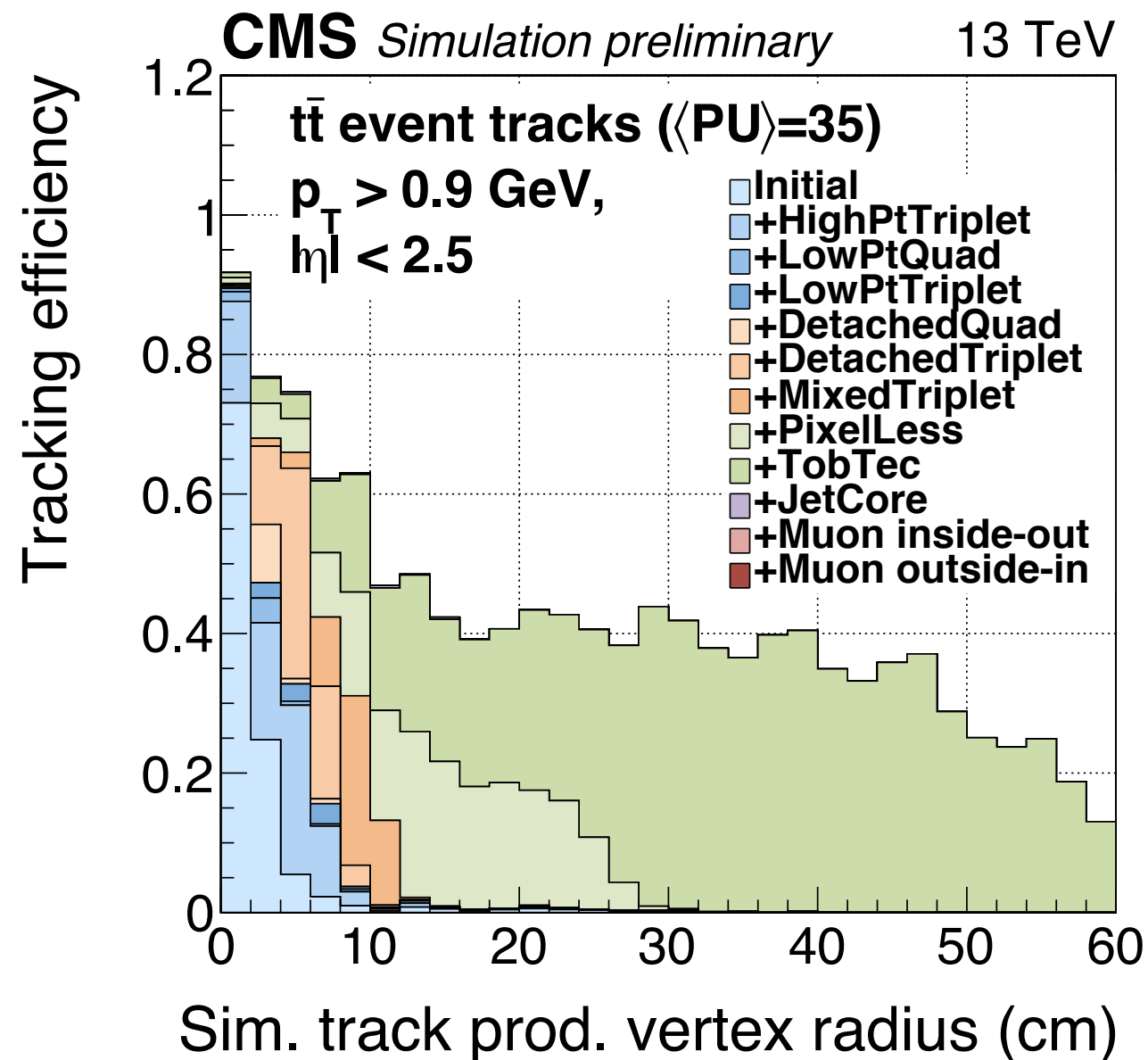- After inside-out and outside-in standard tracking, leftover points can now be used for second-pass tracking

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63

Large radius tracking and ATLAS data flow

- LRT is slow and has a high fake rate: can not run in default reconstruction

- Instead, define filters based on standard reconstruction to identify some fraction of events (currently ~10%)

- These events are separately reconstructed from RAW with all machinery of interest to long lived particle searches

- Get to keep all tracks selected by LRT, but need to sacrifice some events to keep rates low. Adds a trigger-like layer of inefficiency to analyses requiring LRT

Large-radius tracking in CMS

CMS *Simulation preliminary* 13 TeV

tt̄ event tracks (⟨PU⟩=35)

p_T > 0.9 GeV,
|η| < 2.5

- Initial
- +HighPtTriplet
- +LowPtQuad
- +LowPtTriplet
- +DetachedQuad
- +DetachedTriplet
- +MixedTriplet
- +PixelLess
- +TobTec
- +JetCore
- +Muon inside-out
- +Muon outside-in

Tracking efficiency

Sim. track prod. vertex radius (cm)

Lower efficiency, lower fake rate
Efficiency sacrifice worth it to
get to run in all data!

- Large radius tracking run as part of *standard reconstruction* in CMS

- Tracking in 4 steps (seeding, track finding, fitting, selecting good tracks) repeated many times with loosening restrictions. Each pass, used points are removed

- This reduces combinatorics for next pass. Large-radius tracks allowed as late iterations.

ATLAS track triggers in Run 3

- Cancellation of FTK project means need to find an alternative form of pileup suppression in Run 3

- Proposal: full-scan tracking above some p_T threshold (TBD) for events passing jet or MET L1 trigger

- This allows rejection of pileup jet triggered events and more accurate MET

- Tracking in trigger runs within ROIs: even full scan. Identify ROI, use modified fast tracking (different seed finding, fast Kalman filter) to get initial candidates. Offline ambiguity solver produces precision tracks. Probably sacrifice precision tracks in Run 3.

- Tracking in trigger is an opportunity for LLPs - can use MET or jet L1 to seed custom trigger - but it is also a hazard: rejection of jets with tracks not associated to PV could kill displaced signals. Studies ongoing.

ATLAS track trigger in Runs 4-5

- HTT (hardware track trigger) current plan but up in the air: details will depend on readout speed of ITk components.

  - Pattern matching in AM chips

  - First and second stage tracking done by FPGAs

- L1Track: 4 MHz rate, can fit tracks with pT > 4 GeV. First stage fit only, happens in ROI. Can be done on ~10% of detector.

- Global HTT: Second stage (HLT) tracking to be done in full detector using similar associative memory pattern matching. Can run on ~10% of events as requested by Event Filter

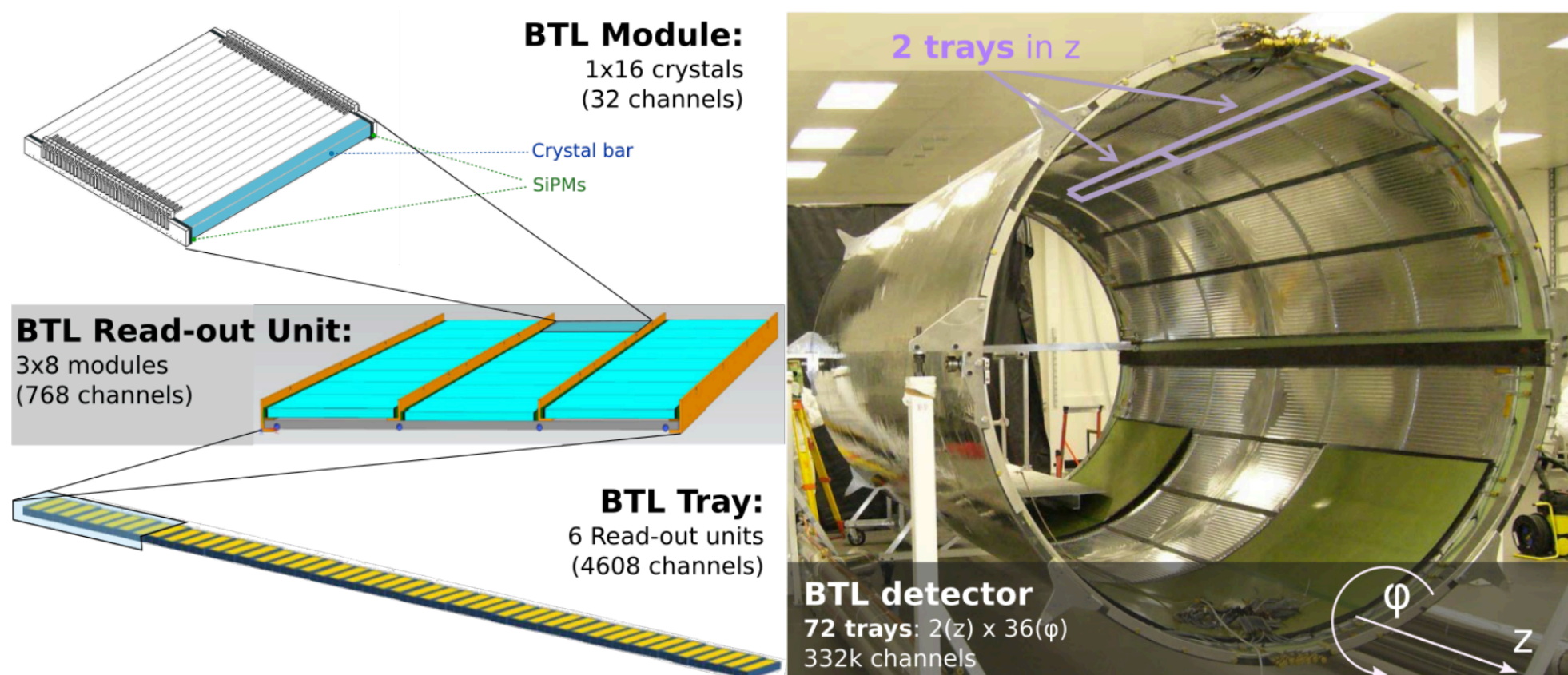- Option to replace global HTT with CPUs if performance and computing budget seem comparable

CMS track trigger in Runs 4-5

- Hardware level at run 1: "stubs" in outer tracker

  - Assume we have a track originating from beam and passing through two closely spaced tracking layers. Pass if two hits + beamline compatible with high pT track

  - FPGA-based second stage will extend stubs into track candidates. Two algorithms being tested, so far similar performance: extending stubs geometrically into tracklets, or Hough transforms + Kalman filters.

- Software at HLT

  - Moving to GPUs allows many-thread processing

  - New algorithms plus smart data formatting/accessing tunes for GPUs make most efficient use of it
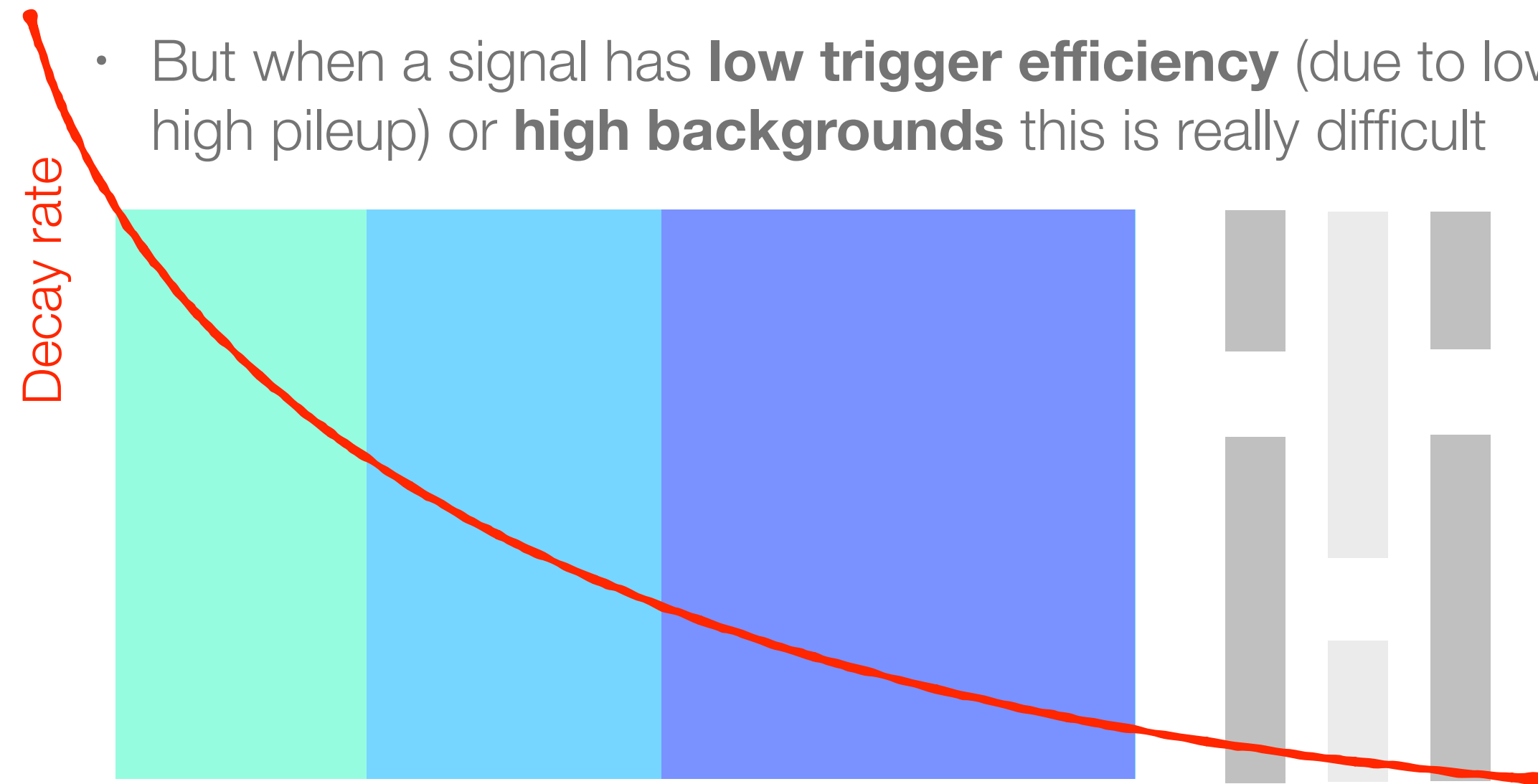
MIP timing detector

- Resolution ~30 ps in timing and ~3mm in z direction

- Barrel coverage (ATLAS only has forward coverage with HGTD): therefore can use for centrally produced LLPs

- Lutetium-yttrium orthosilicate crystals (LYSO) + silicon photomultipliers

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Beyond CMS and ATLAS

- Long lived neutral particle can **only** be seen via decay products

- As long as we can get **full efficiency** and **zero background** with our detector, always better to search closer to collision point

- But when a signal has **low trigger efficiency** (due to low mass or high pileup) or **high backgrounds** this is really difficult
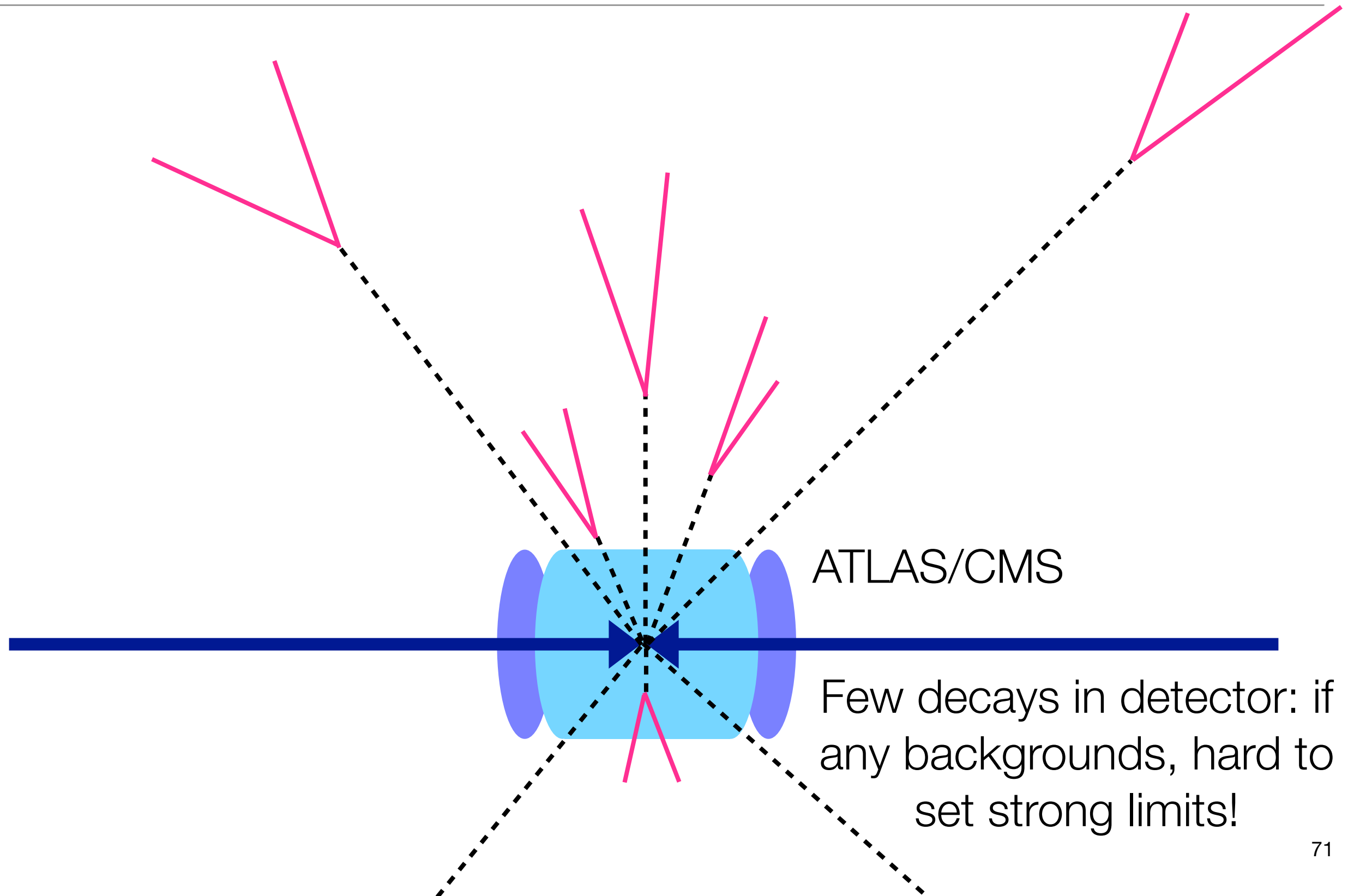

Decay rate

Beyond CMS and ATLAS

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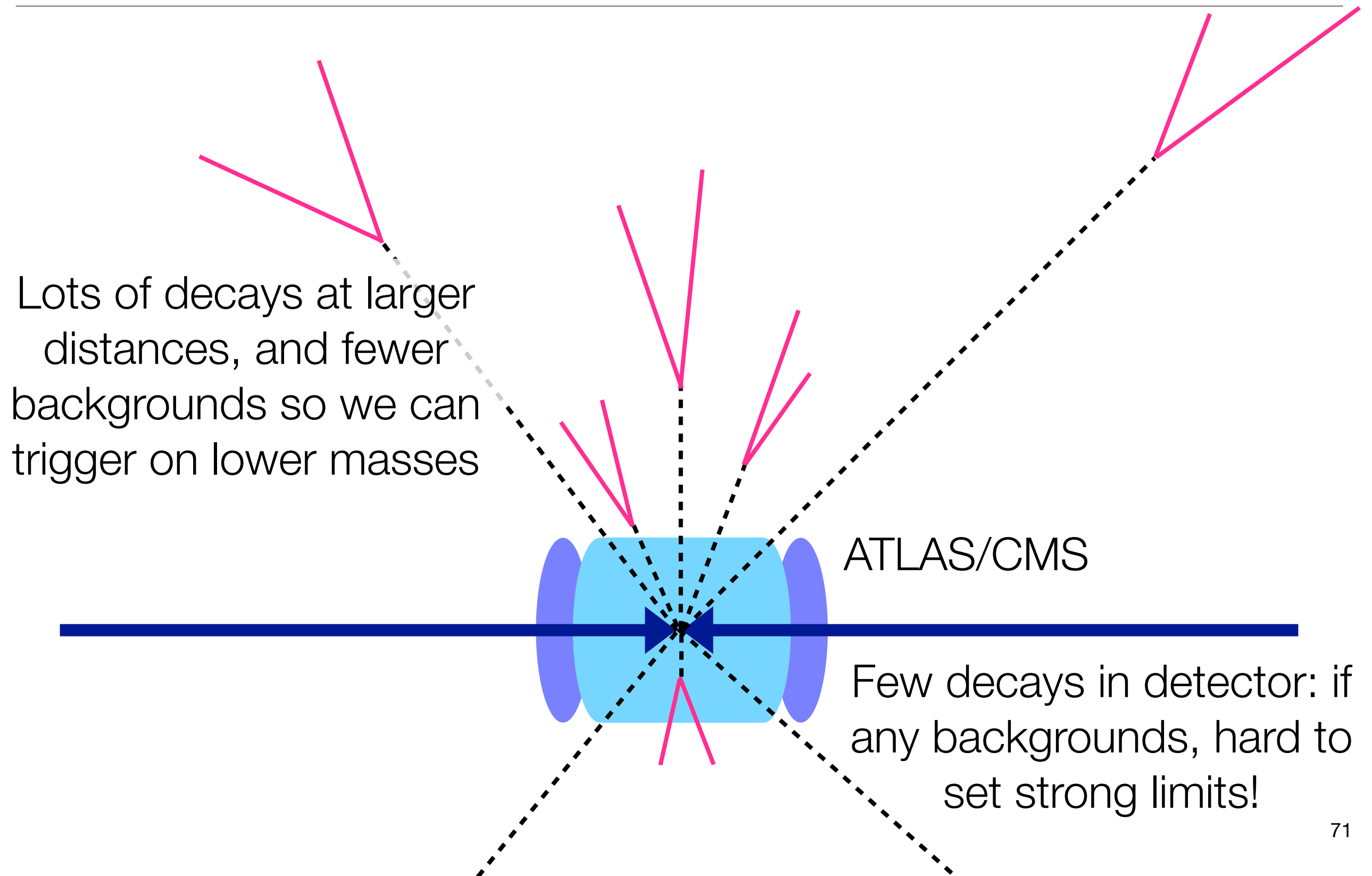
Decay rate

If the lifetime is
long enough…

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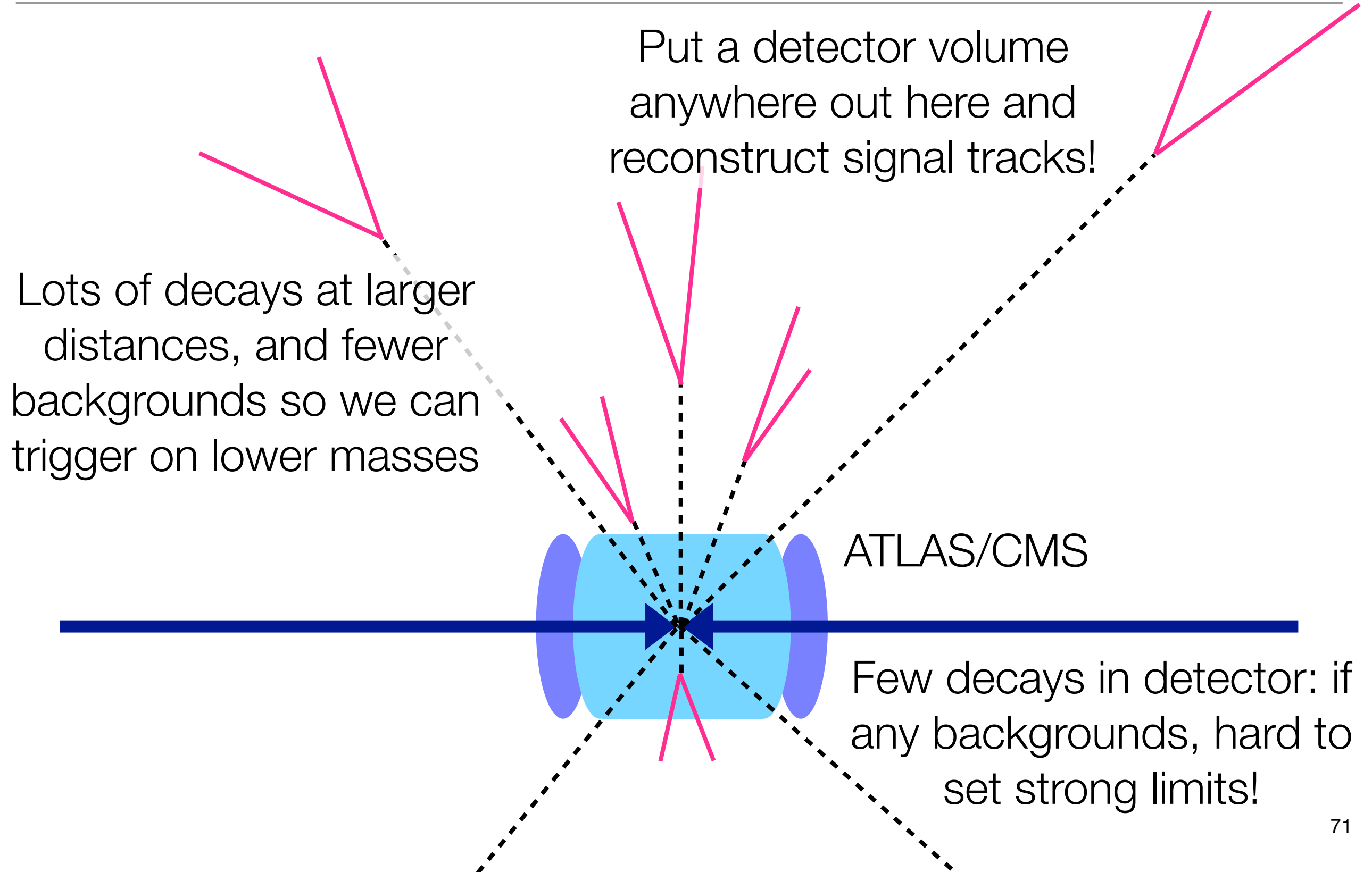
…we do much better by looking out here

70

Why we need a dedicated LLP experiment

ATLAS/CMS

Few decays in detector: if
any backgrounds, hard to
set strong limits!

71

Why we need a dedicated LLP experiment

Lots of decays at larger distances, and fewer backgrounds so we can trigger on lower masses

ATLAS/CMS

Few decays in detector: if any backgrounds, hard to set strong limits!

71

Why we need a dedicated LLP experiment

Put a detector volume anywhere out here and reconstruct signal tracks!

Lots of decays at larger distances, and fewer backgrounds so we can trigger on lower masses

ATLAS/CMS

Few decays in detector: if any backgrounds, hard to set strong limits!

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Why we need a dedicated LLP experiment

ATLAS/CMS

71

Why we need a dedicated LLP experiment

ATLAS/CMS

71

Why we need a dedicated LLP experiment

ATLAS/CMS

71

Why we need a dedicated LLP experiment

Lots of options for location, shape, can deliver similar sensitivity

ATLAS/CMS

As long as there is enough decay volume and solid angle coverage, can get interesting results!

Example: MATHUSLA

- Above-ground detector uses plastic scintillators

- Decay volume 20 m deep

- Several tracking layers above, one triggering layer below
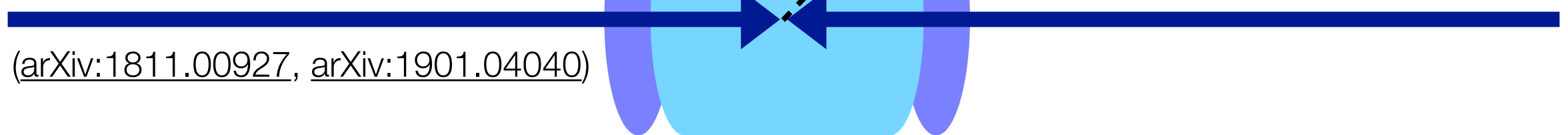
(arXiv:1811.00927, arXiv:1901.04040)

MATHUSLA is a leading proposal today, with **long lifetime reach** and the bonus opportunity to study **cosmic ray showers**

FASER

J. Feng, I. Galon, F. Kling, S. Trojanowski

P. Agrawal et al

M. Raggi, V. Kozhuharov

- FASER experiment now approved by LHCC and moving forward! Only approved dedicated LLP search at LHC.

- Downstream 480m from ATLAS, specialises in sub-GeV signals (e.g. dark photons)

  - Very light signals are produced along the beamline, as opposed to heavier particles which are produced centrally

- Can have a tiny experiment: just 10cm diameter by 5 m long

- Triggering/veto layer, empty decay volume, then 3 tracking layers and an EM calorimeter

Note on dark photons: generic term for neutral vector particle which has some interaction with SM fermions (e.g. kinetic mixing). Considered to have a nonzero but very small mass (viable DM candidate)

MATHUSLA

- Design: nominally 100x100x20 m

  - Modular; can easily scale up or down as needed to fit budget

- Location near CMS site, already discussed

- Technology likely plastic scintillator + SiPM: RPCs considered but gas + high voltage too inconvenient/dangerous

- Cosmic ray backgrounds challenging: down-going easy to veto, but splash back (albedo) requires more work

- However, opportunity for measuring with fine granularity incoming cosmic ray showers also. Physics case document in progress for this.

MATHUSLA, FASER, SHiP, etc

- So many models one could compare in that any specific interpretation would appear biased

- However, can roughly group proposals by type: forward/light and off-axis/ heavier. One of each is complementary but more than one per category is not necessary

CODEX-b EOI

5
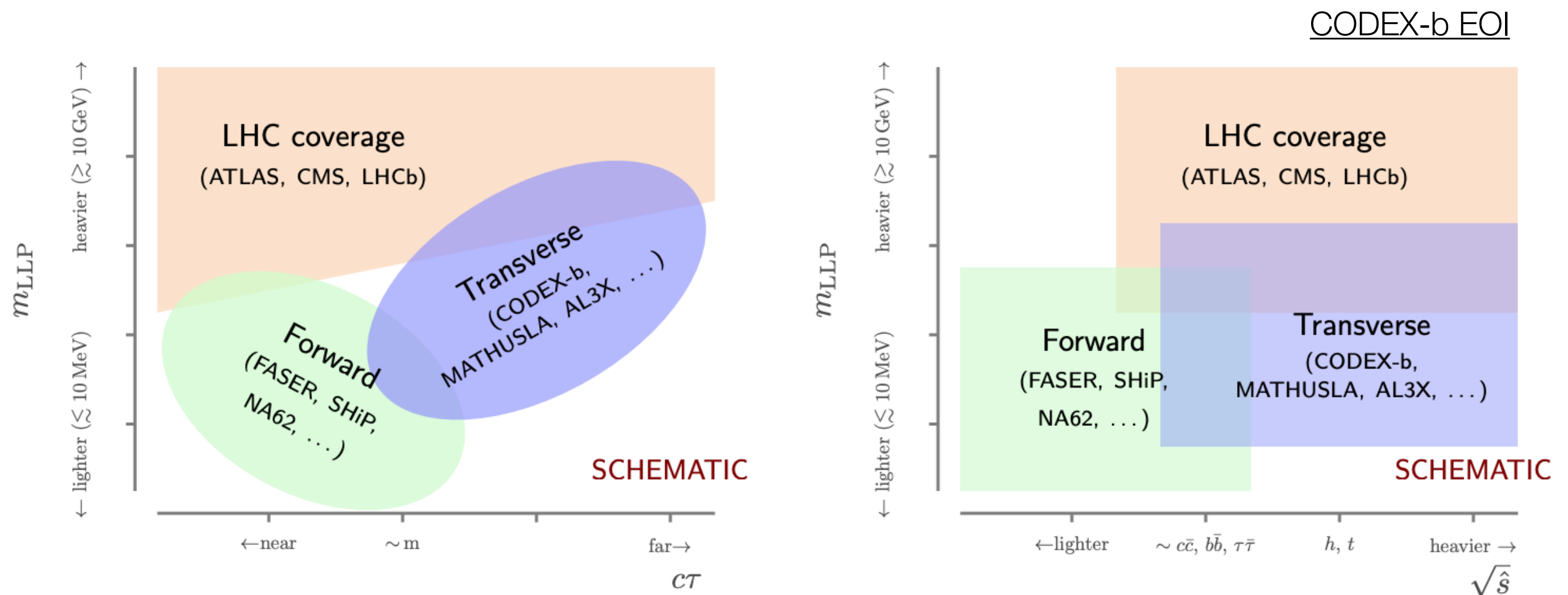
CODEX-b

- Off-axis experiment 25m from LHCb interaction point, volume ~ 10x10x10 m

  - Existing chamber near LHCb where remains of DELPHI currently sit: old detector could be removed for extra space

- Detector design options: 6 layers of RPCs, option for scintillator-based calorimetry.

- Add shielding between LHCb and experiment

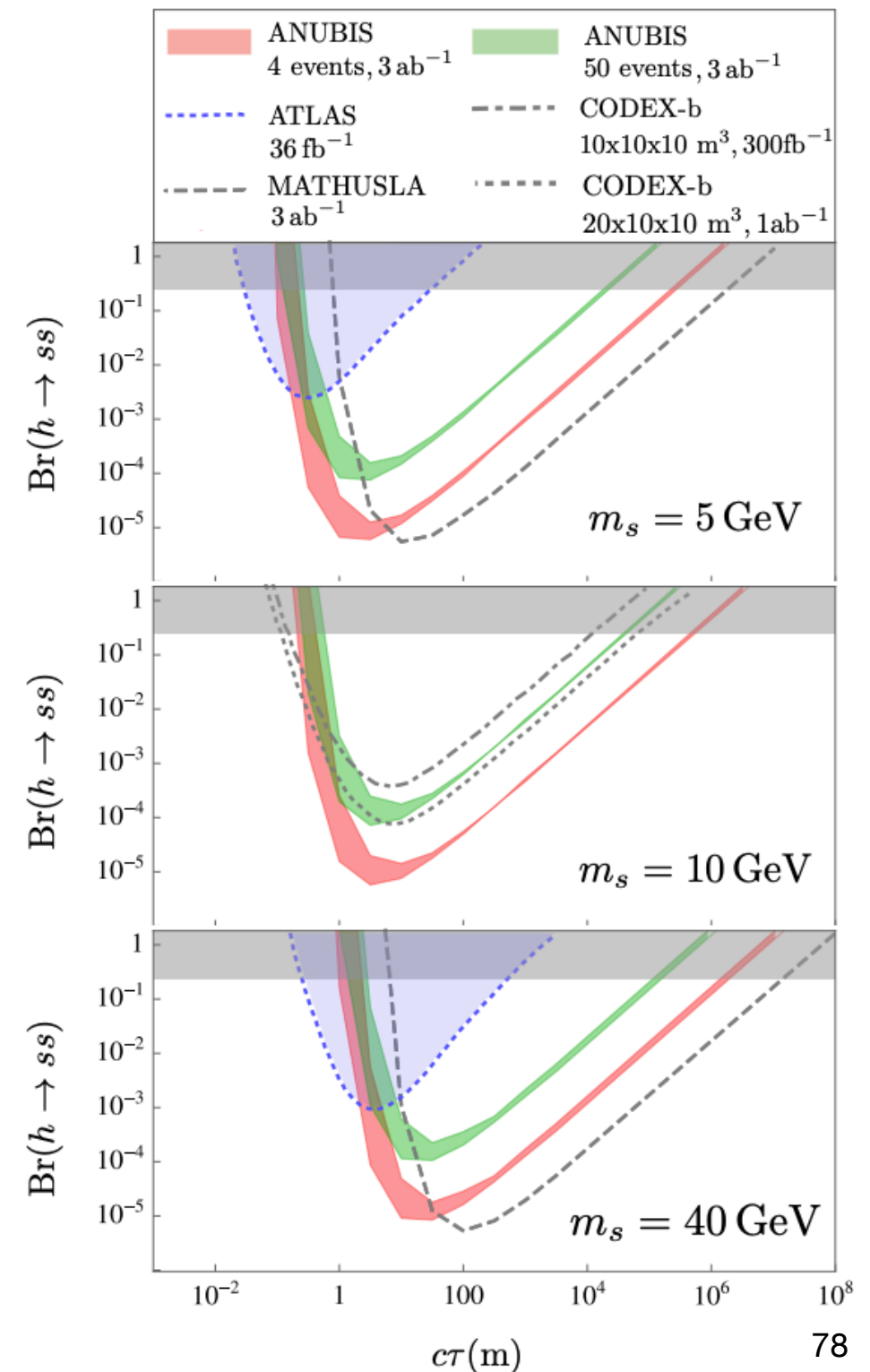- Initial tests of detector tech already completed

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V. Gligorov, S. Knapen, B. Nachman, M. Papucci, D. Robinson
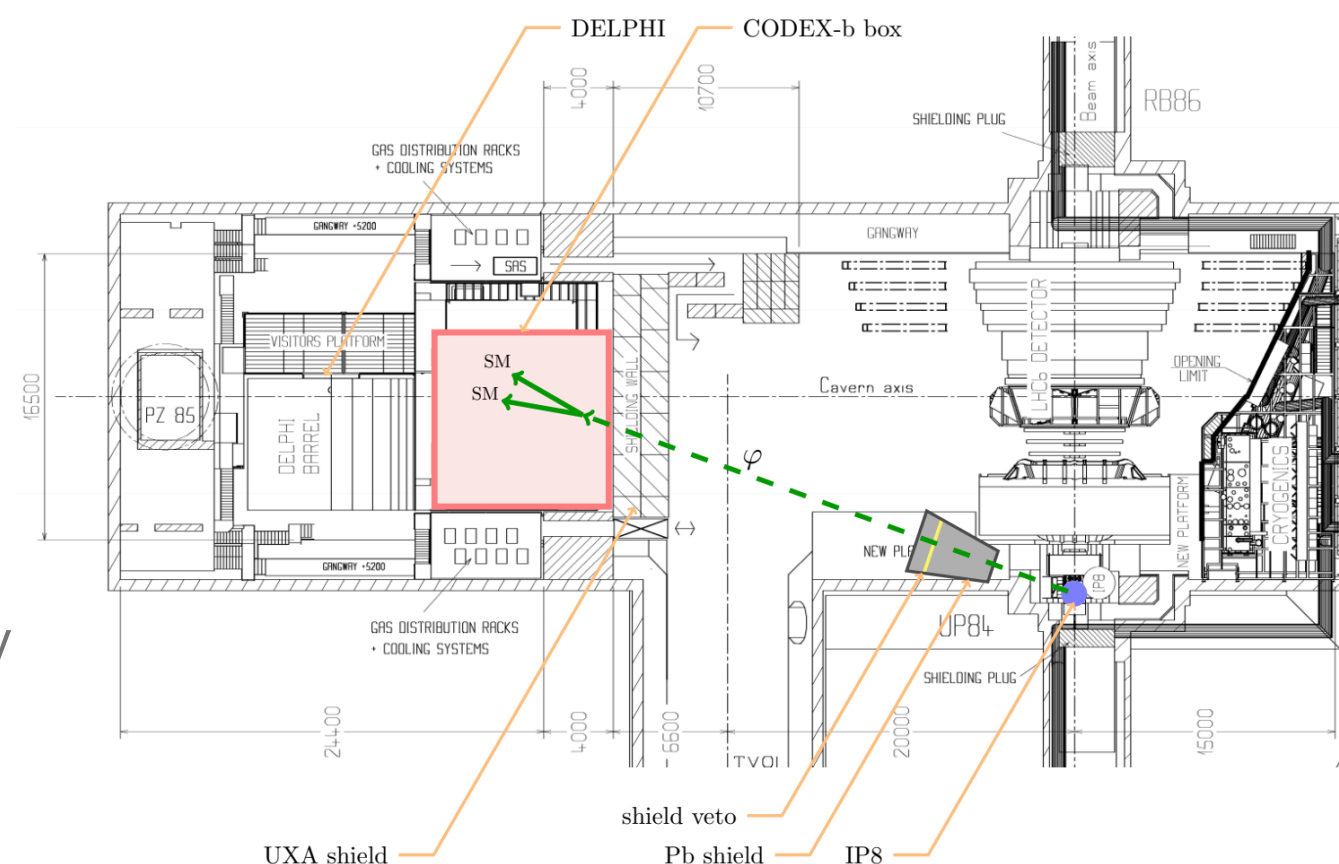
AL3X

- ALICE has no current plans for Run 5, when LHC heavy ion program likely finished

- AL3X would reuse portions of ALICE detector (particularly time projection chamber and L3 magnet) for a LLP search program during Run 5

- Requires modified IP: move it downstream by ~11 m and deliver higher luminosity (100 fb⁻¹). Add additional shielding between IP and experiment

- Experiment affordable; cost of moving IP to be determined

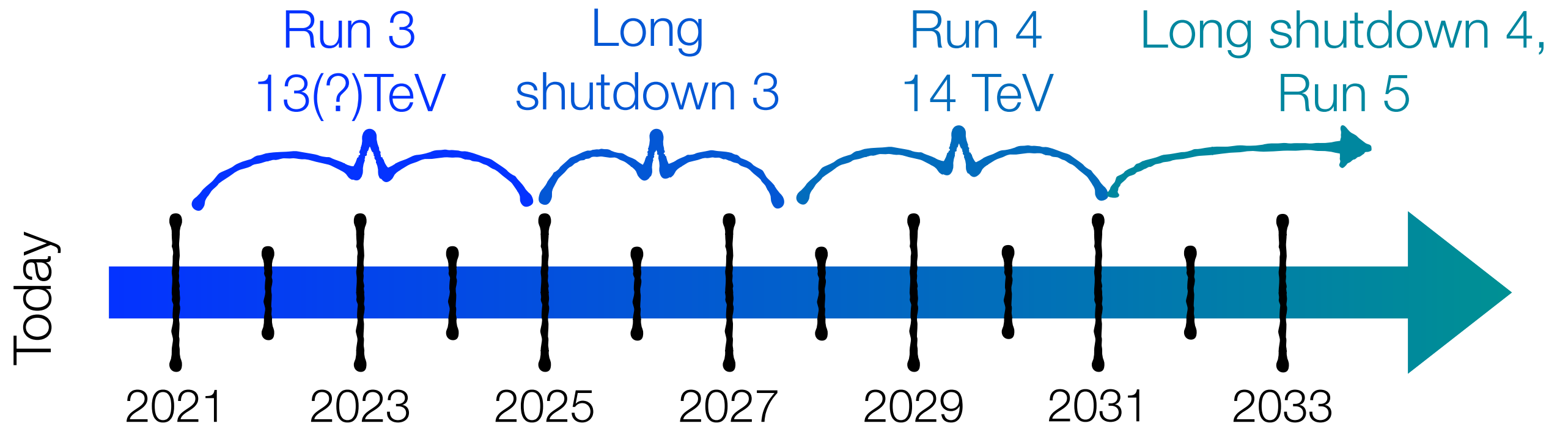77

M. Bauer, O. Brandt, L. Lee, C. Ohm
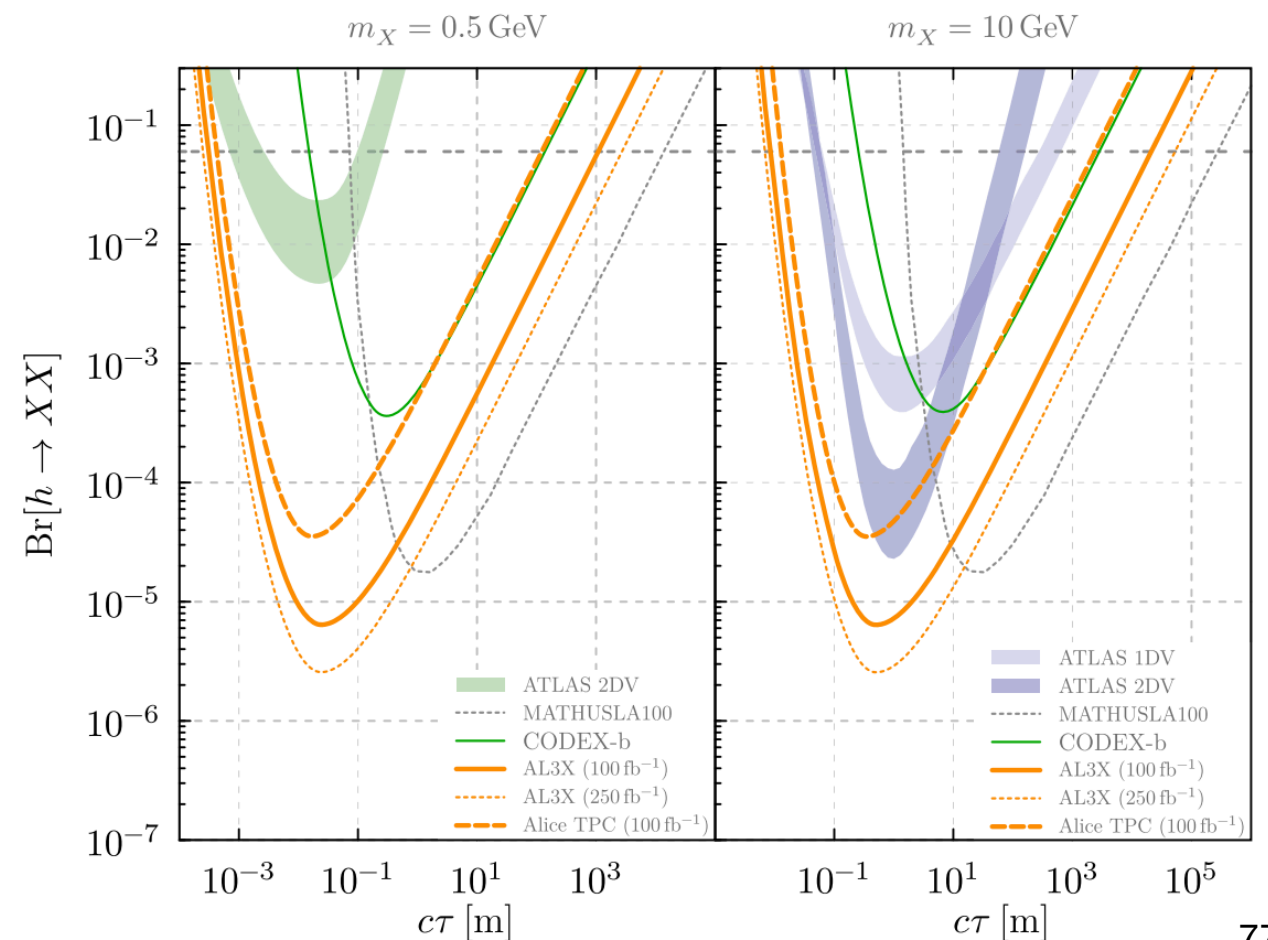
ANUBIS

- Instrument ATLAS access shaft with removable layers of tracking detector (RPCs) in order to use shaft as decay volume

- Close enough to integrate with ATLAS beam crossing information

- 18m vertical depth and 18m diameter. Four equally spaced tracking stations

- Coverage comparable to CODEX-b in lifetime and depth
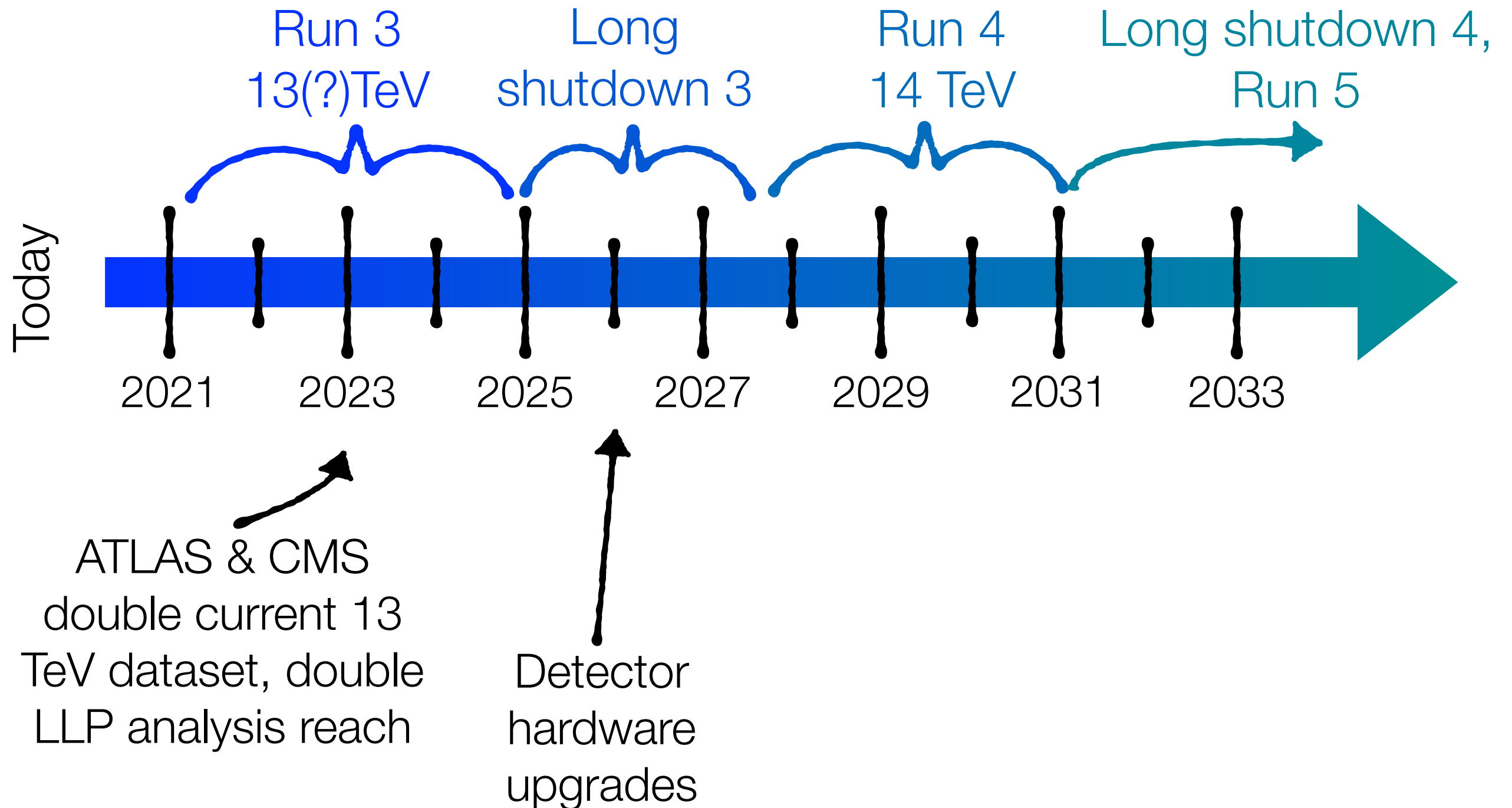
- Budget ~ 10M euros
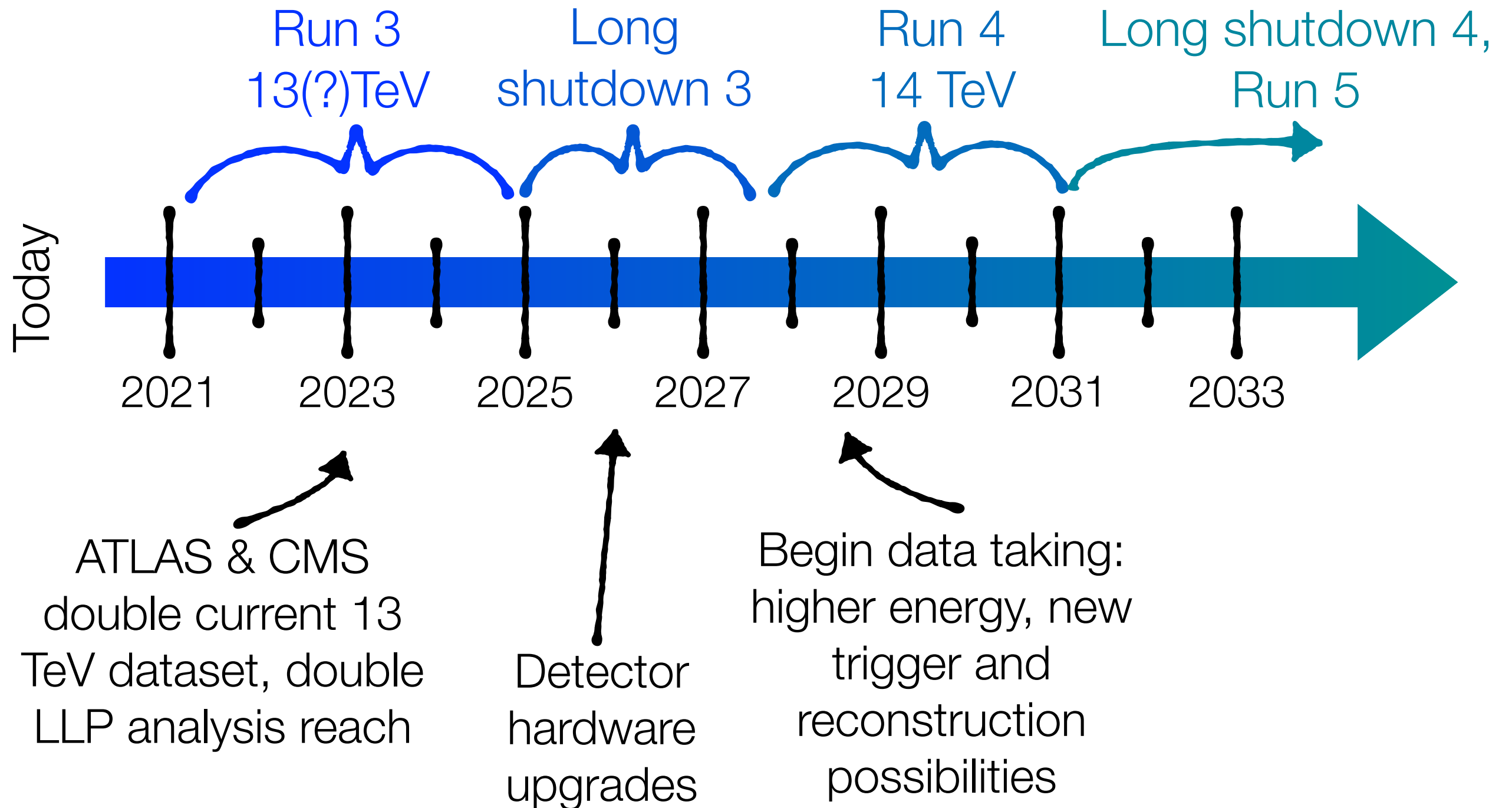

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LHC + LLP timeline

LHC + LLP timeline

LHC + LLP timeline

Run 3
13(?)TeV

Long
shutdown 3

Run 4
14 TeV

Long shutdown 4,
Run 5

Today

2021   2023   2025   2027   2029   2031   2033
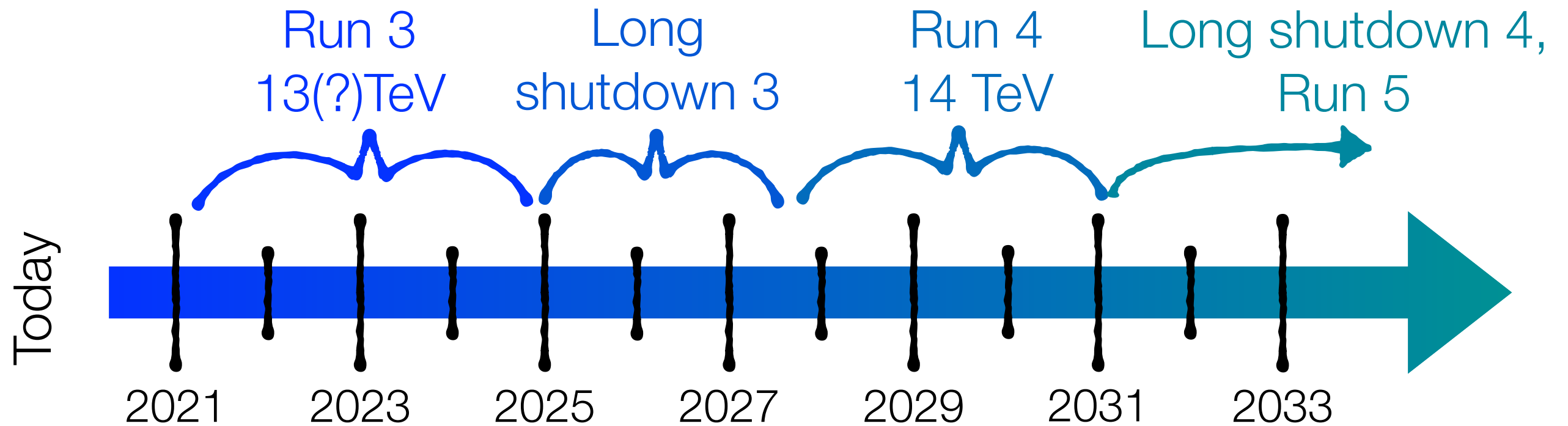
ATLAS & CMS
double current 13
TeV dataset, double
LLP analysis reach

Detector
hardware
upgrades

LHC + LLP timeline

LHC + LLP timeline

LHC + LLP timeline