A New Paradigm for Dark Matter Search at the LHC

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BNL Particle Physics Seminar

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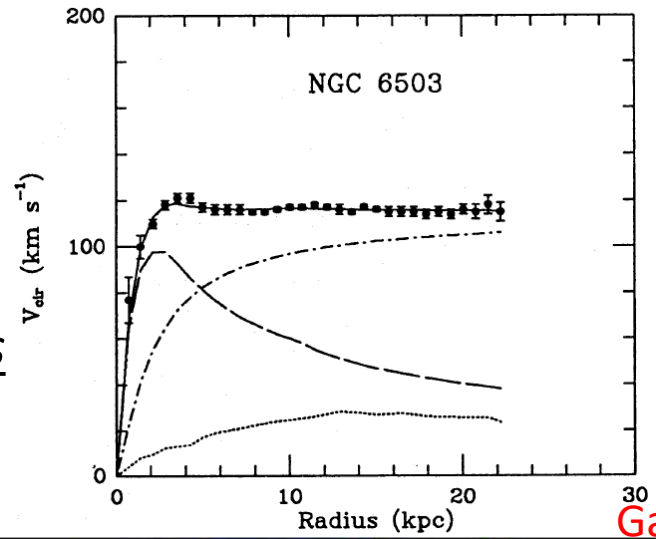
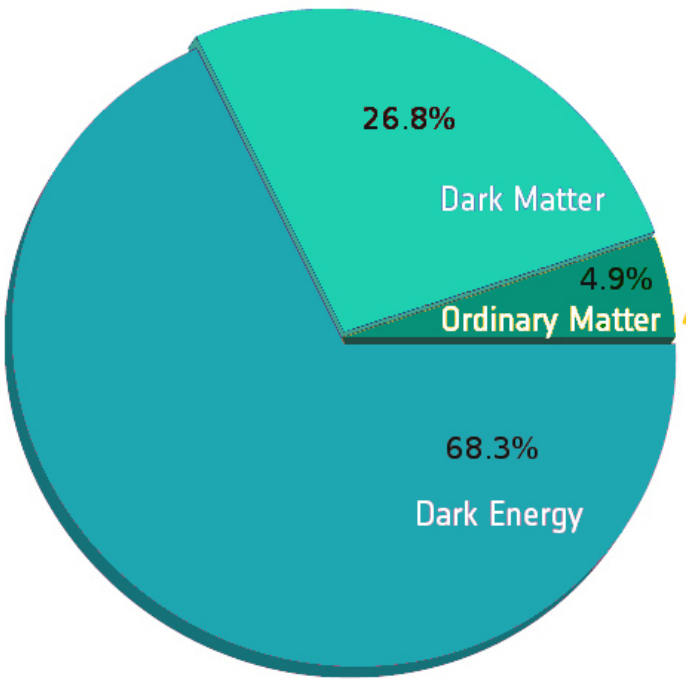
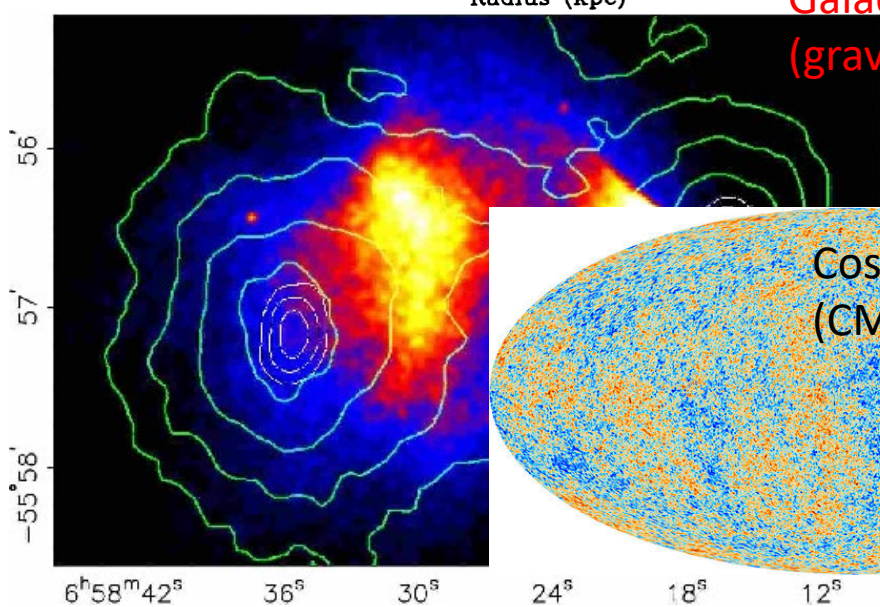
Why Dark Matter?

From *independent* observations on *different* astrophysical scales, **dark matter** is the *only* theory to simulate and reproduce the universe as we know it *on all scales*

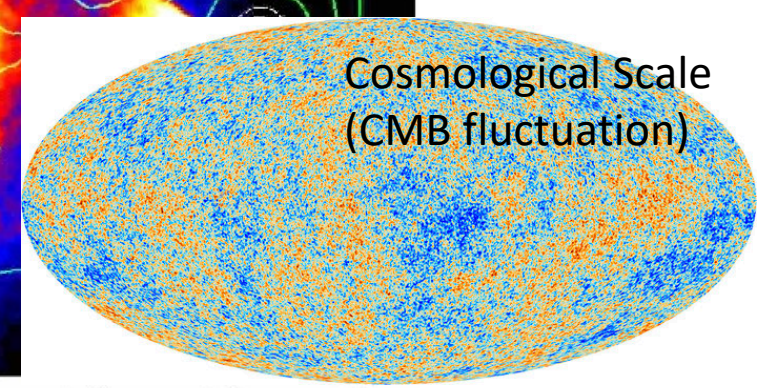


Galactic Scale (rotation curves of galaxies)



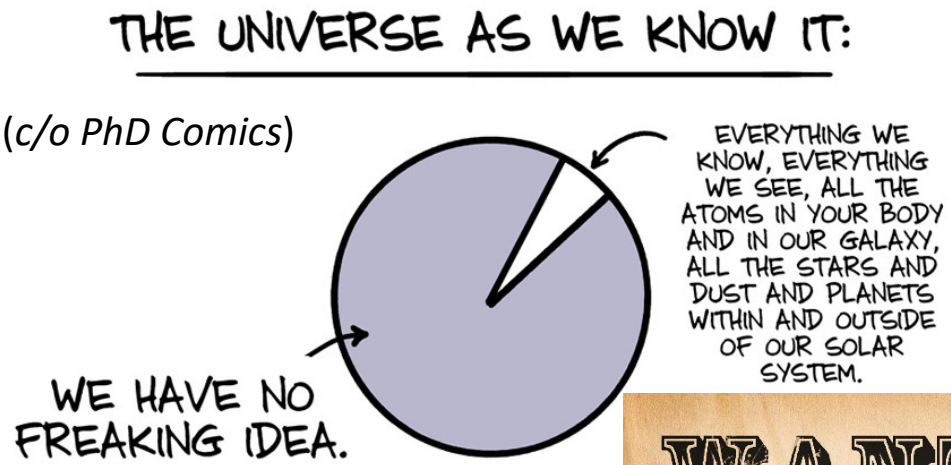


Galactic Cluster Scale (gravitational lensing)



Cosmological Scale (CMB fluctuation)

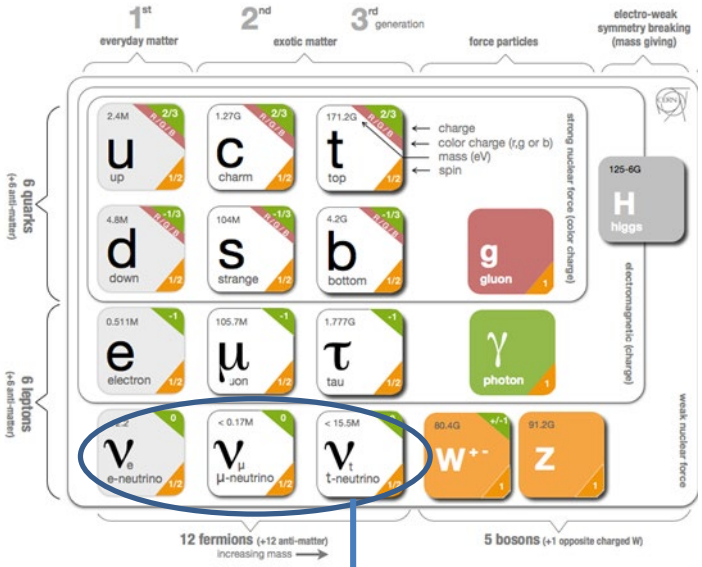
What is Dark Matter?



(*c/o PhD Comics*)

"There are more dark matter models than there are theorists."
-- Patrick Fox (FNAL), at UChicago HEP seminar

If DM is made of particles:
No viable DM candidates in the Standard Model



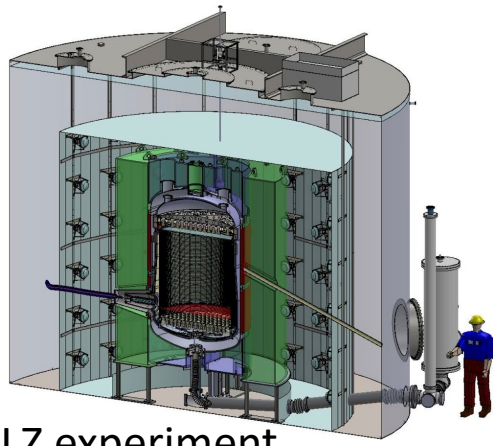
Neutrinos: very light, not cold, not abundant enough → cannot be the dominant source of dark matter

How do We Look for Dark Matter?

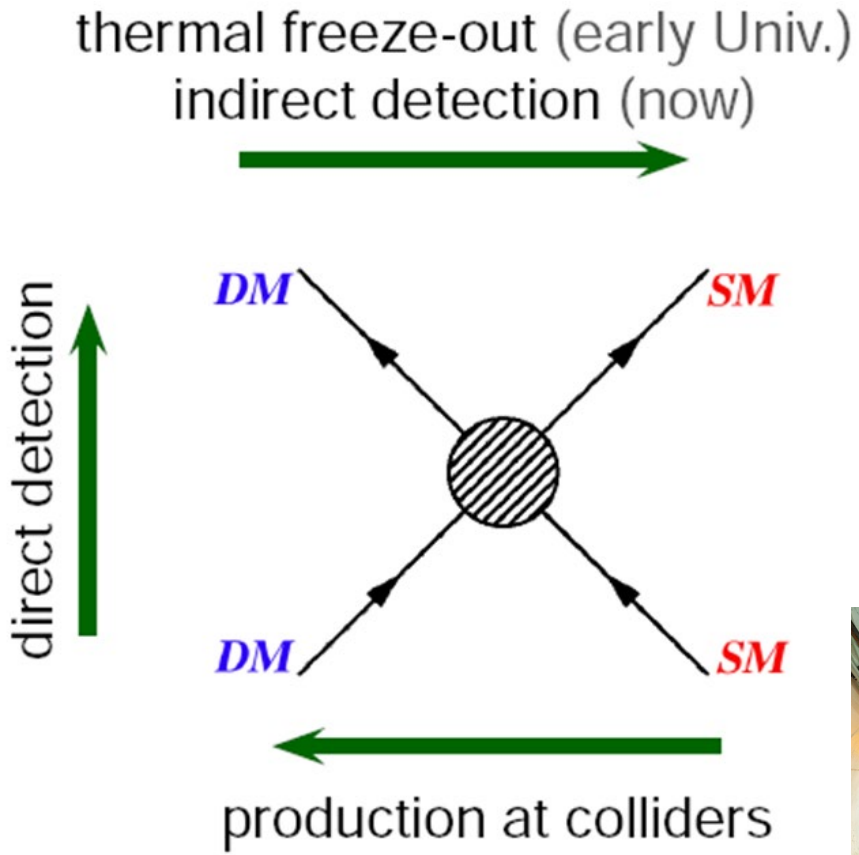
- Physics motivation
- Experimental overview
- Search for WIMP dark matter
- Dark matter beyond WIMPs
- Future dark sector search

Experimental Searches for DM

Three *complementary* methods
for dark matter particle detection:



LZ experiment

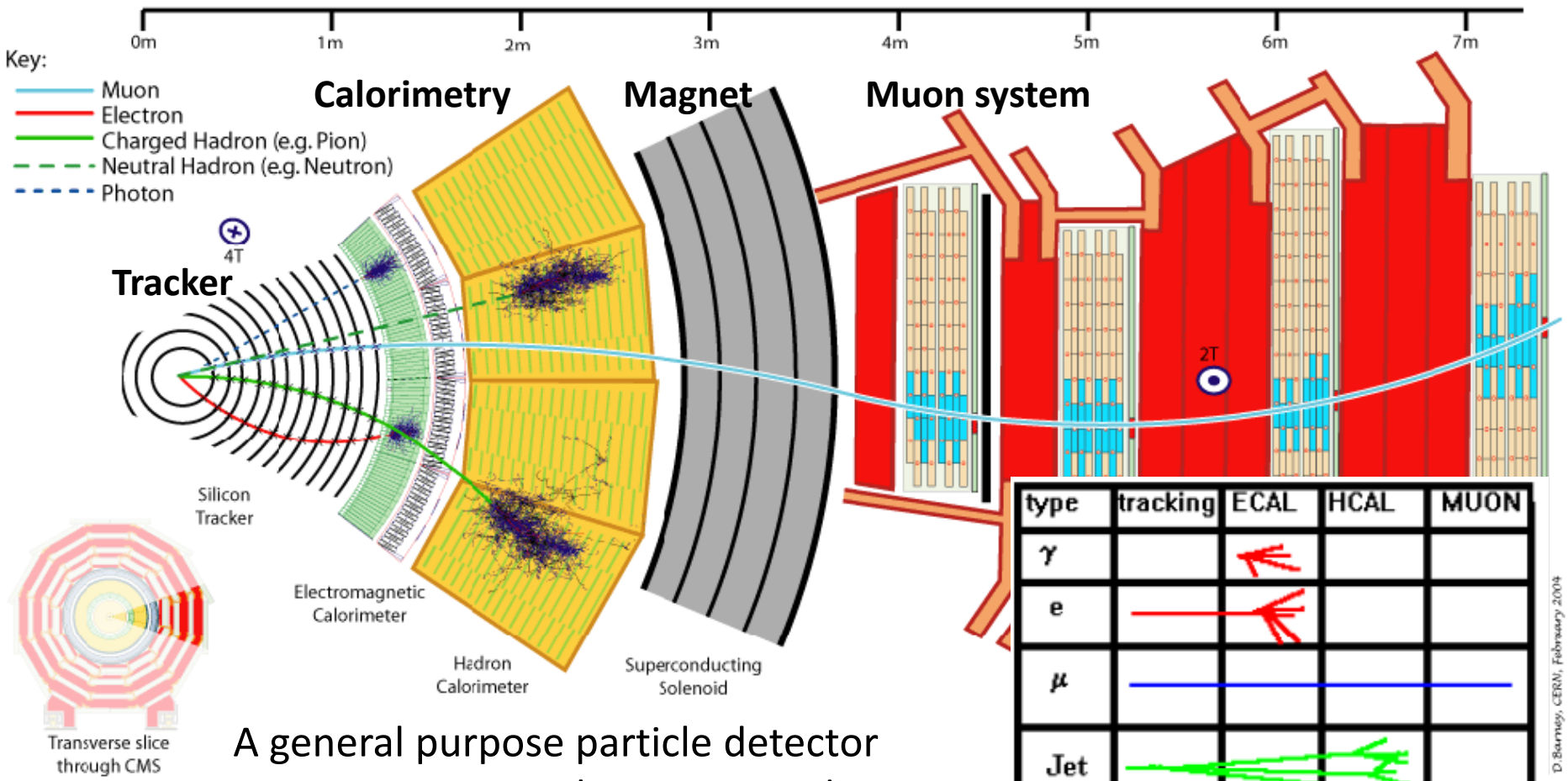


Fermi-LAT

CMS experiment

The LHC

The CMS Detector



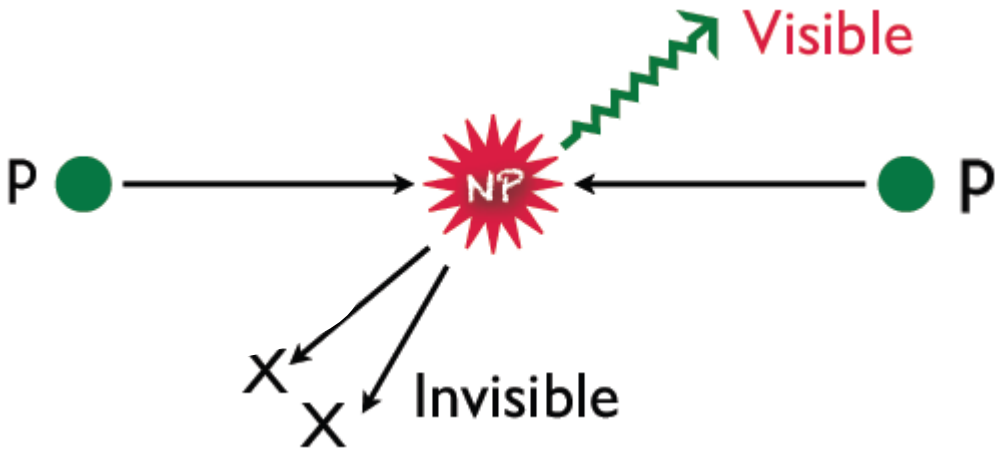
A general purpose particle detector

- 12,500tons, 21m long, 15m in diameter
- 3.8T magnetic field
- multiple sub-detectors

Collider Search for WIMP DM

"Conventional" searches for DM have focused on Weakly Interacting Massive Particles:

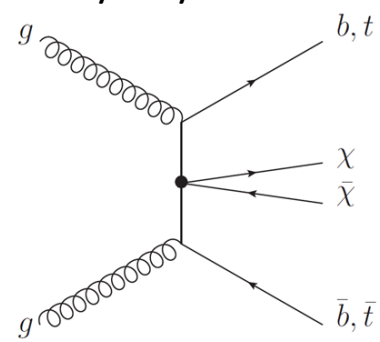
- fit relic density
- predicted in BSM theories



WIMP pair-produced at collider
→ large E_T^{miss}
→ search for excess in E_T^{miss} spectrum

WIMP-pair recoil against one or more visible particles X
→ "**mono-X**" signature
X=jet, γ, W, Z, …

X=b/ bb/ tt

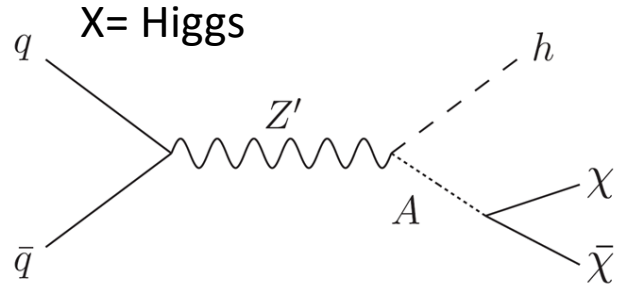


Explore DM interactions with different generations of quarks

arXiv:1410.4031

1st collider search

X= Higgs

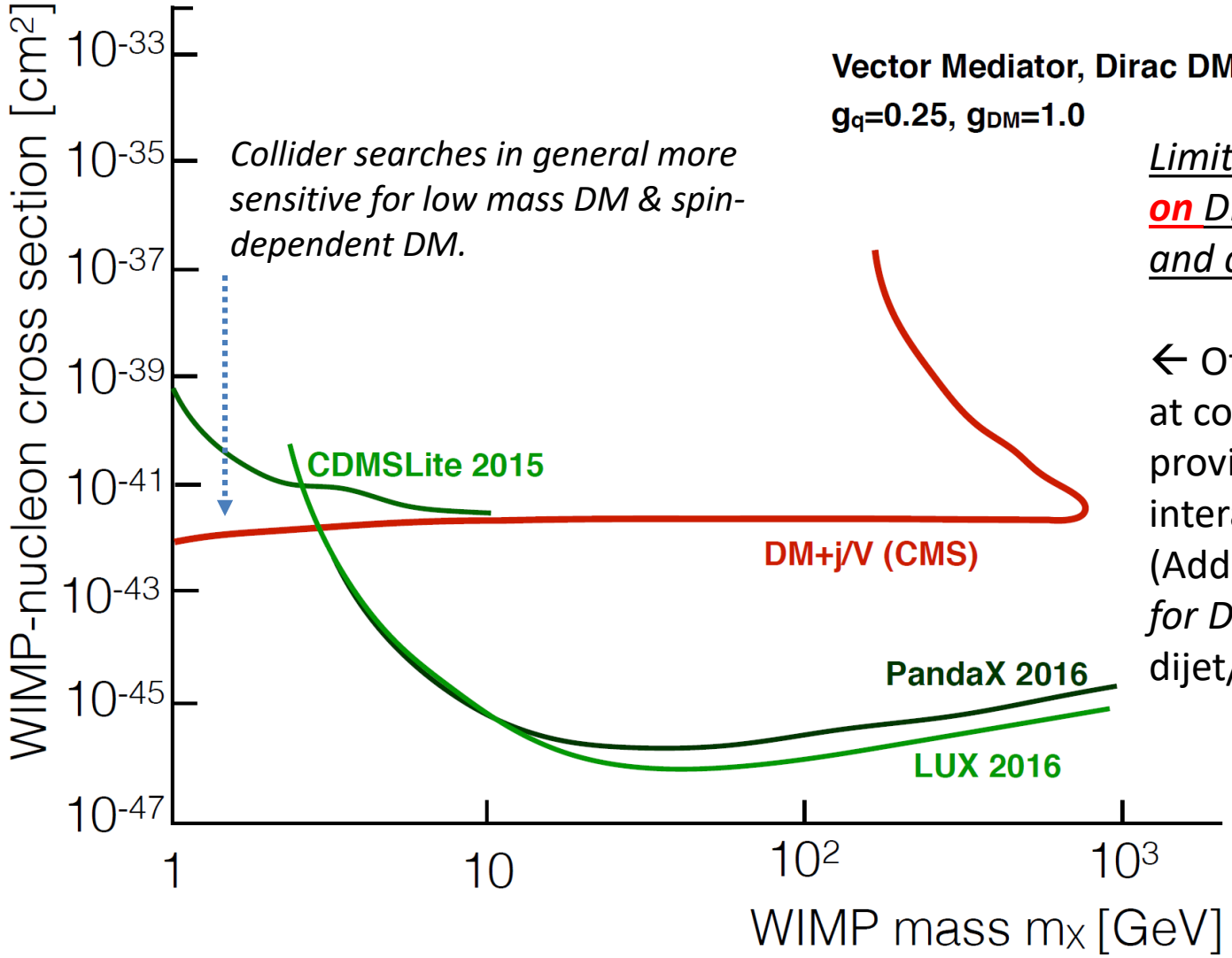


Higgs unlikely from ISR; explore DM-Higgs coupling

arXiv:1510.06218

1st collider search

No WIMPs Found (outside Congress) yet



*Limit interpretations **depend on** DM & mediator types, and coupling assumptions!*

← Other "*mono-X*" searches at collider complementary & provide additional DM-SM interaction info.
(Additional *collider searches for DM-SM mediator* in dijet/dilepton channels.)

How do We Look for Dark Matter?

- Physics motivation
- Experimental overview
- Search for WIMP dark matter
- Dark matter beyond WIMPs
- Future dark sector search

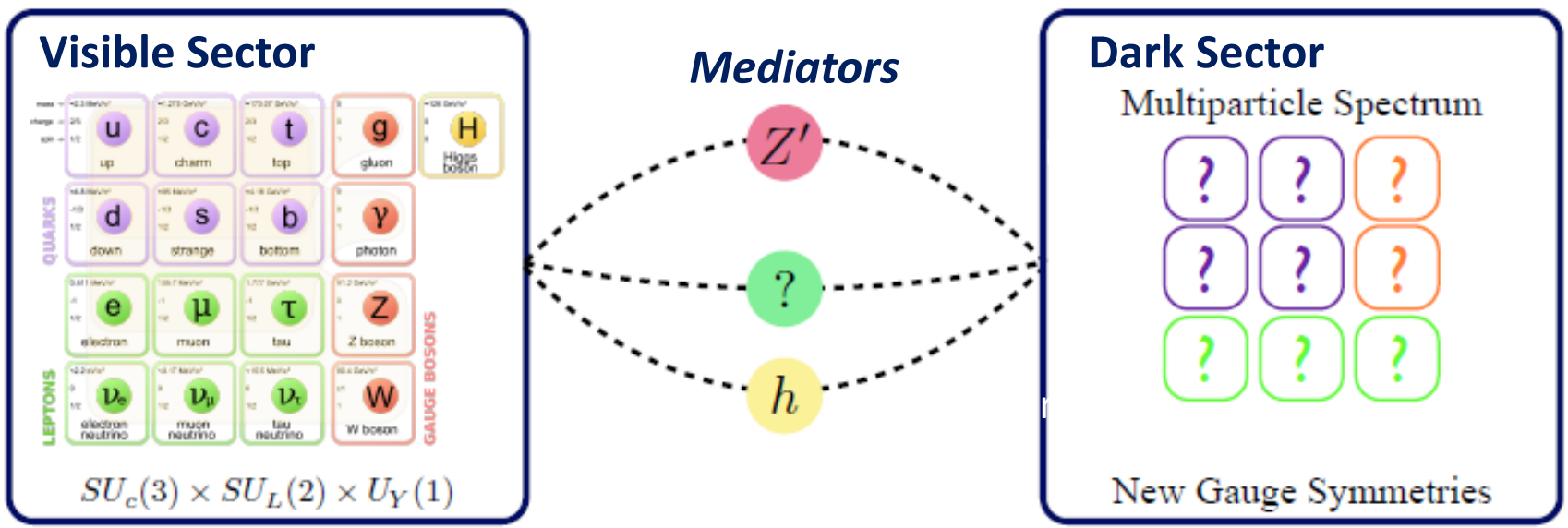
Case for a Complex Dark Sector

Why should the visible world have all the fun?

Why should the dark world be any less complicated?

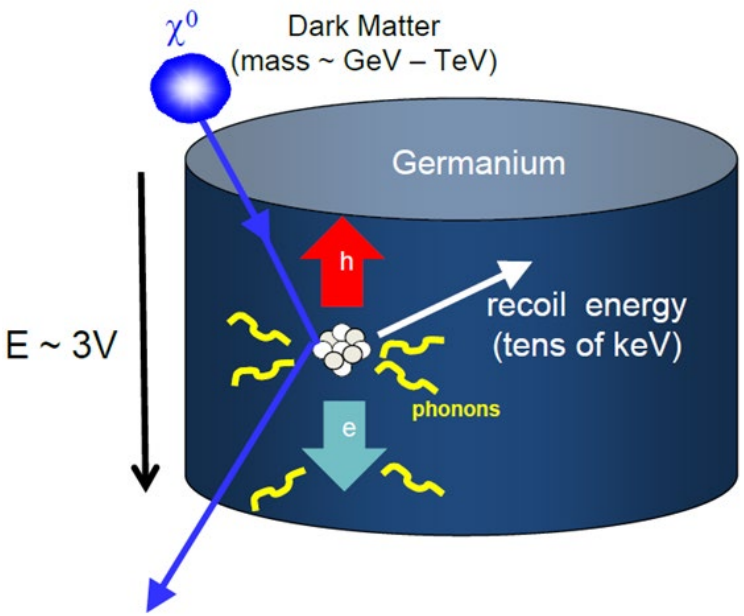
→ Extend SM symmetries to new hidden symmetry with new hidden particles:

- SM particles neutral under hidden symmetry
- Mediator particle(s) for SM-dark sector
- Some dark sector (DS) particles are stable: good dark matter candidate
- Some DS particles are meta-stable: *decay back to SM → experimental observables!*



The Elusive Dark Sector

Evade direct detection

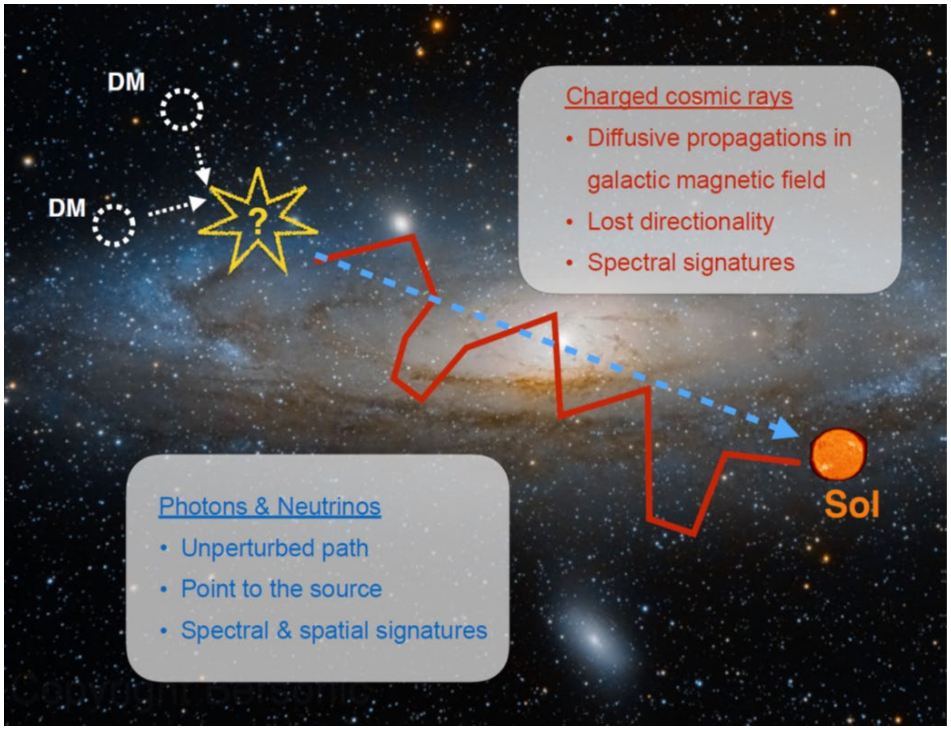


Direct detection is not sensitive when energy transfer in DM-SM scattering is small:

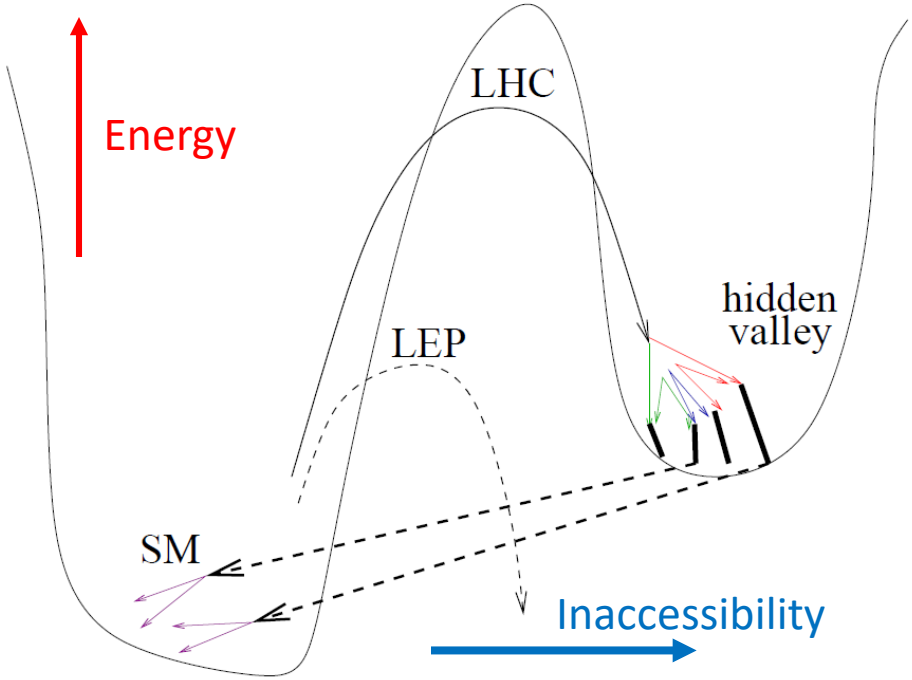
- Scattering is inelastic
- DM mass is very small
- DM-SM coupling is very small when mediated through a complex dark sector

Cosmic connection

- *Bypass* stringent constraints on WIMP-type DM *from indirect detection*
- Fit to observed data
- Explain the evolution of the early universe incl. but not limited to freeze-out model



Search for Dark Sector at Collider



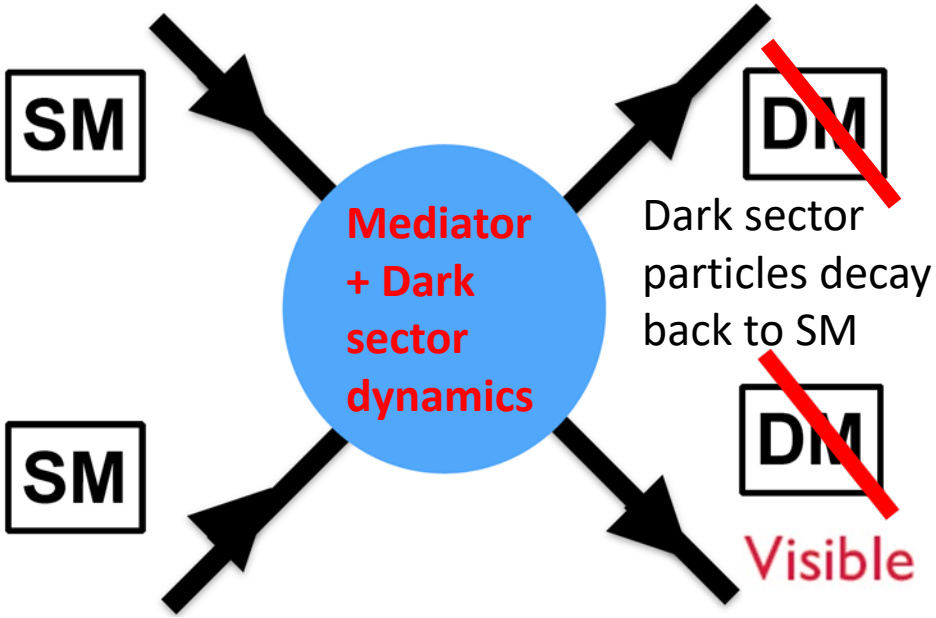
The dark sector may be accessed at a high energy collider through narrow "portal", creating new dark sector particles that can decay *slowly* back to SM particles

→ LHC is a unique machine for discovery!

Striking collider signature:

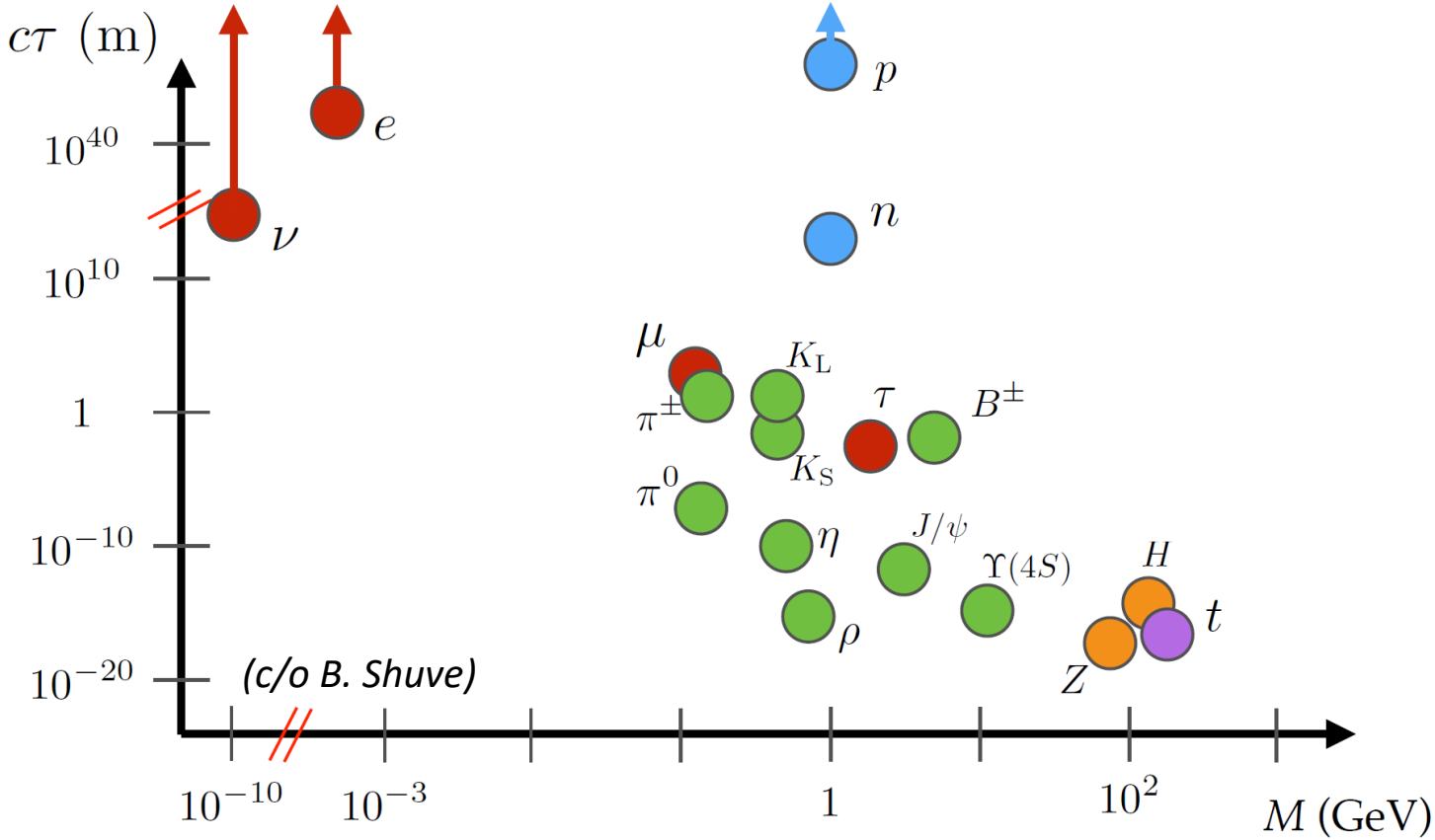
- very different from conventional "mono-X" searches for WIMP DM

→ a <u>*new paradigm*</u> for DM search @ LHC



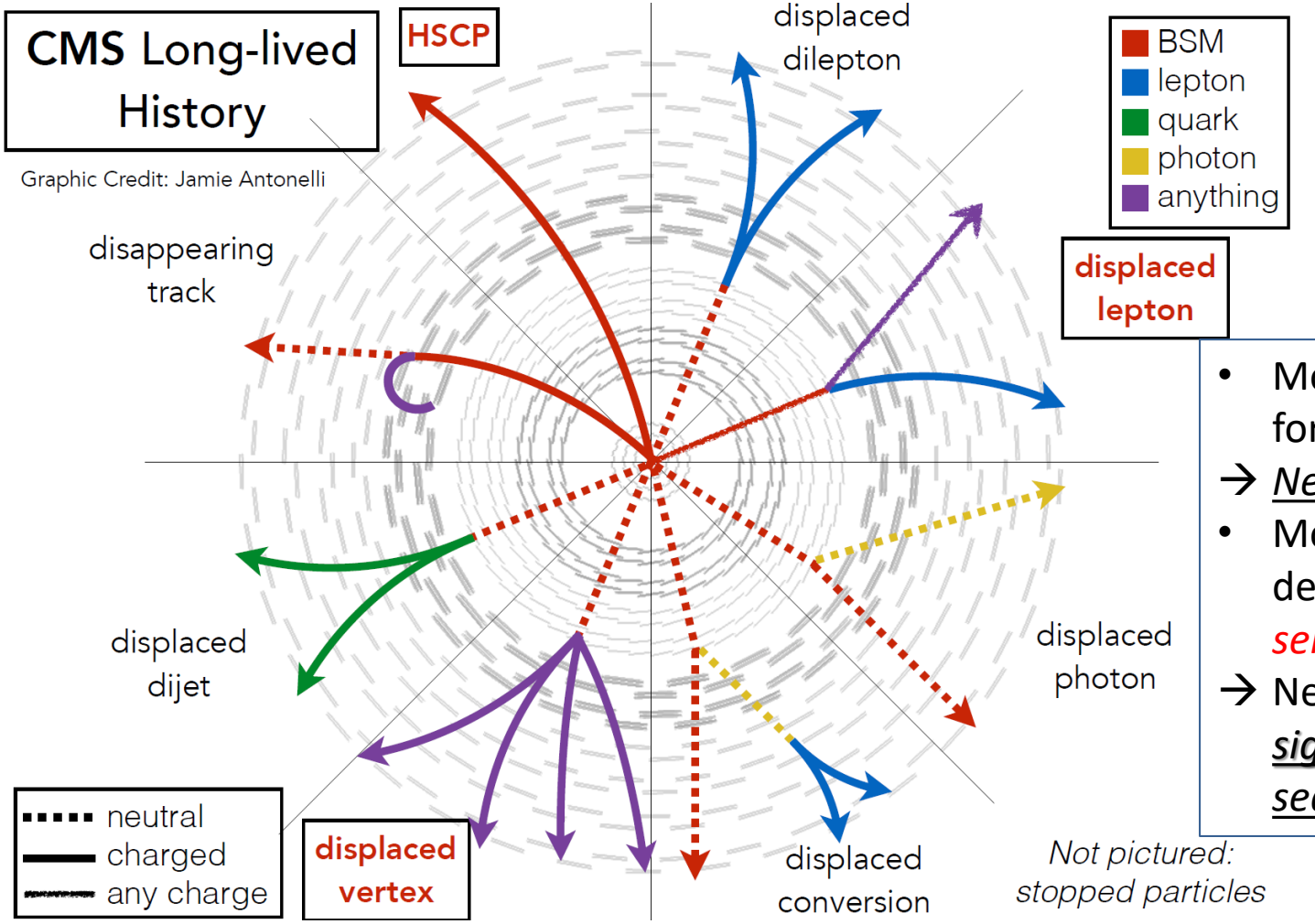
Long Live the Dark Side

SM particles can be long(ish)-lived when the coupling is weak and/or the decay is suppressed. →



Same principles apply to the dark sector:
small couplings and no definite mass scale → <u>long-lived</u>* particles (LLPs)!
* Lifetime upper bound from BBN: O(0.1)sec → *free* parameter for collider search!

Search for Long-lived Particles @ CMS



- Most LHC searches are for prompt decays
  → *New spaces* to uncover!
- Most LLP searches developed for SUSY *not sensitive* to dark sector
  → Need ***dedicated, signature-driven searches*** for dark sector

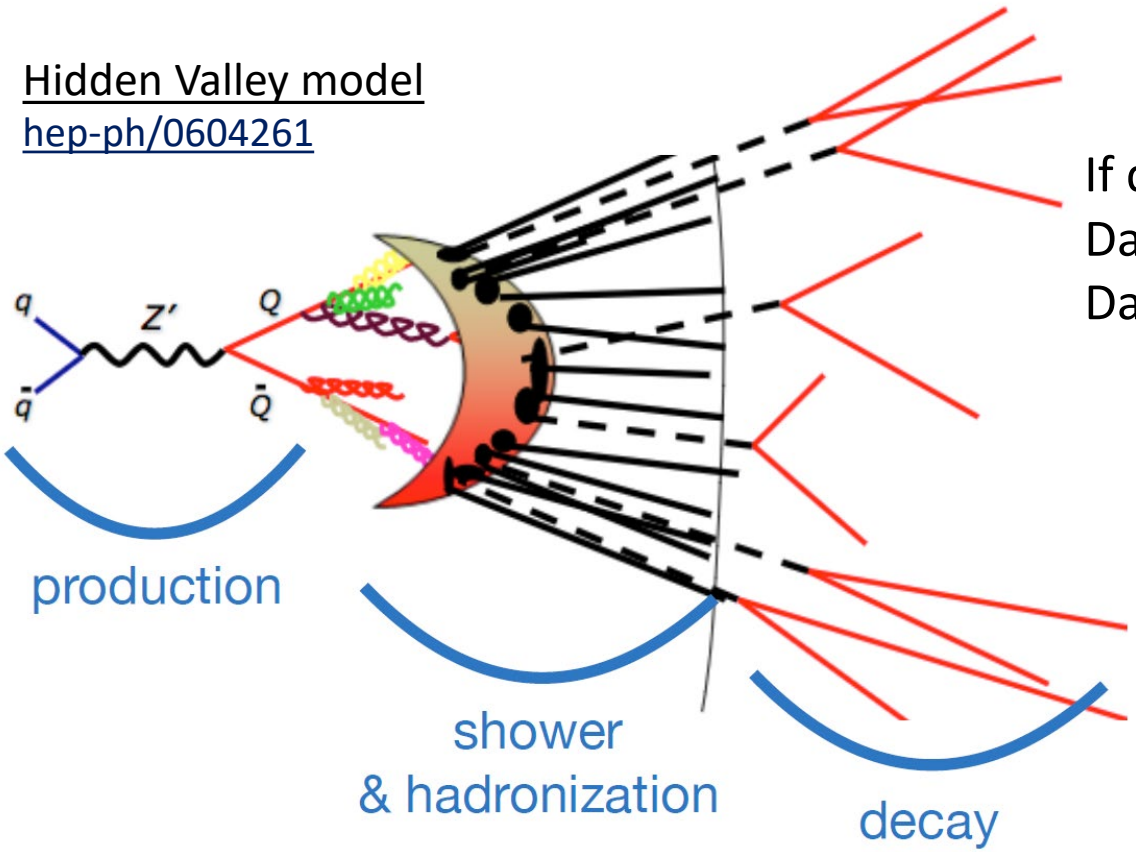
Searches for Dark Sector @ CMS

Dark Shower

Lepton Jets

Collider Signature: Dark Shower

Hidden Valley model
hep-ph/0604261



If dark sector has QCD-like structure:
Dark baryon stable → DM candidate
Dark meson decays

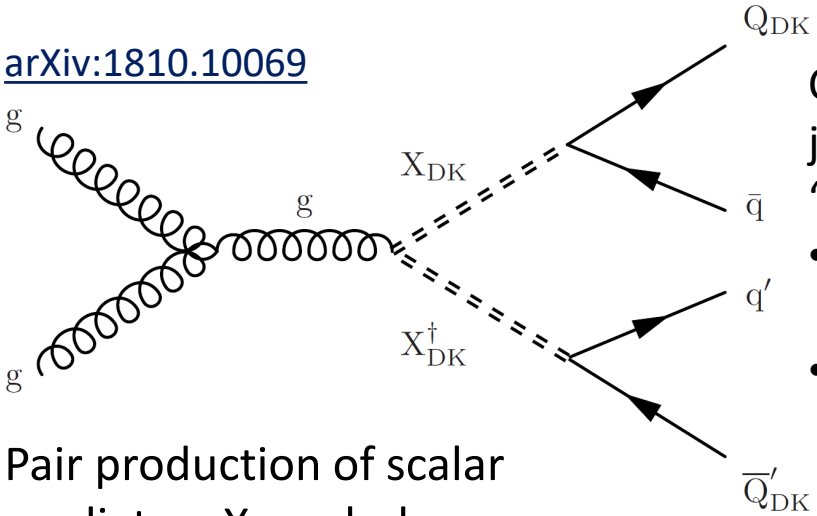
- very light: leptons/ photons
- O(10GeV): quarks, mostly b's
- lifetime as free parameter

→ *Extremely rich final states*
→ *Signature-driven search with broad reinterpretation value*

Other well-motivated models (e.g. twin-Higgs) can also create a dark shower at collider.

Dark Shower: Emerging Jets

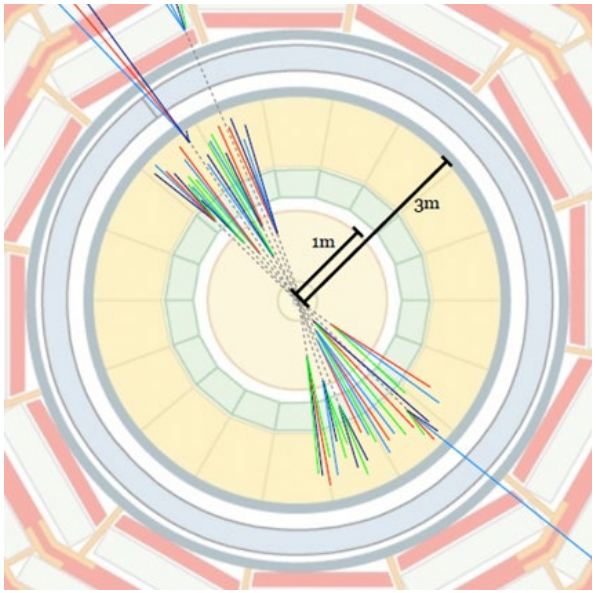
arXiv:1810.10069

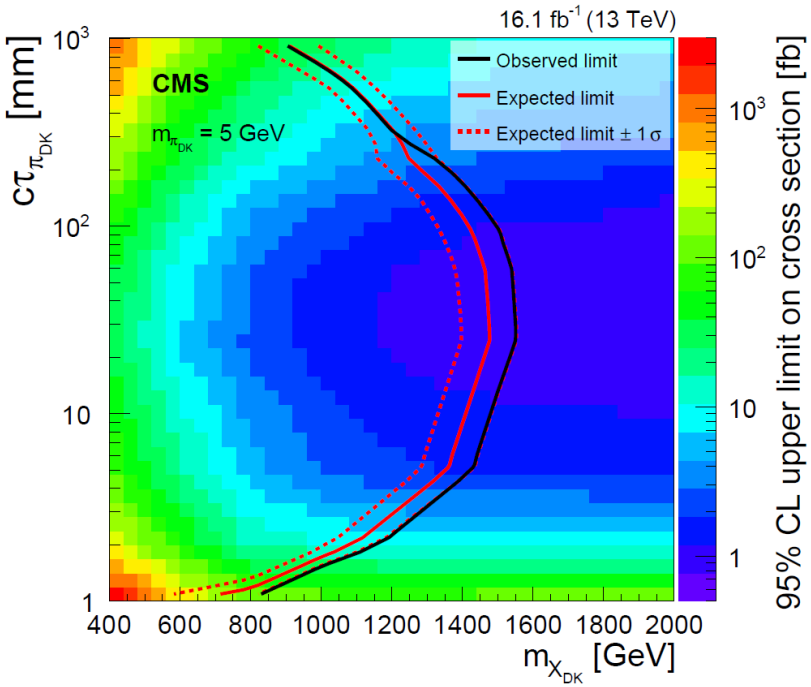


CMS 13TeV (2016 data) analysis: 900GeV HT trigger; 4 jets passing pT & HT requirements, of which 2 are "emerging" or 1 "emerging" + large P_T^{miss}

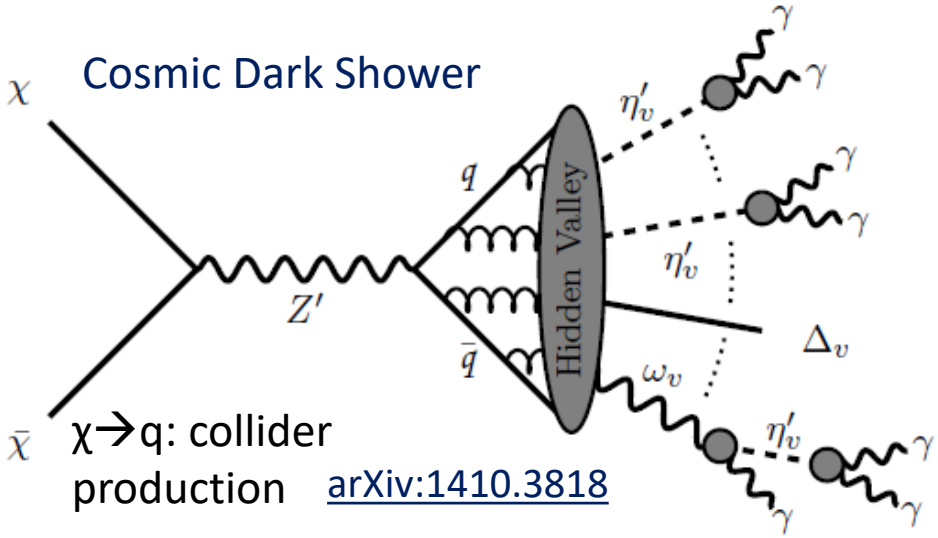
- "Emerging" jets: tracks w/ large impact parameters & less jet pT associated w/ prompt tracks
- Background: SM four-jet process with B's and/or significant pT mismeasurement (fake P_T^{miss})

Pair production of scalar mediators X, each decay to q-dark q pairs → two QCD jets, two emerging* jets
* few tracks starting at a distance





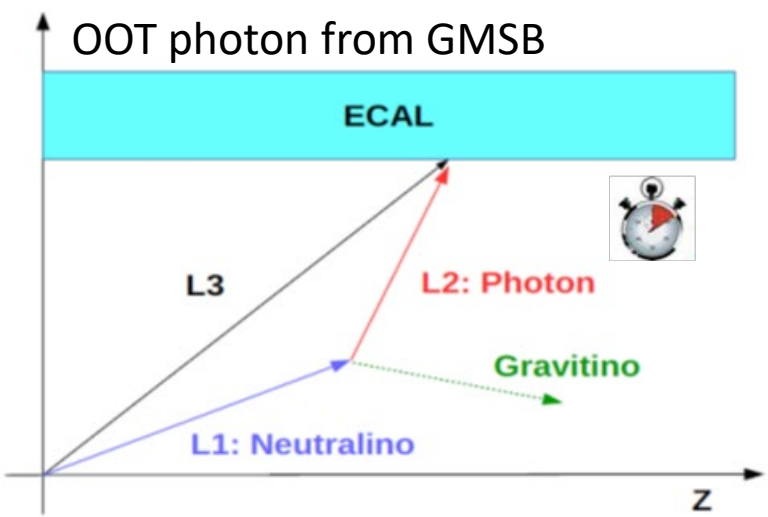
Dark Shower: Displaced Photons

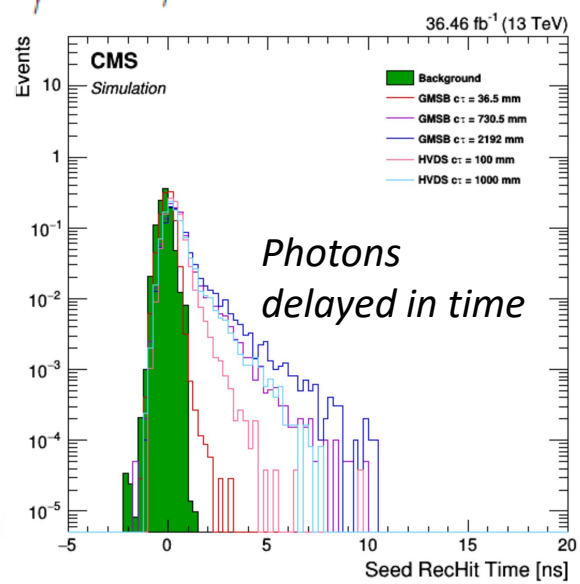


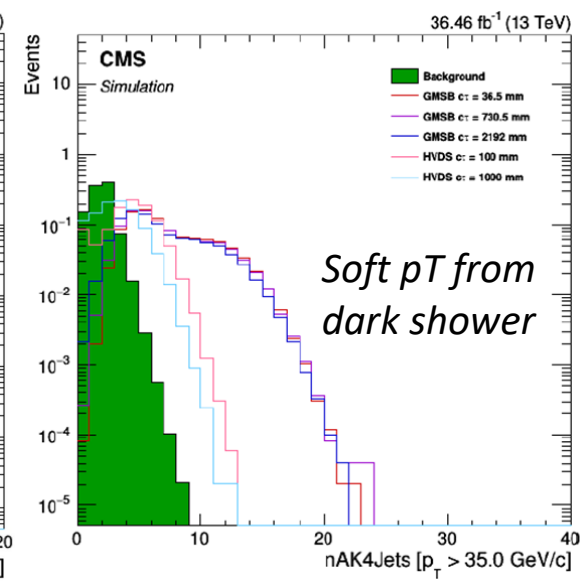
χ→q: collider production arXiv:1410.3818

A hidden valley dark shower process can be used to explain galactic-center gamma excess
→ Same mediator can be produced at LHC
→ Search for out-of-time (OOT) photons!

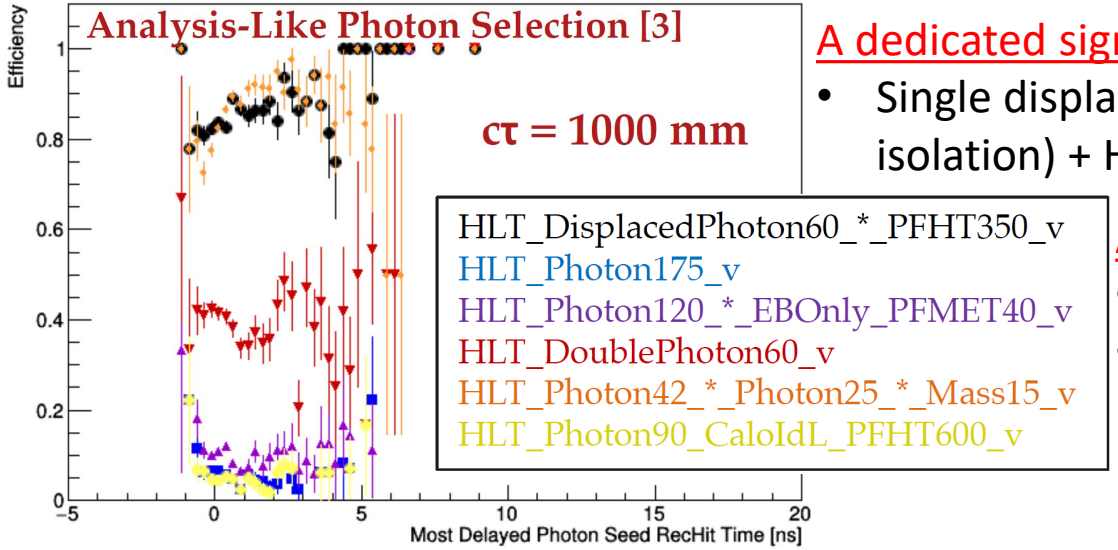
Run1 OOT photon searches focused on GMSB: hard jets + 1 or 2 OOT photon(s) + large E_T^{miss}
→ very different topology from dark shower
→ requires new trigger & signal selections!







Search for Displaced Photons

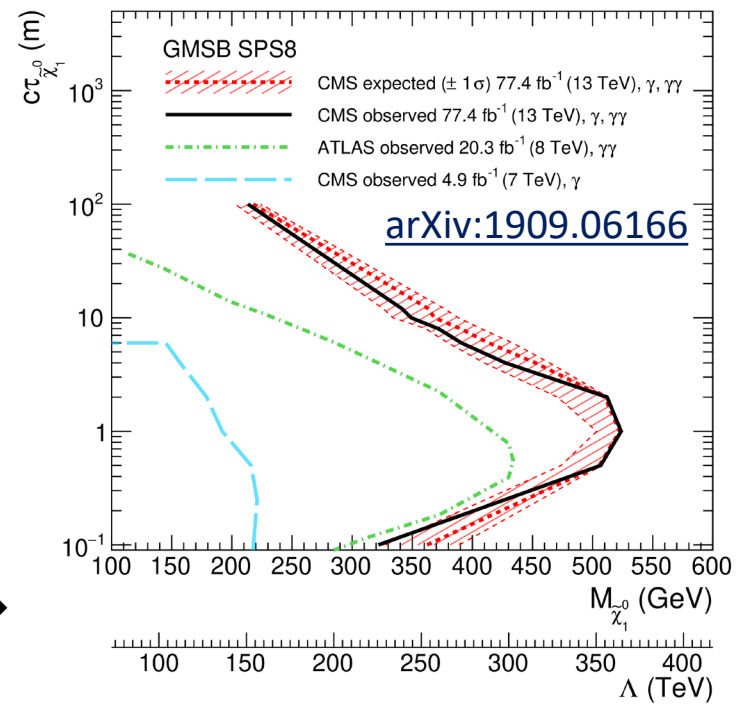


A dedicated signal trigger was developed for 2017 data:

- Single displaced photon (pT, *ECAL cluster shape*, isolation) + HT cut (to lower photon pT threshold)

A new OOT photon ID was developed:

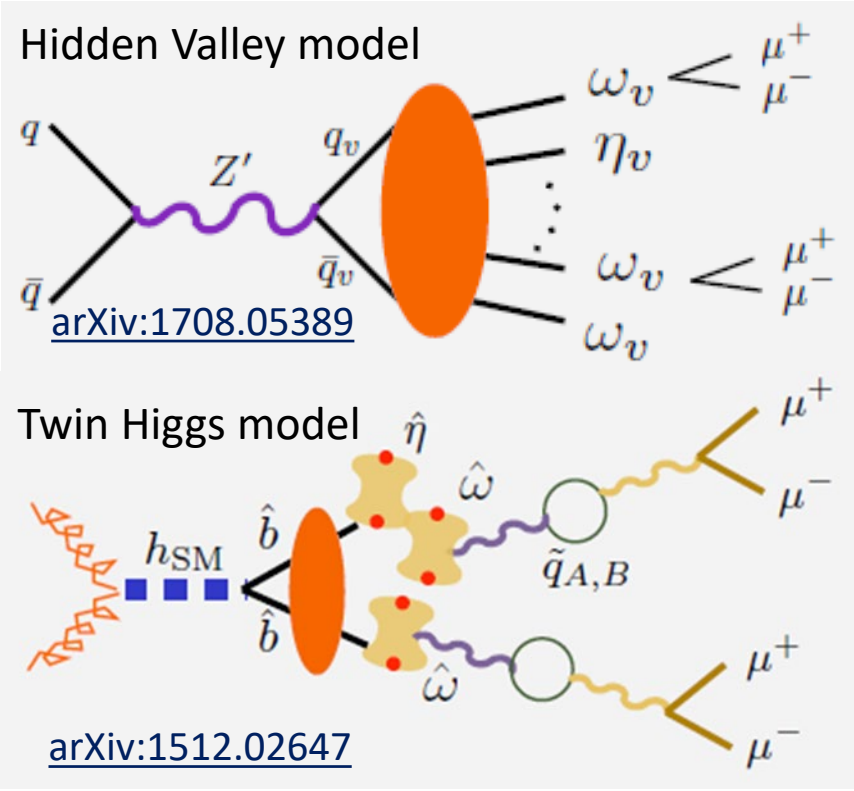
- New collection from OOT seeds
- Combine pT, shower shape, ECAL/HCAL/Trk isolation etc. info



- Signal selection:
  - At least one tightly ID-ed photon
  - nJets>=3; HT>400GeV
- Main backgrounds: γ+jets, QCD
  - additional contribution from electroweak & top
  - dedicated control regions for each process
- Final signal extraction with data-driven ABCD method
  - x-axis: photon time; y-axis: E_T^{miss}

Much improved (~order of magnitude in cτ) sensitivity →

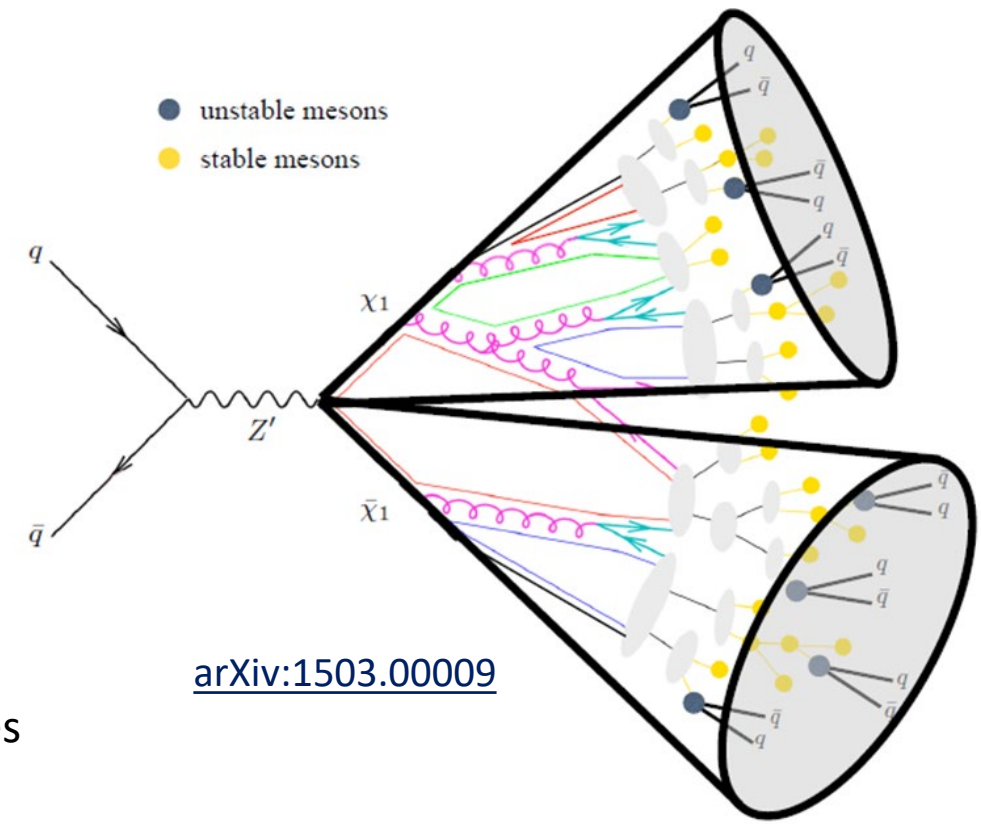
Dark Shower: Other Final States



Light dark mesons, from Hidden Valley or Higgs exotic decay, can also decay to muons:

→ Challenging for ATLAS/CMS with soft muons

→ LHCb has unique advantages in certain phase spaces with its forward coverage & (no-)trigger



Semi-visible Jet:

- A O(TeV), leptophobic gauge boson mediator
- Dark sector with a QCD-like structure.
- Showering from the dark quark observed as a hadronic jet that also contains invisible particles

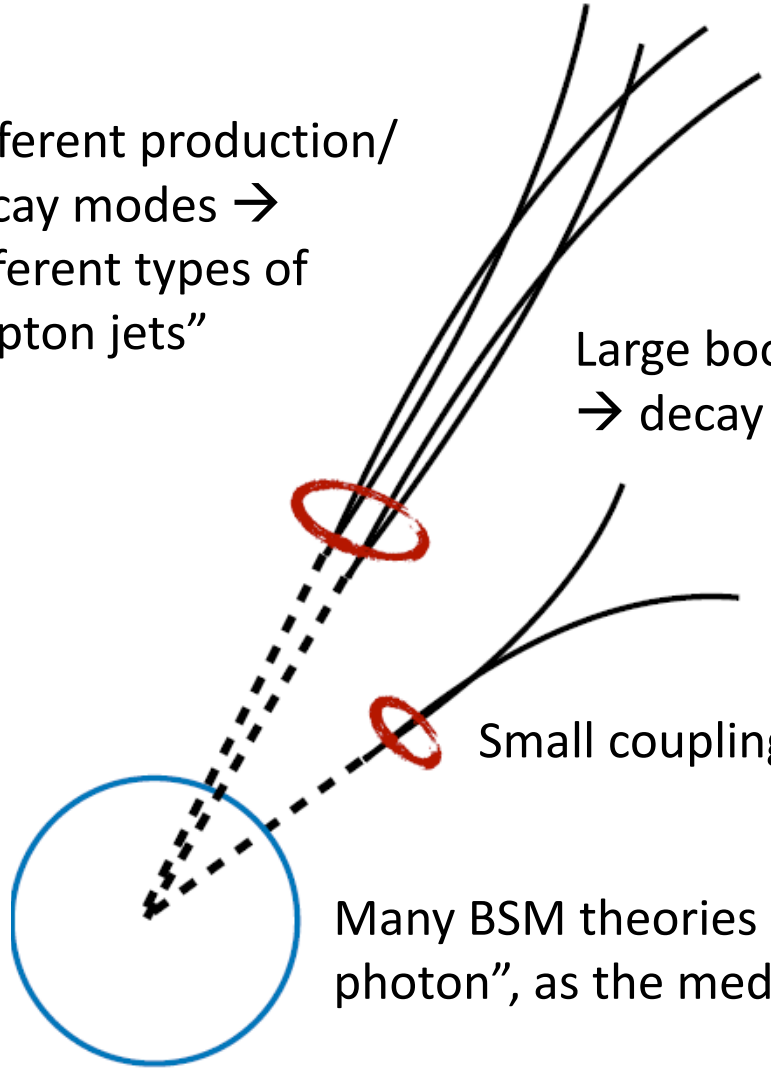
→ Large-R jets with pT aligned with E_T^{miss}

Searches for Dark Sector @ CMS

Dark Shower

Lepton Jets

Collider Signature: Lepton Jets



Different production/ decay modes → different types of "lepton jets"

Large boost from heavy mother particle → decay products are collimated

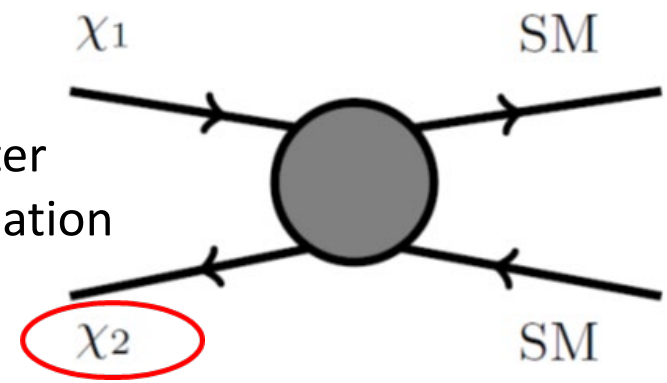
Small couplings → longer lifetime → displaced decays

Many BSM theories predict a massive gauge boson, a "dark photon", as the mediator between SM and dark sector.

Inelastic Dark Matter: Theory

Cosmic Connection

Dark Matter
Co-annihilation



Heavy mass eigenstate χ2

- abundant in early universe

→ efficient co-annihilation

- depleted in current universe

→ *evades indirect detection*

- inelastic scattering

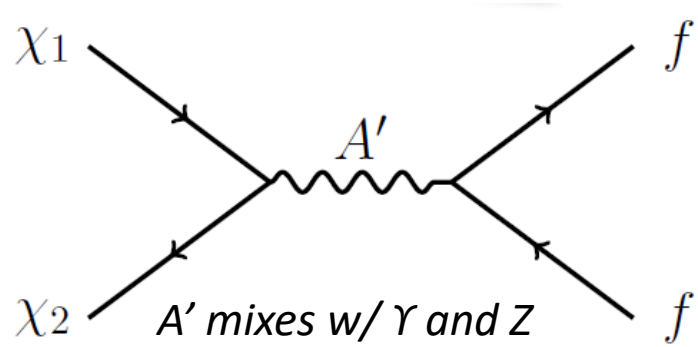
→ bypass existing limits for WIMPs

- large-ish (>100keV) mass splitting

→ *evades most direct detection*

Particle Model

arXiv:1508.03050

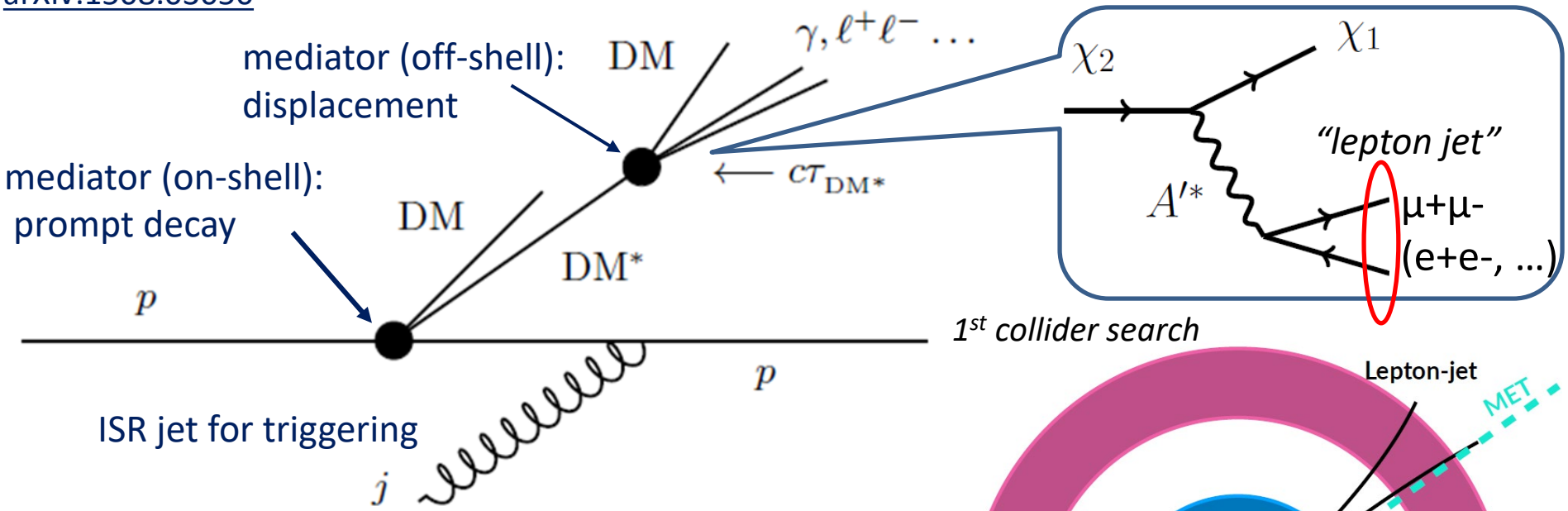


→ Both DM mass eigenstates can be produced at collider

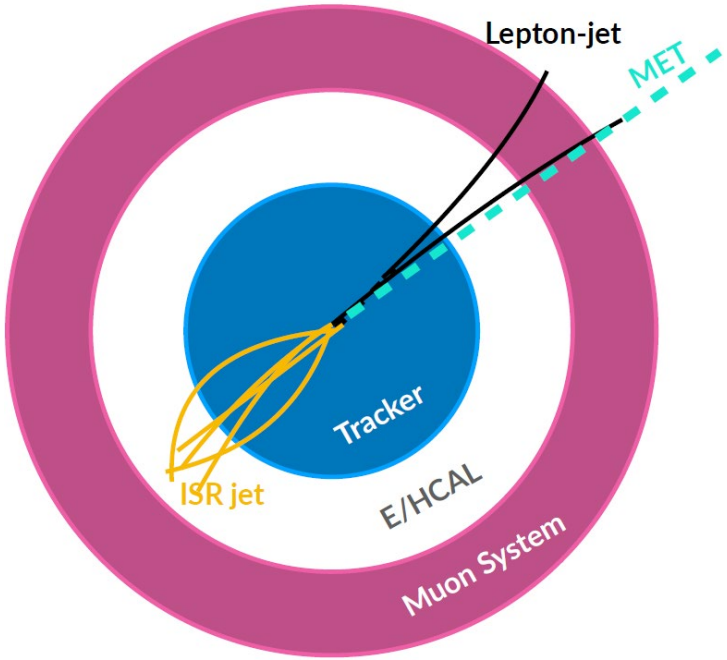
→ The LHC can probe parameter space that *fits relic density*!

Inelastic Dark Matter: Collider Signature

arXiv:1508.03050



1st collider search



- Heavy ("excited") DM* has longer lifetime

→ lepton pair is displaced

- O(GeV)-O(10GeV) DM + O(10%) mass splitting

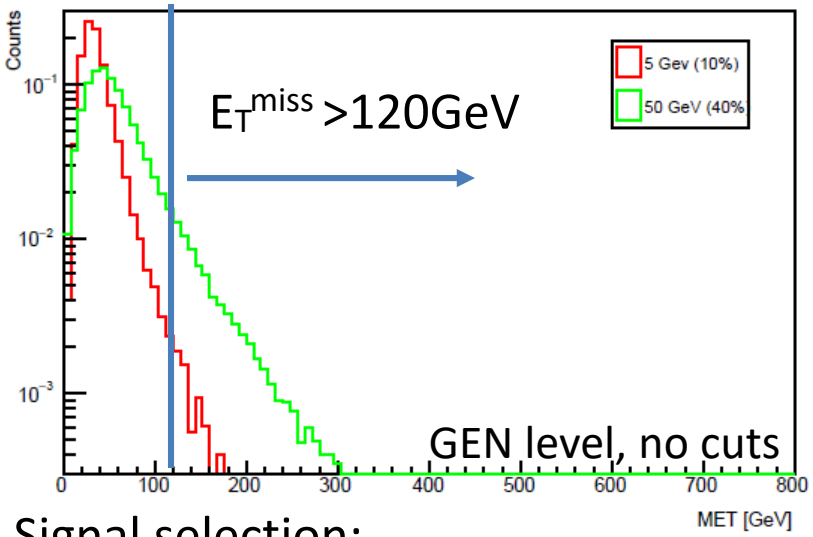
→ lepton pair is soft

- DM-DM* recoil against ISR jet

→ lepton pair is collimated: "lepton jet"

Signature: soft displaced lepton jet collimated w/ E_T^{miss}

Search for Inelastic Dark Matter



Trigger strategy:

- difficult to trigger on soft, displaced muons

→ trigger on E_t^{miss} (>=120GeV)

→ fully efficient ~ 250GeV, data/MC agree well

Muon reconstruction:

want good resolution+sensitivity to wide displacement

→ for all muons, displaced standalone (dSA) muons + additional muon track quality requirements

→ for small displacement, dSA muons matched to global muons when available; remove overlaps

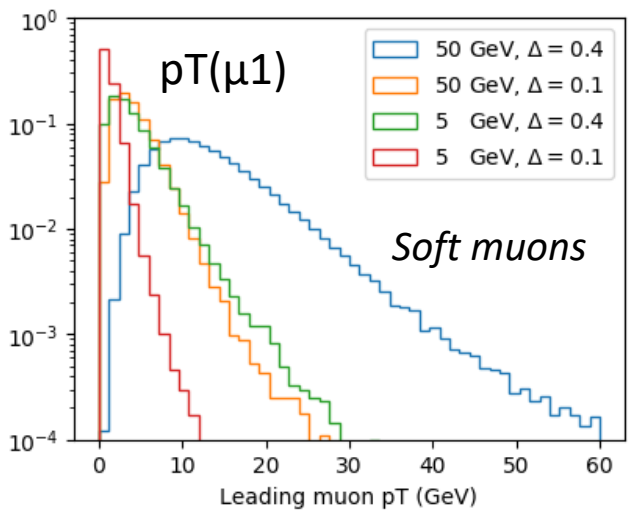
Signal selection:

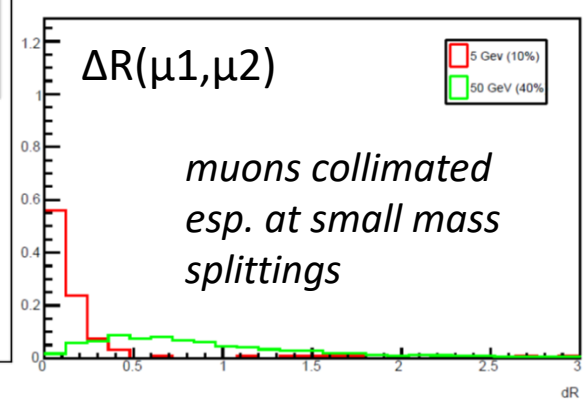
- E_T^{miss} trigger, hard ISR jet
- two collimated dSA muons
- muons collimated w/ E_T^{miss}
- muons & jet back-to-back

Backgrounds: mostly QCD

- + W/Z+jets, diboson, top

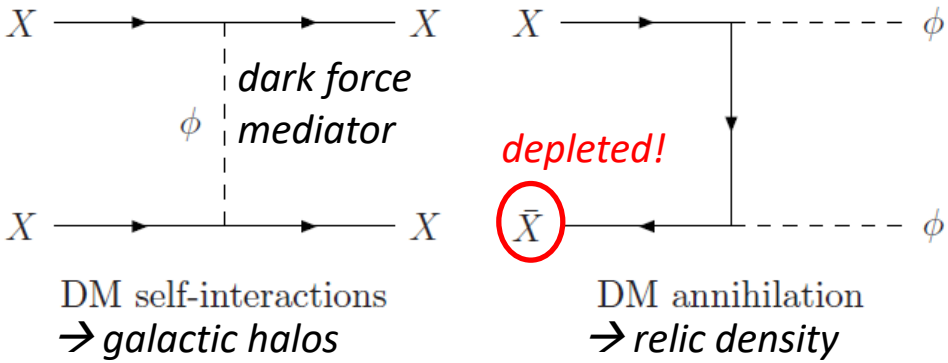
→ ABCD method: muon pair vertex displacement vs $d\phi(E_t^{miss}, \text{muons})$





Self-Interacting Dark Matter: Model

arXiv:1310.7945



Cosmic connection:

- Self-interacting dark matter is proposed to reconcile astrophysical observations.
- The dark force mediator, a dark photon, is much lighter than dark matter particle
- Dark matter bound states can be produced at collider with the same dark photon mediator
  - Complementary to direct detection

Collider signature:

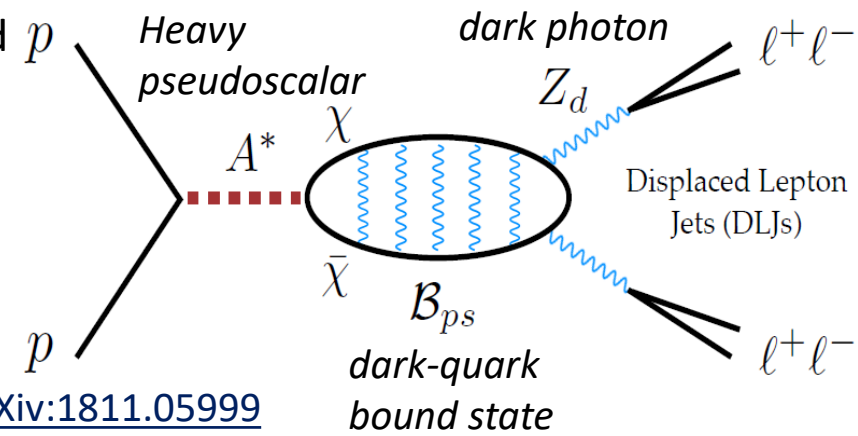
1st collider search

- The heavy O(100)GeV DM bound state, produced at collider, annihilates to two dark photons.
- The dark photon decays to a pair of SM leptons.
- The dark photons are very light: O(0.1)-O(1)GeV

→ boosted, collimated lepton pairs (lepton jets)

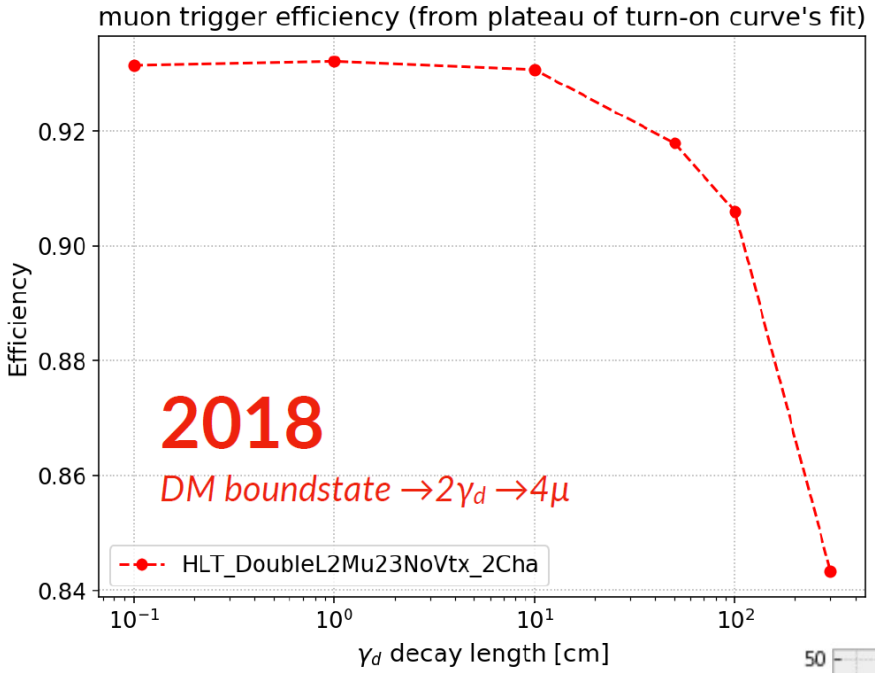
- The dark photon coupling to SM is very small

→ *two displaced lepton jets back-to-back*



arXiv:1811.05999

Search for Self-Interacting Dark Matter



Trigger Strategy:

- 2016 displaced di-muon trigger has >10GeV cut on dimuon invariant mass ☹
  - dark photon mass O(0.1)-O(1)GeV
- 2017 tri-muon trigger has vertex constraint ☹
- Developed dedicated trigger for 2018 data ☺
  - dimuon trigger without vertex constraint
  - low(ish) pT requirement (>23GeV)

  → good efficiency incl. at larger displacement!

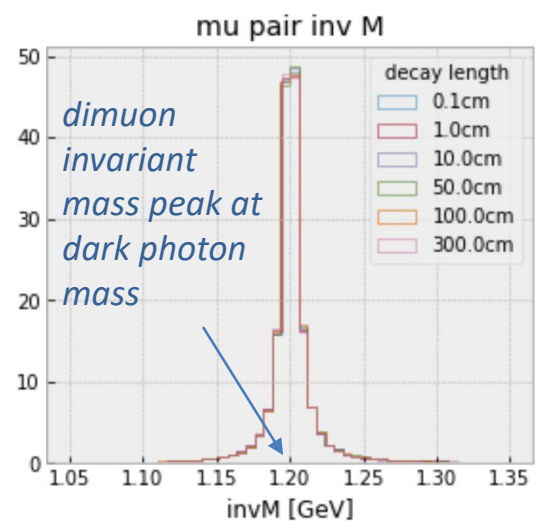
Signal selection:

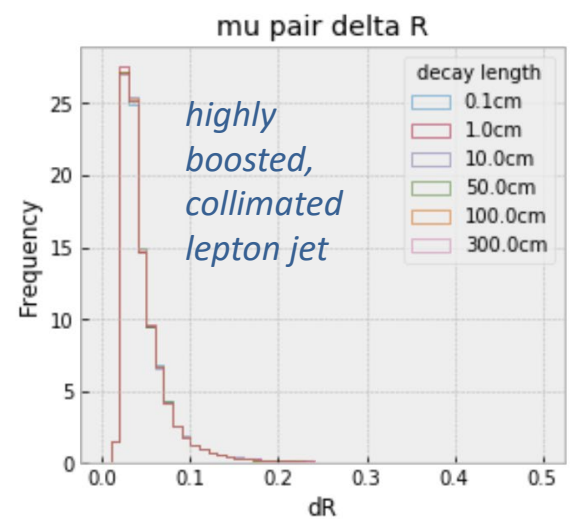
- two isolated, back-to-back lepton jets (e or mu type)

  → dedicated LJ reco algorithm
- fit di-(lepton)jet mass spectrum

Main backgrounds:

- QCD, B-resonance production





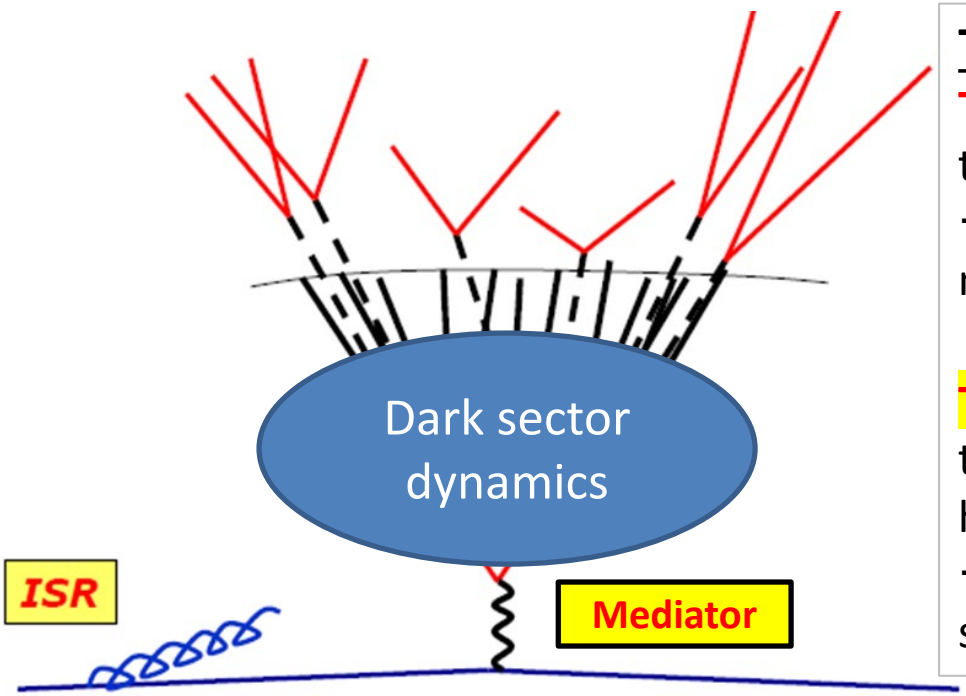
Experimental Challenges to LLP Search

Object reconstruction:

- Conventional reconstruction methods often do not work well for LLPs
- Standard methods to remove noise etc. often remove our signals
    - Increased vulnerability to background
- Rich final state: how to #CatchThemAll?

Background estimation:

- Particles do not point back to primary vertex:
    - detector center: LLPs from SM, pile-up,…
    - detector volume: conversion, …
    - outside detector: cosmics, beam gas, …
- Limits from detector acceptance & resolution



Triggering:

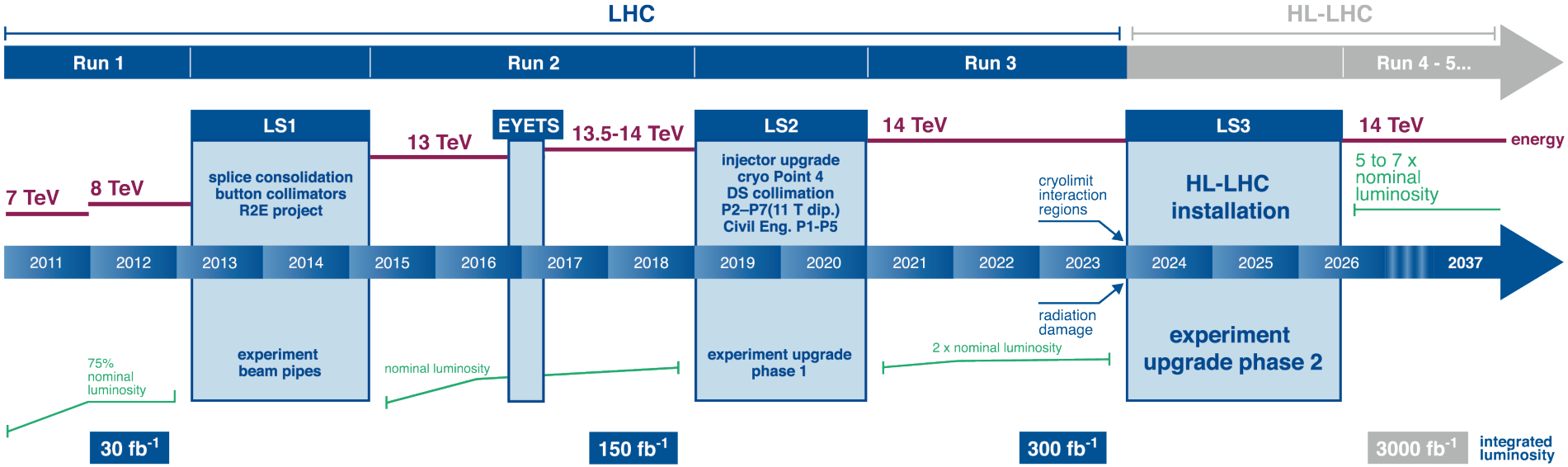
Trigger strategy B:
trigger on decay products
→ displaced objects, soft and/or with high multiplicity, are very difficult to trigger!

Trigger strategy A:
trigger on production process: ISR or new heavy particle(s) (e.g. HT)
→ high threshold leads to significant loss in signal efficiency

How do We Look for Dark Matter?

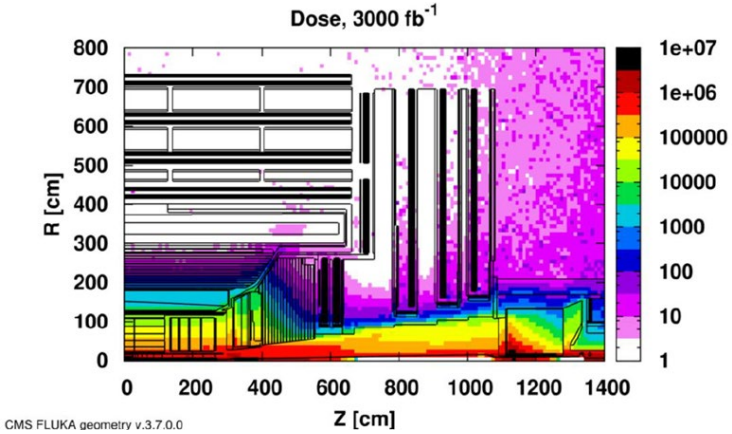
- Physics motivation
- Experimental overview
- Search for WIMP dark matter
- Dark matter beyond WIMPs
- Future dark sector search

LHC in the High-Luminosity Era



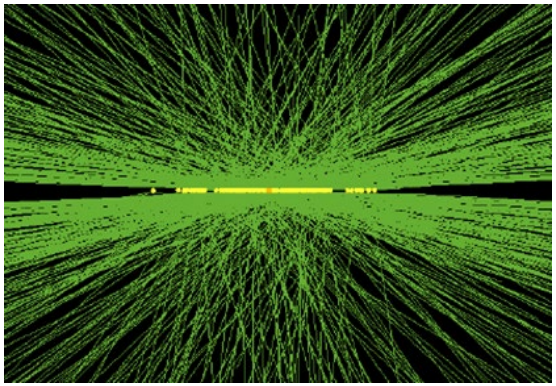
The planned upgrades from LHC to HL-LHC will bring up to an order of magnitude more data (exciting!), but also experimental challenges:

What does collider search for the dark sector look like in the high-luminosity era?



High radiation dose

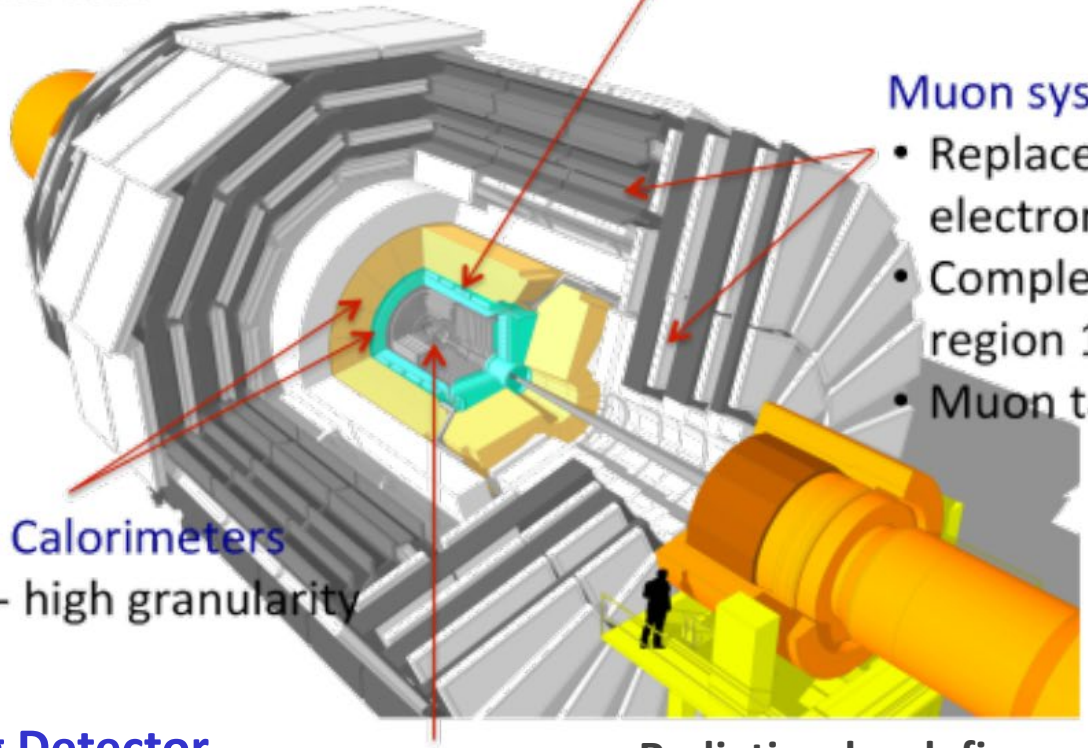
High Pile-up



CMS Upgrade for HL-LHC

Trigger/HLT/DAQ
- Track information at L1-Trigger
- L1-Trigger: 12.5 μs latency - output 750 kHz
- HLT output ≈7.5 kHz

Barrel EM calorimeter
- Replace FE/BE electronics
- Lower operating temperature (8◦)



Muon systems
- Replace DT & CSC FE/BE electronics
- Complete RPC coverage in region $1.5 < \eta < 2.4$
- Muon tagging $2.4 < \eta < 3$

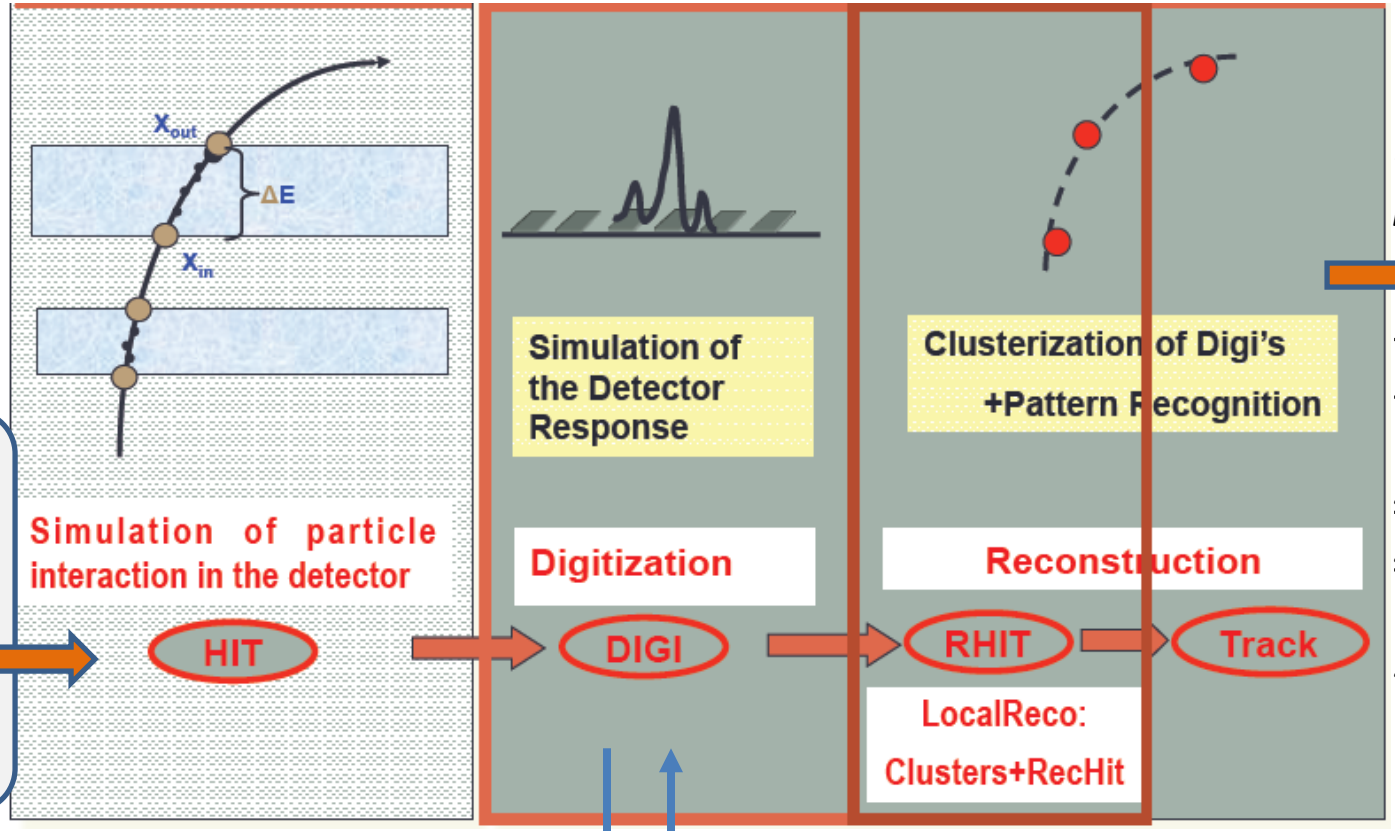
Replace Endcap Calorimeters
- Rad. tolerant - high granularity
- 3D capability

Add MIP Timing Detector
(outside tracker: barrel + endcaps; 30ps timing res.)

Replace Tracker
- **Radiation-hard; fine resolution**
- **Extend |η| coverage up to 4**
- **Dual-side sensor in outer tracker → trigger**

How to Design an Upgrade Detector

Example:
CMS inner pixel detector



Detector design *with input from engineers*

Physics performance

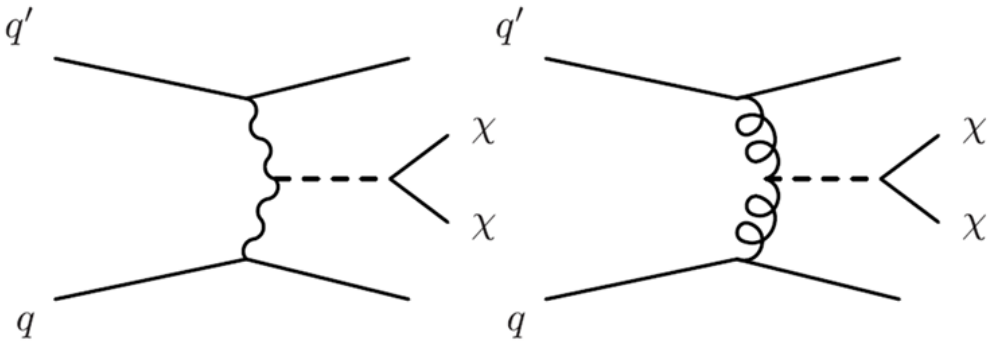
tracking; object reco (lepton, jet…) sensitivity to searches esp. with forward signatures

Customizable simulation to test different designs for optimization

Data format & rate for electronics design

Optimize parameters & reconstruction methods → build physics objects

New Physics with Forward Signature



Dark matter produced in VBF through Higgs-portal or other scalar mediator

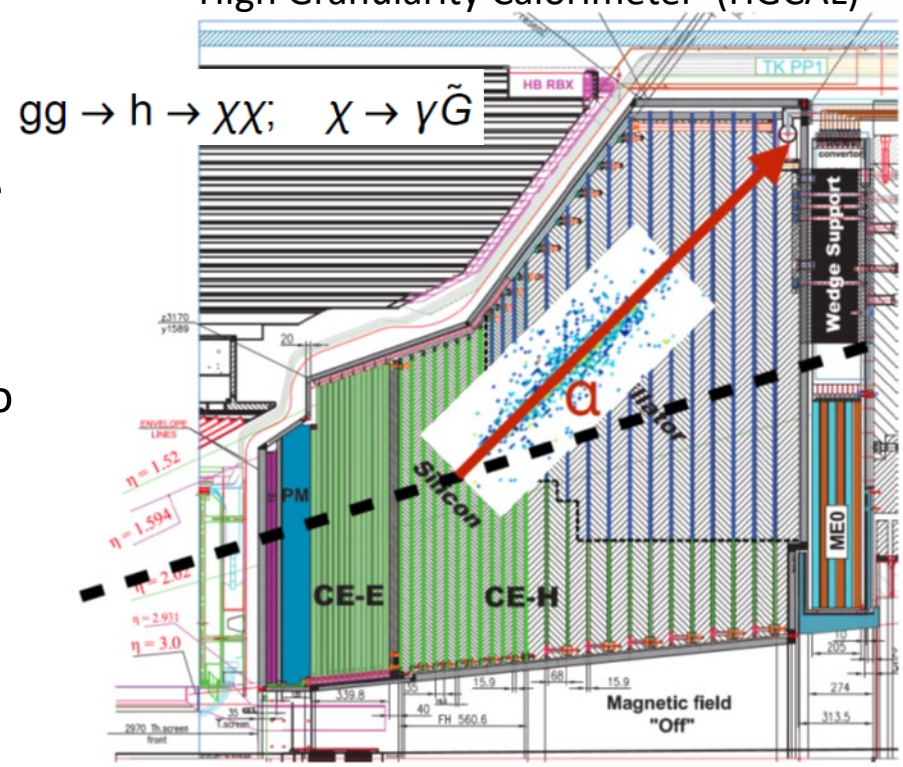
Light resonance decay (Y→XX) when Y is light (e.g. Higgs/Z) & mX ~ mY/2
→ Forward extension in tracker etc. will improve acceptance & sensitivity

If X is *long-lived*, its displaced decay product will have an angular separation from extrapolation to the interaction point.

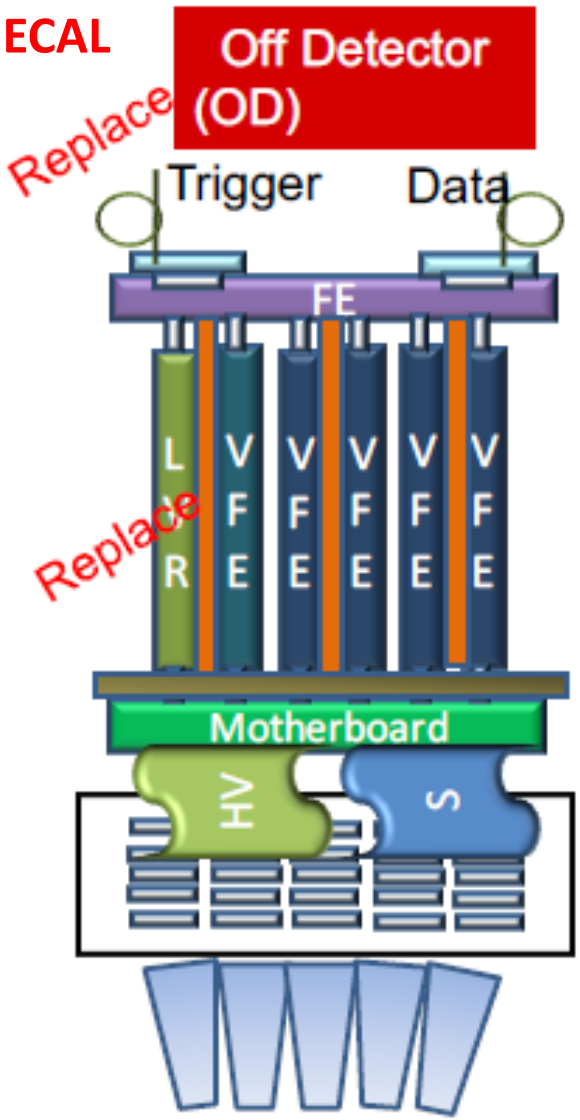
→ Can we use the fine spacial & energy resolution in the HGCAL to <u>*trigger on the angular info*</u>?

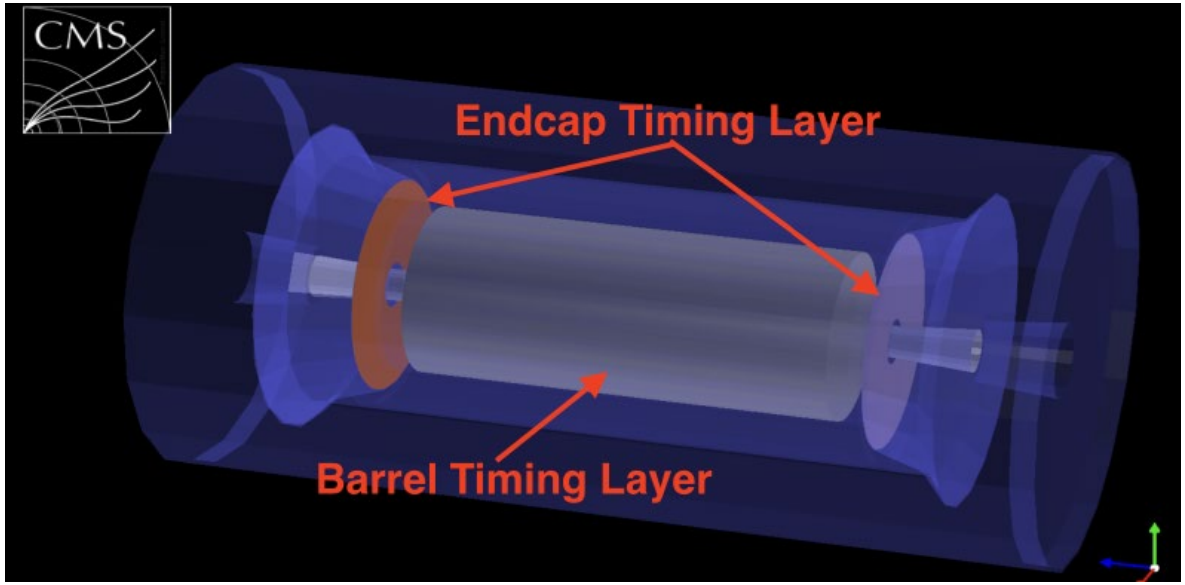
→ Preliminary study very promising!

High Granularity Calorimeter (HGCAL)



Fast Timing Upgrades at HL-LHC





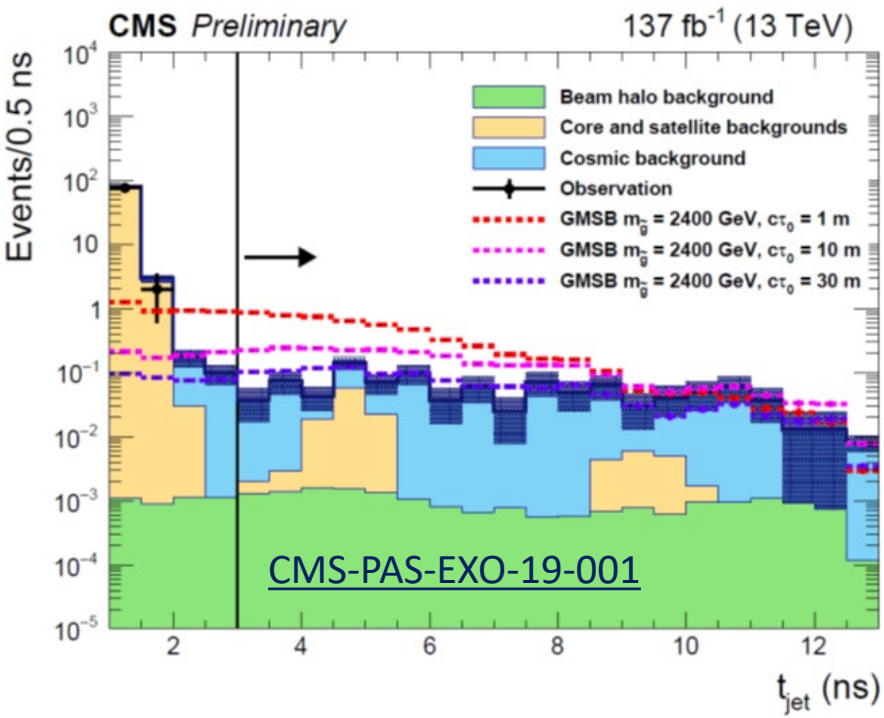
- Calorimeter upgrades (ECAL electronics + HGCAL) will provide precise timing (10s of ps) for high energy photons in barrel + high energy hadrons/photons in endcap
- MIP Timing Detector (MTD) outside tracker volume, can provide precision timing (~30ps) for charged hadrons & converted photons down to a few GeV.
- Muon system timing improvement: 12.5 ns → 1ns in DT

→ ***What does it mean for LLP searches?***

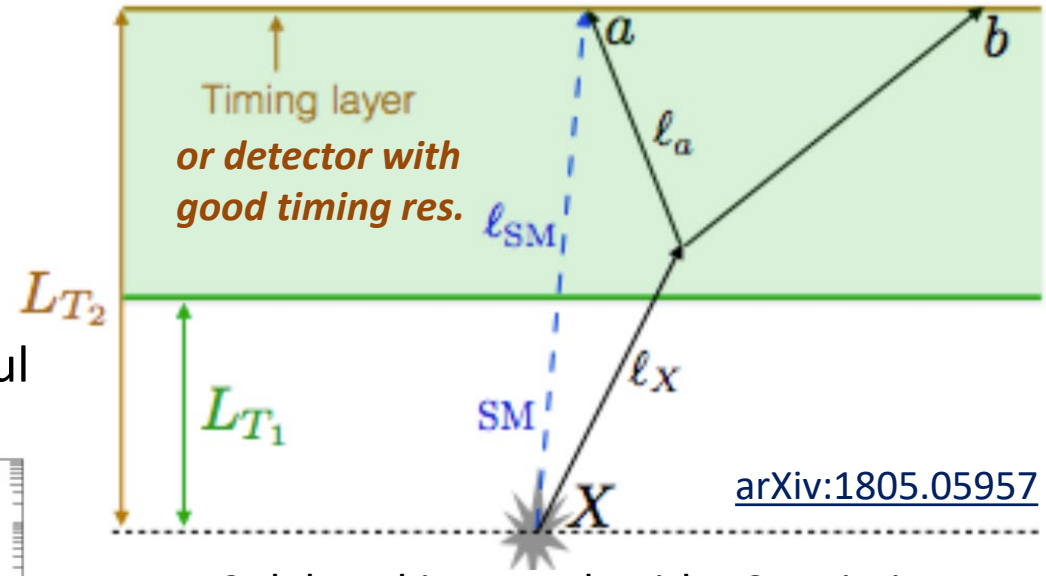
Search for LLPs with Fast Timing

Timing delay from LLPs can come from
1) path length difference
2) slower moving particles
→ applying a cut on timing info can significantly reduce SM background

Analysis level: timing cut ~*always* useful



CMS-PAS-EXO-19-001

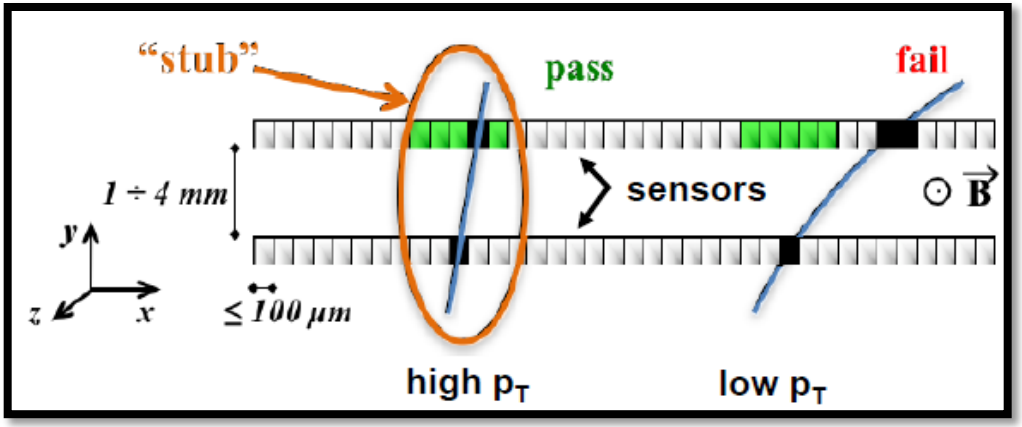


arXiv:1805.05957

New Run2 delayed jet search with ECAL timing (~200ps resolution for >50GeV) →
- Trigger: E_T^{miss} >120GeV
- Signal selection:
  - E_T^{miss} >300GeV
  - jets: pT >30GeV, time delay >3ns & small time spread, large HCAL fraction

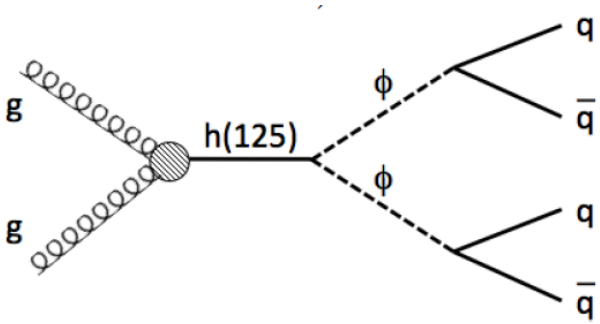
Trigger level: can we use timing info @L1?
→ *prelim. study appear promising!*

Trigger on Displaced Tracks

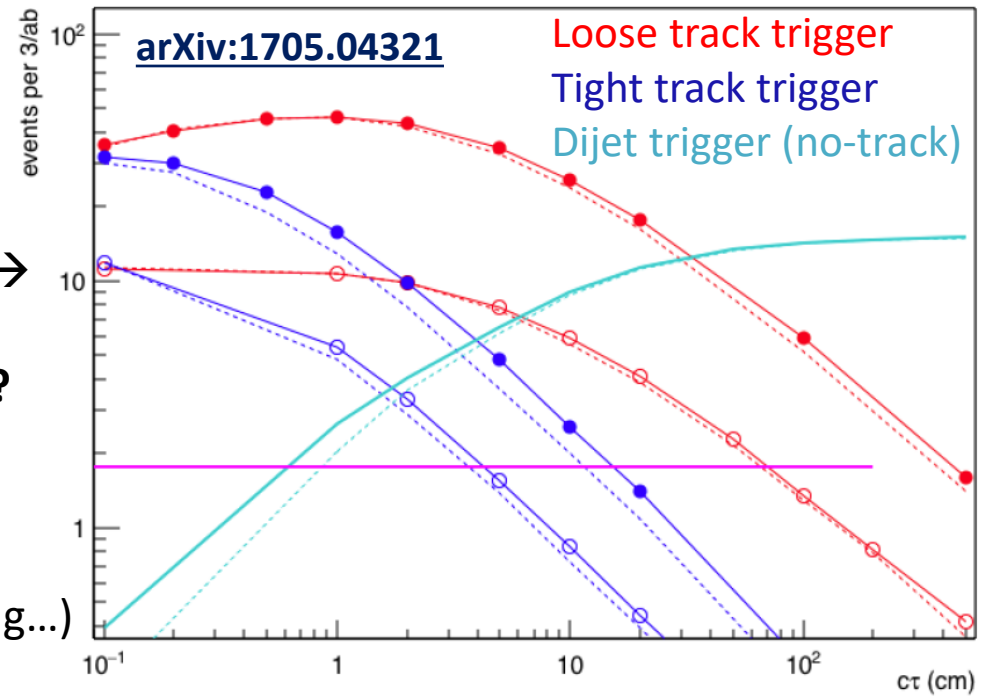


CMS L1 track trigger (L1TT)

- Two-sided sensor modules in OT
→stubs: correlated hit pairs, consistent with >=2GeV track
- Stubs form input to track finding at L1 trigger rate of 750kHz



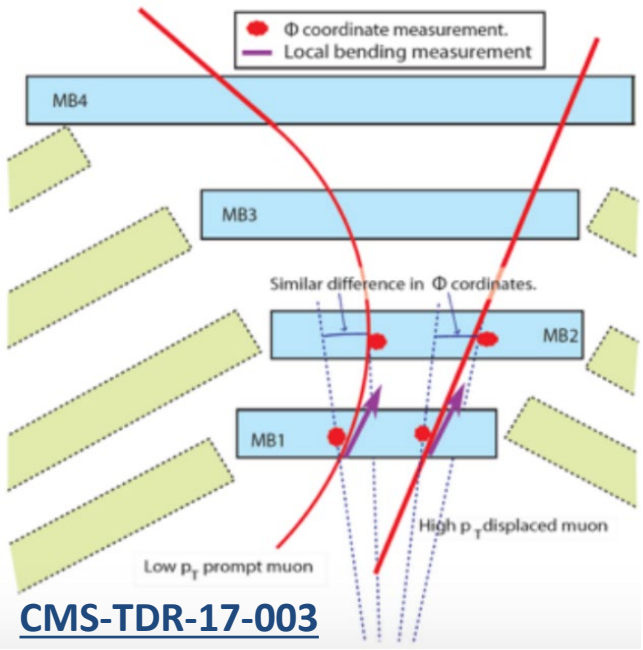
Toy study with displaced jets →



Q: trigger on displaced tracks (jets) with L1TT?

- Require more hardware resources
- Preserve soft LLPs with small displacement
  - Esp. useful for dark sector searches!
- Combine with other detectors (muon, timing…)

Trigger on Displaced Muons



CMS-TDR-17-003

- **Muon system upgrade** with new GEM stations:

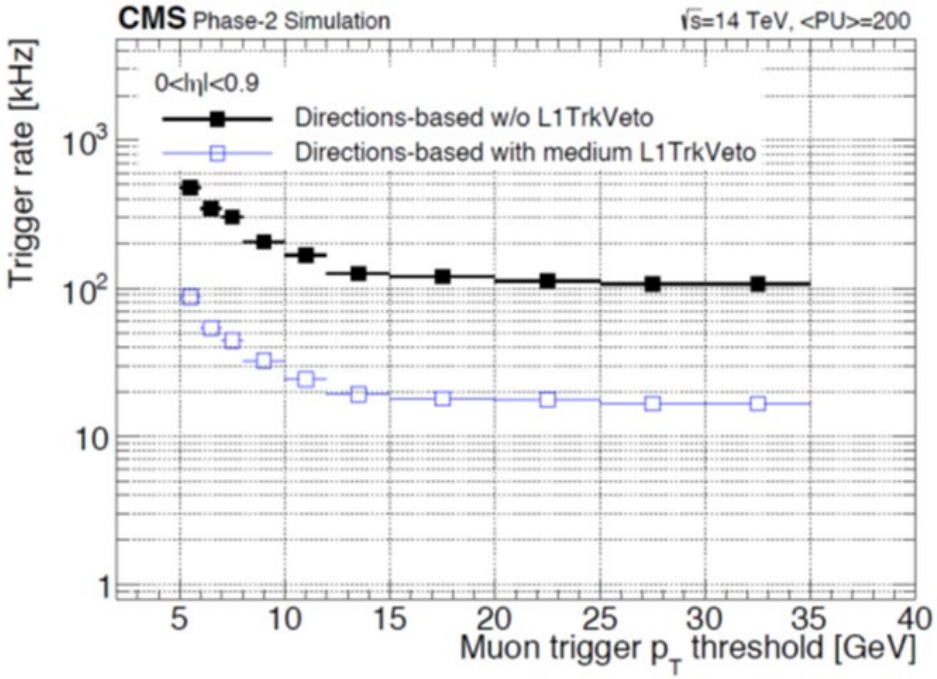
→ measurement of muon direction to distinguish low pT prompt muon vs high pT displaced muon

- **L1 track trigger upgrade** → displaced muon trigger at L1

→ prompt muons, match L1 muon to L1 tracks

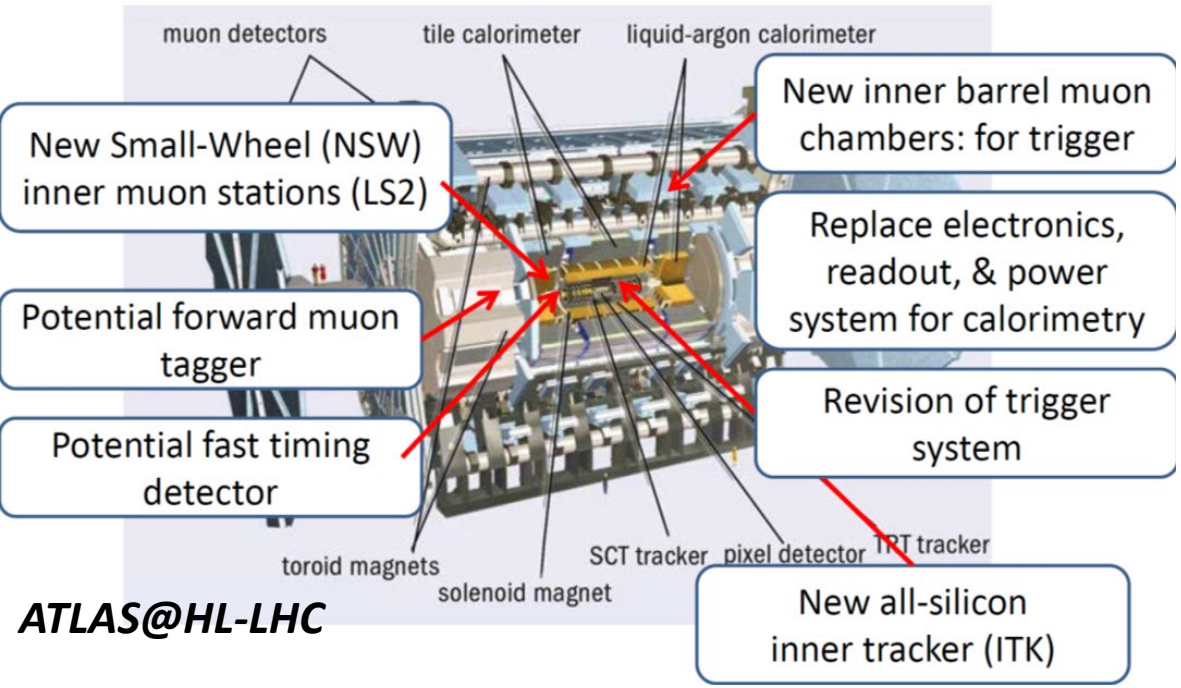
→ displaced muons, ***veto*** events with L1Mu matched to L1 track

  - Limited to muons with large displacement & higher pT



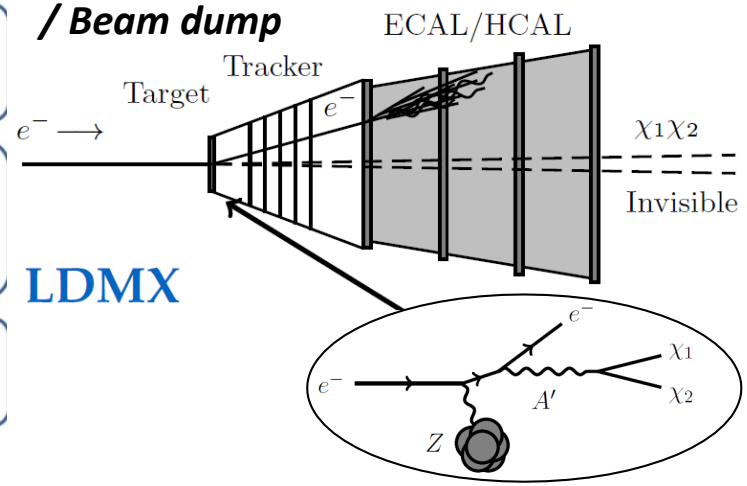
Work in progress:
Can we use muon system + displaced tracks@L1 and/or timing information to lower the pT threshold and trigger on *soft muons?*

Dark Sector Search beyond CMS



ATLAS@HL-LHC

Missing momentum / Beam dump

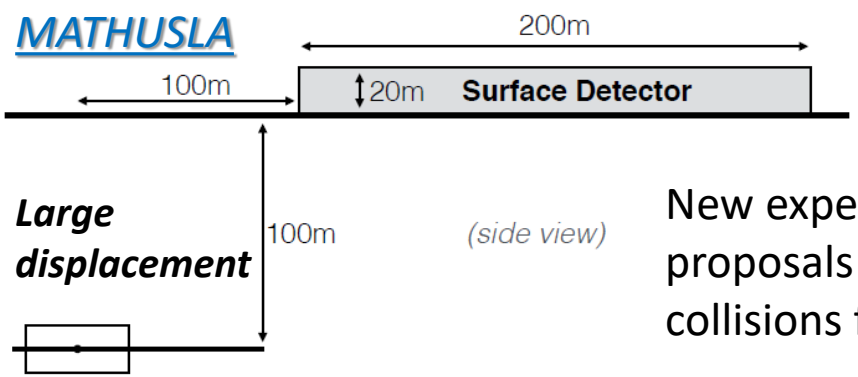


LDMX

B-factory

$$e^+e^- \to \gamma A' \to \gamma\chi_1\chi_2 \to \gamma \not{E} + \ell^+\ell^-$$

MATHUSLA



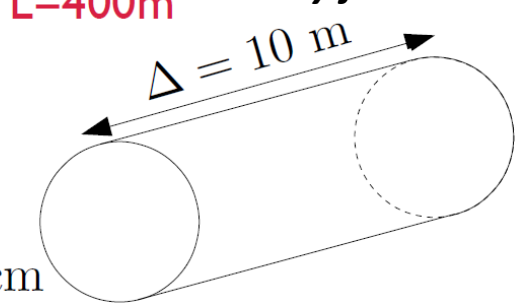
Large displacement

New experiment proposals using LHC collisions for LLPs.

on-axis: L=400m

Very forward

FASER



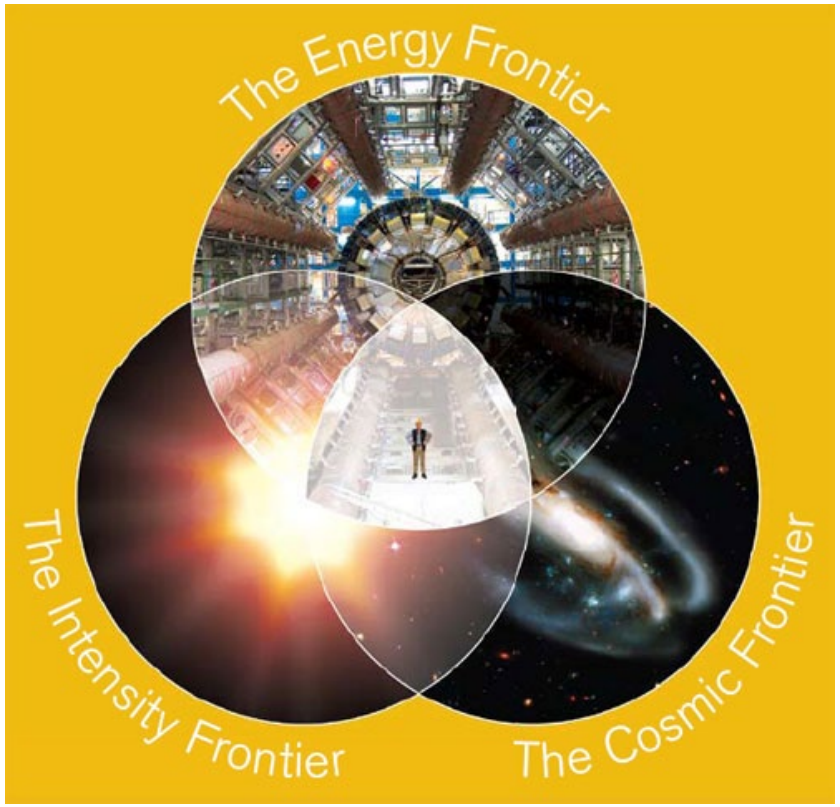
outer radius

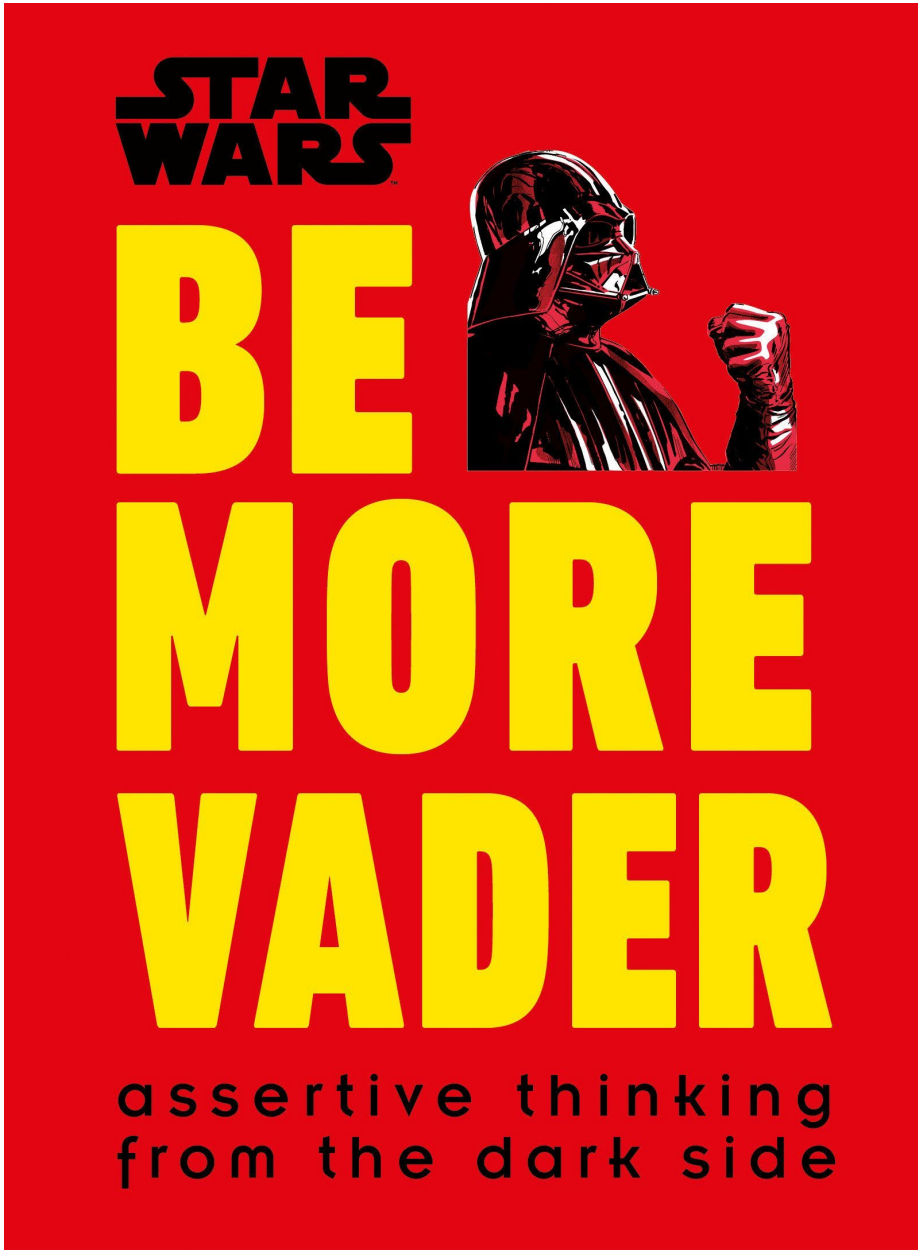
$R_{out} = 20$ cm

Conclusions and Outlook

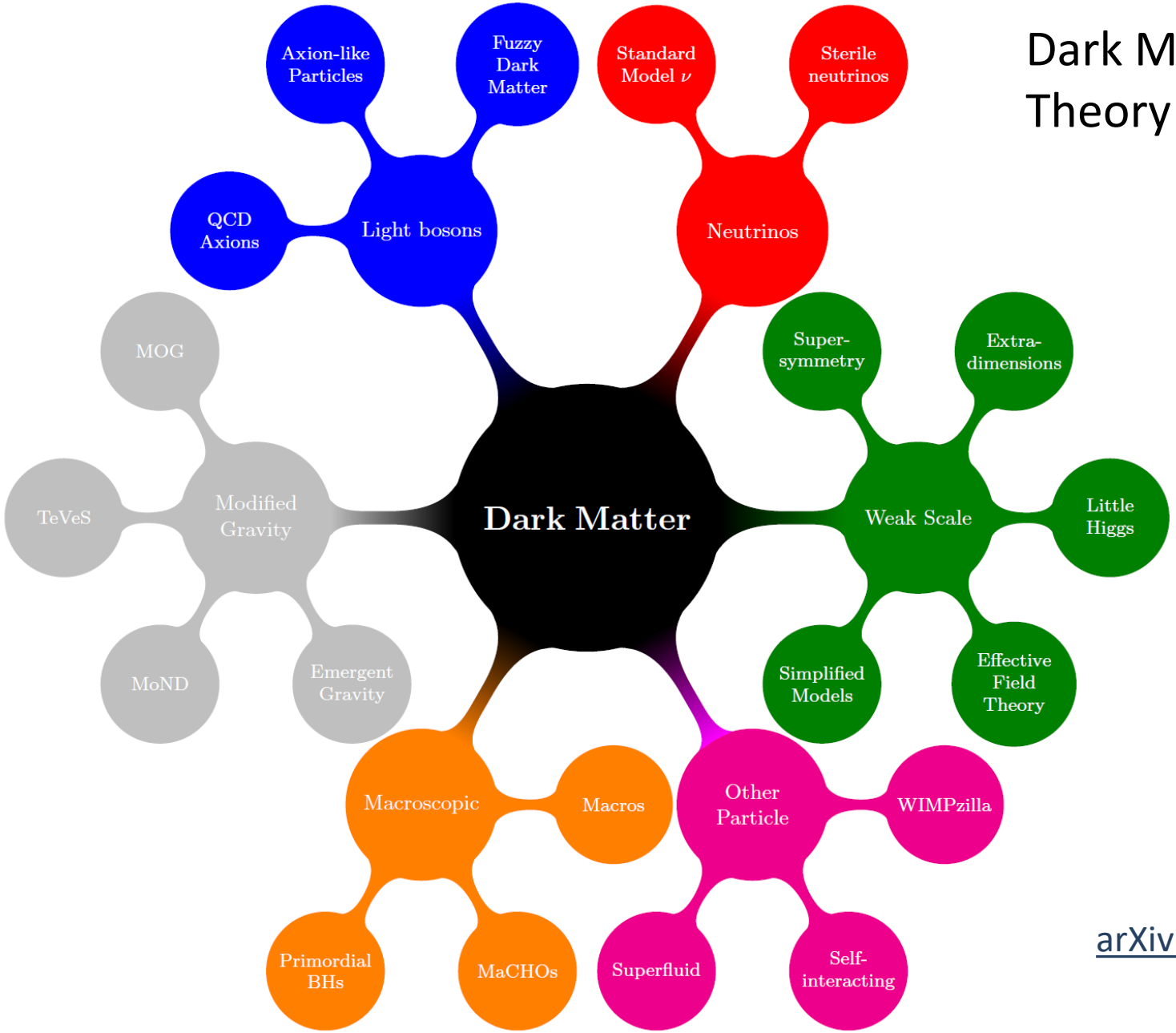
- A complex dark sector is well-motivated in both particle physics & cosmology
  - Bypass stringent WIMP limits from (in)direct detection & collider searches
  - Provide dark matter candidates; explain evolution of early universe
- The LHC is a *unique machine* to probe the dark sector
  - Broad range of lifetime & decay products → need dedicated searches!
- New *signature-driven* dark sector searches are underway with LHC Run2 data
  - Results have broad reinterpretation value
  - Challenges in trigger, reconstruction, & background estimation
- Detector and trigger upgrades @HL-LHC bring tantalizing prospects
  - Increased forward acceptance and improved resolution
  - New L1 trigger capabilities open up new possibilities
- Searches @ ATLAS and CMS complementary to other (non-) collider experiments

THANK YOU!


The Energy Frontier
The Intensity Frontier
The Cosmic Frontier


STAR WARS
BE MORE VADER
assertive thinking from the dark side

Dark Matter Theory Landscape



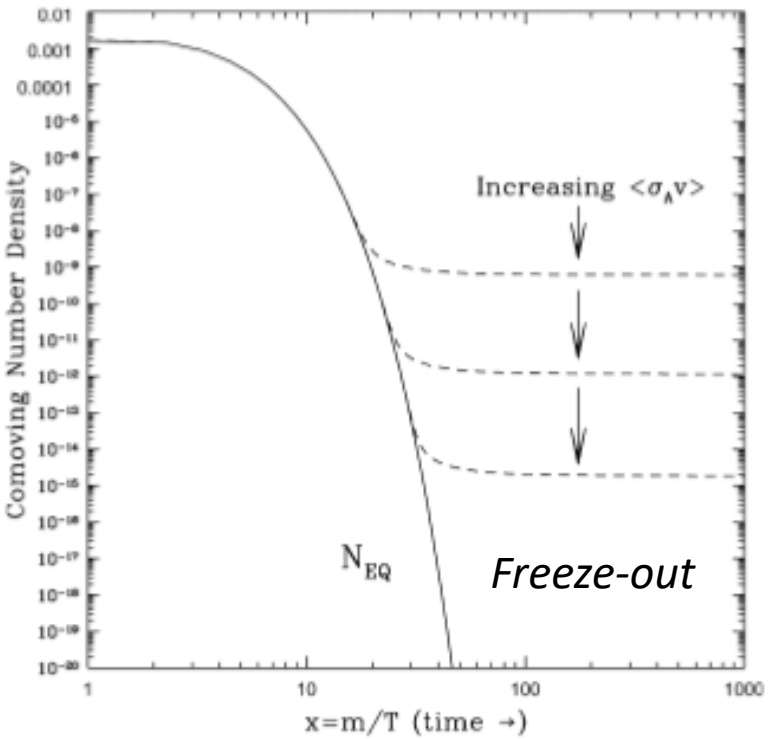
arXiv:1810.01668

The WIMP Paradigm

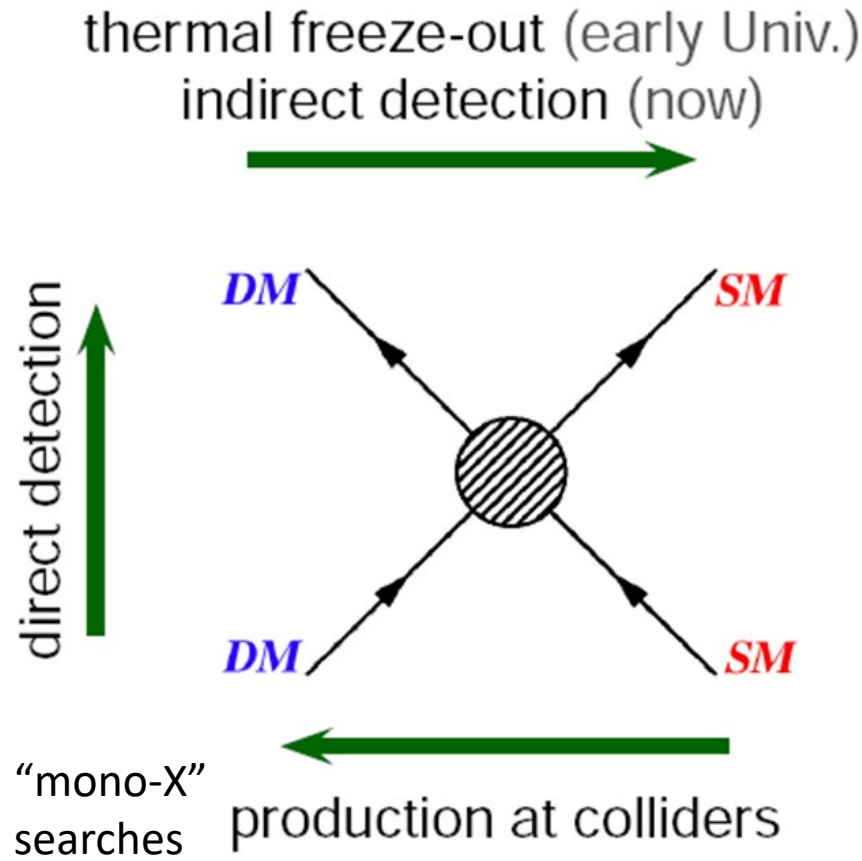
If DM is <u>made of particles</u>

→ **WIMP Miracle**

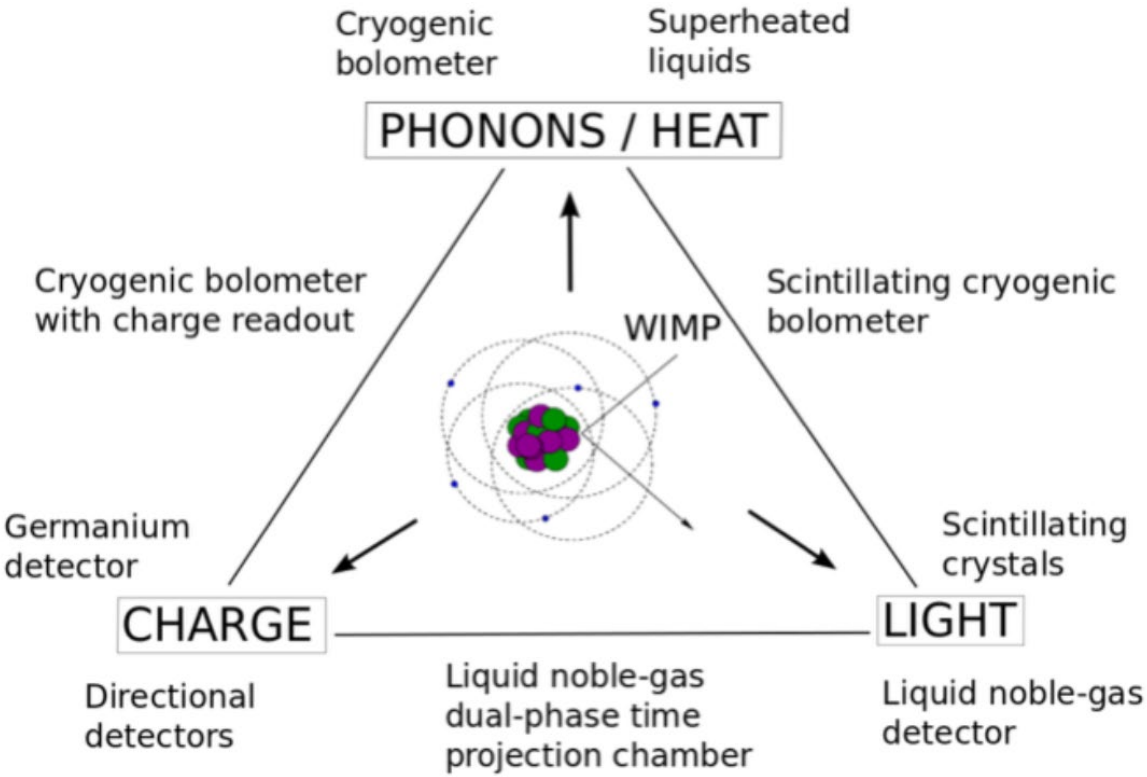
- single, stable particle ~O(100GeV)
- fits relic density
- viable candidates in BSM theories

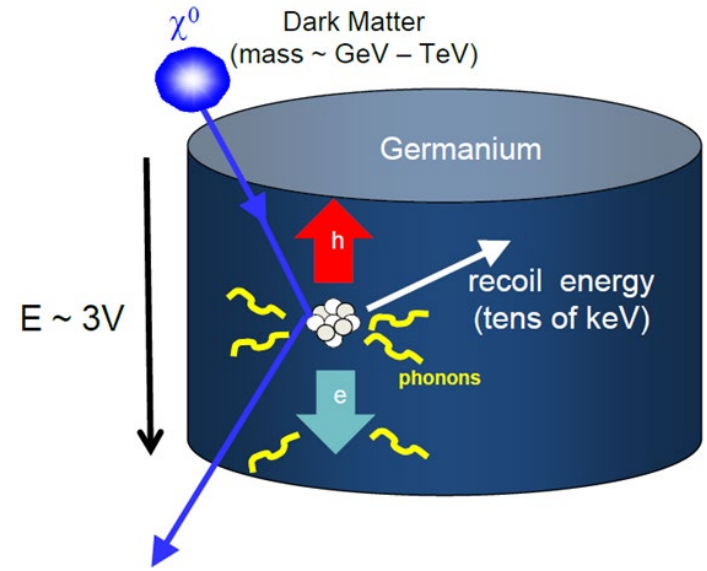


Three *COMPLEMENTARY* experimental methods



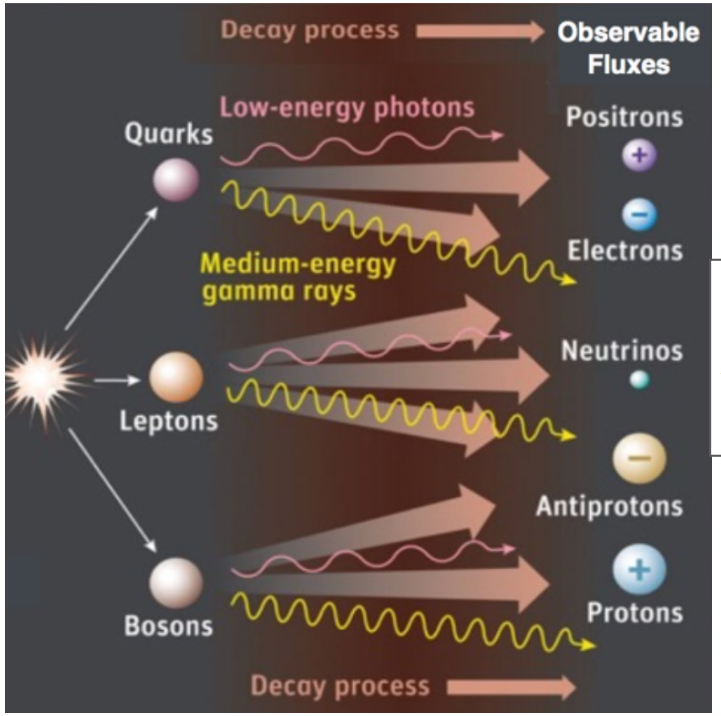
Dark Matter Direct Detection





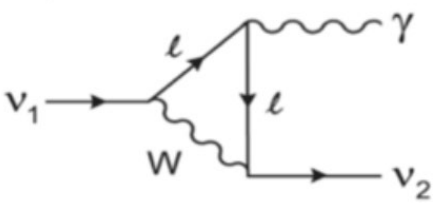
$$\frac{dR}{dE}(E,t) = \frac{\rho_0}{m_\chi \cdot m_A} \cdot \int v \cdot f(\mathbf{v},t) \cdot \frac{d\sigma}{dE}(E,v)\ \mathrm{d}^3 v,$$

Dark Matter Indirect Detection



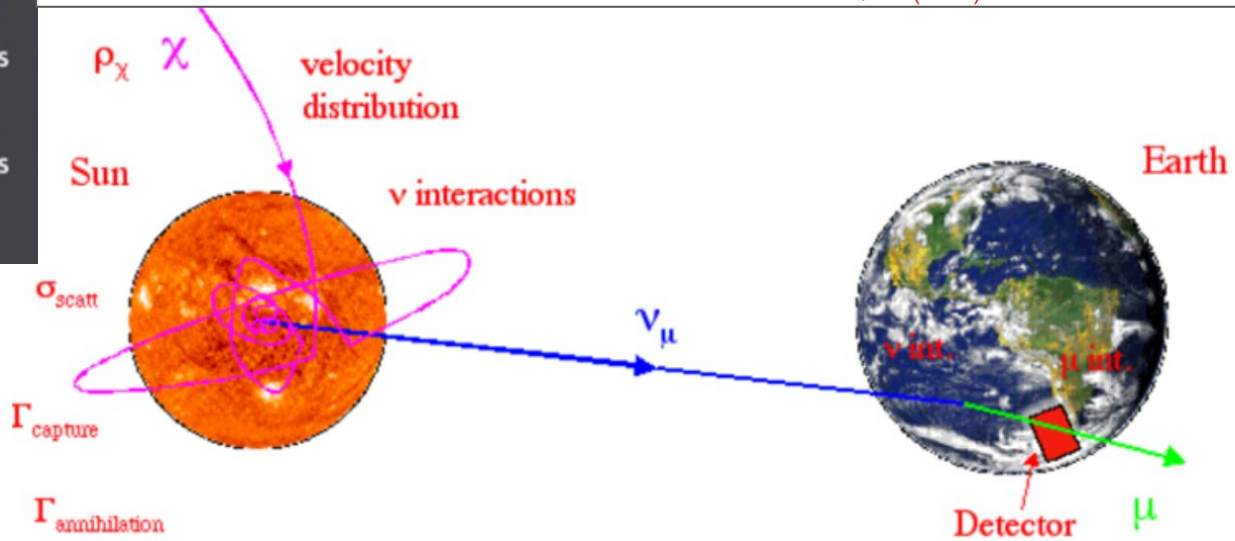
Annihilation

Decay

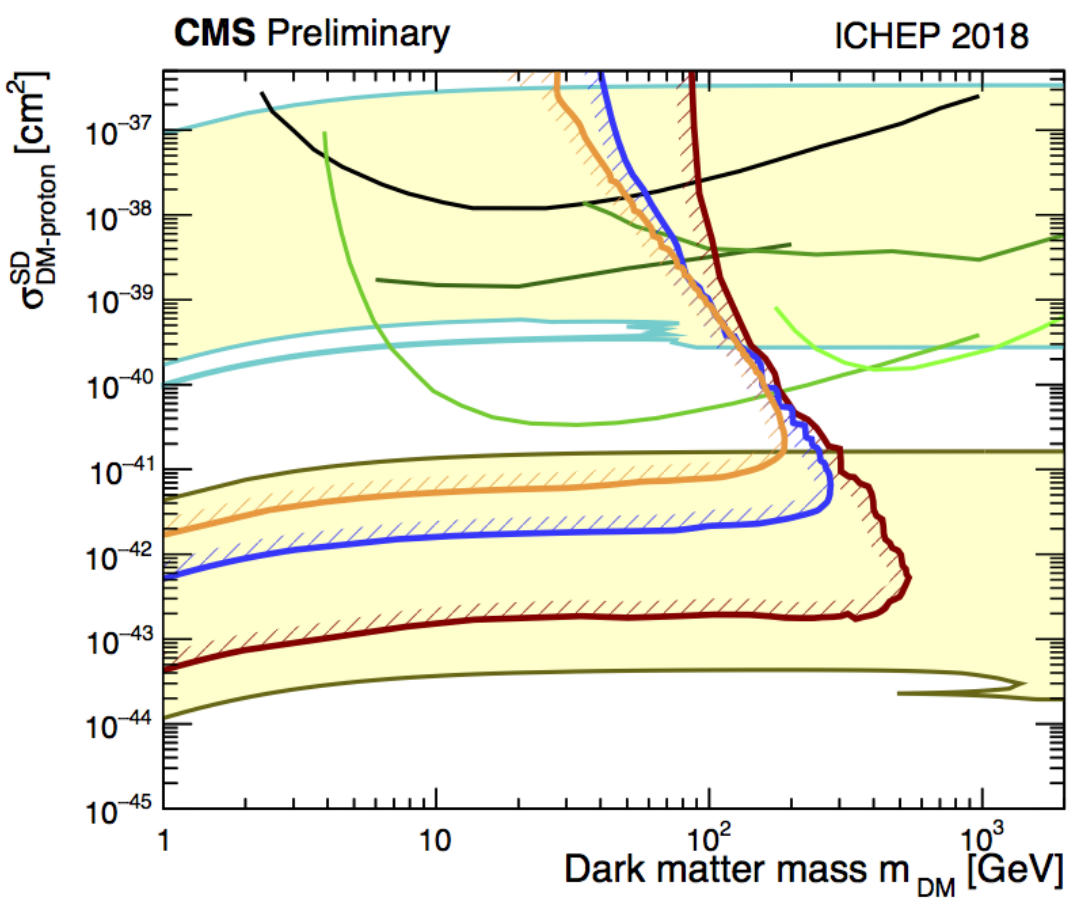


$$\chi\chi \to \left\{ \begin{array}{c} ZZ,\ W^+W^-,\ \gamma\gamma \\ q\bar{q},\ \ell^+\ell^-,\ \nu\bar{\nu} \end{array} \right\} \xrightarrow{\text{had./decay}} \gamma, e^\pm, \mu^\pm, p/\bar{p}, \pi^\pm, \nu/\bar{\nu}, \ldots$$

$\mathcal{O}$(GeV) - $\mathcal{O}$(TeV) from dark matter
$E_\nu \sim \mathcal{O}$(MeV) from sun



No WIMPs Found (outside Congress) yet



CMS observed exclusion 90% CL
Axial-vector med., Dirac DM; $g_q = 0.25$, $g_{DM} = 1.0$

- **Boosted dijet** (35.9 fb^{-1}) *[arXiv:1710.00159]*
- **Dijet** (35.9 fb^{-1}) *[arXiv:1806.00843]*
- **DM + j/V(qq)** (35.9 fb^{-1}) *[arXiv:1712.02345]*
- **DM + γ** (35.9 fb^{-1}) *[EXO-16-053]*
- **DM + Z(ll)** (35.9 fb^{-1}) *[arXiv:1711.00431]*

DD/ID observed exclusion 90% CL

- **PICASSO** *[arXiv:1611.01499]*
- **PICO-60** *[arXiv:1702.07666]*
- **Super-K ($b\bar{b}$)** *[arXiv:1503.04858]*
- **IceCube ($b\bar{b}$)** *[arXiv:1612.05949]*
- **IceCube ($t\bar{t}$)** *[arXiv:1601.00653]*

Search for DM-SM mediators decay to jets

Limit interpretations ***depend on*** *DM & mediator types, and coupling assumptions!*

- Collider/DD/ID combination plot shown as scattering xsec vs WIMP DM mass
  - Spin-Dependent: *less sensitive* at direct detection due to coupling to nuclear spin
  - In general, collider searches are more sensitive for low mass WIMP DM

Displaced Photon Search: Trigger

HLT_DisplacedPhoton60_R9Id90_CaloIdL_IsoL_PFHT350_v1

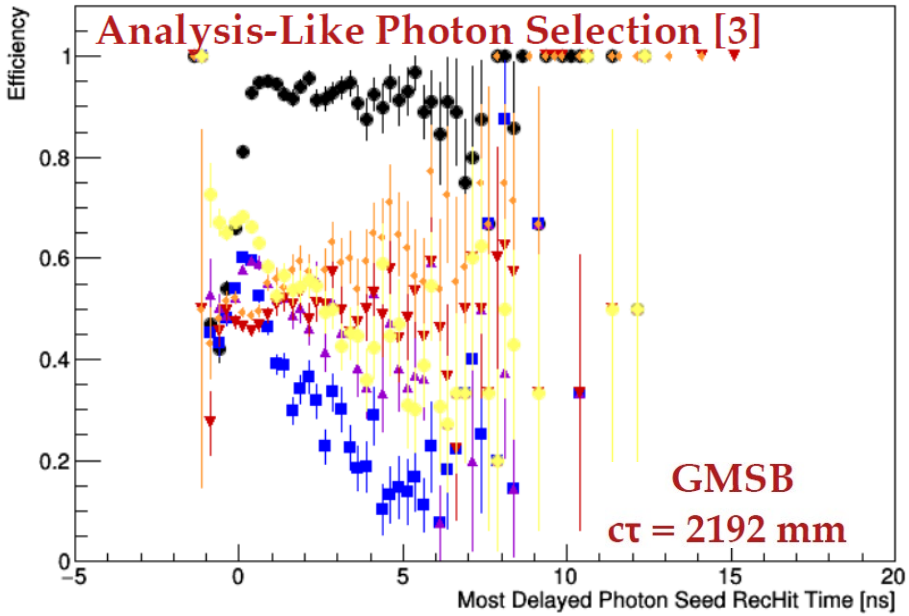
L1 Seed	HLT EG E_T	HoverE (EB)	HoverE (EE)	R9 (EB/EE)	$\sigma_{i\eta i\eta}$ (EB)	$\sigma_{i\eta i\eta}$ (EE)
L1SingleEG40	60 GeV	0.15	0.1	0.9	0.014	0.035

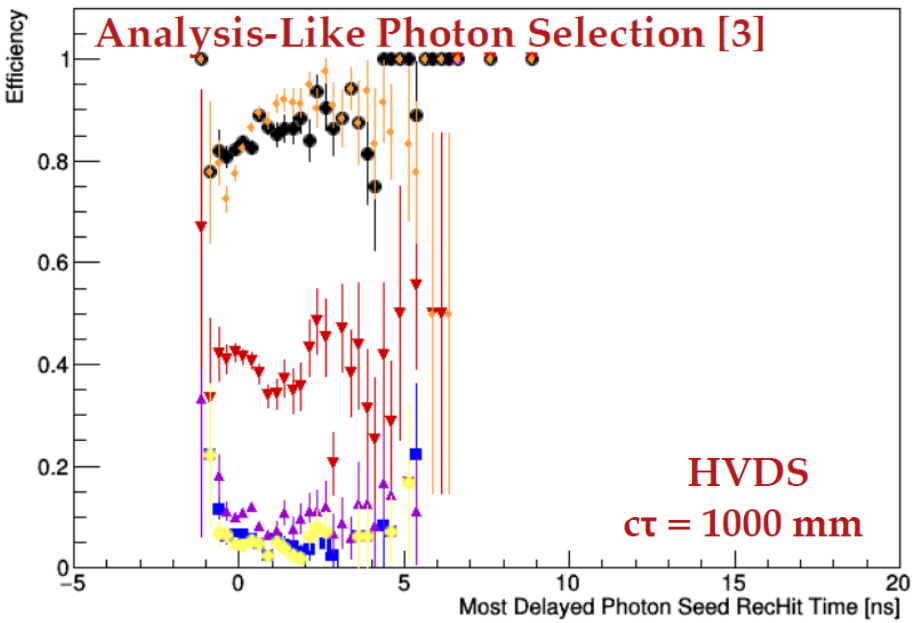
S_{major} Max	S_{major} Min	S_{minor} Max	S_{minor} Min	Track Veto	Min Track p_T	ΔR	nTracks
1.5	0.0	0.4	0.0	Yes	5 GeV	0.2	1

	EB			EE		
Constant	a	b	c	a	b	c
Isolation	$(a + b * E_T + c * E_T * E_T)$					
Photon	5.0	0.01	0.0	8.0	0.007	0.0
Neutral Hadron	12.5	0.03	3E-5	7.5	0.032	3E-5
Hollow Track	6.0	0.002	0.0	6.0	0.002	0.0

Min Calo Jet p_T	Calo H_T	Min PF Jet p_T	PF H_T
10 GeV	175 GeV	15 GeV	350 GeV

Displaced Photon Search: Trigger





- HLT path chosen for best efficiency for *both* GMSB and Hidden Valley Dark Shower models
- Lowest possible threshold on single photon pT (combined with HT) for acceptable trigger rate
- *Unique filters* on ECAL cluster shape info to identify displaced photons
- Improvements possible for future search dedicated to dark showers

HLT_DisplacedPhoton60_*_PFHT350_v
HLT_Photon175_v
HLT_Photon120_*_EBOnly_PFMET40_v
HLT_DoublePhoton60_v
HLT_Photon42_*_Photon25_*_Mass15_v
HLT_Photon90_CaloIdL_PFHT600_v

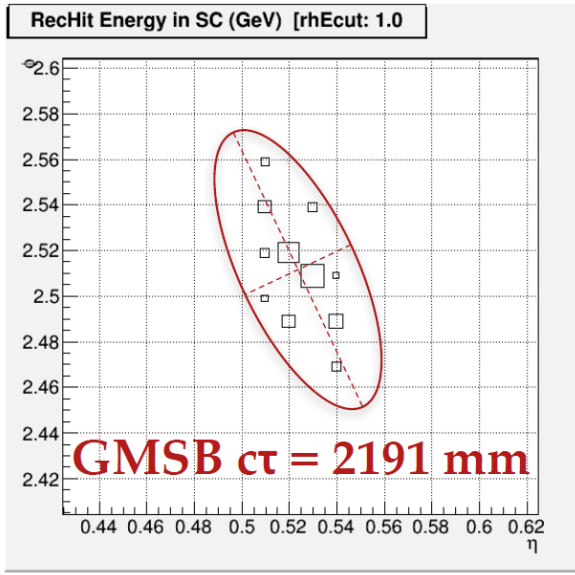
Displaced Photon Search: OOT Photon ID

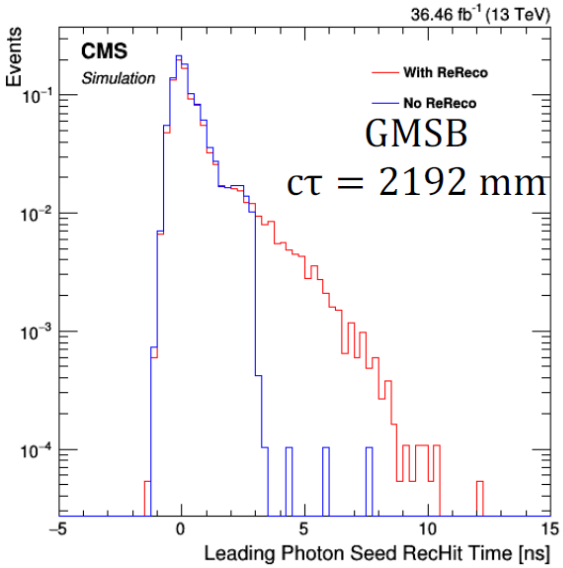
- Standard photon reconstruction removes ECAL hits above a few GeV & seed time >|3|ns → removes our signal!

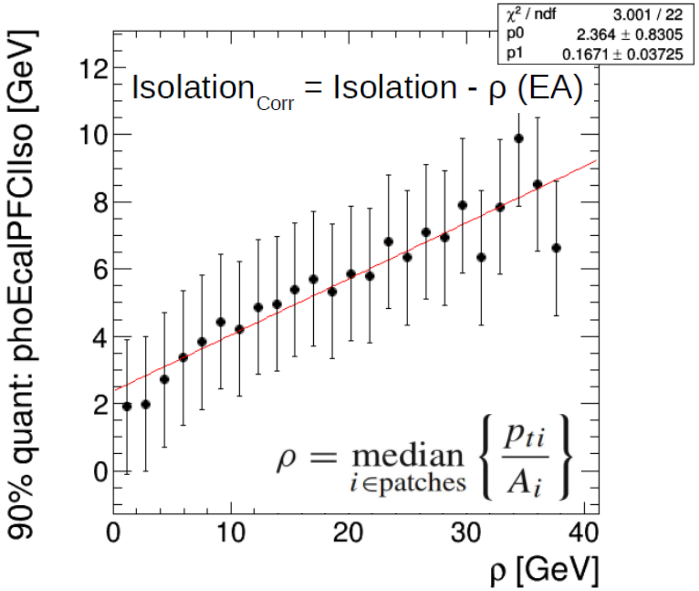
→ build dedicated, custom out-of-time (OOT) photon collection

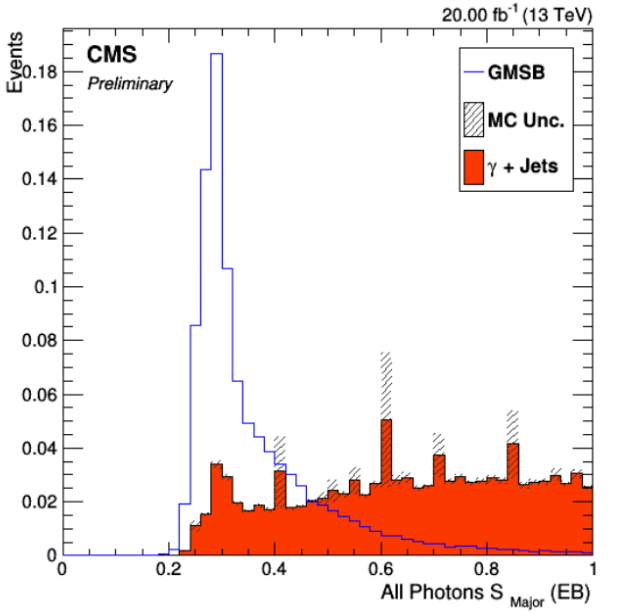
  – RecHits → Clusters → SuperClusters → Photon Producer

- New shower shape variables added to standard photon ID variables: OOT photon clusters more elliptical than prompt
- Recalculated effective areas & pT scaling for isolations
  – Selections are optimized with multi-variant analysis





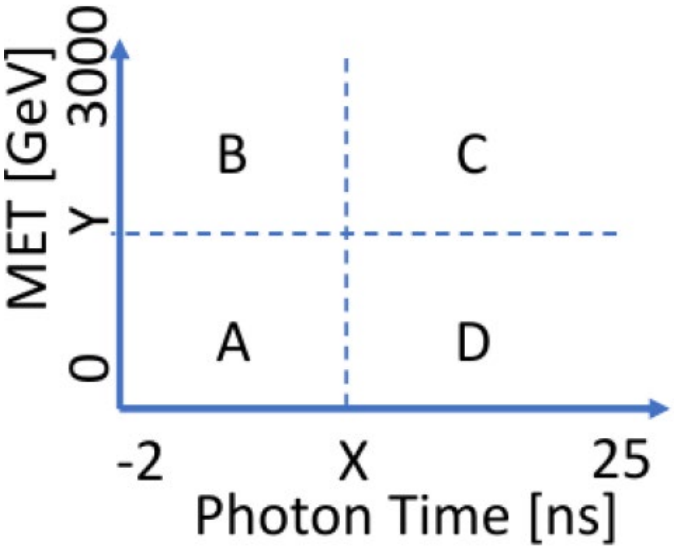




Displaced Photons: ABCD method

- Signal selection:
  - Single photon dataset, signal trigger
  - At least one tightly ID-ed photon
  - nJets>=3; HT>400GeV
- Background estimation:
  - Final yield estimated with ABCD method
  - Assuming photon time & E_T^{miss} uncorrelated
  - Four equations with μfour unknowns: Bkg_A, c1, c2, μ
    - Count data in each category
    - Count expected signal in each category
    - Solve the equations!
  - Validated in control regions
    - γ+jets; QCD; DY+LL

$$N_A = Bkg_A + \mu \times Sig_A$$
$$N_B = c_1 \times Bkg_A + \mu \times Sig_B$$
$$N_D = c_2 \times Bkg_A + \mu \times Sig_D$$
$$N_C = c_1 \times c_2 \times Bkg_A + \mu \times Sig_C$$



Displaced Photon Search: Signal Region

- Leading photon:
  - $p_T^{\gamma} > 70$
  - $|\eta_{\gamma}| < 1.4442$
  - $R_9 > 0.9$
  - $S_{minor} < 0.4$ (will be updated)
  - Pass tight GED/OOT photon ID + $|\Delta R(\gamma, \text{All Tracks})| > 0.2$
- Signal trigger fired
- nJets ≥ 3
  - Jet selection:
    - $p_T^{jet} > 30$
    - $|\eta_{jet}| < 3$
    - Pass tight jet ID (2017)
    - If γ_0 passes loose GED ID H/E and $\sigma_{i\eta i\eta}$, then $\Delta R(\text{jet}, \gamma_0) > 0.3$
- $H_T > 400$ (using jets as above)

	GMSB Parameter Space							
cτ (cm)	0.1	10	200	**400**	600	800	1000	1200
Λ (TeV)	100	150	200	**250**	300	350	400	

	HVDS Parameter Space						
cτ (cm)	0.1	10	50	100	250	500	1000
$m_{Z'}$ (GeV)	300	500	800	1000			
$m_{\pi,dark}$ (GeV)	20	40	60				

Displaced Photon Search: Control Region I

γ + jets control region selection

- Leading Photon:
  - $|\eta_\gamma| < 1.4442$
  - $p_T^\gamma > 70$
  - Pass tight GED + no pixel seed / OOT photon ID + $|\Delta R(\gamma, \text{All Tracks})| > 0.2$
- Subleading Photon:
  - $p_T^\gamma > 25$
  - $H/E < 0.12$
- **(nJets == 1) OR (nJets == 2 AND $p_T^{jet_1}/p_T^{\gamma_0} < 0.2$)** $[p_T^{jet} > 30]$
- $|\Delta\phi(\gamma_0 - Jet_0)| > 2.1$
- Apply optional MET filters
- Diphoton trigger fired

QCD control region selection

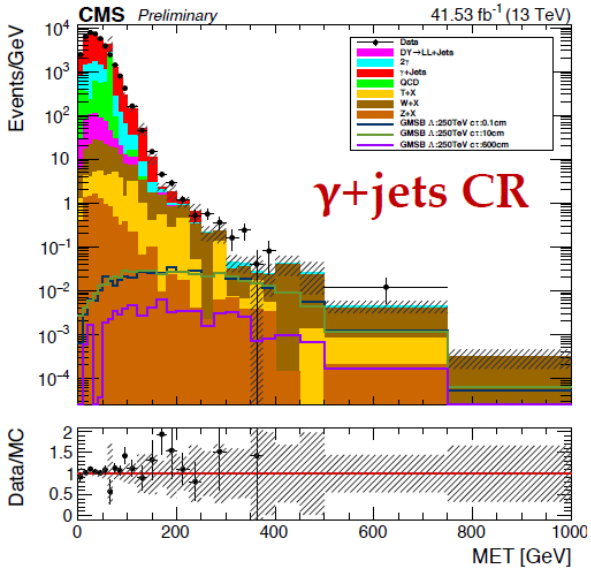
- Leading Photon:
  - $|\eta_\gamma| < 1.4442$
  - $p_T^\gamma > 70$
  - $R_9 > 0.5$
  - $H/E < 0.12$
  - $\sigma_{i\eta i\eta} < 0.015$
  - **Fail loose GED/OOT photon ID Charged Hadron Iso > 5 || Neutral Hadron Iso > 10 || Photon Iso > 4.0 (GED), Track Iso > 7 (OOT)**
- Subleading Photon:
  - $p_T^\gamma > 25$
  - $H/E < 0.12$
- nJets ≥ 3 $[p_T^{jet} > 30]$
- Apply optional MET filters
- Diphoton trigger fired

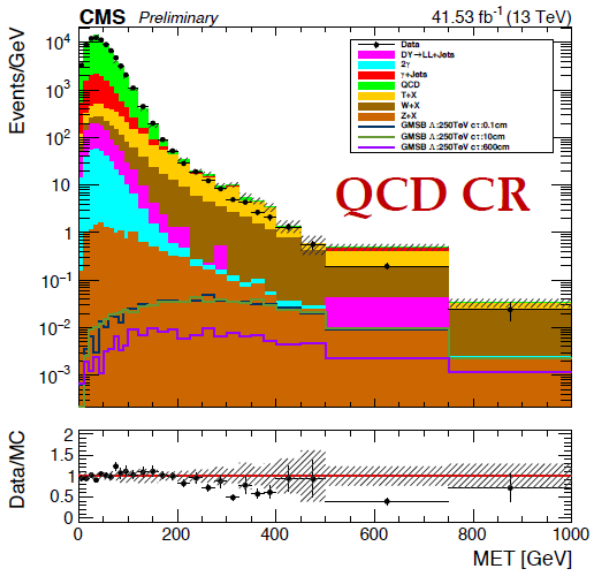
Displaced Photon Search: Control Region II

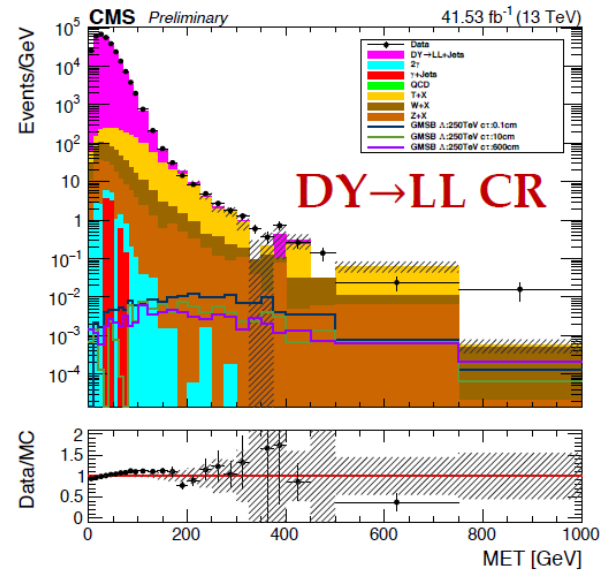
DY→LL selection

- Two photons:
  - $|\eta_\gamma| < 1.4442$
  - $p_T^\gamma > 40$
  - Pass tight GED + **HAVE pixel seed**/OOT photon ID + $\mathbf{|\Delta R(\gamma, \text{All Tracks})| < 0.2}$
- $60 <$ diphoton invariant mass < 150
- Apply optional MET filters
- DoubleEle trigger fired

Displaced Photon Search: ABCD Closure





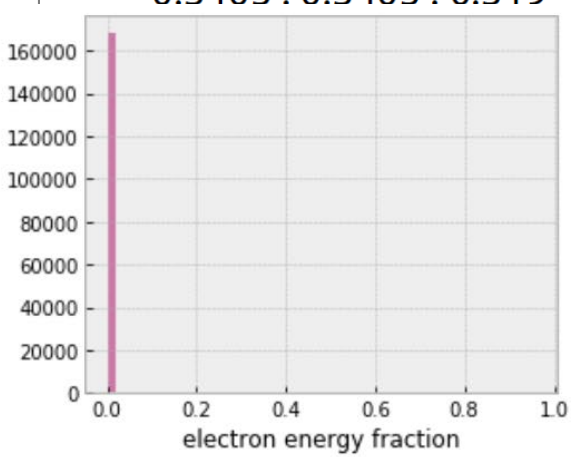


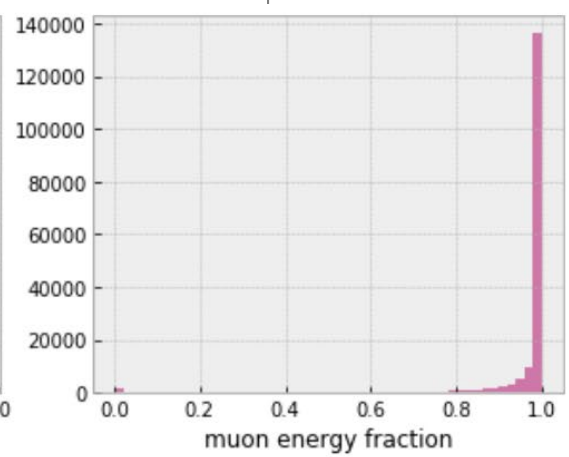
Control Region [Data]	Boundary		Observed				Predicted
	Time [ns]	MET [GeV]	A	B	C	D	C = B*D/A
γ+jets	1	150	3.8e+05 ± 617	345 ± 18.6	4 ± 2	4.16e+03 ± 64.5	3.77 ± 0.211
QCD	1	150	7.67e+05 ± 876	6.62e+03 ± 81.4	78 ± 8.83	7.53e+03 ± 86.8	65.1 ± 1.1
DY→LL	1	150	2.98e+06 ± 1.73e+03	1.96e+03 ± 44.2	19 ± 4.36	2.96e+04 ± 172	19.4 ± 0.453

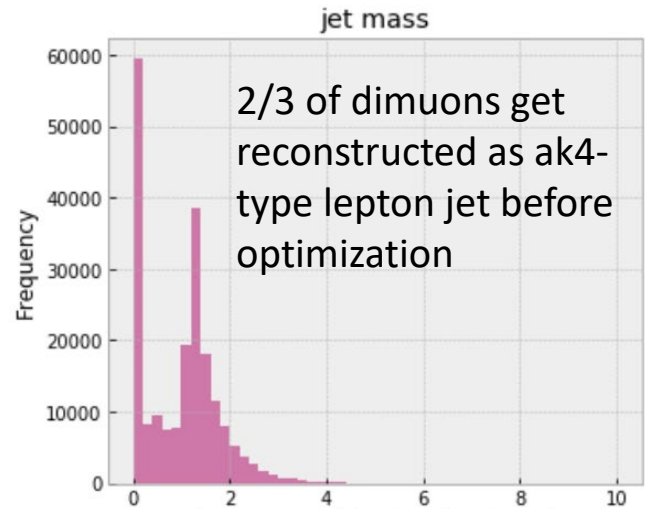
Object Reconstruction: Lepton Jet

- Preliminary lepton jet reconstruction studied using a dark photon particle gun for all three (e, mu, pi) lepton jet types: results promising w/ muon type showing best performance

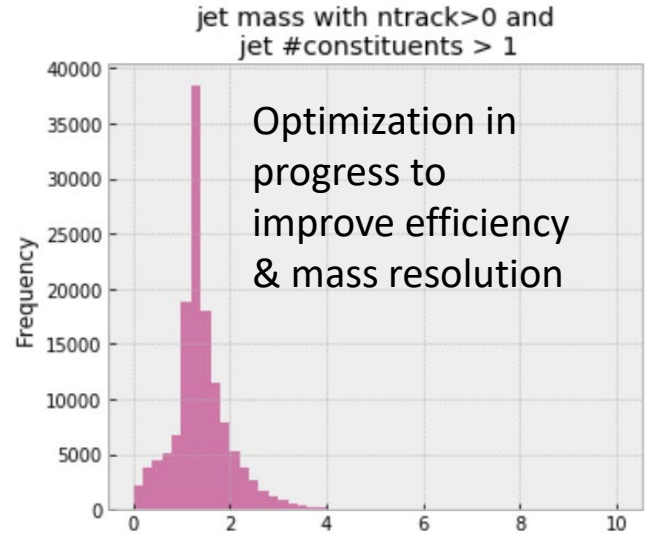
- **dark photon**
  - mass: 1.2 GeV
  - eta: (-3,3)
  - phi: (-pi, pi)
  - pT: 0-100 GeV, flat
  - decay length: 1m, exponential falling
- **decay product**
  - di-electron, di-muon, di-pion ratio
  - 0.3405 : 0.3405 : 0.319





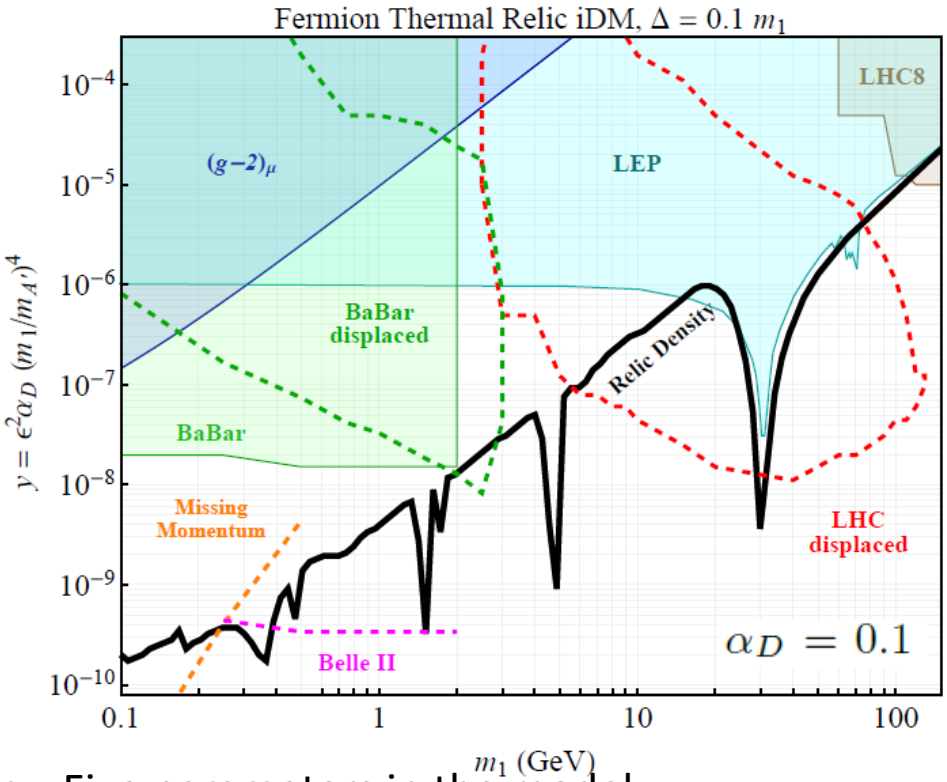


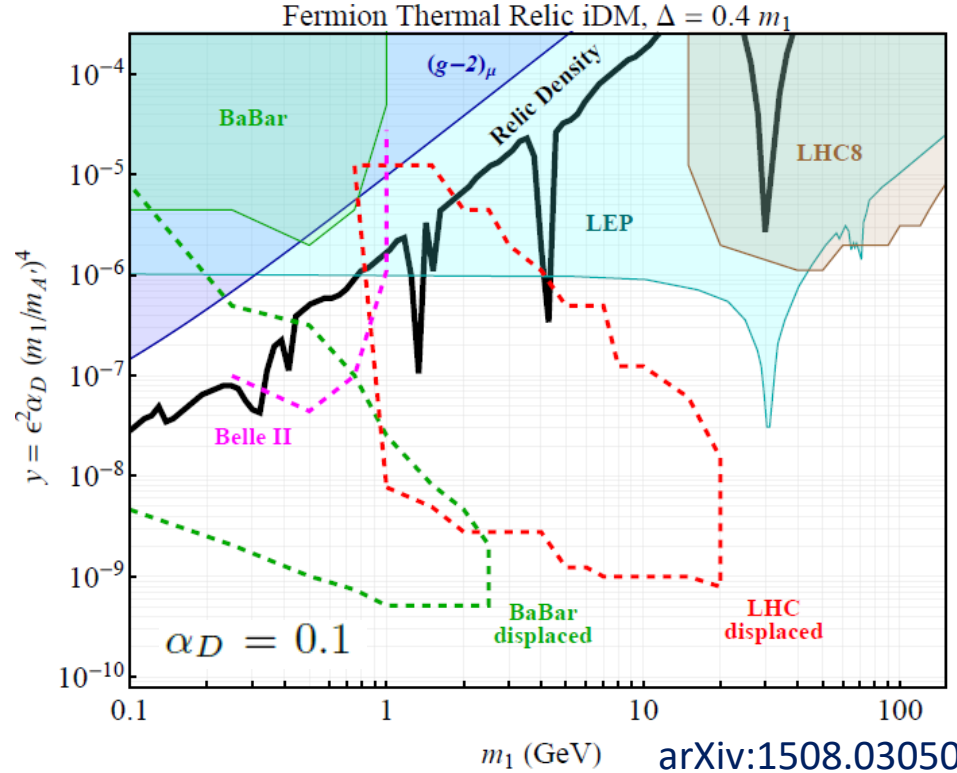
2/3 of dimuons get reconstructed as ak4-type lepton jet before optimization



Optimization in progress to improve efficiency & mass resolution

iDM: Parameter Space





arXiv:1508.03050

- Five parameters in the model:
  - **DM mass (ground state) m1, mass splitting Δ, dark photon mass mA'**
  - dark gauge coupling αD, mixing parameter ε
- Small mass splitting & mA'>~m1+m2 for relic density from co-annihilation
- Annihilation rate depends on m1 & interaction strength y

$$\epsilon^2 \alpha_D \left(\frac{m_1}{m_{A'}}\right)^4 \equiv y$$

→ Set mA' = 3x m1, choose two mass splitting (10%, 40%) consistent w/ theory paper

- Scan χ1 mass & χ2 decay length for collider search: scale xsec by corresponding couplings

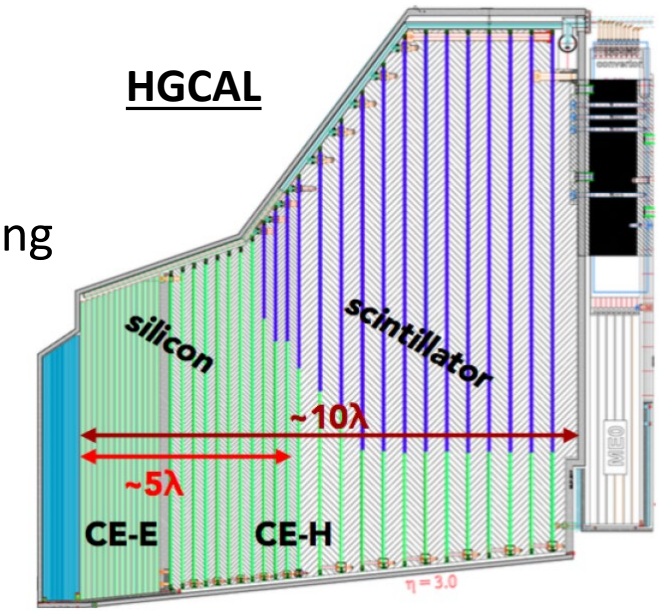
Detector Upgrade in the Forward Region

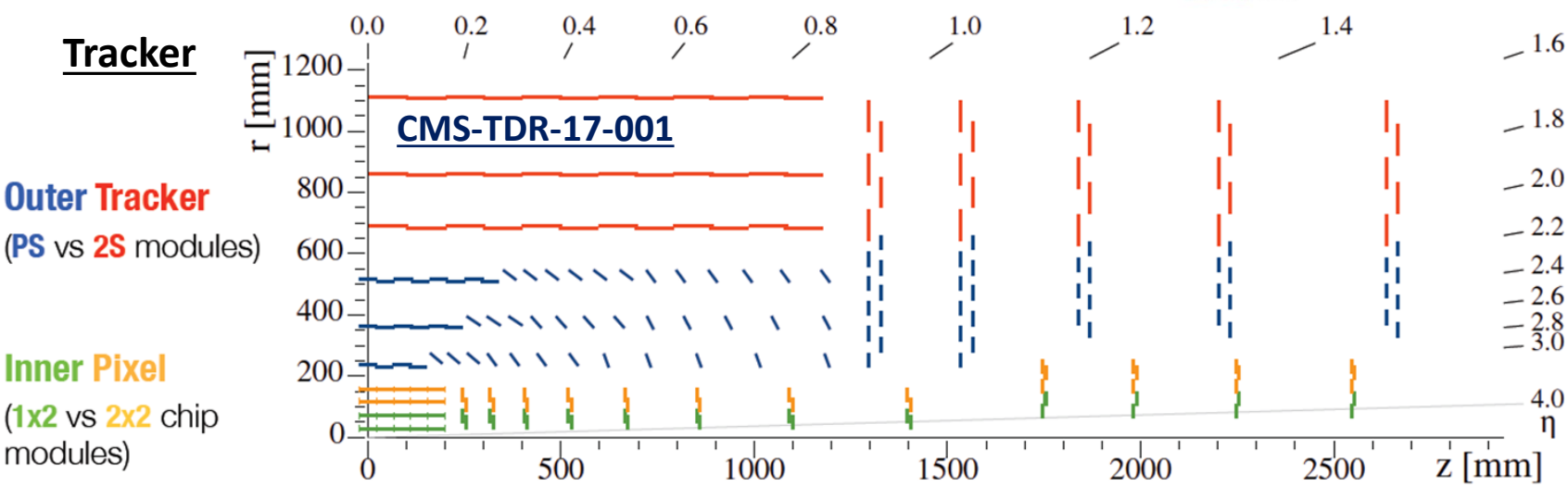
Inner pixel detector:
- small & thin (radiation hard) pixels; |η|~2.5 → |η|~4

Outer Tracker (OT):
- Two-sided sensor modules → stubs → L1 tracking finding

Endcap calorimeter (high granularity calorimeter):
- high granularity and 3D imaging; 1.5<|η|<3
- fast timing capability (few tens of ps)

Muon system
- extend forward coverage to |η|< 2.4 (2.9 for trigger)

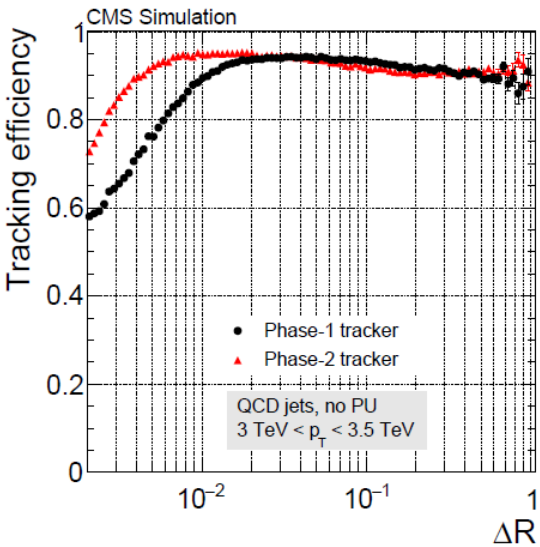




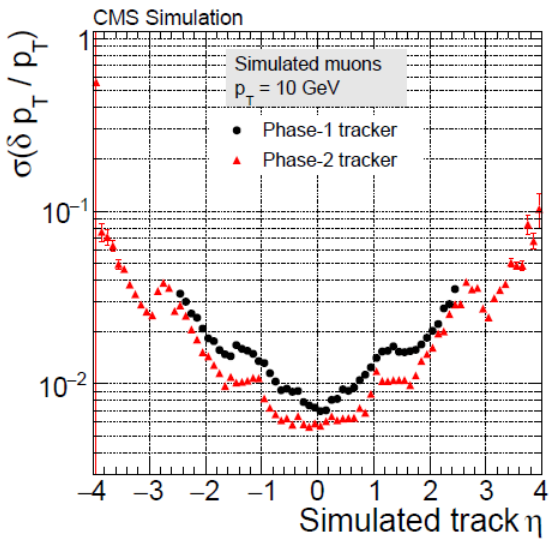
Tracker Upgrade: Performance

Tracking

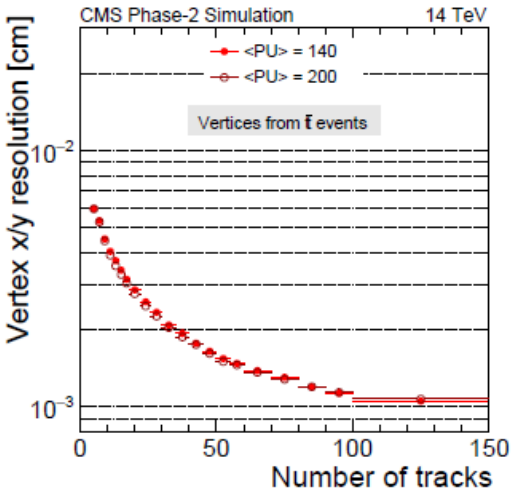
CMS-TDR-17-001

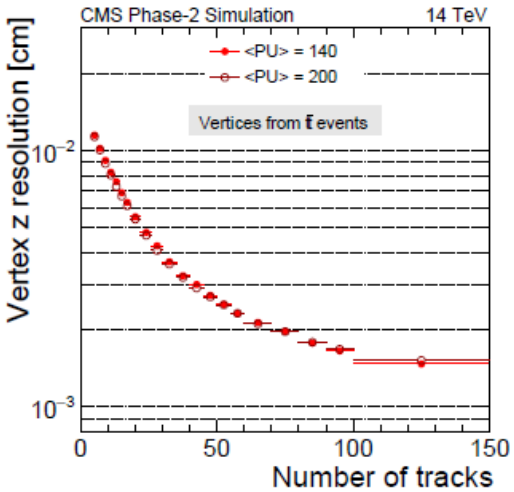


Excellent tracking performance with increased coverage and better resolution!



Vertexing



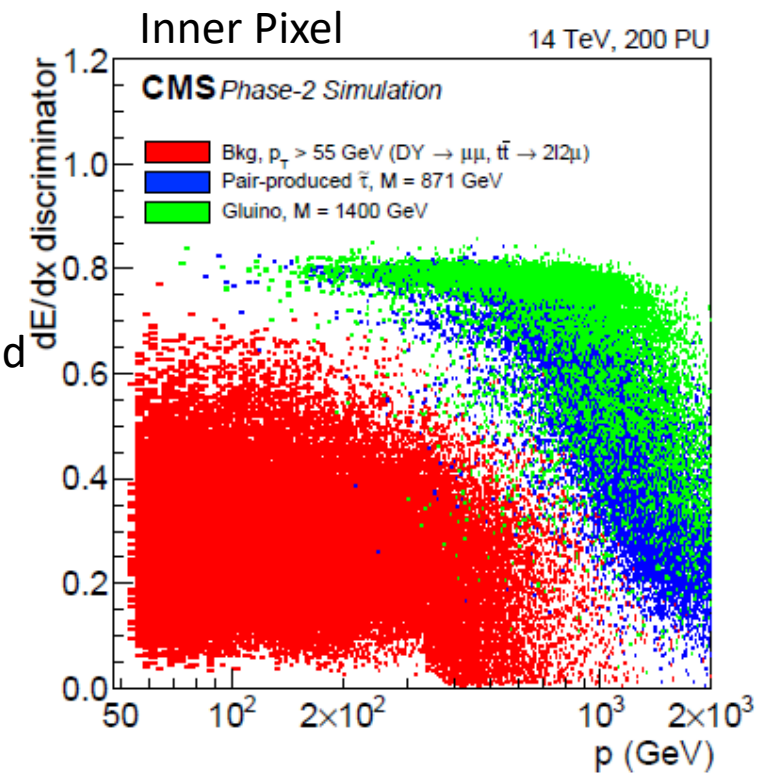


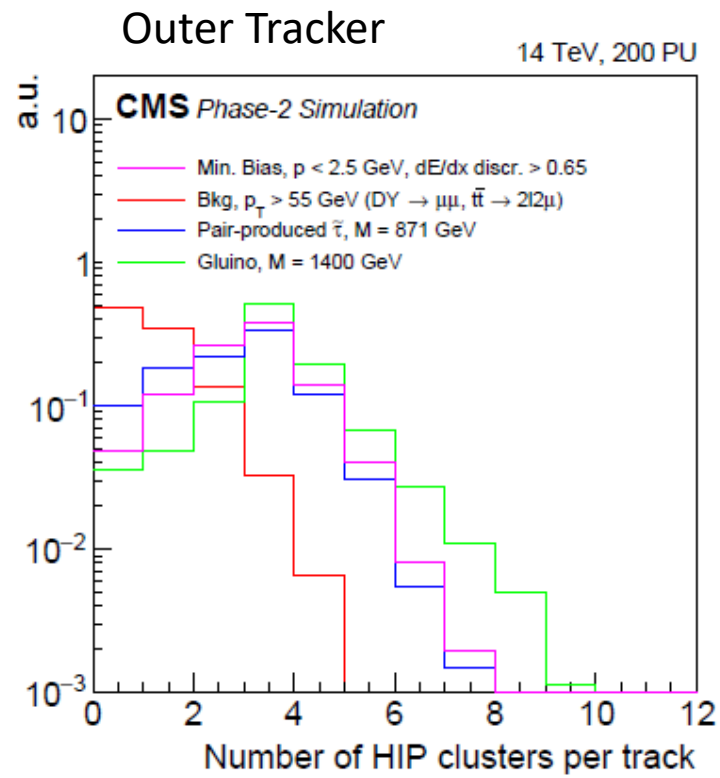
Vertexing resolution almost independent of pile-up; longitudinal resolution only ~50% worse than transverse (with 25x100x150 pixels)

Tracker Upgrade: LLP Prospects

- Heavy stable charged particles (e.g. split SUSY): high dE/dx in silicon sensor
- Phase2 inner pixel has analogue readout:
    - 4 (maybe more?) bit time-over-threshold info provides good resolution
- Phase2 outer tracker has digital readout + dedicated overthreshold bit (HIP flag) with programmable threshold (currently set at 1.4MIP)

Good separation between background and signal in dE/dx and number of overthreshold clusters per track





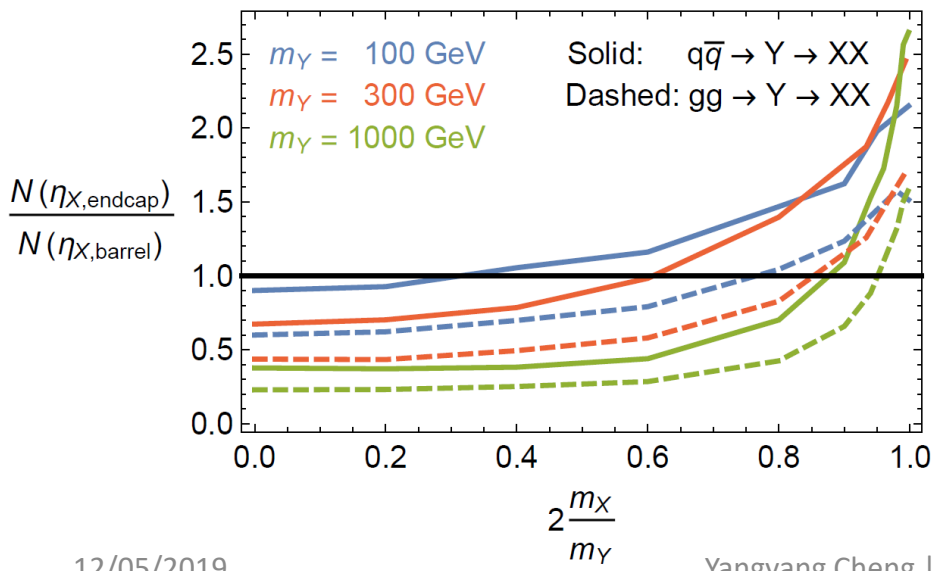
CMS-TDR-17-001

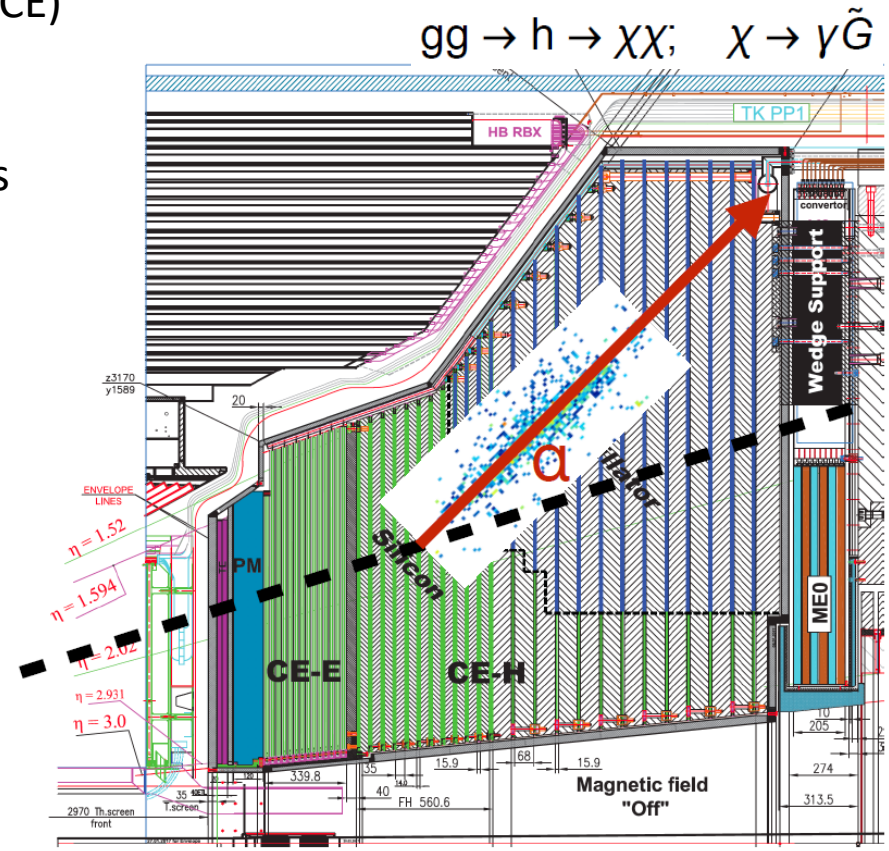
Trigger on Forward LLPs with HGCAL

Toy simulation:

- Work in η-ϕ depth space in calorimeter endcap (CE)
  - 2D cluster on layer → 3D shower
- Trigger cells (2x2 or 3x3) with >=2MIP energy
- Linear fit of energy-weighted η vs depth and ϕ vs depth
- Calculate total angle α between shower axis and fitted line back to primary vertex

→ Very promising! Further studies in full simulation



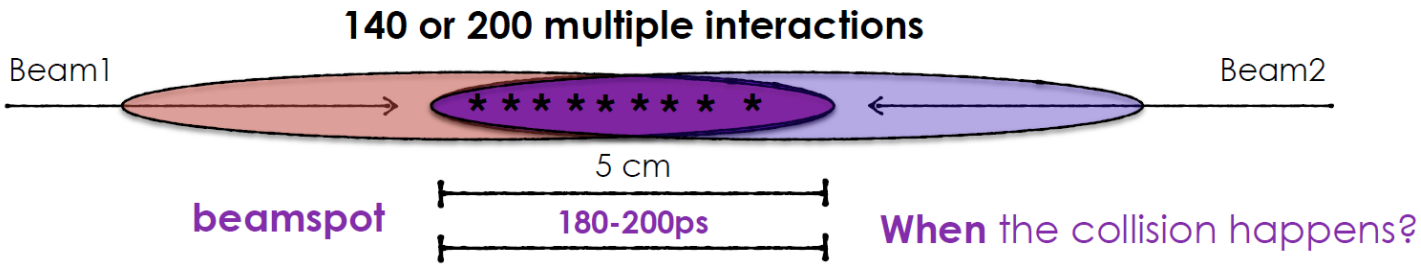


Calorimeter Endcap Trigger Primitives

Quantities	Bits	Total bits
E_T with and without PU subtraction	16, 16	32
Endcap, fraction in CE-E, fraction in back CE-H, max energy layer	1, 13, 12, 6	32
Shower start η, ϕ, z	11, 11, 10	32
Number of cells, quality flags, extra data flags	8, 12, 12	32
Minimum total		128
Optional shape quantities	8×16	128
Optional e/γ reco E_T with and without PU subtraction	16, 16	32
Optional subcluster 0 E_T, $\Delta\eta$, $\Delta\phi$	16, 8, 8	32
Optional subcluster 1 E_T, $\Delta\eta$, $\Delta\phi$	16, 8, 8	32
Optional subcluster 2 E_T, $\Delta\eta$, $\Delta\phi$	16, 8, 8	32
Optional subcluster 3 E_T, $\Delta\eta$, $\Delta\phi$	16, 8, 8	32
Maximum total		416

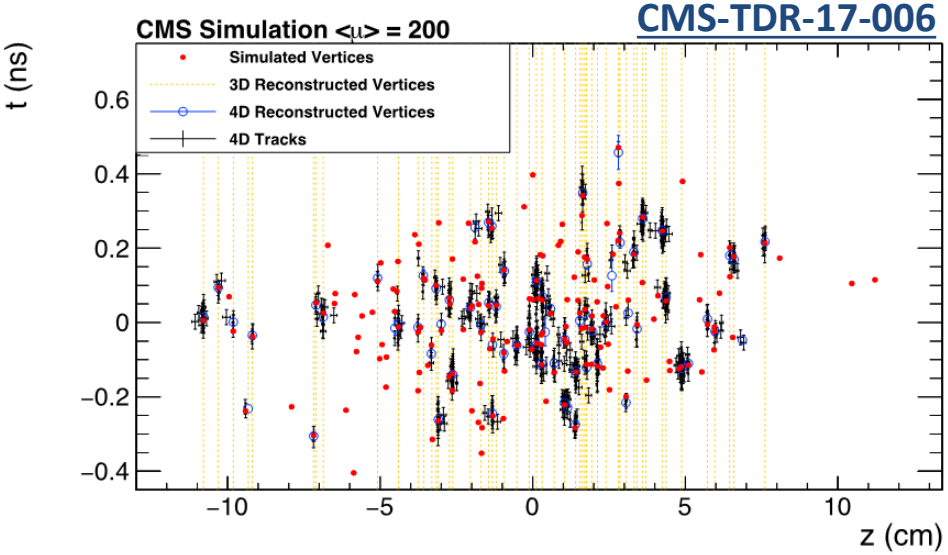
for each cluster

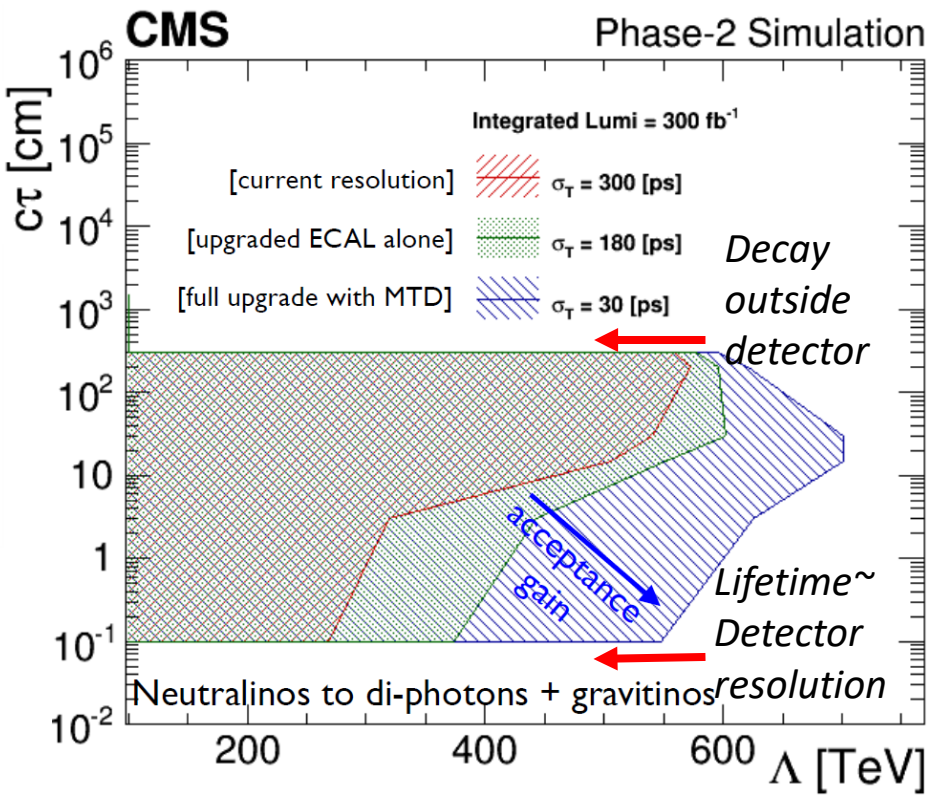
Fast Timing: Displaced Photon



ECAL upgrade will improve sensitivity, but limited by beamspot & only for >O(10GeV) particles.

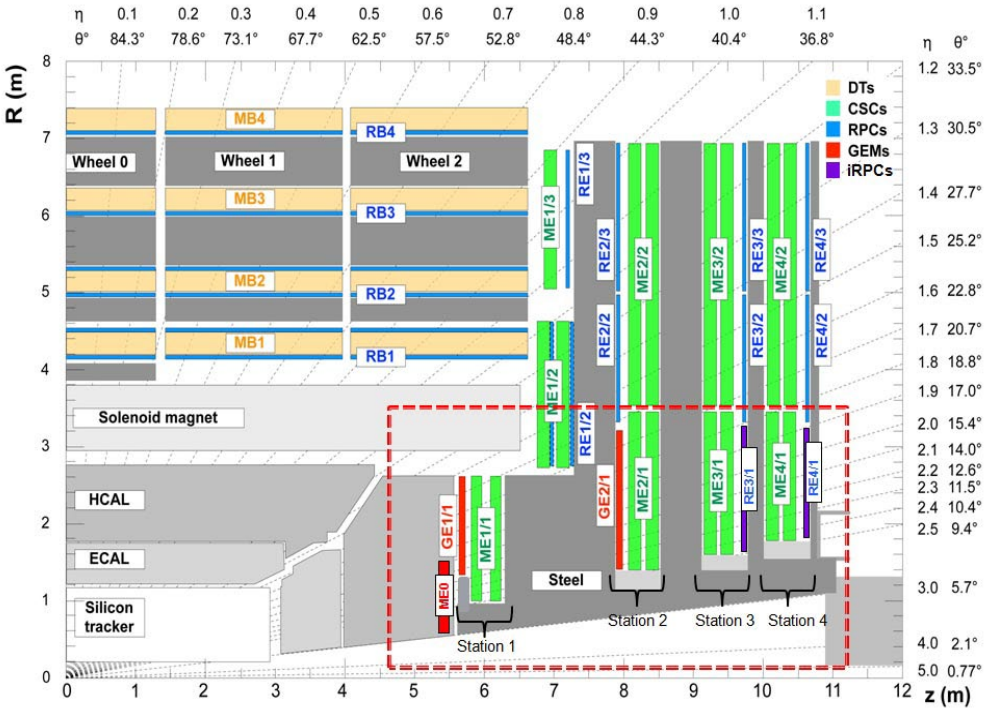
CMS-TDR-17-006





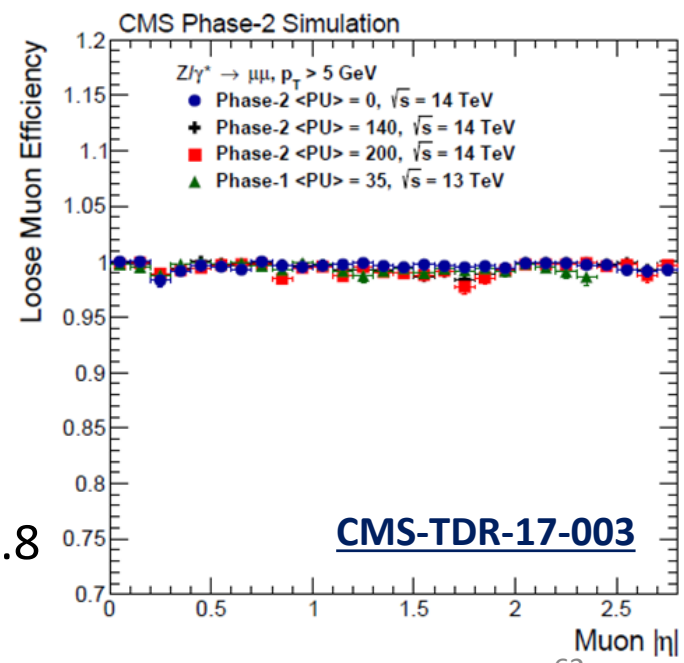
Precision timing w/ MTD will help remove spurious secondary vertices & tracks from PU; improve mass resolution in reconstruction; & open up new capabilities in LLP searches.

HL-LHC Upgrade: Muon System



Muon system upgrade scope for HL-LHC:

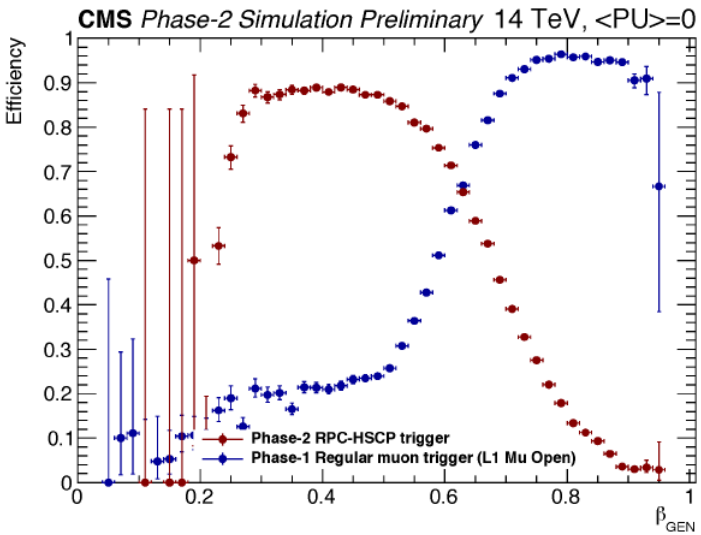
- Existing detectors:
  - upgrade barrel DT and endcap CSC electronics for 40MHz readout
- Extend forward coverage:
  - GEM & RPC detectors: 1.6<η<2.4
  - ME0 (for trigger): 2.4< η<2.9



Improved performance with HL-LHC upgrade:

- Higher efficiency: minimal dependency on pile-up
- Lower rate: better measurement → purer sample
- Improved timing resolution w/ eletronics upgrade
  - 12.5 ns → 1ns in DT
- Extended forward trigger coverage: |η|<2.4 → |η|< 2.8
- Benefits from the L1 track trigger for prompt muons

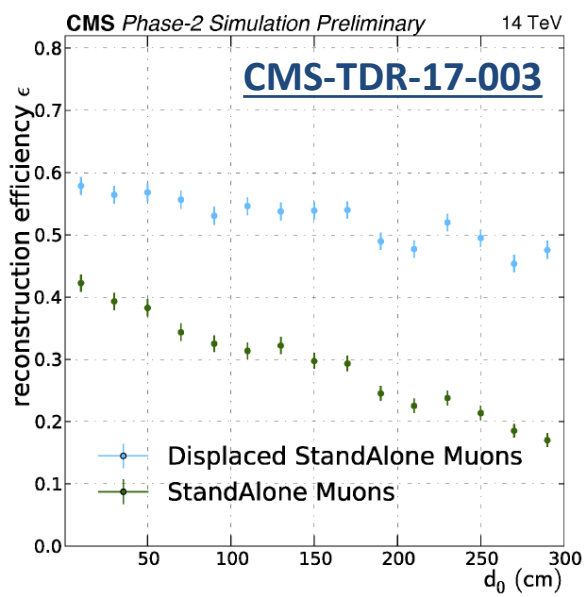
Muon Upgrade: LLP Prospects

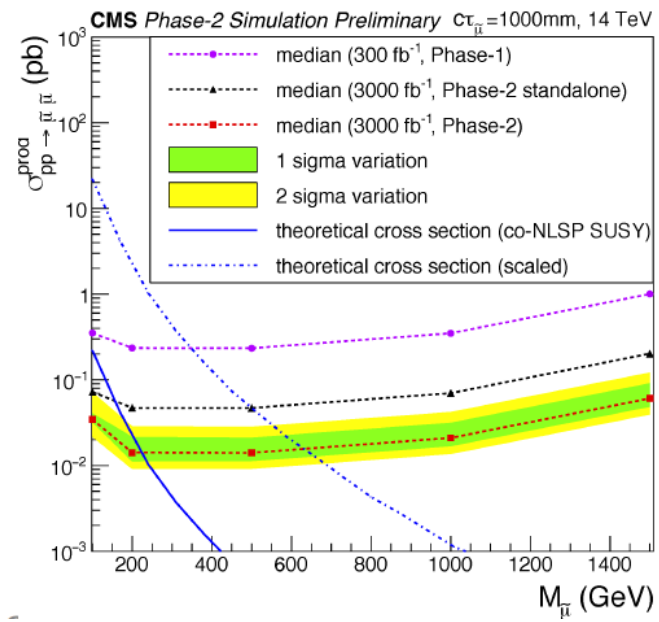


HSCP: heavy, slow-moving, highly-ionizing → muon system

- **RPC upgrade**: ~1.5ns TOF resolution to each RPC station → **RPC-HSCP trigger**: linear fit to time vs distance from IP
- Improve mass resolution:
  - Ph2 trigger level comparable to Ph1 offline level
- Ability to trigger on, at the correct BX, HSCP with velocity as low as β~0.25
  - Increase reconstruction efficiency for low β

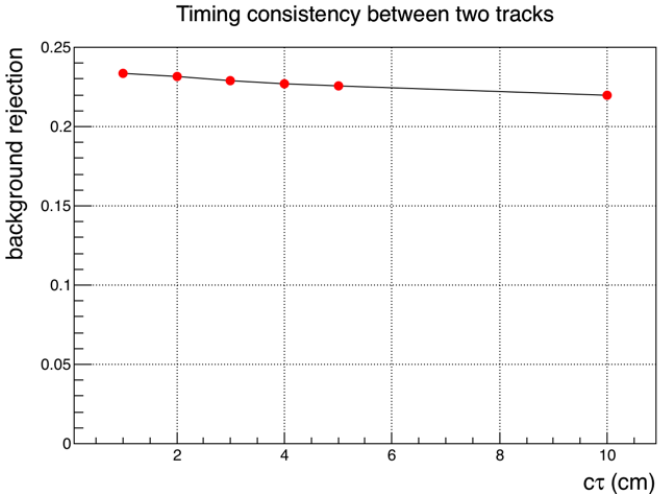
Dedicated "**Standalone displaced muon**" reconstruction algorithm w/ HL-LHC upgrade, using on hits in muon system w/o constraints wrt IP:
Improve reconstruction eff. & sensitivity (GMSB smuon projection) compared w/ "Standalone muon"



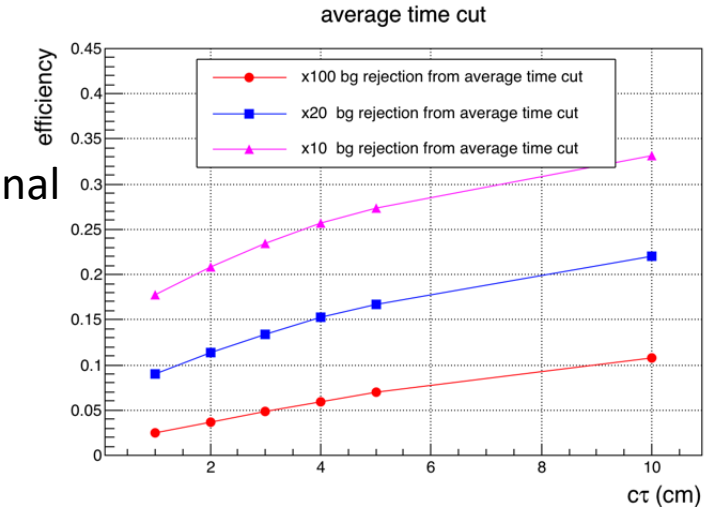


Trigger for displaced (soft) dimuon

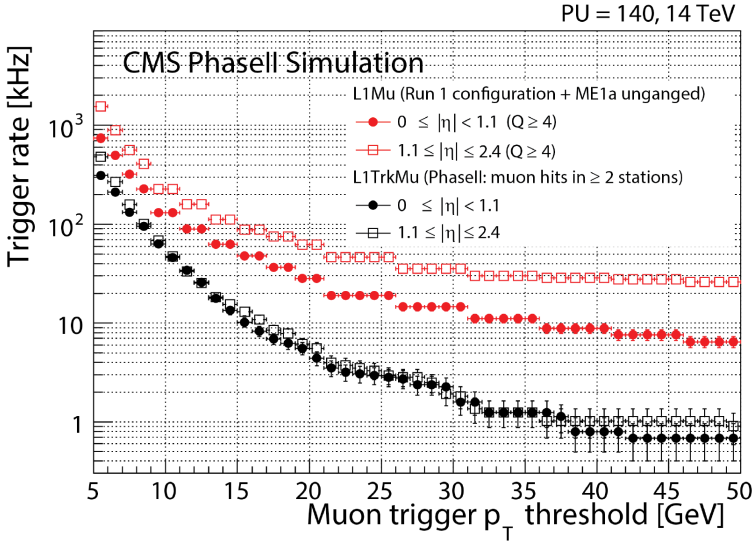
L1 stubs + MTD timing



signal



L1 stubs + muon matching

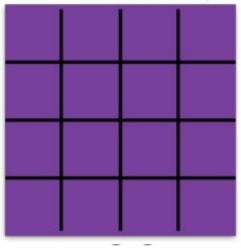


- ~A factor of 10 rate reduction by matching L1stubs to muon hits
- Current L1 displaced muon trigger uses L1Trk veto: suited for large displacement
- Can we match muon hits to displaced tracks at L1 to trigger on muons w/ small displacement?

LLP w/ Fast Timing: Trigger Potential

- On-chip filtering: read out delayed hits only
  - need 20x-100x suppression for acceptable rate: what's the threshold?

mtd chip



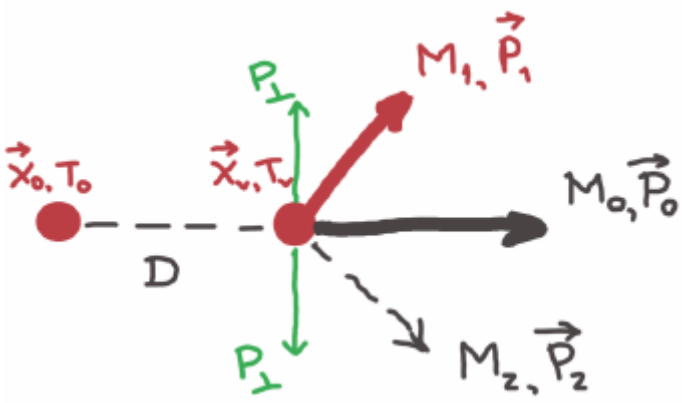
(4cmx4cm)

# of Coincidences	Threshold for 20x suppression	Threshold for 100x suppression
1	350ps	440ps
2	185ps	290ps
3	115ps	200ps

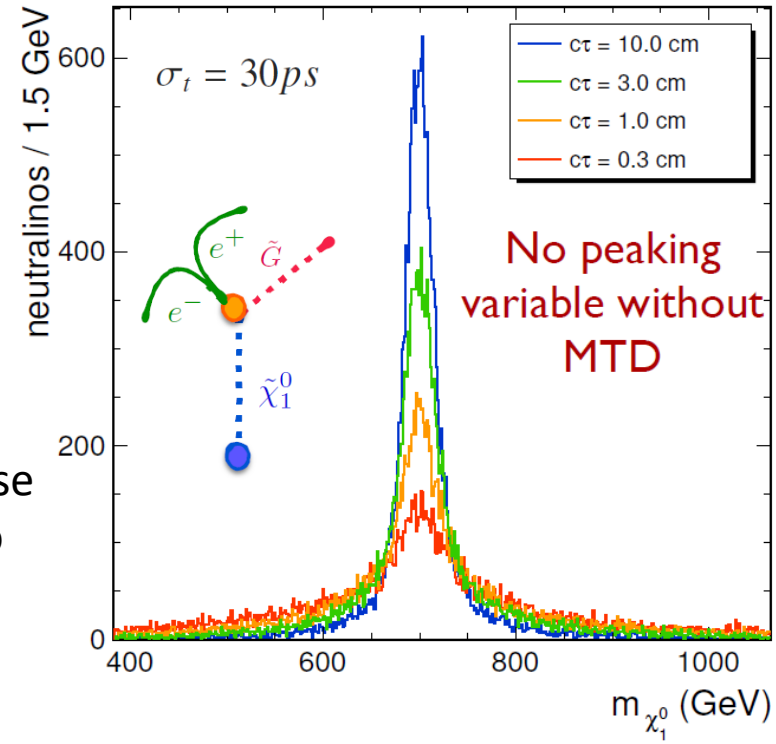
(Delphes simulatin of QCD sample; tracks w/ pT>2GeV)

- Calo-based ROI: trigger for delayed jets
  - improve trigger efficiency for signal by lowering pT threshold
  - compute time delay threshold for sufficient bkgd reduction
    - calo-trigger seed, use mean timestamp of hits in jet cone (dR<0.4)
    - 20x suppression @180ps; 100x suppression @250ps
      - Background: Delphes simulation of QCD sample, jpT>30GeV
      - 250ps timing cut retains Higgsino signal efficiency of O(10%)
  - precision timing particularly useful for light LLPs

Fast Timing: LLP Mass Resonance

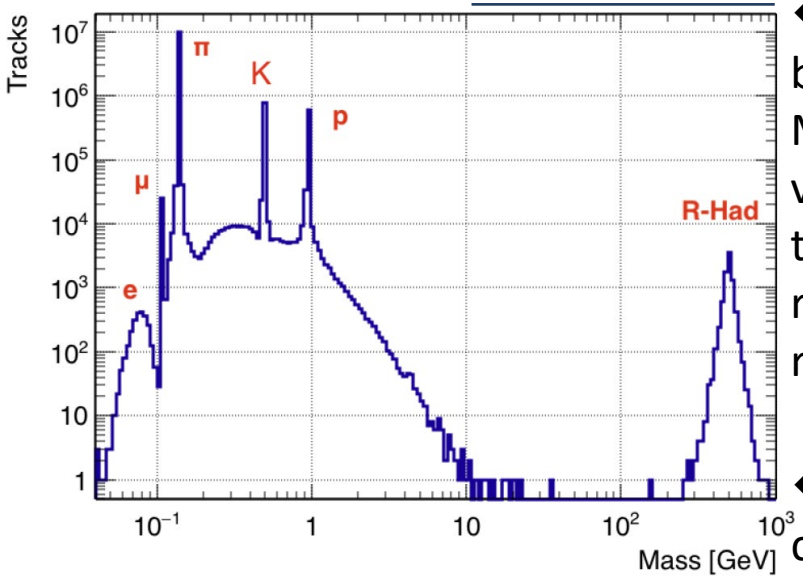


With displacement & additional timing info, LLP decay (visible and invisible particles) has unique solution
→Reconstruct peaking variable (mass or mass splitting)



TOF Particle ID

arXiv:1807.05453



← Use TOF between PV and MTD to compute velocity β, then use track trajectory to reconstruct mass resonance

← Achieve 5-10 times better sensitivity than current HSCP search at CMS!