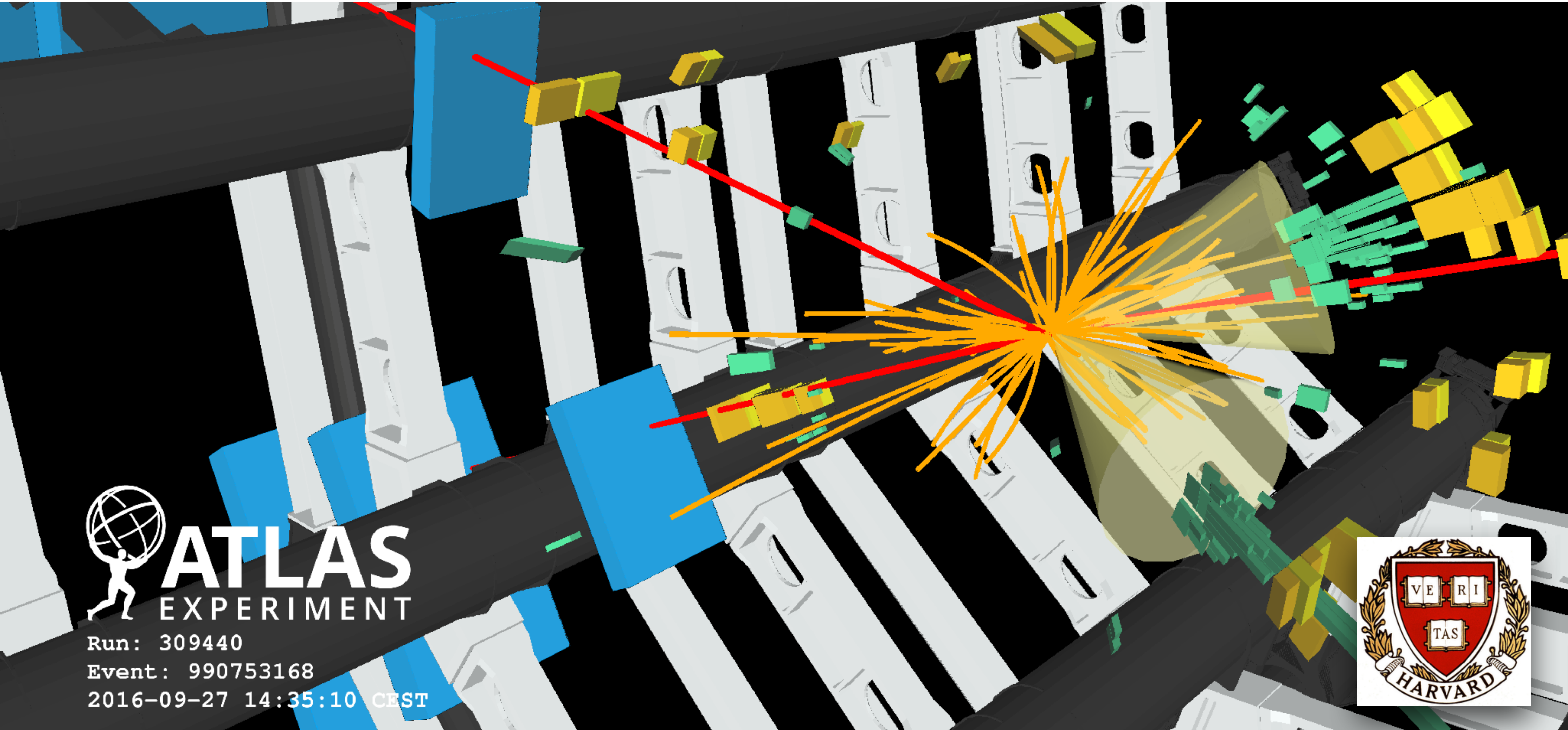
Stefano Zambito, Harvard University

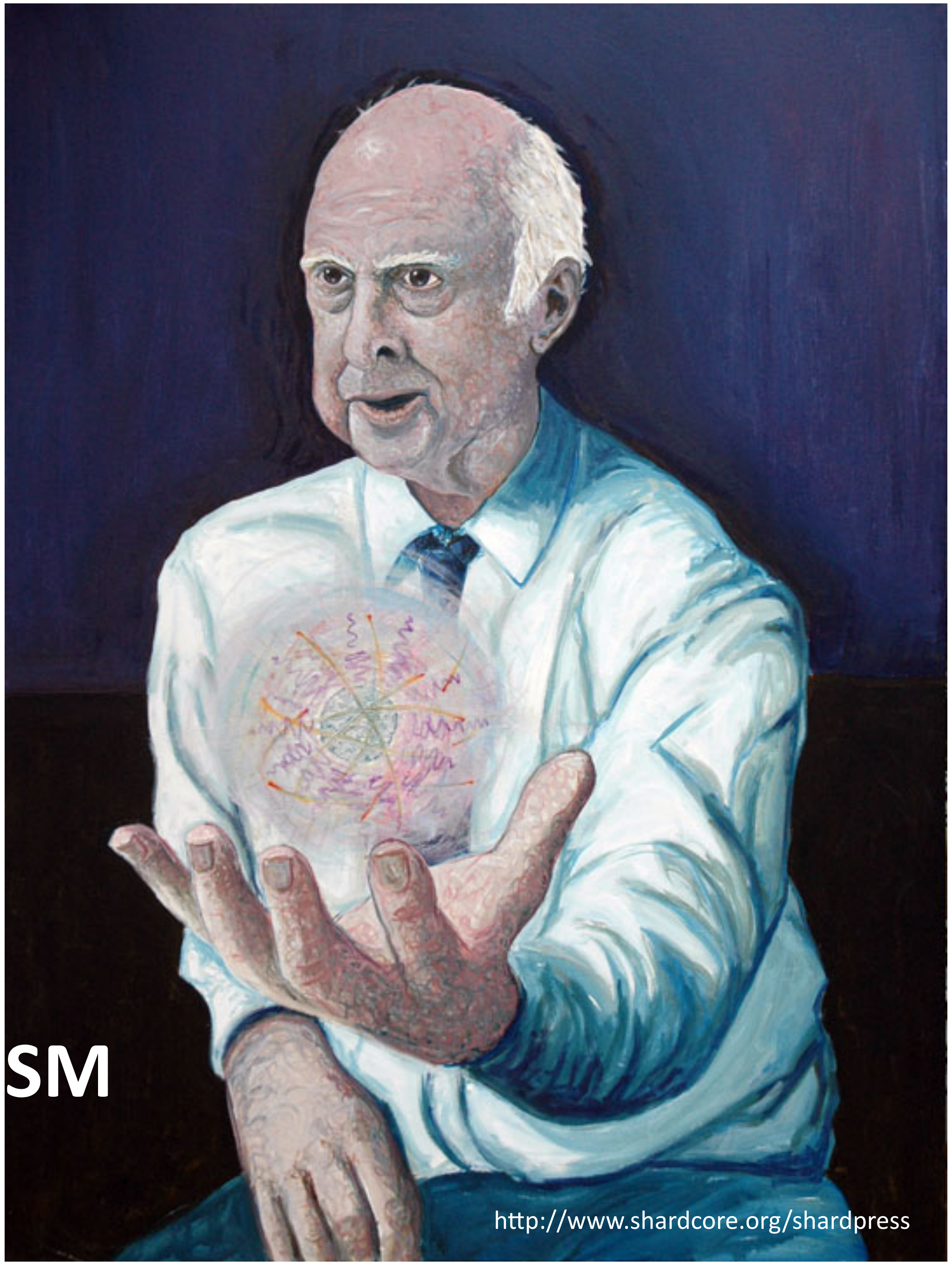
Hunting for Supersymmetry at the LHC

A Dive Into Naturalness… And Beyond?



The Standard Model, After The Higgs Discovery

$SU(3) \otimes SU(2)_L \otimes U(1)$



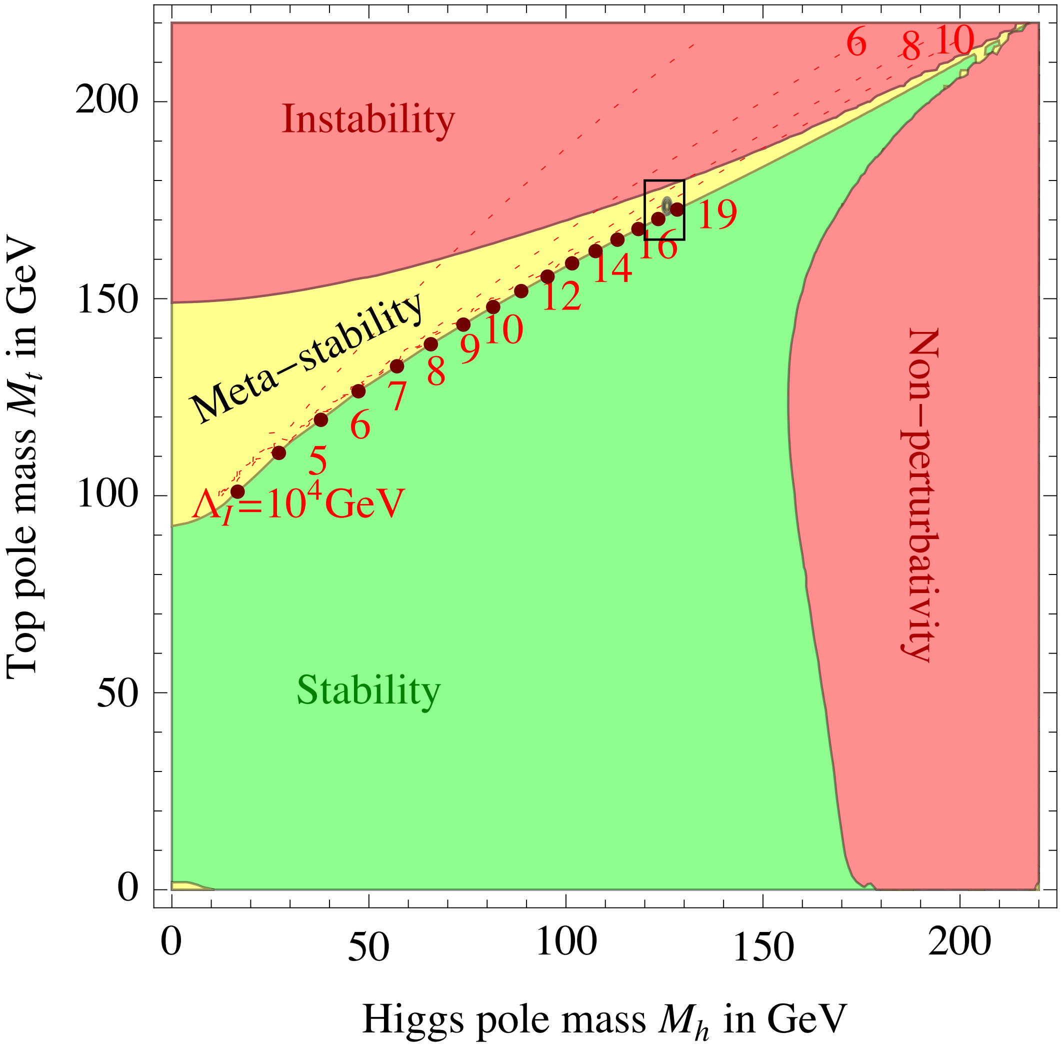
http://www.shardcore.org/shardpress

The Standard Model, After The Higgs Discovery

SM phase diagram

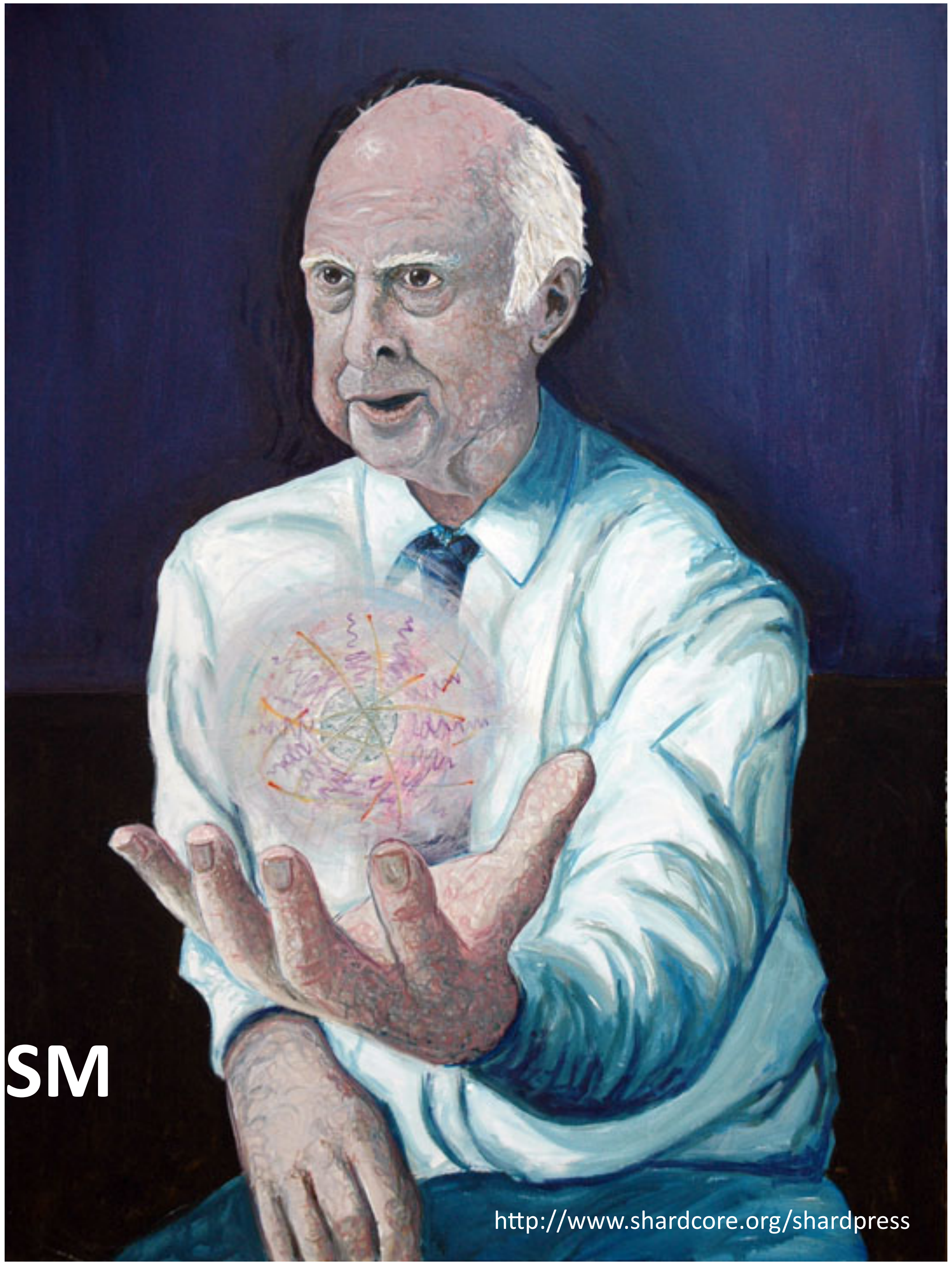
Vacuum stability excluded at ≈3σ

G. F. Giudice *et al* (arXiv:1307.3536v4)



Higgs near criticality:
hint of need for new physics?

SU(3) ⊗ SU(2)$_L$ ⊗ U(1)



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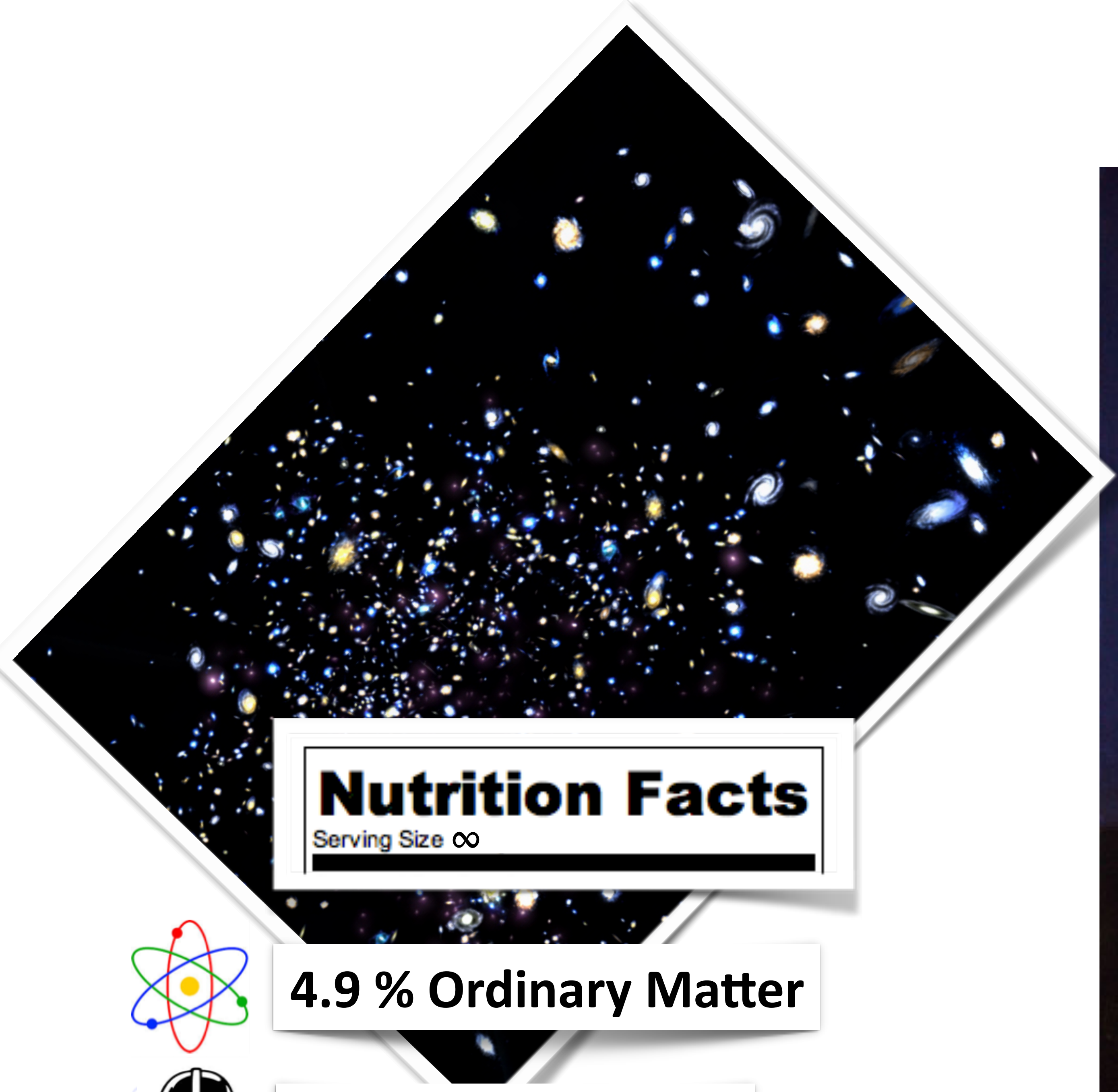
The Standard Model, After The Higgs Discovery



Nutrition Facts

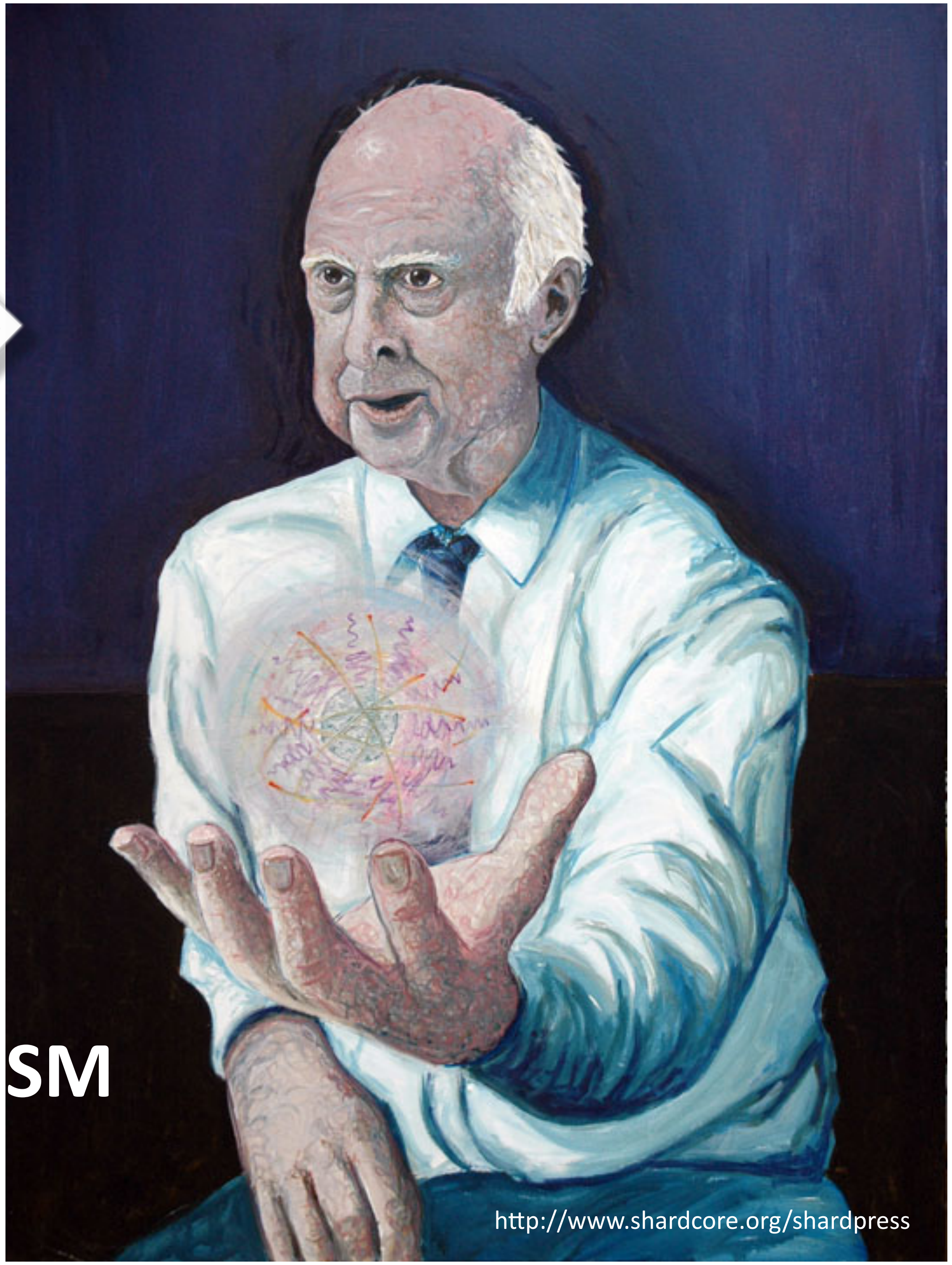
Serving Size ∞

4.9 % Ordinary Matter

26.8 % Dark Matter

68.3 % Dark Energy

$SU(3) \otimes SU(2)_L \otimes U(1)$



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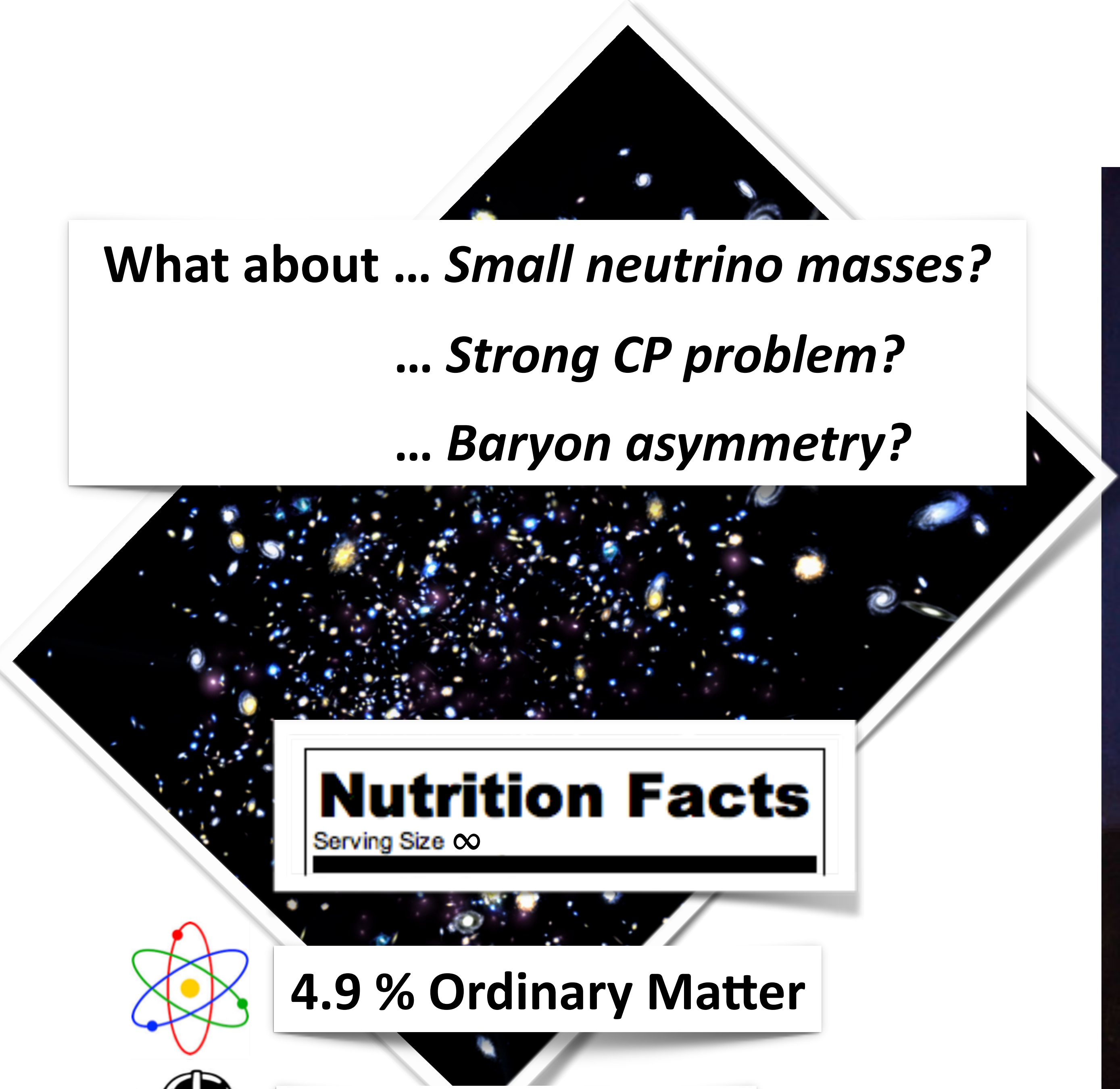
The Standard Model, After The Higgs Discovery



What about … *Small neutrino masses?*

… Strong CP problem?

… Baryon asymmetry?

Nutrition Facts

Serving Size ∞

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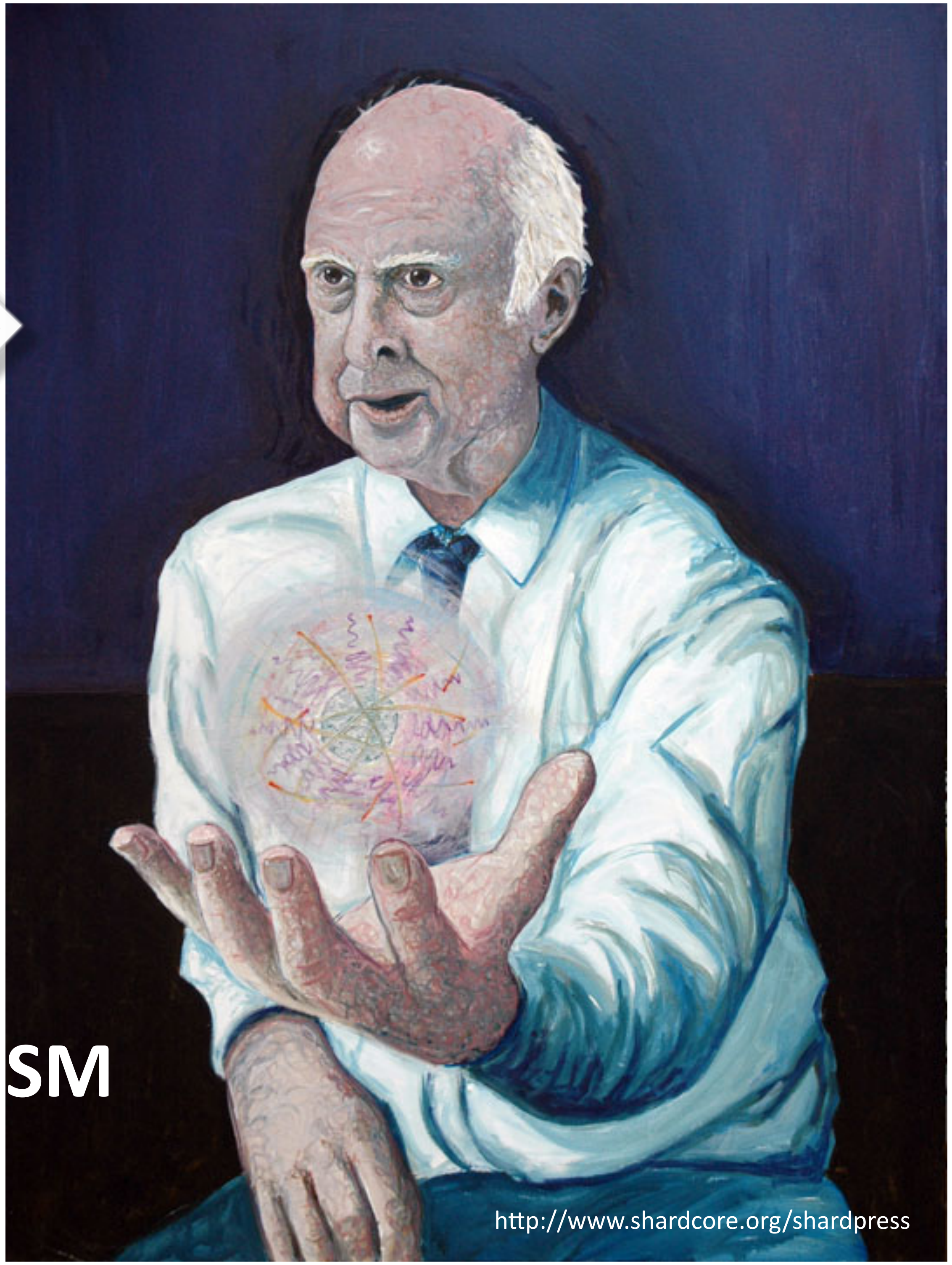
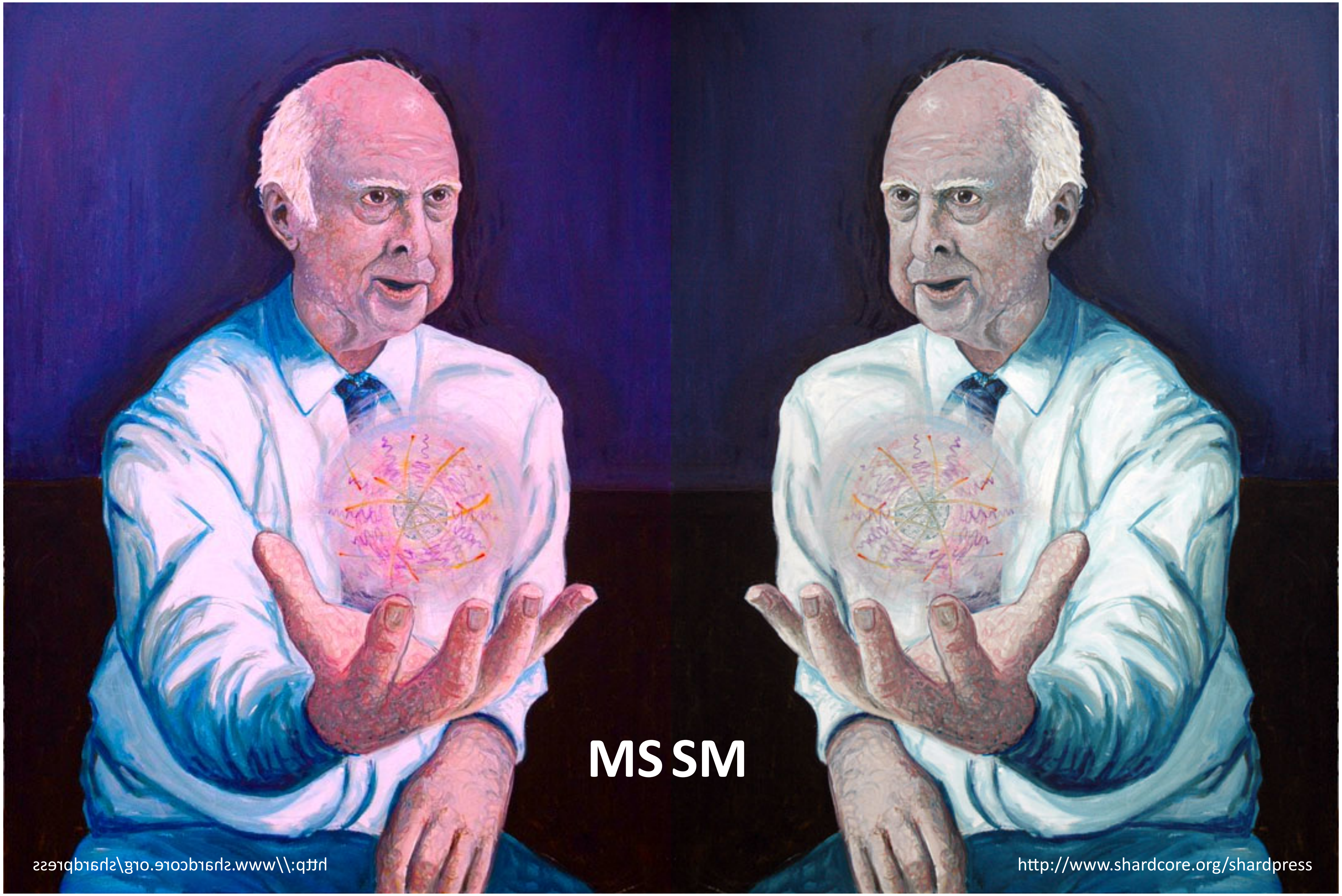


http://www.shardcore.org/shardpress

The Standard Model, After The Higgs Discovery

Additional symmetry?

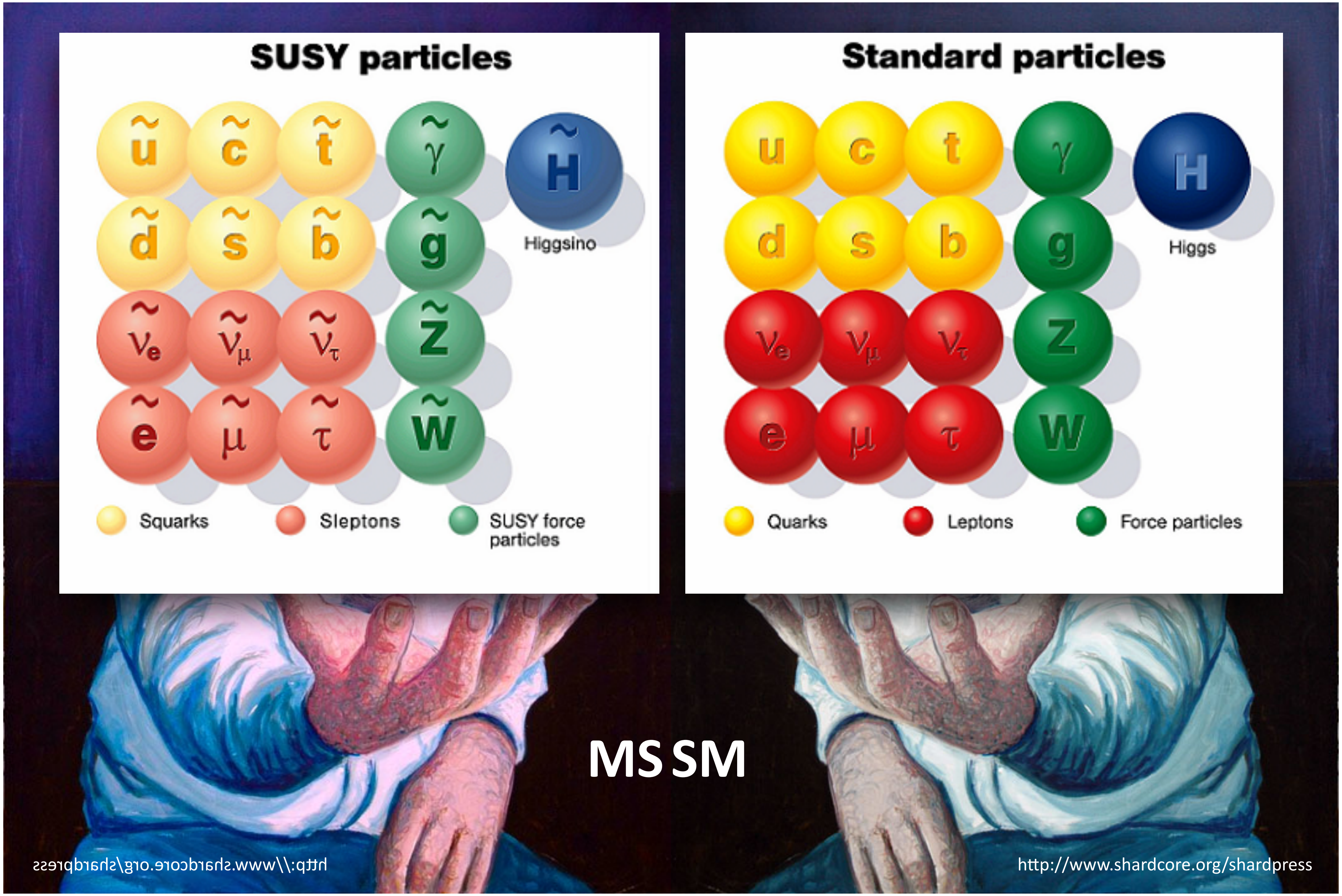
$SU(3) \otimes SU(2)_L \otimes U(1)$



Supersymmetry

Additional symmetry?

$SU(3) \otimes SU(2)_L \otimes U(1)$

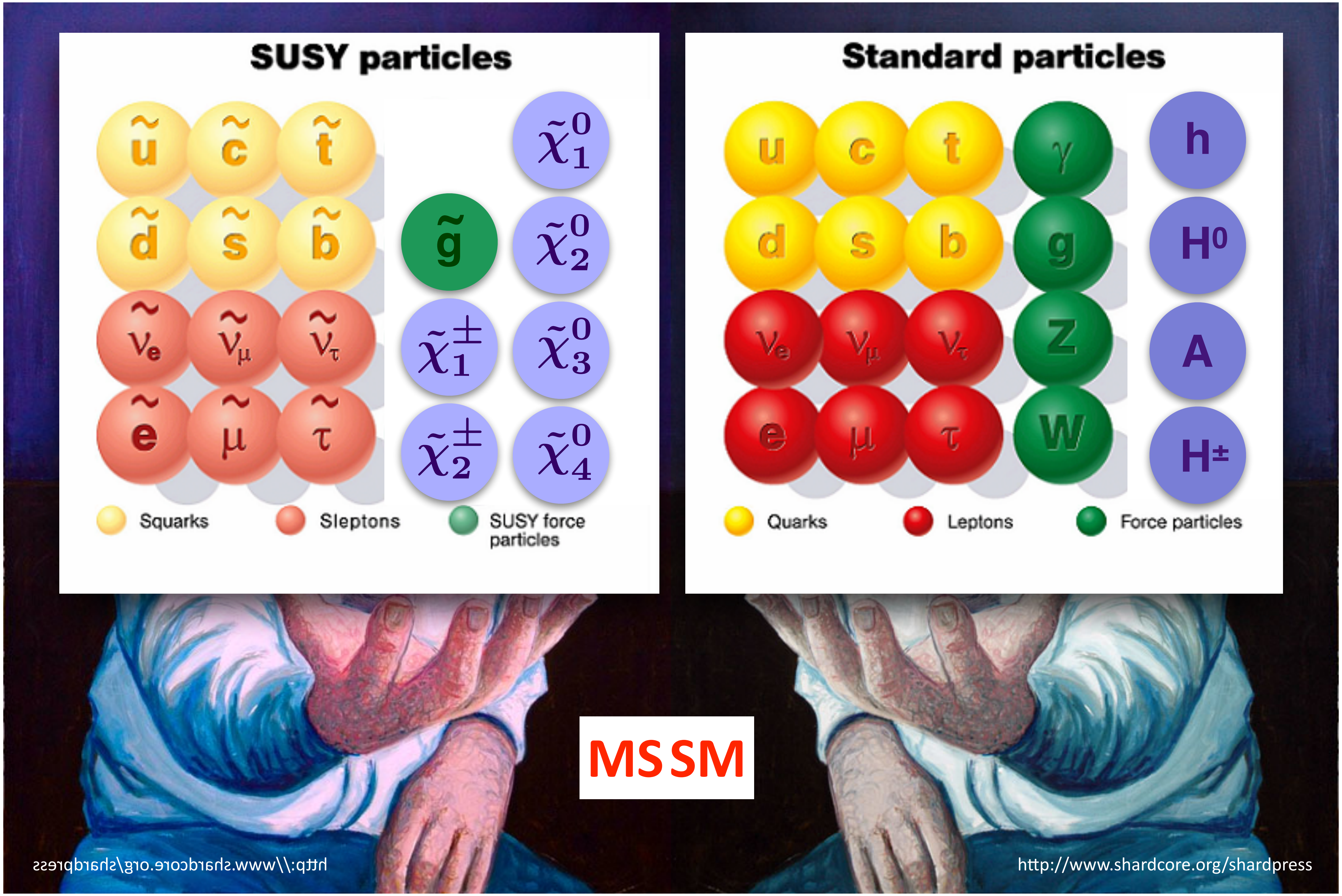


http://www.shardcore.org/shardpress

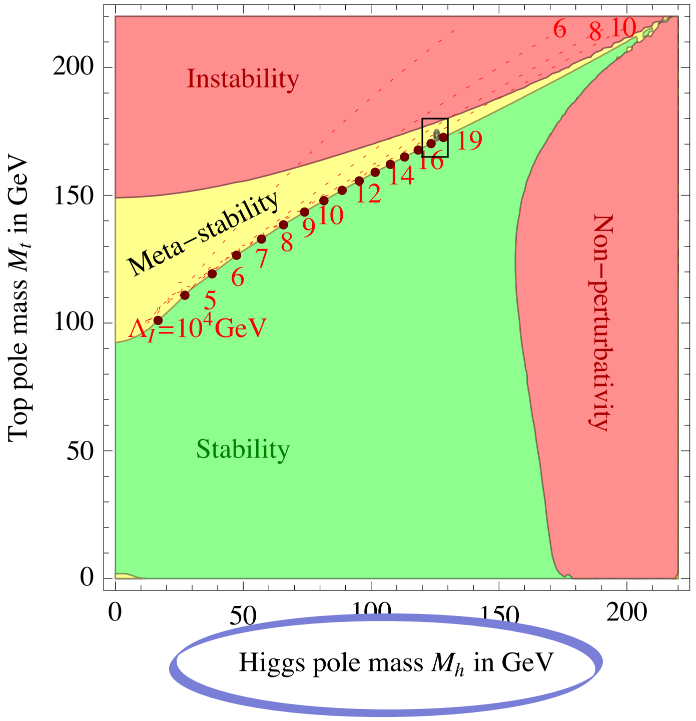
Supersymmetry

Additional symmetry?

$SU(3) \otimes SU(2)_L \otimes U(1)$



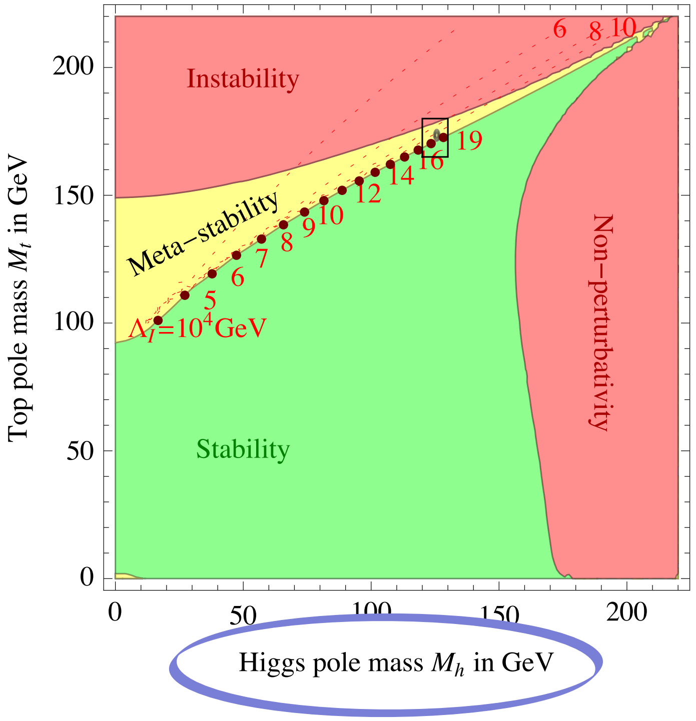
Fine Tuning Vs Naturalness



physical m_h: 125 GeV

$$\boxed{m_h^2} \approx \underbrace{m_{h\,0}^2}_{\text{bare mass}} - \underbrace{\frac{\lambda_f^2}{8\pi^2} N_c^f \int^{\Lambda} \frac{d^4p}{p^2}}_{\text{1-loop correction}} + \ldots \approx m_{h\,0}^2 + \frac{\lambda_f^2}{8\pi^2} N_c^f \underbrace{\Lambda^2}_{\text{ultraviolet cutoff}} + \ldots$$

Fine Tuning Vs Naturalness



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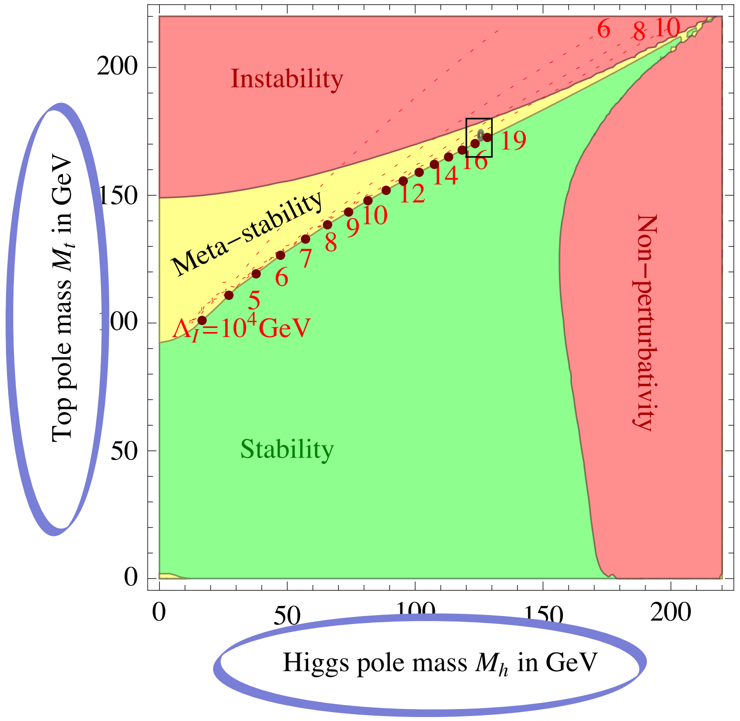
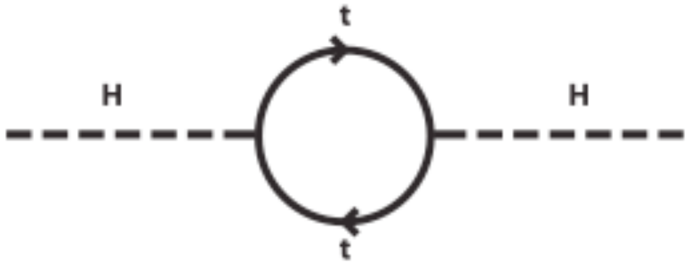
***Fine tuning**: if Λ ≈ plank mass, need cancellation between bare mass and corrections across <u>many</u> orders of magnitude to get 125 GeV!*

Fine Tuning Vs Naturalness





main “SM” term:
top’s loop ($\lambda_t \approx 1$)

physical m_h: 125 GeV

$$\boxed{m_h^2} \approx \underbrace{m_{h\,0}^2}_{\text{bare mass}} \underbrace{- \frac{\lambda_f^2}{8\pi^2} N_c^f \int^\Lambda \frac{d^4p}{p^2}}_{\text{1-loop correction}} + \ldots \approx m_{h\,0}^2 + \overbrace{\frac{\lambda_f^2}{8\pi^2} N_c^f \underbrace{\Lambda^2}_{\text{ultraviolet cutoff}}} + \ldots$$

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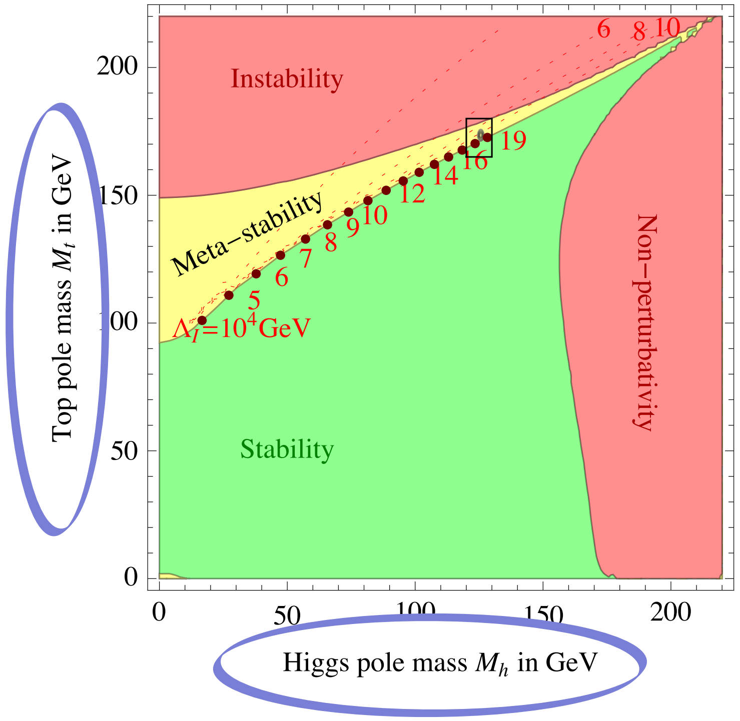
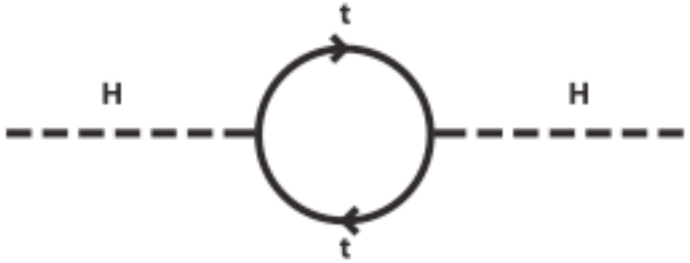
Fine Tuning Vs Naturalness



Hierarchy problem: SUSY's solution

stop's loop
(opposite sign)

+



main "SM" term:
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$$m_h^2 \approx \underbrace{m_{h\,0}^2}_{\text{bare mass}} - \underbrace{\frac{\lambda_f^2}{8\pi^2} N_c^f \int^{\Lambda} \frac{d^4p}{p^2}}_{\text{1-loop correction}} + \ldots \approx m_{h\,0}^2 + \overbrace{\frac{\lambda_f^2}{8\pi^2} N_c^f \underbrace{\Lambda^2}_{\text{ultraviolet cutoff}}} + \ldots$$

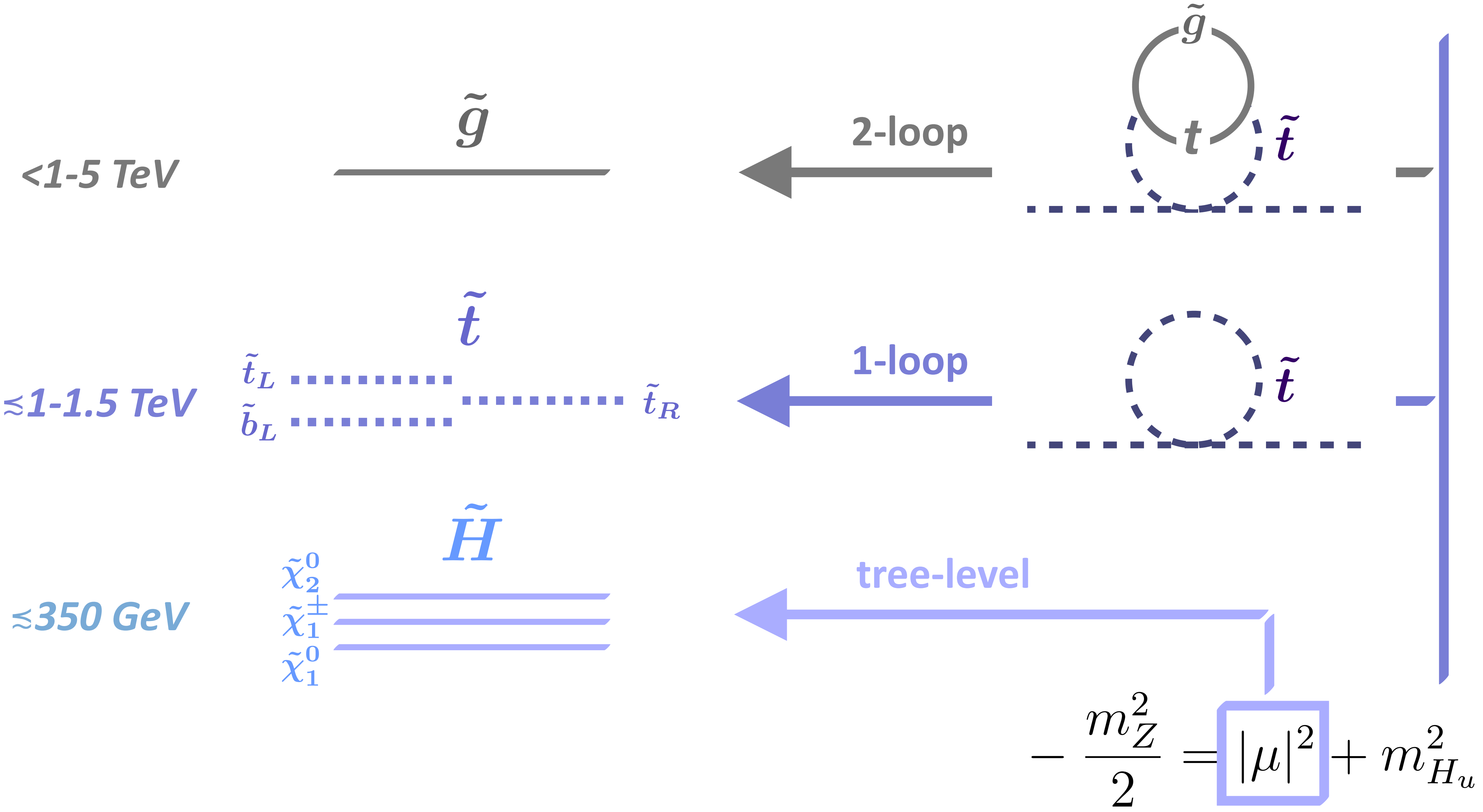
natural
cancellation (*)

~~***Fine tuning**: if Λ ~ plank mass …*~~

(*) provided a light stop!

Natural SUSY Spectrum

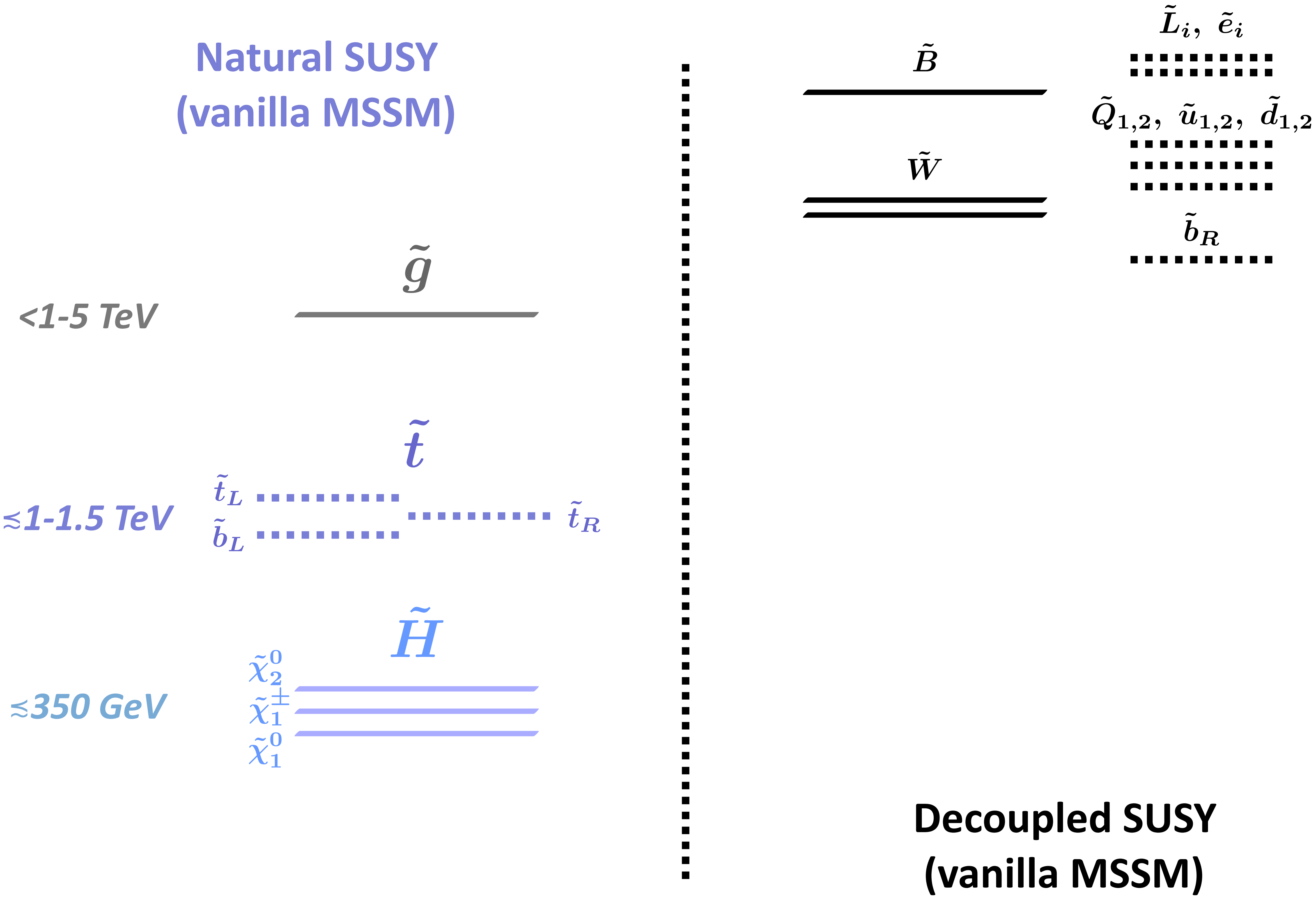
**Natural SUSY
(vanilla MSSM)**



$$-\frac{m_Z^2}{2} = \boxed{|\mu|^2} + m_{H_u}^2$$

arXiv:1110.6926v1

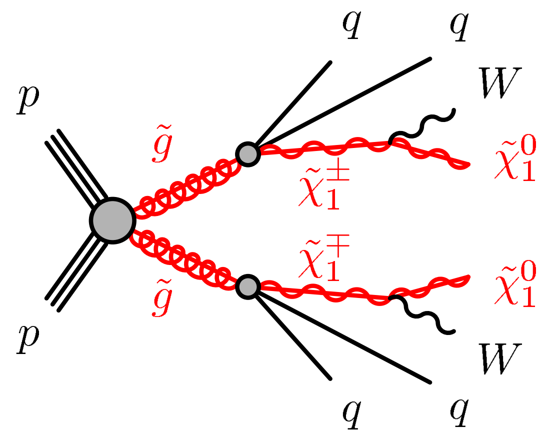
Natural SUSY Spectrum



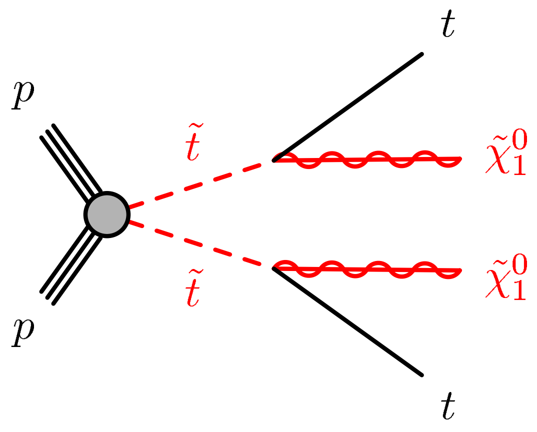
arXiv:1110.6926v1

SUSY After √s=7 & 8 TeV LHC

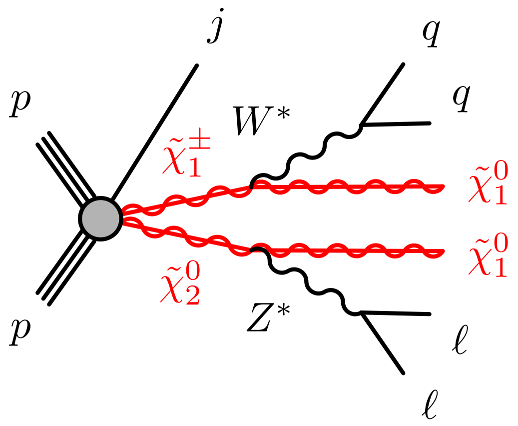
gluinos



scalar top



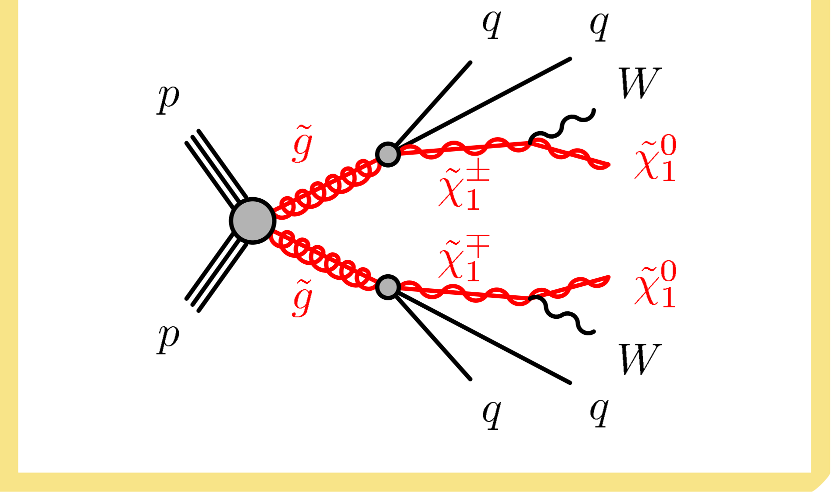
higgsinos



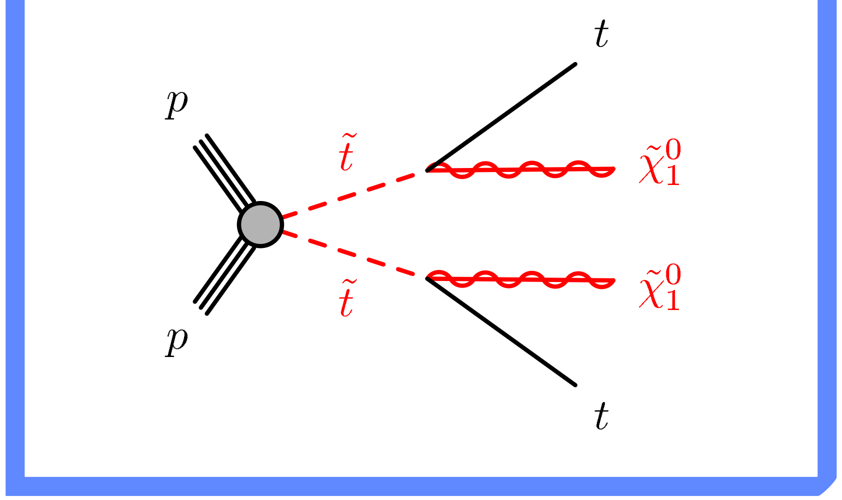
Simplified models **to cope with complex, model-dependent phenomenology**

SUSY After √s=7 & 8 TeV LHC

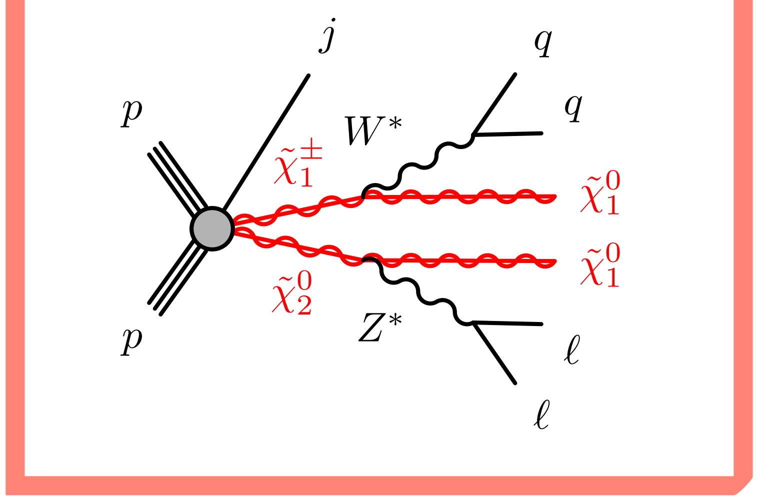
gluinos



scalar top



higgsinos

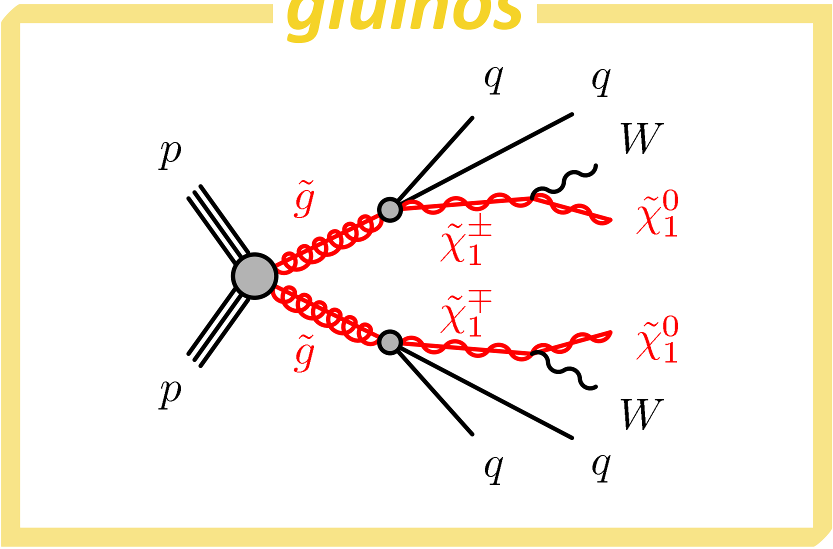


Simplified models **to cope with complex, model-dependent phenomenology**

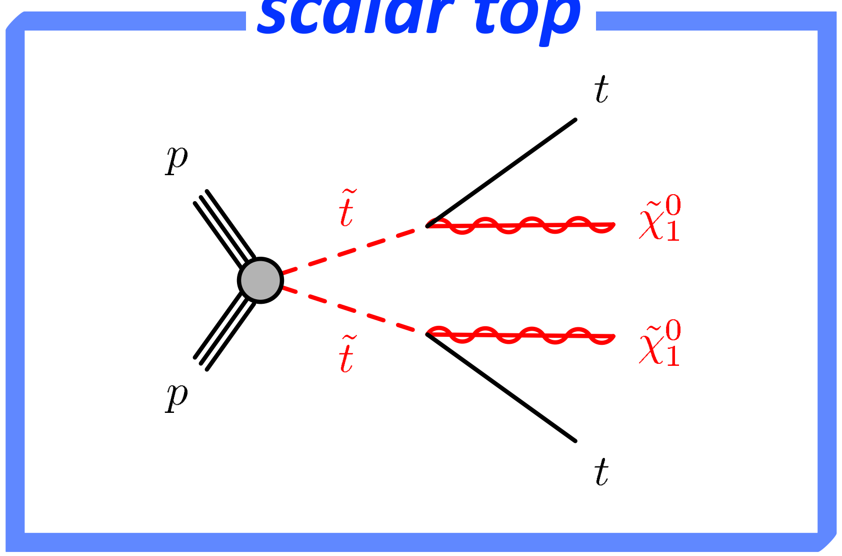
branching ratios in decay vertices **set to 100%** (except for SM particles)

SUSY After √s=7 & 8 TeV LHC

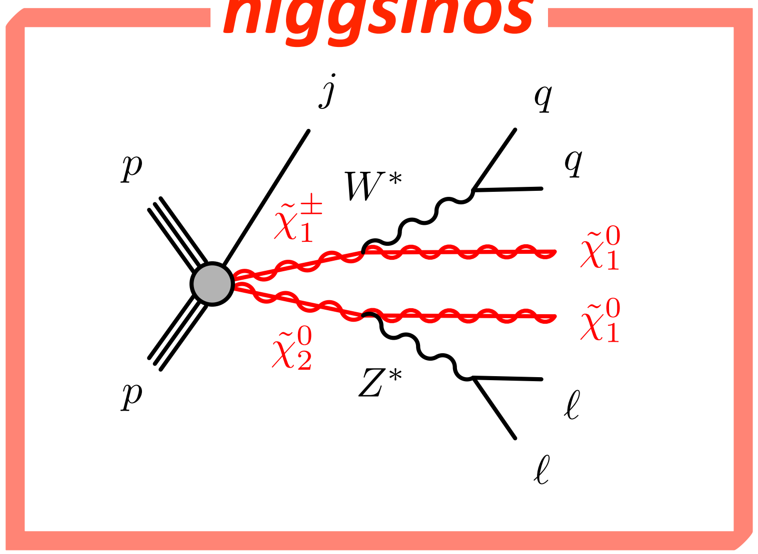
gluinos



scalar top



higgsinos



Simplified models **to cope with complex, model-dependent phenomenology**

branching ratios in decay vertices **set to 100%** (except for SM particles)

"R-parity" conservation assumed: SUSY particles produced in pairs, and lightest neutralino doesn't decay: dark matter candidate!

(models with"R-parity" violation not covered in this talk)

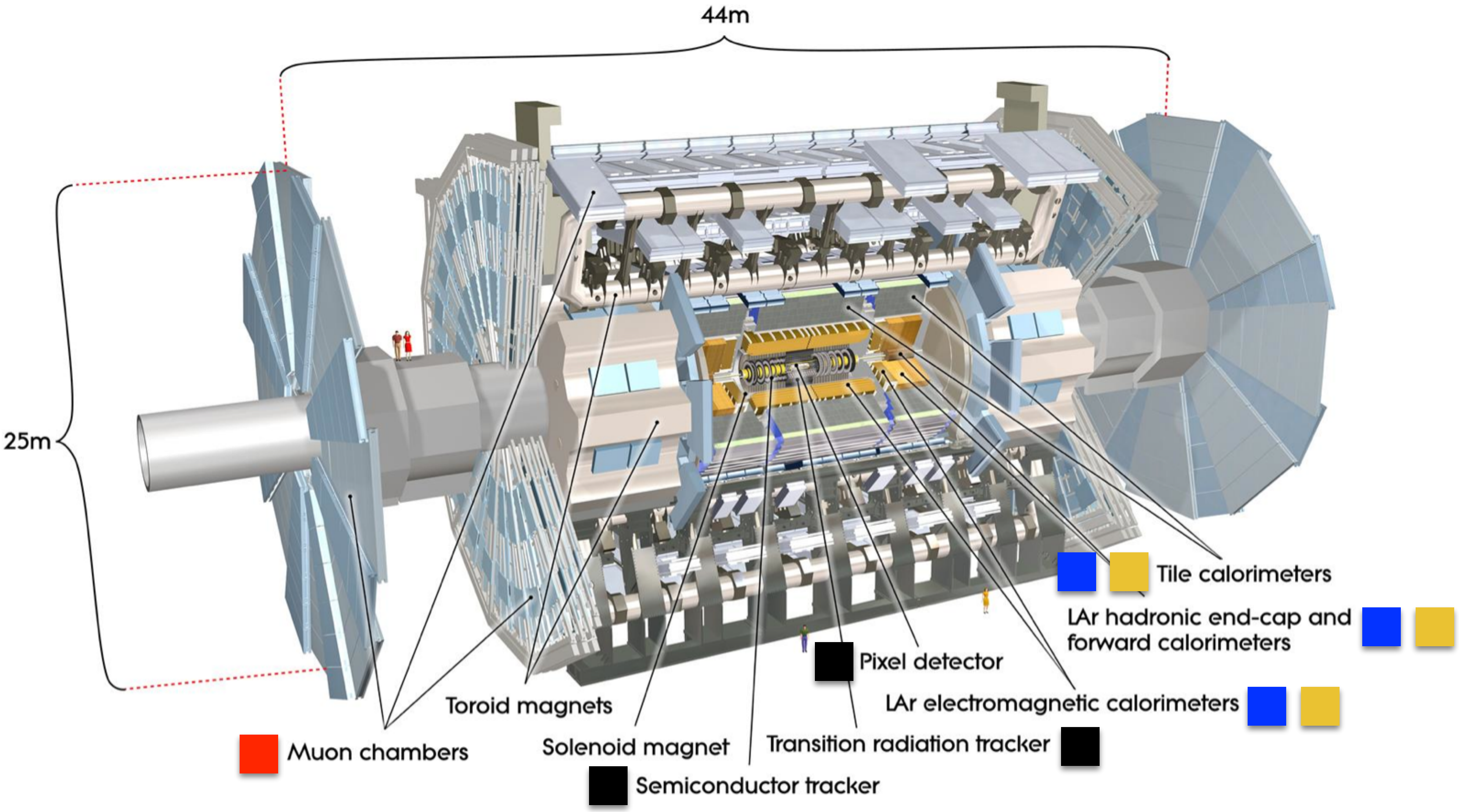
The ATLAS Detector

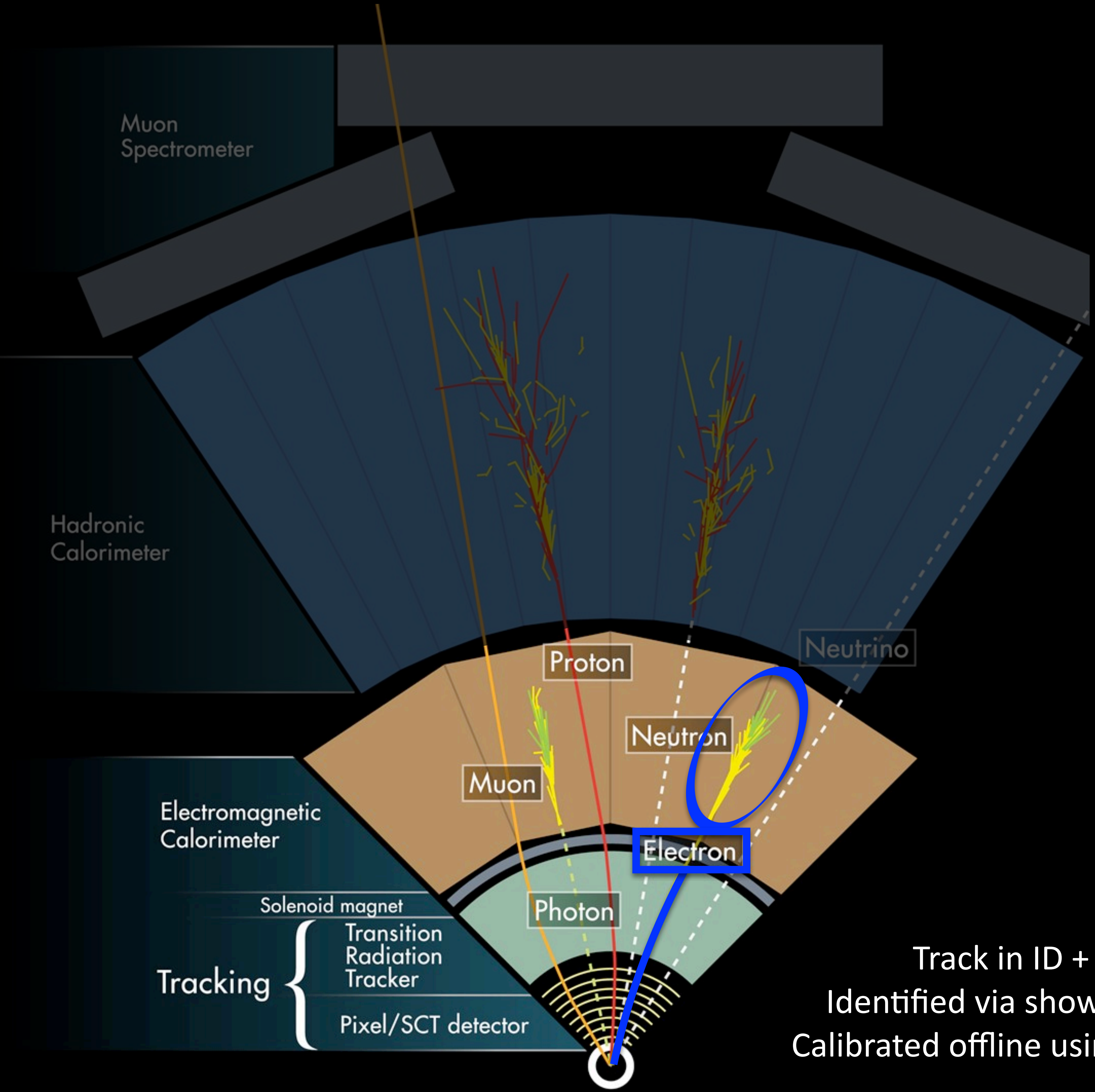
Inner detector (ID): tracks → charged particles & vertices

EM calorimeter: energy depositions → electrons and photons

Hadronic calorimeter: energy depositions → jets of hadrons

Muon spectrometer (MS): tracks → muons



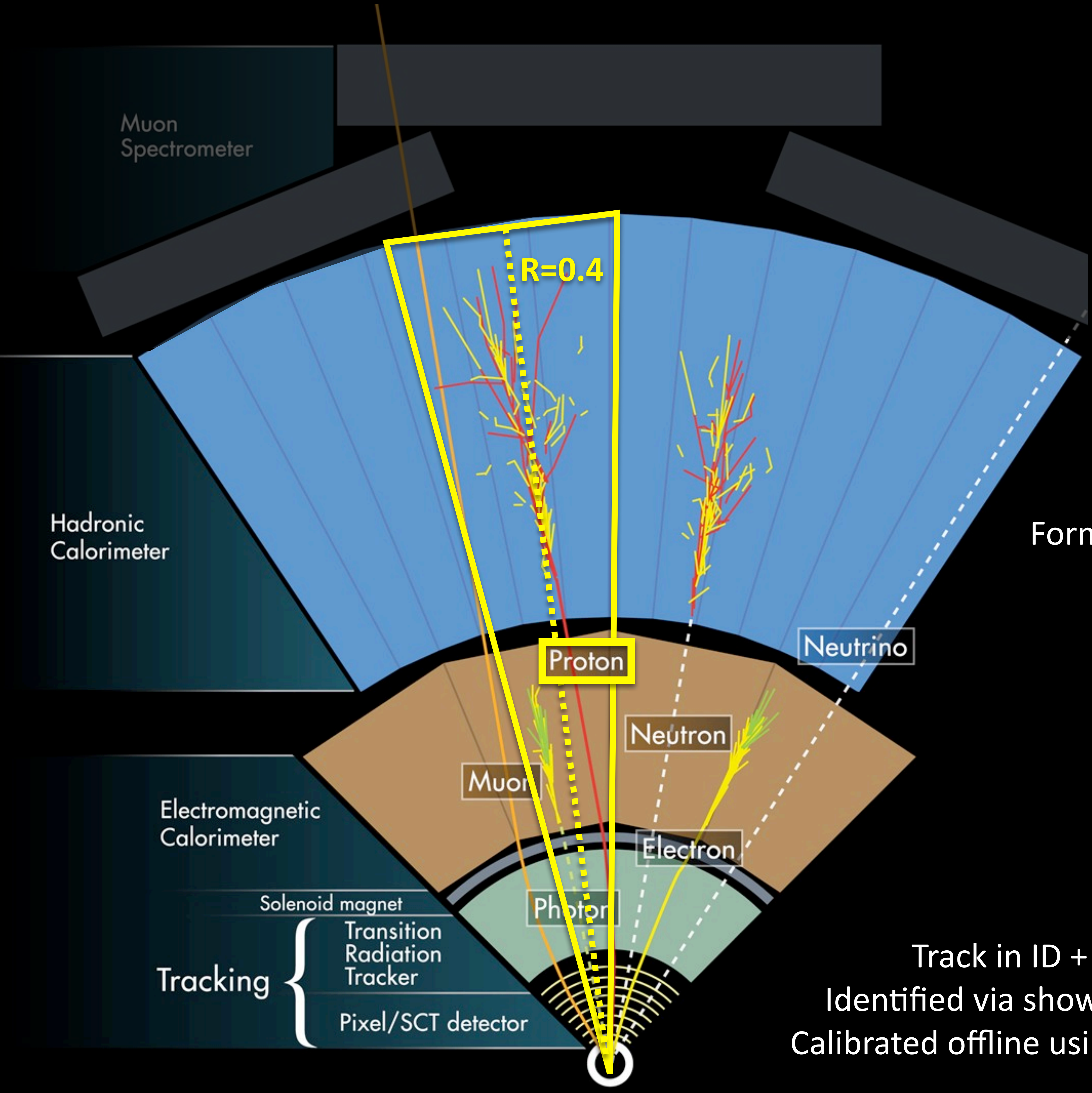


Electrons

Track in ID + E cluster in EM calorimeter

Identified via shower shape + radiation in TRT

Calibrated offline using standard candles (J/Ψ,Z)



Jets of hadrons

Formed from energy clusters in EM + HAD calorimeters

(anti-k_T R=0.4)

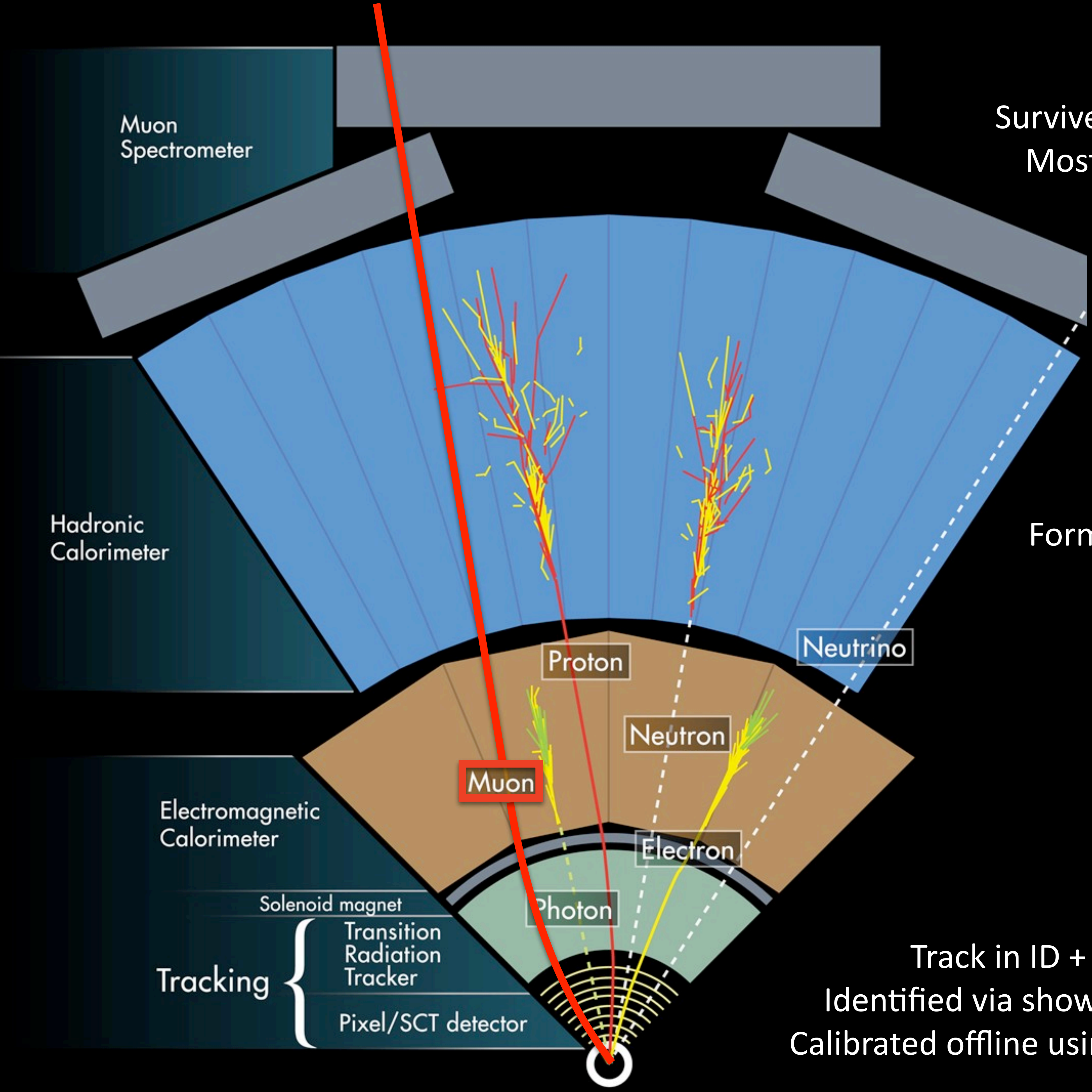
Calibrated offline

Electrons

Track in ID + E cluster in EM calorimeter

Identified via shower shape + radiation in TRT

Calibrated offline using standard candles (J/Ψ,Z)



Muons

Survive calorimeters - E_{loss}≈3 GeV
Mostly formed as ID +MS tracks
Calibrated offline (J/Ψ,Z)

Jets of hadrons

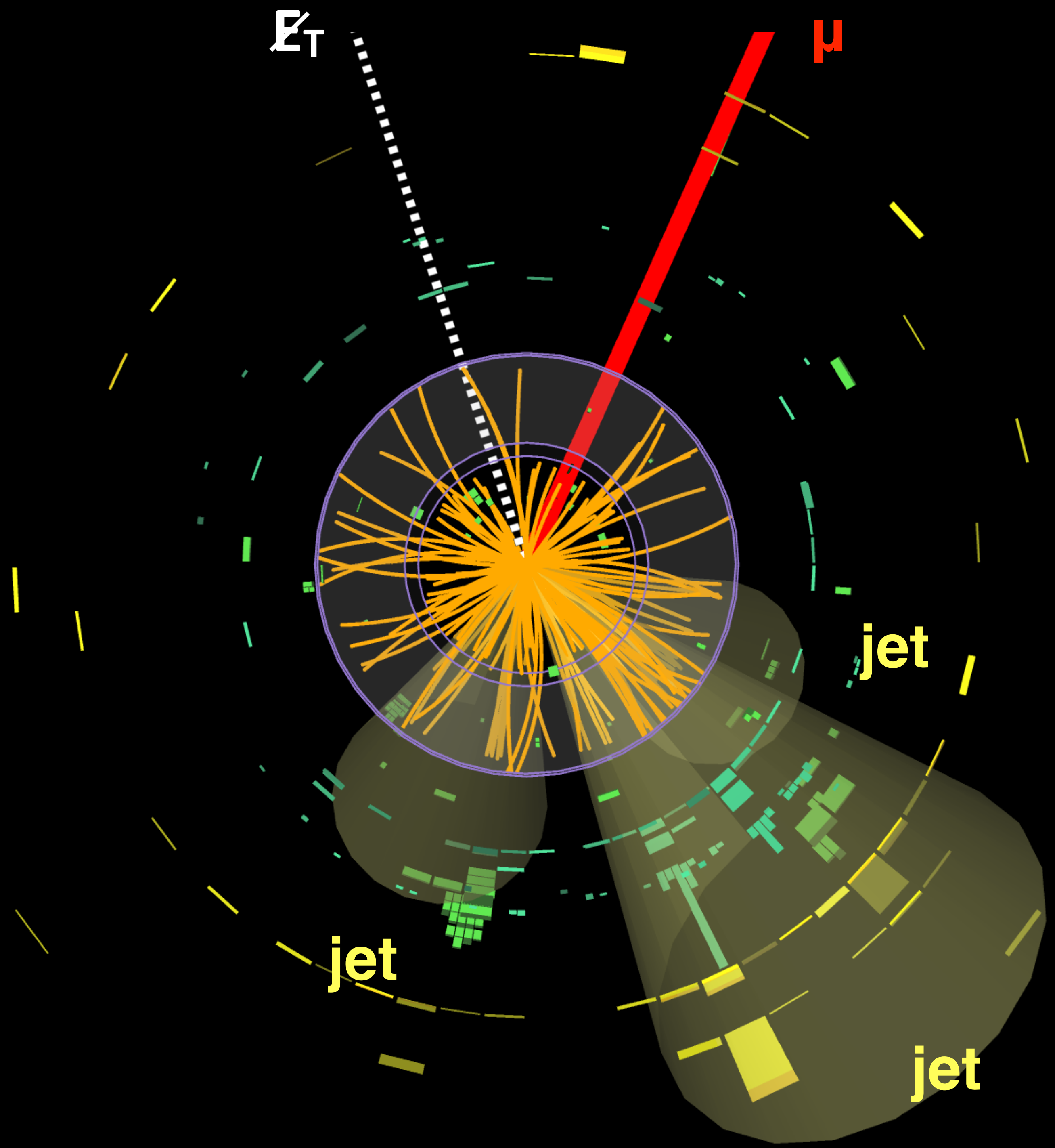
Formed from energy clusters in EM + HAD calorimeters
(anti-k_T R=0.4)
Calibrated offline

Electrons

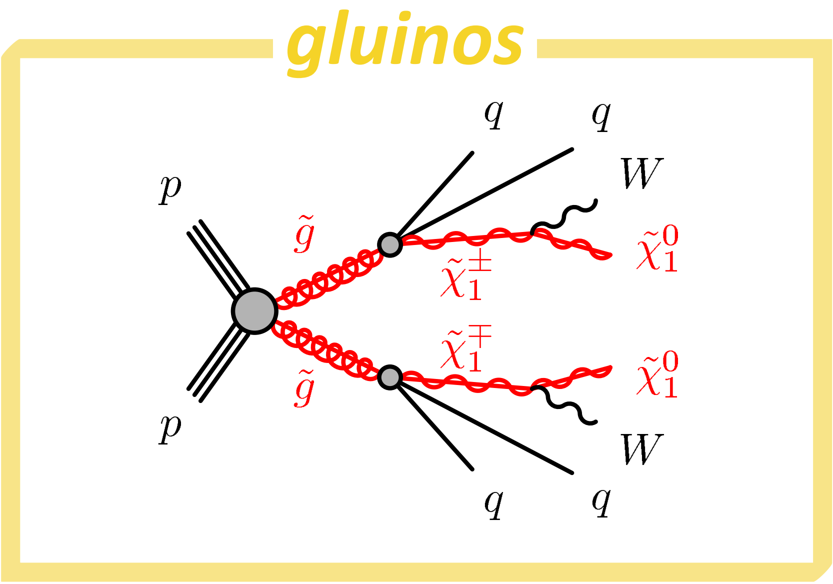
Track in ID + E cluster in EM calorimeter
Identified via shower shape + radiation in TRT
Calibrated offline using standard candles (J/Ψ,Z)

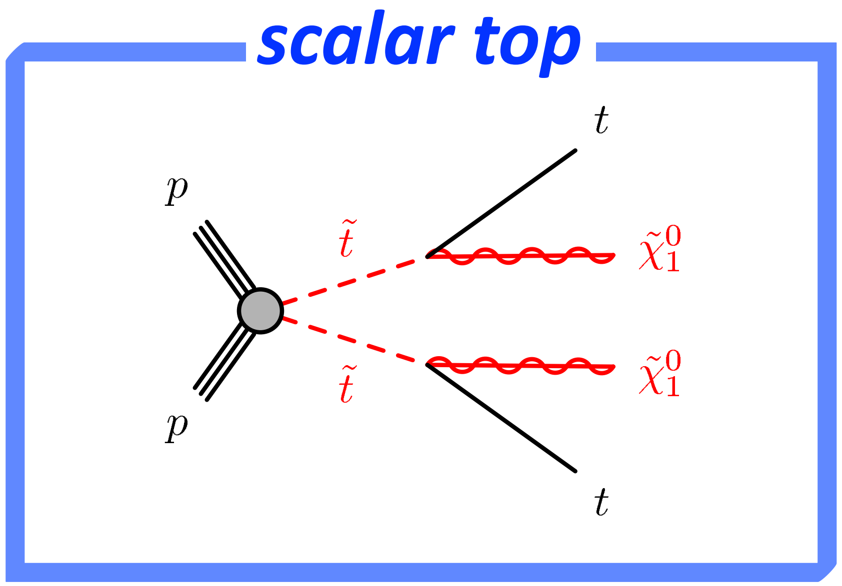
Missing transverse energy: $\not{E}_T = |\vec{p}_{T,\text{miss}}|$

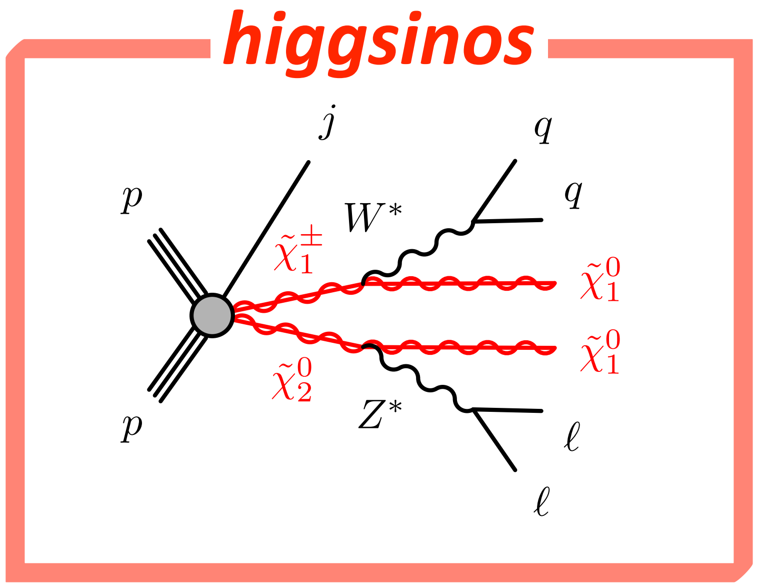
negative vector sum of transverse momenta of all reconstructed
& identified particles + all remaining tracks



SUSY After √s=7 & 8 TeV LHC



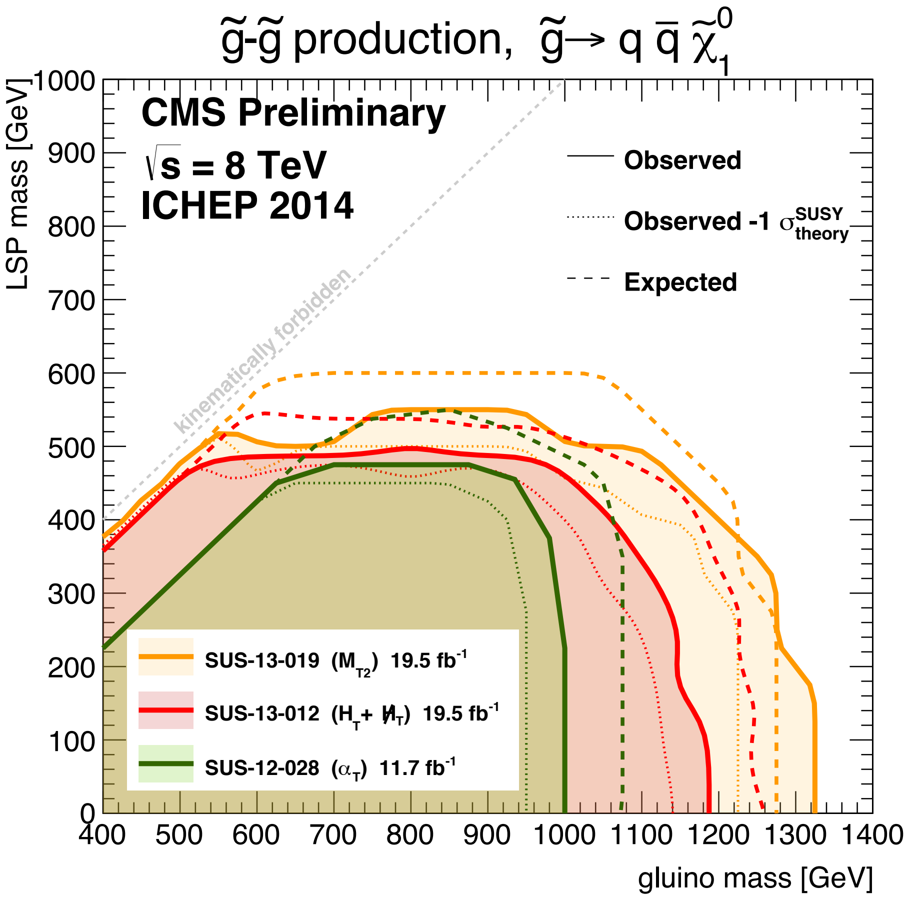


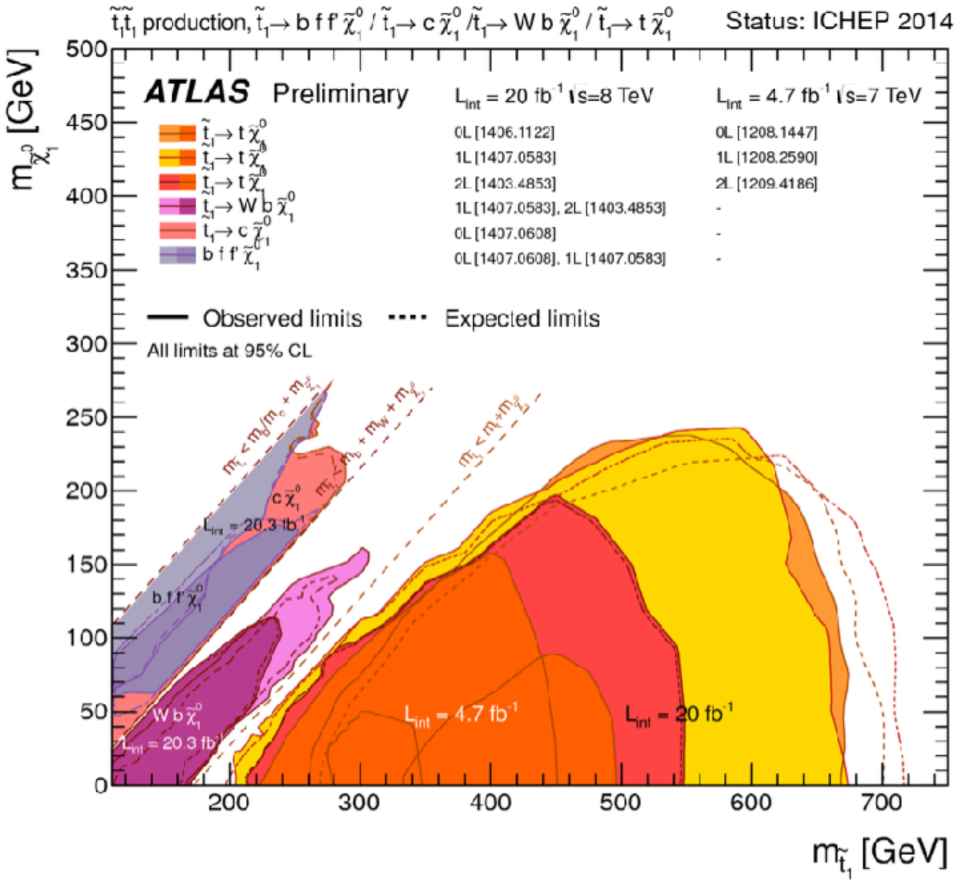


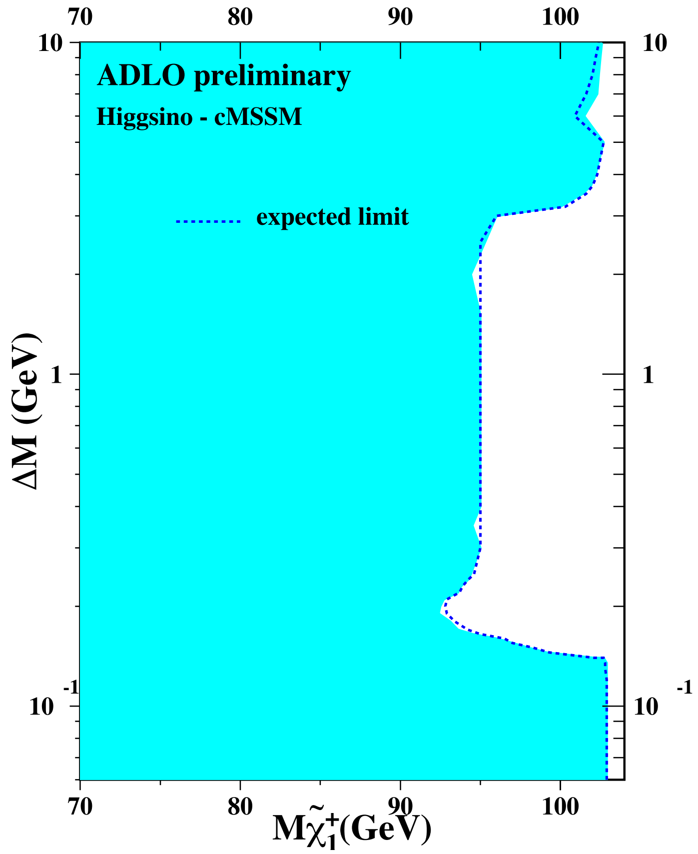
excluded m<1.3 TeV

excluded m<650 GeV

excluded m<110 GeV

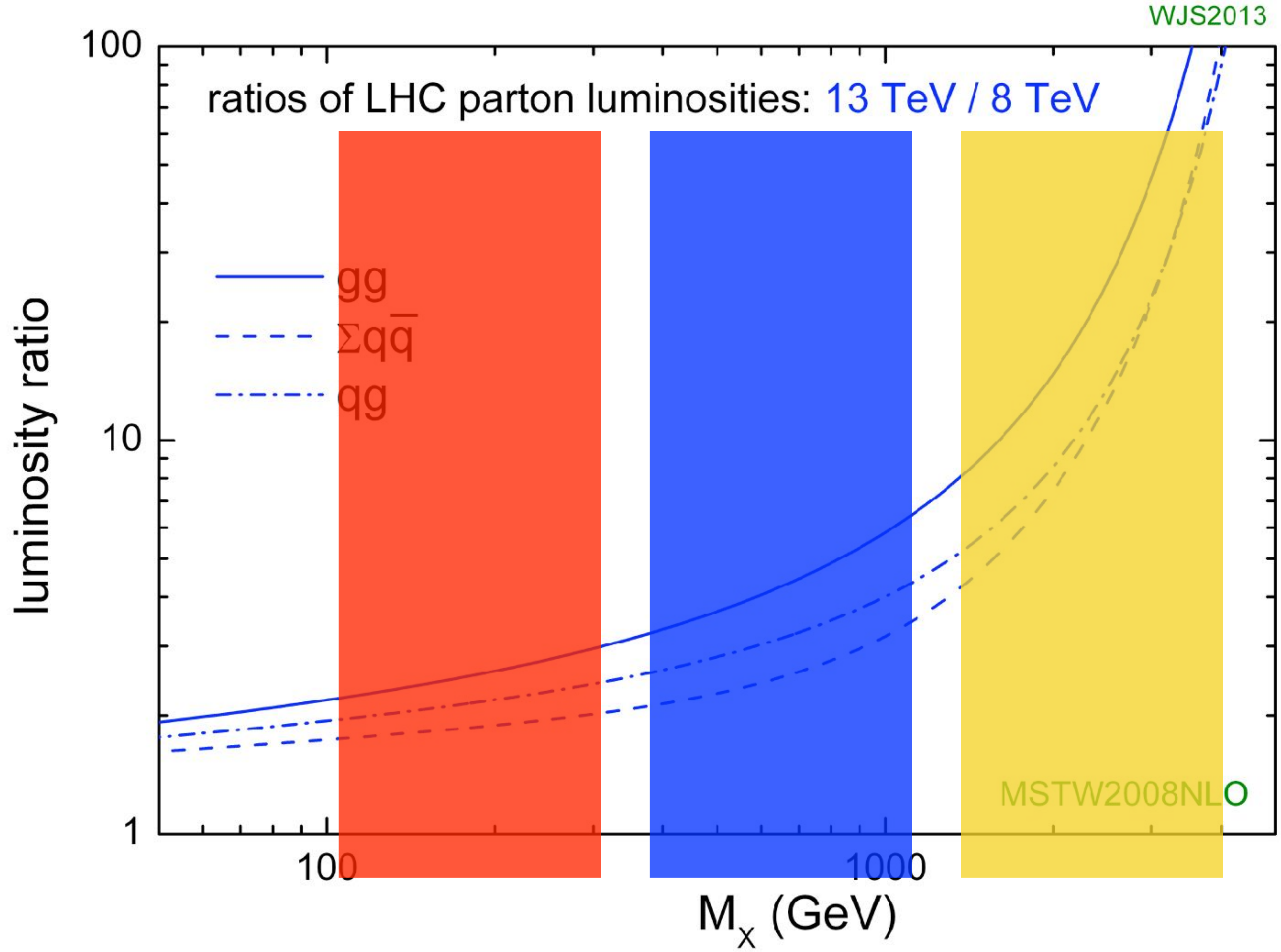






S. Zambito | *Harvard University*

Hunting For SUSY @ √s=13 TeV

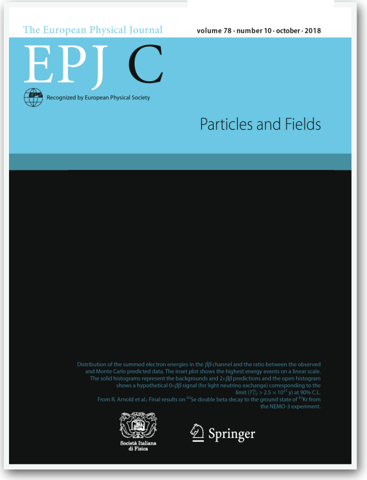


higgsinos / EWK-inos *scalar top* *gluinos / squarks*

Hunting For SUSY: *The Roadmap*

gluinos

arXiv:1605.04285

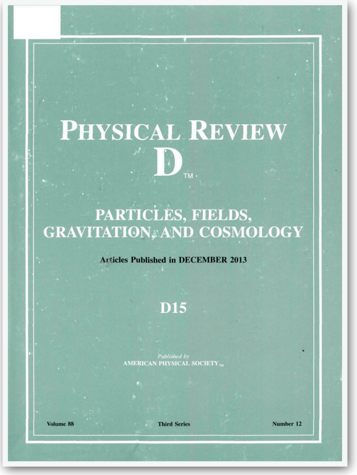


3.2 fb^{-1}

Dec 2015

gluinos

arXiv:1708.08232

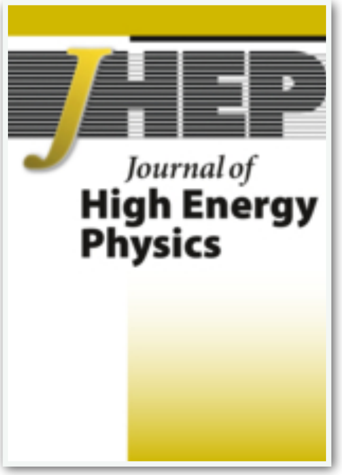


36.1 fb^{-1}

Mar 2017

scalar top

arXiv:1711.11520

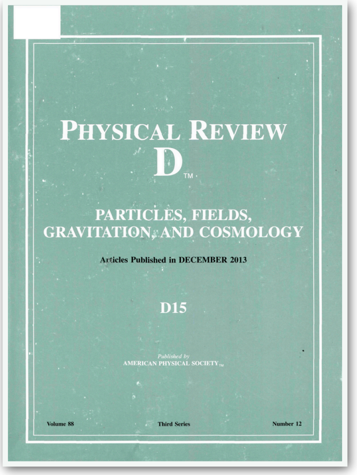


36.1 fb^{-1}

Jul 2017

higgsinos

arXiv:1712.08119



36.1 fb^{-1}

Dec 2017

higgsinos

PRD
(soon)

139 fb^{-1}

Today

$\sqrt{s}$=13 TeV

Appointed Roles

Analysis Coordinator
Paper Editor

Analysis Coordinator
Paper Editor

Muon Identification Convener

SUSY Background Forum Convener

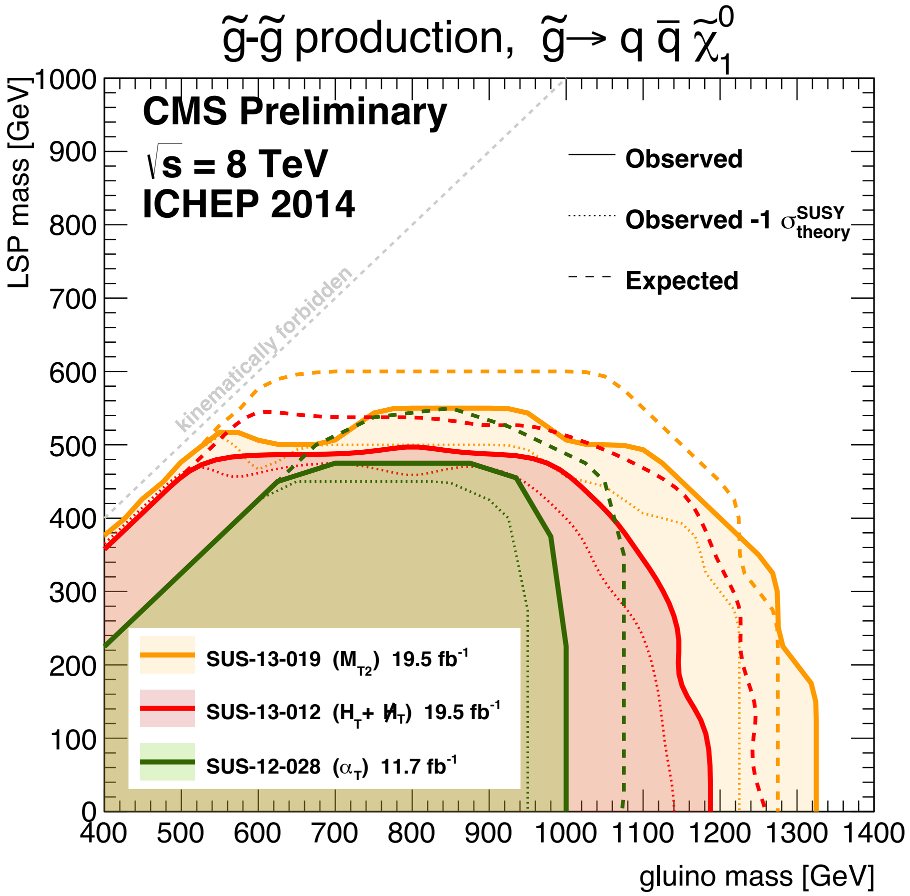
Muon Performance Convener

S. Zambito | *Harvard University*

Hunting for Natural SUSY at the LHC

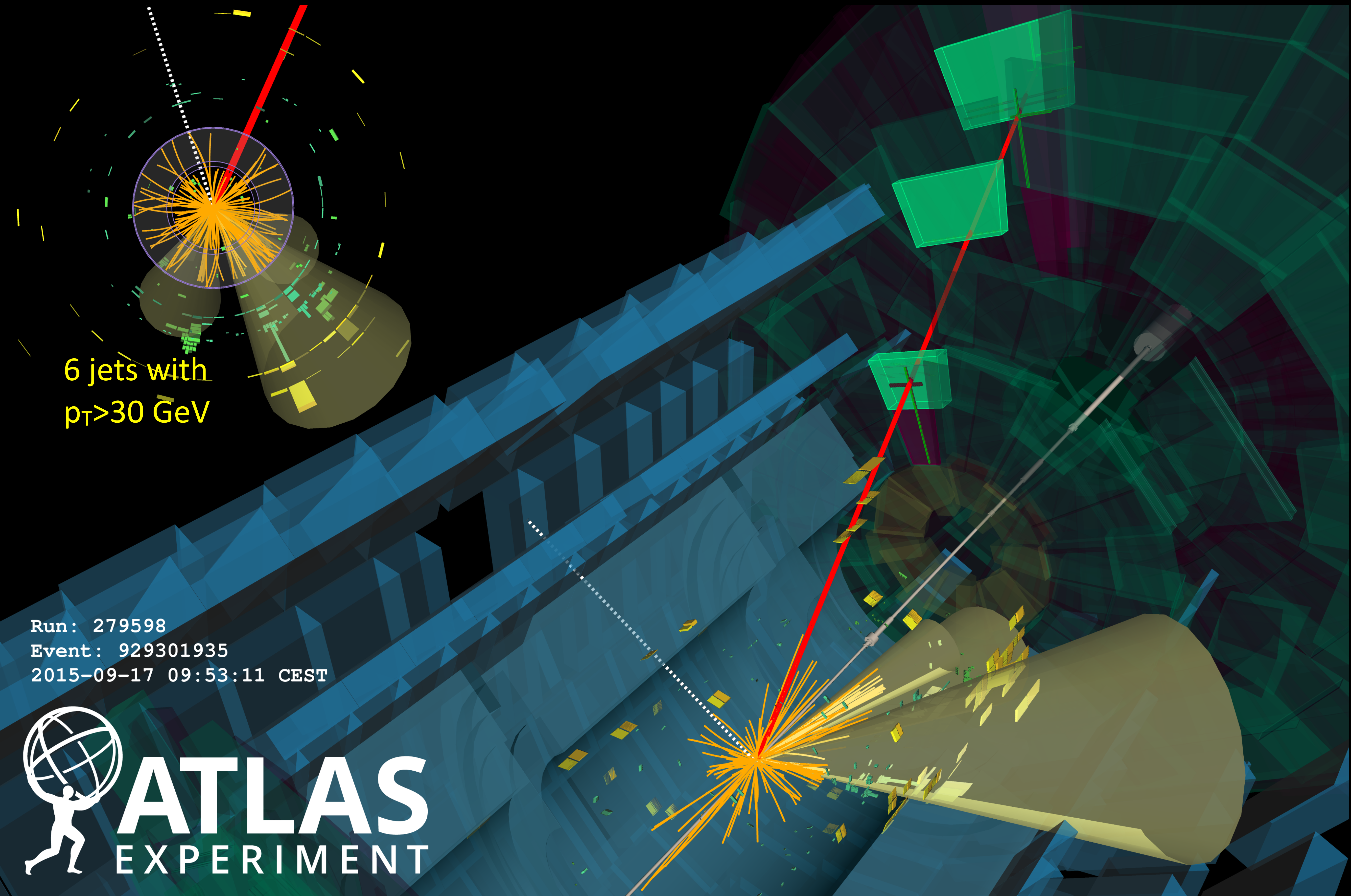
Part I - The Gluinos

Excluded up to 1.3 TeV after the LHC run1

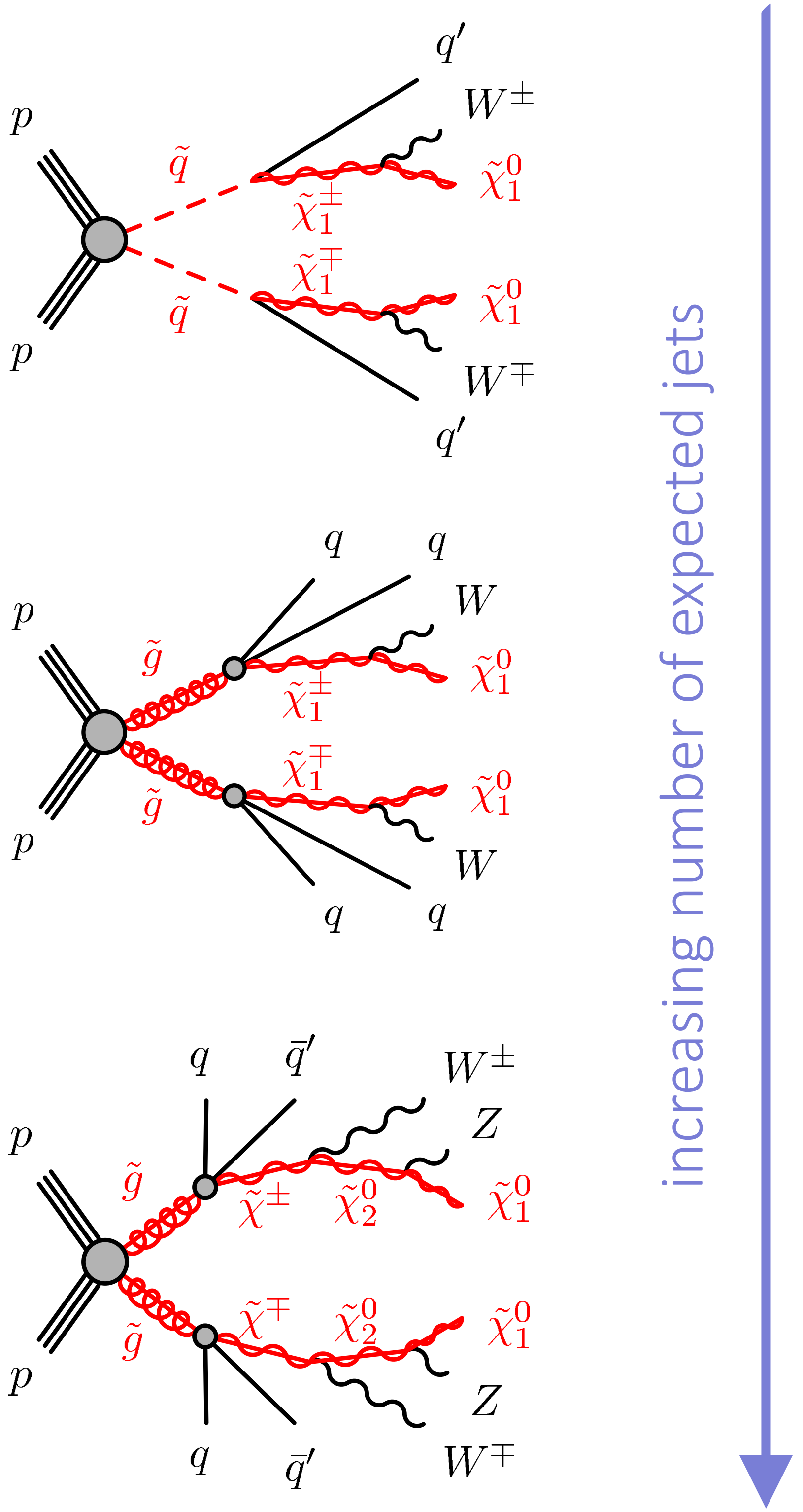


Selecting **spectacular** events!

Exploring tails of kinematic distributions



Hunting Gluinos & Squarks



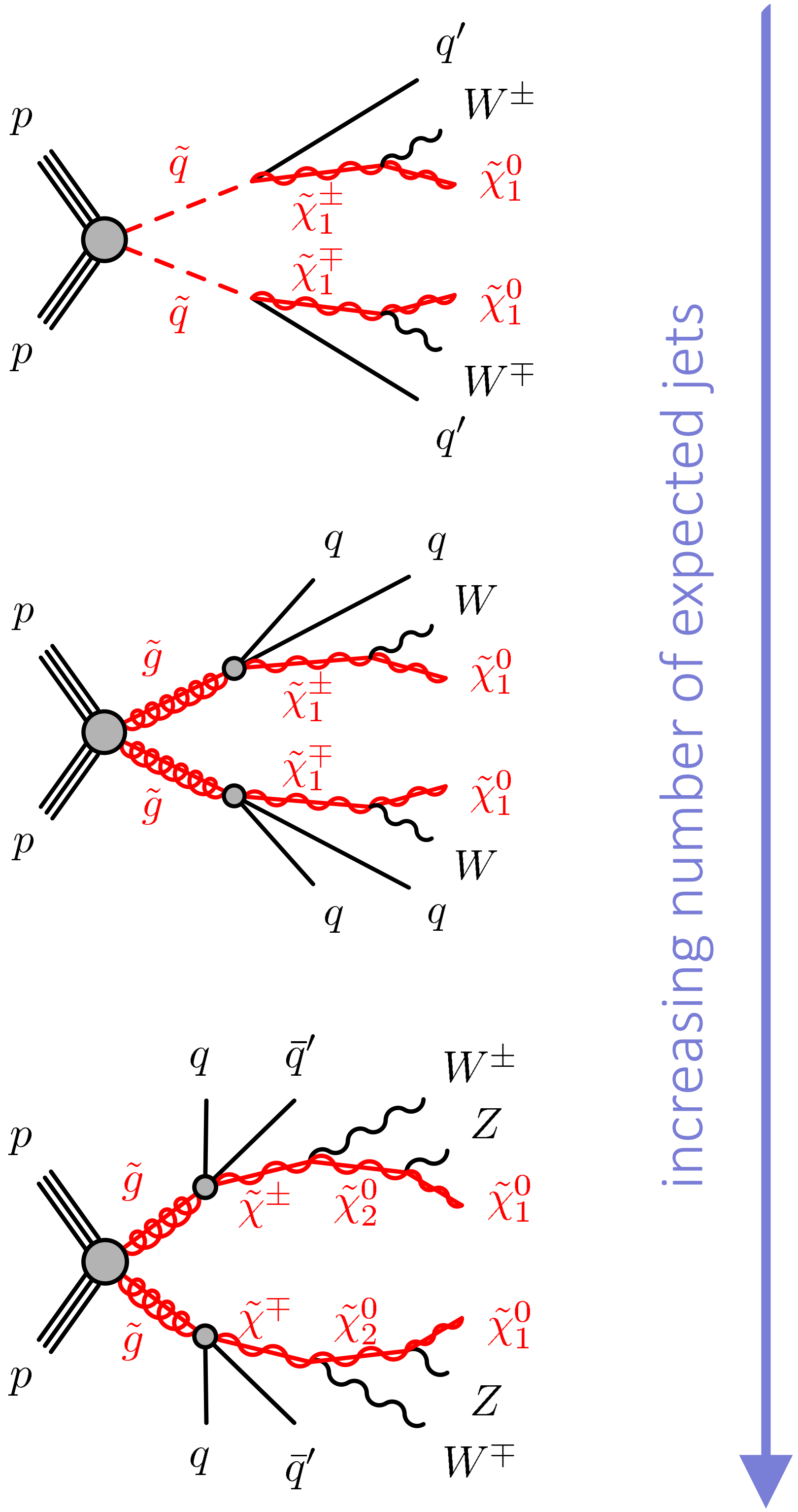
Select interesting events:

one electron or muon from $W\rightarrow\ell\nu$ decay

many jets from gluinos/squarks decay chain

large $\not{E}_T$ from undetected neutralinos

Hunting Gluinos & Squarks



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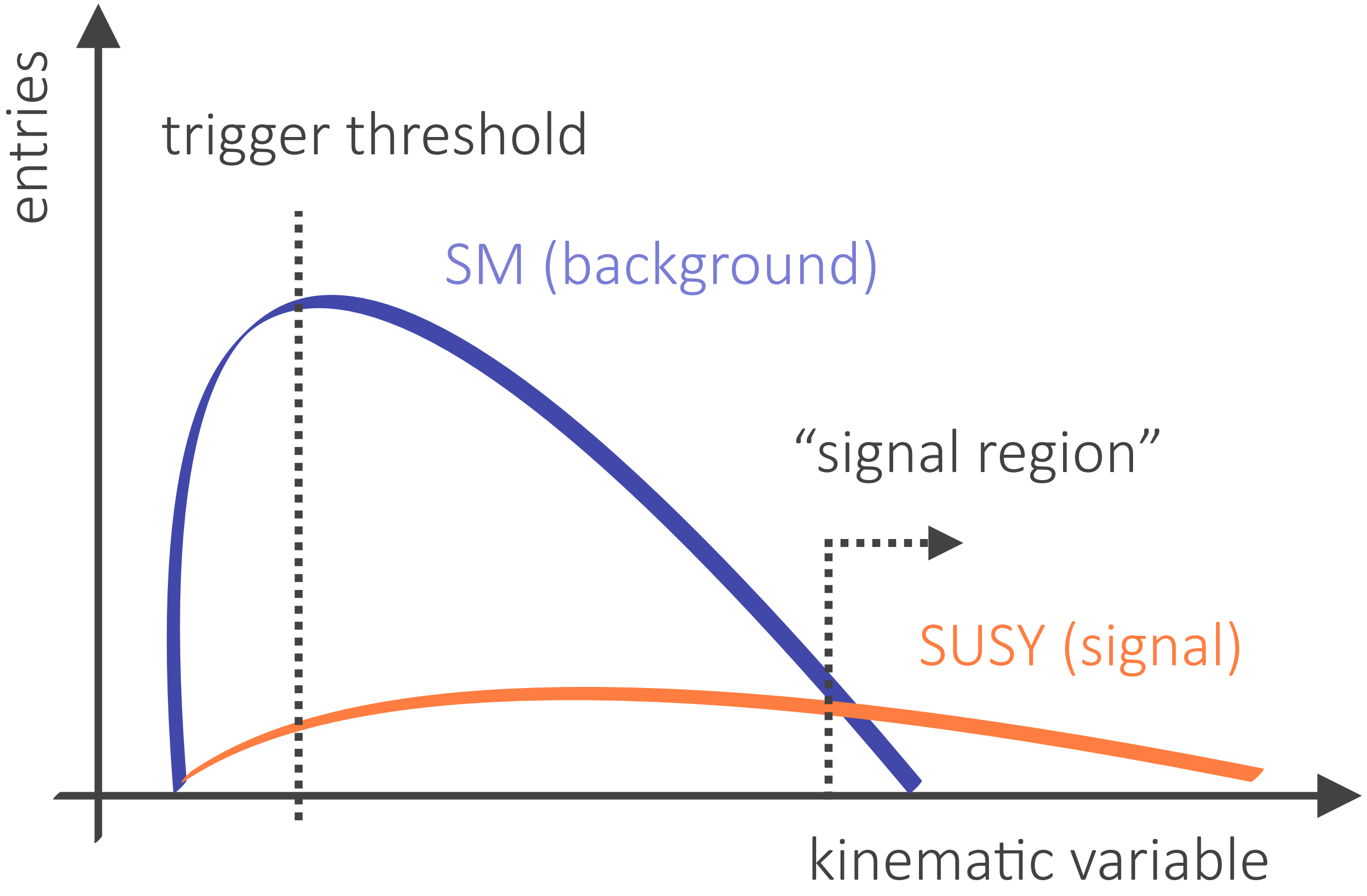
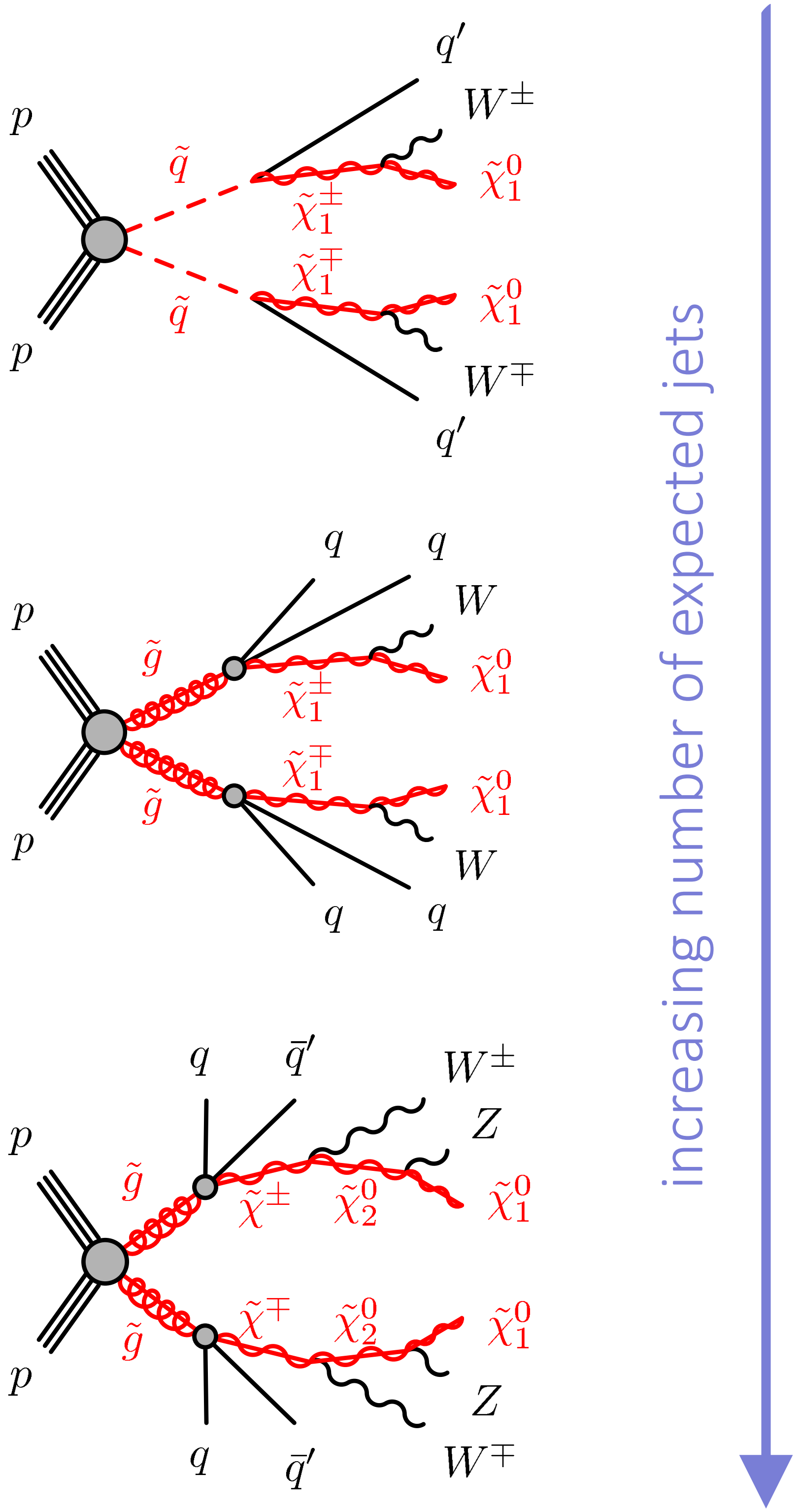


Hunting Gluinos & Squarks



Select interesting events:

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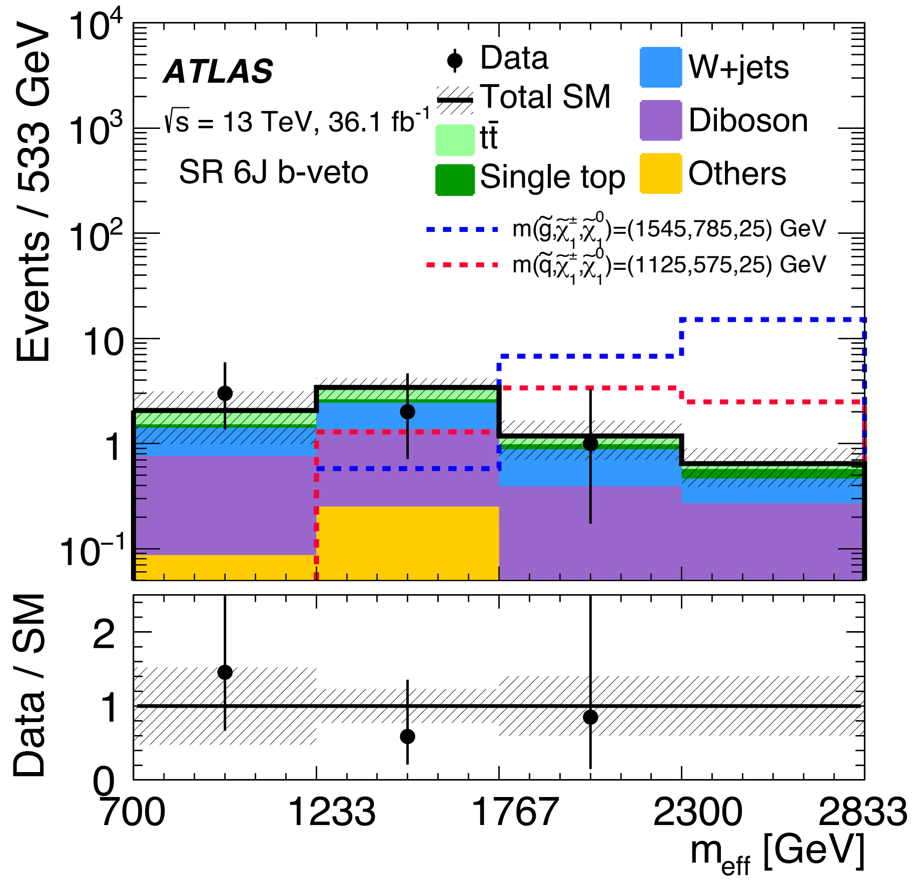
large $\not{E}_T$ from undetected neutralinos

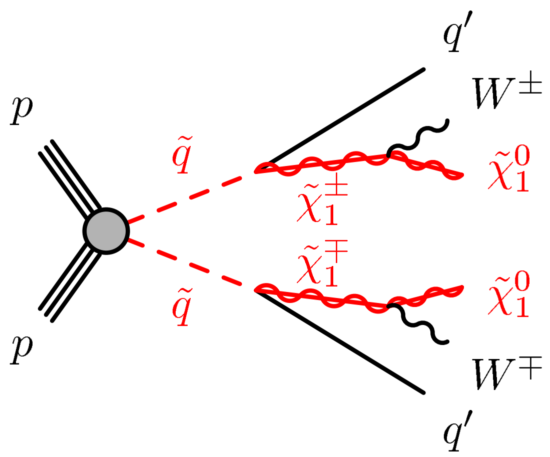
effective mass

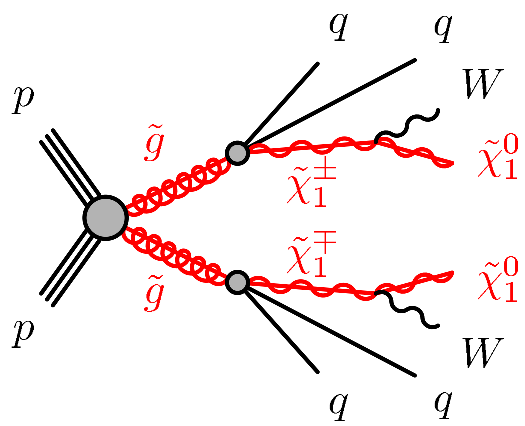
$$m_{\rm eff}^{incl} = H_T + E_{\rm T}^{\rm miss} = \sum p_T^{\ell} + \sum p_T^{jet} + E_{\rm T}^{\rm miss}$$

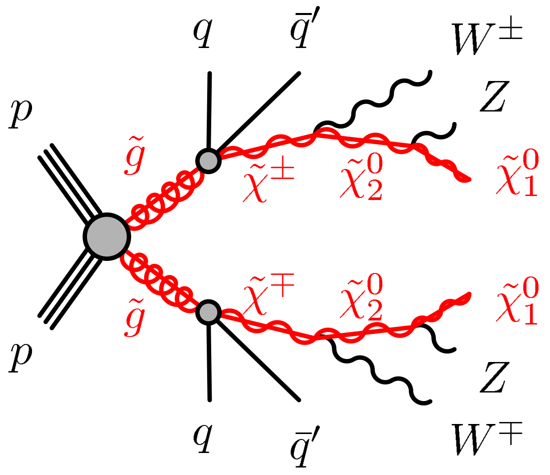
sensitive to SUSY mass scale



Hunting Gluinos & Squarks







increasing number of expected jets

Select interesting events:

one electron or muon from $W \rightarrow \ell\nu$ decay

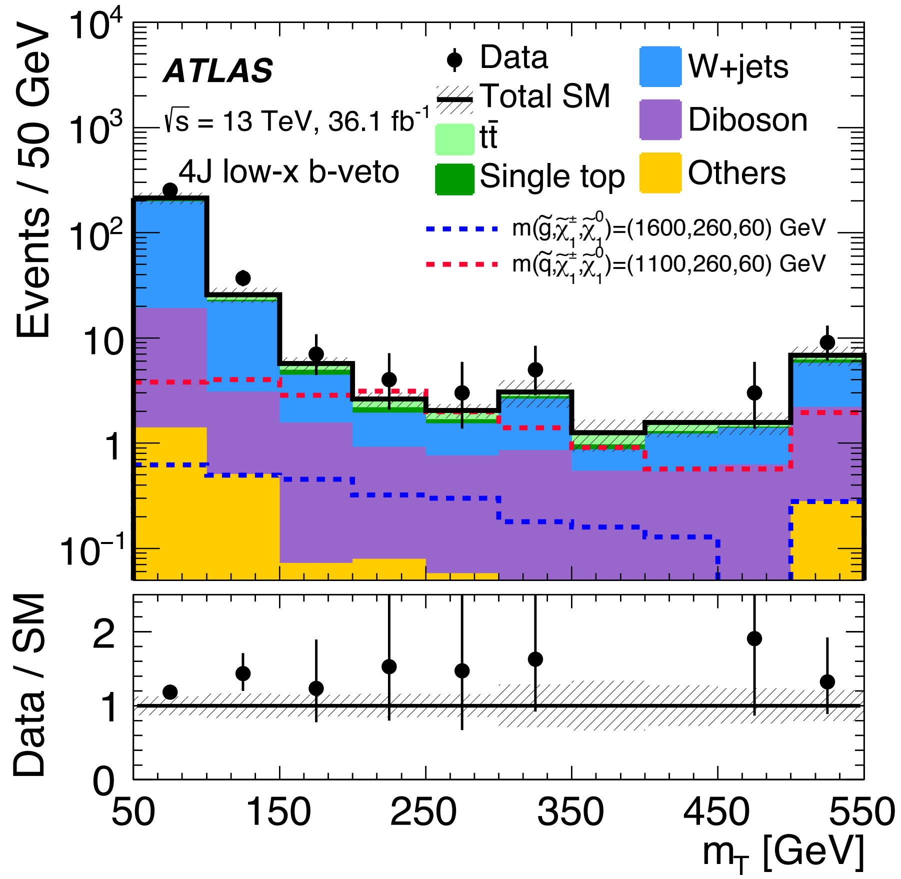
many jets from gluinos/squarks decay chain

large $E\!\!\!/_T$ from undetected neutralinos

transverse mass

$$m_{\mathrm{T}} = \sqrt{2 \cdot p_T^{\ell} \cdot E_{\mathrm{T}}^{\mathrm{miss}} \cdot (1 - cos(\Delta\phi(\ell, E_{\mathrm{T}}^{\mathrm{miss}})))}$$

edge at m_W for backgrounds with on-shell W

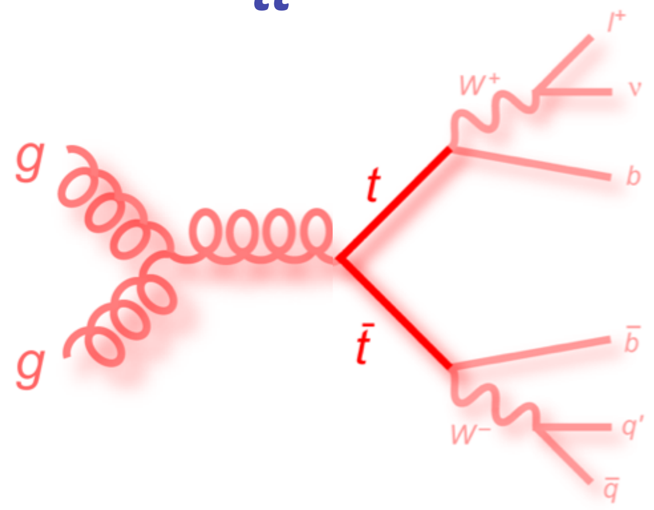


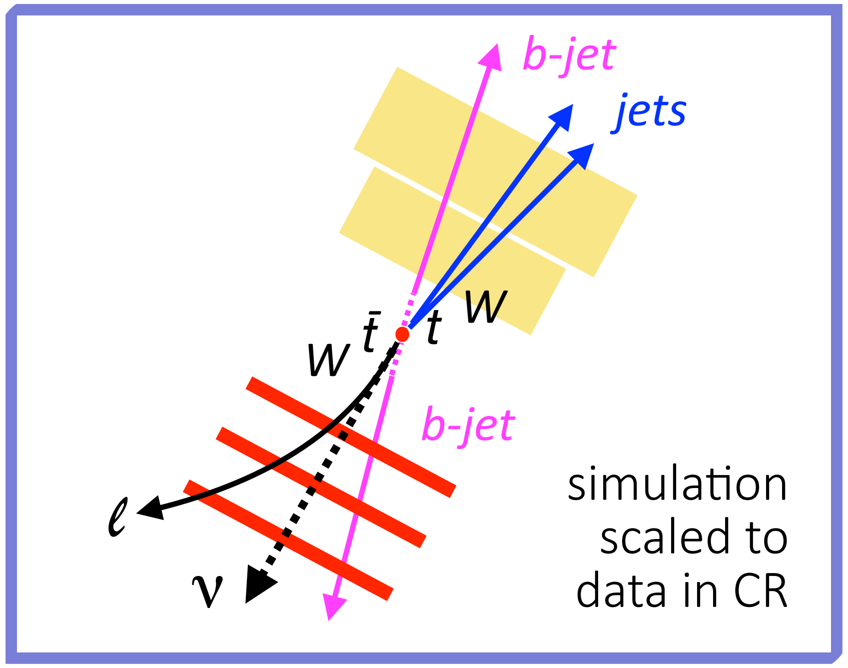
Main Backgrounds

Experimental signature involves large $\not\!\!E_{\mathrm{T}}$, many jets and 1 isolated lepton

Control (CR) and validation (VR) regions used to extract / x-check background predictions

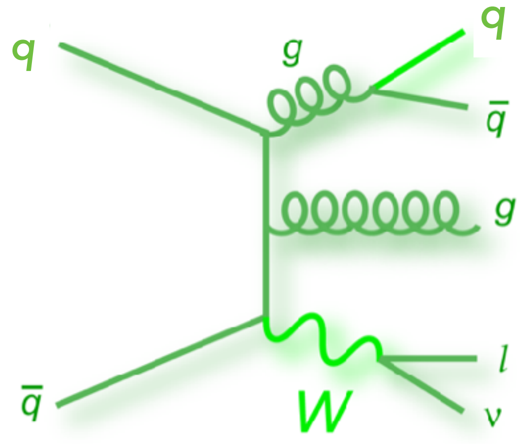
$t\bar{t}$

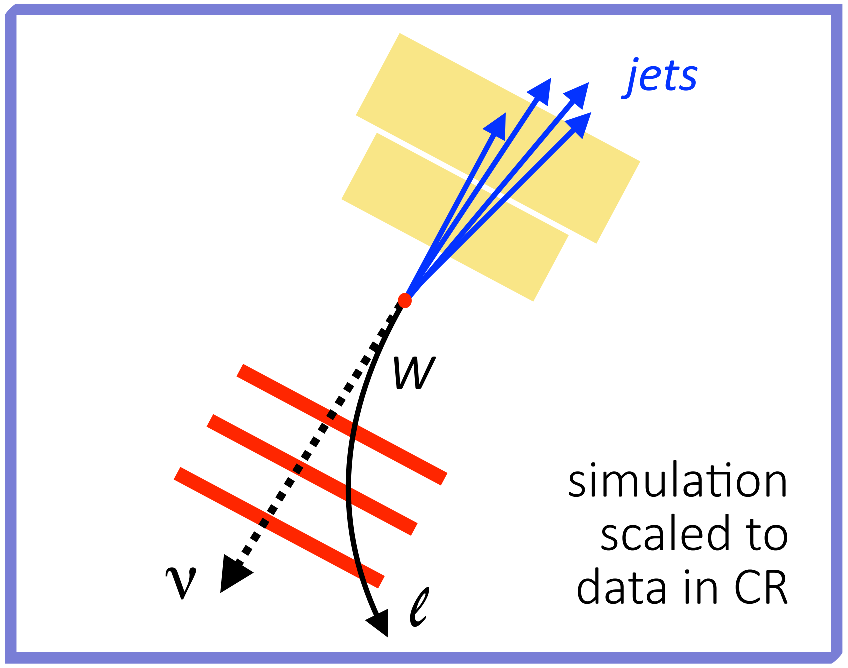




simulation scaled to data in CR

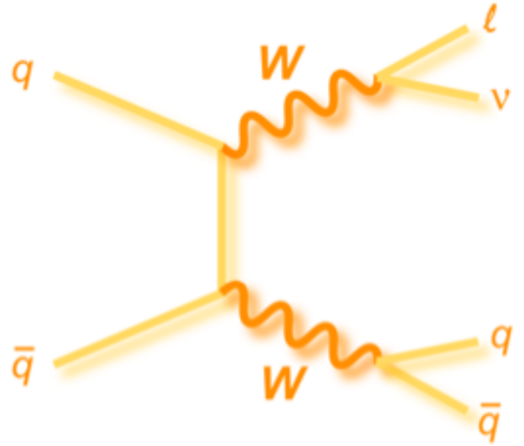
W+jets

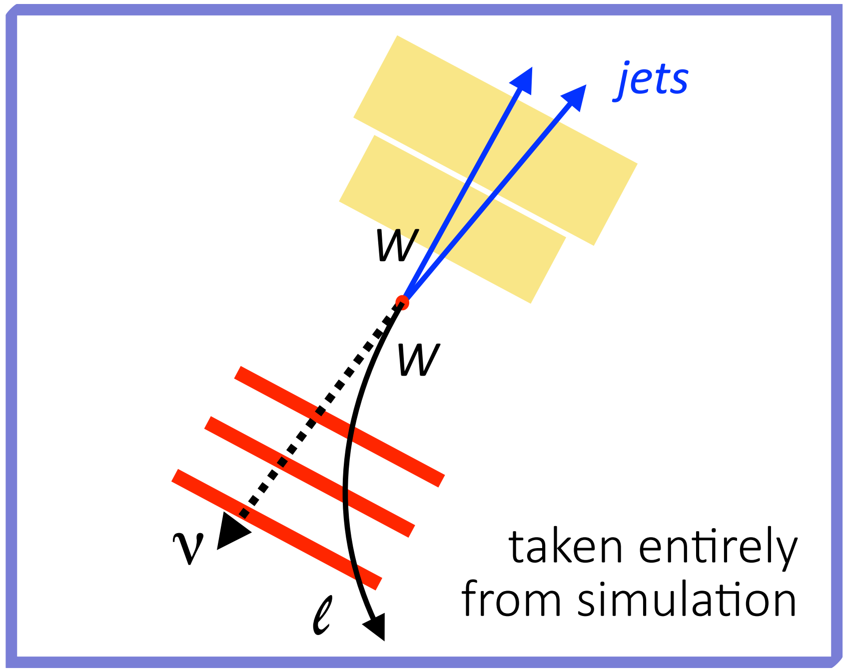




simulation scaled to data in CR

Diboson



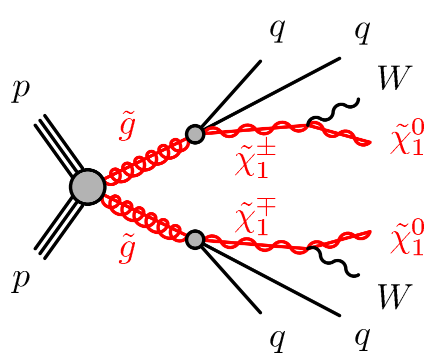


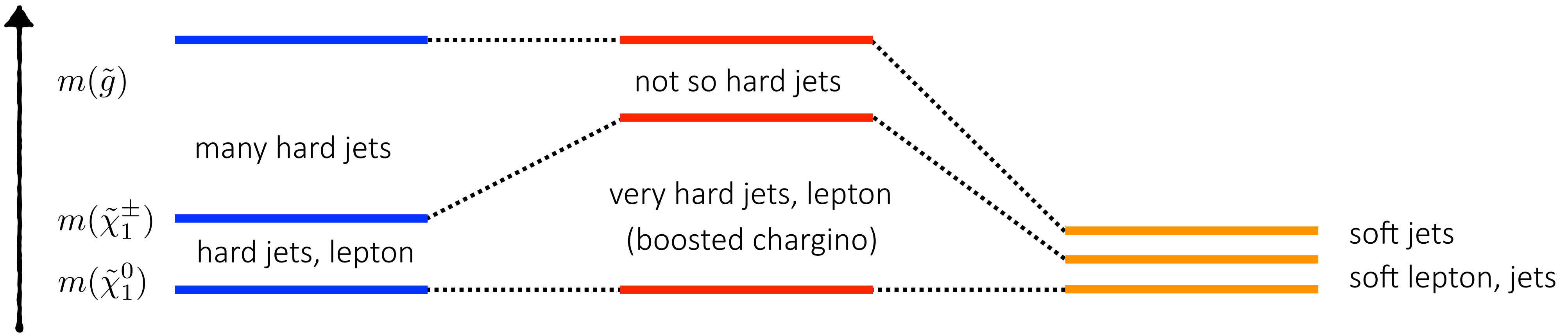
taken entirely from simulation

Signal Selection

The challenge: signal kinematics *strongly* depend on *sparticles' masses*!

targeting whole parameter space in one analysis is very complicated…





many hard jets

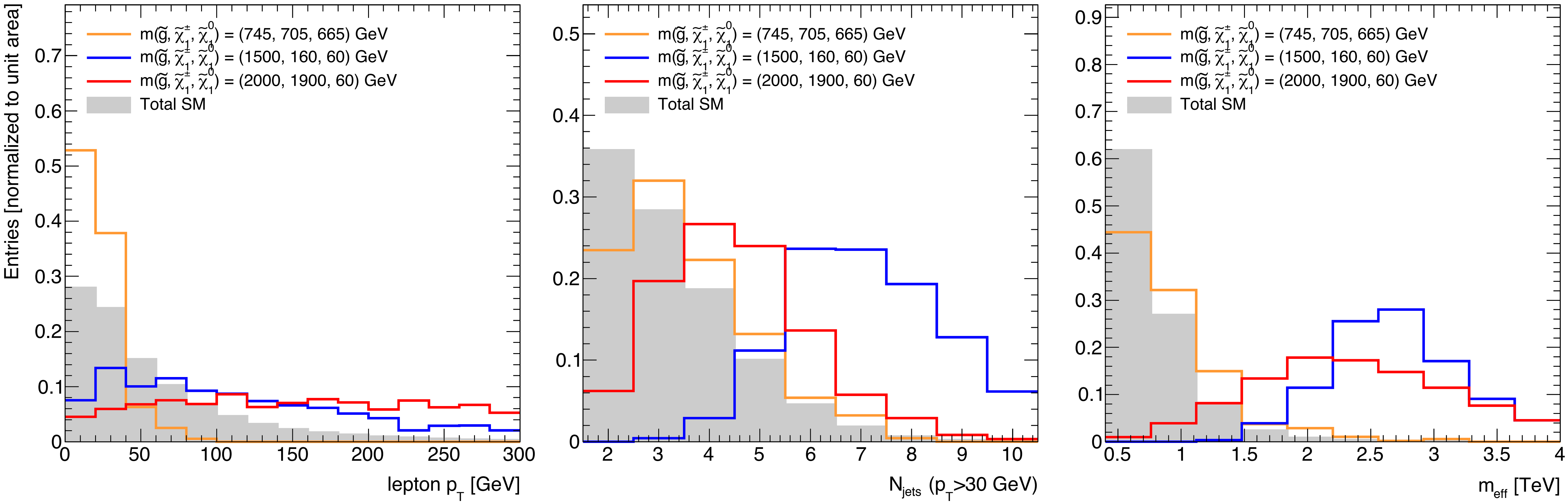
hard jets, lepton

not so hard jets

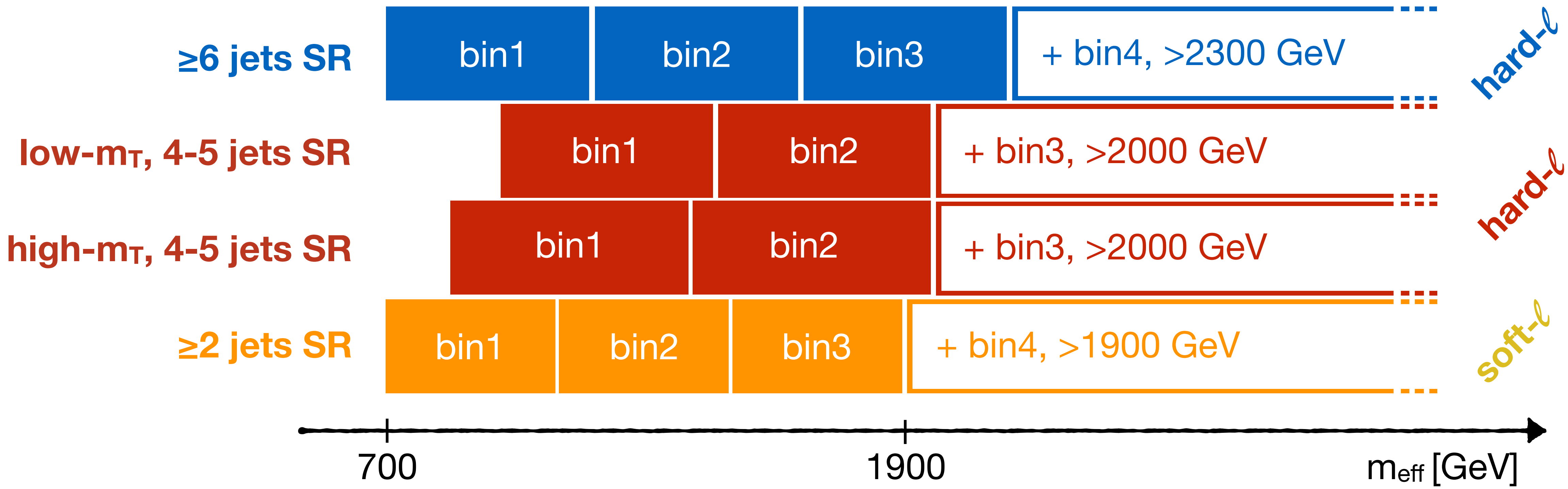
very hard jets, lepton
(boosted chargino)

soft jets

soft lepton, jets



Signal Selection: Multi-Bin Fit



≥6 jits SR

bin1 | bin2 | bin3 | + bin4, >2300 GeV

low-m_T, 4-5 jets SR

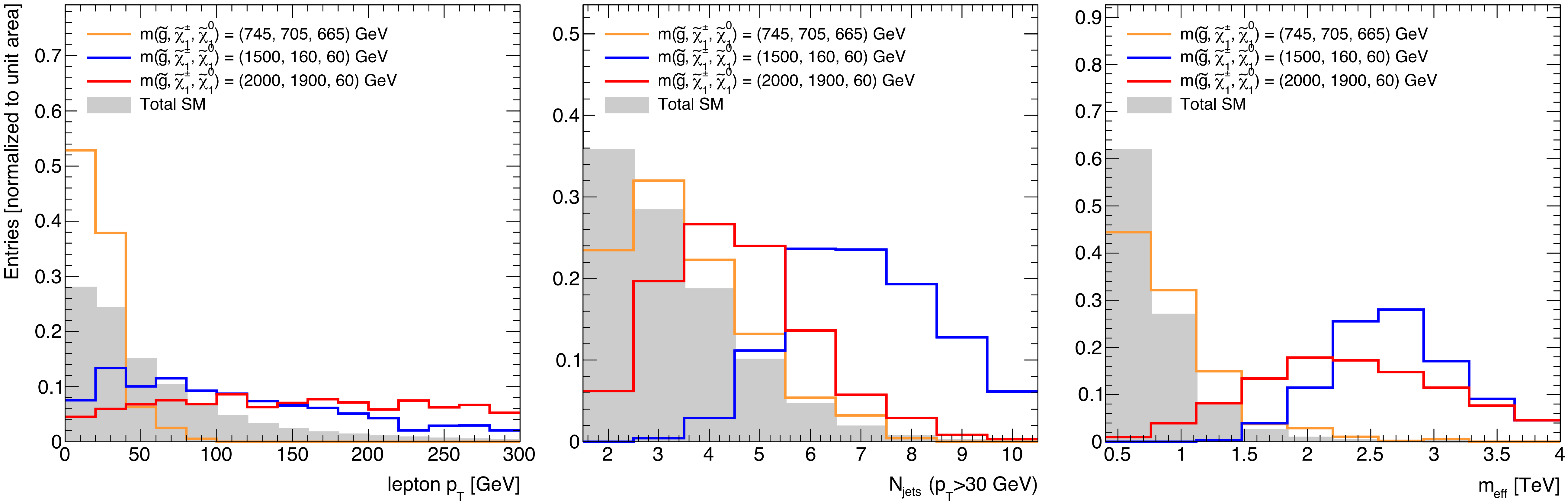
bin1 | bin2 | + bin3, >2000 GeV

high-m_T, 4-5 jets SR

bin1 | bin2 | + bin3, >2000 GeV

≥2 jets SR

bin1 | bin2 | bin3 | + bin4, >1900 GeV

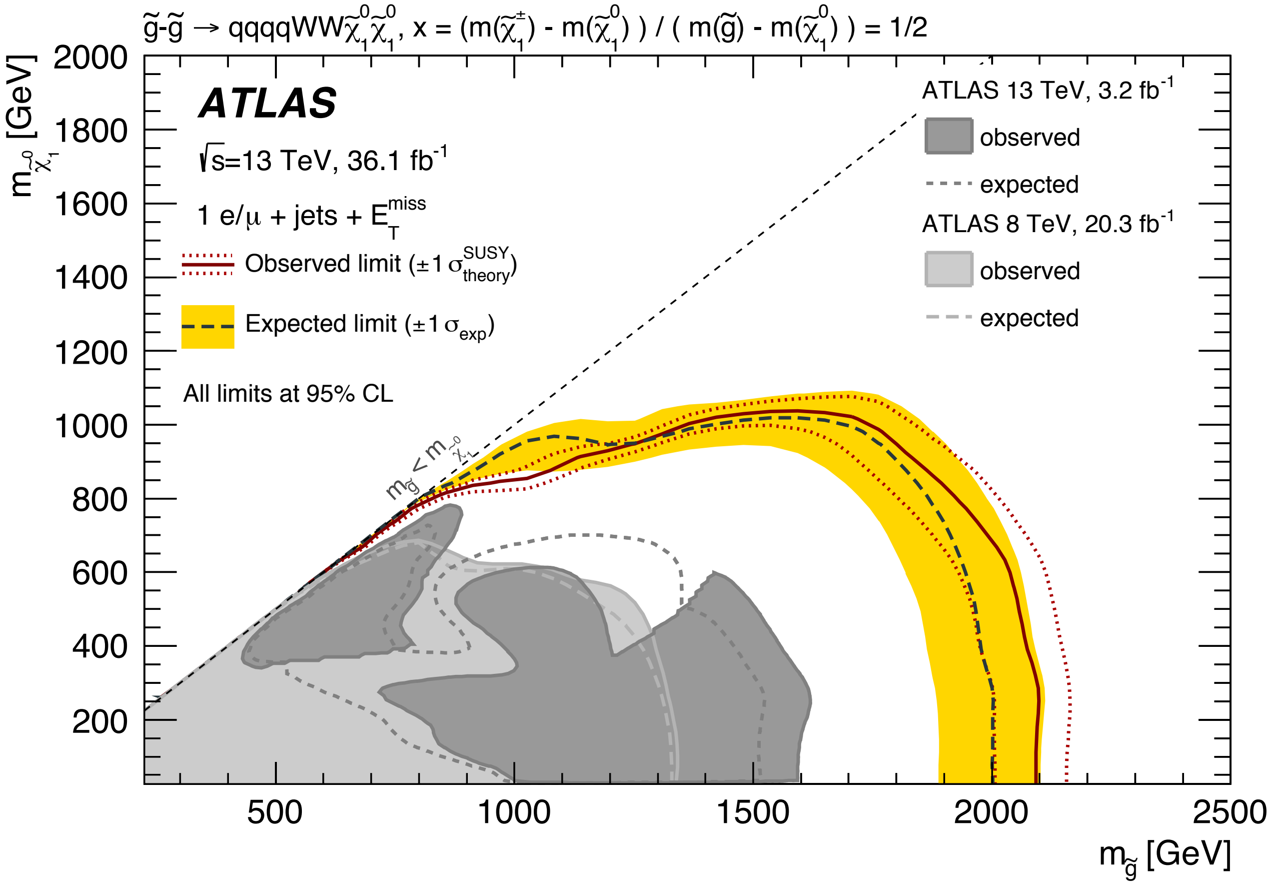


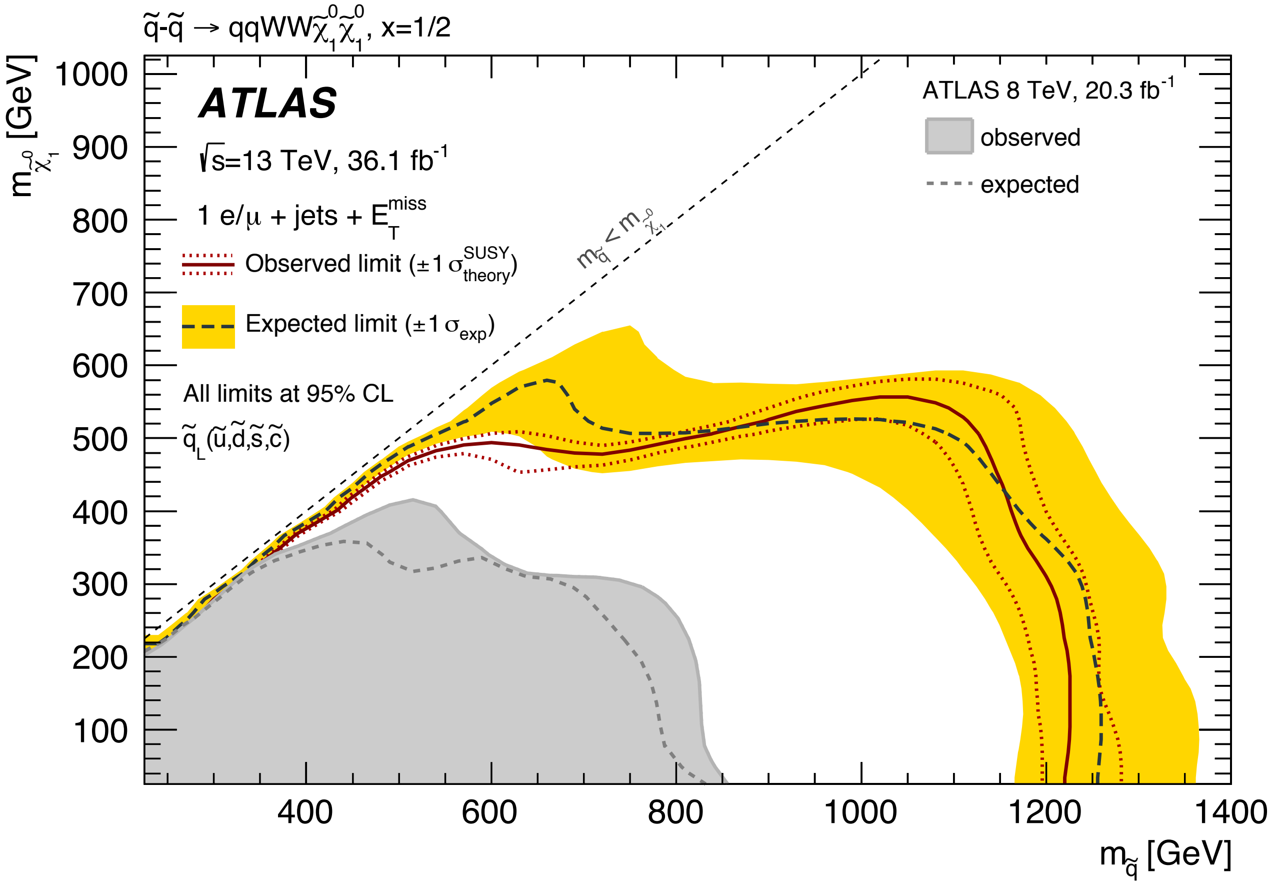
Results: 95% CL Limits

Observed event yields (*simplified SR* for model-independent limits)

$\mathbf{SR_{disc}}$	**2J**	**4J high-x**	**4J low-x** (gluino)	**4J low-x** (squark)	**6J** (gluino)	**6J** (squark)
Observed events	80	16	24	50	0	28
Fitted bkg events	67 ± 6	17.7 ± 2.7	17.2 ± 3.2	47 ± 7	2.6 ± 0.6	23.4 ± 3.1
S^{95}_{exp}	$21.6^{+9.2}_{-5.6}$	$10.8^{+3.7}_{-3.0}$	$11.8^{+4.8}_{-2.7}$	$19.9^{+7.5}_{-5.6}$	$4.5^{+1.8}_{-1.0}$	$12.7^{+5.0}_{-4.0}$
$p(s=0)$	0.10	0.50	0.10	0.35	0.50	0.21

Exclusions: simulated SUSY signal rejected, or not, via fit to pseudo/observed data



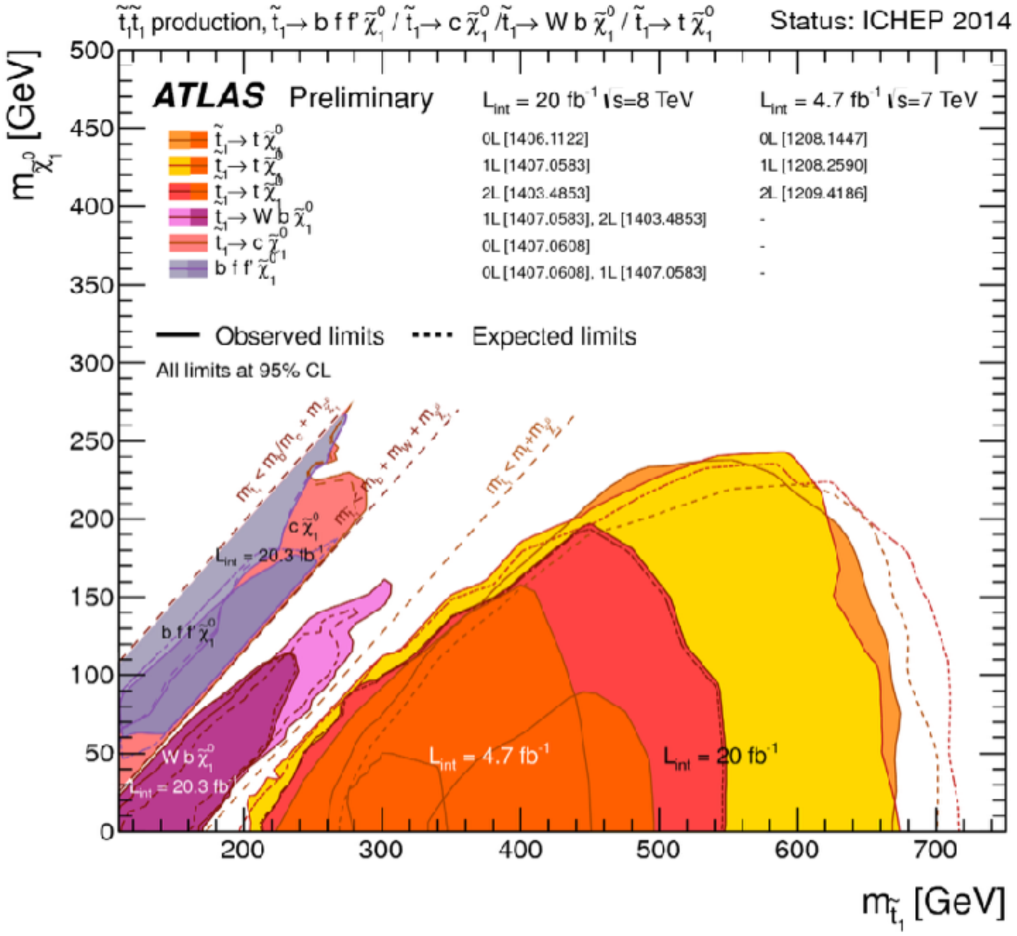


S. Zambito | *Harvard University*

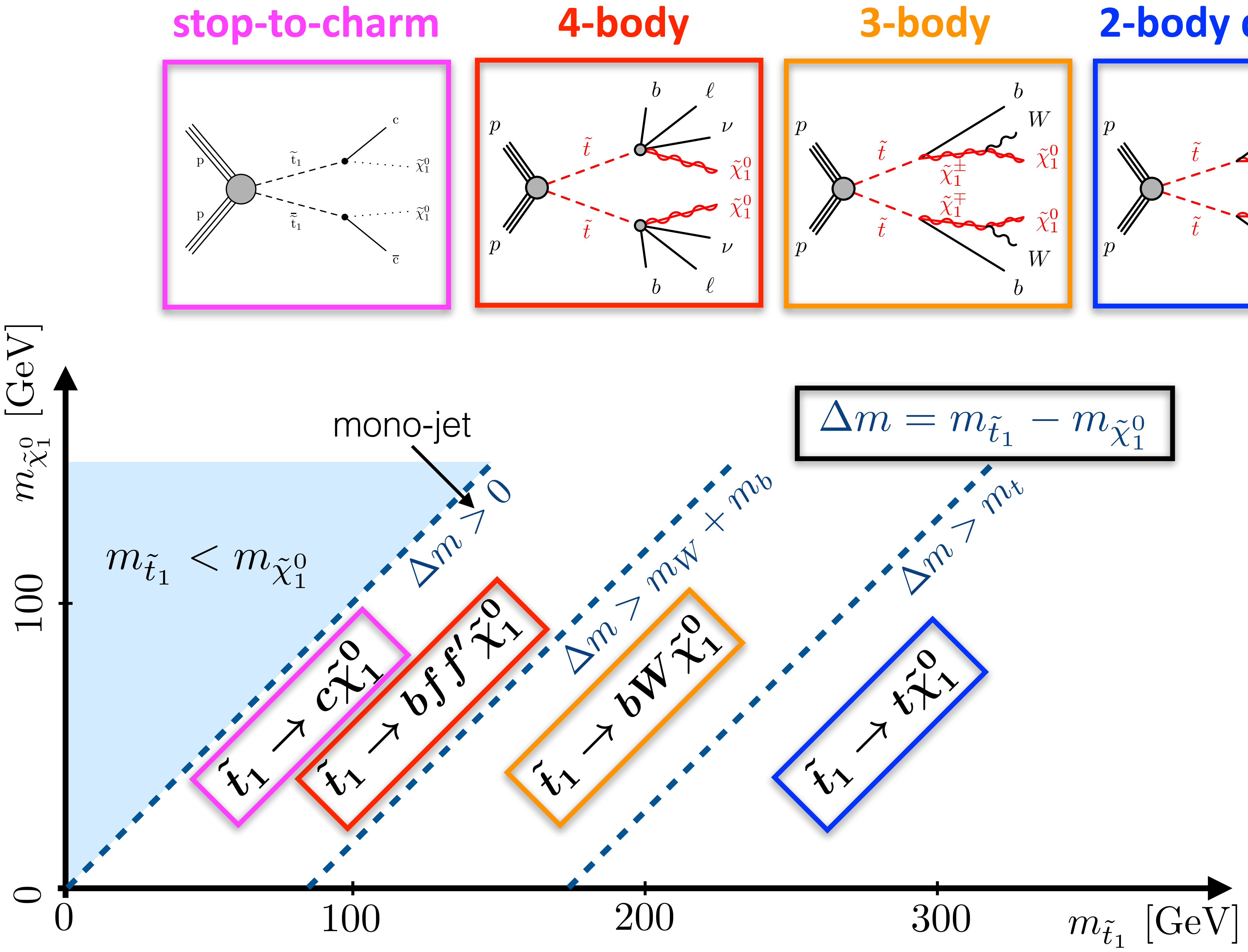
Hunting for Natural SUSY at the LHC

Part II - The Stops

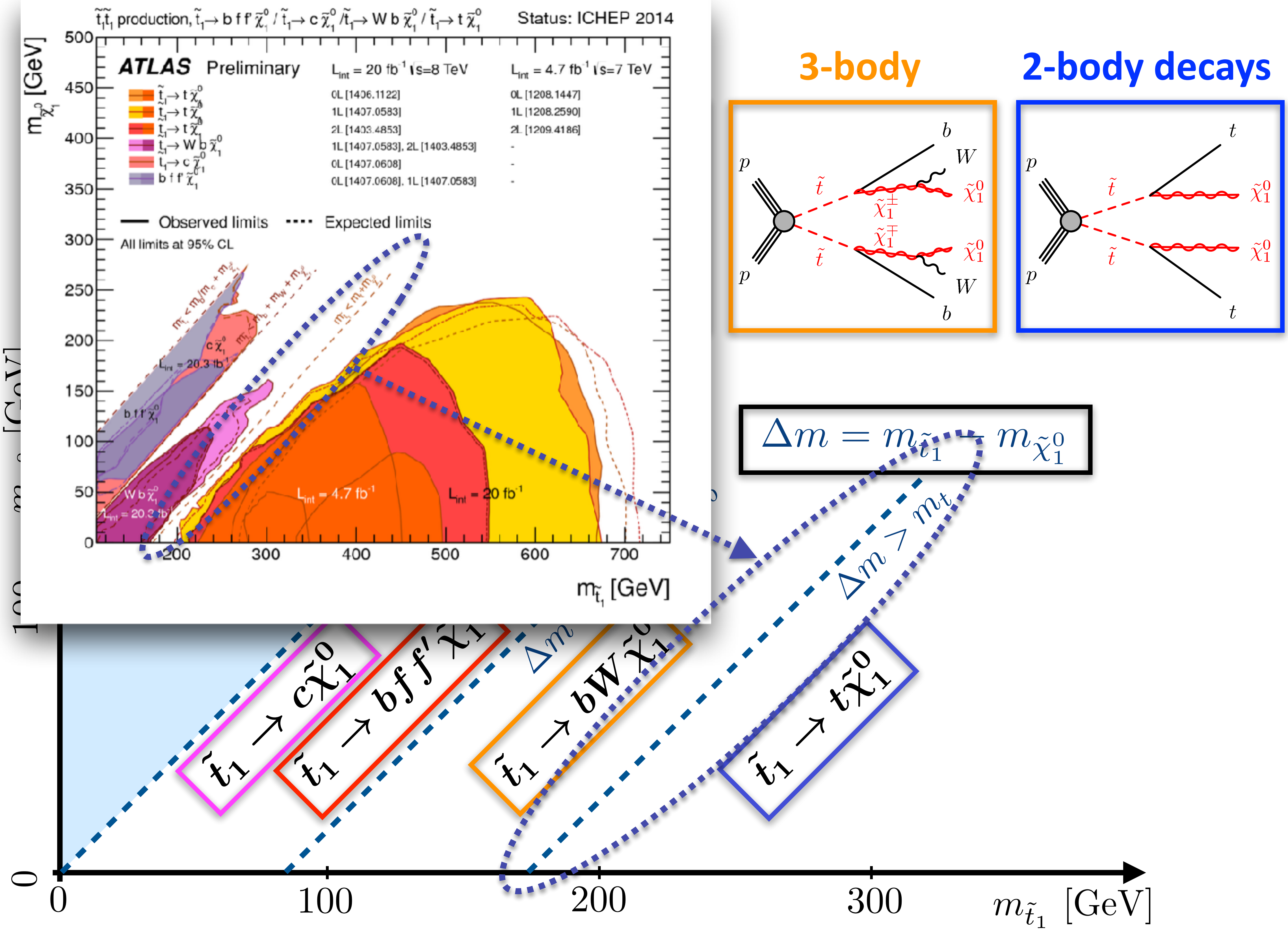
Excluded up to 650 GeV after the LHC run1



Hunting Stops: Decays



Hunting Stops: Decays

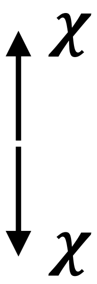


$$\Delta m = m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0}$$

Hunting Diagonal Stops

$m_{\tilde{t}} - m_{\tilde{\chi}_1^0} \approx m_t$: $\tilde{t}\tilde{t}$ kinematics close to $t\bar{t}$

need ISR activity
to “misalign” $\chi\chi$
and get tangible
contribution to $\not{E}_T$



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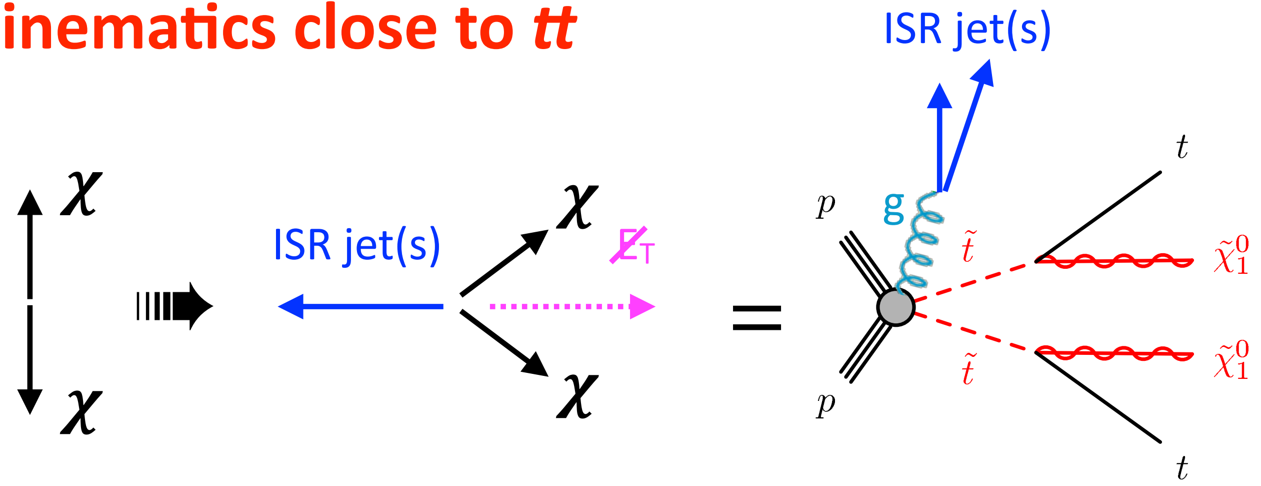

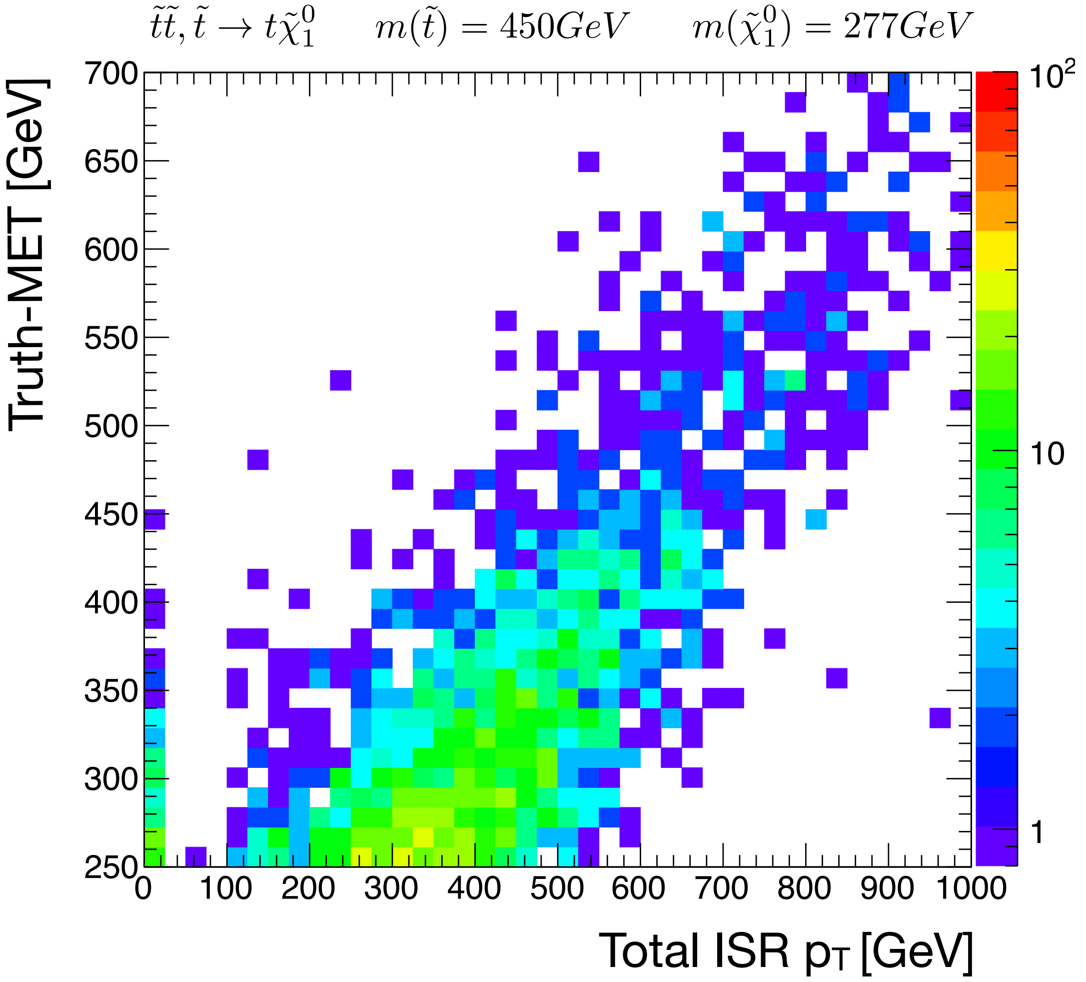

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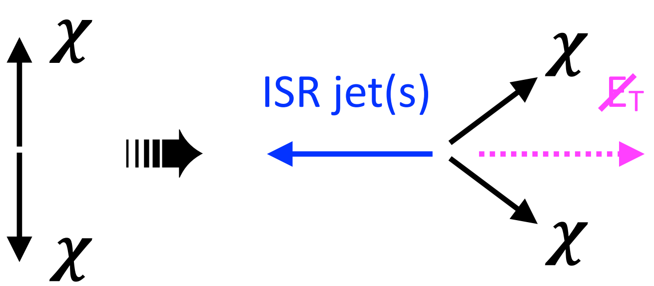

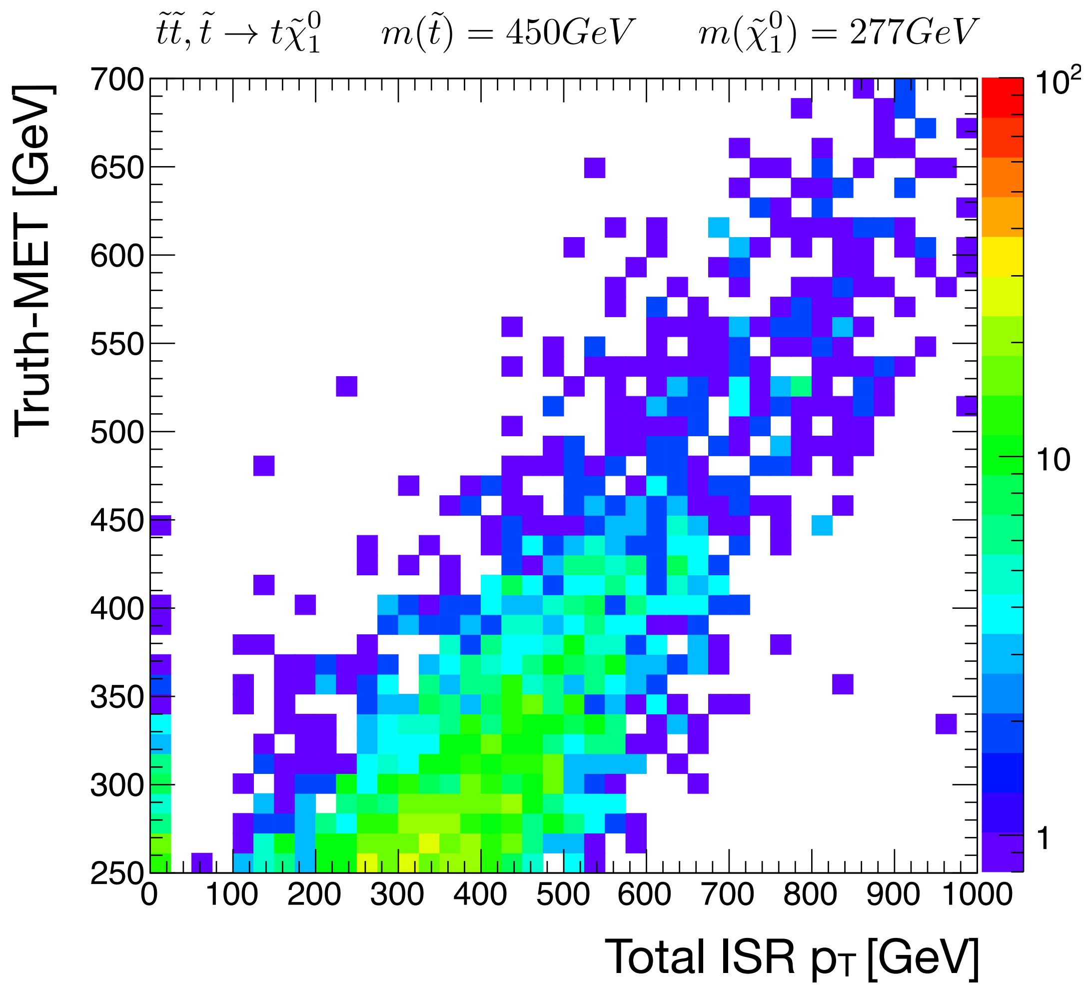

plethora of pheno. papers:

$$p_{T,ISR} \approx -(p_T(\tilde{t}_1) + p_T(\tilde{t}_2))$$

$$\frac{\not{E}_T}{p_{T,ISR}} \approx \frac{m(\tilde{\chi}_1^0)}{m(\tilde{t})}$$

K. Hagiwara et al, 2015:
arXiv:1307.1553v3

H. An et al, 2015:
arXiv:1506.00653v2

S. Macaluso et al, 2015:
arXiv:1506.07885.

H. Cheng et al, 2016:
arXiv:1604.00007v1

etc…

Hunting Diagonal Stops

$m_{\tilde{t}} - m_{\tilde{\chi}_1^0} \approx m_t$: $\tilde{t}\tilde{t}$ **kinematics close to *$t\bar{t}$***

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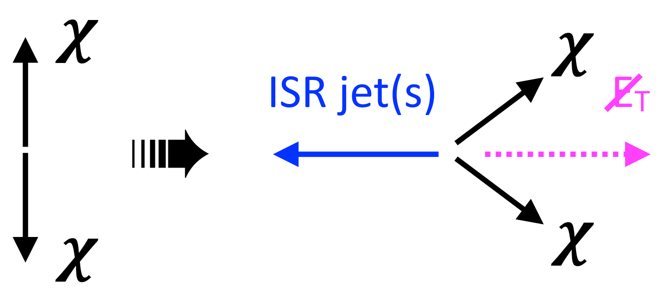

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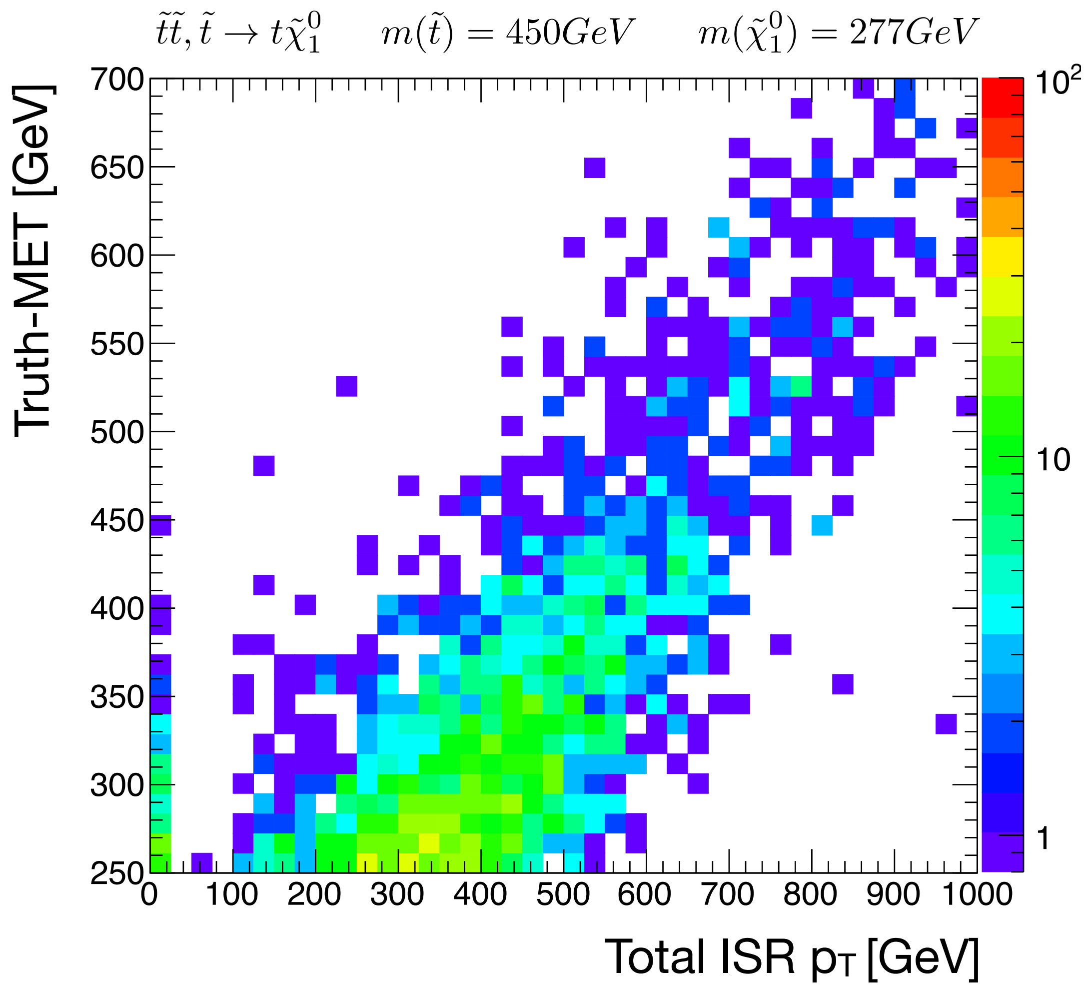

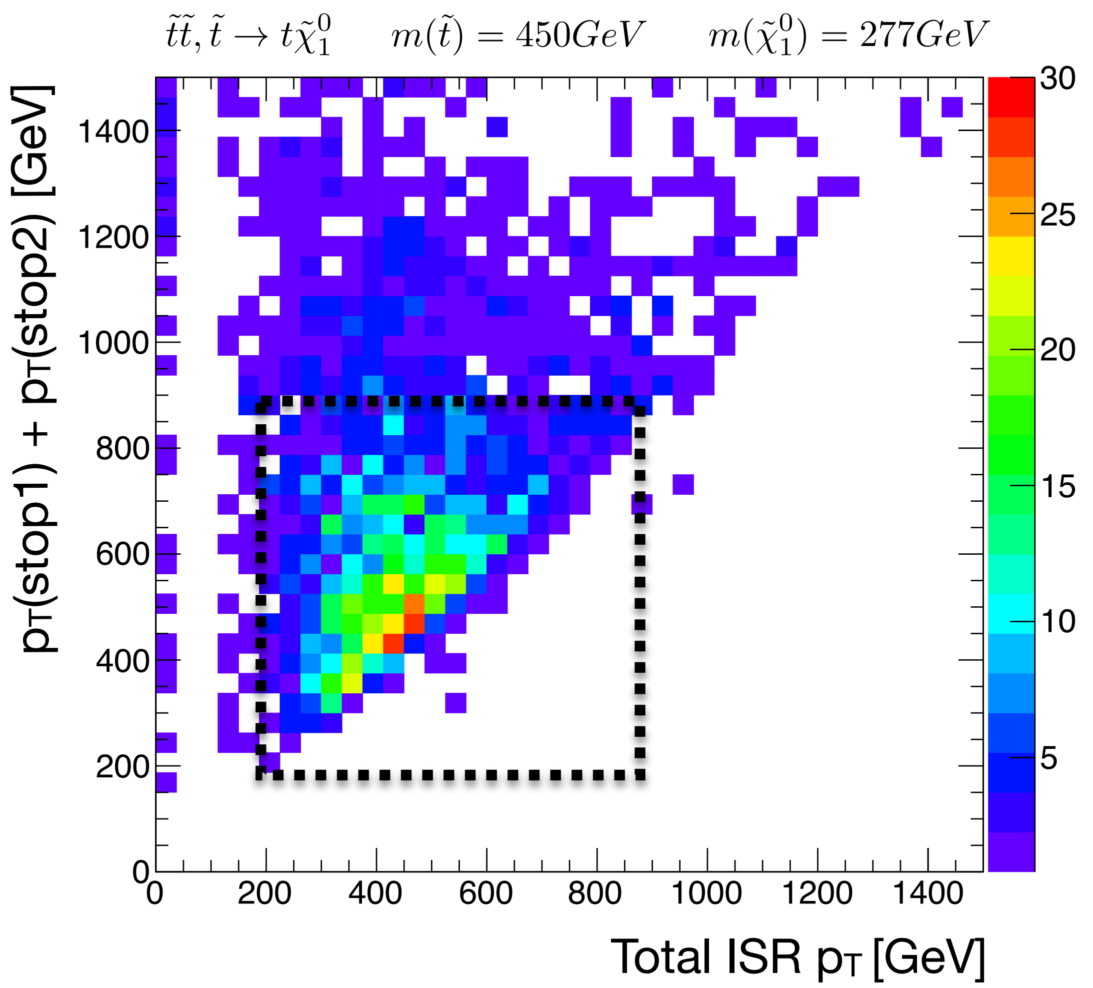

Hunting Diagonal Stops

easier said than done... among the many jets, which ones are from ISR?

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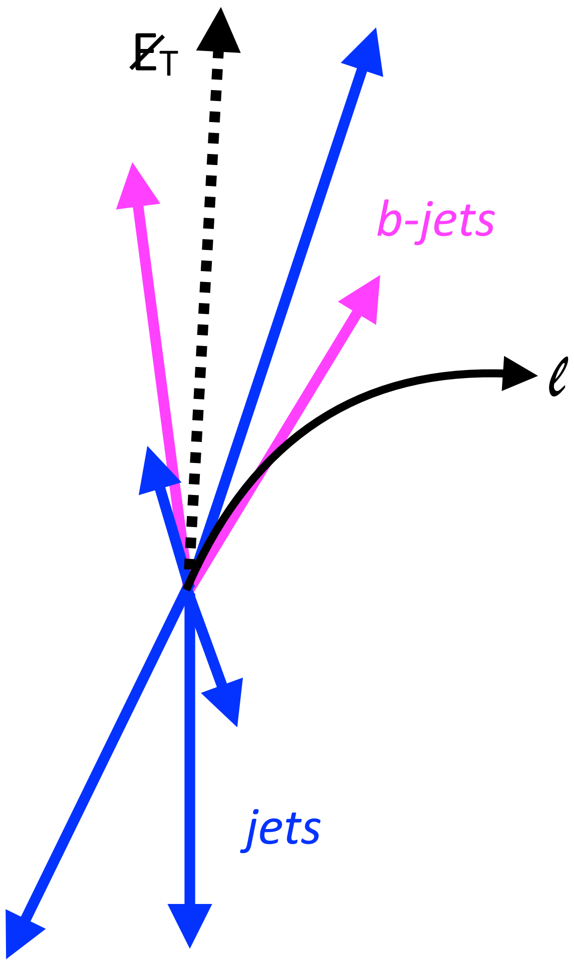
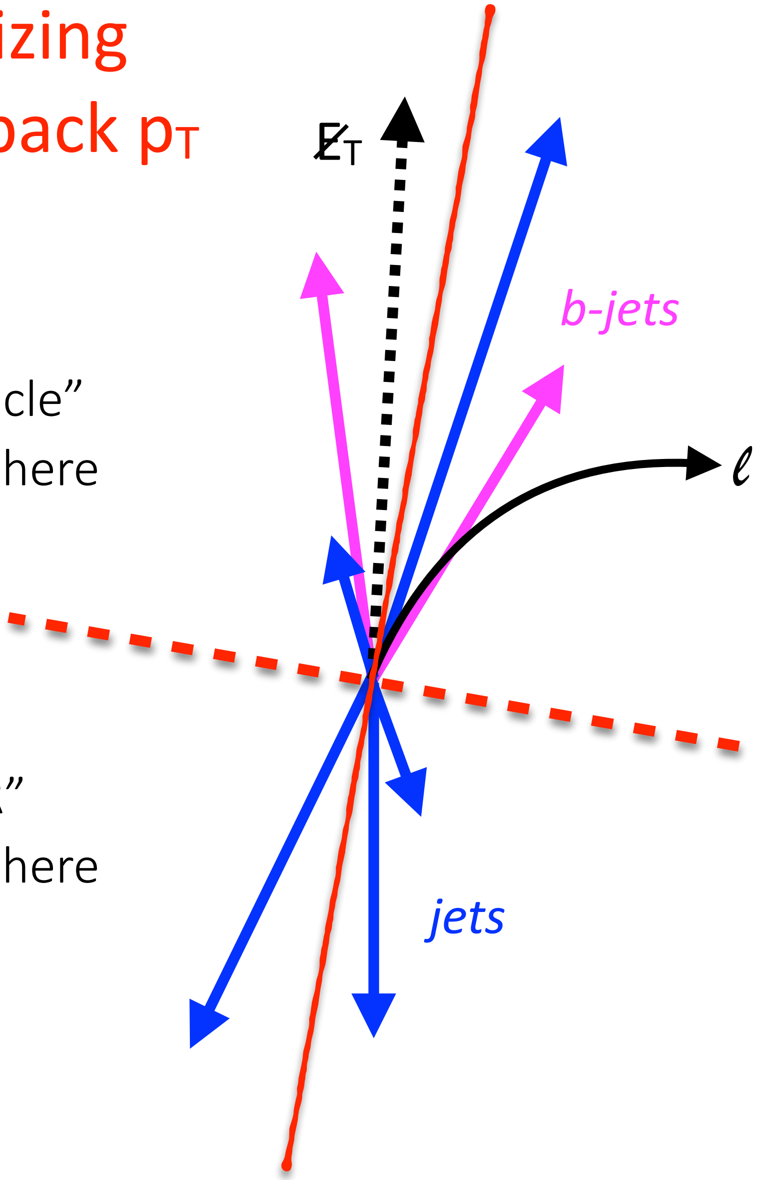


Thrust-Based ISR Identification

easier said than done… among the many jets, which ones are from ISR?

thrust axis: direction maximizing back-to-back p_T



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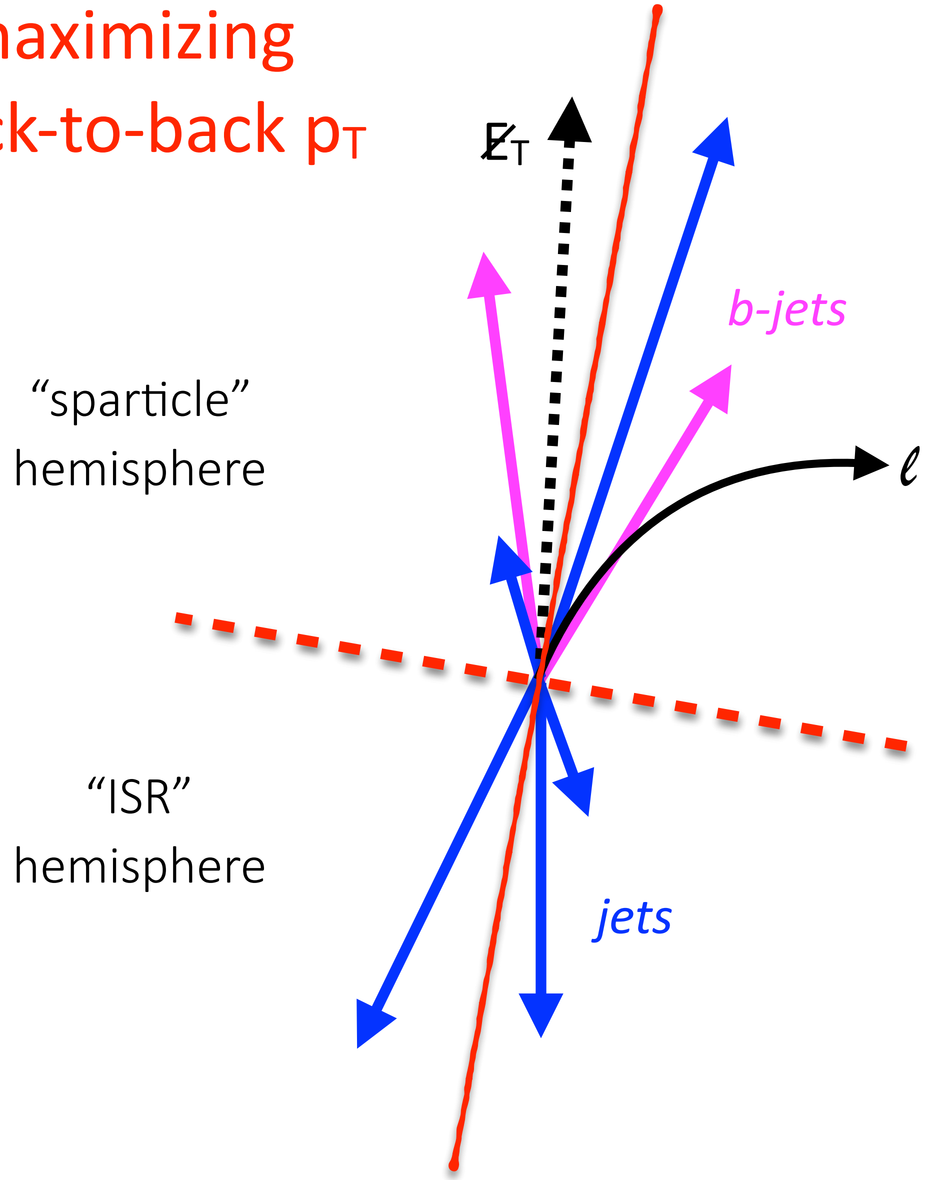

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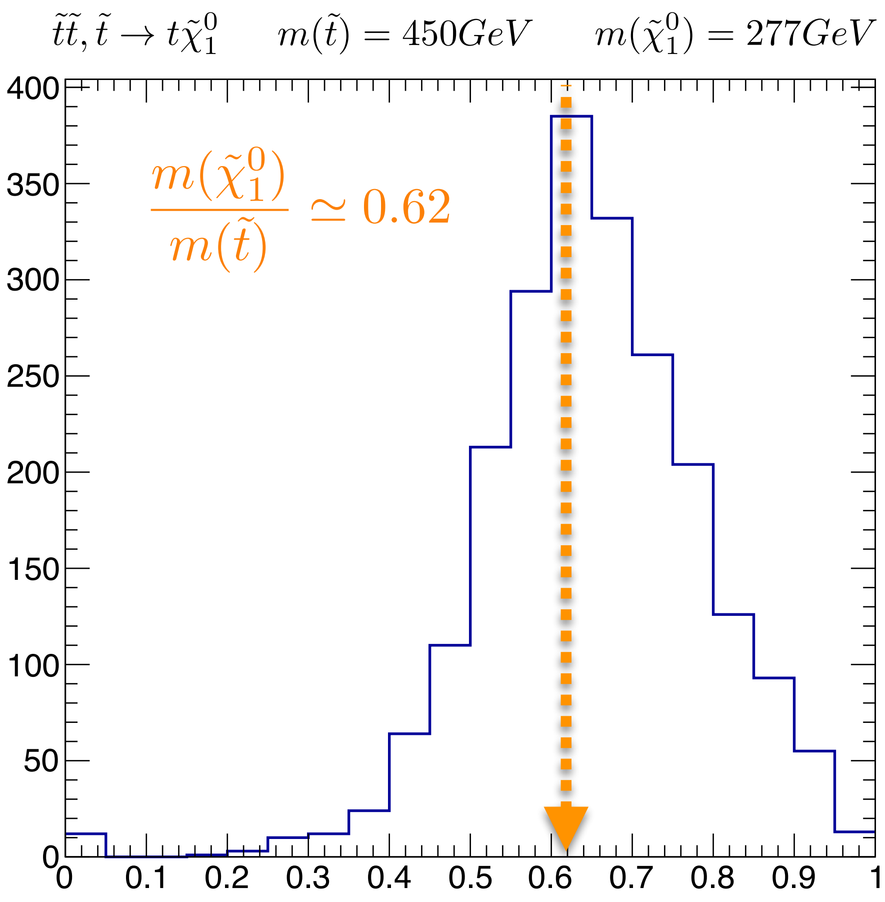


$R_{ISR}=\not{E}_T/p_{T,ISR}$ (thrust-based)

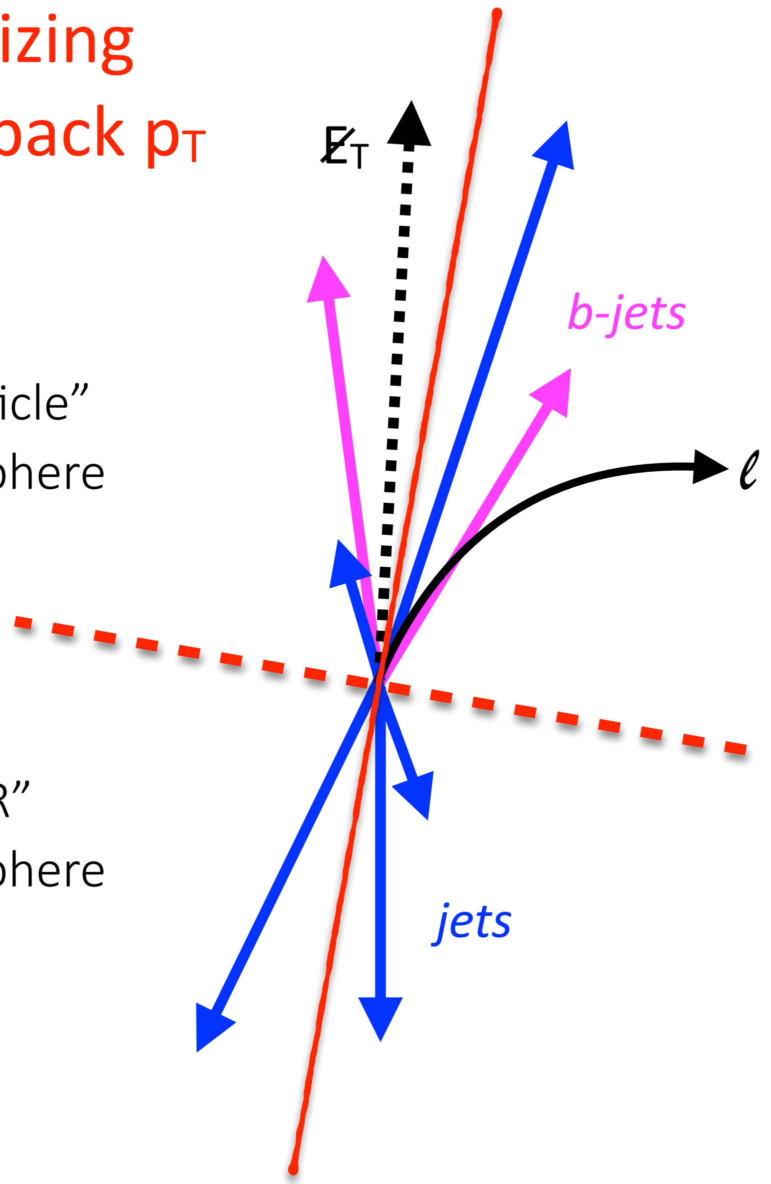
Thrust-Based ISR Identification

easier said than done... among the many jets, which ones are from ISR?

thrust axis: direction maximizing back-to-back p$_T$

“sparticle” hemisphere

“ISR” hemisphere



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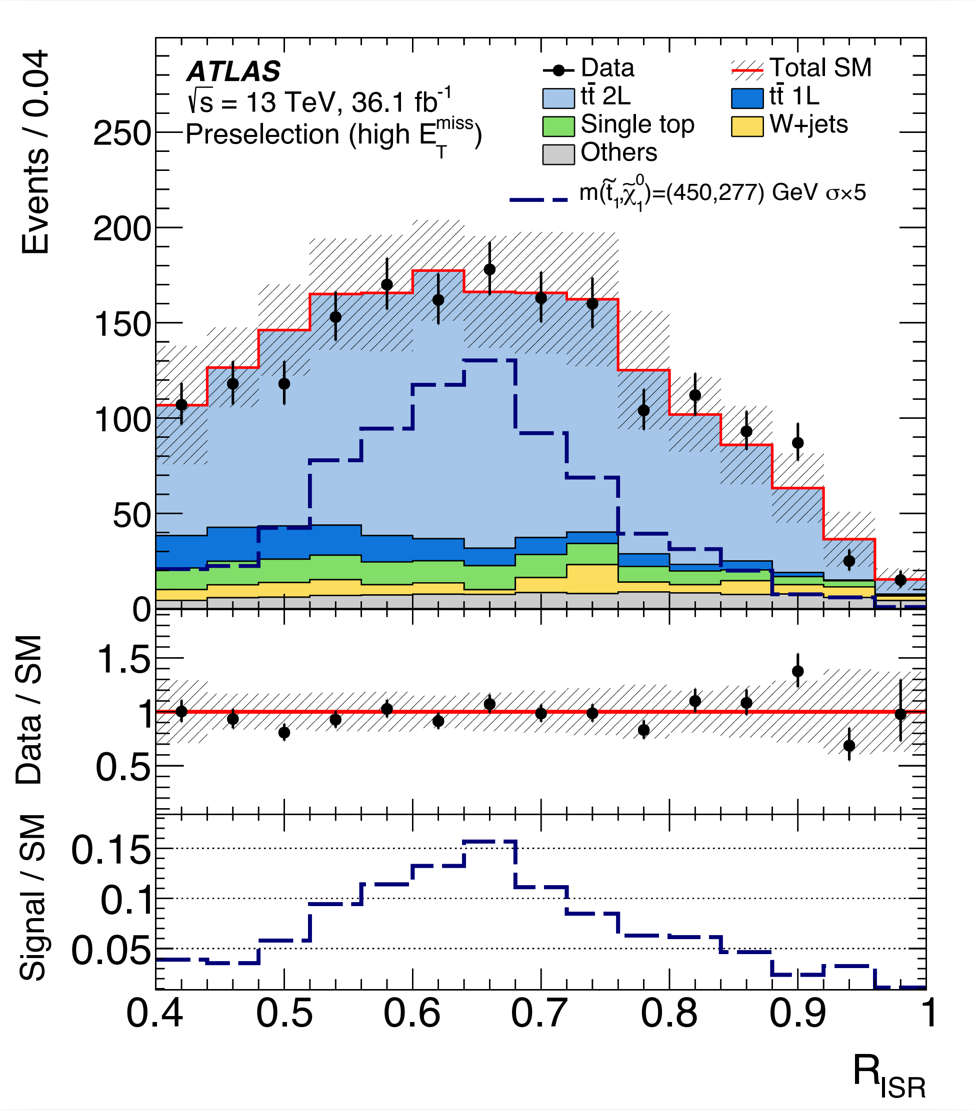
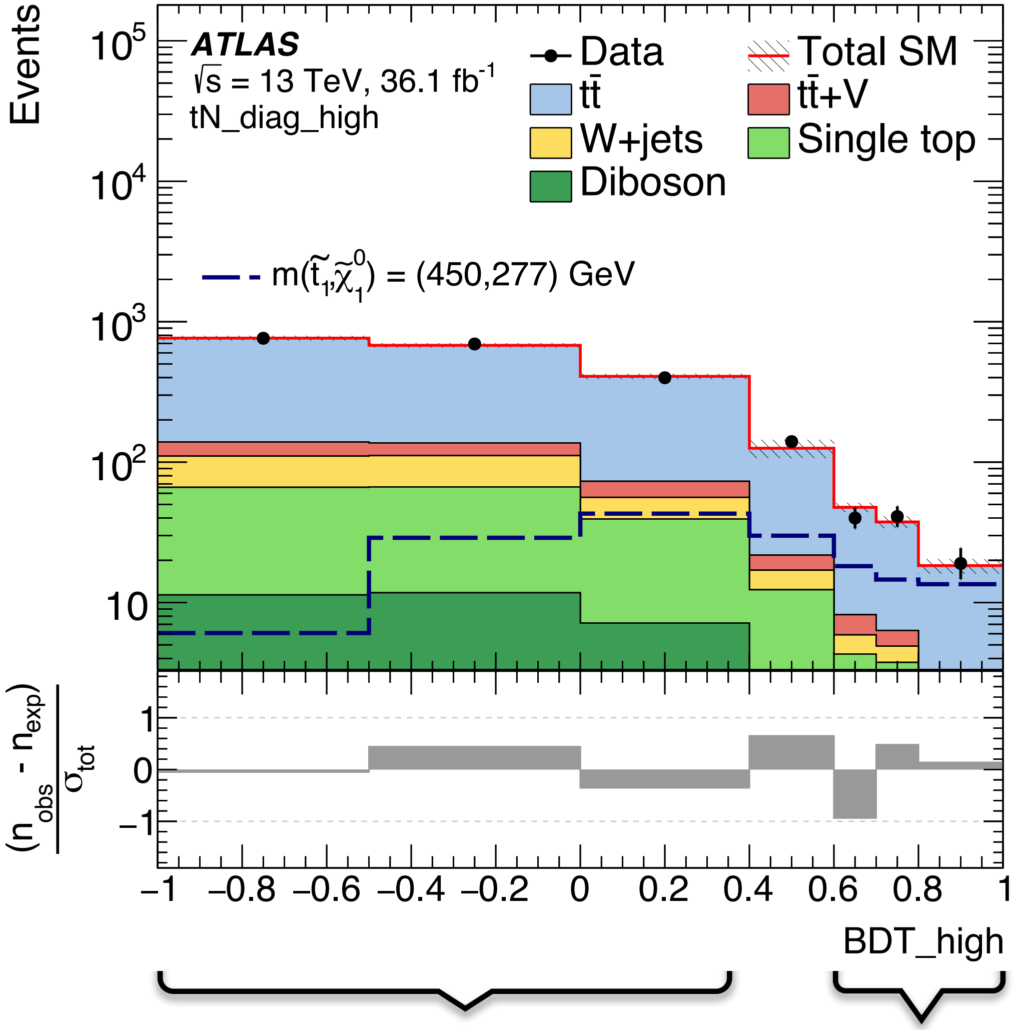


Signal Selection: Boosted Decision Tree (BDT)

Analysis strategy based on BDT discriminant - trained to select *stop* and reject $t\bar{t}$



$t\bar{t}$ control region

signal region

Observed	40	41	19
Total background	47.3 ± 3.6	37.5 ± 3.5	18.3 ± 2.2

10 variables used, some computed using thrust-based ISR identification (e.g. R_{ISR})

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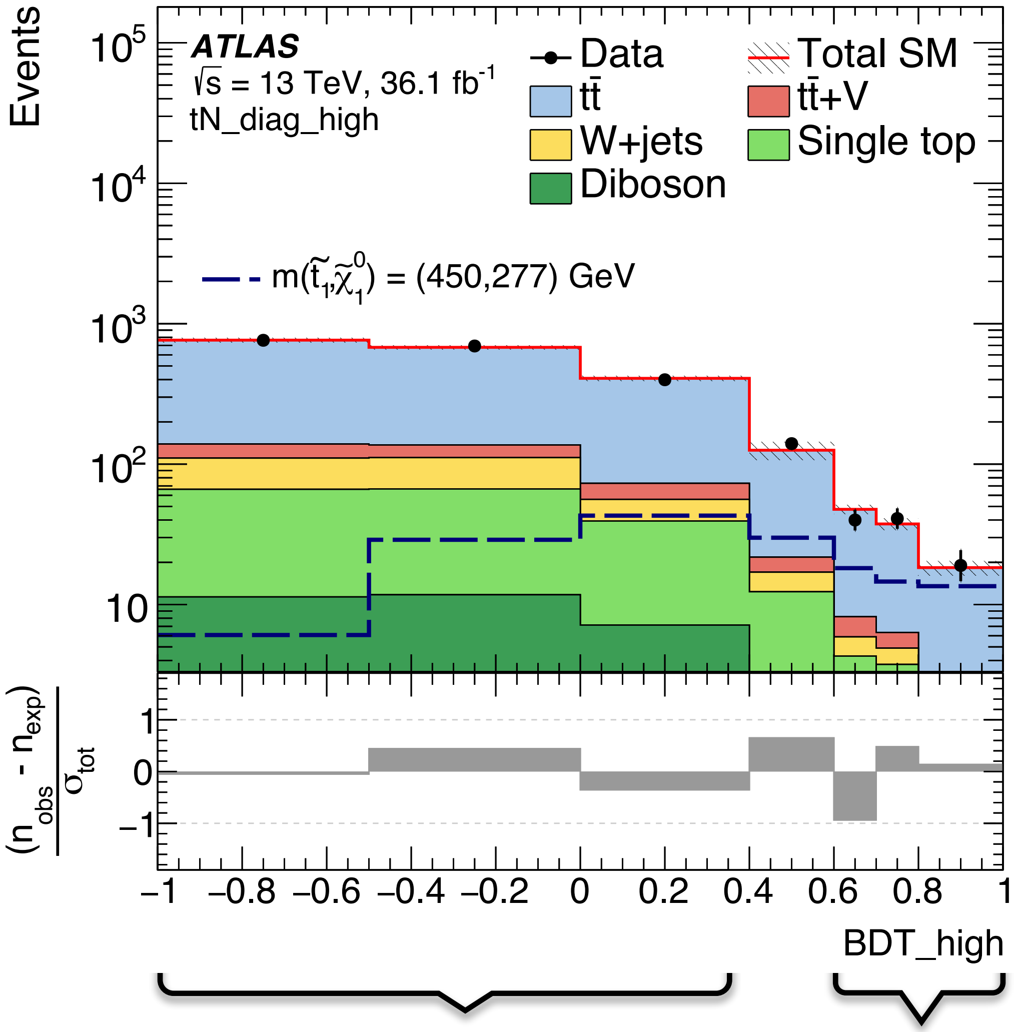
Analysis strategy based on BDT discriminant - trained to select *stop* and reject $t\bar{t}$



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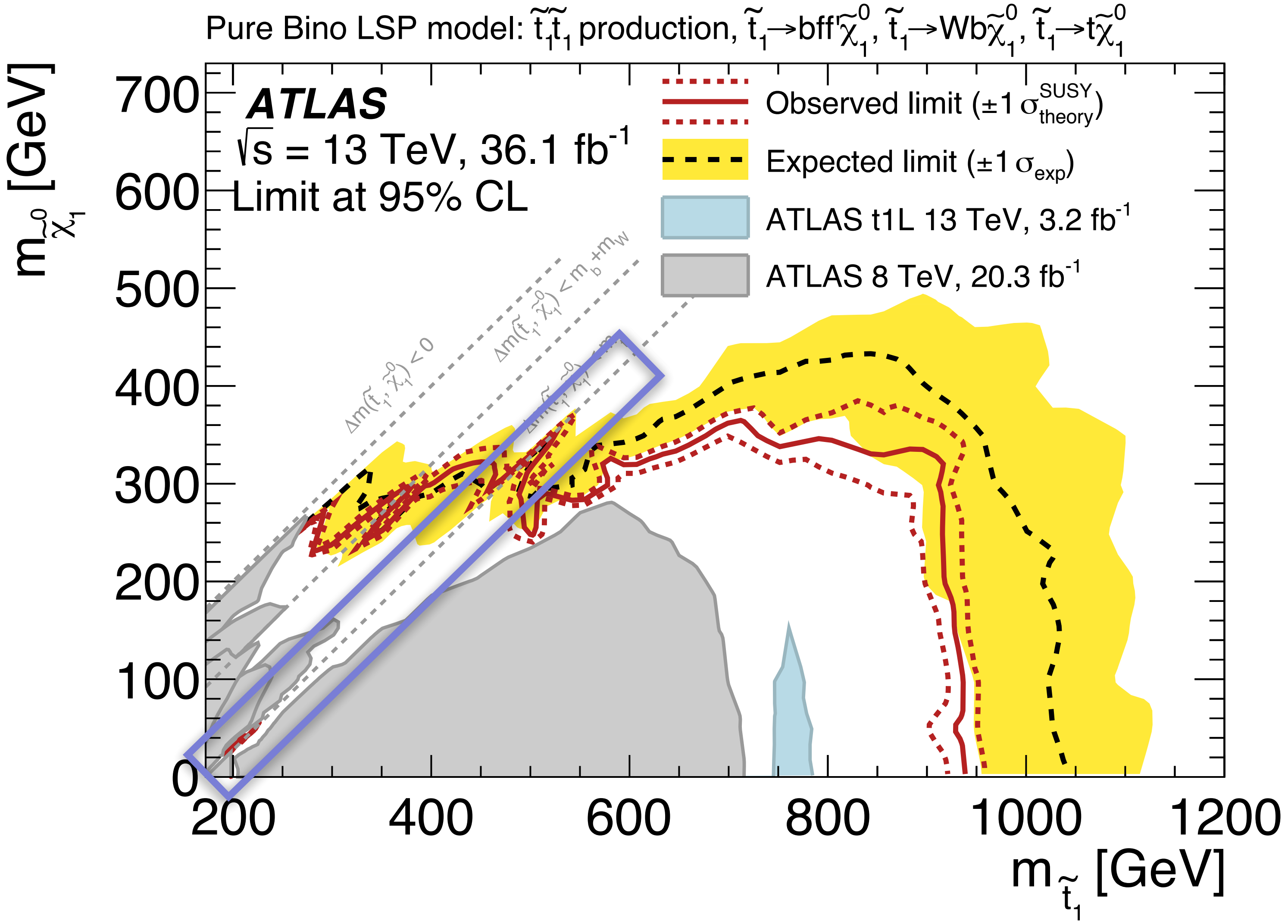
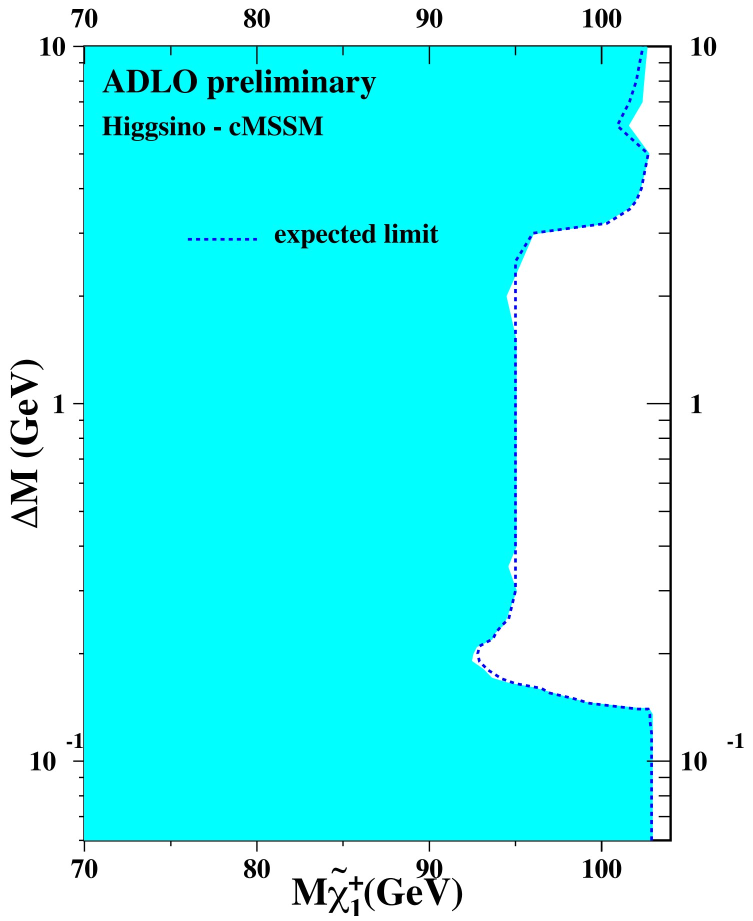


10 variables used, some computed using thrust-based ISR identification (e.g. R_{ISR})

Hunting for Natural SUSY at the LHC

Part III - The Higgsinos

Excluded up to 110 GeV at LEP



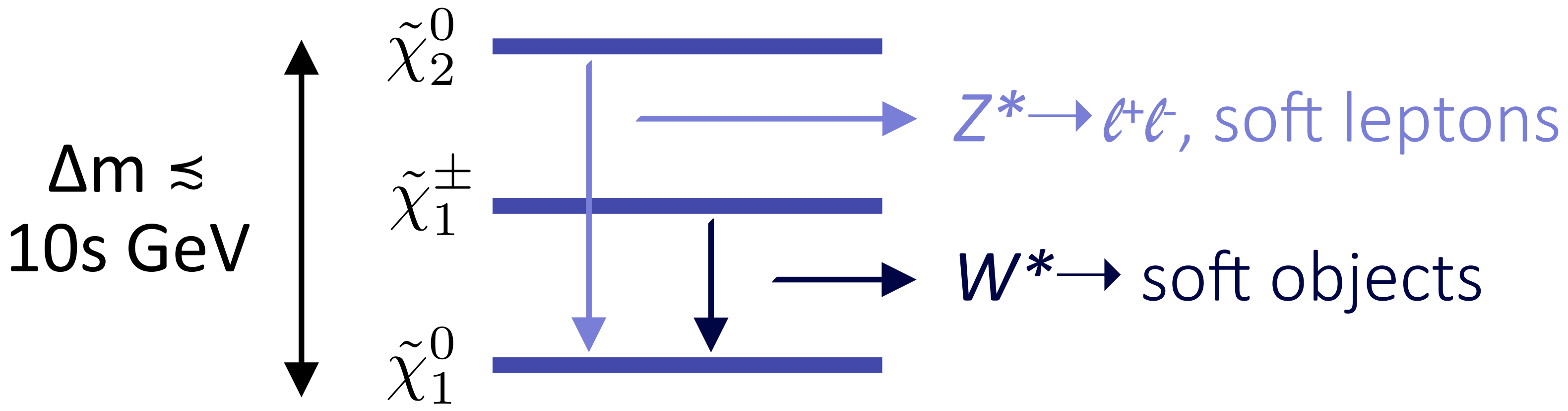
Hunting Higgsinos

As for “diagonal” stop, sensitivity driven by ISR-induced MET

$\not\!\!E_T$ is the only way we can *trigger* on these events

Higgsinos mix with other EWKinos:

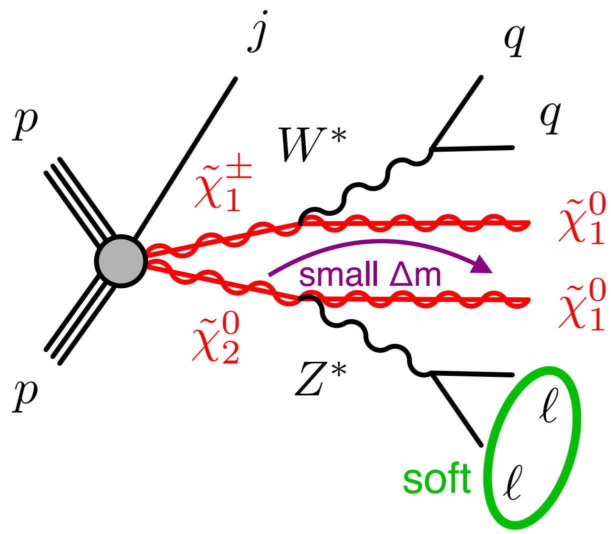
multiplets of neutralinos and charginos



Δm ≲ 10s GeV

$Z^* \rightarrow \ell^+\ell^-$, soft leptons

$W^* \rightarrow$ soft objects



Main analysis challenge: soft leptons!

Hunting Higgsinos

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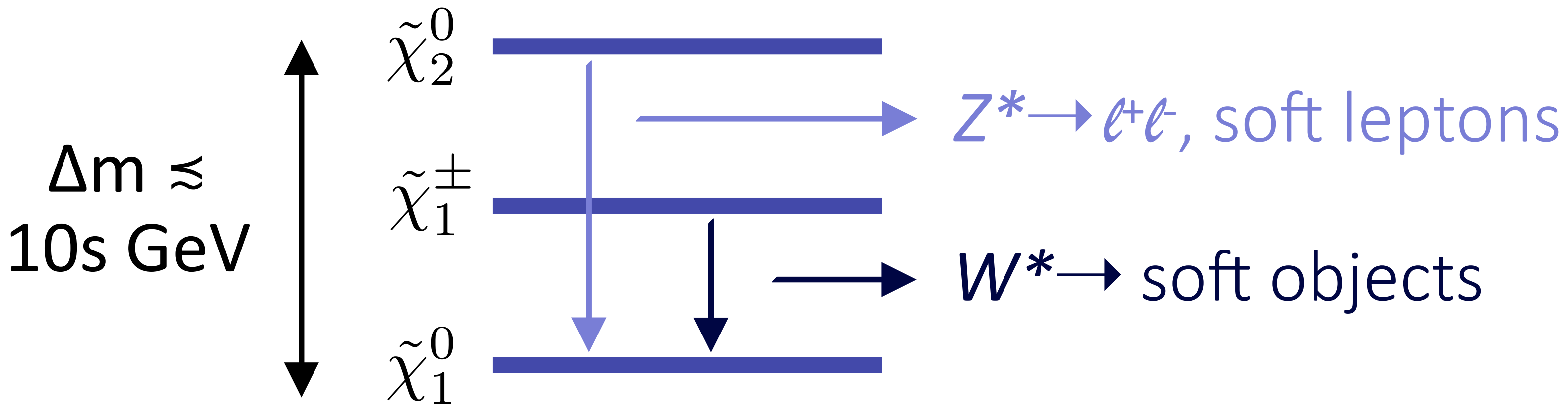

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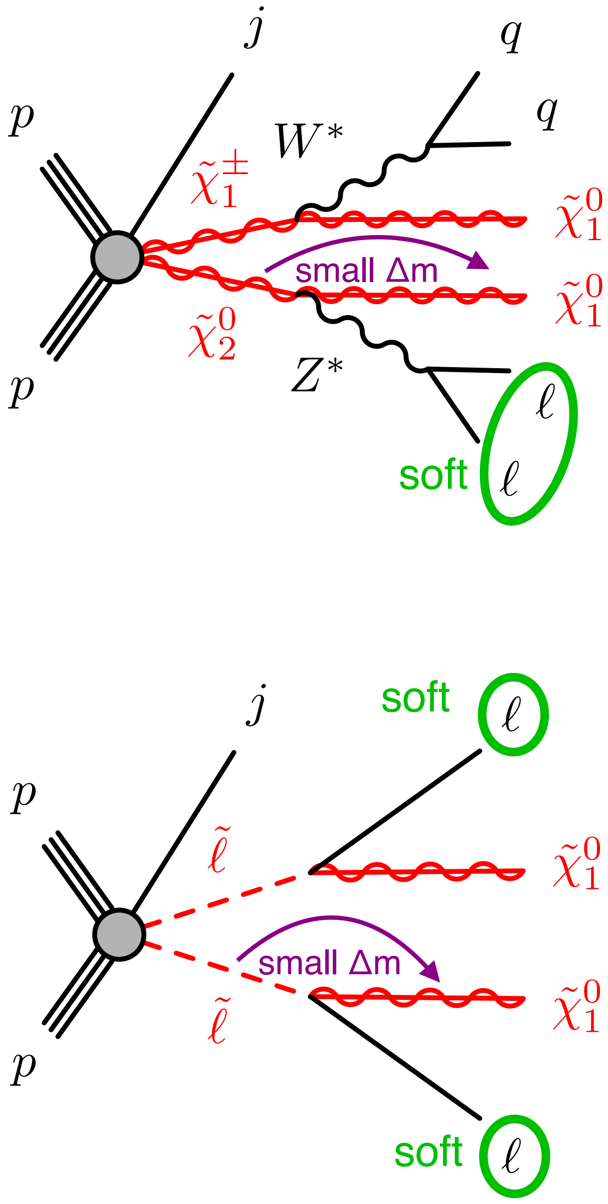


Main analysis challenge: soft leptons!

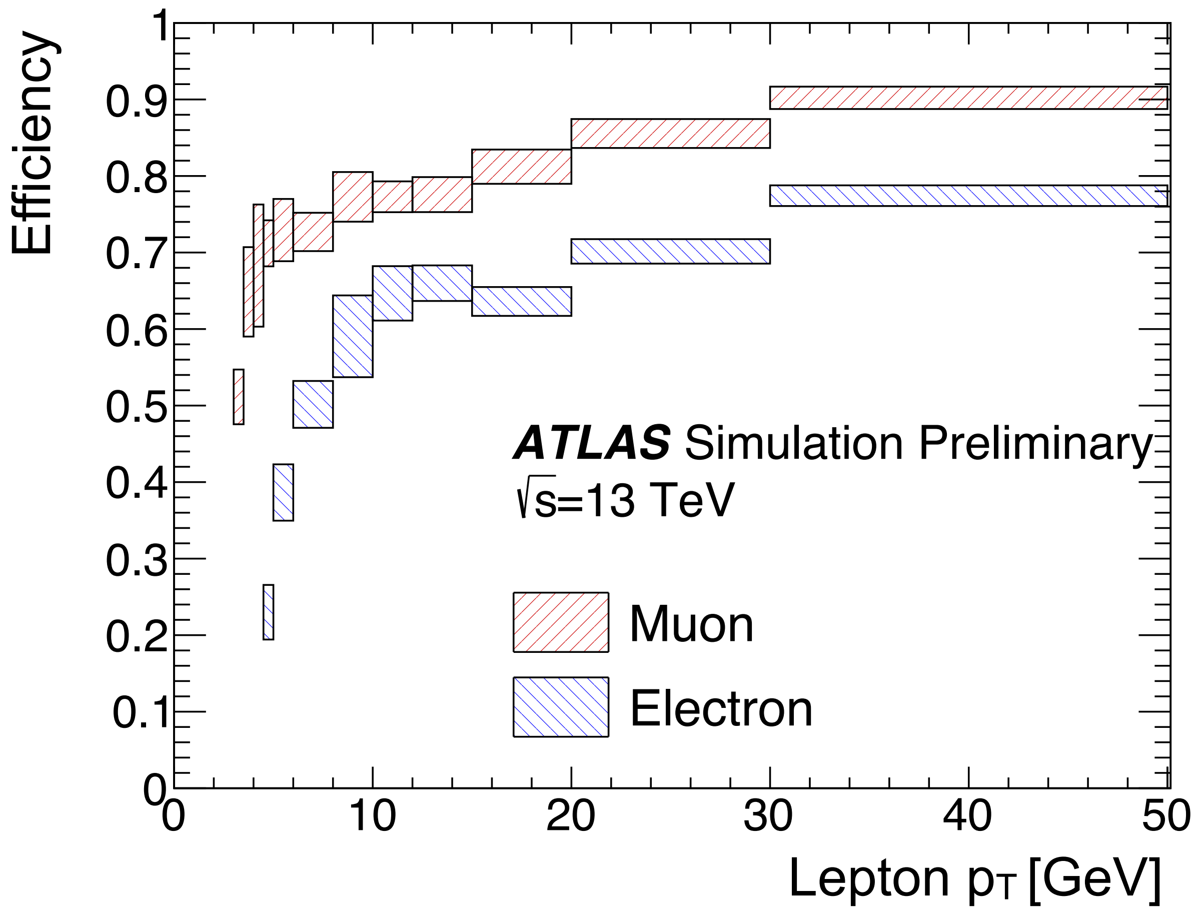
Low-p_T Leptons: Performance

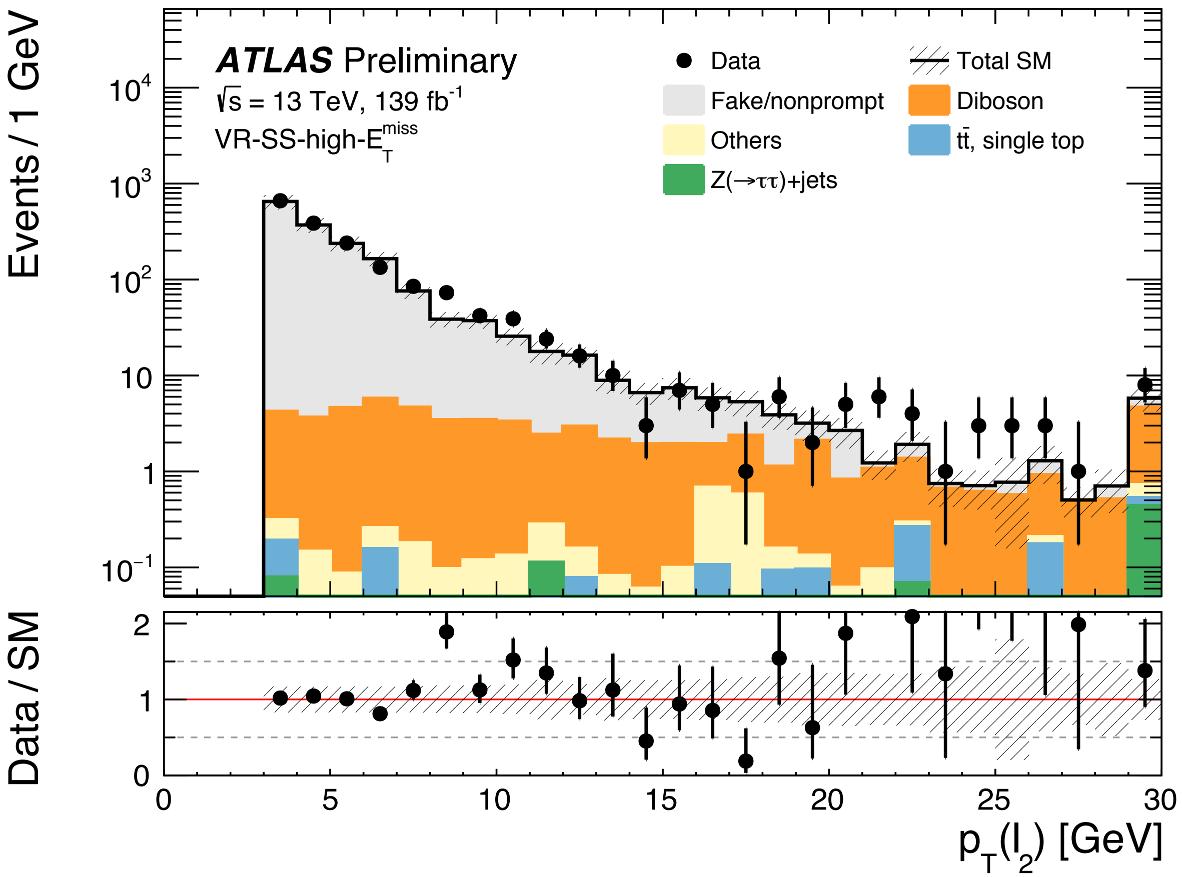
Quasi-degenerate higgsinos decay into final states with ***soft leptons***

Analysis' sensitivity completely driven by soft lepton performance!

key to *signal acceptance…* …and *background rejection* (lepton mis-ID)

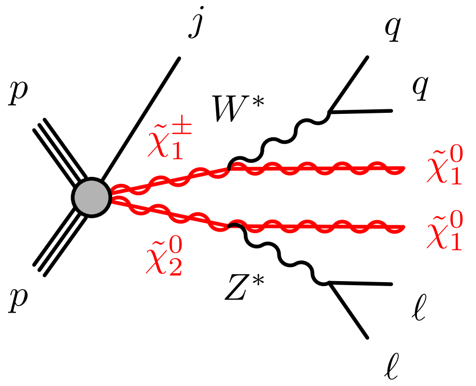
also connected to ***largest source of uncertainty*** in the analysis!



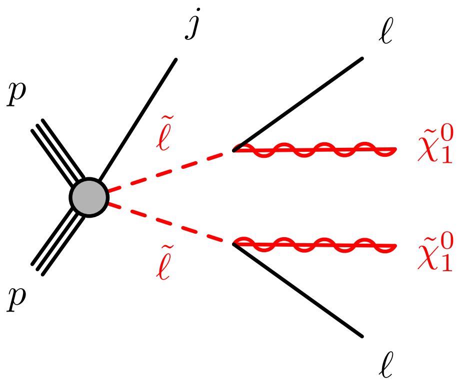


Signal Selection

Key variables: $m_{\ell\ell}$ (higgsinos) or m_{T2} (sleptons)

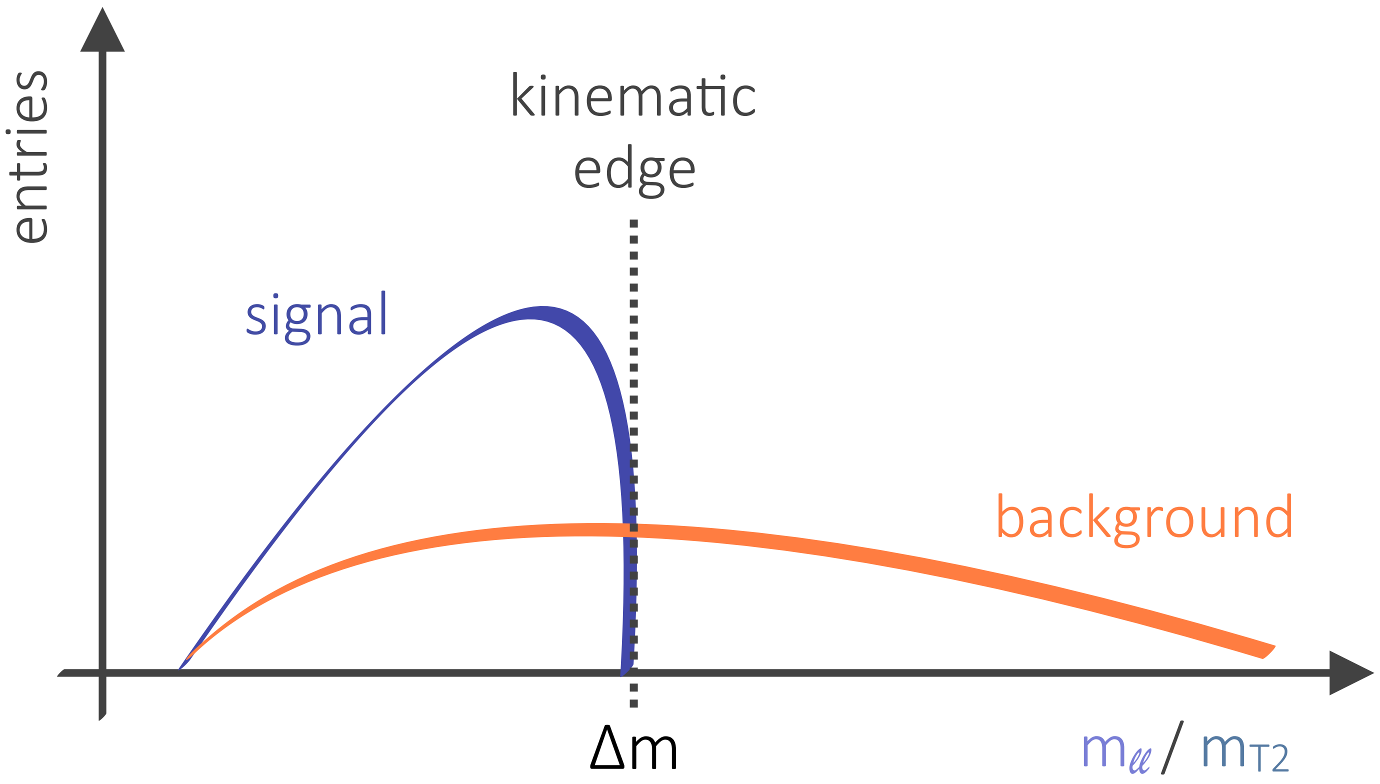


expect kinematic edge in $m_{\ell\ell}$ at $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$



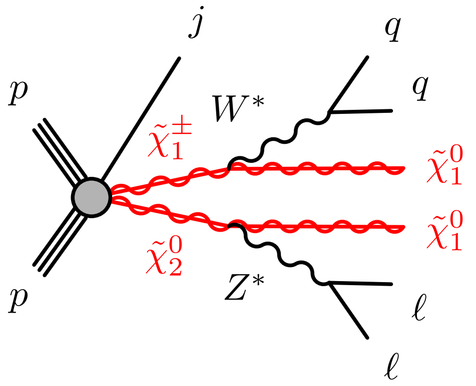
expect kinematic edge in m_{T2} at $\Delta m(\tilde{\ell}, \tilde{\chi}_1^0)$

Analysis strategy: *fit to* distribution's shape!



2017 Results

Key variables: $m_{\ell\ell}$ (higgsinos) or m_{T2} (sleptons)



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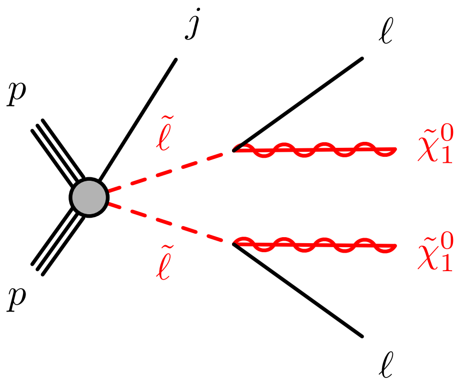

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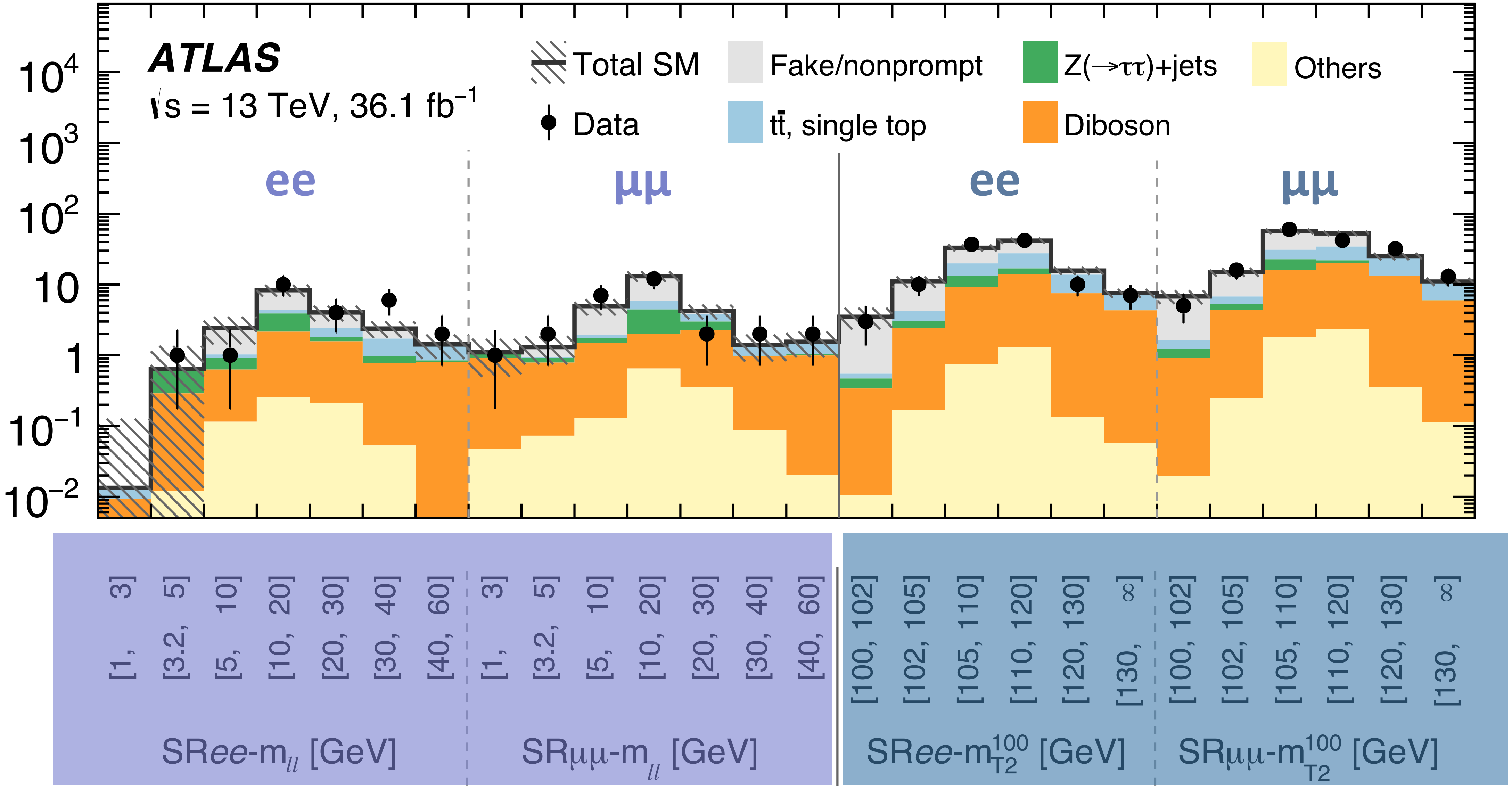
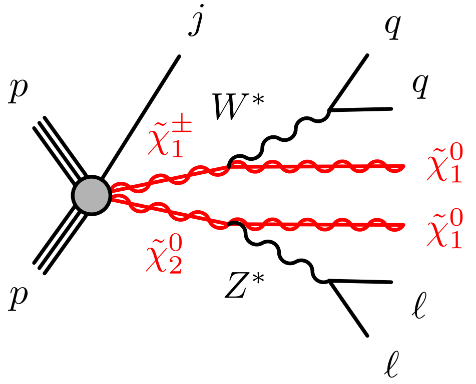
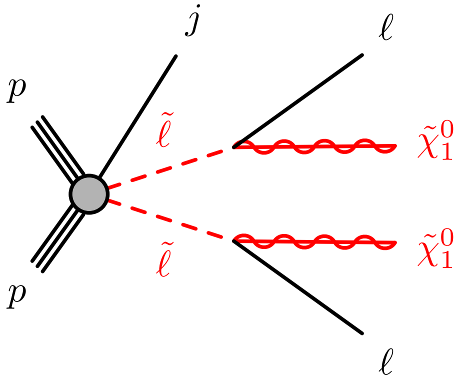


2017 Results

Key variables: $m_{\ell\ell}$ (higgsinos) or m_{T2} (sleptons)



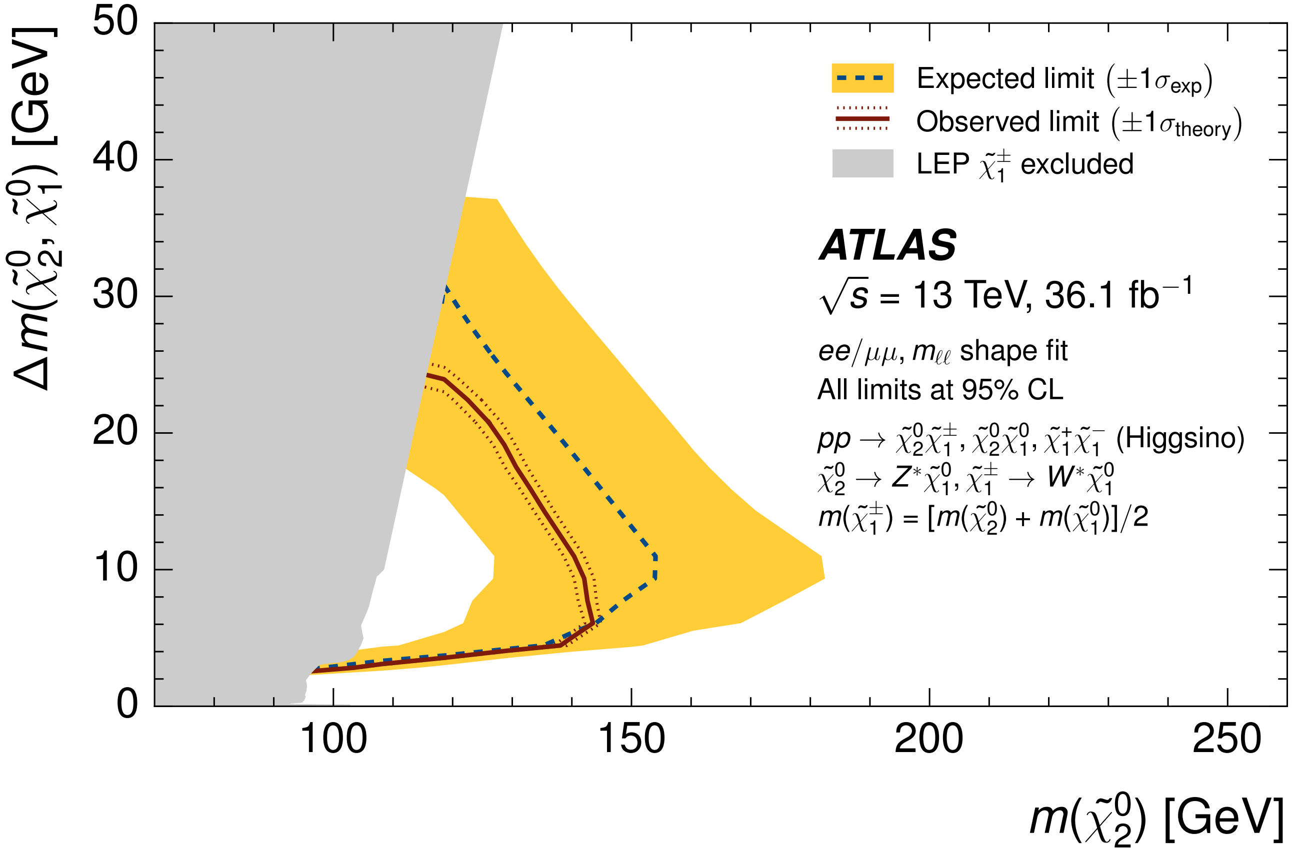
expect kinematic edge in $m_{\ell\ell}$ at $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$



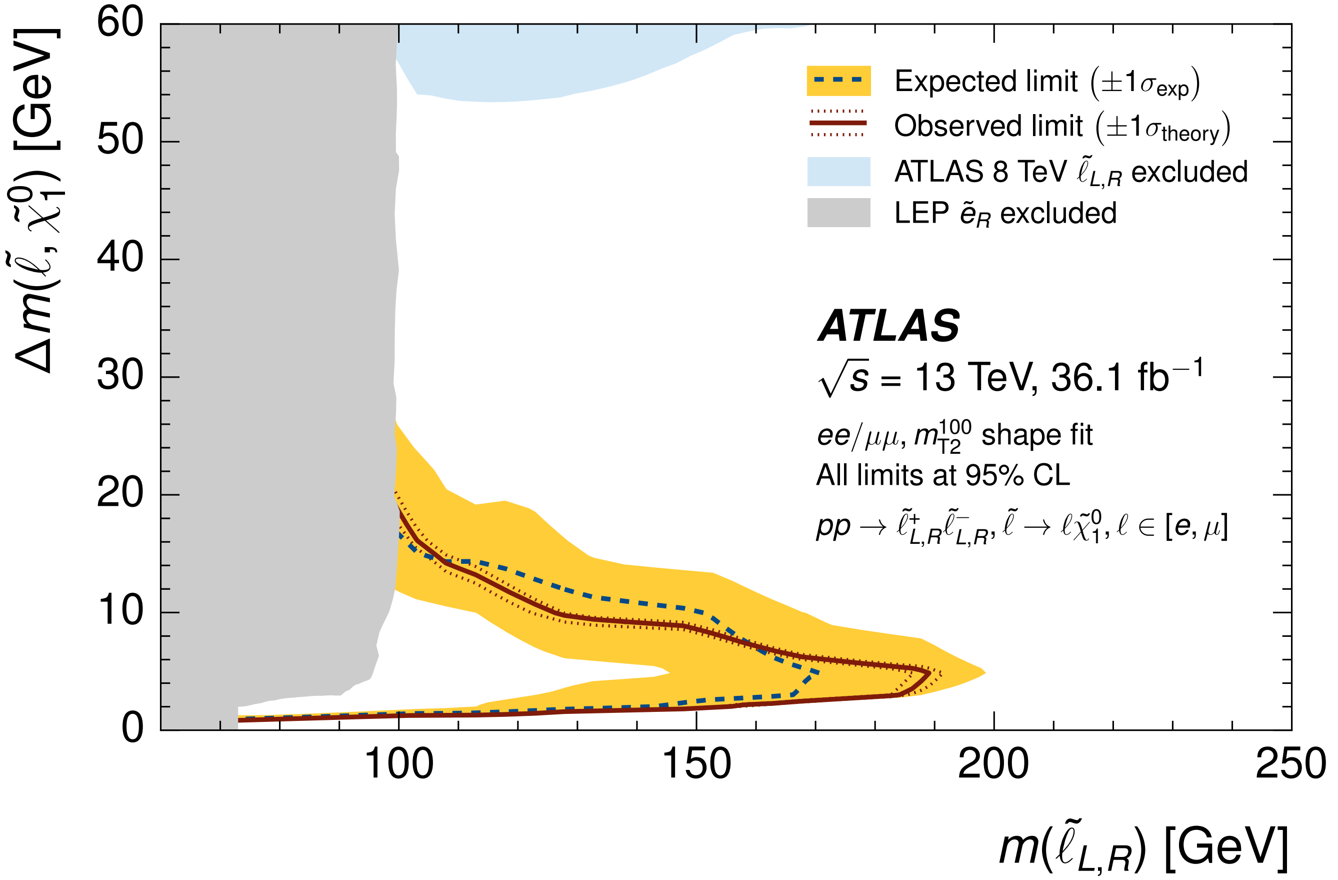
expect kinematic edge in m_{T2} at $\Delta m(\tilde{\ell}, \tilde{\chi}_1^0)$

No significant excess: model-dependent exclusion limits (95% CL) extracted

Higgsinos: shape fit to $m_{\ell\ell}$



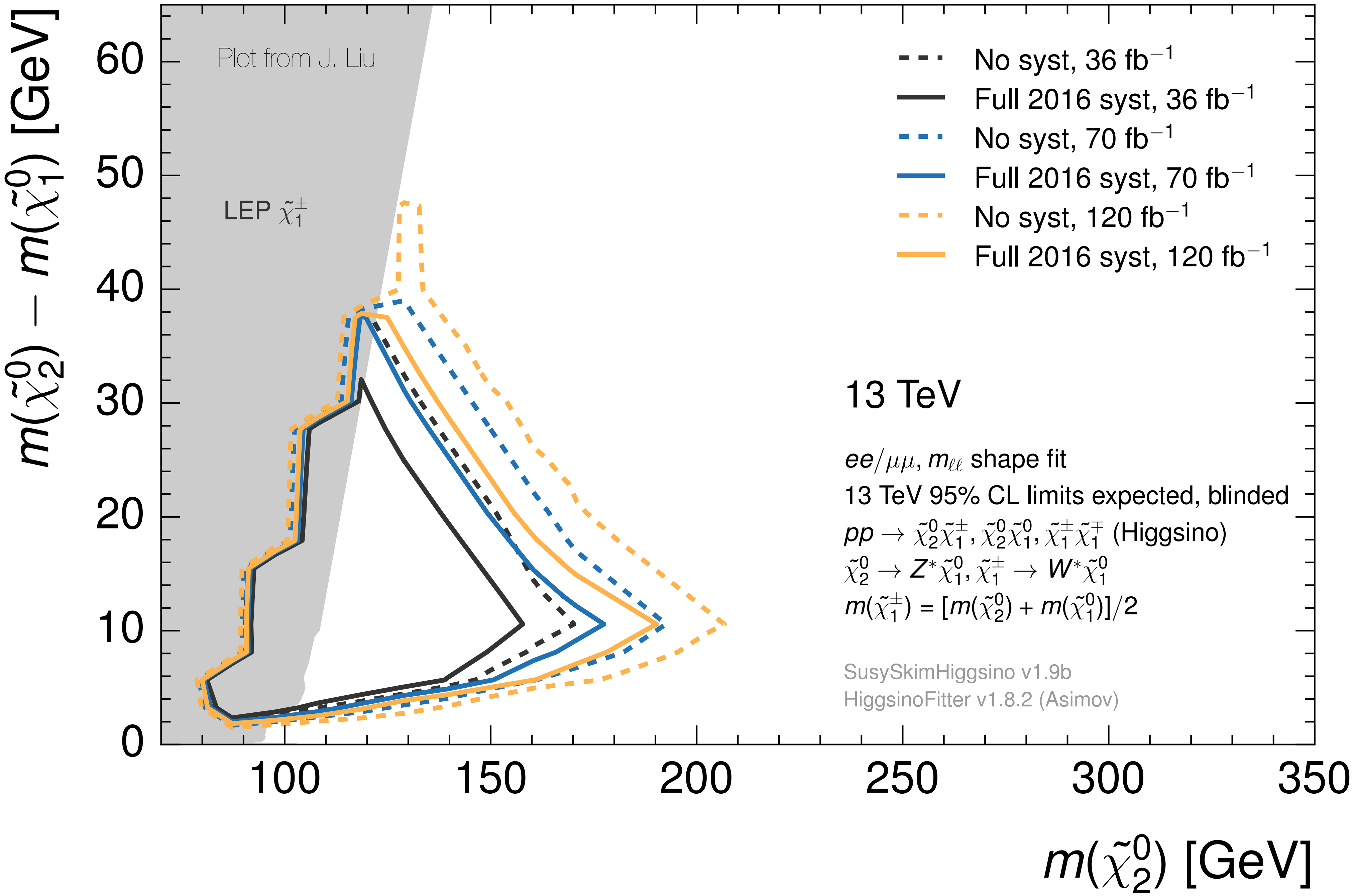
Sleptons: shape fit to m_{T2}



2017 Results ➙ Full √s=13 TeV Dataset?

x3 data now available: however, modest increase in mass reach expected

At *pp* colliders, sensitivity of searches for new (heavy) physics mostly driven by √s



2017 Results → Full √s=13 TeV Dataset?

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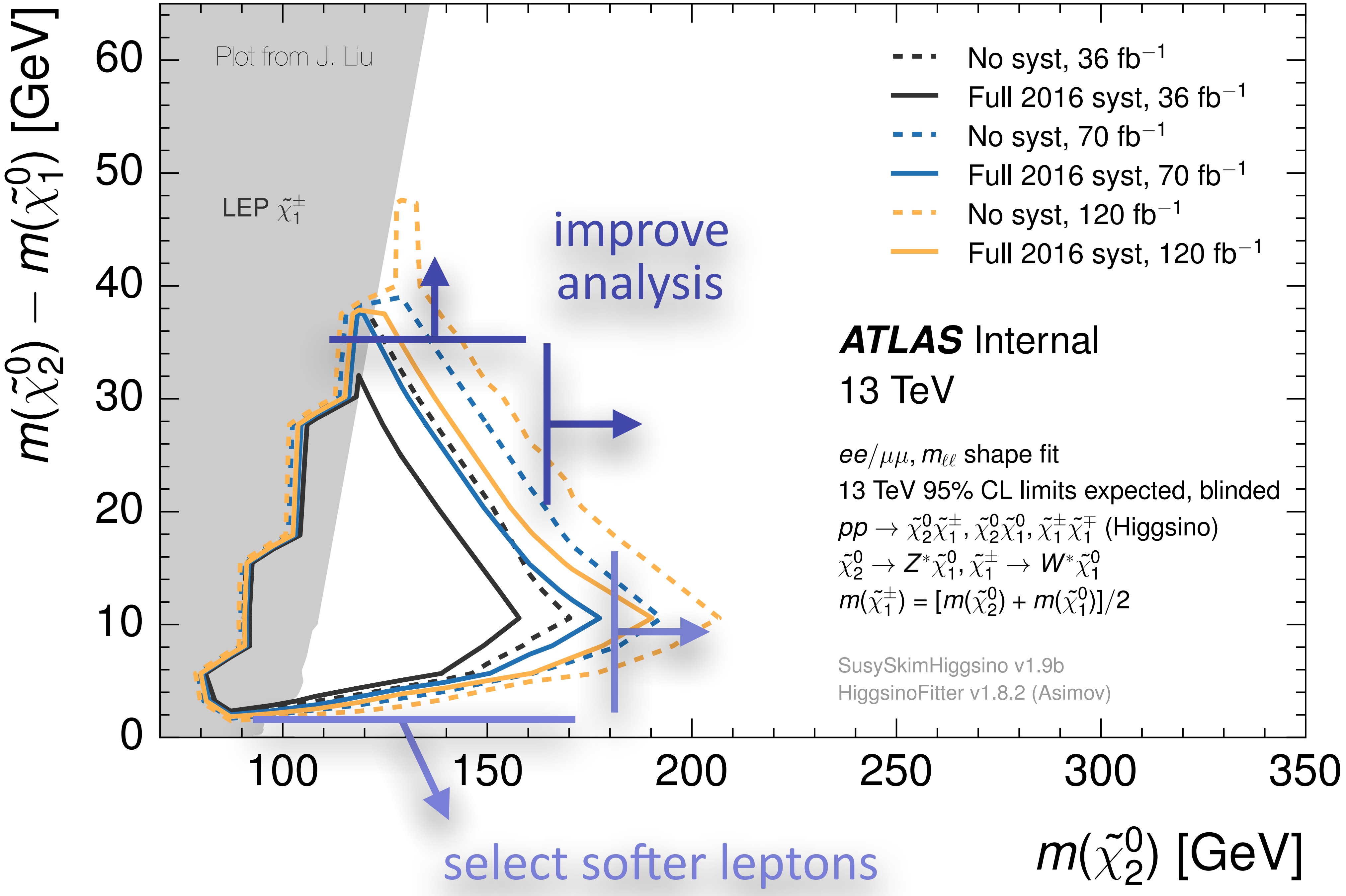


Reconstructing ≈3 GeV Muons

Muons identified requesting 2 muon spectrometer "stations" in coincidence

↳ further, tracks in the spectrometer and inner detector are matched

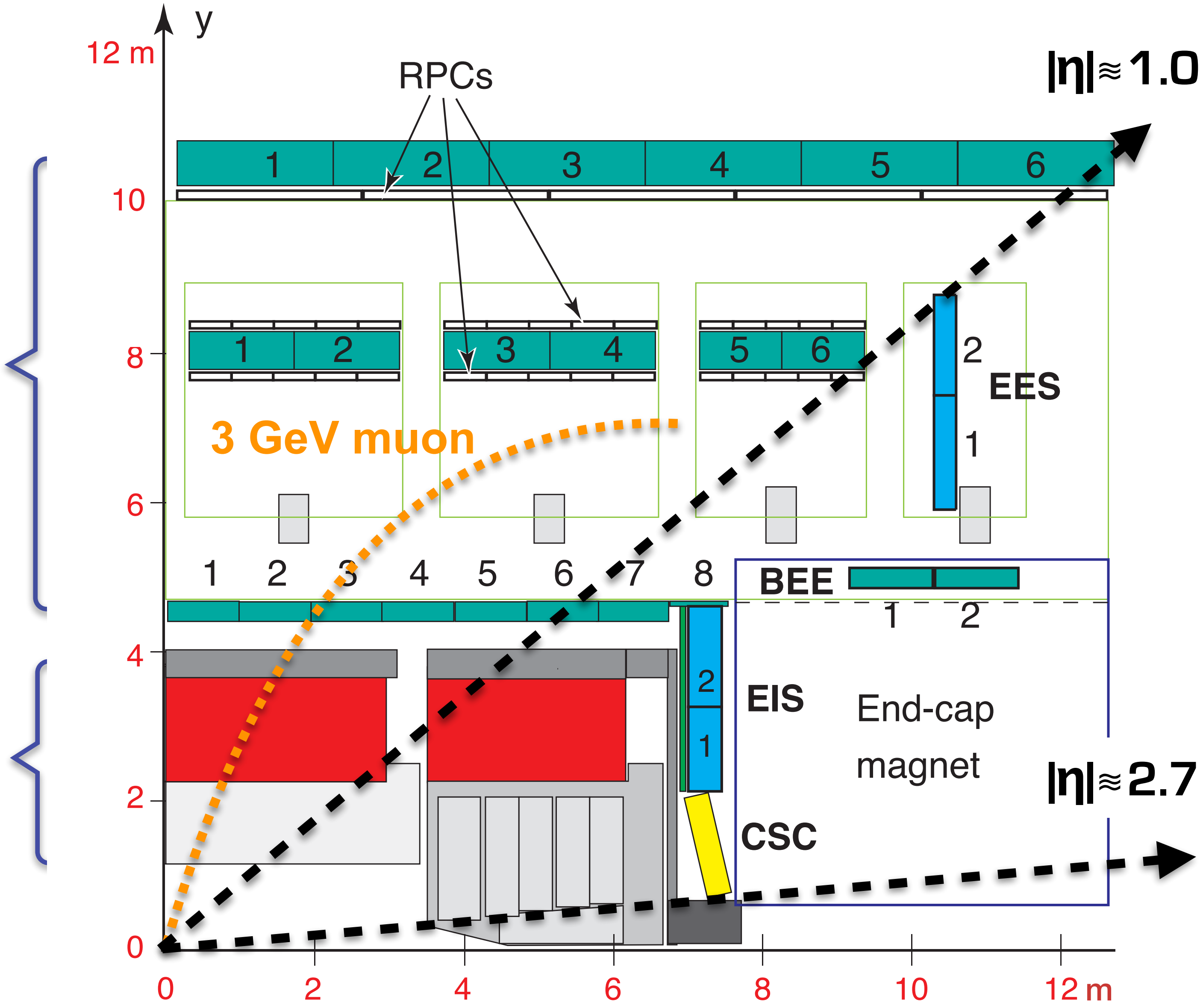
Muon Spectrometer

On average, B-field bending power requires *0.5-1 GeV to reach 2nd station*

Calorimeters

muons are M.I.P., and *lose about 3 GeV of their energy* In the calorimeters

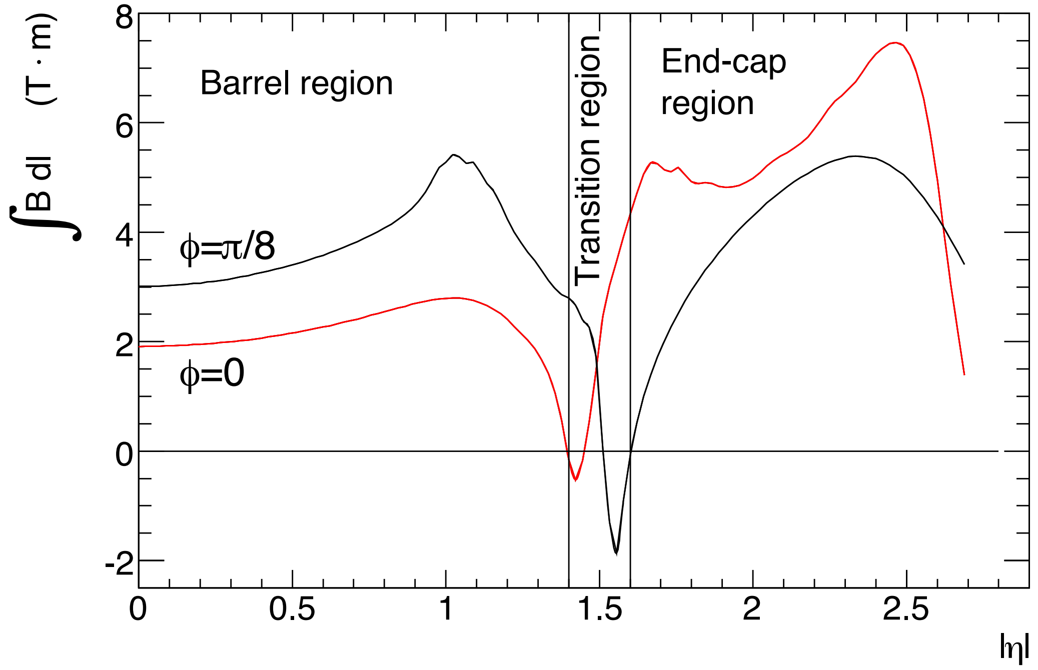
schematics of ATLAS (central part)

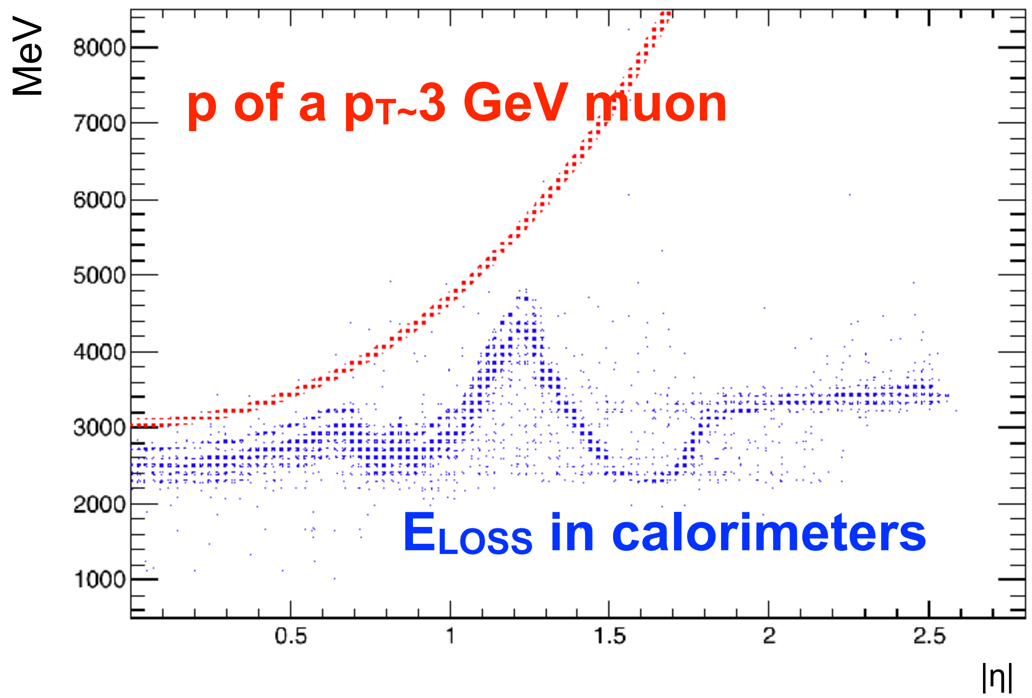


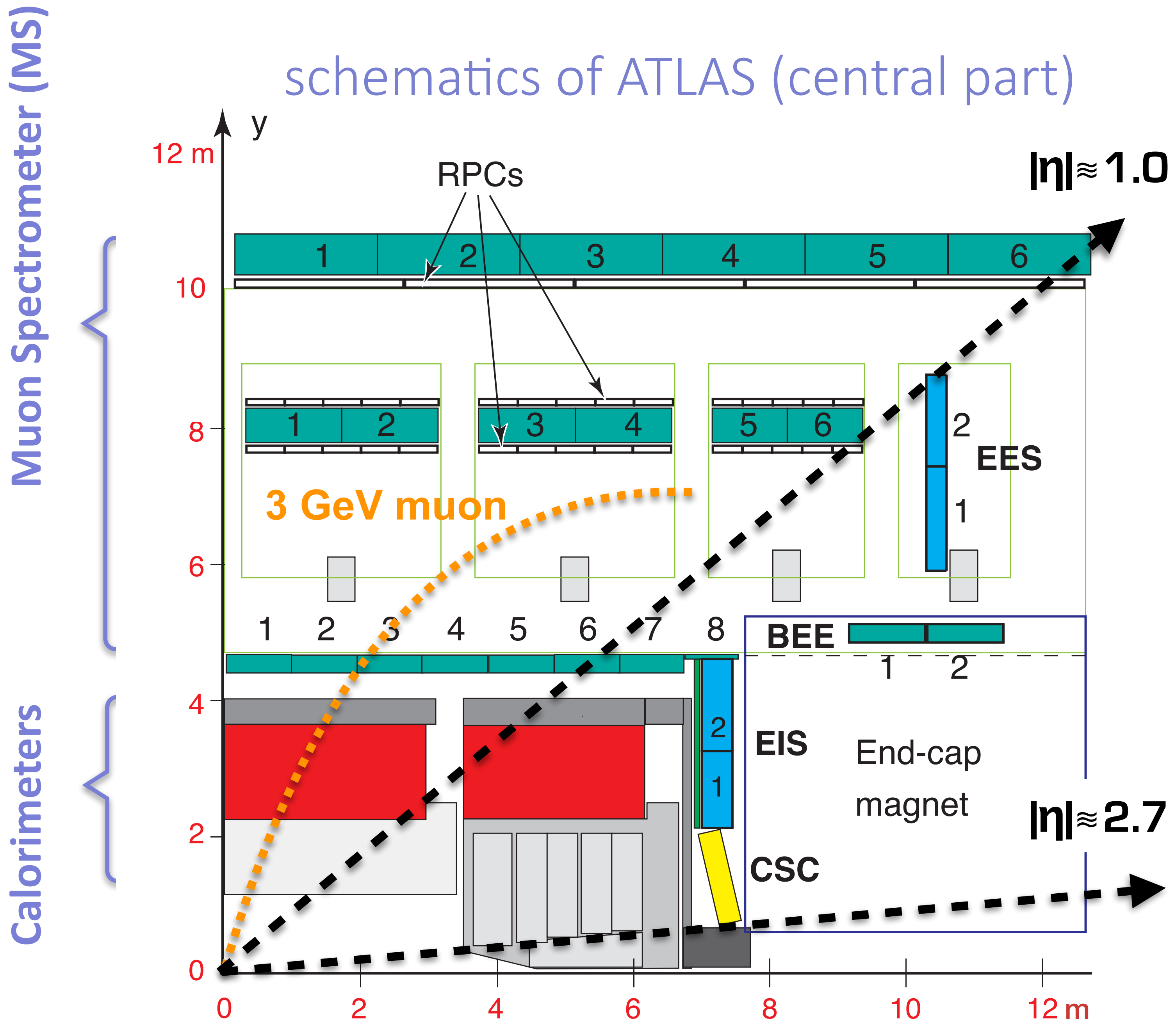
Reconstructing ≈3 GeV Muons

Muons identified requesting 2 muon spectrometer “stations” in coincidence

↳ to reach second station, need $p[GeV] = 0.3 * r[m] * B[T] \approx 0.5\text{-}1.0$ GeV






schematics of ATLAS (central part)

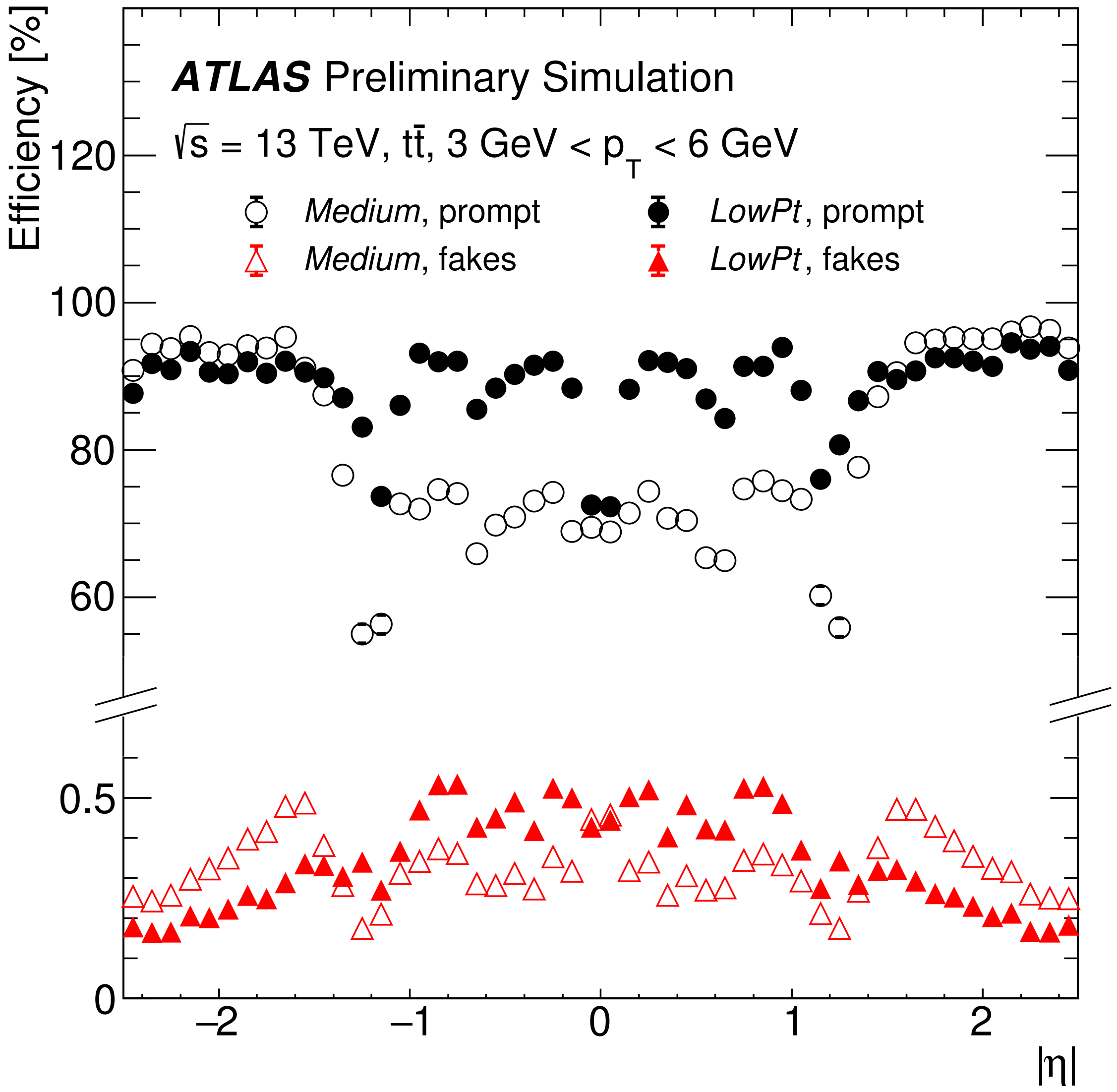
Reconstructing ≈3 GeV Muons

Muons identified requesting 2 muon spectrometer "stations" in coincidence

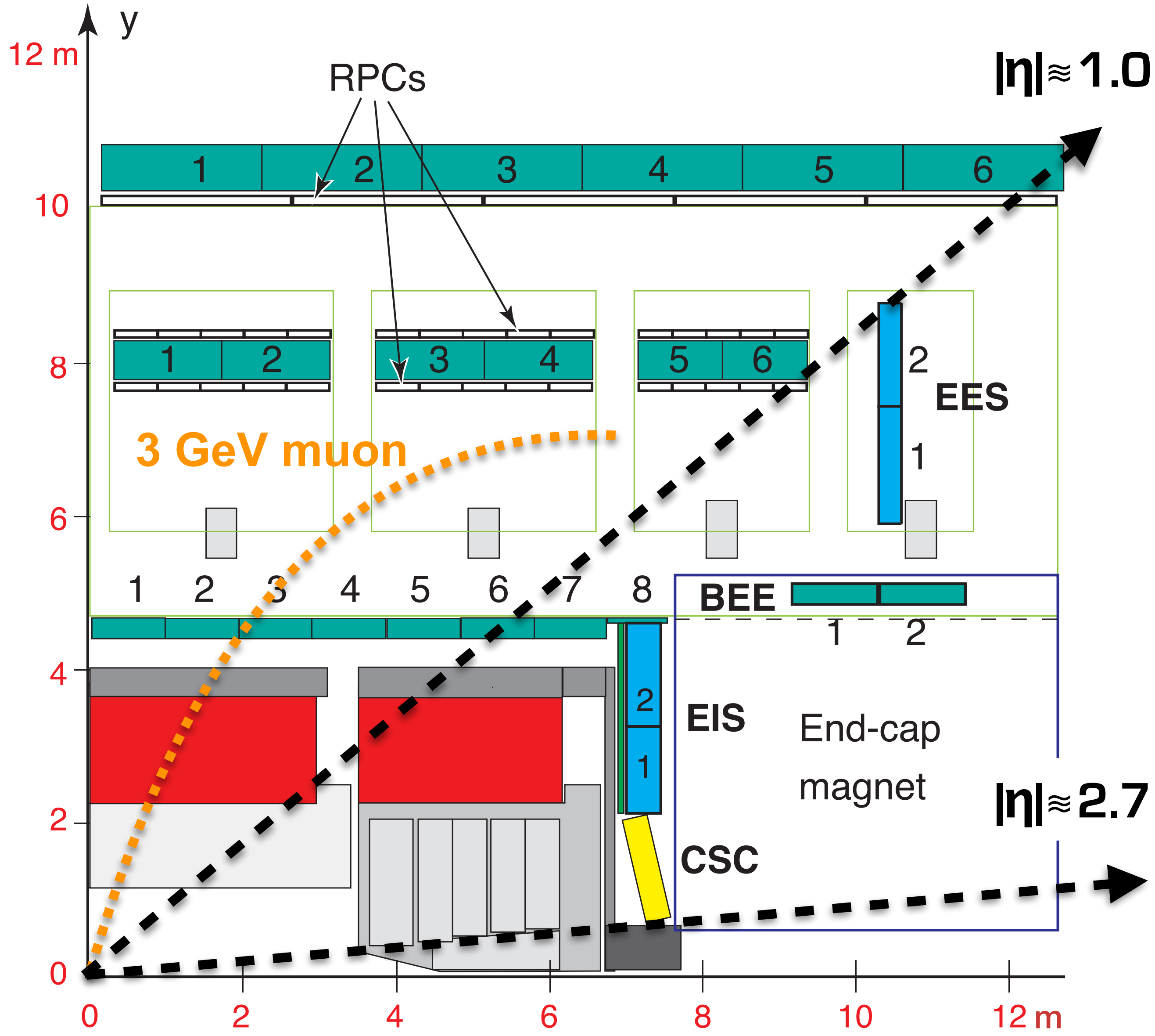
↳ to reach second station, need $p[GeV] = 0.3 * r[m] * B[T] \approx 0.5\text{-}1.0$ GeV

New PID for soft muons

allows for "1-station" tracks

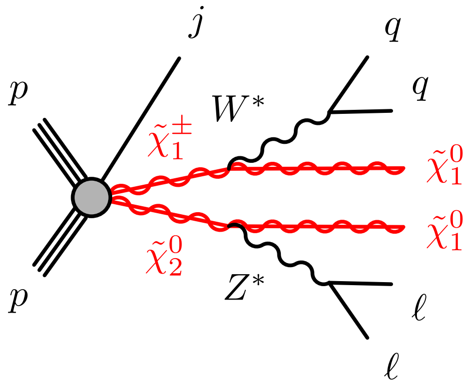


schematics of ATLAS (central part)



Exclusion Limits

Key variables: $m_{\ell\ell}$ (higgsinos) or m_{T2} (sleptons)



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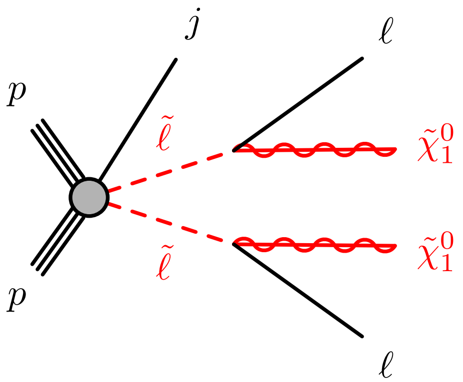

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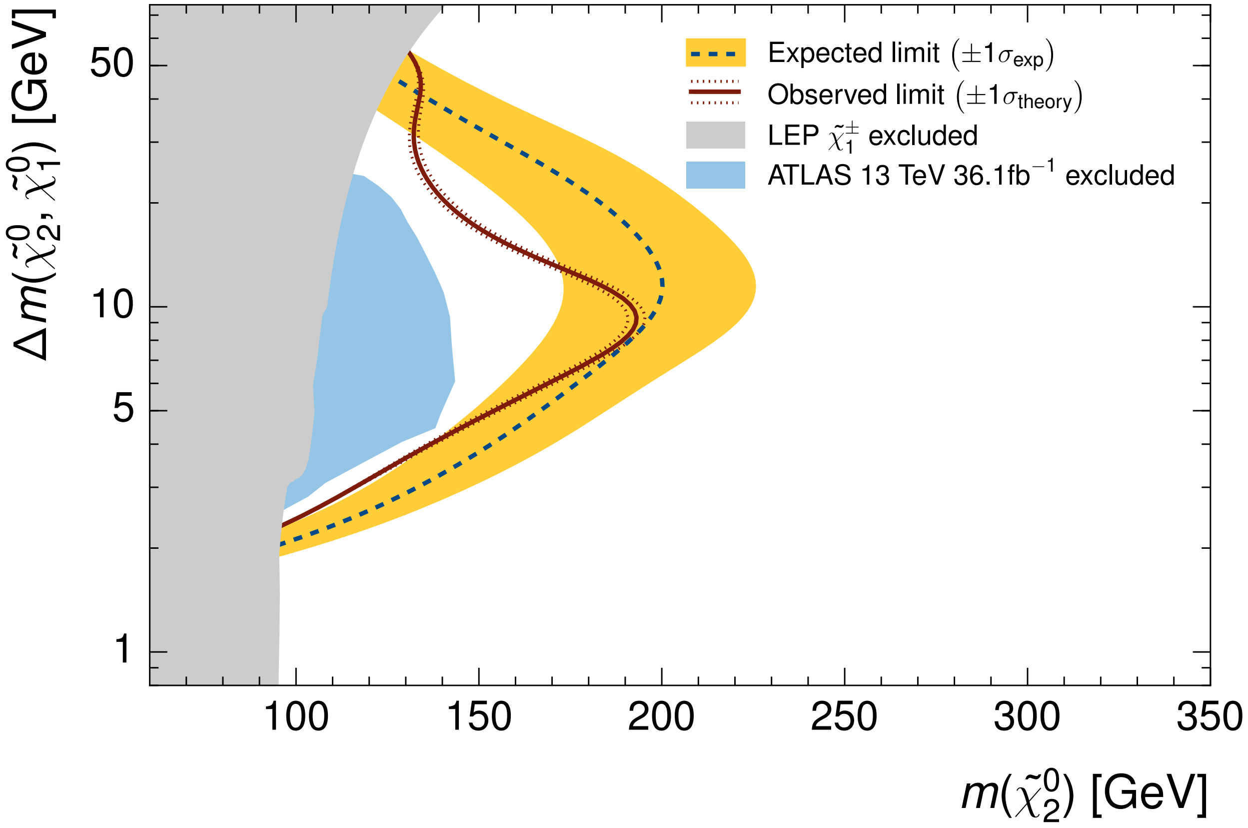
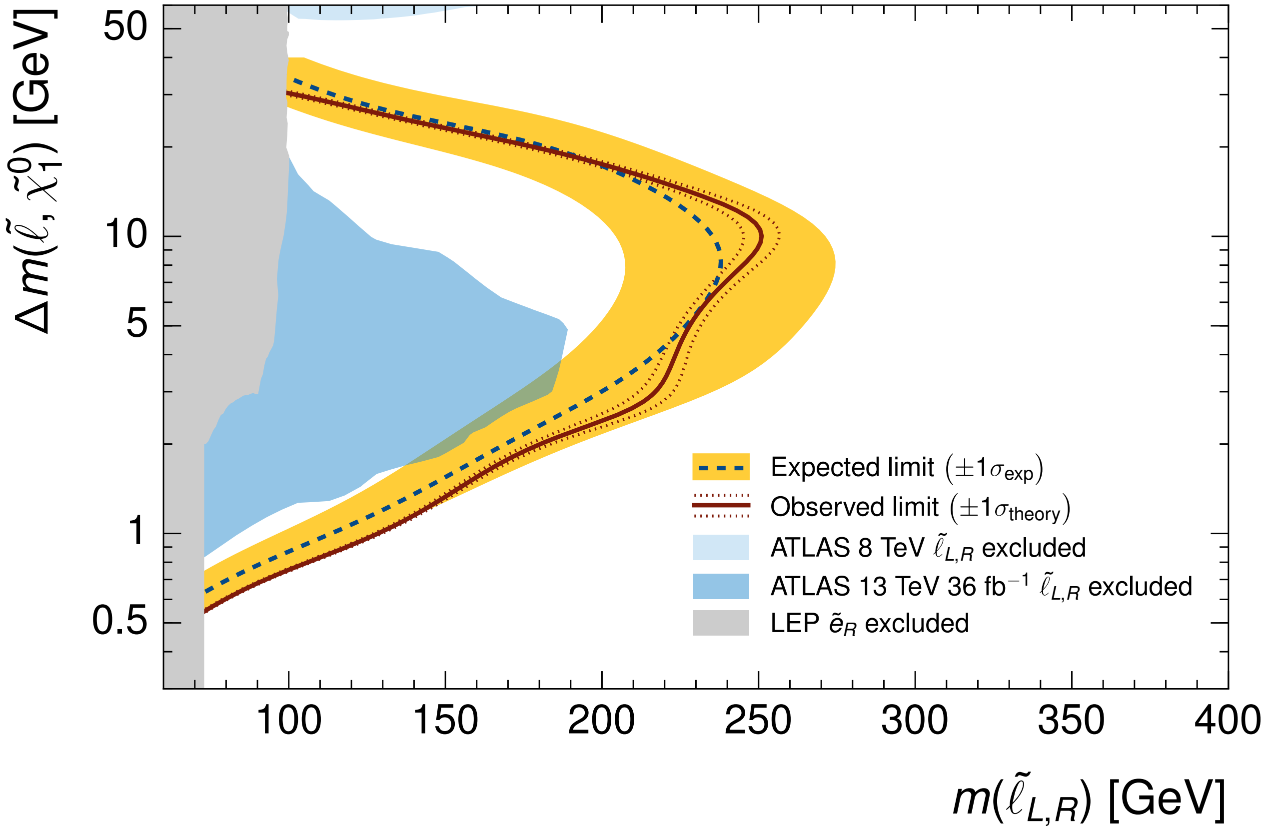
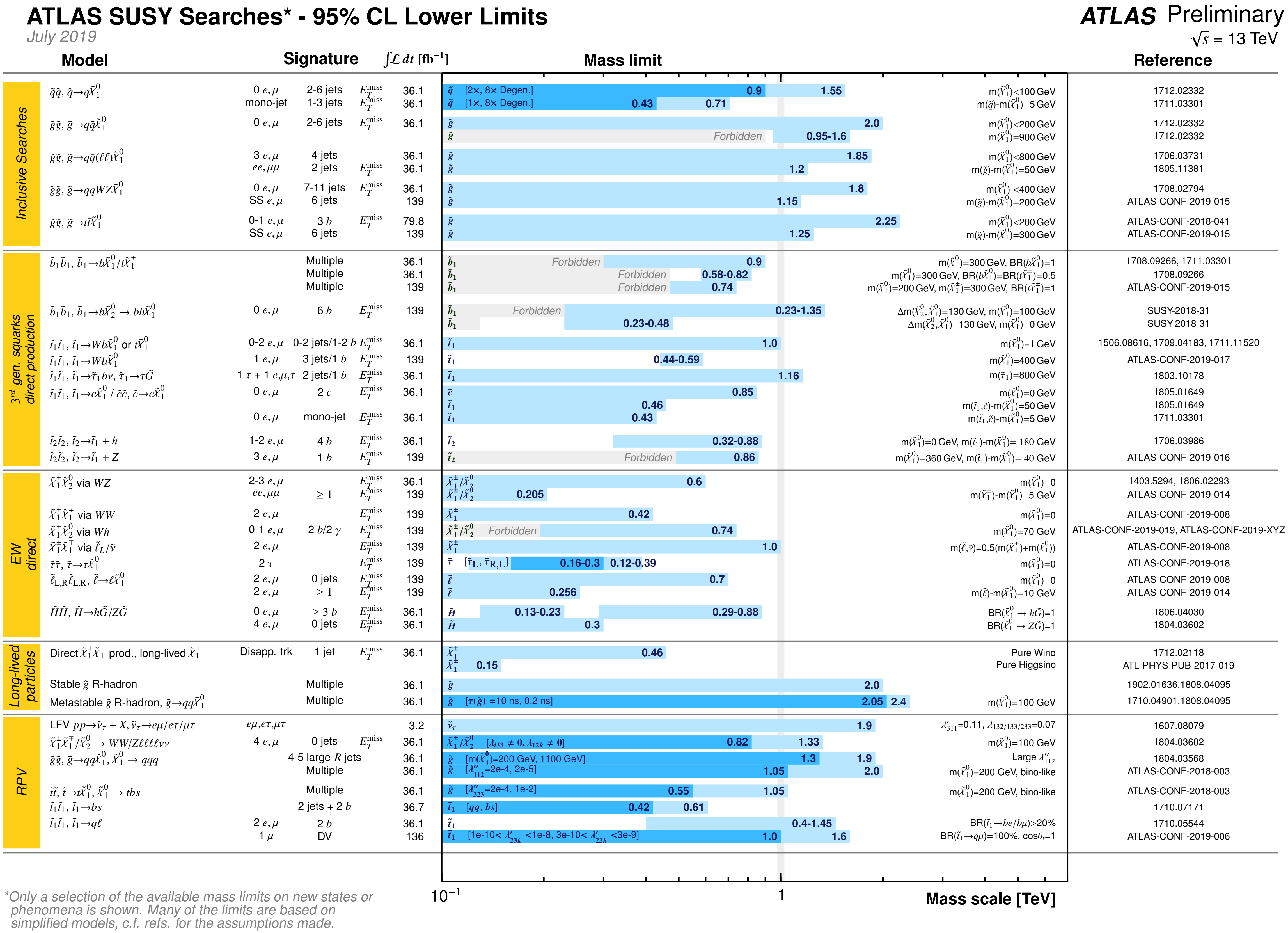




A Bit Of Fortune-Telling…

Part IV - What next?

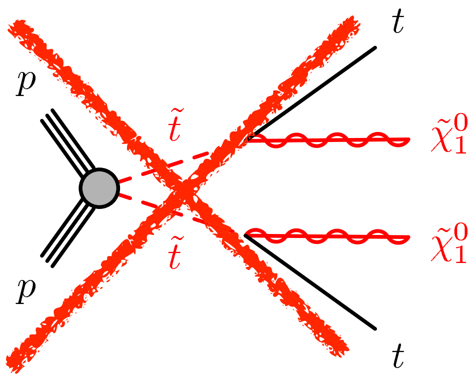
LHC: No New Physics, Stringent Limits…



	Model	Signature			$\int\mathcal{L}\,dt$ [fb^{-1}]	Mass limit			Reference
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}^0_1$	0 e,μ	2-6 jets	$E_T^{\rm miss}$	36.1	$\tilde{q}$ [2×, 8× Degen.]	0.9 1.55	m($\tilde{\chi}^0_1$)<100 GeV	1712.02332
		mono-jet	1-3 jets	$E_T^{\rm miss}$	36.1	$\tilde{q}$ [1×, 8× Degen.]	0.43 0.71	m($\tilde{q}$)-m($\tilde{\chi}^0_1$)=5 GeV	1711.03301
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}^0_1$	0 e,μ	2-6 jets	$E_T^{\rm miss}$	36.1	$\tilde{g}$	2.0	m($\tilde{\chi}^0_1$)<200 GeV	1712.02332
						$\tilde{g}$	Forbidden 0.95-1.6	m($\tilde{\chi}^0_1$)=900 GeV	1712.02332
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}^0_1$	3 e,μ	4 jets		36.1	$\tilde{g}$	1.85	m($\tilde{\chi}^0_1$)<800 GeV	1706.03731
		$ee,\mu\mu$	2 jets	$E_T^{\rm miss}$	36.1	$\tilde{g}$	1.2	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=50 GeV	1805.11381
	$\tilde{g}\tilde{g}, \tilde{g}\to qqWZ\tilde{\chi}^0_1$	0 e,μ	7-11 jets	$E_T^{\rm miss}$	36.1	$\tilde{g}$	1.8	m($\tilde{\chi}^0_1$) <400 GeV	1708.02794
		SS e,μ	6 jets		139	$\tilde{g}$	1.15	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=200 GeV	ATLAS-CONF-2019-015
	$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}^0_1$	0-1 e,μ	3 b	$E_T^{\rm miss}$	79.8	$\tilde{g}$	2.25	m($\tilde{\chi}^0_1$)<200 GeV	ATLAS-CONF-2018-041
		SS e,μ	6 jets		139	$\tilde{g}$	1.25	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=300 GeV	ATLAS-CONF-2019-015
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}^0_1/t\tilde{\chi}^\pm_1$		Multiple		36.1	$\tilde{b}_1$	Forbidden 0.9	m($\tilde{\chi}^0_1$)=300 GeV, BR($b\tilde{\chi}^0_1$)=1	1708.09266, 1711.03301
			Multiple		36.1	$\tilde{b}_1$	Forbidden 0.58-0.82	m($\tilde{\chi}^0_1$)=300 GeV, BR($b\tilde{\chi}^0_1$)=BR($t\tilde{\chi}^\pm_1$)=0.5	1708.09266
			Multiple		139	$\tilde{b}_1$	Forbidden 0.74	m($\tilde{\chi}^0_1$)=200 GeV, m($\tilde{\chi}^\pm_1$)=300 GeV, BR($t\tilde{\chi}^\pm_1$)=1	ATLAS-CONF-2019-015
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}^0_2 \to bh\tilde{\chi}^0_1$	0 e,μ	6 b	$E_T^{\rm miss}$	139	$\tilde{b}_1$	Forbidden 0.23-1.35	Δm($\tilde{\chi}^0_2,\tilde{\chi}^0_1$)=130 GeV, m($\tilde{\chi}^0_1$)=100 GeV	SUSY-2018-31
						$\tilde{b}_1$	0.23-0.48	Δm($\tilde{\chi}^0_2,\tilde{\chi}^0_1$)=130 GeV, m($\tilde{\chi}^0_1$)=0 GeV	SUSY-2018-31
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to Wb\tilde{\chi}^0_1$ or $t\tilde{\chi}^0_1$	0-2 e,μ	0-2 jets/1-2 b	$E_T^{\rm miss}$	36.1	$\tilde{t}_1$	1.0	m($\tilde{\chi}^0_1$)=1 GeV	1506.08616, 1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to Wb\tilde{\chi}^0_1$	1 e,μ	3 jets/1 b	$E_T^{\rm miss}$	139	$\tilde{t}_1$	0.44-0.59	m($\tilde{\chi}^0_1$)=400 GeV	ATLAS-CONF-2019-017
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to\tilde{\tau}_1 b\nu, \tilde{\tau}_1\to\tau\tilde{G}$	1 τ + 1 e,μ,τ	2 jets/1 b	$E_T^{\rm miss}$	36.1	$\tilde{t}_1$	1.16	m($\tilde{\tau}_1$)=800 GeV	1803.10178
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}^0_1$ / $\tilde{c}\tilde{c}, \tilde{c}\to c\tilde{\chi}^0_1$	0 e,μ	2 c	$E_T^{\rm miss}$	36.1	$\tilde{c}$	0.85	m($\tilde{\chi}^0_1$)=0 GeV	1805.01649
						$\tilde{t}_1$	0.46	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}^0_1$)=50 GeV	1805.01649
		0 e,μ	mono-jet	$E_T^{\rm miss}$	36.1	$\tilde{t}_1$	0.43	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}^0_1$)=5 GeV	1711.03301
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1 + h$	1-2 e,μ	4 b	$E_T^{\rm miss}$	36.1	$\tilde{t}_2$	0.32-0.88	m($\tilde{\chi}^0_1$)=0 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}^0_1$)= 180 GeV	1706.03986
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1 + Z$	3 e,μ	1 b	$E_T^{\rm miss}$	139	$\tilde{t}_2$	Forbidden 0.86	m($\tilde{\chi}^0_1$)=360 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}^0_1$)= 40 GeV	ATLAS-CONF-2019-016
EW direct	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2$ via WZ	2-3 e,μ		$E_T^{\rm miss}$	36.1	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$	0.6	m($\tilde{\chi}^0_1$)=0	1403.5294, 1806.02293
		$ee,\mu\mu$	≥ 1	$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$	0.205	m($\tilde{\chi}^\pm_1$)-m($\tilde{\chi}^0_1$)=5 GeV	ATLAS-CONF-2019-014
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1$ via WW	2 e,μ		$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1$	0.42	m($\tilde{\chi}^0_1$)=0	ATLAS-CONF-2019-008
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2$ via Wh	0-1 e,μ	2 b/2 γ	$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$	Forbidden 0.74	m($\tilde{\chi}^0_1$)=70 GeV	ATLAS-CONF-2019-019, ATLAS-CONF-2019-XYZ
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1$ via $\tilde{\ell}_L/\tilde{\nu}$	2 e,μ		$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1$	1.0	m($\tilde{\ell}$,$\tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}^0_1$))	ATLAS-CONF-2019-008
	$\tilde{\tau}\tilde{\tau}, \tilde{\tau}\to\tau\tilde{\chi}^0_1$	2 τ		$E_T^{\rm miss}$	139	$\tilde{\tau}$ [$\tilde{\tau}_{\rm L}$, $\tilde{\tau}_{\rm R,L}$]	0.16-0.3 0.12-0.39	m($\tilde{\chi}^0_1$)=0	ATLAS-CONF-2019-018
	$\tilde{\ell}_{\rm L,R}\tilde{\ell}_{\rm L,R}, \tilde{\ell}\to\ell\tilde{\chi}^0_1$	2 e,μ	0 jets	$E_T^{\rm miss}$	139	$\tilde{\ell}$	0.7	m($\tilde{\chi}^0_1$)=0	ATLAS-CONF-2019-008
		2 e,μ	≥ 1	$E_T^{\rm miss}$	139	$\tilde{\ell}$	0.256	m($\tilde{\ell}$)-m($\tilde{\chi}^0_1$)=10 GeV	ATLAS-CONF-2019-014
	$\tilde{H}\tilde{H}, \tilde{H}\to h\tilde{G}/Z\tilde{G}$	0 e,μ	≥ 3 b	$E_T^{\rm miss}$	36.1	$\tilde{H}$	0.13-0.23 0.29-0.88	BR($\tilde{\chi}^0_1 \to h\tilde{G}$)=1	1806.04030
		4 e,μ	0 jets	$E_T^{\rm miss}$	36.1	$\tilde{H}$	0.3	BR($\tilde{\chi}^0_1 \to Z\tilde{G}$)=1	1804.03602
Long-lived particles	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^\pm_1$	Disapp. trk	1 jet	$E_T^{\rm miss}$	36.1	$\tilde{\chi}^\pm_1$	0.46	Pure Wino	1712.02118
						$\tilde{\chi}^\pm_1$	0.15	Pure Higgsino	ATL-PHYS-PUB-2017-019
	Stable $\tilde{g}$ R-hadron		Multiple		36.1	$\tilde{g}$	2.0		1902.01636,1808.04095
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}^0_1$		Multiple		36.1	$\tilde{g}$ [$\tau(\tilde{g})$ =10 ns, 0.2 ns]	2.05 2.4	m($\tilde{\chi}^0_1$)=100 GeV	1710.04901,1808.04095
RPV	LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu$,$e\tau$,$\mu\tau$			3.2	$\tilde{\nu}_\tau$	1.9	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1/\tilde{\chi}^0_2 \to WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ	0 jets	$E_T^{\rm miss}$	36.1	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ [$\lambda_{i33} \neq 0, \lambda_{12k} \neq 0$]	0.82 1.33	m($\tilde{\chi}^0_1$)=100 GeV	1804.03602
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}^0_1, \tilde{\chi}^0_1 \to qqq$		4-5 large-R jets		36.1	$\tilde{g}$ [m($\tilde{\chi}^0_1$)=200 GeV, 1100 GeV]	1.3 1.9	Large λ''_{112}	1804.03568
			Multiple		36.1	$\tilde{g}$ [λ''_{112}=2e-4, 2e-5]	1.05 2.0	m($\tilde{\chi}^0_1$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}, \tilde{t}\to t\tilde{\chi}^0_1, \tilde{\chi}^0_1 \to tbs$		Multiple		36.1	$\tilde{g}$ [λ''_{323}=2e-4, 1e-2]	0.55 1.05	m($\tilde{\chi}^0_1$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to bs$		2 jets + 2 b		36.7	$\tilde{t}_1$ [qq, bs]	0.42 0.61		1710.07171
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to q\ell$	2 e,μ	2 b		36.1	$\tilde{t}_1$	0.4-1.45	BR($\tilde{t}_1\to be/b\mu$)>20%	1710.05544
		1 μ	DV		136	$\tilde{t}_1$ [1e-10< λ'_{23k} <1e-8, 3e-10< λ'_{23k} <3e-9]	1.0 1.6	BR($\tilde{t}_1\to q\mu$)=100%, cosθ_t=1	ATLAS-CONF-2019-006

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

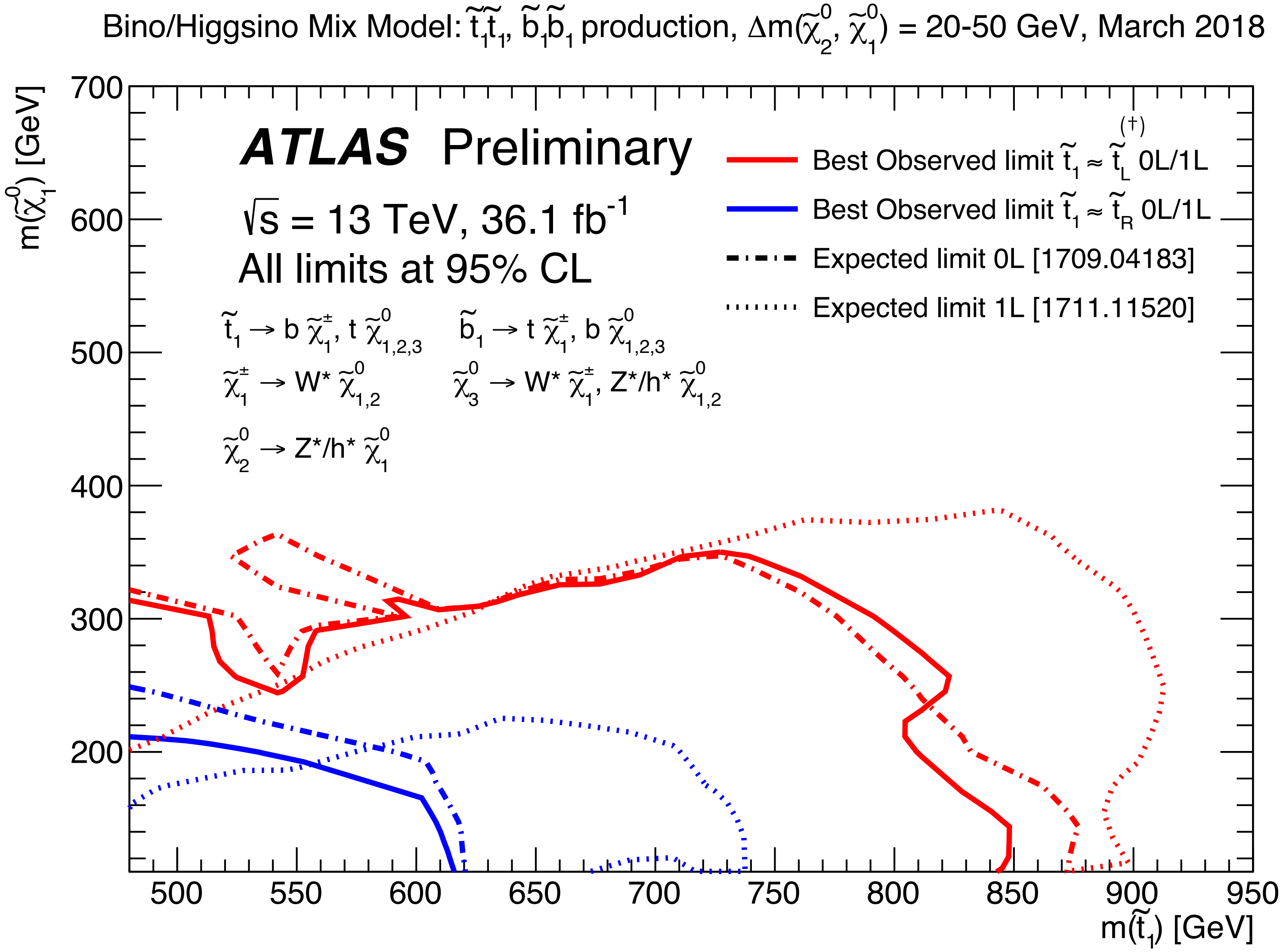
Hunting For ~~Vanilla~~ realistic? Stops

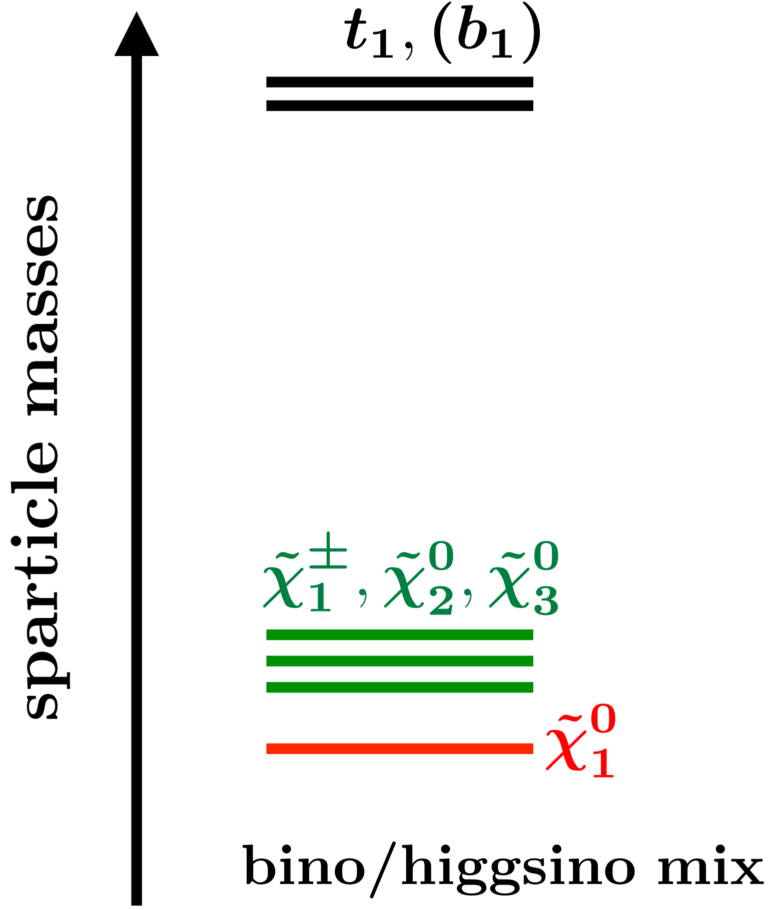


Stop searches reinterpreted for a pMSSM-inspired model:

- ➙ correct dark matter relic abundance: $0.10<\Omega h^2<0.12$
- ➙ natural, compressed EWKinos mass spectrum

A light stop with a light higgsino-like LSP is still allowed!

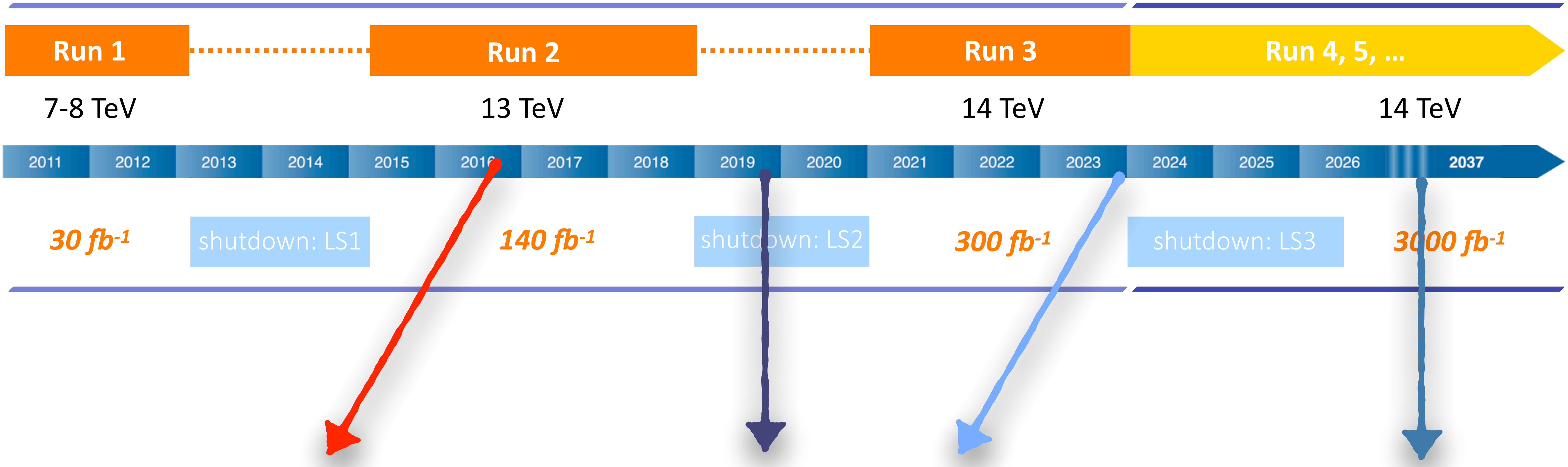




(†) "handedness" of scalar top comes from couplings (SM partner, top, is a fermion)

LHC Long-Term Schedule

LHC



Run 1		Run 2		Run 3	Run 4, 5, …
7-8 TeV		13 TeV		14 TeV	14 TeV
2011, 2012	2013, 2014	2015, 2016, 2017, 2018	2019, 2020	2021, 2022, 2023	2024, 2025, 2026, 2037
30 fb^{-1}	shutdown: LS1	*140 fb^{-1}*	shutdown: LS2	*300 fb^{-1}*	shutdown: LS3 · *3000 fb^{-1}*

analyses presented:
36 fb^{-1}

today:
x3 more data

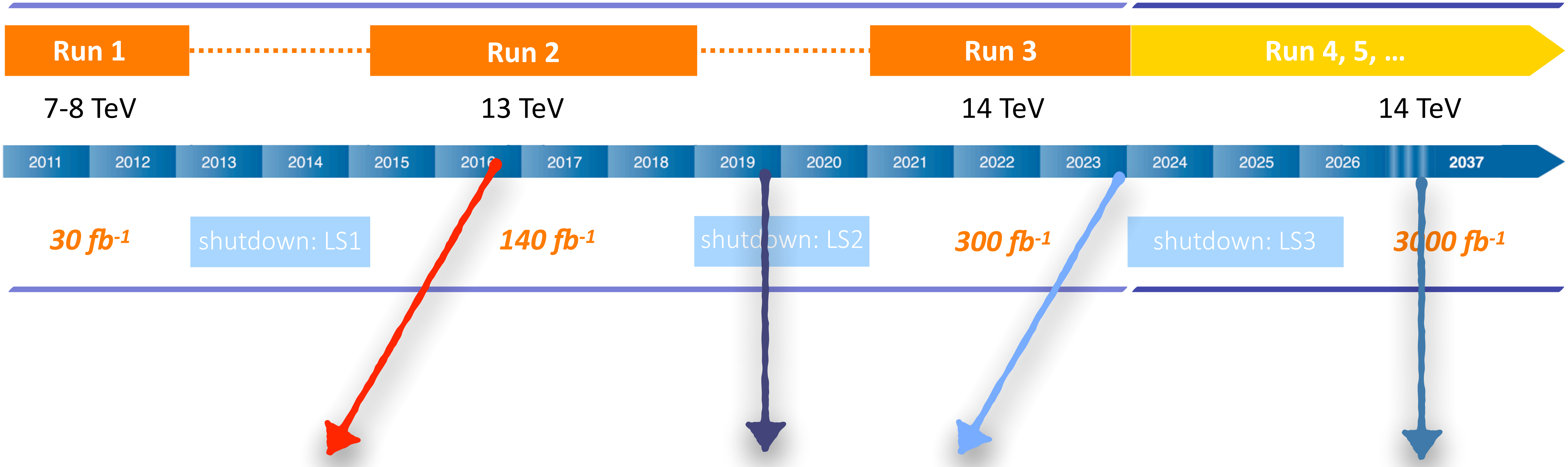
in 5 years:
x10 more data

in 20 years:
x100 more data

LHC Long-Term Schedule

LHC

HiLumi HL-LHC PROJECT



analyses presented:
36 fb^{-1}

<pileup> ≈20

today:
x3 more data

<pileup> ≈40

in 5 years:
x10 more data

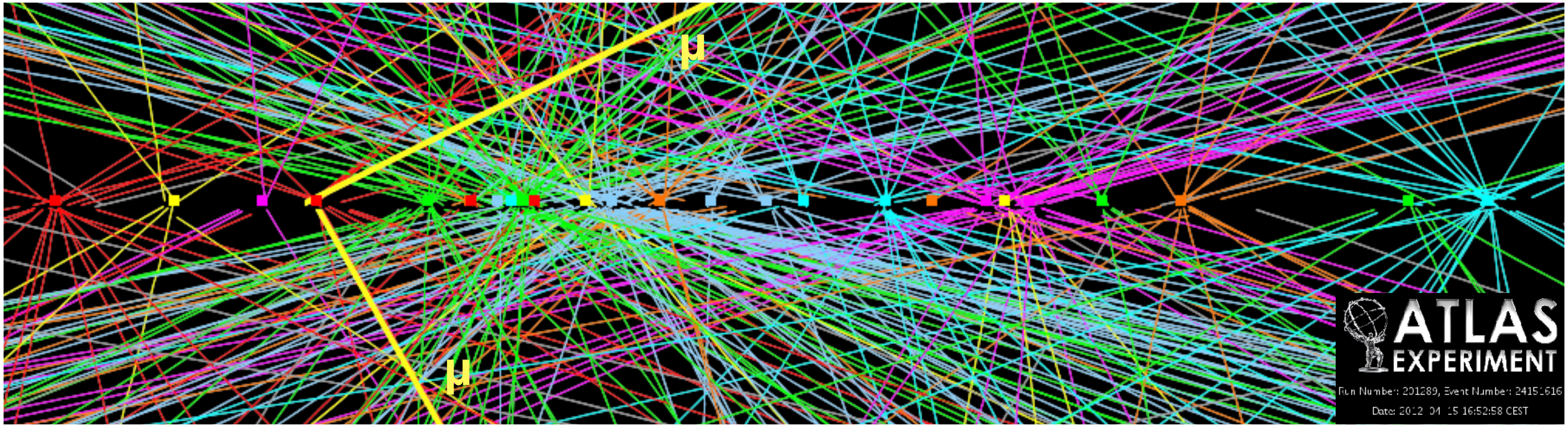
<pileup> ≈60

in 20 years:
x100 more data

<pileup> ≈140

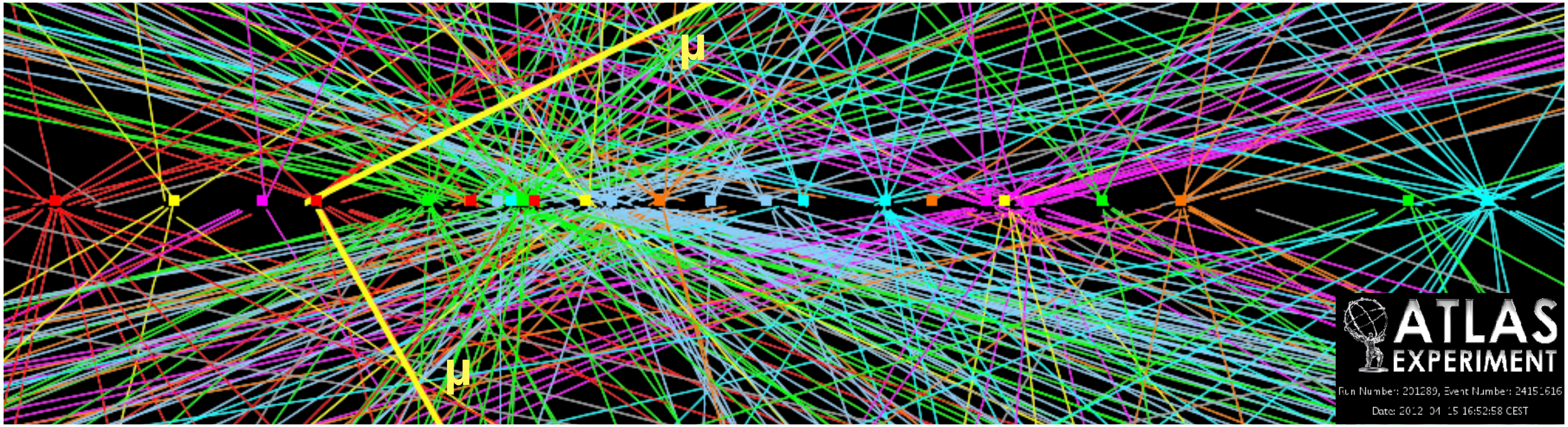
The Pileup Challenge

***The past:* Z→μμ event recorded in 2012, with 25 p-p pileup collisions**

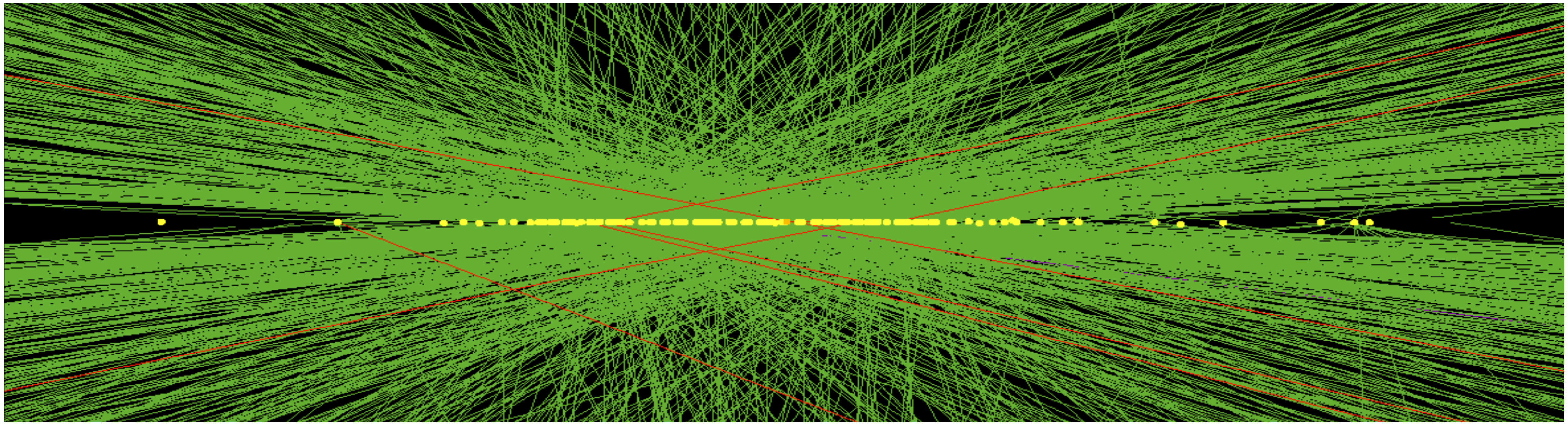


The Pileup Challenge

The past: Z→μμ event recorded in 2012, with 25 p-p pileup collisions



The future: simulation of 140 p-p pileup collisions (CMS)



ATLAS Needs To Be *Upgraded*!

To withstand pileup challenge, upgrading trigger, tracker and muon system

below: testing prototypes of silicon strip detectors for upgraded *I*nner *T*rac*k*er (*ITk*)

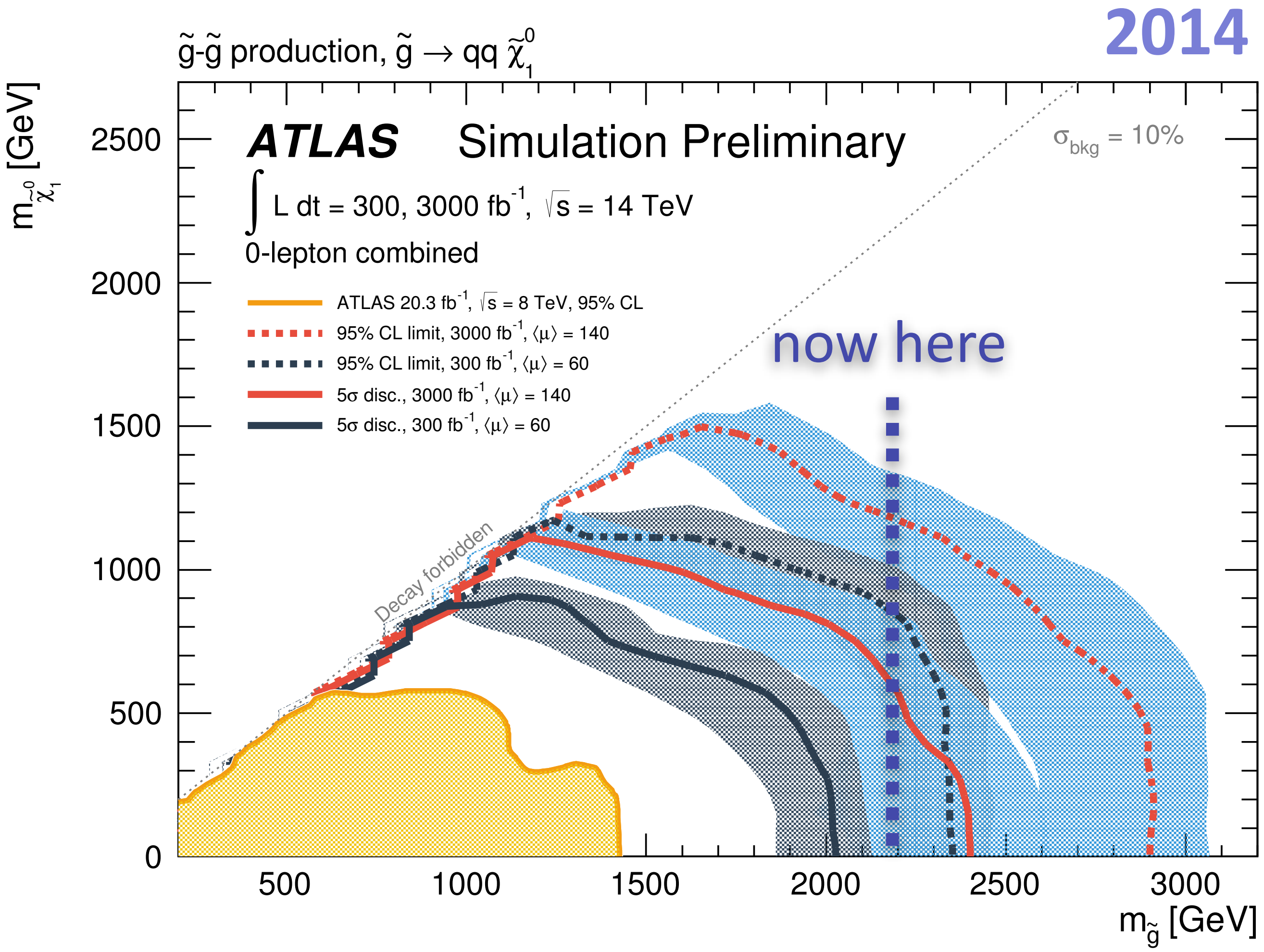
HL-LHC Prospects For SUSY

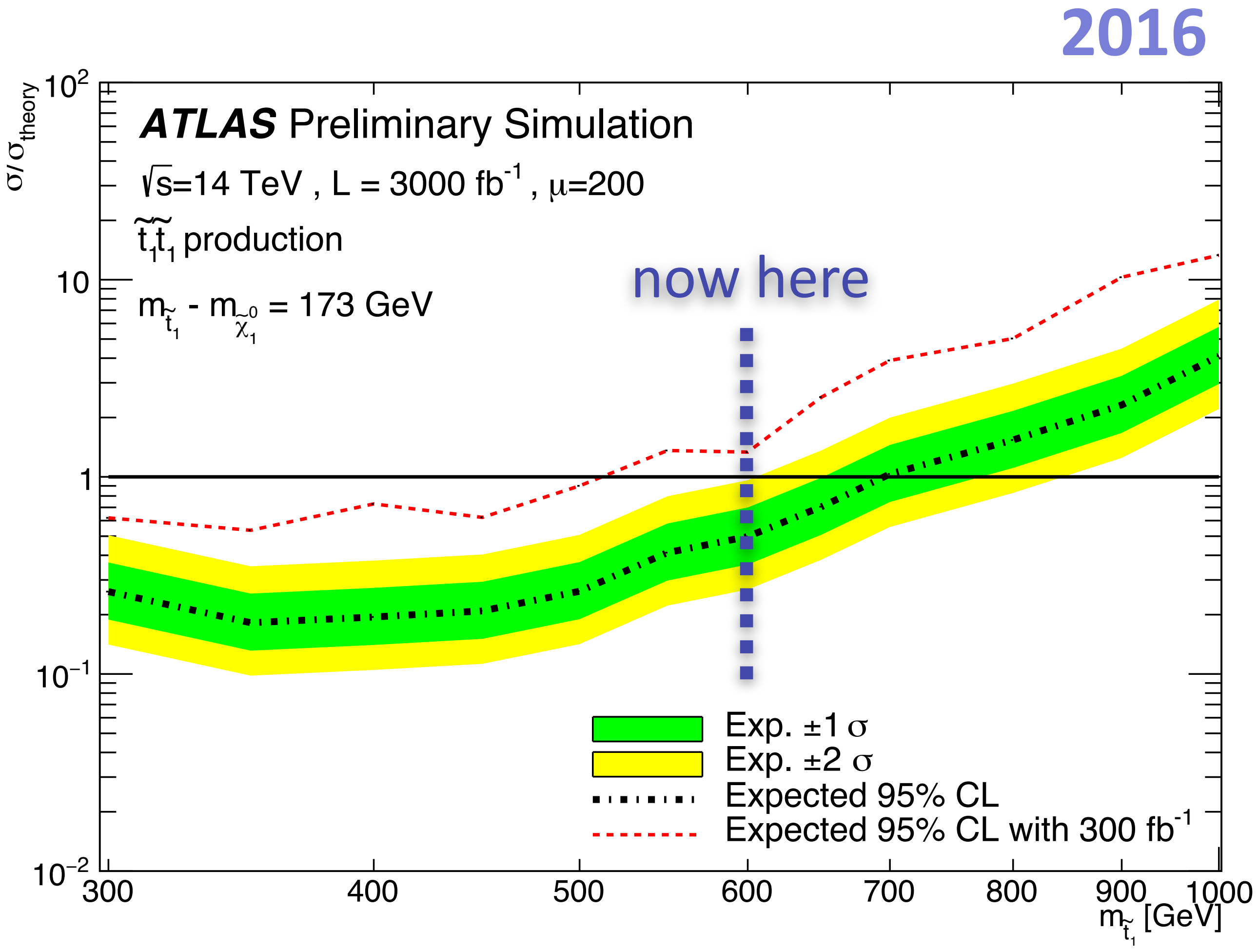
100x data (so 3000 fb^{-1}) expected to bring <50% improvements in mass reach

extrapolations based on simple analyses → probably over-conservative…

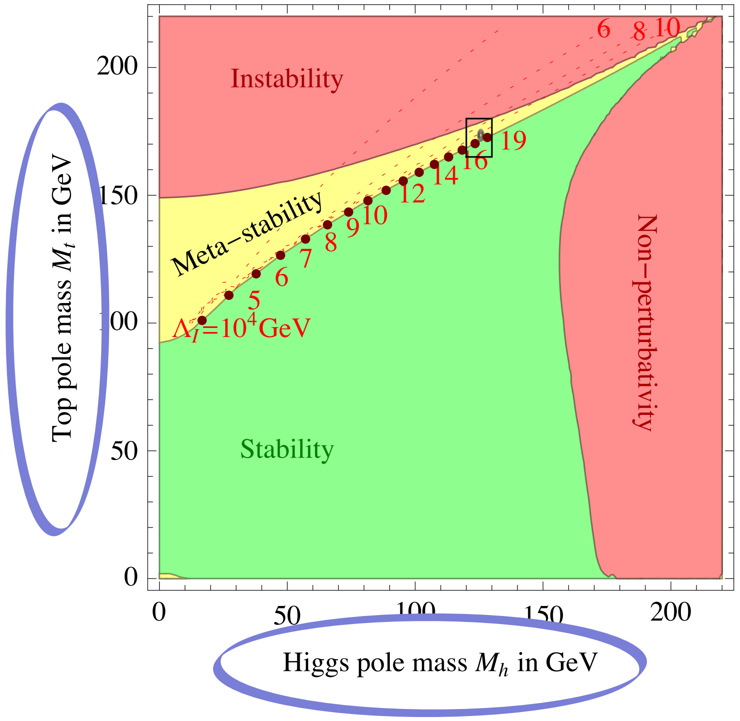
…however, the main message stands!

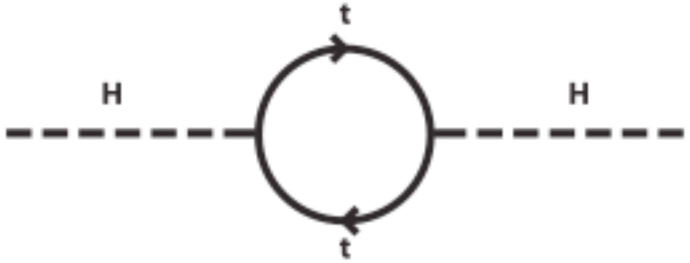
searches will have to move toward more *sophisticated analysis techniques* and more *complex signatures*





A Way Forward?





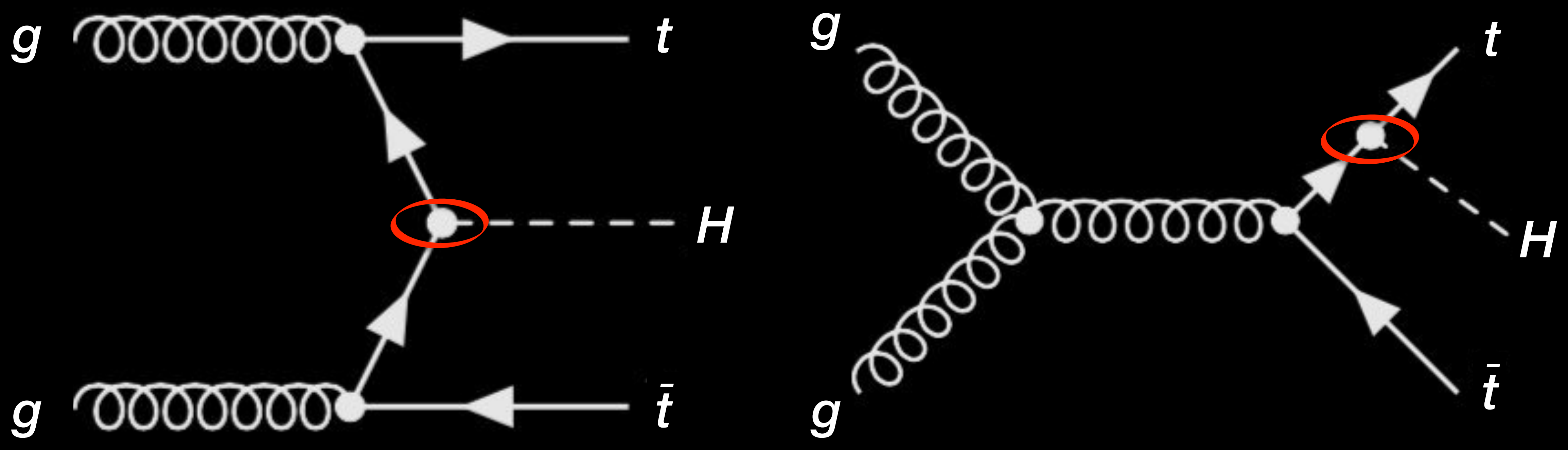
main “SM” term:
top’s loop ($\lambda_t \approx 1$)

physical m_h: 125 GeV

$$m_h^2 \approx \underbrace{m_{h\,0}^2}_{\text{bare mass}} - \underbrace{\frac{\lambda_f^2}{8\pi^2} N_c^f \int^{\Lambda} \frac{d^4p}{p^2}}_{\text{1-loop correction}} + \ldots \approx m_{h\,0}^2 + \overbrace{\frac{\lambda_f^2}{8\pi^2} N_c^f}\,\underbrace{\Lambda^2}_{\text{ultraviolet cutoff}} + \ldots$$

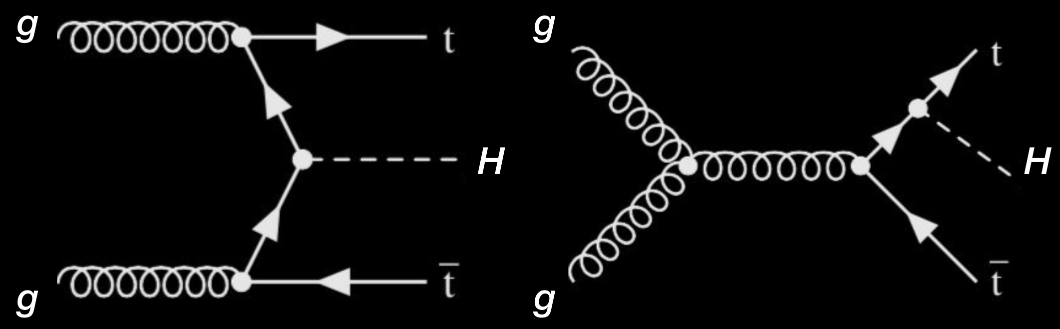
A Way Forward: *Top Yukawa Coupling*

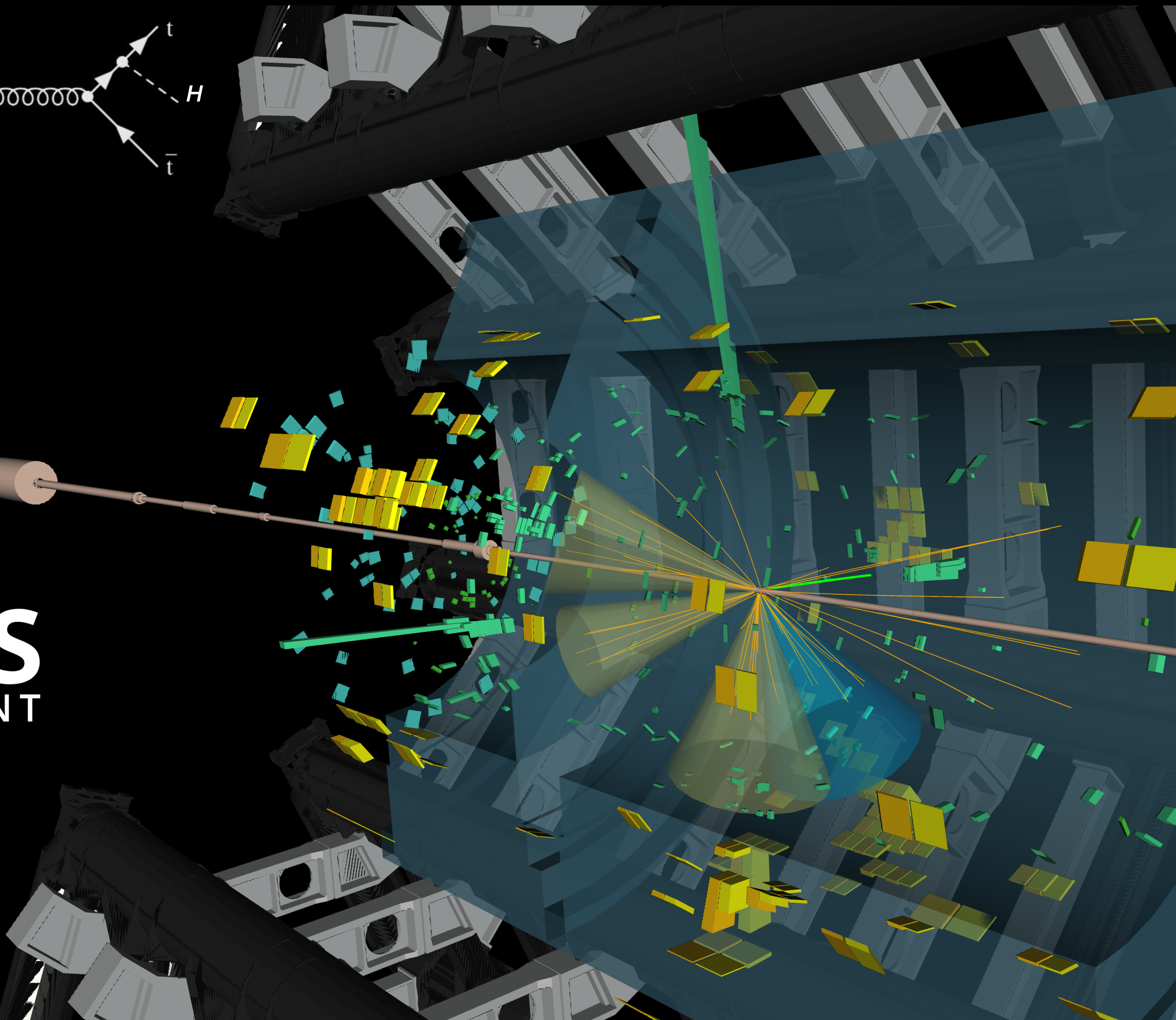
Probing the EWSB mechanism where Higgs couplings are strongest



A Way Forward: *Top Yukawa Coupling*

Probing the EWSB mechanism where Higgs couplings are strongest



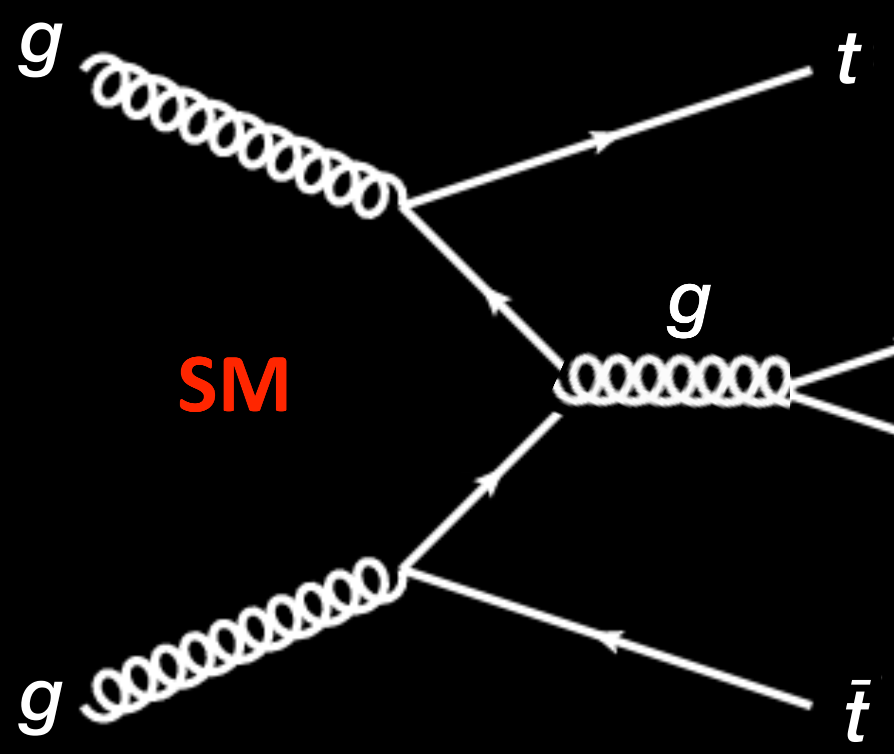


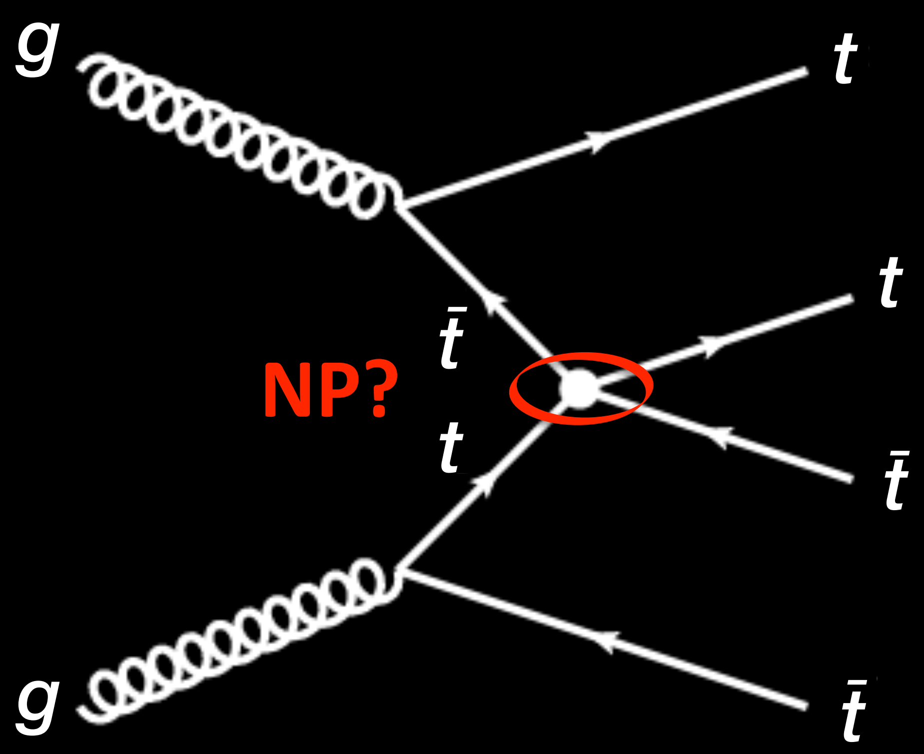
ATLAS
EXPERIMENT

Run: 331742
Event: 1873900334
2017-08-04 21:48:42 CEST

A Way Forward: *A Rare Process*

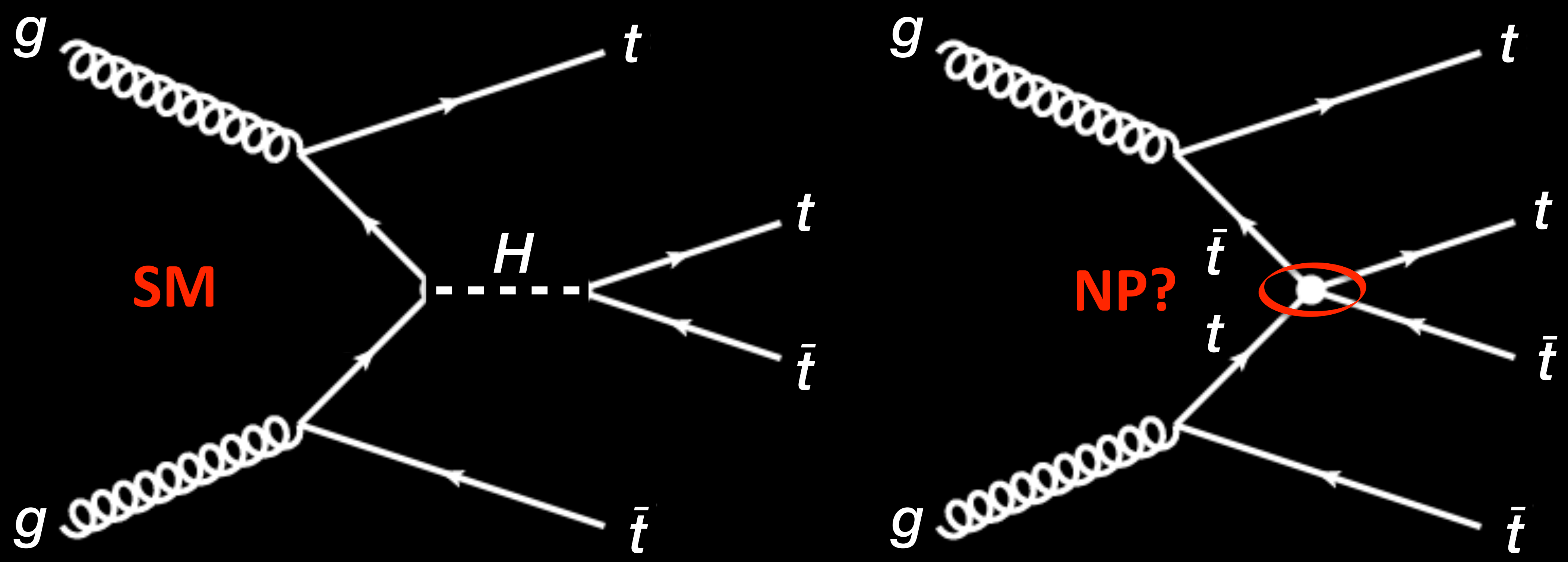
Four top quarks production: test SM, and search for new physics (NP)





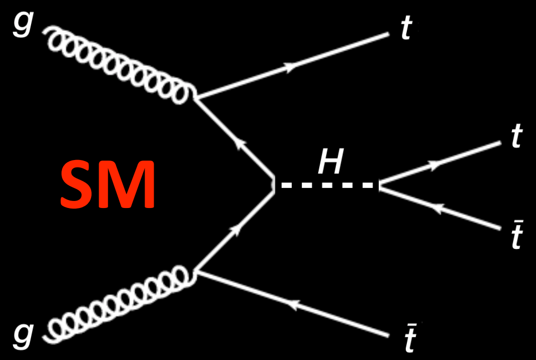
A Way Forward: *A Rare Process*

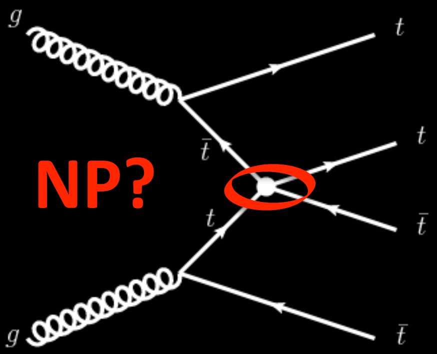
Four top quarks production: test SM, and search for new physics (NP)

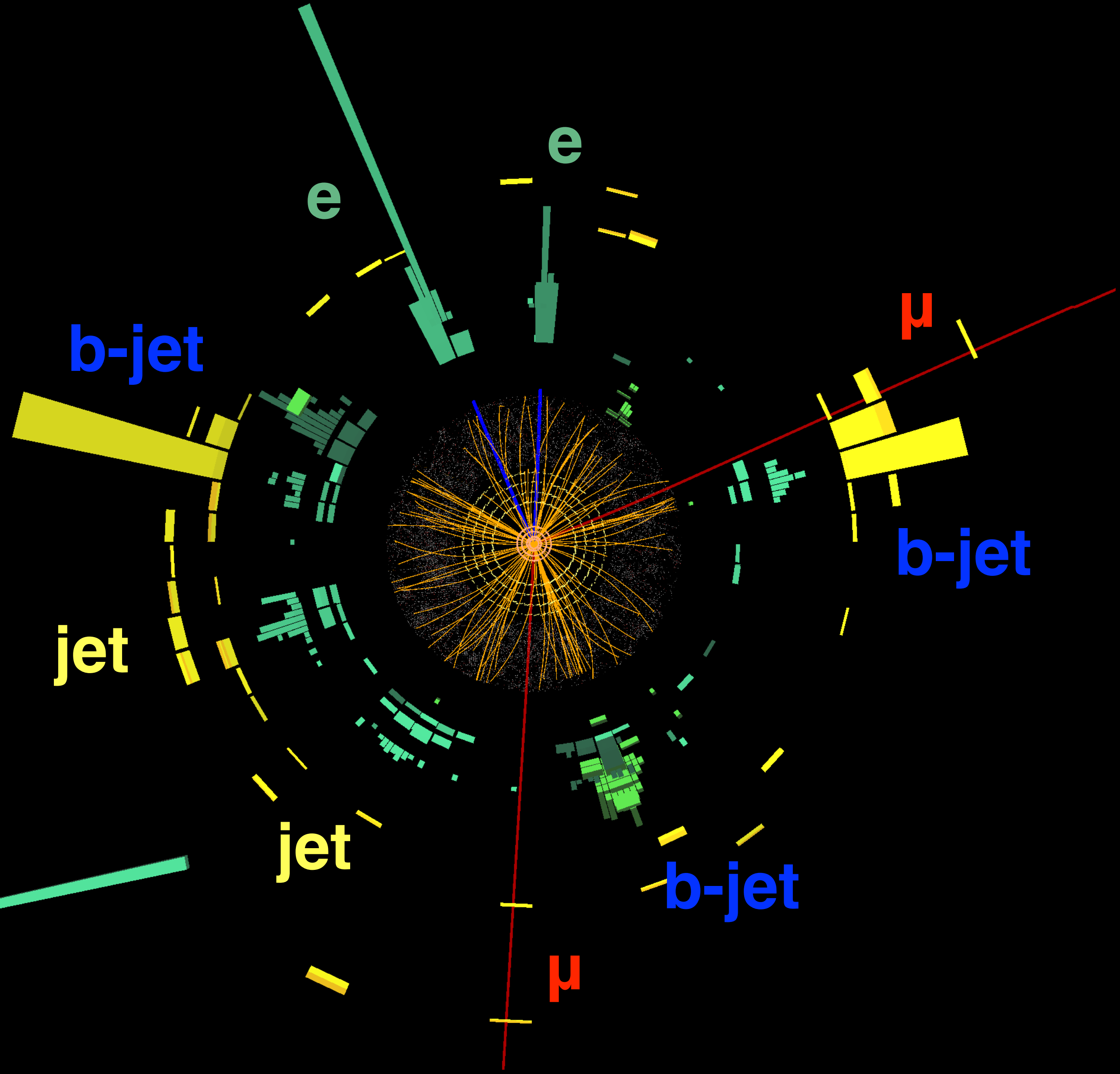


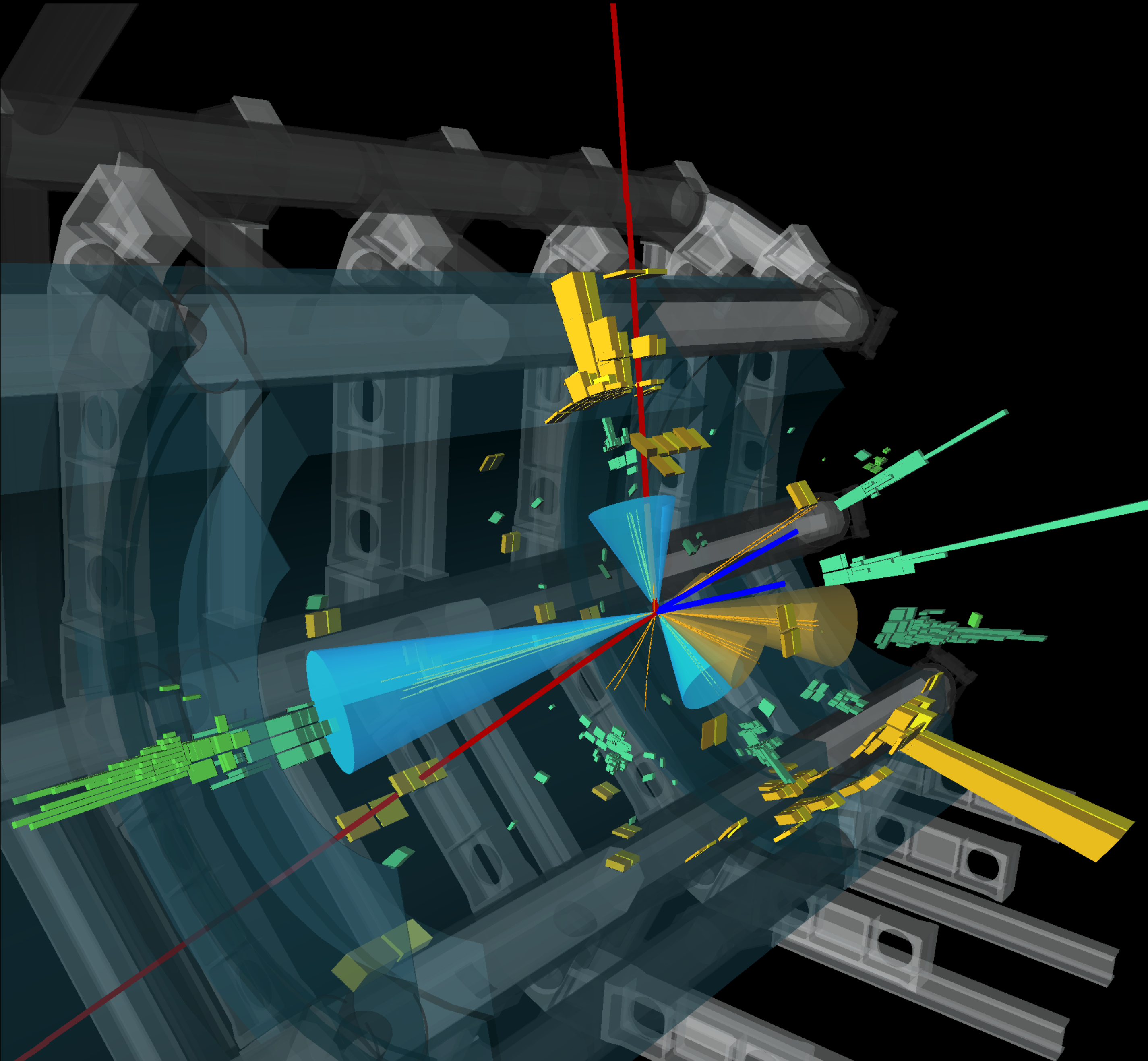
A Way Forward: *A Rare Process*

Four top quarks production: test SM, and search for new physics (NP)









ATLAS
EXPERIMENT

Run: 282712
Event: 1212489545
2015-10-21 09:39:30 CEST

Conclusions & Outlook

- ➙ **Natural SUSY is surely challenged by LHC constraints… but not *dead yet***
  - ↳ Expanding sensitivity requires *new analysis techniques* and *capabilities*
  - ↳ Follow the path of Higgsino analysis: improve *performance* → improve *reach*
- ➙ **Don't be fooled: the LHC journey has just begun…**
  - ↳ We *analyzed less than 5%* of the data we expected to get by 2040!
  - ↳ We must *tie up all loose ends* in our search program: is new physics just hiding?
  - ↳ *In parallel*, get as much information as possible on *Higgs and its interactions*
- ➙ **My personal plans?**

Exciting analyses! *Higgs-top* associate production, *four top* production

Detector upgrade

Tracking performance

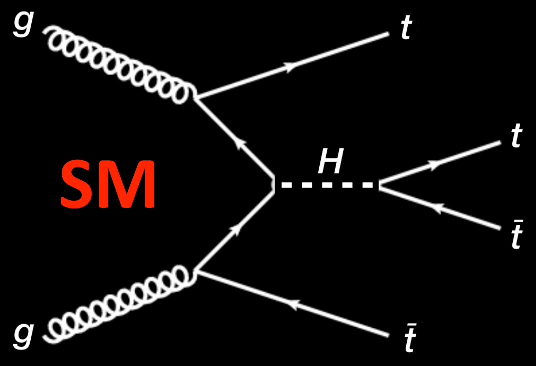
Top-tagging

- ➙ **These are just ideas, not the *only* ideas… *Plenty* of exciting opportunities ahead of us!**

Spares

A Way Forward: *A Rare Process*

Four top quarks production: test SM, and search for new physics (NP)



PHYSICAL REVIEW D **95,** 053004 (2017)

Probing Higgs width and top quark Yukawa coupling from $t\bar{t}H$ and $t\bar{t}t\bar{t}$ productions

Qing-Hong Cao,[1,2,3,*] Shao-Long Chen,[4,3,†] and Yandong Liu[1,‡]
[1]*Department of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China*
[2]*Collaborative Innovation Center of Quantum Matter, Beijing 100871, China*
[3]*Center for High Energy Physics, Peking University, Beijing 100871, China*
[4]*Key Laboratory of Quark and Lepton Physics (MoE) and Institute of Particle Physics, Central China Normal University, Wuhan 430079, China*

(Received 15 June 2016; published 10 March 2017)

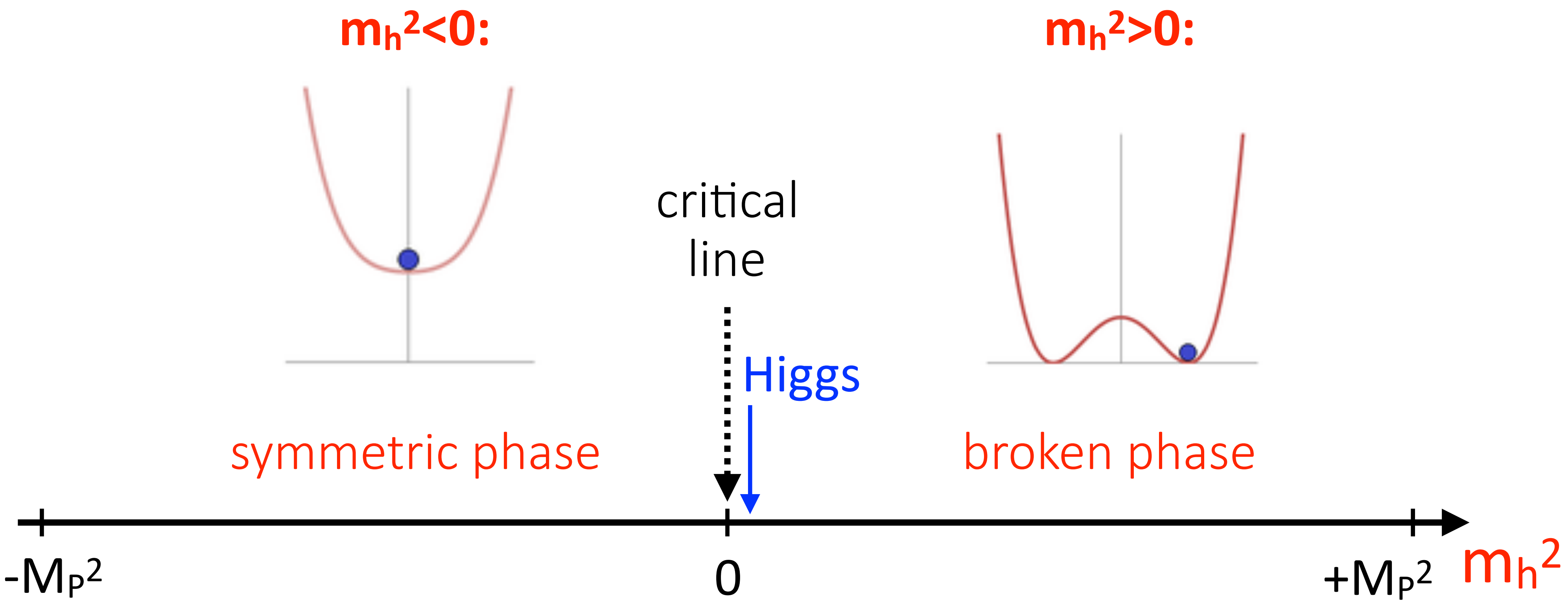
We demonstrate that four top-quark production is a powerful tool to constrain the top Yukawa coupling. The constraint is robust in the sense that it does not rely on the Higgs boson decay. Taking into account the projection of the $t\bar{t}H$ production by the ATLAS Collaboration, we obtained a bound on the Higgs boson width, $\Gamma_H \leq 2.57\Gamma_H^{\mathrm{SM}}$, at the 14 TeV Large Hadron Collider with an integrated luminosity of 300 fb^{-1}.

DOI: 10.1103/PhysRevD.95.053004

Supersymmetry As "Criticality" Condition

Why the Higgs so close to criticality? ➠ Additional symmetry?

Higgs Potential: $V(\phi) = -m_h^2\ |\phi|^2 + \lambda\ |\phi|^4$

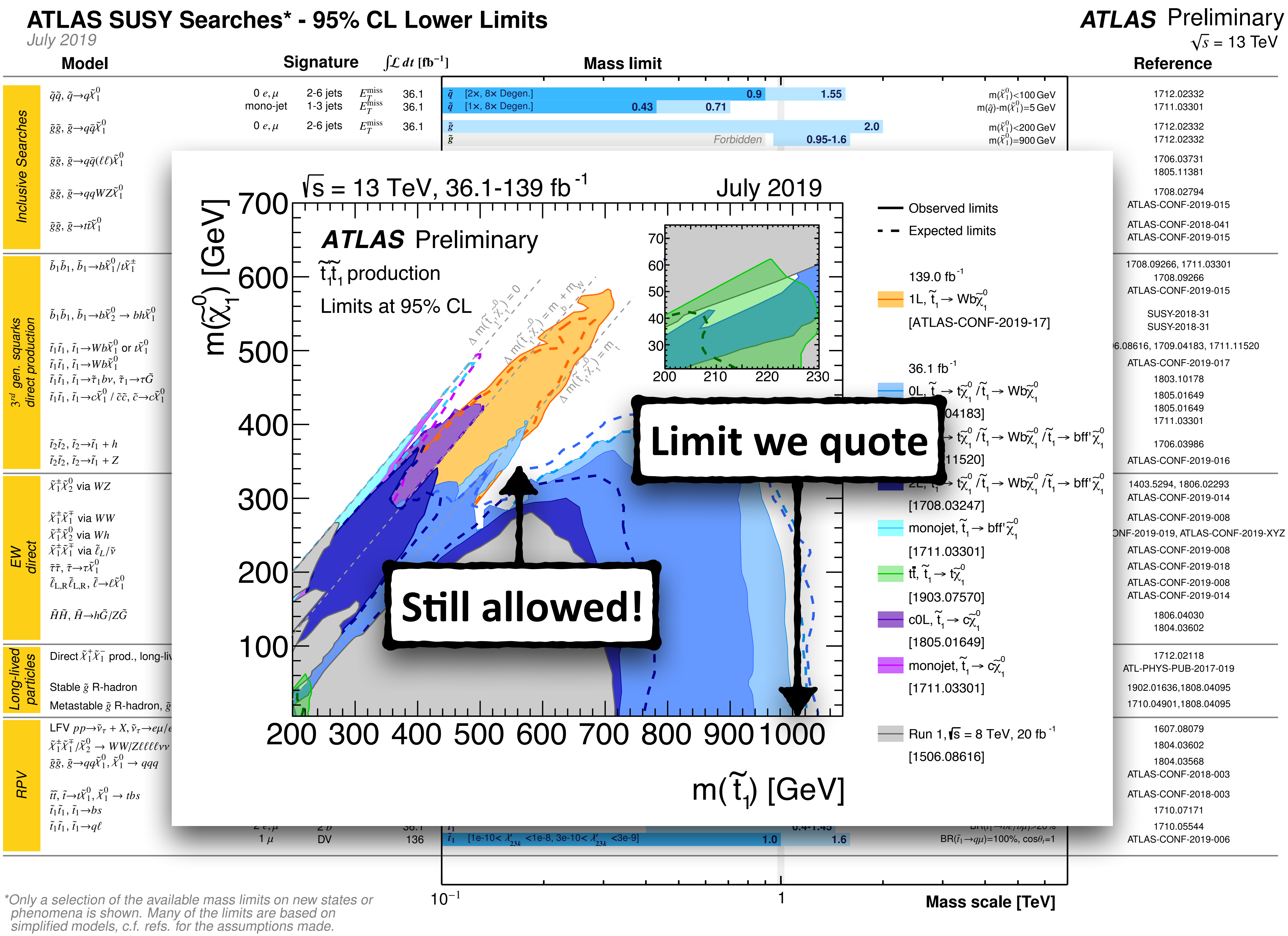


SUSY predicts $v = \langle 0|\phi|0\rangle \Leftrightarrow m_h^2=0$

(softly) broken SUSY can allow $m_h^2 \gtrsim 0$ ($v \cong 246$ GeV)

Inspired from https://cds.cern.ch/record/2639759

LHC: No New Physics, Stringent Limits…

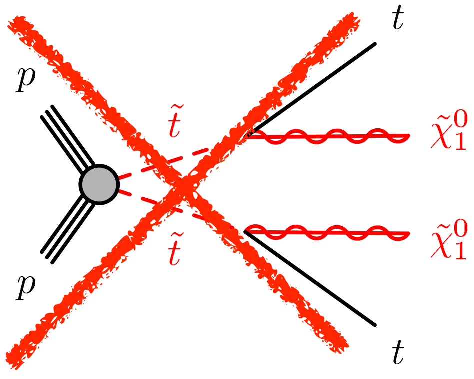


Limit we quote

Still allowed!

S. Zambito | *Harvard University*

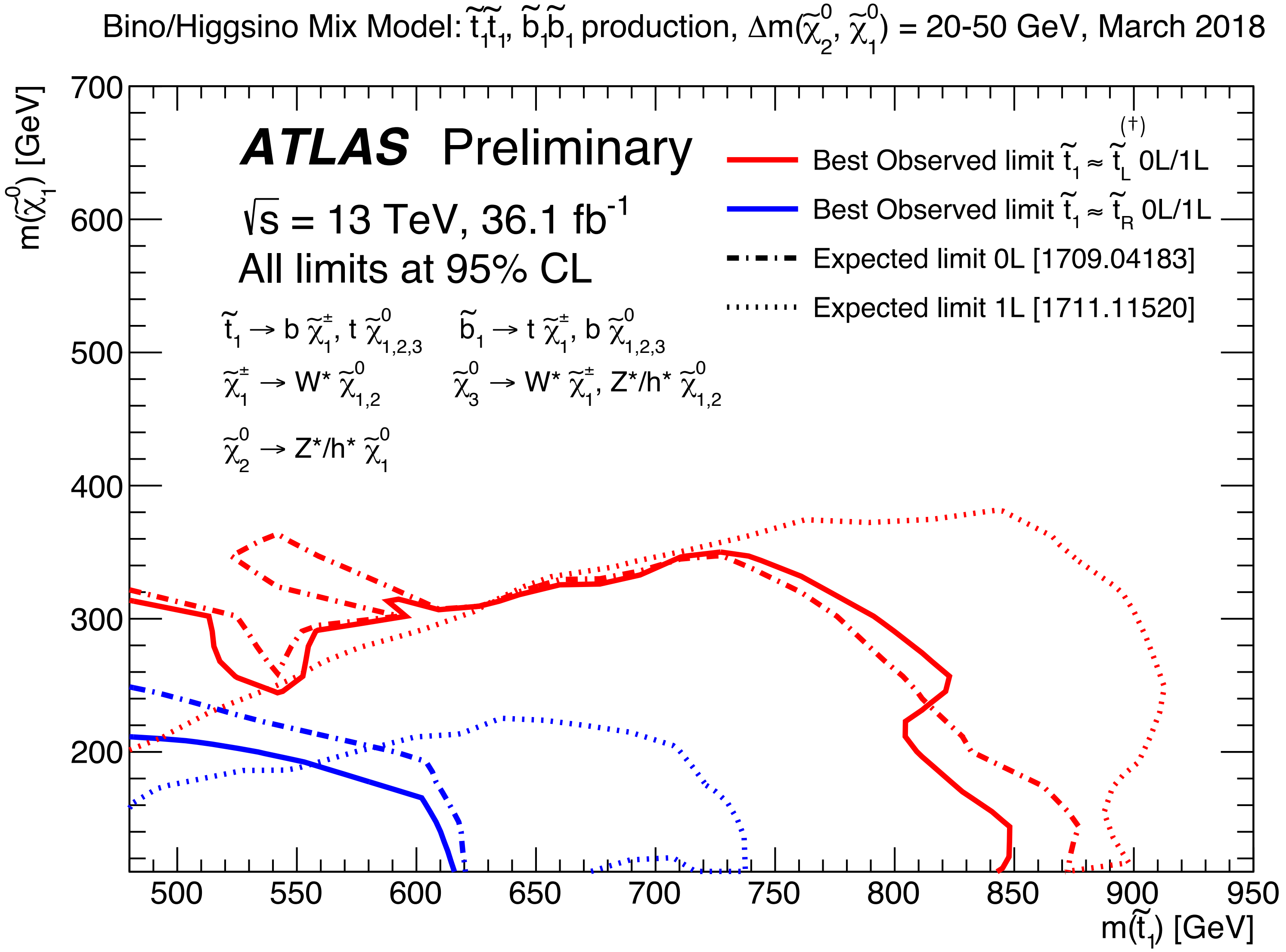
Hunting For ~~Vanilla~~ realistic? Stops

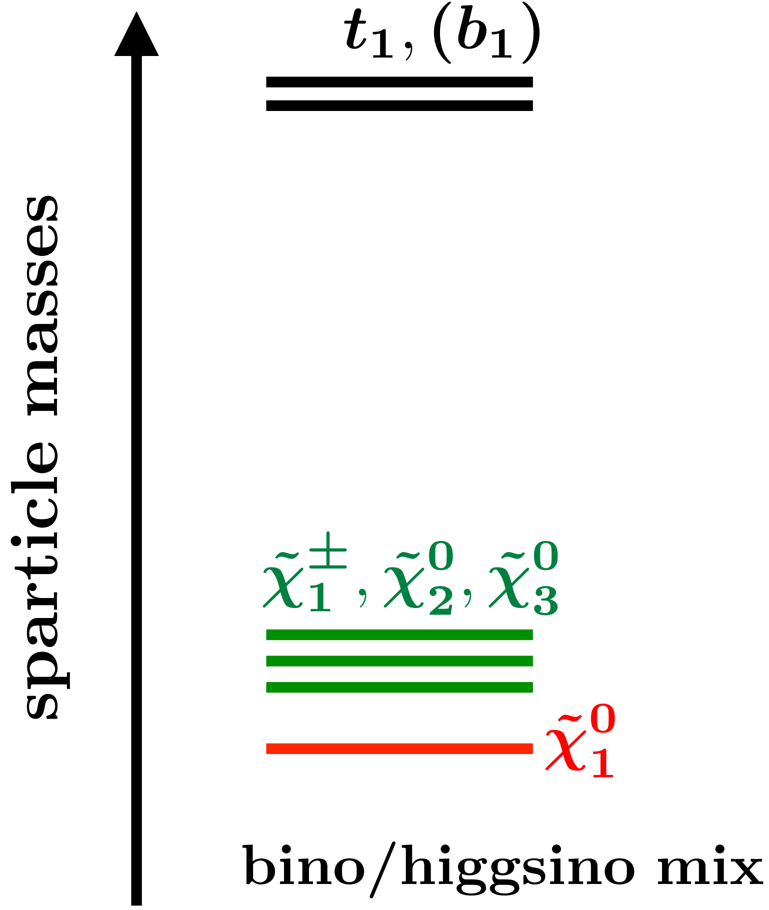


Stop searches reinterpreted for a pMSSM-inspired model:

- ➞ correct dark matter relic abundance: $0.10<\Omega h^2<0.12$
- ➞ natural, compressed EWKinos mass spectrum

A light stop with a light higgsino-like LSP is still allowed!



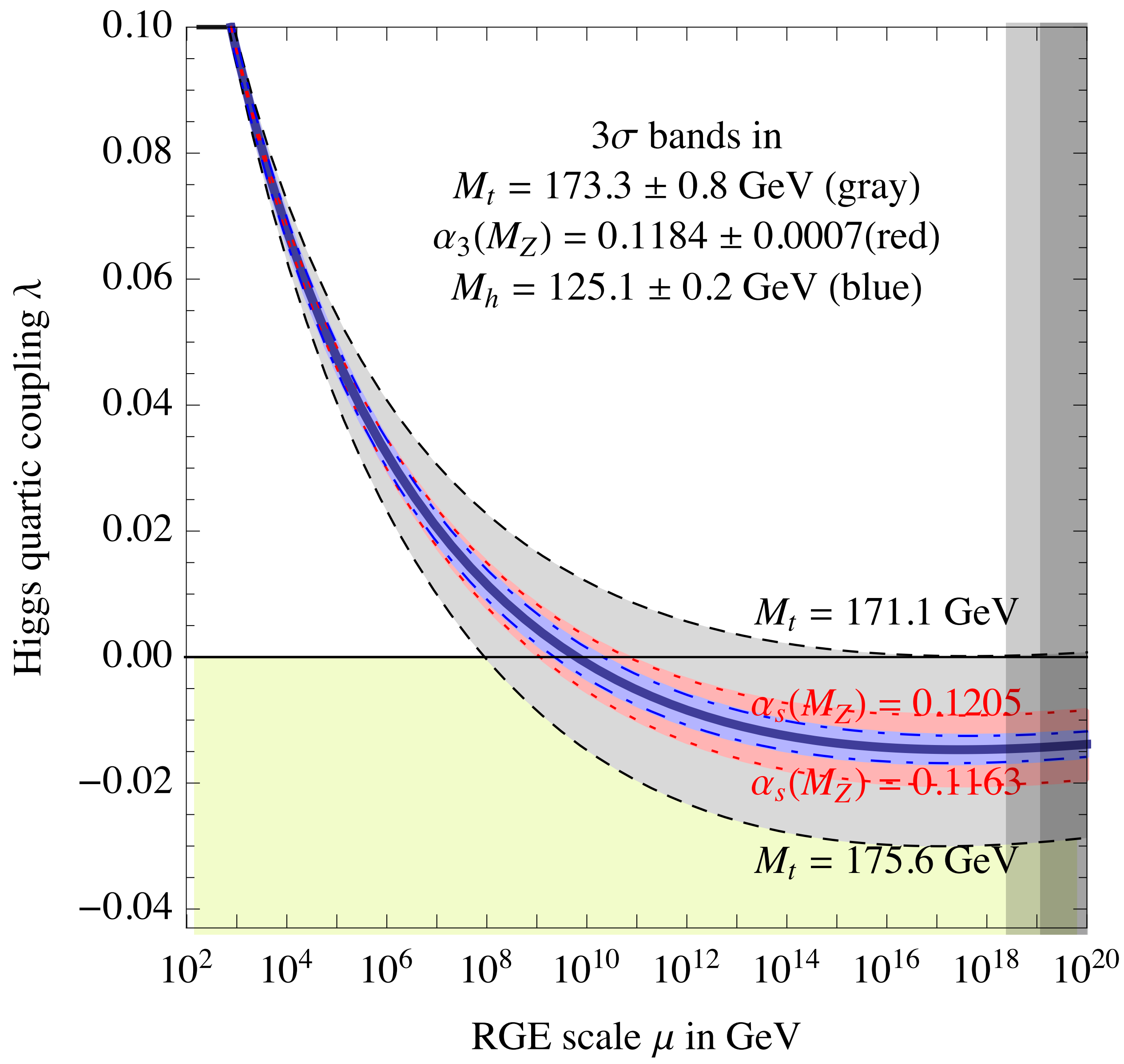


(†) "handedness" of scalar top comes from couplings (SM partner, top, is a fermion)

Running Of Higgs Self-Couplings

Investigating the near-criticality of the Higgs boson

Dario Buttazzo[a,b], Giuseppe Degrassi[c], Pier Paolo Giardino[a,d],
Gian F. Giudice[a], Filippo Sala[b,e], Alberto Salvio[b,f],
Alessandro Strumia[d]



SUSY Breaking Scale?

While “*Natural SUSY* Endures”, *Split SUSY* also an interesting possibility

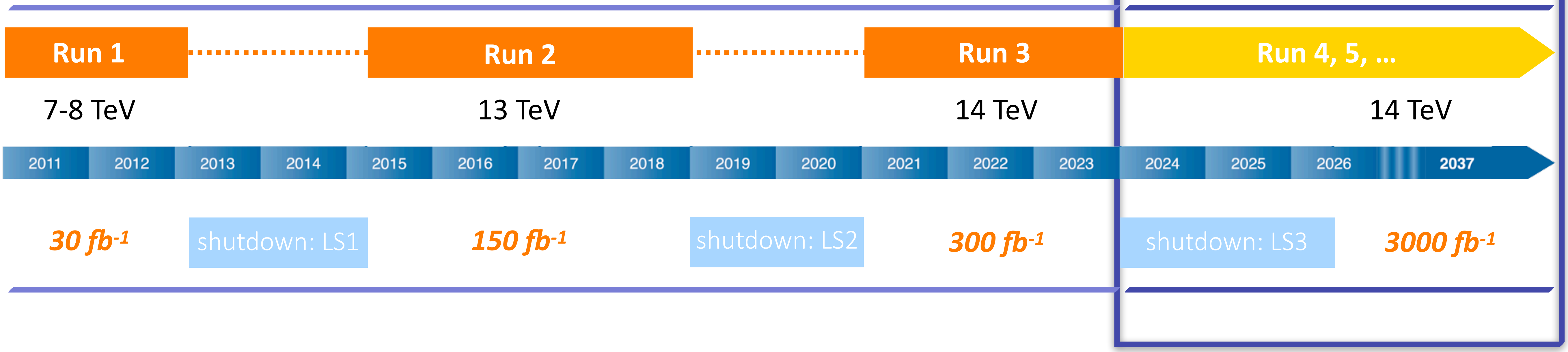
long-lived and/or highly-ionizing particles (“R-hadrons”) are among its consequences

G. F. Giudice - https://cds.cern.ch/record/2639759

The Way Forward: *HL-LHC Phase*

LHC

HiLumi HL-LHC PROJECT

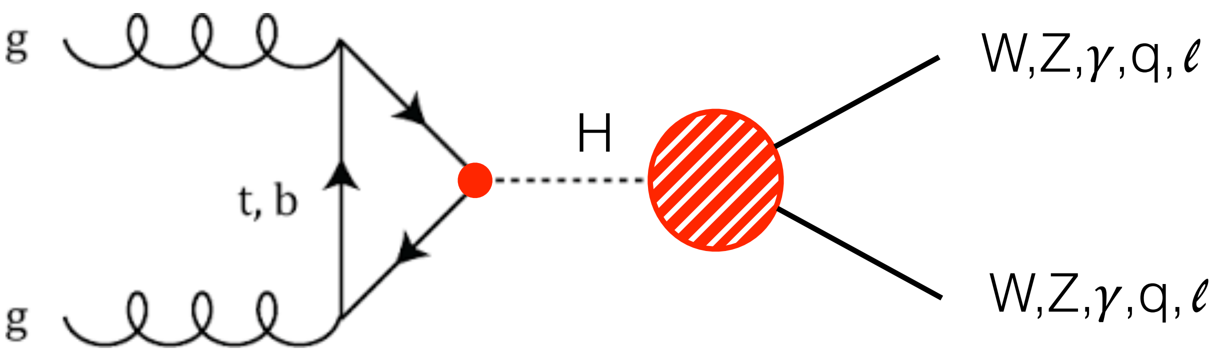


Run 1		Run 2		Run 3	Run 4, 5, …
7-8 TeV		13 TeV		14 TeV	14 TeV
2011, 2012	2013, 2014	2015, 2016, 2017, 2018	2019, 2020	2021, 2022, 2023	2024, 2025, 2026 … 2037
30 fb^{-1}	shutdown: LS1	***150 fb^{-1}***	shutdown: LS2	***300 fb^{-1}***	shutdown: LS3 — ***3000 fb^{-1}***

High intensity @ HL-LHC: shifting toward precision physics

e.g. fingerprinting Higgs sector

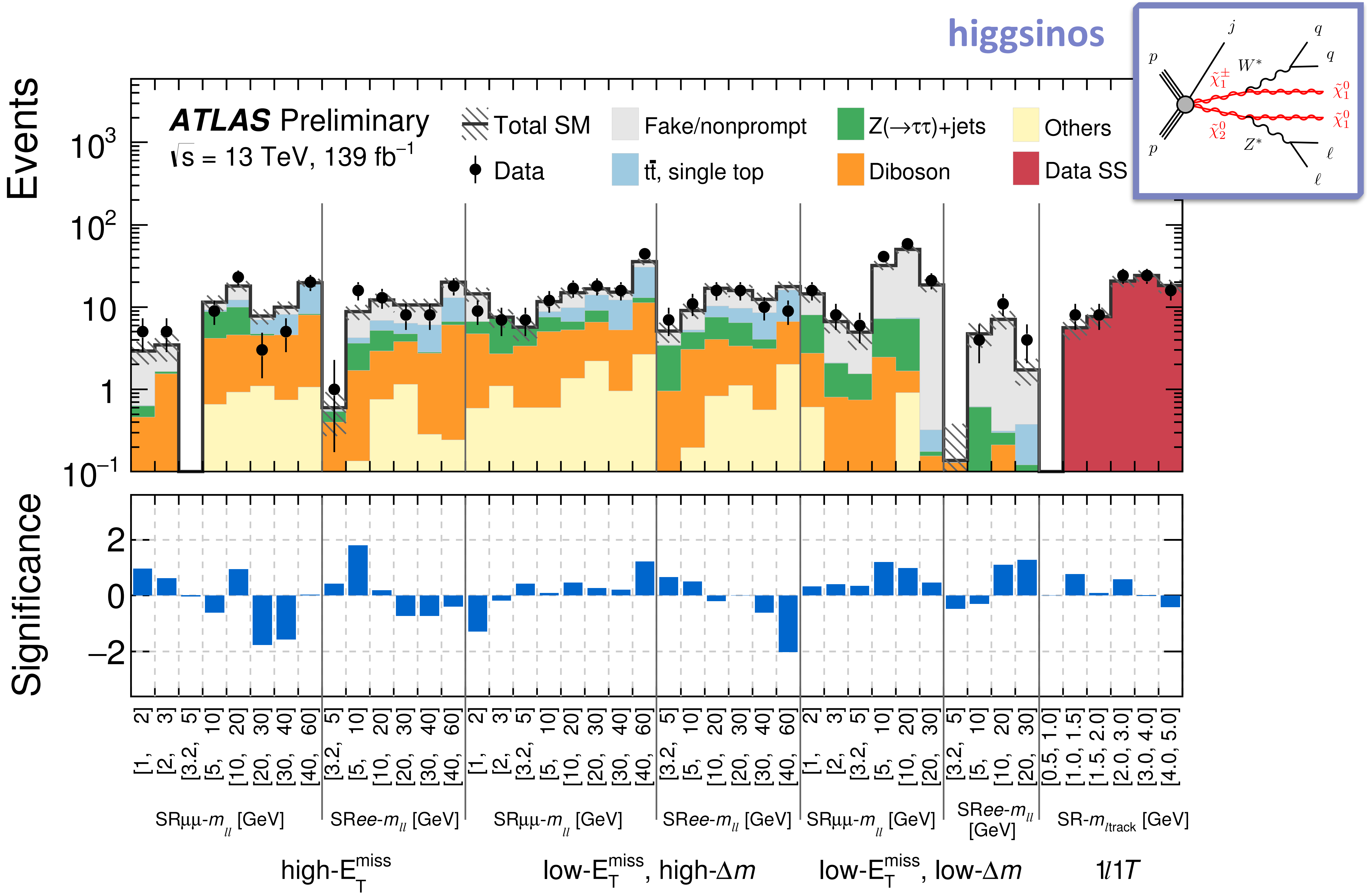
In 20 years…



≈5% precision on Higgs couplings: SM-like or not?

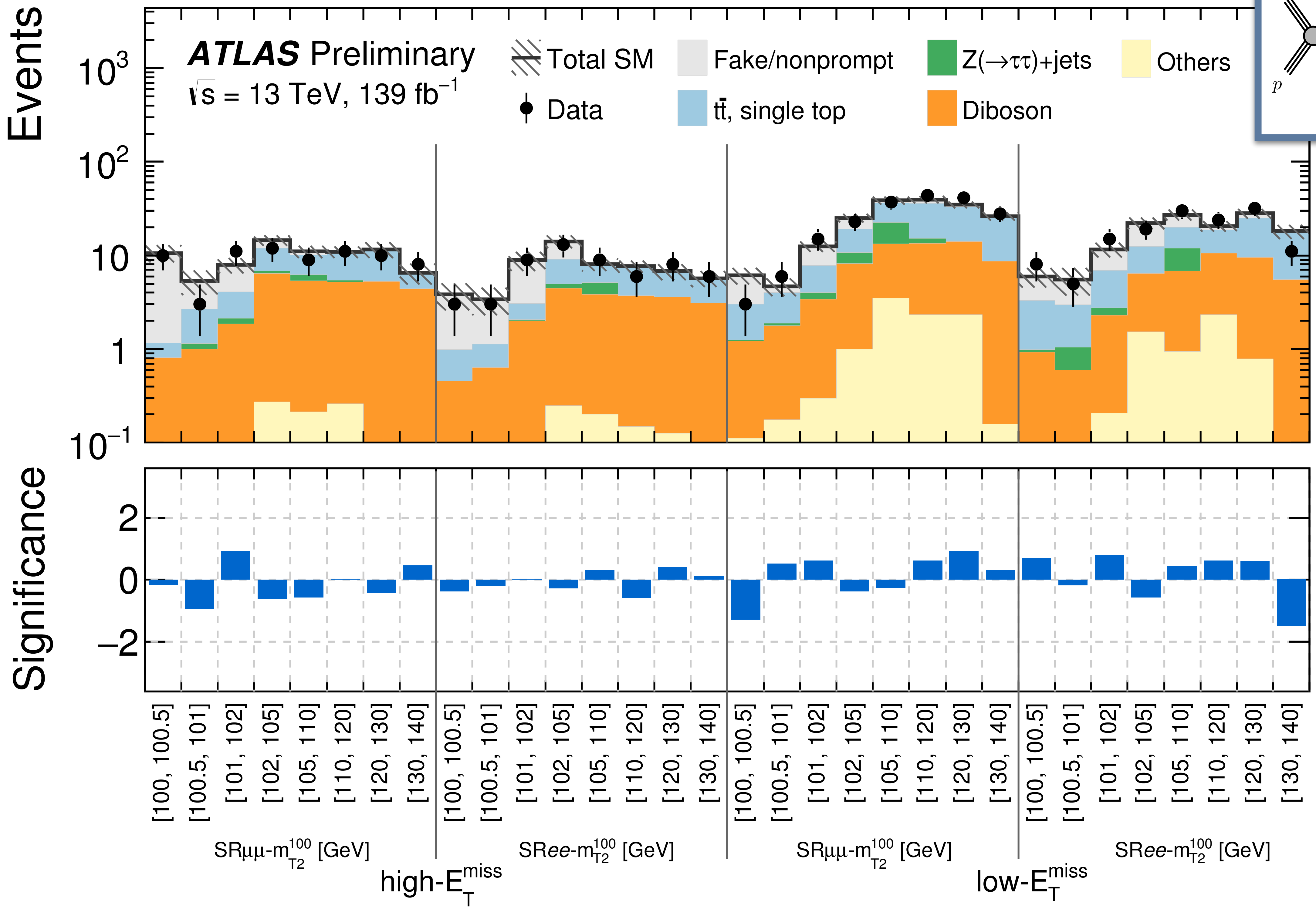
New Result: Data/MC

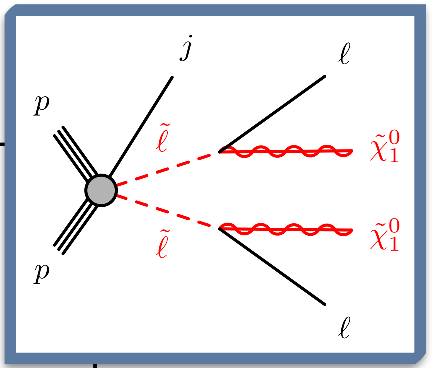
higgsinos



New Result: Data/MC

sleptons

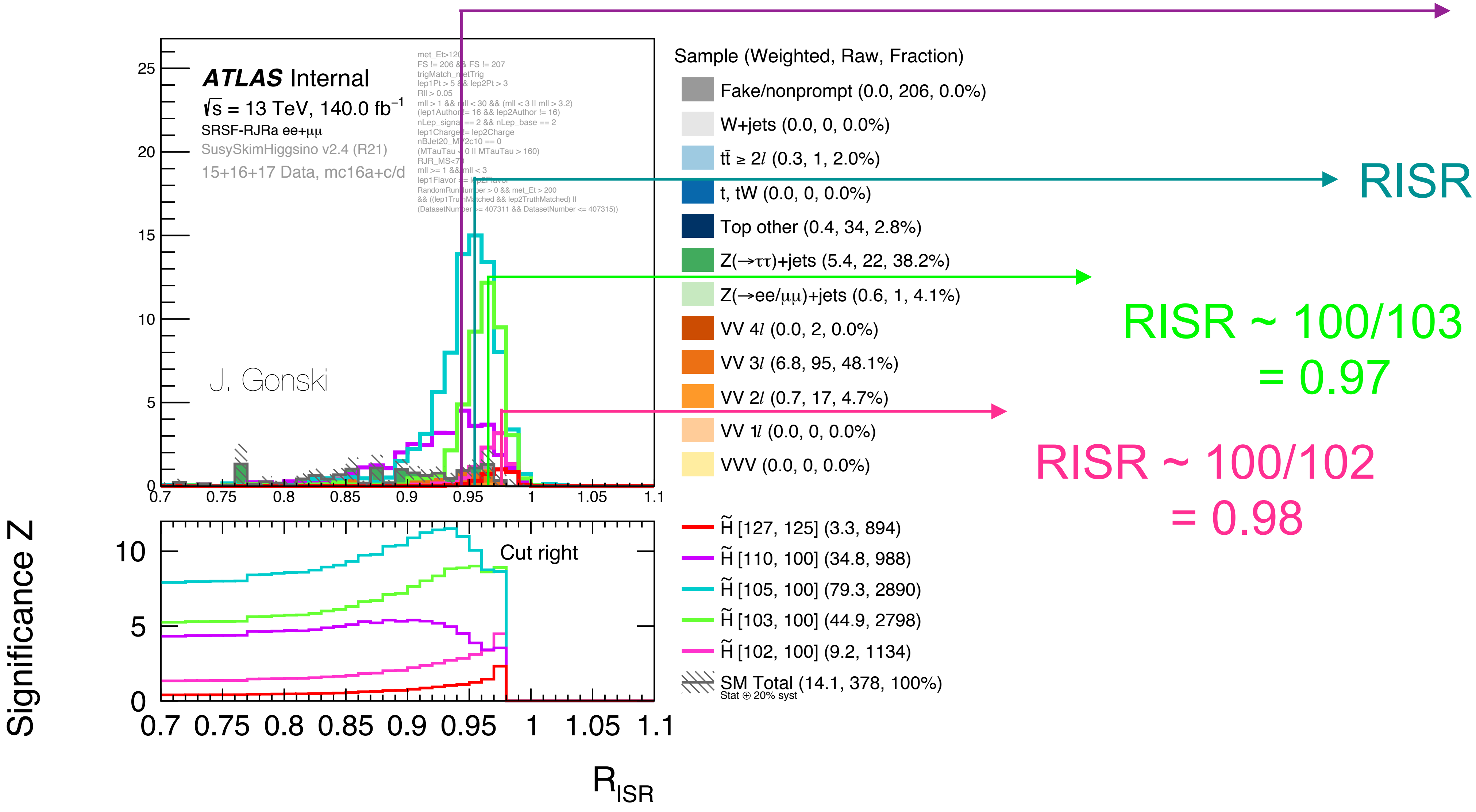




Analysis Strategy: Thrust-based ISR Identification

$$R_{ISR} \approx \frac{\not{E}_T}{p_{T,ISR}} \approx \frac{m(\tilde{\chi}_1^0)}{m(\tilde{\chi}_2^0)}$$

thrust axis: direction maximizing back-to-back p_T



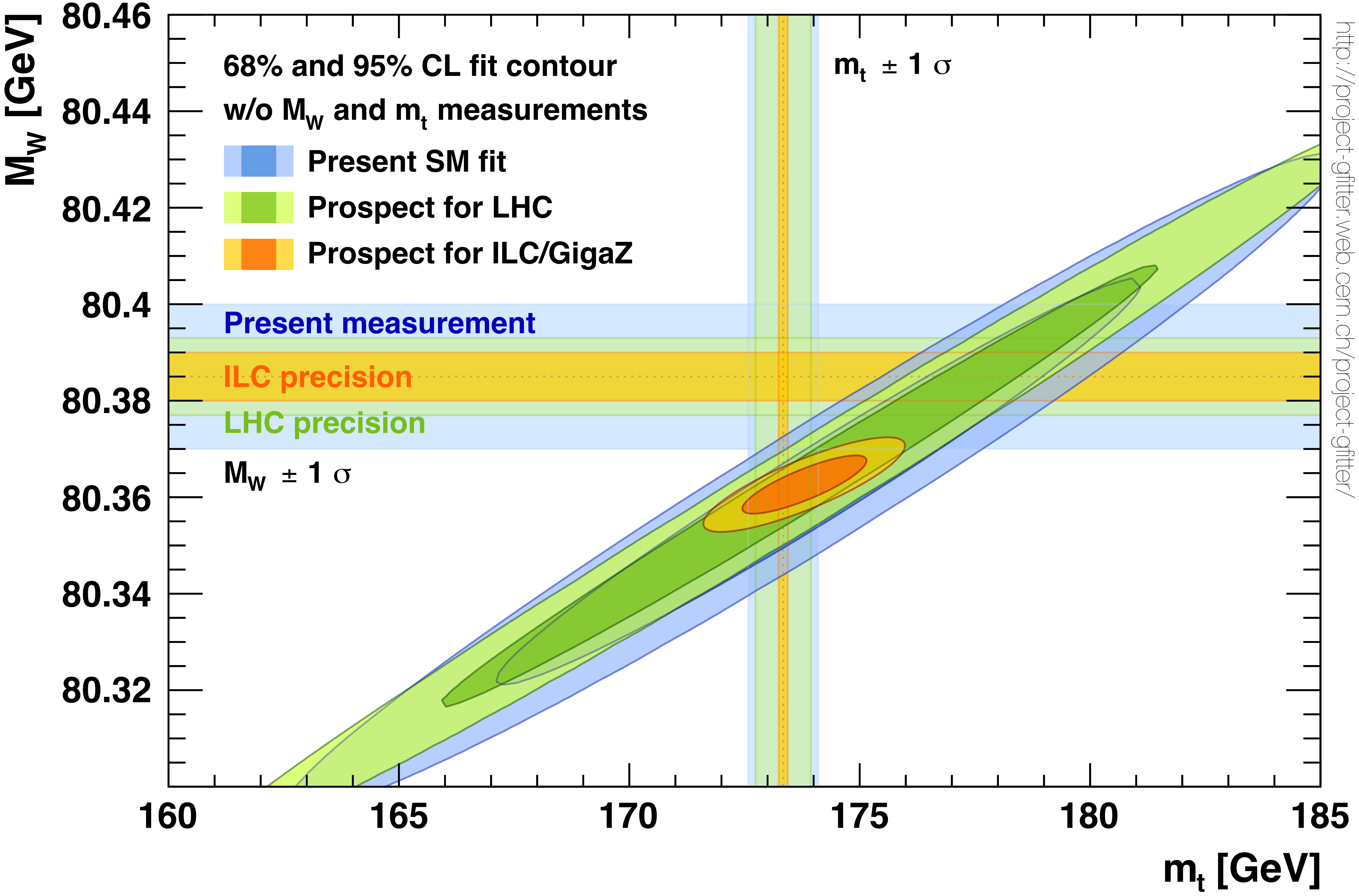
RISR ~ 100/110
= 0.91

RISR ~ 100/105
= 0.95

RISR ~ 100/103
= 0.97

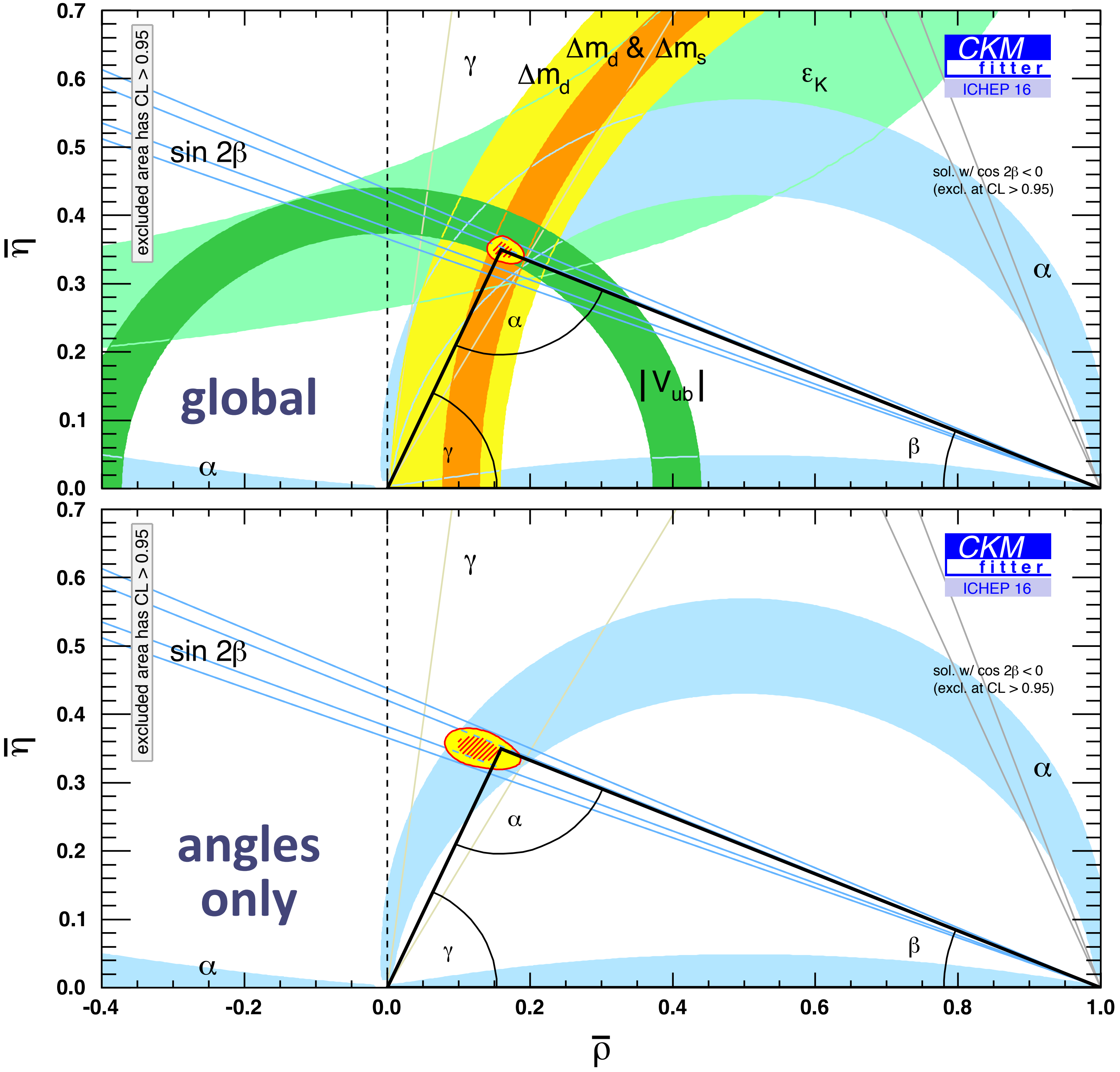
RISR ~ 100/102
= 0.98

Precision Measurements Of SM Parameters



CKM Matrix: Measuring γ

γ: least constrained angle of unitary triangle!



Insensitive to "pollution" from BSM physics: perfect reference to seek for SM deviations using global fits

Accessible in B→DK decays involving tree-level processes with ≈ no hadronic uncertainties

Currently knows within a ≈5° accuracy: beating the 1° barrier is one of LHCb goals

“Flavor Anomalies”

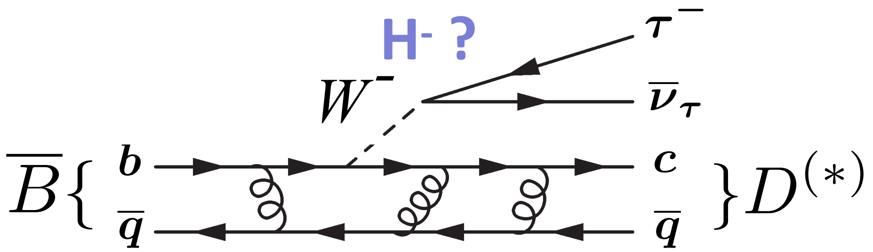
New physics can show up first from indirect constraints (LHCb - intensity frontier)

first evidences of lepton flavor universality violation in b→c and b→s transitions?

Charged current

NP at tree level?

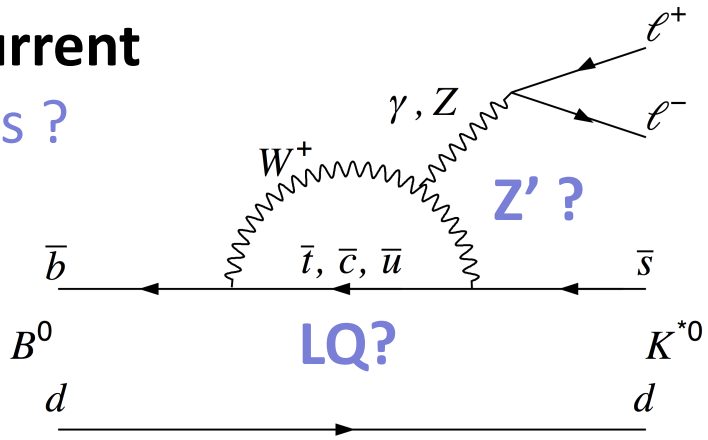
R→ $\frac{\tau\nu_\tau}{\mu\nu_\mu}$

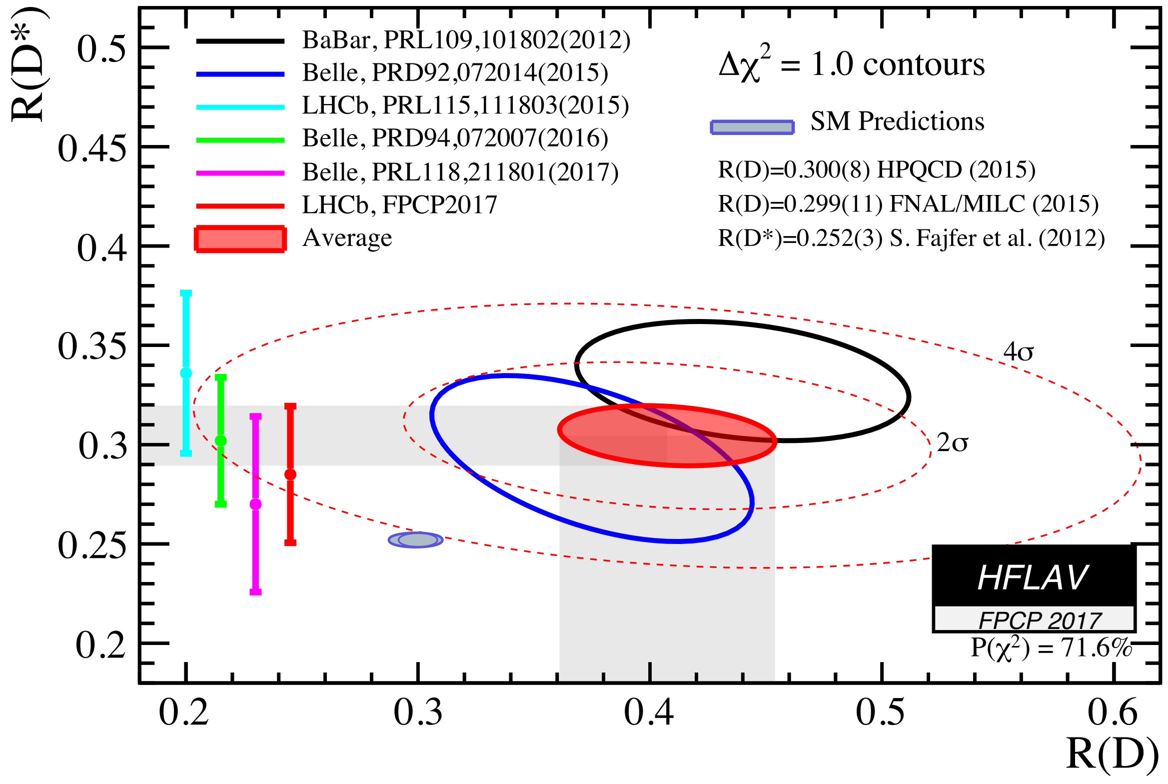


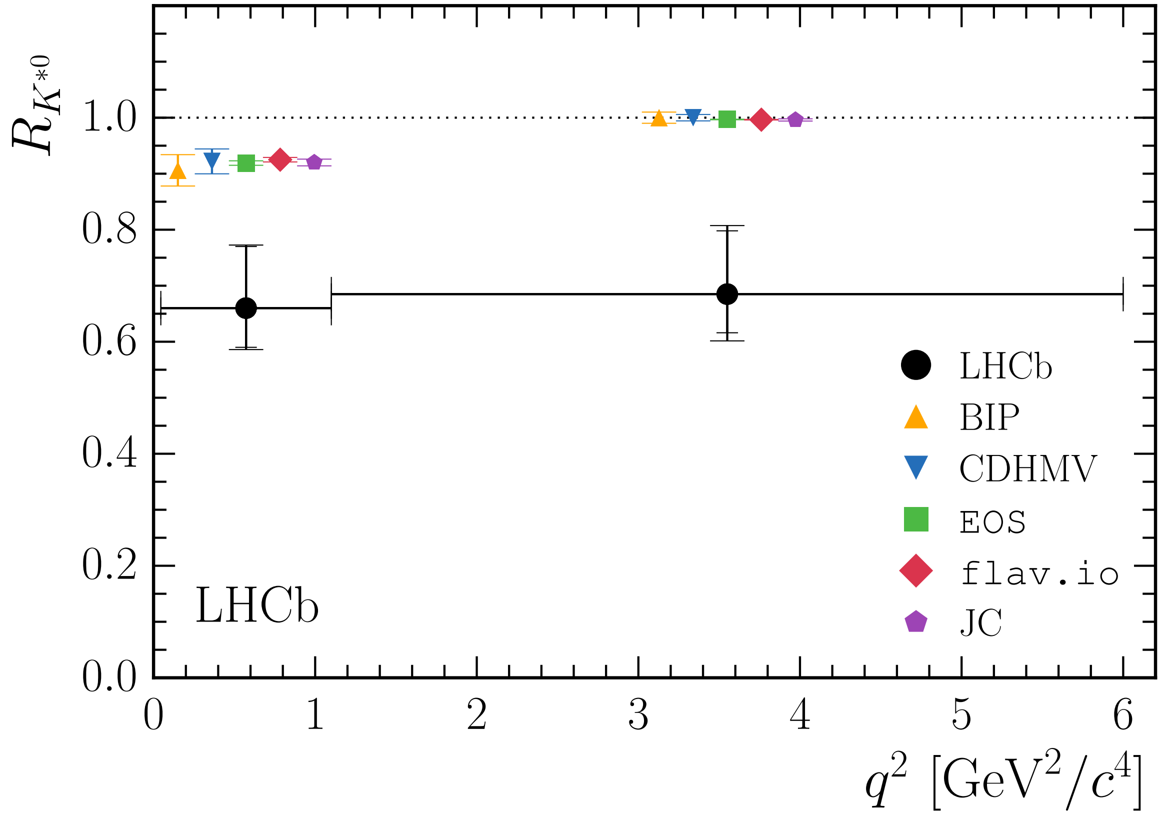
Neutral current

NP in loops ?

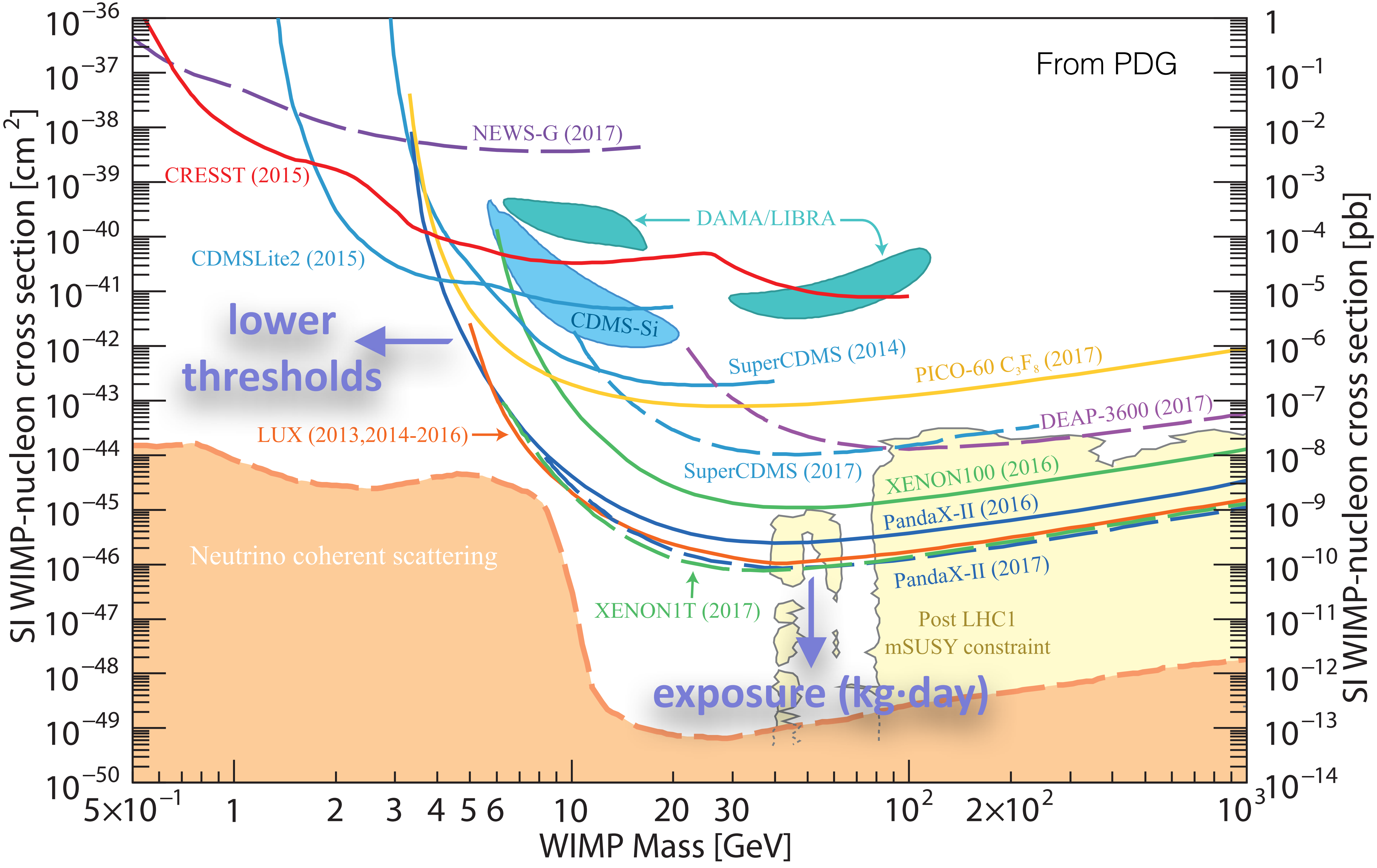
R→ $\frac{\mu\mu}{ee}$







Dark Matter: Direct Detection

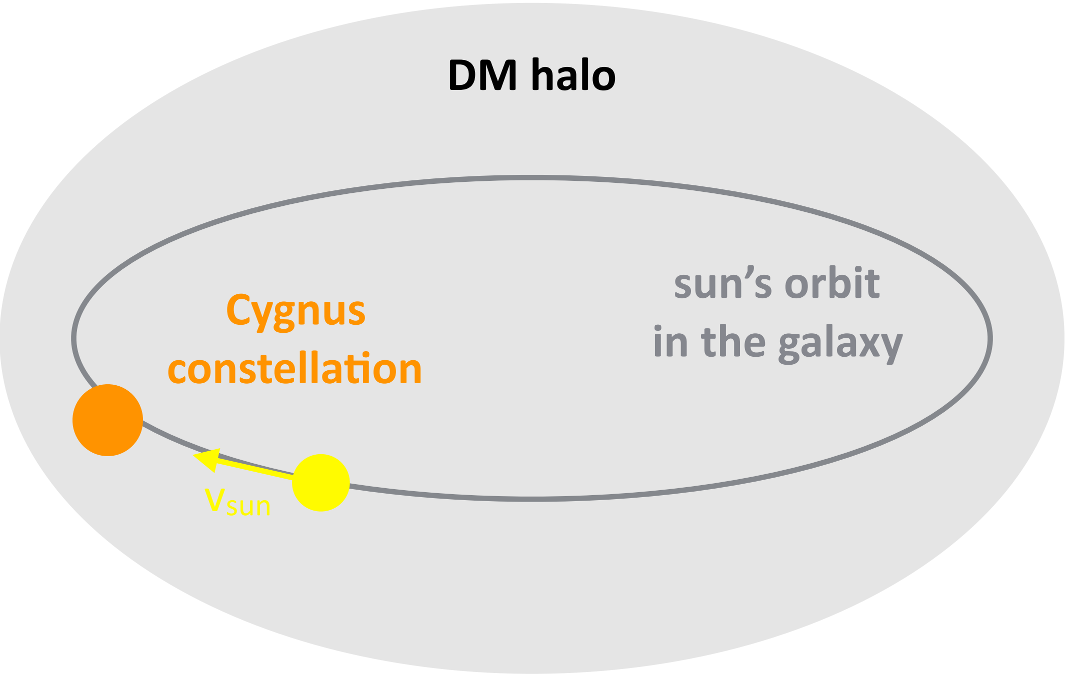


S. Zambito | *Harvard University*

Dark Matter: Directional Direct Detection

Anisotropic signal

“wind” of WIMPs in the direction of sun’s motion (≈Cygnus)



DM halo

Cygnus constellation

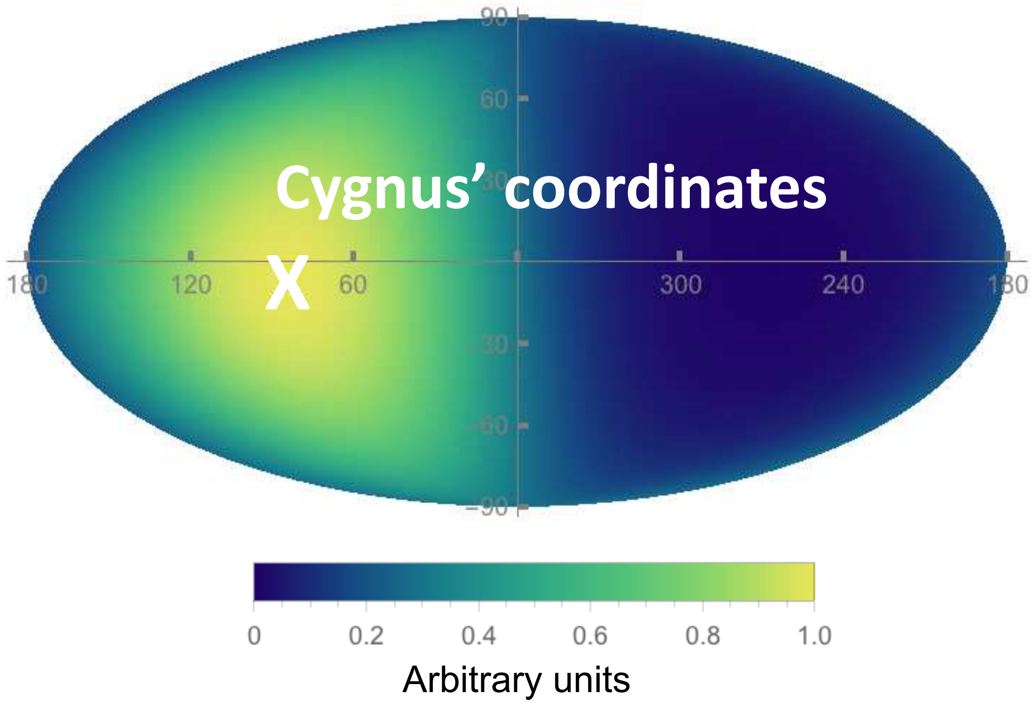
sun’s orbit in the galaxy

v_{sun}

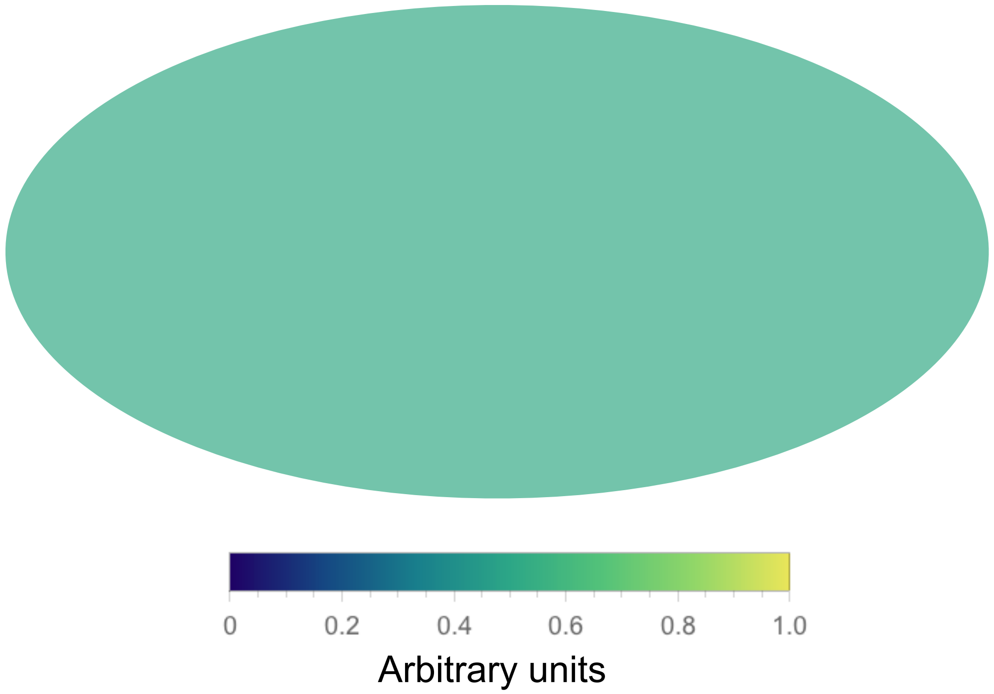
Annual modulation

Earth’s motion induces (small) annual modulation

Expected WIMP signal distribution



Expected background distribution



arXiv:1602.03781

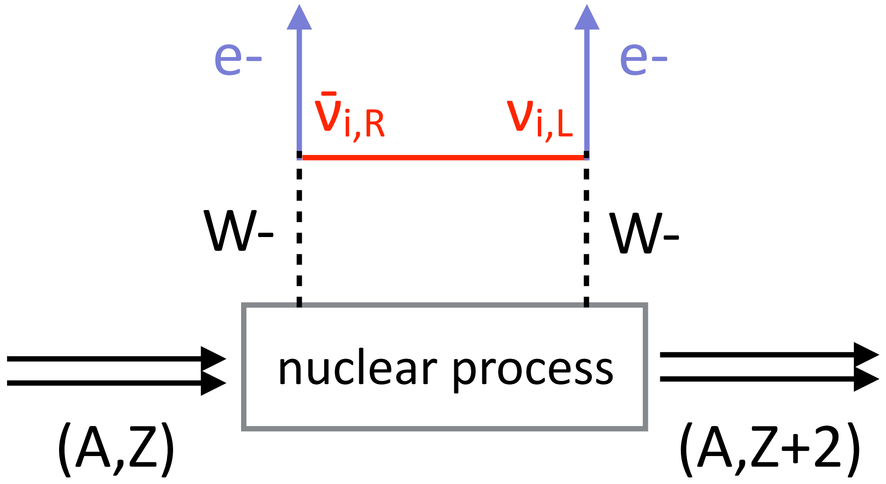
Neutrinoless Double-β Decay

Are neutrinos Dirac or Majorana particles?

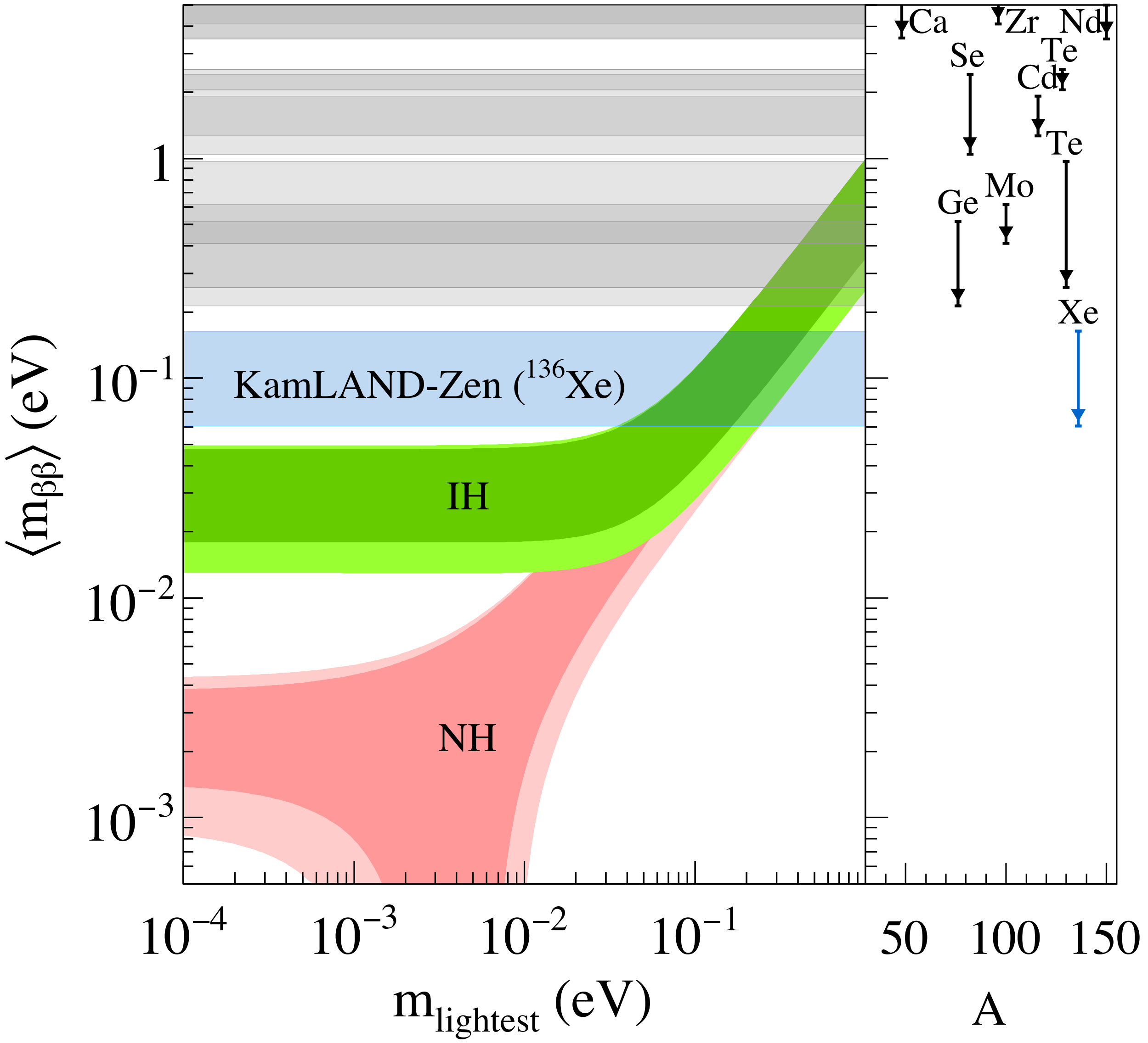
0νββ aim to address this question, measure ν mass scale, test lepton number conservation

can probe new physics contributions: need multi-isotope comparative analysis!

$$(T_{1/2}^{0\nu})^{-1} = \overbrace{G^{0\nu}}^{\textit{phase space integral}} \cdot \underbrace{|M^{0\nu}|^2}_{\textit{nuclear matrix element}} \cdot \overbrace{|\sum_i \underbrace{U_{ei}^2}_{\textit{PMNS matrix}} m_i|^2}^{\langle m_{\beta\beta}\rangle}$$

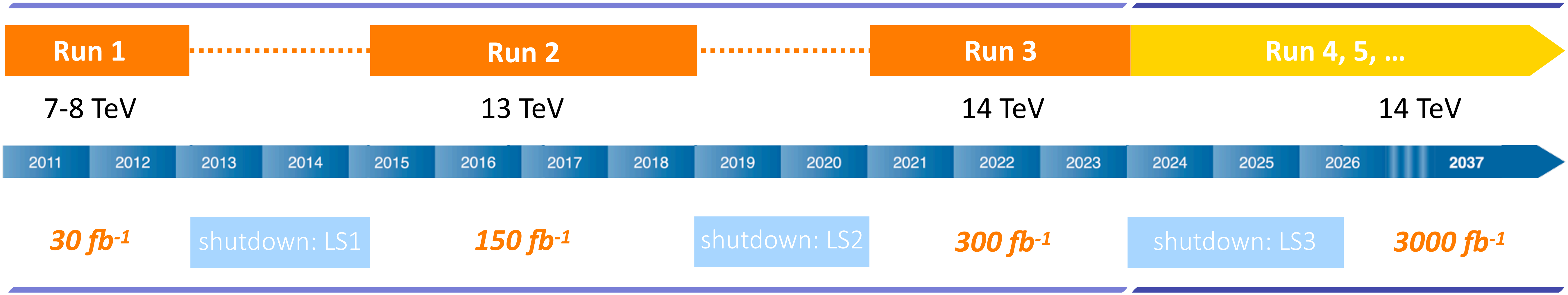


As of July ’16 - arXiv:1605.02889



LHC Long-Term Schedule + Future Colliders?

LHC



Run 1 · Run 2 · Run 3 · Run 4, 5, ...

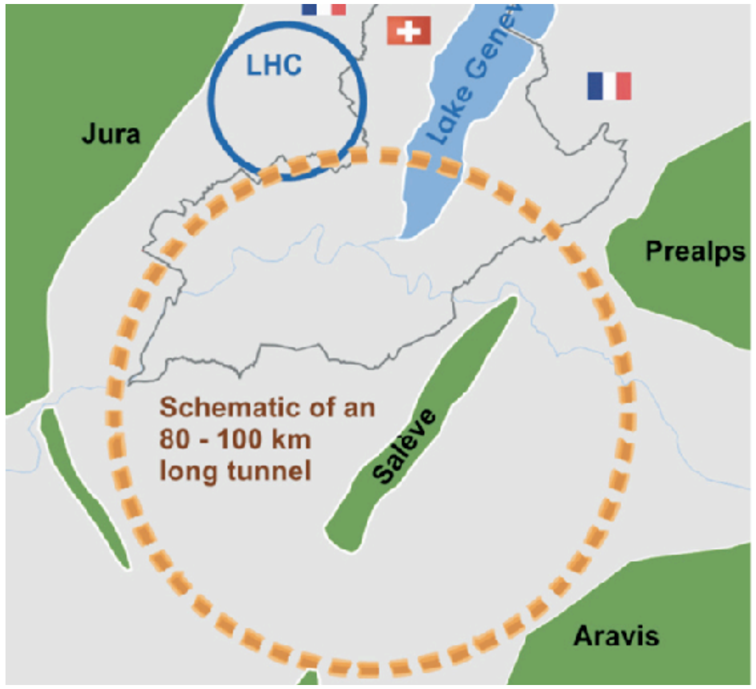
7-8 TeV · 13 TeV · 14 TeV · 14 TeV

2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2037

$30\ fb^{-1}$ · shutdown: LS1 · *$150\ fb^{-1}$* · shutdown: LS2 · *$300\ fb^{-1}$* · shutdown: LS3 · *$3000\ fb^{-1}$*

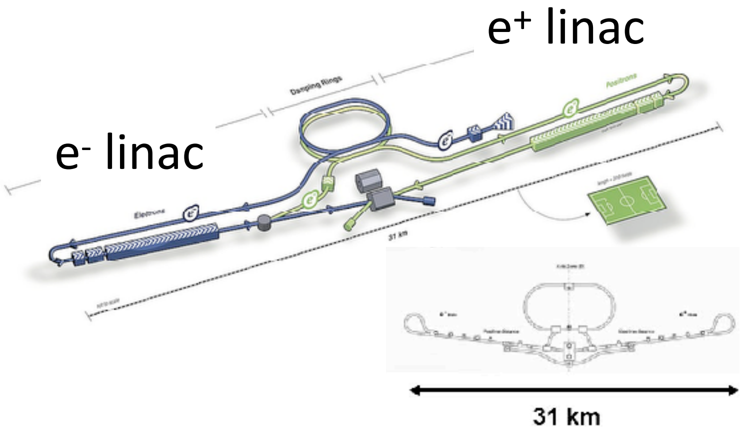
FCC - reach $\sqrt{s}$=100 TeV

search/study new physics



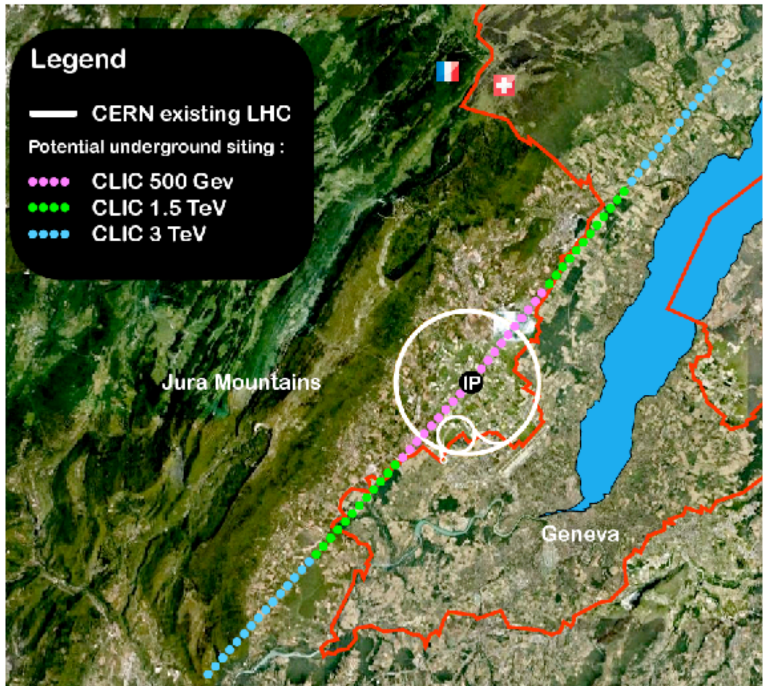
ILC - mature technology

characterize the Higgs



CLIC - new technology

Higgs and new physics?



Gluinos: Background Estimation

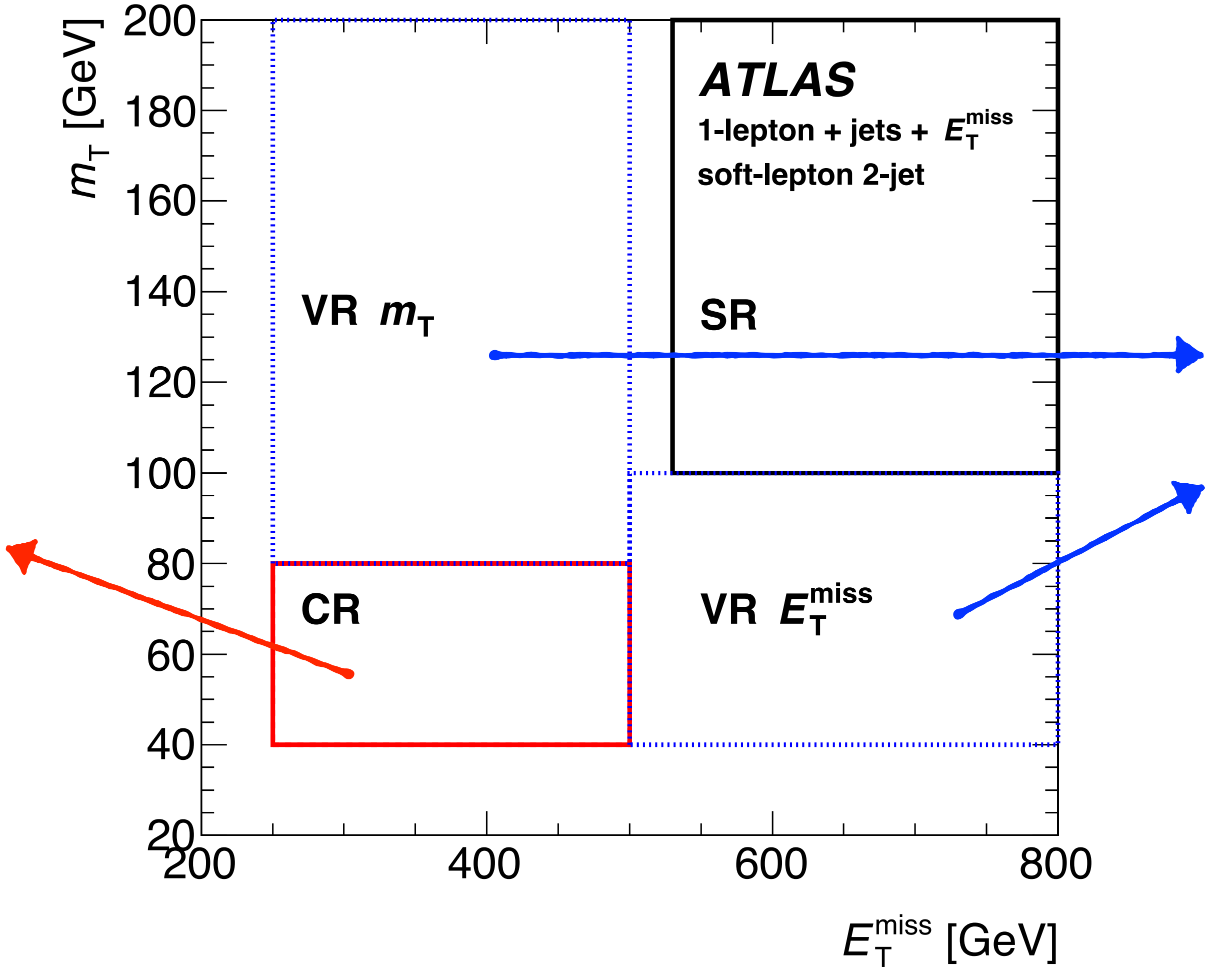
Two *well-understood* and *well-modeled* variables define CR/VR/SR plane

Control Regions (CR) ➝ normalize simulated backgrounds to data

↳ select or veto b-jets to enrich in *$t\bar{t}$* or *W+jets*

↳ extrapolate to SR using MC-based transfer factors

Validation Regions (VR) ➝ validate background estimates against data



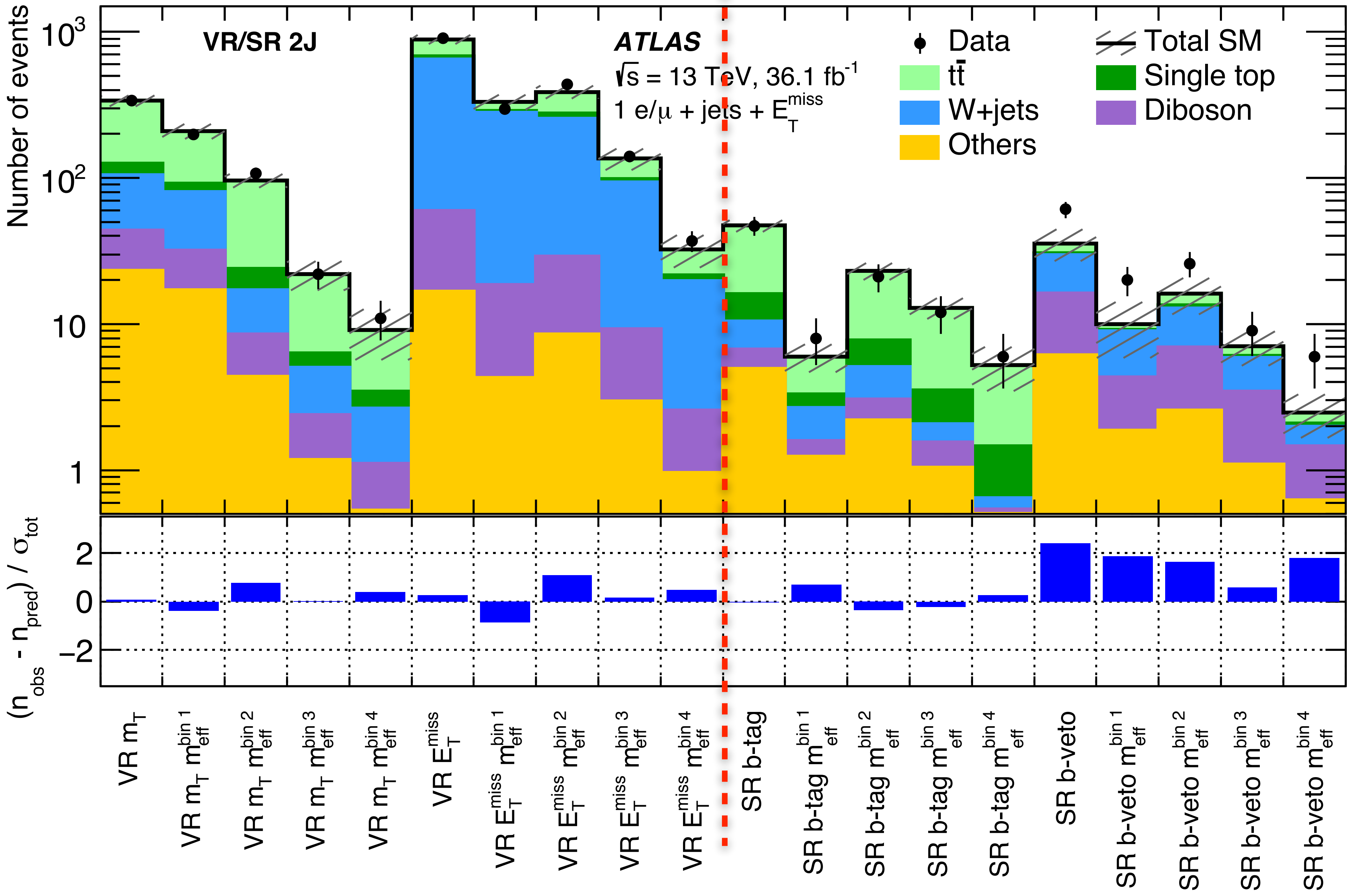
kinematic region close to SR, with negligible signal contamination

validate CR → SR extrapolation along each variable, separately

Gluino Search: Observed Event Yields

validation regions

signal regions



validate
m_T extrapolation

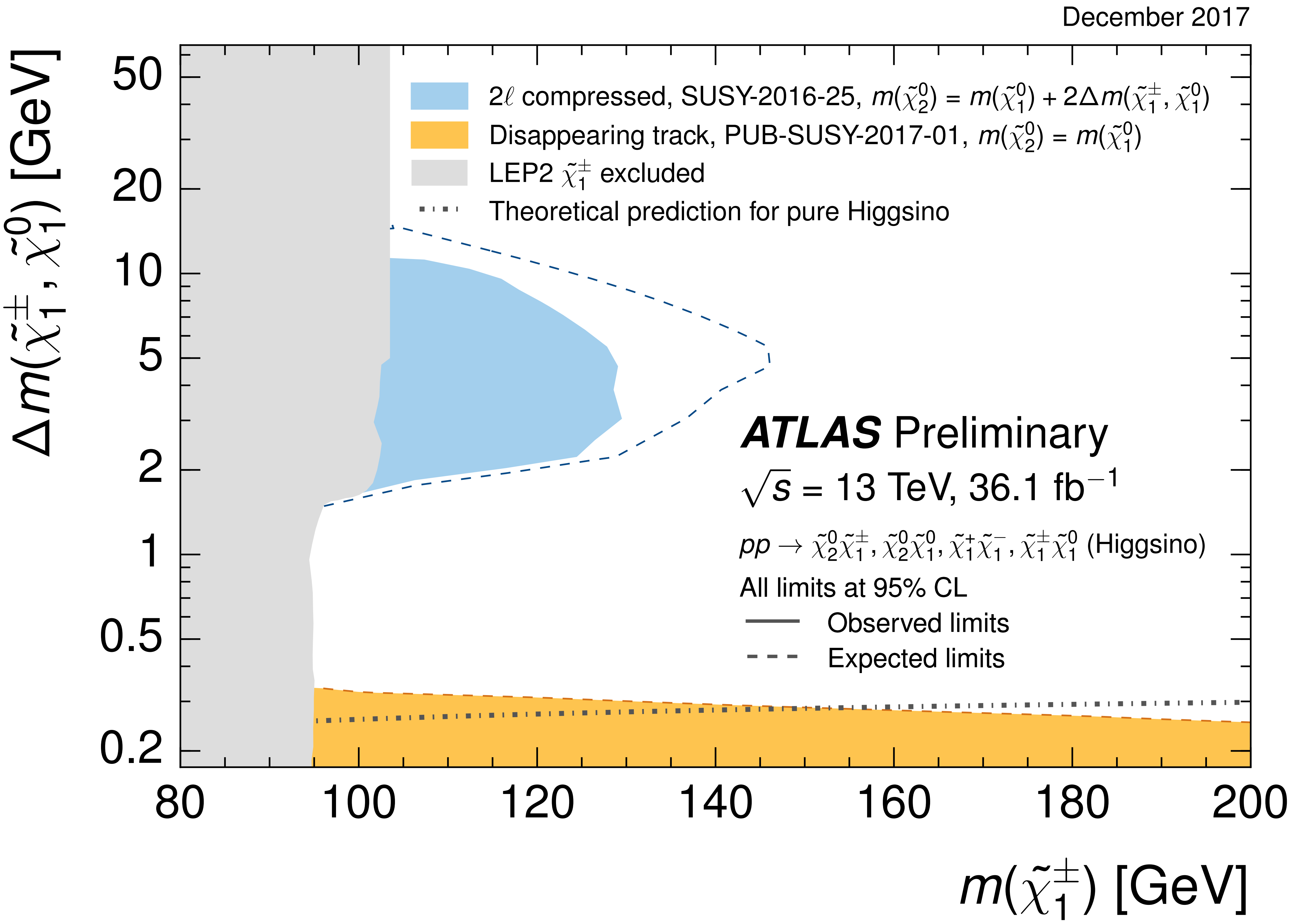
validate
$\cancel{E}_T$ extrapolation

≥1 b-jet

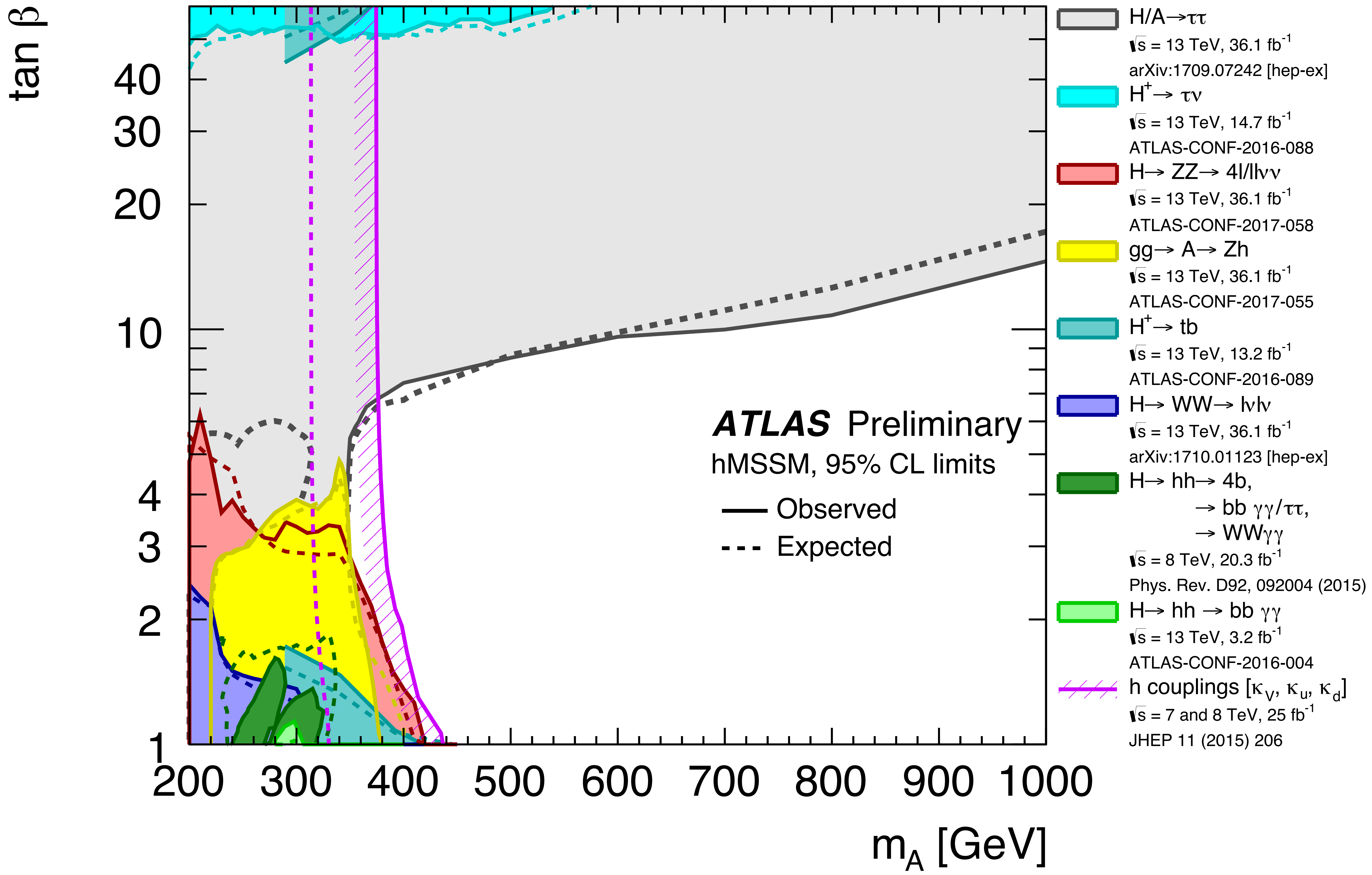
no b-jets

Ultra-compressed Higgsinos

near future



hMSSH - Higgs Sector



Higgsino Searches - CMS