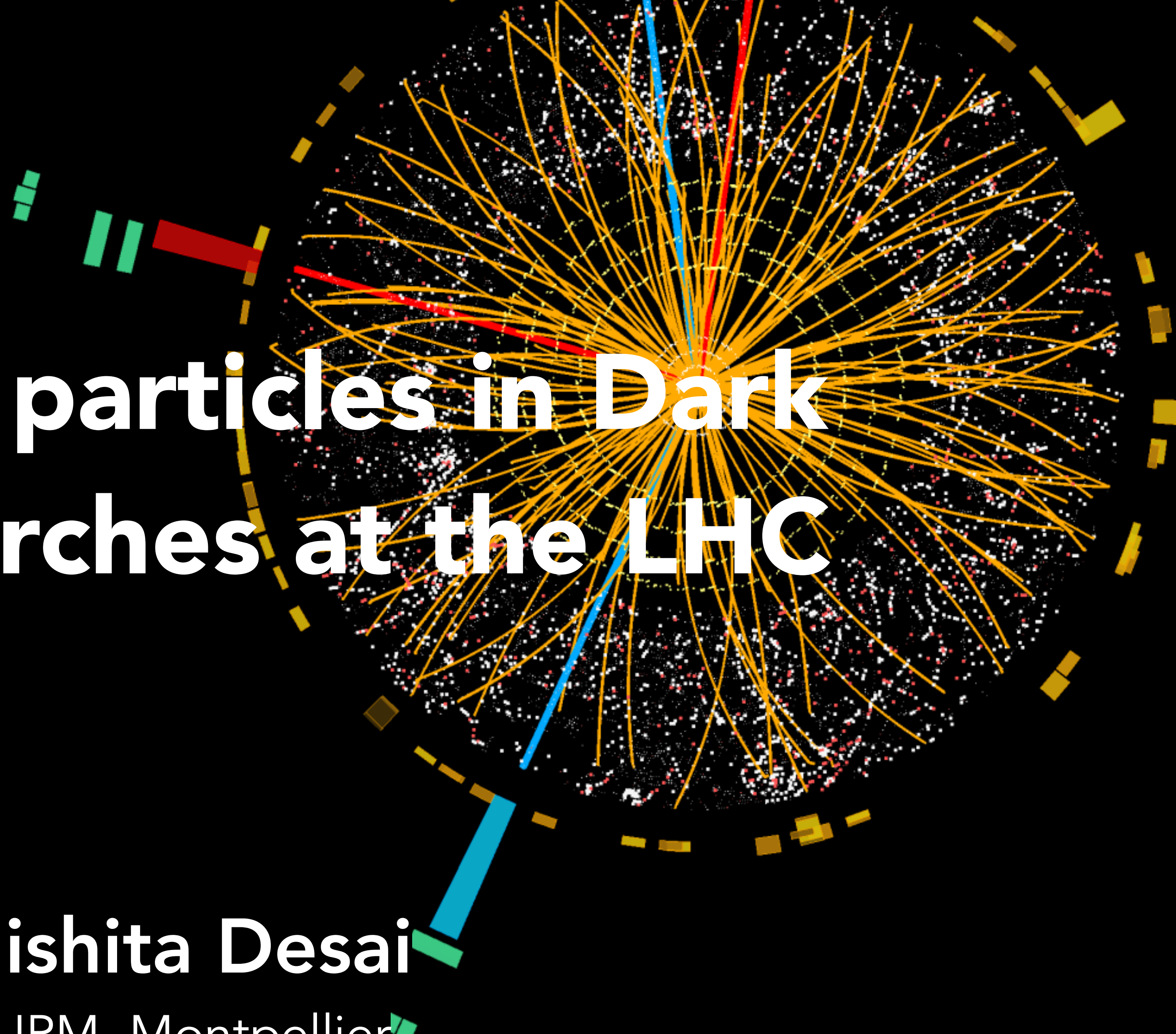


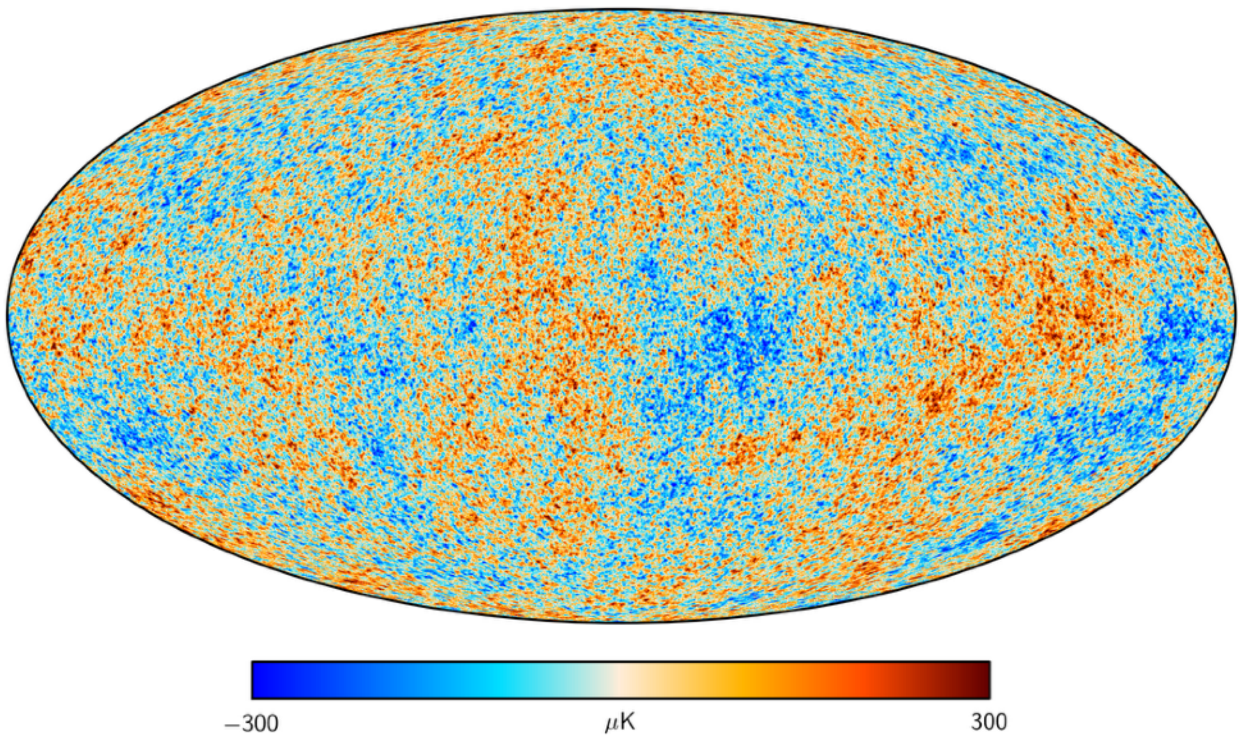
Long-lived particles in Dark Matter searches at the LHC

Nishita Desai
LUPM, Montpellier

Based on: arXiv:1804.02357, 1803.10379, 1606.03099, 1611.09908 and 1404.5061
With: B. Allanach, M. Badziak, M. Bauer, A. Butter, G. Cottin, A. Bharucha, F. Brümmer, J. Ellis, J. Gonzalez-Fraile, C. Hugonie, F. Luo, J. Marrouche, T. Plehn, R. Ziegler

20 June 2018; HEPHY, Vienna

Manifold evidence for Dark Matter



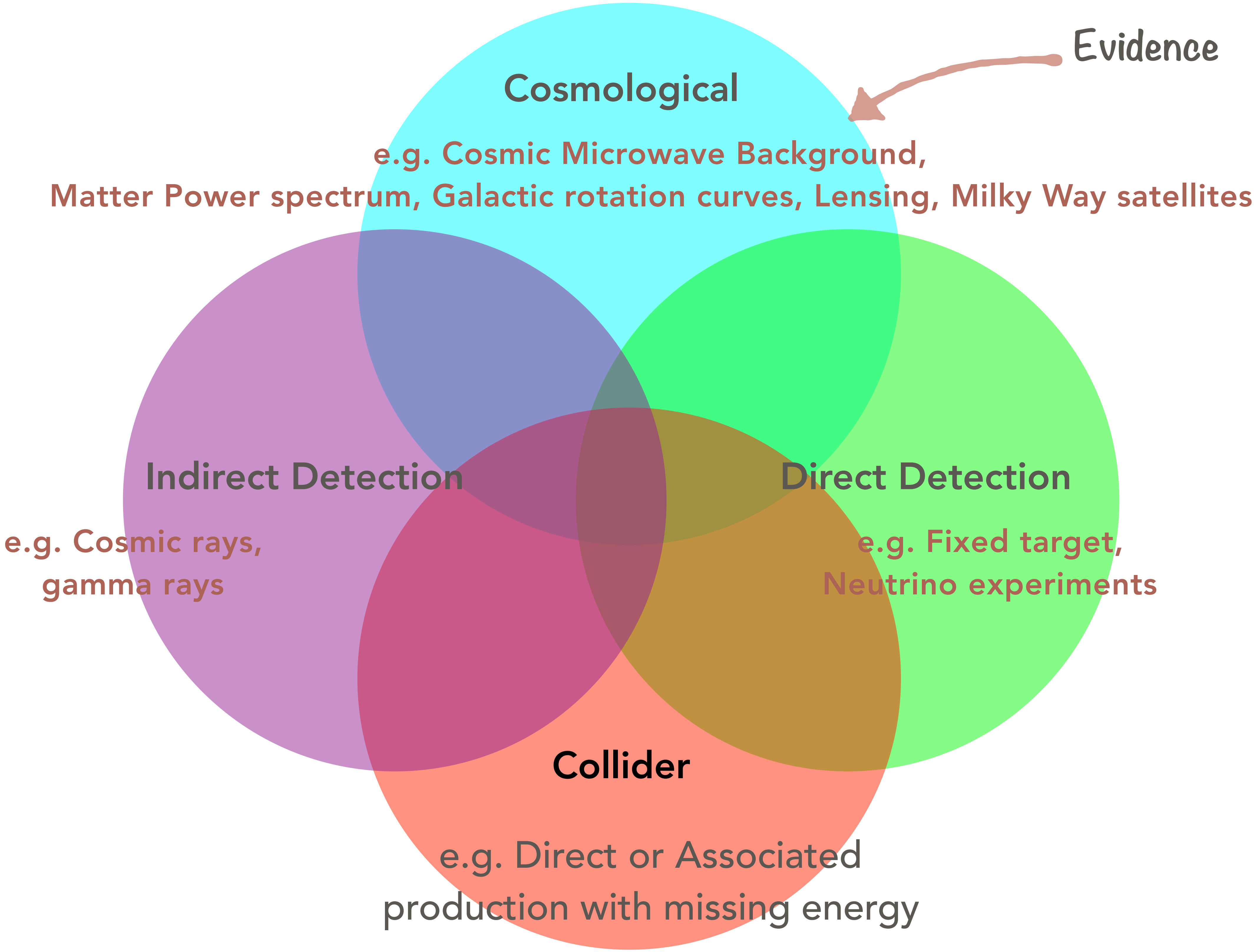
PLANCK Collaboration (2015)

1E 0657-558 (“Bullet Cluster”)

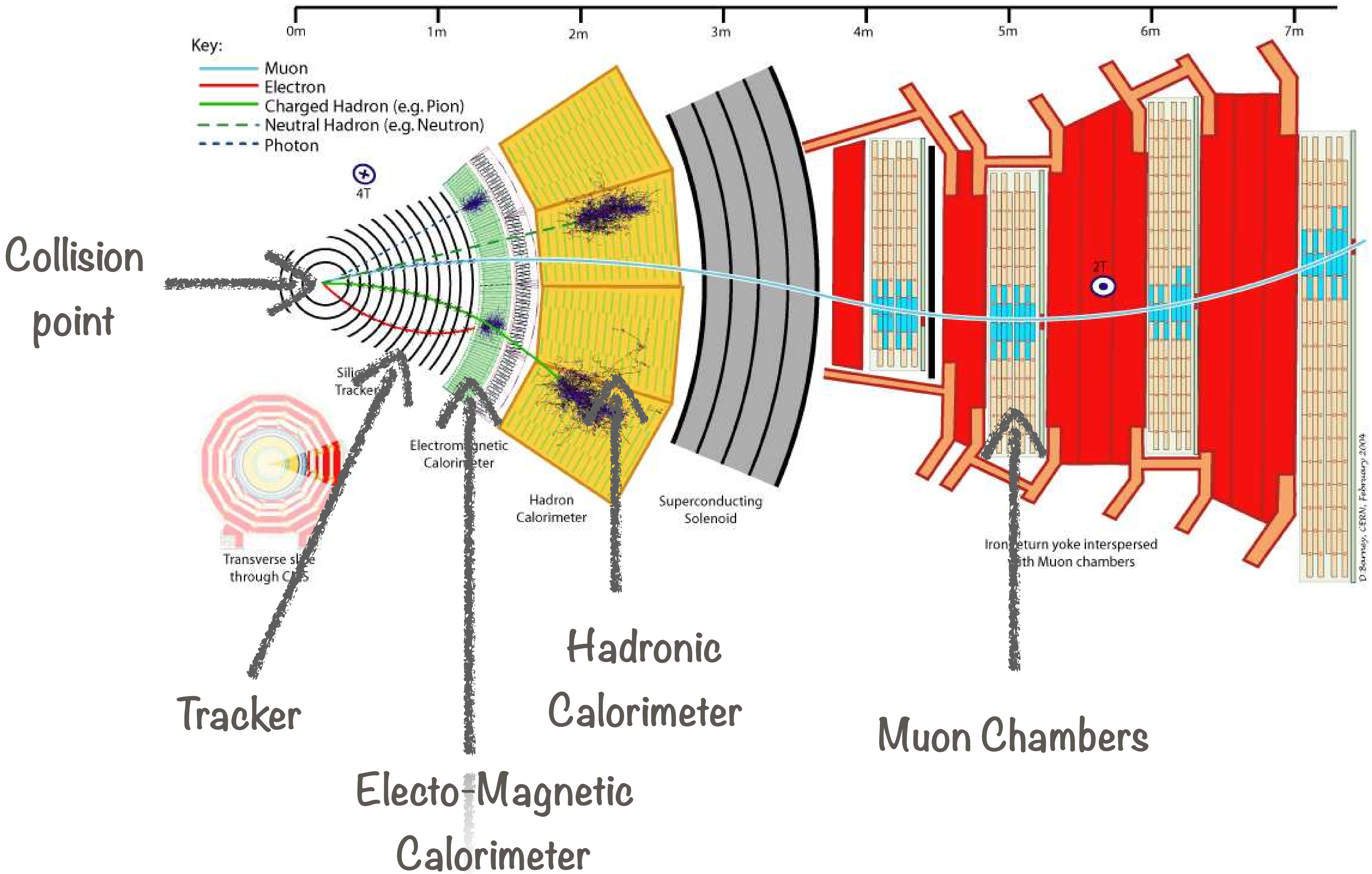
$$\Omega_m h^2 = 0.1415 \pm 0.0019$$
$$\Omega_b h^2 = 0.02226 \pm 0.00023$$
$$\Omega_c h^2 = 0.1186 \pm 0.0020$$

A Dark Matter particle should be: **massive**, **neutral**, **non-relativistic** at present time

Complementarity of searches

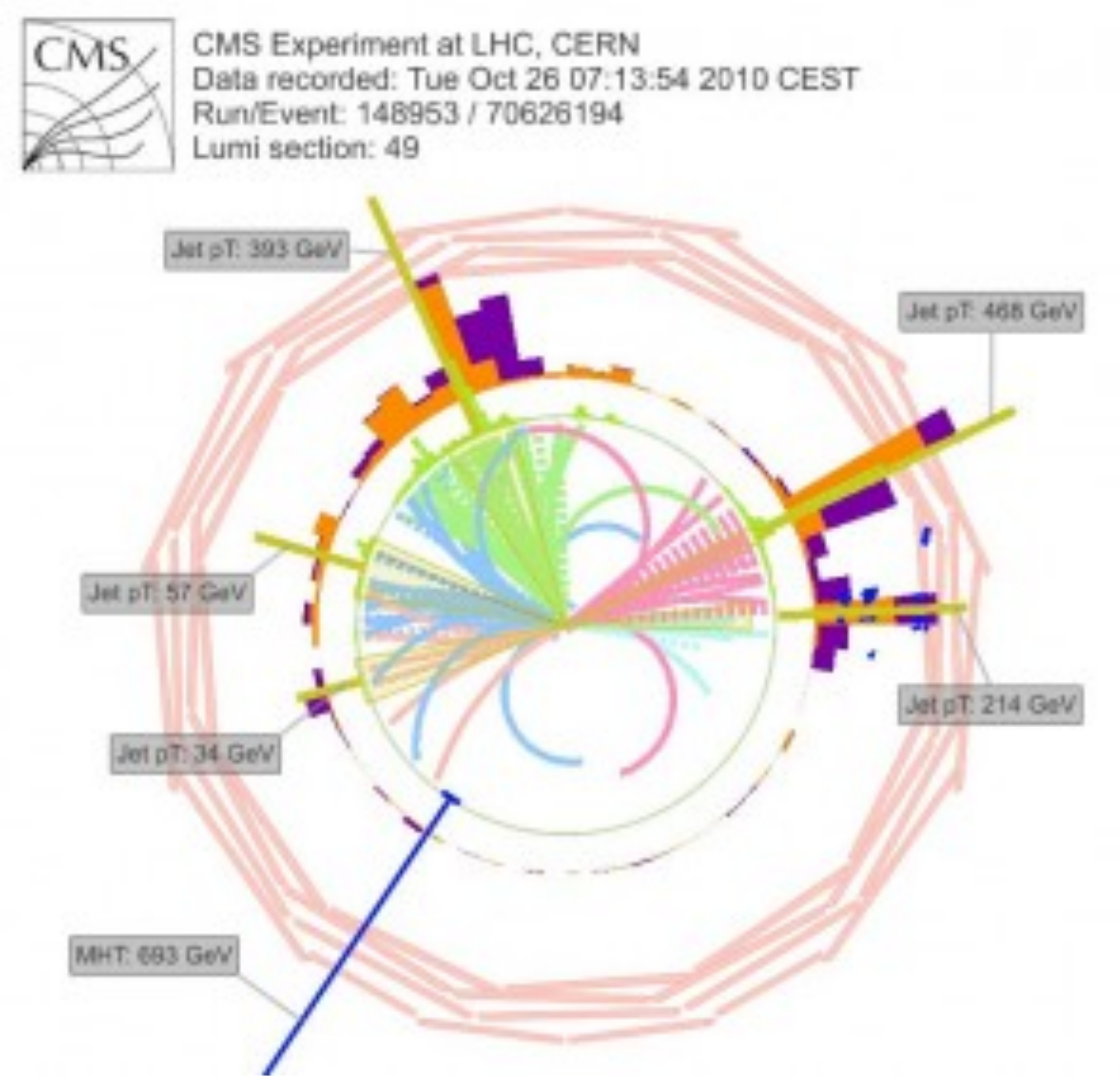


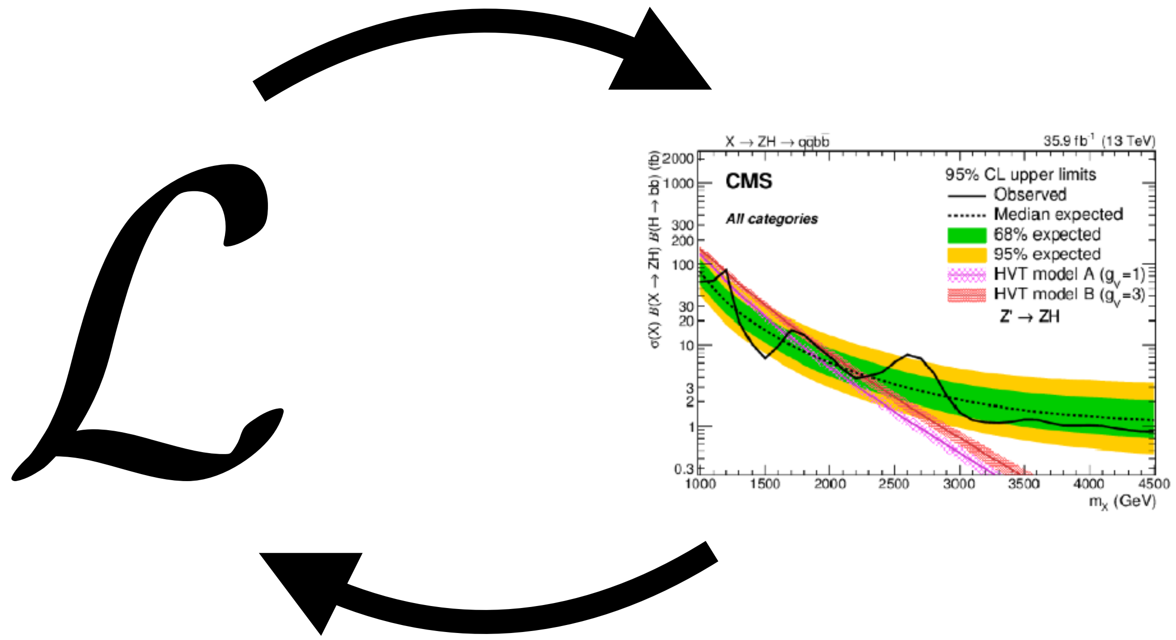
Anatomy of a typical detector @ LHC



What does a collision event look like?

- Detectable objects are **photons**, **electrons**, **muons**, hadrons (which form **jets**), and invisible neutrinos (in the form of **missing momentum or MET**)
- Most new particles will decay into SM particles
- We use **kinematic distributions** of detectable objects to define **signal** (i.e. new physics) and **background** (i.e. SM physics)





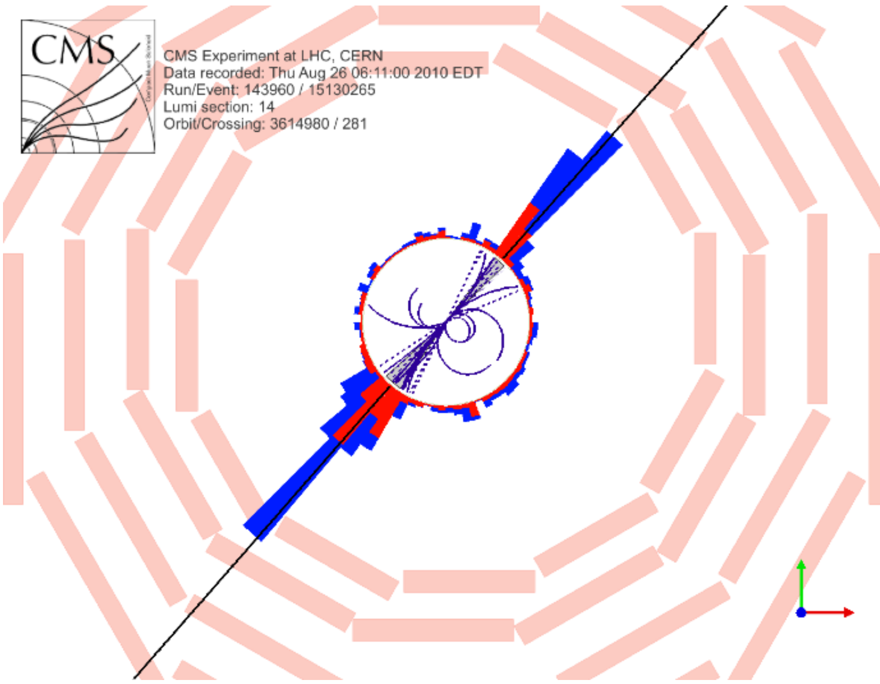
Prediction & Inference

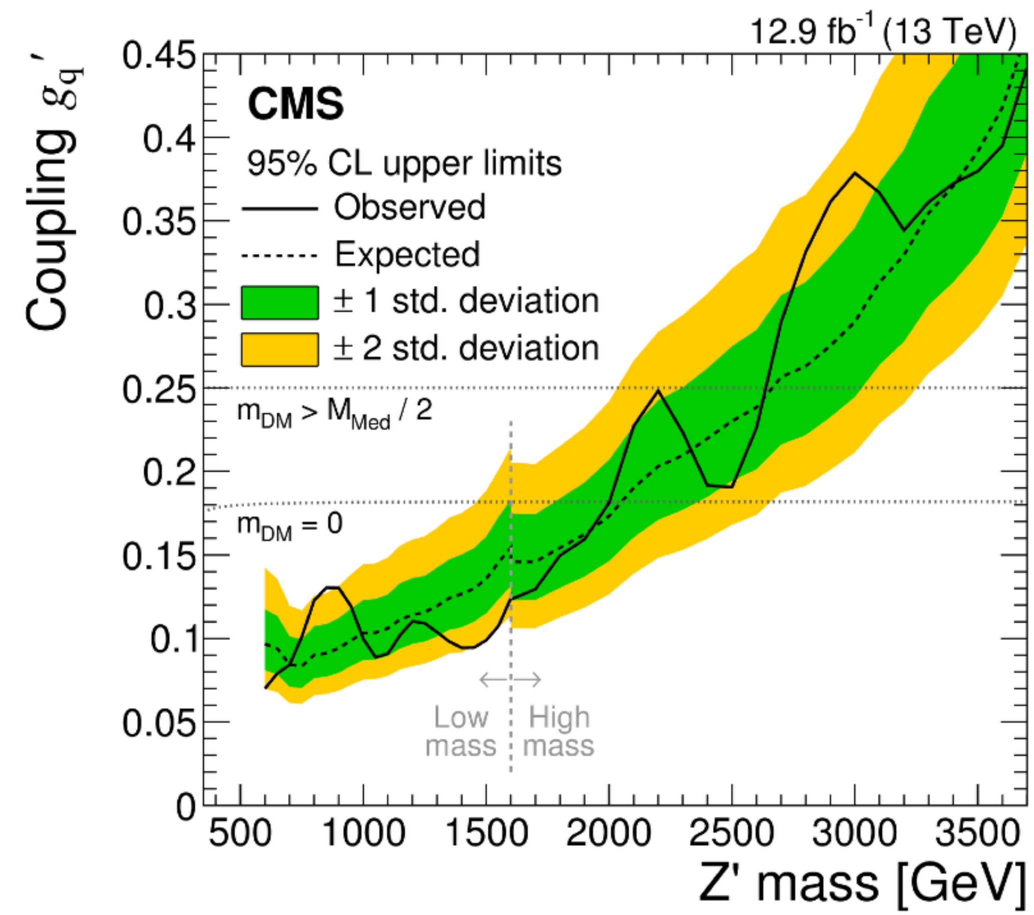
(i.e. If the LHC sees something, how well can we pinpoint the underlying theory?)

To be able to use LHC data for model building & testing:

1. Experimentalists should provide their results in a “model-independent” way (e.g. 95% observed ULs instead of exclusion curves in model parameters)
2. There should be a standard way of re-using experimental searches. This is called **“Recasting”**.

Data from experiments





A. Experiments provide "high-level" information, e.g. **number of observed events** with X jets + Y electrons/muons + large MET; **signal strength** in a particular channel, etc.

B. Kinematic requirements (a.k.a **cuts**) are placed to discriminate new physics "signal" from Standard Model "background". Experiments provide **cut flows**, **efficiency maps** for benchmark models.

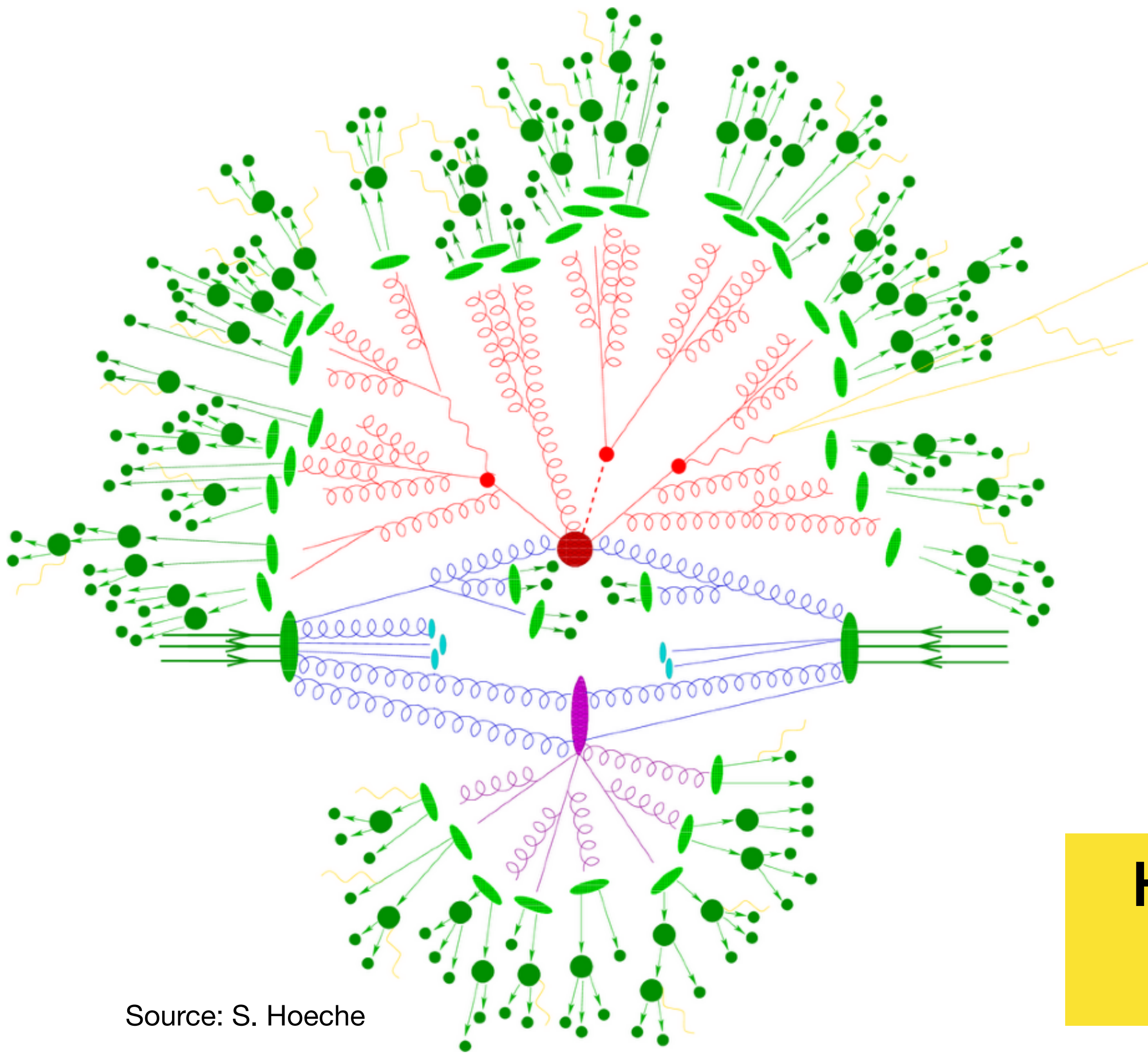
C. Complex statistical machinery used — likelihoods, MVA, Neural Nets etc. to get best **upper limits**, **signal strengths**, or **cross section measurements**.

Lagrangian
+
parameters

Data to Theory:
How to test your own theory against data?

Recast accurately reproduces kinematic effects.

Simulating signal and background



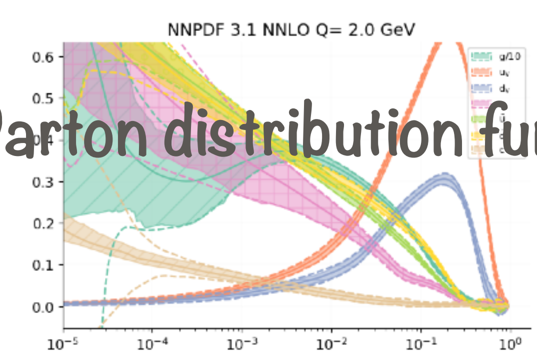
Source: S. Hoeche

- **Hard Process:** production & decay
- **Parton showers:** radiation from quarks and gluons
- **Hadronisation:** formation of hadrons (baryons and mesons)
- **Multi-parton interactions:** more than one interacting parton from the same proton

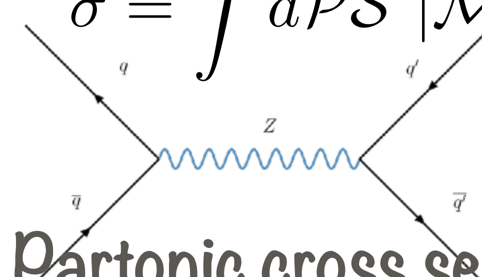
High-scale New Physics shows up mainly in the hard process

$$\sigma_{pp} = \int\int dx_1 dx_2 f(x_1) f(x_2) \hat{\sigma}(x_1, x_2)$$

$$\hat{\sigma} = \int d\mathcal{PS}\ |\mathcal{M}|^2$$

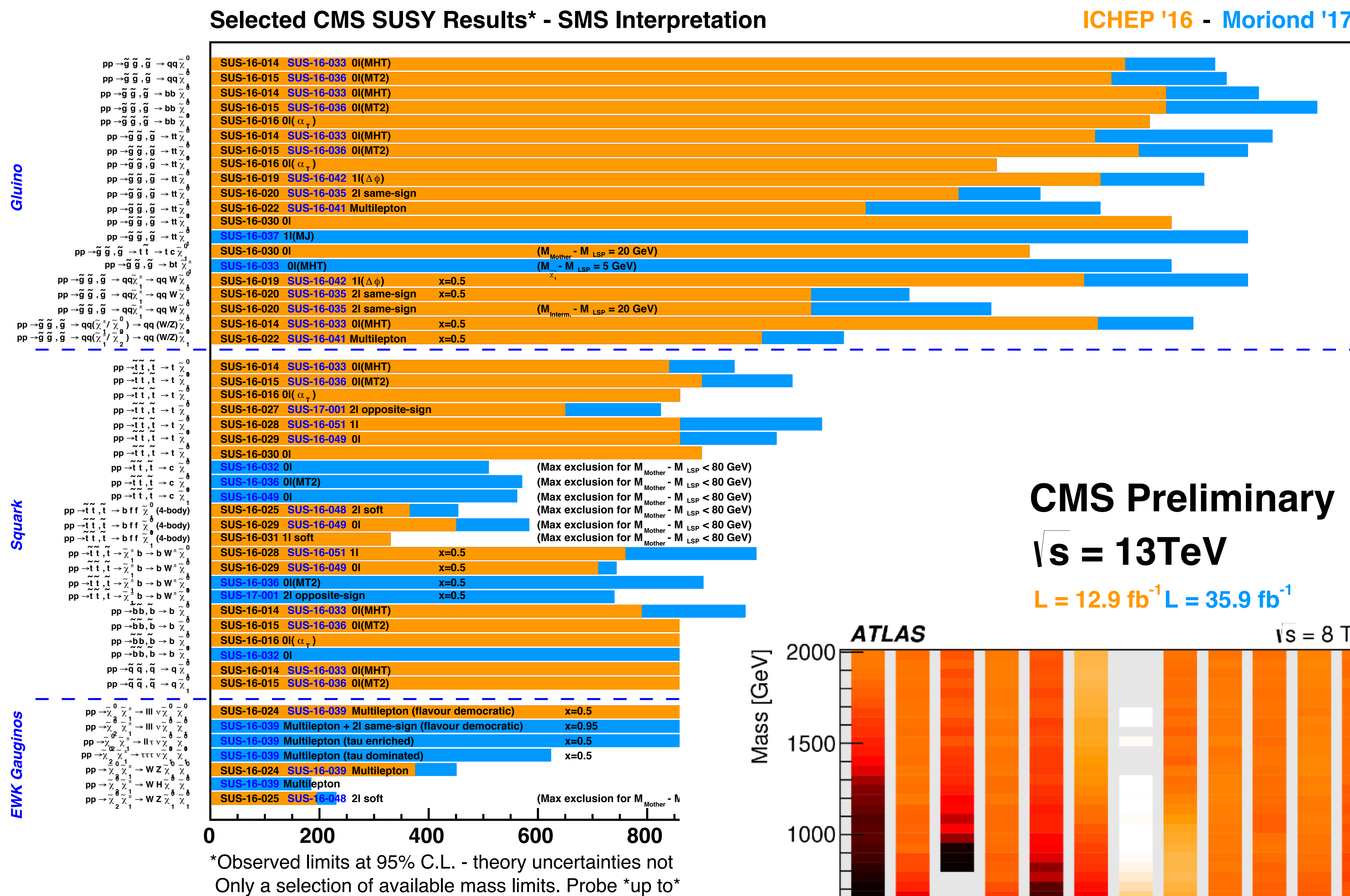


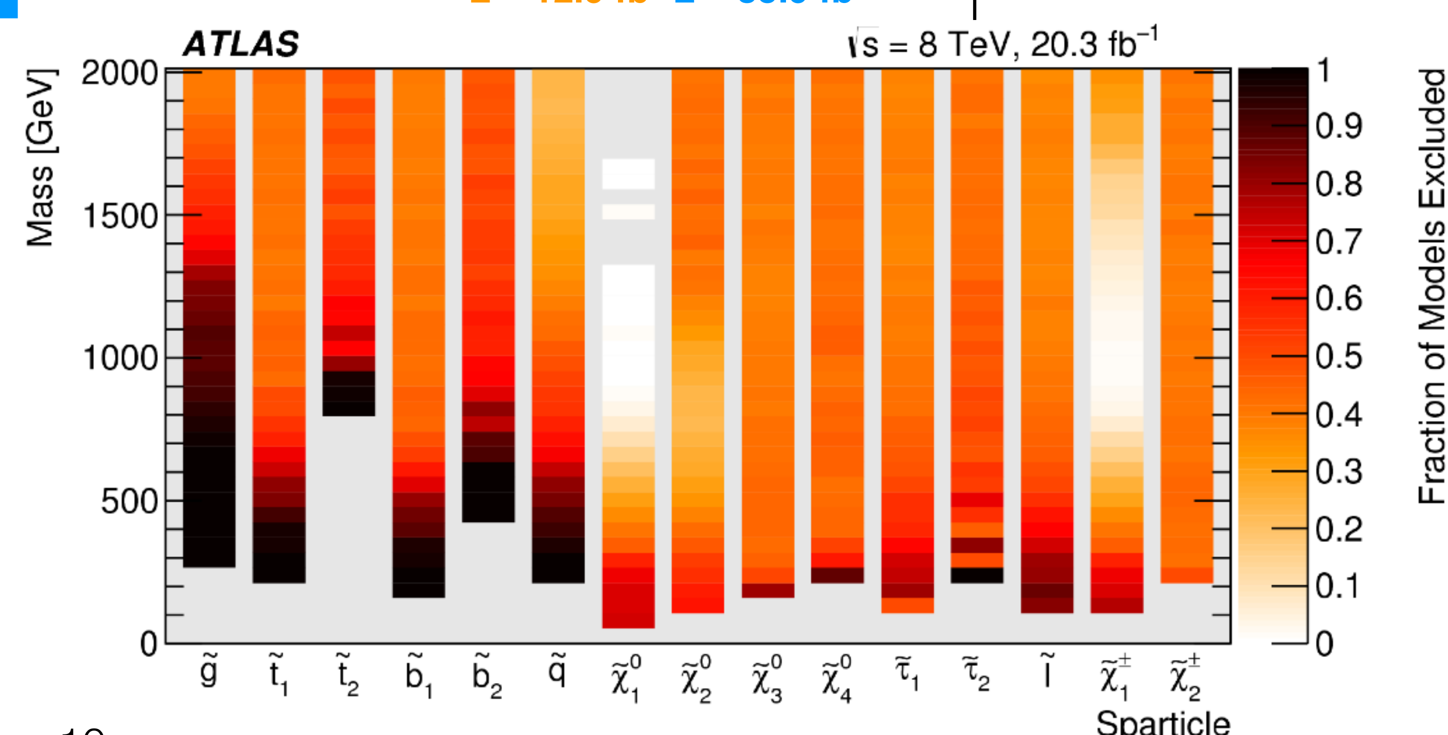
Parton distribution functions



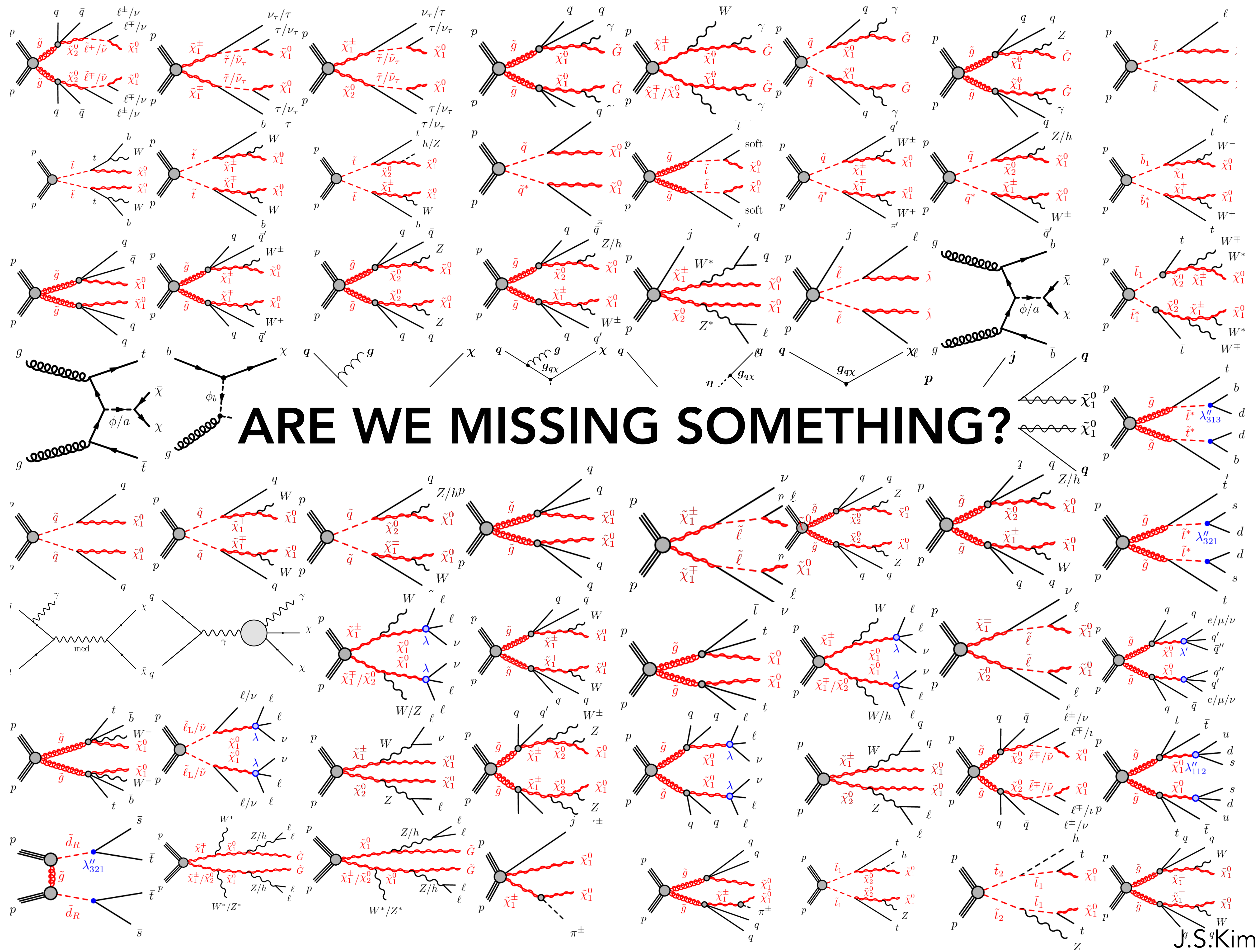
Partonic cross section

Coverage of prompt signatures





ARE WE MISSING SOMETHING?

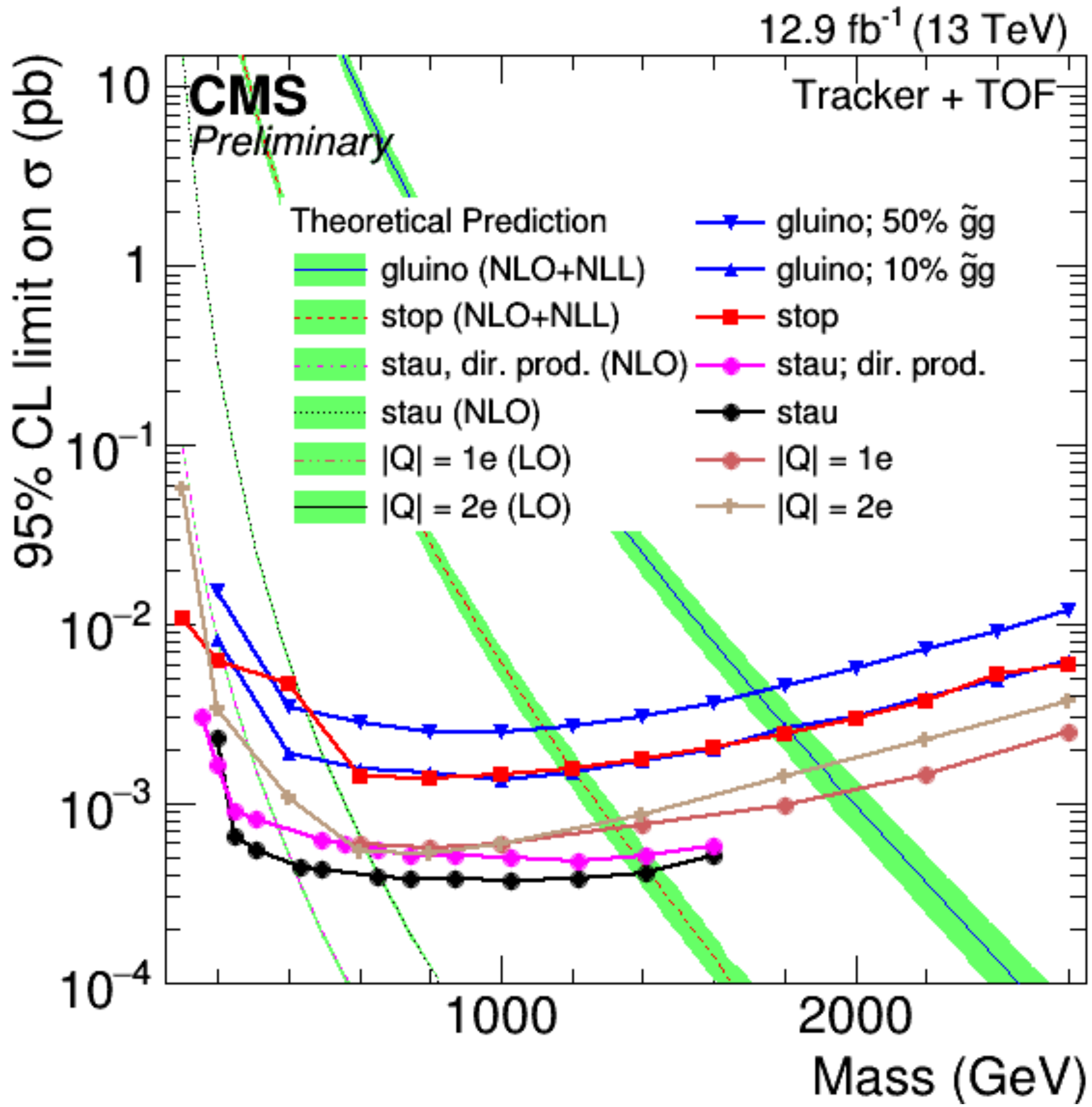


J.S.Kim

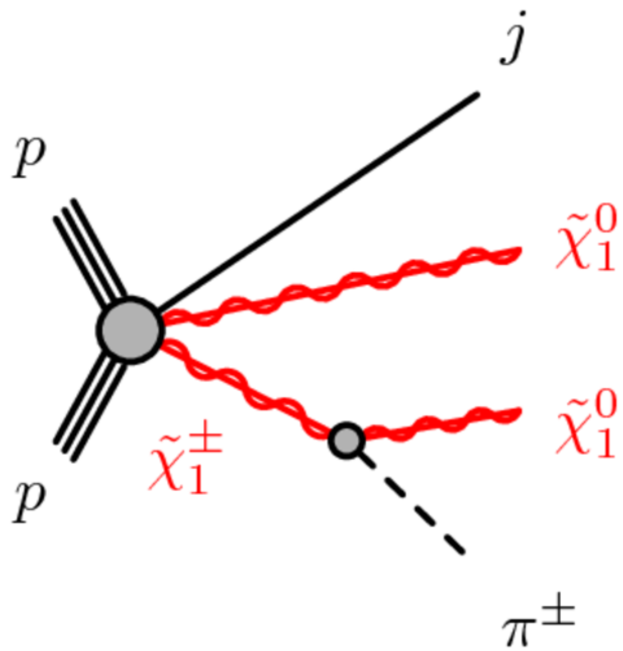
Models predicting long lived particles

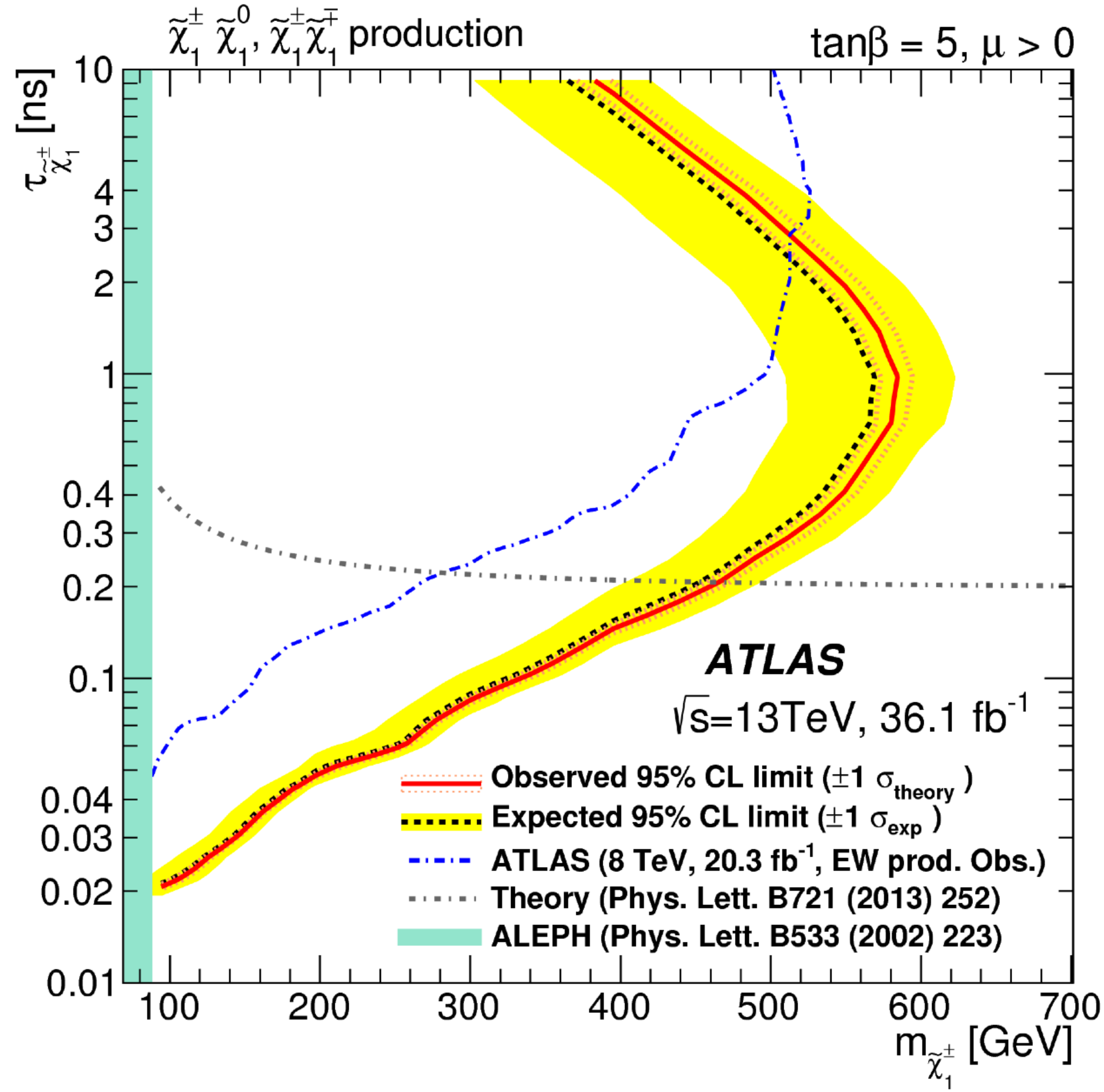
Dark Matter	SUSY (i.e. Winos, Higgsinos) Coannihilation with scalars Dark Photon Higgs Portal Freeze-in
Naturalness	Hidden valleys GMSB SUSY RPV SUSY
Neutrino Masses Flavour Anomalies	Sterile Neutrinos L-R models (Z' & W's) …

Charged track searches



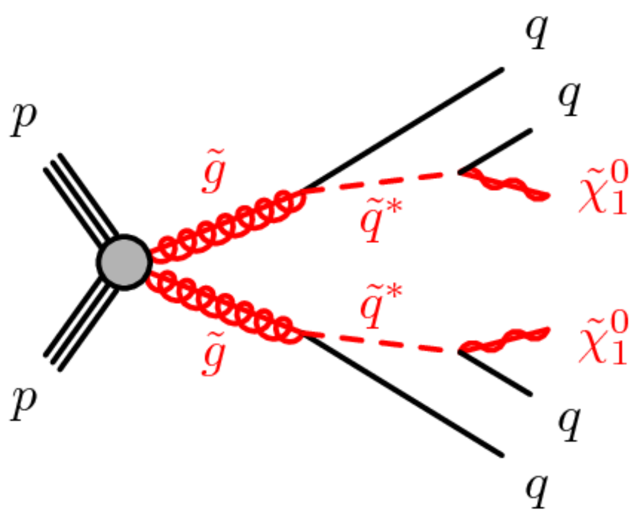
Disappearing track searches

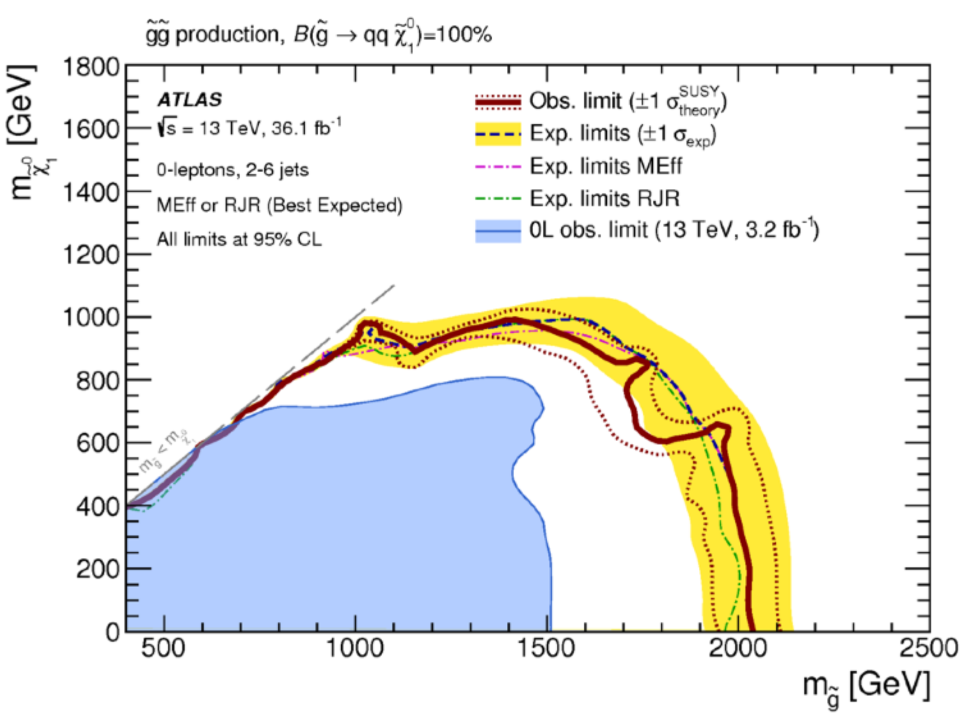


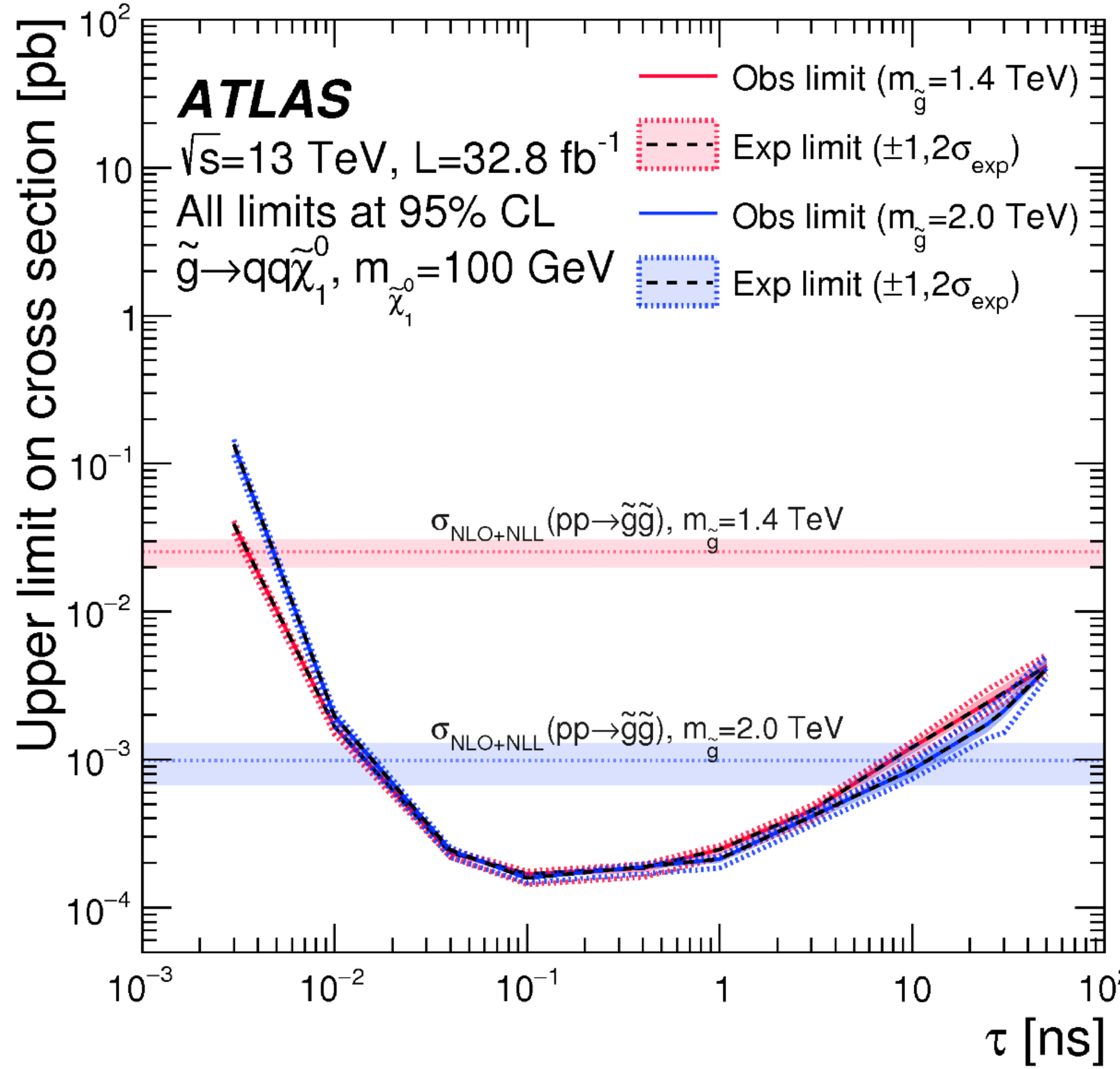


arXiv:1712.02118

Displaced Vertices

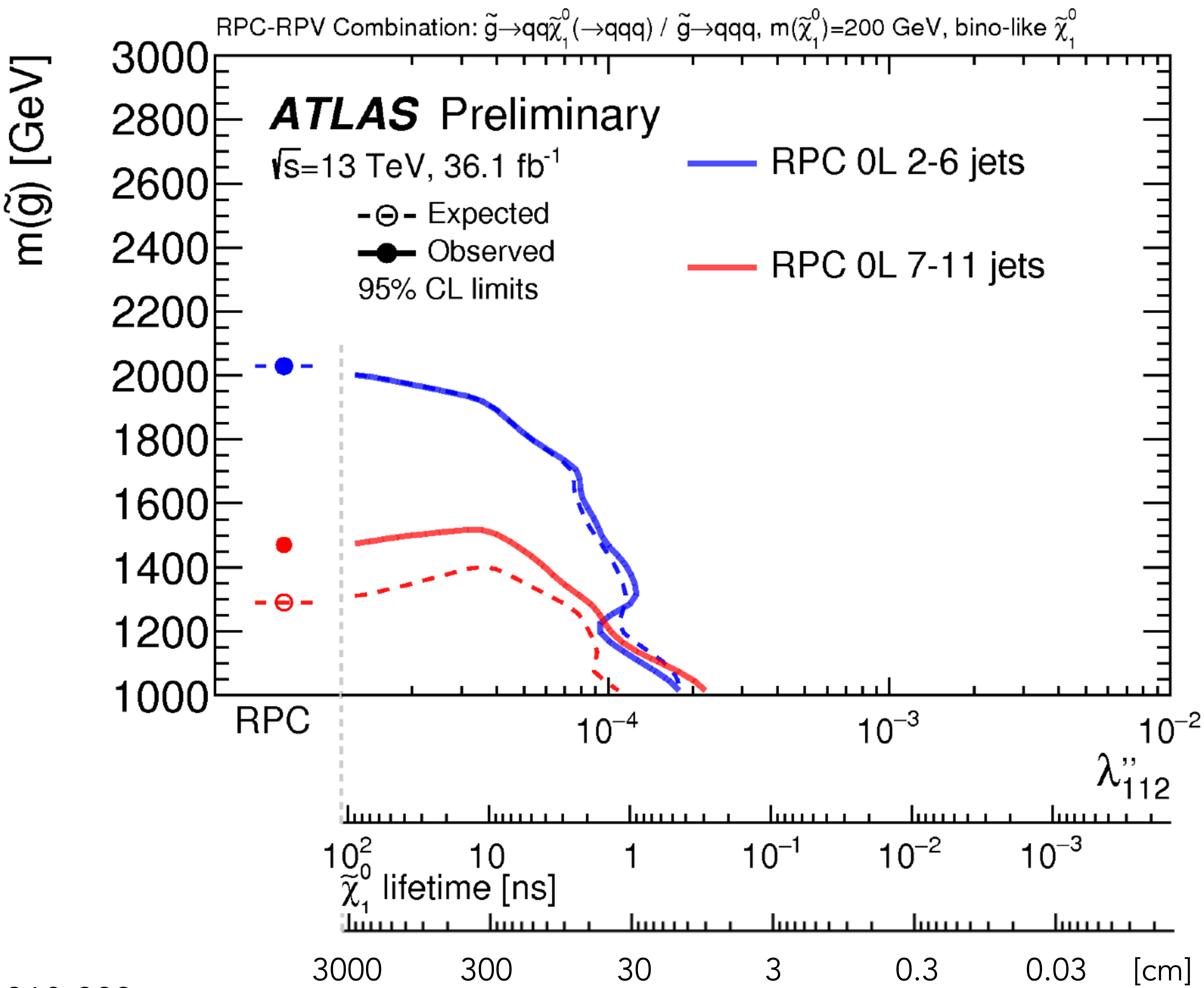






arXiv:1710.04901

Traditional searches fail for LLPs



ATLAS-CONF-2018-003

“Unexpected” cuts may restrict what we choose to see

ATLAS-CONF-2018-003

Looking at the simplest jets + MET search:

Selection GeV	RPC	$\tau = 100$ ns	$\tau = 10$ ns	$\tau = 1$ ns	$\tau = 0.1$ ns	$\tau = 0.01$ ns
DxAOD skimming	94.0	82.0	86.0	75.0	77.0	78.0
Jet/$E_{\mathrm{T}}^{\mathrm{miss}}$ cleaning	98.9	93.9	76.7	96.0	100.0	100.0
Cosmic muon cut	98.9	98.7	97.0	93.1	77.9	78.2
Lepton veto	58.7	53.9	54.7	47.8	43.3	39.3
$N_{\mathrm{jets}} \geq 4$	98.1	97.6	97.1	100.0	100.0	100.0
$\mathbf{p}_{\mathrm{T}}^{\mathrm{miss,track}} > 30$ GeV	71.7	75.0	85.3	90.6	88.5	87.5
$N_{b-\mathrm{jet}} \geq 1$	92.1	90.0	93.1	89.7	100.0	100.0
$E_{\mathrm{T}}^{\mathrm{miss}} > 250$ GeV	60.0	59.3	44.4	15.4	12.6	10.5
$\left\lvert\Delta\phi\left(\mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss,track}}\right)\right\rvert < 1/3\pi$	95.2	93.8	91.7	72.5	72.4	63.6
$\left\lvert\Delta\phi\left(\mathrm{jet}^{0,1,2}, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}\right)\right\rvert > 0.4$	95.0	93.3	85.5	65.5	71.4	71.4
$m_{\mathrm{jet},R=1.2}^{0} > 120$ GeV	73.7	78.6	75.5	78.9	86.7	90.0

Already approx. 50% loss before MET cuts

Important to map all possible signatures to avoid the same mistakes!

Moral of the story so far…

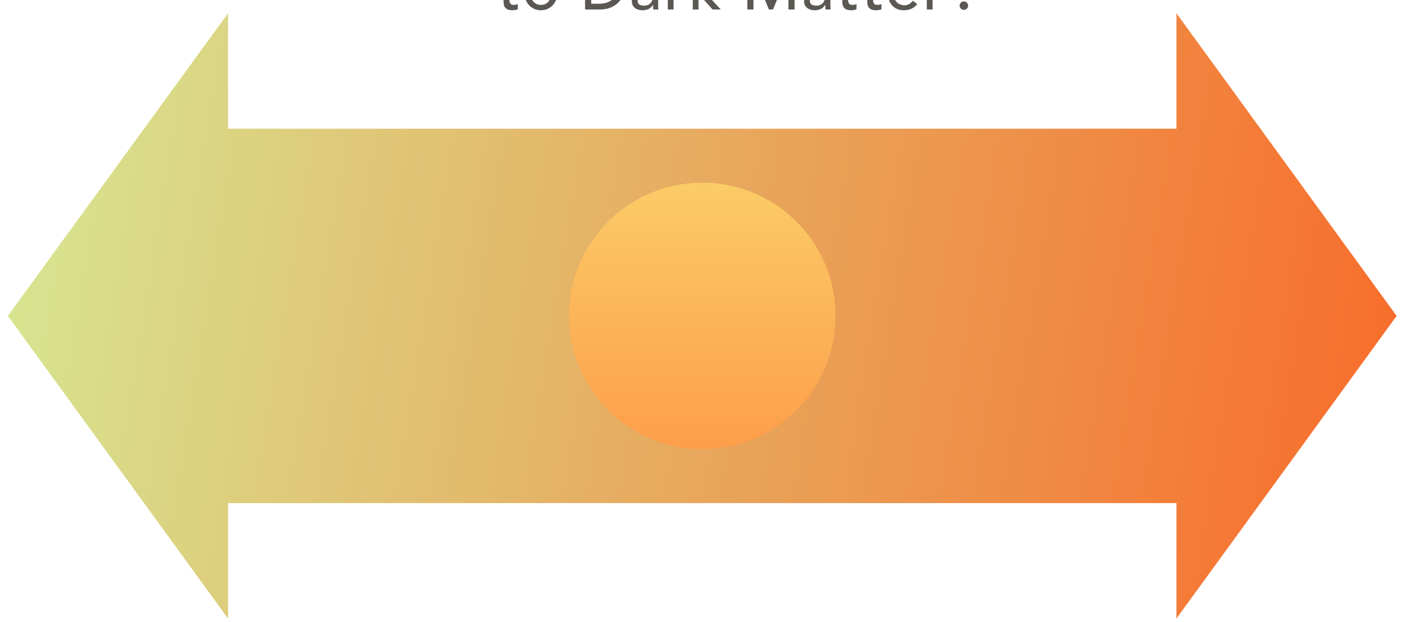
- Sophisticated machinery needed to “see” new physics and to understand what we see.
- Many searches for promptly decaying particles, not so many for long-lived ones
- There might be unexpected, unnecessary assumptions because all our benchmarks look the same; important to have as much variety as possible to make sure we’re not missing anything.

Writing down a model for DM

Is it a Scalar? Vector? Dirac or Majorana Fermion?

Does it couple directly to some SM particle (Z, h) ?
If there is a mediator, how does the mediator couple to SM?
to Dark Matter?

Effective Field Theory



Complete Models
eg. SUSY, Universal Extra Dim,
Little Higgs,…

PRO: Simple, Easy to relate observables

CON: bad high-energy behaviour

Simplified models

Trying to get the best of both worlds

IDEA: write down the simplest field content (often a DM field + one mediator)

PRO: Theoretically well motivated, fully calculable, extra particles

CON: Model Prejudices, complicated to understand

List of EFT Operators

S-channel Scalar mediator

S-channel Vector mediator

Scalar portal

Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

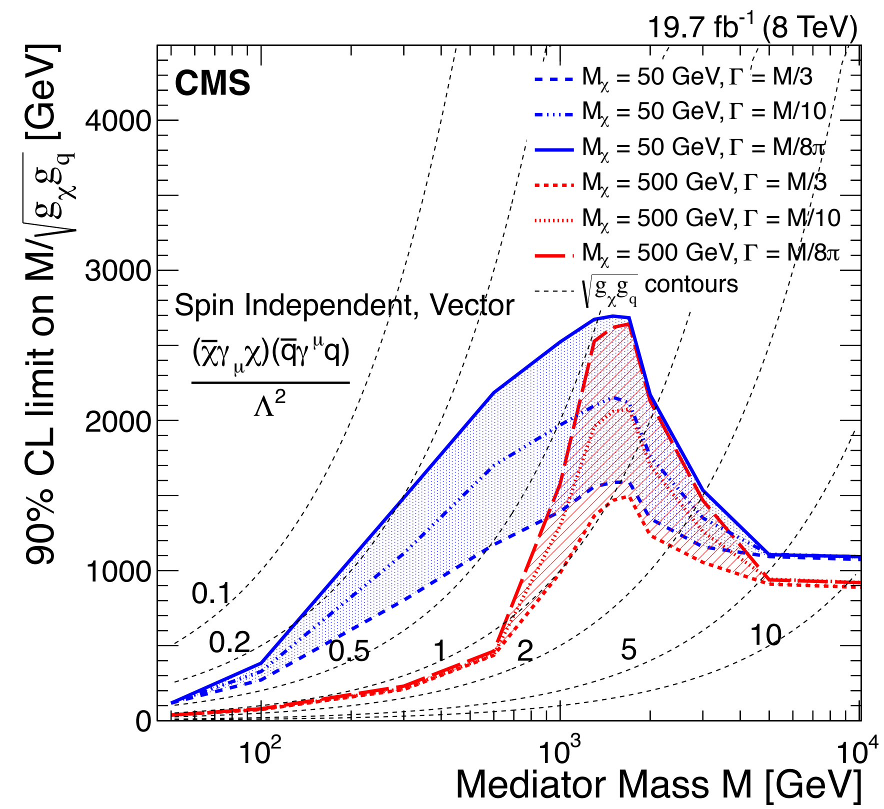
Name	Operator	Coefficient
C1	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar{q}\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$
R1	$\chi^2\bar{q}q$	$m_q/2M_*^2$
R2	$\chi^2\bar{q}\gamma^5 q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

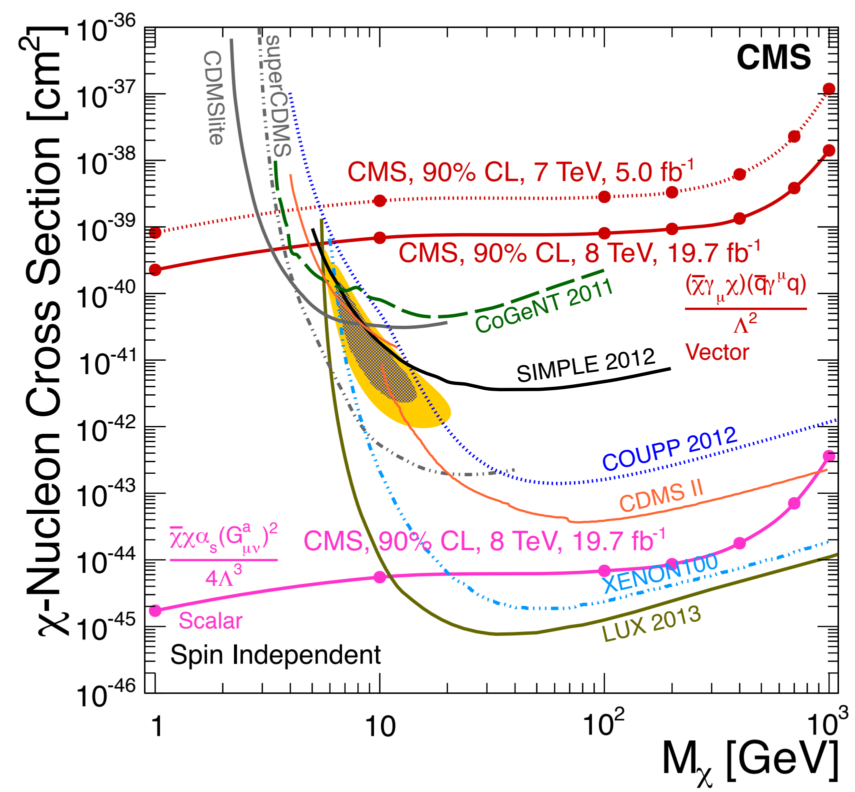
Goodman et al. (2010)

Translation of Limits on EFT operators

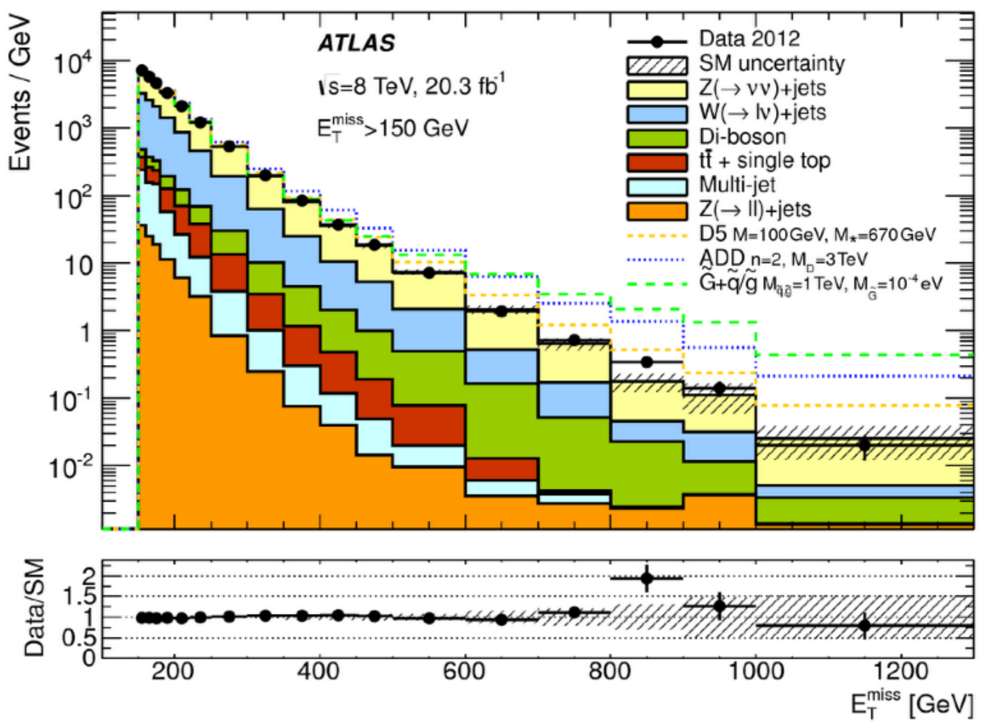
- Can be interpreted both in terms of mediator mass and in terms of DD cross section
- Relatively insensitive to underlying Lorentz structure (i.e. "axial-vector" or "pseudo-scalar" operators does not suffer from suppression)
- Strong limits in low mass region (where DD loses sensitivity)

Truly complementary to DD searches!

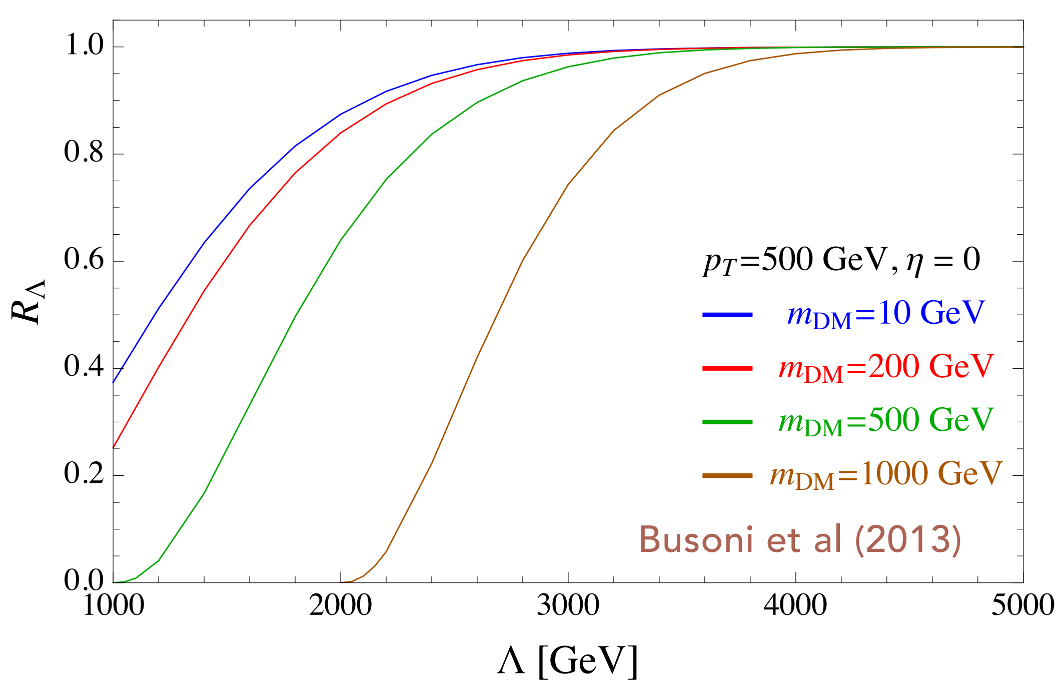


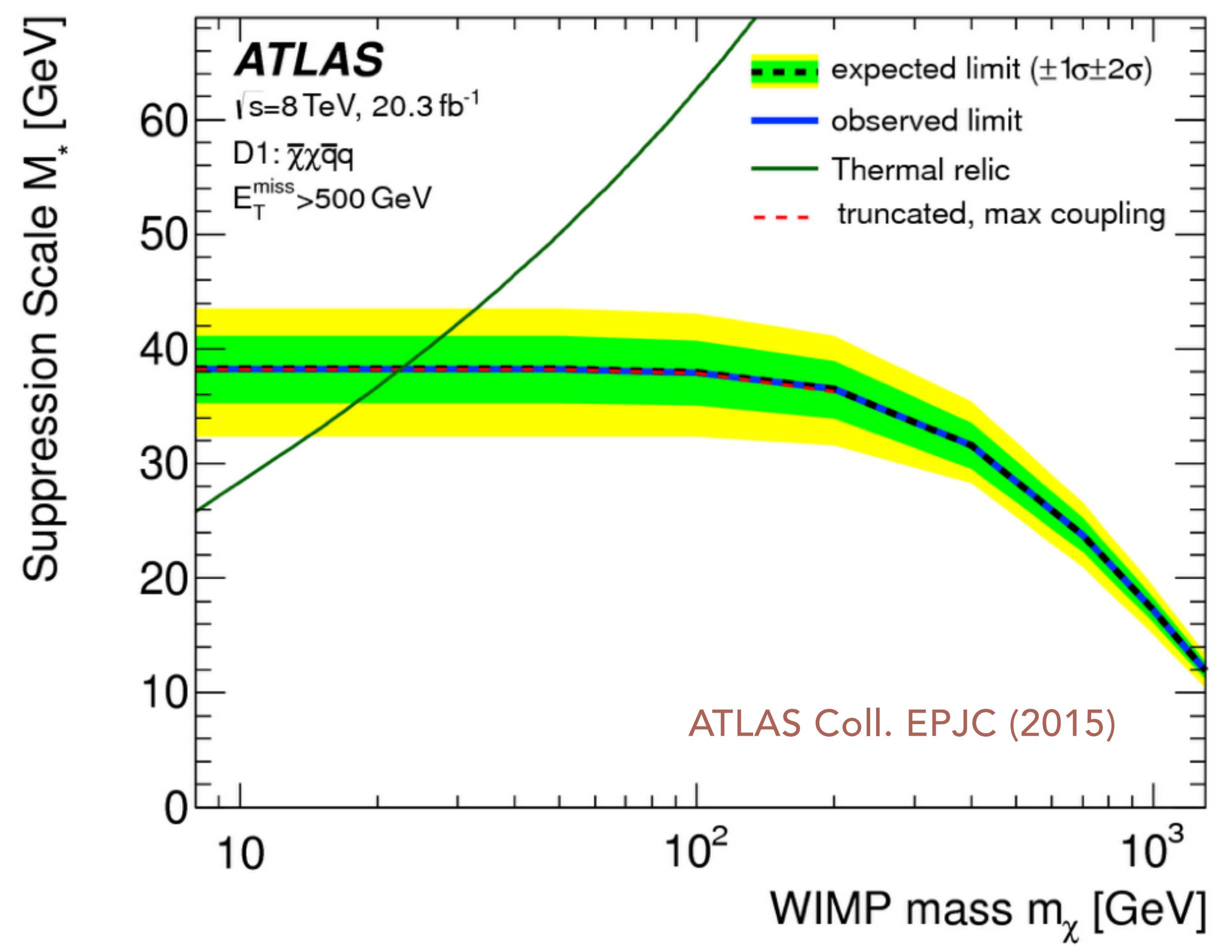


Interpreting results in EFT



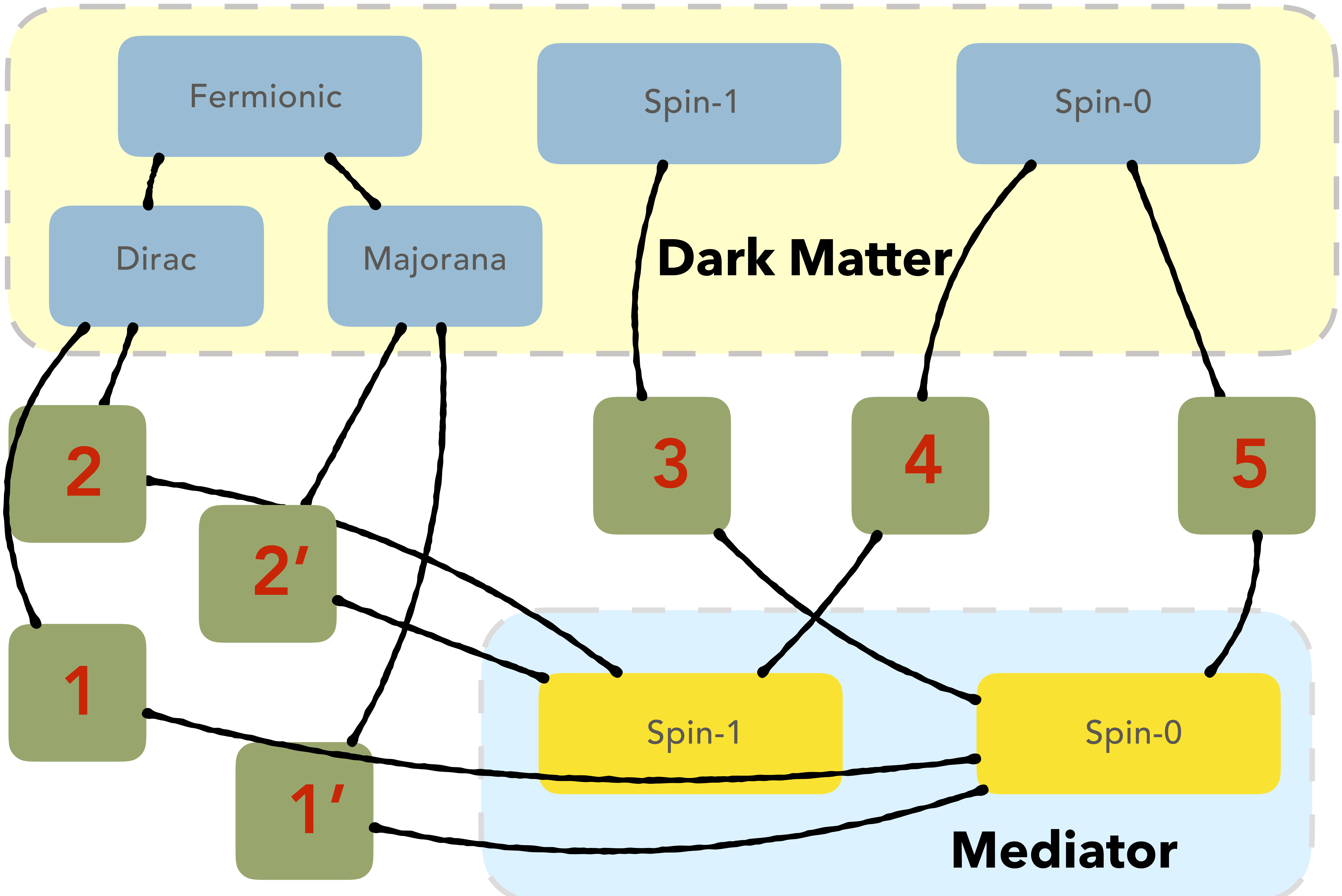
$$\bar{q}q\frac{g^2}{Q_{\rm tr}-M^2}\bar{\psi}\psi \rightarrow \frac{g^2}{M^2}\bar{q}q\bar{\psi}\psi$$





Demanding self-consistency (i.e. truncation) results in very diluted limits!

How to write a Simplified Model?



Simplified models with Fermionic DM

1

$$\mathcal{L}_S = \frac{1}{2}\partial_\mu S \partial^\mu S - m_S^2 S^2 + \sum g_{s\chi\bar{\chi}} \bar{\chi}\chi S + \sum g_{sq\bar{q}} \bar{q} q S + \bar{\chi}(i\partial_\mu\gamma^\mu - m_\chi)\chi$$

$$\mathcal{L}_P = \frac{1}{2}\partial_\mu P \partial^\mu P - m_P^2 P^2 + \sum g_{s\chi\bar{\chi}} \bar{\chi}\gamma^5\chi P + \sum g_{sq\bar{q}} \bar{q}\gamma^5 q P + \bar{\chi}(i\partial_\mu\gamma^\mu - m_\chi)\chi$$

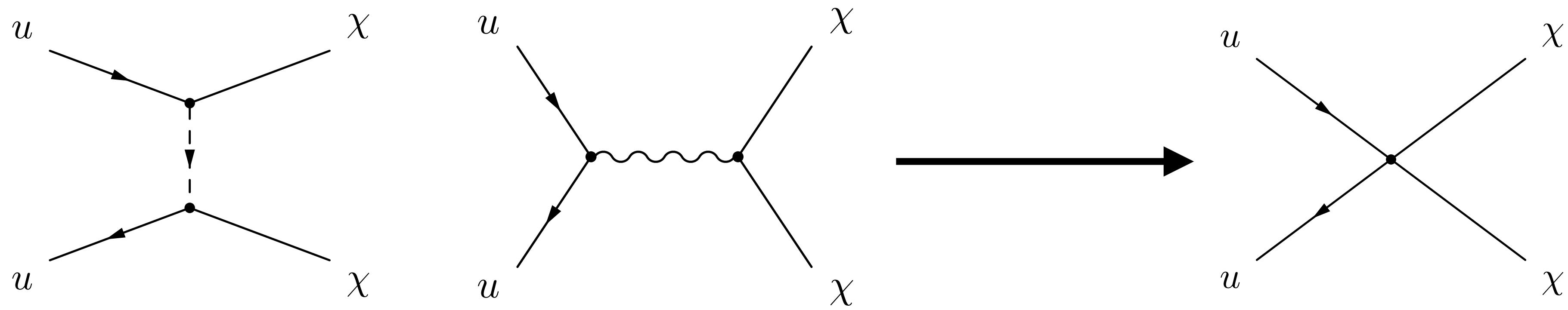
$$\begin{aligned}\mathcal{L}_T \quad &= \quad \frac{1}{2} D_\mu T D^\mu T - m_T^2 T^2 + \sum g_{T\chi\bar{\chi}} (\bar{\chi} q T^* + \text{c.c.}) \\ &\quad + \bar{\chi}(i\partial_\mu\gamma^\mu - m_\chi)\chi\end{aligned}$$

2

$$\begin{aligned}\mathcal{L}_{Z'} \quad &= \quad \sum g_{Z'\chi\bar{\chi}} \bar{\chi}\gamma^\mu\chi Z'^\mu + \sum g_{Z'q\bar{q}}\ \bar{q}\gamma^\mu q Z'^\mu \\ &\quad + \bar{\chi}(i\partial_\mu\gamma^\mu - m_\chi)\chi + \text{gaugeterms}\end{aligned}$$

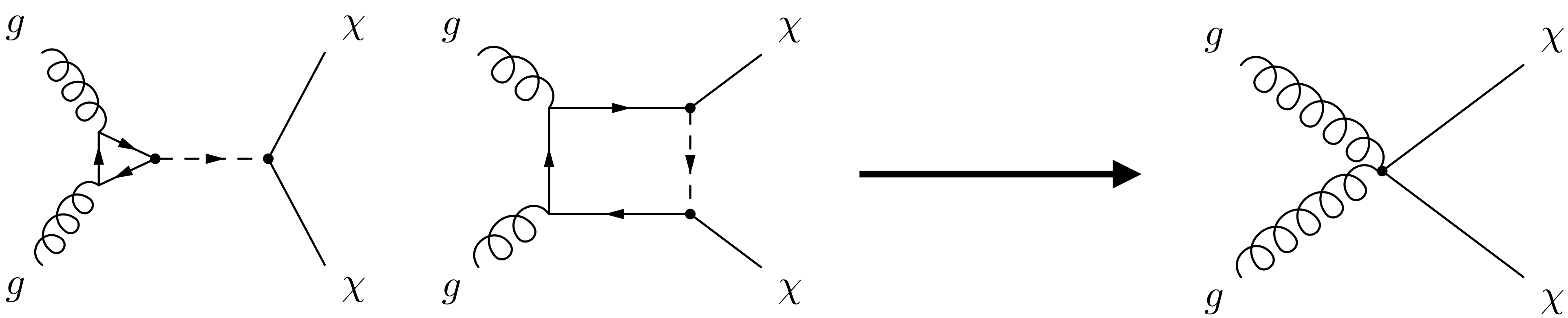
$$\begin{aligned}\mathcal{L}_{A'} \quad &= \quad \sum g_{A'\chi\bar{\chi}} \bar{\chi}\gamma^\mu\gamma^5\chi A'^\mu + \sum g_{A'q\bar{q}}\ \bar{q}\gamma^\mu\gamma^5 q A'^\mu \\ &\quad + \bar{\chi}(i\partial_\mu\gamma^\mu - m_\chi)\chi + \text{gaugeterms}\end{aligned}$$

EFT to simplified models



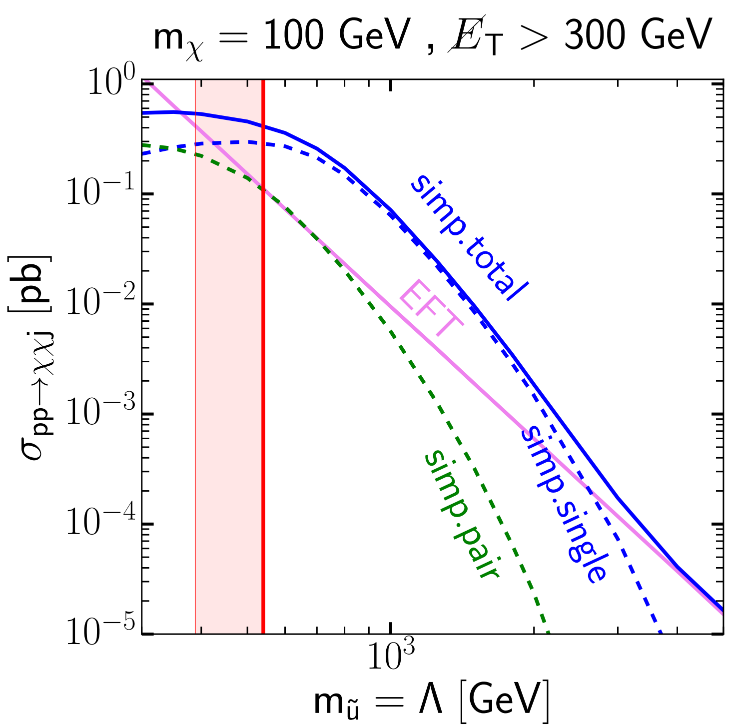
$$\mathcal{L}_{eff} \sim \frac{c_1}{\Lambda^2}(\bar{f}f)(\bar{\chi}\chi) + \frac{c_2}{\Lambda^2}(\bar{f}\gamma_\mu f)(\bar{\chi}\gamma^\mu\chi) + \frac{c_3}{\Lambda^2}(\bar{f}\gamma_5 f)(\bar{\chi}\gamma_5\chi) + \frac{c_4}{\Lambda^2}(\bar{f}\gamma_\mu\gamma_5 f)(\bar{\chi}\gamma^\mu\gamma_5\chi)$$

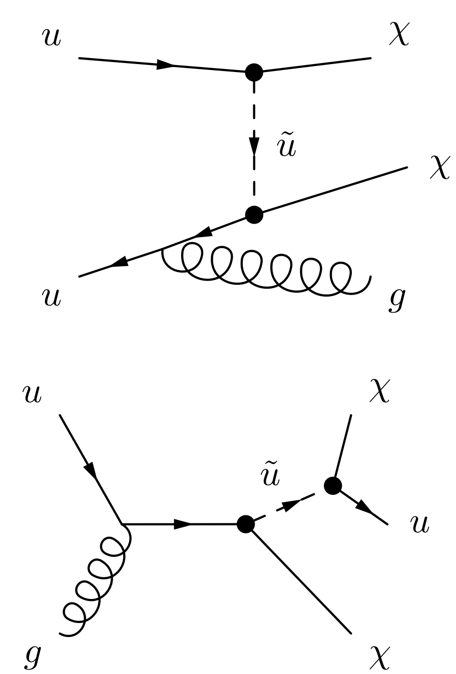
Scalar s-channel — Vector s-channel — Pseudo-scalar s-channel — Axial Vector s-channel

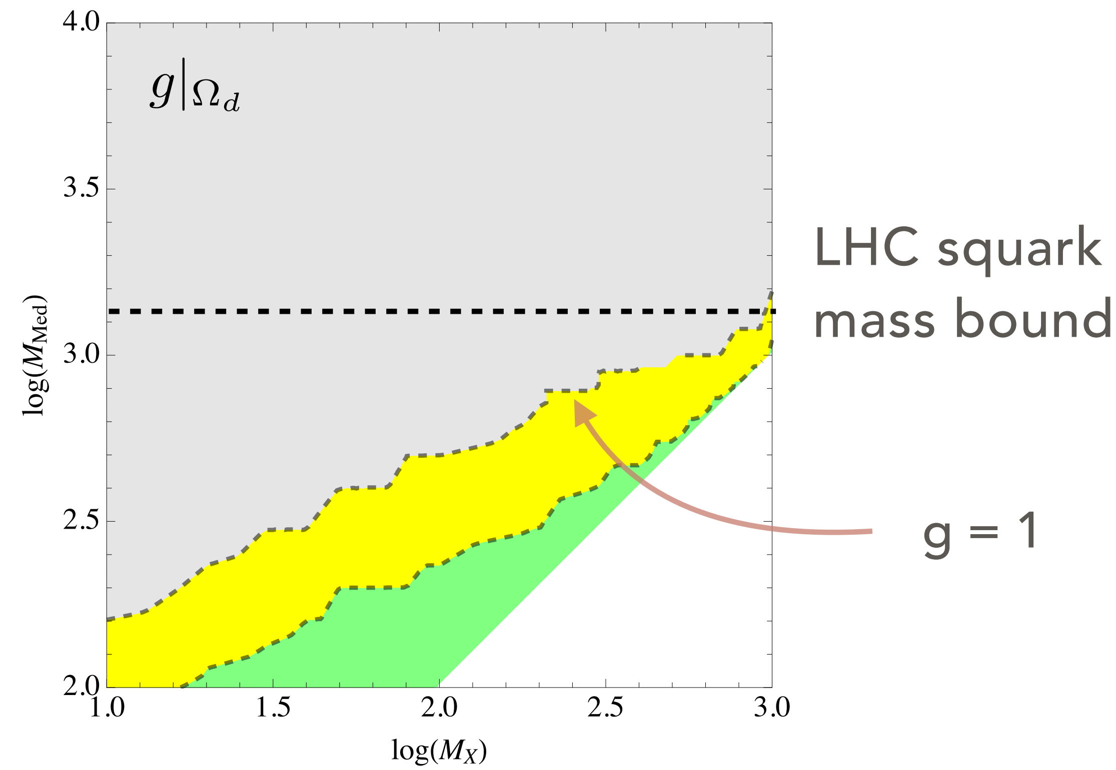


$$\mathcal{L}_{eff} \sim \frac{c_5}{\Lambda^3}(\bar{\chi}\chi)G_{\mu\nu}G^{\mu\nu} + \frac{c_6}{\Lambda^3}(\bar{\chi}\chi)G_{\mu\nu}\tilde{G}^{\mu\nu}$$

Comparison of EFT with UV completion







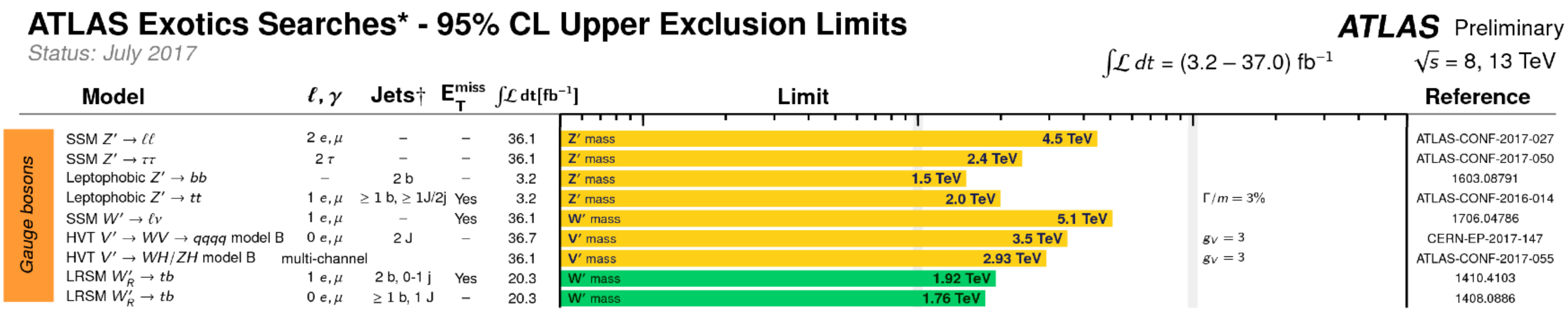
- No obvious resonance in t-channel; but bad behaviour nonetheless due to slow decoupling of mediator

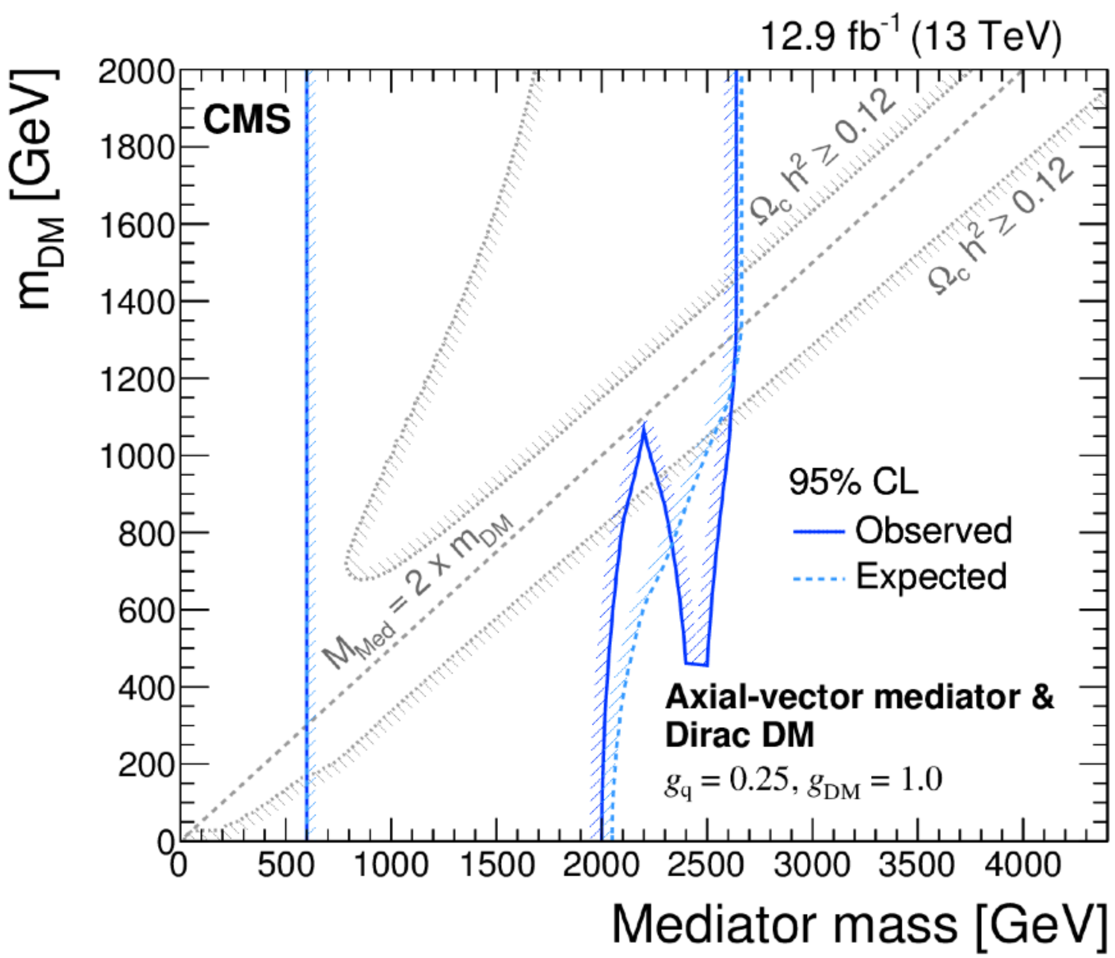
- Direct mediator search (a.k.a. squark search) has much higher reach.

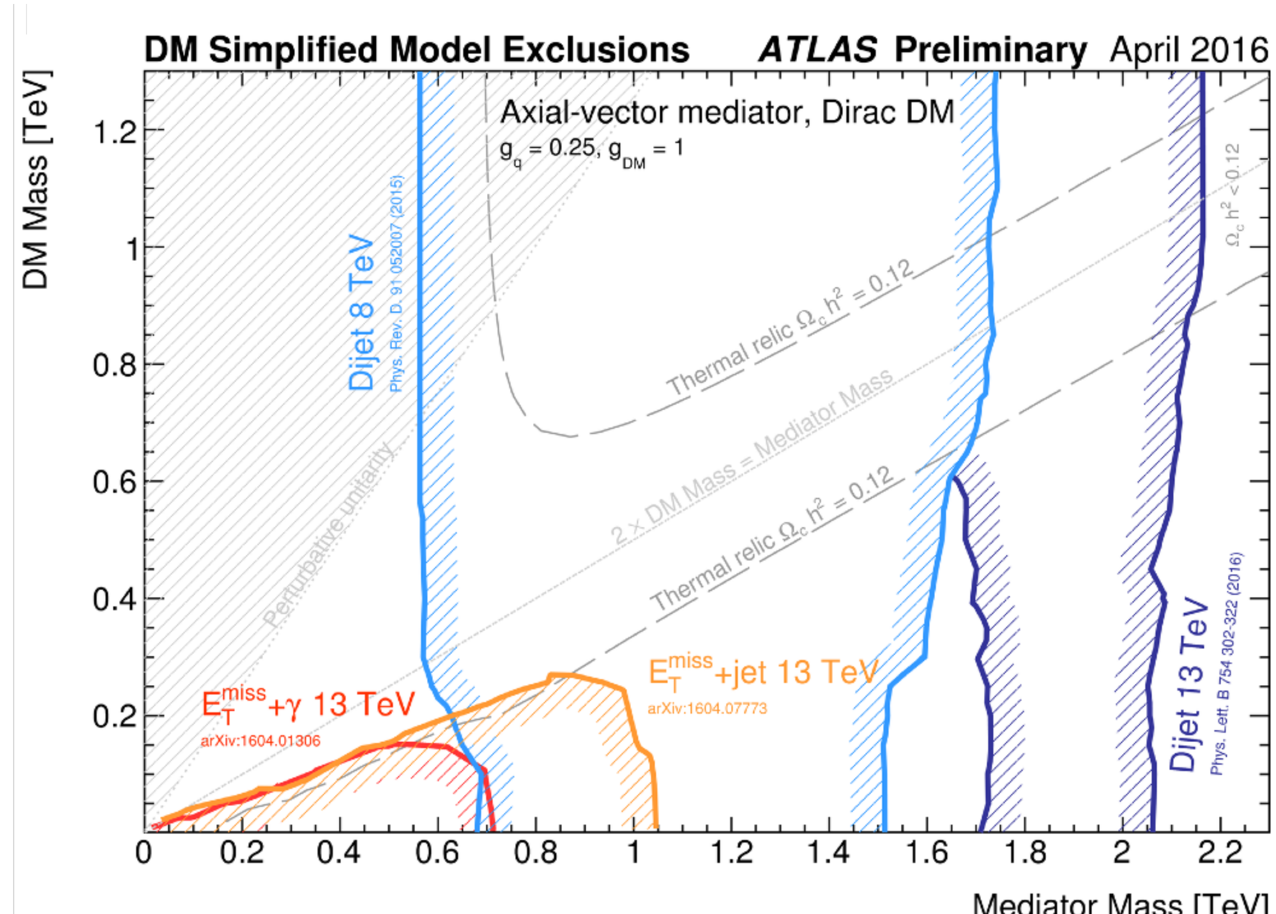
- All viable t-channel mediated DM parameter space ruled out (for coupling to light quarks).

Bauer, Desai, et al (2016)

Looking for the mediator







Moral of the story (part 2)…

- Dark Matter EFT simple, but not very useful at the LHC

- Simplified models do better, but are strongly constrained by direct mediator searches; don’t say much about dark matter because of ambiguity in coupling/mass. (Maybe if we see a new resonance and can probe its line shape, i.e. calculate invisible width, we may do better but that is a long way away.)

What else can we do?

Classifying UV-complete DM models

New Fields \ New Symmetries	0	1 Mostly Z_2 or $U(1)$
1	"Minimal DM"	Pure "Higgsino" or "Wino" Scalar singlet DM Inert doublet DM
2	t-channel charged scalar + fermionic DM	Singlet-Doublet (N,N+1 plet) DM Higgs Portal DM s-channel scalar mediator Dark Photon
3	??	Z′ mediator (with new scalar) L-R models Hidden Valley models

Minimal ideas for Dark Matter

Dark Matter makes up ~20% of our universe; an EW scale particle (a.k.a. WIMP) seems to be a good fit

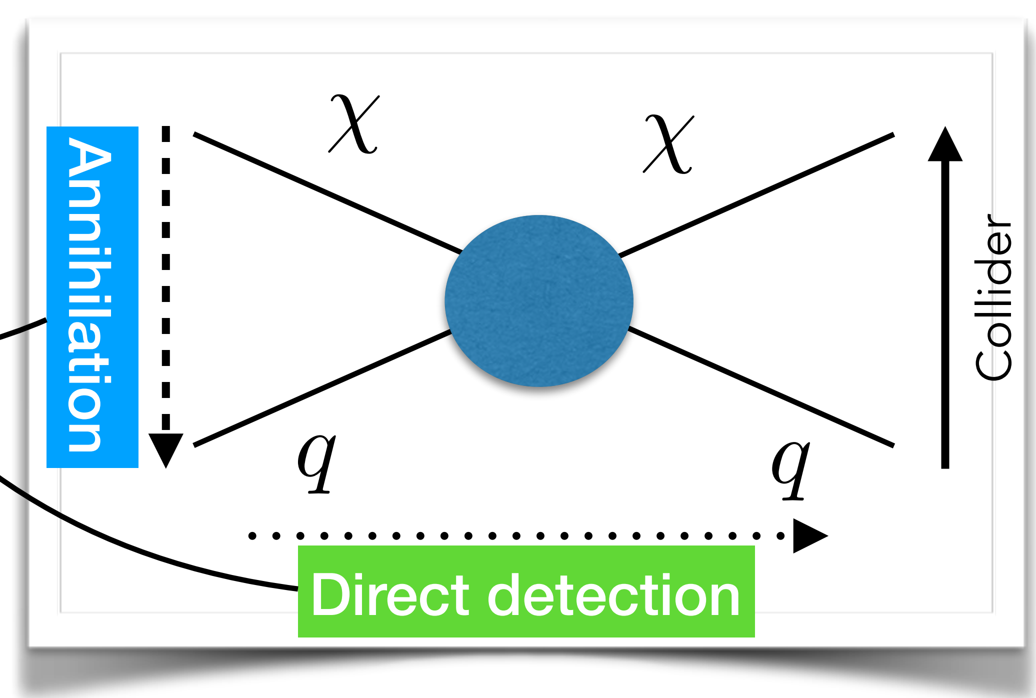
$$\Omega h^2 \sim 0.1 \Rightarrow \langle \sigma v \rangle \sim 1\ \mathrm{pb} \cdot c$$

$$\Rightarrow m_\chi \sim O(10^2 - 10^3)\ \mathrm{GeV}; g \sim g_{\mathrm{EW}}$$

What are minimal EW possibilities?

- SU(2) doublet fermion (a.k.a. Higgsino) ⇒ ~ 1.2 TeV
- SU(2) triplet fermion (a.k.a Wino) ⇒ 2.7 TeV
- SU(2) 5-plet fermion (MDM) ⇒ ~10 TeV
- SU(2) 7-plet scalar (MDM) ⇒ ~10 TeV

Cirelli et al; arXiv:hep-ph/0512090



100 TeV collider?

Next-to-minimal DM

What about next-to-minimal scenarios?

- One SU(2) x U(1) singlet χ + one SU(2) N-plet ψ
- $\mathbb{Z}_2$ stabilises the lightest state

$$\mathcal{L}_{\rm DM} = i\,\psi^\dagger\bar{\sigma}^\mu D_\mu\psi + i\,\chi^\dagger\bar{\sigma}^\mu\partial_\mu\chi - \left(\frac{1}{2}M\psi\psi + \frac{1}{2}m\chi\chi + \text{ h.c.}\right) + \mathcal{L}_{\rm quartic} + \mathcal{L}_{\rm mix}$$

$$\mathcal{L}_{\rm quartic} = \frac{1}{2}\frac{\kappa}{\Lambda}\phi^\dagger\phi\chi\chi + \frac{1}{2}\frac{\kappa'}{\Lambda}\phi^\dagger\phi\psi^A\psi^A$$

Strong limits from DD

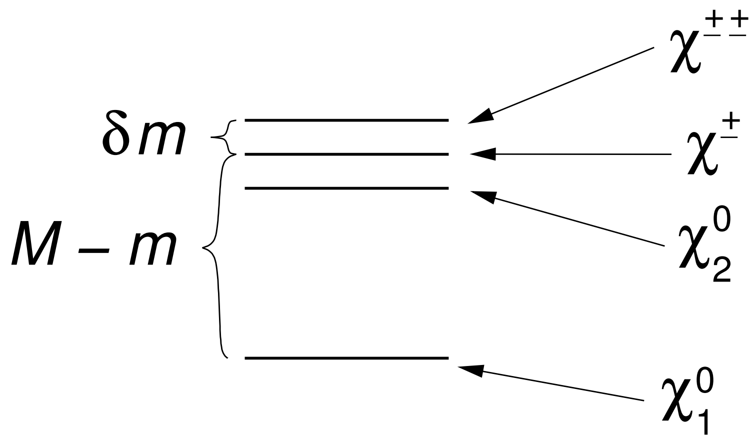
$$\mathcal{L}_{\rm mix} = \frac{\lambda}{\Lambda}\phi^\dagger\tau^a\phi\;\psi^a\chi + \text{ h.c.} \longrightarrow \theta \approx \frac{\sqrt{2}\lambda v^2}{\Lambda(M-m)}$$

N=3

$$\mathcal{L}_{\rm mix} = \frac{\lambda}{\Lambda^3}\,C^{j\ell}_{A\,ik}\,\phi^{\dagger i}\phi_j\phi^{\dagger k}\phi_\ell\psi^A\chi + \text{ h.c.} \longrightarrow \theta \approx \sqrt{\frac{2}{3}}\frac{\lambda v^4}{\Lambda^3(M-m)}\,.$$

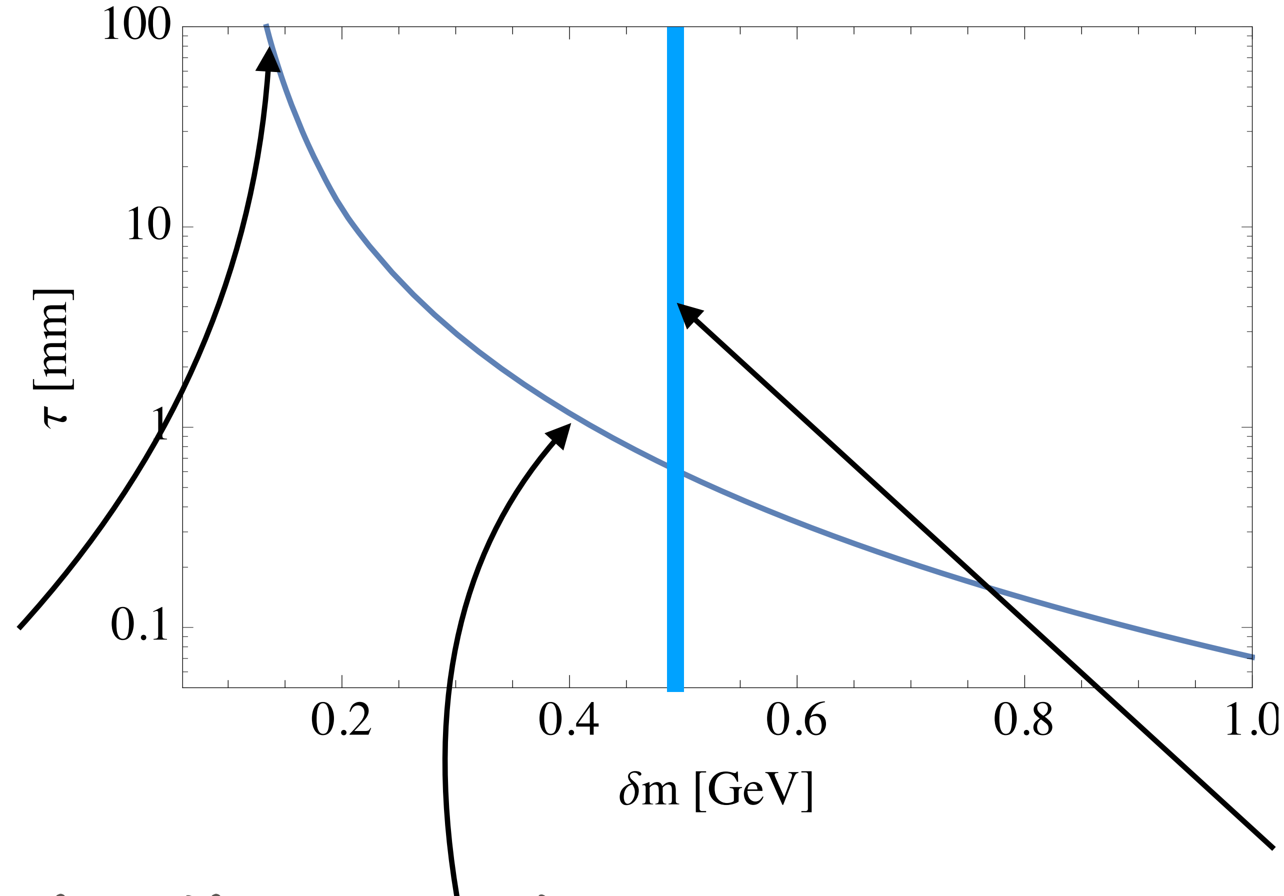
N=5

Collider searches: Quintuplet model



$$\chi^{++} \to \chi^{+}\pi^{+}$$
$$\chi^{+} \to \chi_1^0 W^* \to \ell\nu\chi_1^0$$
$$\chi_2^0 \to \chi_1^0 h^* \to b\bar{b}\chi_1^0$$

Large lifetime for the doubly charged partner

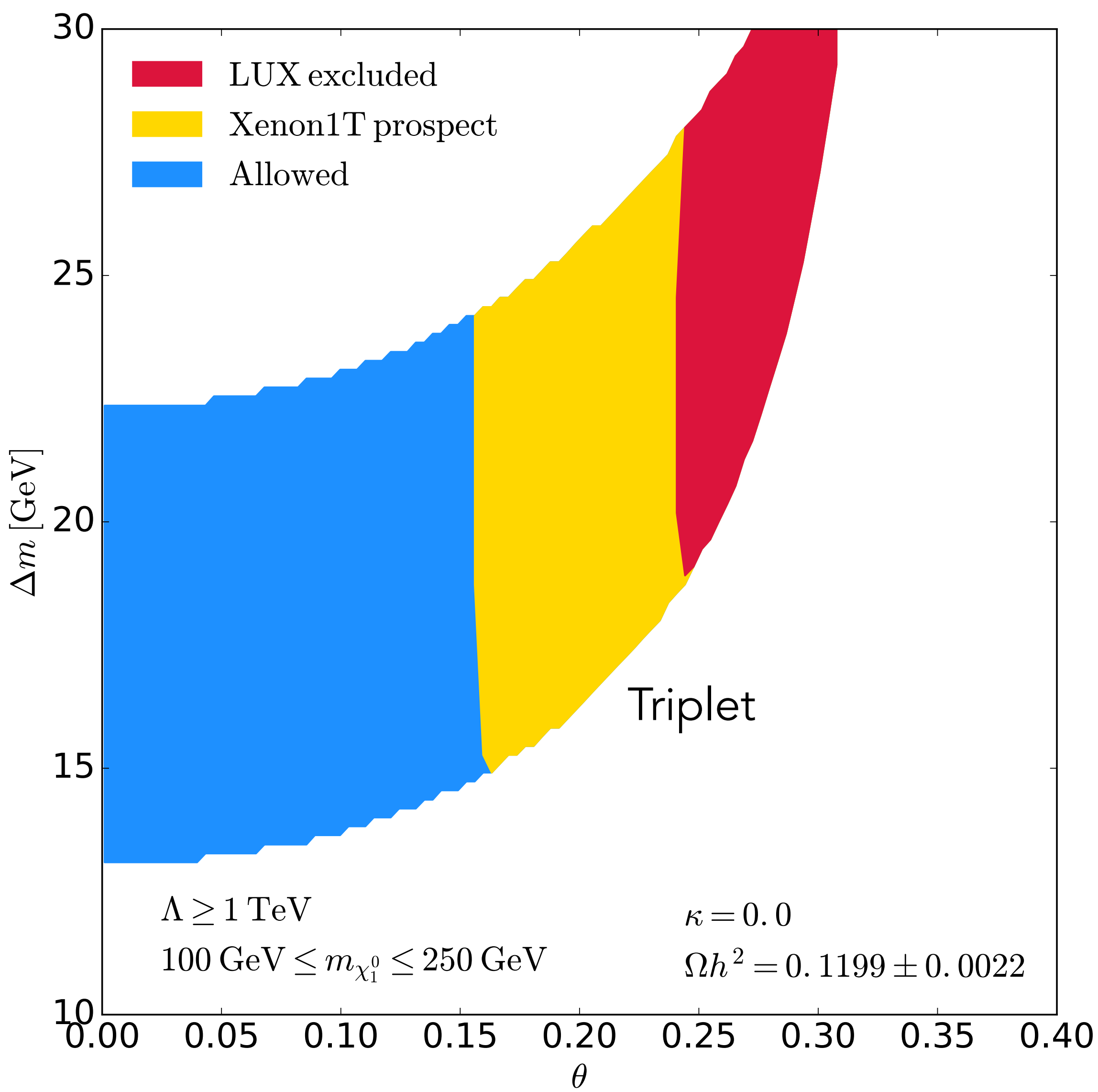


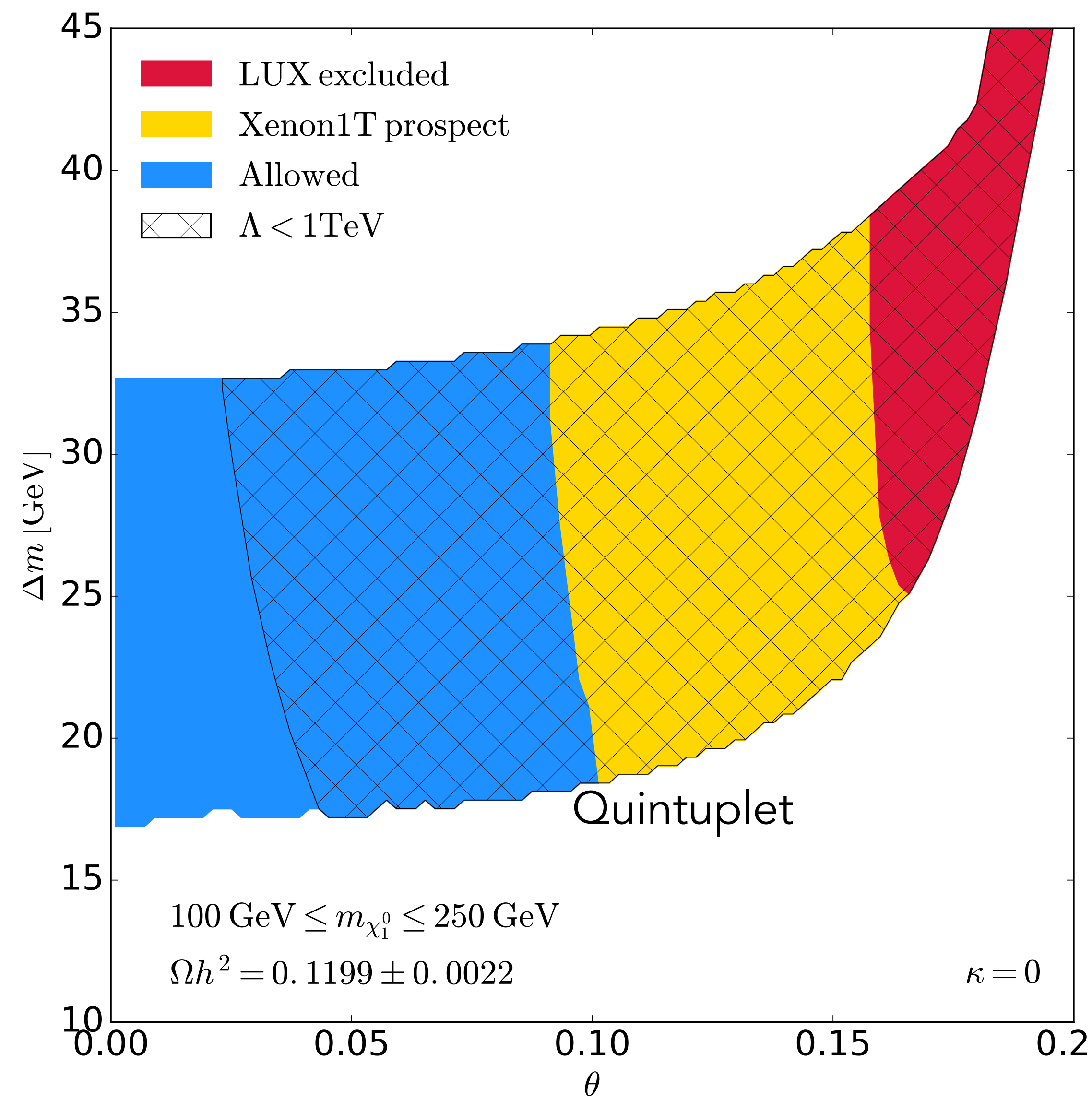
Charged track searches

Displaced lepton search

From 1-loop only

Direct Detection constraints



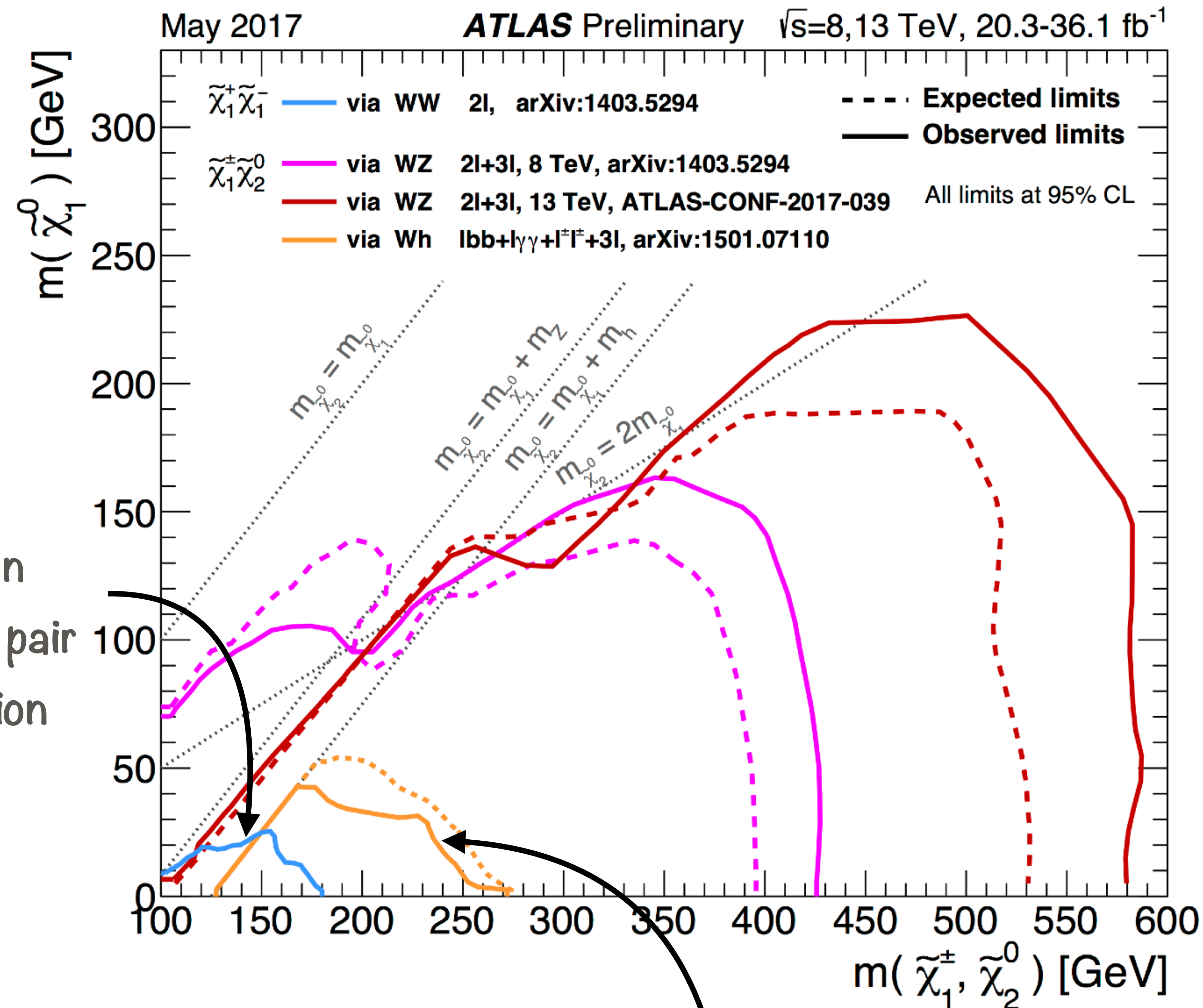


- Look at parameters that gives right relic density
- Low mixing angle gives low DD cross section; however, not a problem at the LHC because production is primarily Drell-Yan!

Brümmer et al; arXiv:1703.00370
Brümmer, Bharucha, Desai; arXiv:1804.02357

Prompt search limits: SUSY searches

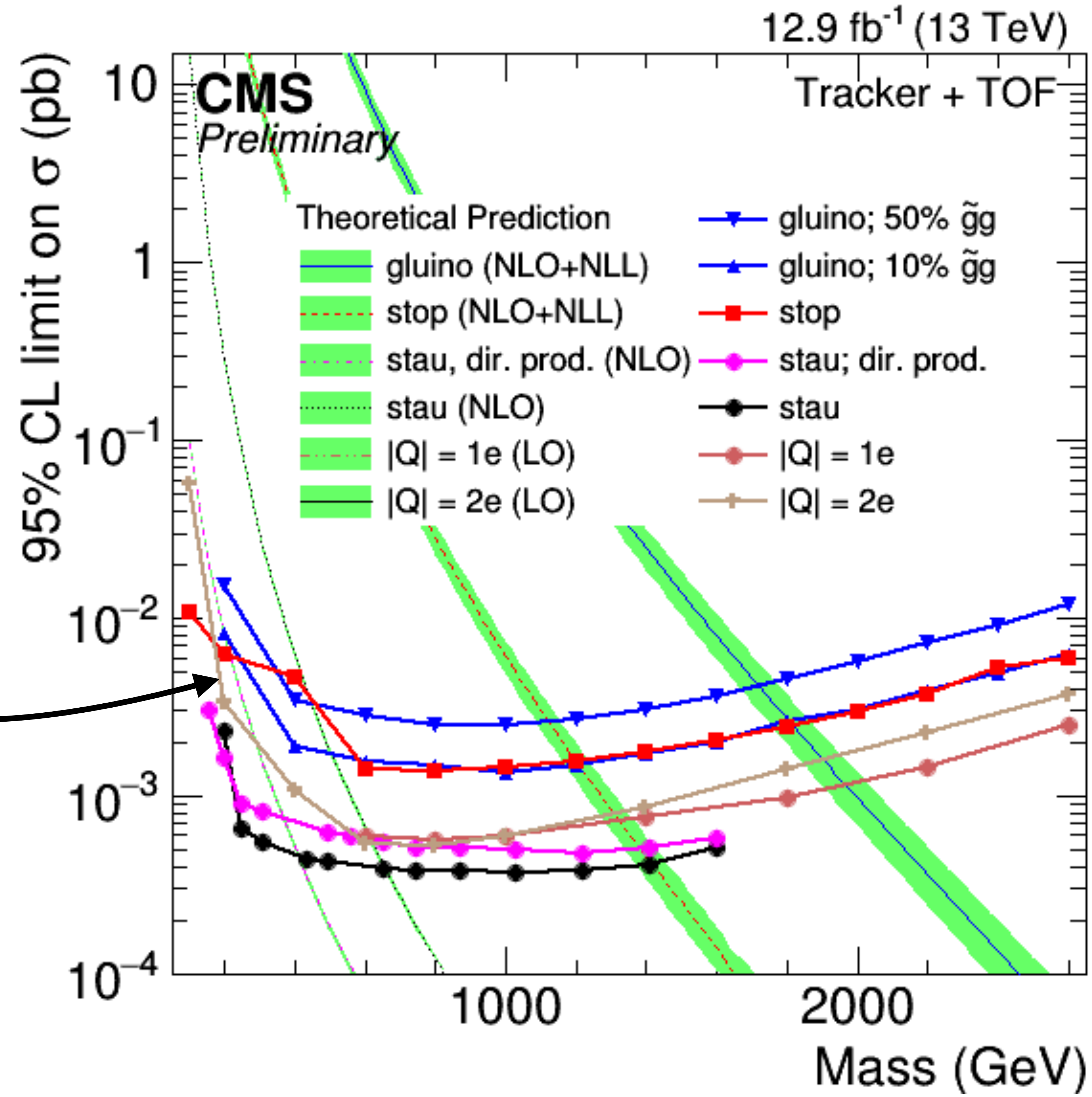
Limit on Chargino pair production



LHC limit on WH final state; not stronger than displaced leptons

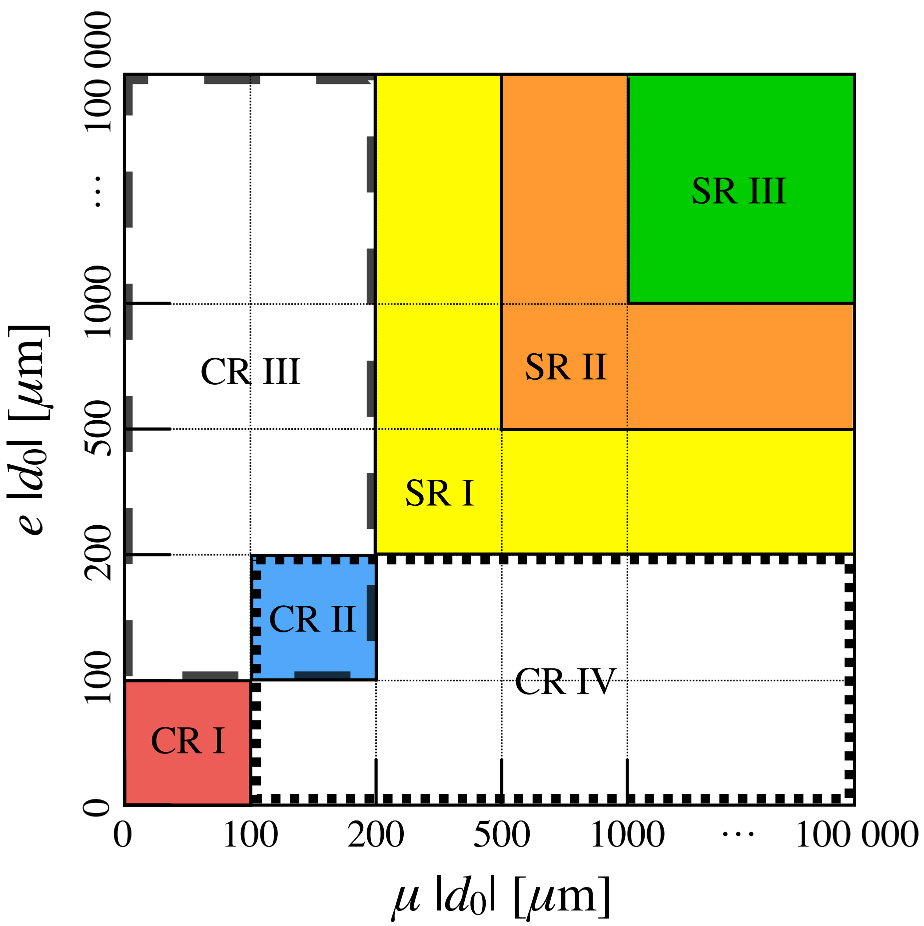
Other limits: charged track searches

Doubly charged



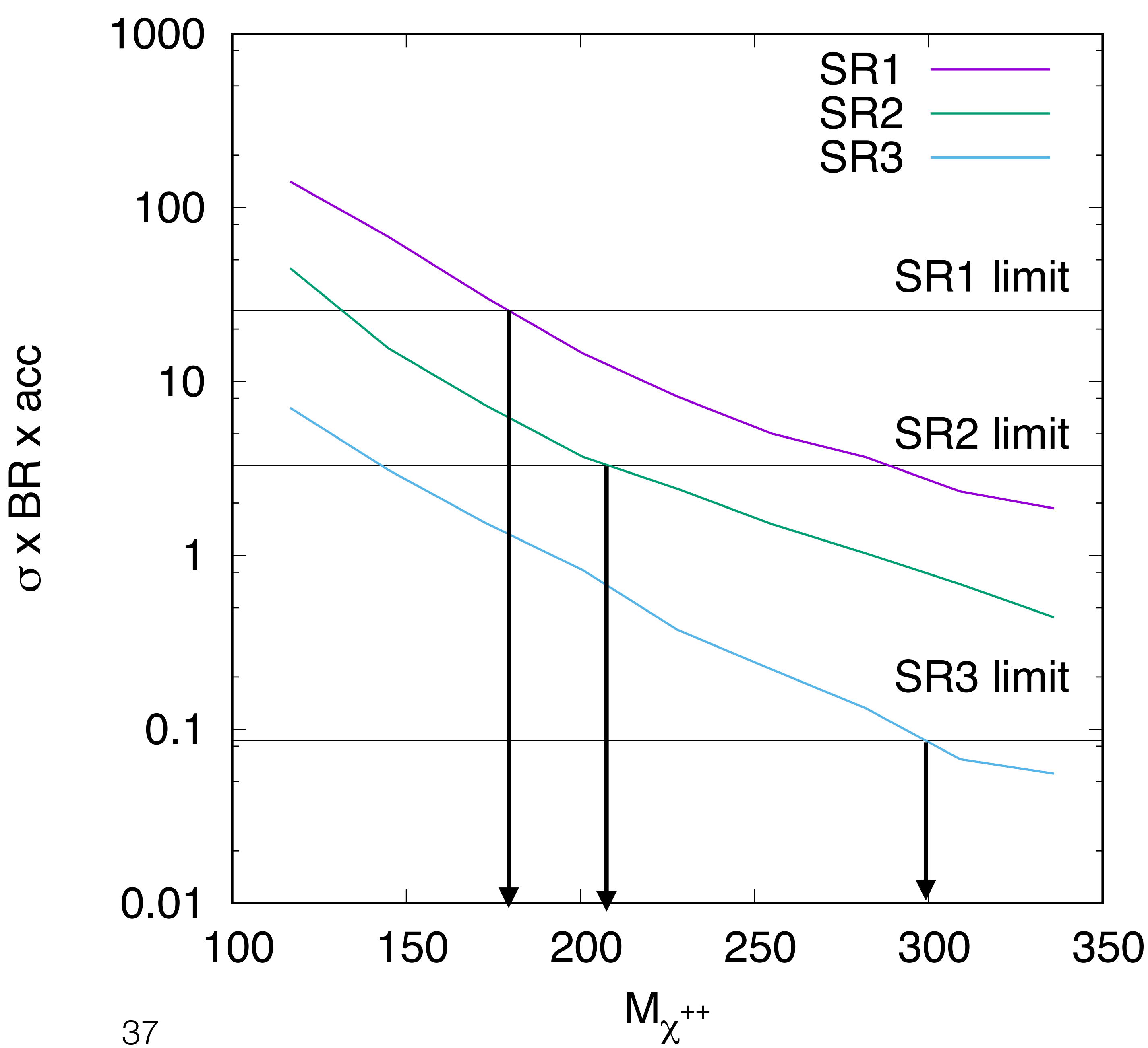
Rule out long-lived region i.e. when mass difference is smaller than pion mass

The CMS displaced lepton search



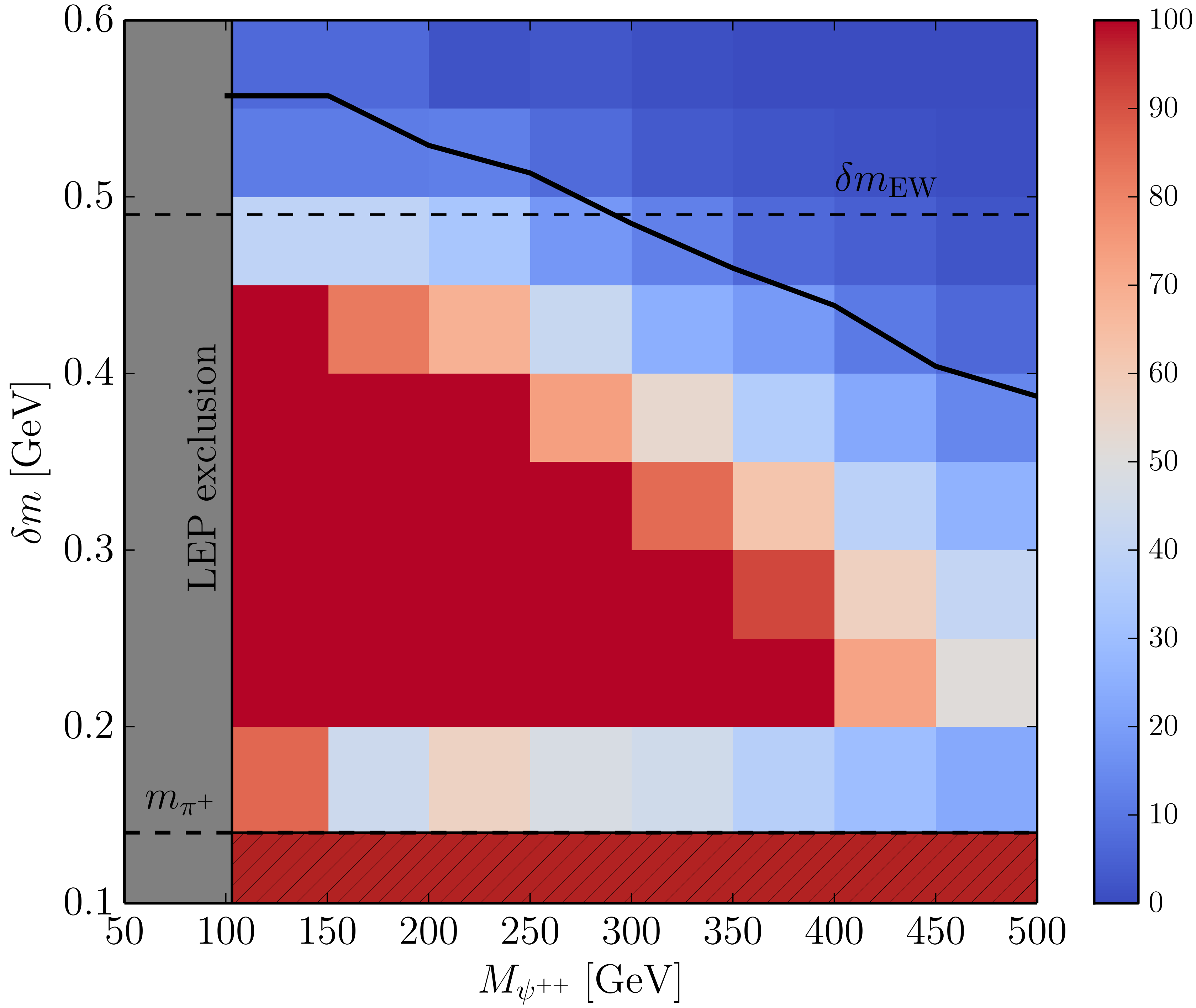
Validation

Lifetime	1 mm	10 mm	100 mm
SR1	34.4 (30 ± 5)	28.3 (35 ± 7)	4.83 (4 ± 1)
SR2	8.76 (6.5 ± 1)	24.6 (30 ± 5)	5.73 (5 ± 1)
SR3	1.69 (1.3 ± 0.3)	53.6 (51 ± 10)	24.6 (26 ± 5)



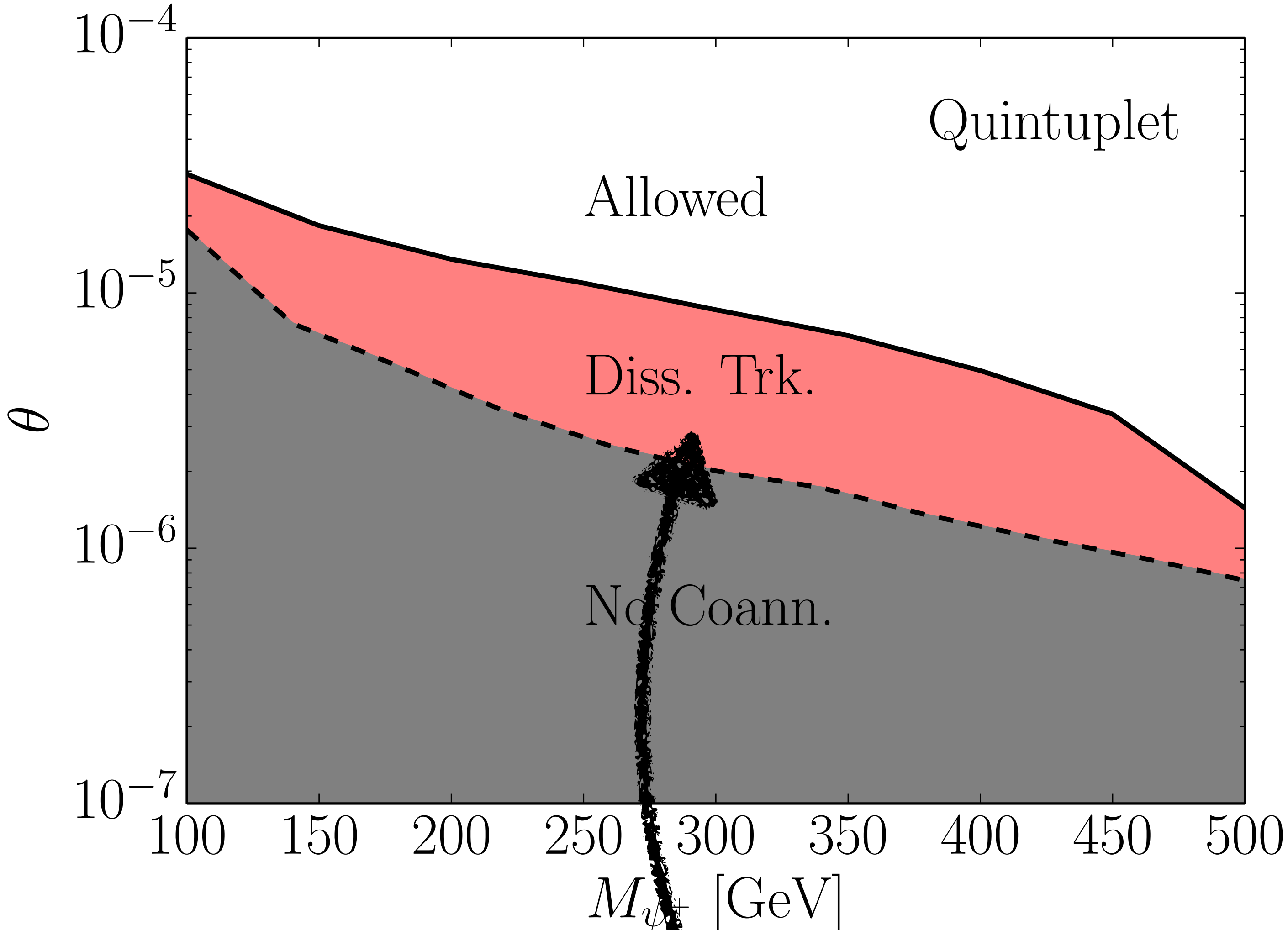
arXiv:1409.4789

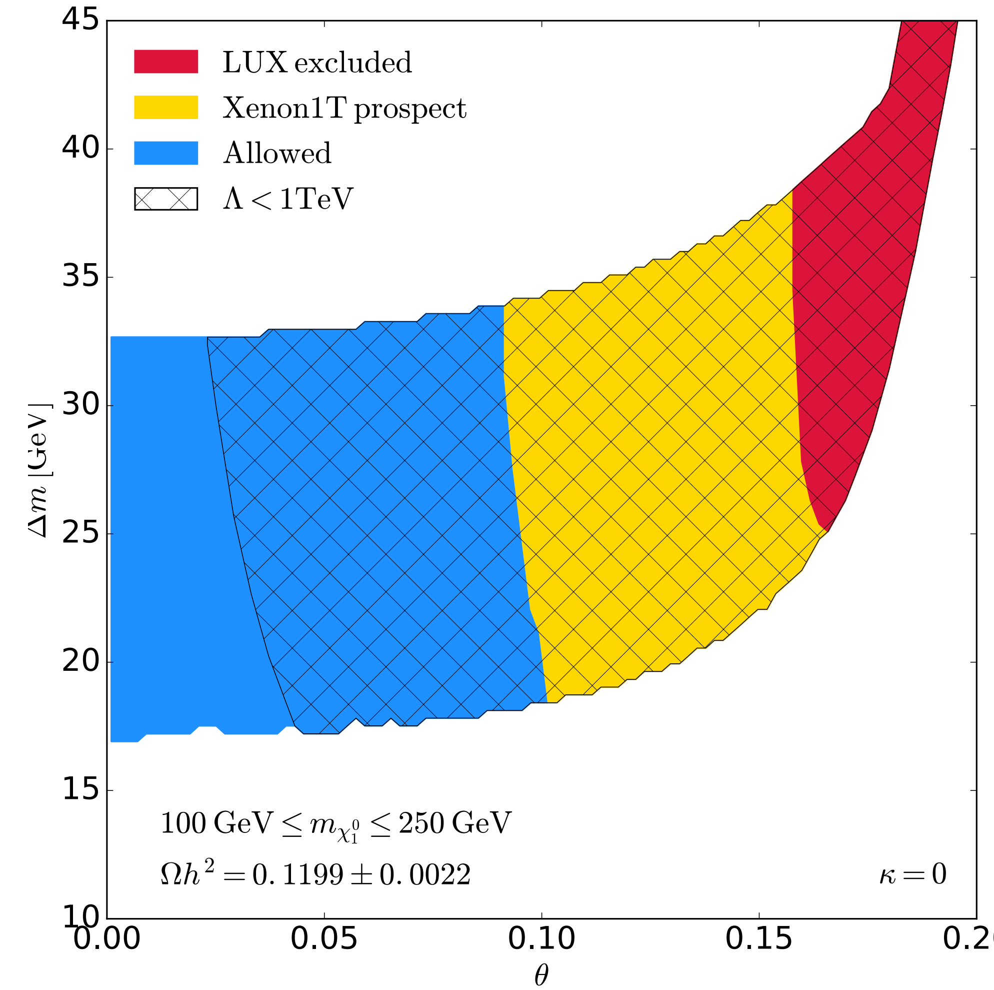
Combination of displaced lepton and charged tracks



Brümmer, Bharucha, Desai; arXiv:1804.02357

Limits on mixing angle

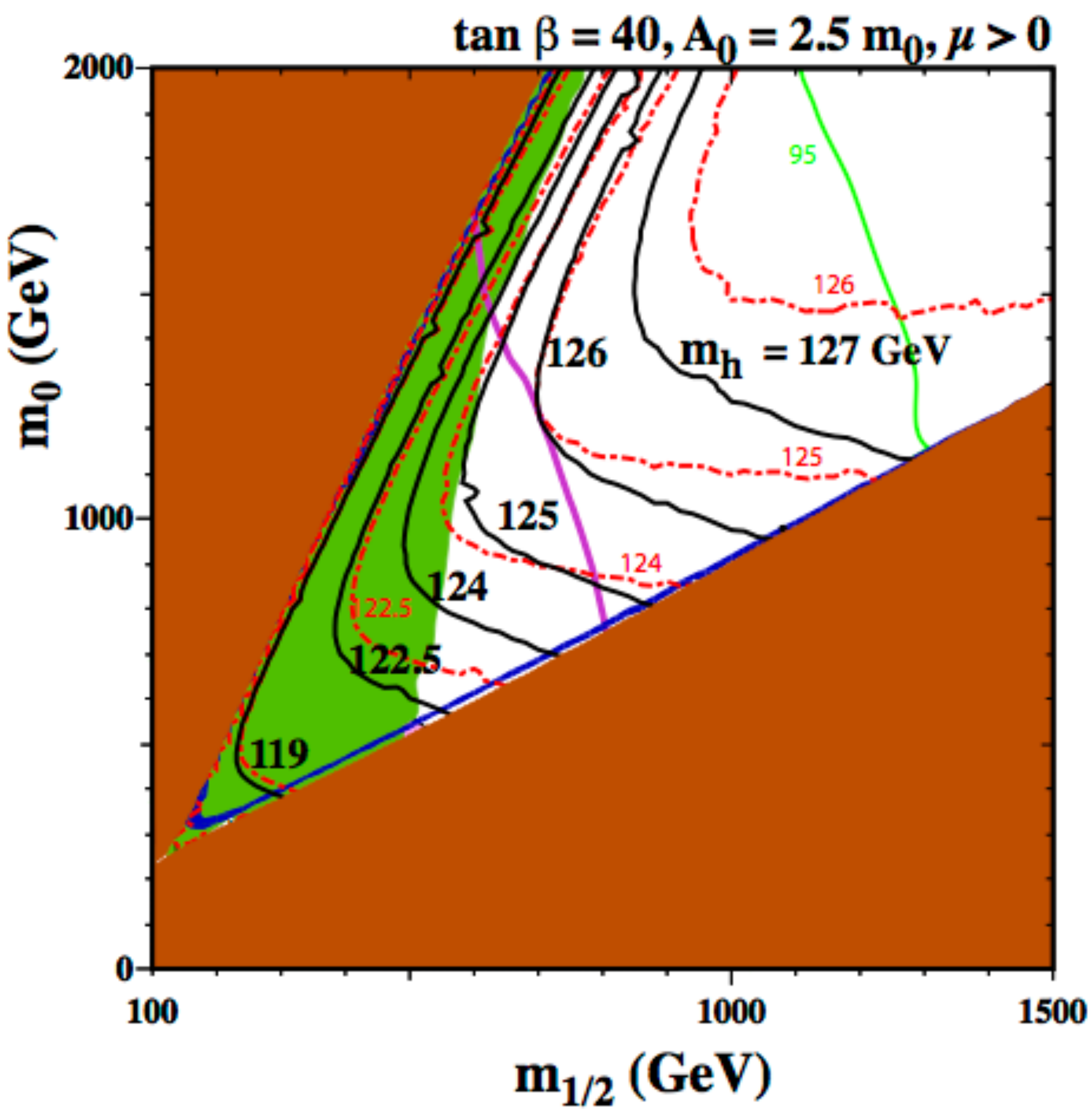




Provides a complementary lower limit on mixing

Stau Co-annihilation

CMSSM after Run I



Questions to ask:

1. Does it give the correct Higgs mass?
2. Does it give the right relic density?
3. Does it satisfy constraints from the LHC?

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1. Does it give the correct Higgs mass?
2. Does it give the right relic density?
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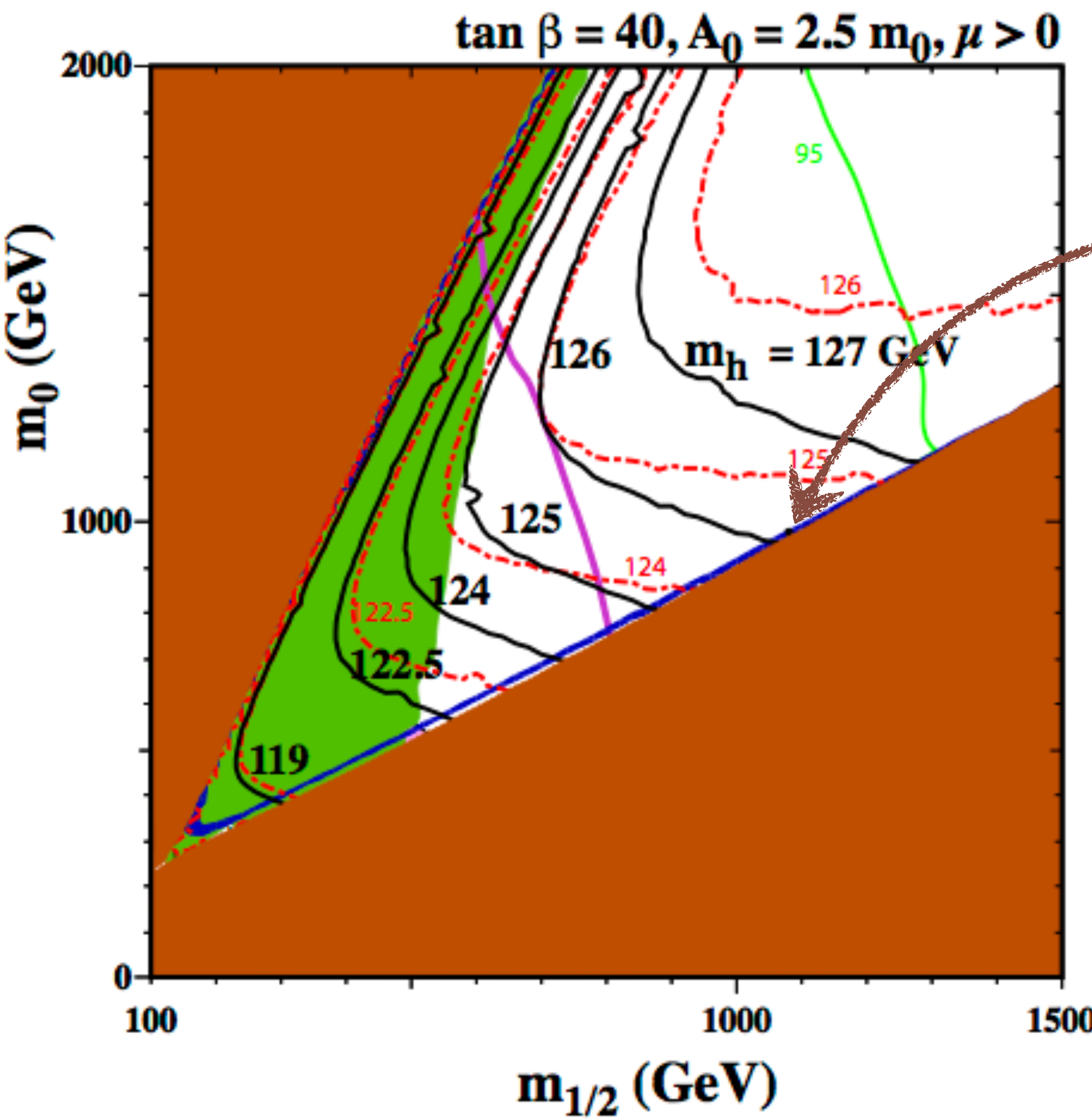
Fittino	MasterCode	Sfitter
$M_{1/2} = 1016$ GeV	$M_{1/2} = 1040$ GeV	$M_{1/2} = 999$ GeV
$M_0 = 504$ GeV	$M_0 = 670$ GeV	$M_0 = 442$ GeV
$\tan\beta = 18$	$\tan\beta = 21$	$\tan\beta = 24.6$
$A_0 = -2870$ GeV	$A_0 = -3440$ GeV	$A_0 = -1347$ GeV

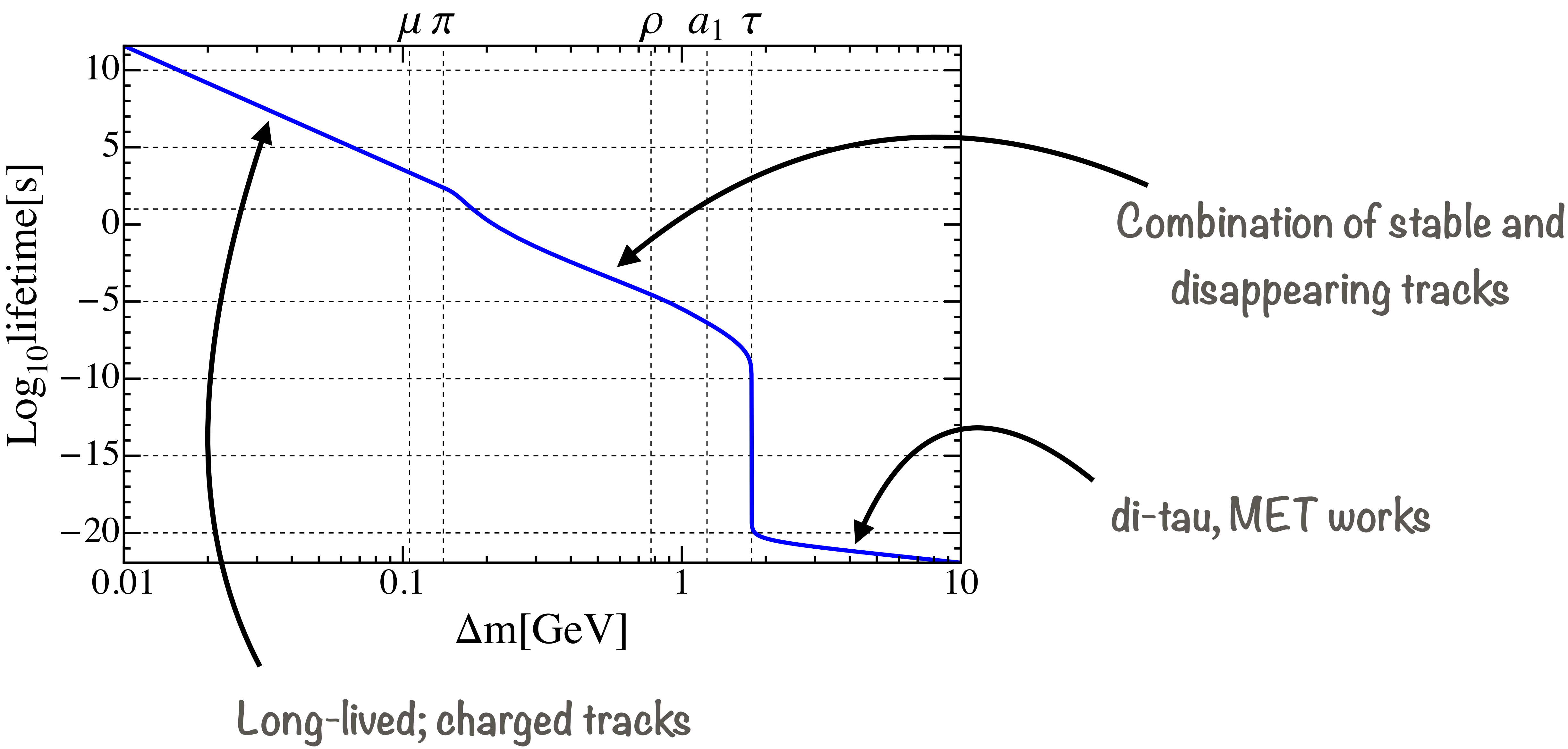
All of them in the stau co-annihilation strip!

Stau Co-annihilation strip after Run I



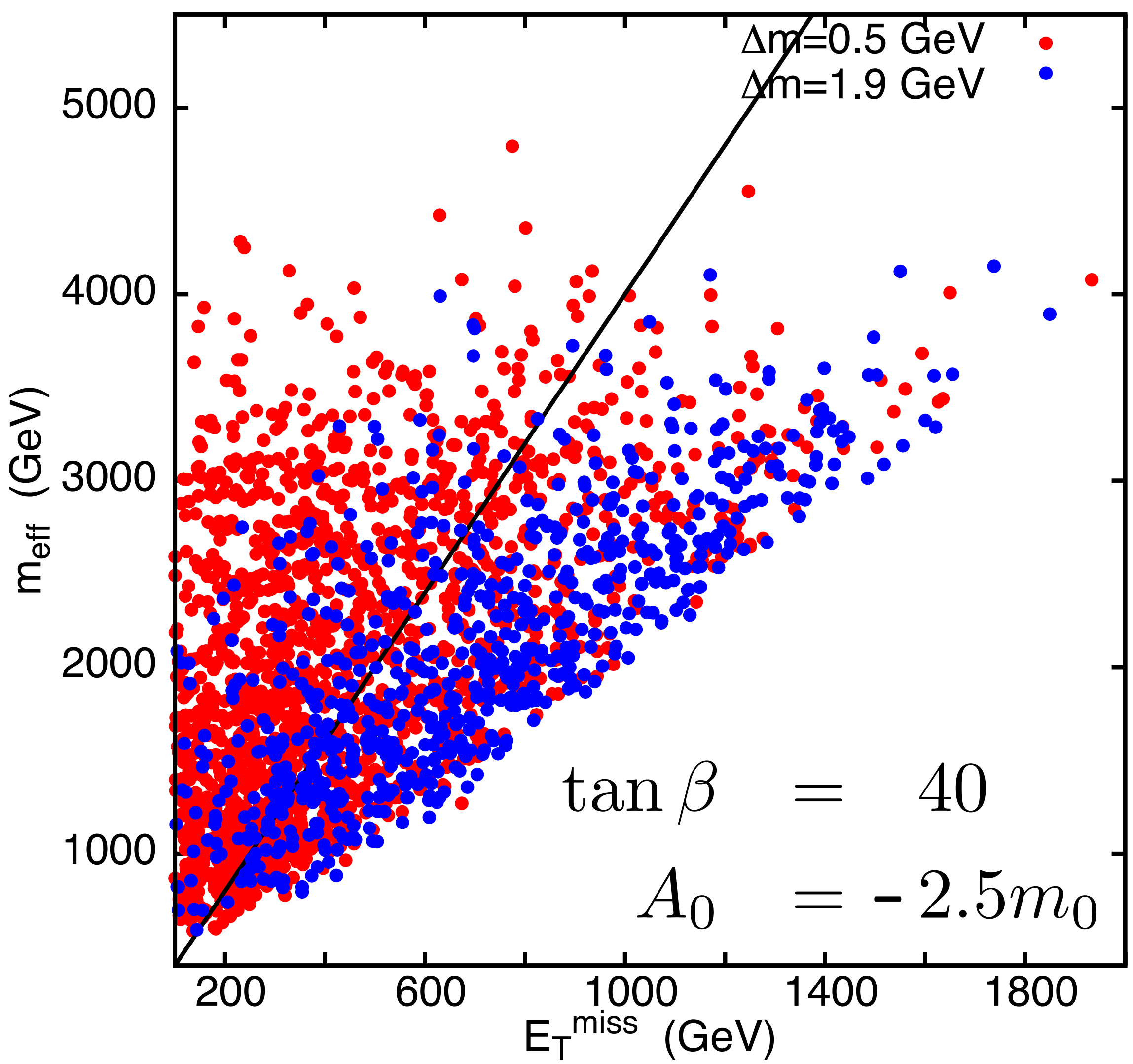
Compressed stau
and neutralino

Lifetime of the stau

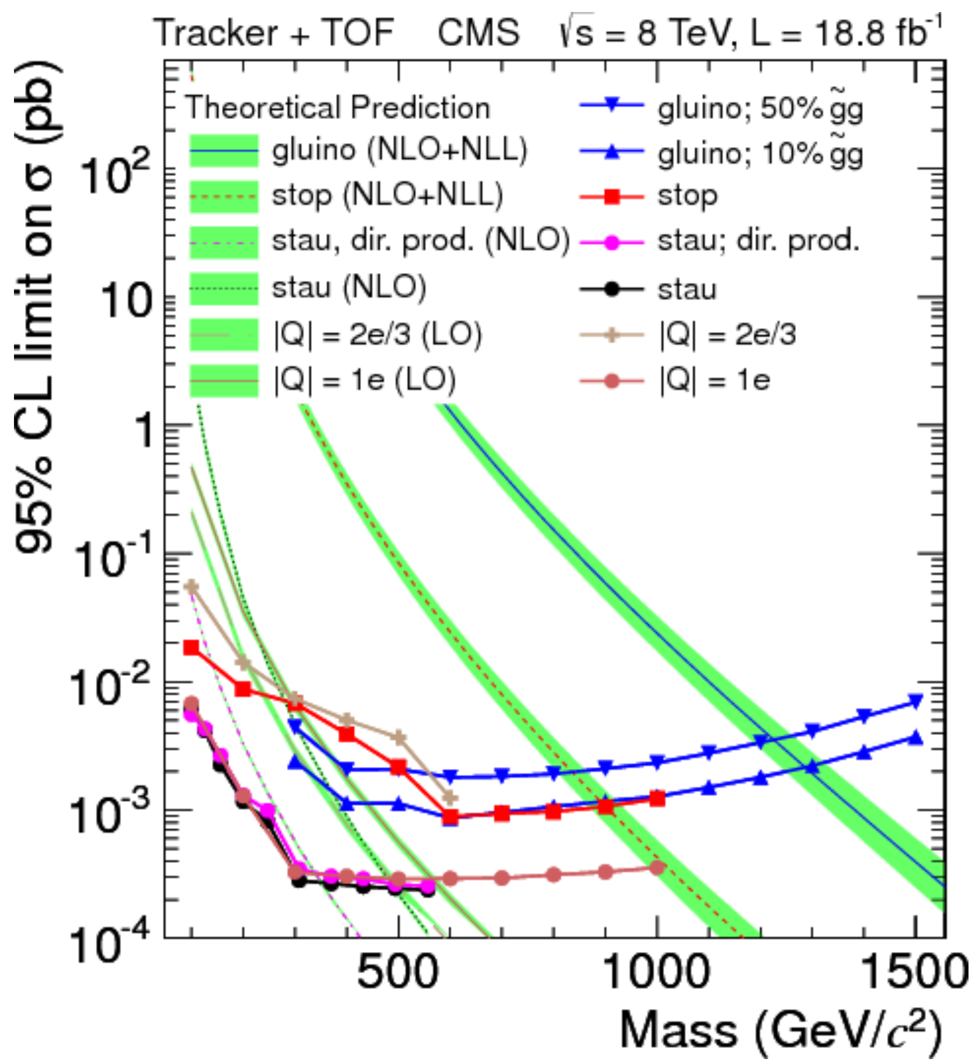


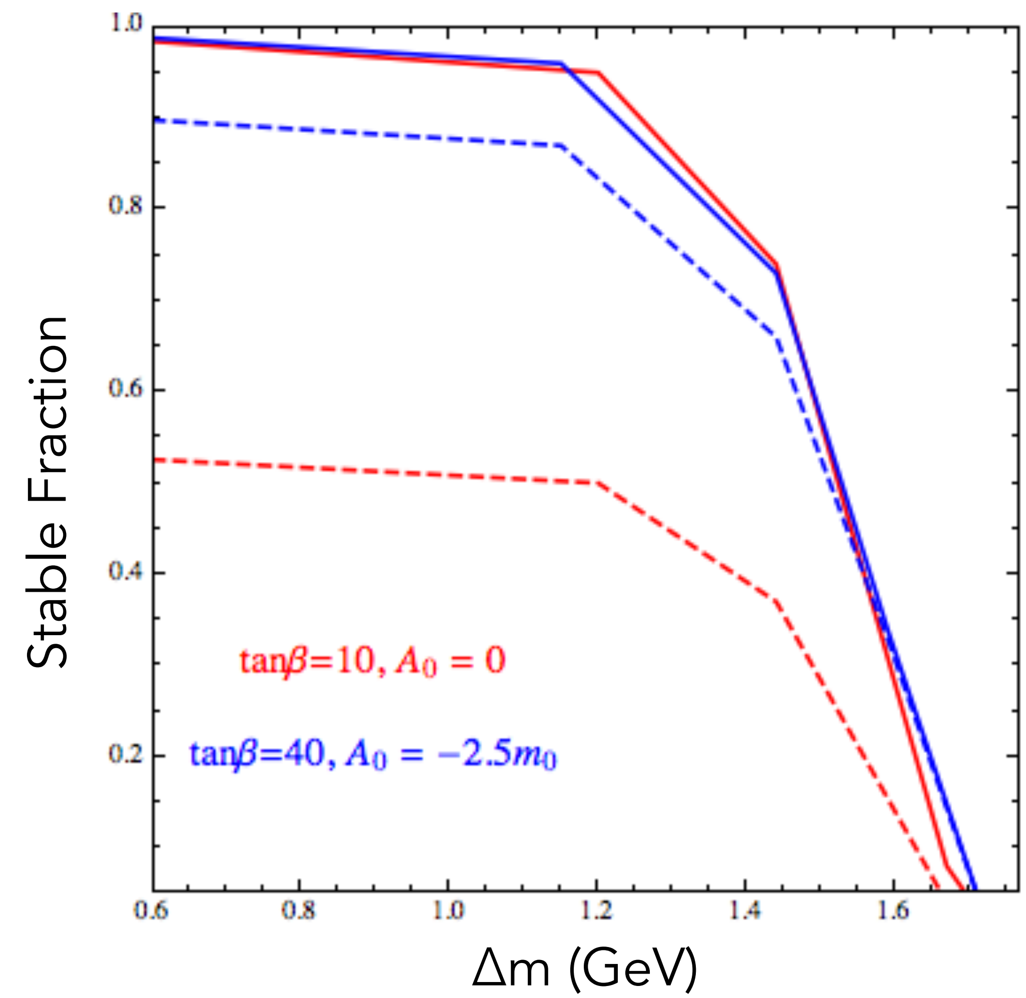
Not enough missing energy!

Requirement	Signal Region 2jW	Signal Region 3j
$E_{\mathrm{T}}^{\mathrm{miss}}[\mathrm{GeV}] >$	160	
$p_{\mathrm{T}}(j_1)$ [GeV] $>$	130	
$p_{\mathrm{T}}(j_2)$ [GeV] $>$	60	
$p_{\mathrm{T}}(j_3)$ [GeV] $>$		60
$p_{\mathrm{T}}(j_4)$ [GeV] $>$		
$\Delta\phi(\mathrm{jet}_{1,2,(3)}, \mathbf{E}_{\mathrm{T}}^{\mathrm{miss}})_{\mathrm{min}} >$	0.4	
$\Delta\phi(\mathrm{jet}_{i>3}, \mathbf{E}_{\mathrm{T}}^{\mathrm{miss}})_{\mathrm{min}} >$		
W candidates	$2(W \to j)$	–
$E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$ [GeV$^{1/2}$] $>$		
$E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}}(N_{\mathrm{j}}) >$	0.25	0.3
$m_{\mathrm{eff}}(\mathrm{incl.})$ [GeV] $>$	1800	2200



Long-lived charged tracks

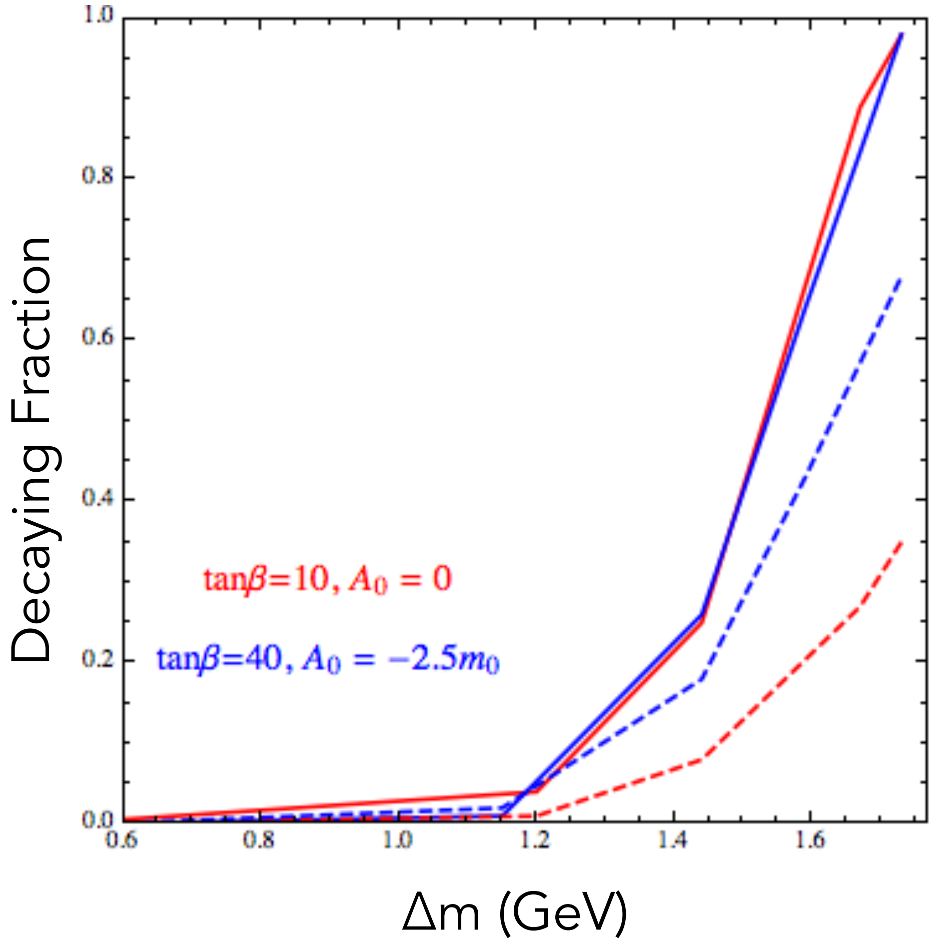




- Charged particle searches are specialised to take time of flight into account
- Fraction of staus that are stable on the detector scale decreases with increasing mass difference
- Run I limit on fully stable staus is ~550 GeV; since not all our staus exit the detector, we get a limit ~300 GeV.

ATLAS: disappearing track search

Selection requirement
~~Quality requirements and trigger~~
~~Jet cleaning~~
Lepton veto
Leading jet $p_{\mathrm{T}} > 90$ GeV
$E_{\mathrm{T}}^{\mathrm{miss}} > 90$ GeV
$\Delta\phi_{\mathrm{min}}^{\text{jet-}E_{\mathrm{T}}^{\mathrm{miss}}} > 1.5$
High-p_{T} isolated track selection
Disappearing-track selection



↓

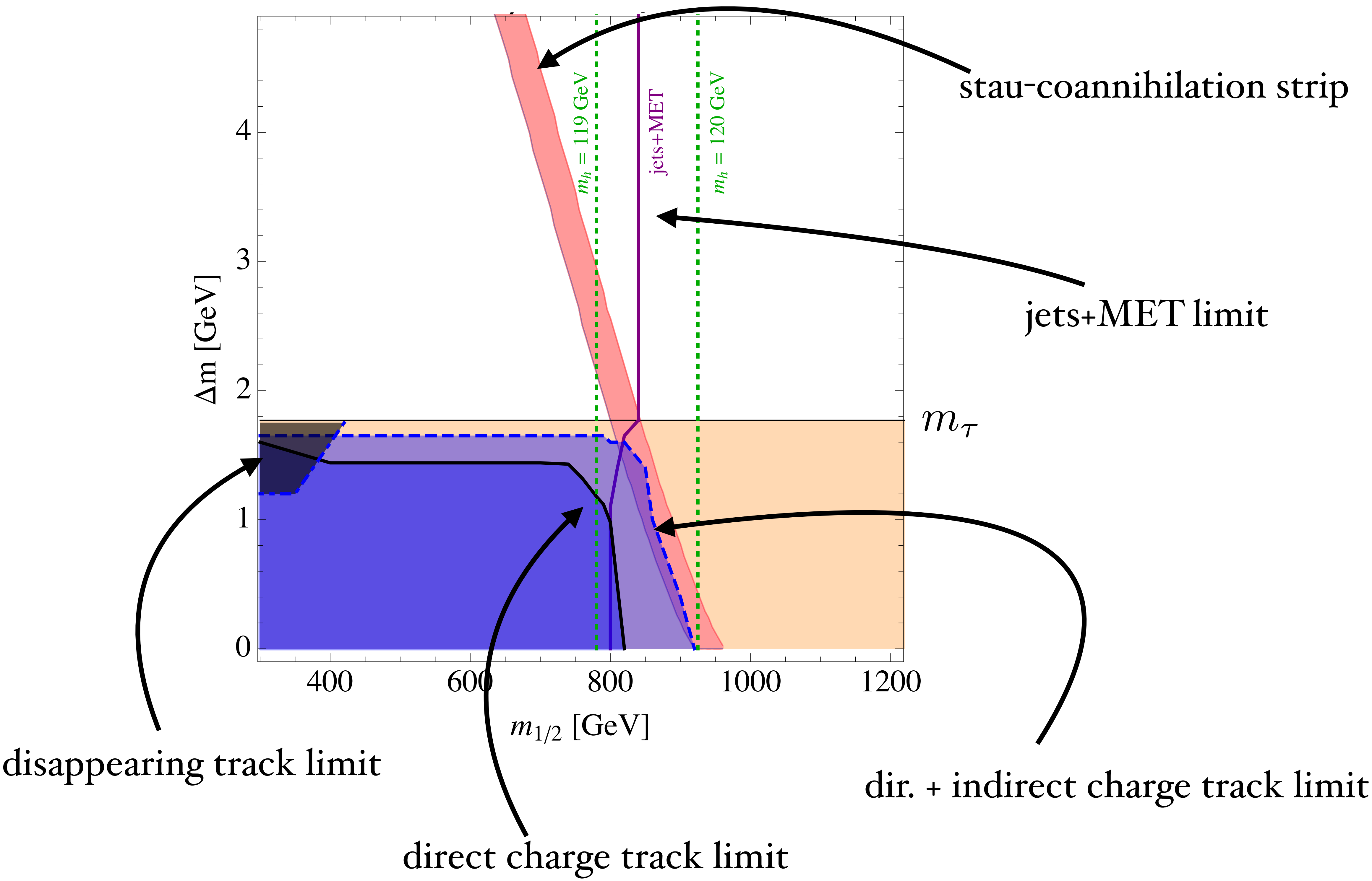
Validate efficiencies against their AMSB benchmark

↓

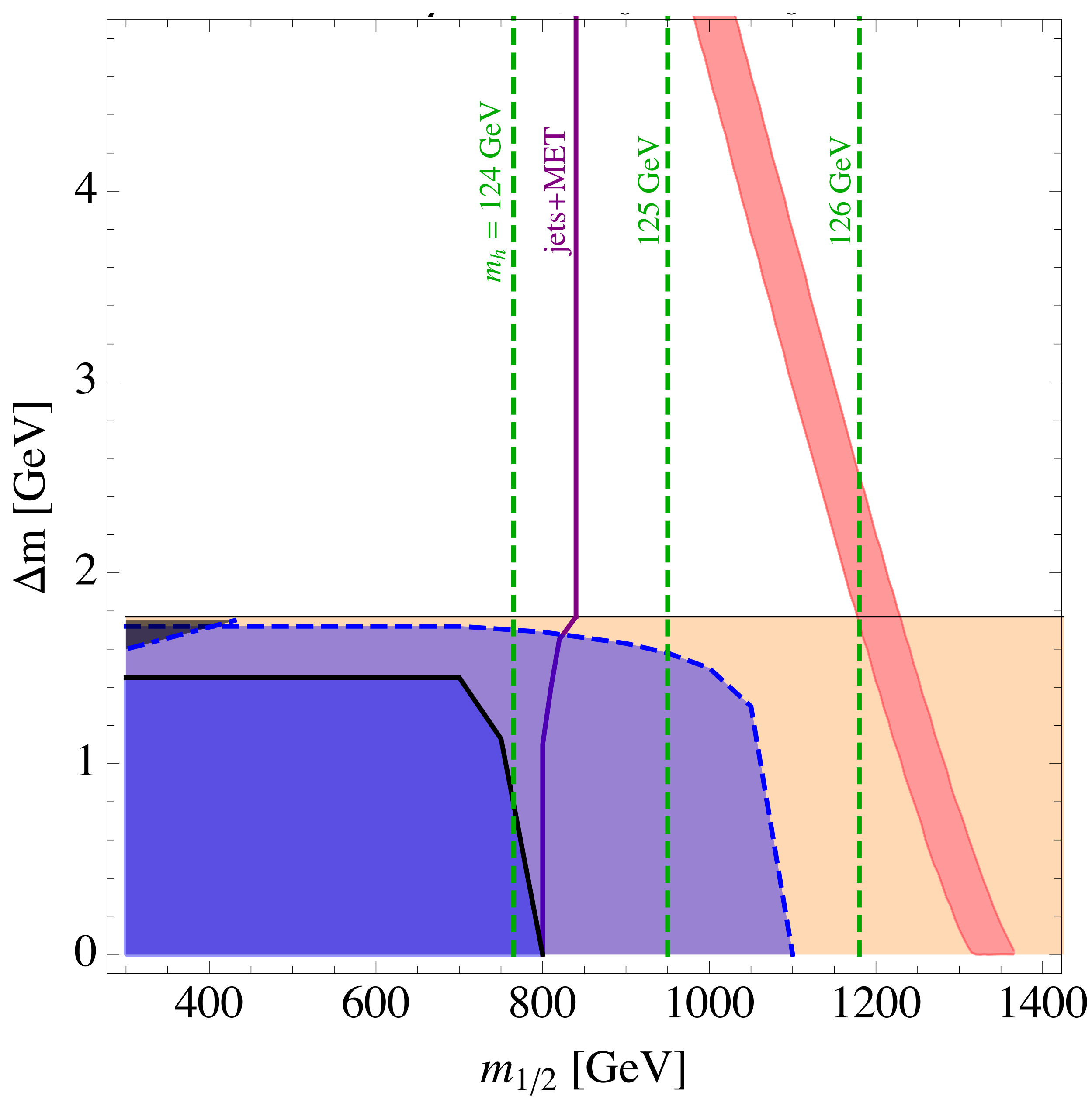
TABLE III. Numbers of observed and expected background events as well as the probability that a background-only experiment is more signal-like than observed (p_0) and the model-independent upper limit on the visible cross-section ($\sigma_{\mathrm{vis}}^{95\%}$) at 95% CL.

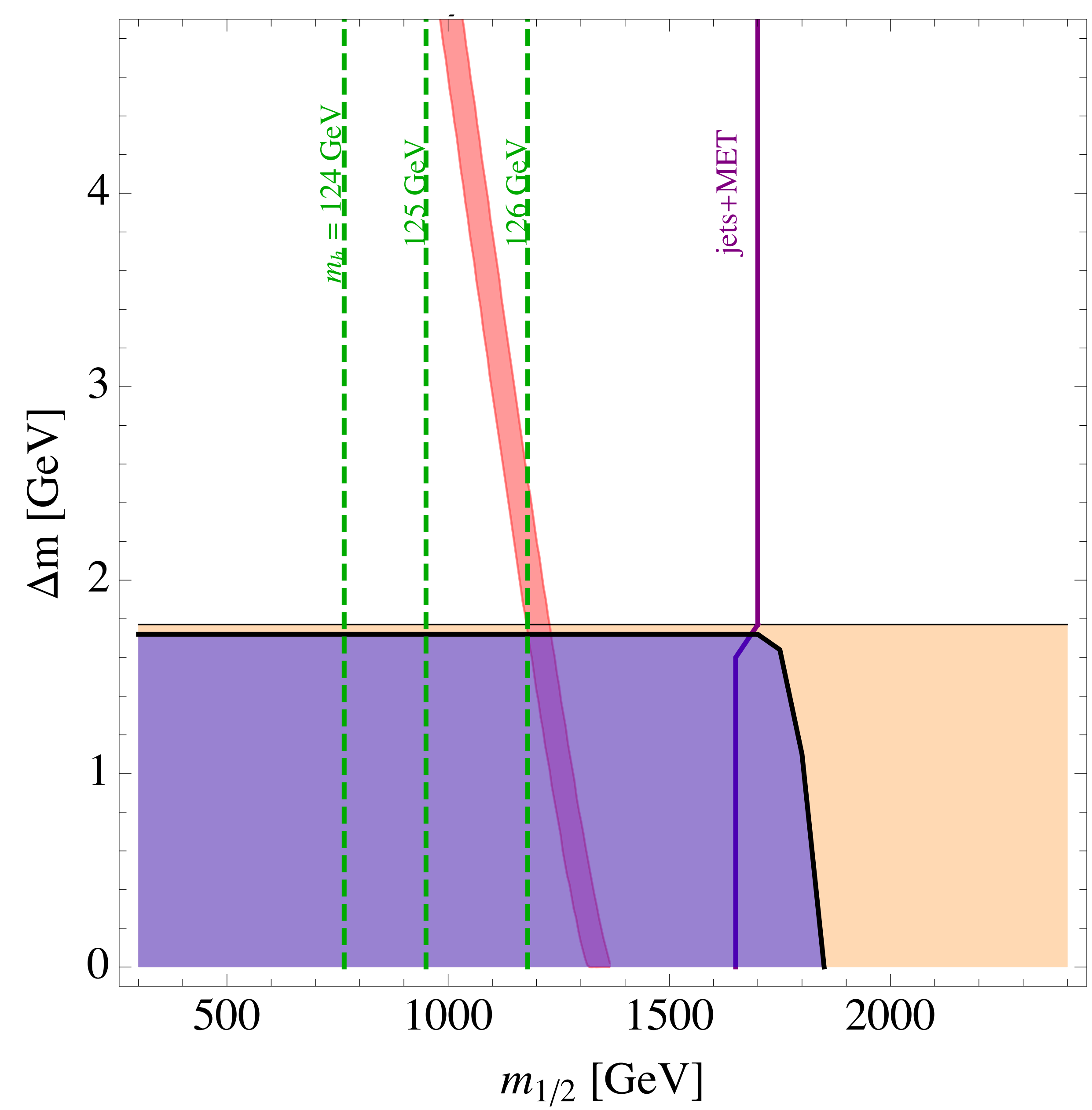
	$p_{\mathrm{T}}^{\mathrm{track}} > 75$ GeV	$p_{\mathrm{T}}^{\mathrm{track}} > 100$ GeV	$p_{\mathrm{T}}^{\mathrm{track}} > 150$ GeV	$p_{\mathrm{T}}^{\mathrm{track}} > 200$ GeV
Observed events	59	36	19	13
Expected events	48.5 ± 12.3	37.1 ± 9.4	24.6 ± 6.3	18.0 ± 4.6
p_0 value	0.17	0.41	0.46	0.44
Observed $\sigma_{\mathrm{vis}}^{95\%}$ [fb]	1.76	1.02	0.62	0.44
Expected $\sigma_{\mathrm{vis}}^{95\%}$ [fb]	$1.42^{+0.50}_{-0.39}$	$1.05^{+0.37}_{-0.28}$	$0.67^{+0.27}_{-0.19}$	$0.56^{+0.23}_{-0.16}$

combining multiple searches



CMSSM Stau co-annihilation is (probably) dead



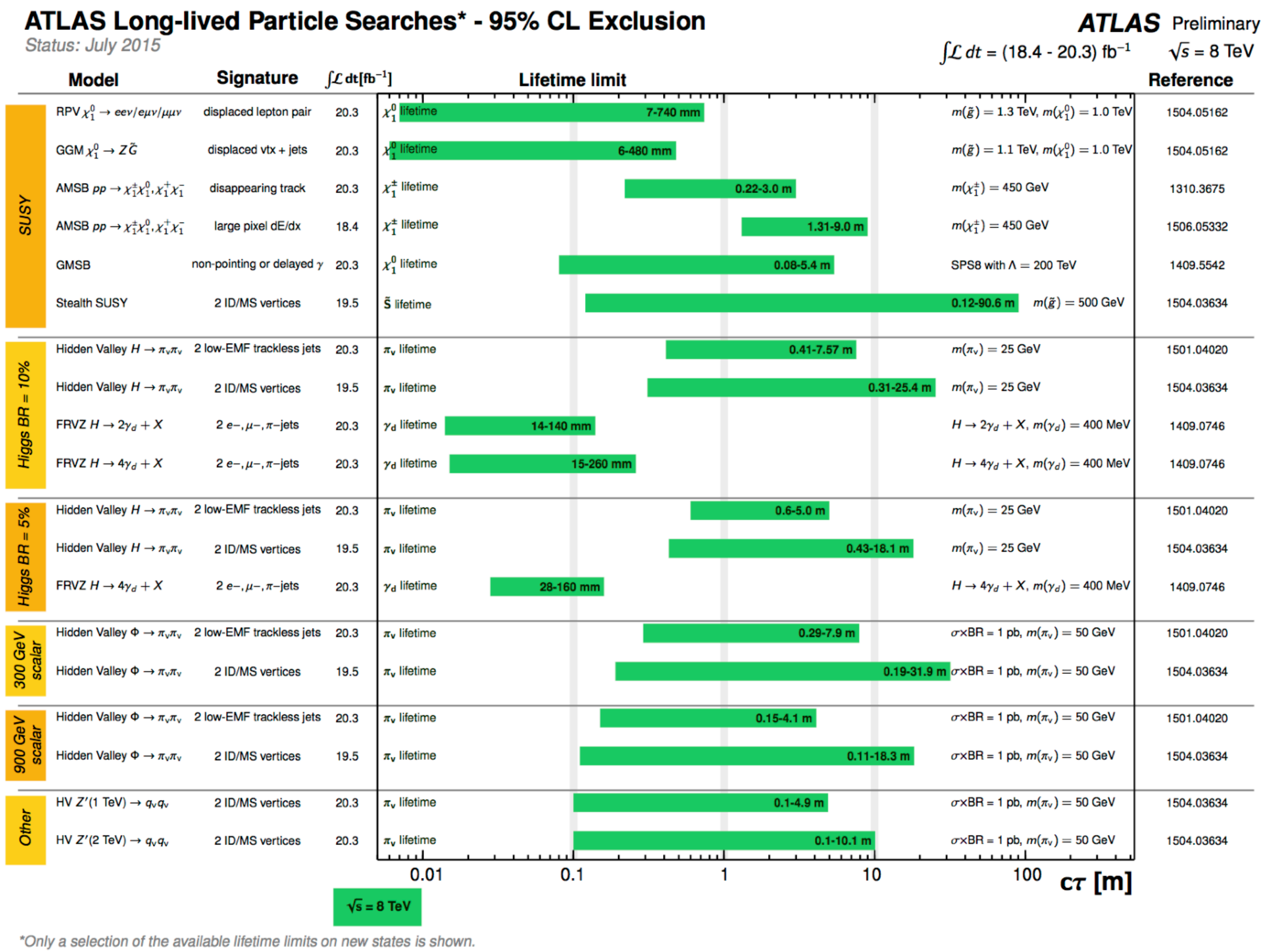


Coannihilation region not fully probed at 8 TeV; **we await 13 TeV data results in this Winter** to discover (or exclude!) the final part of the co-annihilation strip

Filling the gaps in DM searches

DM + s-channel mediator	Dilepton, dijet, mono-jet, displaced vertices
DM + t-channel mediator	“squark” & “slepton” searches, (disappearing) charged tracks, displaced leptons
SU(2) n-plets	jets+MET, di-lepton+MET searches, mono-jet, mono-photon, (disappearing) charged tracks, displaced leptons
ALPs	Di-gamma, non-pointing photons
Sterile Neutrinos, Heavy Neutral leptons	leptons+MET, Z/higgs+MET displaced vertices, displaced leptons

Some LLP limits



ARE WE MISSING SOMETHING?

Summary

- Long-lived particles predicted by many theories as a natural consequence
- LLP searches often have nearly **zero background** and can provide a clean signature
- If a model predicts LLPs, these searches are **more sensitive** than traditional searches
- **Co-annihilation partners** in DM models are often long-lived and can provide the first indications of signal
- Important to look at LLPs to **cover full range of DM theory** possibilities.