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Physics beyond the Standard Model — HL-LHC Prospects

Sukanya Sinha
University of Manchester
(on behalf of ATLAS, CMS & LHCb)

ECFA-UK Physics Workshop
Durham, 26/9/2024

ATLAS EXPERIMENT

Physics beyond the Standard Model — HL-LHC Prospects

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(Disclaimer: “slightly” biased, and a subset of case studies discussed)

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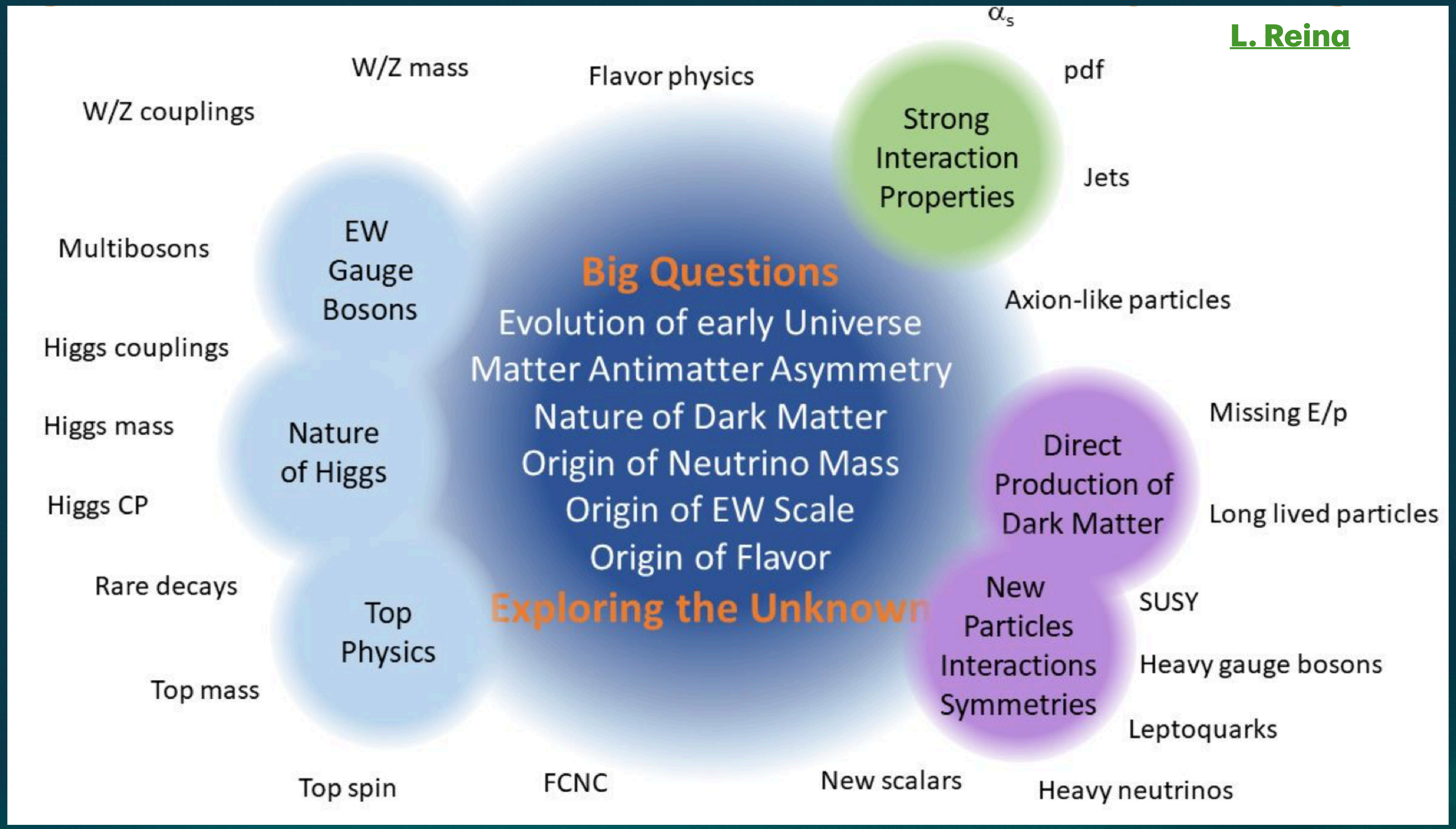
Primary sources of plots (unless stated otherwise):

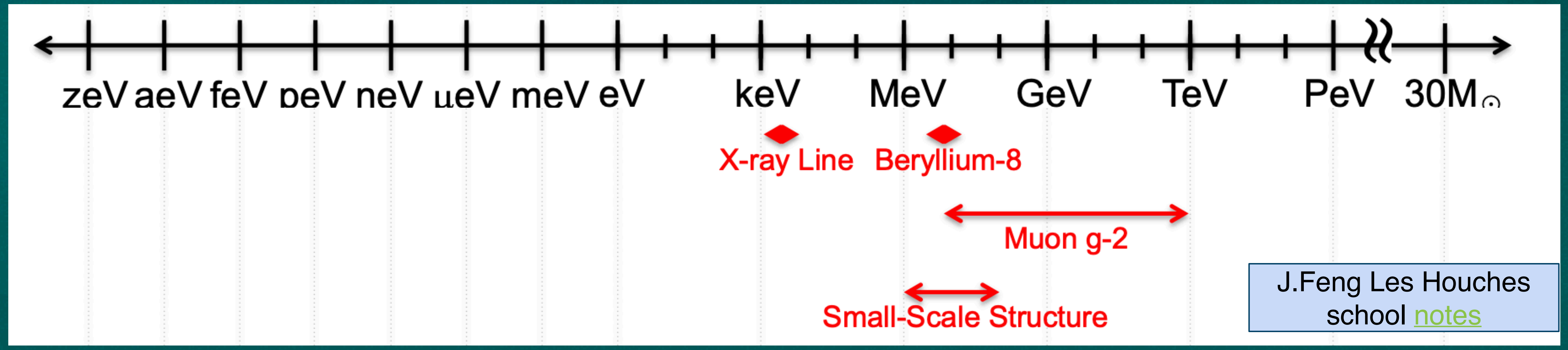
ATL-PHYS-PUB-2022-018, CMS-PAS-FTR-22-001, HL-LHC YR

Why BSM Physics?

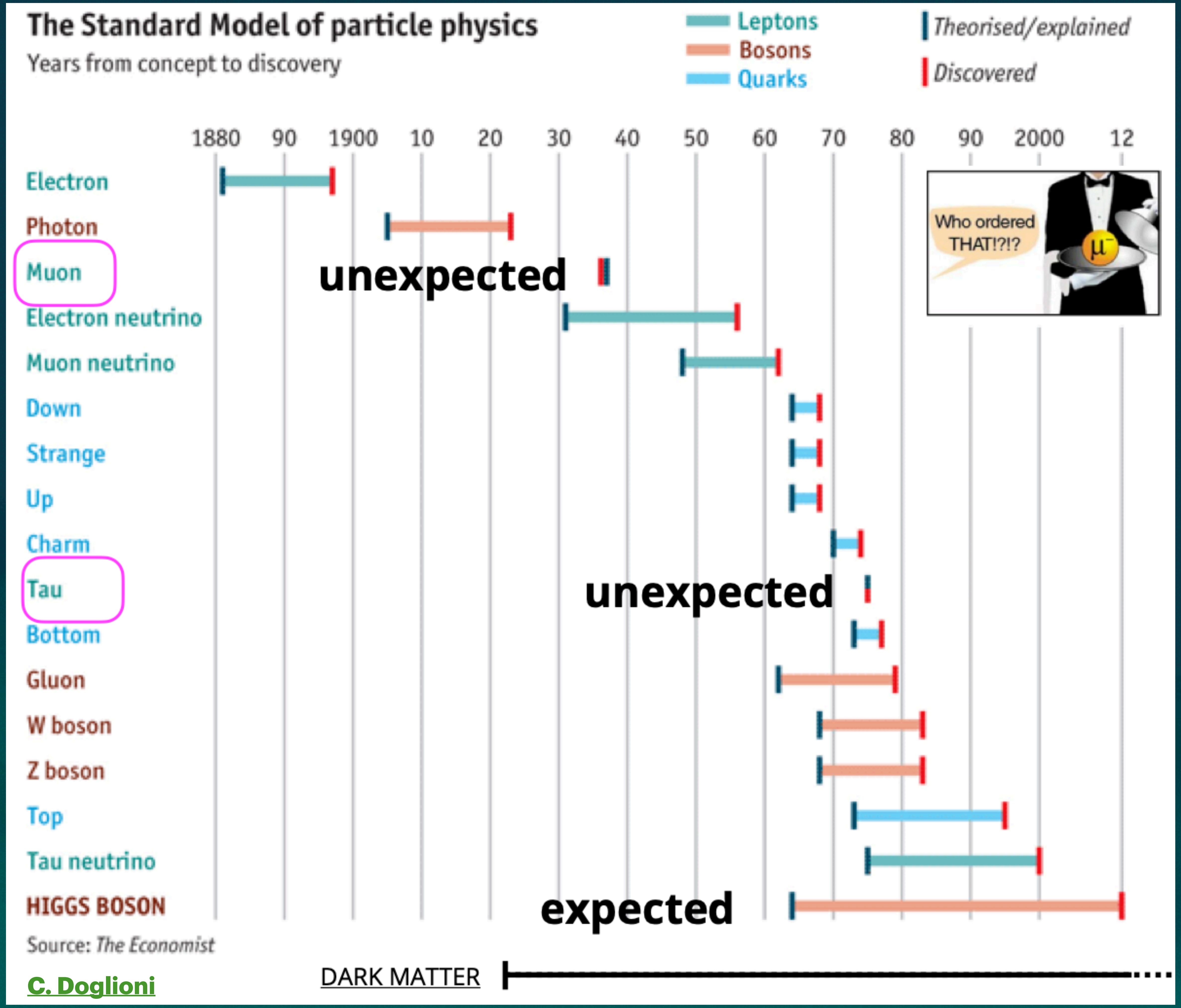
Several open questions that cannot be accommodated in the SM framework



Several anomalies



Hope for unexpected discoveries!



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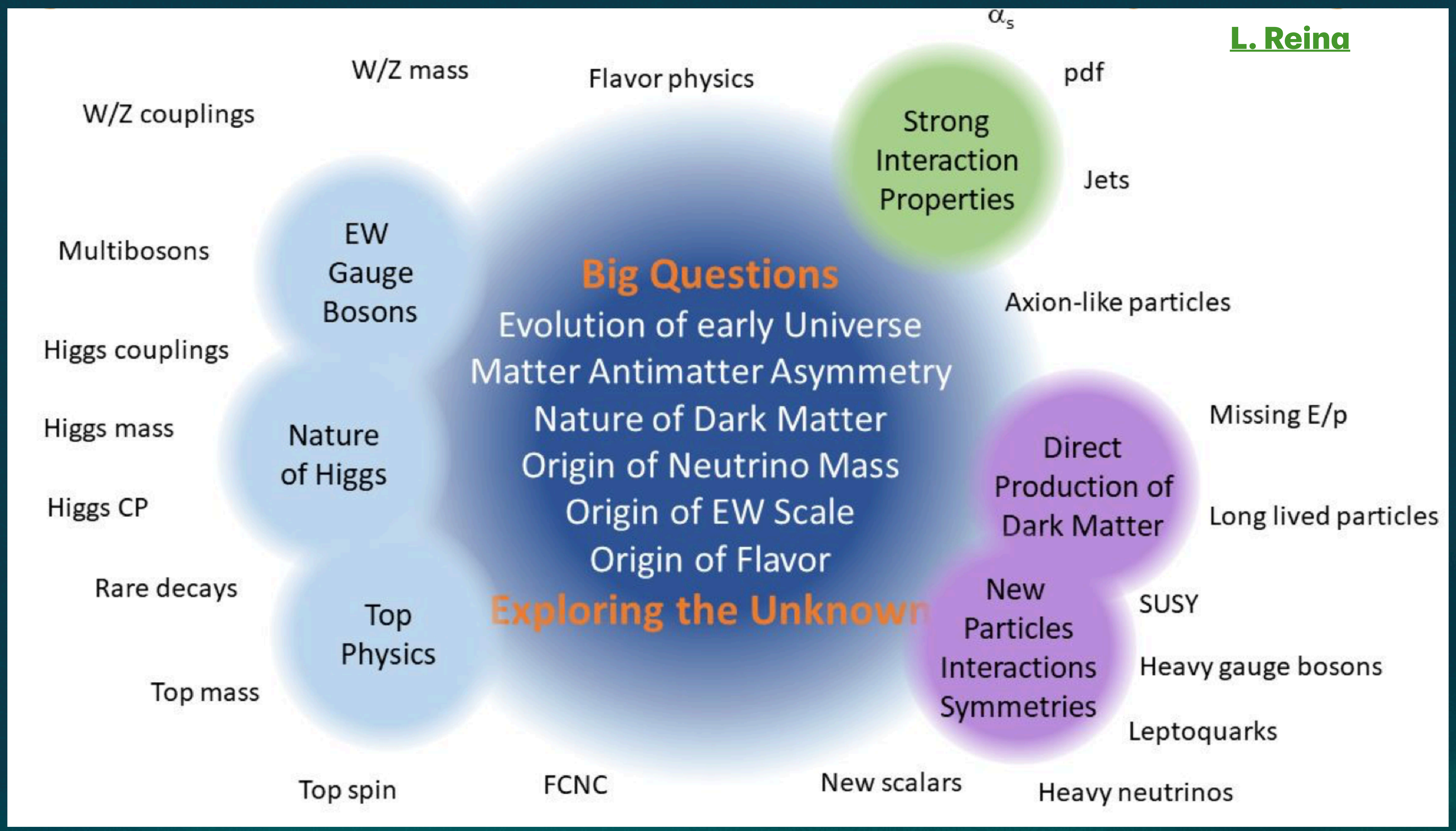

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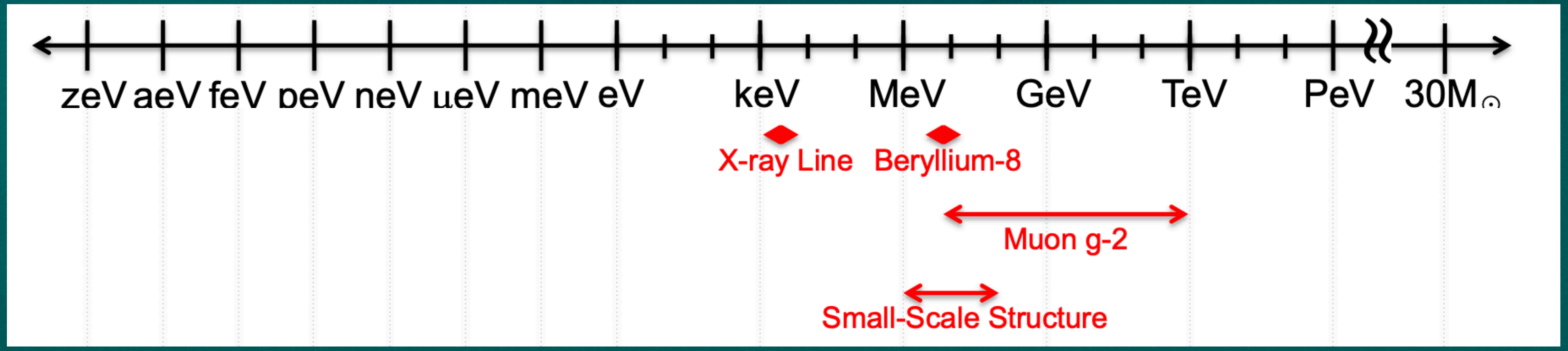


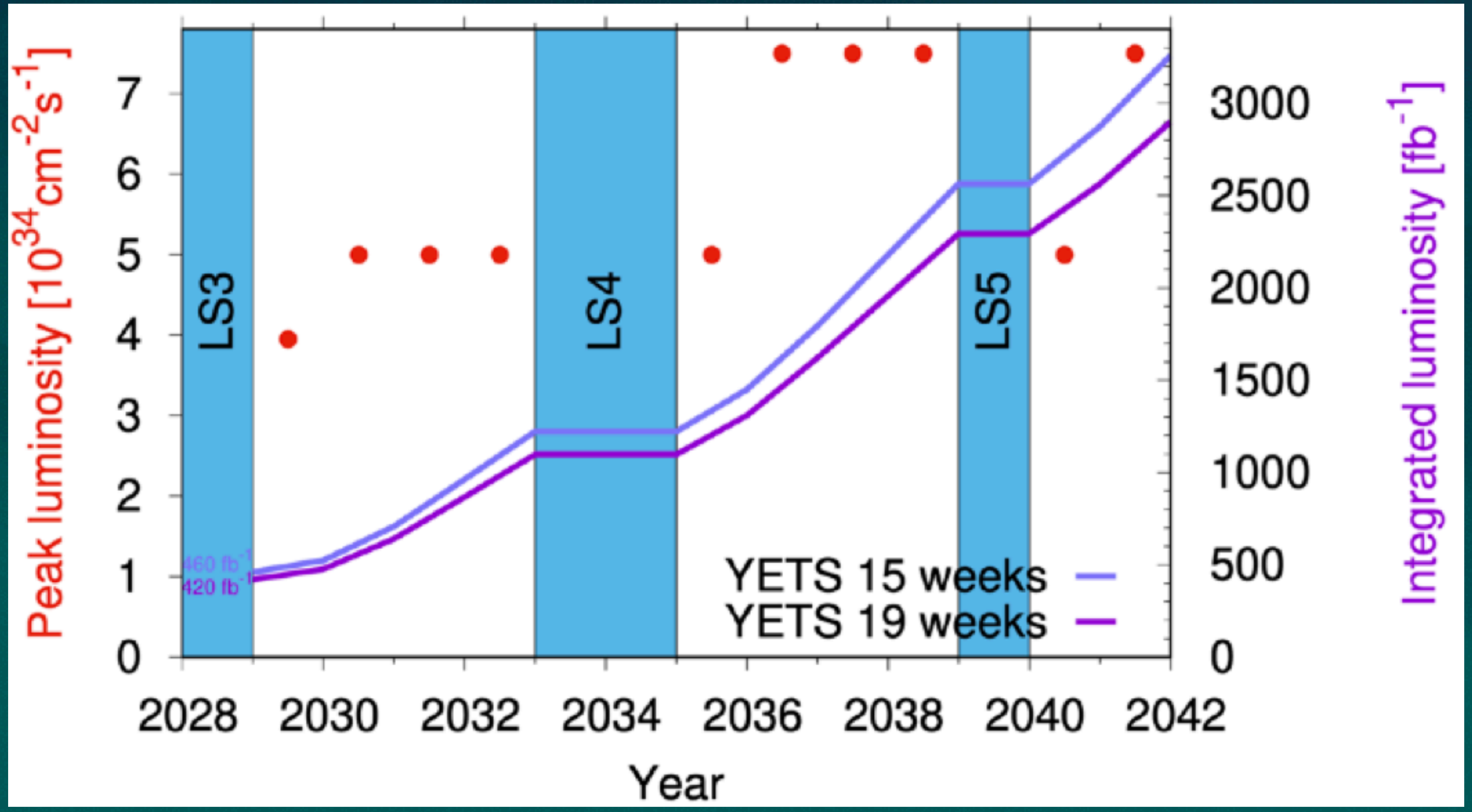
Why HL-LHC?

The obvious: Only high energy collider that will be taking data in the next decade

Sort of obvious: accumulating and analysing data will take time

Not always apparent (?): We have done many cool searches using existing LHC dataset, so priors exist

- Major upgrades for all experiments mentioned
  - Higher-bandwidth/rate **data acquisition/selection** (DAQ/trigger)
  - More performant **tracking detectors**
  - New **timing detectors** with picosecond precision

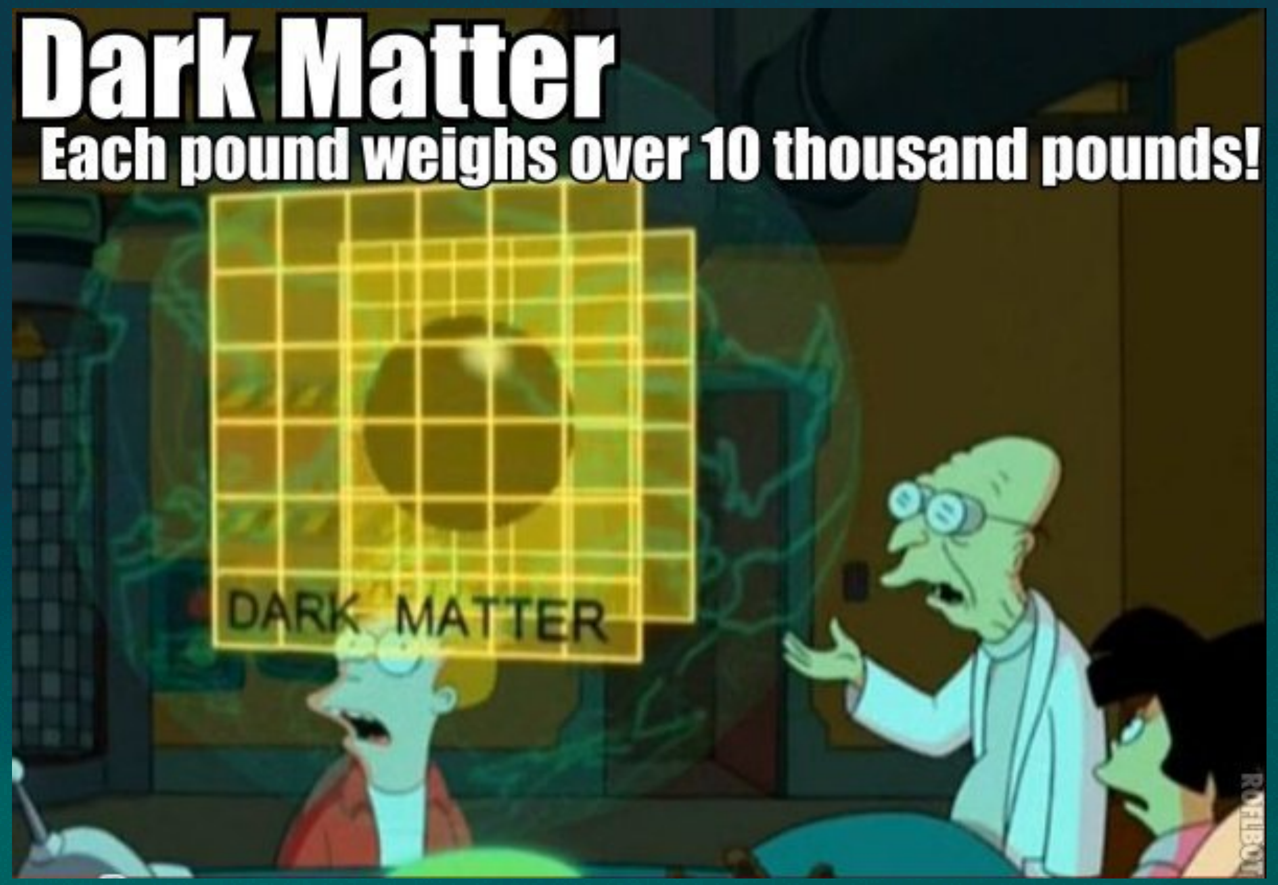


Hidden Sectors

SM Sector — Connectors / Portals — Hidden Sectors

Connectors / Portals: Z′, SUSY particles, Higgs, Extra Dim, Leptoquarks, CP-odd..

Hidden Sectors: can be strongly or weakly coupled i.e., dark Higgs, dark photon, dark SU(N), Asym DM...



When a Hidden Sector particle is (quasi-)stable, a dark matter candidate can potentially exist

We have not found any concrete sign of new physics … yet!

Looking at unusual topologies and hidden corners of the phase space

→ **signature based searches, using benchmark models.**

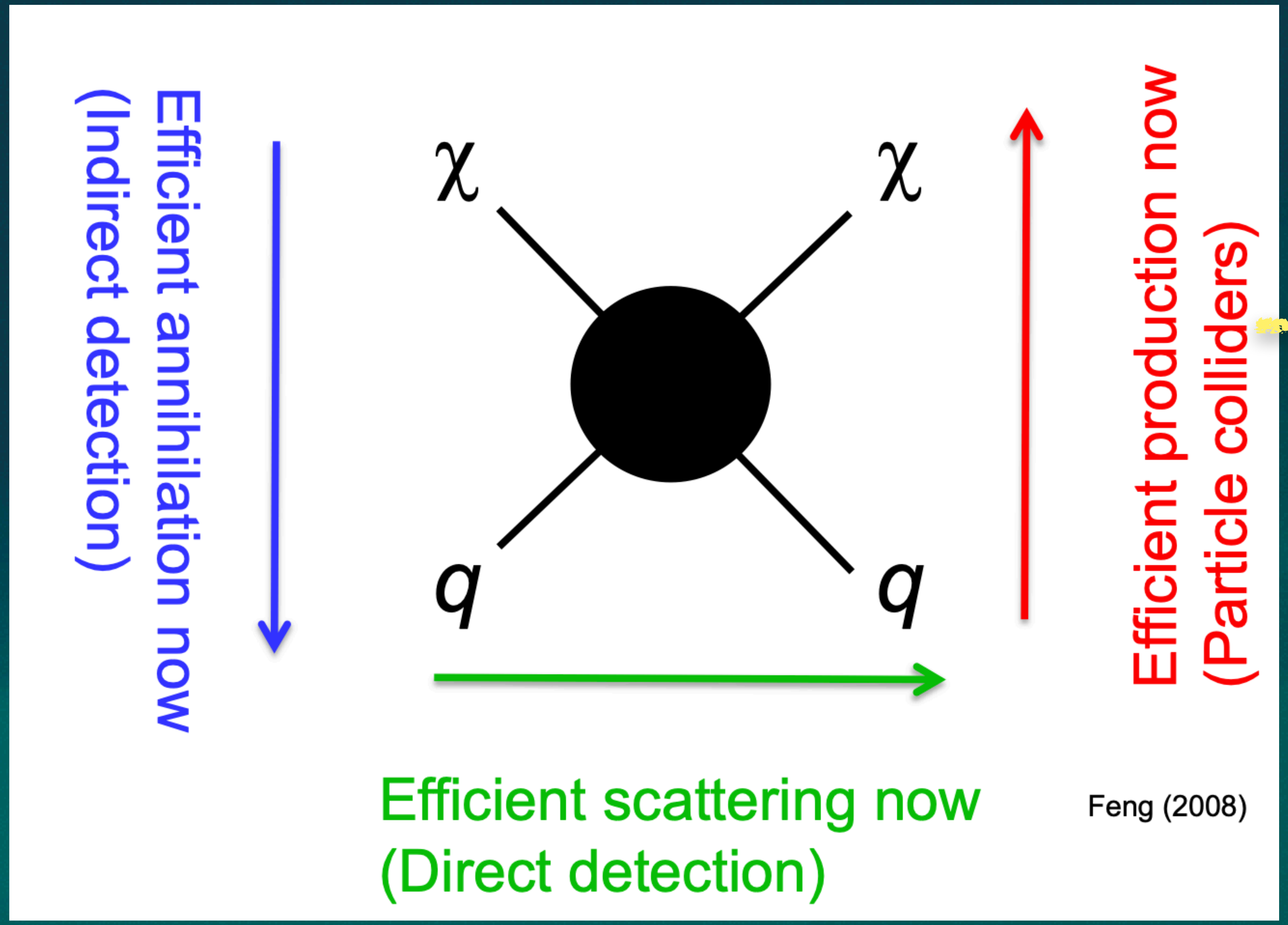
What are the ingredients for a simplified/collider-friendly New Physics model?

Basic Ingredients:
- *Generic* signatures
- *Evades constraints*
- *Manageable* no. of parameters
- *Promising* dark matter candidate
  - ability to satisfy relic density (if predicting DM candidate)

Spices/garnishes:
- Wide range of possible signatures
- Interesting phenomenology
- Potential synergies
  - decays: prompt vs LLP vs invisible
  - resonant vs non-resonant production
  - complementarity with direct/indirect detection (if predicting DM candidate)

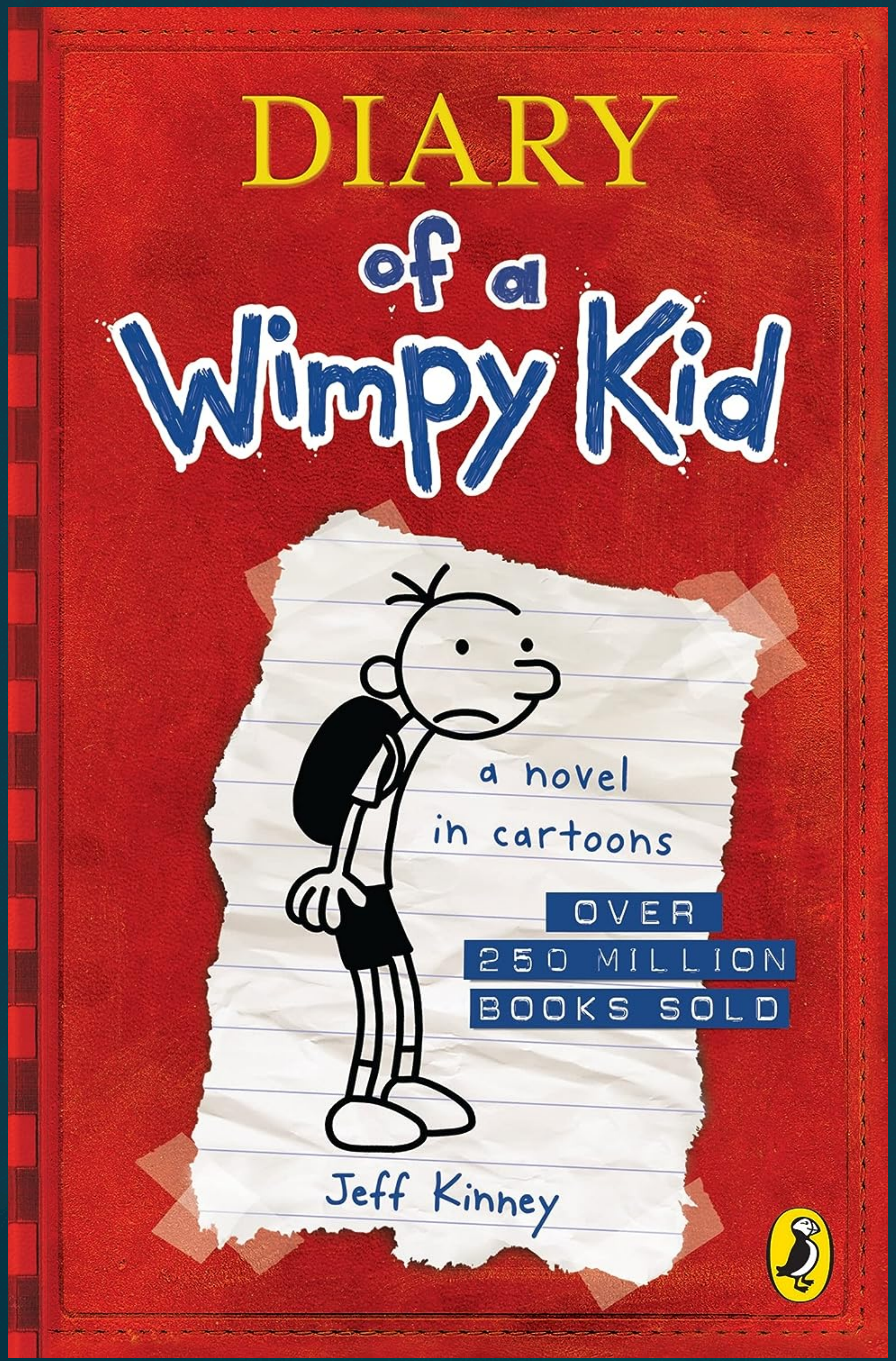
WIMPs

The miracle… WIMPs motivated by
- cosmology (production mechanism of thermal freeze-out, expected to have right relic density)
- particle theory (i.e. present in many BSM models)
- particle experiment (accessible in current and near-future energy scales)



Complementarity of various WIMP dark matter detection methods

Direct WIMP production of $\chi\chi$ pairs is invisible
→ must look for signatures of WIMPs produced in conjunction with other particles.



If SUSY: pair of squarks/gluinos → neutralino WIMP (i.e. MET)

Simplified models: DM + few other particles → few defining parameters

WIMPs

CMS Collaboration, V. Khachatryan et a
unparticles in monojet events in proton?pi
C75 (2015), no. 5 235, [arXiv:1408.3583

ATLAS Collaboration, G. A

Search for new phenomena with top quark pairs in final states with one lepton, jets, and missing transverse momentum in pp collisions at $\sqrt{s}$= 13 TeV with the ATLAS detector

ATLAS uses the Higgs boson as a tool to search for Dark Matter

29th October 2020 | By ATLAS Collaboration

Phys. Rev. **D90** (2014) 012004, [arXiv:

state at $\sqrt{s} = 13$ TeV with the ATLAS detector

ATLAS Collaboration, G. Aad et al., *Search for energetic*
the ATLA
Eur. Phys
with the

nically
3 TeV
7].

Search for direct pair production of supersymmetric partners to the τ lepton in proton-proton collisions at $\sqrt{s} = 13$ TeV

CMS Collaboration • Albert M Sirunyan (Yerevan Phys. Inst.) et al. (Jul 30, 2019)

Published in: *Eur.Phys.J.C* 80 (2020) 3, 189 • e-Print: 1907.13179 [hep-ex]

WIMPs

Over the years, hund... been proposed….

CMS Collaboration, V. K... *unparticles in monojet eve...* **C75** (2015), no. 5 235, [ar...

ATLAS Collabo... *and missing tra... detector*, *Phys. R...* Rev.D92,no.5,05...

ATLAS uses ... arch for Dark Matter

ATLAS Collaborati... *missing transverse m...* *Phys.Rev.* **D90** (201...

29th October 2020 | By ATL...

ATLAS Collaboration, G... *energetic jet and large mi... the ATLAS detector*, Eur. Phys. J.C75,no.9,408...

ATLAS Collaborati... *decaying W or Z bos... with the ATLAS det...*

Search for Dire... proton collision...

CMS Collaboration... Published in: *Eur.P...*

...al states with one lepton, ...ns at $\sqrt{s}$= 13 TeV with the

...with a photon ...ATLAS ...n: Phys.

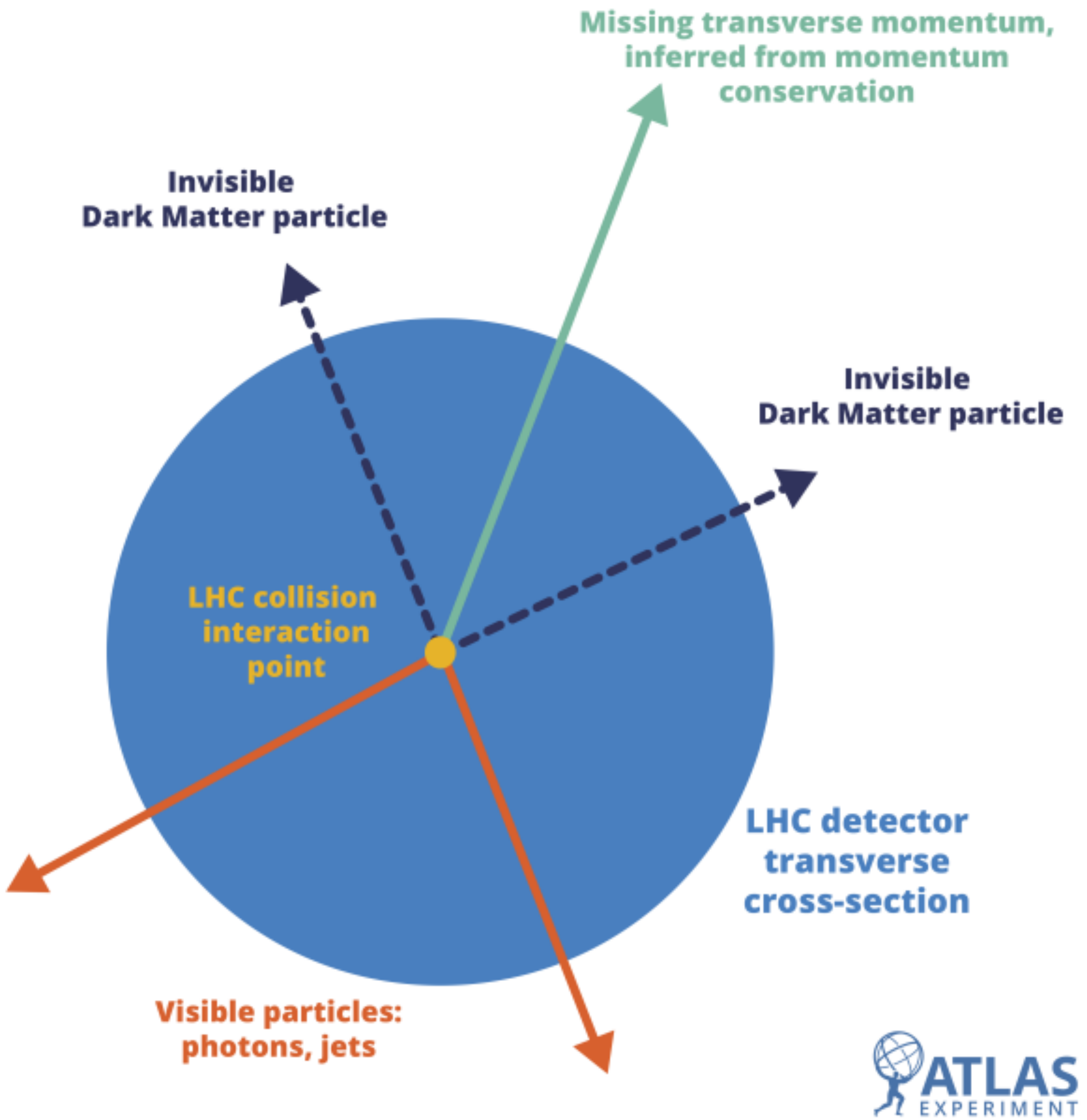
...ed: 13 August 2020

...th a Z boson and ...op quark in the all-... *...AS detector,* ...e momentum final ...AS detector

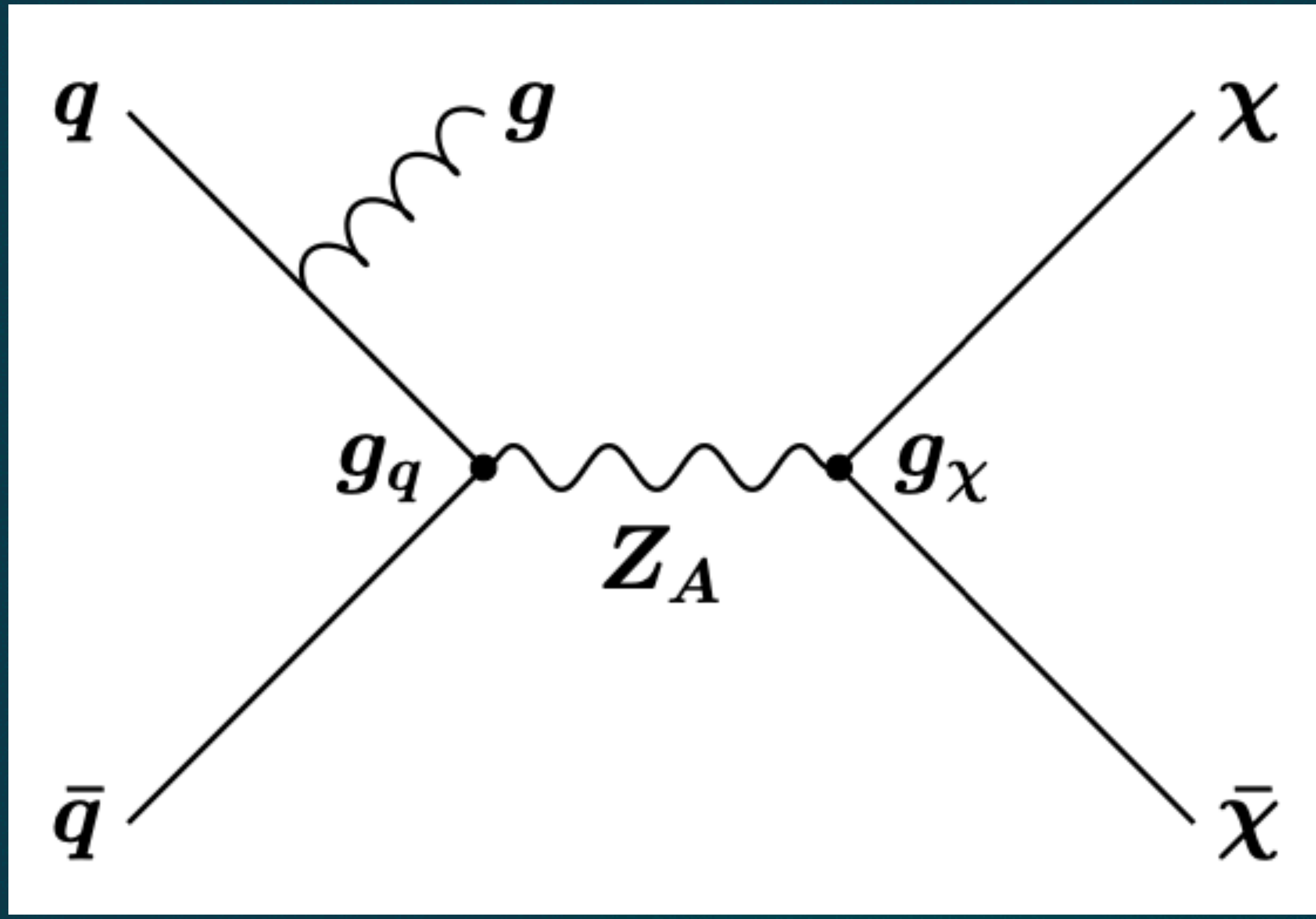
...in proton-

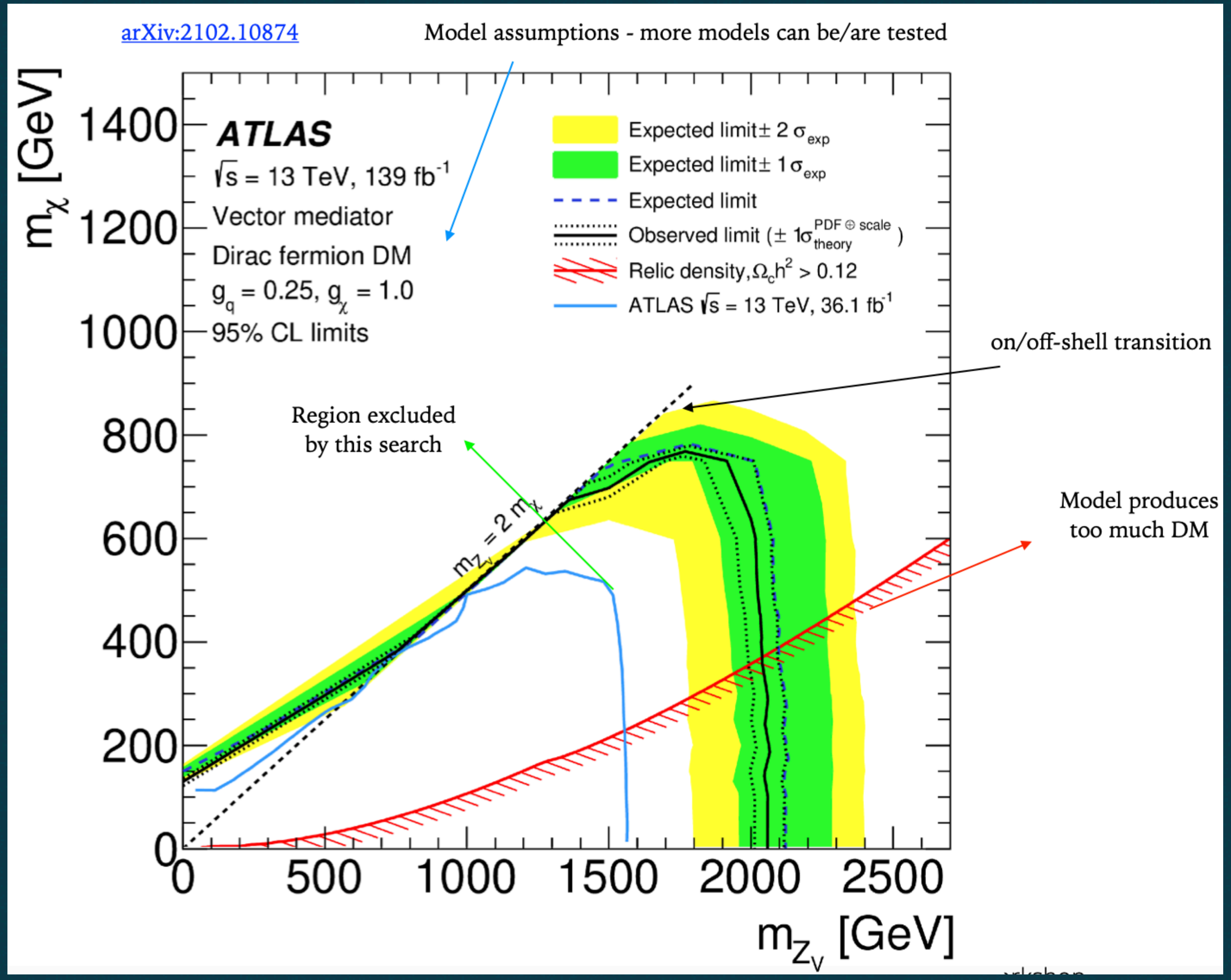
...h a hadronically ...at $\sqrt{s}$ = 8 TeV

...:1309.4017].



WIMPS: Mono-X @ HL-LHC





Current exclusions:
In the region $m_{Z_A} > 2m_\chi$, mediator masses up to about 2.1 TeV are excluded for m_χ= 1 GeV

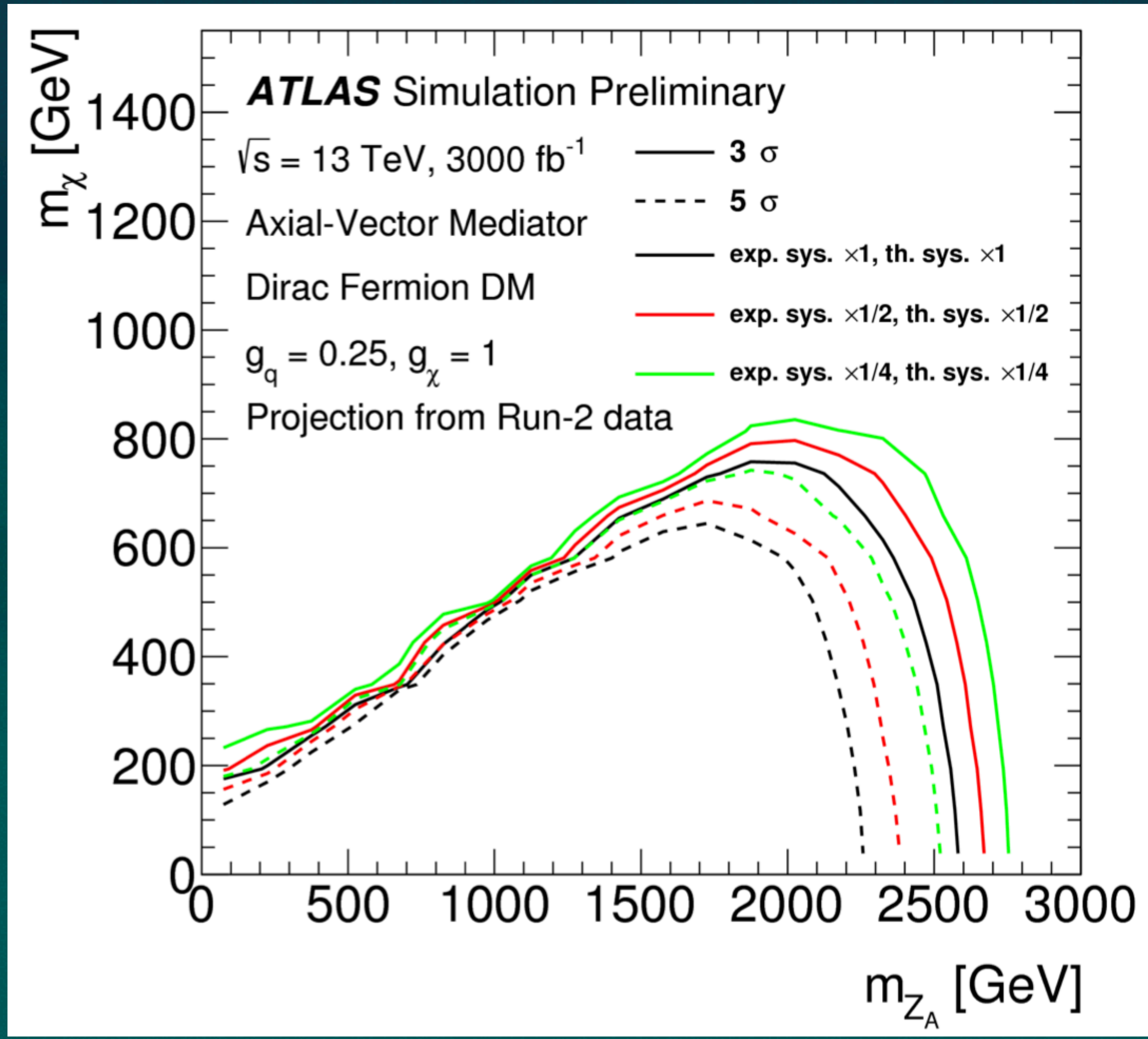
Phys. Rev. D 103, 112006 (2021)

Mono-jet: WIMP pair production with ISR gluon

HL-LHC case study: WIMPs are pair-produced from the s-channel exchange of an axial vector Z_A mediator

Z_A couples to neutralino (χ) and to gluons (g)

HL-LHC discovery potential/exclusion power ⟷



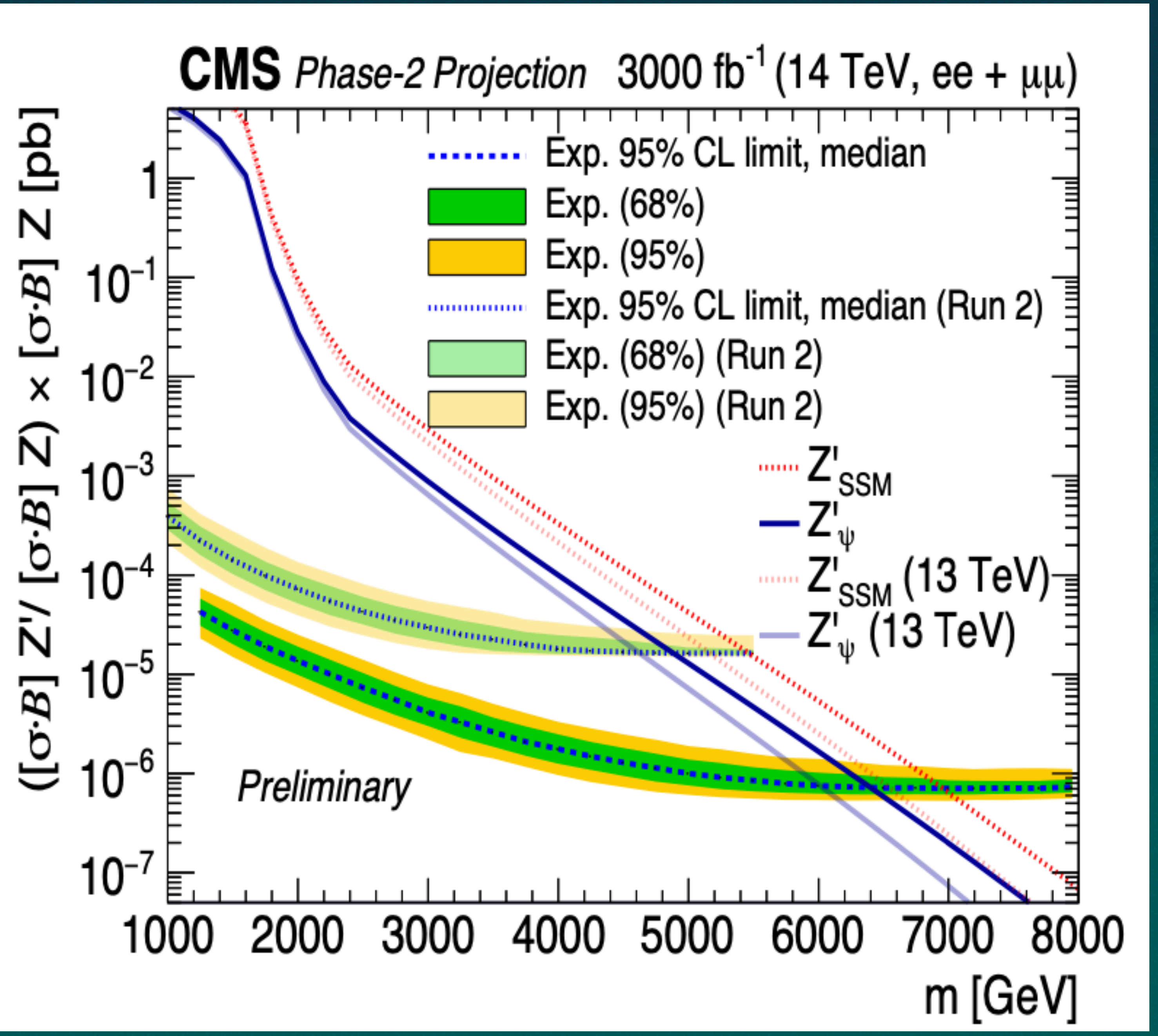
(mono-photon plots in Backup slides)

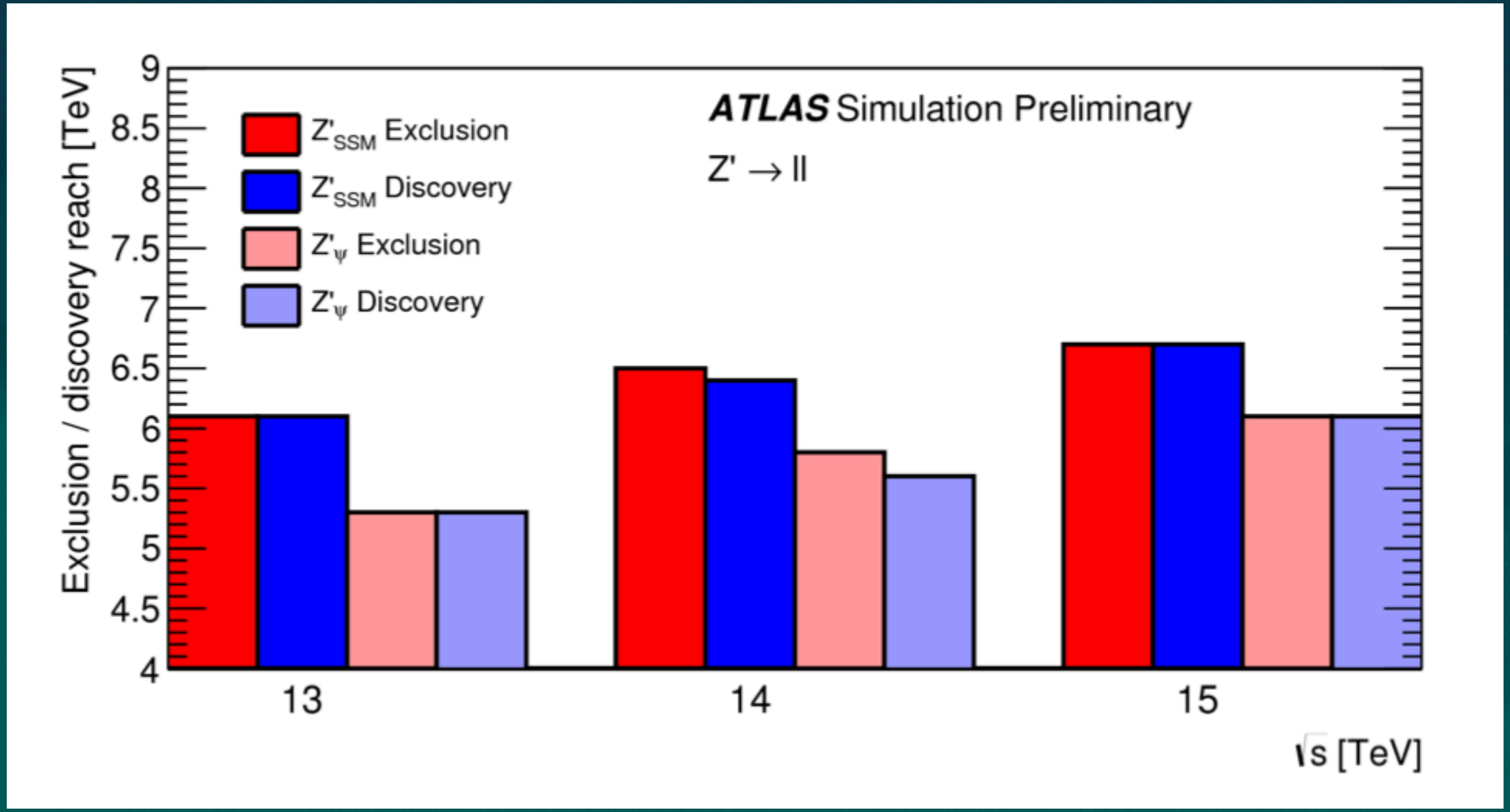
WIMPS: di-lepton resonances @ HL-LHC

Resonance searches usually characterised by production coupling and resonance mass → decay coupling replaced by branching fraction.

Preferred benchmark model for Z′ is the Sequential SM (follows similar coupling pattern as SM Z) or the lepton-specific Z′ that can explain the g-2 anomalies.

HL-LHC case study: Narrow resonance decaying to ee, mm in two models, Z_{SSM} and Z_{ψ} → Dilepton continuum bkg. from EW production via DY lower than Z′ masses → extends the discovery potential of Z_{SSM} to 6.3 TeV.

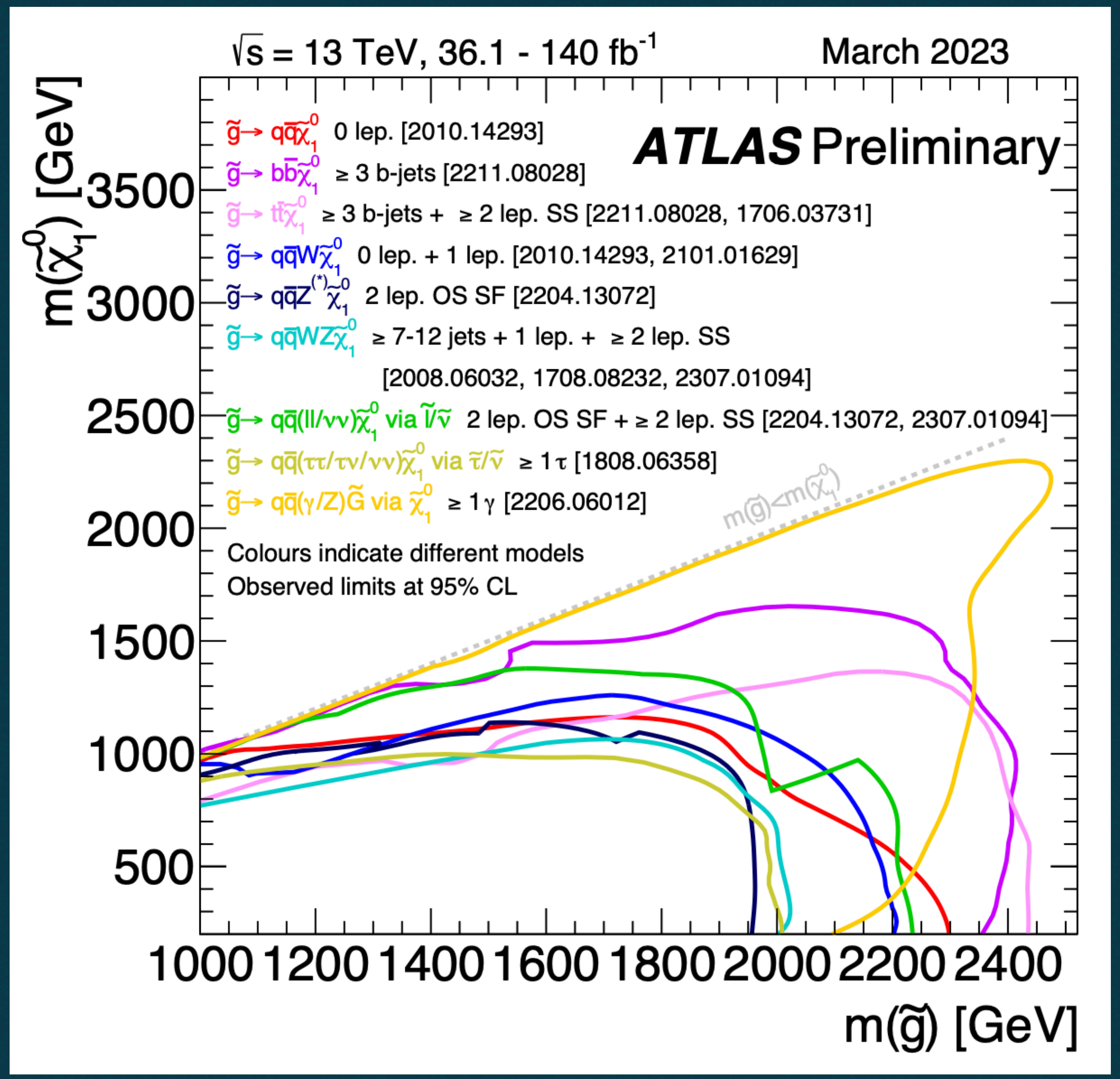




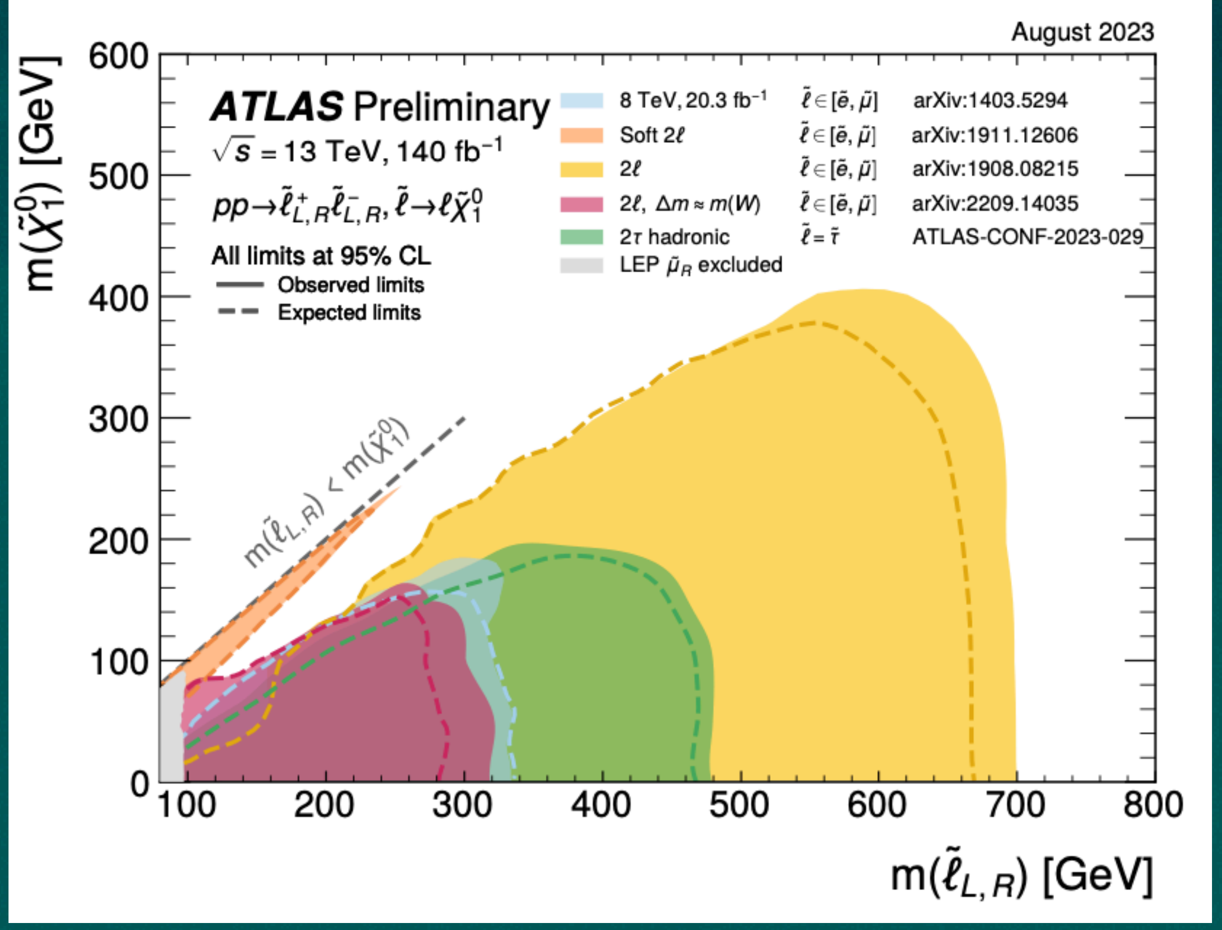
SUSY - what more can be done?

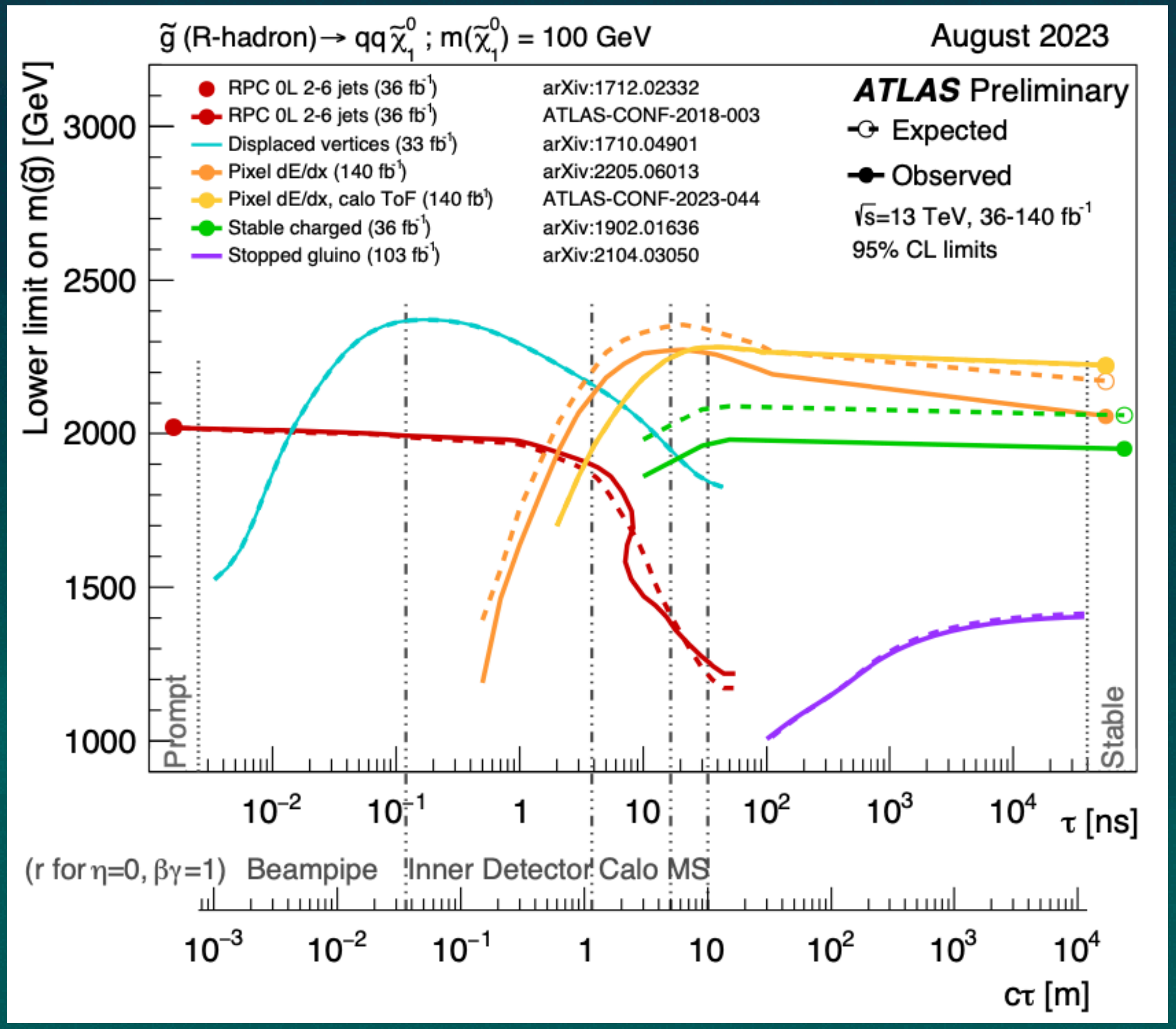
Current collider bounds have excluded most of the natural SUSY parameter space

* Most strongly coupled SUSY models assume existence of discrete R-parity symmetry [even parity for SM, odd parity for SUSY partners] → leads to stability of LSP (neutral & DM candidate) [gluino bounds > 2 TeV]
* RP violation possible (can explain flavor anomalies) → leads to highly hadronic/leptonic decays of heavy coloured SUSY particles [bounds > 1 TeV]
* Weakly interacting SUSY bounds is O(100 GeV) - 1 TeV
* stringent limits for squarks and gluinos with large mass difference b/w relevant states



ATL-PHYS-PUB-2023-025



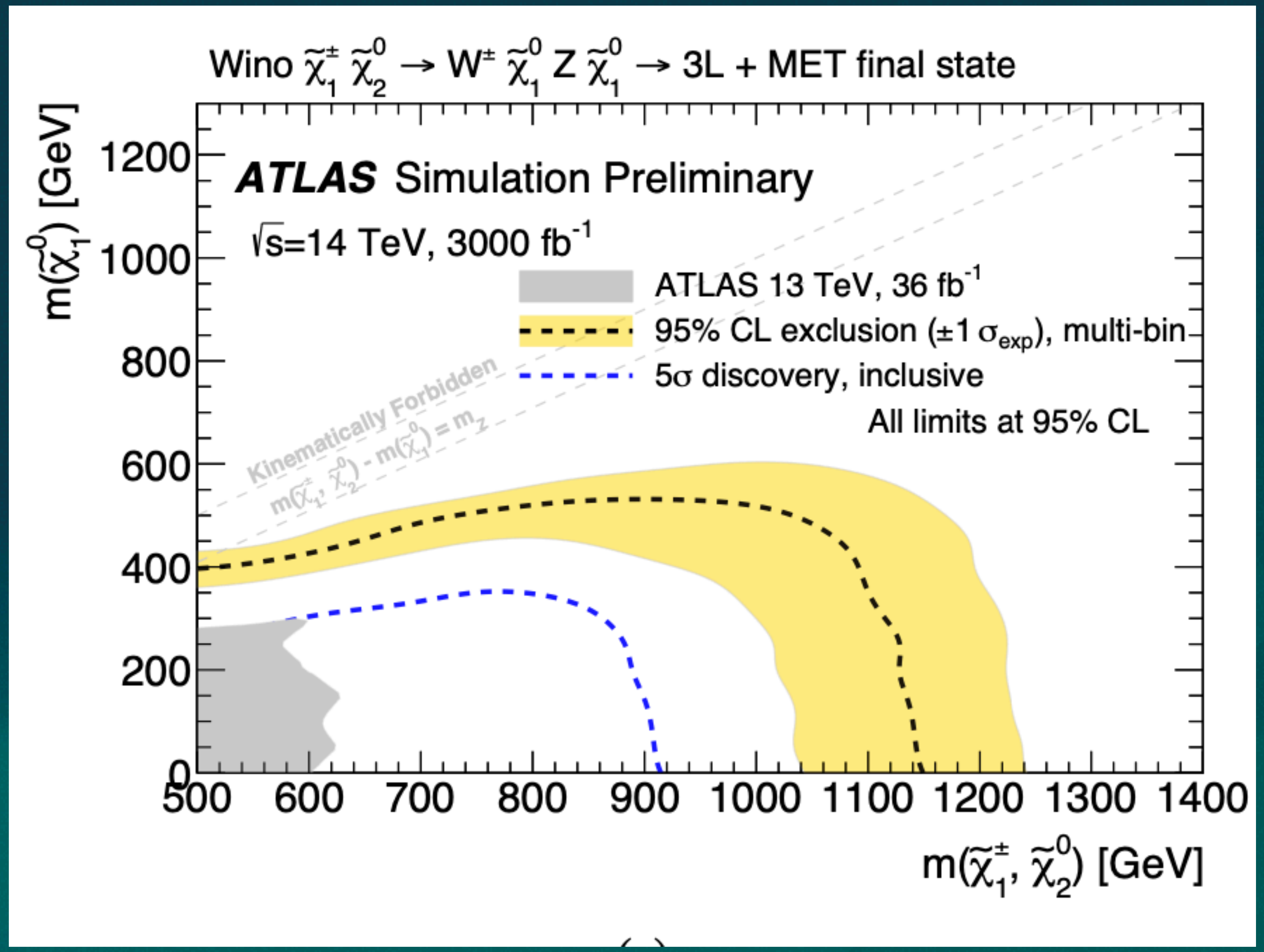


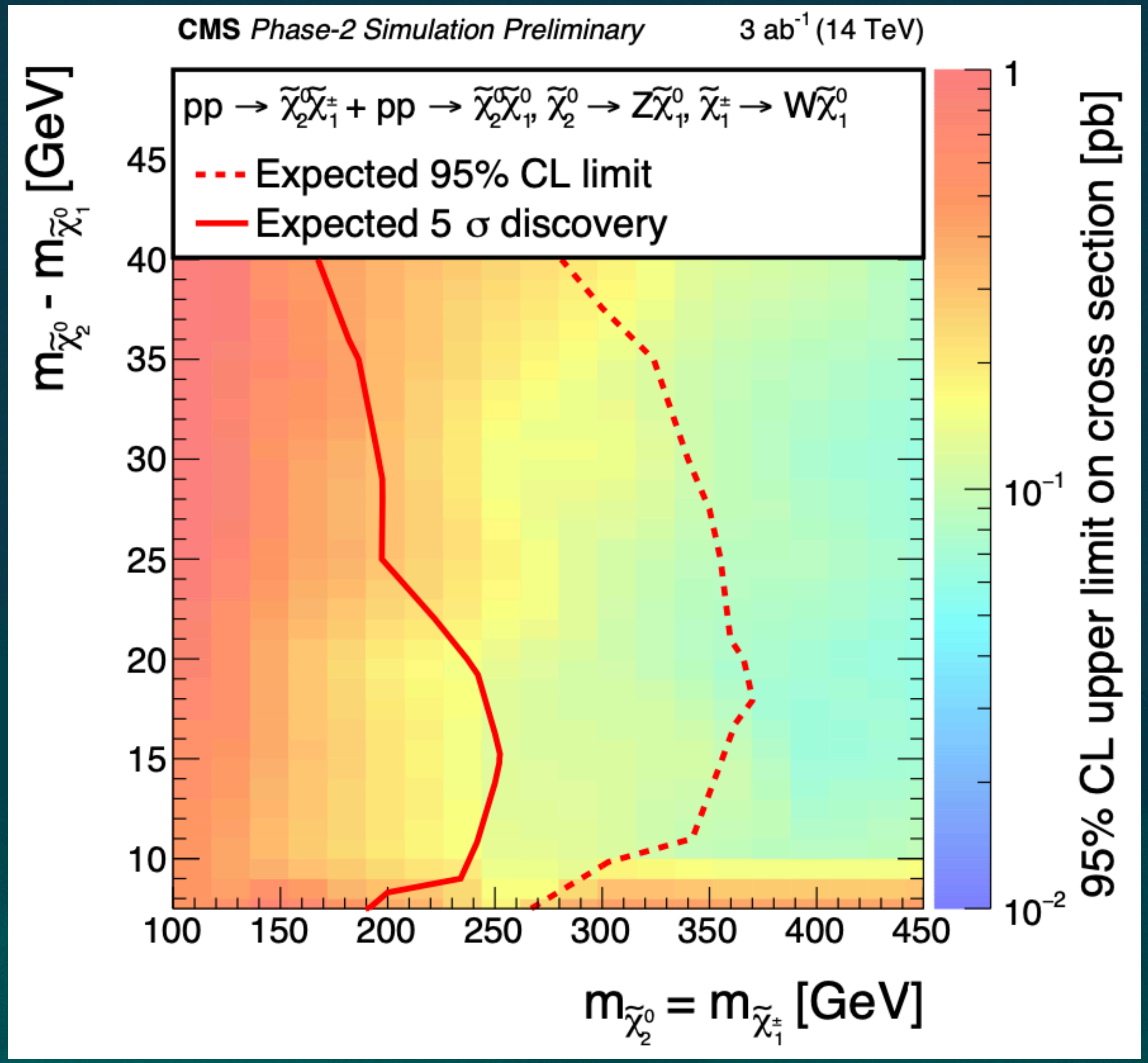
SUSY - what more can be done?

HL-LHC case studies: processes with small cross-sections (EWK sector) and small mass splittings

EWKinos (wino-, bino-, higgsino-like) have masses $\mathcal{O}$(100 GeV) → accessible at HL-LHC

wino-like $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ with WZ decay: discovery potential reaches ~920 GeV

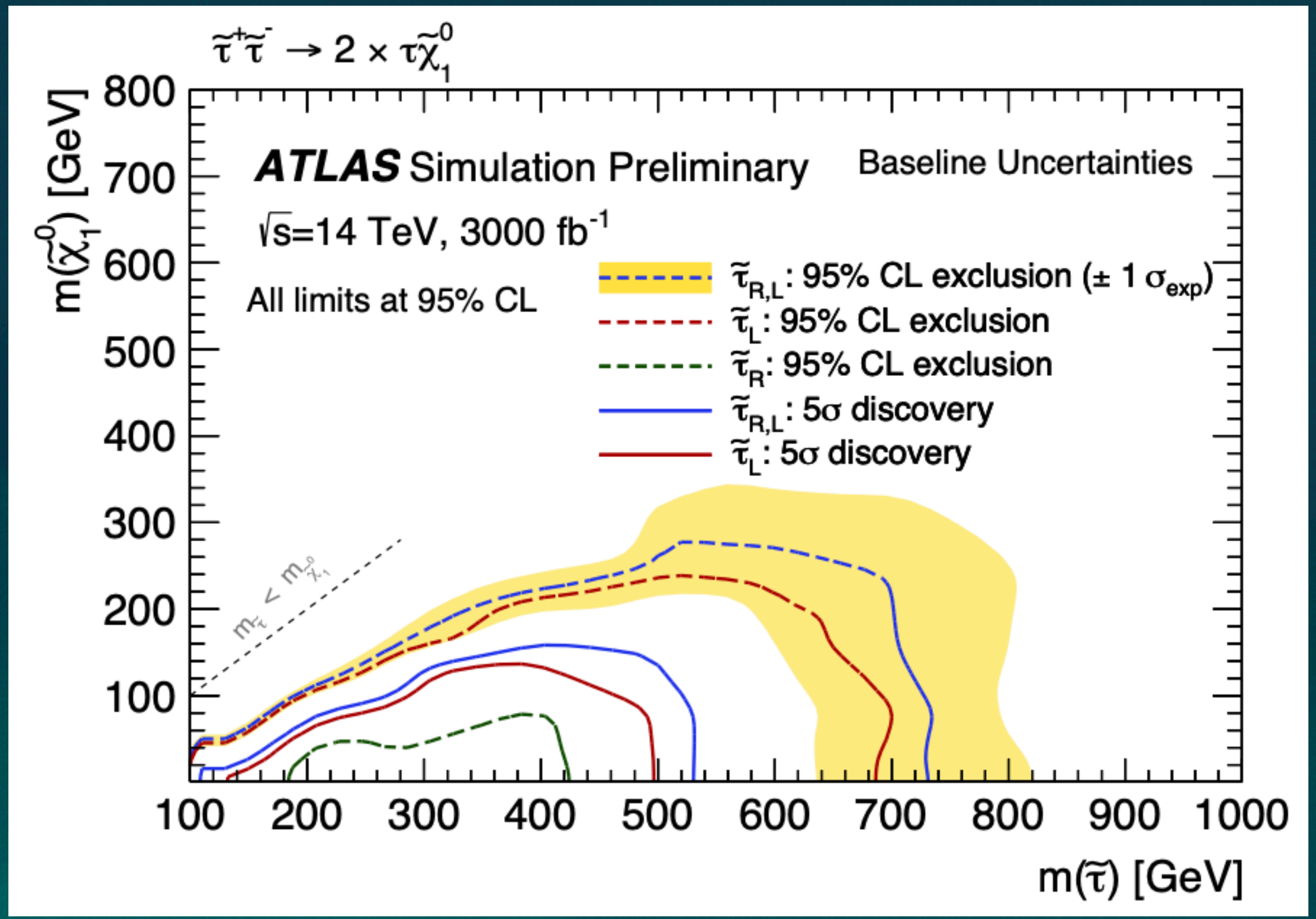




Direct production of higgsino states, with mass degenerate $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$ states:

discovery potential ~ 250 GeV, for 15 GeV mass difference wrt lightest $\tilde{\chi}^0$

Staus can give the correct DM relic density in the $\tilde{\chi}^0 - \tilde{\tau}$ coannihilation region → challenging collider signatures



2HDM+a

2HDM containing an additional pseudoscalar boson which mediates the interactions between the visible and the dark sector

- gauge invariant & renormalisable extension of simplified pseudoscalar model
- DM candidate: singlet under SM gauge group, usually a Dirac fermion
- CP-odd mediator [pseudo scalar to bypass constraints from DD]

FREE PARAMETERS OF THE THEORY:

* masses of the heavy Higgs ($m_A = m_H = m_{H\pm}$)
* mass of pseudo-scalar mediator, ma
* mass of DM particle, m_χ
* sine of mixing angle b/w CP-odd states a & A, $\sin\theta$
* VEV ratio, $\tan\beta$

2HDM+a

FREE PARAMETERS OF THE THEORY:

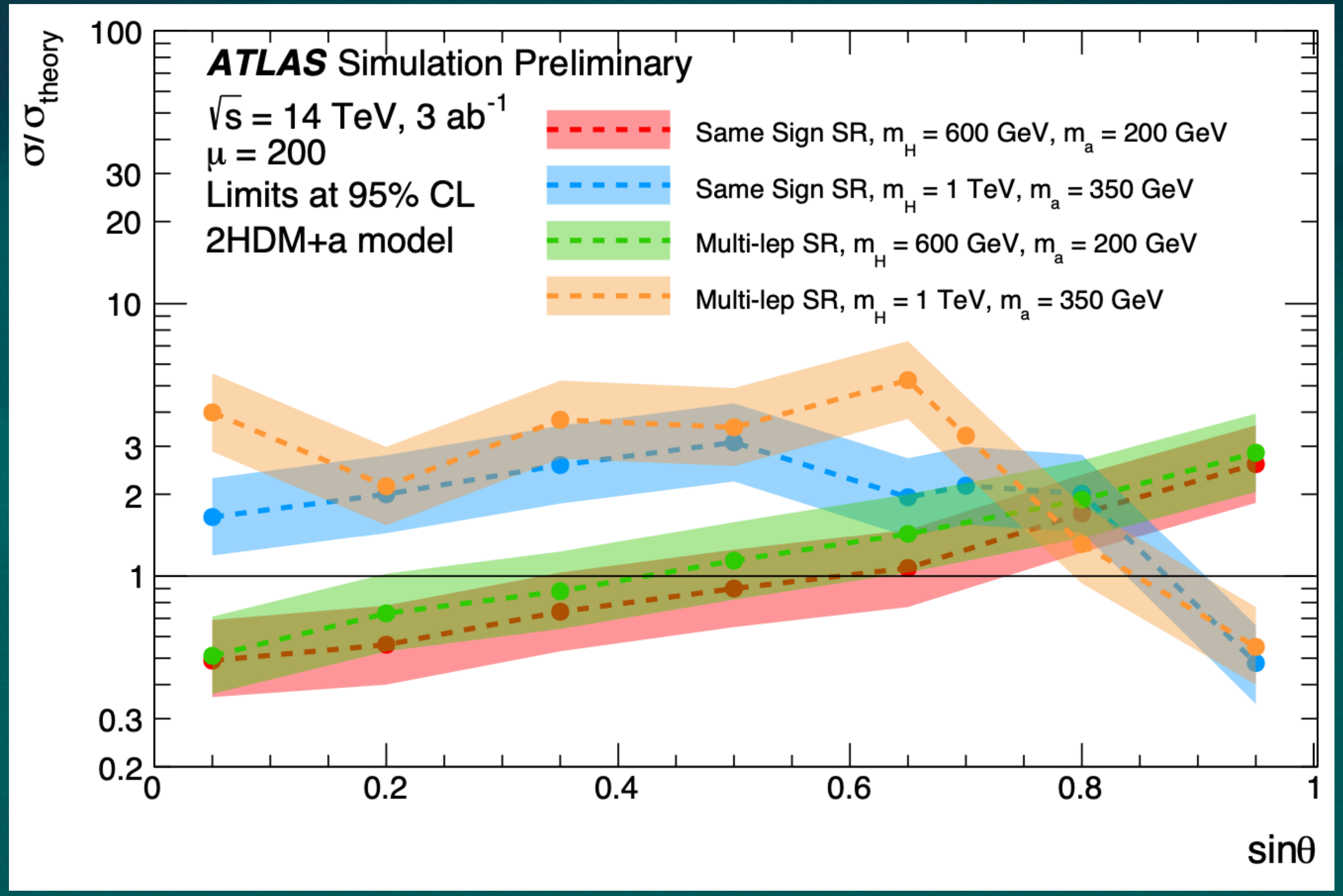
- masses of the heavy Higgs ($m_A = m_H = m_{H\pm}$)
- mass of pseudo-scalar mediator, ma
- sine of mixing angle b/w CP-odd states a & A, $\sin\theta$

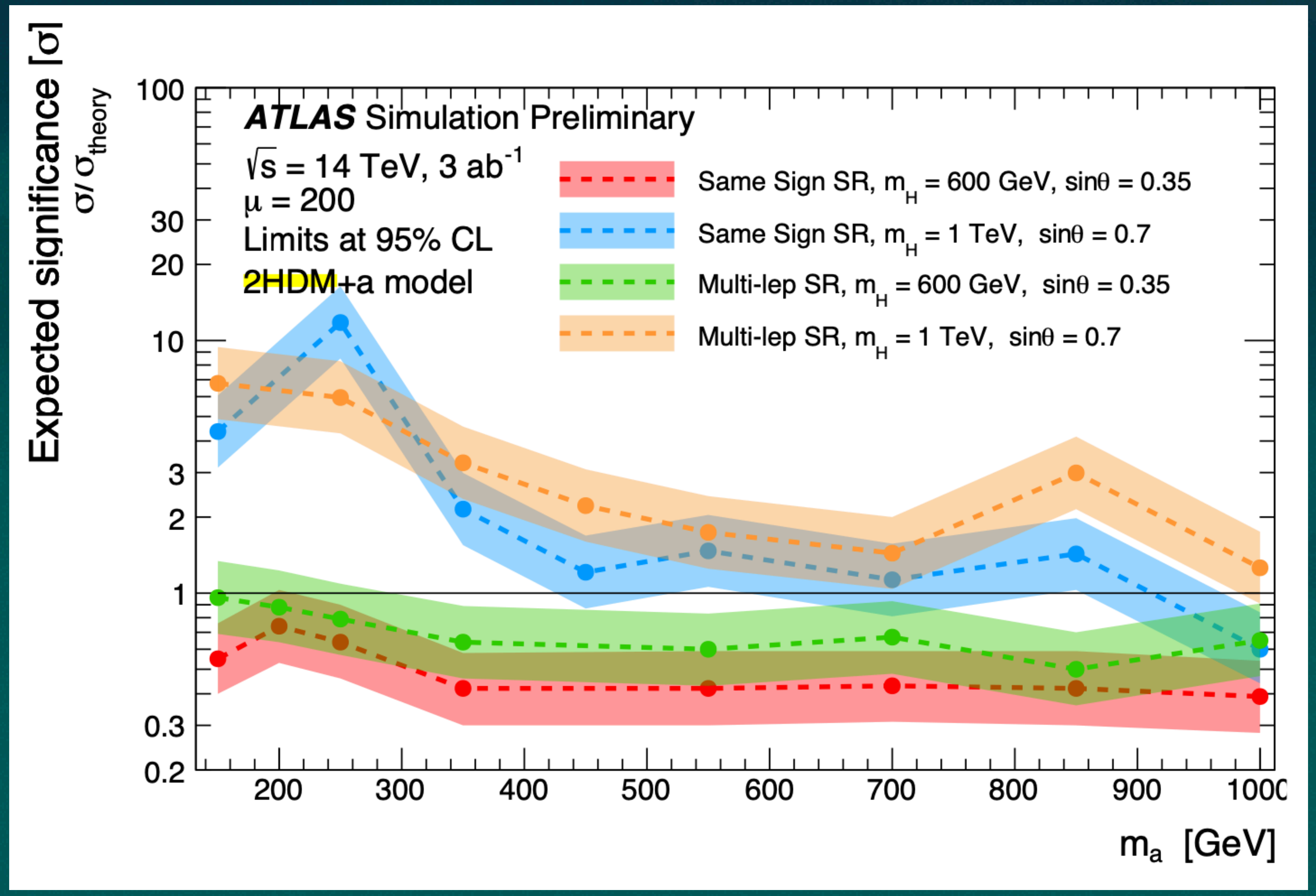
HL-LHC case study: 4 benchmark models with different light/heavy CP-odd/even m_H, with different θ.

Study targets models decaying into four top-quarks.

Search targets final state with 2 same-charge l or $\geq$ 3 l, as well as at least 3 b-tagged jets.

Exclusions: For $\sin\theta$ < 0.35, $ma \lesssim$ 1 TeV expected to be excluded for mH = 600 GeV.
3σ is expected if mH = 600 GeV and sin θ = 0.35 (benchmark is expected to be excluded for all pseudoscalar masses and for sin θ < 0.35 if ma = 200 GeV)
sin θ > 0.95 also expected to be excluded for ma = 350 GeV, mH = 1 TeV. Finally, sin θ < 0.4 is excluded for mH =600GeV,ma =200GeV.





Long-lived particles

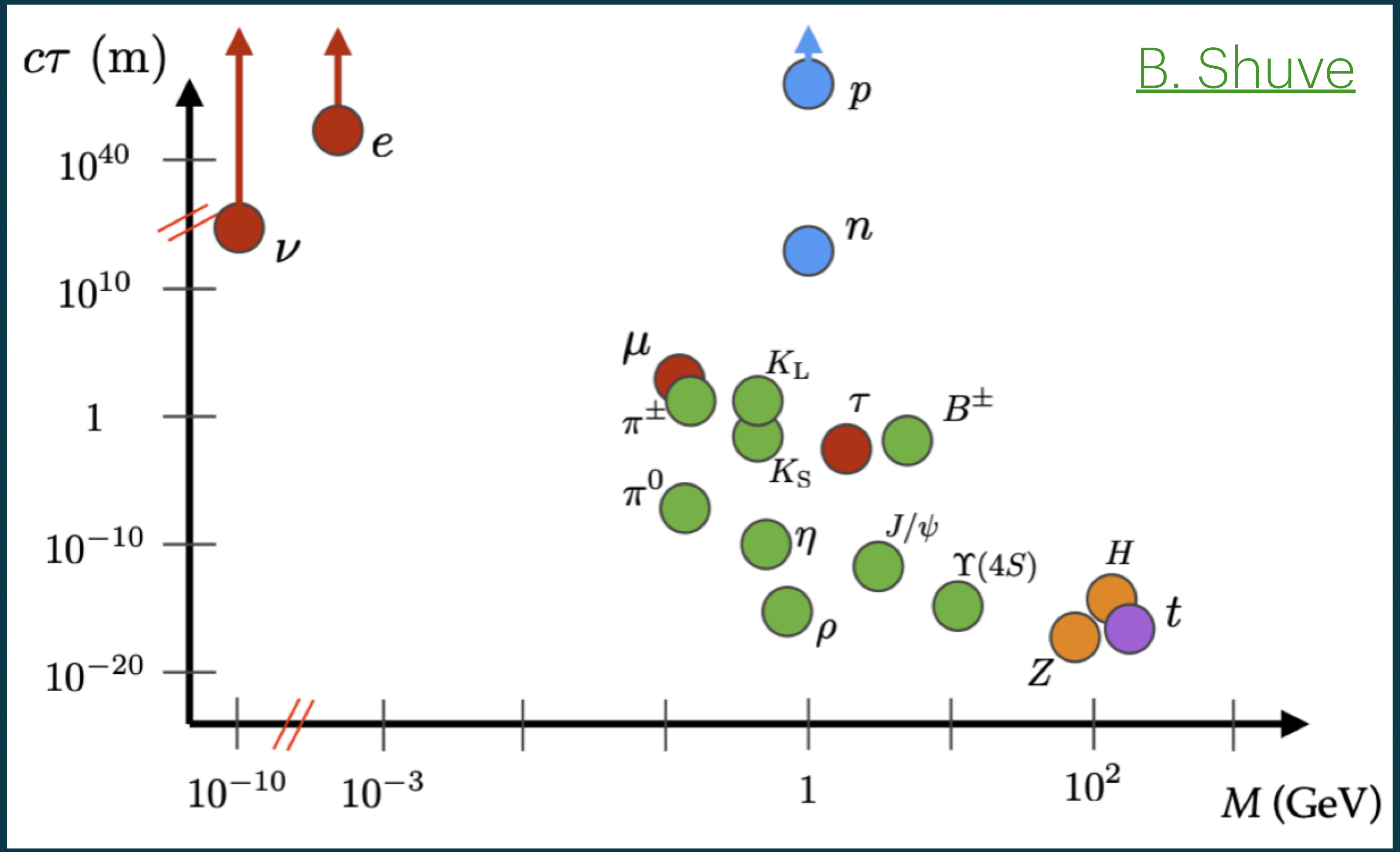
Long-lived particles exist because SM is equipped with approximate symmetry (flavor) and hierarchy of scales (QCD vs electroweak), → some particles are more long-lived than others

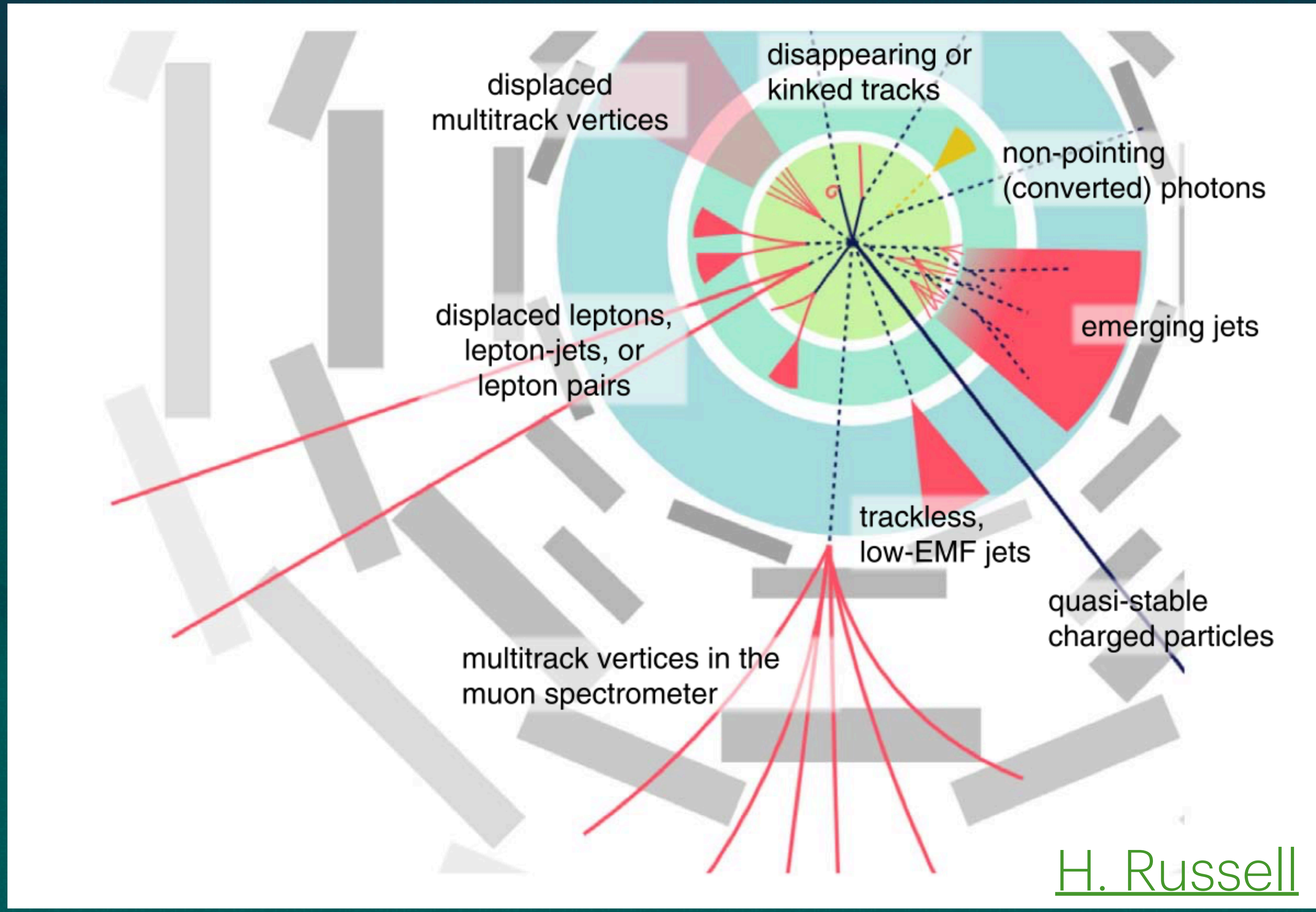
Any hidden sector with more than one particle in it generically contains unstable particles → often long-lived due to tiny SM portal couplings being the only decay (and collider production) channel

Same kinds of models make DM or LLPs (depending on the stabilising symmetry being exact or slightly broken)

SUSY & DM models with compressed mass spectra generate long lifetimes for charged particles [O(ns)]

Different possible collider signatures ⟷



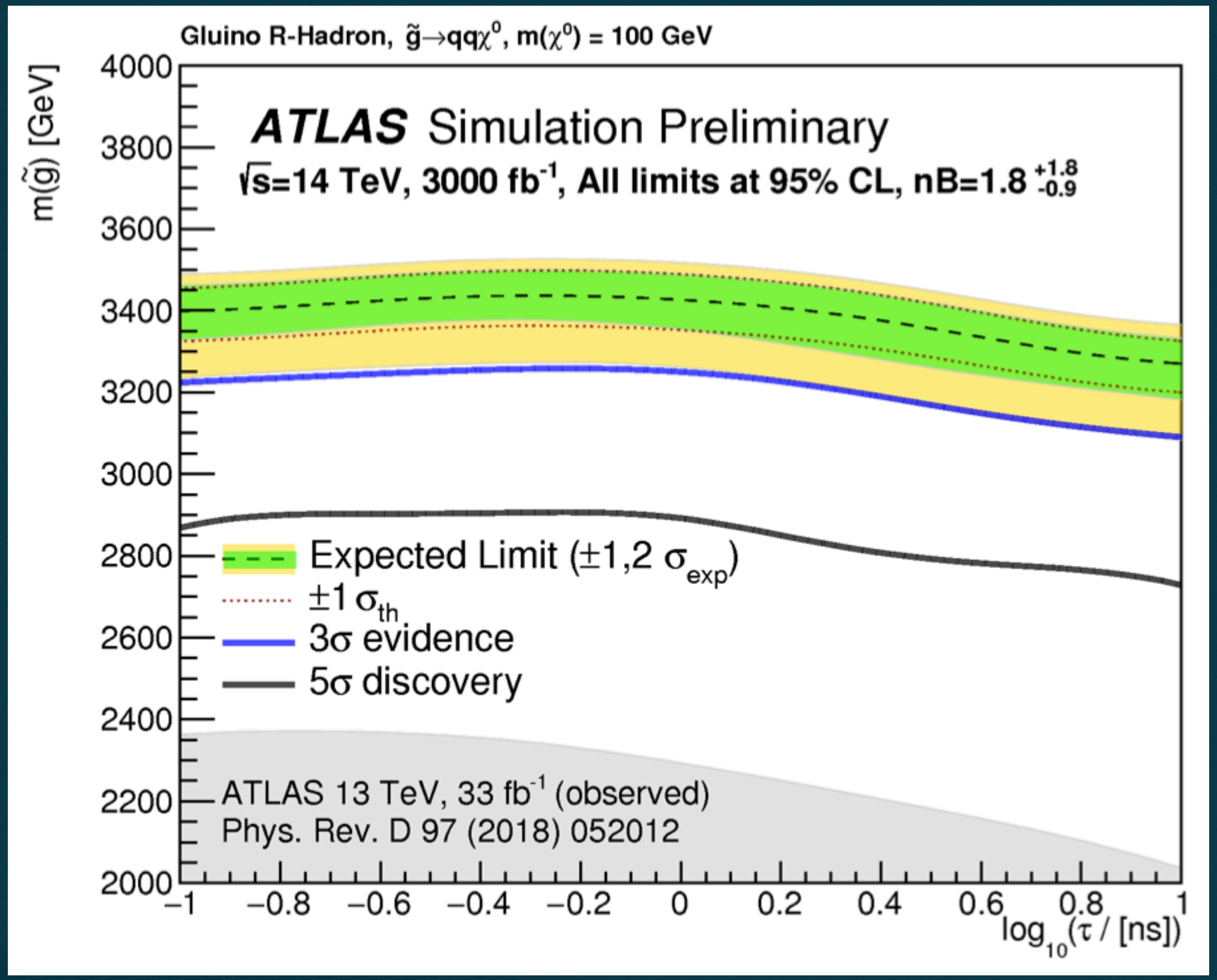


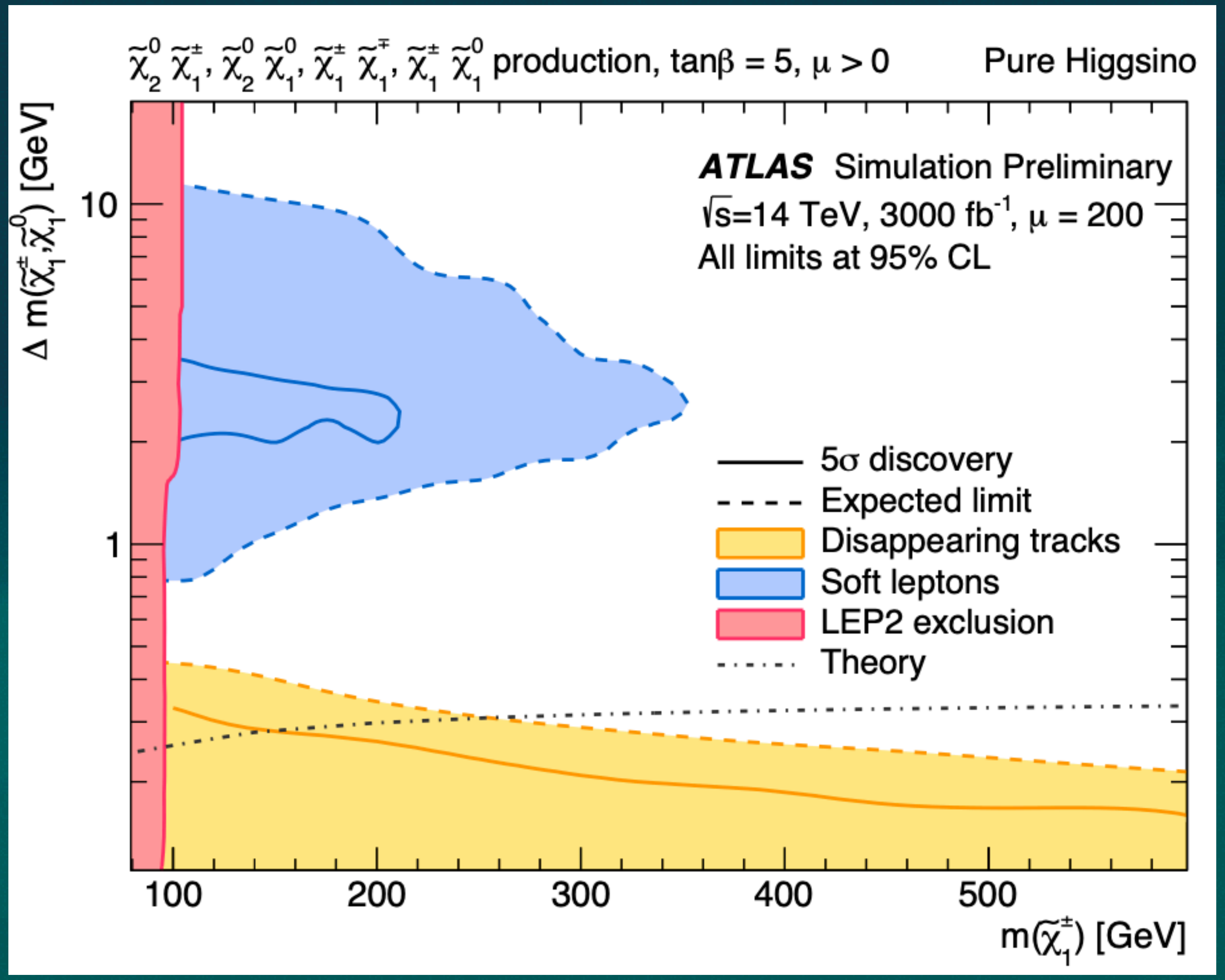
Long-lived particles & SUSY

HL-LHC Case study:

LLP decaying within tracking volume → signature of displaced vertex and MET (long-lived gluinos decaying to SM quarks and neutralino used as a benchmark)

Full silicon inner tracker (ITk) for ATLAS increases search sensitivity: potential to discover R-hadrons with lifetimes from 0.1 to 10 ns with masses up to 2.8 TeV





Prospective studies for disappearing tracks searches using simplified models of $\tilde{\chi}_1^\pm$ production → factor of 2-3 more sensitive than Run-2 mass reach

(Long-lived) Dark-photons

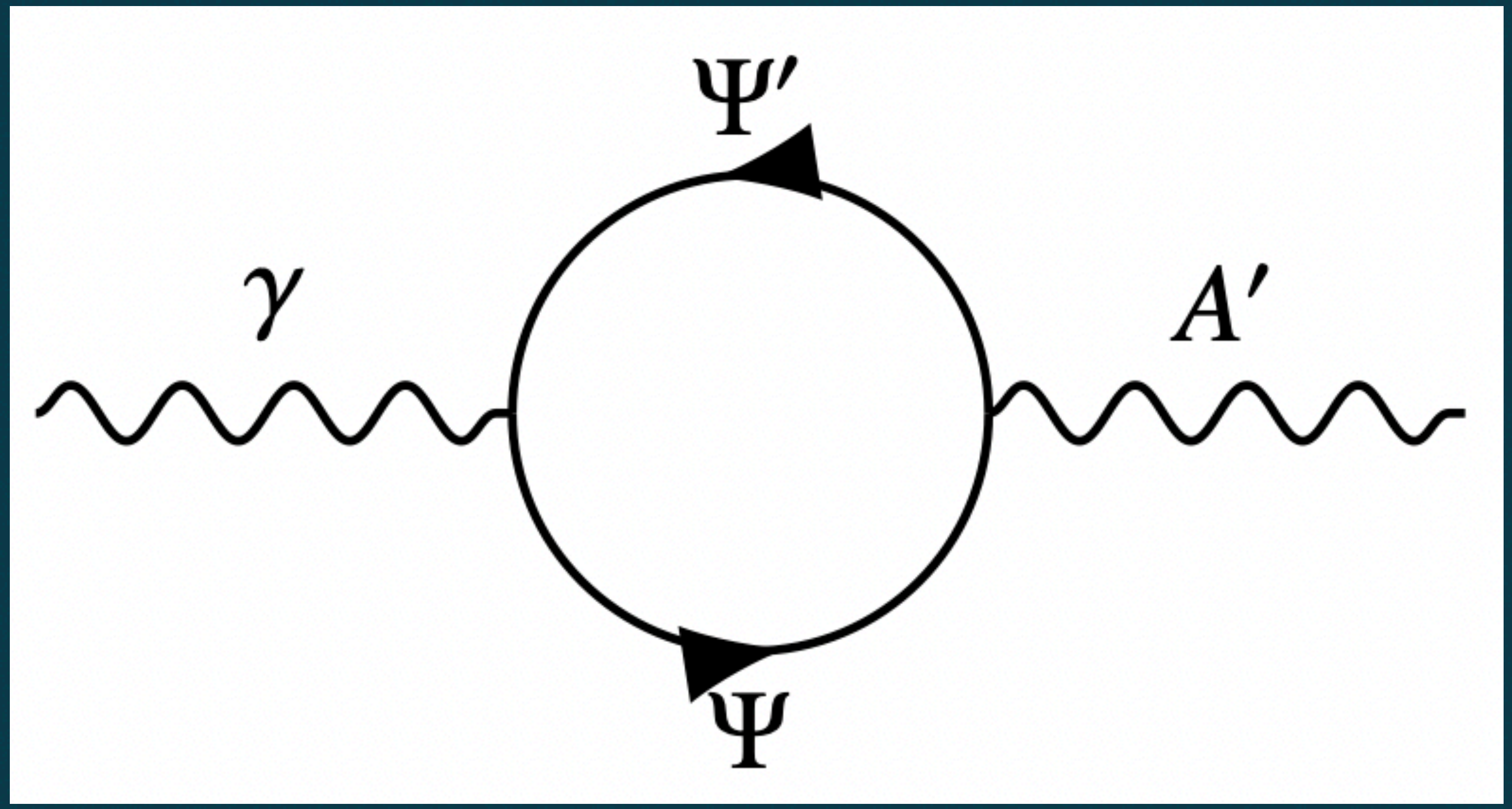
Compelling scenario in search for dark forces and other portals between the visible and dark sectors is that of the dark photon A′

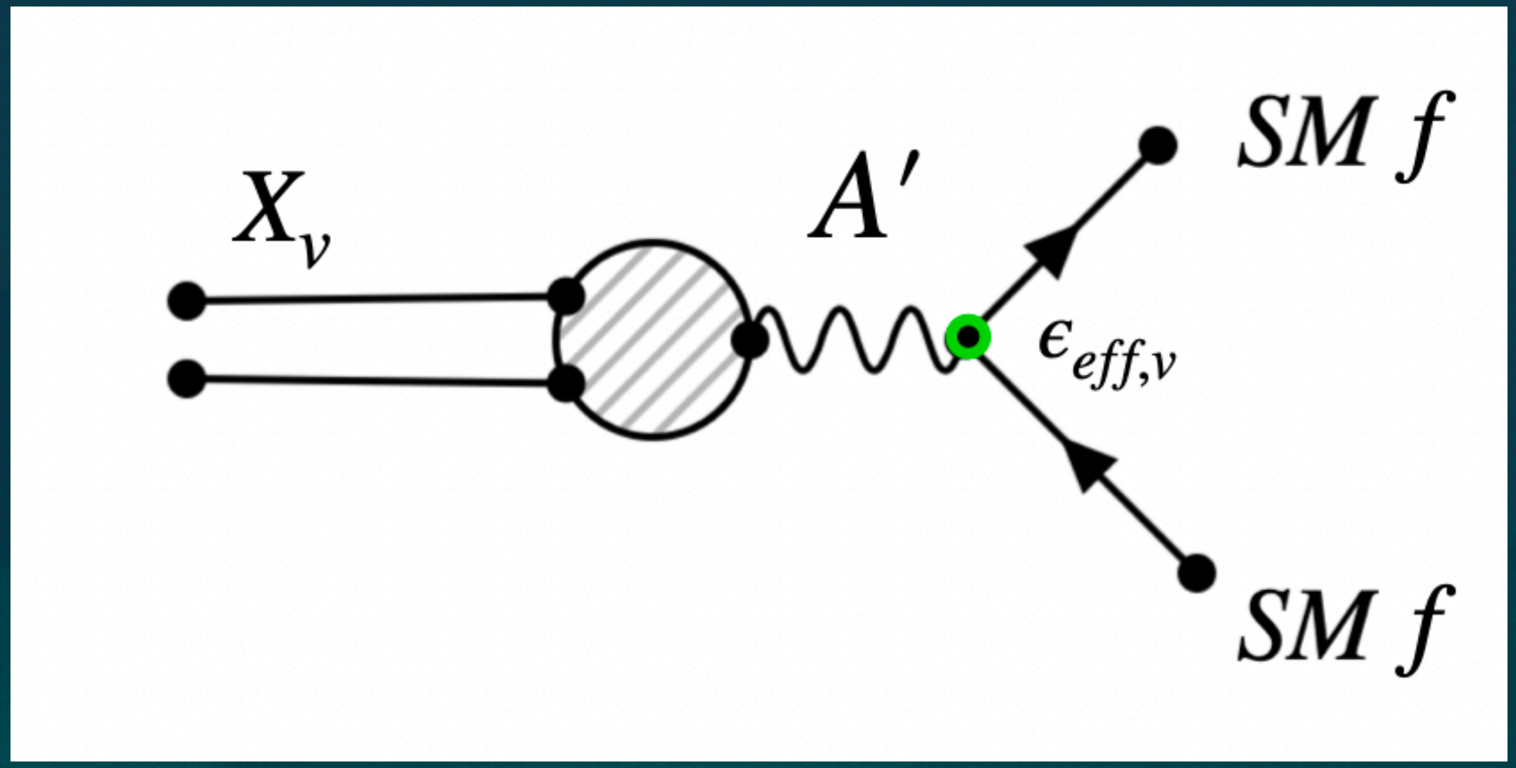
Vector Portal: Add a U(1)′ whose massive "dark" gauge boson mixes kinetically with SM photon

Higgs Portal: Add dark scalar singlet that spontaneously breaks U(1)′ and mixes with SM Higgs

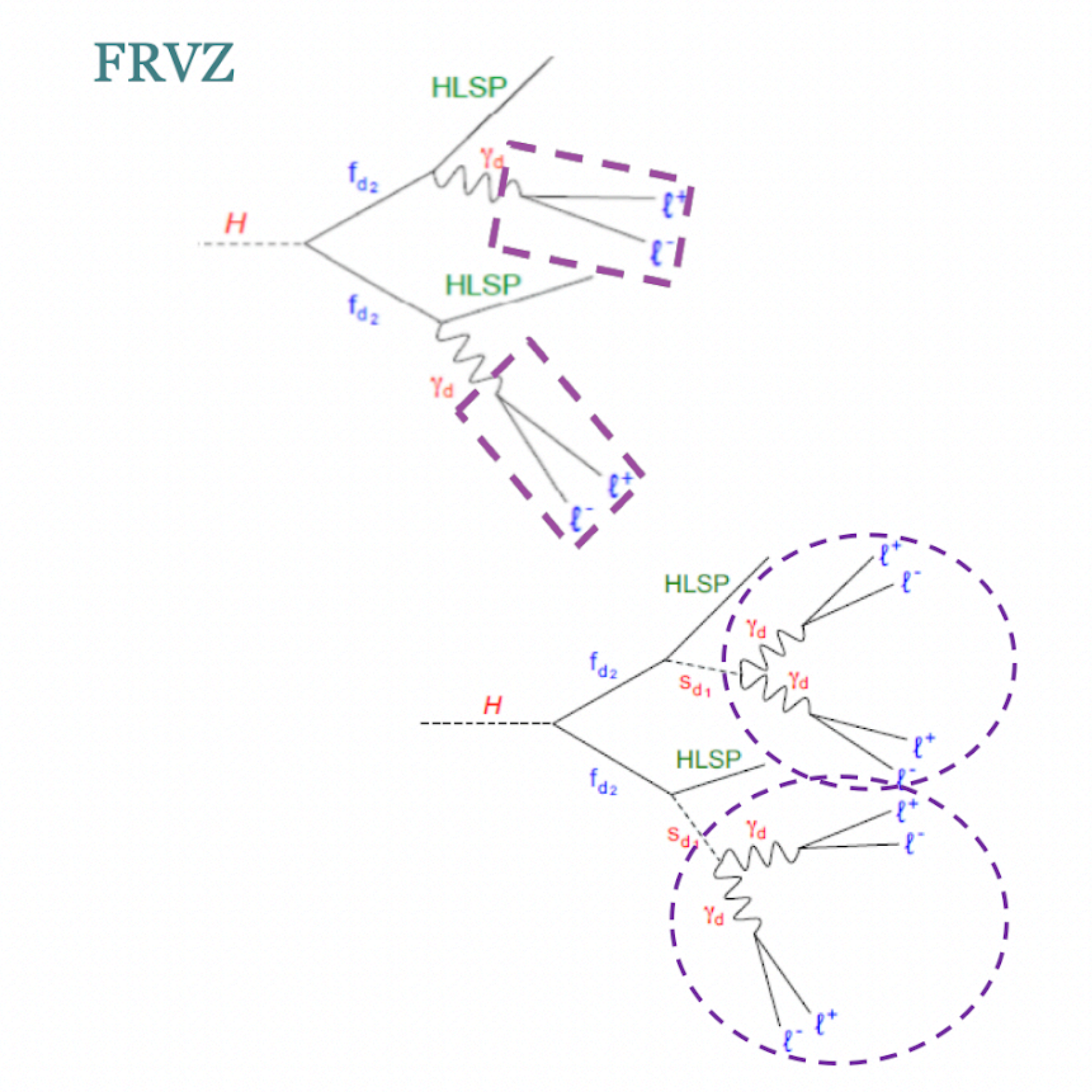
Hidden Valley: sector of dark particles, interacting amongst themselves

- Lowest particle in Valley forced to decay to SM due to mass gap or symmetry
- "Portal" coupling both to SM and HV operators, can be A′





(Long-lived) Dark-photons

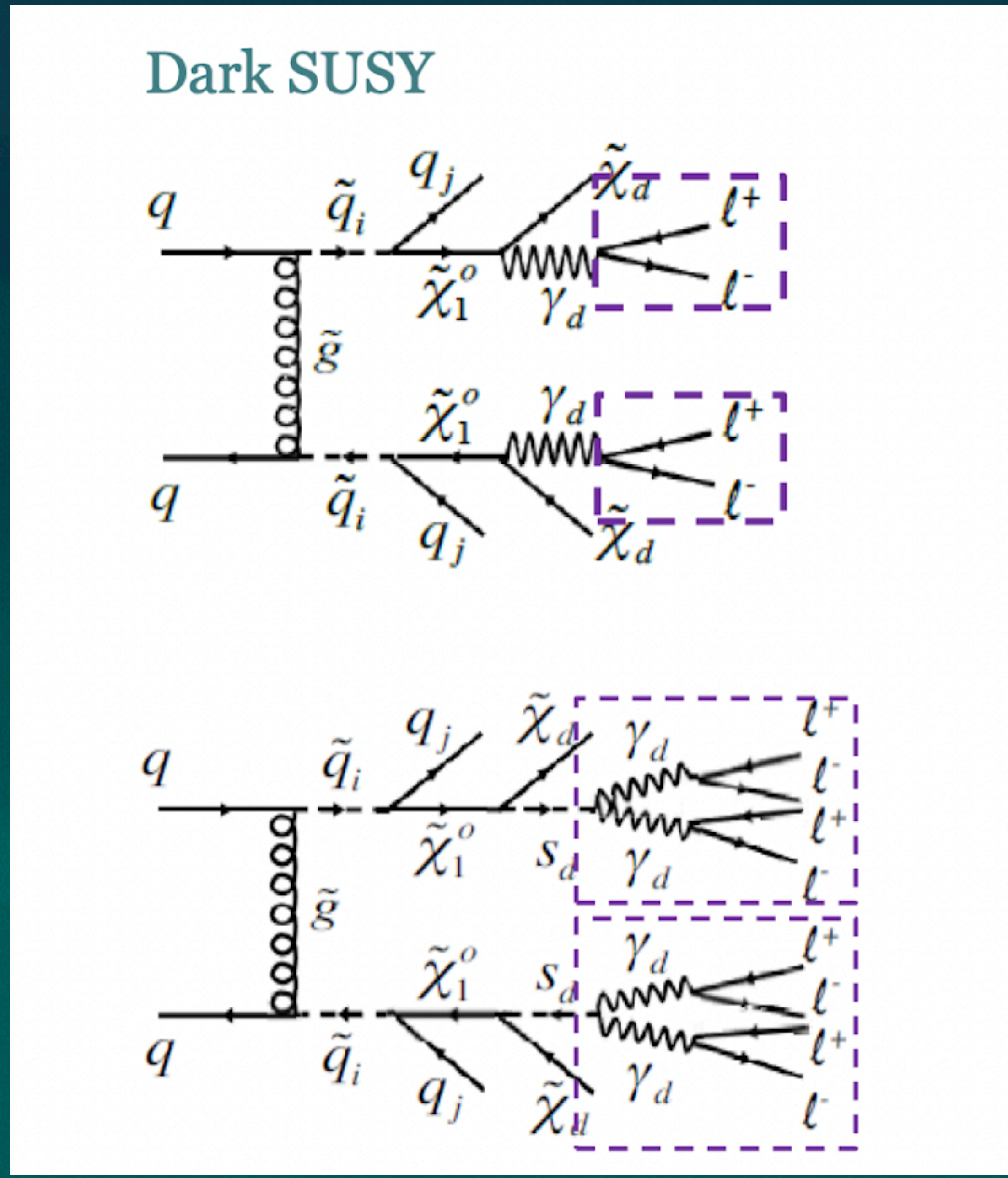


Falkowsky-Ruderman-Volansky-Zupan model:

Pair of dark fermions produced in the Higgs boson decay

dark fermion decays in turn to a dark photon + a lighter dark fermion assumed to be the Hidden Lightest Stable Particle (HLSP).

dark photon (vector mediator) mixes kinetically with the SM photon and decays to leptons or light hadrons.



Dark SUSY:

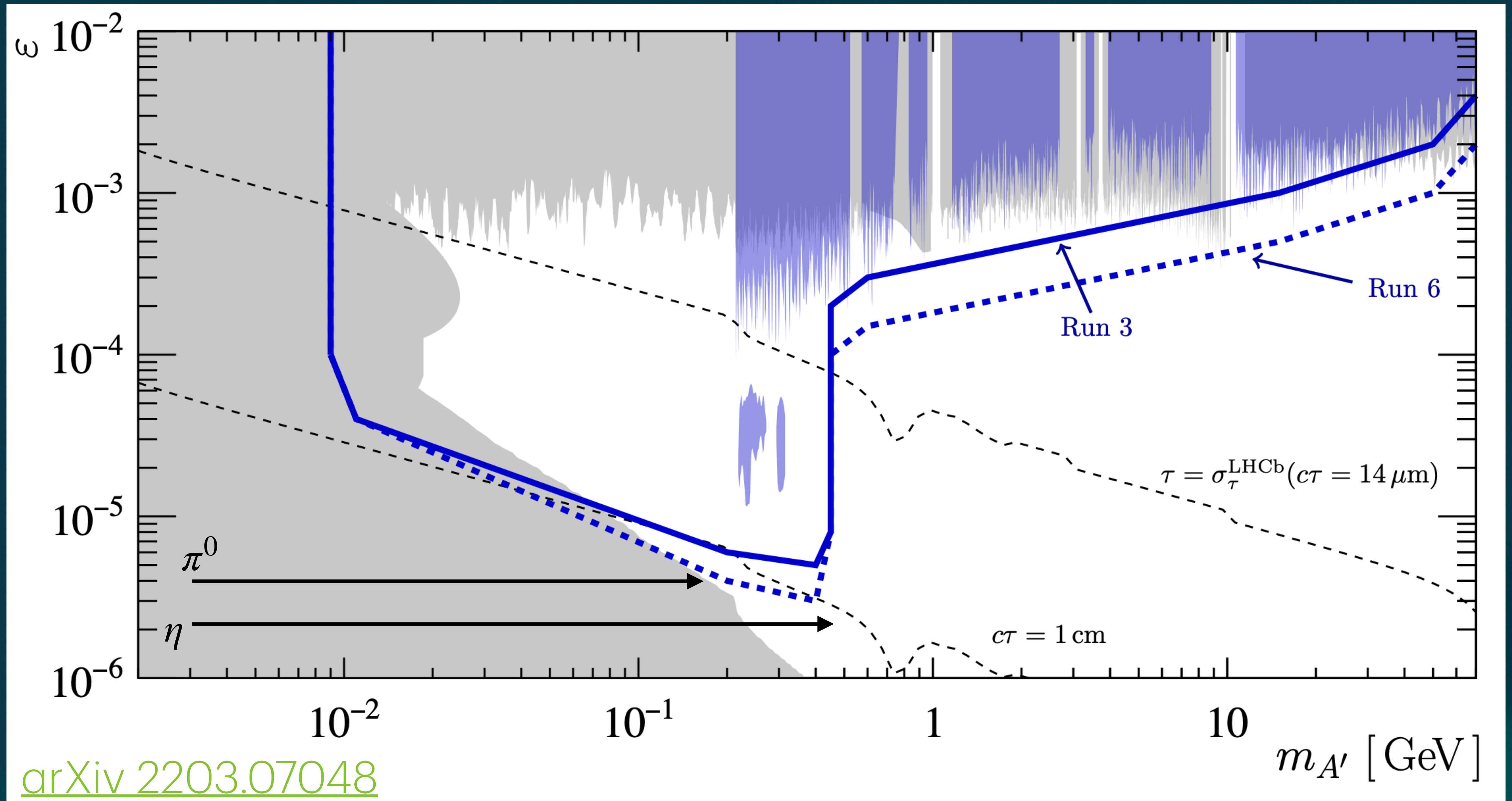
Neutralino → dark photon and susy DM, and dark photon decaying to pair of leptons

Neutralino → susy DM, and pair of dark photons decaying to pair of leptons

Can be prompt or displaced (long-lived)

(Long-lived) Dark-photons

HL-LHC Case study: LHCb focuses mainly on light dark photons, dark scalar and ALPs (in backup!) → dark photons in (Run-3 &) HL-LHC gain from new NN-based PID on GPUs deployed recently [triggerless readout enabled by Allen (GPU HLT)] → not well reflected on these projections plots [quantatitive estimate pending]



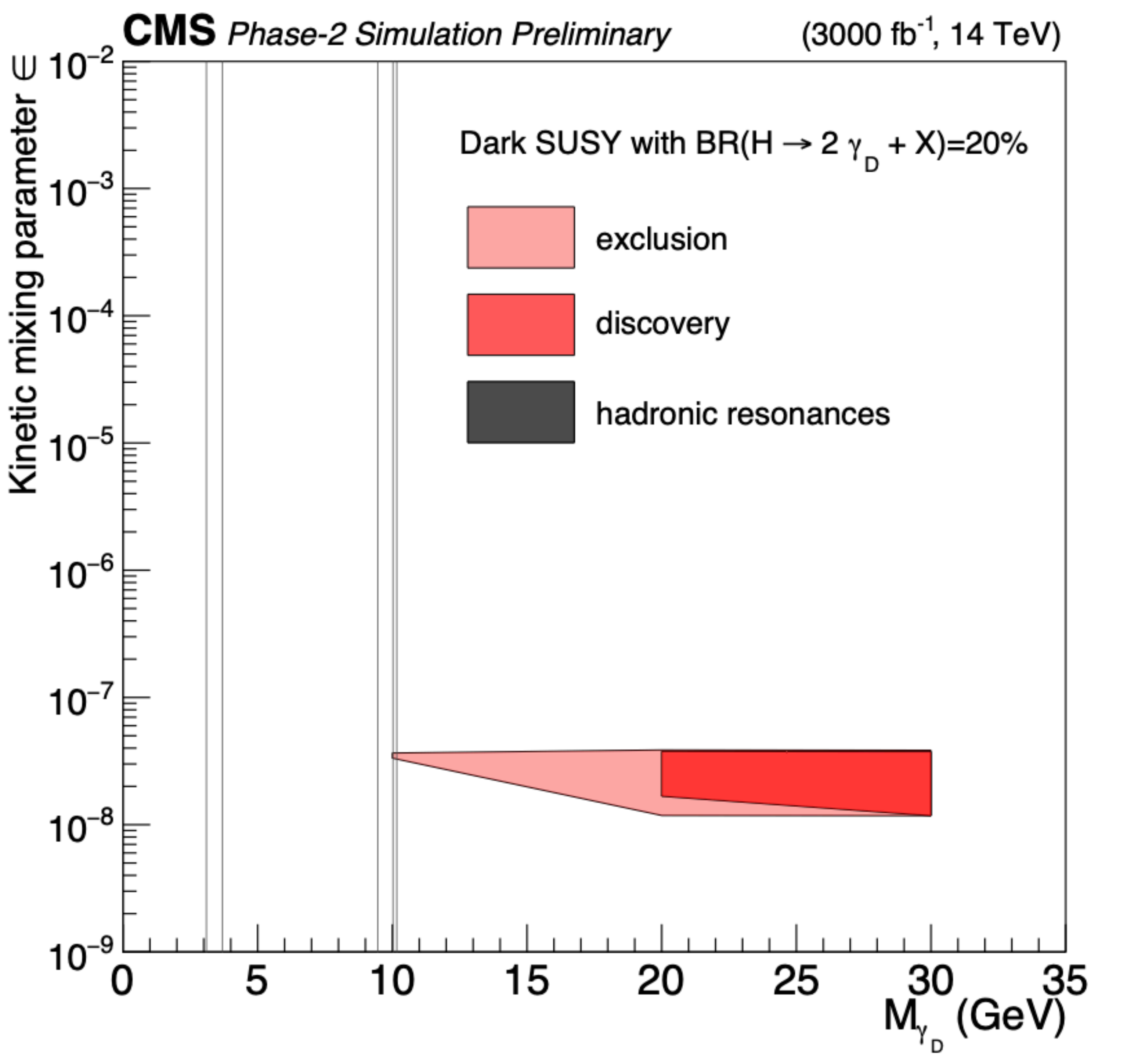
arXiv 2203.07048

$A' \to \mu^+\mu^-$

$D^{*0} \to D^0 A', \quad A' \to e^+e^-$

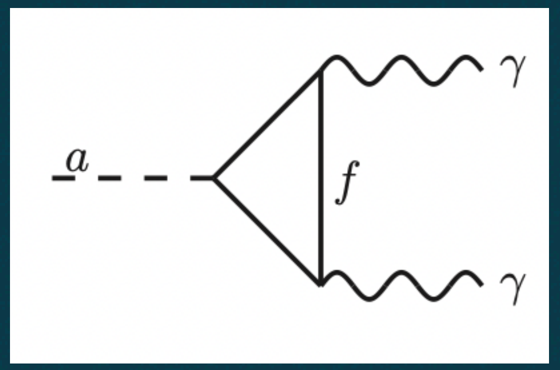
$\pi^0 \to e^+e^-\gamma$ and $\eta \to e^+e^-\gamma$ (arrows)

The mixing term, ϵ, can be interpreted as the ratio of the dark force strength to the EM force strength → long γ_d lifetimes = small values of ϵ



HL-LHC Case study: The CMS case study relies on the displaced standalone algorithm (DSA) that is designed to identify highly displaced muons → makes the lower ϵ ranges accessible.

ALPs

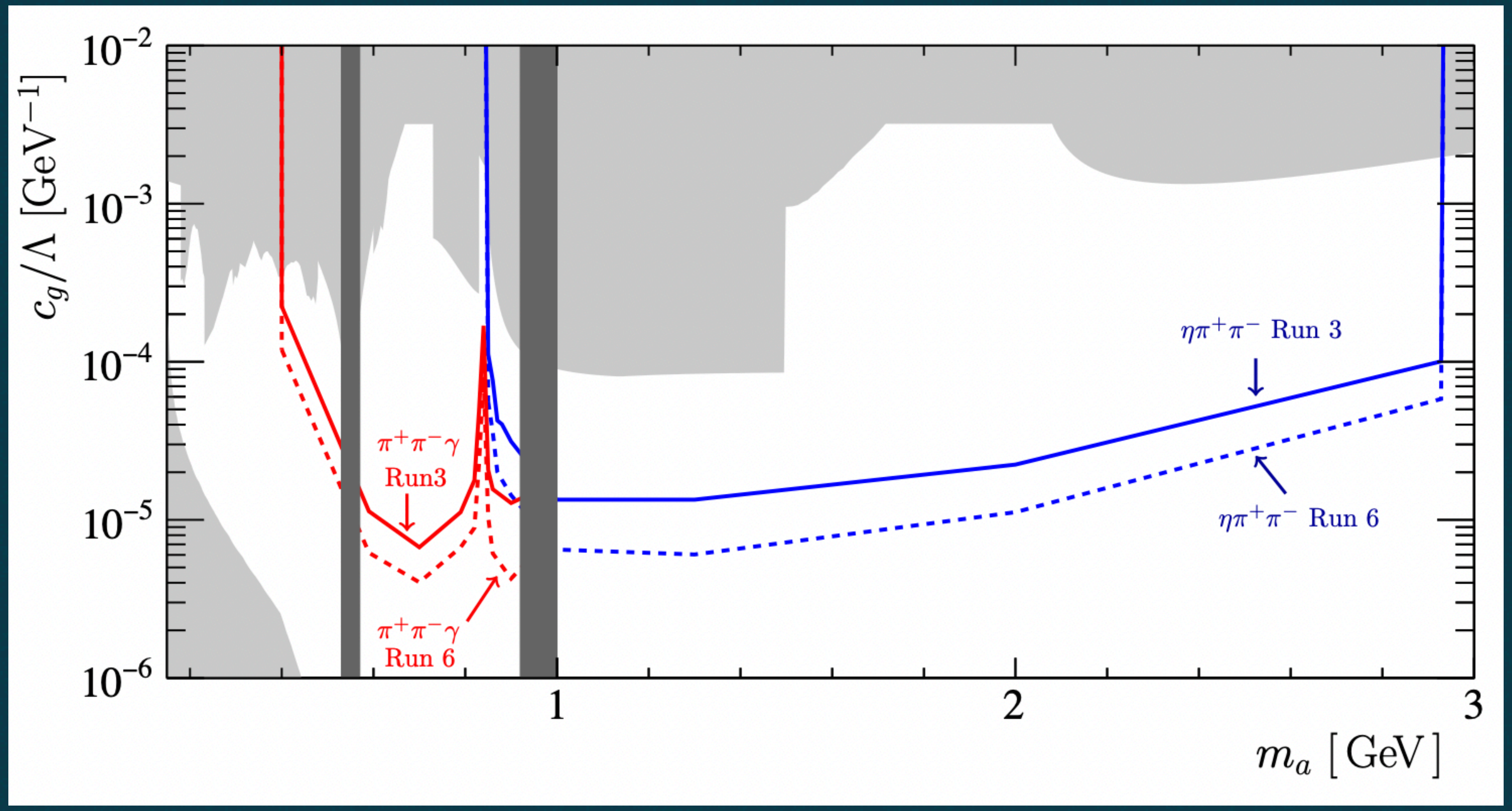


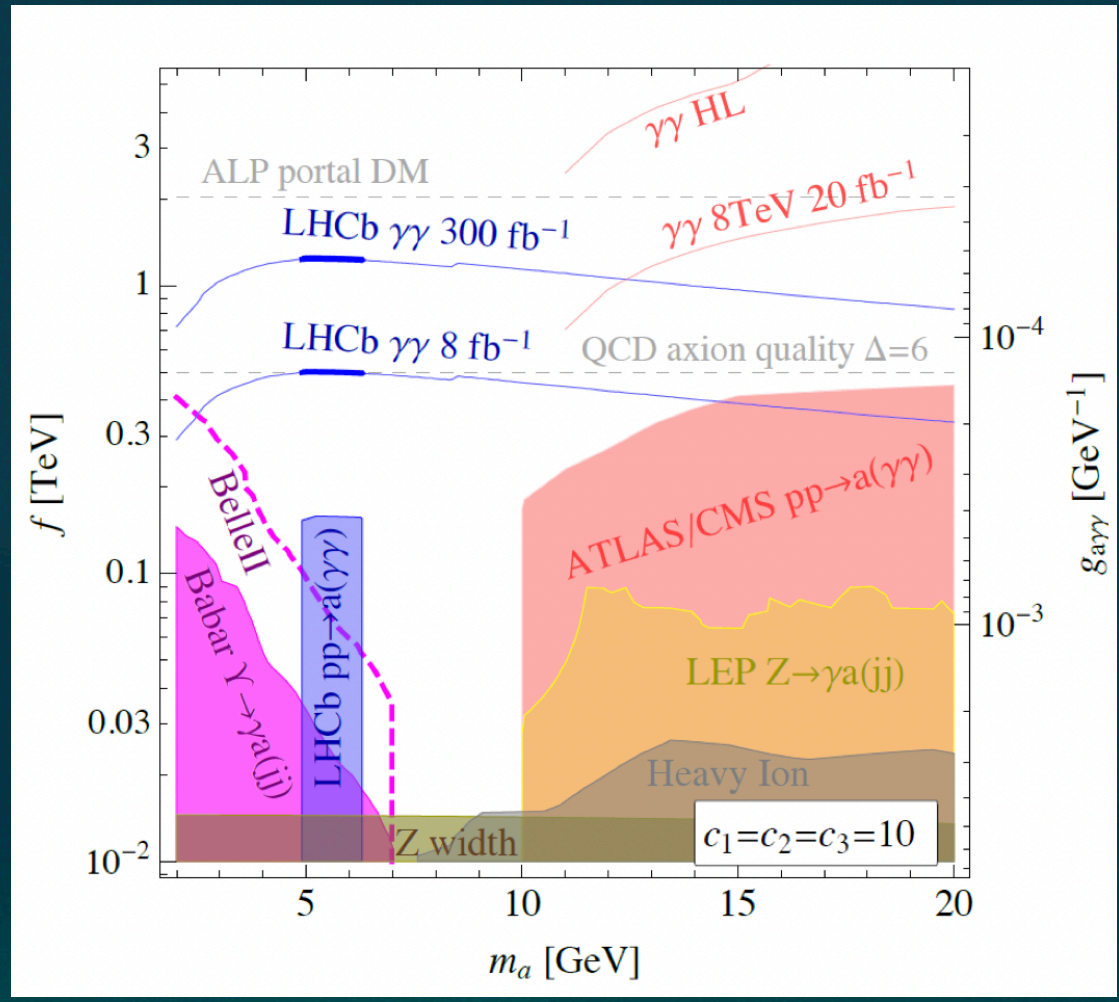
* New pseudoscalar particles, with Lagrangian interactions governed by discrete shift symmetry.
* Characterised by a decay constant, f_a, associated with the PNGB nature → ALP masses can be treated as a free parameter

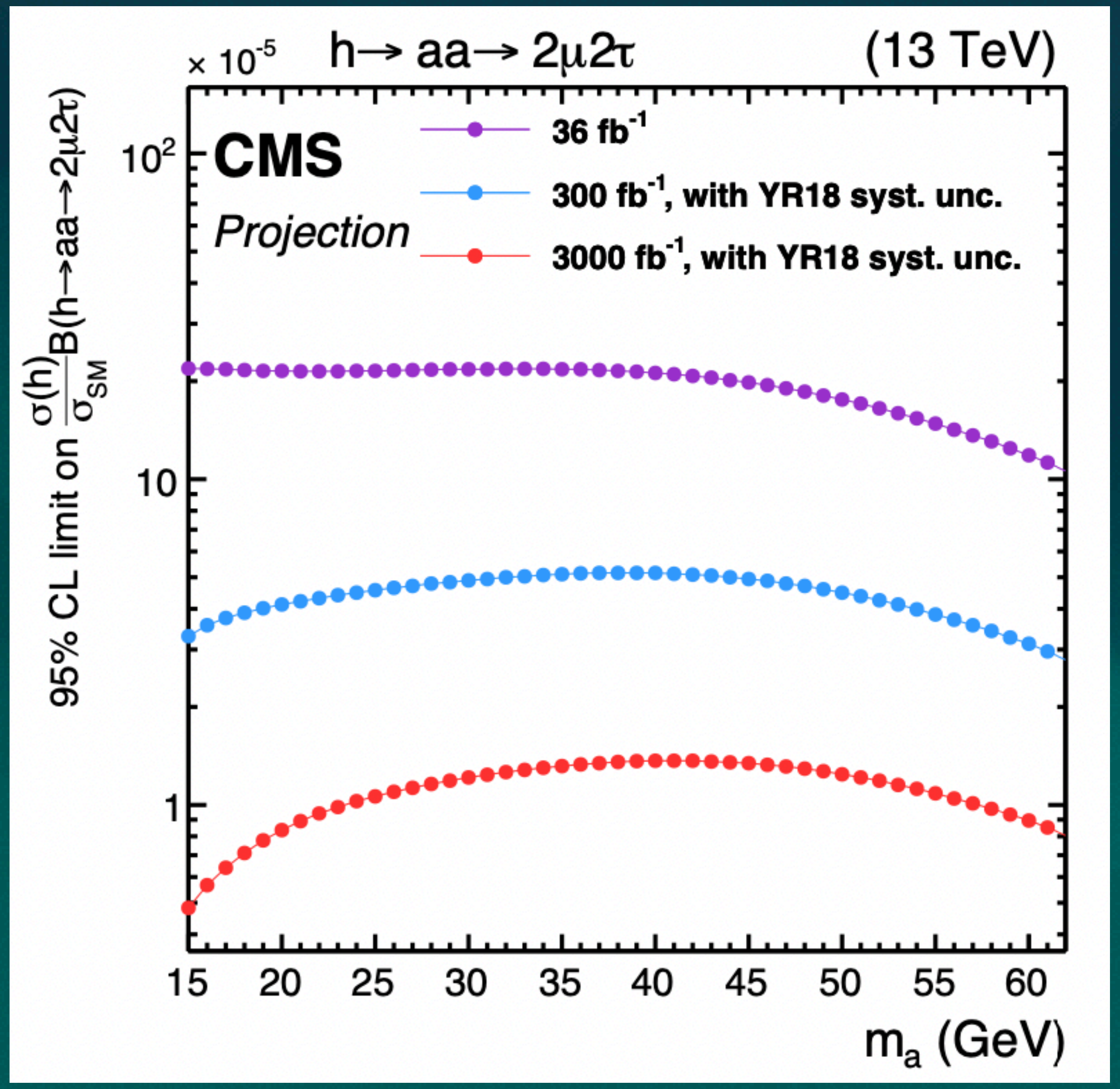
HL-LHC Case studies:

→ LHCb: targets light ALPs that interact with SM via coupling to gluons or photons. Produced via $a \to \eta\pi\pi$ and $a \to 3\pi$

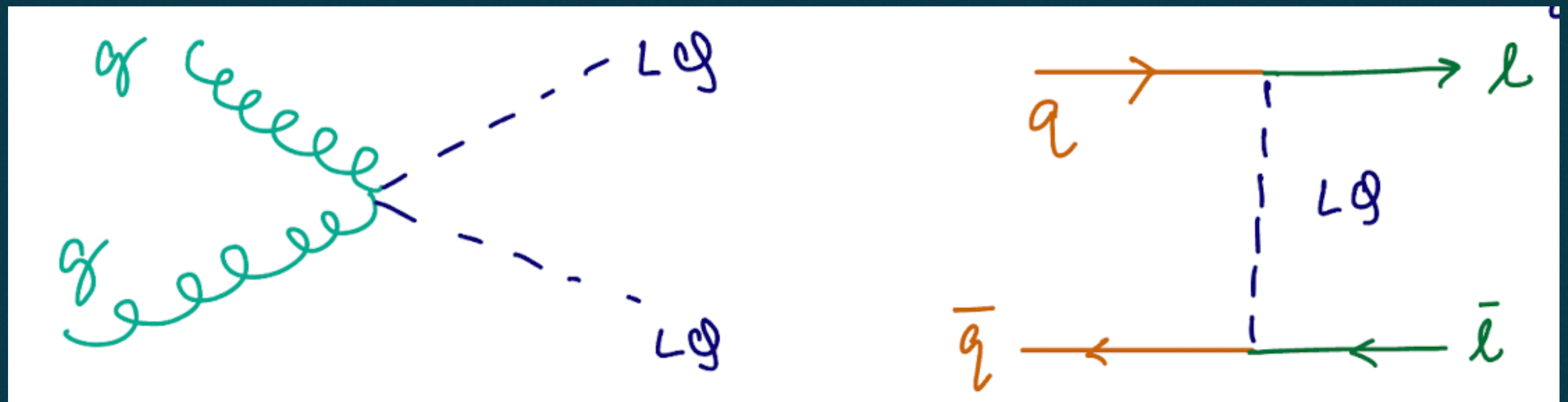
→ CMS: $H \to aa \to 2\mu2\tau$ projections available







Leptoquarks



* Particles that mediate quark <—> lepton conversion

* 3rd generation LQs gained traction as an elegant and preferred explanation for flavour anomalies

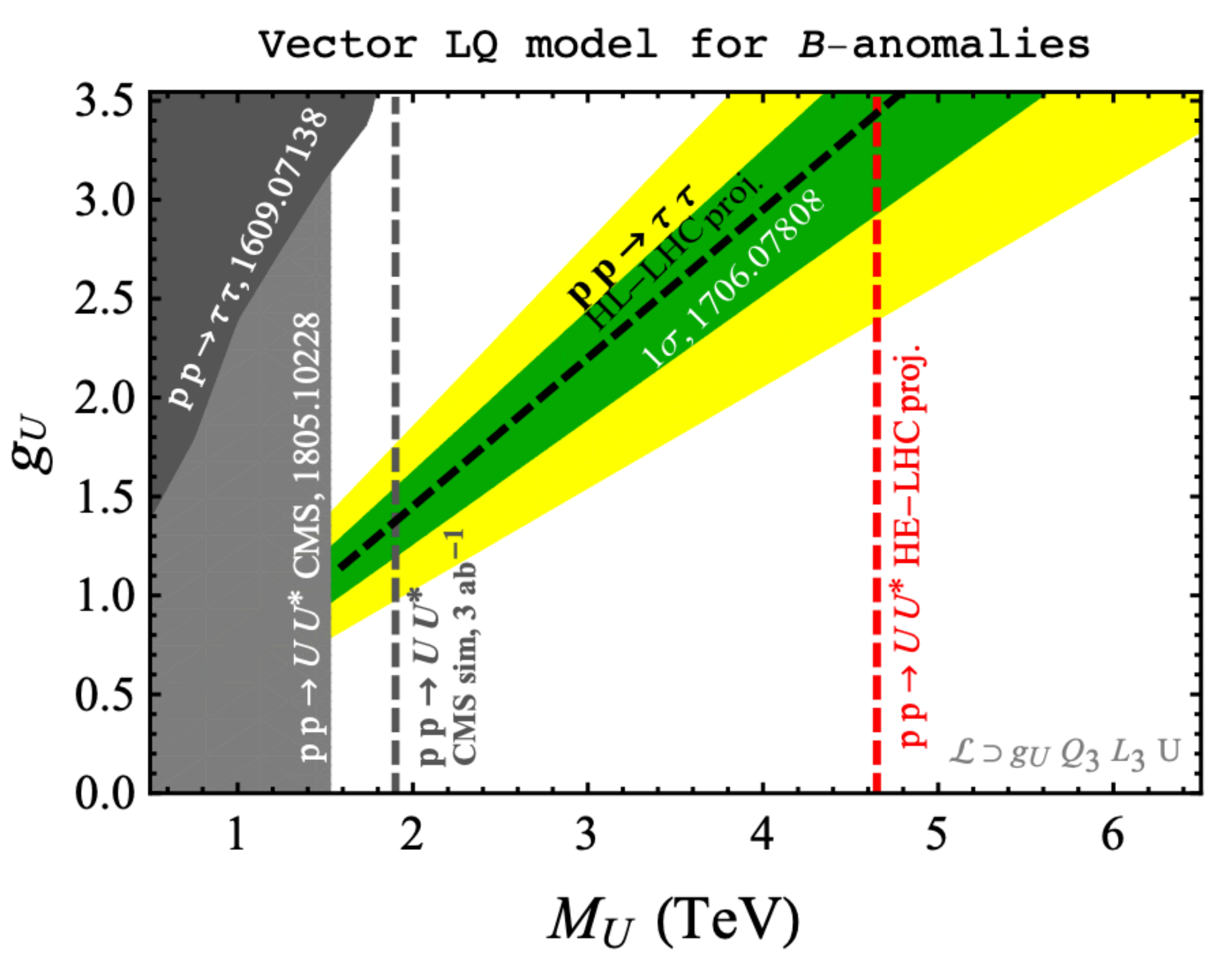
  —> for LQs with large couplings ($\lambda \sim m_{LQ}$)

* Current LHC constraints on m_{LQ} reaches ~ 1 TeV [production @ hadron colliders driven by strong interaction]

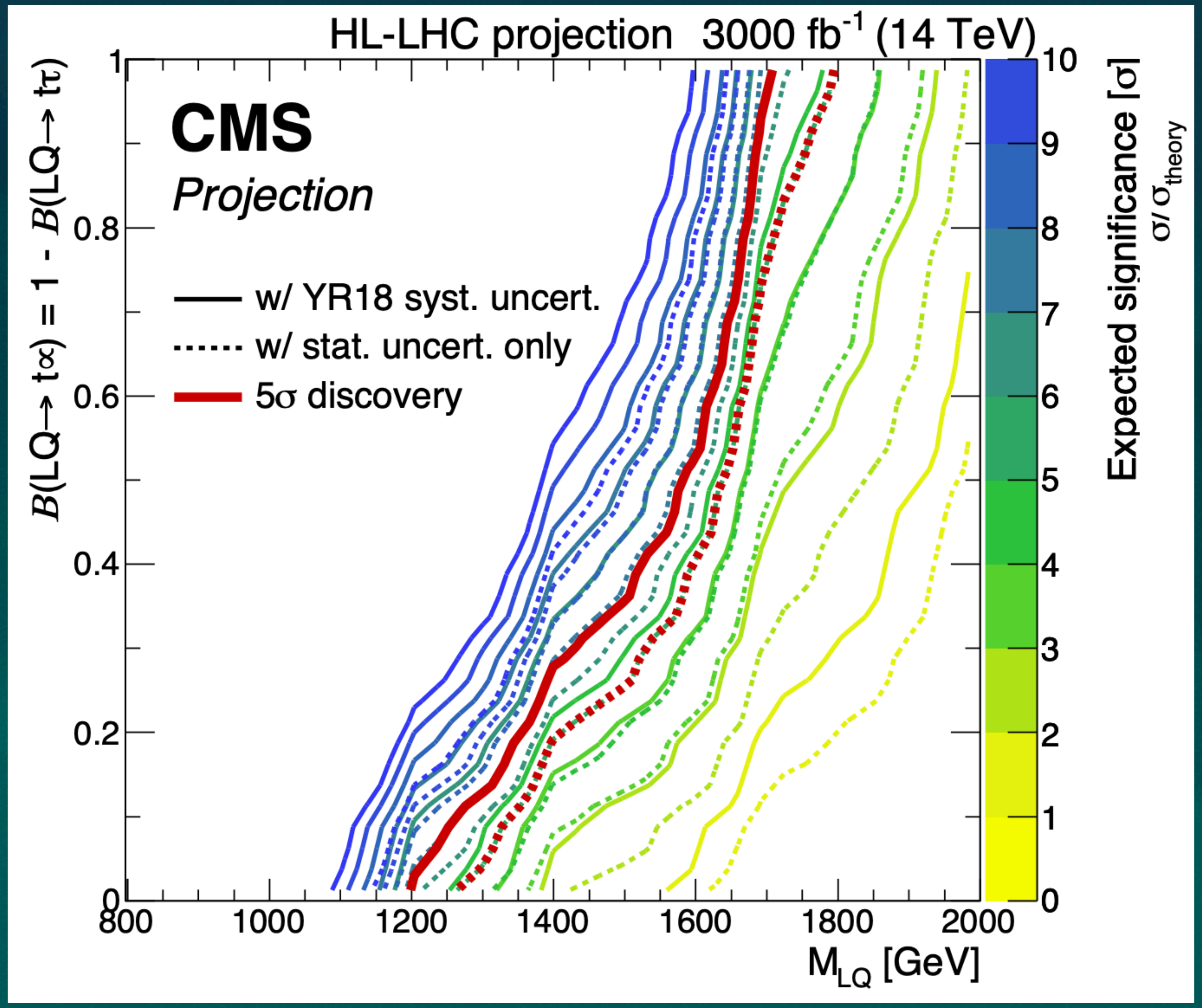
* **HL-LHC case study:** single & pair-produced 3rd gen scalar LQs, where LQ → τb [hadronically decaying τ and 1/2 jets]

  * Single production: exclusion 1130 GeV/ discovery 800 GeV

  * Pair production of LQ is model-independent ⟷



arXiv 1812.07638



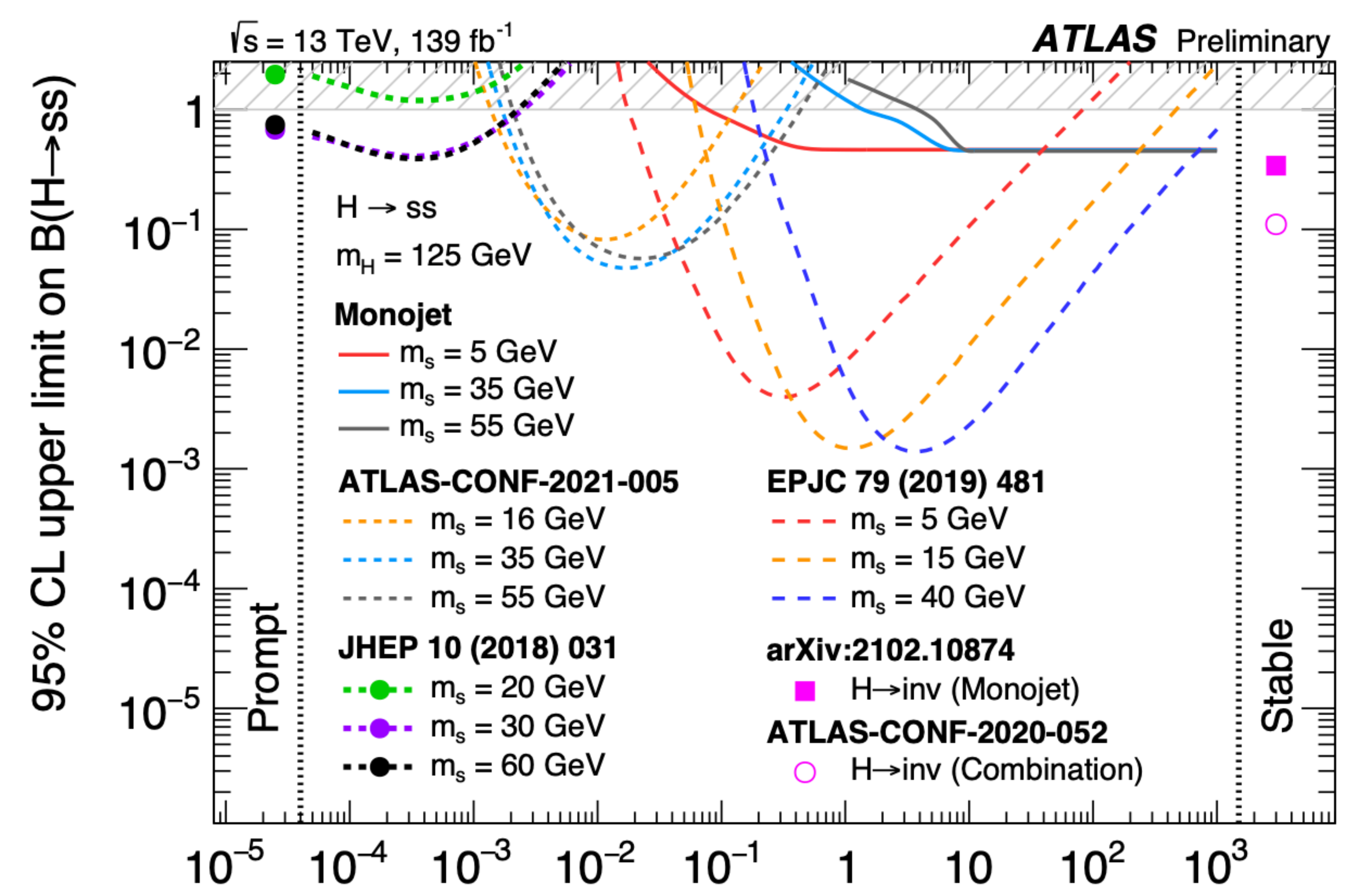
Potential for reinterpretation

REINTERPRETATION!

Whether measurement or search, LHC results are effectively a measurement of the no. of events/cross-section in a particular phase-space.

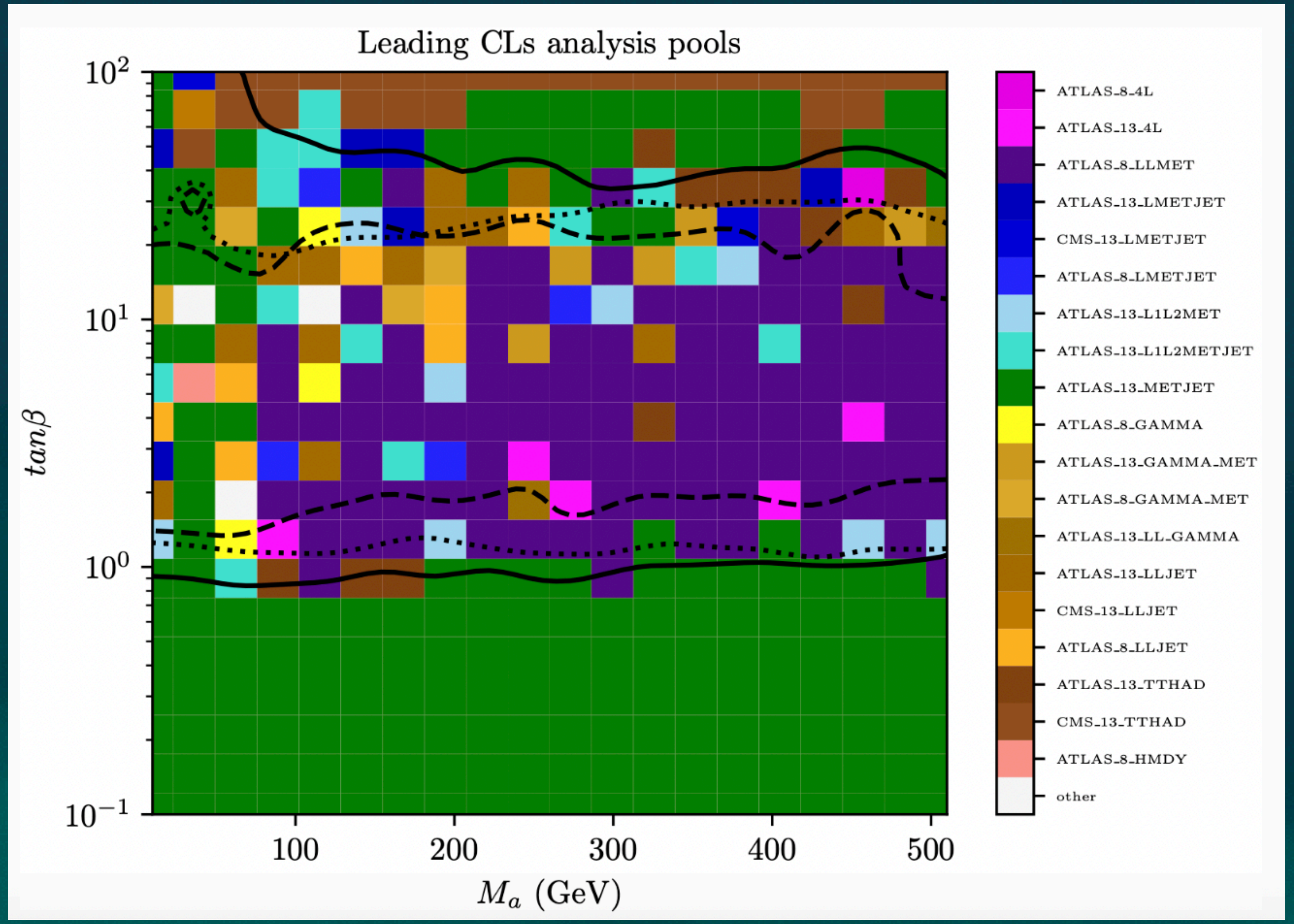
Precision measurements @ (HL-)LHC can also act as a probe for new physics
→ ALLOWS TO PROBE BSM PHYSICS WITH SIMILAR FINAL STATES

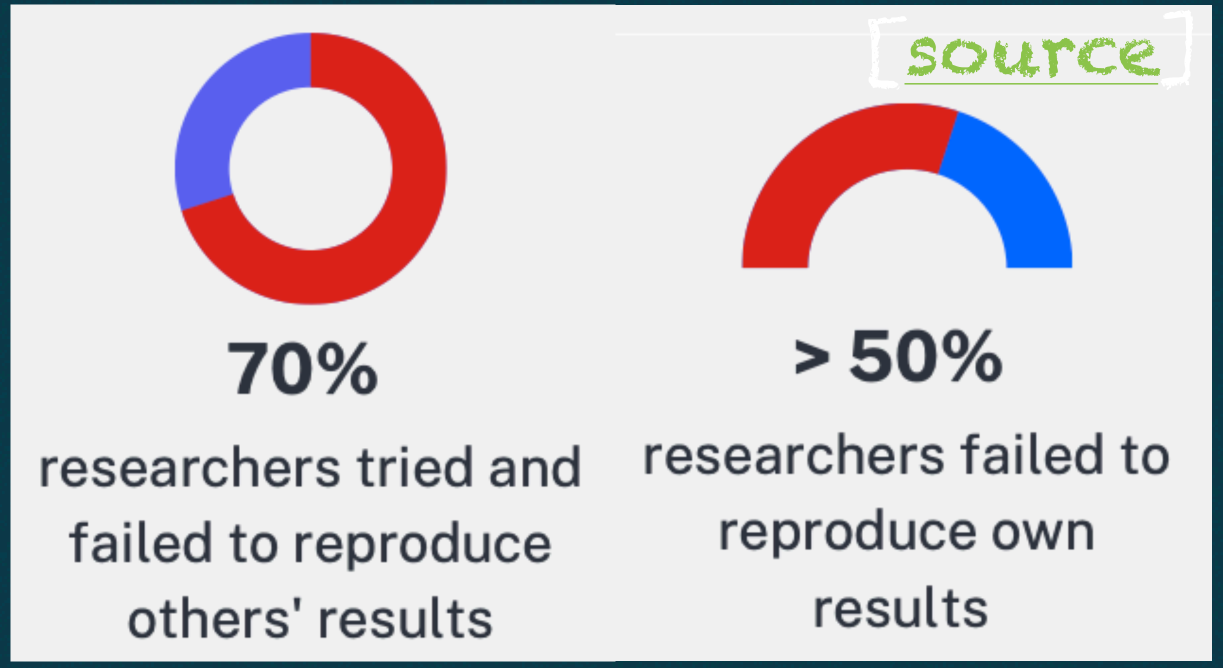
Example: Constraining the dark sector with the mono-jet signature



Exclusion contours on BR(H → ss) at 95% CL obtained in the mono-jet analysis reinterpretation shown as a function of the s particle proper decay length, compared to dedicated searches

Example: Constraining 2HDM+a using analyses in CONTUR





CONTUR toolkit exploits the fact that particle-level differential measurements made in fiducial regions of phase-space have a high degree of model-independence.

Is BSM physics is close enough to the EW symmetry-breaking scale to be within direct reach of the (HL-)LHC? → Combination of measurements in CONTUR, and specific searches for less generic final states (such as LLP, or dark showers) could answer it.

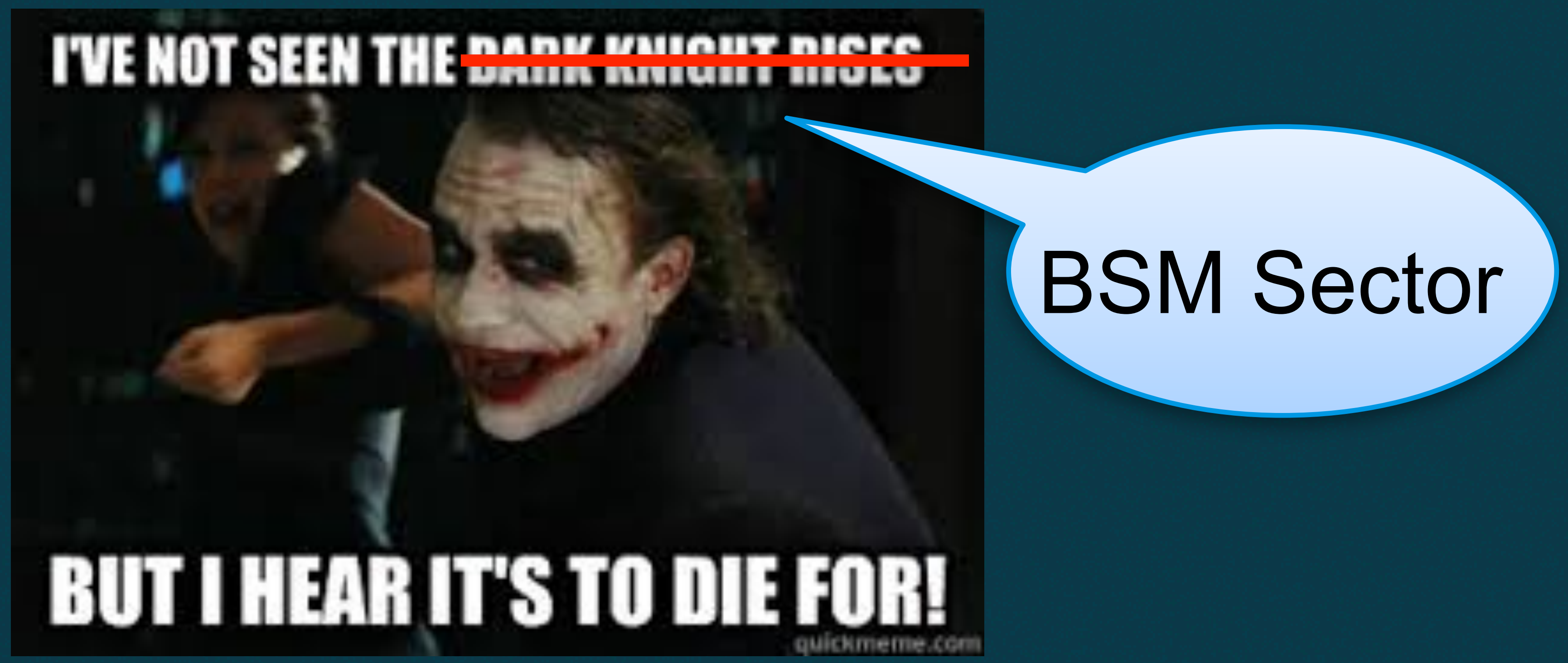
Food for thought: DM Complementarity going forward?

[Inspired by link]

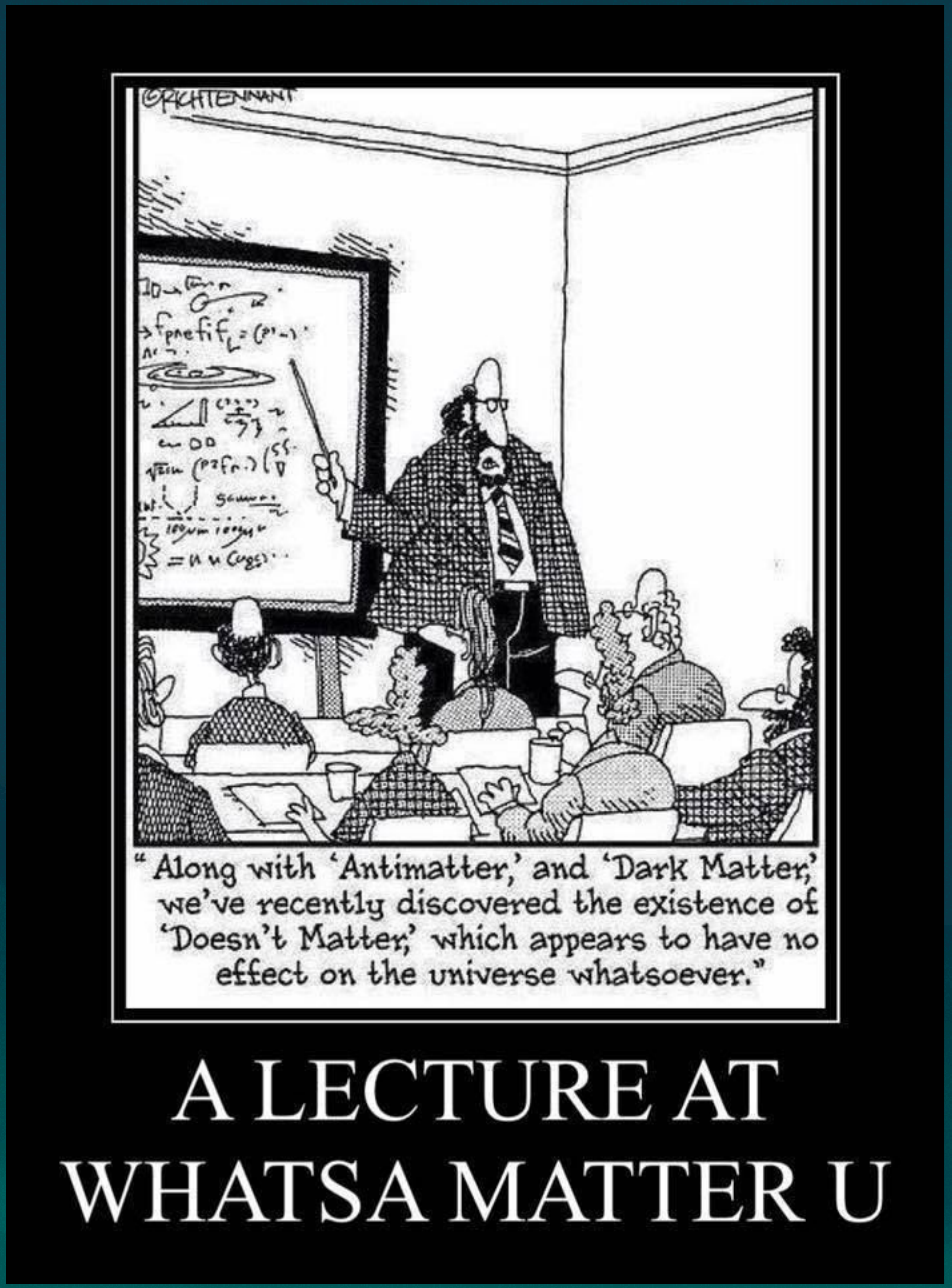
Multiple observations, experiments and coherent theories are needed for DM discovery

- Observations motivating DM arise from astrophysics & cosmic probes
- Theoretical frameworks are crucial to put different observations into context
- Direct Detection → can discover DM with cosmological origin
- Indirect Detection → can probe decays of cosmological DM into SM particles
- Colliders / accelerators → can produce DM and probe its dark interactions

Conclusions

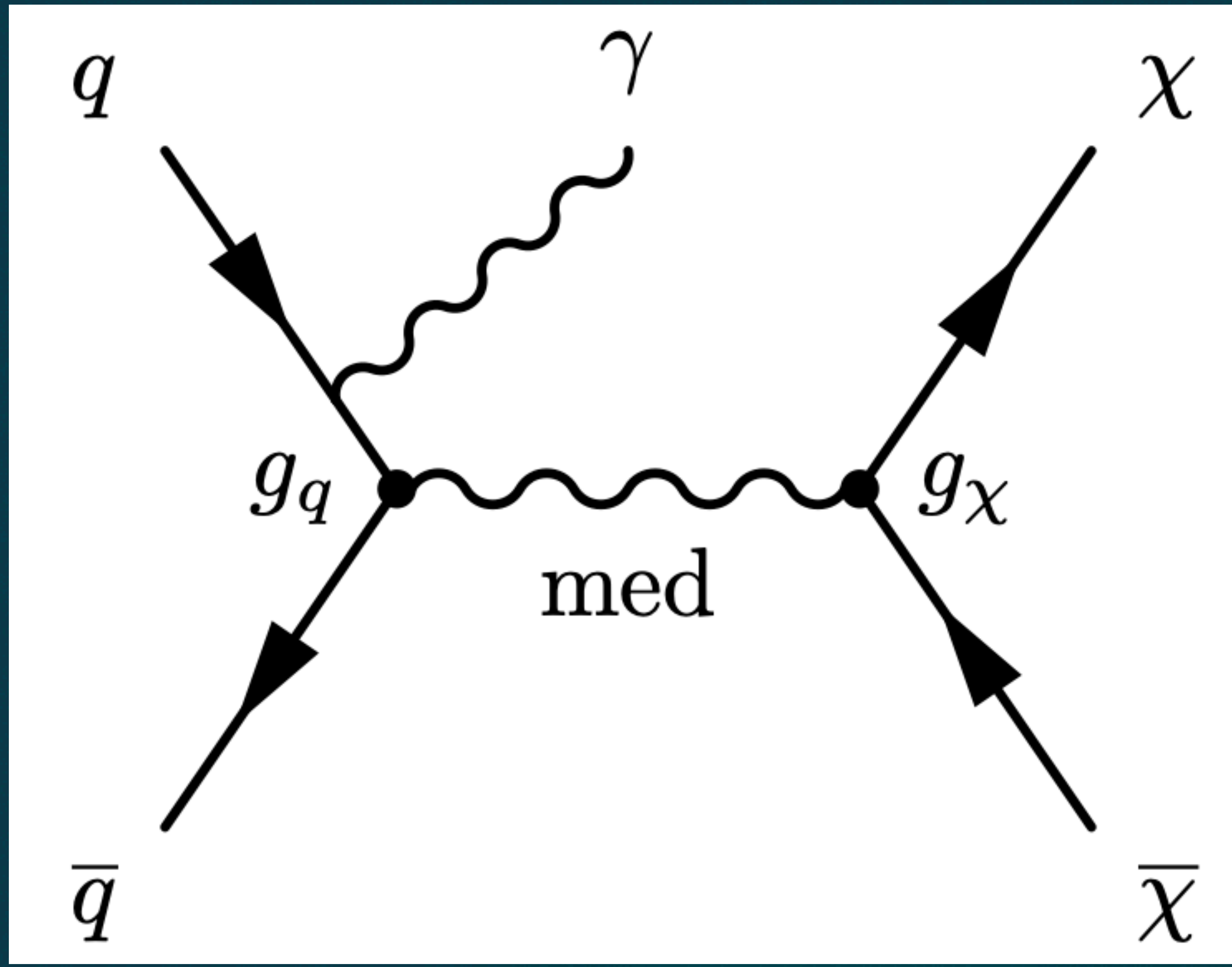


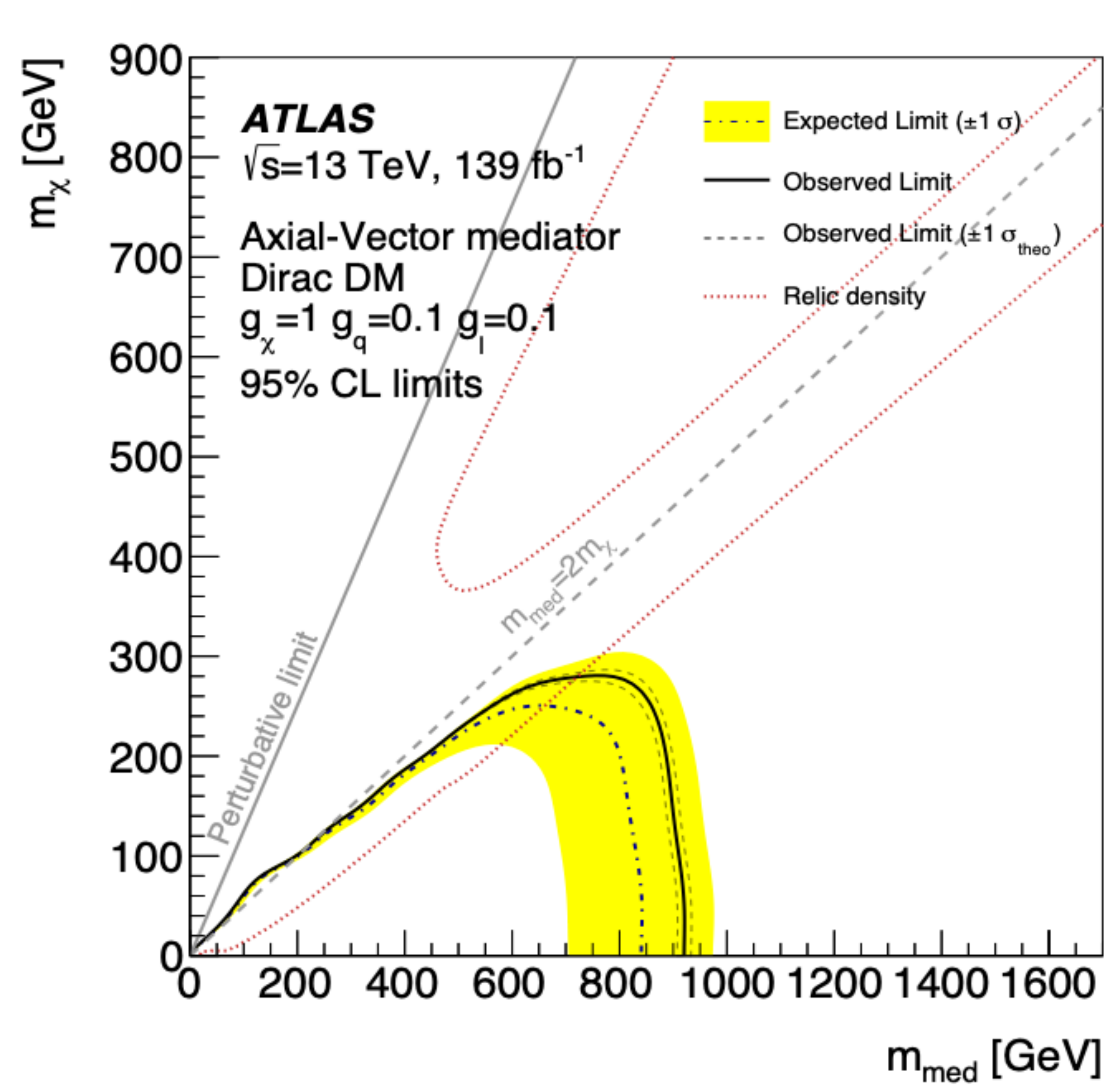
- Several avenues of BSM sector open for exploration @ HL-LHC
- General idea evolving around the need of more signature based searches
- Multiple projections and case-studies available
- Steps to enhance chances at discovery/extended exclusion
  - By developing a search program spanning across energy scales, as unbiased as possible, starting with HL-LHC
  - By extending searches for BSM particles with the highest possible lab-accessible masses
  - By constraining properties of SM - DM mediators and/or portal interactions, using both measurements and searches



BACKUP

WIMPS: Mono-X @ HL-LHC





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Current exclusions:

Mediator	g_q	g_χ	g_ℓ	m_{med} [GeV]	m_χ [GeV]
Axial-vector	0.25	1	0	1460	415
Axial-vector	0.1	1	0.1	920	280
Vector	0.25	1	0	1470	580
Vector	0.1	1	0.01	950	400

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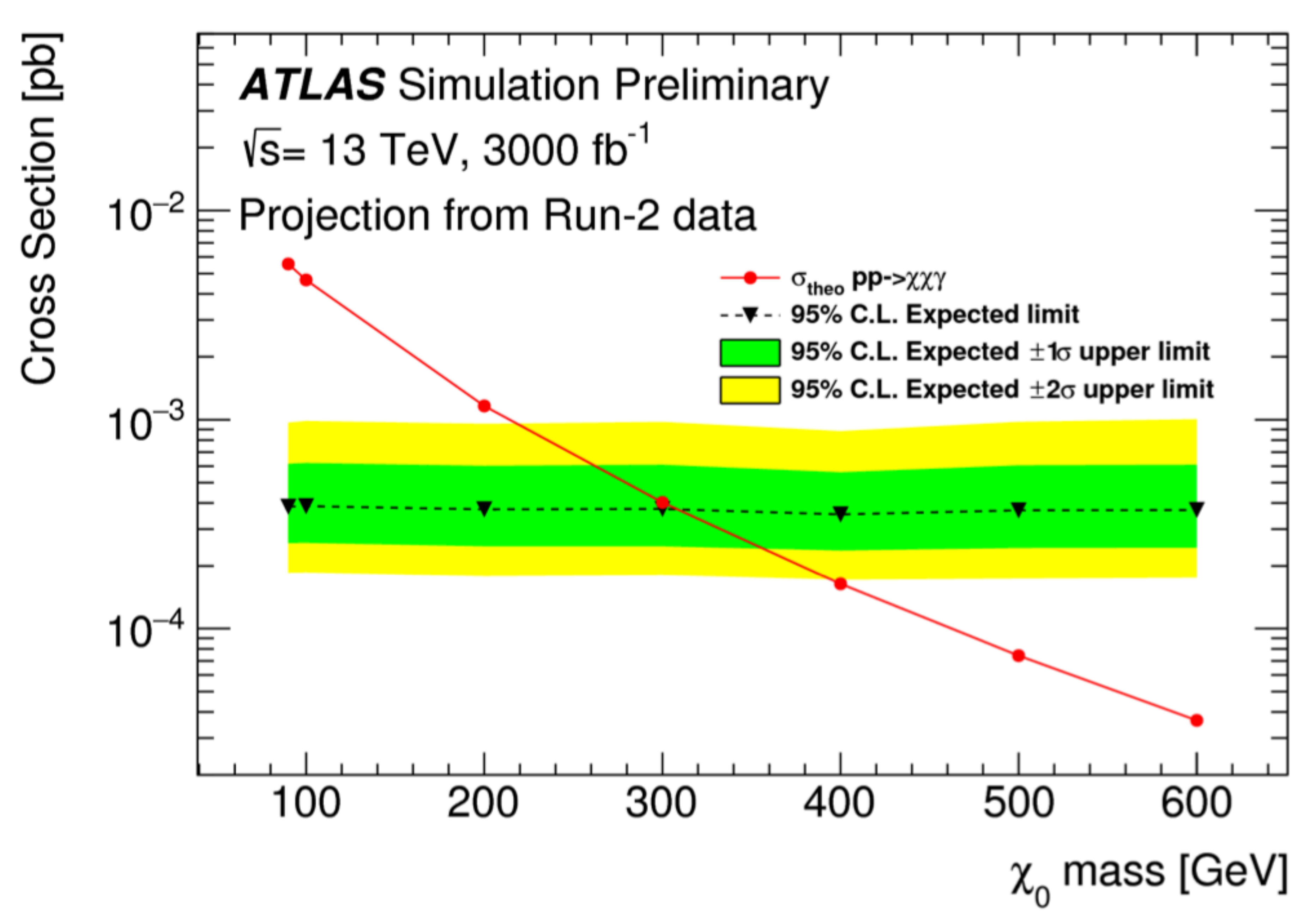

Mono-photon: WIMP pair production with ISR photon

WIMPs are pair-produced from the s-channel exchange of an axial vector Z_A mediator

Z_A couples to neutralino (χ) (g) and to gluons (g)

HL-LHC discovery potential/exclusion power ⟷