Karlsruhe Institute of Technology

Experimental Physics at Hadron Colliders

CERN Summer Students Lectures, July 24-26, 2024 - Lecture 4/4

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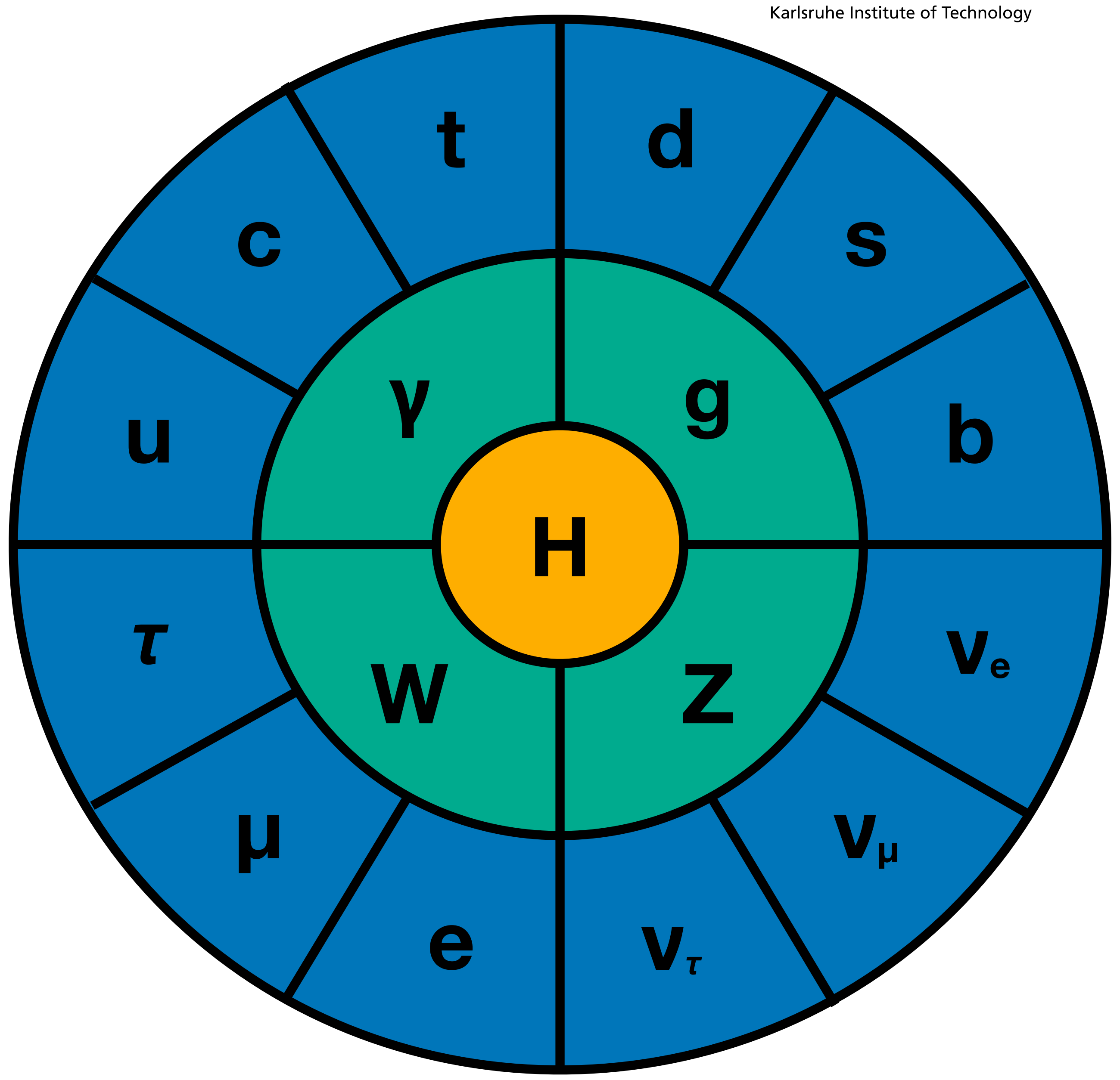
Work Plans

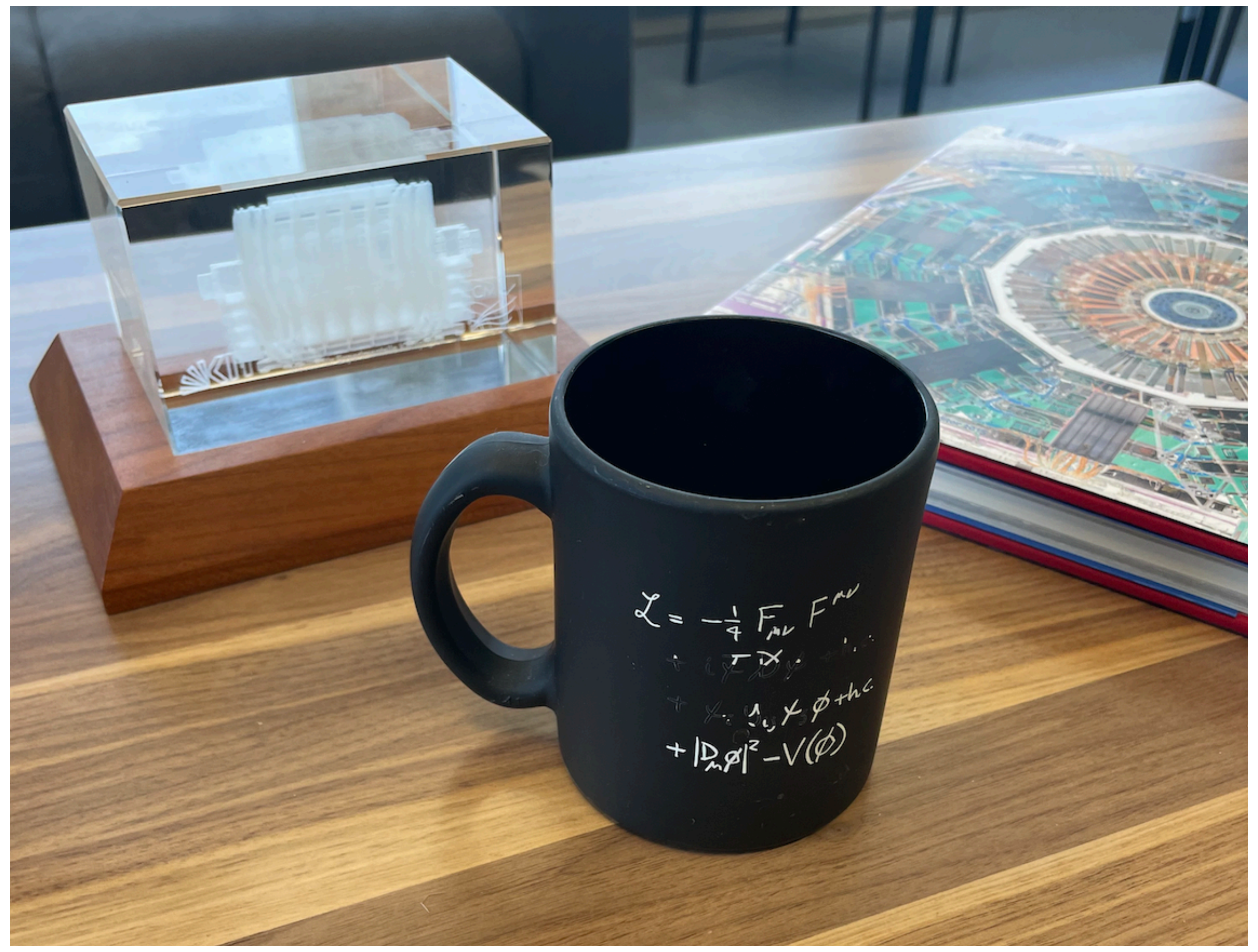
- Lecture 1: Introduction, fundamentals, cross sections
- Lecture 2: Standard model measurements
- Lecture 3: Higgs physics
- Lecture 4: Searches for new physics

Standard Model (recap)

- **Our best theory to describe the most basic building block of the universe**
  - Relativistic Quantum Field Theory
  - Data: symmetries SU(2)xU(1)xSU(3) and fields

gauge sector	Higgs sector	flavor sector
$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + h.c.$	$+ \lvert D_\mu \phi \rvert^2 - V(\phi)$	$+ \psi_i y_{ij} \psi_j \phi + h.c.$
describes the gauge interactions of the quarks and leptons	breaks electro-weak symmetry and gives mass to the $W^\pm$ and Z bosons	leads to masses and mixings of the quarks and leptons
parametrized by 3 gauge couplings g_1, g_2, g_3	2 free parameters Higgs mass Higgs vev	22 free parameters to describe the masses and mixings of the quarks and leptons

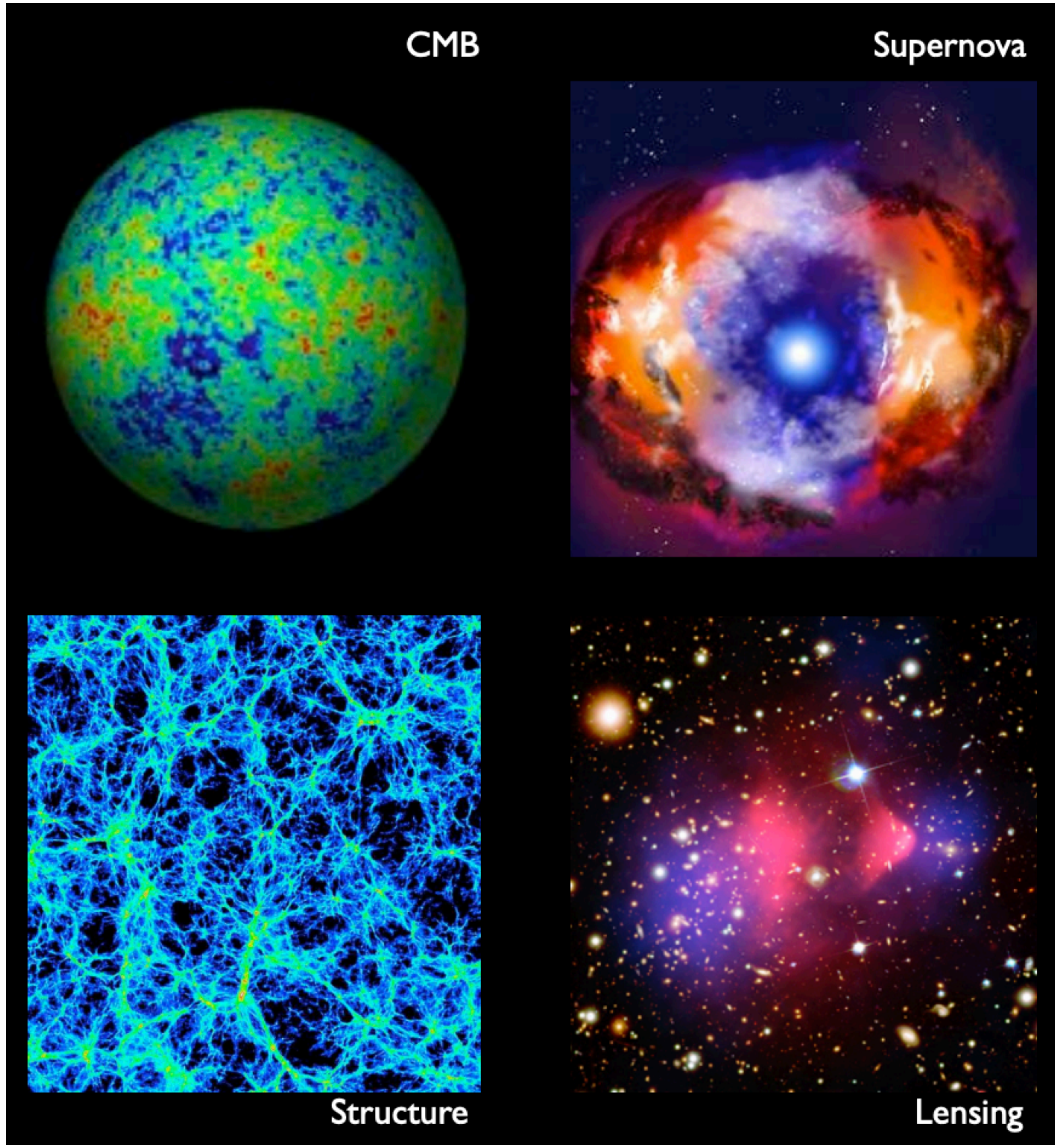




- **Ordinary matter consists only of three types of matter particles: the up and down quark and electrons**

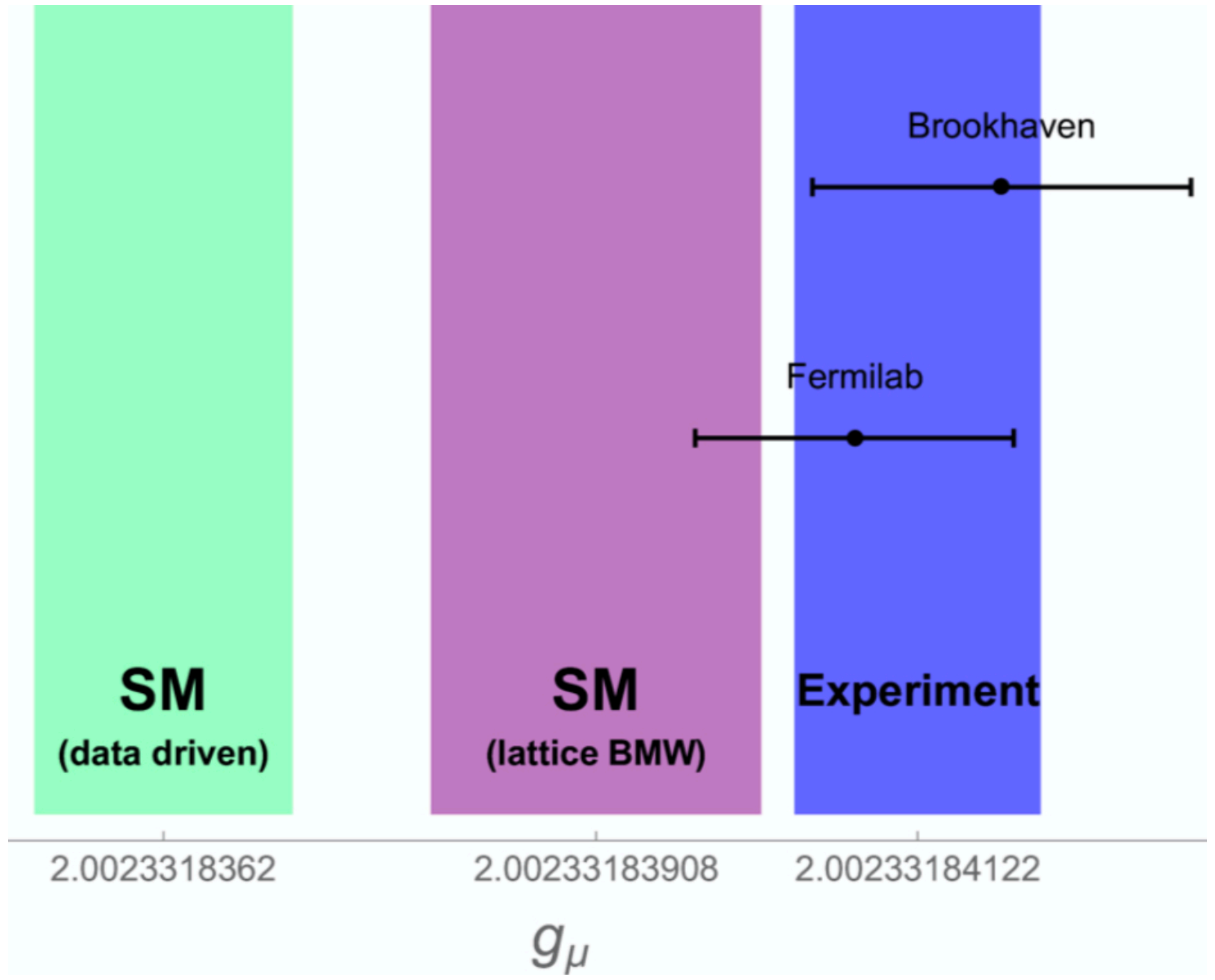
Physics Beyond the Standard Model

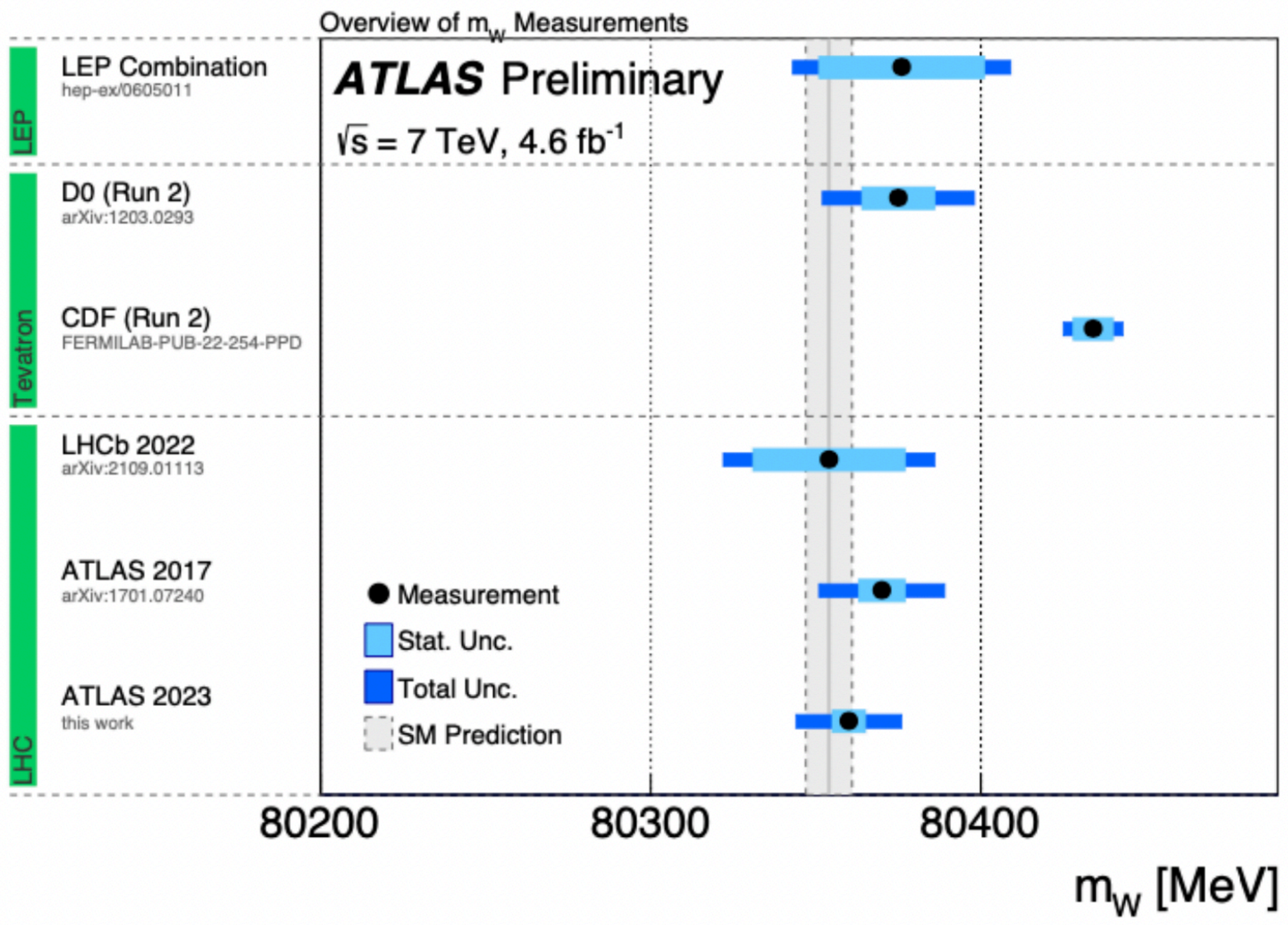
- **Phenomena not explained**
  - Gravity
  - Dark Matter
  - Dark Energy
  - Neutrino Masses
  - Matter-antimatter asymmetry
  - …
- **Theory problems**



Physics Beyond the Standard Model

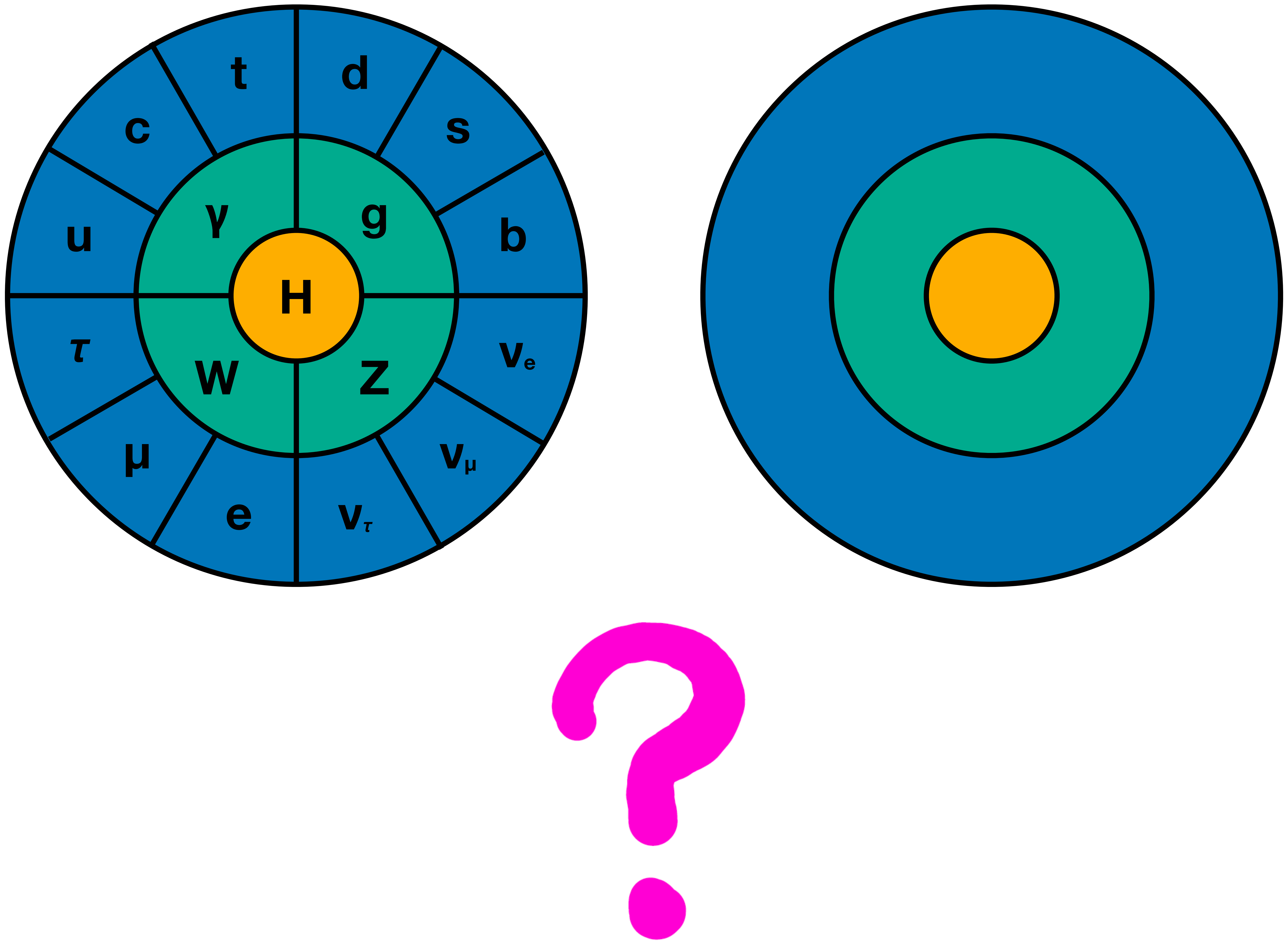
- **Experimental results not explained**
  - No experimental result is accepted as definitively contradicting the SM
  - At any given moment several experimental results differ significantly from SM predictions.
  - Some examples include
    - Anomalous magnetic dipole moment of muon
    - Flavor anomalies
    - W mass measurements
  - Are these statistical fluctuations, systematic biases, or first evidence for BSM?





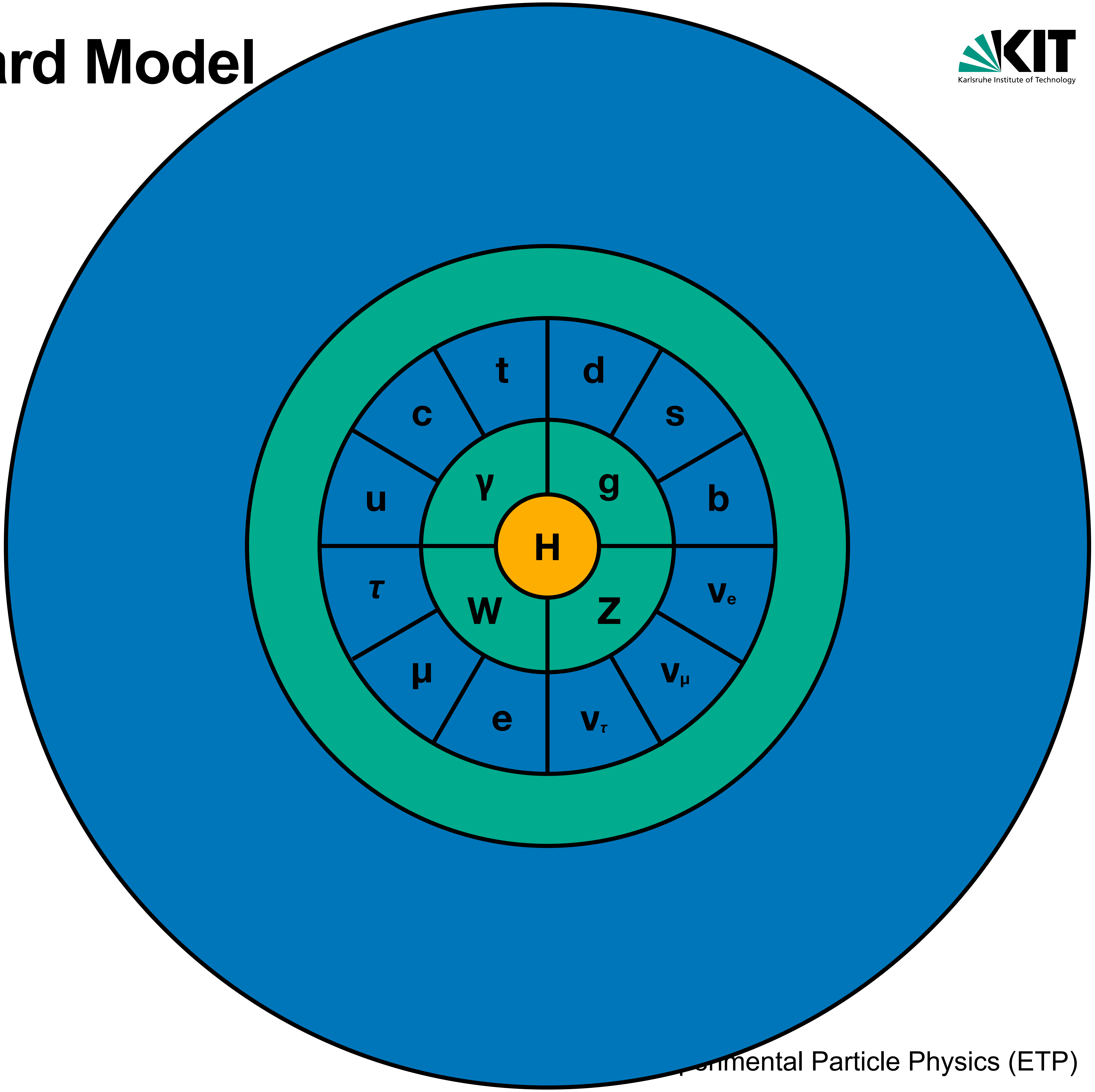
Physics Beyond the Standard Model

- What makes a BSM candidates and good or attractive BSM theory?



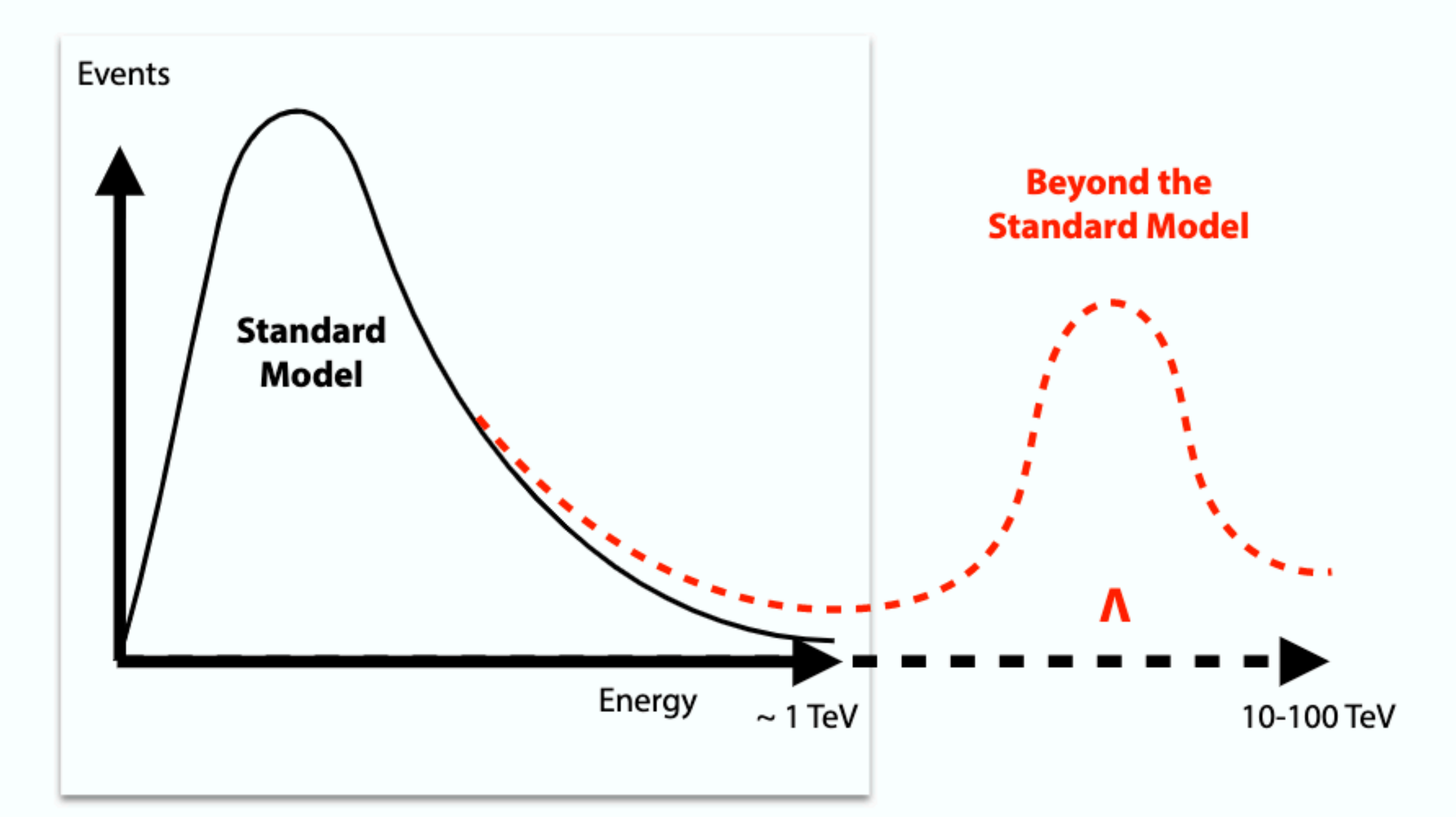
Physics Beyond the Standard Model

- What makes a BSM candidates and good or attractive BSM theory?
  - Containment as low-energy approximation
  - Predictive power - it explains new phenomena
  - Simplicity - it has a simpler structure
  - Deductibility - it has fewer ad hoc assumptions and free parameter
  - Completeness - inherent reasons for nonexistence of otherwise possible effects



Effective Field Theory Approach

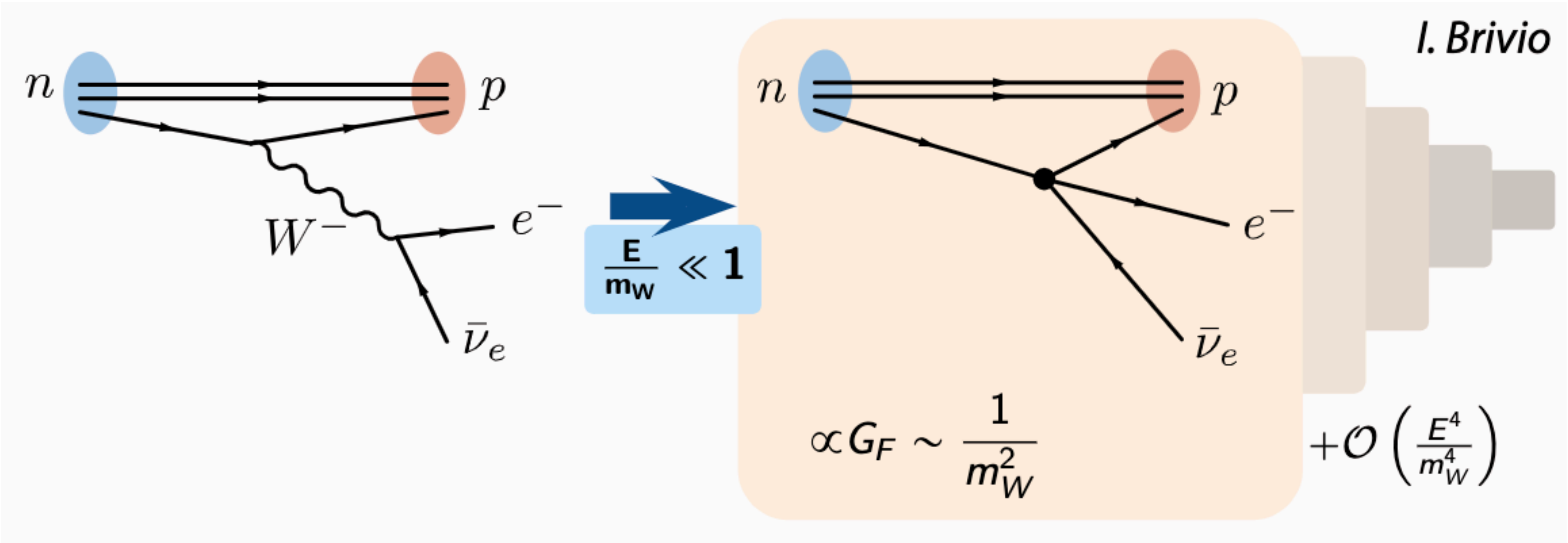
- Motivation for ETFs
  - Energy scale of new physics (Λ) might be out of reach for direct searches



  - Not insensitive to its effects, but the pattern in our data may be more subtle, i.e. we find small deviations from the SM requiring high precision measurements

Effective Field Theory Approach

- Not a new idea. Long history in particle physics - e.g. Fermi theory of decay



- In low energy regime, we can "integrate out" the W boson and replace it with a four-fermion interaction of strength GF
  - Full theory replaced by a Taylor expansion in terms of E/m_W
  - Accurate predictions up to a scale $\Lambda \sim m_W$
  - No knowledge of the SM required. Follows from know fields (fermions) and symmetries (QED)

Effective Field Theory Approach

- Expanding w/o explicit new physics model
  - Provides a renormalisable quantum field theory
  - Results are universal and can be propagate to other experiments
  - Minimal non-redundant set of operators is called bases.
  - It gets complicated quickly. “Warsaw” basis includes 2499 distinct operators

$$L_{\mathrm{EFT}} = L_{\mathrm{SM}} + \cancel{\sum_i \frac{C_i^{(5)}}{\Lambda}\mathcal{O}_i^{(5)}} + \sum_i \frac{C_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \cancel{\sum_i \frac{C_i^{(7)}}{\Lambda^3}\mathcal{O}_i^{(7)}} + \sum_i \frac{C_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \ldots$$

Lepton-number violating

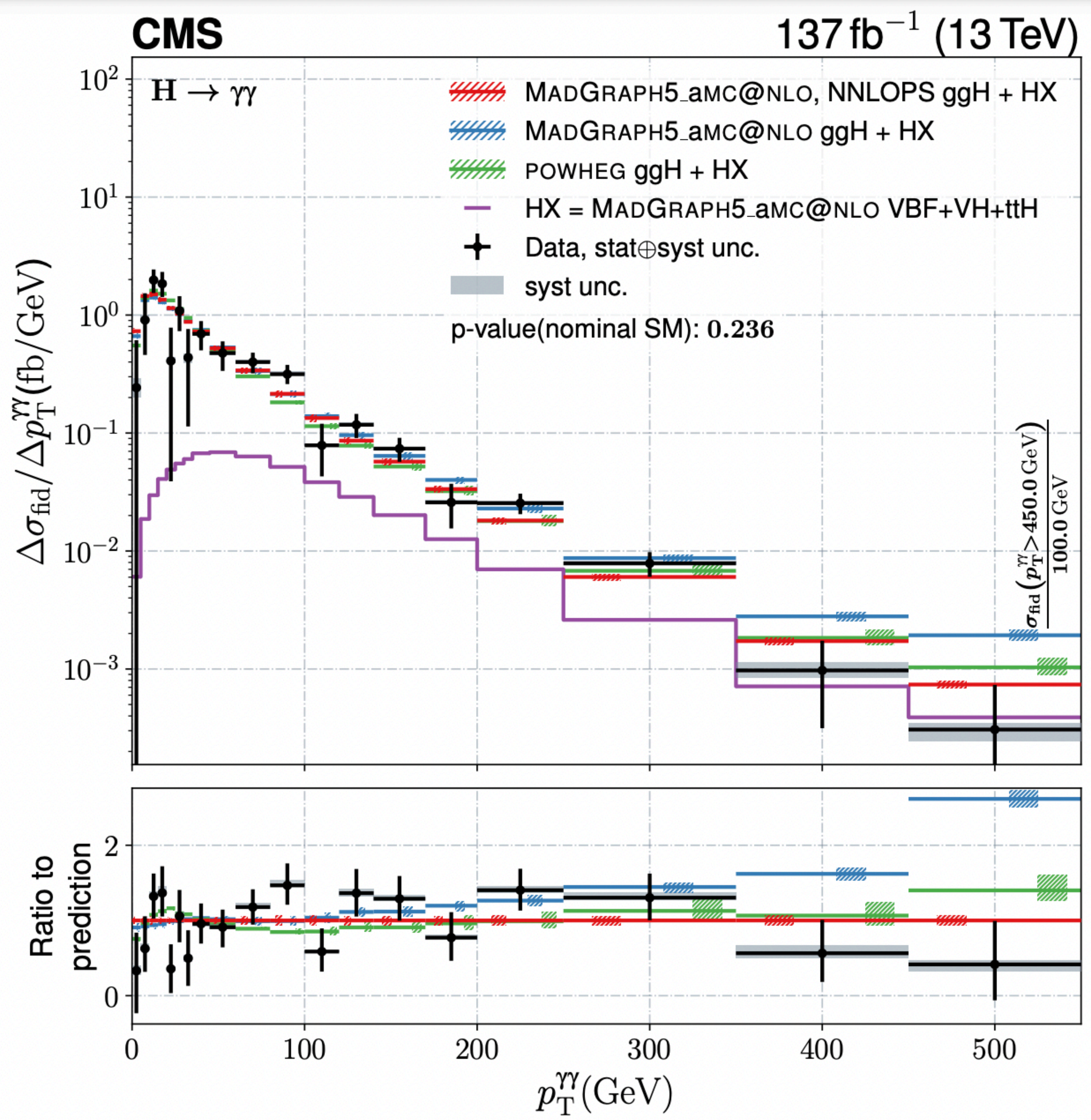
Violates B-L

$\mathcal{O}_i$: operators = interaction terms at a given expansion order

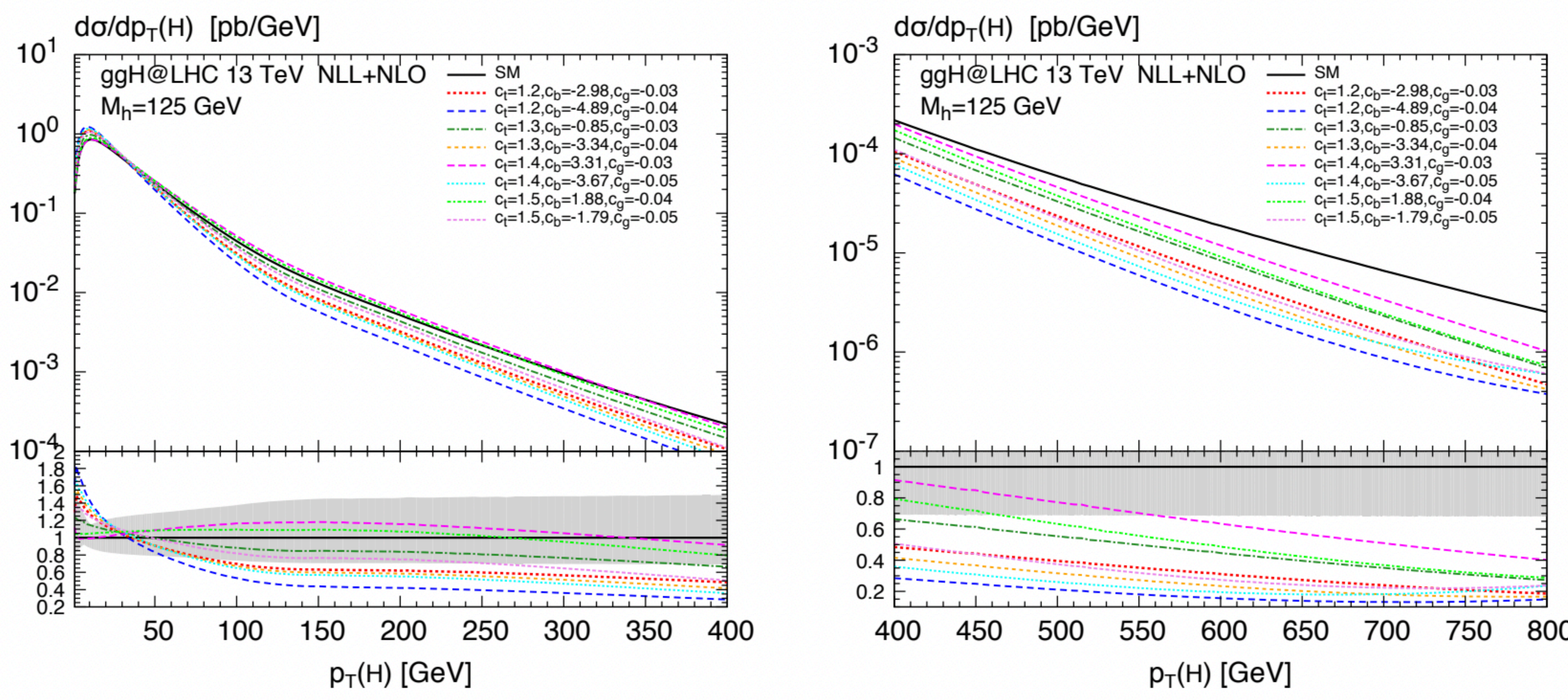
C_i : operators = Wilson coefficients, free parameters

Effective Field Theory Approach

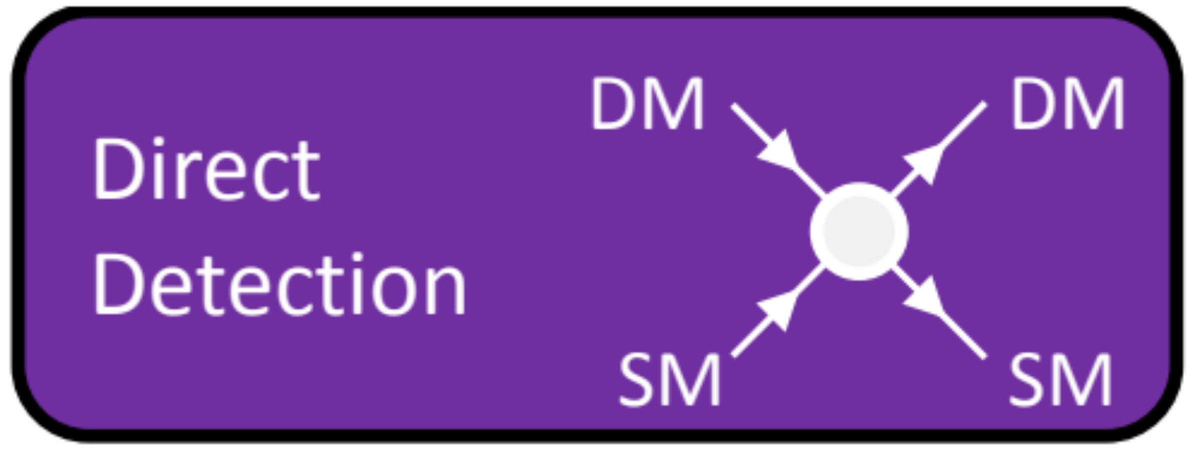
- Example Higgs Physics



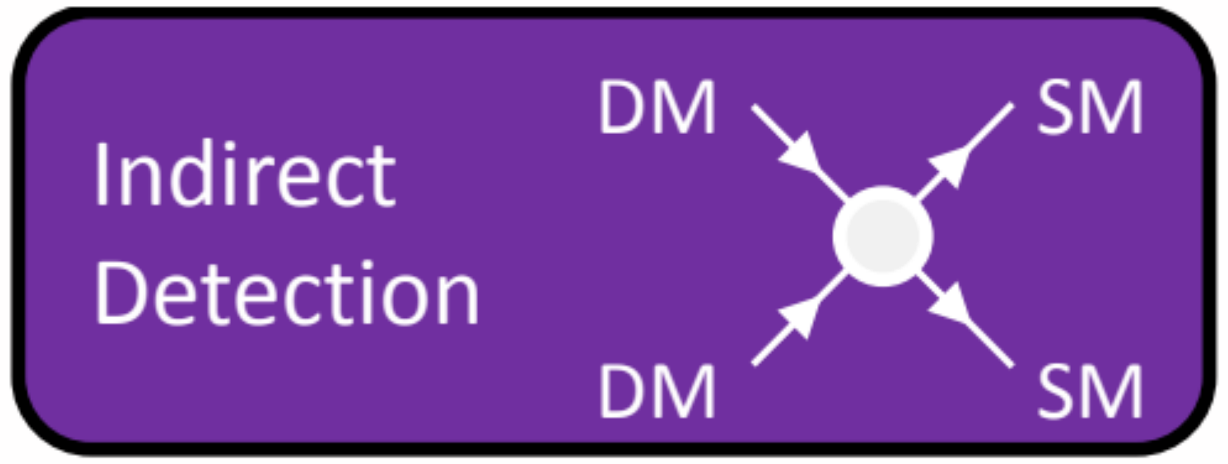
arXiv:1612.00283

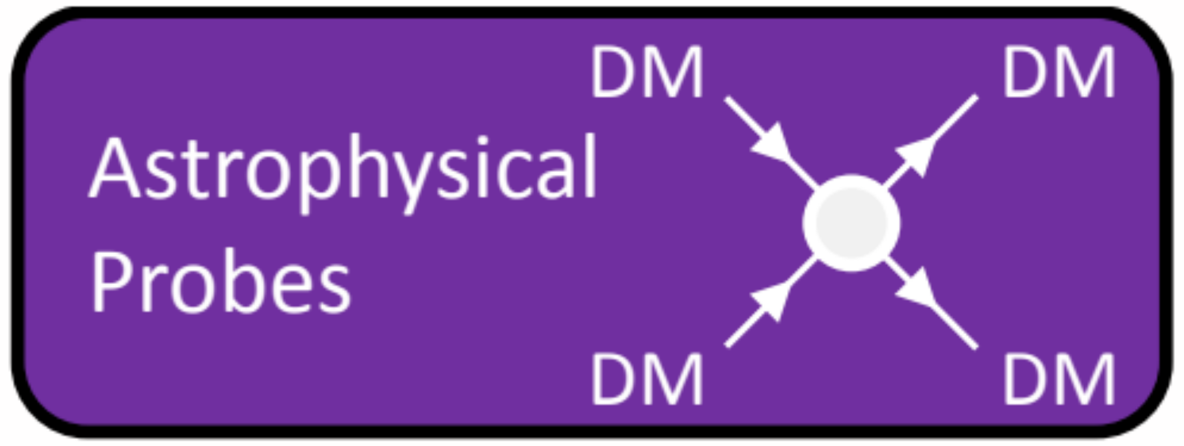


Dark Matter Searches

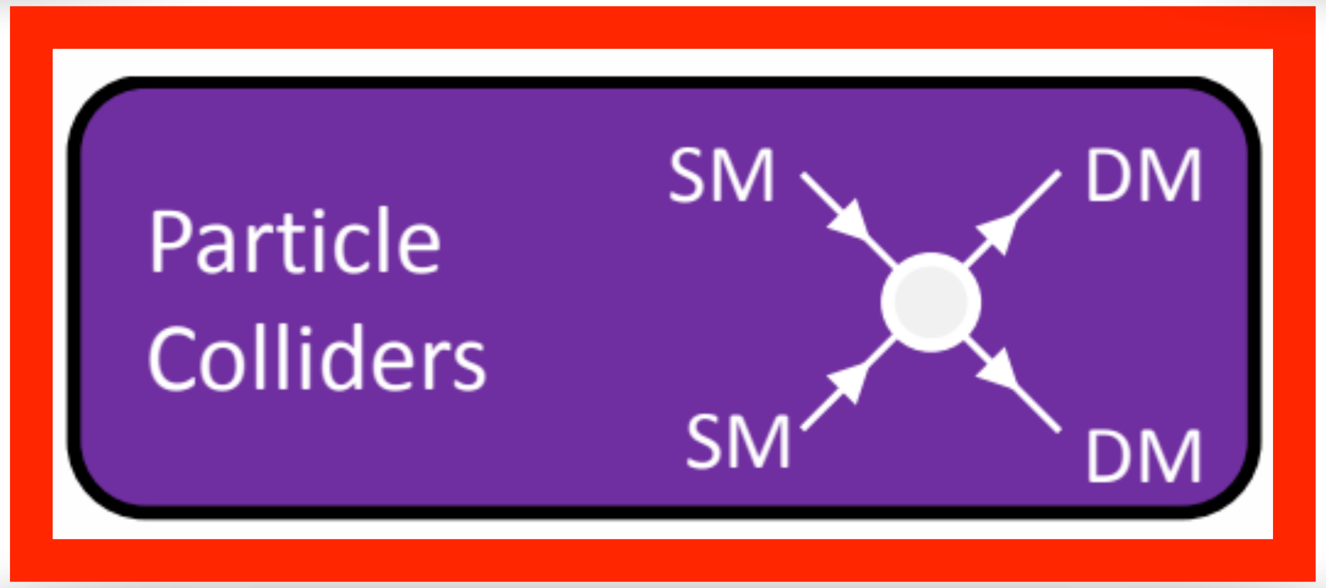


Seek evidence for DM particle interactions with targets in terrestrial detectors
- Nucleons, nuclei, electrons, photons …
- May prove DM but not identify particle





Seek evidence for annihilation or decay products of DM particles trapped in galactic / solar / planetary potential wells
- X-rays, gamma rays, neutrinos, anti-matter …
- May prove DM but not identify particles



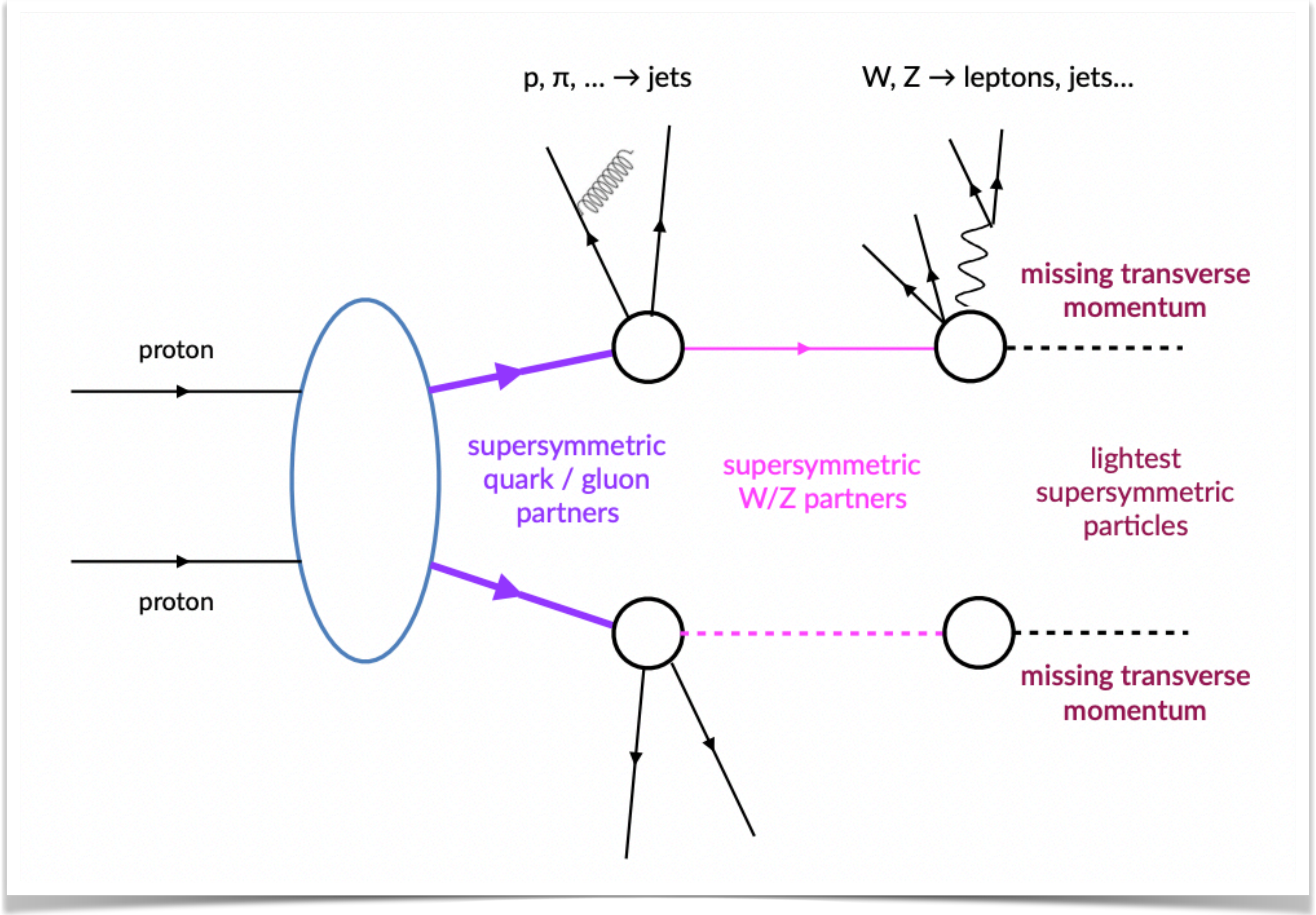
Seek evidence for invisible particle production in SM particle collisions
- May identify particle but cannot prove DM

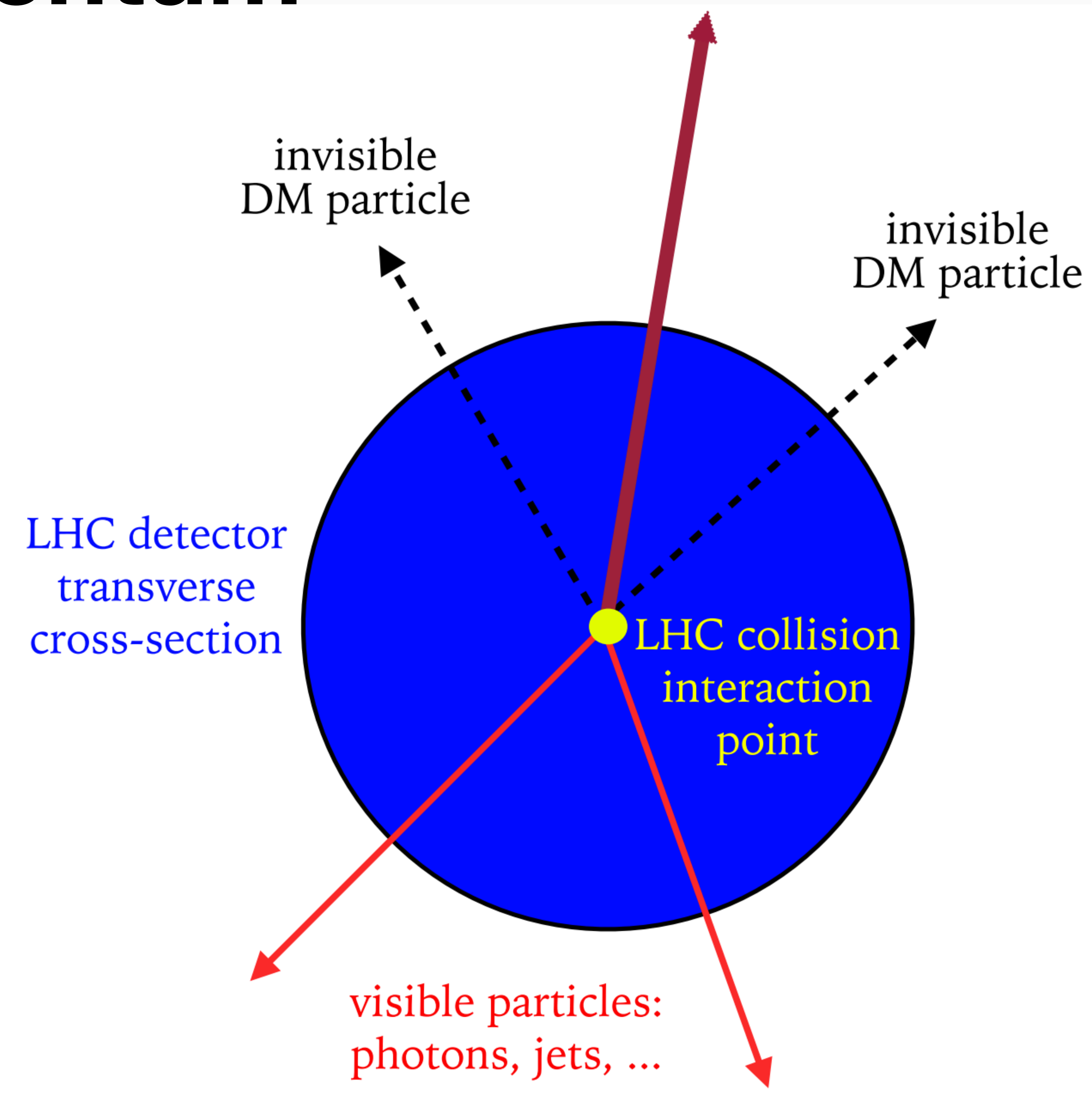
Pingo

- What is dark matter?
  - 1) WIMP
  - 2) Axion
  - 3) MACHOs (Massive Compact Halo Objects)
  - 4) Sterile Neutrinos
  - 5) Primordial black whole
  - 6) None of the above
  - 7) I don’t have an opinion

Dark Matter Searches at Colliders

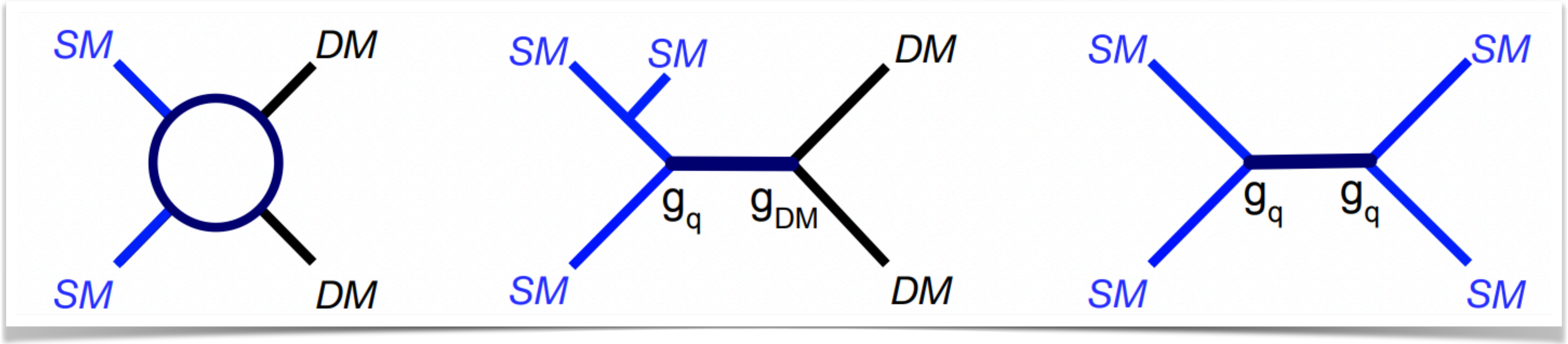
- DM particle do not leave visible signatures in collider experiments
- DM inferred using missing energy, missing mass, or **missing transverse momentum**





EFT approach

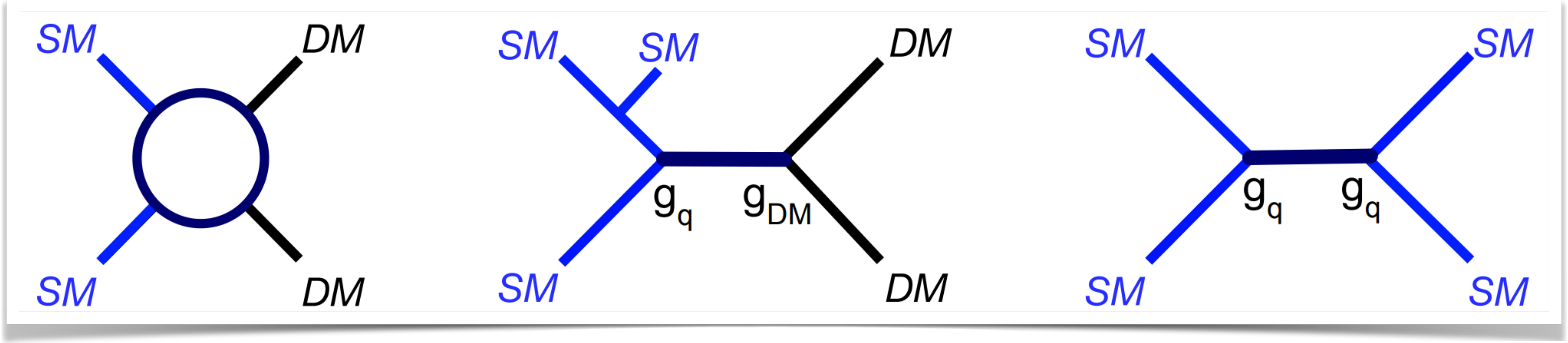
Simplified Model

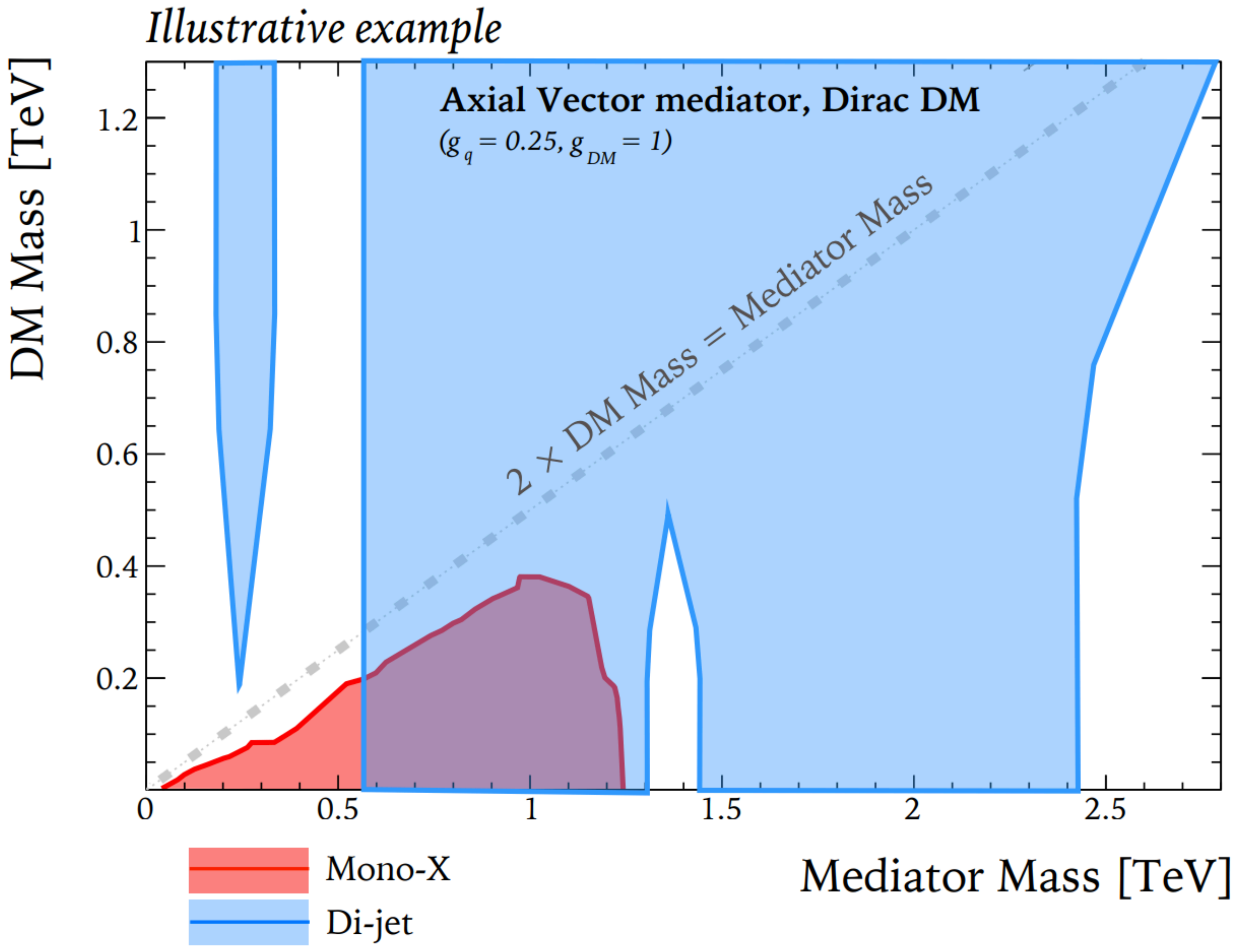


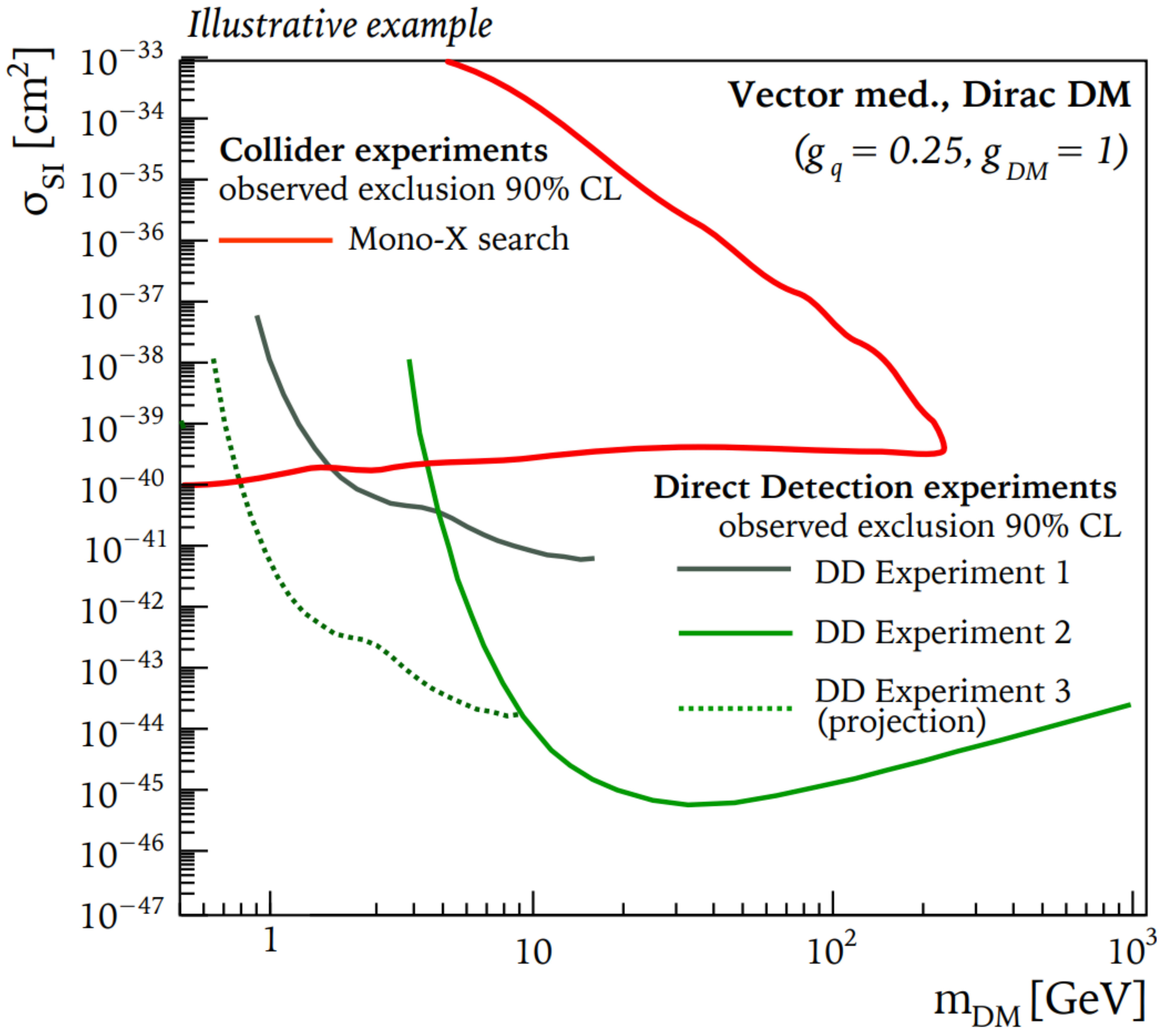
Source: arXiv:1912.12739

Dark Matter Searches

EFT approach Simplified Model

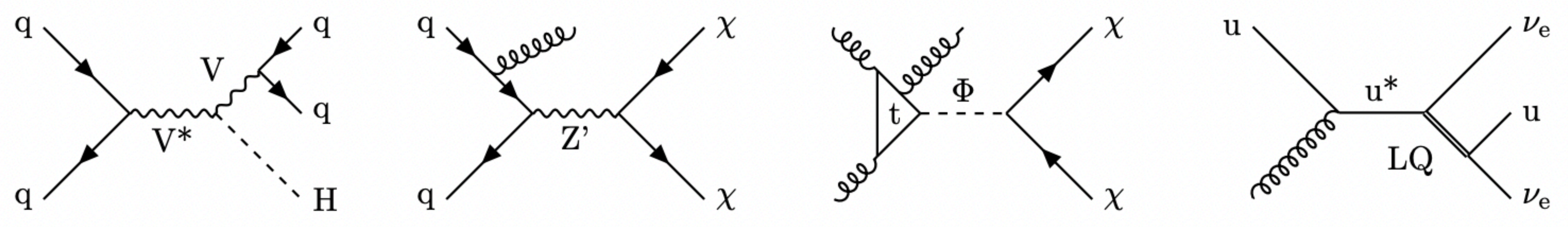


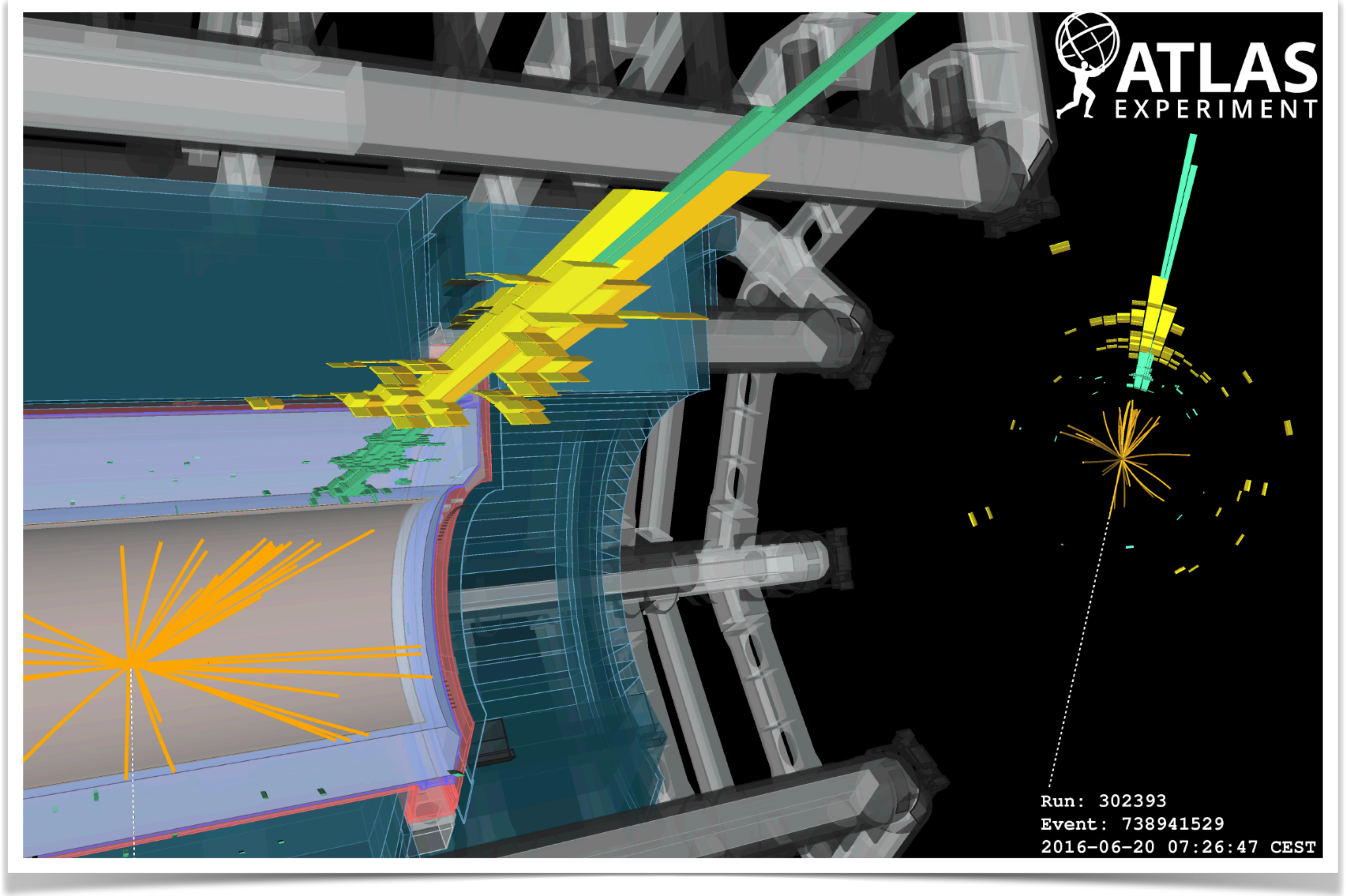




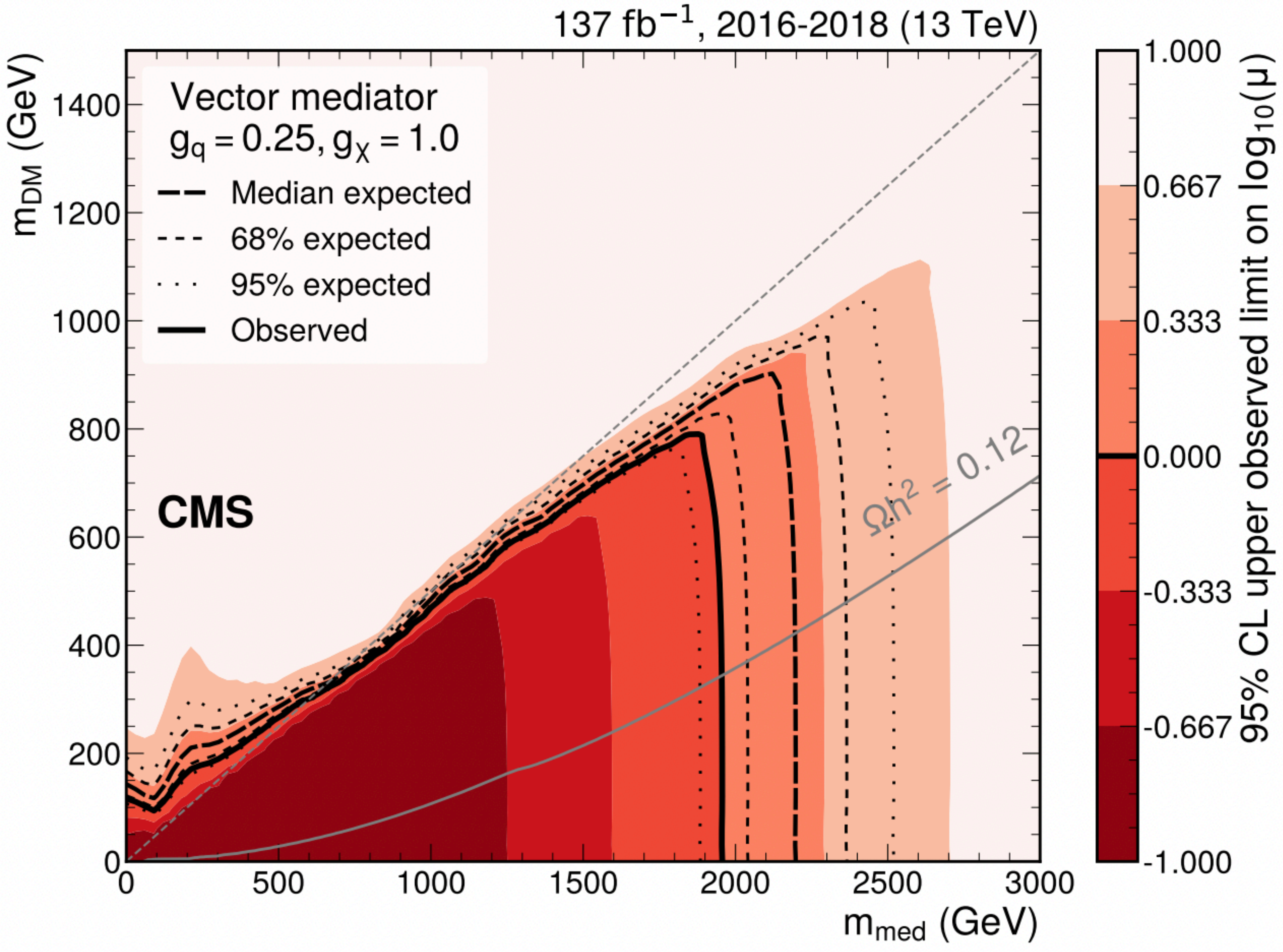
Dark Matter Searches

- Mono-jet analysis



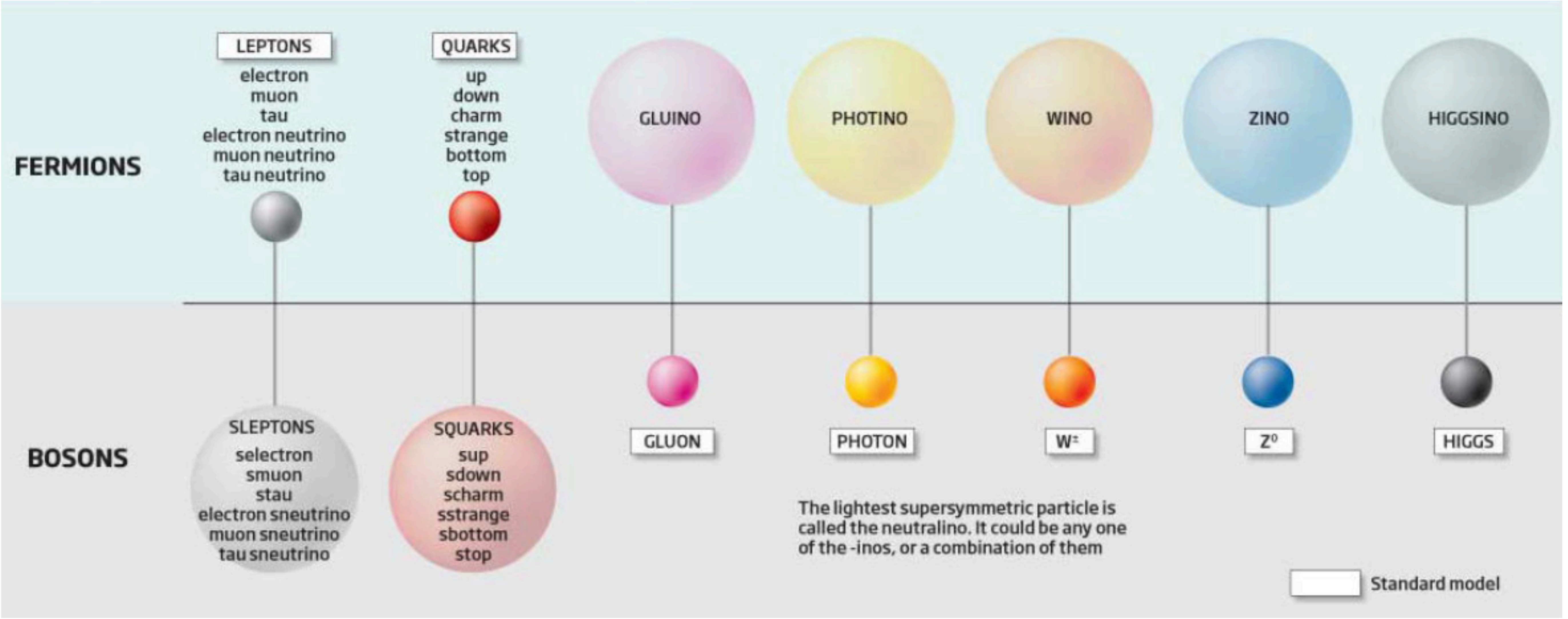


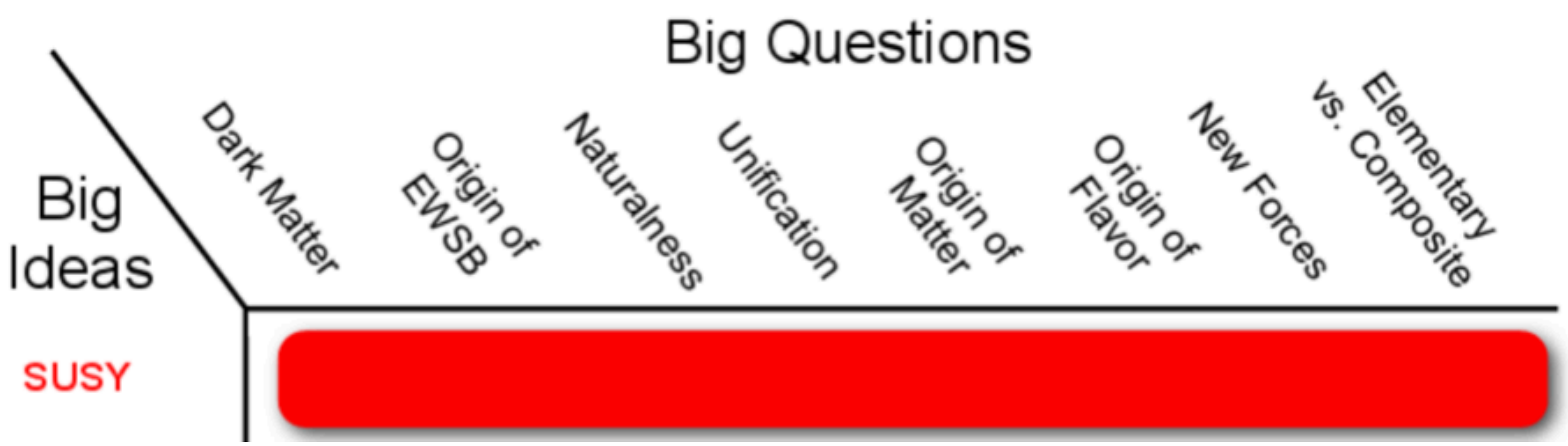
Impressive event with ~1.7 TeV jet
and ~1.7 TeV missing transverse energy



Direct Searches for Supersymmetry

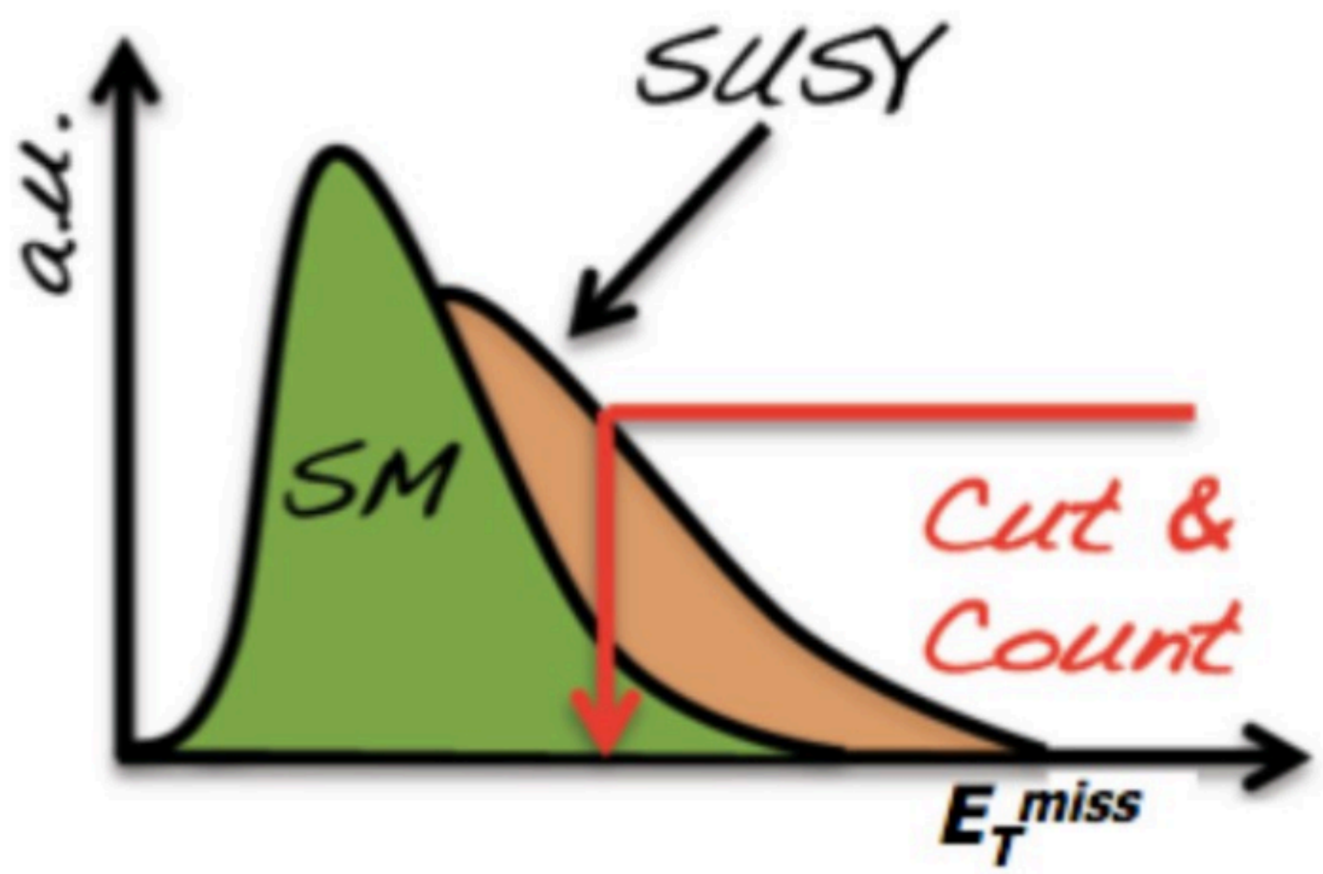
- Generalization of the space-time symmetries of QFT that transforms bosons and fermions and vice versa
- Provides a framework to answer many questions and puzzles in particle physics
- If SUSY were an exact symmetry of nature, particles and superpartners would differ in spin by 1/2 and degenerate in mass. Superpartners have not been observed!

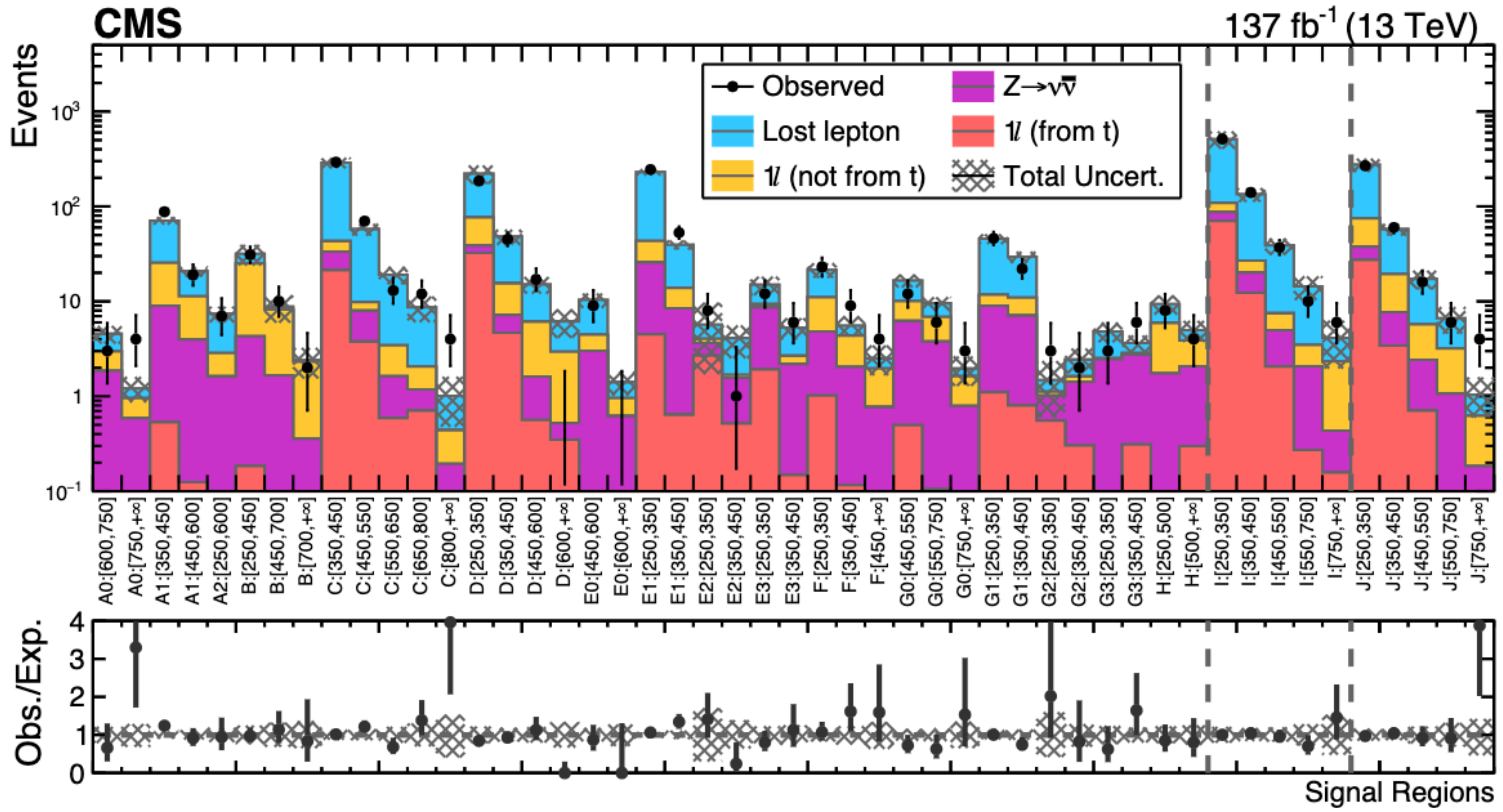




Direct Searches for Supersymmetry

- General strategy and typical SUSY signatures
  - High-pT jets from heavy squark and gluinos
  - Missing momentum from two LSPs produced at the end of a decay chain
  - Electroweakino decays with leptons
- Selection variables
  - H_T, E_T^{miss}, m_{eff}, …
  - Long-lived particles
  - …





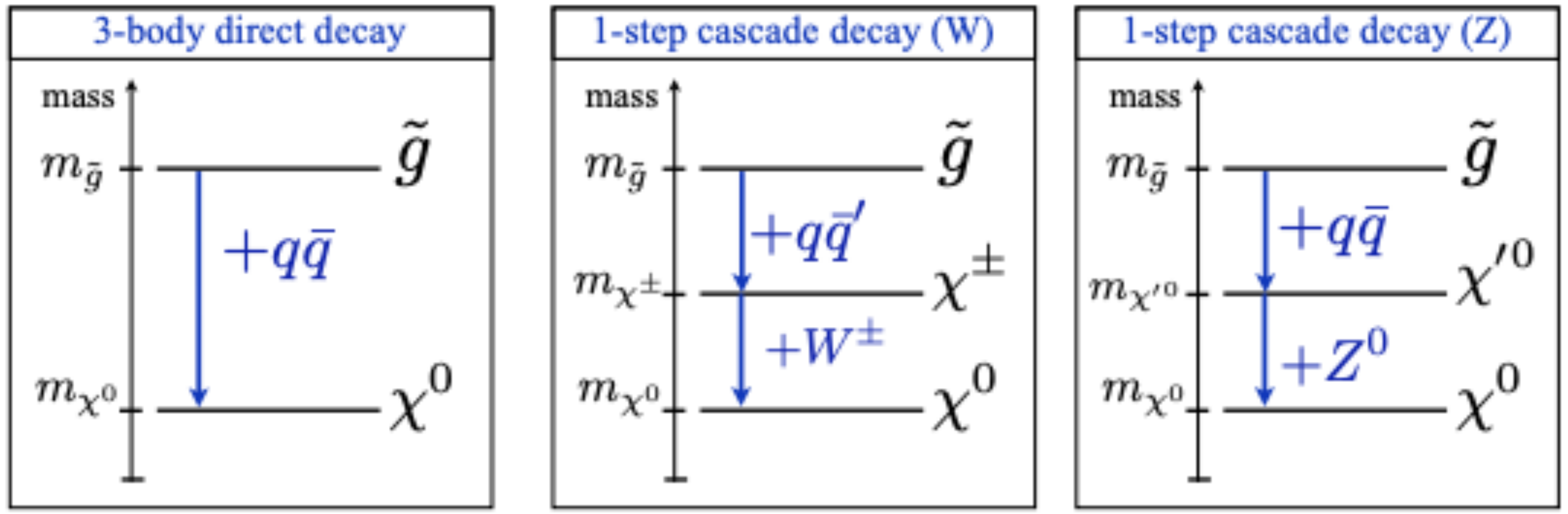
	N_J	t_{mod}	$M_{\ell b}$ [GeV]
A	2–3	> 10	≤ 175
B	2–3	> 10	> 175
C	≥ 4	≤ 0	≤ 175
D	≥ 4	≤ 0	> 175
E	≥ 4	0–10	≤ 175
F	≥ 4	0–10	> 175
G	≥ 4	> 10	≤ 175
H	≥ 4	> 10	> 175

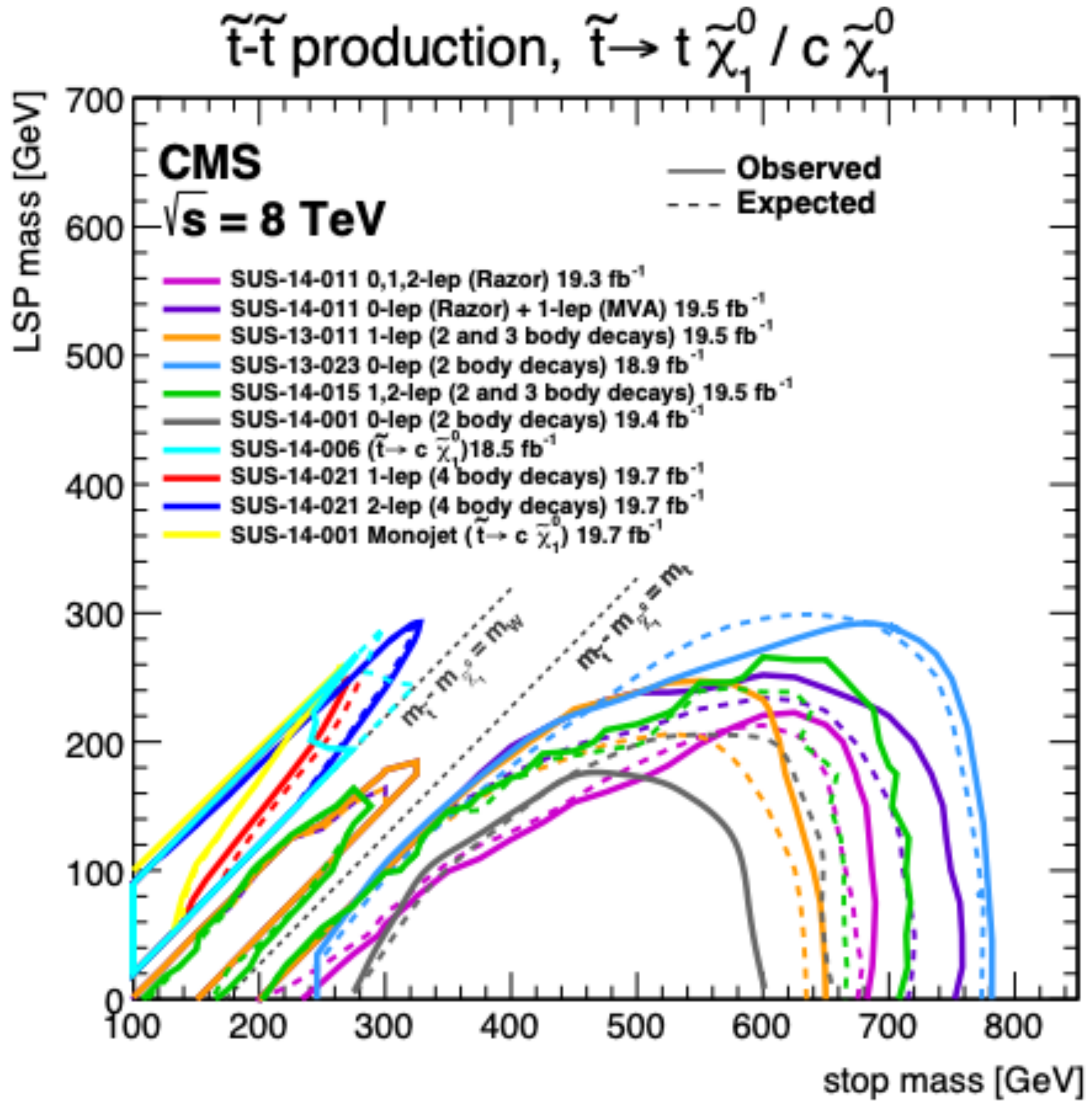
X0: Inclusive
X1: Untagged
X2: Merged t quark tag
X3: Resolved t quark tag

I: $N_J \geq 5$, $N_{b,med} \geq 1$
J: $N_J \geq 3$, $N_{b,soft} \geq 1$

Direct Searches for Supersymmetry

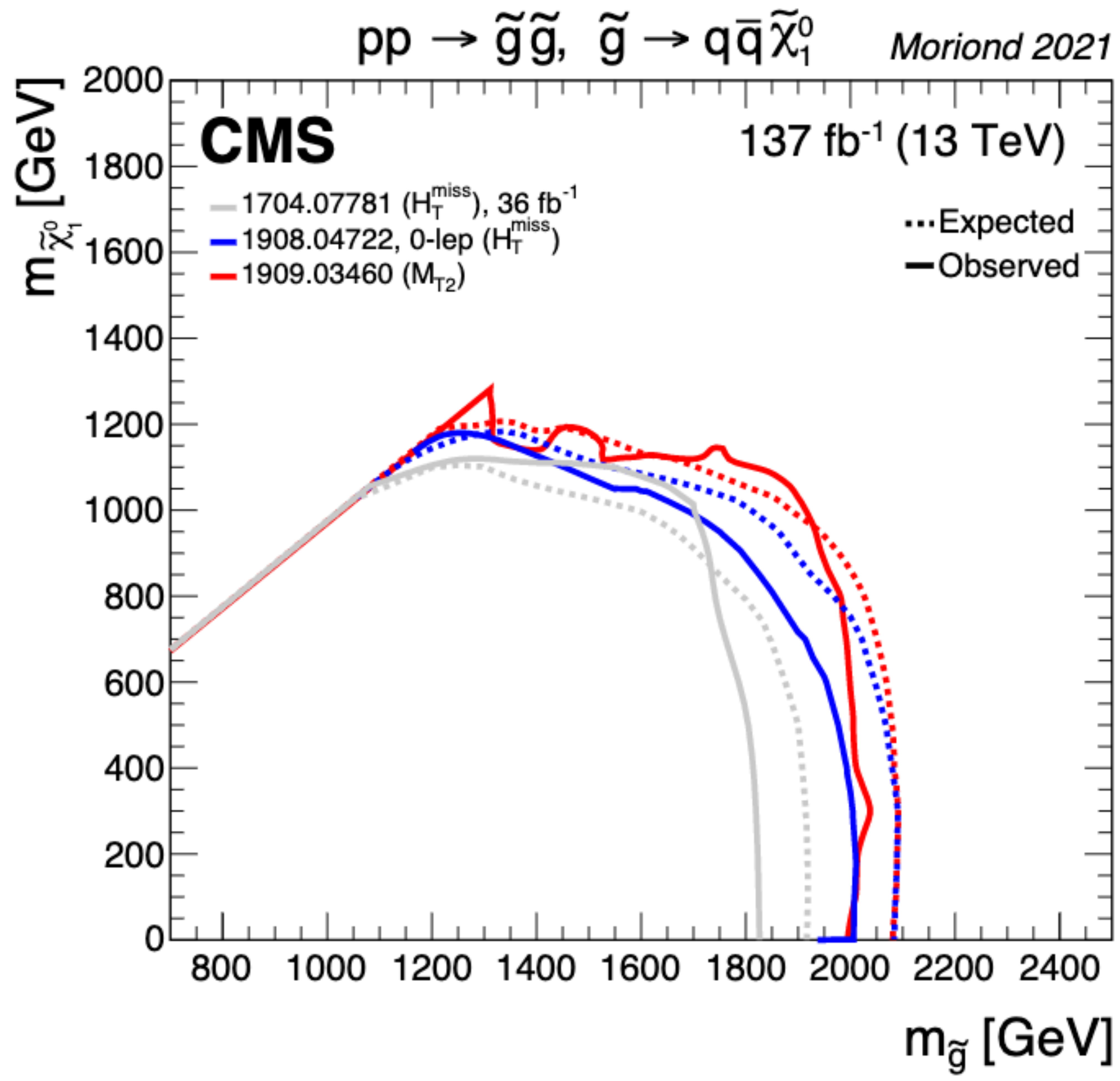
- Simplified models
- Historically, searches were performed on full SUSY models
  - In Run 1, simplified models became the standard
  - Focus on a specific process X decay chain
  - Interpret the analysis in this context
- Avoid tailored analysis for specific benchmarks
- More robust analysis strategies

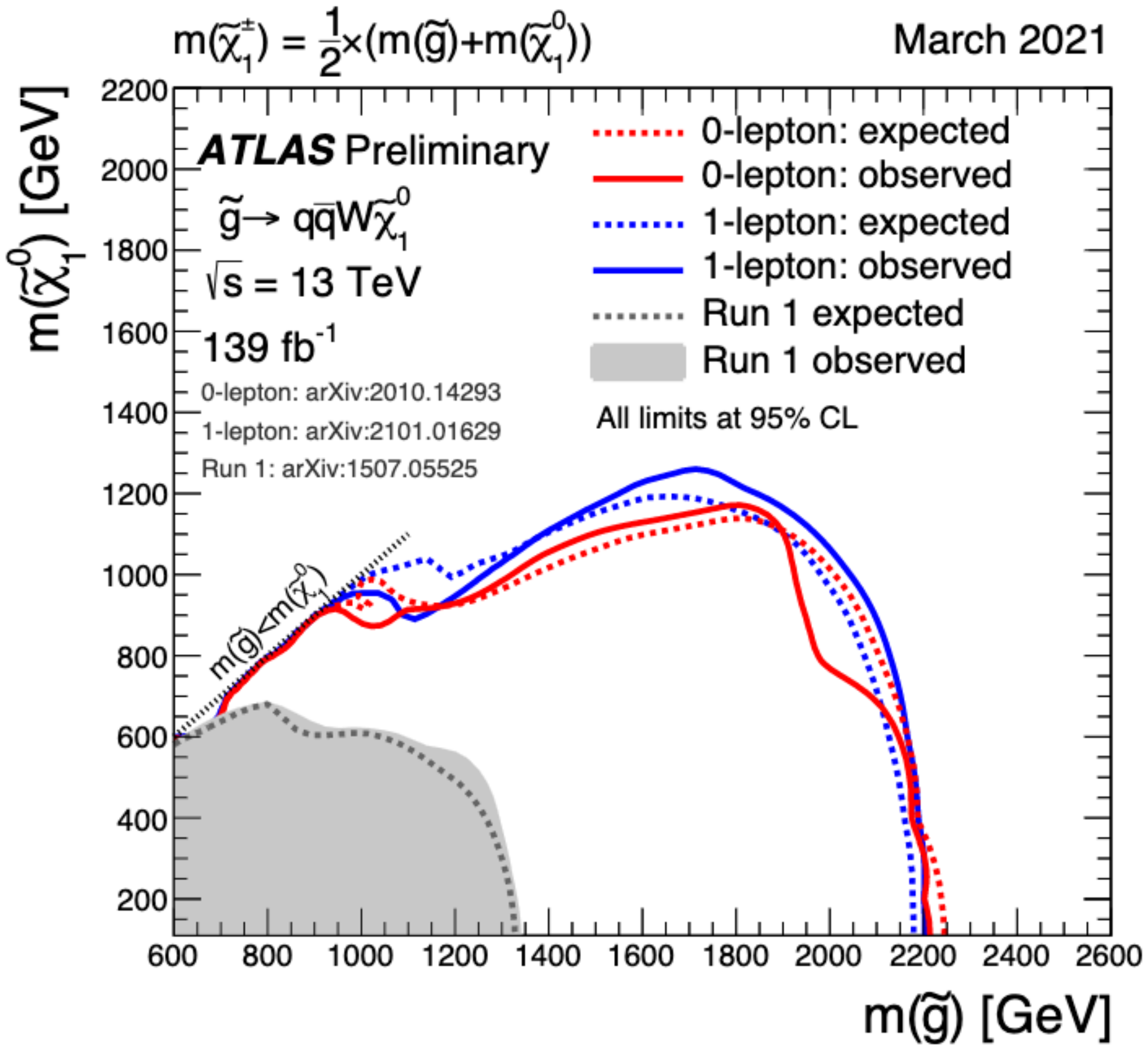




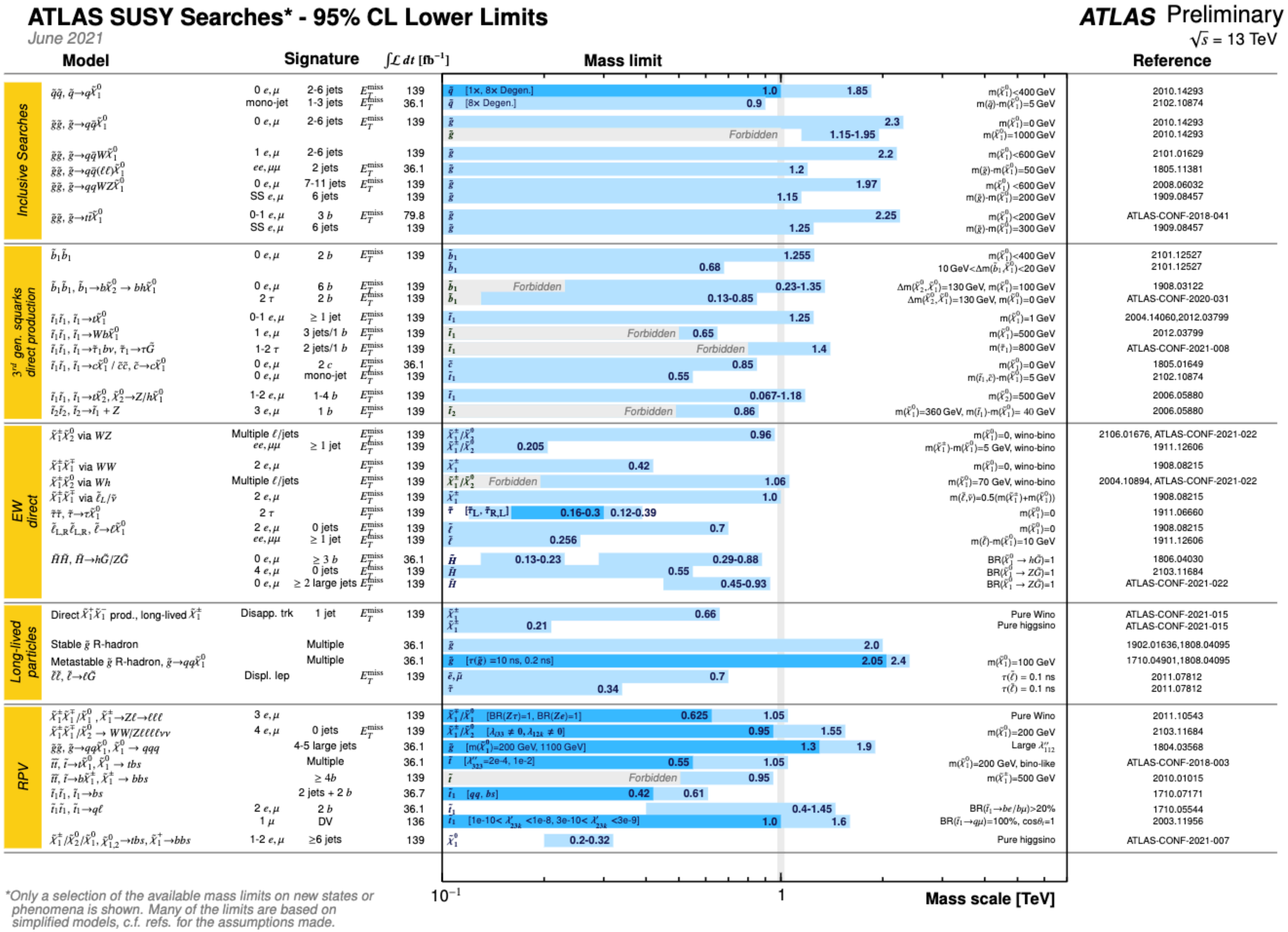
Direct Searches for Supersymmetry

- Gluino Searches



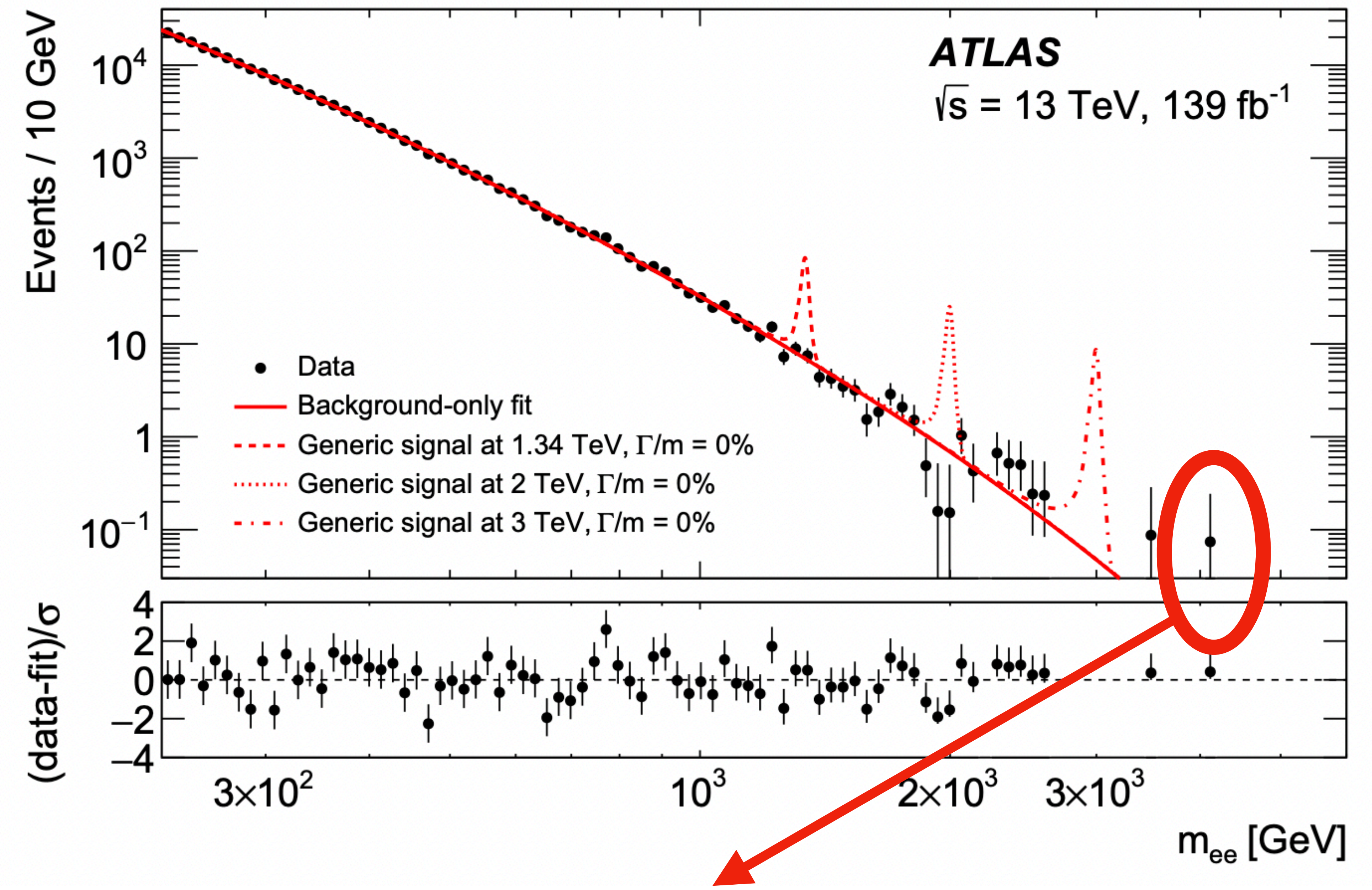


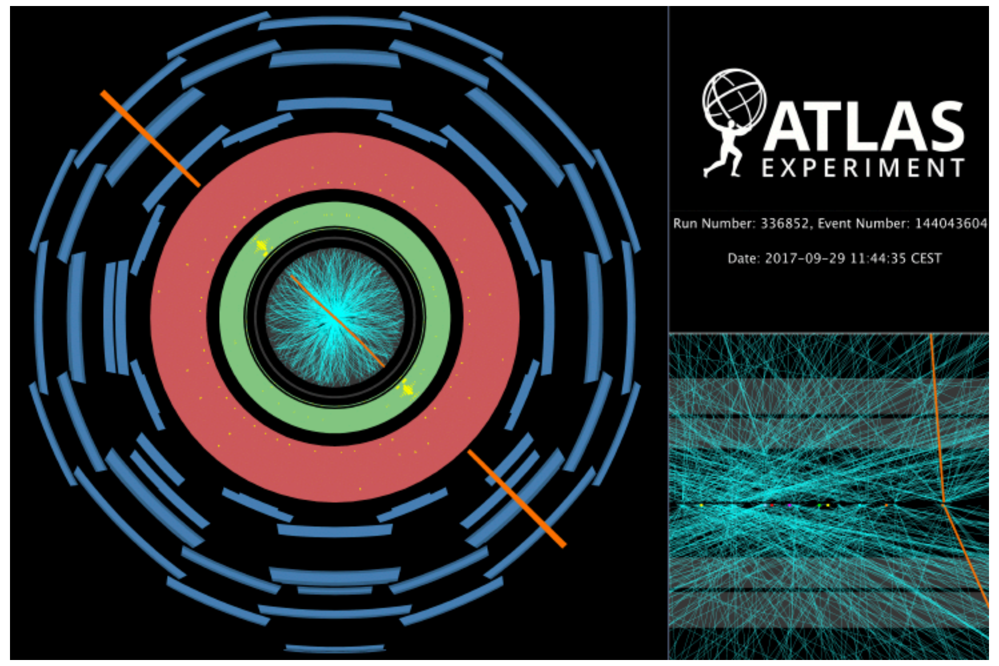
Direct Searches for Supersymmetry



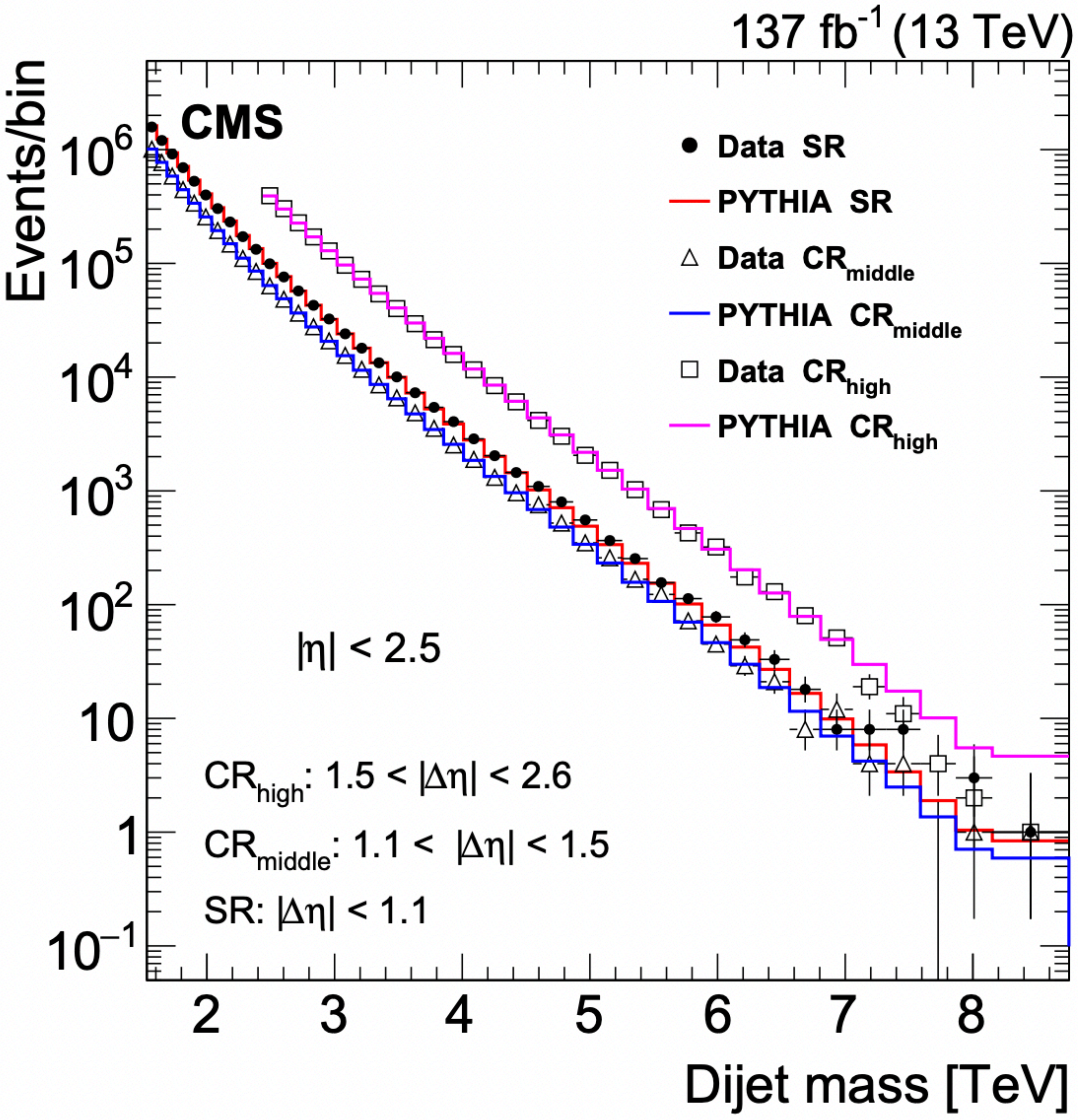
BSM Searches Beyond SUSY

- High mass resonances

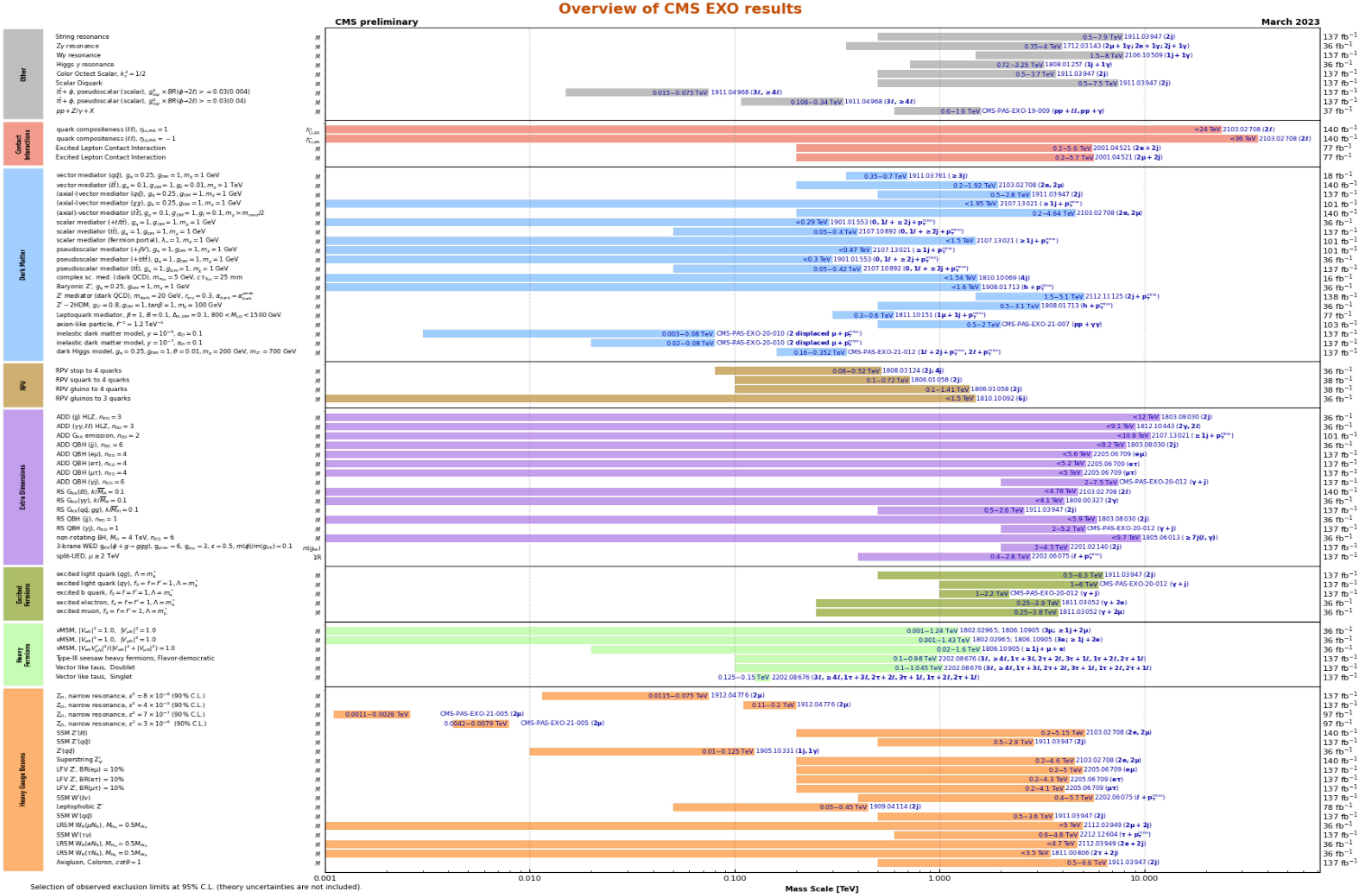




4 TeV di-electron Event

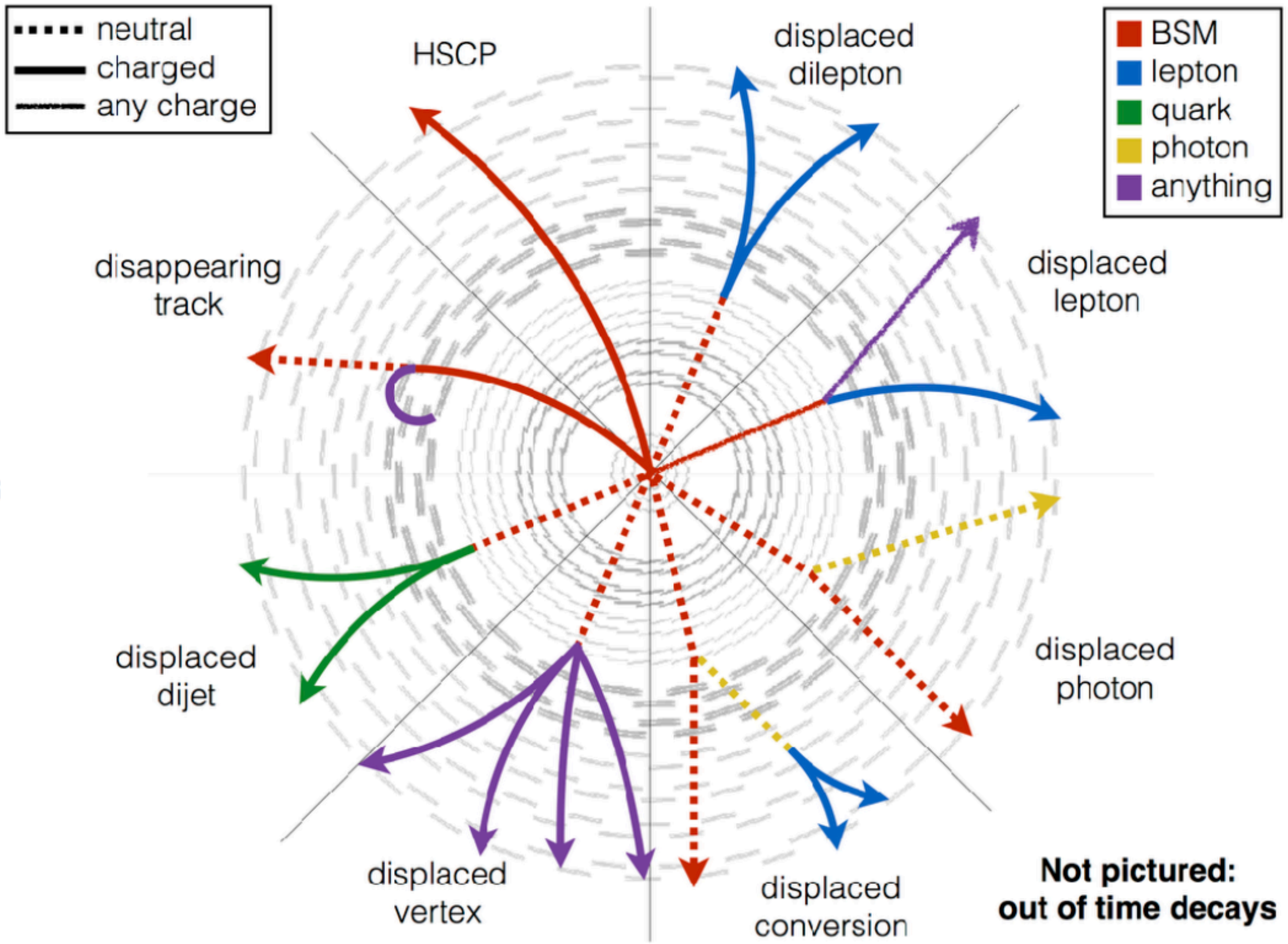


BSM Searches Beyond SUSY



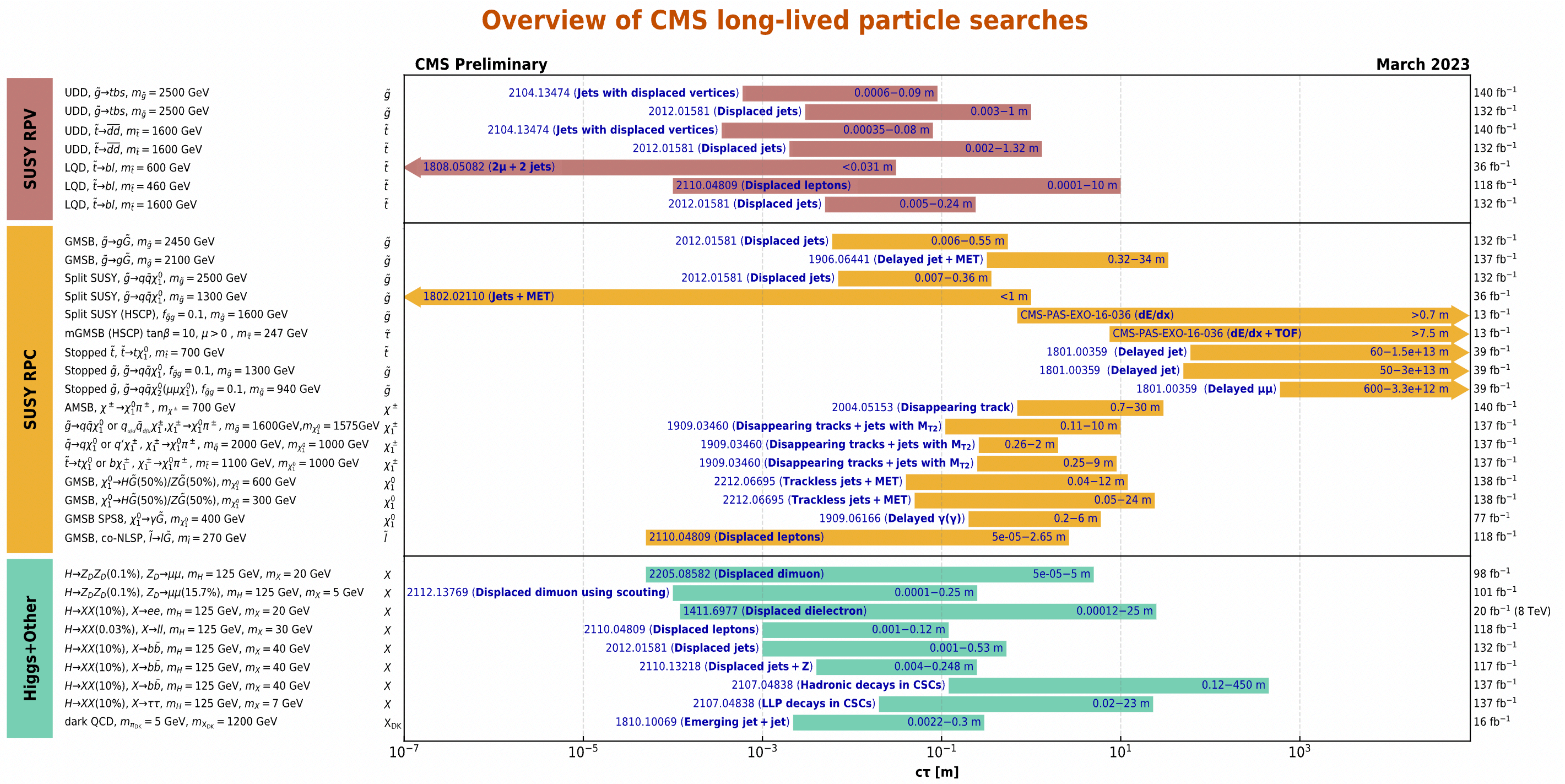
BSM Searches with Exotic Signatures

- Signatures depend on charge and lifetime
  - Muon-like particles with large mass (large dE/dx)
  - Track segments
  - Displaced particles (tracks, leptons, jets)
  - …
  - For very long lifetimes, particles can be trapped in calorimeters and decay after months



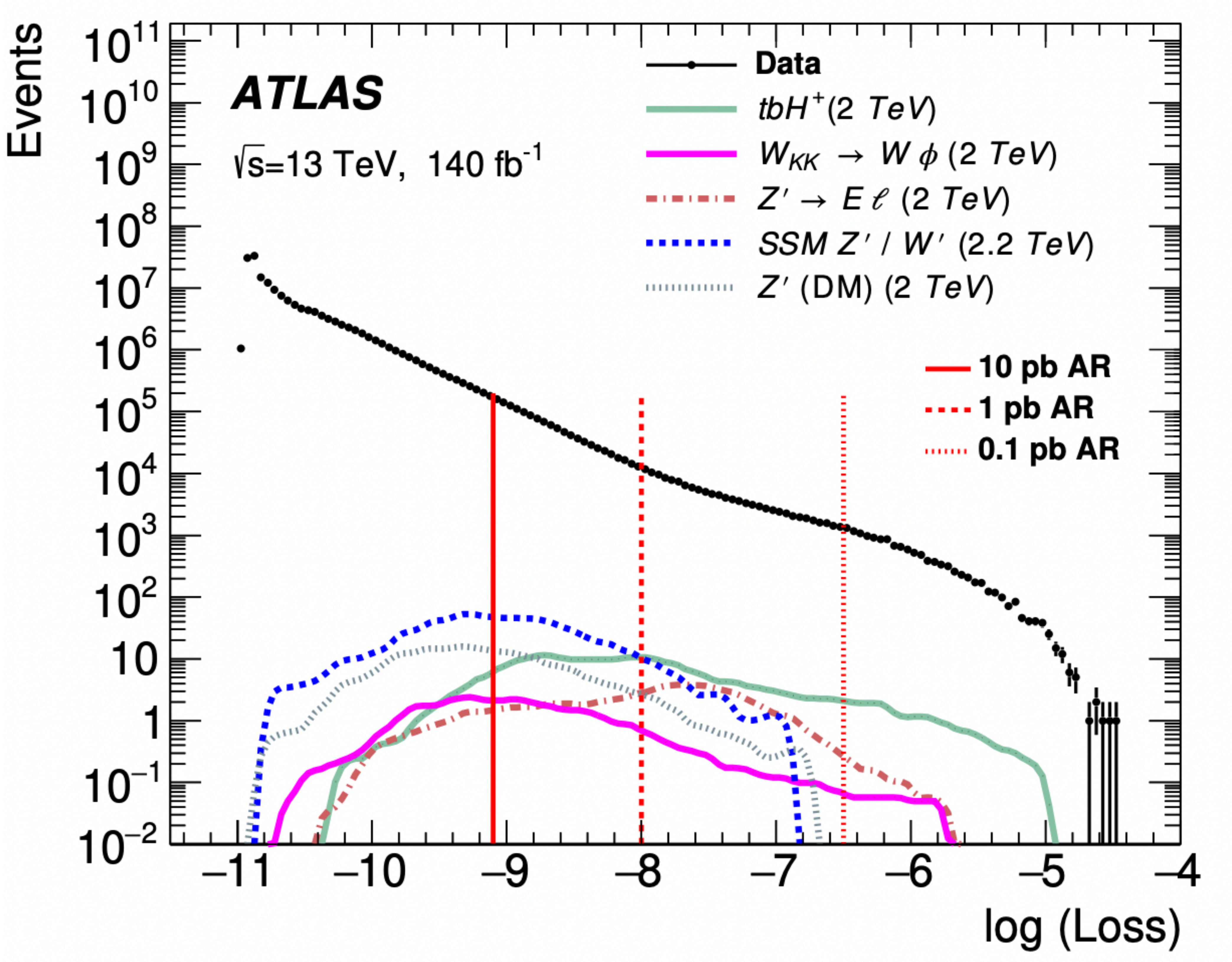
BSM Searches with Exotic Signatures

KIT Karlsruhe Institute of Technology

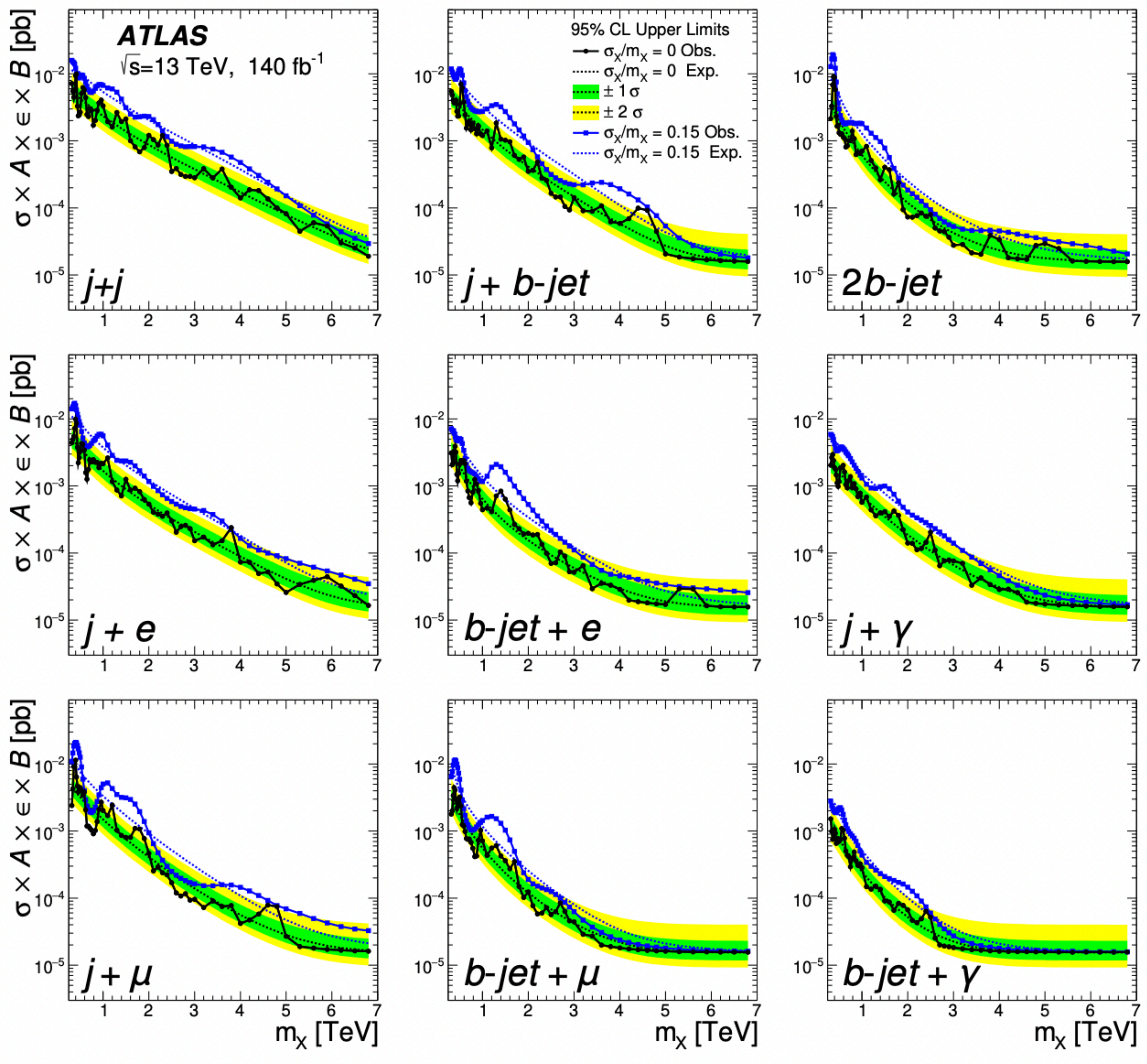


Let the machine search …

- Unsupervised machine learning with autoencoder for anomaly detection
- Mass spectrum analysed using bumb hunter with two different width assumption



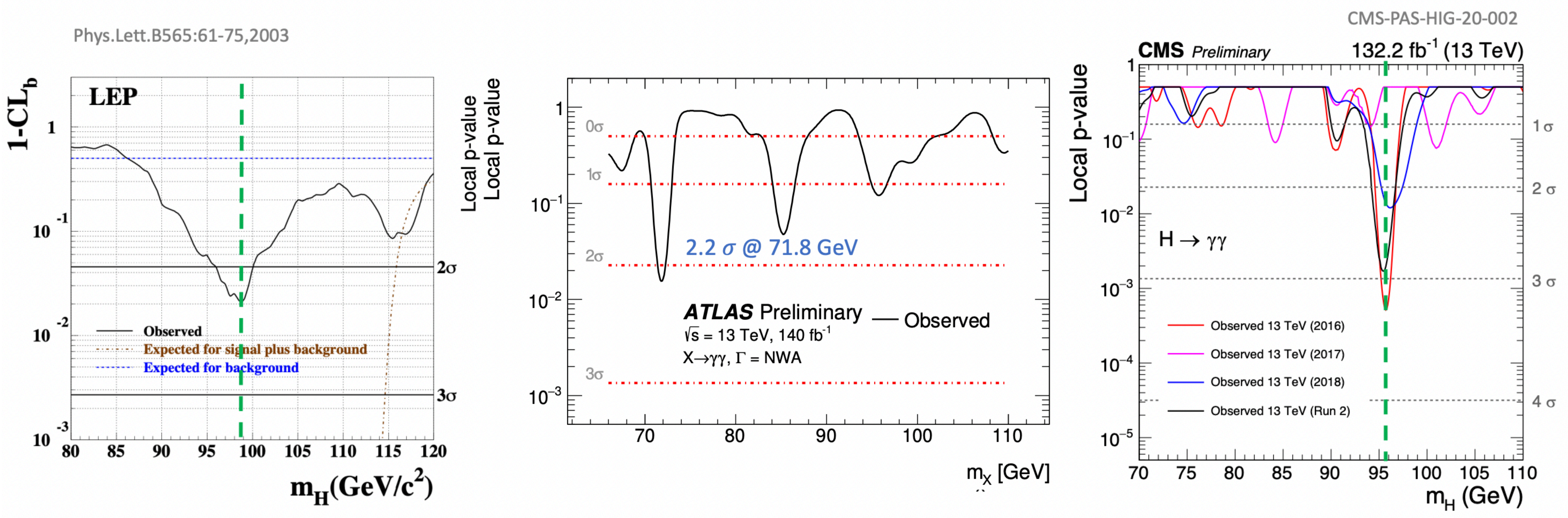
https://arxiv.org/abs/2307.01612



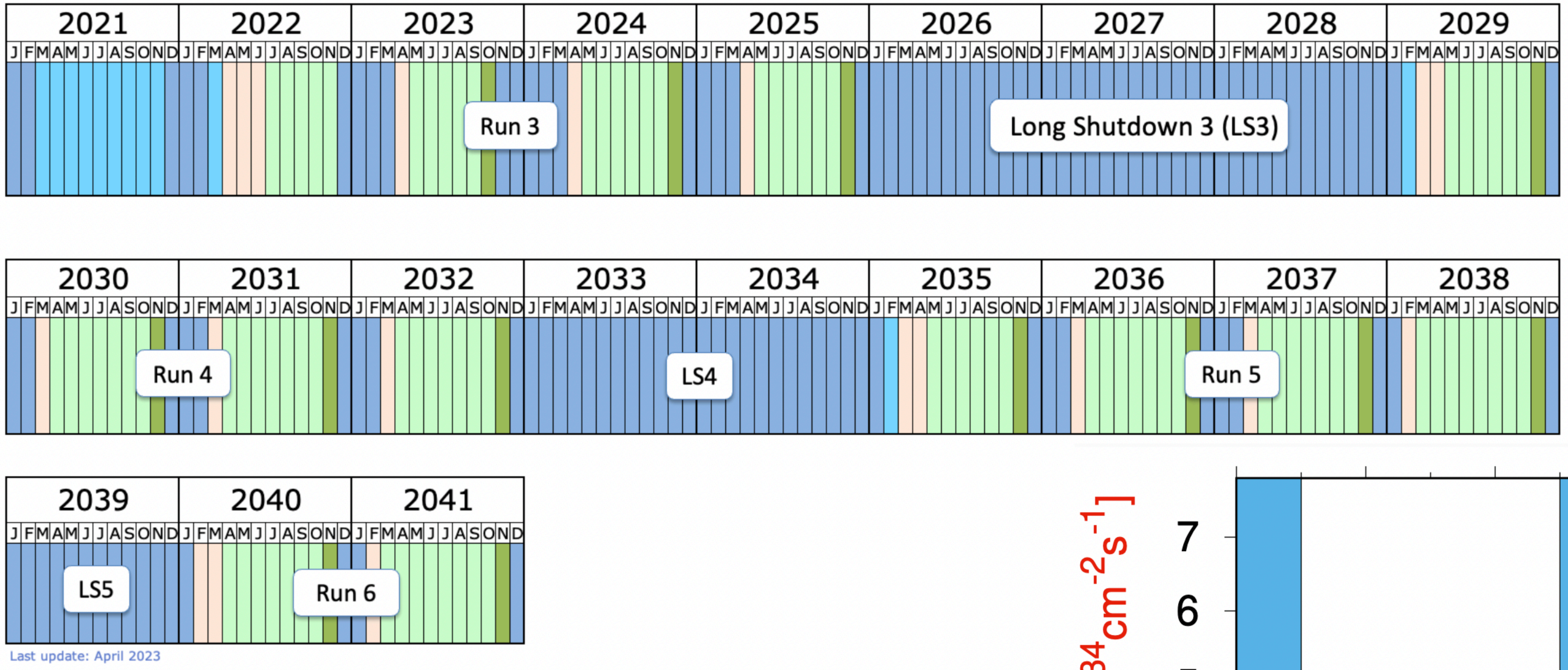
It's not all limits …

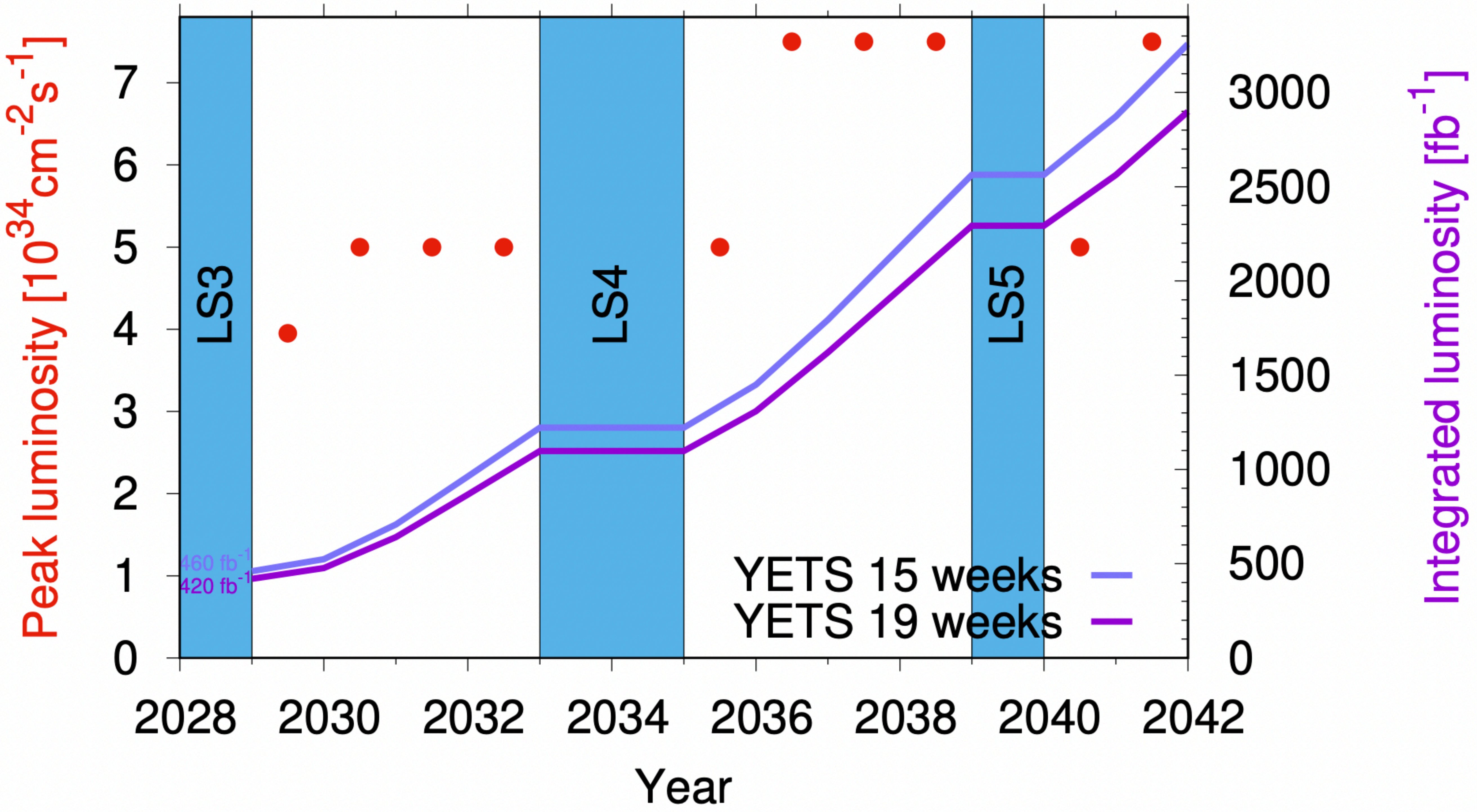
- Example: di-photon excess at 95 GeV

arXiv:2303.12018 arXiv:2306.03889



Towards the HL-LHC

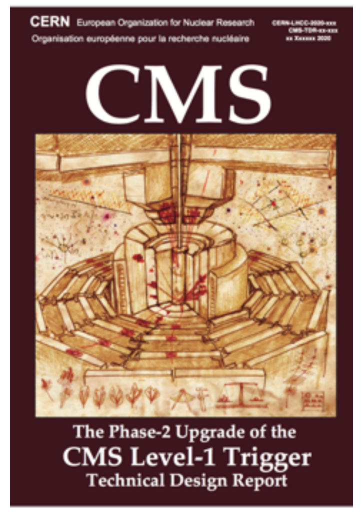




- Run 2: 140/fb
- Run 3: ~450/fb
- HL-LHC: ~3000/fb (~20 x today's dataset)

Towards the HL-LHC

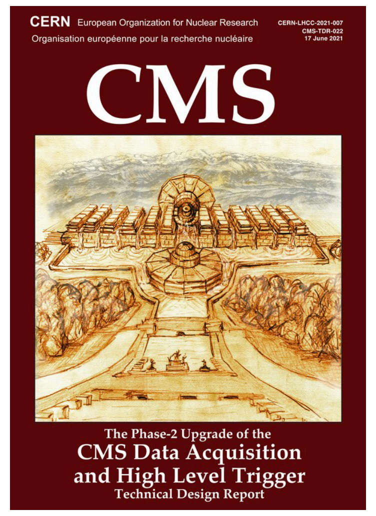
- ATLAS and CMS upgrades entering production



L1-Trigger

https://cds.cern.ch/record/2714892

- Tracks in L1-Trigger at 40 MHz
- Particle Flow selection
- 750 kHz L1 output
- 40 MHz data scouting



DAQ & High-Level Trigger

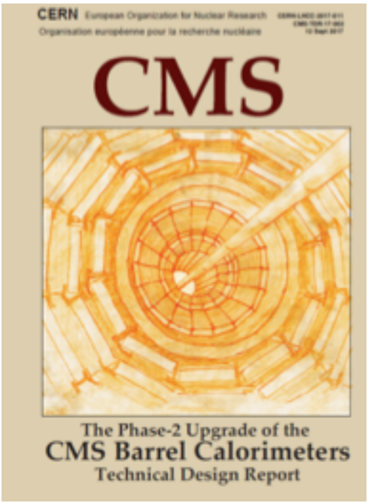
https://cds.cern.ch/record/2759072

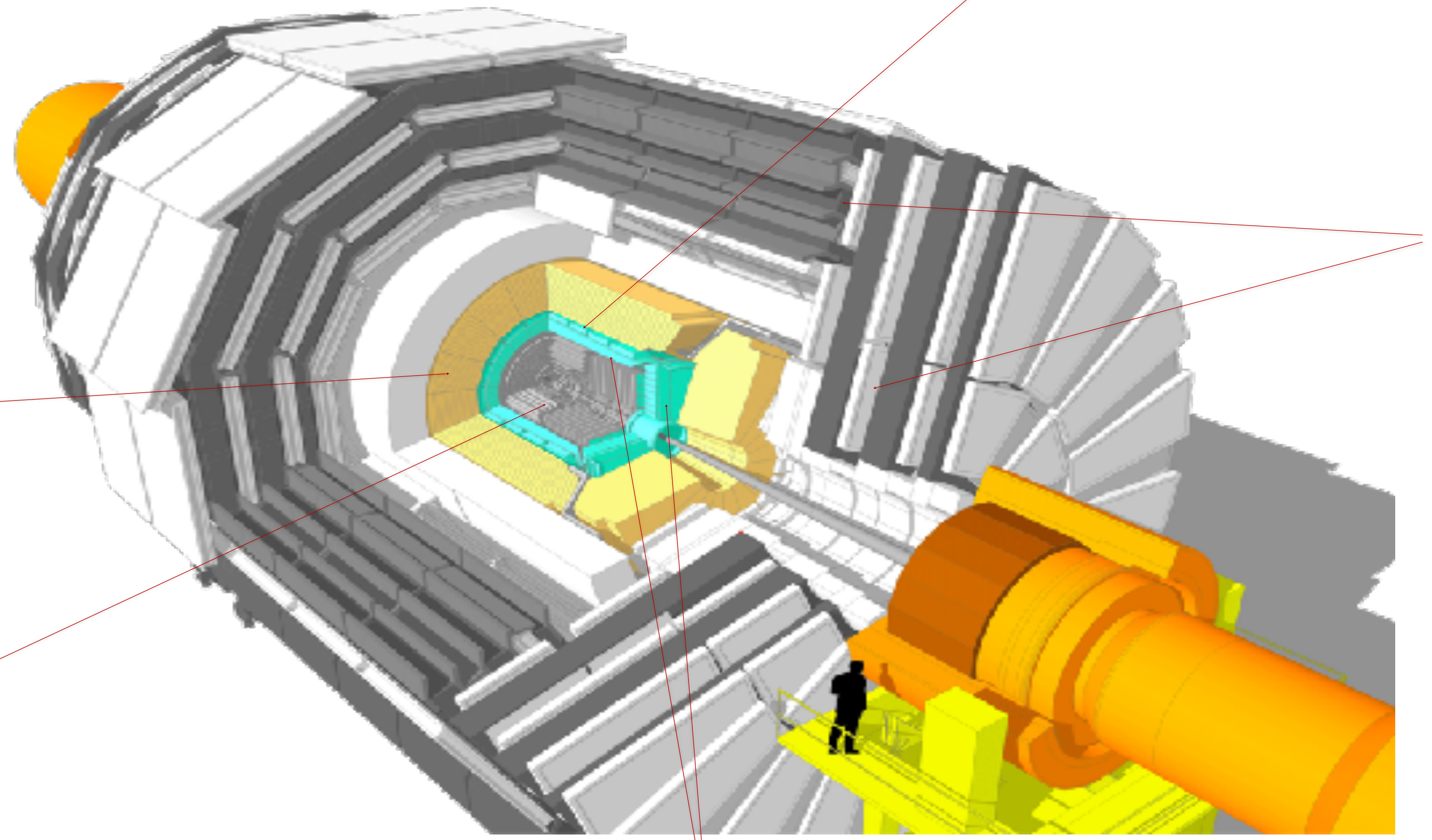
- Full optical readout
- Heterogenous architecture
- 60 TB/s event network
- 7.5 kHz HLT output

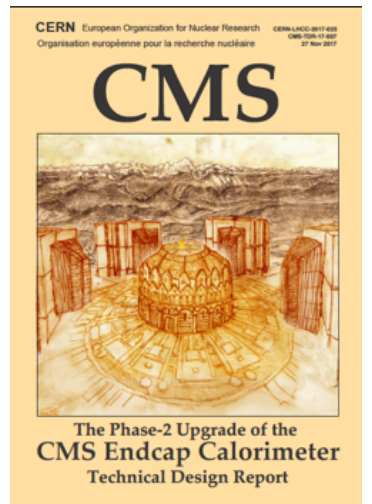
Barrel Calorimeters

https://cds.cern.ch/record/2283187

- ECAL single crystal granularity at L1 trigger with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards







Calorimeter Endcap

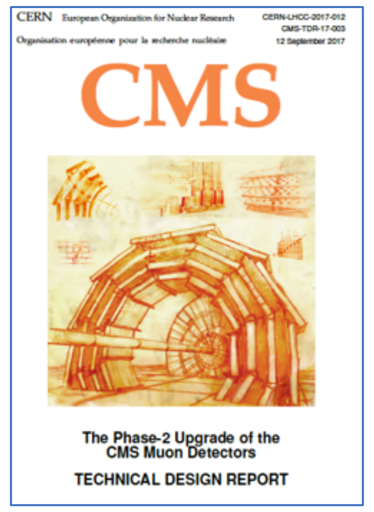
https://cds.cern.ch/record/2293646

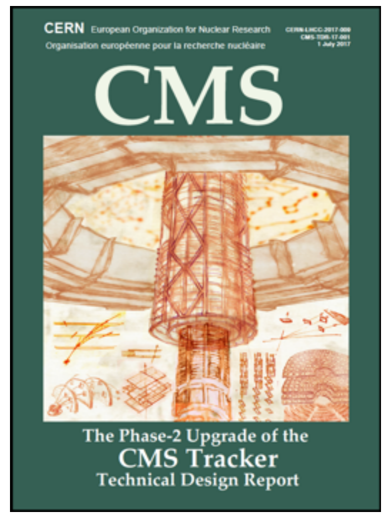
- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS

Muon systems

https://cds.cern.ch/record/2283189

- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC 1.6 < η < 2.4
- Extended coverage to η ≈ 3

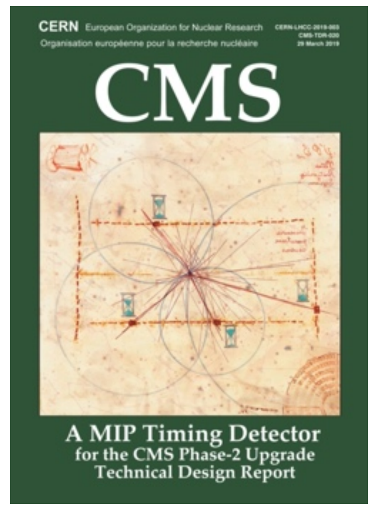




Tracker

https://cds.cern.ch/record/2272264

- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to η ≈ 3.8



MIP Timing Detector

https://cds.cern.ch/record/2667167

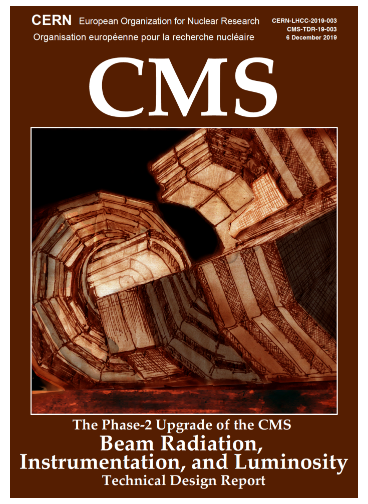
Precision timing with:

- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

Beam Radiation Instr. and Luminosity

http://cds.cern.ch/record/2759074

- Beam abort & timing
- Beam-induced background
- Bunch-by-bunch luminosity: 1% offline, 2% online
- Neutron and mixed-field radiation monitors

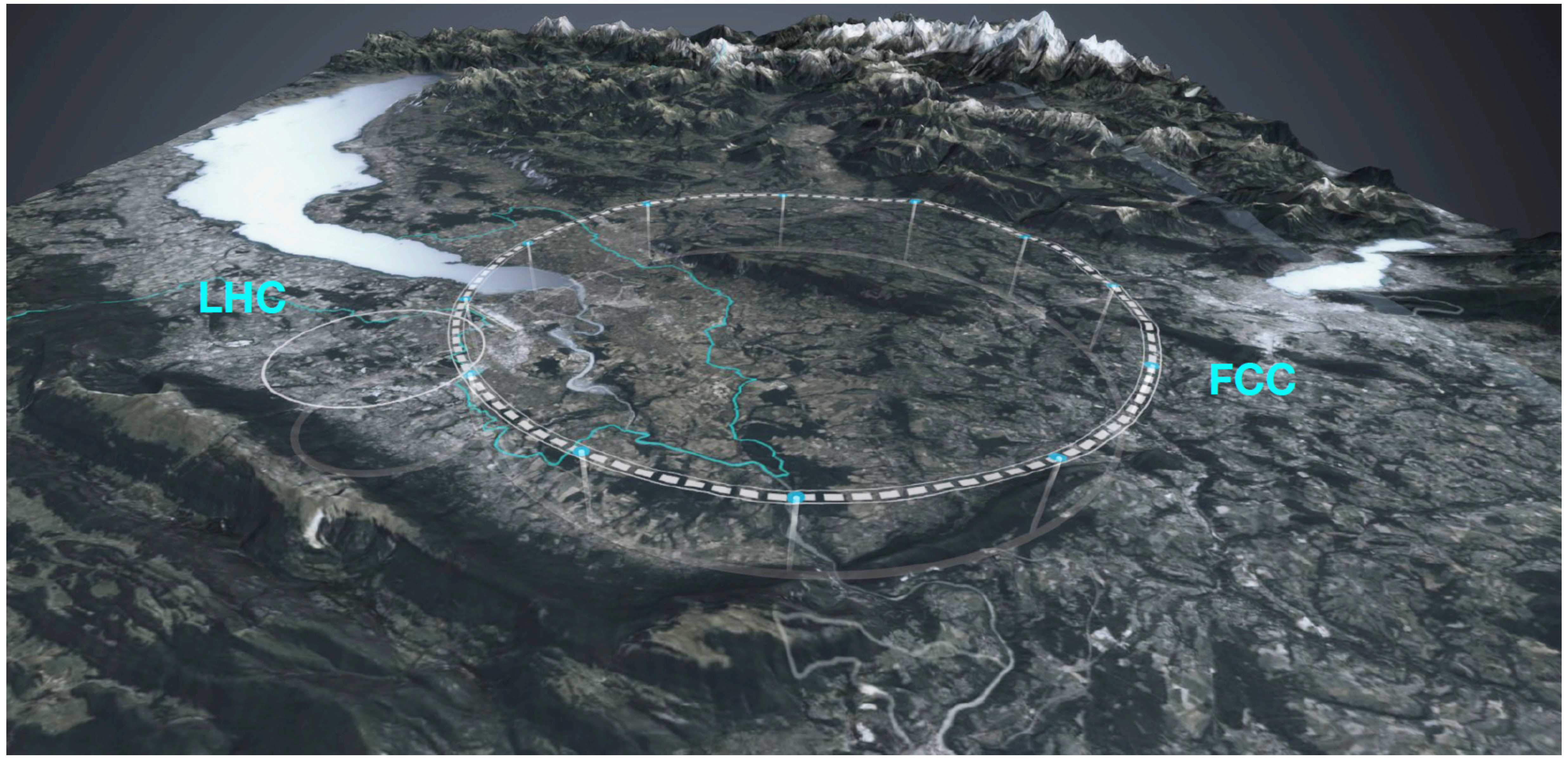


Quiz

- Why do you think the Standard Model is incomplete?
- How should a “good” extension of the Standard Model look like?
- How can we search for DM at the LHC?
- How can we study energy scales beyond the reach of the LHC?
- What is the most exciting opportunity at CERN for you?

Conclusion

- We have seen a broad physics program from ATLAS and CMS highlighted by the discovery of the Higgs Boson
- There are many **open fundamental questions** in particle physics
- **New tools** are available to address these questions
- The (physics) program of the LHC is filled with **exciting opportunities** for you!
- Outlook:



References and further reading

- Textbooks
  - Modern Particle Physics by Mark Thomson
  - QCD at Colliders by Ellis, Stirling, and Weber
- Pictures
  - CERN Document Server
  - Wikipedia
  - Or reference on page
- References
  - Previous CERN Summer Lectures - https://indico.cern.ch/category/97/
  - MIT's OCW 8.701 and 8.811
  - KIT's Particle Physics master courses (you can contact me)
  - Public results from ATLAS, CMS, and LHC combination groups
  - Or reference on page