Direct Searches from New Physics at the LHC

From Run 2 to the HL-LHC era

On behalf of the LHC Collaborations

Iacopo Vivarelli - PASCOS 2026 - Sheffield - 22-26/6/2026

Istituto Nazionale di Fisica Nucleare

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

This talk includes AI-generated images produced with GPT 5.5 and input from the author

Introduction

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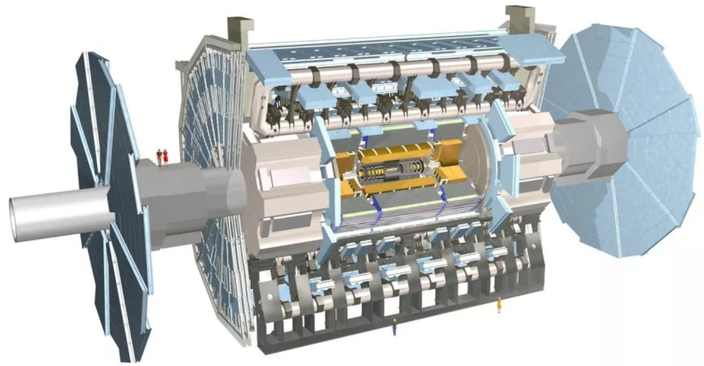
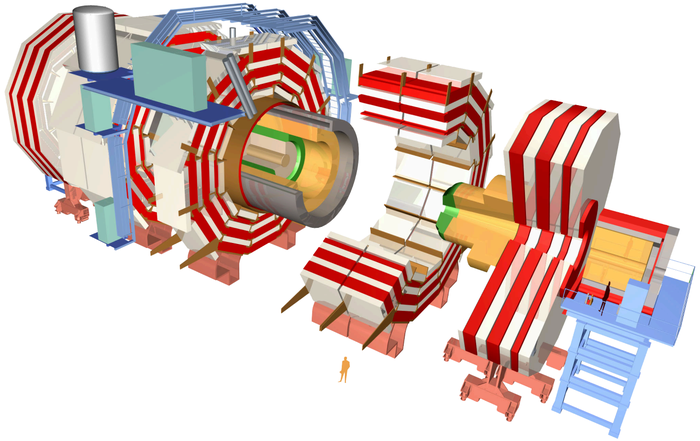
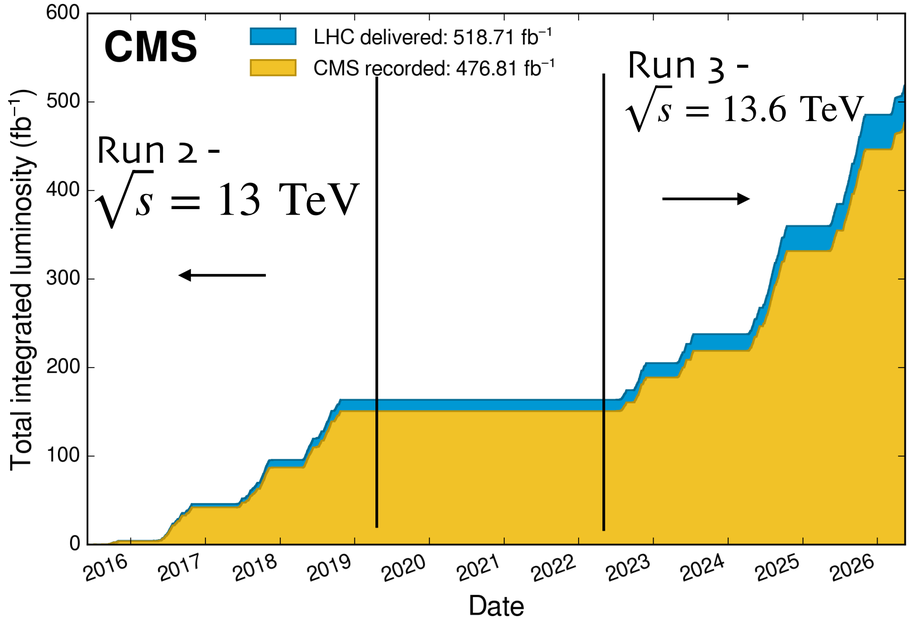
- A quick journey from **LHC early days** to the (immediate) future: an overview of **personal favourites** (based on the effort going into the analyses):
  - And also **a celebration to the creativity** of the LHC collaborations.
- On the menu for today:
  - Chapter 1: **resonances and the dark sector** - from simple to challenging scenarios
  - Chapter 2: **compressed scenarios** - a physics-driven strive to improve detector reconstruction.
  - Chapter 3: taking the most from the detector for **long-lived particle searches**.
  - Chapter 4: **a glance into HL-LHC**

ATLAS & CMS






CMS
LHC delivered: 518.71 fb⁻¹
CMS recorded: 476.81 fb⁻¹
Run 2 -
$\sqrt{s} = 13$ TeV
Run 3 -
$\sqrt{s} = 13.6$ TeV
Total integrated luminosity (fb⁻¹)
0
100
200
300
400
500
600
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
Date


LHC
High luminosity LHC
Run 2
Long shutdown 2
Run 3
Long shutdown 3
Run 4 - 5...
...
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
...
140 fb-1
Recorder ~480 fb-1 per experiment
3000 - 4000 fb-1

The textbook search for new physics

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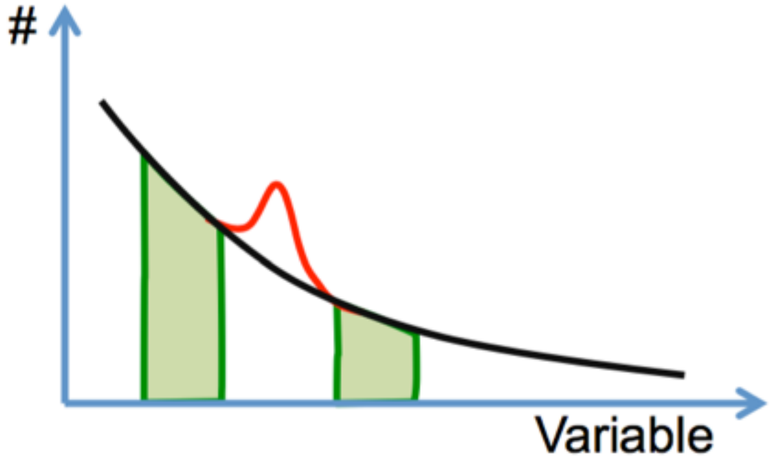
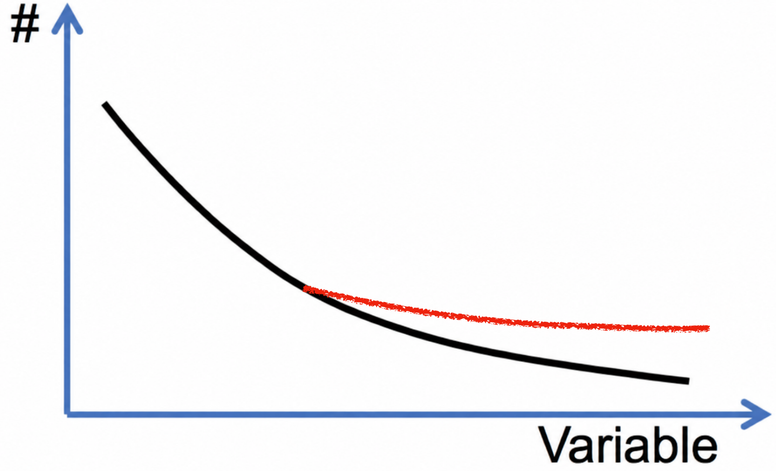
- "Back in my days" new physics searches meant:
  1. Look for a resonance over a smooth background.
  2. Look for an excess of events over a distribution
- Things have changed a bit…





Among other things:
- Stunning **detector stability** and understanding
- Exquisite **quality of reconstruction** enabling study of **complex final states**
- **Dedicated triggers** and increased bandwidth
- Advanced **machine learning techniques**

Always going above and beyond $\sqrt{\mathcal{L}}$

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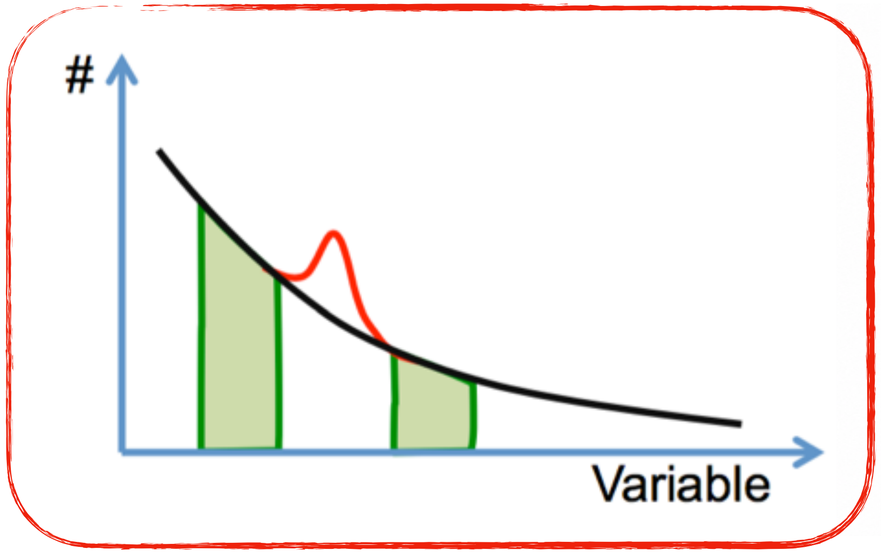

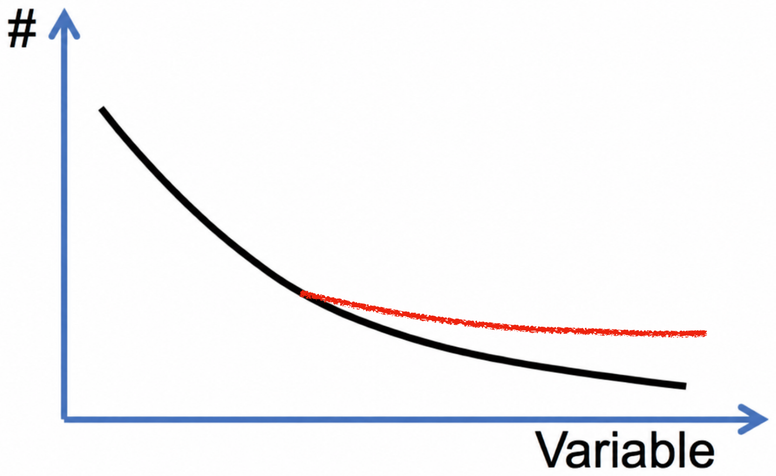

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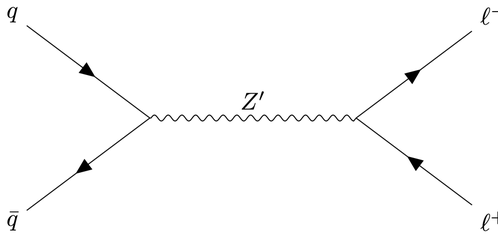
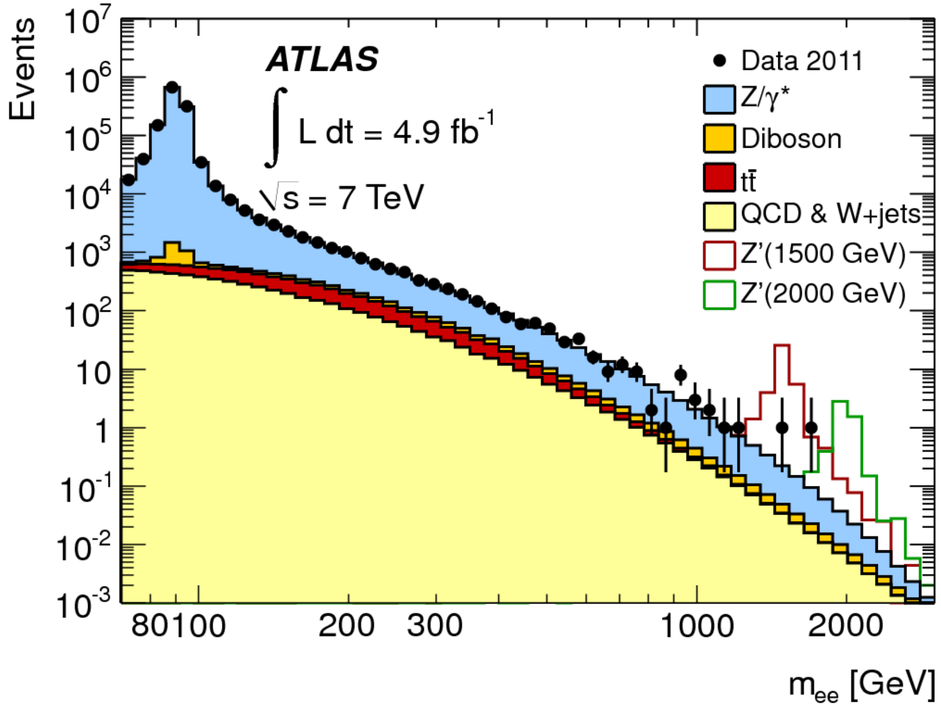
Chapter 1: resonance and the dark sector

See also D. Hayden and S. Sekmen at LHCP

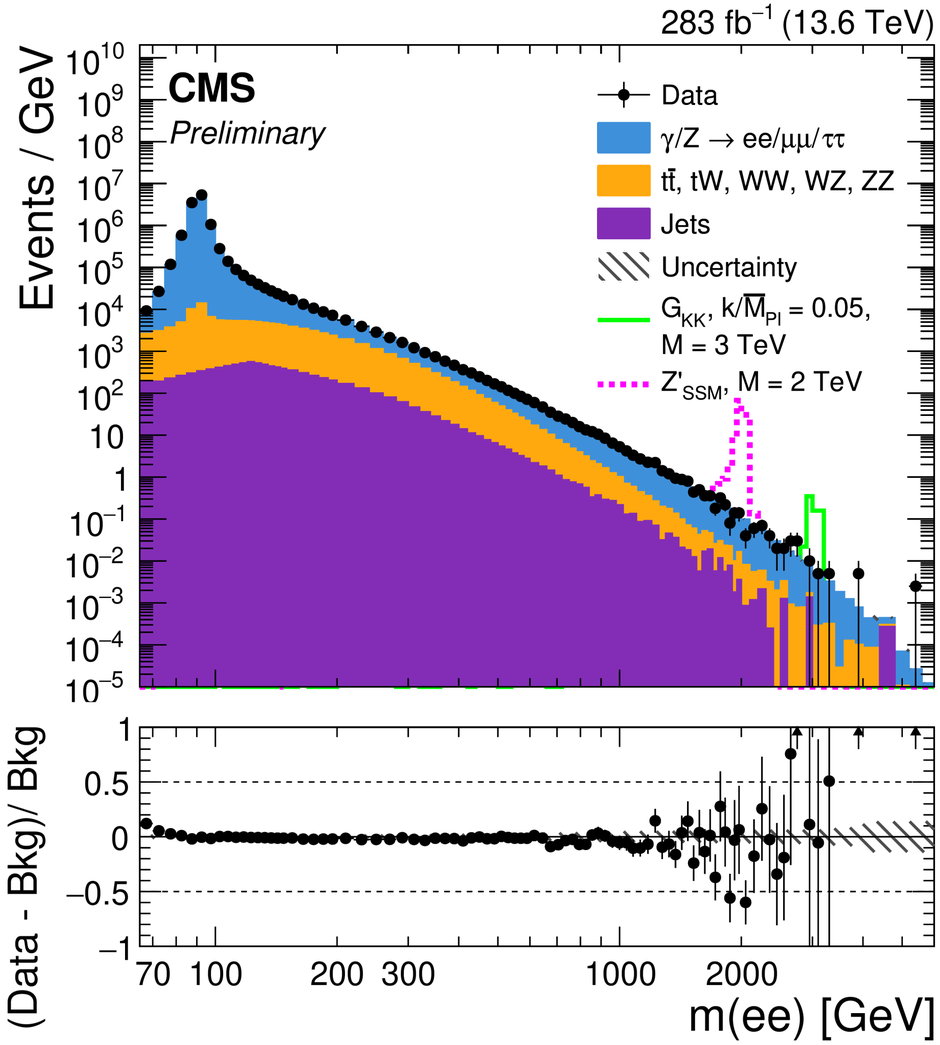
"Easy" new physics does not appear to exist….



- Dilepton resonances, from the first to the latest result
  - For example, limit to Z'_{SSM} grew from ~ 2.2 TeV to ~ 5.5 TeV



CMS-PAS-EXO-25-021



Low-mass resonances with data parking

CMS-PAS-EXO-2025-019

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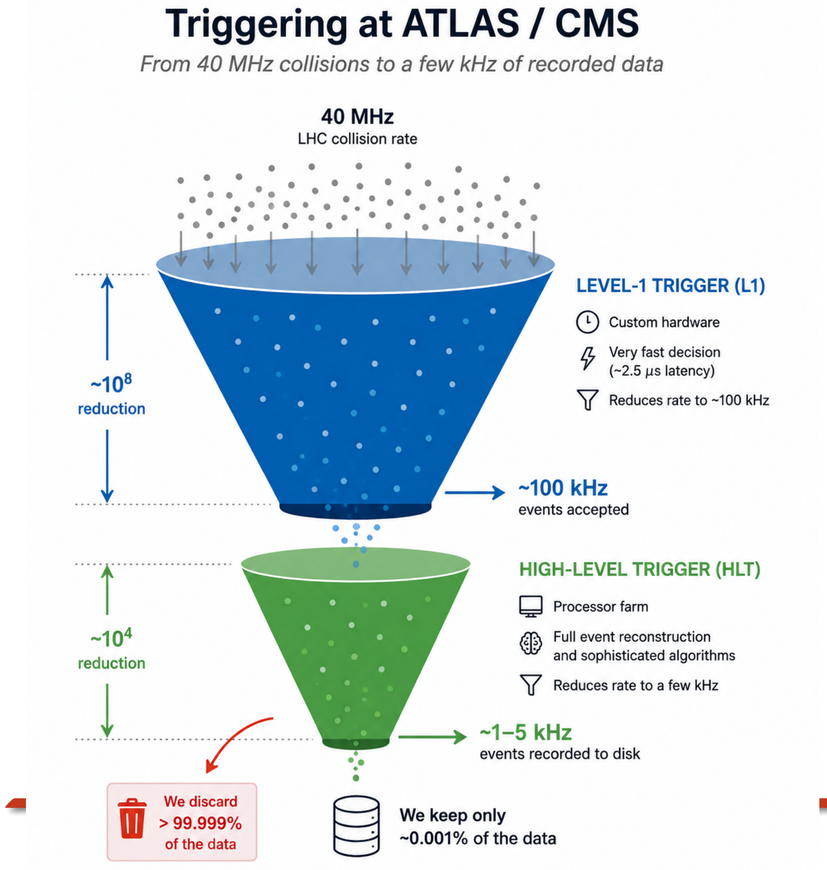
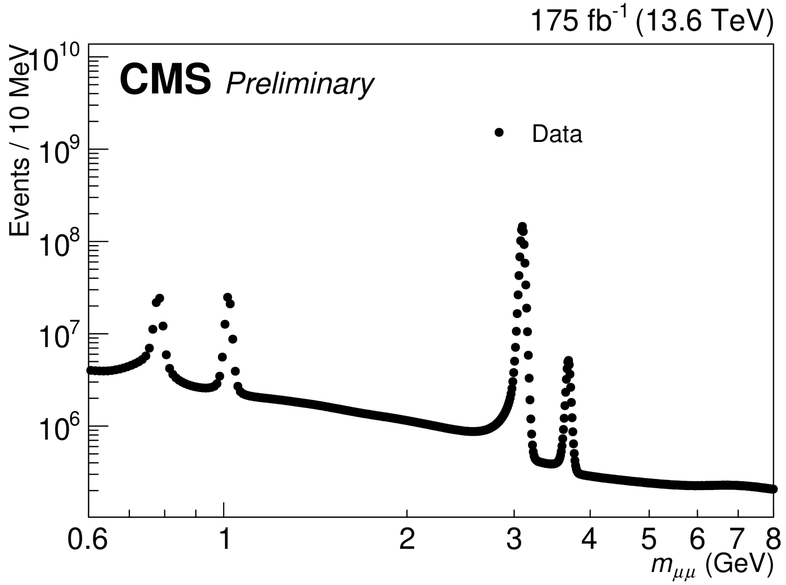
- Dark photon/ALP decaying into lepton resonances is a compelling scenario.
- CMS goes as low as $m_{ll} > 0.88$ GeV using **data parking** in Run 3 (di-muon trigger thresholds with $p_T > 3{,}4$ GeV)



- Sliding window fit against a background parameterisation.
- Largest excess at 2.43 GeV (2.8σ local - same position as a 3.1σ excess from LHCb)
- Improving sensitivity with respect to LHCb and BaBar



Low-mass resonances with data parking

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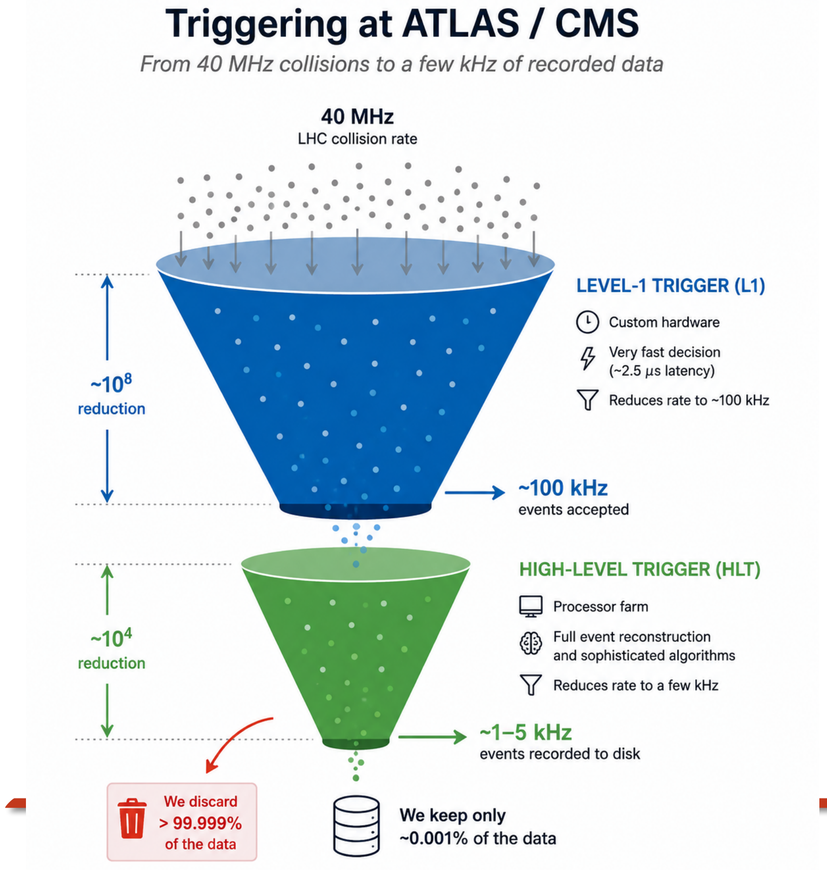
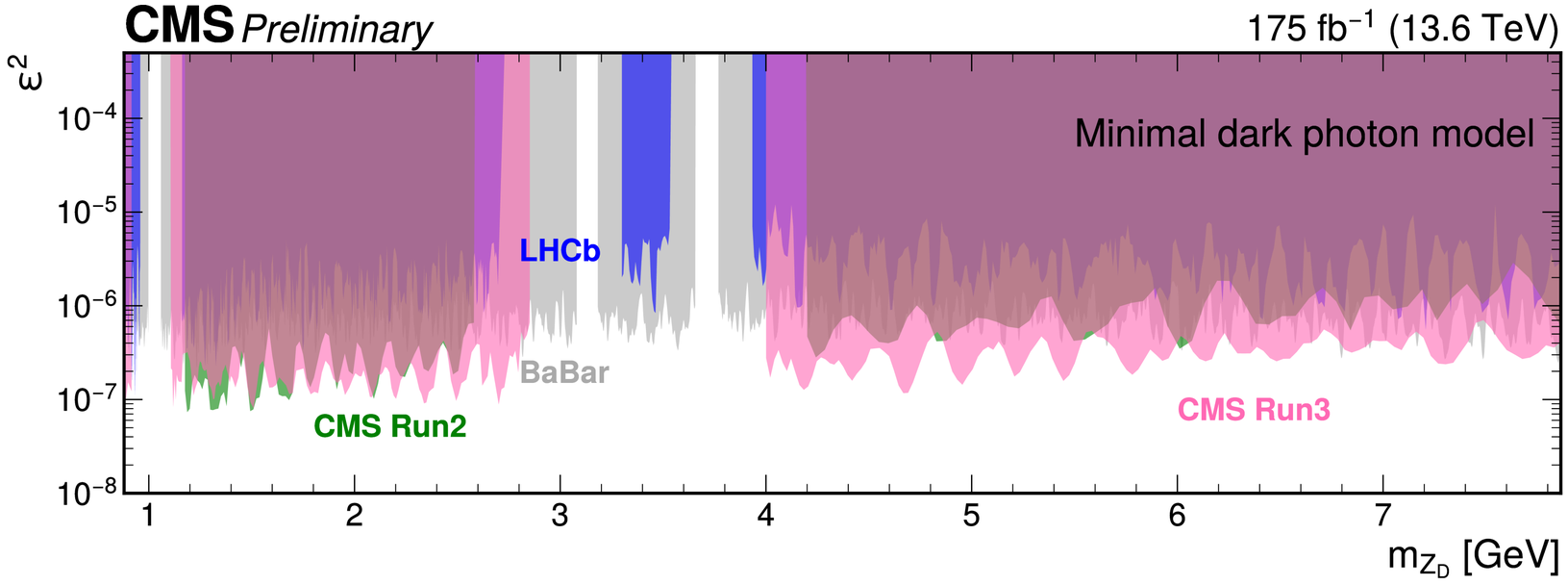
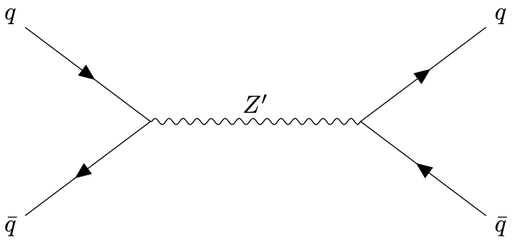
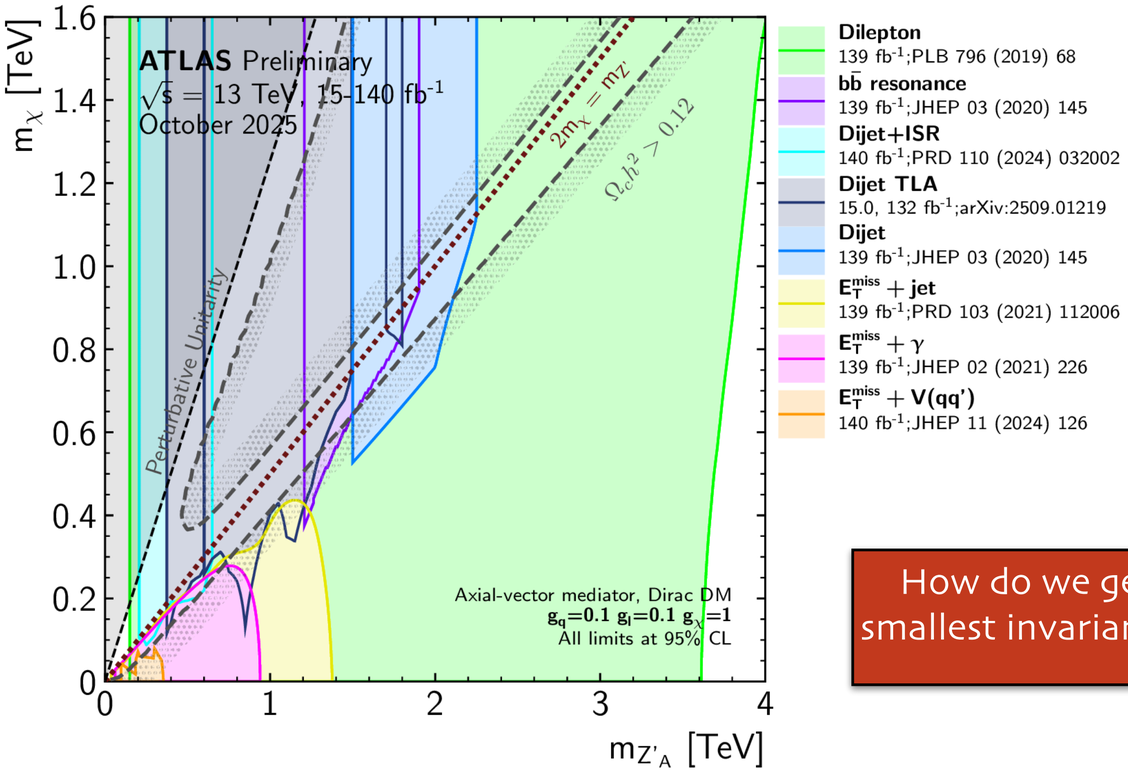




Dark sector - simplified models

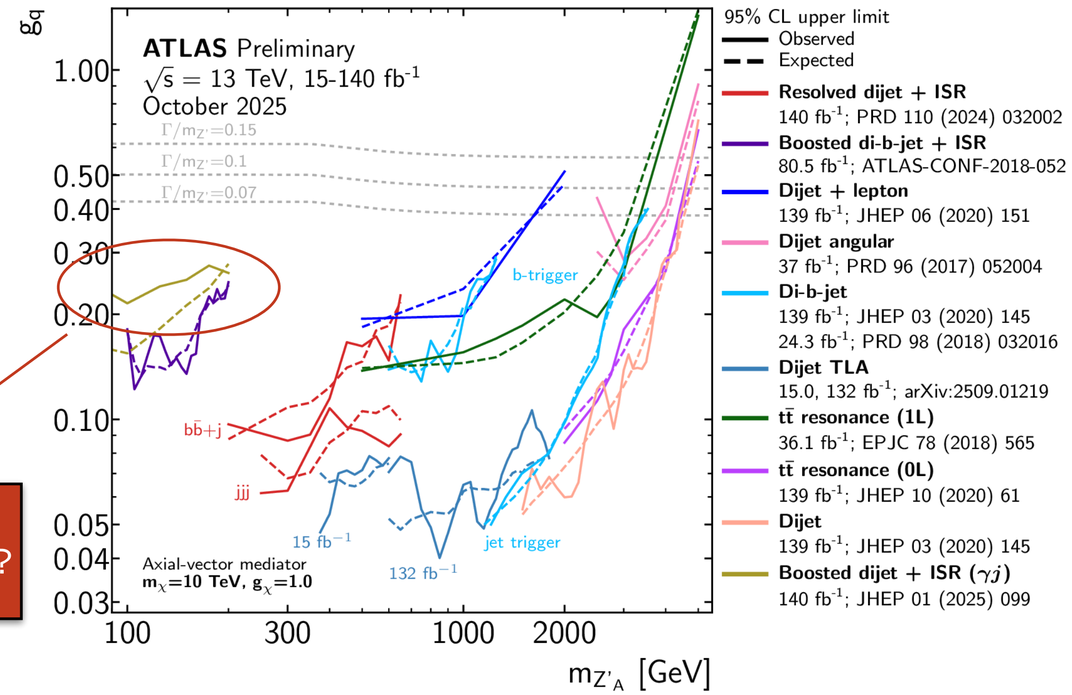


- Dark matter approached with a suite of analyses targeting different paradigms and final states
- In simple final states (e.g., single mediator), mono-X analyses often used together with (mostly) diet resonant searches



A constant battle against jet thresholds, with a few different solutions

How do we get to the smallest invariant masses?



ISR γ + Z'

CMS-PAS-EXO-24-027

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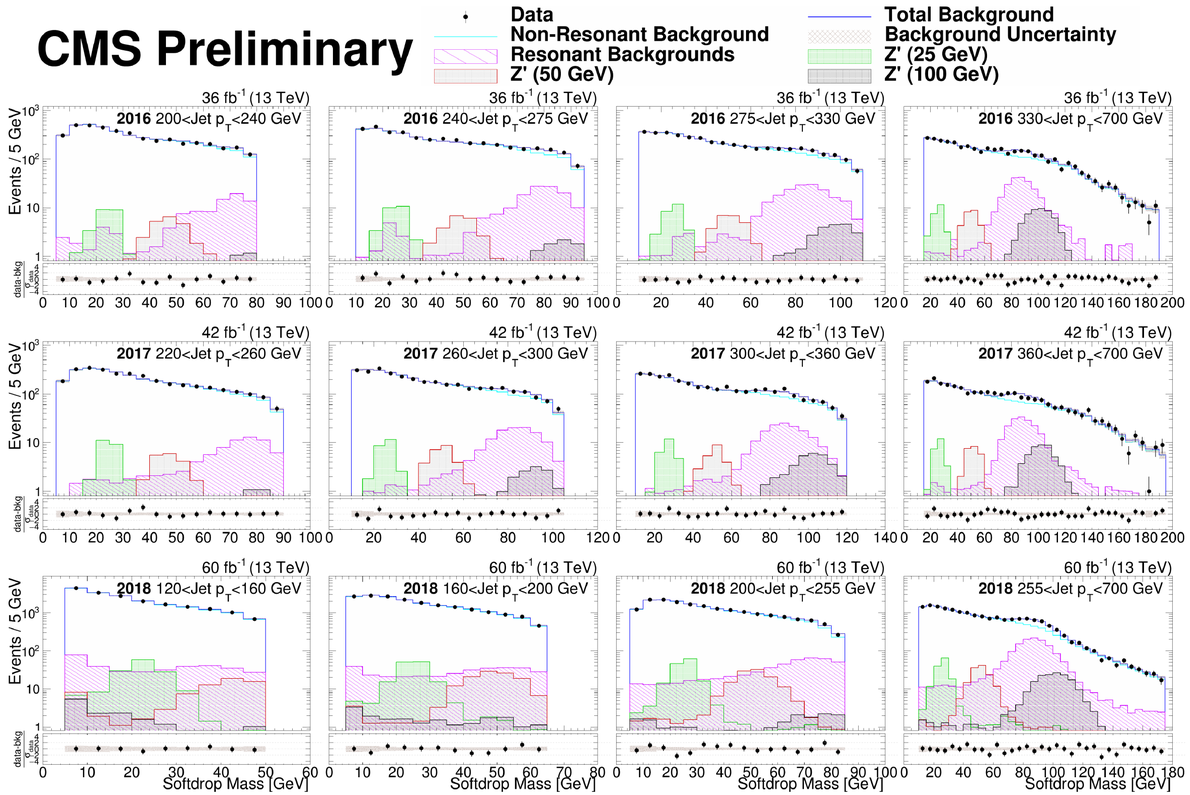
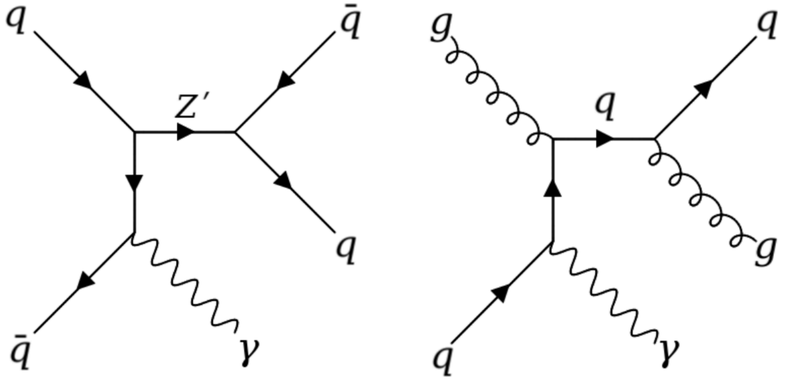
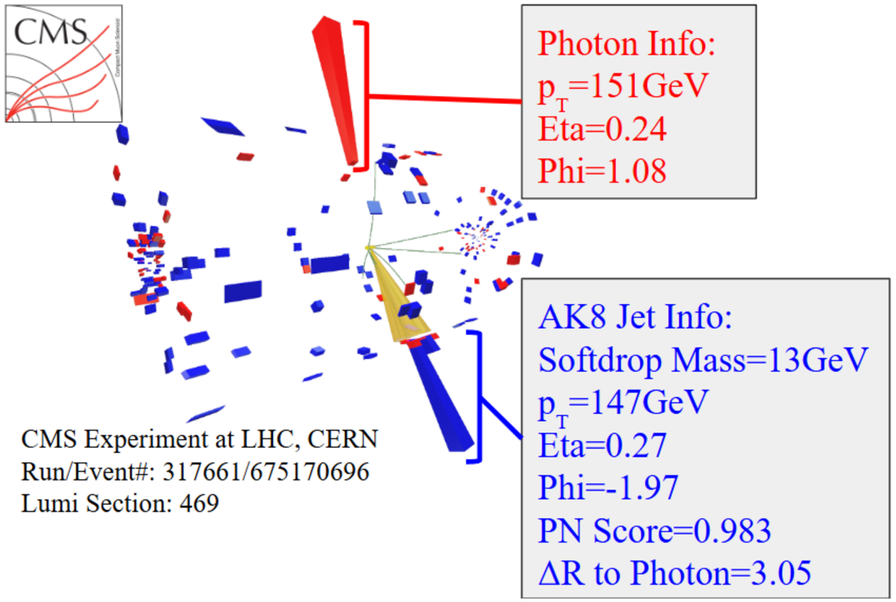
- Single ISR photon recoiling against a large-R jet (identified via ParticleNet)
  - Improved photon trigger thresholds in 2018
- Data driven background estimate for non-resonant and resonant ($W\gamma, Z\gamma, tt\gamma$) background







Jets from pileup

EXOT-2022-32

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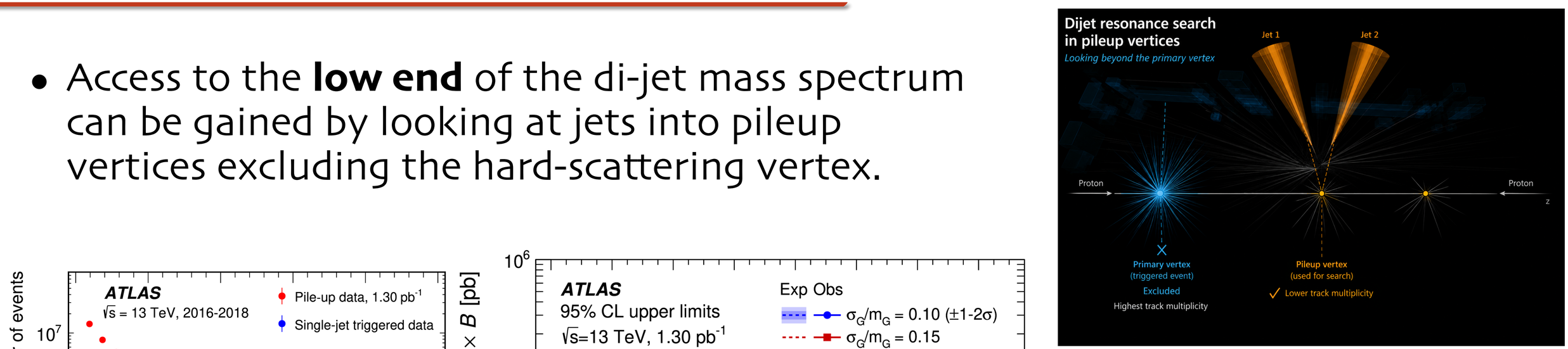
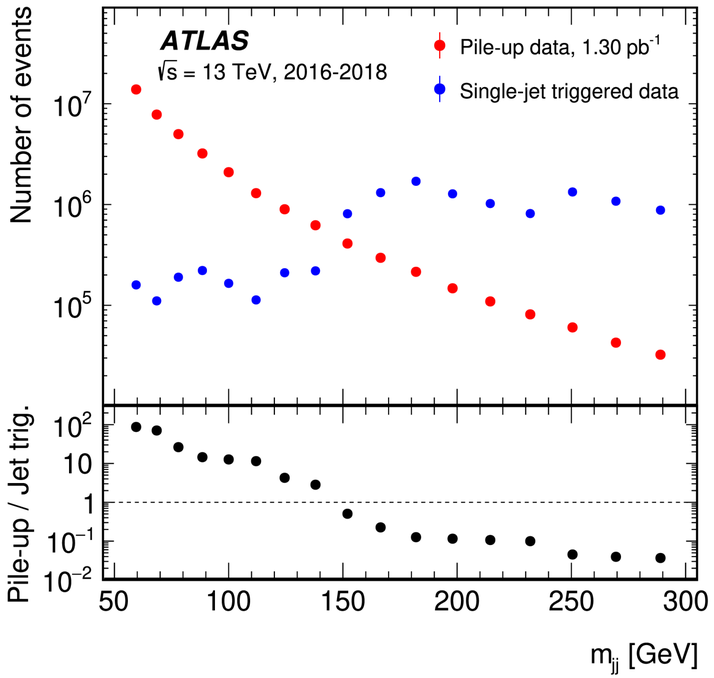
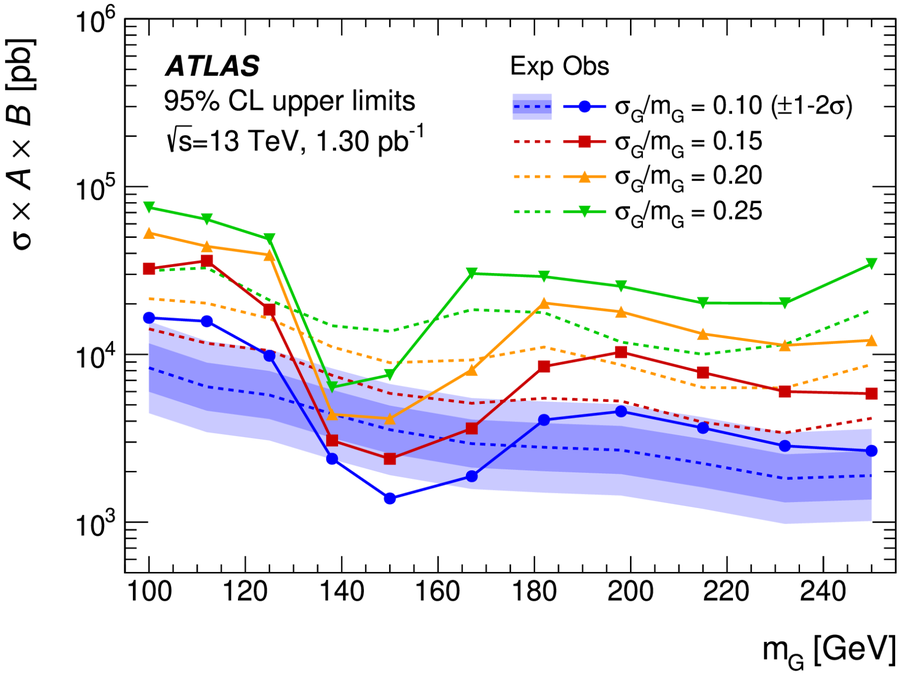
- Access to the **low end** of the di-jet mass spectrum can be gained by looking at jets into pileup vertices excluding the hard-scattering vertex.



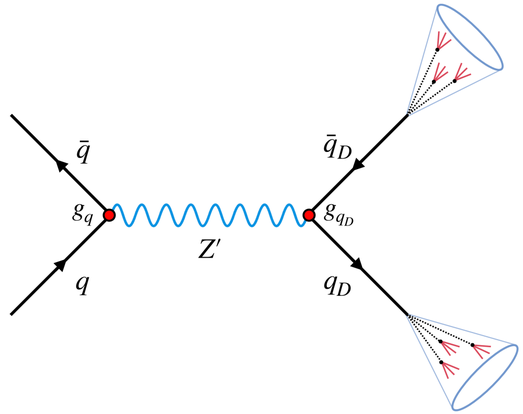




Di-jet mass reconstructed from jets attached to pile-up vertices thanks to particle flow association.

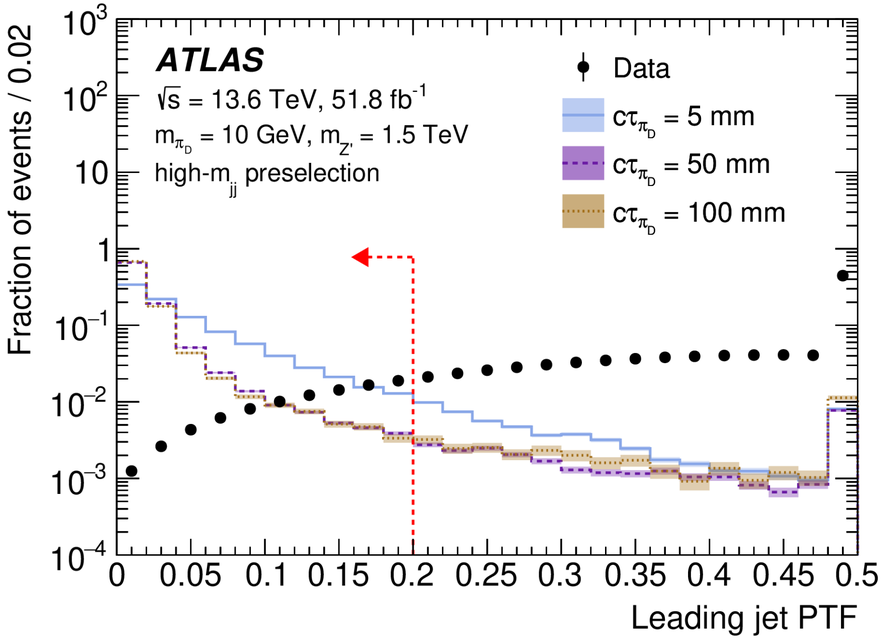
Emerging jets

EXOT-2021-31

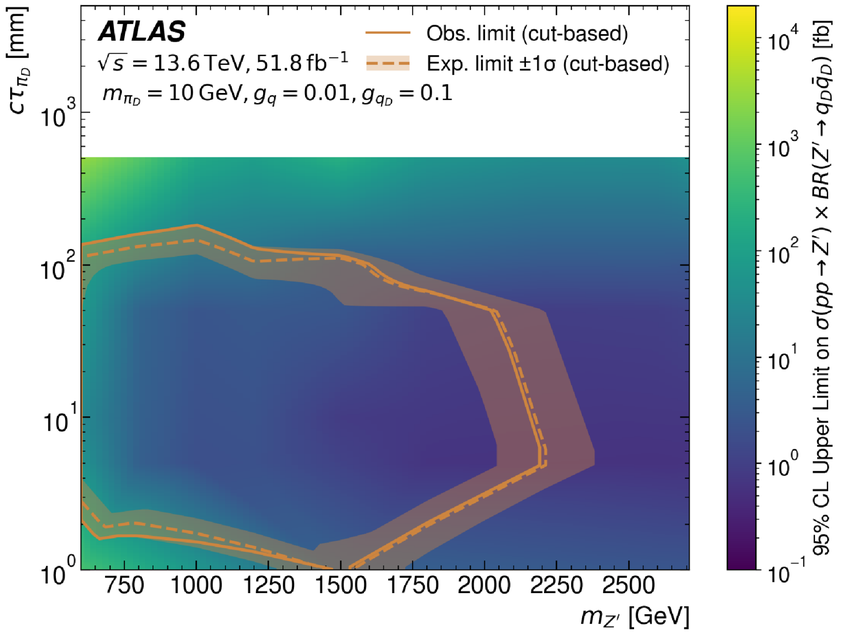


- If the Z' goes into long-lived dark-sector quarks, jets may "emerge" directly in the calorimeters. Signature: energy clusters with no tracks associated.

- Two different selections: **cut-based and ML.**
- Di-jet topology, event selection based on **number of tagged jets** and the **dijet invariant mass.**
- **Dedicated Run-3 trigger** selecting low-PTF jets at the high level trigger improves the sensitivity at low mass.



$$\mathrm{PTF} = \frac{\sum p_T^{\mathrm{track}}}{p_T^{\mathrm{jet}}}$$



Chapter 2: compressed EWkinos scenarios

See R. Franceschini's talk at LHCP

The textbook search for new physics

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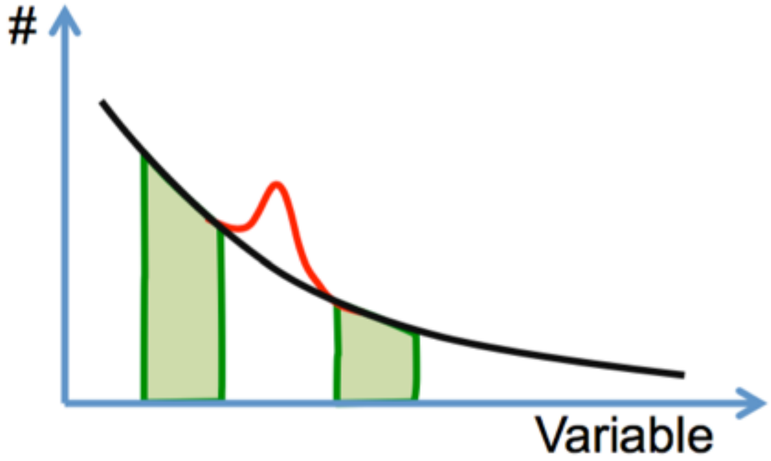

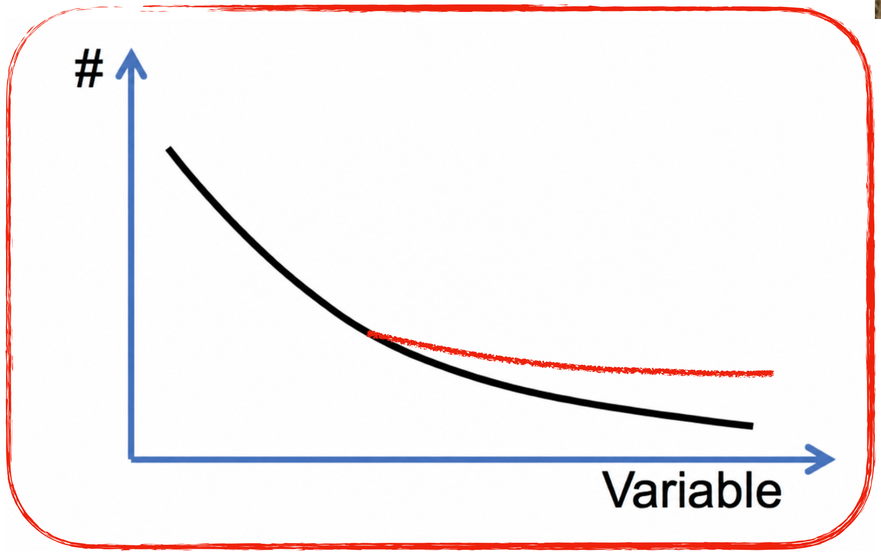

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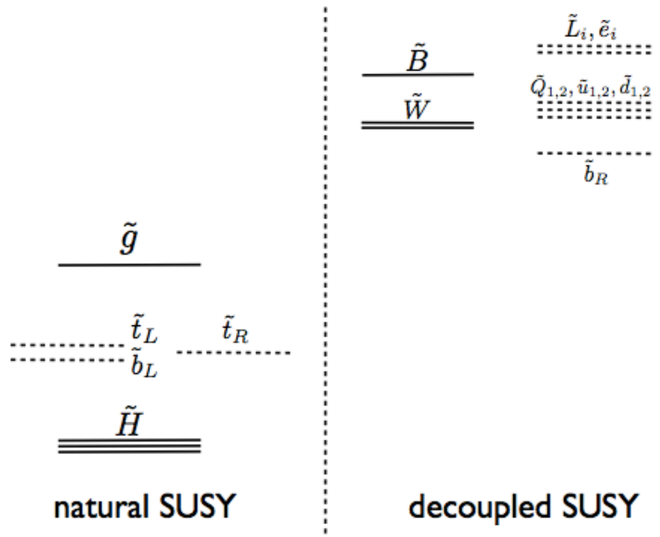
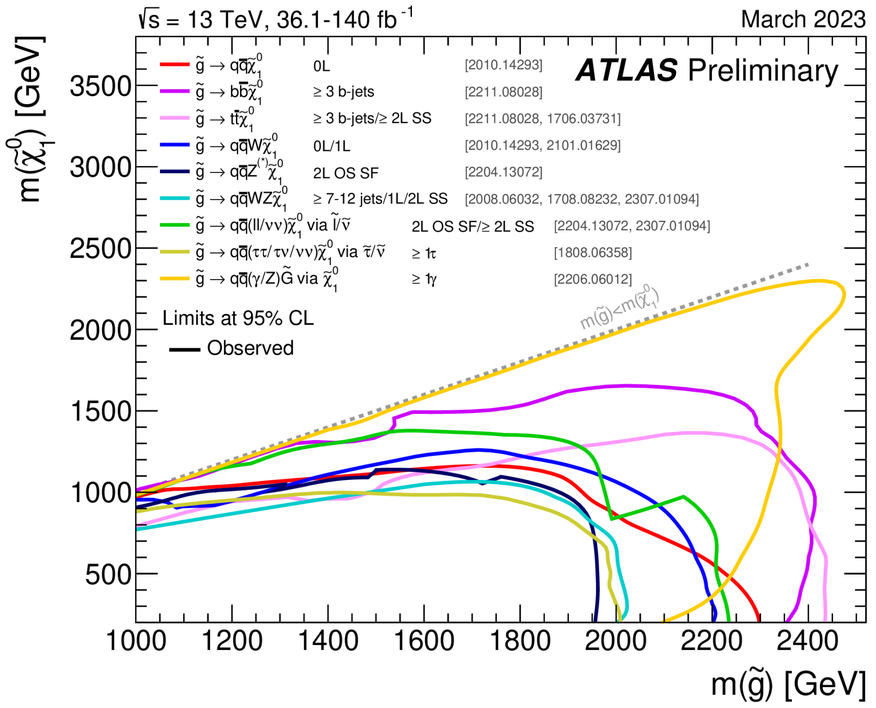
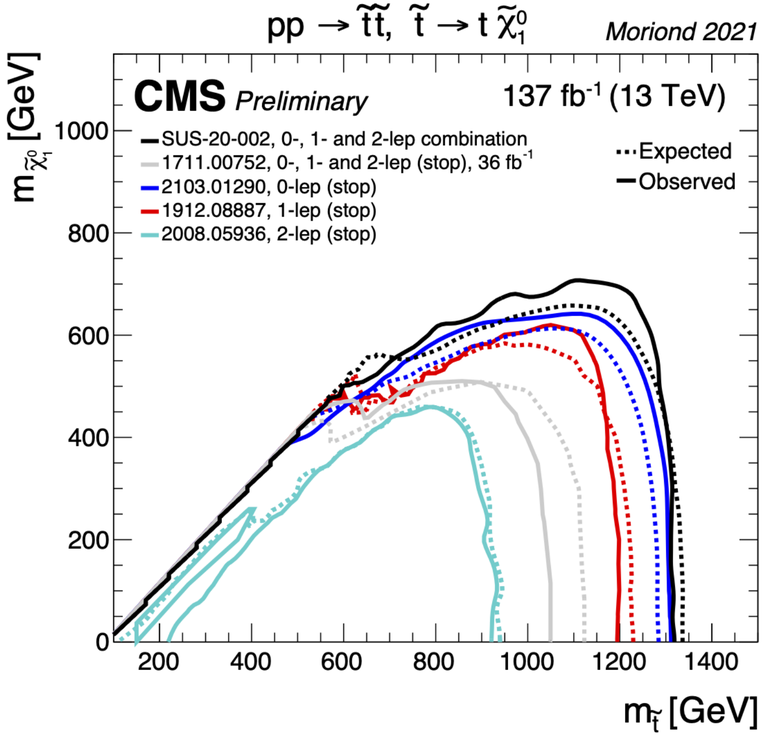
- The naturalness of the Higgs boson mass requires:
  - A **Higgsino mass** of maximum **few hundred GeV**.
  - A **top partner** mass at the TeV scale.
  - A **gluino mass** of maximum few TeV.

$$m_h^2 = m_Z^2 \cos^2 2\beta + \frac{3y_t^2 m_t^2}{4\pi^2}\left[\log\left(\frac{m_S^2}{m_t^2}\right) + X_t^2\left(1 - \frac{X_t^2}{12}\right)\right] + \cdots$$

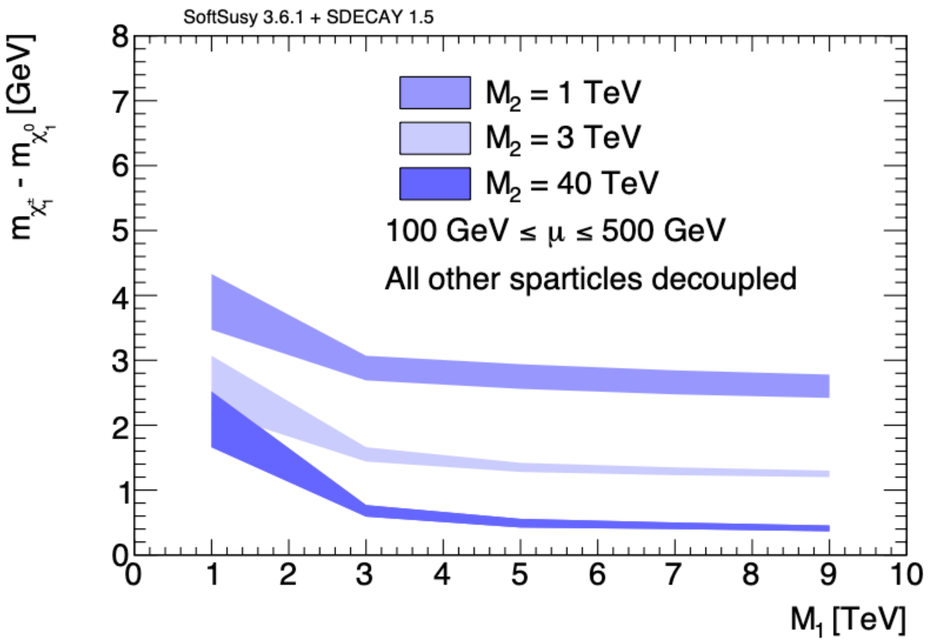


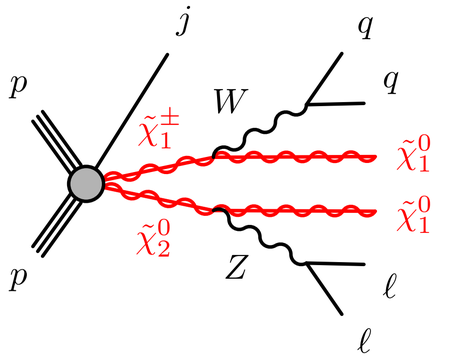


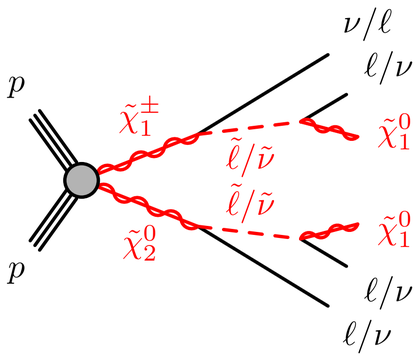


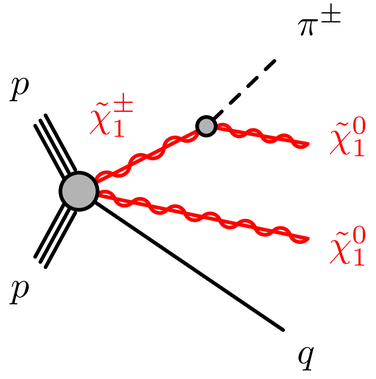
Compressed states

- The EW side of **naturalness**:
  - Generic name for a set of EW-produced set of states with "small" mass separations
  - Generically appearing in models of **dark matter** where relic density needs to be regulated.
    - In SUSY they are the **trademark of higgsino production.**
    - The mass separation can be anywhere from hundreds of MeV to tens of GeV.

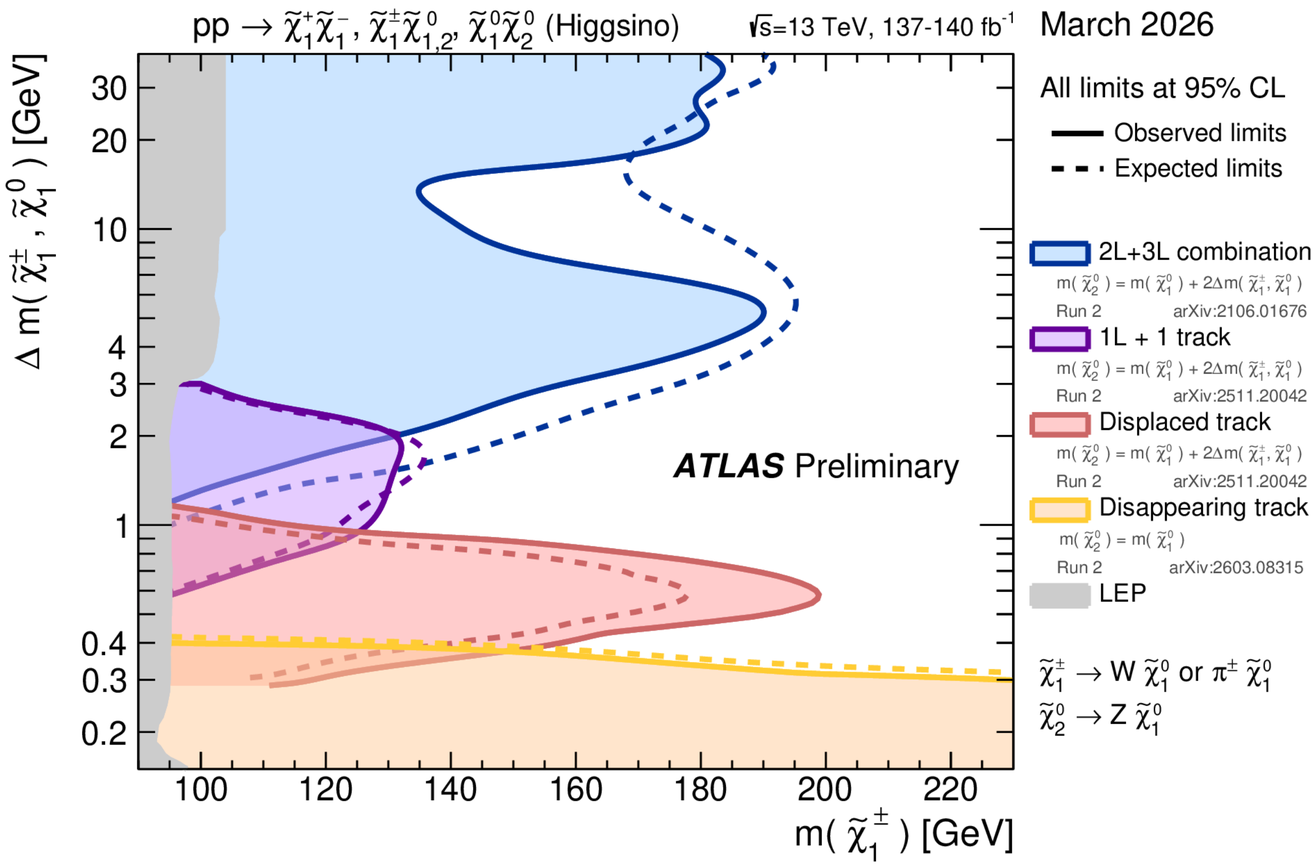








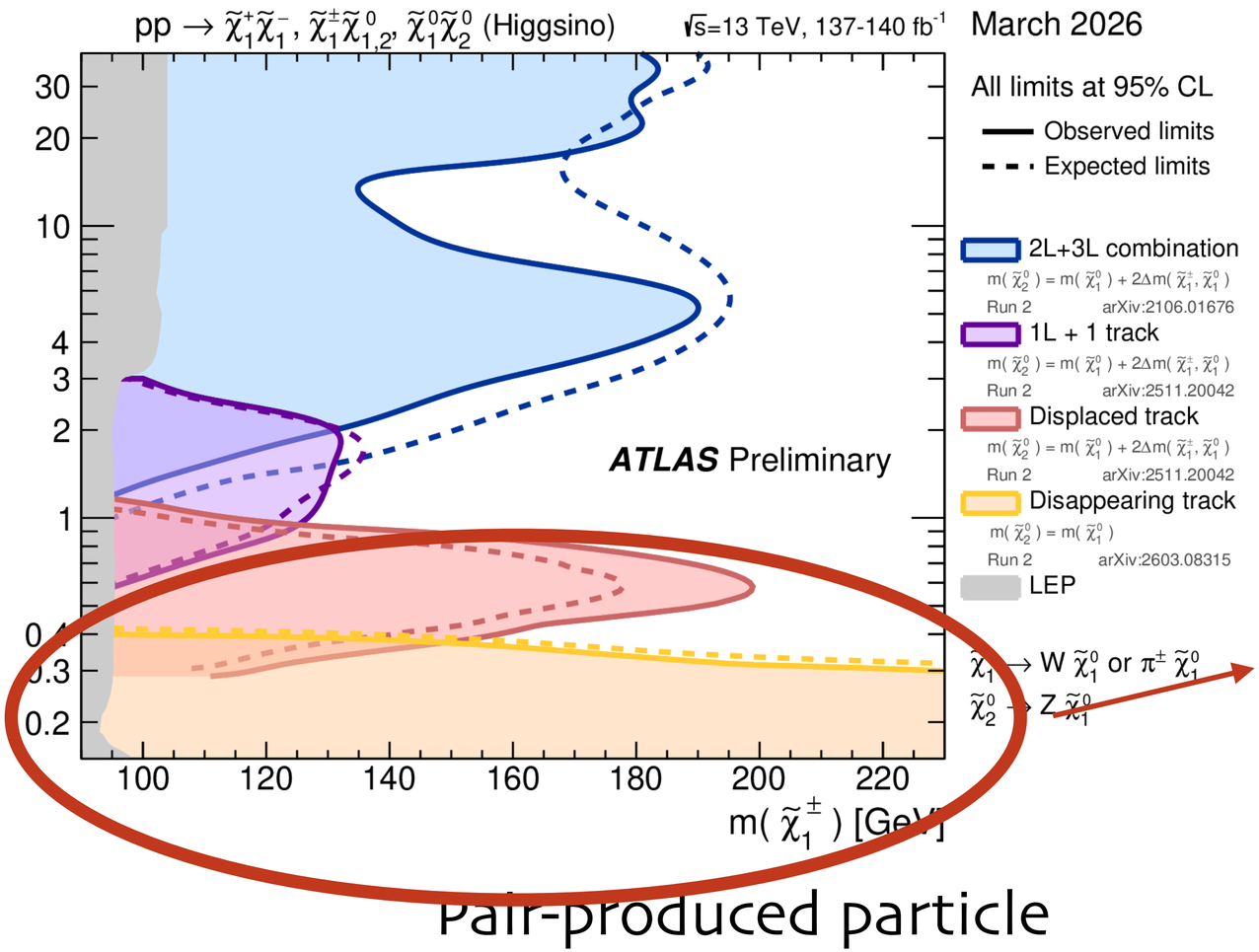
Compressed states



Mass separation to the LSP

Pair-produced particle

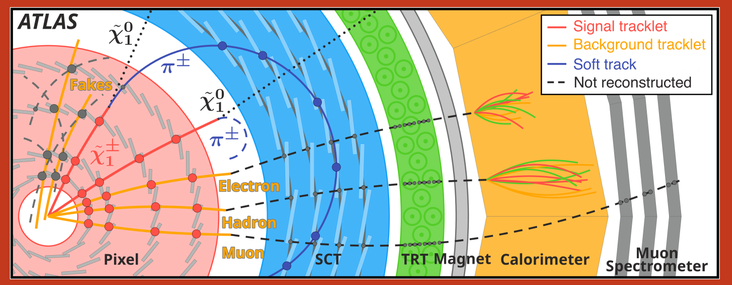
Compressed states



Mass separation to the LSP

Pair-produced particle

- Mass separation so small that the pair-produced particle lives a bit
- Now reconstructing also the secondary pion



HMBS-2024-66

Compressed states

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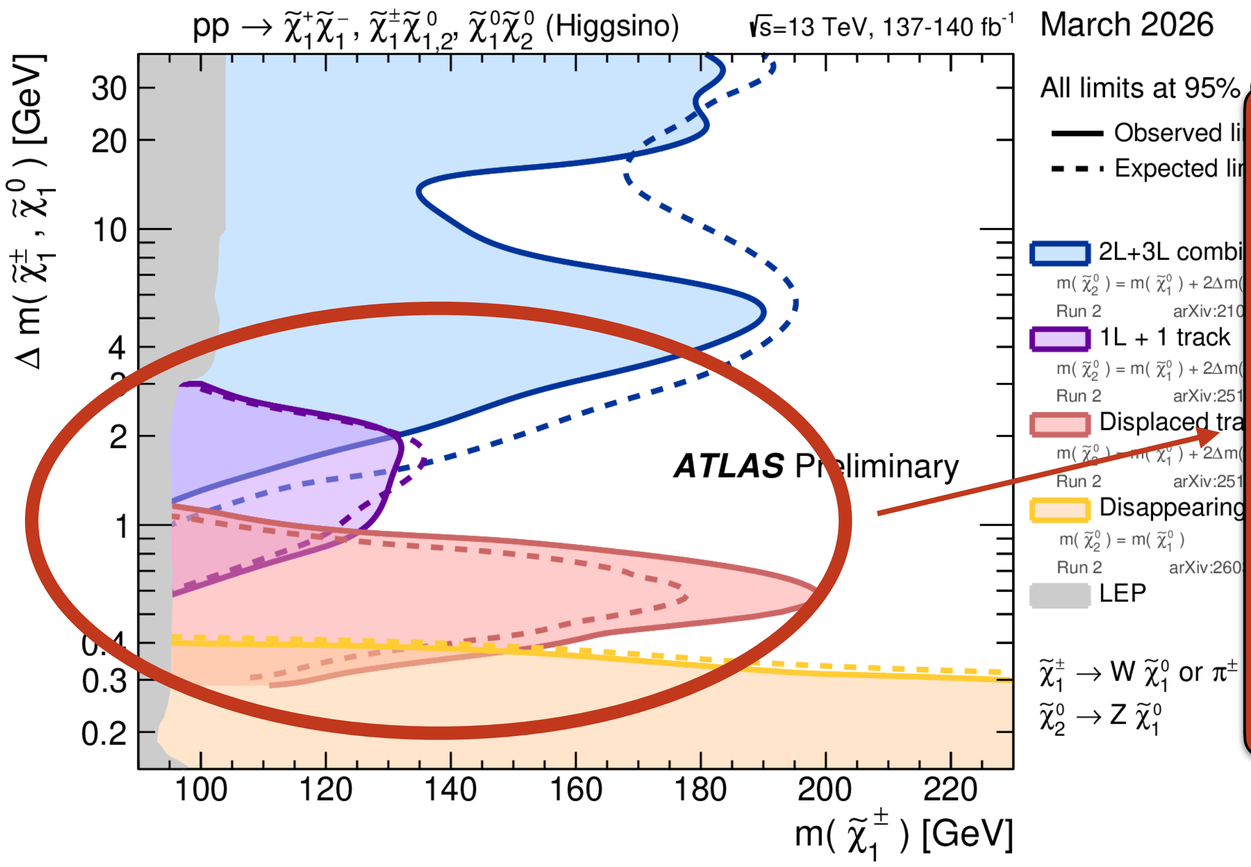
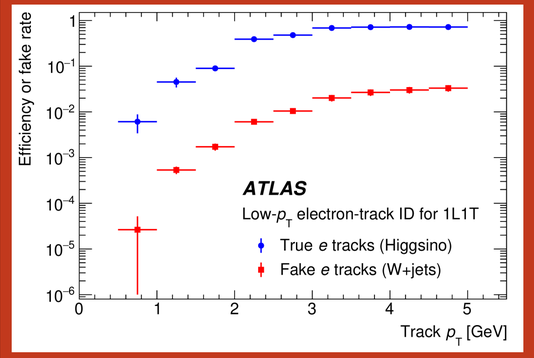
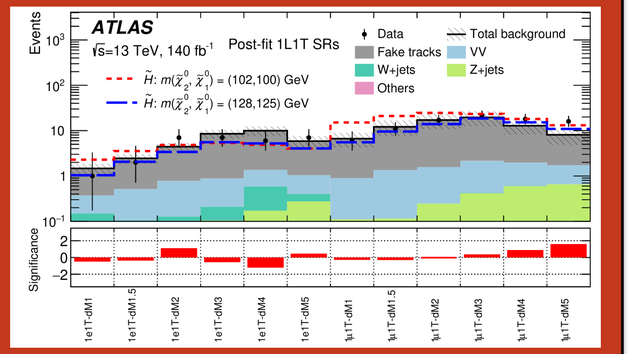
Mass separation to the LSP



- Leptons are low-pT. Depending on the mass separation, do not attempt their reconstruction, but rather look for a (displaced) track.

HMBS-2025-65

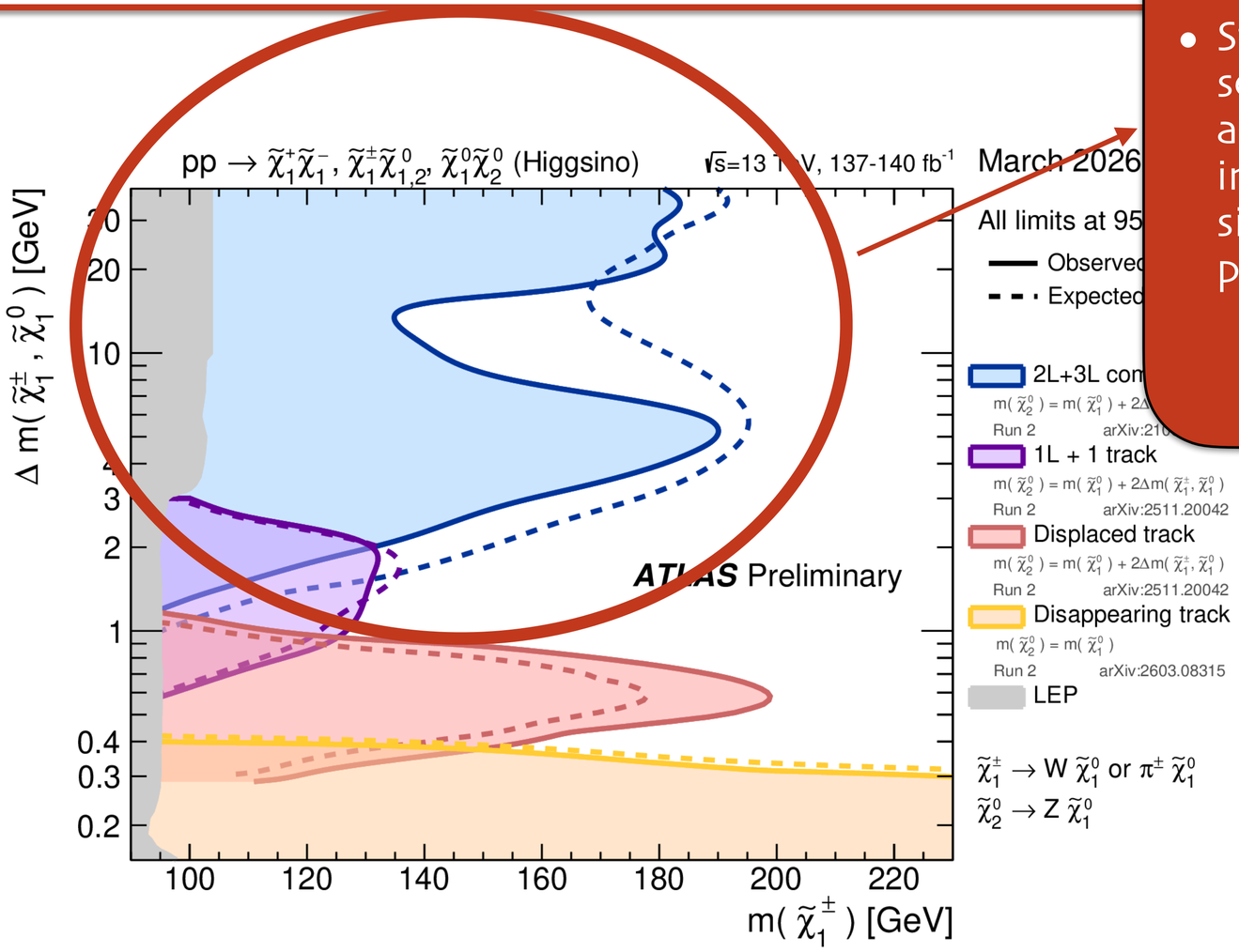




Pair-produced particle

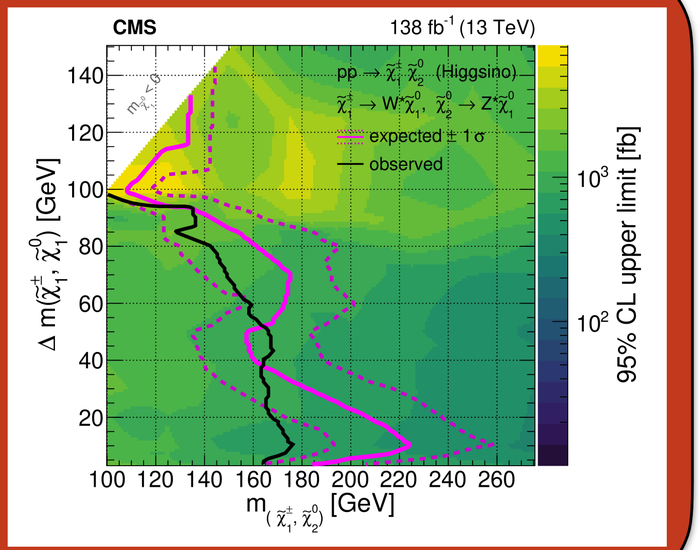
Compressed states

Mass separation to the LSP



Pair-produced particle

- Standard 2L/3L search. Interesting access showing up in CMS as well for similar mass parameters



Chapter 3: Long-lived particle searches

Taking the most from the detector

For more info and more results see K. Di Petrillo's talk at LHCP

Long-lived particle searches

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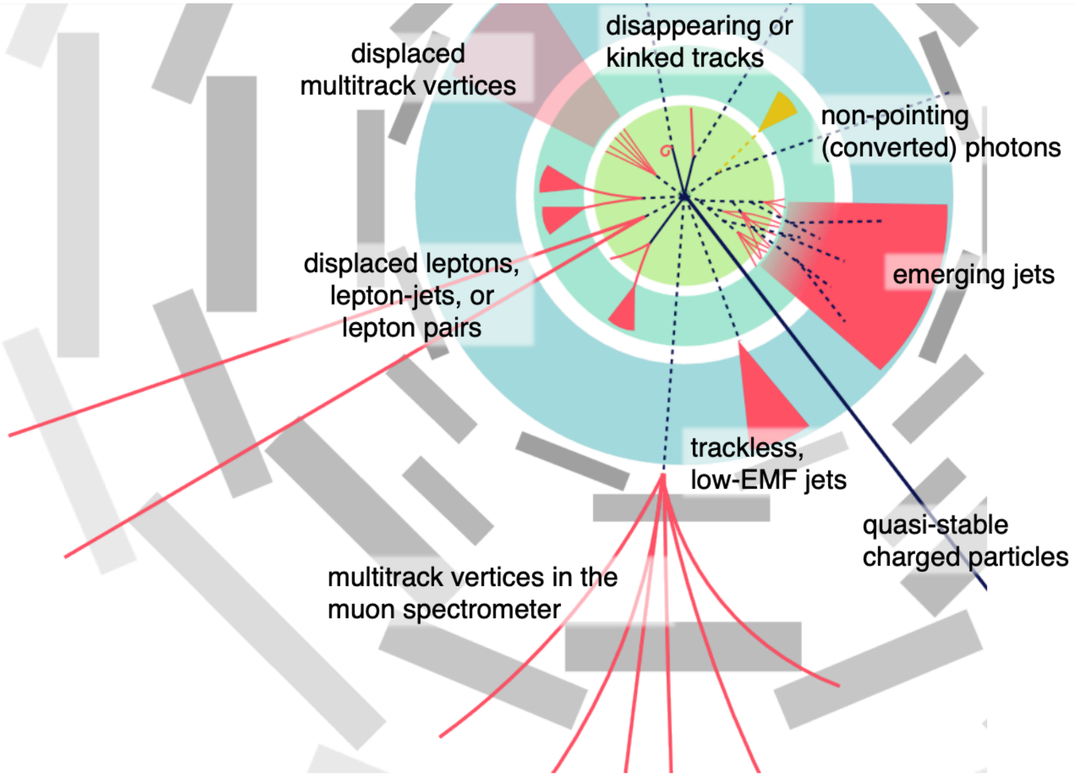
- Run 3 has seen a significant increase of "unconventional searches" for long-lived particles (LLP).
- While the LLP programme was already thriving in early Run 2, a "creative" use of the detector has marked a change of perspective.



Improved reconstruction for Run 3

SUSY-2022-11

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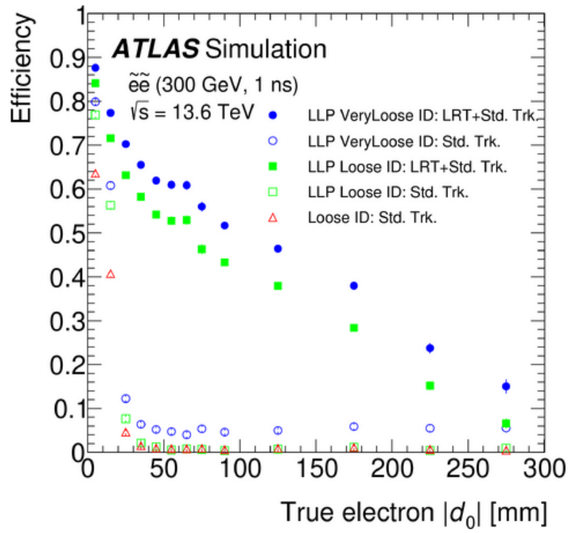
- Early Run 3 results started to show the true LLP potential
- Improved **tracking with large impact parameter and vertexing** (and imported into high-level triggering).



Improved reconstruction for Run 3

SUSY-2022-11

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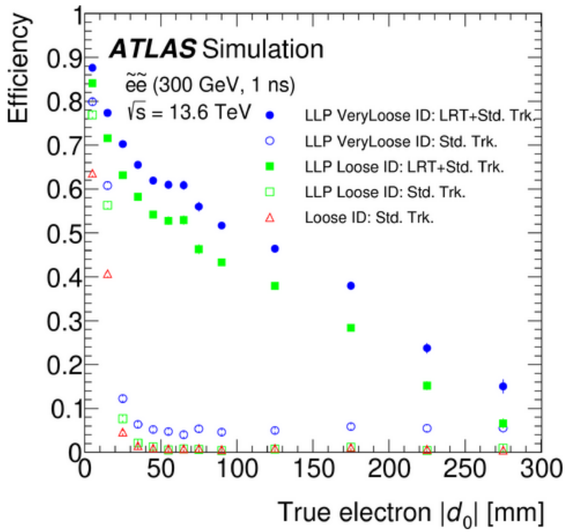
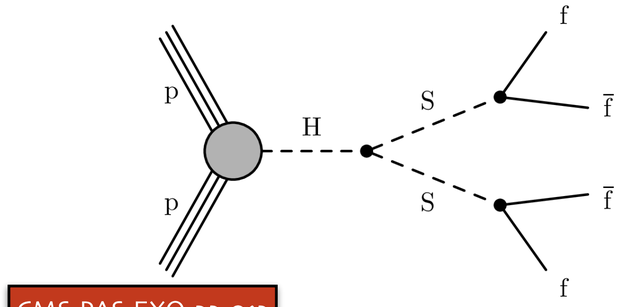
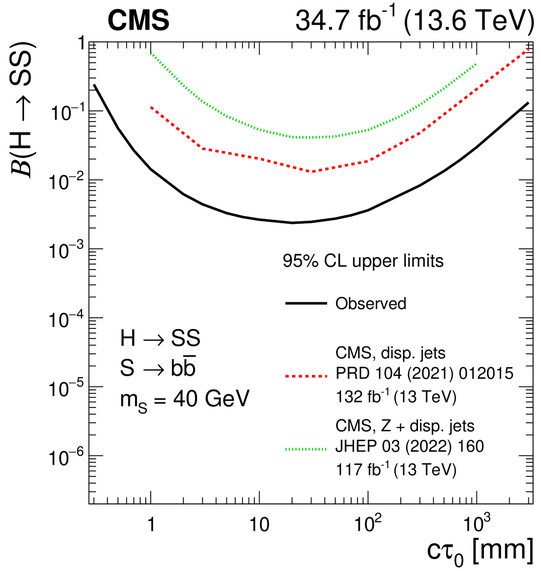
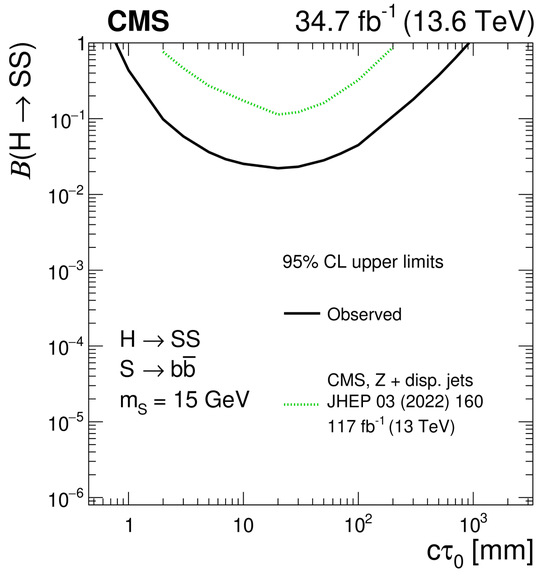
- Early Run 3 results started to show the true LLP potential
- Improved **tracking with large impact parameter and vertexing** (and imported into high-level triggering).
- **Dedicated triggers** and **improved tagging** of, e.g., displaced jets (benchmark dark sector Higgs decay $H \rightarrow SS$ with S long lived)
- Improved analysis techniques.



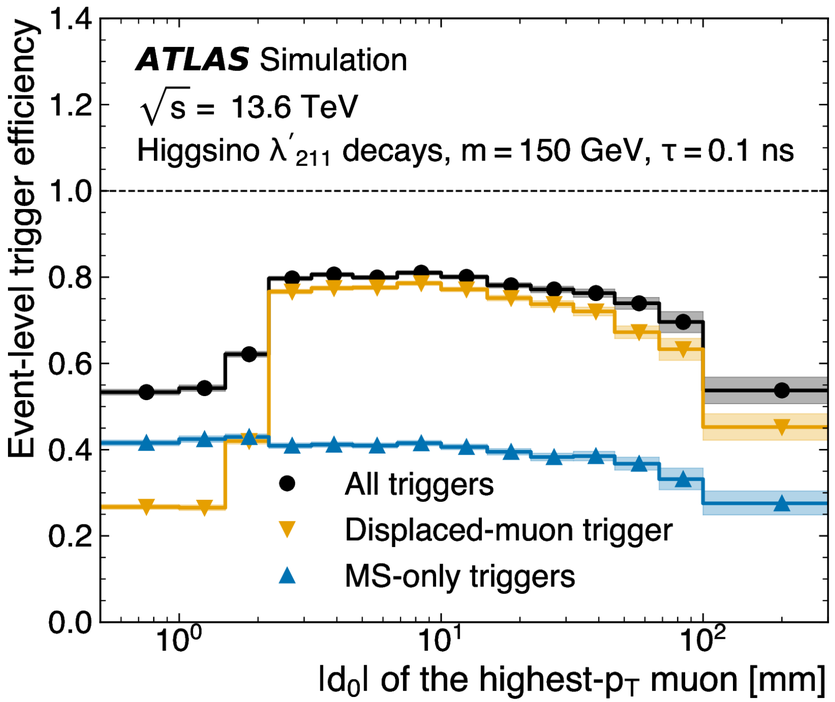


CMS-PAS-EXO-23-013

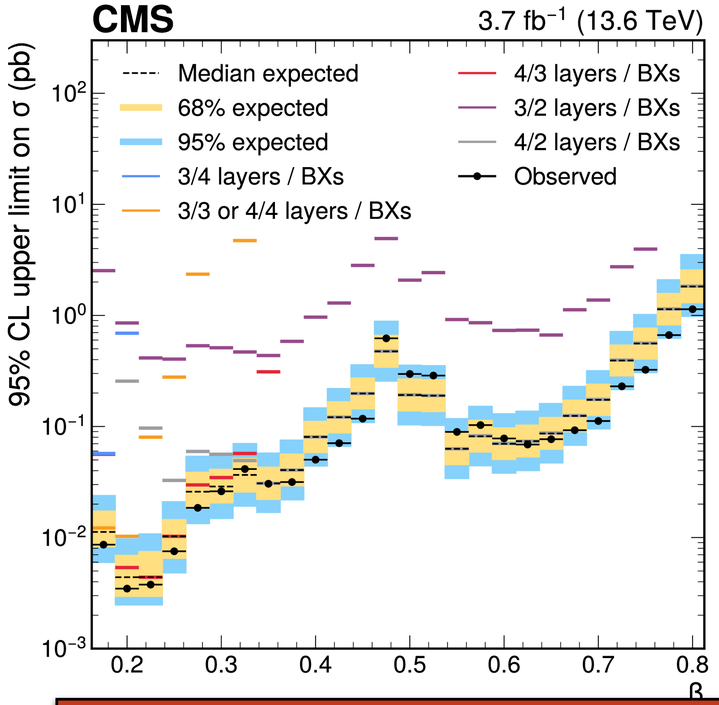




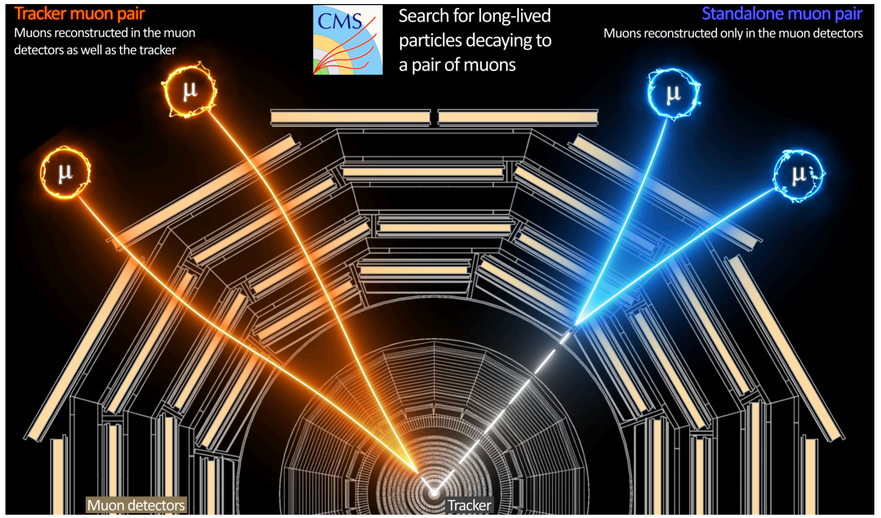
New Run-3 results



ATLAS displaced vertices + displaced muons



CMS ToF search using L1 scouting

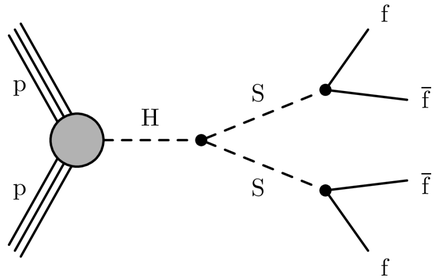


CMS displaced dimuon vertices

Improved triggers for Run 3

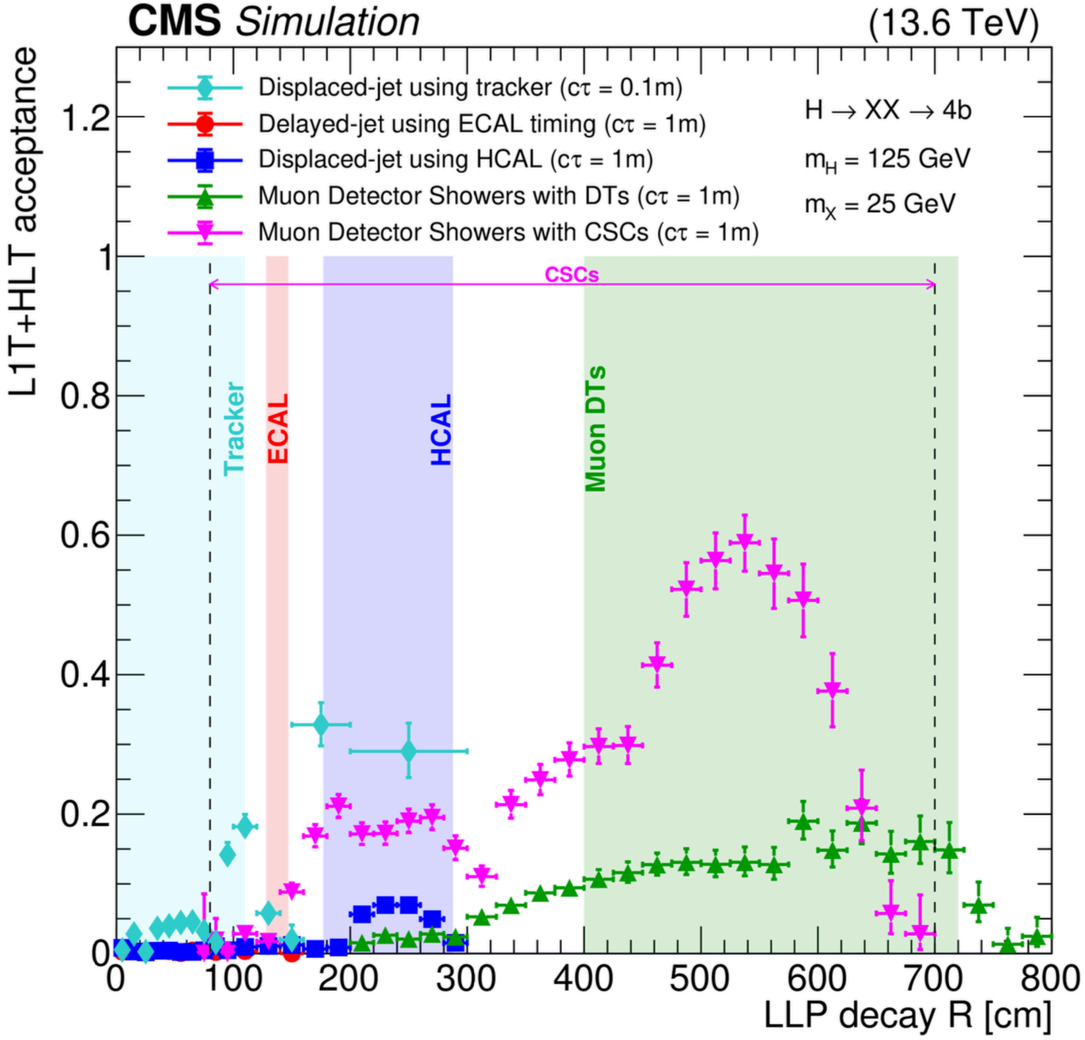
- A lot of work went into improving triggers - CMS published recently a dedicated paper about it.

Improving at L1, by tagging late showers in HCAL



Improving at L1, by triggering on the number of muon spectrometer clusters produced by a late shower

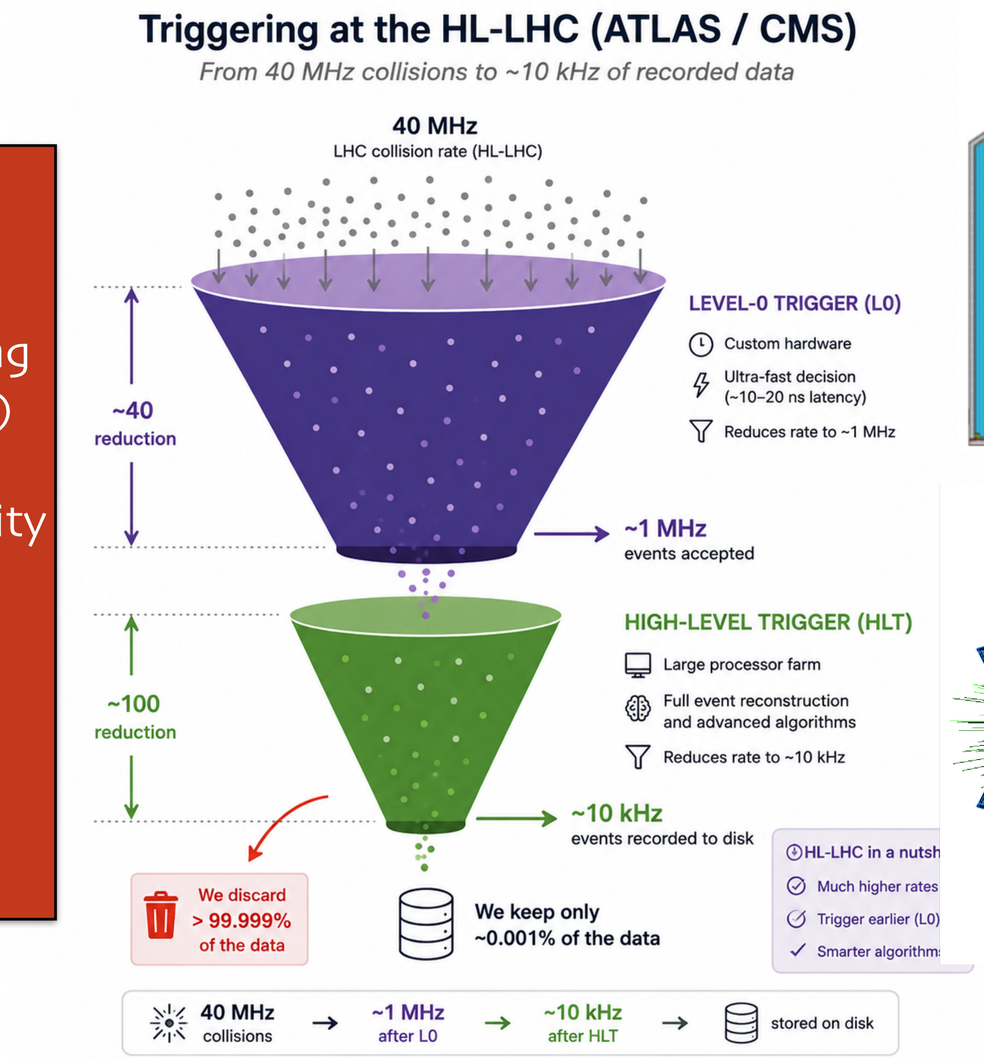
ATLAS: 2401.06630
CMS: 2601.17544

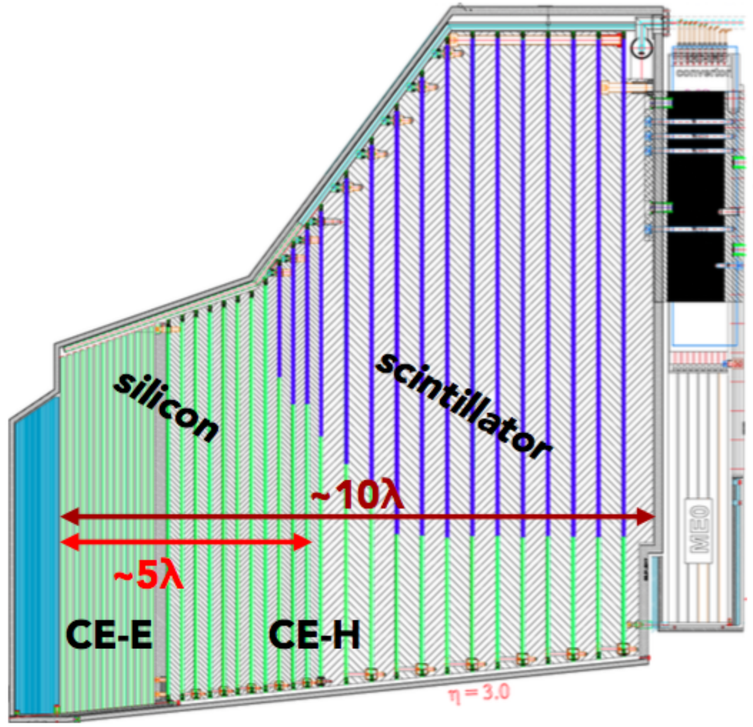


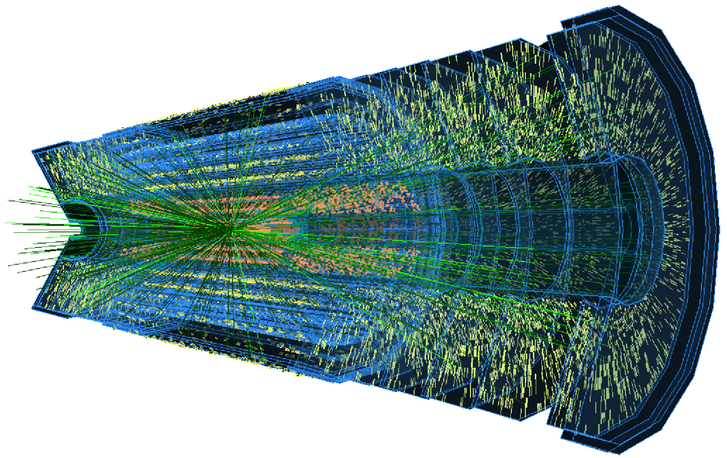
Chapter 4: a glance into HL-LHC

A glance into HL-LHC

- Largely new detectors, often with increased granularity and timing capability.
- Improved trigger systems (including a higher incoming rate for HL-LHC) and tracking at L1 (for CMS).
- High luminosity + detector flexibility = dramatic improvements for weakly and feebly interacting low-mass states.
- Improved opportunities already on the table (and many will be fully studies during LS3)





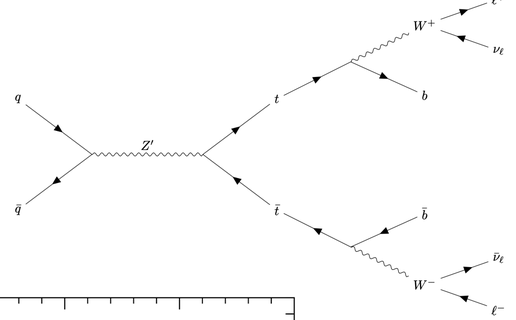


Conclusions

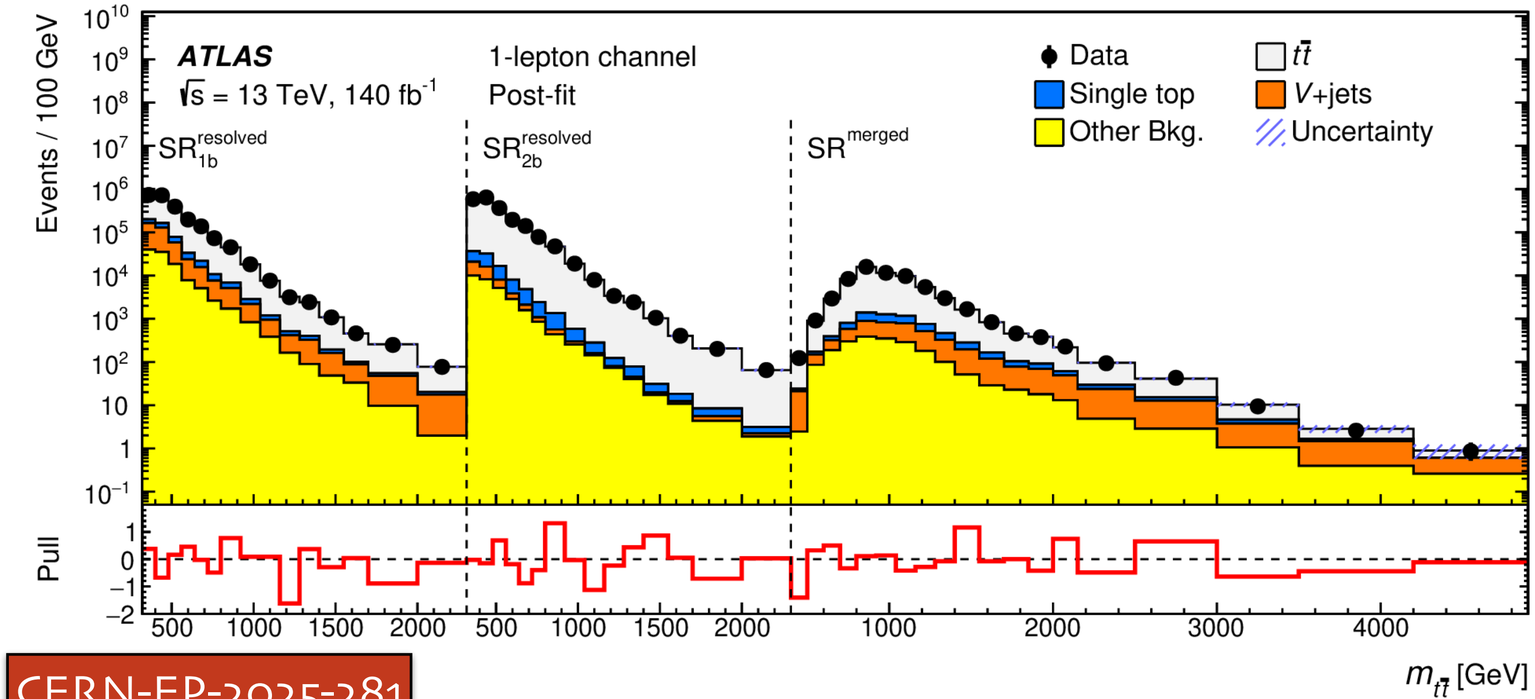
- Hail to the creativity of the LHC collaborations! I have touched upon:
  - Pushing searches for resonances to their limit.
  - Challenging reconstruction targeting specific, compelling physics scenarios.
  - Getting the most from the detector with long lived searches.
  - Creative new avenues on reducing trigger limitations.
- Let's get the most from this awesome scientific tool with Run 3 and HL-LHC data!

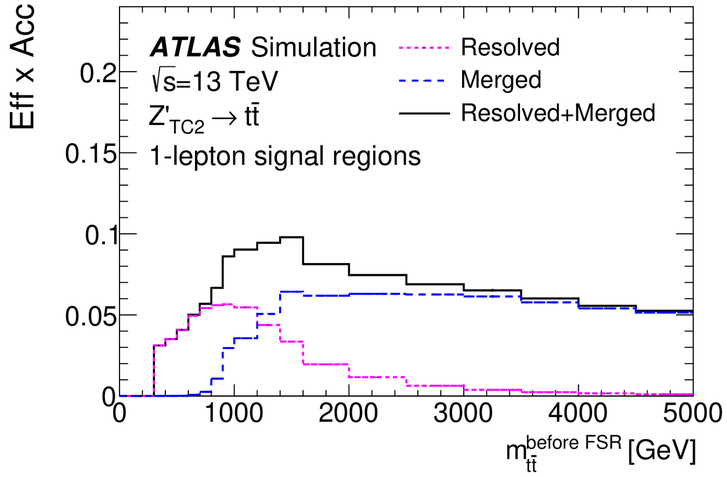
Backup

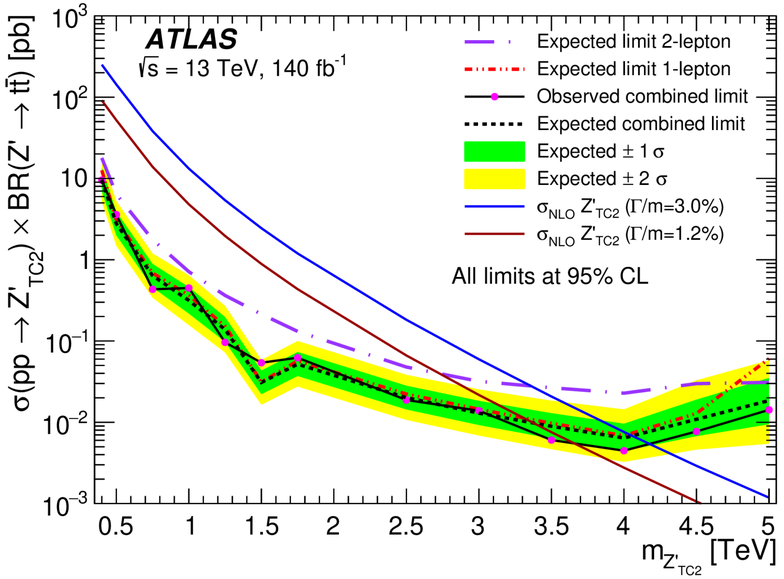
$t\bar{t}$ resonances



- Looking for $t\bar{t}$ resonances:
  - Complexity goes up: **combined fit of 1L** (separated in a "boosted" and "resolved" categorie) **and 2L signal regions**.
  - Limit extraction in several scenarios., including G_{KK} and g_{KK}.







CERN-EP-2025-281

Excesses

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- https://lhc-bsm-wg.docs.cern.ch/excesses/

Resonances to semi-invisible jets

EXOT-2021-19

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- Single Z' going into two dark quarks decaying to partially invisible decay products.
- Bump hunt search in $m_T(JJ, E_T^{\text{miss}})$, after selecting events with either a supervised DNN (PFN) trained on an event-level collection of tracks, or a variational autoencoder (ANTELOPE)

- Best limits on models used in training from PFN
- But ANTELOPE yields best results on models not seen during training