Search for dark matter candidates produced in Z(ℓℓ) + E_T^{miss} events in 13 TeV pp collisions with the ATLAS detector at the LHC

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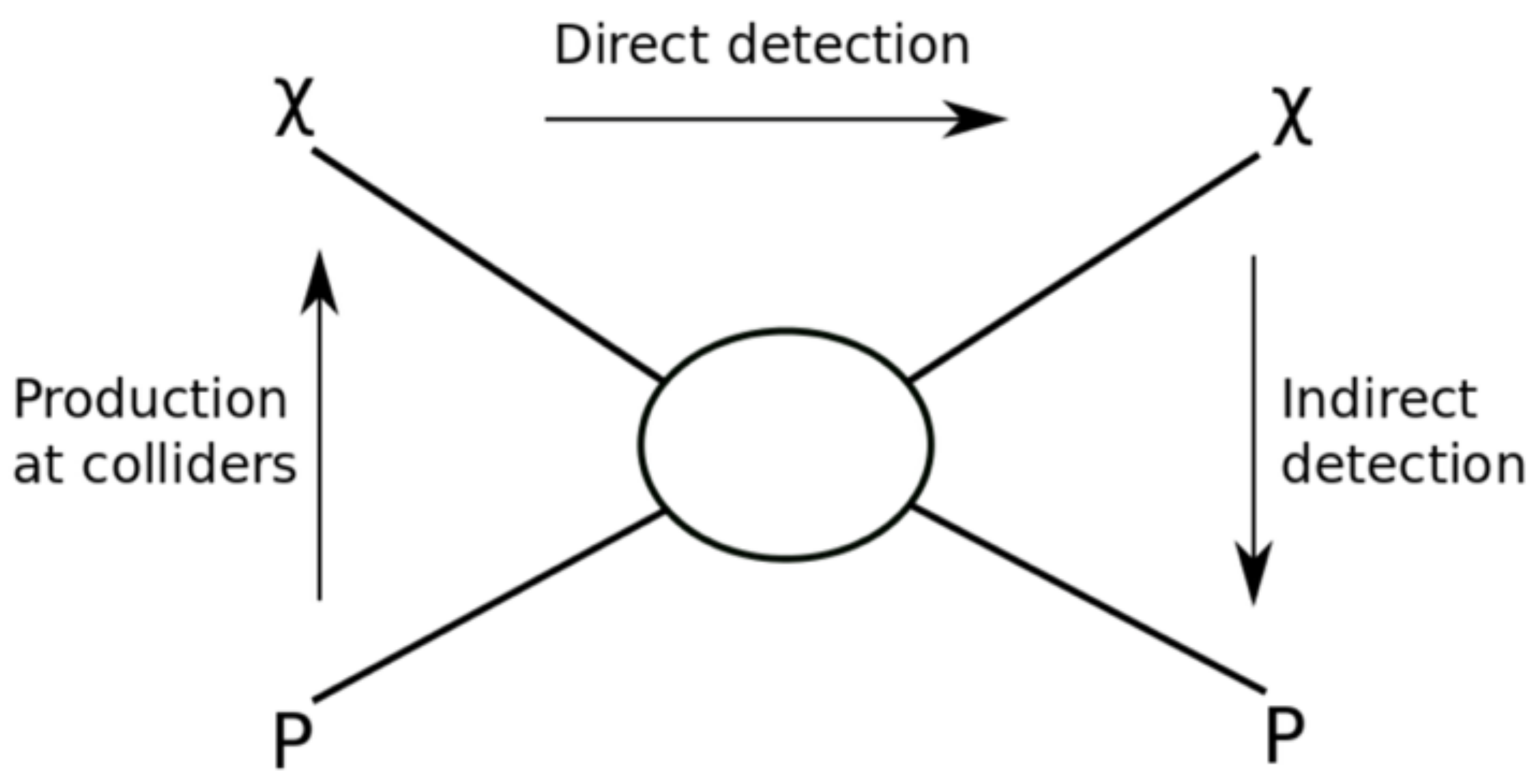
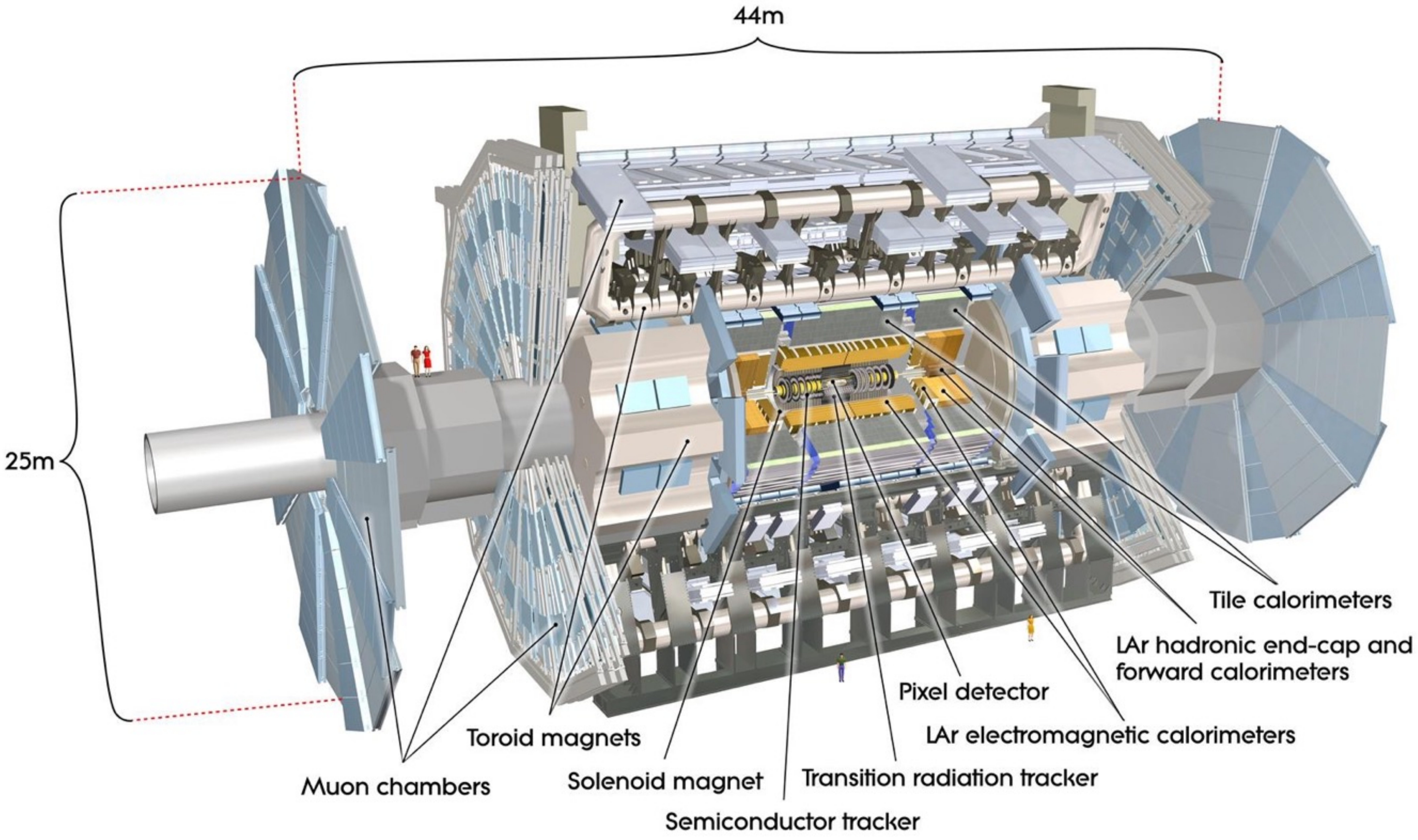
Dark matter

- The **Standard Model** is a successful theory but fails to explain the existence of **dark matter**, for which there is much evidence from astronomical measurements
- Dark matter makes up **> 80% of all matter** in the universe
- It is commonly described as a weakly interacting massive particle (**WIMP**), Dirac fermion; interacts gravitationally and potentially through other forces; mass from 1 GeV - 100 TeV



- Three categories of DM search experiments:
  1. **Direct detection** - measure the recoil of Standard Model particles scattering with dark matter
  2. **Indirect detection** - measure decay products from dark matter self-annihilation
  3. **Collider production** - produce dark matter by colliding Standard Model particles (**protons at the LHC**)

The ATLAS detector and luminosity



Integrated luminosity:

$$N = \sigma \int L dt = \sigma \mathcal{L}$$

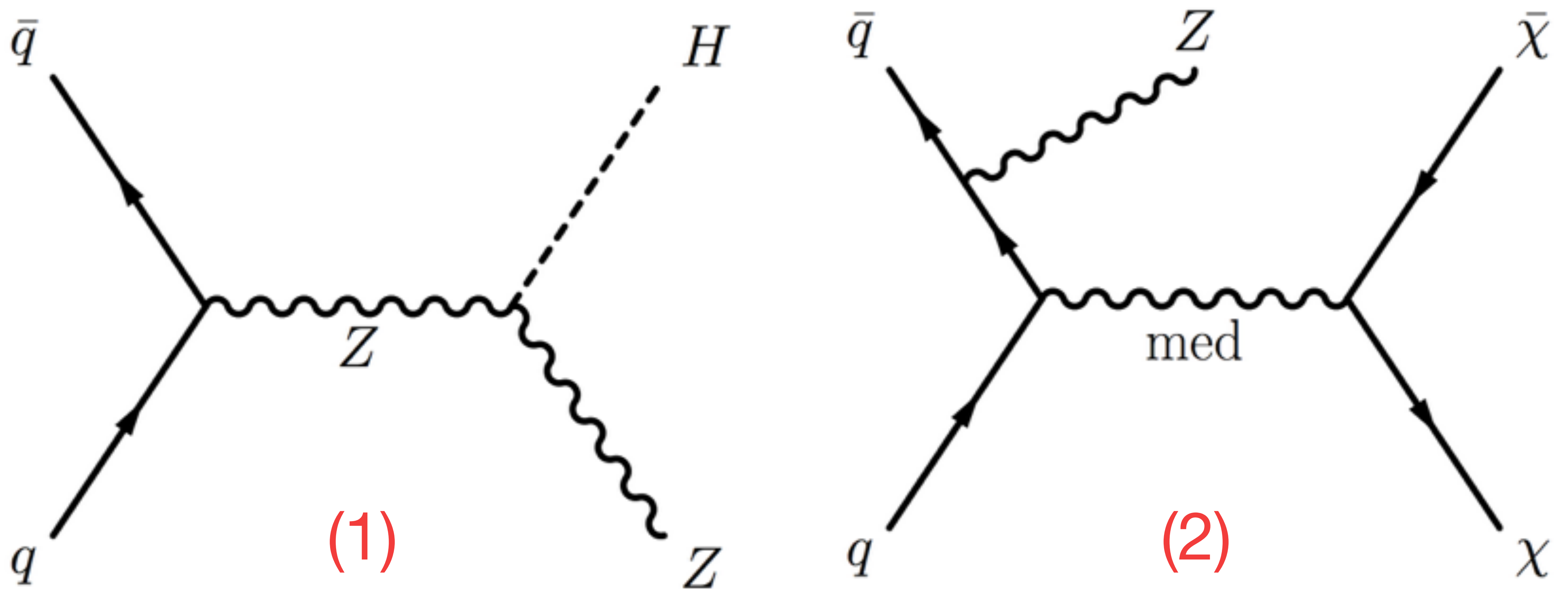
Cumulative datasets:

- 2015: 3.2 fb^{-1}
- 2016: 36.1 fb^{-1}
- 2017: 79.8 fb^{-1}
- 2018: 140 fb^{-1} projected

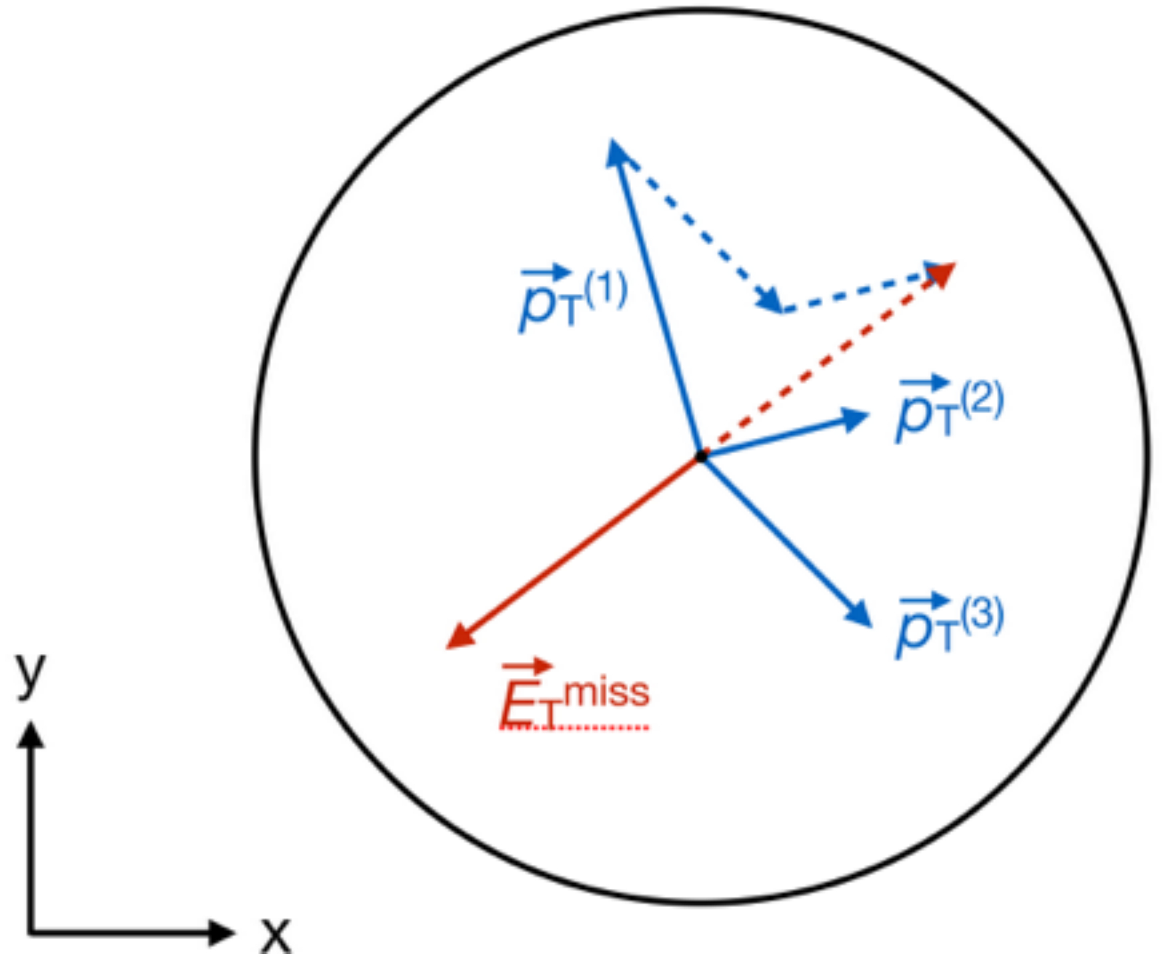
This talk will cover 2015+2016 results and discuss prospects for the full 2015-2018 (Run 2) dataset.

Analysis overview

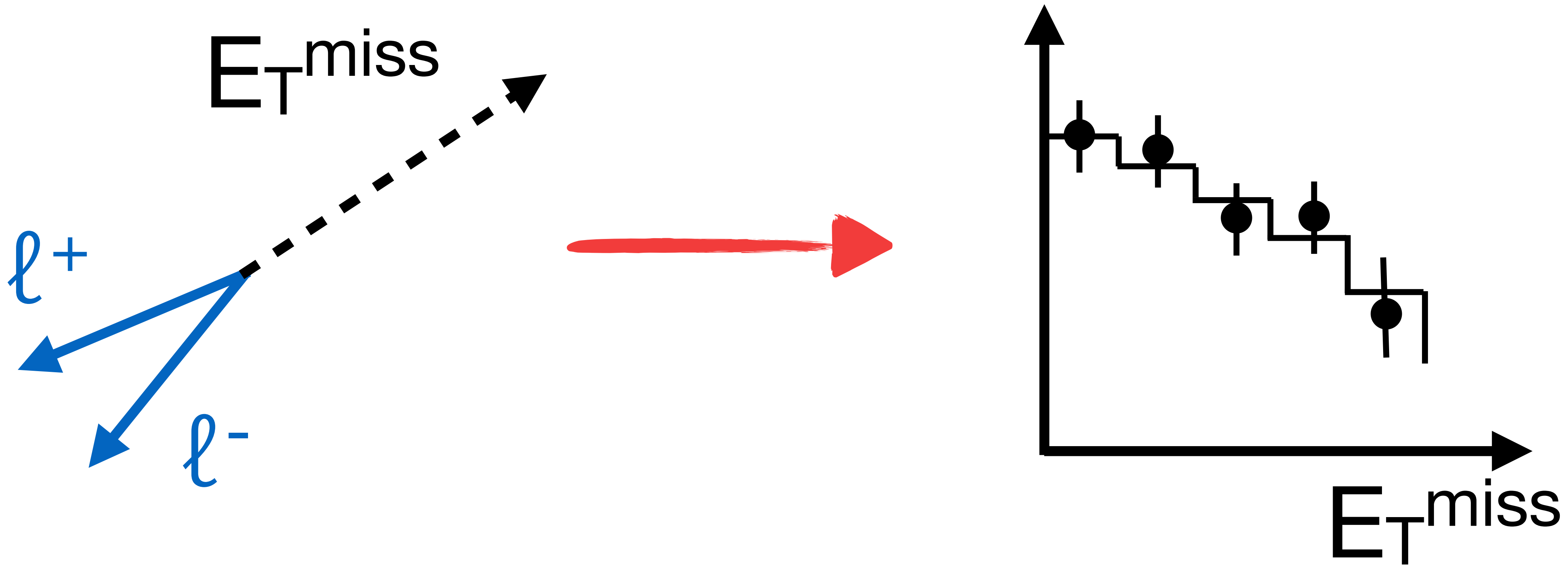
- Two searches carried out in the $Z(\ell\ell) + E_T^{miss}$ final state:
  1. Search for **invisible Higgs decays**
     - Consider m_H = 125 GeV and 110-400 GeV
  2. Search for **dark matter candidates** produced through a **mediator** particle (s-channel, axial-vector and vector mediators)



- Discriminating variable: $\mathbf{E_T^{miss}}$



- Study events with $Z(\ell\ell)$ recoiling against E_T^{miss}, look for **excess of events** in the $\mathbf{E_T^{miss}}$ **spectrum**



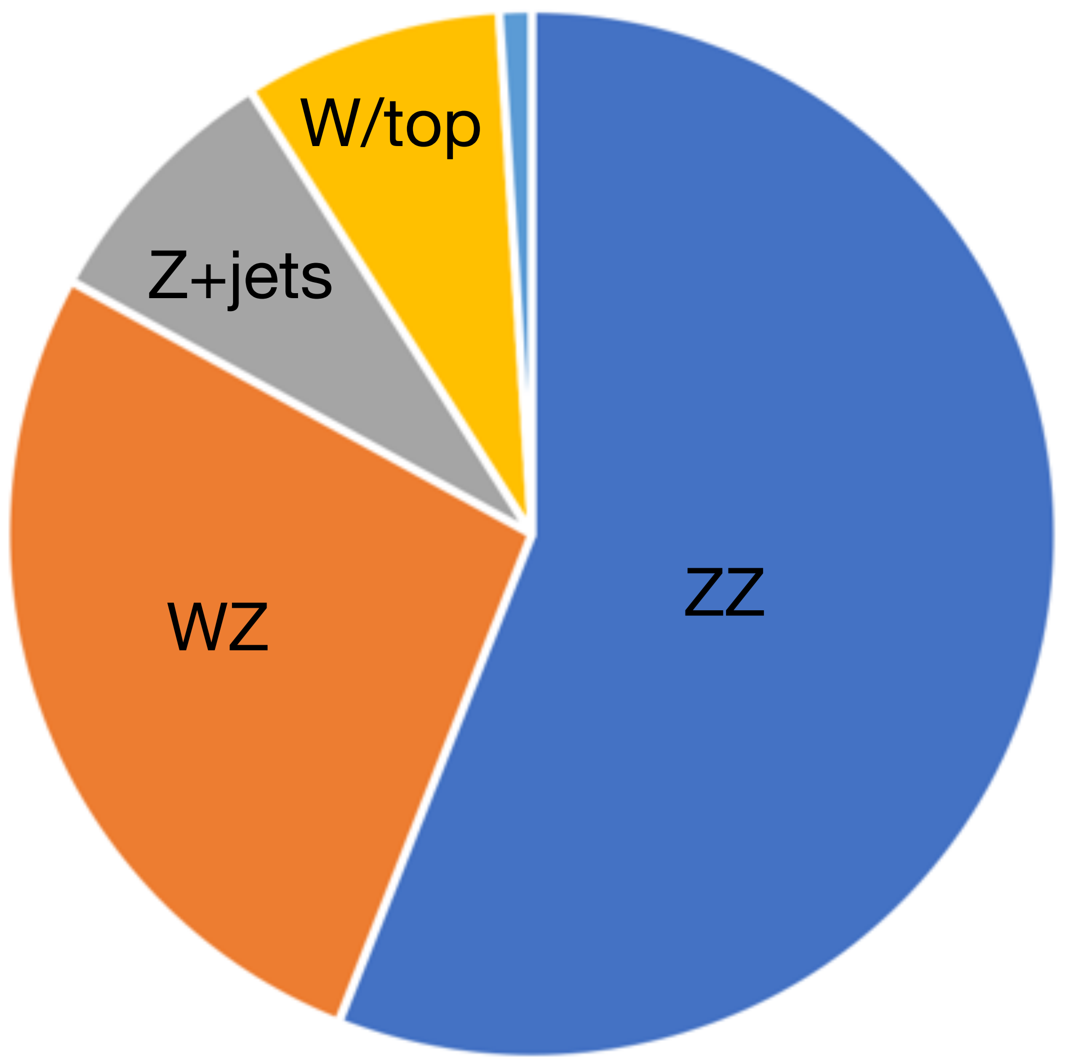
Event selection

- Goal to **isolate events with large E_T^{miss} recoiling against $Z \to \ell\ell$**, and **reduce backgrounds**
- **Two signal regions:** $Z \to ee$, $Z \to \mu\mu$

Selection criteria	Background reduced
Exactly one $\ell\ell$ (= ee or μμ) pair with opposite charge	
Veto events with 3rd lepton (e or μ) with $p_T > 7$ GeV	WZ
Z mass window: $76 < m_{\ell\ell} < 106$ GeV	$WW/Wt/t\bar{t}/Z(\tau\tau)$
$E_T^{miss} > 90$ GeV	Z+jets
$\Delta R(\ell\ell) < 1.8$	Z+jets, $WW/Wt/t\bar{t}/Z(\tau\tau)$
$\Delta\phi(Z, E_T^{miss}) > 2.7$	Z+jets, $WW/Wt/t\bar{t}/Z(\tau\tau)$
$\lvert p_T(\ell\ell) - \lvert \vec{E}_T^{miss} + \vec{p}_T(\text{jets})\rvert \rvert / p_T(\ell\ell) < 0.2$	Z+jets
$E_T^{miss}/H_T > 0.6$ ($H_T = p_T(\text{jets}) + p_T(\ell_1) + p_T(\ell_2)$)	Z+jets
b-jet veto	$t\bar{t}$

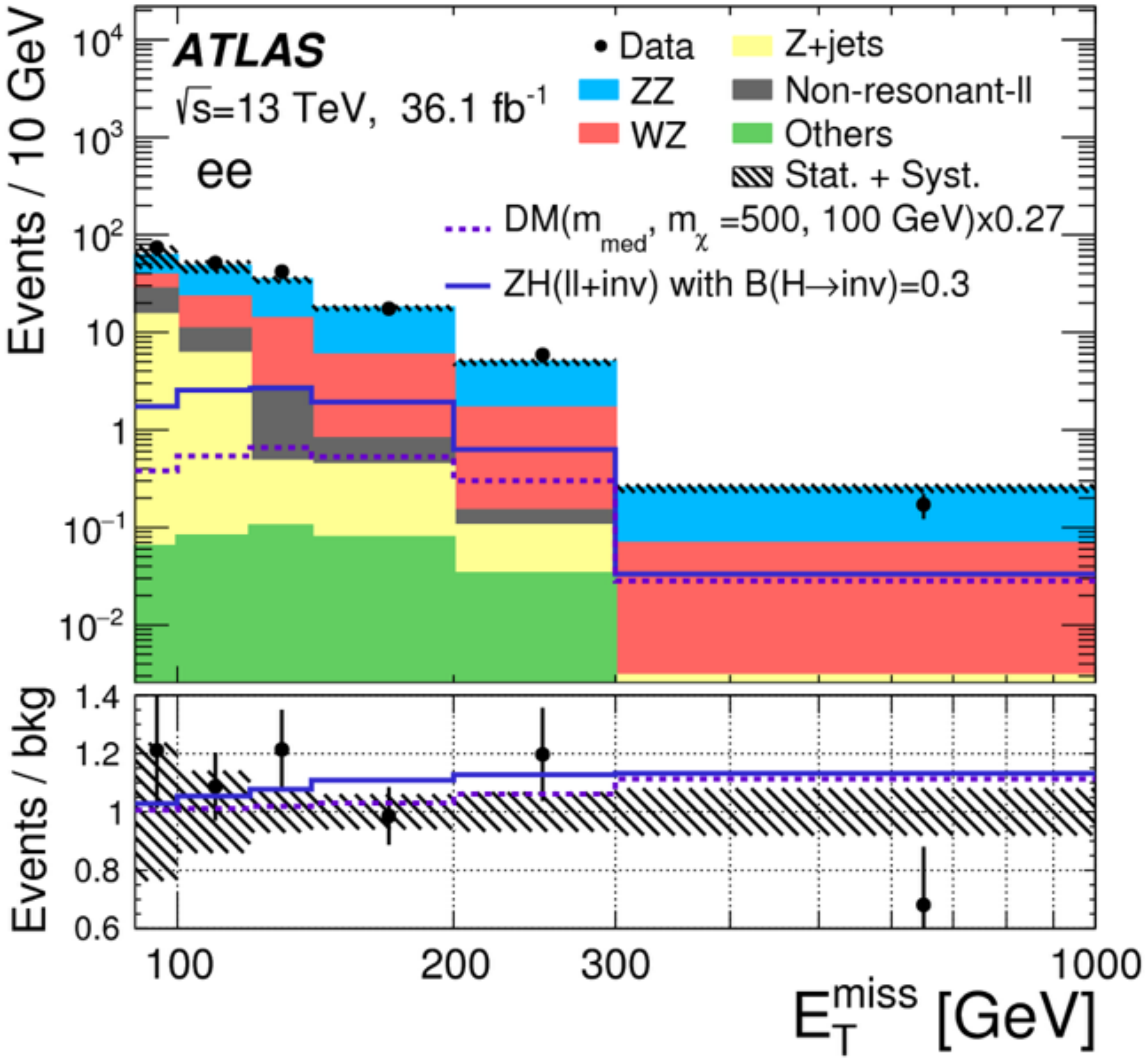
Backgrounds

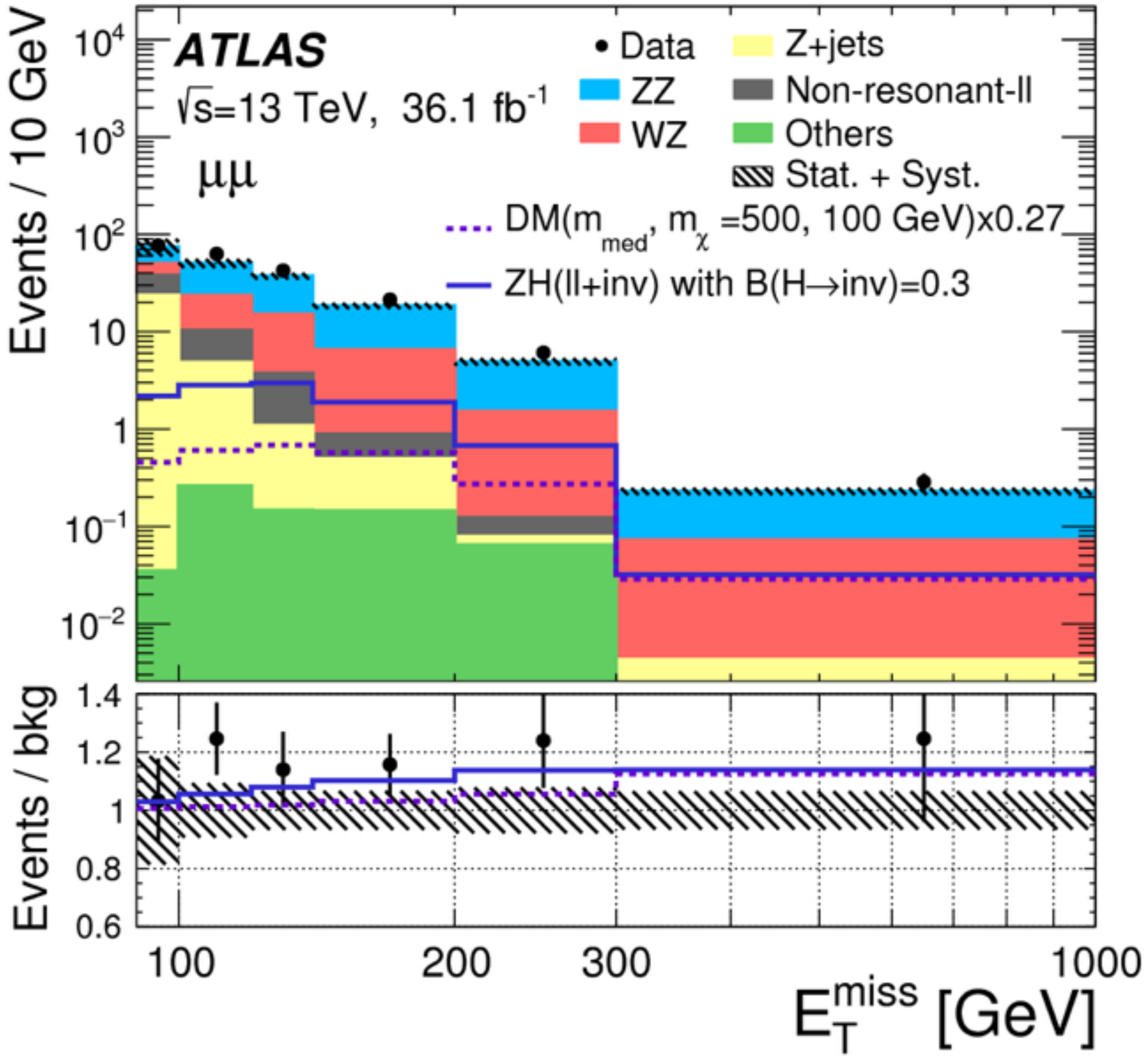
Background	Source	Estimation
ZZ	ZZ → $\ell\ell\nu\nu$, irreducible	MC
WZ	WZ → $\ell\nu\ell^+\ell^-$ ℓ from W not reconstructed	Data (yield), MC (shape)
Z+jets	Z(ee) / Z(μμ) + jets jets mis-measured as fake E_T^{miss}	Data (yield), MC (shape)
W/top	WW / Wt / $t\bar{t}$ / Z(ττ) → $\ell^+\nu\ell^-\nu$ $\ell\ell$ do not come from a Z	Data
W+jets	W($\ell\nu$) + jets ℓ mis-identified from a jet	Data
$t\bar{t}V/t\bar{t}VV/VVV$ (V=Z,W)	e.g. $t\bar{t}W$ → $(\ell^+\nu b)(q_1q_2b)(\ell^-\nu)$	MC



Results (I): Signal region E_T^{miss} distributions

- Perform statistical analysis on E_T^{miss} in signal regions
    - Inputs: observed data, signal and background estimates, systematic errors
- Assuming the null hypothesis (no signal), there is a small excess of 2.2σ significance observed in the μμ signal region
- Combined significance (ee +μμ channels) of 1.5σ





- As no significant excess is observed, we set limits on the H→*inv* branching ratio and dark matter masses

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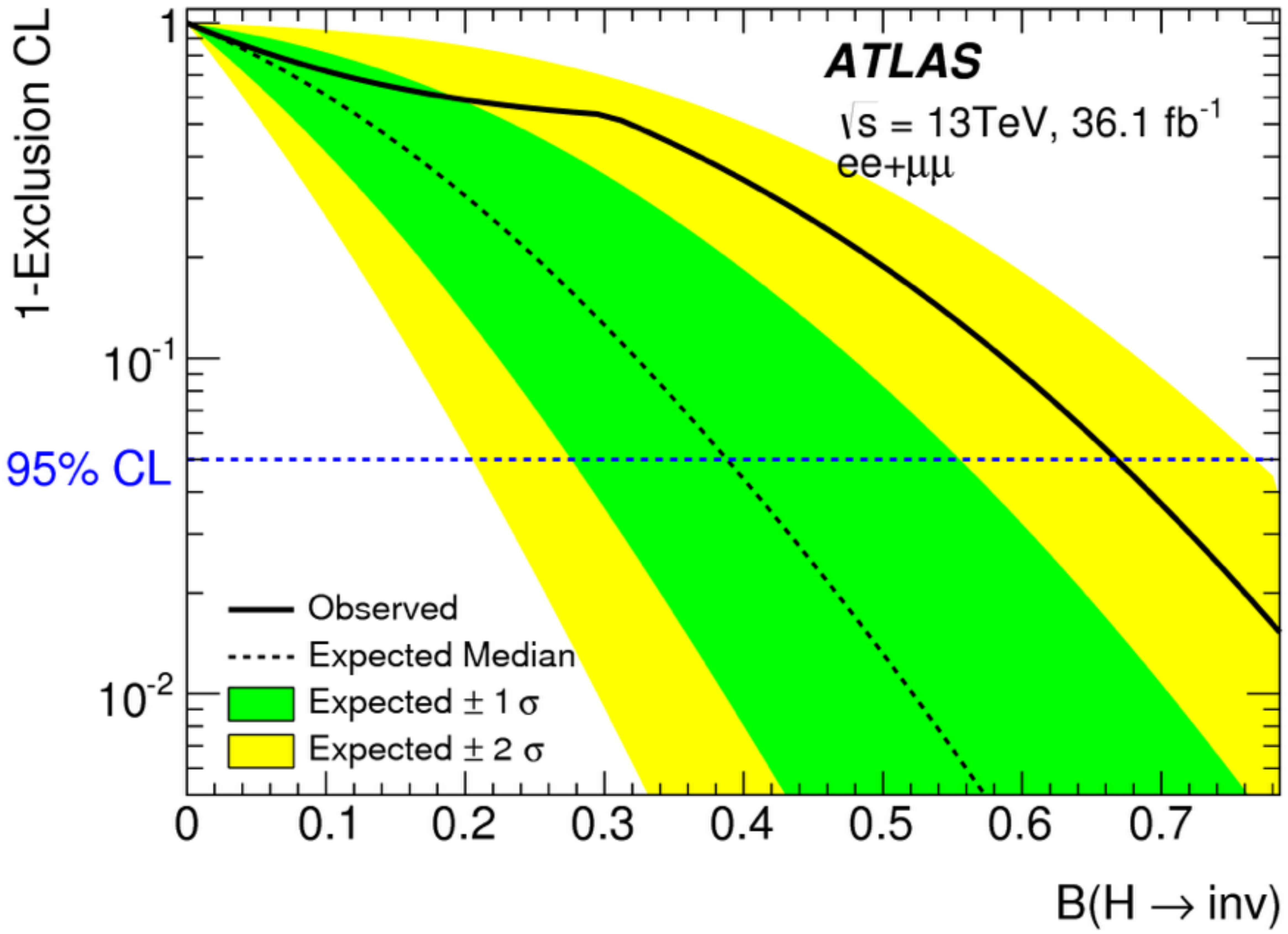
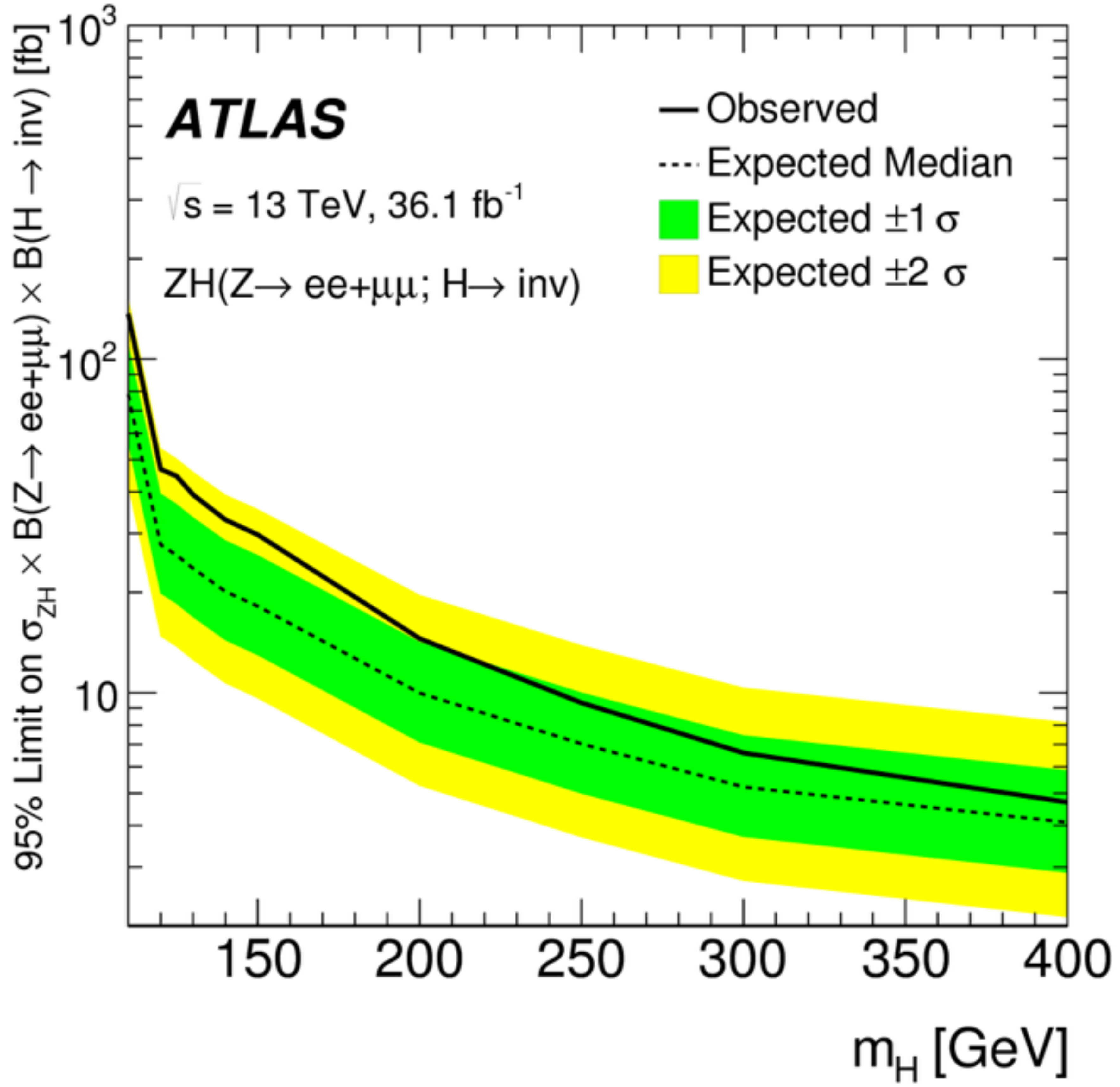
Results (II): Invisible Higgs limits





- Upper limit on the branching ratio for H→*inv* = **67% (39%)** observed (expected) at 95% CL
- Upper limit on σ(pp→ZH→ℓℓ+*inv*) = **40 (23) fb** at 95% CL

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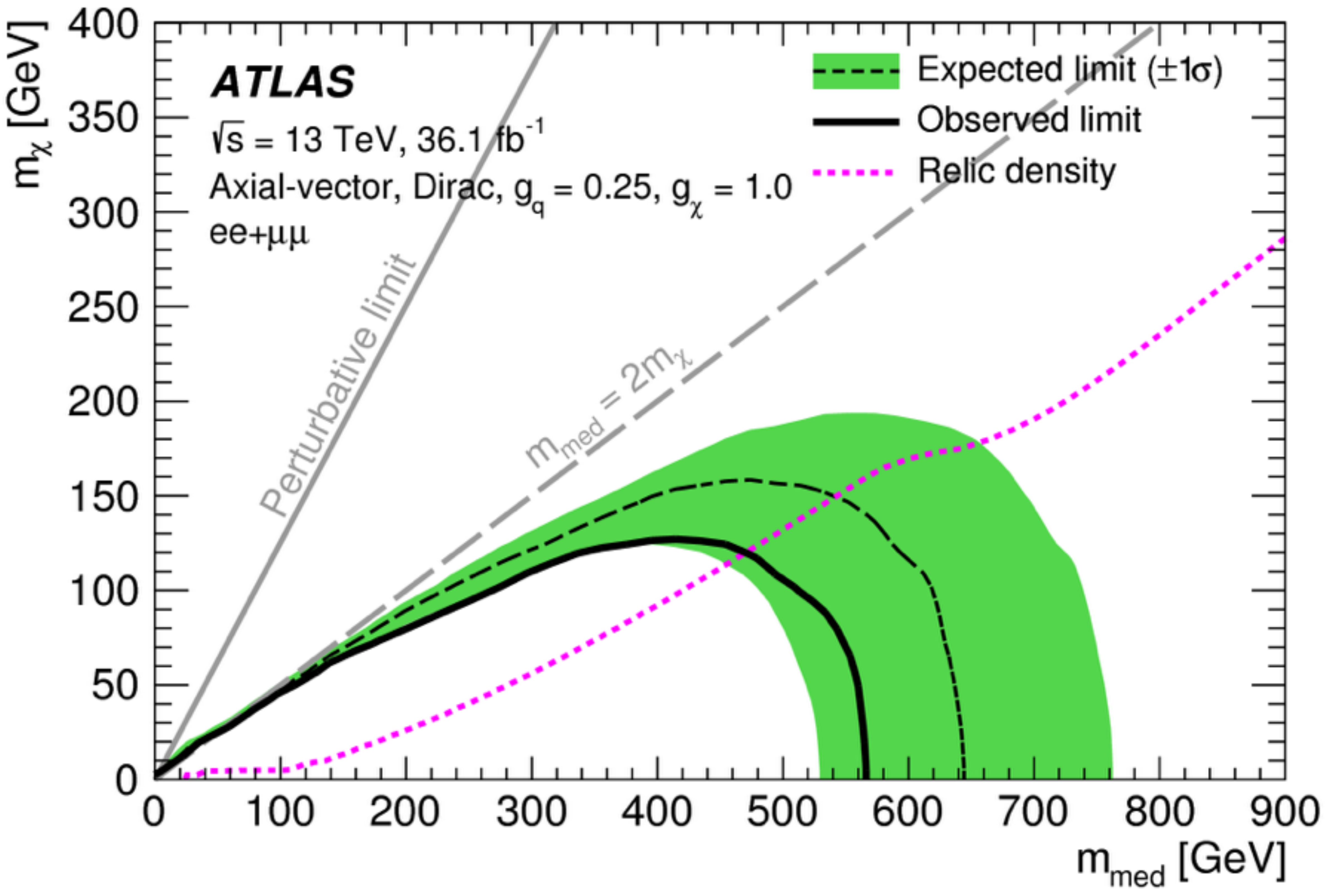
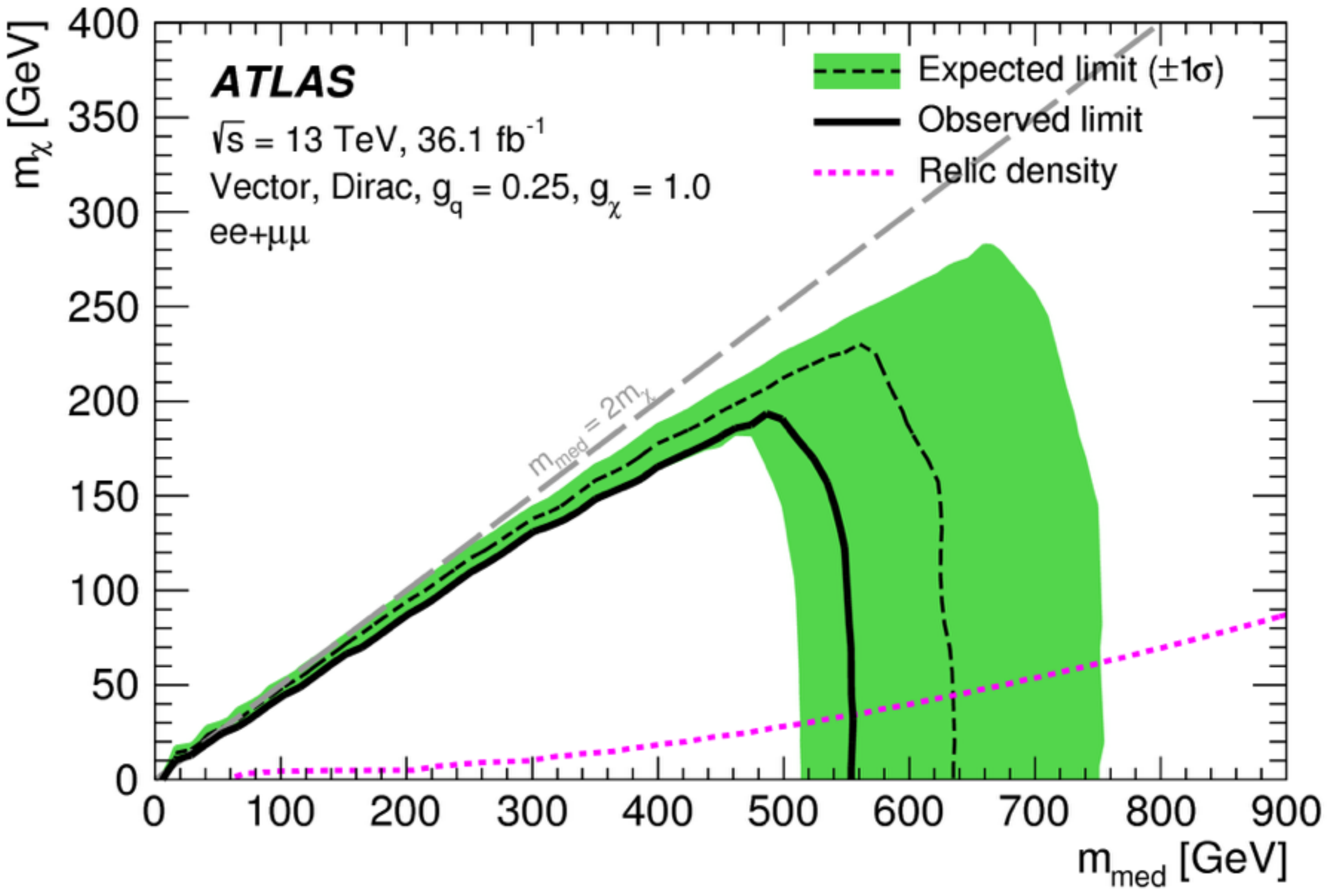
Results (III): Simplified model 2D mass limits





- For vector and axial-vector simplified models, exclusion limits set for a grid of samples with different m_χ, m_{med}
- Similar reach for both models in m_{med} for low m_χ; vector models exclude more phase space

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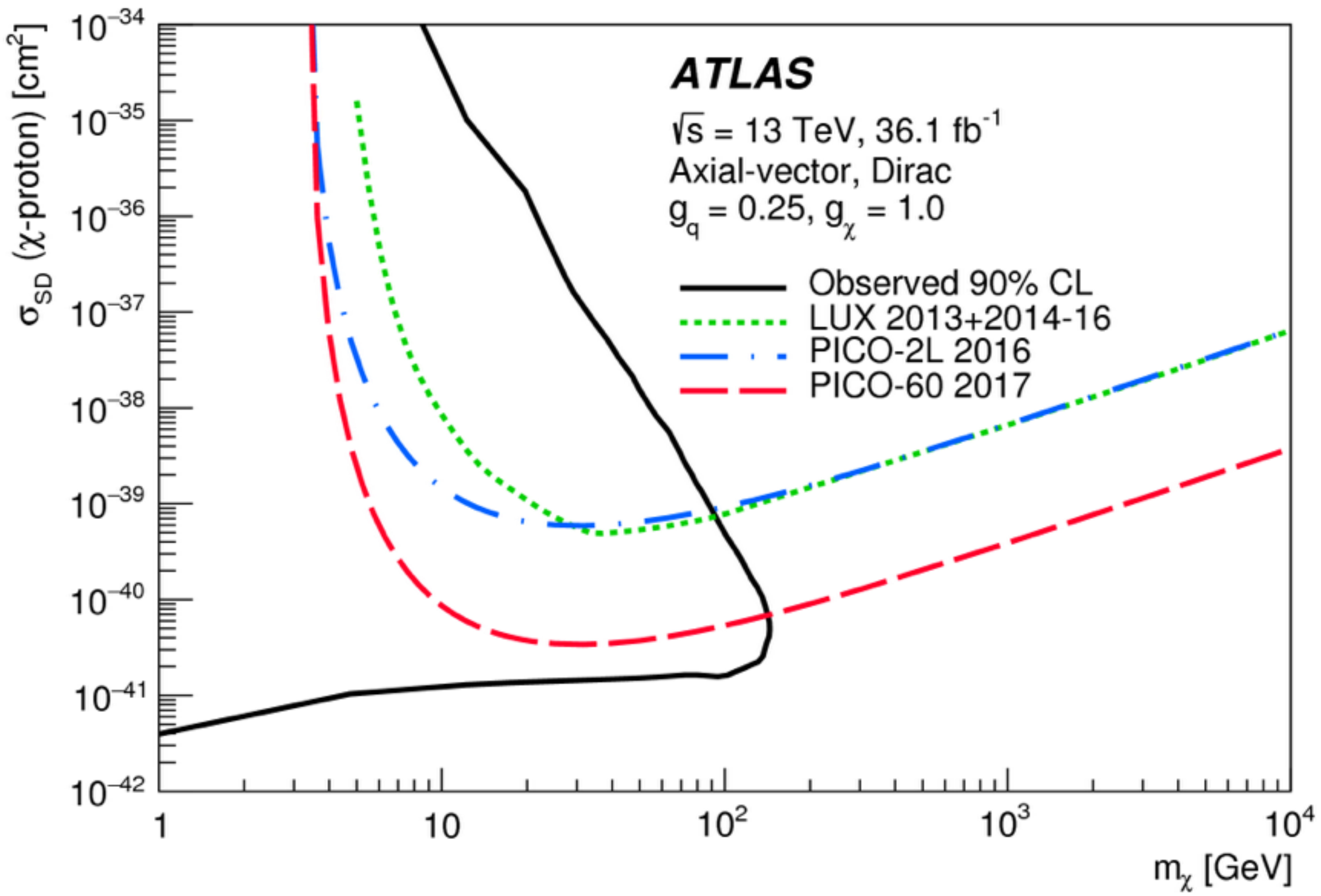
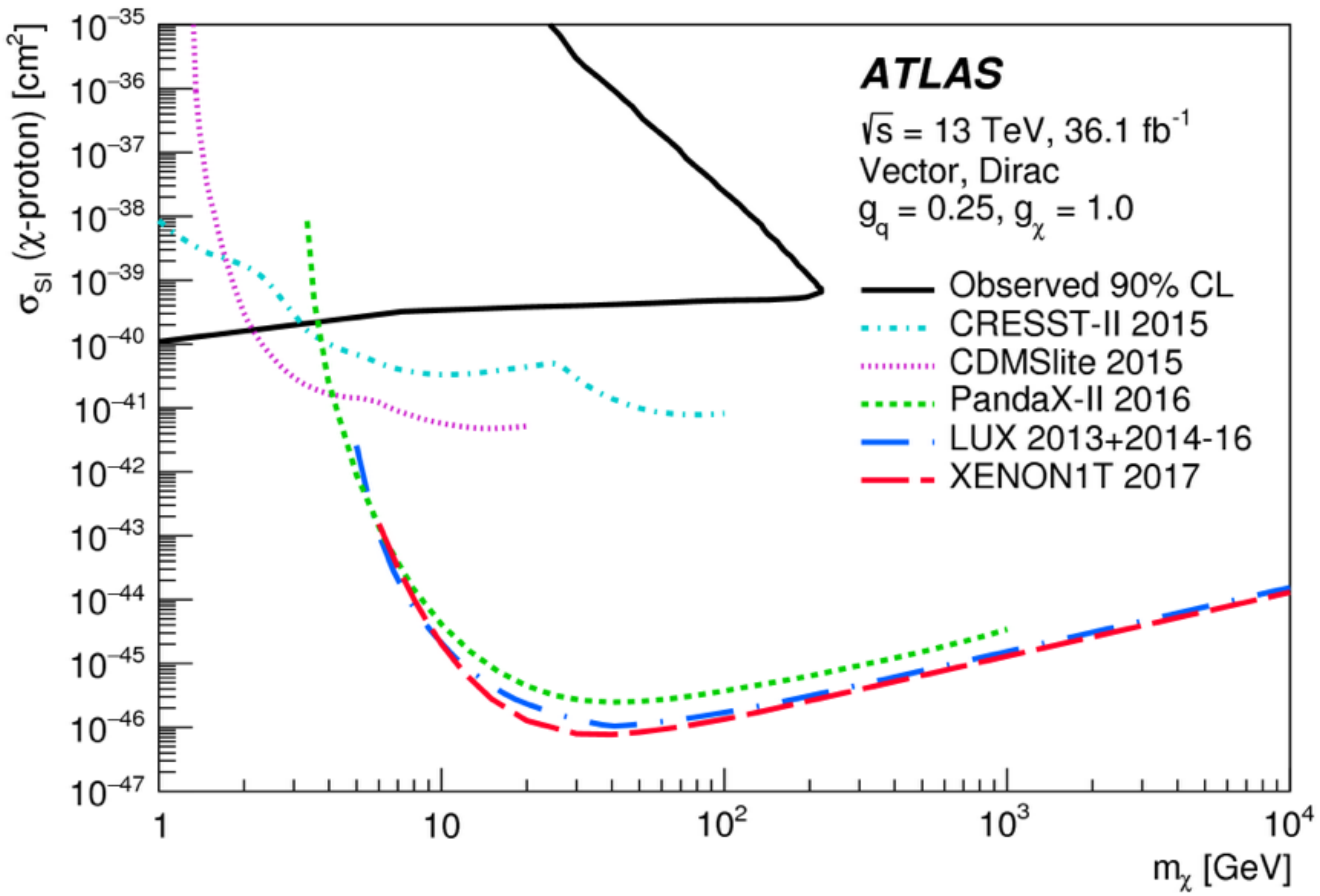
Results (IV): Comparison with direct detection experiments





- Limits also set on **DM-nucleon scattering cross section** for comparison with **direct detection** experiments
- Axial-vector limits are **best at low m_χ** where direct detection experiments lose sensitivity

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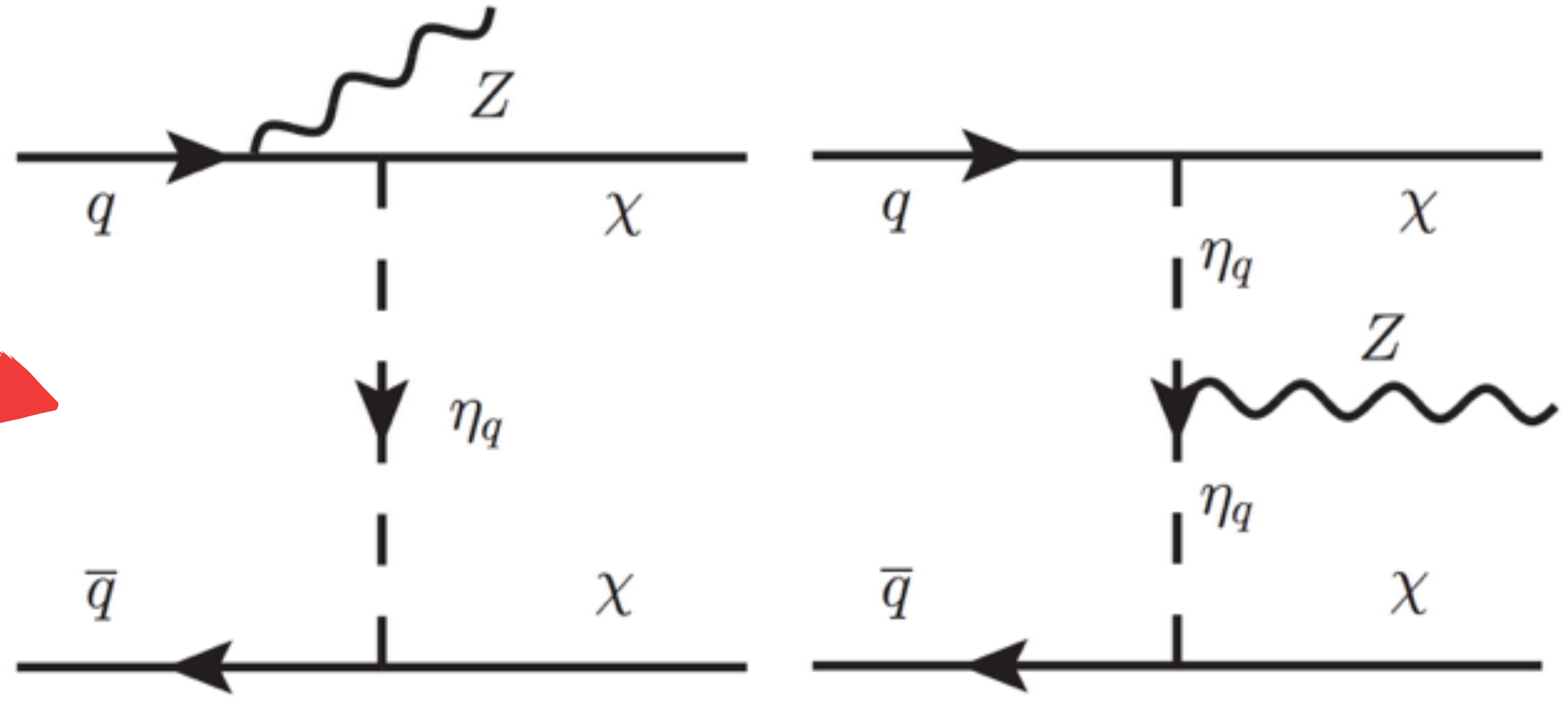
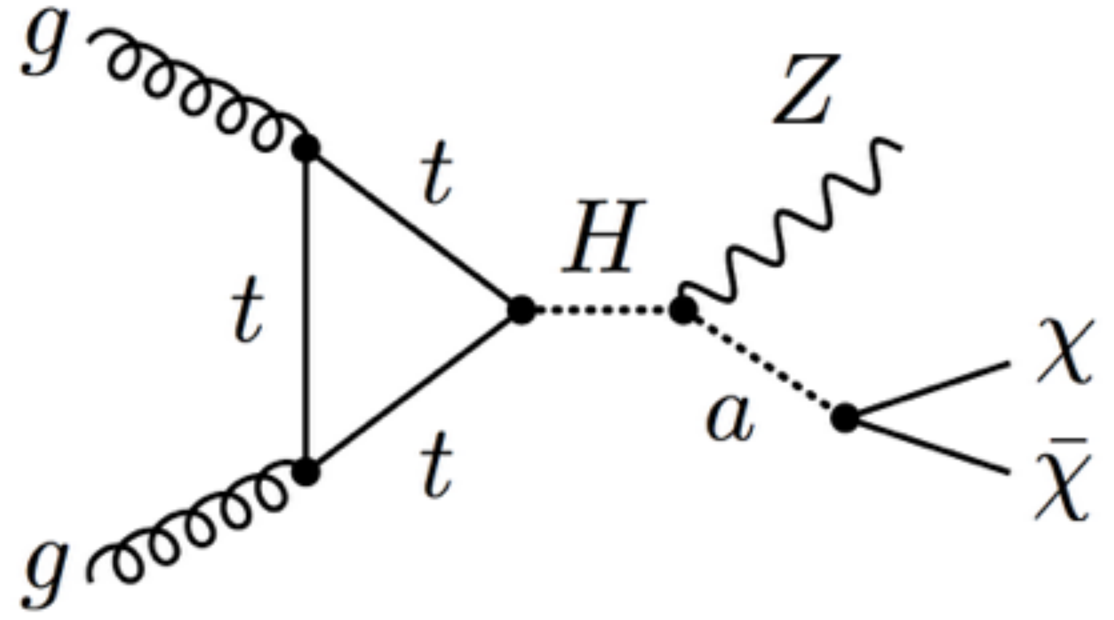
Some outlooks for the full 2015-2018 analysis

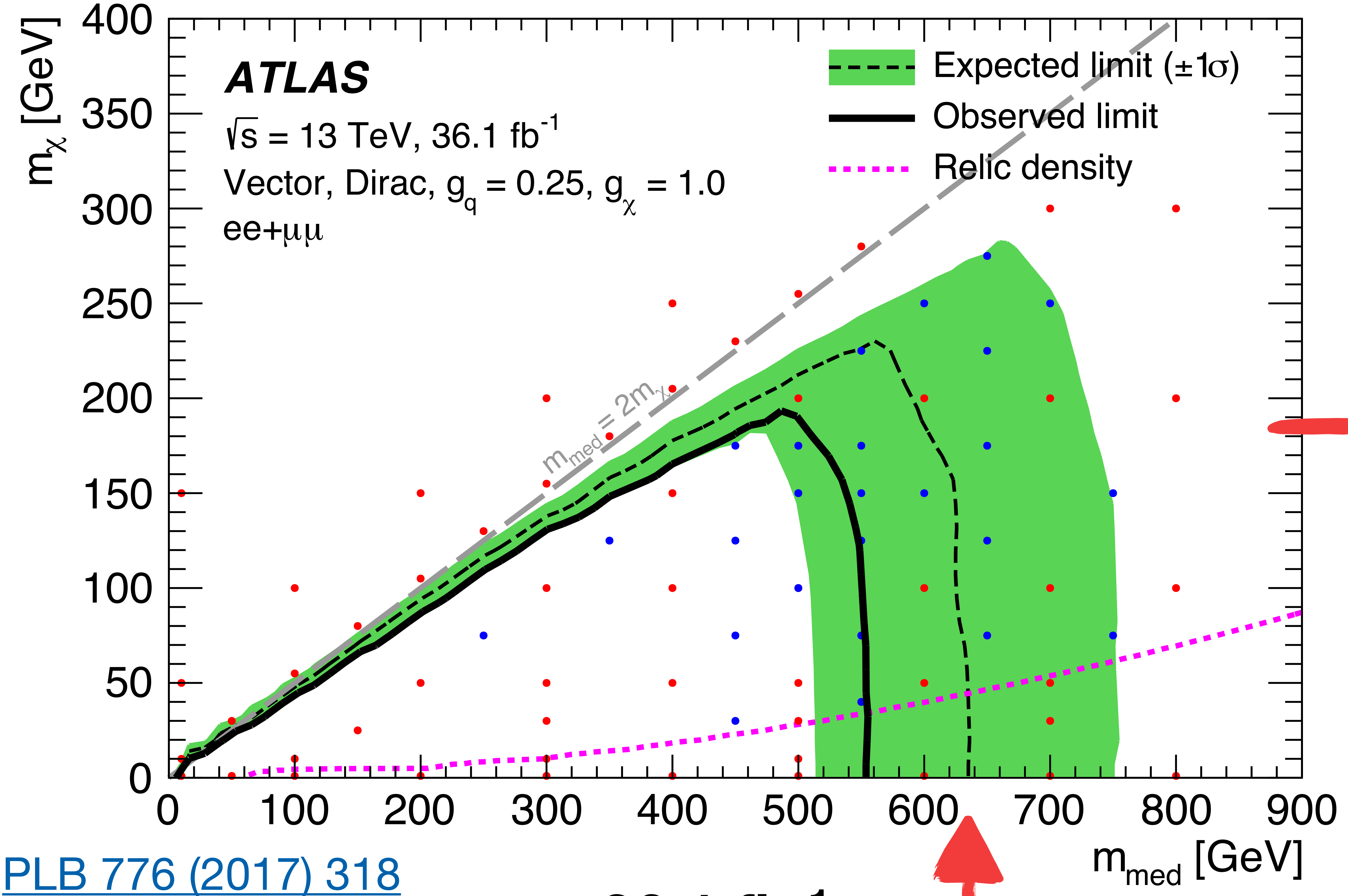
- **New signal models**
  - Simplified models to be simulated at NLO in QCD, some to include mediator-lepton couplings
  - t-channel simplified models with mediator-Z couplings
  - Two-Higgs-doublet + pseudo-scalar models are becoming a new standard; well-motived, mature, and theoretically complete

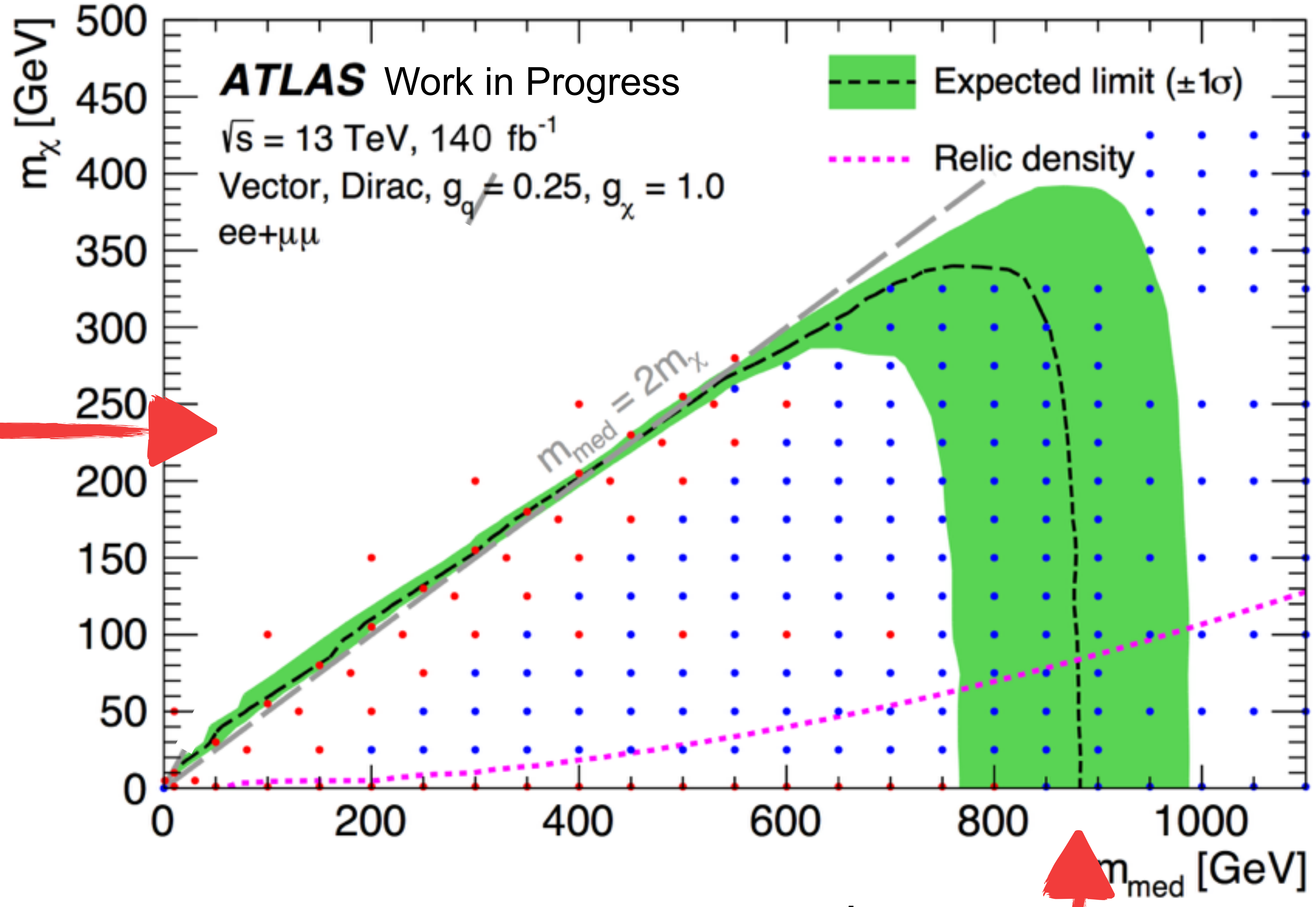




- **New background estimation techniques**
  - Data-driven estimates of the ZZ background using Zγ and ZZ→4ℓ events
  - Technique to estimate Z+jets background using γ+jets events
- **140 fb^{-1} expected, more statistical power**
  - For example, expected reach in m_{med} for low m_{χ} expected to extend from 640 → ~900 GeV when moving from 36.1 fb^{-1} to 140 fb^{-1} (next slide)

Projected expected sensitivity





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36.1 fb^{-1}

140 fb^{-1}

- Prospective expected limits with 140 fb^{-1} for vector mediator simplified model
- Simple scaling of published result (background estimates + systematic errors) up to projected luminosity

Conclusions

- Paper published for **result on 2015+2016** dataset (https://arxiv.org/abs/1708.09624)
- Similar sensitivity seen by CMS (https://arxiv.org/abs/1711.00431)
- In process of **analyzing 2017 dataset**
- Preparing analysis for the **full 2015-2018 dataset**, with focus on:
  - Expanding the types of **dark matter models** we study
  - Signal detection **optimization**
  - Improving **data-driven background estimates**

Thank you!

Backup

Two-Higgs-doublet + pseudo-scalar model

- Introduction of a **second Higgs doublet** is **well-motivated theoretically**
  - e.g. Supersymmetry, CP violation (baryogensis, axions)
- **Model has a total of 6 bosons:**
  - **h** = light scalar, identified as SM Higgs
  - **H** = heavy scalar
  - **H$^{\pm}$** = 2 heavy charged scalars
  - **A** = heavy pseudo-scalar
  - **a** = light pseudo-scalar, couples to SM and DM particles
- **Free parameters:**
  - m_a, m_H, m_A, sinθ (θ = mixing angle of A, a), tanβ (β = ratio of Higgs vevs), m_χ
- Mono-Z signature enhanced by **resonant production of H (or A)**