

# DM SEARCHES @ THE LHC

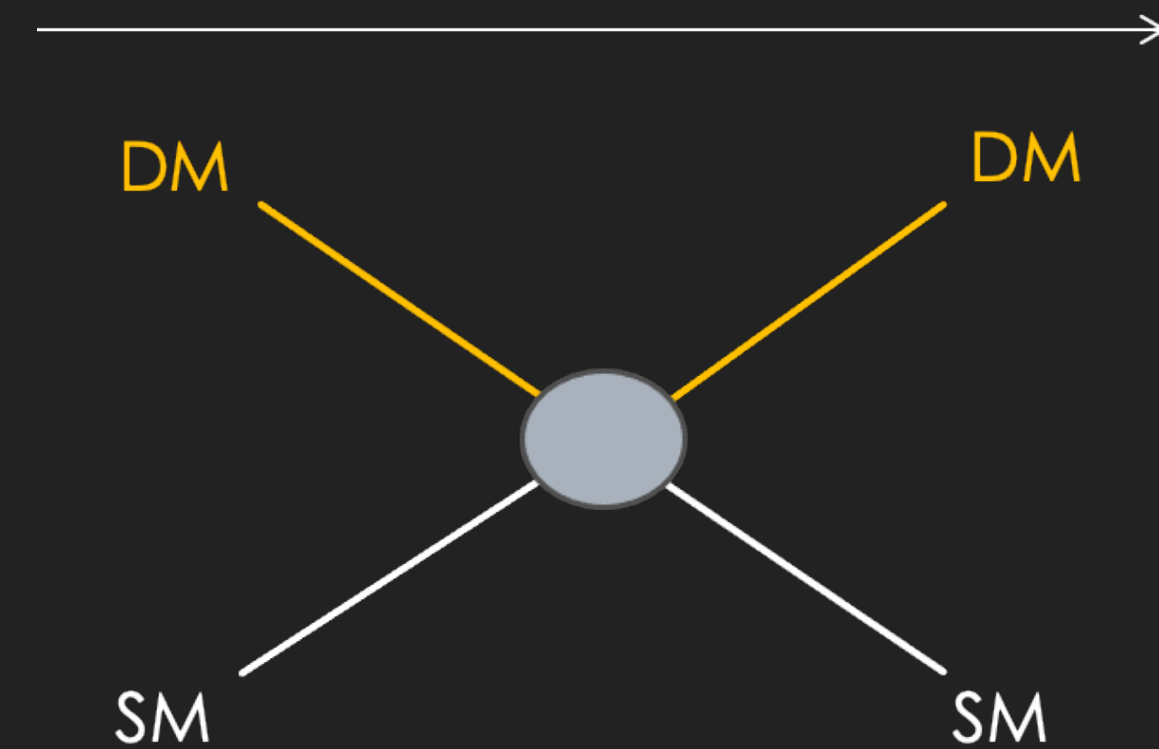
MARIE-HÉLÈNE GENEST

COSPT / MAY 10TH 2022

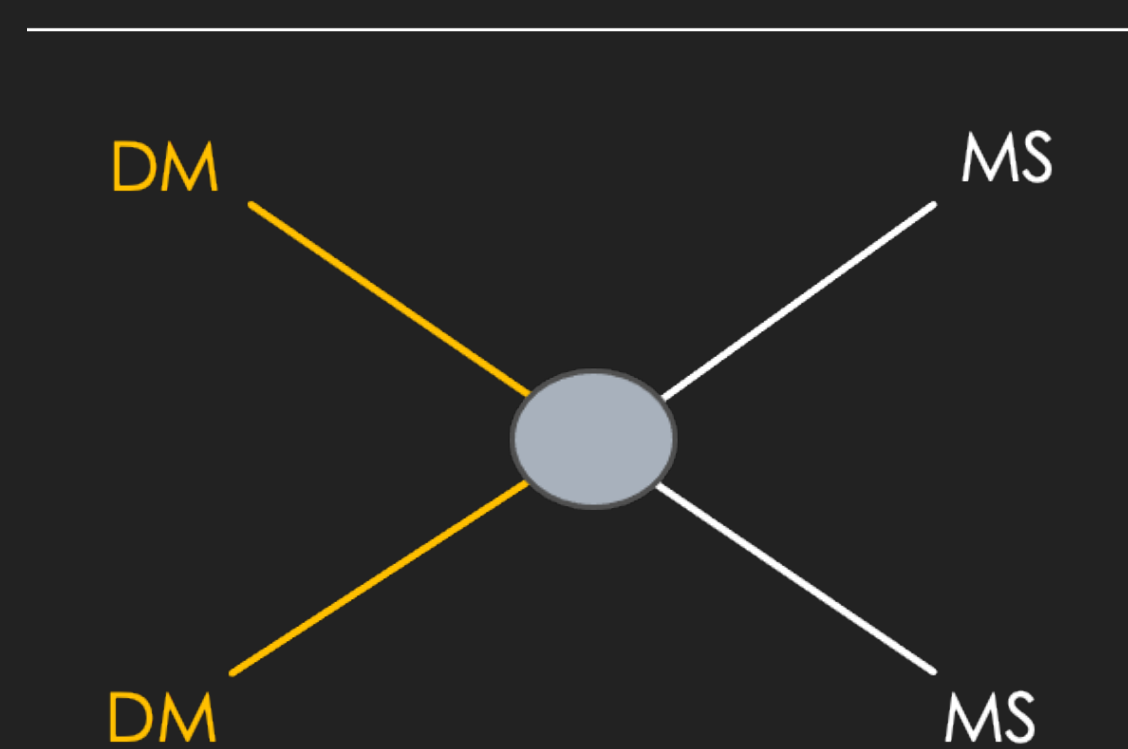


# SEARCHING FOR DARK MATTER ...

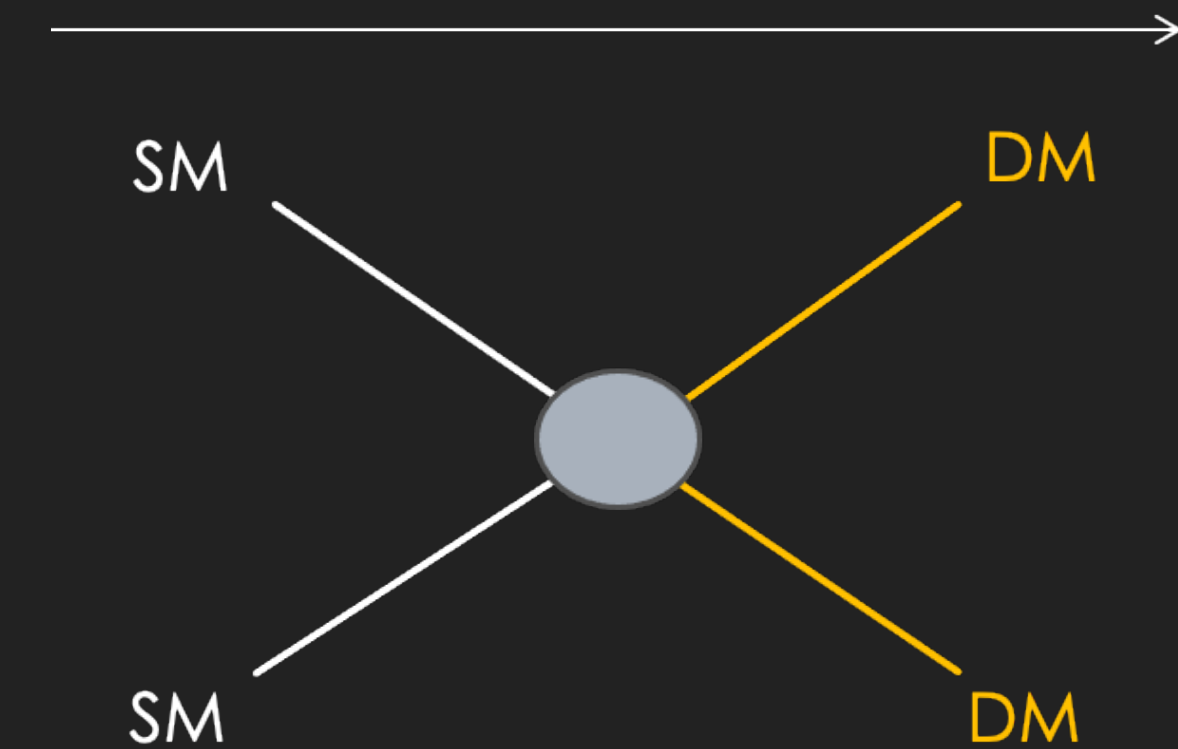
- ▶ 85% of the matter in the universe is in the form of DM according to cosmological/astrophysical evidences



Direct detection



Indirect detection



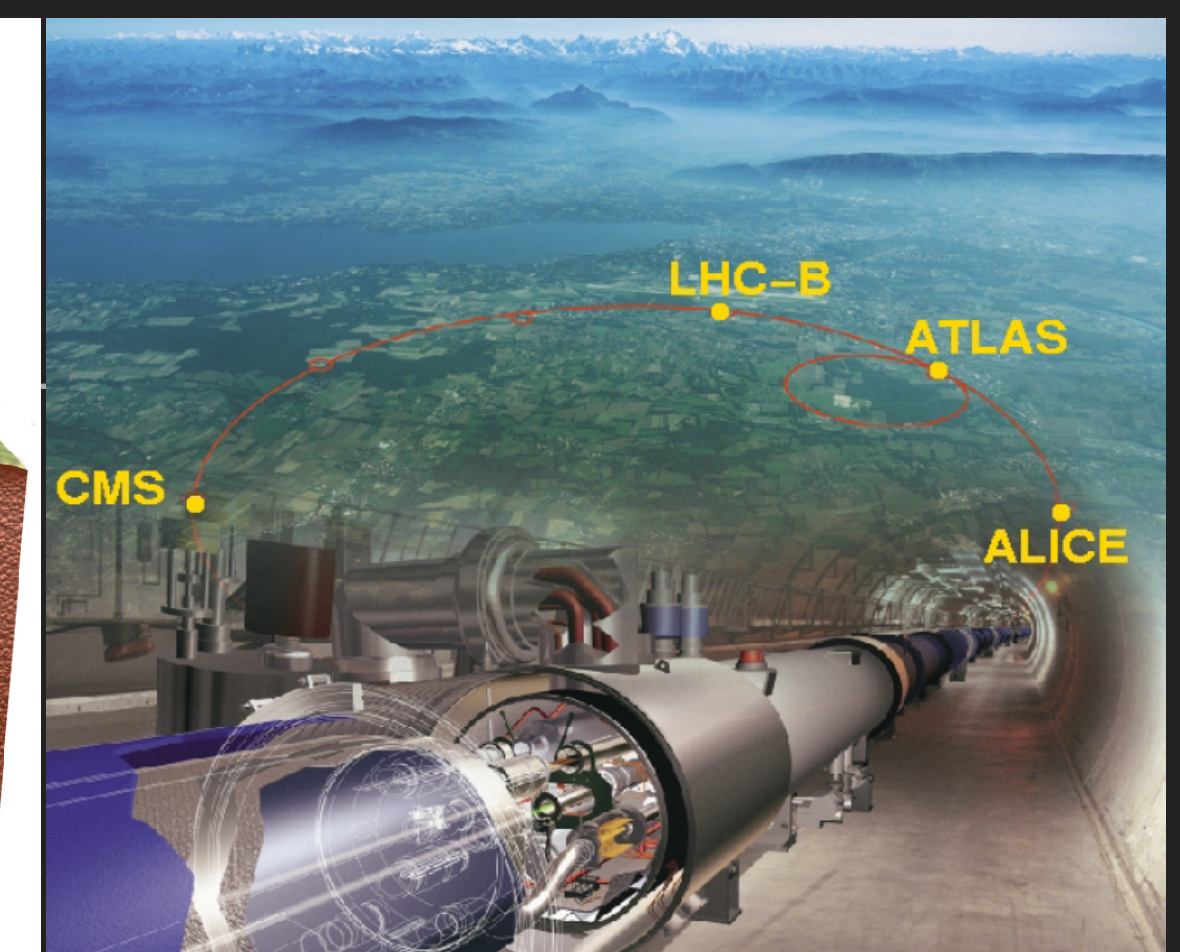
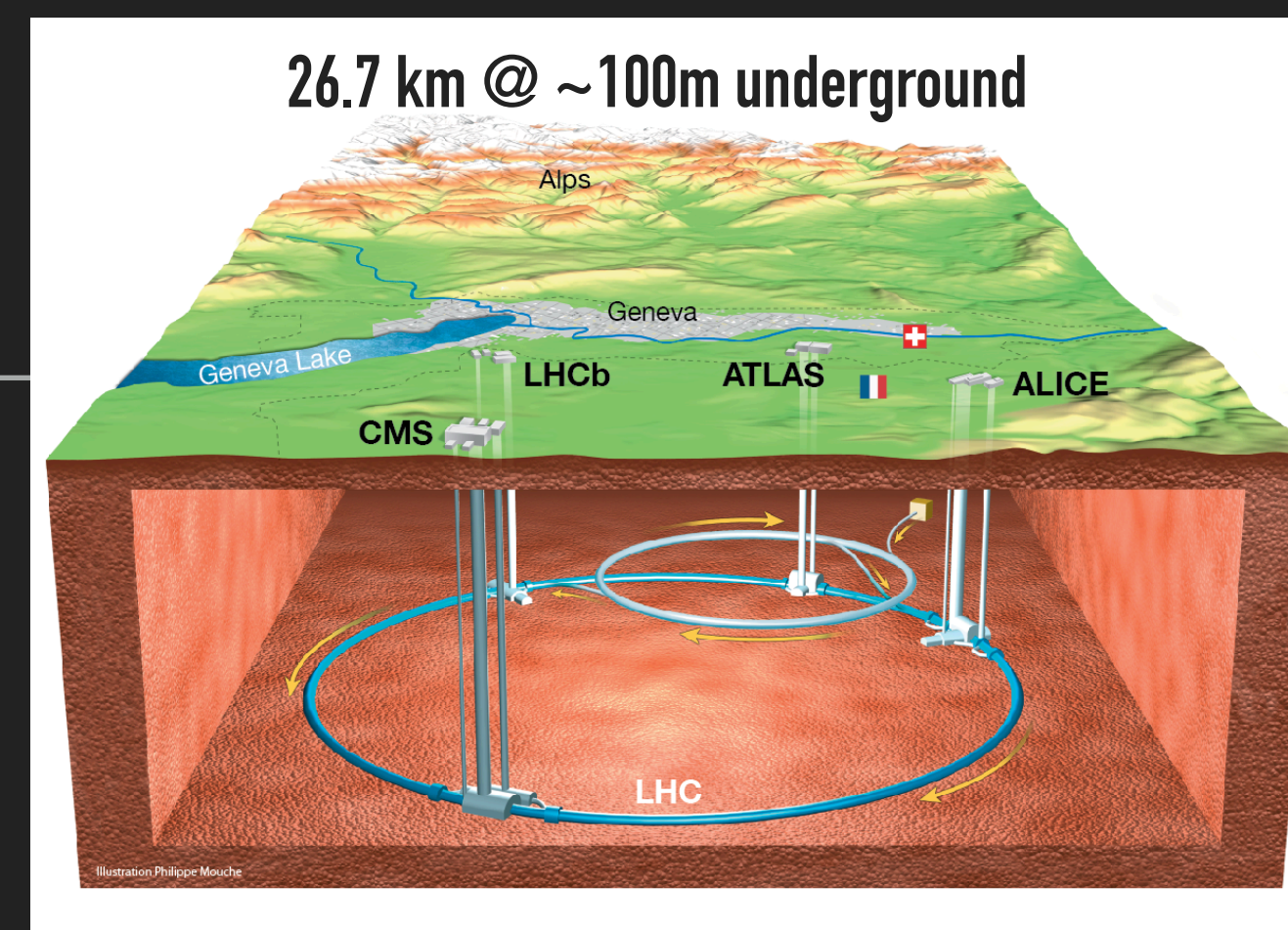
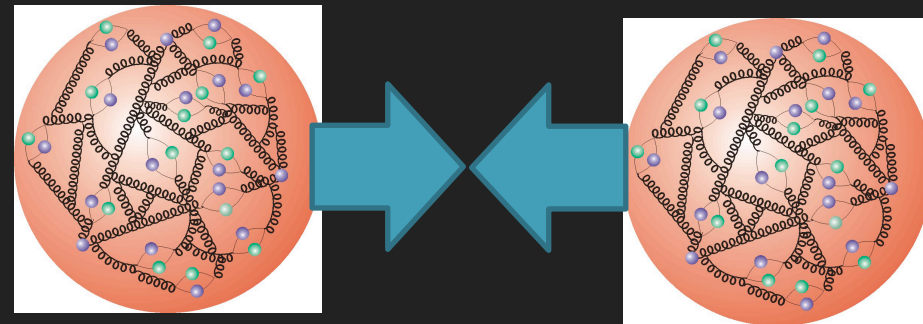
Production





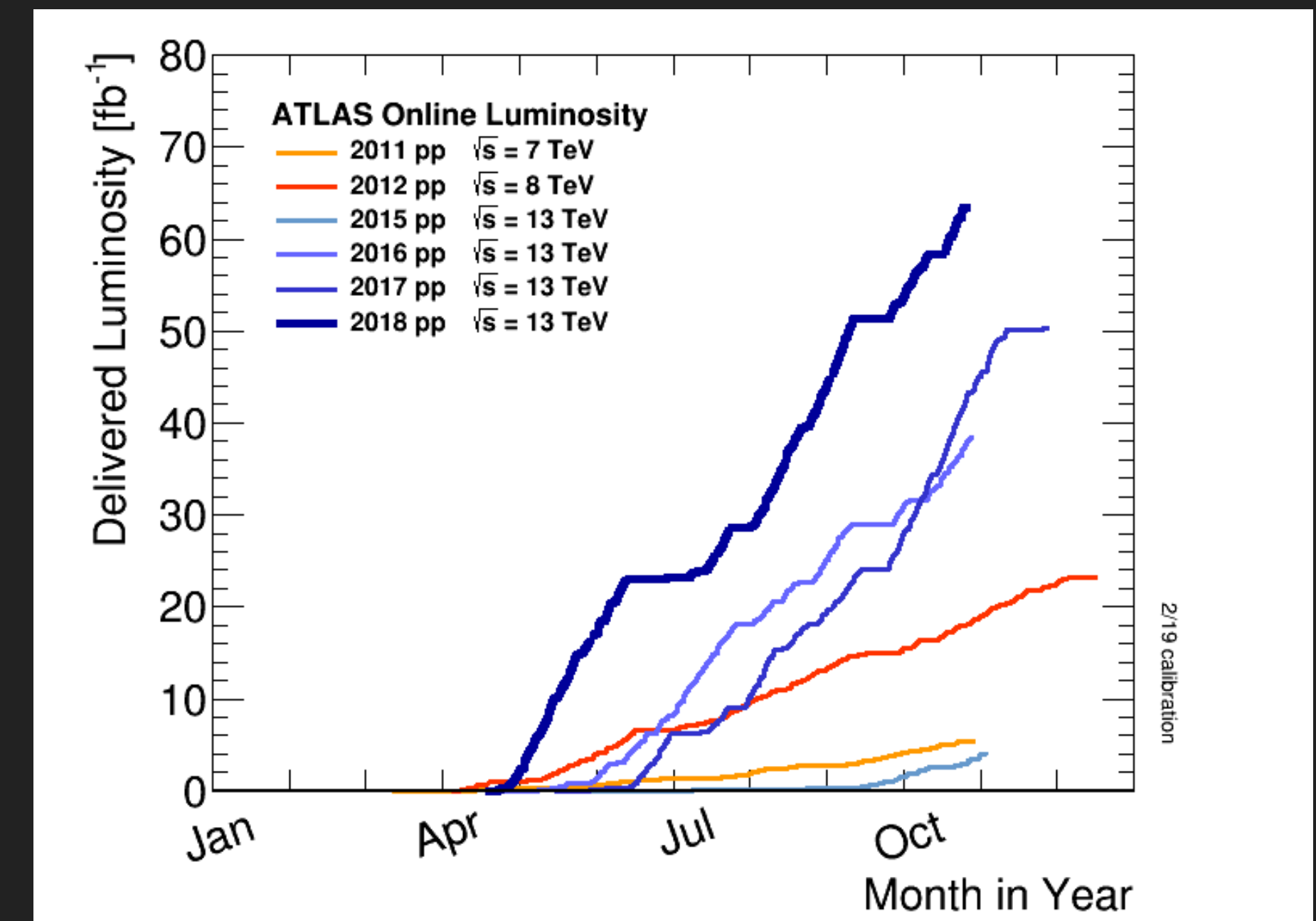
# ... @ THE LHC

- ▶ proton-proton collider\*



- ▶ pp center-of-mass energy:

- ▶ Run-1: 2009 @ 900 GeV, 2010-11 @ 7 TeV, 2012 @ 8 TeV
  - ▶ Long shutdown 1 (LS1): 2013-14 (maintenance/upgrade)
- ▶ Run-2: 2015-18 @ 13 TeV
  - ▶ **LS2: 2018-22 ~140 fb<sup>-1</sup> of data**
- ▶ Run-3: 2022-2025 @ 13.6 TeV ; ~300 fb<sup>-1</sup>
- ▶ LS3: 2026-2028
- ▶ High-luminosity LHC (HL-LHC) 2029-... @ 14 TeV => 3 ab<sup>-1</sup>



\* may contain some heavy ions ... :)



# BEFORE WE START, A DISCLAIMER

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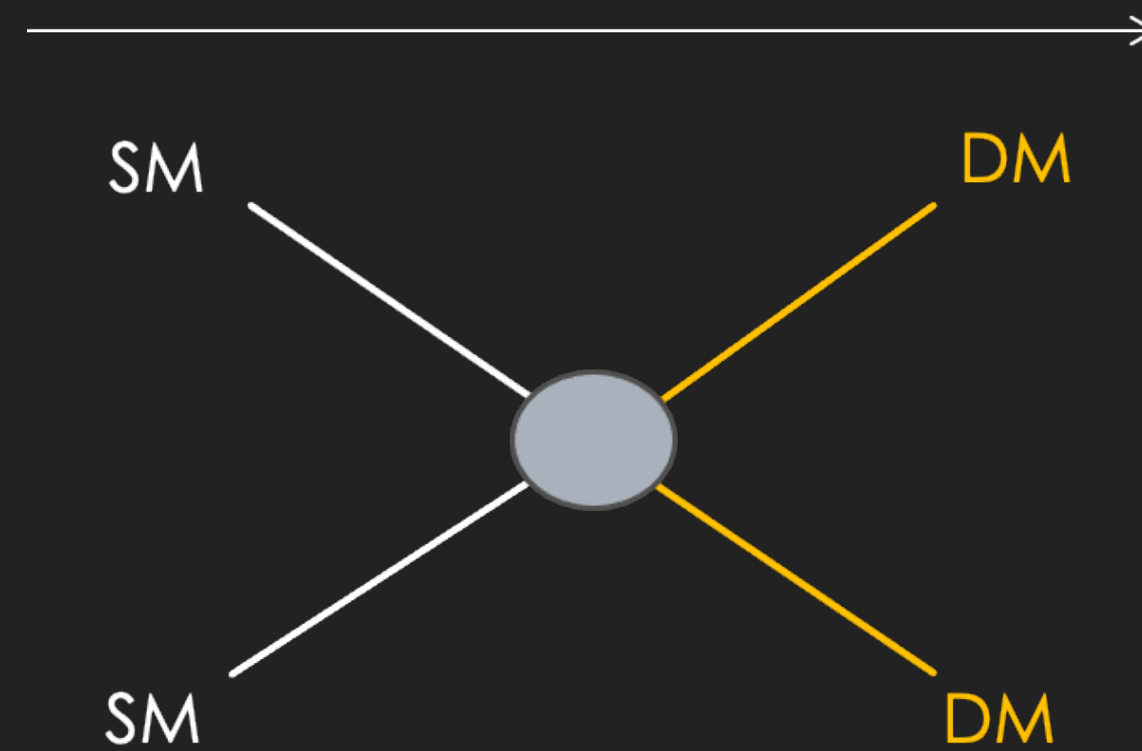
- ▶ Impossible to do justice to all results as this is a broad program:
  - ▶ I will only present a few examples, picking amongst the latest results of DM searches at the LHC
  - ▶ Also, not covering the searches for supersymmetry, which would require another, dedicated talk!
- ▶ CMS and ATLAS both have similar programs and comparable results; LHCb has some relevant searches too!
- ▶ For more information:
  - ▶ [CMS](#) , [ATLAS](#) & [LHCb](#) public results



# SEARCHING FOR A DM CANDIDATE AT THE LHC

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- ▶ If DM is made of BSM particles which interact weakly with SM particles, then couldn't it be possible to produce some in pp collisions at the LHC?

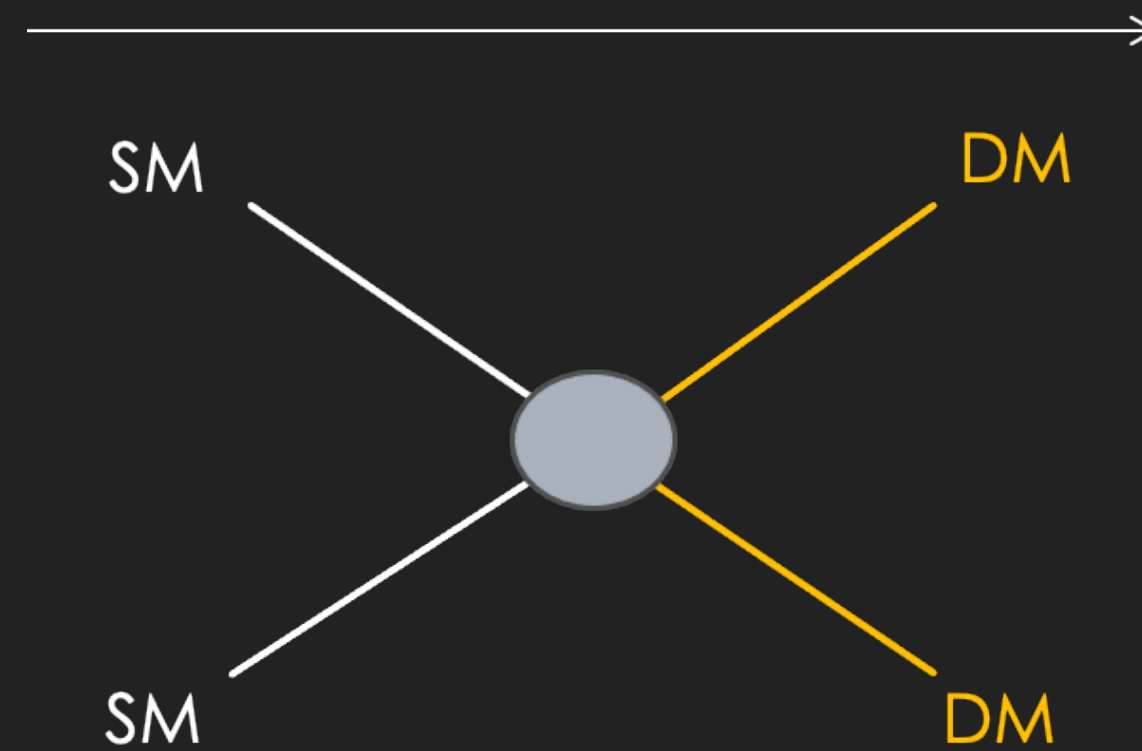


But if DM interacts only weakly... how can we detect it?

# SEARCHING FOR A DM CANDIDATE AT THE LHC

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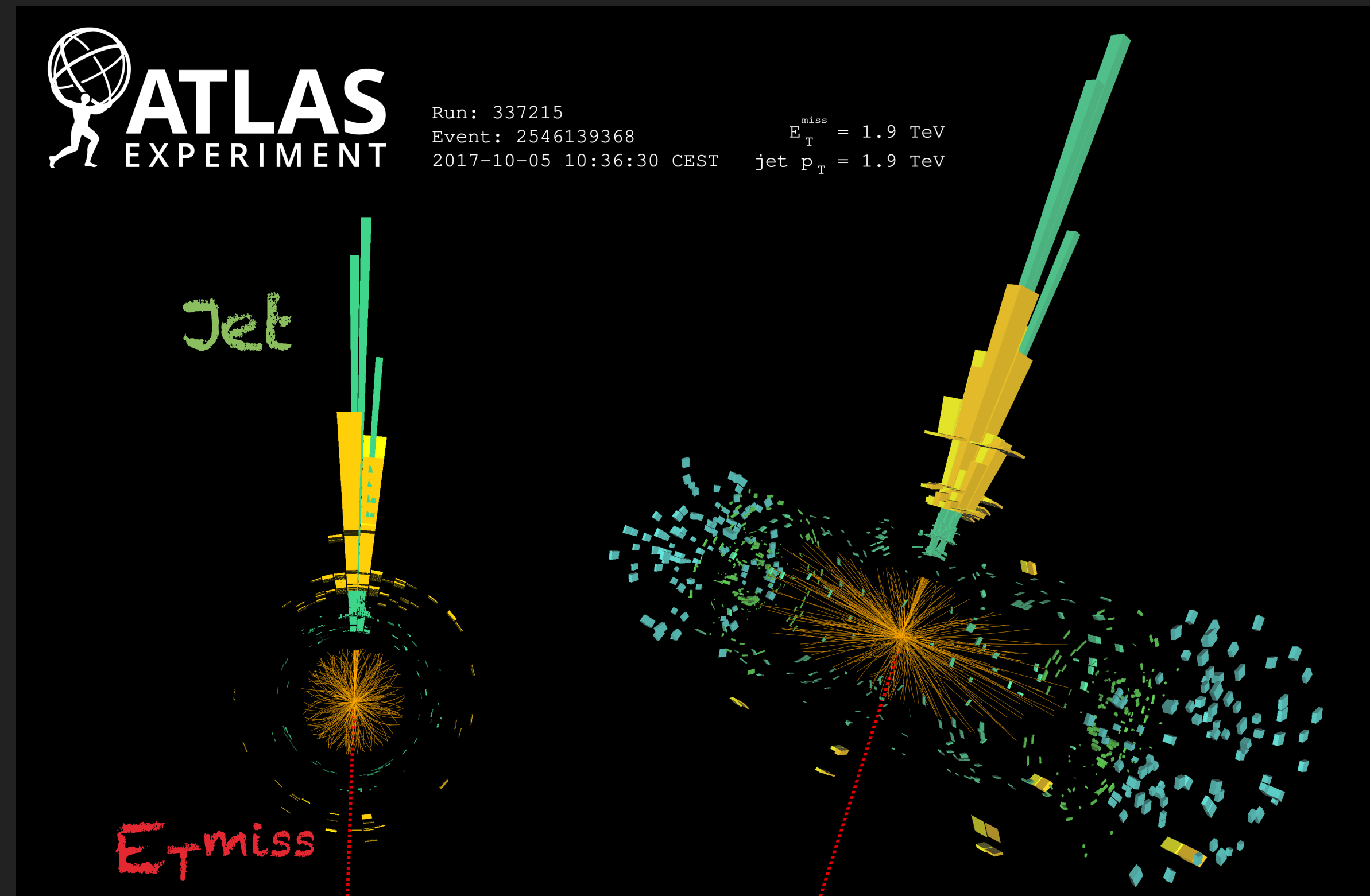
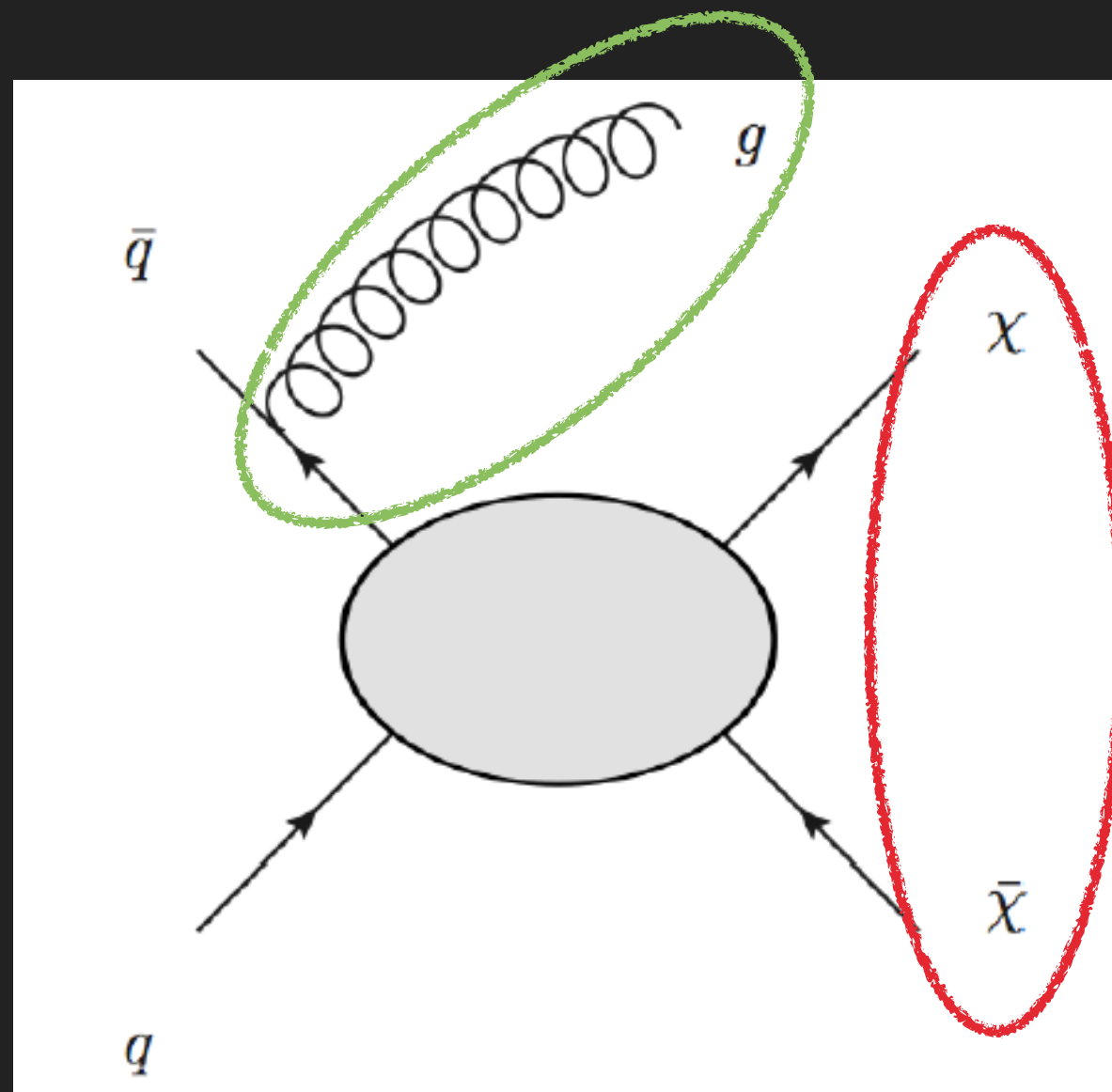


How can we even know this event occurred? Untriggerable?



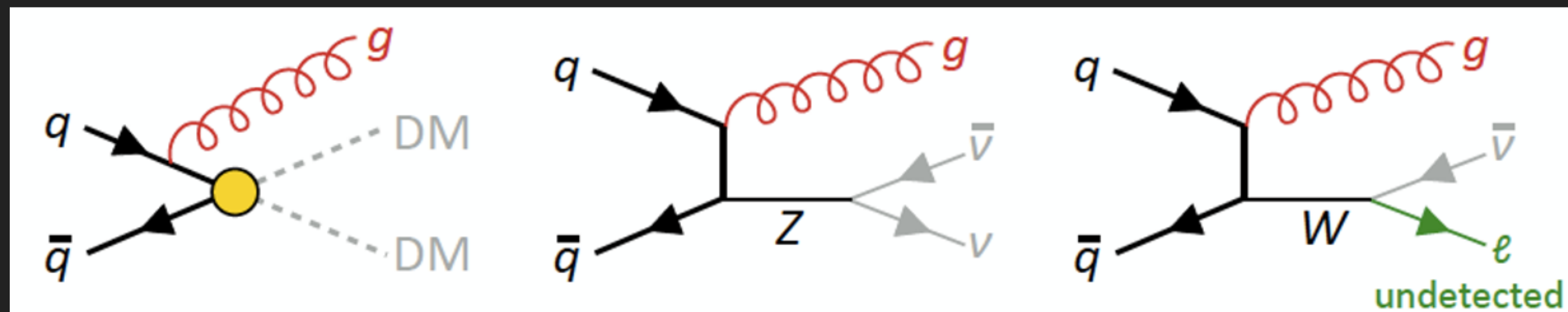
# SEARCHING FOR A DM CANDIDATE AT THE LHC

- ▶ Need to rely on the visible presence of other objects produced along DM
- ▶ First example: initial-state radiation => observable object which allows to compute a missing transverse momentum ... « mono-jet » analysis



# JET+E<sub>T</sub><sup>MISS</sup> ANALYSIS

- ▶ Trigger based on ETmiss : high threshold (removes the dominant QCD multi-jet BG)
- ▶ At least one energetic jet in the events (allow some more, eg up to 4 in ATLAS)
- ▶ Veto on the presence of other objects ( $\mu$ ,  $e$ ,  $\tau$ , or  $\gamma$ )
- ▶ Require a large azimuthal angle between the leading jet(s) and the direction of ETmiss (avoid misreconstructed QCD jets)
- ▶ After these selections (signal region):



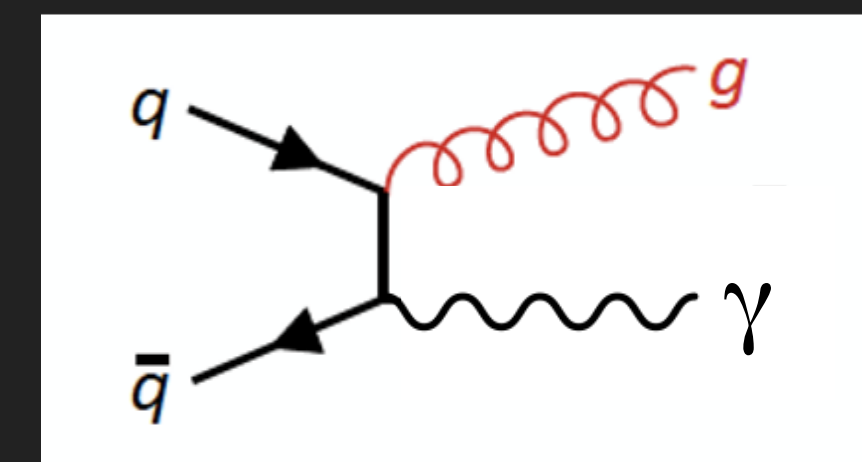
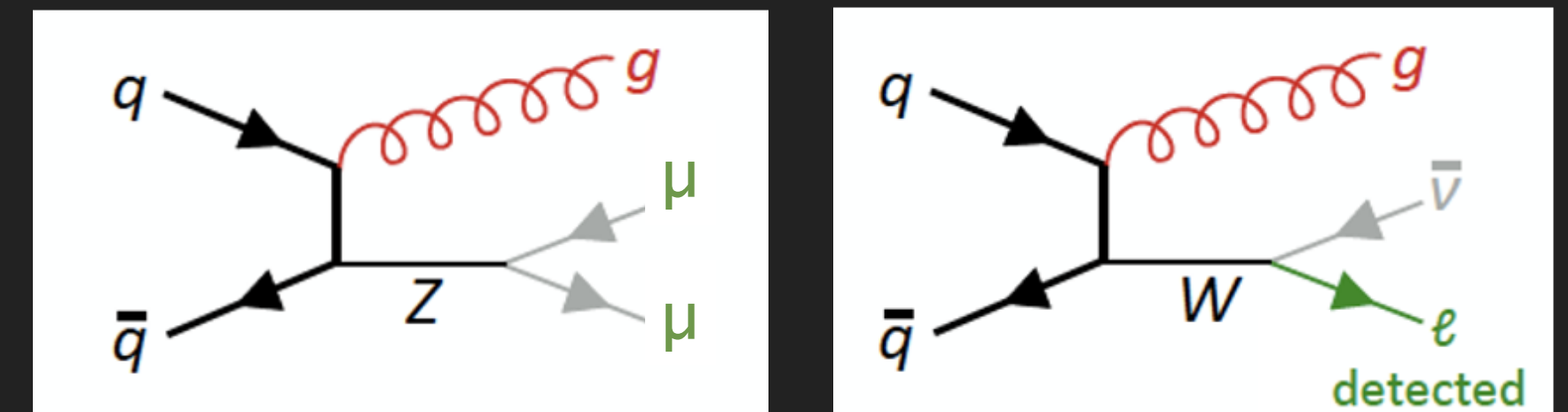
Signal

Irreducible

Reducible

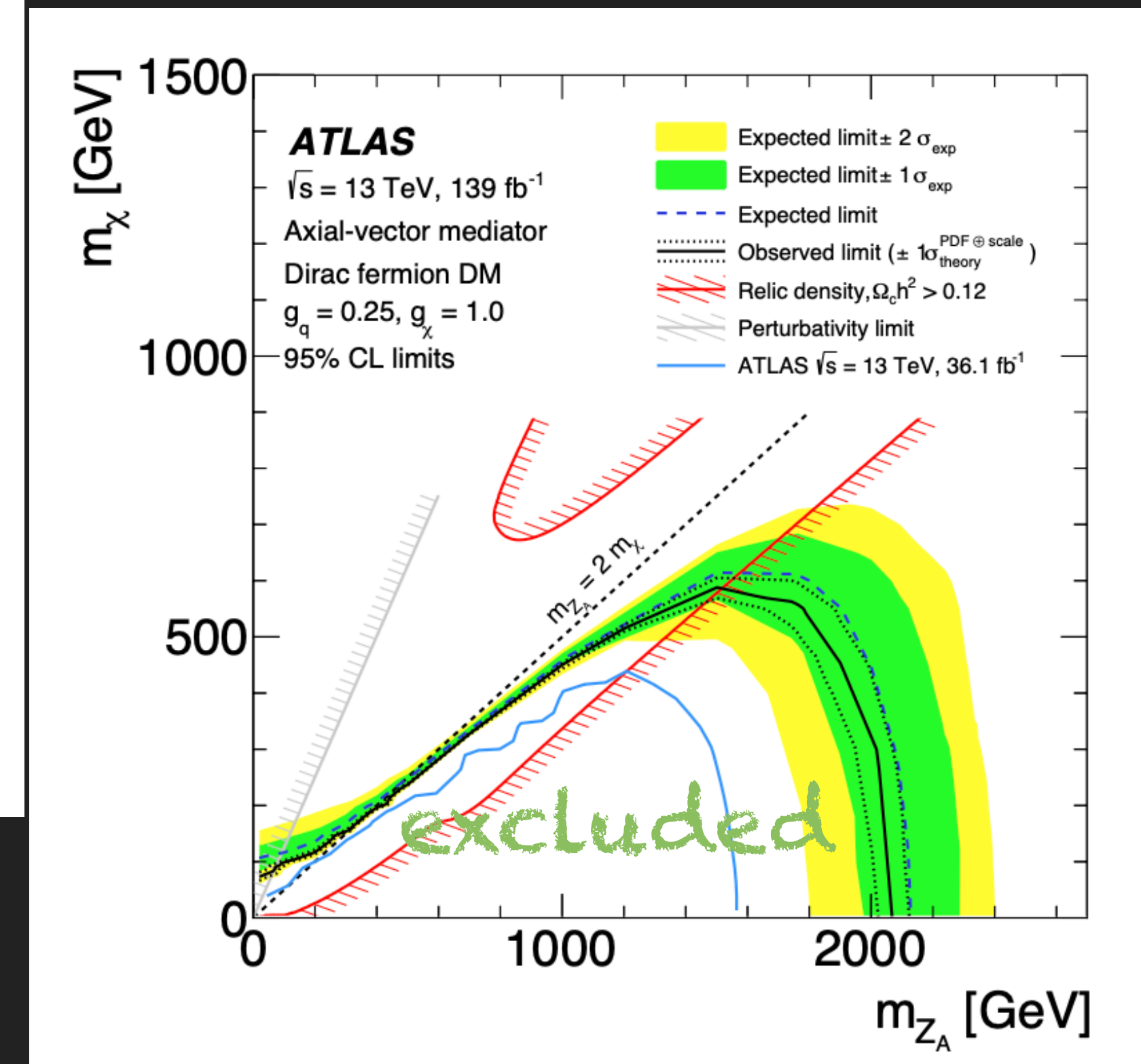
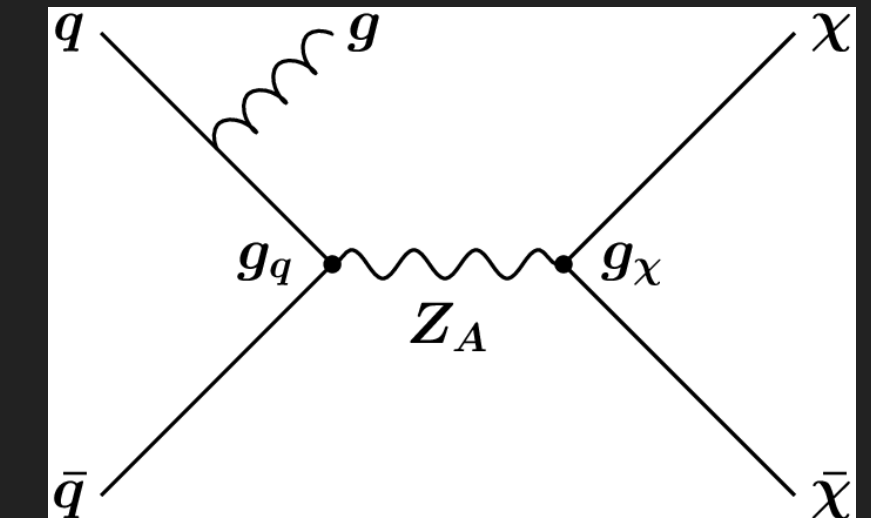
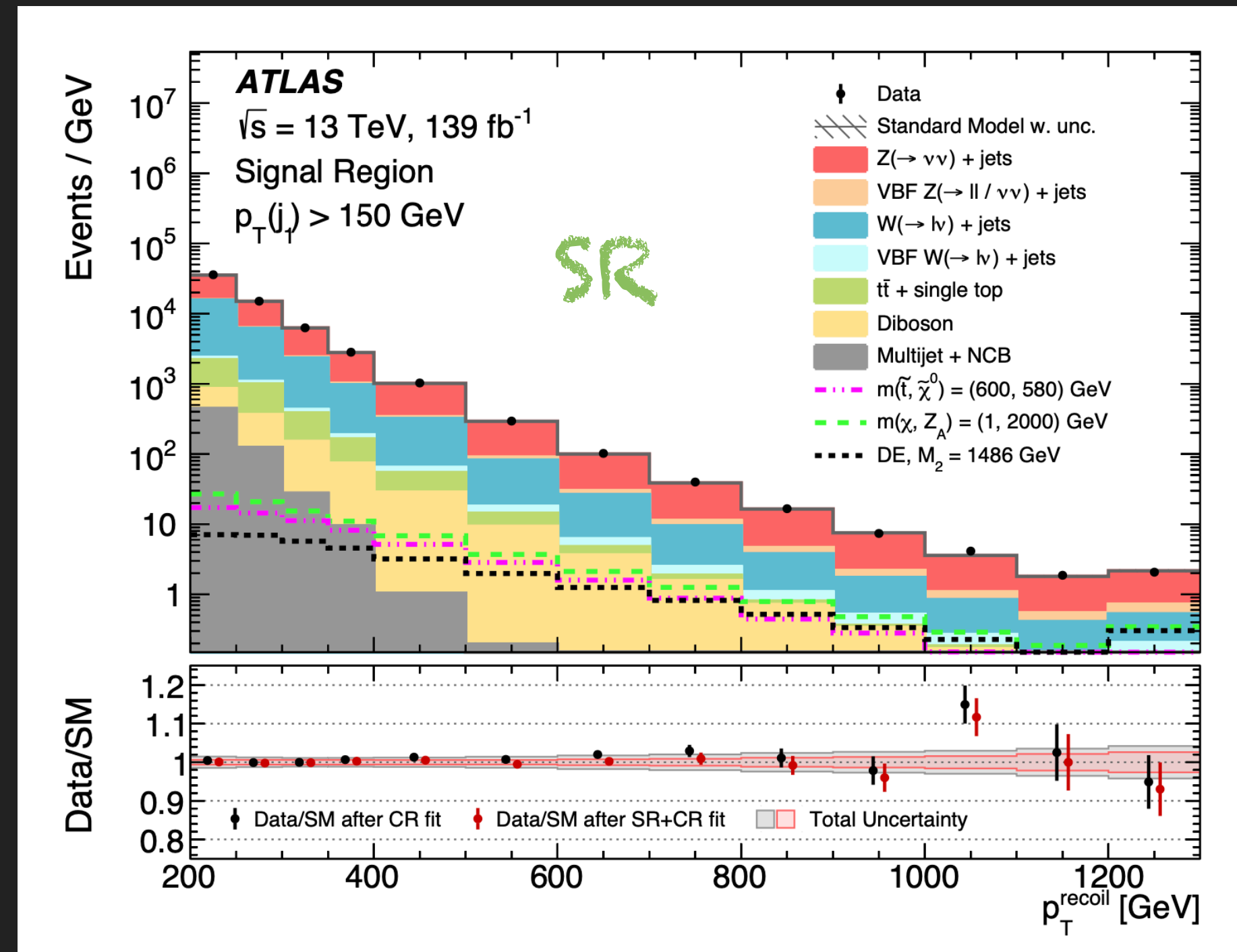
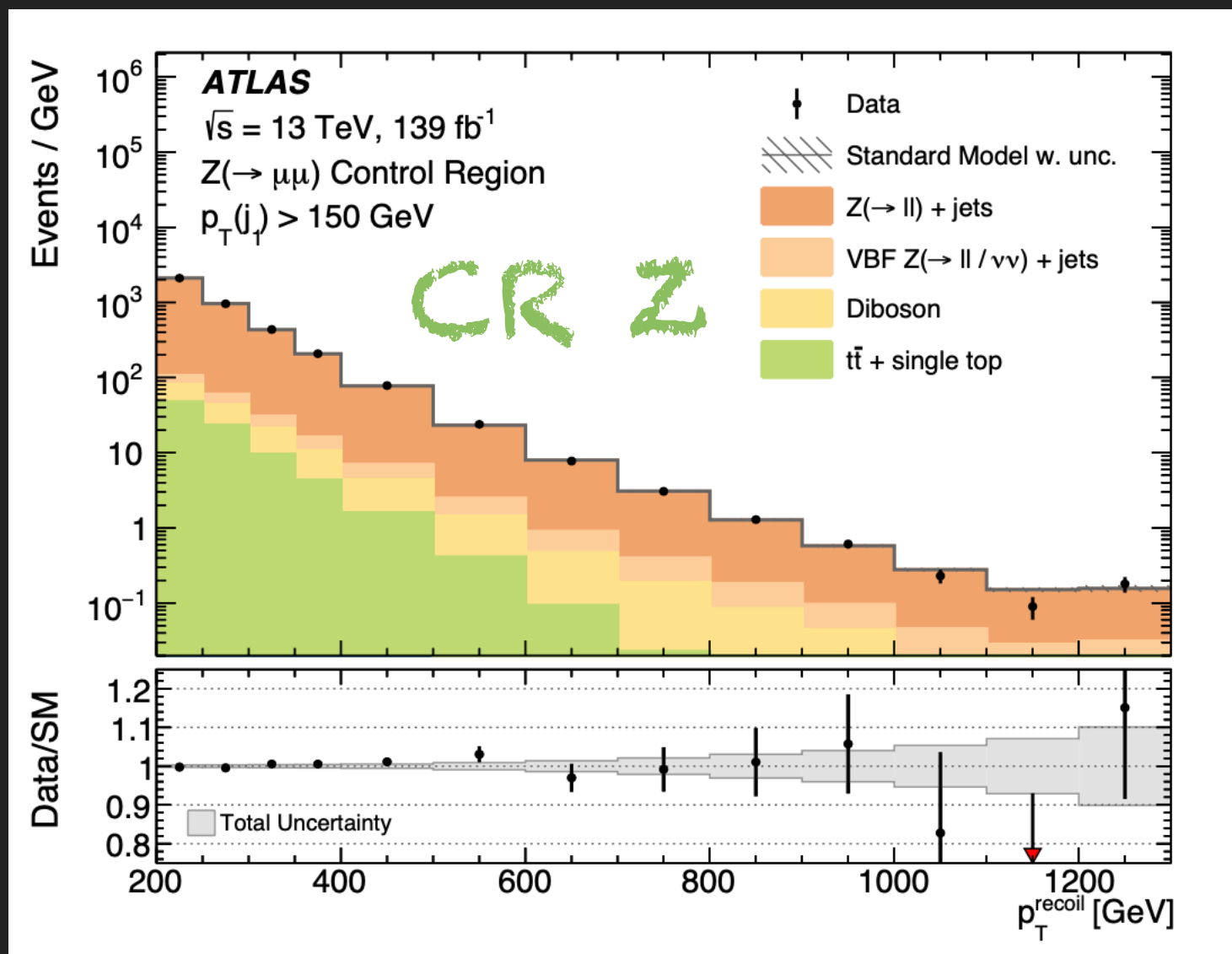
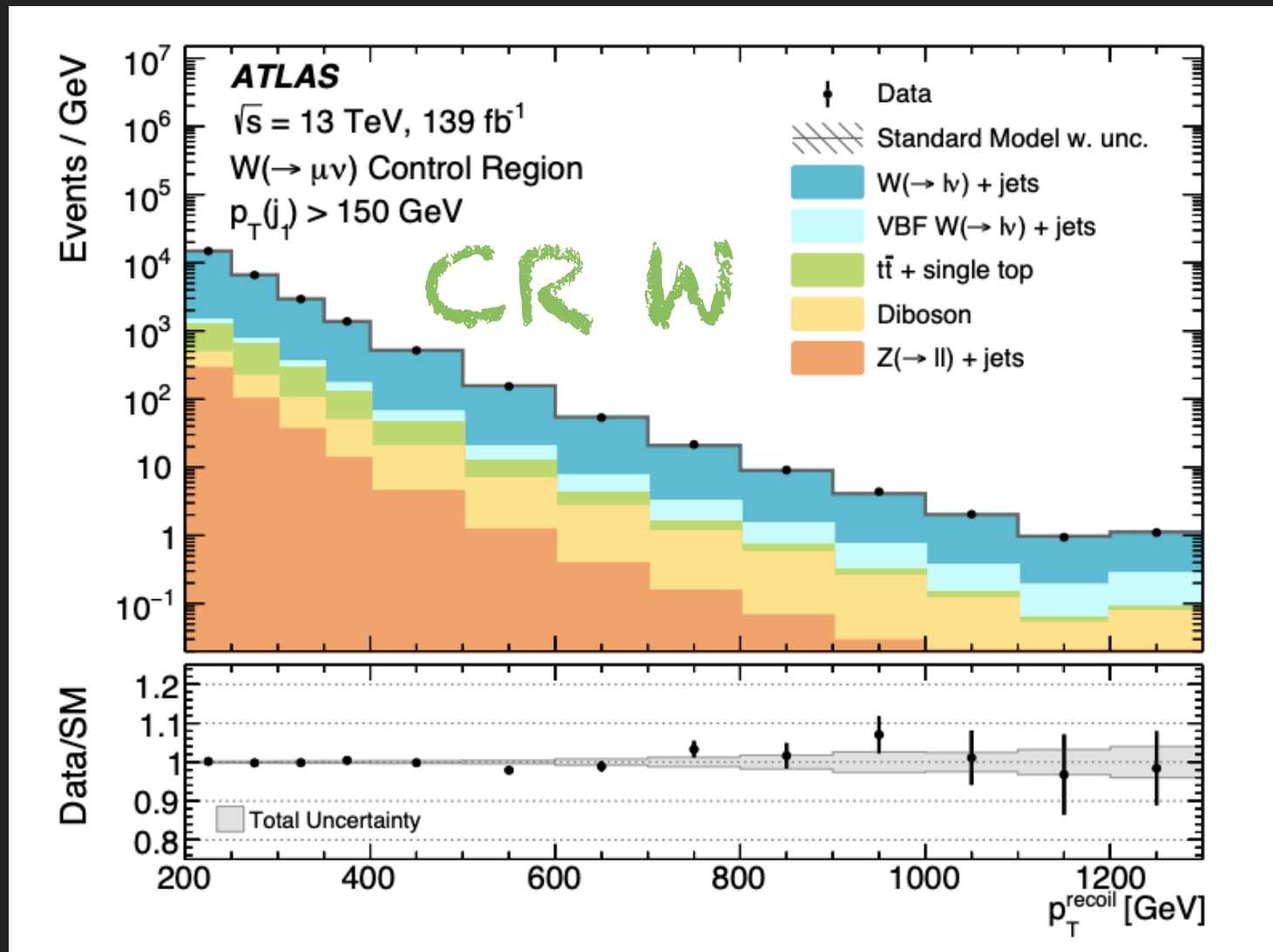
Main BG

Normalise predictions in control regions with leptons or photon:

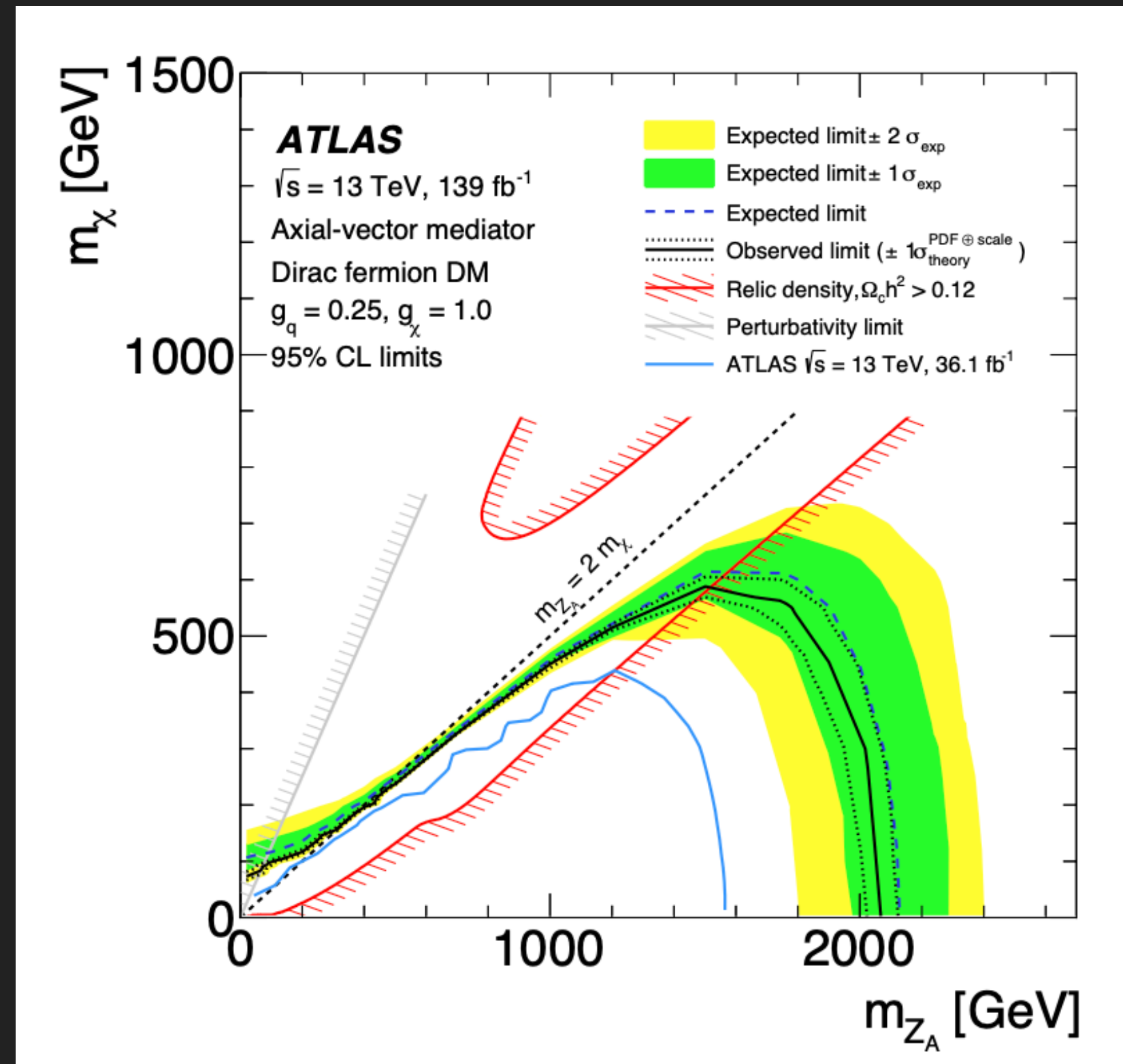
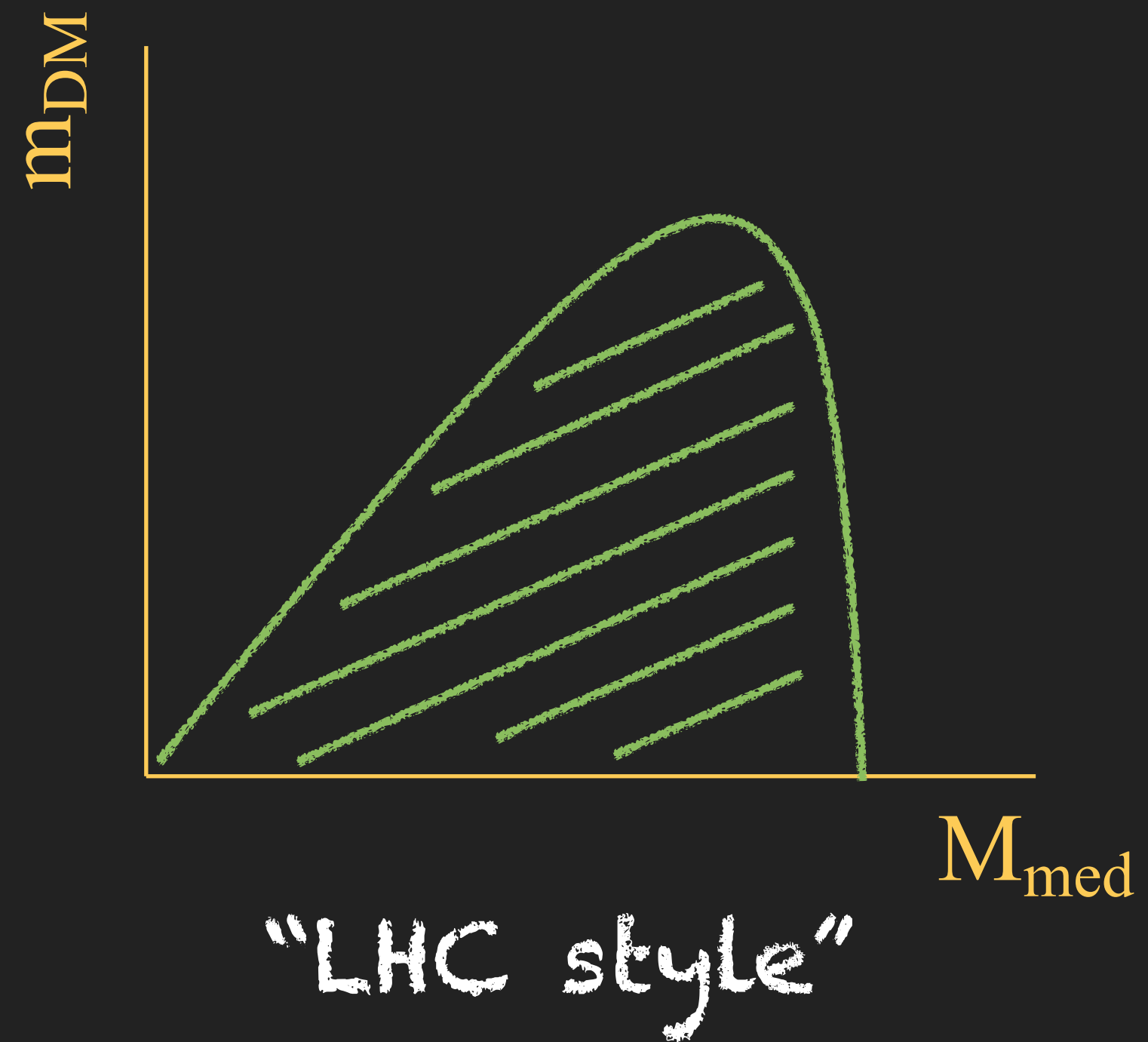




# JET+E<sub>T</sub><sup>MISS</sup> IN ATLAS

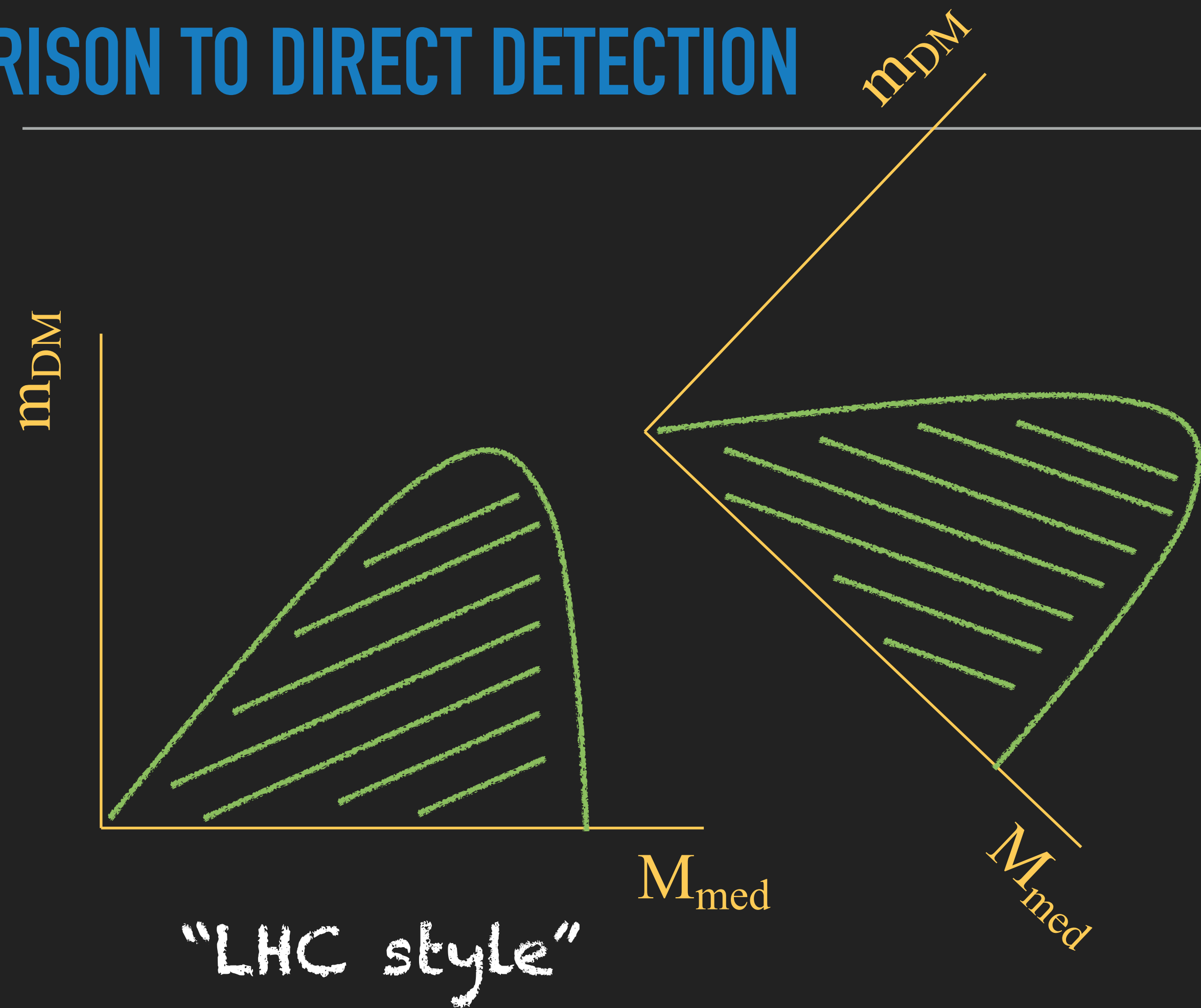


# COMPARISON TO DIRECT DETECTION

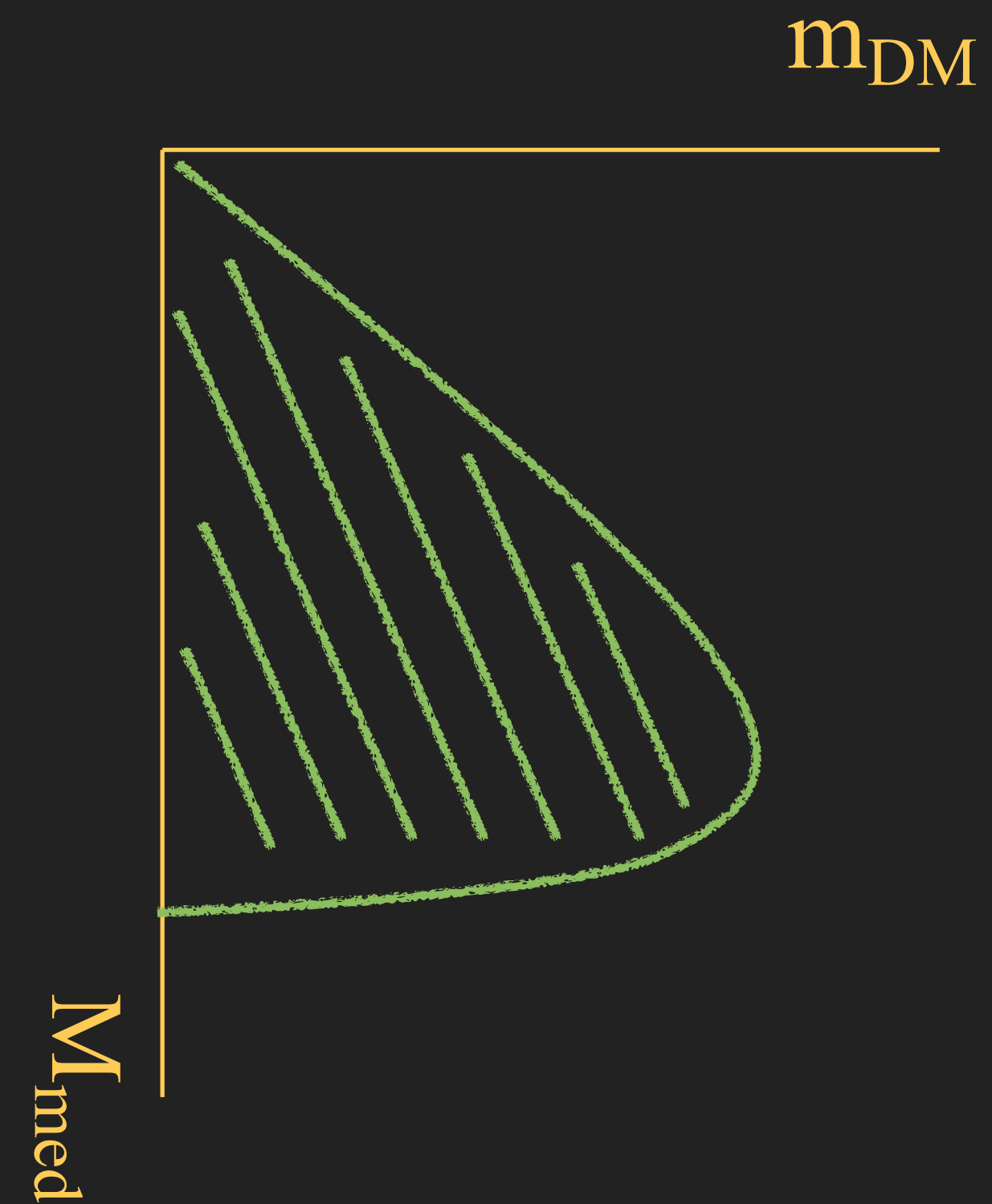
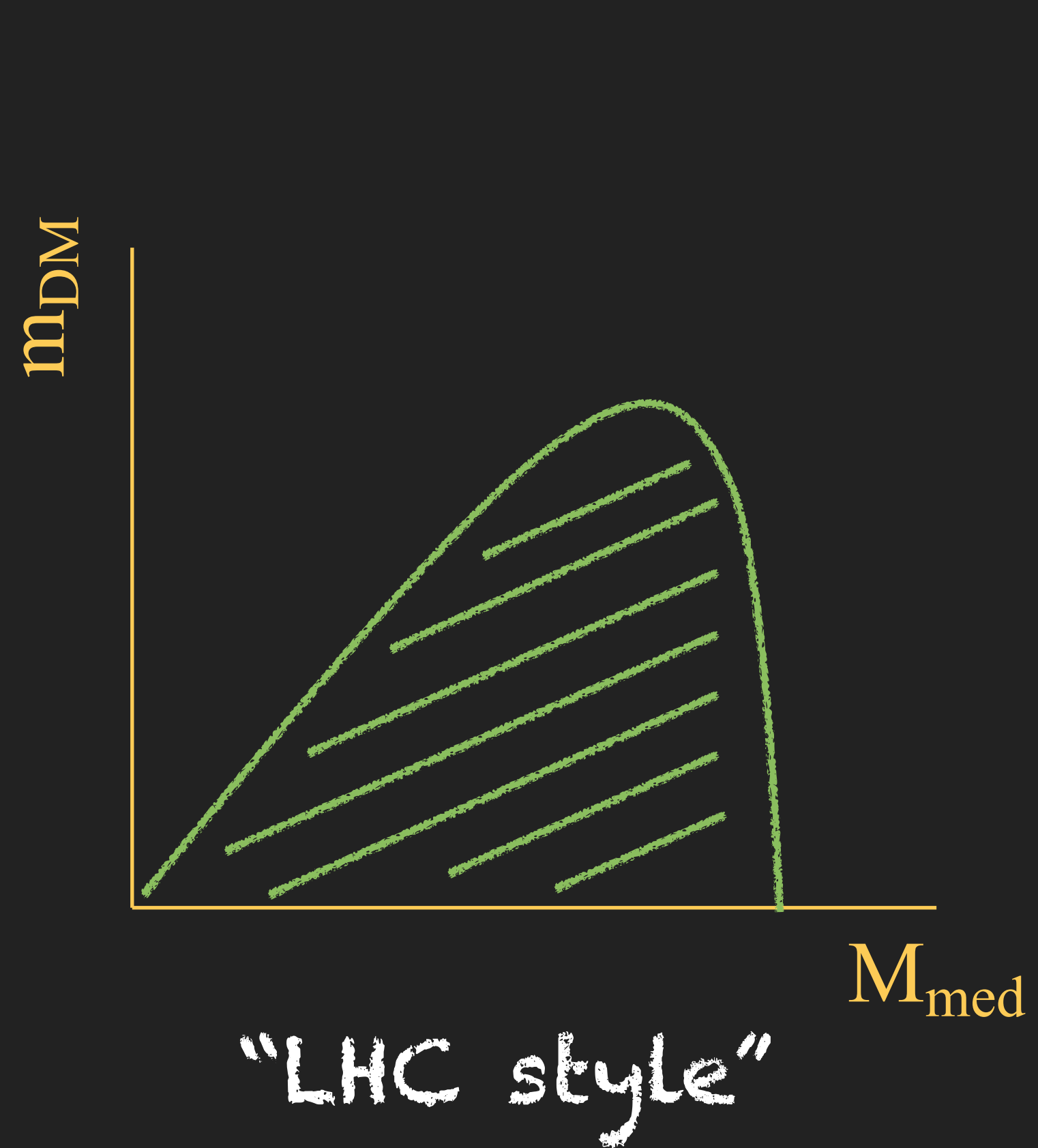




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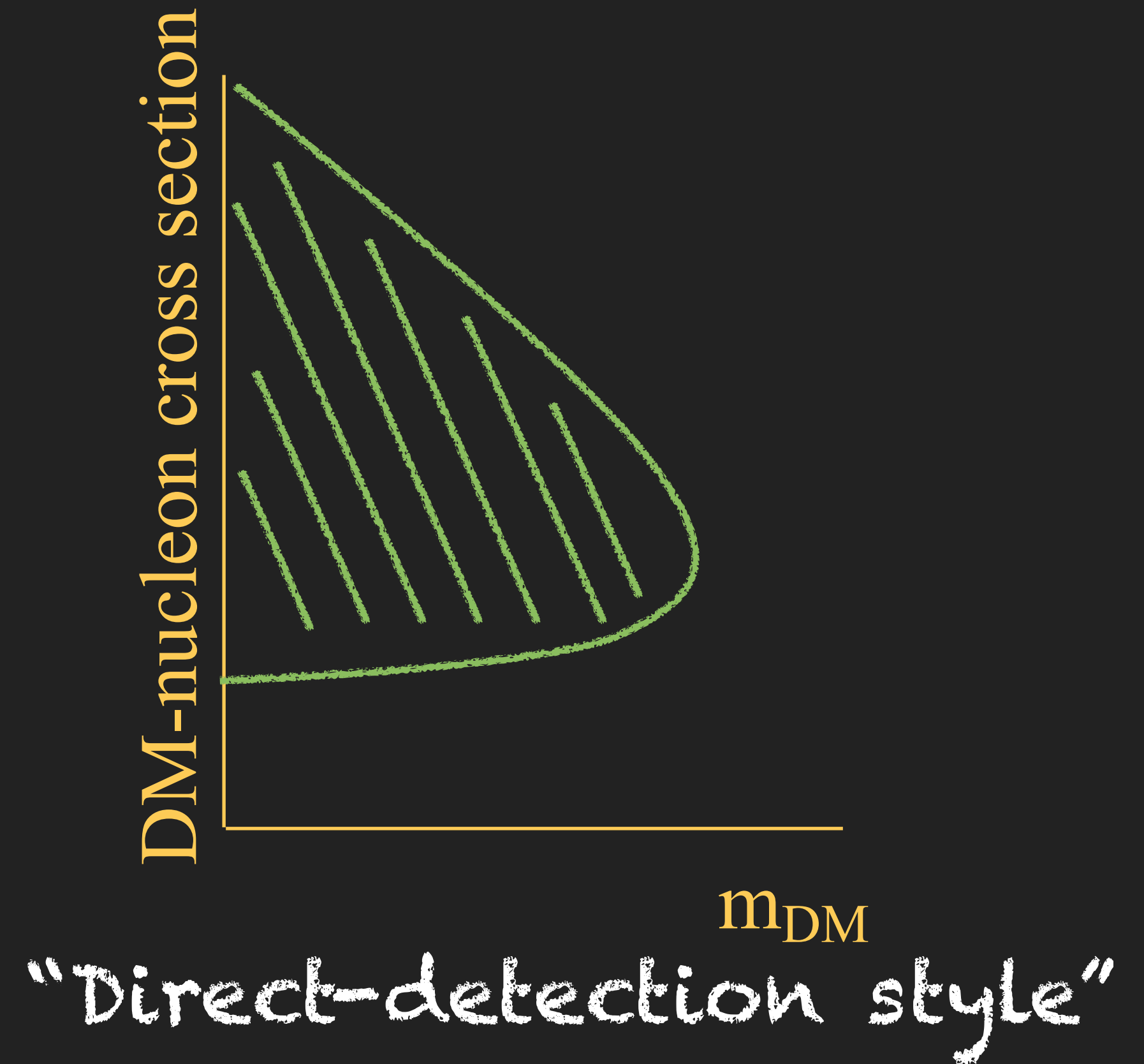
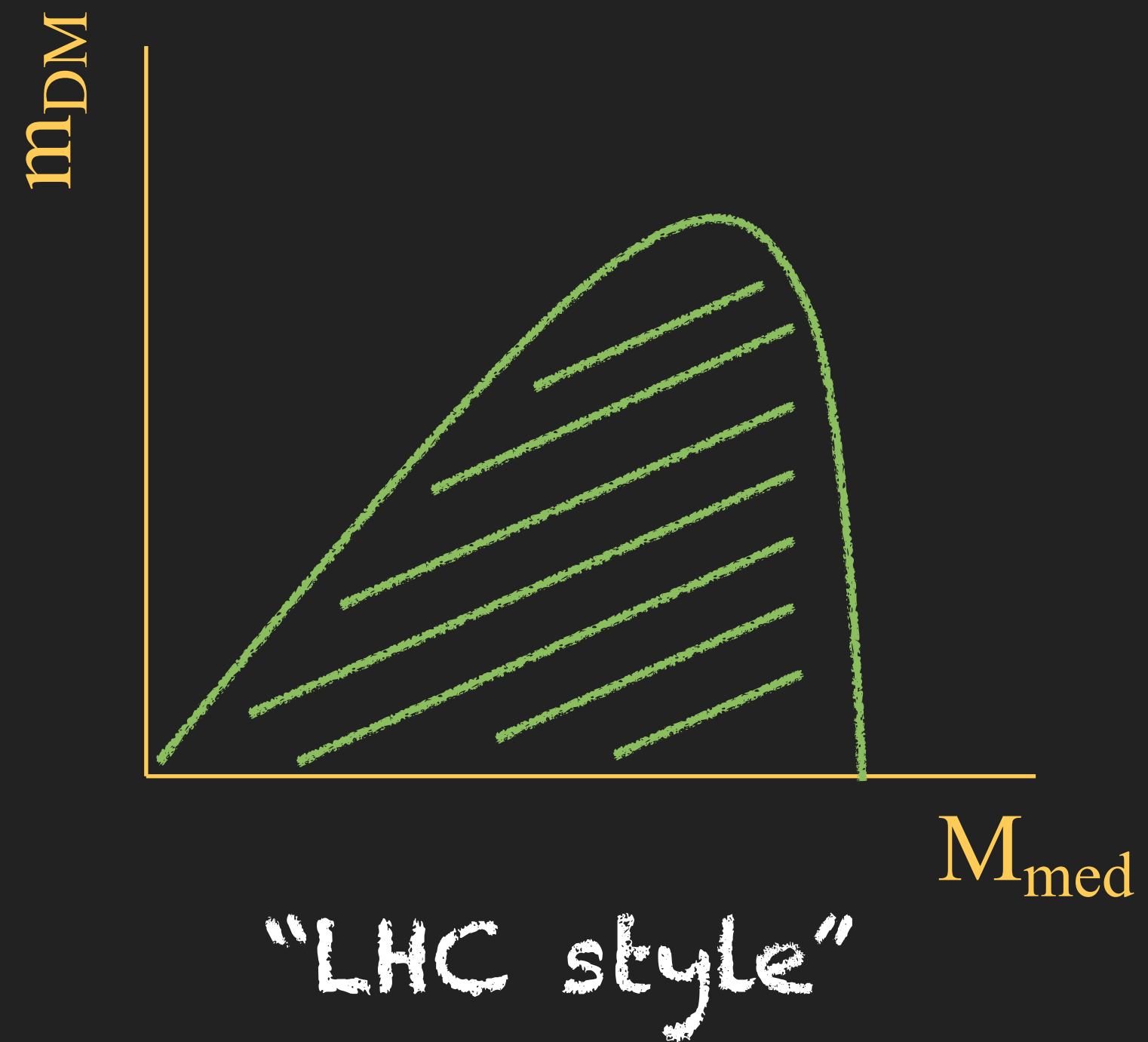


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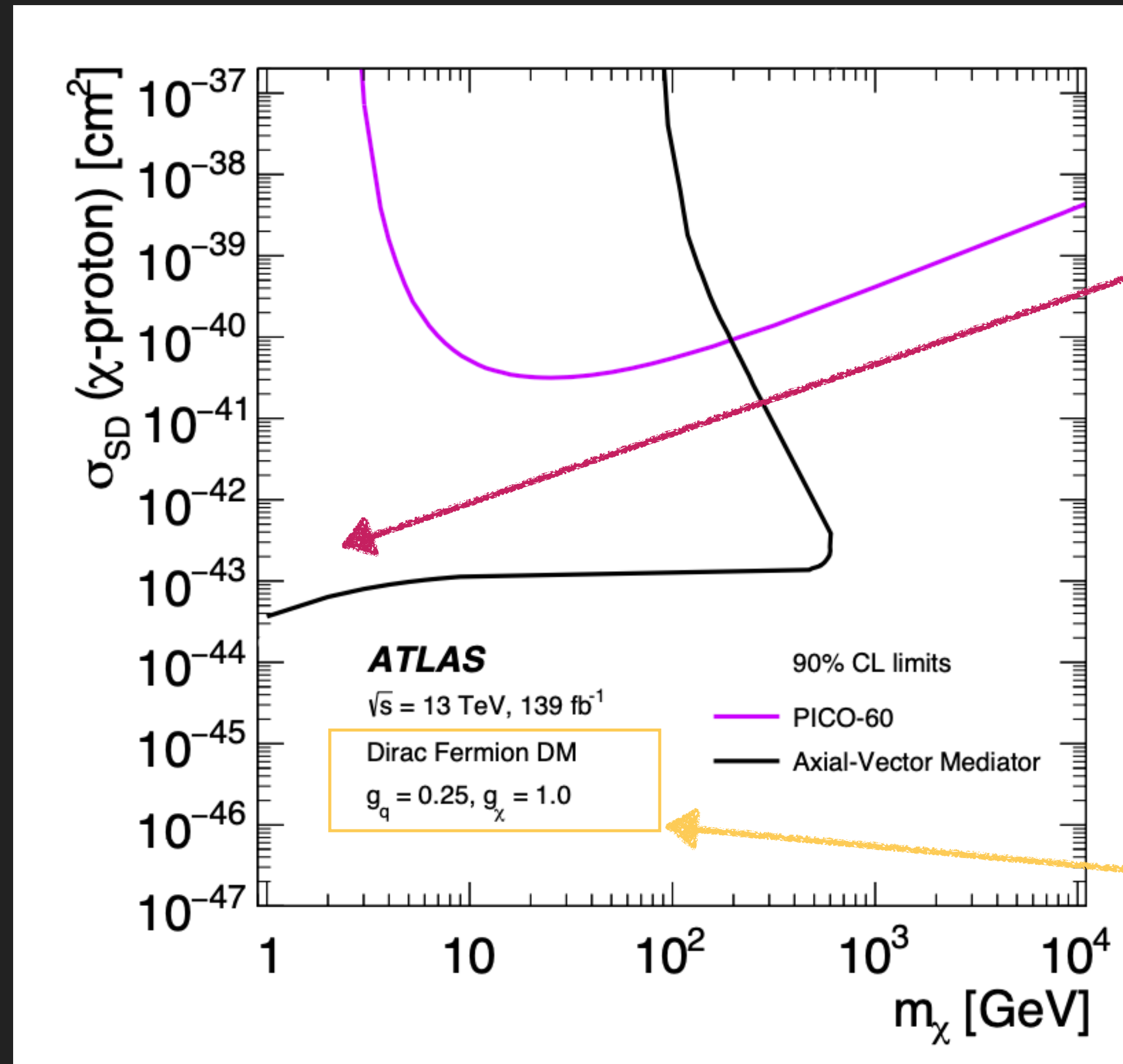




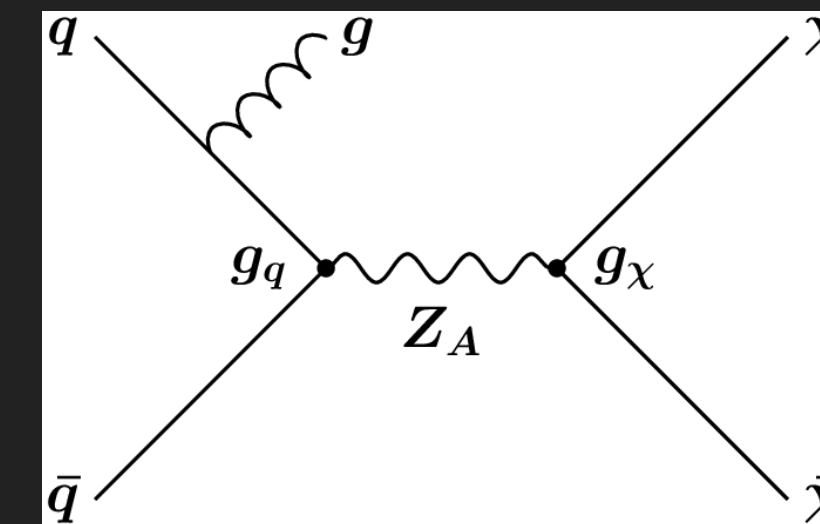
# COMPARISON TO DIRECT DETECTION



# COMPARISON TO DIRECT DETECTION: AN EXAMPLE



The LHC is able to probe the very low masses (they are easy to produce!)



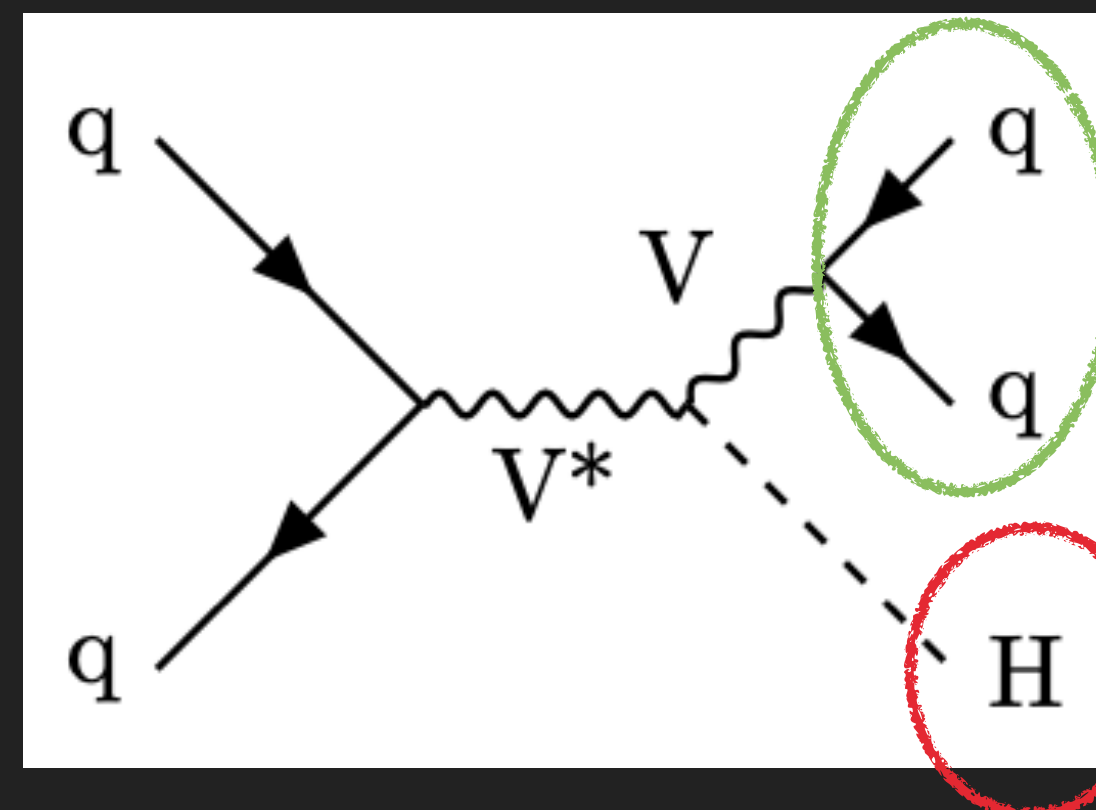
But one must remember the assumption of the model considered. It is not a competition with direct detection: we are complementary!\*

\* + the LHC can only look for DM 'candidates'



# JET+ $E_T^{\text{MISS}}$ IN CMS

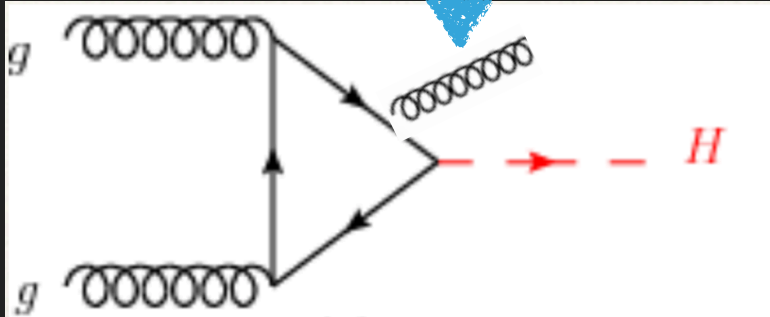
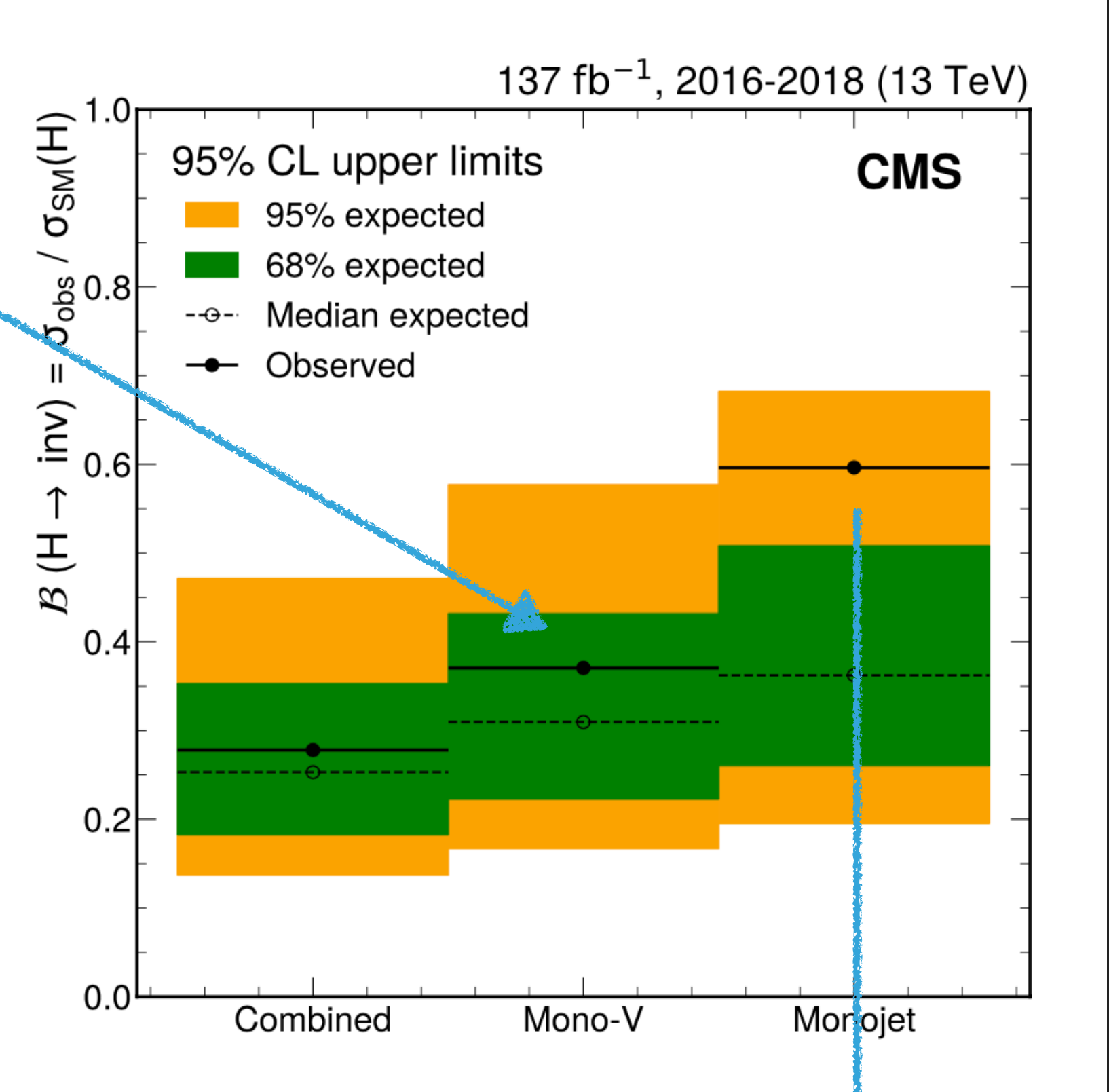
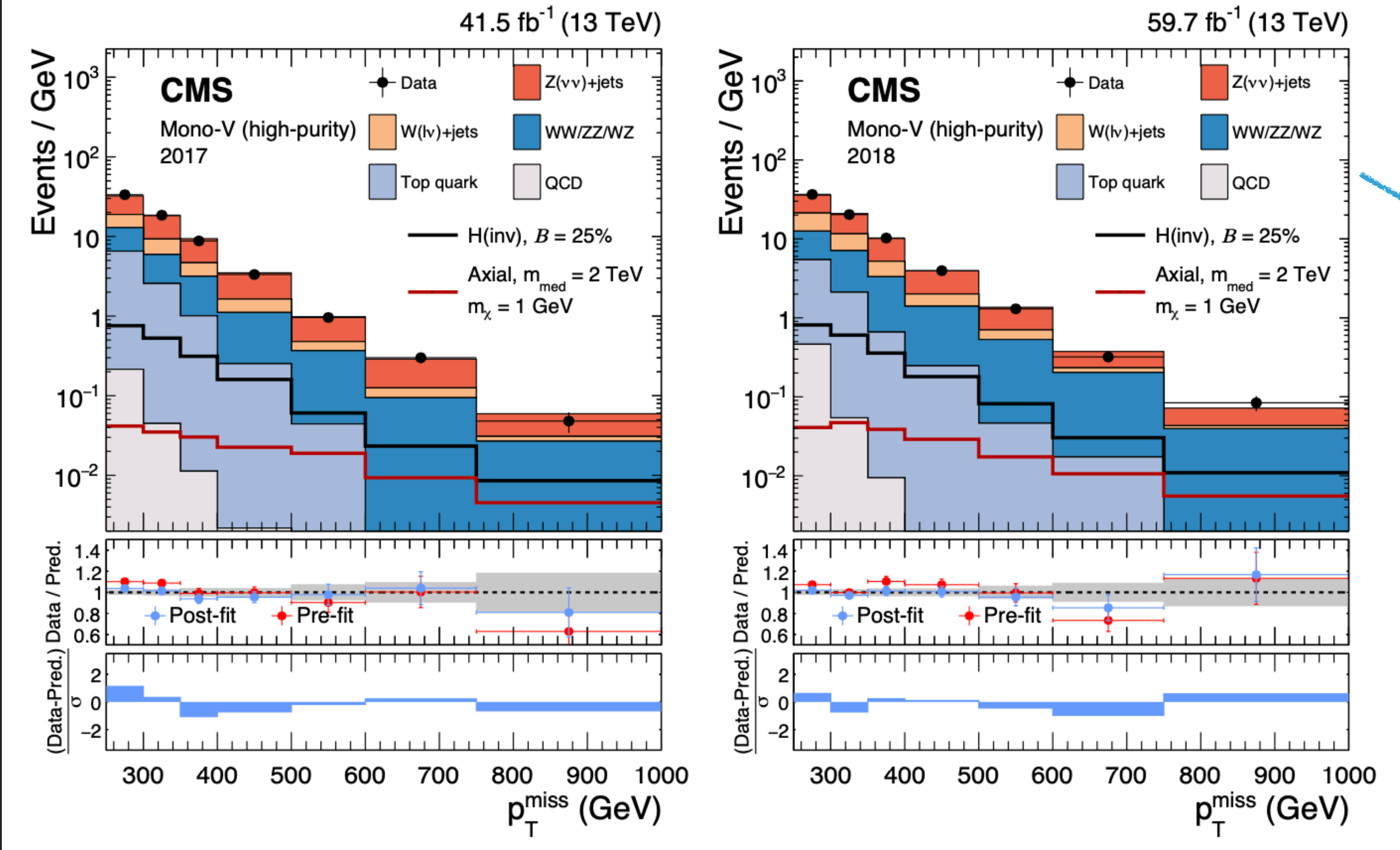
- ▶ One can also have a similar analysis in which the jet is a large ('fat') jet produced by a boosted  $W/Z \rightarrow qq$  decay
- ▶ Tag the large-jet with ML techniques
  - ▶ Use jet substructure to reject QCD BG
- ▶ Same idea of using the leptonic / photon CRs to estimate the SM  $V$ +jets BG
- ▶ Can help look for different DM models, such as the Higgs to DM (invisible!) decay, when the Higgs is produced in association with a vector boson:



Fat jet with  $W/Z$  mass  
and a two-prong  
substructure

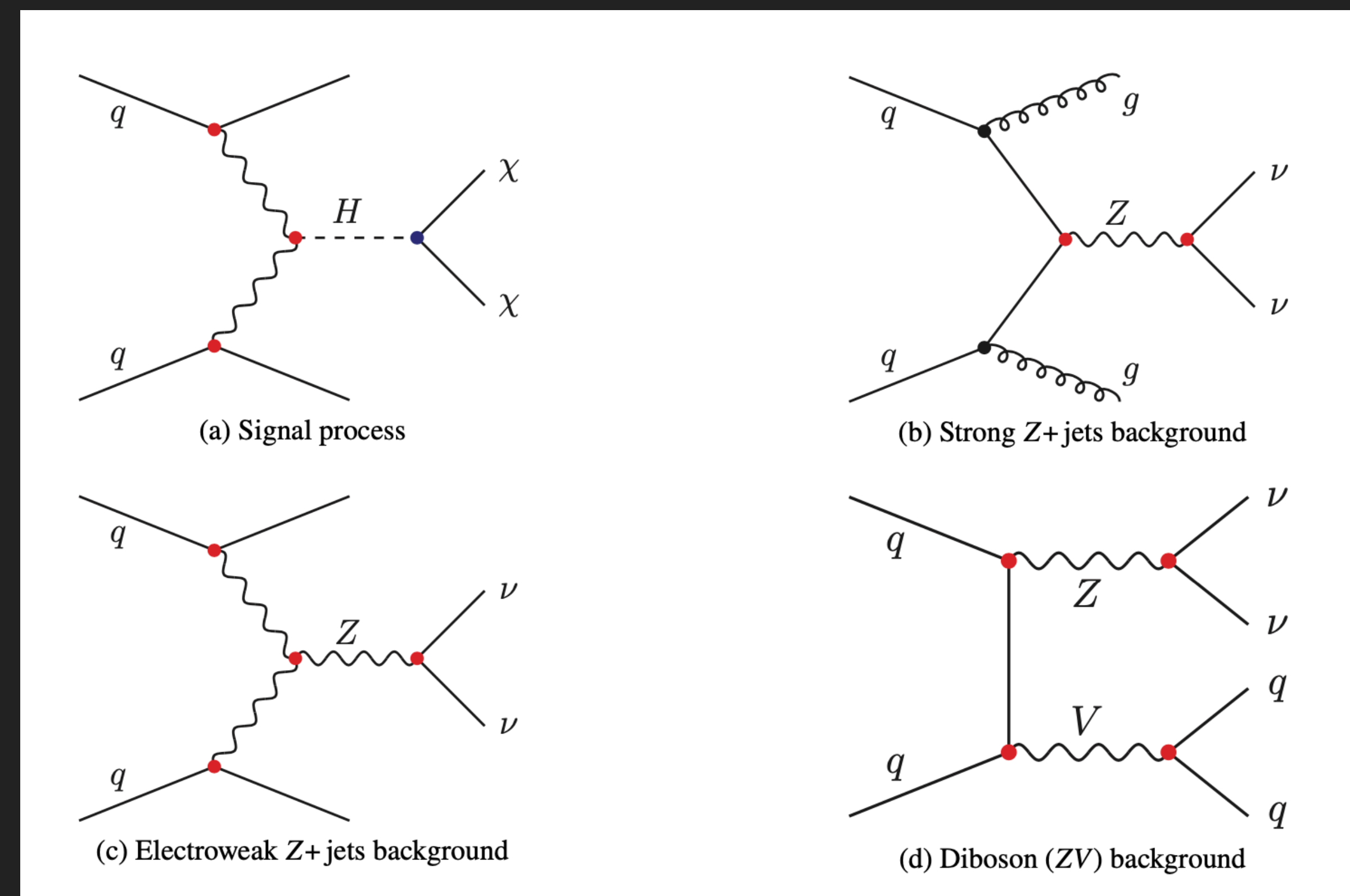
$E_T^{\text{miss}}$

# JET+E<sub>T</sub><sup>MISS</sup> IN CMS



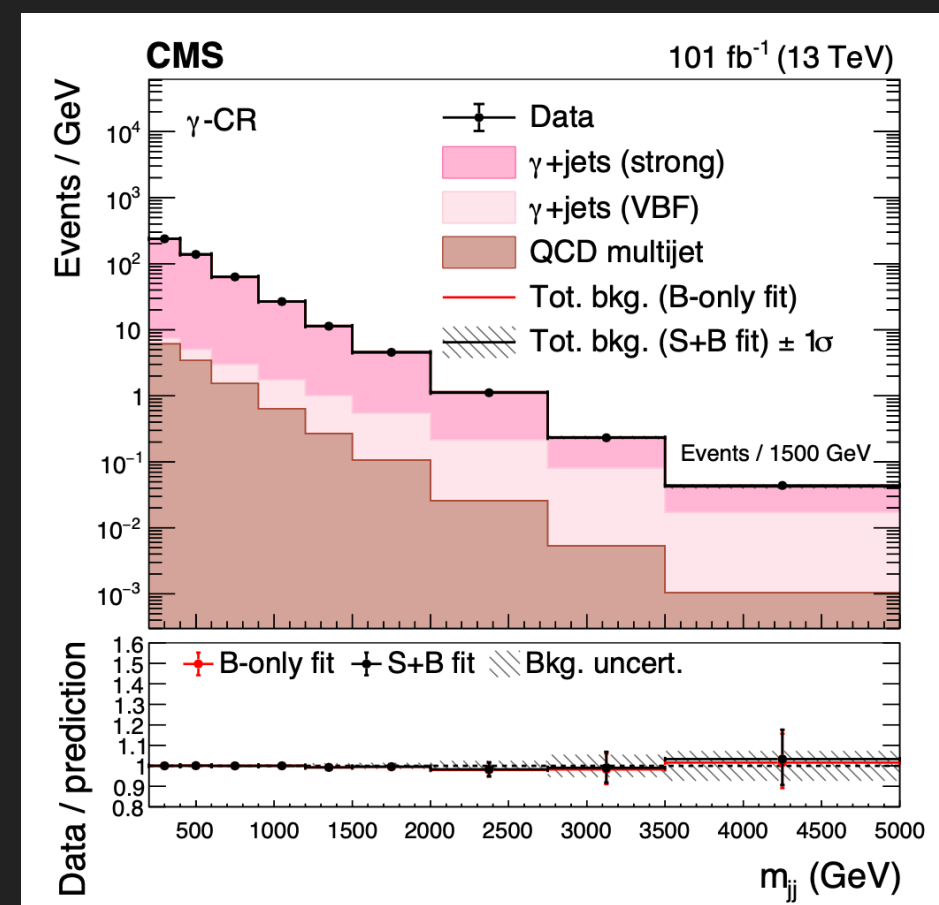
# VECTOR-BOSON FUSION: THE GOLDEN CHANNEL FOR INVISIBLE H

- ▶  $E_T^{\text{miss}}$  and VBF-like triggers
- ▶ VBF kinematics : 2 jets, well separated and in opposite detector hemispheres, with a large dijet mass
- ▶ Veto charged leptons and photons
- ▶ BG estimation: similar as the mono-jet strategy - normalisation in CRs with leptons or photon

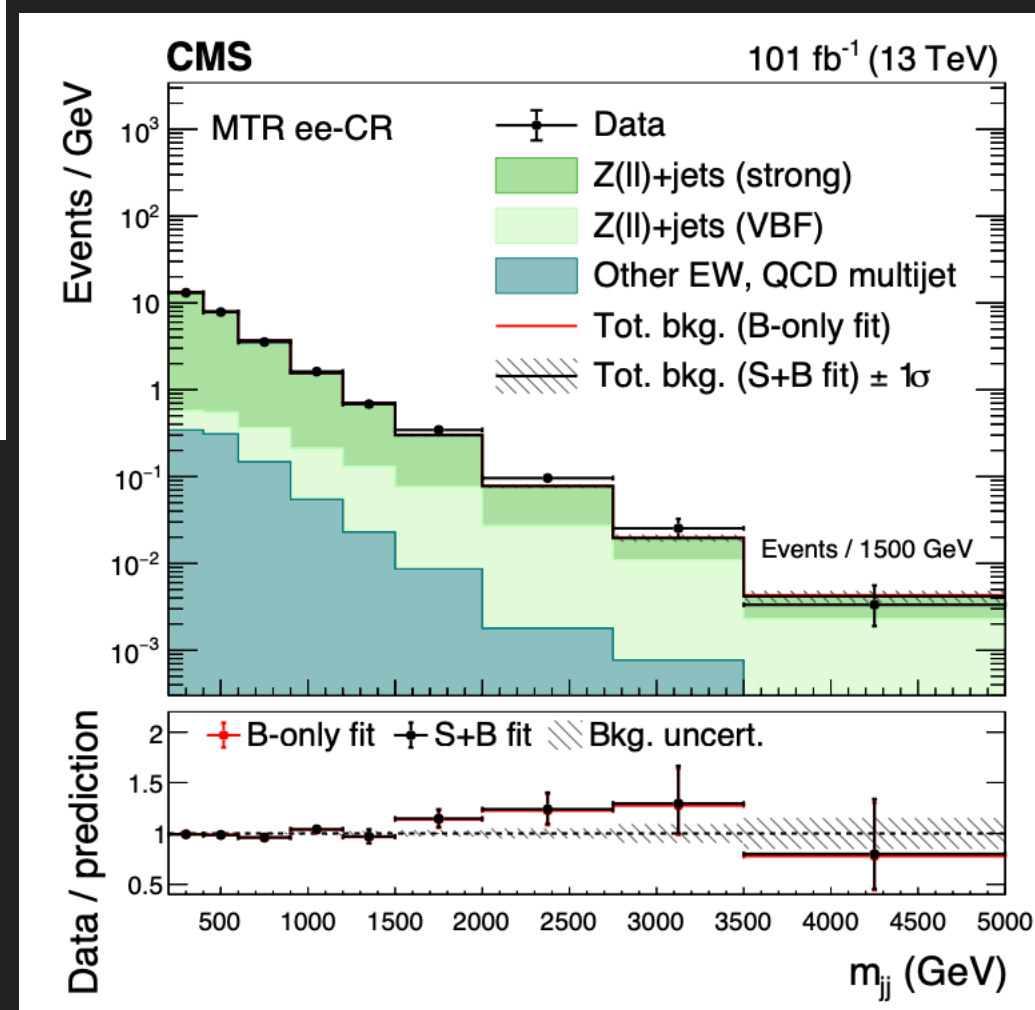




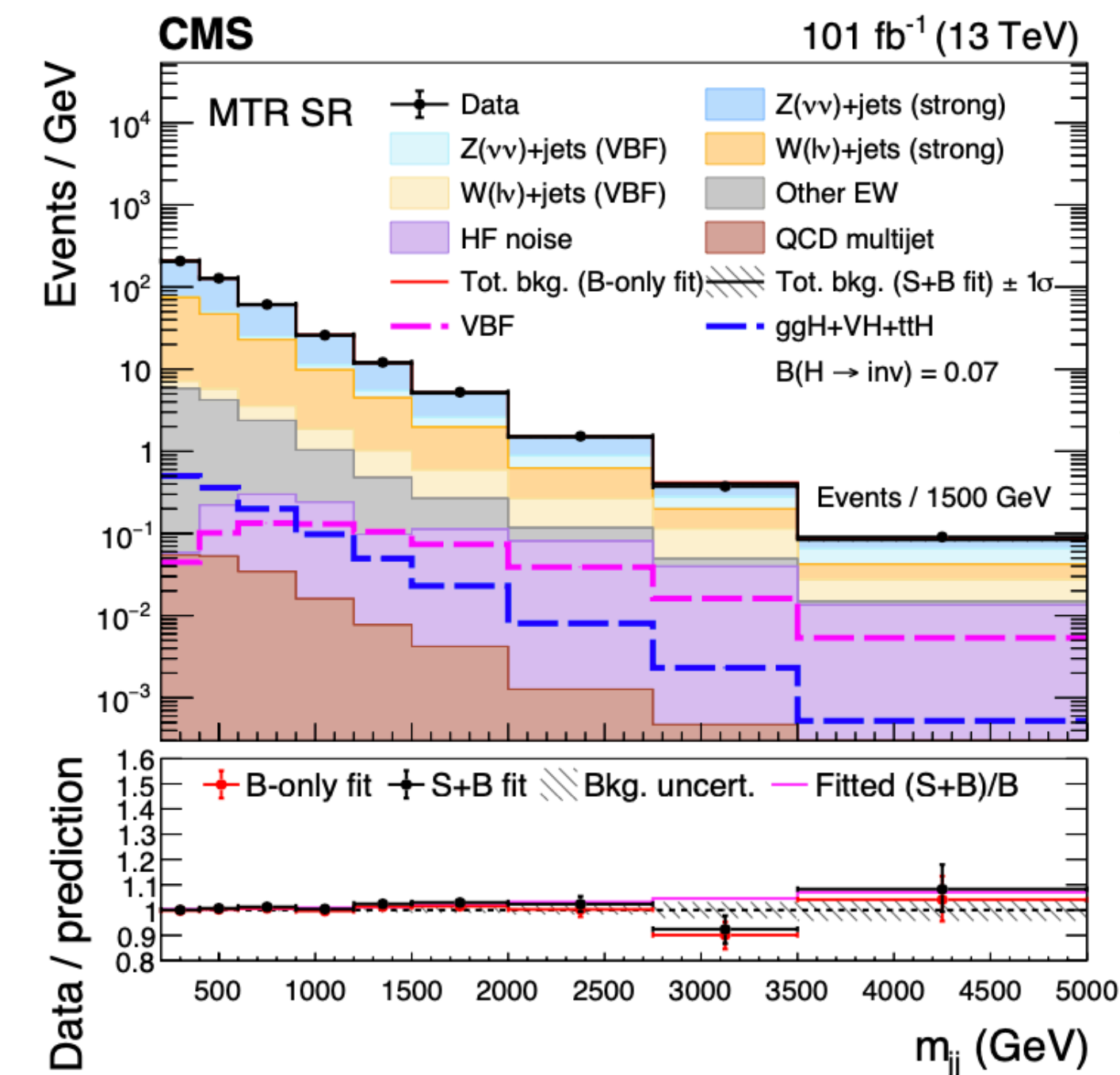
- Two SRs in  $E_T^{\text{miss}}$ : moderate(VTR) and high (MTR), binned in  $m_{jj}$



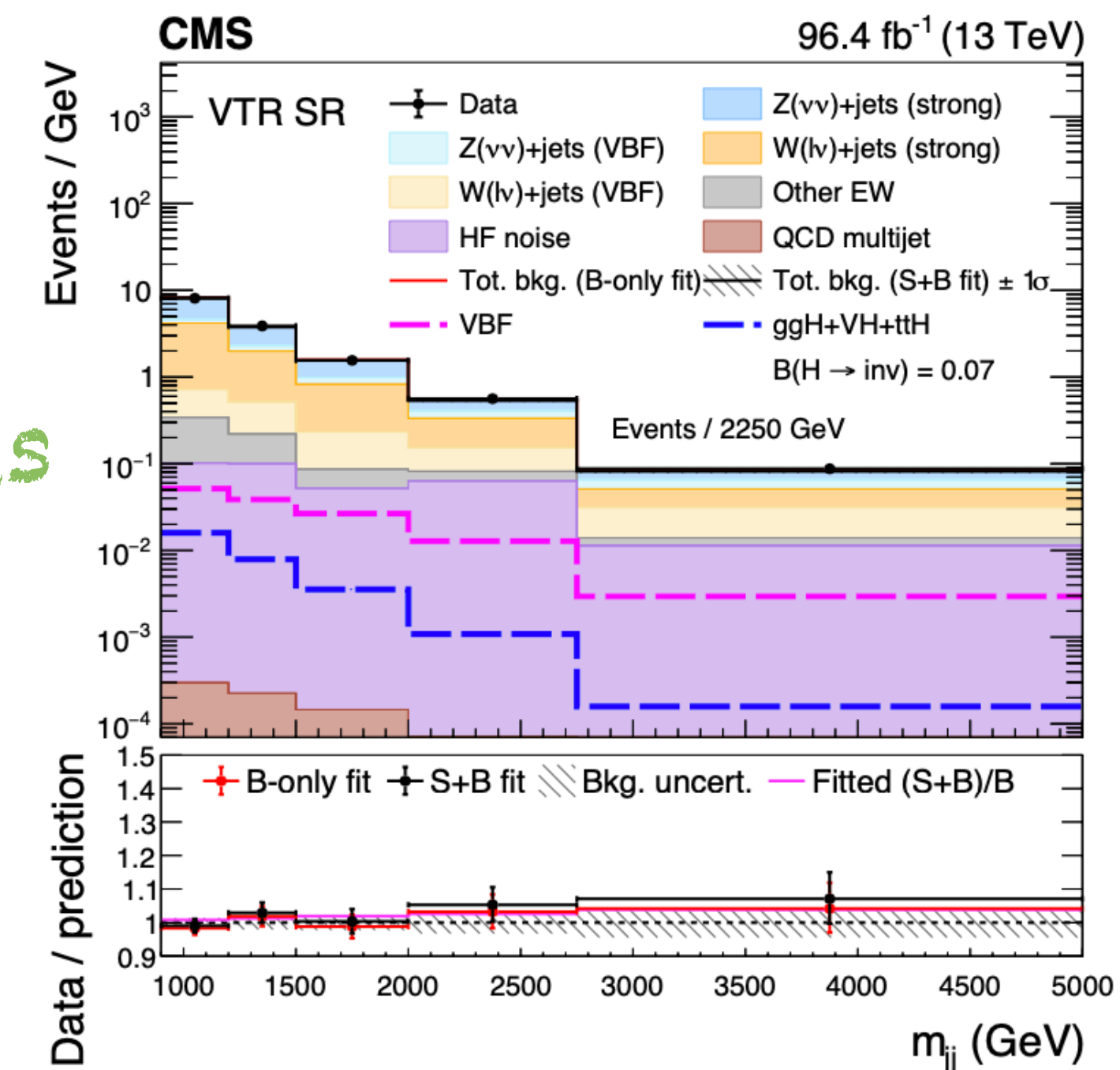
CR Y



CR Z

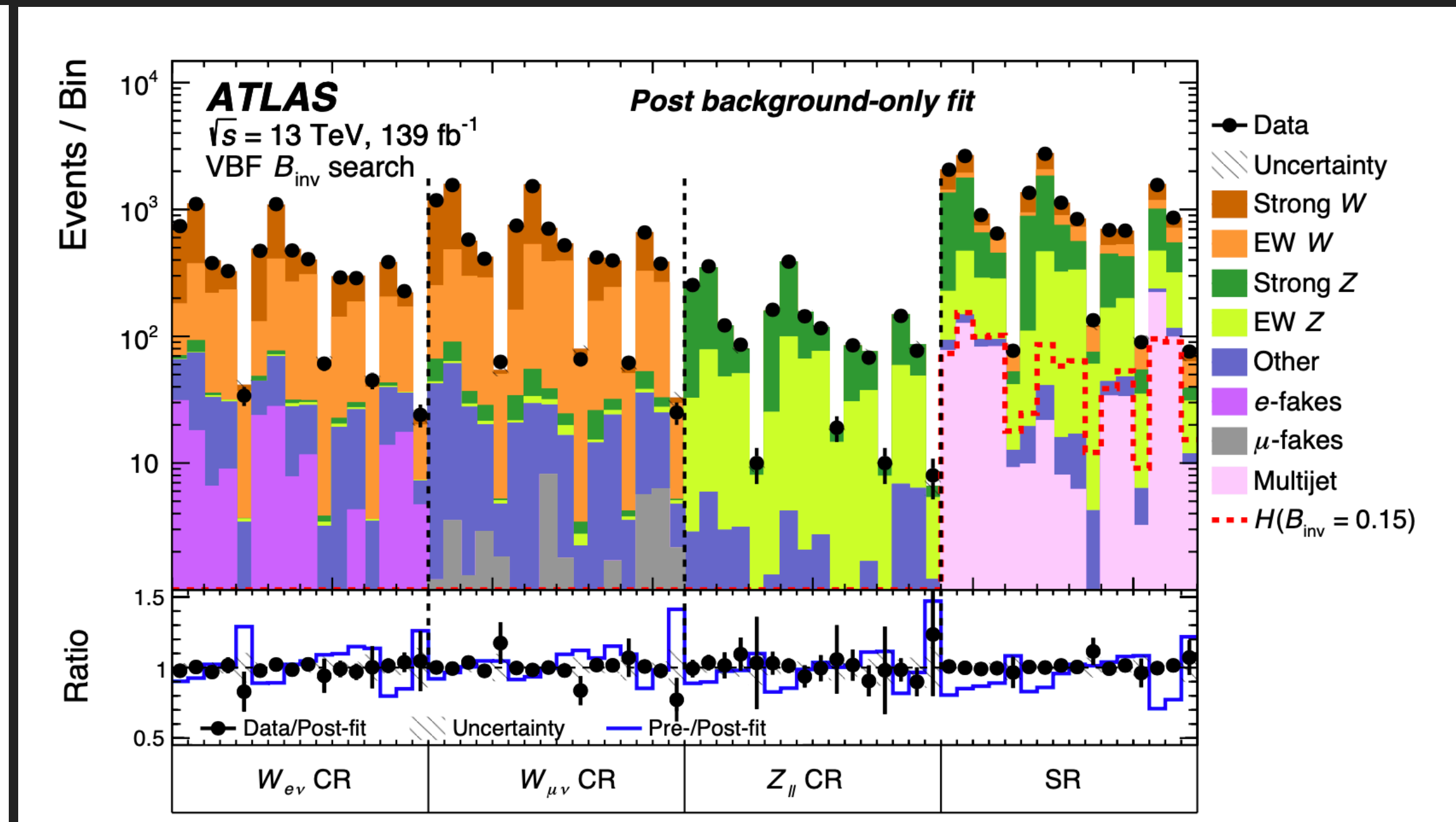
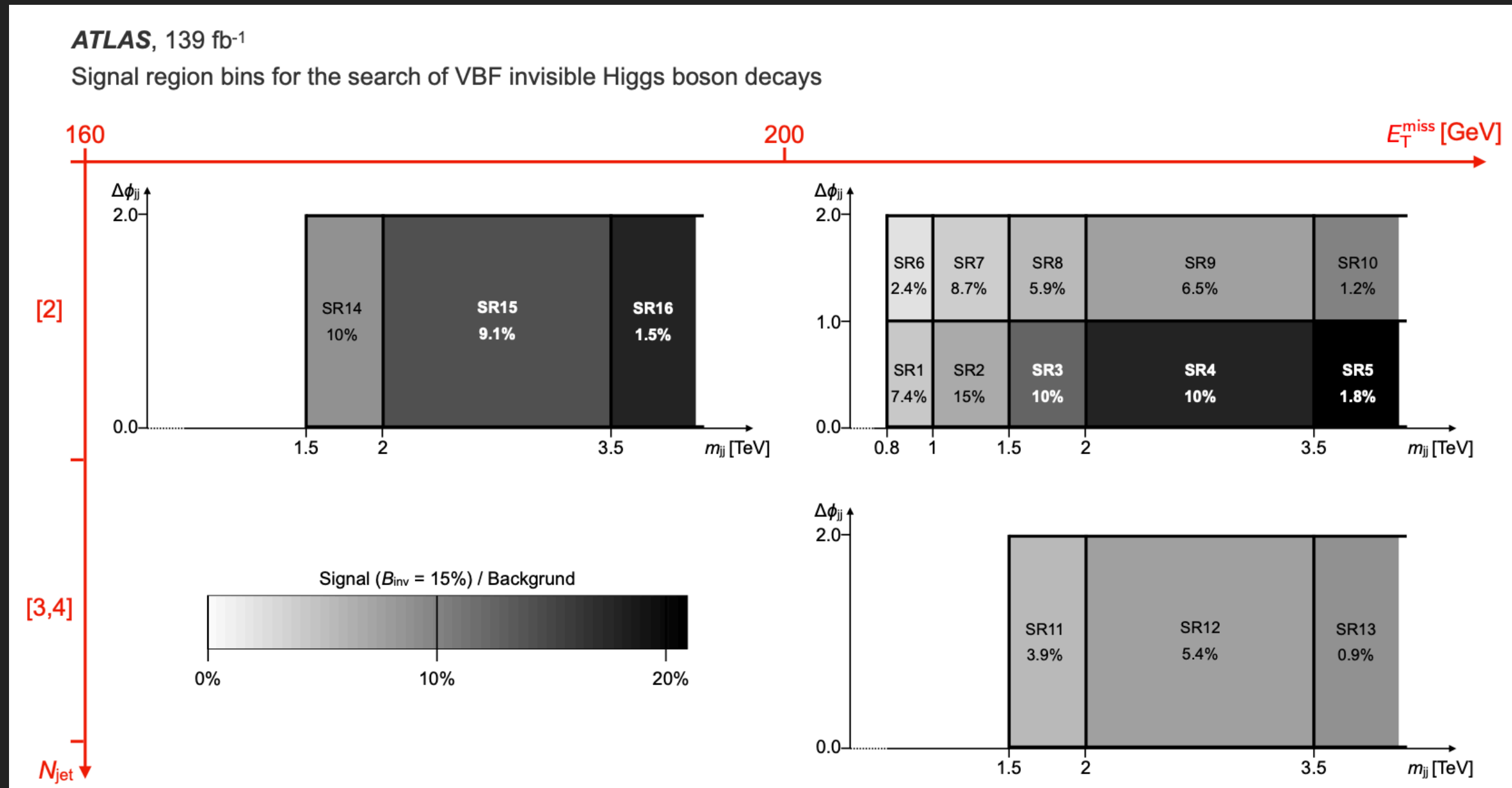


SRs



- $\text{BR}(H \rightarrow \text{inv}) < 0.18$  (0.12) obs (exp)  $\Rightarrow < 0.18$  (0.10) when combined with Run-1

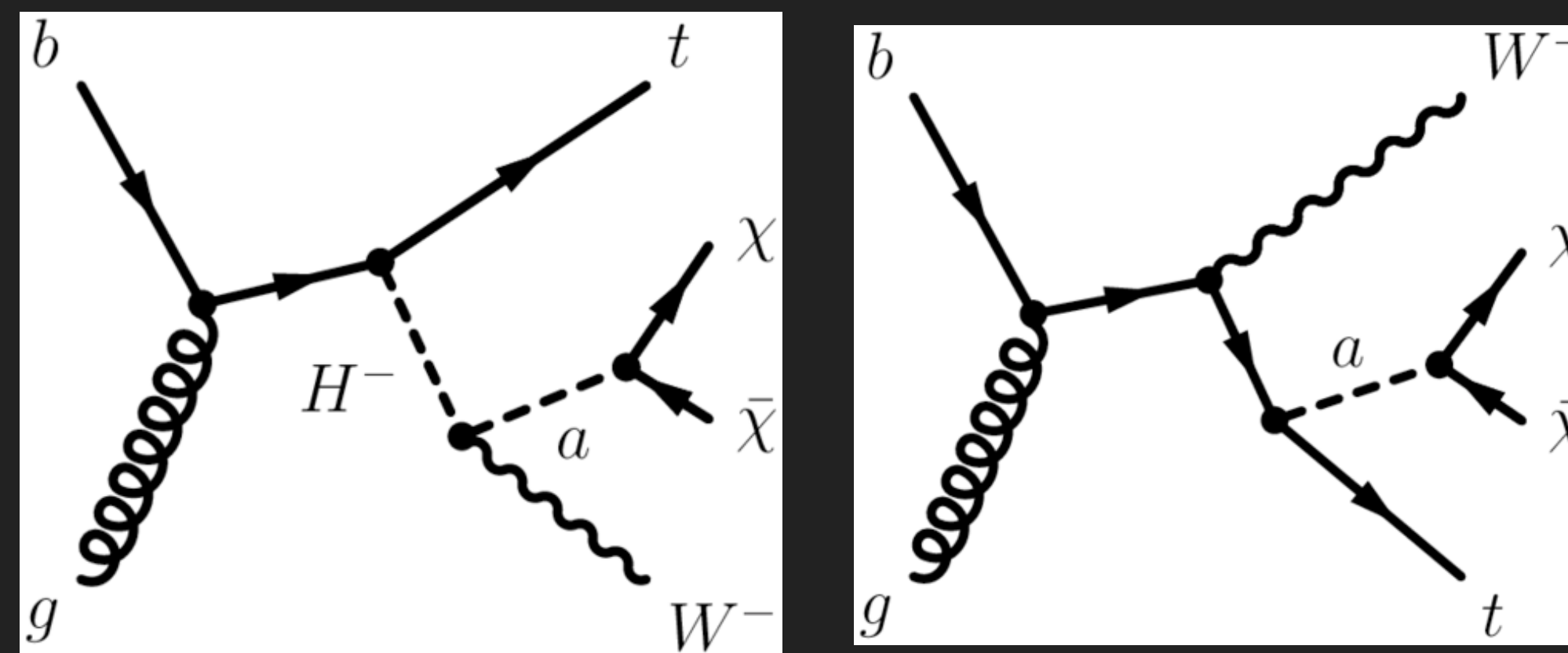
- ▶ 16 SRs split according to  $E_T^{\text{miss}}$ ,  $N_{\text{jet}}$ ,  $m_{jj}$
- ▶ Leptonic CRs:  $Z(\nu\nu)+\text{jets}$  and  $W(l\nu)+\text{jets}$  constrained together via NLO-accurate  $R^{W/Z}$



- ▶  $\text{BR}(H \rightarrow \text{inv}) < 0.145 \text{ (0.103)}$

# A PSEUDOSCALAR PORTAL?

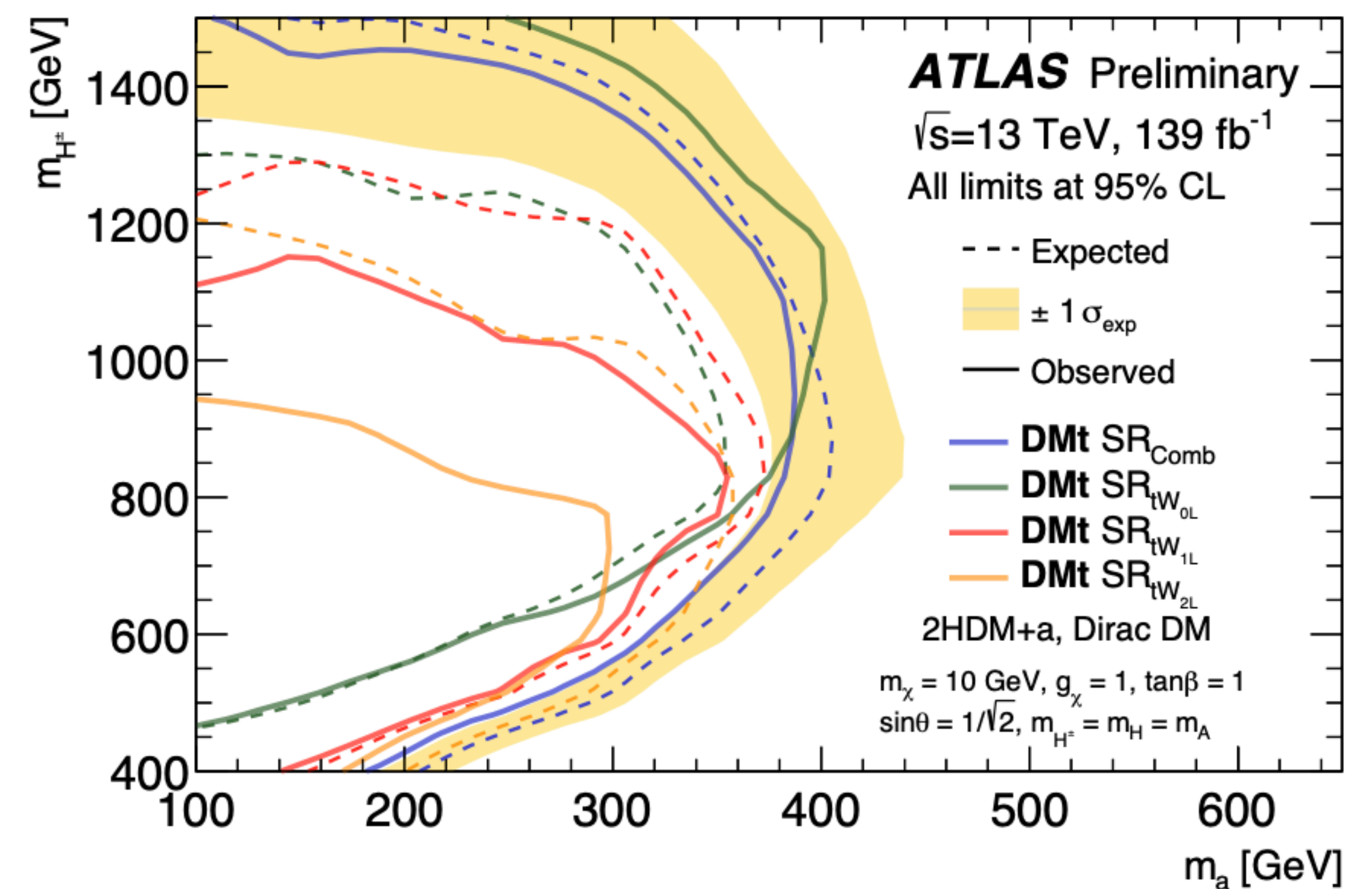
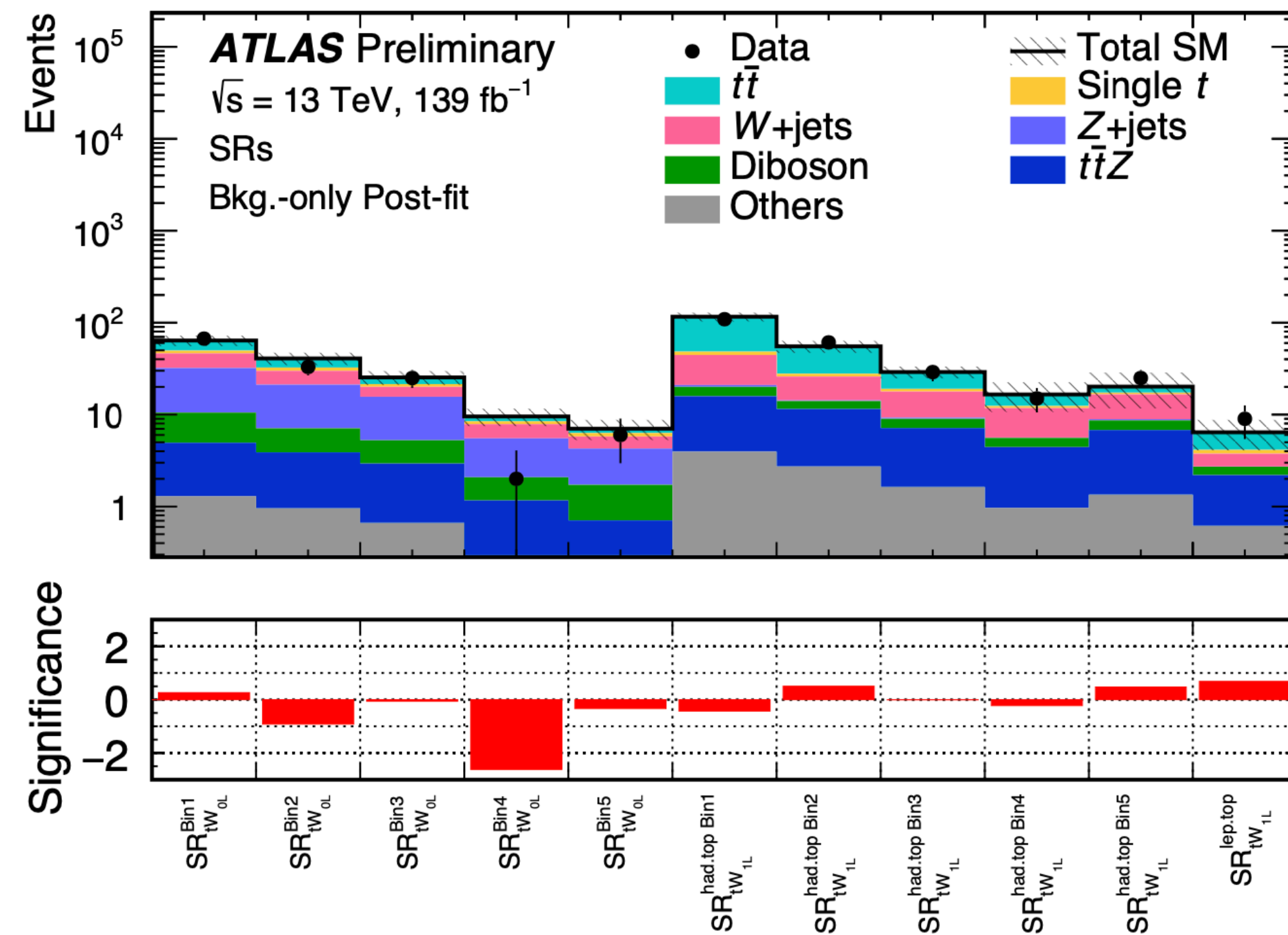
- ▶ Pseudoscalar mediator: avoid constraints from DM direct detection
- ▶ Simplest gauge-invariant and renormalisable extension of simplified pseudoscalar model: 2HDM ( $h, H, H^\pm, A$ ) +  $a$  decaying to DM
- ▶ Multiple signatures, here reviewing a recent analysis looking for the prevalent coupling to top quarks (Yukawa-like couplings) in a  $Wt + E_T^{\text{miss}}$  final state:





# ATLAS $WT + E_T^{\text{MISS}}$

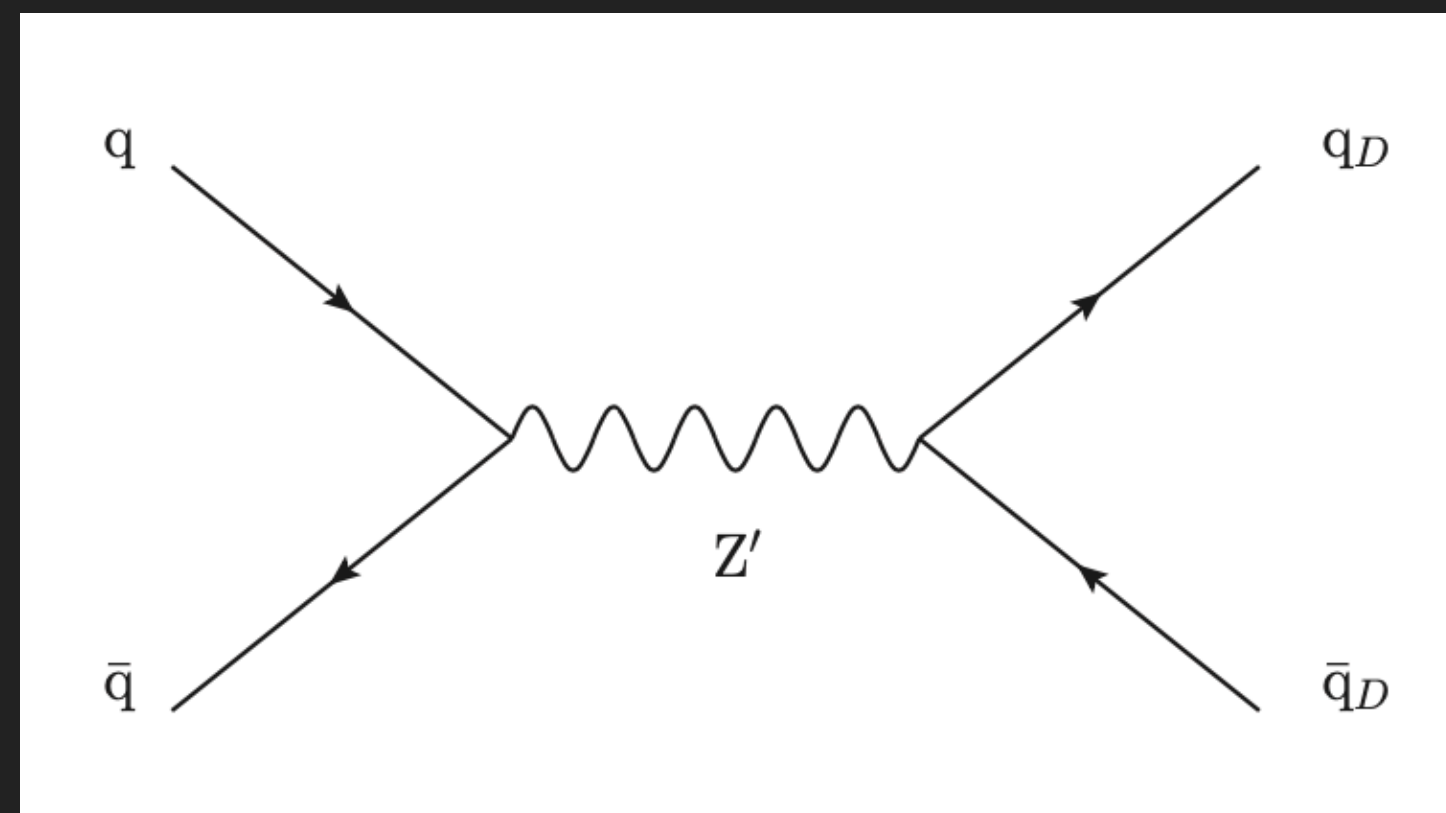
- ▶  $E_T^{\text{miss}}$  for triggering + final discriminant, require  $\geq 1$  b-tagged jet
- ▶ 0 lepton +  $\geq 4$  small-R jets + W-tagged fat jet
- ▶ 1 lepton from top:  $\geq 2$  jets + W-tagged fat jet; OR from W:  $\geq 3$  jets



# DM IN A HIDDEN SECTOR WITH STRONG DYNAMICS?

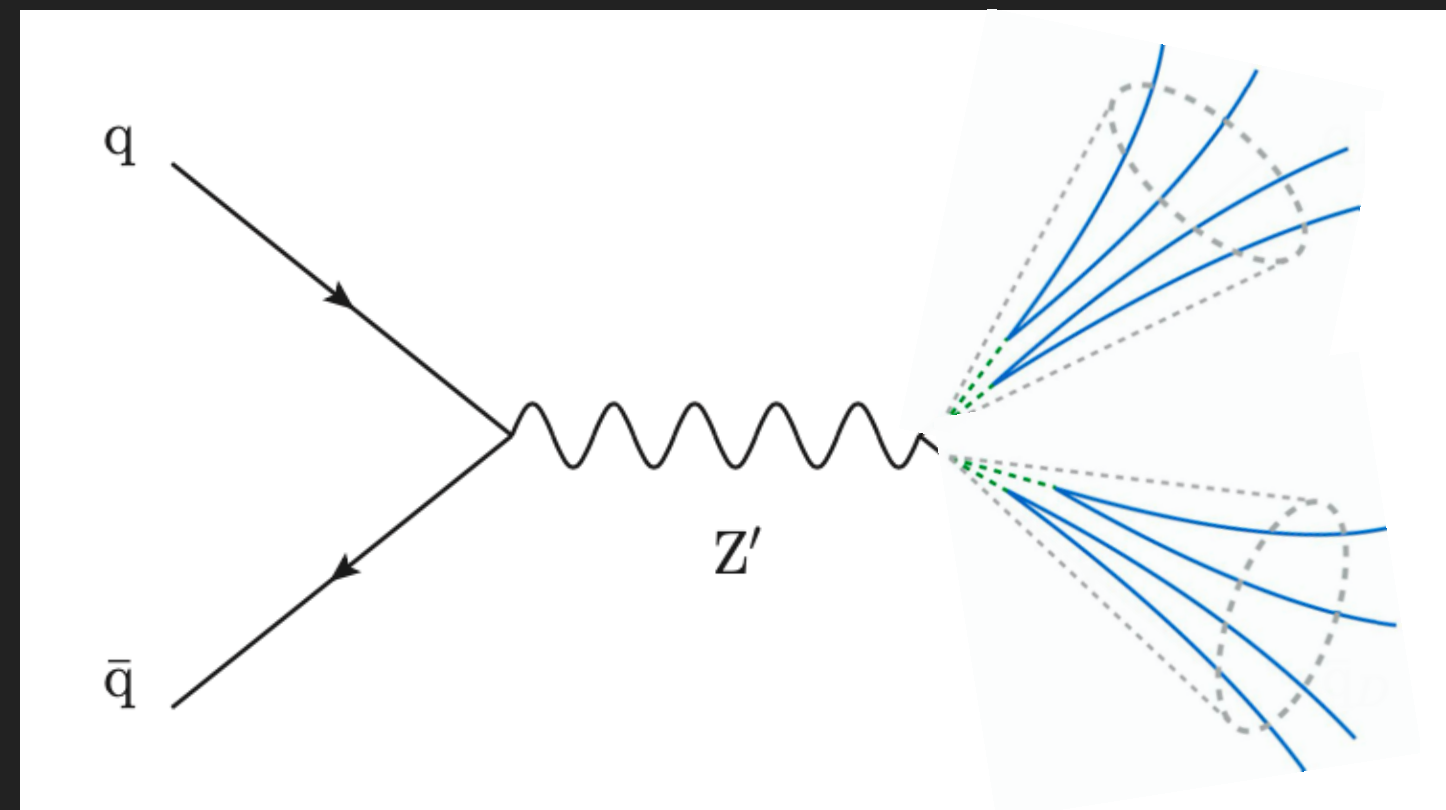
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- ▶ Hidden sector analogous to QCD
- ▶ Dark quarks are produced through the portal and hadronise into dark hadrons, some stable (DM candidates!), some decaying back to the standard model through the portal:  $r_{inv} = \# \text{ stable hadrons} / \# \text{ unstable hadrons}$



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- ▶  $r_{\text{inv}} \sim 0$  : visible jets  $\Rightarrow$  dijet resonance

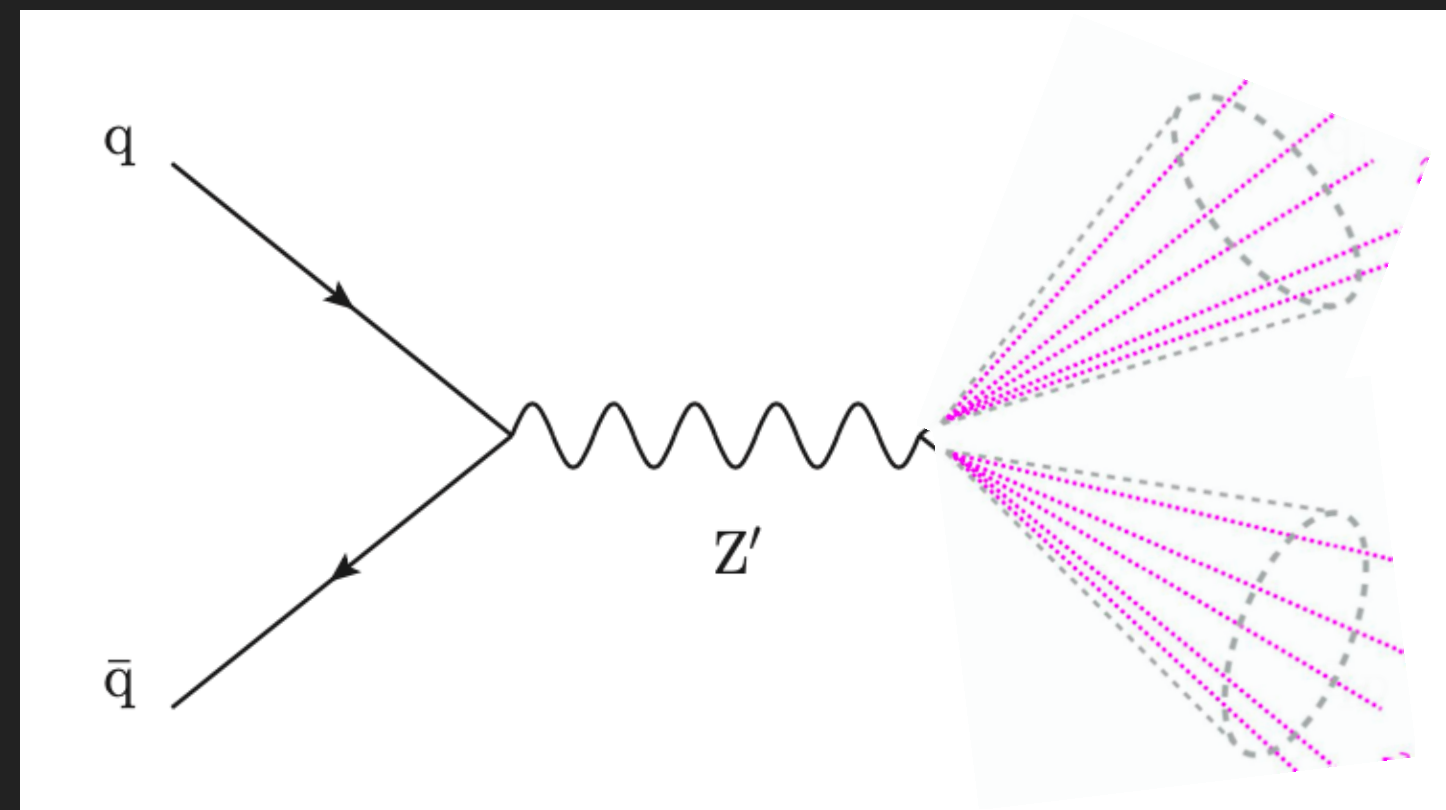




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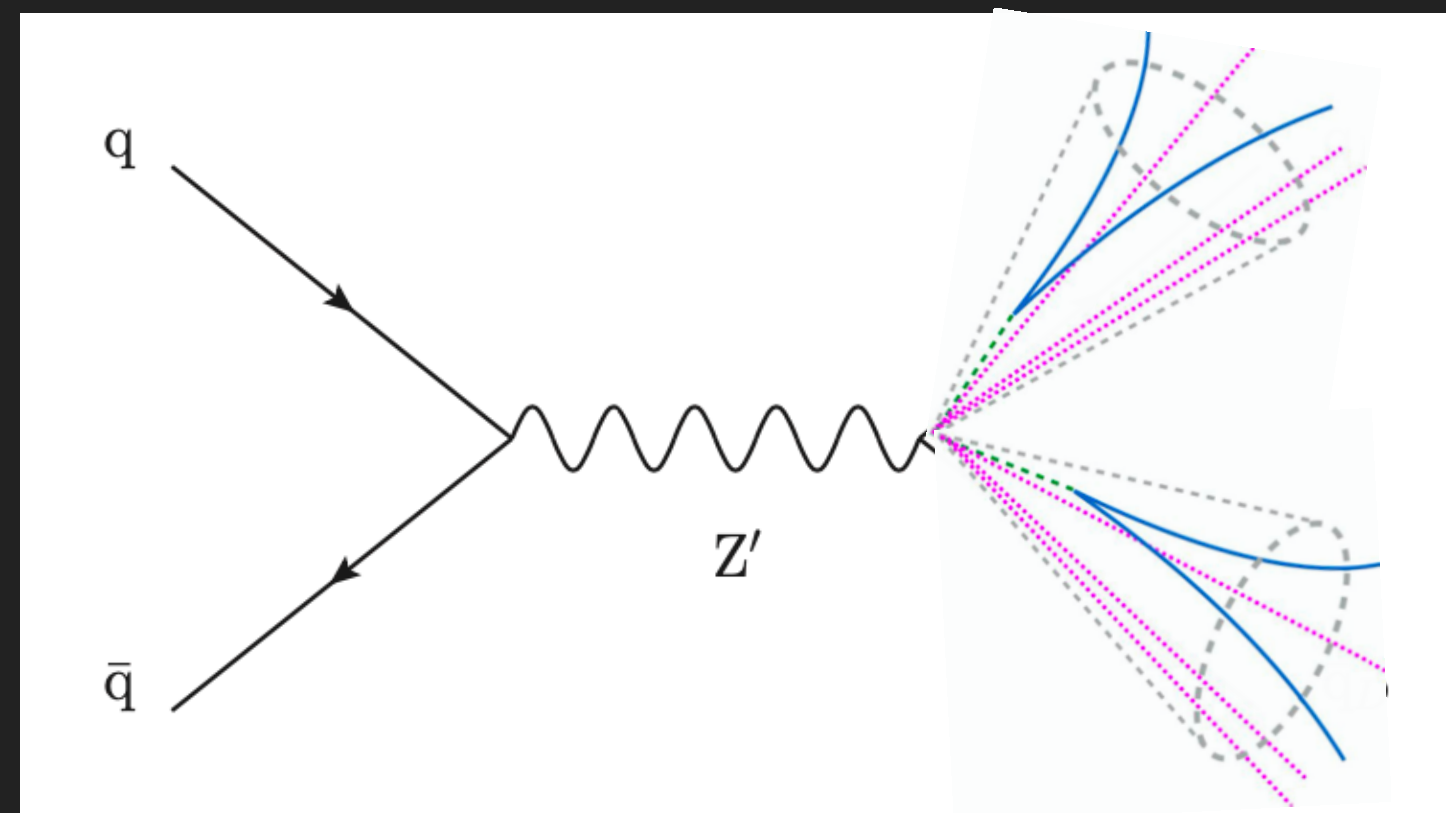
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- ▶  $r_{\text{inv}} \sim 1$  : invisible jets  $\Rightarrow$  think mono-jet again!



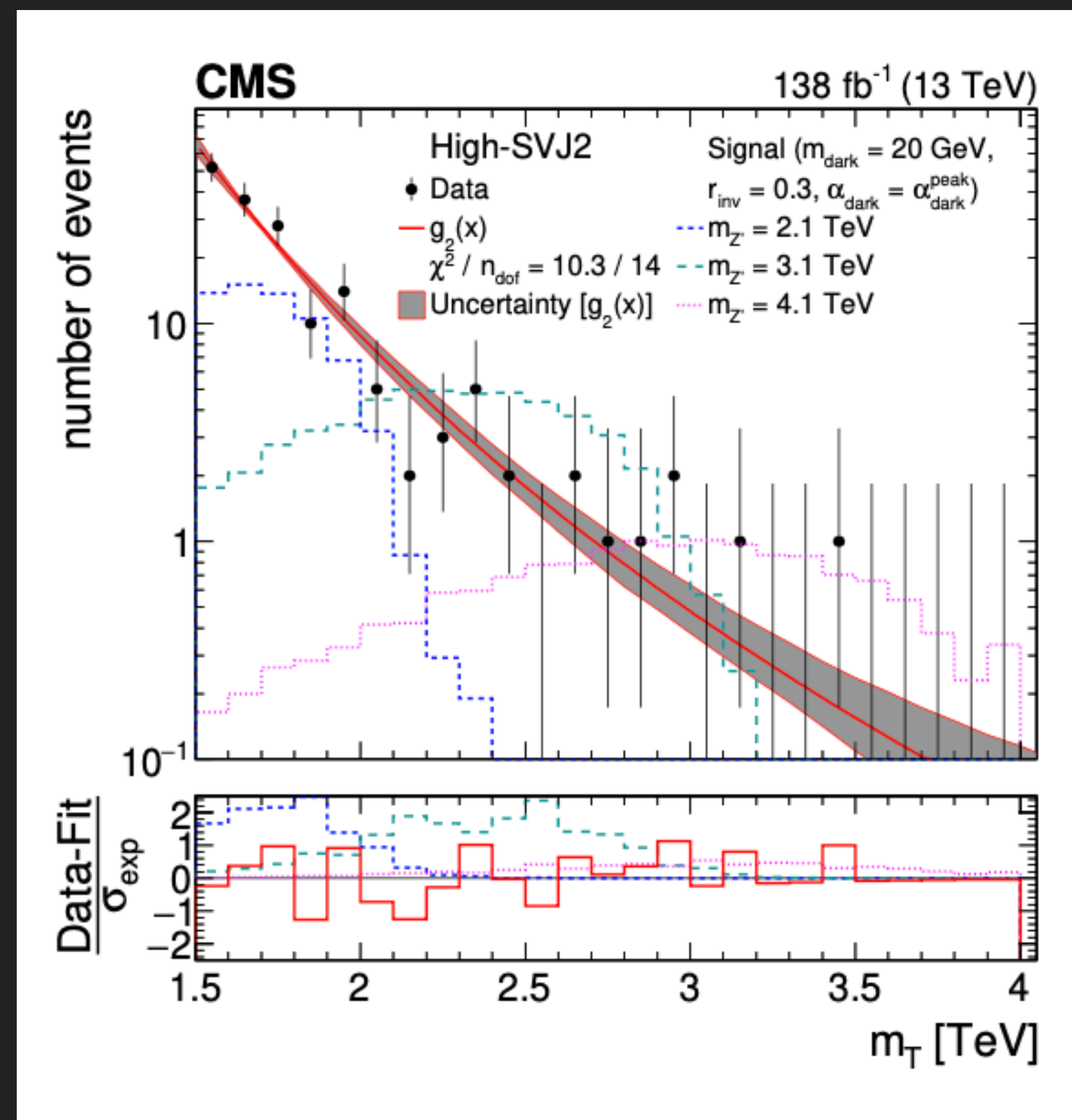
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- ▶  $0 < r_{\text{inv}} < 1$ : semi-visible jets  $\Rightarrow E_{\text{T}}^{\text{miss}}$  aligned with one jet if back to back



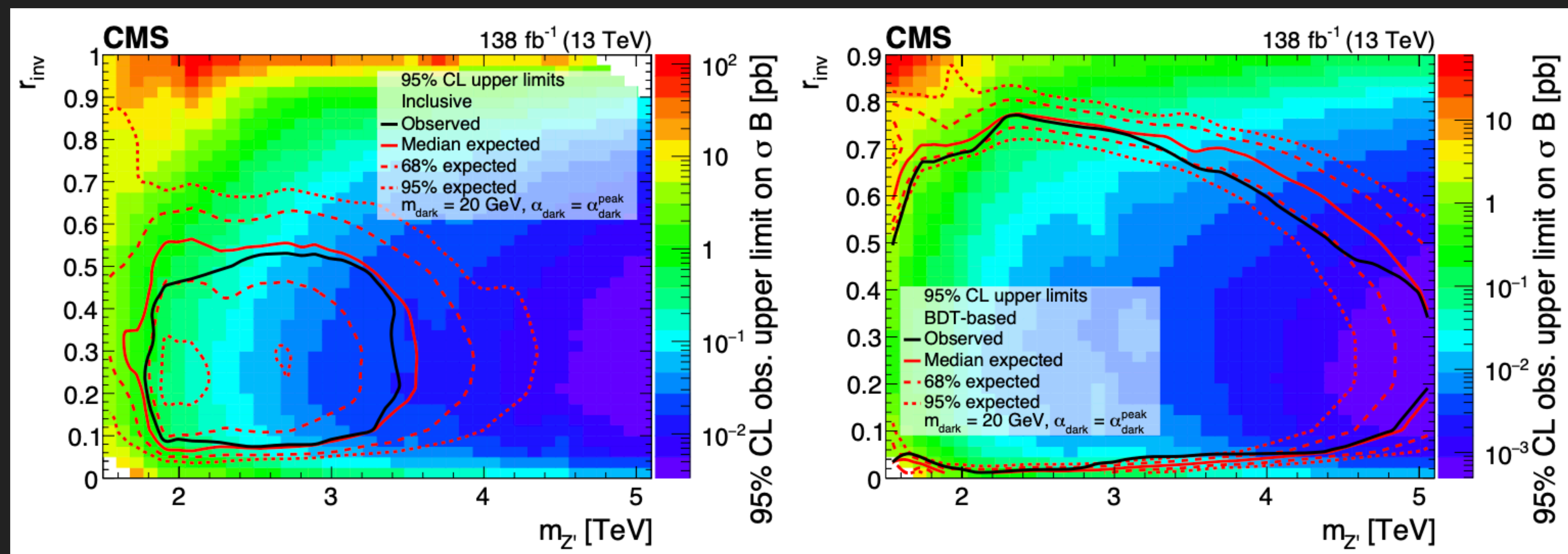
# CMS SEMI-VISIBLE JETS

- ▶ 2 high- $p_T$  large- $R$  jets +  $E_T^{\text{miss}} \Rightarrow m_T$
- ▶ Reject QCD BG by asking for a large  $R_T = E_T^{\text{miss}} / m_T$  (2 SRs)
- ▶ Veto leptons, small angle between the jets and  $E_T^{\text{miss}}$
- ▶ Analytic smoothly falling function for BG estimation





# CMS SEMI-VISIBLE JETS



Model-independent  
Limits: cut and count

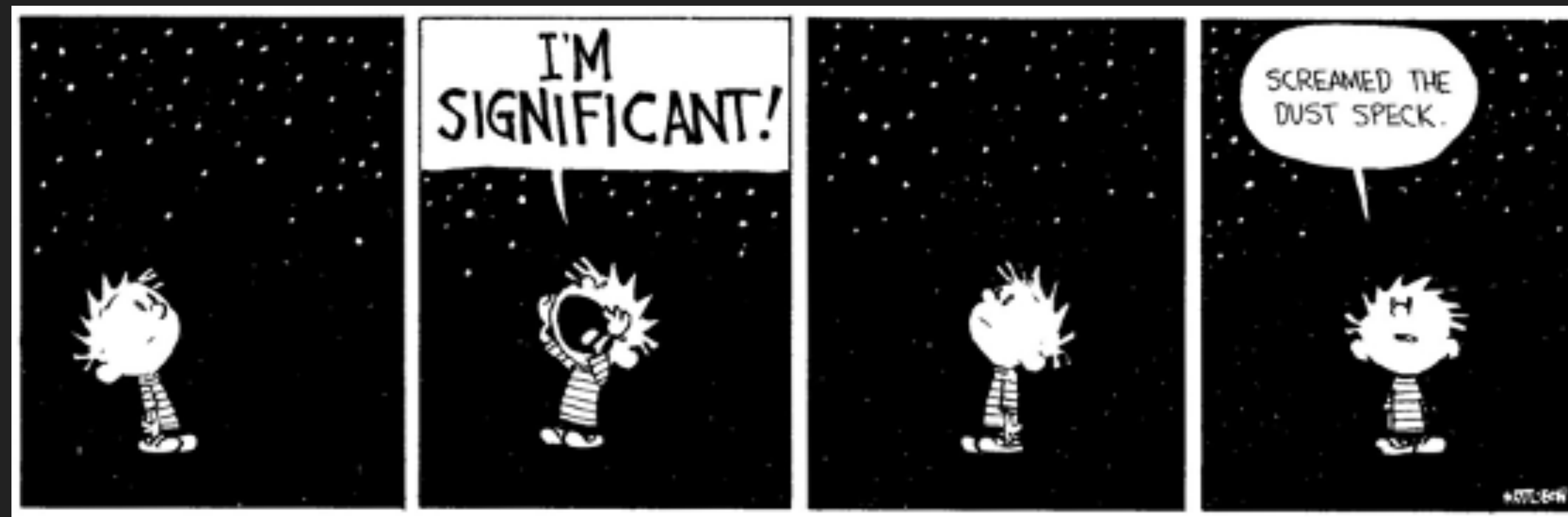
Model-dependent  
Limits: BDT tagging  
semi-visible jets

$$m_{\text{SD}}, \Delta\phi(\vec{J}, \vec{p}_T^{\text{miss}}), \tau_{21}, \tau_{32}, \text{ and } D_{p_T}$$

# SUMMARY

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- ▶ Dark matter is still a puzzle today...
- ▶ Many recent results from the LHC using the full Run-2 dataset bring complementary information to other types of searches
- ▶ ... but no significant deviation seen yet

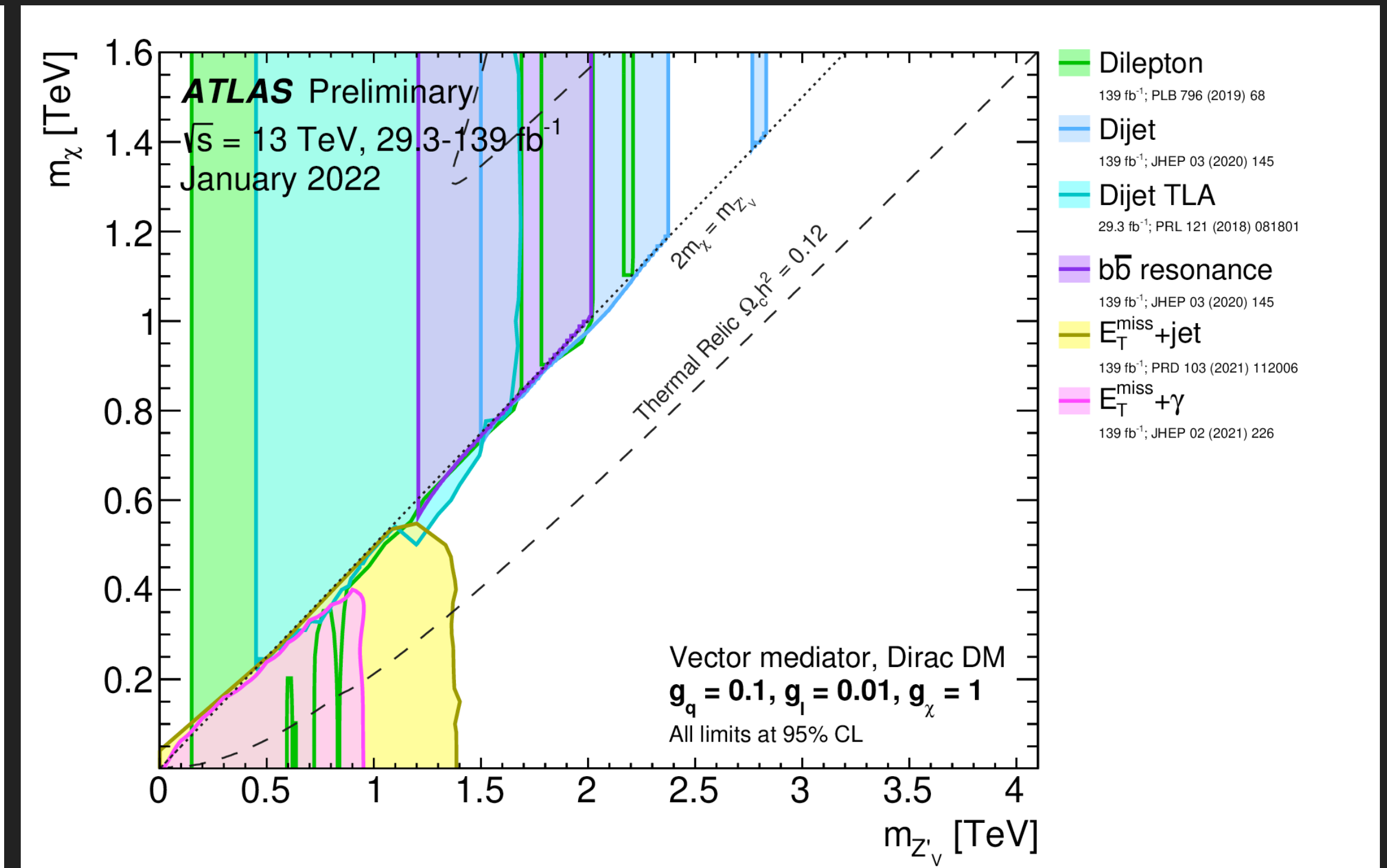
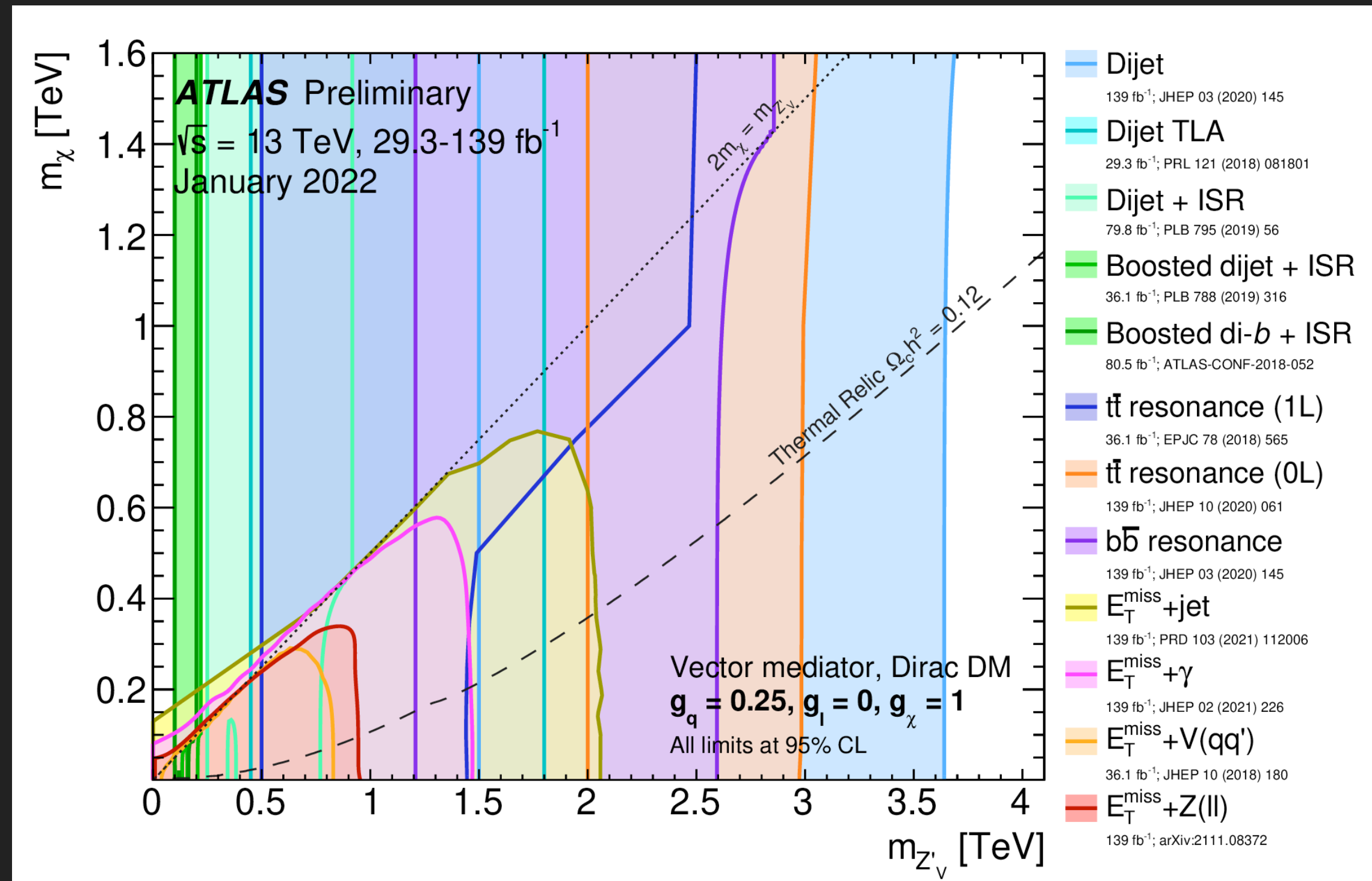


- ▶ Diversification of the searches to cover more and more scenarios
- ▶ Onto Run-3 and beyond!





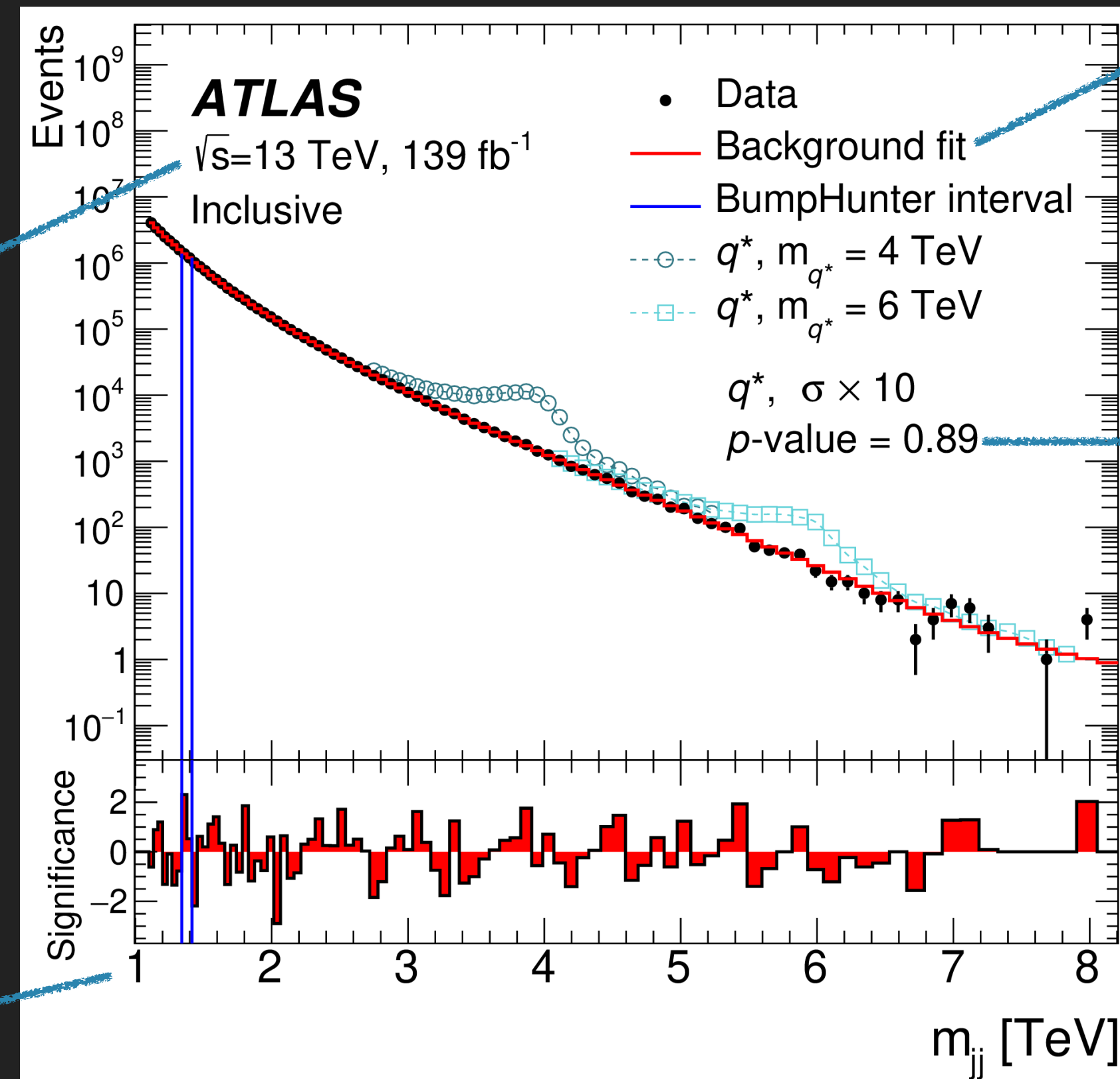
# COMPLEMENTARITY OF DM VS MEDIATOR SEARCHES



# DI-JET RESONANCE

Ask for events with  $\geq 2$  high- $p_T$ , central jets

Full Run-2 dataset



Smoothly-falling background:  
 fit a function to the data -  
 find the best function  
 (flexibility vs sensitivity)

No significant excess found

Lower  $m_{jj}$   
 threshold from  
 trigger

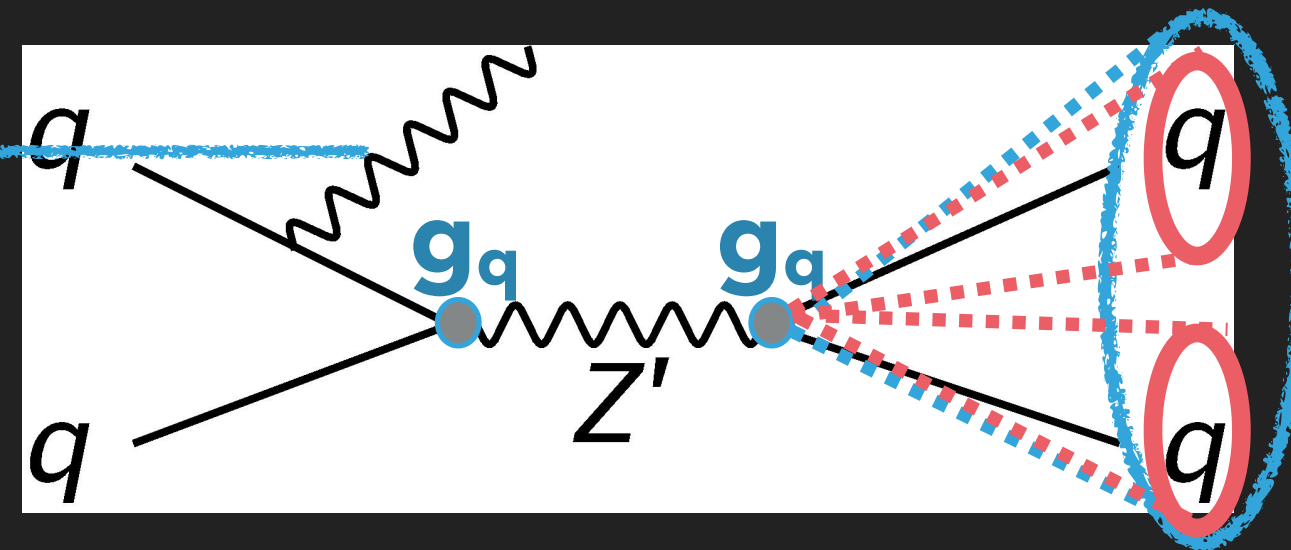




# LOW MASS BOOSTED DI-JET RESONANCES

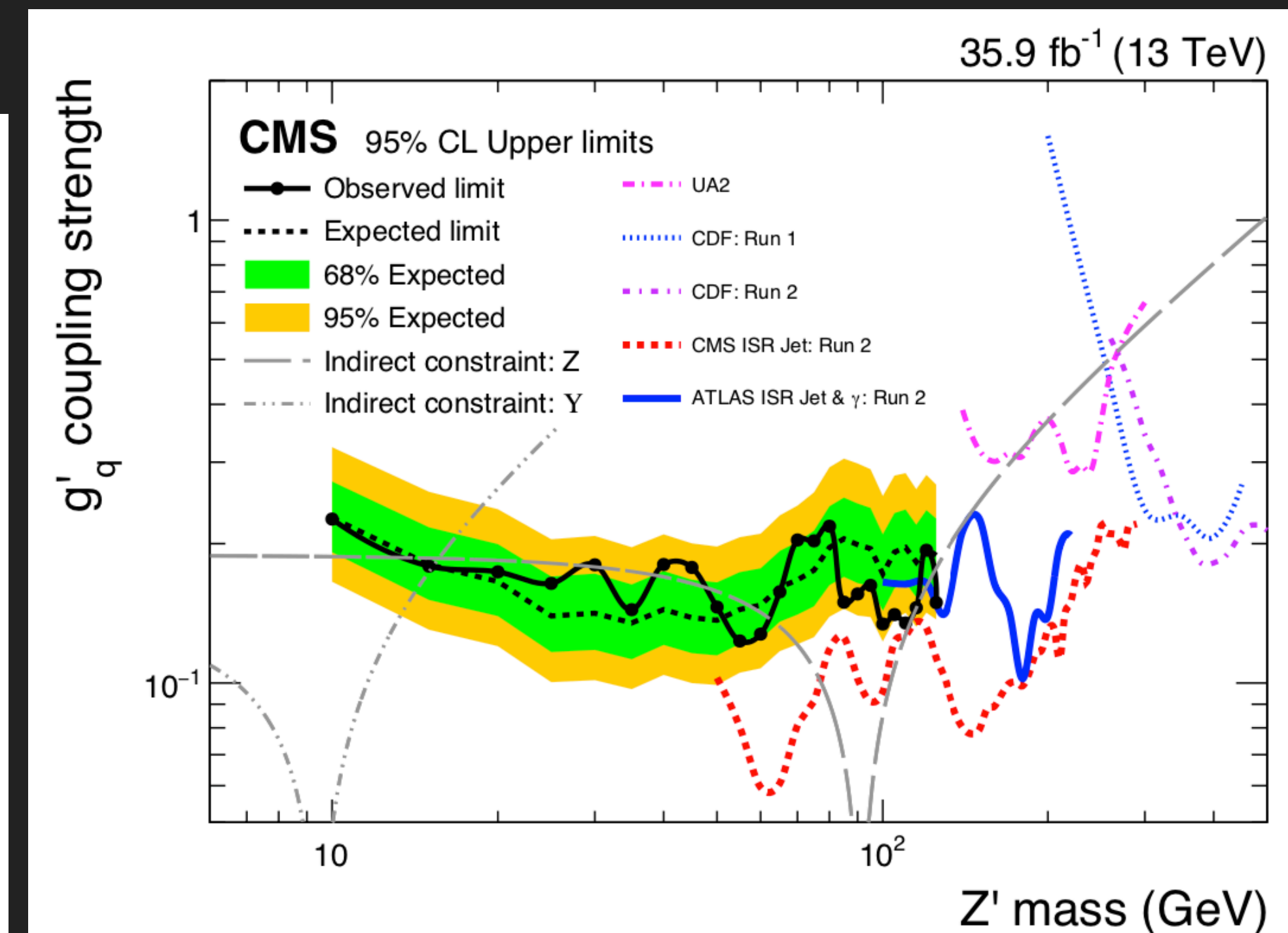
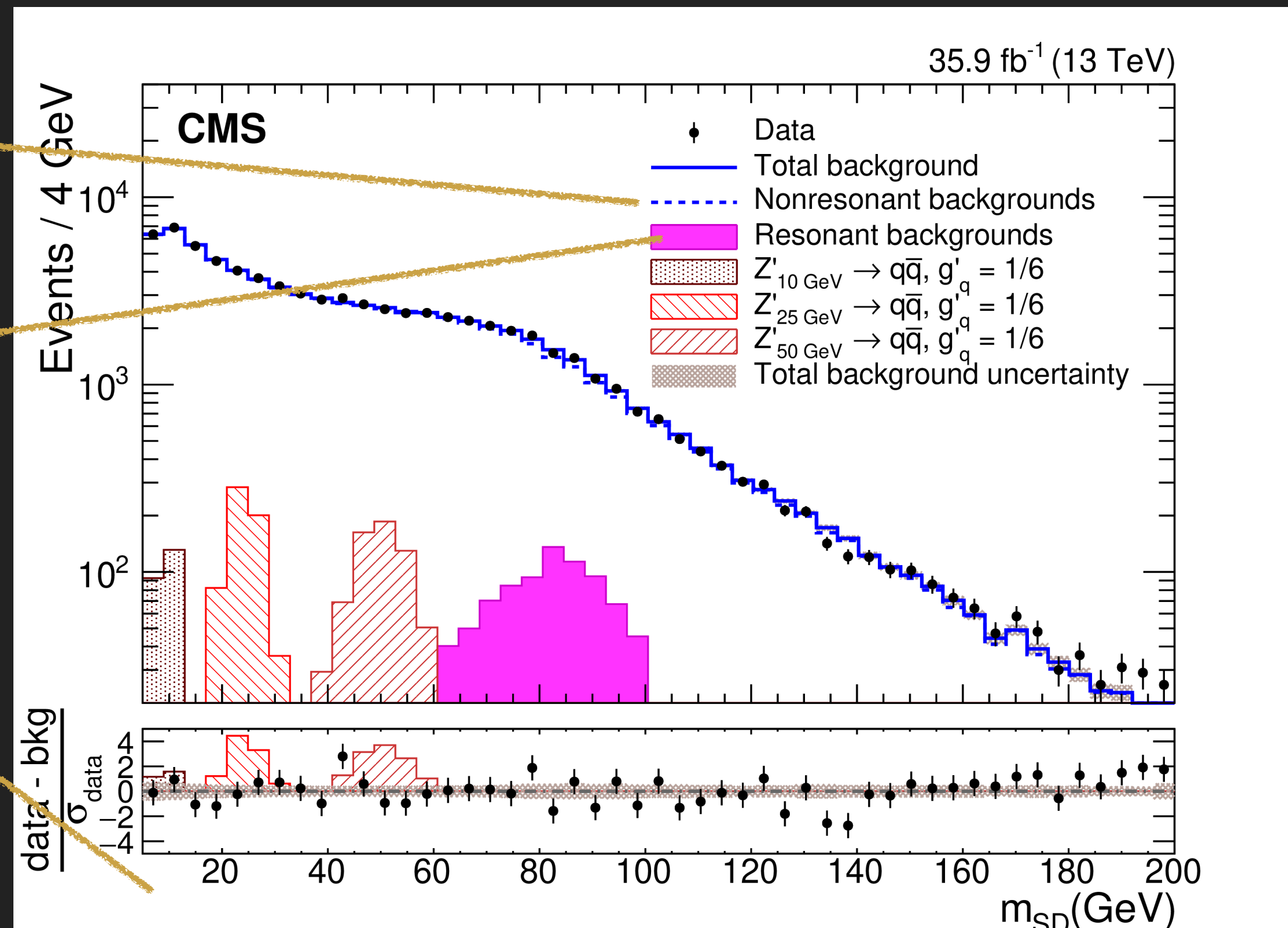
Phys. Rev. Lett. 123, 231803 (2019)

Trigger on ISR  
photon:  $p_T > 175$  GeV



Boosted  $Z' \rightarrow qq$ : large-R jet,  
2-prong substructure

From fit  
From MC  
normalised  
in control  
regions  
Jet masses  
down to  
10 GeV!



► Limit on  $g_q$  for  $m_{Z'}$  from 10 to 125 GeV  
(Other types of searches cover the  
intermediate masses)



# A HDM+A ; A RICH SIGNATURE SPACE

## 2HDM+a model parameters

**Masses:**  $M_h \simeq 125$  GeV  
 $M_H, M_{H^\pm}, M_A, M_a, M_\chi$

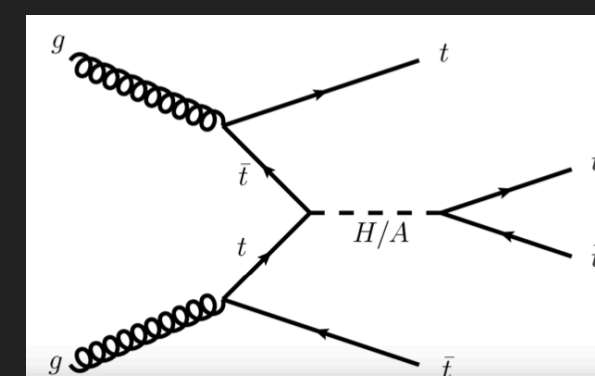
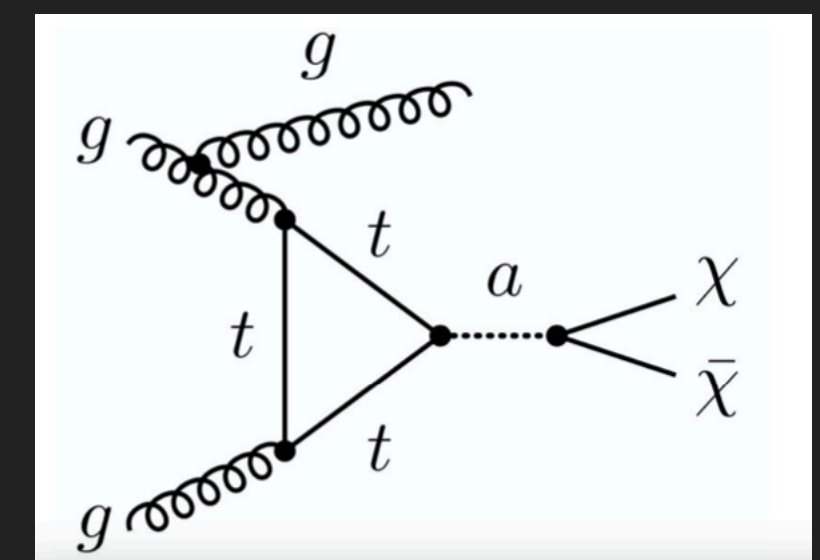
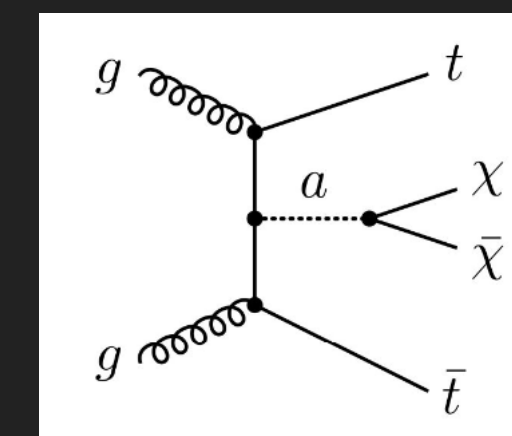
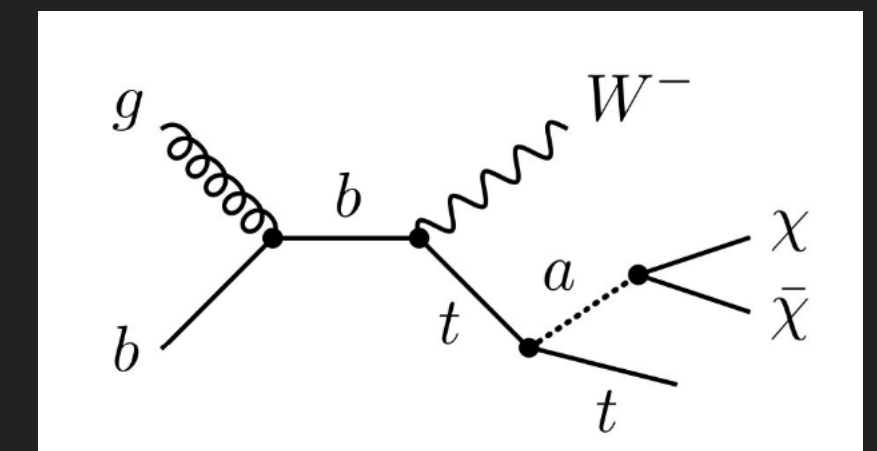
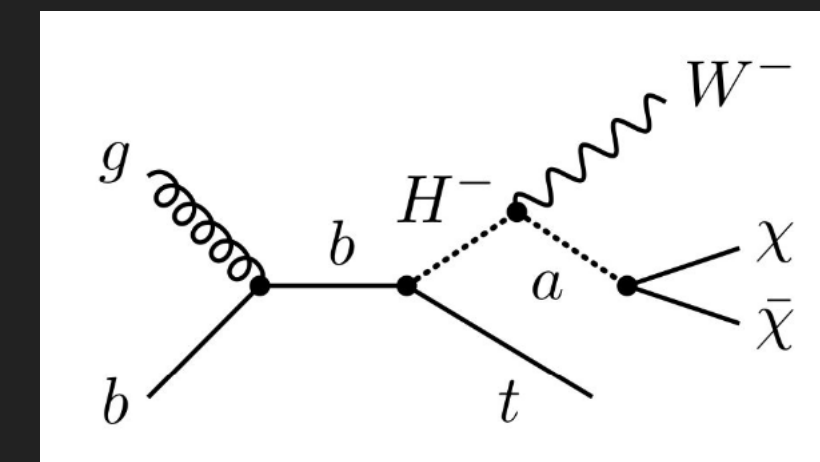
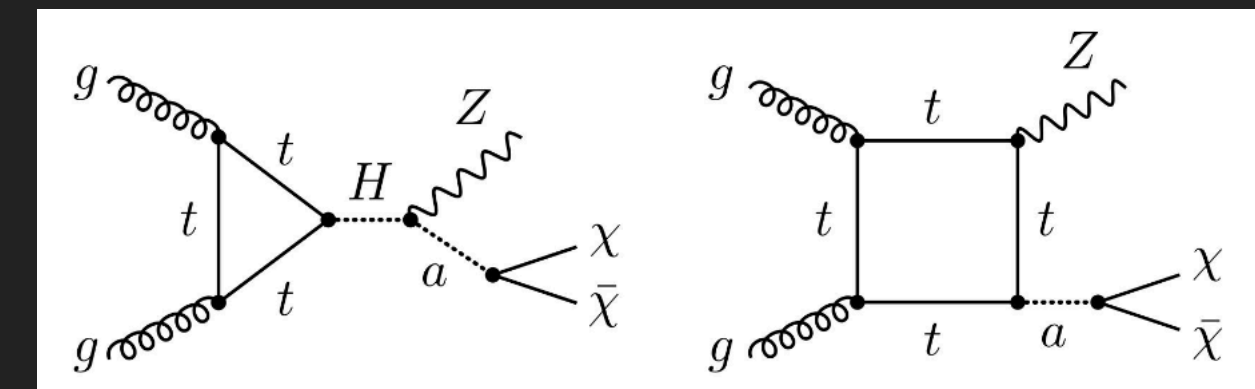
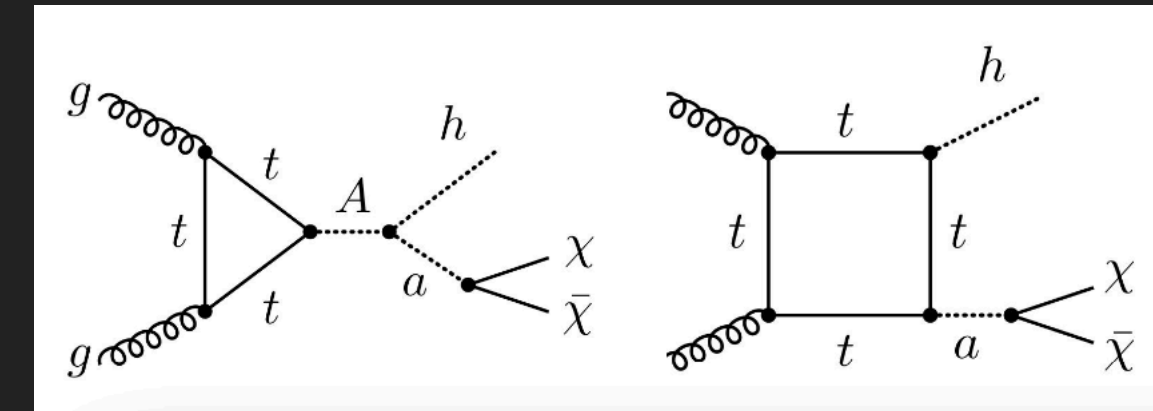
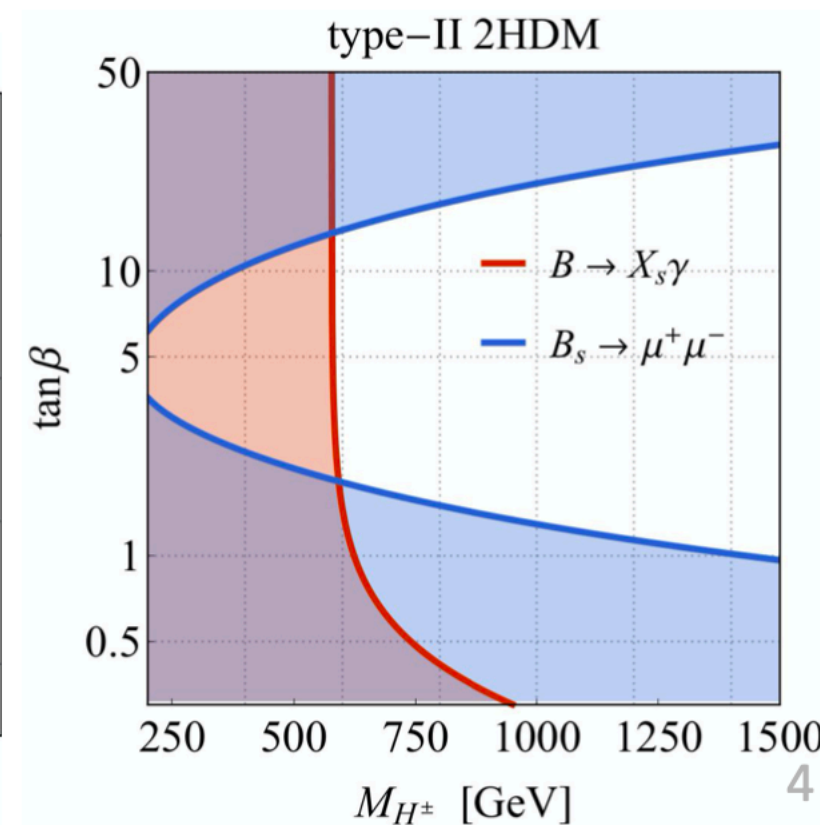
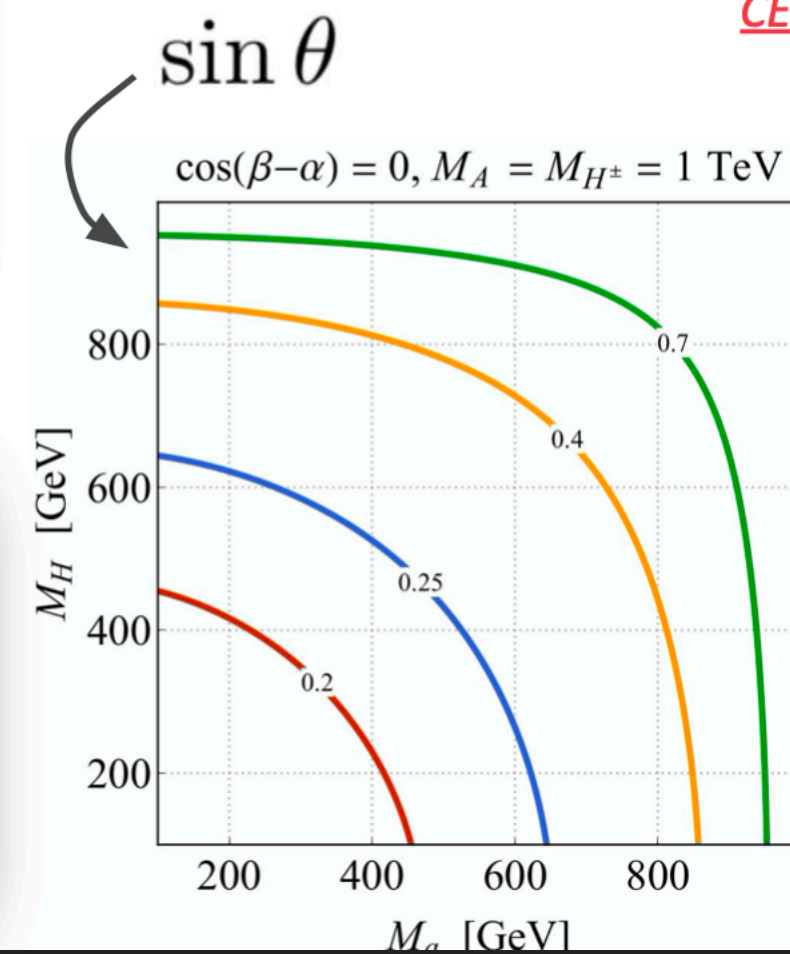
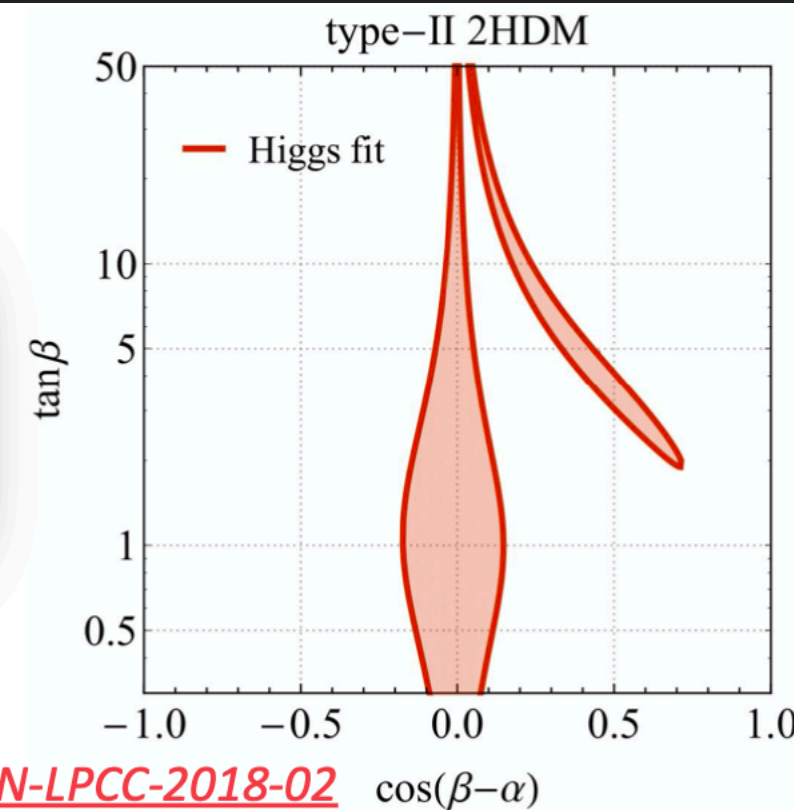
**Quartic couplings:**  
 $y_\chi, \lambda_3, \lambda_{P1}, \lambda_{P2}$

### Mixing angles:

- Between **h** and **H**:  $\alpha$
- Between **a** and **A**:  $\theta$
- VEV ratio of Higgs doublet:  $\tan \beta$

### Benchmark parameters:

- $\cos(\beta - \alpha) = 0$  (Alignment limit)
- $M_H = M_A = M_{H^\pm}$
- $\lambda_3 = \lambda_{P1} = \lambda_{P2} = 3$
- $M_\chi = 10$  GeV,  $y_\chi = 1$



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