DM SEARCHES @ THE LHC AND SOME DISCUSSION ON COMPLEMENTARITY WITH DIRECT AND INDIRECT DETECTION

MARIE-HÉLÈNE GENEST

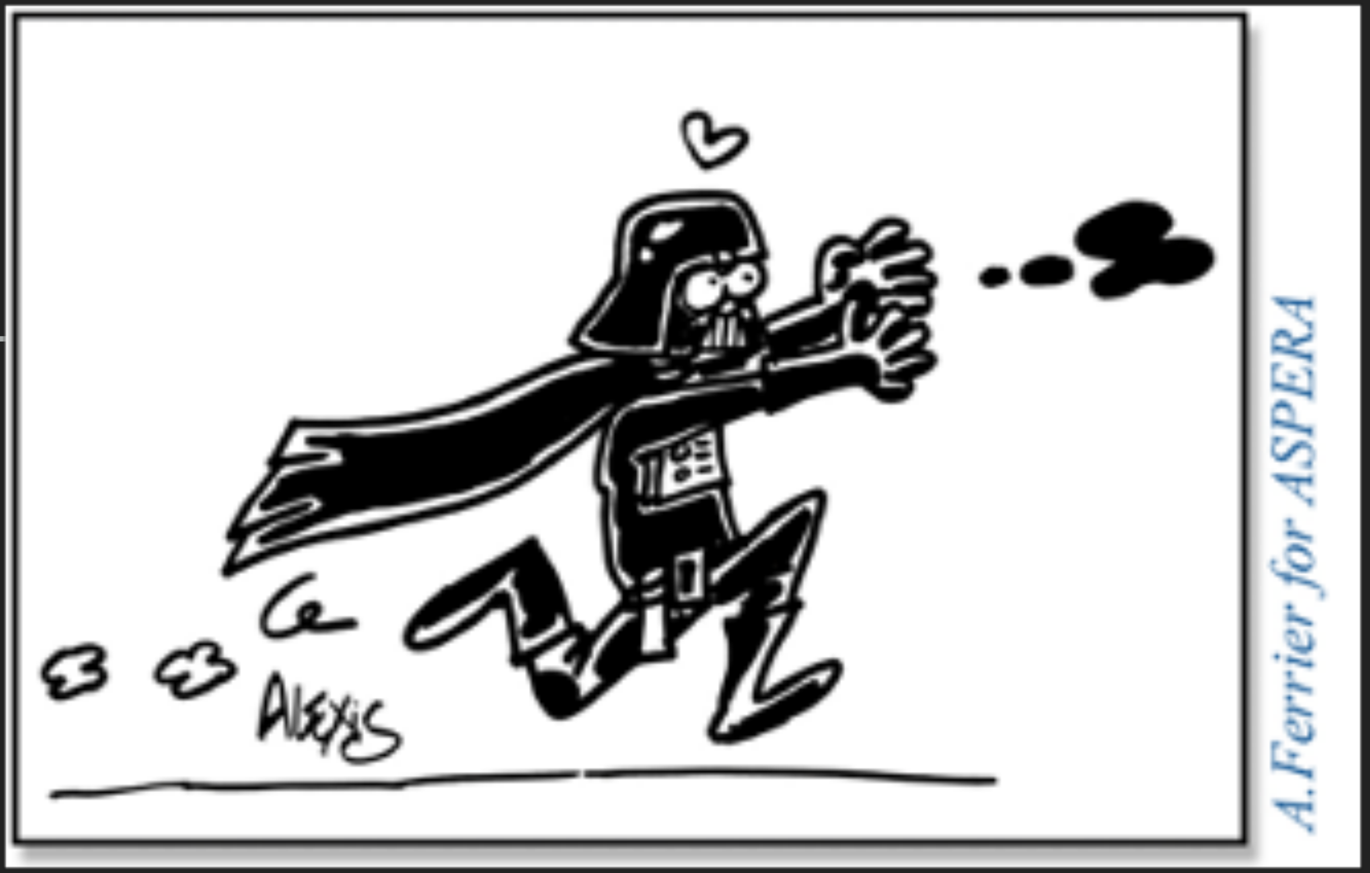
IRN TERASCALE + MDR DUPHY

OCT 19TH 2022

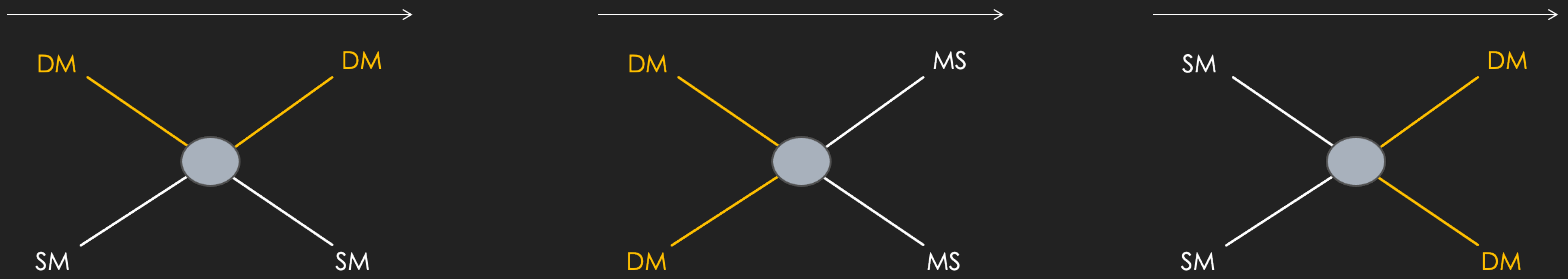
LPSC GRENOBLE | MODANE

CNRS IN2P3 Les deux infinis

SEARCHING FOR DARK MATTER …

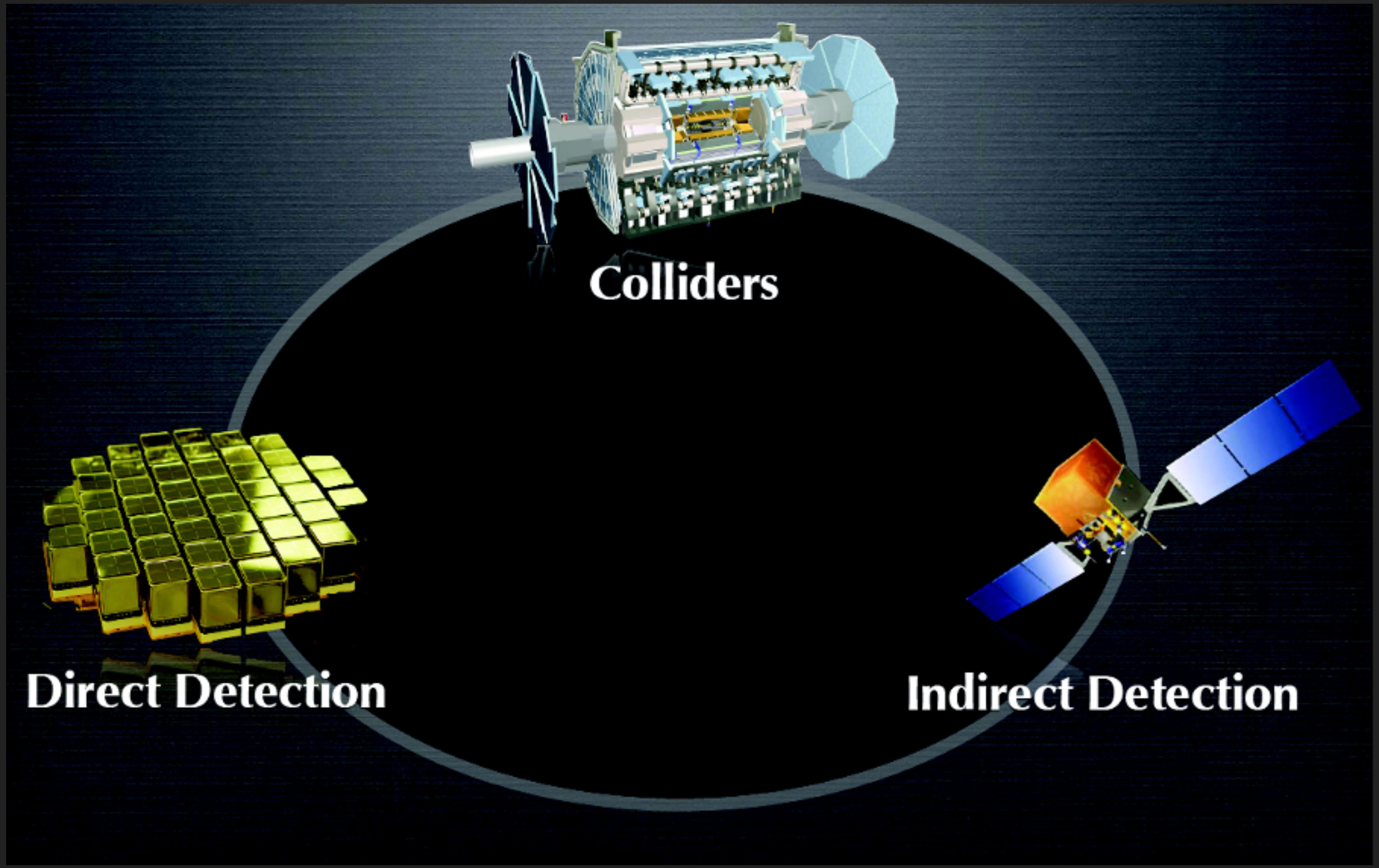


- 85% of the matter in the universe is in the form of DM according to cosmological/astrophysical evidences



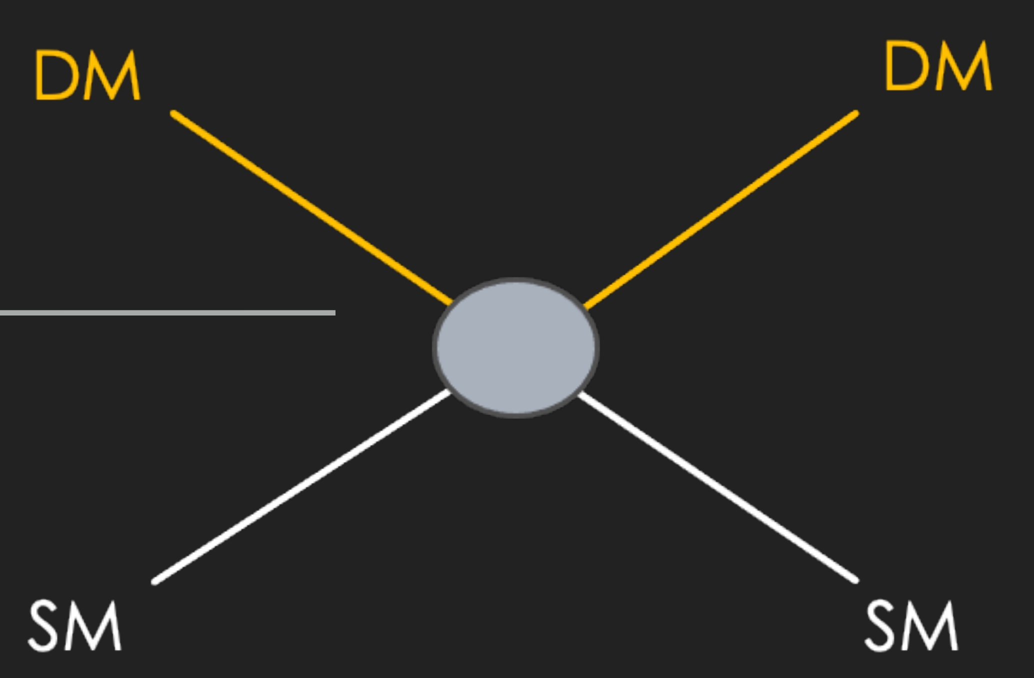
Direct detection | Indirect detection | Production

COMPLEMENTARITY !



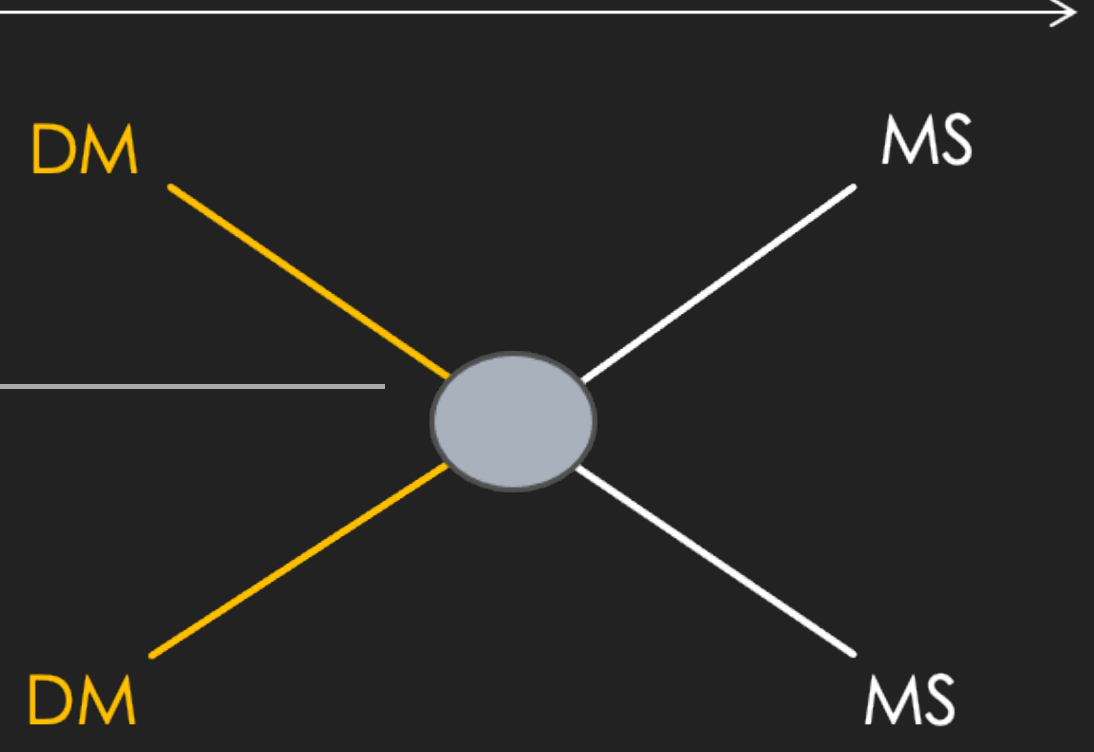
- Need to be careful about the assumptions when comparing different experiments
- Would be especially helpful in case we see a signal to determine the nature of DM!

DIRECT DETECTION



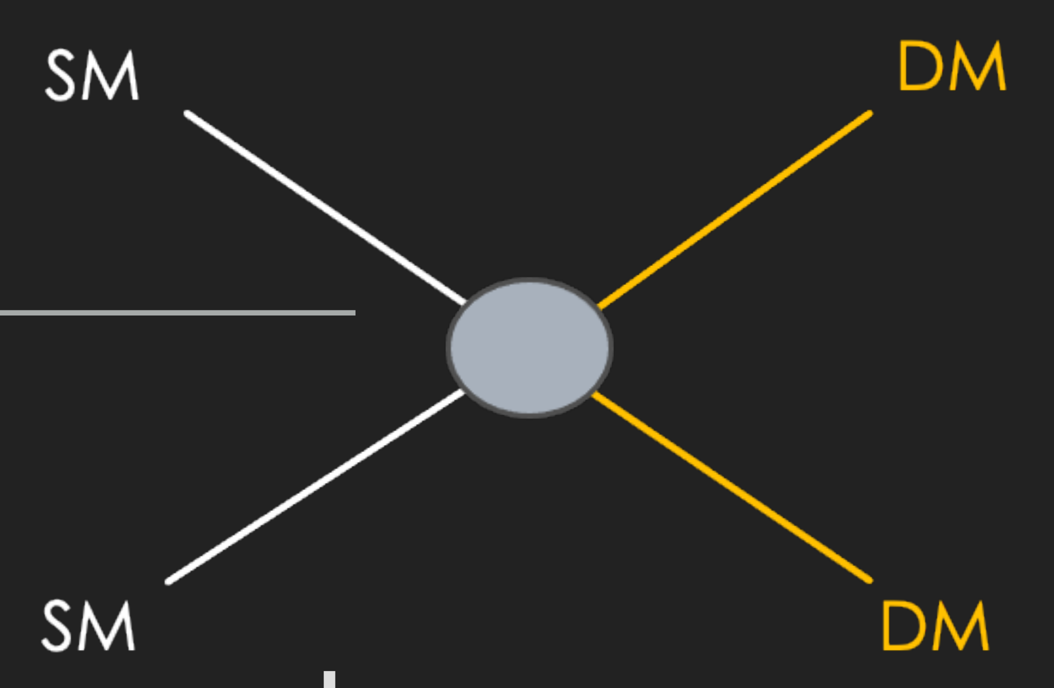
- Probably the most *straightforward* detection method
- Requires a very careful control of low-energy backgrounds
- Low-mass is more difficult to access (although there has been great progress recently!), same for leptophilic DM (but again, some recent results use electron recoils!)
- Can constrain the DM mass + elastic scattering cross sections with protons and neutrons
- Assume a given DM halo (local density at 0.3 GeV/cm^3 and v/c of order10^{-3}) and one DM component (otherwise: scaling of the limits)

INDIRECT DETECTION



- Can probe interactions with multiple SM particles using space-based detectors, telescopes, neutrino detectors…
- Limits are set on the cross section $\langle \sigma v_{rel} \rangle$ to annihilate to a single particle-anti-particle final state as a function of the DM mass
- Requires a good understanding of astrophysical backgrounds & of propagation models for some species
- Assume a DM distribution (+ scaling of limits if more than one component)

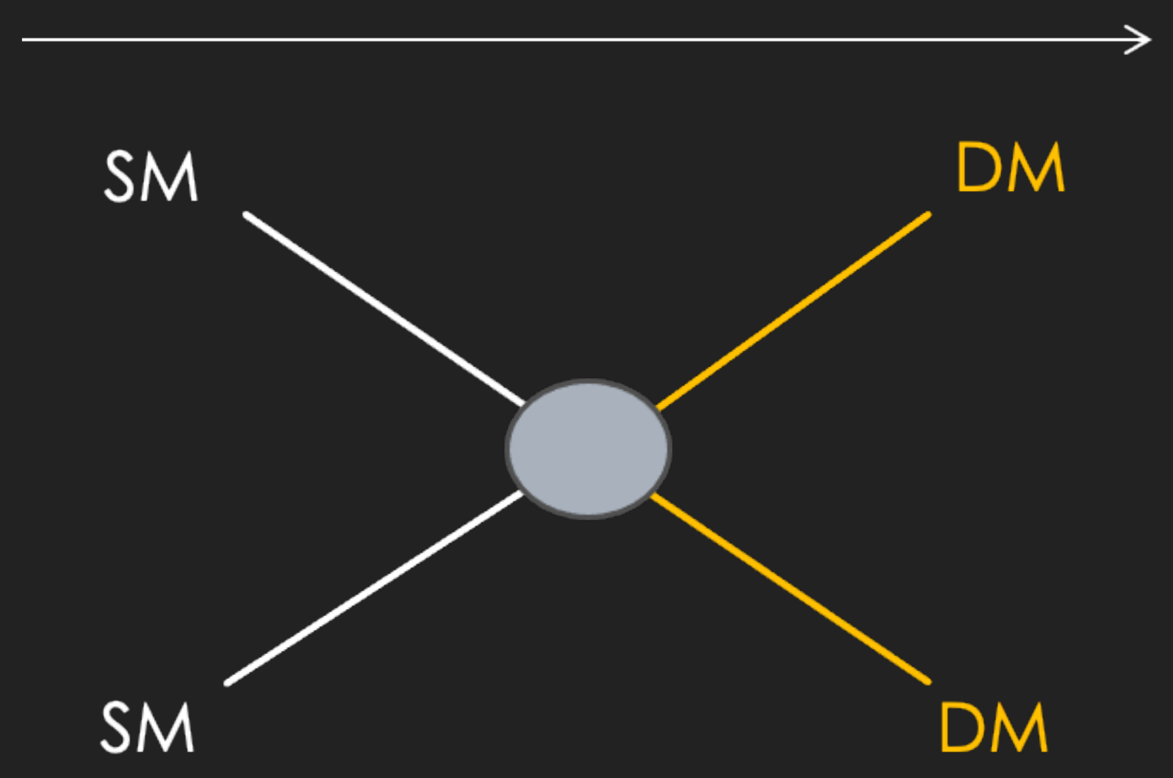
COLLIDER PRODUCTION – FOCUS TODAY



- Controlled laboratory environment
- Potentially sensitive to a wide variety of models / could also discover the 'accompanying' particles
- Can't probe very massive DM candidates (need to be produced!)
- Can only look for DM *candidates* : unable to determine whether a new weakly interacting particle is stable on a cosmologically relevant timescale - this would require an extrapolation in lifetime of 24 orders of magnitude (!)
- At the LHC energy, an EFT contact interaction approximation is usually not valid as one might well be able to resolve the mediator of the interaction => interpretation in specific models

SEARCHING FOR A DM CANDIDATE AT THE LHC

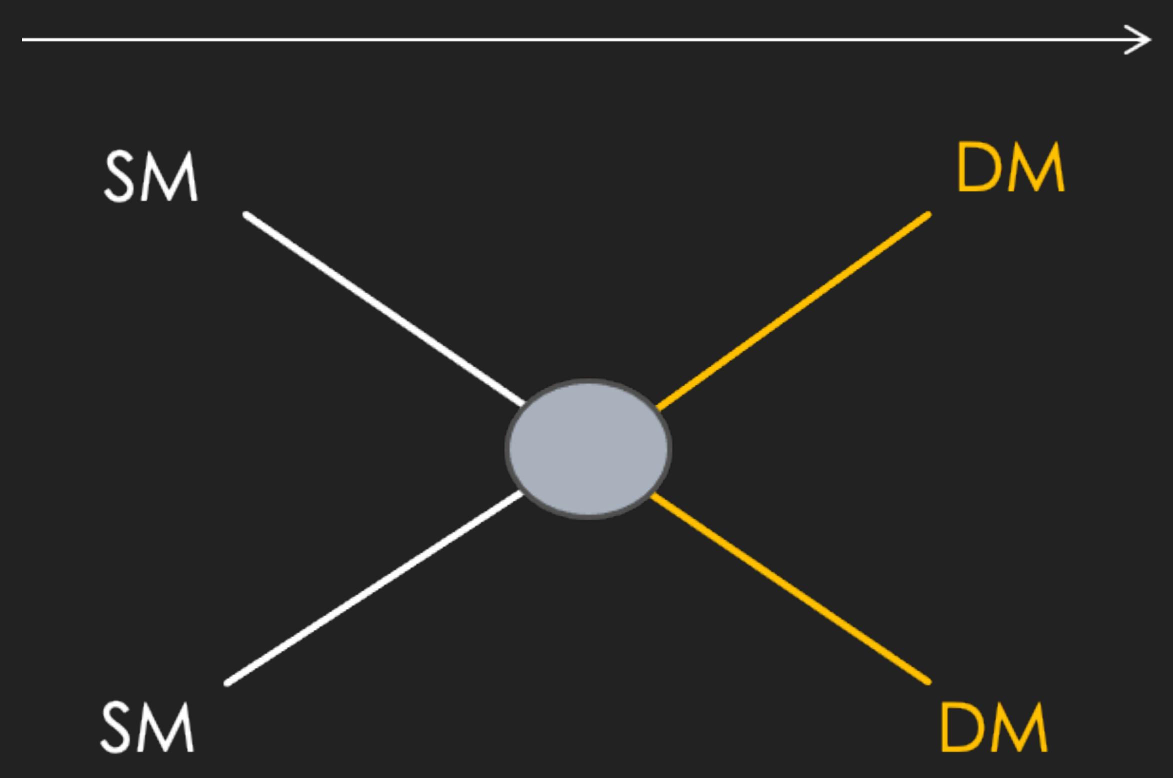
- If DM is made of BSM particles which interact weakly with SM particles, then couldn't it be possible to produce some in pp collisions at the LHC?



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

SEARCHING FOR A DM CANDIDATE AT THE LHC

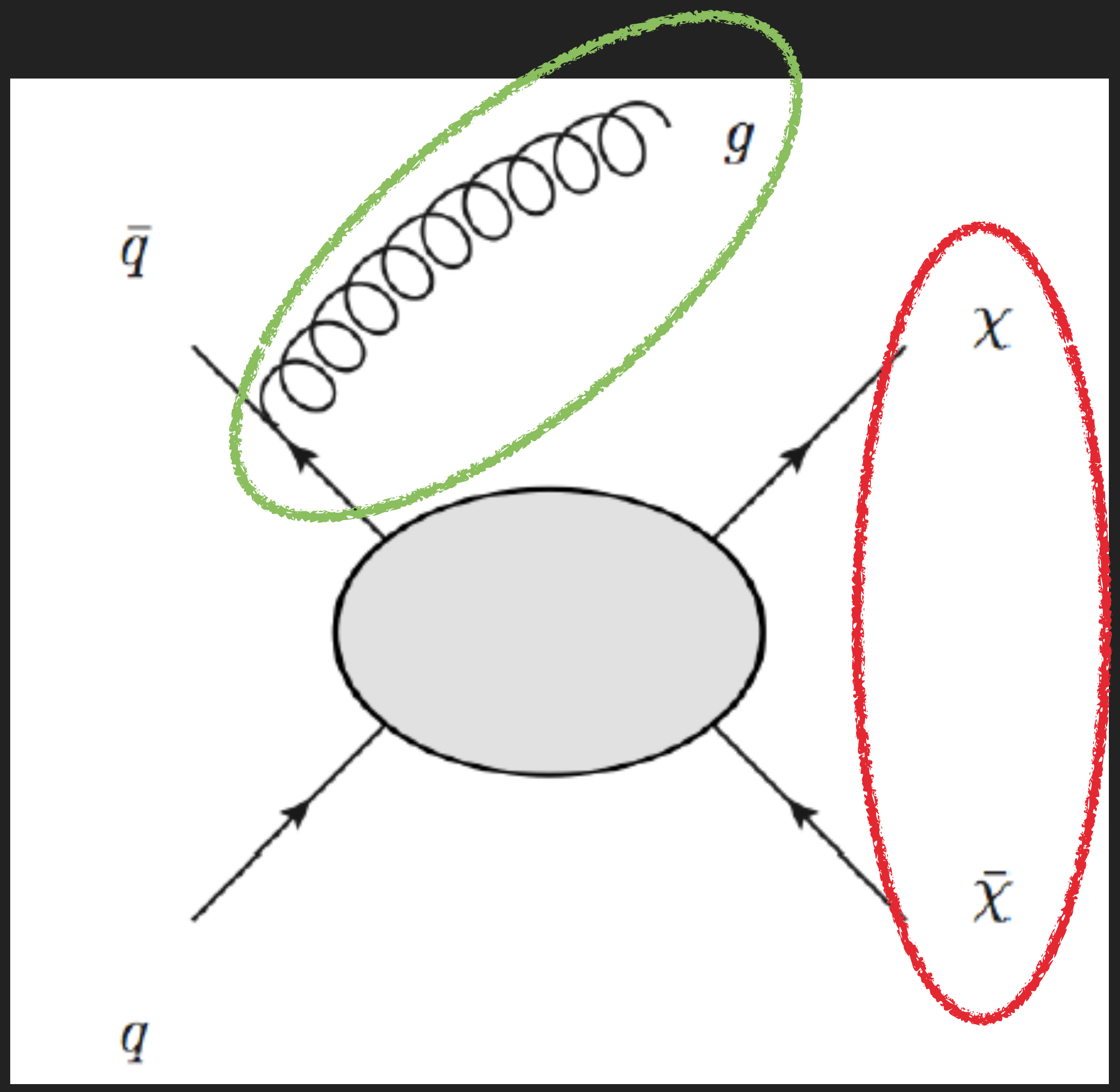
- If DM is made of BSM particles which interact weakly with SM particles, then couldn't it be possible to produce some in pp collisions at the LHC?

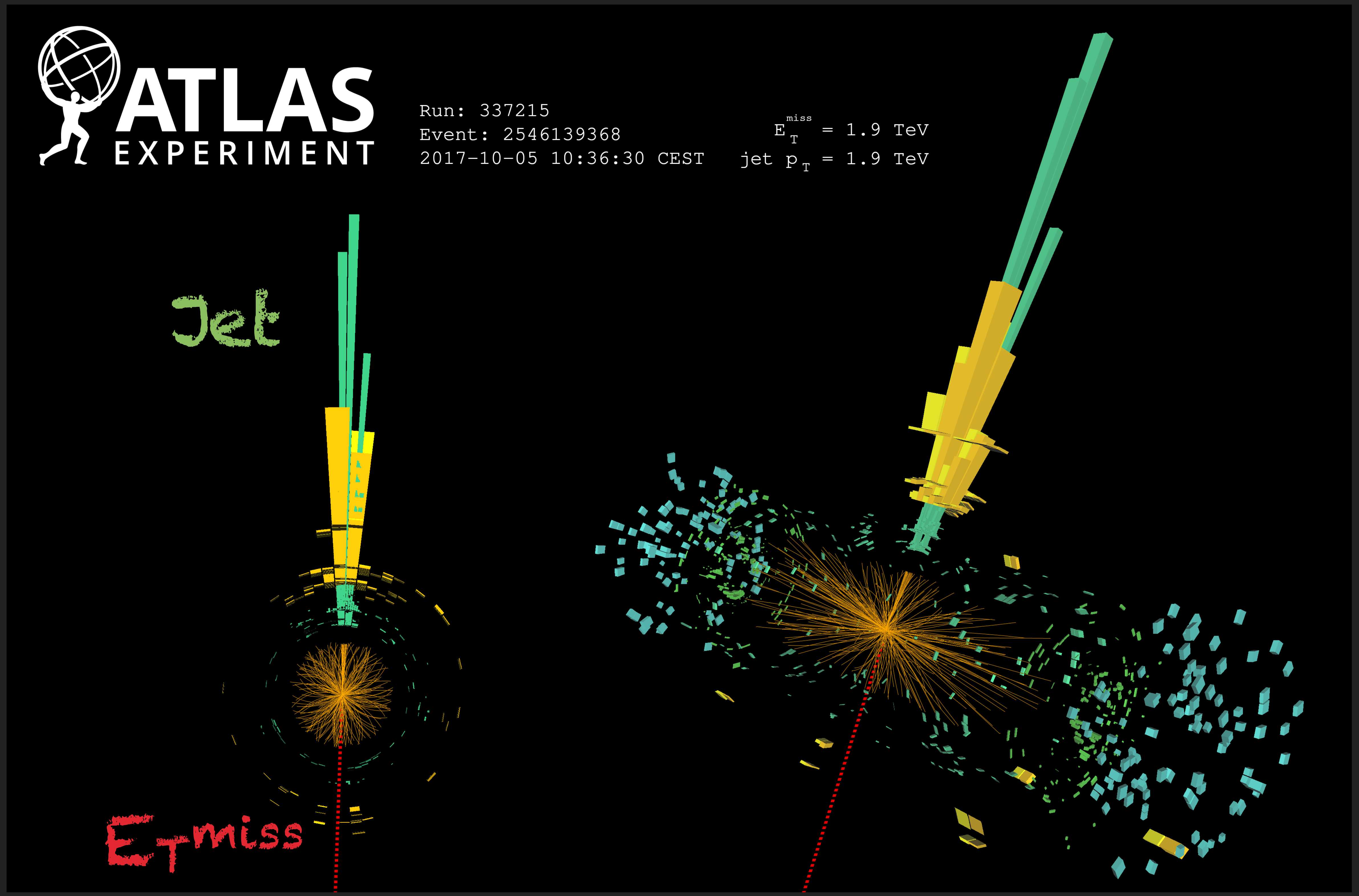


How can we even know this event occurred? Untriggerable?

SEARCHING FOR A DM CANDIDATE AT THE LHC

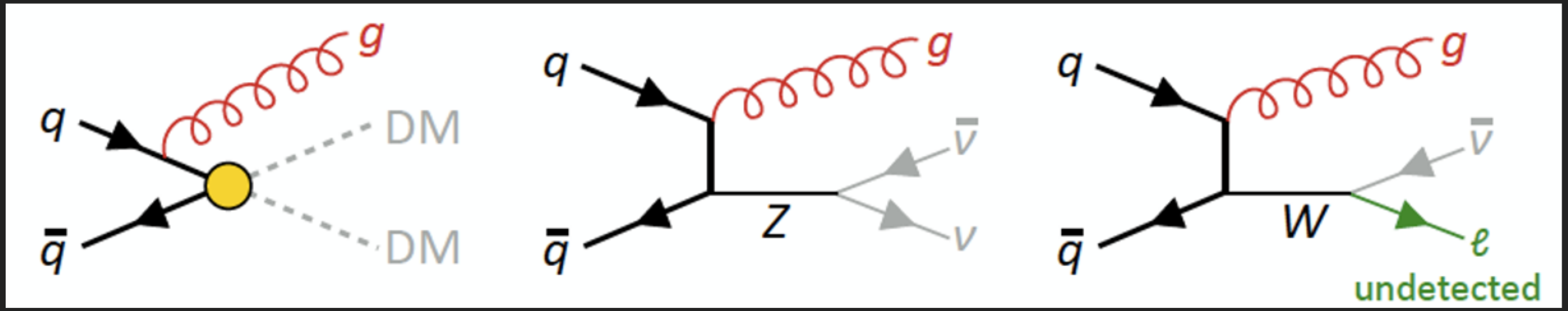
- Need to rely on the visible presence of other objects produced along DM
  - First example: initial-state radiation => observable object which allows to compute a missing transverse momentum … « mono-jet » analysis





JET+E_T^{MISS} ANALYSIS

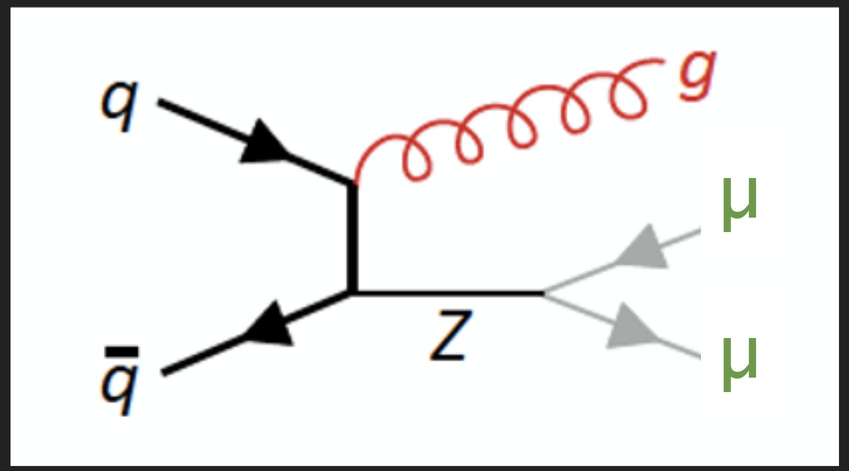
- Trigger based on ETmiss : high threshold (removes the dominant QCD multi-jet BG)
- At least one energetic jet in the events (allow some more, eg up to 4 in ATLAS)
- Veto on the presence of other objects (μ, e, τ, or γ)
- Require a large azimuthal angle between the leading jet(s) and the direction of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

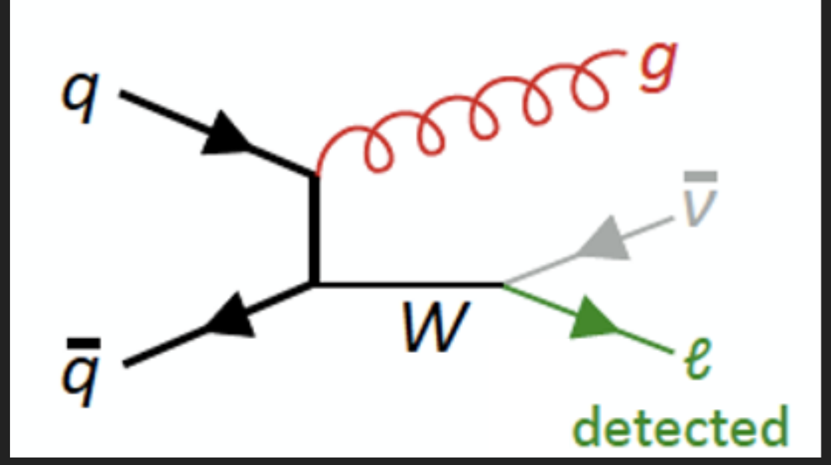


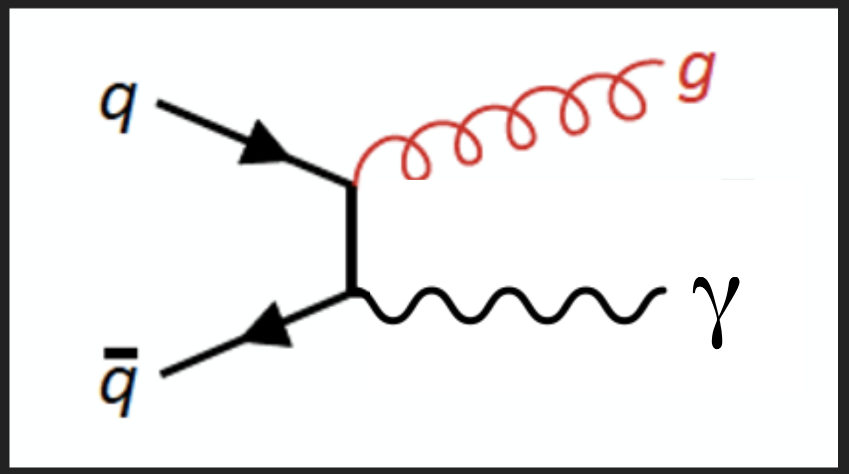
Signal Irreducible Reducible

Main BG

Normalise predictions in control regions with leptons or photon:

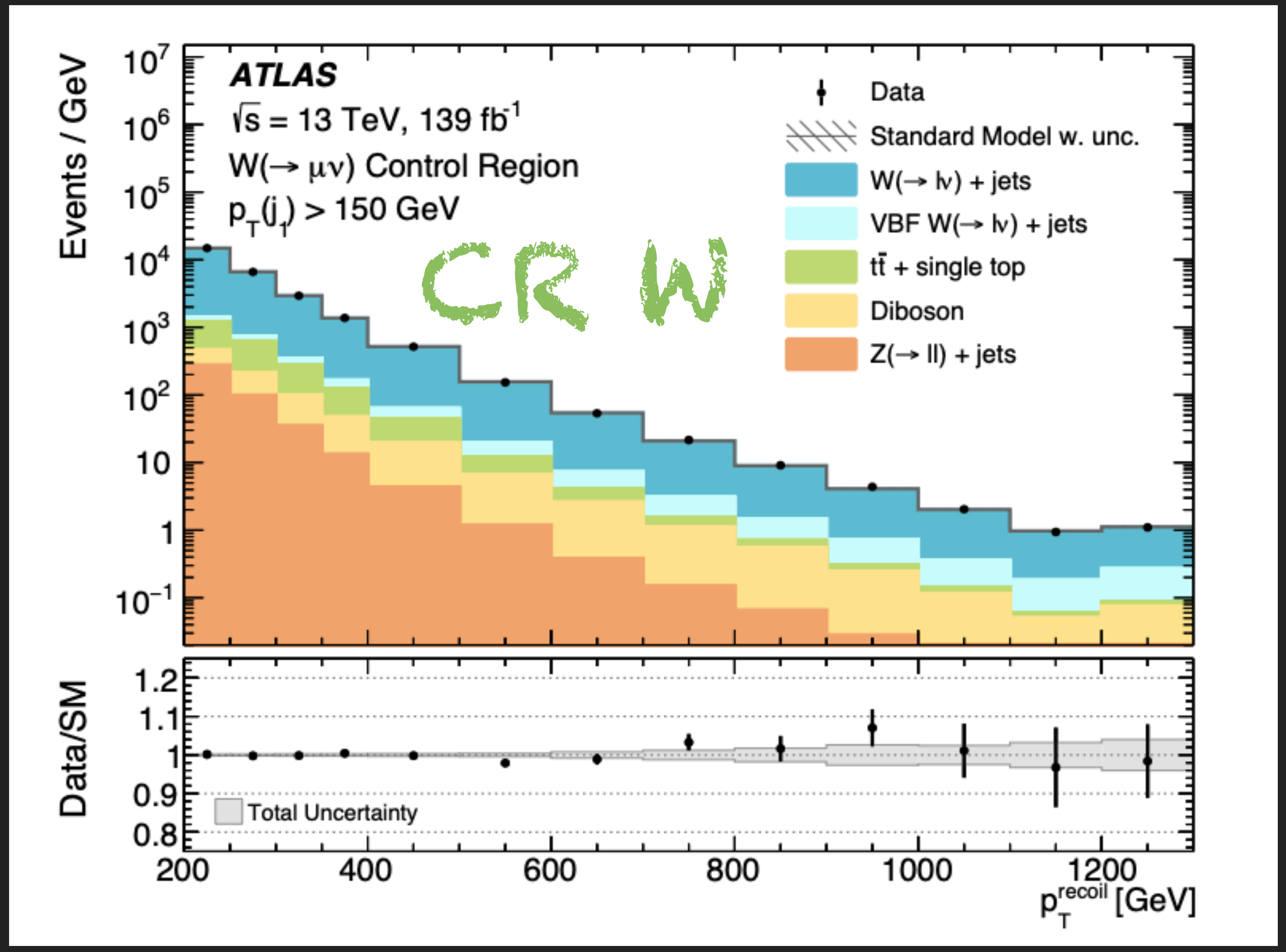


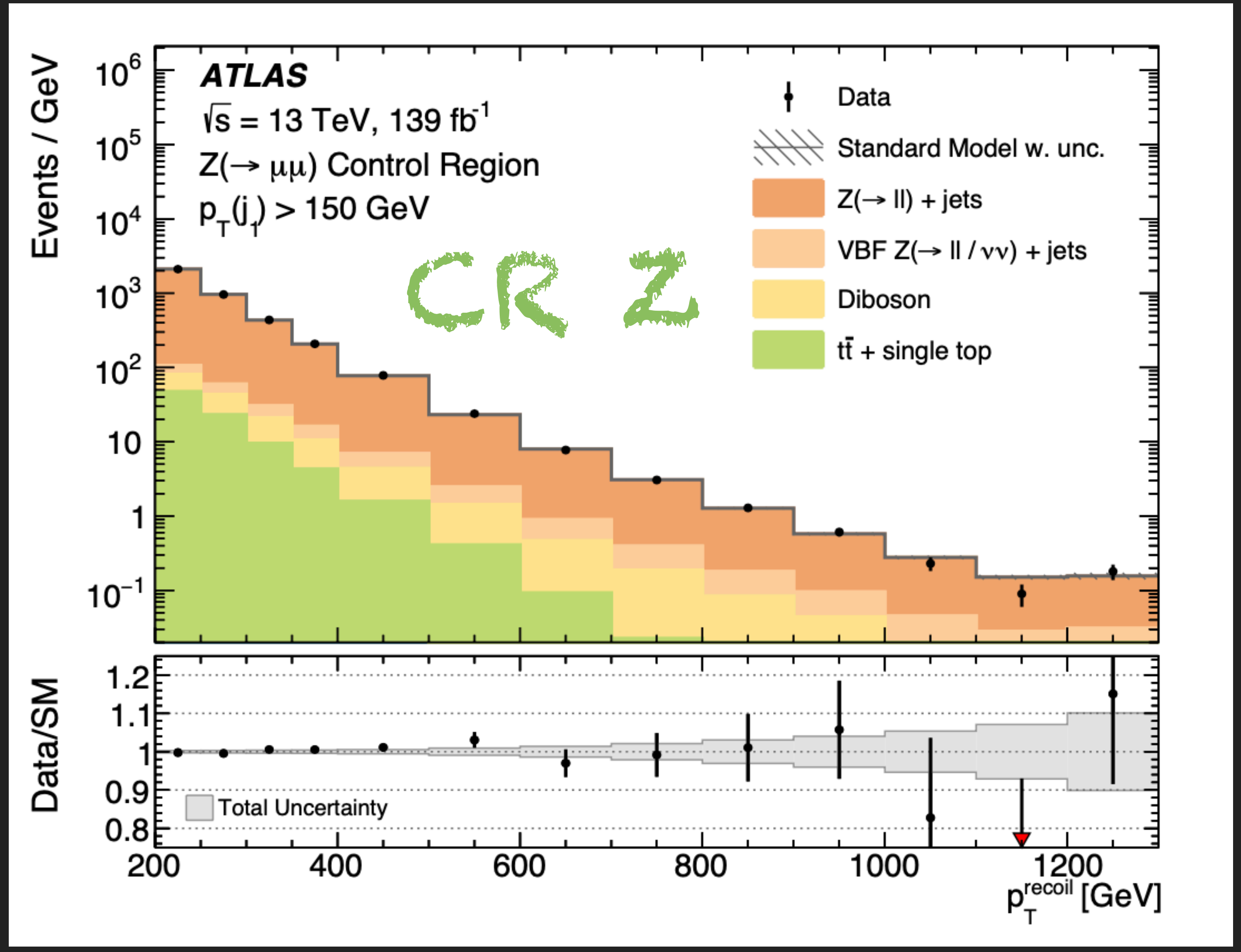


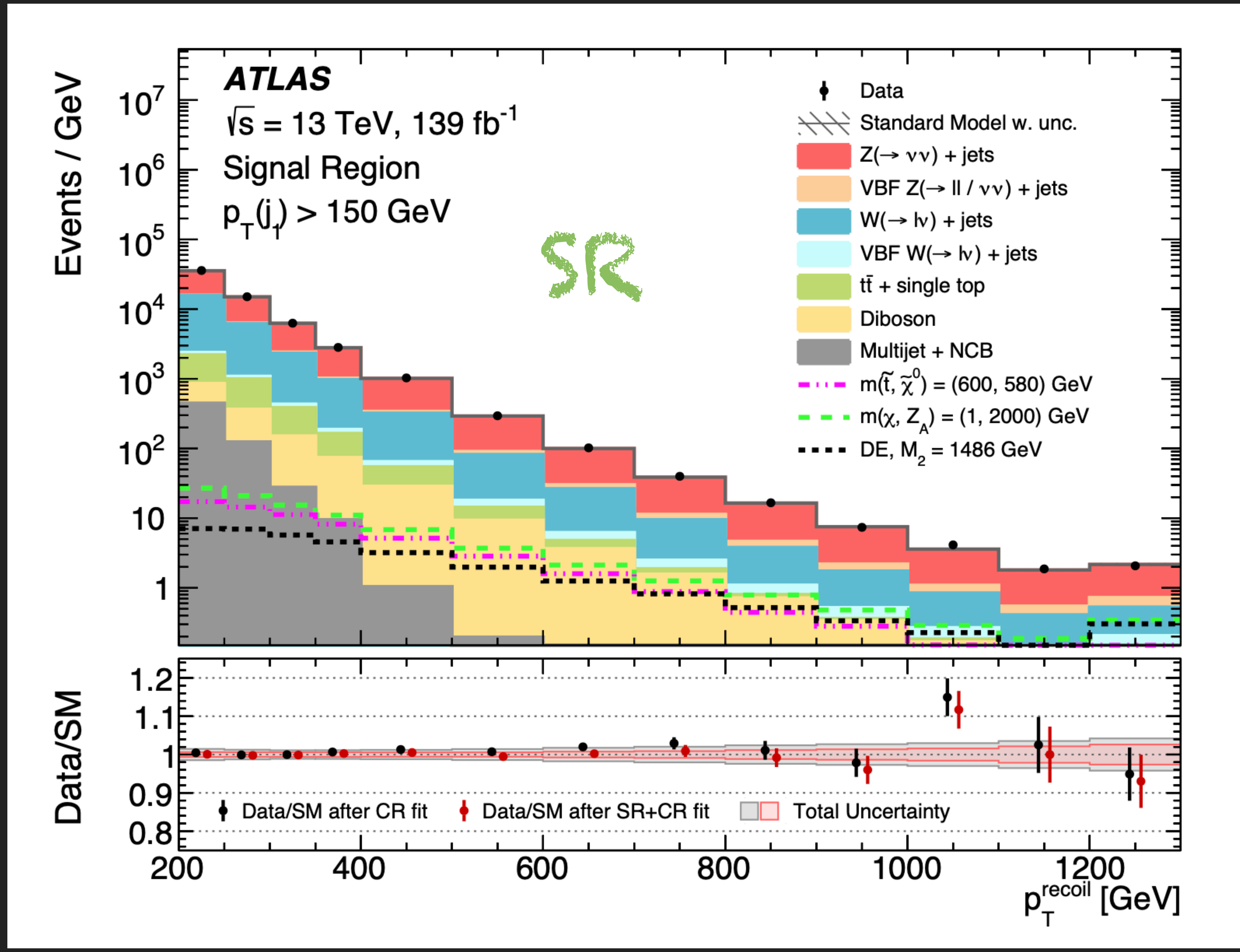


JET+E_T^{MISS} IN ATLAS

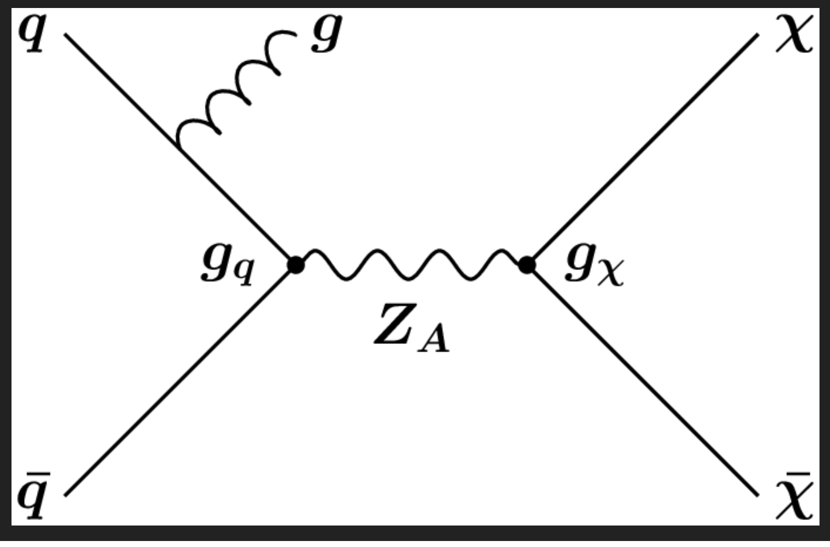
Phys. Rev. D 103, 112006 (2021)

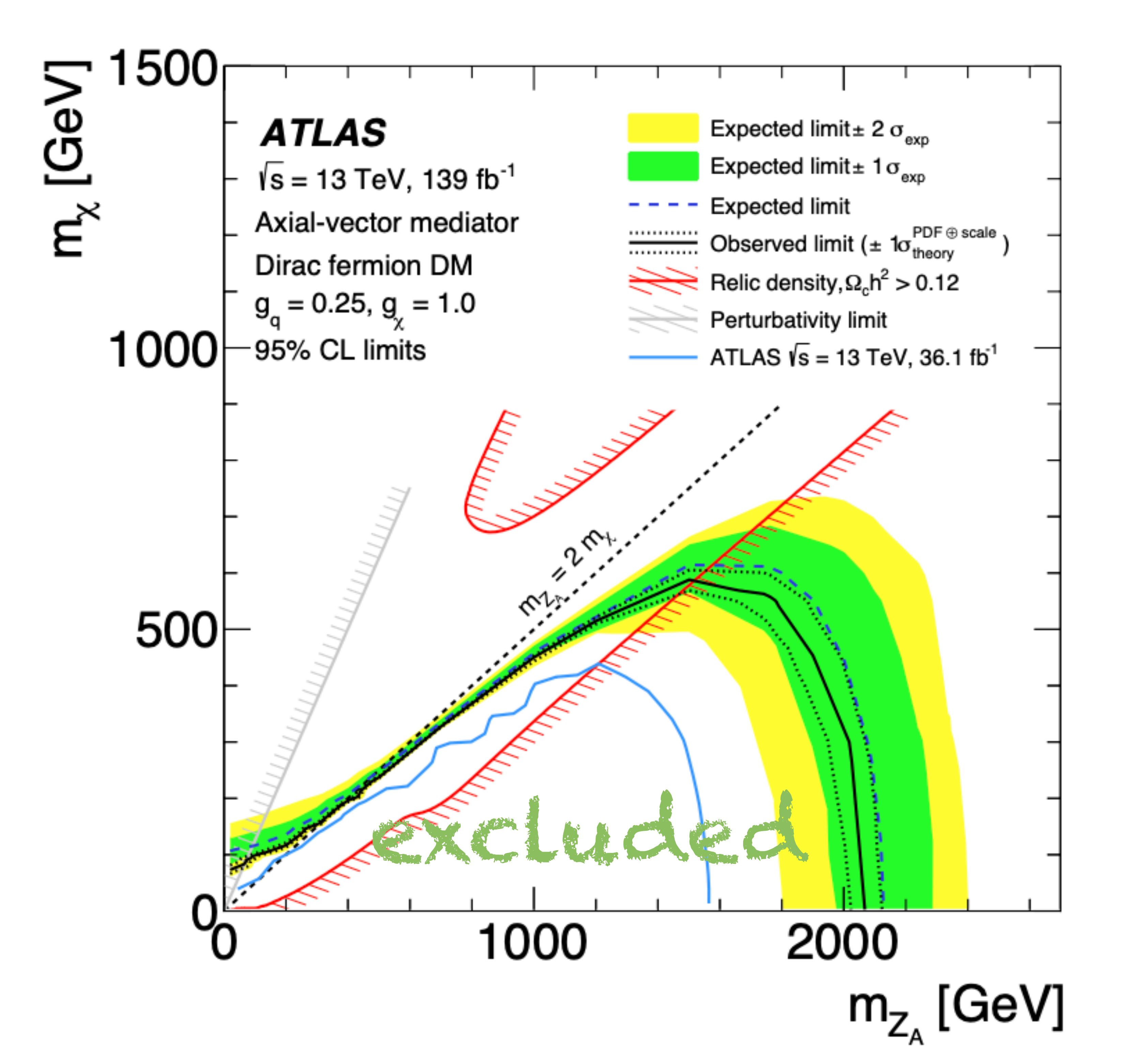






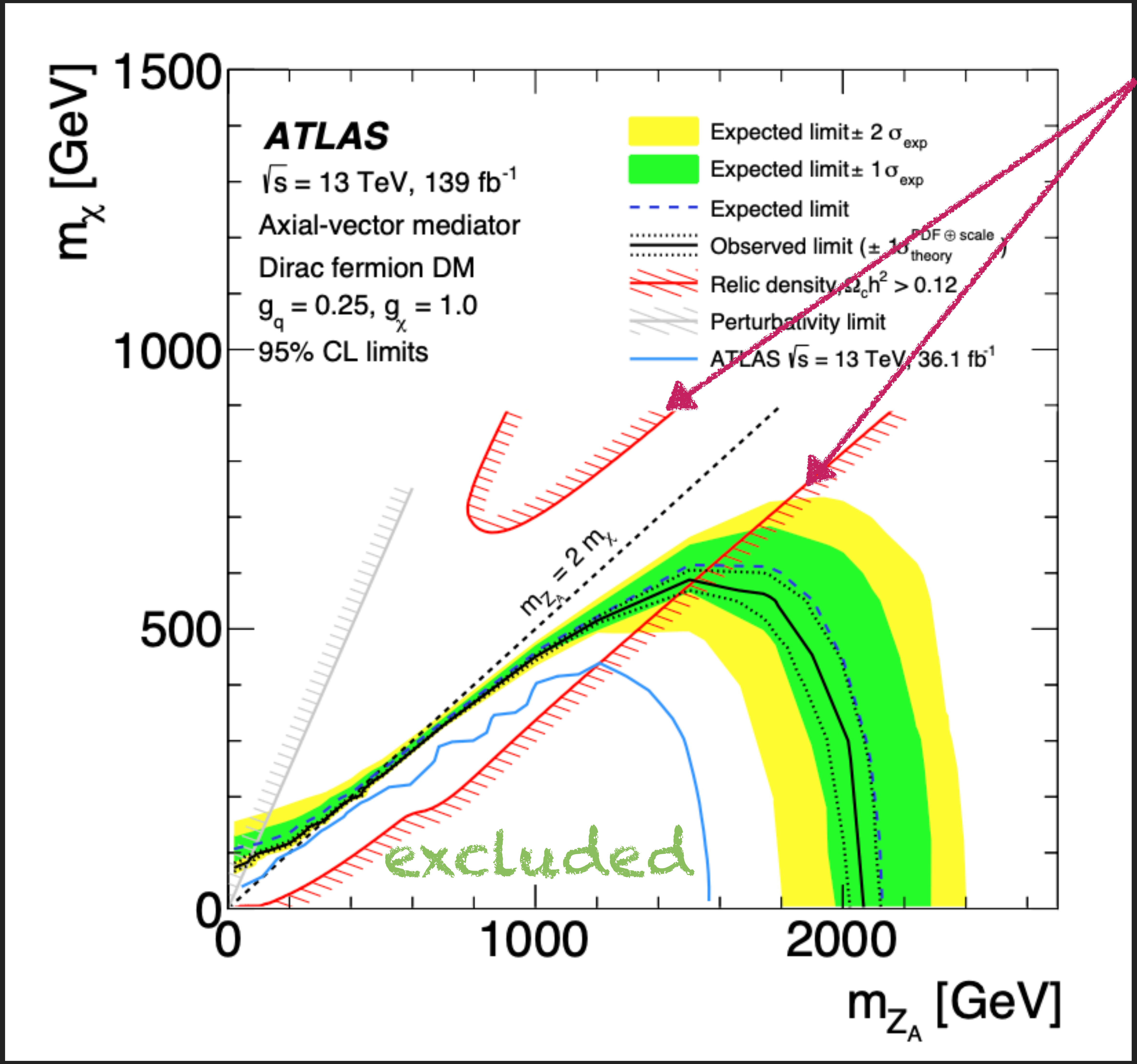
Interpretation in a simplified model:



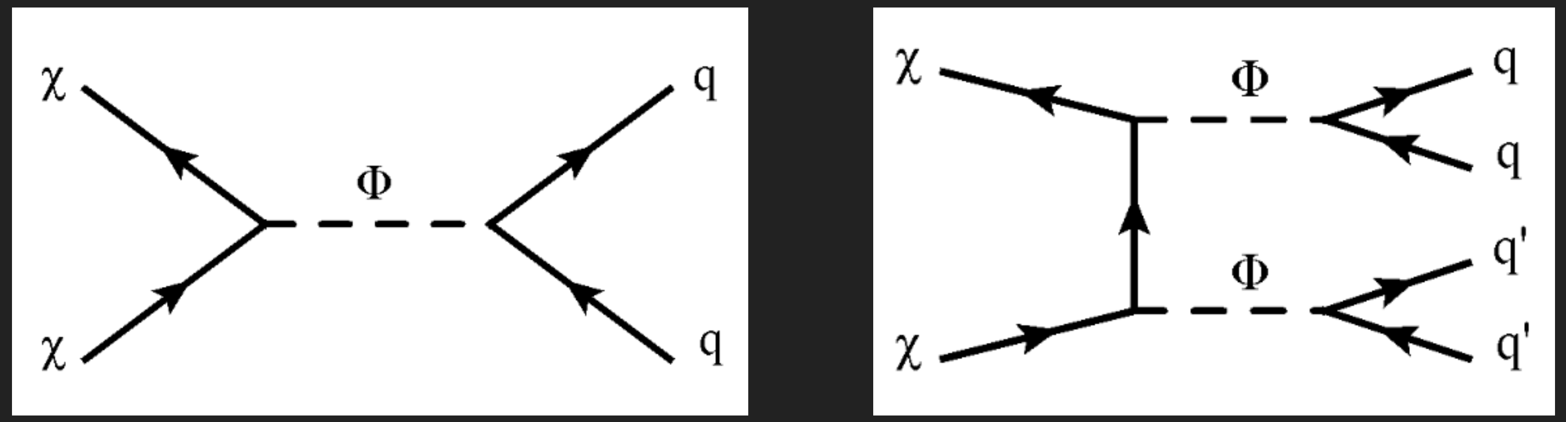


Phys.Dark Univ. 26 (2019) 100377

A CLOSER LOOK AT THE EXCLUSION PLOT



Relic density lines:

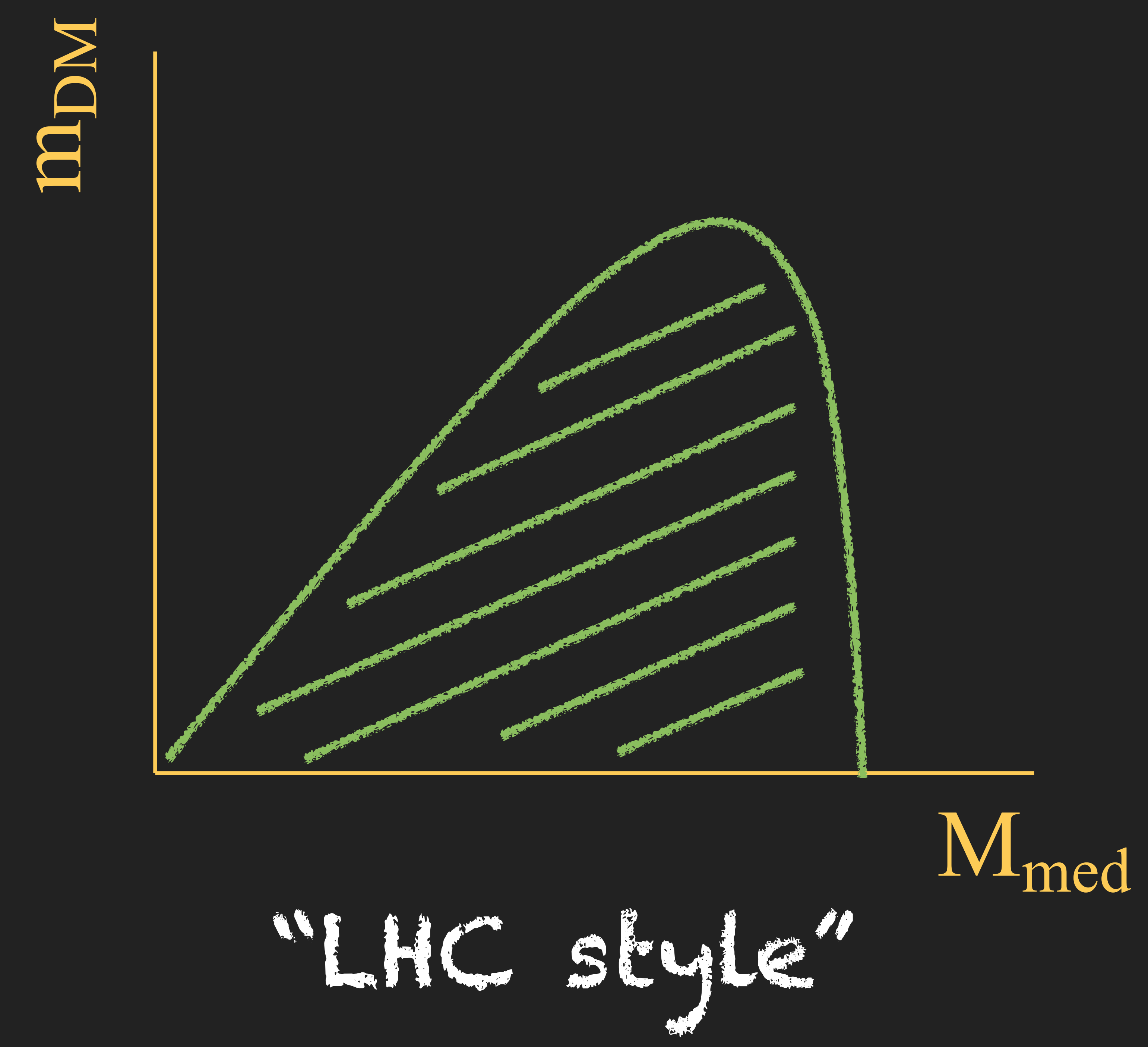


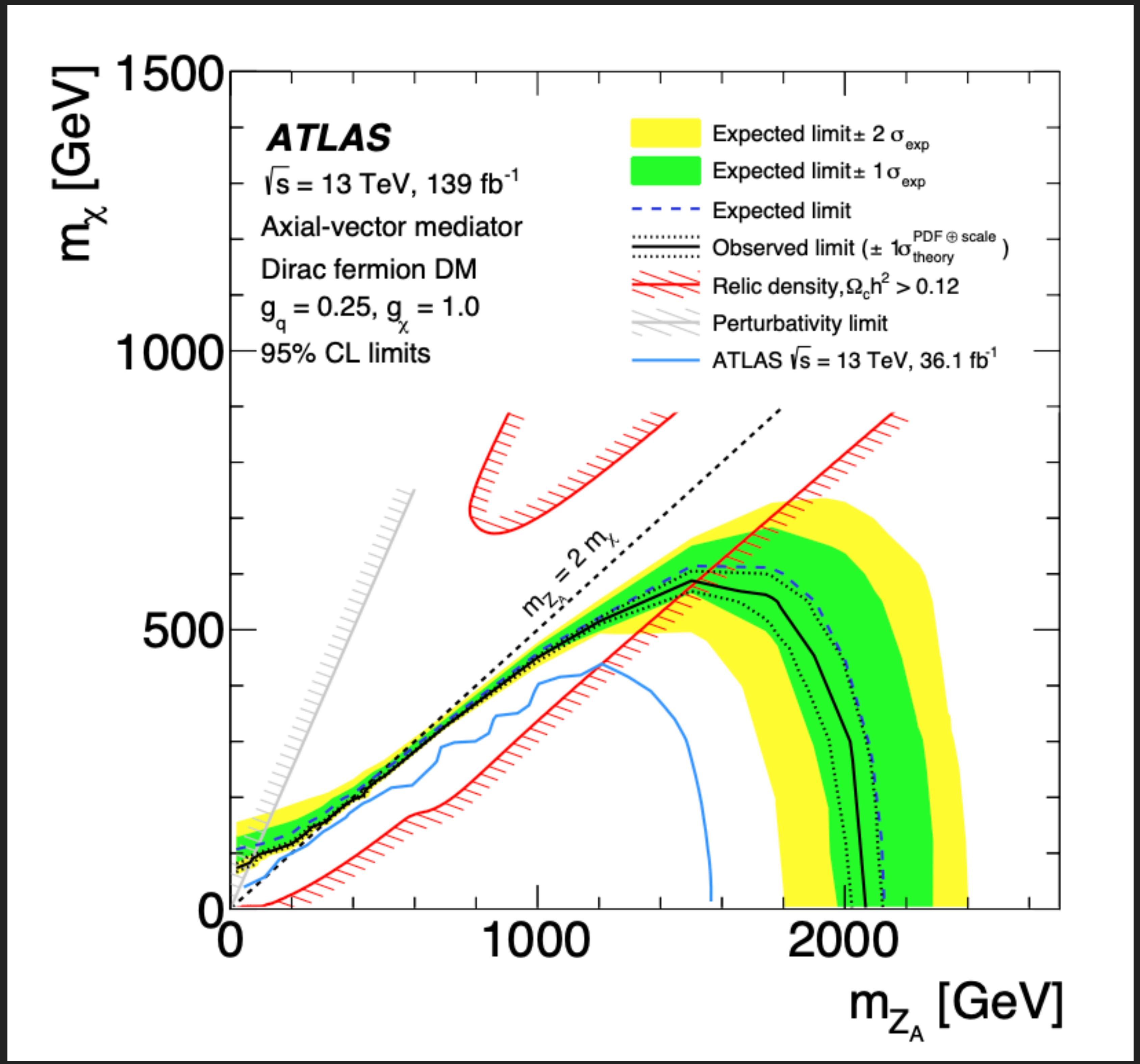
Outside these lines in the plane, the relic density is greater than the one measured

This should not be taken ***too*** seriously, as this is a simplified model:

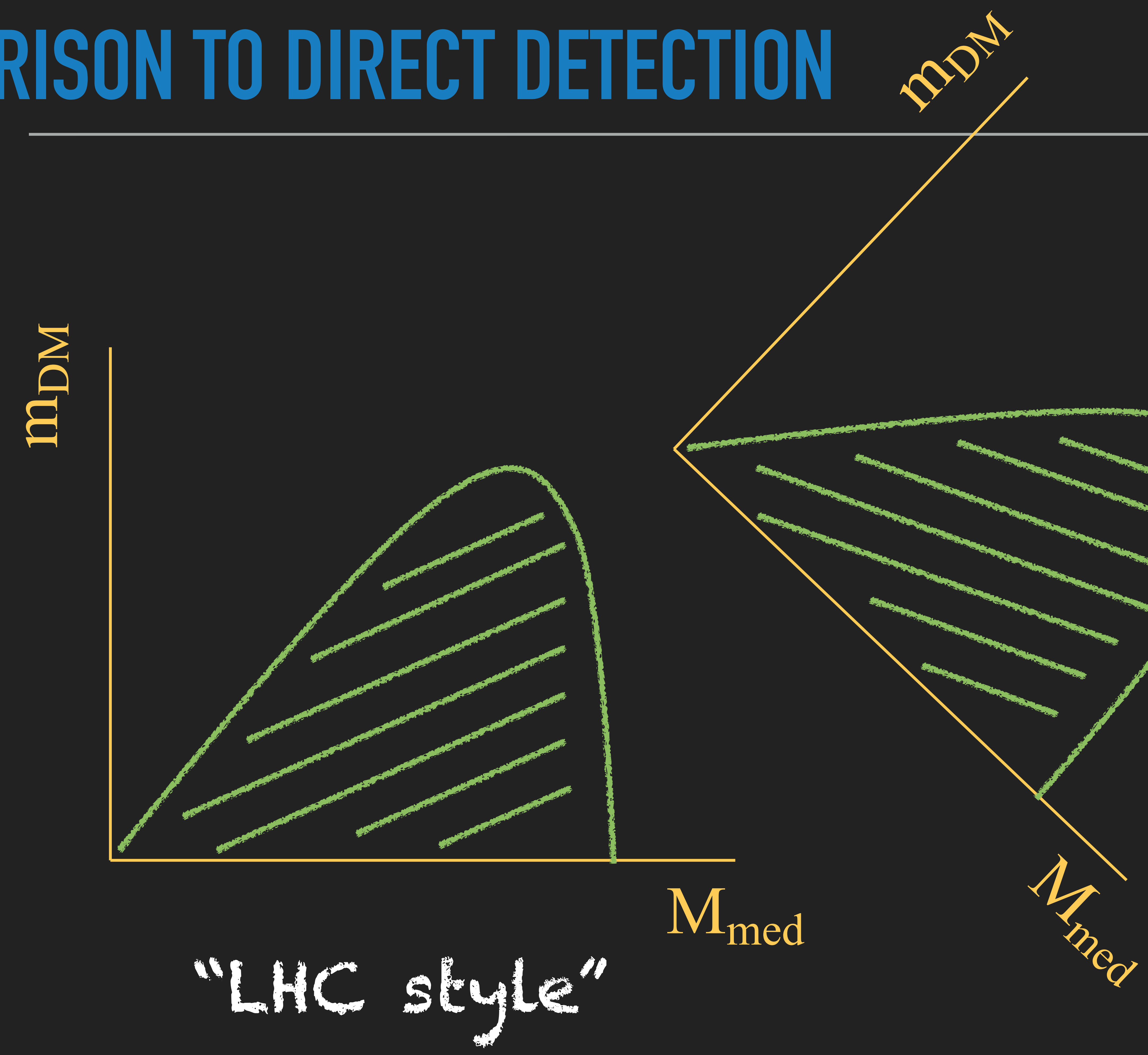
Even if nature has chosen such a mediator and DM, there might well be other new particles in a UV complete theory, ie other processes changing the annihilation rate in the early universe!

COMPARISON TO DIRECT DETECTION

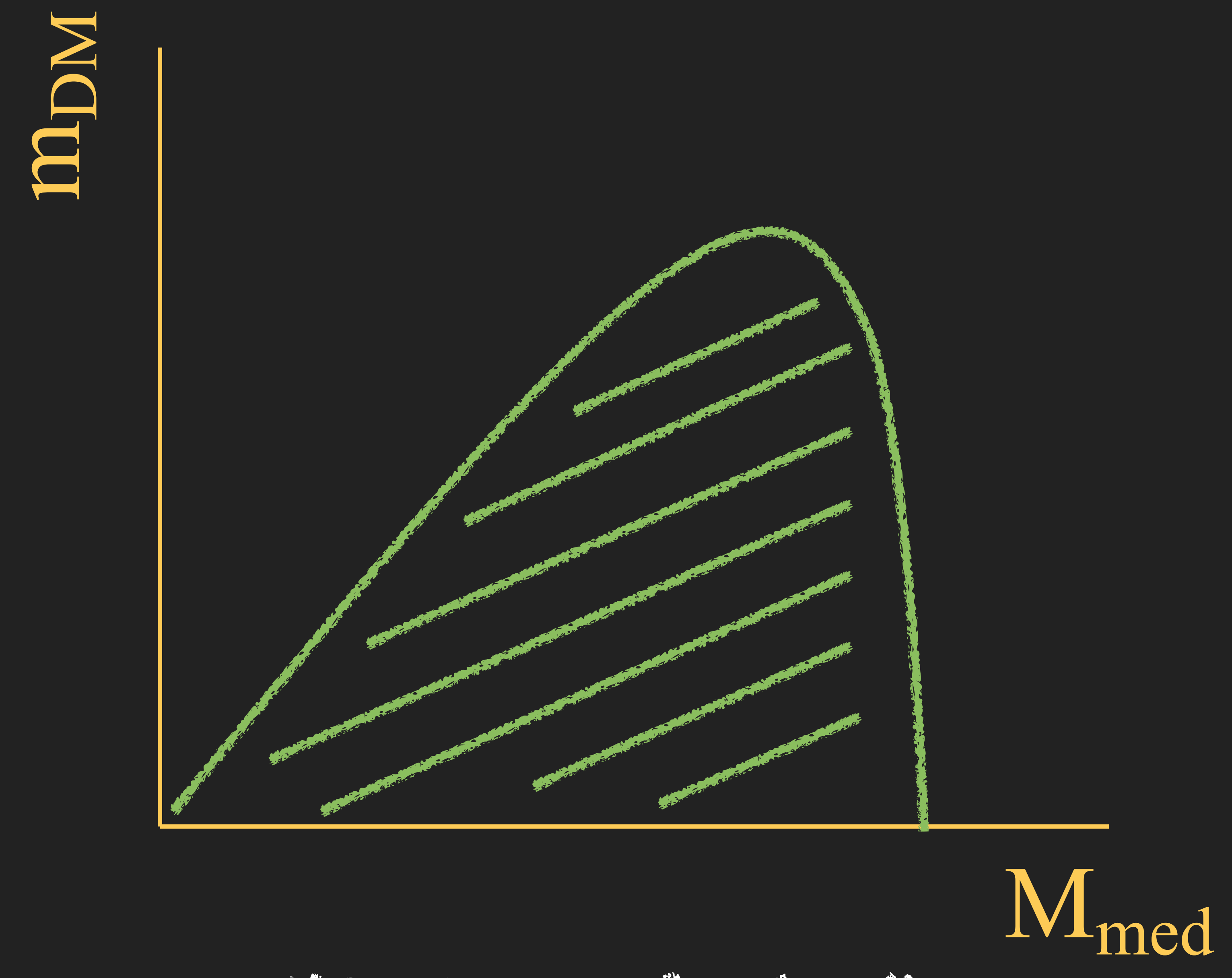




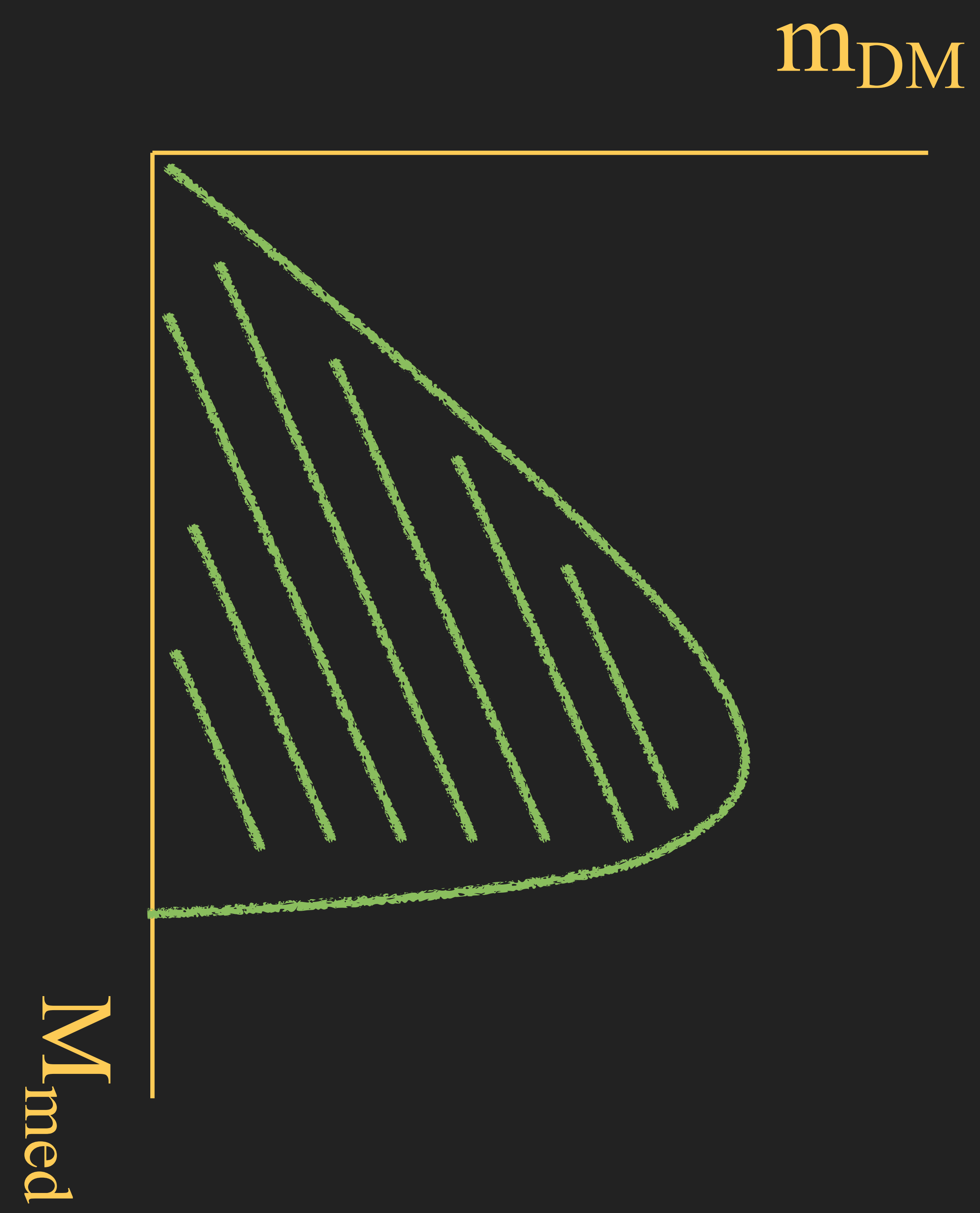
COMPARISON TO DIRECT DETECTION



COMPARISON TO DIRECT DETECTION

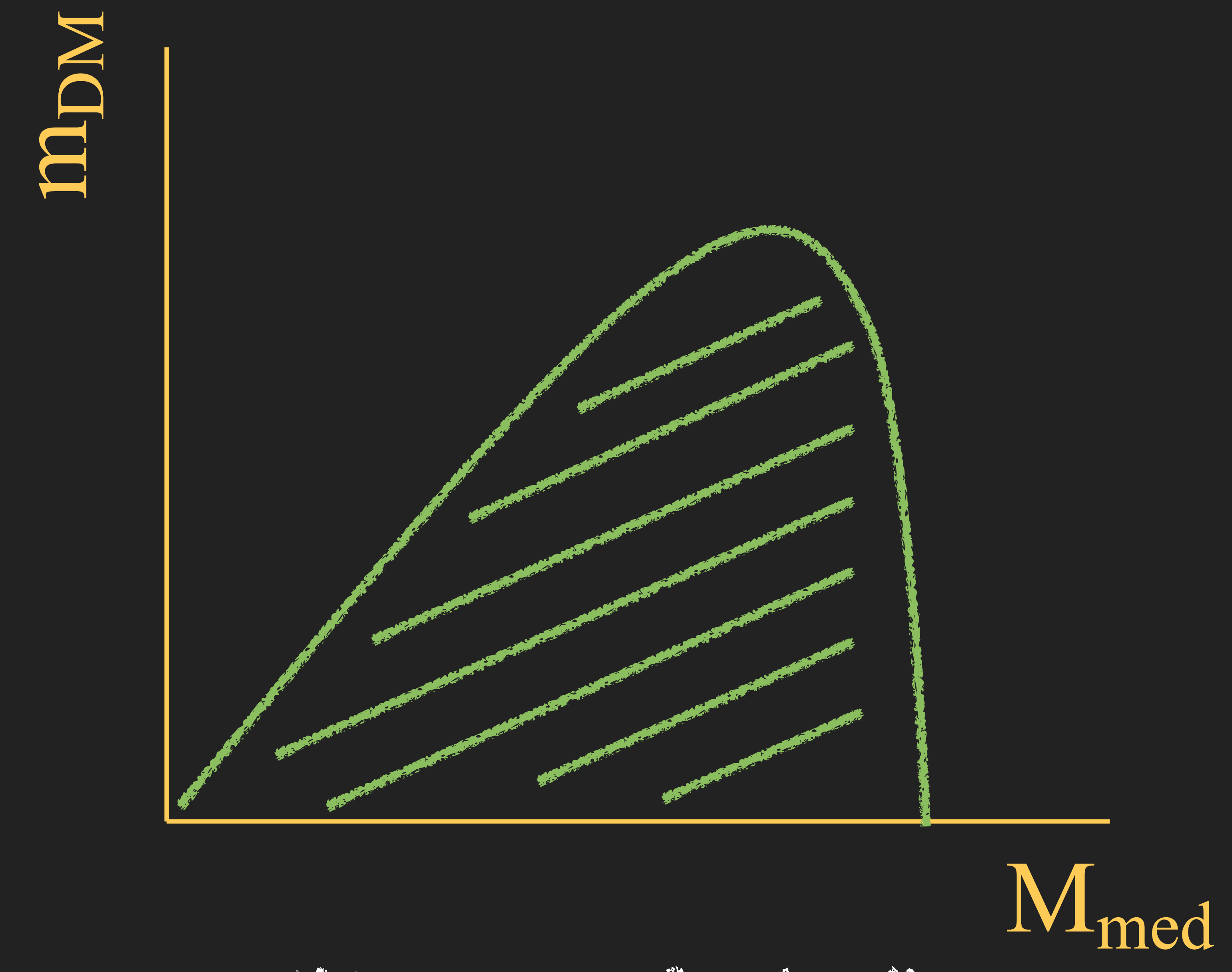


"LHC style"



Phys.Dark Univ. (2019) 100365

COMPARISON TO DIRECT DETECTION



"LHC style"

"Direct-detection style"

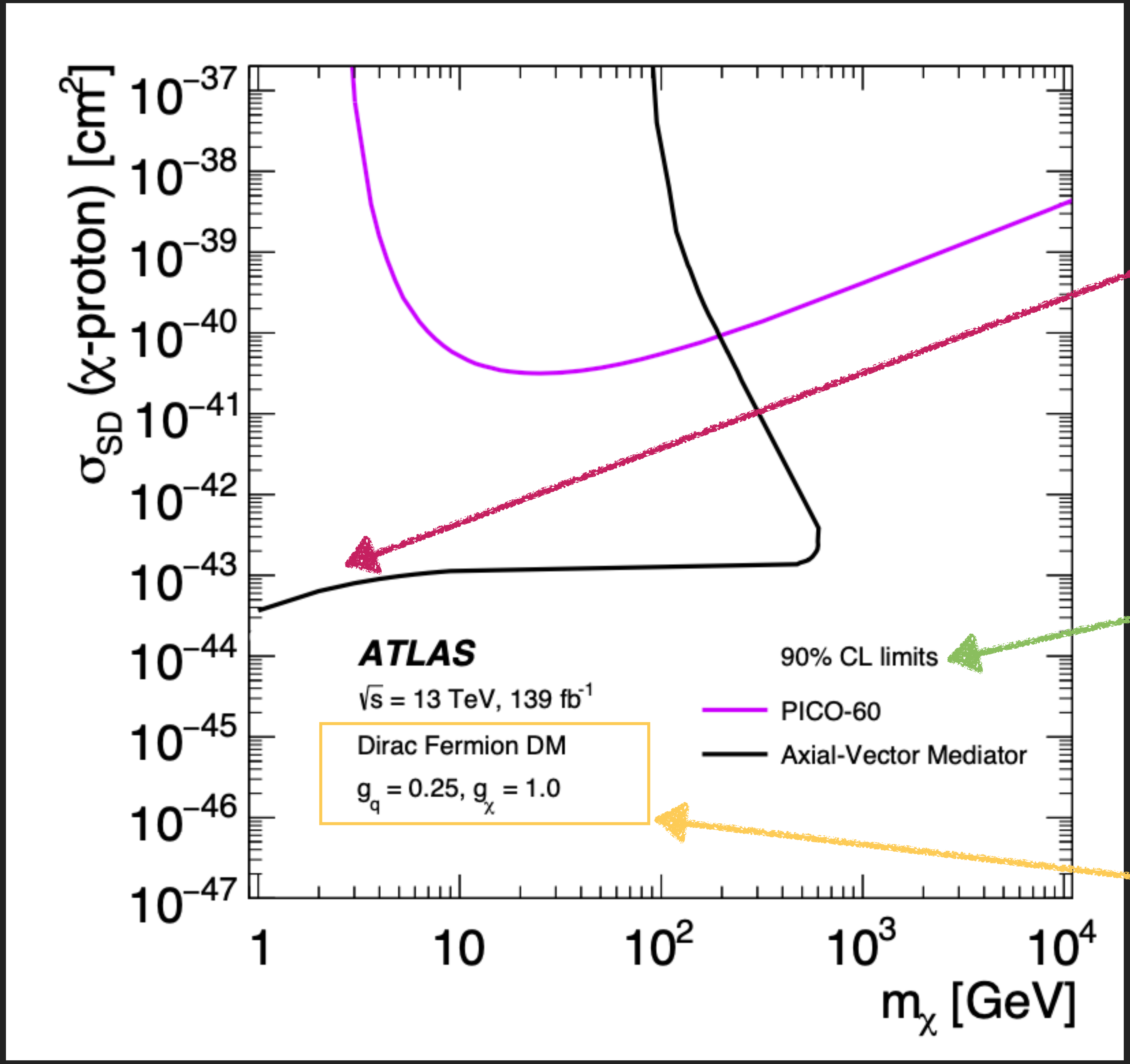
For vector or axial-vector mediators:

$$\sigma_{SI} \simeq 6.9 \times 10^{-41}\ \text{cm}^2 \cdot \left(\frac{g_q g_{DM}}{0.25}\right)^2 \left(\frac{1\,\text{TeV}}{M_{med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\,\text{GeV}}\right)^2$$

$$\sigma^{SD} \simeq 2.4 \times 10^{-42}\ \text{cm}^2 \cdot \left(\frac{g_q g_{DM}}{0.25}\right)^2 \left(\frac{1\,\text{TeV}}{M_{med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\,\text{GeV}}\right)^2$$

Phys. Rev. D 103, 112006 (2021)

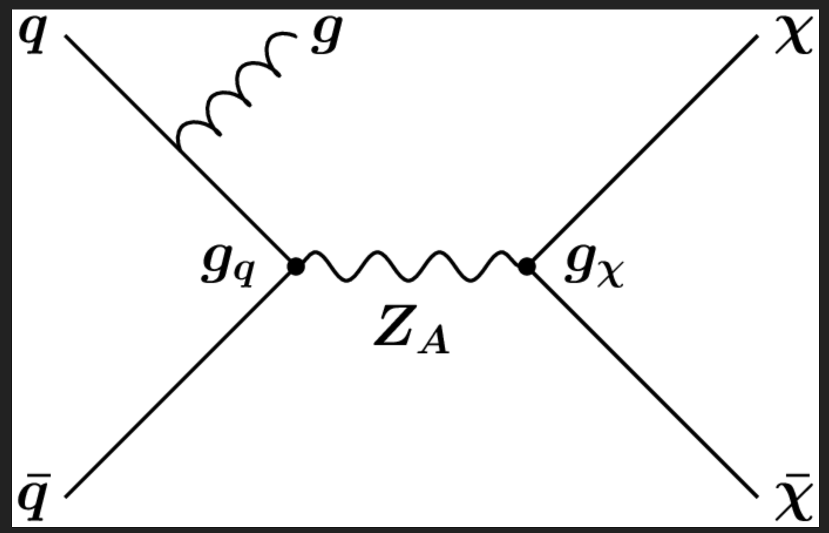
COMPARISON TO DIRECT DETECTION: AN EXAMPLE



The LHC is able to probe the very low masses (they are easy to produce!) … a region difficult to access for DD experiments …

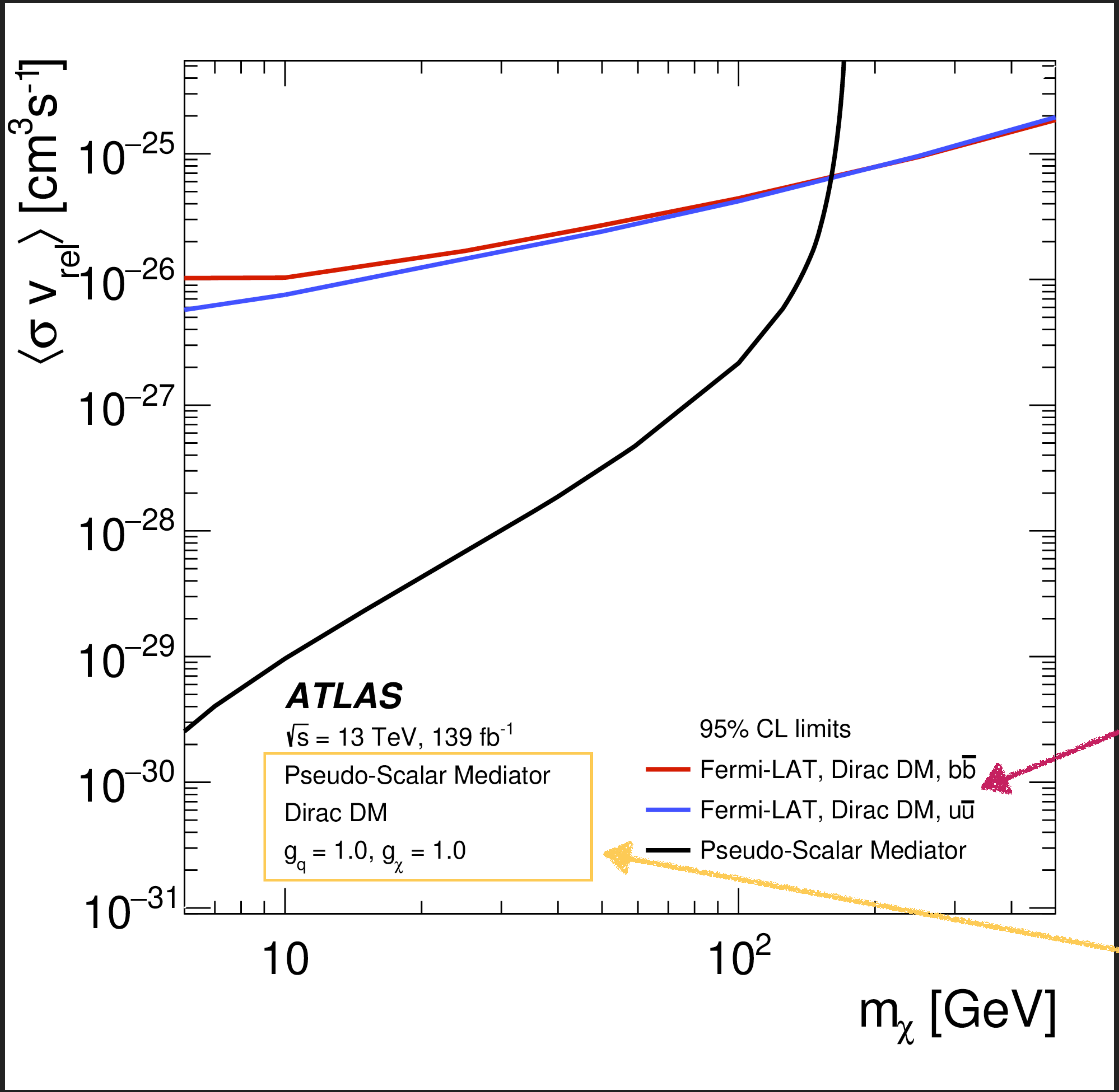
90% CL limits to compare to DD!

But one must remember the assumption of the model considered…



Phys.Dark Univ. (2019) 100365
Phys. Rev. D 103, 112006 (2021)

COMPARISON TO INDIRECT DETECTION: AN EXAMPLE



Ex: translation of the limit into an annihilation cross section for quarks for a pseudoscalar mediator:

$$\langle \sigma v_{\rm rel} \rangle_q = \frac{3 m_q^2}{2\pi v^2} \frac{g_q^2 g_{\rm DM}^2 m_{\rm DM}^2}{(M_{\rm med}^2 - 4 m_{\rm DM}^2)^2 + M_{\rm med}^2 \Gamma_{\rm med}^2} \sqrt{1 - \frac{m_q^2}{m_{\rm DM}^2}}$$

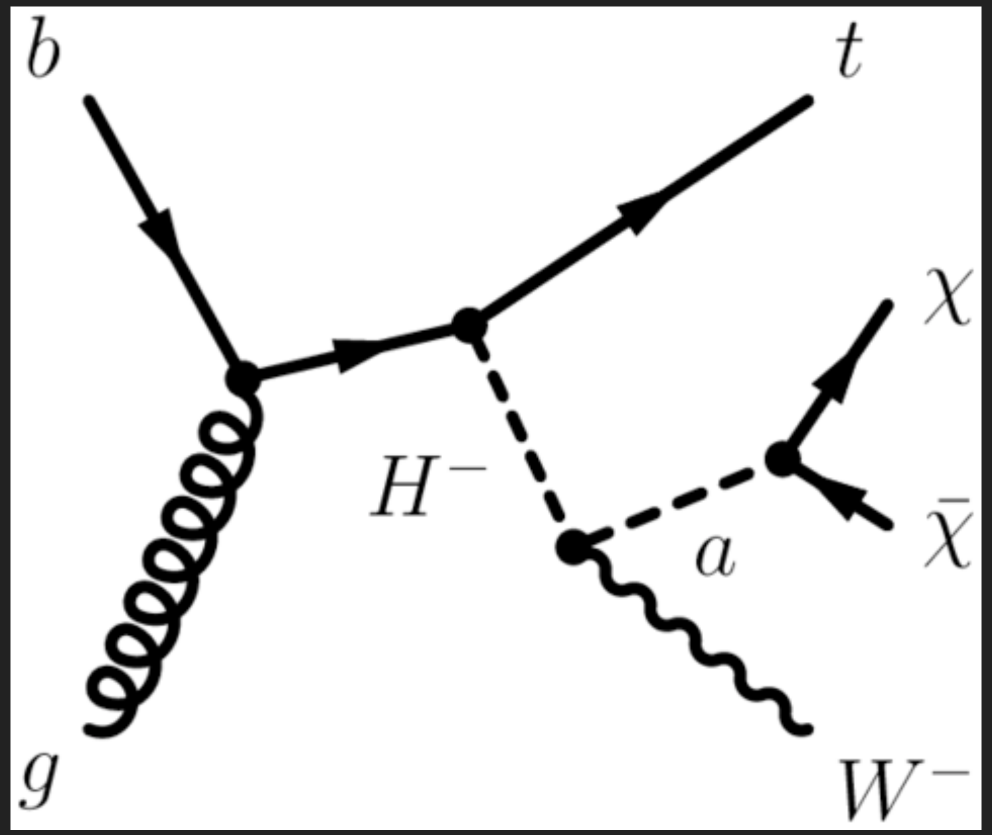
Assumption: Majorana (ID) vs Dirac (LHC) DM assumed - factor of 2

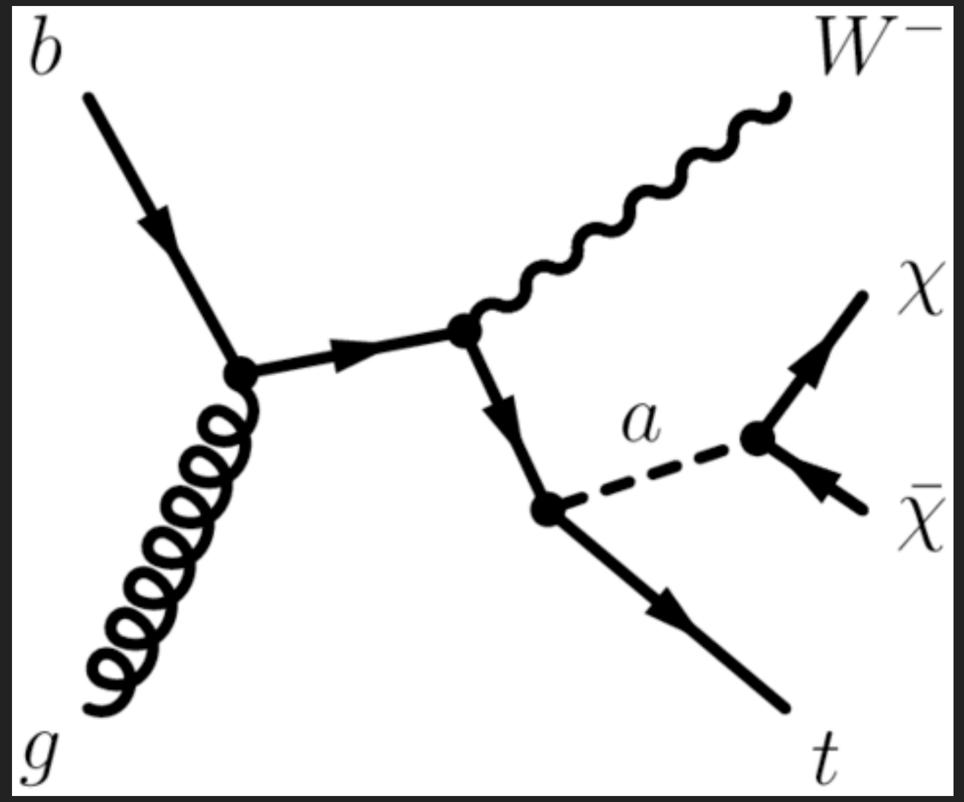
But one must remember the assumption of the model considered.

Theory: JHEP05(2017)138

A PSEUDOSCALAR MEDIATOR?

- Pseudoscalar mediator: avoid constraints from DM direct detection (vanishing in the low-velocity limit which applies for $v/c=10^{-3}$)
- Simplest gauge-invariant and renormalisable extension of simplified pseudoscalar model: 2HDM *(h, H, H±, 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^{miss} final state:

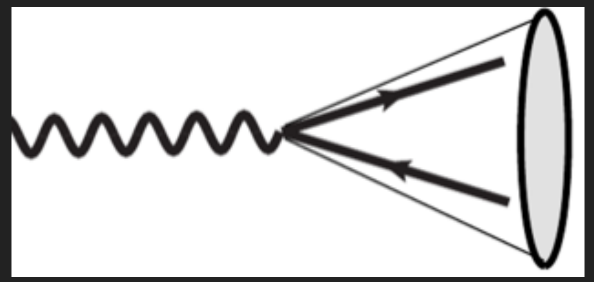




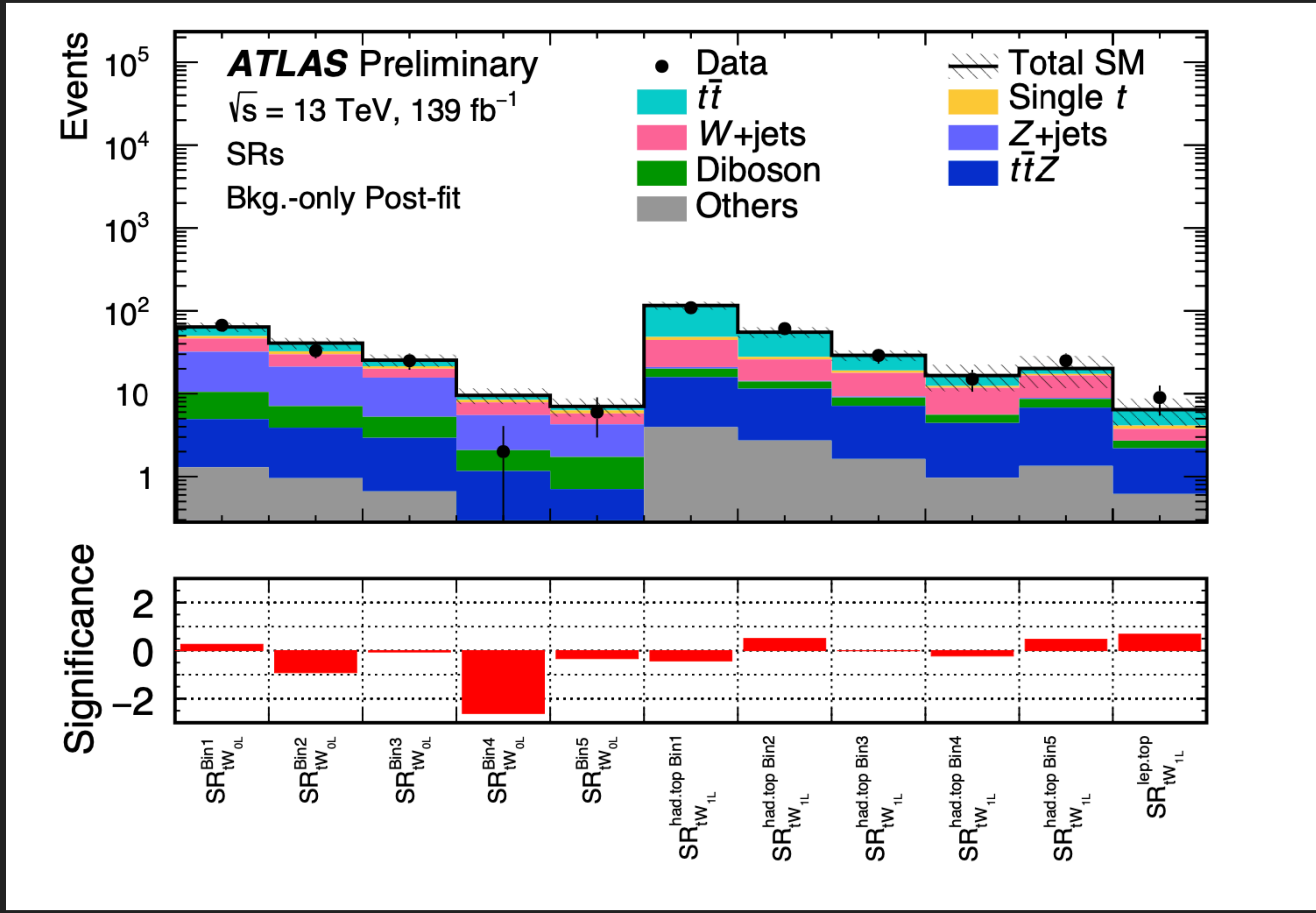
ATLAS-CONF-2022-012

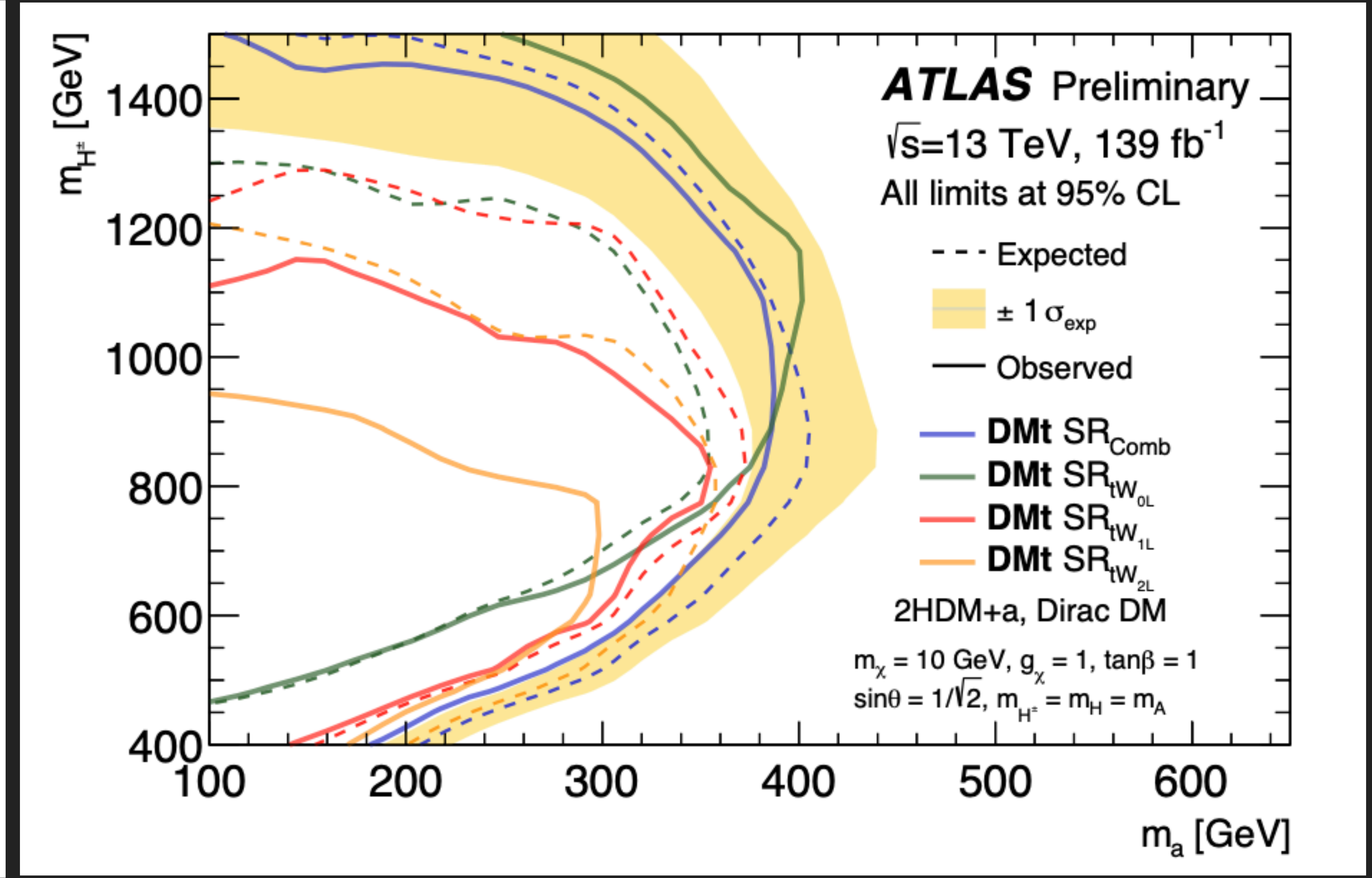
ATLAS WT+E_T^{MISS}

- E_T^{miss} for triggering + final discriminant, require ≥1 b-tagged jet
- 0 lepton + ≥ 4 small-R jets + W-tagged fat jet



- 1lepton from top: ≥2 jets + W-tagged fat jet; OR from W: ≥ 3 jets



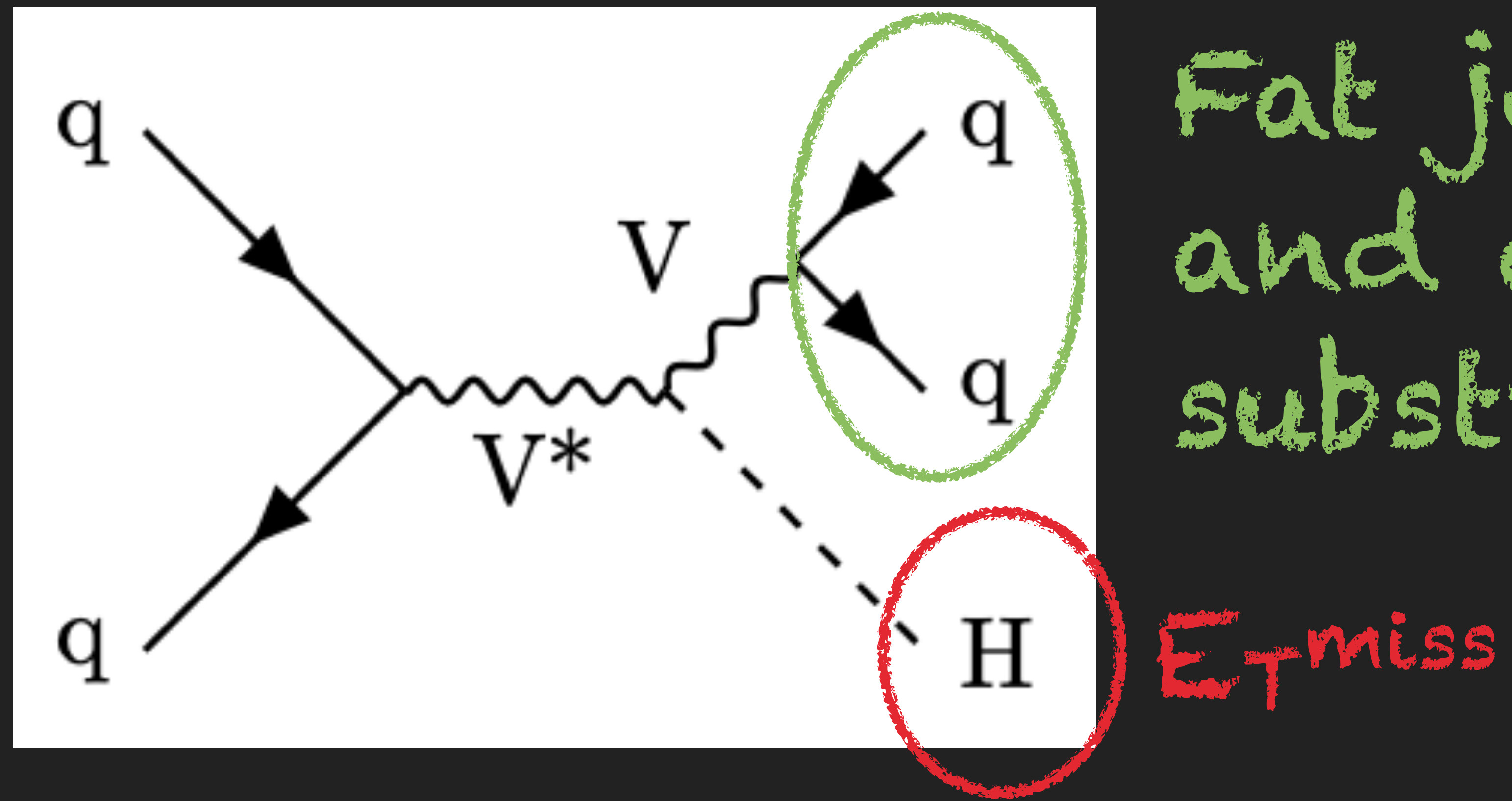


JHEP 11 (2021) 153

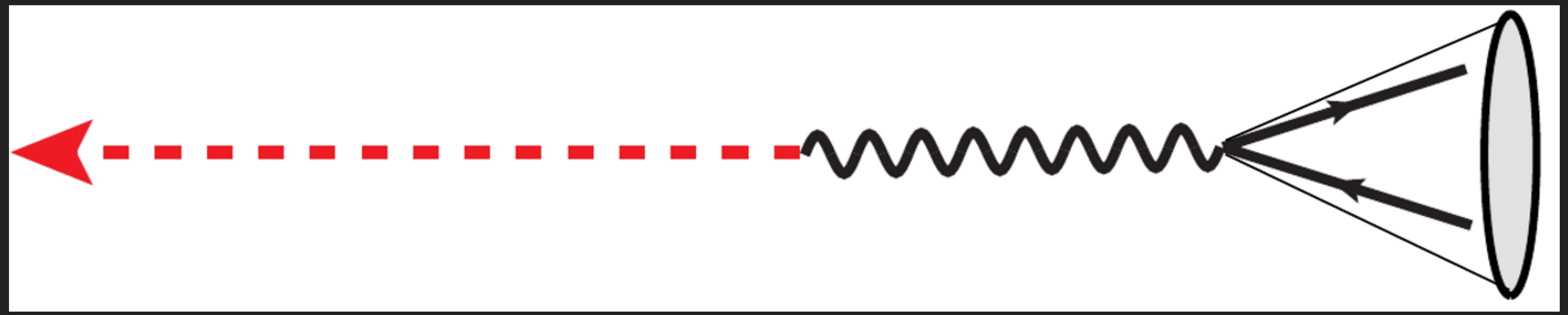
WHAT IF THE PORTAL TO DM IS SIMPLY THE HIGGS?

Also see the talk by Thomas Biekötter yesterday

- Look for a Higgs produced in association with a vector boson:



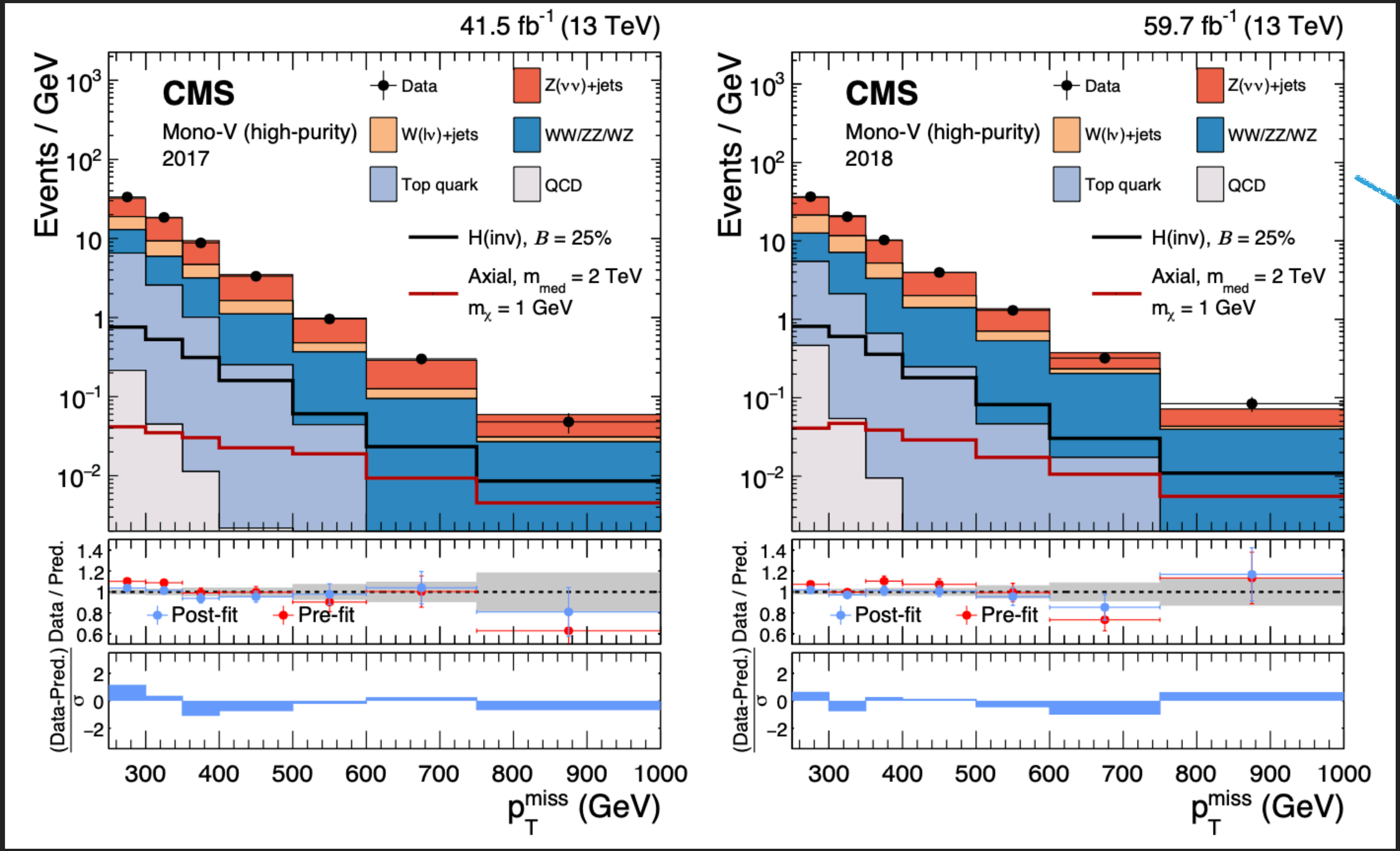
- « Mono-jet analysis » with a large ('fat') jet
- Tag the large-jet with ML techniques
  - Use jet substructure to reject QCD BG

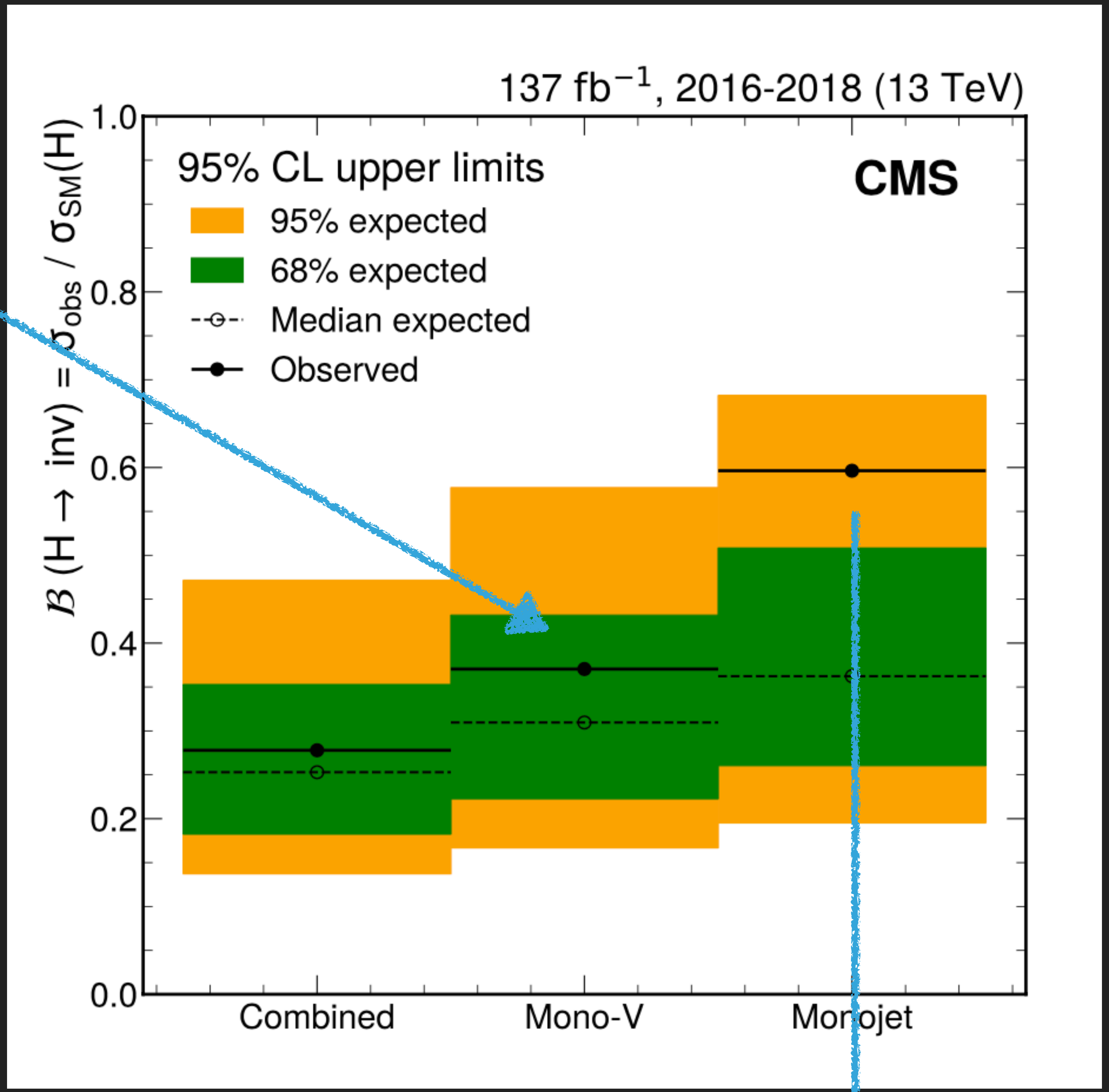


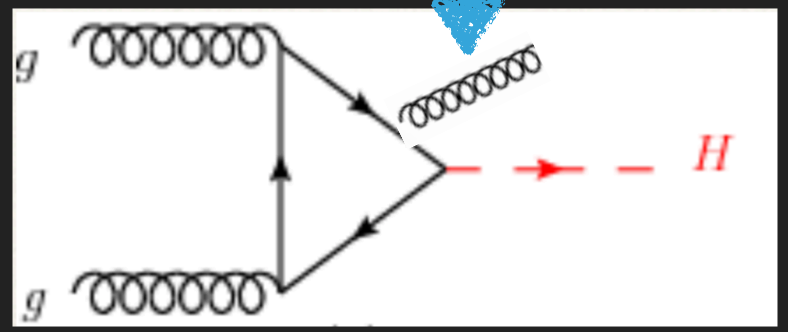
- Same idea of using the leptonic / photon CRs to estimate the SM V+jets BG

JHEP 11 (2021) 153

JET+E_T^{MISS} IN CMS

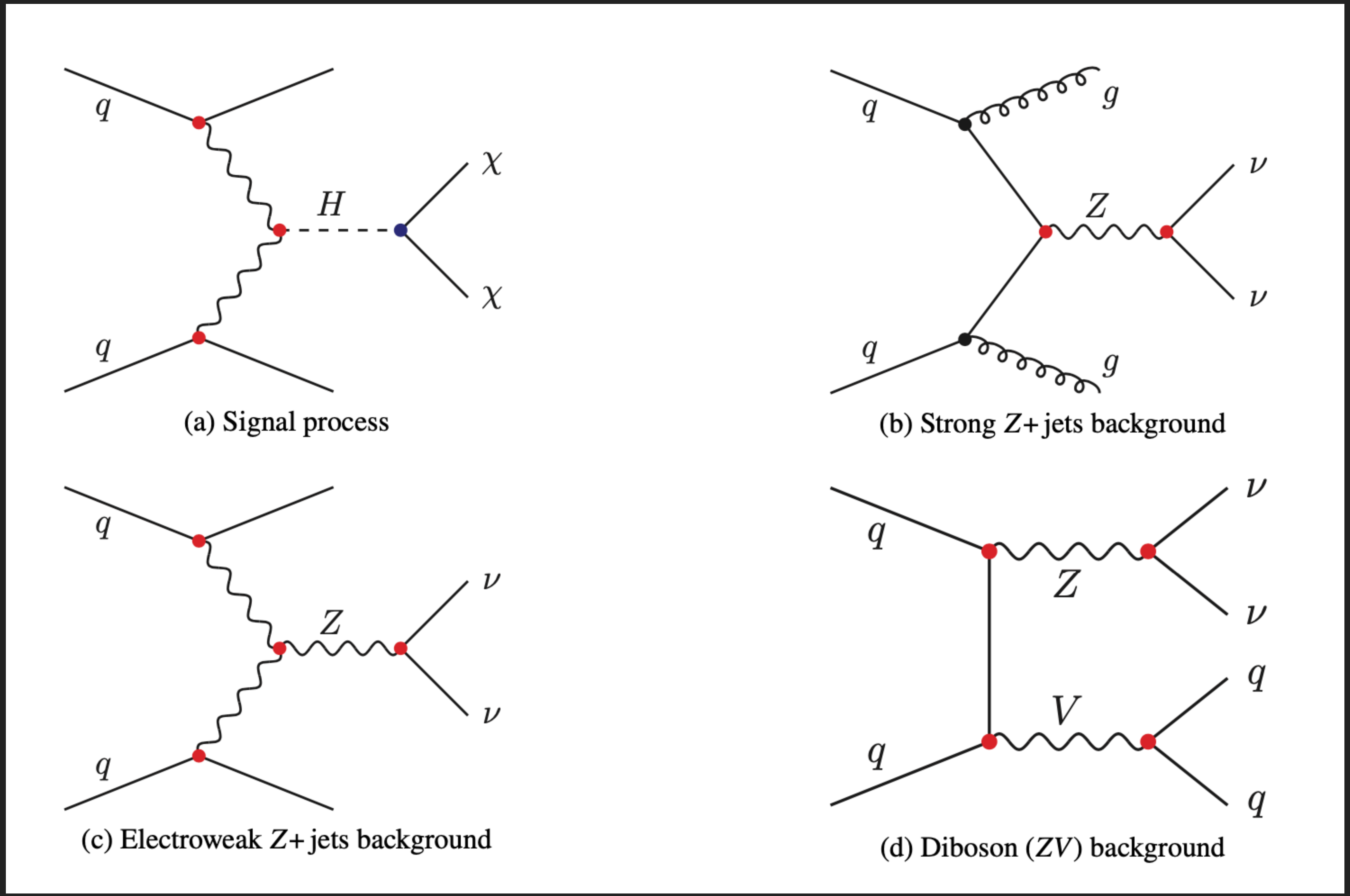






VECTOR-BOSON FUSION: THE GOLDEN CHANNEL FOR INVISIBLE H

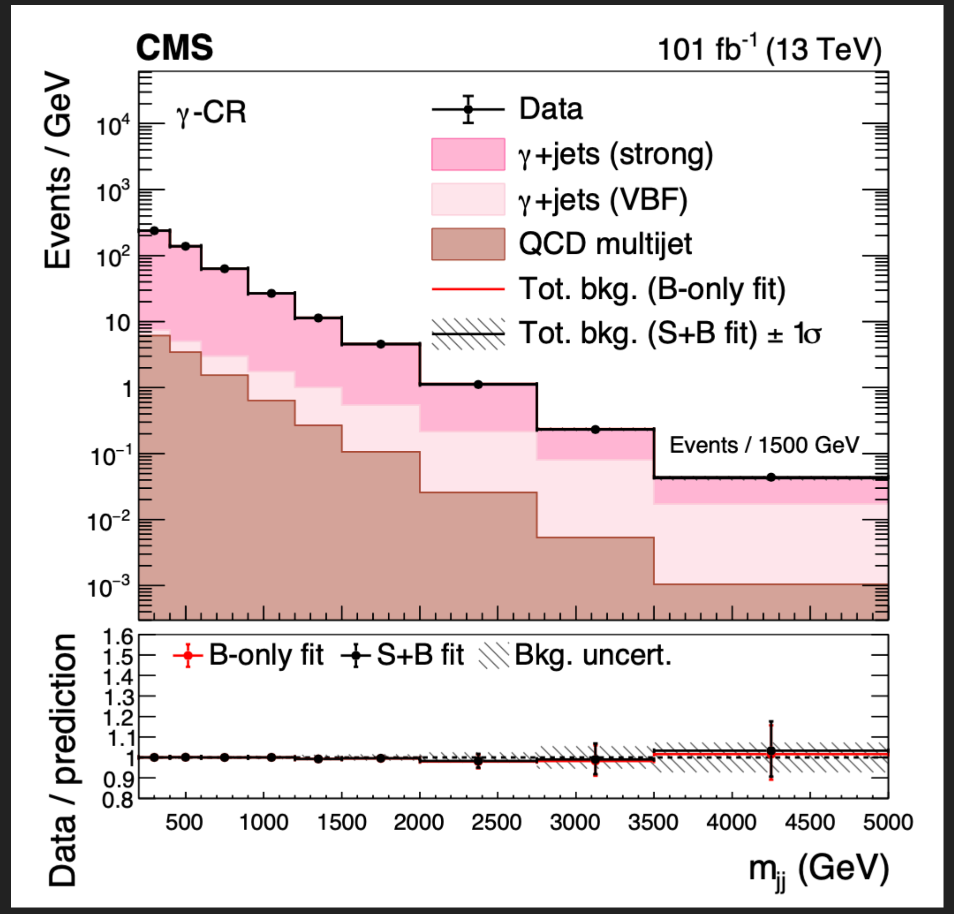
- E_T^{miss} and VBF-like triggers
- VBF kinematics : 2 jets, well separated and in opposite detector hemispheres, with a large dijet mass
- Veto charged leptons and photons
- BG estimation: similar as the mono-jet strategy - normalisation in CRs with leptons or photon



Phys. Rev. D 105 (2022) 092007

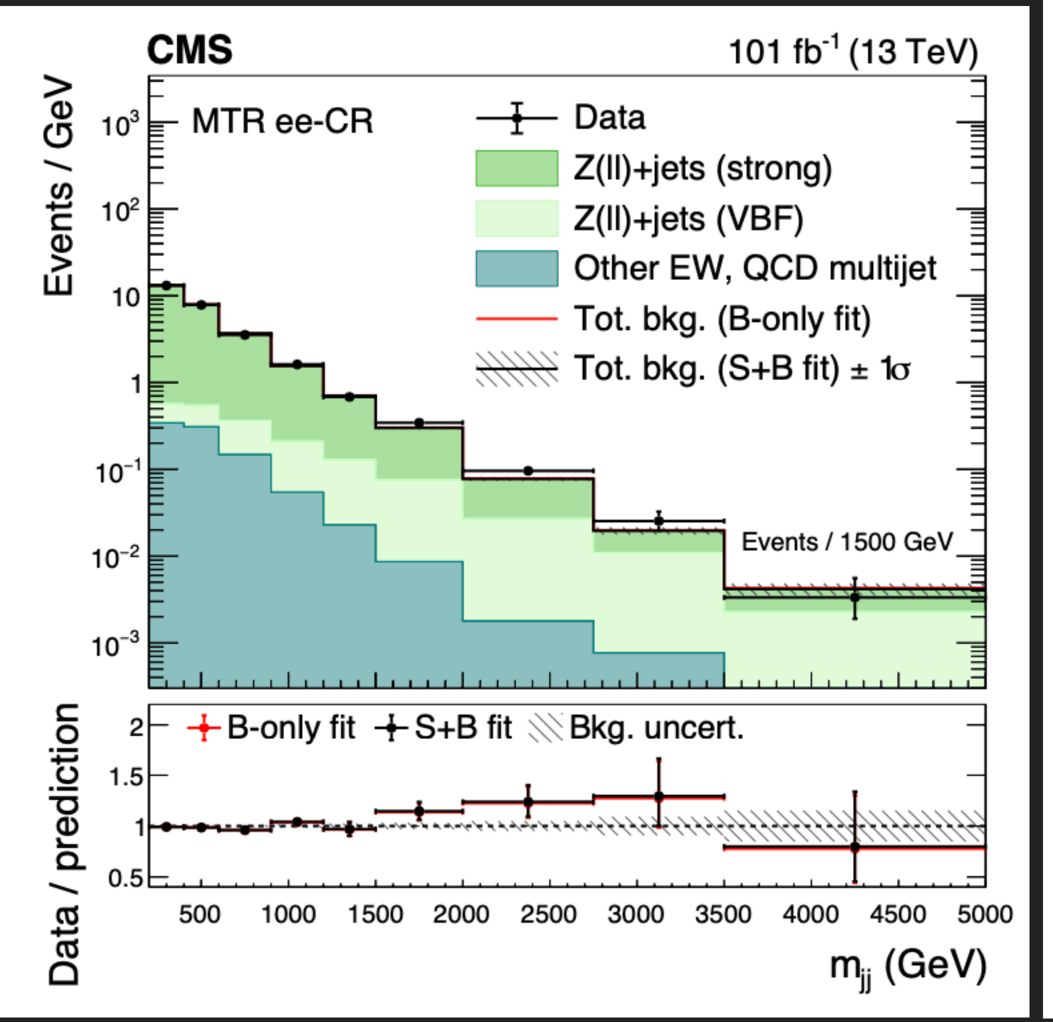
CMS VBF+E_T^{MISS}

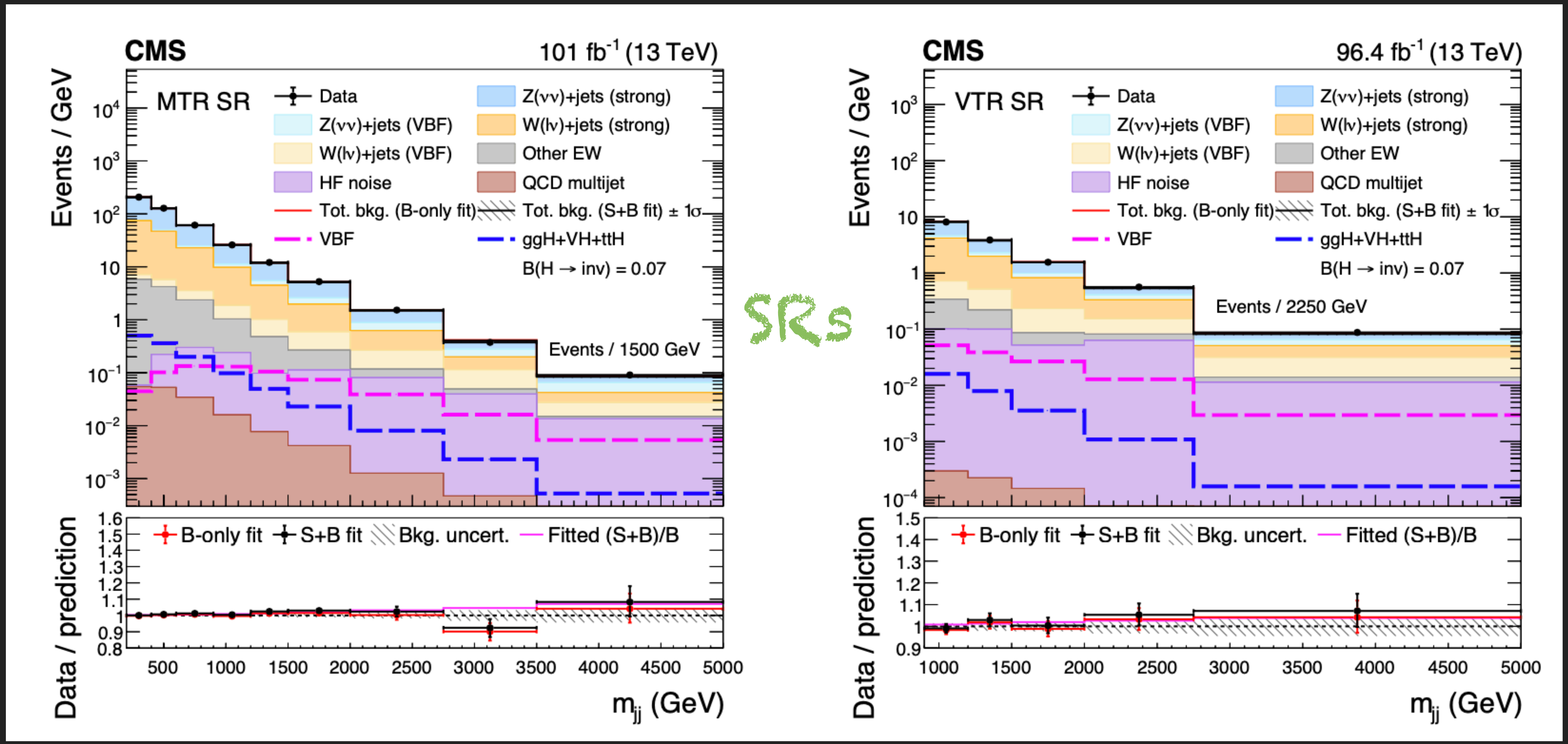
- Two SRs in E_T^{miss}: moderate(VTR) and high (MTR), binned in m_{jj}



CR γ

CR Z



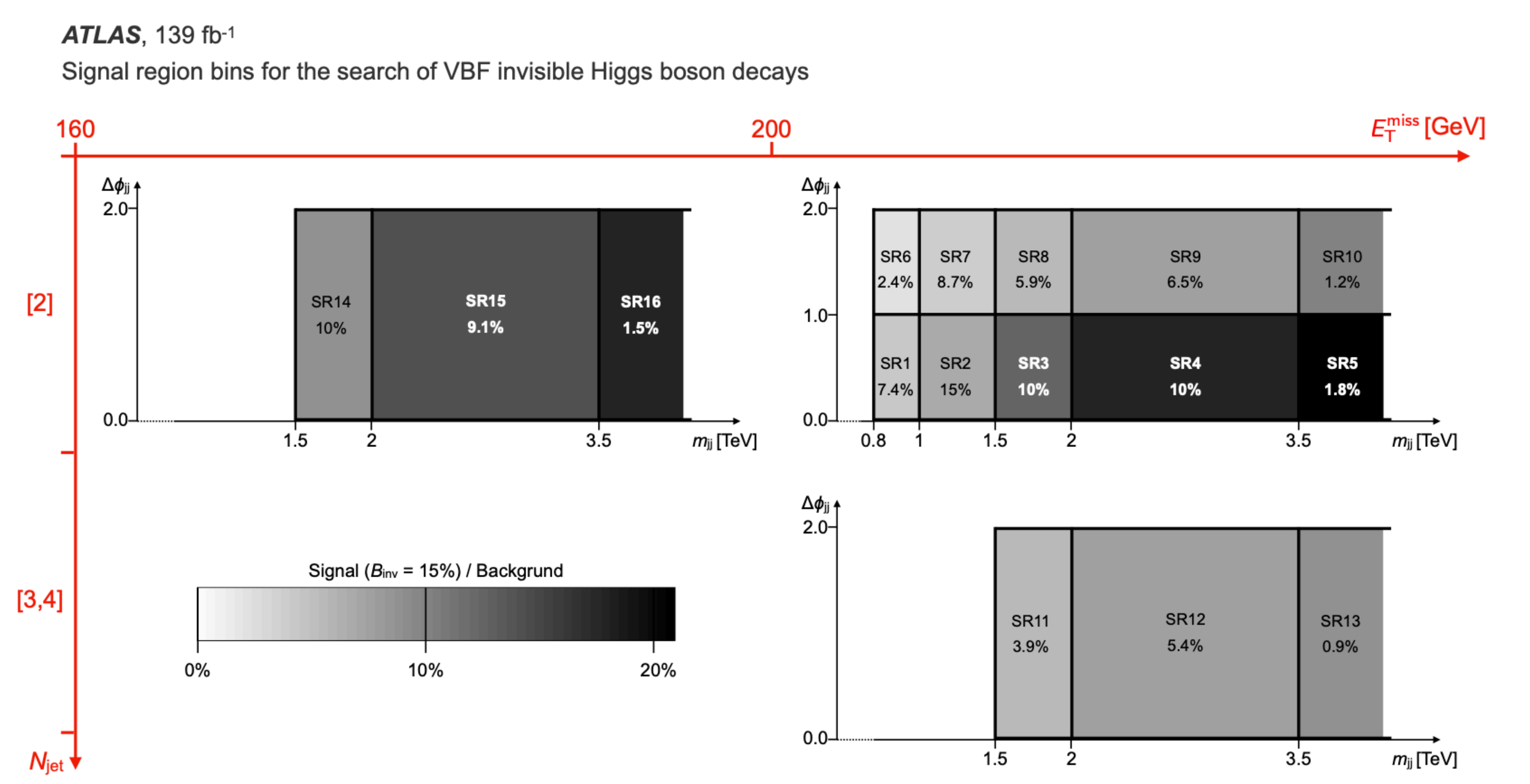


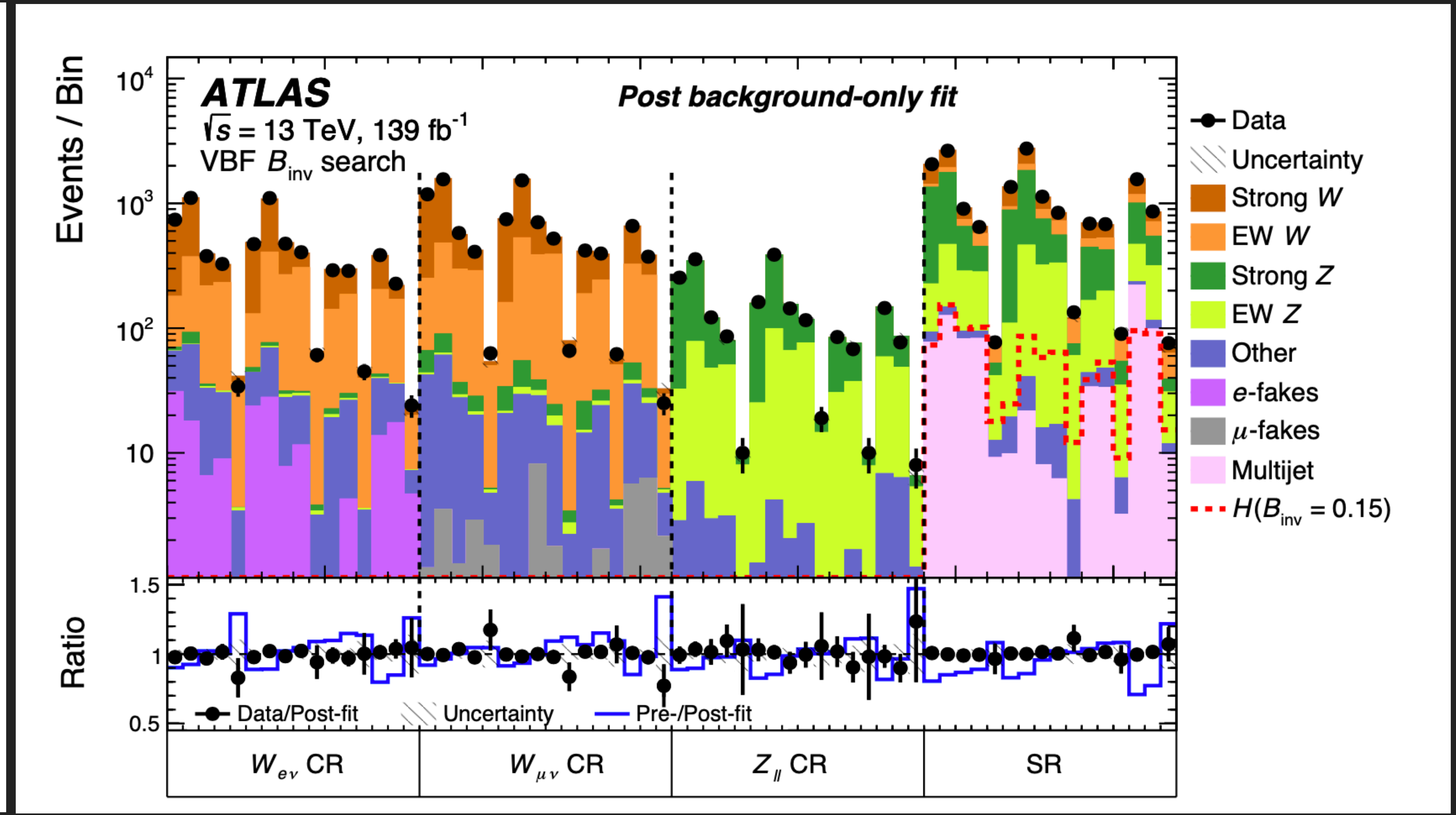
SRs

- BR(H–>inv) < 0.18 (0.12) obs (exp) => <0.18 (0.10) when combined with Run-1

ATLAS VBF+E_T^{MISS}

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

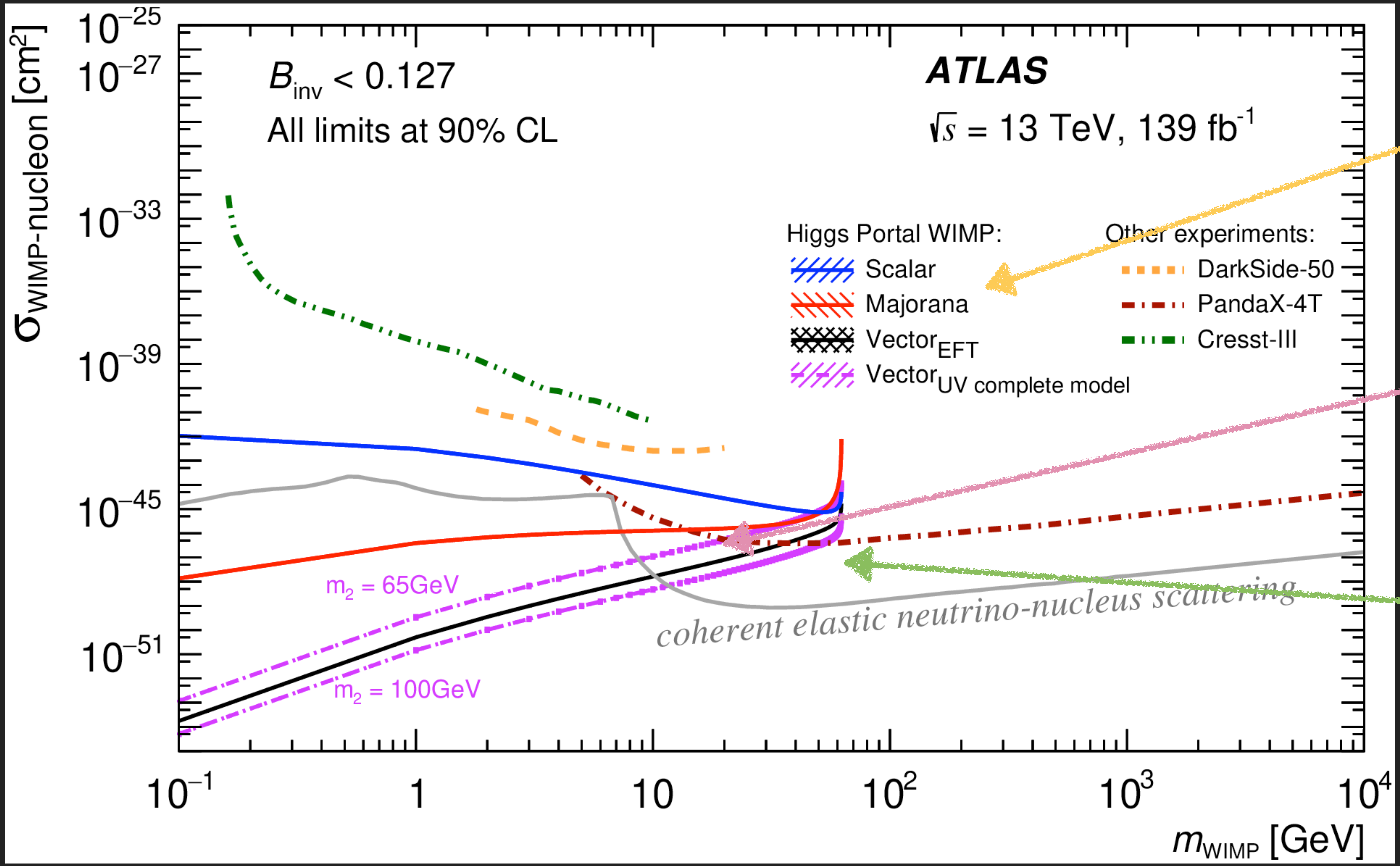




- BR(H→inv) < 0.145 (0.103)

COMPARISON WITH DIRECT DETECTION

- Can again translate in the DD SI plane, putting limits at 90% CL



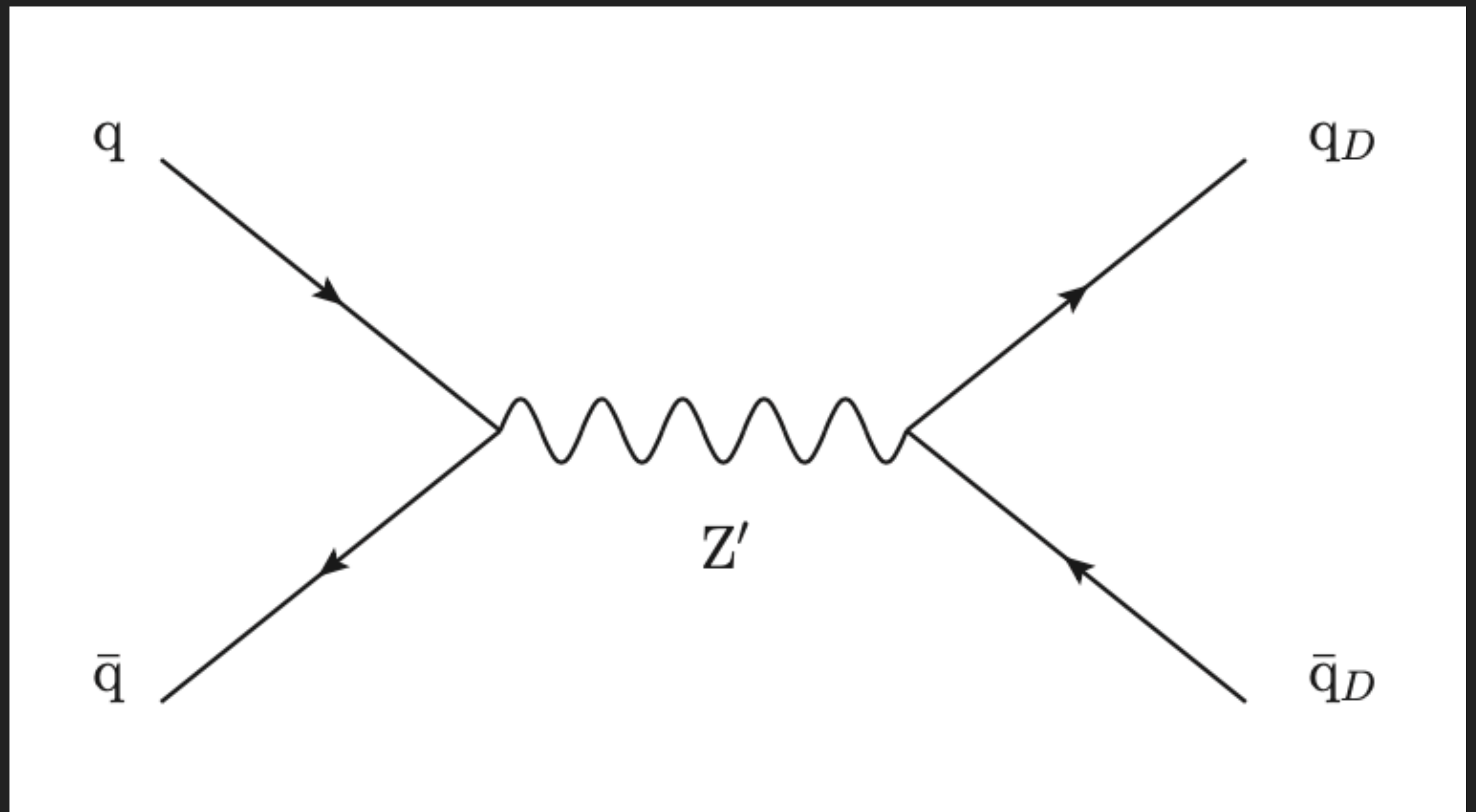
Translation depends on the assumed nature of DM

+ renormalisable mechanism to generate a vector DM mass can scale the limit

Kinematic edge due to Higgs boson mass

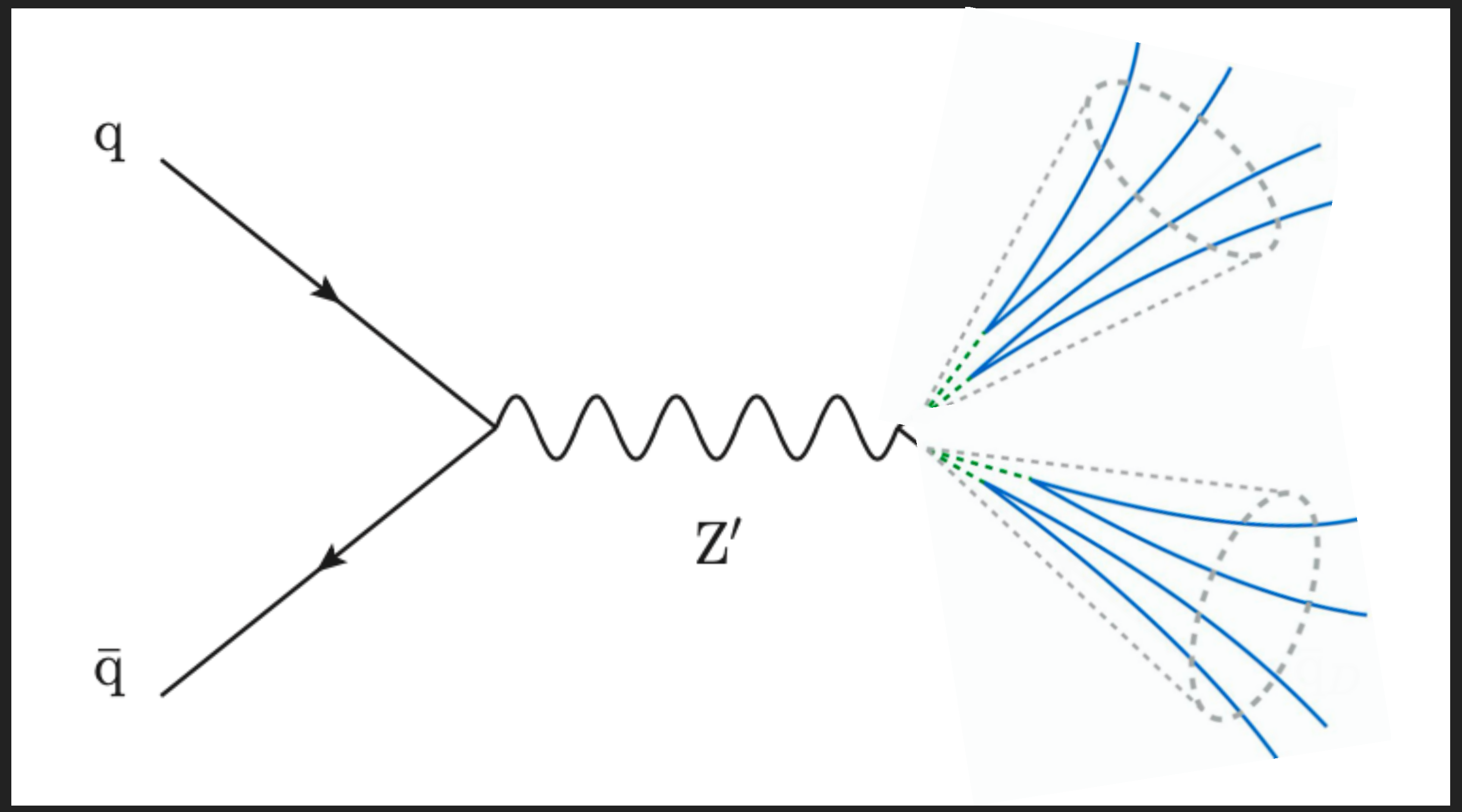
A MORE COMPLICATED DM SECTOR WITH A STRONG DYNAMIC?

- Hidden sector analogous to QCD
- Could make asymmetric DM : relic density = density remaining after DM-antiDM annihilation in the early universe
  - Could hence avoid indirect detection constraints!
- 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} = # stable hadrons / # unstable hadrons



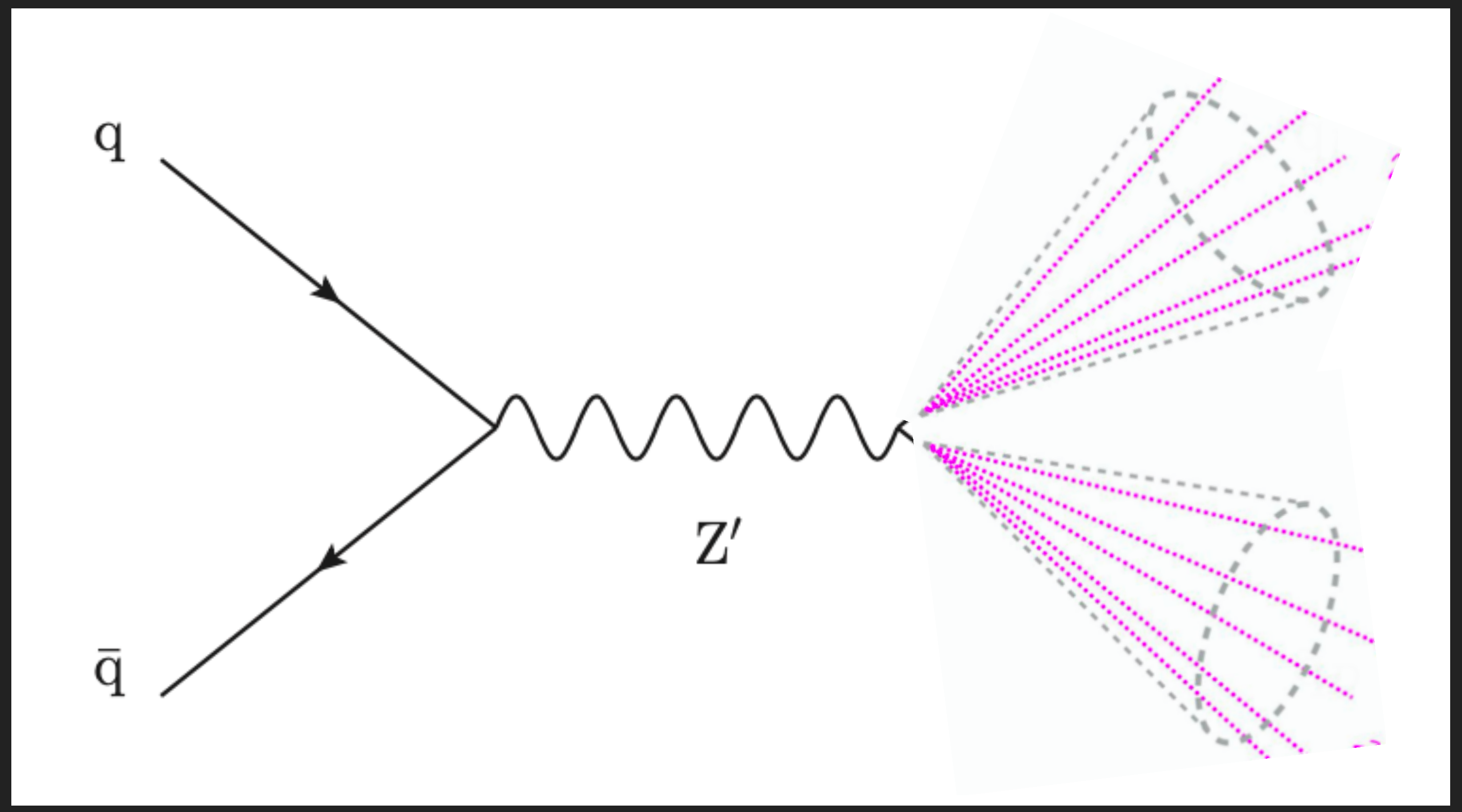
DM IN A HIDDEN SECTOR WITH STRONG DYNAMICS?

- 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} = # stable hadrons / # unstable hadrons
- $r_{inv} \sim 0$: visible jets => dijet resonance



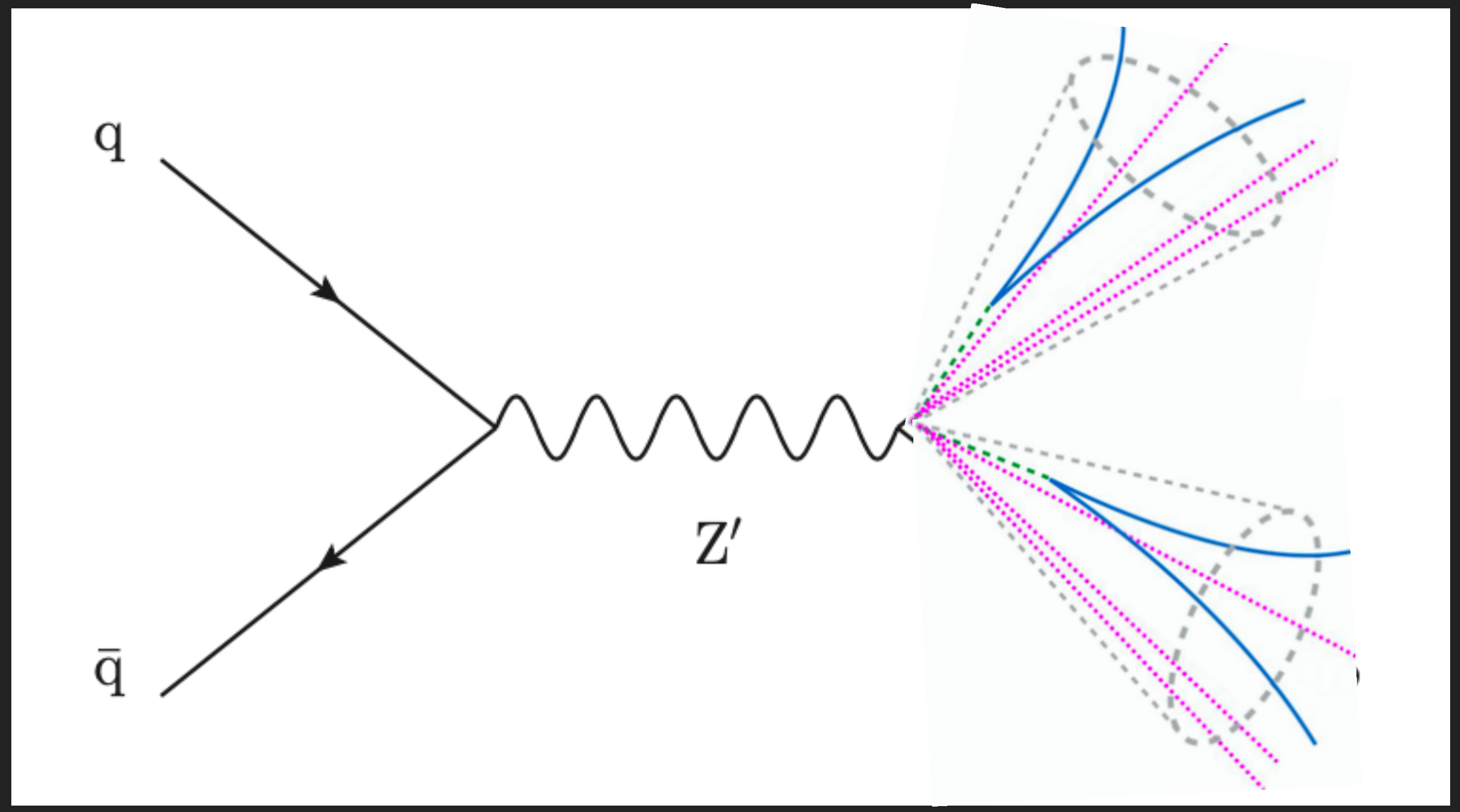
DM IN A HIDDEN SECTOR WITH STRONG DYNAMICS?

- 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} = # stable hadrons / # unstable hadrons
- $r_{inv} \sim 1$: invisible jets => think mono-jet again!



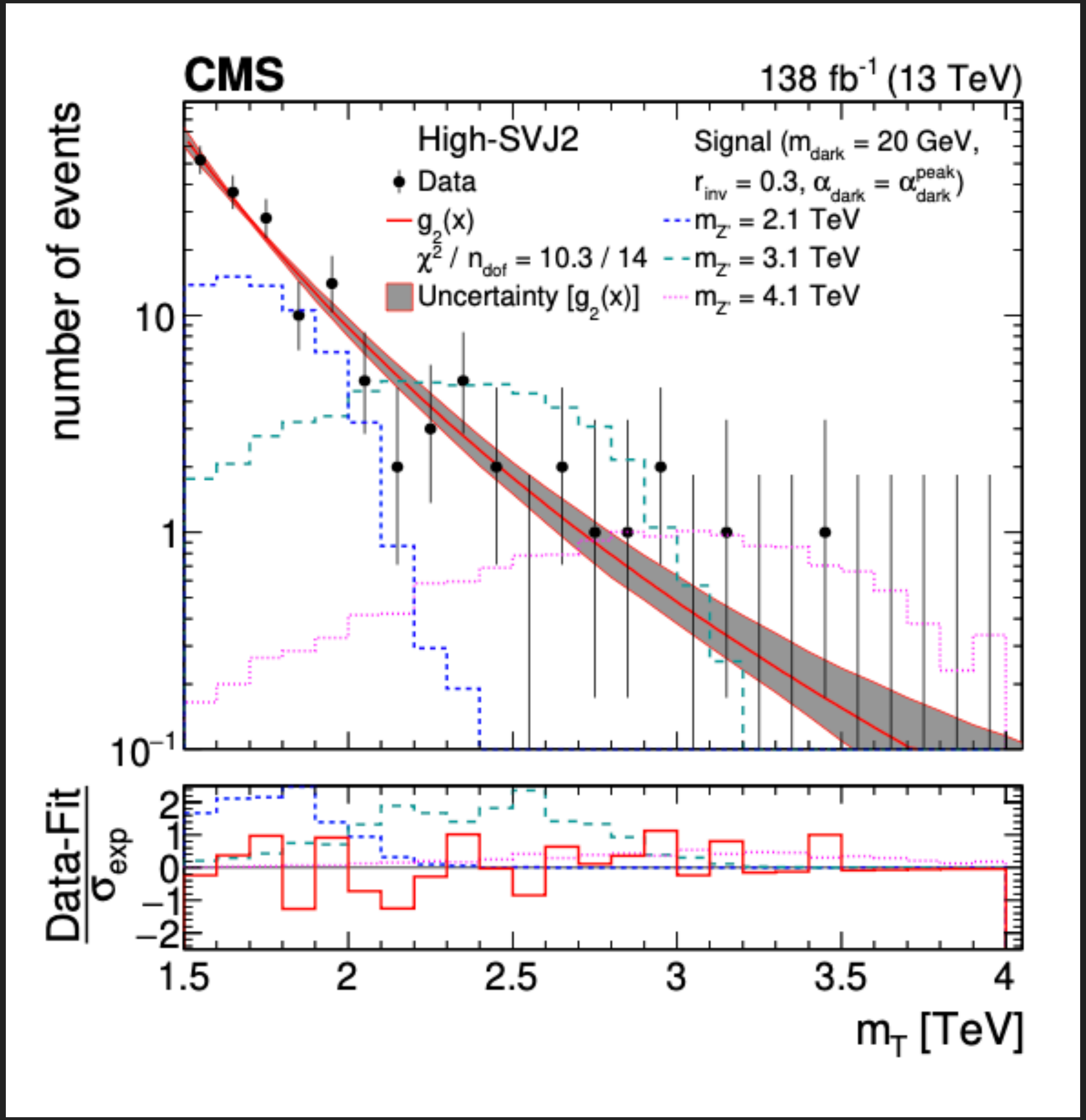
DM IN A HIDDEN SECTOR WITH STRONG DYNAMICS?

- 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} = # stable hadrons / # unstable hadrons
- $0 < r_{inv} < 1$: semi-visible jets => E_T^{miss} aligned with one jet if back to back



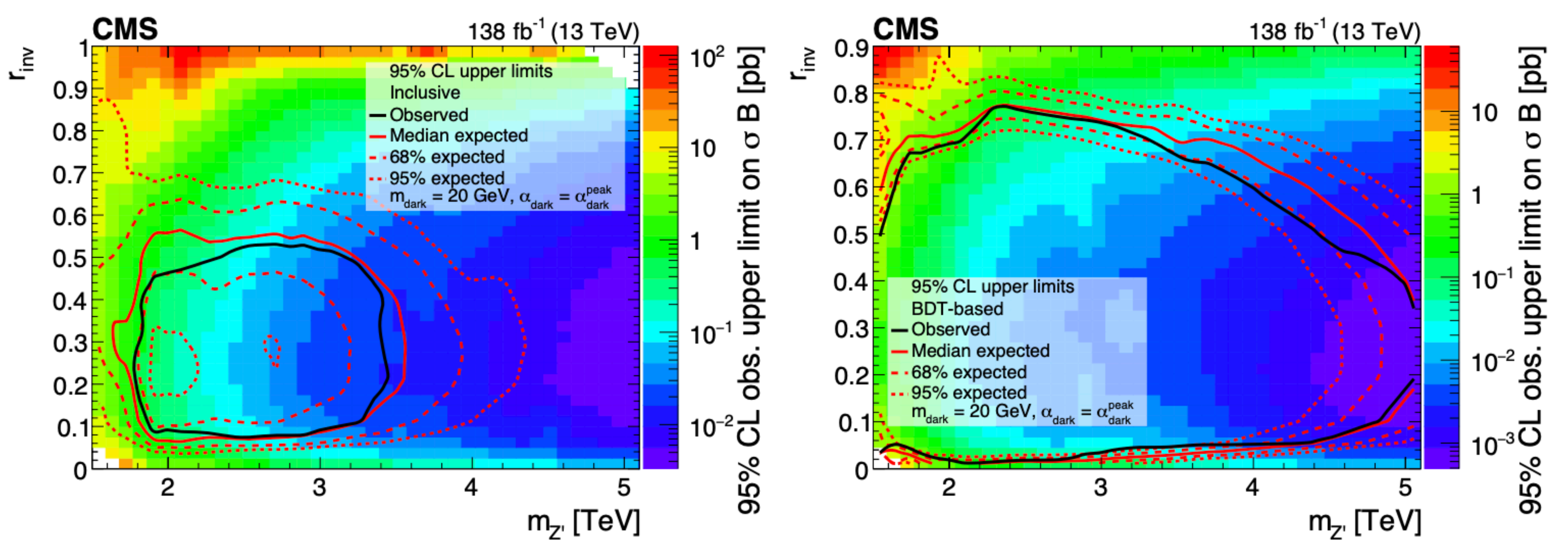
CMS SEMI-VISIBLE JETS

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



arXiv:2112.11125

CMS SEMI-VISIBLE JETS



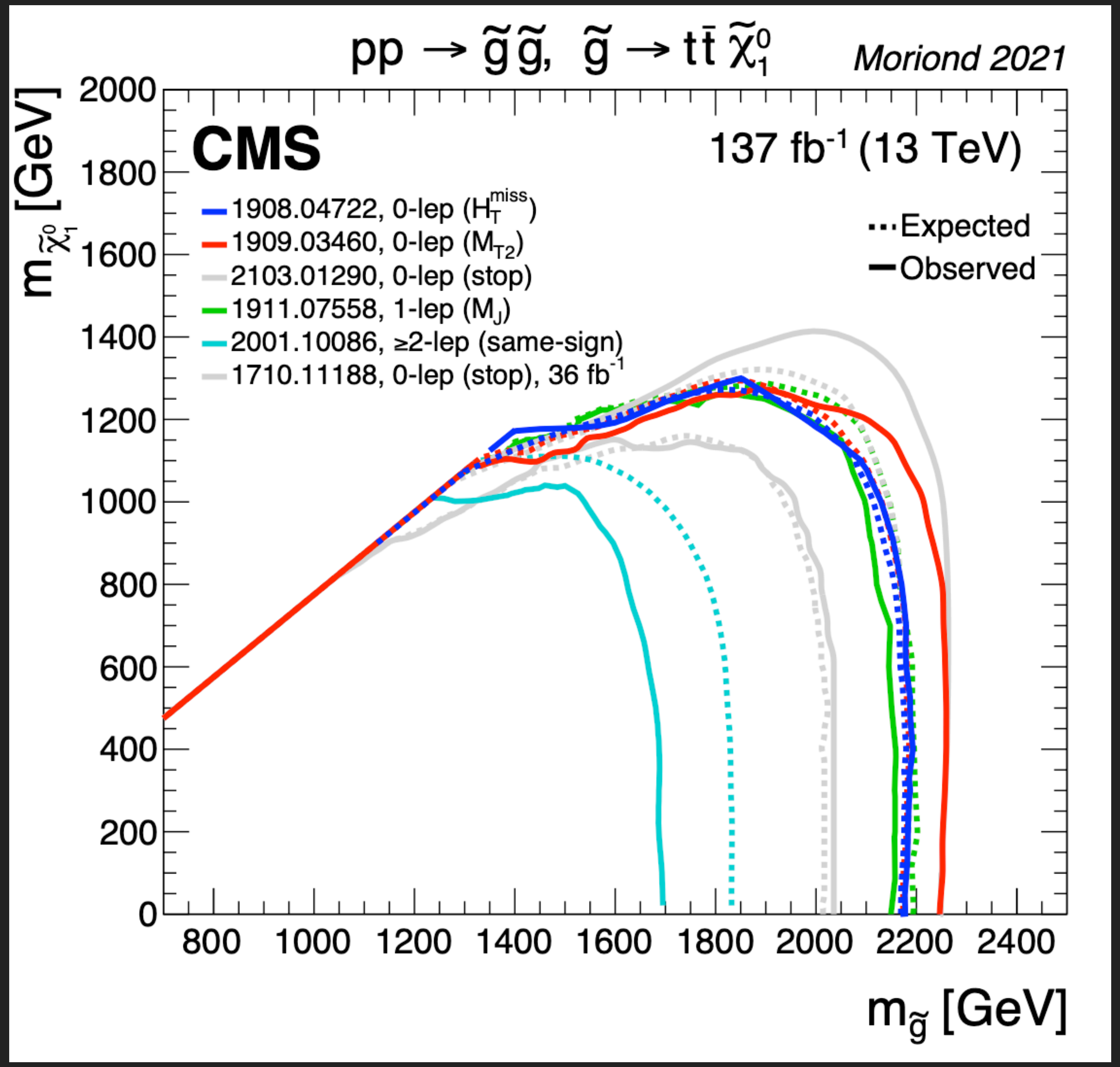
Model-independent limits: cut and count

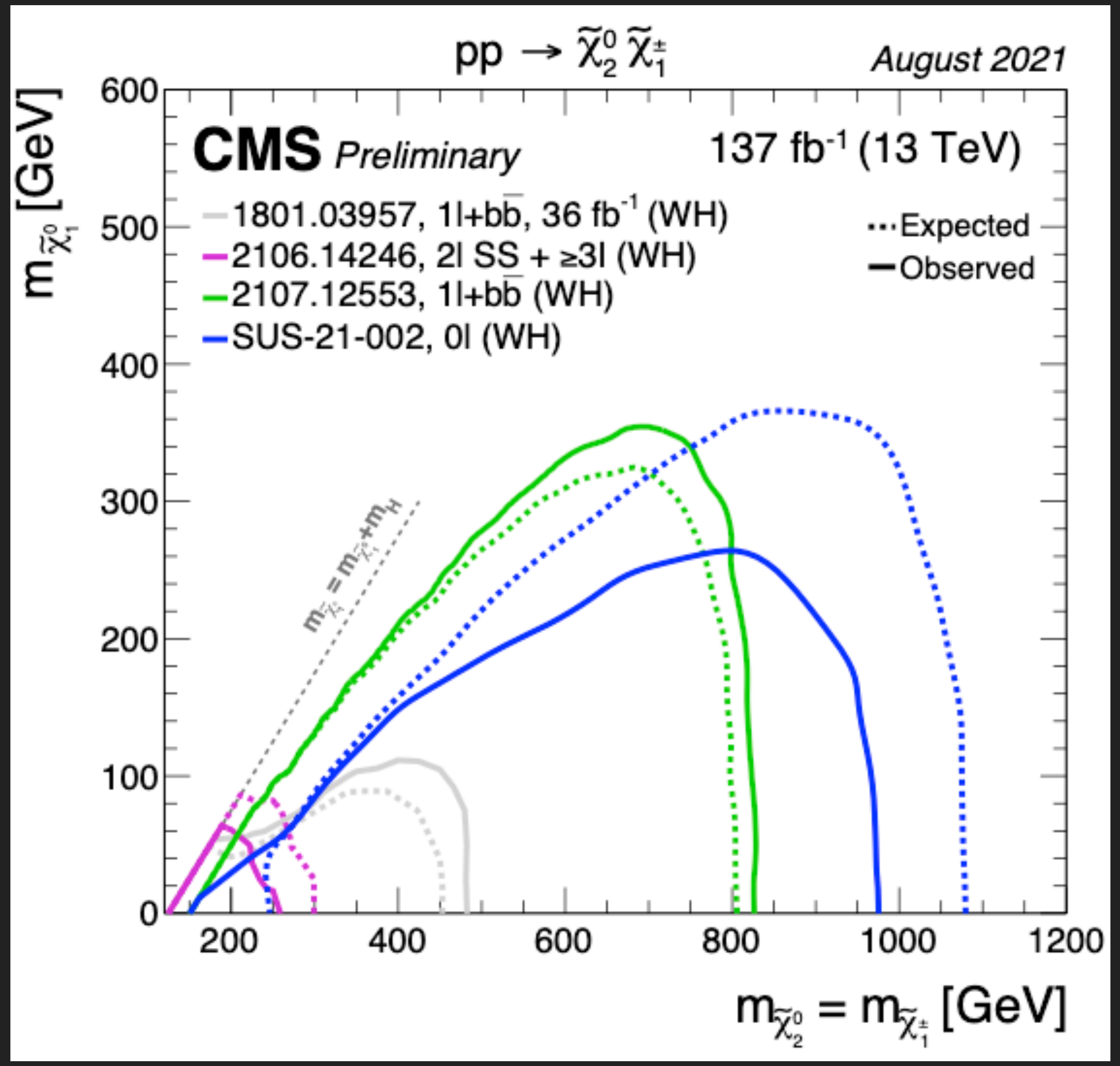
Model-dependent limits: BDT tagging semi-visible jets

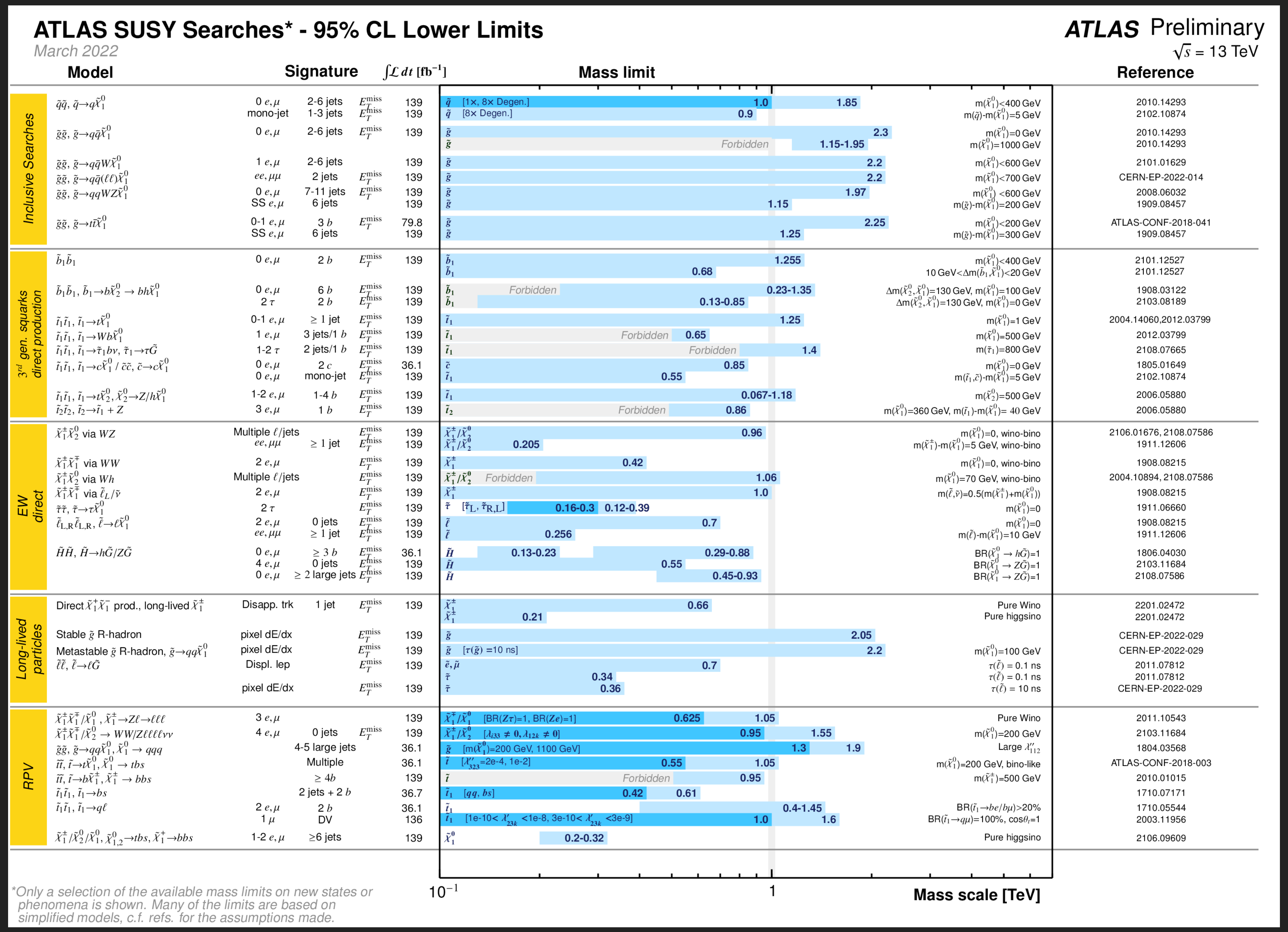
m_{SD}, $\Delta\phi(\vec{J}, \vec{p}_T^{miss})$, τ_{21}, τ_{32}, and D_{p_T}

WHAT ABOUT SUPERSYMMETRY?

- A favorite model for many, can provide eg a neutralino WIMP candidate
- Plethora of signatures to look for at the LHC given the large number of sparticles predicted + constraints coming as well from flavour physics, Higgs couplings, heavy Higgs searches, … ***Need a dedicated talk!!!***
  - Can look for strongly produced sparticles (squarks, gluinos) or even electroweak ones (charginos, neutralinos…)
  - Can place limits eg on simplified SUSY models (consider one production mode and one decay, all else decoupled):



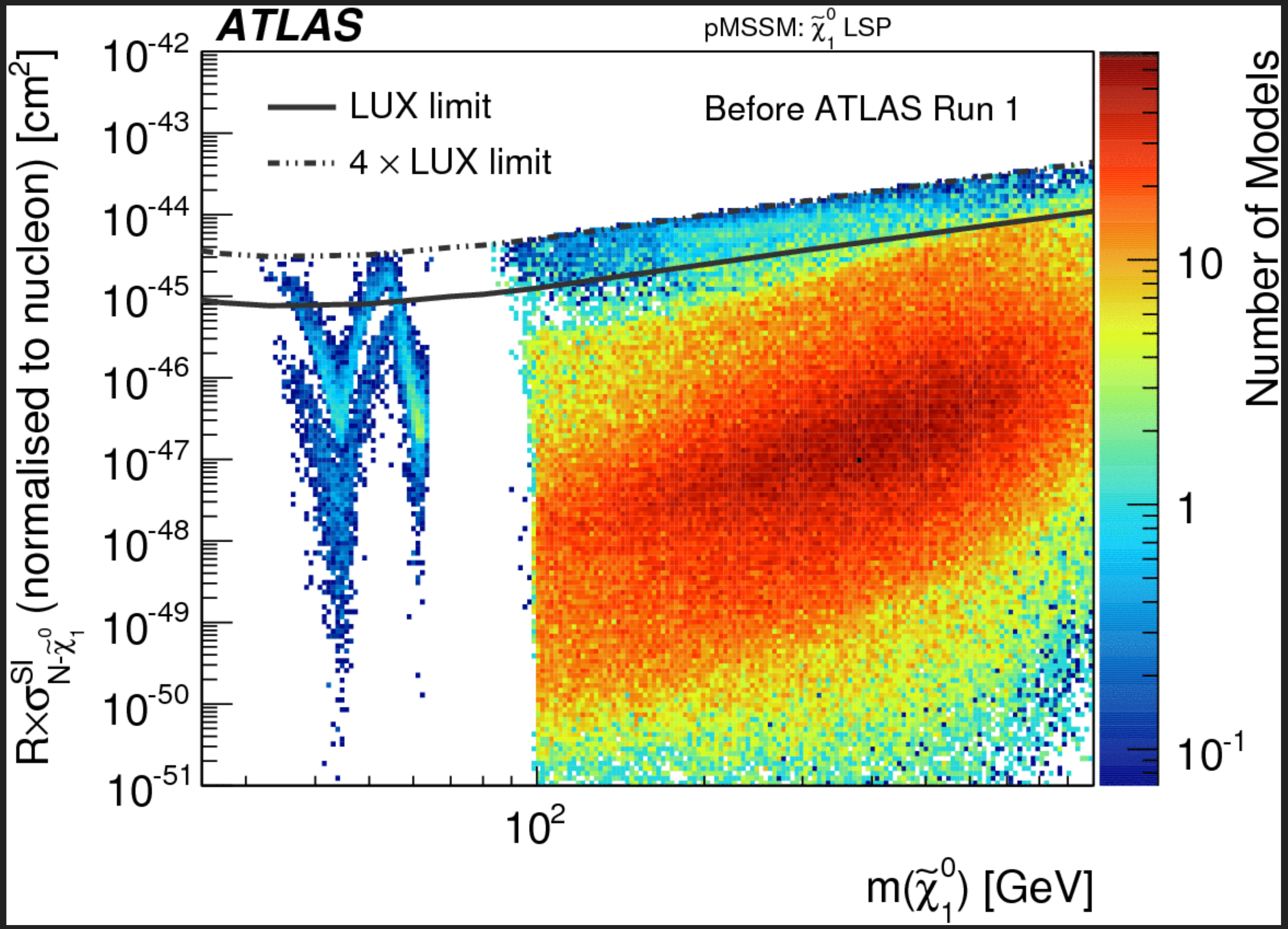


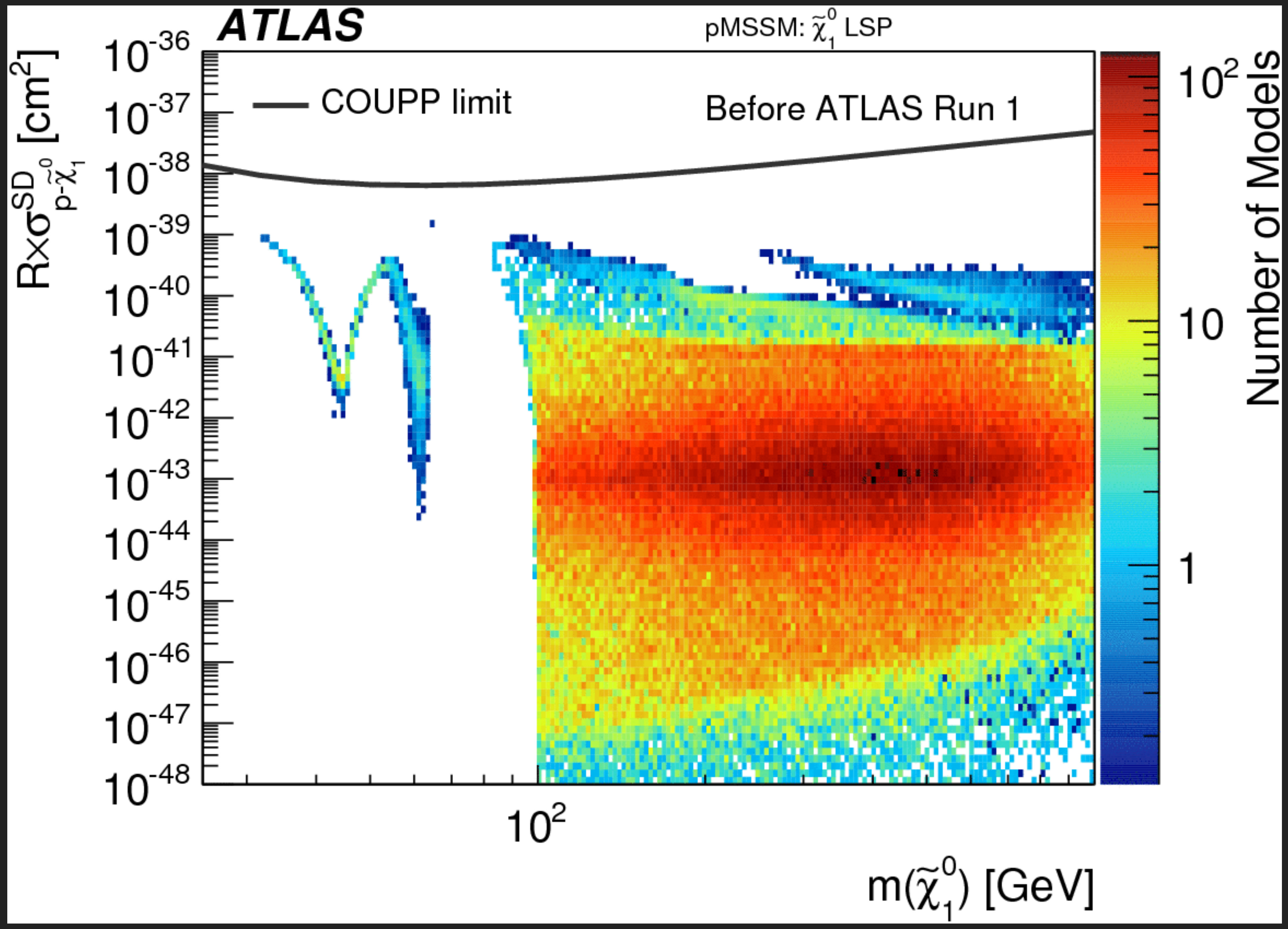


JHEP 10 (2015) 134

WHAT ABOUT SUPERSYMMETRY?

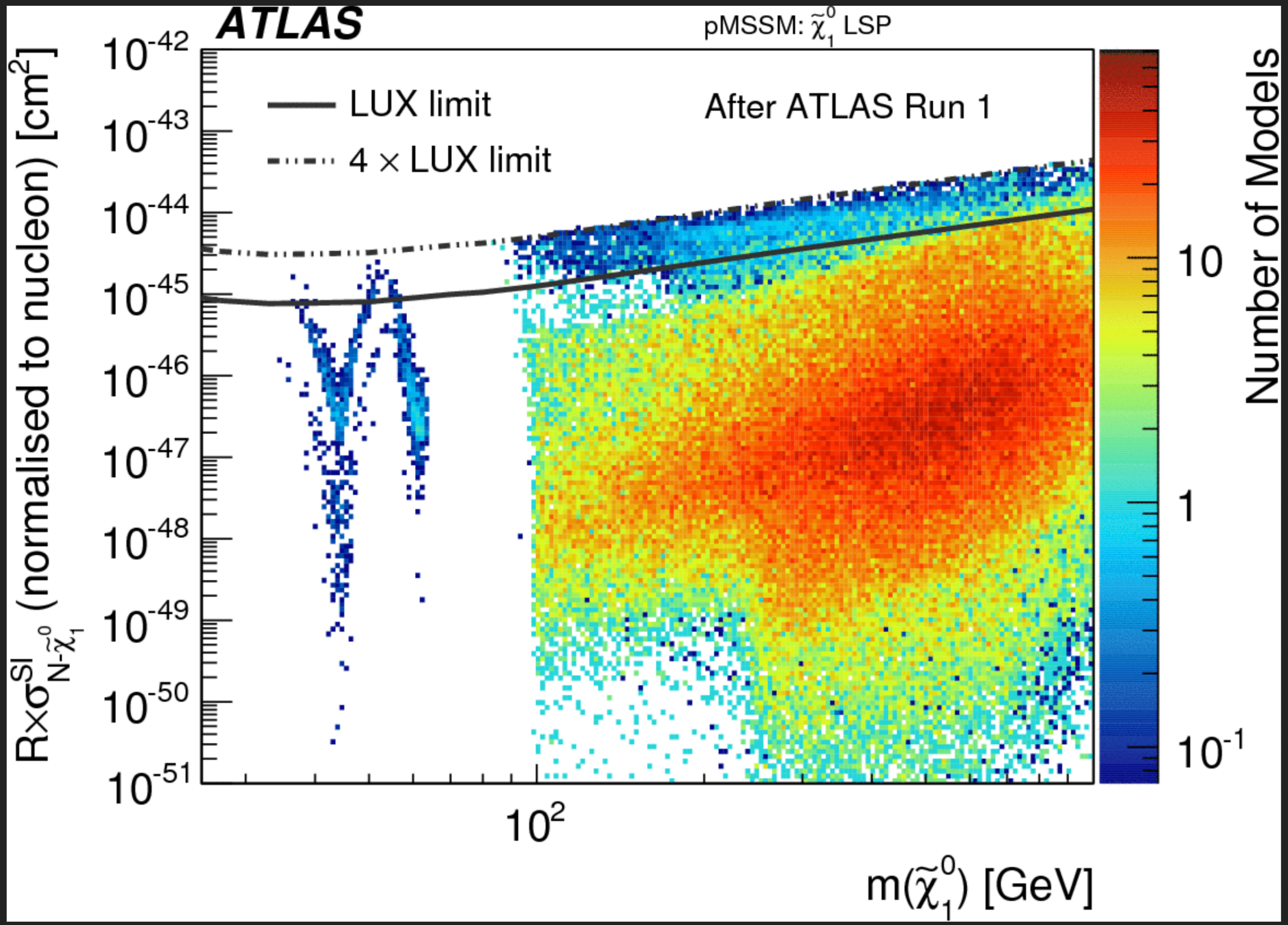
- How do all these translate into DM limits? SUSY is a vast parameter space…
- Scan the pMSSM (most general CP and R-parity conserving scenario assuming minimal flavour violation, described by 19 parameters), applying other known constraints, to see what remains after the LHC constraints…

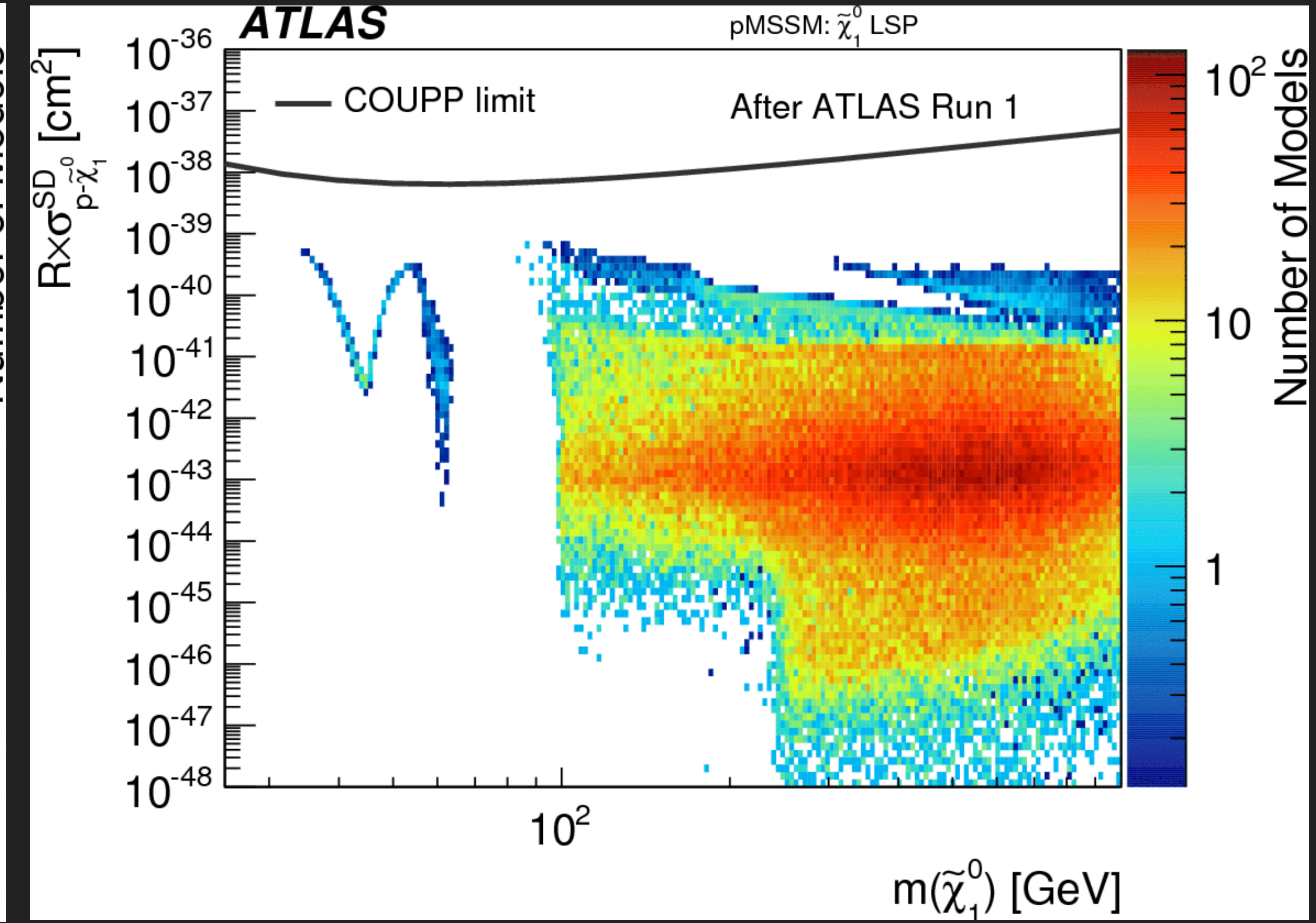




WHAT ABOUT SUPERSYMMETRY?

- How do all these translate into DM limits? SUSY is a vast parameter space…
- Scan the pMSSM (most general CP and R-parity conserving scenario assuming minimal flavour violation, described by 19 parameters), applying other known constraints, to see what remains after the LHC constraints…

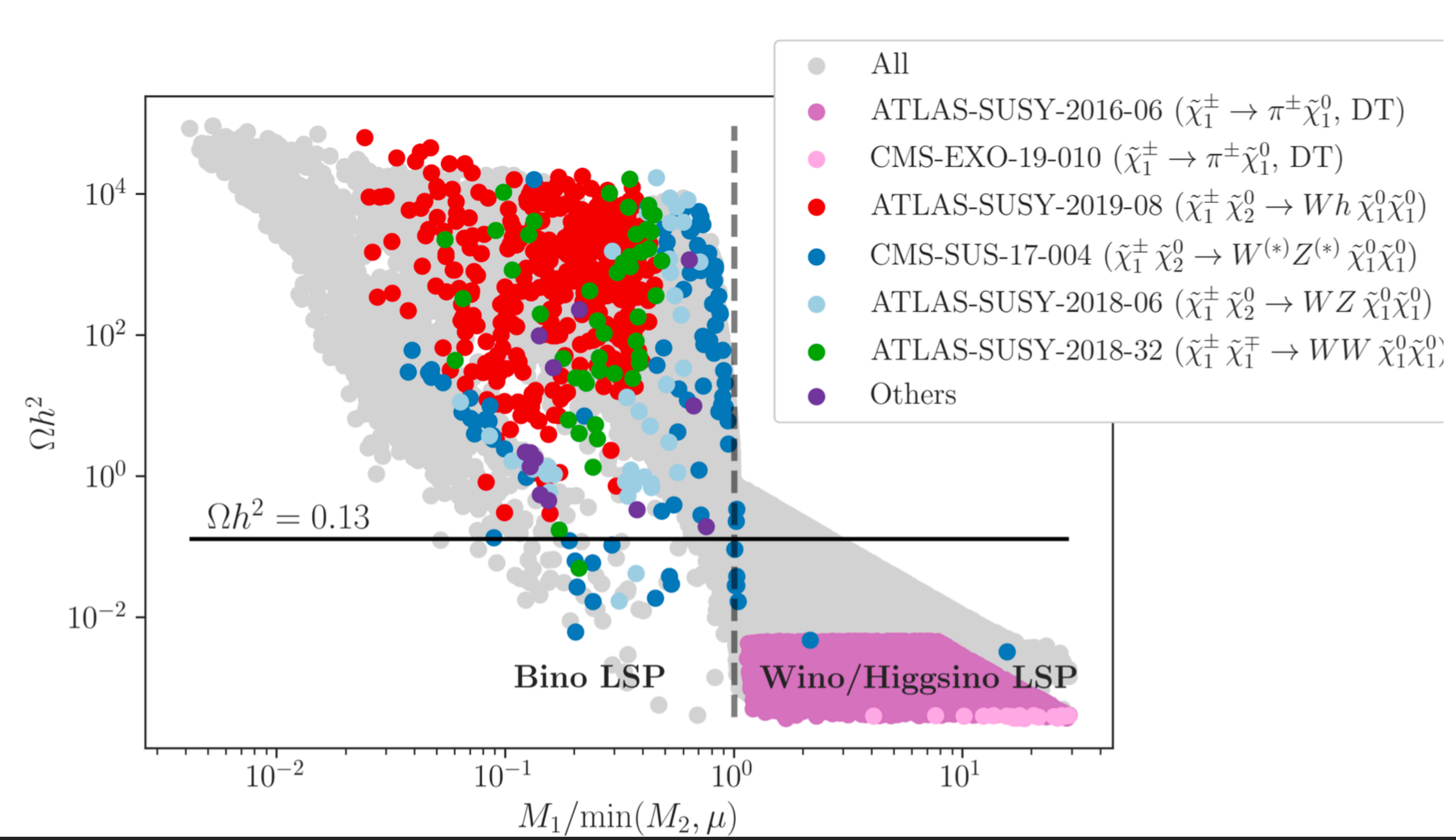


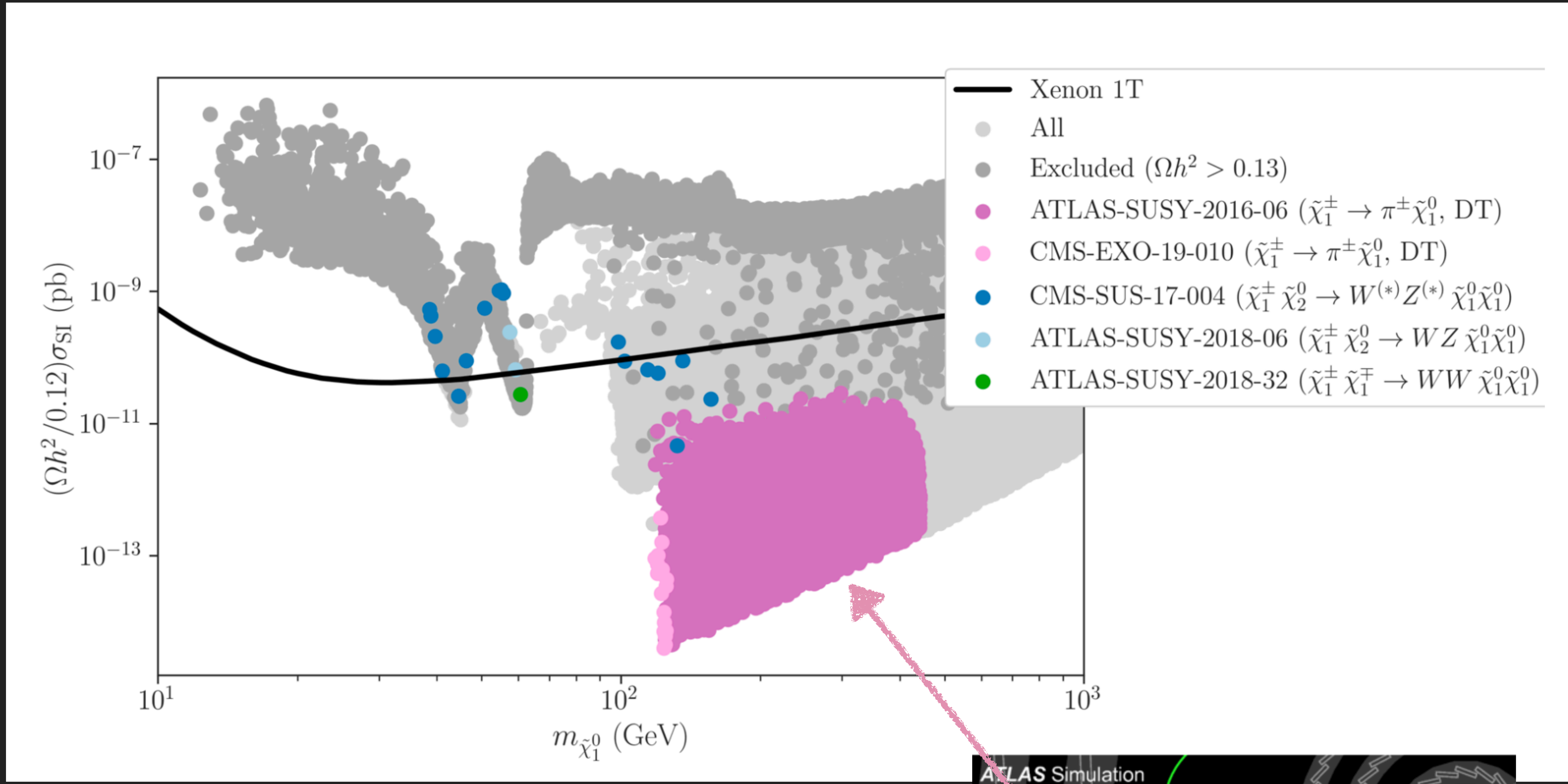


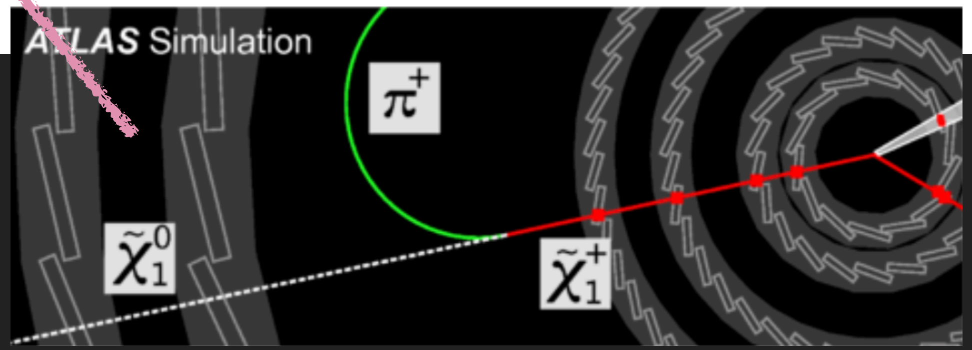
JHEP 08 (2022) 068

WHAT ABOUT SUPERSYMMETRY?

- We have a lot more results now, at the end of Run-2 but no public pMSSM scan from the collaborations yet
- But theorists do scans too with tools like MadAnalysis 5, **SModels**, … (see the Tools session from yesterday :))

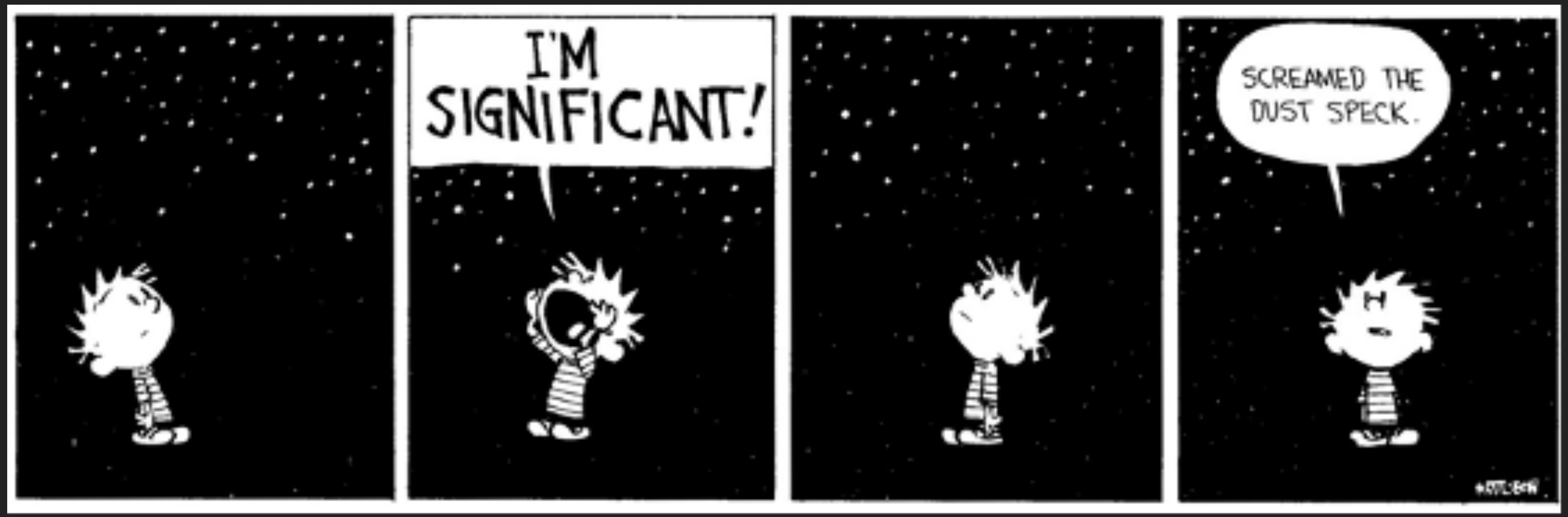






SUMMARY

- 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



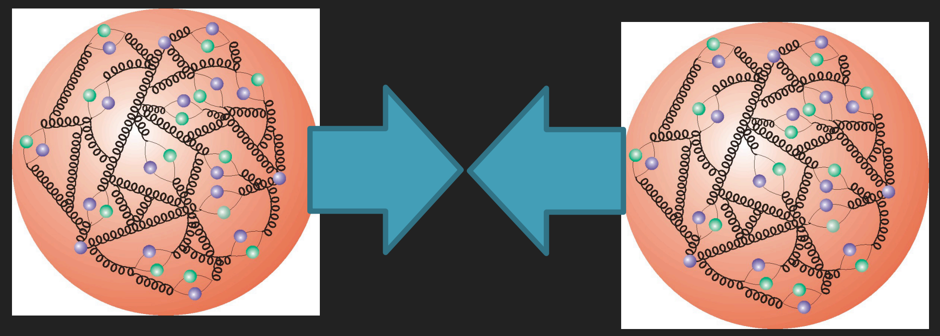
- Diversification of the searches to cover more and more scenarios
- Run–3 has started! More to come!

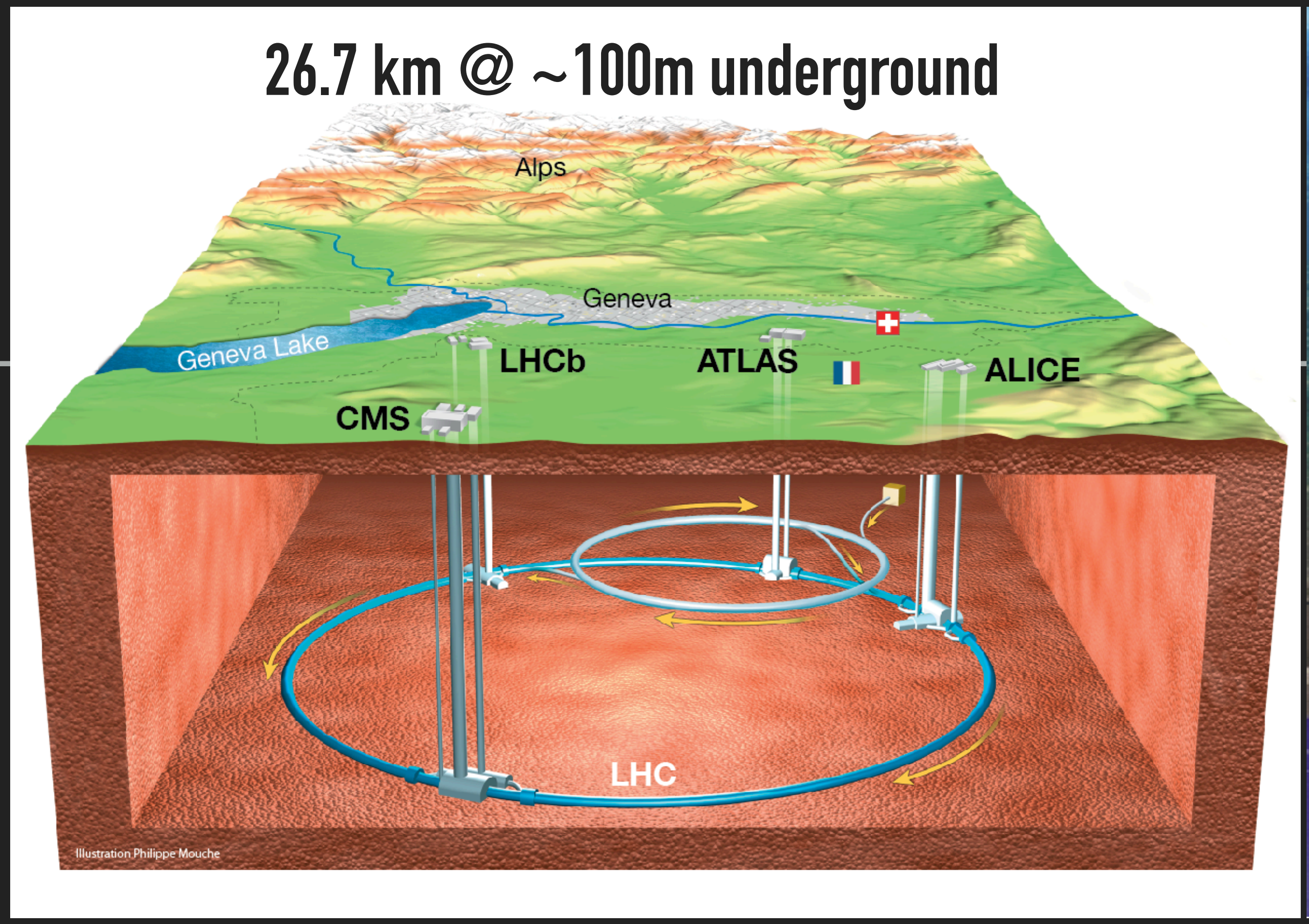
A DISCLAIMER

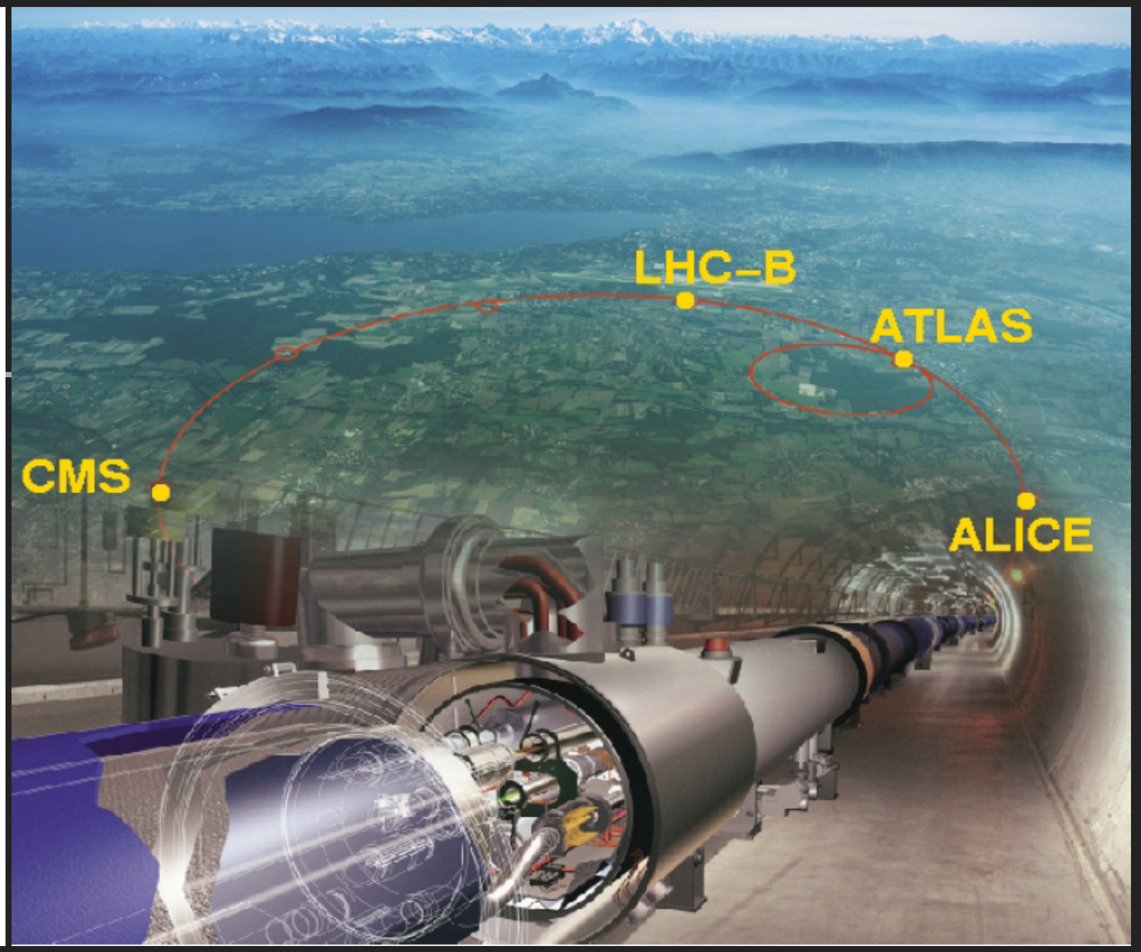
- Impossible to do justice to all results as this is a broad program:
  - I only presented a few examples
- CMS and ATLAS both have similar programs and comparable results; LHCb has some relevant searches too!
- For more information:
  - CMS , ATLAS & LHCb public results

… @ THE LHC

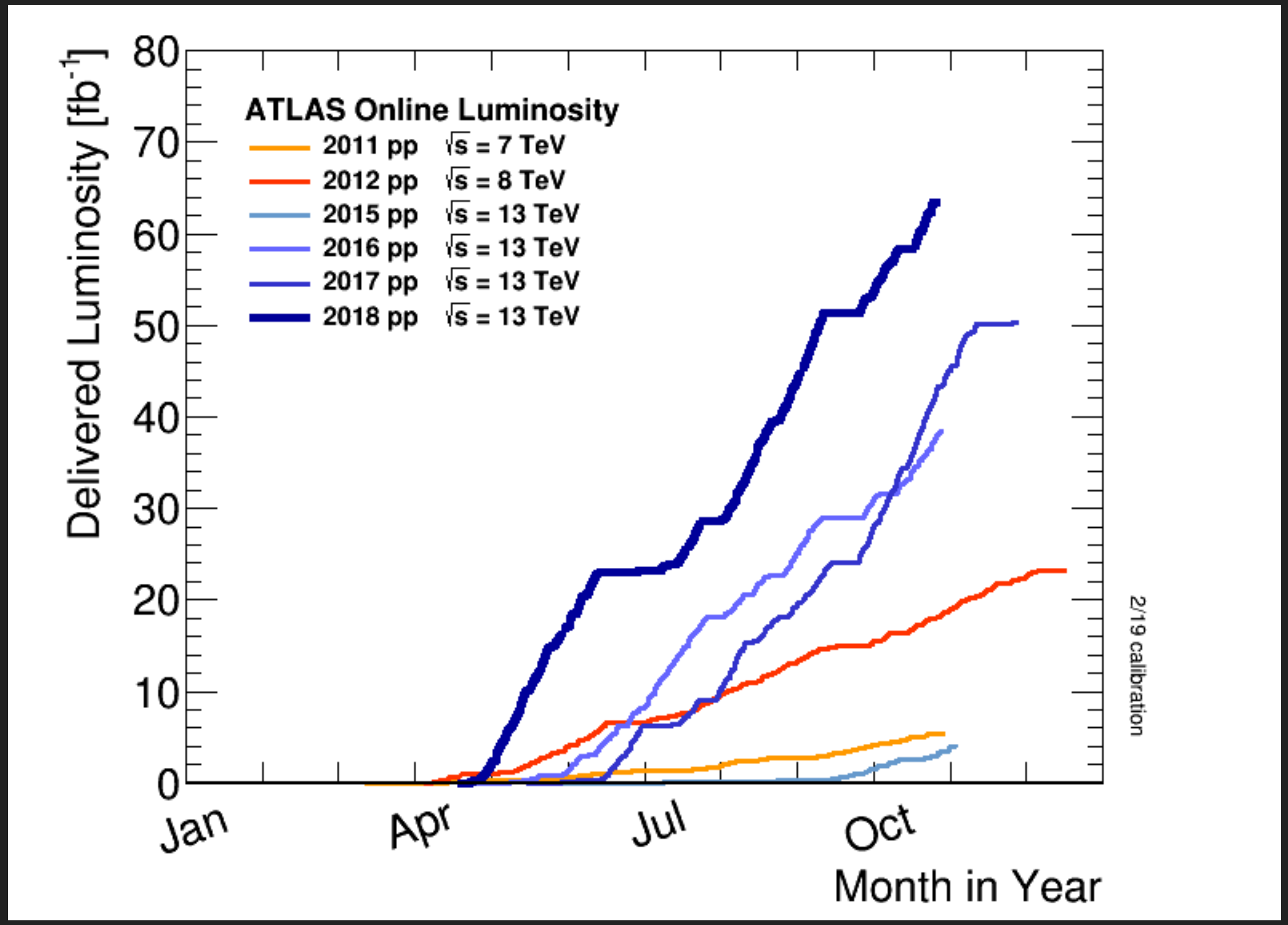
- proton-proton collider*





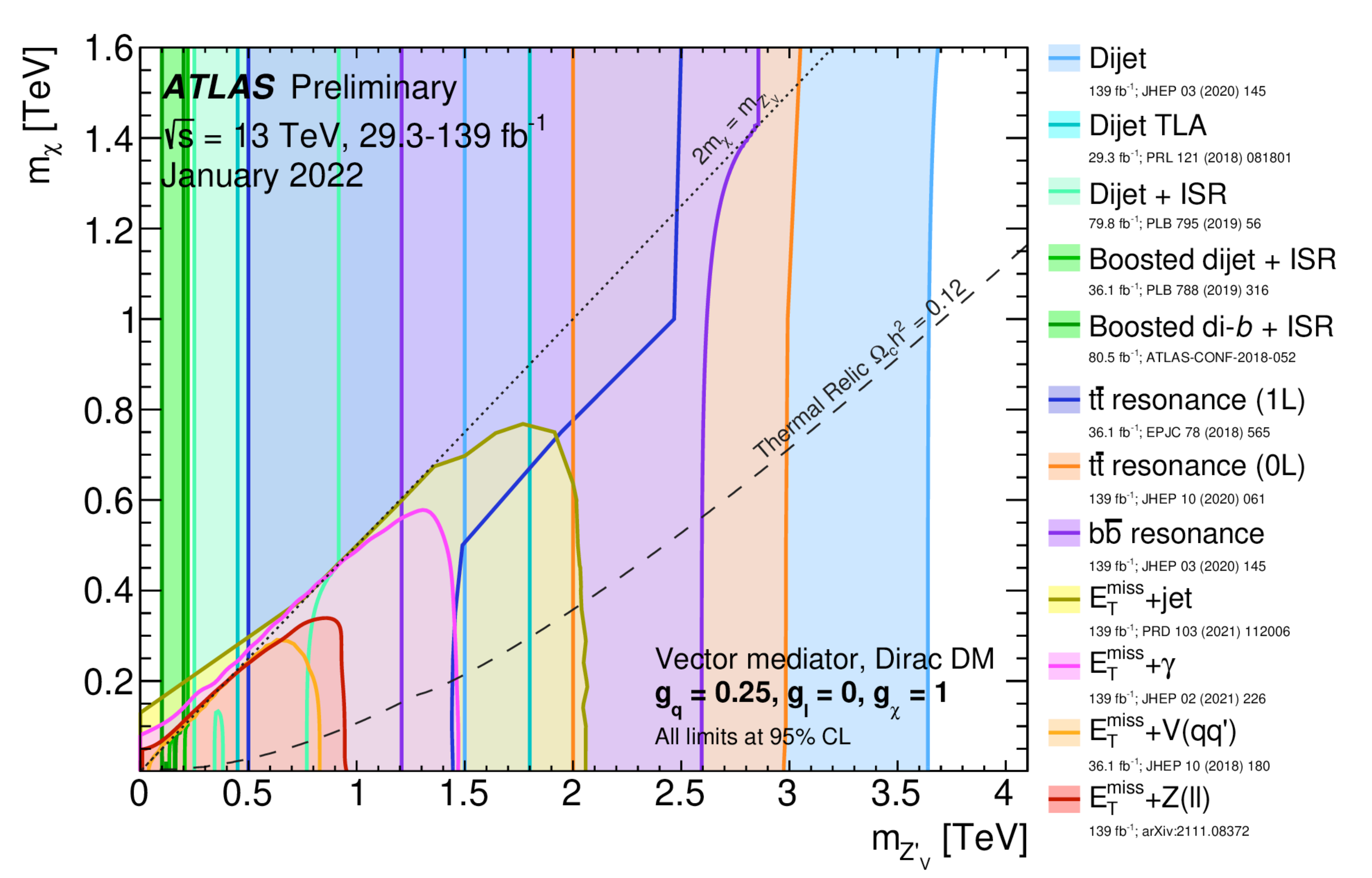


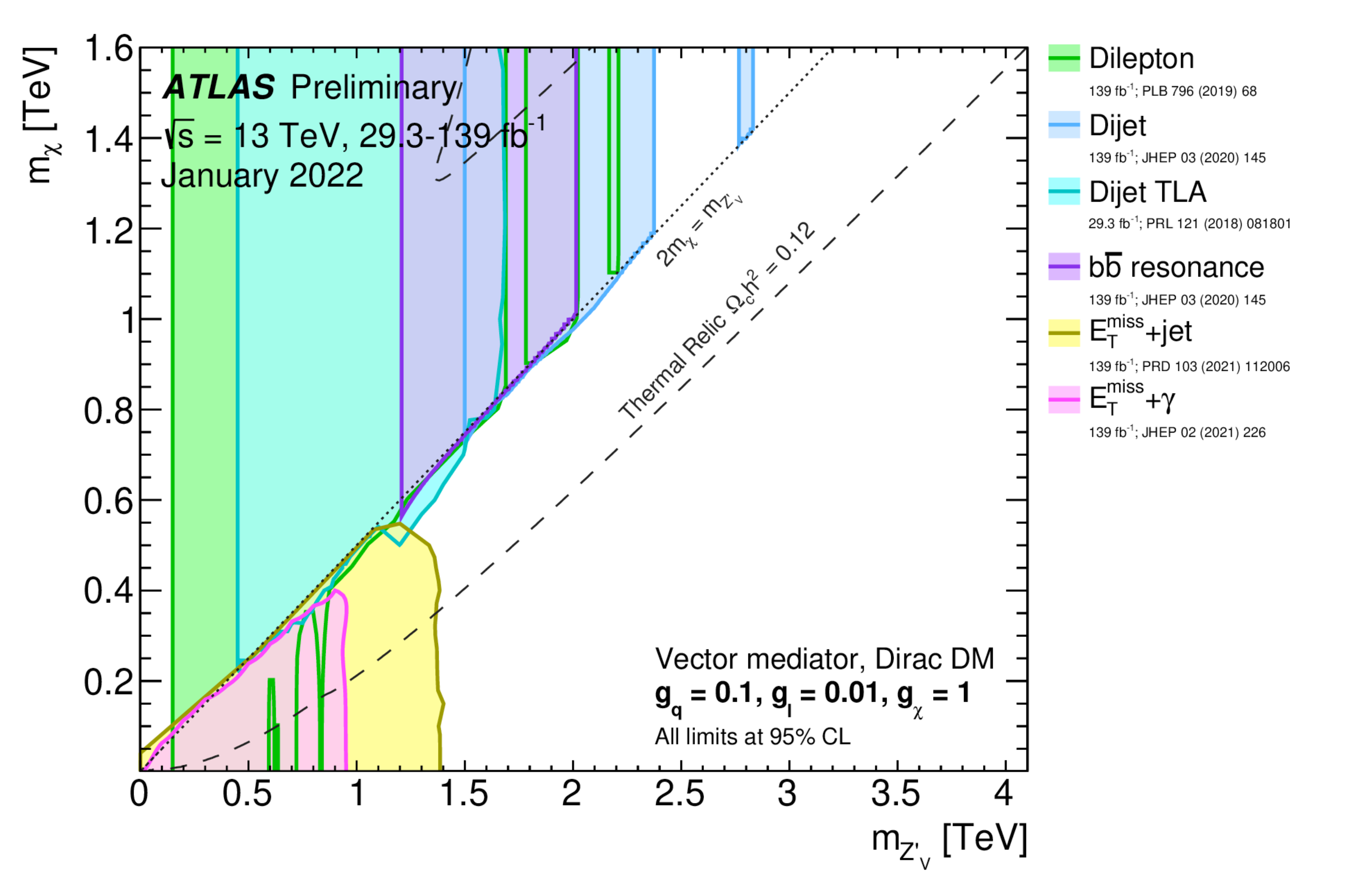
- pp center-of-mass energy:
  - Run-1: 2009 @ 900 GeV, 2010-11 @ 7 TeV, 2012 @ 8 TeV
    - *Long shutdown 1 (LS1): 2013-14 (maintenance/upgrade)*
  - Run-2: 2015-18 @ 13 TeV
    - *LS2: 2018-22* ***~140 fb^{-1} of data***
  - Run-3: 2022-2025 @ 13.6 TeV ; ~300 fb^{-1}
  - LS3: 2026-2028
  - High-luminosity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



* *may contain some heavy ions … :)*

COMPLEMENTARITY OF DM VS MEDIATOR SEARCHES

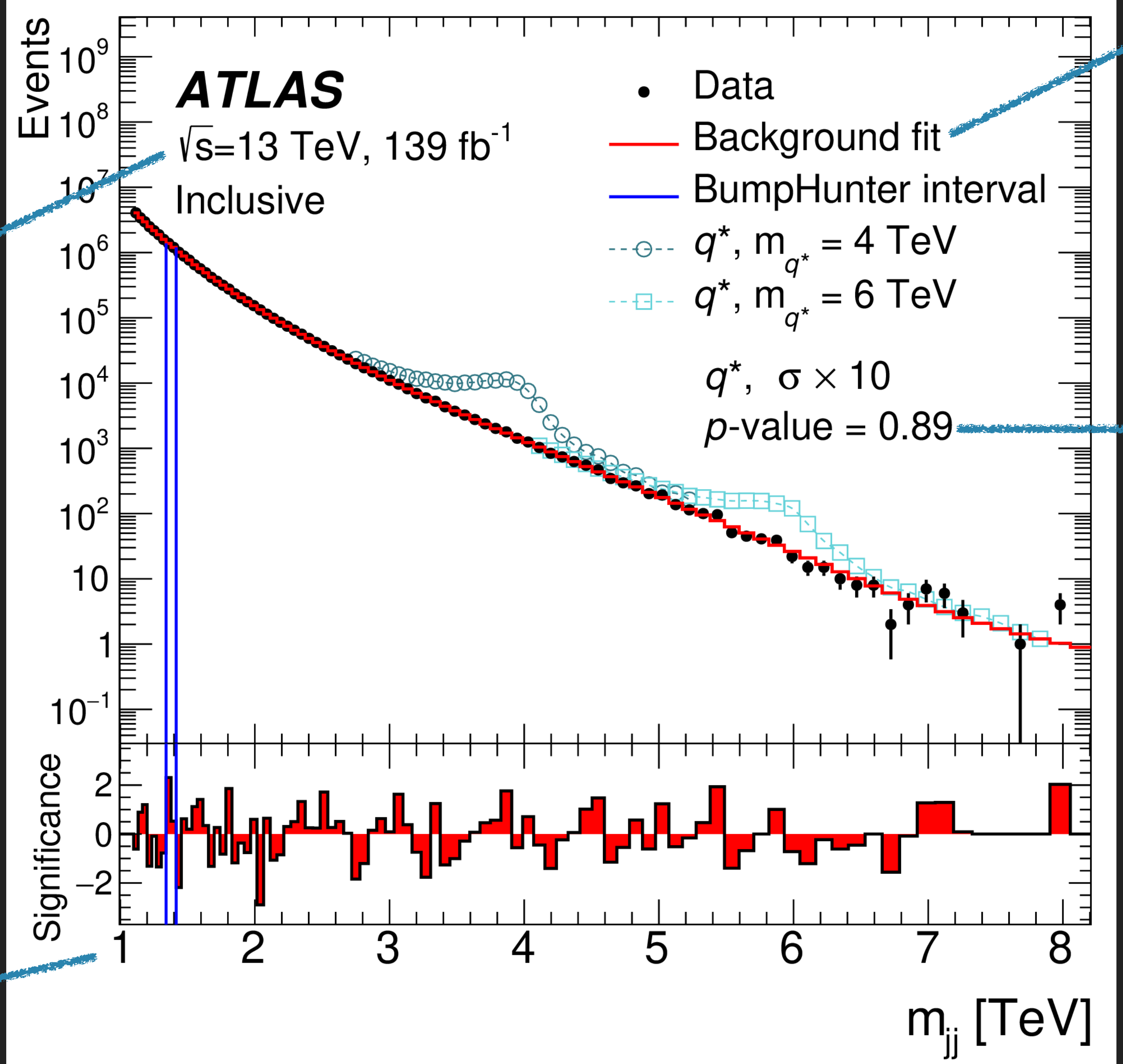




JHEP 03 (2020) 145

DI-JET RESONANCE

Ask for events with ≥ 2 high-p_T, central jets

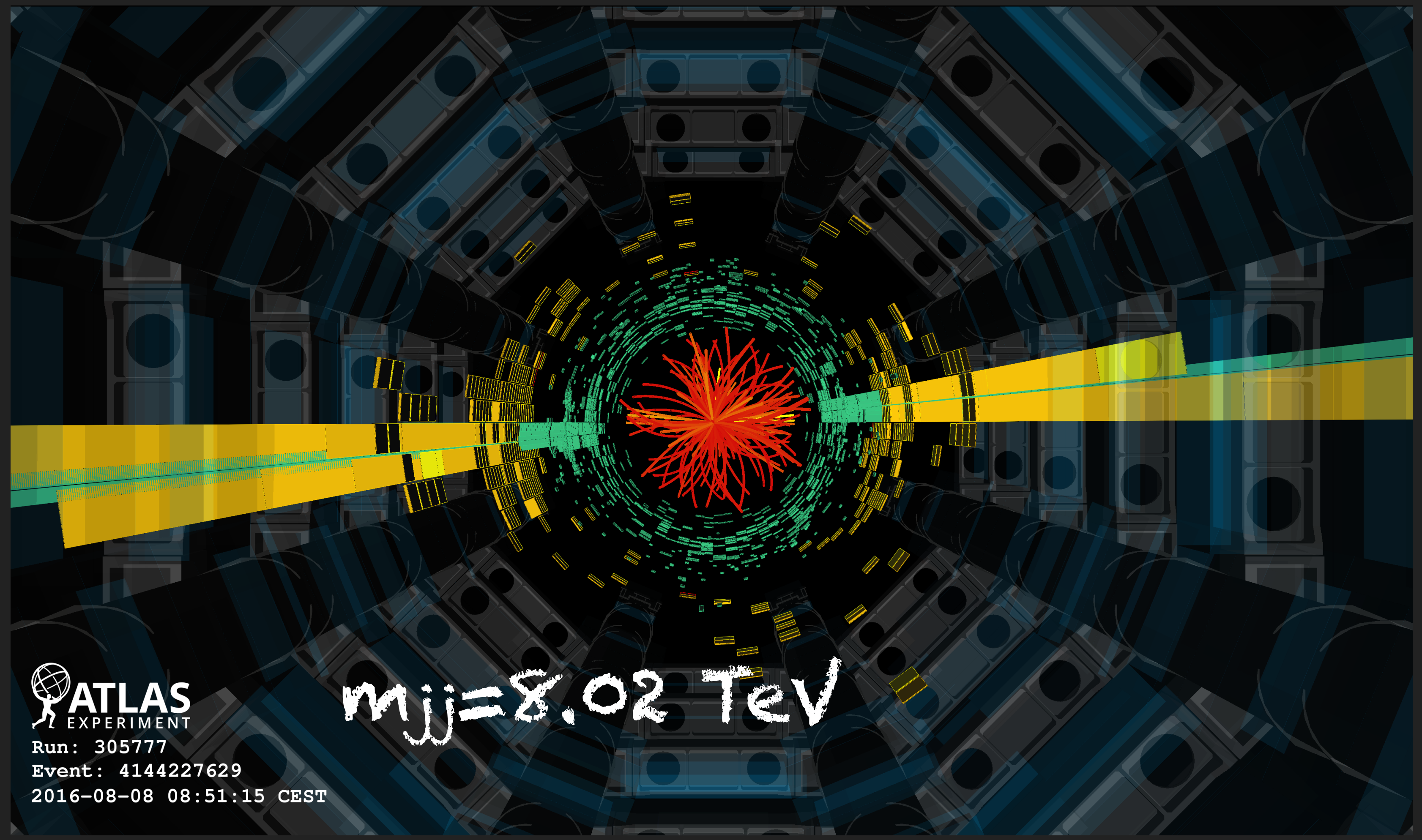


Full Run-2 dataset

Lower mjj threshold from trigger

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

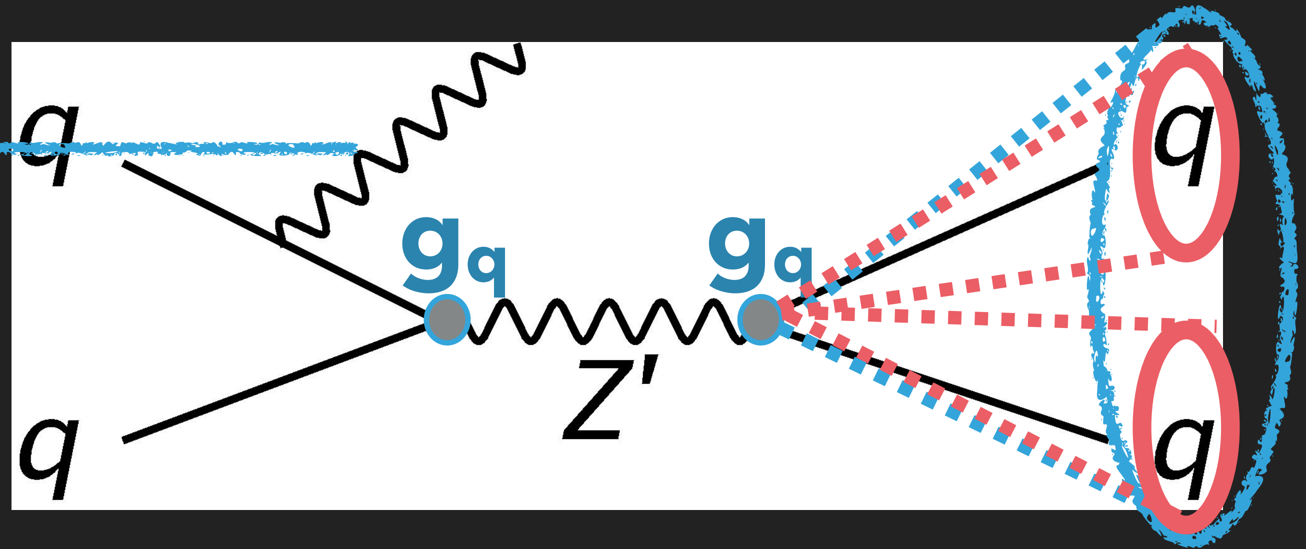
No significant excess found



LOW MASS BOOSTED DI-JET RESONANCES

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

Trigger on ISR photon: p_T > 175 GeV

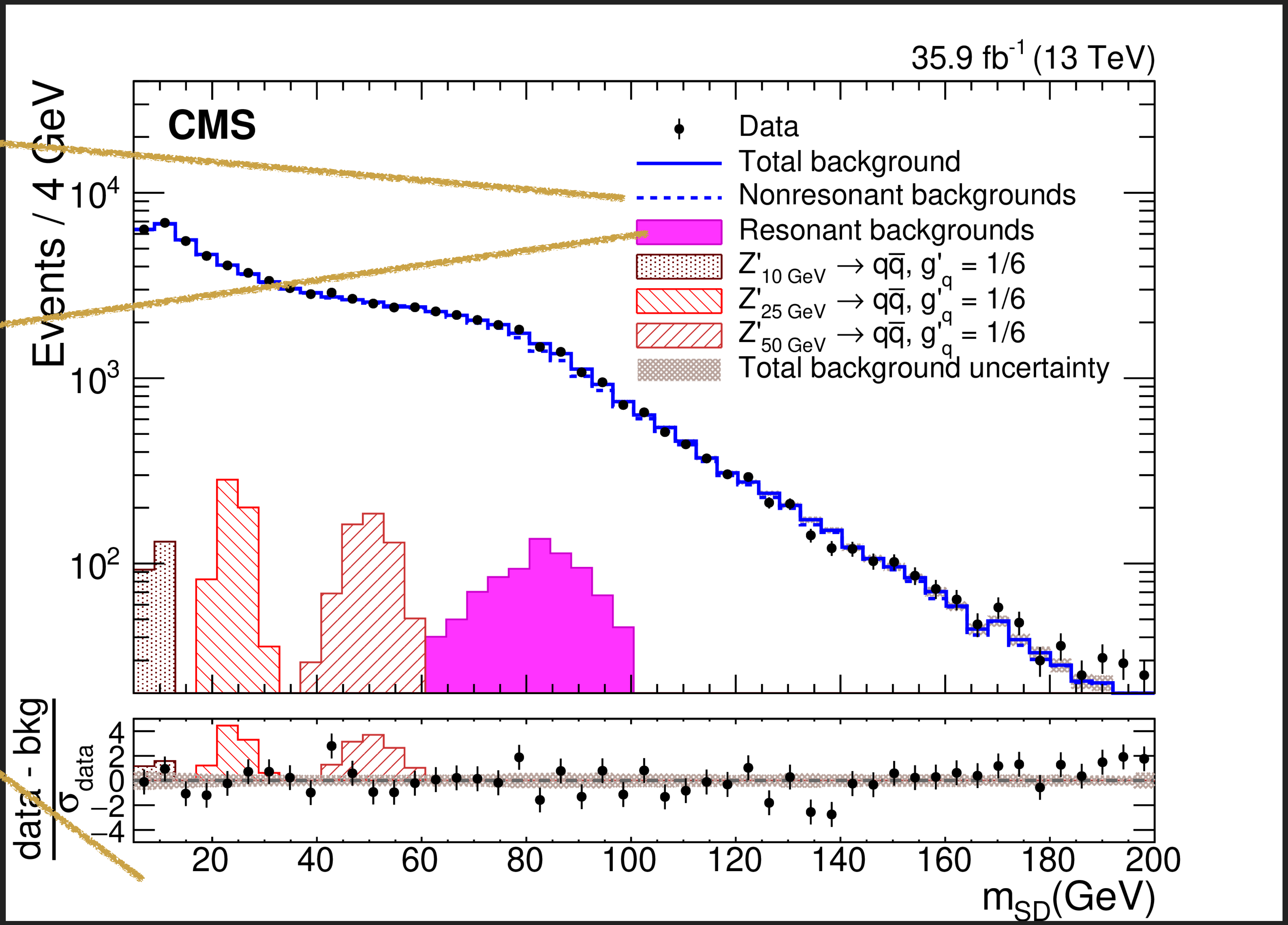


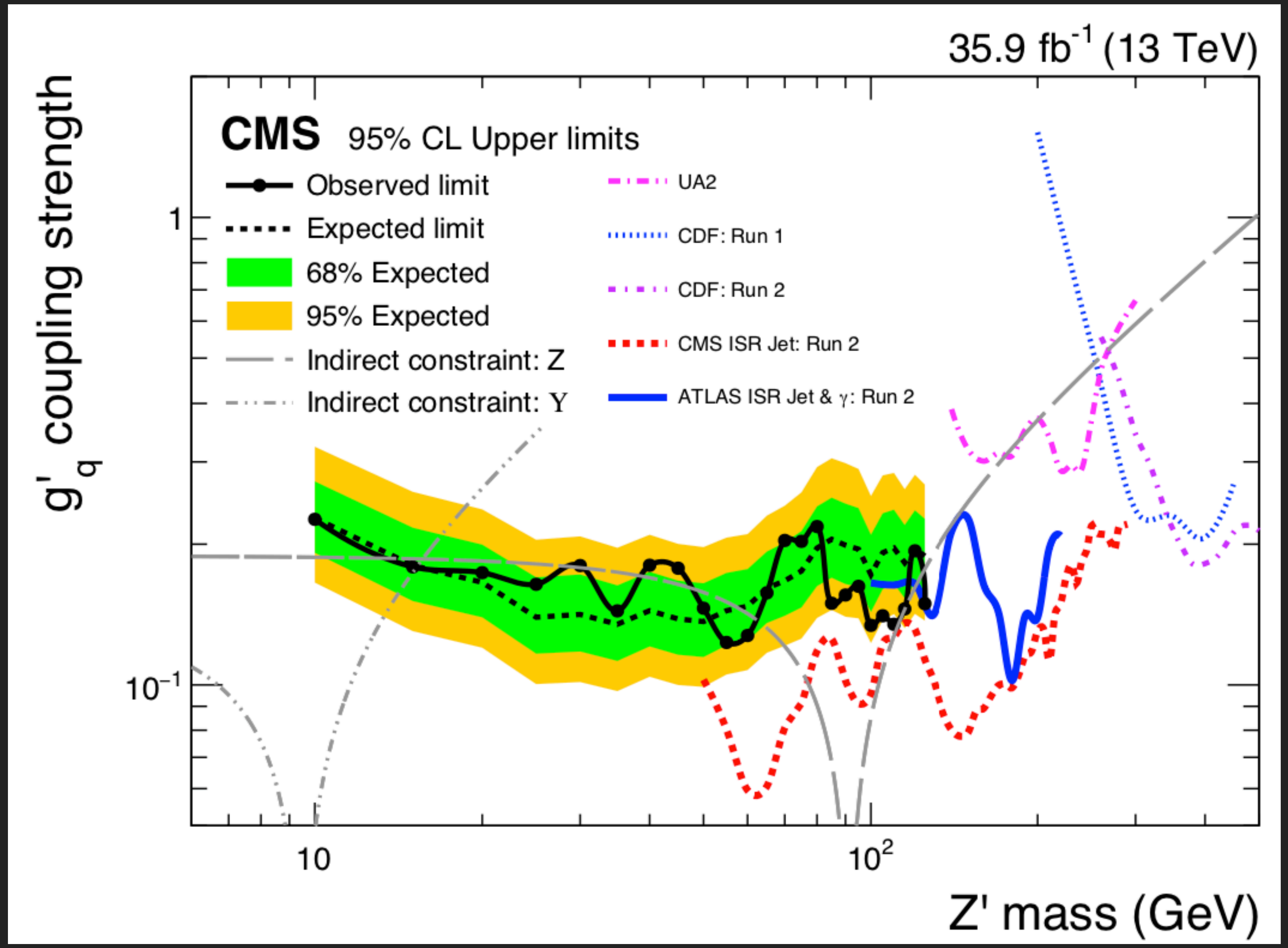
Boosted Z'→qq : large-R jet, 2-prong substructure

From fit

From MC normalised in control regions

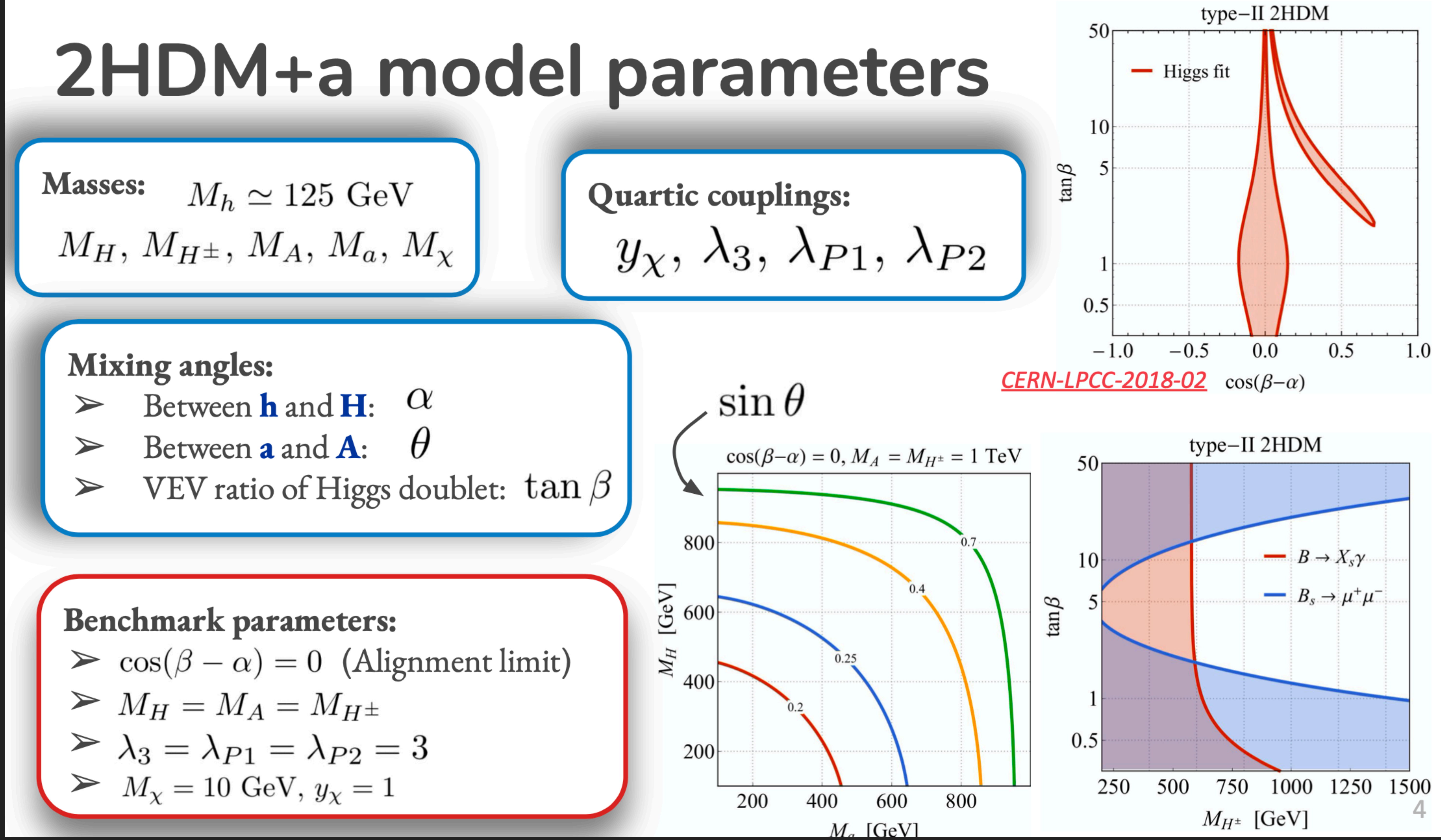
Jet masses down to 10 GeV!





- 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



Kristian Bjørke
Dark Matter @ LHC 2020