Search for Dark Matter in Mono-X Final States in CMS

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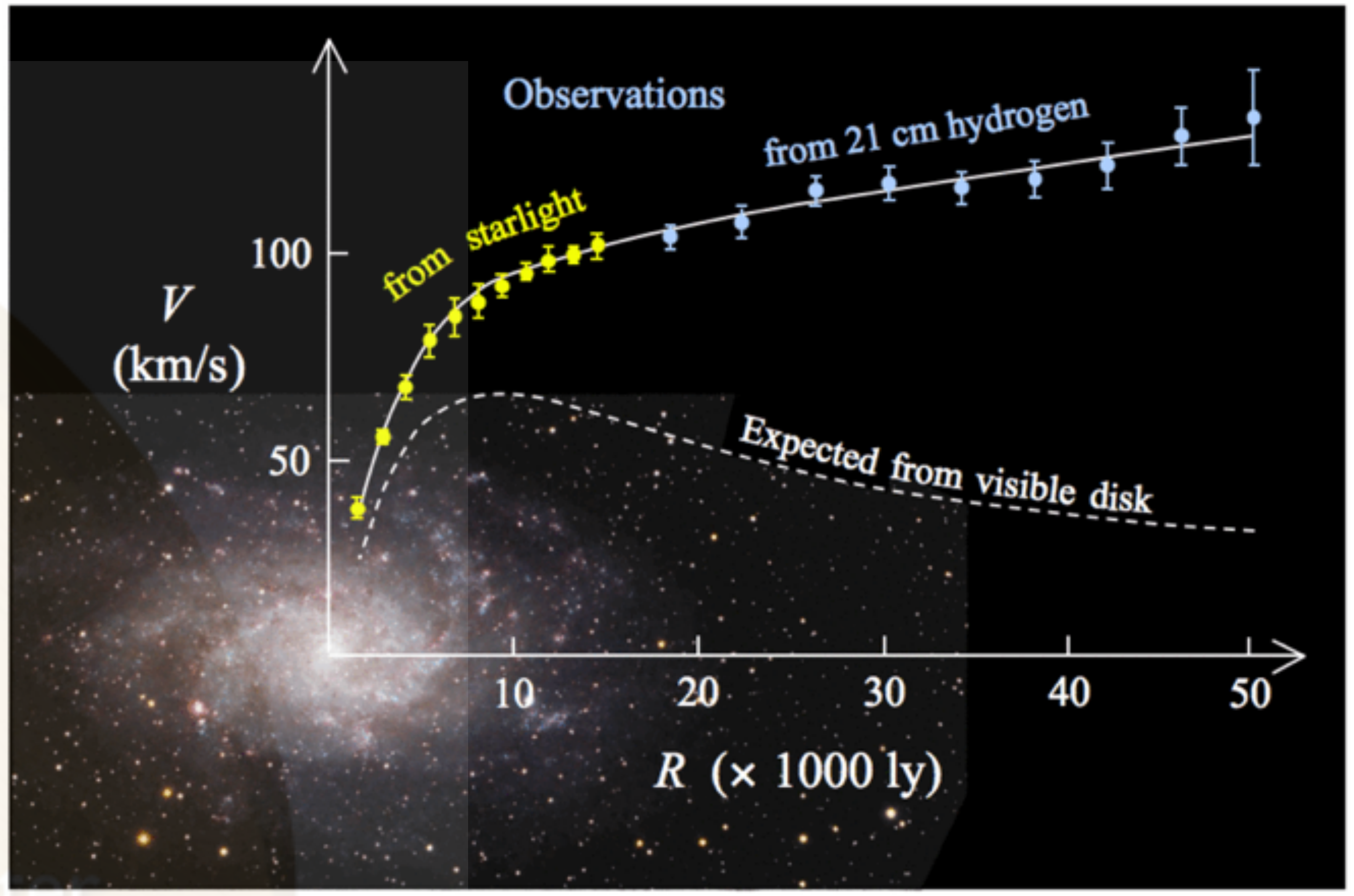
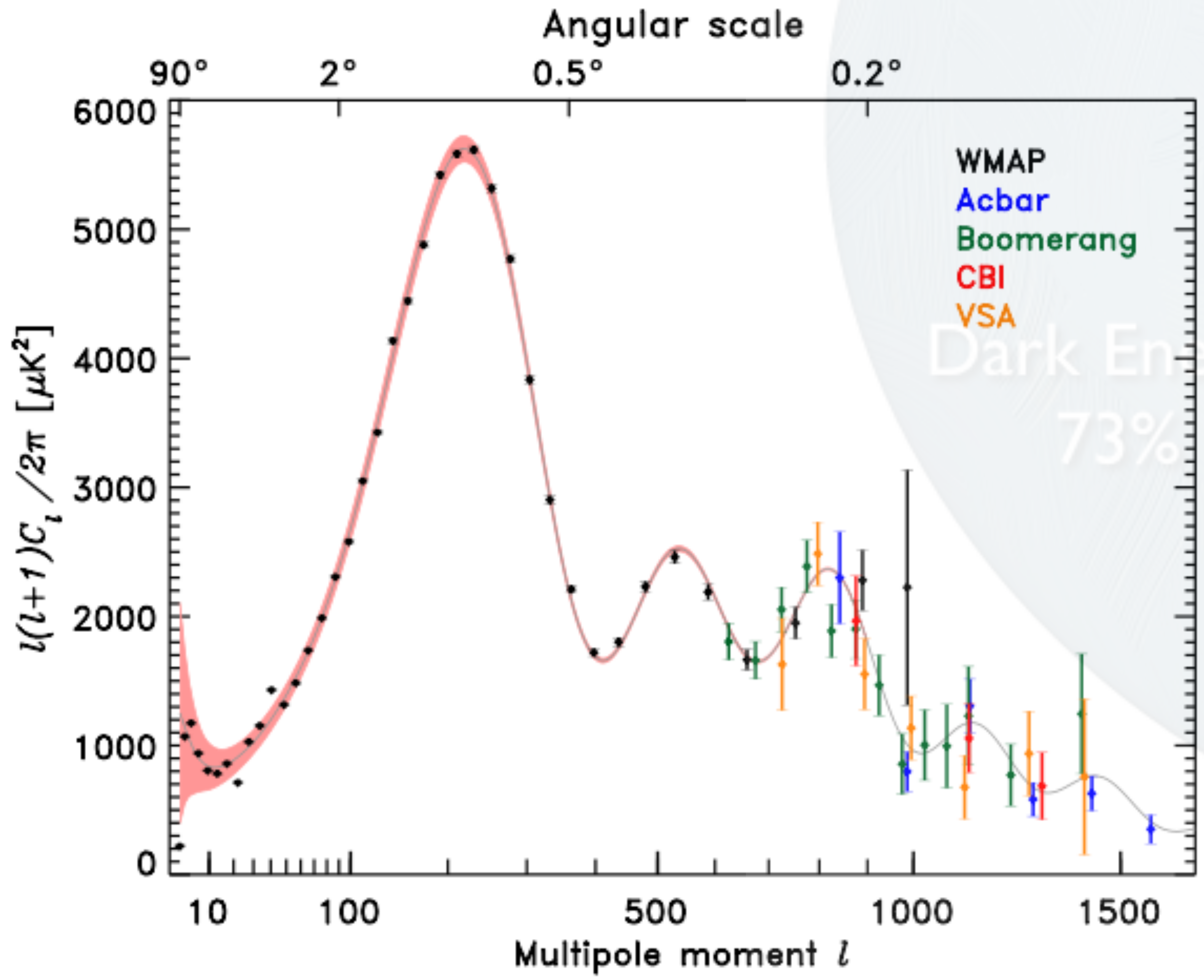
Dark Matter

- 1930s: Mass to light ratio other than unity came from measurements of galaxy rotation curves
- 1980s: Gravitational lensing of background objects by galaxy clusters





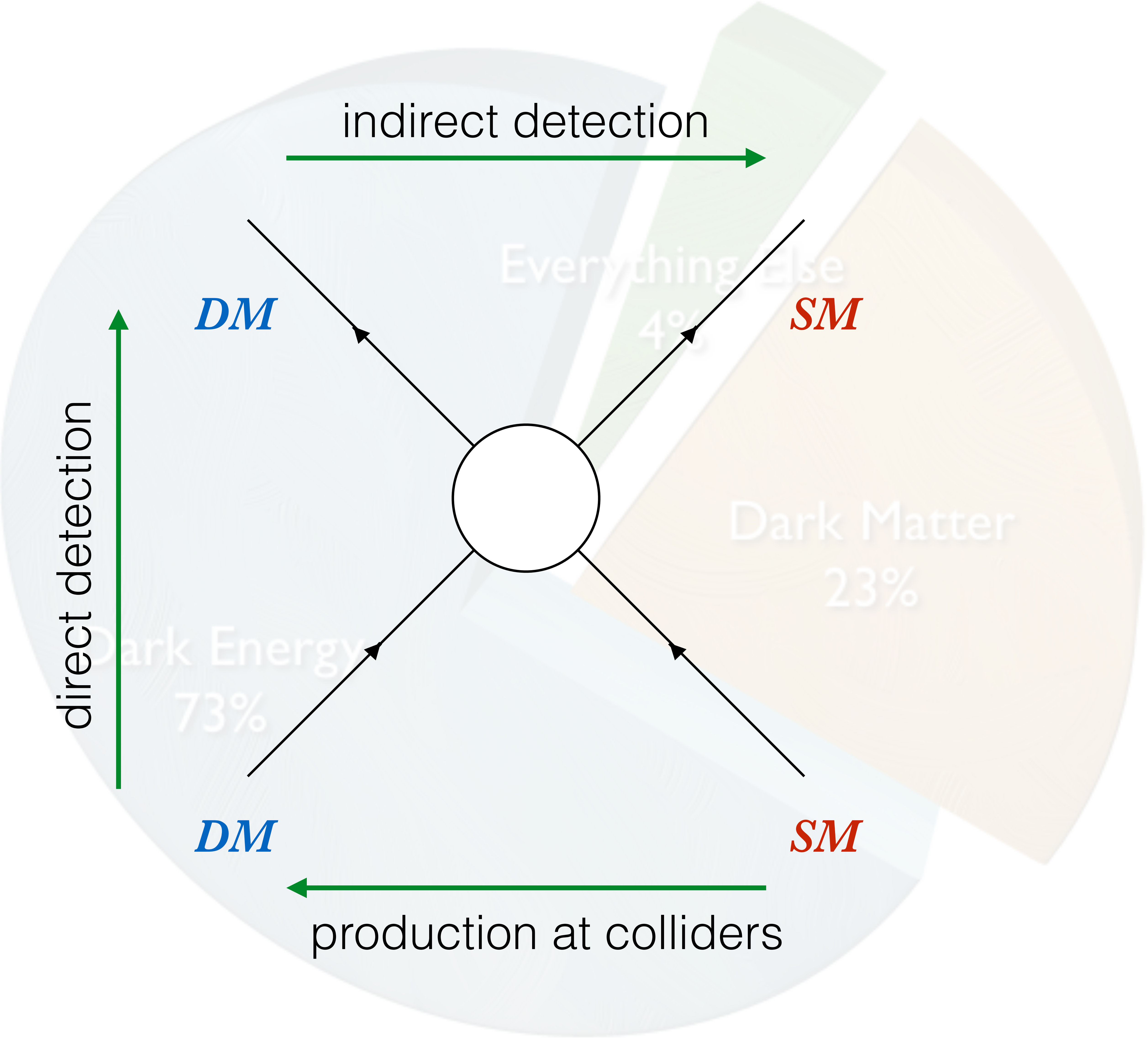
Most recently…

- 2000s: The observed pattern of anisotropies in the cosmic microwave background

Consensus:

Dark Matter is (or composed of) a not yet observed type of subatomic particle.

Dark Matter (at the LHC)

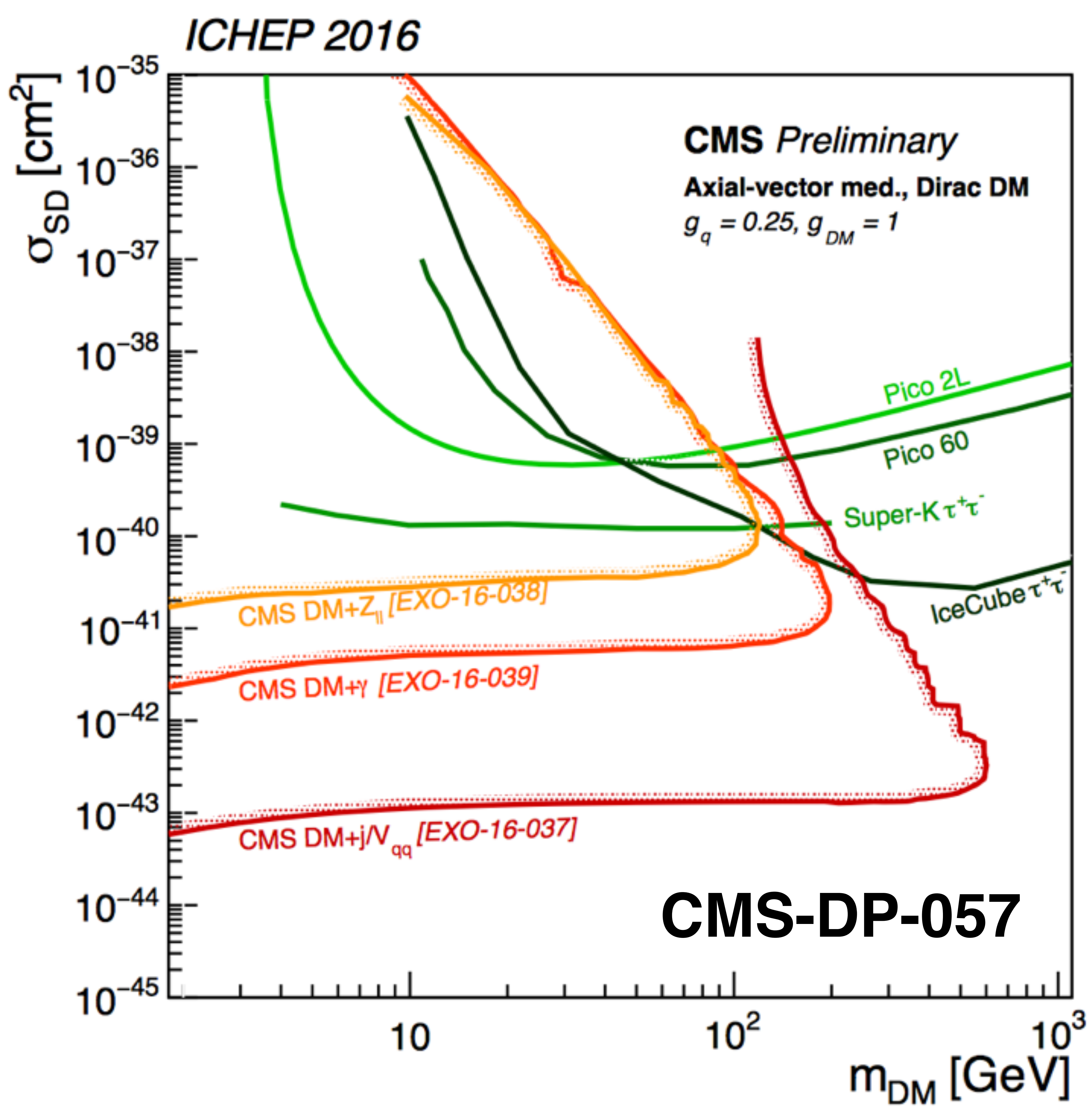


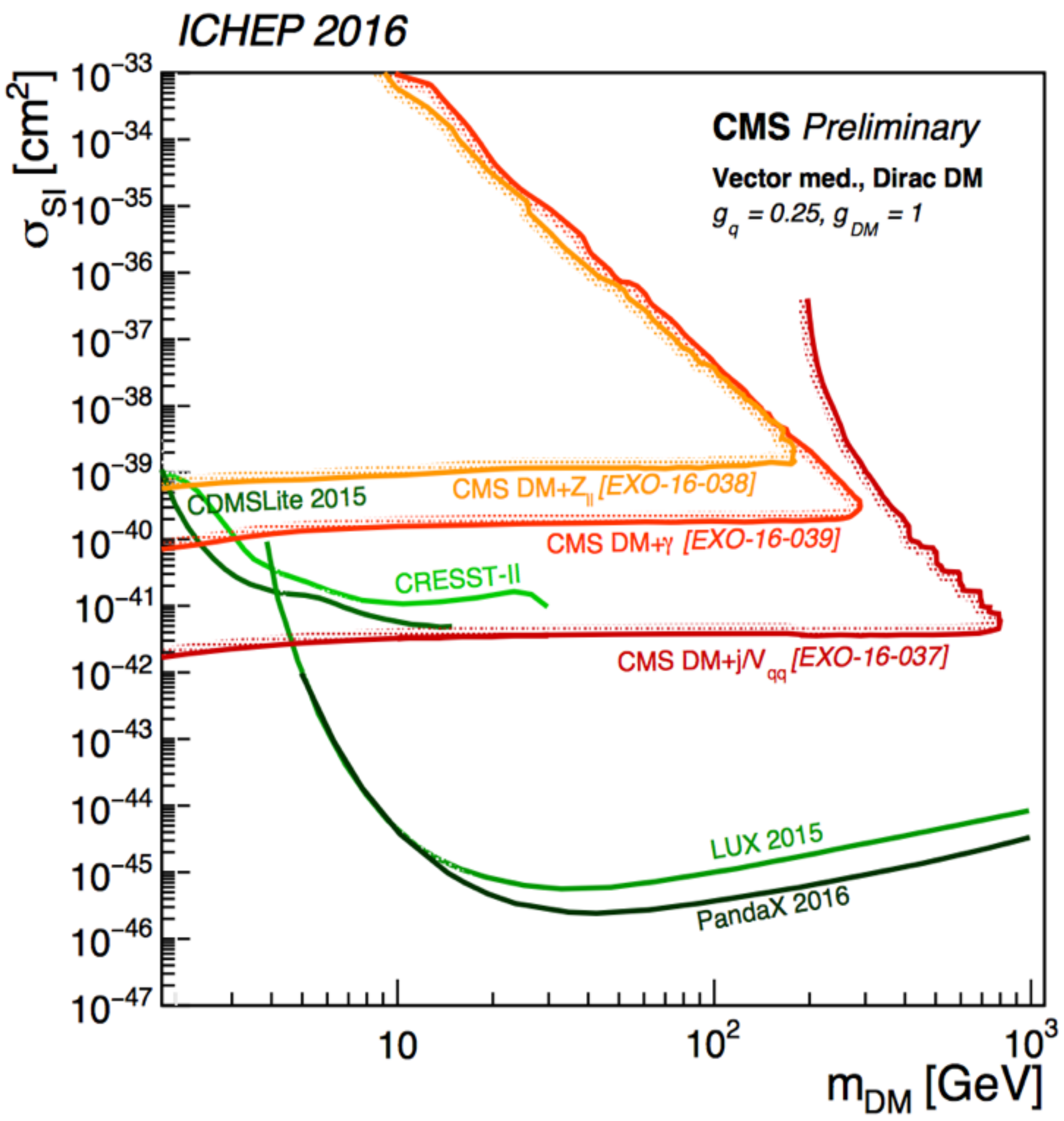
Three main approaches:

(topological permutations of the same Feynman diagram)

- DM-nucleon scattering
  - (direct detection)
- Annihilation
  - (indirect detection)
- Pair production at colliders

Complementarity of the Collider Searches



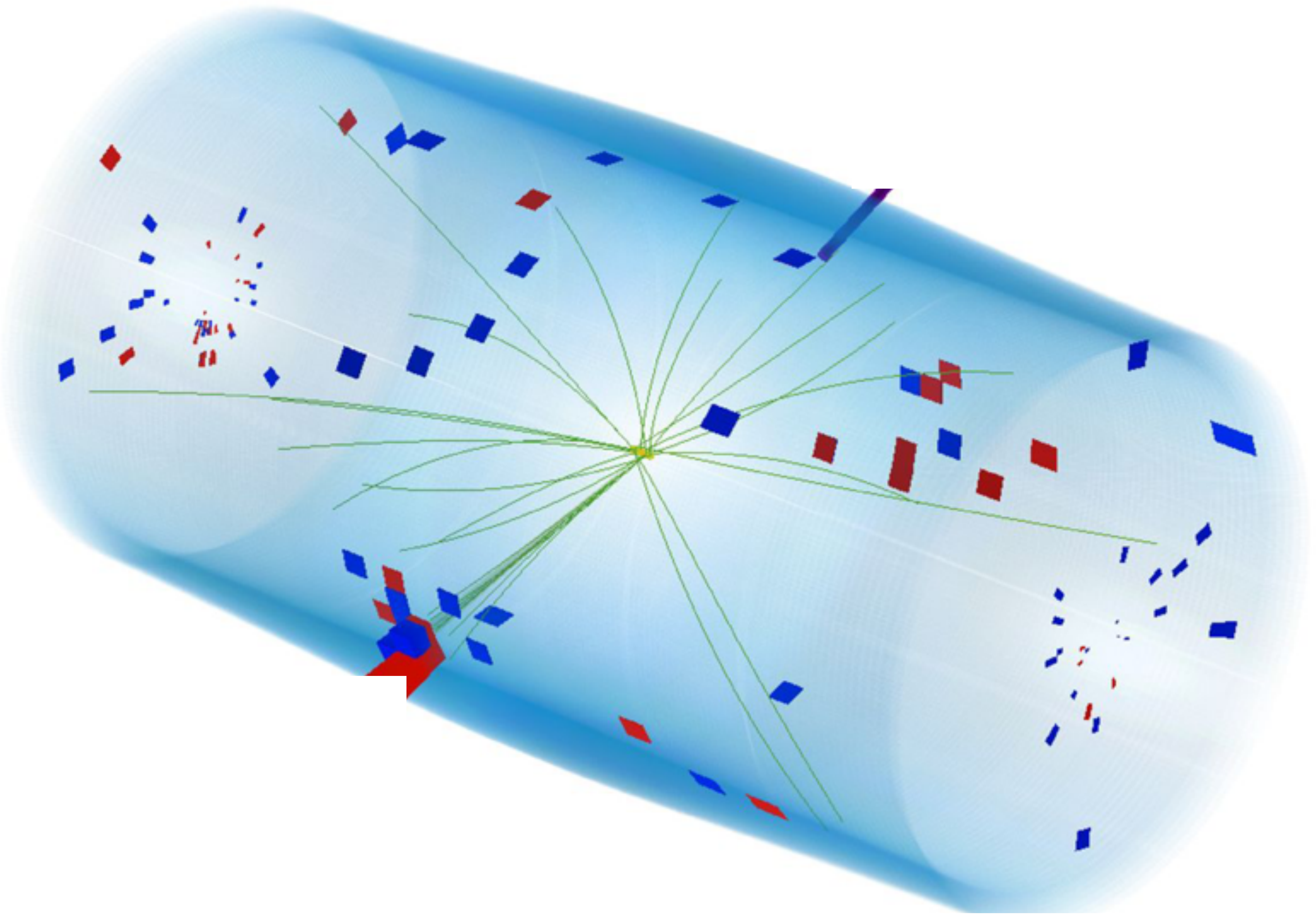


<u>For light DM</u>, LHC has higher sensitivity.

At colliders, sensitivity is limited by threshold effects, resolution and background estimation.

Dark Matter in association with Mono-X: Experimental Signature

CMS-EXO-16-037



What is the signature of dark matter?

Dark Matter in association with Mono-X: Experimental Signature

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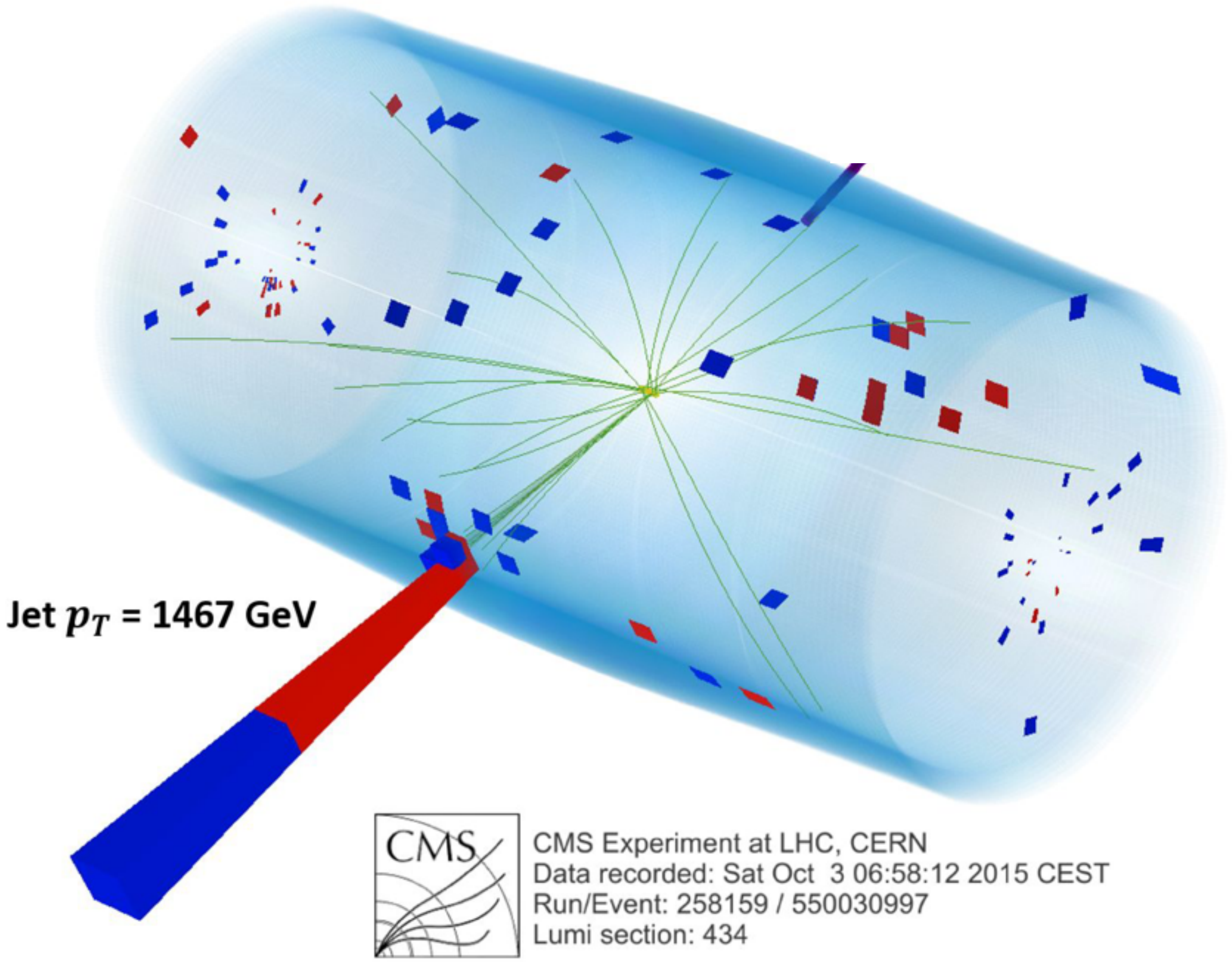
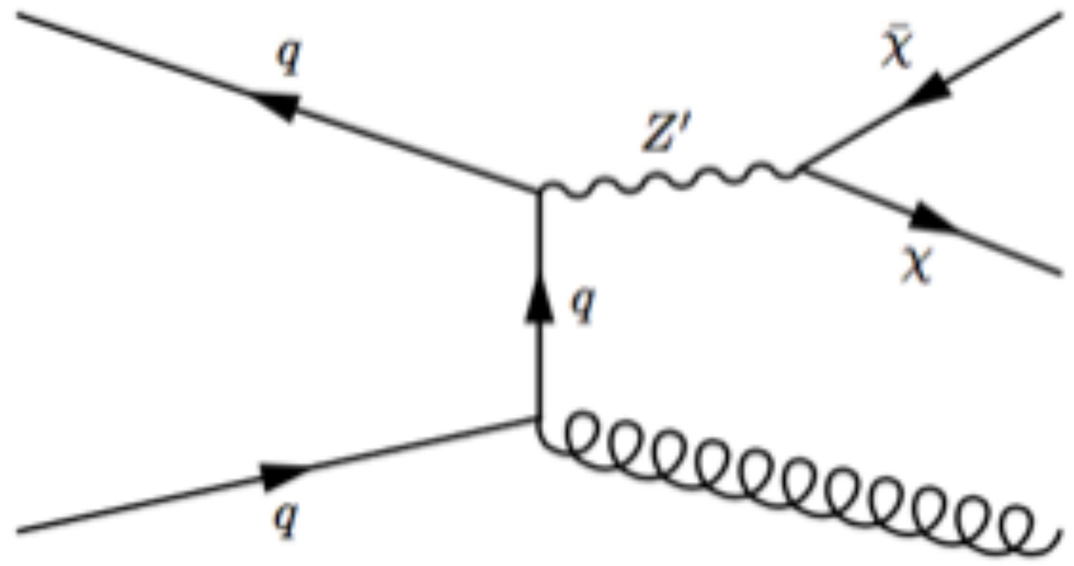


What is the signature of dark matter?

- **weakly interacting**, and they will leave **no signature in the detector**!
  - can only be detected when DM is produced in **associated** to an **initial state radiation**



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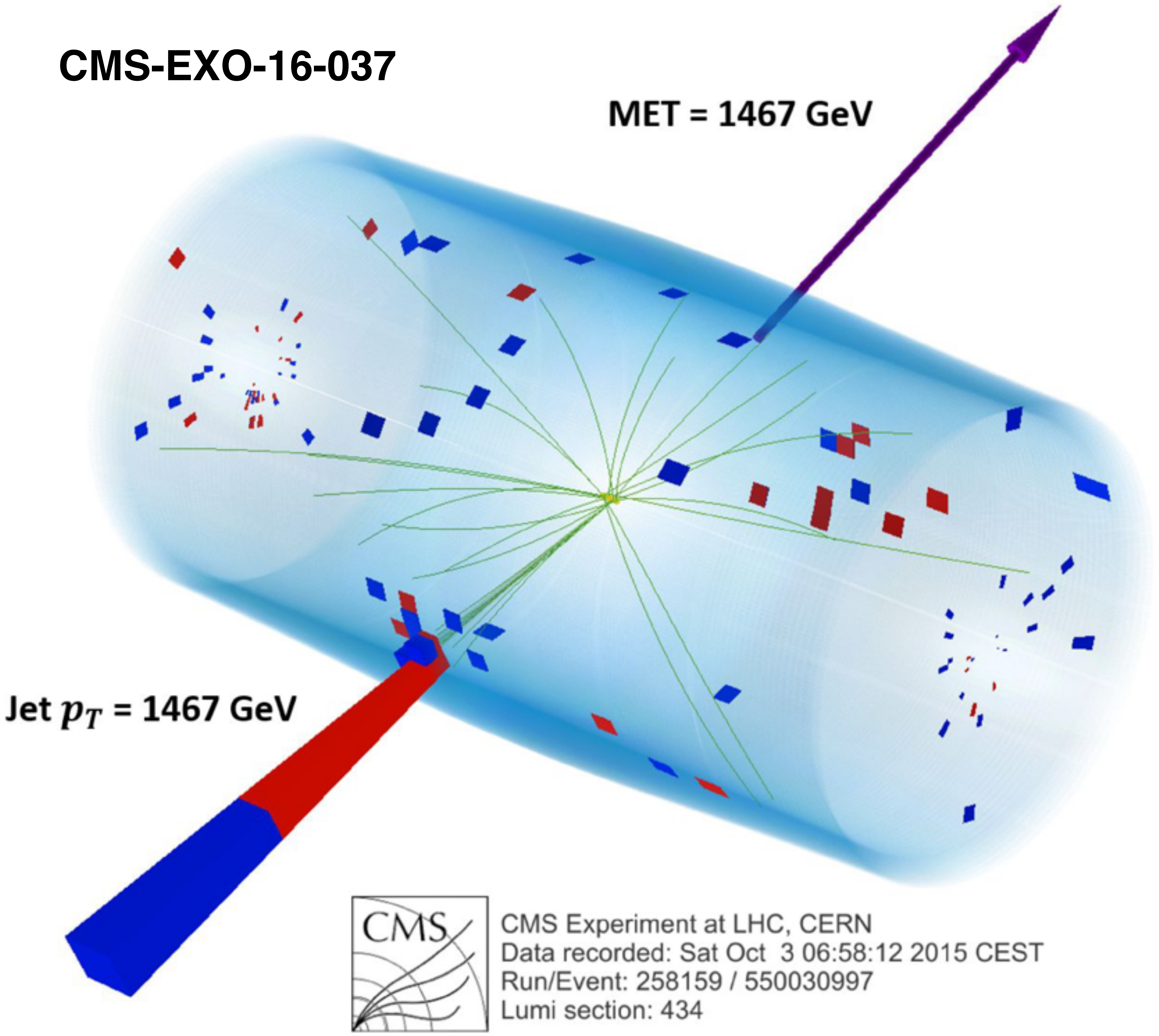

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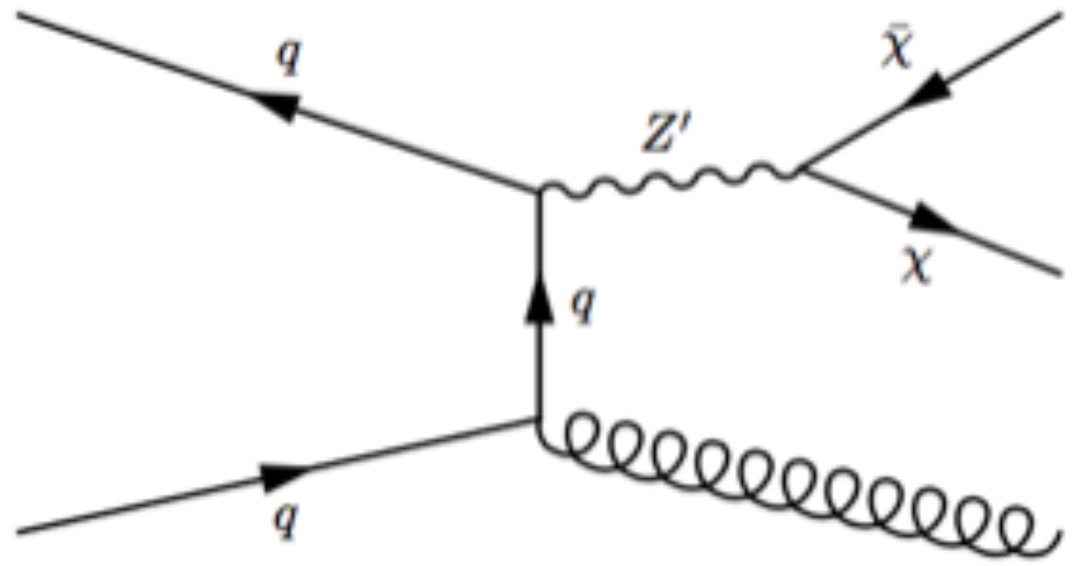

Total momentum in the event has to be balanced!

The existence of **Missing Transverse Energy** in the event could mean => **Dark Matter**

Looking at the Recorded Data

How do we analyze the recorded data?

Strategy is to estimate all the “known” standard model processes in the final state of interest, and **look for deviations** from standard model that is compatible with the signal expectation.

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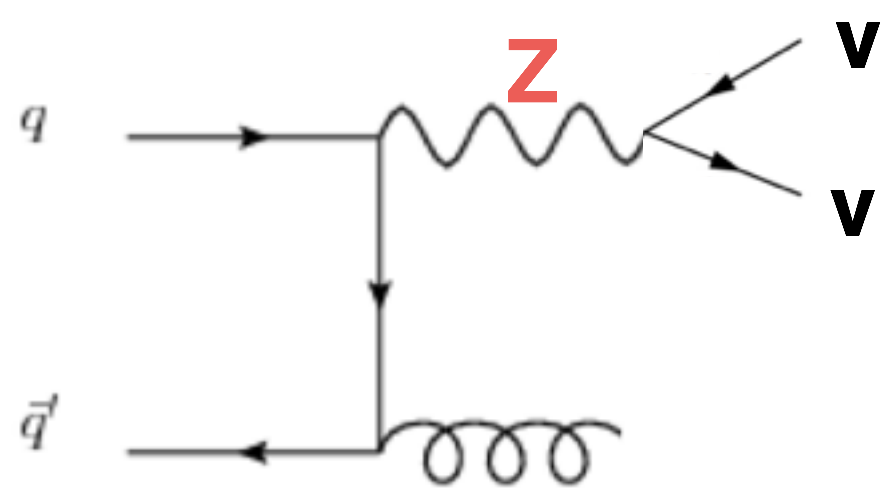
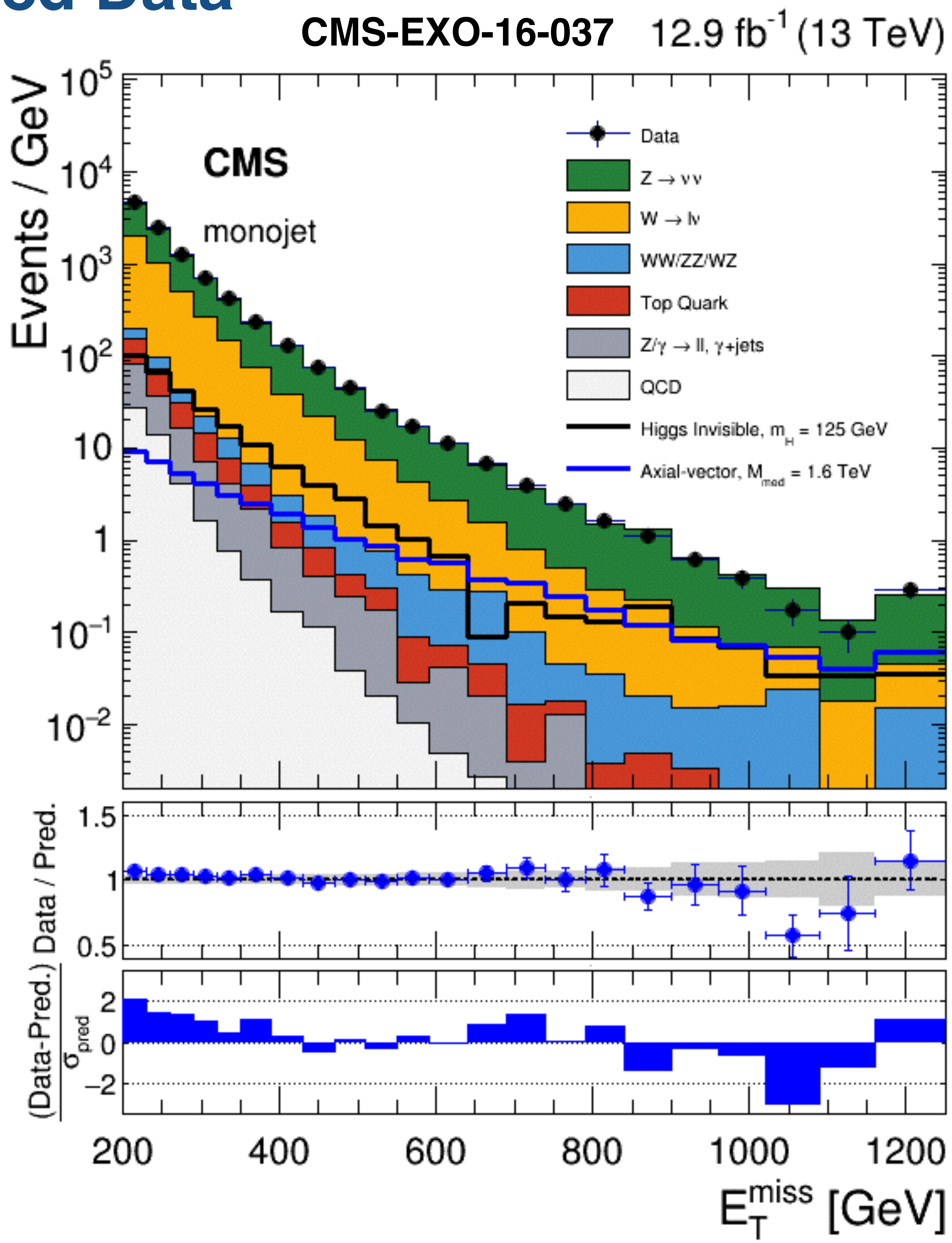


Irreducible largest background (Standard Model)



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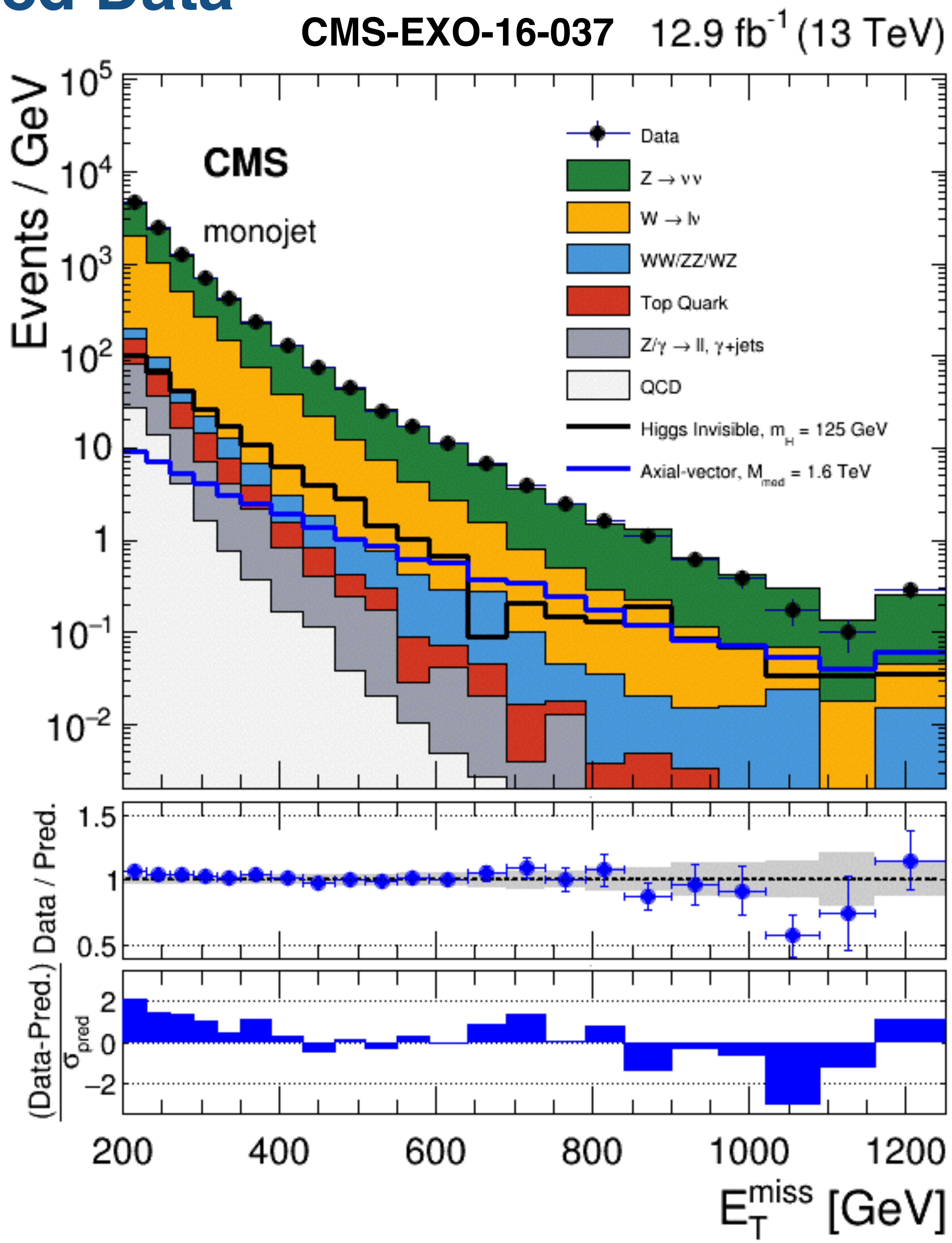
Irreducible largest background (Standard Model)

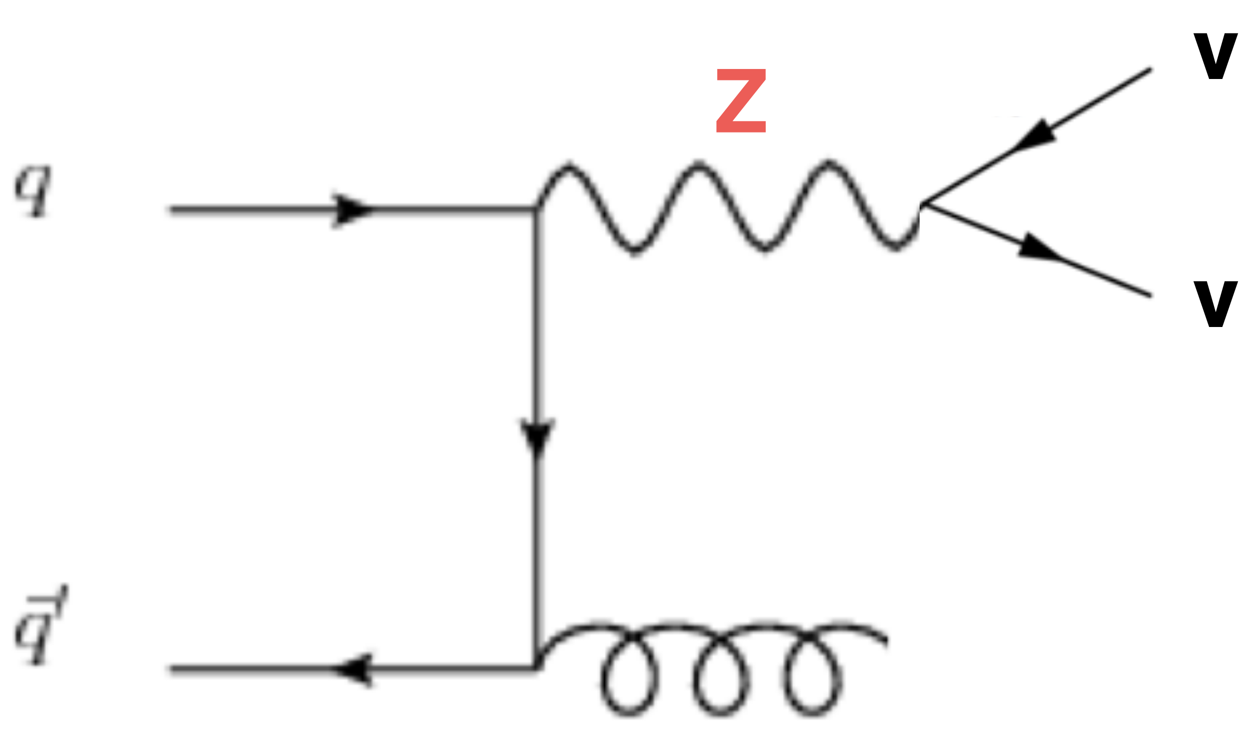
Dark Matter Signal

Not so easy to distinguish! Identical in signature.

Conclusion: Have to measure the standard model background very precisely (with lowest possible uncertainty)



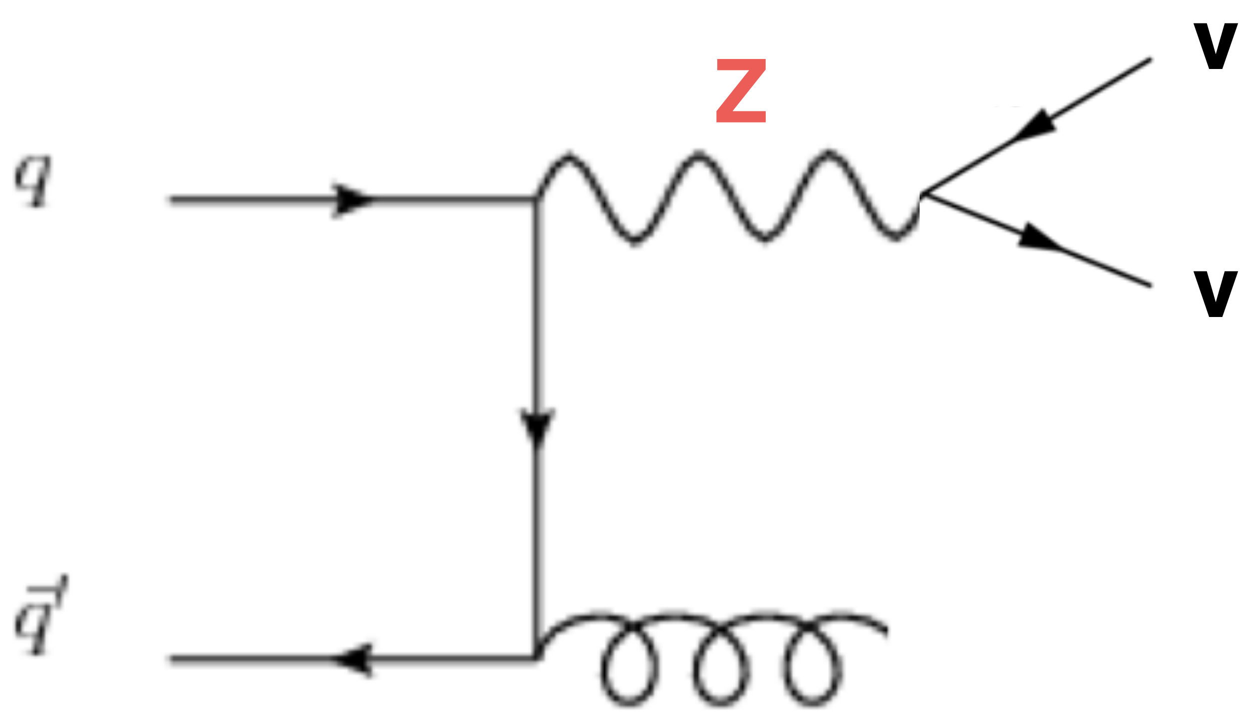
Leading Background Estimation

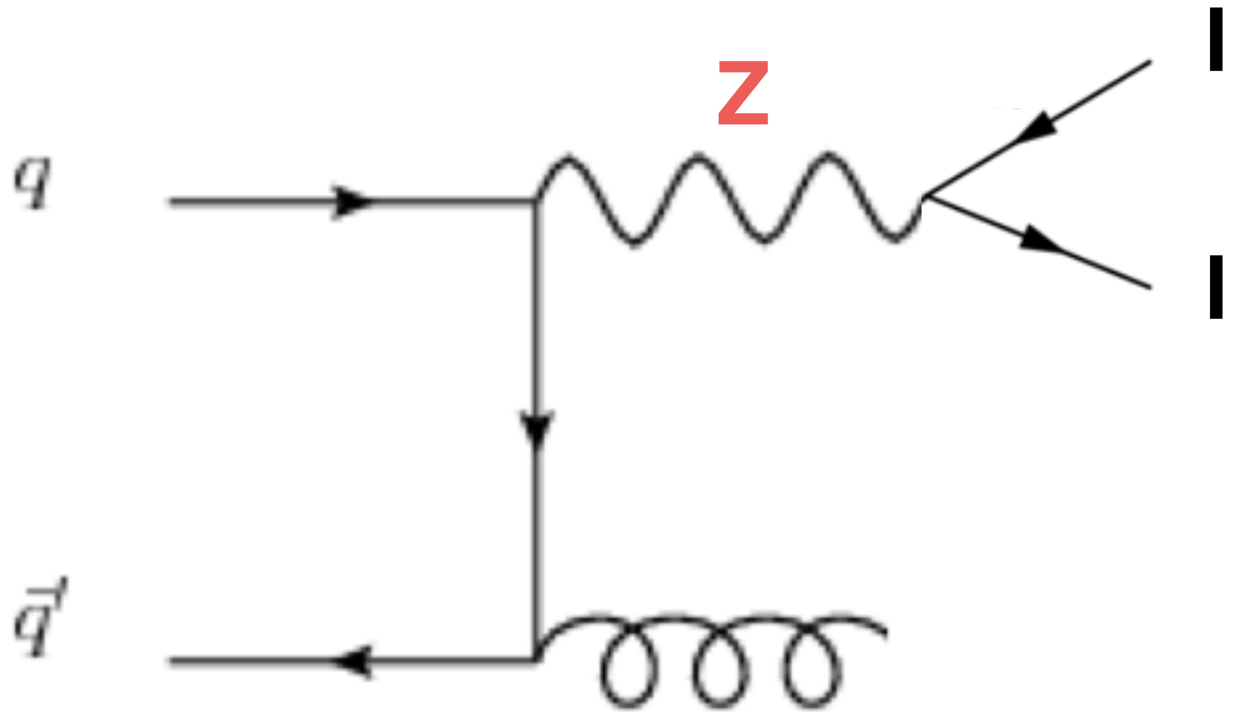


Z(vv)+jets: Irreducible background and makes up 50 to 80% of the total background estimation!

To overcome the shortcomings of the simulation (MC) we use data to measure the background

Leading Background Estimation





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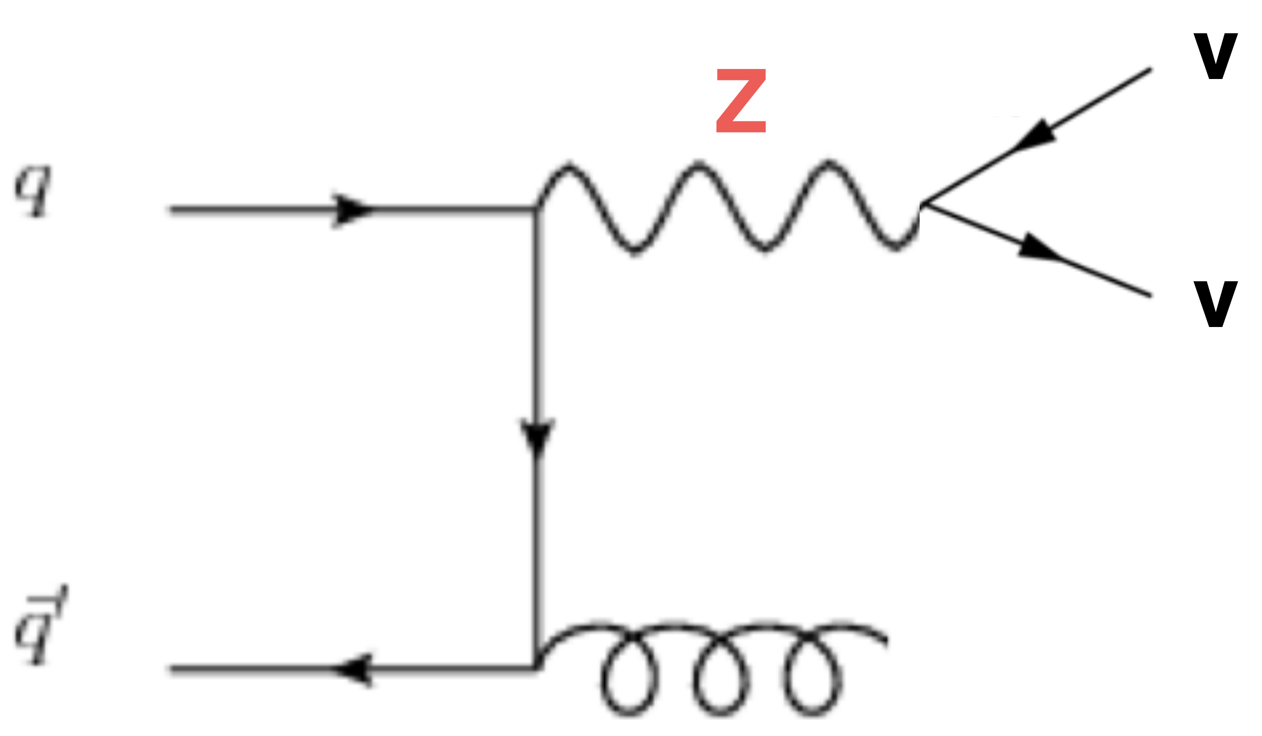
Question: What other standard model processes can we use to estimate the leading background more precisely?

Leading Background Estimation



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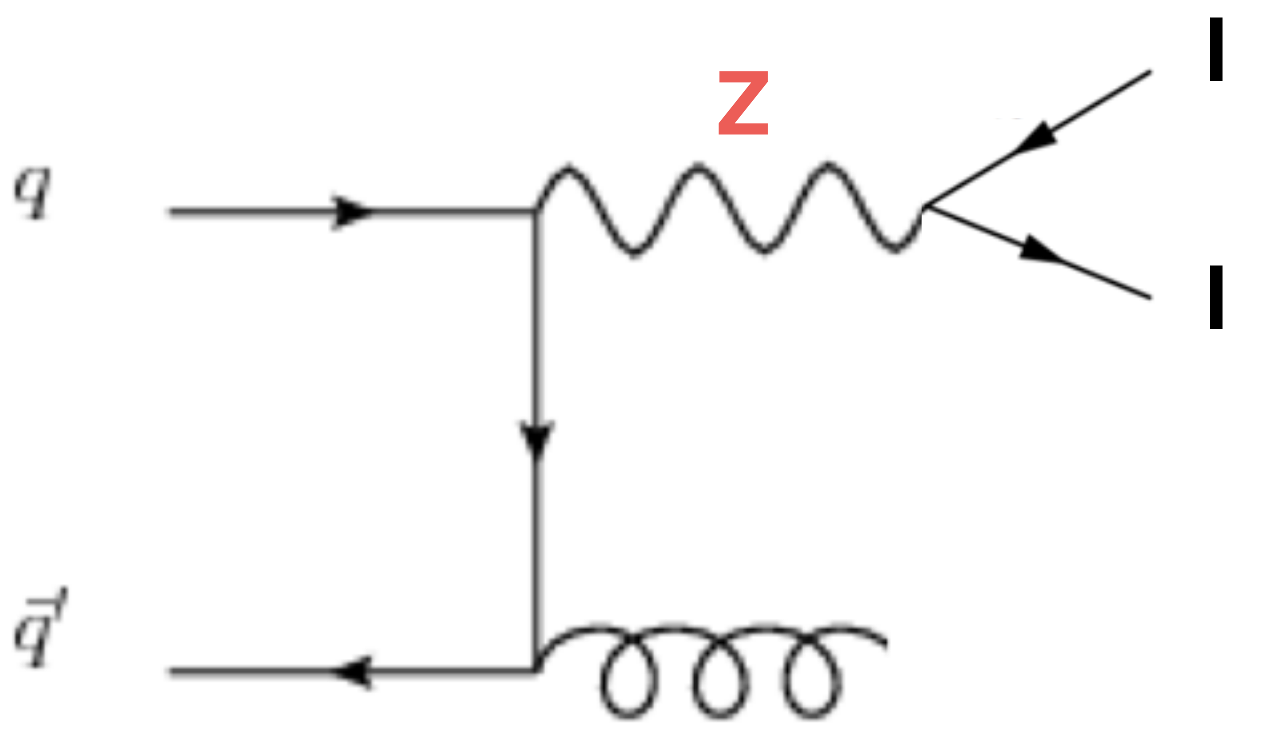


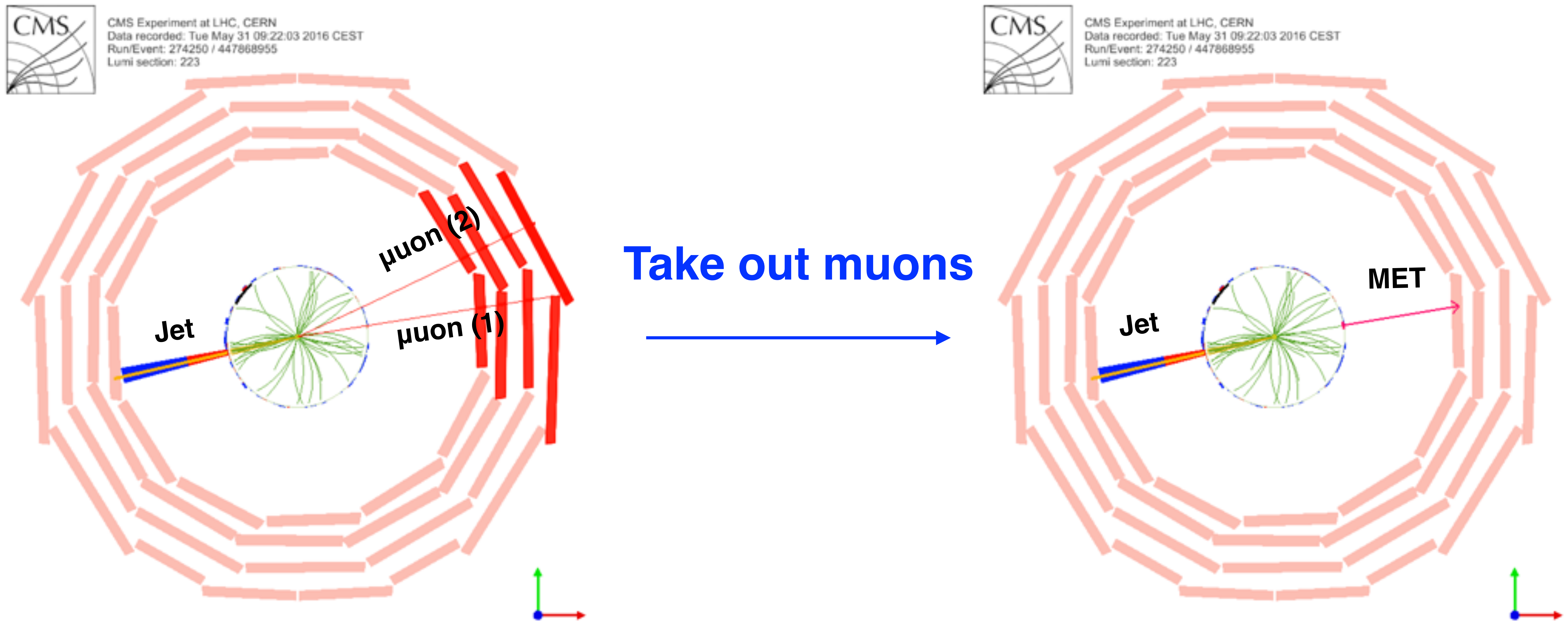
Same pT spectra as Z→νν

but… statistically limited

Z→μμ branching ratio ~3%

Z→νν branching ratio 20%

If we remove the muons from a Z→μμ event, it mimics a Z→νν event



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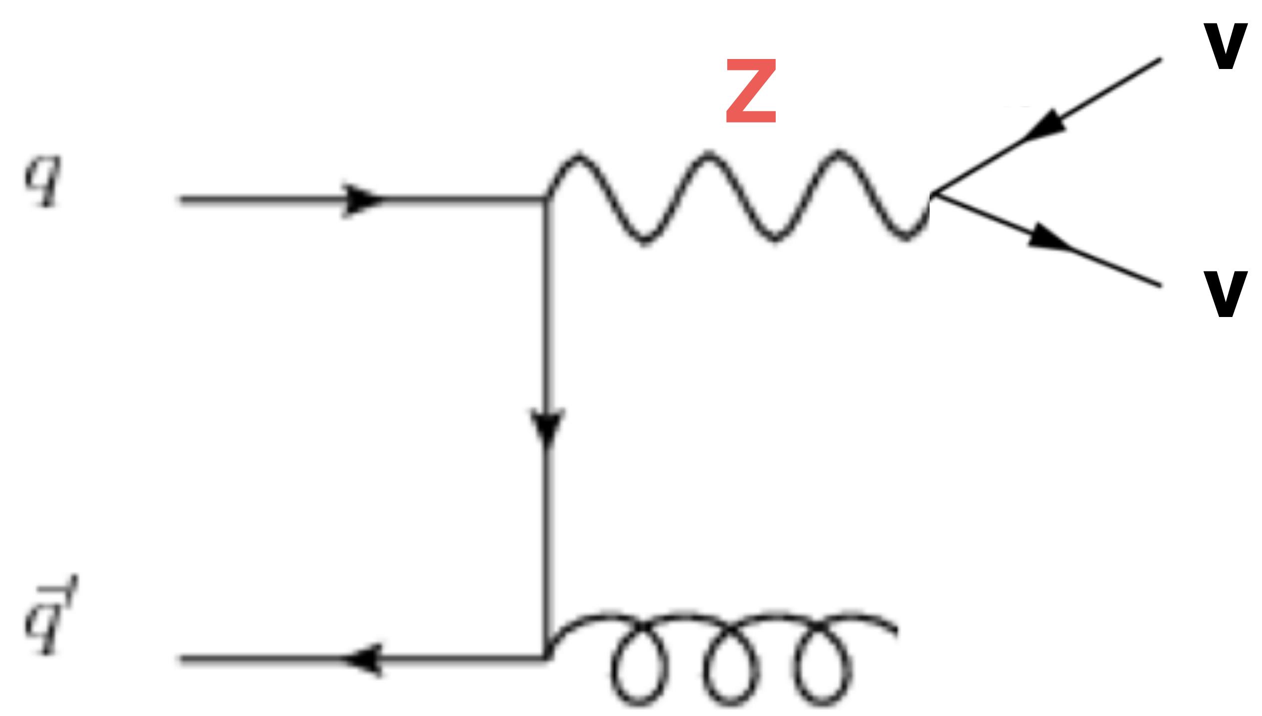

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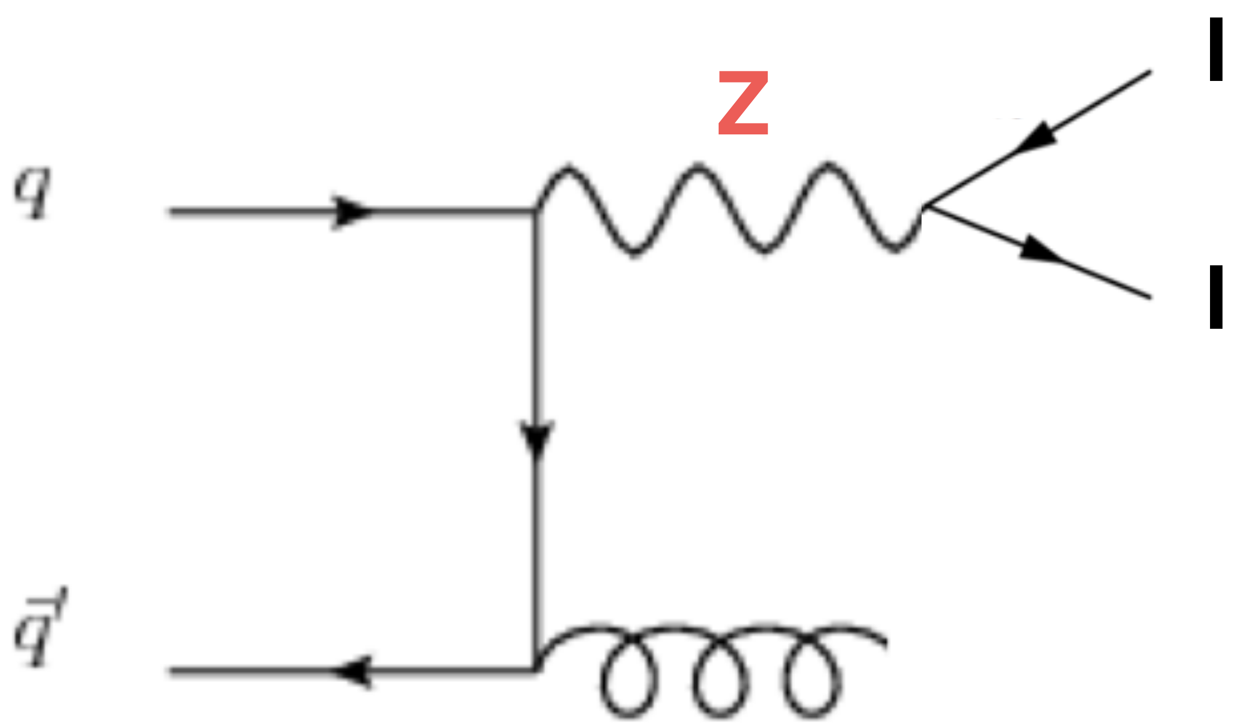

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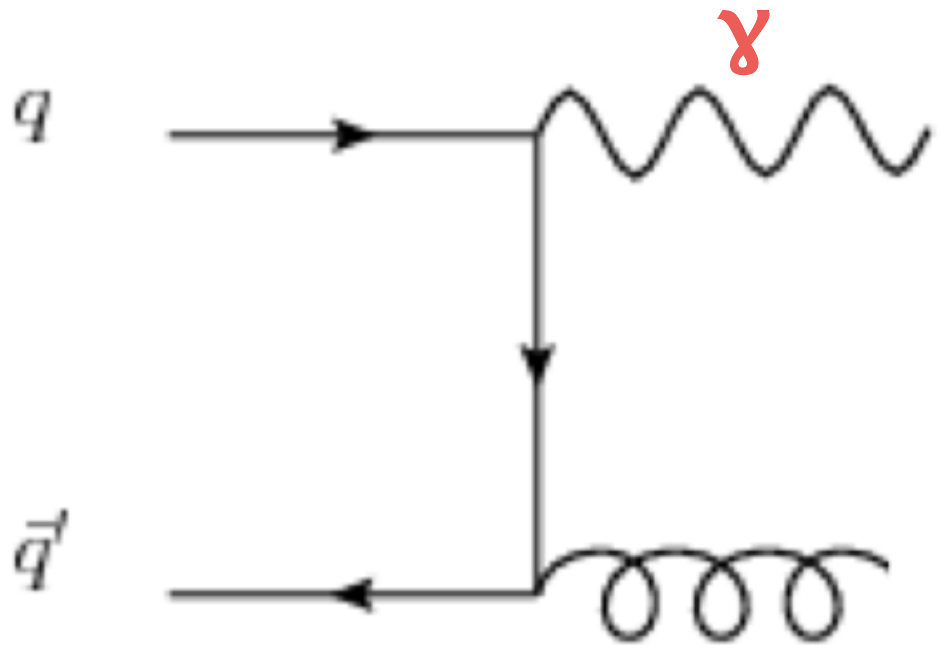
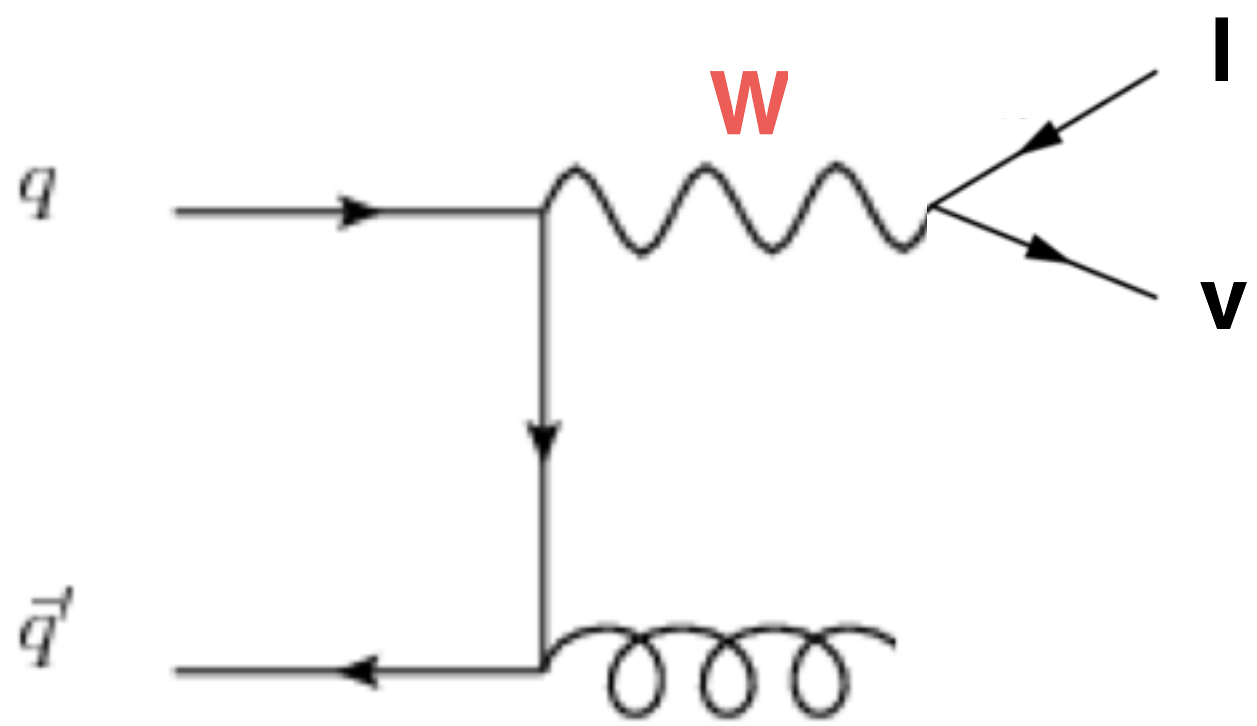


Similar pT spectra as Z→vv

Statistically rich!

but…

adds theory uncertainties



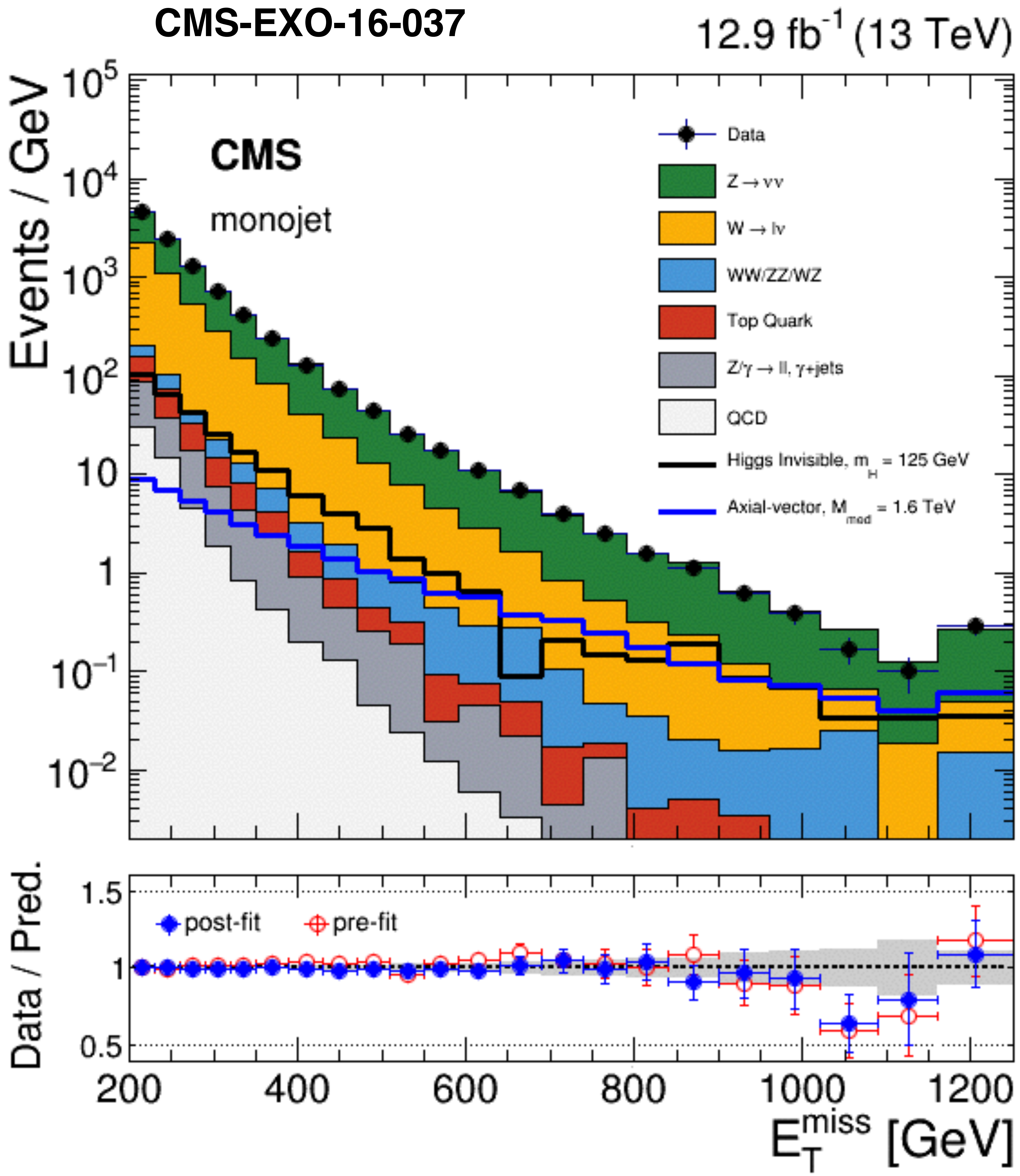
Similar pT spectra as Z→vv

Statistically ~ Z (vv)

but…

adds theory uncertainties

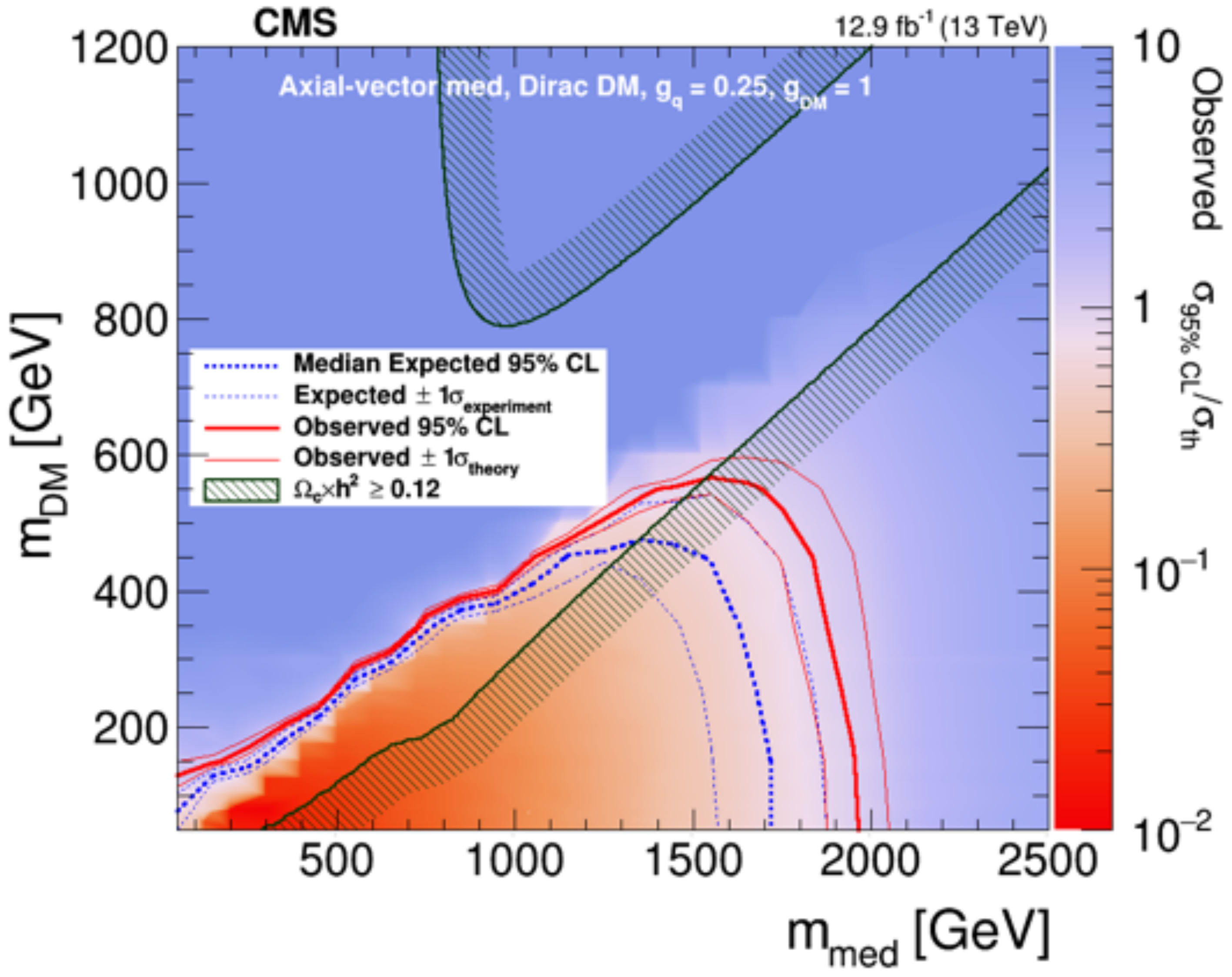
Results

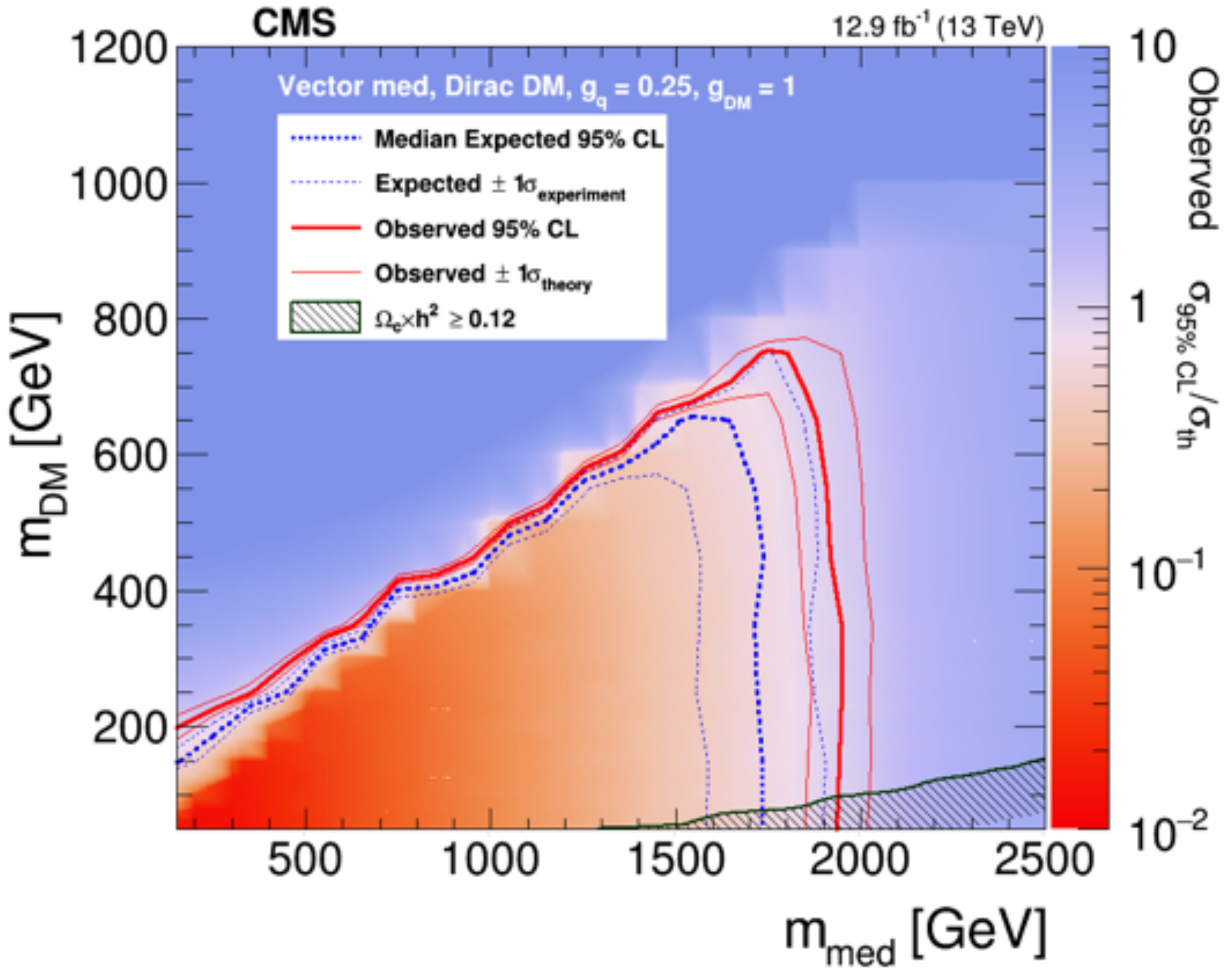


Unfortunately… data is found to be compatible with background observation..

This means we can exclude the existence of the dark models we have been testing.

Using the 13 TeV data from 2016 we can set the **most stringent exclusion on Dark Matter to date!**





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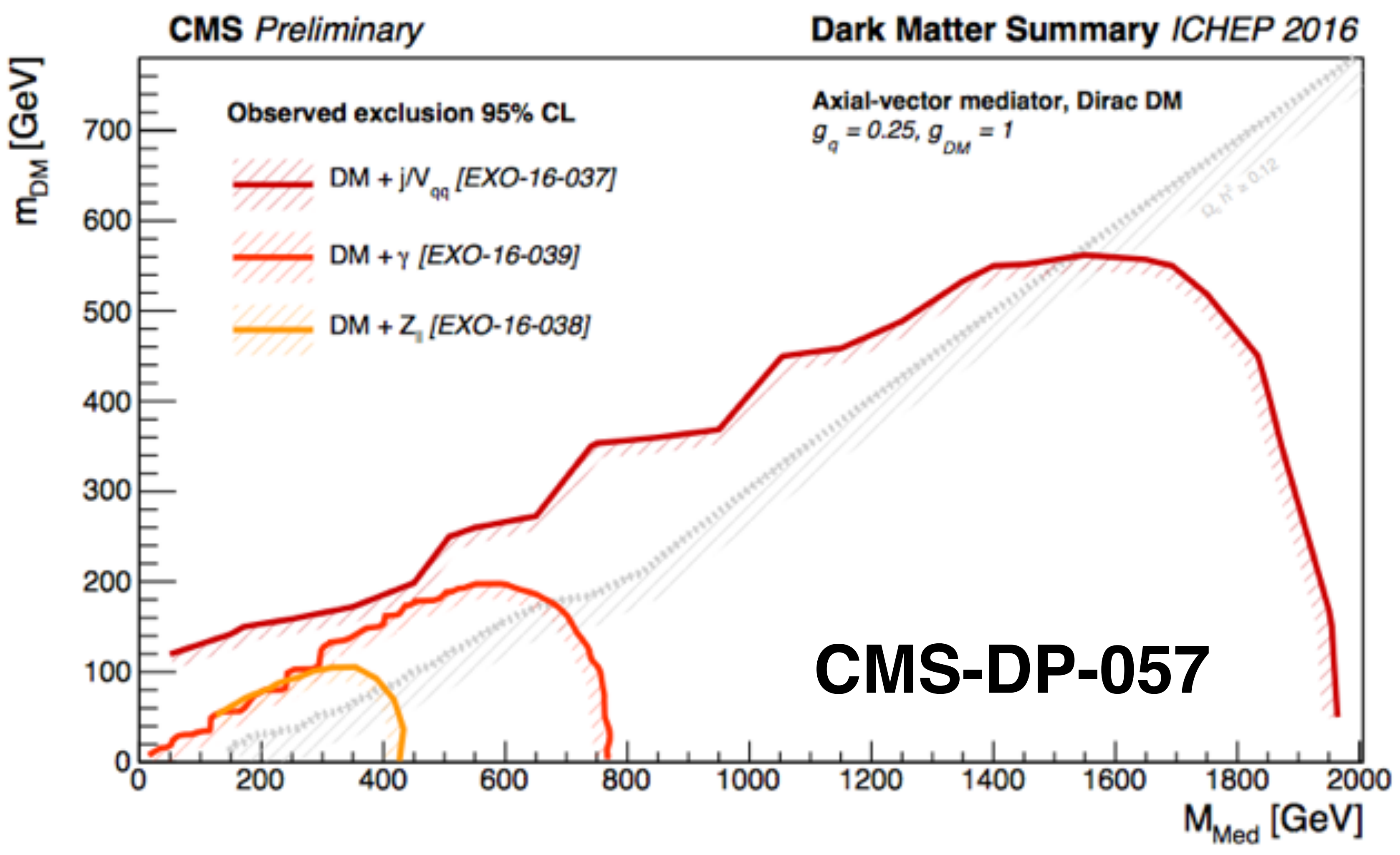
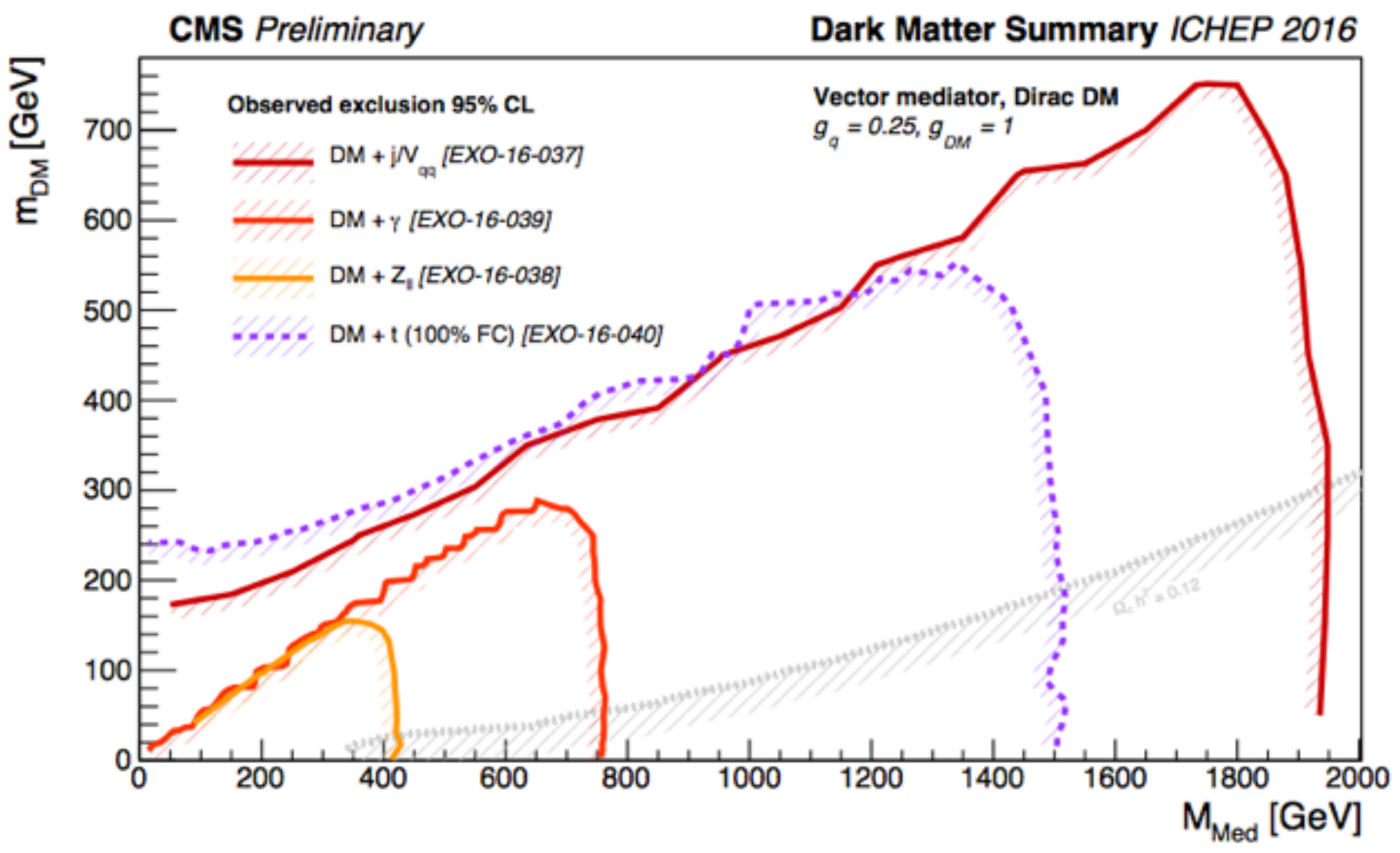
Comparison with other Mono-X Channels

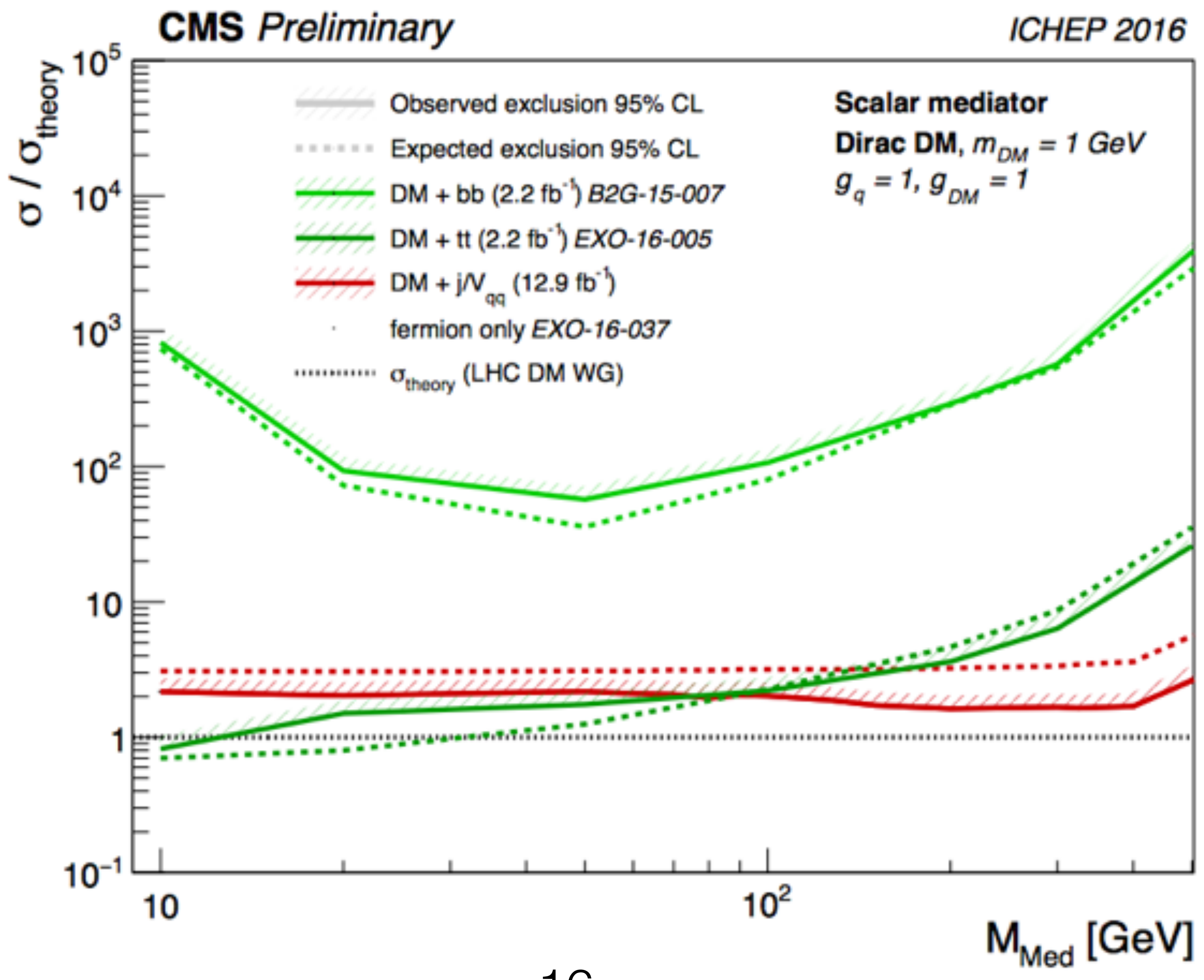


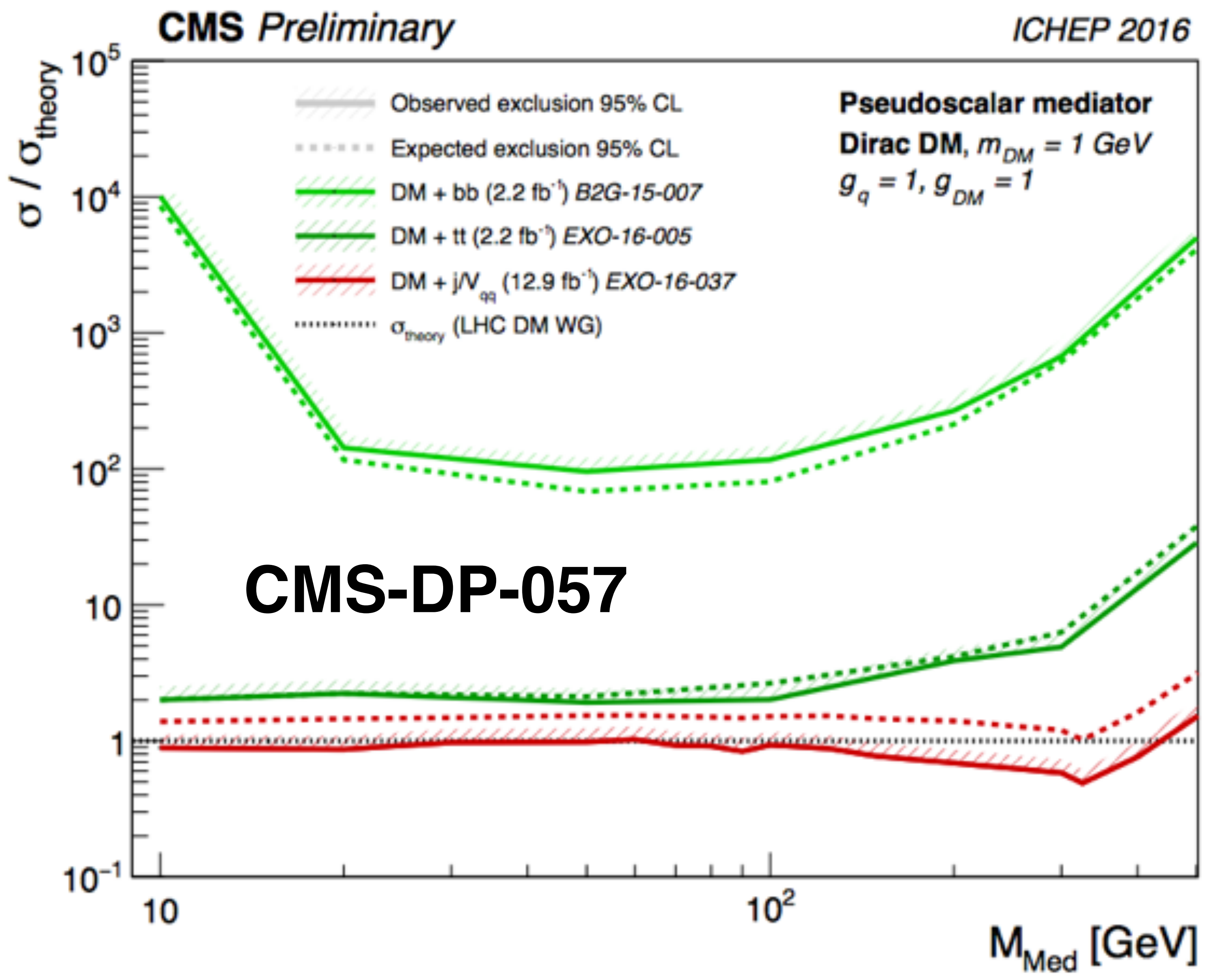


Monojet + MonoV final states, serve as the **most sensitive invisible** channels in CMS

But exclusion is not the goal..

All channels will be important in case of an excess!





Back up

Simultaneous Fit

CR: Gamma Jets

CR: W (ev) Jets

Fit performed simultaneously
in different regions.

SR: Z (vv) Jets

SR: W (lv) Jets

5 Control Regions
(Zee, Wen, Zmm, Wmn, GJets)
to estimate major backgrounds in the
Signal Region.

CR: Z (mm) Jets

CR: Z (ee) Jets

CR: W (mv) Jets

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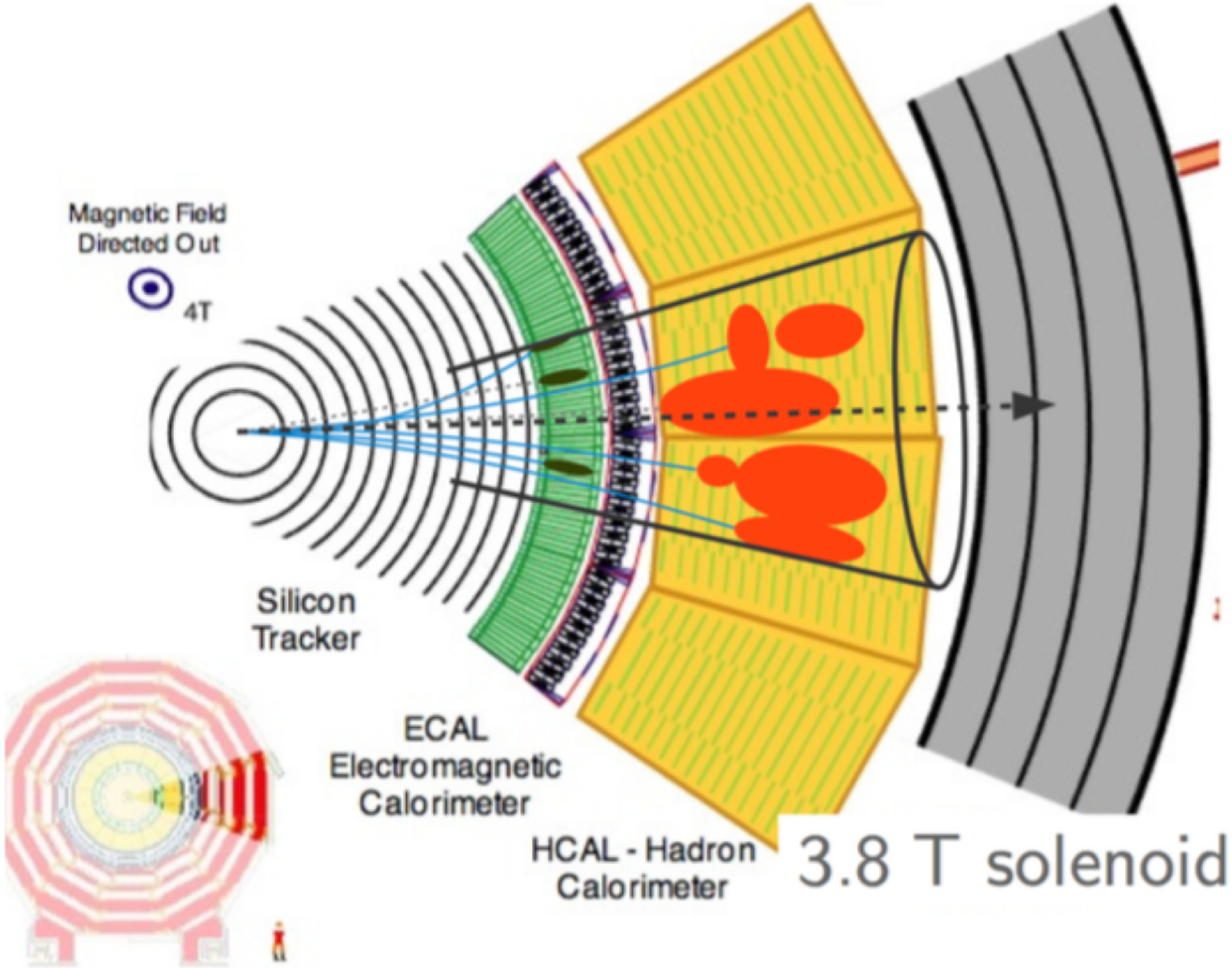
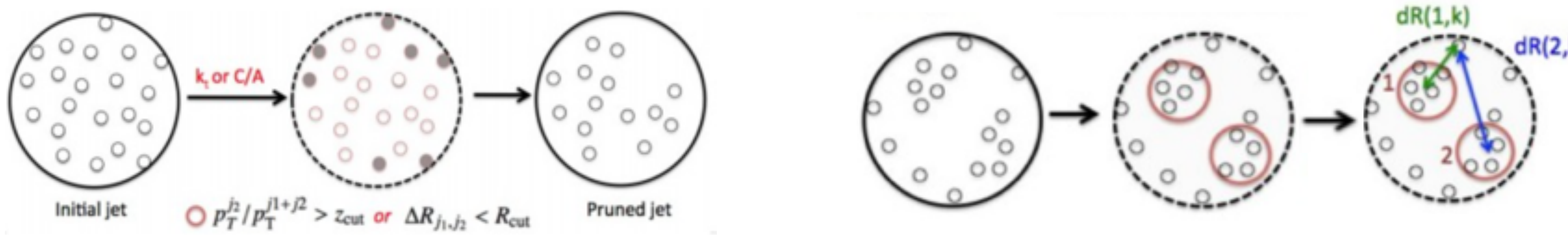
Jets and Boson Tagging



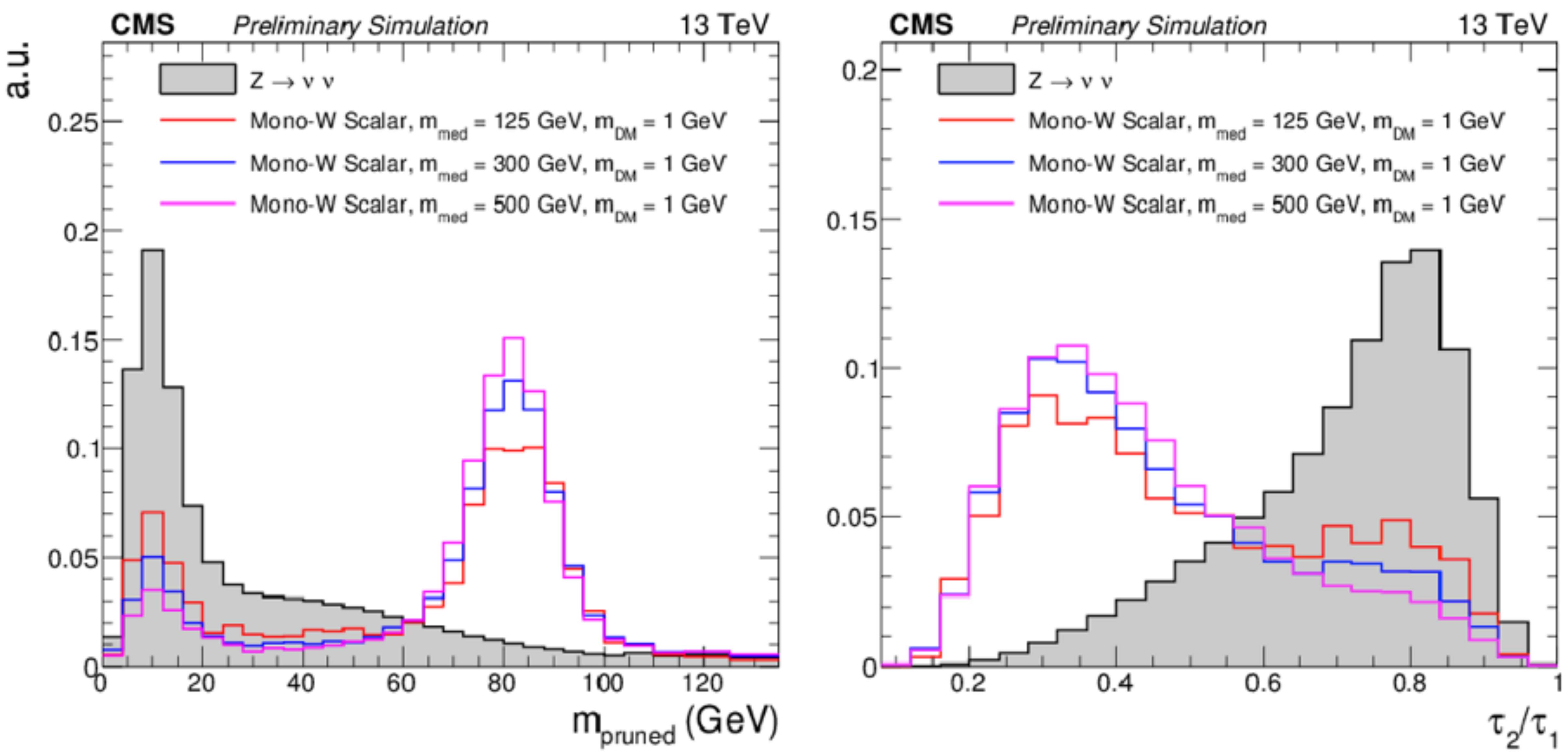
Jet reconstruction uses the information from the silicon tracker, ECAL and HCAL
Each jet then needs to be calibrated

Tagging is used distinguish single-jet objects that originate from the merging of the decay products of W/Z bosons produced with high transverse momenta from jets initiated by single partons



Remove softer constituents

Quantify how well a jet can be subdivided into sub-jets.



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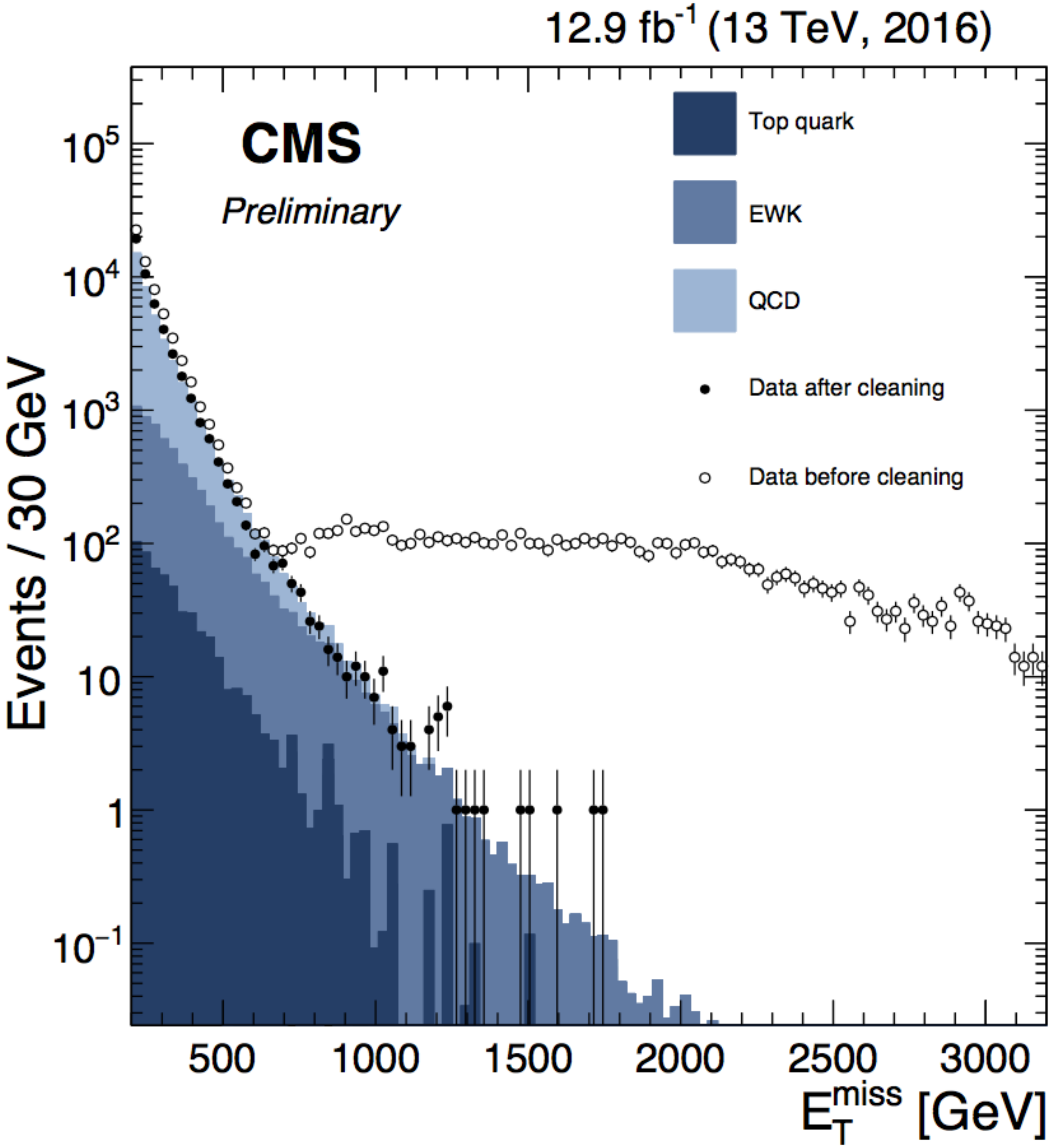
Missing Transverse Energy



Spurious detector signals can cause fake MET signatures that must be identified and suppressed.

Anomalous high MET can be due to:

- Particles striking sensors in the ECAL photodetectors
- Beam halo particles
- ECAL dead cells (real energy to have been missed)
- Noise in photodiode & readout box electronics in HCAL

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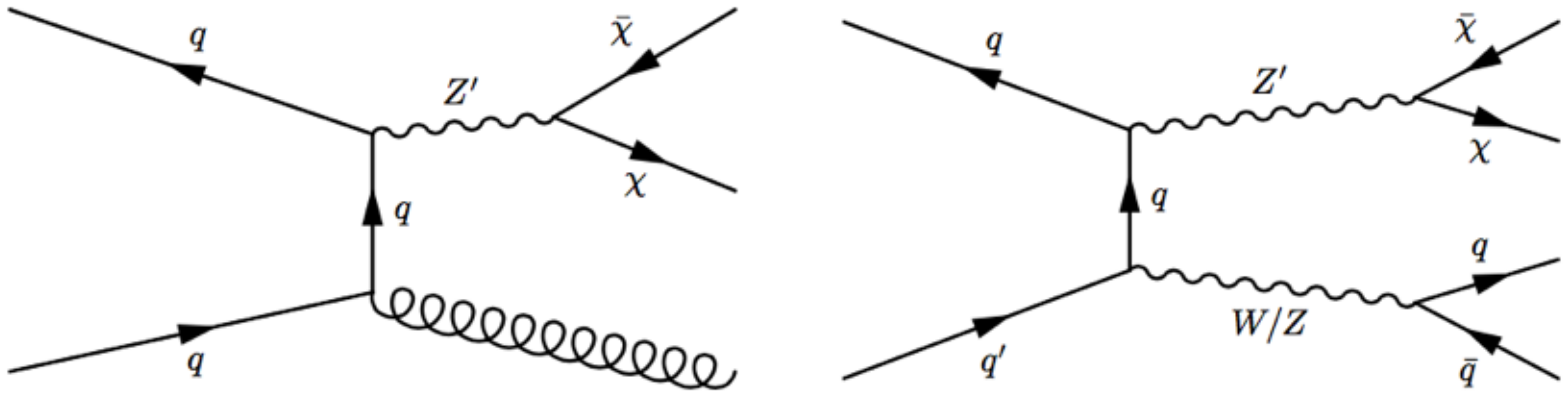
Introduction

Search for the pair production of DM in association with a jet from initial-state radiation, which is used to tag and/or trigger the event. Focusing on simplified models with Vector / Axial-vector / Scalar / Pseudo-scalar mediators

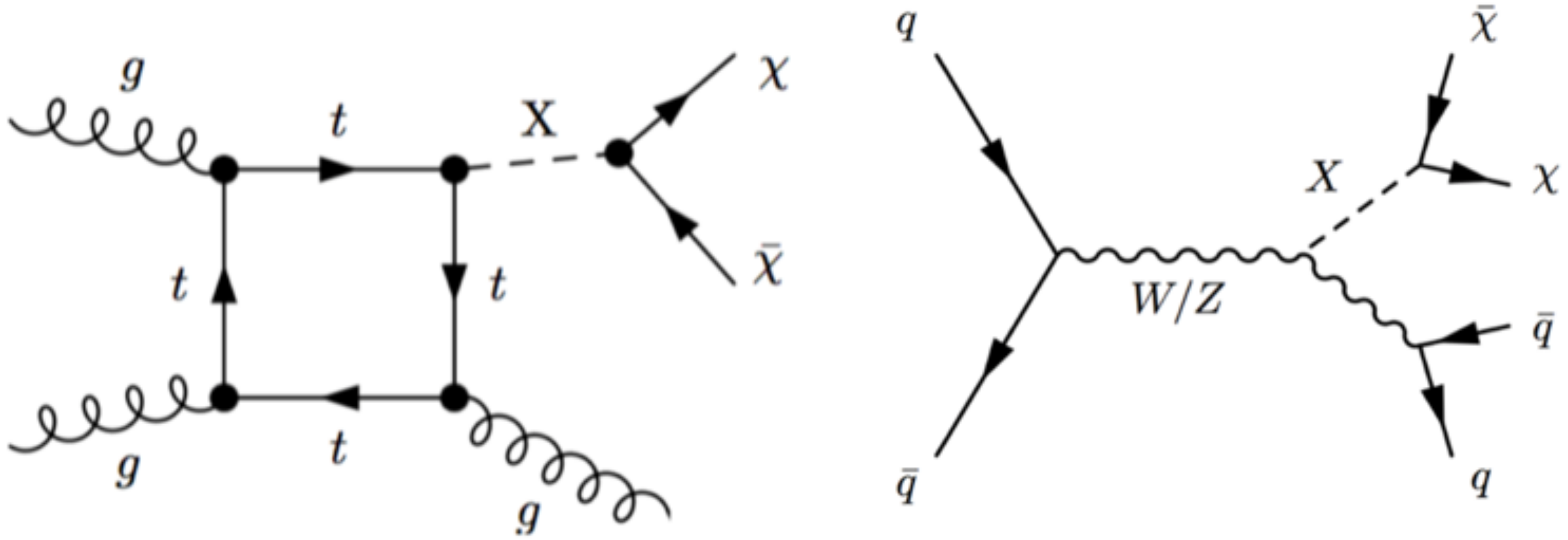


Vector & Axial-vector Mediator

σ(mono-jet) ≥ 100 x σ (mono-W)

Scalar & Pseudo-scalar Mediator

σ(mono-jet) ~ 10 x σ (mono-W)



Signal extraction is based on **MET** distribution, fitting 1 parameter in each bin

5 Control Regions (Zee, Wen, Zmm, Wmn, GJets) to estimate major backgrounds. **Fit performed simultaneously** in different categories.

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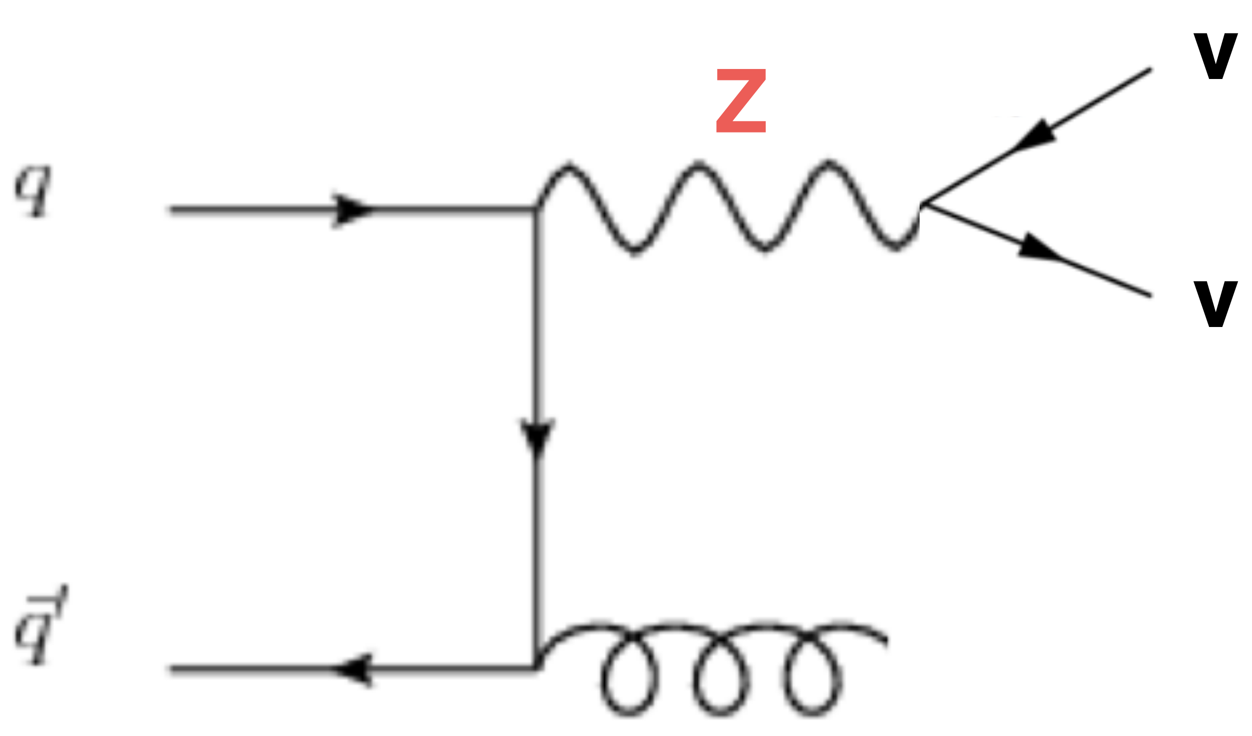
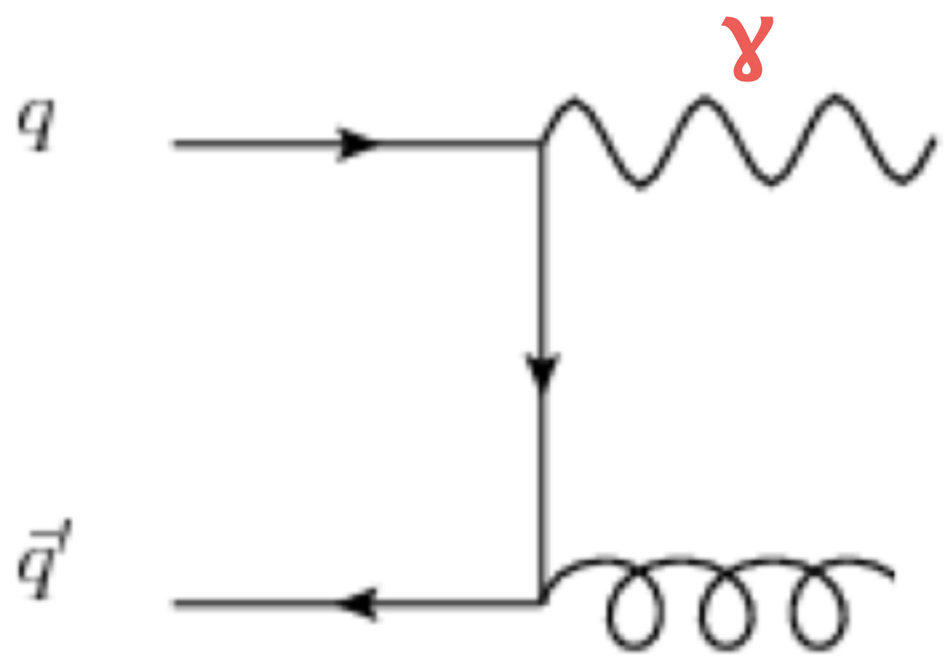
Background Composition Estimation



Z(vv)+jets: Irreducible background and makes up 50 to 80% of the total background estimation!

What processes can we use to estimate this background?



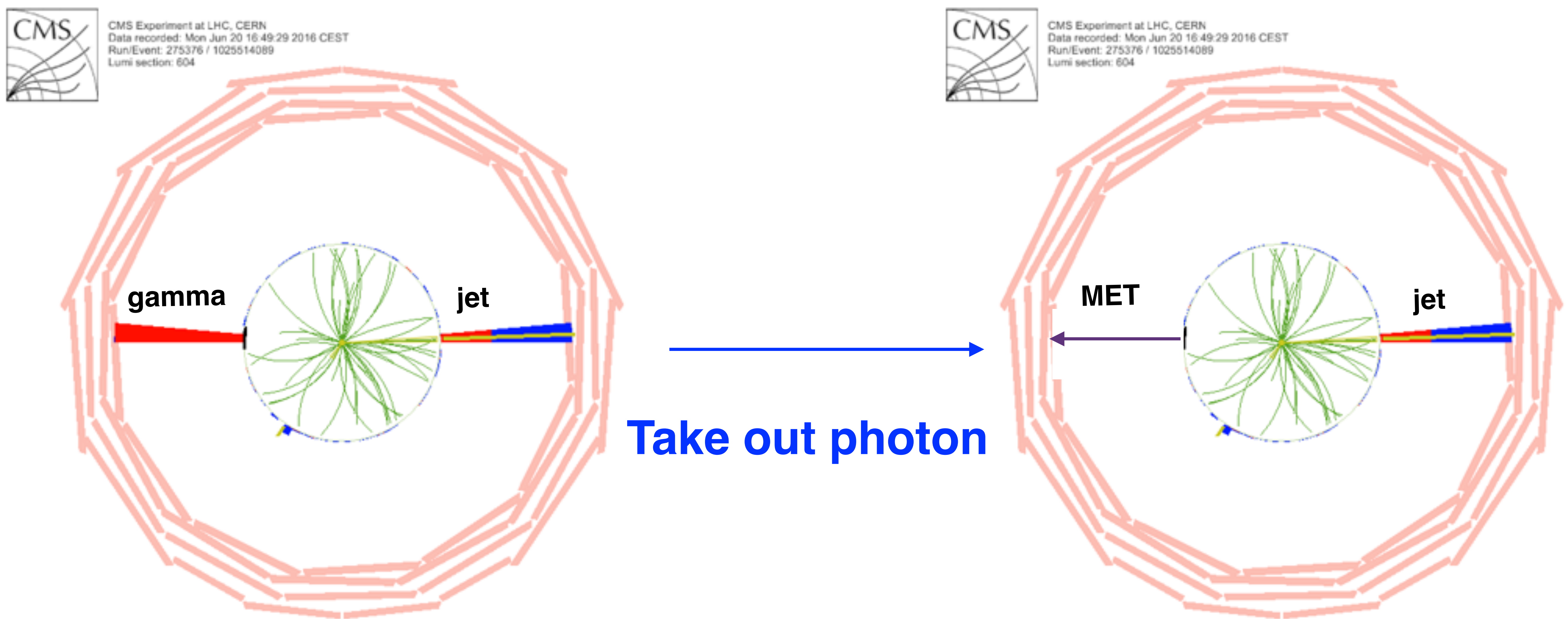
Similar pT spectra as Z→vv

Statistically rich

but…

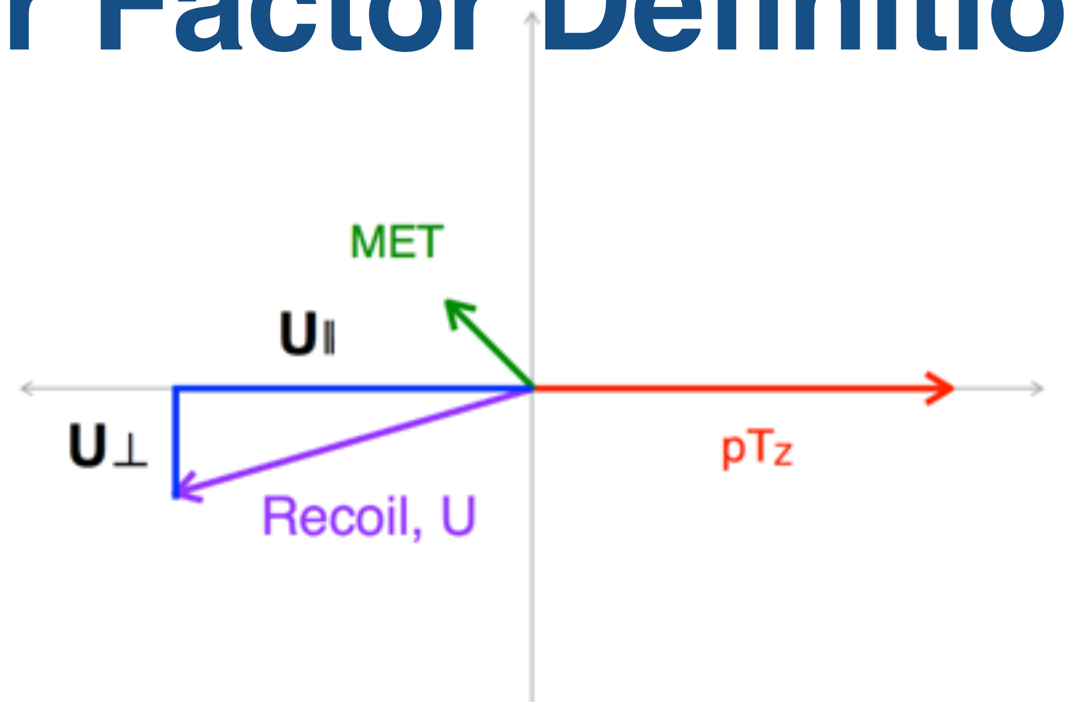
Underlying theory differences

If we remove the photon from a γ+jets event, it mimics a Z→vv event

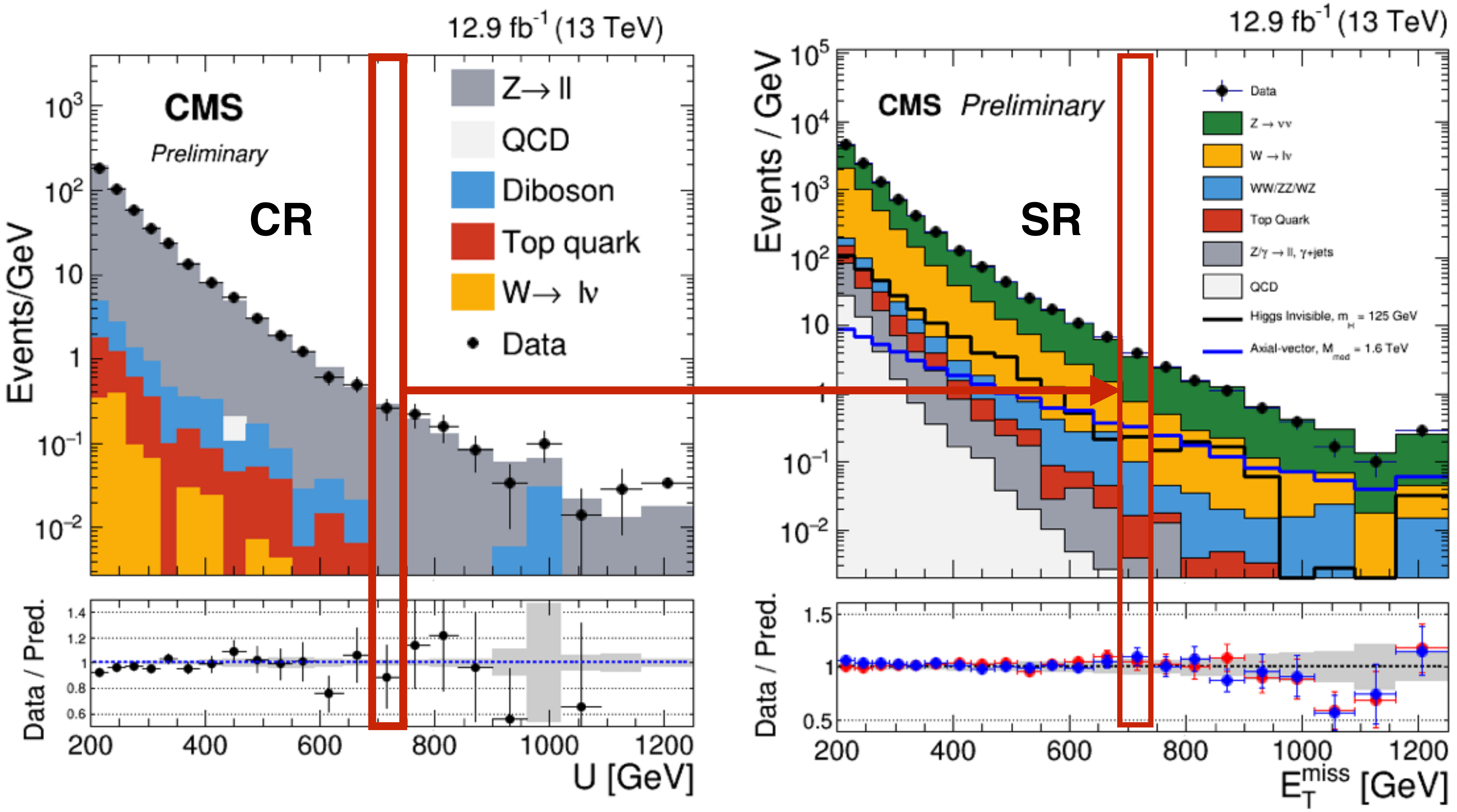


Background Estimation Method: Transfer Factor Definition

Procedure



- **Step 1:** Compute a “Recoil” Variable (U) in the Control Regions (CRs)
  - U = Met + Pt $^{\mu\mu/ee}$ or Met + Pt $^{\mu/e}$ or Met + $P_T\gamma$
- **Step 2:** Compute “Transfer Factors” for each bin of recoil to translate between CRs to Signal Region (SR):
  - $R_i\gamma$ or R_i^Z or R_i^W



$$R_i^Z = \frac{N_{i,MC}^{Z\to\mu^+\mu^-}}{N_{i,MC}^{Z\to\nu\nu}}$$

N_i is the number of events in bin i of the recoil distribution

- **Step 3:** Embed uncertainties (θ) in the likelihood as constrained additive perturbations to the transfer factors $R^{\gamma/Z/W}$

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Background Estimation Method: Likelihood

Objective: Define a partial likelihood for each event category as the product over Poisson likelihoods for each bin in recoil, in each of the control regions

$$\mathcal{L}_c(\mu, \boldsymbol{\mu}^{Z\to\nu\nu}, \boldsymbol{\theta}) = \prod_i \text{Poisson}\left(d_i^\gamma | B_i^\gamma(\boldsymbol{\theta}) + \frac{\mu_i^{Z\to\nu\nu}}{R_i^\gamma(\boldsymbol{\theta})}\right)$$
$$\times \prod_i \text{Poisson}\left(d_i^Z | B_i^Z(\boldsymbol{\theta}) + \frac{\mu_i^{Z\to\nu\nu}}{R_i^Z(\boldsymbol{\theta})}\right)$$
$$\times \prod_i \text{Poisson}\left(d_i^W | B_i^W(\boldsymbol{\theta}) + \frac{f_i(\boldsymbol{\theta})\,\mu_i^{Z\to\nu\nu}}{R_i^W(\boldsymbol{\theta})}\right)$$
$$\times \prod_i \text{Poisson}\left(d_i | B_i(\boldsymbol{\theta}) + (1 + f_i(\boldsymbol{\theta}))\mu_i^{Z\to\nu\nu} + \mu S_i(\boldsymbol{\theta})\right)$$

Number of observed events, in a particular bin in CR

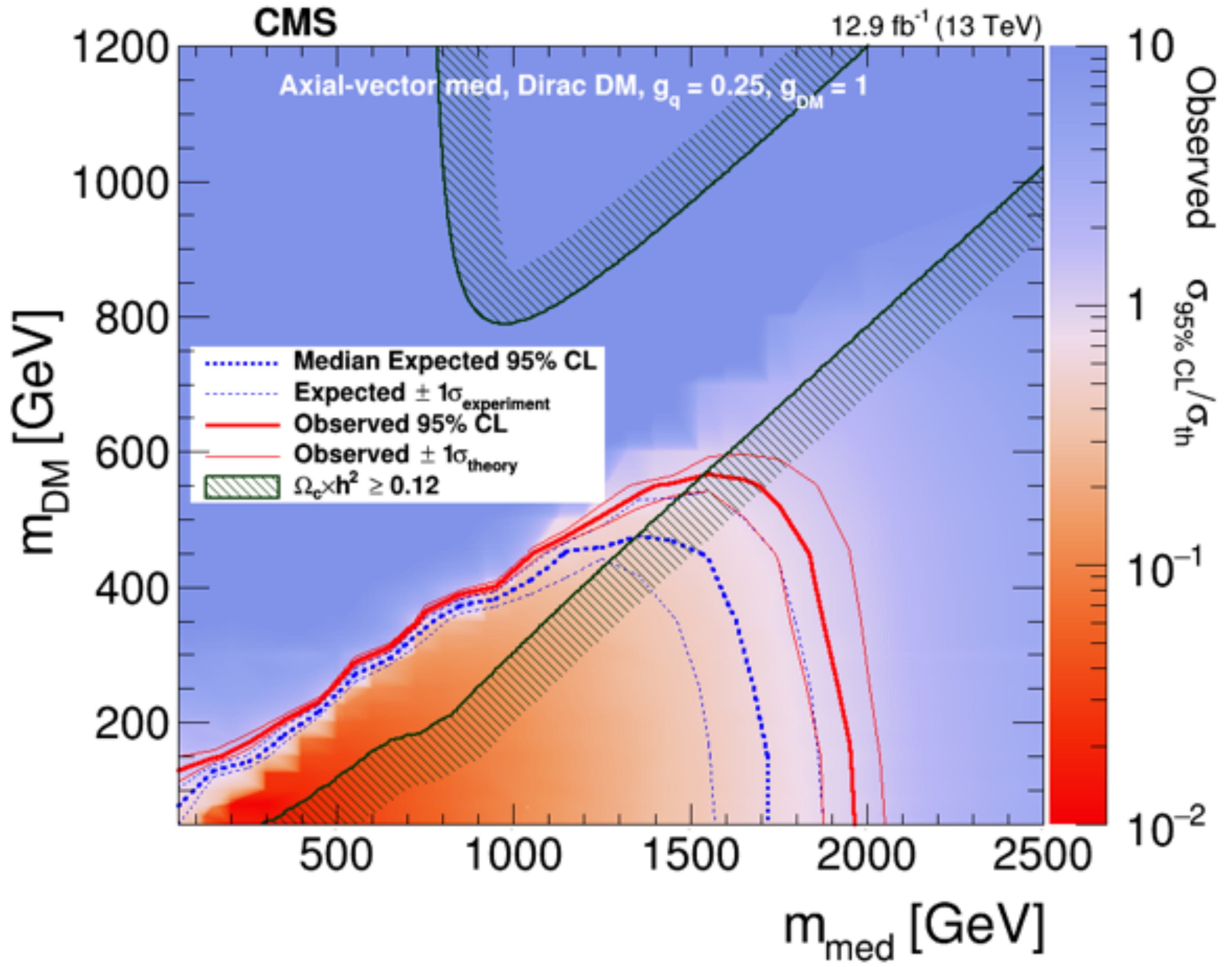
Number of background events in a particular CR bin. Uncertainties incorporated via nuisances $\boldsymbol{\theta}$ (for eg. photon efficiency)

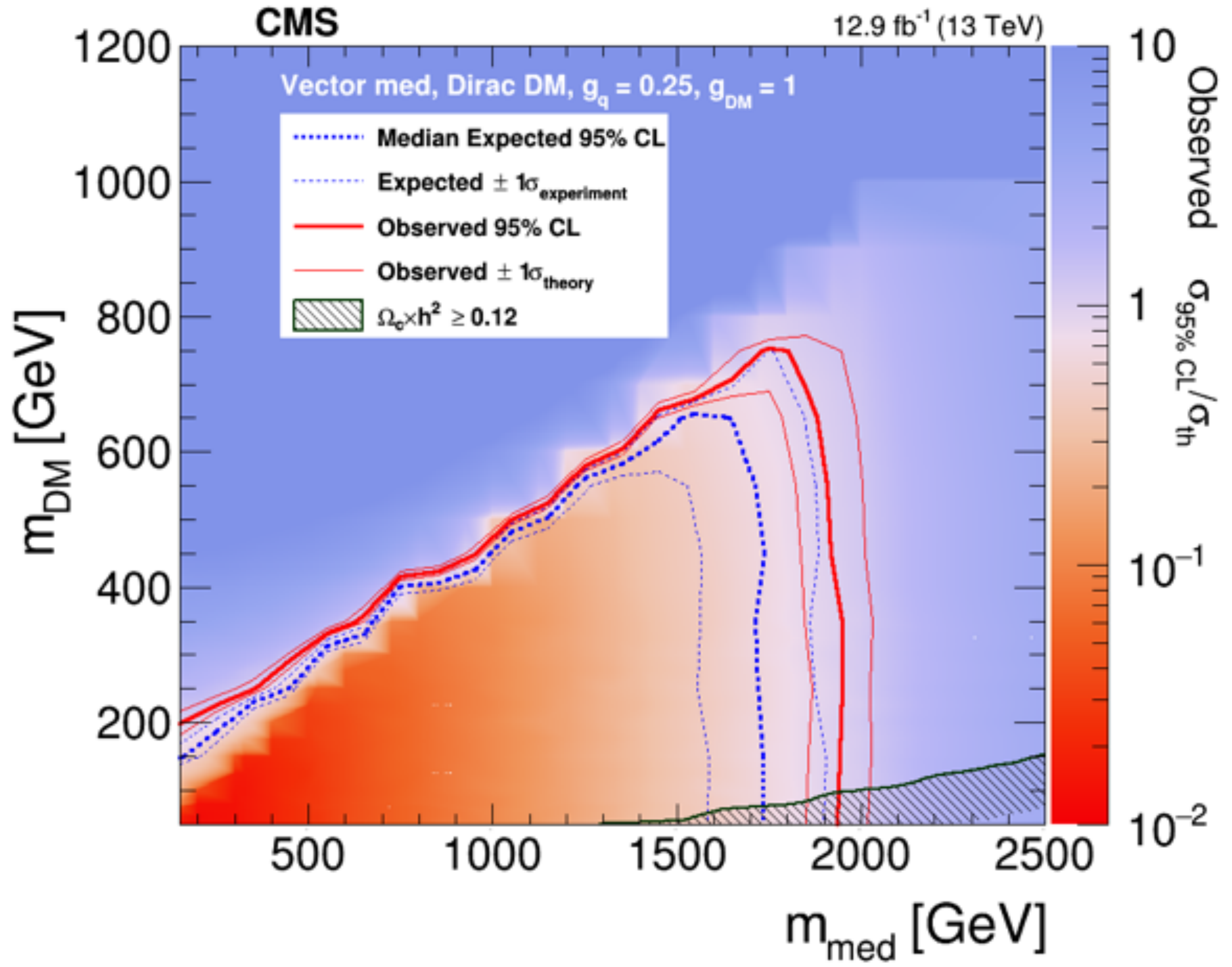
$$\mu_i^{W\to l\nu} \to f_i(\boldsymbol{\theta}) \cdot \mu_i^{Z\to\nu\nu}$$

f_i ratio in the signal region :

- Relies on theoretical prediction for differential xsec and lepton acceptance

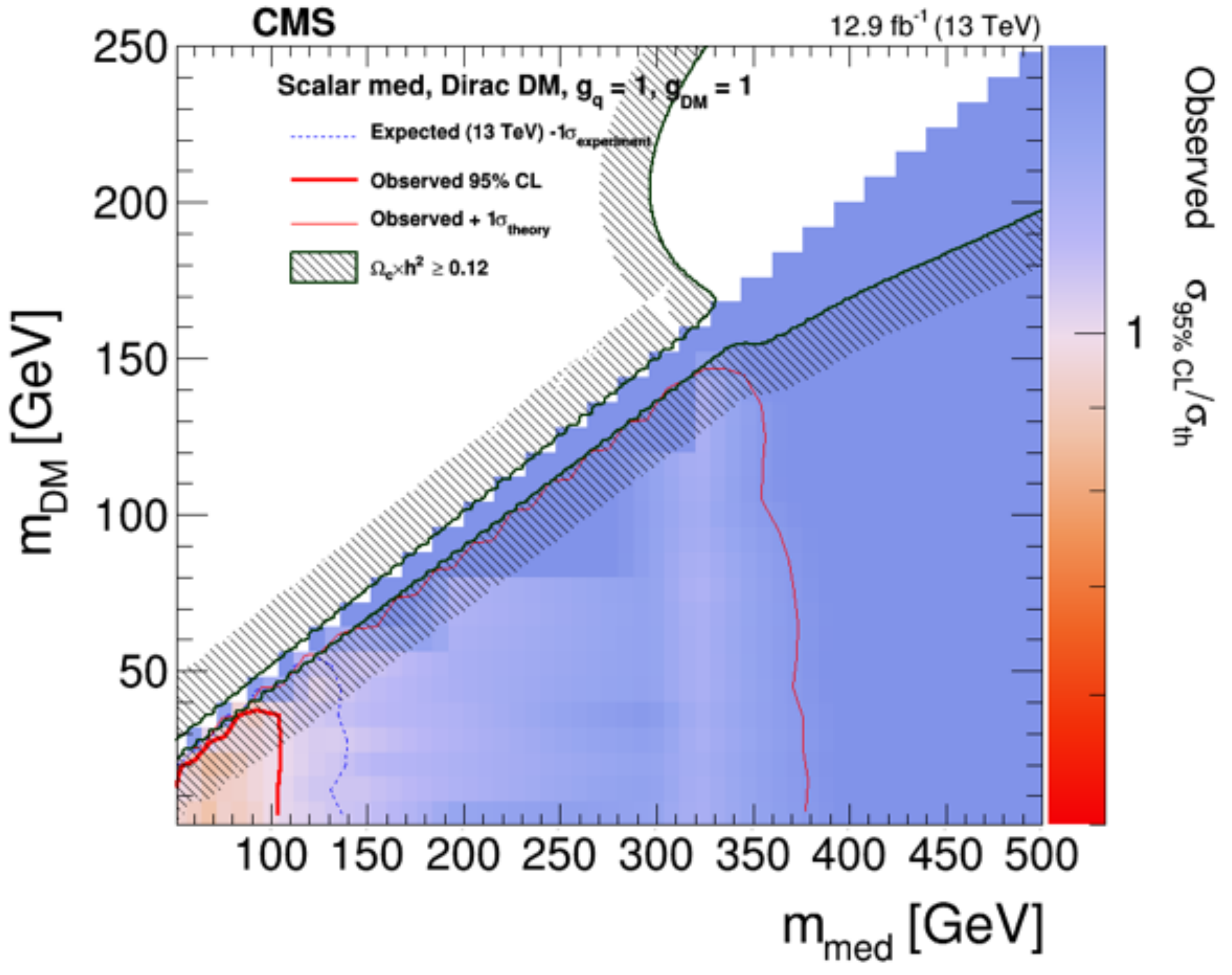
Results & Conclusion

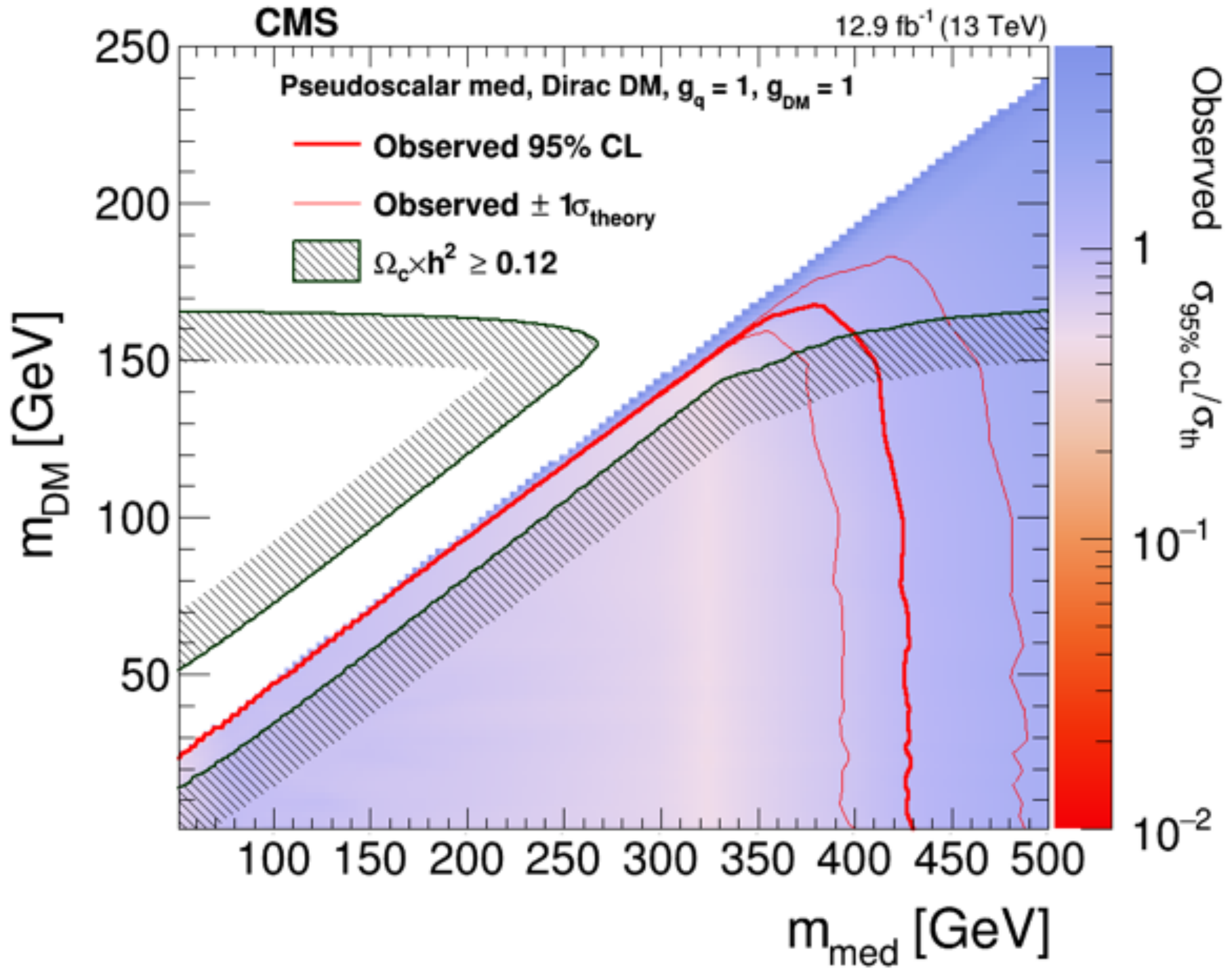




Performed a 2 category analysis. Leading backgrounds are estimated from 5 control regions throughout a simultaneous fit.

The most stringent exclusion on Dark Matter from the collider side to date!





Large Hadron Collider (LHC)

LHC is world’s largest and most powerful particle accelerator

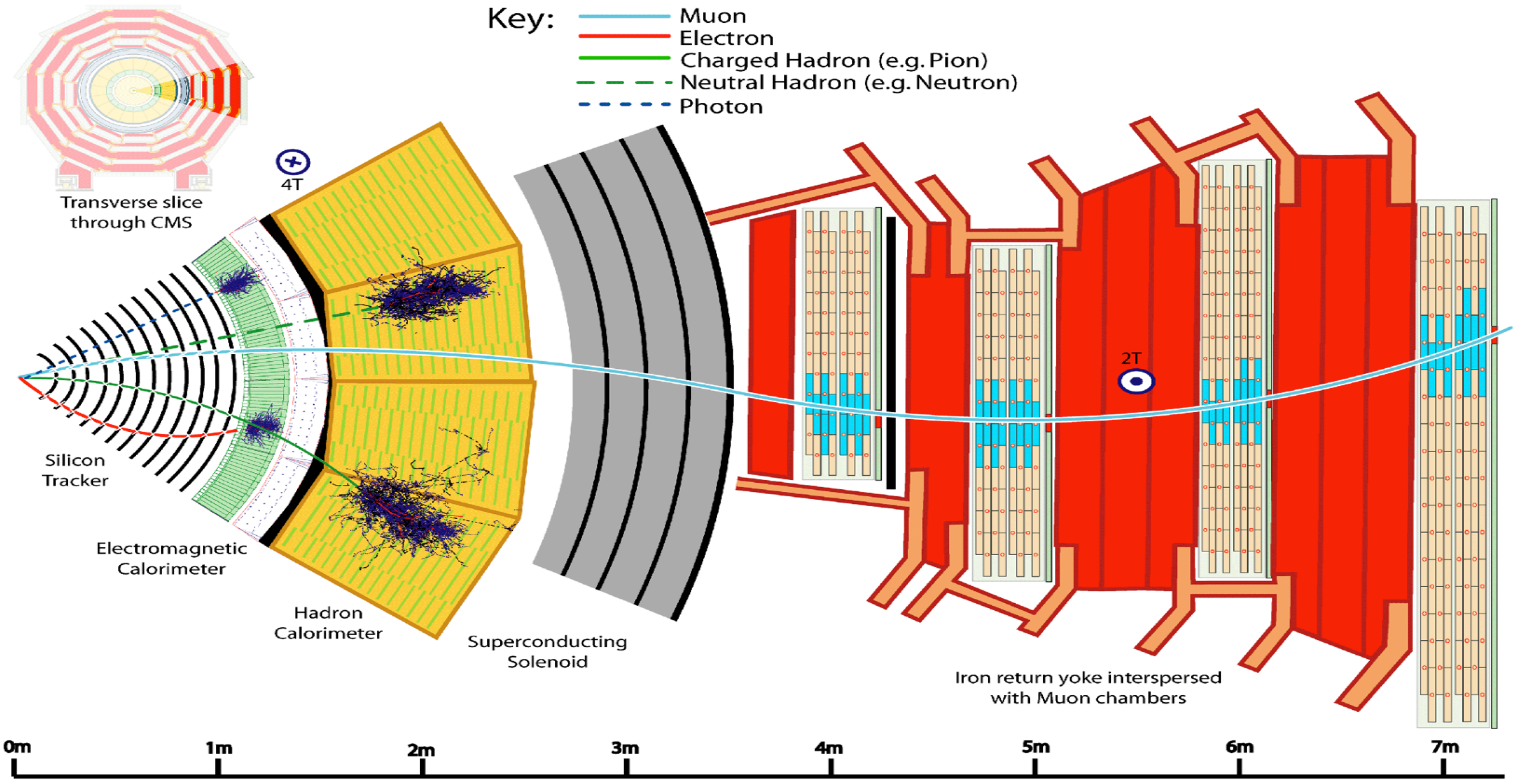
It is designed to collide protons (and heavy ions) at a center of mass energy of 14 TeV

2 General Purpose Detectors

and 2 Dedicated Detectors for B Physics &Heavy Ions

Compact Muon Solenoid (CMS)

CMS is one of two general-purpose experiments built to search for **new physics**



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Compact Muon Solenoid (CMS)

At the end of the day…
CMS is like a camera with 80 Million pixels

CMS can take up to 40 million pictures per second

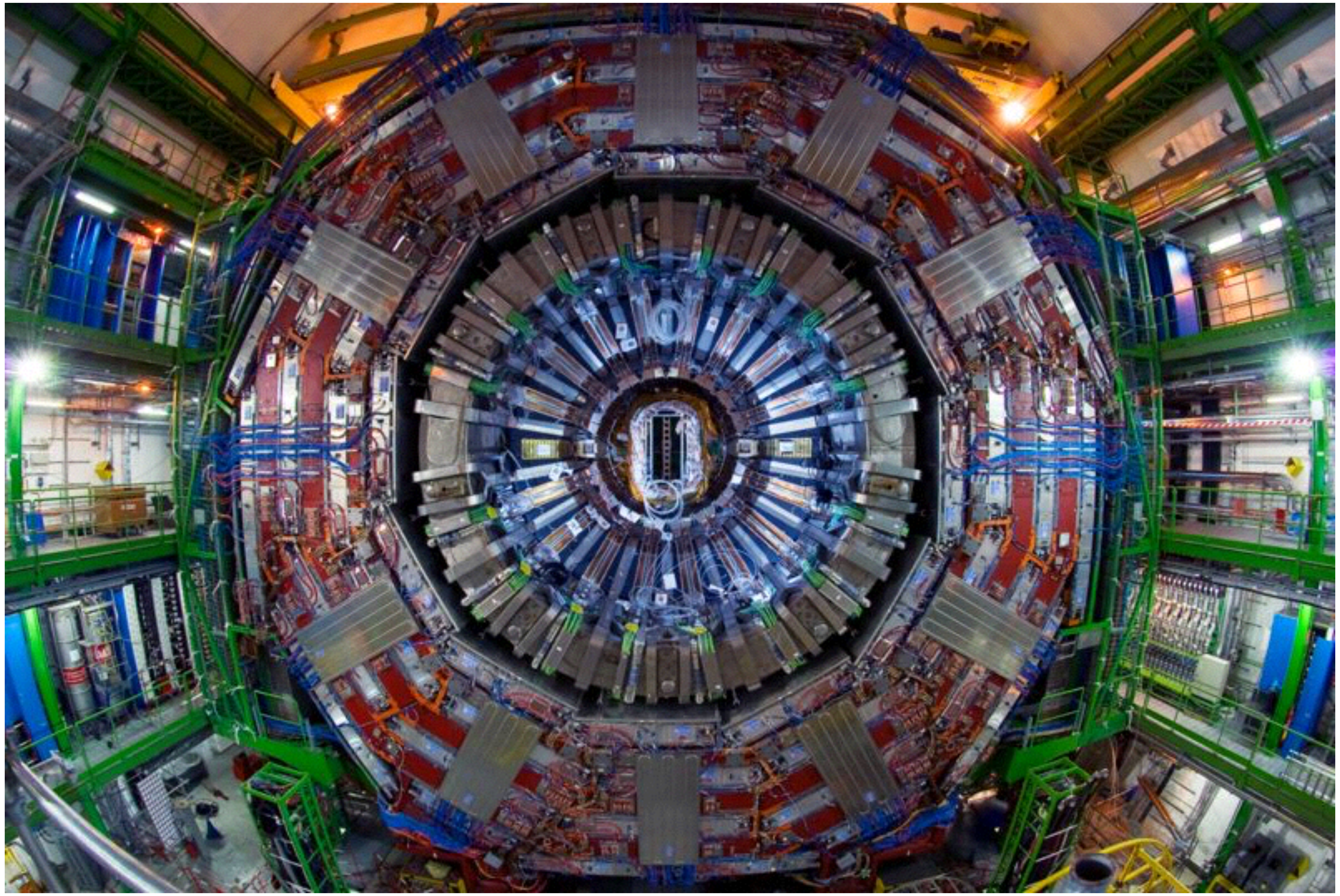
but.. we cannot store all the pictures.. We can record only ~ 1000 events /s

but..
Interesting collisions are very rare (some < 1 per 10 billion!)

We must pick the good ones and decide fast!

The first analysis of data is done in a **few millionths of a second:**

keep? throw away ?



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