Search for Dark Matter with the CMS Experiment

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Outline

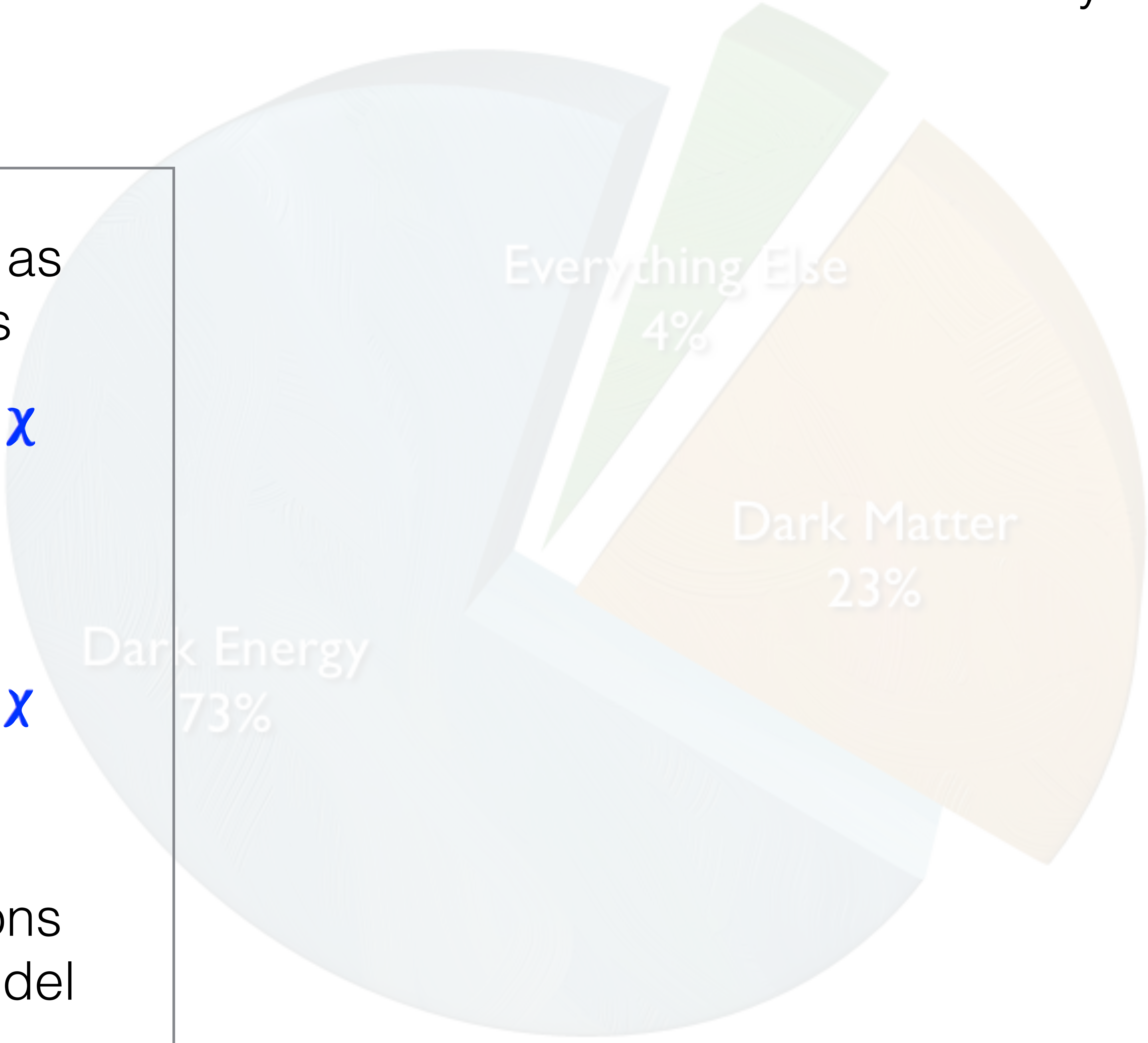
It has been a fruitful data analysis year with **MANY** (!) dark matter results

Not all will be covered… But we will have:

- Overview of the DM search strategy in CMS:
  - Mono-X / MET-less / Higgs Portal searches
  - Experimental approaches to background estimation
  - Experimental techniques and challenges
- Interpretations of the results and how they fit in the big picture

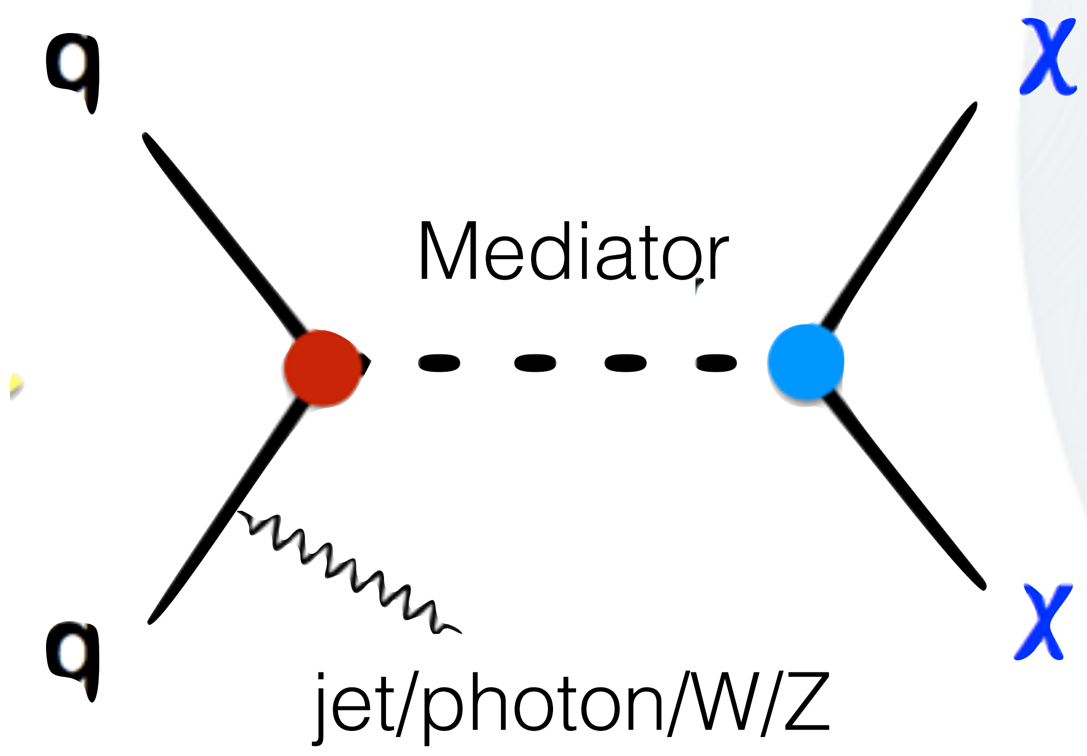
Dark matter (DM) searches at CMS

The CMS Collaboration searches for DM in many ways:



Direct Production

Generally referred to as "Mono-X" searches



Searches for deviations from the standard model expectation

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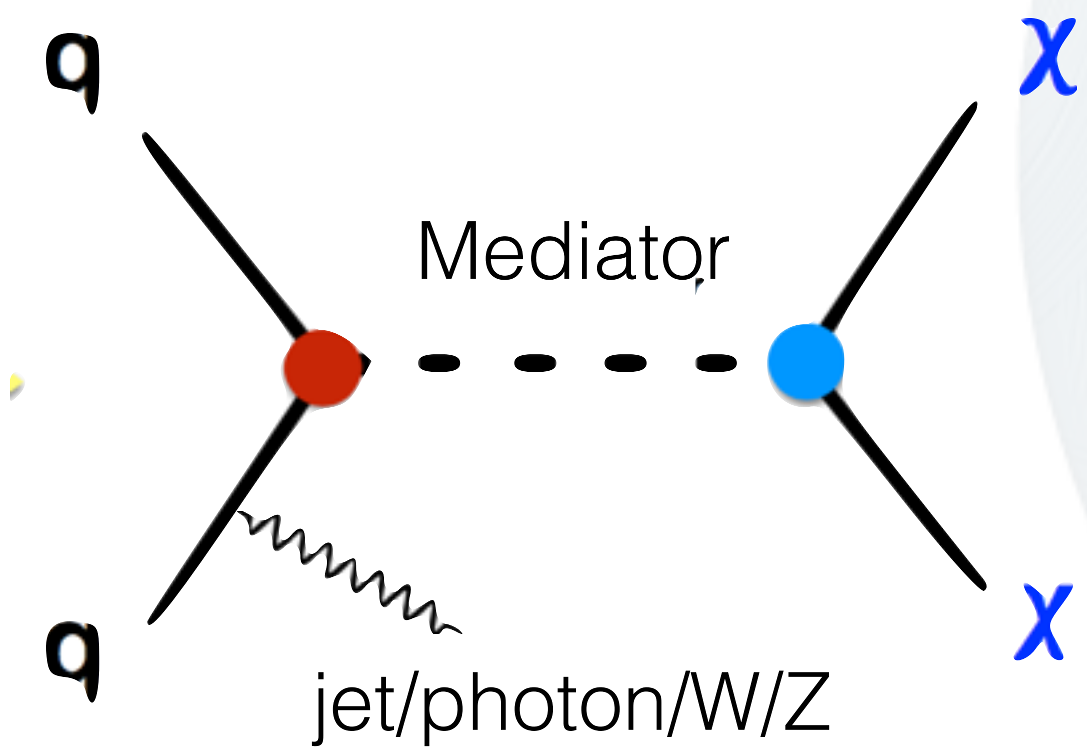
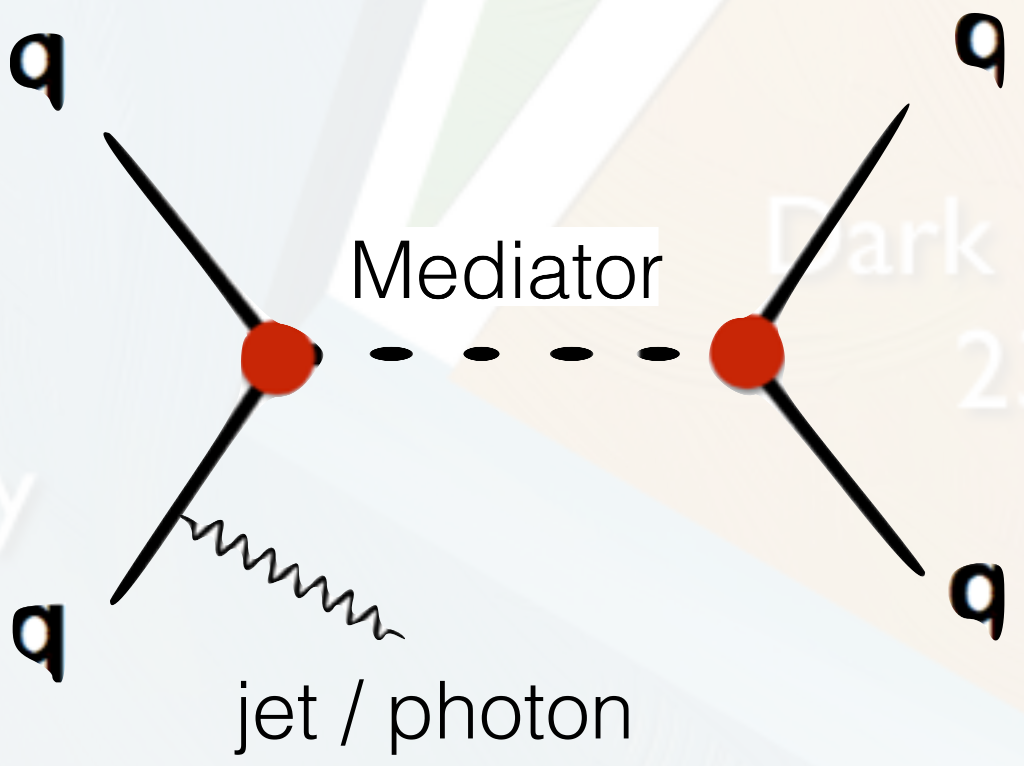


Searches for deviations from the standard model expectation

Mediator Search

No DM in the final state! But instead searching for the mediator



Traditionally a bump hunt with very large background!

(QCD -Multijet)

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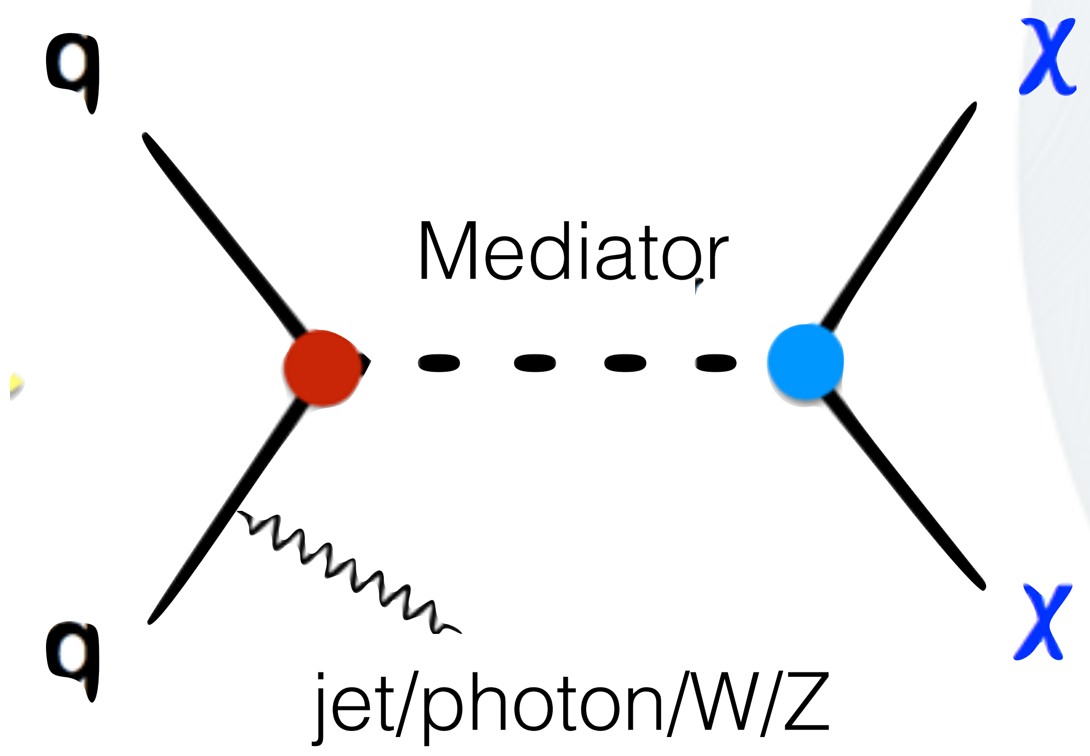

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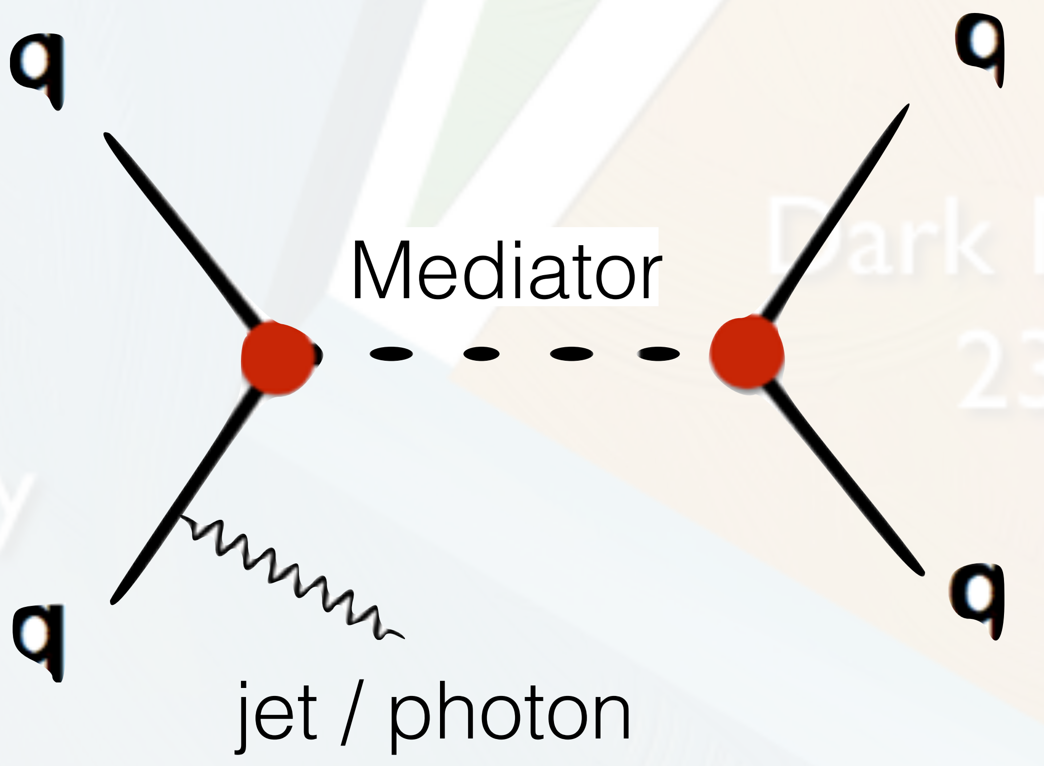

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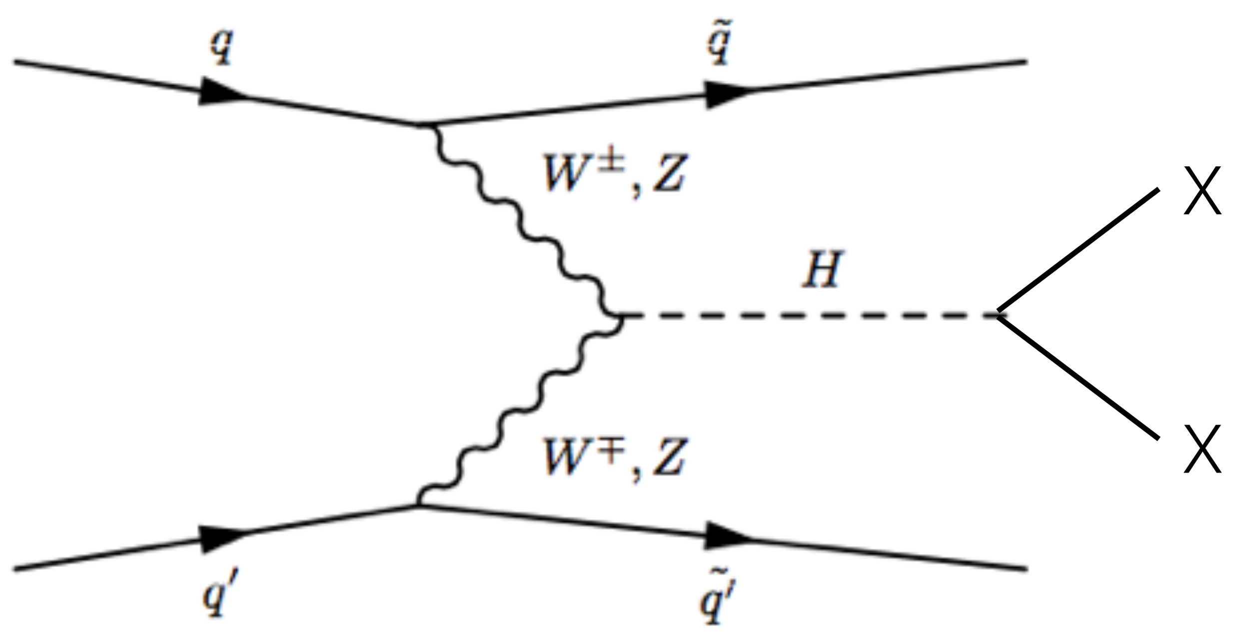
Higgs Portal

DM production through the Higgs portal!



Higgs boson can couple directly to the W/Z

(not recommended for simplified scalar models)

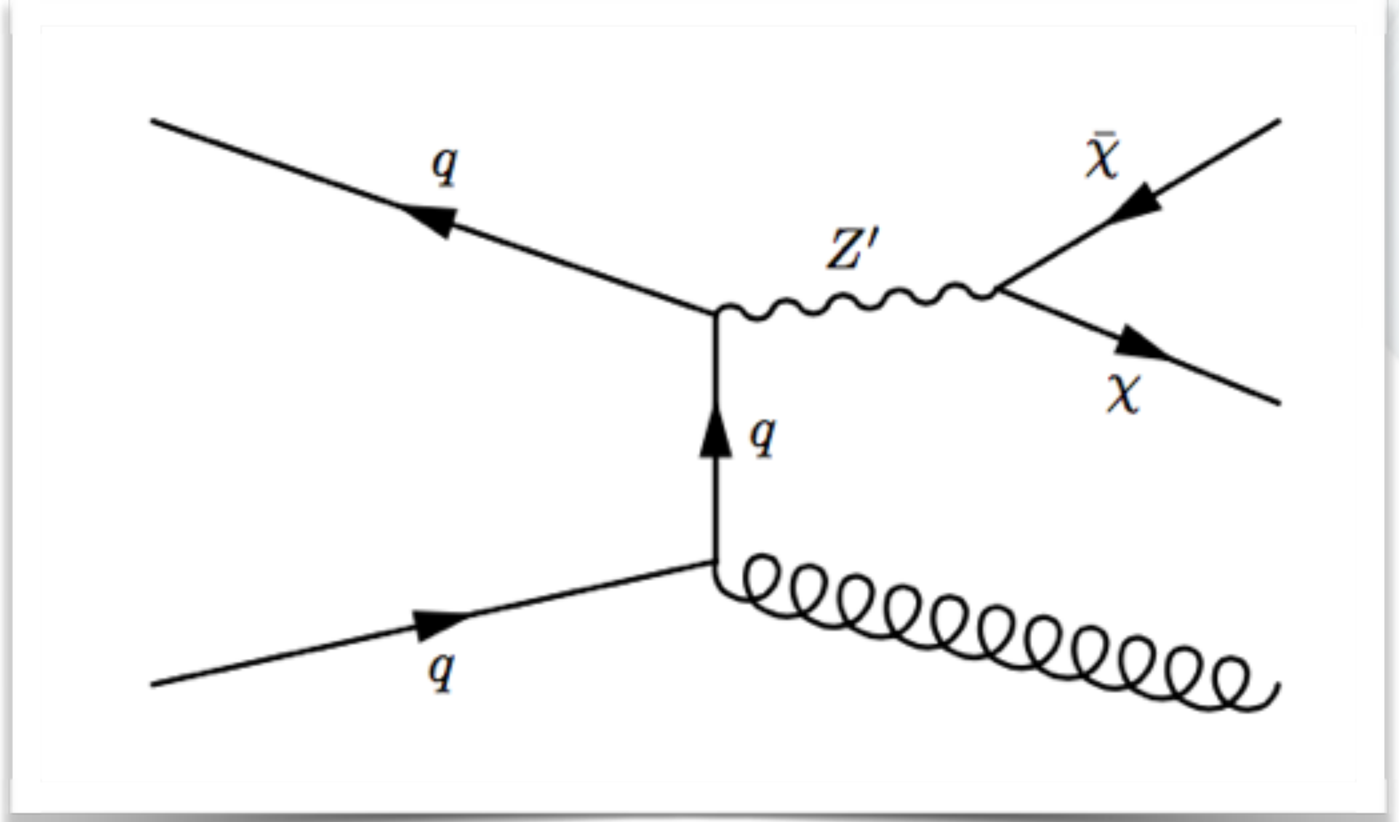
Interpretations

Many of the DM search results in CMS are interpreted using s-channel simplified models (arXiv:1507.00966).

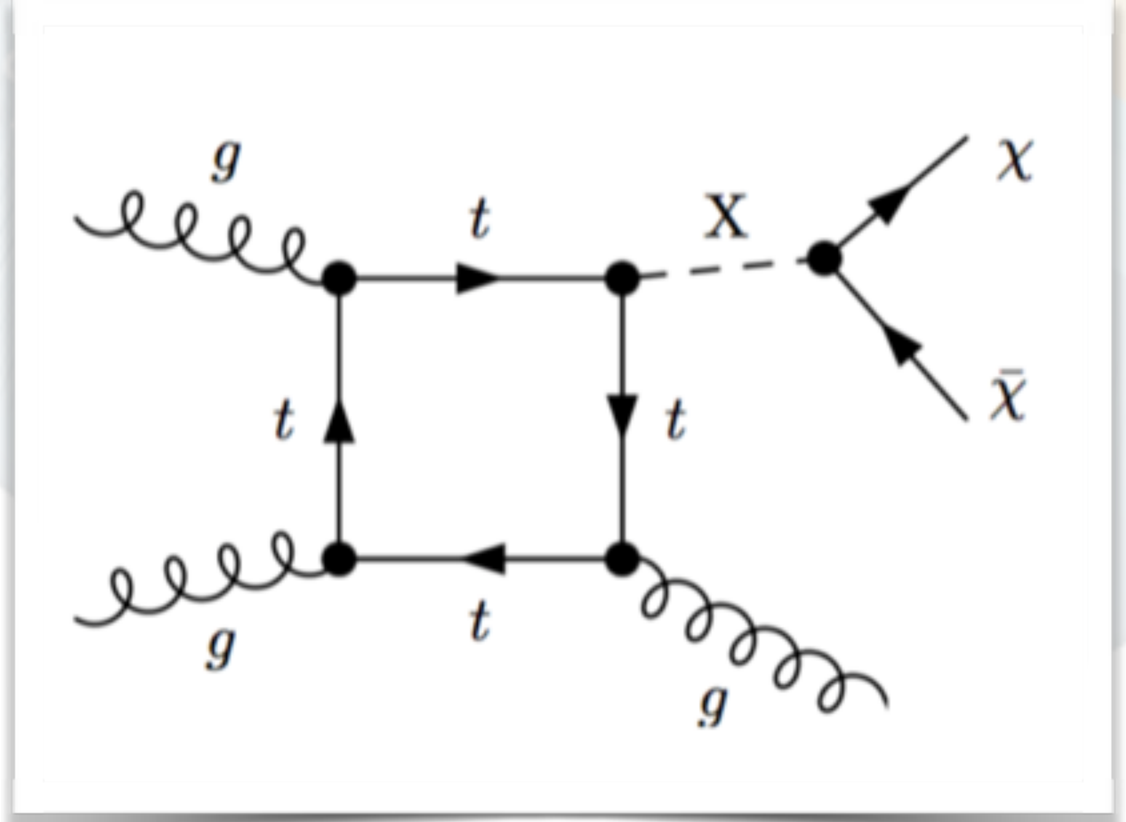
These simplified models assume:

- Fermionic DM (produced in pairs)
- A boson that mediates the interaction between DM and SM quarks

spin 1



spin 0

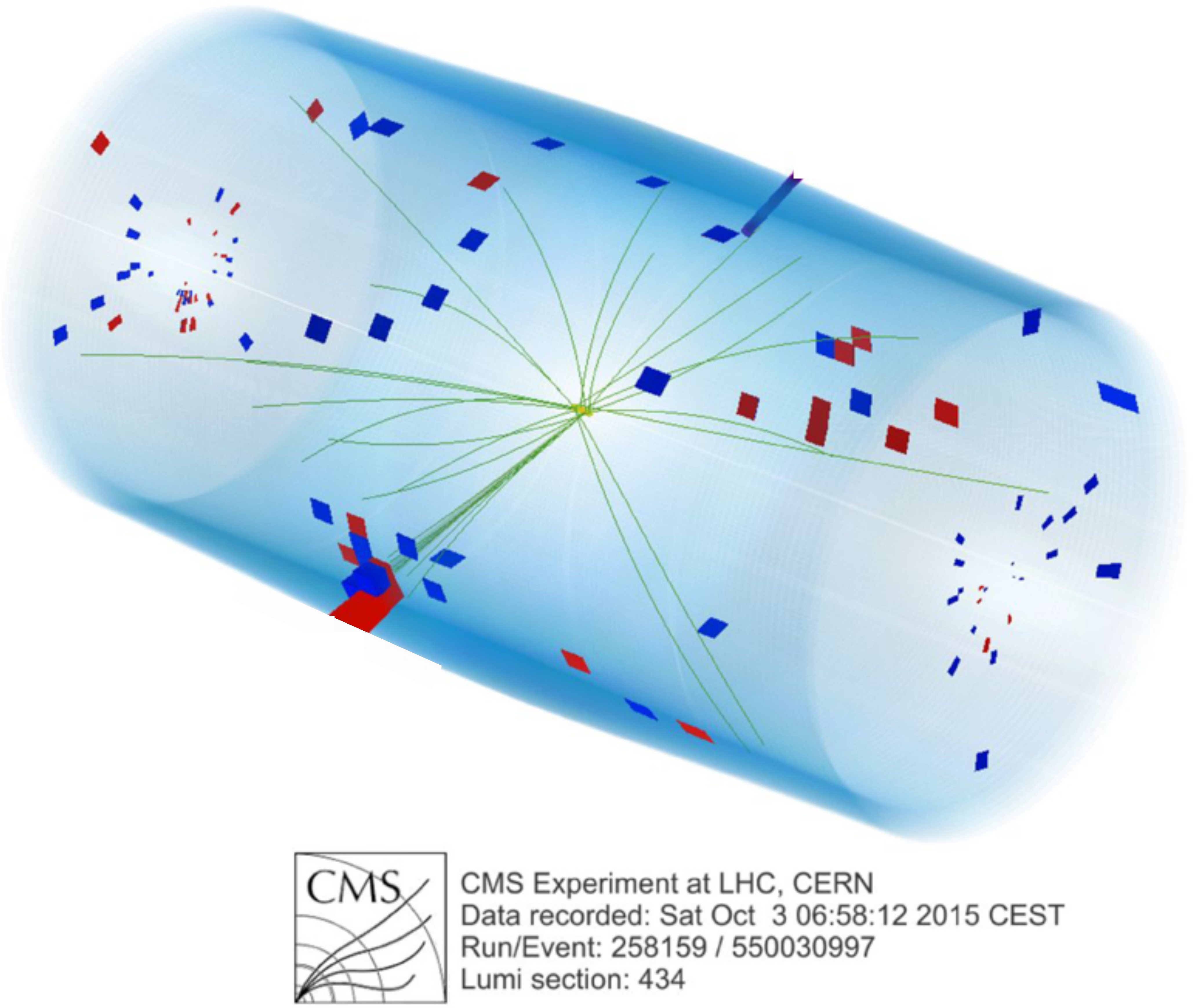


Model Parameters:

- Dark matter Mass (m_{DM})
- Mediator Mass (m_{MED})
- Coupling to quarks (g_q)
- Coupling to DM (g_{DM})

Mono-X Searches

Mono-X Searches: Experimental Signature



<u>What is the signature of dark matter?</u>

- DM assumed to be **weakly interacting**, and will leave **no signature in the detector**!

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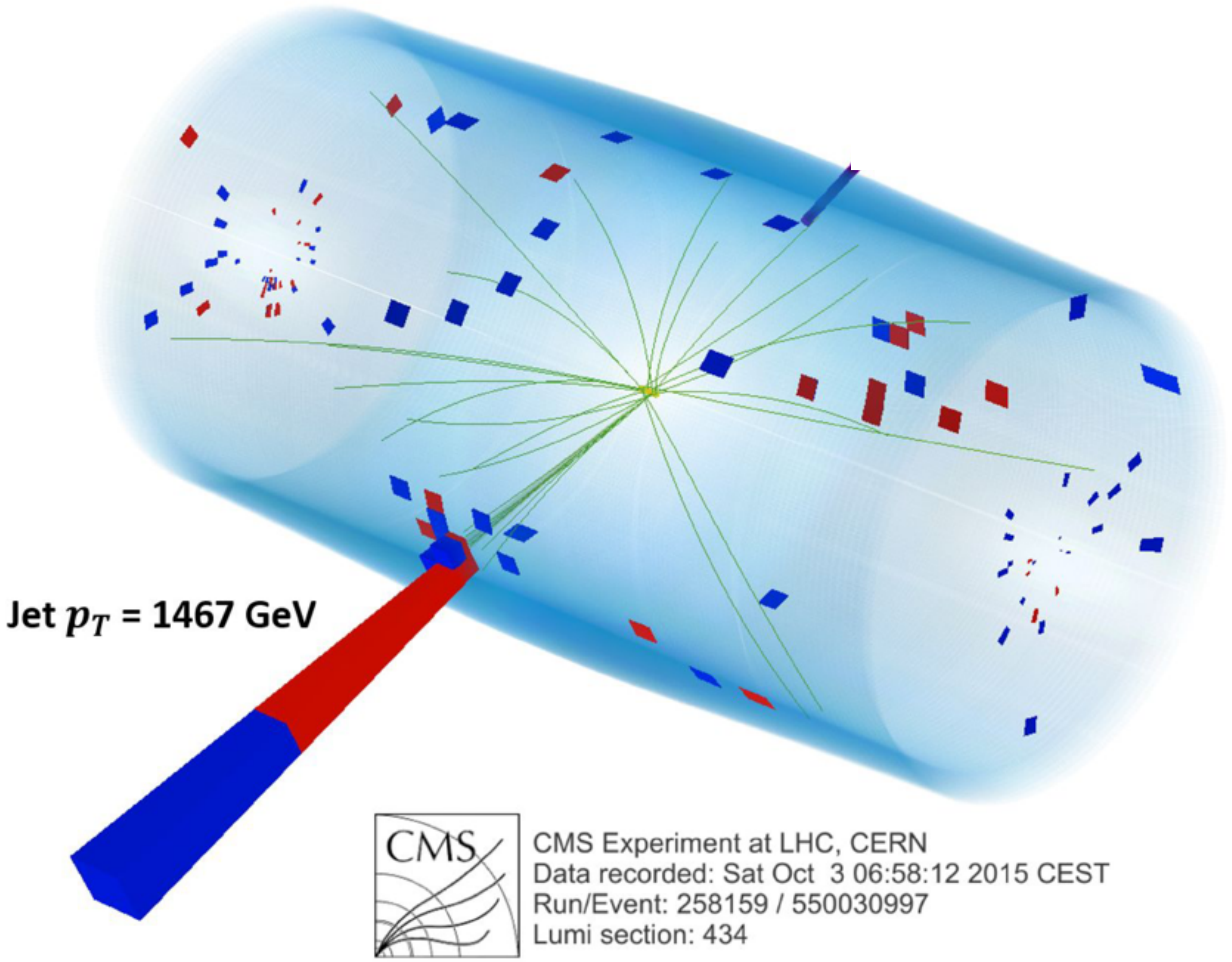

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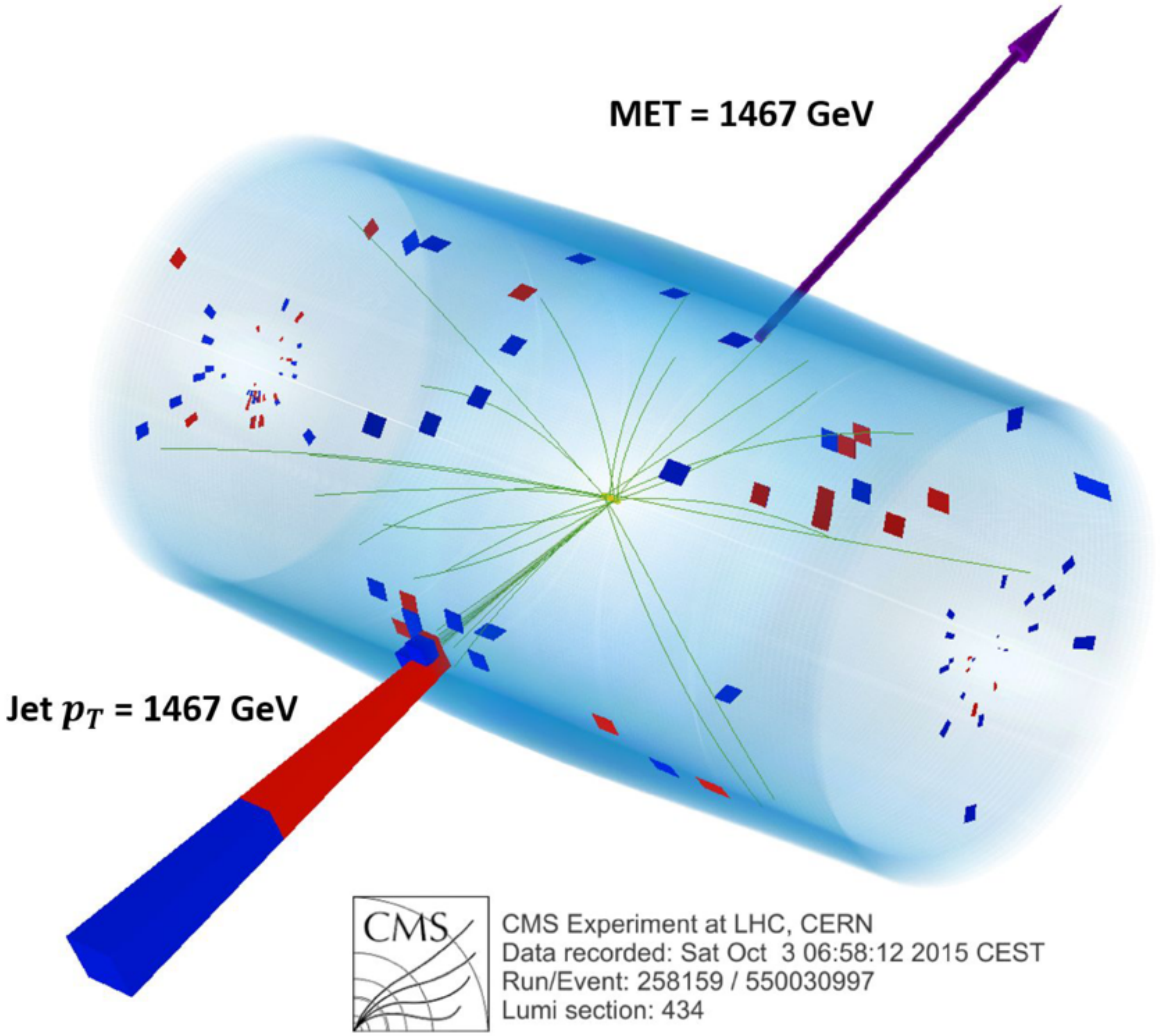

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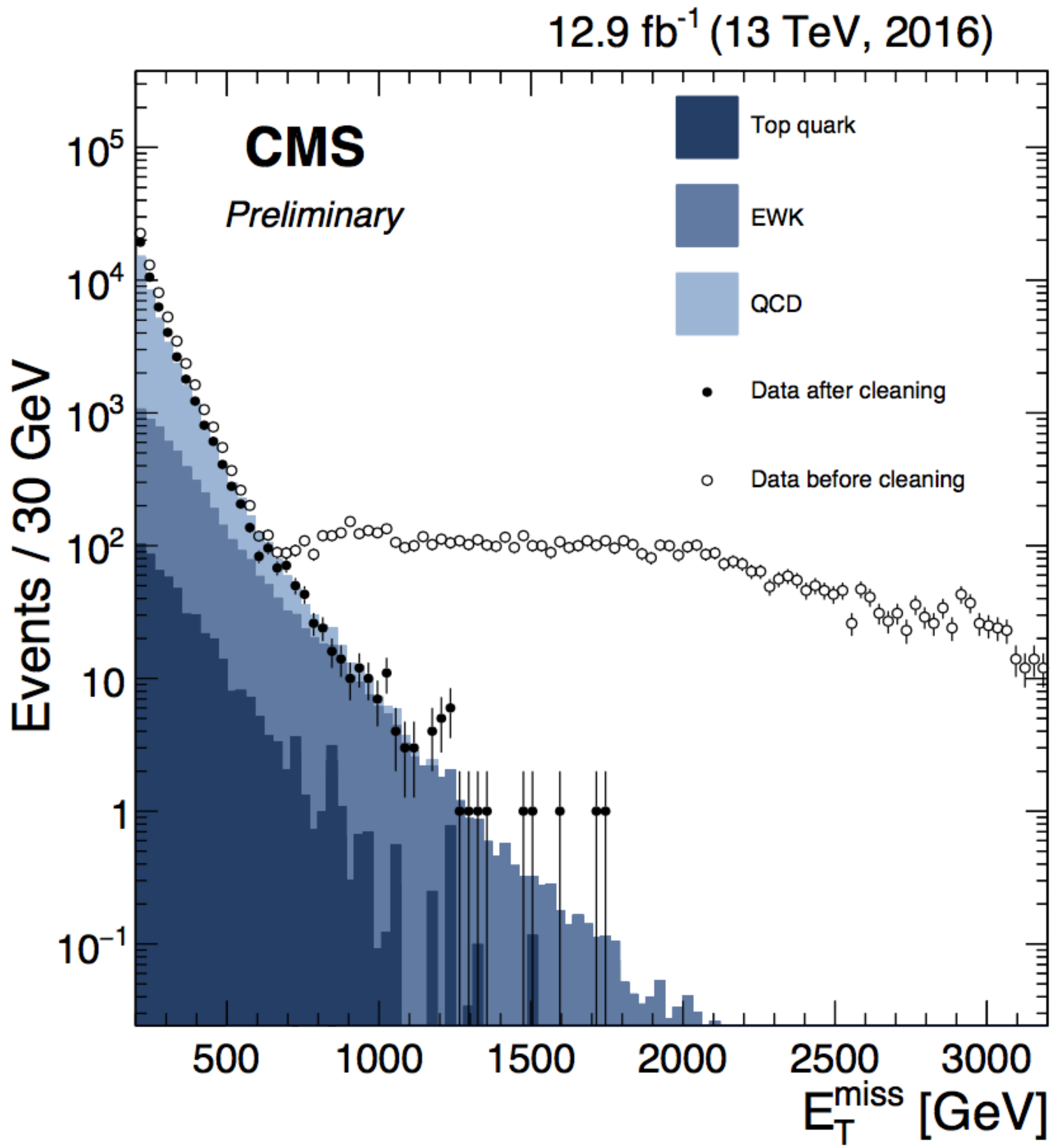
Total transverse momentum in the event has to be balanced!

Key observable: Missing transverse energy (MET) defined as the imbalance in the transverse momentum of all particles that interact with the detectors

The existence of **MET** in the event => **Dark Matter ?**

Challenges with 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

Mono-X Searches: Analysis Strategy

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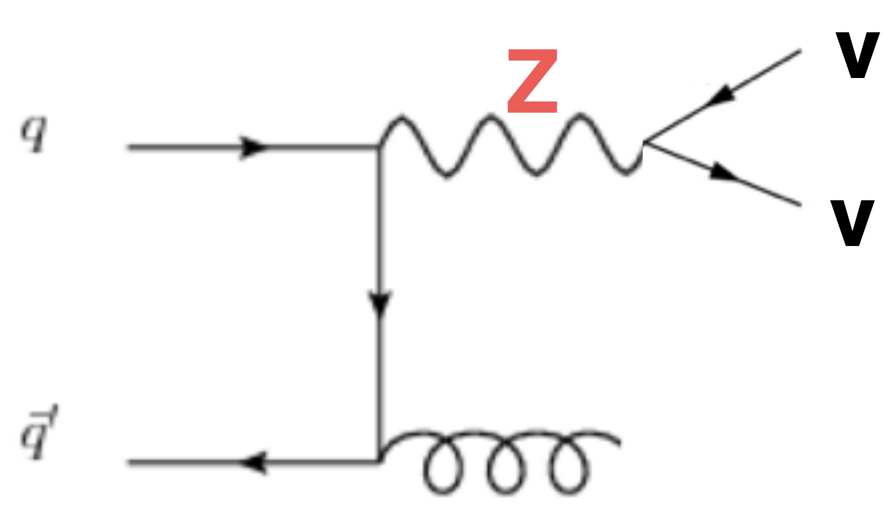
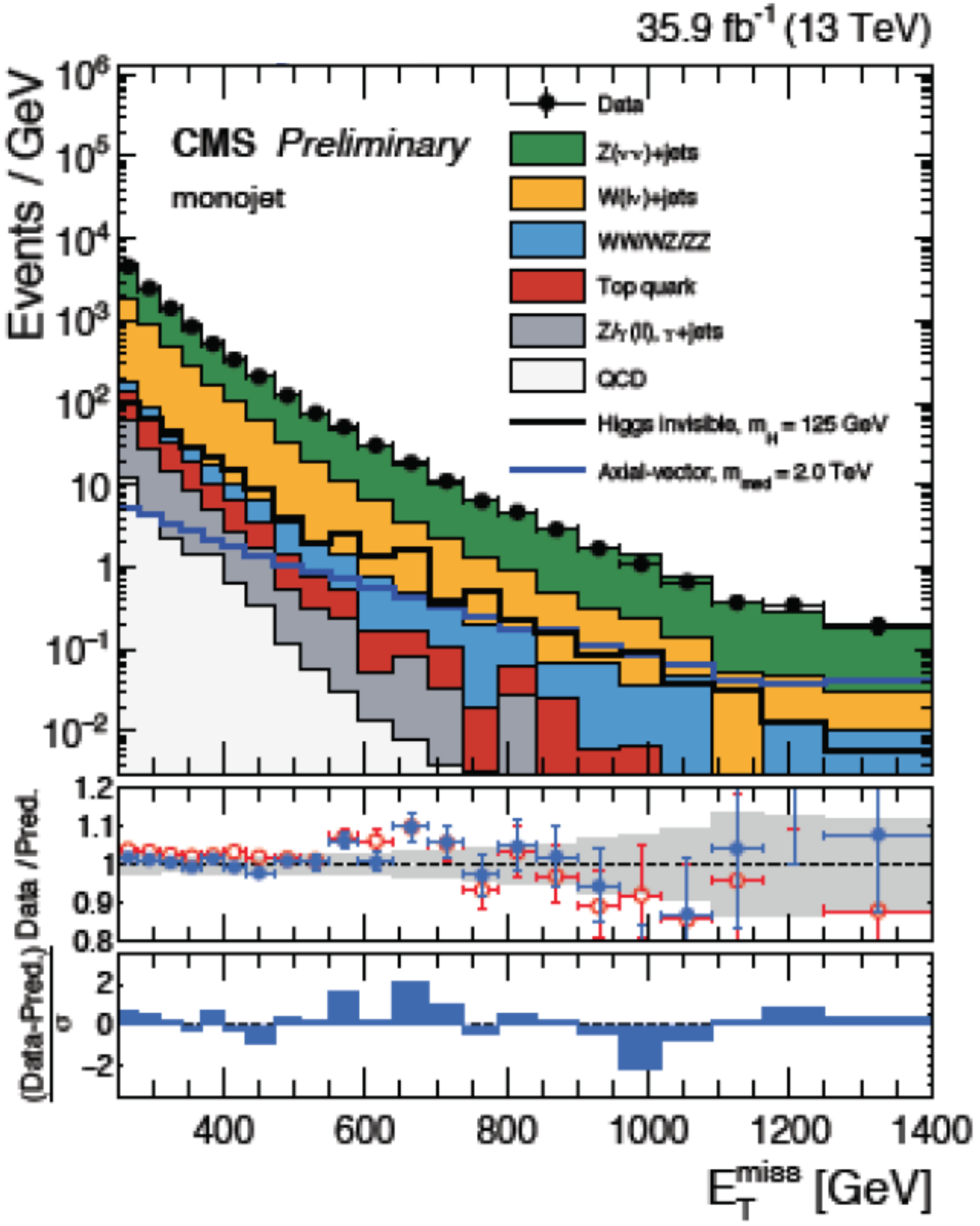
Analysis Strategy: Mono-X

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.



Irreducible largest background (Standard Model)



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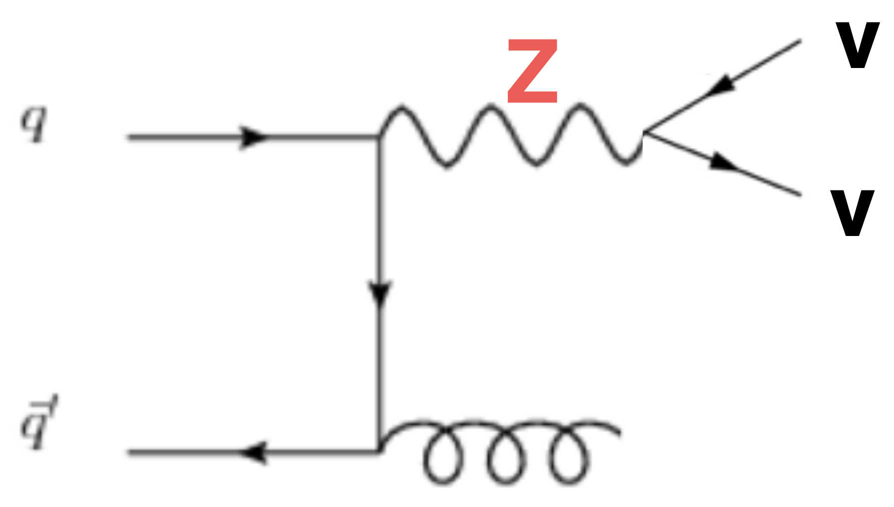

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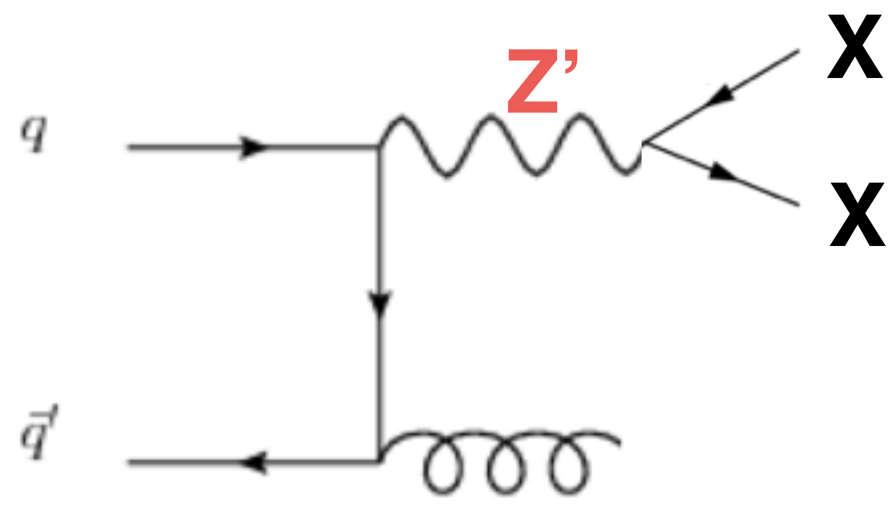
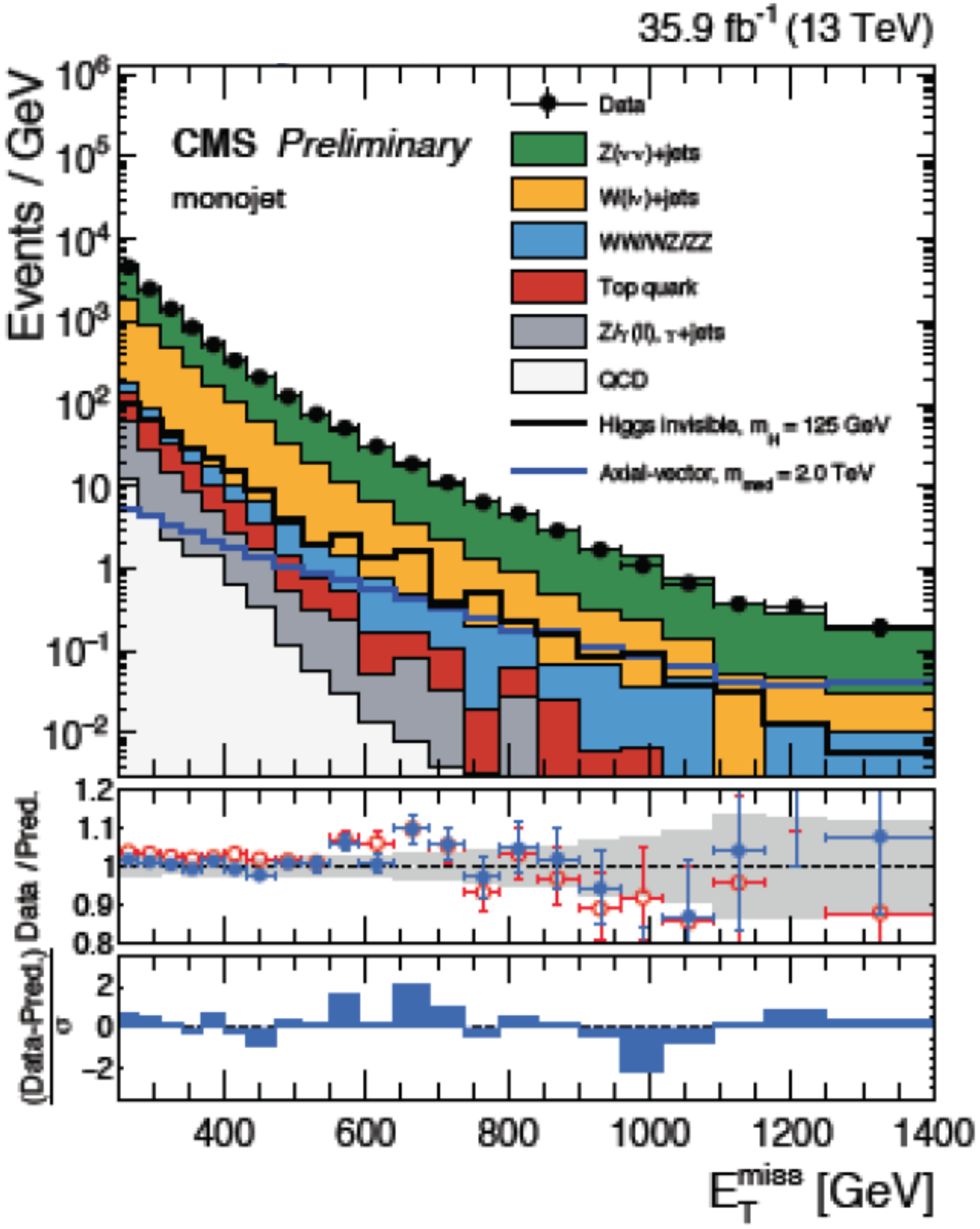


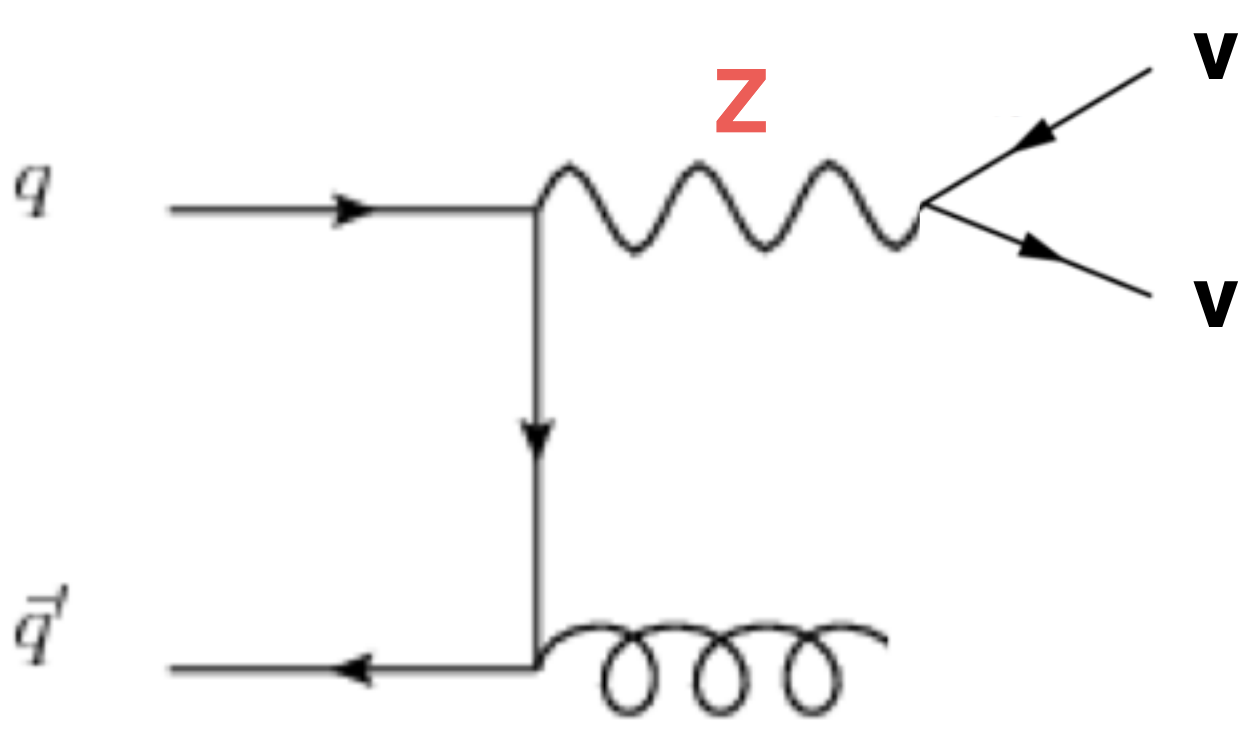
Dark Matter Signal

Not so easy to distinguish! Identical in signature.

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

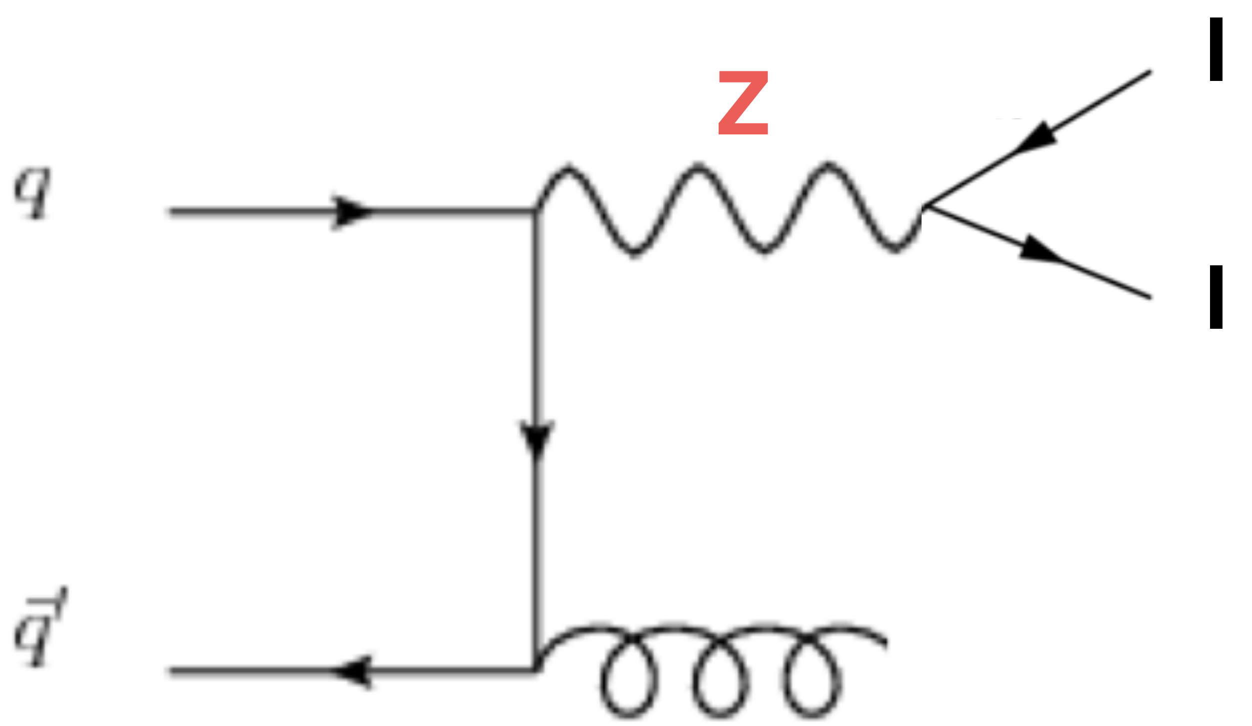


Leading background estimation case study: Monojet



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

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



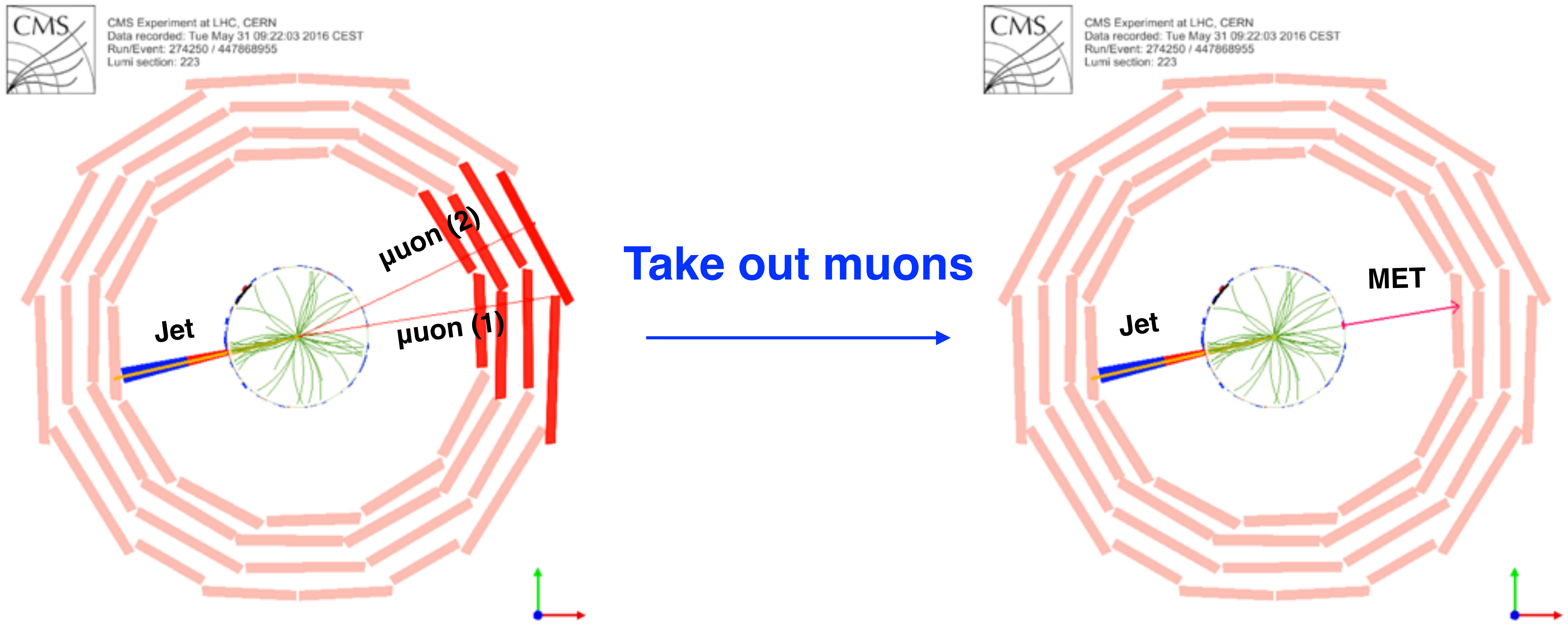
Same pT spectra as Z→vv

but… statistically limited

Z→μμ branching ratio ~3%

Z→vv branching ratio 20%

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



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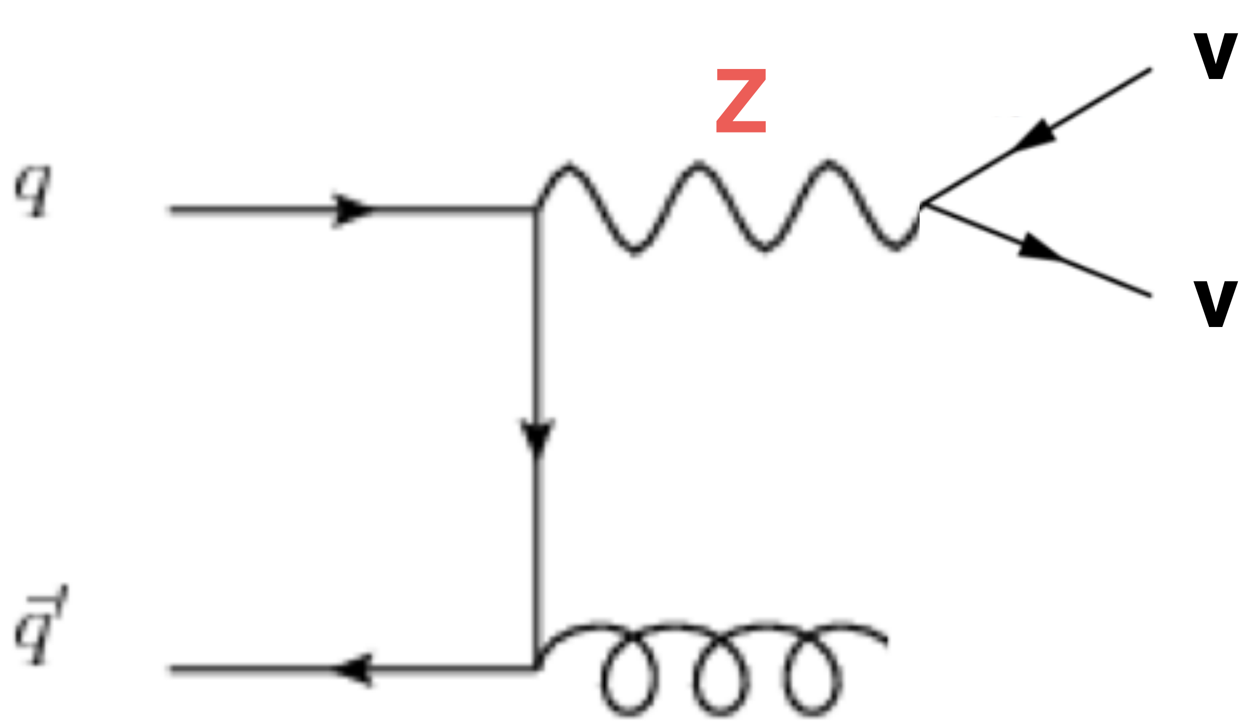

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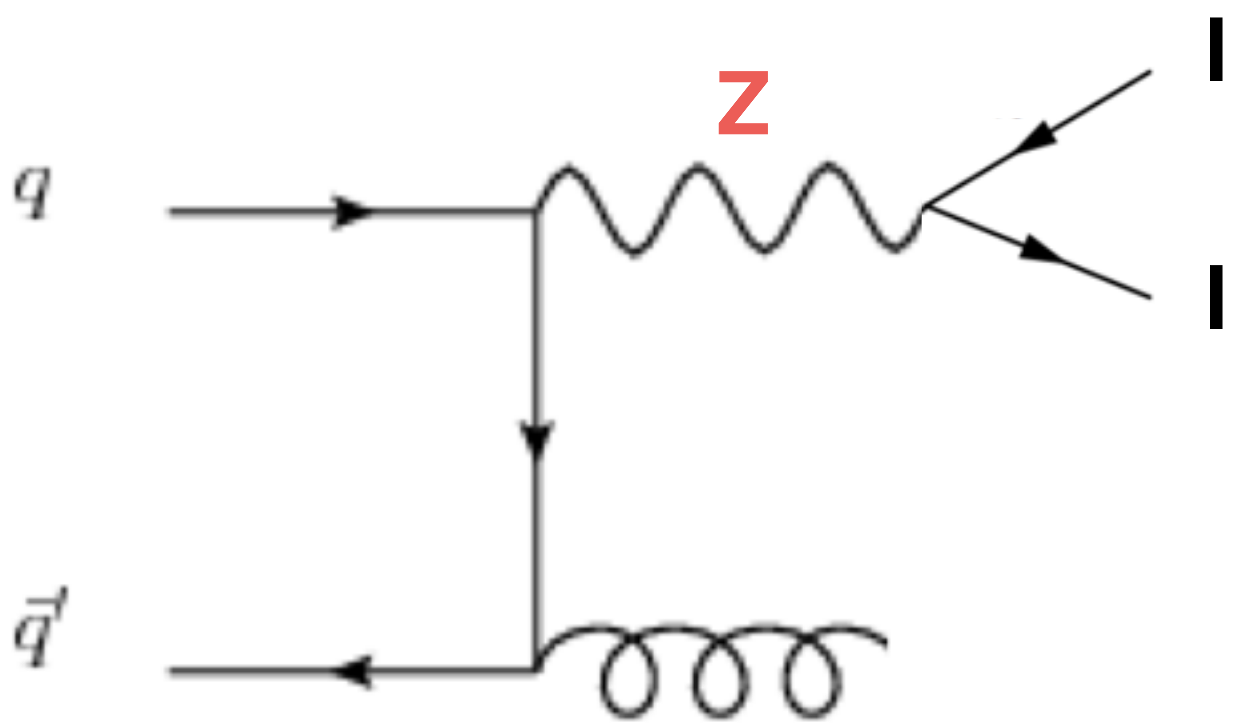

Same pT spectra as $Z\rightarrow\nu\nu$

but… statistically limited

$Z\rightarrow\mu\mu$ branching ratio ~3%

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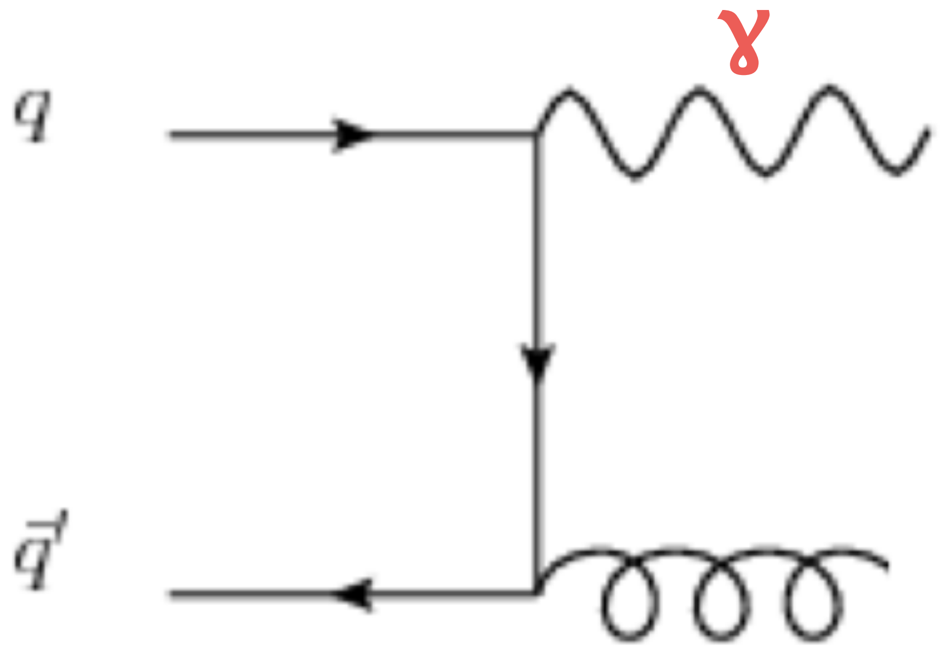
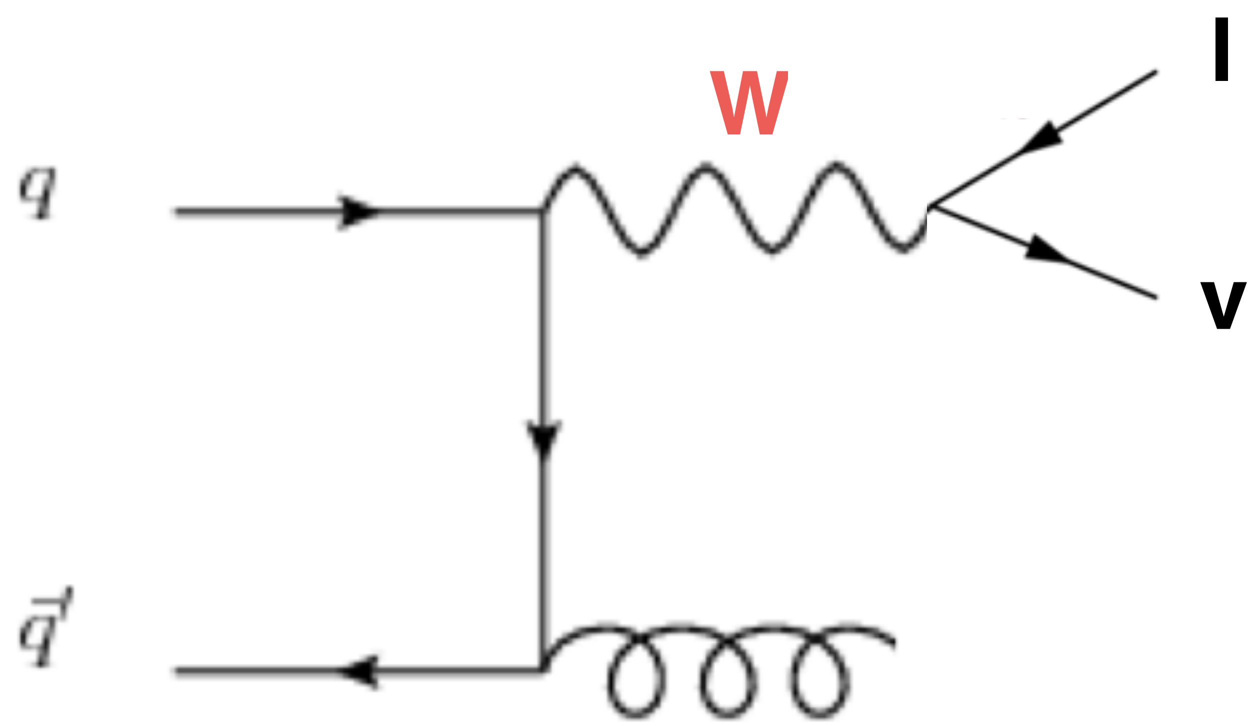


Similar pT spectra as $Z\rightarrow\nu\nu$

Statistically rich!

but…

large theory uncertainties



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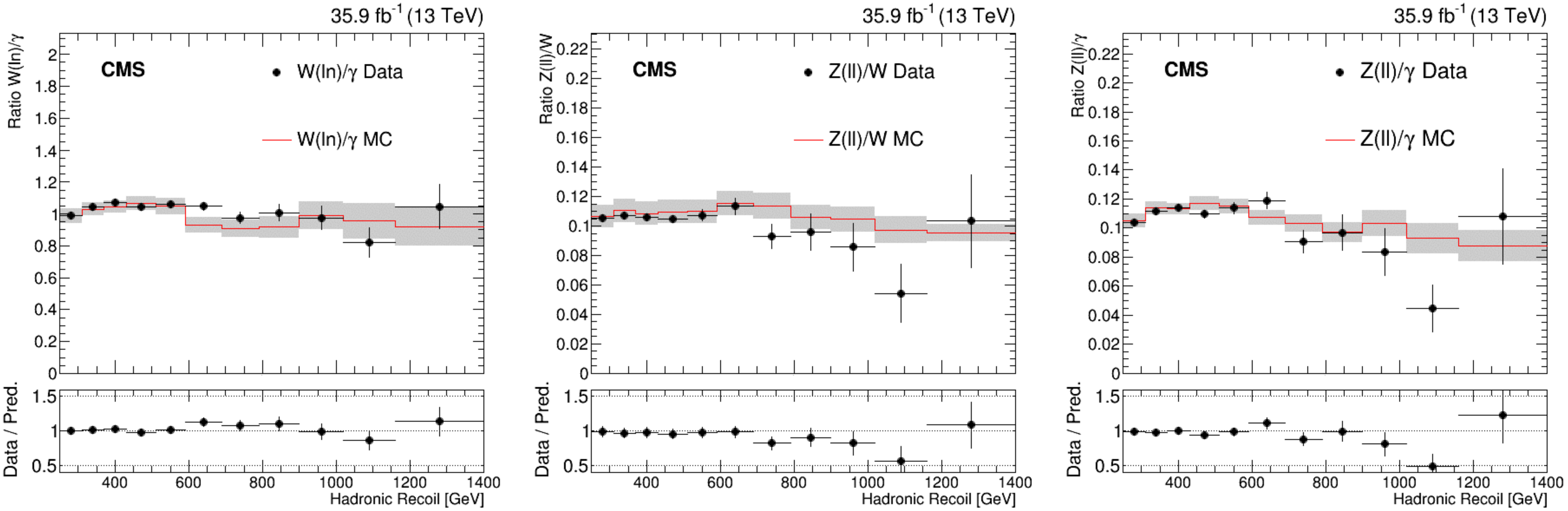
Statistically ~ Z (νν)

but…

large theory uncertainties

Collaboration with theorists arXiv:1705.04664



Black ratio from data and statistical uncertainties / Red from MC

Grey band is stat. + sys uncertainty on MC. Sys uncertainty includes theoretical uncertainties

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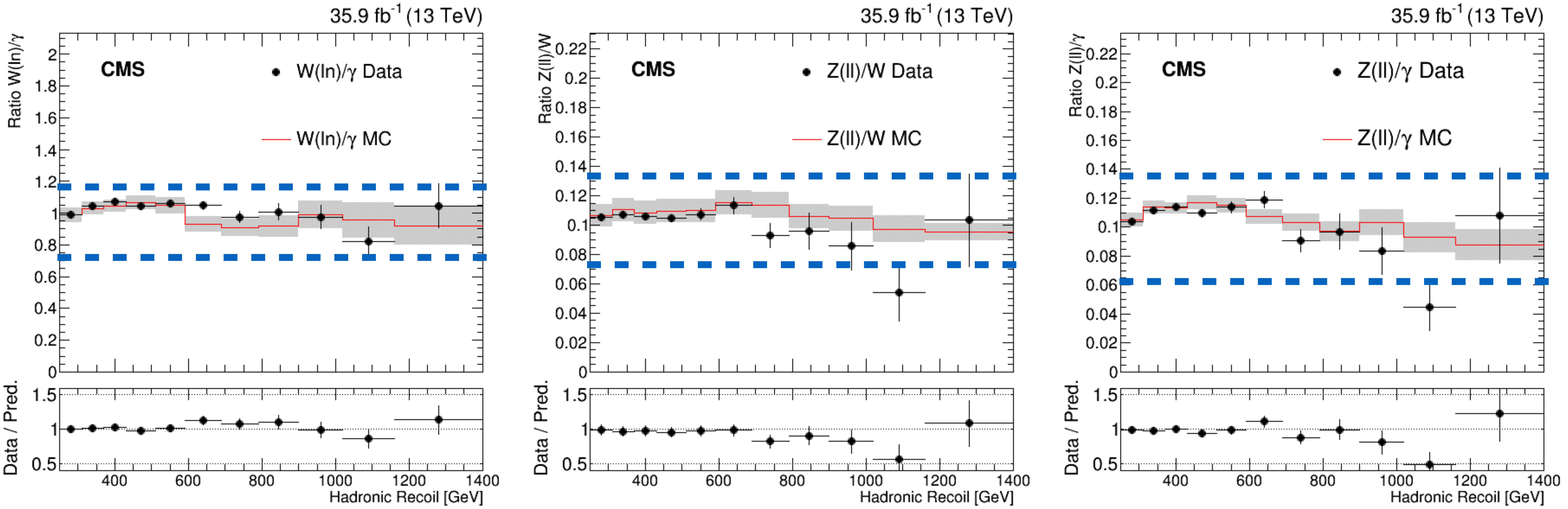

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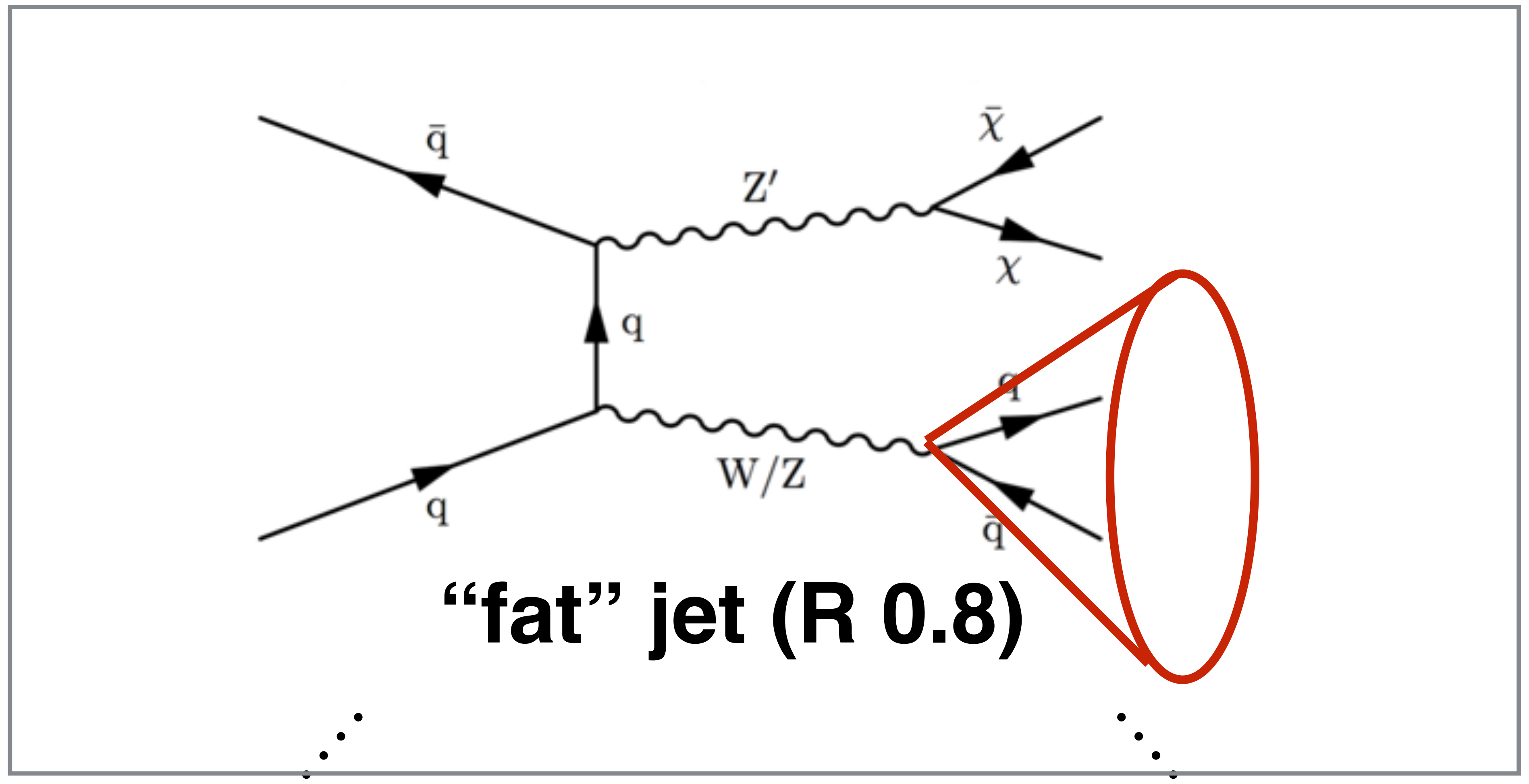
Grey band is stat. + sys uncertainty on MC. Sys uncertainty includes theoretical uncertainties

dashed lines -> what the uncertainties would have been without the work of the theory community

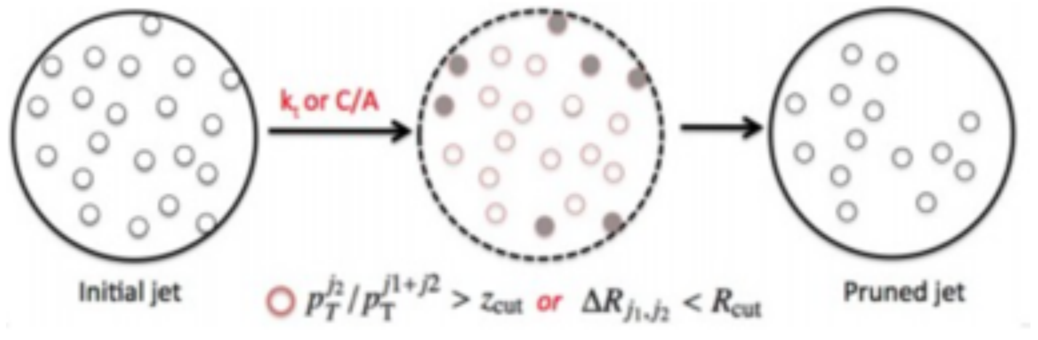
Mono-X Searches: Experimental Techniques

Experimental techniques case study: Mono-V

… even with state of the art background estimation strategies, we are often overwhelmed by SM rescue: **boosted topologies** & **substructure**

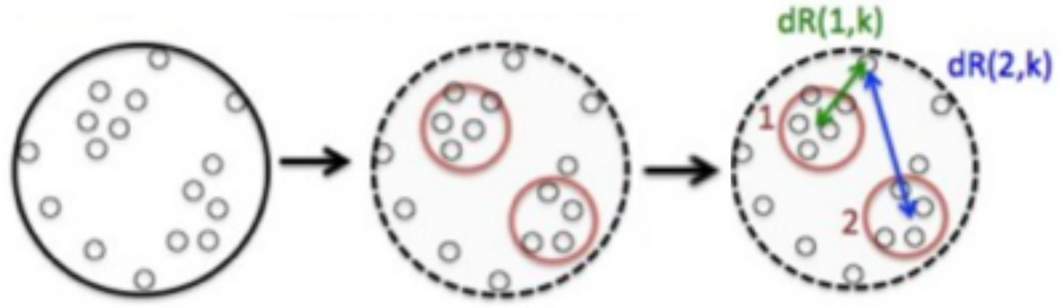


Pruned Mass



Remove softer constituents

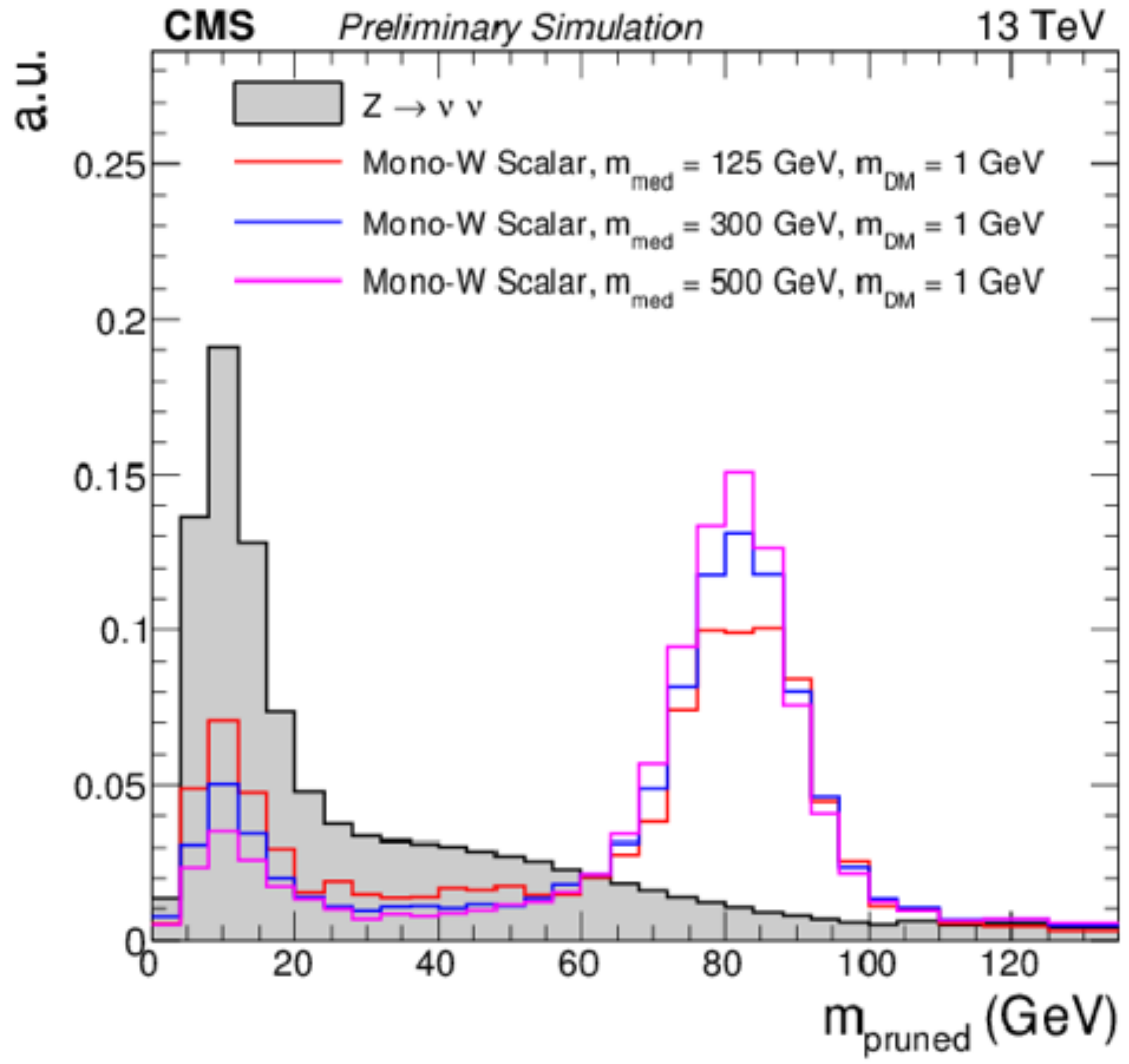
N-subjetiness

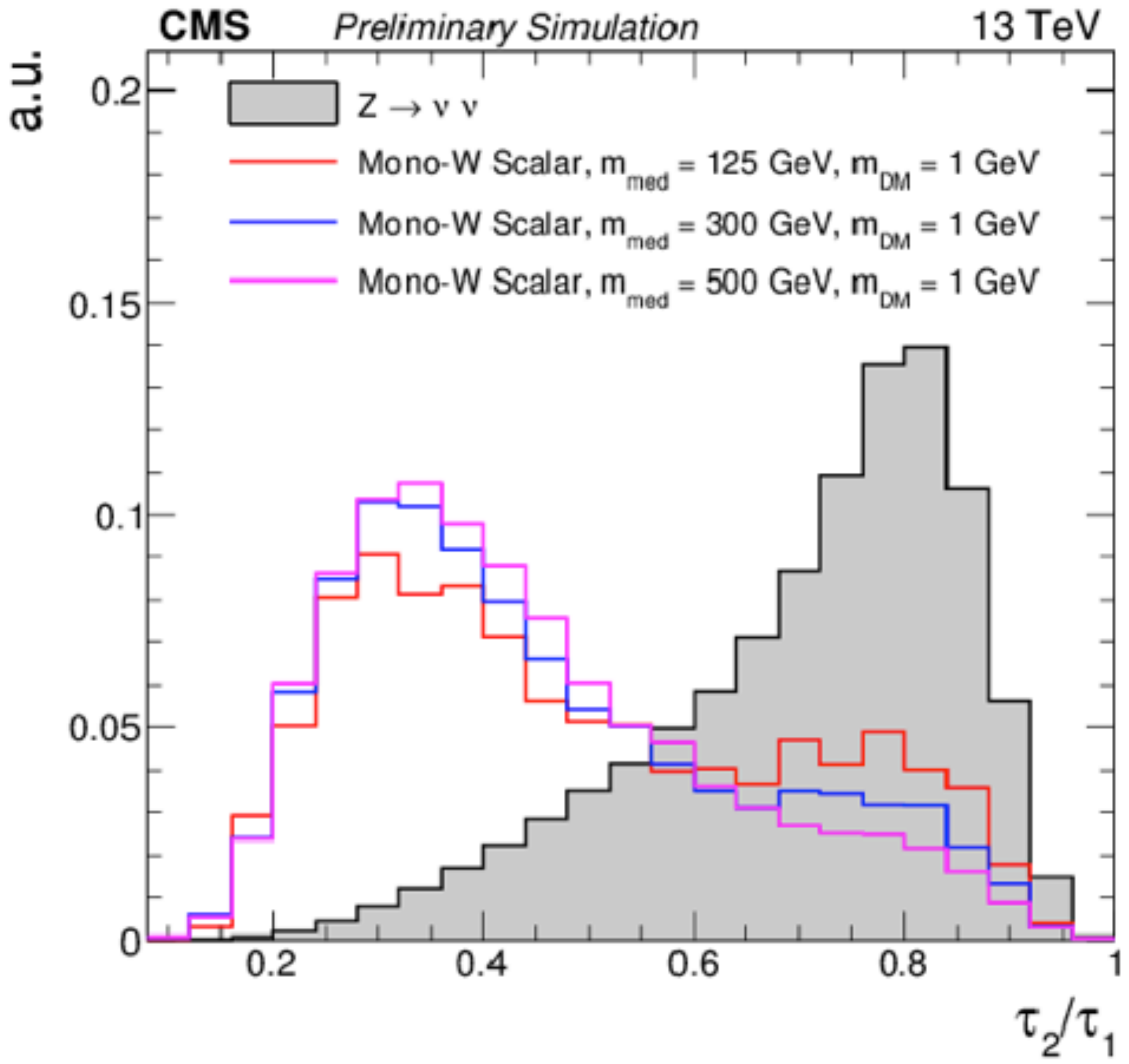


Quantify how well a jet can be subdivided into sub-jets.

Models (scalar): **σ(monojet) ~ 30 x σ (mono-W)**

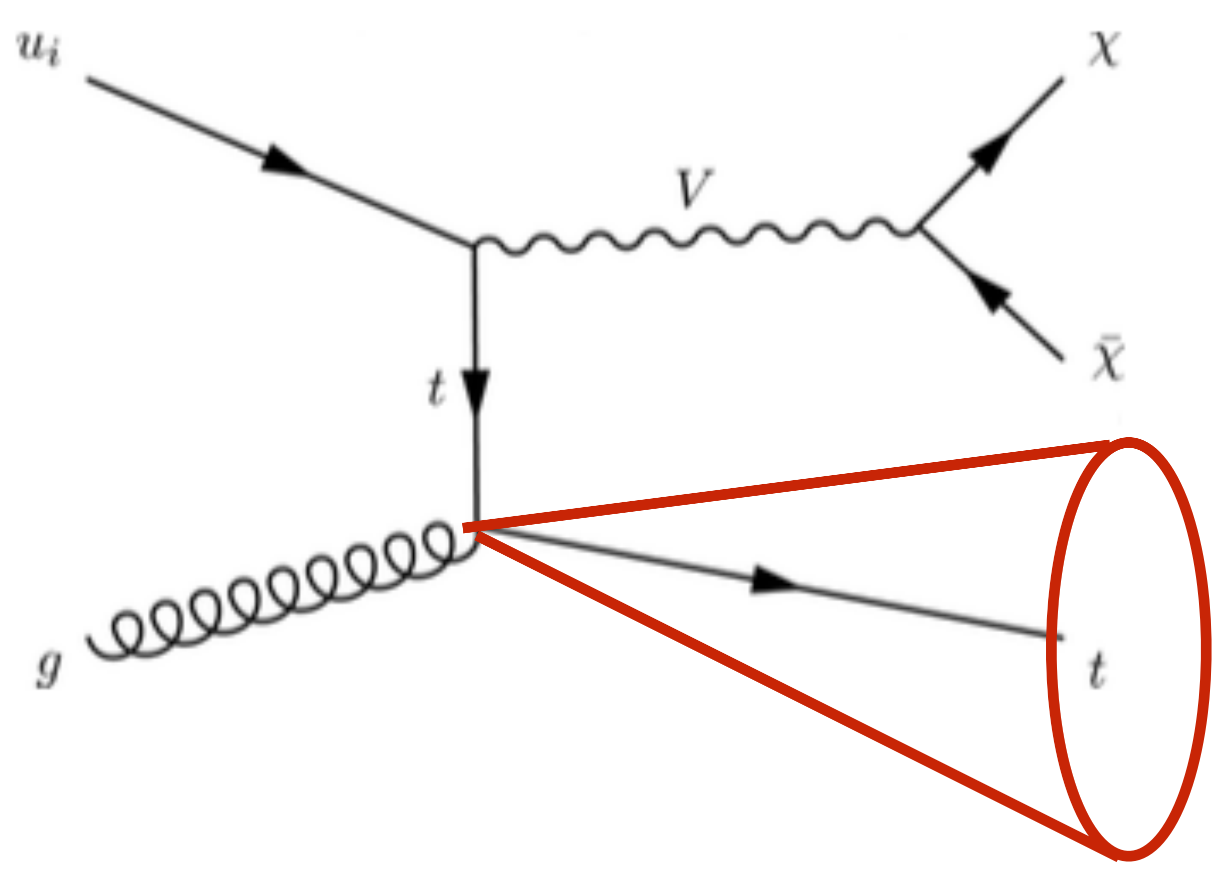
… but same sensitivity in mono-V and monojet categories!





Experimental advancements case study: Mono-top

… and there are even more ***novel*** techniques now being used



“fatter” jet (R = 1.5)

Puppi jets & MET!

Energy correlation functions (ECFs): arXiv:1609.07473

N-point correlation functions of the constituents’ momenta, weighted by the angular separation of the constituents.

$$e(o,N,\beta) = \sum_{i_1<i_2<\cdots<i_N\in J}\left[\prod_{1\le k\le j}\frac{p_T^{i_k}}{p_T^J}\right]\times \min\left\{\prod_{k,l\in \text{pairs}\{i_1,\ldots,i_N\}}^{o}\Delta R_{kl}^{\beta}\right\}$$

Angular weighting (β)

Number of pairwise angles entering the product (o)

n particles in the jet - order of correlation fcn (N)

An N-pronged jet will have eM ≪ eN for M > N

⇒ e(N = 4)/e(N = 3) is the analog to τ3/τ2 for top-tagging

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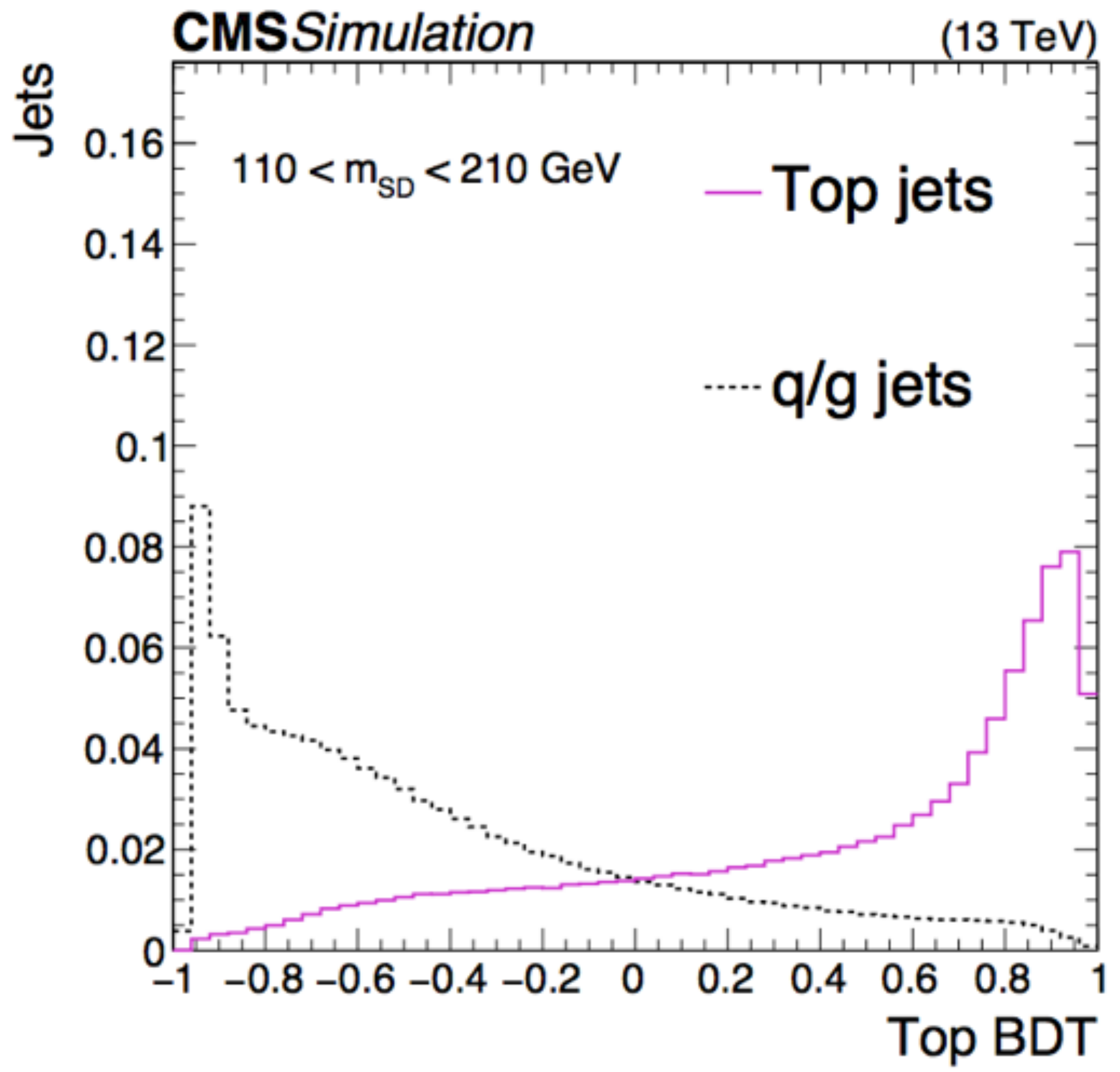

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in mono-top analysis:

> 30 % improvement in **background rejection** with **no loss** of **signal** acceptance!

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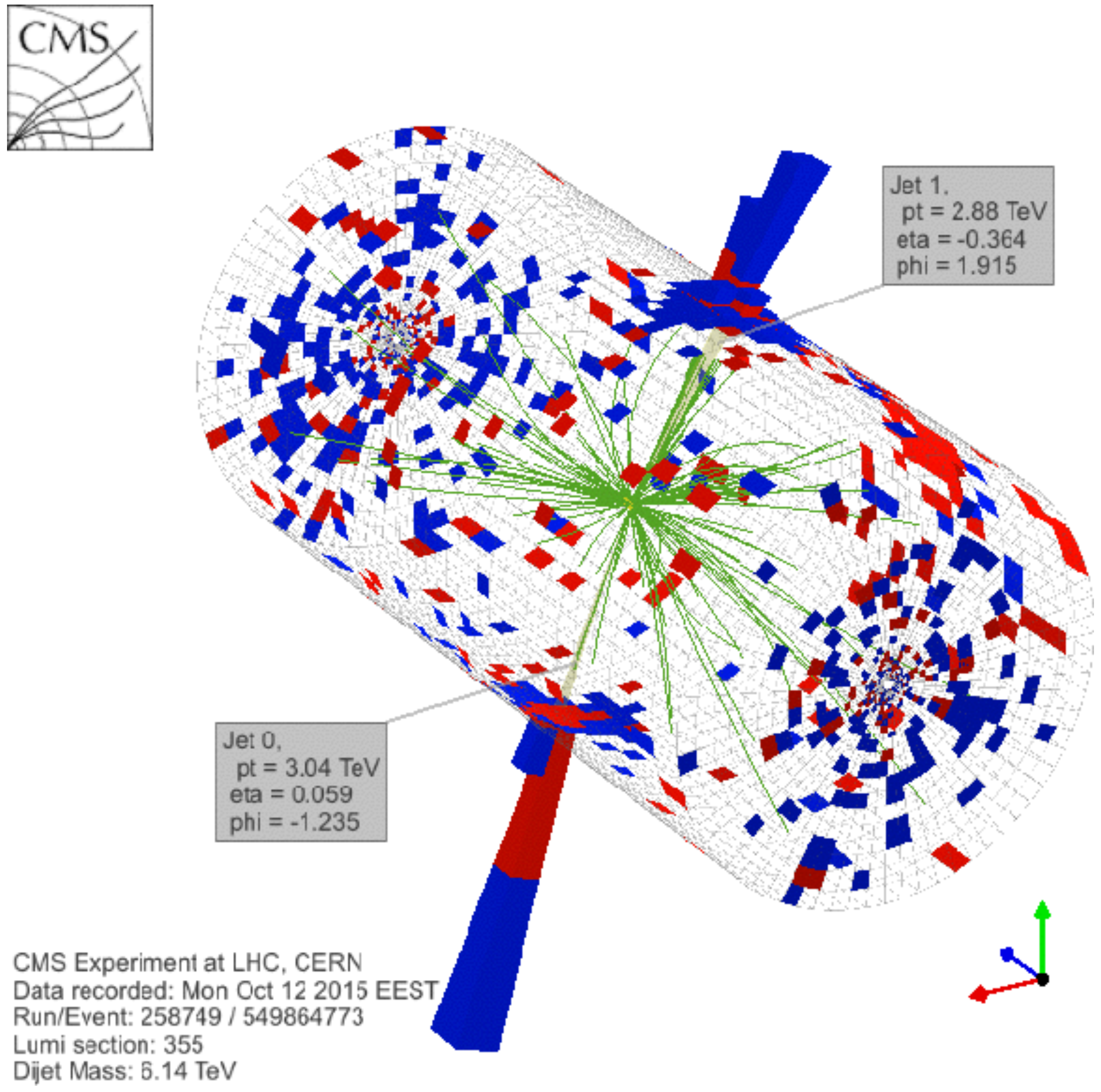
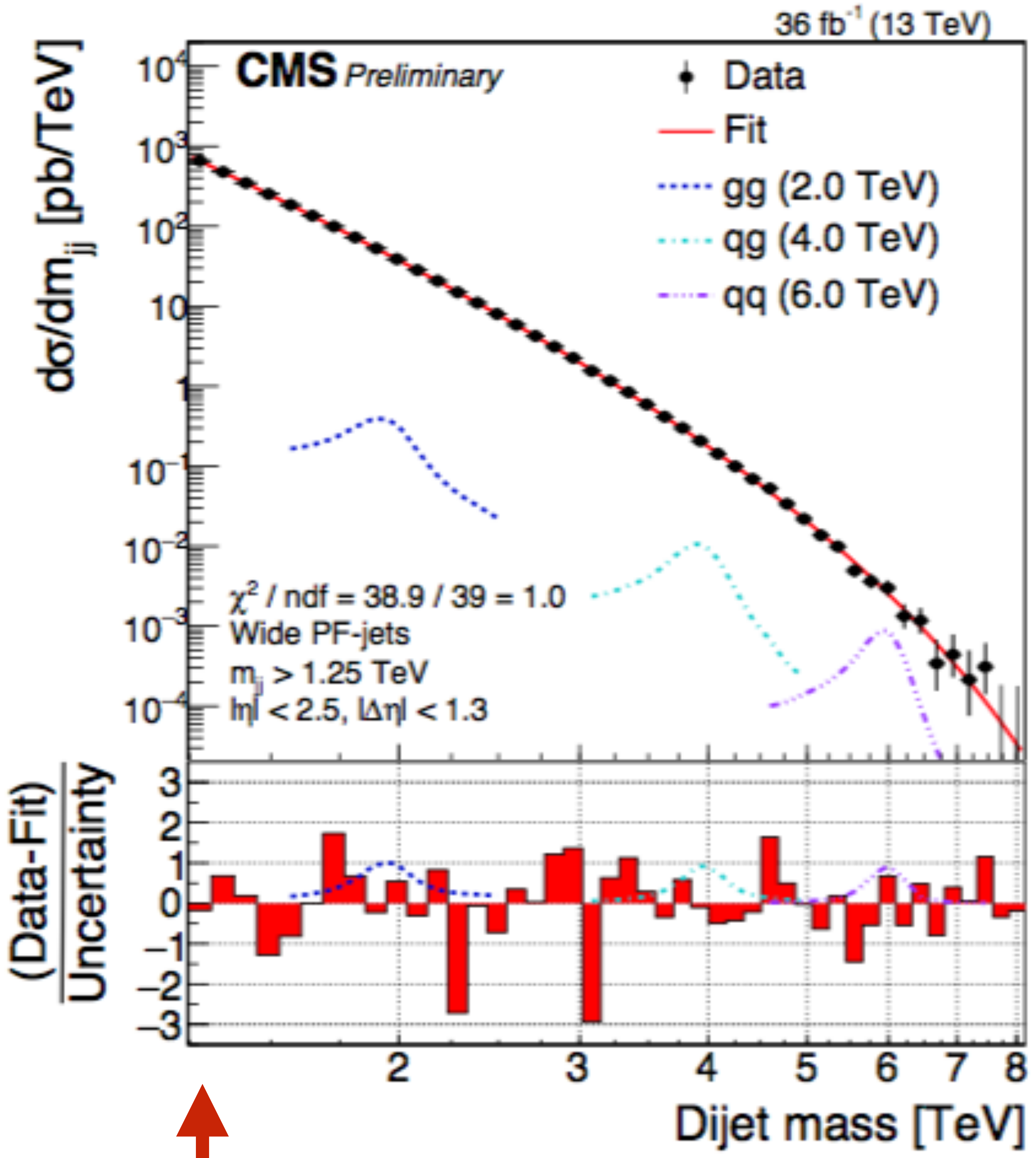
Mediator Searches

Mediator Searches: Experimental Signature

Mediator searches are MET-less! Instead they rely on jets.

Have large QCD multi-jet background, therefore **VERY hard** to keep low thresholds for the **triggers**!





1 TeV **(Traditional data taking)**

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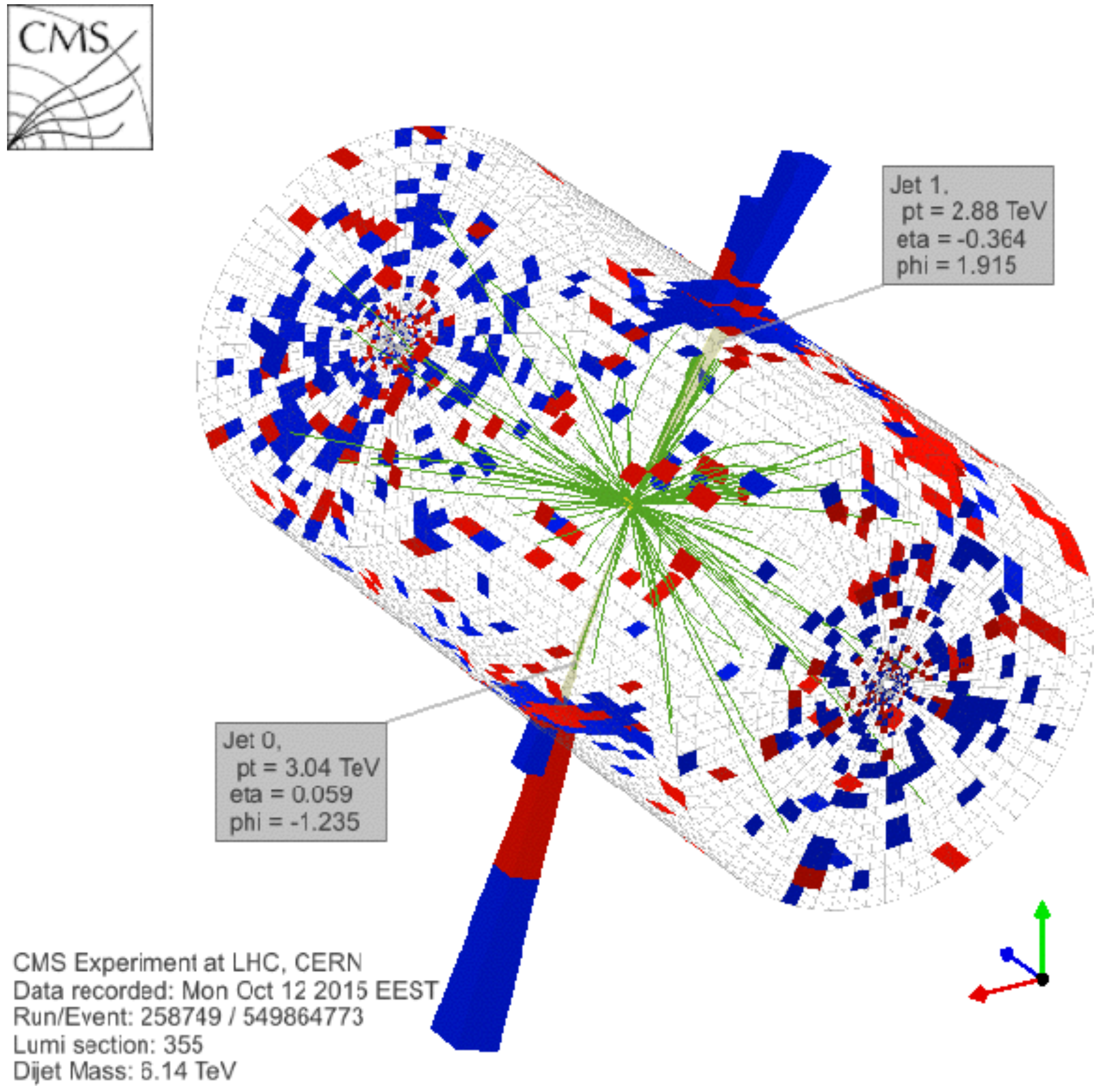
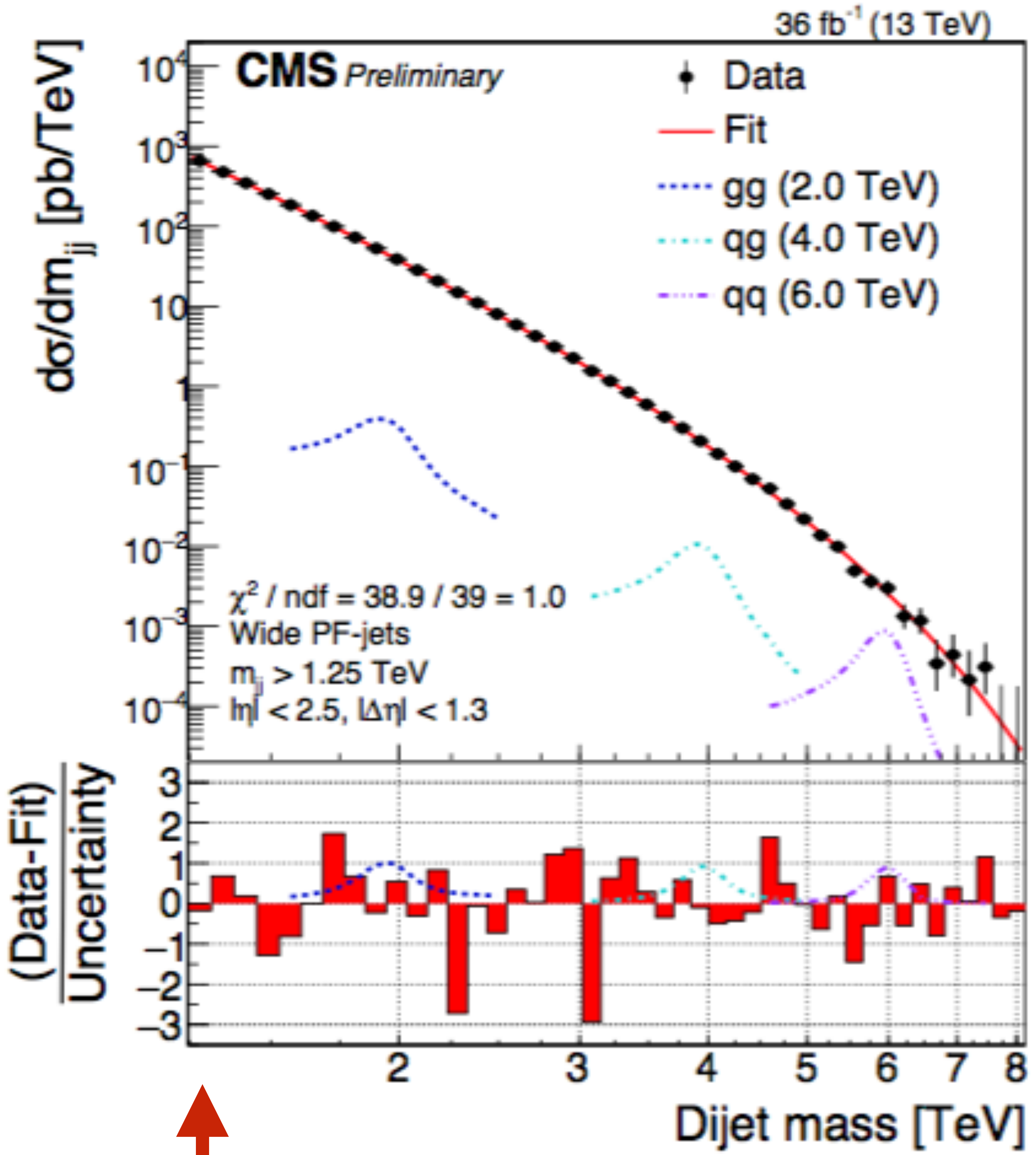
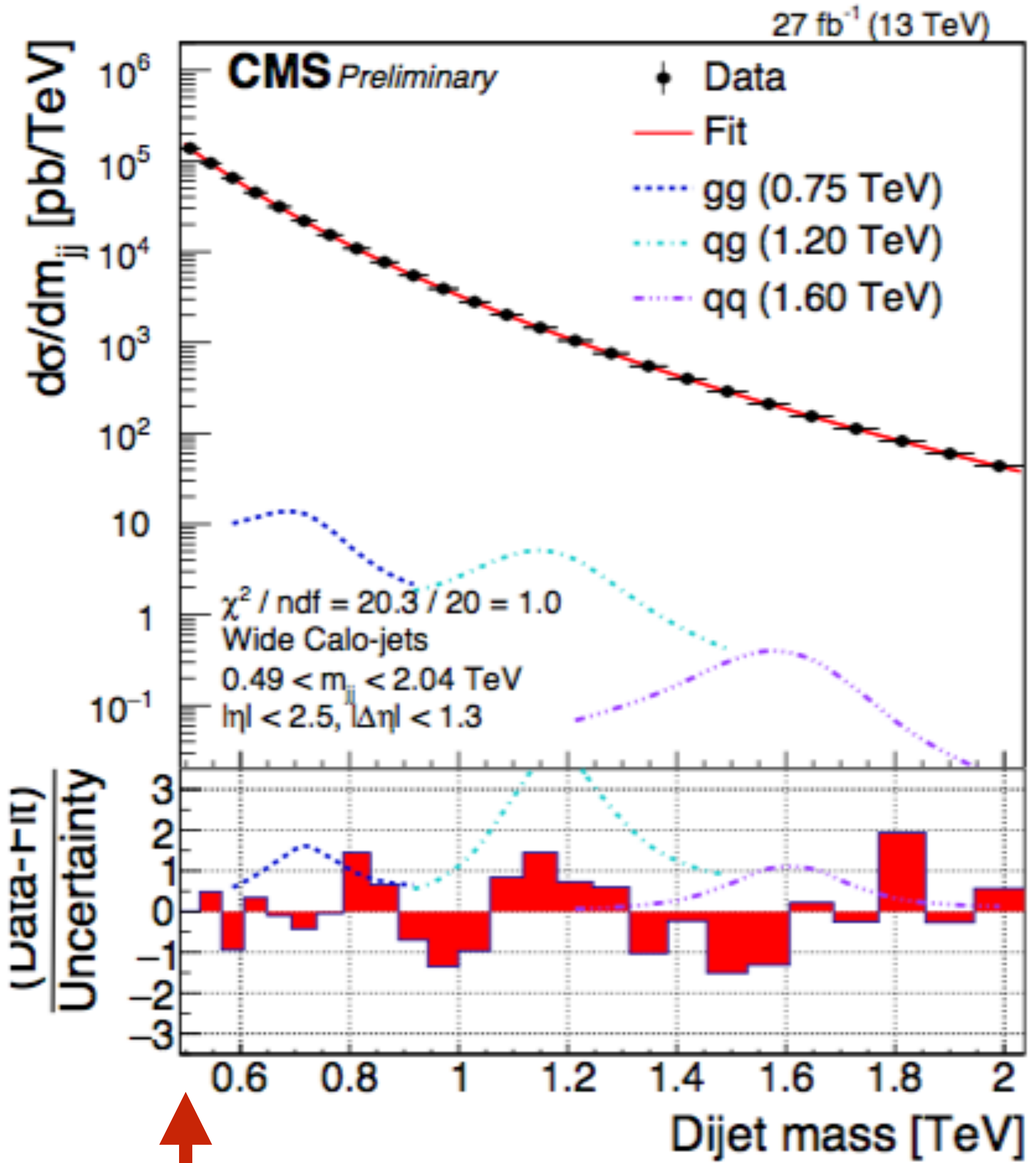






1 TeV **(Traditional data taking)**

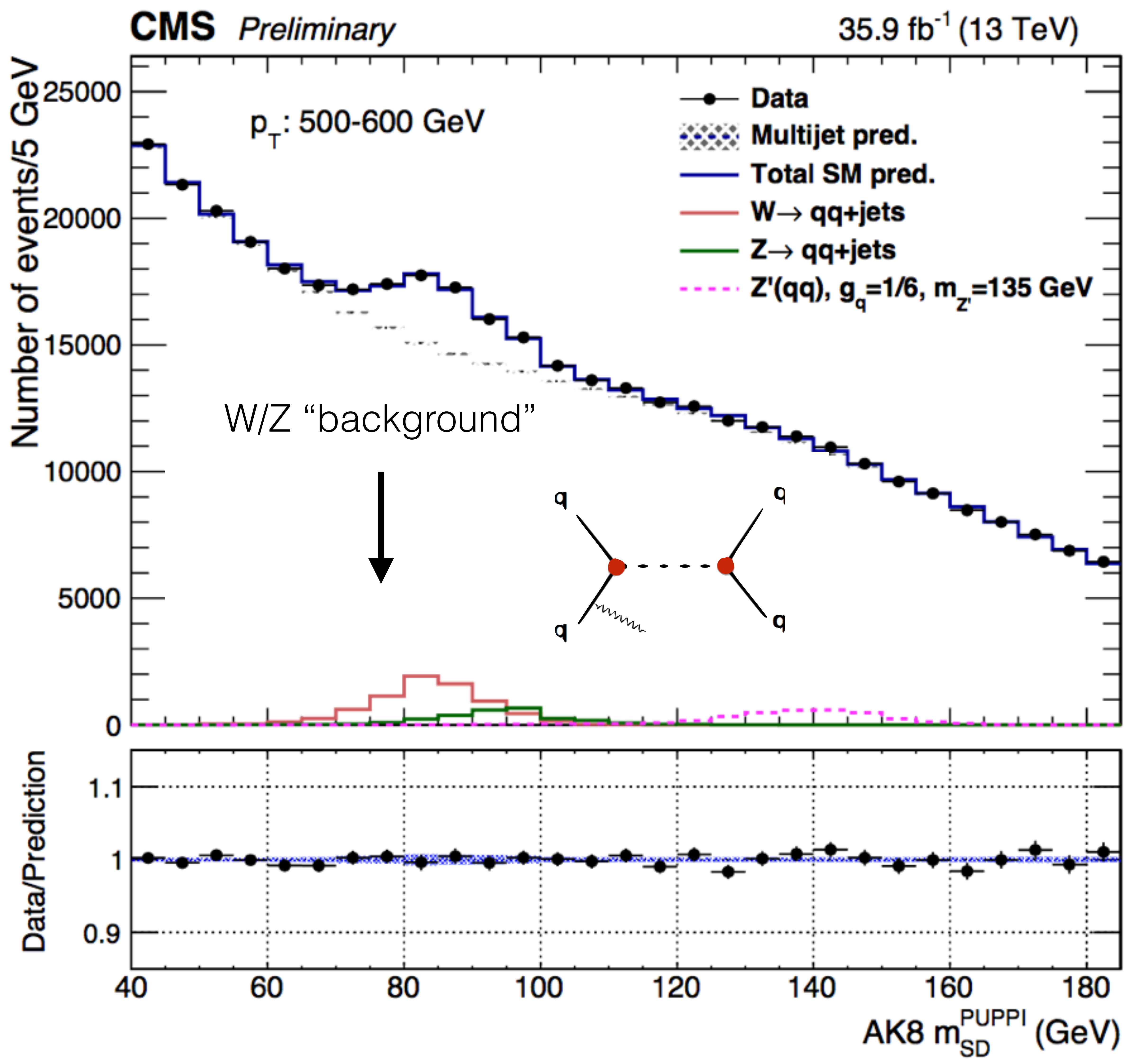
450 GeV **(Data Scouting)**

Data Scouting: Limited event content is kept …

… enables us to record data with lower trigger thresholds!

Mediator Searches: Experimental Techniques

Case study: Boosted dijets + ISR jet



One way to "cope with QCD" is to go to high pTs, and use substructure:

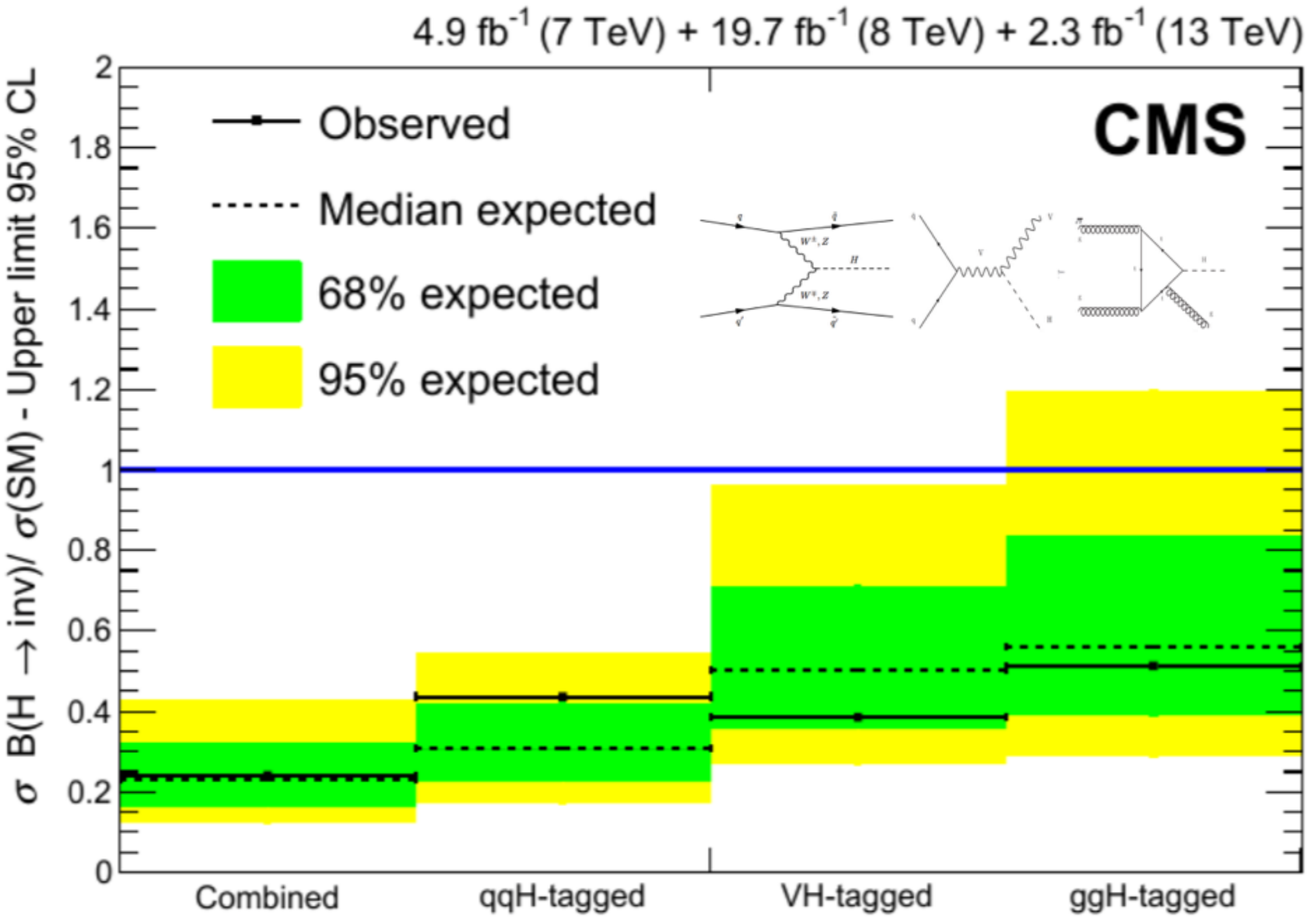
- Soft drop groomed jets & ECFs :
  - The ratio of 2-point correlation and a 3-point correlation function.
- **Danger:** Selection **sculpts the jet mass!** Searching for a resonant peak in the jet mass over a large range becomes challenging.
- **Solution**: Define a transformation to de-correlate the shape sculpting from pt and ensure a constant QCD background efficiency of 5% across all the pT range.

Higgs Portal: Combination

It all comes together : Part 1 (Higgs Portal)

At the LHC we have discovered a particle: **Higgs Boson** … but we do not know enough about it.

Question: Does it decay into BSM particles, like.. DM?



The most sensitive channel for this kind of search is through VBF topology!

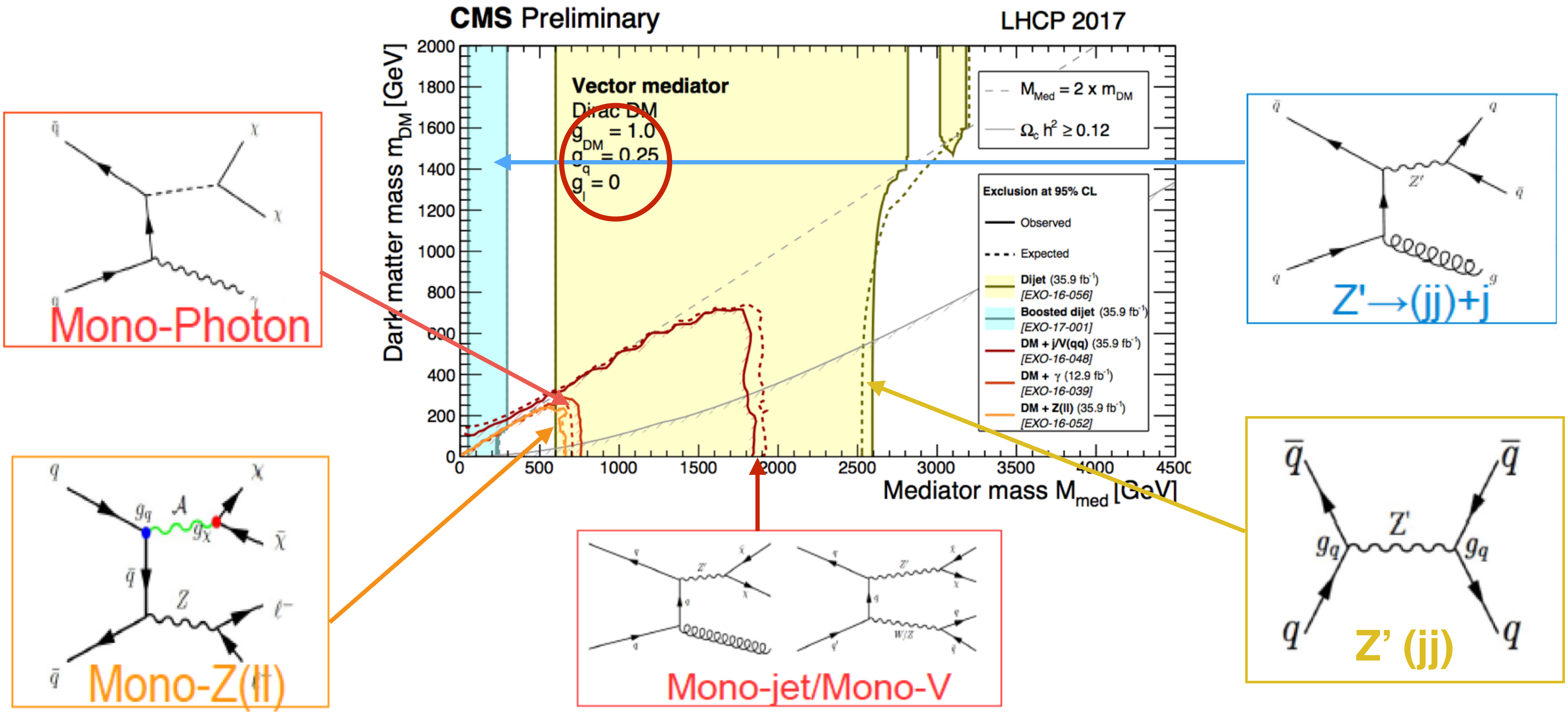
Combination has been performed using data from 7, 8 and 13 TeV and using:

- qqH VBF channel
- Z(→ll) H(→inv) channel
- Z(→vv) H(→inv) and Z(→qq) H(→inv)

BR(H→inv) < 24%

Summary plots

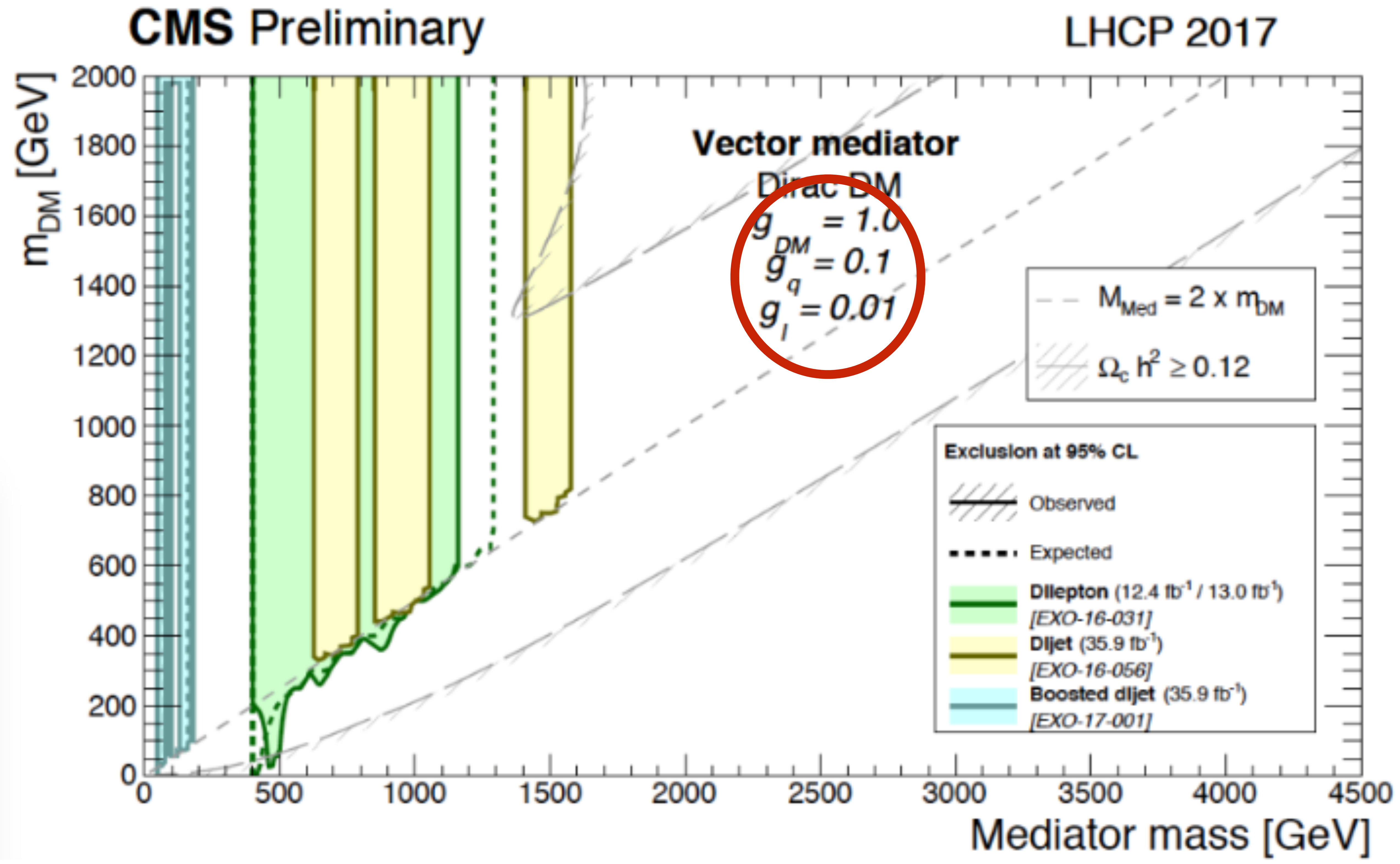
It all comes together : Part 2 (Summary)



Coupling strength matters…

With a simple change of coupling strength (g_q = 0.25 —> 0.1), the sensitivity is back to square one!

and we don't know what the coupling really is …



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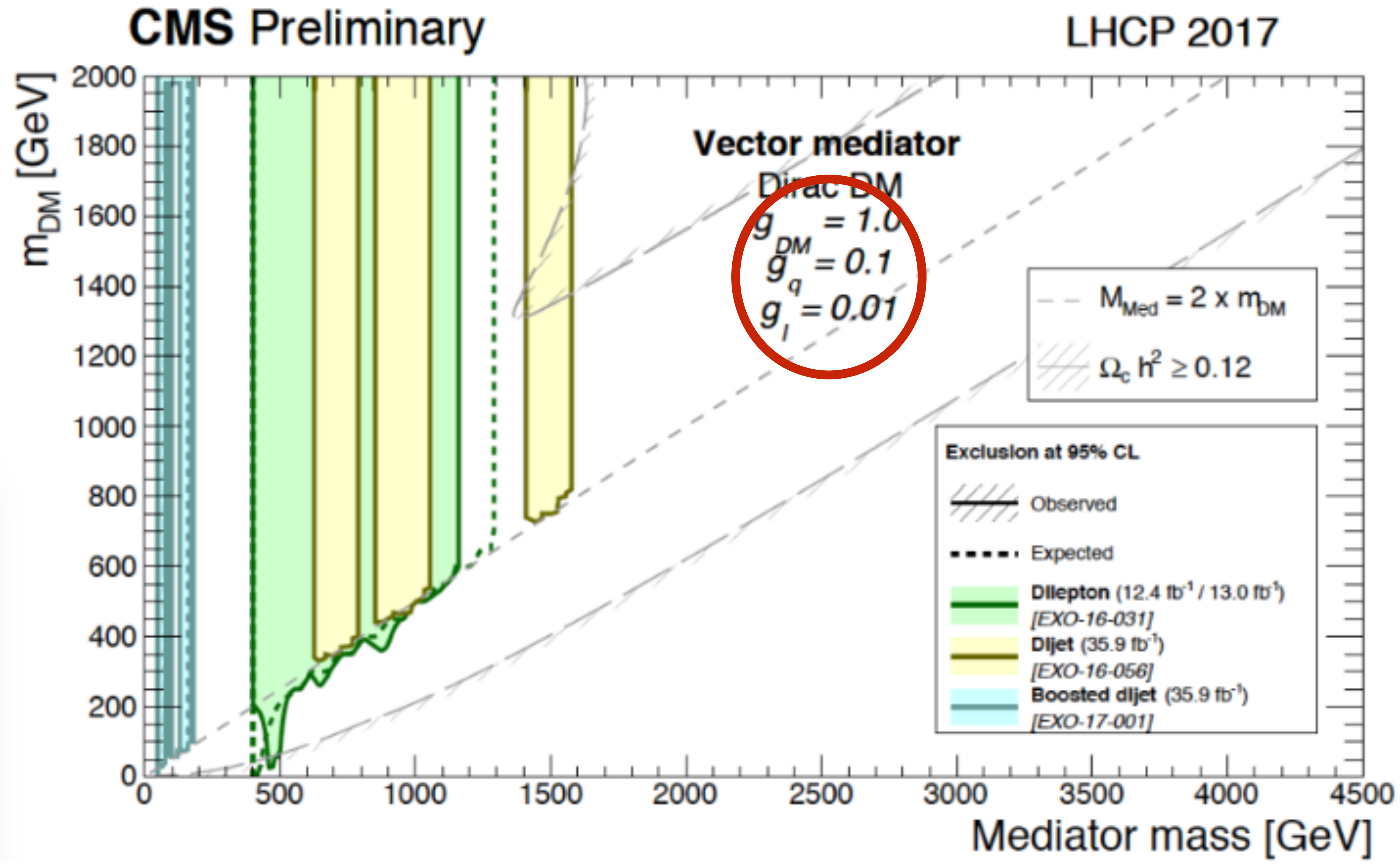
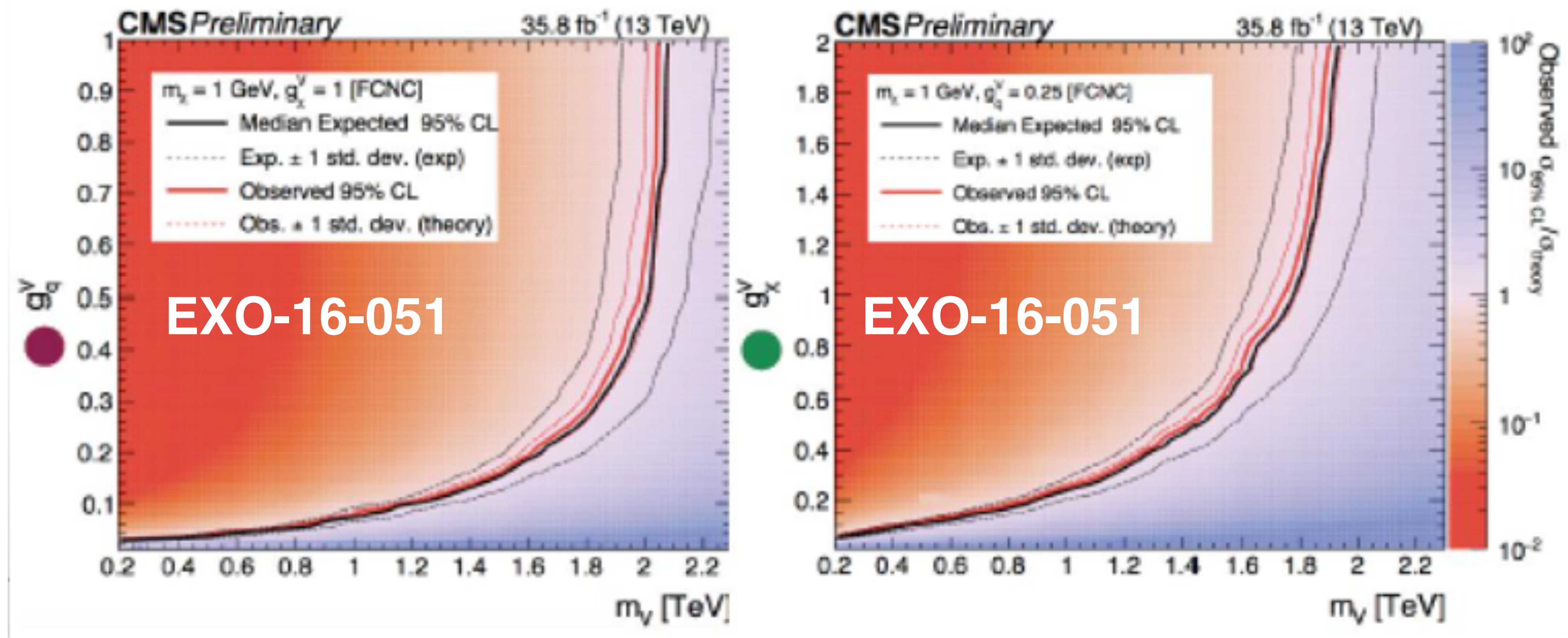
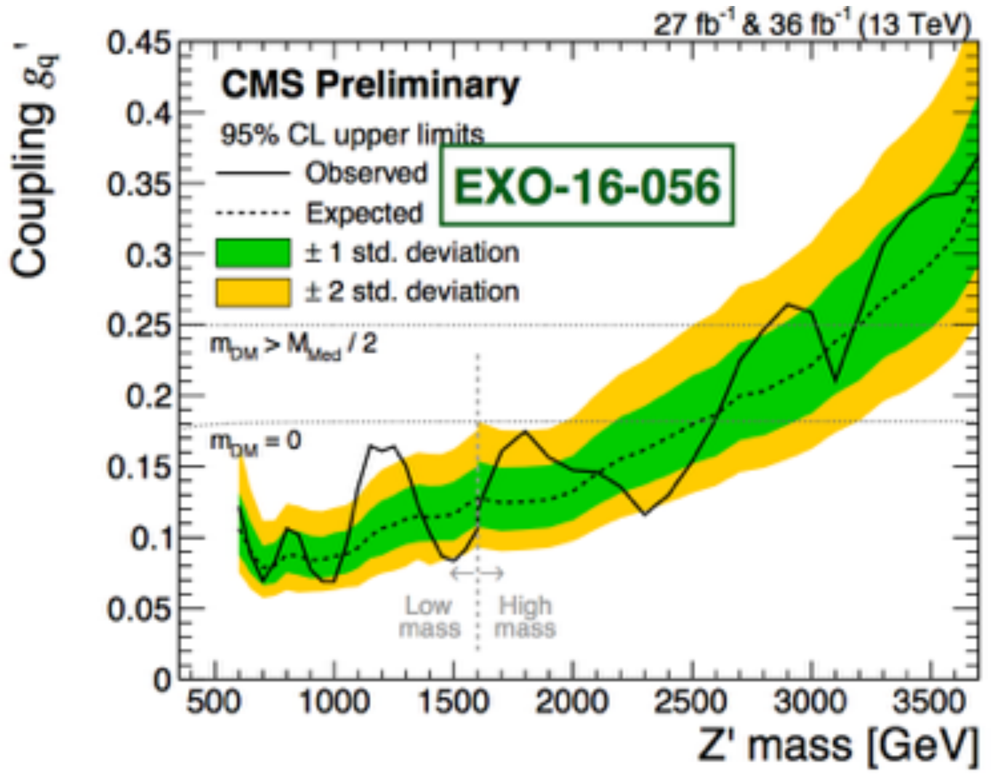


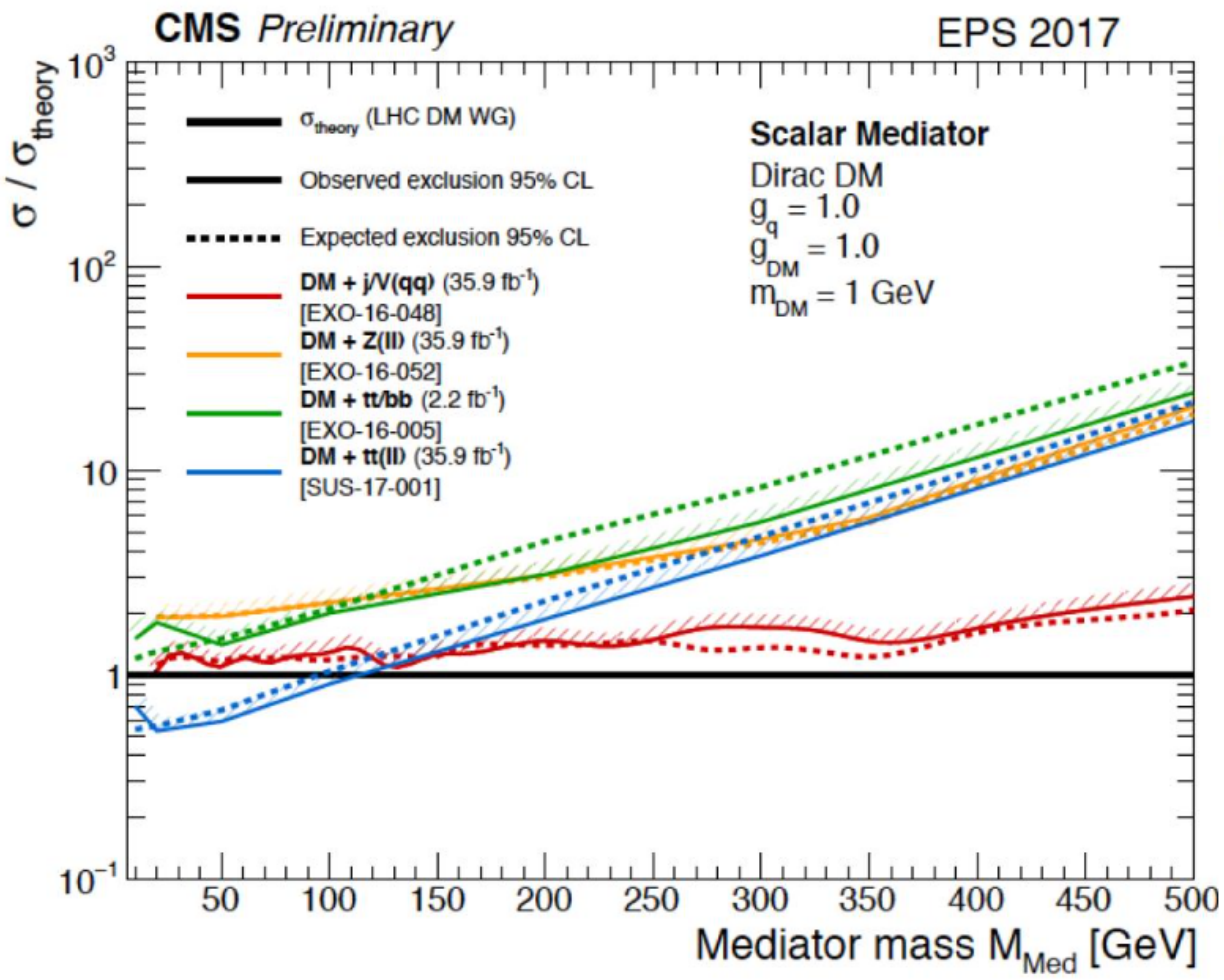


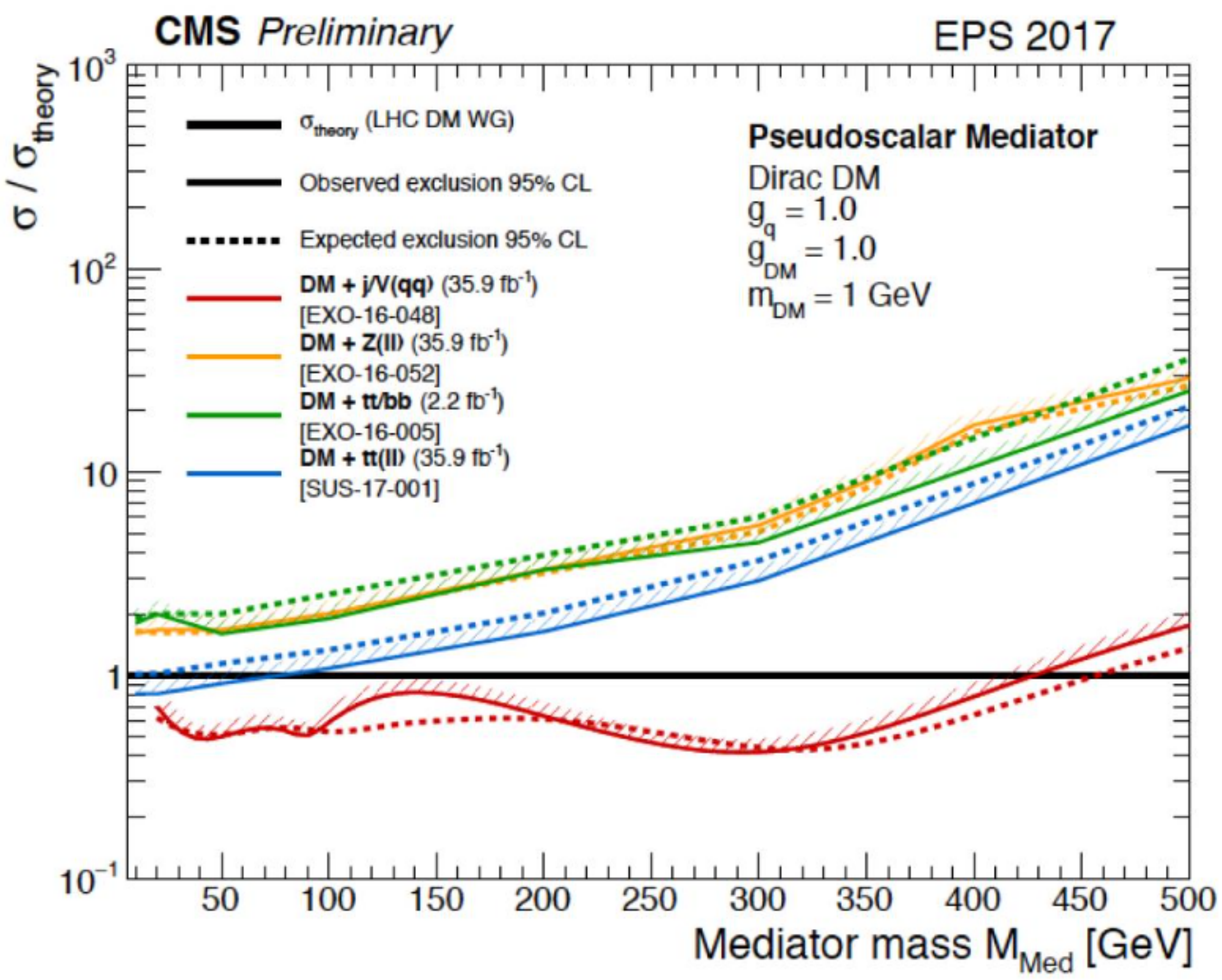


CMS has started presenting the results in terms of the coupling reach!

Discussions on going on the "next generation" of coupling plots

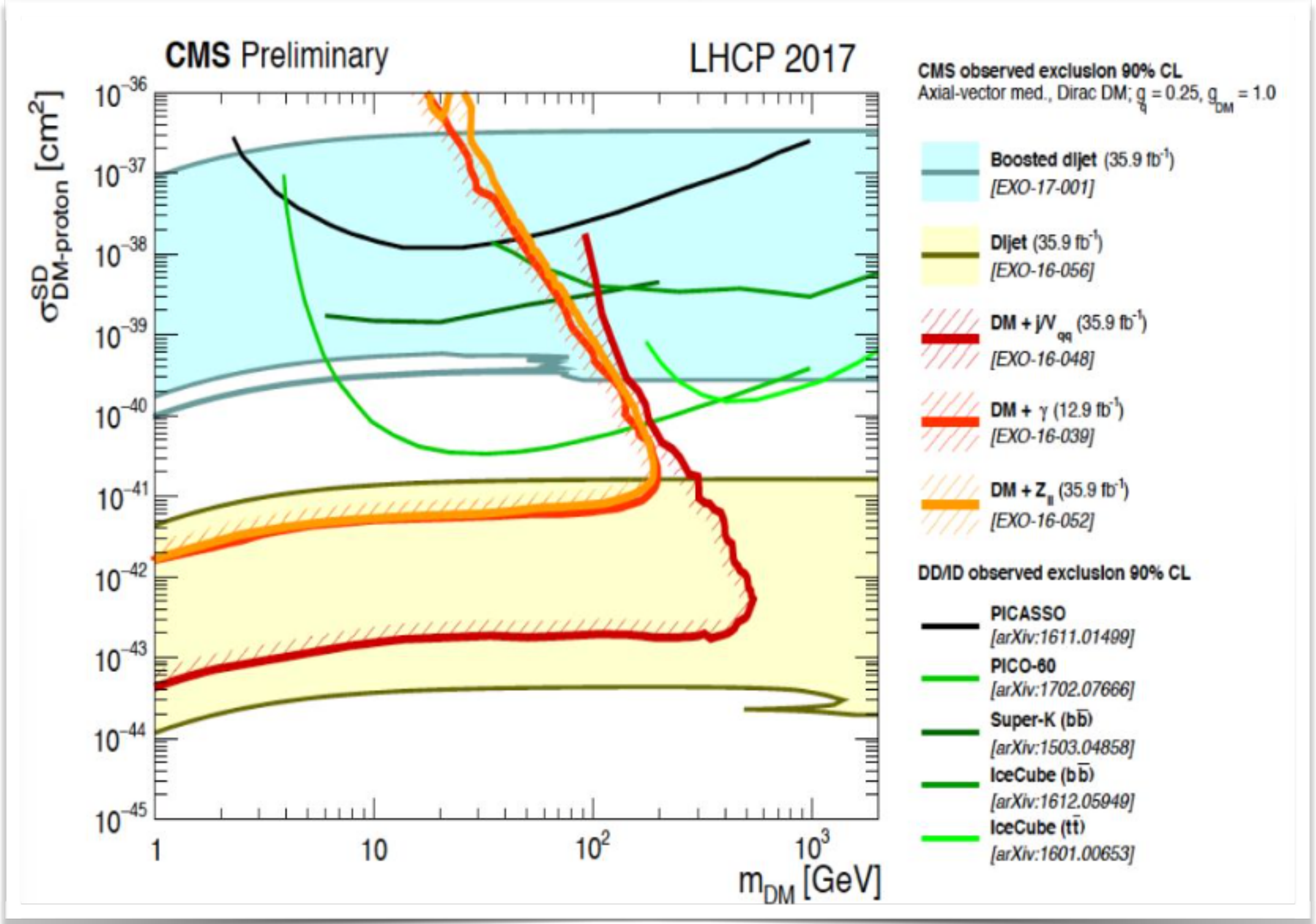
It all comes together : Part 3 (Summary)

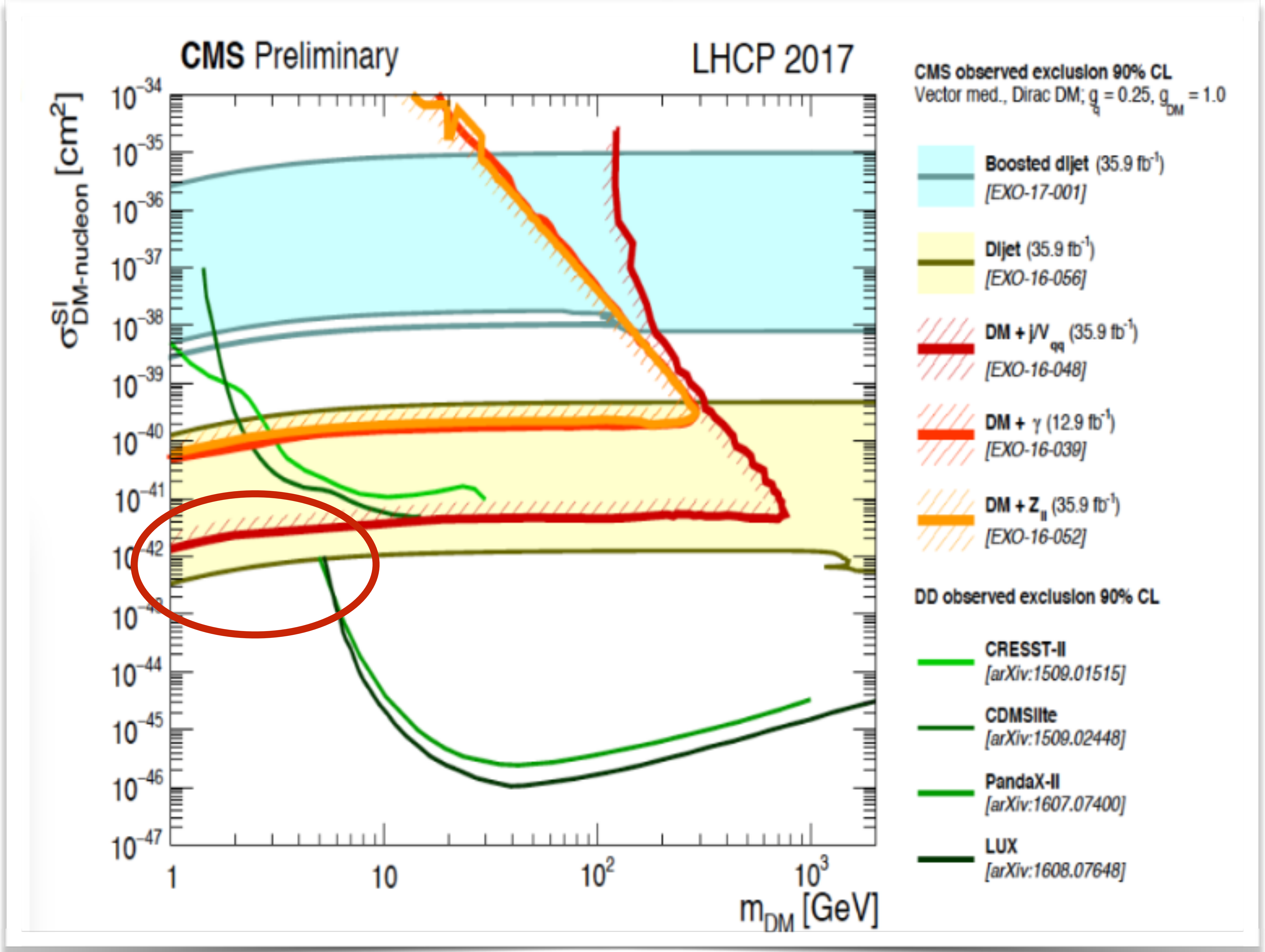




Reach for scalar and pseudo scalar mediators

Global Picture: Comparison to everyone else





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

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

Outlook & Conclusion

Very successful 2016 DM search program has been conducted using simplified models resulting in many public results! In these results:

- **Precision background estimation** techniques are becoming more common!
- Novel **substructure algorithms** are being used leading to significant sensitivity increase!

On the other hand, 2017 Data taking is on going, and we are expected to collect ~45/fb of data!

Where do we go next?

- Smarter triggers / data taking techniques to explore low pT regime ?
- More realistic models ?
- New mediators ? (spin-2 mediators, long-lived mediators)

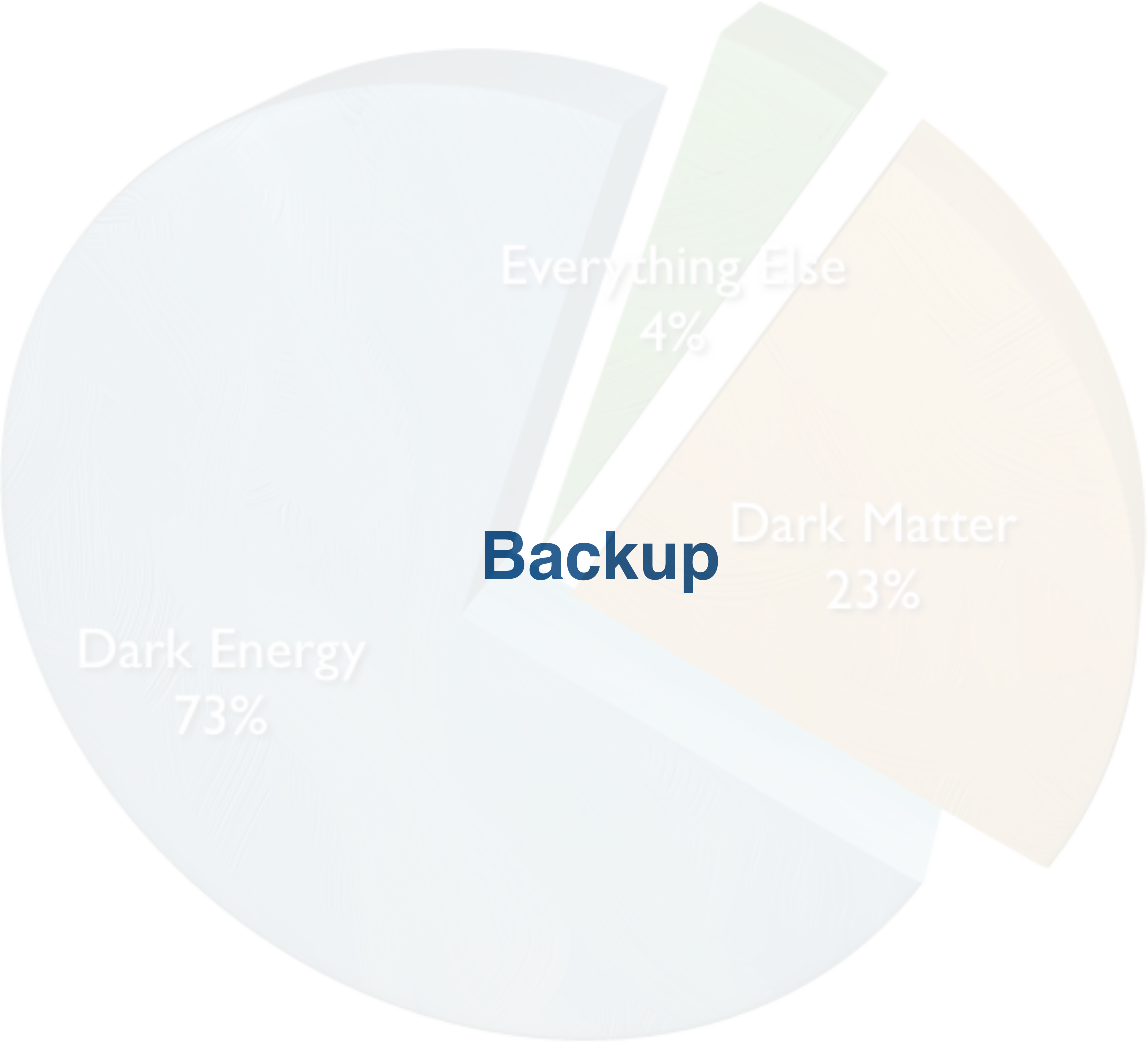
Looking forward to fruitful discussion at the workshop to figure out!

Final Remarks

There are simply too many analysis we have performed as a collaboration to cover in this talk. Please refer to following for further reading:

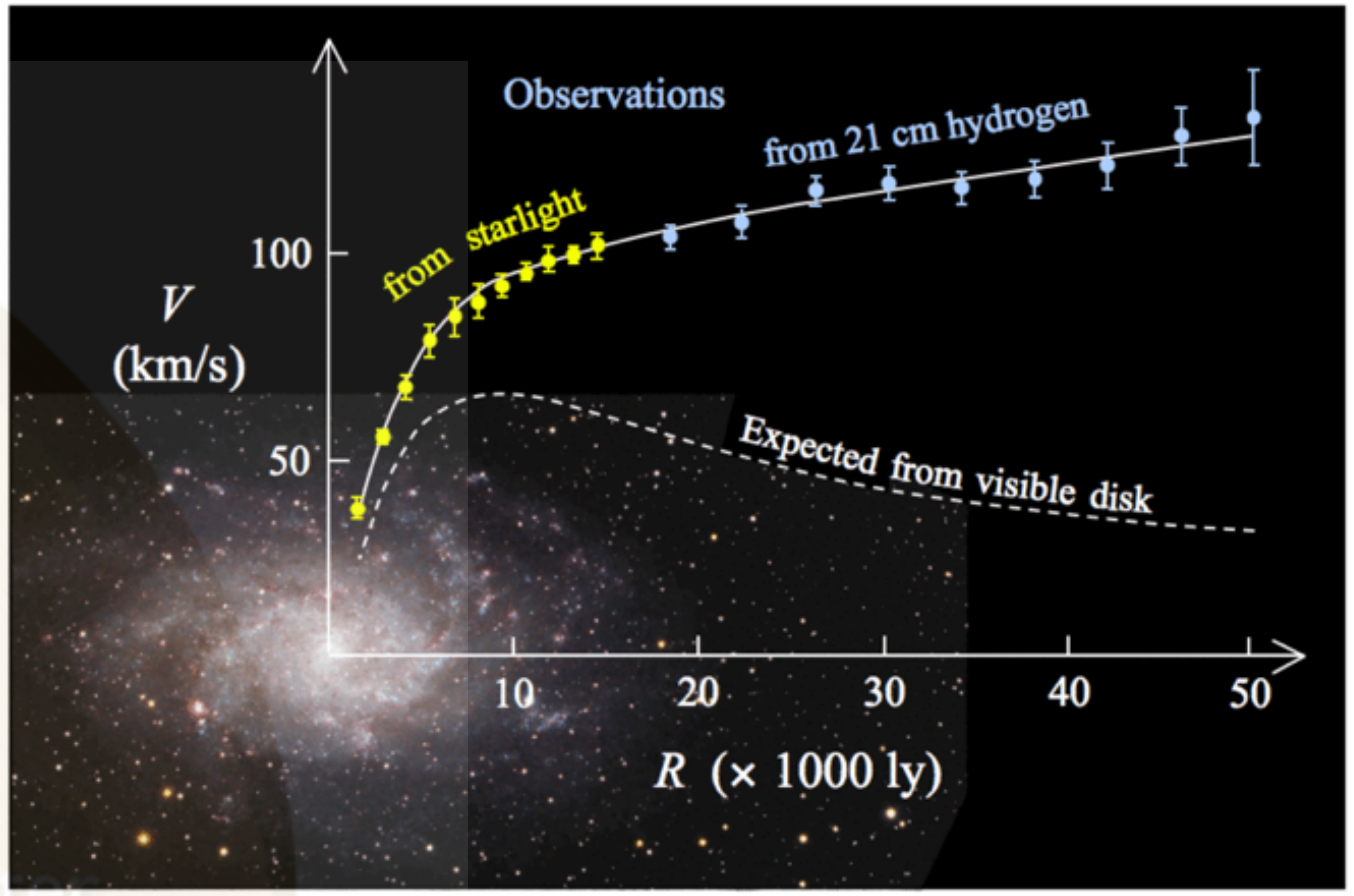
Analysis	Documentation
Mono-jet or V-had	CMS-PAS-EXO-16-048
Mono-photon	arXiv:1706.03794
Mono-Z (ll)	CMS-PAS-EXO-16-052
Mono-Higgs (gg)	CMS-PAS-EXO-16-054
Mono-tt/bb	CMS-PAS-SUS-17-001
Mono-top	CMS-PAS-EXO-16-051
Dijet	CMS-PAS-EXO-16-046
Boosted dijet	CMS-PAS-EXO-17-001
Invisible Higgs	JHEP 02 (2017) 135
Summary Plots	CMS Summary

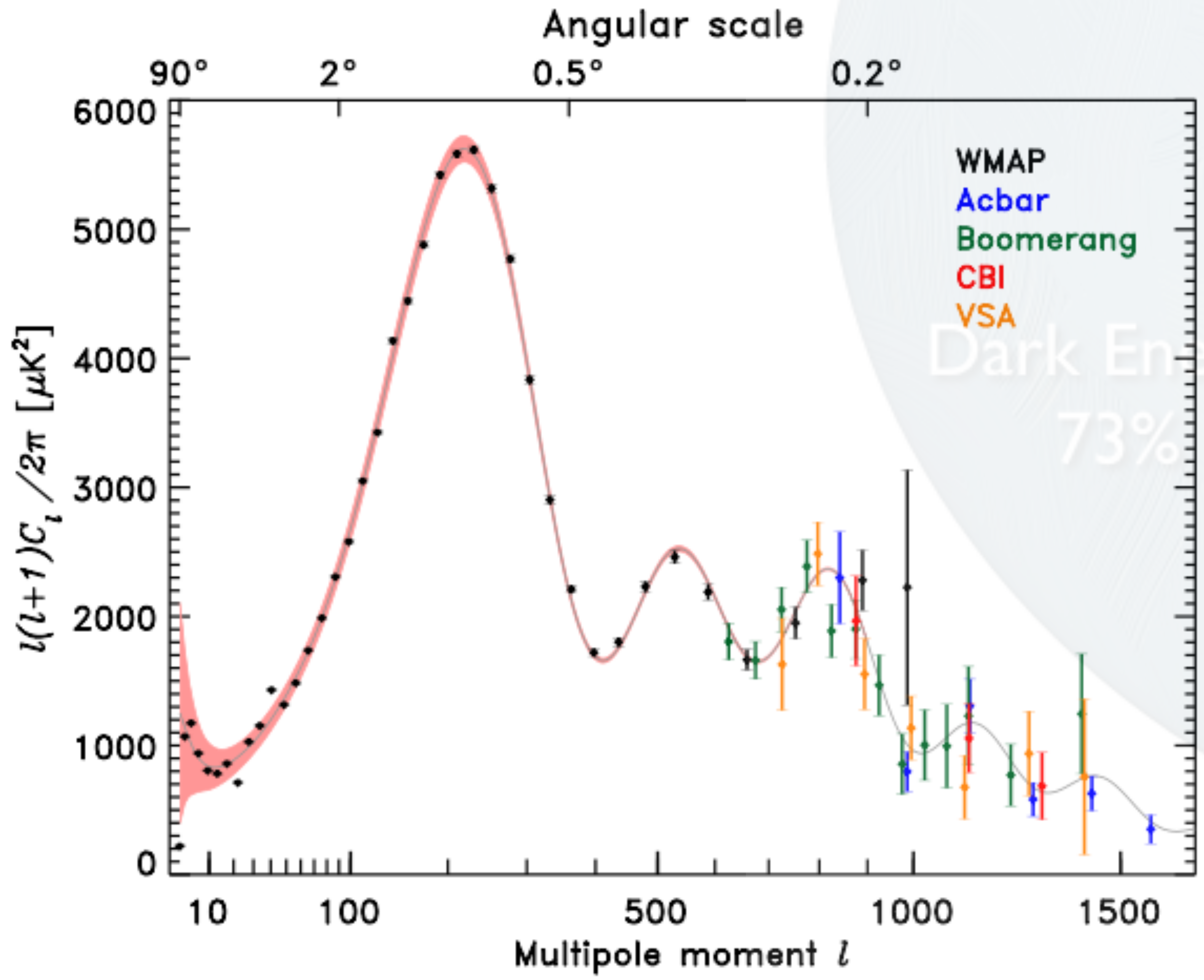
Backup



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





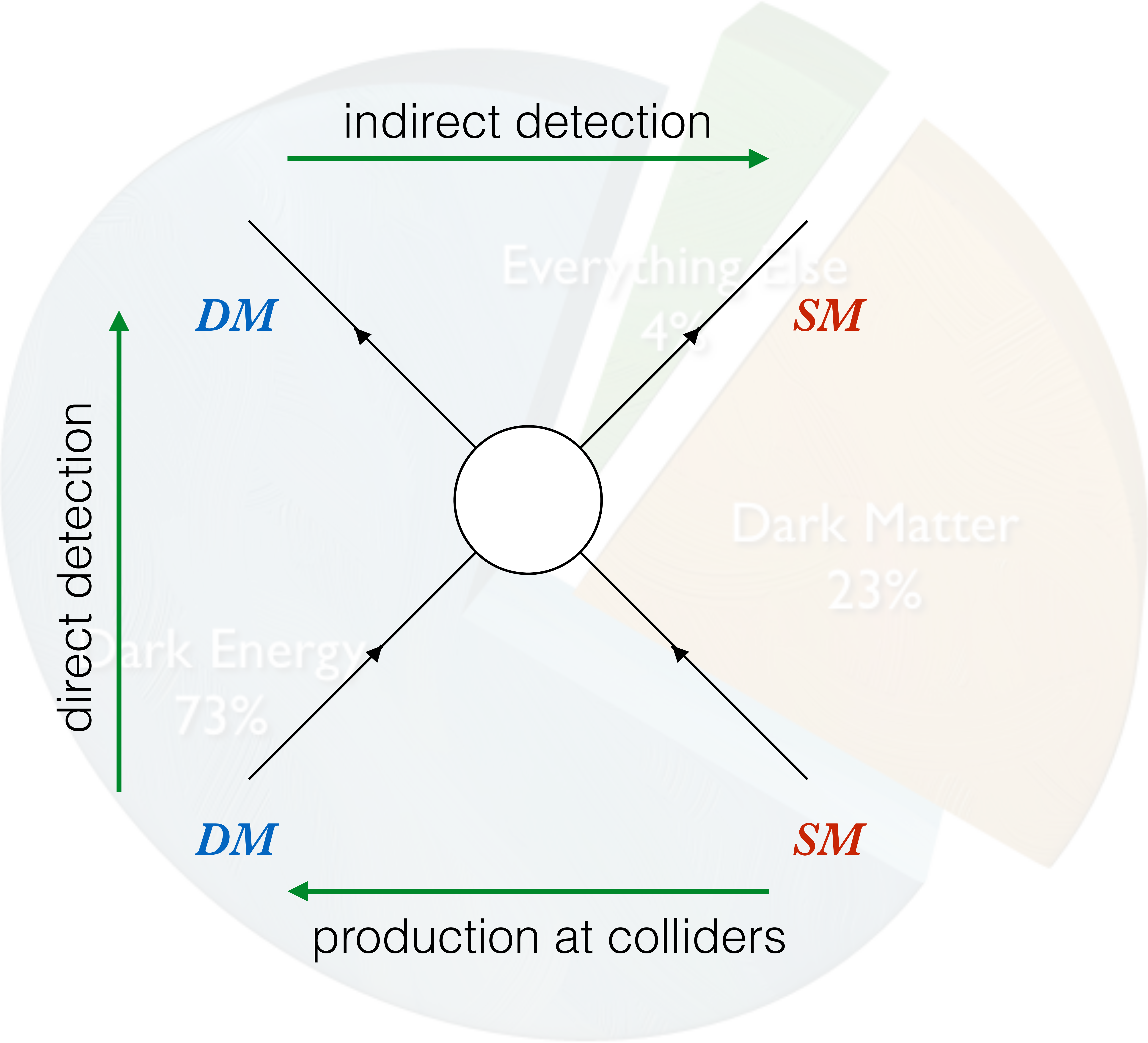
Most recently…

- 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)

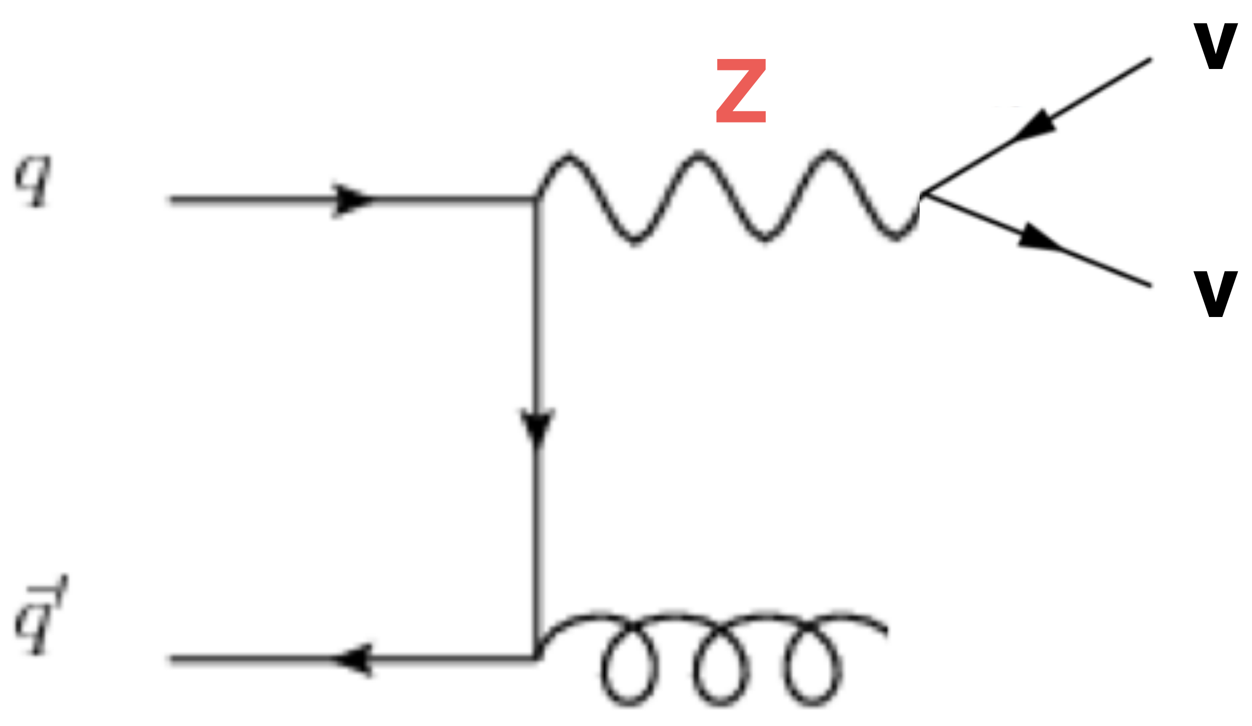


Three main approaches:

(topological permutations of the same Feynman diagram)

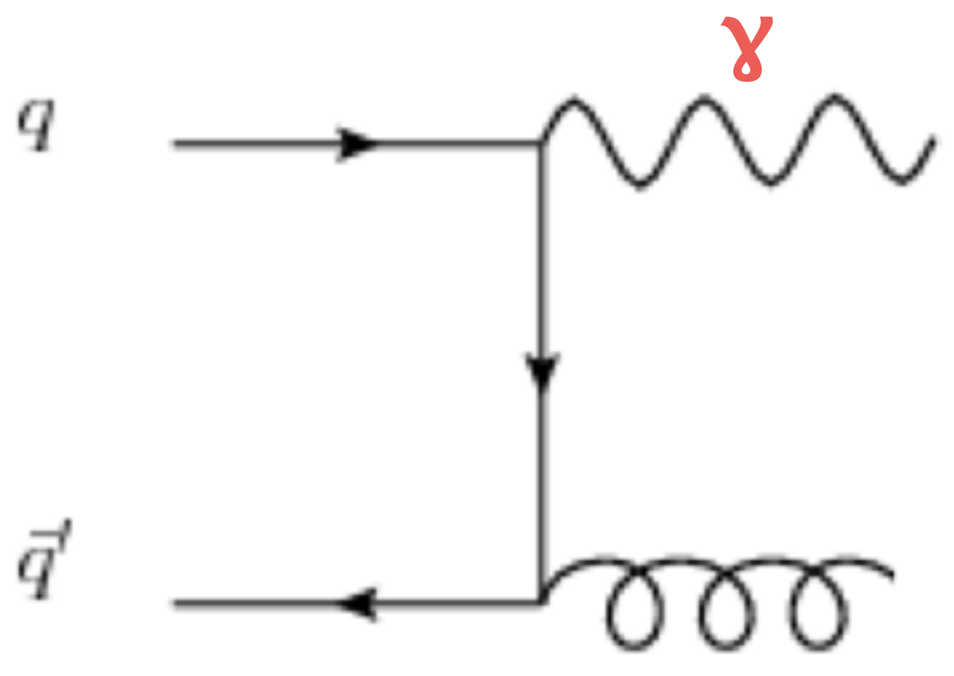
- DM-nucleon scattering (direct detection)
  - Ex: LUX, CDMSLite, PandaX …
- Annihilation (indirect detection)
  - Ex: Fermi-LAT
- Production at colliders

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?



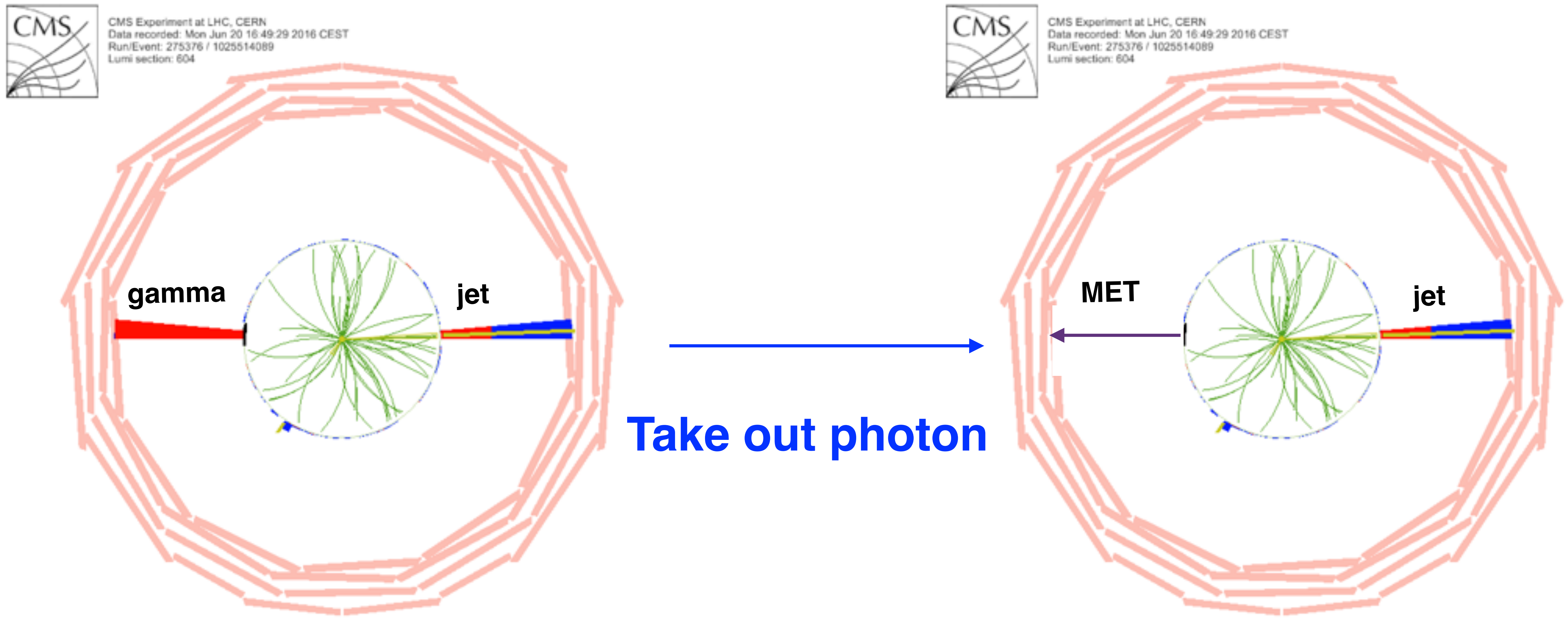
Similar pT spectra as Z→vv

Statistically rich

but…

Underlying theory differences

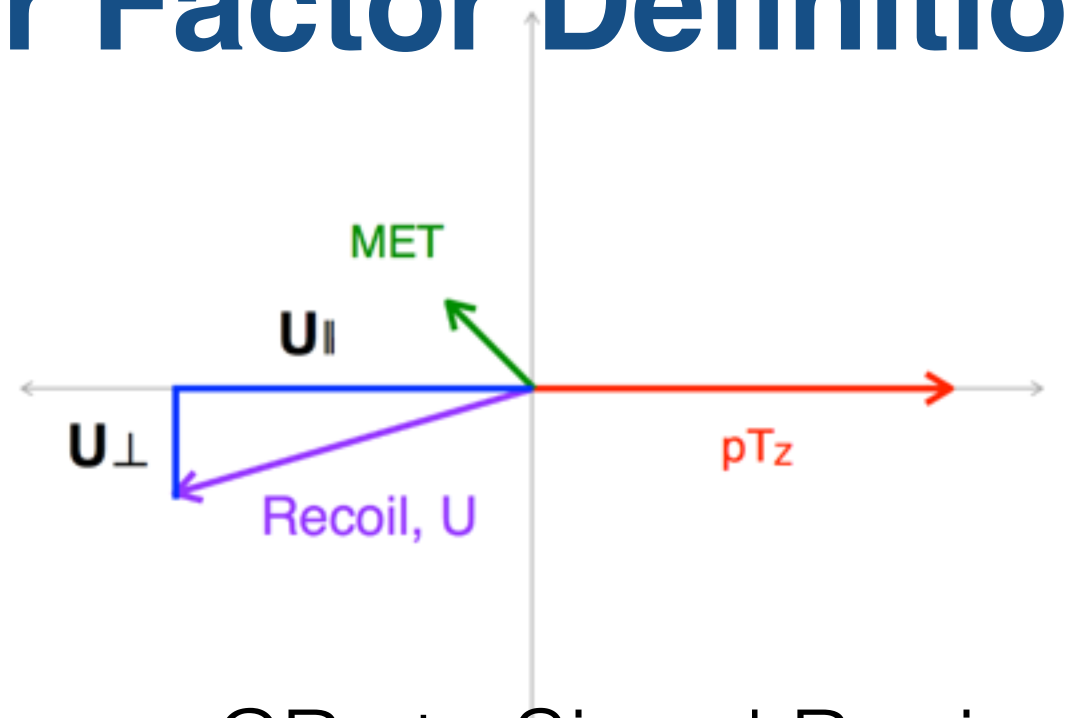
If we remove the photon from a γ+jets event, it mimics a Z→vv event



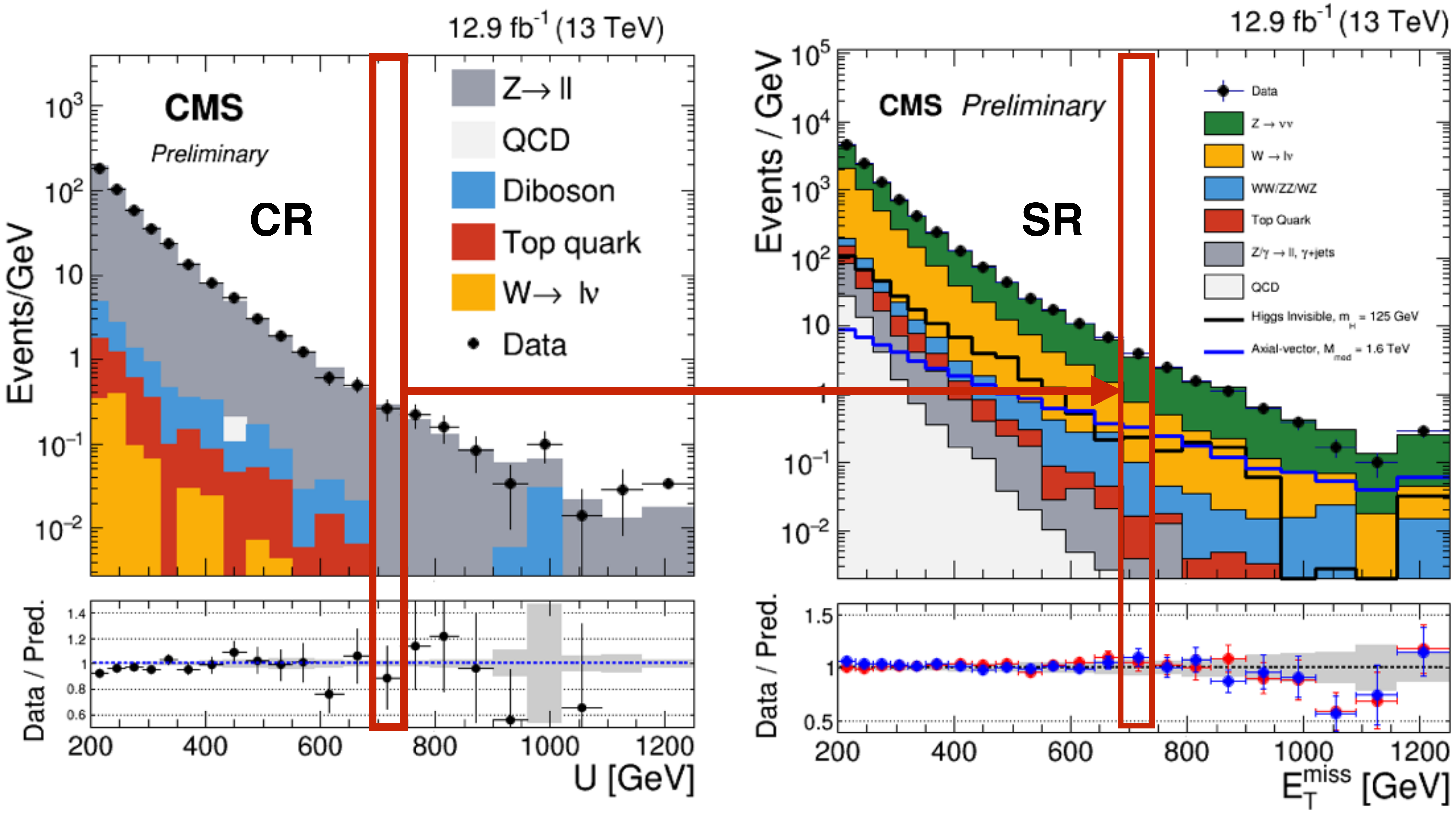
Background Estimation Method: Transfer Factor Definition

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 $R^{\gamma/Z/W}$

Zeynep Demiragli

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)

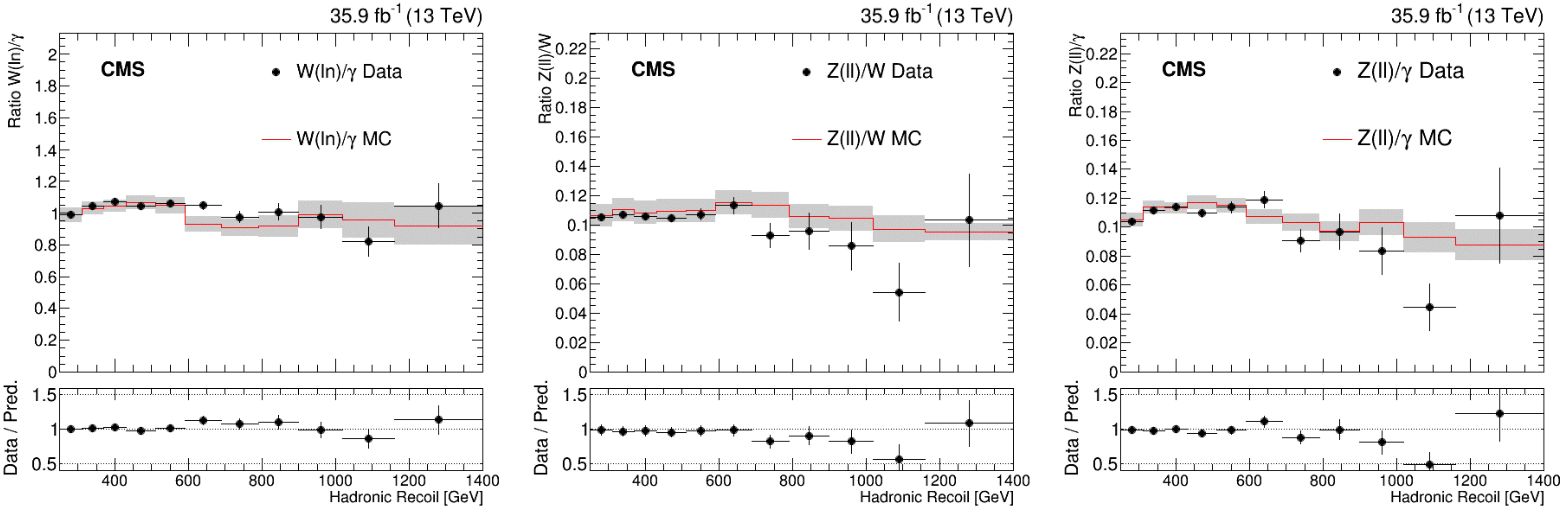
$$\mu_i^{W\to l\nu} \to f_i(\boldsymbol{\theta}) \cdot \mu_i^{Z\to\nu\nu}$$

f_i ratio in the signal region :

- Relies on theoretical prediction for differential xsec and lepton acceptance

Zeynep Demiragli

Data validation of the ratios in the control regions



Black ratio from data and statistical uncertainties / Red from MC

Grey band is stat. + sys uncertainty on MC. Sys uncertainty includes theoretical uncertainties

Difference between data / simulation TF is covered by stat+sys uncertainty along the full recoil range

Compact Muon Solenoid (CMS)

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