Experimental Overview of Dark Matter Searches at LHC

Adish Vartak [CERN]

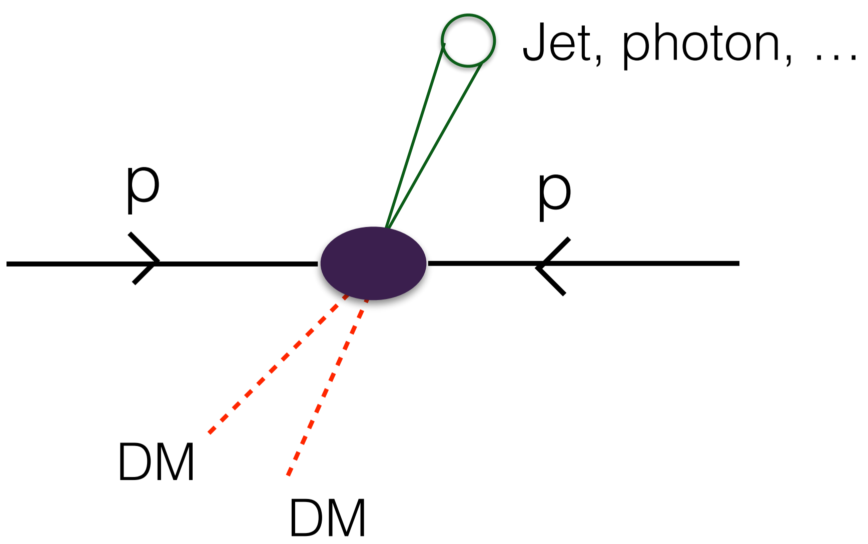
On behalf of CMS, ATLAS & LHCb Collaborations

Dark Matter Searches at LHC

Dark matter searches at LHC are built on a basic premise

- If DM particles are produced in pp collisions they would leave no trace in the detector
- But they may create a transverse momentum imbalance in the event (**MET**)
- To produce large MET, DM particles must recoil against some **high p_T, visible system "X"**

Visible, high p_T object(s)



Large MET

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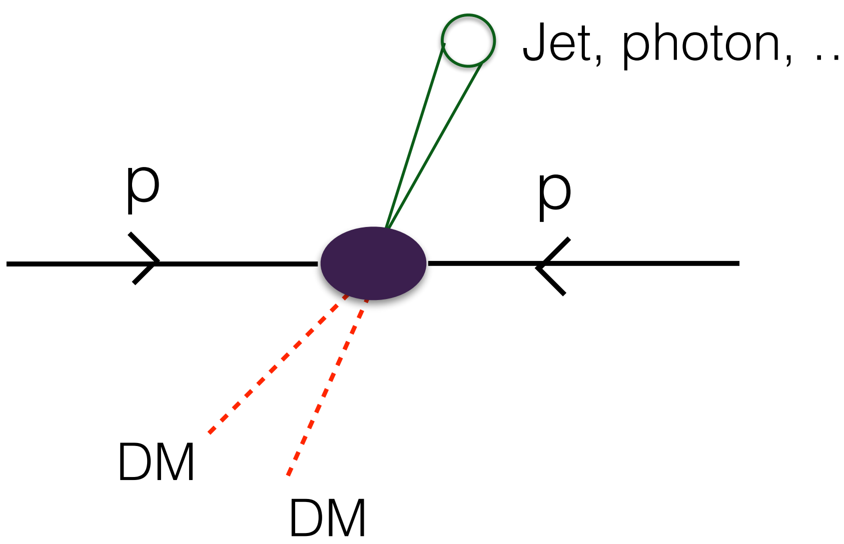
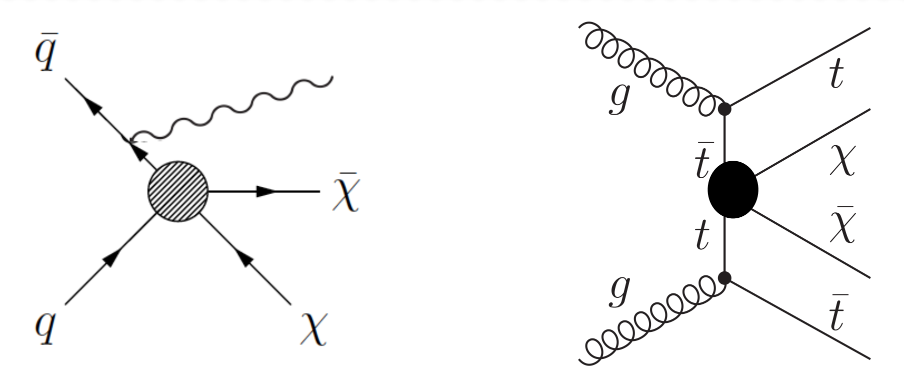


Large MET

Wide range of possibilities for X

- X could be **gluon (jet), photon, W, Z, H, top, …**

- ***This has led to a rich and diverse DM search program at the LHC***

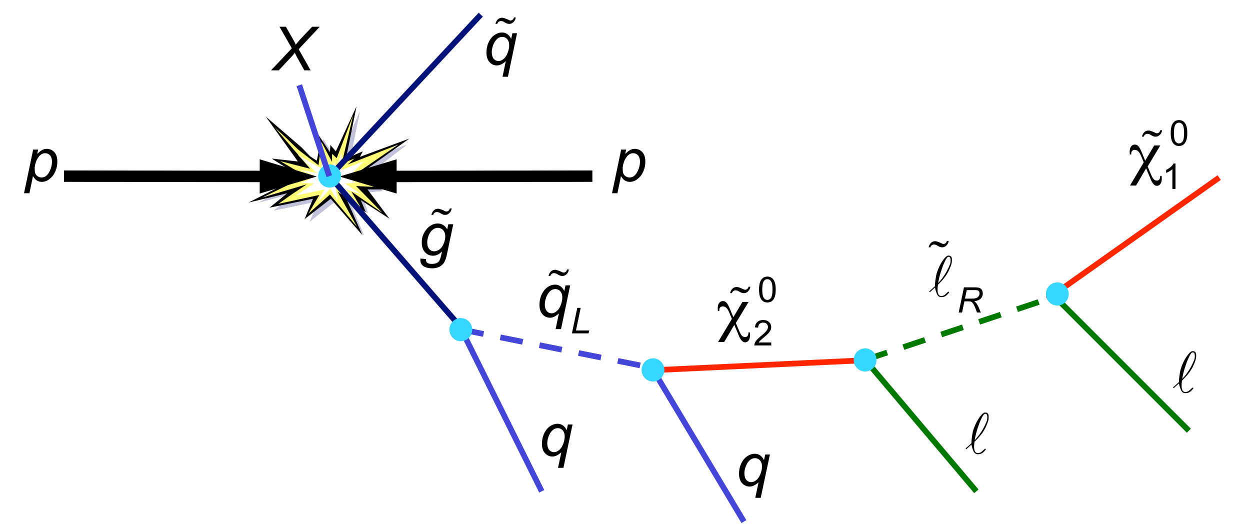


photon+DM **tt+DM**

Dark Matter Production

How would dark matter be produced at LHC ?

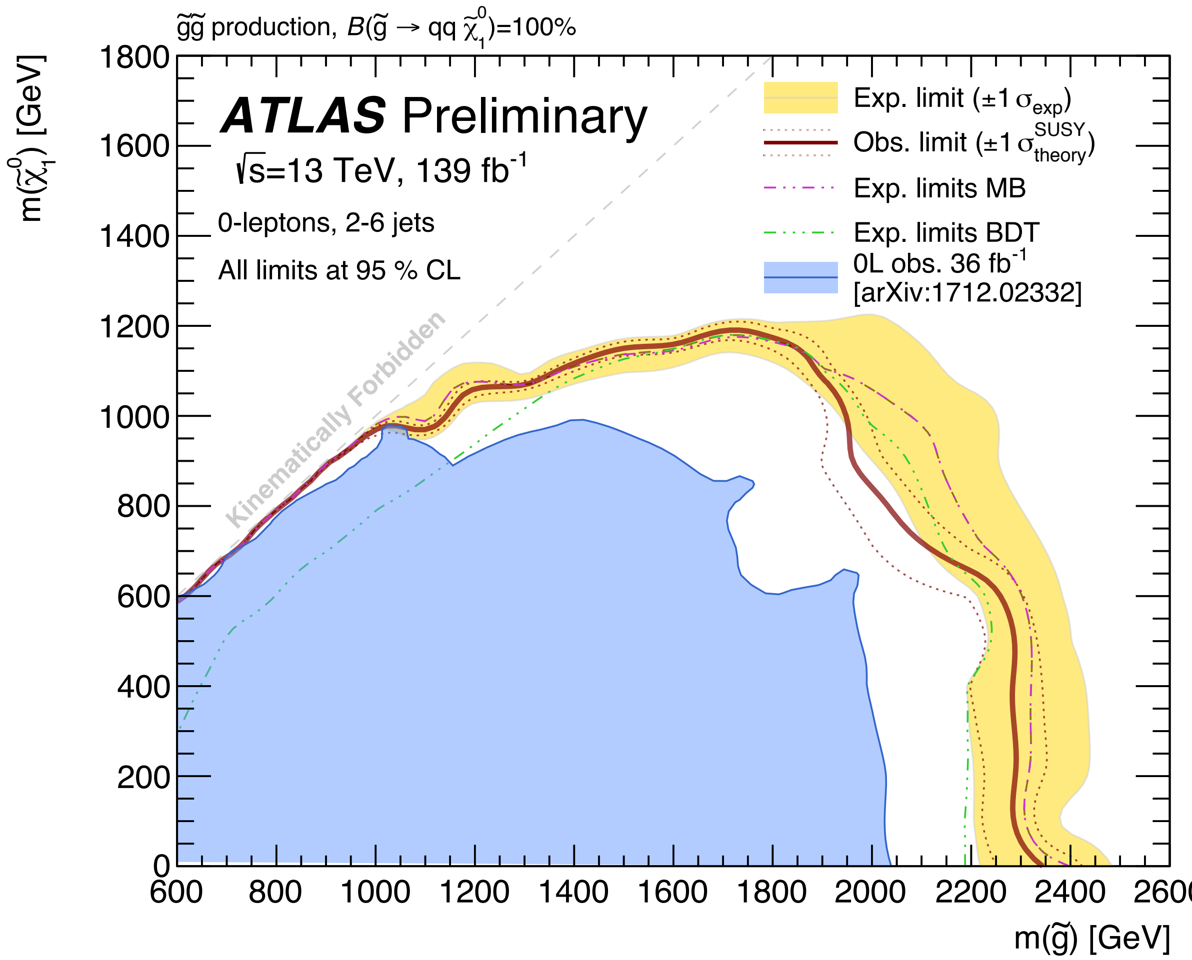
- There are well-motivated, complete theories that predict WIMP-like DM : ***SUSY***
- ***LSP*** in R-parity preserving SUSY has long been a popular DM candidate



Dark Matter Production

How would dark matter be produced at LHC ?

- There are well-motivated, complete theories that predict WIMP-like DM : ***SUSY***
- ***LSP*** in R-parity preserving SUSY has long been a popular DM candidate
- Extensive, on-going program at the LHC is looking for SUSY signal in a wide range of channels



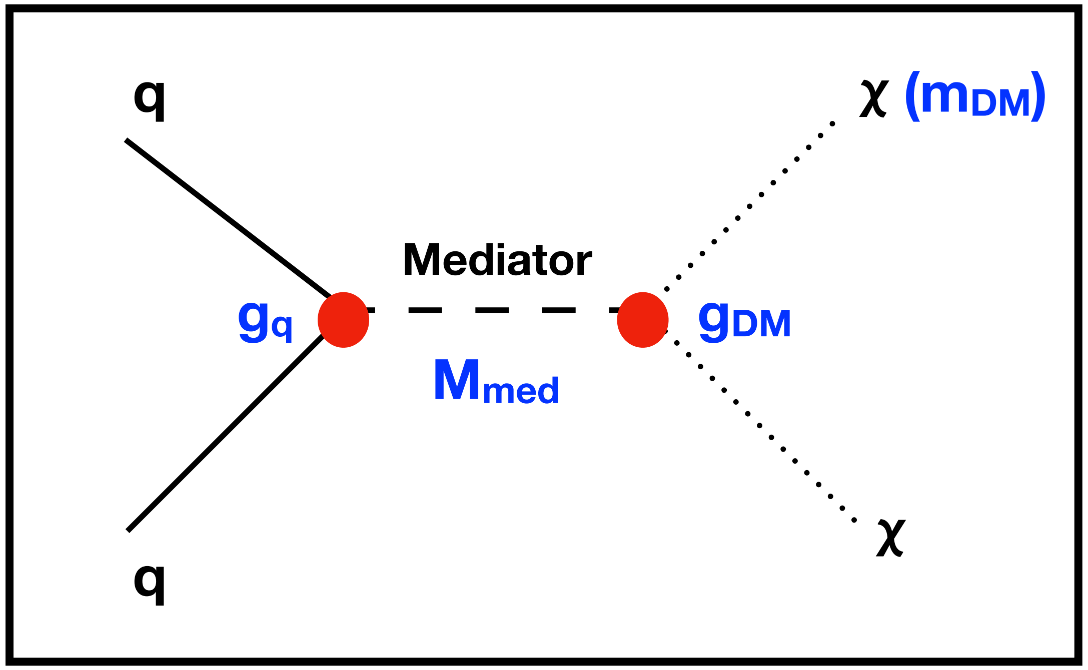
Will not be covering the SUSY searches here in this talk
Dedicated talk by Z. Wu

Simplified Dark Matter Models

- Dark matter production in pp collisions described using ***'simplified models'***
- Capture the essential features of a variety of DM signals through a minimal set of parameters

arXiv:1507.00966

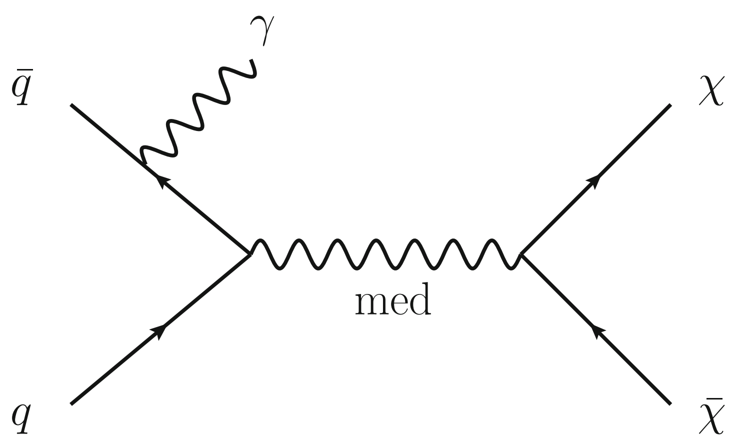
- **Model parameters:**
  - ➡ Spin/parity of the mediator
  - ➡ Mediator mass (M_{med})
  - ➡ DM mass (m_{DM})
  - ➡ Mediator coupling to quarks (g_q)
  - ➡ Mediator coupling to DM (g_{DM})



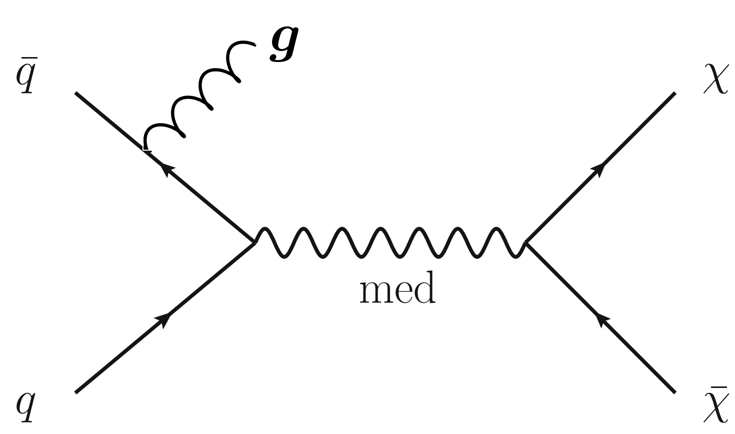
Spin-1 Mediator

- Probed through several **ISR based MET+X searches**
- Look for MET + a high p_T photon, Z or jet

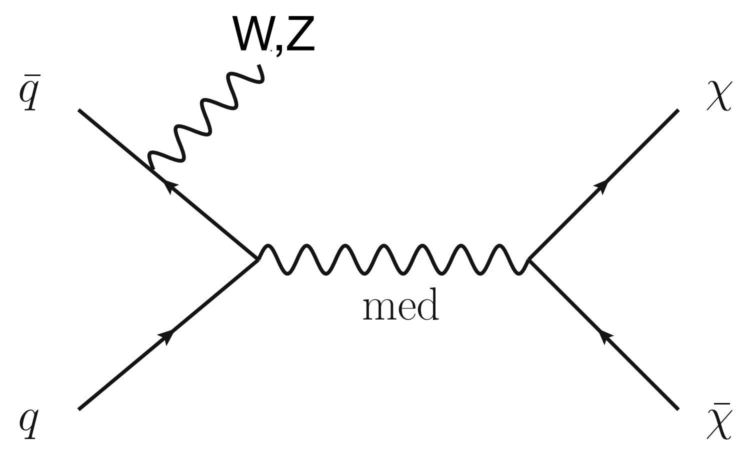
Photon+MET



Monojet



V+MET



ATLAS :
- EPJC 77 (2017) 393

CMS :
- JHEP 02 (2019) 074

ATLAS :
- JHEP 01 (2018) 126

CMS Monojet :
- PRD 97 (2018) 092005

ATLAS Mono-Z(ll) :
- PLB 776 (2017), 318

ATLAS Mono-V(had) :
- JHEP 10 (2018) 180

CMS Mono-Z(ll) :
- EPJC 78 (2018) 291

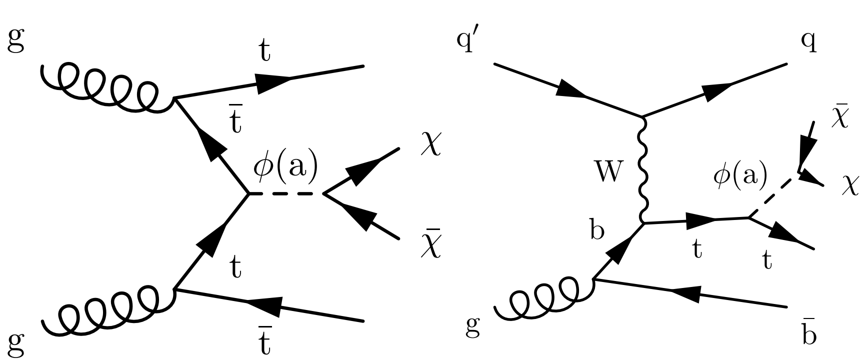
CMS Mono-V(had) :
- PRD 97 (2018) 092005

More in talks by N. Kohler, K. McLean, J. Lindon

Spin-0 Mediator

- Interaction between spin-0 mediator and quarks required to have the SM Yukawa structure (Minimal Flavor Violation)
- Coupling to quarks proportional to the quark mass (like the SM Higgs boson)
- **Spin-0 mediator couples preferentially to the top quark**

Top+DM



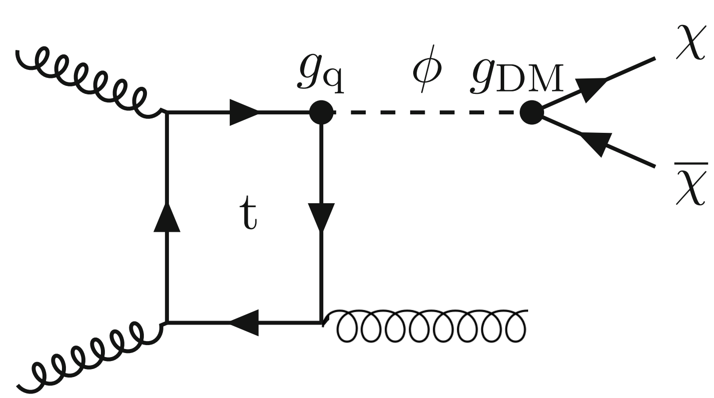
ATLAS tt+DM :
- JHEP 06 (2018) 108
- EPJC 78 (2018) 18

ATLAS t+DM :
- JHEP 05 (2019) 41

CMS tt+DM :
- PRL 122, (2019) 011803

CMS t+DM :
- JHEP 03 (2019) 141

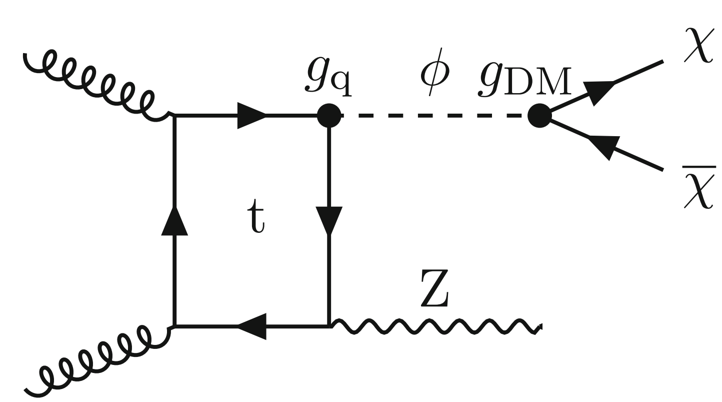
Monojet



ATLAS :
- JHEP 01 (2018) 126

CMS :
- PRD 97 (2018) 092005

V+MET



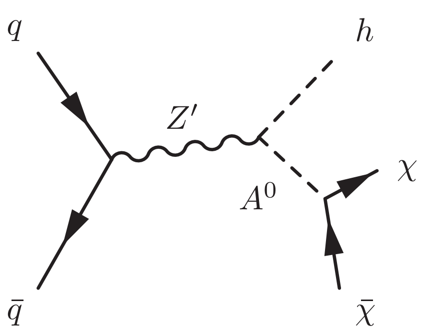
CMS Mono-Z(ll) :
- EPJC 78 (2018) 291

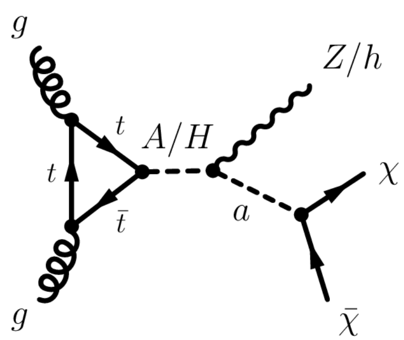
CMS Mono-V(had) :
- PRD 97 (2018) 092005

More in talks by B. Kilminster, M. T. Anthony

Some More Specialized Models

Higgs+MET (2HDM+Z', 2HDM+a)

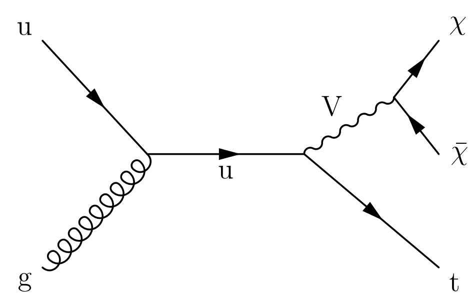




ATLAS :
- PRL 119, 181804 (2017)
- PRD 96 (2017) 112004
- JHEP 05 (2019) 142

CMS :
- EPJC 79 (2019) 280
- arXiv:1908.01713

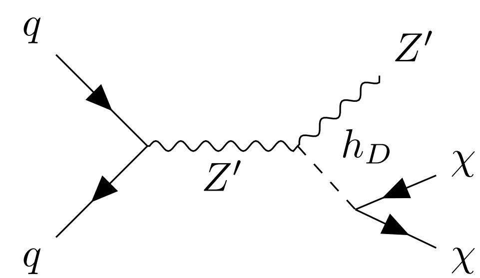
Top+MET (FCNC)



ATLAS :
- JHEP 05 (2019) 41

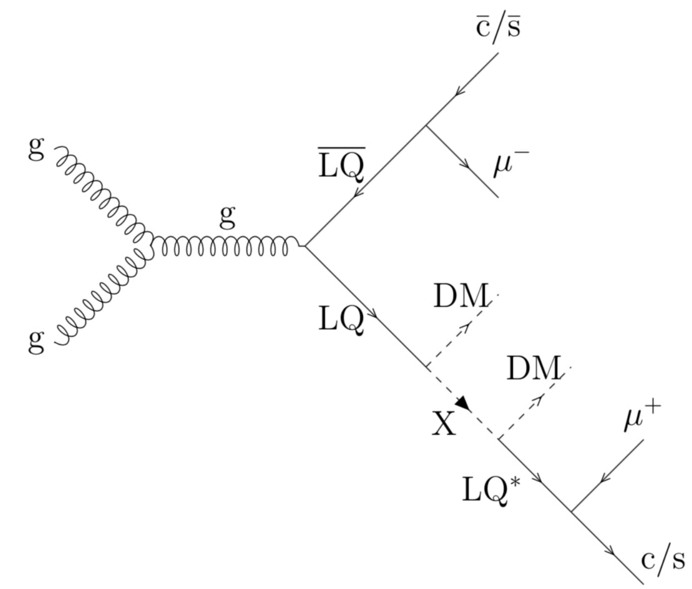
CMS :
- PRD 97 (2018) 092005

Z'+MET (Dark Higgs)



ATLAS :
- JHEP 10 (2018) 180

LQ+MET



CMS :
- Phys. Lett. B 795 (2019) 76

- Final state involves large MET + single, boosted heavy object
- Heavy object could be Higgs, top, Z', leptoquark ….

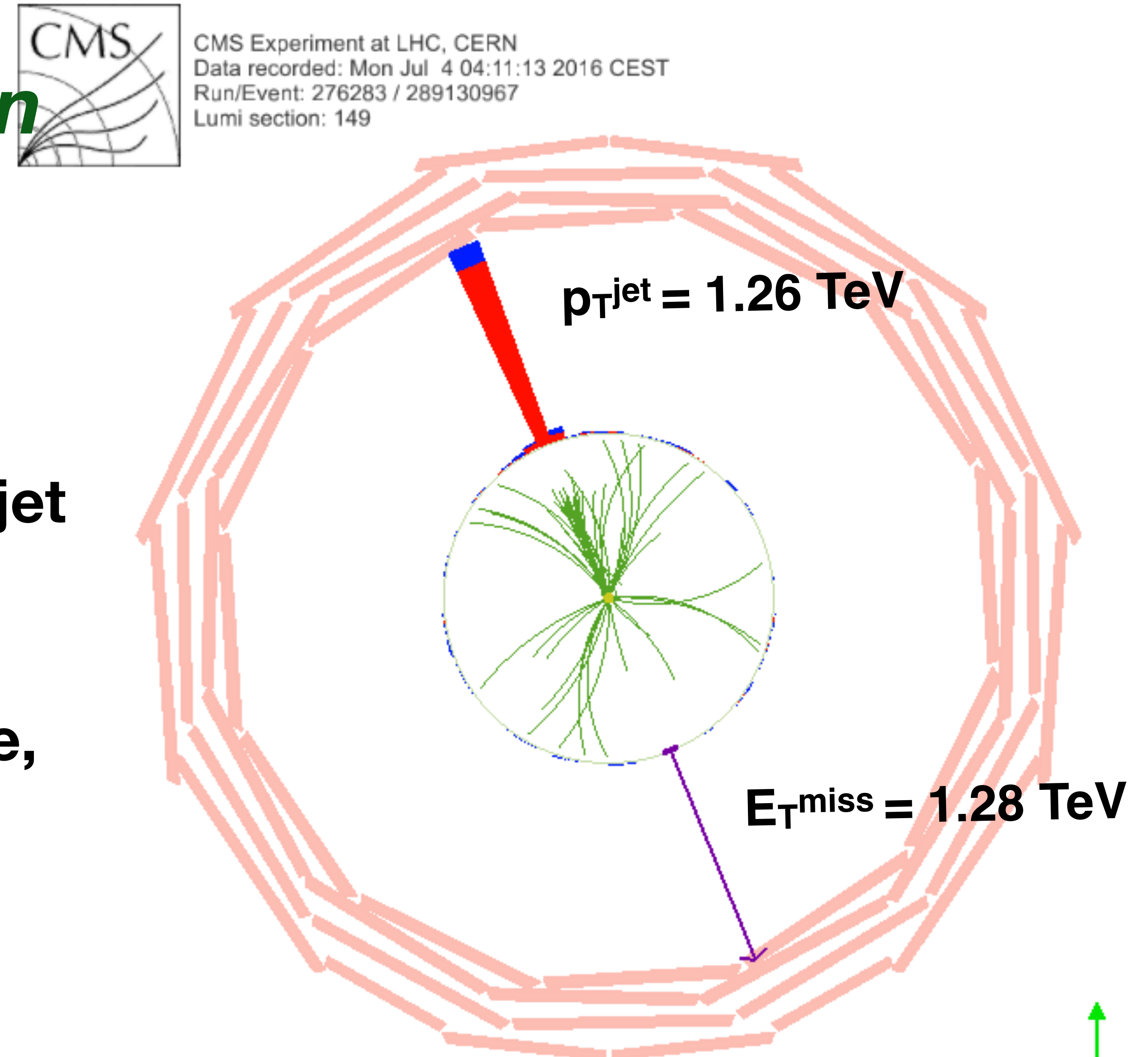
Talks by S. Liu, B. Kilminster

Brief Review of Dark Matter Searches

- Dark matter search program has gone through an intense period of evolution in Run-2
- Too little time to cover everything here
- Will use the example of the monojet analysis to demonstrate some of the key challenges and developments

Monojet Search

Key features of event selection



- **Large MET (250 GeV or more)**
  - ➡ Driven by trigger thresholds
- **At least one high p_T, central ($|\eta| < 2.4$) jet**
  - ➡ $p_T > 100$ (250) GeV for CMS (ATLAS)
- **Remove fake MET from detector noise, non-collision bkg**
  - ➡ For example : energy fraction due to charged particles in leading jet > 0.1
- **Lepton & b-jet veto to suppress W, top bkg.**

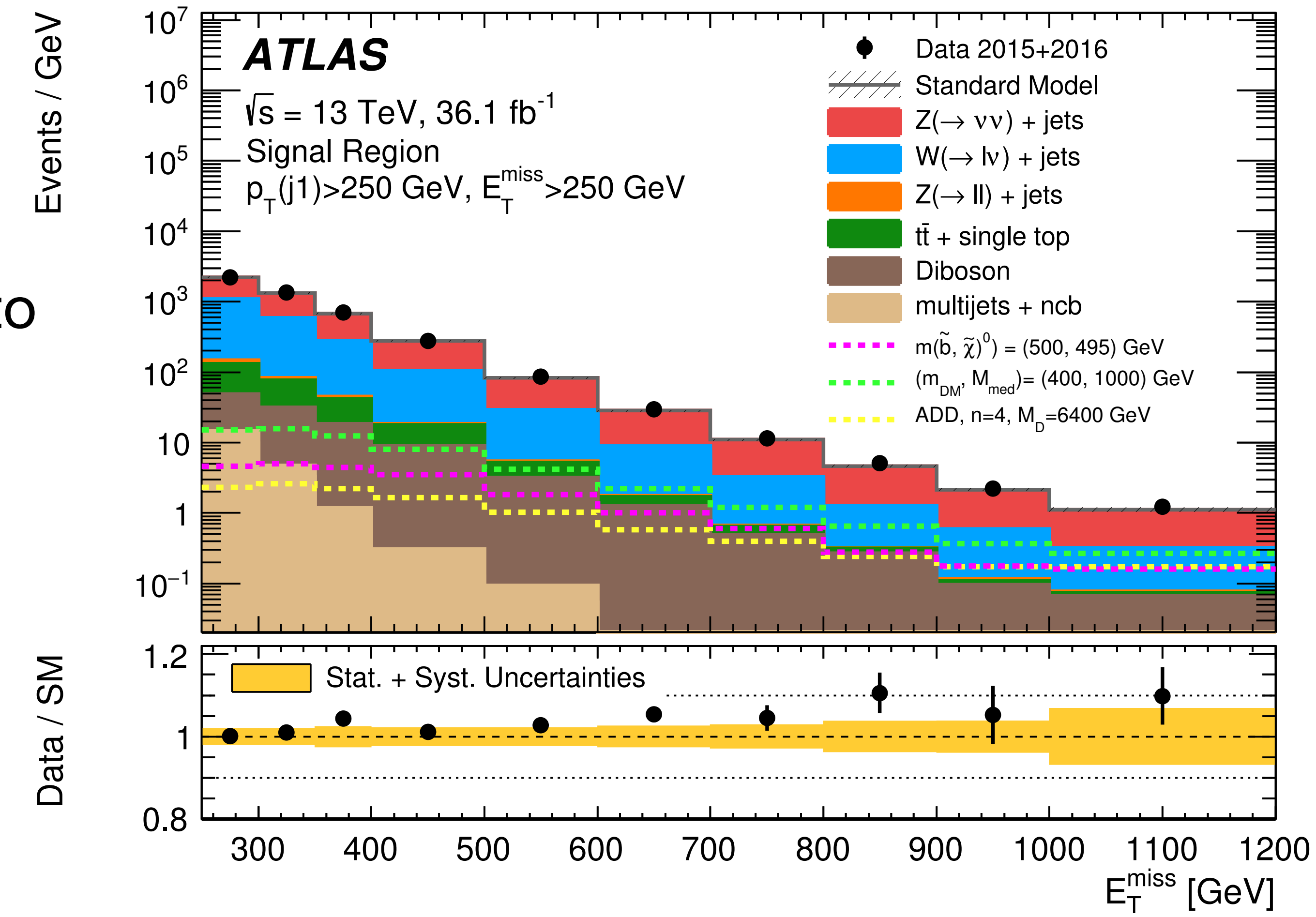
Main backgrounds

- ➡ Z(νν)+jets (~ 60%)
- ➡ W(lν)+jets where lepton is lost (~30%)
- ➡ Minor bkg : Top, dibosons, etc.

Monojet Analysis Strategy

- No mass peak or kinematic end-points (e.g. m_T)
- MET shape is the discriminant between signal and background
- Signal has a harder MET spectrum compared to the background
- **Main thrust of this analysis is accurate determination of the Z+jets (and W+jets) p_T spectrum**

ATLAS : JHEP 01 (2018) 126



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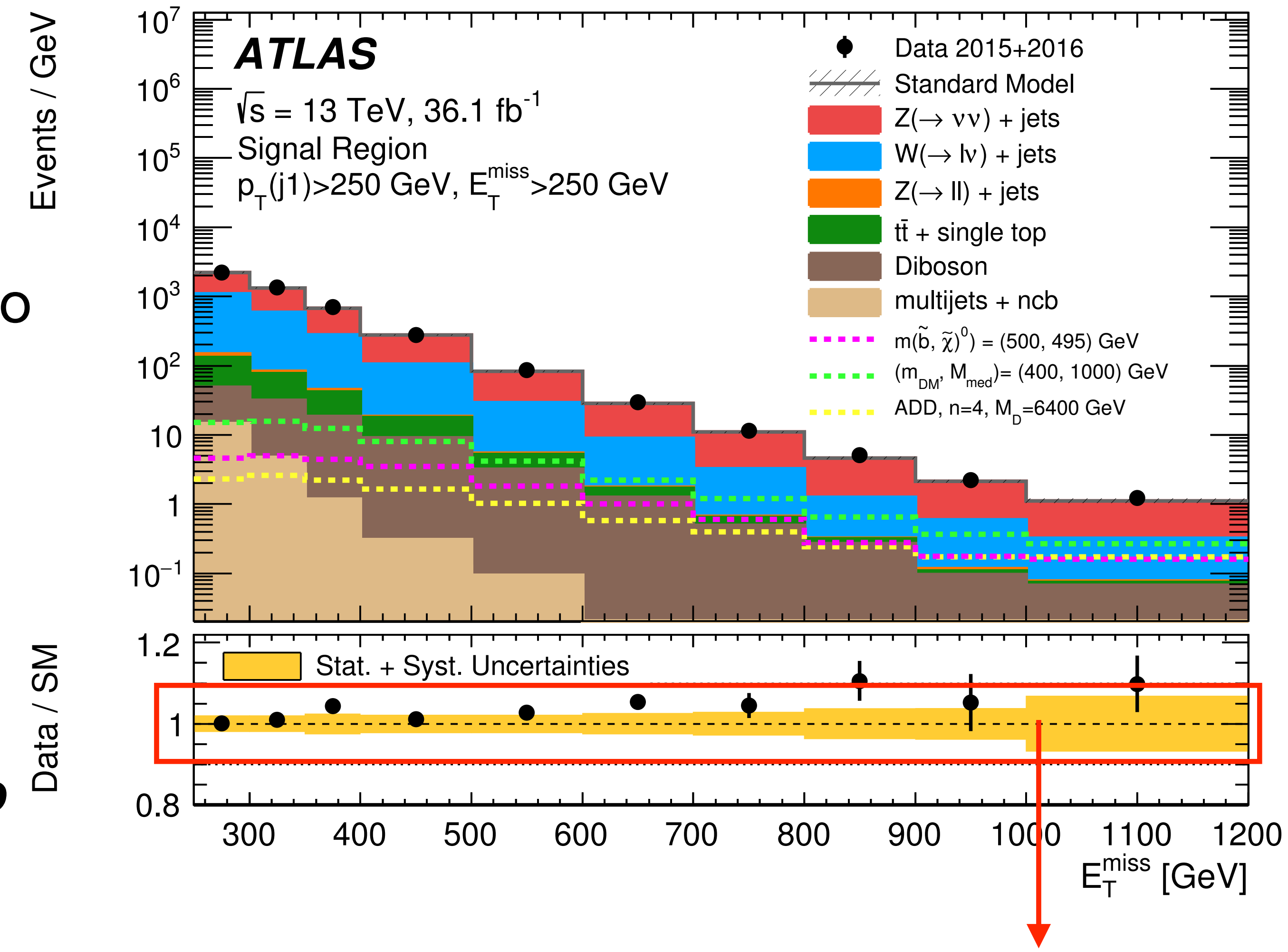
- **Main thrust of this analysis is accurate determination of the Z+jets (and W+jets) p_T spectrum**
- ***Multiple control regions employed in data to constrain the background***
  - ➡ Z(ll)+jets events (dilepton events)
  - ➡ W(lν)+jets (single lepton events)
  - ➡ And ɣ+jets events (by CMS only)

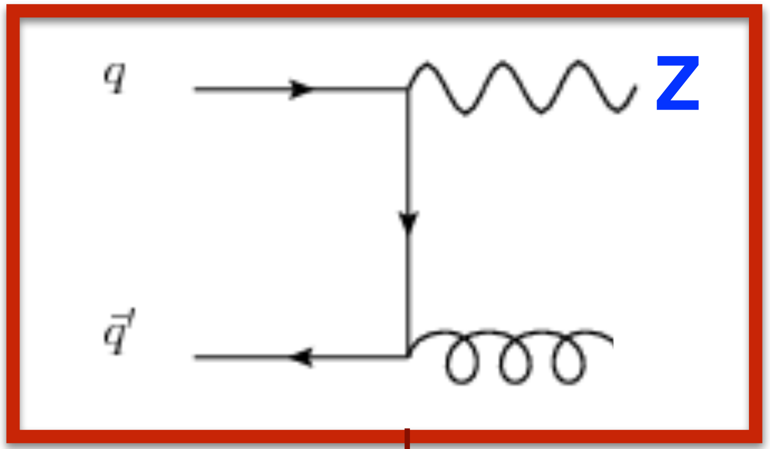
ATLAS : JHEP 01 (2018) 126



- Background uncertainty constrained to
- **About 2% at MET ~ 250 GeV**
- **Within 10% at MET ~ 1 TeV**

Control Regions In Monojet Analysis

Z→ll



Same process as Z→νν, same p_T spectrum

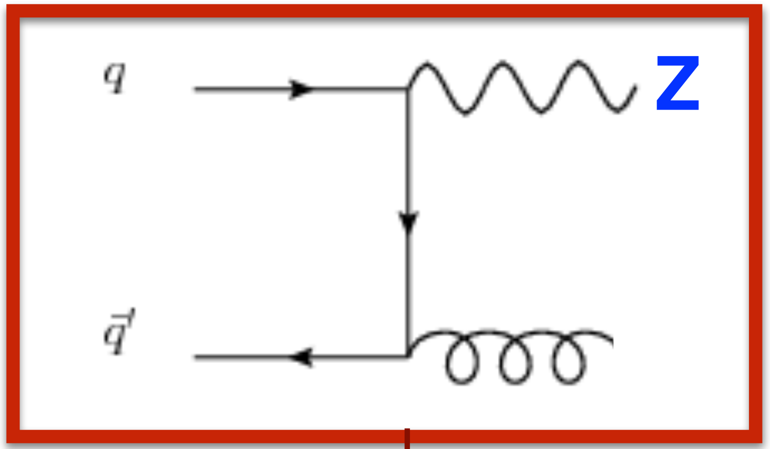
But statistically limited

Z→μμ branching ratio ~3%

Z→νν branching ratio 20%

Control Regions In Monojet Analysis

$Z \to ll$



Same process as $Z \to \nu\nu$, same p_T spectrum

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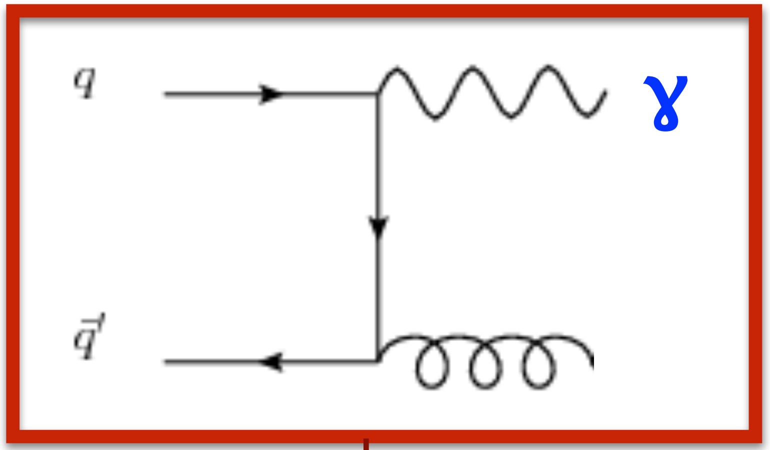
γ+jets



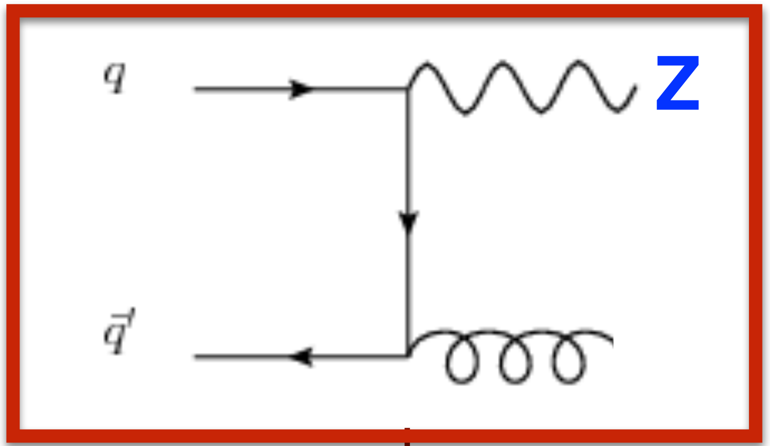
Similar p_T spectra to $Z \to \nu\nu$

Statistically rich

Event rate ~ $Z \to \nu\nu$ x 2

Control Regions In Monojet Analysis

Z→ll



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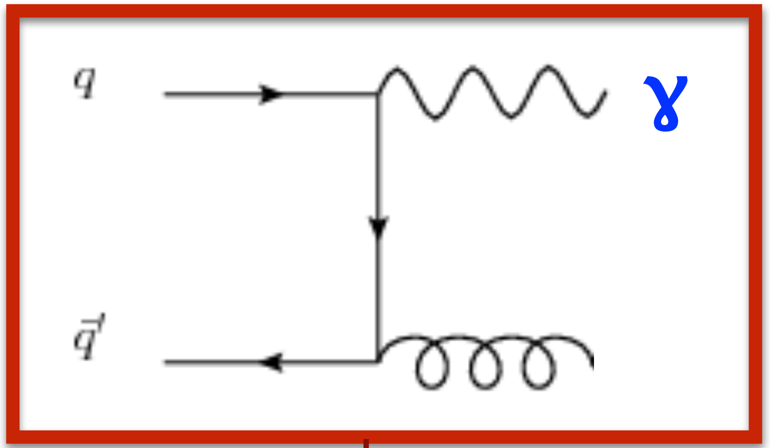

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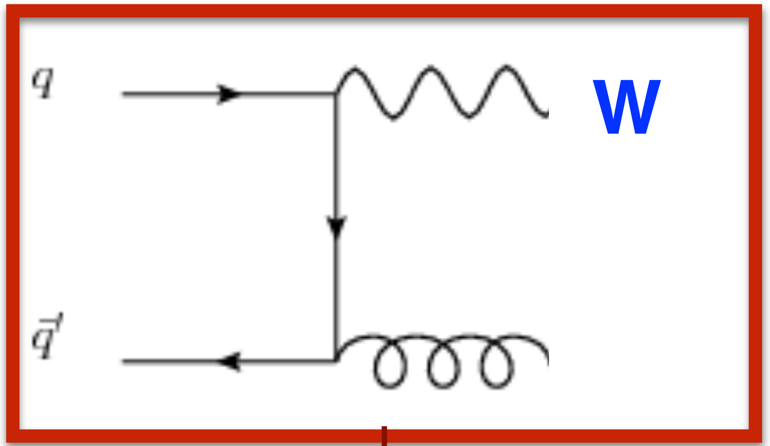
W→lν



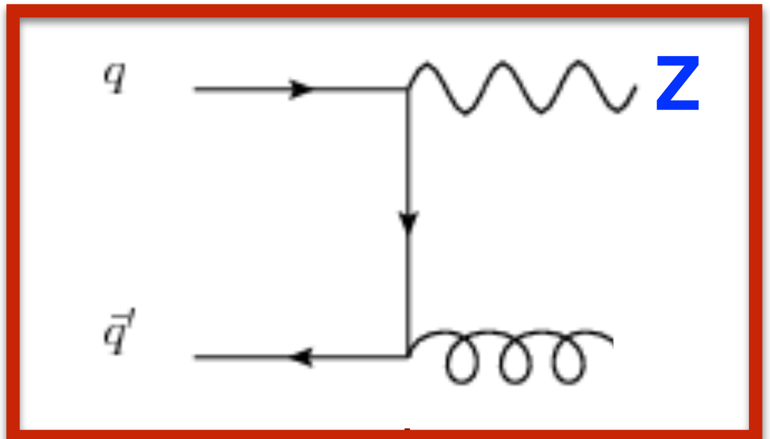
Similar p_T spectra to Z→νν

Event rate ~ Z→νν

Also used to estimate W+jets background

Control Regions In Monojet Analysis

$Z \to ll$



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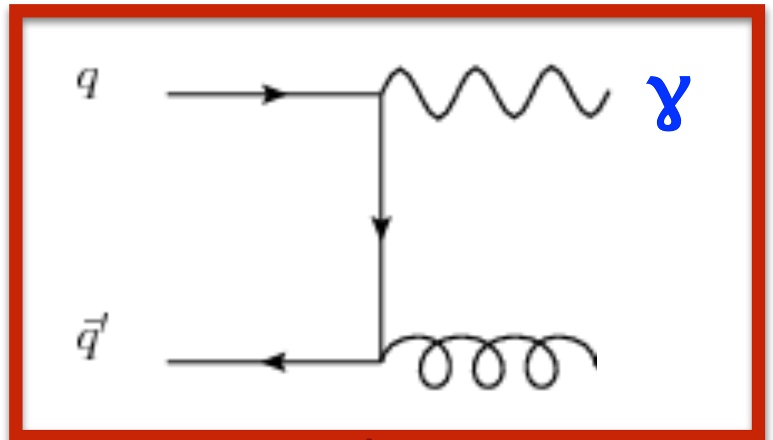

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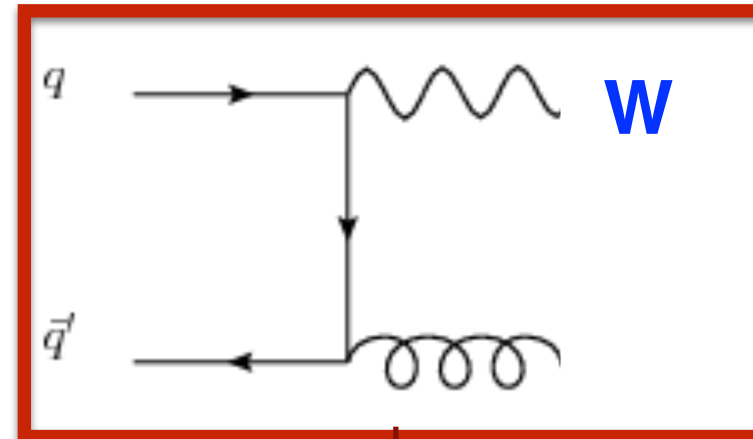
$W \to l\nu$



Similar p_T spectra to $Z \to \nu\nu$

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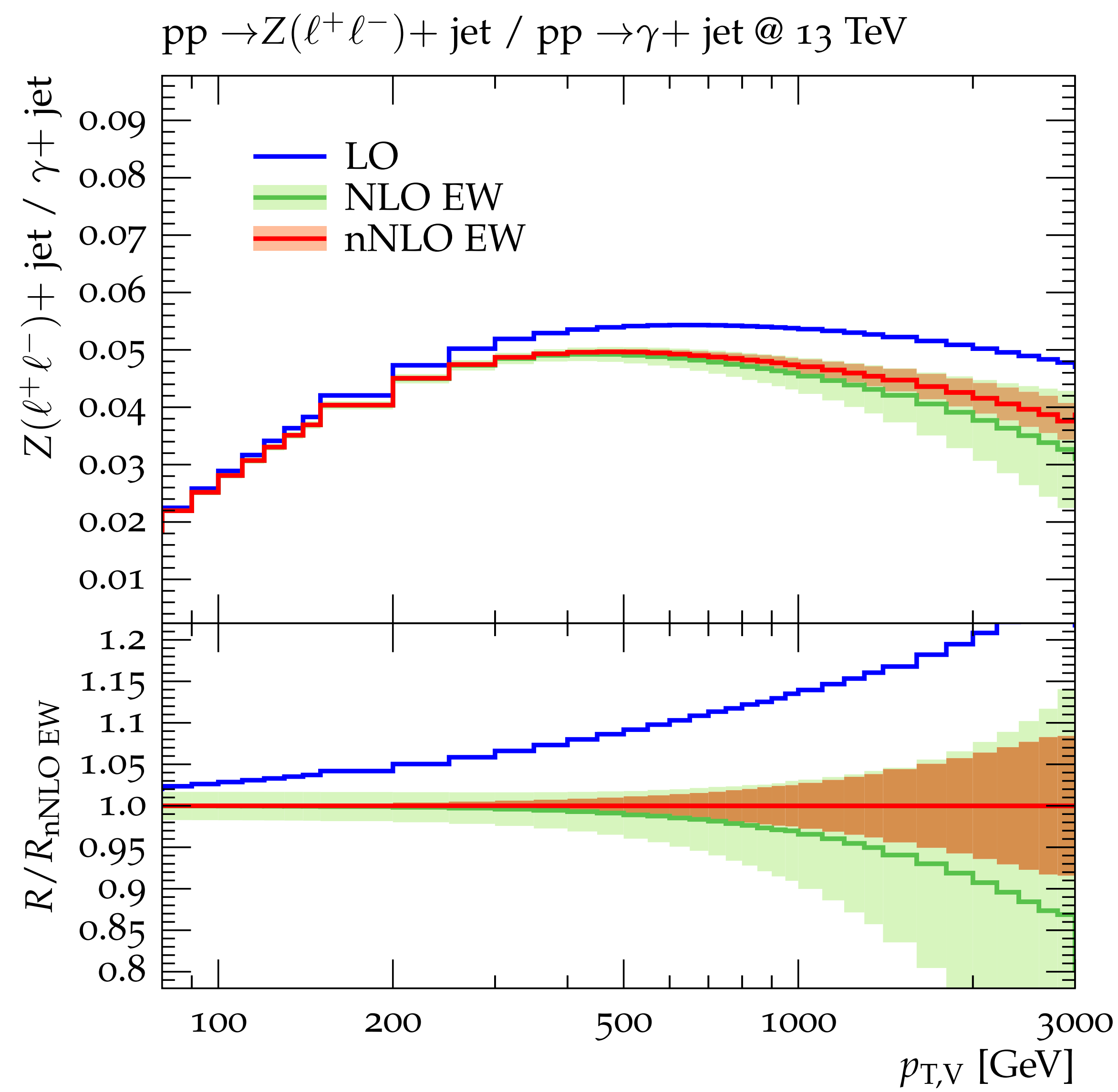
Also used to estimate W+jets background

Need transfer factors to determine background in the signal region from event yields in the control regions

Electroweak Background Estimation

- ***Transfer factors rely on precise estimates of Z/W and Z/ɣ cross section ratios***
- Predictions from **LO simulations are not satisfactory**
- Significant contributions from higher order corrections (particularly **NLO EWK**) need to be taken into account
- Need to also include contributions from **photon PDFs** at large boson p_T

Electroweak corrections to Z(ll)/ɣ ratio



Intense & fruitful effort supported by the LHC DMWG helped to nail this down

Lindert, et al : EPJC (2017) 77: 829

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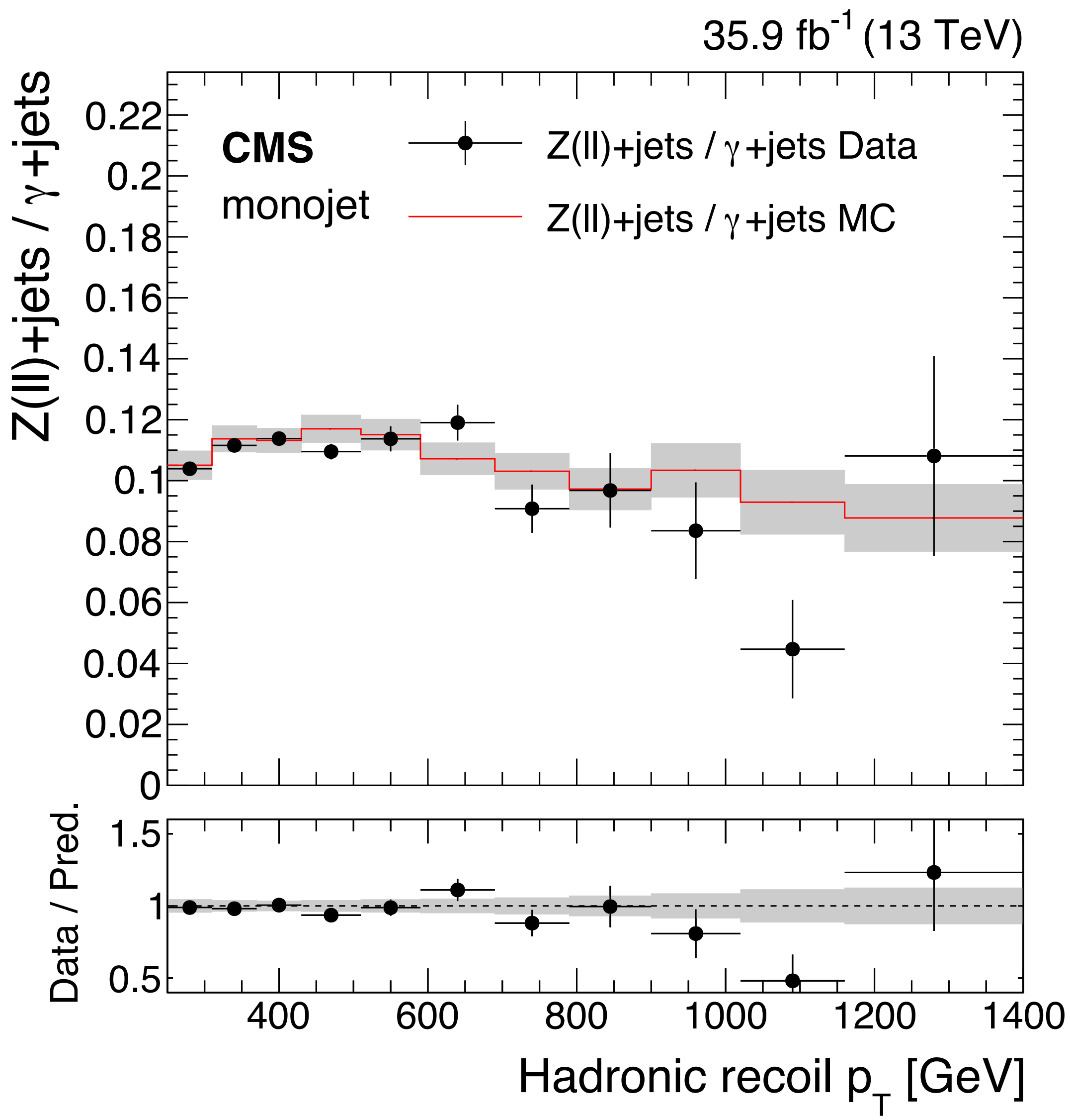
Intense & fruitful effort supported by the LHC DMWG helped to nail this down

Z(ll)/ɣ ratio in data

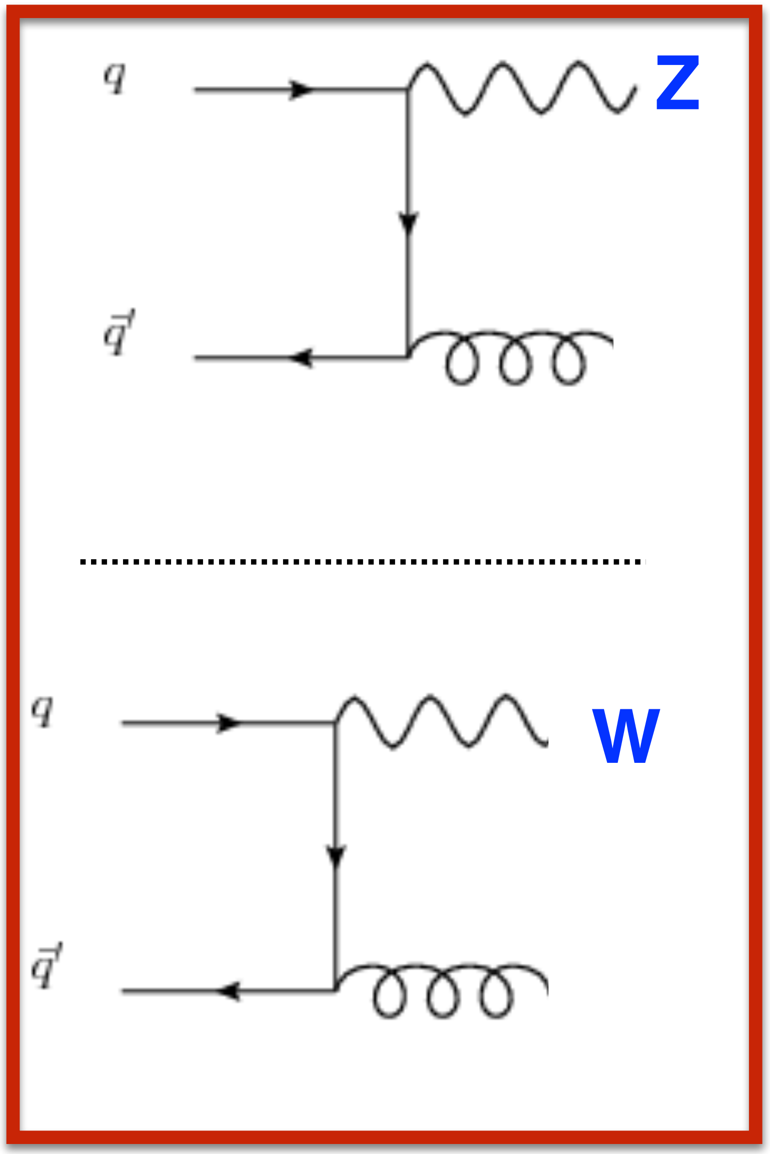


PRD 97 (2018) 092005

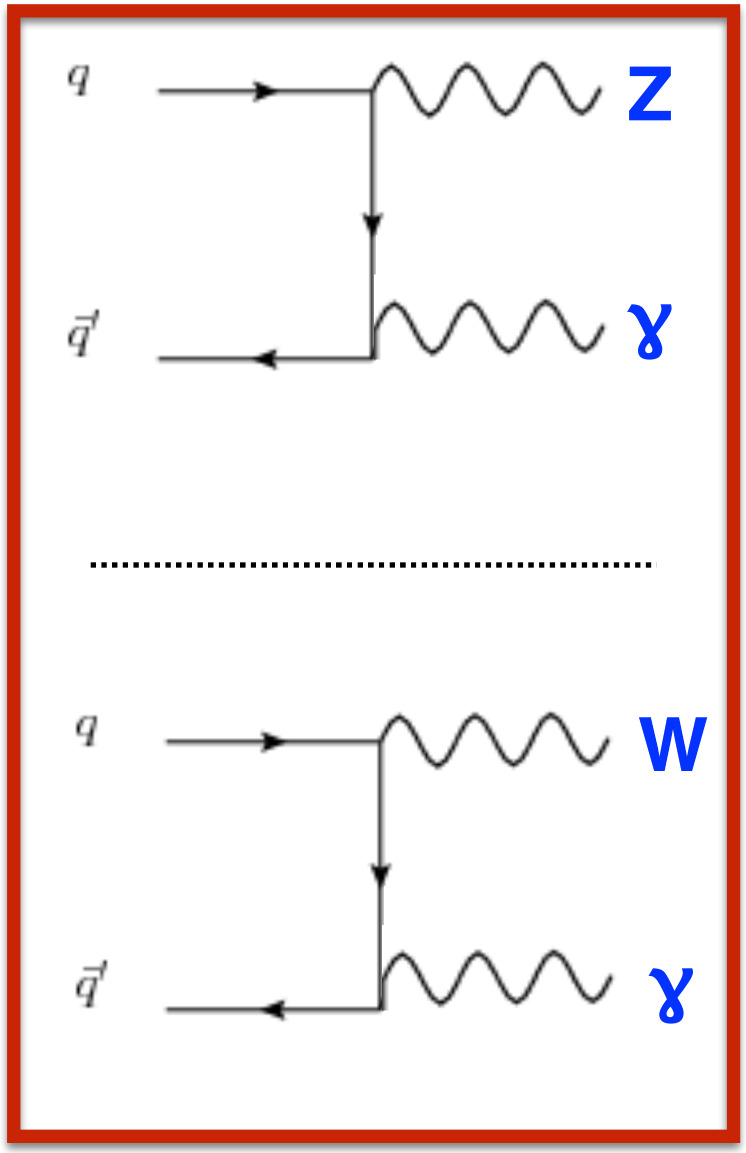
From Z/W Ratio to Z(V)/W(V) Ratio

Dominant bkg. in mono-γ and mono-Z analyses due to diboson processes : Zγ, Wγ & ZZ, WZ

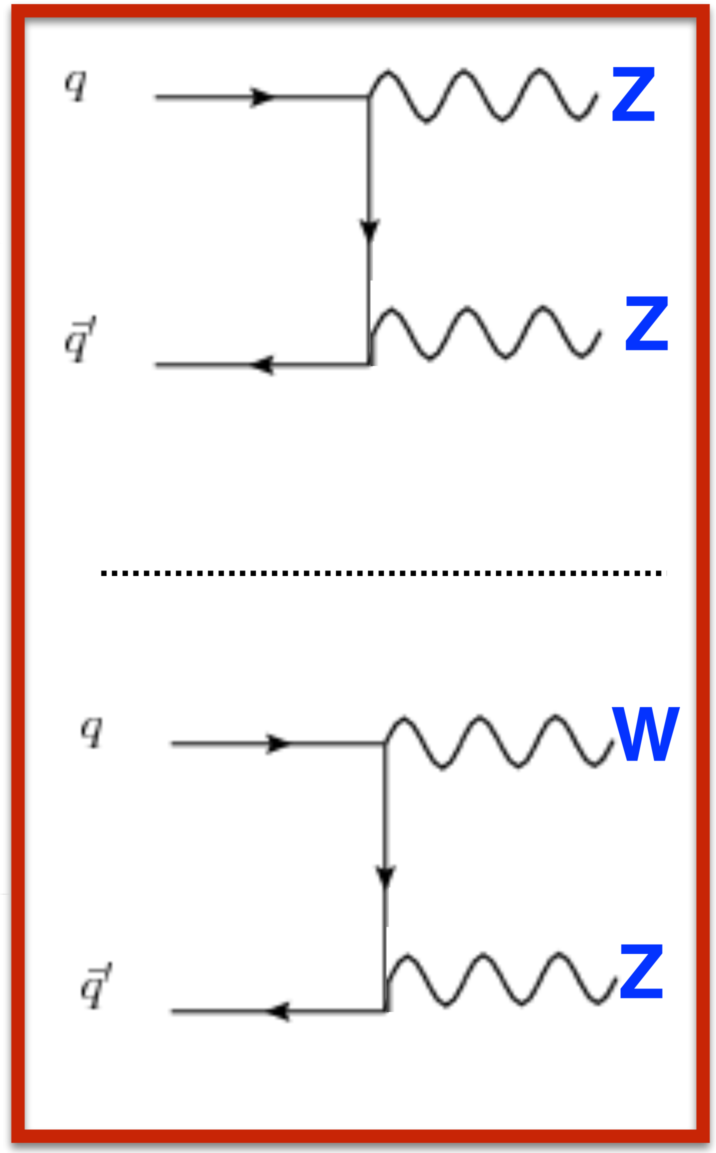
Monojet



γ+MET



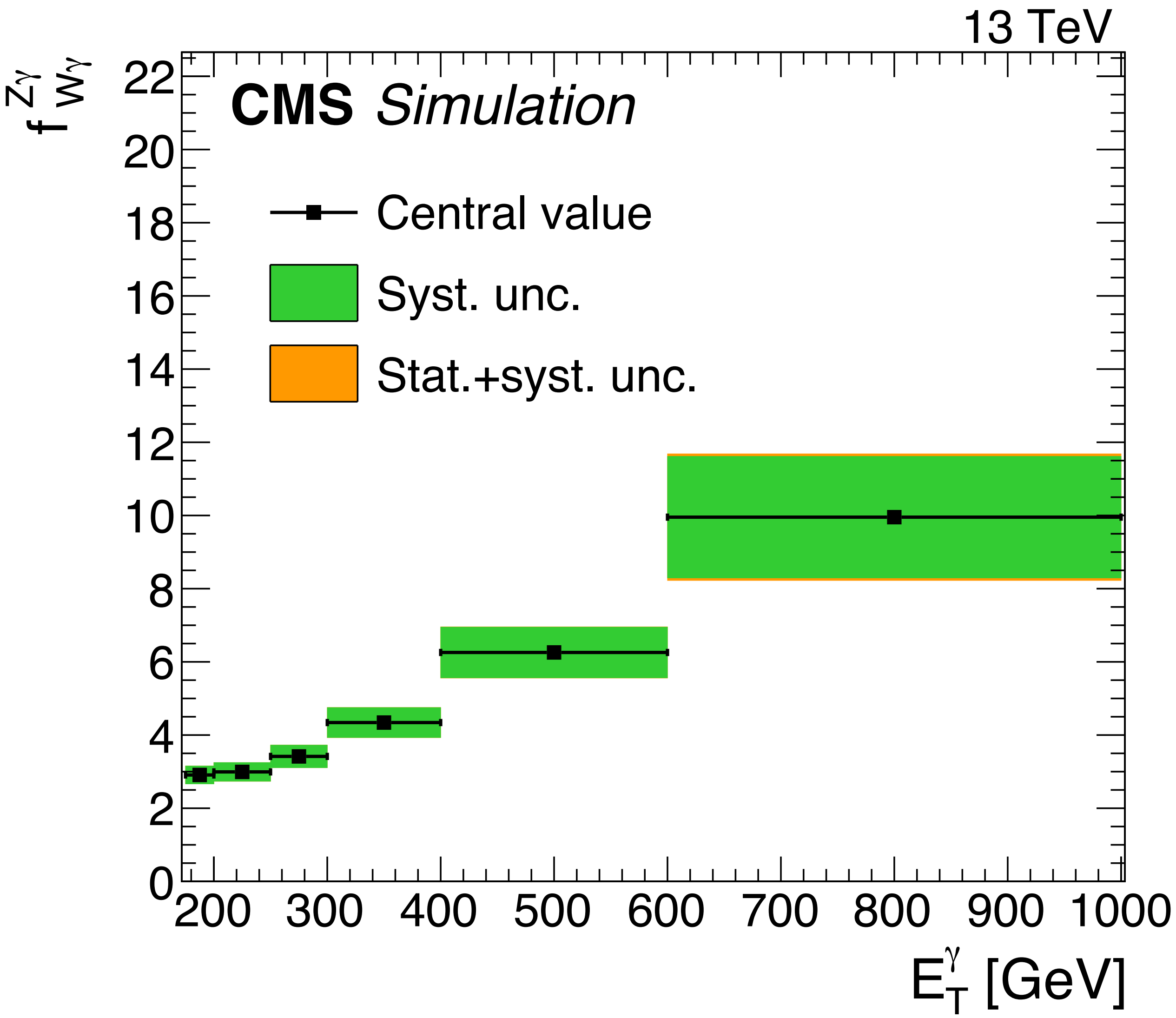
Z+MET



Use the same approach to estimate electroweak bkg. in γ+MET, Z+MET

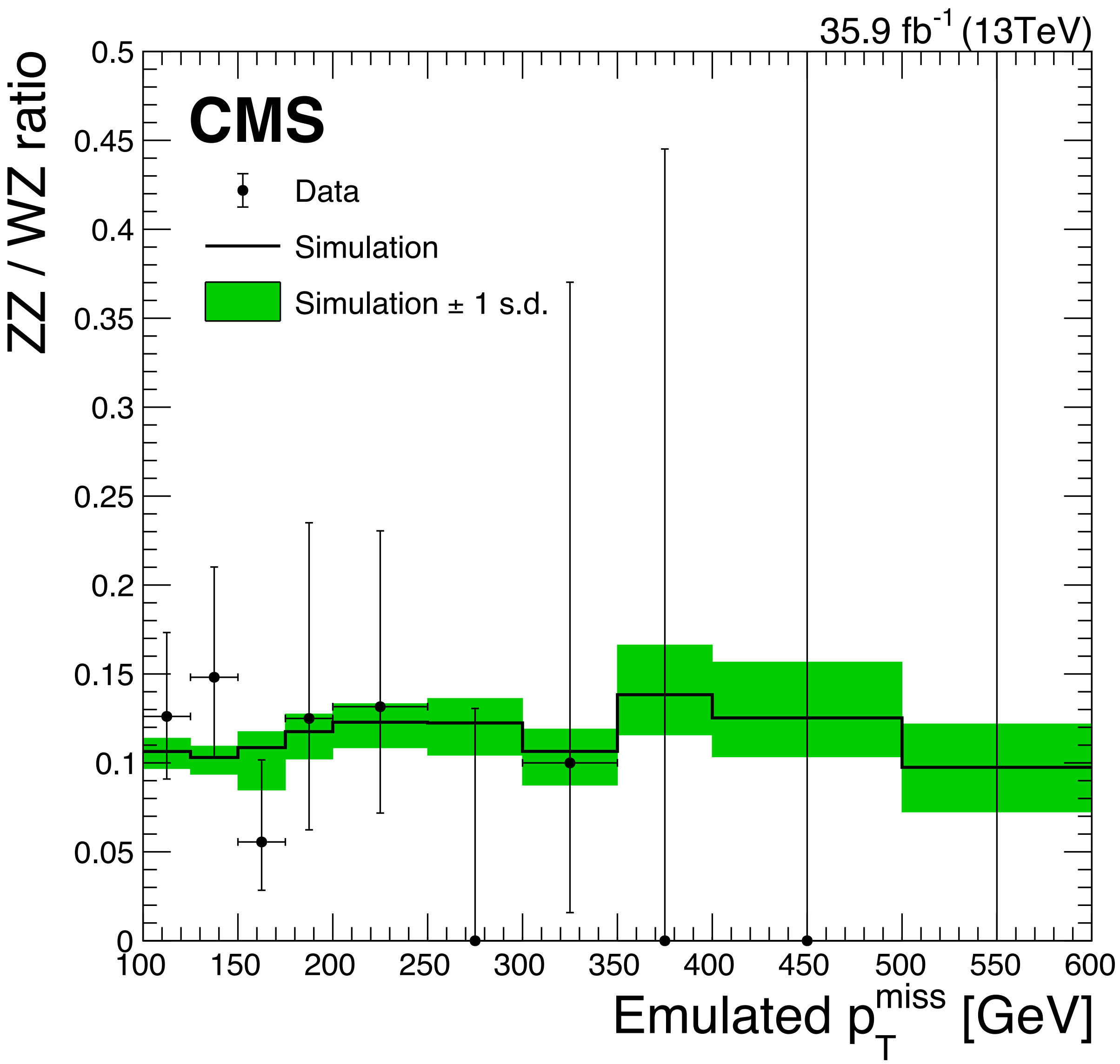
From Z/W Ratio to Z(V)/W(V) Ratio

Predicted Zɣ/Wɣ ratio in signal region from simulation in mono-ɣ analysis



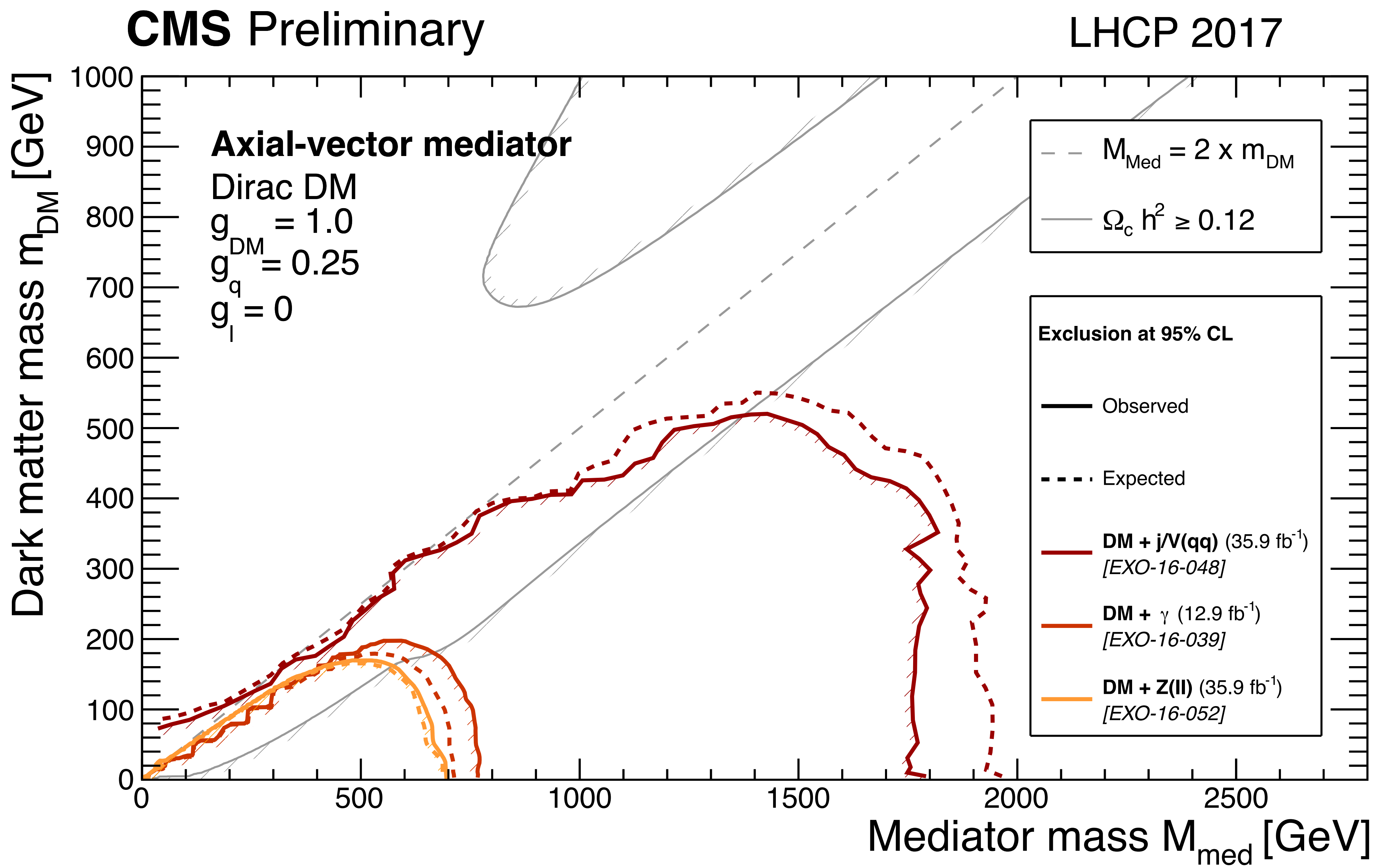
JHEP 02 (2019) 074

ZZ/WZ ratio in mono-Z control regions



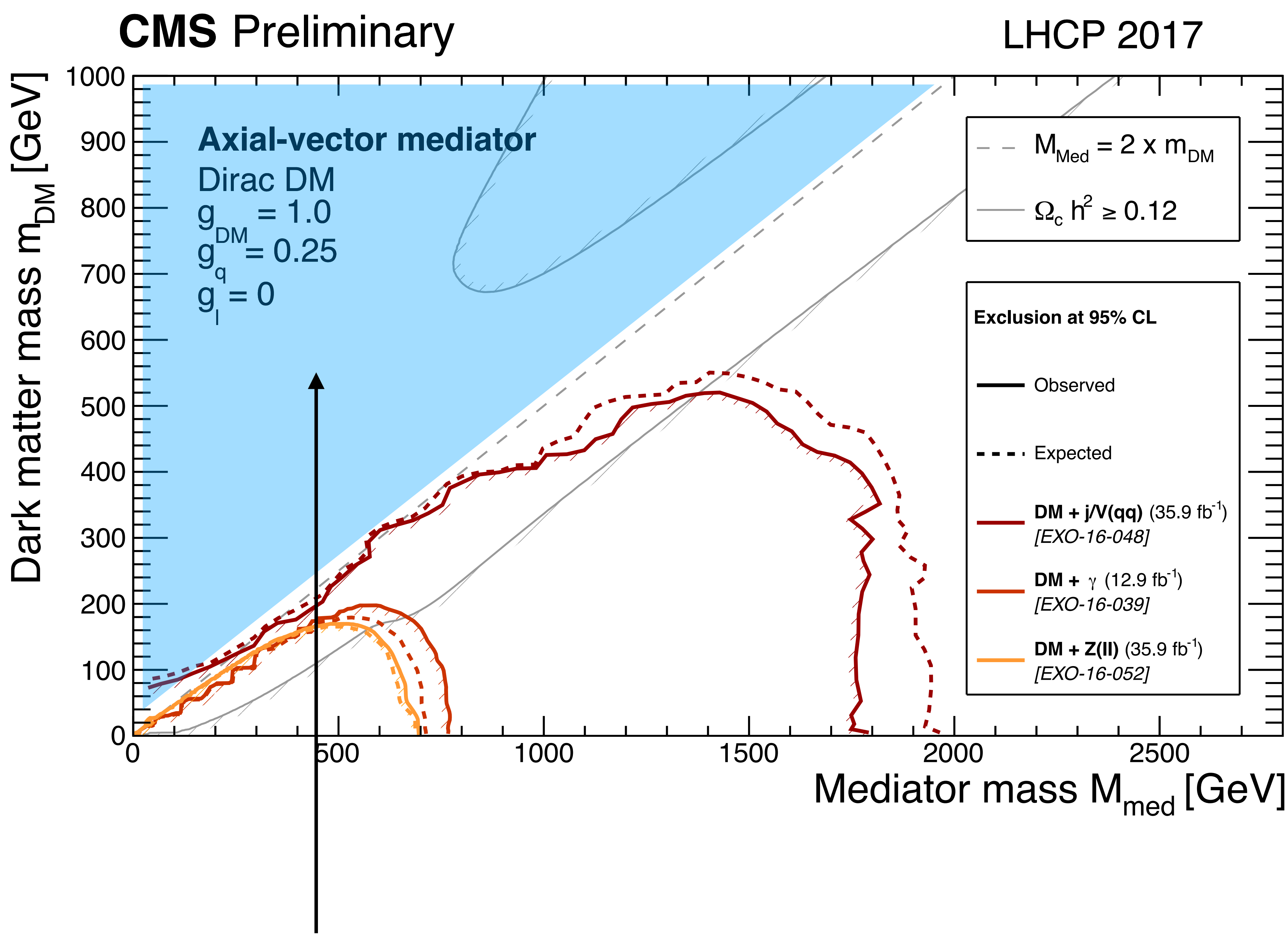
EPJC 78 (2018) 291

Spin-1 Mediator Results



Results shown for an axial vector mediator
Similar results for the vector mediator

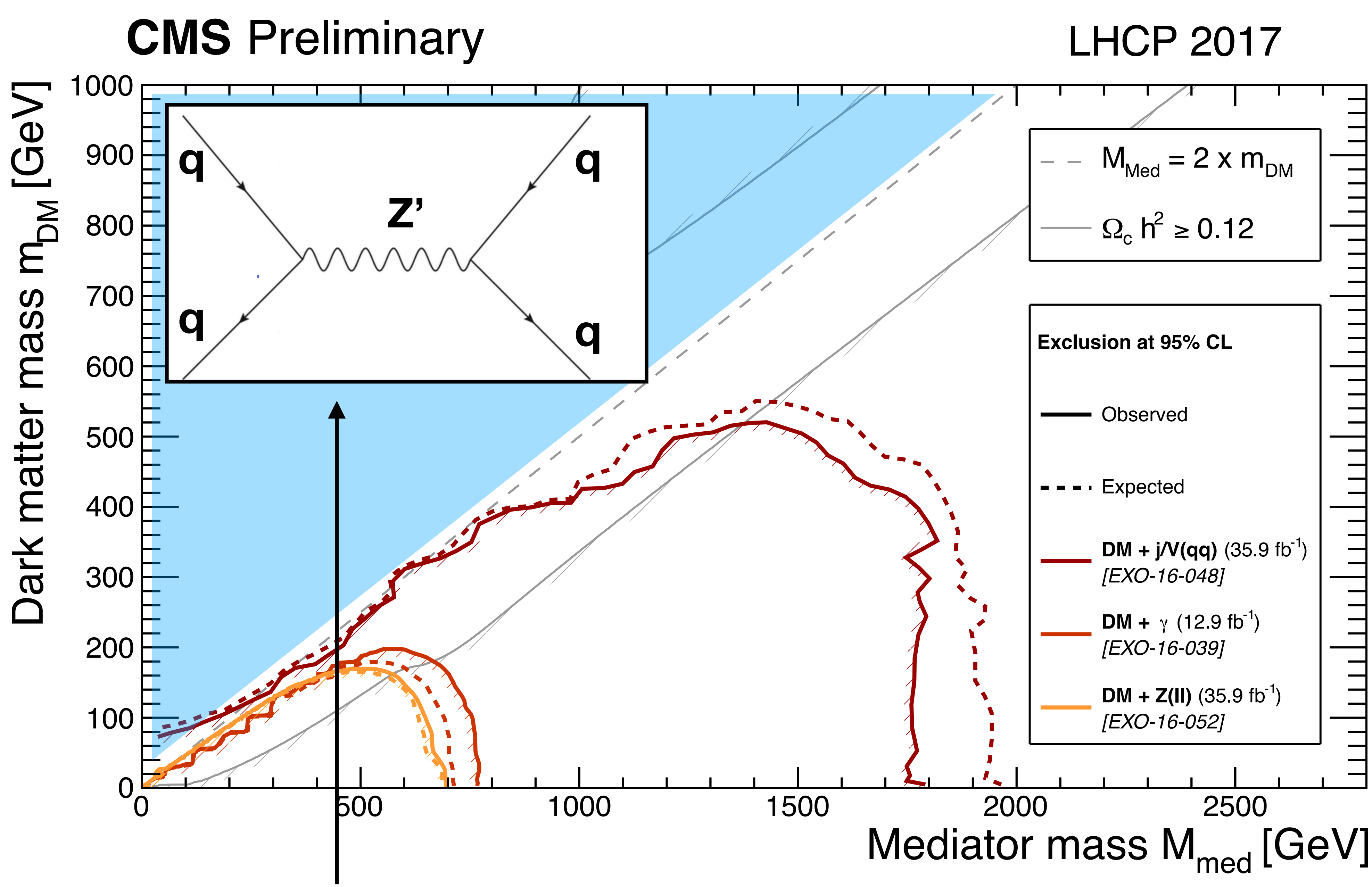
Spin-1 Mediator Results



MET+X searches **not sensitive to the off-shell region** **($M_{med} < 2\ m_{DM}$)**

- *Cross section is heavily suppressed*

Spin-1 Mediator Results

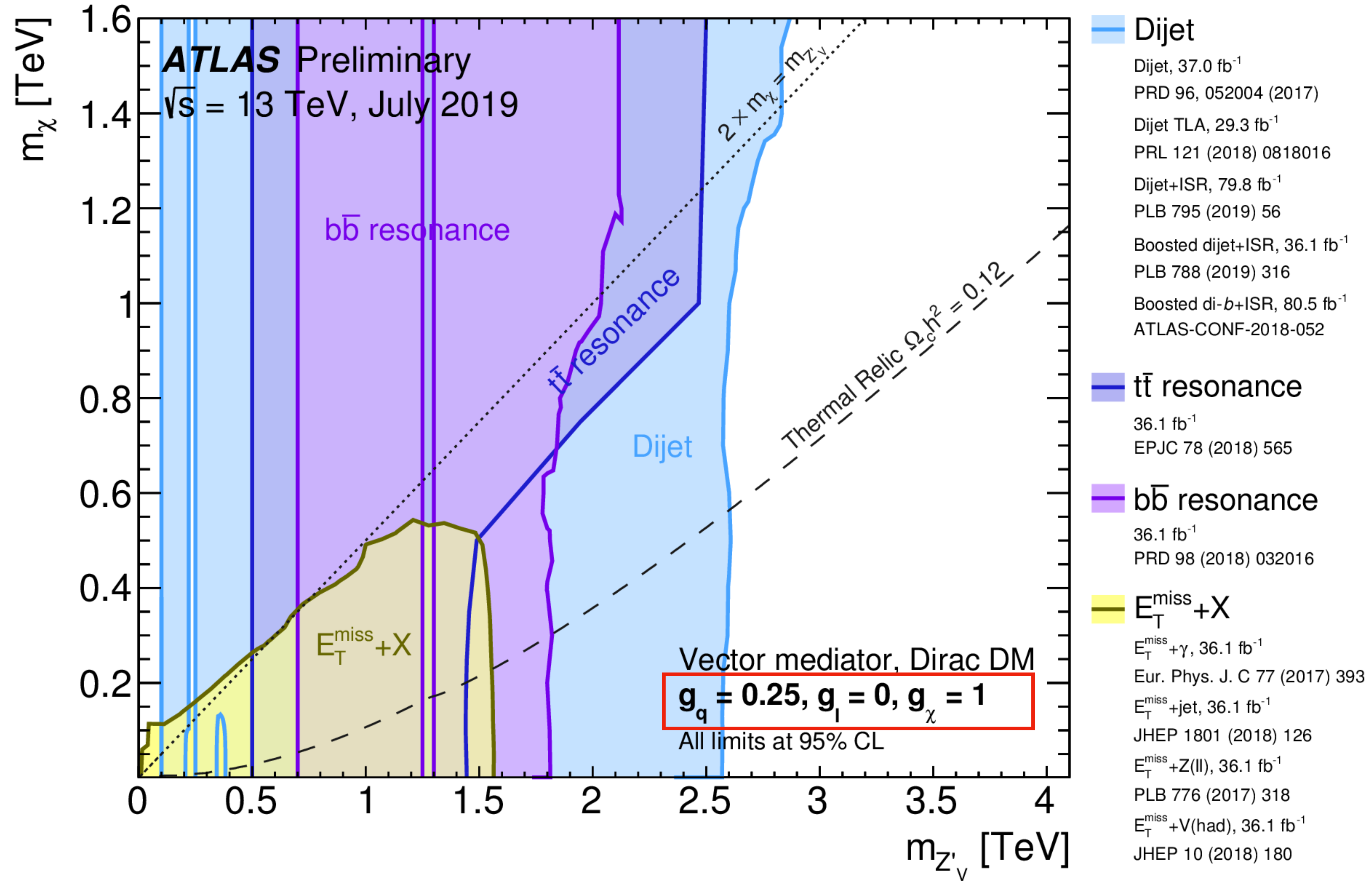


But Z' could decay to quarks (or even leptons)

- *Derive constraints from searches looking for visible Z' decays*

See talks by K. Whalen, T. Poulsen

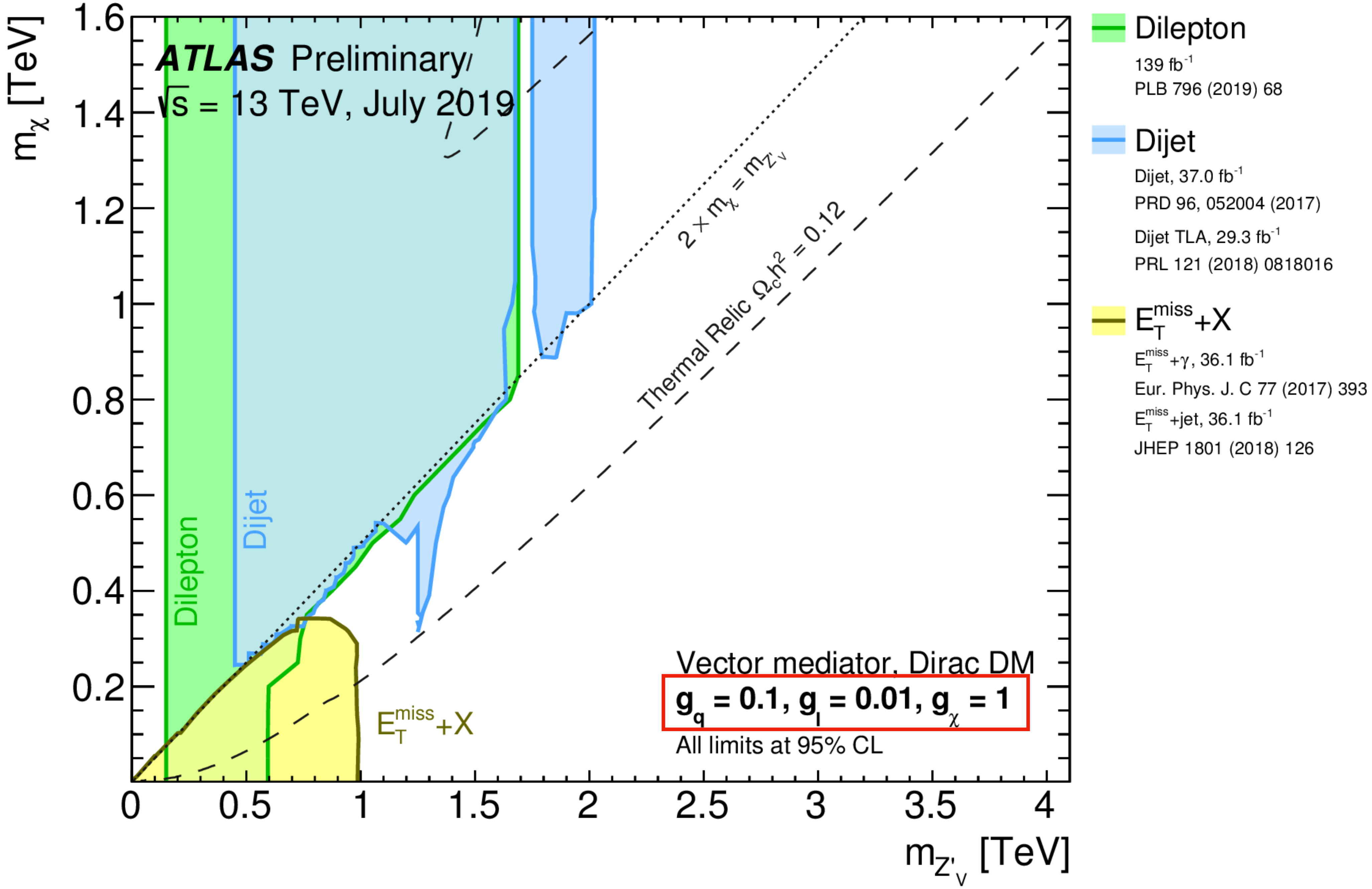
Spin-1 Mediator Results



Constraints on Z' from visible and invisible decays

For g_q ~ 0.25 couplings stronger constraints from visible searches w.r.t. MET+X

Spin-1 Mediator Results



Constraints on Z' from visible and invisible decays

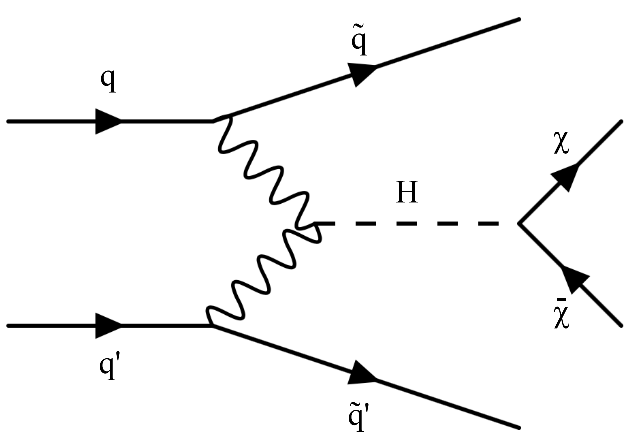
For g_q ~ 0.1 couplings the dijet searches contribute mainly to the off-shell region

Search For H→Invisible Decays

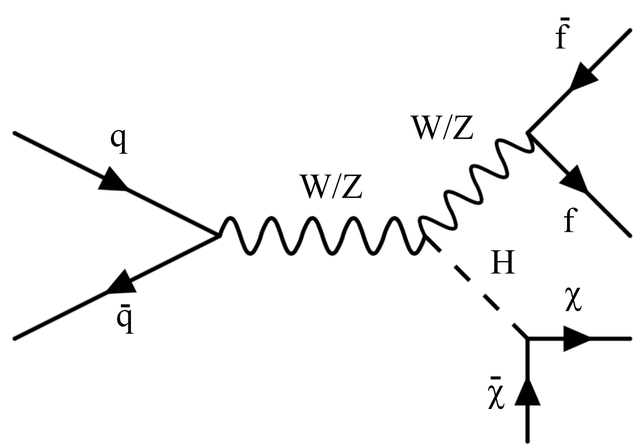
- We still don't know a lot about the 125 GeV Higgs boson
- It is possible that dark matter may couple to the SM through the Higgs boson
- SM BR(H→inv.) ~ 0.1% ; but could get significantly enhanced due to DM interactions

H decay to invisible particles

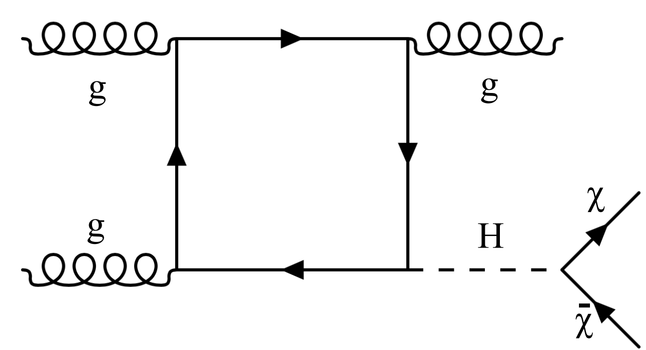
VBF+MET



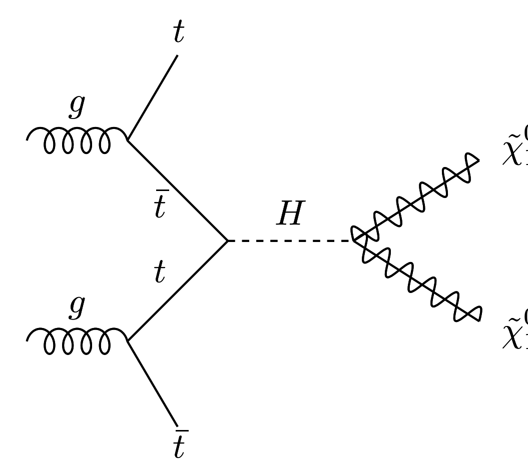
V+MET



Monojet



tt+MET



ATLAS :

- **Phys. Lett. B 793 (2019) 499**
- **Phys. Rev. Lett. 122, 231801 (2019)**

CMS :

- **Phys. Lett. B 793 (2019) 520**
- **HIG-18-008**

See talk by A. Elliot

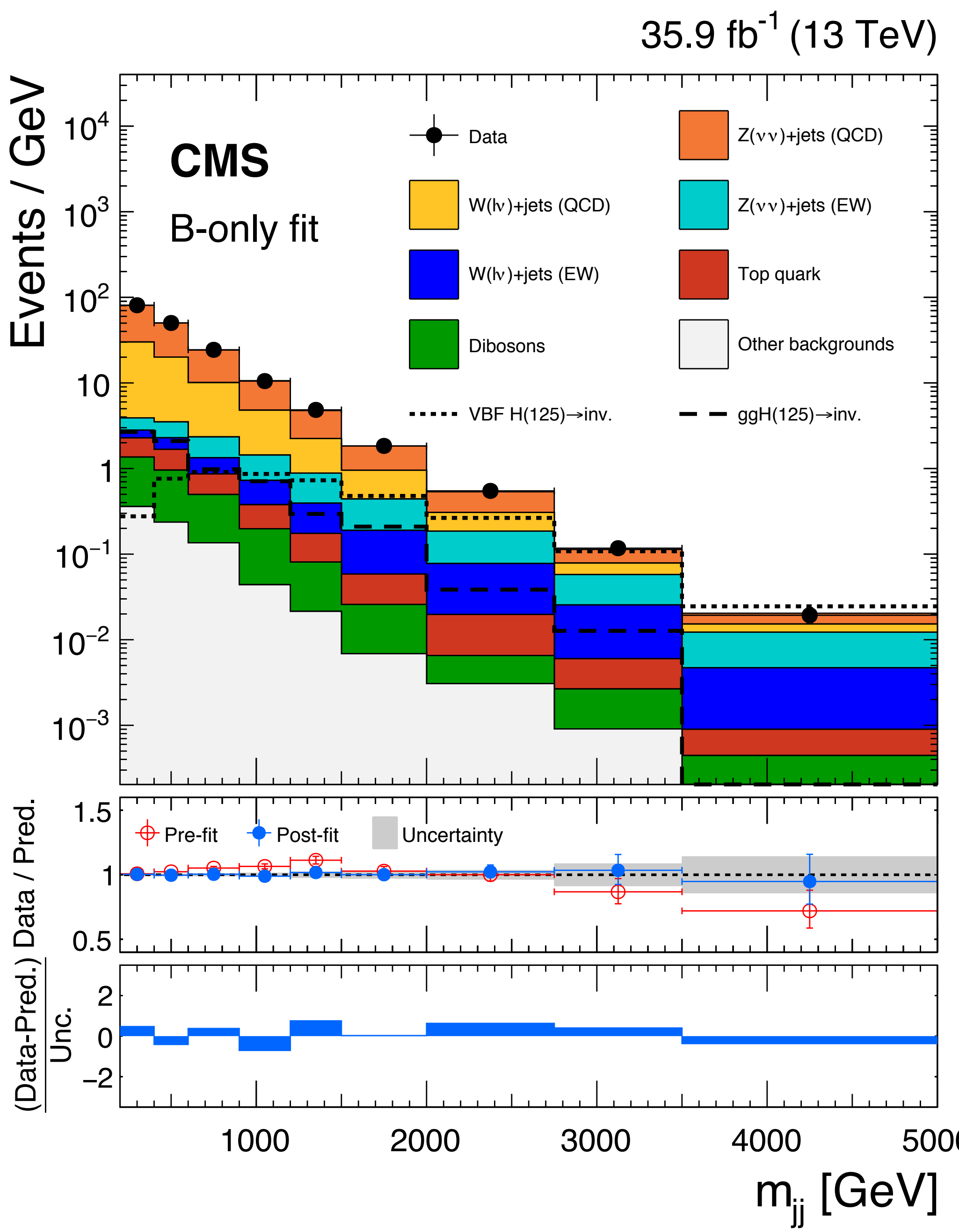
VBF H→Invisible

Most sensitive channel to look for H→inv. decays

- **VBF signature:** two jets with ***large η-gap*** & ***dijet mass***
- Require **large MET** in the event
  - MET > 250 (180) GeV in CMS (ATLAS)
- Lepton veto to suppress W+jets, top bkg.
- Key discriminating variables : $|\Delta\eta_{jj}|$, $|\Delta\phi_{jj}|$, m_{jj}

Main backgrounds : Z(νν)+jets, W(ℓν)+jets

Fit to the dijet mass spectrum to extract signal

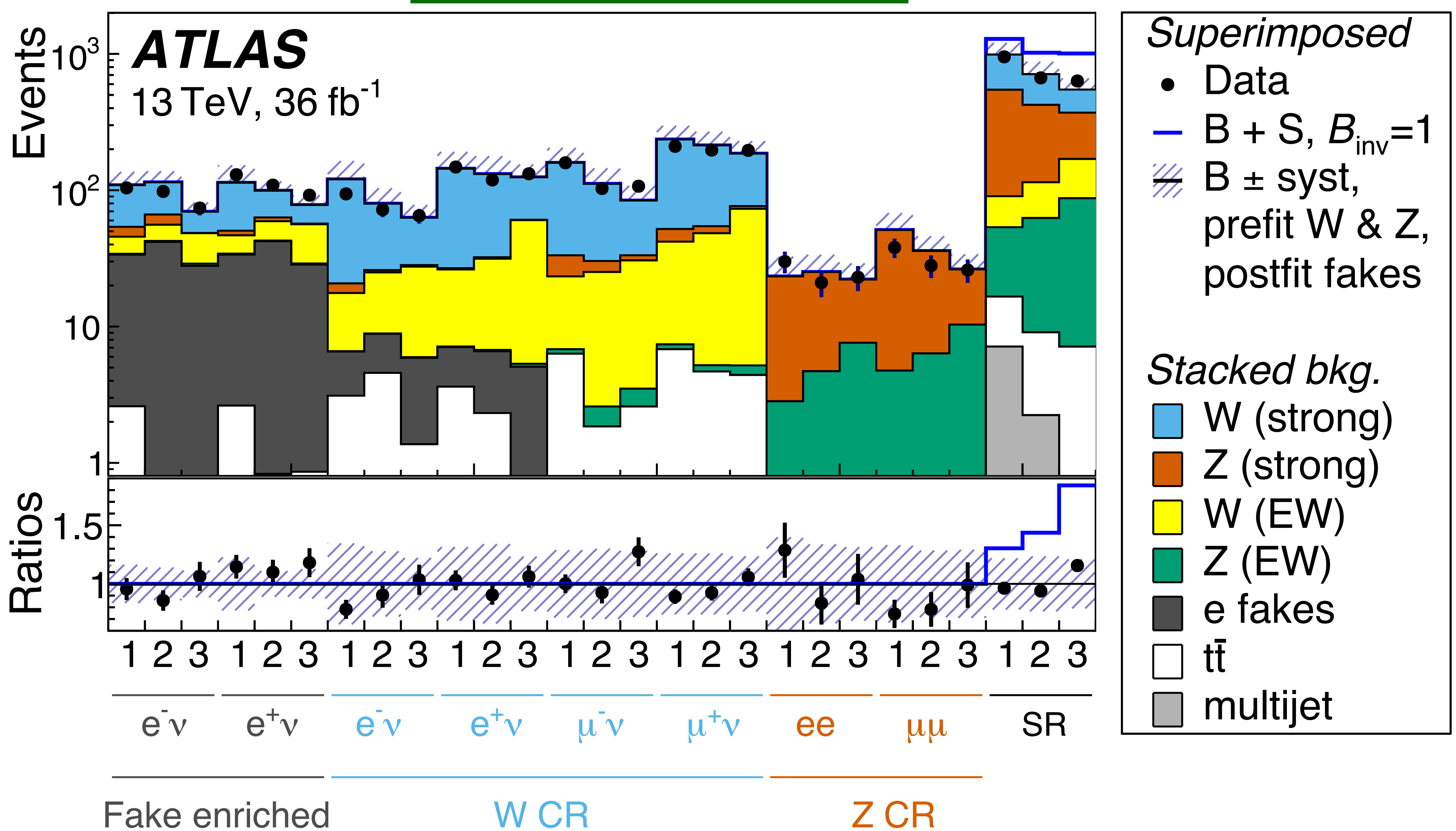


Phys. Lett. B 793 (2019) 520

Electroweak Backgrounds

- Main backgrounds similar to monojet : Z(vv)+jets, W(lv)+jets
- EWK production of Z and W contributes at large m_{jj}
- Dilepton and single-lepton CRs used to estimate the Z, W backgrounds

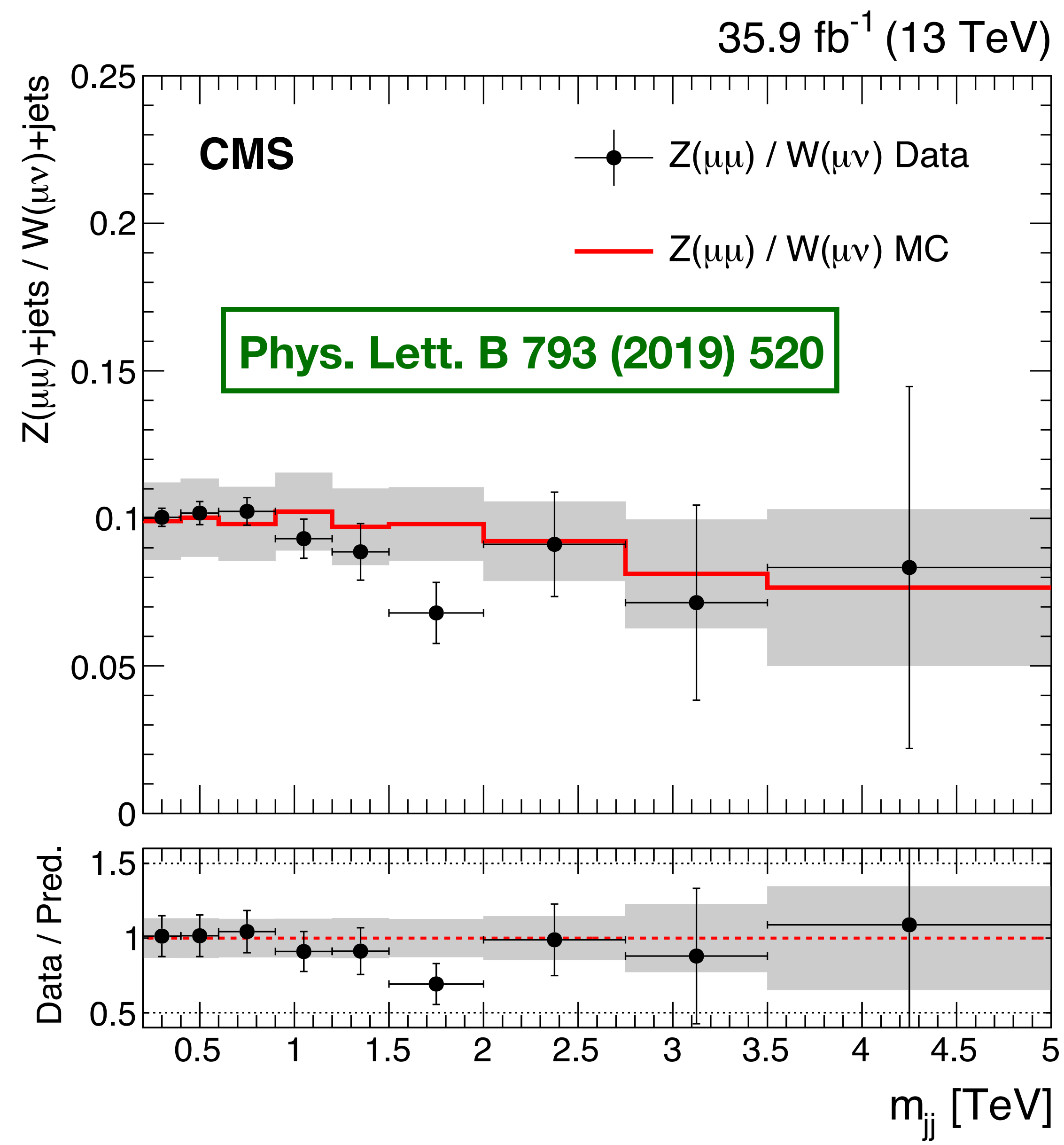
Phys. Lett. B 793 (2019) 499



1,2,3 refer to m_{jj} bins [1.0, 1.5 TeV], [1.5, 2.0 TeV], > 2 TeV

Z, W Control Regions

- CMS uses the constraint from the Z/W cross section ratio when fitting the CRs with the SR
- Not used in the ATLAS analysis
  - No significant gain in sensitivity
- Two competing systematics
  - Modeling uncertainty on Z/W ratio
  - Statistical uncertainty in the Z(ll) sample
- These seem to balance out in the ATLAS analysis
- CMS analysis goes a lot higher in m_{jj}
  - Last bin starts at 3.5 TeV (v/s 2 TeV in ATLAS)
  - Lack of stat. power in Z(ll) sample hurts more



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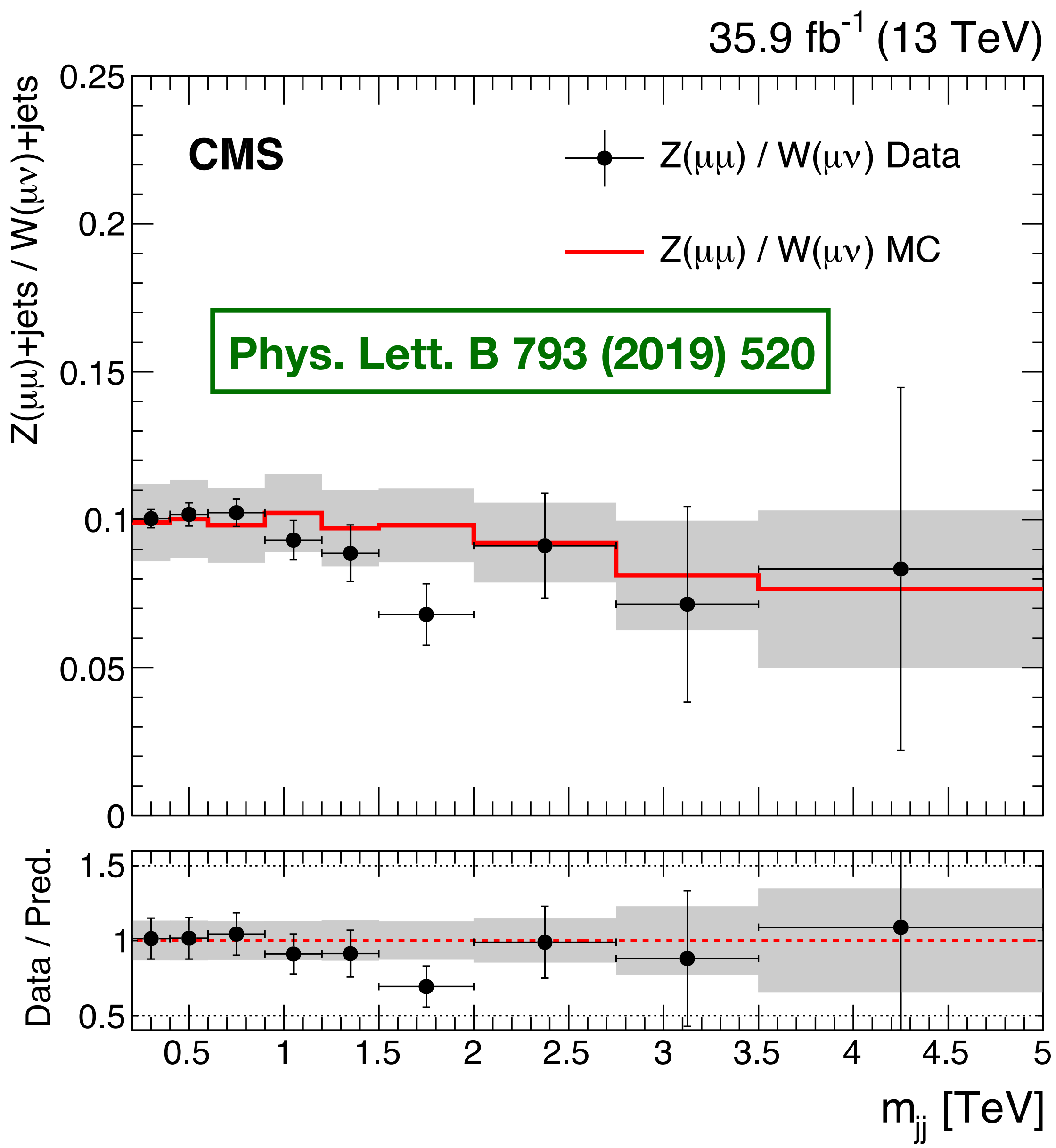
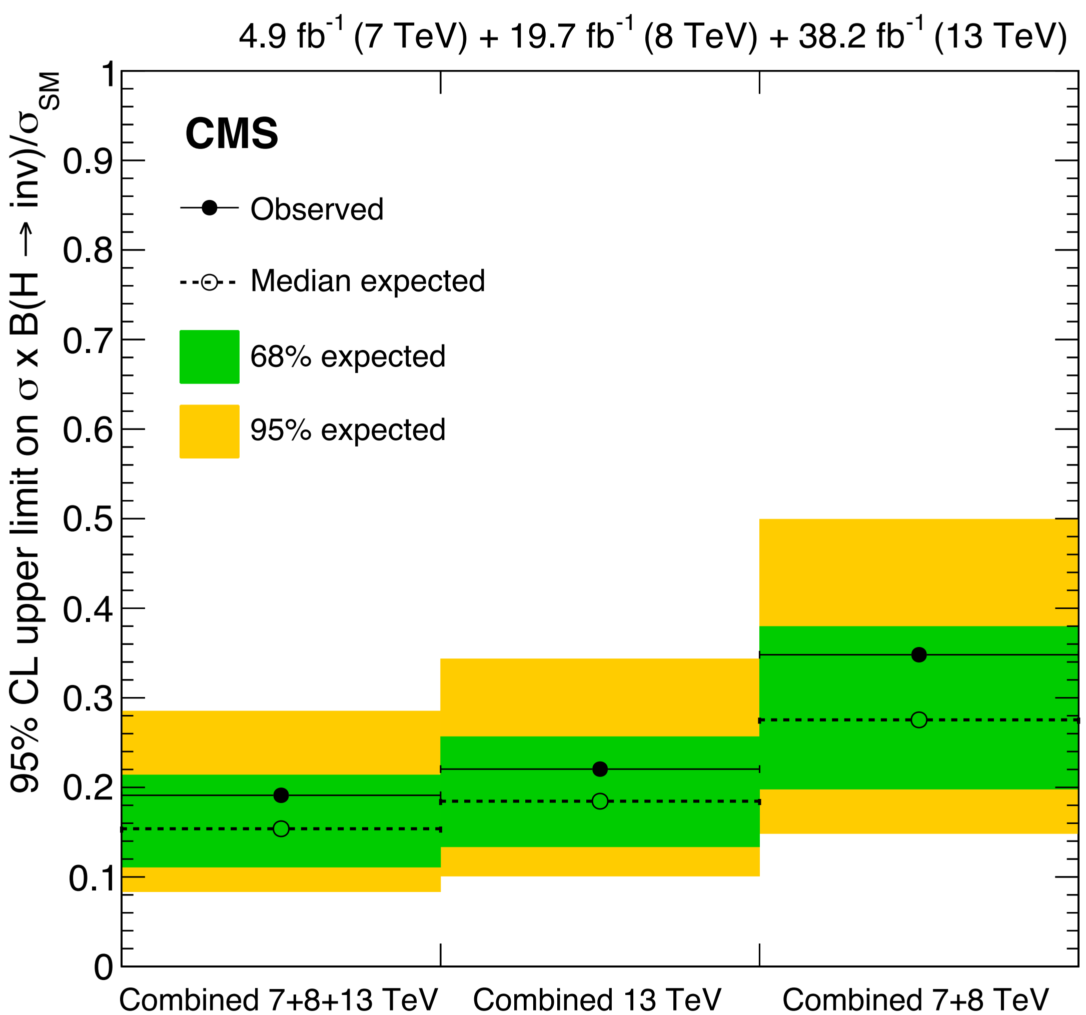


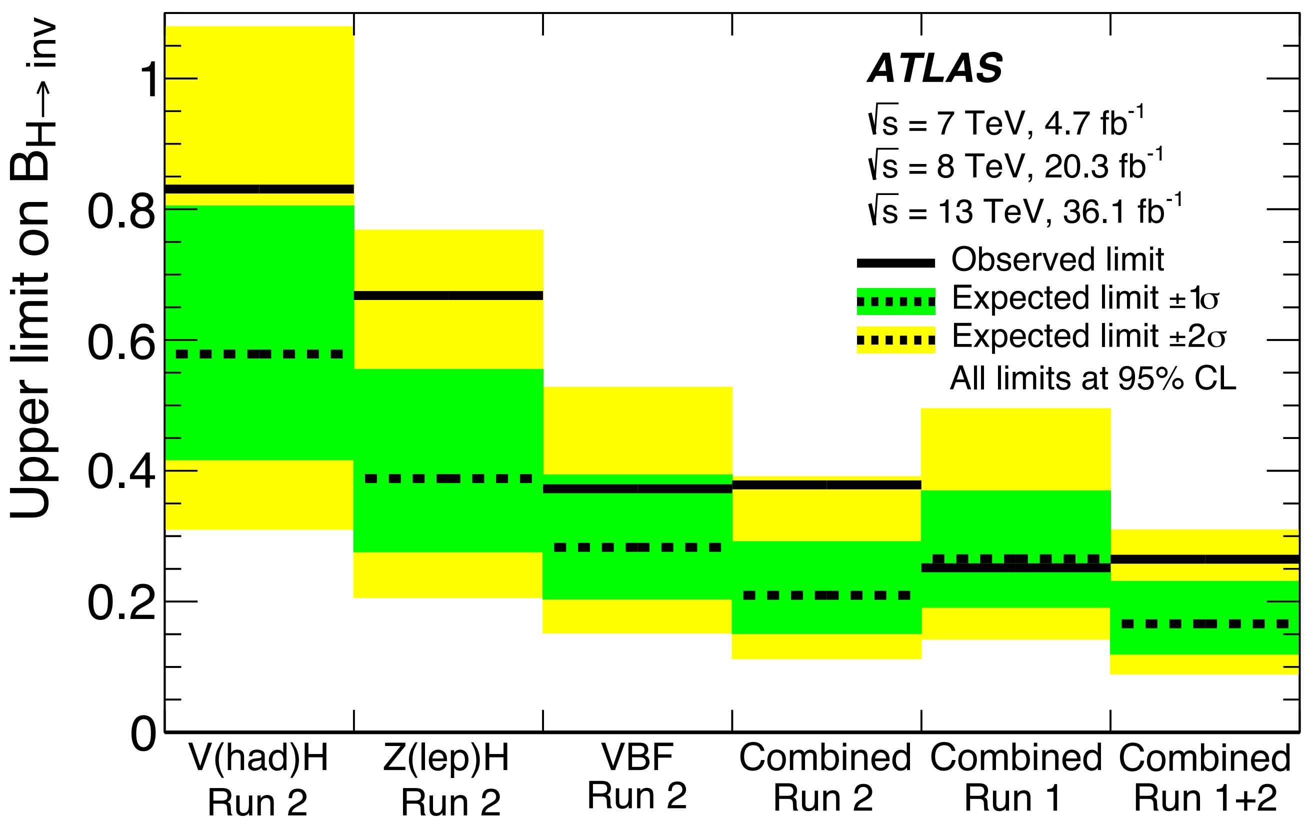
- ***Concerted effort to study (and reduce) the uncertainty on the Z/W ratio, as was done in the monojet analysis, will also help here***
- ***Some discussions started during (and after) DM@LHC 2018 ; should be followed up for the full-Run2 results***

H→Invisible Combination Results

CMS : Phys. Lett. B 793 (2019) 520



ATLAS : PRL 122 (2019) 231801

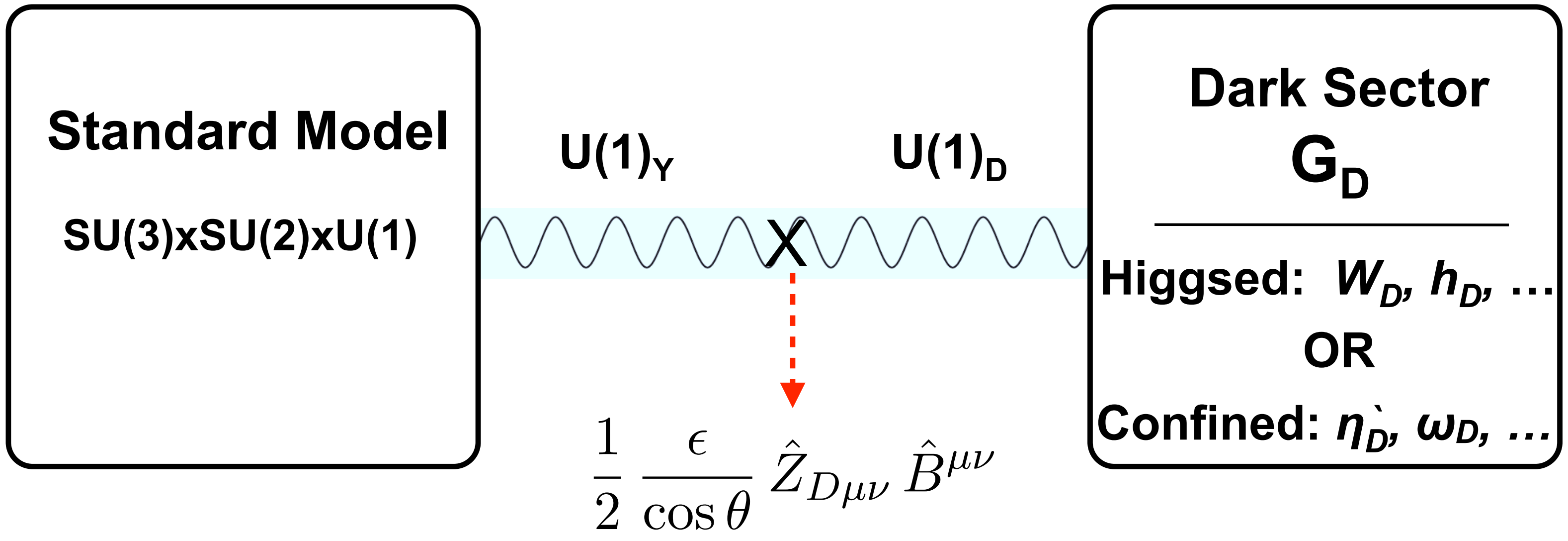


95% CL upper limit : Obs (Exp)
VBF 13 TeV, 36 fb^{-1} : 0.33 (0.25)
Combination : 0.19 (0.15)

95% CL upper limit : Obs (Exp)
VBF 13 TeV, 36 fb^{-1} : 0.37 (0.28)
Combination : 0.26 (0.17)

New Directions : Beyond MET searches

Dark Photon



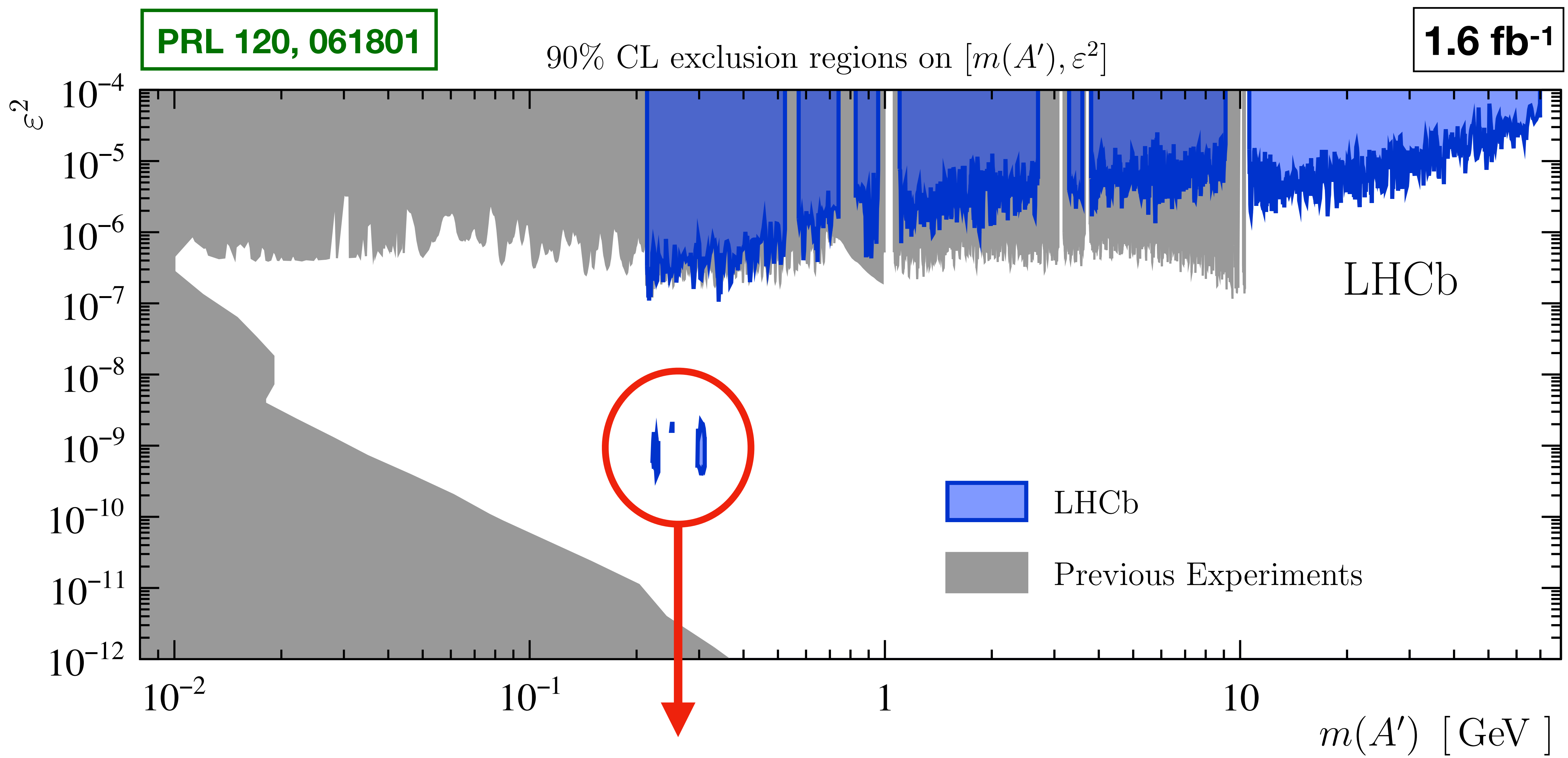
PRD 80 (2009) 015003

- Dark photon (Z_D): Connection between the SM and a hidden, dark sector of particles
- Couples withSM particles via kinetic mixing ($\epsilon \rightarrow$ kinetic mixing coeff.)
- In the most minimal scenario Z_D can be produced in a DY-like process
- Interaction of Z_D with SM fermions is similar to Z/γ (x-sec suppressed by ϵ^2)
- Assuming Z_D decays only to SM, its width (lifetime) depends on ϵ
  - Prompt regime : $\epsilon > 10^{-3}$
  - Displaced regime : $\epsilon < 10^{-4}$ … O(1mm) $c\tau$ for sub-GeV dark photons

LHCb Dark Photon Results

Getting competitive with BaBar below 10 GeV

First limits on dark photons above 10 GeV

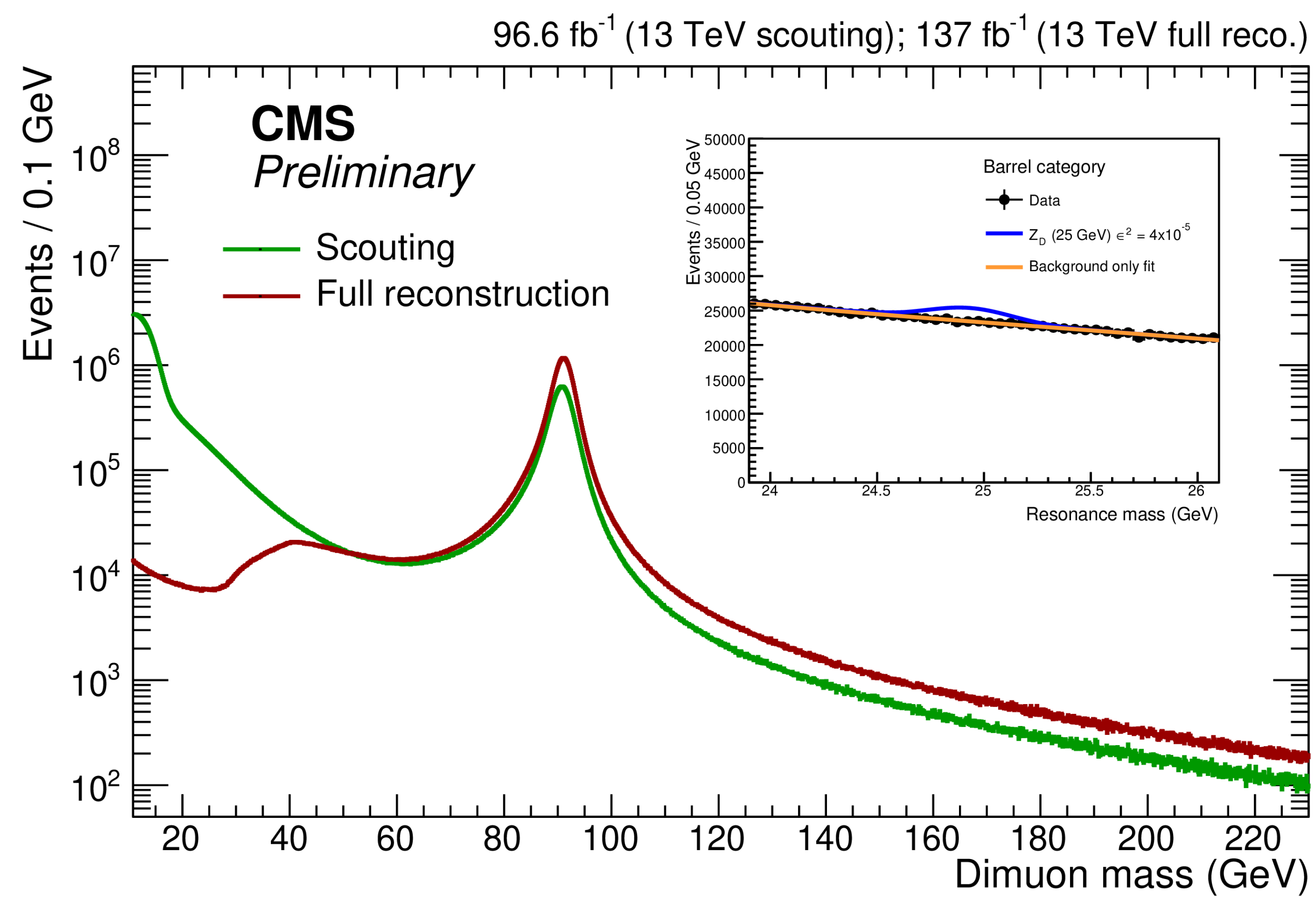


Sensitivity to long-lived dark photons

Talk by F. L. Redi

New CMS Dark Photon Search

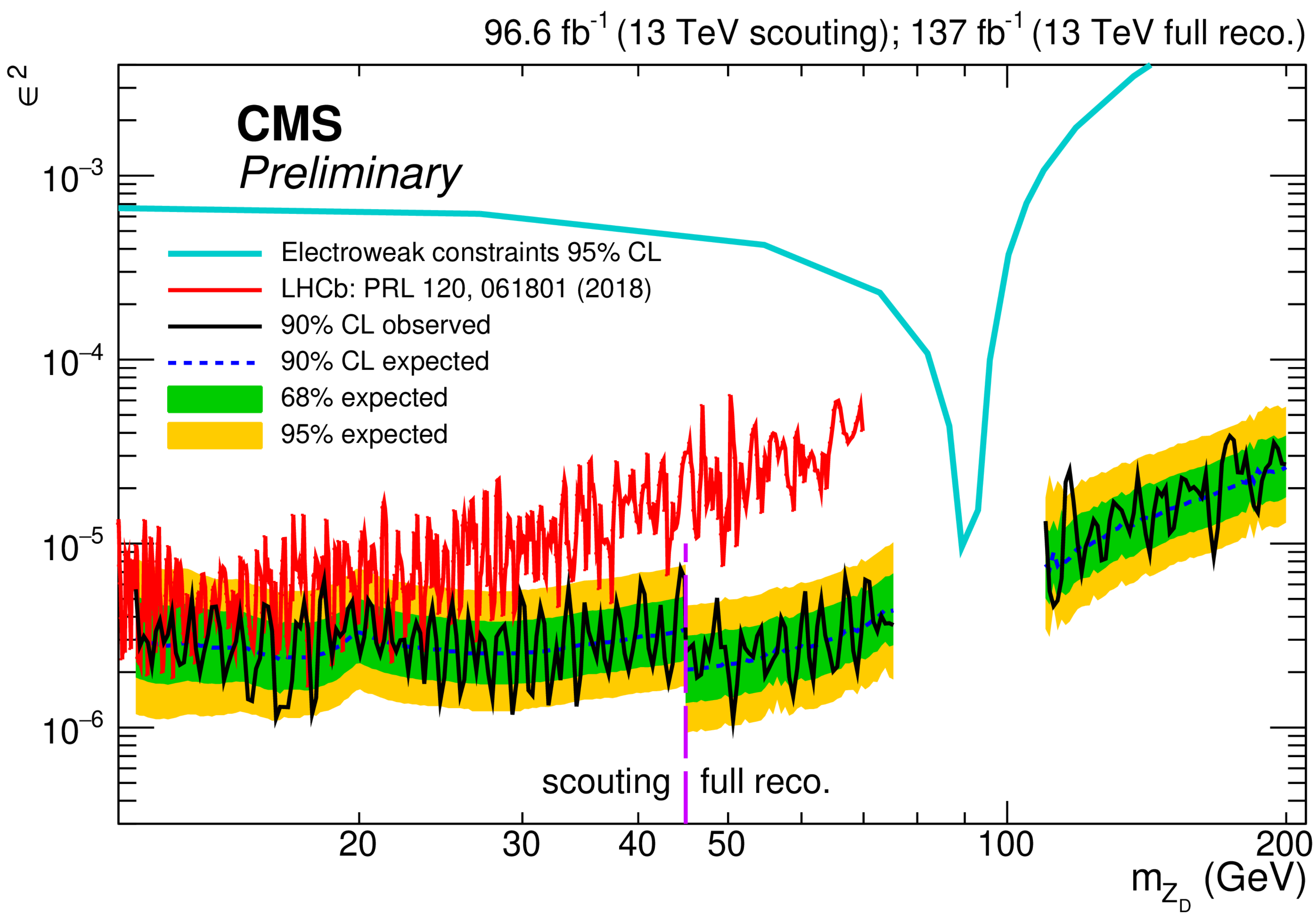
- **Standard dimuon triggers :**
  - 12,5 (15, 7) GeV p_T thresholds on muons at L1 in 2017 (2018)
  - 17, 8 GeV p_T thresholds at HLT
  - Lose a lot of acceptance for dimuon masses below ~40 GeV
- Data collected with ***muon scouting*** in 2017, 2018
  - **Lower p_T thresholds** on muons
  - But **save only trigger-level information** about the muons
- Helps to **recover acceptance** for low mass dark photons



For masses ~ 10-20 GeV
Scouting trigger @L1 :
7 < m(μμ) < 18 GeV + p_T > 4.5 GeV
3 GeV p_T threshold @ HLT

For masses above 20 GeV
Standard dimuon triggers

New CMS Dark Photon Search



Search for dark photons heavier than 11.5 GeV

For masses below Z peak, 90% CL upper limit on $\epsilon^2 \sim 3 \times 10^{-6}$

Much to Explore in the Dark Sector

- Dimuon bump searches explore the most minimal interaction between dark photons and the SM
- Interplay between the dark sector and SM can lead to several new, unexplored final states
  - ➡ $H \rightarrow Z_{(D)} Z_D \rightarrow 4$ leptons (ATLAS JHEP 06 (2018) 166)
  - ➡ Emerging jets (CMS JHEP 02 (2019) 179)
  - ➡ Semi-visible jets (See talk by Colin Terrence Fallon)
  - ➡ Long-lived dark photons (See talk by Yangyang Cheng)

Final Remarks

- Dark matter searches at LHC have evolved a lot during Run-2
  - We should keep pushing to improve them further
- Dark matter (sector) program at the LHC is also evolving in scope
  - New models and signatures being explored
- The goal is to make a comprehensive sweep (invisible, visible, long-lived) of the dark sector with the full Run-2 data set
- The enormous experience from Run-2 will certainly be useful to push the dark matter searches further in Run-3