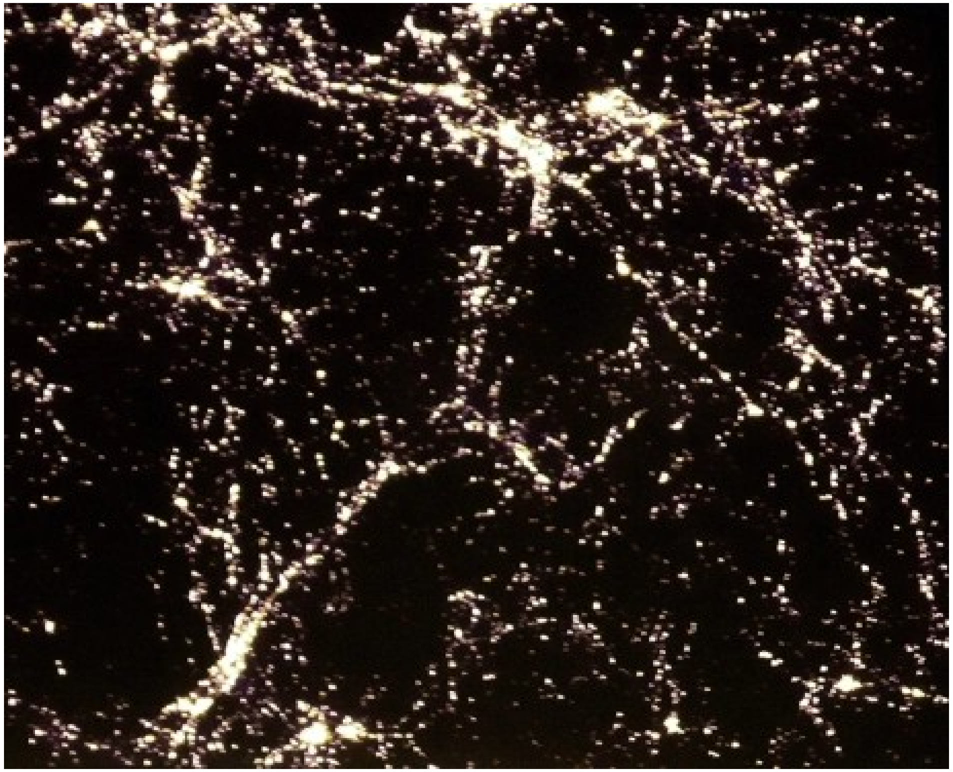
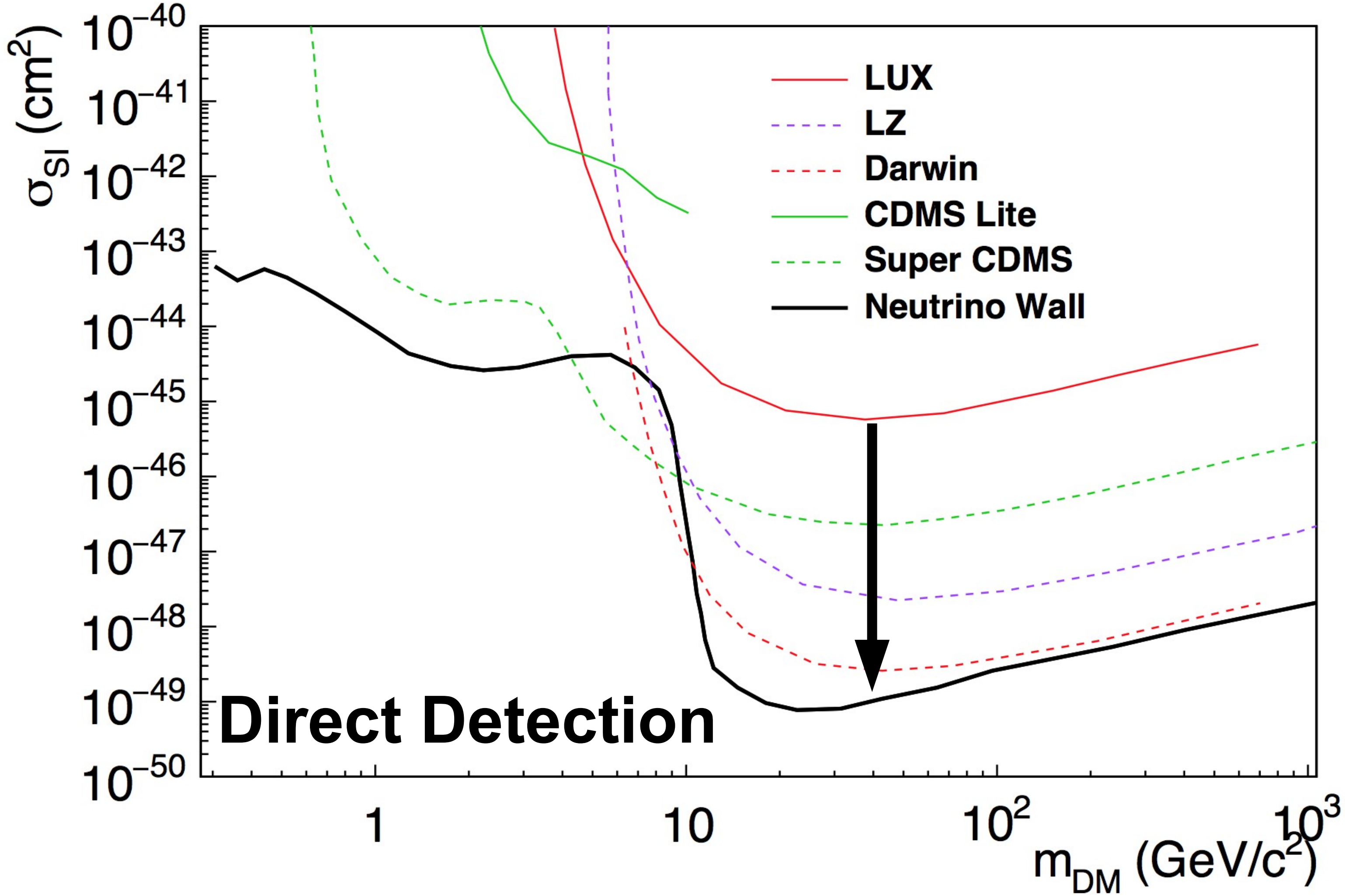
Dark Matter Mediators @ Colliders



Phil Harris
MIT

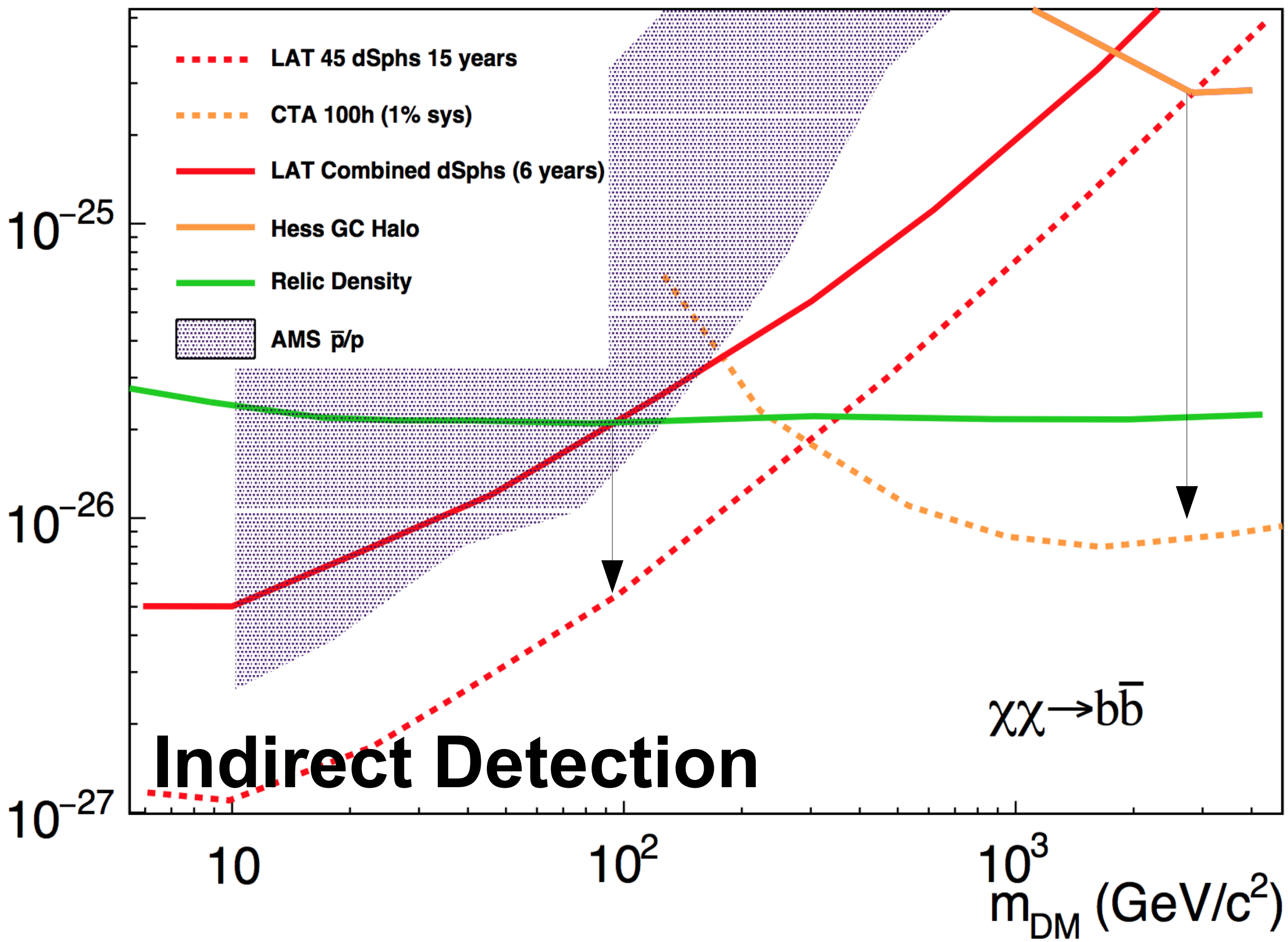
Dark Matter searches not @ collider

Dark matter searches not at colliders have clear benchmarks



Goal: get to the Neutrino background wall

Dark Matter searches not @ collider



Goal: get to the Relic density

Question:

- Whats the simplest way to present LHC results in the context of Dark Matter?

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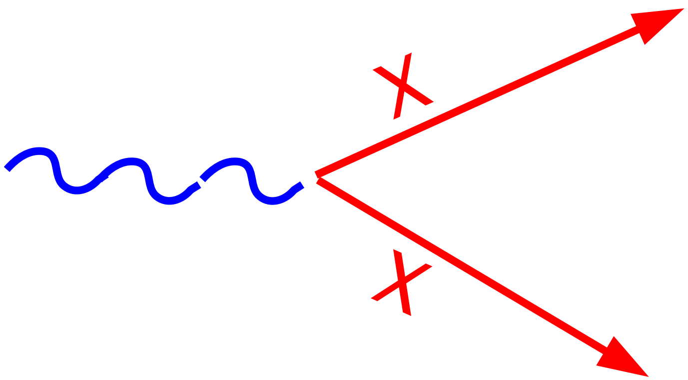
- Answer:
  - $\sigma_{Invisible}$



- Assumes dark matter coupling to standard model
  - $\mathcal{L} = g_{DM}\bar{\chi}\chi Y$ → Mediator + SM interactions

Dark Matter

Adding Dark Matter

- What drives dark matter interaction is production
  - Take the approach that this is defined by the mediator

- $\mathcal{L}' = g_{DM}\chi\chi Y$

Z'^{μ} Spin 1

Uniform coupling to SM

$$\mathcal{L}' = \mathcal{L}' + g_{SM} Z'_{\mu} \bar{q} \gamma^{\mu} q$$

S Spin 0

Yukawa* couplings to SM

$$\mathcal{L}' = \mathcal{L}' + g_{SM} S \bar{q} q$$

Preserving Generality?

To compare with other (low energy) searches :
split by spin dependence

$$\mathcal{L} = g_{DM}\chi\chi Y$$

Spin 1

Z'^{μ} Vector

$$\mathcal{L} = \mathcal{L} + g_{SM} Z'_{\mu} \bar{q}\gamma^{\mu} q$$

γ^5

Z'^{μ} Axial-Vector

$$\mathcal{L} = \mathcal{L} + g_{SM} Z'_{\mu} \bar{q}\gamma^{\mu}\gamma^5 q$$

Spin 0

S Scalar

$$\mathcal{L} = \mathcal{L} + g_{SM} S \bar{q} q$$

γ^5

P Pseudoscalar

$$\mathcal{L} = \mathcal{L} + g_{SM} P \bar{q}\gamma^5 q$$

Strategy of searches in LHC does not change much
Interpretation agains Direct Detection/Indirect Changes a lot

Simplified Models 101

Vector

$$g_{\mathrm{DM}} Z'_\mu \bar{\chi} \gamma^\mu \chi$$

EWK style coupling
(equal to all quarks/leptons)

Axial vector

$$g_{\mathrm{DM}} Z''_\mu \bar{\chi} \gamma^\mu \gamma^5 \chi$$

EWK style coupling
(equal to all quarks/leptons)

Scalar

$$g_{\mathrm{DM}} S \, \bar{\chi} \chi$$

Yukawa style coupling
(Mass based coupling)

Pseudoscalar

$$g_{\mathrm{DM}} P \, \bar{\chi} \gamma^5 \chi$$

Yukawa style coupling
(Mass based coupling)

With Direct Detection

Vector(SI)

Spin independent

Extremely good

Axial(SD)

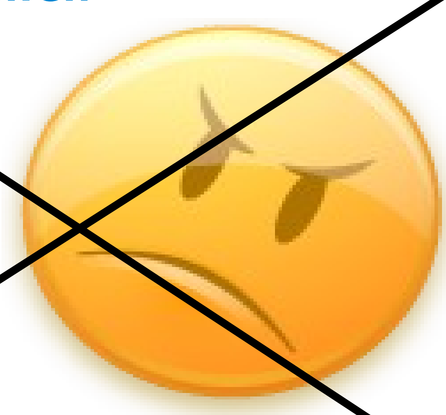
Spin dependent

Not so great

Scalar(SI)

So-so
Spin independent

~~Pseudoscalar~~

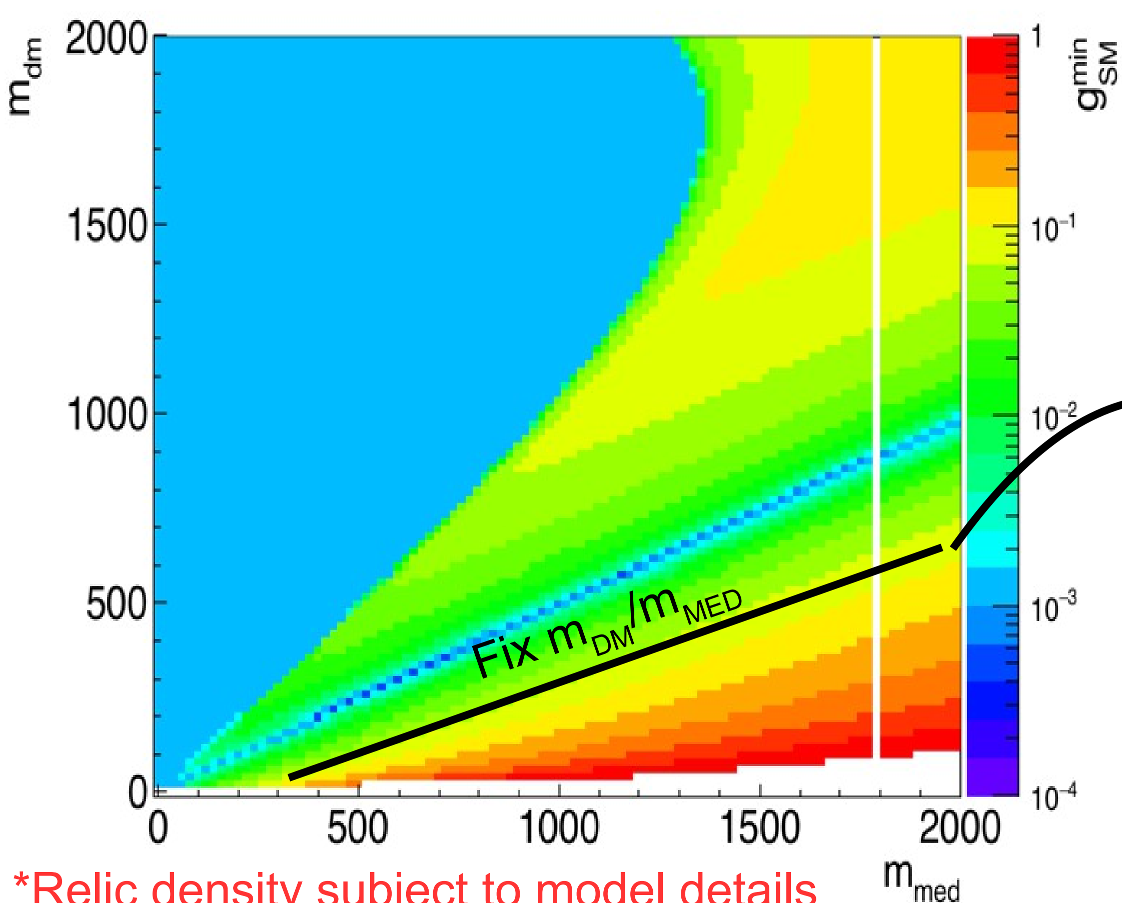


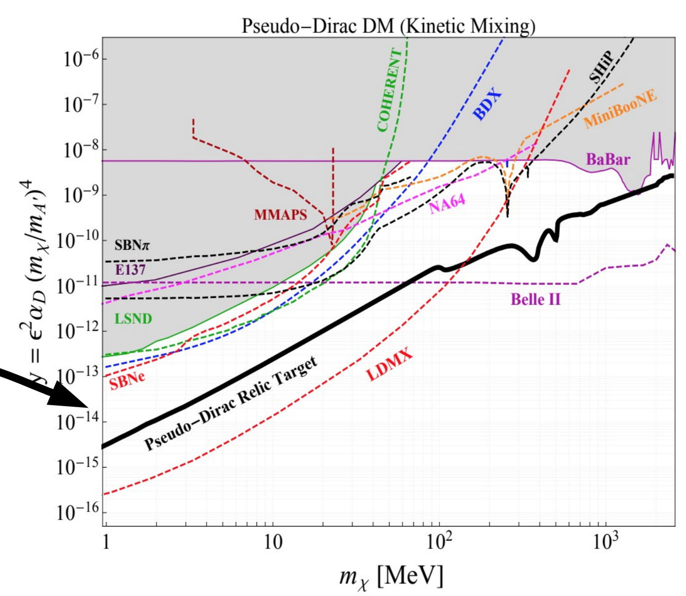
Use indirect detection

And the relic Density?

For simplified model if you scan the coupling you find

Minimum allowed coupling for each model*





Same line used as a target in beam dump experiments

*Relic density subject to model details

And the relic Density?

For simplified model if you scan the coupling you find

Minimum allowed coupling for each model*

$$\frac{(g_q g_{DM})^2}{M^2} = C$$

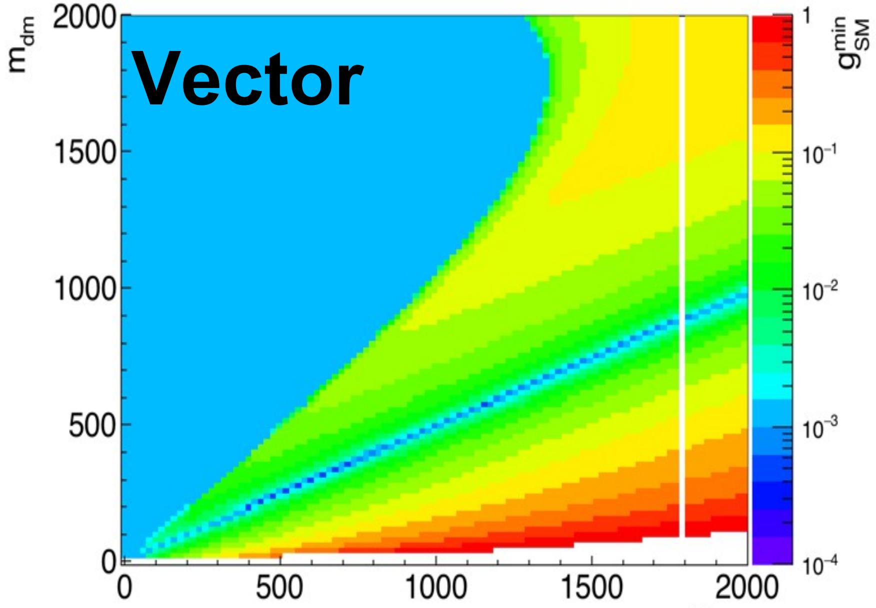
Fix to 1

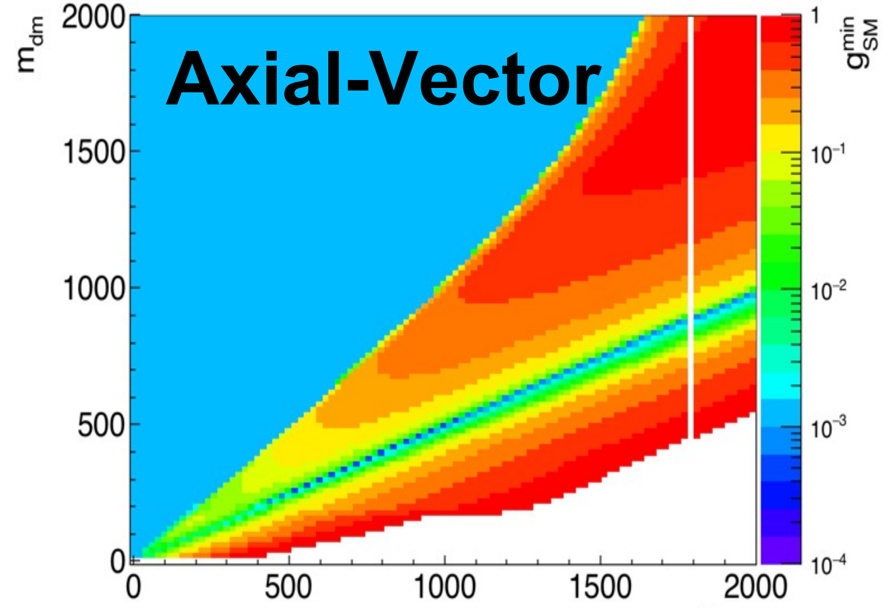
For fixed m_{DM}/M_{med}

Large couplings & Large masses or

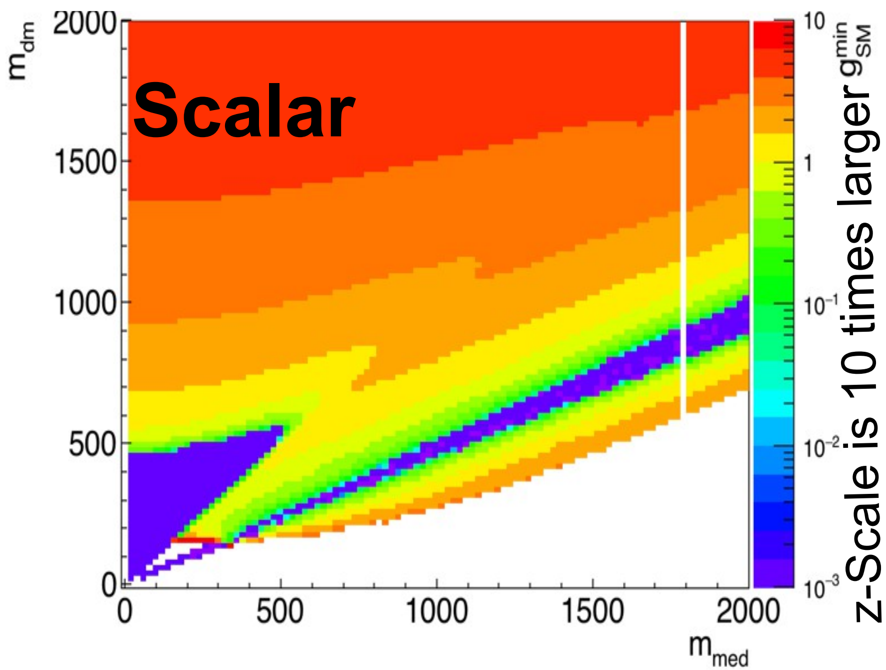
Small couplings & Small masses

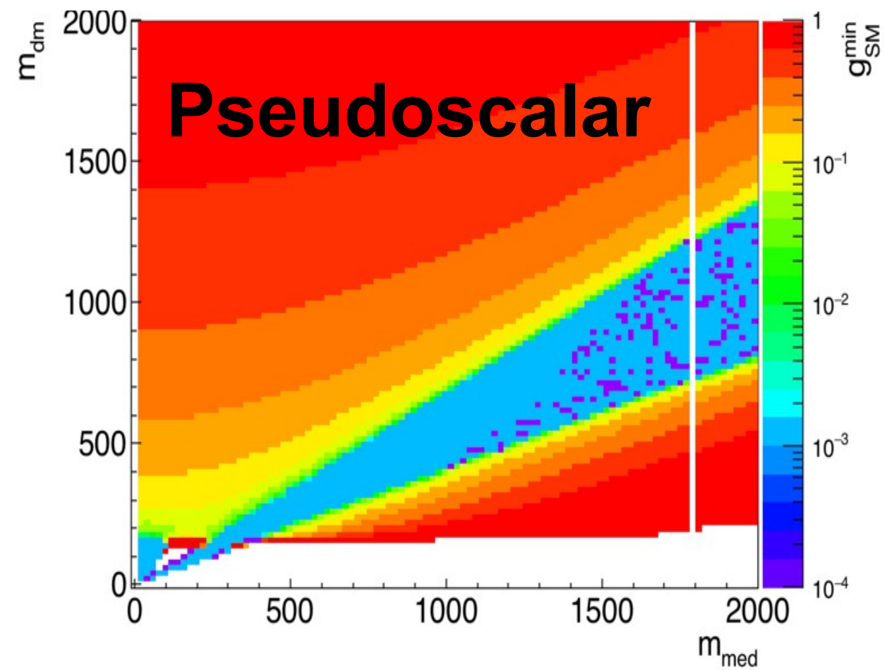
And the relic Density?





Minimum allowed coupling for each model



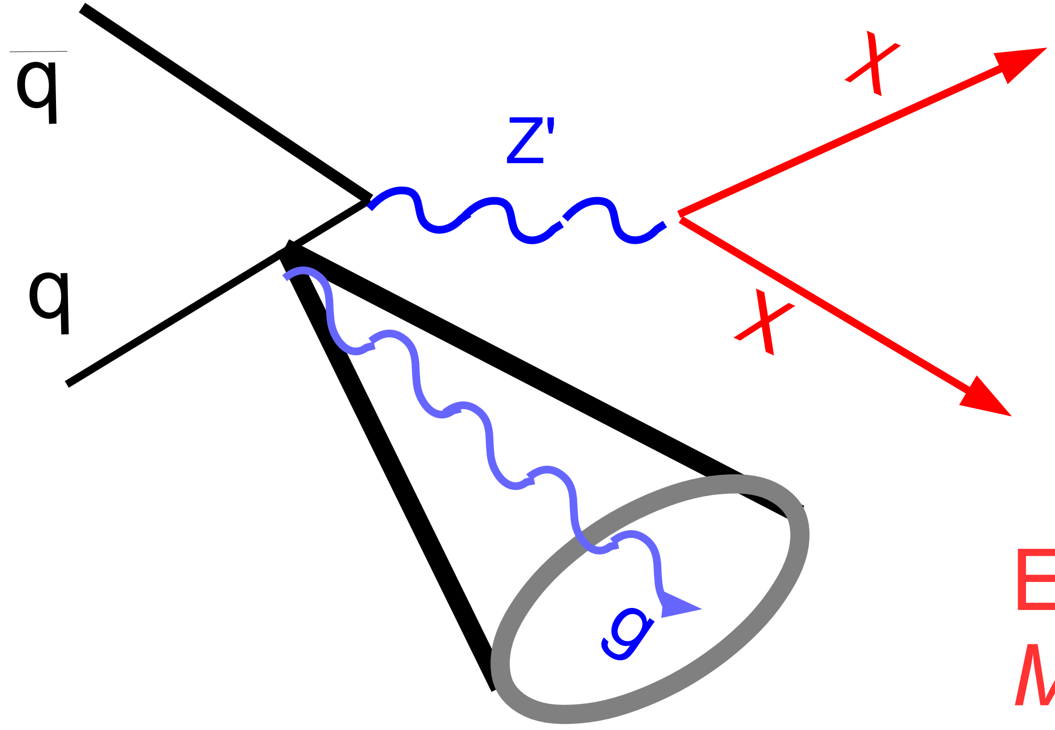


Summary

- Two benchmarks for collider searches
  - Reaching a minimum allowed coupling
    - Given the relic density
  - Covering/complementing phase space of:
    - Indirect detection
    - Direct detection

Understanding The Background

Searching for *MET*



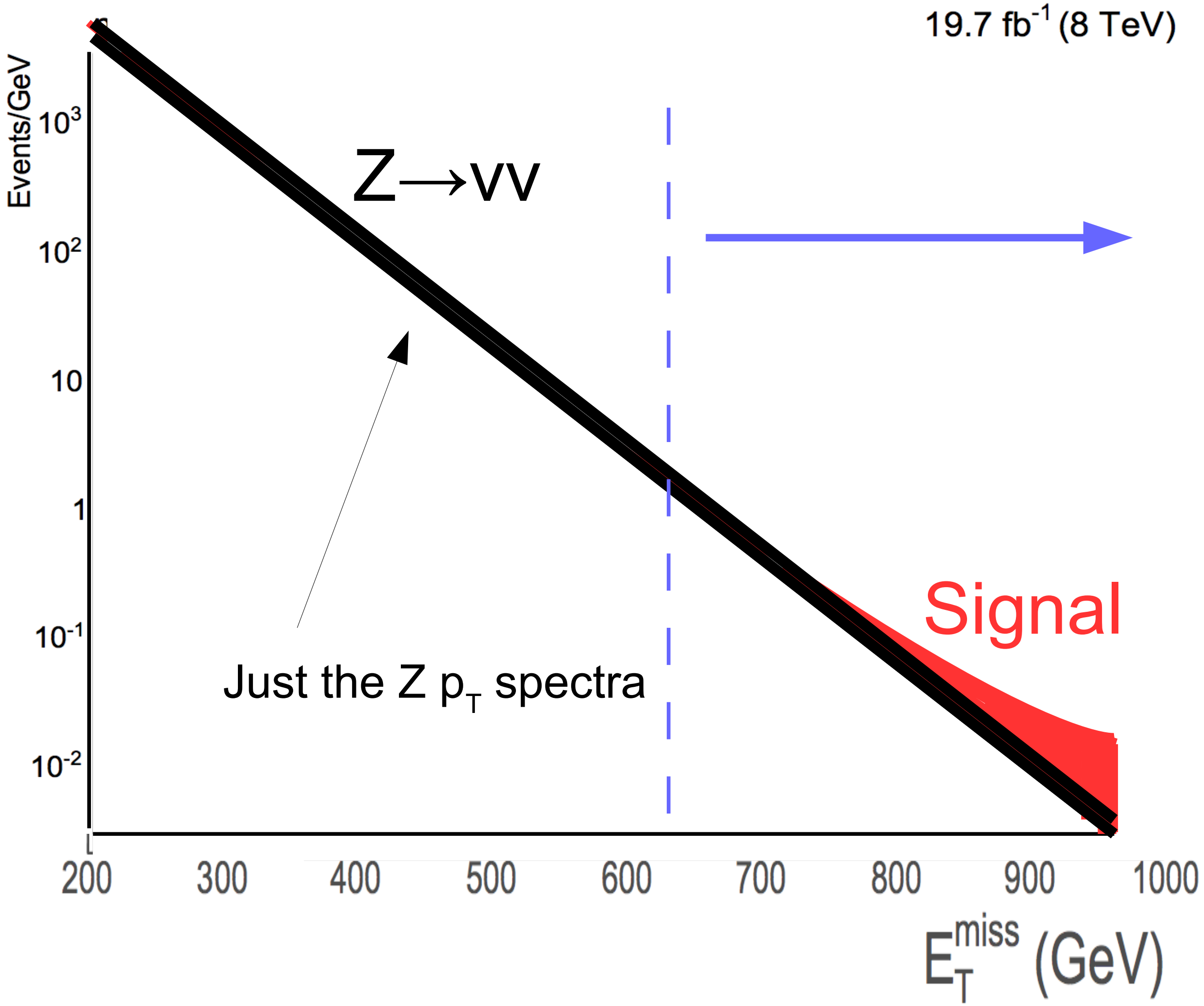
Escapes detector
MET

"To find nothing you have to reconstruct everything"[1]

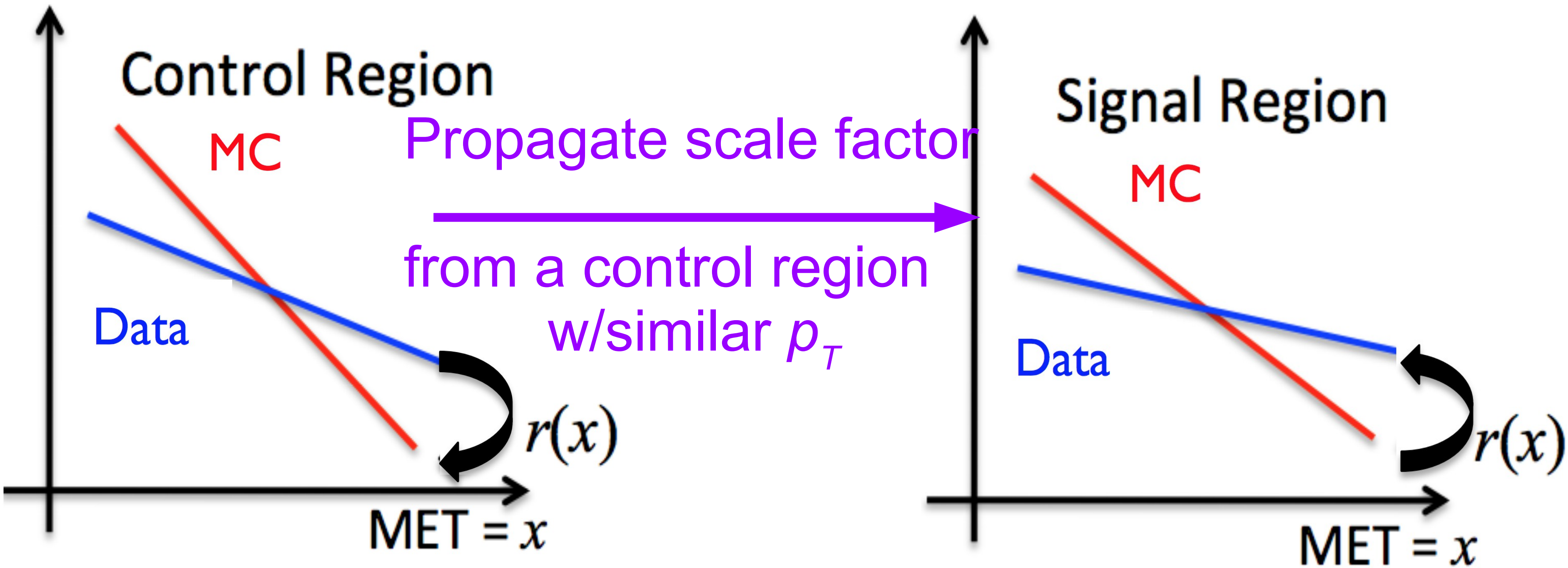
$$-\Sigma_{All\ particles}\ p_T = MET_{(E_T^{Miss})}$$

$$-\text{Boson}\ p_T = MET_{(E_T^{Miss})}$$

How do we search?



Strategy to fix agreement



Control: another decay of a Z boson

~~Z→μμ~~ → Z→νν

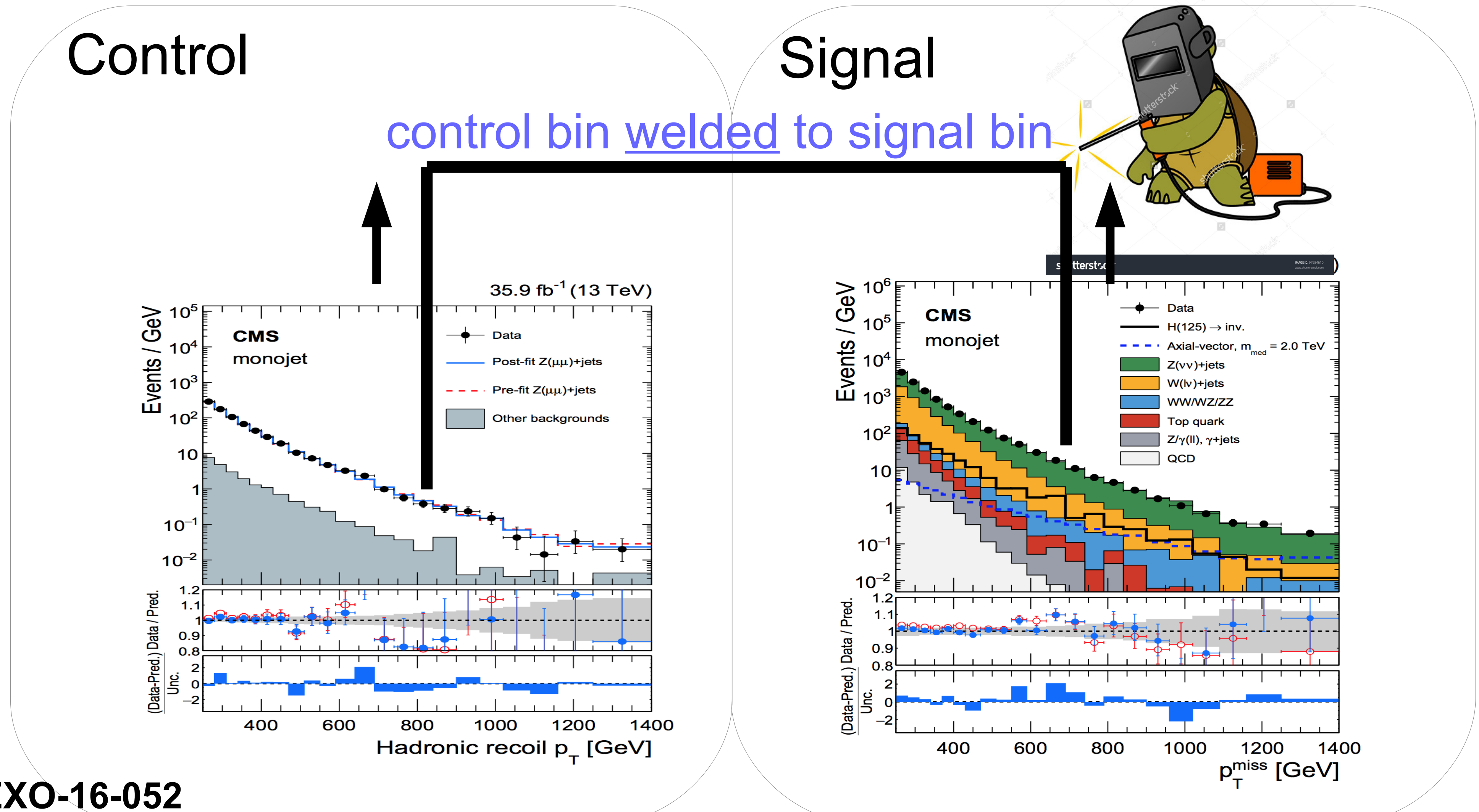
Remove

hadronic recoil : Transverse sum of all particles in event excluding leptons/photons

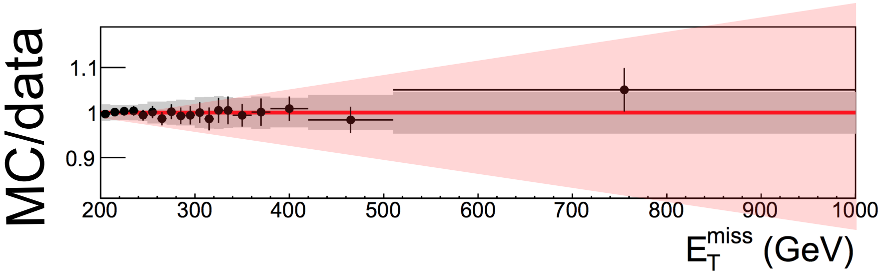
CMS-EXO-16-037
CMS-EXO-16-010
CMS-EXO-12-055

What is the transfer factor?

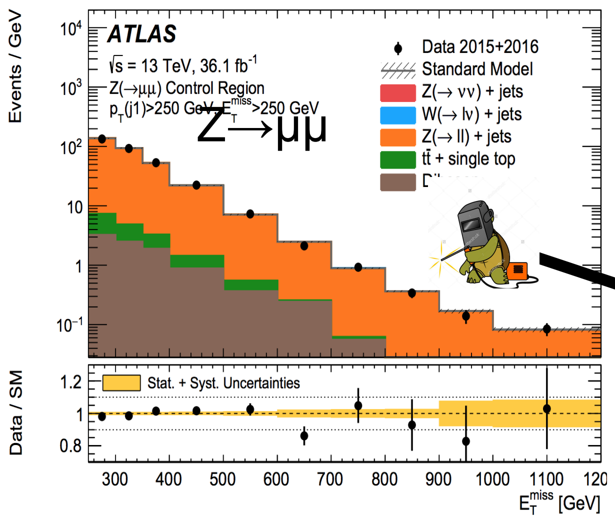
Propagate the data/MC agreement of the hadronic recoil
From a control region to a signal region

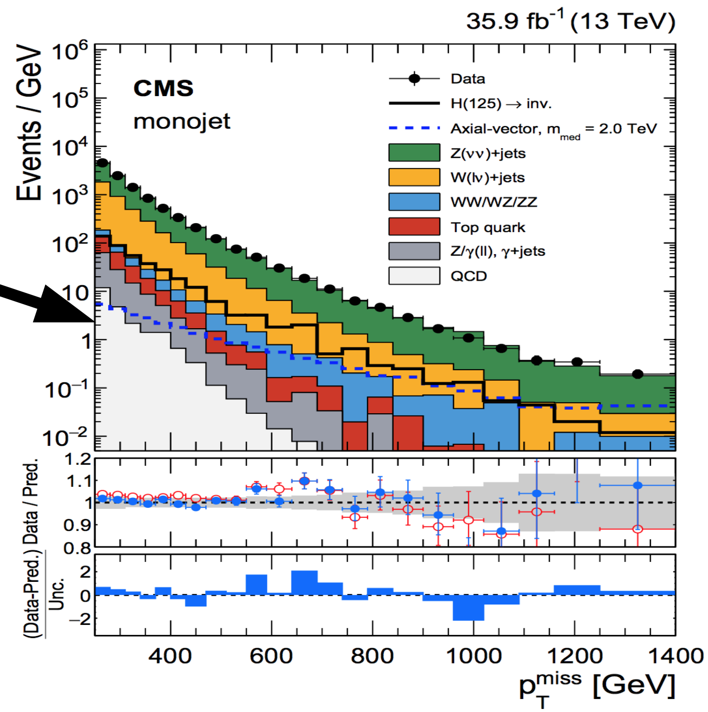


CMS-EXO-16-052



1 Control region
100% uncertainty @ 1 TeV





Control regions have less events than signal

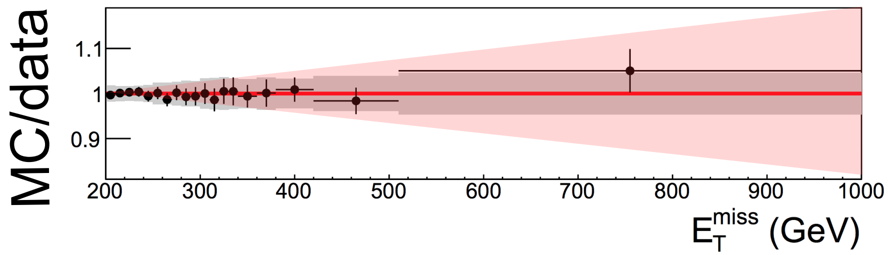
$\sigma_{\mu\mu} = 0.1\ \sigma_{\nu\nu}$

Statistical precision is 4x worse

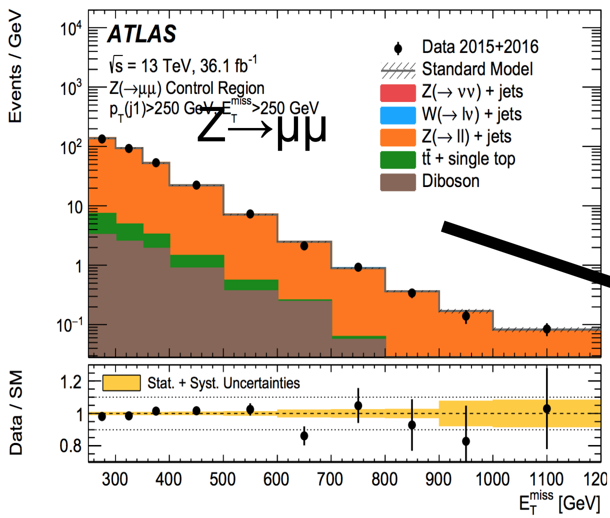
Not good enough!

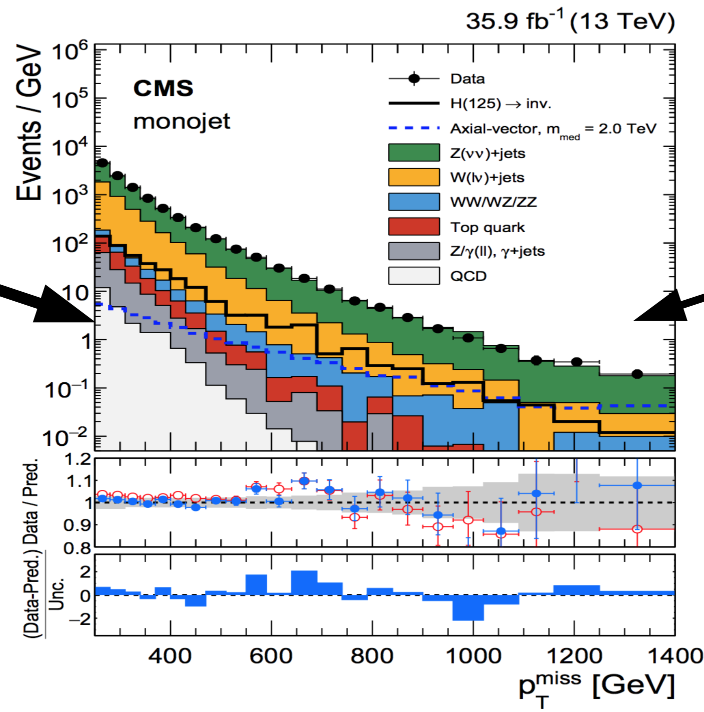
arXiv:1711.03301

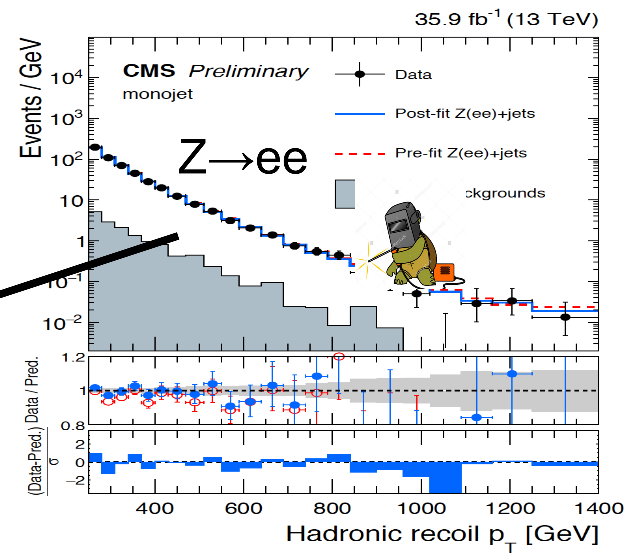
arXiv:1712.02345



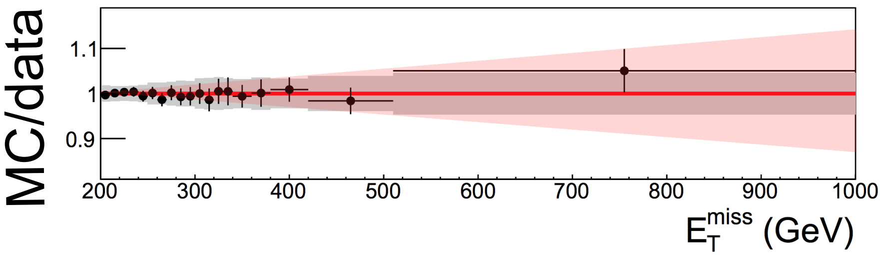
2 Control regions
60% uncertainty @ 1 TeV



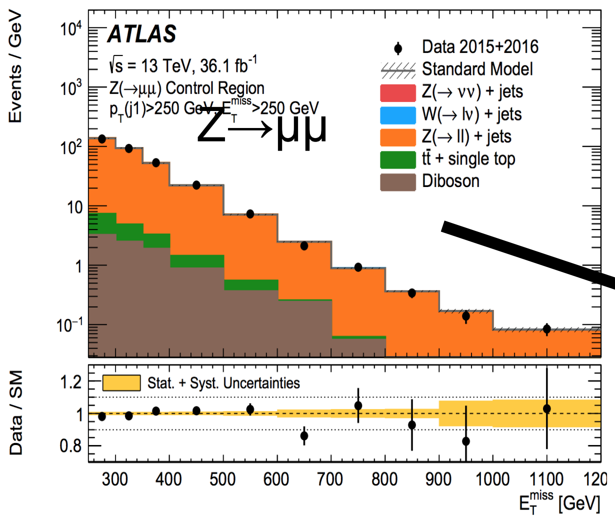


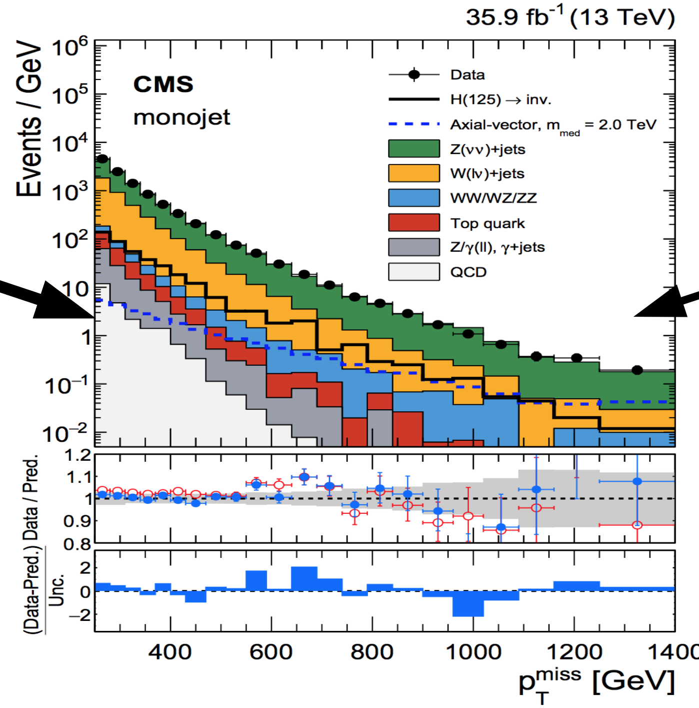


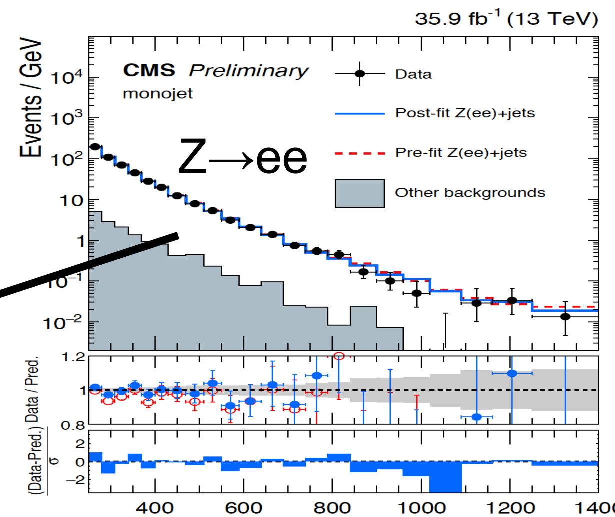
arXiv:1711.03301
arXiv:1712.02345

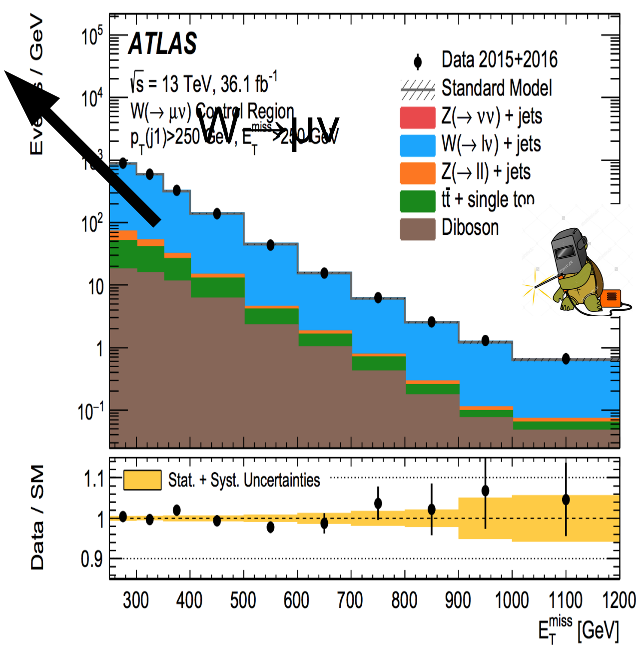


3 Control regions
40% uncertainty @ 1 TeV

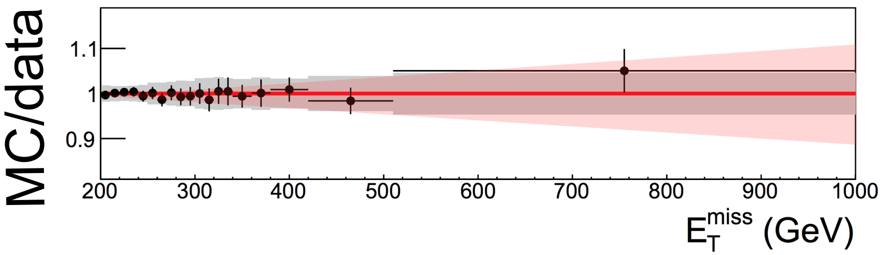




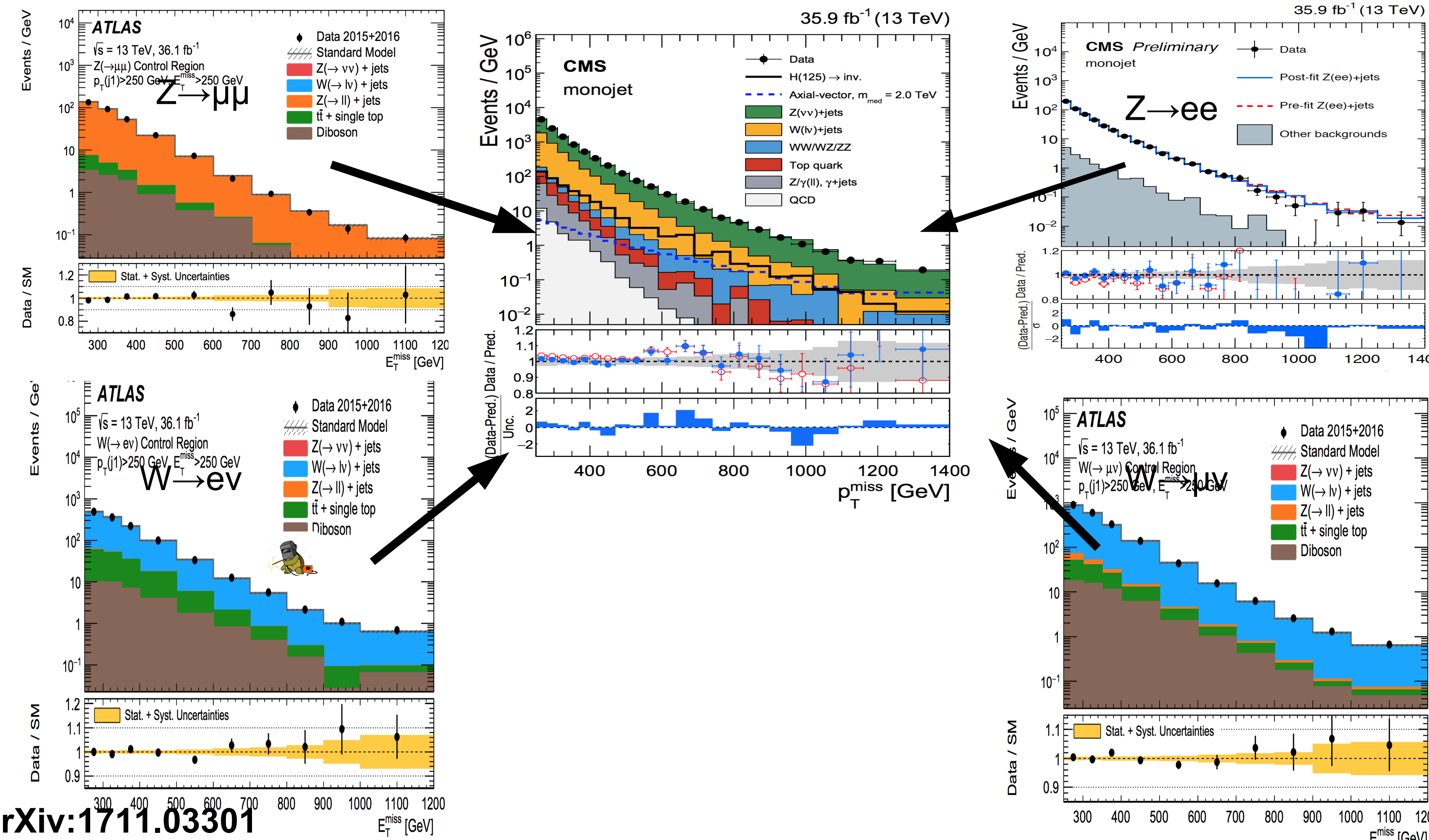




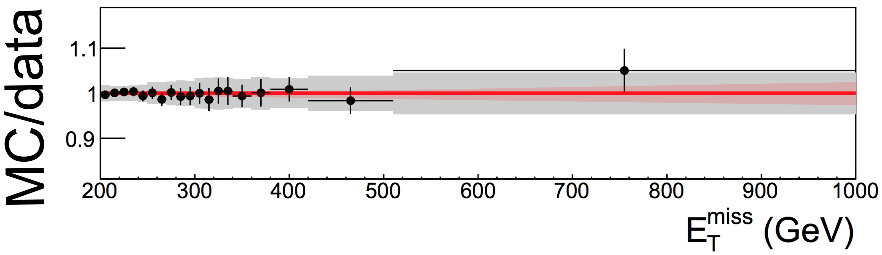
arXiv:1711.03301
arXiv:1712.02345



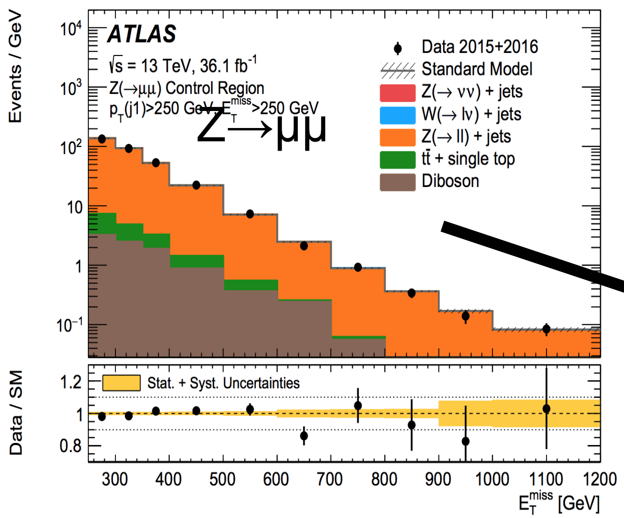
4 Control regions
30% uncertainty @ 1 TeV

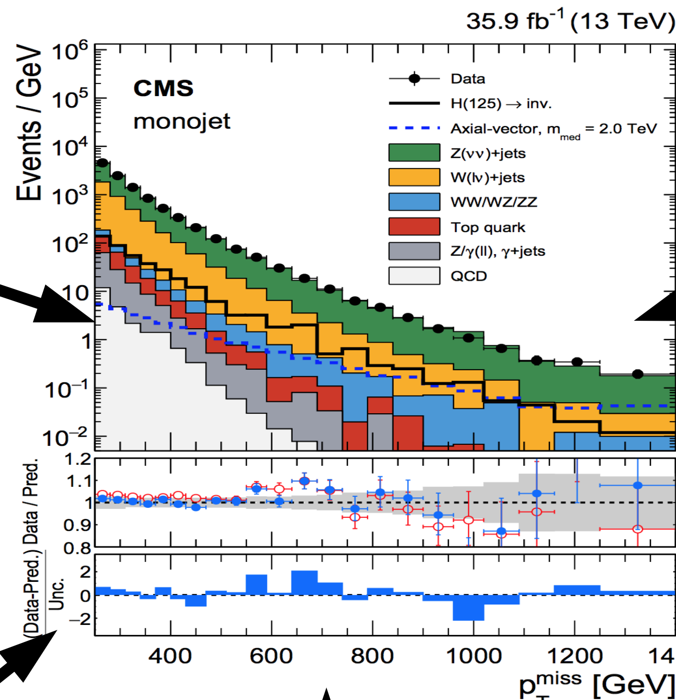


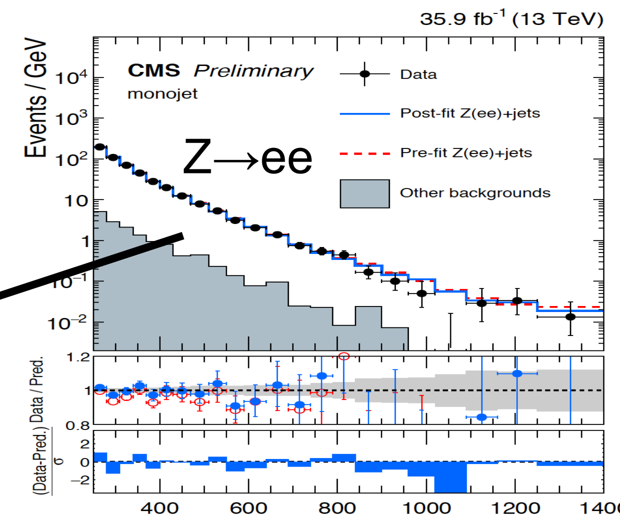
arXiv:1711.03301
arXiv:1712.02345

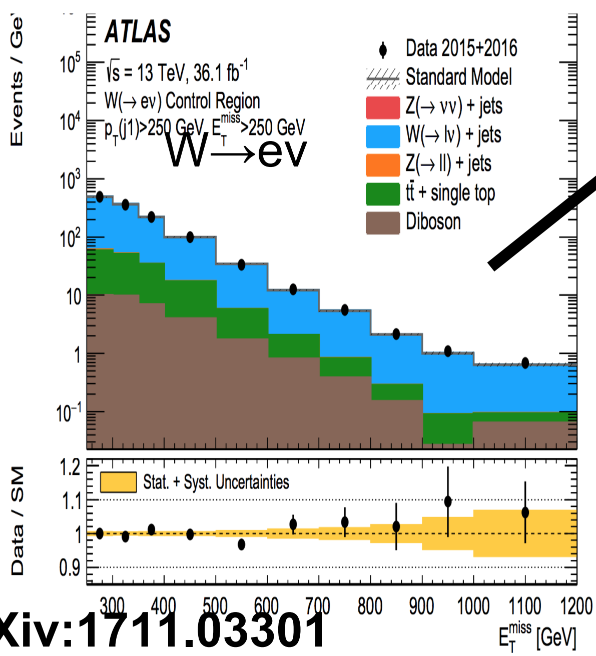


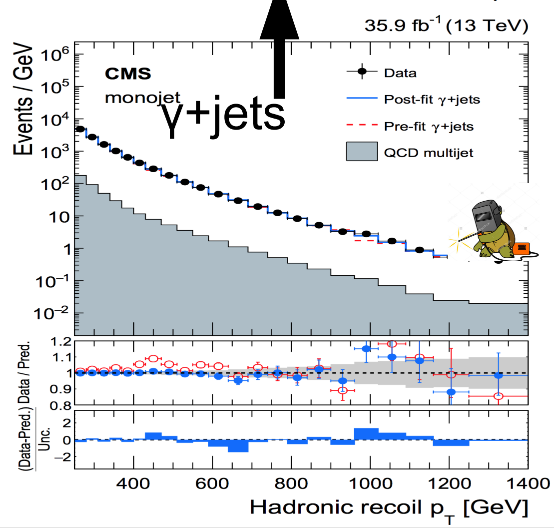
5 Control regions
15% uncertainty @ 1 TeV

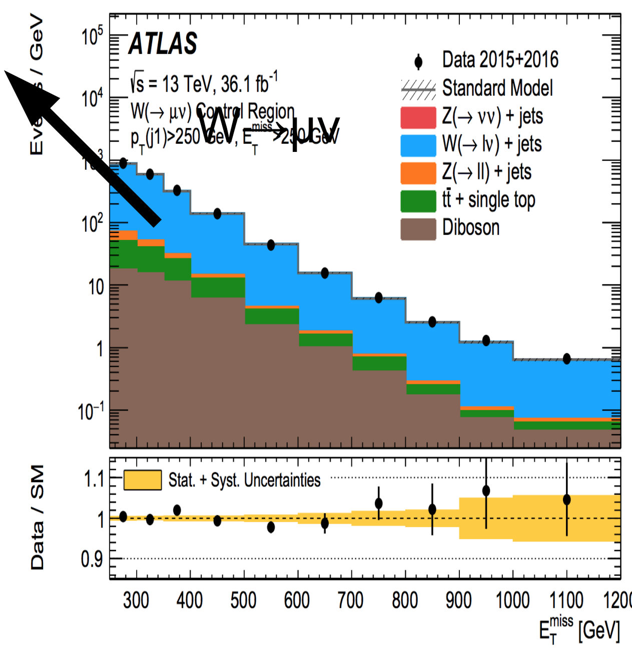












arXiv:1711.03301
arXiv:1712.02345

However we still have a problem!

Going from γ or W → Z

Unc. → $\dfrac{d\sigma^{\gamma(W)}}{dp_T} \Big/ \dfrac{d\sigma^{Z}}{dp_T}$

Need to know the uncertainty on the ratios
@NNLO QCD @NLO EWK
This is not a light statement!

However we still have a problem!

Going from γ or W $\rightarrow$ Z

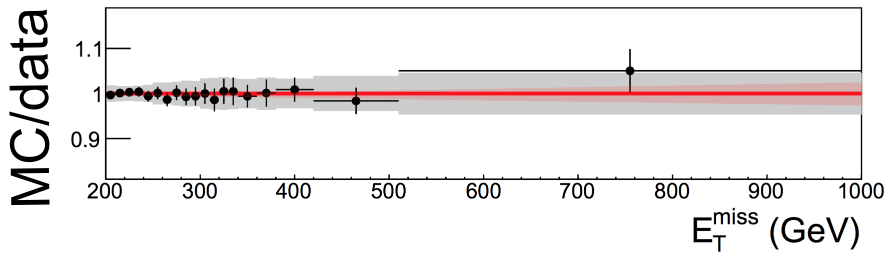
Unc. $\longrightarrow$ $\dfrac{d\sigma^{\gamma(W)}}{dp_T} \Big/ \dfrac{d\sigma^{Z}}{dp_T}$

Need to know the uncertainty on the ratios
@NNLO QCD @NLO EWK
This is not a light statement

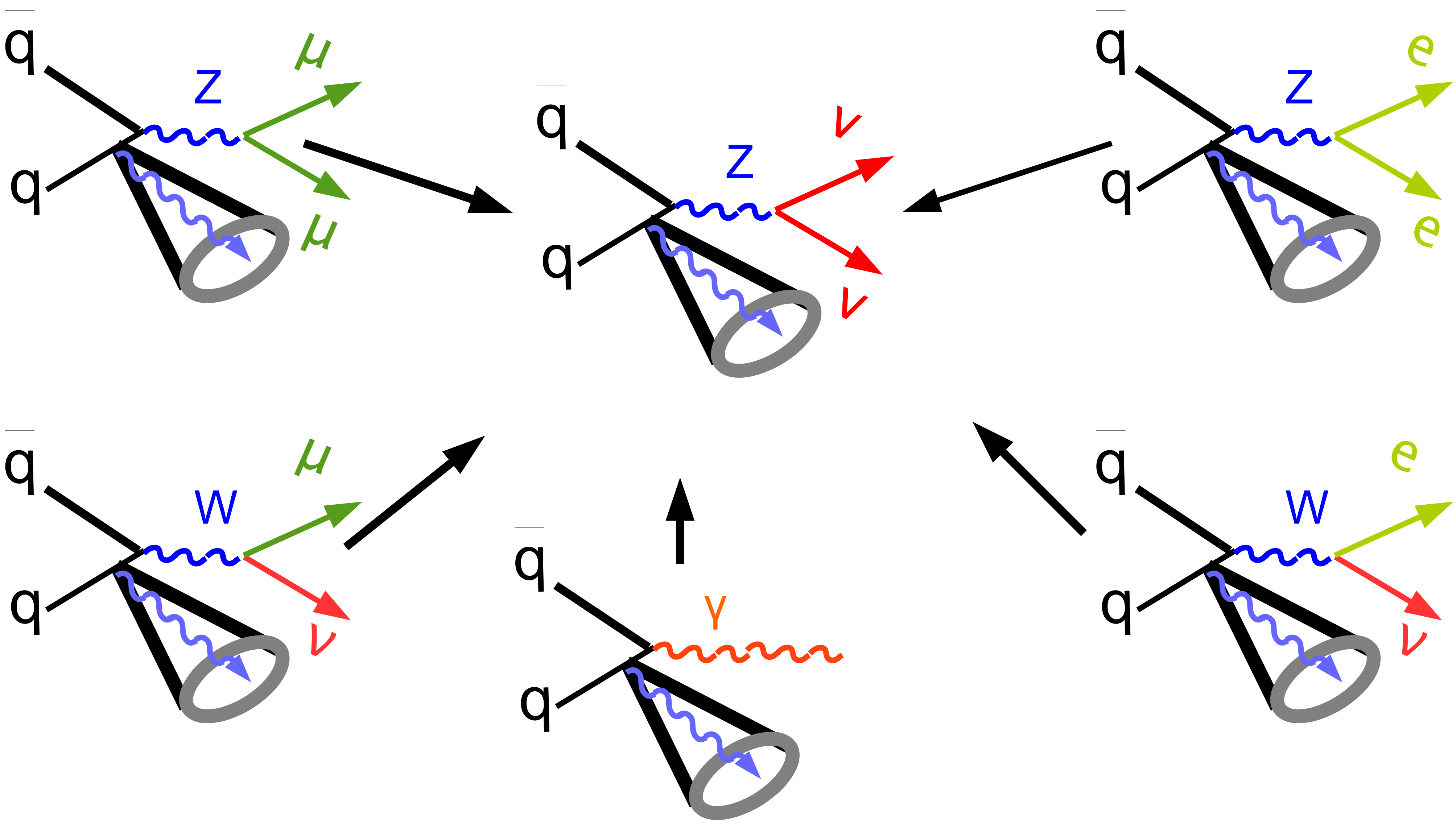
Arxiv:1705.04664

Precise predictions for V+jets dark matter backgrounds

J. M. Lindert[1], S. Pozzorini[2], R. Boughezal[3], J. M. Campbell[4], A. Denner[5], S. Dittmaier[6], A. Gehrmann-De Ridder[2,7], T. Gehrmann[2], N. Glover[1], A. Huss[7], S. Kallweit[8], P. Maierhöfer[6], M. L. Mangano[8], T.A. Morgan[1], A. Mück[9], F. Petriello[3,10], G. P. Salam*[8], M. Schönherr[2], and C. Williams[11]



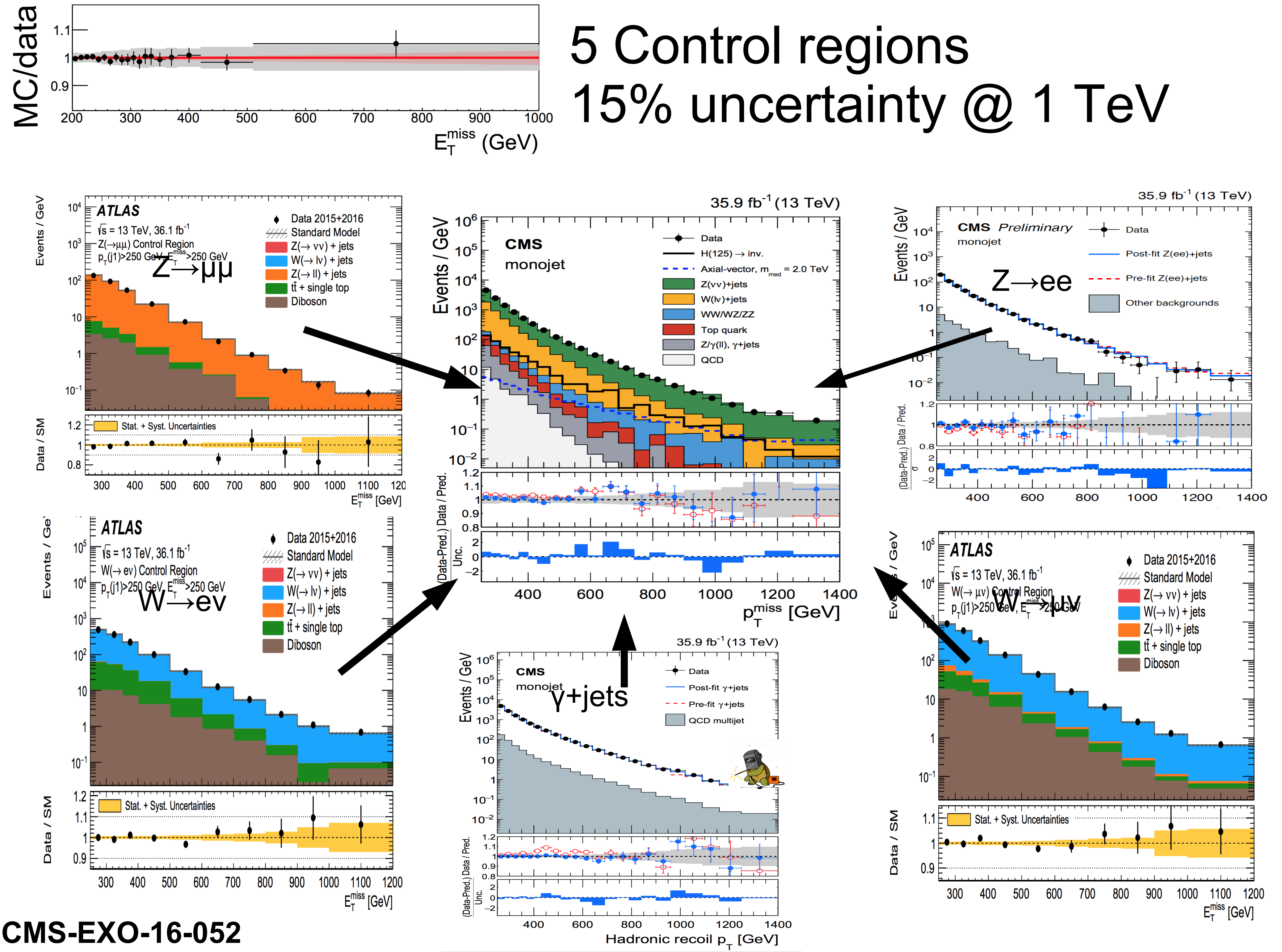
5 Control regions
15% uncertainty @ 1 TeV



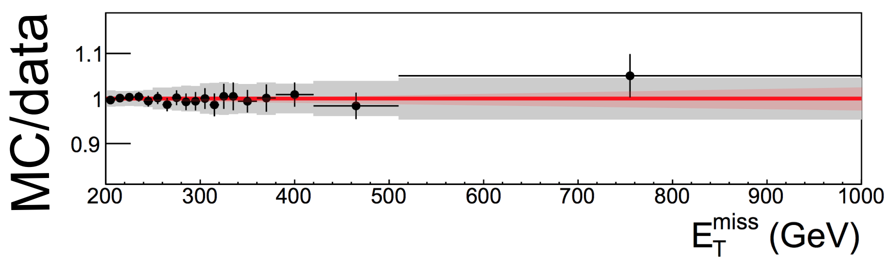
CMS-EXO-16-052

CMS-EXO-16-052

5 Control regions
15% uncertainty @ 1 TeV



CMS-EXO-16-052



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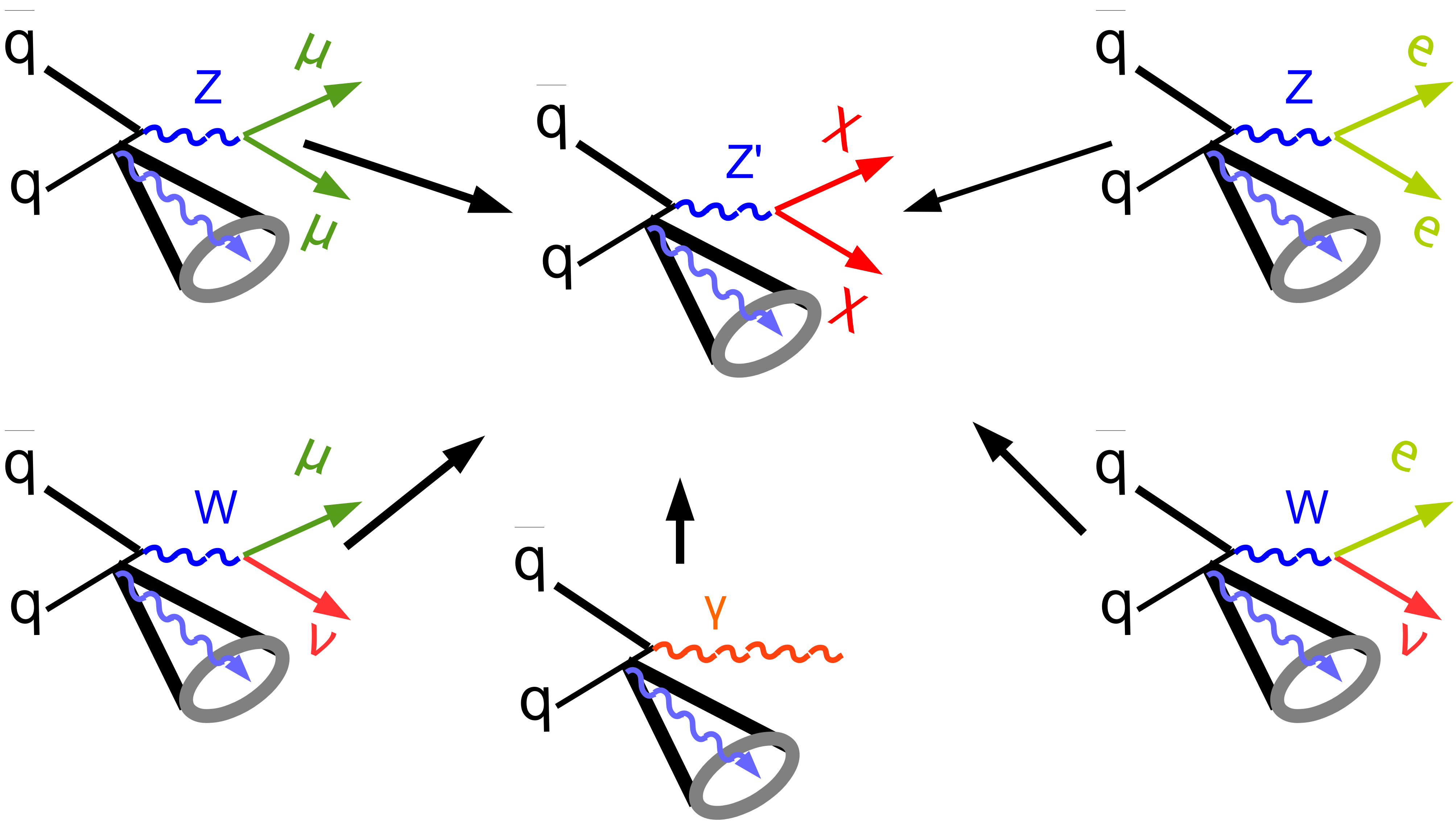
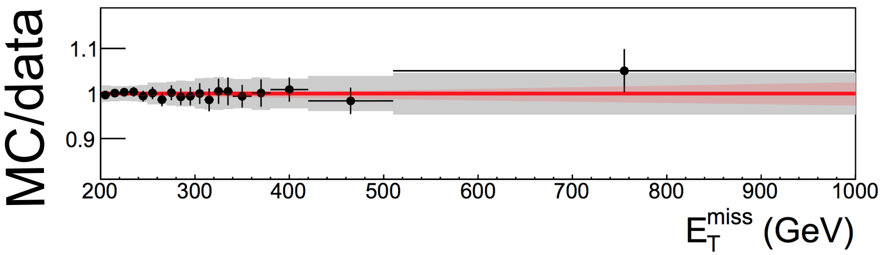


CMS-EXO-16-052

CMS-EXO-16-052



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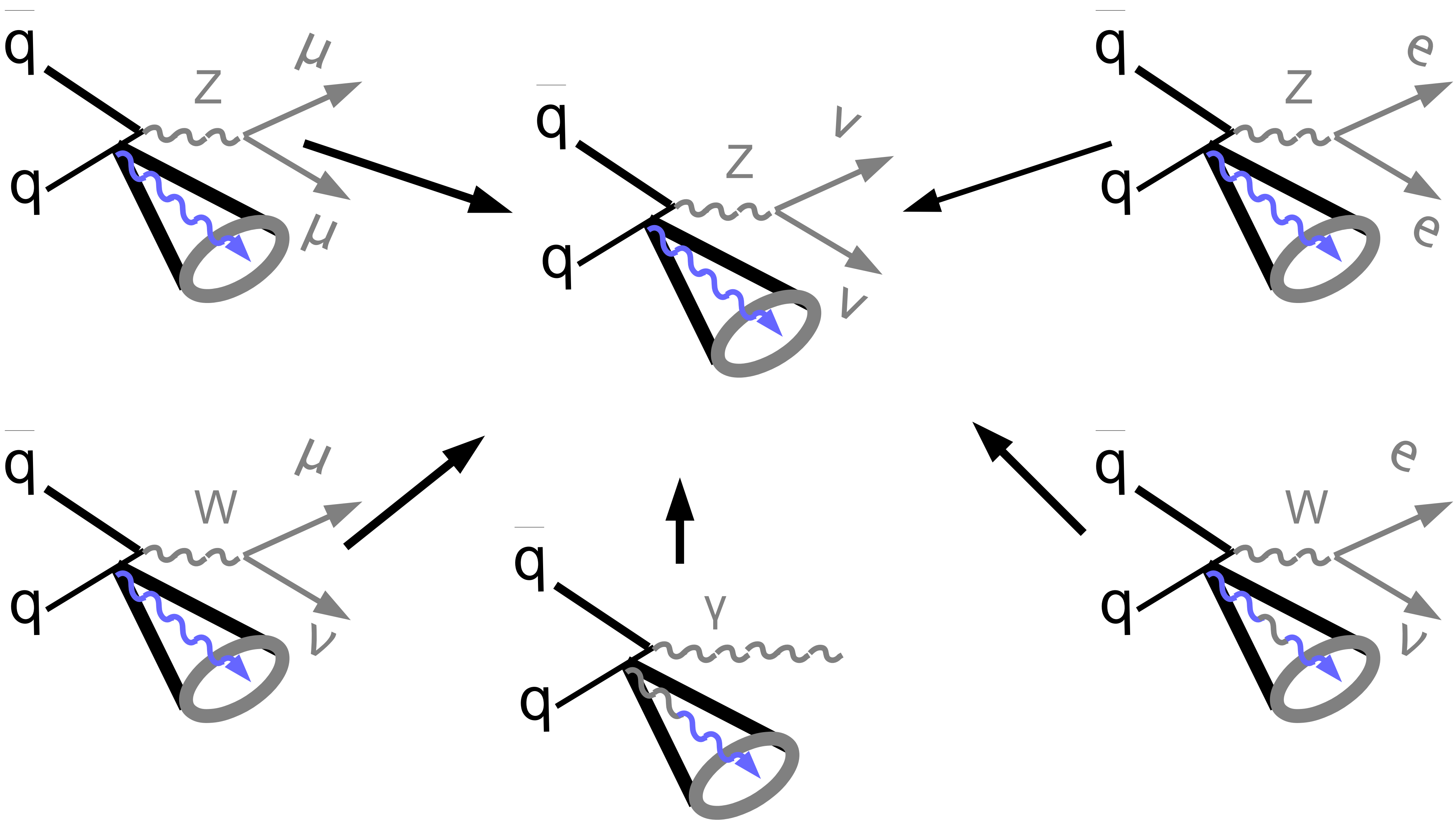
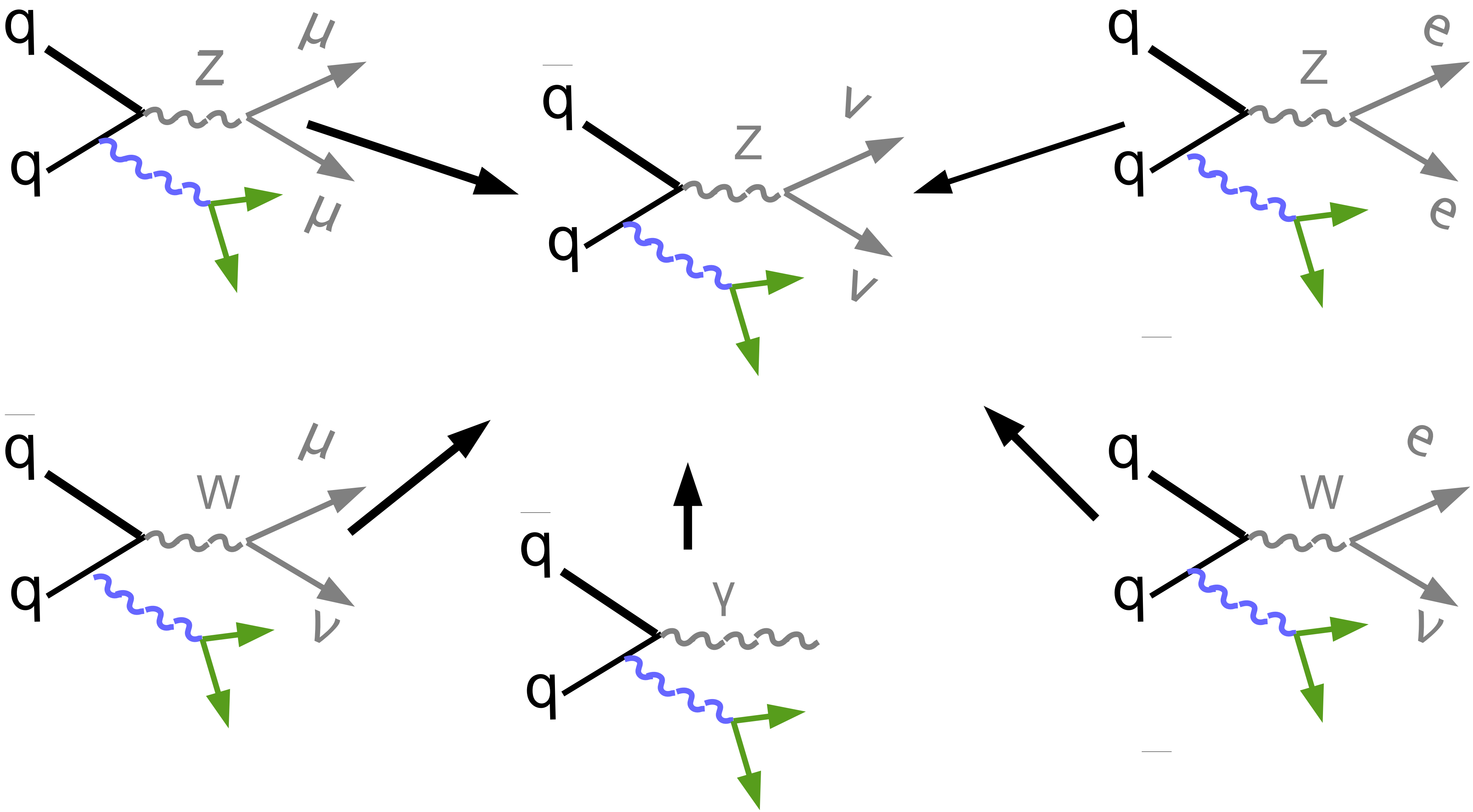


CMS-EXO-16-052

CMS-EXO-16-052

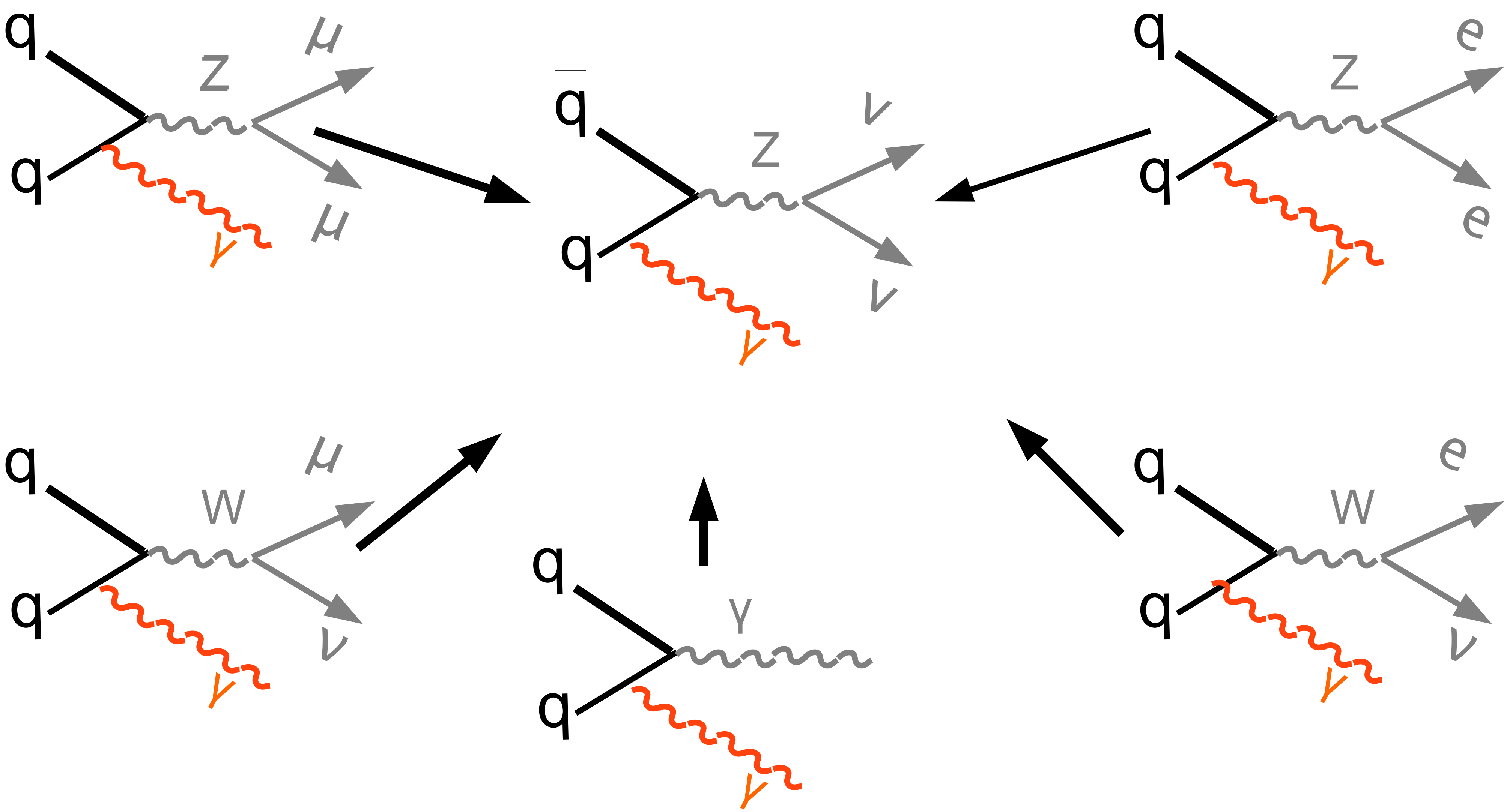
MC/data

Approach to background can be used on different ISR types



MC/data

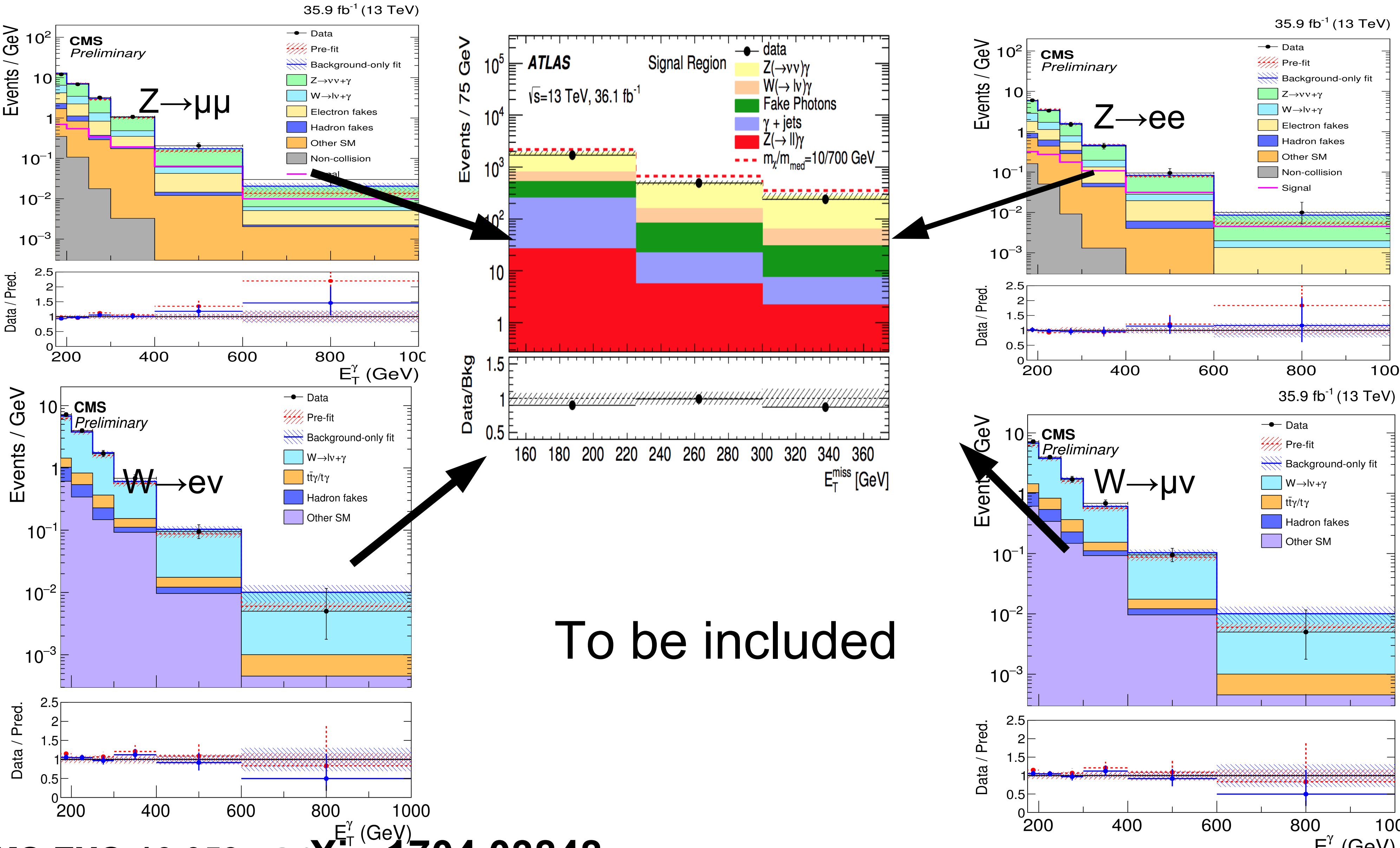
Some complications with the production process



CMS-EXO-16-053

MC/data

Fits in Monophoton Final State

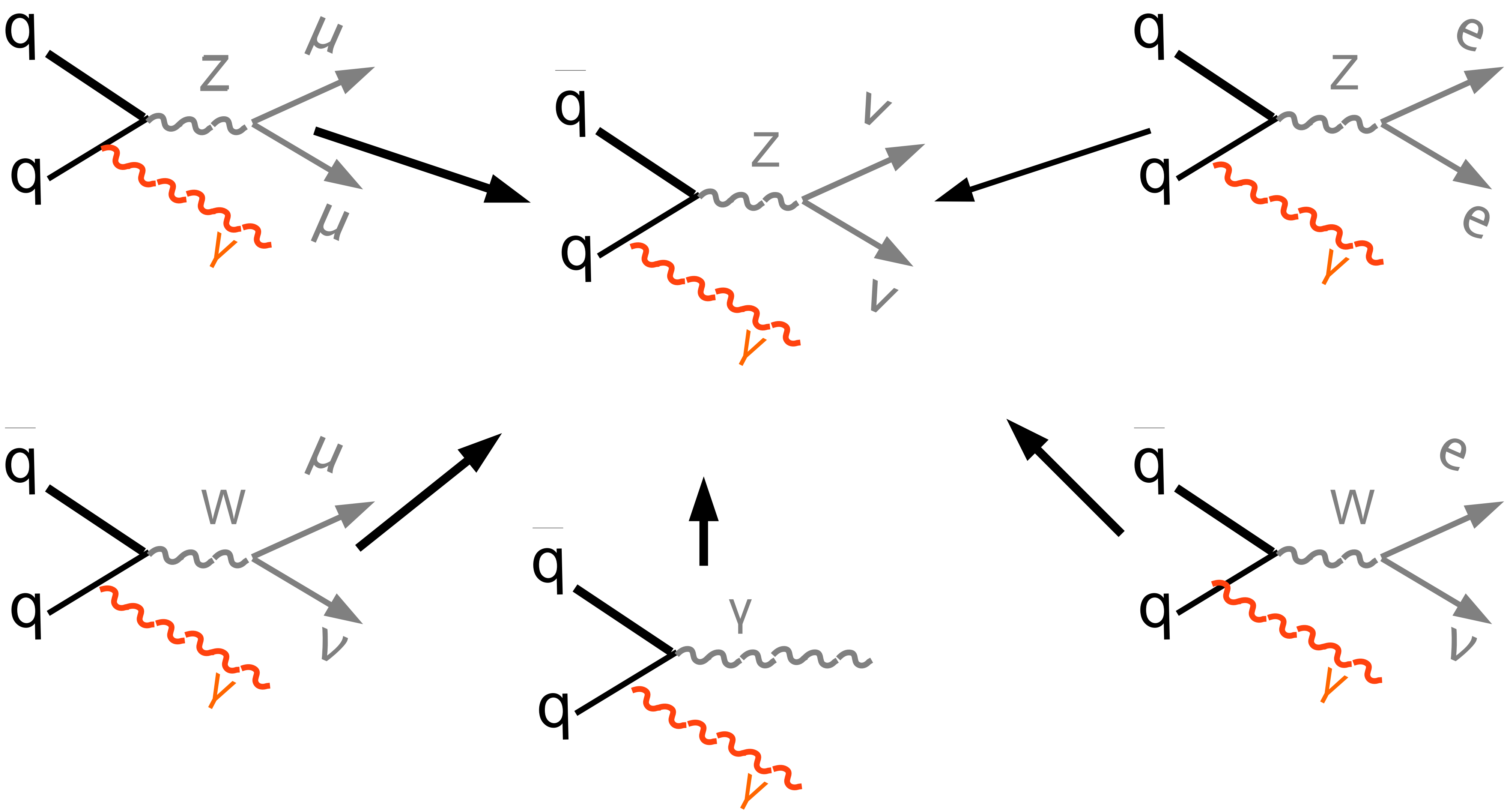


To be included

CMS-EXO-16-053 arXiv:1704.03848

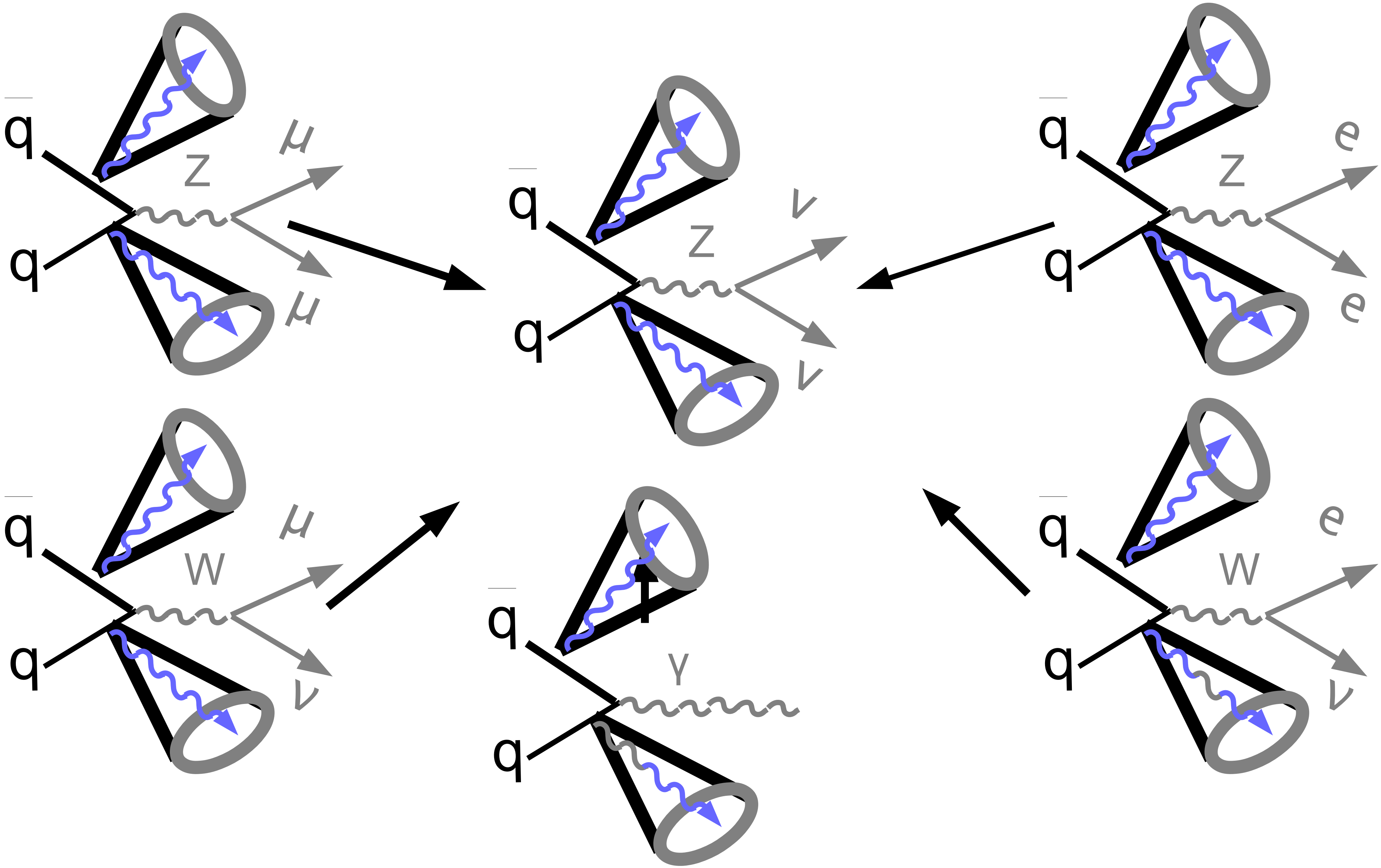
MC/data

Can we generalize to all final states?



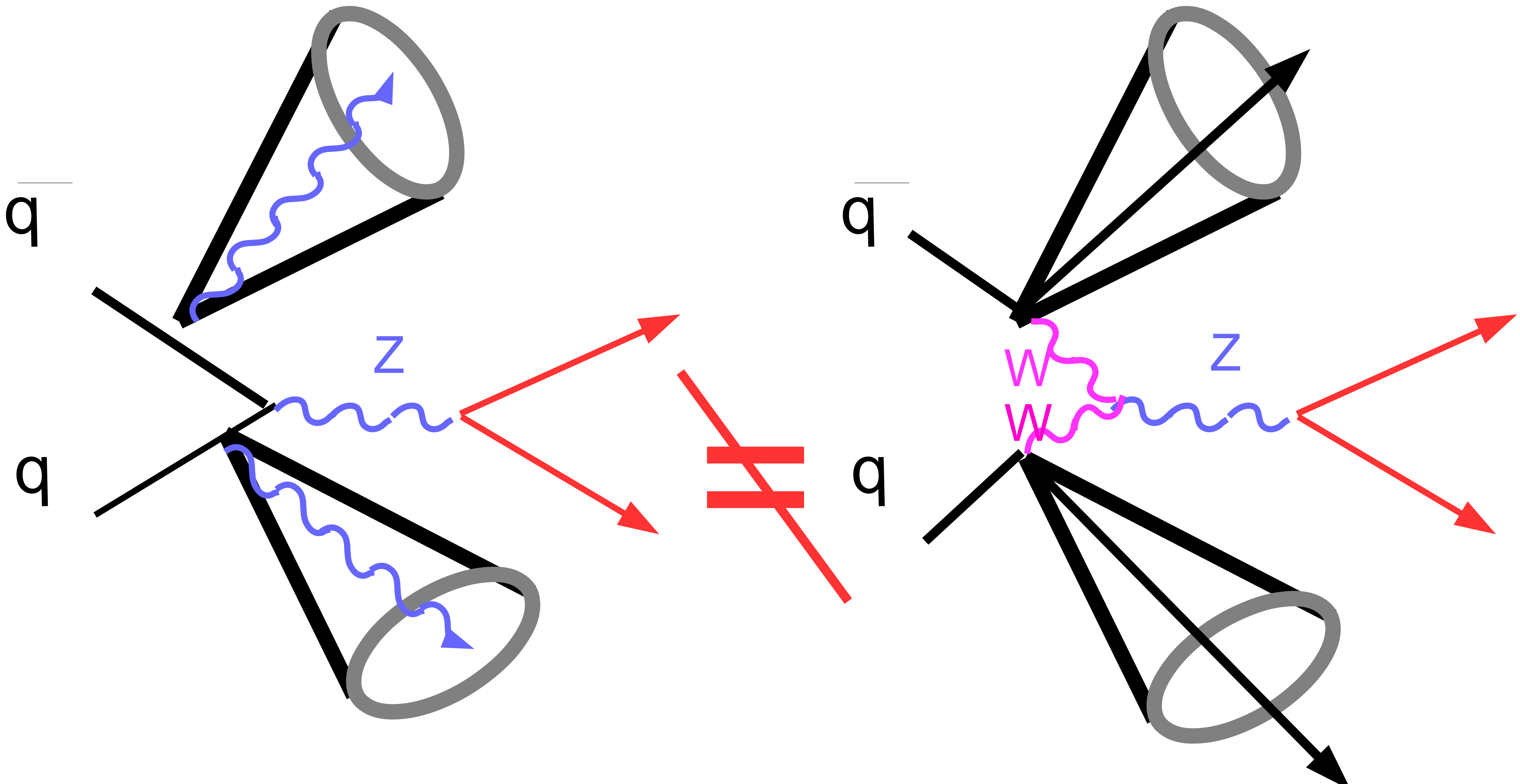
CMS-EXO-16-053

Consider modeling the two jet final state?



CMS-EXO-16-052

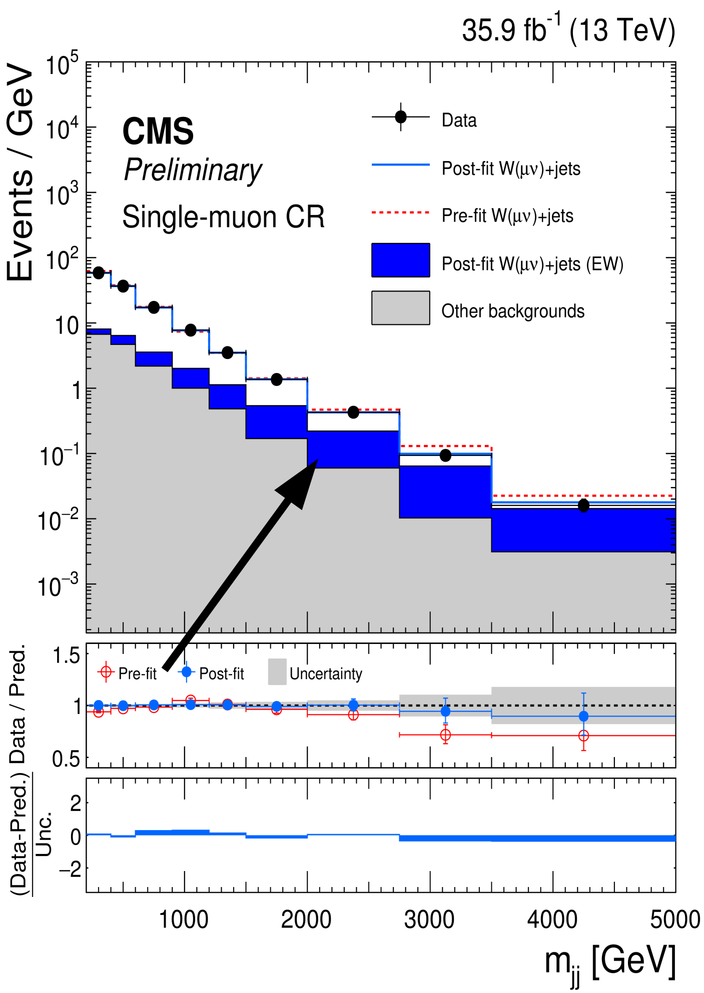
Complications of ISR production

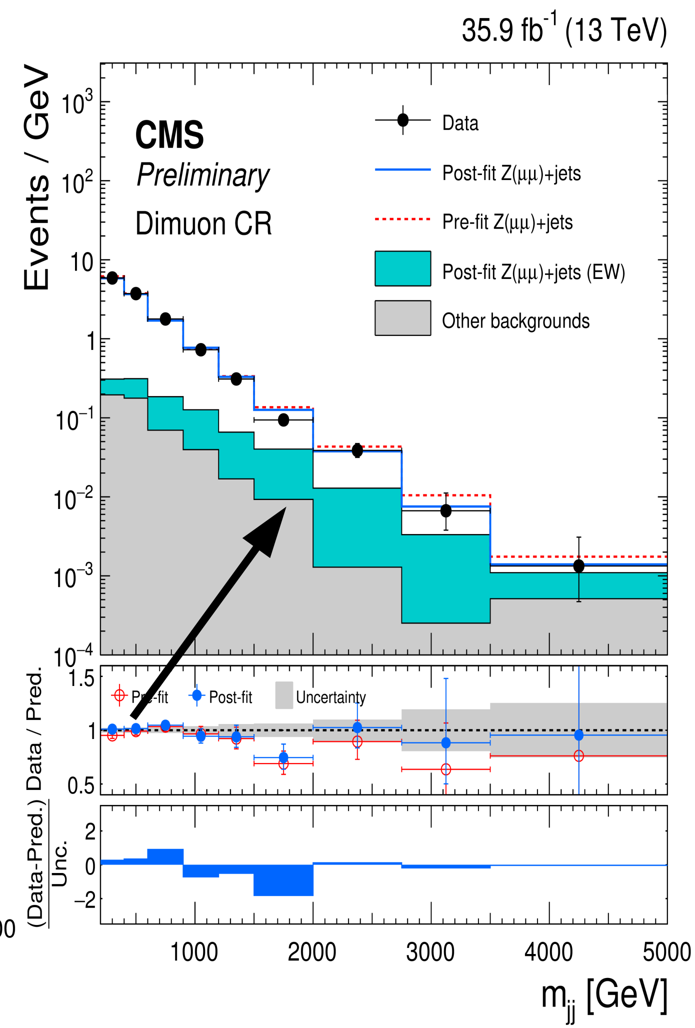


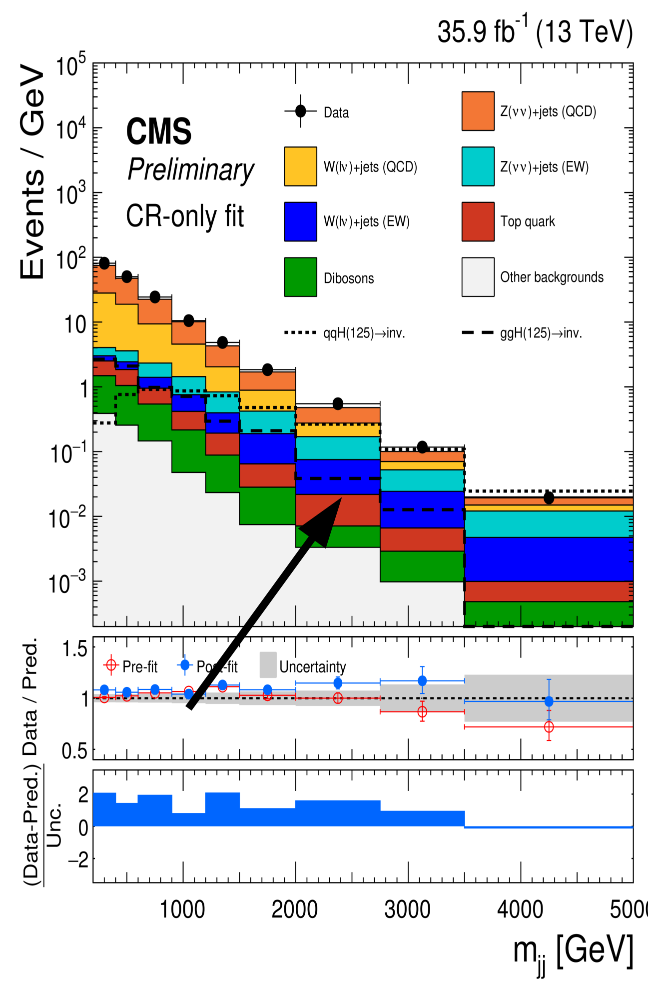
- As we increase the complexity of the topology
  - There is need to resolve addition production issues
  - Often these require dedicated studies of production

Understanding Electroweak production

- A key element to VBF+invisible search
  - Understanding Z production induced form EWK bosons



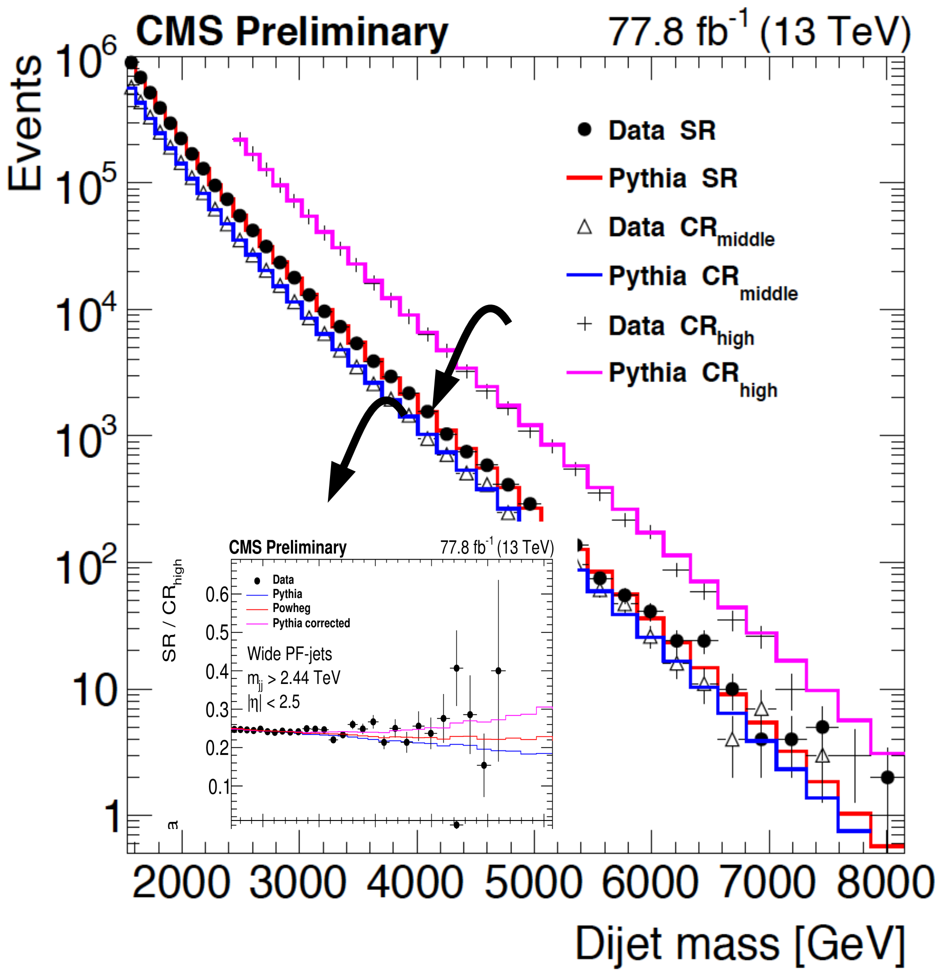


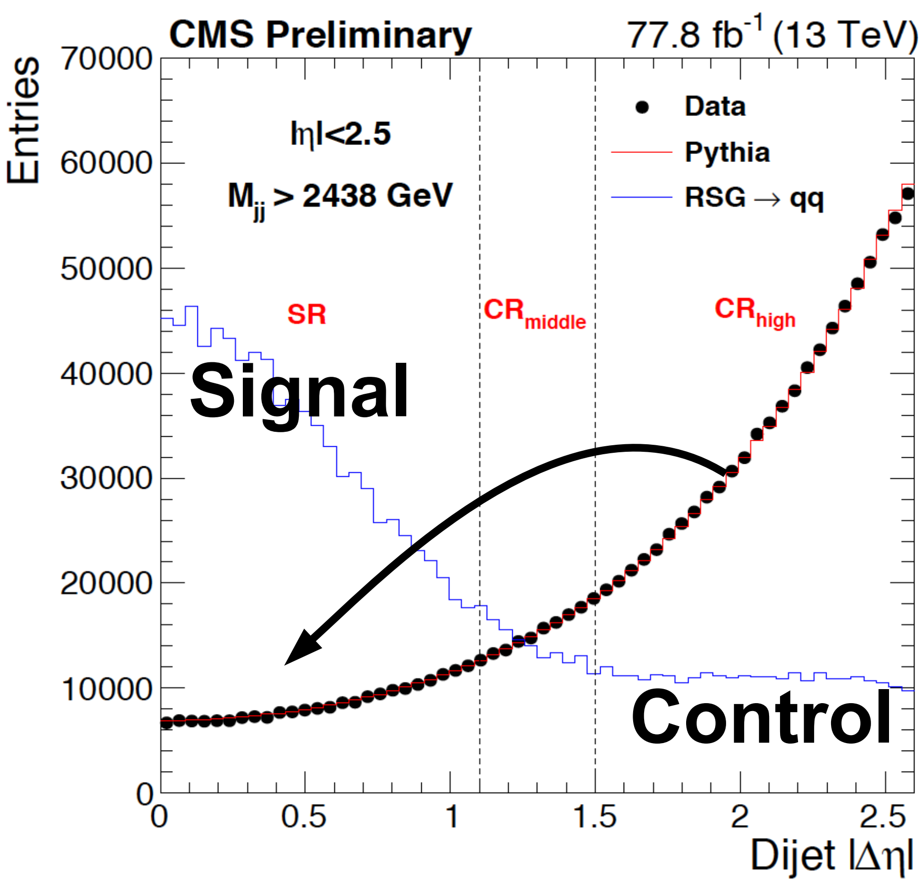


arXiv:1809.05937

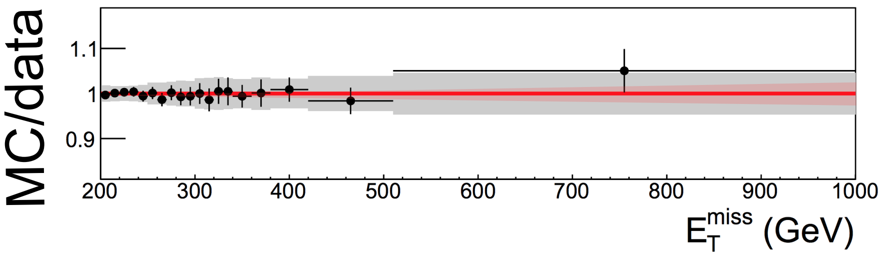
Template methods other approaches

- Bump hunts are starting to be replaced
  - Control region propagation more robust that template

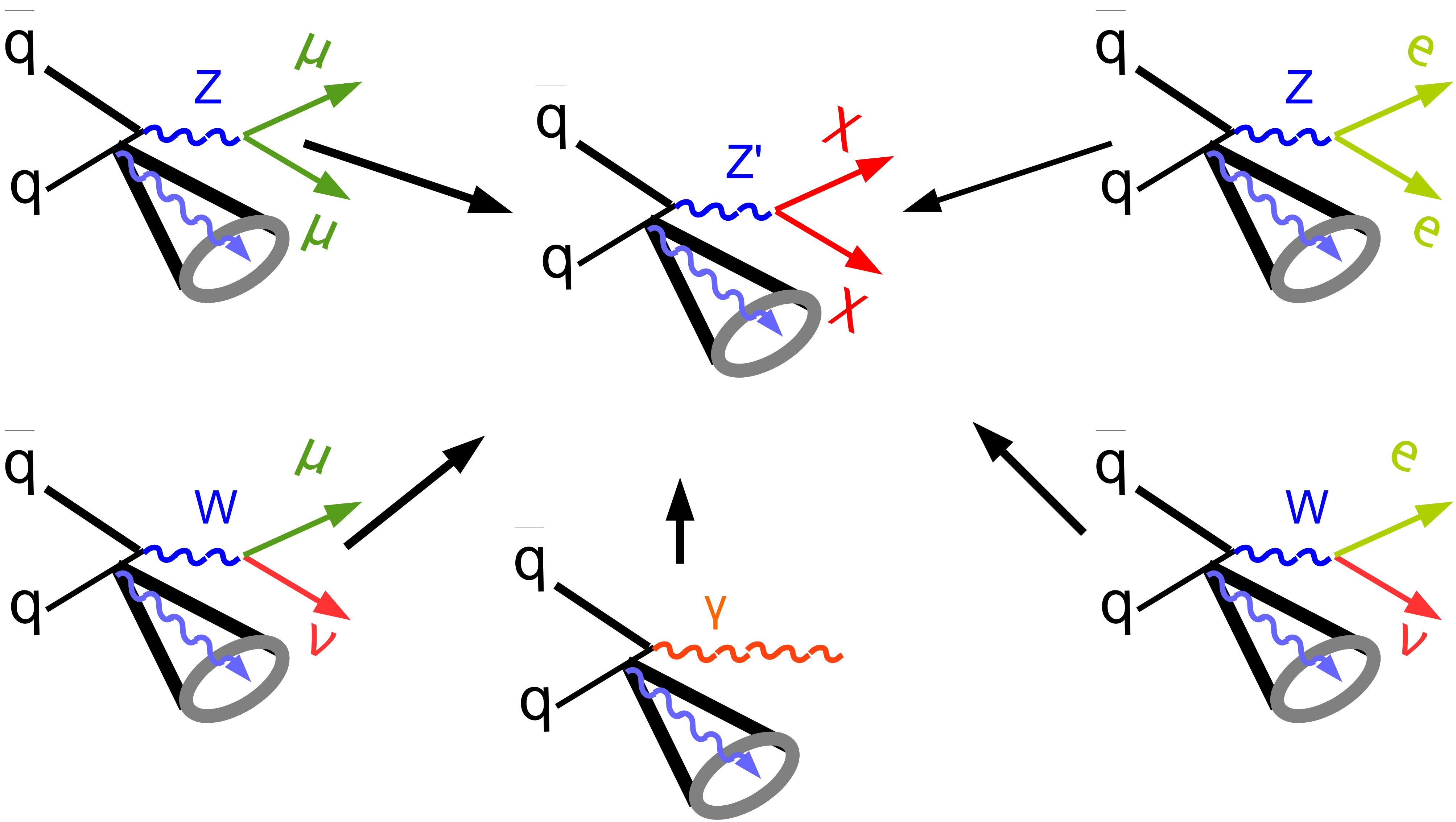




CMS-EXO-17-026

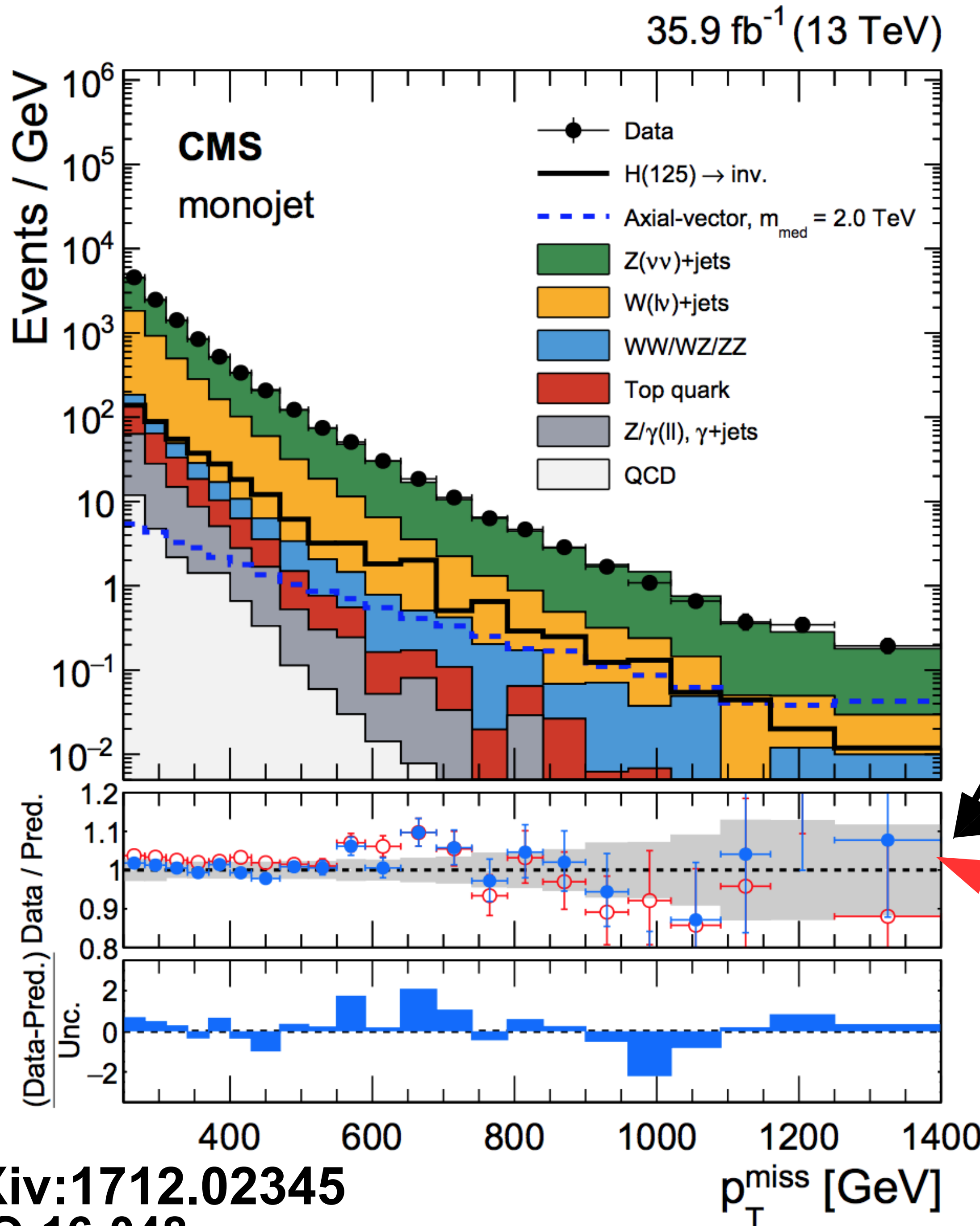


5 Control regions
15% uncertainty @ 1 TeV



CMS-EXO-16-052

Current Monojet Sensitivity



Uncertainty Now at 1% level

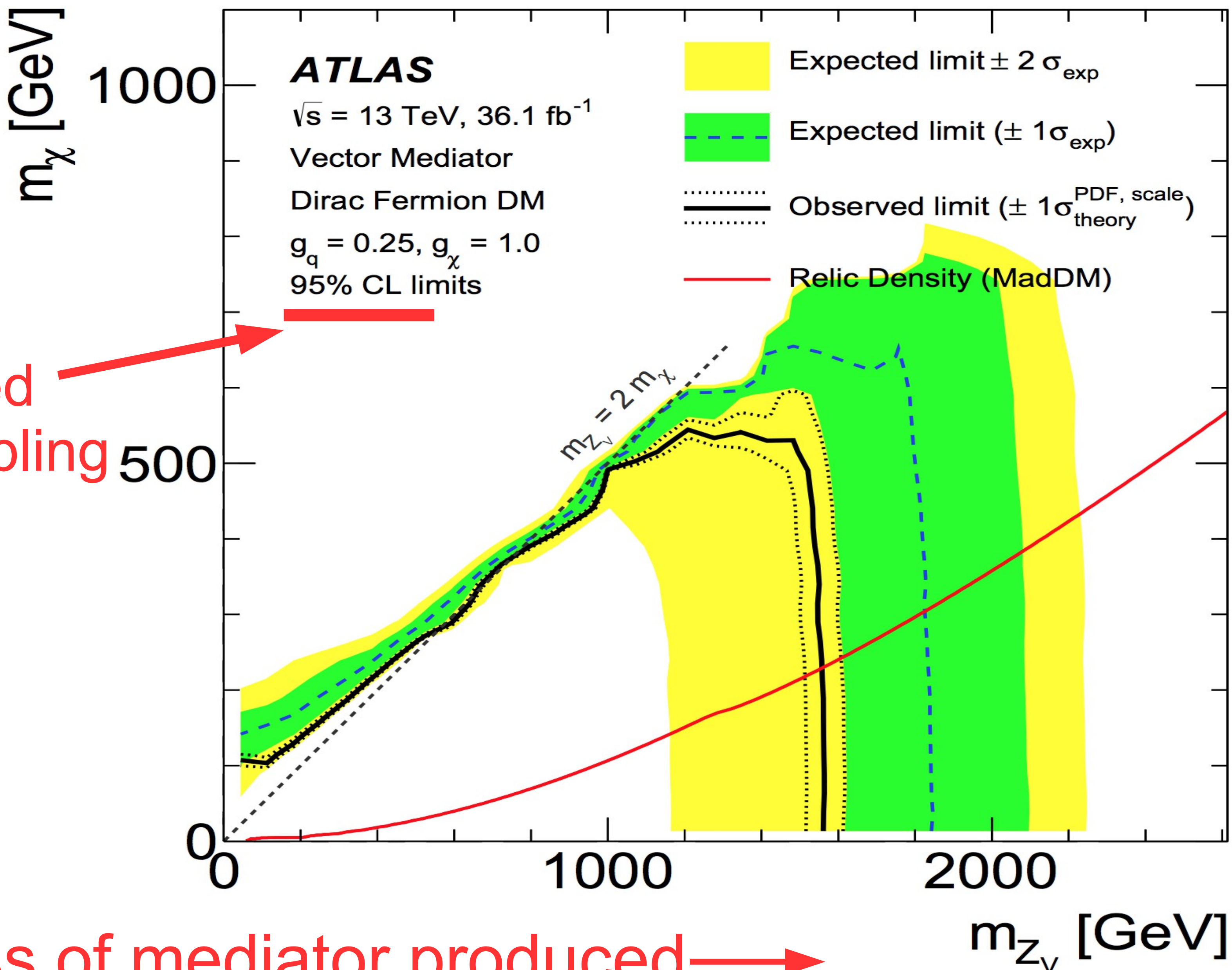
No excess

Almost no systematic wall

arXiv:1712.02345
EXO-16-048

Pick a Model

Dark Matter Mass

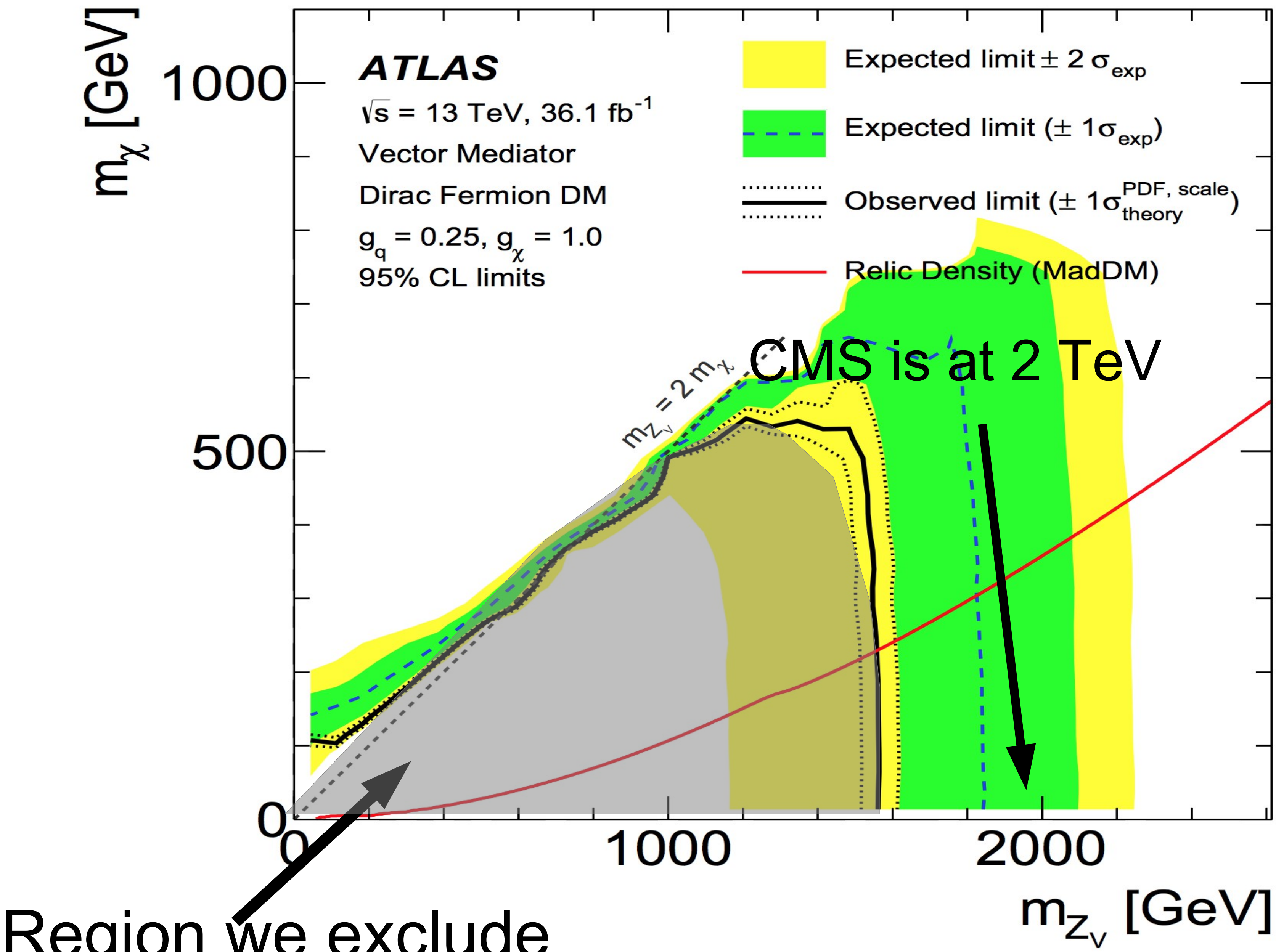


Fixed coupling

Mass of mediator produced

Arxiv:1711.03301

Understanding sensitivity

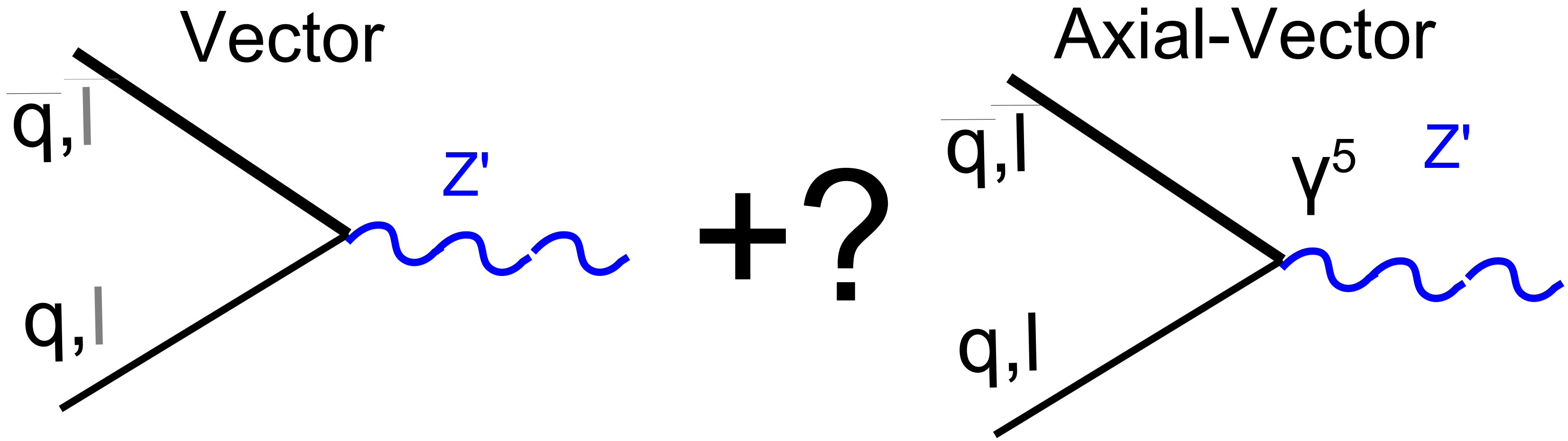


Arxiv:1711.03301

How do we interpret our results? (Spin 1)

What do we mean by spin 1?

- A spin-1 particle has uniform couplings to fermions

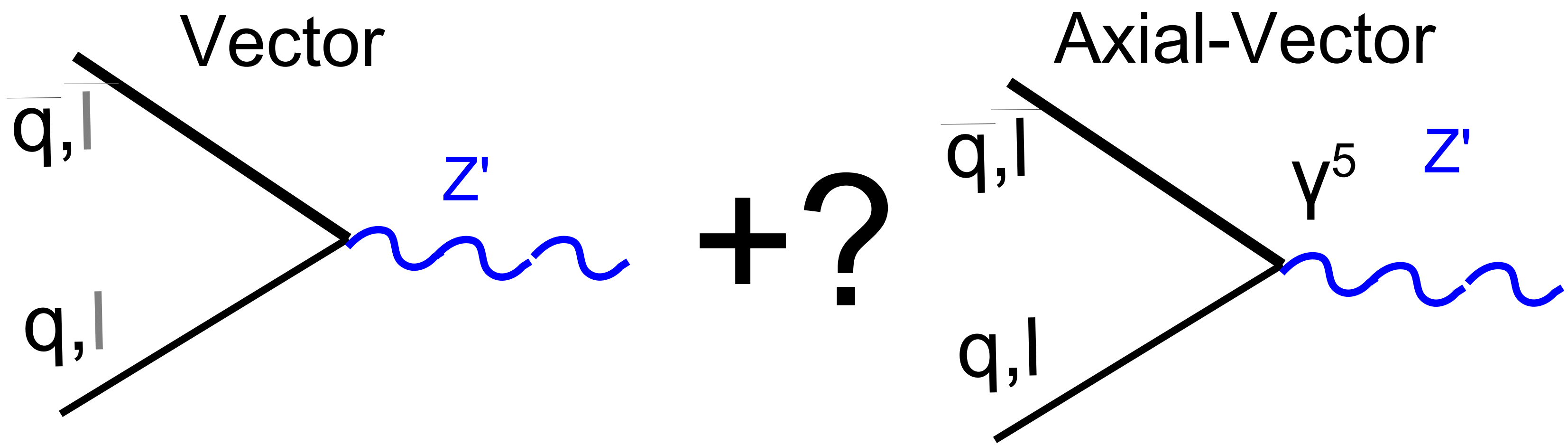


How do we build a model with all the features we want?

a. Z' couples to quarks (we produce it)
b. Z' couples to dark matter

What do we mean by spin 1?

- A spin-1 particle has uniform couplings to fermions



How do we build a model with all the features we want?

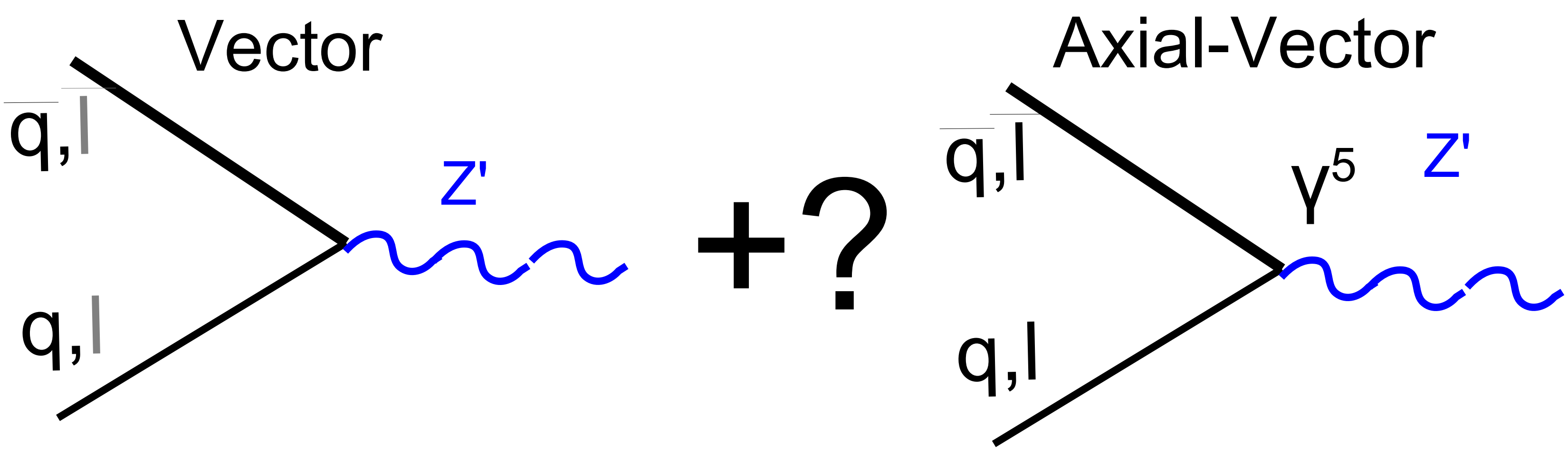
To compare with direct detection:

Pure Vector coupling (Spin-Independent)

Pure Axial-Vector coupling (Spin-Dependent)

What do we mean by spin 1?

- A spin-1 particle has uniform couplings to fermions



How do we build a model with all the features we want?

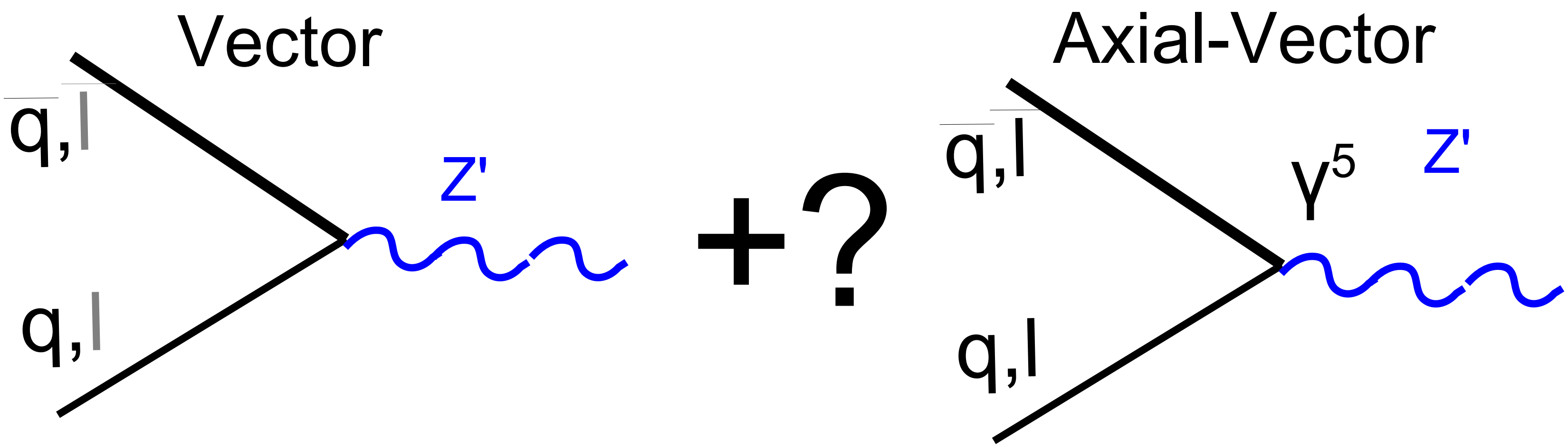
What about divergences?

Axial-vector needs lepton coupling to avoid them

Vector can couple to either quarks or leptons

What do we mean by spin 1?

- A spin-1 particle has uniform couplings to fermions



How do we build a model with all the features we want?

What about mass?

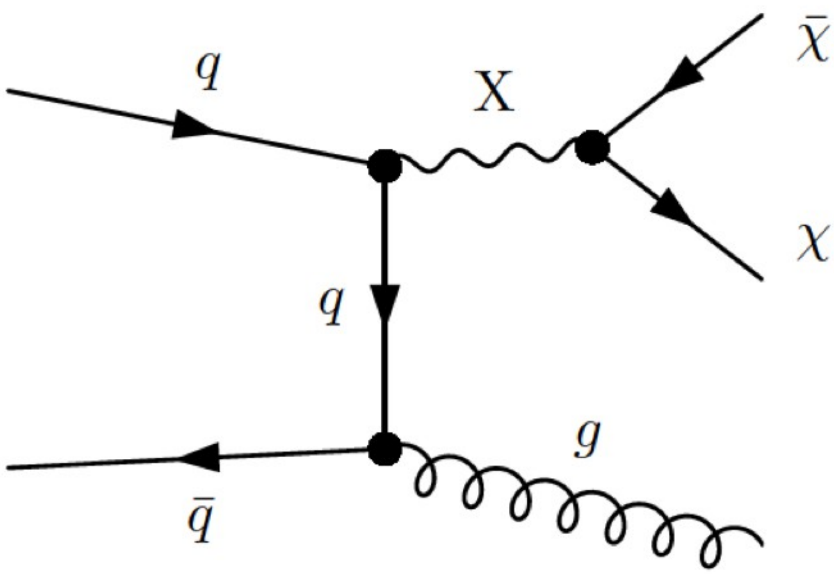
Z' can get mass from the Higgs

Z' can then radiate a Higgs (gives mono-Higgs)

Z' can get mass from a dark higgs or something else

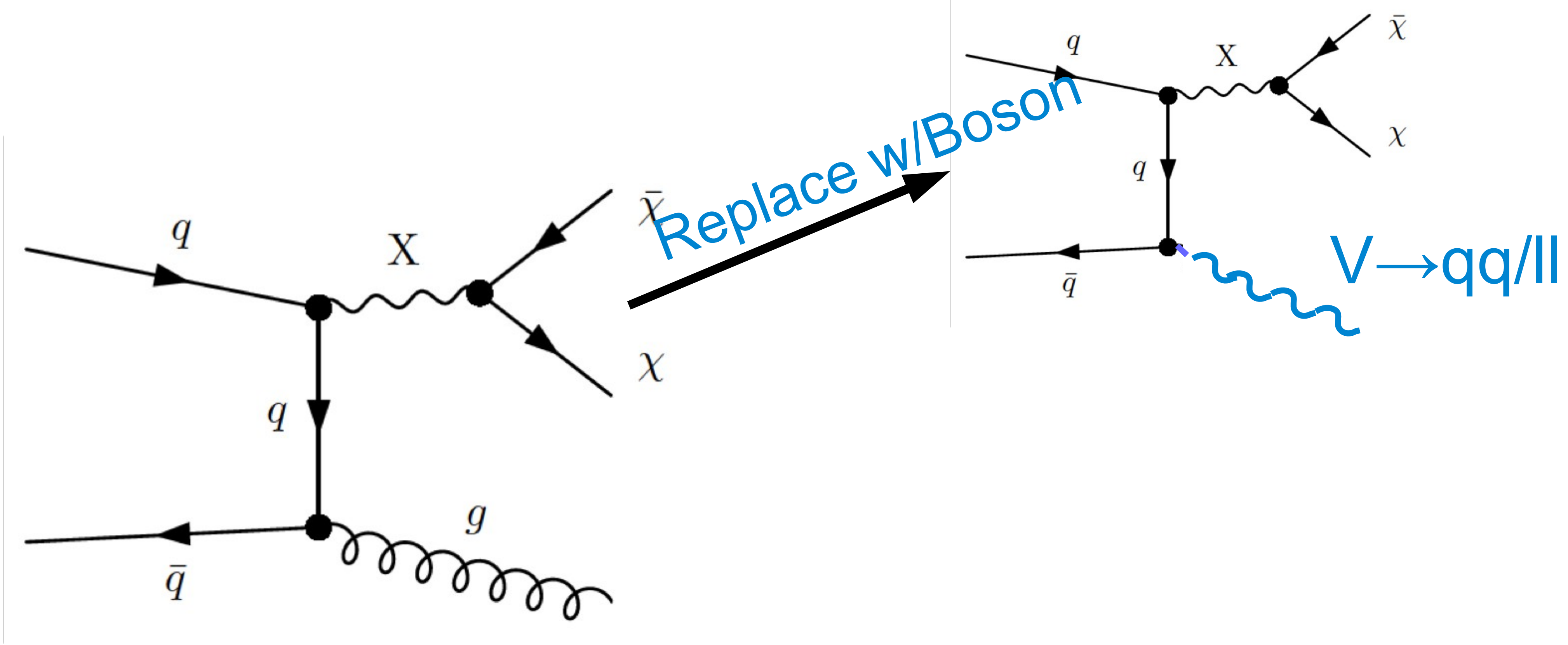
Spin 1 DM Searches

Spin 1 production on SM couplings for final state
Easily extend this to other final states



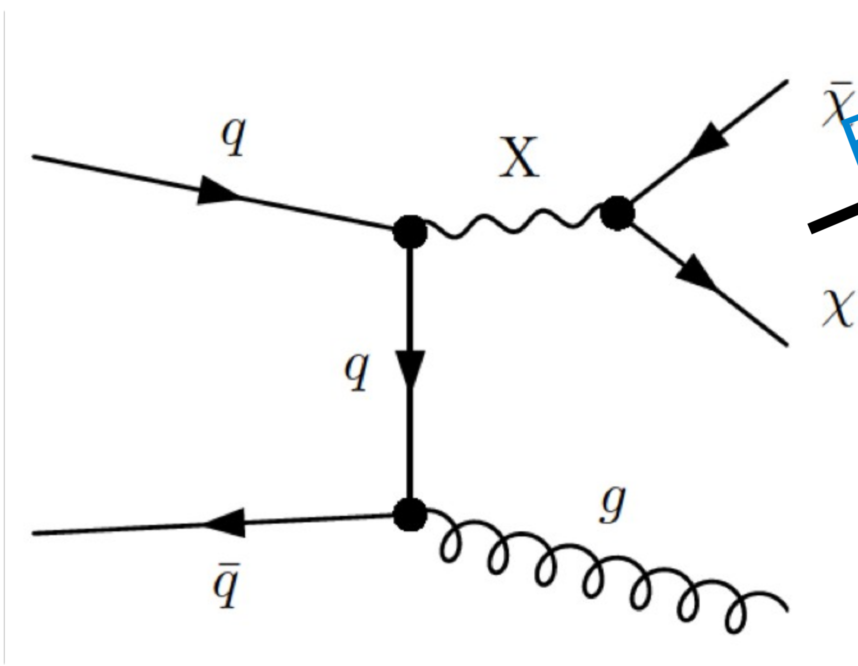
Spin 1 DM Searches

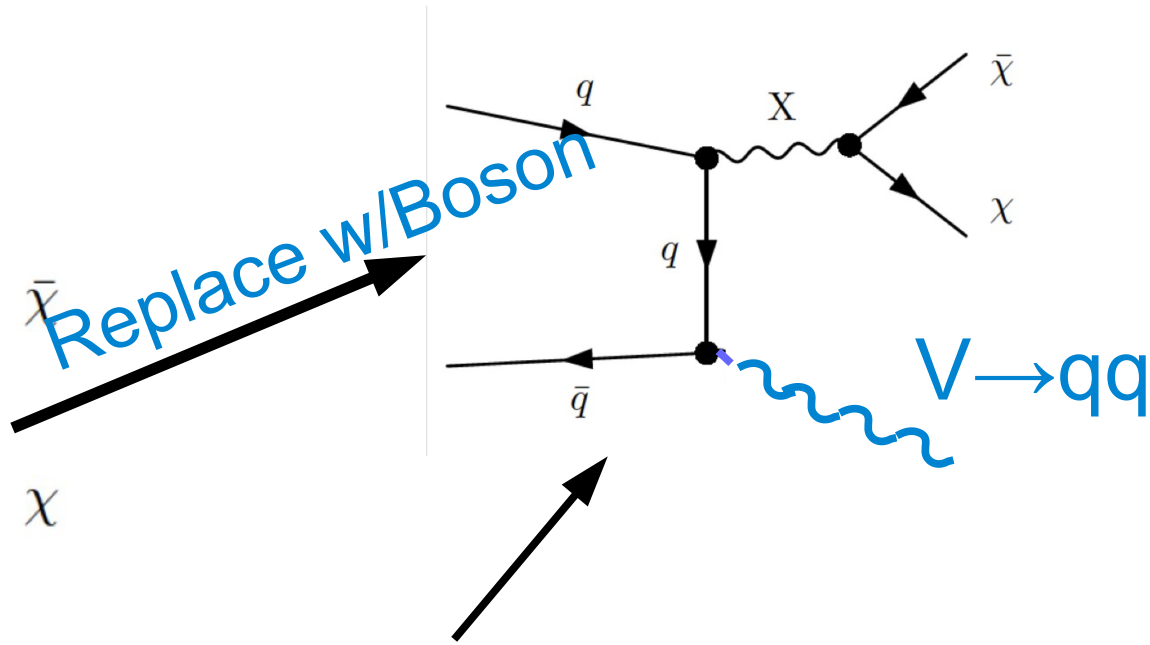
Can look for a Vector boson+*MET* as well



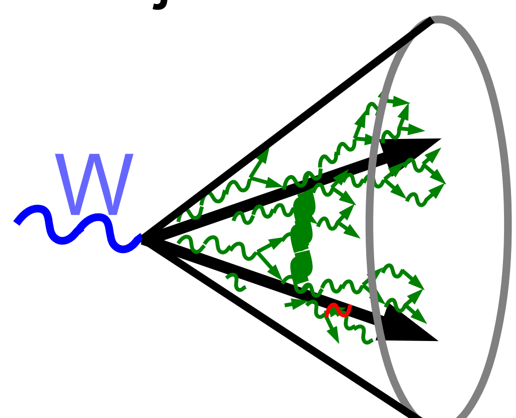
The split in simplified model terms

- With spin 1 can generate other final states :



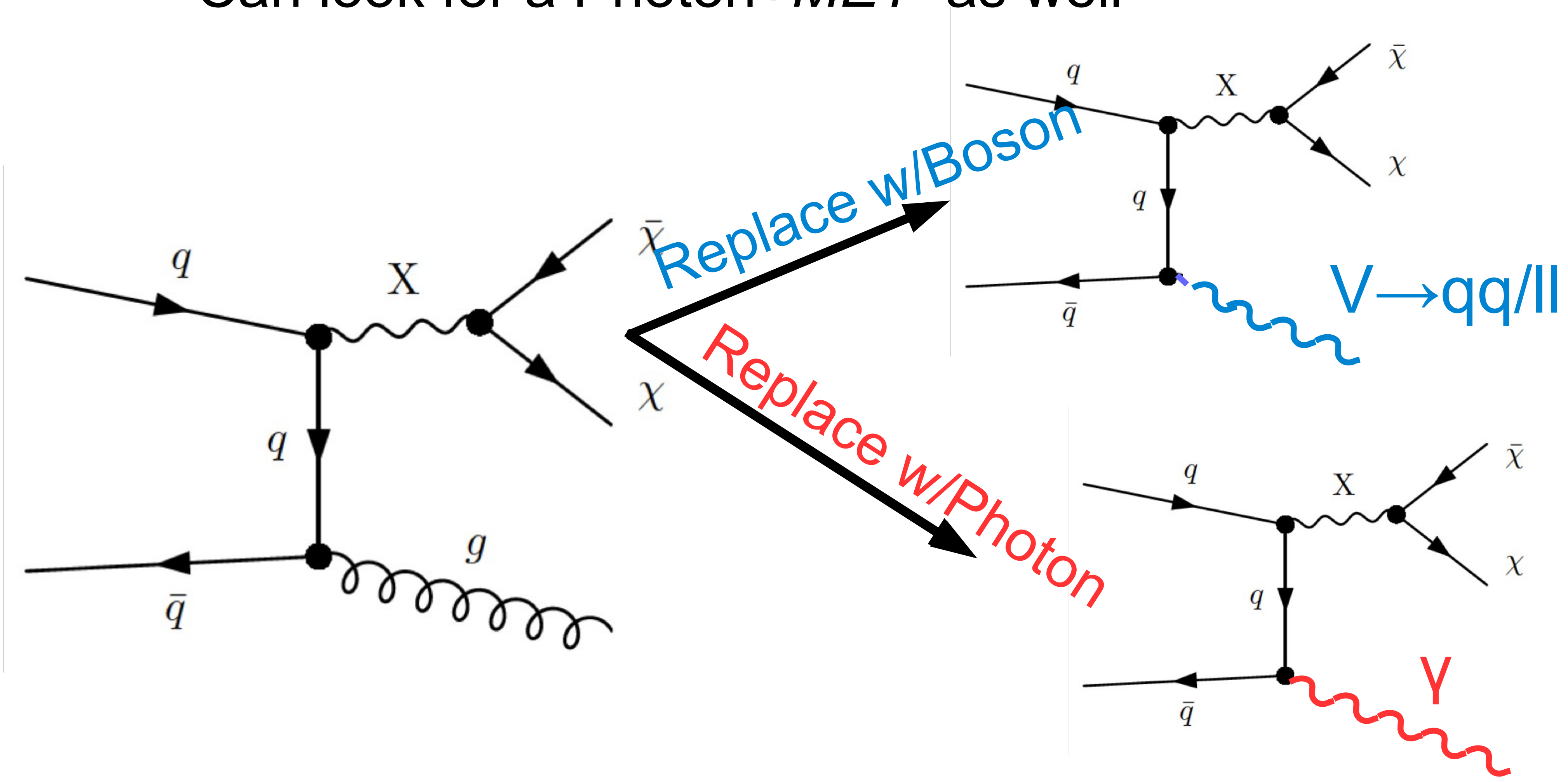


This is just a monojet



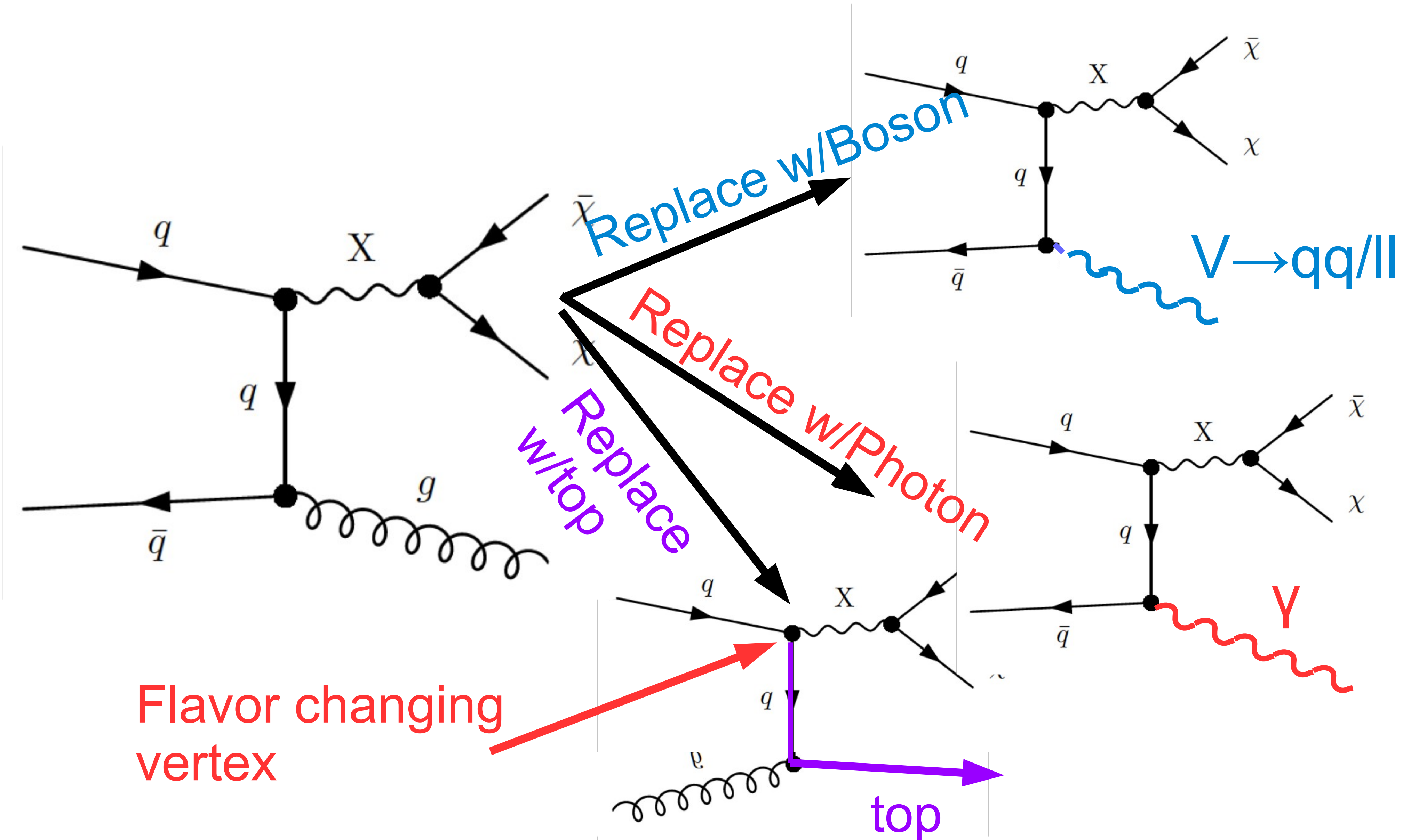
Spin 1 DM Searches

Can look for a Photon+*MET* as well



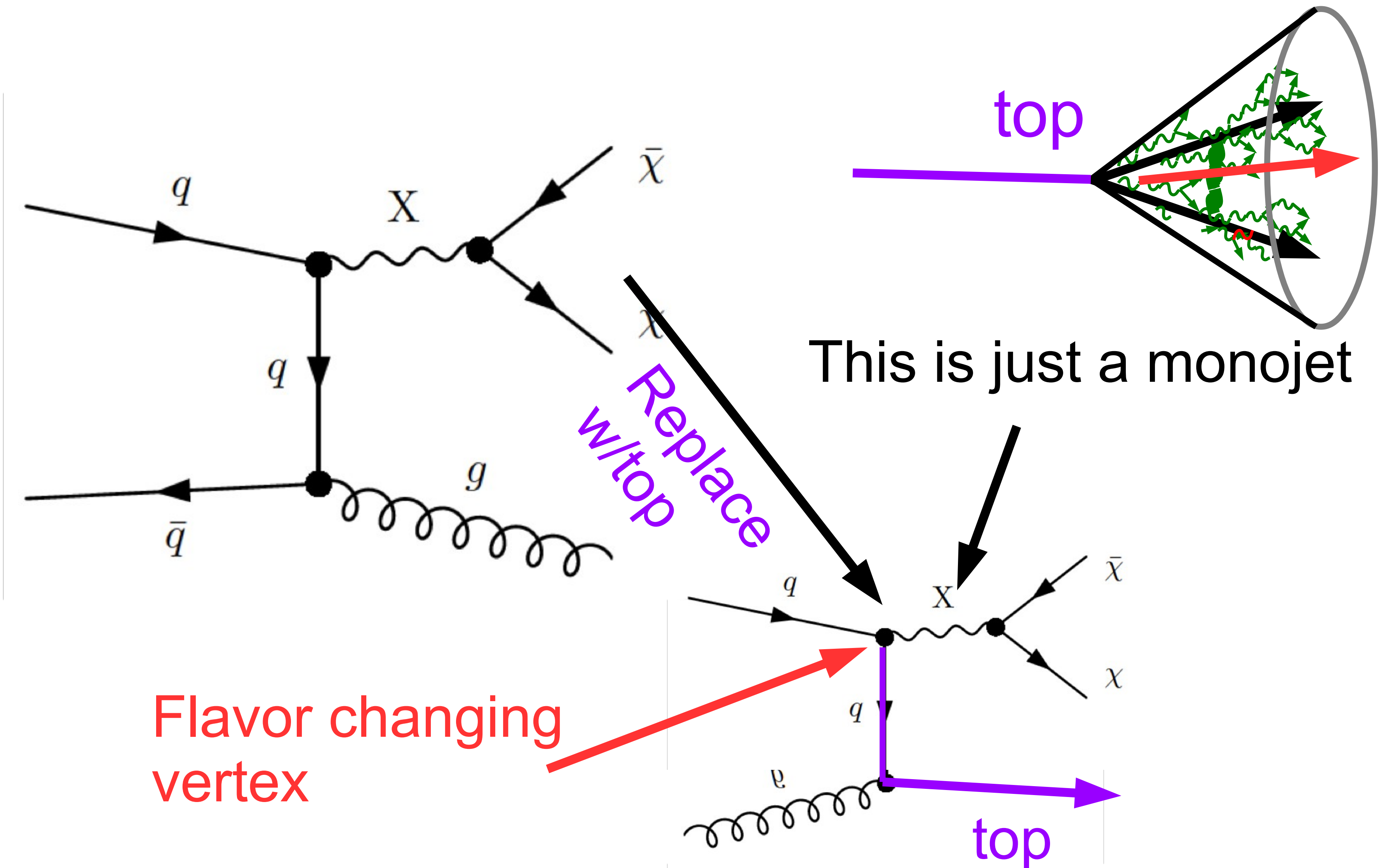
Spin 1 DM Searches

If vertex is flavor changing



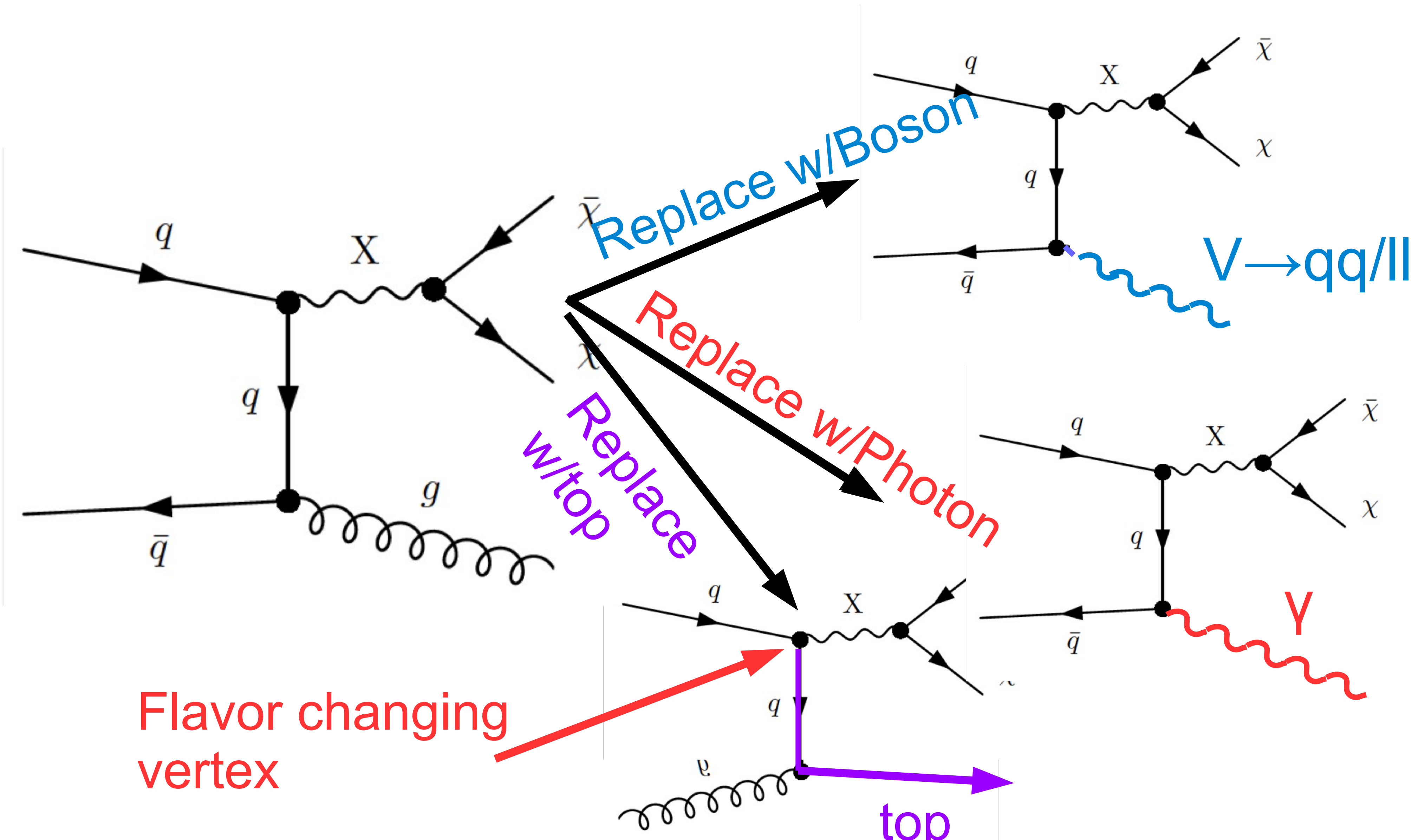
The split in simplified model terms

- With spin 1 can generate other final states :

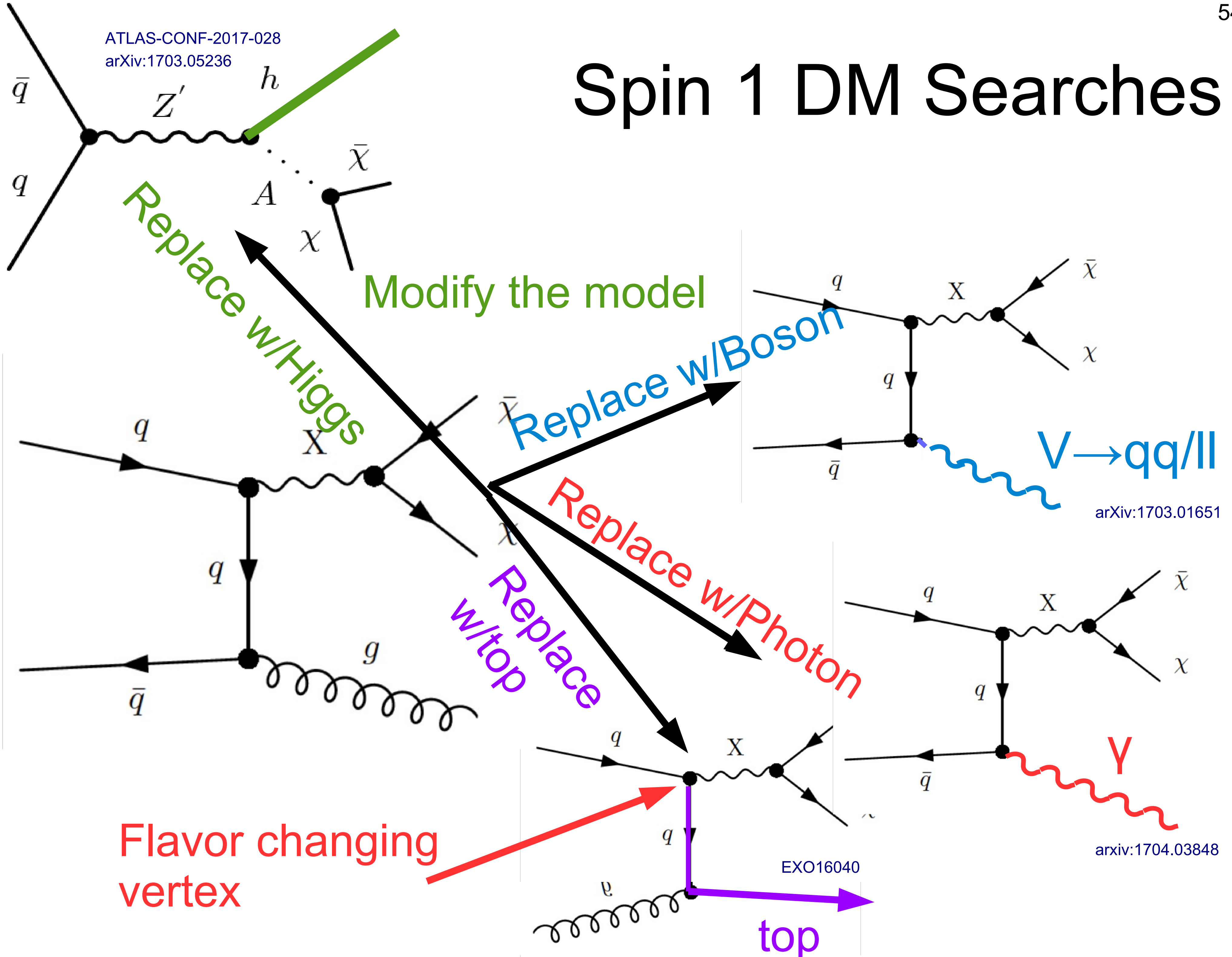


Spin 1 DM Searches

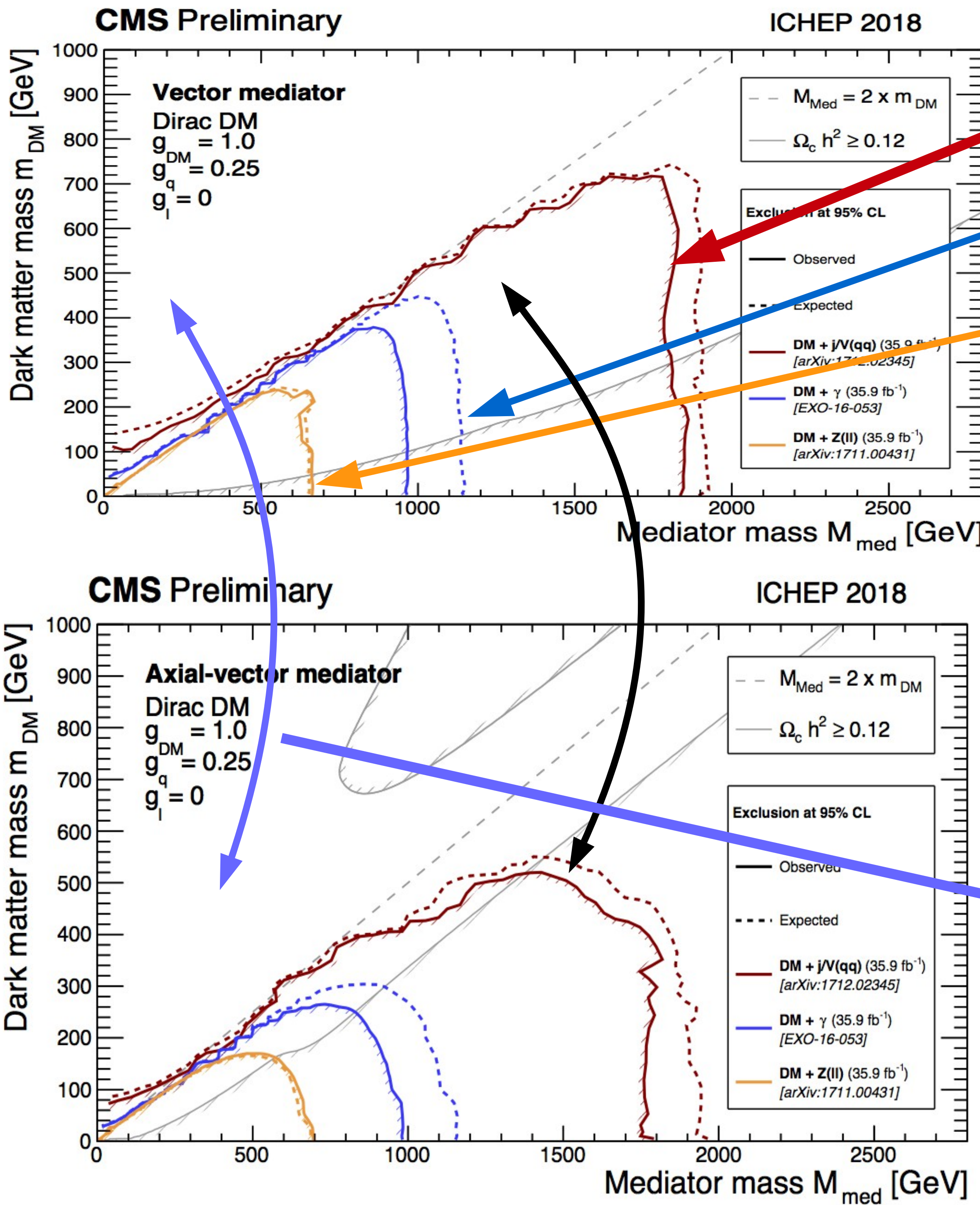
If vertex is flavor changing



Spin 1 DM Searches



Bounds Tagging the ISR shape



Mono-jet+Mono-V(qq)

Monophoton

Mono-Z(leptons)

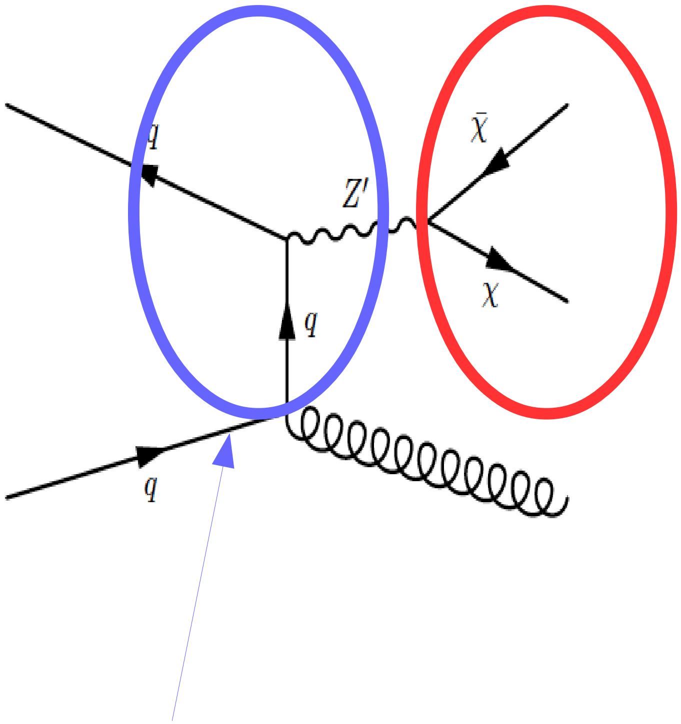
Differences in shape result from the width of the mediator

Region where relic density is not over produced with simplified model

Beyond Invisible Searches

What else?

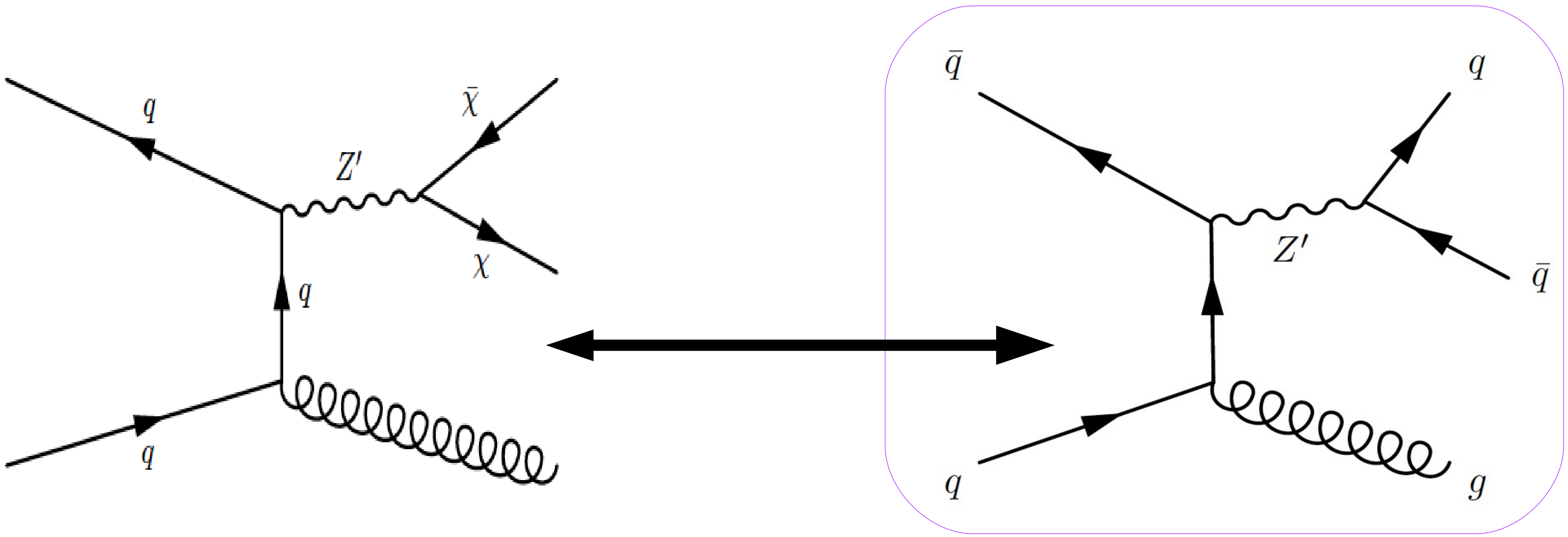
- Without loss of generality we also have dijets



Mediator is coupling to quarks and to Dark matter

What else?

- Without loss of generality we also have dijets

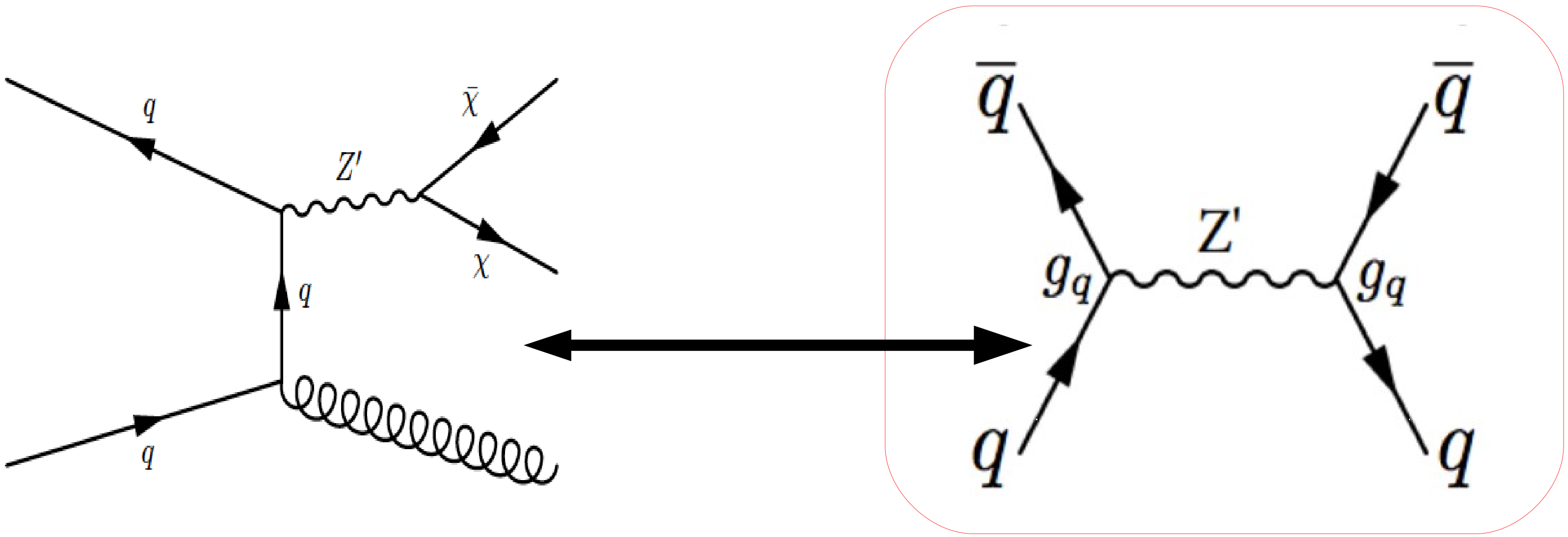


This is a dijet+ISR search

Mediator is coupling to quarks and to Dark matter
Mediator can decay to quarks

What else?

- Without loss of generality we also have dijets



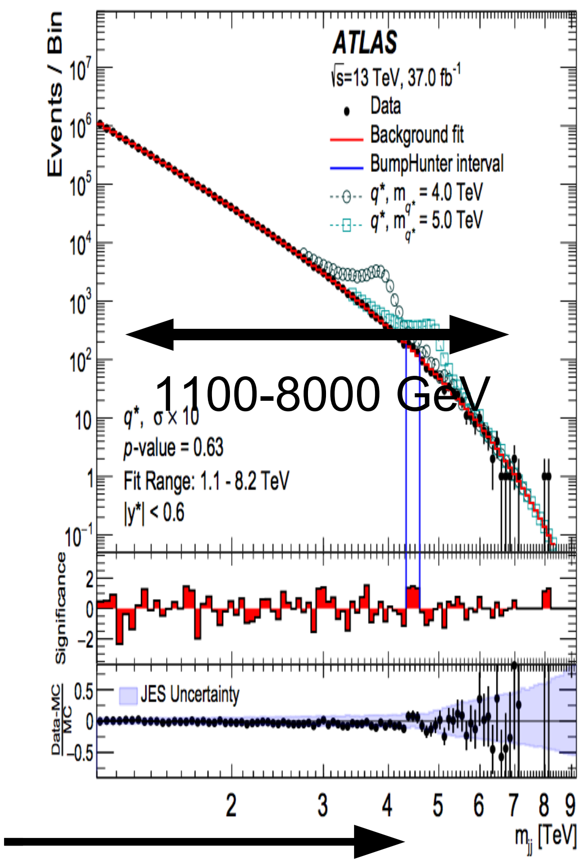
Can also just do a plain dijet search

When doing a dijet search don't need additional jet

BR(Z'→qq) ≈0.5BR(Z'→   )

Probing the Mass range

Like Monojet
we can expand to further regions
By tagging other objects

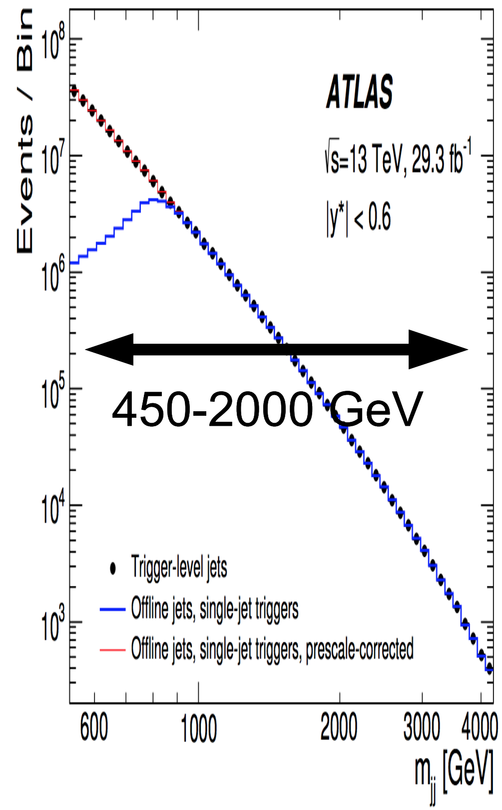


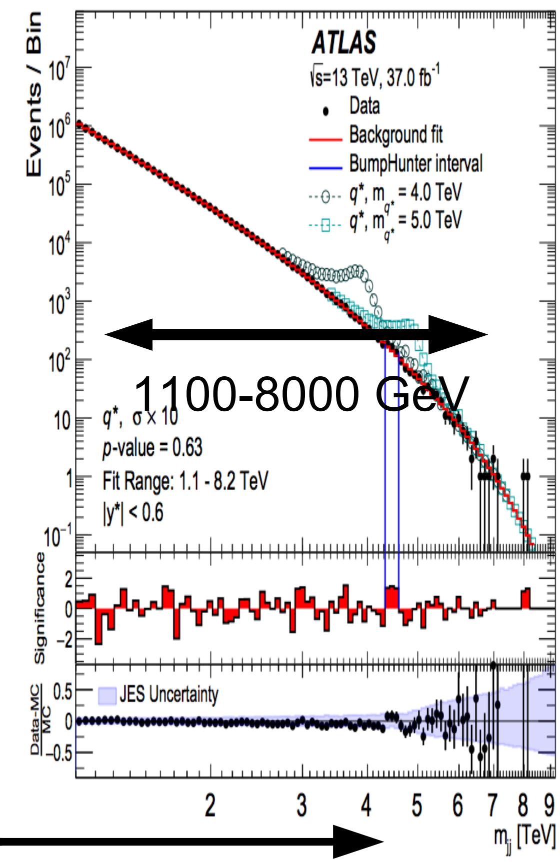
Standard jet triggers

No tag

arXiv:1703.0912

Probing the Mass range





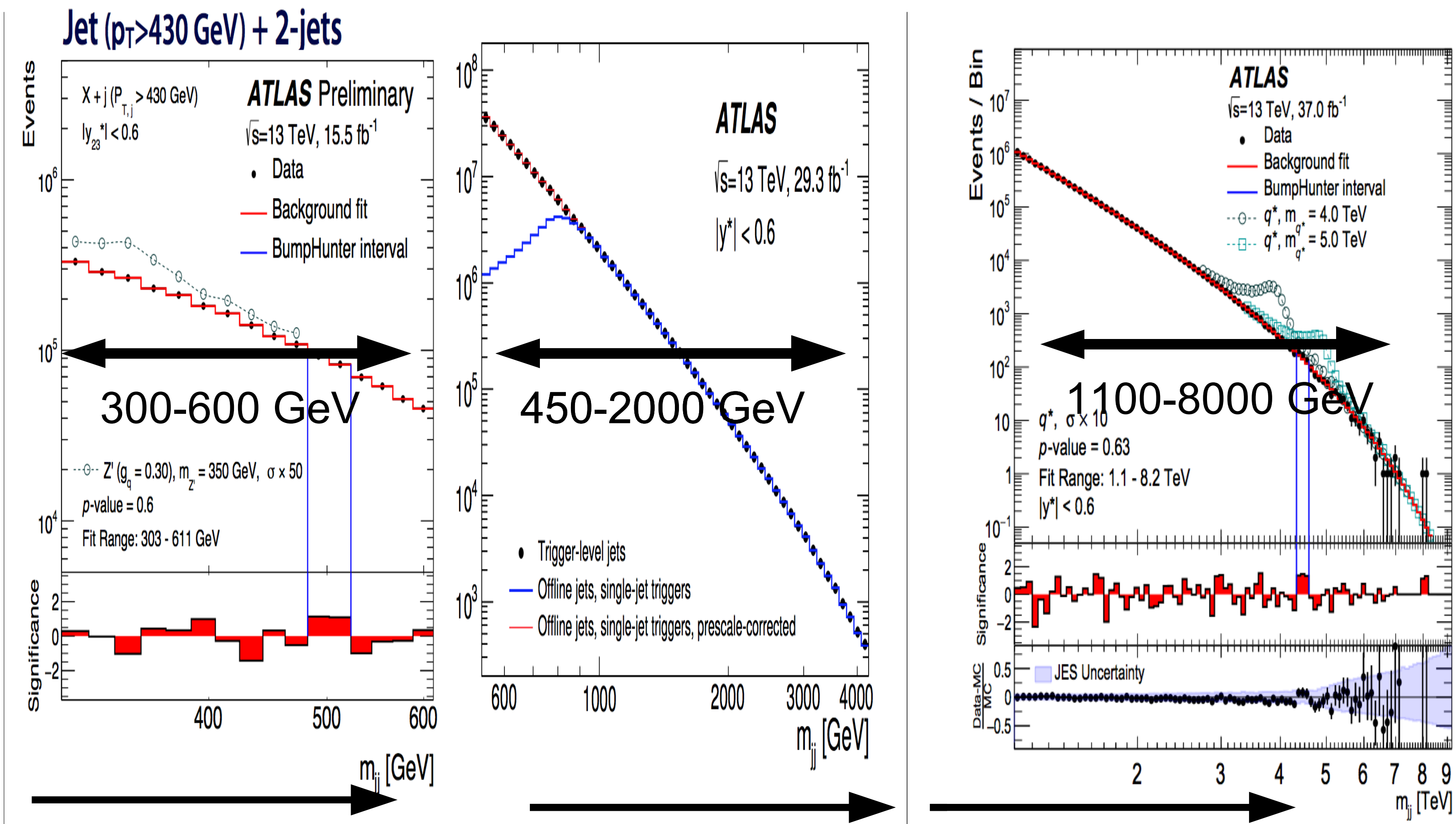
Trigger Level analysis

Standard jet triggers

Jets in trigger

arXiv:1804.03496

Probing the Mass range



jj+j ISR analysis

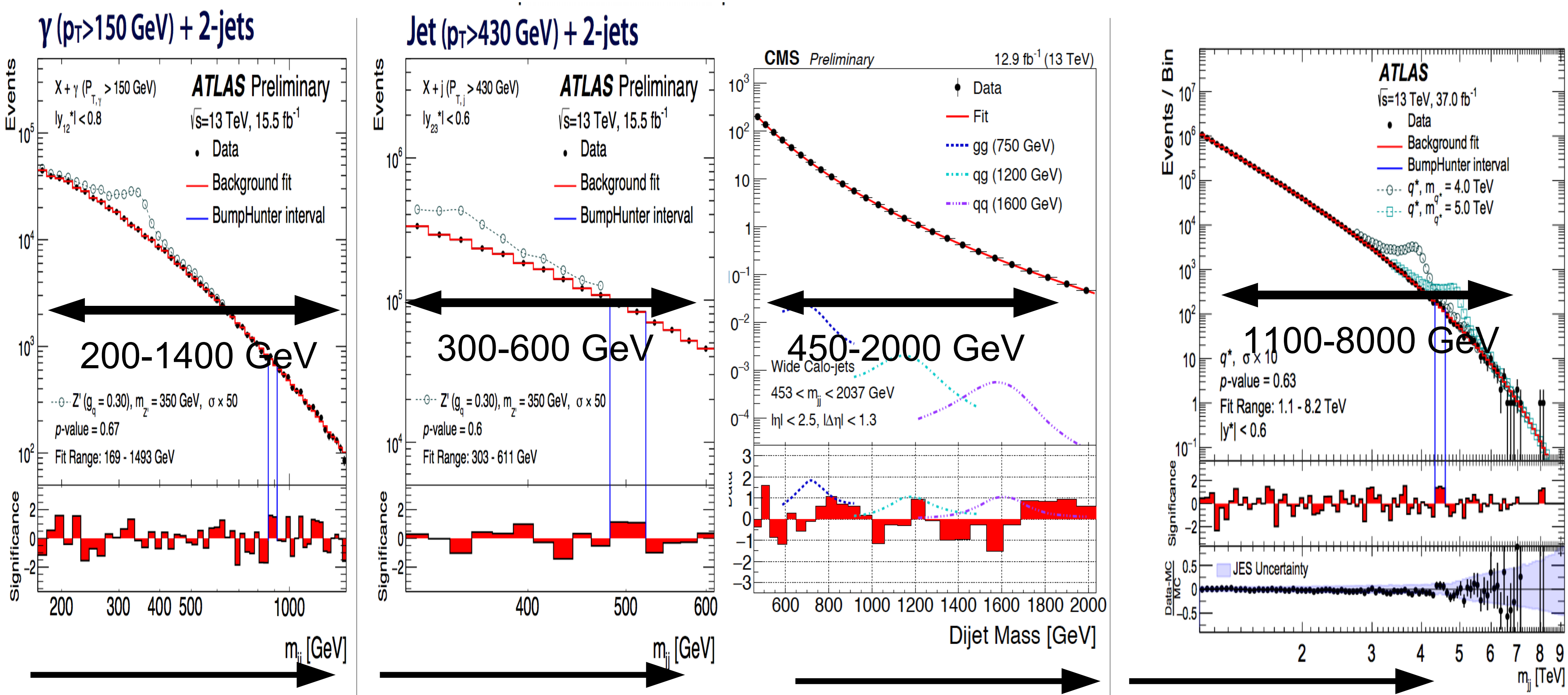
Trigger Level analysis

Standard jet triggers

Additional jet (like monojet) ATLAS

ATLAS-CONF-2016-070

Probing the Mass range



jj+γ ISR analysis

jj+j ISR analysis

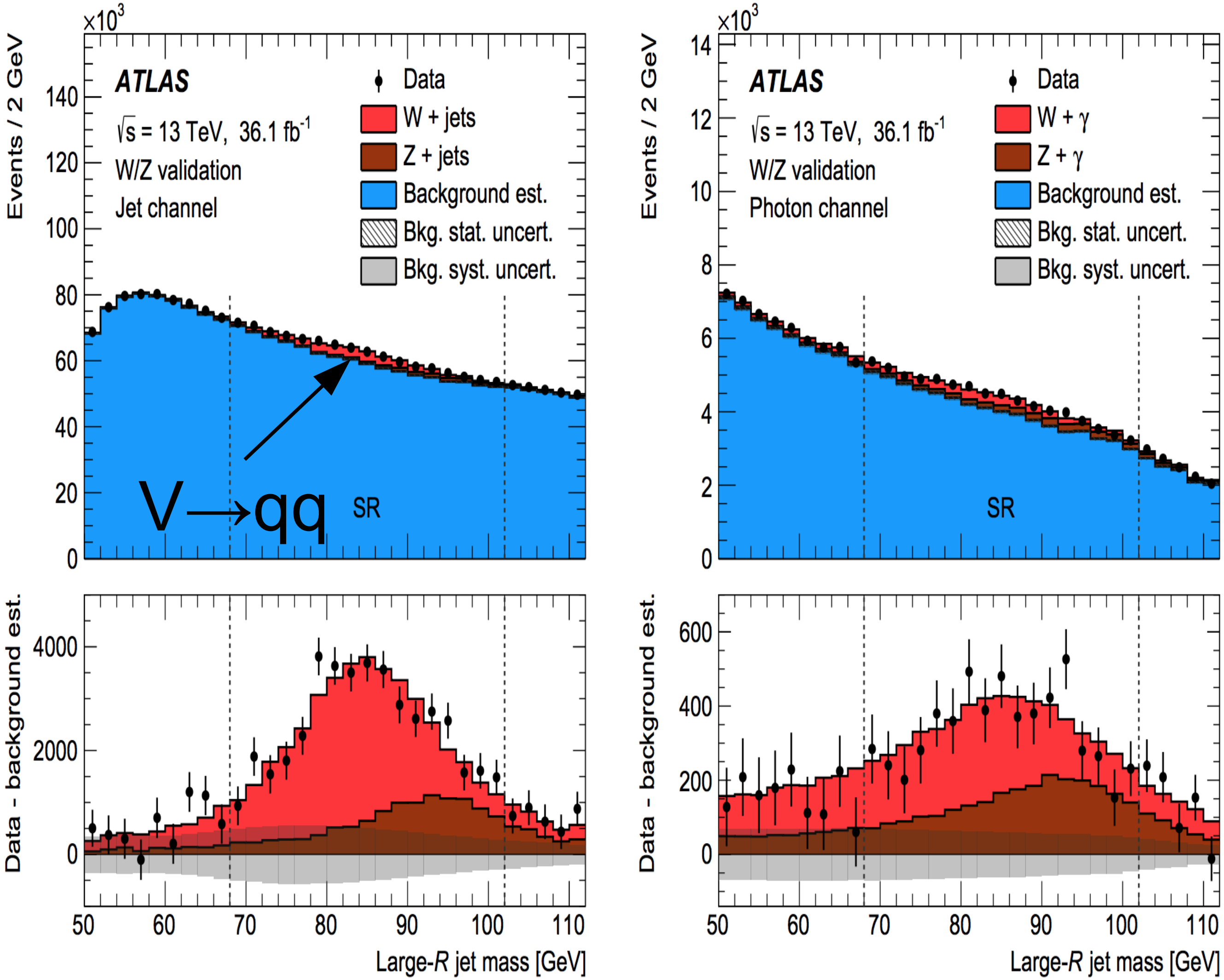
Trigger Level analysis

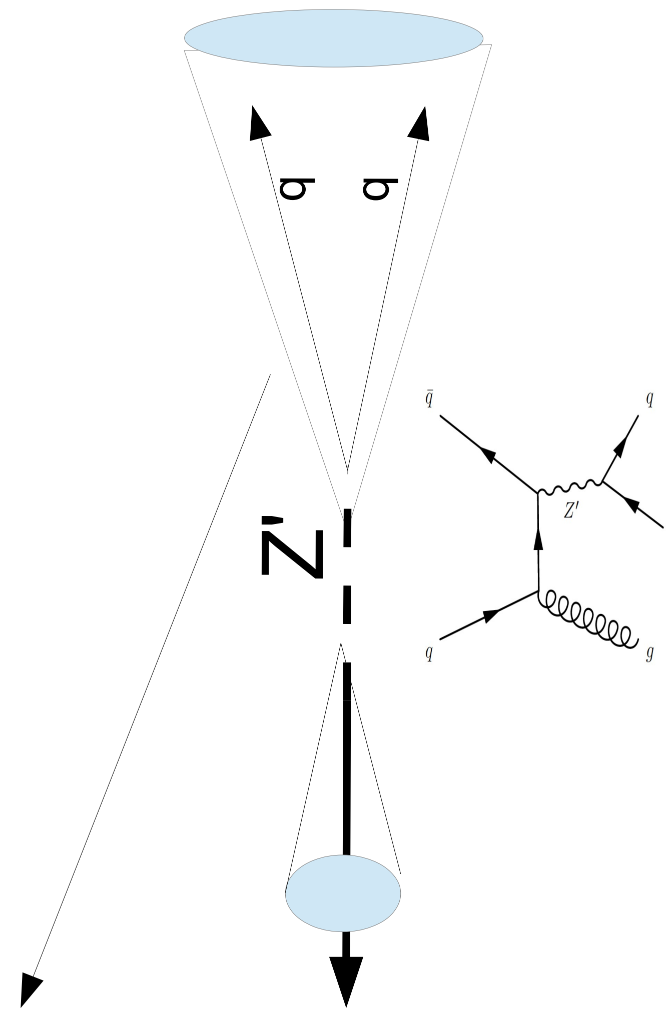
Standard jet triggers

Additional photon (like monophoton) ATLAS

ATLAS-CONF-2016-070

Going all the way down





Fat jet + ISR

arXiv:1710.00159

arXiv:1801.08769

arXiv:1603.00027

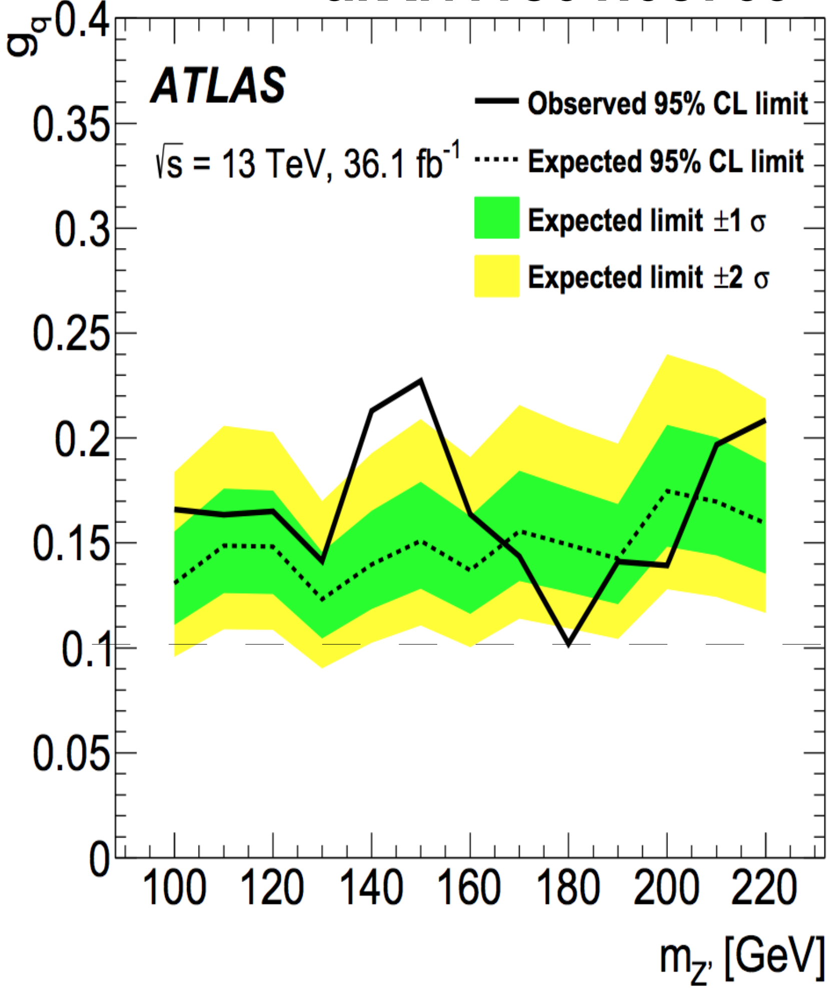
For this plot we invented a new substructure var

What are the results?

At Low mass

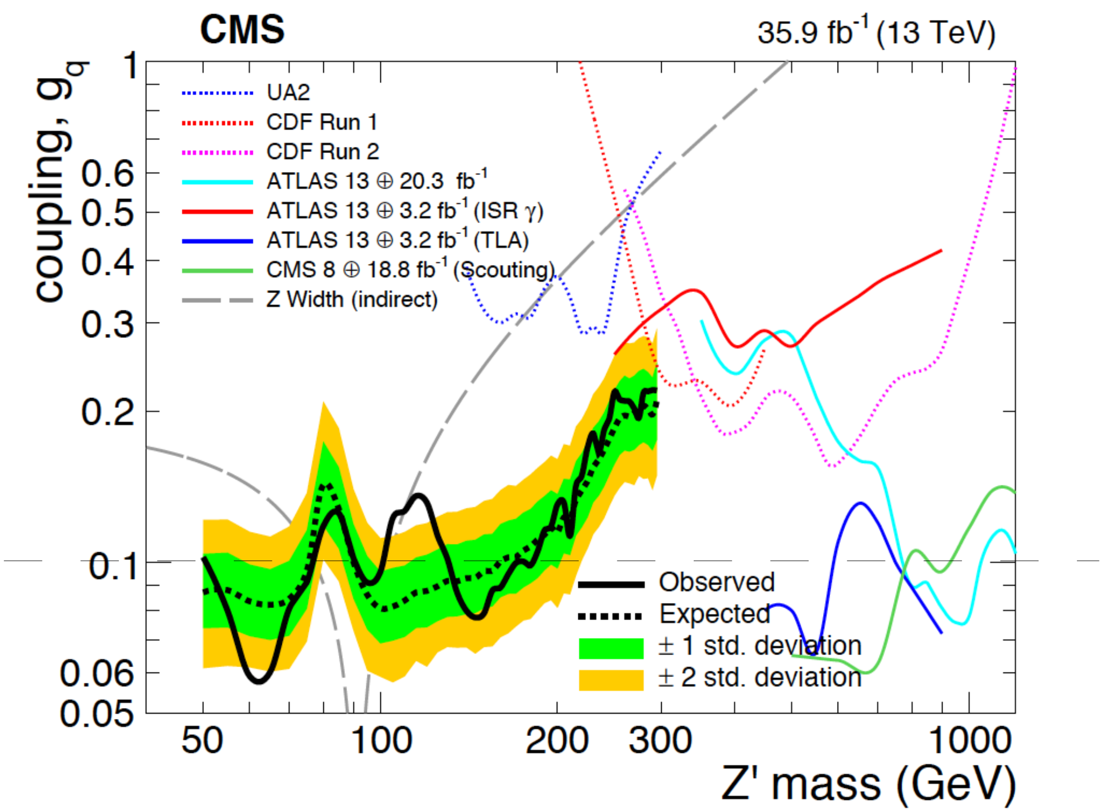
ATLAS

arXiv:1801.08769



CMS

arXiv:1710.00159



CMS has a 3 sigma excess not excluded by ATLAS

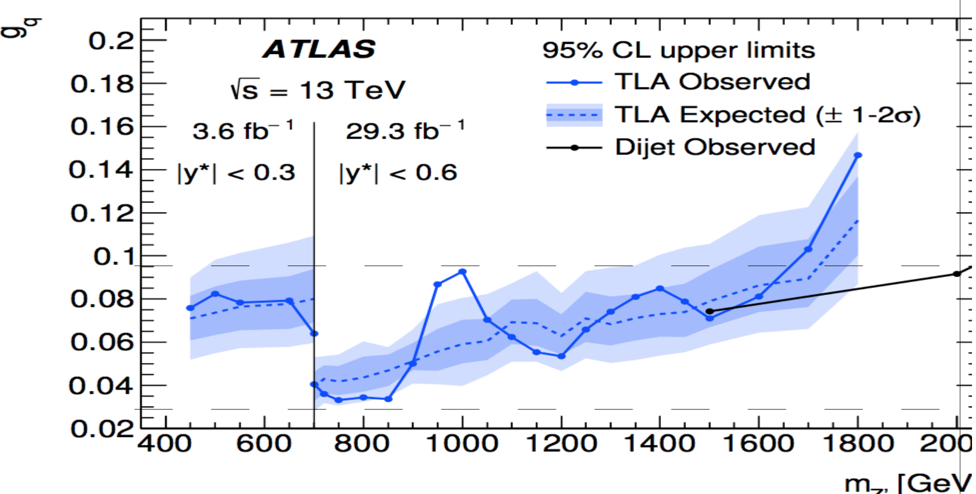
What are the results?

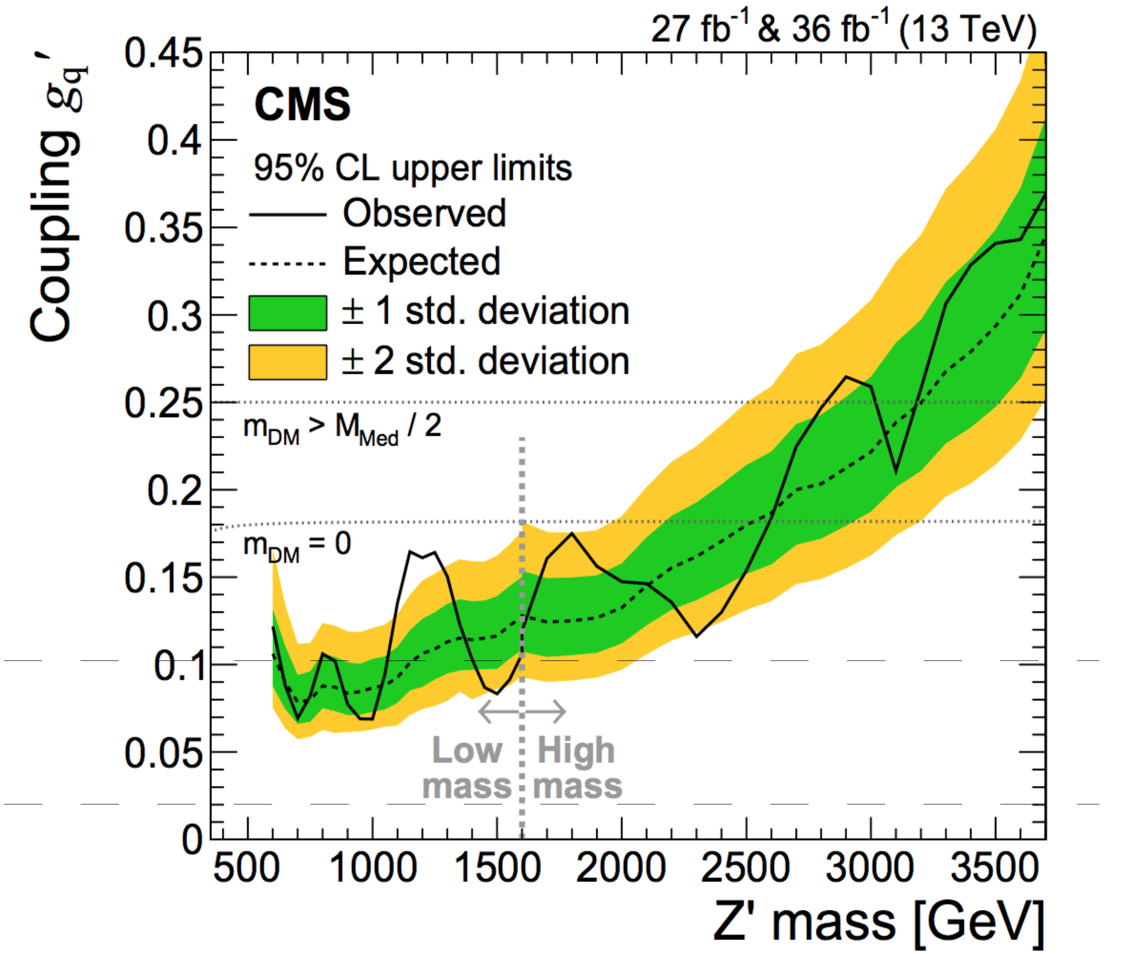
At Intermeidate mass

ATLAS

CMS

arXiv:1804.03496

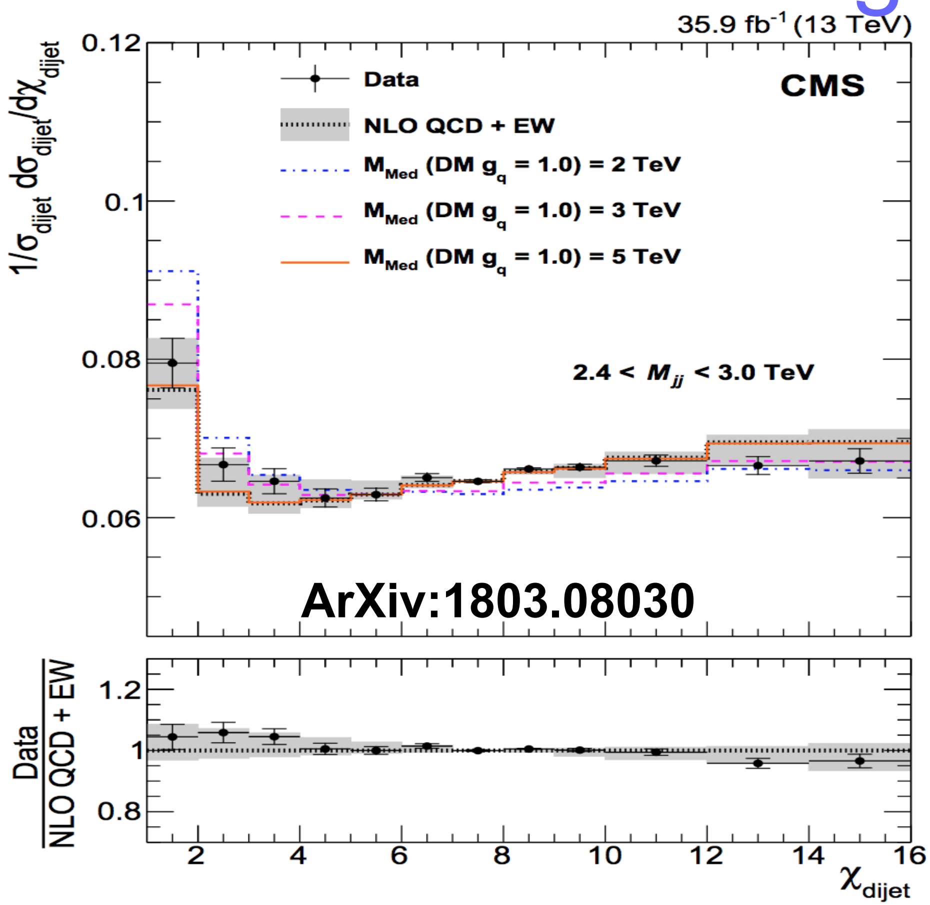


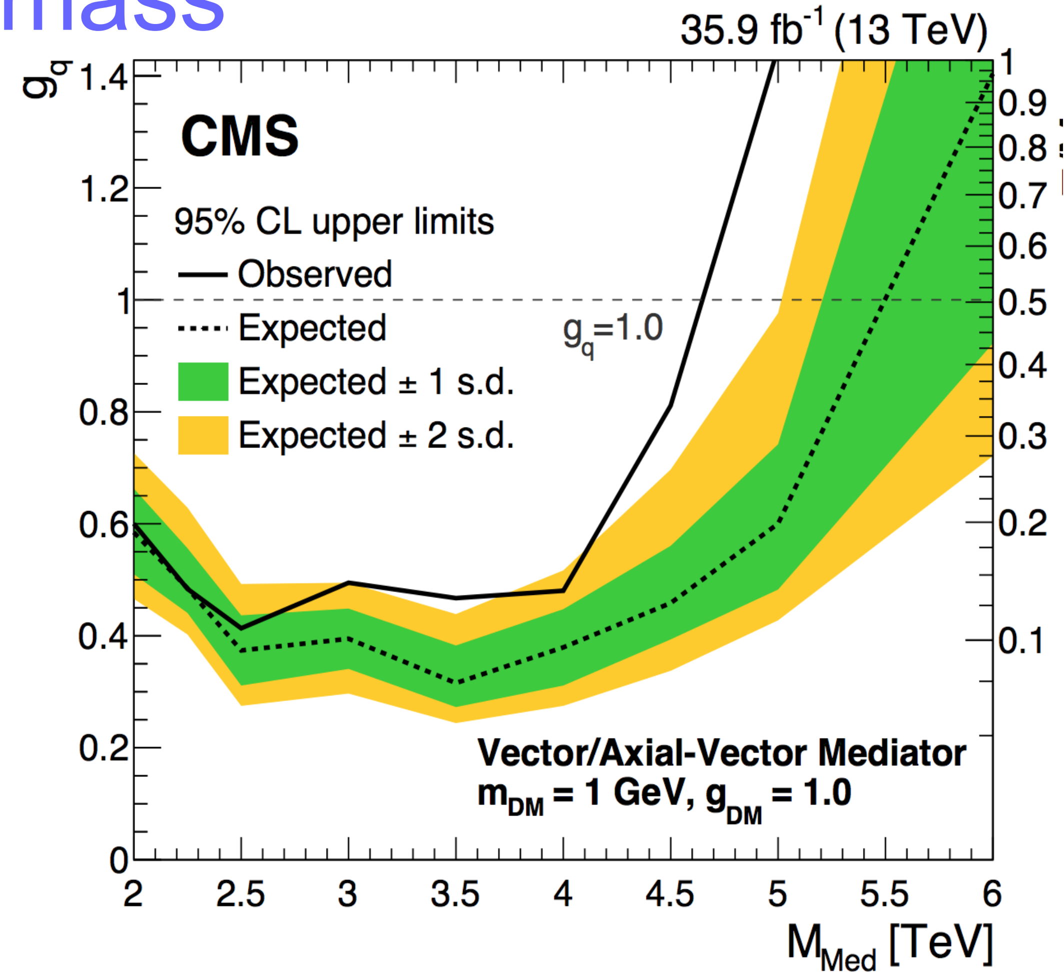


CMS and ATLAS don't have excesses in synch

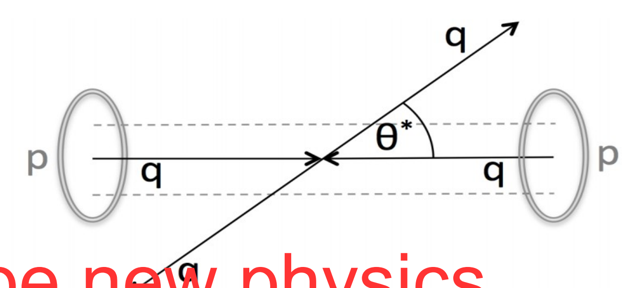
What are the results?

At High mass

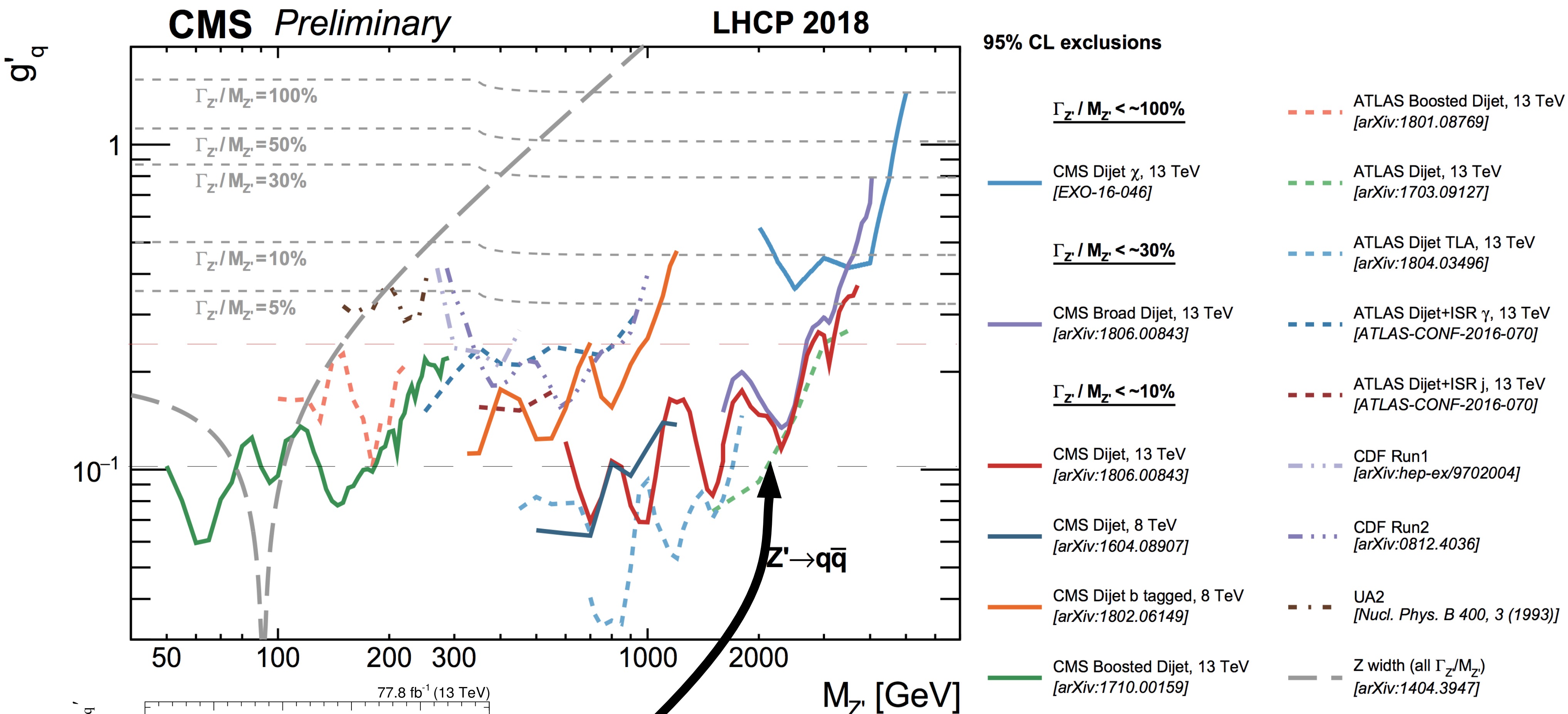


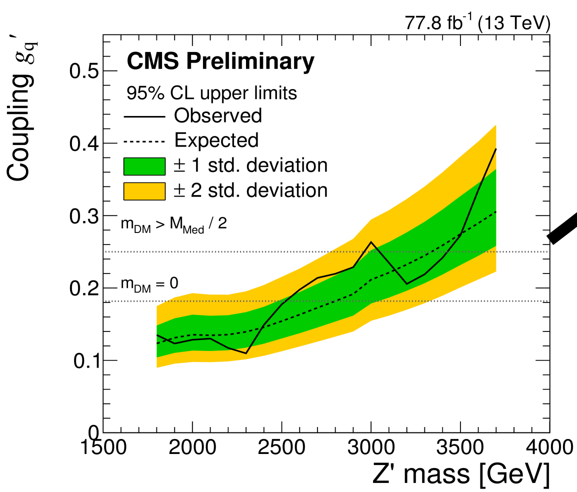


$$\chi_{dijet} = e^{|y_1 - y_2|} \sim \frac{1 + |\cos\theta^*|}{1 - |\cos\theta^*|}$$



Use angular information to probe new physics

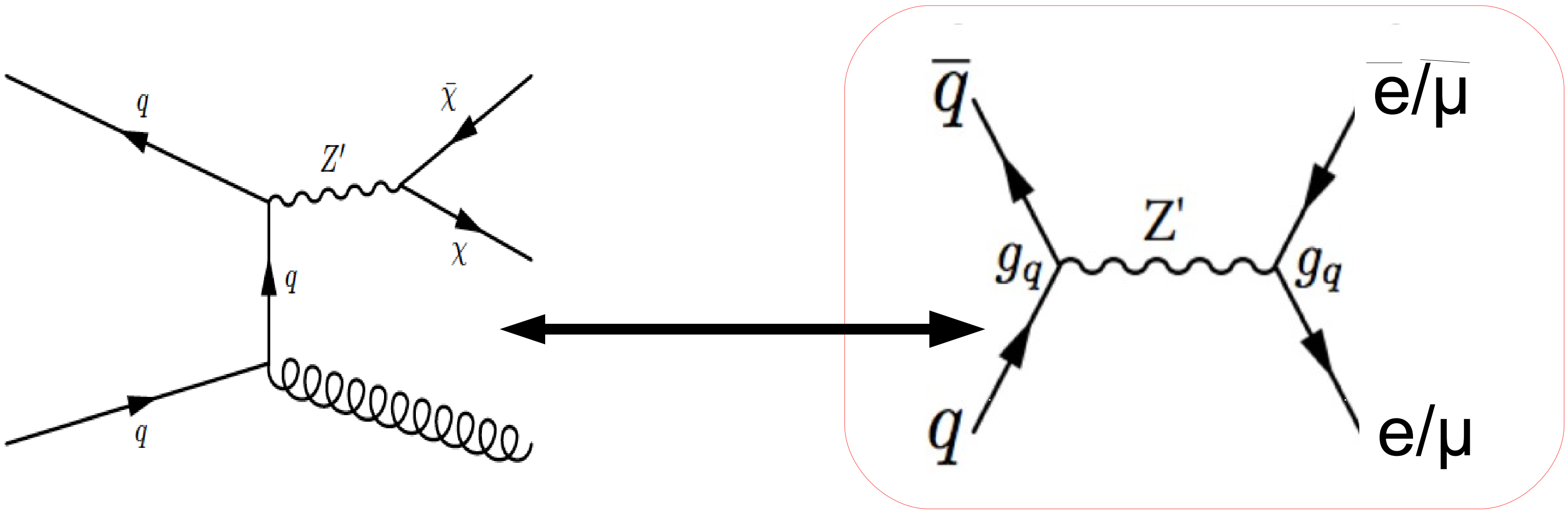




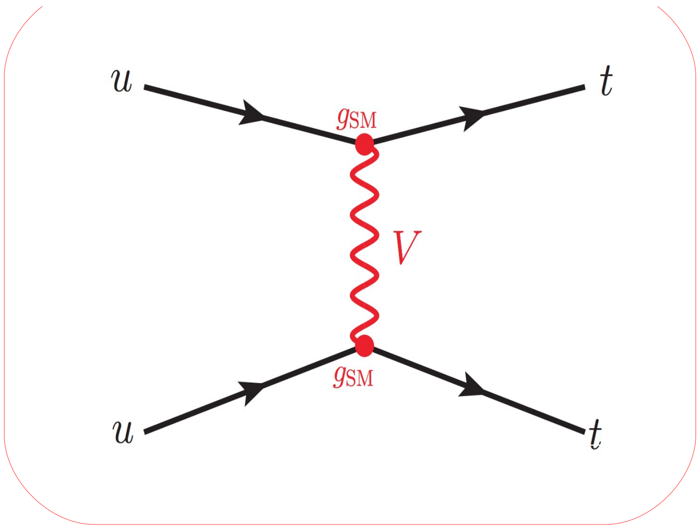
Improvement Since July

What else?

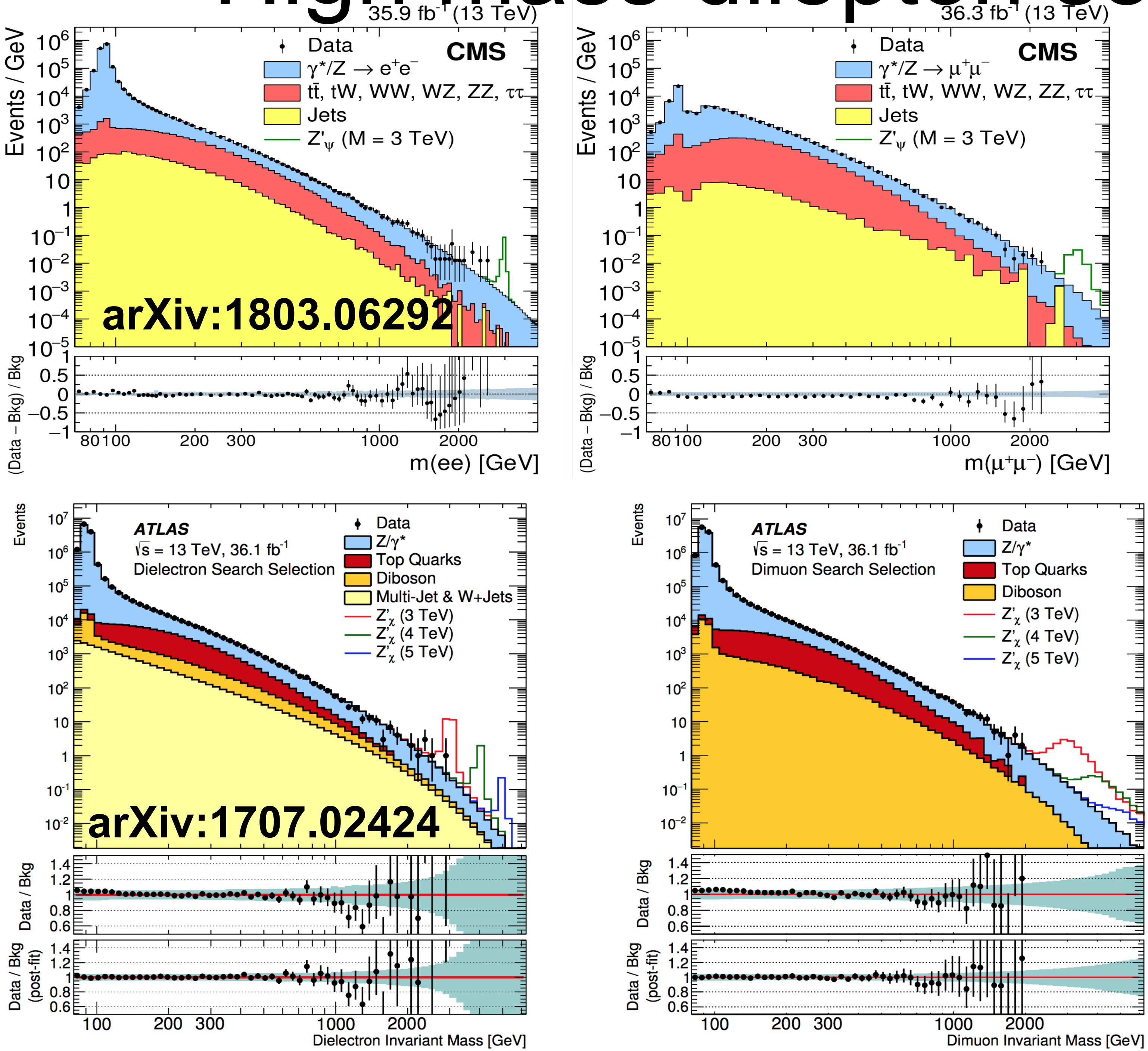
- Without loss of generality we also others!



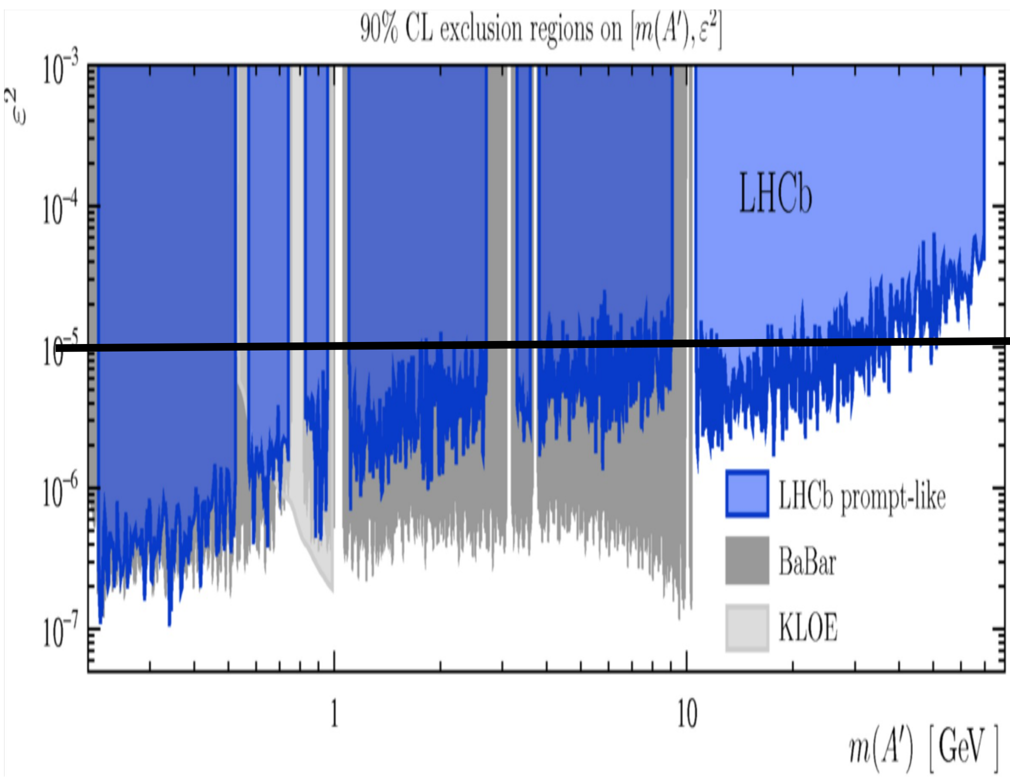
Can also have
even more complicated scenarios
when
coupling schemes differ?

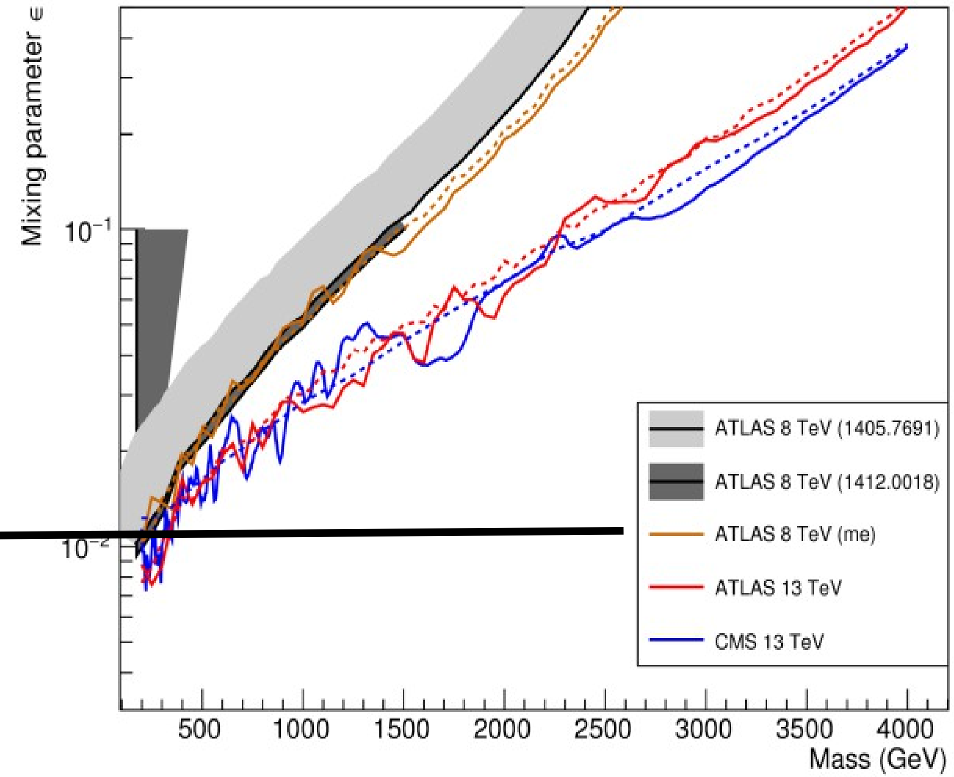


High mass dilepton search



Translating to Couplings



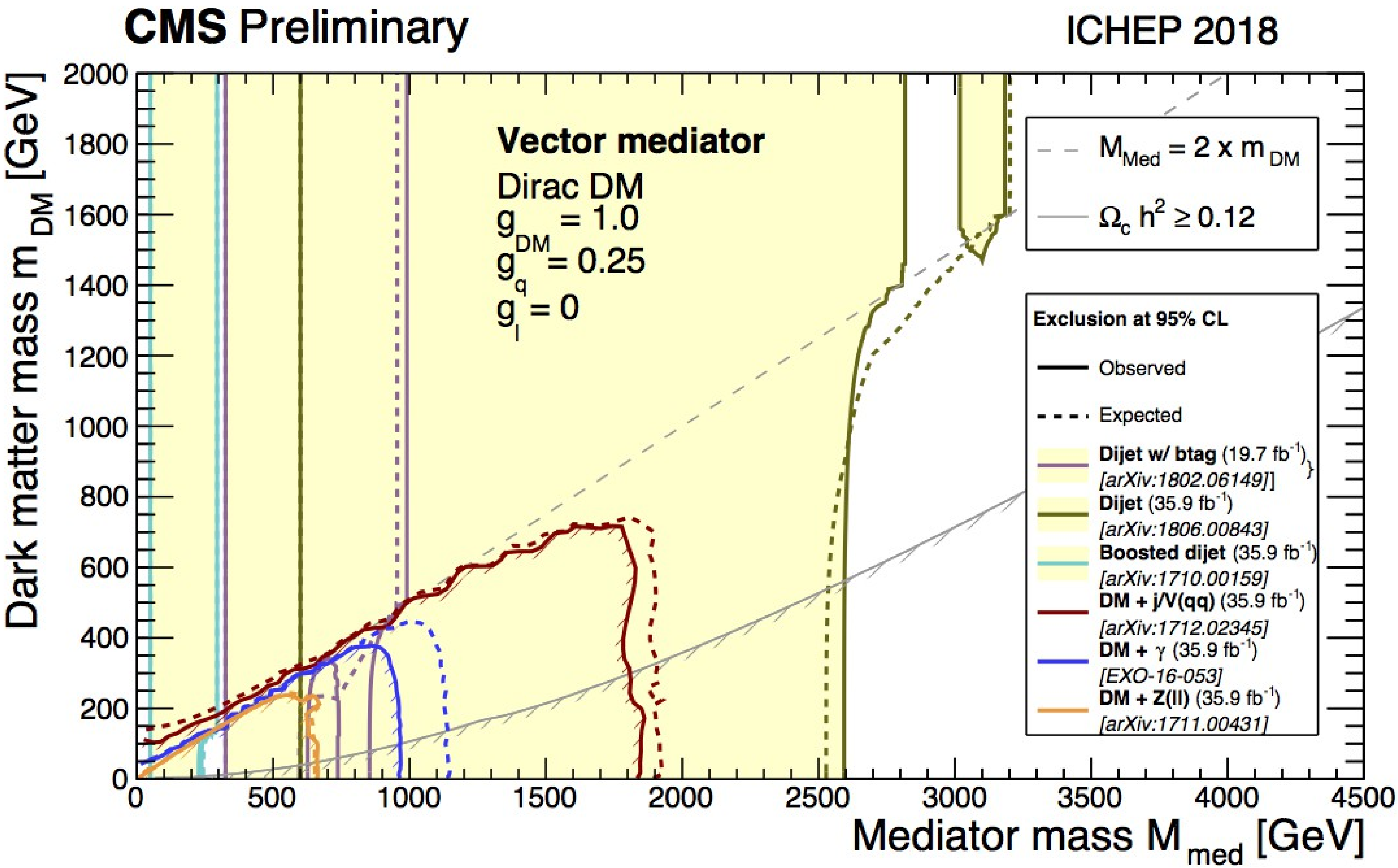


Story of Dark photons at the LHC is still very young

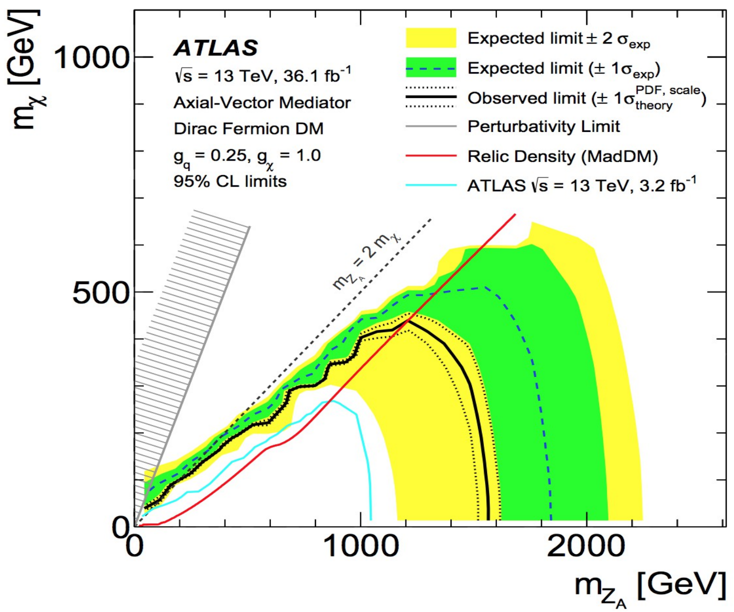
There are a lot of parameters to explore

- Including long lived
- Low mass in ATLAS/CMS

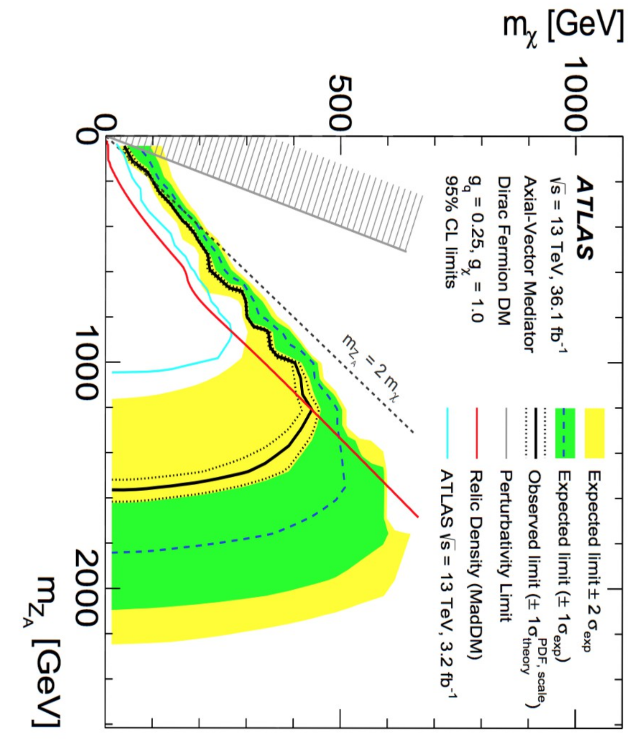
CMS



https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryPlotsEXO13TeV

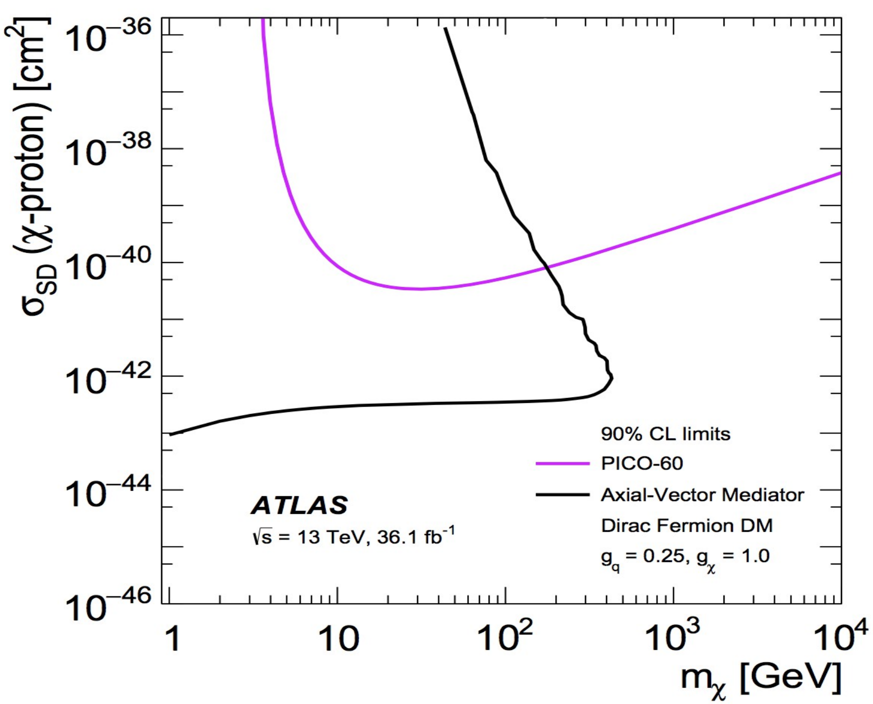


Rotate Plot



Axis

$$\sigma_{\rm SI} = \frac{f^2(g_q) g_{\rm DM}^2 \mu_{n\chi}^2}{\pi M_{\rm r}^4}$$

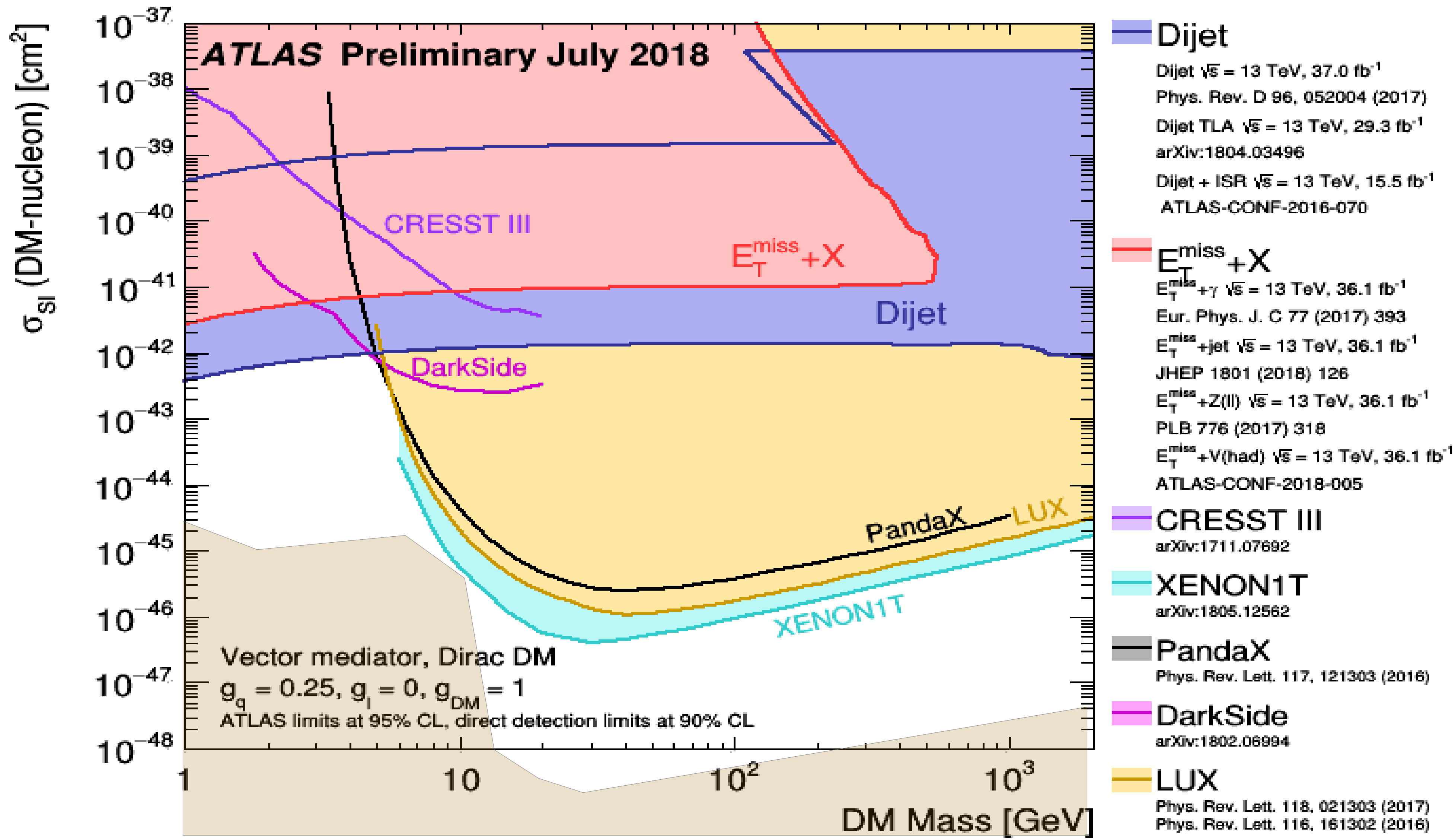


Now that search is cast in terms of mediator

No concerns in the translation
Fixed couplings

1605.04917

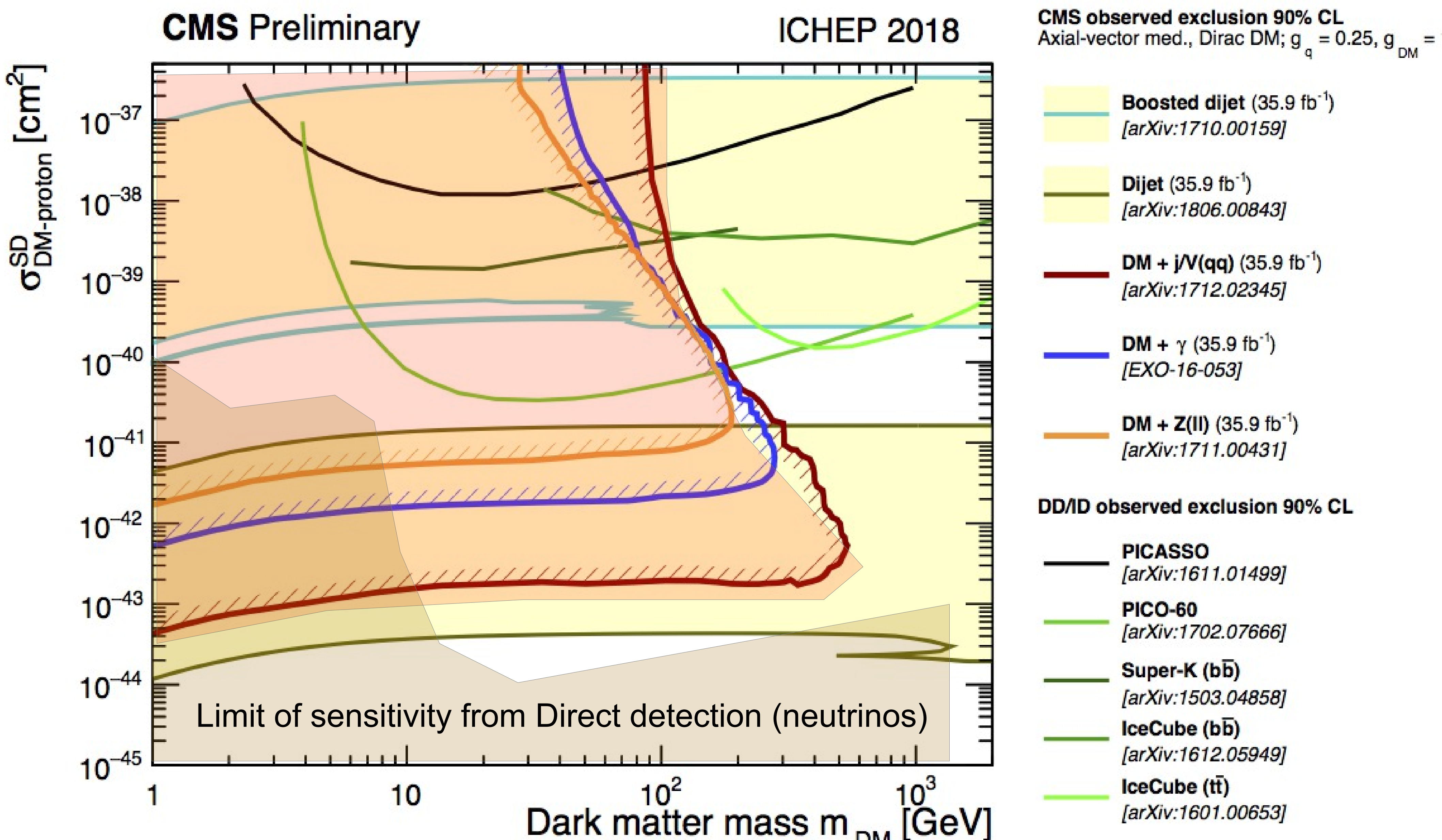
Direct Detection



Limit of sensitivity of direct detection

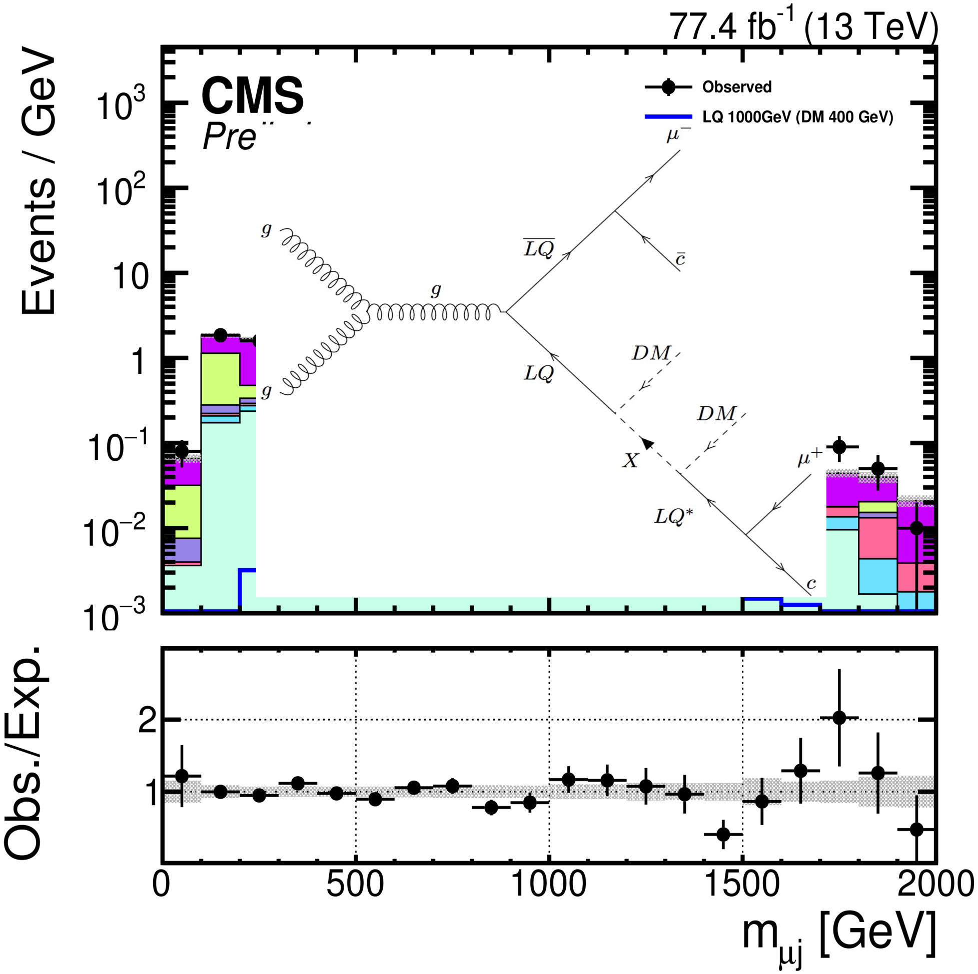
CMS-DP-2016-057

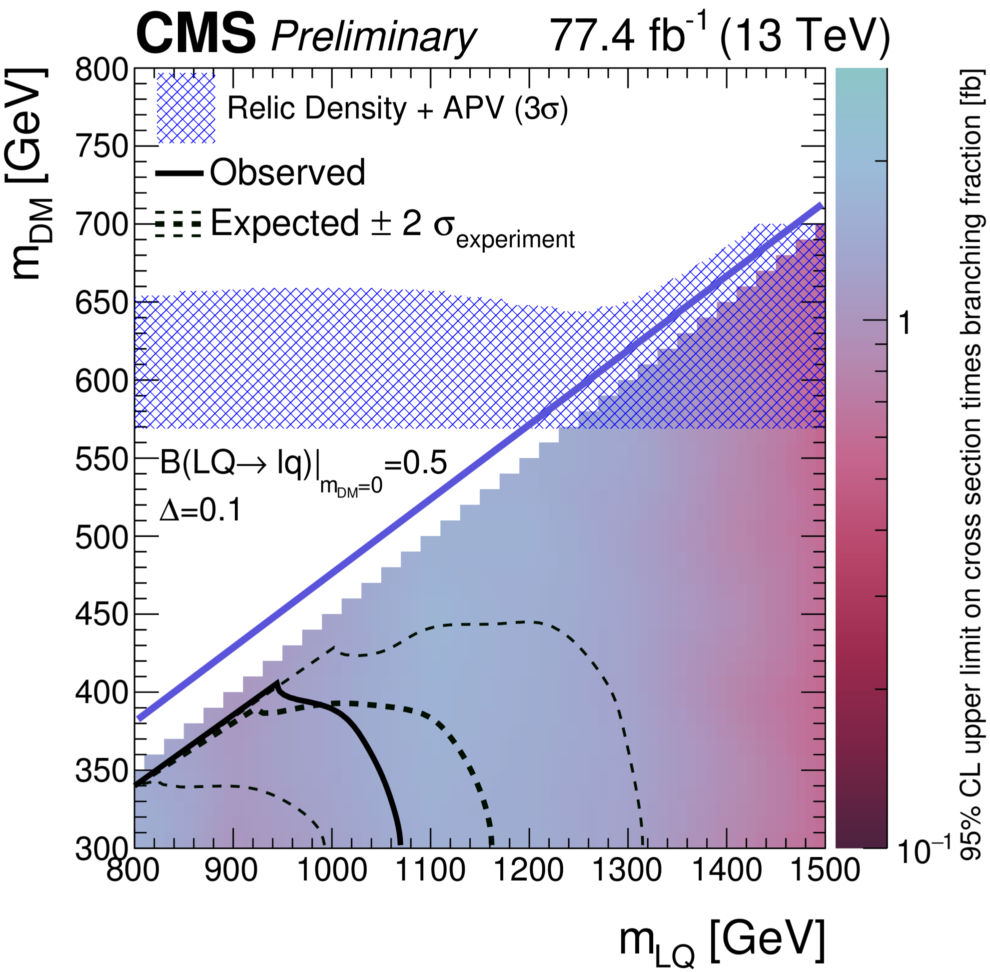
Axial Mediator



More Exotic Results?

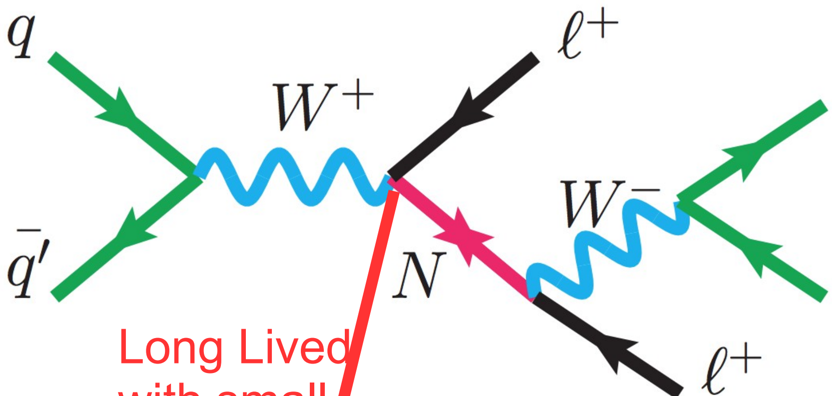
- MET+Leptoquark final state
  - A missing, but important final states from before





CMS-PAS-EXO-17-015

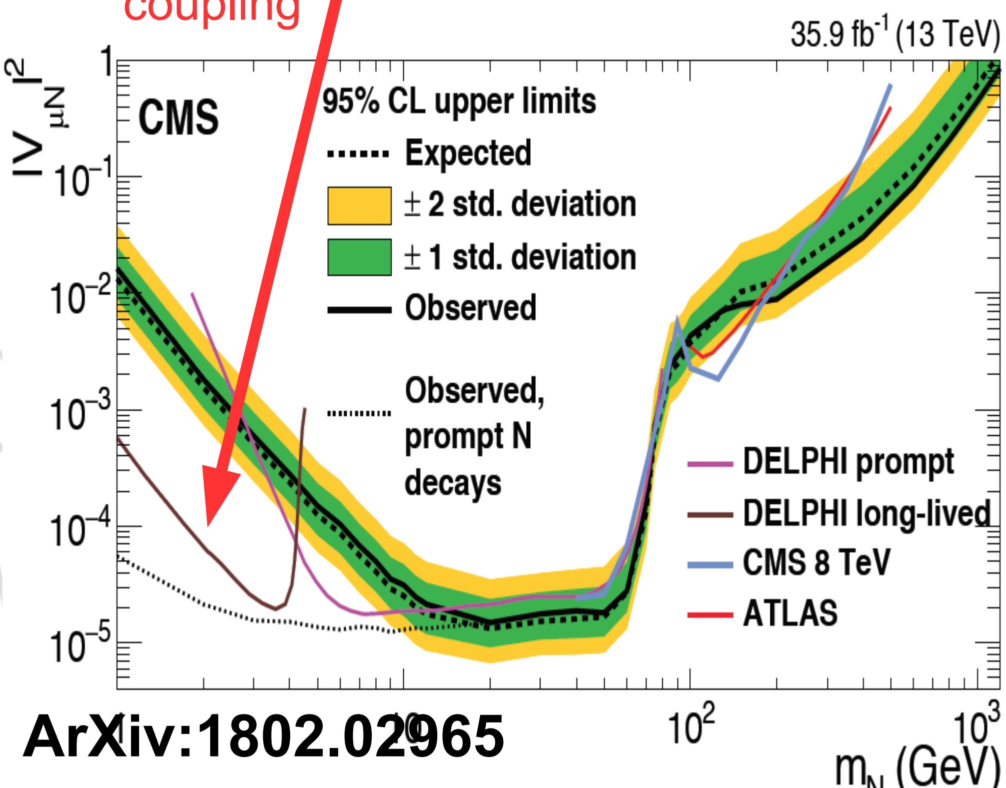
Right Handed Neutrinos

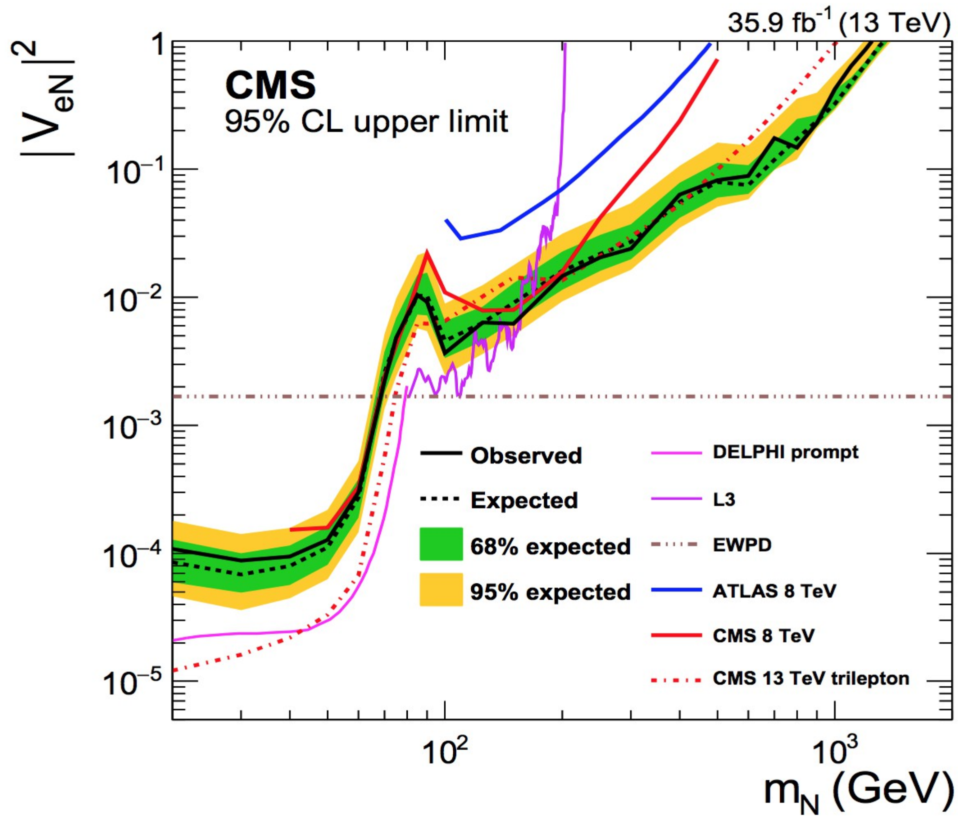


Long Lived with small coupling

Expect Bounds at low mass to improve

Once long lived analysis is performed





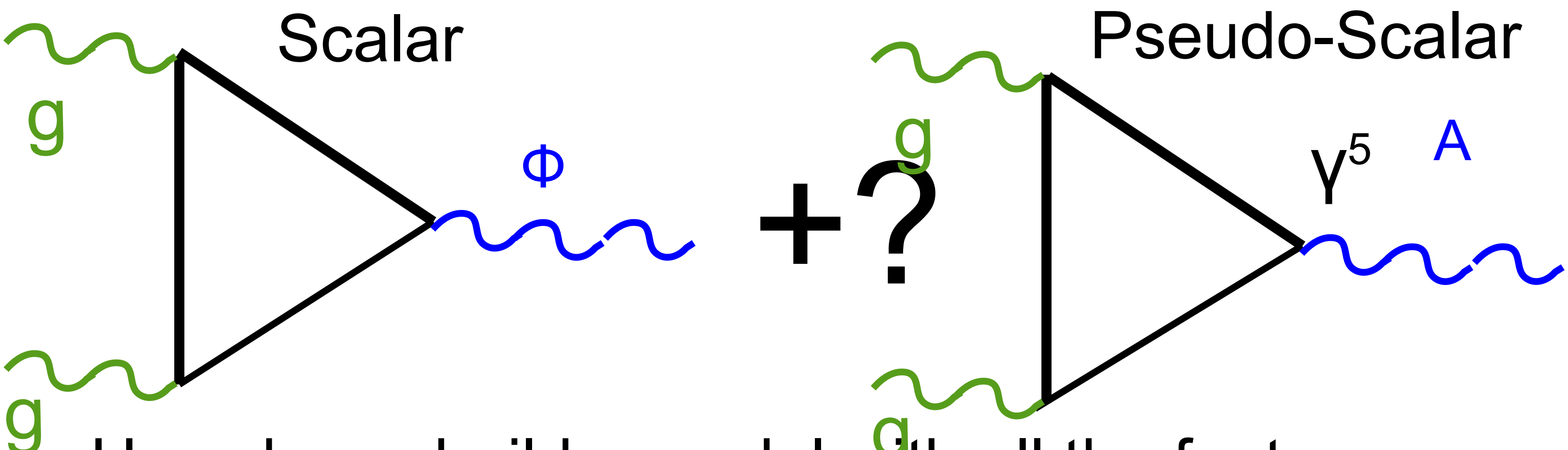
ArXiv:1802.02965

CMS-EXO-17-028

Spin 0

What do we mean by spin 1?

- A spin-1 particle has uniform couplings to fermions

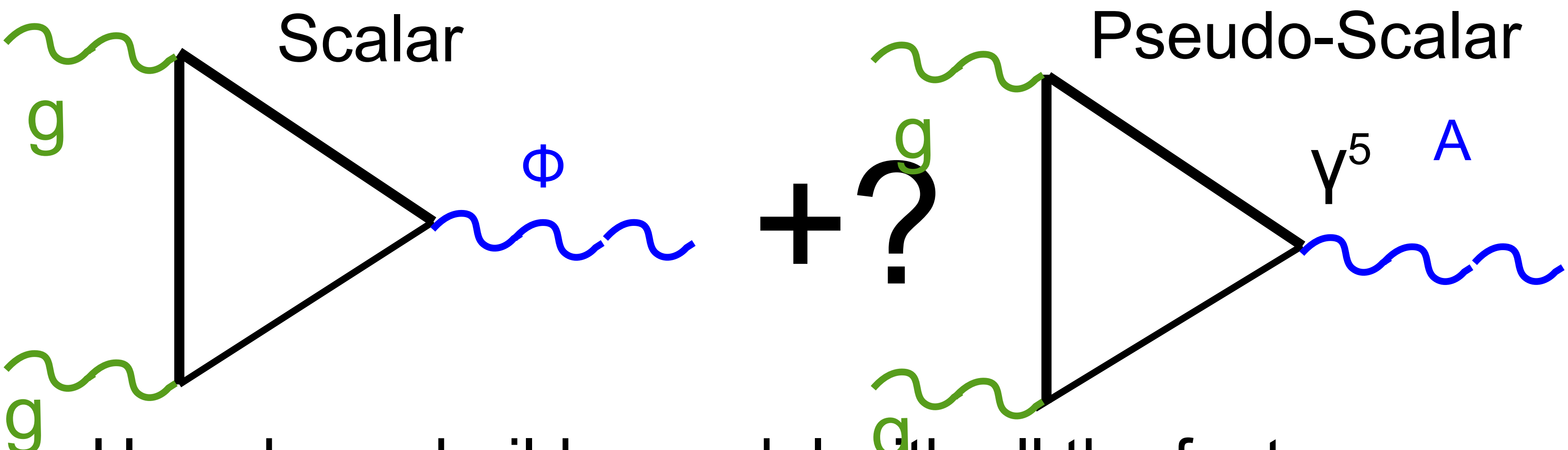


How do we build a model with all the features we want?

a. (Pseudo)scalar couples to heavy quarks (yukawa)
b. (Pseudo)scalar couples to dark matter

What do we mean by spin 1?

- A spin-1 particle has uniform couplings to fermions



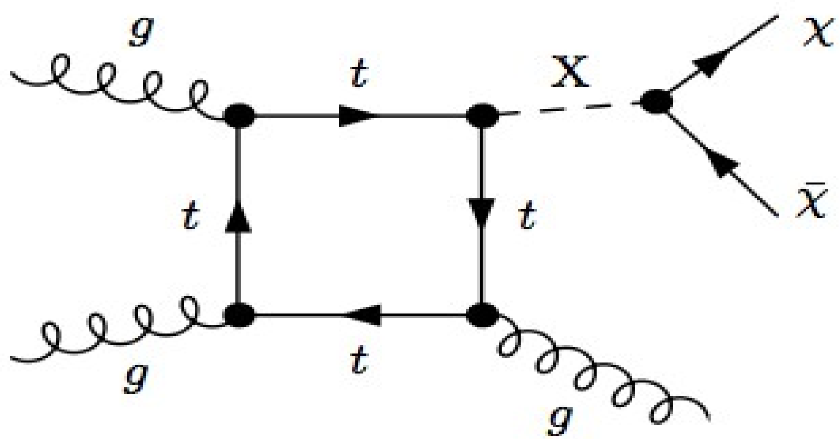
How do we build a model with all the features we want?

What about electroweak couplings?
Mostly driven by Higgs invisible (mixes w/Higgs)

What about more complete models?
Can be embedded in 2HDM

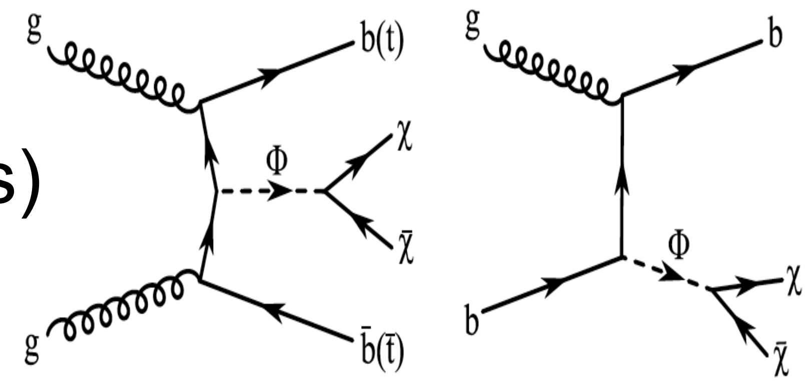
What can you do with Spin 0?

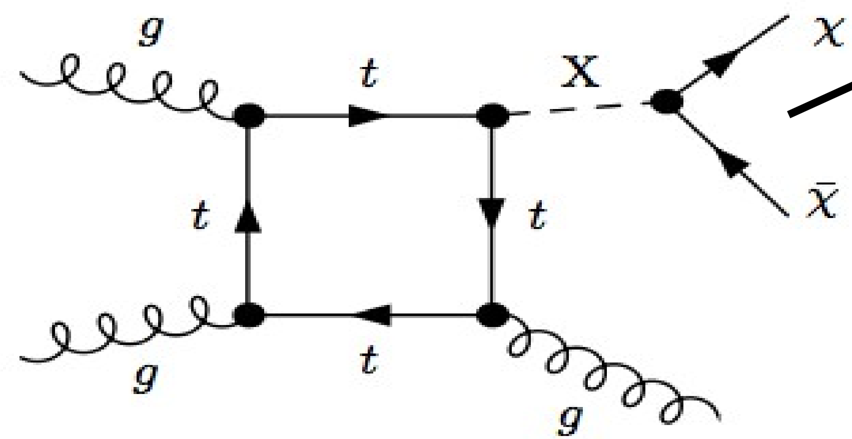
Basic production is gluon fusion
Amplitude is double for pseudoscalar mediator



What can you do with Spin 0?

Heavy flavor channels
Can be added with (same couplings)

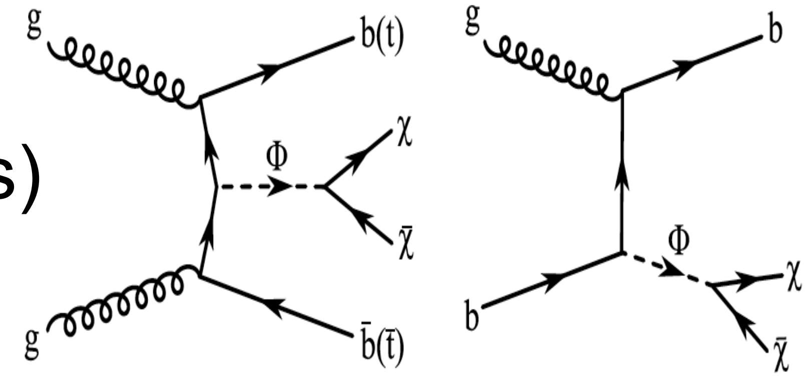


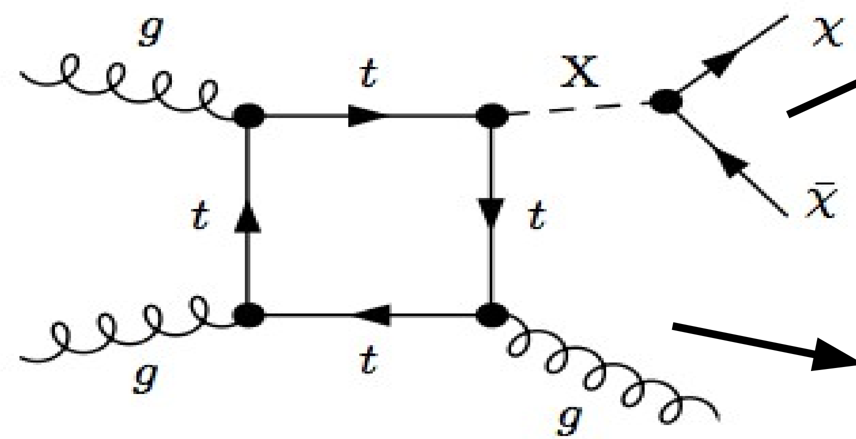


Heavy Flavor
final states

What can you do with Spin 0?

Heavy flavor channels
Can be added with (same couplings)

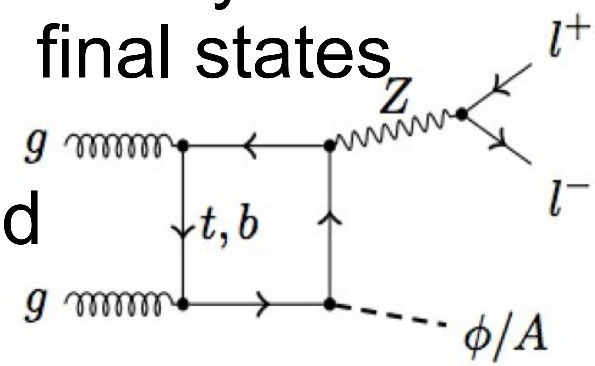




Loop induced
Z boson

Heavy Flavor
final states

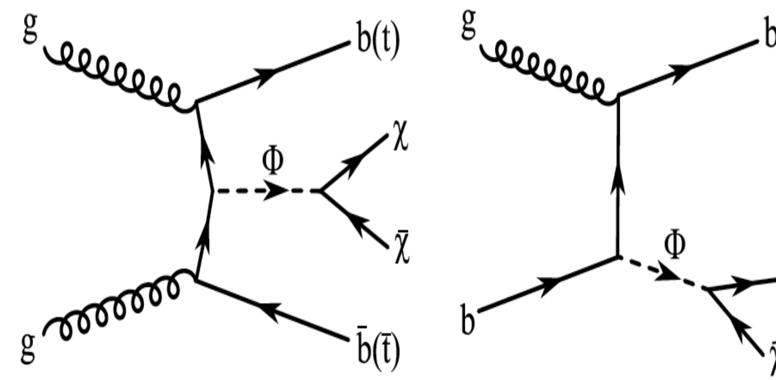
EXO16028



EXO16052

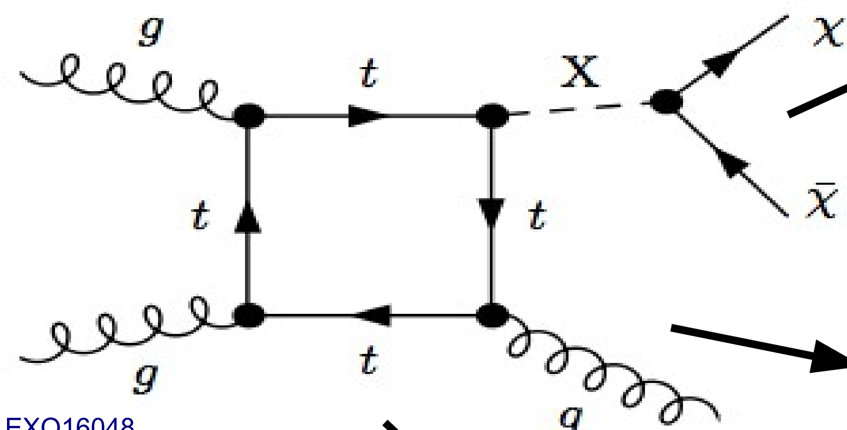
What can you do with Spin 0?

Big Assumption :
No mixing w/Higgs



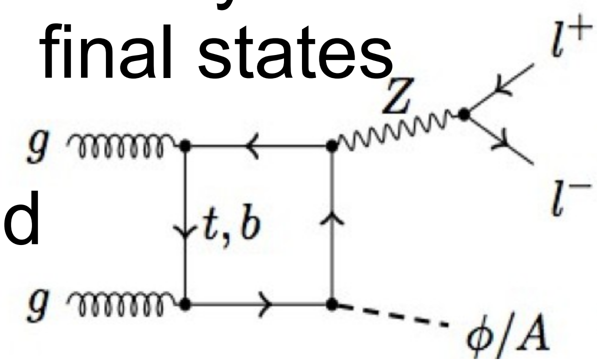
EXO16028

Heavy Flavor
final states



EXO16048

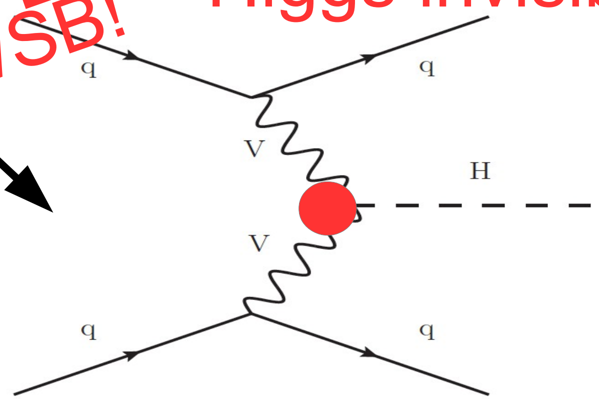
Loop induced
Z boson

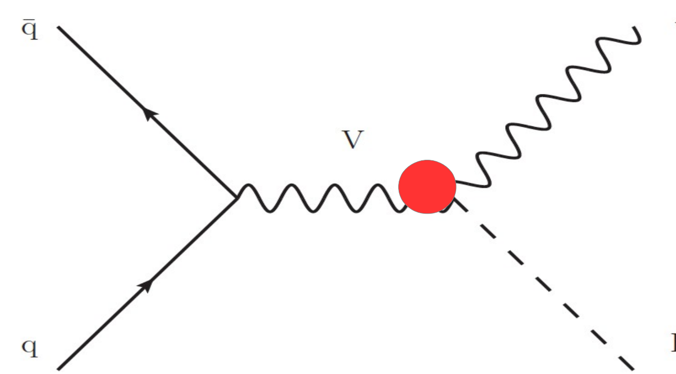


EXO16052

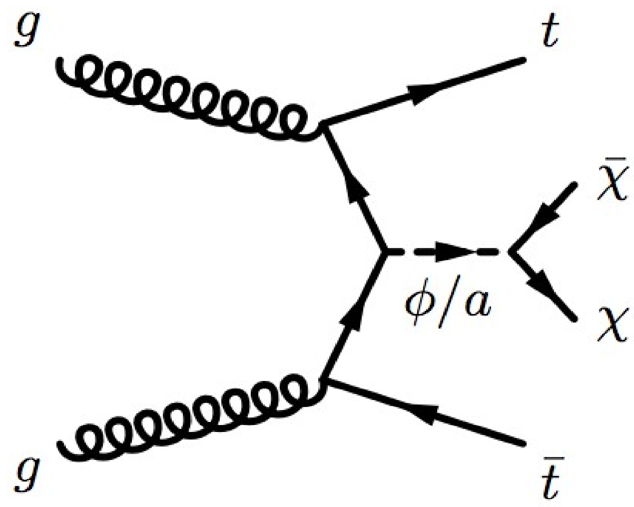
Higgs invisible or Scalar w/EWSB

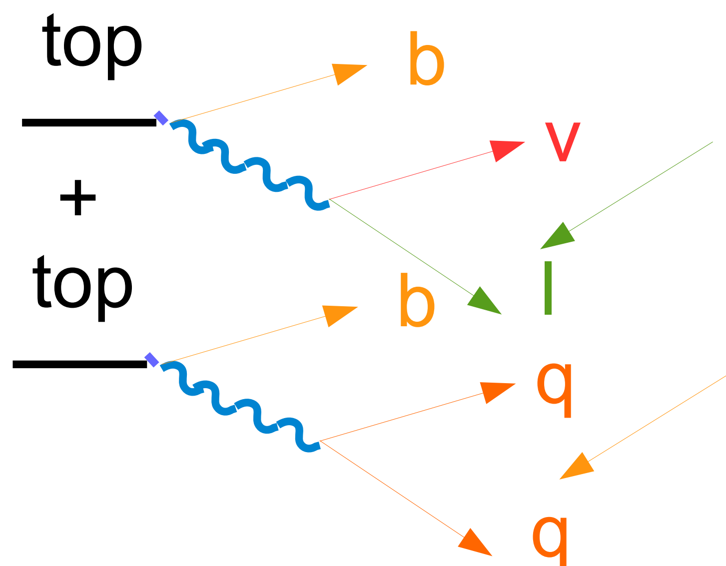
Applying EWSB!





Understanding the Scalar



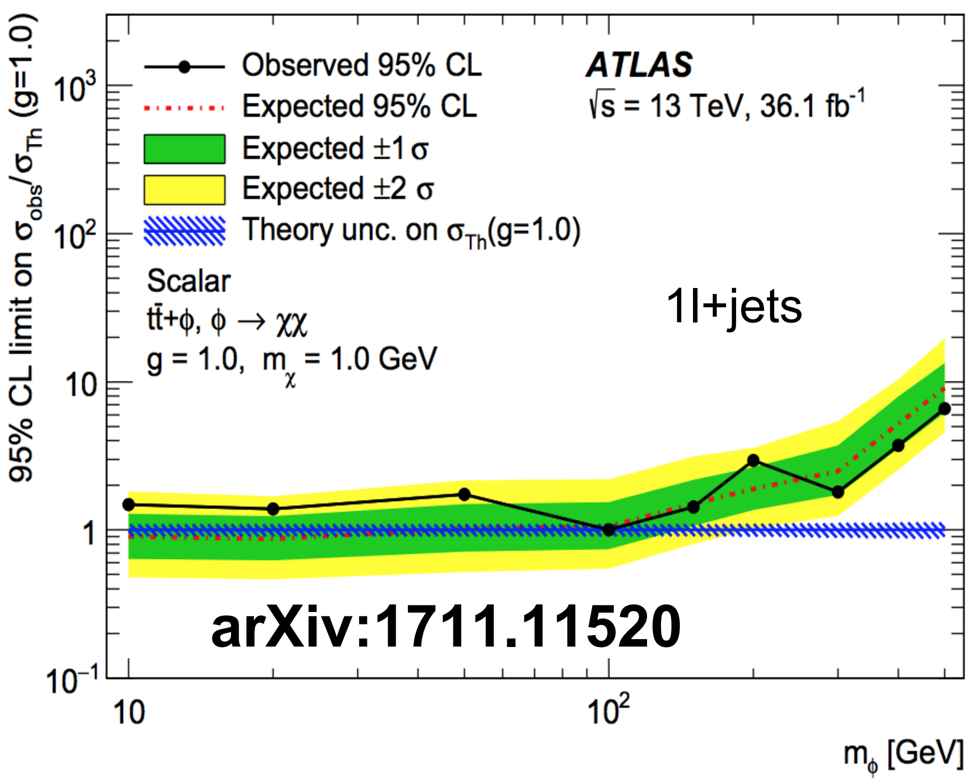


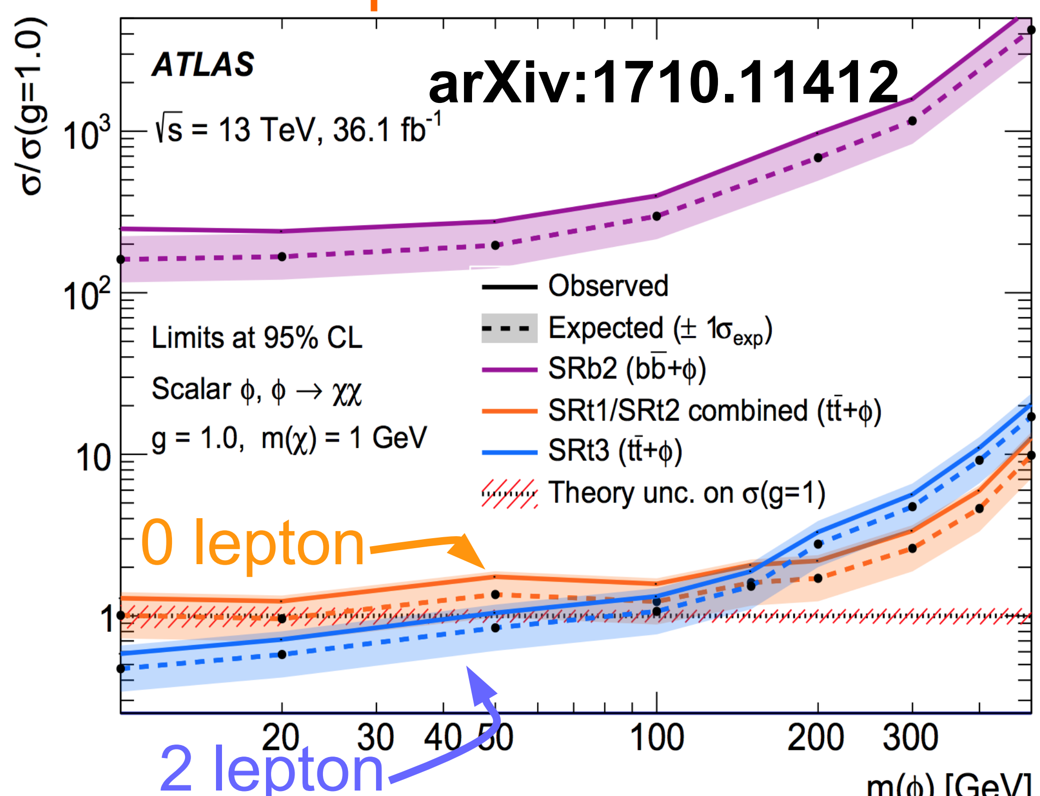
Yields 3 cats:

2 lepton

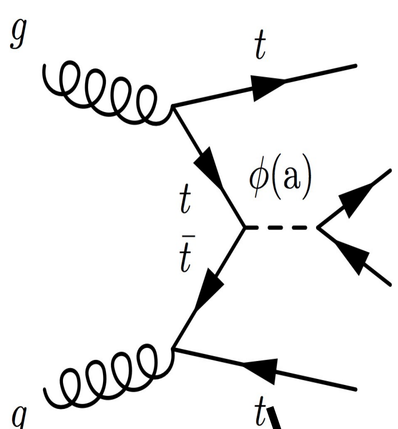
1 lepton

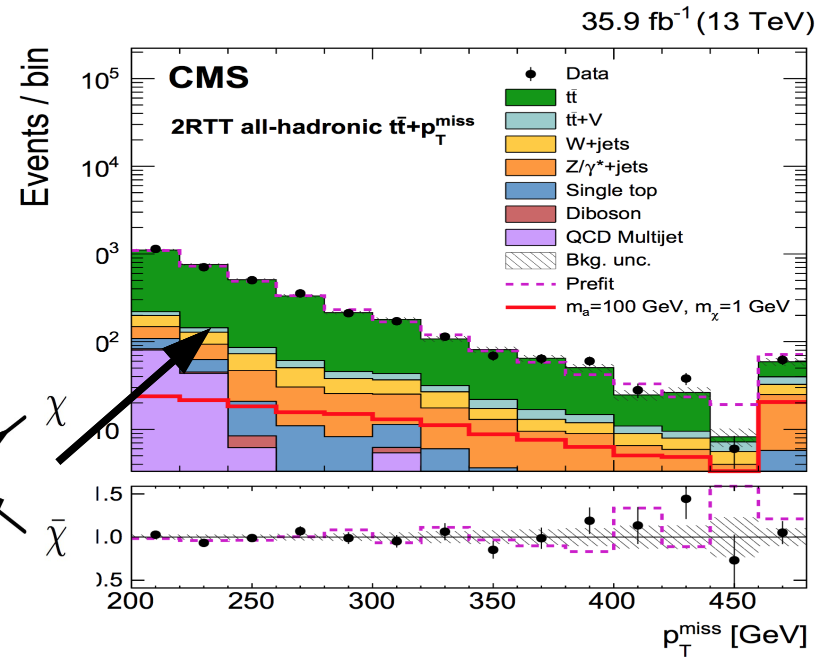
0 lepton

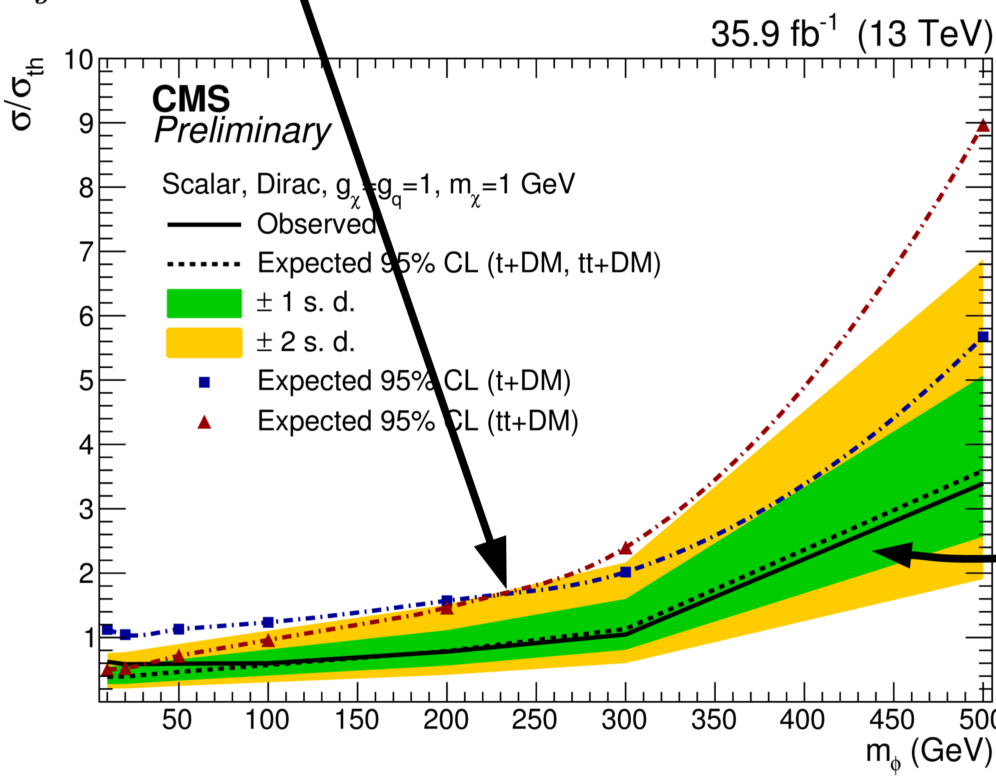


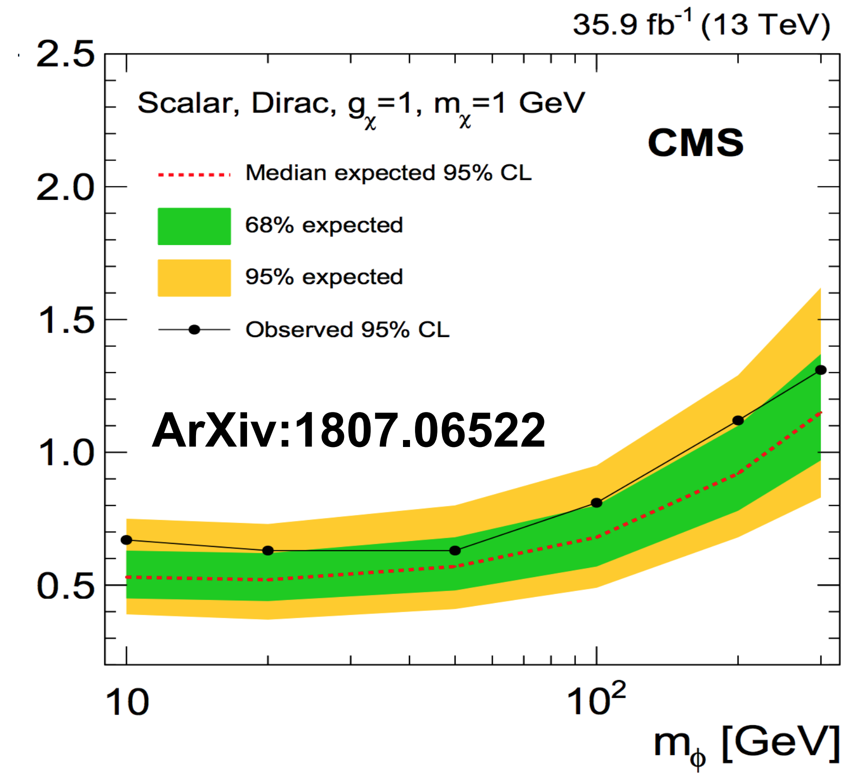


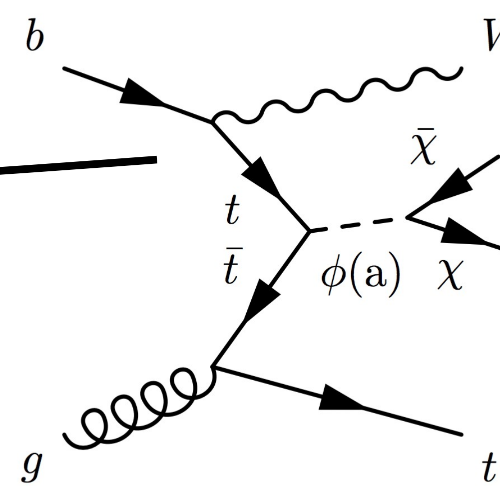
And from CMS







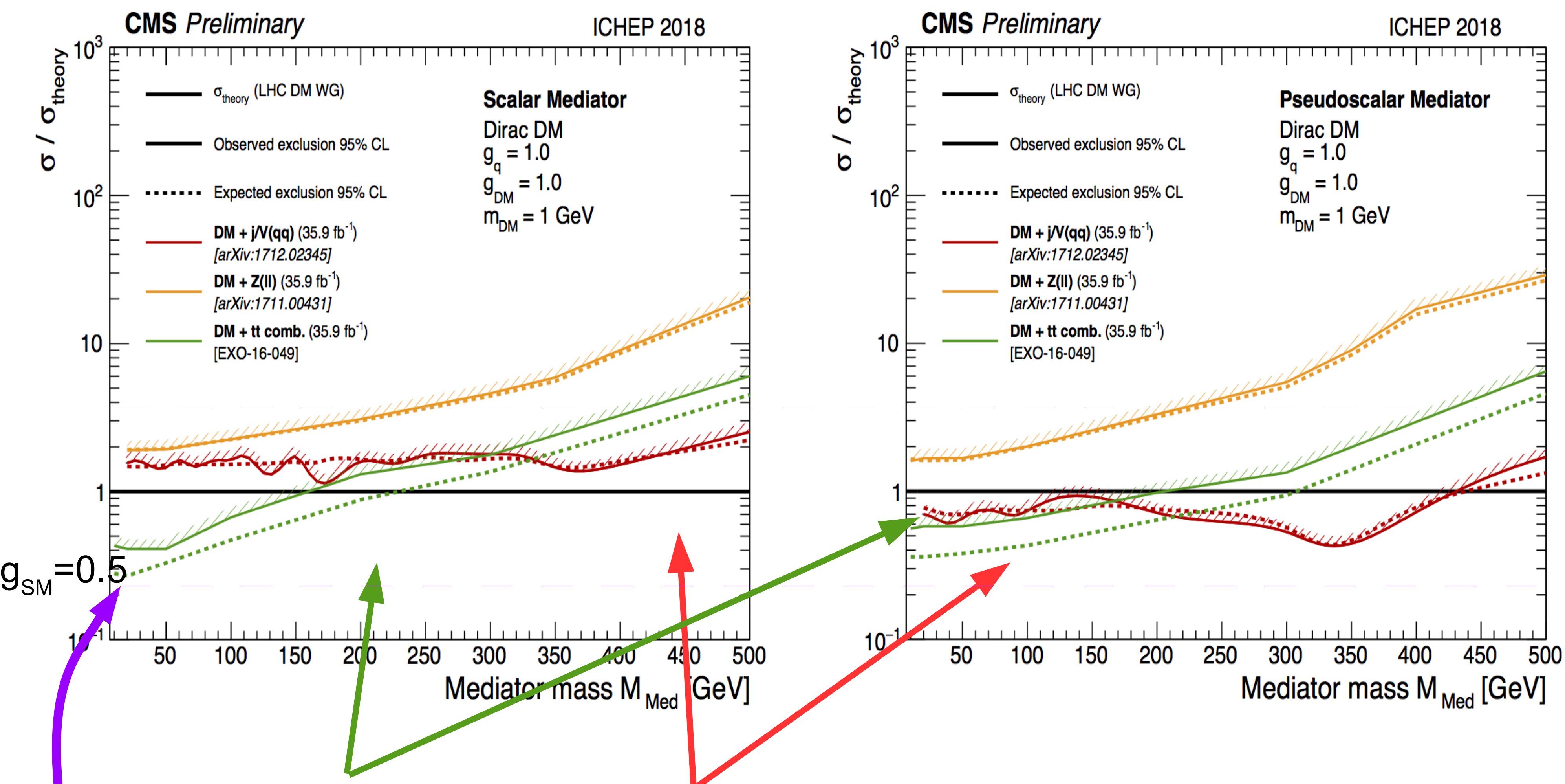




CMS-EXO-18-010

No EWSB

Comparing all channels

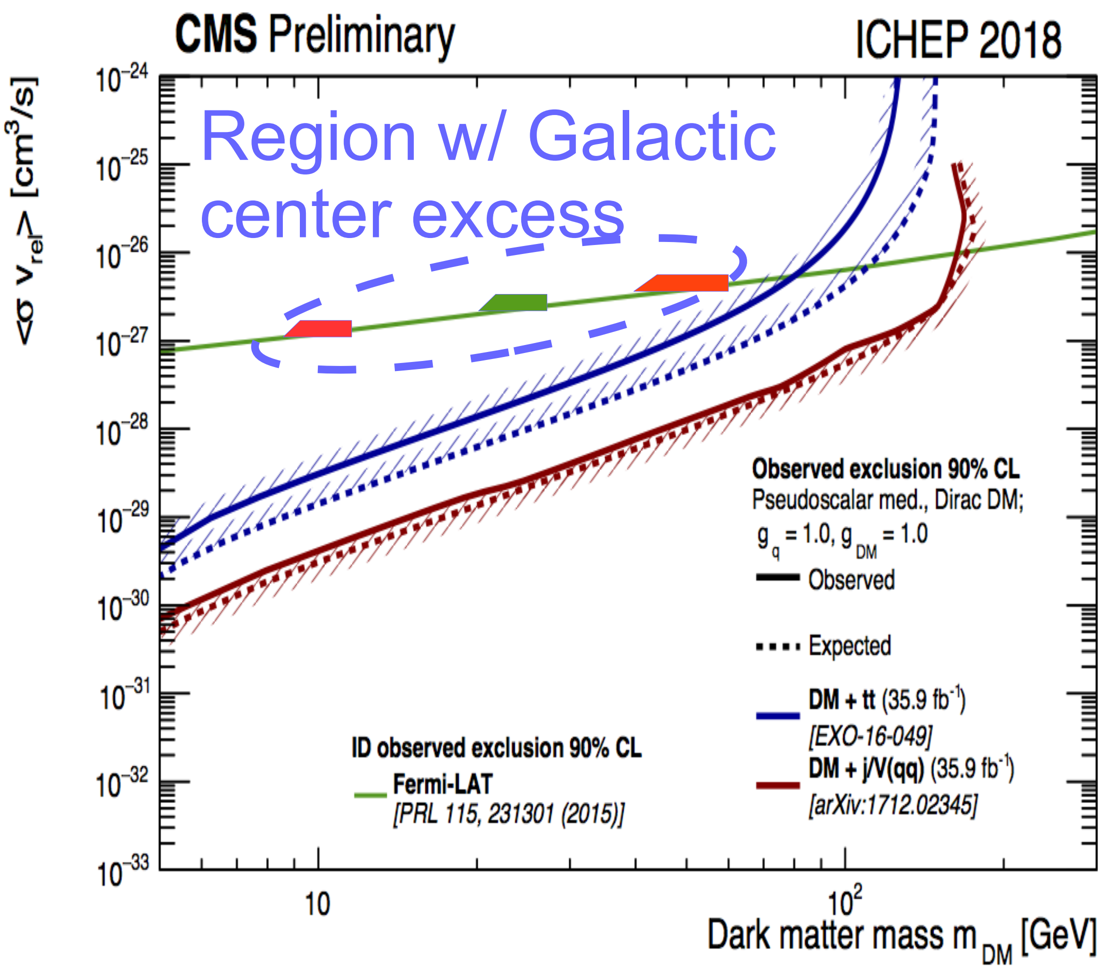


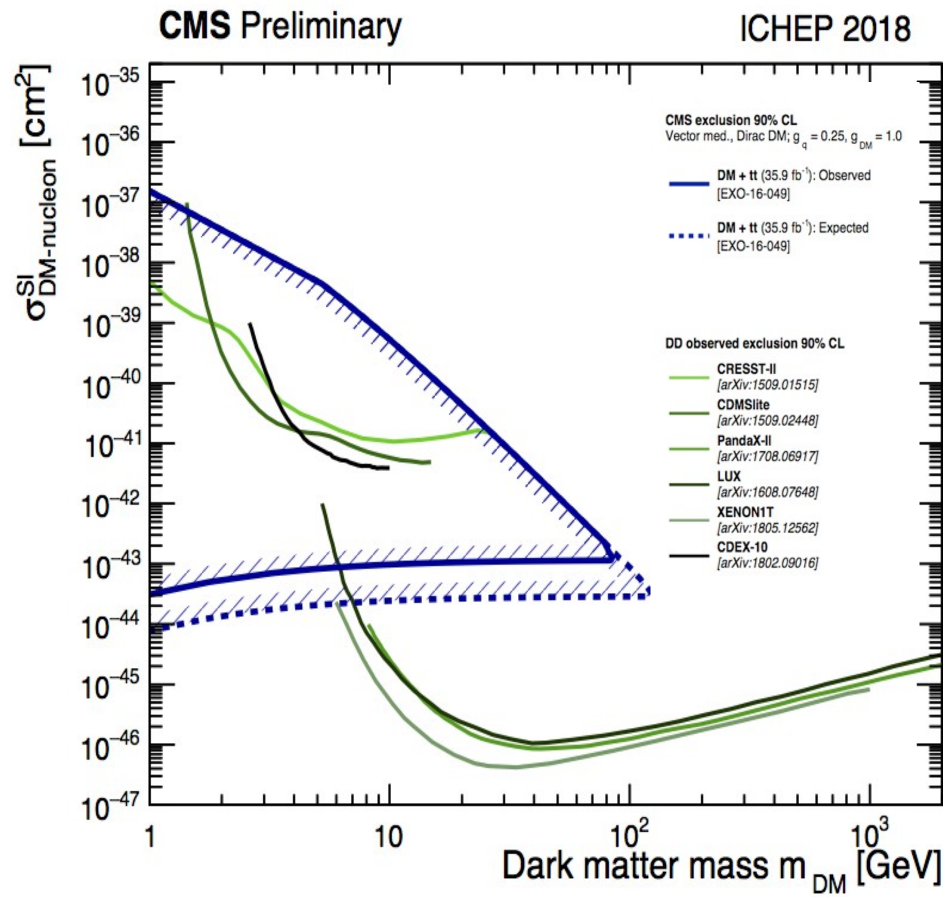
tt+DM and monojet drive the high mass

Not far from an intermediate benchmark of g_{SM} = 0.5

Whats the impact?

No EWSB





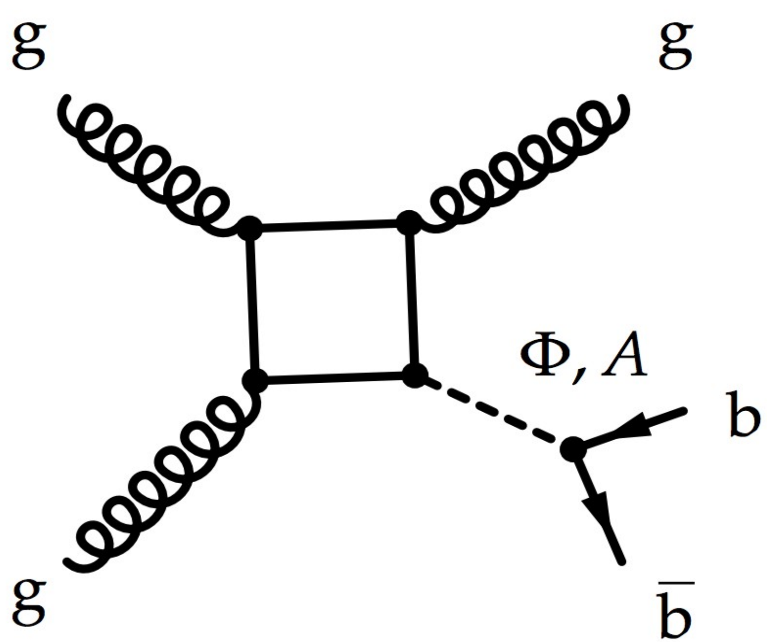
Indirect detection (Pseudoscalar)

direct detection (Scalar)

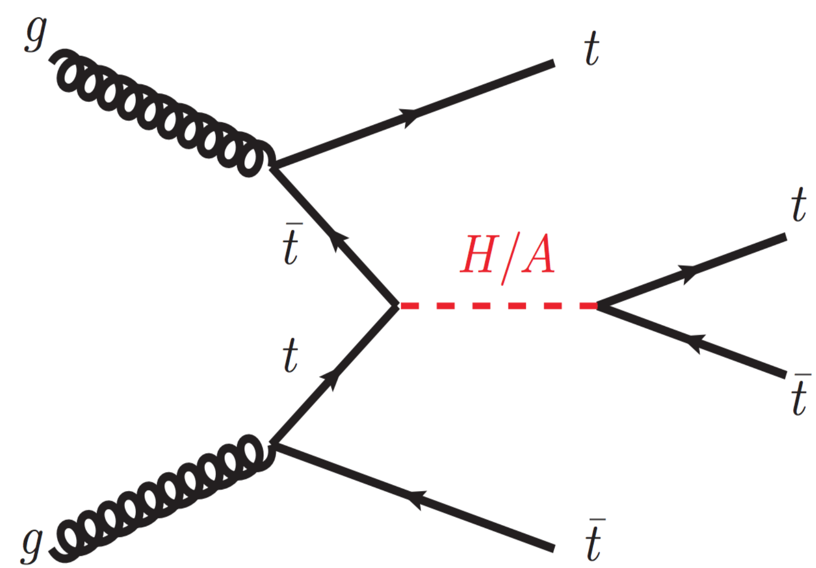
https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryPlotsEXO13TeV

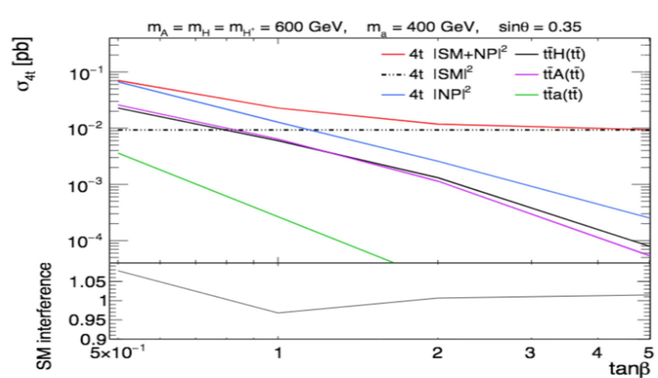
What about visible channels?

Low mass scalar/Pseudo scalar search



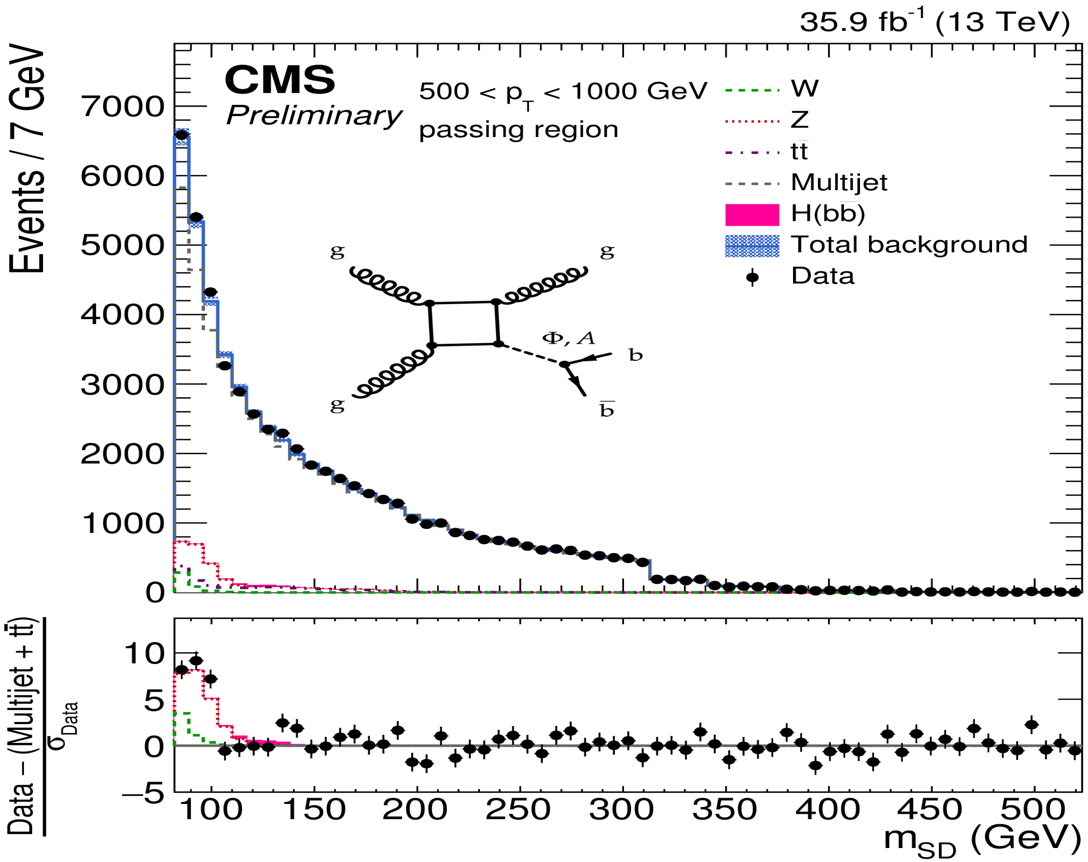
High mass scalar/Pseudo scalar search



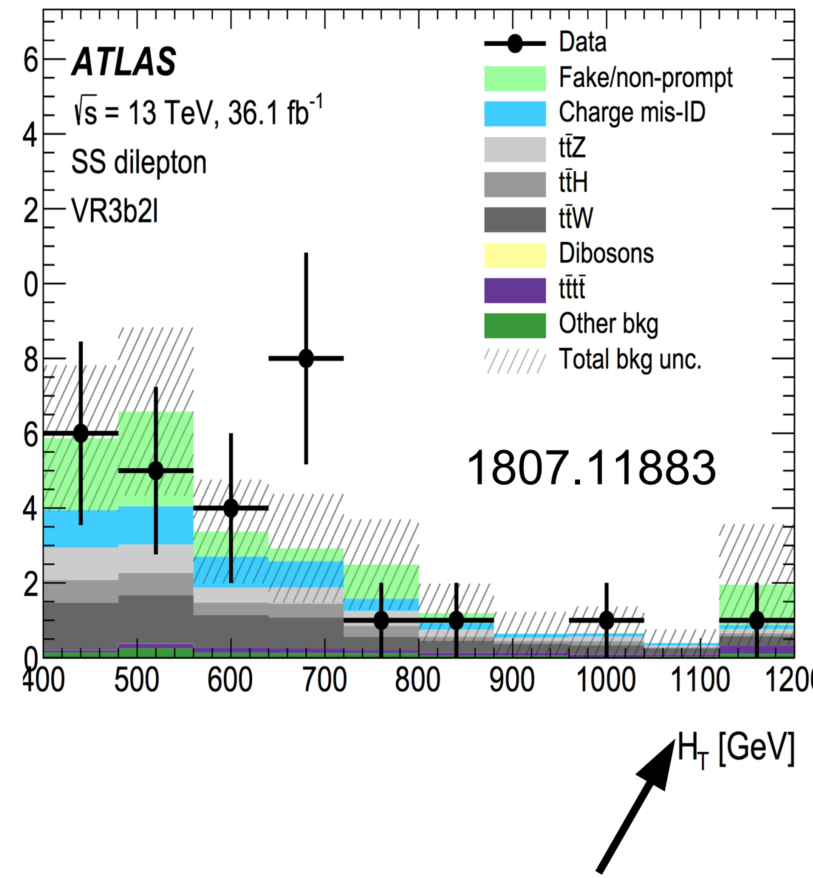


For scalars we traditionally embed them into 2HDM models
See upcoming DMWG report for extensive details!

What about visible state?

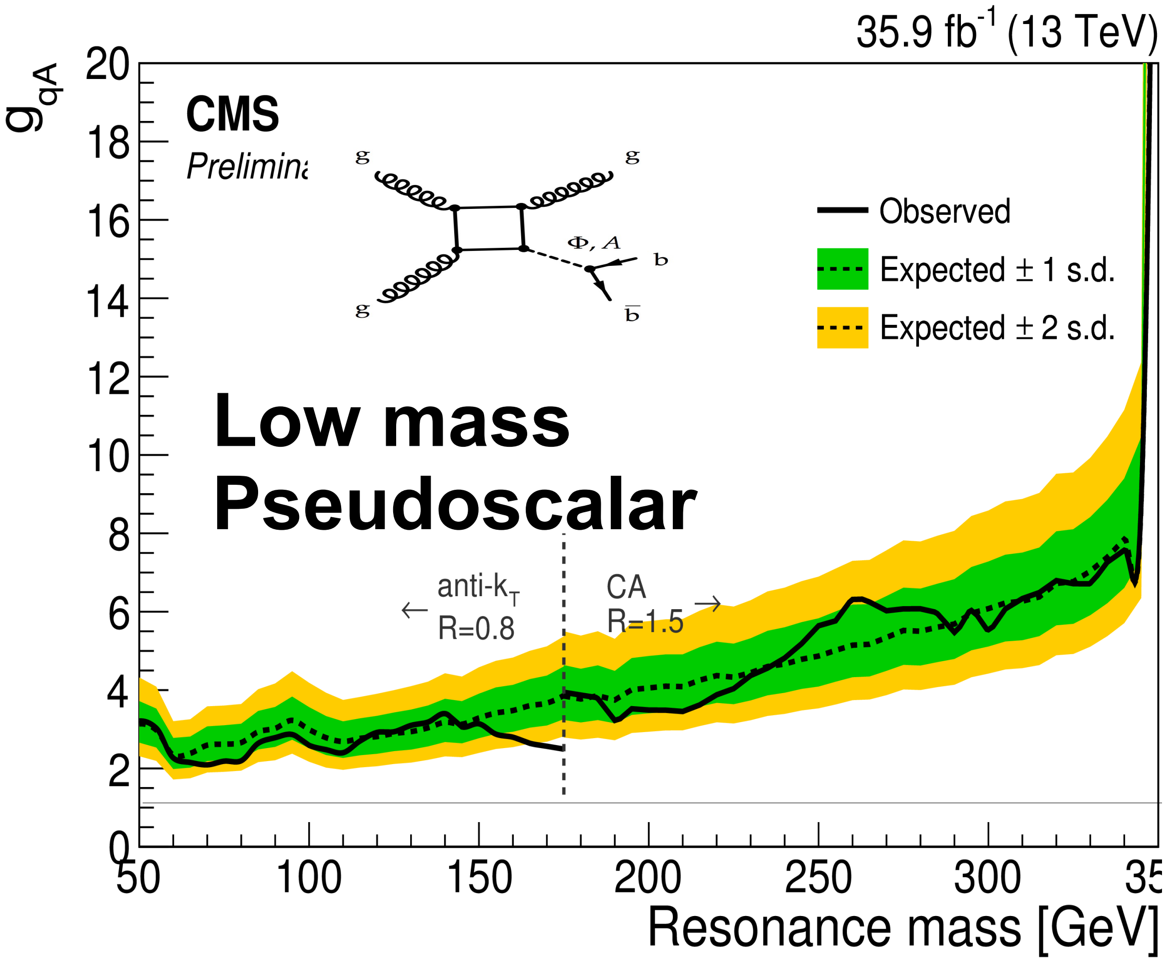


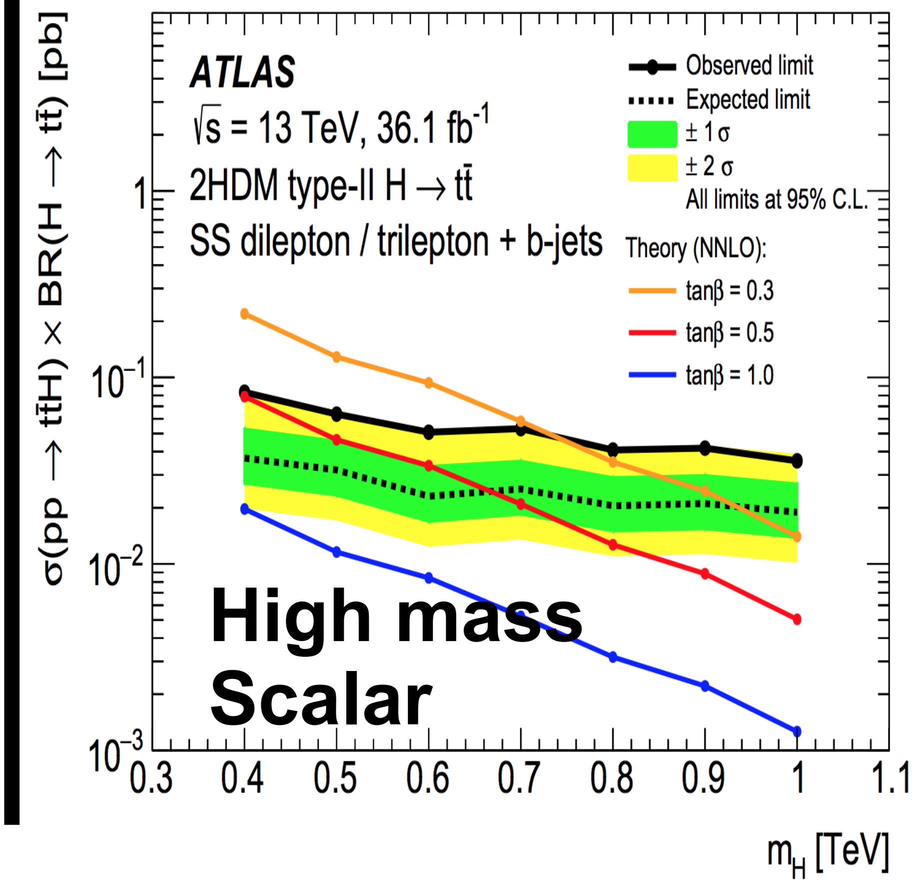
Fit in jet mass for double b-taggged jets



Fit in same-signed letons With b-tags

What about visible state?



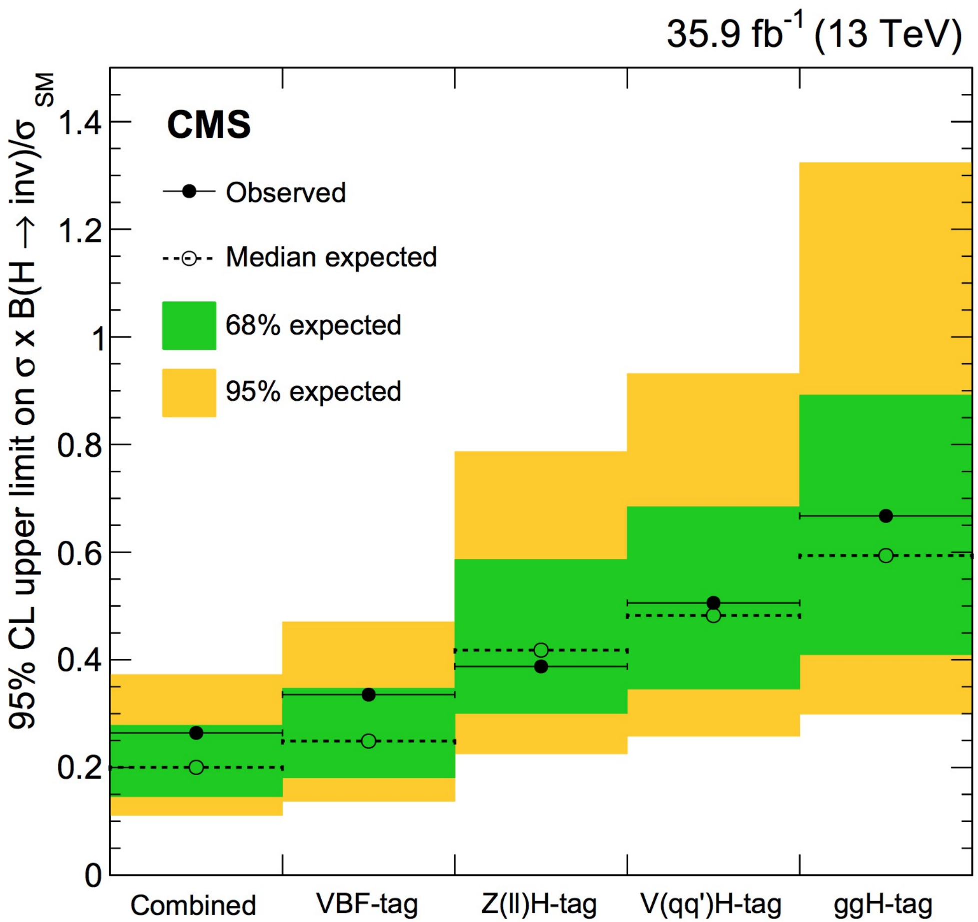


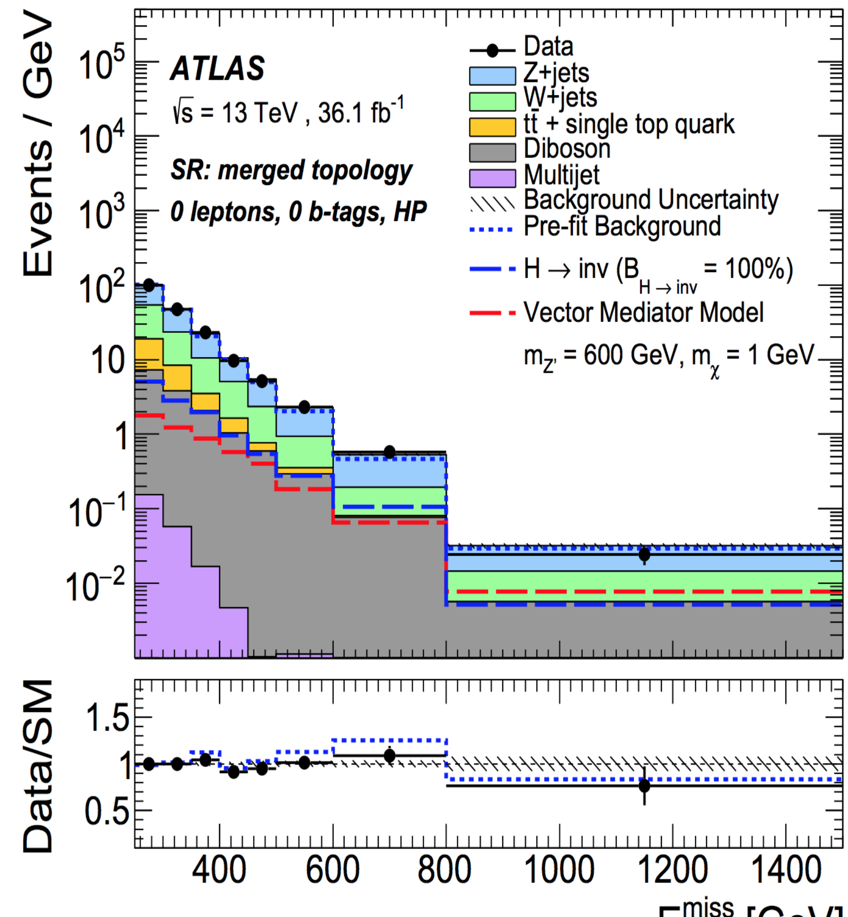
Currently probing cross sections that are
4 times larger than invisible searches

EWSB

At the Higgs mass

- This model is the same as Higgs invisible search





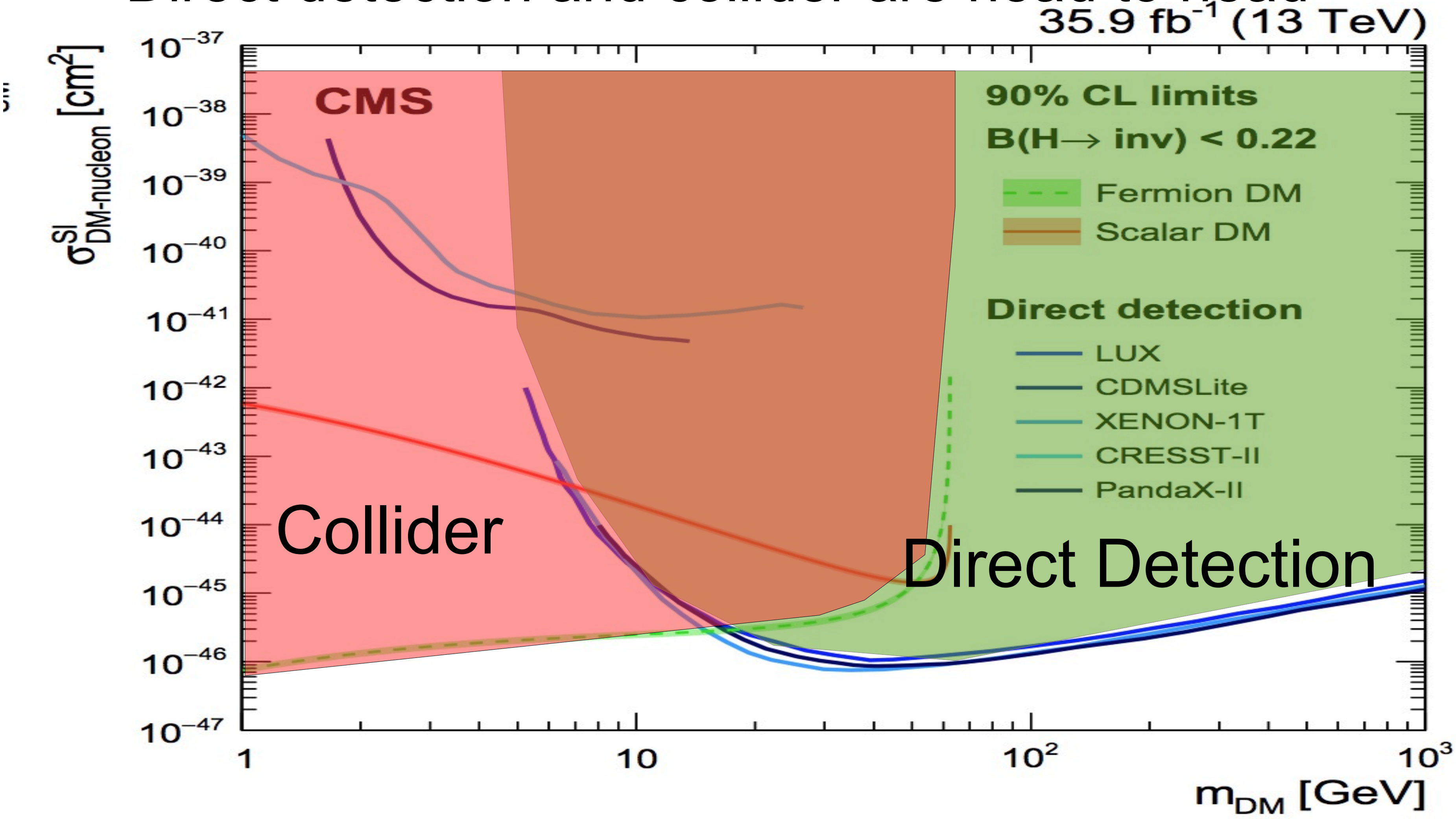
arXiv:1809.05937
arXiv:1809.06682

1807.11471 1809.06682

BR(H→Inv) < 26%(20% exp)(CMS) 25%(27% exp) (ATLAS)

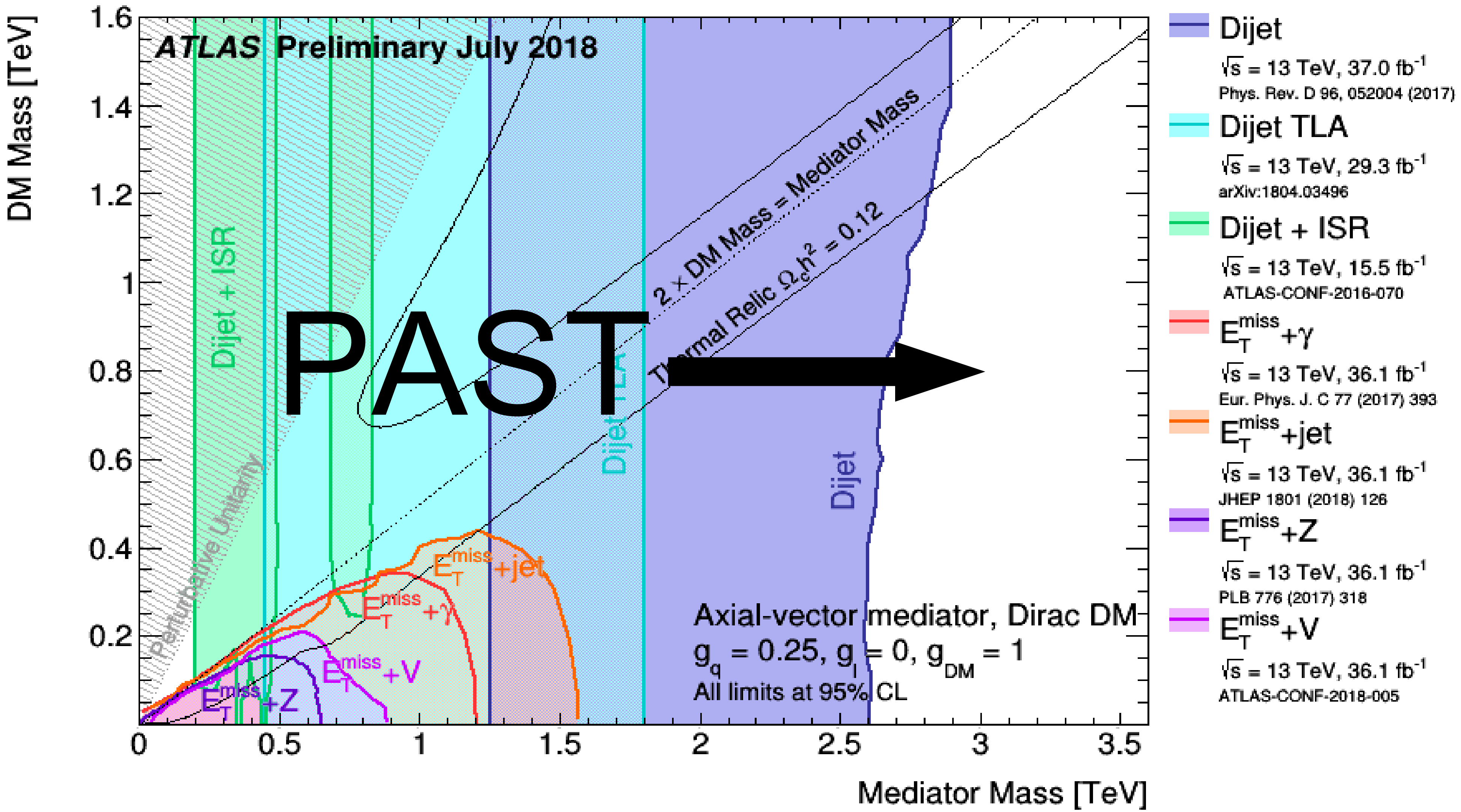
At the Higgs mass

- Higgs to invisible :
  - Direct detection and collider are head to head



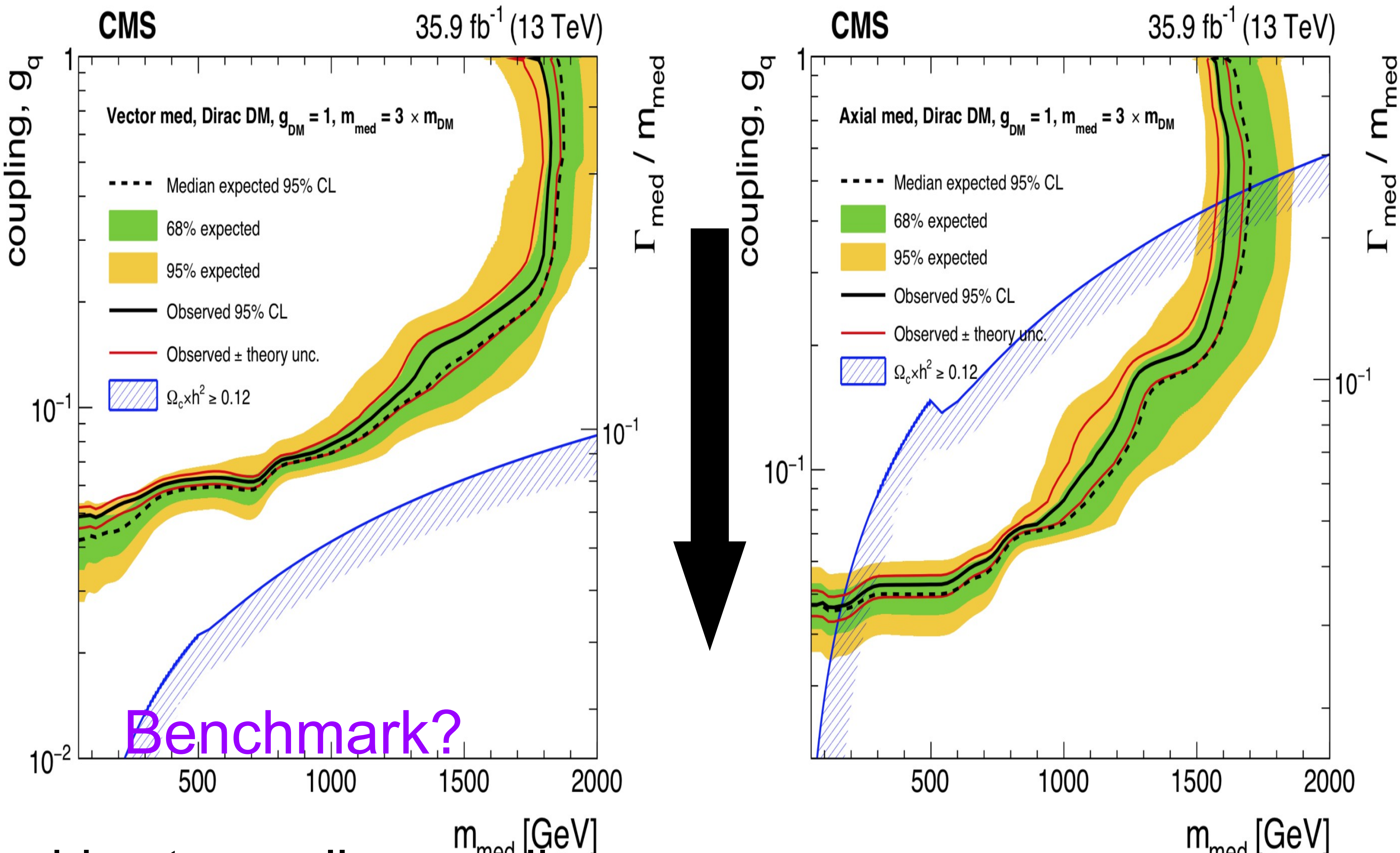
BR(H→Inv) < 26% (CMS) 25% (ATLAS)

Conclusions



Pushing to higher masses

Present Conclusions



Pushing to smaller couplings

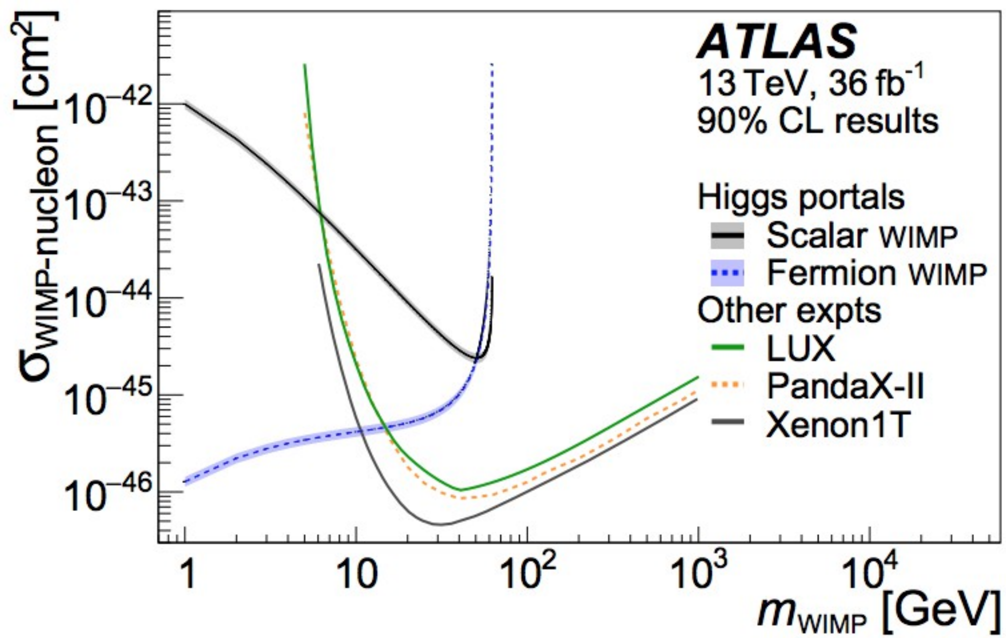
Forever

SM BSM

Thanks!

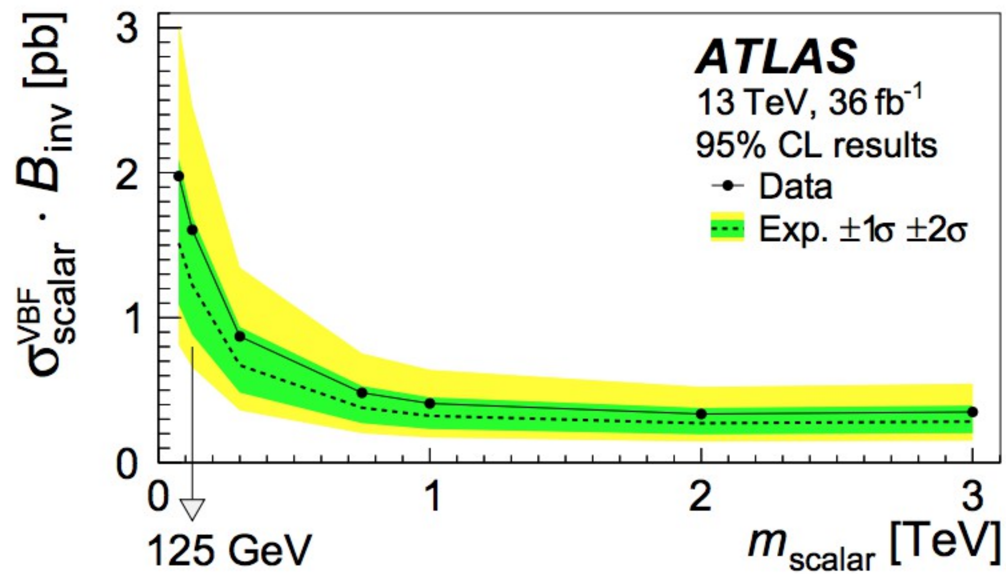
ATLAS Higgs Invisible

(a)



Direct Detection in VBF

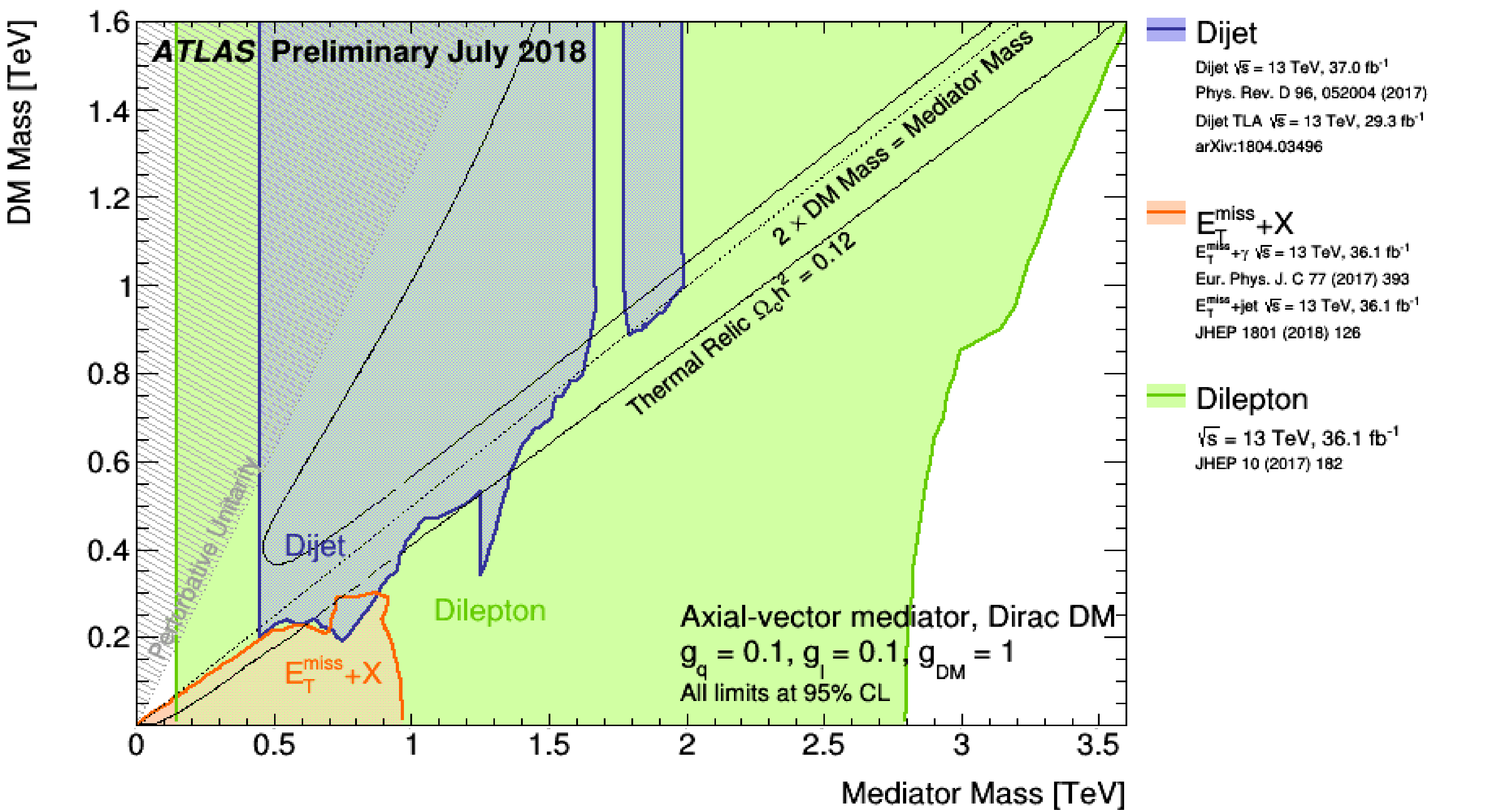
(b)



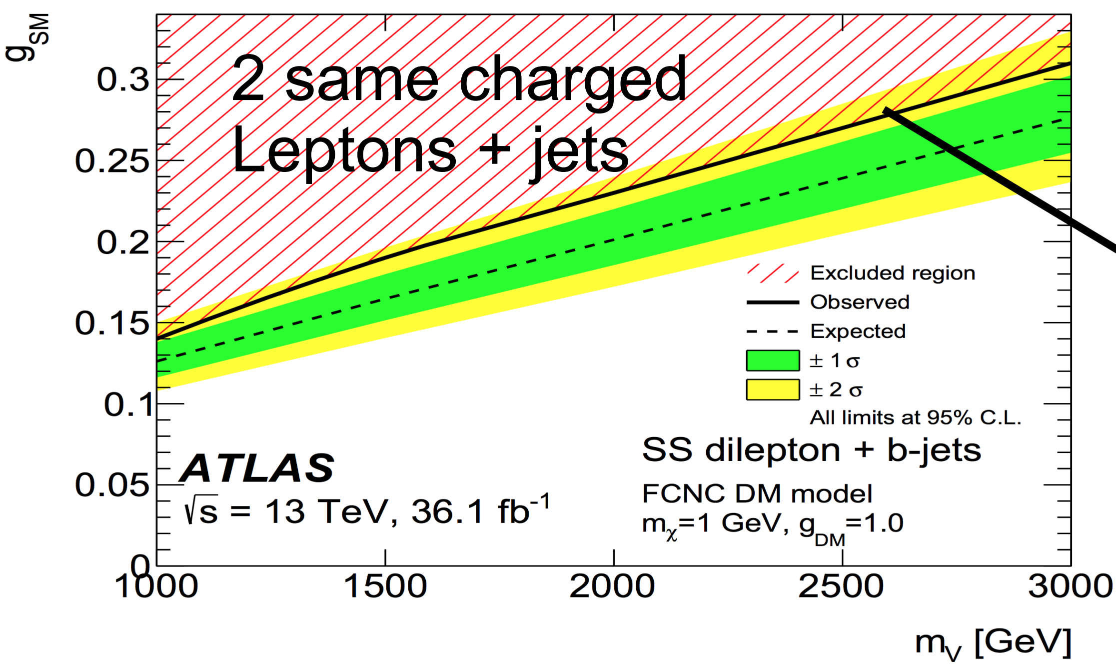
Scalar bounds in VBF

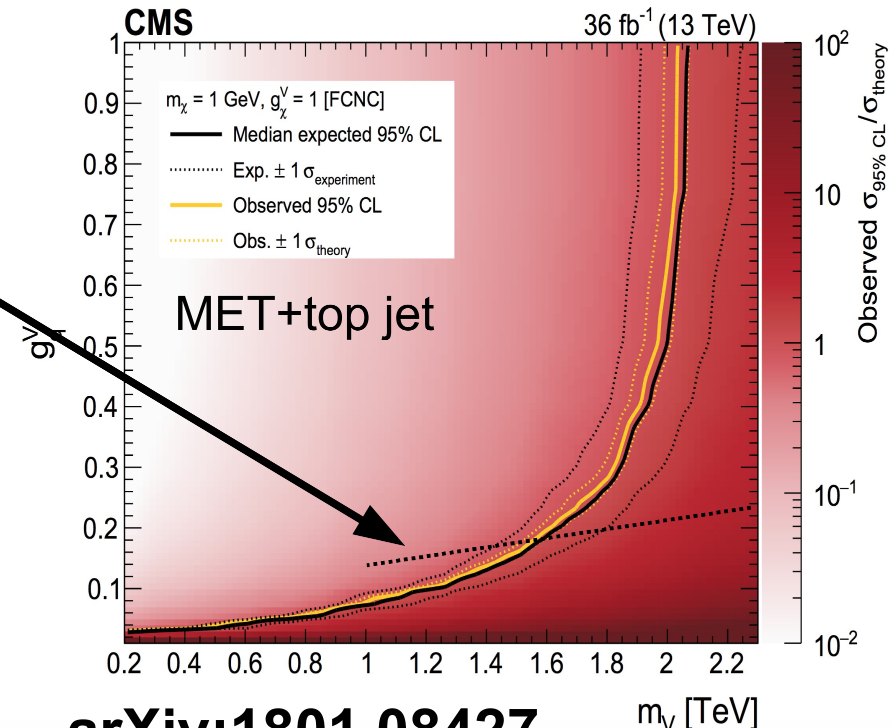
Now with adding the leptons

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/index.html#



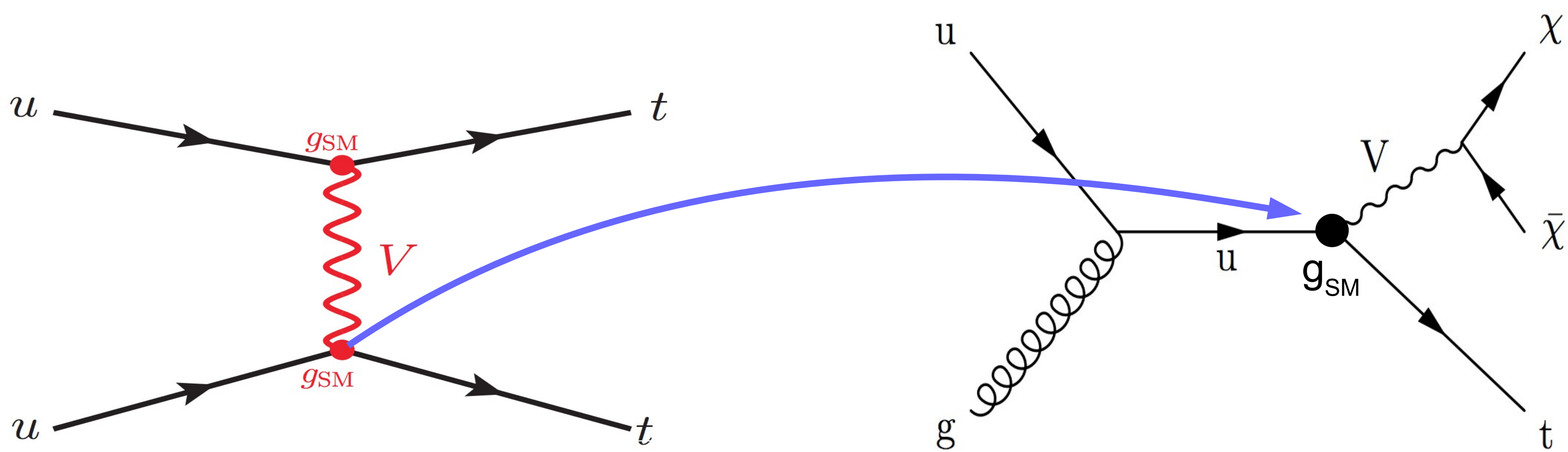
Some of the more creative combos



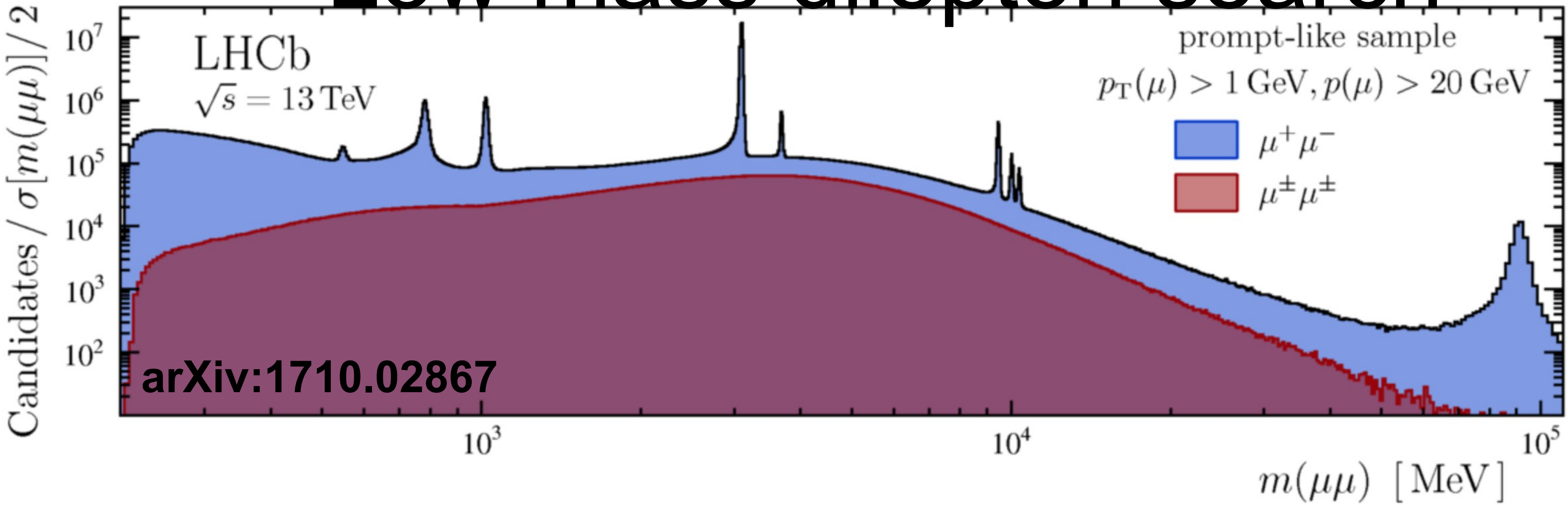


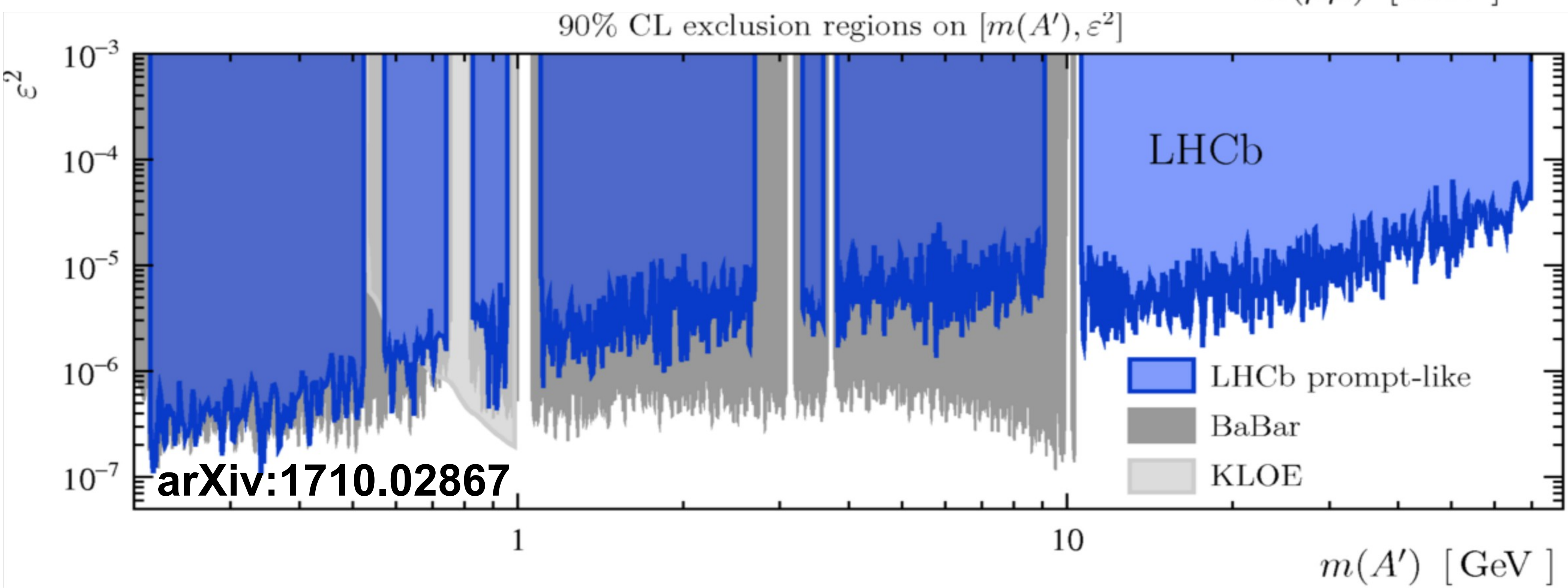
arXiv:1807.11883

arXiv:1801.08427

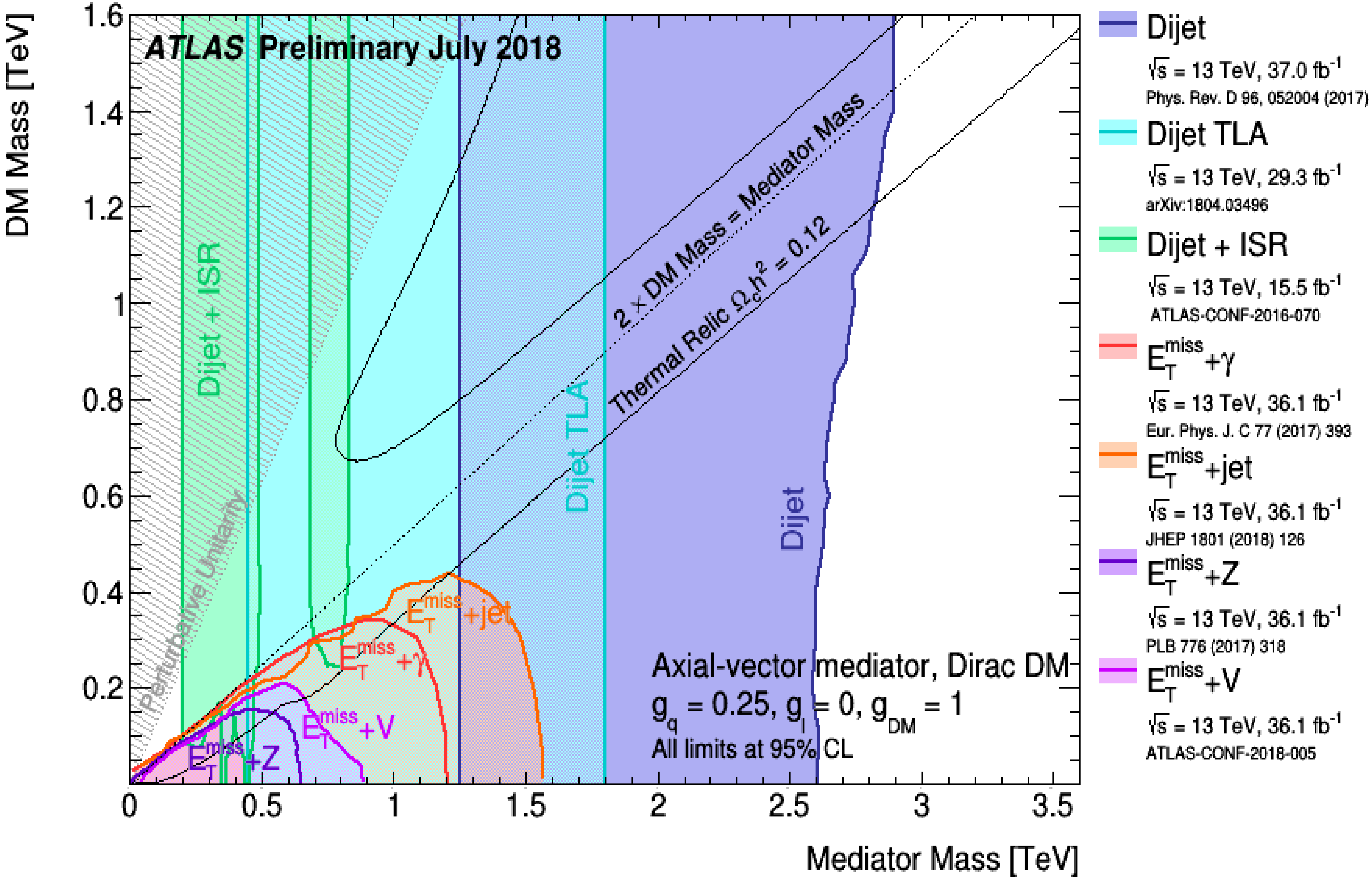


Low mass dilepton search





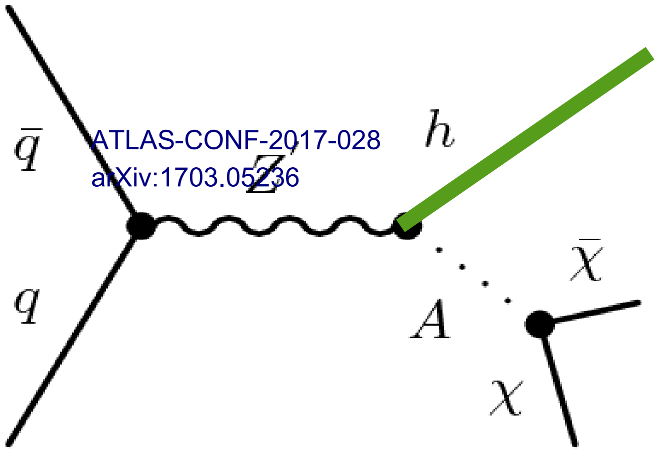
Looking at bounds from ATLAS



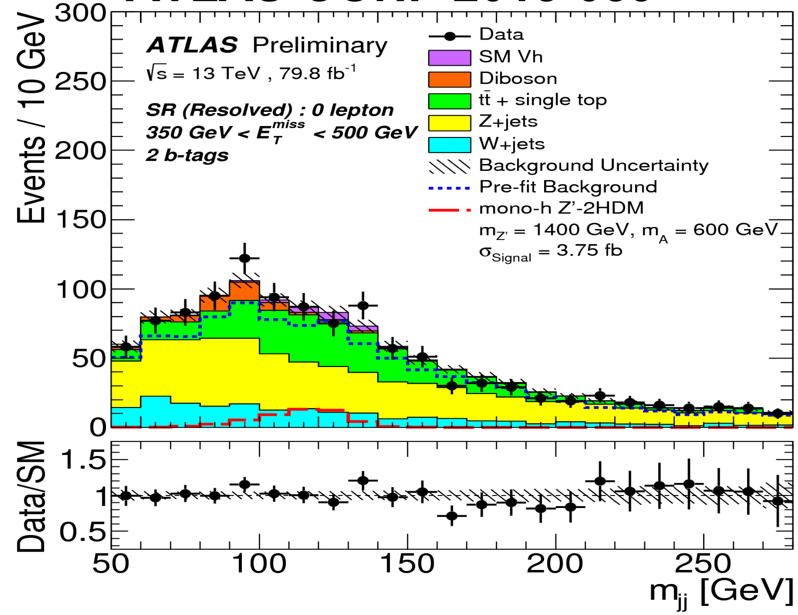
tml#

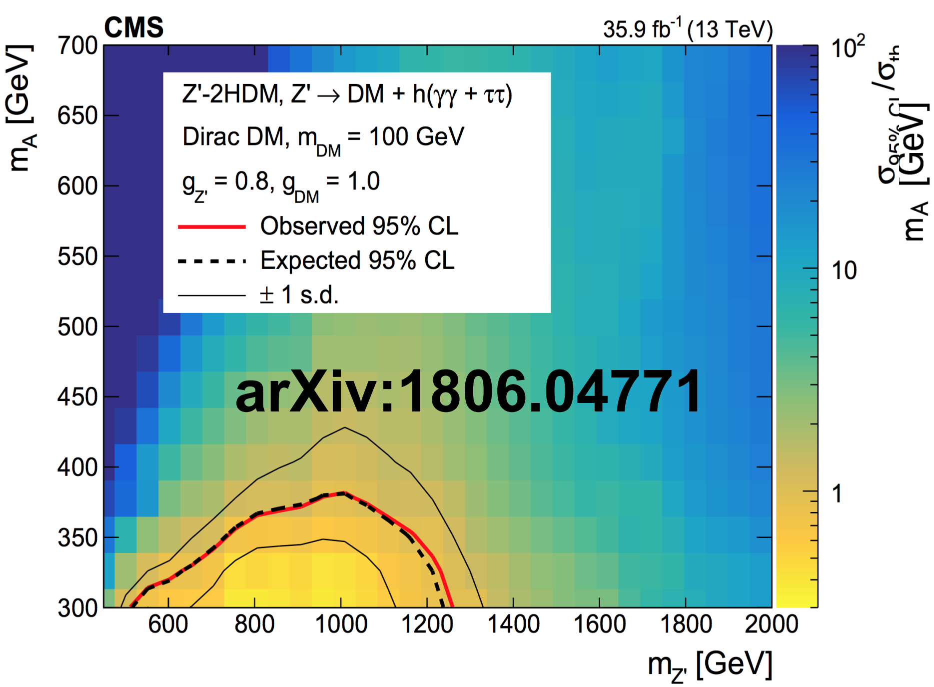
Mono-Higgs

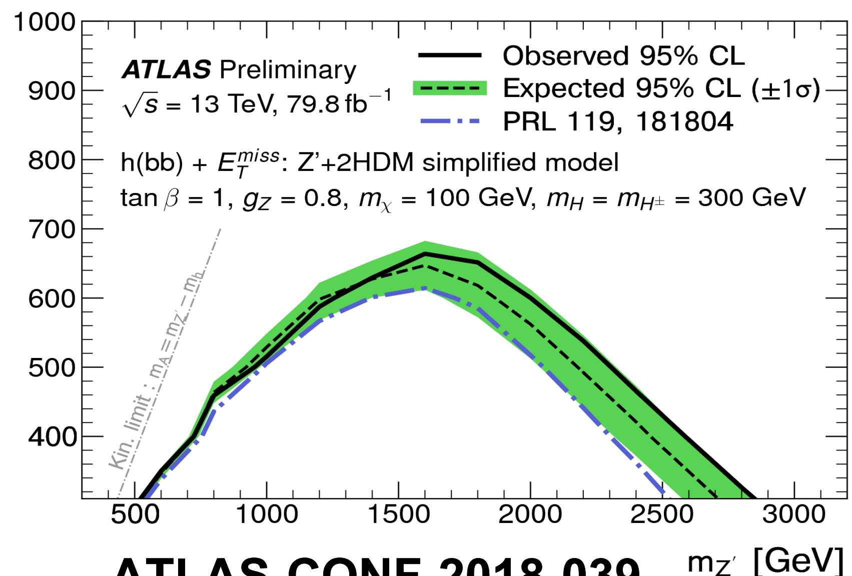
- Mono-Higgs targets a number of models



ATLAS-CONF-2018-039



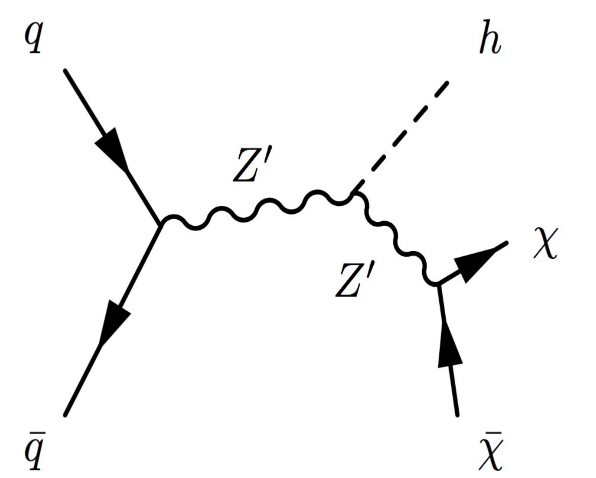


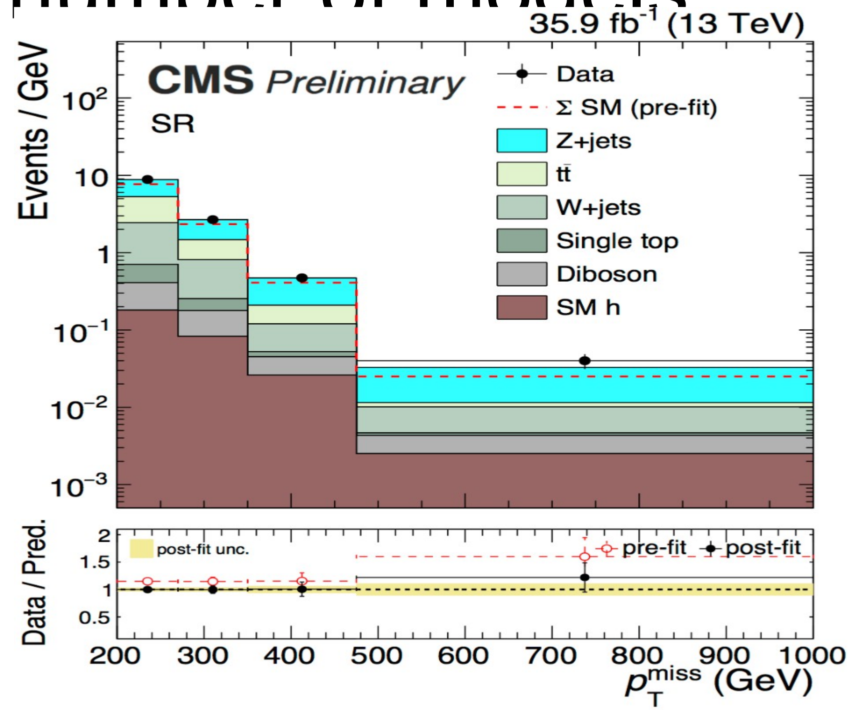


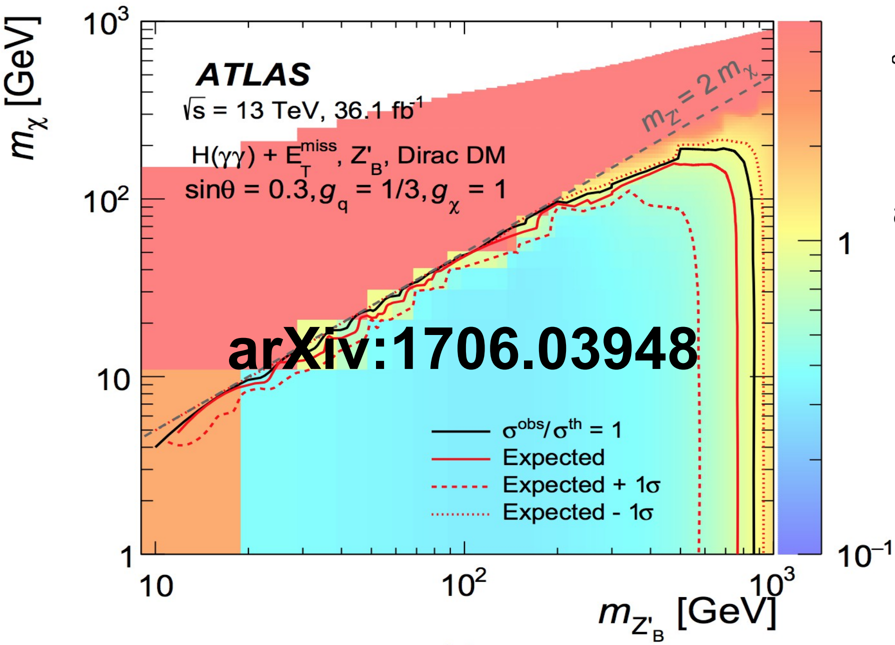
ATLAS-CONF-2018-039

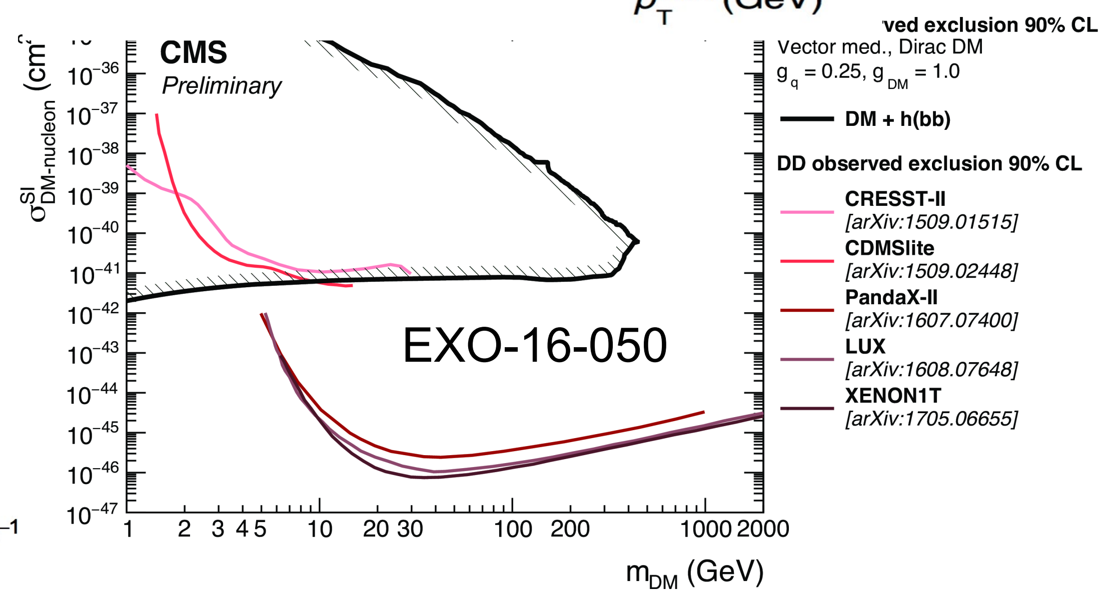
Mono-Higgs

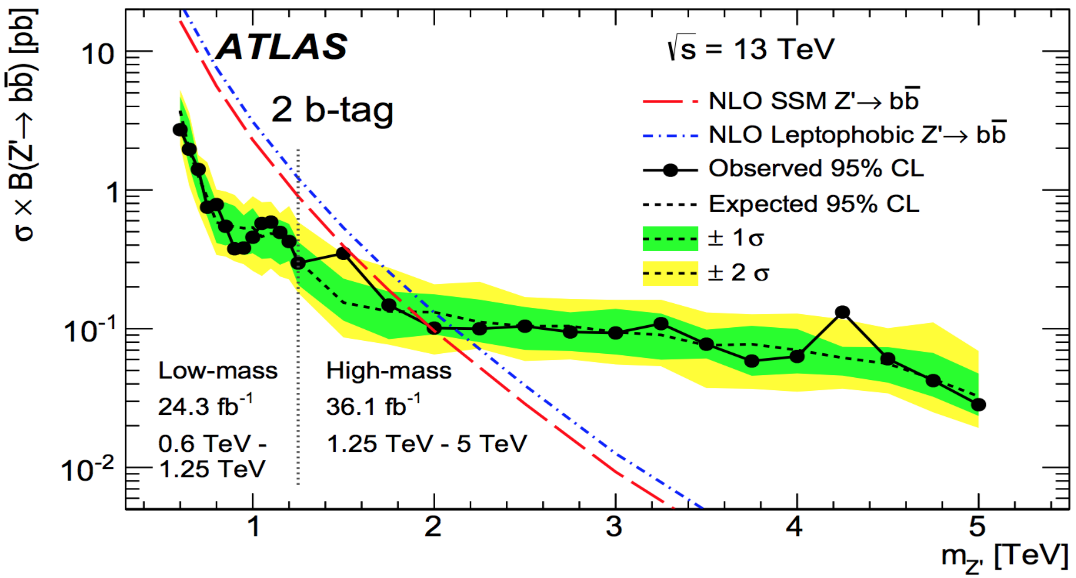
- Mono-Higgs targets a number of models



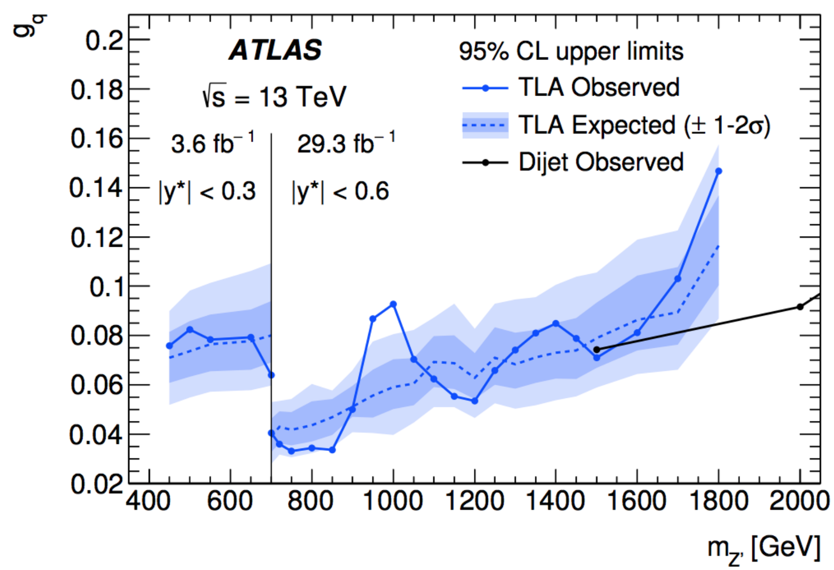




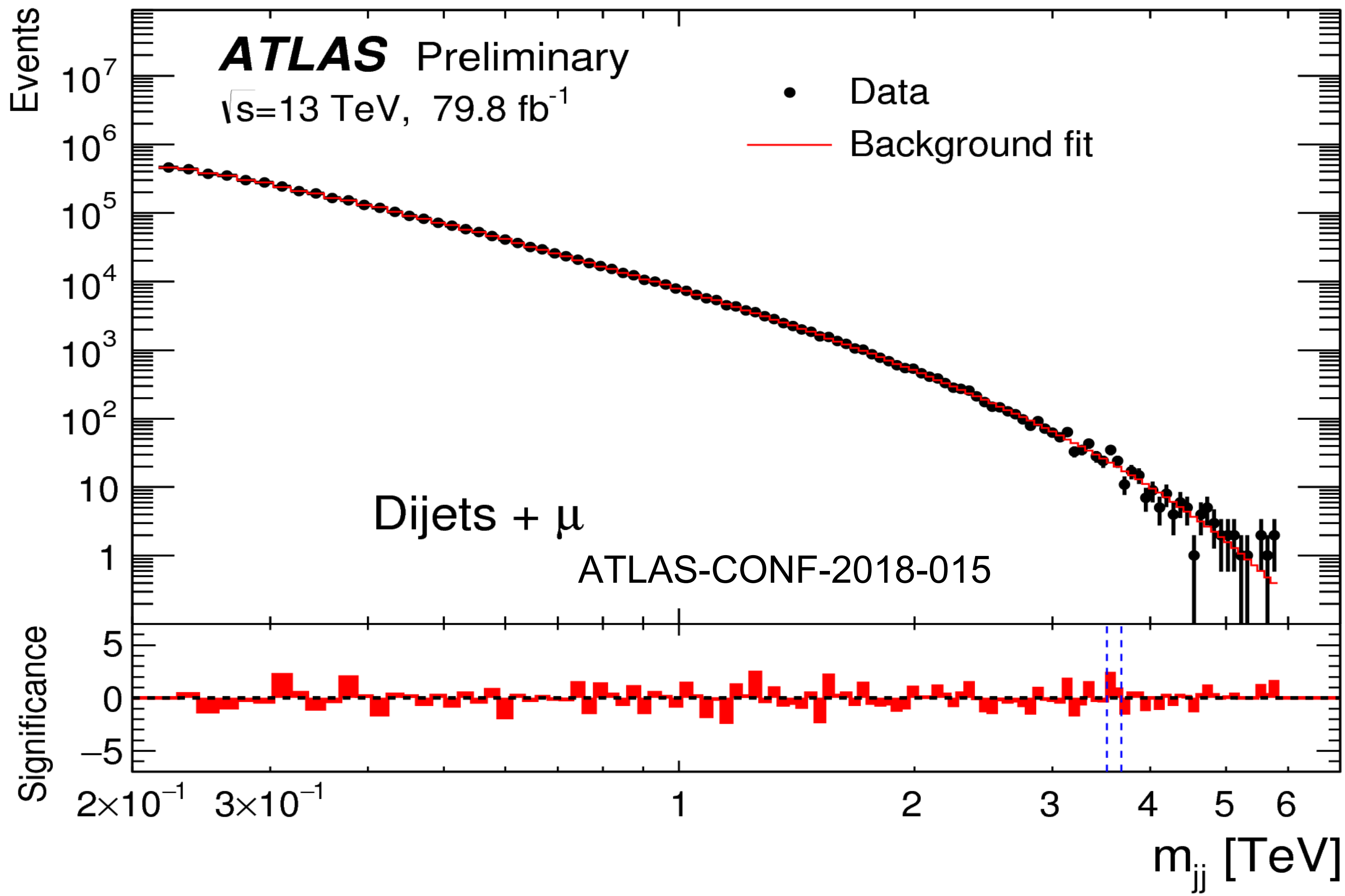




arXiv:1805.09299



Â arXiv:1804.03496



ATLAS Preliminary
√s=13 TeV, 79.8 fb⁻¹
Data
Background fit
Dijets + μ
ATLAS-CONF-2018-015
Events
Significance
m_jj [TeV]

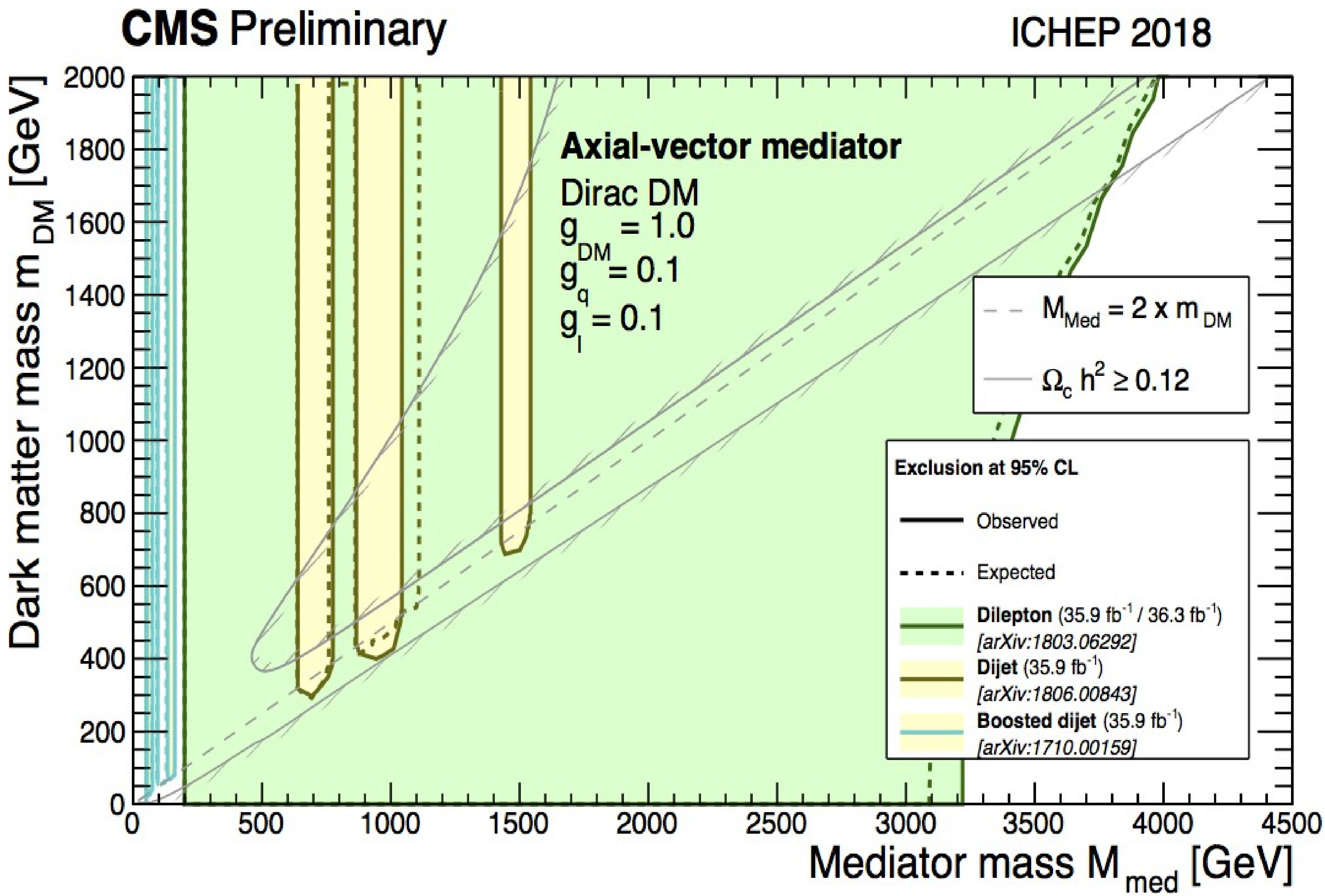
Summary Benchmarks

- Spin 1 :
  - Aim to probe couplings down 0.01 for m_{Med} > 100 GeV
  - For 10 < m_{Med} < 100 GeV aim to probe down to 10^{-3}
  - For m_{Med} < 10 GeV aim to probe coupling to 10^{-4}

- Spin 0 :
  - Aim to probe couplings down 0.1 for m_{Med} > 300 GeV
  - Try to cover m_{Med} < 300 by any means possible

- Covers most of the phase space

CMS



https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryPlotsEXO13TeV

Vector Mediator