Dark Matter searches in final states with jets at ATLAS and CMS at LHC

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Istituto Nazionale di Fisica Nucleare

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Dark matter search at LHC

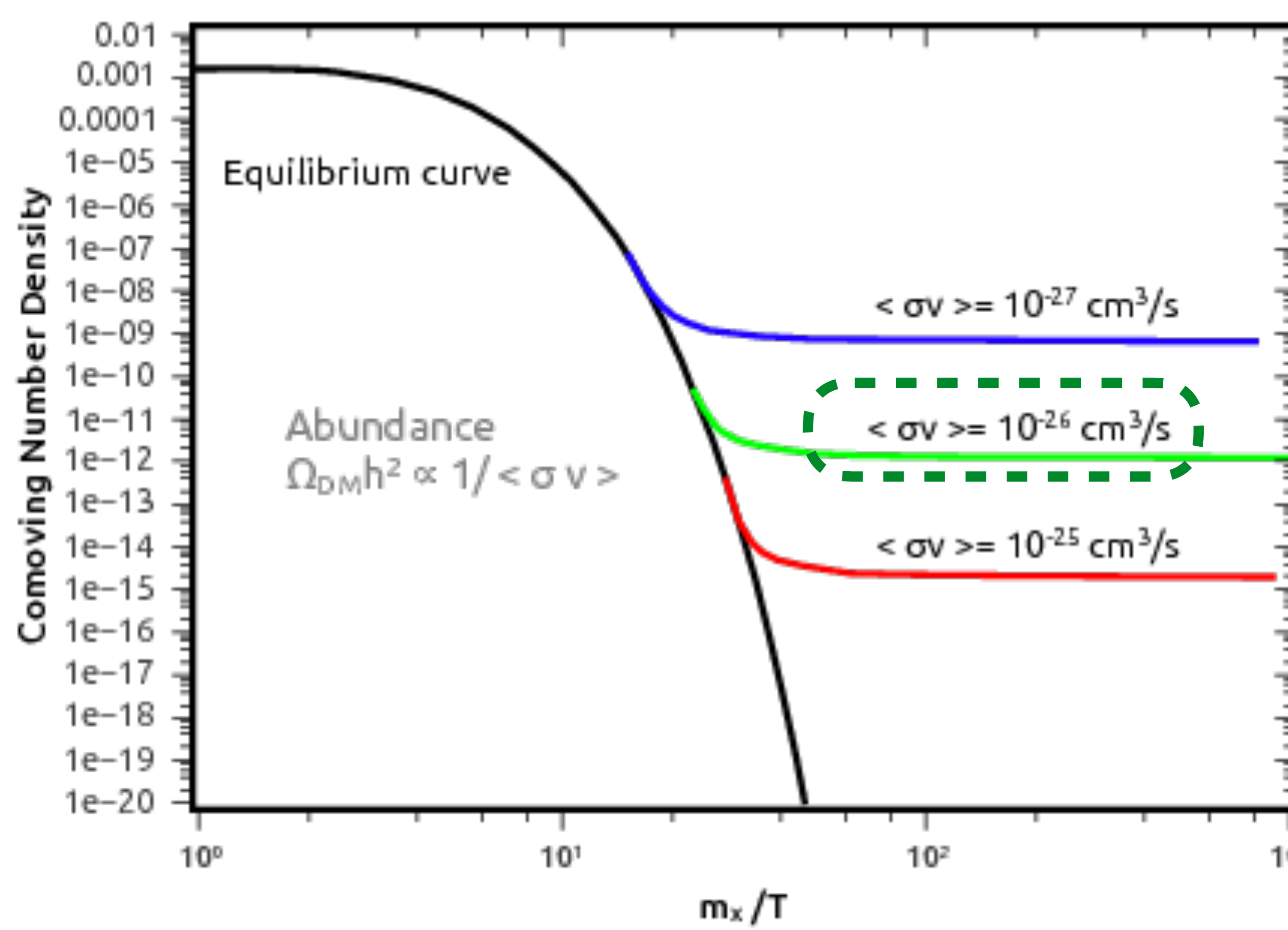
- **Abundant evidence for the presence of dark sector**
- Two big explanations: **gravitational effects** and **matter** (→ **new particle!**)
- Considering the existence of a new particle as DM candidate:
  - DM and SM particles in thermal equilibrium in the past
  - As the Universe expands, the annihilation depletes the DM density and freeze out
  - DM abundance determined by annihilation cross-section at freeze-out

$$\Omega_\chi h^2 \simeq 0.1 \times \left(\frac{3 \times 10^{-26} cm^3 s^{-1}}{\langle \sigma v \rangle}\right)$$

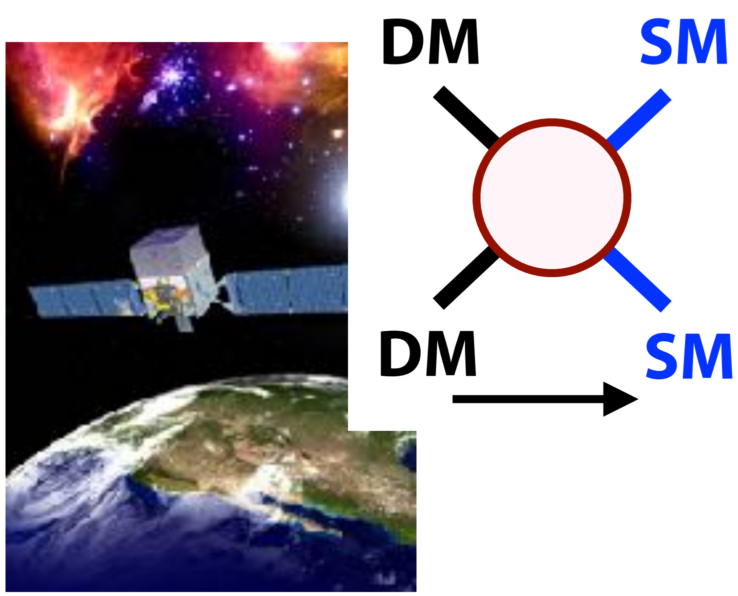
$$\langle \sigma v \rangle \sim 3 \times 10^{-26} cm^3 s^{-1} \sim \pi\alpha^2/(100\ \mathrm{GeV})^2$$

☞**DM at the weak scale** (WIMPS)!

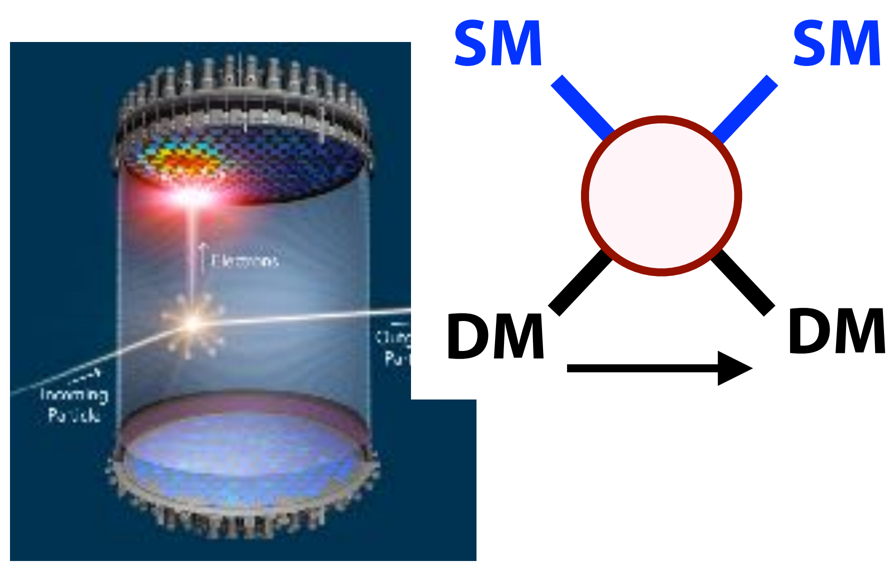
Motivation to consider collider searches for DM



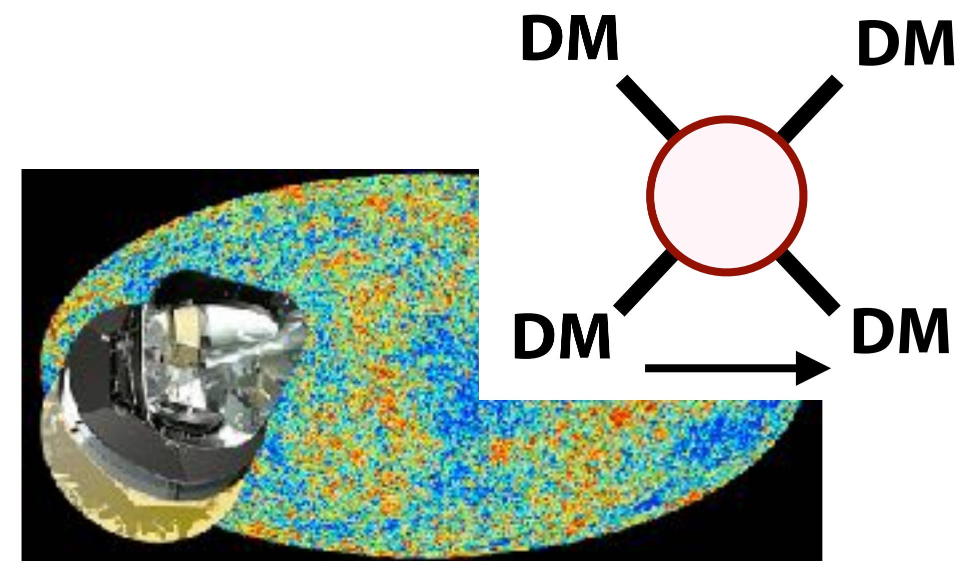
Experimental probes



Indirect detection

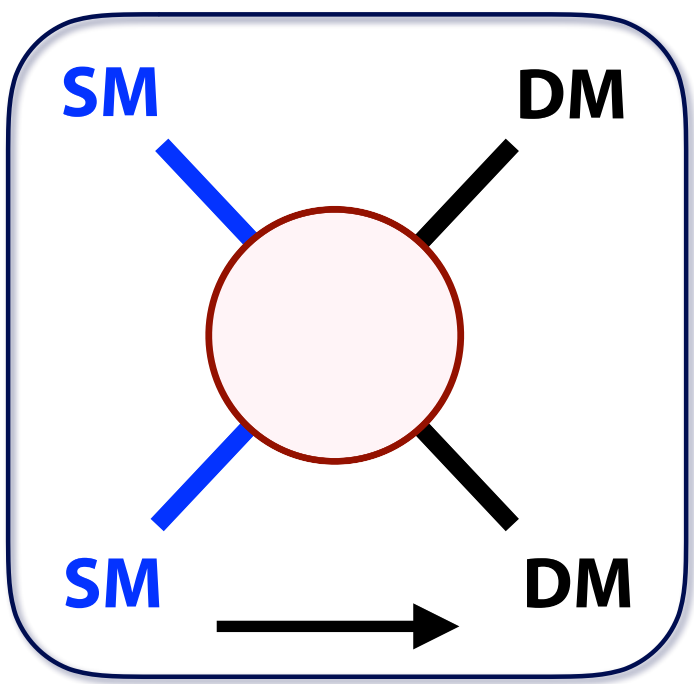


Direct detection



Astrophysical probes

☞Collider searches means DM production



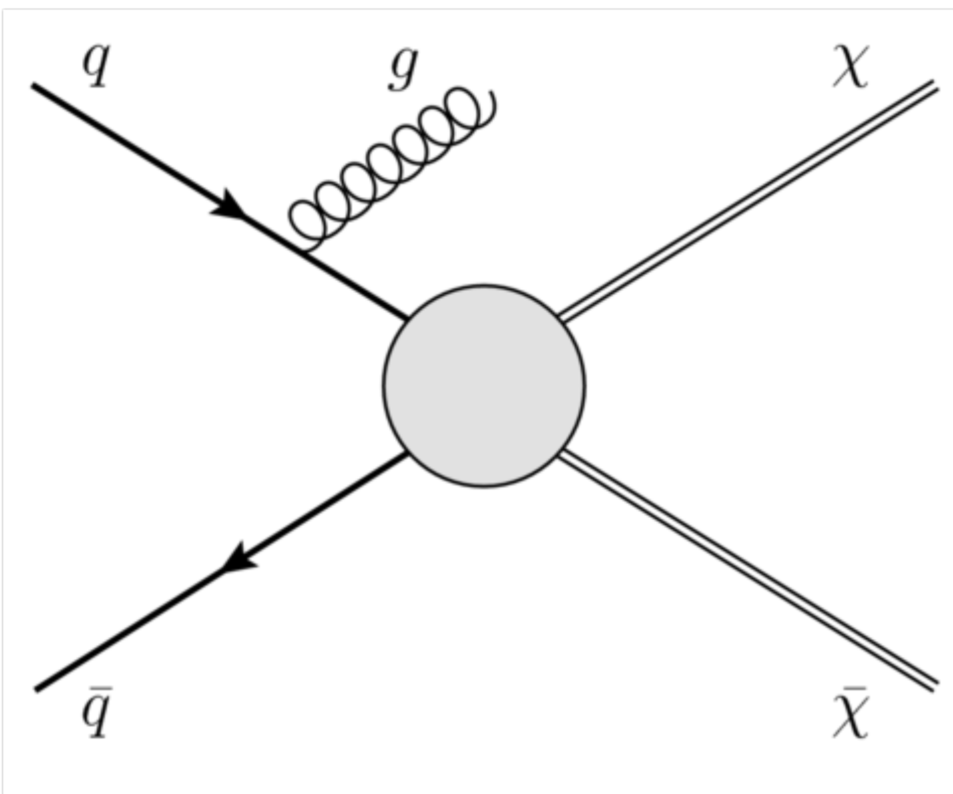
What can we do at LHC?

- **Direct search for WIMP & mediator particles**
- WIMP search in cascade decays
  - e.g. SUSY, Kaluza-Klein…
- Hidden (dark) sector search

DM at Collider: models

Effective field theories (EFT)

Mediator energies >>
energy transfer at the LHC

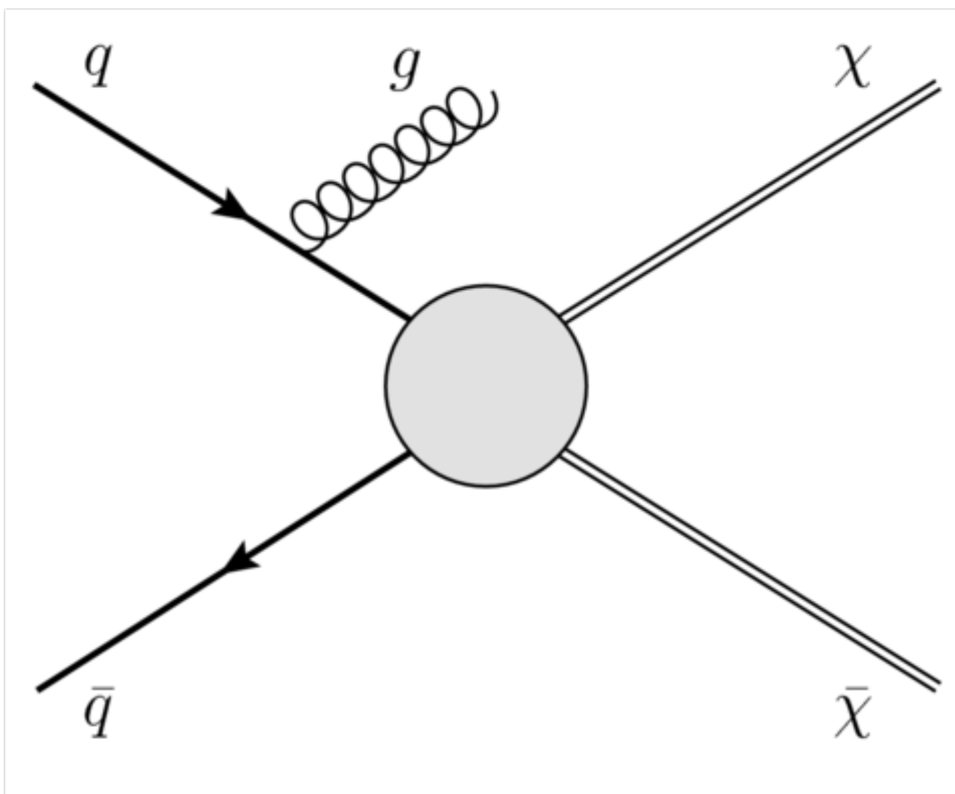


- Contact interaction theory
- Model independent: compares with DD
  - parameters: **m_{DM}, cut-off scale**
- used in LHC Run 1

DM at Collider: models

Effective field theories (EFT)

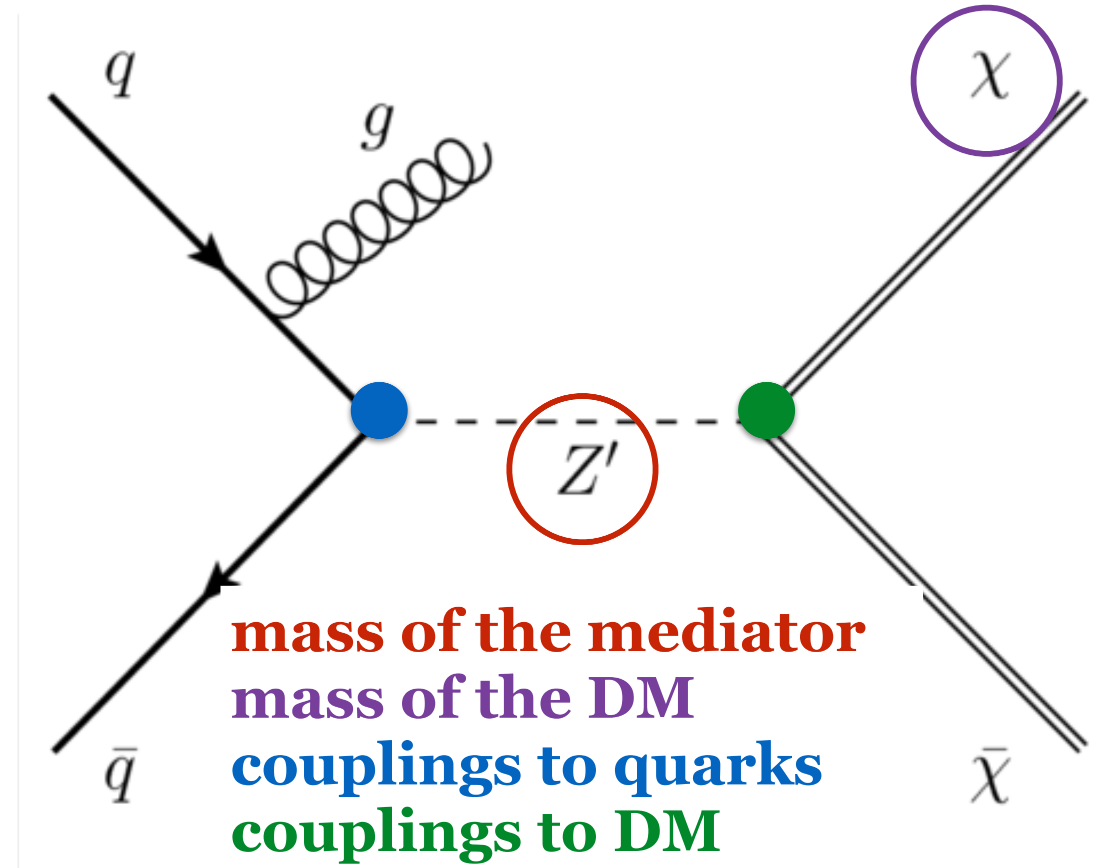
Mediator energies >>
energy transfer at the LHC



- Contact interaction theory
- Model independent: compares with DD
  - **2 parameters**: **m_{DM}, cut-off scale**

Simplified models

Mediator is light enough to be produced at the LHC!

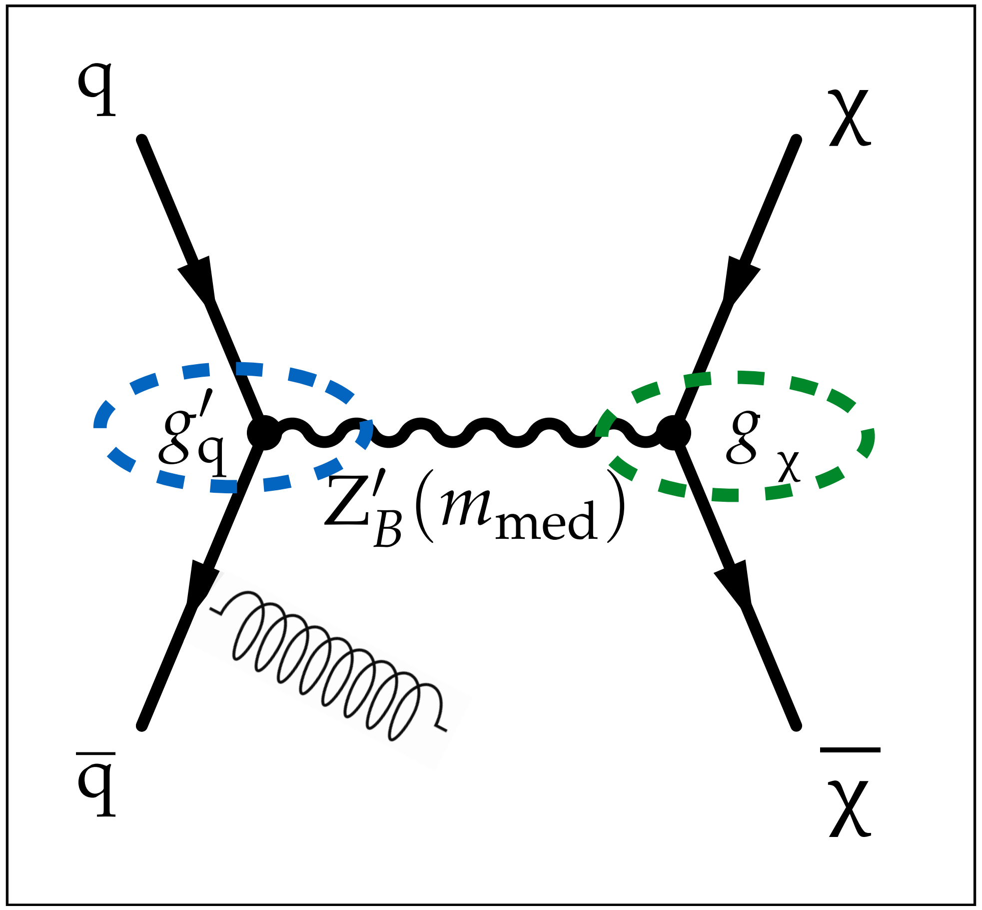


- Mediators: vector, axial-vector, scalar, pseudoscalar
- Model dependent
  - **4 parameters**: **m_{med}, m_{DM}, g_q, g_{DM}**

Simplified Models

SM→mediator→DM

☞ **mono-X searches**

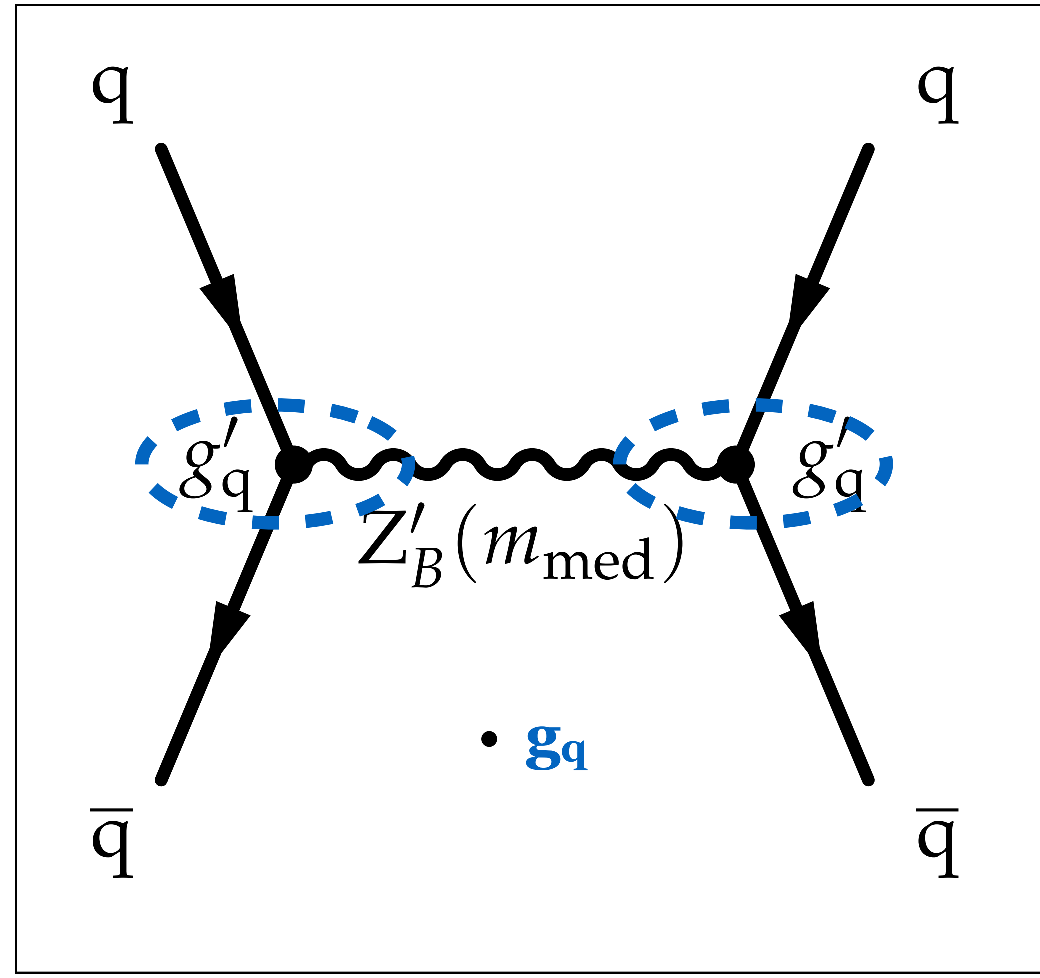


⇨E_T^{miss}+ jet,W/Z/H, γ, tt,…

Searches for deviations from the SM expectations interpretation model dependent

SM→mediator→SM

☞ **Visible signature**



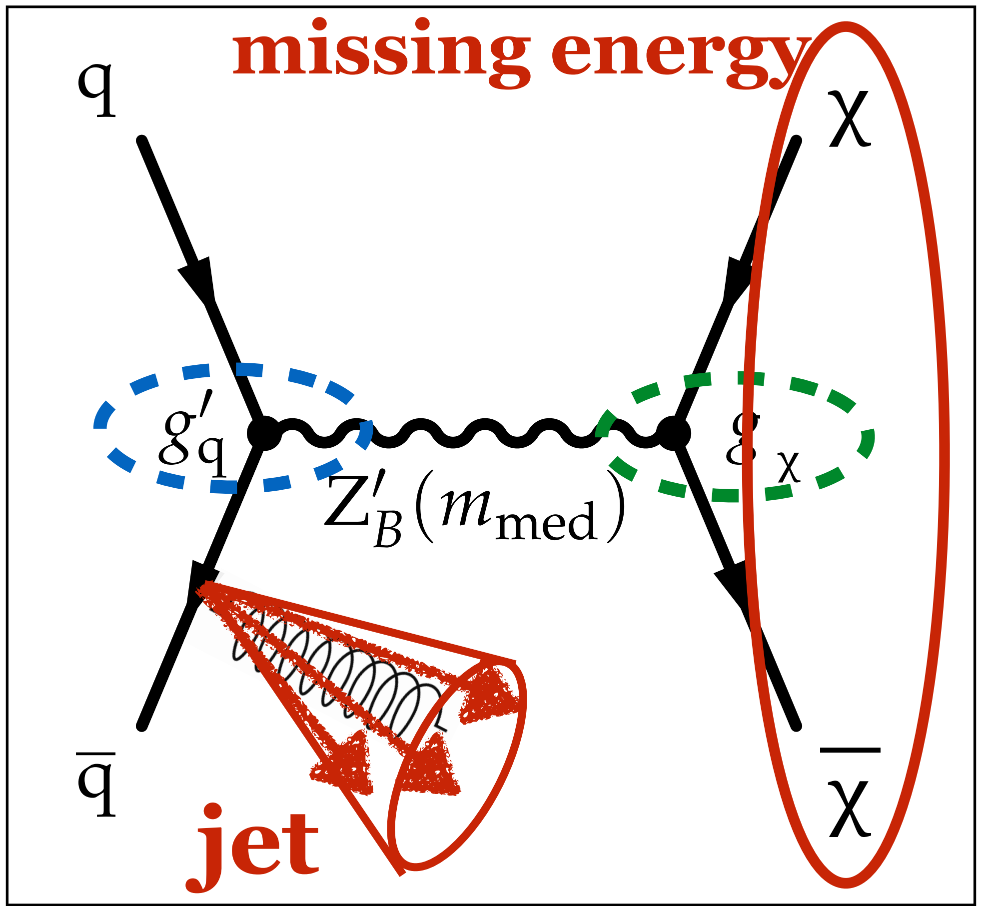
⇨di-jet, ditop, dilepton **resonances**

Bump hunt searches ~model independent

Experimental signatures

SM→mediator→DM

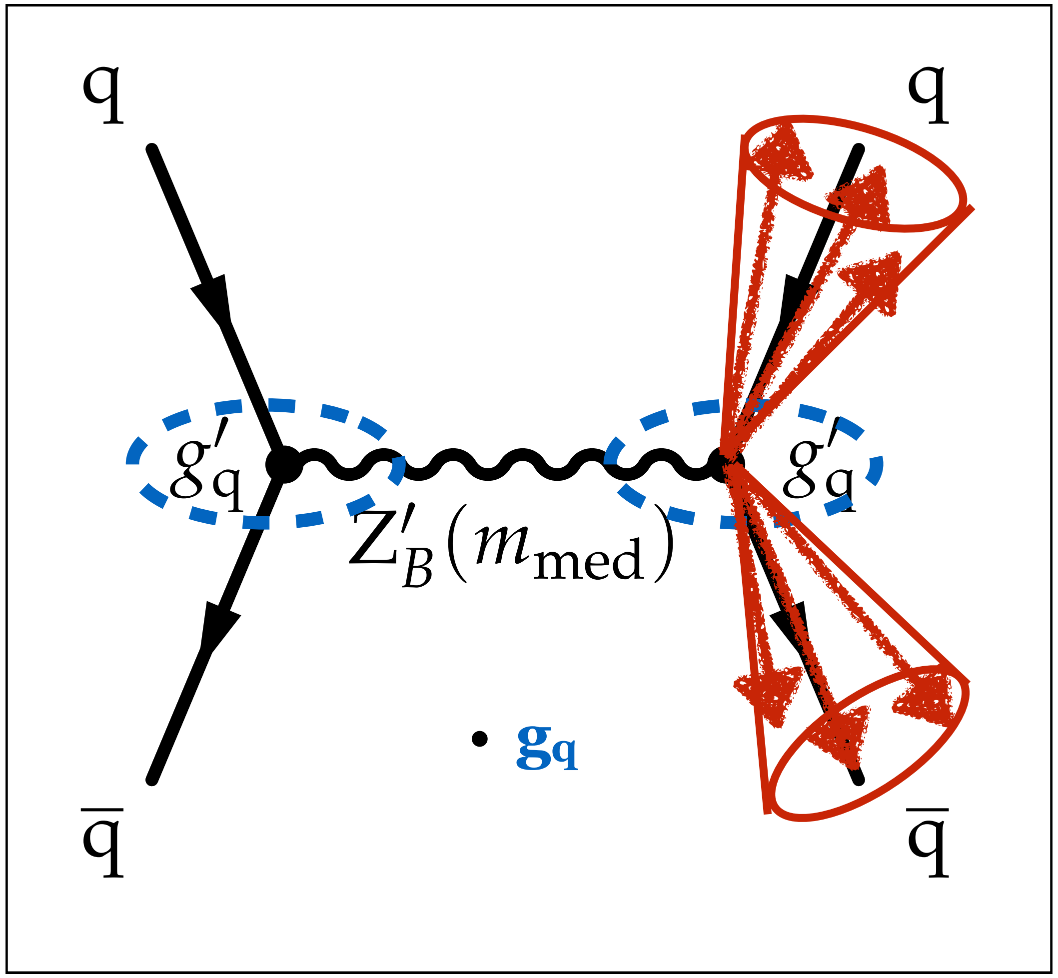
☞ **mono-X searches**



DM in the final state, **invisible:**
missing energy +
need **One jet** = hadronization of a gluon from Initial State Radiation (ISR) of the incoming parton **to tag the event**
(aditional signatures: W,Z,γ possible ISR)

SM→mediator→SM

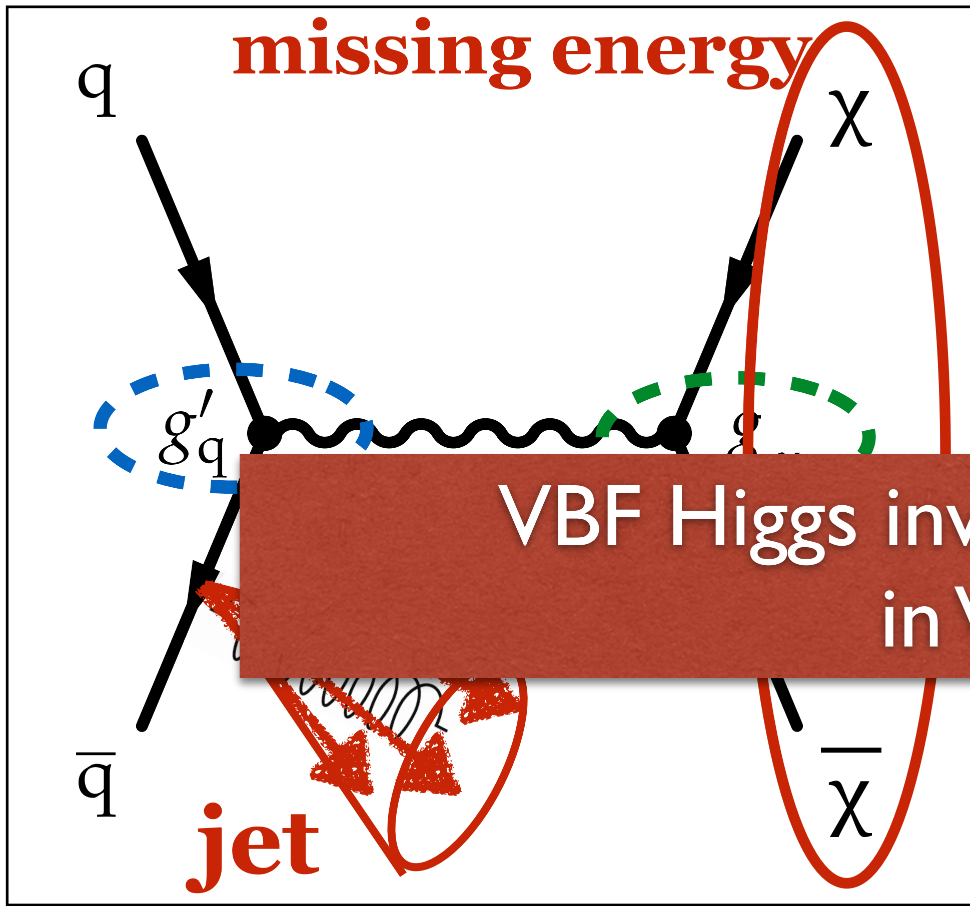
☞ **Visible signature**



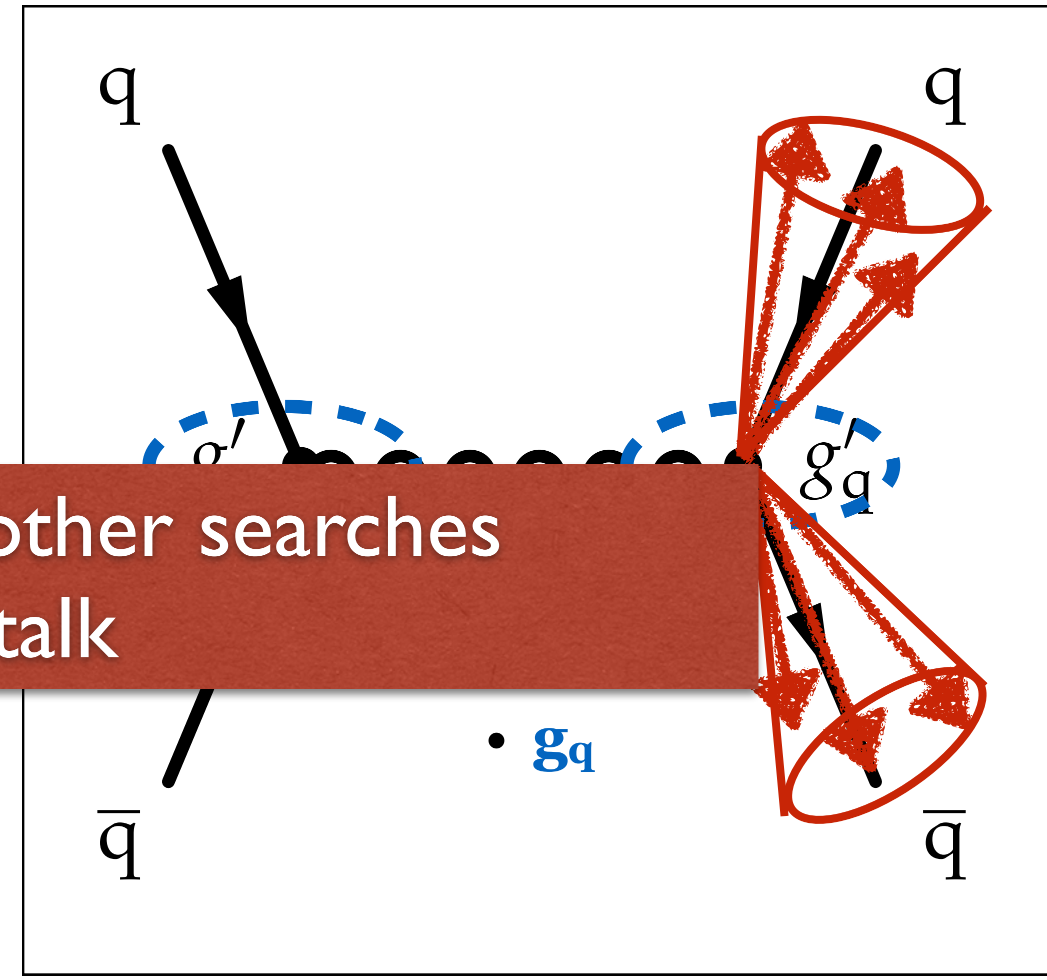
no DM in the final state, **visible:**
Two jets = hadronization of quarks
resonance in di-jet invariant mass
(alternative signatures: di-leptons)

Experimental signatures

SM→mediator→DM
☞ **mono-X searches**



SM→mediator→SM
☞ **Visible signature**



VBF Higgs invisible and other searches
in V. Ippolito's talk

DM in the final state, **invisible:**
missing energy +
need **One jet** = hadronization of a gluon
from Initial State Radiation (ISR)
of the incoming parton **to tag the event**
(aditional signatures: W,Z,γ possible ISR)

no DM in the final state, **visible:**
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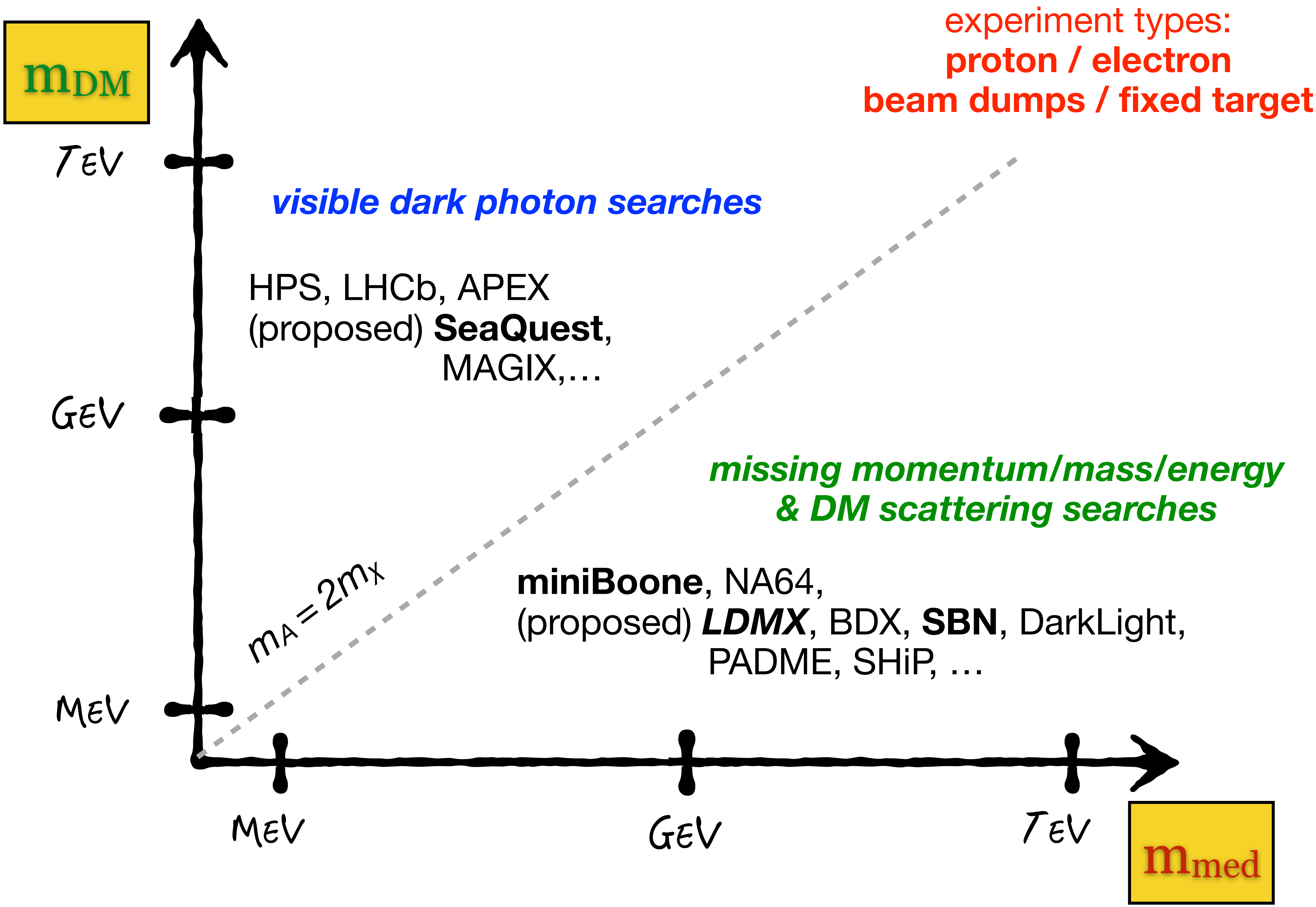
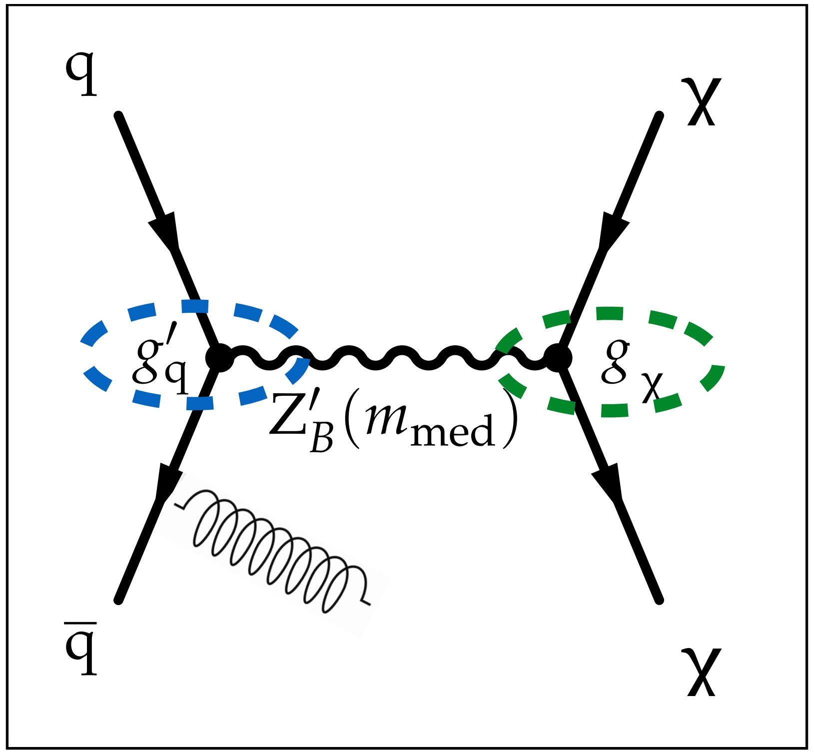
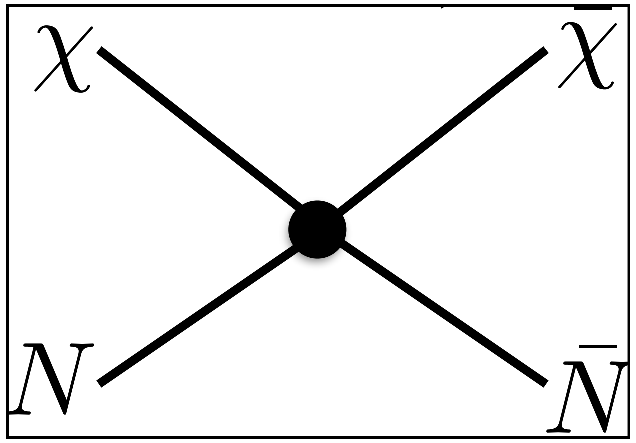
Complementarity of searches



Compare with ID/DD searches

- Limits on (m_{DM}, m_{med}) plane can be convertd in limits on the (m_{DM}, $\sigma_{DM\text{-}n}$) plane to compare with ID/DD dark matter experiments





- For axial-vector mediator with universal quark coupling g_q', mediator-nucleon coupling is

$$f^p = f^n = 0.32 g'_q.$$

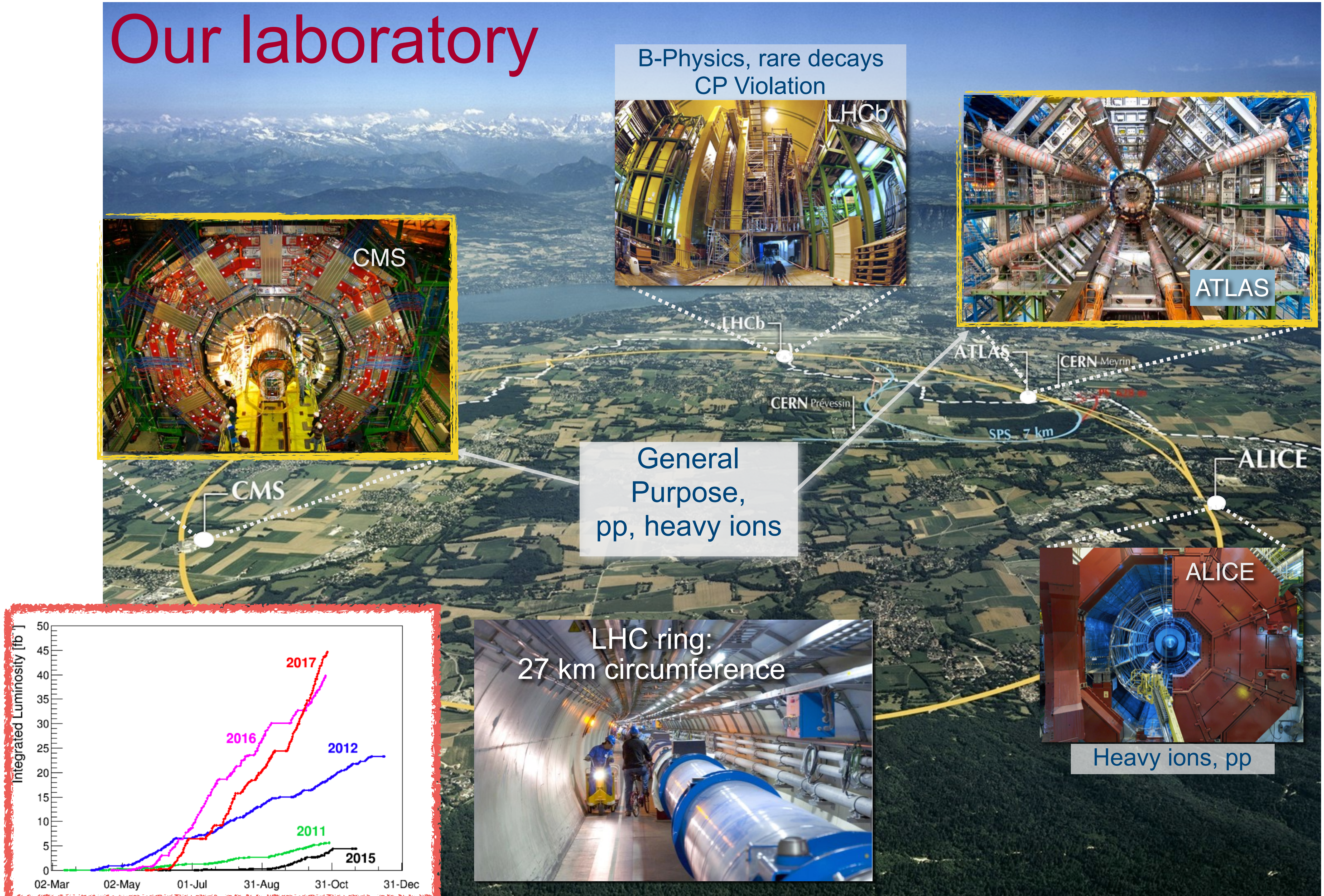
$$\sigma^{SD}_{DM\text{-}p} = \frac{3 f^2(g'_q) g^2_{DM} \mu_{N\chi}}{\pi m^4_{med}}$$

$$\simeq 2.4 \times 10^{-42}\,\text{cm}^2 \cdot \left(\frac{g'_q g_{DM}}{0.25}\right)^2 \left(\frac{1\,\text{TeV}}{m_{med}}\right)^4 \left(\frac{\mu_{N\chi}}{1\,\text{GeV}}\right)^2$$

arXiv:1603.04156

The experimental setup

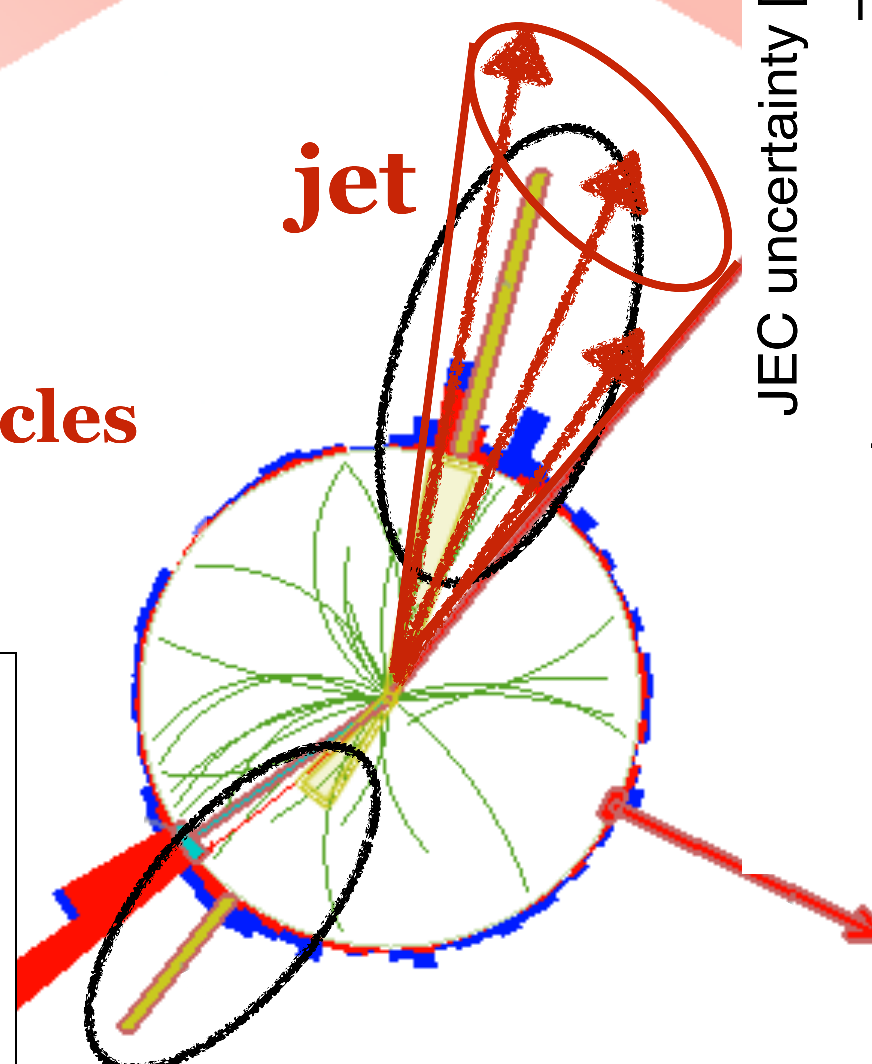
LHC & its experiments

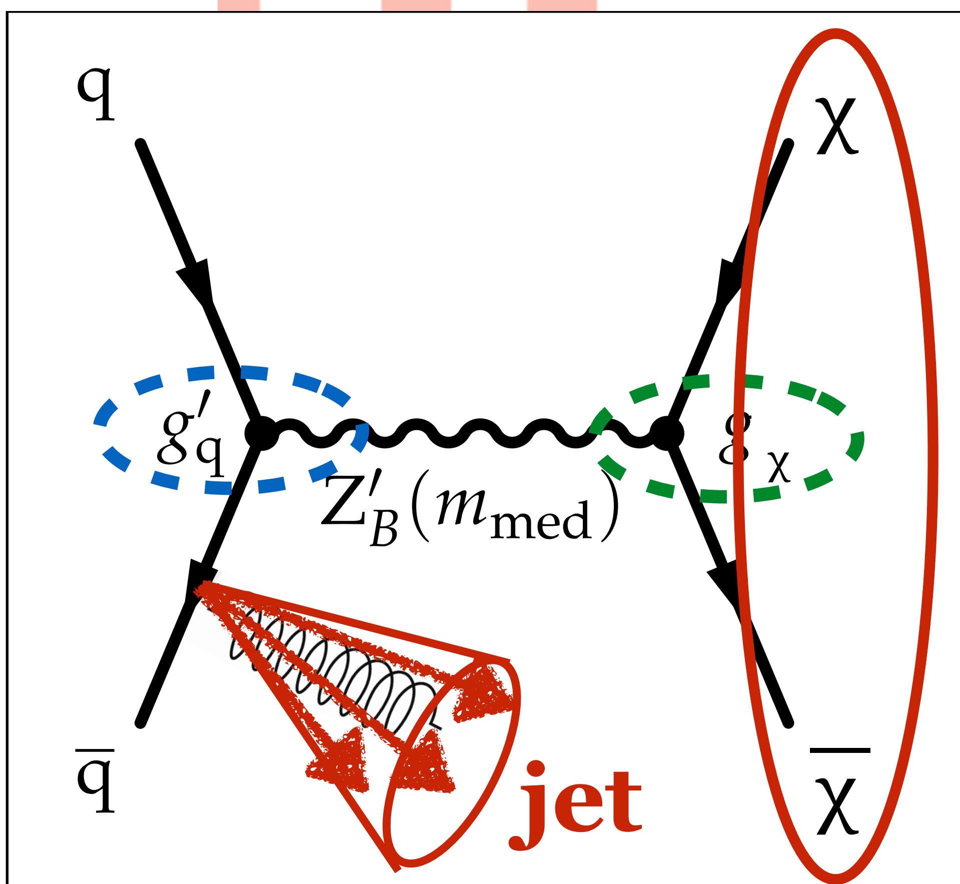


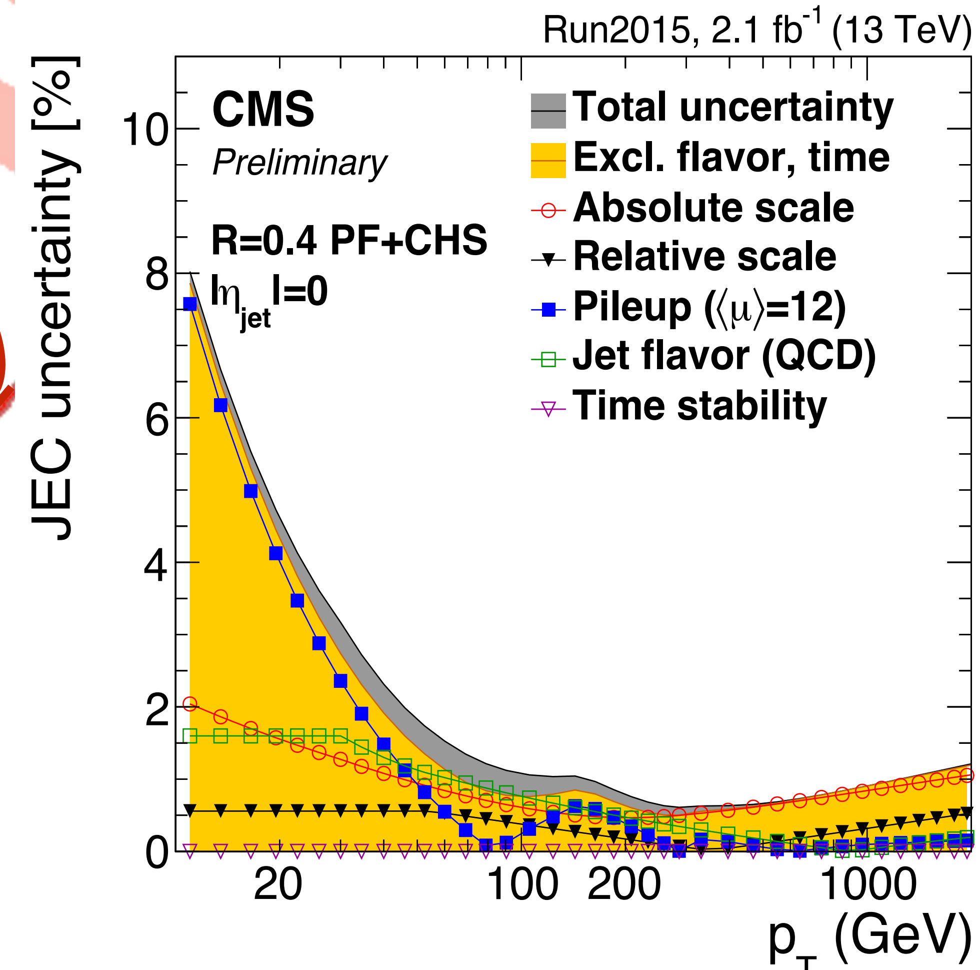
Jets

1) Jets

Build jets from
detector deposits
or
reconstructed particles

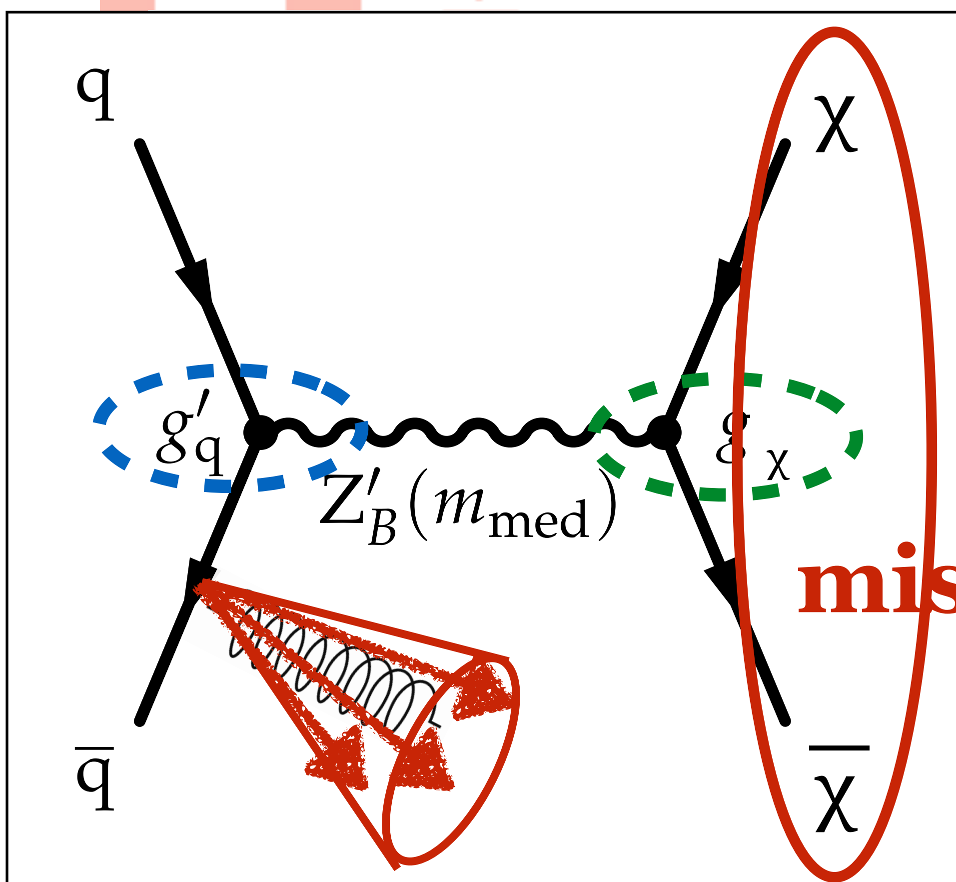




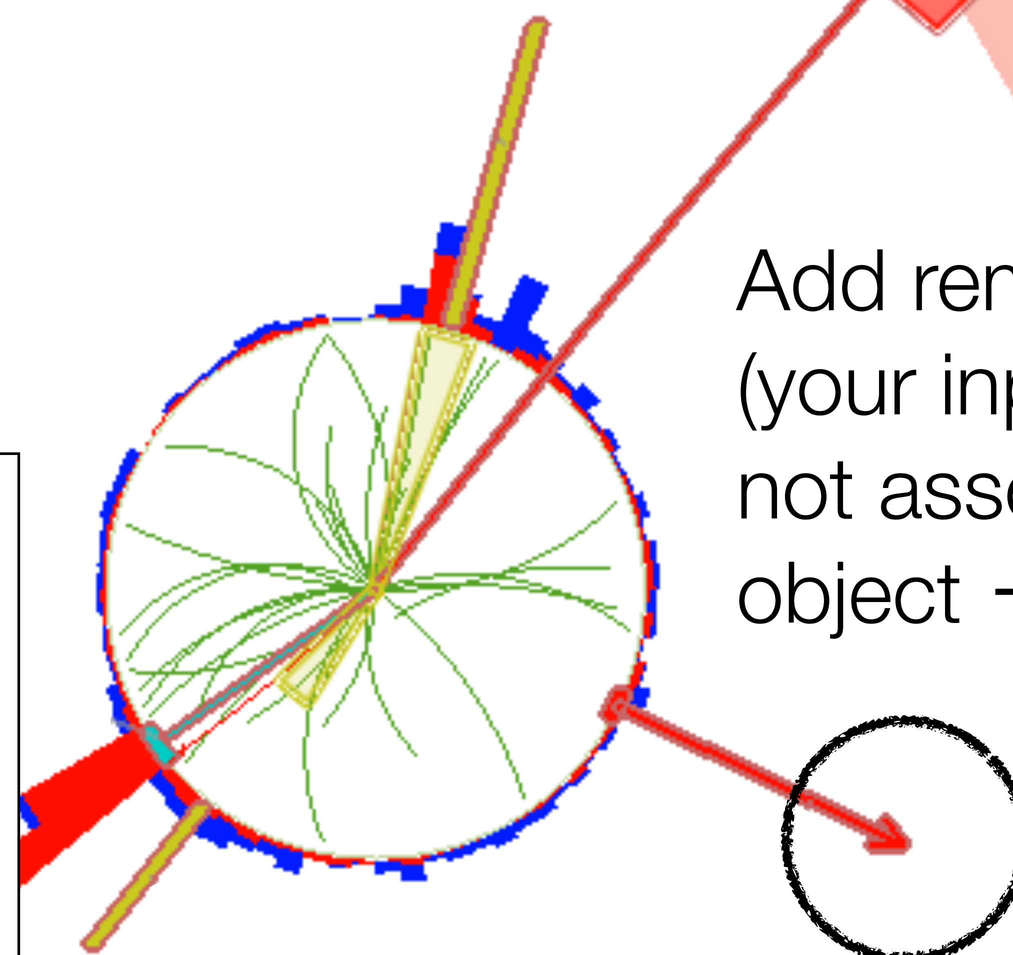


2) MET=Missing Transverse Energy

Add together well-calibrated electrons, muons, …



missing energy



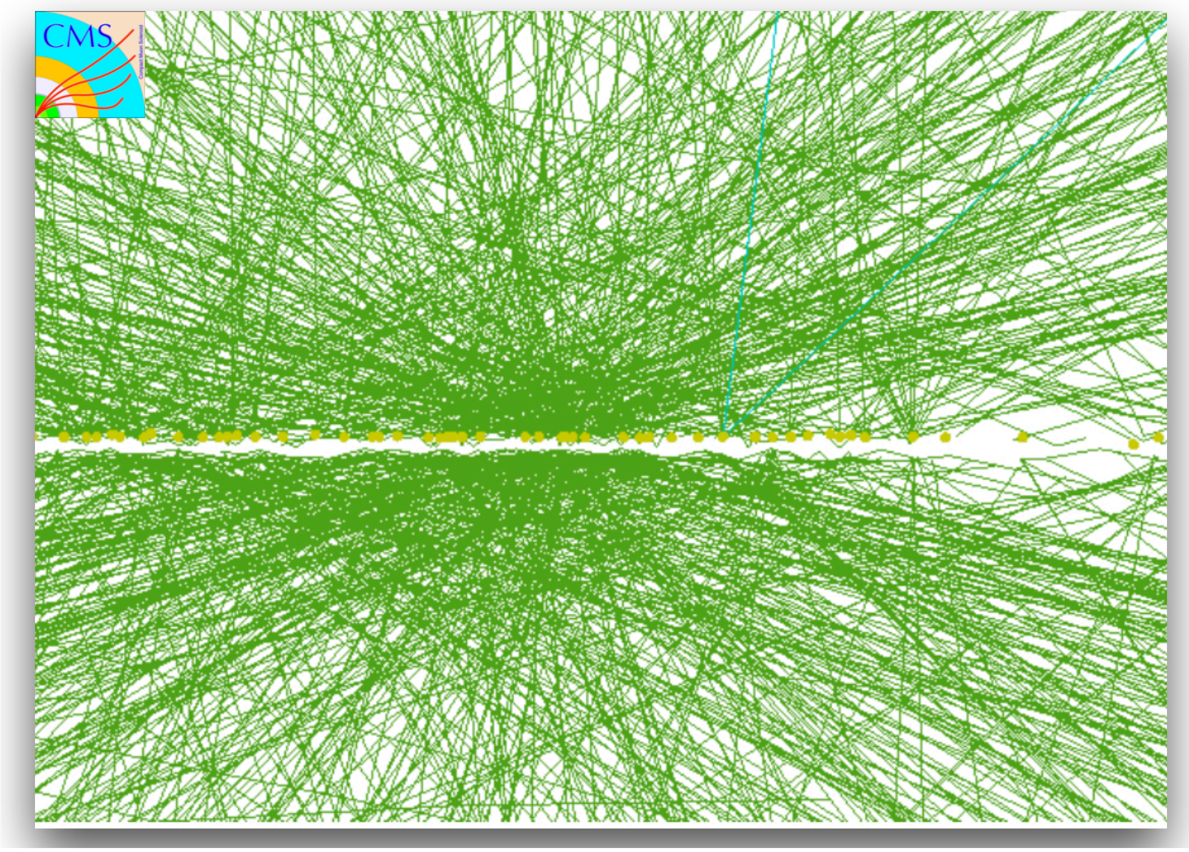
Add remaining activity (your input of choice) not associated to an object → "soft term"

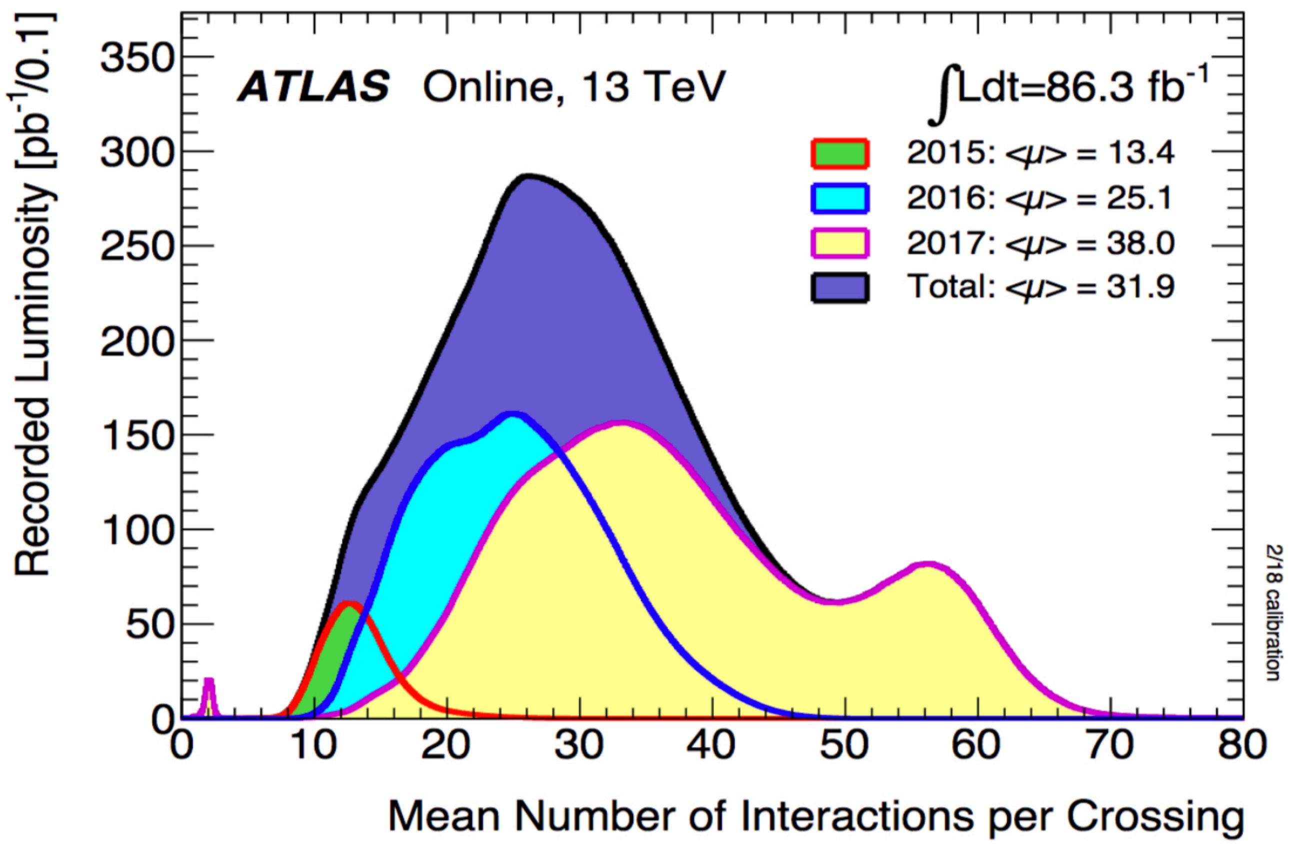
Vector needed for sum to equal zero is the missing transverse momentum (MET)

The price of so much data: *pile-up*

LHC produced **~5 × 10^{15} pp collisions** up to 2017
Number of simultaneous proton-proton collisions per bunch crossing:

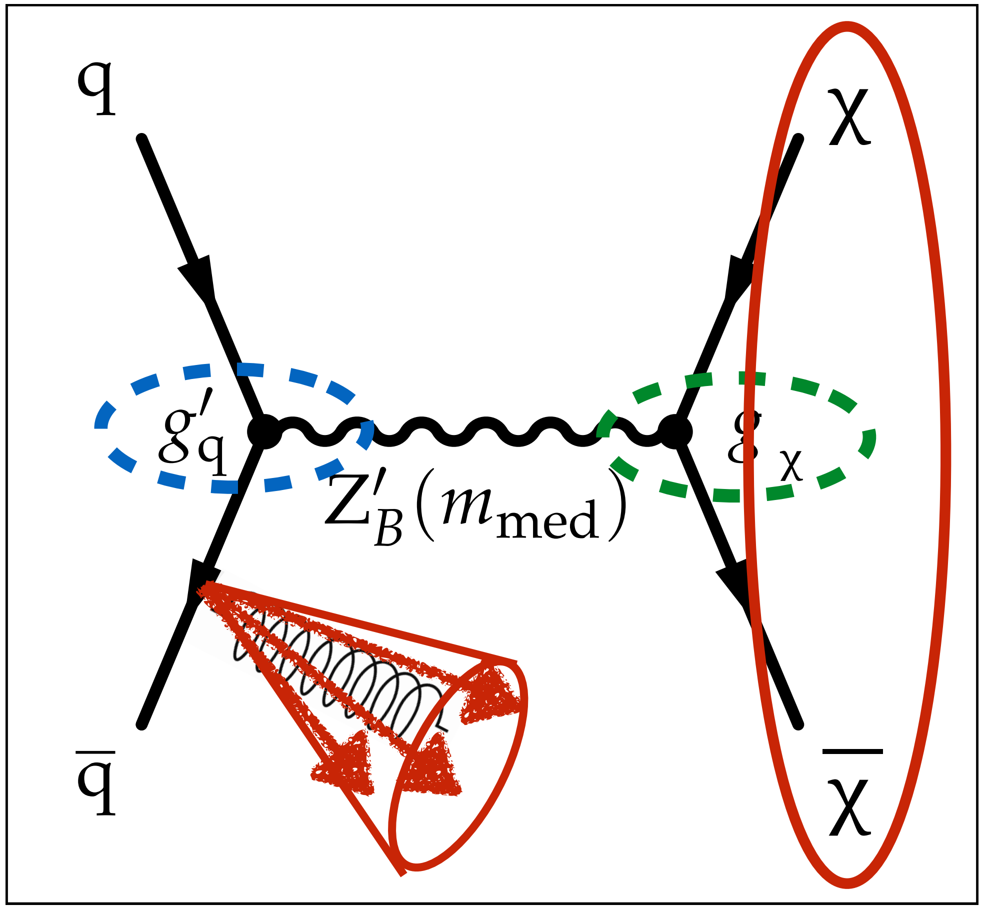
$\mathscr{L}$ x total cross section x bunch separation time
~1.5 x 10^{34} $cm^{-2}s^{-1}$ x 100 mb x 25 ns ~**38**





Consequences on the particles reconstruction
ATLAS & CMS managed to maintain high performances

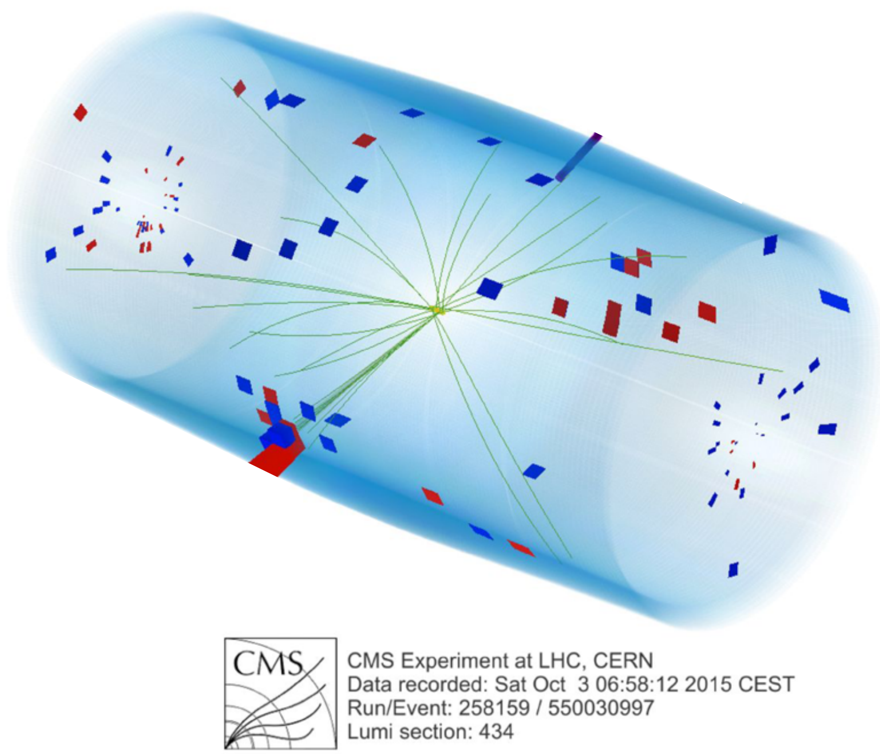
Mono-X searches



Mono-X searches

Experimental signature: MET + X

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



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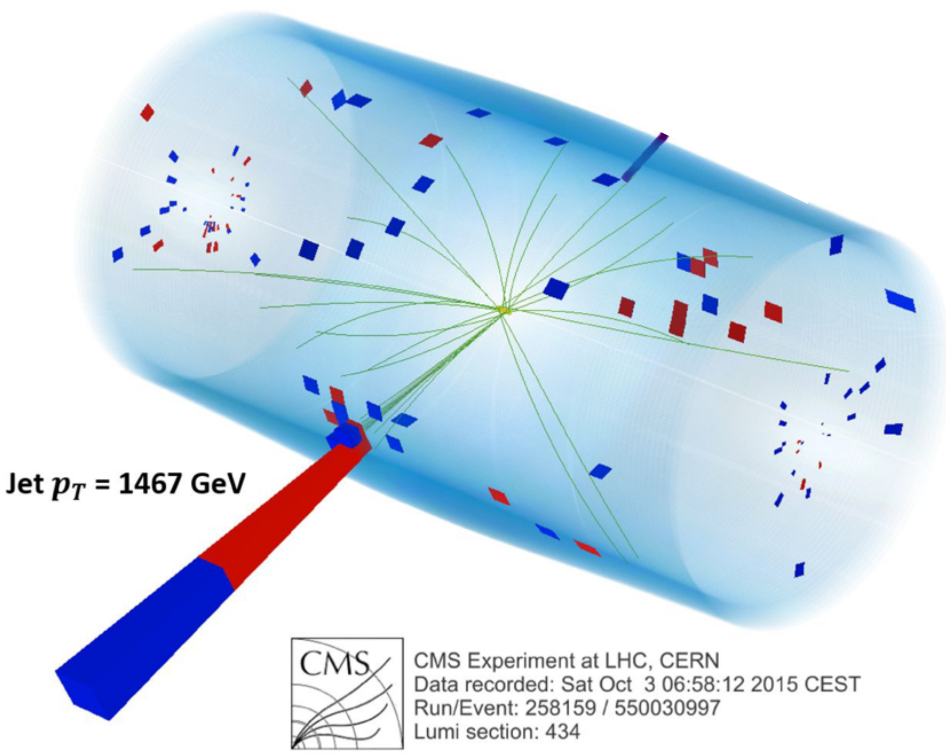

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- we can record these events if the DM is produced in association to an initial state radiation

Mono-X searches

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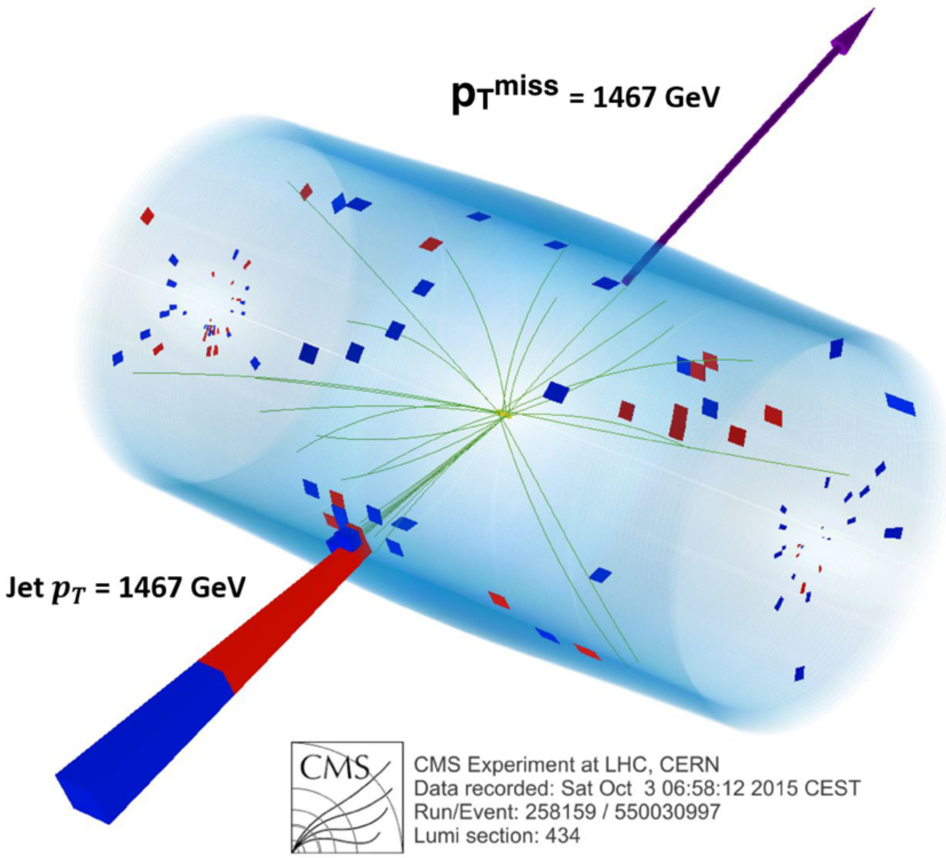


- DM assumed to be weakly interacting, and will leave no signature in the detector!
- we can record these events if the DM is produced in association to an initial state radiation

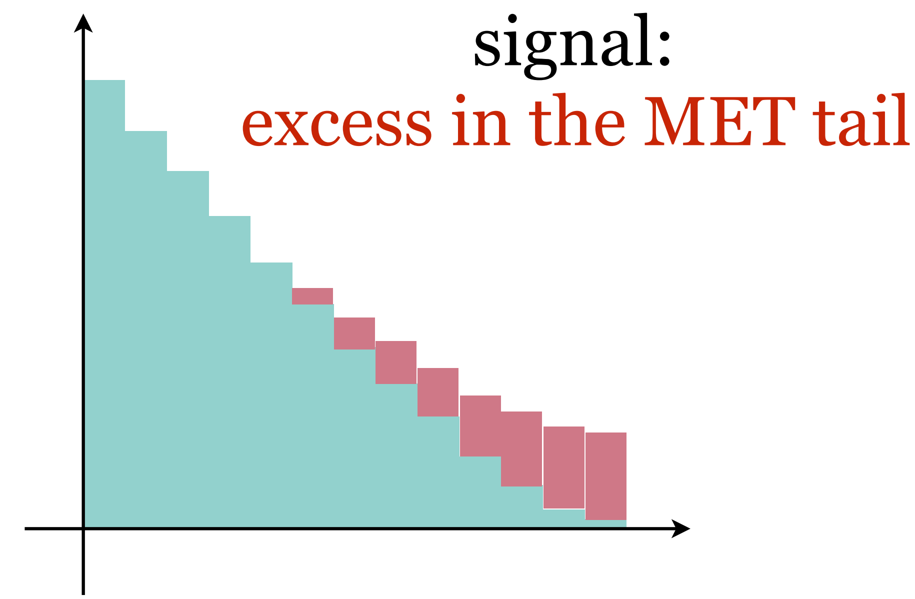
Total transverse momentum in the event needs to be balanced.

Initial transverse momenta = 0 !

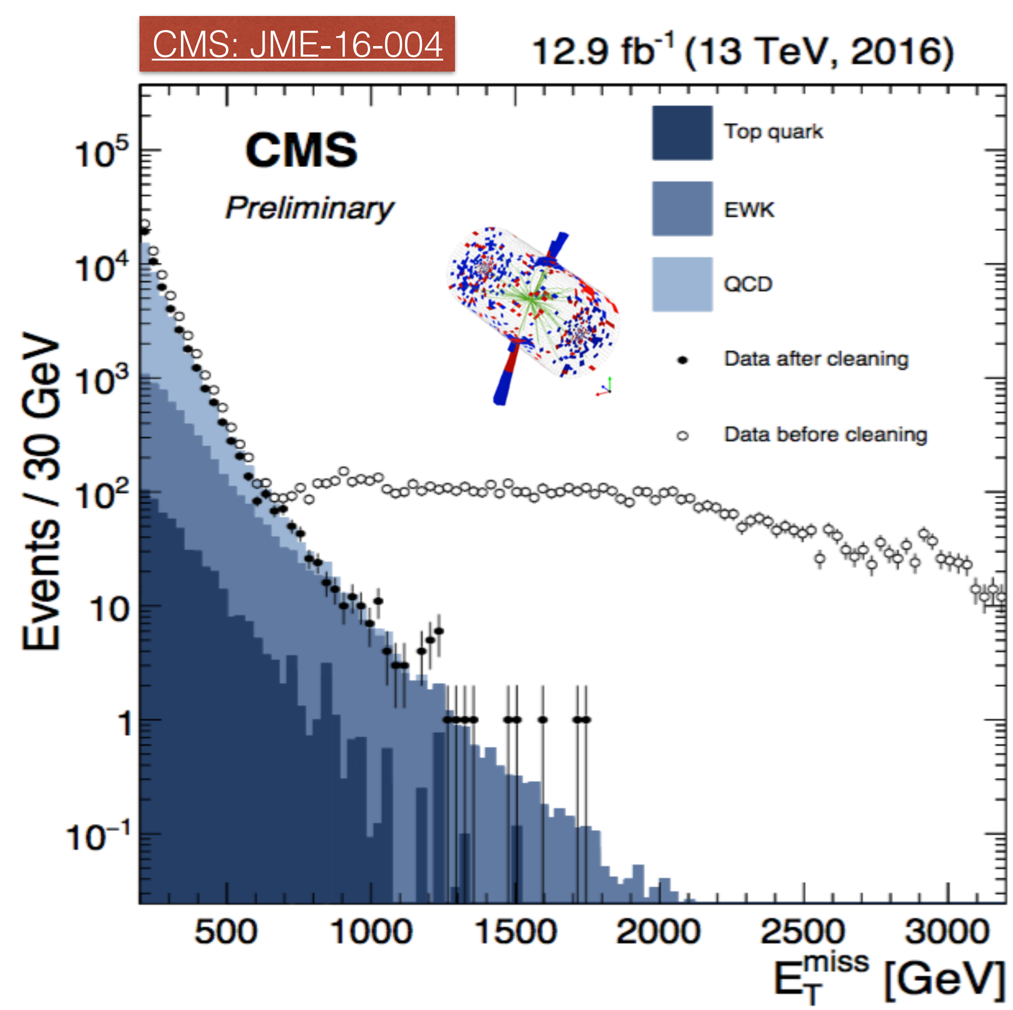
key observable: Missing transverse momentum (p_T^{miss})

Detector challenges

- Triggering these events: both CMS & ATLAS rely on inclusive p_T^{miss} triggers.
  - CMS: p_T^{miss} > 120 GeV / ATLAS: p_T^{miss} > 90 GeV
  - to sustain low thresholds, mitigate the **pileup contribution** to MET resolution

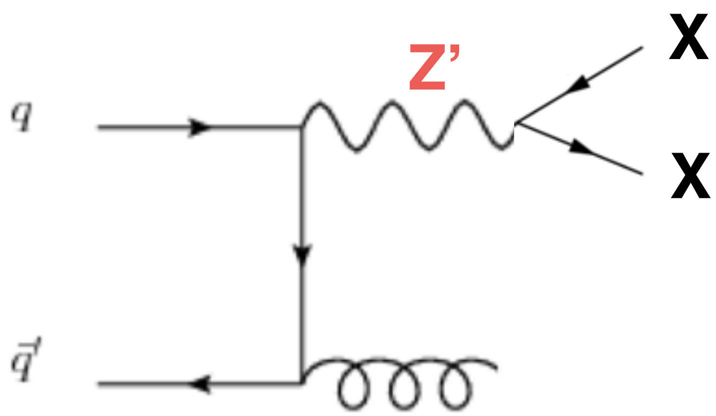


- **Spurious detector signals** can cause fake missing transverse momentum!
  - Anomalous high p_T^{miss} can be due to:
  - Beam halo particles
  - Particles striking sensors in the calorimeter photodetectors
  - Dead cells in the calorimeters
  - Noise in readout box electronics in calorimeters

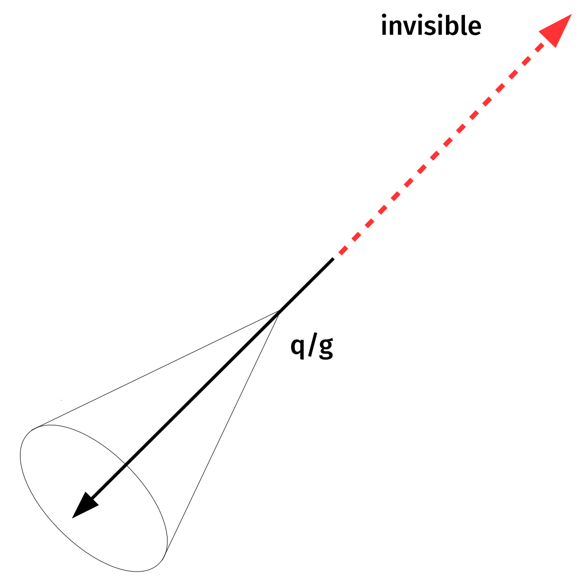


SM background

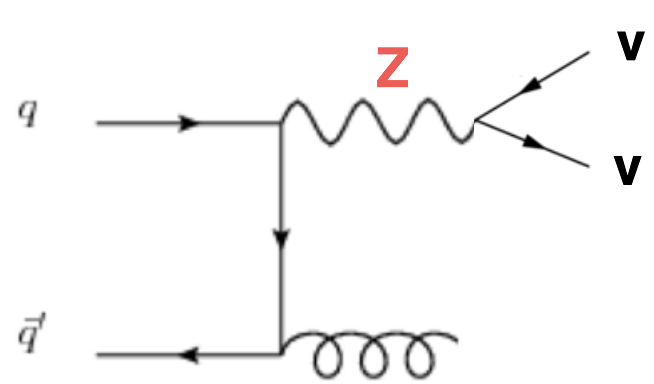
- Strategy is to estimate all the "known" standard model processes in the final state of interest, and look for deviations from standard model that is compatible with the signal expectation



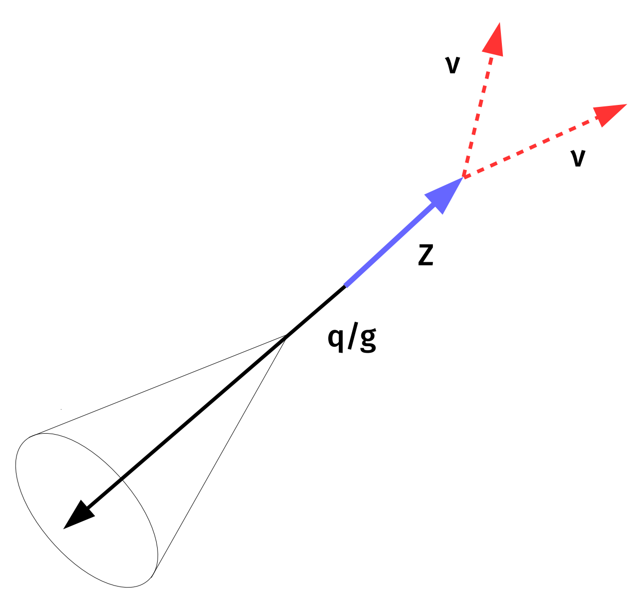
Dark Matter Signal



Reconstructed mono-jet event

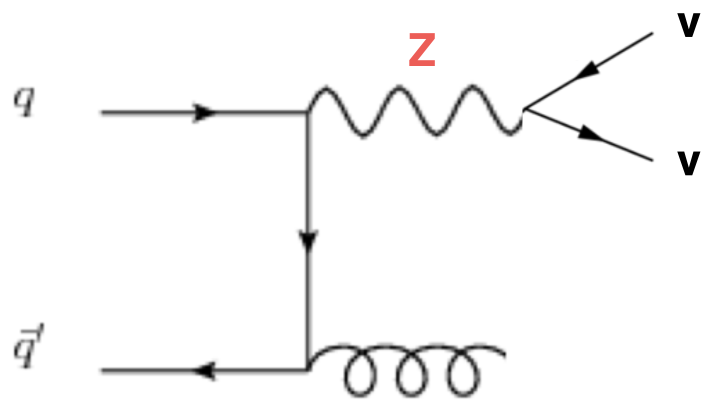


Irreducible largest background (Standard Model)



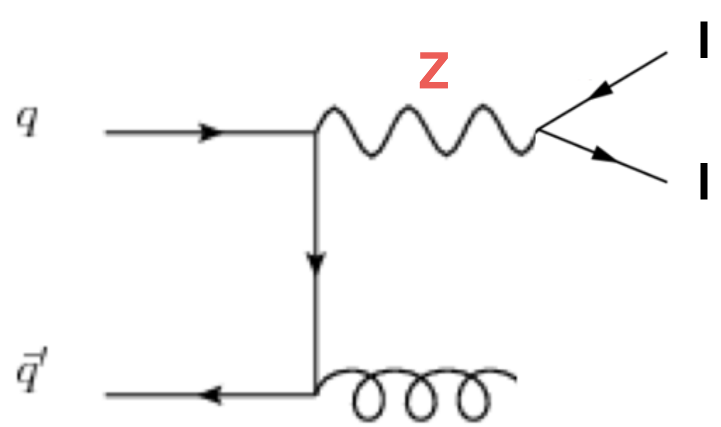
SM background
Identical signature!

Z→νν background estimation



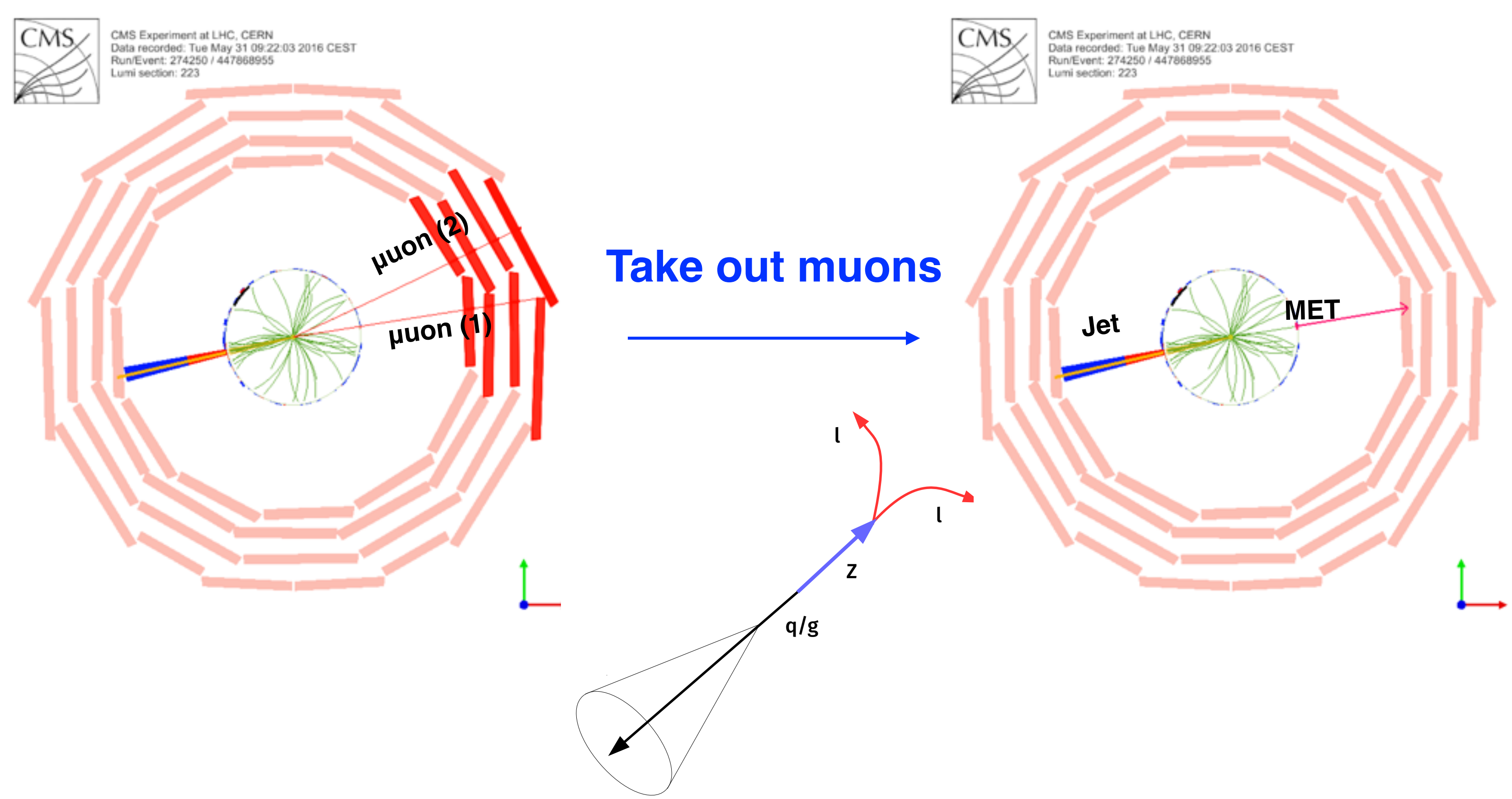
- Z(νν)+jets: it constitutes >50% of the total background
- Z(ll) p_T spectrum is very similar to Z(νν) p_T^{miss} spectrum.
  - It can be used to estimate the irreducible background

The Z(ll)+jets removing the charged leptons mimicks the Z(νν)+jets events

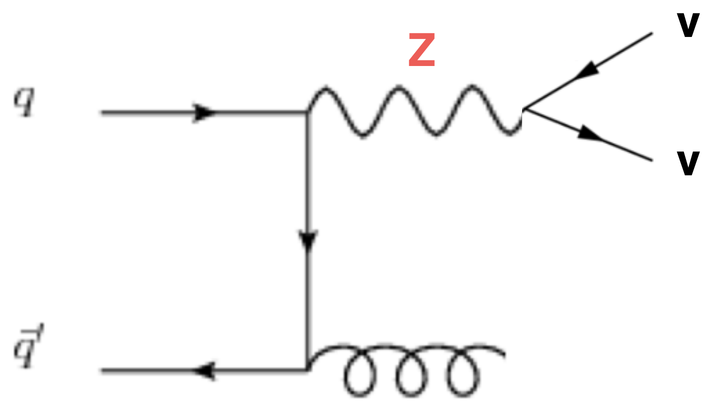


statistically limited

~no theory uncertainties

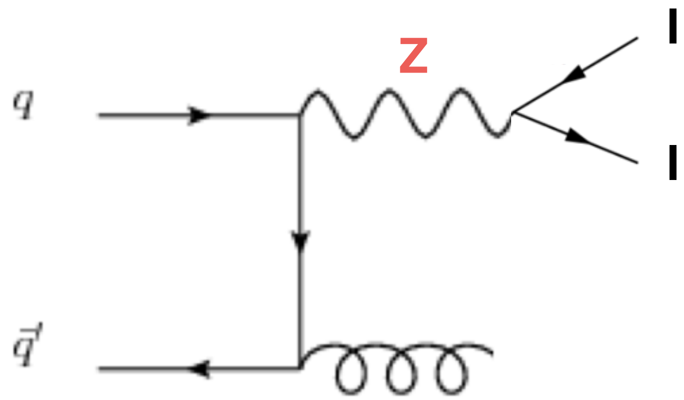


Z→νν background estimation



– Z(νν)+jets: it constitutes >50% of the total background

- **Exploit all possible orthogonal control regions (V+jets)**
- **Need state of the art prediction of the differential rates, uncertainties on V+jets/Z(νν)+jets**



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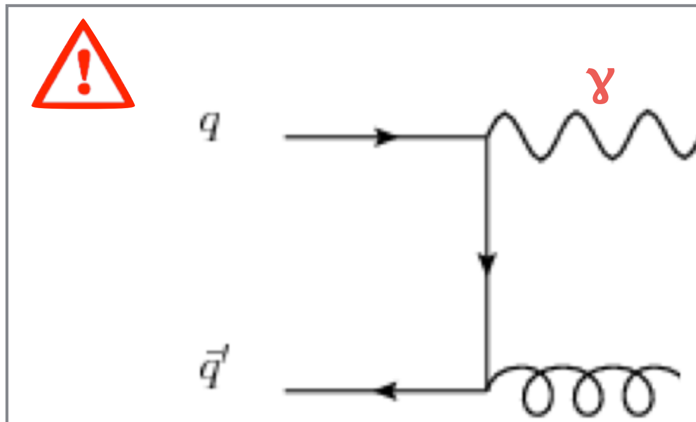
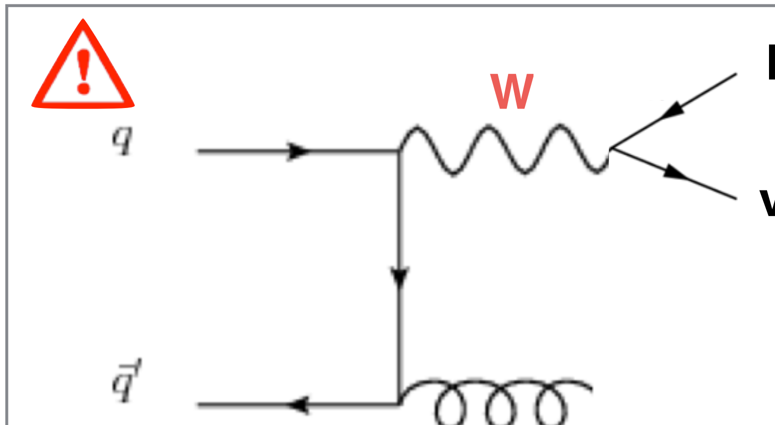


statistically rich!

large theory uncertainties

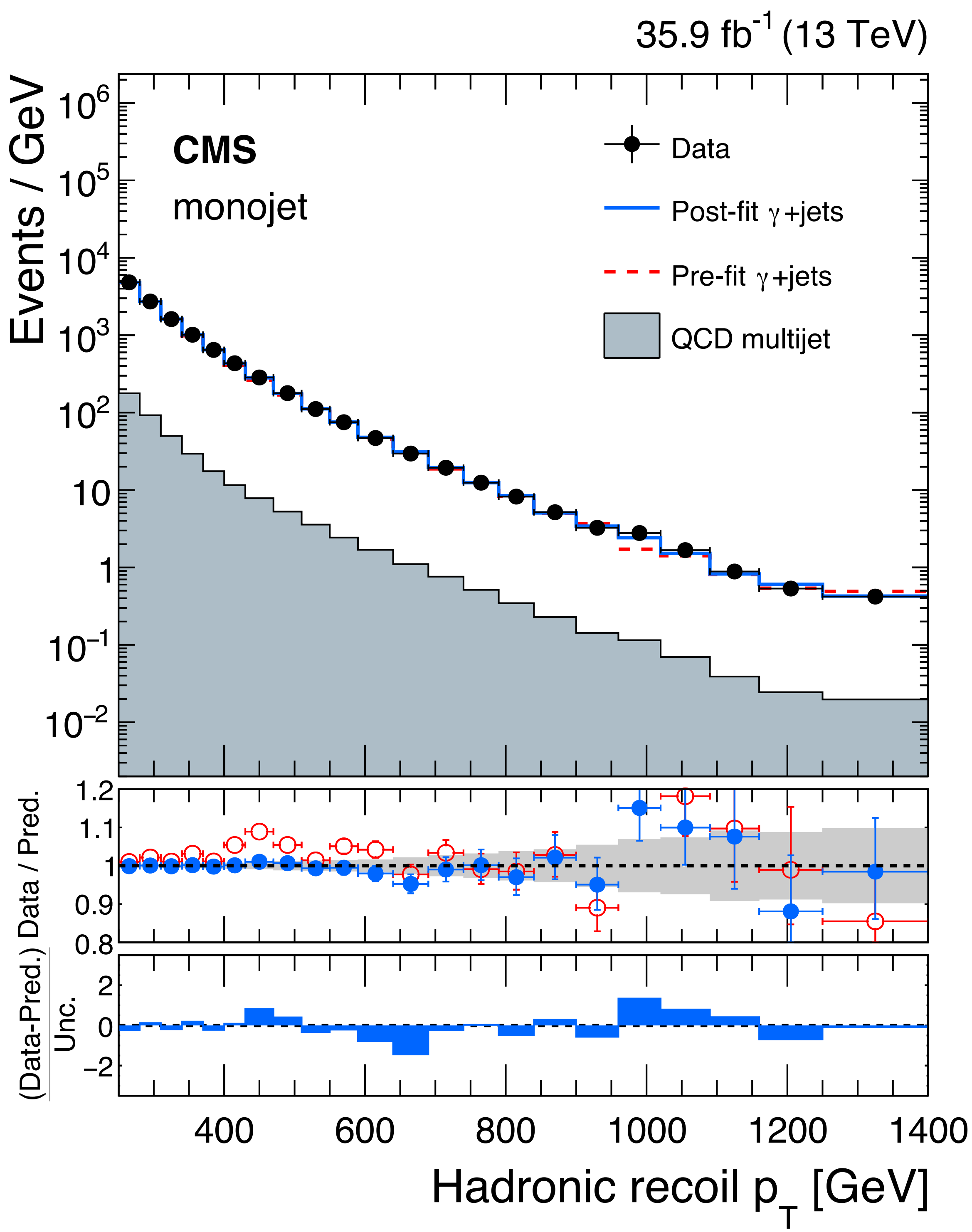


statistically ~ Z (νν)

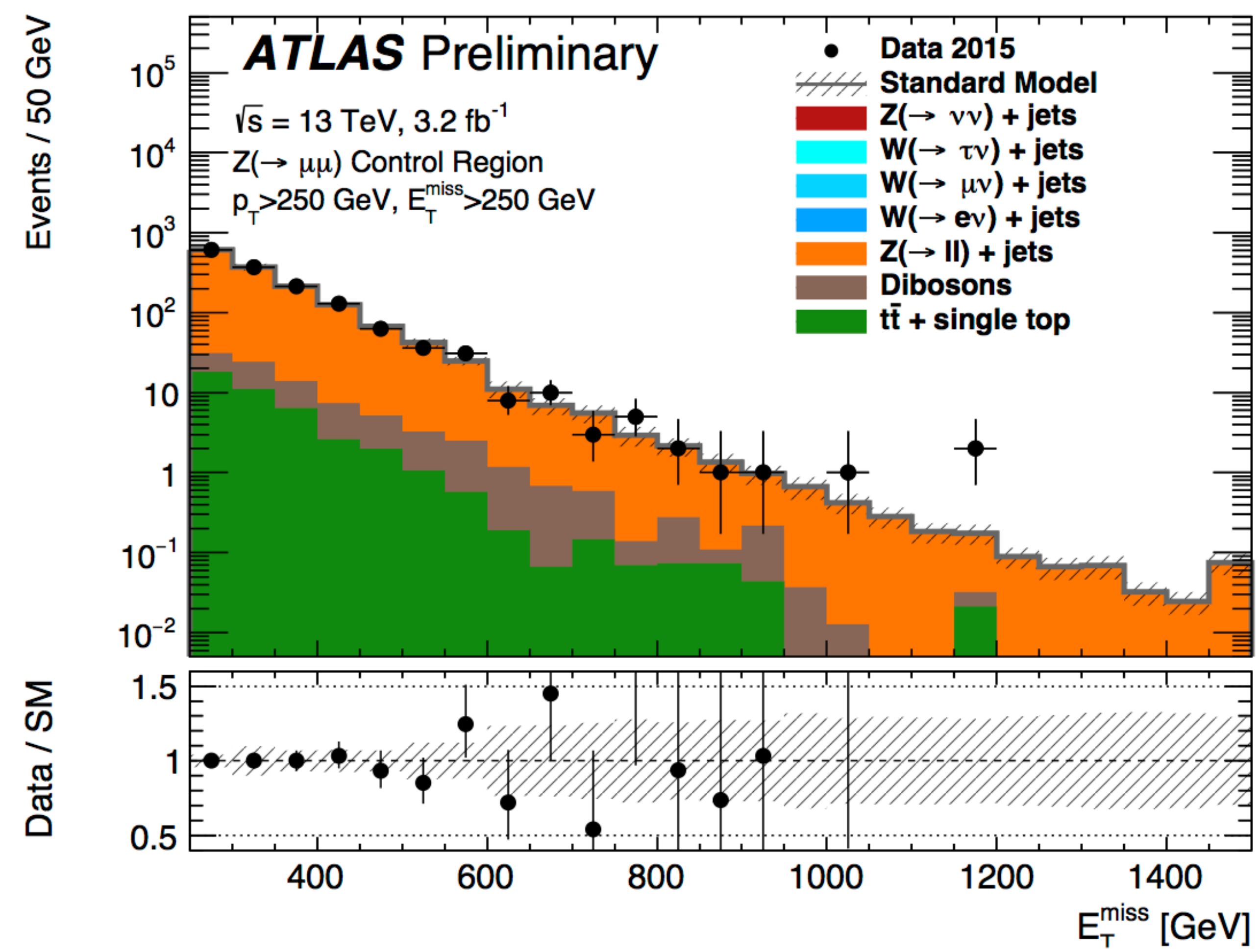
large theory uncertainties

Main control regions

γ as a proxy for Z(νν)

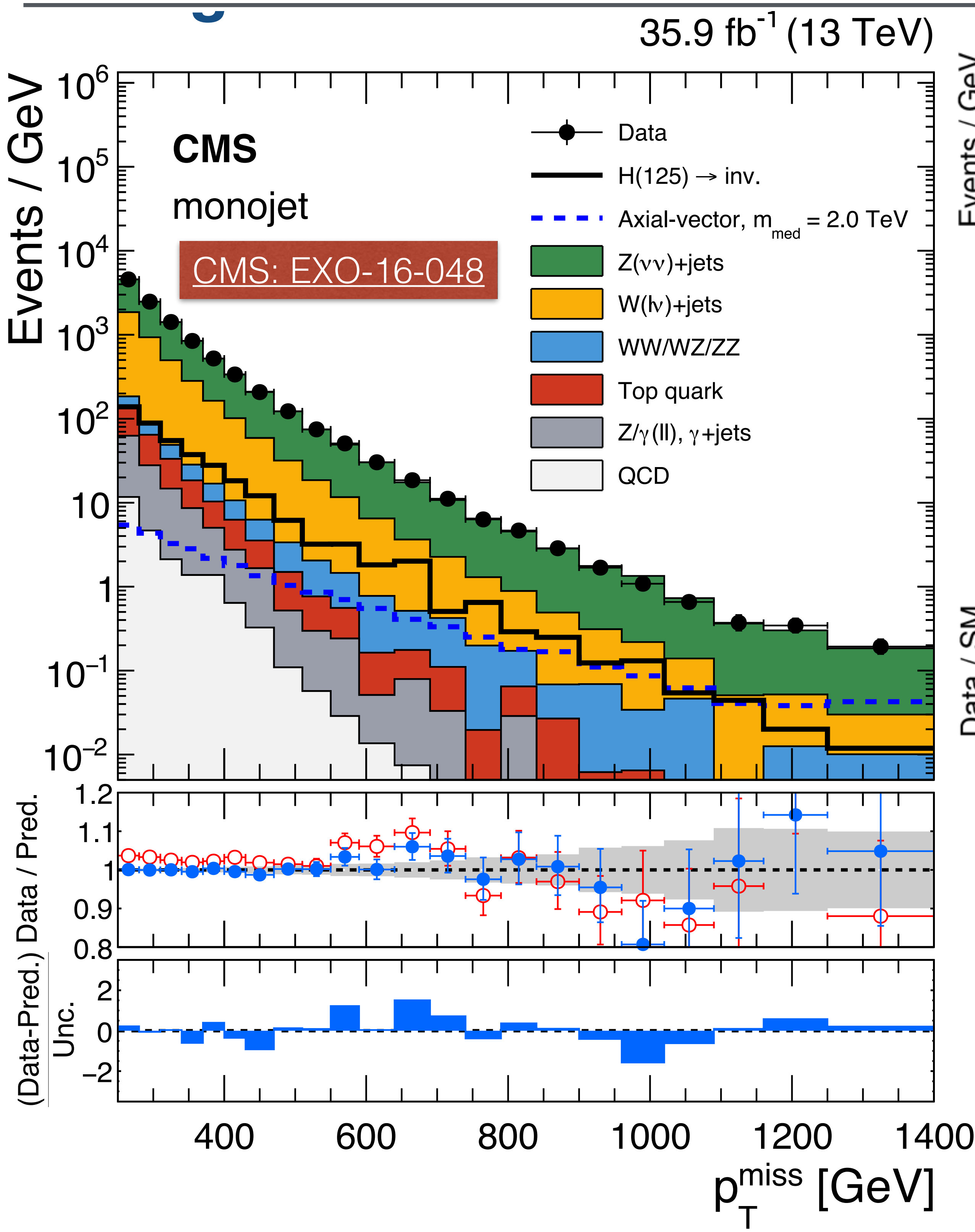


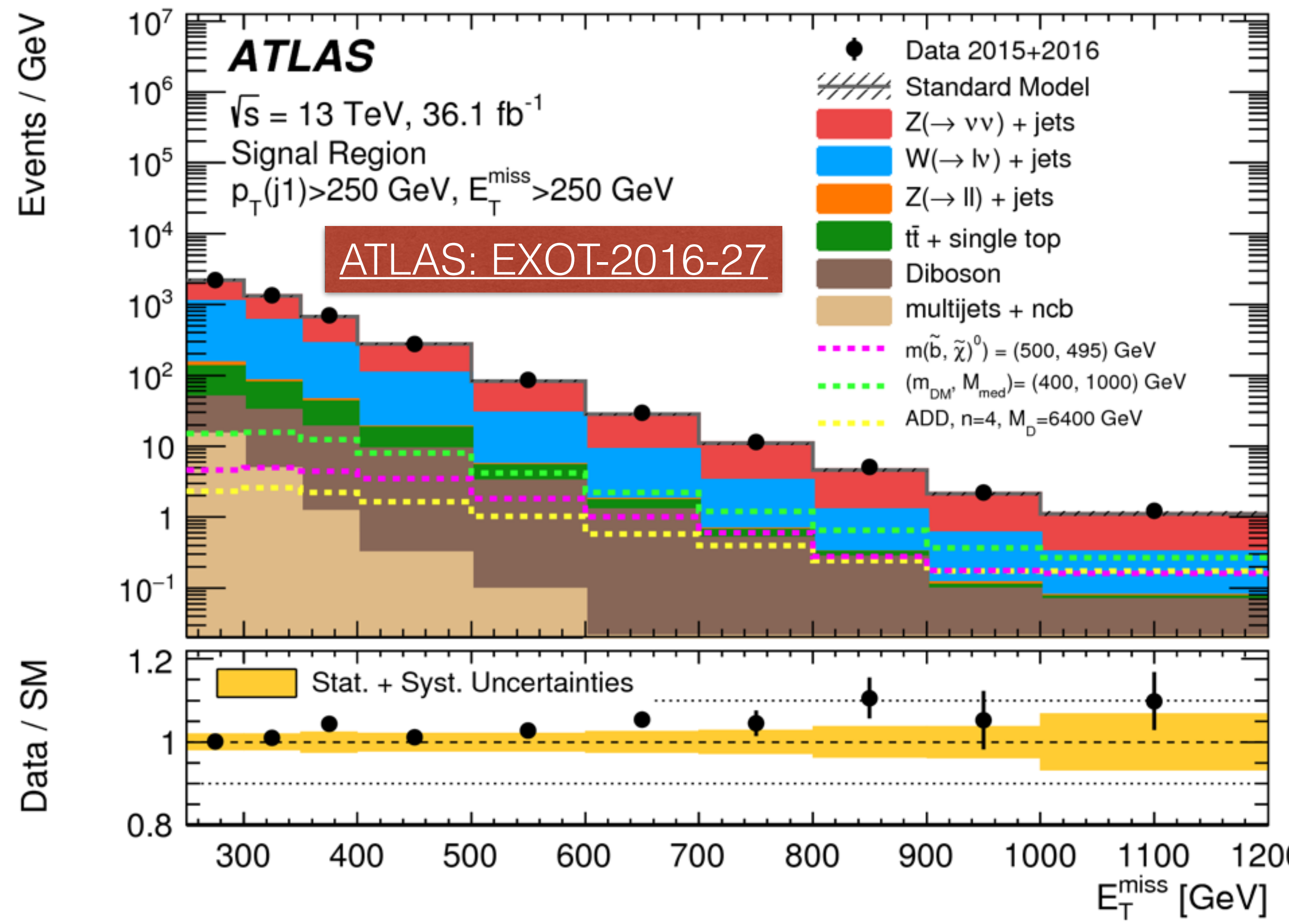
Z(ll) as a proxy for Z(νν)



Showing that detector effects and SM backgrounds are well understood

Results: no signal



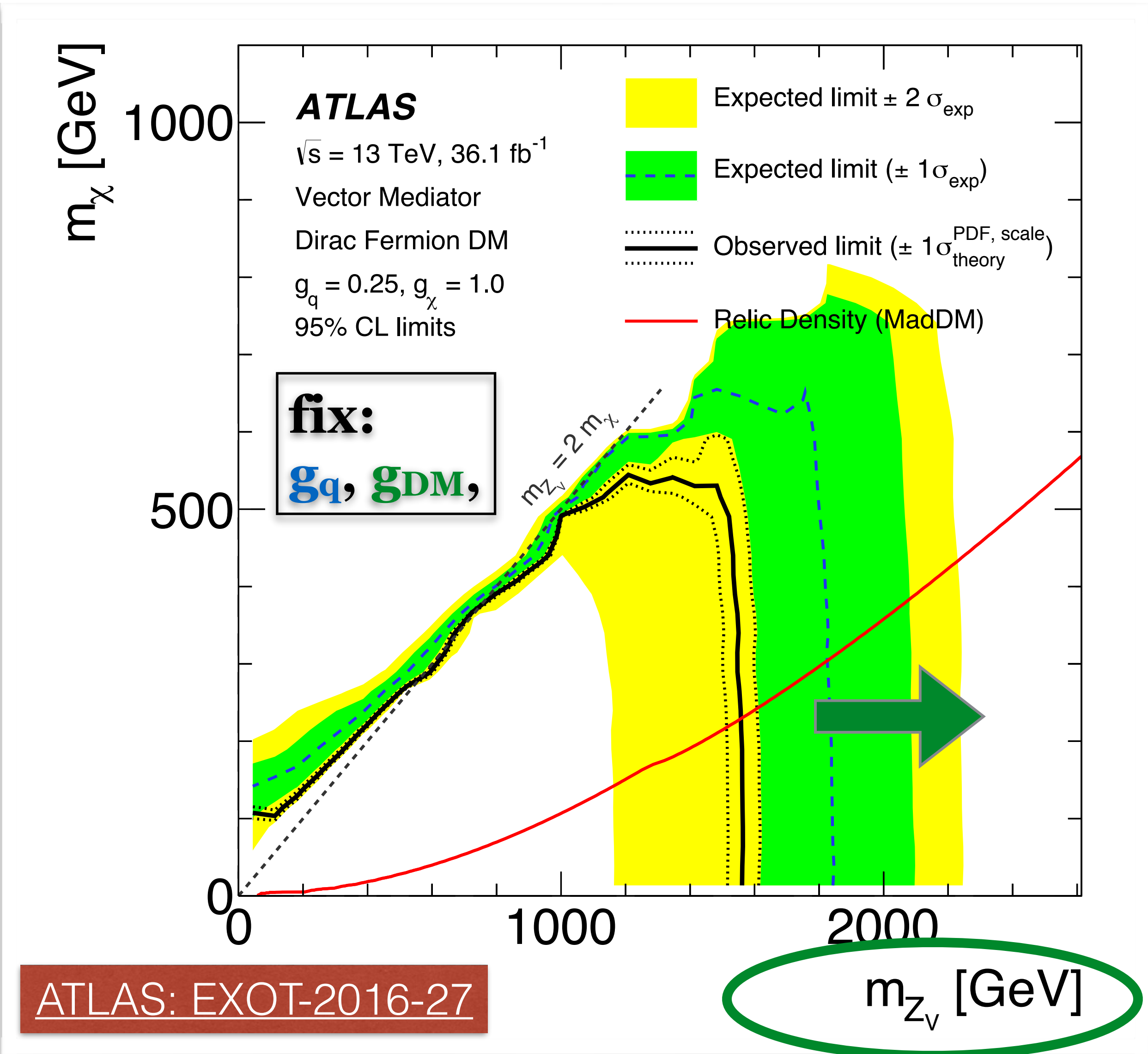


Clear challenge:

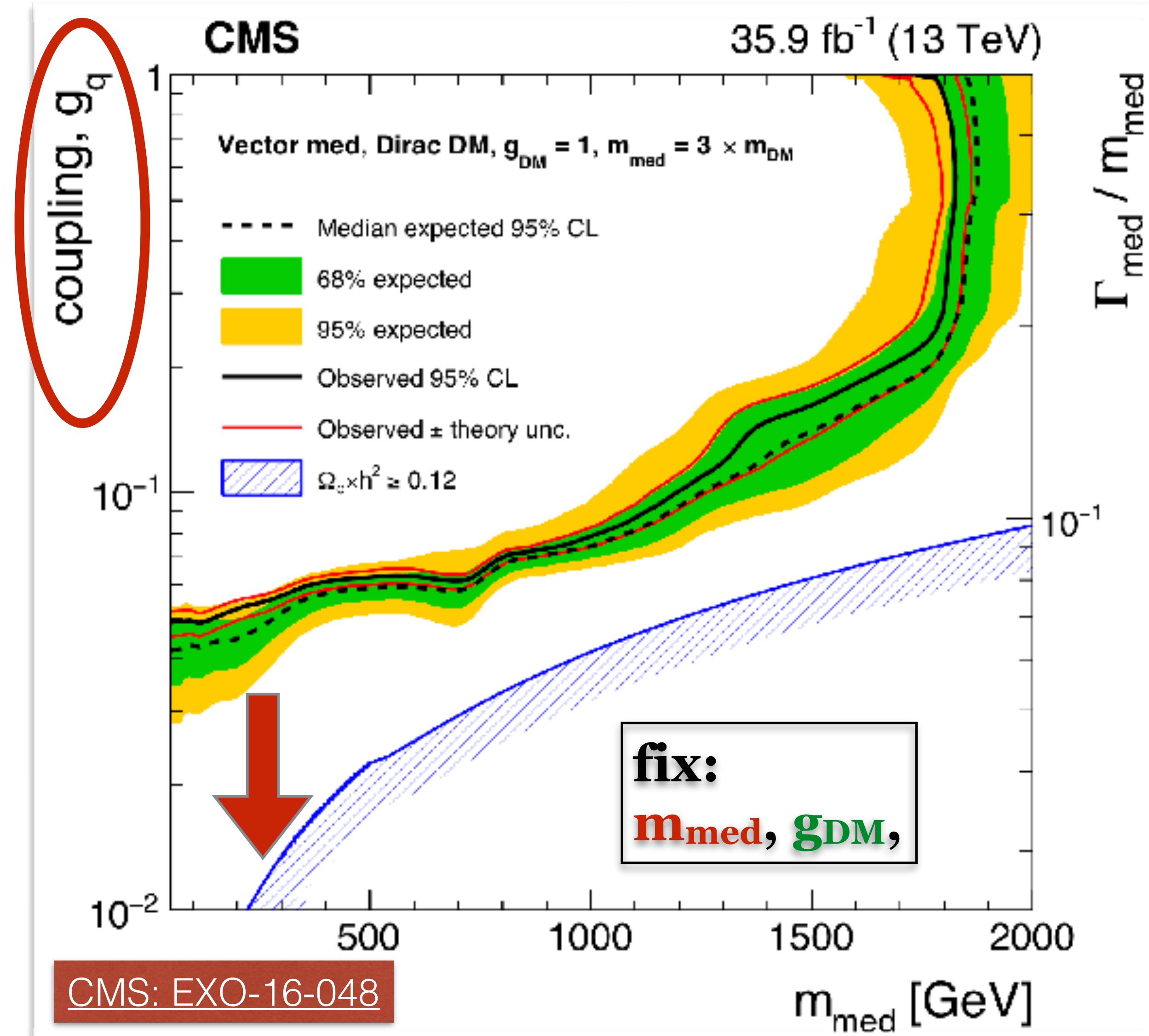
- The shape of signal and backgrounds are similar
  - ☞ **the MET tail** is the sensitive part of the spectrum
  - ☞ need to **control the SM background at % level**

Vector mediator limits

Interpretation depends on the chosen model.
E.g.: vector mediator, fixing 2/4 parameters among m_{med}, m_{DM}, g_q, g_{DM}, scanning the others



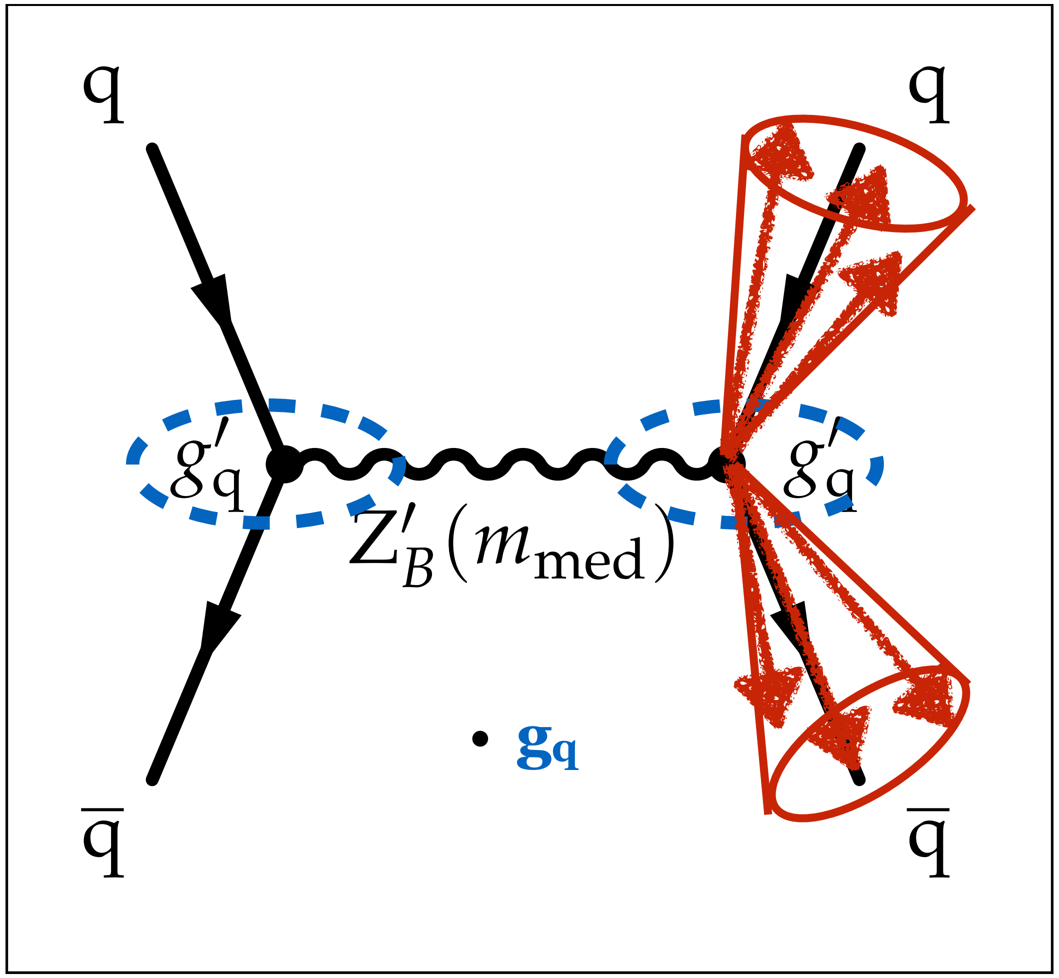
ATLAS: EXOT-2016-27



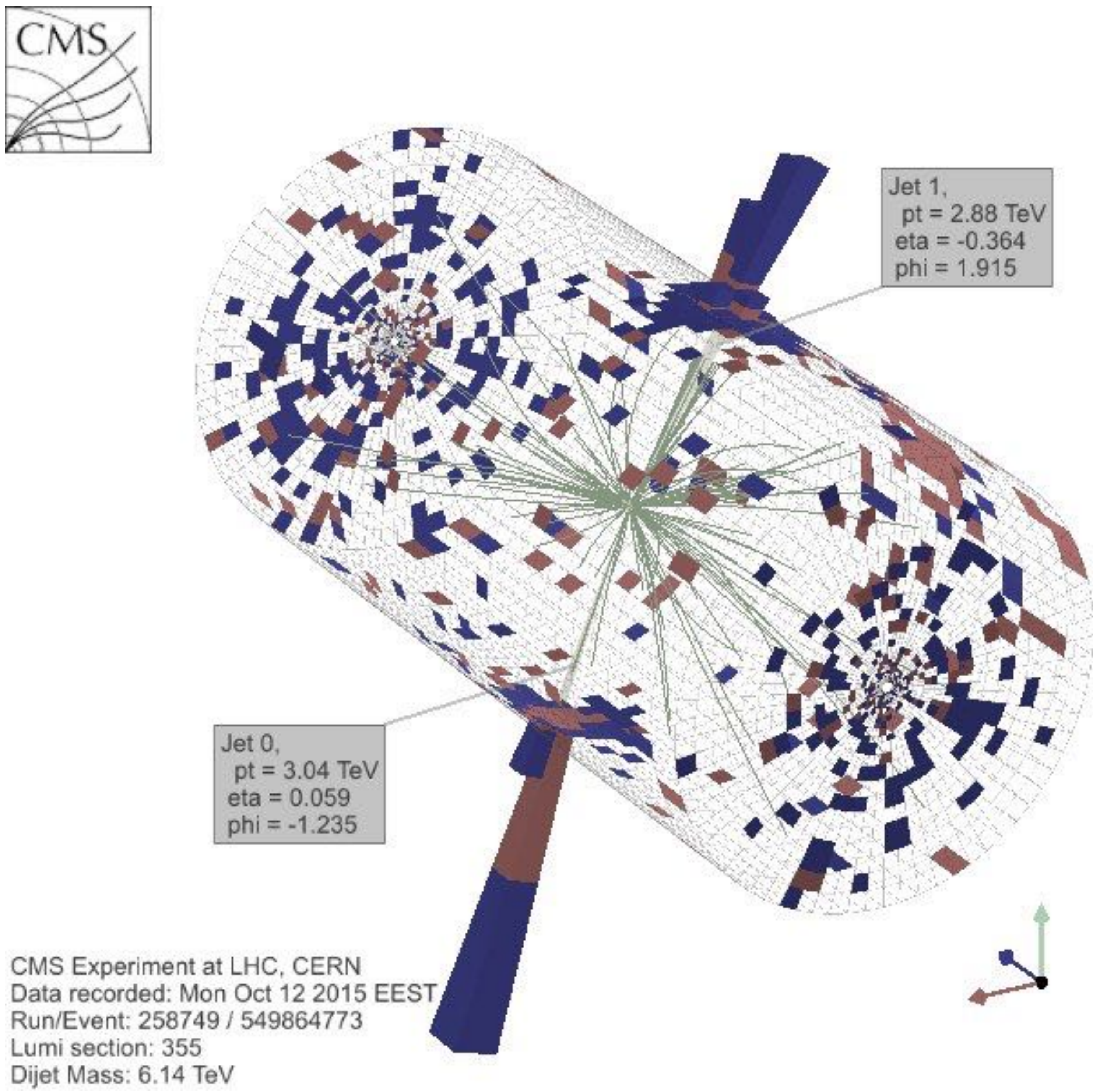
CMS: EXO-16-048

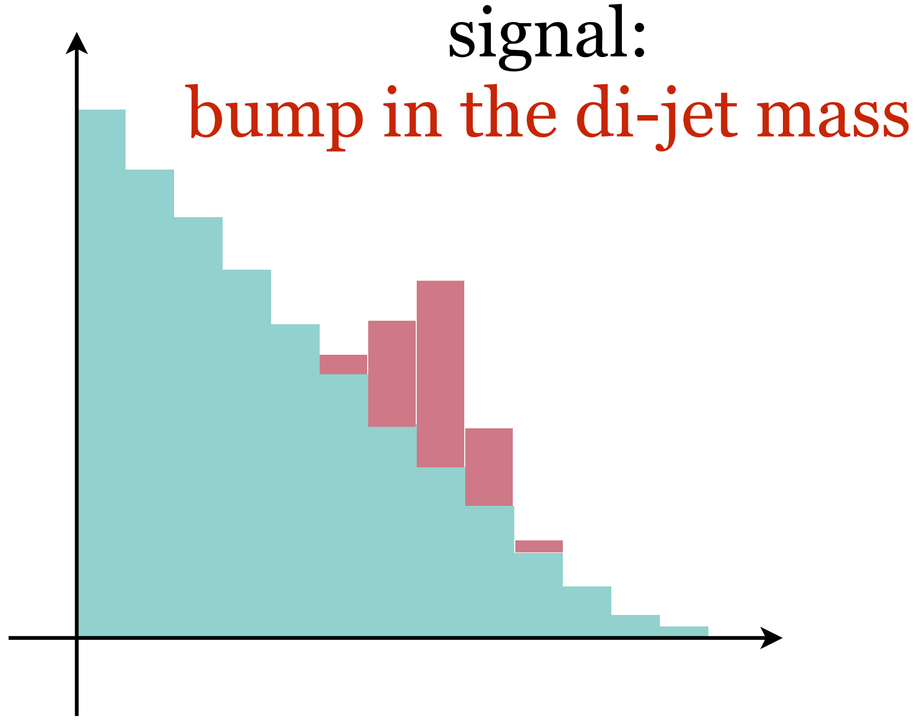
Pushing the limit on m_{med} to >1.5 TeV
Pushing the limit on couplings <5%

Dark mediator searches



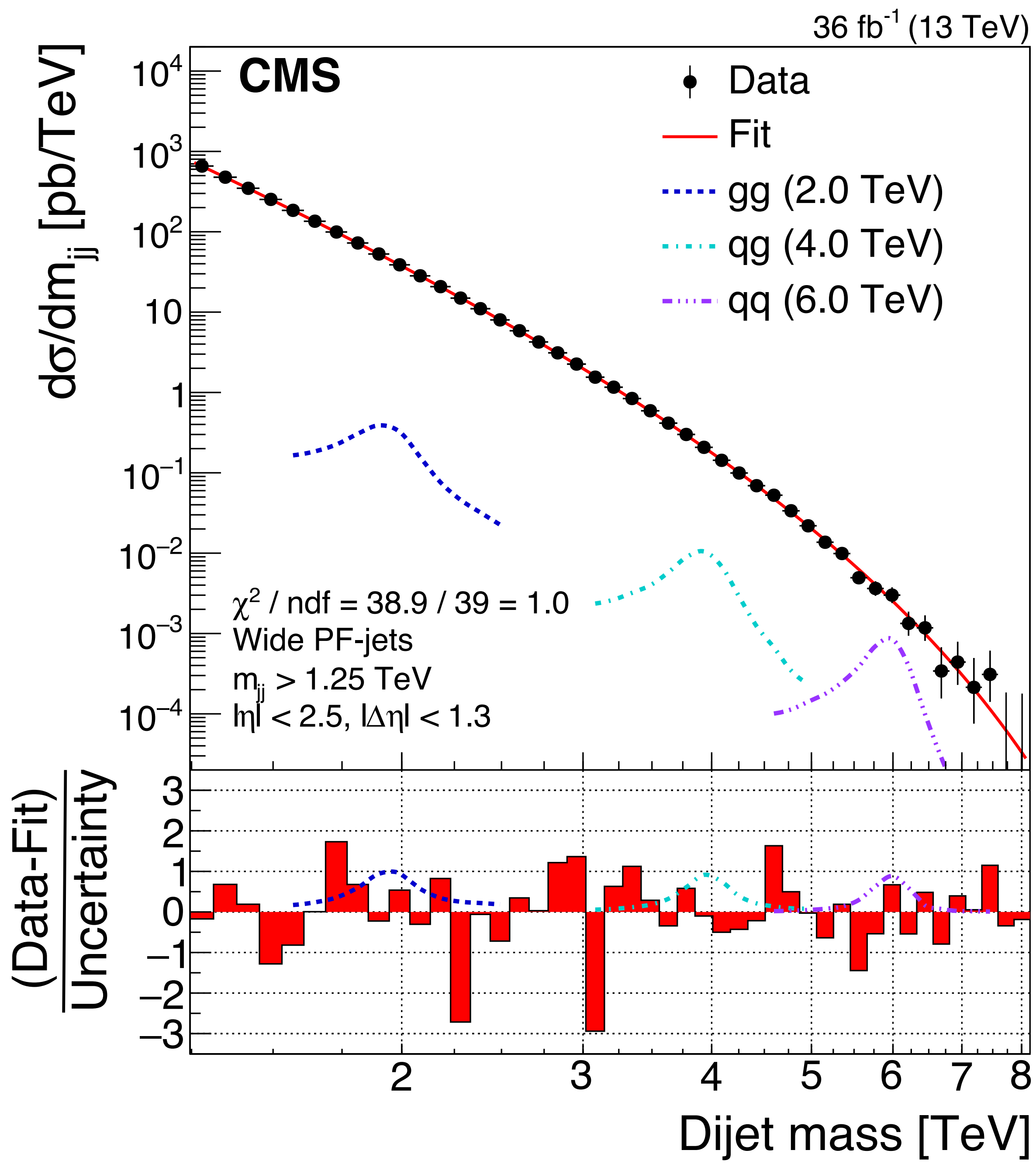
6 TeV dijet event

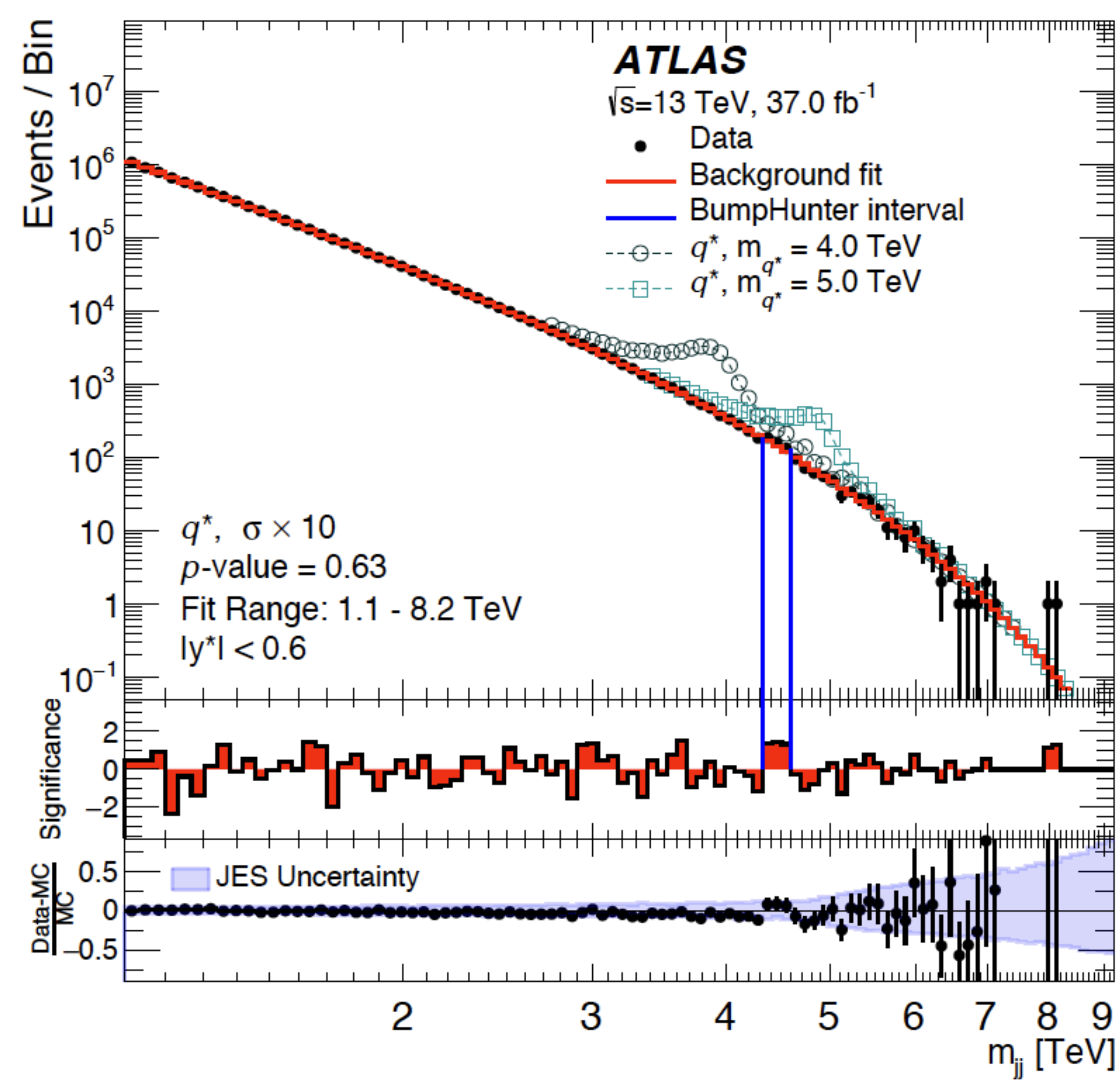




high mass di-jet spectra

- Collect data with jets trigger
- Cluster and select two jets
- Fit di-jet invariant mass
  - **Huge background!**

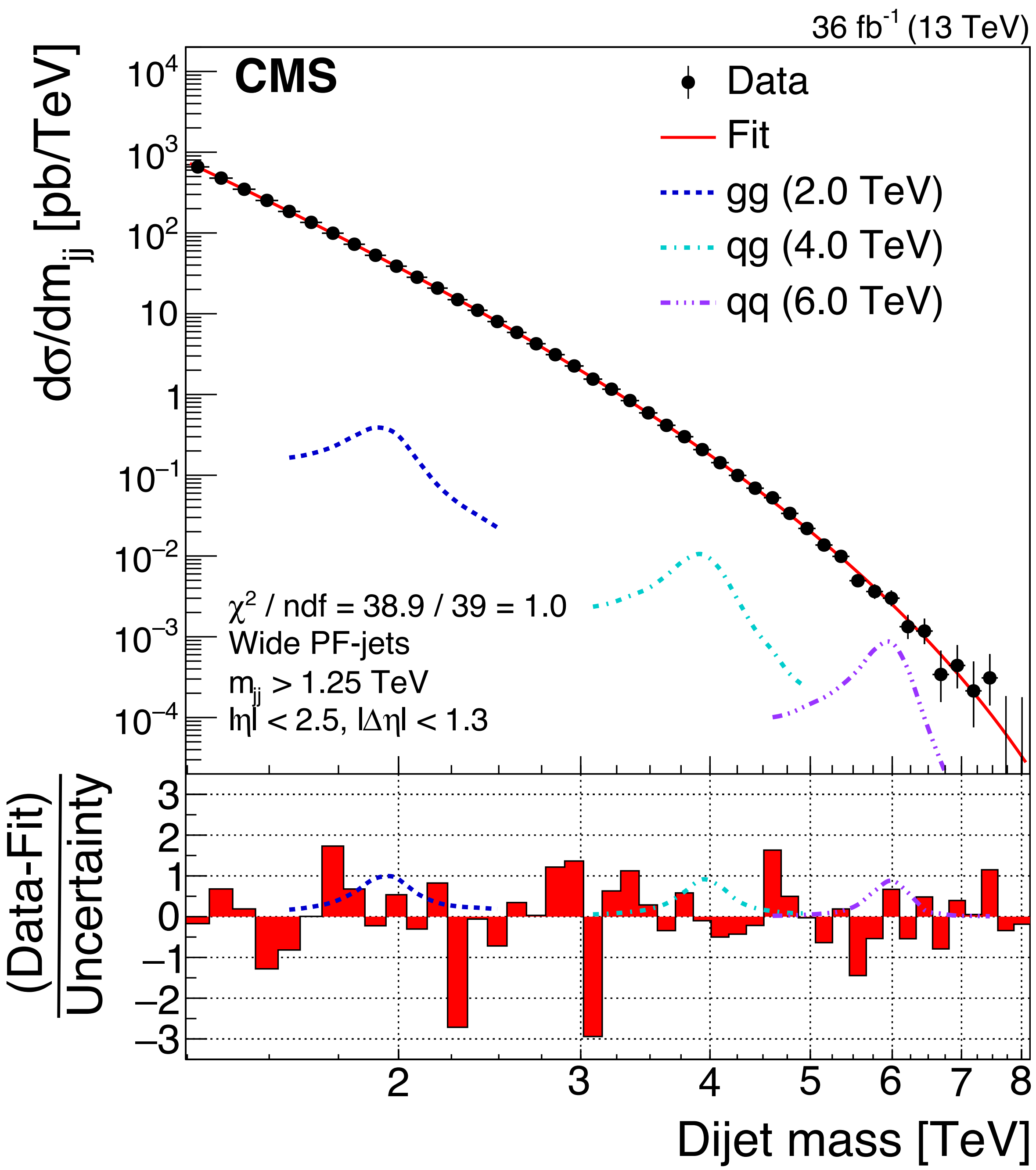


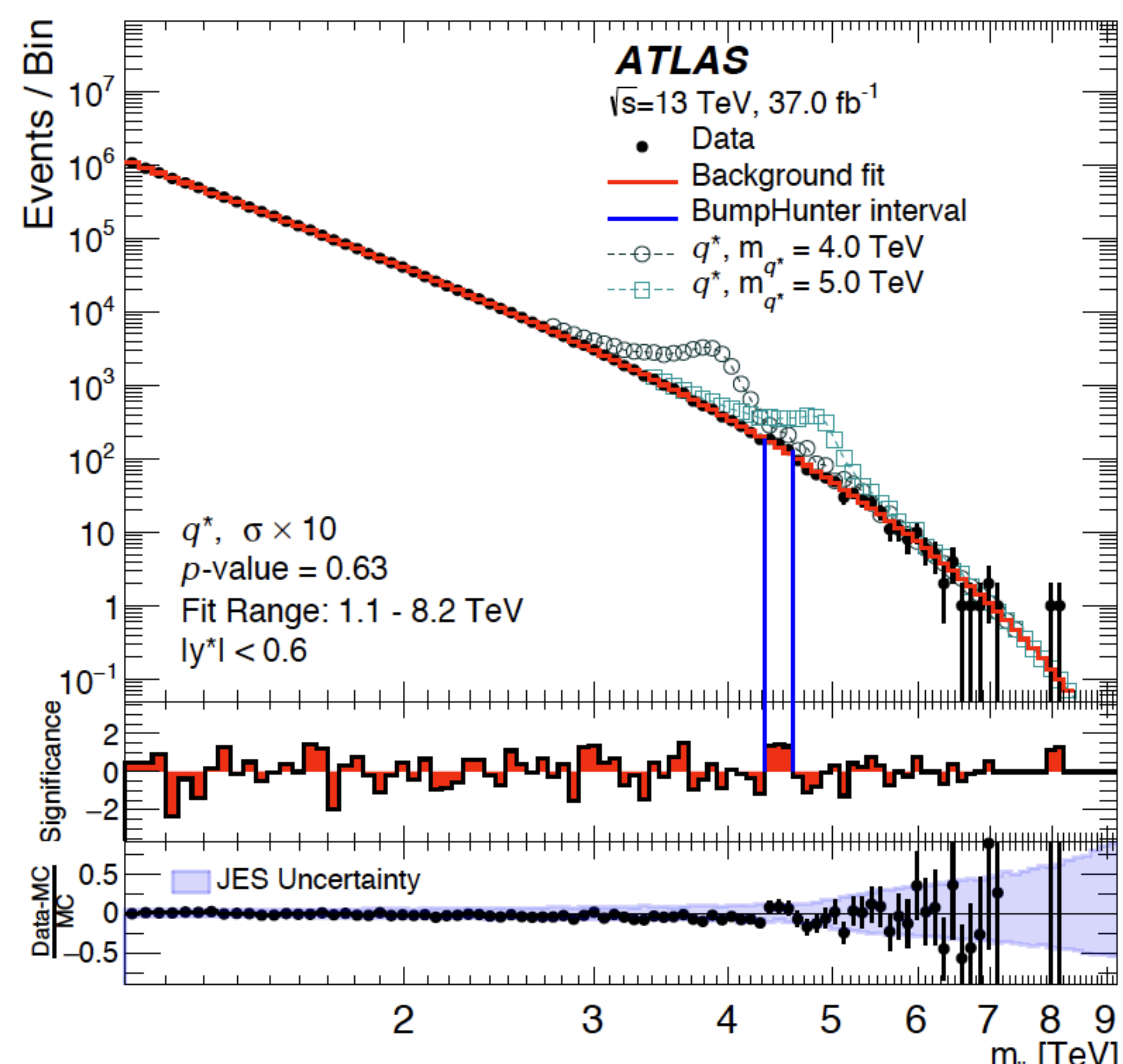


high mass di-jet spectra

- Coll
- Clus
- Fit c
  - F

Note: with H_T>~900 GeV,
high mass spectrum to fit starts at m_{jj}>1.25 TeV
=> need alternatives for lower masses

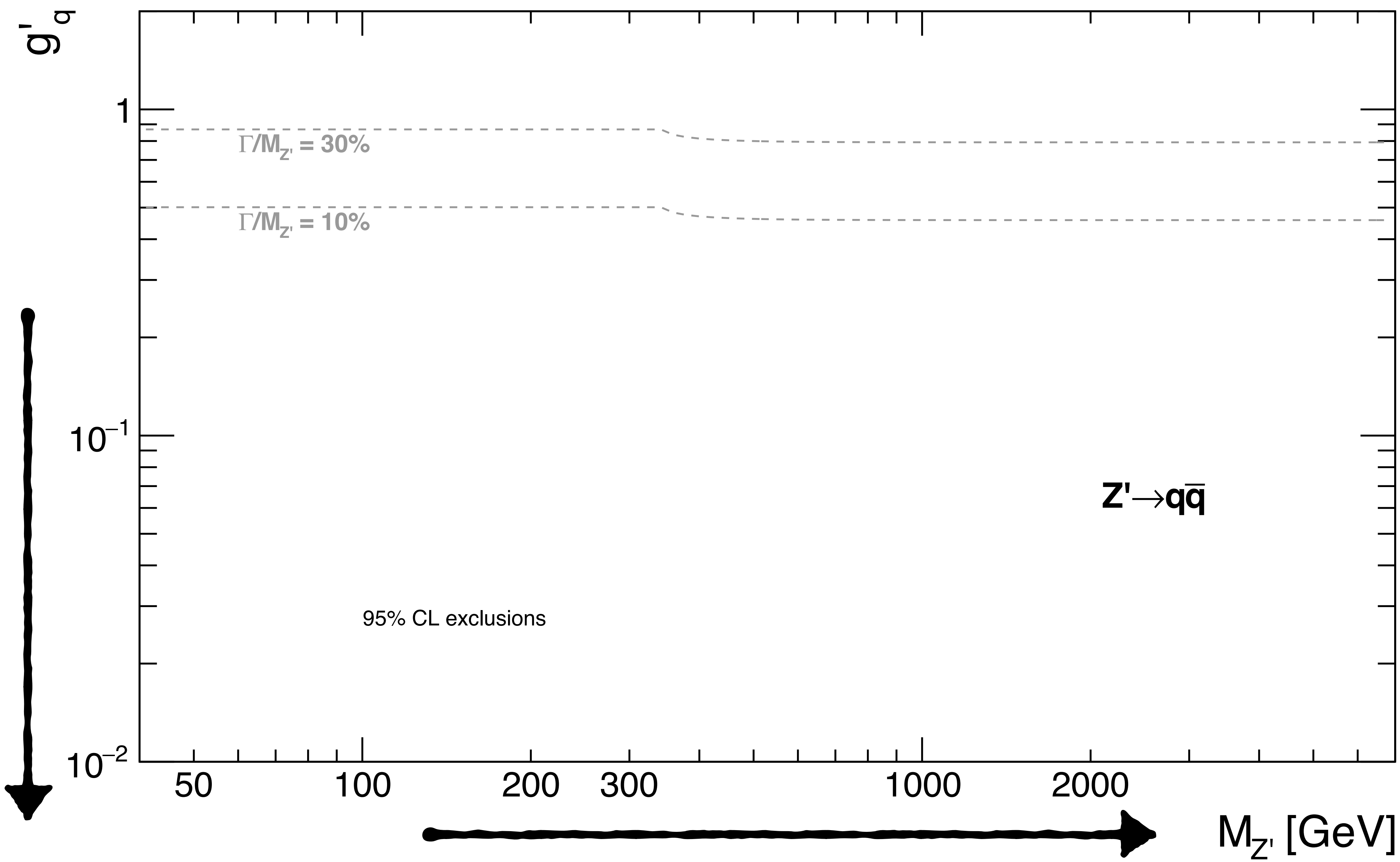




dark mediator interpretation

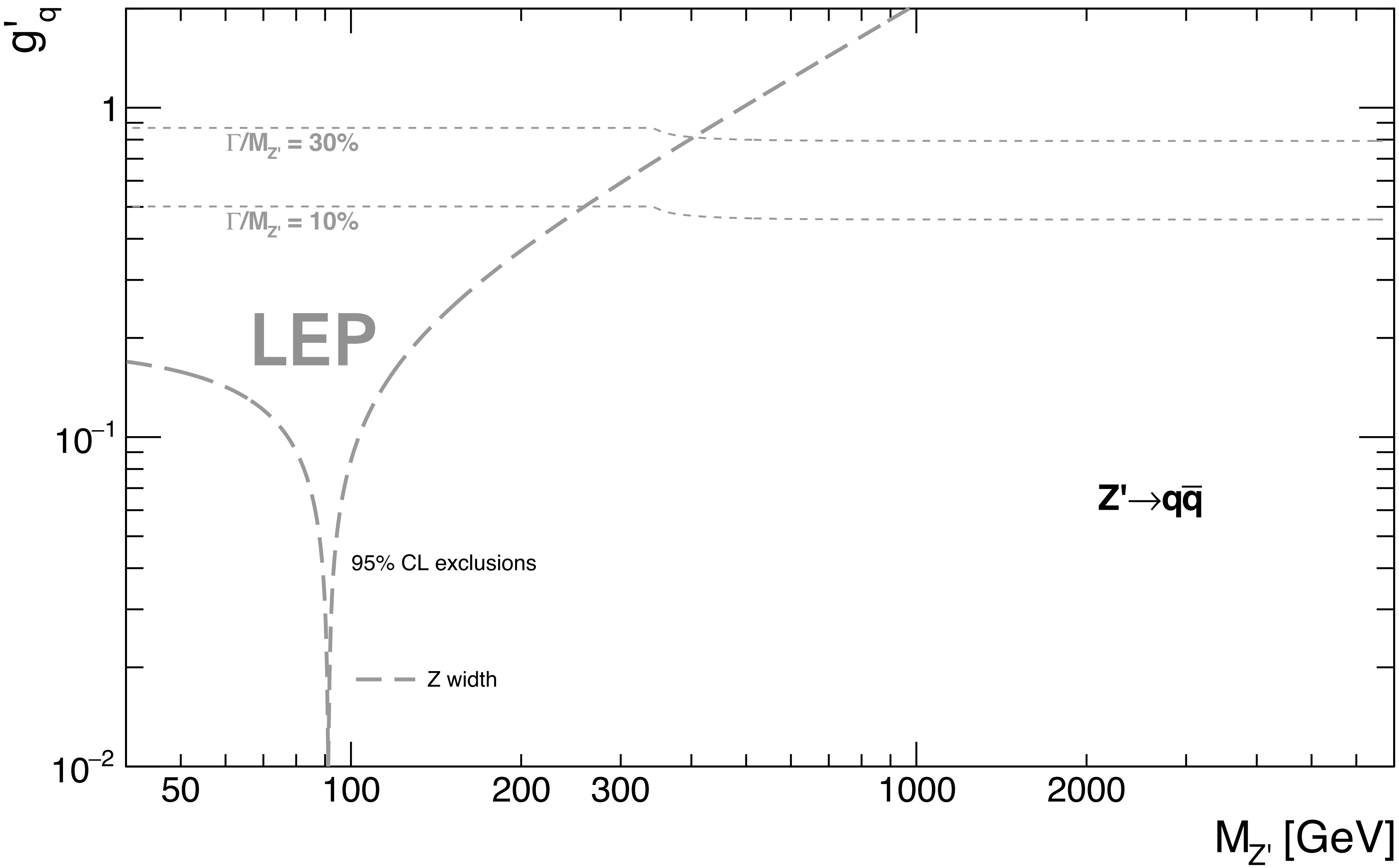
- A simplified model of a dark matter mediator

weaker quark coupling
→ smaller cross section



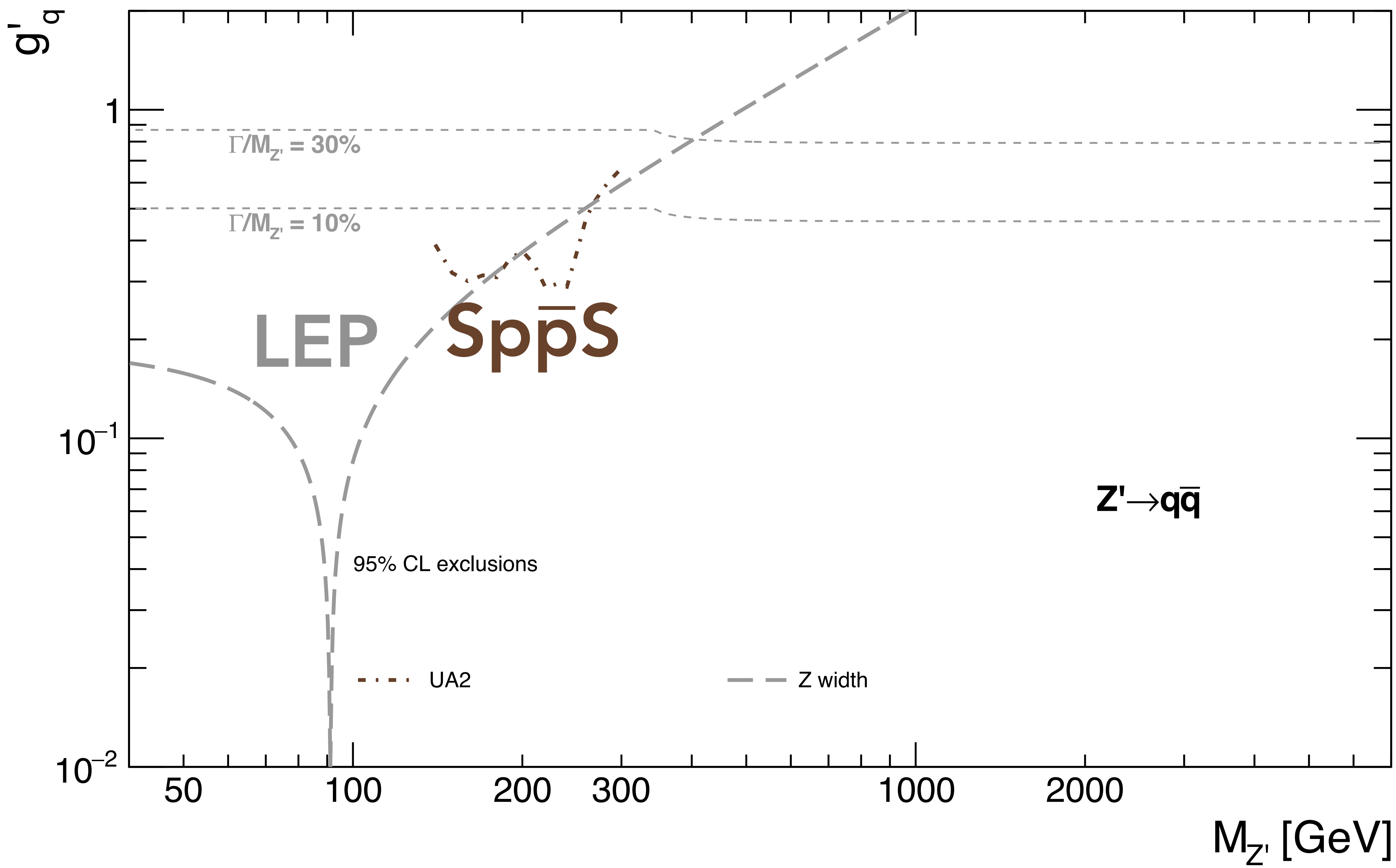
higher resonance mass

dark mediator interpretation



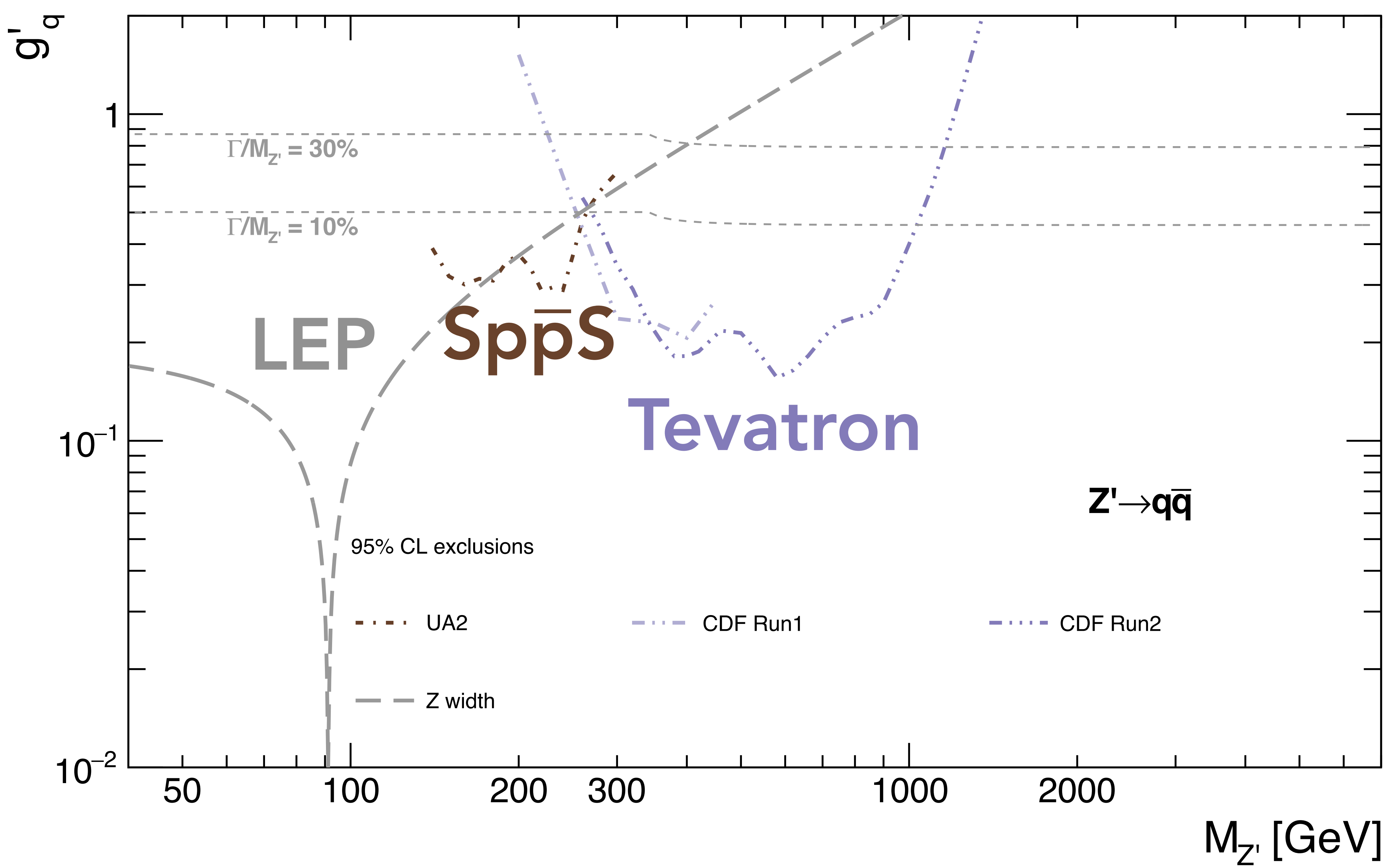
Precision measurements of the Z boson width from **LEP**

dark mediator interpretation

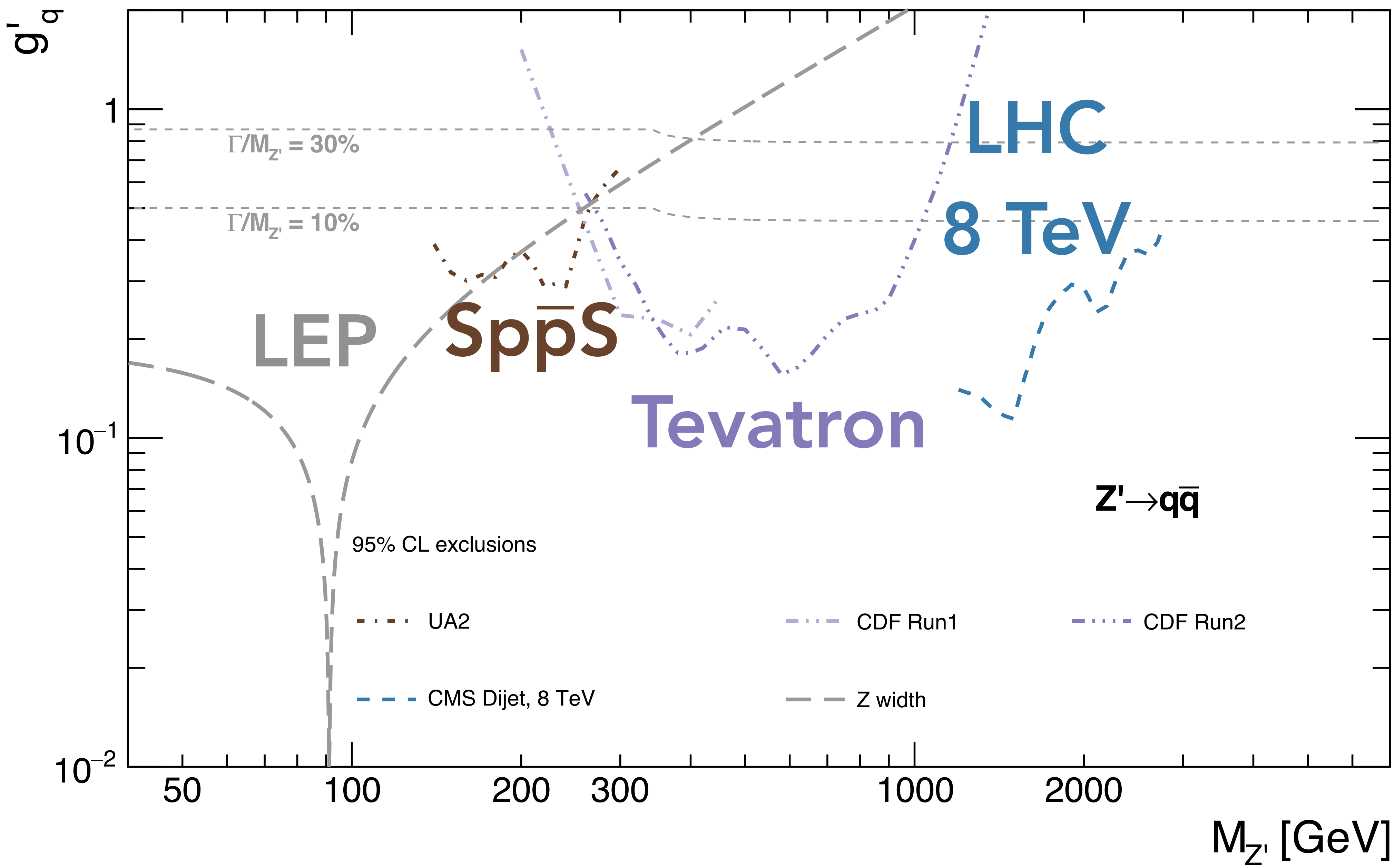


UA2 dijet search at the **SppS** at CERN, 1993

dark mediator interpretation



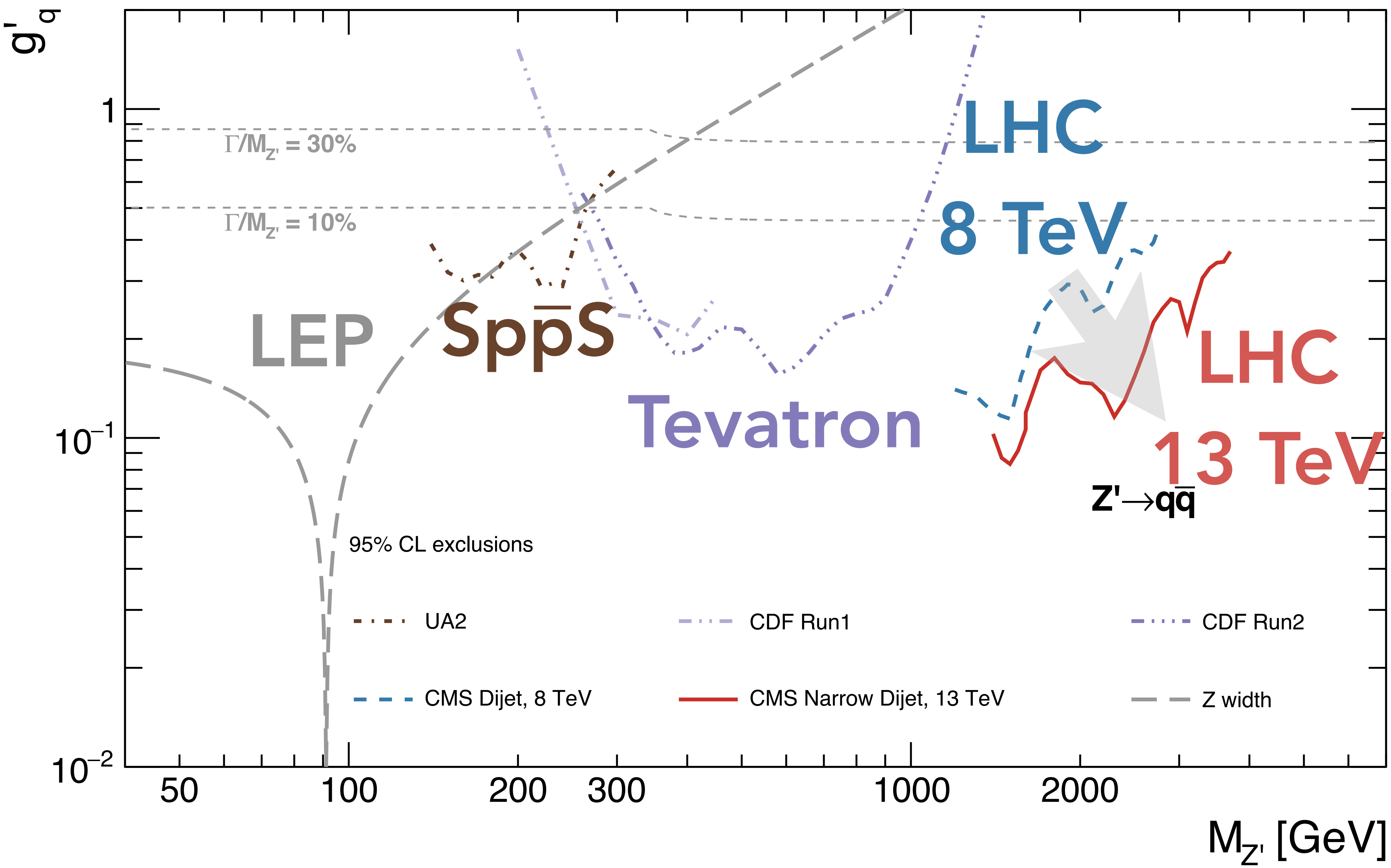
CDF dijet search at the Tevatron at Fermilab, 2009



LHC dijet search the LHC (8 TeV), 2012

dark mediator interpretation

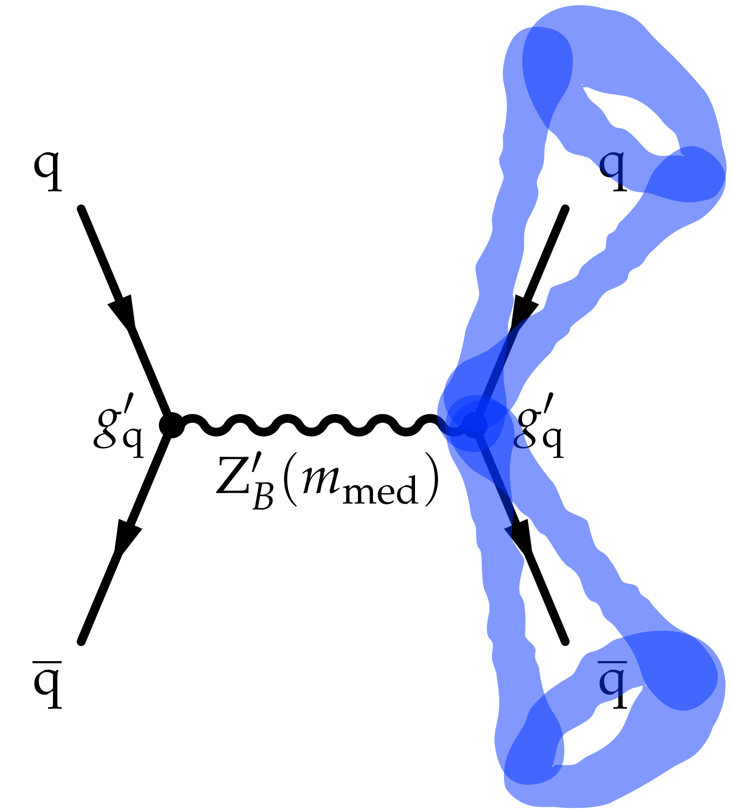
Higher energies probes only *higher masses* of DM mediators



LHC dijet search the LHC (13TeV)

Low mass di-jets

- ***Data scouting (CMS) / Trigger-object Level Analysis (ATLAS)*:**
  lower trigger thresholds
  by recording only information necessary to perform certain analyses:
  - ☞ **reduced information saved**



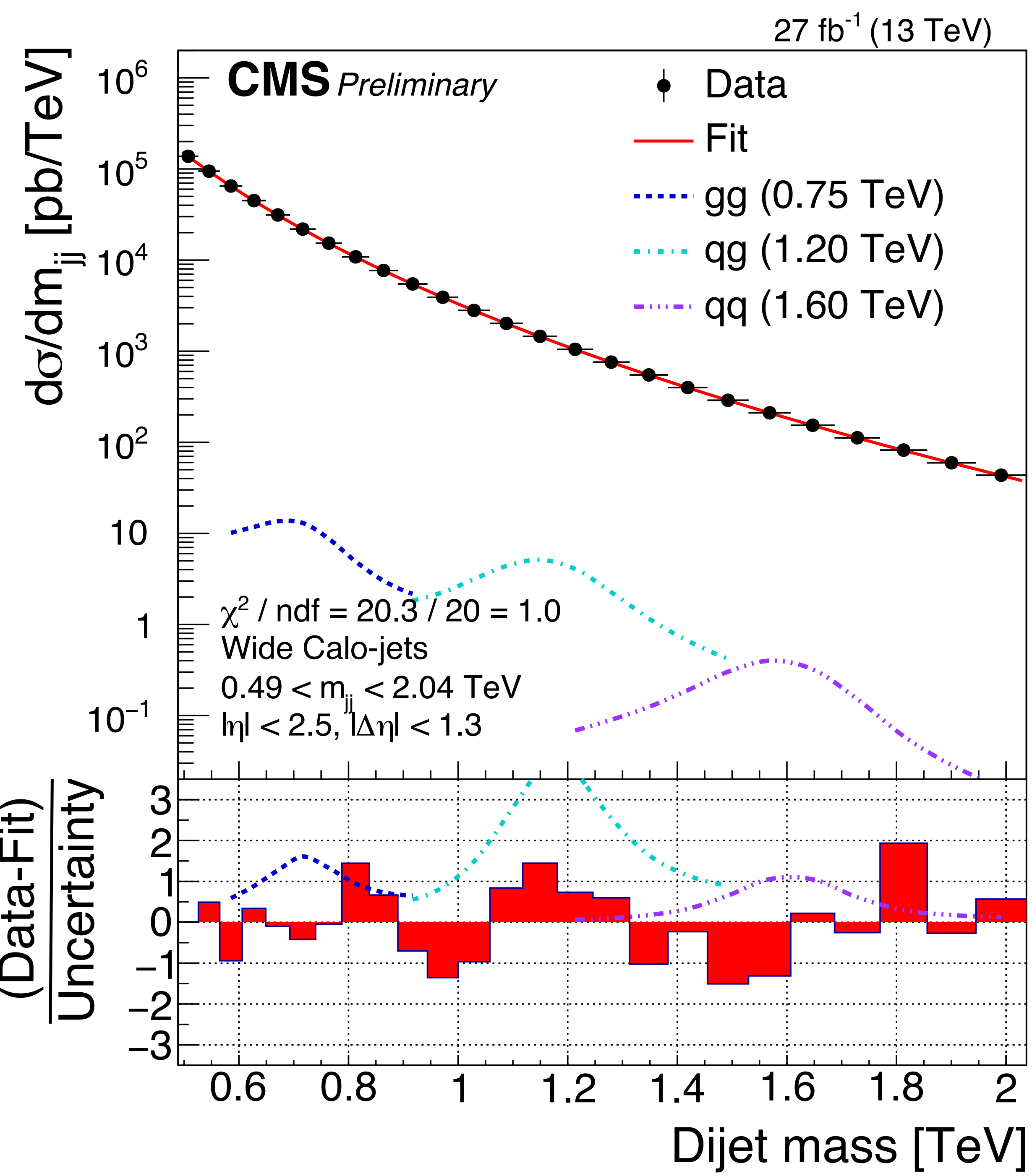
Total Bandwidth = event size × event rate

= **1 MB** × **1 kHz**

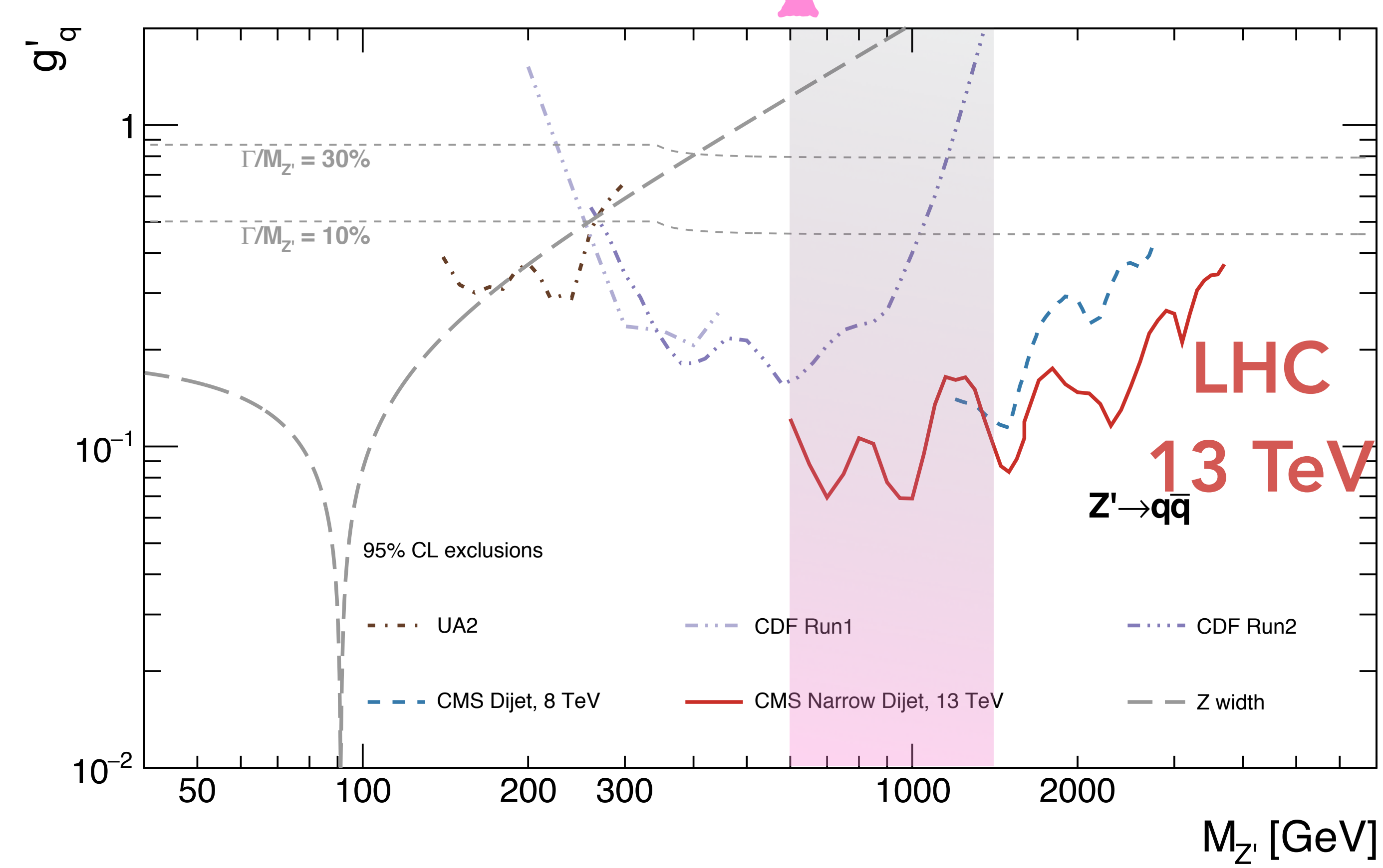
↓ ↑

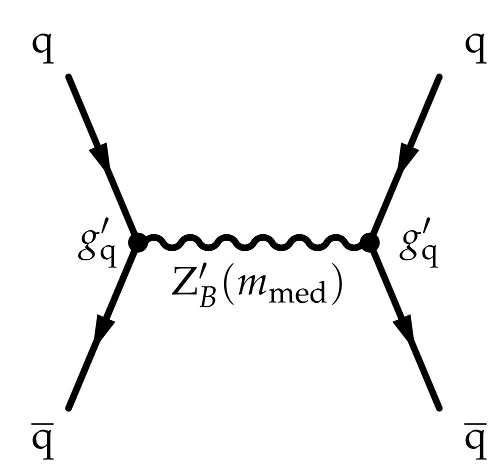
Can we shrink **size** to increase **rate** ?

low-mass dijet spectra



Expands LHC reach down to ~600 GeV

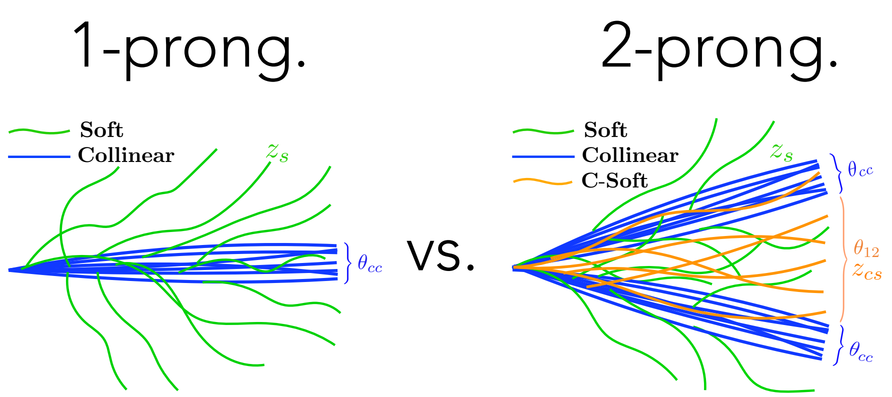




Boosted di-jets

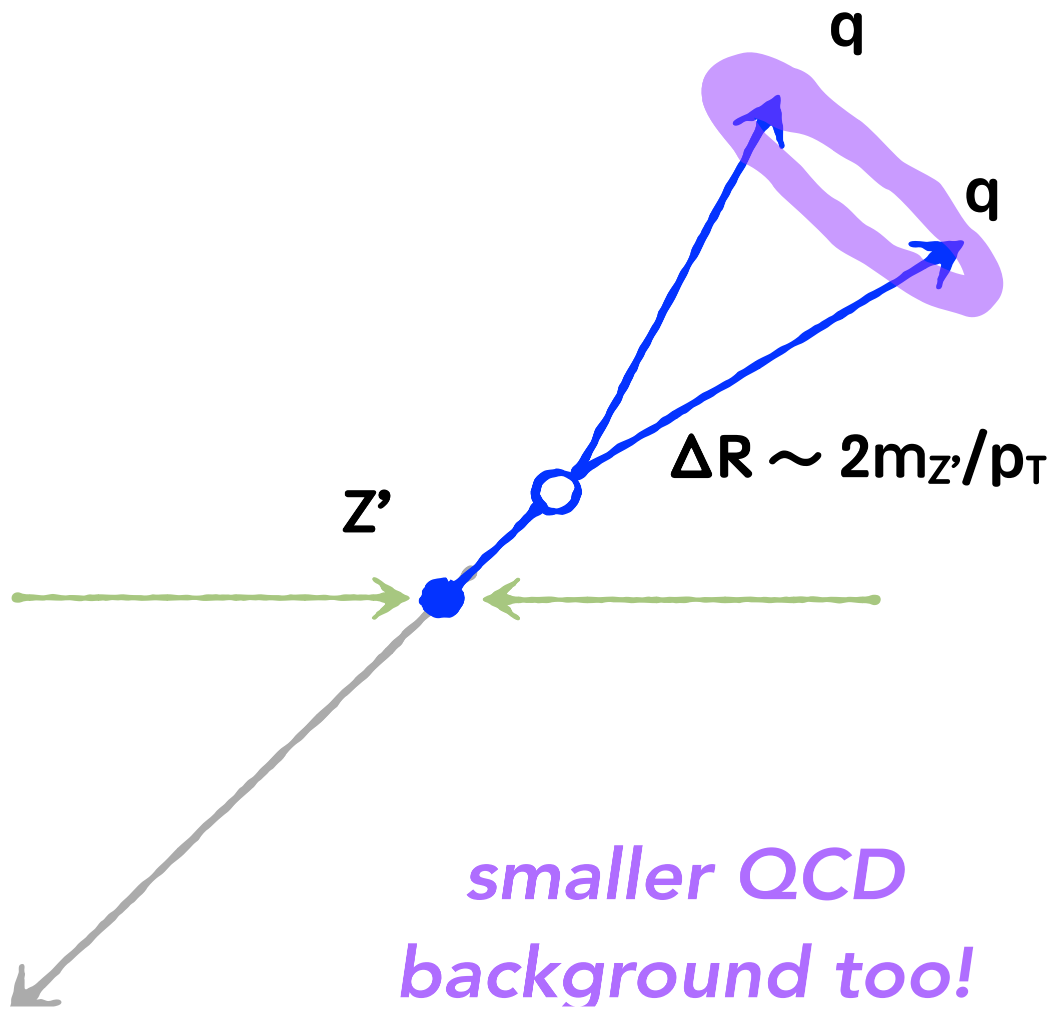
- At high p_T, the quarks are boosted into a single large-radius jet
- ISR gets us above the **trigger** threshold

Ingredients:
1. High p_T jets
2. **Jet substructure** topology

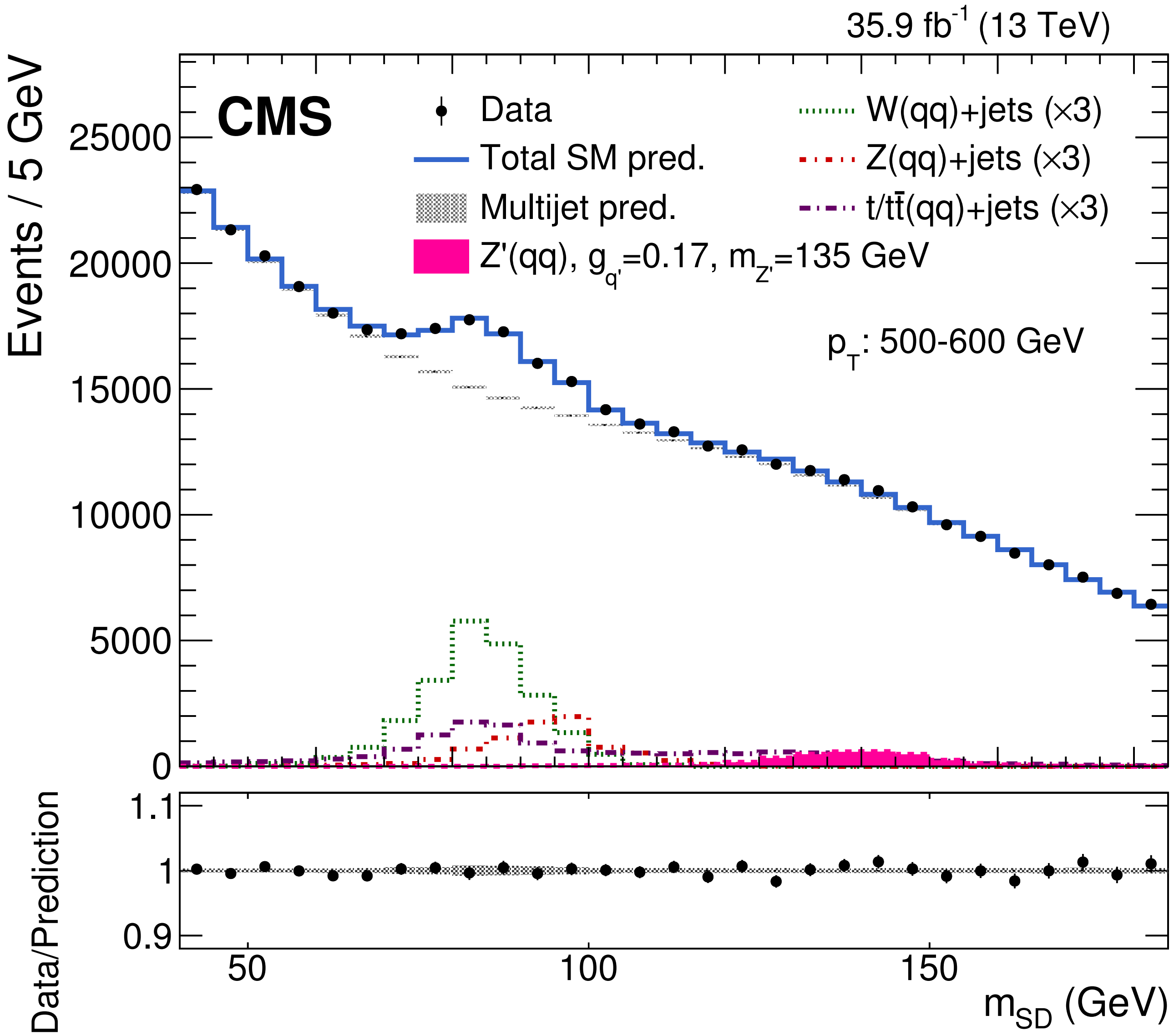


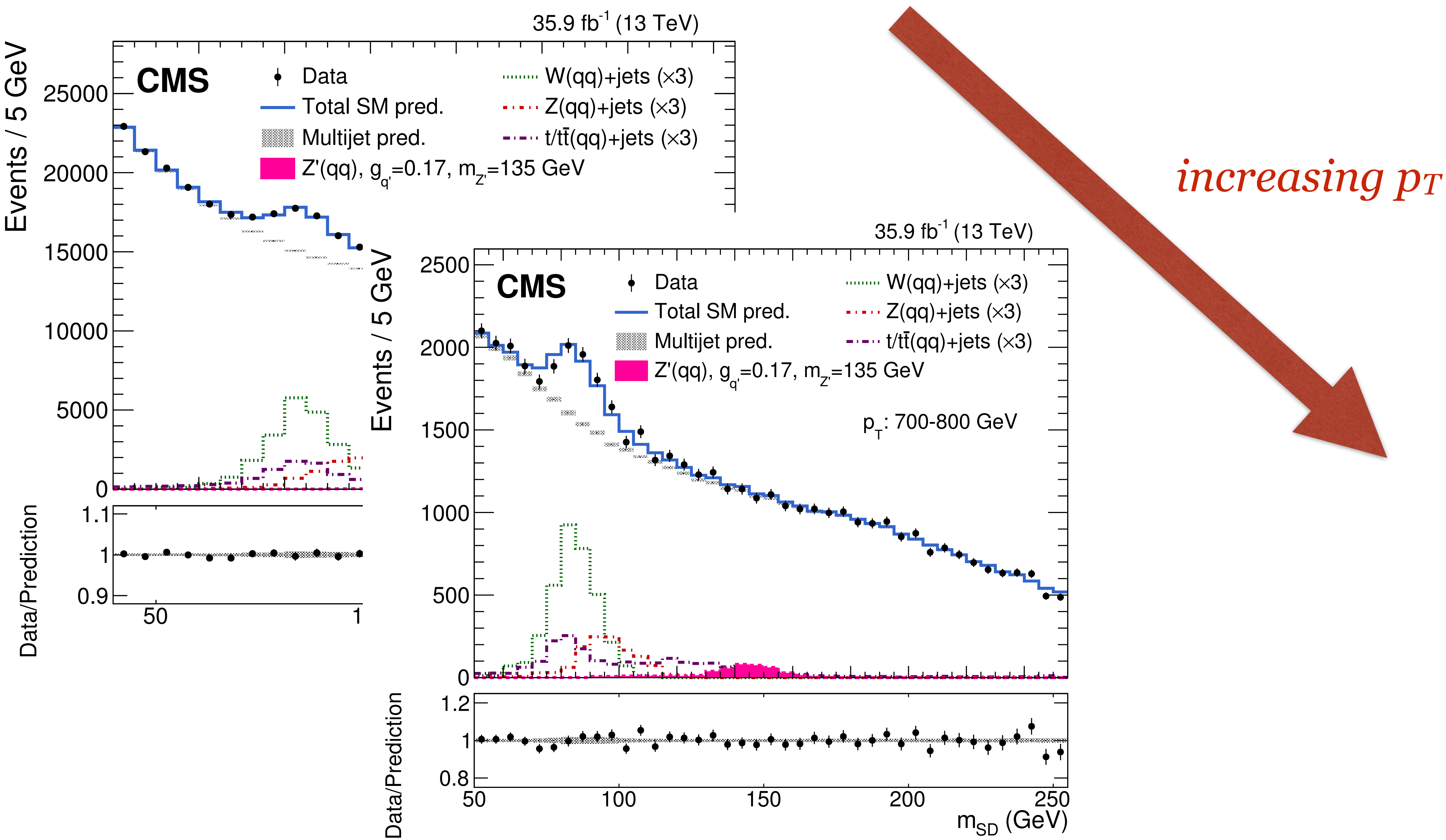
arXiv:1609.07483

Backgrounds:
1. QCD
2. **SM candles**: W/Z+jets

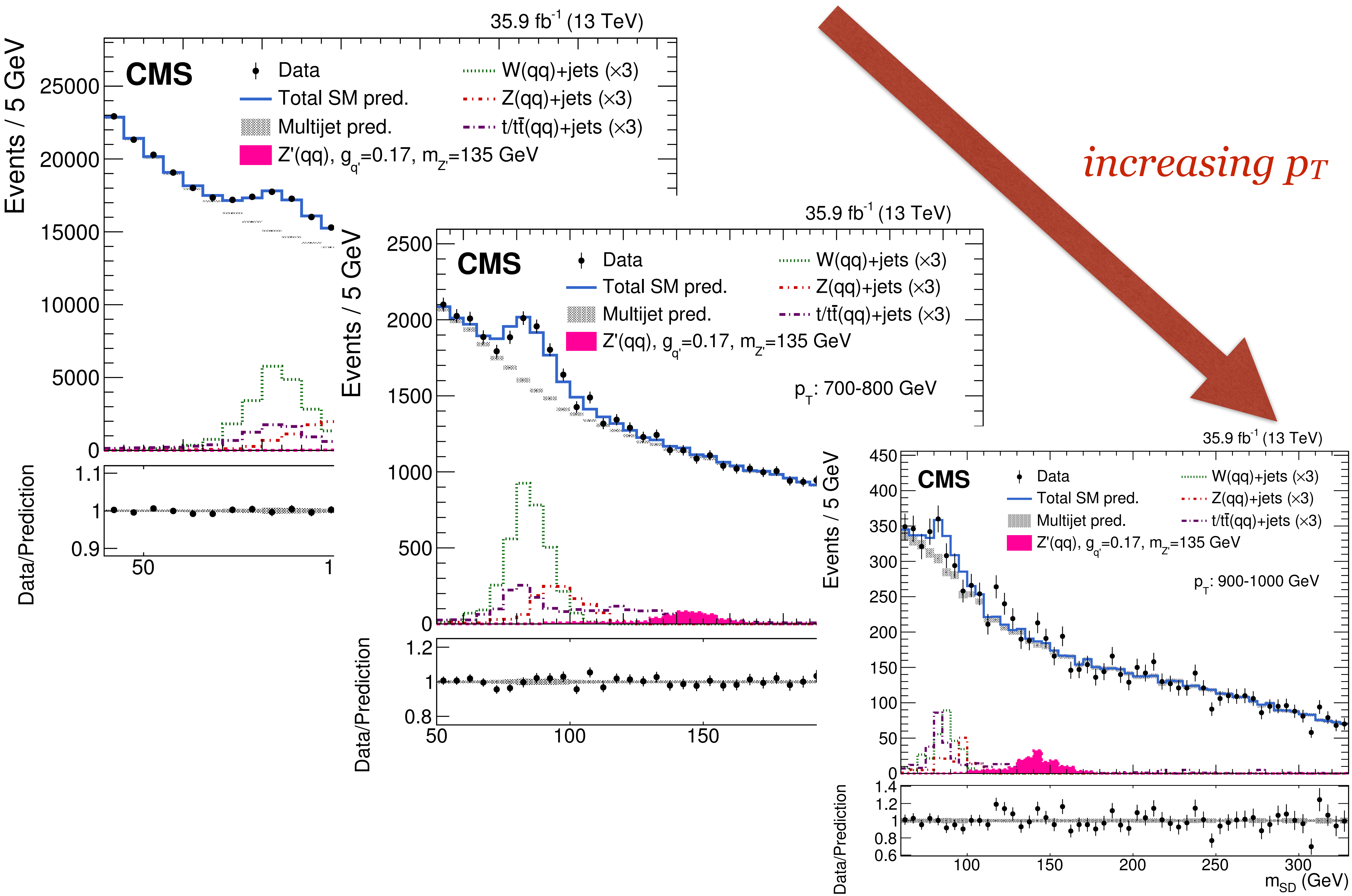


Jet mass spectra



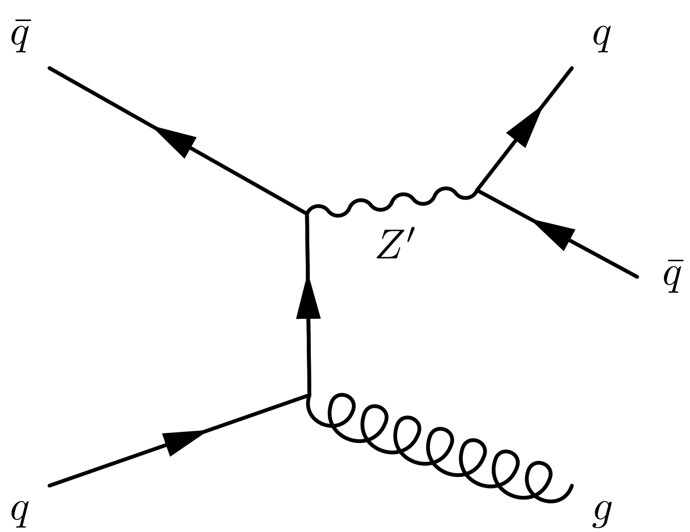

35.9 fb^{-1} (13 TeV)
CMS
Data
Total SM pred.
Multijet pred.
Z'(qq), $g_{q'}$=0.17, $m_{Z'}$=135 GeV
W(qq)+jets (×3)
Z(qq)+jets (×3)
t/t$\bar{t}$(qq)+jets (×3)
Events / 5 GeV
Data/Prediction
35.9 fb^{-1} (13 TeV)
CMS
Data
Total SM pred.
Multijet pred.
Z'(qq), $g_{q'}$=0.17, $m_{Z'}$=135 GeV
W(qq)+jets (×3)
Z(qq)+jets (×3)
t/t$\bar{t}$(qq)+jets (×3)
p_T: 700-800 GeV
Events / 5 GeV
Data/Prediction
m_{SD} (GeV)
increasing p_T

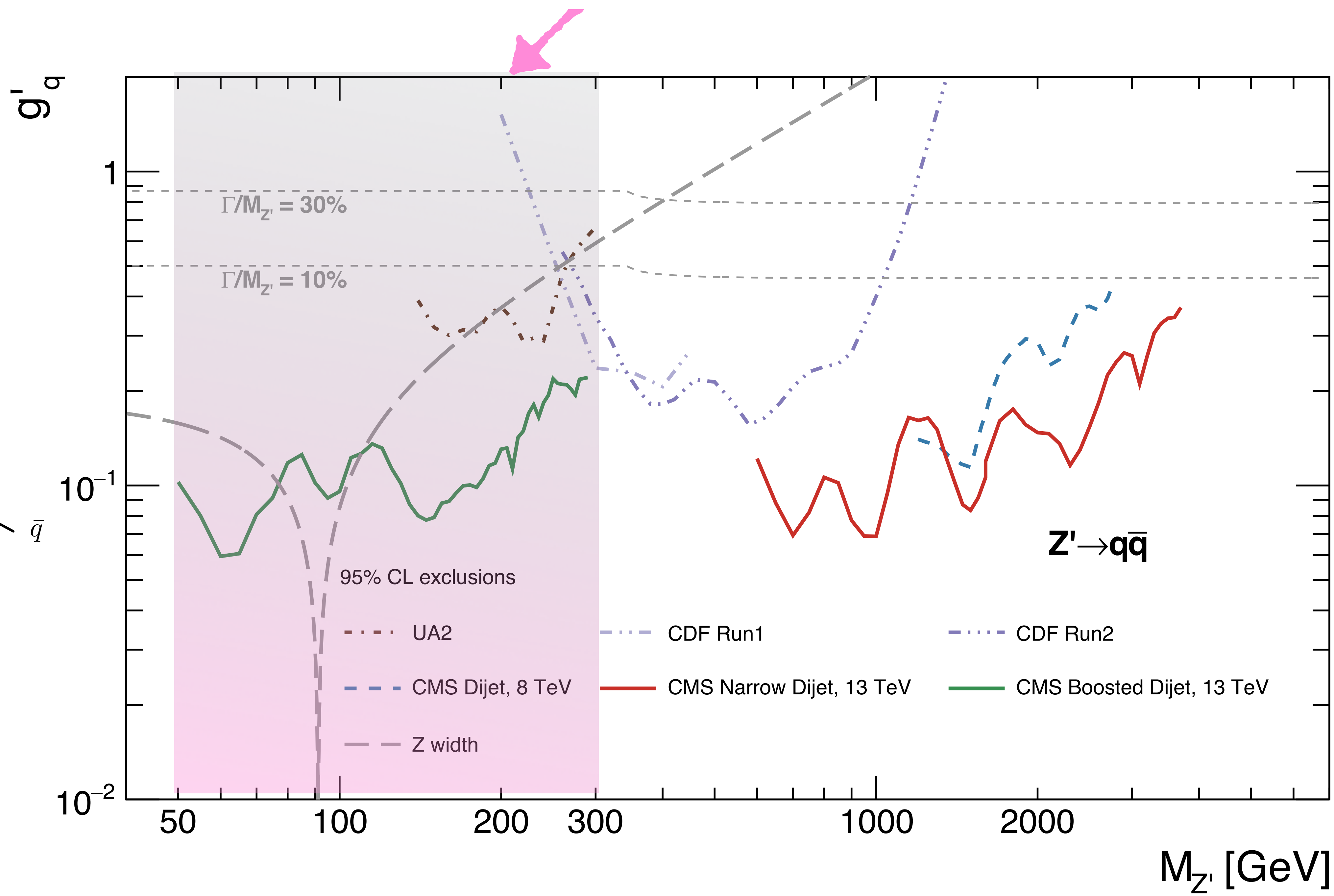
Jet mass spectra



Z' interpretation

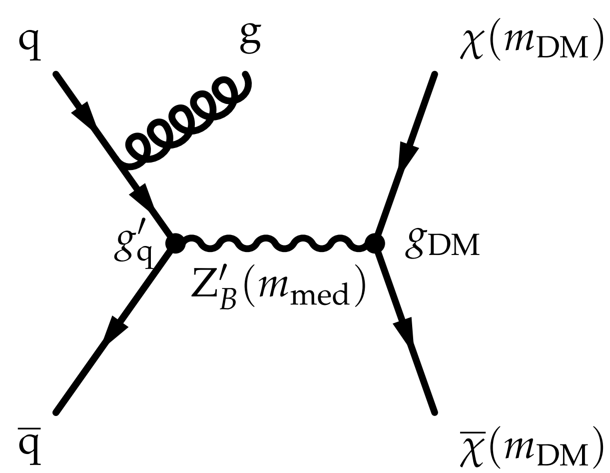
- Expands LHC reach down to 50 GeV



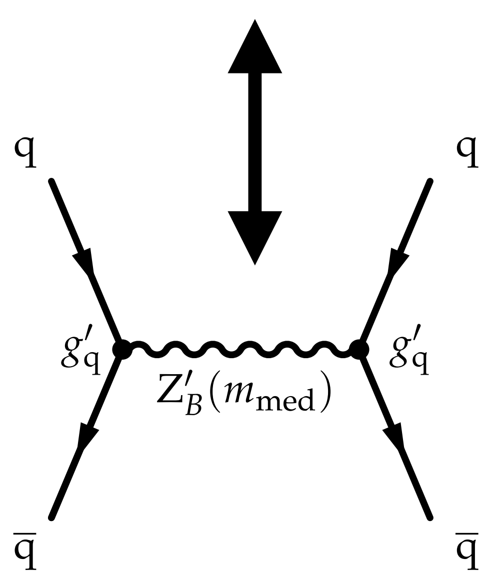


Mono-X vs di-jets

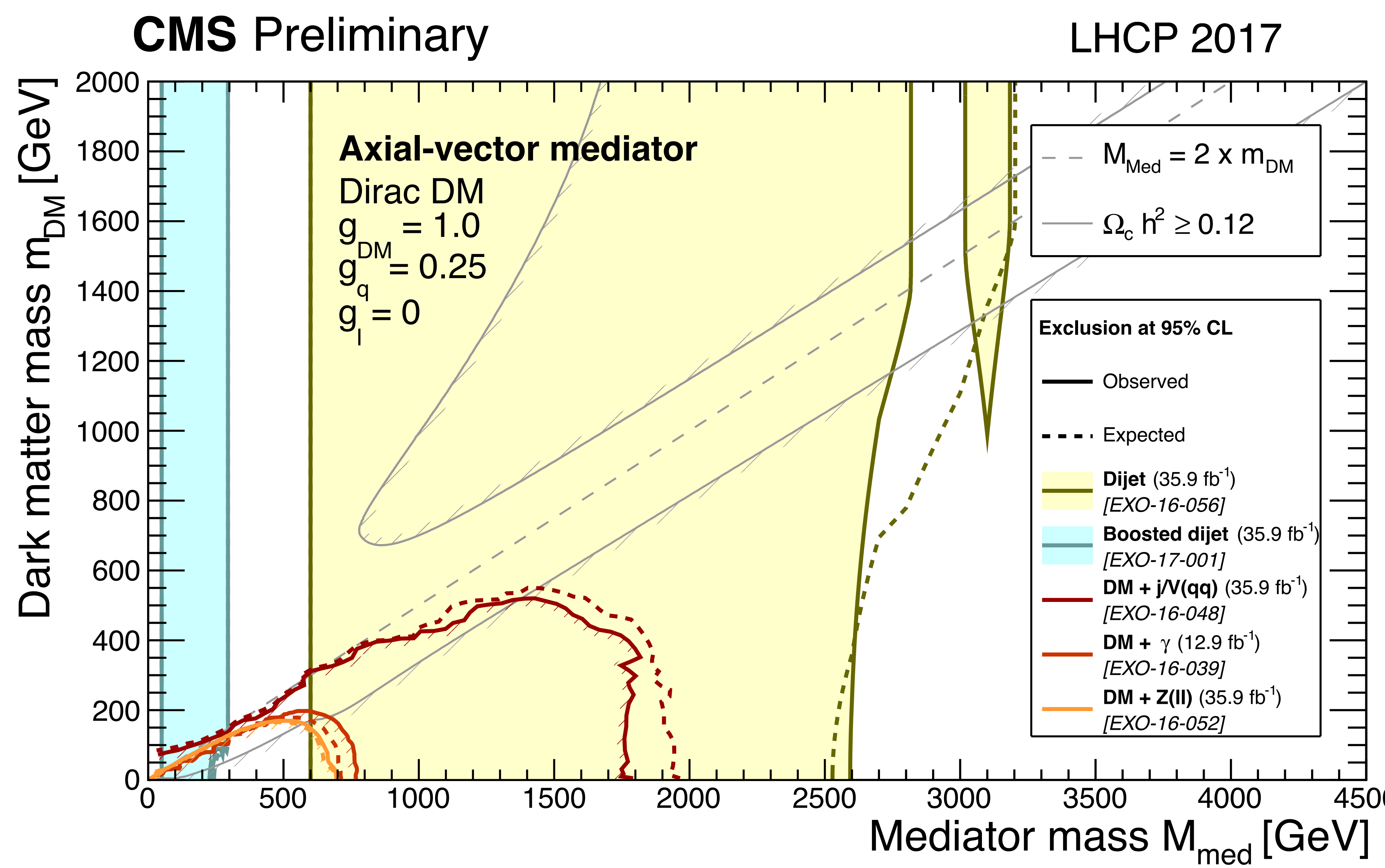
- Mono-X sensitive to both DM and mediator mass
- Di-jets sensitive to large range of dark matter parameter space by looking directly for resonant production of the mediator



Mono-X

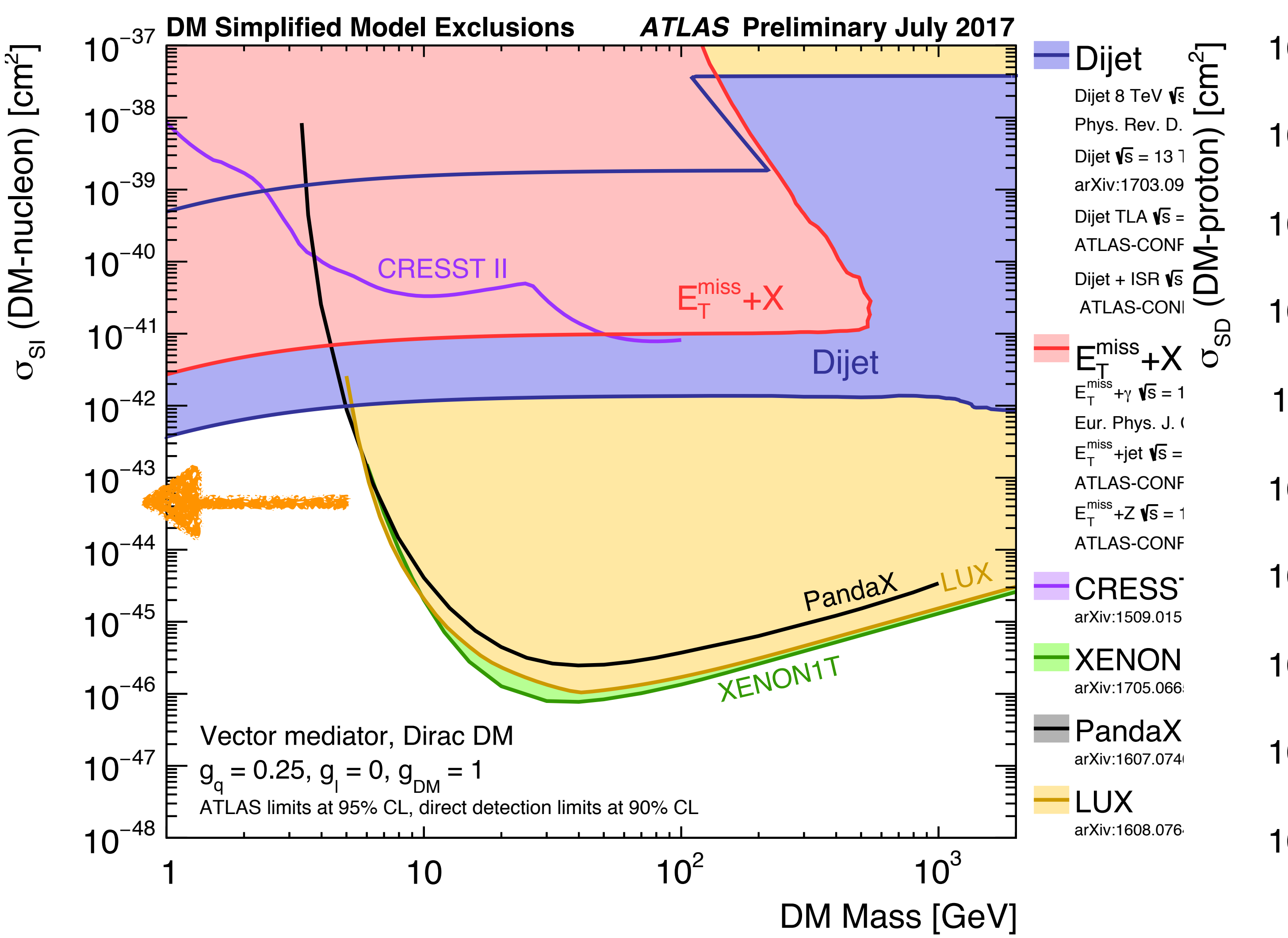


di-jet

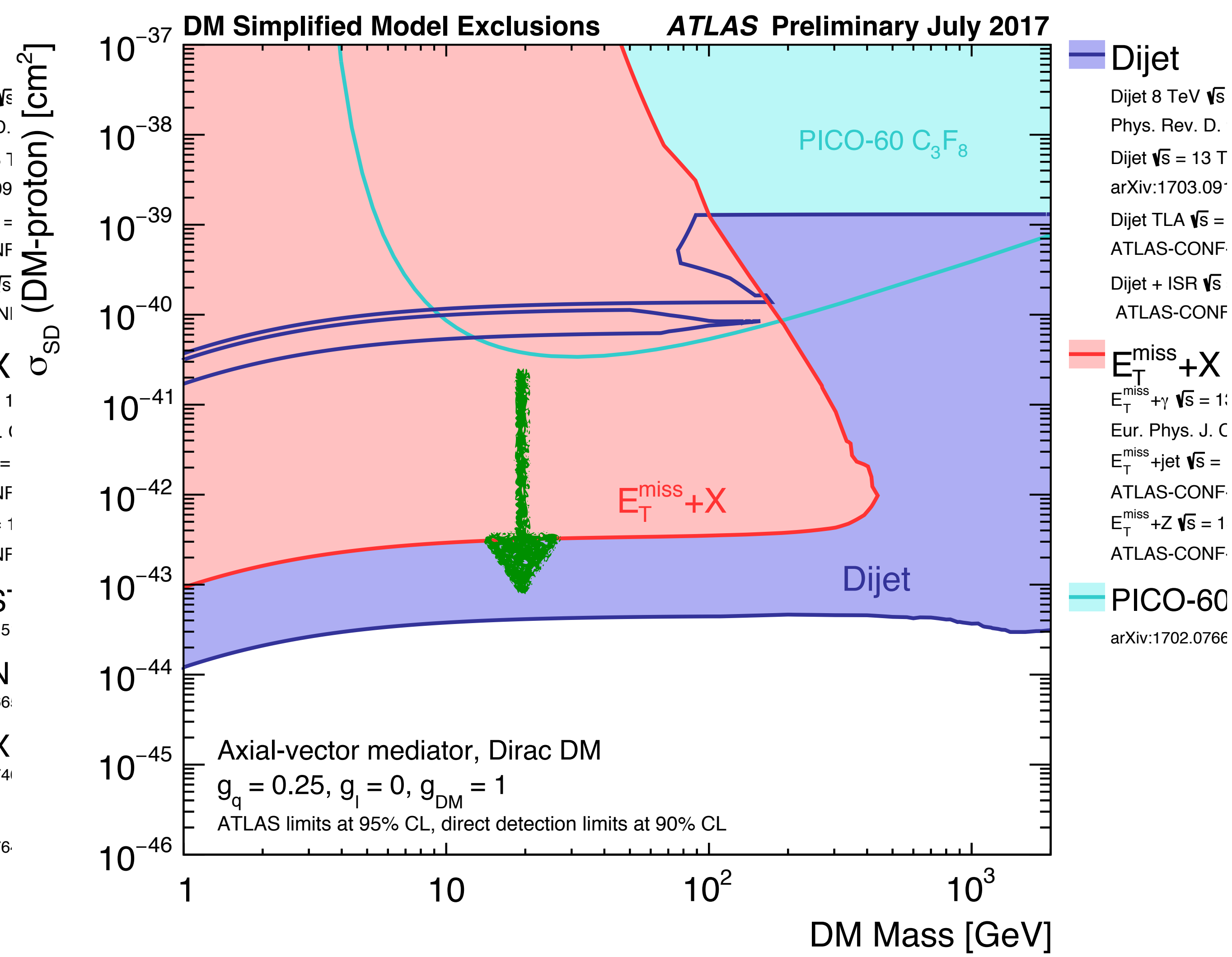


Comparison with DD

Spin-independent DM-nucleon cross section vs m_{DM}



Spin-dependent DM-proton cross section vs m_{DM}



- Collider searches of DM:
  - are sensitive to **low DM mass** (<5 GeV) for spin-independent interactions
  - have **~3 order of magnitude better sensitivity** for spin-dependent interactions

Conclusions

LHC collaborations search extensively for Dark Matter.

***No excess** was observed in the **2015 + 2016** data analysis in CMS and ATLAS in mono-X or multi-jet final states.*

☞ *Mediator mass up to 1.6-1.8 TeV*

☞ *DM mass up to 0.4-0.7 TeV*

*But ~**40/fb more data** is being analyzed from **2017**!*

We are in the era of precision searches!

Mono-X searches: Need to measure the backgrounds at % level. Need both experimental and QCD theory improvements

Di-jet searches: new experimental ideas being exploited to cover the remaining gaps

LHC complements direct searches for m_{DM}<O(10) GeV

Backup

Huge data delivery

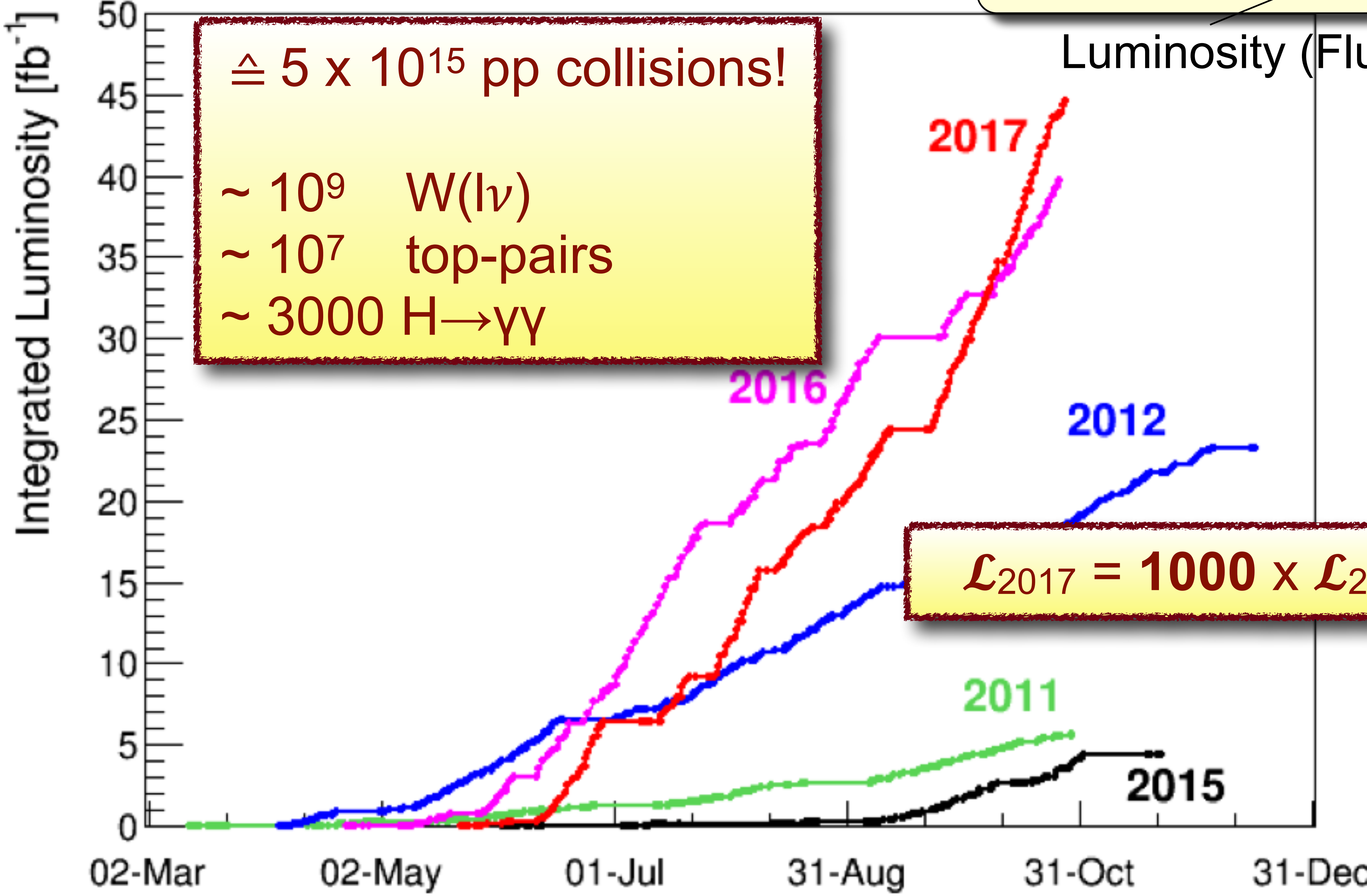
$$N_{ev} = \mathcal{L} \times \sigma$$

Luminosity (Flux) [cm^{-2}]

≙ 5 x 10^{15} pp collisions!

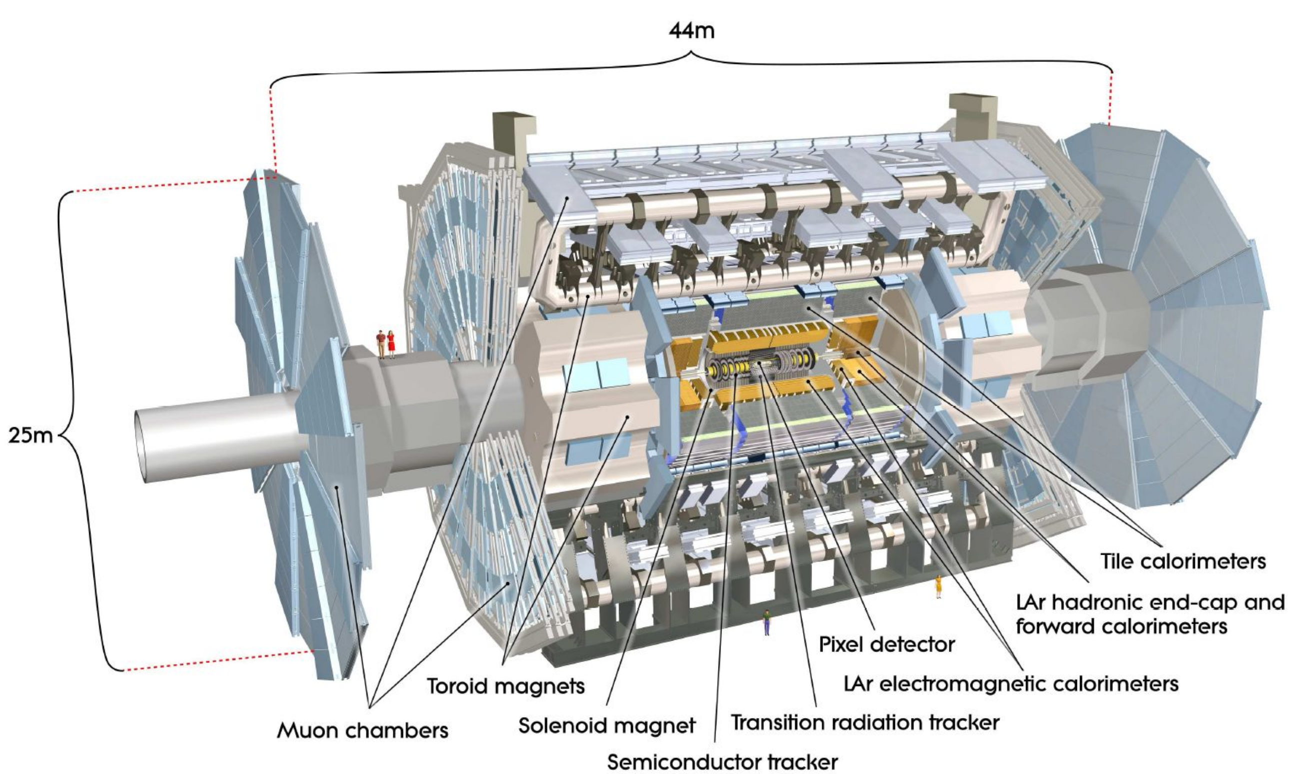
~ 10^9 W(lν)
~ 10^7 top-pairs
~ 3000 H→γγ

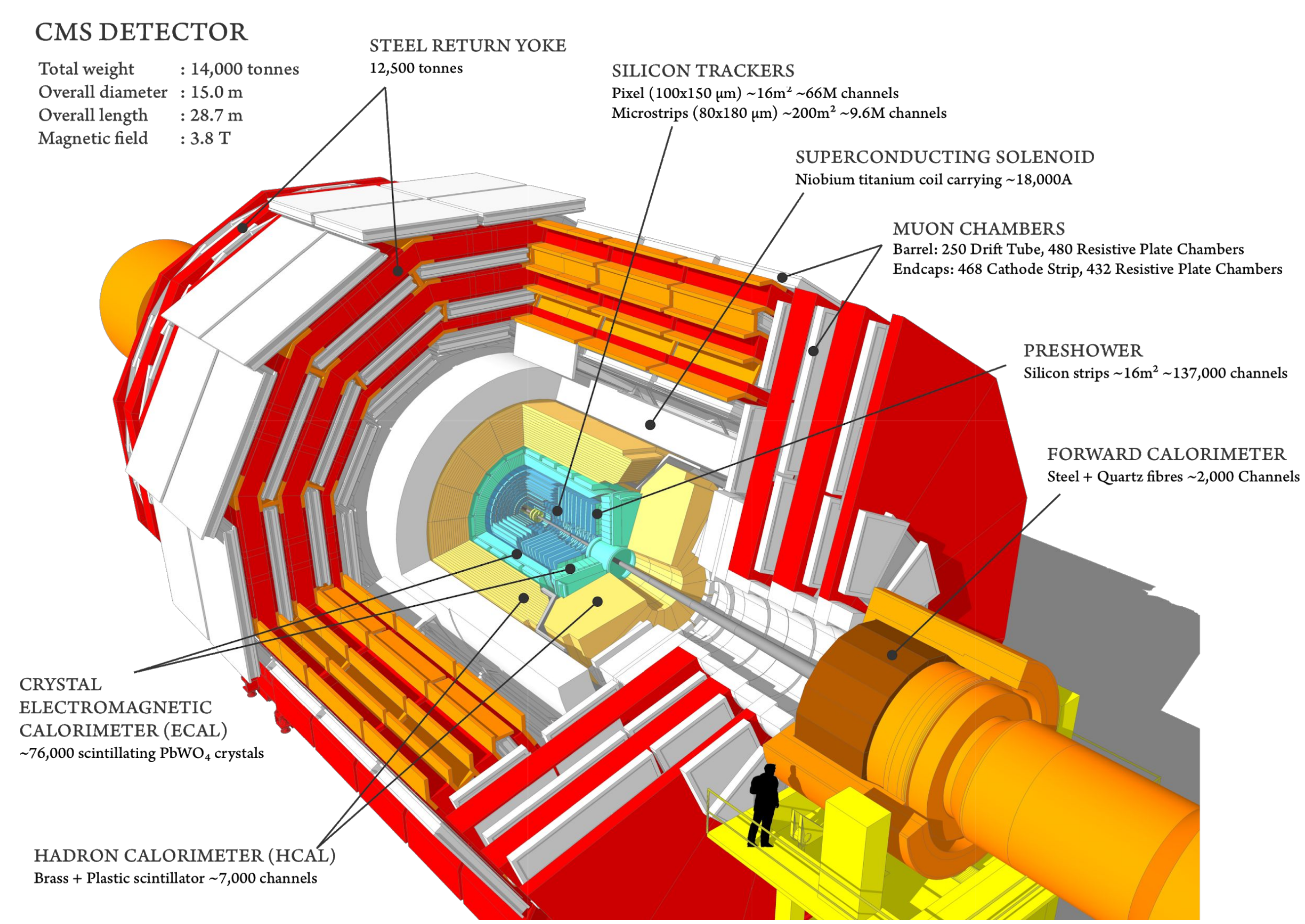
$\mathcal{L}_{2017}$ = **1000** x $\mathcal{L}_{2010}$!!



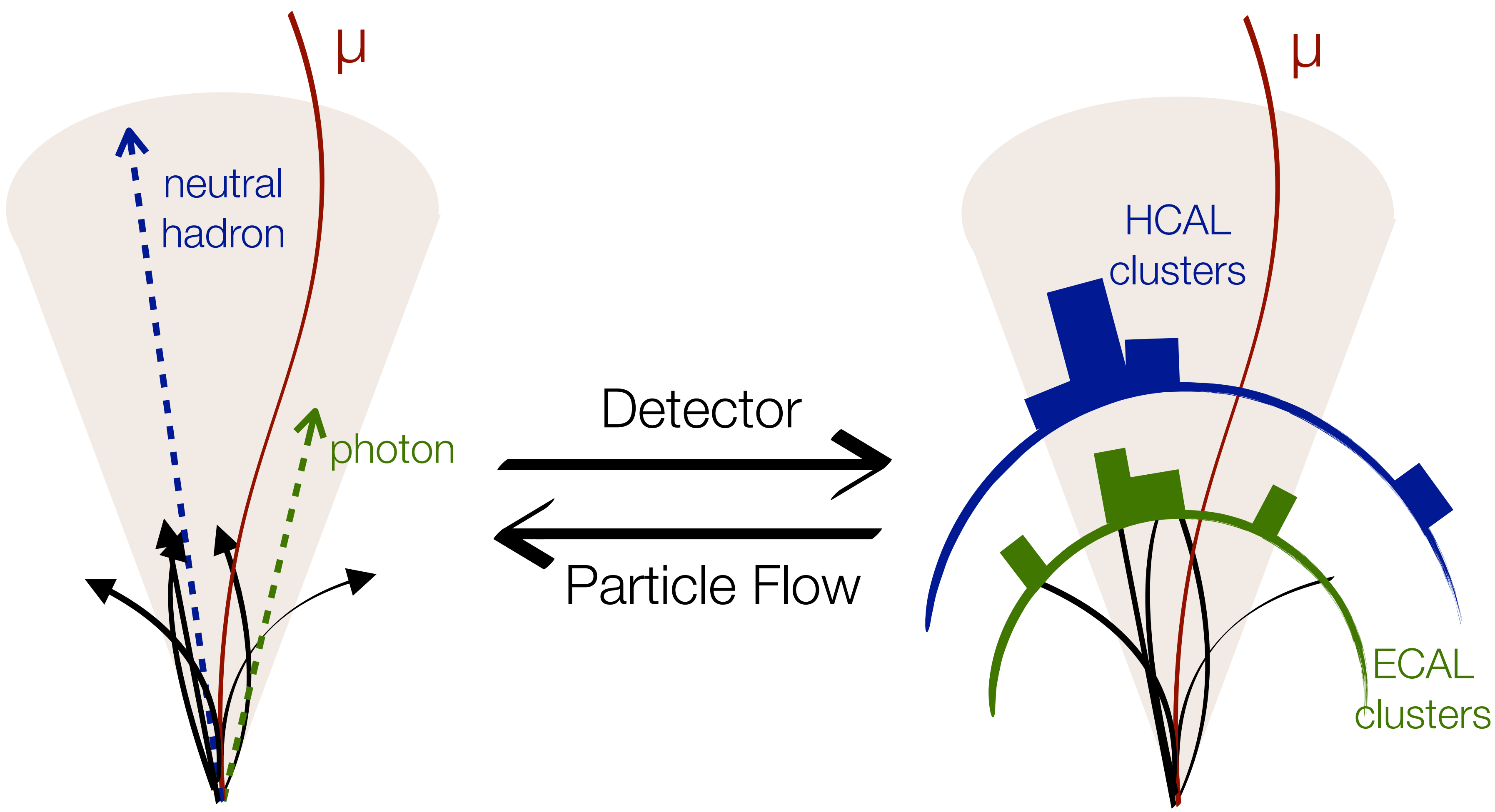
ATLAS & CMS

- Two general purposes experiments
- Different technologies used in each component, to get the same targets
  - currently taking data at the LHC Run2





From detector to particles



First compute "easy" objects: **charged leptons, photons**
Then **jets** (collimated particles from the hadronization of partons)
Finally **MET** = Missing Transverse Energy

MonoX signal extraction (CMS)

Gamma Jets

W (ev) Jets

Signal yield is measured by fitting p_T^{miss} ,
1 rate parameter / bin

Z (vv) Jets

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

W (lv) Jets

Simultaneous fit to different categories
(signal + control regions) x
mono-jet and **mono-V** (=hadronic W,Z)

Z (mm) Jets

Z (ee) Jets

W (mv) Jets

MonoX signal extraction (ATLAS)

~~Gamma Jets~~

W (ev) Jets

Signal yield is measured by fitting p_T^{miss} ,
1 rate parameter / bin

Z (vv) Jets

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

W (lv) Jets

Simultaneous fit to different categories
(signal + control regions) in **mono-jet**

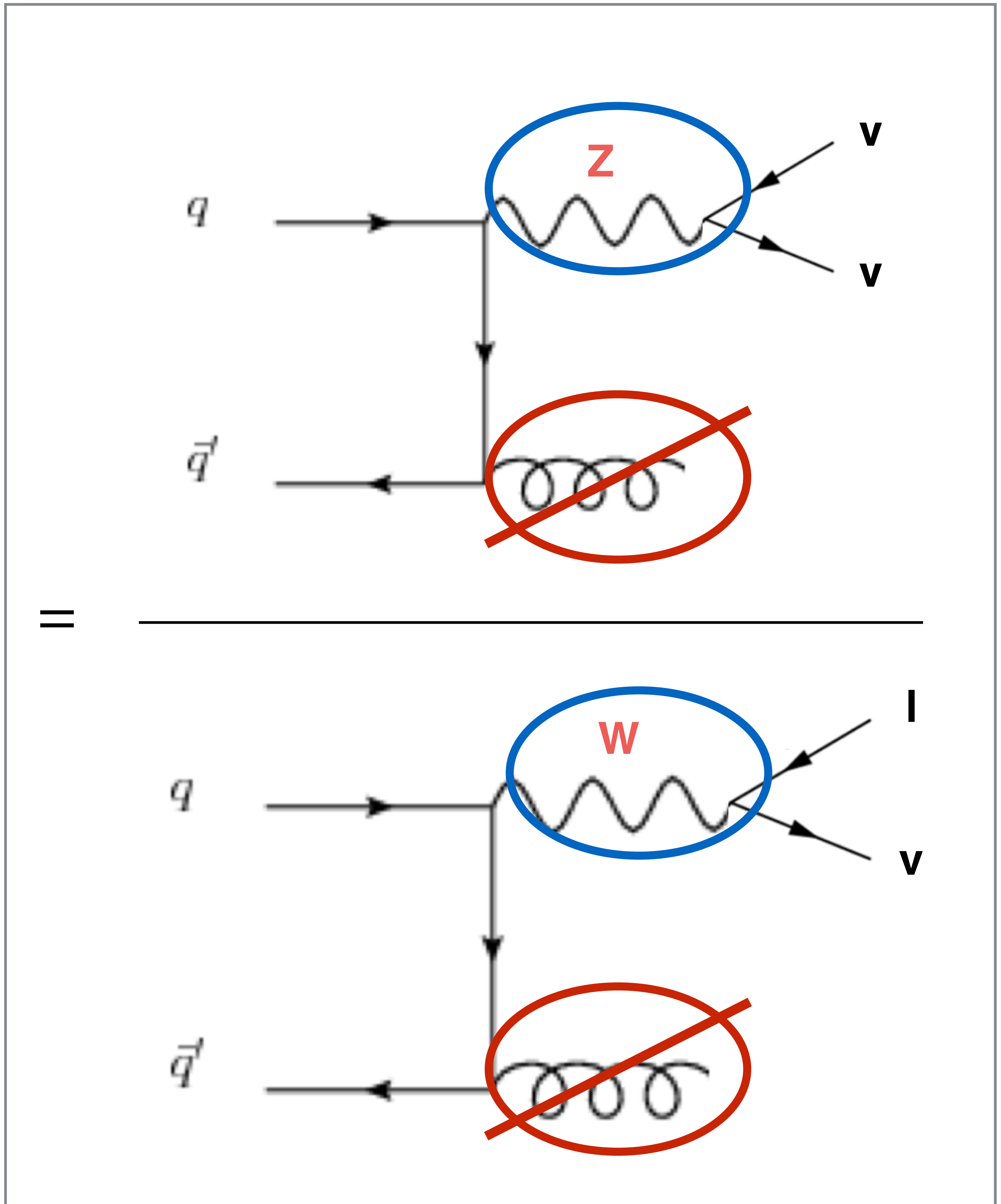
Z (mm) Jets

~~Z (ee) Jets~~

W (mv) Jets

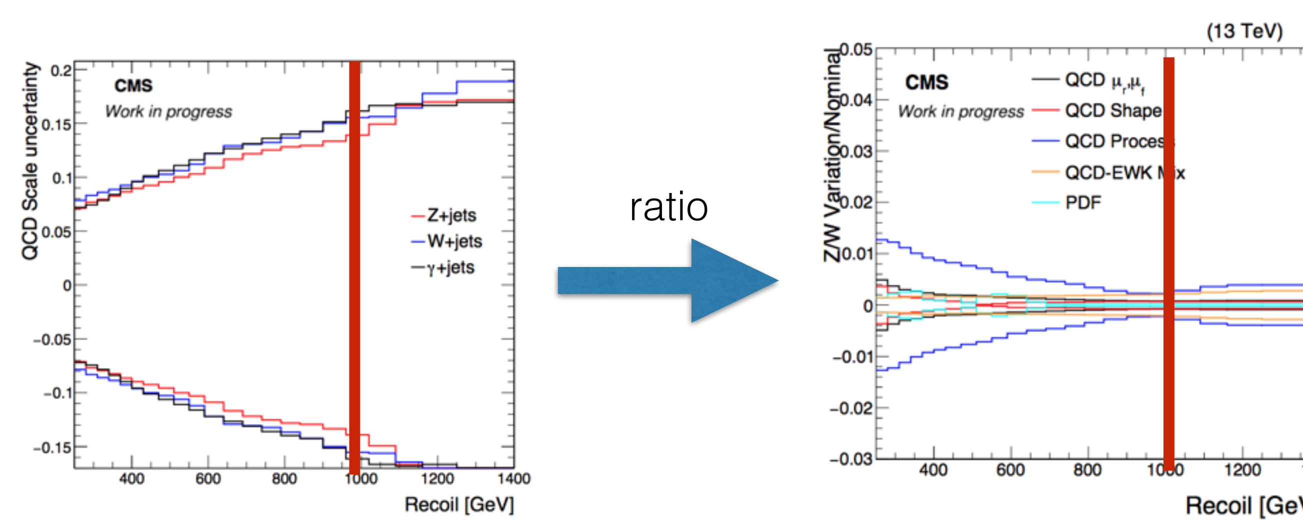
top-quark control region
to estimate top background in the signal region

Using ratios

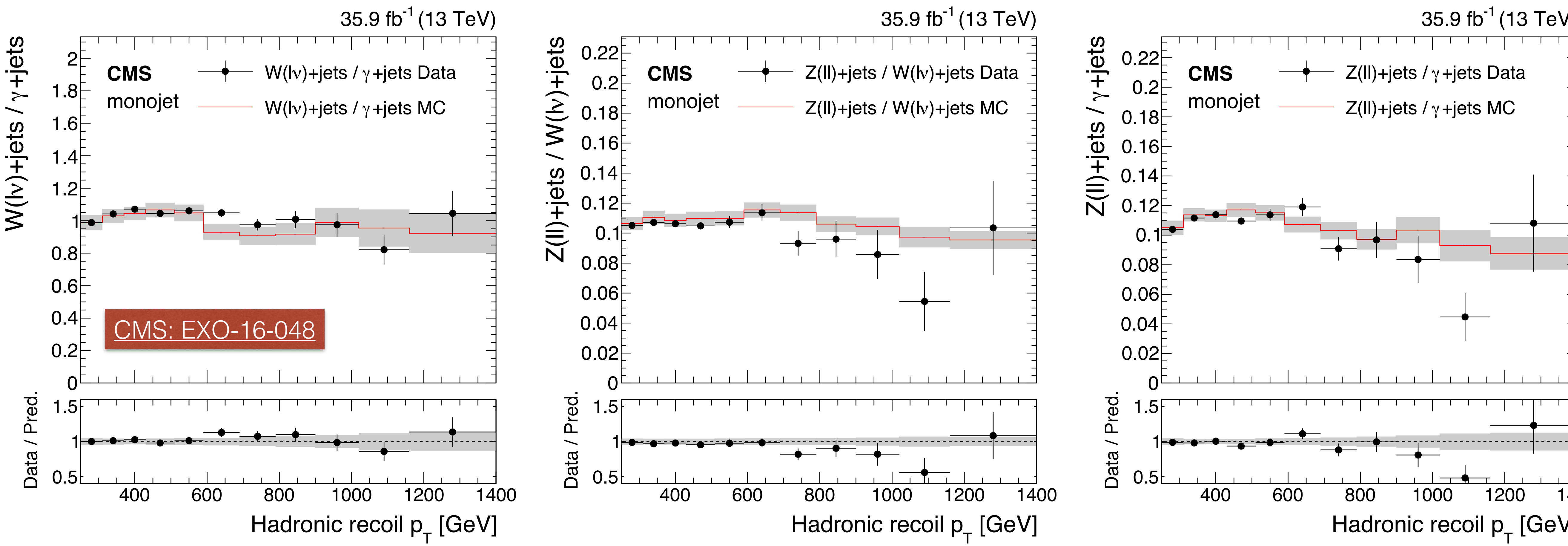


- Common **experimental** systematic uncertaities cancel:
  - jet energy scale and resolution
  - luminosity measurement
  - pileup

- Common **theoretical** systematic uncertaities reduces
  - need the best calculation (higher order corrections in QCD) to have the best ratios estimate



Ratios in data



Black ratio from data and statistical uncertainties / Red from MC

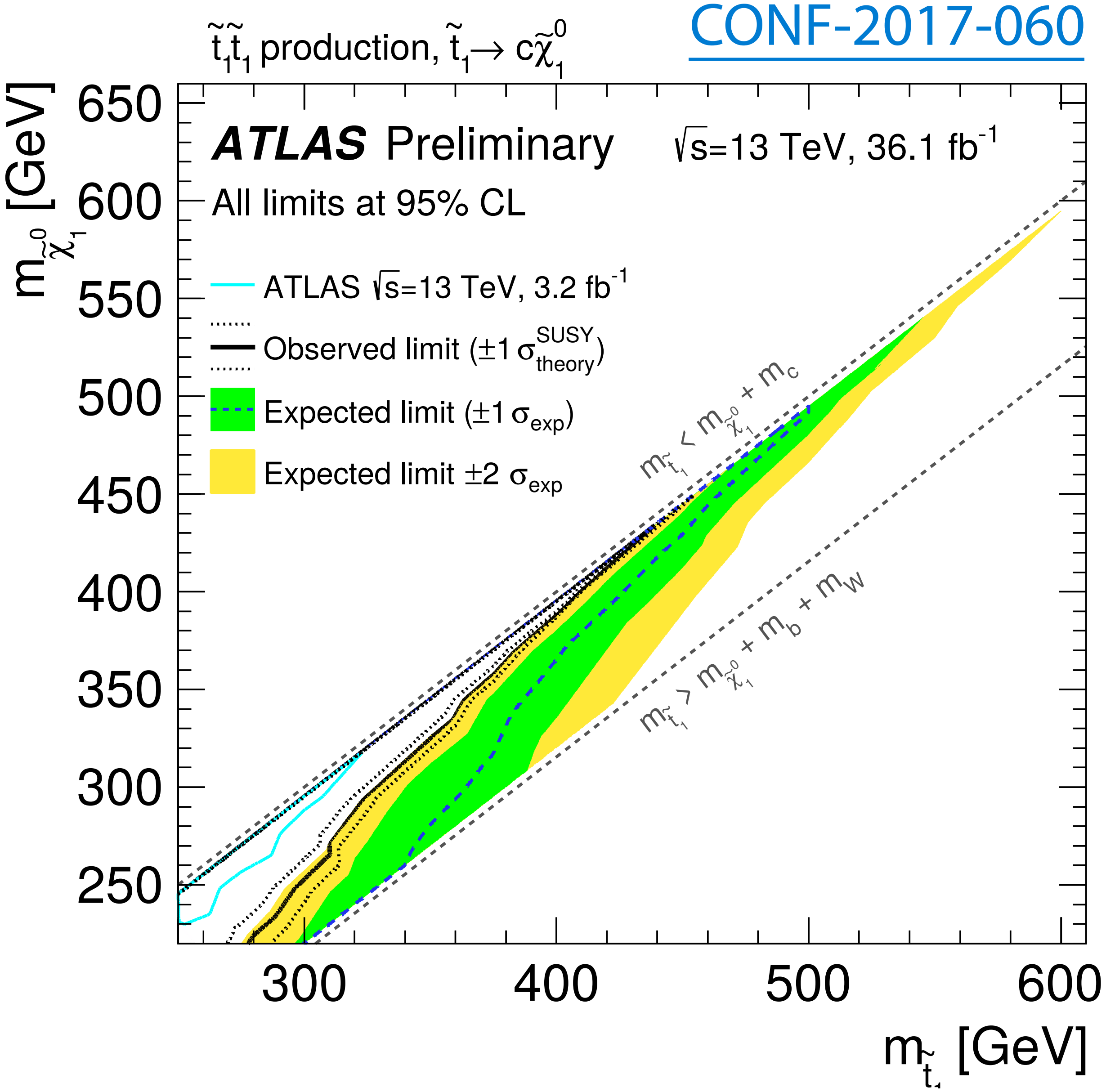
Grey band includes theoretical uncertainties

(improvements in the QCD calculation reduced the theory uncertainty of factor 4-5 in the last years)

Stop/Colored scalar limits

Stop Model

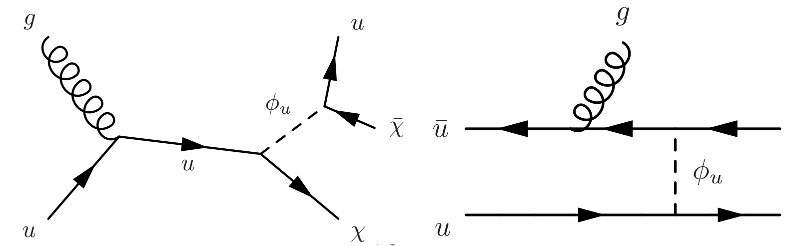
CONF-2017-060



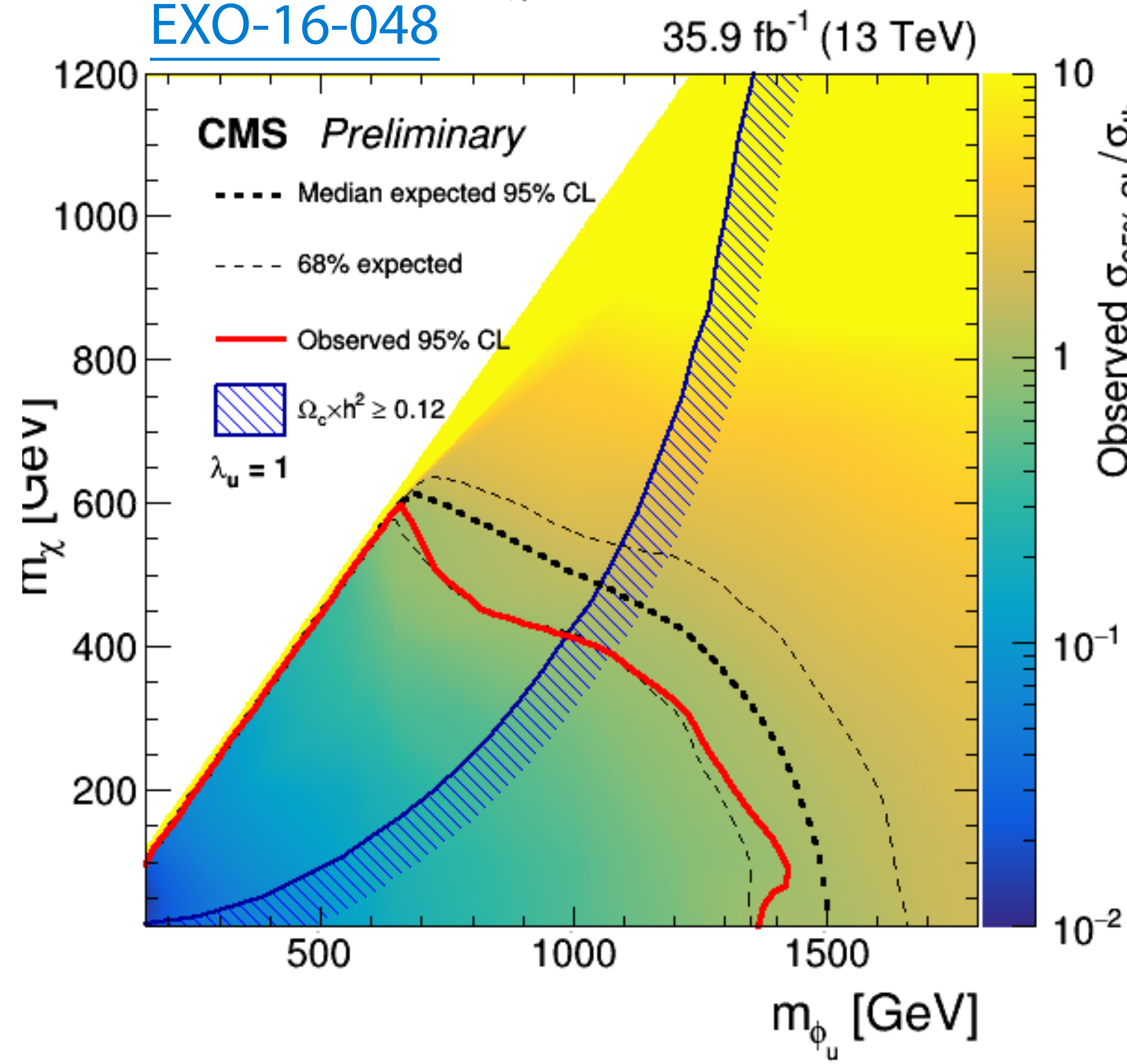
Stop→Charm+neutralino (DM)

Stop mass excluded up to 430 GeV

Fermion Portal Model



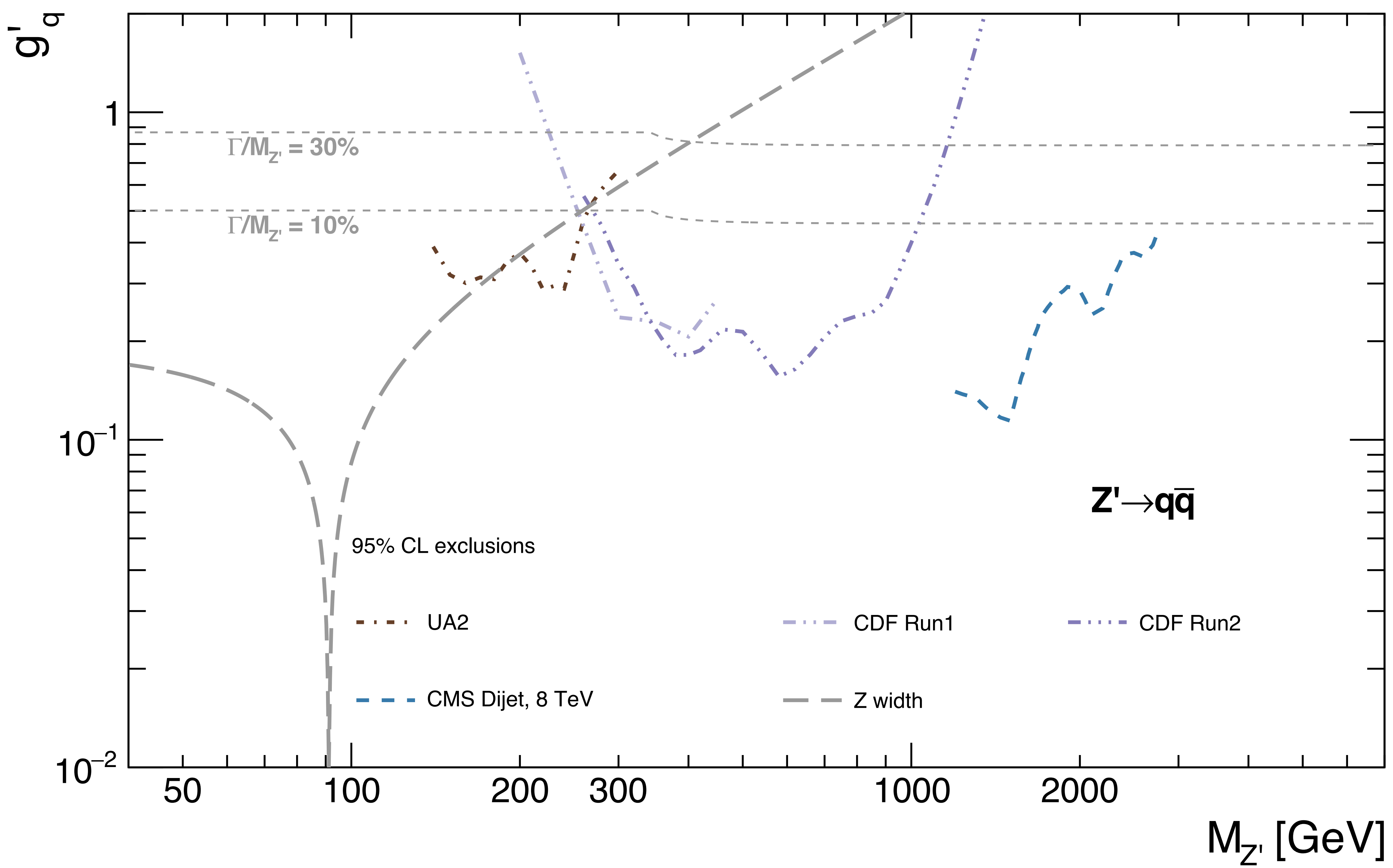
EXO-16-048



Mediator mass excluded up to ~1.4 TeV

DM mass < 600 GeV

mediators: putting all together



mediators: putting all together