Searches for Dark Matter mediators with the ATLAS Detector

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On behalf of the ATLAS Collaboration

ATLAS EXPERIMENT

CoEPP
ARC Centre of Excellence for Particle Physics at the Terascale

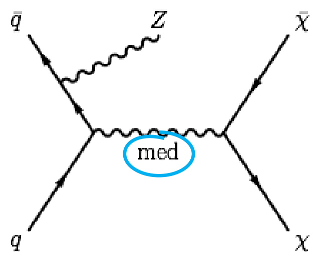
THE UNIVERSITY OF MELBOURNE

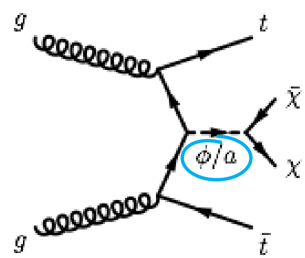
Searches for Dark Matter Mediators

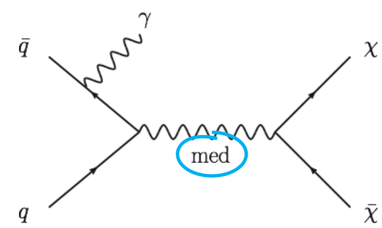
Dark Matter searches at the LHC use simplified models

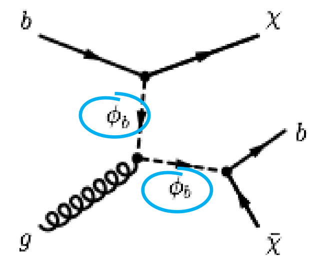
- Production of Dark matter goes via a mediator

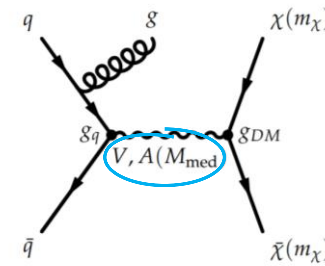
See Young-Kee Kim's talk





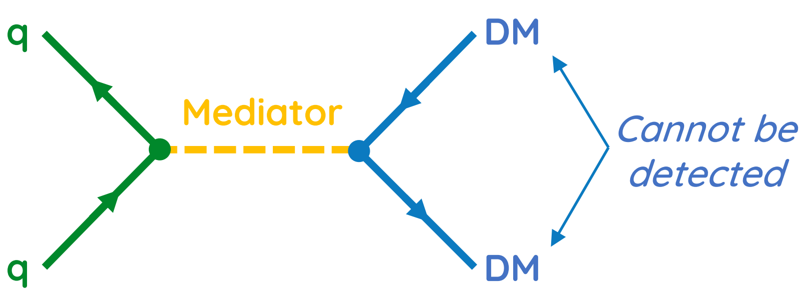




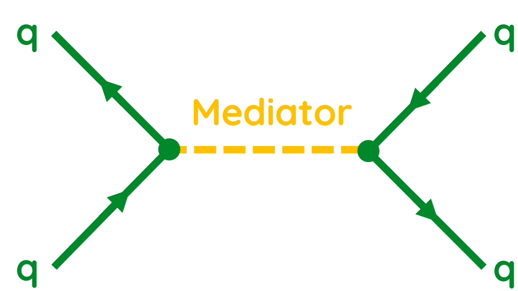


Resonance searches are complimentary to these direct DM searches

- Look for mediators decaying into quarks (dijet resonance)



Mediators produced by quarks …
(which decay to Dark Matter)

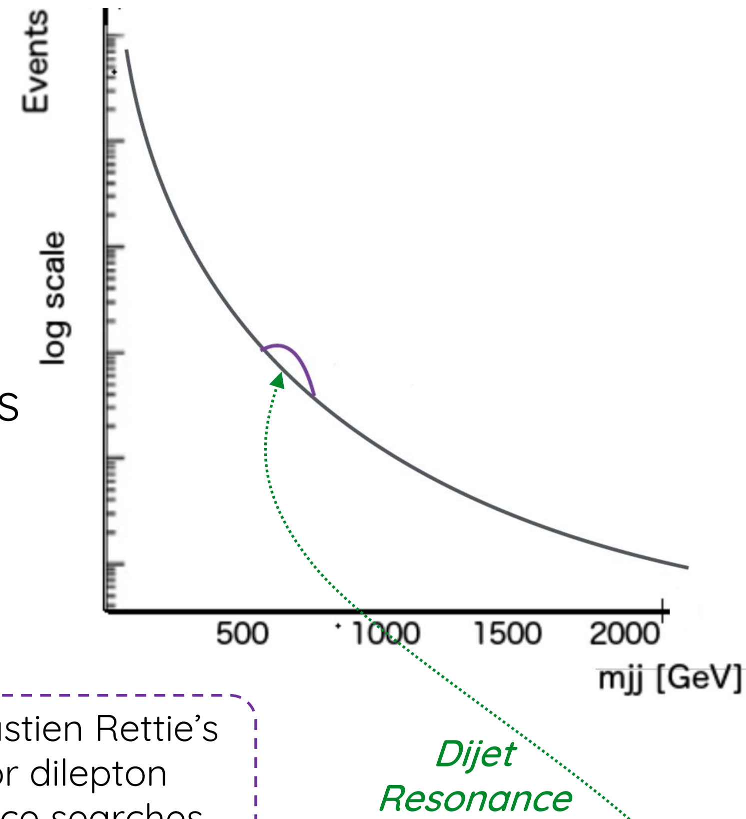


also decay to quarks
(producing jets)

Dijet Searches

QCD predicts smoothly falling dijet invariant mass (m_{jj})

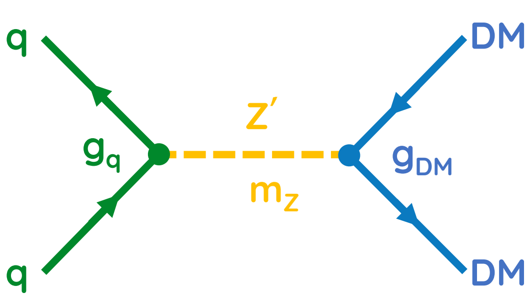
- New mediator decaying to jets will introduce a bump



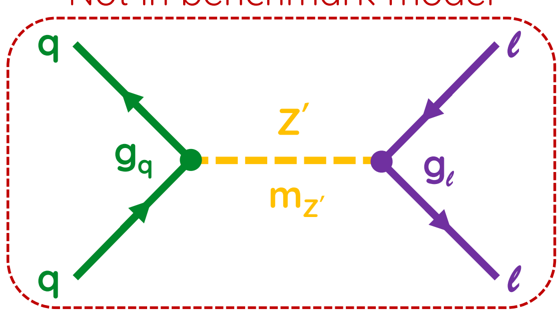
Benchmark Leptophobic Z′ model parameters

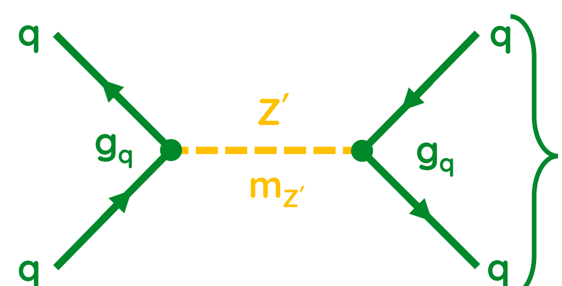
- Axial-vector (or vector) mediator (Z′)
- Coupling to quarks - g_q (universal)
- Coupling to leptons - $g_\ell = 0$ (leptophobic)
- Coupling to dark matter – g_{DM}
- Mediator mass - $m_{Z'}$
- Dark matter mass - m_{DM}

See Sébastien Rettie's talk for dilepton resonance searches



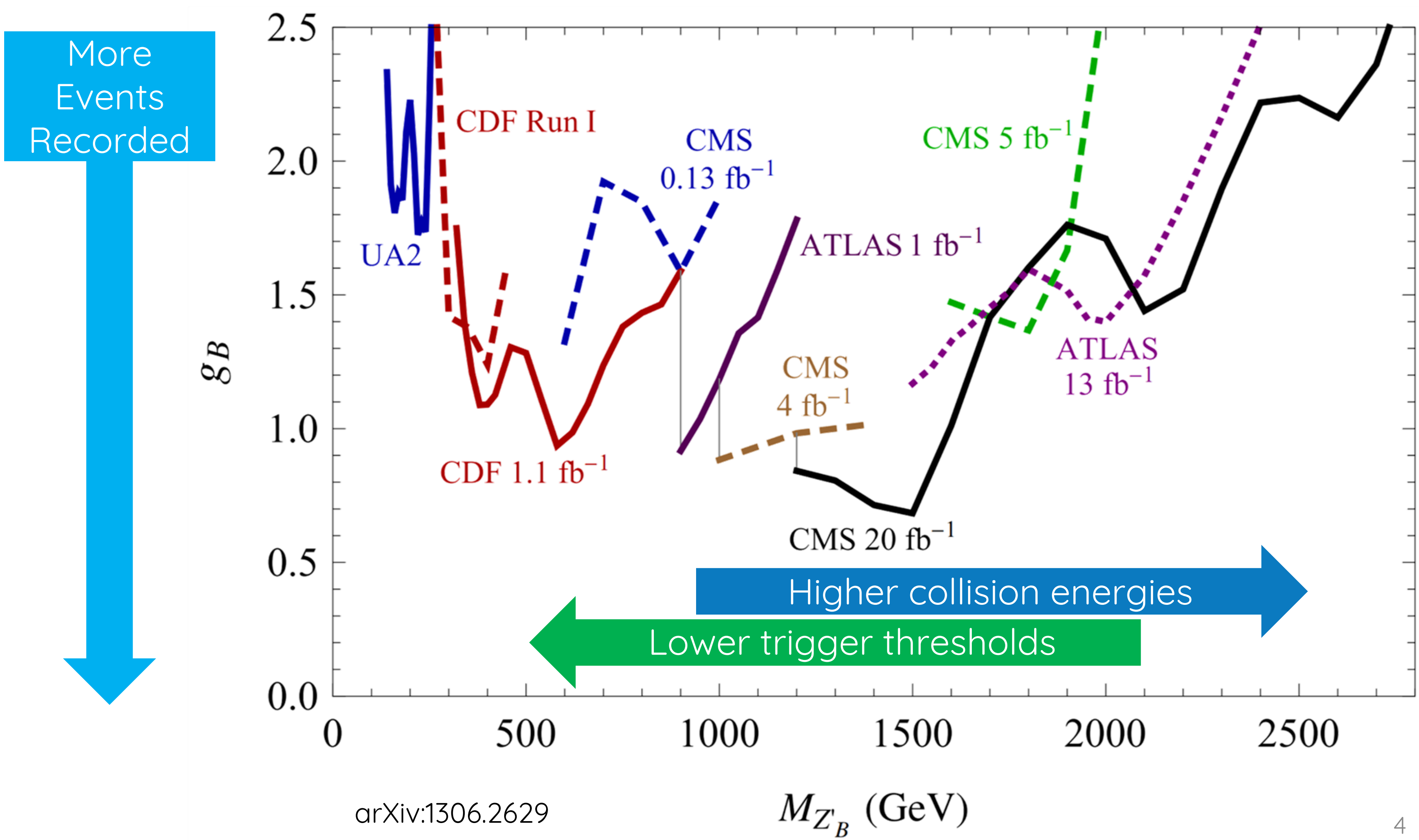
Not in benchmark model





Dijet Searches Prior to Run 2

Limits are dependent on a number of factors



arXiv:1306.2629

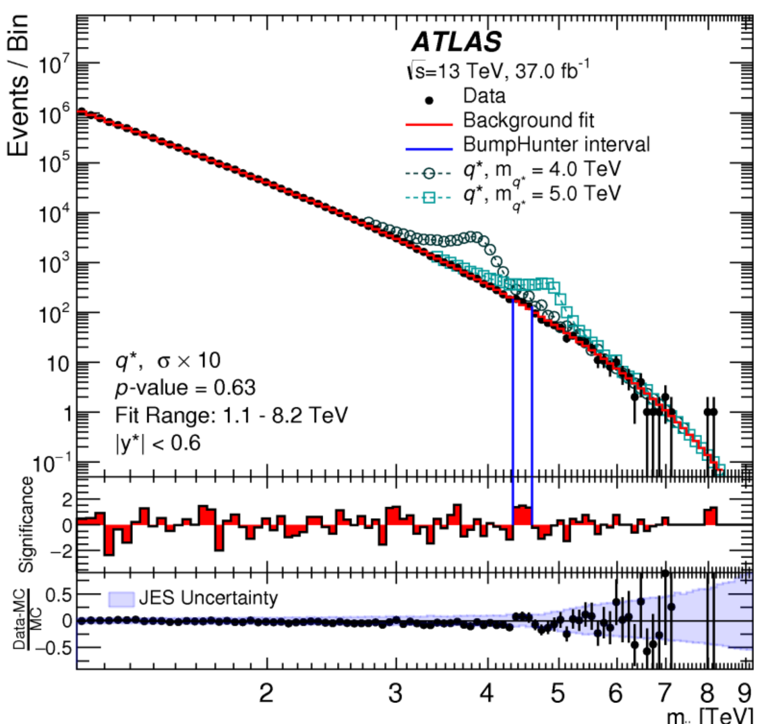
Baseline Dijet Search

Selections are applied to
- Ensure trigger and selection efficiency
- Reduce backgrounds (y* rapidity difference)

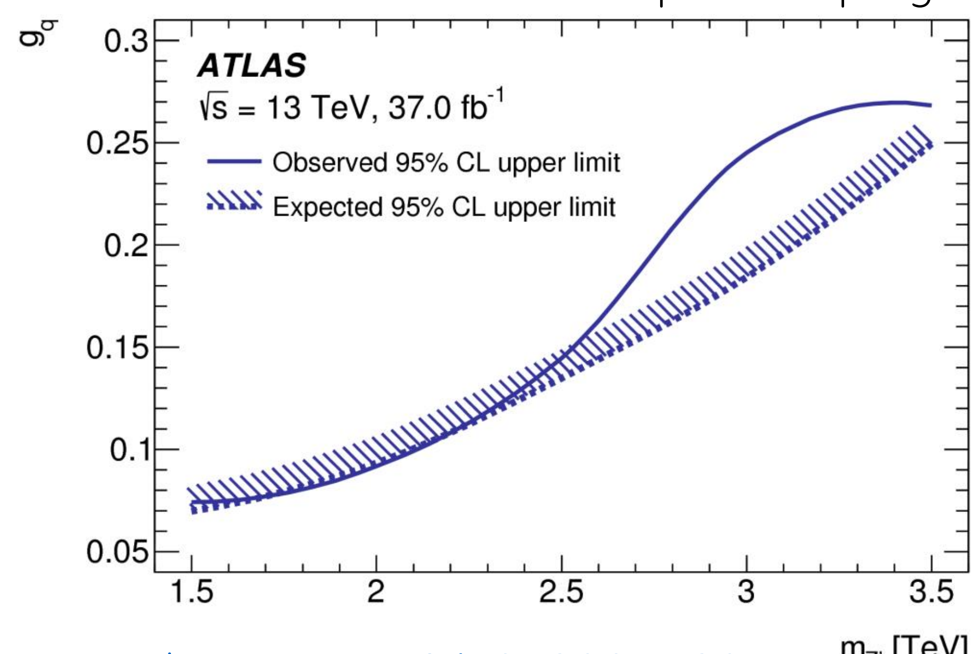
Selections	
Lead Jet pT	> 440 GeV
Second Jet pT	> 60 GeV
m_{jj}	> 1.1 TeV
$\lvert y^* \rvert = 0.5 \lvert y_1 - y_2 \rvert$	< 0.6

Estimate background from sliding window fit using $f(z) = p_1(1-z)^{p_2} z^{p_3}$ $z = m_{jj}/\sqrt{s}$

Search for excess with bumphunter algorithm



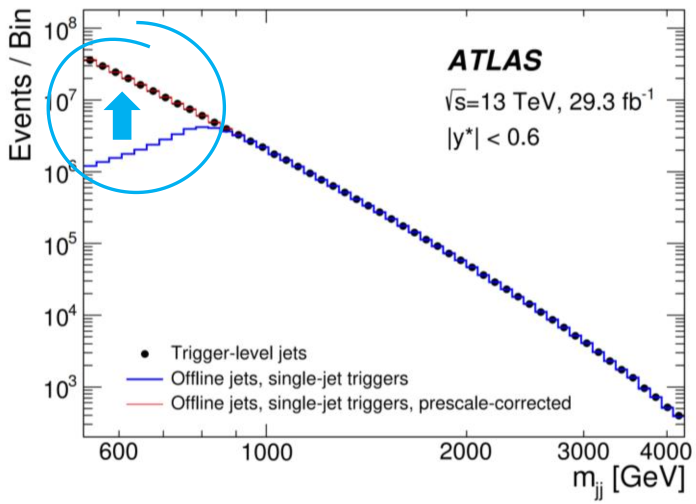
Limit on axial vector Z' quark coupling

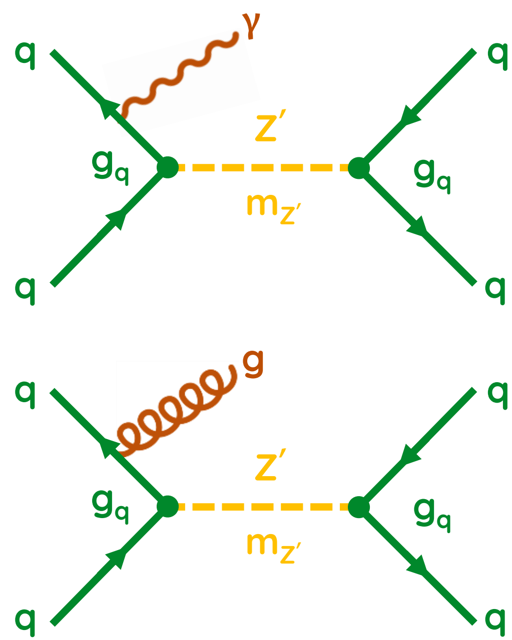


Phys. Rev. D 96, 052004 (2017)

Probing Lower Masses

How do you access lower masses?





Trigger Level Analysis (TLA)

Lower the trigger threshold by reducing amount of data saved per event, keep only trigger level objects

Initial State Radiation (ISR) Selection

Examine a boosted signature by requiring an ISR photon or jet to pass the trigger threshold

Trigger Level Analysis

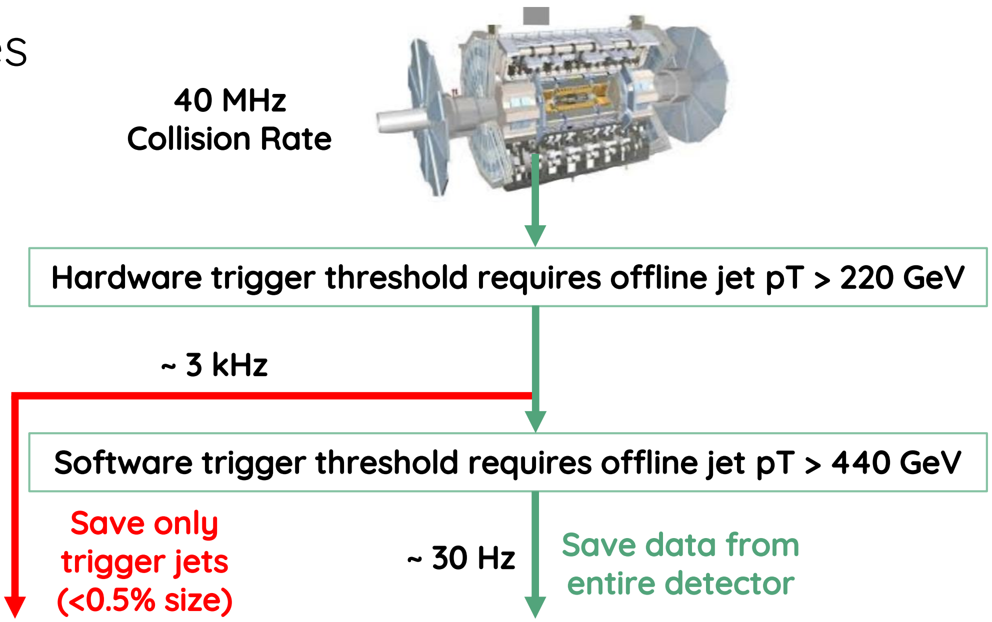
First stage hardware trigger identifies jets using coarse calorimeter information

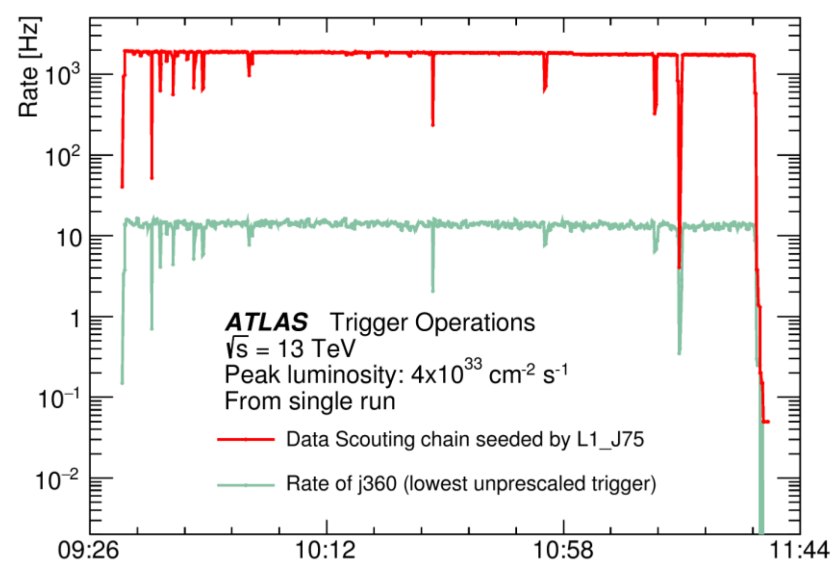
Second stage software trigger then reconstructs jets using same algorithm as offline jets (anti kt)

Limited bandwidth so high threshold required to save entre event

Save only trigger jets

- Small size
- Higher rate
- Similar bandwidth





Trigger Level Analysis

Jet energies are calibrated similarly to offline jets (Eur. Phys. J. C 76 (2016) 581)

Jet-area based pileup correction → **Absolute MC-based calibration** → **Global sequential calibration** → **Eta intercalibration** → **Trigger-to-offline data-derived correction** → **Residual *in-situ* calibration**

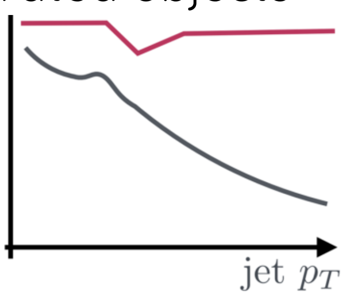
- **Jet-area based pileup correction**: *Applied as a function of event pileup p_T density and jet area only*
- **Absolute MC-based calibration**: *Corrects the jet 4-momentum to the particle-level energy scale. Both the energy and direction are calibrated*
- **Global sequential calibration**: *Reduces flavor dependence and energy leakage using calorimeter variables only*
  - Jet Energy resolution improved by 8% (jet p_T 85 GeV) to 40% (1 TeV)
- **Eta intercalibration**
- **Trigger-to-offline data-derived correction**: *Corrects trigger-level jets to the scale of offline jets, applied only to data*
  - Correction is 1% on average up to 4% at high eta
- **Residual *in-situ* calibration**: *A smooth residual calibration is derived by fitting in-situ measurements and applied only to data*

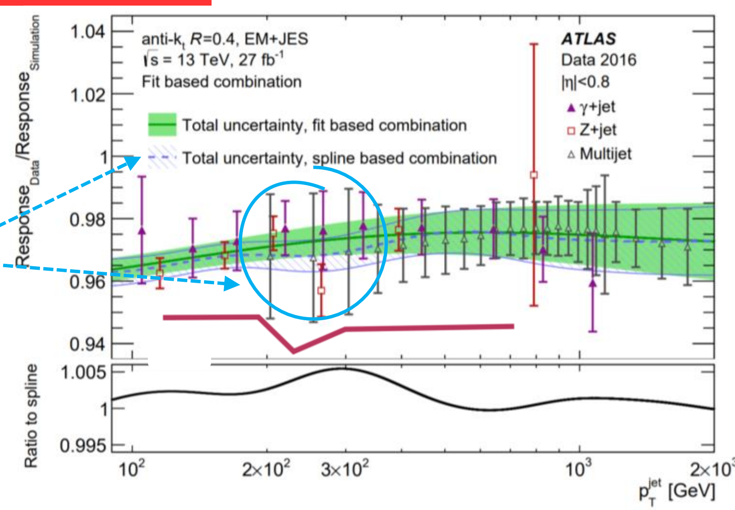
—— Derived for offline jets

······ Derived specifically for trigger jets

Calibrate using momentum balance of offline jets against well calibrated objects

- Needs to be smooth as can introduce bumps
- Use polynomial fit in $\log(p_T)$ rather than spline





After calibration energy of trigger and offline jets agree within 0.05%

Jet energy scale uncertainty is 1-2%, similar to that of offline jets

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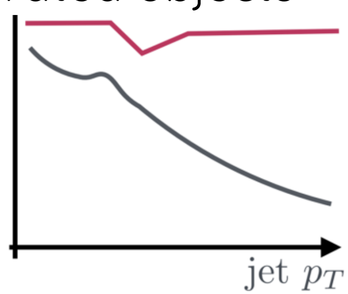

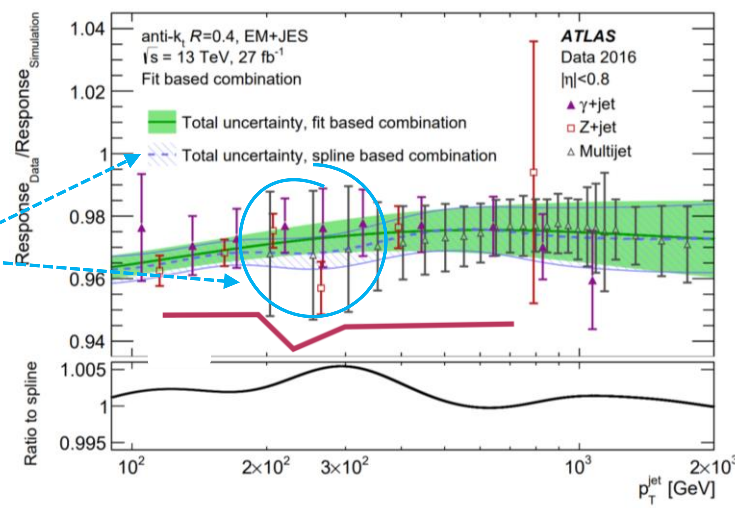

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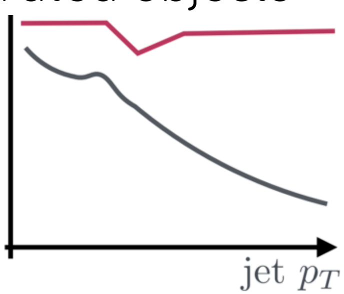

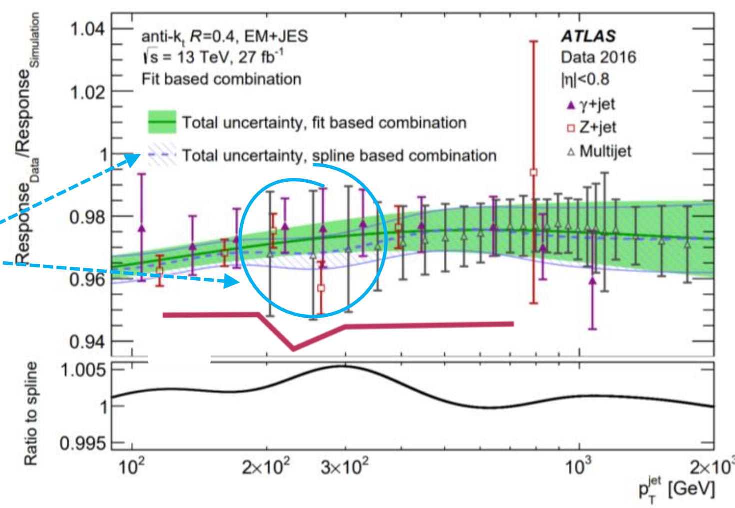

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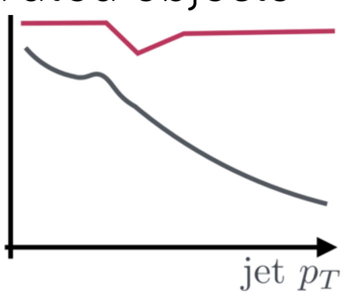

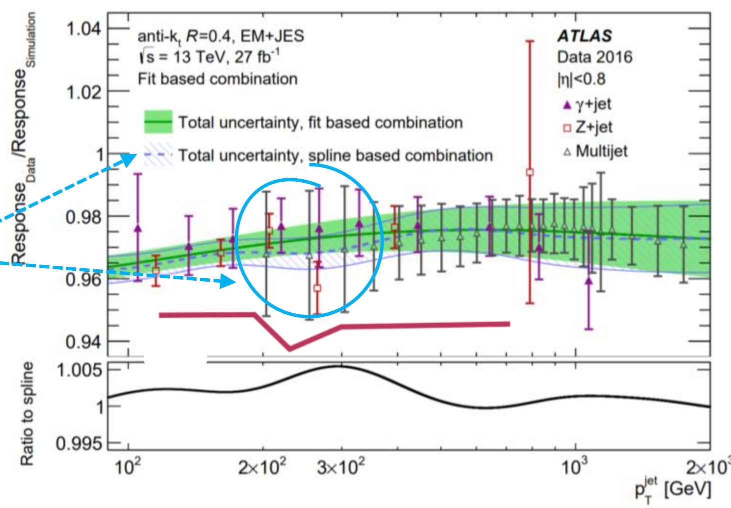

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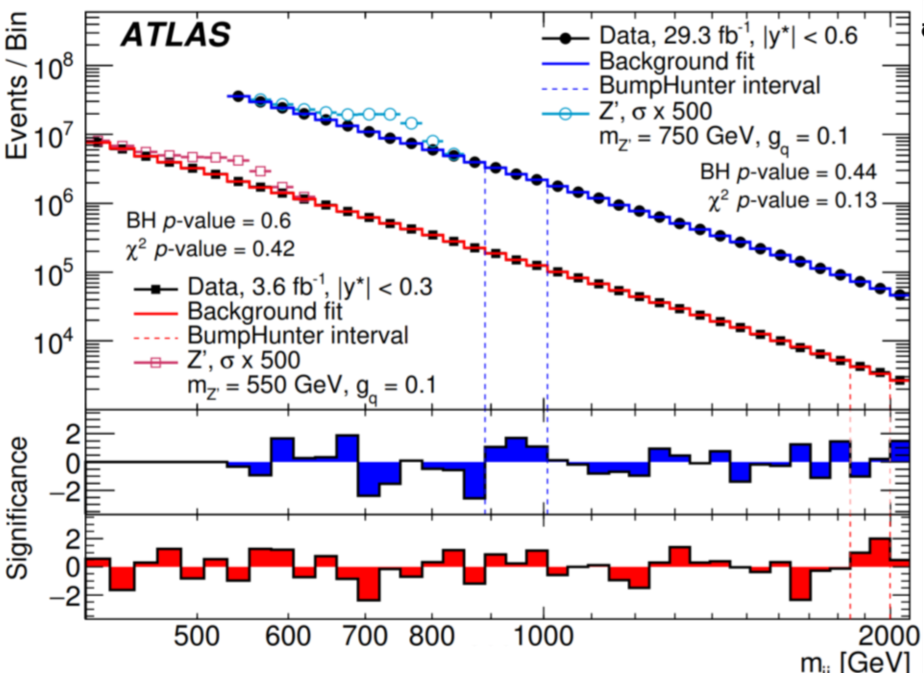
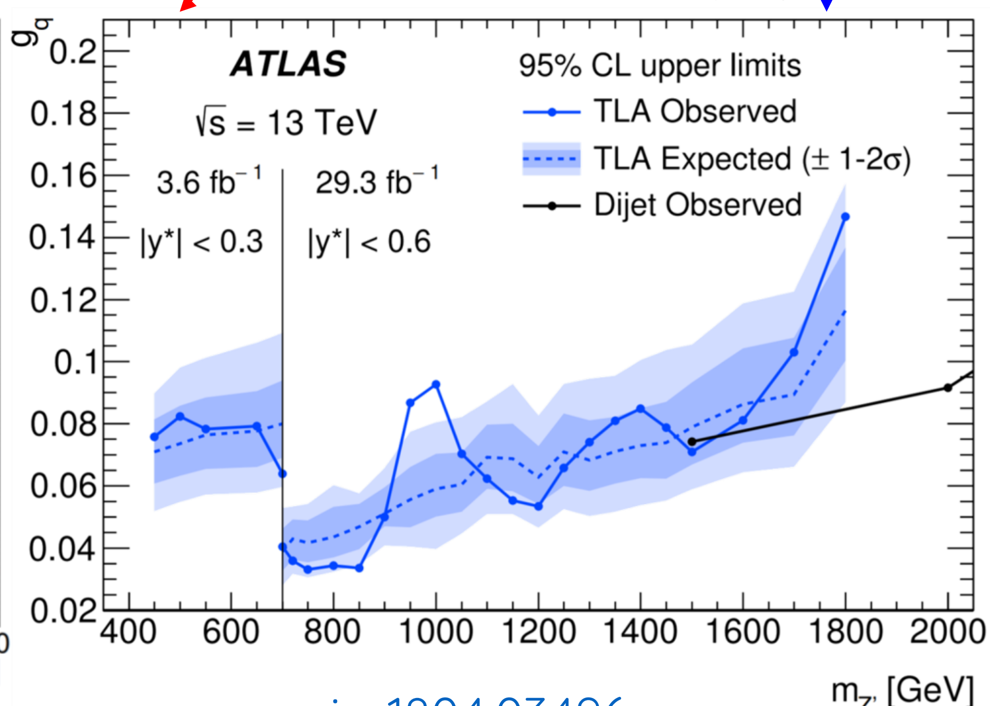
Trigger Level Analysis

- Two selections based on trigger threshold target different mass ranges
- Fit background and look for bumps
- Set Bayesian limit

Selections	HW 75 GeV Trigger ($3.6\ fb^{-1}$)	HW 100 GeV Trigger ($29.3 fb^{-1}$)
Lead Jet pT	> 185 GeV	> 220 GeV
Second Jet pT	> 85 GeV	> 85 GeV
m_{jj}	> 450 GeV	> 700 GeV
$\lvert y^* \rvert = 0.5 \lvert y_1 - y_2 \rvert$	< 0.3	< 0.6

Limit on axial vector Z' coupling



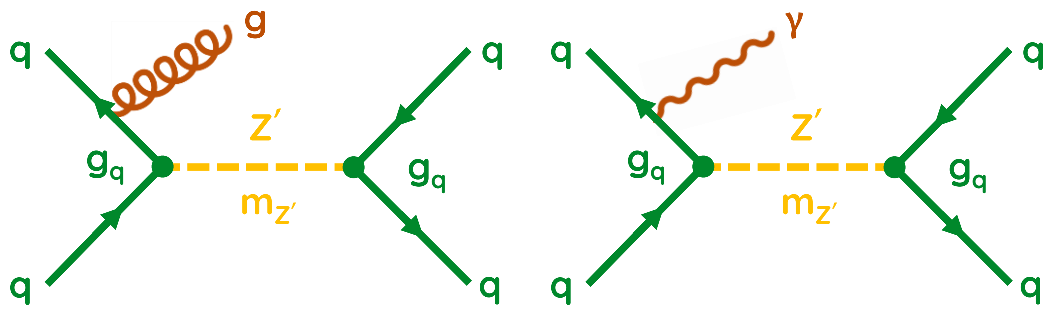


[arxiv: 1804.03496](https://arxiv.org/abs/1804.03496)

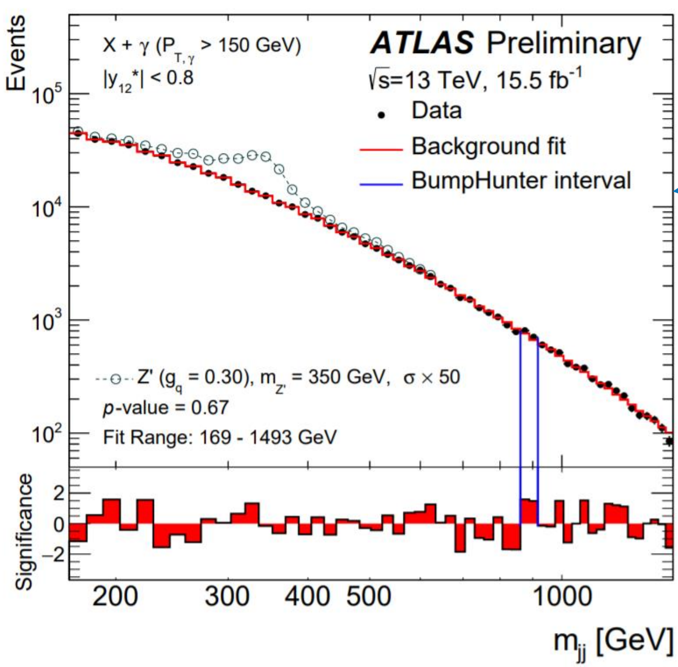
ISR Dijet Search

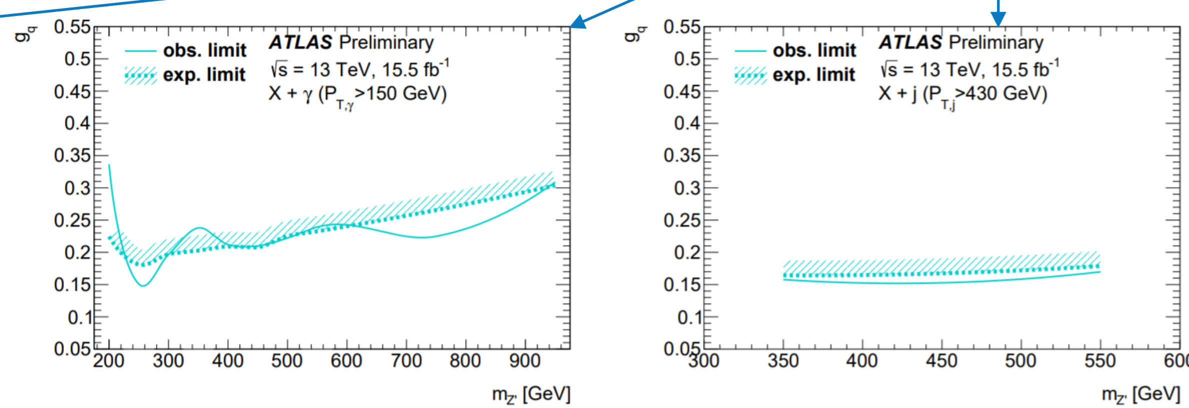
Add energetic ISR photon or jet to signature to allow better sensitivity to light resonances

- satisfies the trigger threshold
- allows lower masses to be examined
- reduced production rates



Selections	ISR Photon	ISR Jet
ISR Object	> 150 GeV	> 430 GeV
First (Second) Jet p_T	> 25 GeV	
Second (Third) Jet p_T	> 25 GeV	
$\lvert y^*\rvert = 0.5\ \lvert y_1 - y_2\rvert$	< 0.8	< 0.6



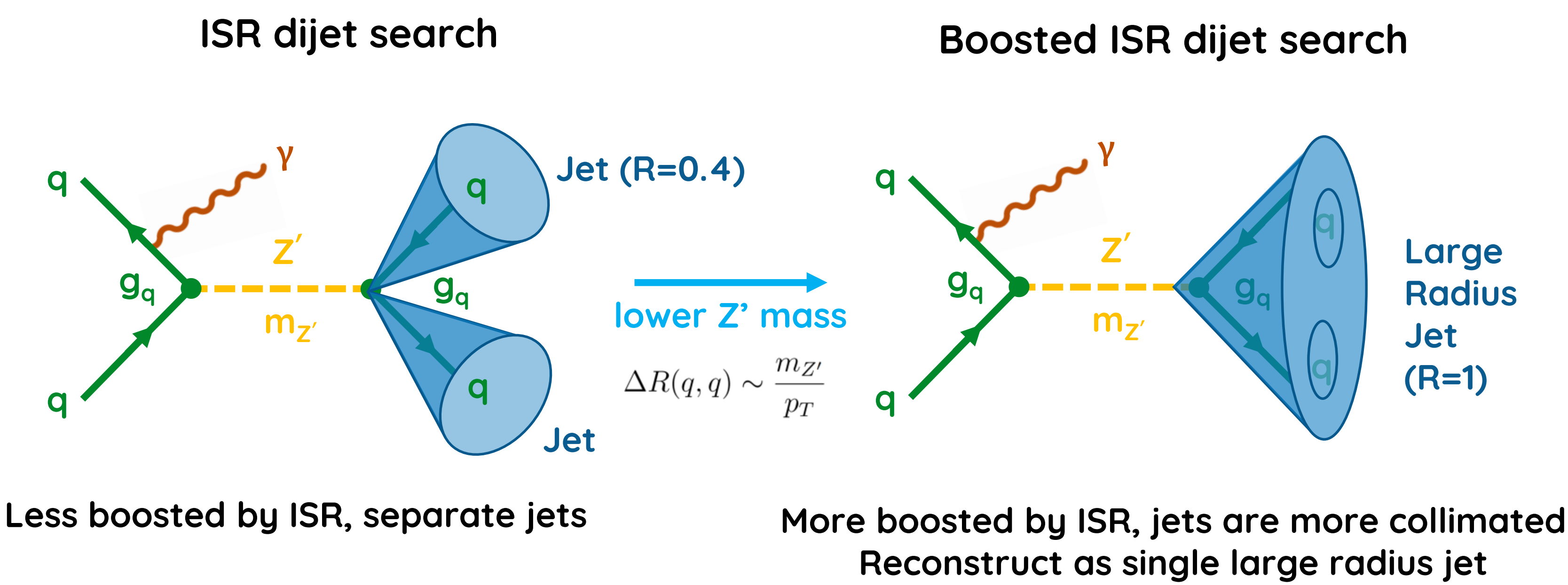


ATLAS-CONF-2016-070

Boosted ISR Dijet Search

ISR selection has allowed masses down to 200 GeV to be examined

- Targets regime where jets from the mediator are separated
- To go lower examine a larger single jet instead



To reduce pileup and soft radiation effects, large radius jets are trimmed

- Reclustered with smaller radius using kt algorithm
- Removed if smaller clusters if carry < 5% of total jet pT (Eur. Phys. J. C 76 (2016) 154)

Use jet substructure to reduce background and select the signal

Boosted ISR Dijet Search

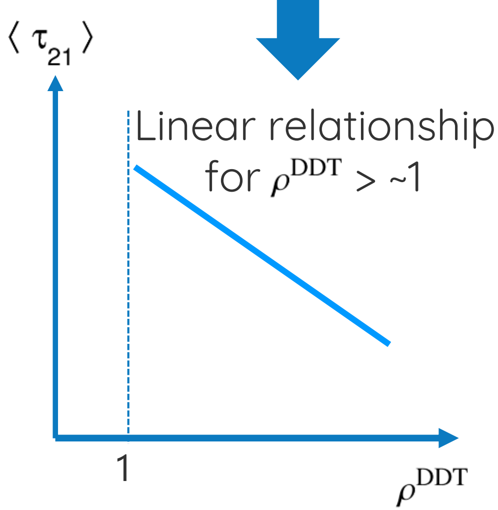
Signal has two particles in the jet vs one for the background

- τ_N is a measure of jet's compatibility with having N subjets
- $\tau_{21} = \tau_2 / \tau_1$ discriminates between jets due to one particle and two

However τ_{21} is correlated with the large radius jet's mass (m_j)

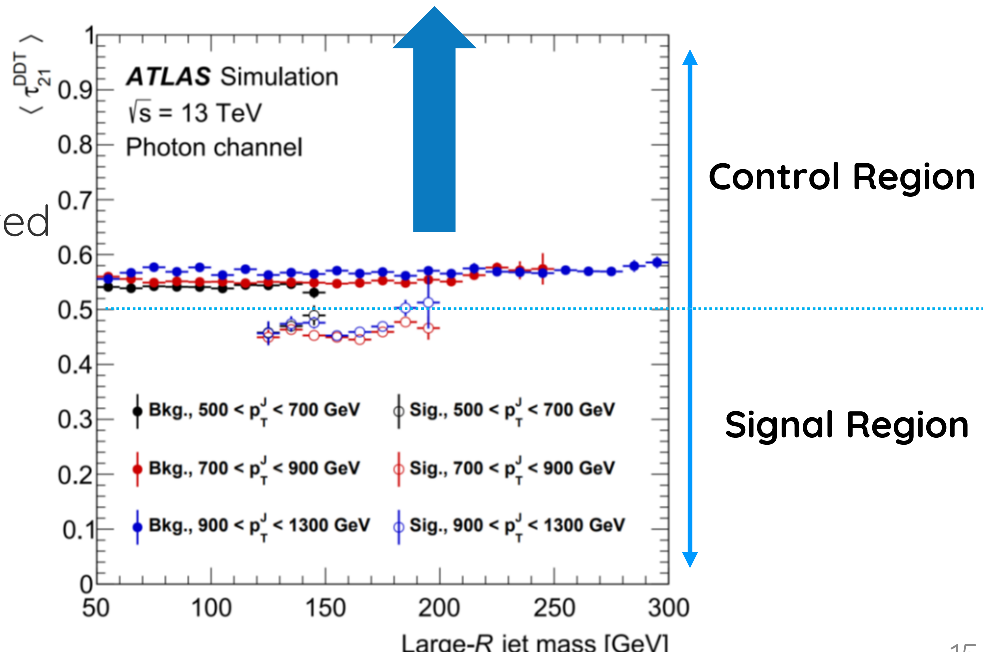
Use designated decorrelated tagger method [JHEP 05 (2016) 156]

$$\rho^{\mathrm{DDT}} \equiv \log\left(\frac{m_J^2}{p_T^J \times \mu}\right)$$



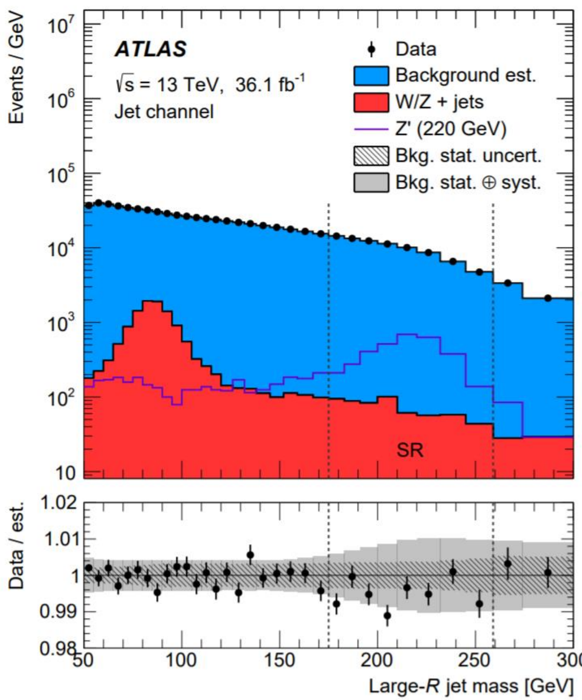
Define τ_{21}^{DDT} a linearly corrected version of τ_{21}

Now independent of jet mass

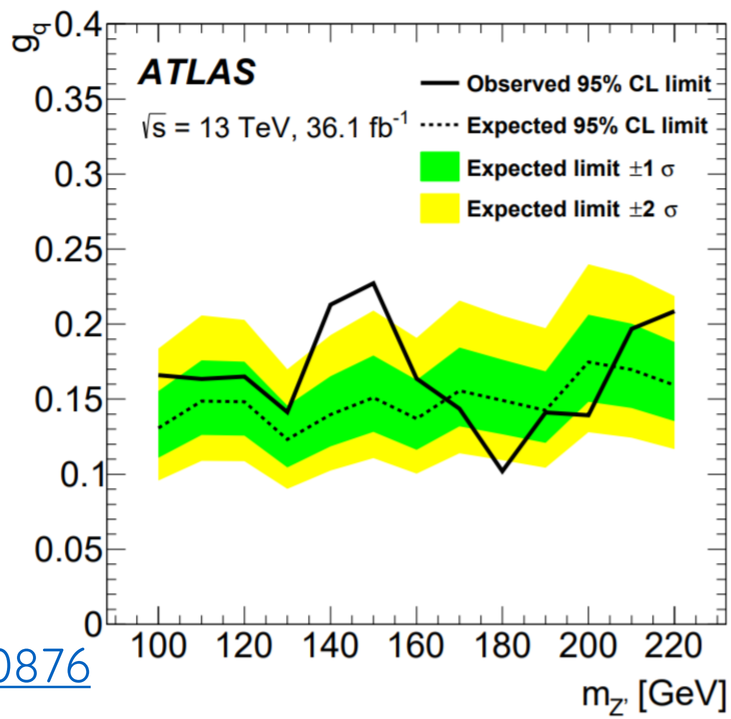


Boosted ISR Dijet Search

Signal Region Selections	ISR Photon	ISR Jet
ISR Object pT	> 155 GeV	> 420 GeV
Large Radius Jet pT	> 200 GeV	> 450 GeV
Δφ(Large Jet, photon/jet)	> π/2	
Large jet momentum	> 2 x the jet mass	
τ_{21}^{DDT}	< 0.5	
ρ^{DDT}	> 1.5	



Probes Z' masses down to 100 GeV



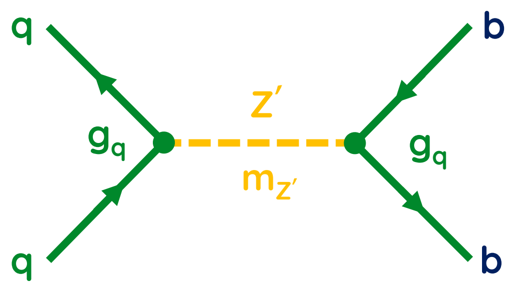
[arxiv: 1801.0876]

Specific final state quarks

Specific searches for resonances with pairs bottom or top quarks in the final dijet resonance

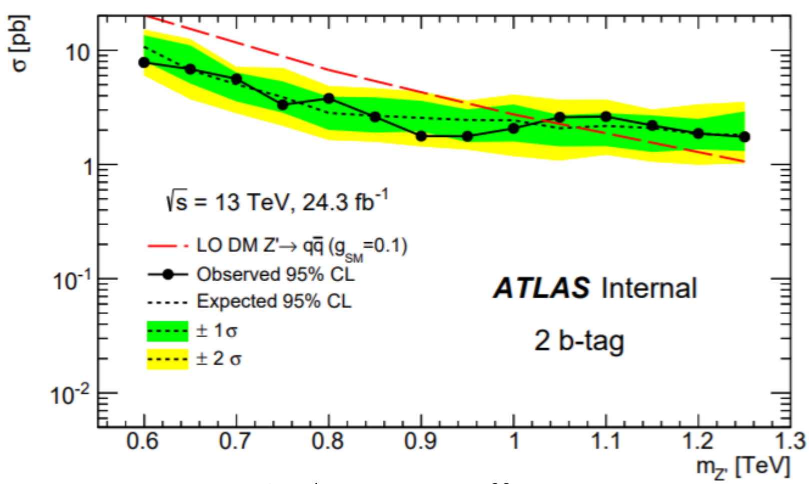
See Siyuan Sun's talk for details

Di b-jet search



For lower mediator masses

Excludes masses up to 1.02 TeV (**g_q=0.1**)

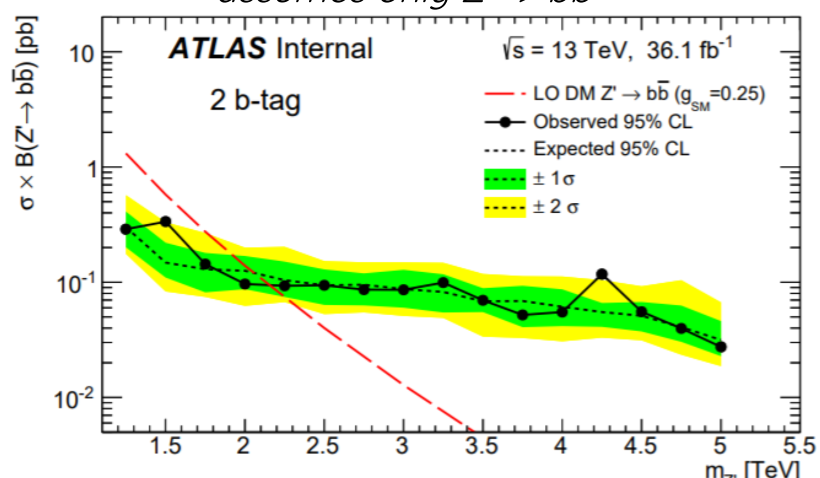


70% b-tagging efficiency

For higher mediator masses

Excludes masses up to 2.1 TeV (**g_q=0.25**)

assumes only Z' -> bb



85% b-tagging efficiency

EXOT-2016-33

Specific final state quarks

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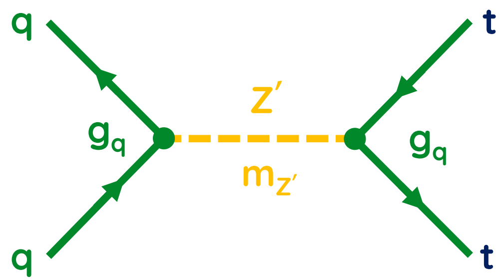
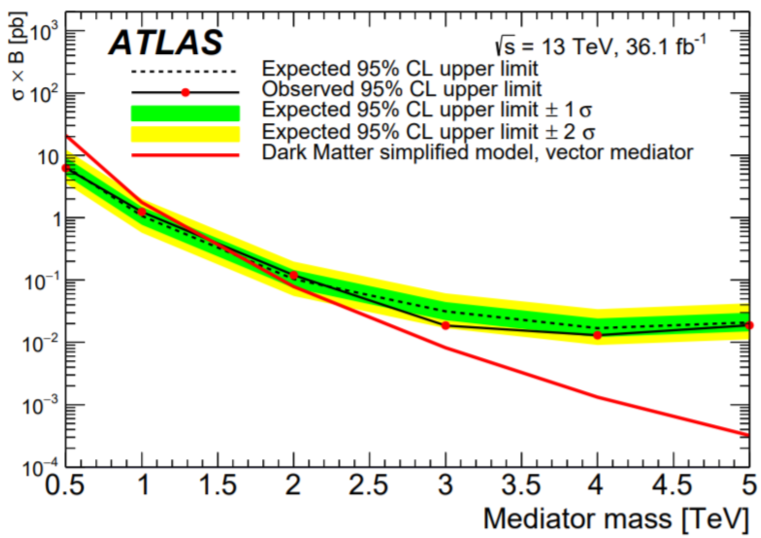
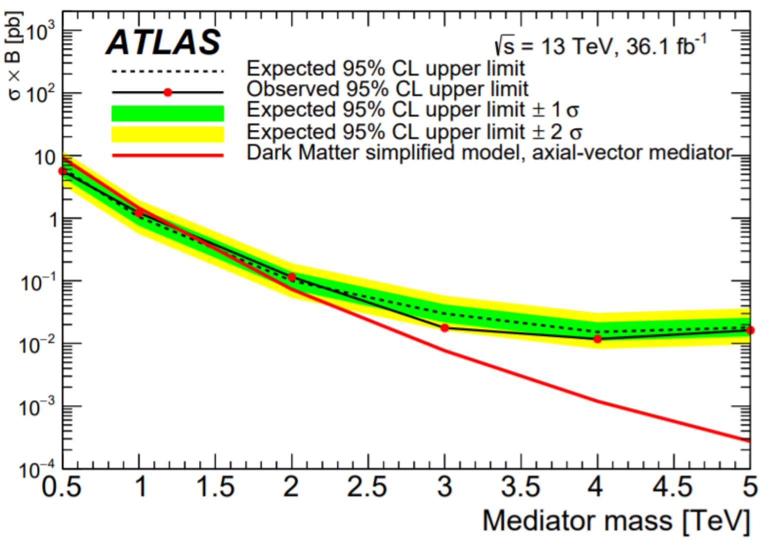
Search for top quark pairs



Vector Mediator $g_q = 0.25$ $g_{DM} = 1$ $g_\ell = 0$ *Axial vector Mediator*



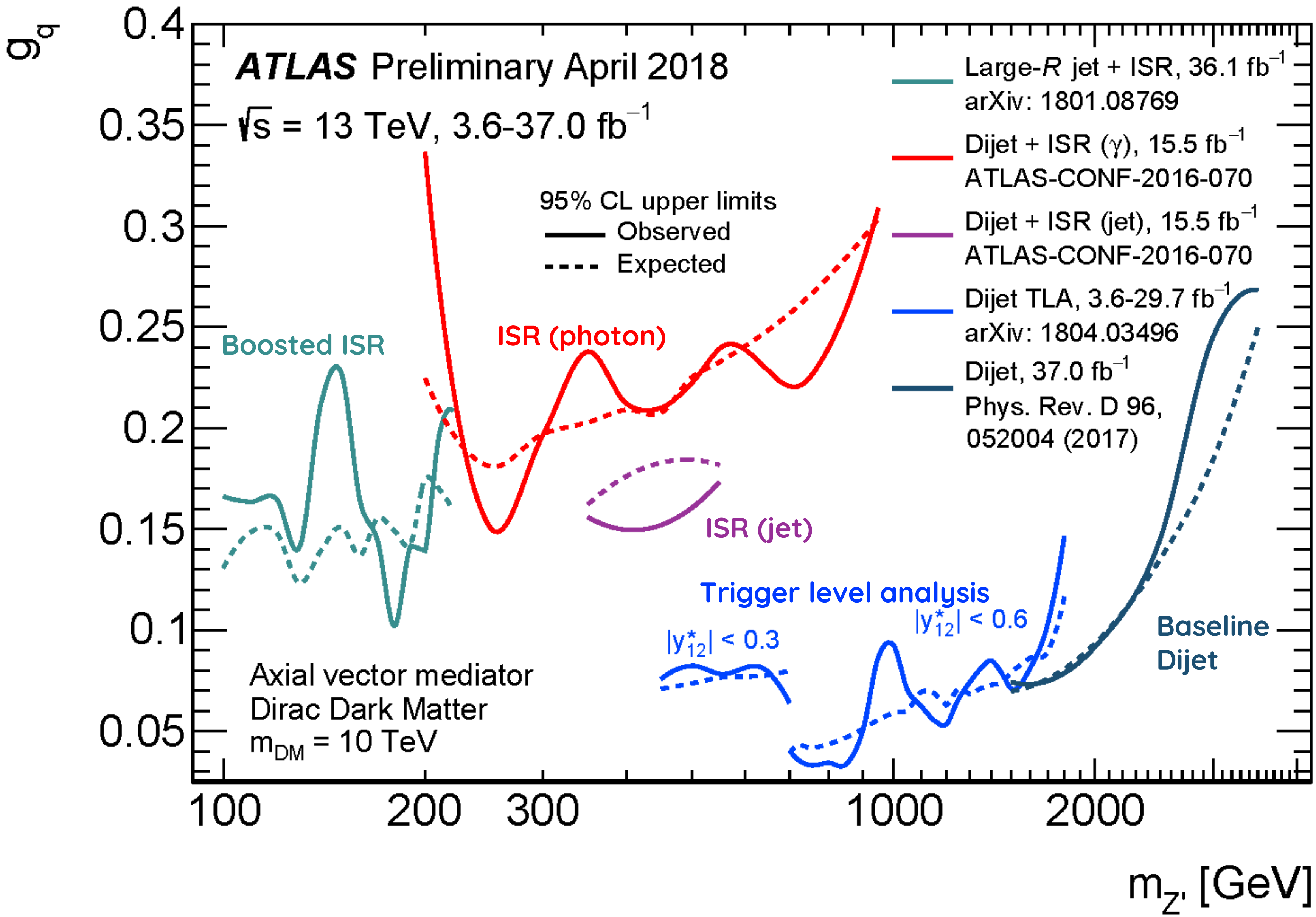
Excludes masses up to 1.4 TeV



Excludes masses up to 1.2 TeV

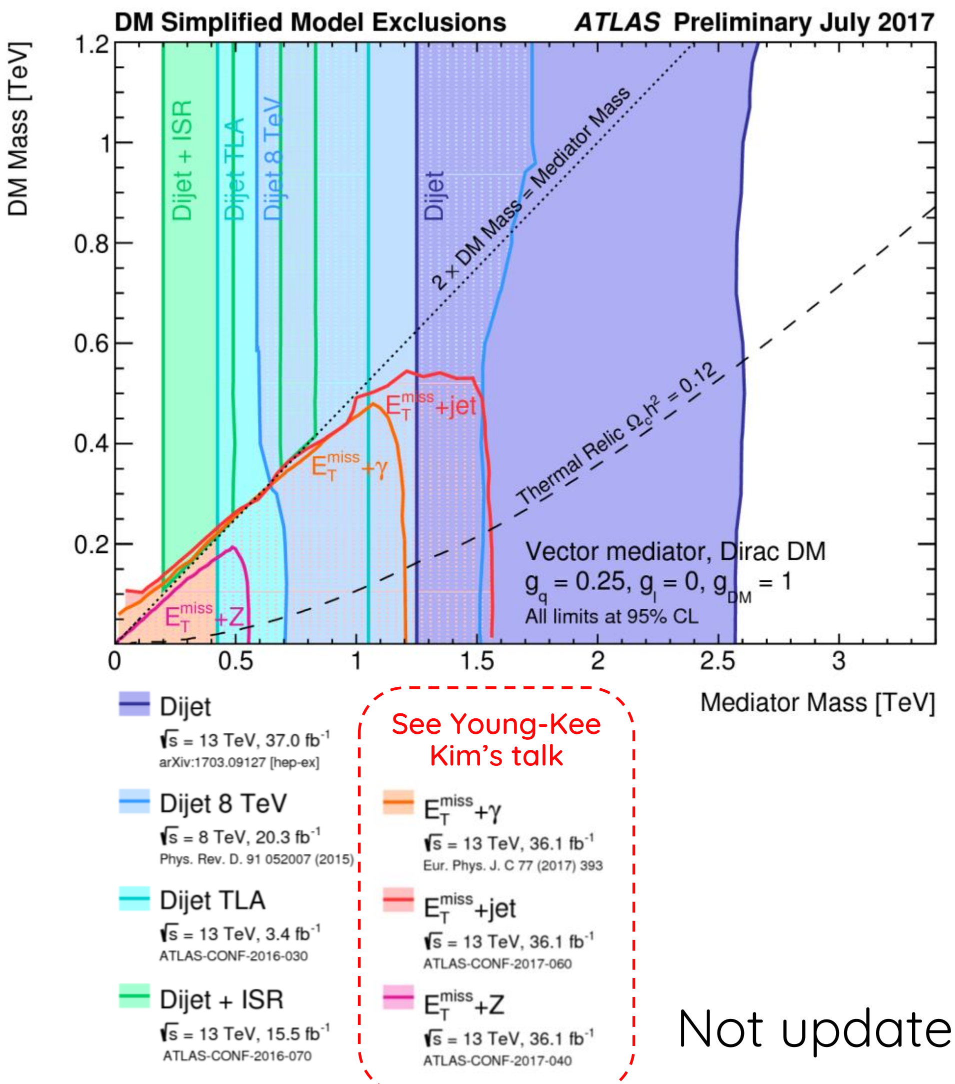
arxiv: 1804.10823

Dijet Summary



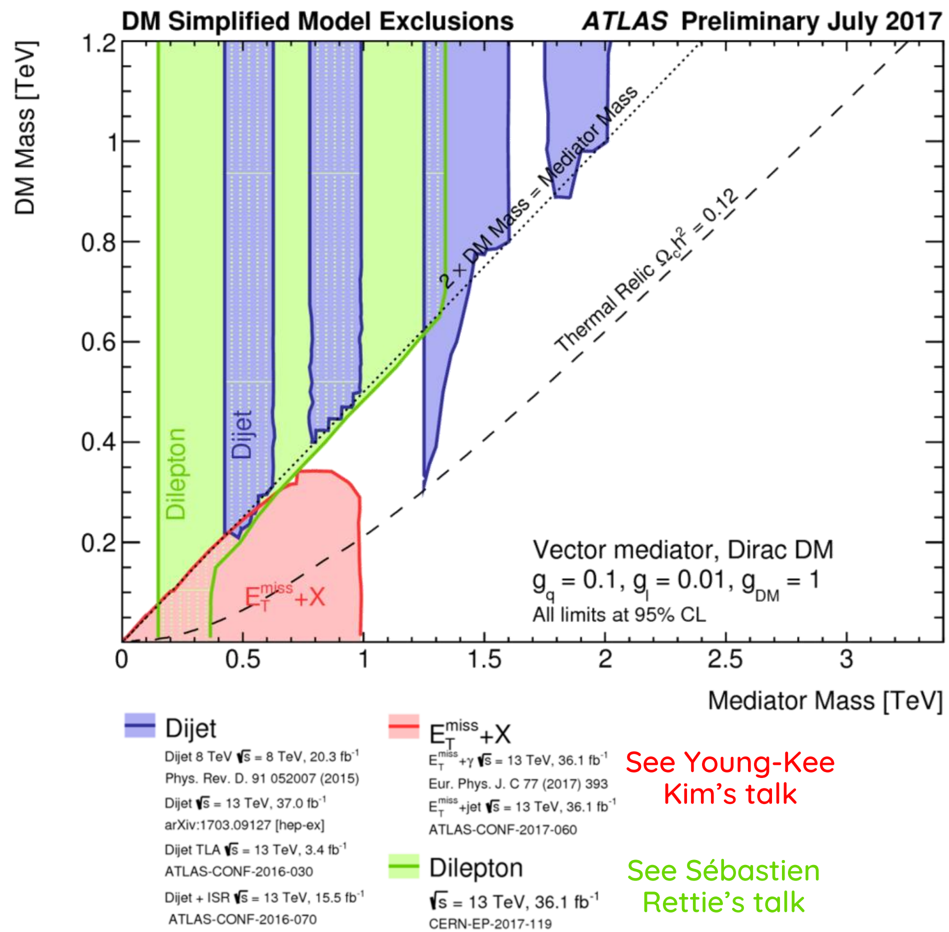
Summary

$g_q = 0.25$ $g_{DM} = 1$ $g_\ell = 0$



See Young-Kee Kim's talk

$g_q = 0.1$ $g_{DM} = 1$ $g_\ell = 0.01$



See Young-Kee Kim's talk

See Sébastien Rettie's talk

Not updated for latest TLA and ISR results

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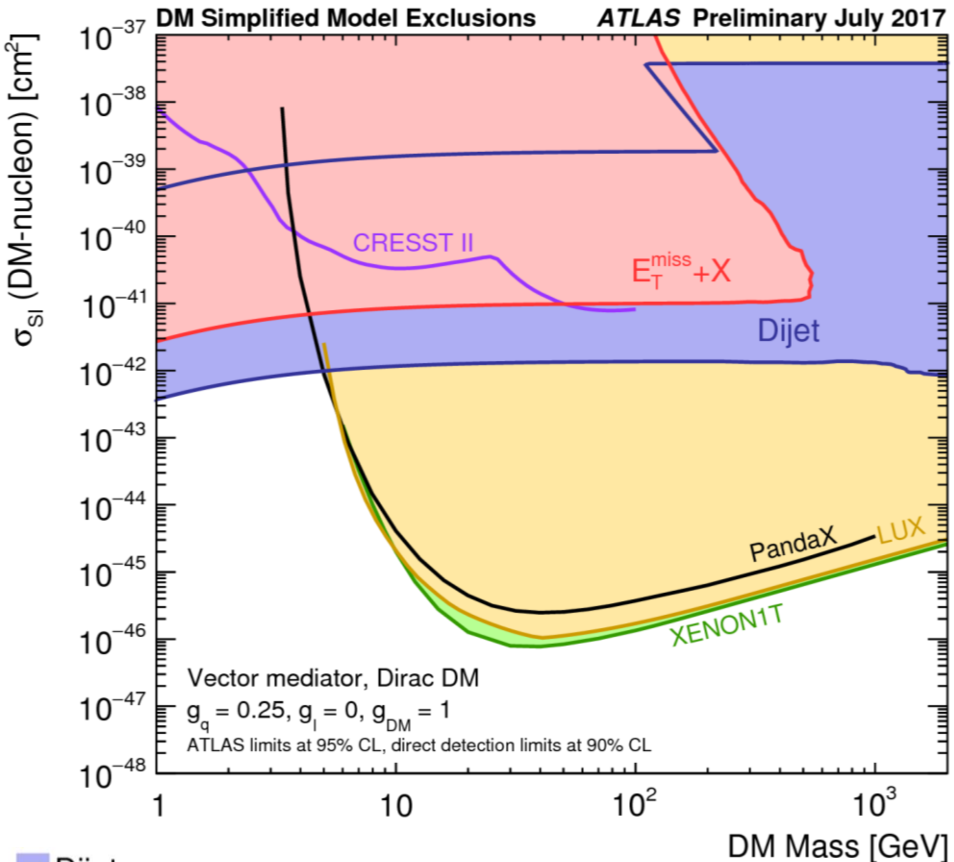
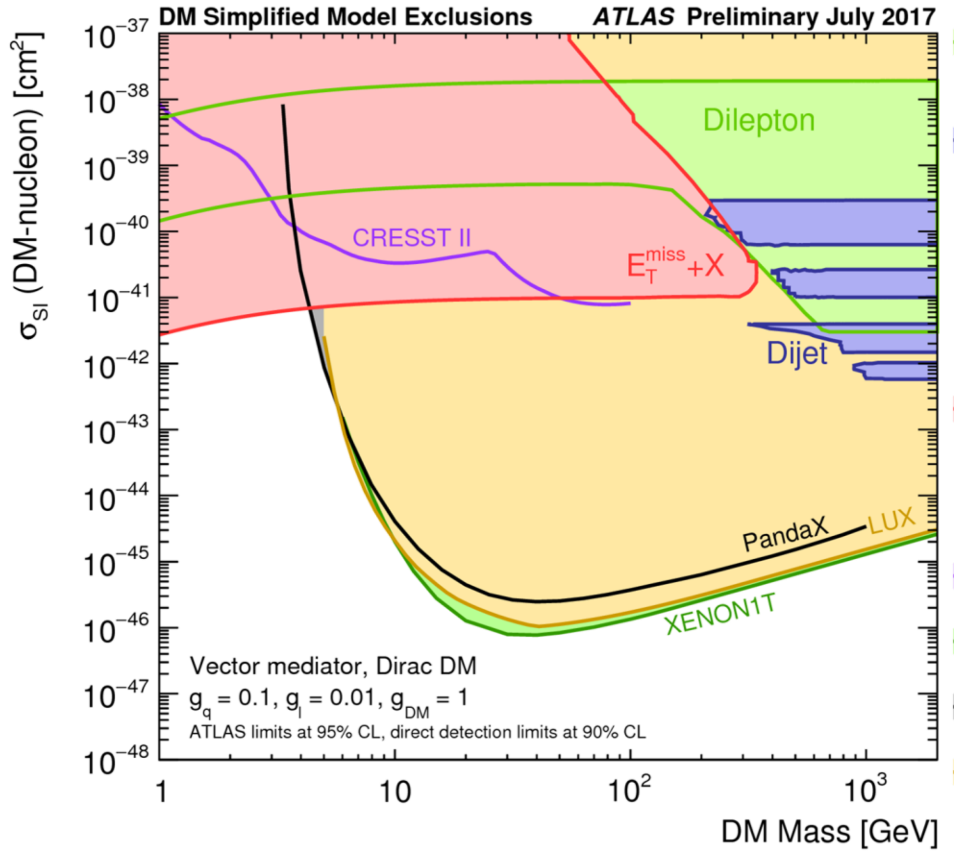


$g_q = 0.1$ $g_{DM} = 1$ $g_\ell = 0.01$



Dijet
Dijet 8 TeV $\sqrt{s}$ = 8 TeV, 20.3 fb^{-1}
Phys. Rev. D. 91 052007 (2015)
Dijet $\sqrt{s}$ = 13 TeV, 37.0 fb^{-1}
arXiv:1703.09127 [hep-ex]
Dijet TLA $\sqrt{s}$ = 13 TeV, 3.4 fb^{-1}
ATLAS-CONF-2016-030
Dijet + ISR $\sqrt{s}$ = 13 TeV, 15.5 fb^{-1}
ATLAS-CONF-2016-070

E_T^{miss}+X
E_T^{miss}+γ $\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
Eur. Phys. J. C 77 (2017) 393
E_T^{miss}+jet $\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
ATLAS-CONF-2017-060
E_T^{miss}+Z $\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
ATLAS-CONF-2017-040

CRESST II
arXiv:1509.01515v1

XENON1T
arXiv:1705.06655v2

PandaX
arXiv:1607.07400

LUX
arXiv:1608.07648; arXiv:1602.03489

Not updated for latest TLA and ISR results

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Dilepton
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
CERN-EP-2017-119

E_T^{miss}+X
E_T^{miss}+γ $\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
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arXiv:1608.07648; arXiv:1602.03489

Summary

ATLAS has an ***extensive program of searches for dark matter mediators*** in run 2

- Complementarity between dedicated searches for mediators and dark matter candidates

Searches for mediators with dijets in run 2 are examining:

- ***Lower couplings*** thanks to a large number of recorded events
- ***Higher masses*** thanks to higher collision energies
- ***Lower masses*** thanks to new experimental techniques
  - ***Trigger level analysis*** extending to ***lower masses and low couplings***
  - ***ISR search*** extends search to ***lower masses***
  - ***Boosted ISR*** further extends search to ***even lower masses***

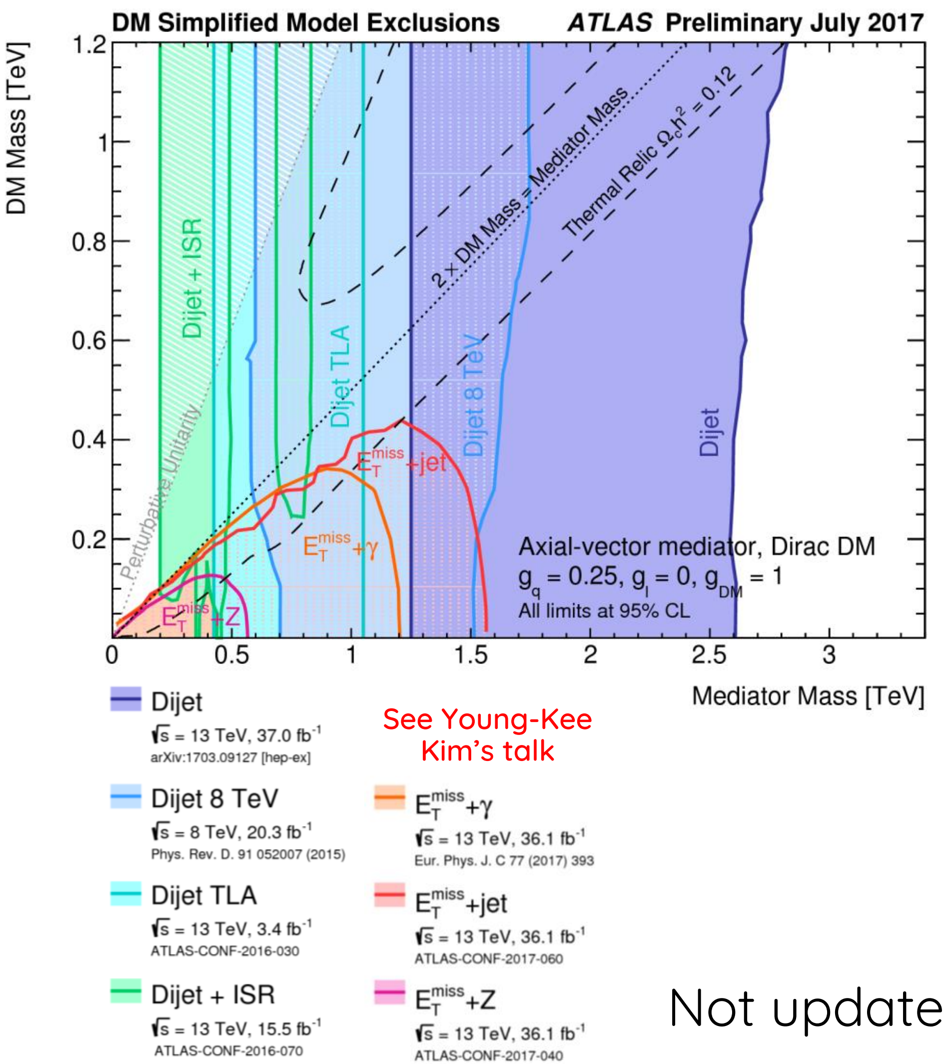
Searches ***cover all mediator masses between 100 GeV and 3.5 TeV***

Looking forward to the full run 2 results

Additional Slides

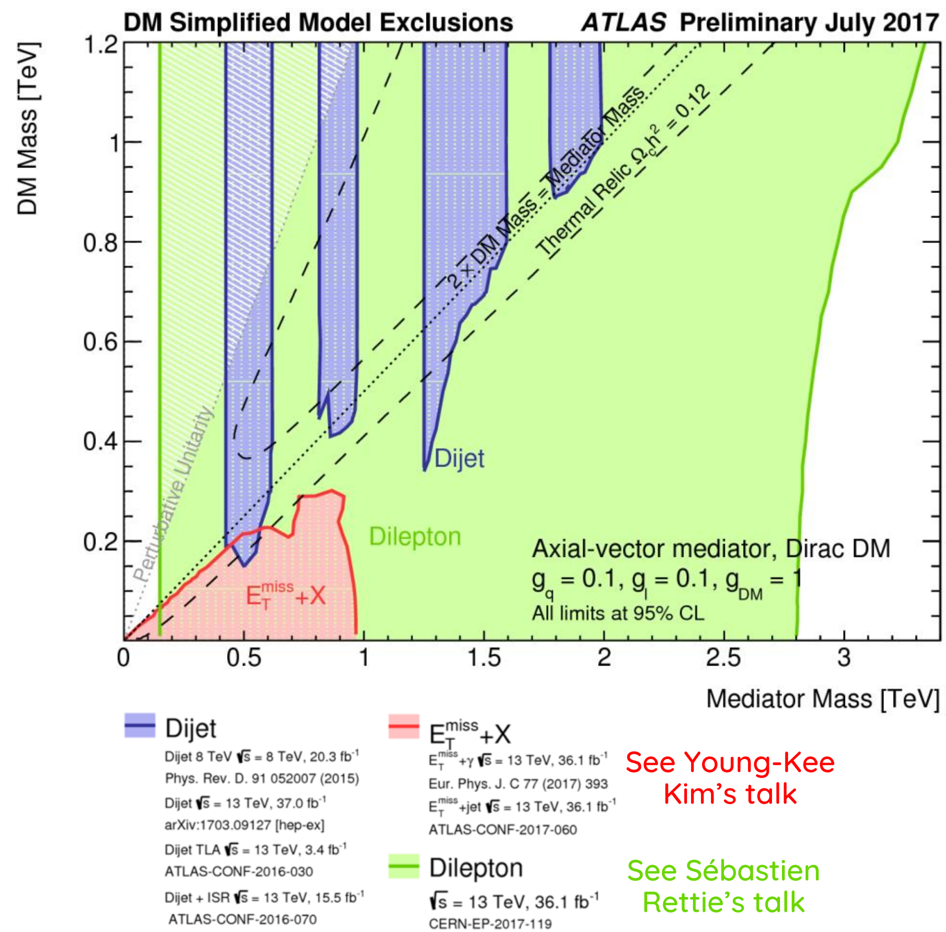
Summary

$g_q = 0.25$ $g_{DM} = 1$ $g_\ell = 0$



See Young-Kee Kim's talk

$g_q = 0.25$ $g_{DM} = 1$ $g_\ell = 0.1$



See Young-Kee Kim's talk

See Sébastien Rettie's talk

Not updated for latest TLA and ISR results

ATLAS EXPERIMENT

Translation to DD plane

THE UNIVERSITY OF MELBOURNE

$$\sigma_{\rm SI} \simeq 6.9 \times 10^{-41}\ {\rm cm}^2 \cdot \left(\frac{g_q g_{\rm DM}}{0.25}\right)^2 \left(\frac{1\,{\rm TeV}}{M_{\rm med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\,{\rm GeV}}\right)^2$$

Vector

$$\sigma^{\rm SD} \simeq 2.4 \times 10^{-42}\ {\rm cm}^2 \cdot \left(\frac{g_q g_{\rm DM}}{0.25}\right)^2 \left(\frac{1\,{\rm TeV}}{M_{\rm med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\,{\rm GeV}}\right)^2$$

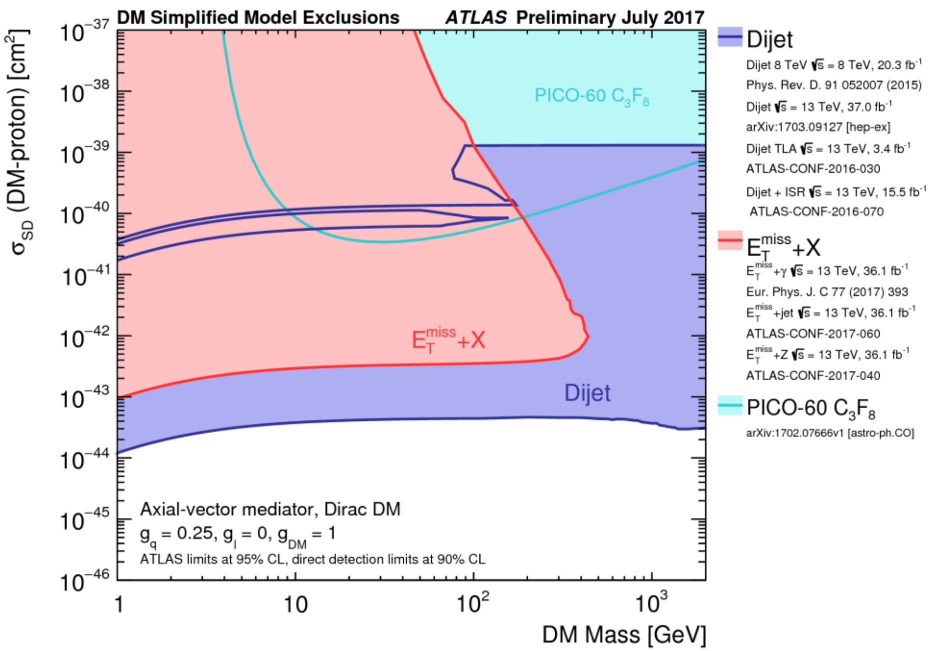
Axial vector

$$\mu_{n\chi} = m_n m_{\rm DM}/(m_n + m_{\rm DM})$$

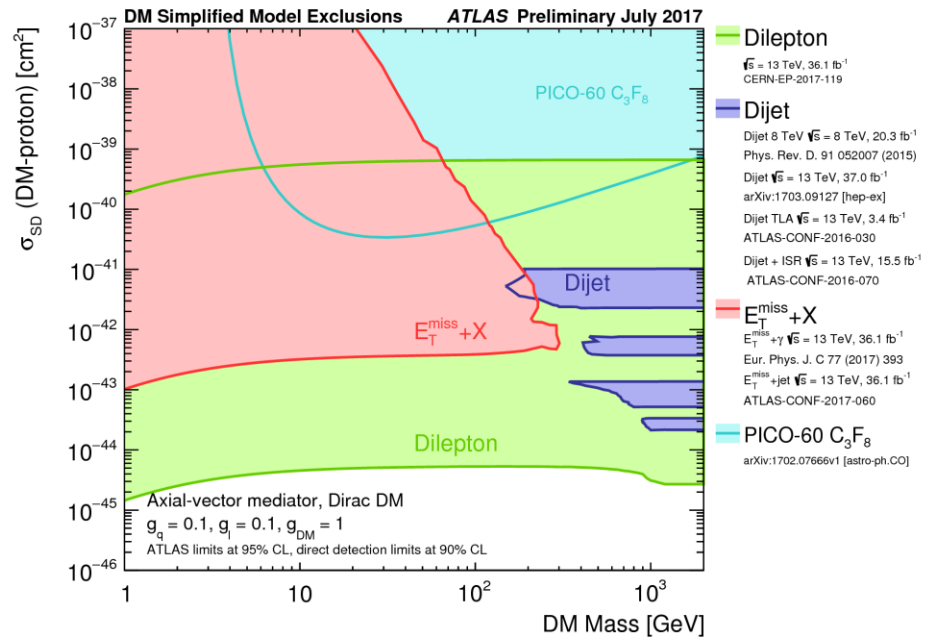
Arxiv: 1603.04156

Summary

$g_q = 0.25$ $g_{DM} = 1$ $g_\ell = 0$



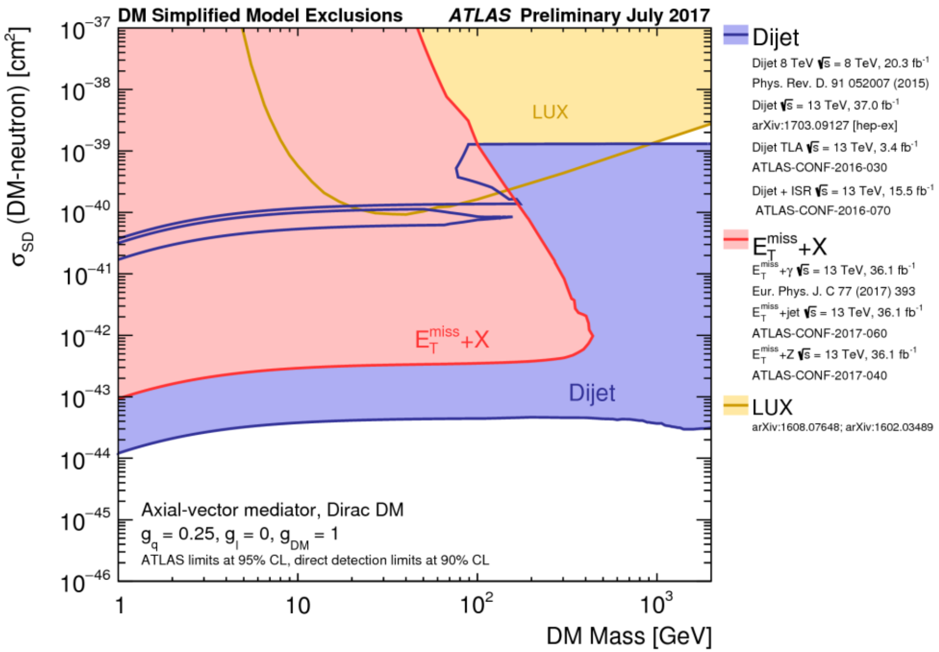
$g_q = 0.1$ $g_{DM} = 1$ $g_\ell = 0.1$



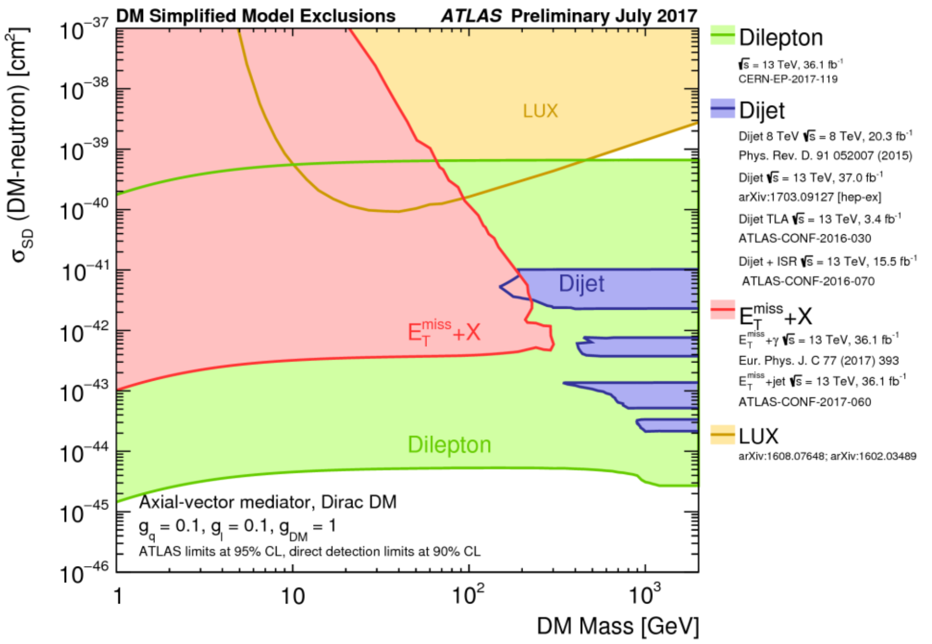
Not updated for latest TLA and ISR results

Summary

$g_q = 0.25$ $g_{DM} = 1$ $g_\ell = 0$



$g_q = 0.1$ $g_{DM} = 1$ $g_\ell = 0.1$

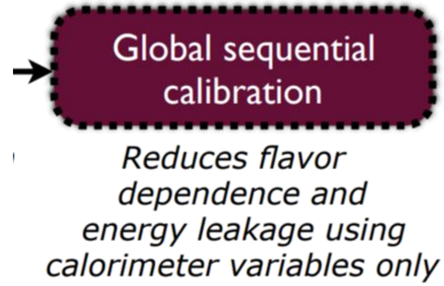


Not updated for latest TLA and ISR results

TLA - GSC

Uses (at trigger level)

- Energy fraction in Electromagnetic Calorimeter
- Energy fraction in Hadronic Calorimeter
- Minimum number of Calorimeter cells which contain 90% of the jet energy



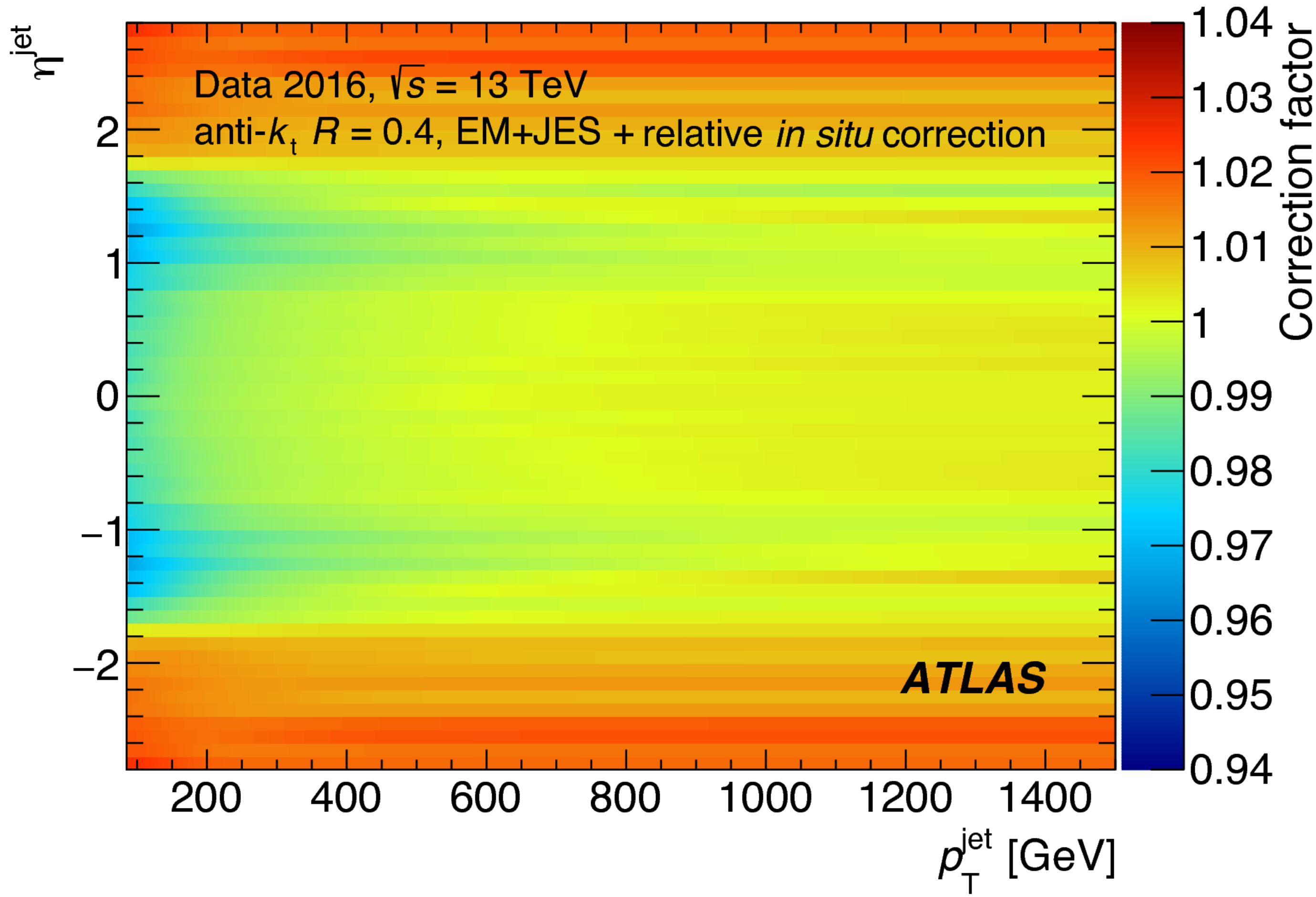
No track based variables available

TLA - Correction

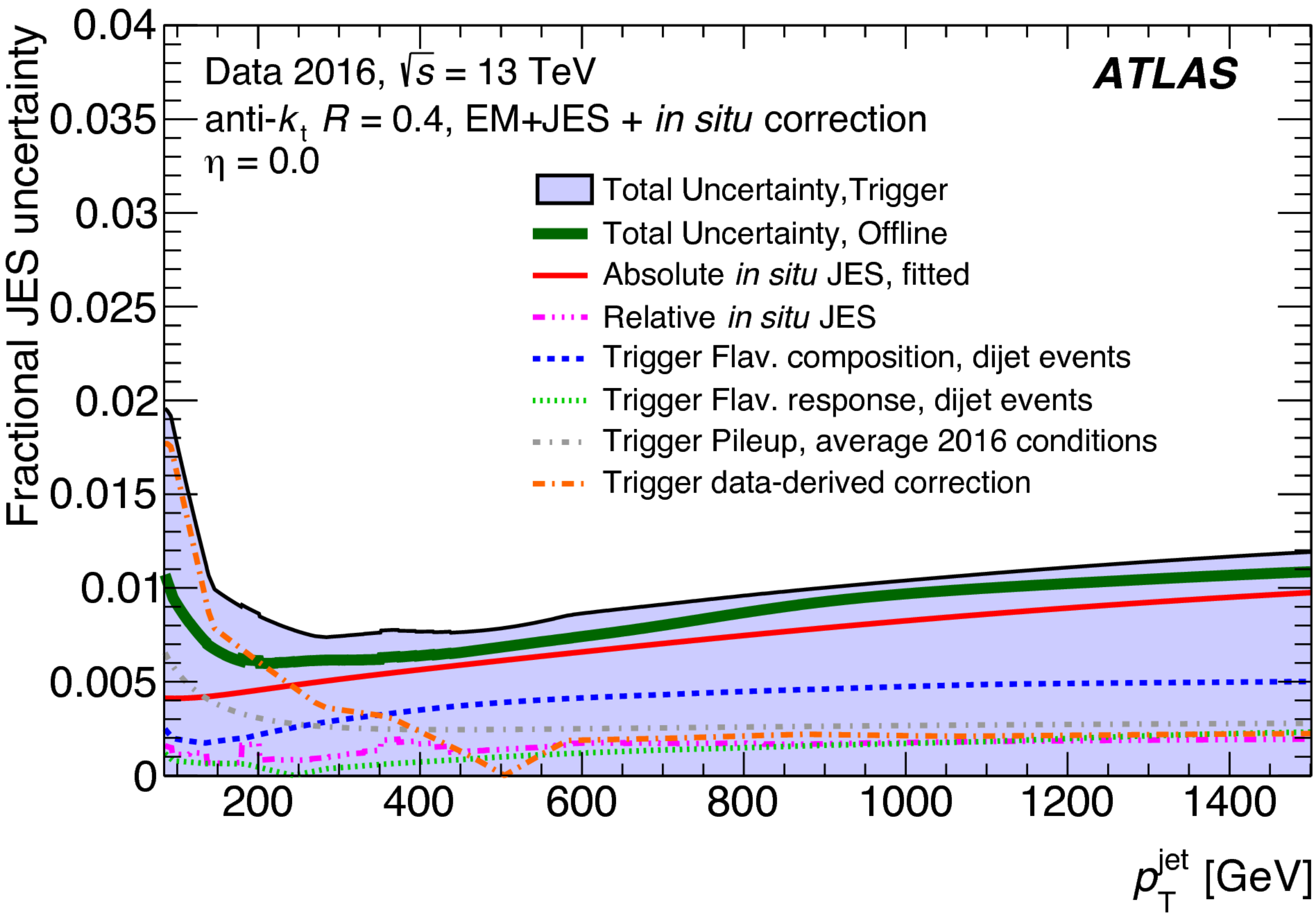
Correction factor applied to trigger-level jets using the p_T response between trigger-level and offline jets split by η and p_T of the jet

Trigger-to-offline data-derived correction

Corrects trigger-level jets to the scale of offline jets, applied only to data



TLA – JES Uncertainty



TLA Sliding window fit

Fit over mjj performed in a sliding window to estimate background

Three functions are used to fit to the data

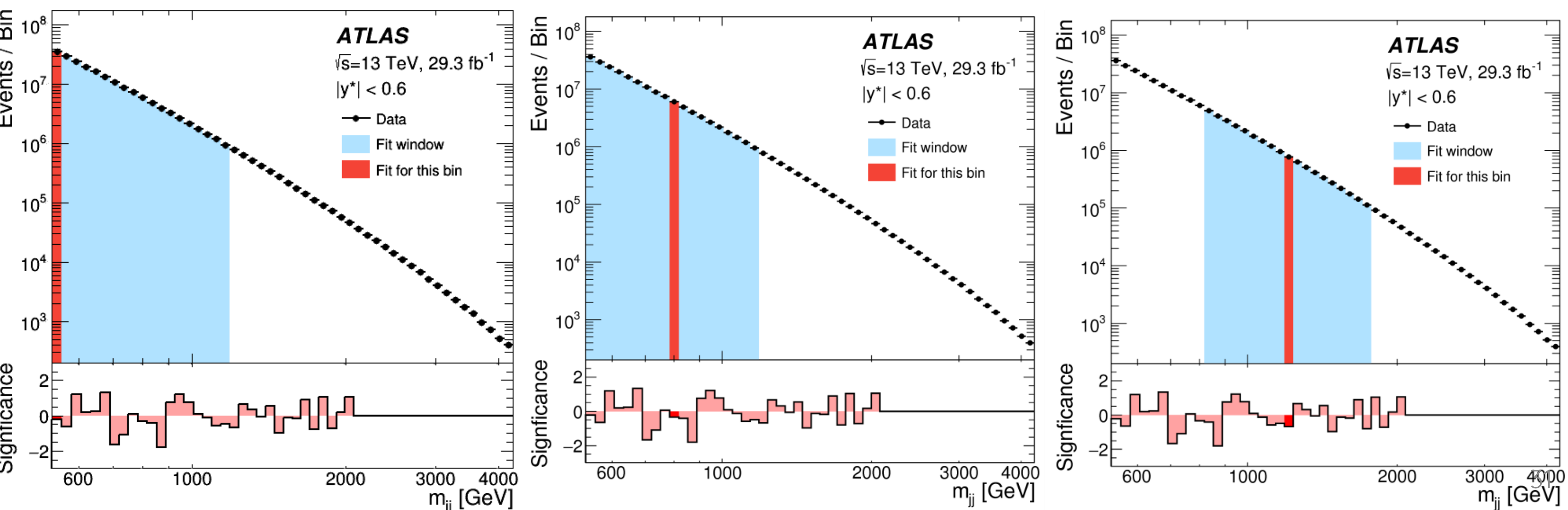
- Final function used has best chi squared over the full range
- Systematic uncertainty uses alternate function

|y*| < 0.6 (0.3) uses first (second) function

$$f(x) = p_1(1-x)^{p_2} x^{p_3 + p_4 lnx + p_5 lnx^2}$$

$$f(x) = p_1(1-x)^{p_2} x^{p_3 + p_4 lnx} \quad \text{(ISR)}$$

$$f(x) = \frac{p_1}{x^{p_2}} e^{-p_3 x - p_4 x^2}$$



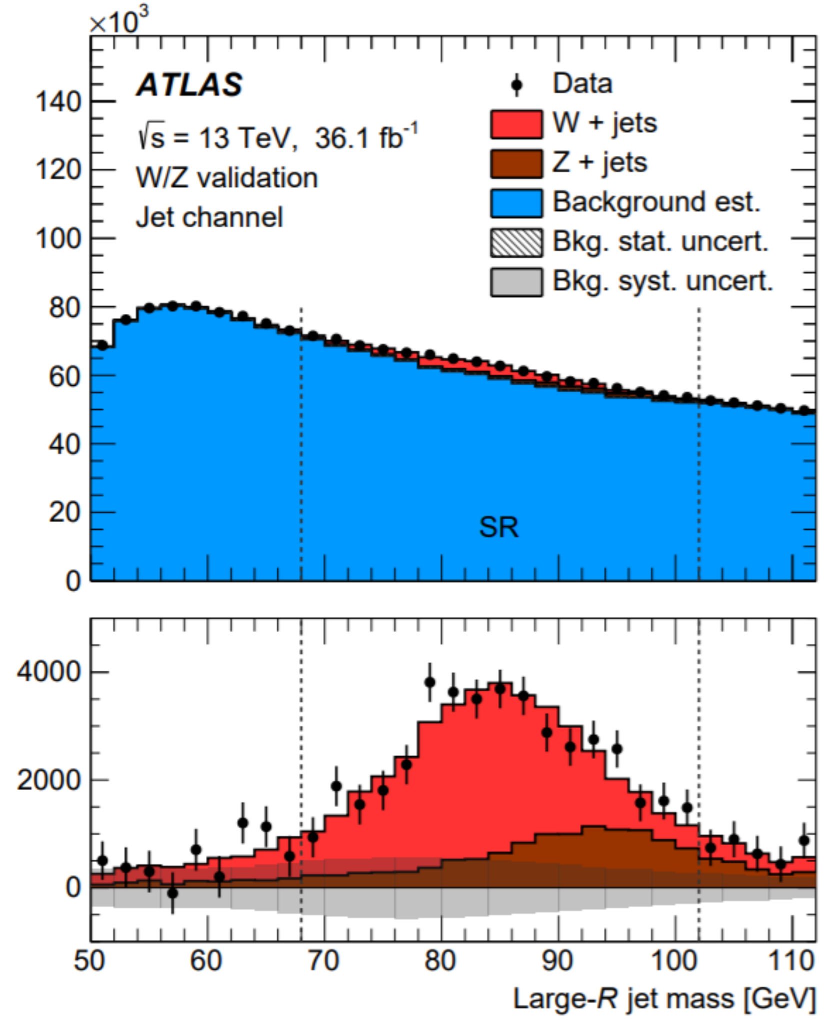
Boosted ISR - Control region

Control region inverts τ_{21}^{DDT} selection

- Background estimated in SR using transfer factor
- Method Validated on W/Z peak

Largest (systematic) uncertainty is from the transfer factor

- 90% for $M_{Z'}$ of 160 GeV



Boosted ISR - Transfer factor

BG = TF * (Number in CR - Expected number from production with an associated vector boson)

Transfer factor = expected ratio of events which pass τ_{21}^{DDT} to those which fail

- Data measured away from Z' mass under consideration (20% buffer)
- Parameterised by log(Large radius jet pT /μ) and ρ^{DDT}

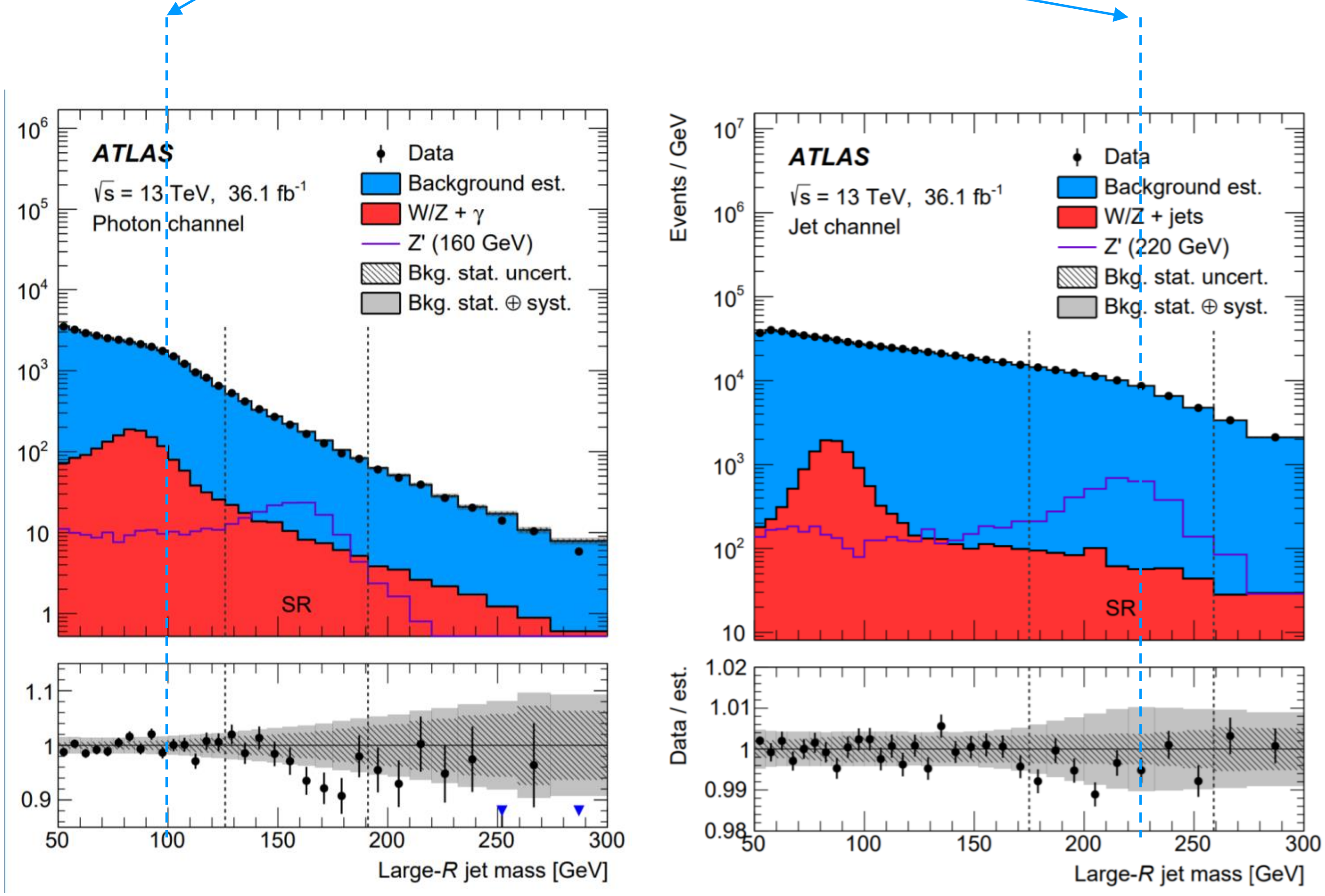
Boosted ISR - Uncertainty

Uncertainty source	$\Delta\mu/\mu$ [%] $m_{Z'} = 160$ GeV	$m_{Z'} = 220$ GeV
Transfer factor	90	88
Large-R jet	25	17
Total systematic uncertainty	93	91
Statistical uncertainty	10	11

Boosted ISR - mj Shape

Boosted requirement of large jet momentum > 2 x the jet mass results in altered slope

Large Radius Jet pT	> 200 GeV	> 450 GeV



Leptophobic Z'

$$\mathcal{L}_{\text{vector}} = -g_{\text{DM}} Z'_\mu \bar{\chi}\gamma^\mu \chi - g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q}\gamma^\mu q \,,$$

$$\mathcal{L}_{\text{axial-vector}} = -g_{\text{DM}} Z'_\mu \bar{\chi}\gamma^\mu \gamma_5 \chi - g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q}\gamma^\mu \gamma_5 q \,.$$

Trigger Level Analysis

Jet energies are calibrated similarly to offline jets

Jet-area based pileup correction → **Absolute MC-based calibration** → **Global sequential calibration** → **Eta intercalibration** → **Trigger-to-offline data-derived correction** → **Residual *in-situ* calibration**

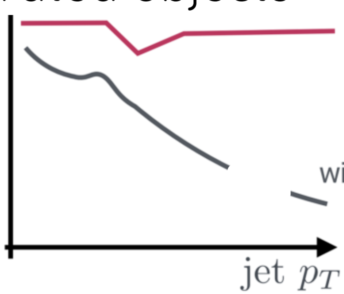
- Jet-area based pileup correction: *Applied as a function of event pileup p_T density and jet area only*
- Absolute MC-based calibration: *Corrects the jet 4-momentum to the particle-level energy scale. Both the energy and direction are calibrated*
- Global sequential calibration: *Reduces flavor dependence and energy leakage using calorimeter variables only*
  - Jet Energy resolution improved by 8% (jet p_T 85 GeV) to 40% (1 TeV)
- Eta intercalibration: *Corrects the scale of forward jets in data to that of central jets, using the p_T balance ratio between data and simulation, applied only to data*
- Trigger-to-offline data-derived correction: *Corrects trigger-level jets to the scale of offline jets, applied only to data*
  - Correction is 1% on average up to 4% at high eta
- Residual *in-situ* calibration: *A smooth residual calibration is derived by fitting in-situ measurements and applied only to data*

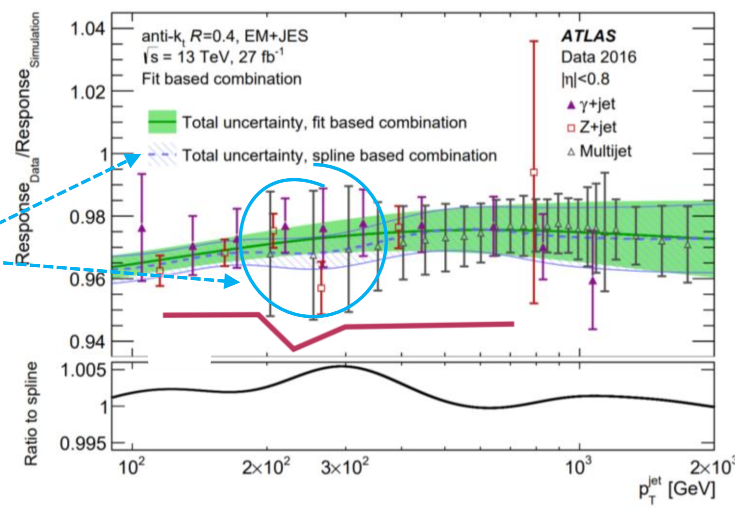
——— *Derived for offline jets*

······ *Derived specifically for trigger jets*

Calibrate using momentum balance of offline jets against well calibrated objects

- Needs to be smooth as can introduce bumps
- Use polynomial fit in $\log(p_T)$ rather than spline





After calibration energy of trigger and offline jets agree within 0.05%

Jet energy scale uncertainty is 1-2%, similar to that of offline jets