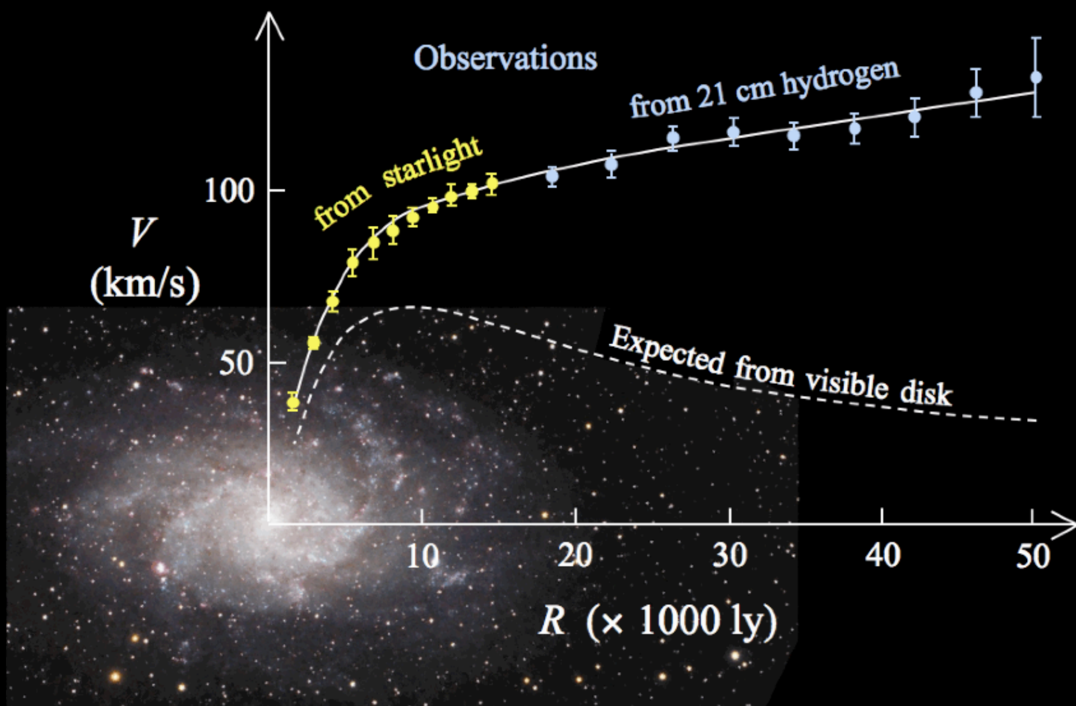
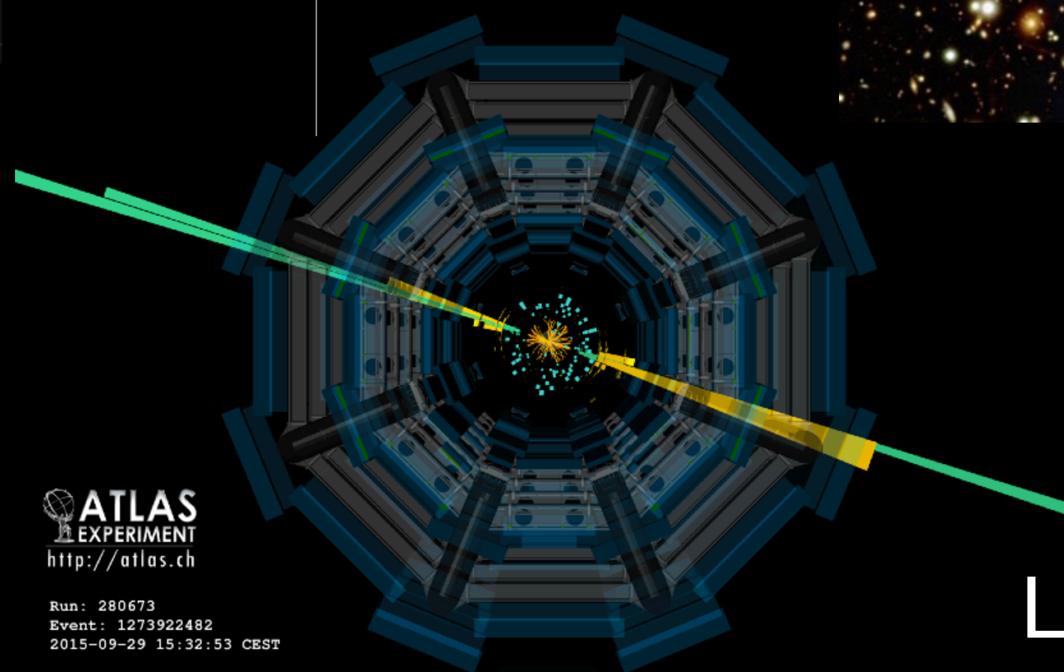
Dark Matter searches with the ATLAS Detector



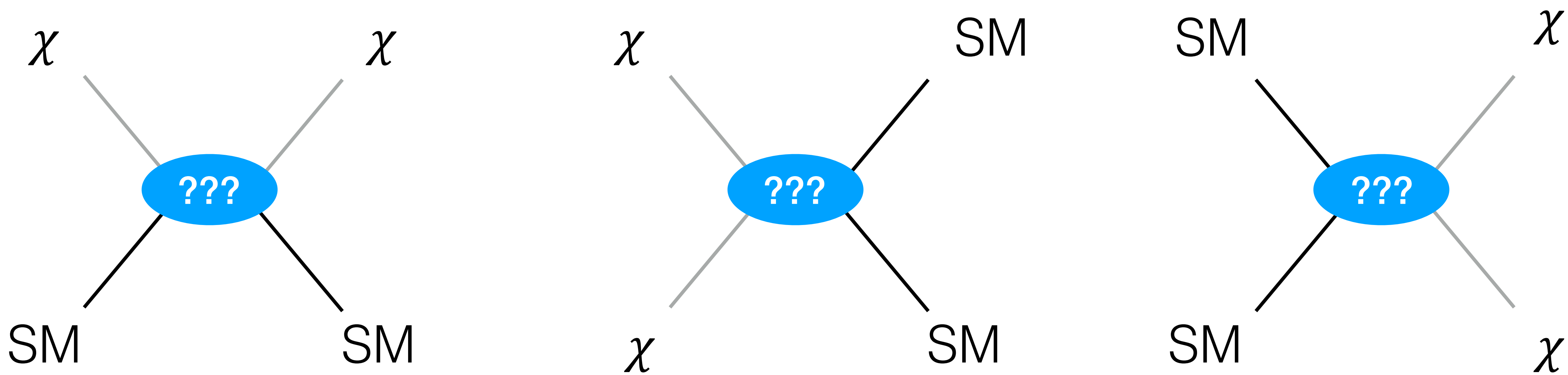


DIS Kobe
18.04.18

Will Kalderon,
Lund University (SE)

on behalf of the ATLAS Collaboration

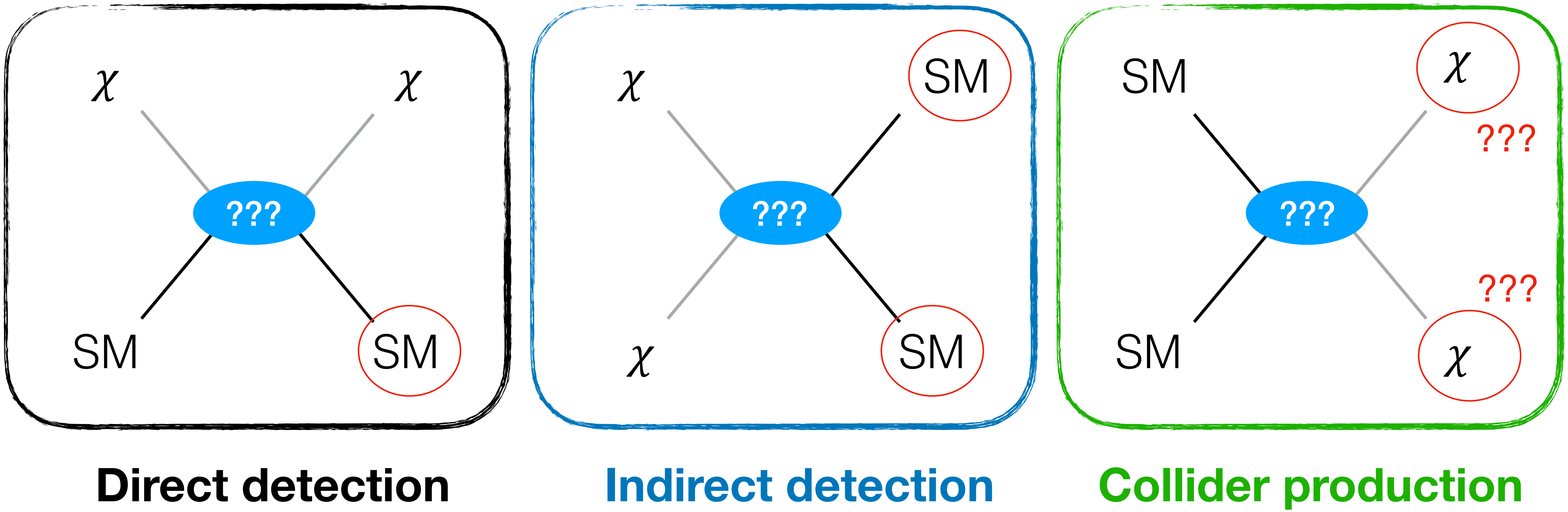
DM signatures



=

Gravitational ✓
Electromagnetic ✗
Strong ✗
Weak-strength **?**

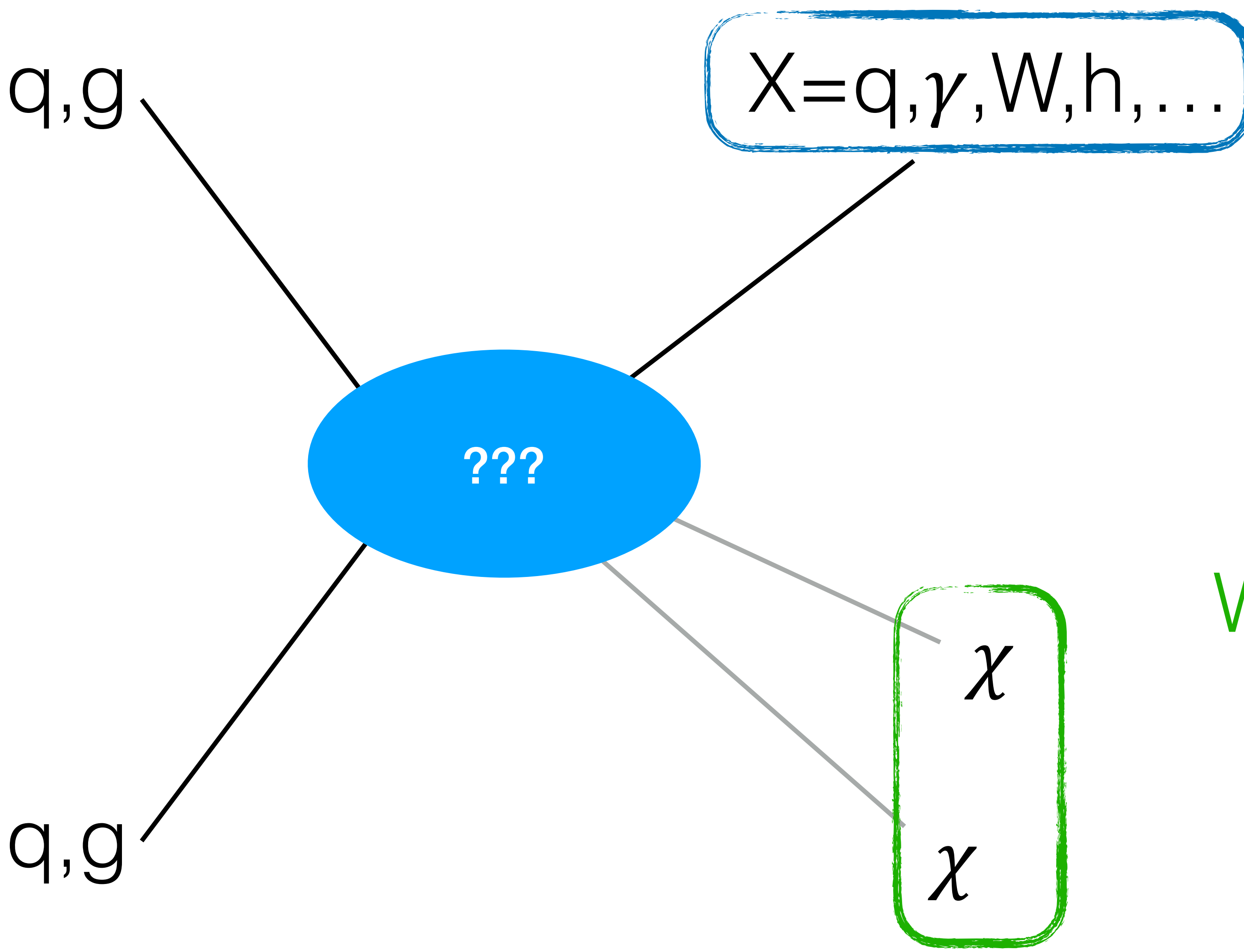
How to search for them



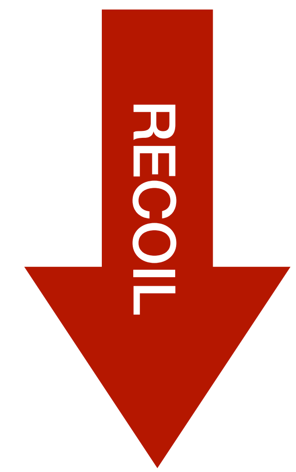
Collider: how do we search for nothing?

Option 1: require something to happen!

In a hadron collider, "SM" initial state = quarks and gluons

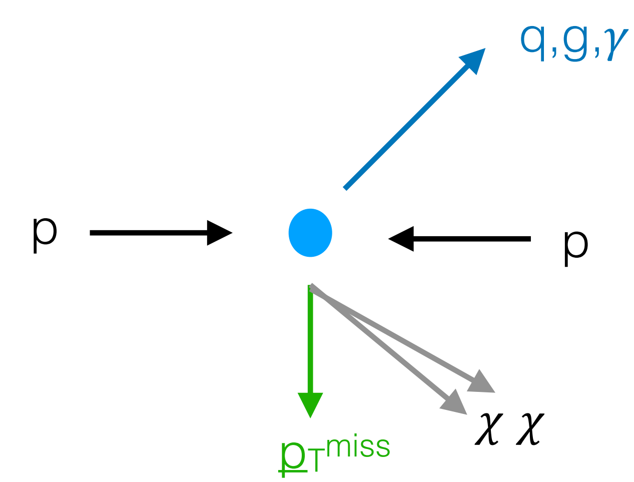


We can see this

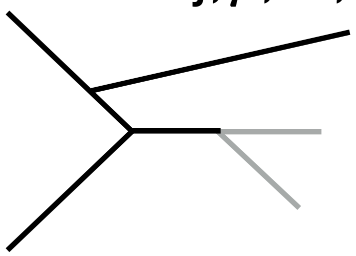


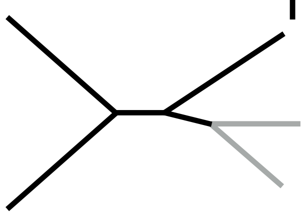
Which also allows us to notice this as p_T^{miss}

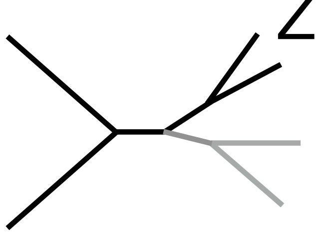
"Mono-X searches"



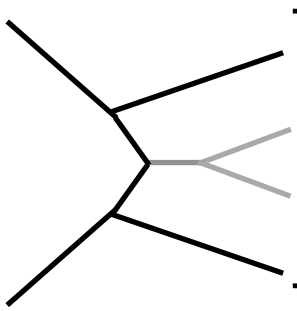
ATLAS mono-X / associated production







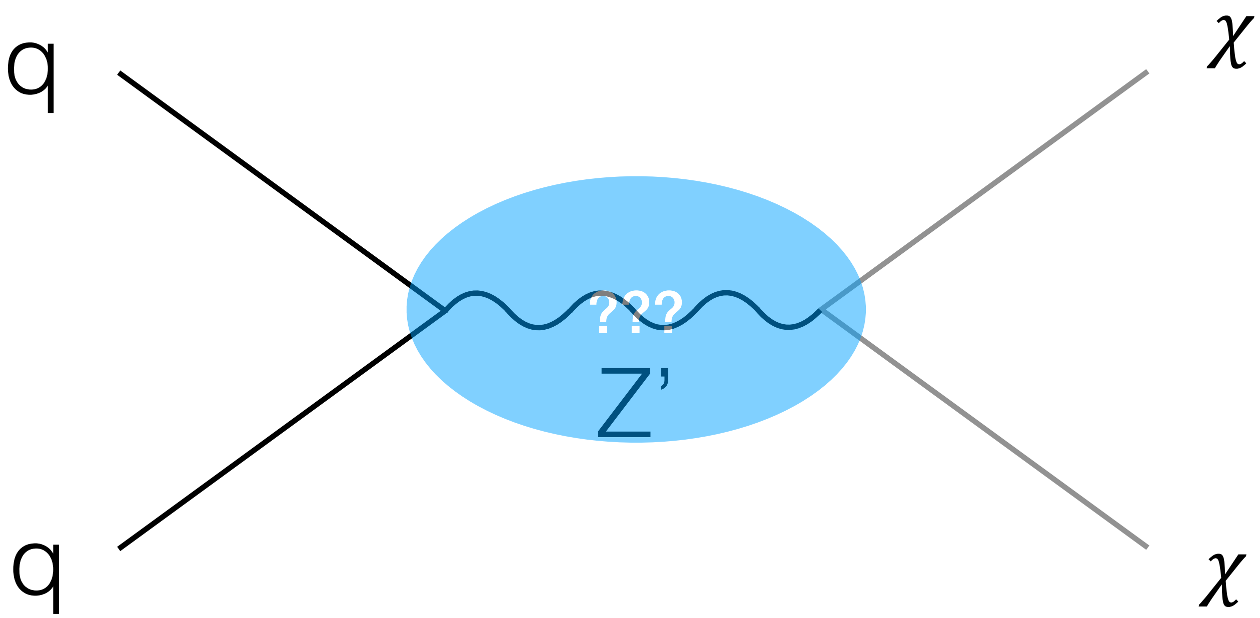
mono-X	Dataset	Reference
jet	36.1 fb^{-1}	JHEP 01 (2018) 126
γ	36.1 fb^{-1}	Eur. Phys. J. C 77 (2017) 393
Z ($\rightarrow \ell\ell$)	36.1 fb^{-1}	PLB 776 (2017) 318
W/Z ($\rightarrow$ qq)	3.2 fb^{-1}	PLB 763 (2016) 251
h ($\rightarrow$ bb)	36.1 fb^{-1}	PRL 119 (2017) 181804
h ($\rightarrow \gamma\gamma$)	36.1 fb^{-1}	PRD 96, 112004 (2017)
Z' ($\rightarrow$ qq)	36.1 fb^{-1}	ATLAS-CONF-2018-005



scalar mediator, 3rd-gen couplings

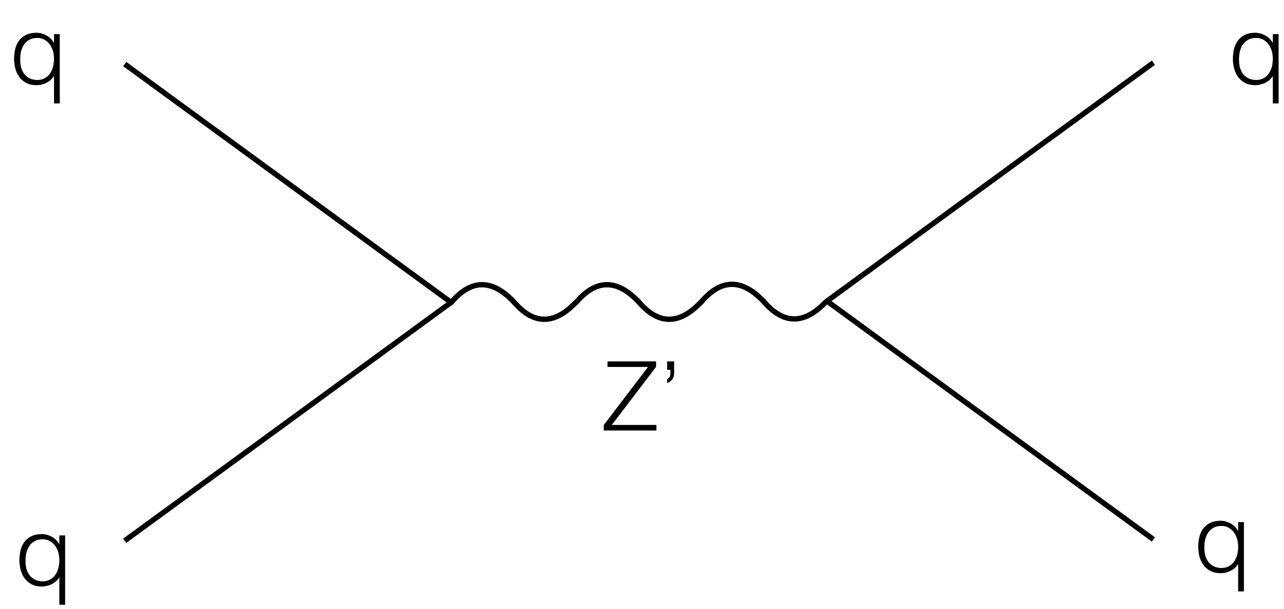
Associated production	Dataset	Reference
tt/bb/b+MET	36.1 fb^{-1}	Eur. Phys. J. C 77 (2017) 393

Option 2: dark matter? What dark matter?



If there is a mediator that couples to quarks and DM…

… then we can forget about the DM and look for the mediator



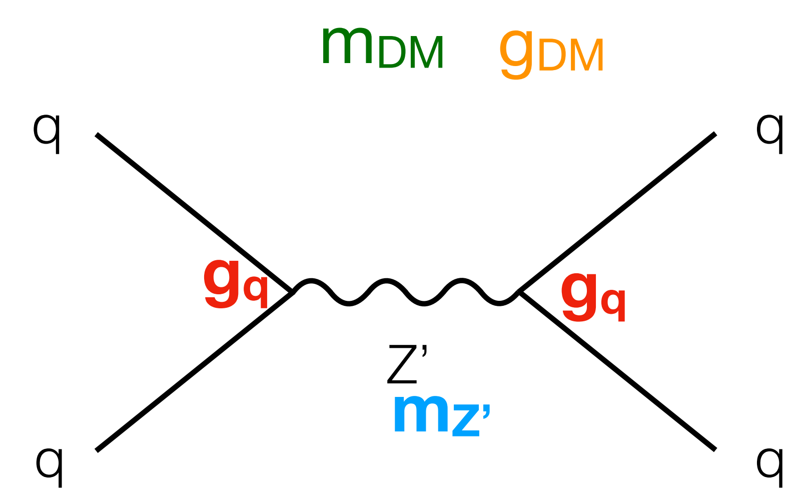
“Dijet* resonance searches”

*One can also imagine the Z’ coupling to leptons -> dilepton resonances, lower BR to dijet

Dijet limits on Z’, at end of run 1

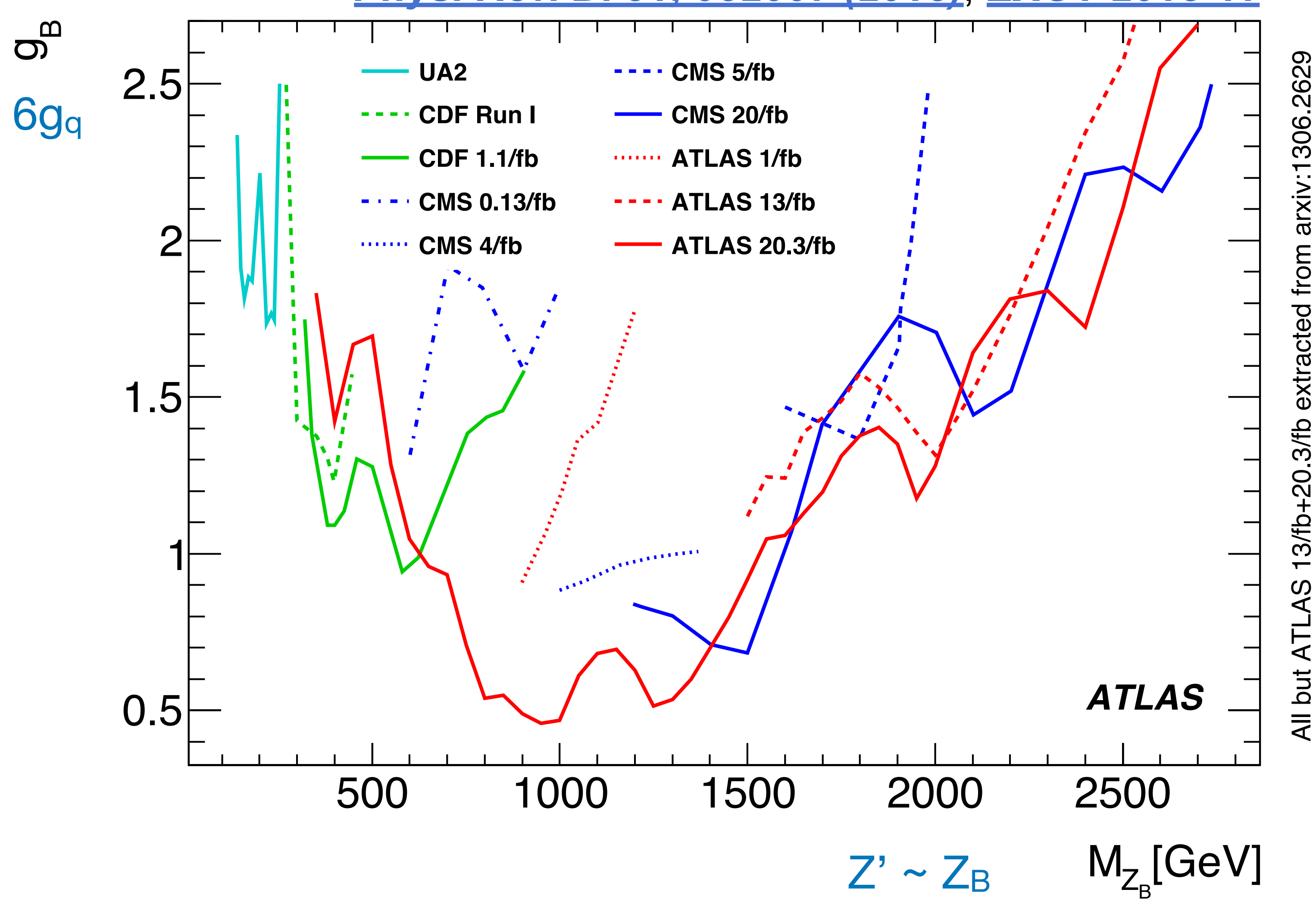
Model has **four parameters**:

1. Mediator coupling to quarks **g_q** (usually assumed universal, but dijets ignore Z’ -> tt)
2. Mediator mass **$m_{Z'}$**
3. Dark Matter mass m_{DM} - set well above 0.5 $m_{Z'}$ (eg 10 TeV) -> kinematically inaccessible
4. Mediator coupling to Dark Matter, g_{DM} - not very relevant given 3, often set to 1



Phys. Rev. D. 91, 052007 (2015), *EXOT-2013-11*

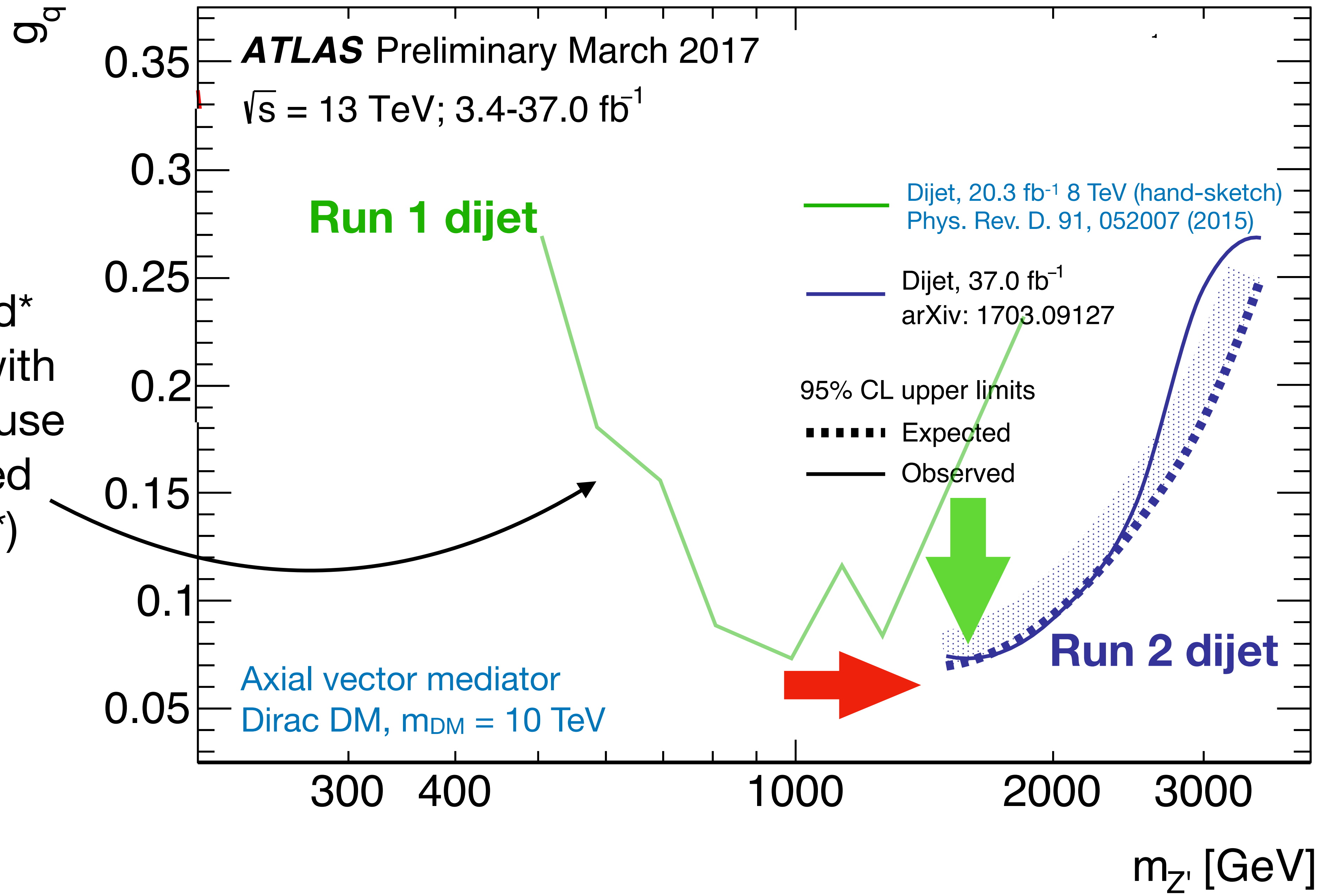
$g_B = 6g_q$



Z’ ~ Z_B

Dijet limits, run 1 vs run 2

Prescaled* triggers (with extensive use of delayed stream**)



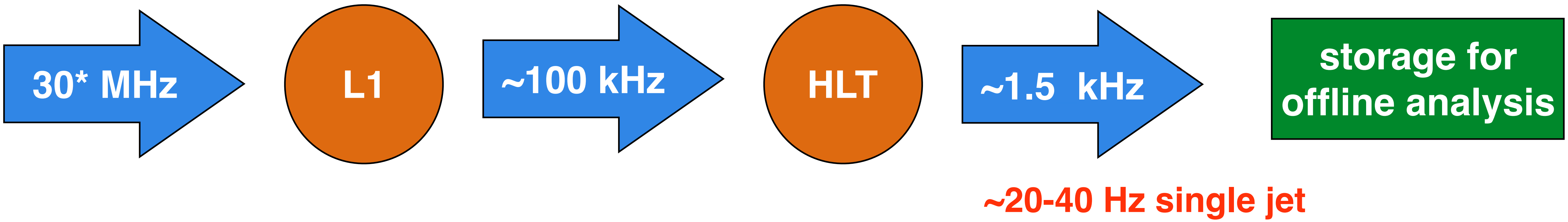
Lower coupling g_q for given mass $m_{Z'}$:
more data ($\sigma \sim g_q^2$ => limit(g_q)~data$^{1/4}$), better mass resolution

Higher bottom mass edge to exclusion: trigger limitations

* Prescaled: only a fraction of events accepted by a trigger are recorded

** Delayed stream: events accepted by some triggers are written to a separate stream that is not reconstructed until computing resources become available over a shutdown

What limits the ATLAS trigger?



Limitations:

detector readout

total: storage & processing cost

single jet: competing demands

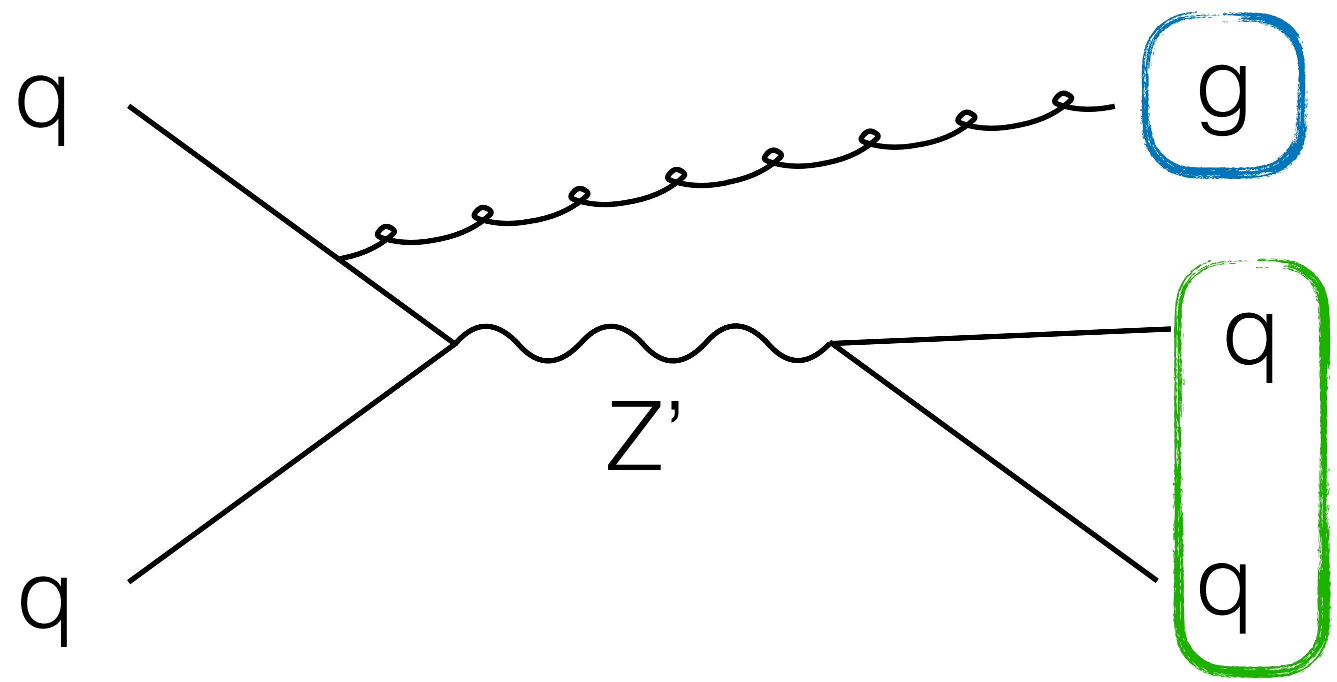
Higher instantaneous luminosity -> higher rate of high-p_T jet production

=> with rising instantaneous luminosity, must raise jet p_T threshold for recording events

- Empirical observation: at high p_T (>100 GeV or so), rate ~ p_T^{-5}
- 2016: record events containing jets with E_T > 380 GeV -> efficient by p_T > 440 GeV in analysis

* 25ns bunch spacing gives 40 MHz, but the ring is not full

Overcoming trigger 1: ISR

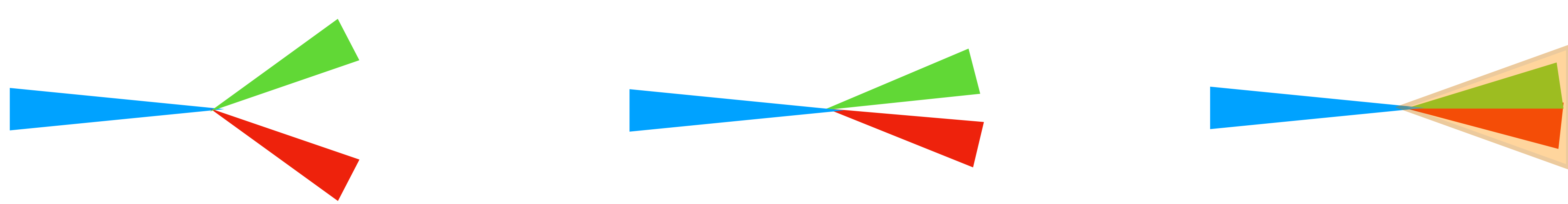


Trigger on ISR j/γ
$E_T(j)>380$, $E_T(\gamma)>140$

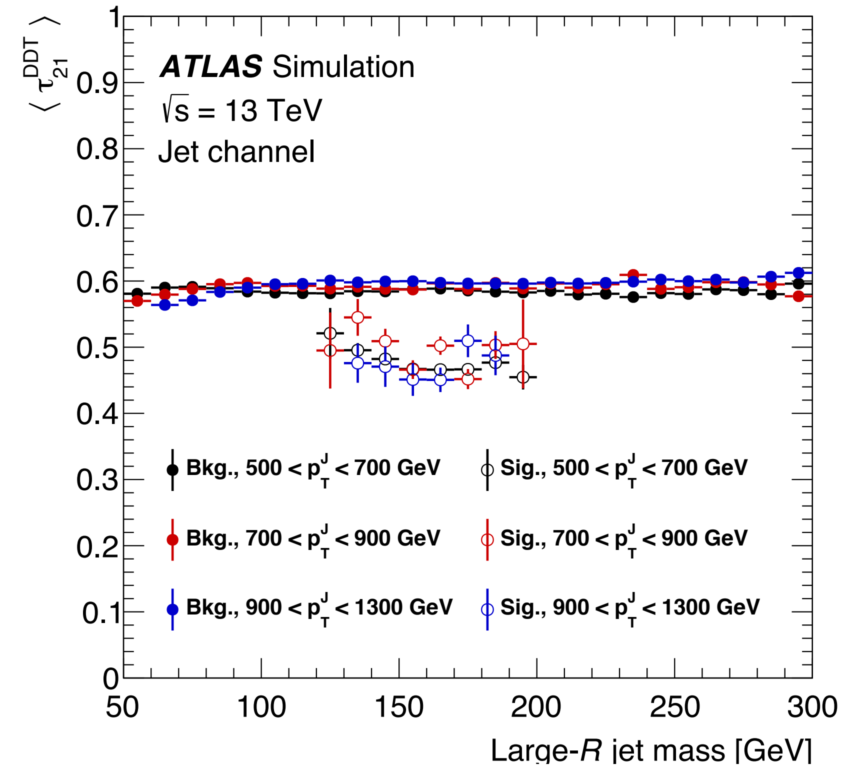
Jets from resonance can be much softer

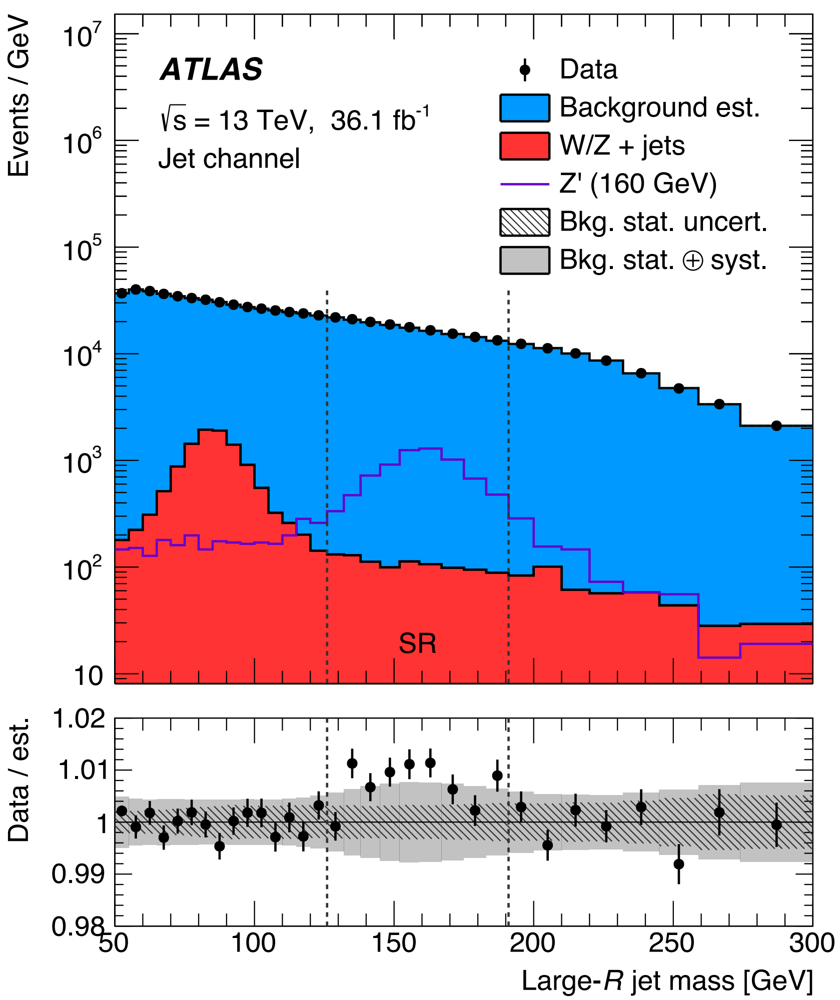
- ATLAS has preliminary results (ATLAS-CONF-2016-070) using photon and jet using initial state radiation to trigger on => resonance can be much lower p_T (lead resonance jet p_T > 25 GeV, vs 440 GeV)

- At Z' masses below ~ 200 GeV, resonance jets merge -> large-R jet



Quick overview: Large-R + ISR

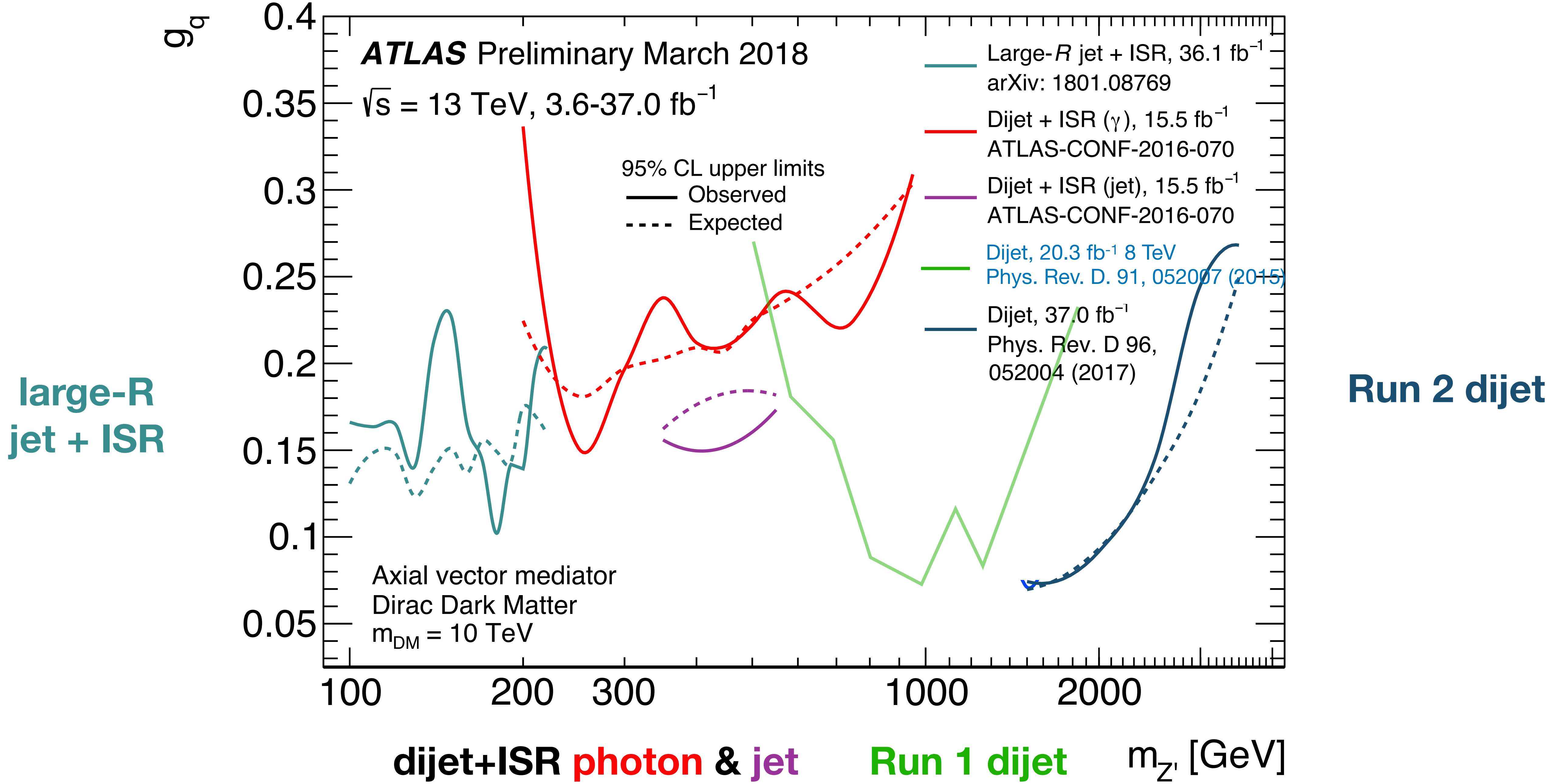




arxiv: 1801.08768, EXOT-2017-01

- Use substructure τ_{21} to distinguish 2-subjet signal from single-subjet QCD background
  - Use "designed decorrelated tagger" method to decorrelate from jet mass
- Main background QCD
  - Data-driven method for background estimation based on inverted τ_{21}^{DDT}
  - Method validated on W/Z peak
  - Separate signal region for each mass point

Dijet (merged & resolved) + ISR limits

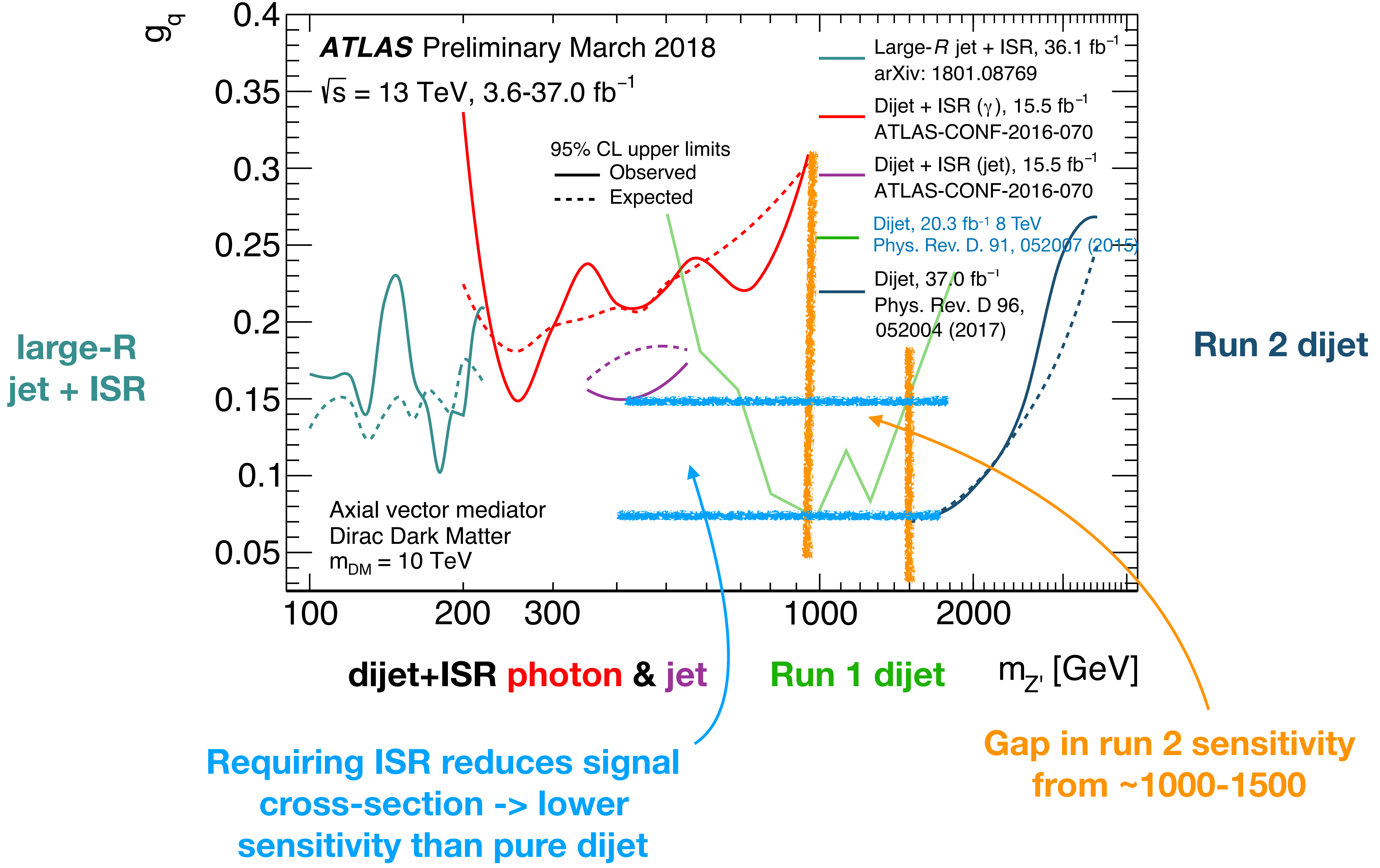


ISR -> sensitivity down to 200 GeV

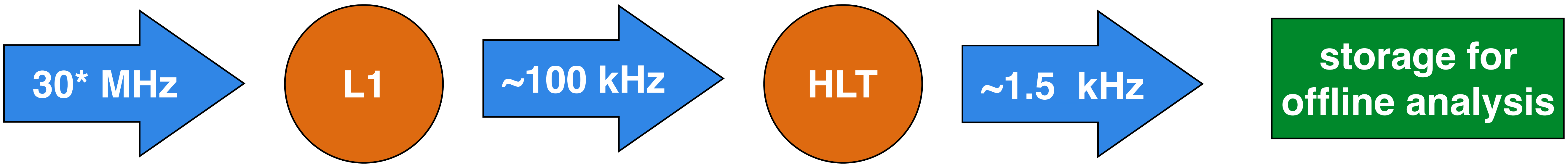
200 GeV = crossover between merged and resolved

Large-R jet -> takes this down to 100 GeV

Dijet (merged & resolved) + ISR limits



2: Revisit trigger limitations



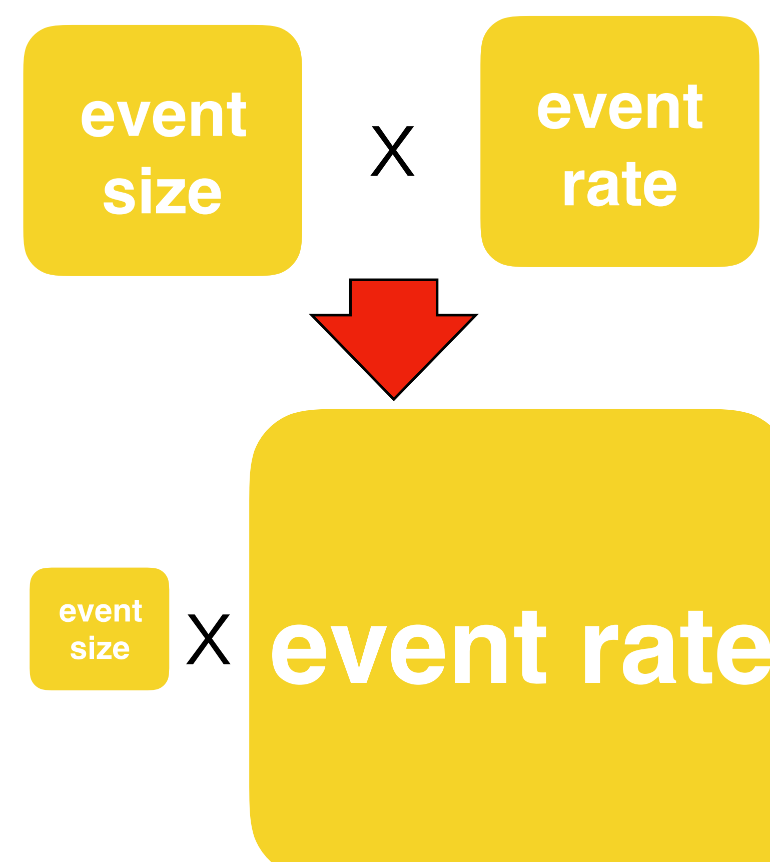
~20-40 Hz single jet

Limitations:

- **detector readout**
- **total: storage & processing cost**
- **single jet: competing demands**

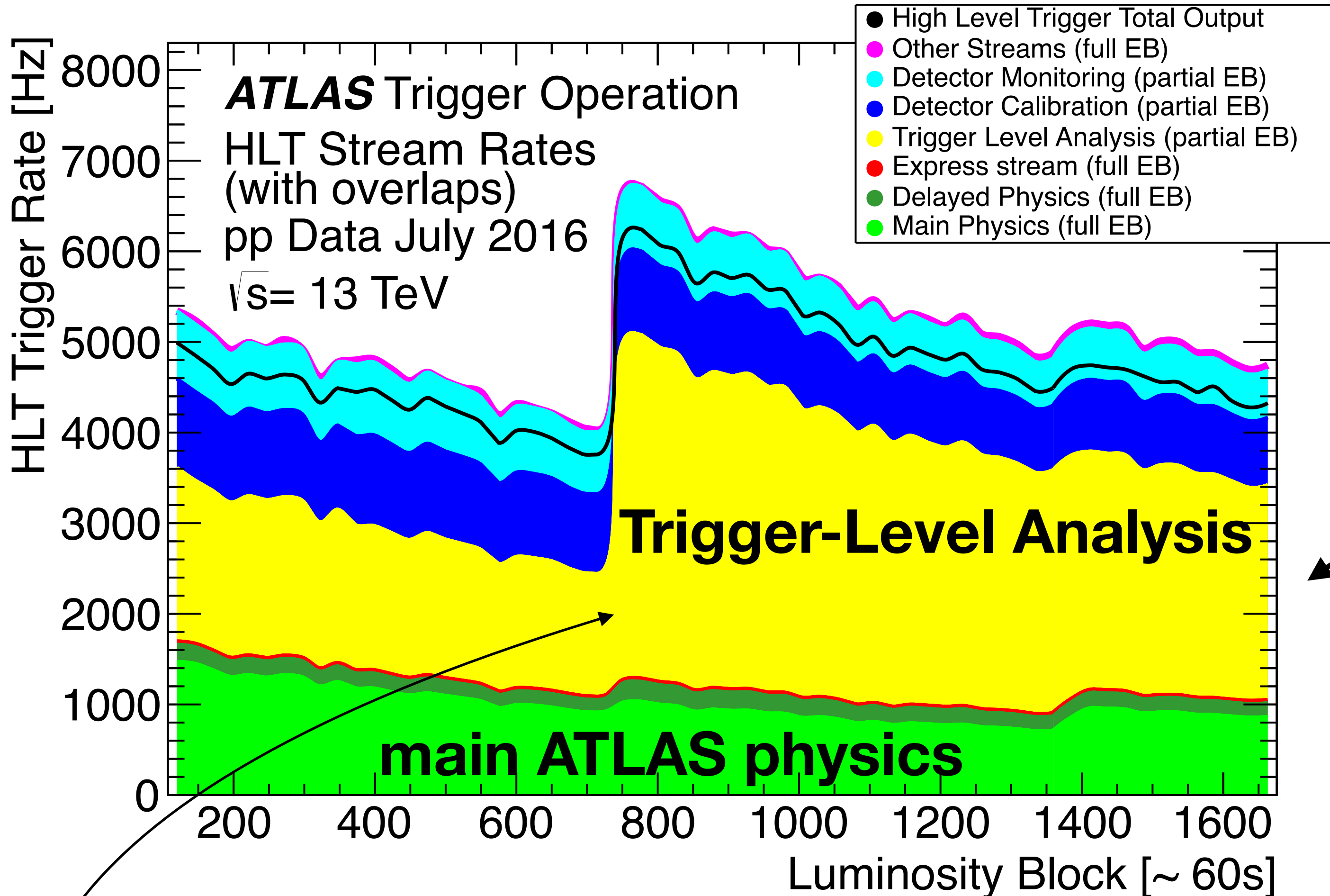
Storage and processing drives 1.5 kHz limit for ATLAS

- dijet resonance search only uses jets - no leptons, no p_T^{miss}, etc.
- we already build and calibrate jets in the trigger… just save these
- **record minimal events at high rate**



* 25ns bunch spacing gives 40 MHz, but the ring is not full

Evade trigger bandwidth limits

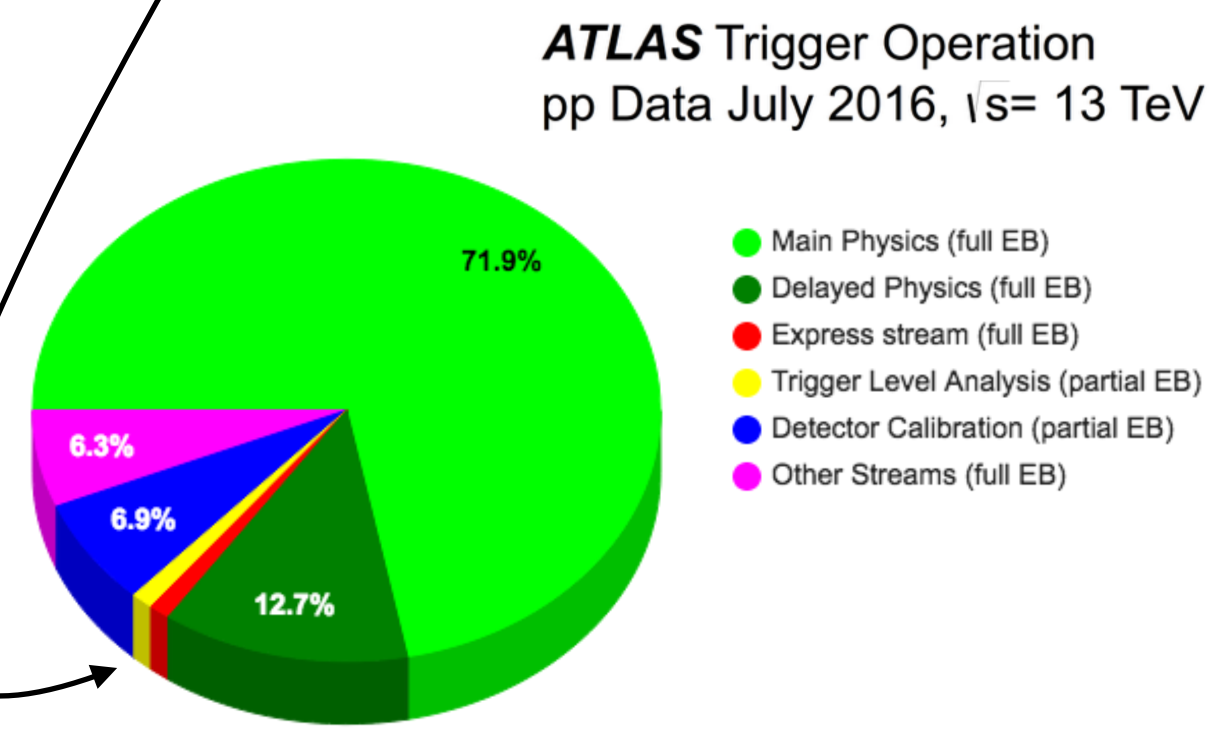


LHCb: "Turbo stream" [1]
CMS: "Data Scouting" [2]
ATLAS: "Trigger Level Analysis"
(arXiv: 1804.03496, April 11th!)

Huge TLA rate but tiny bandwidth since ~0.5% of full event size

Instead of 20-40 Hz for a dijet resonance search, we now have 1-3 kHz!

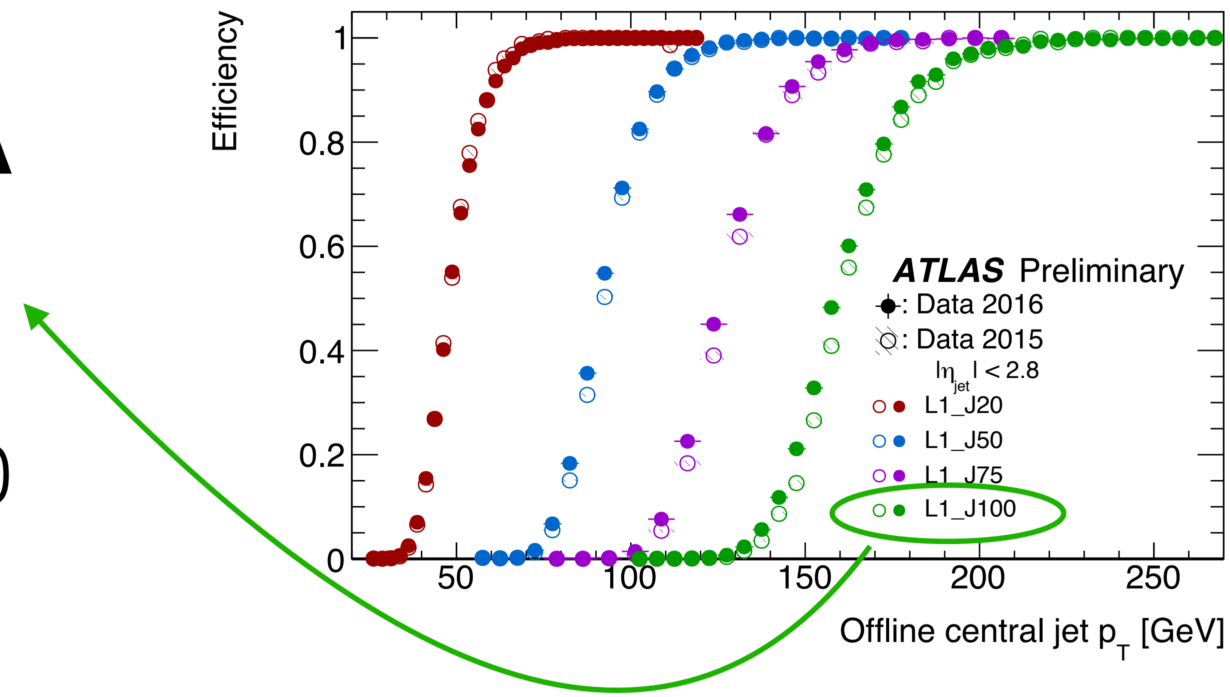
jump: sometimes recorded more TLA data once the luminosity had fallen



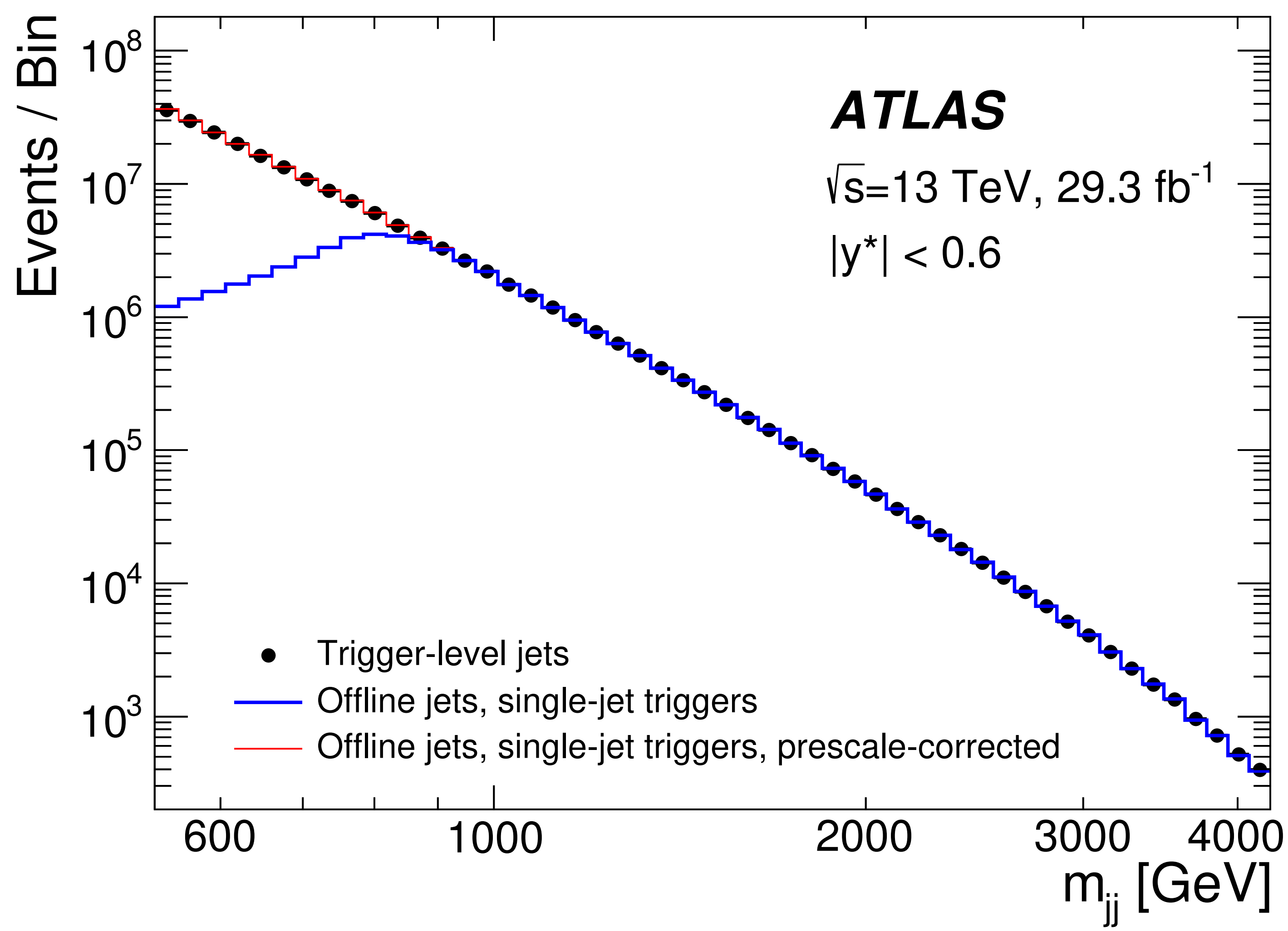
[1] LHCb Collaboration, *Tesla : an application for real-time data analysis in High Energy Physics*, Comput. Phys. Commun. **208** (2016) 35, arXiv: 1604.05596 [physics.ins-det].
[2] CMS Collaboration, *Search for dijet resonances in proton–proton collisions at $\sqrt{s}$ = 13 TeV and constraints on dark matter and other models*, Phys. Lett. B **769** (2017) 520, arXiv: 1611.03568 [hep-ex].

The payoff

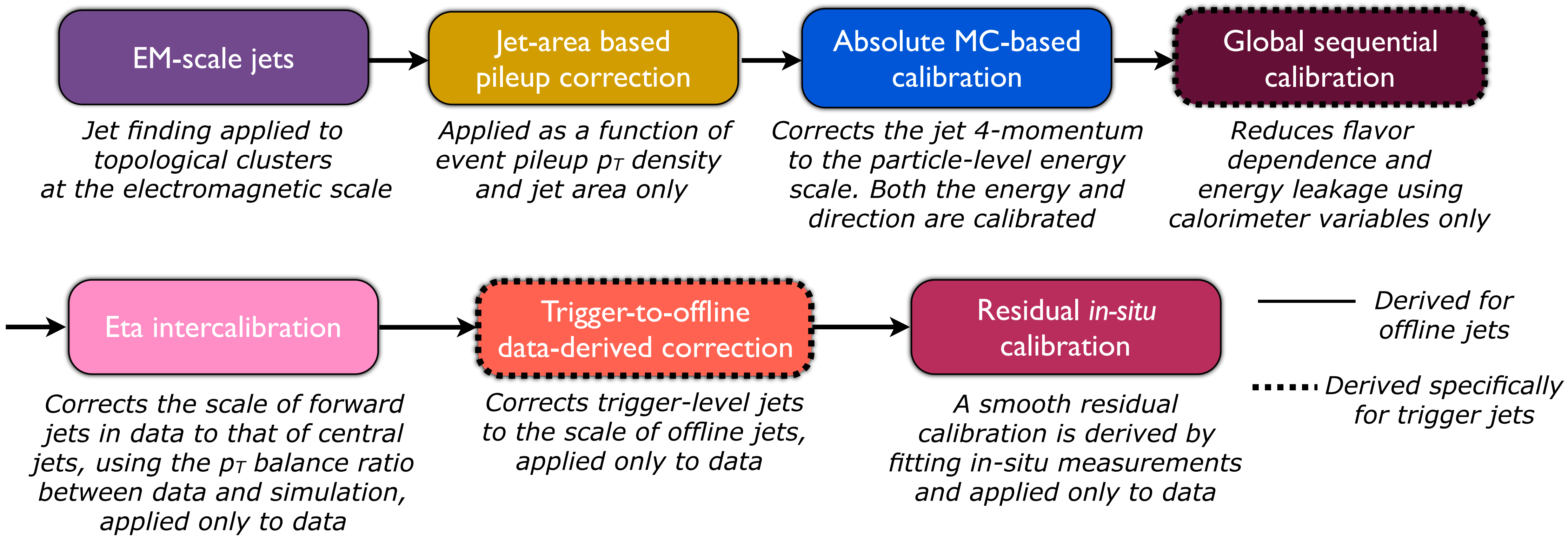
	"'standard" dijet	TLA
lead jet p_T >	440	220
sublead jet p_T >	60	85
m_{jj} >	1100	520

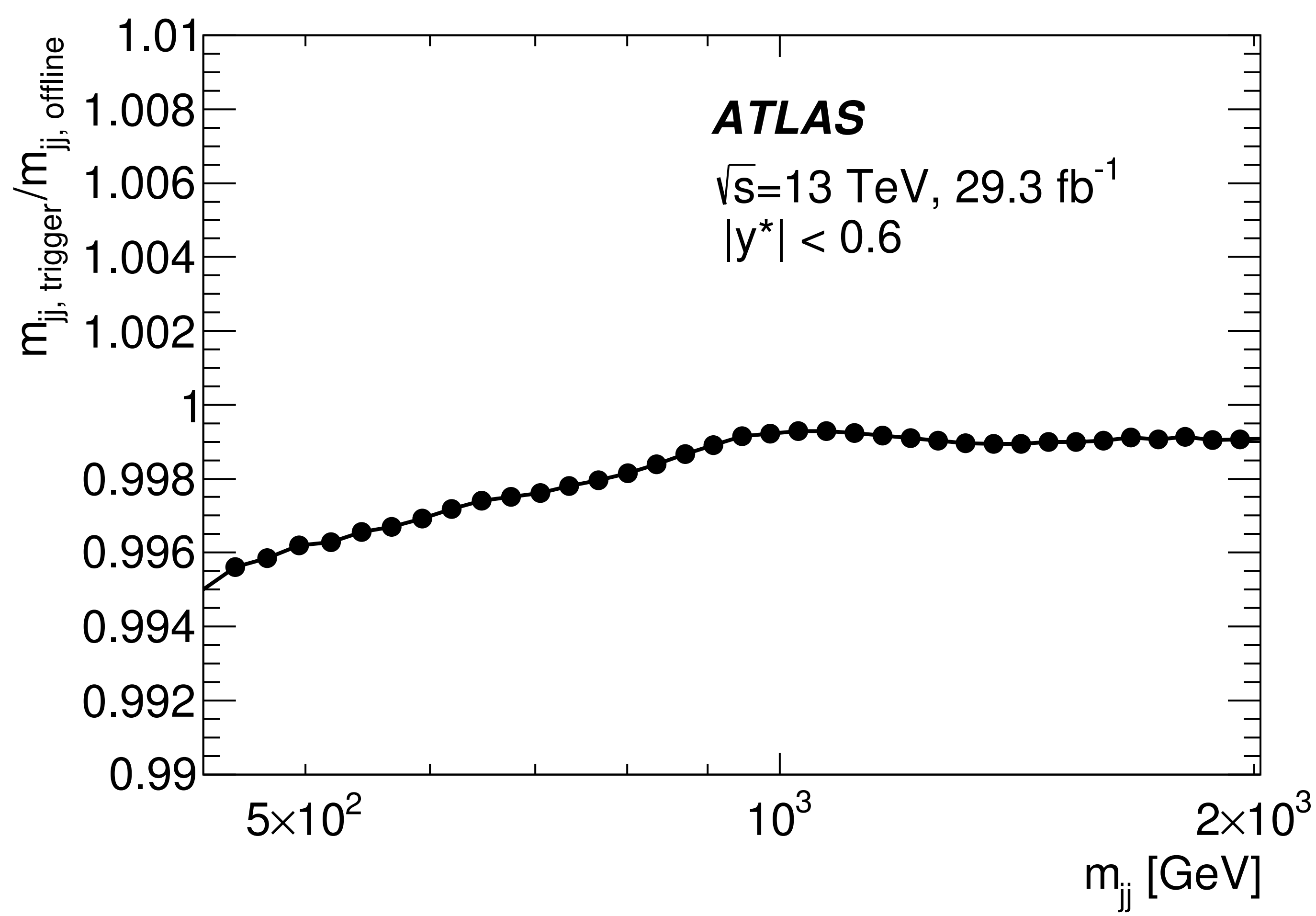


4x10⁷ events in first bin in 29.3 fb⁻¹ of 2016 data



TLA calibration





- Write out sufficient information to be able to redo calibration offline
- Some parts rederived since TLA data lacks eg track information
- End result: excellent agreement between offline and recalibrate trigger m_{jj}

Background estimation

- Fit to functional form
  - Choose one with best χ^2
- Very large number of events -> very little scope for QCD to deviate from functional form
- In 2015, could not fit whole m_{jj} range, hence truncated fit at 1250 GeV
- Solution, also used by high-mass dijet 37 fb^{-1} result: fit sub-ranges

Functional form
$f(x) = p_1(1-x)^{p_2}x^{p_3}$
$f(x) = p_1(1-x)^{p_2}x^{p_3+p_4 \ln x}$
$f(x) = p_1(1-x)^{p_2}x^{p_3+p_4 \ln x * p_5 \ln x^2}$
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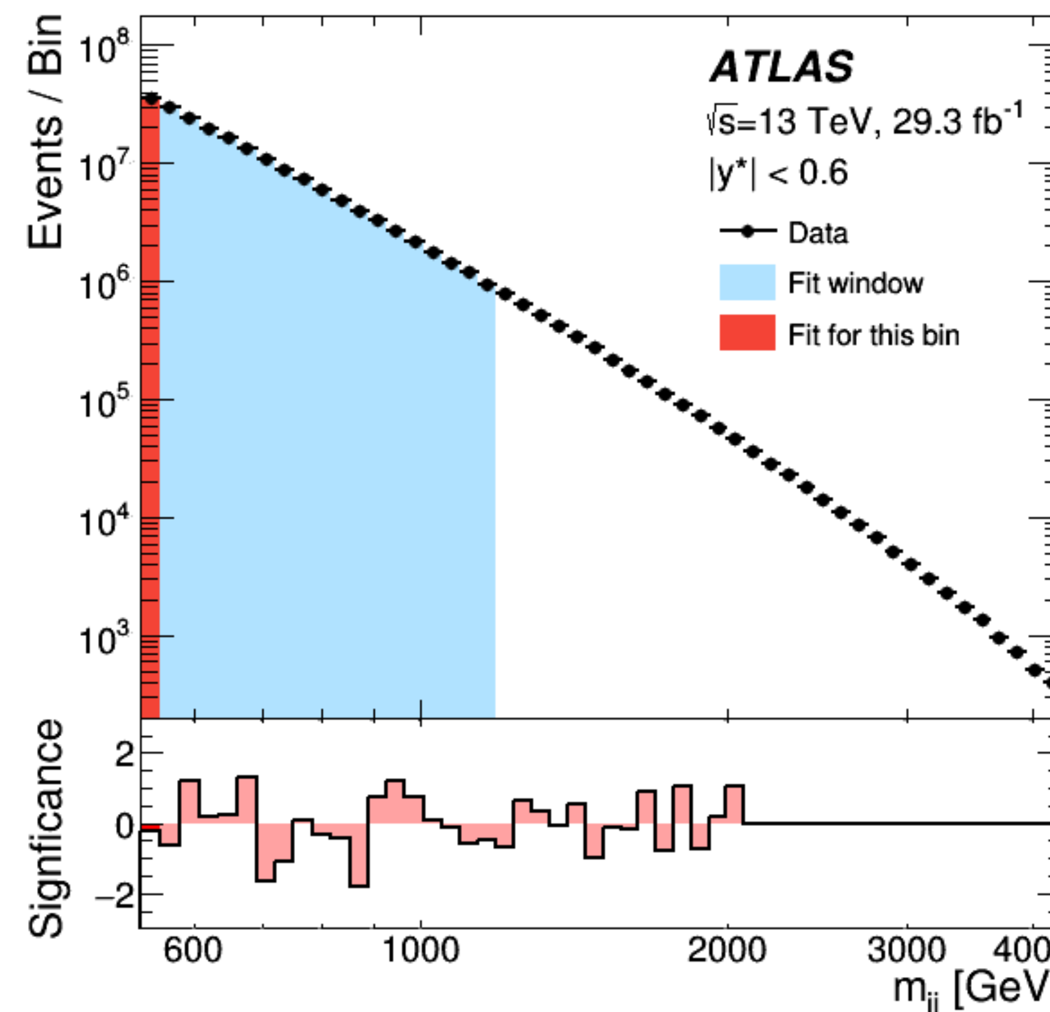

animation **here**

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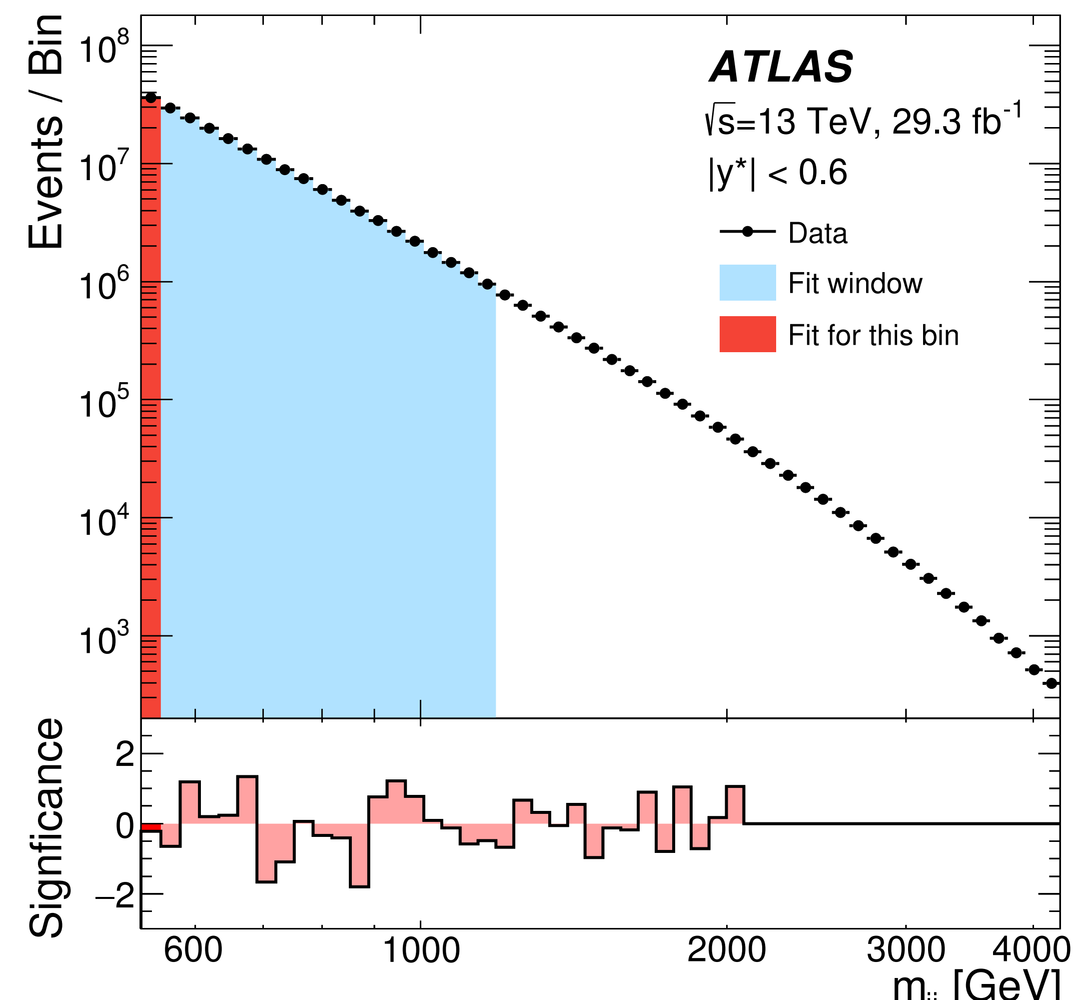

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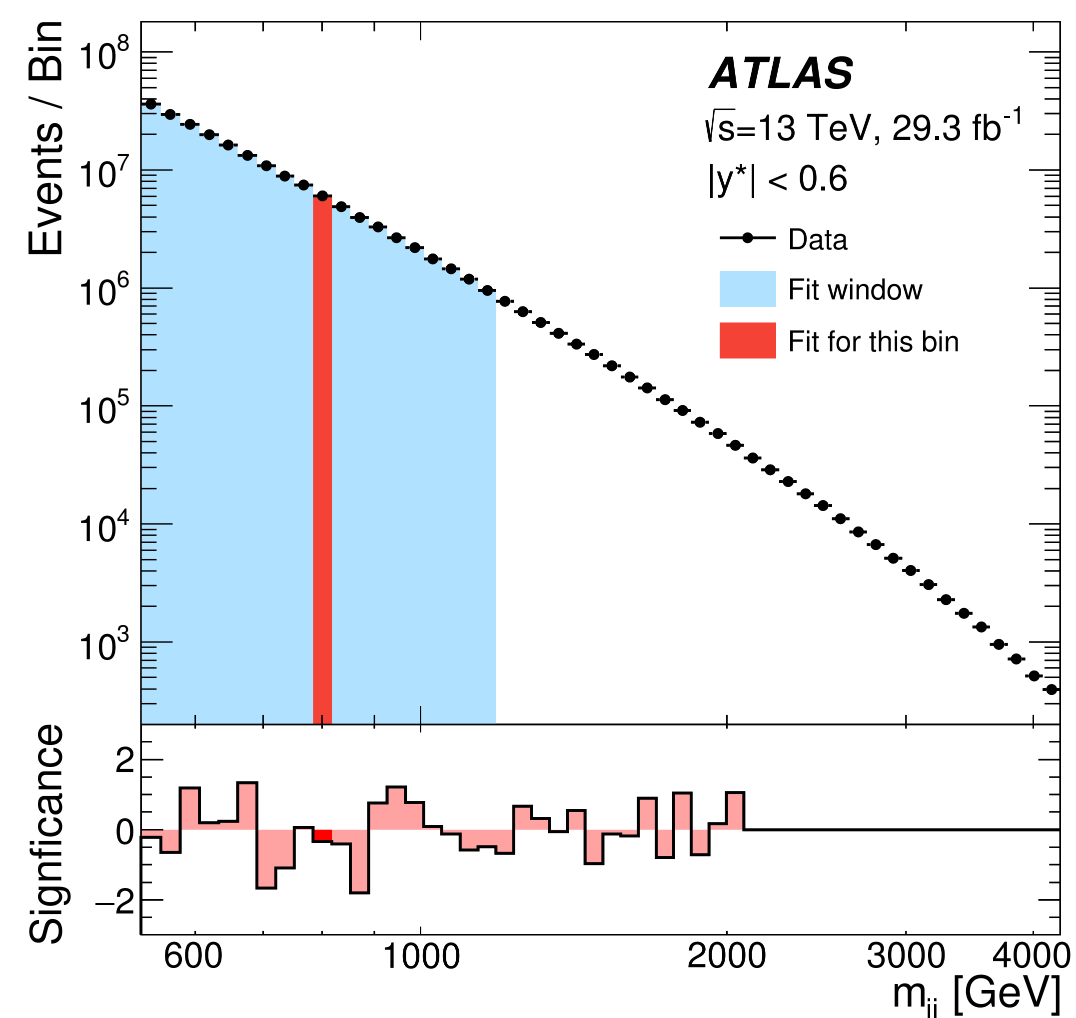

animation here

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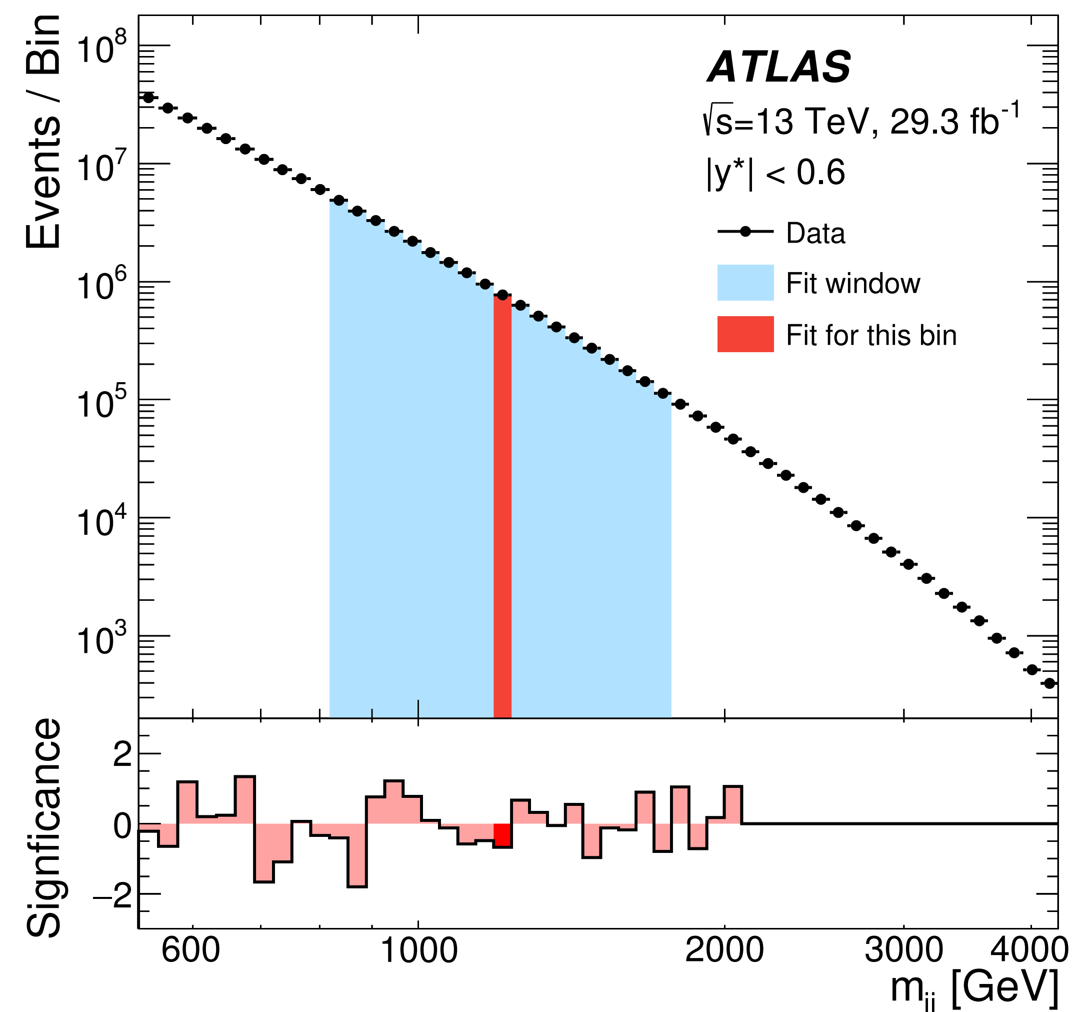

animation **here**

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  - |y*|<0.3: 27 bins, |y*|<0.6: 19

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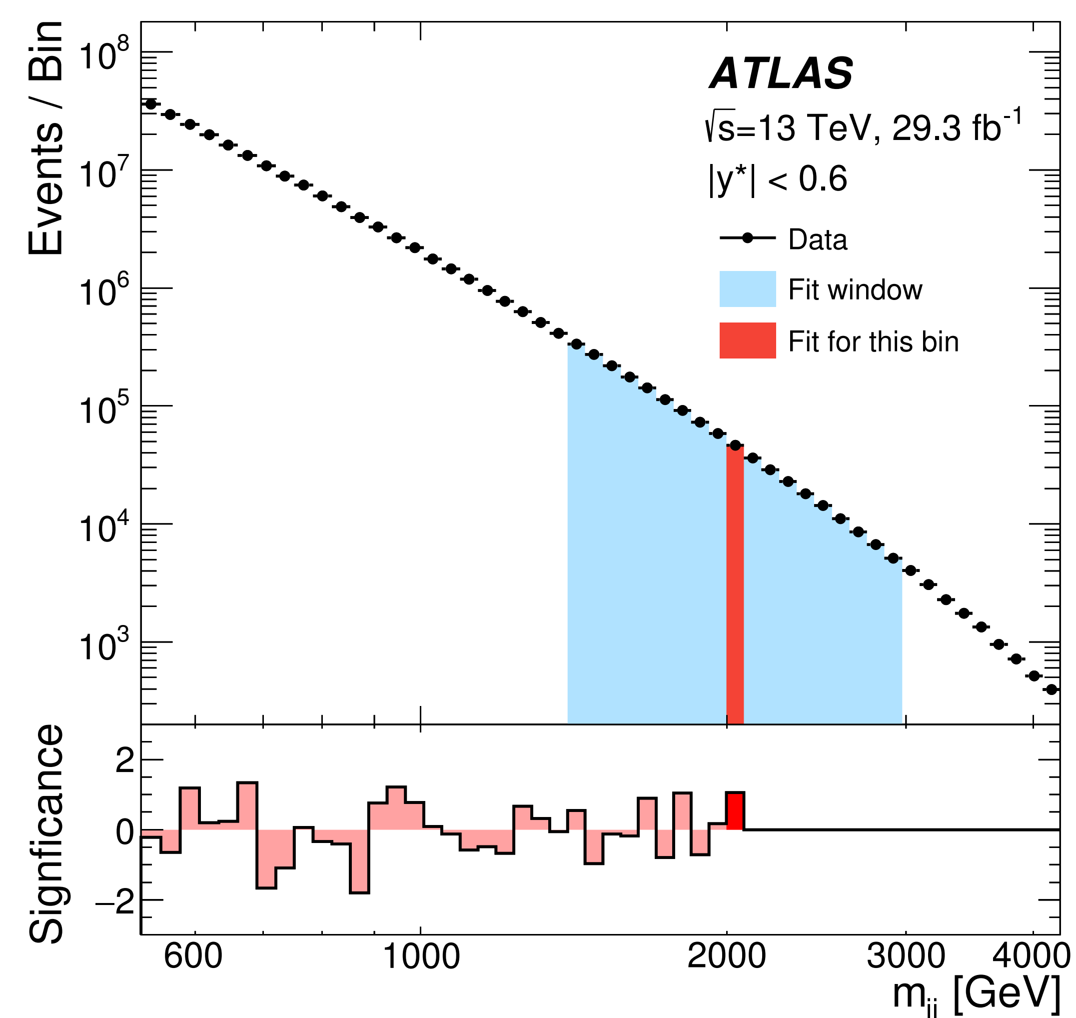
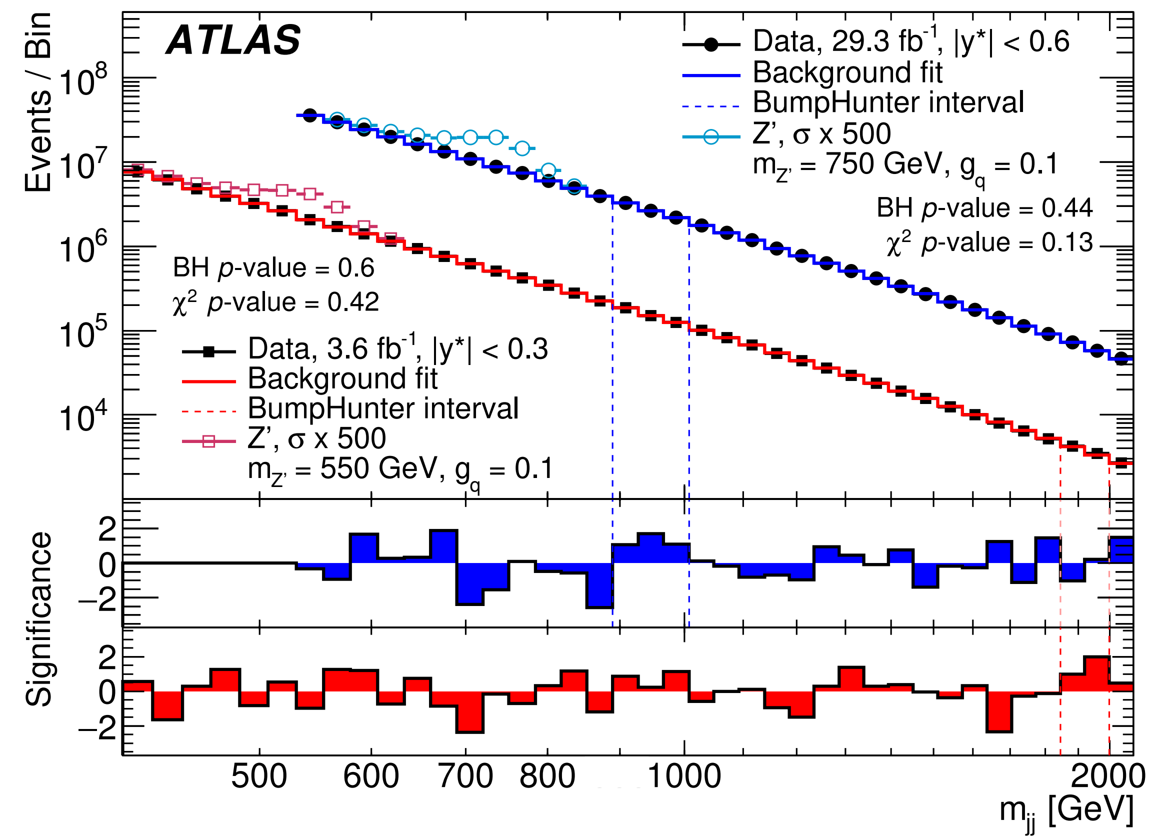
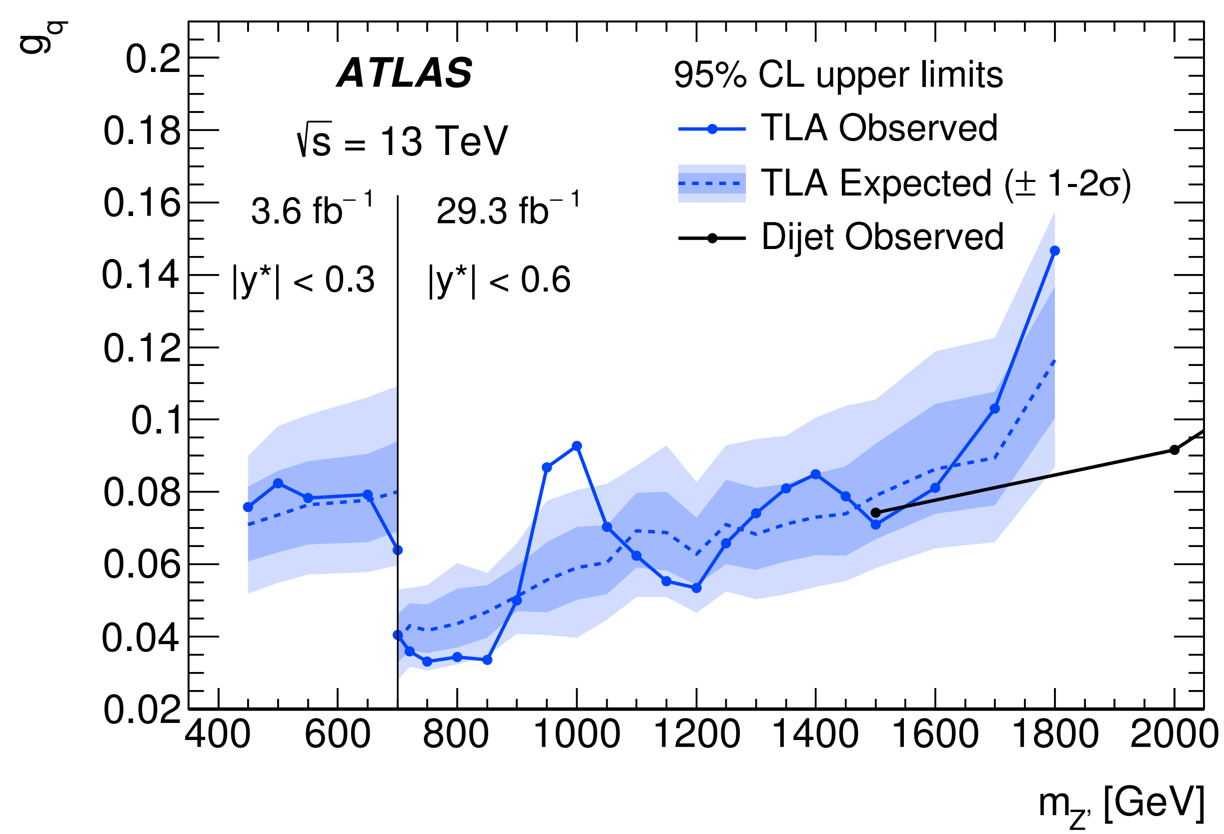


animation <u>here</u>

Results

- "BumpHunter" with background-only fit: no significant excesses found
- Signal + Background fit: set limits (areas of flexibility give observed - expected differences)
- Similar sensitivity to conventional dijet resonance search at 1.5 TeV
- Can go much lower in $m_{Z'}$
  - 450-700 GeV using dedicated signal region with L1_J75 for some of 2016

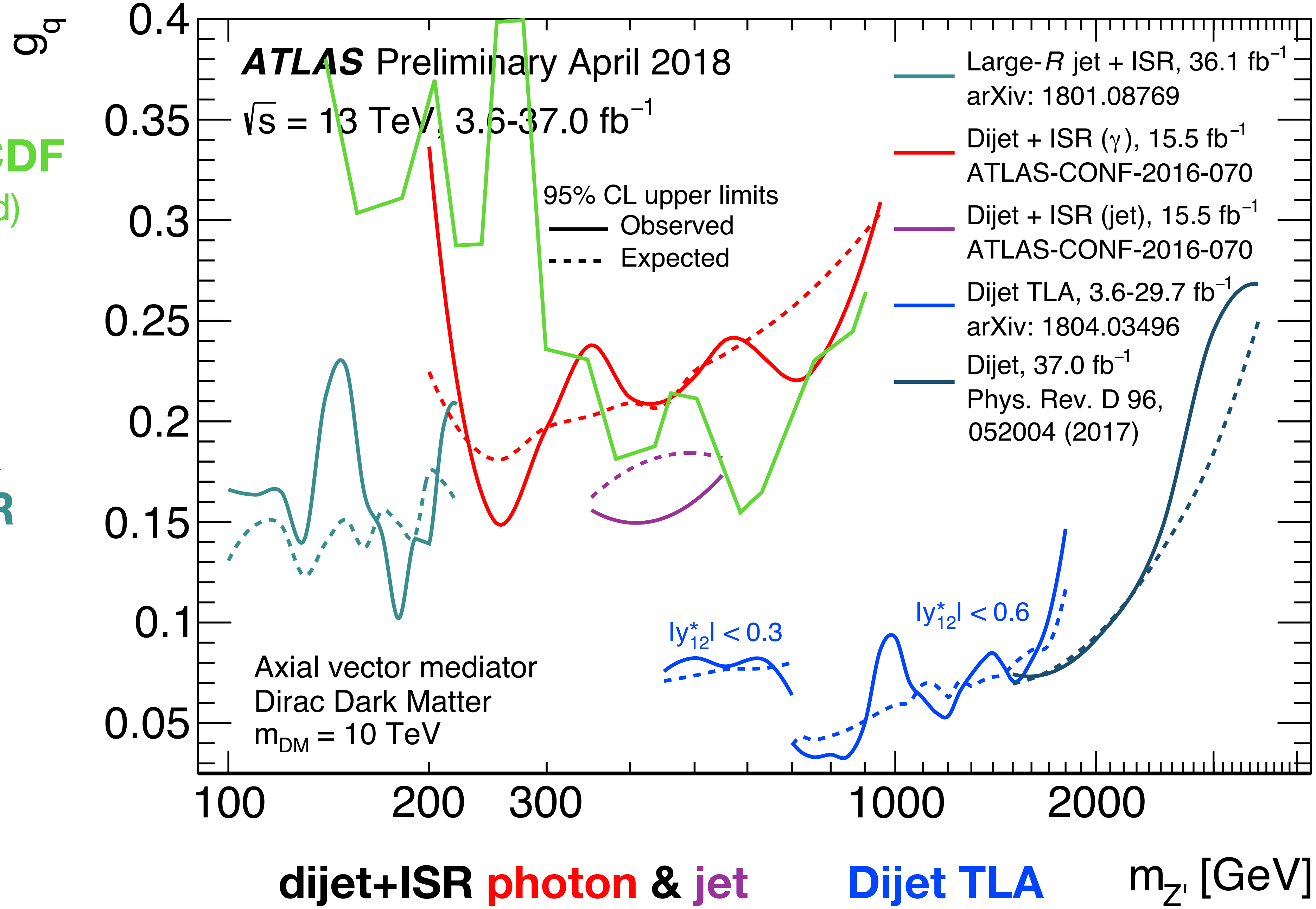




Limits, March 2018

UA2 & CDF
(overlaid)

large-R
jet + ISR



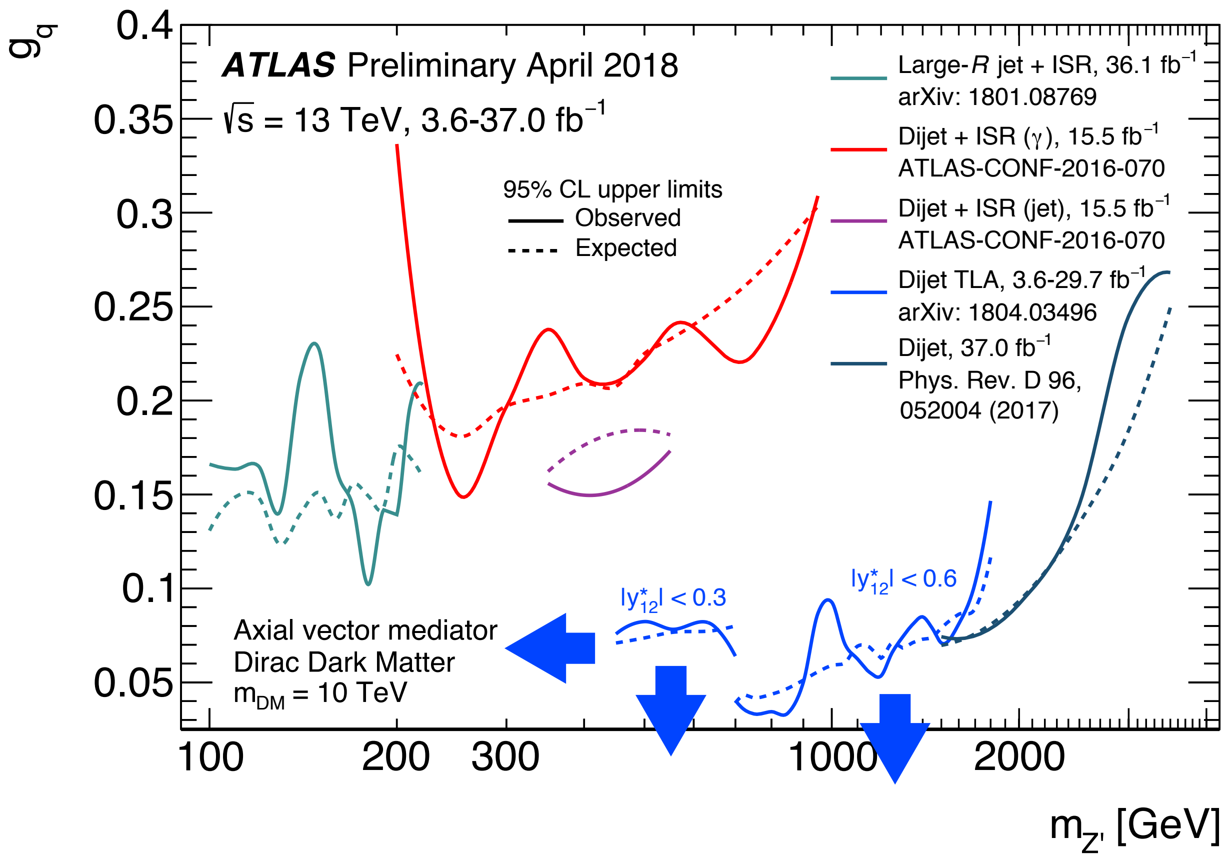
Run 2 dijet

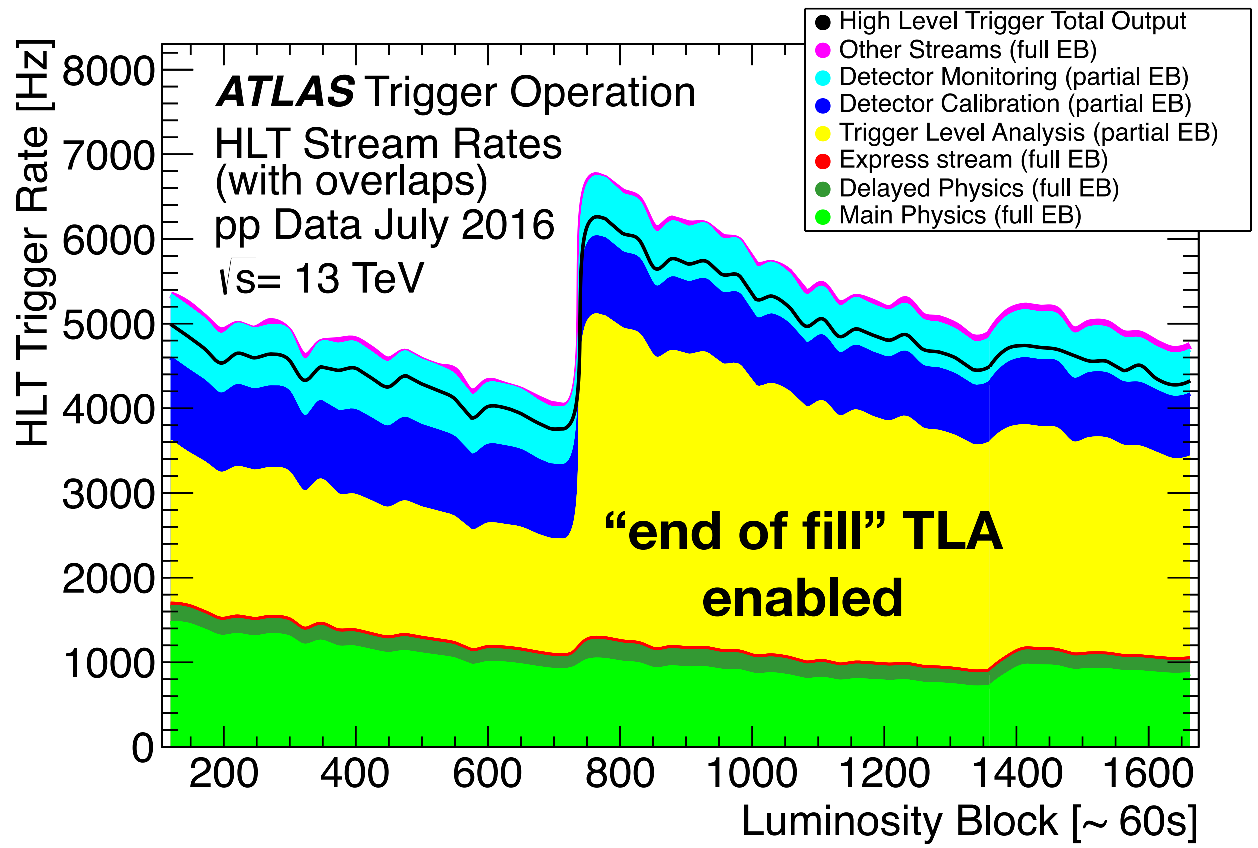
dijet+ISR photon & jet **Dijet TLA**

Trigger-level analysis greatly improves sensitivity

New results mean that we surpass pre-LHC constraints everywhere

Prospects, TLA

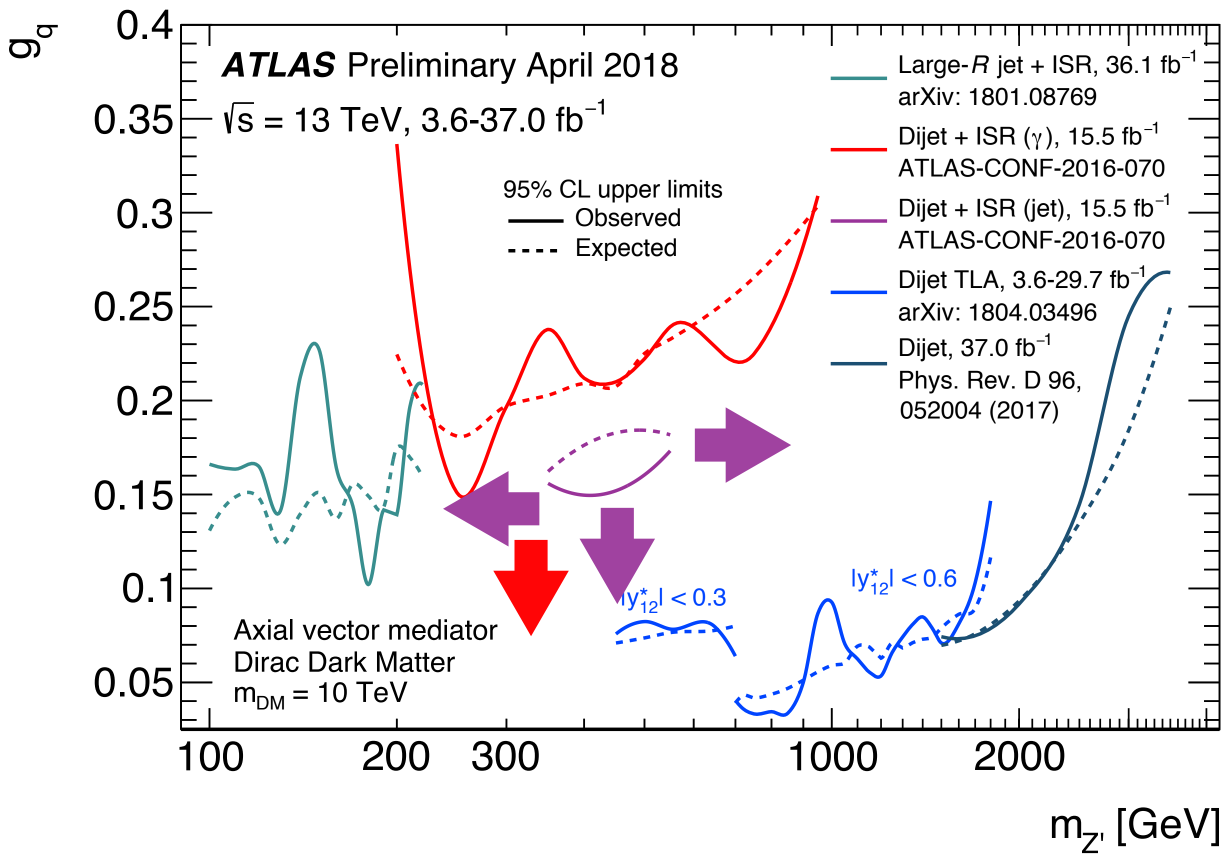


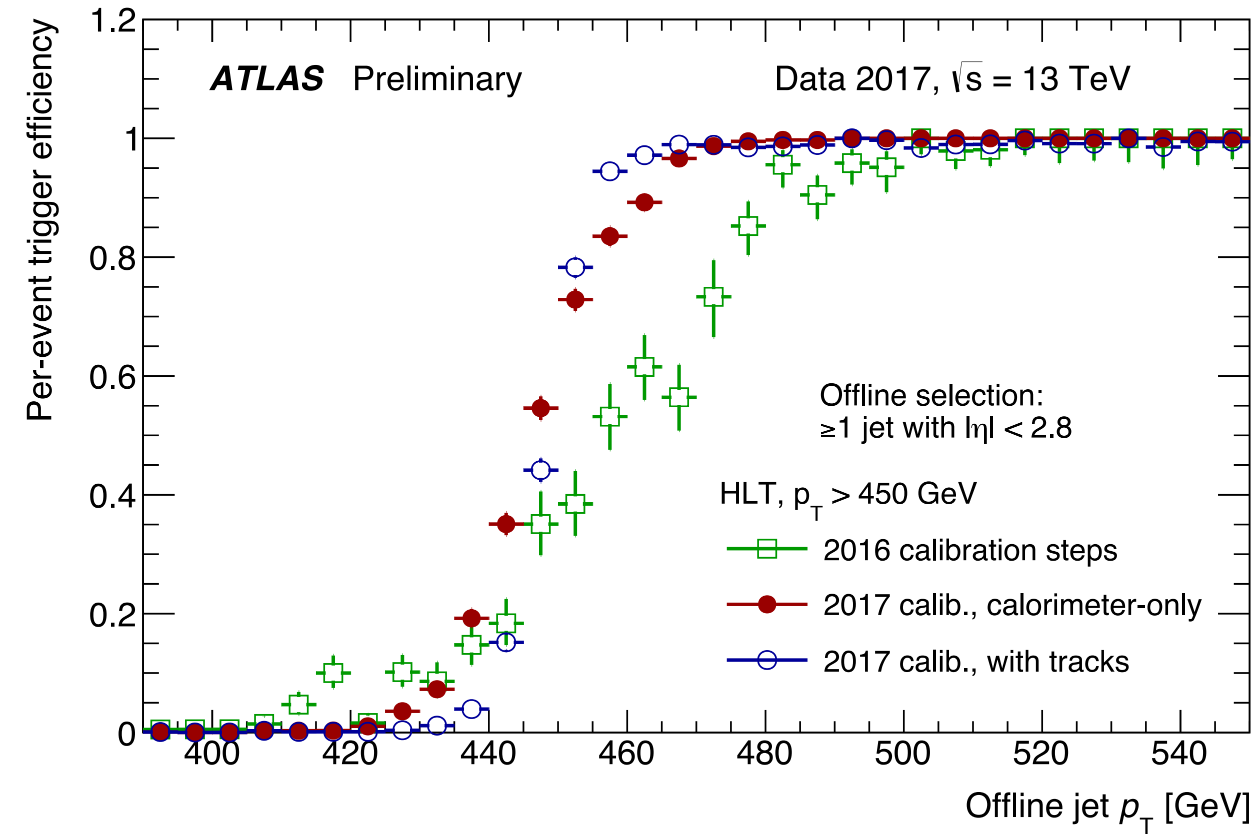


- 2017/8: improve calibration of trigger jets, take advantage of unused L1 rate towards end of fill to run new triggers allowing lower masses to be probed (J50 vs J75/J100)
- Run 3: improve reconstruction of L1 objects with new hardware => can probe lower mass for given rate
- Run 3: FTK -> full tracking at HLT -> pileup rejection possible -> can go well below 85 GeV

ATL-DAQ-PUB-2017-003

Prospects, resolved dijet + ISR

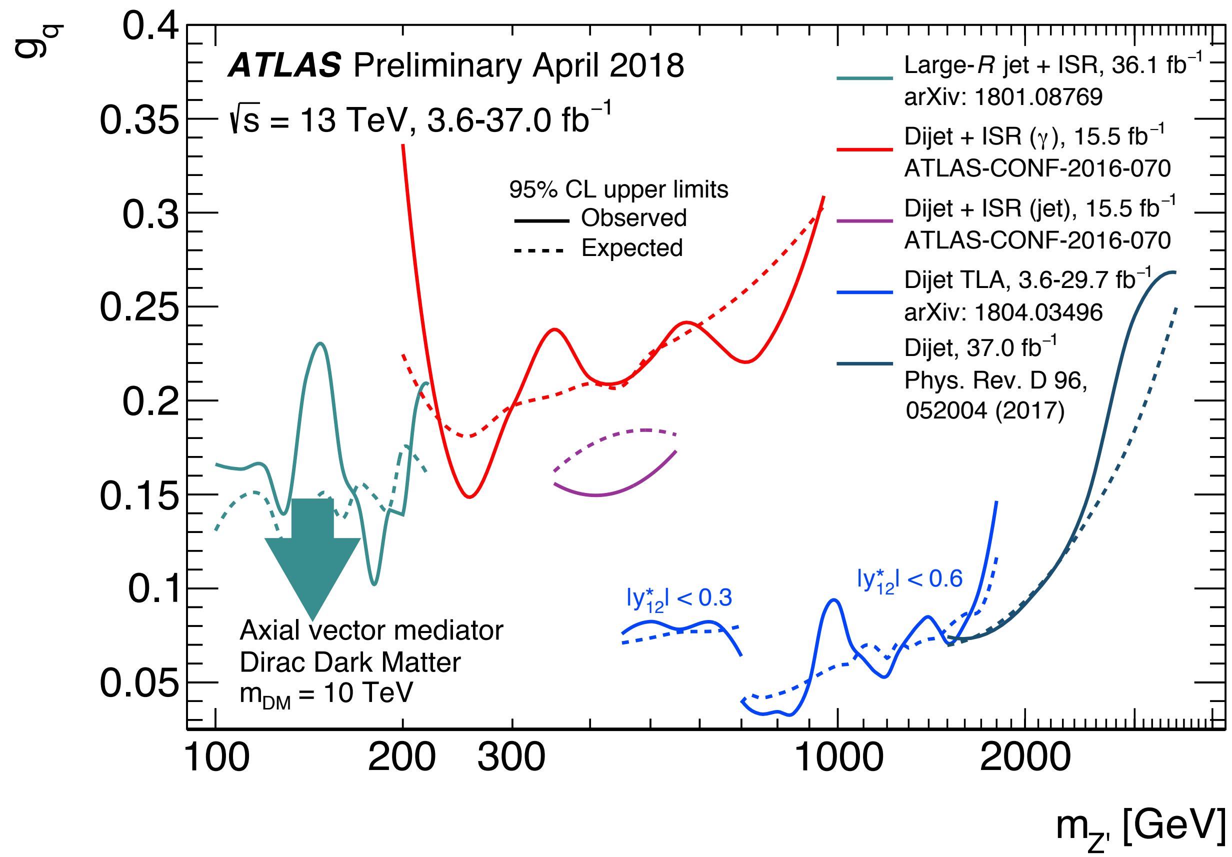


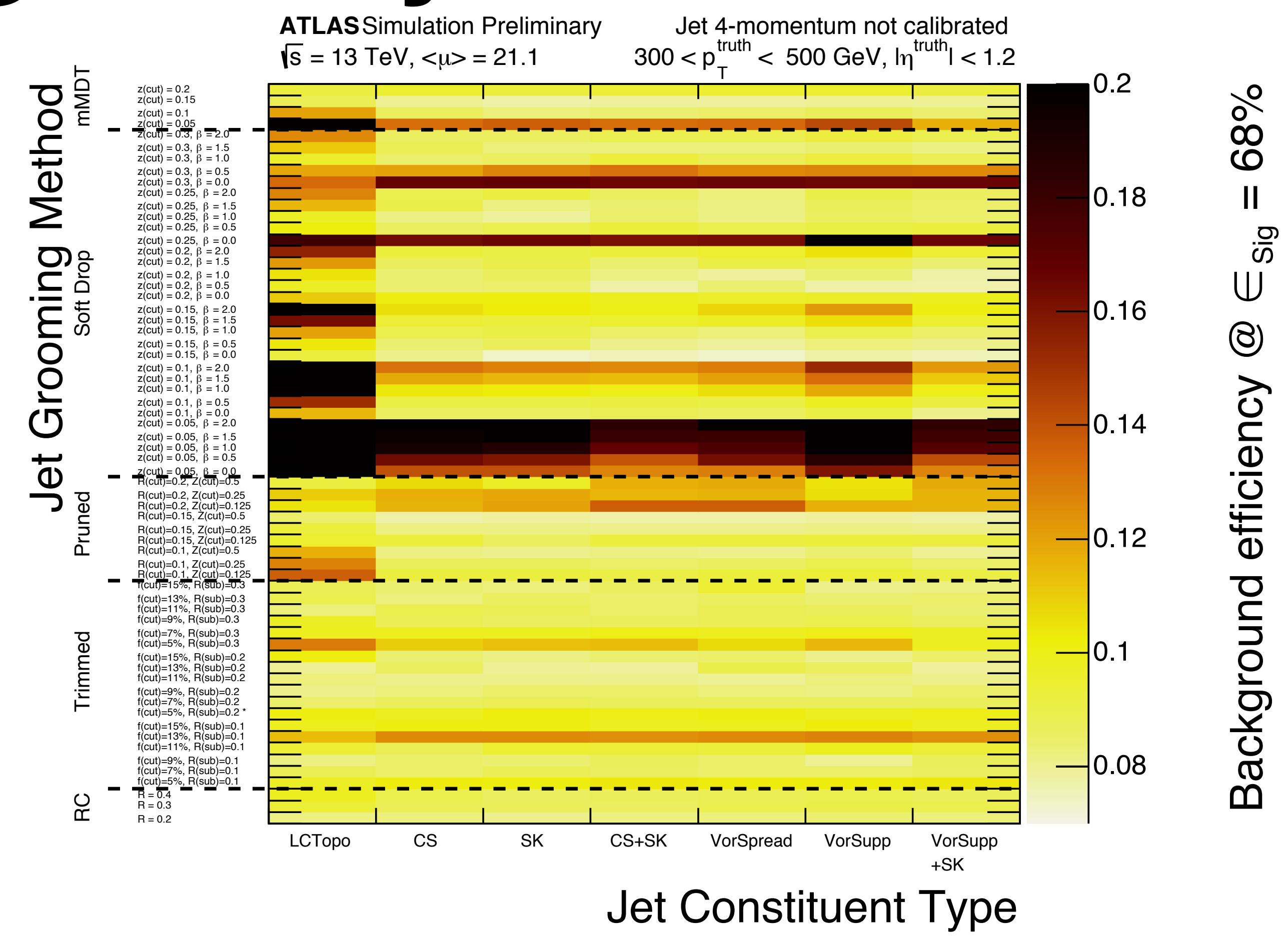


plateau of j380 in 2016 ~ j420 in 2017

- g_q limit scales as data$^{1/4}$ => 15.5 to 120 fb^{-1} = factor 1.7
- Higher instantaneous luminosity -> higher trigger thresholds, mitigated by improved jet trigger performance
- Combinatorics in jet channel can improve mass reach and sensitivity
- Potential for TLA technique in run 3 with FTK

Prospects, merged dijet + ISR

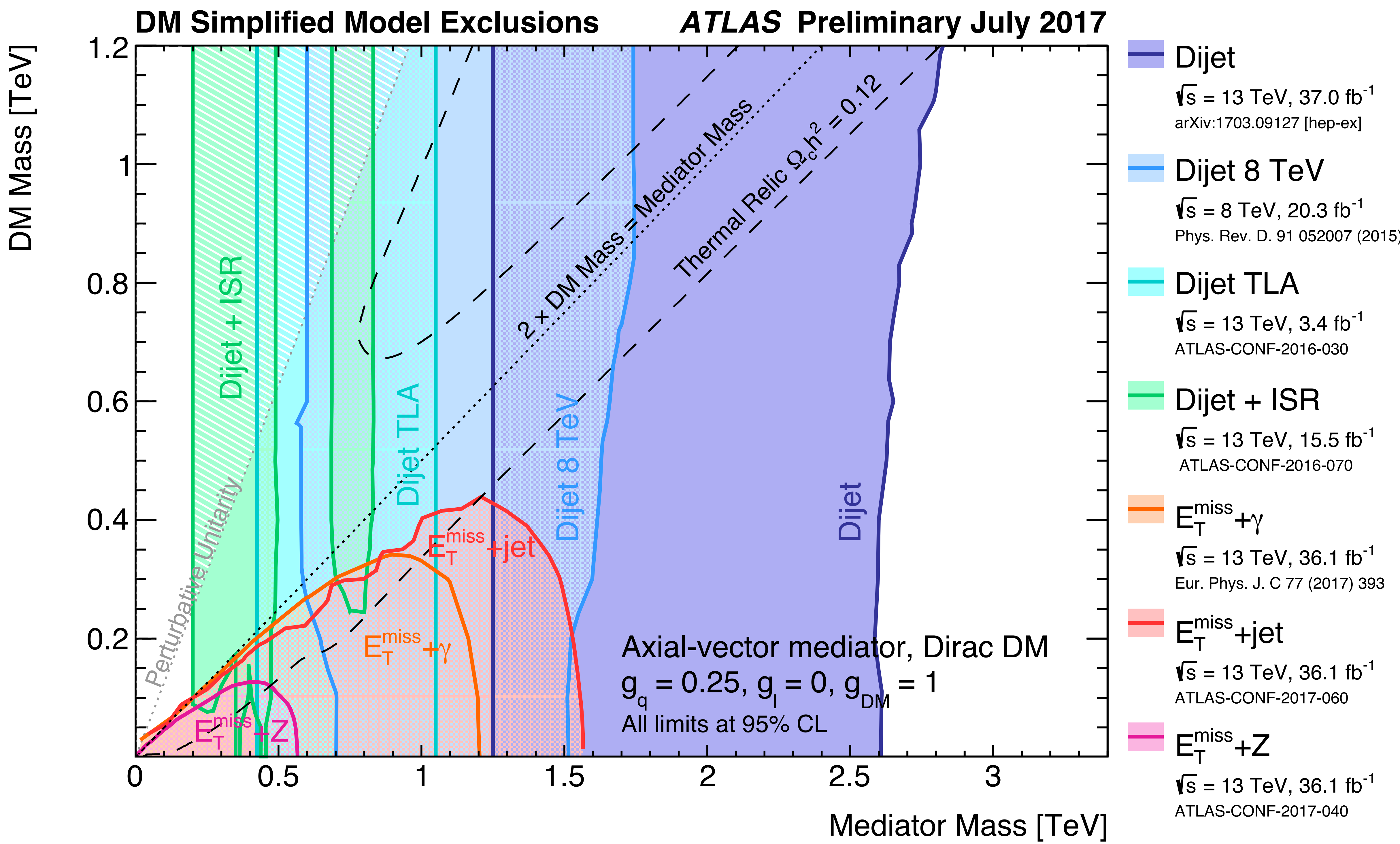




- g_q limit scales as data$^{1/4}$ => 37 to 120 fb^{-1} = factor 1.3
- New trigger strategies for large-R, including substructure information in the trigger (2017 has mass, run 3 will have more) -> much more data
- Optimised grooming methods ATL-PHYS-PUB-2017-020 -> better S/B
- Also improvements in jet substructure resolution thanks to track information in jet reconstruction inputs ATL-PHYS-PUB-2017-015

More details on substructure in Jason Veatch's WG4 talk yesterday

Complementarity between DM searches

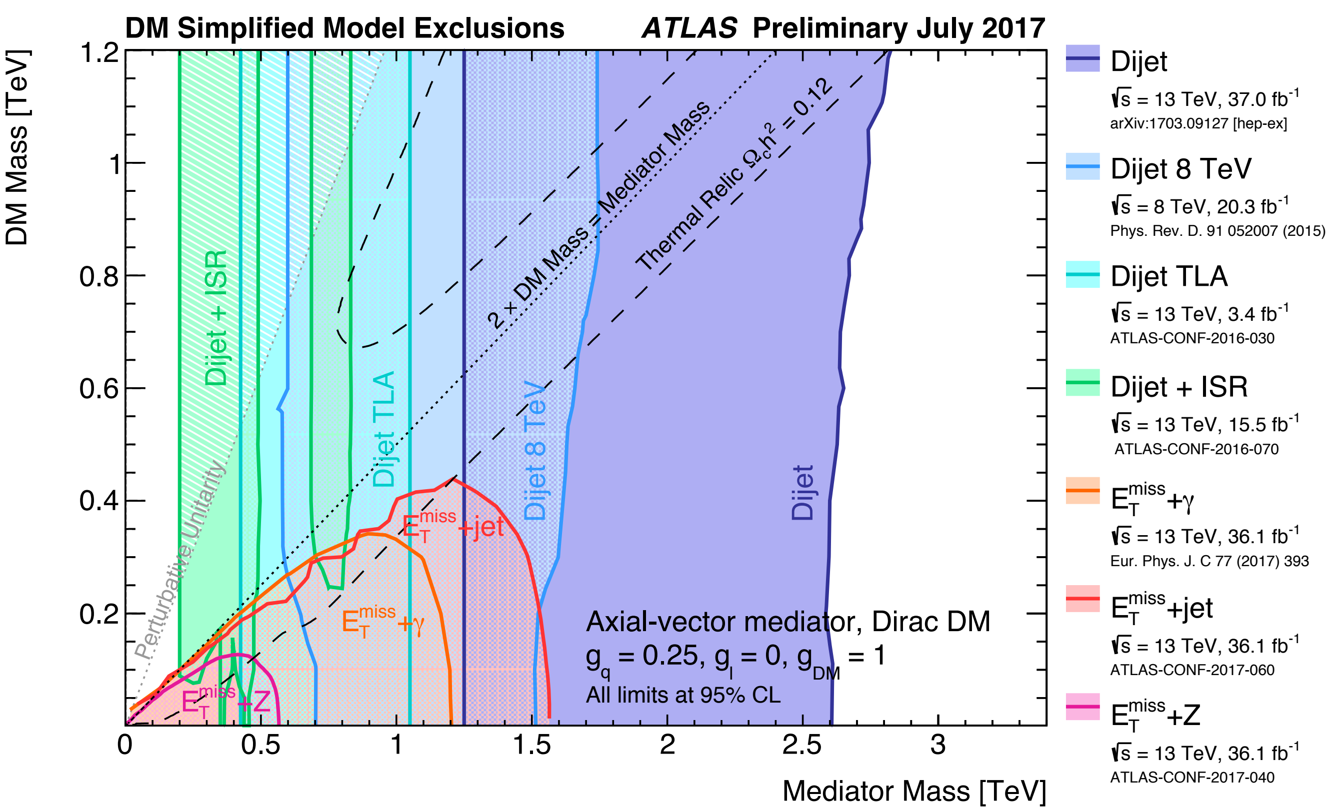


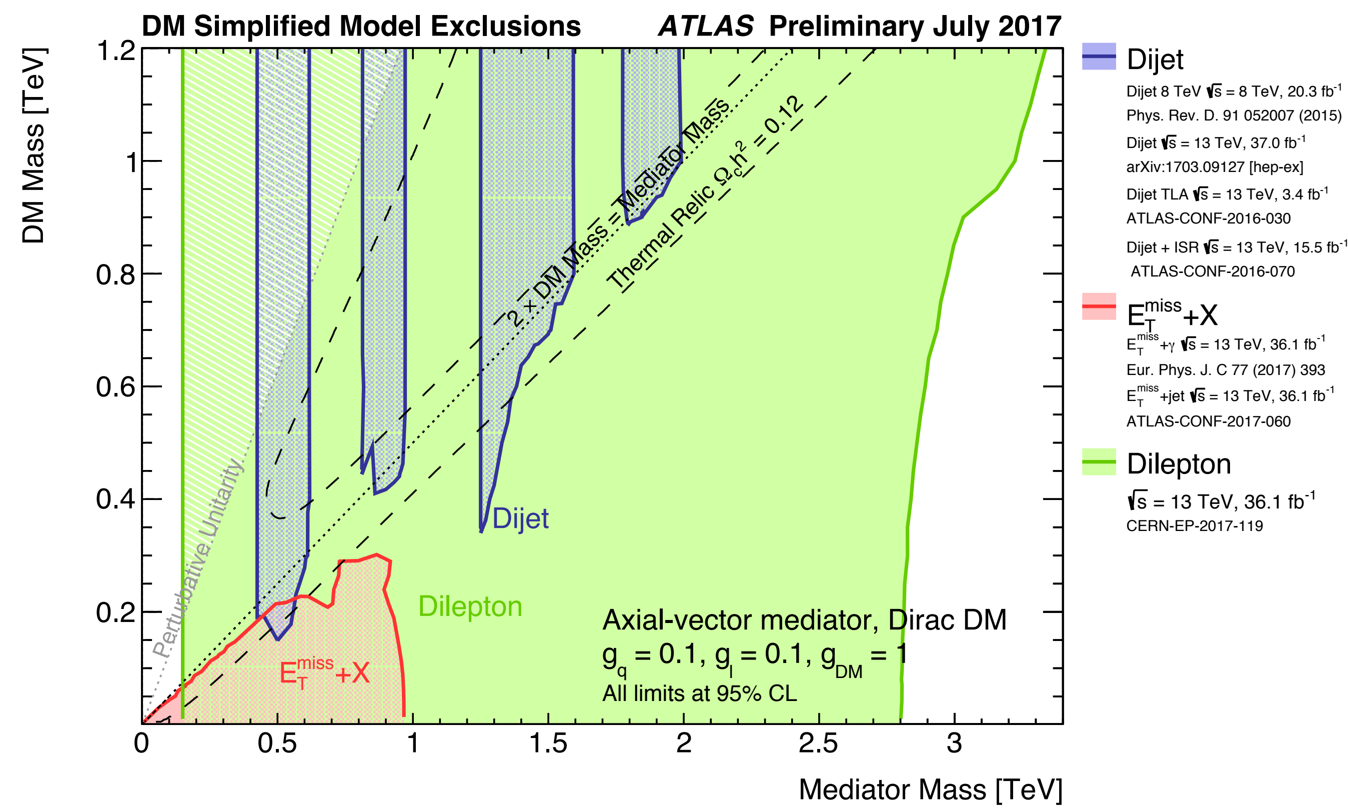
mono-X and resonance searches complement each other

Caveats:

- plot is ~ 1 year old, doesn't include latest TLA, large-R+ISR or mono-X results

Complementarity between DM searches



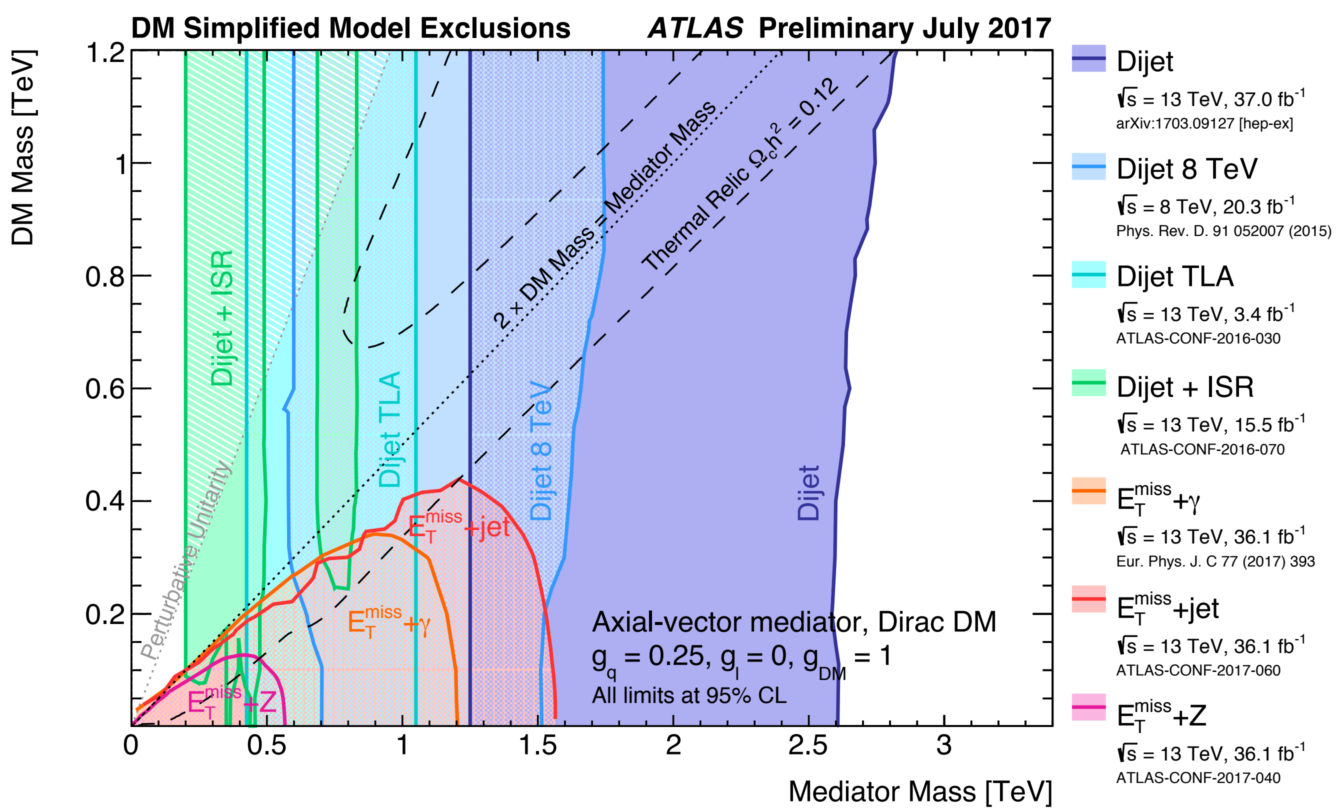


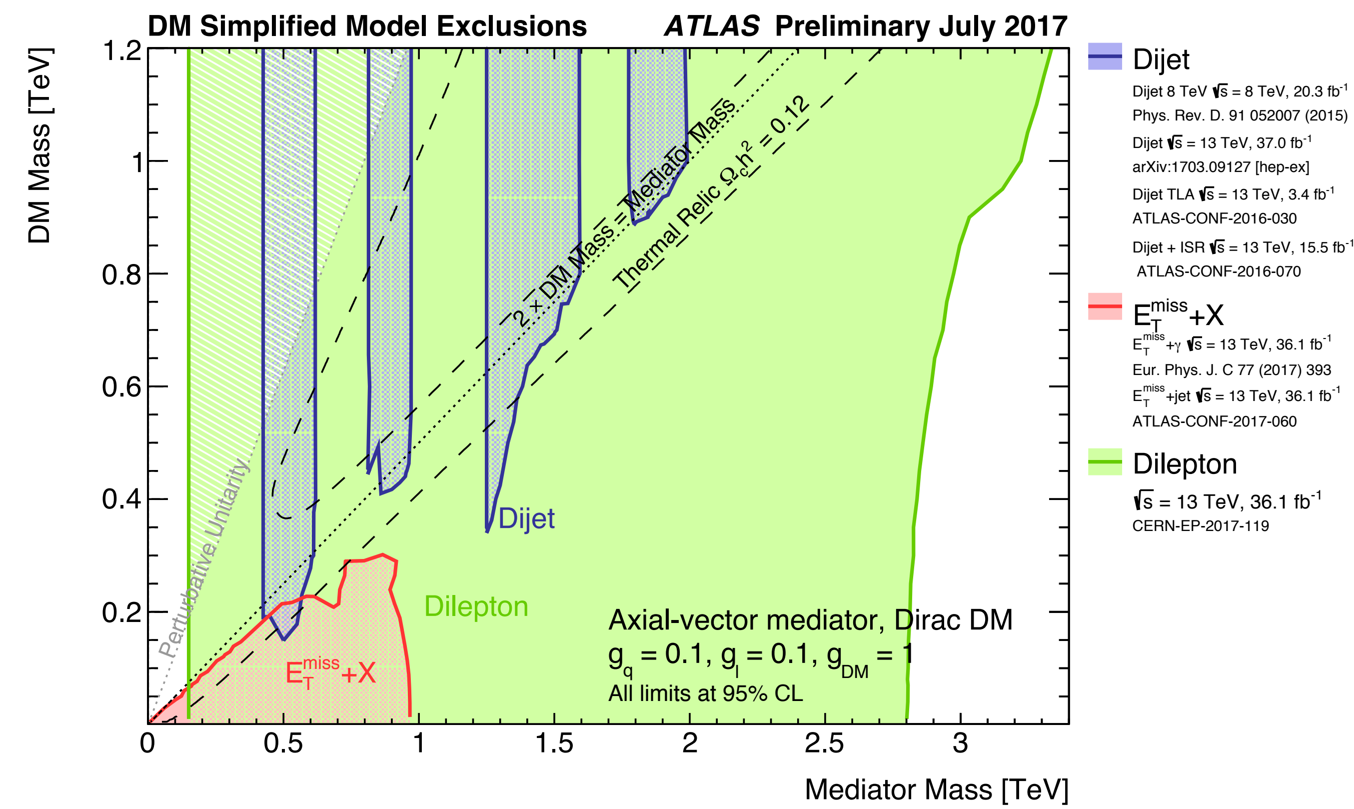
Caveats:

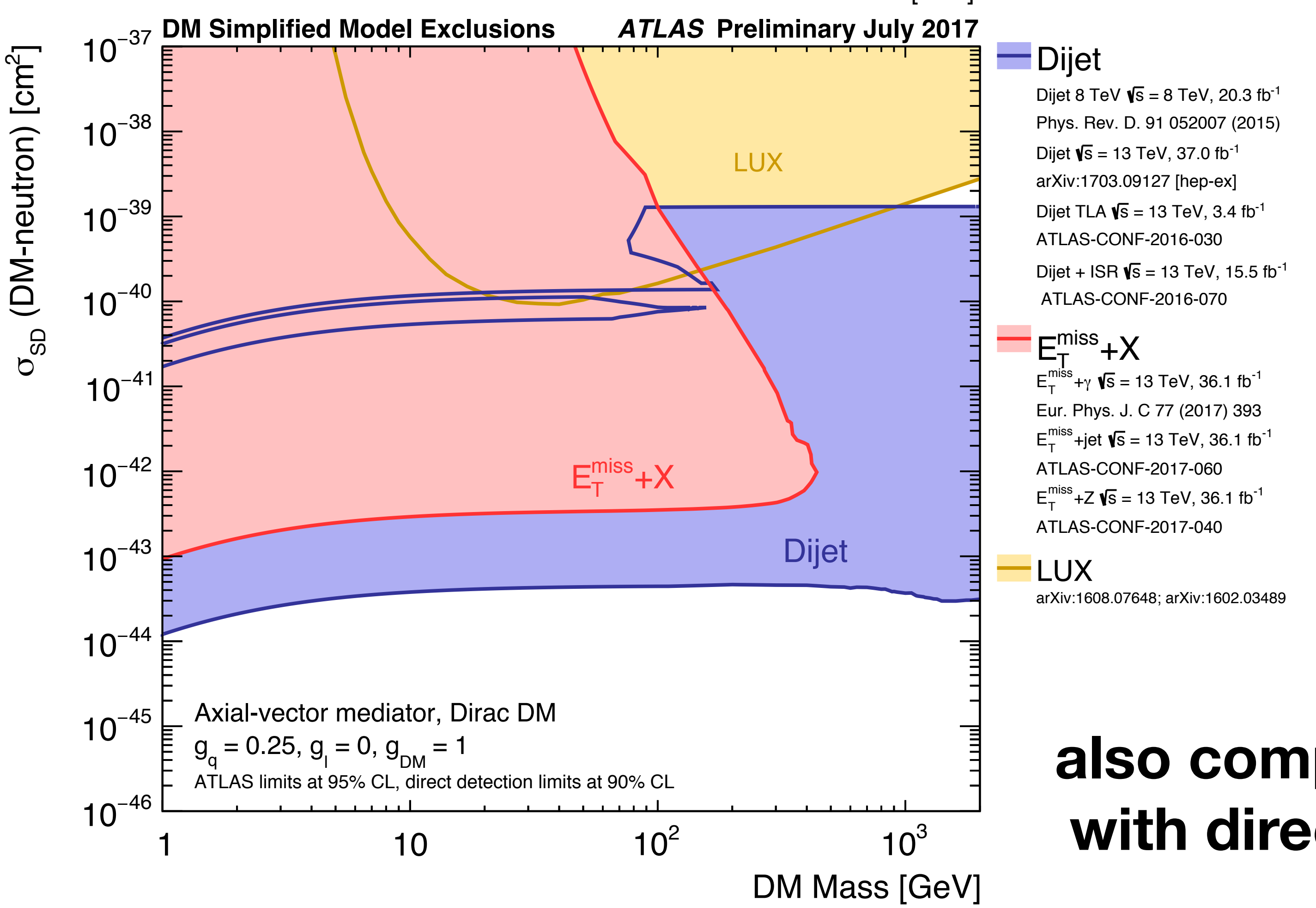
- plots are ~ 1 year old, don't include latest TLA, large-R+ISR or mono-X results
- very model-dependent (eg non-zero lepton coupling causes large changes)

other channels (eg dilepton resonance) cover other model scenarios

Complementarity between DM searches







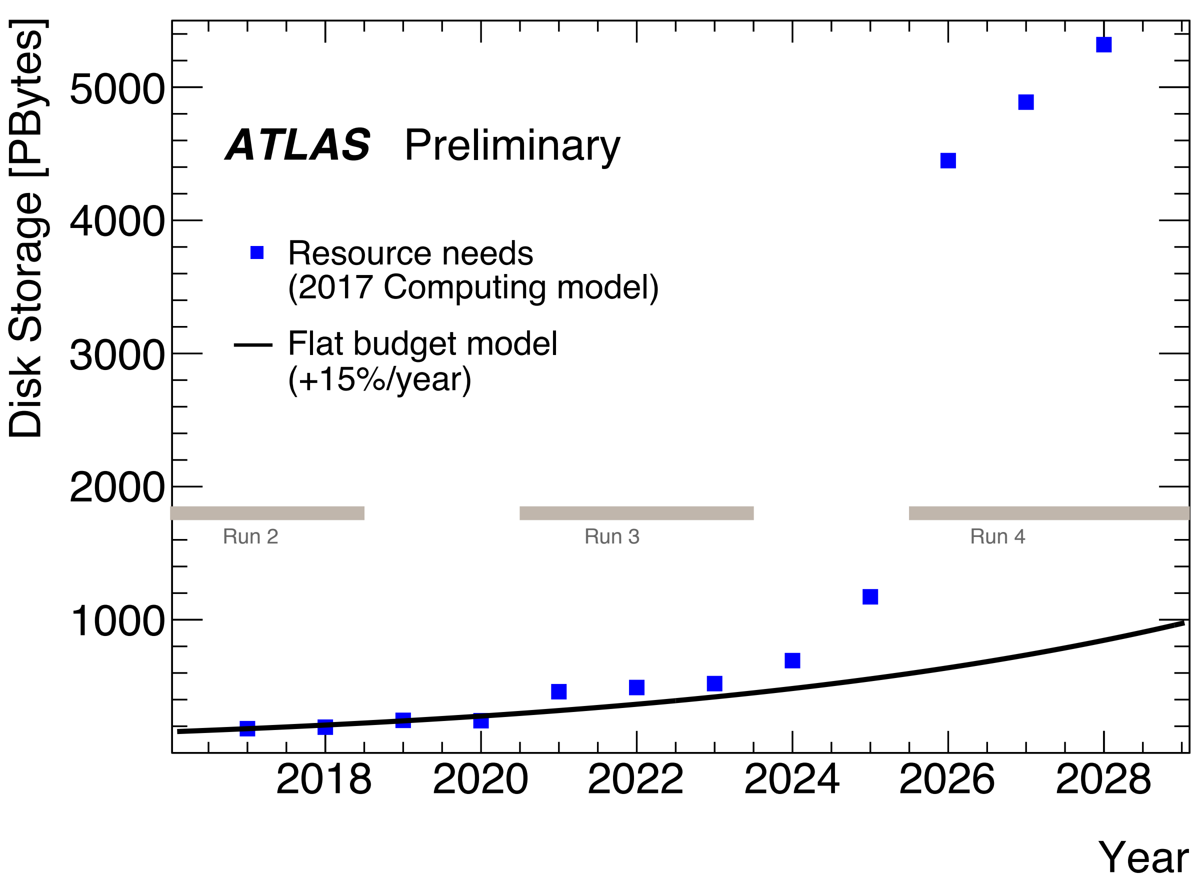
Caveats:

- plots are ~ 1 year old, don't include latest TLA, large-R+ISR or mono-X results
- very model-dependent (eg non-zero lepton coupling causes large changes)
- DD limits 90% CL, collider 95%

also complementarity with direct detection

Conclusions

- Broad set of approaches to searching for Dark Matter with ATLAS
- Various new techniques being exploited to go lower in mass
  - Initial state radiation to evade trigger limitations
  - Substructure to take this into the merged regime
  - Borrowing methods from LHCb and CMS to make the best use of jet trigger system and do a dijet analysis with partial events

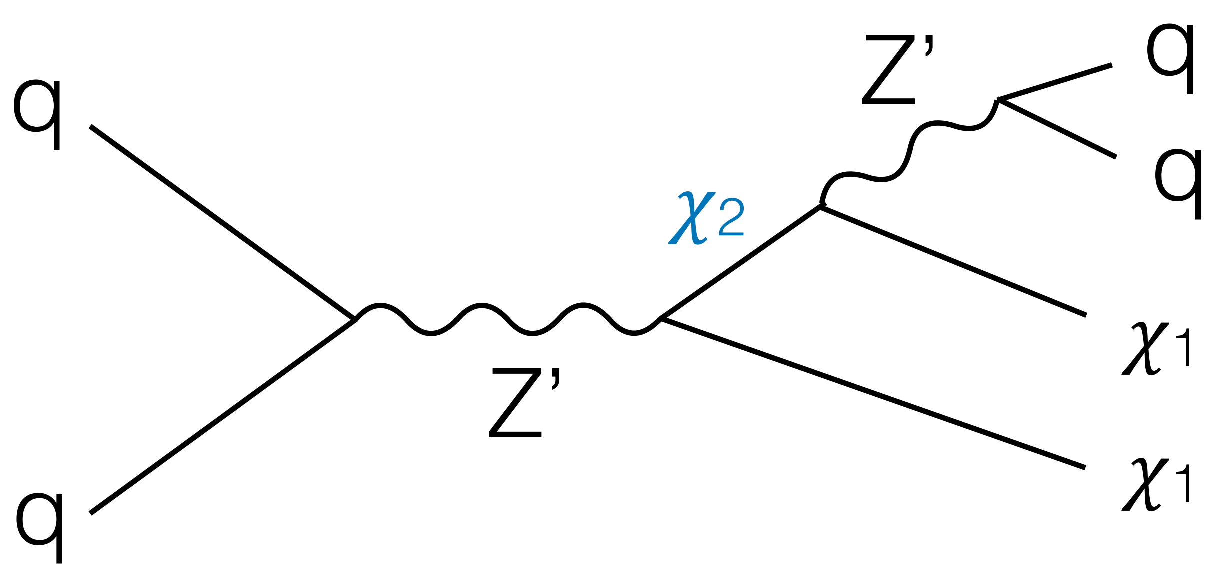


- New methods can all take advantage of LS2 trigger upgrades for sensitivity scaling much better than integrated luminosity alone
- Can also help with significant computing and storage pressures in the future

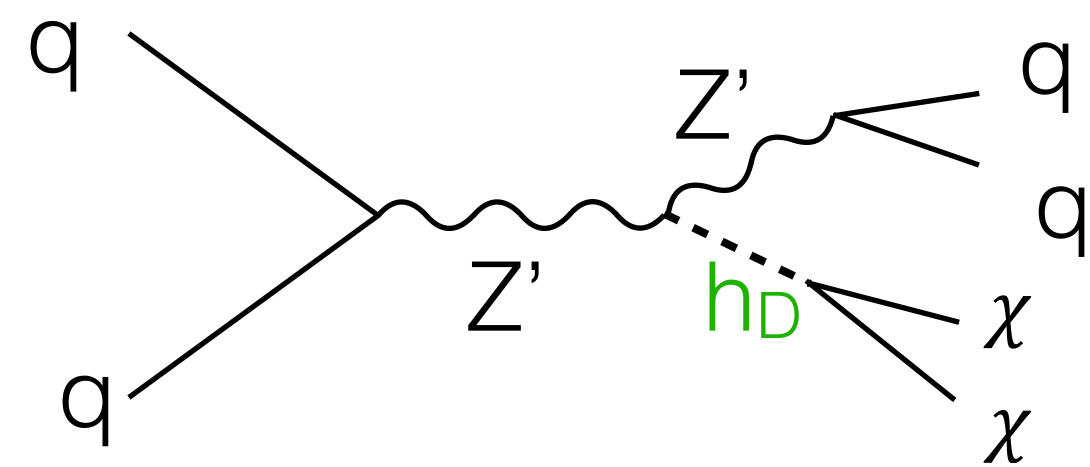
Backup

New: mono-Z’

ATLAS-CONF-2018-005, April 4th



Dark Fermion



Dark Higgs

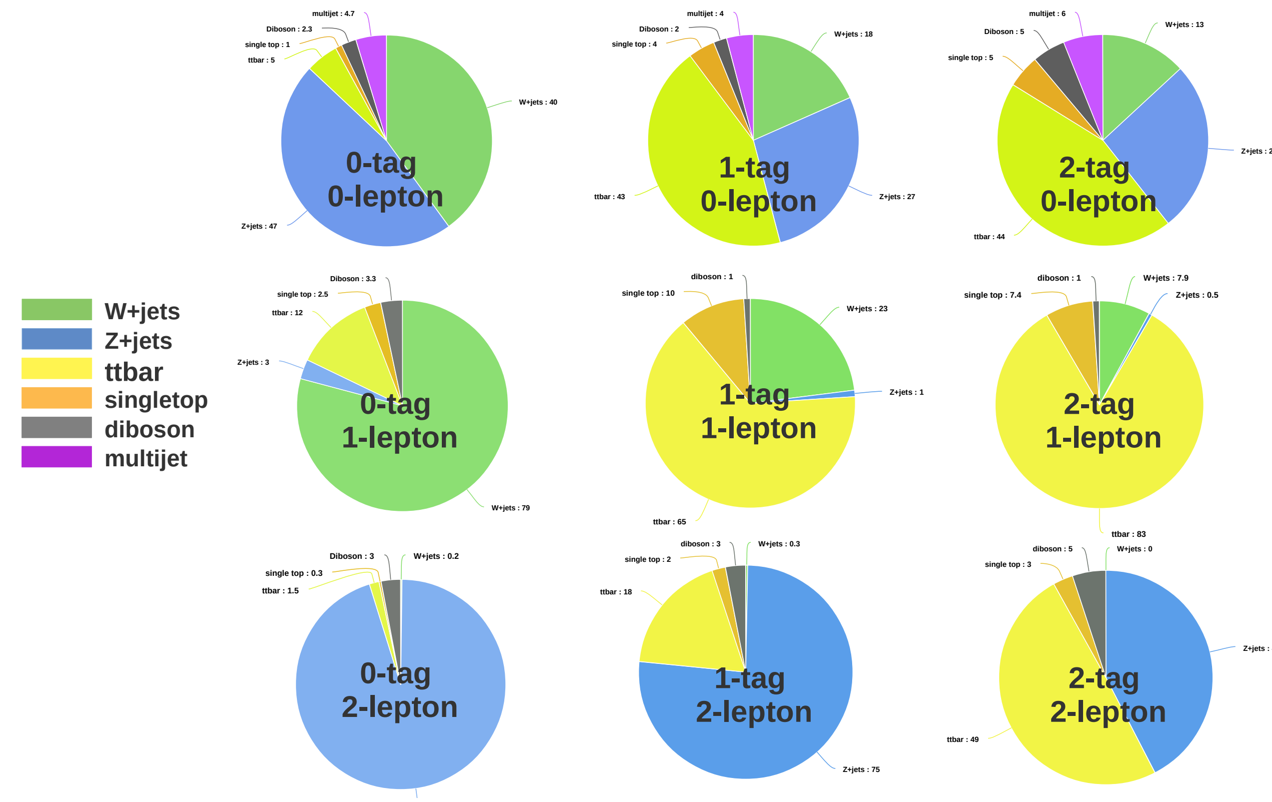
Dijet resonance + MET

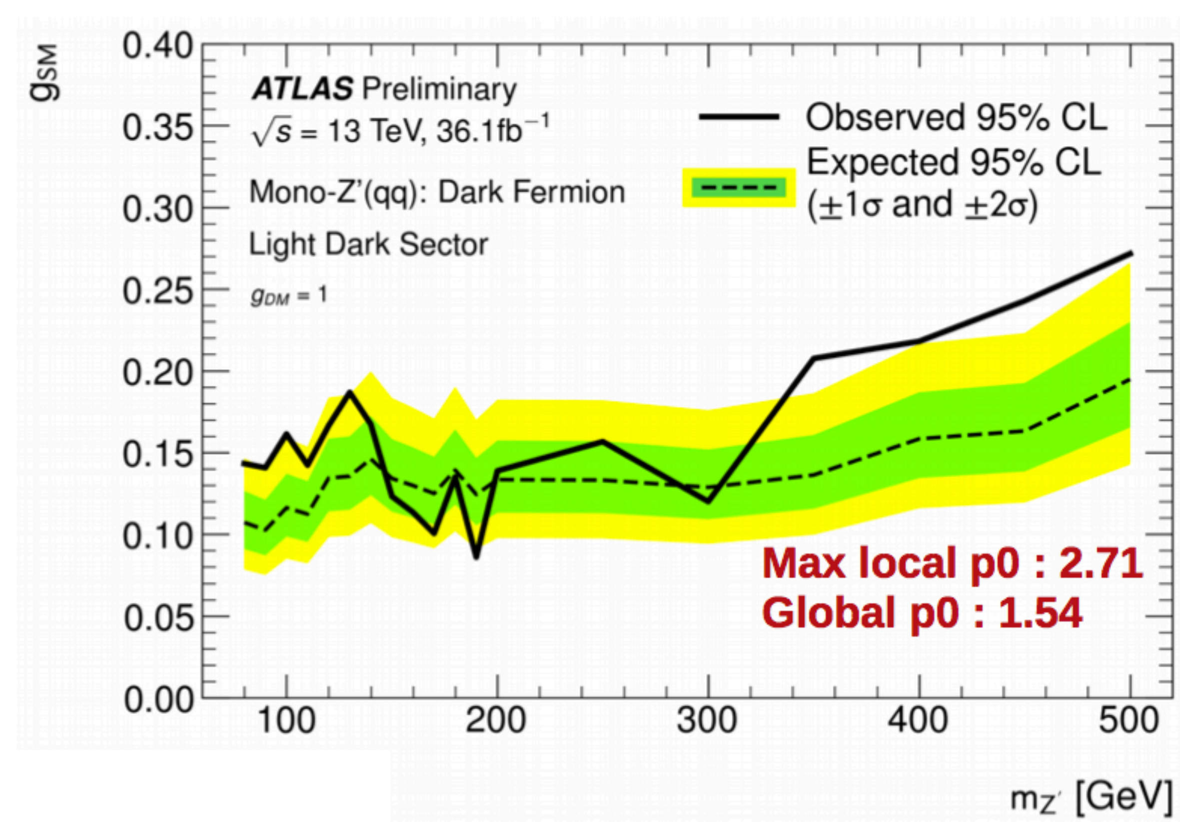
Scenario	Dark-fermion model	Dark-Higgs model
Light dark sector	$m_{\chi_1} = 5$ GeV $m_{\chi_2} = m_{\chi_1} + m_{Z'} + 25$ GeV	$m_\chi = 5$ GeV $m_{h_D} = \begin{cases} m_{Z'} & , m_{Z'} < 125 \text{ GeV} \\ 125 \text{ GeV} & , m_{Z'} > 125 \text{ GeV} \end{cases}$
Heavy dark sector	$m_{\chi_1} = m_{Z'}/2$ $m_{\chi_2} = 2m_{Z'}$	$m_\chi = 5$ GeV $m_{h_D} = \begin{cases} 125 \text{ GeV} & , m_{Z'} < 125 \text{ GeV} \\ m_{Z'} & , m_{Z'} > 125 \text{ GeV} \end{cases}$

Quick overview: Mono-Z’

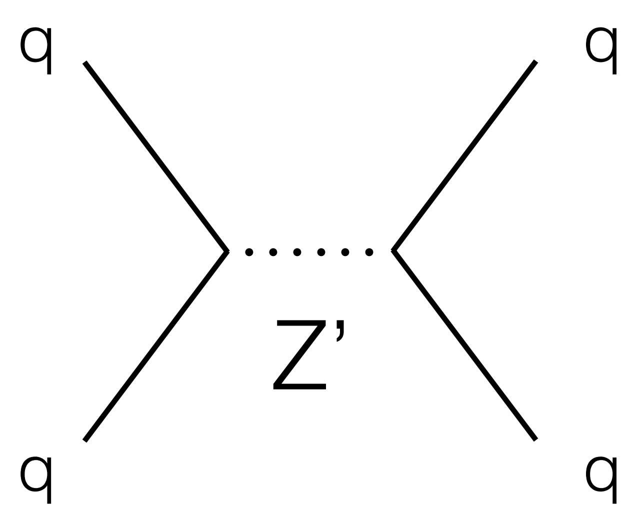
- E_T^{miss} trigger
- Merged and resolved jet resonance search
- Use of btagging to enhance sensitivity to Z’ -> bb
- Combined fit of MC normalisations in 1&2-lepton CRs and 0-lepton SRs
- Limits: heavy dark sector comparable to dijet searches, stronger with light dark sector
- Systematically limited => foresee improvement

* Example background composition for mZ’ = 90 GeV, resolved topology.



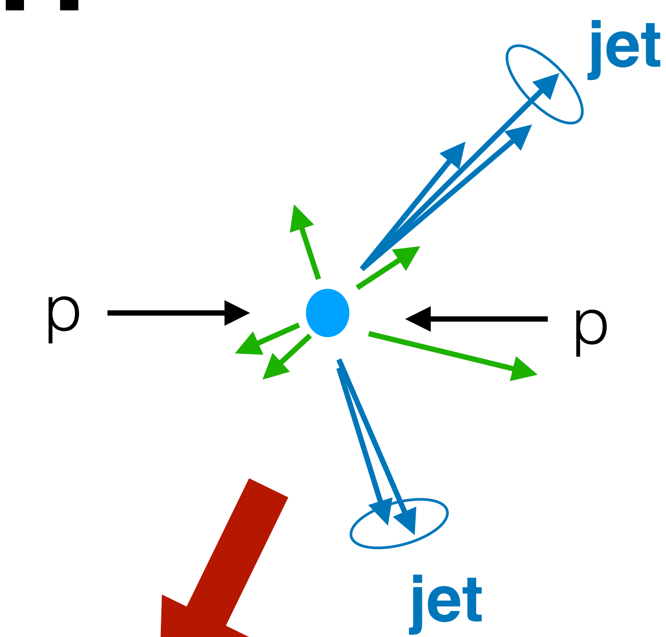


Resonance search

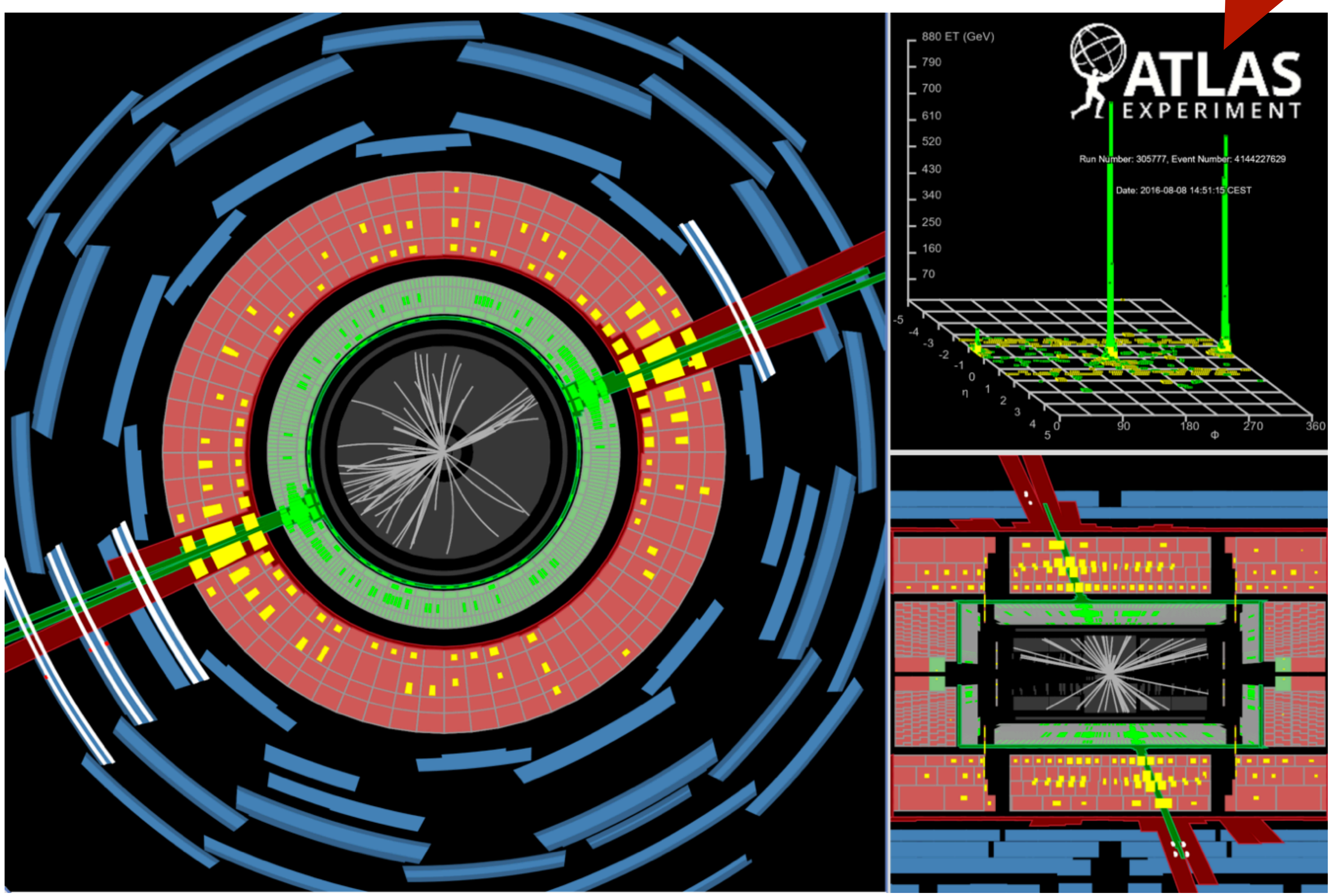


hadronisation of final state quarks

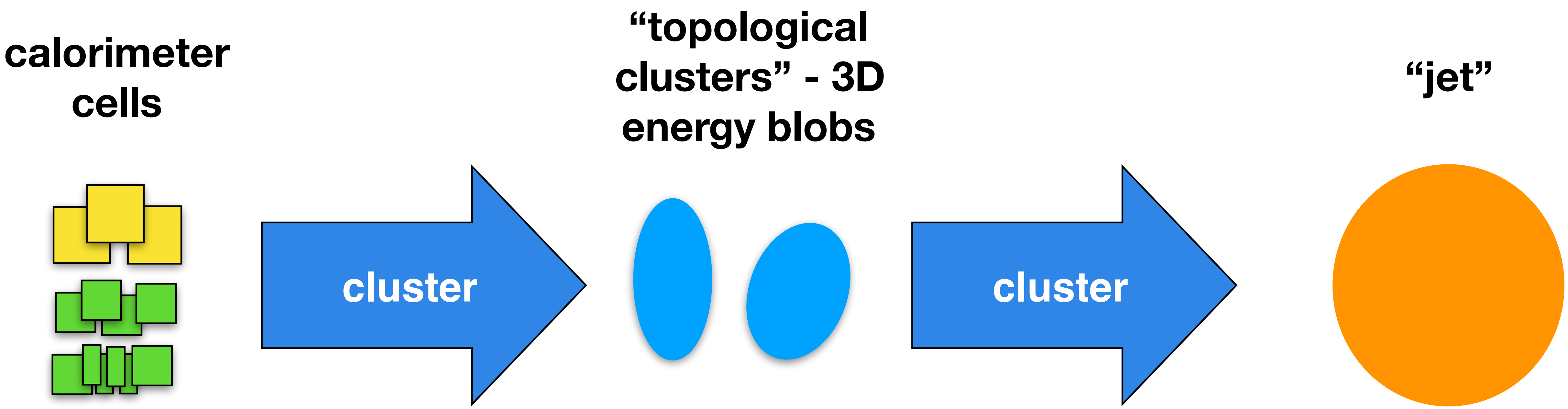
"pile-up" - simultaneous p-p interactions



highest-mass dijet event in 2016
$p_T(j1,j2)$ = 3.79
m_{jj} = 8.12 TeV



Jet reconstruction



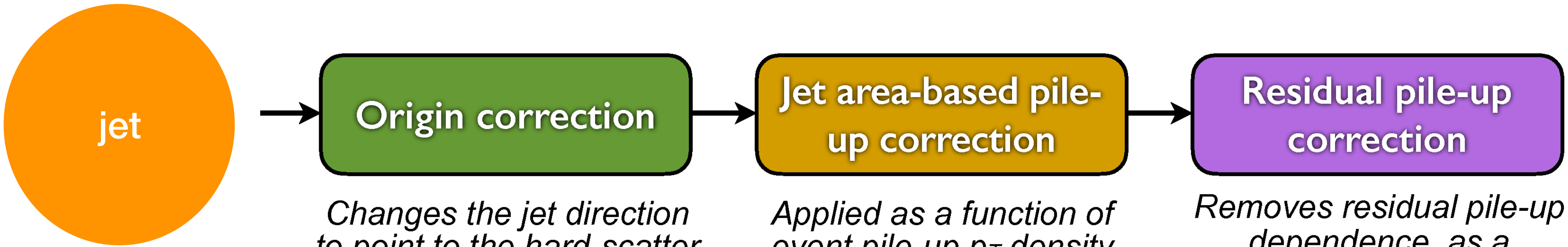
- Seed from cells with S/N > 4
- Grow with cells S/N > 2
- Split local maxima (EM calorimeter)

- Sequentially merge topoclusters
- Start from highest E_T
- Size controlled by 'radius' parameter, $\Delta R = \Delta\eta \oplus \Delta\phi = 0.4$
- End with a 2D object - ~ circular in η-ϕ (except when touch)

Jet calibration

- Built from raw energy recorded by calorimeter
- **sampling** calorimeters -> don't record all the energy
- Also have energy deposits from other p-p collisions in same event

Jet calibration



Changes the jet direction to point to the hard-scatter vertex. Does not affect E.

Applied as a function of event pile-up p_T density and jet area.

Removes residual pile-up dependence, as a function of μ and N_{PV}.

- Built from raw energy recorded by calorimeter
- **sampling** calorimeters -> don’t record all the energy
- Also have energy deposits from other p-p collisions in same event

look at average p_T density of event in the calorimeter, subtract this approximated pileup contribution

Jet calibration

jet

Origin correction → **Jet area-based pile-up correction** → **Residual pile-up correction**

Changes the jet direction to point to the hard-scatter vertex. Does not affect E.

Applied as a function of event pile-up p_T density and jet area.

Removes residual pile-up dependence, as a function of μ and N_{PV}.

→ **Absolute MC-based calibration** → **Global sequential calibration** → **Residual *in situ* calibration**

Corrects jet 4-momentum to the particle-level energy scale. Both the energy and direction are calibrated.

Reduces flavor dependence and energy leakage effects using calorimeter, track, and muon-segment variables.

*A residual calibration is derived using in situ measurements and is applied **only to data**.*

- Built from raw energy recorded by calorimeter
- **sampling** calorimeters -> don't record all the energy
- Also have energy deposits from other p-p collisions in same event

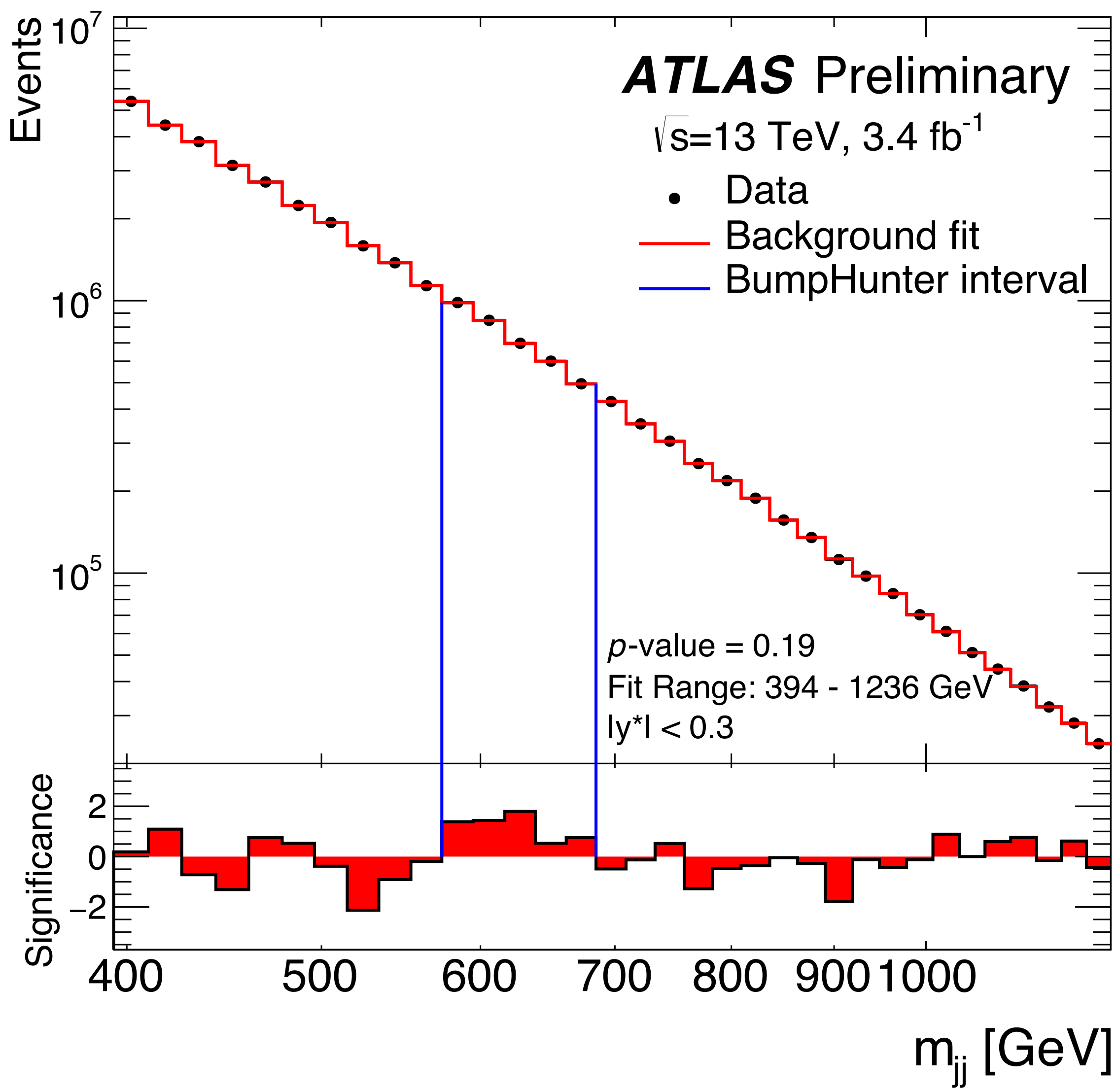
at this point, have only discriminated based on event pileup and jet origin, η and p_T. We have more information than this!

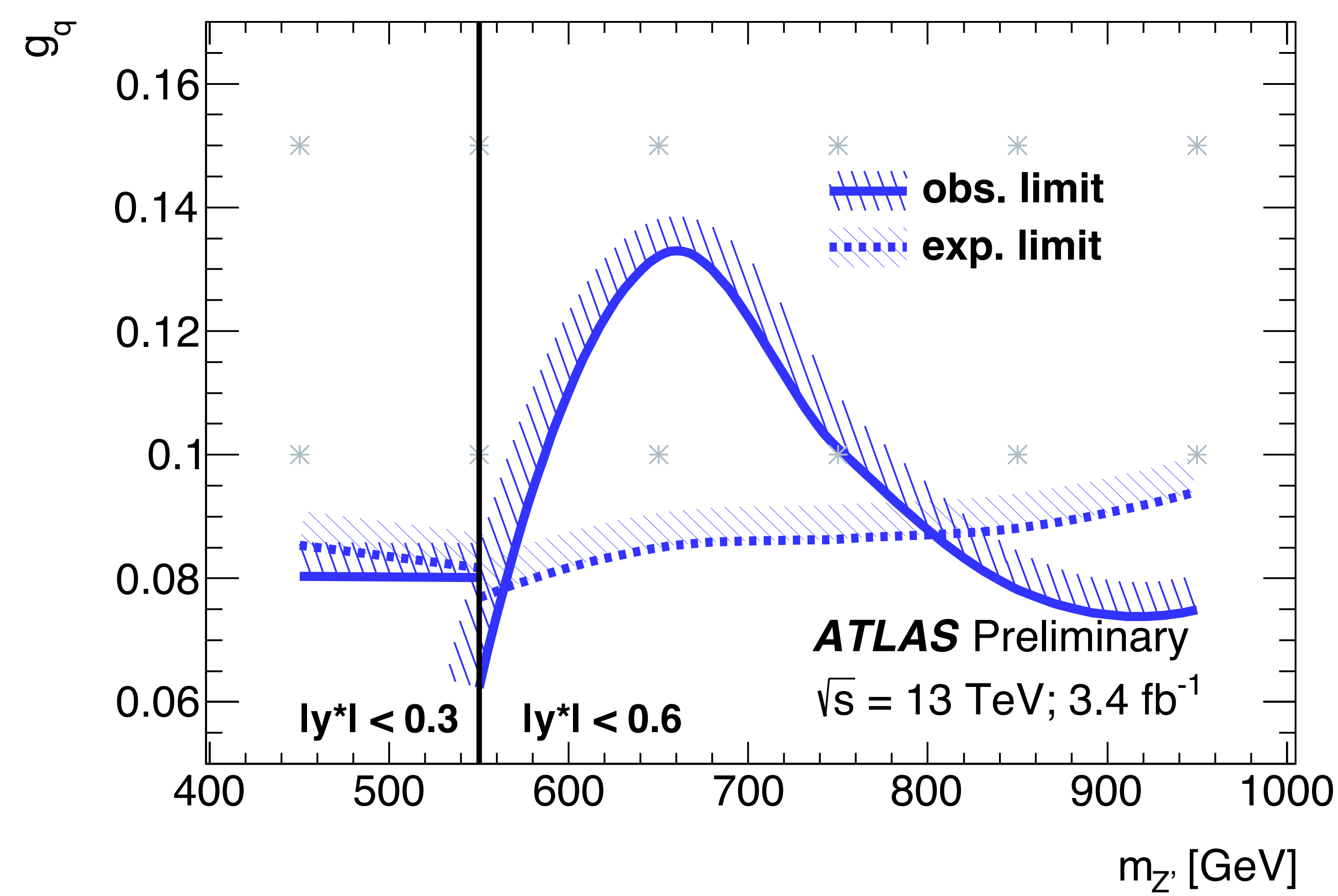
final corrections to get back to "truth" scale

TLA fitting

ATLAS-CONF-2016-030

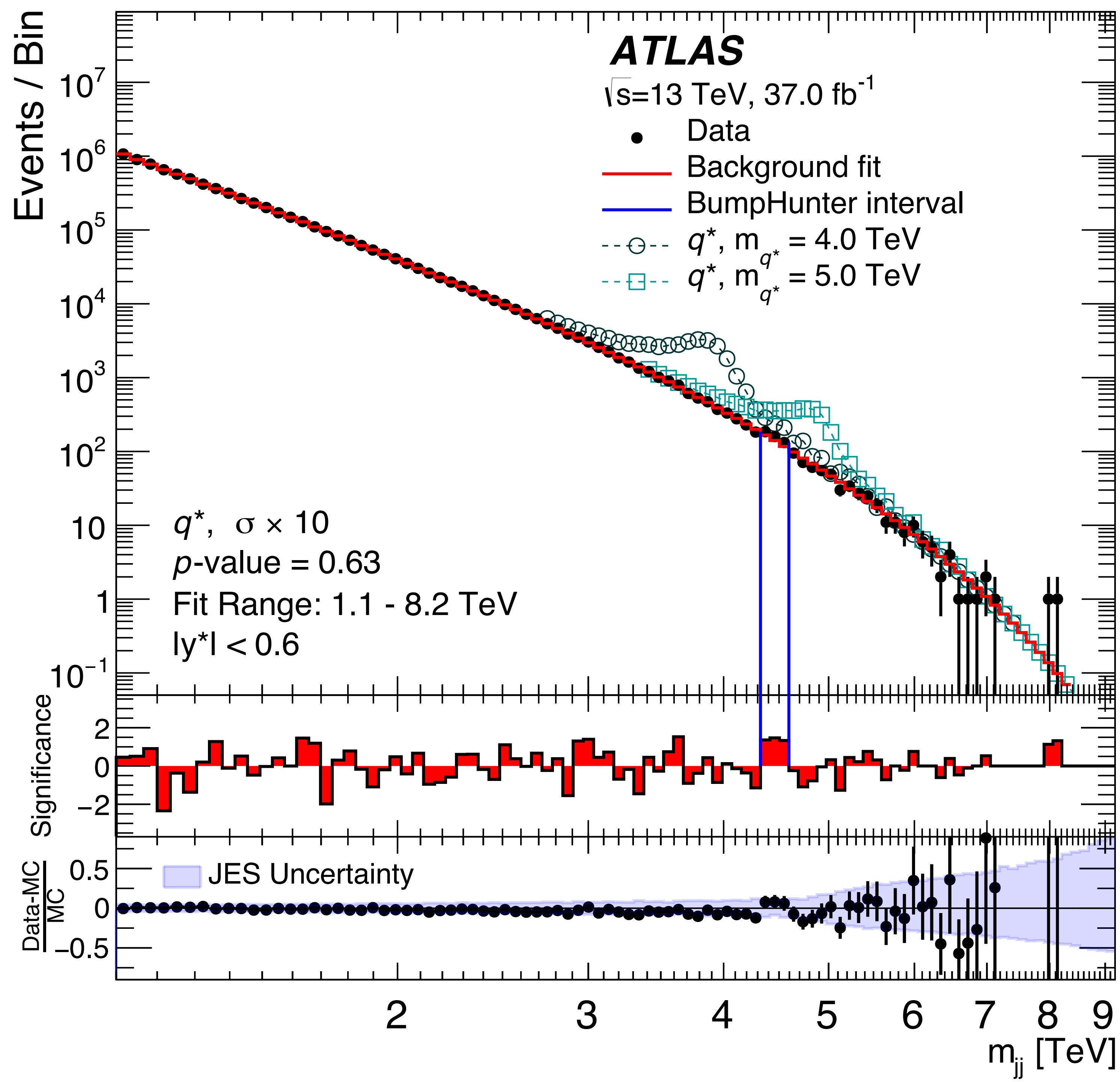
- Very large number of events -> very little scope for QCD to deviate from functional form
- In 2015, could not fit whole m_{jj} range, hence truncated fit at 1250 GeV





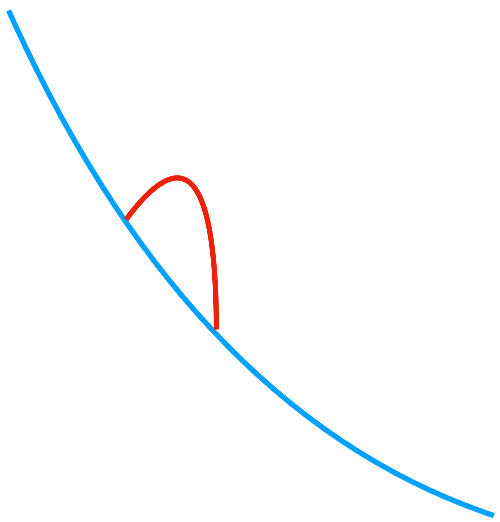
BumpHunter - high-mass dijet

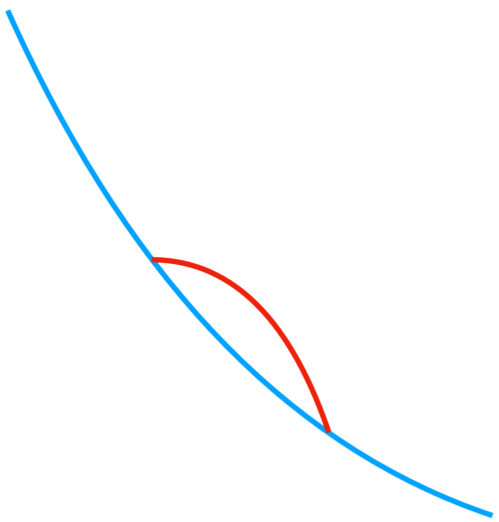
- "BumpHunter" - scans all widths from 1 to Nbins/2, finds maximally discrepant interval
- p-value < 0.05 => there is something there with 95% confidence
- p-value > 0.05 => there is not something there



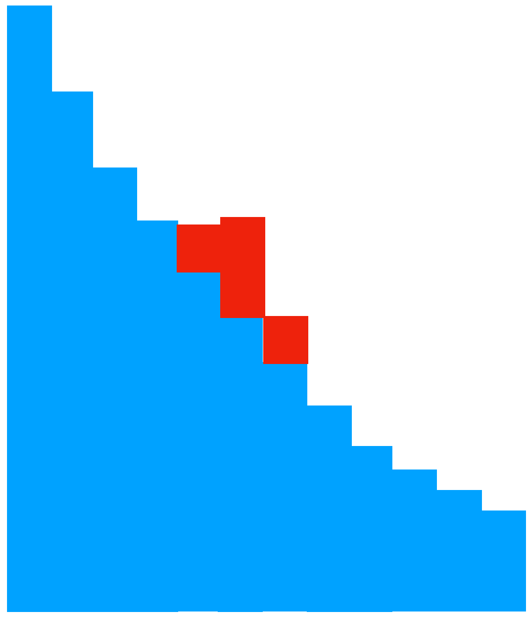
Limits on the limits: m_{jj} resolution

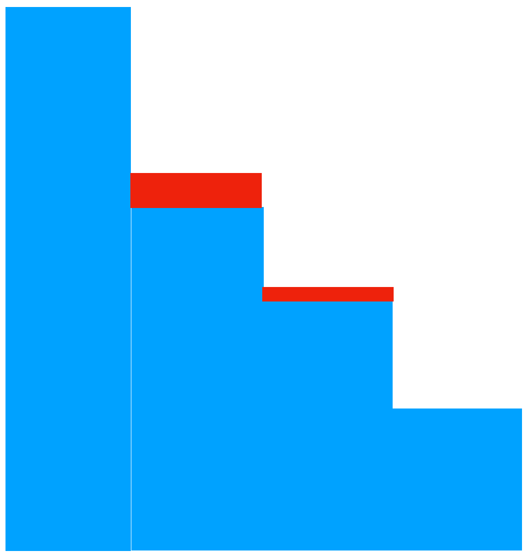
Good resolution | **Bad resolution**





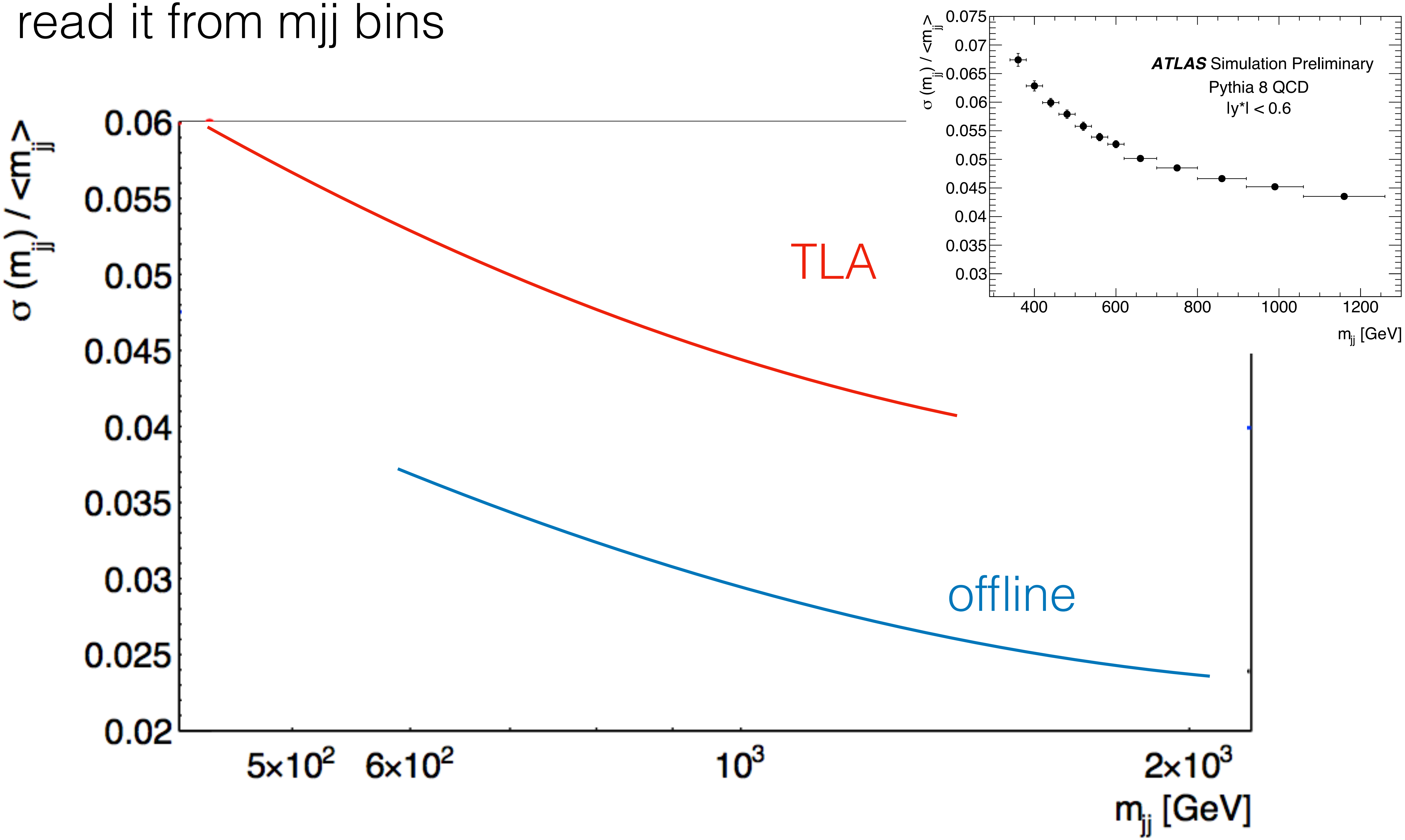
Bad resolution: signal smears out, covers wider m_{jj} range, trying to extract same number of signal events from more background events





m_{jj} resolution

Cartoon because offline plot is internal… but you can read it from mjj bins



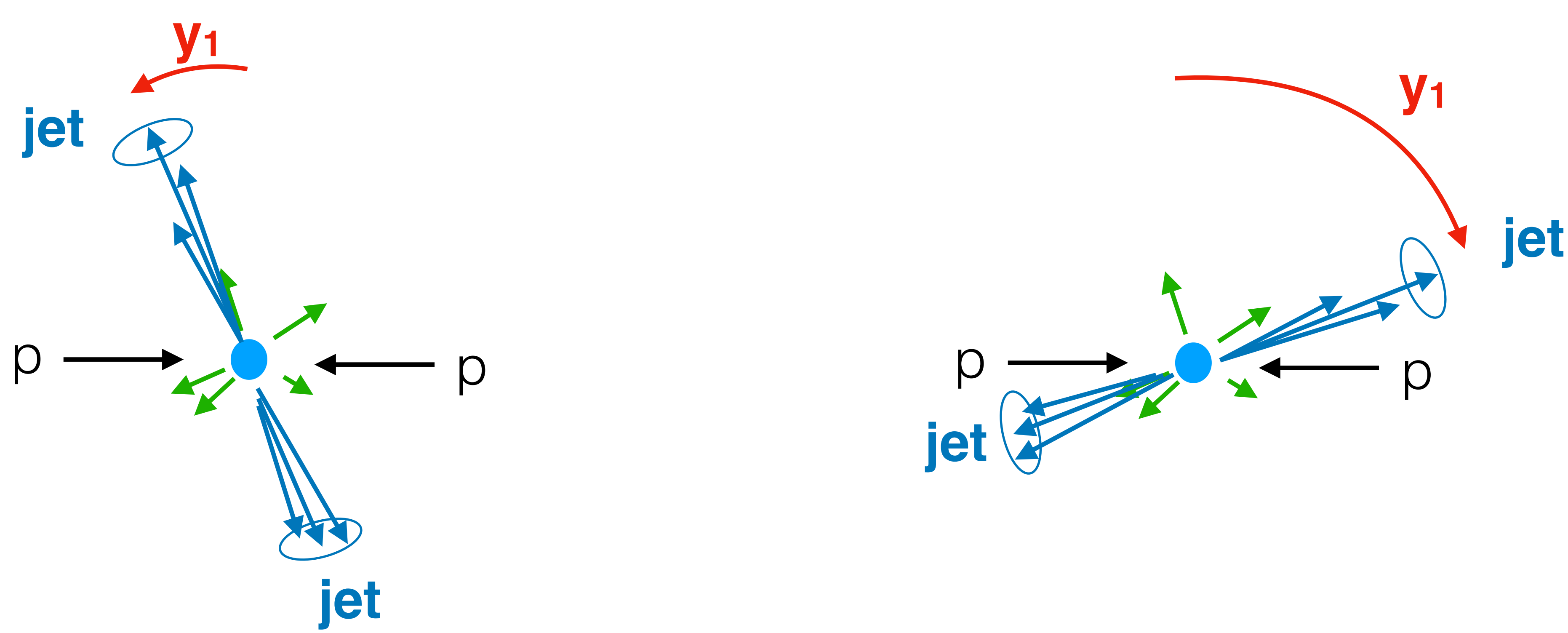
Lower still: exploiting the Kinematics

The dijet searches use $|y^*| < 0.6$

$y^* = {}^1/_2\,(y_1 - y_2)$

Imagine a centrally produced Z':

i.e. quarks back to back, $y_1 = -y_2,\ y^* = y_1$



small Δy, large p_T large Δy, small p_T

TLA: Imposing $|y^*|<0.3$ => higher $\langle p_T \rangle$ from given Z' mass => sensitive to lower Z' mass for given p_T (**394** vs 443)

(signal and background both lose a factor of ~ 2-3)

Trigger evolution over time

1. LHC performance increases
2. Decide rate allocation
3. Adjust jet pT threshold to fit
4. Evaluate performance of this trigger to determine analysis selections

year	L / 10^{34} cm^{-2} s^{-1}	jet p_T threhsold	single jet trigger rate	offline turnon
2015	0.5	260	18	400
2016	1.2	380	38	420
2017	1.7	420	33	435

Jet trigger performance

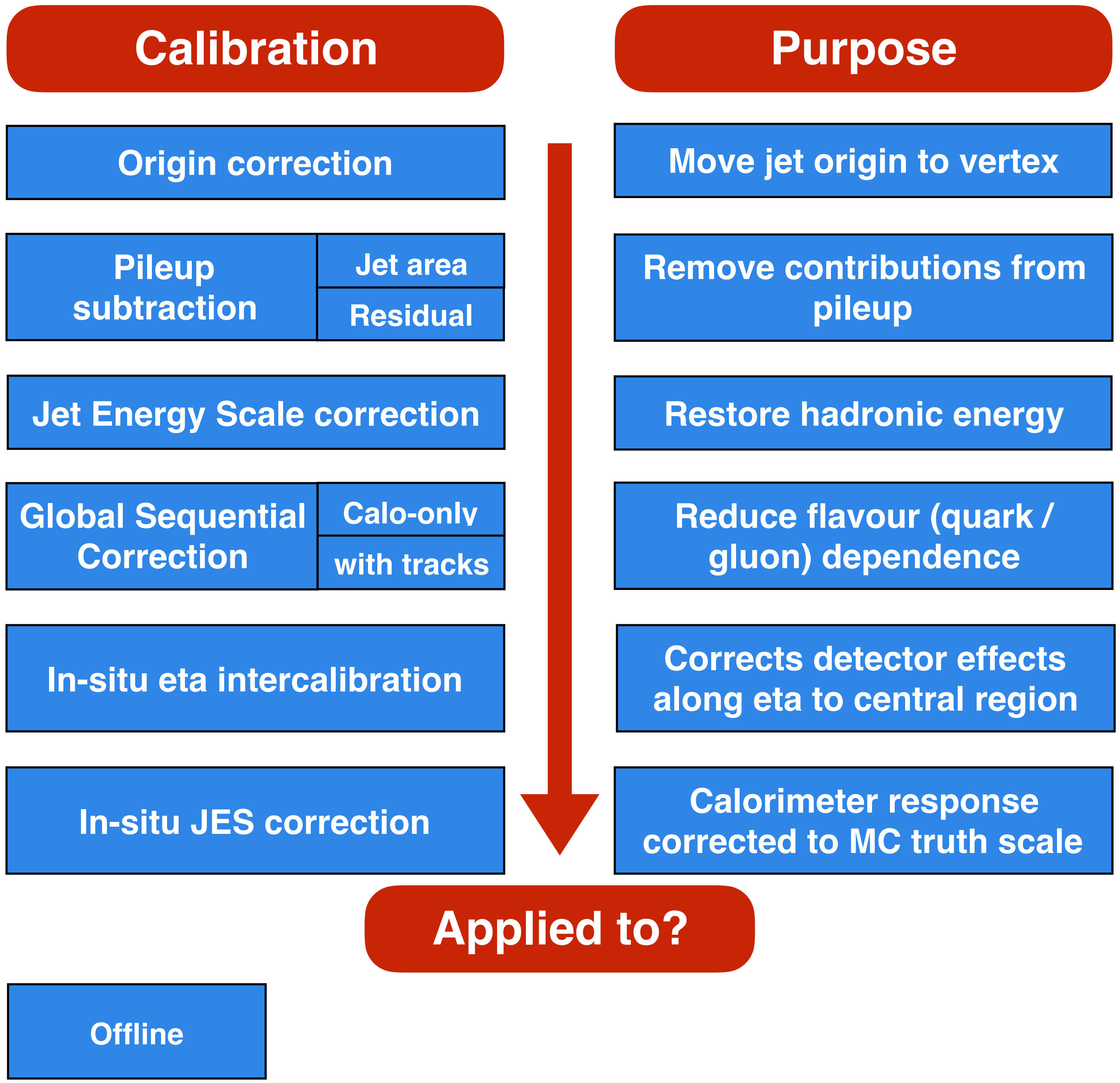
Before: offline - truth resolutions for width of m_{jj} peak

For triggers: trigger - offline resolution, i.e. how good are we at selecting the events we want to analyse?

This is set by how similar we can make trigger jets to offline jets, given:

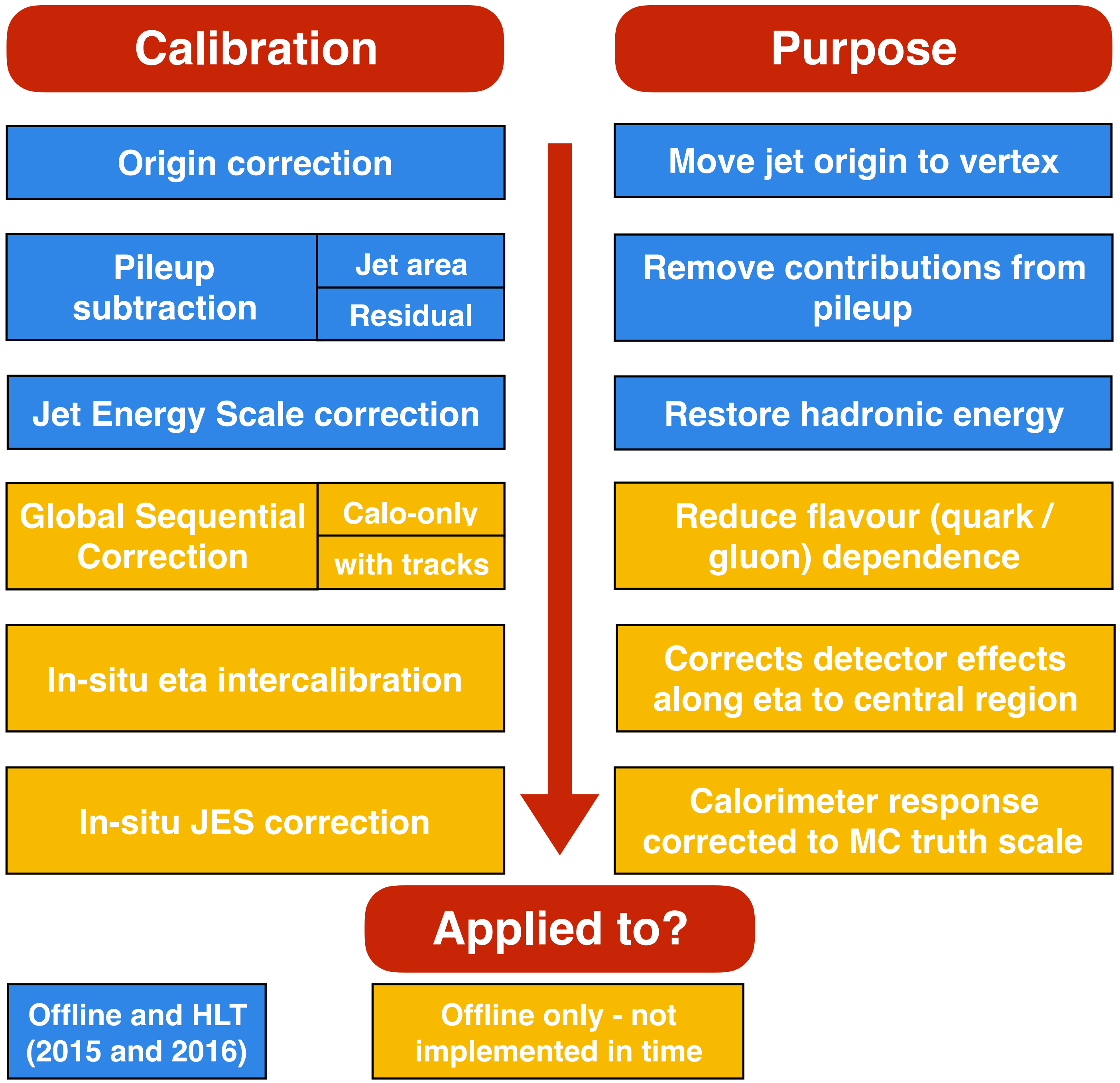
- partial event information (eg restricted / no tracking)
- trigger calibrations determined before data-taking, offline afterwards!

Jet trigger calibration



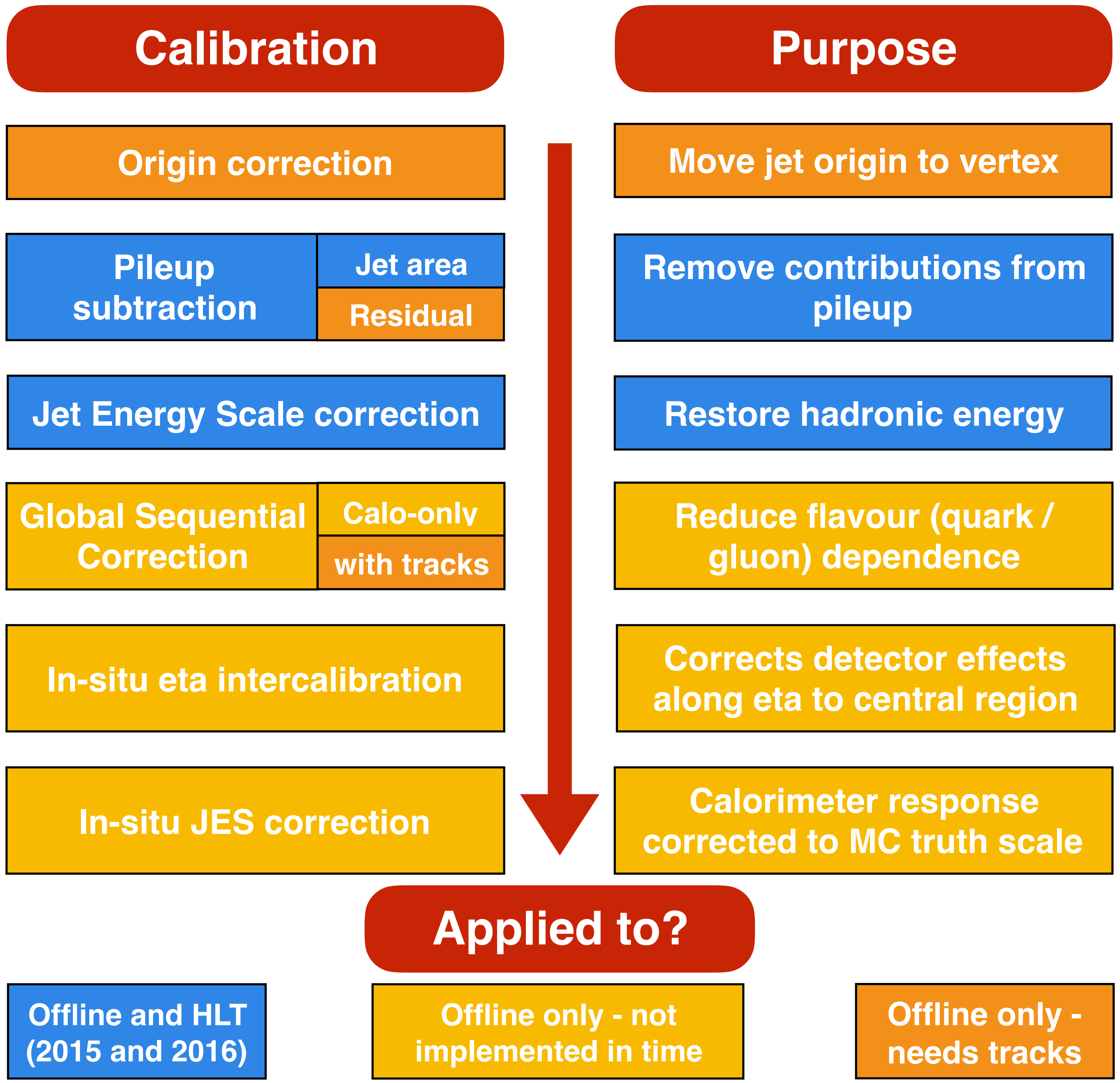
- Start with offline calibration chain

Jet trigger calibration



- Start with offline calibration chain
- No GSC or in-situ in 2015/16 data (developed using 2015 data!)

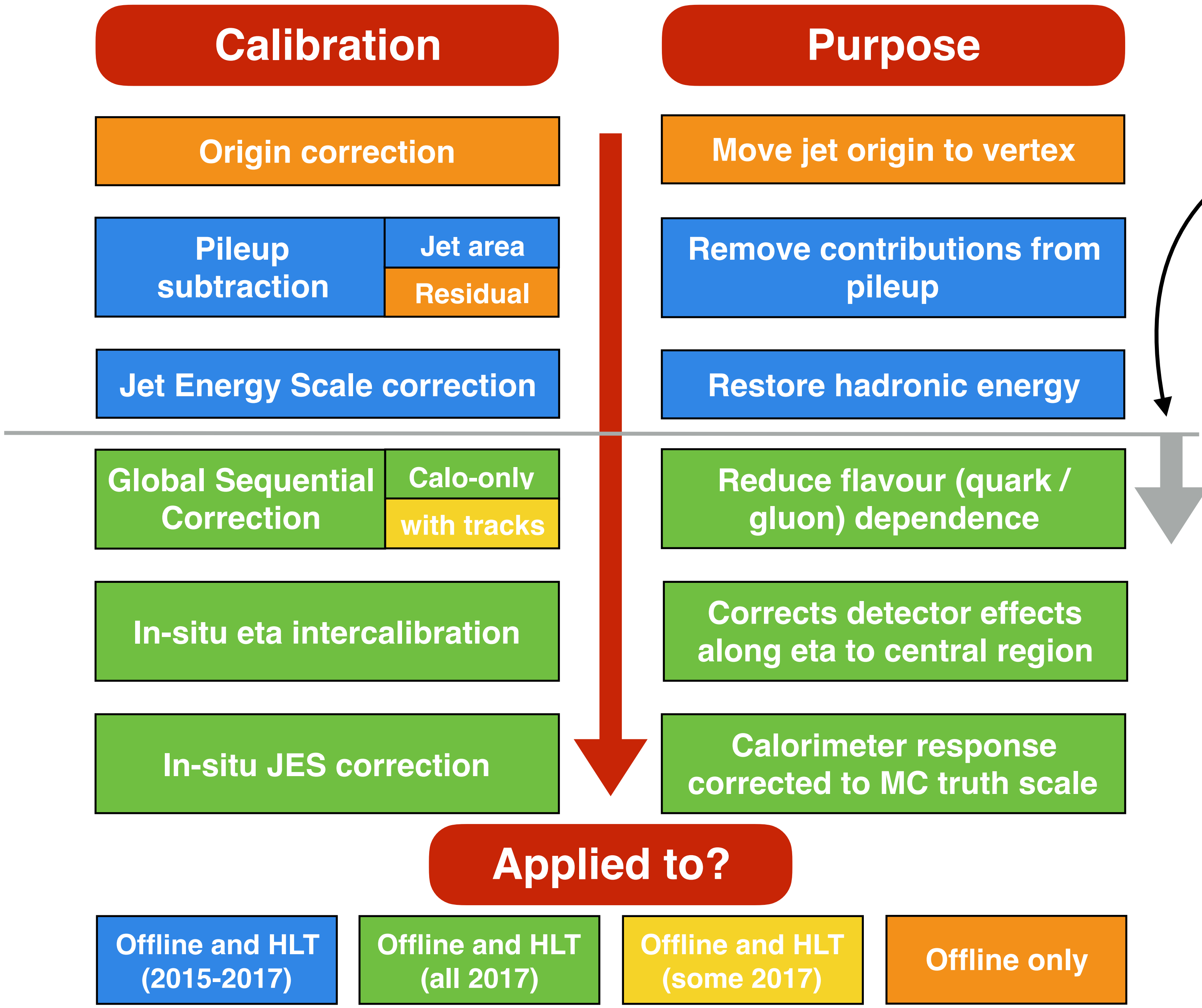
Jet trigger calibration



Status in 2015 and 2016 data

- Start with offline calibration chain
- No GSC or in-situ in 2015/16 data (developed using 2015 data!)
- Also: no tracks!
  - very CPU intensive in ATLAS trigger -> infeasible to run full tracking

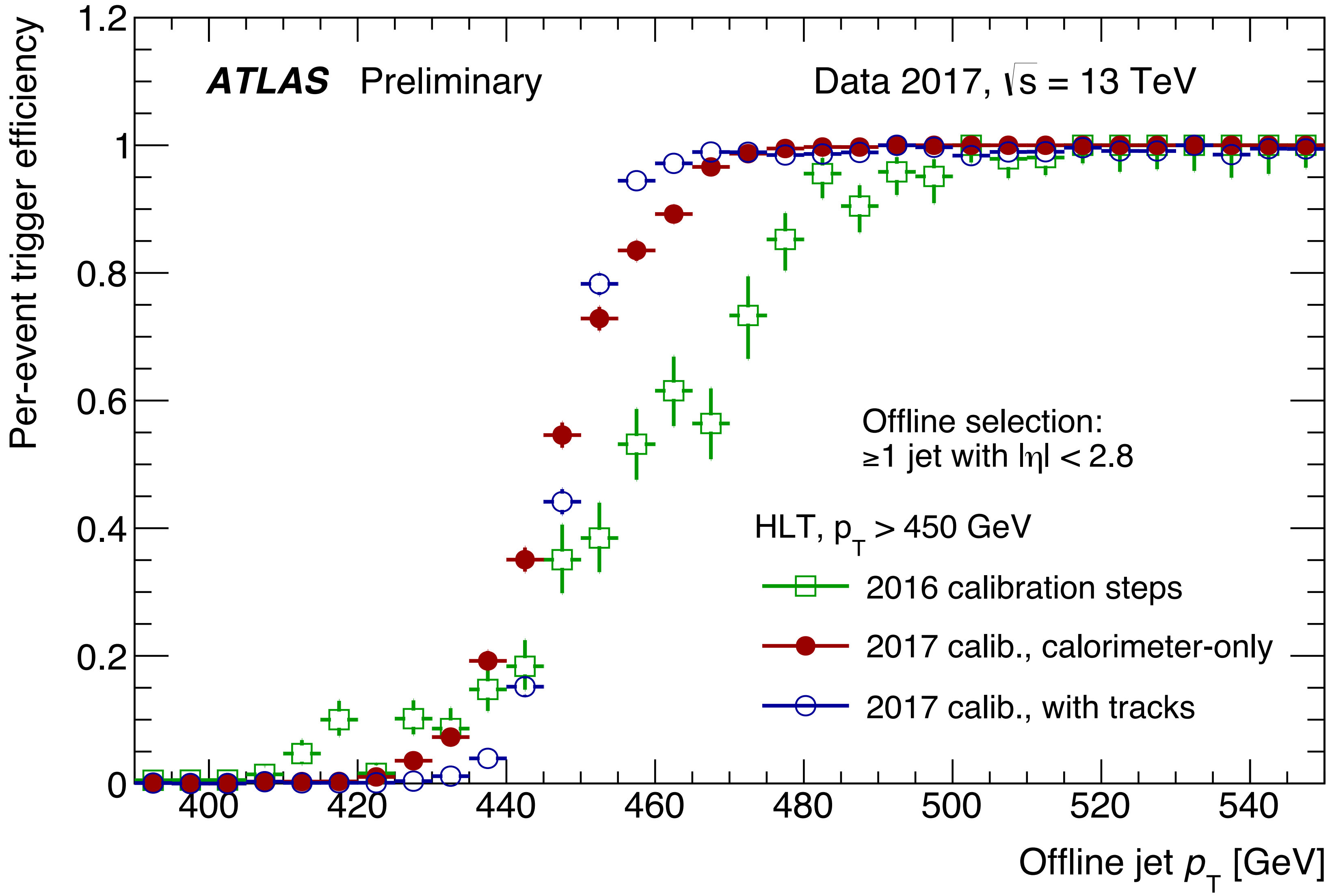
Jet trigger calibration



Status in 2017 data

- New in 2017
  - Apply partial GSC and in-situ calibrations to all trigger jets
  - Some HLT tracking in jets is possible within CPU constraints - can apply GSC to some trigger jets

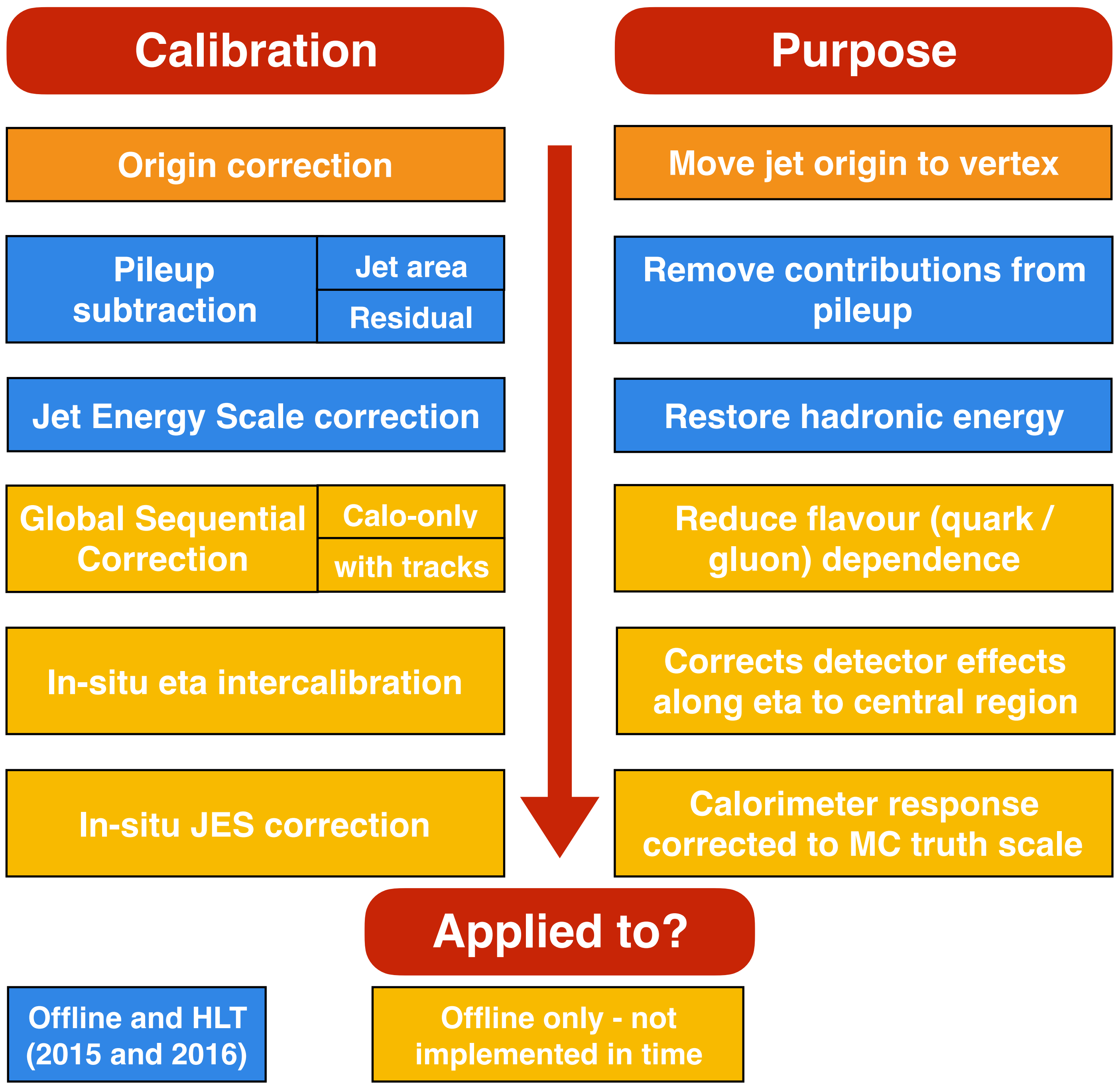
Jet trigger calibration



jet area
+ etaJES
+ calo GSC
+in-Situ
+track GSC

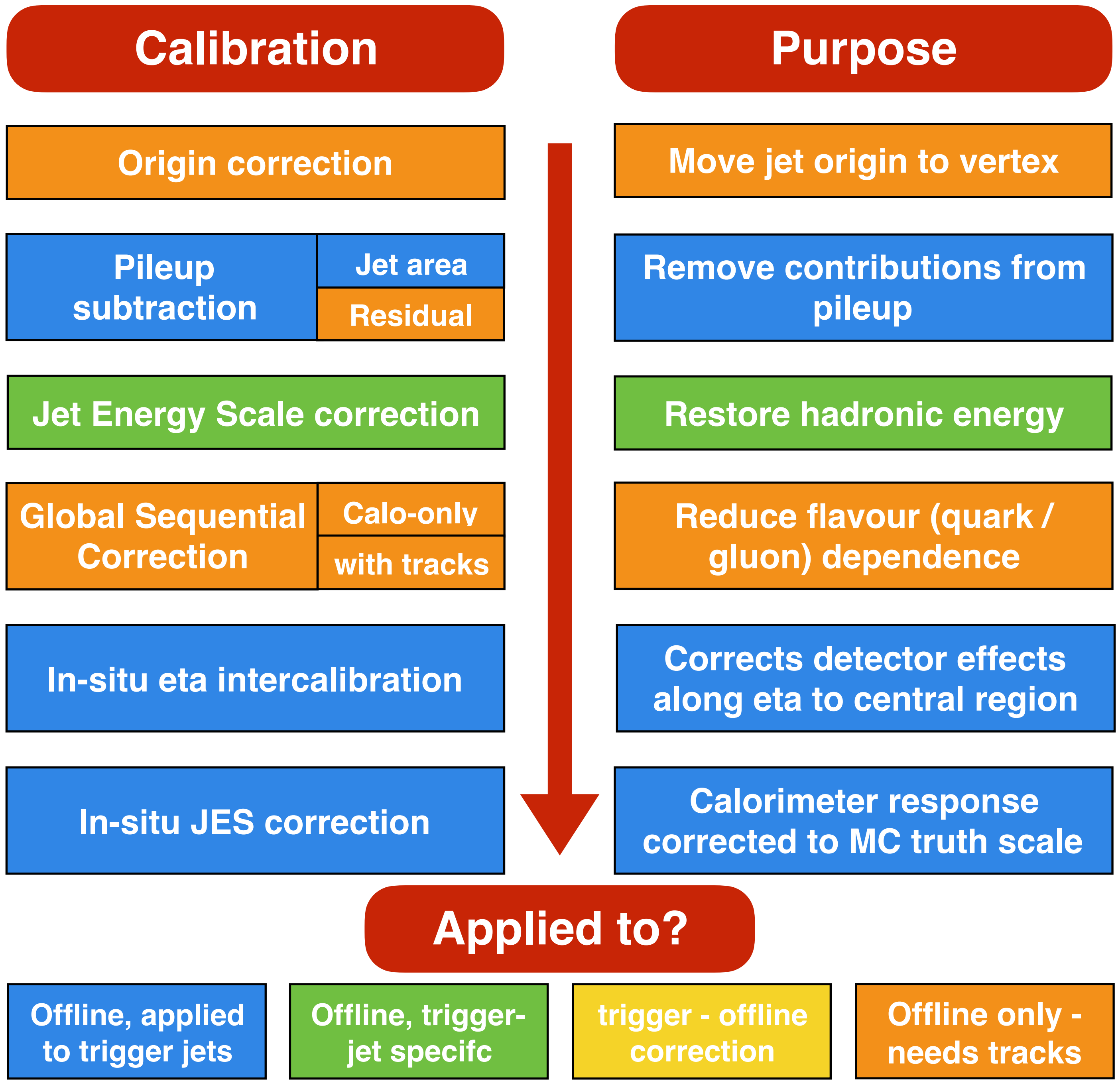
- Application of more steps in calibration chain hugely improves resolution and turnon
- Partially offsets threshold increases required from luminosity increases

Offline trigger jet calibration



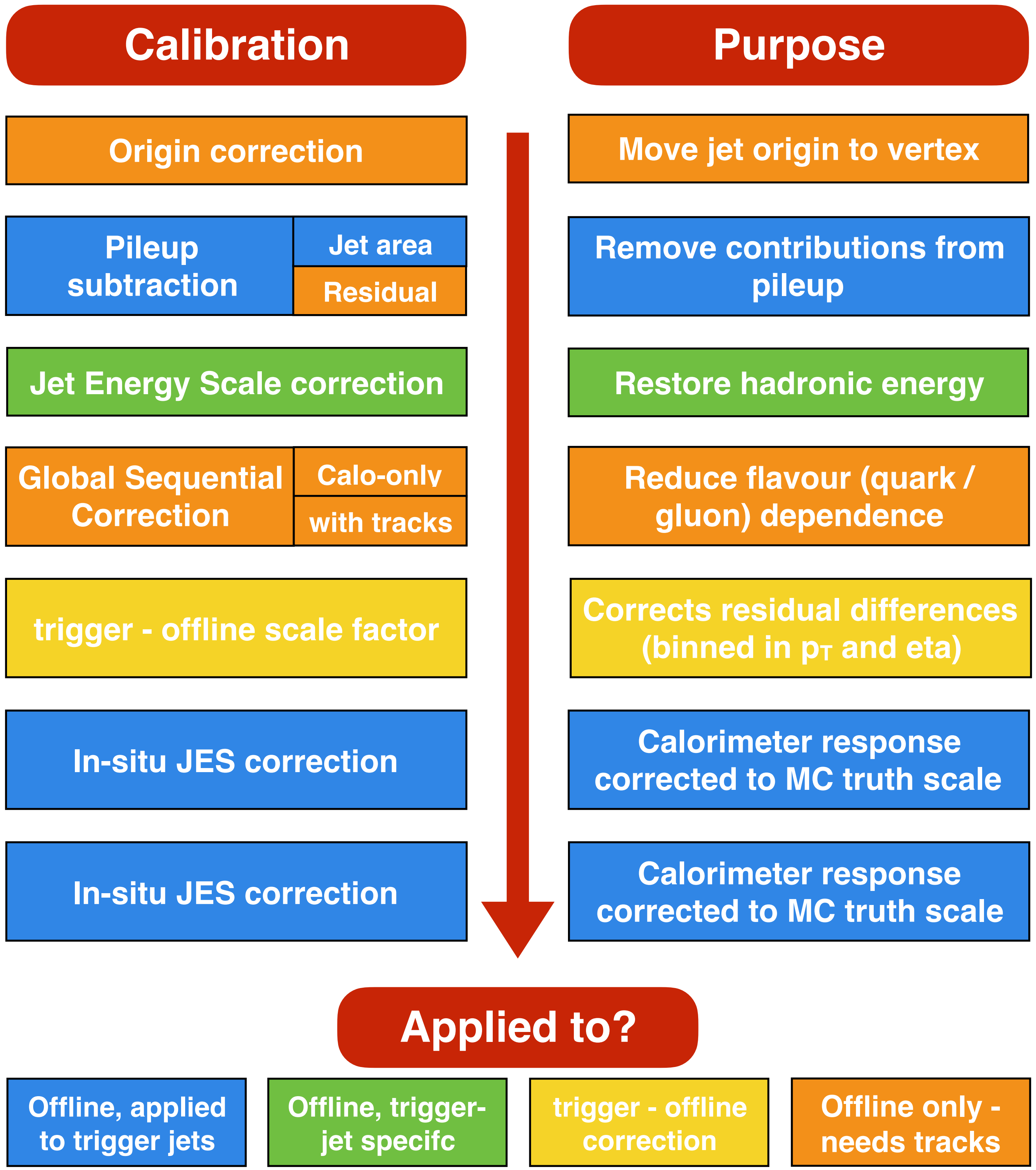
- We save enough information to be able to (re)do most of the calibration offline

Offline trigger jet calibration



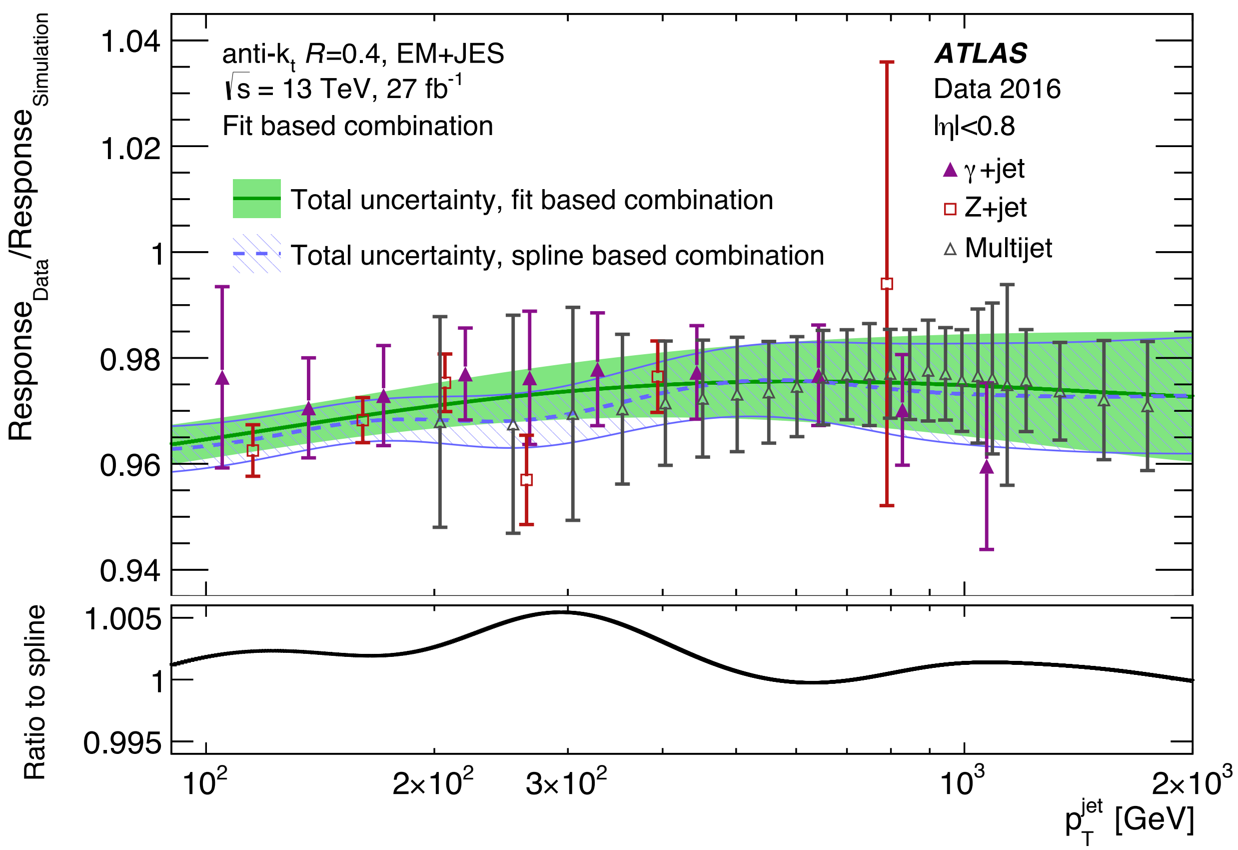
- We save enough information to be able to (re)do most of the calibration offline
- Some parts specifically redefined for trigger jets

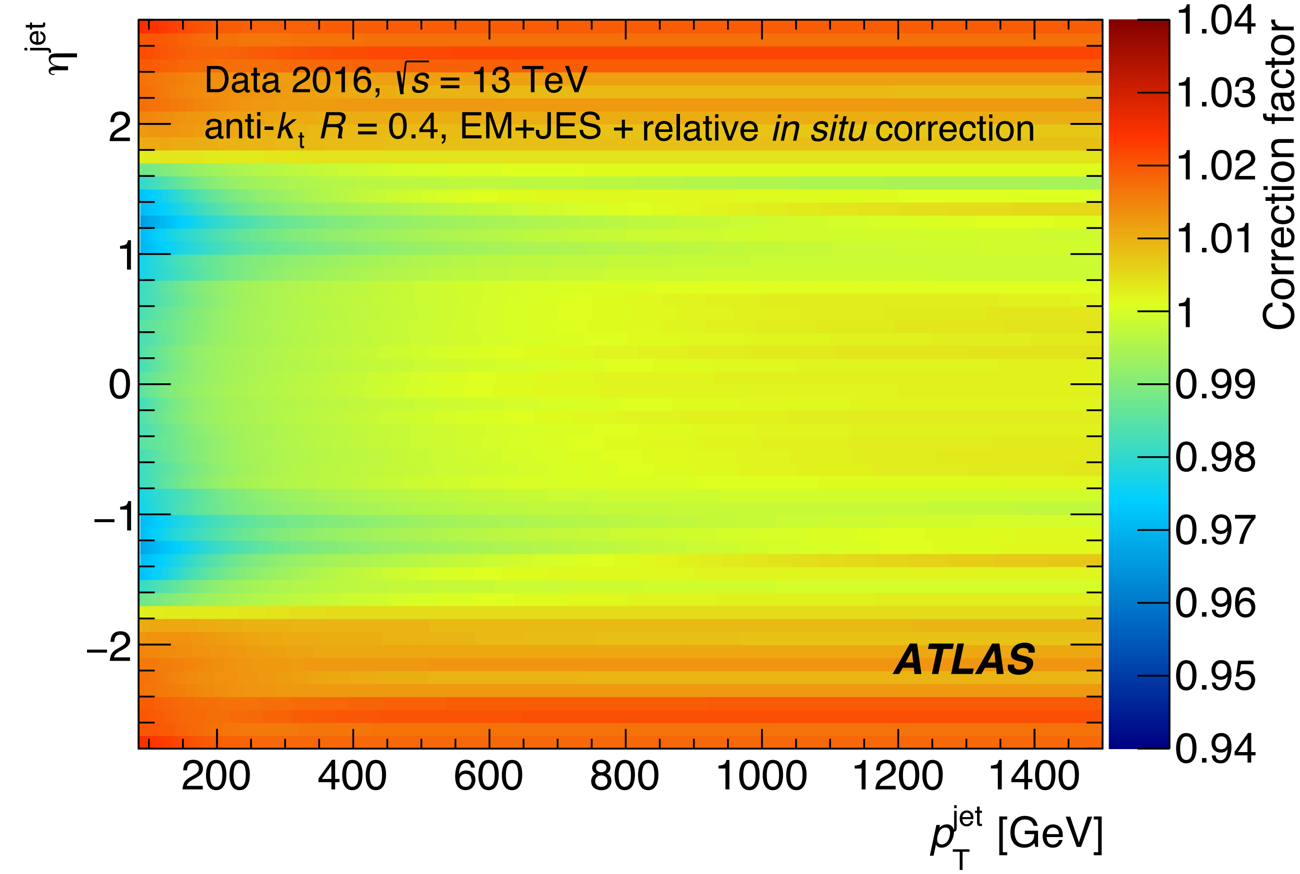
Offline trigger jet calibration



- We save enough information to be able to (re)do most of the calibration offline
- Some parts specifically redefined for trigger jets
- Apply scale factor between trigger and offline jets to correct residual differences

TLA trigger jet calibration





Custom "in-situ" step to ensure smoothness - statistical fluctuation in normal spline-based combination leads to bump in p_T and hence m_{jj}

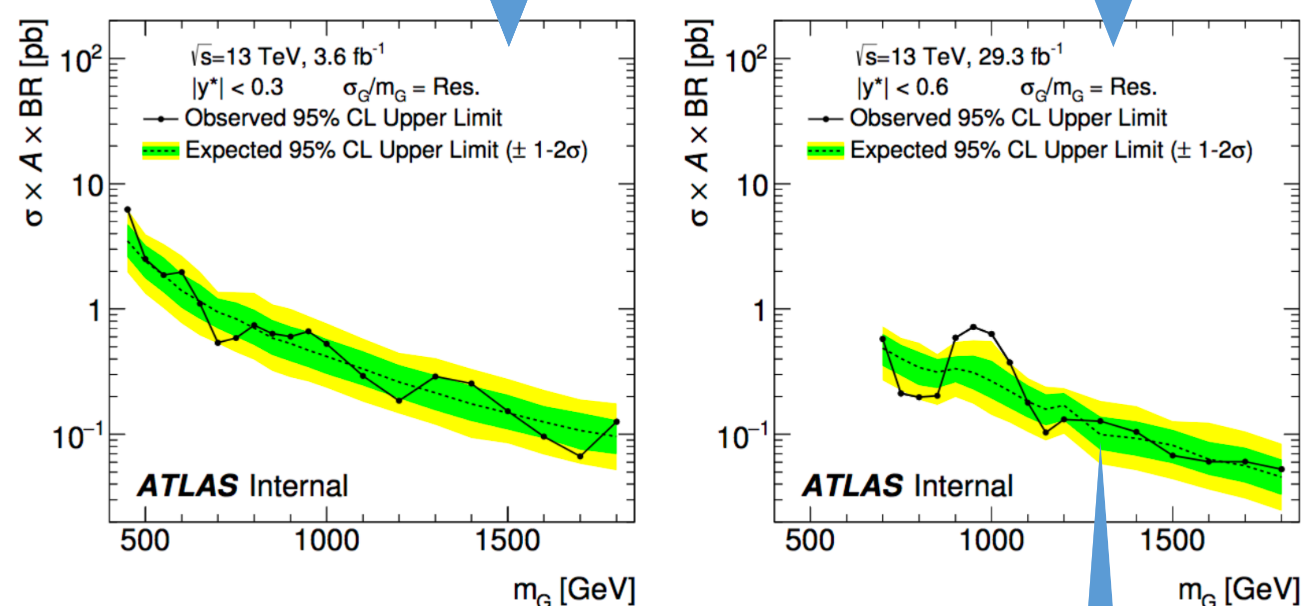
Excellent trigger : offline agreement

Expected limits fluctuations

- Real signal can exist in data, but expected limits need to represent signal-free background
    - Fit signal+background model for each signal point
    - Set signal component to zero & throw toys for expected limit
- Thus the model used to generate the expected limits is **different for each signal point**, since a different signal is included in each signal+background fit
    - Results in wobbly expected limits
    - **More pronounced the more "flexible" the background estimation is**

Window half-width = 13

Window half-width = 9

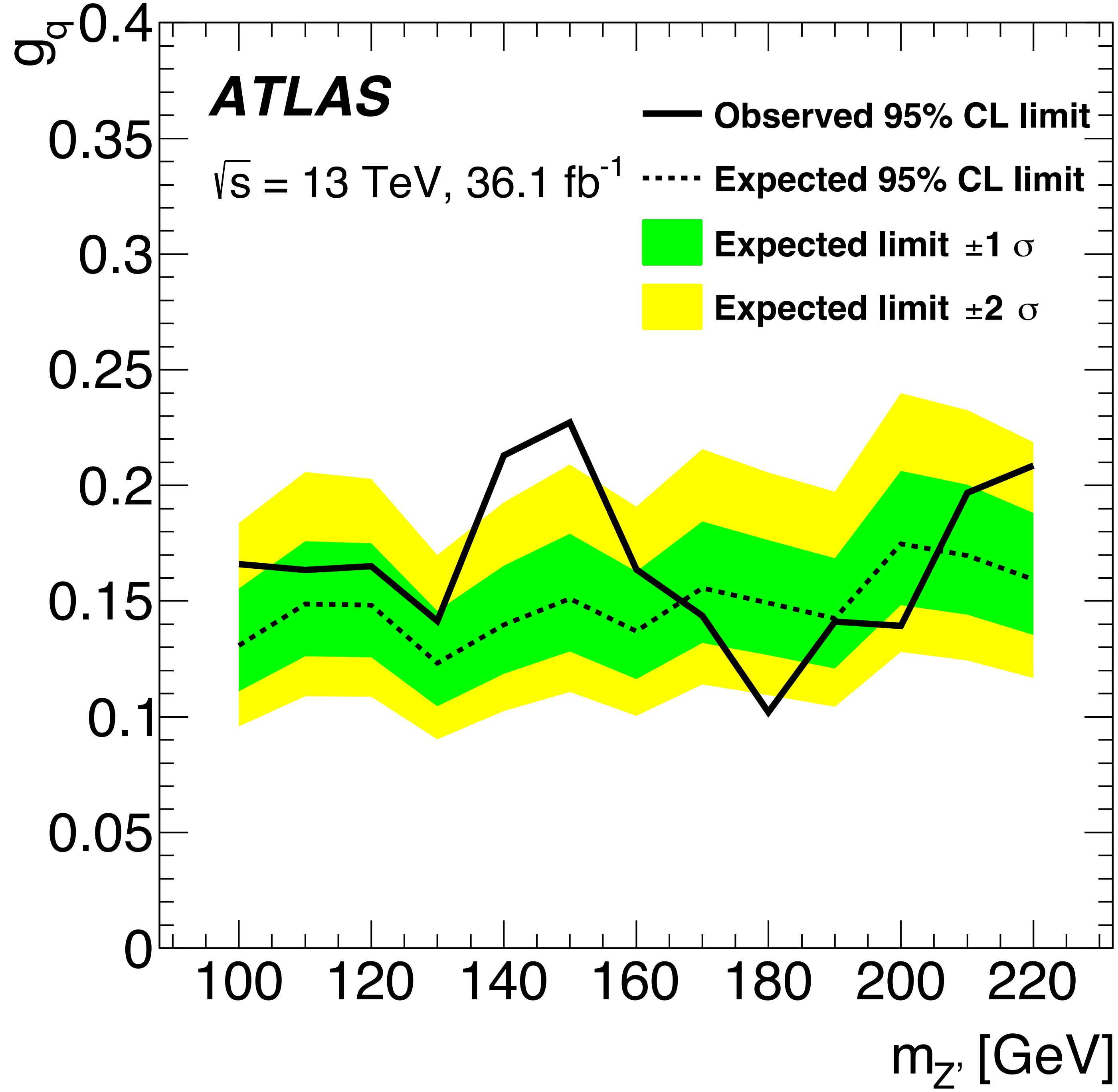


(a) $|y^*| < 0.3, \sigma_G/m_G$ = Res. (b) $|y^*| < 0.6, \sigma_G/m_G$ = Res.

wobbly!

Large-R + ISR results

arxiv: 1801.08768, EXOT-2017-01



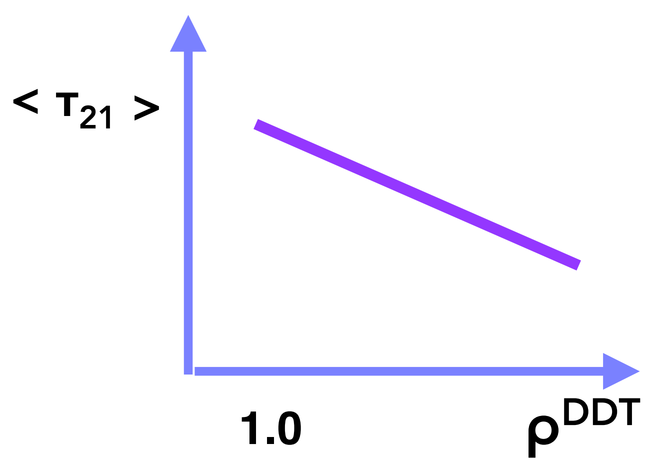
Observed and expected limits at 95% confidence level on the coupling (g_q), for the combination of the ISR jet and ISR γ channels

Large-R + ISR DDT

arxiv: 1801.08768, EXOT-2017-01

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

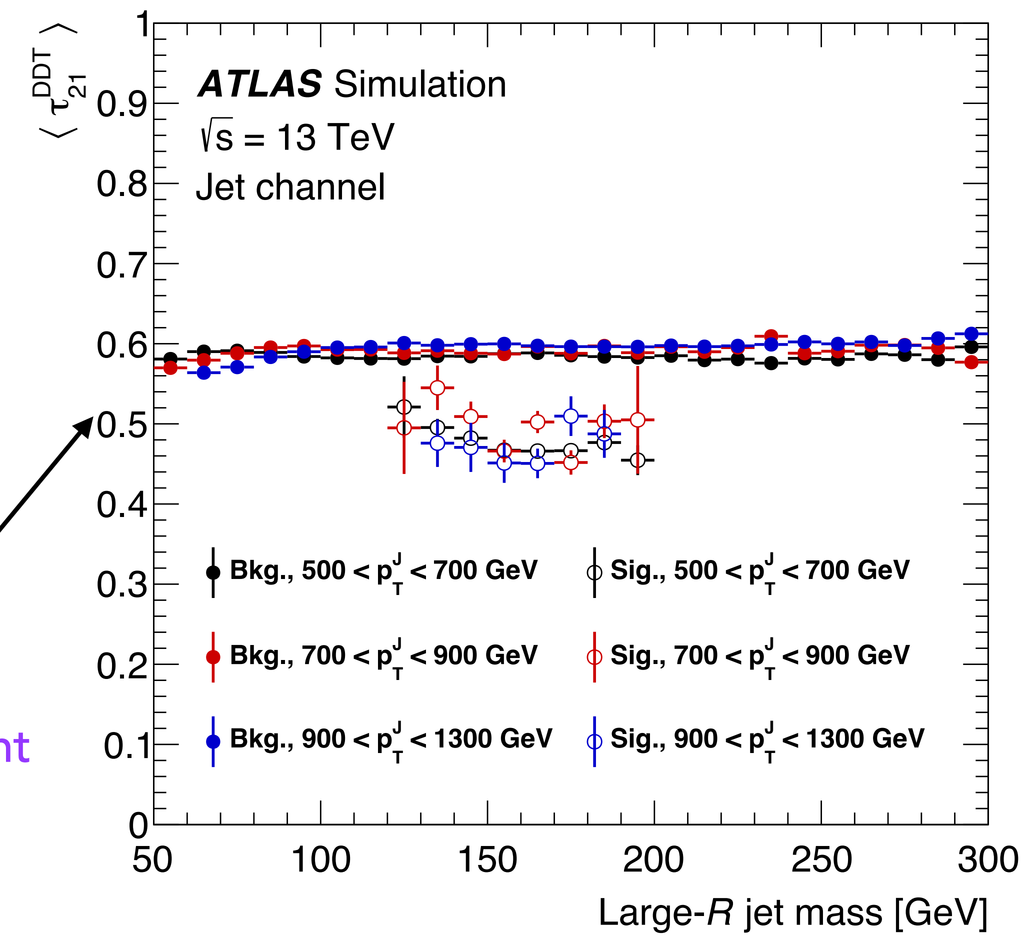
Linear relationship between $\boldsymbol{\rho}^{\mathrm{DDT}}$ and $< \boldsymbol{\tau}_{21} >$ for $\boldsymbol{\rho}^{\mathrm{DDT}} > \sim 1$



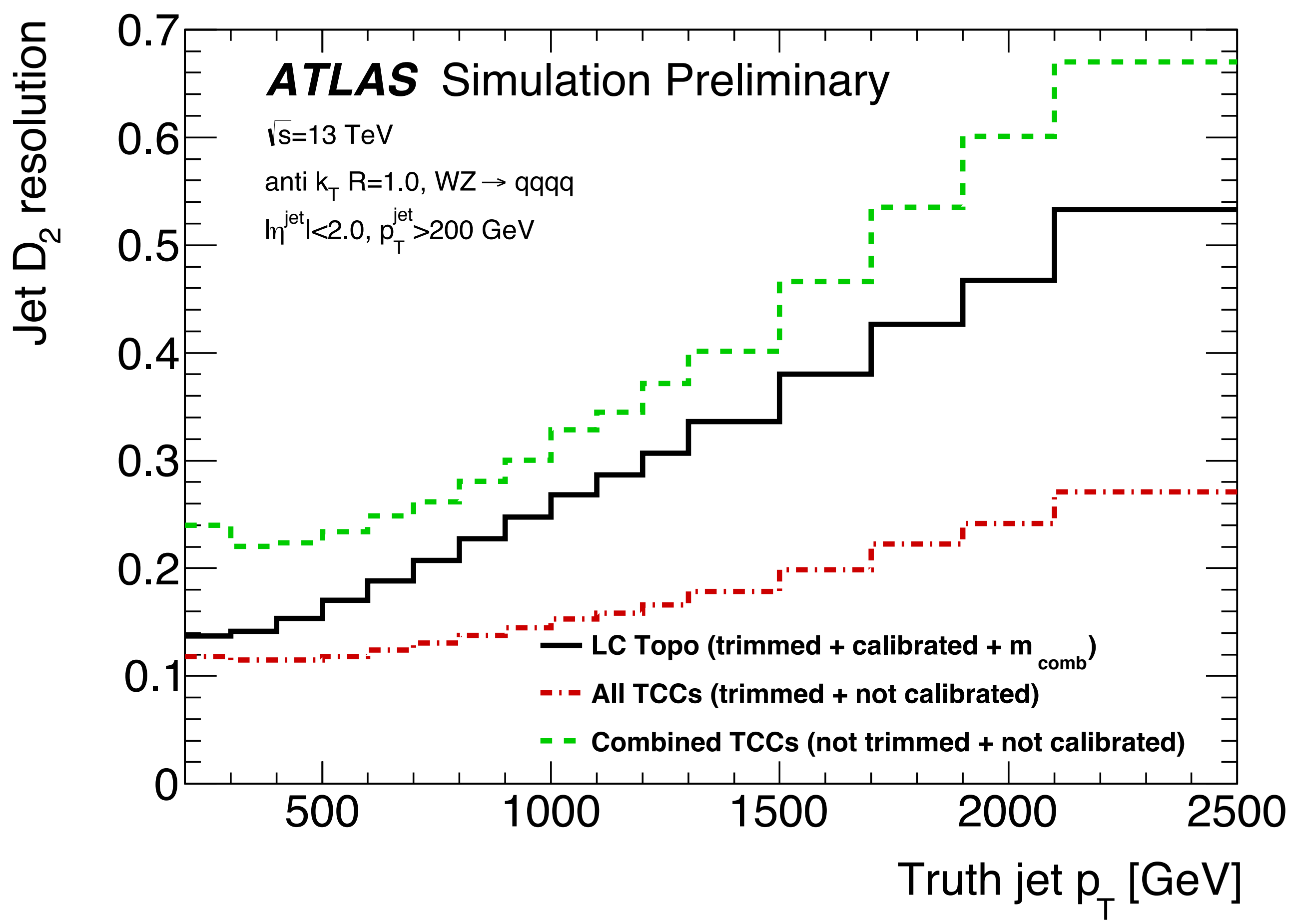
Define $\boldsymbol{\tau}_{21}{}^{\mathrm{DDT}}$: linearly corrected version of $\boldsymbol{\tau}_{21}$

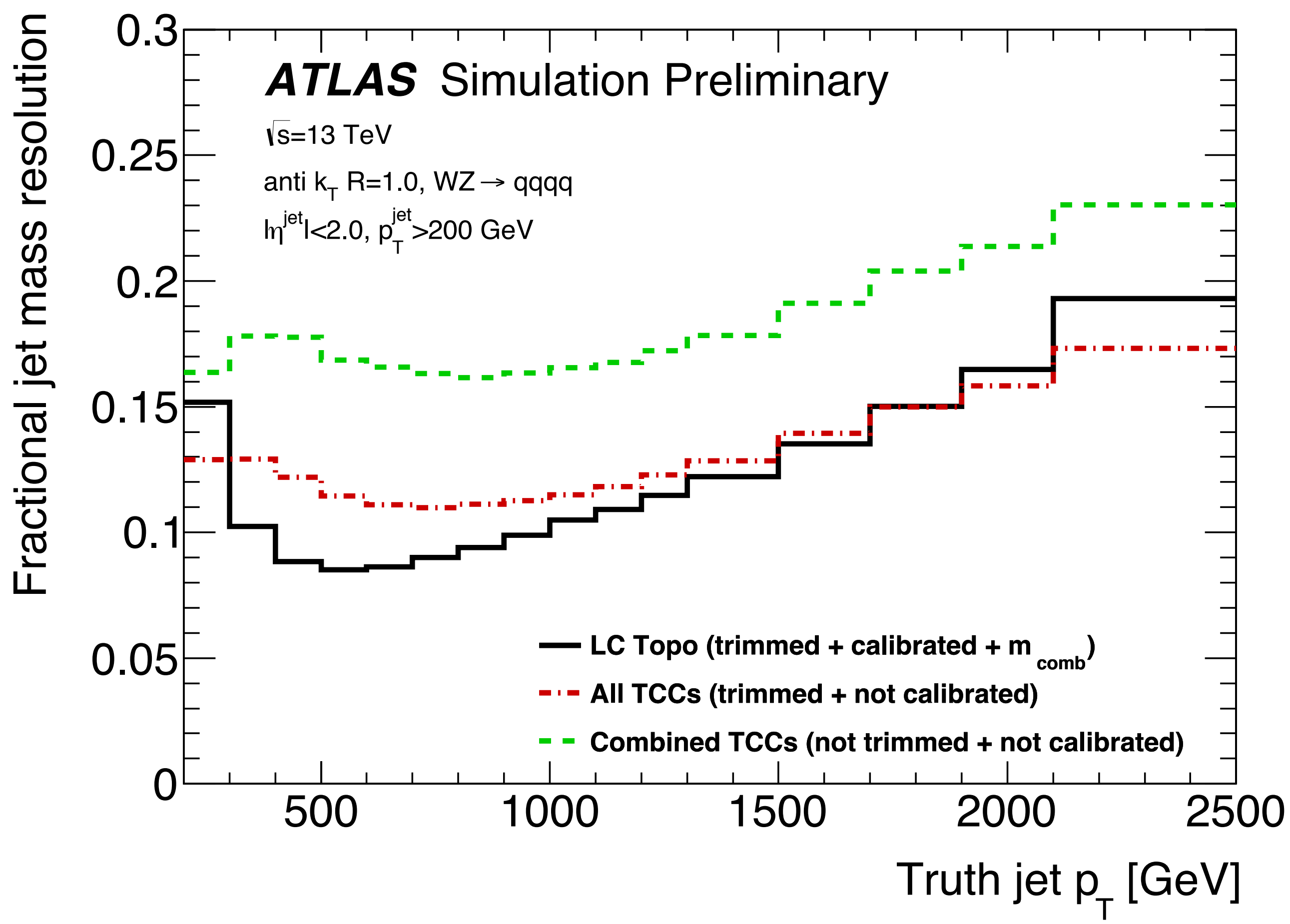
$\boldsymbol{\tau}_{21}{}^{\mathrm{DDT}}$ independent of jet mass

arXiv:1801.08769



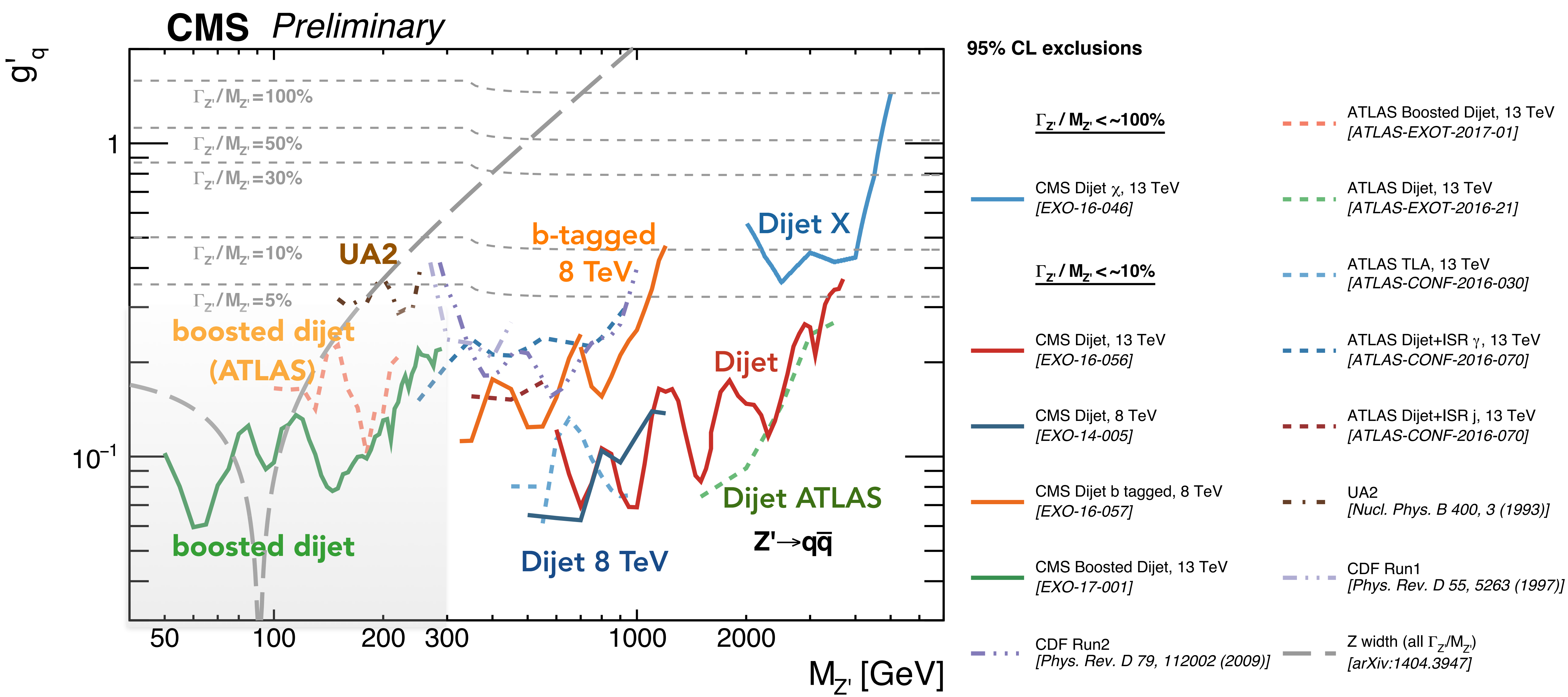
Tracking in CaloClusters





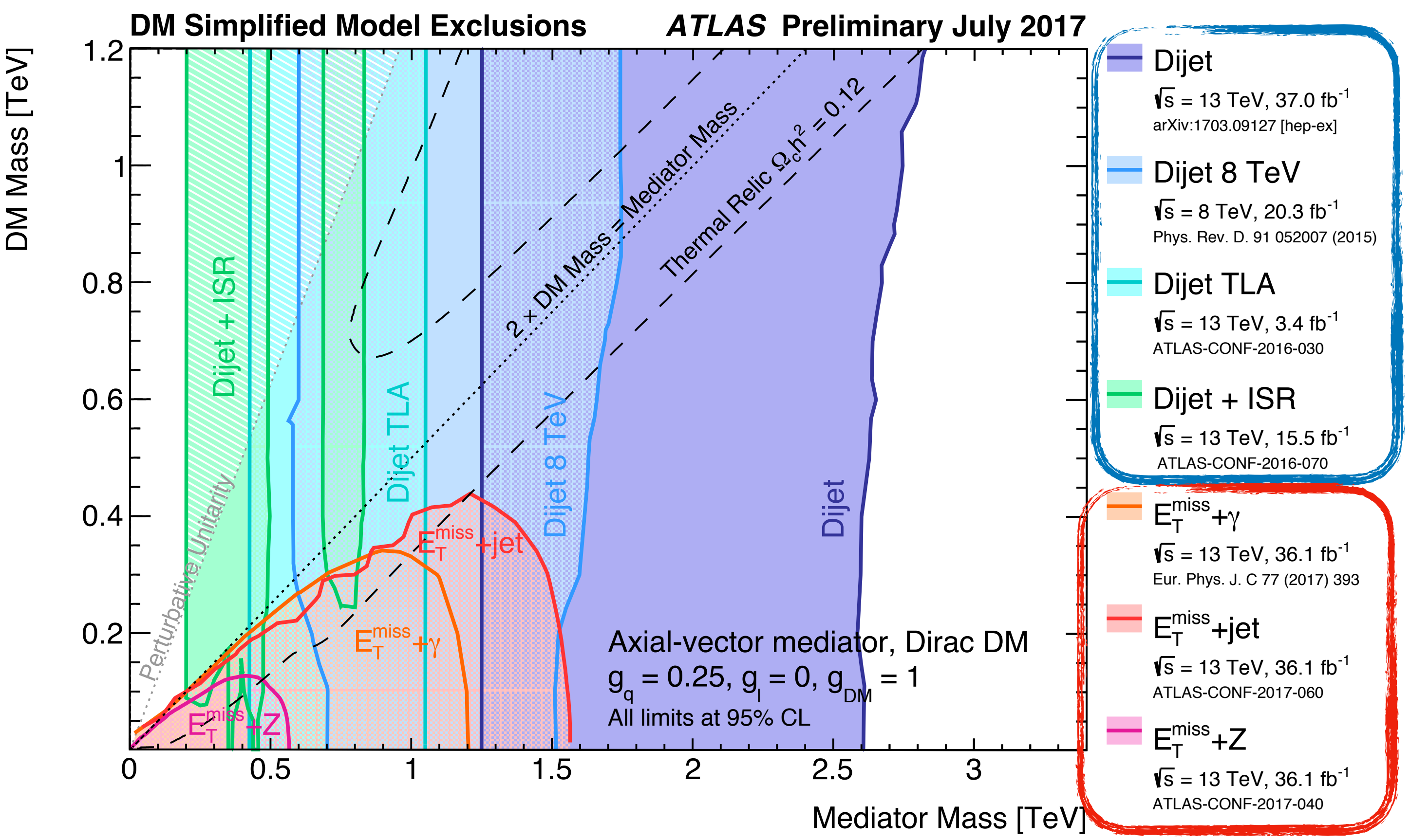
- Improvements in jet substructure resolution thanks to track information in jet reconstruction inputs ATL-PHYS-PUB-2017-015
- Black -> Red
  - Mostly low p_T -> improvement in D2, degradation in mass

CMS and ATLAS limits



ATLAS TLA updated since this plot

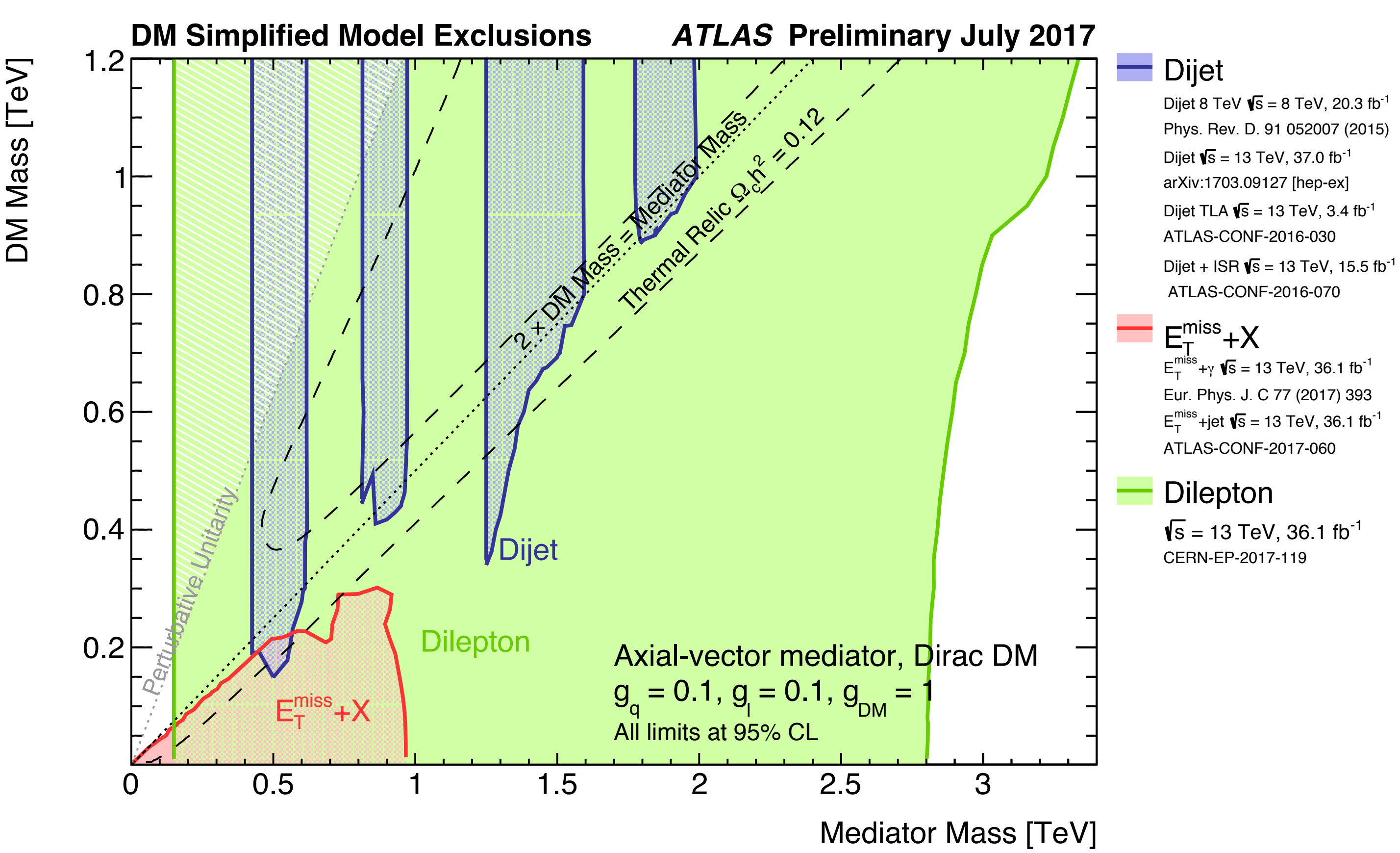
Wider context



dijet

mono-X

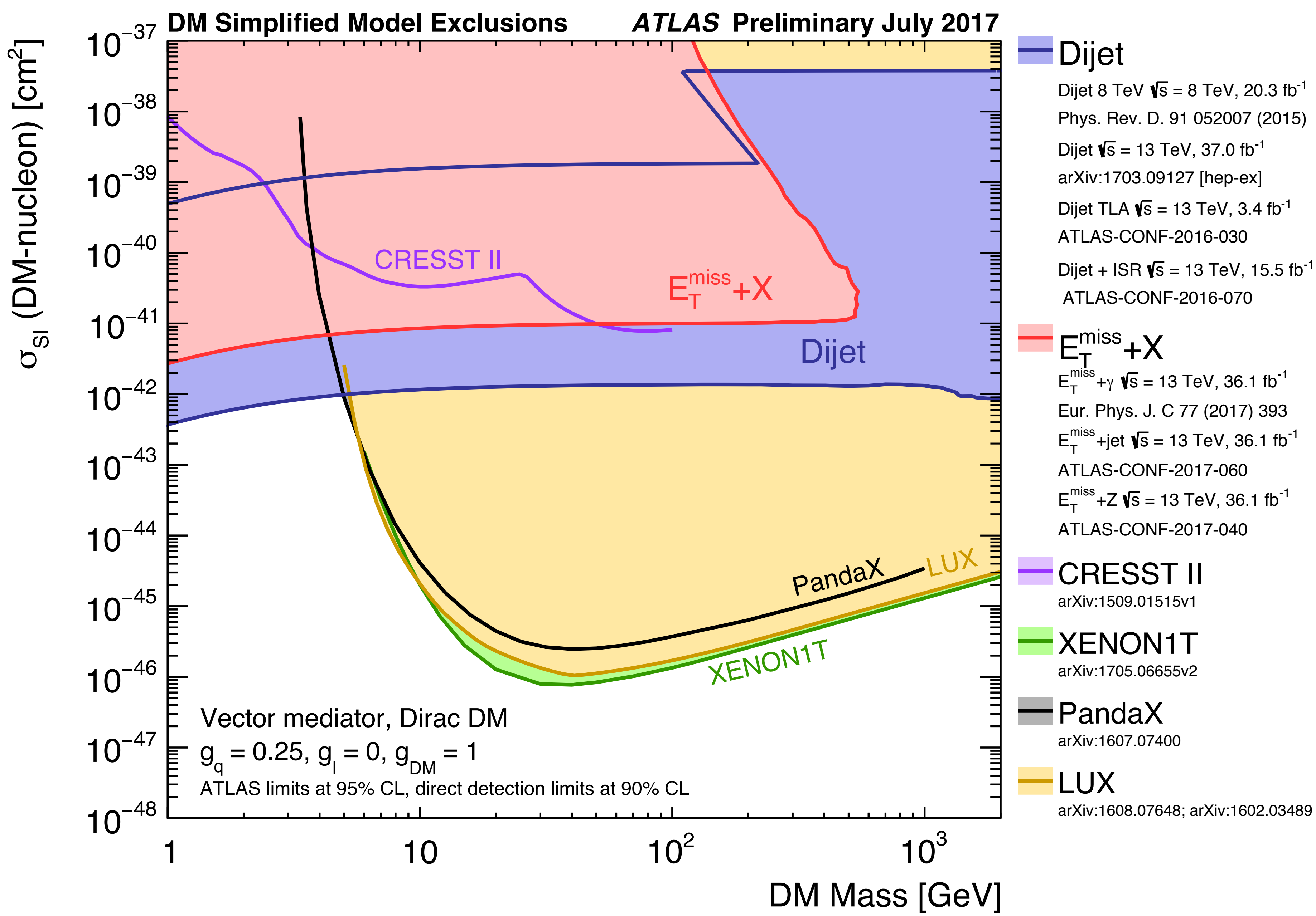
Sensitivity decreases as DM mass decreases (Z’ branching ratio to dijets decreases) -> covered by mono-X searches



Interpretation is very model-dependent

Sensitivity decreases as lepton coupling g_l increases and quark coupling g_q decreases -> covered by dilepton resonance searches

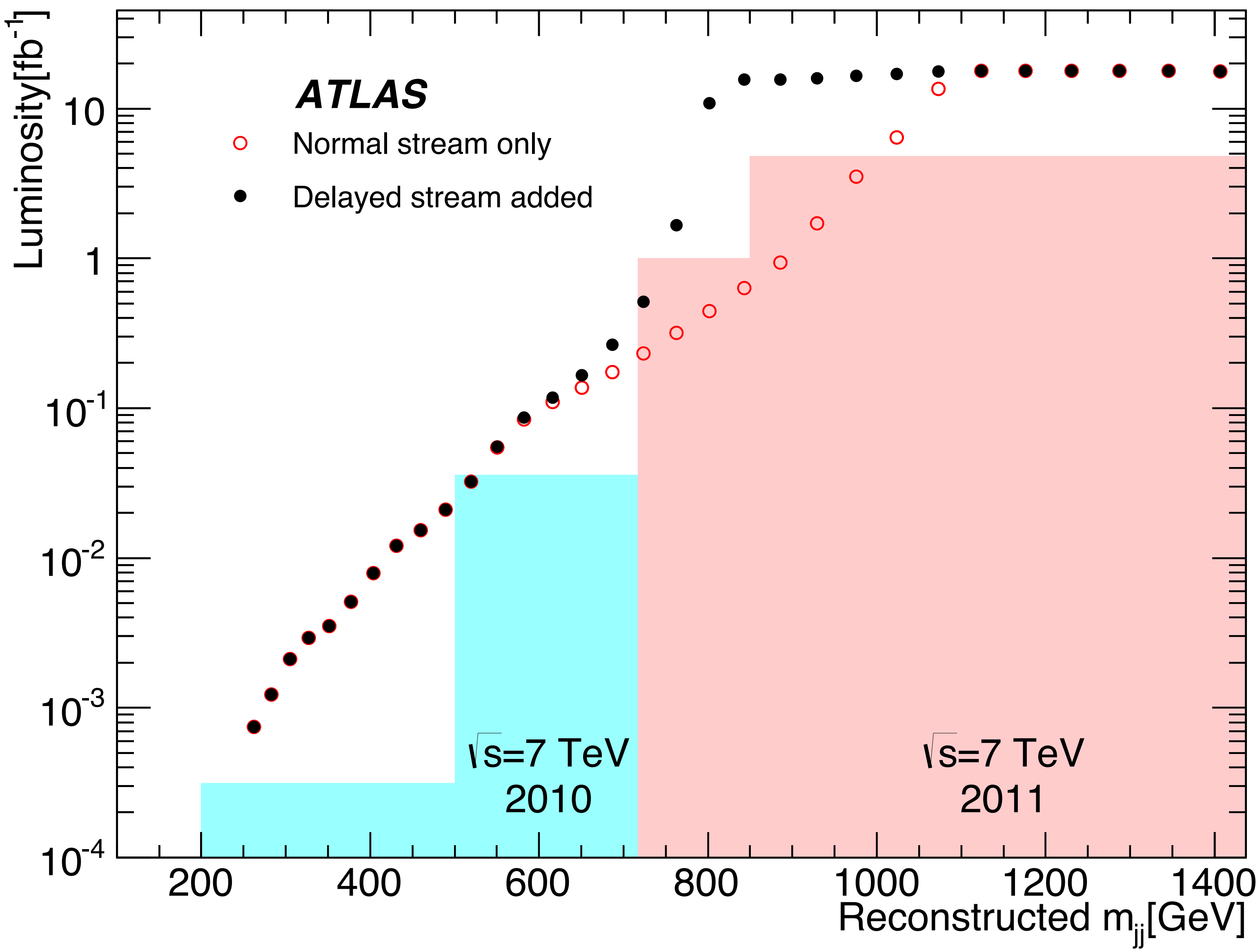
Even wider context



Interpretation is even more model-dependent

Nice complementarity between direct detection, collider production with mono-X and "indirect searches" with dijet resonances

8 TeV 20.3 fb^{-1} triggers



prescaled single jet triggers
plus delayed stream