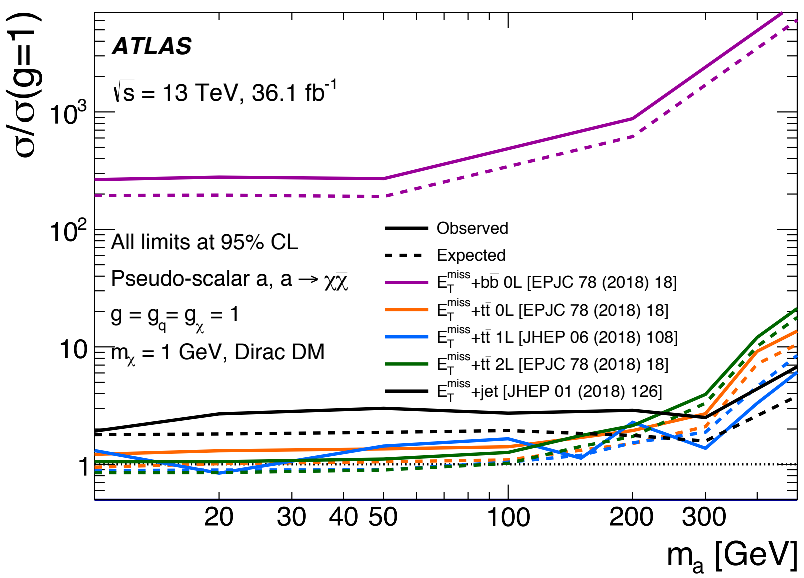
Recent results on searches for Dark Matter in ATLAS

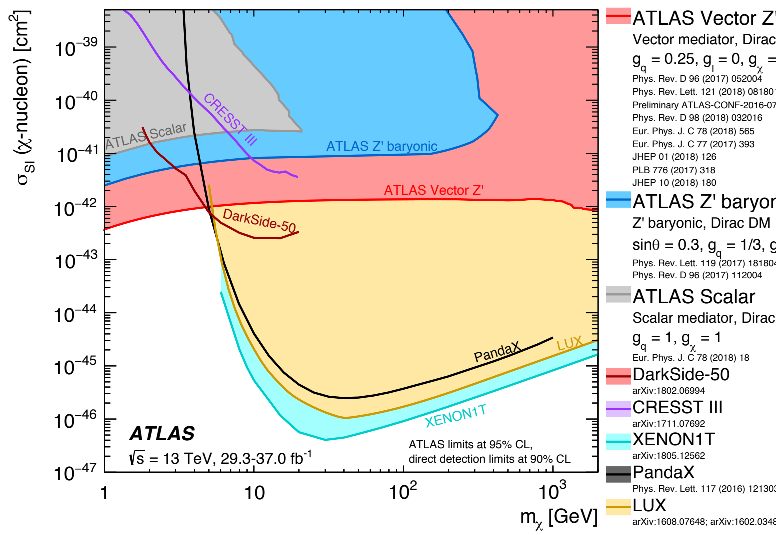
LHCP Puebla
23.05.19

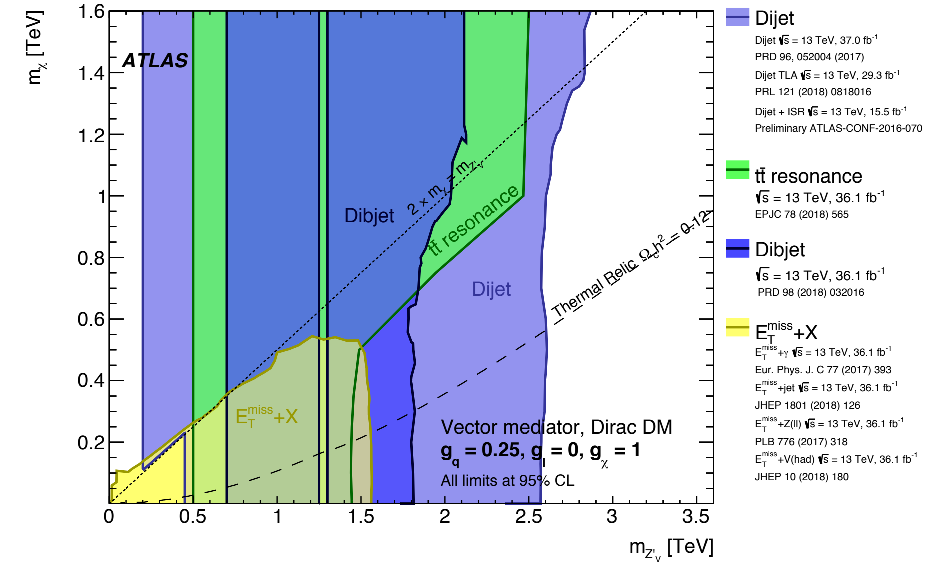
Will Kalderon,
Lund University (SE)

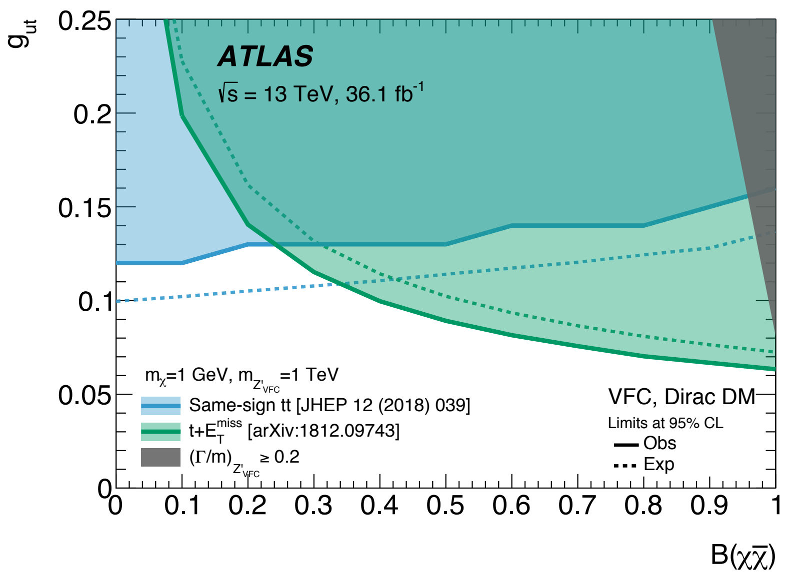
on behalf of the ATLAS Collaboration

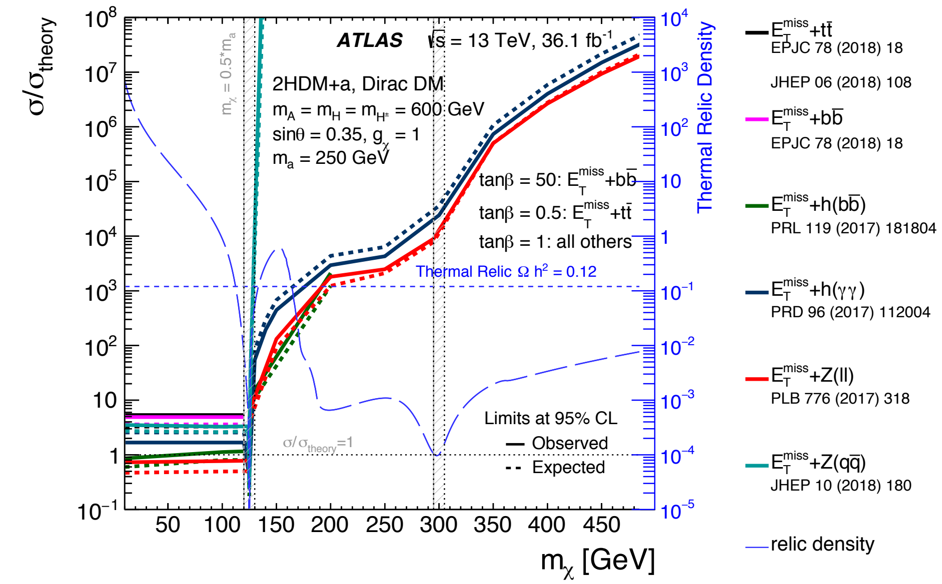
Recent (summary paper of) results





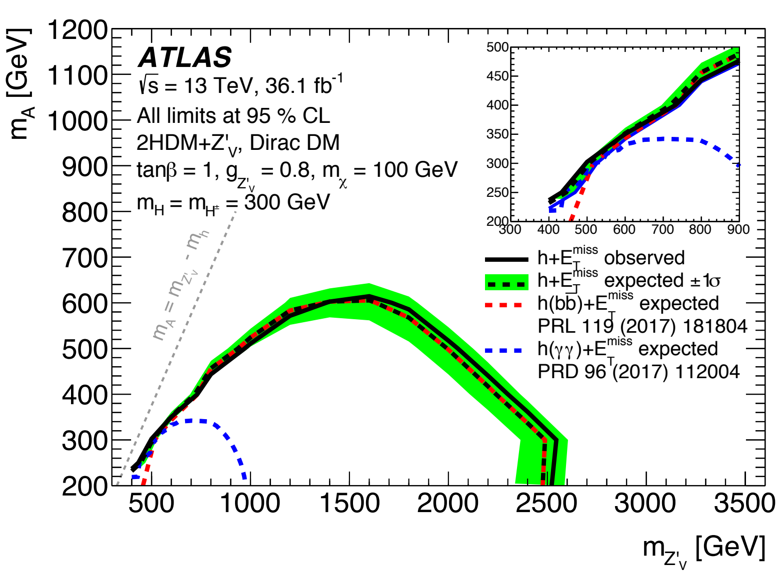


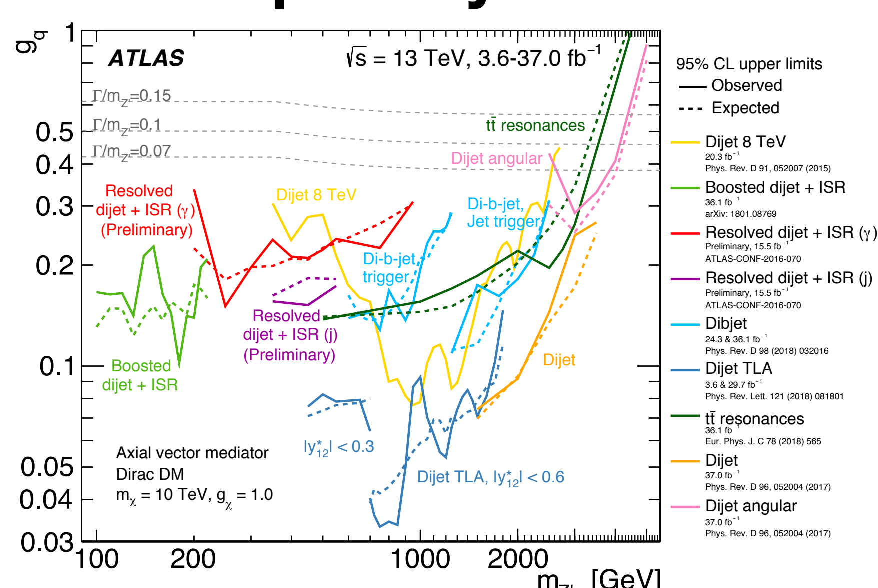


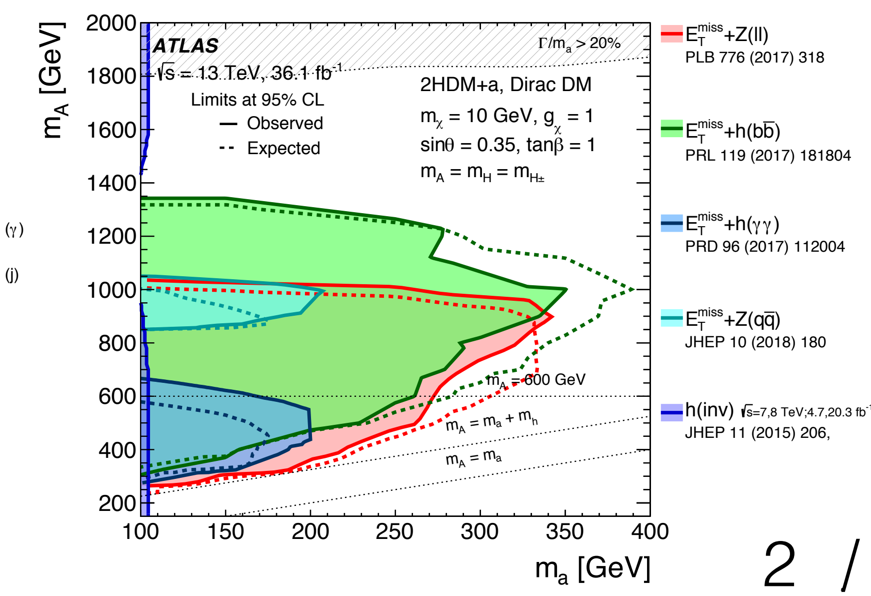


Constraints on mediator-based dark matter and scalar dark energy models using √s=13 TeV pp collision data collected by the ATLAS detector

<u>arXiv: 1903.01400</u>, accepted by JHEP

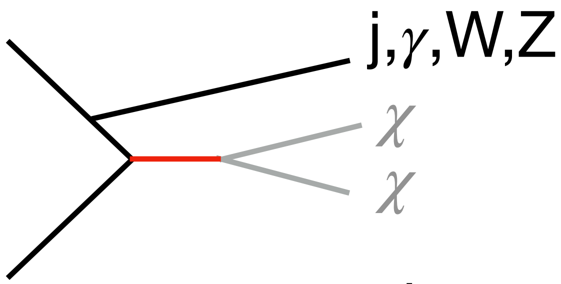


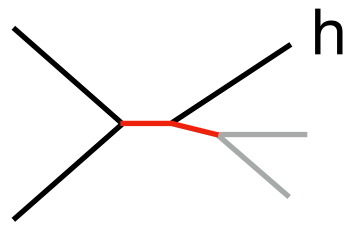


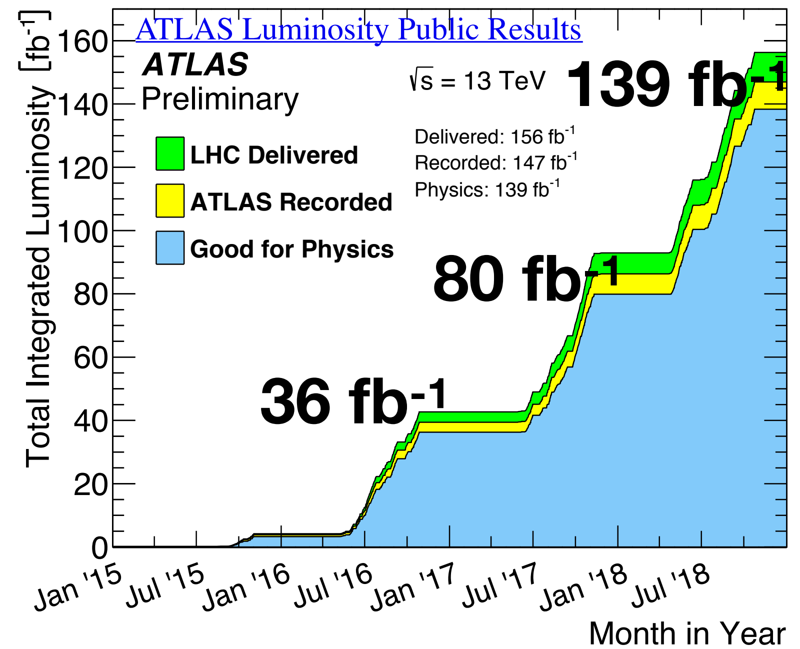


2017-19 ATLAS DM-related results

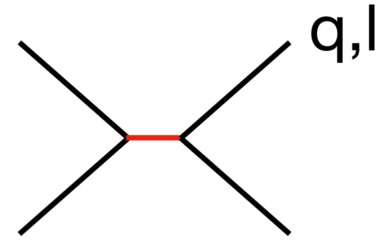
- E_T^{miss} + jet 36 fb^{-1}, JHEP 01 (2018) 126
- E_T^{miss} + photon 36 fb^{-1}, Eur. Phys. J. C 77 (2017) 393
- E_T^{miss} + Z(ll) 36 fb^{-1}, PLB 776 (2017) 318
- E_T^{miss} + V(qq) 36 fb^{-1}, JHEP 10 (2018) 180
- E_T^{miss} + top 36 fb^{-1}, JHEP 05 (2019) 41
- E_T^{miss} + h($\gamma\gamma$) 36 fb^{-1}, Phys. Rev. D 96 (2017) 112004
- E_T^{miss} + h(bb) **80 fb^{-1}**, ATLAS-CONF-2018-039



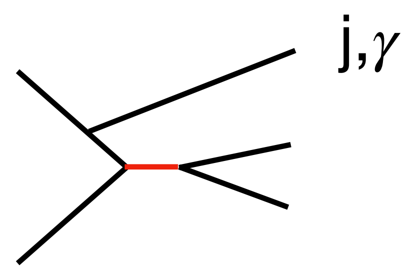




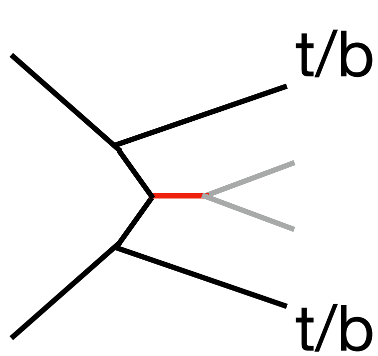
- Dijet resonances **139 fb^{-1}**, ATLAS-CONF-2019-007
- Angular dijet resonances 37 fb^{-1}, Phys. Rev. D 96 (2017) 052004
- Resolved dijet+ISR (+bjet) **80 fb^{-1}**, arXiv:1901.10917
- Di-b-jet resonances 36 fb^{-1}, Phys. Rev. D 98 (2018) 032016
- Dijet Trigger-Level Analysis 29 fb^{-1}, Phys. Rev. Lett. 121 (2018) 081801
- Boosted dijet+ISR 36 fb^{-1}, Phys. Lett. B 788 (2019) 316
- Boosted di-b-jet+ISR **81 fb^{-1}**, ATLAS-CONF-2018-052
- 1lepton ttbar resonances 36 fb^{-1}, Eur. Phys. J. C 78 (2018) 565
- Hadronic ttbar resonances 36 fb^{-1}, Phys. Rev. D 99 (2019) 092004
- Dilepton resonances **139 fb^{-1}**, arXiv:1903.06248

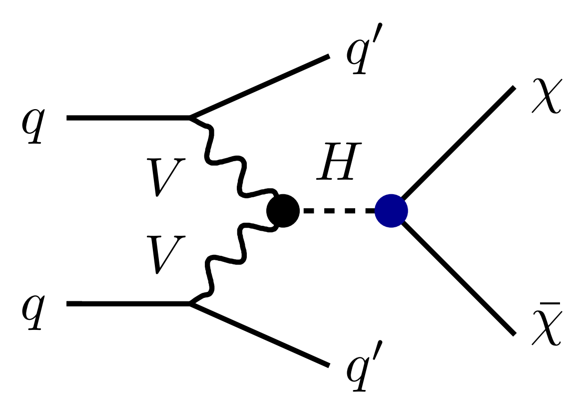


In DM summary
Updated since
Not included (new!)



- H->inv 36 fb^{-1}, arXiv:1809.06682
- Same-sign tt 36 fb^{-1}, JHEP 12 (2018) 039
- 4-top 36 fb^{-1}, JHEP 09 (2017) 088
- bb/tt+MET (0l) 36 fb^{-1}, EPJC 78 (2018) 18
- tt+MET (1l) 36 fb^{-1}, JHEP 06 (2018) 108





"Mono-X", E_T^{miss} + X

- E_T^{miss} + jet 36 fb^{-1}, JHEP 01 (2018) 126
- E_T^{miss} + photon 36 fb^{-1}, Eur. Phys. J. C 77 (2017) 393
- E_T^{miss} + Z(ll) 36 fb^{-1}, PLB 776 (2017) 318
- E_T^{miss} + V(qq) 36 fb^{-1}, JHEP 10 (2018) 180
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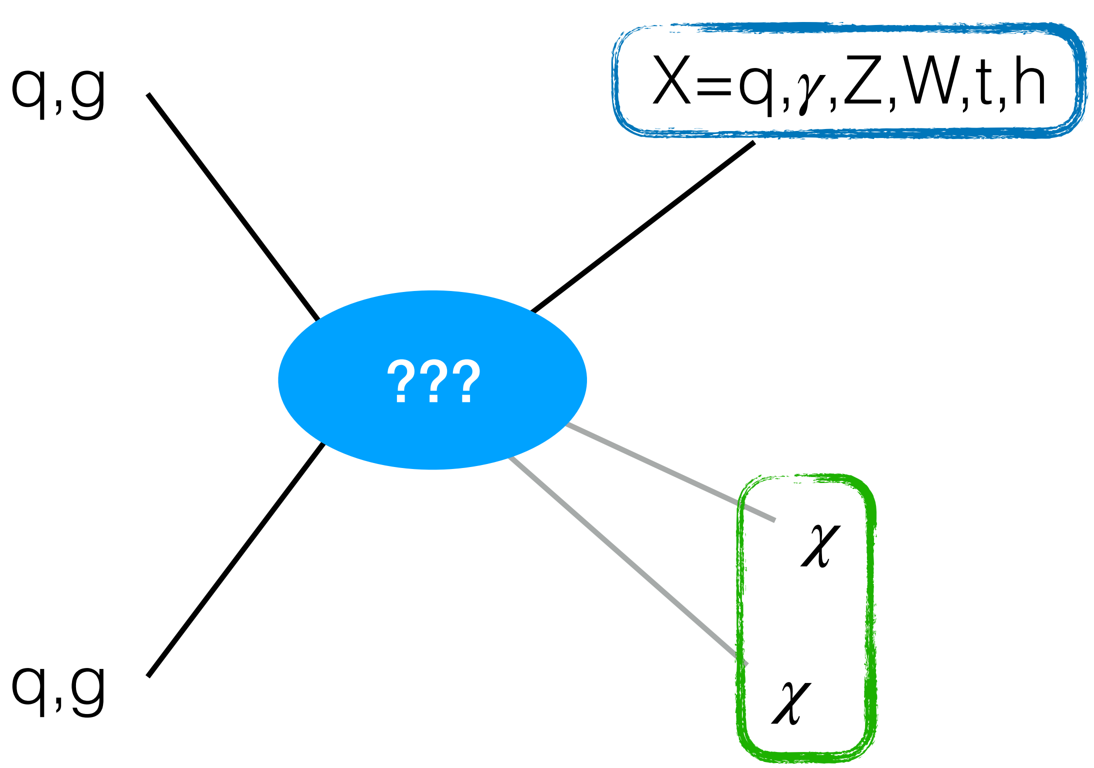
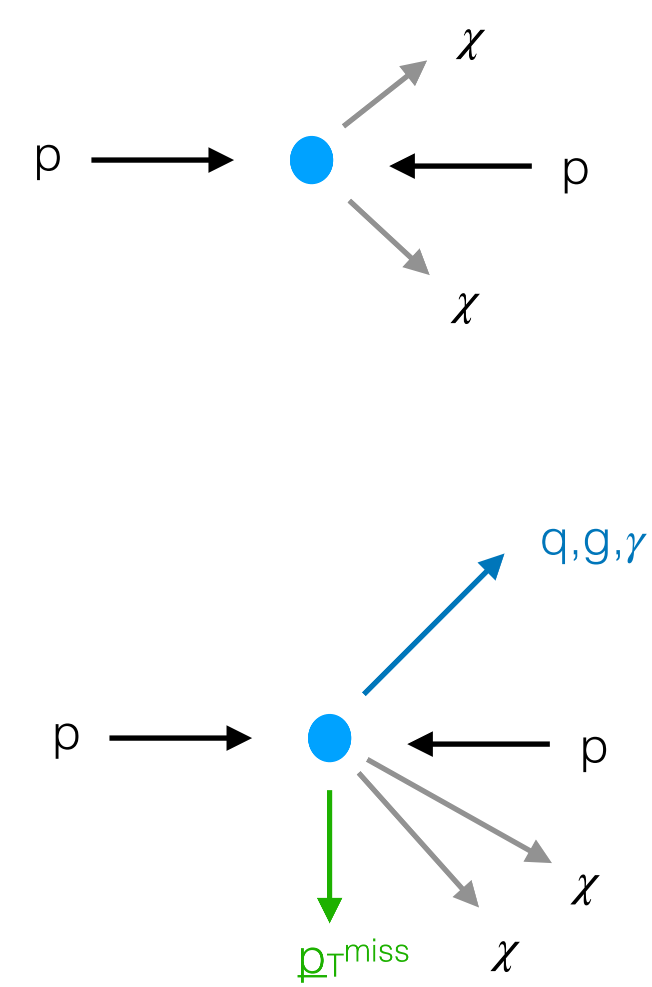
- E_T^{miss} + h(bb) **80 fb^{-1}**, ATLAS-CONF-2018-039



Invisible final state -> require presence of something else

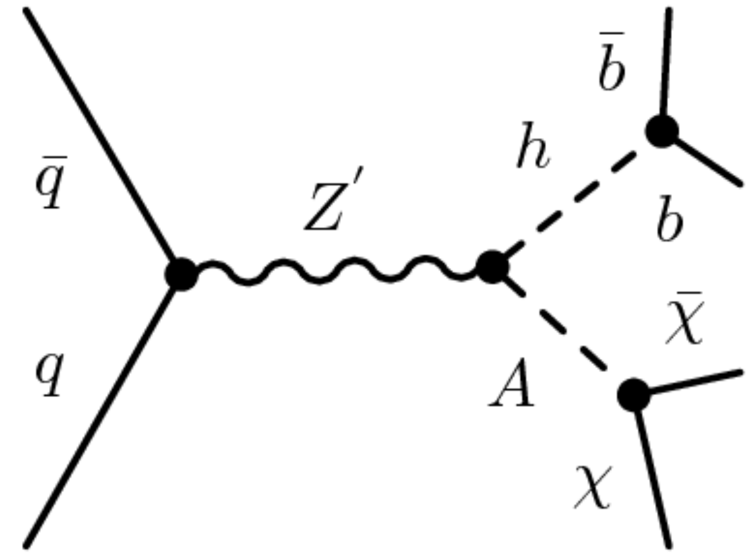
Invisible DM becomes visible as E_T^{miss}

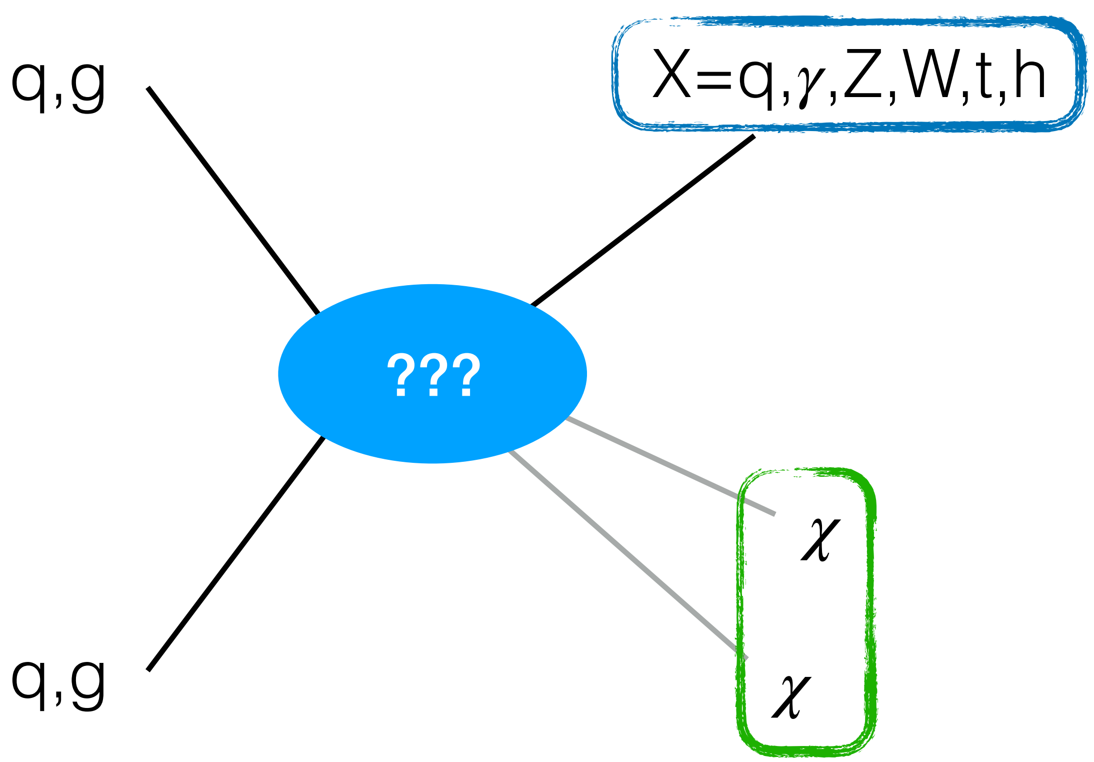


E_T^{miss} + h(bb)

- E_T^{miss} + h(bb) **80 fb^{-1}**
  ATLAS-CONF-2018-039

Techniques used similar to other mono-X searches





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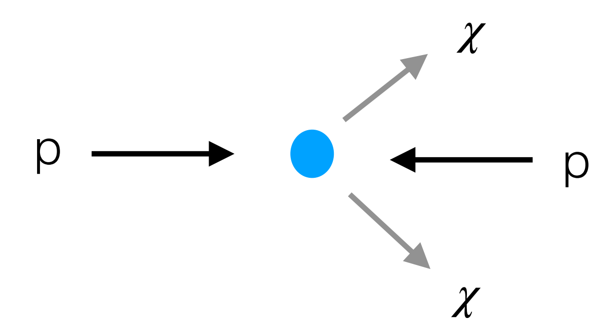

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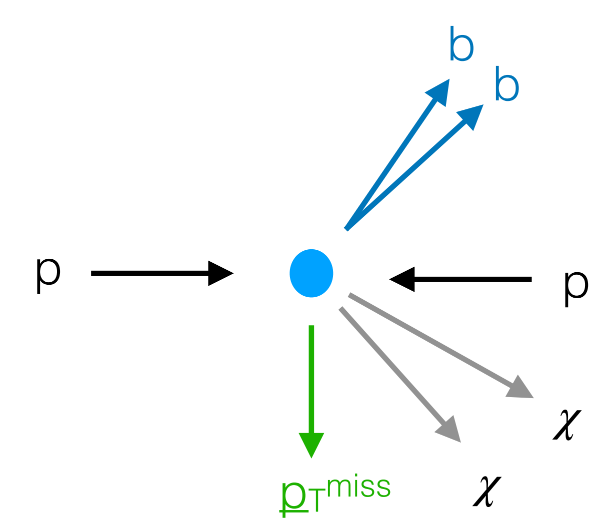
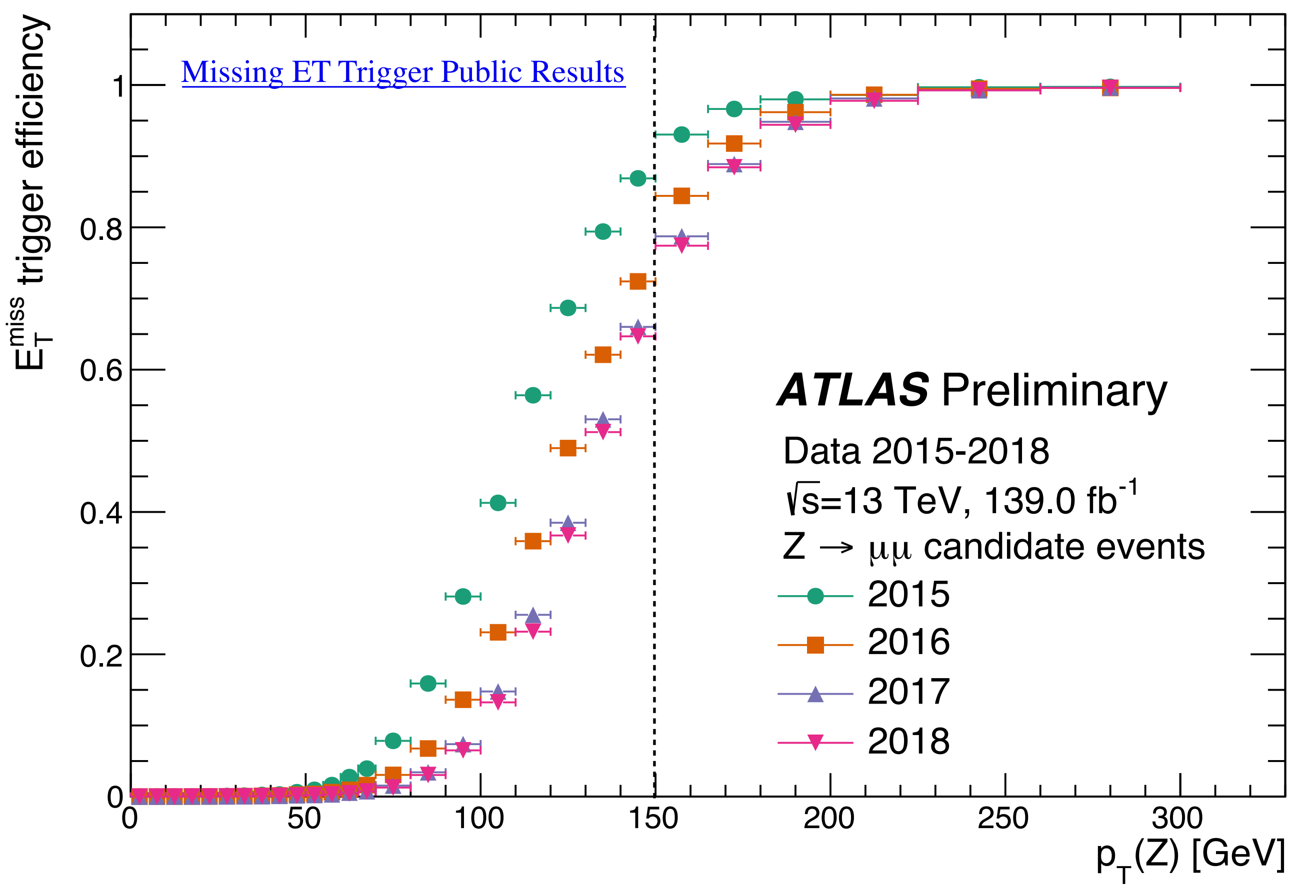


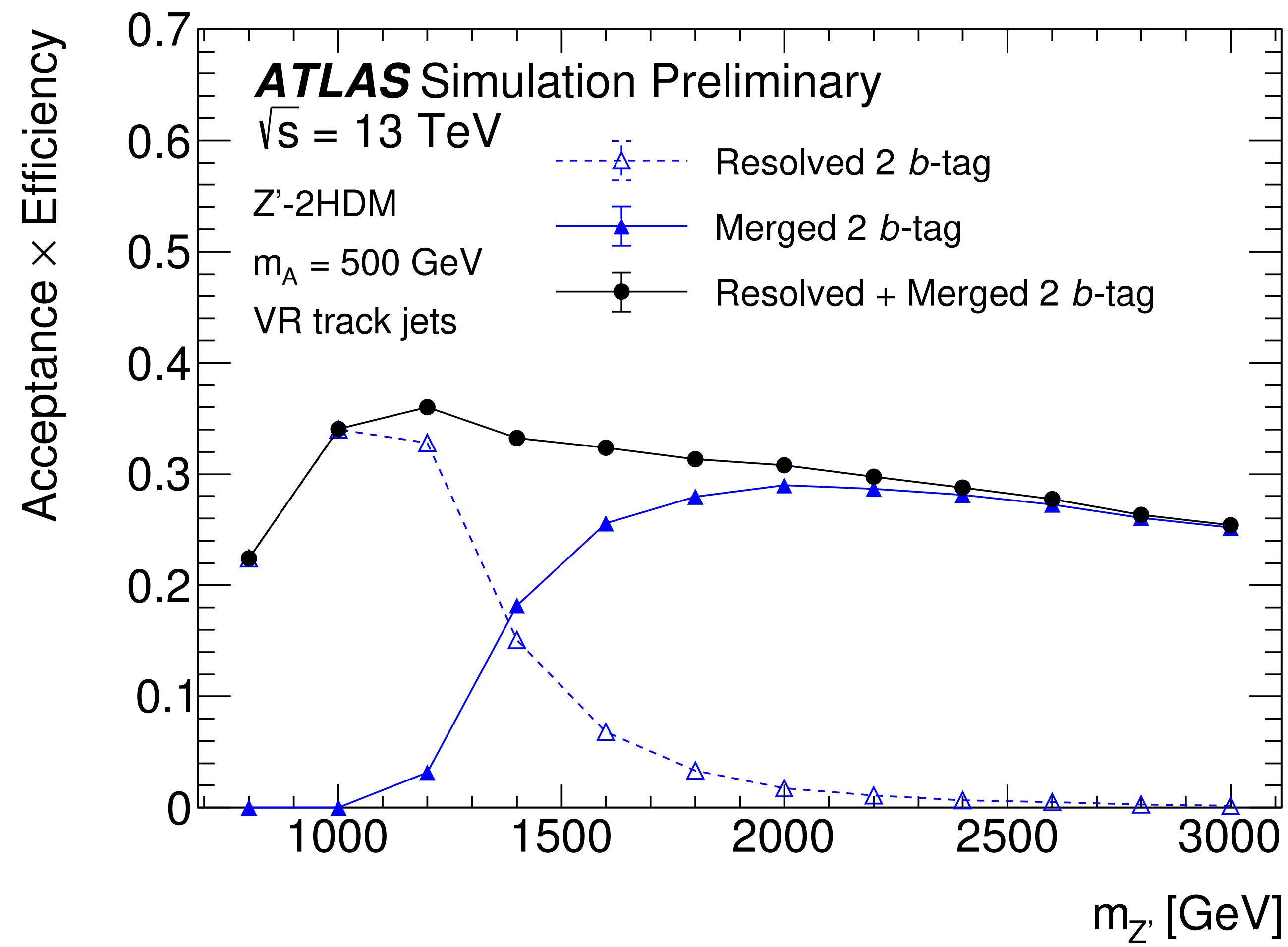
E_T^{miss} + h(bb): selection

E_T^{miss} trigger; efficiency measured in data to push below turnon

Resolved	Merged
trigger	
lepton veto (SR) or selection (CRs)	
(modified) $E_T^{miss} > 150\,\mathrm{GeV}$	

Leptons (incl τ) vetoed in signal regions (SR), selected in control regions (CR)





E_T^{miss} + h(bb): selection

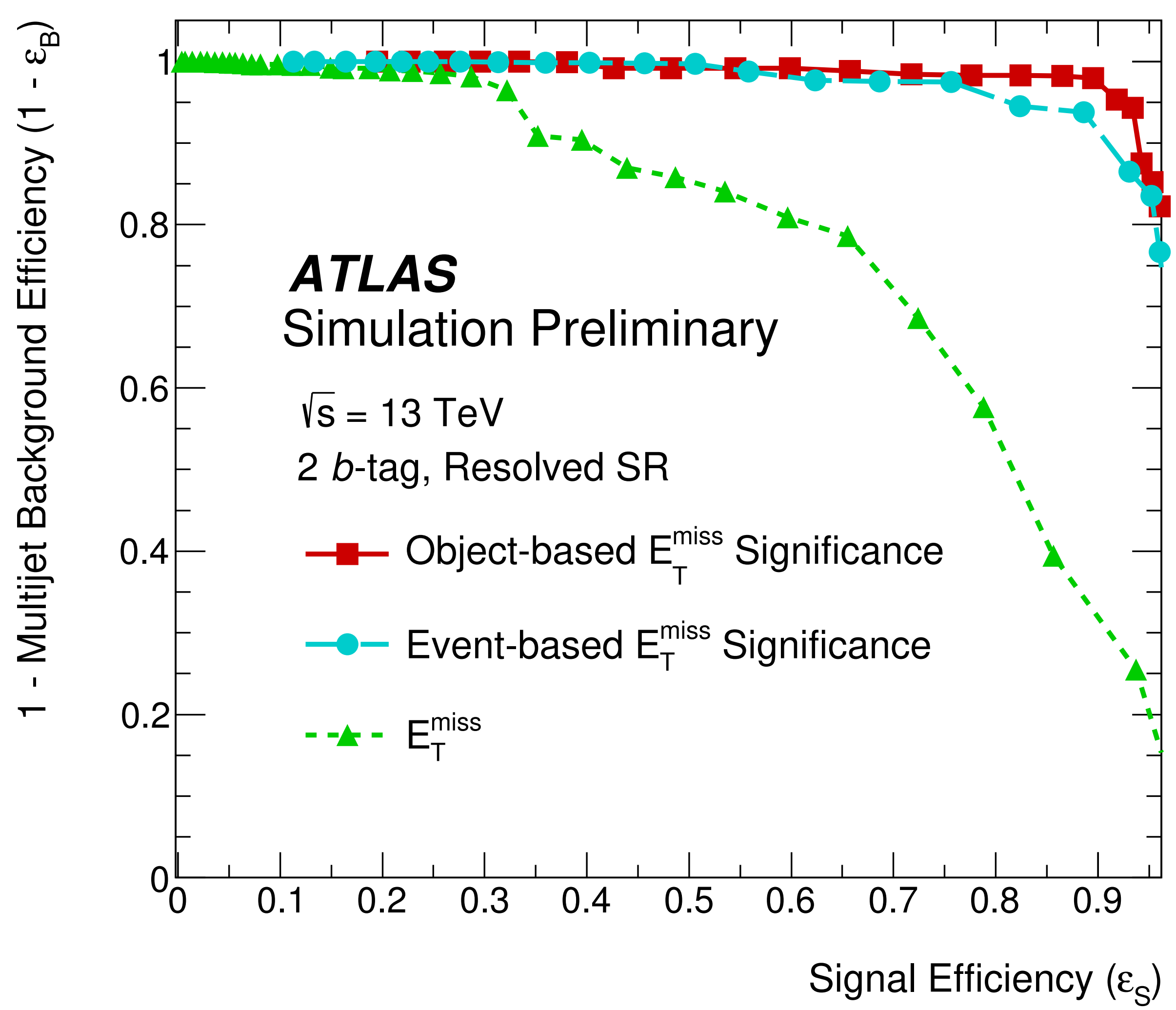
E_T^{miss} trigger; efficiency measured in data to push below turnon

Suppress QCD contribution from mismeasured jets

Resolved	Merged
trigger	
lepton veto (SR) or selection (CRs)	
(modified) $E_T^{miss} > 150$ GeV	
min $\Delta\phi(E_T^{miss}, \text{jets}) > 20°$	
$\Delta\phi(E_T^{miss}, p_T^{miss}) < 90°$	
S >16 (SR only)	—
0ℓ SR: $E_T^{miss} < 500$ GeV	0ℓ SR: $E_T^{miss} > 500$ GeV

Leptons (incl τ) vetoed in signal regions (SR), selected in control regions (CR)

Track vs "overall" E_T^{miss}



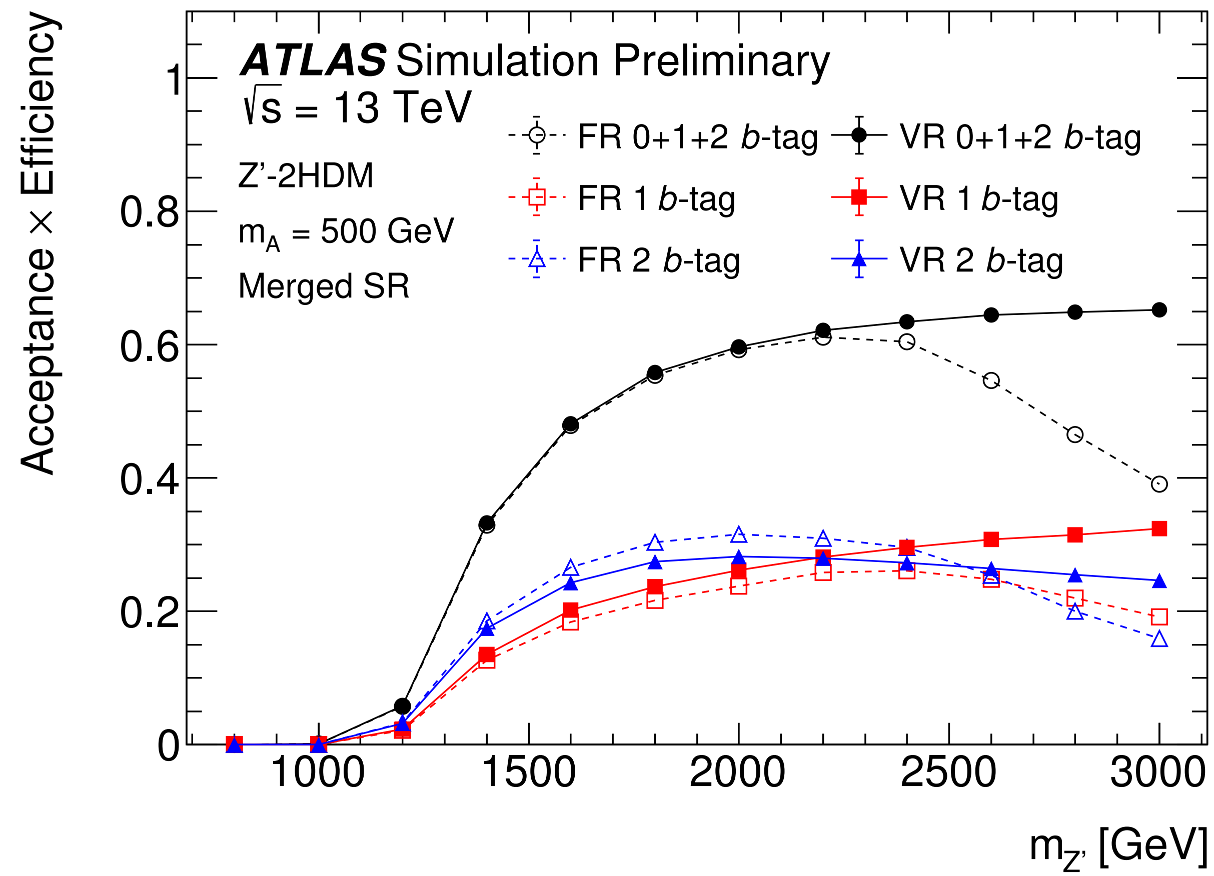
New!

E_T^{miss} + h(bb): selection

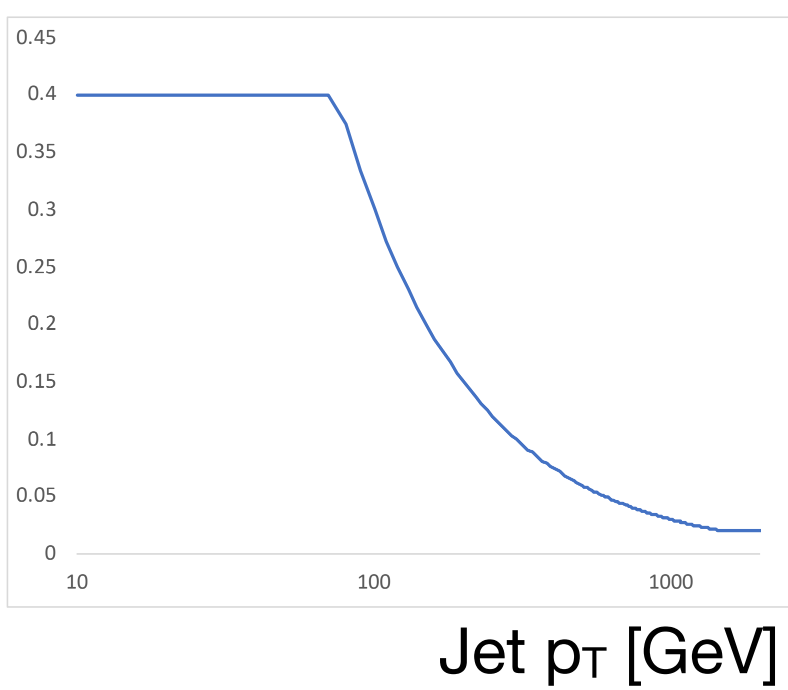
Additional kinematic and topological selections

N(central small-R jets) ≥ 2	N(central large-R jets) ≥ 1
$p_T^{jet_1} > 45 \parallel p_T^{jet_2} > 45$	—
$\sum_{i=1}^{2(3)} p_T^{jet_i} > 120\ (150)$ GeV	—
$\Delta\phi(jet_1, jet_2) < 140°$	—
$\Delta\phi(E_T^{miss}, h) > 120°$	—
τ-veto	
additional b-jet veto	
H_T ratio	
$\Delta R(jet_1, jet_2) < 1.8$	$\frac{\Delta R(VR_1, VR_2)}{R_{min}} > 1$
b-tag requirement on small-R jets	b-tag requirement on track-jets

FR: fixed radius   VR: variable radius



VR jet radius



b-tagging done with variable-radius track jets:

$$R \rightarrow R_{eff}(p_T) \approx \frac{\rho}{p_T}$$

$0.02 < R < 0.4$, $\rho = 30$ GeV

E_T^{miss} + h(bb): background estimate

0ℓ SR: $E_T^{miss} < 500$ GeV	0ℓ SR: $E_T^{miss} > 500$ GeV
1μ-CR: $E_T^{miss, no\,\mu} < 500$ GeV	1μ-CR: $E_T^{miss, no\,\mu} > 500$ GeV
2ℓ-CR: $p_T^{\ell\ell} < 500$ GeV	2ℓ-CR: $p_T^{\ell\ell} > 500$ GeV

tt, W(lν)+jets, Z(νν)+jets:

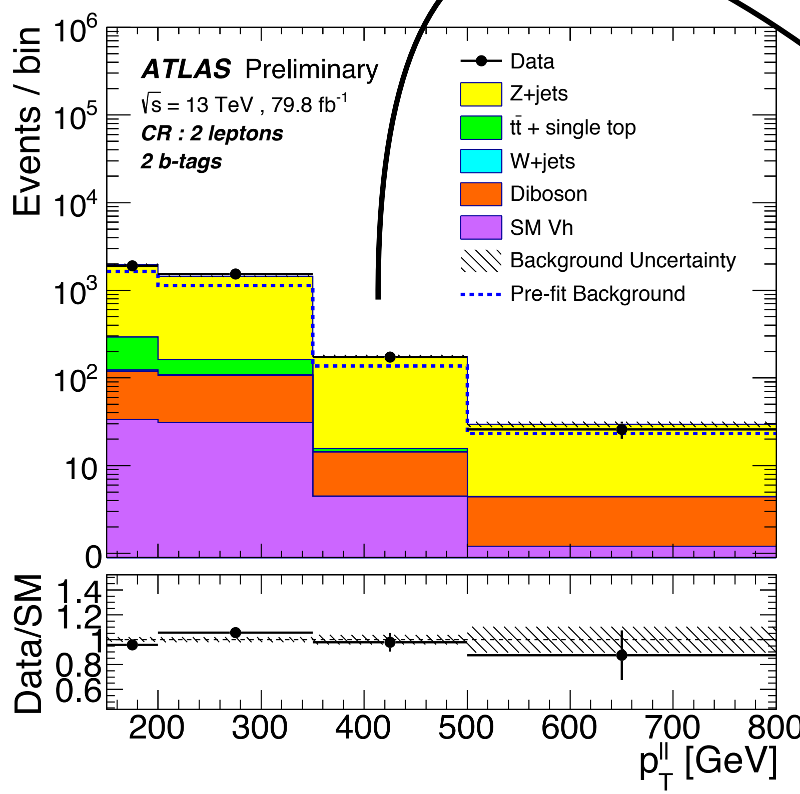
Simultaneous fit across multiple regions and variables

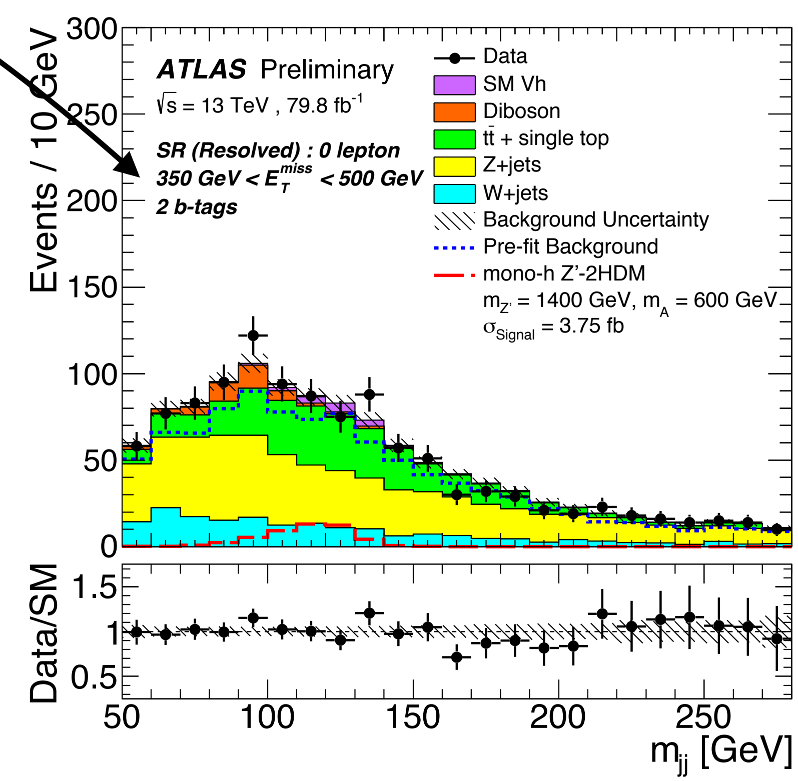
	0 lepton	**1 muon**	**2 leptons**
Region	SR	$t\bar{t}$ and W+jets CR	Z+jets CR
E_T^{miss} or E_T^{miss} proxy	E_T^{miss}	$E_T^{miss, no\,\mu}$	$p_T^{\ell\ell}$
	Resolved: [150,200), [200,350) and [350,500) GeV		
	Merged: Larger than 500 GeV		
Fit variable in each E_T^{miss} bin	m_h	muon charge	Event yield

Fits per E_T^{miss} bin

Z(νν)+jets:

- treat leptons as E_T^{miss}
- Overall yield in each bin





E_T^{miss} + h(bb): background estimate

0ℓ SR: $E_T^{miss} < 500$ GeV	0ℓ SR: $E_T^{miss} > 500$ GeV
1μ-CR: $E_T^{miss,\,no\,\mu} < 500$ GeV	1μ-CR: $E_T^{miss,\,no\,\mu} > 500$ GeV
2ℓ-CR: $p_T^{\ell\ell} < 500$ GeV	2ℓ-CR: $p_T^{\ell\ell} > 500$ GeV

tt, W(lν)+jets, Z($\nu\nu$)+jets:

Simultaneous fit across multiple regions and variables

	0 lepton	1 muon	2 leptons
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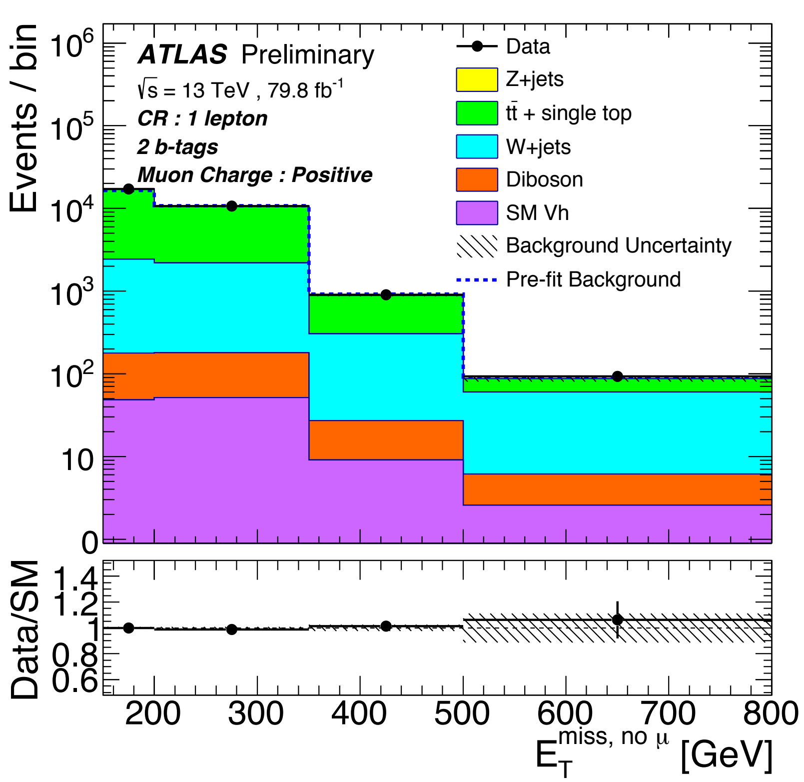
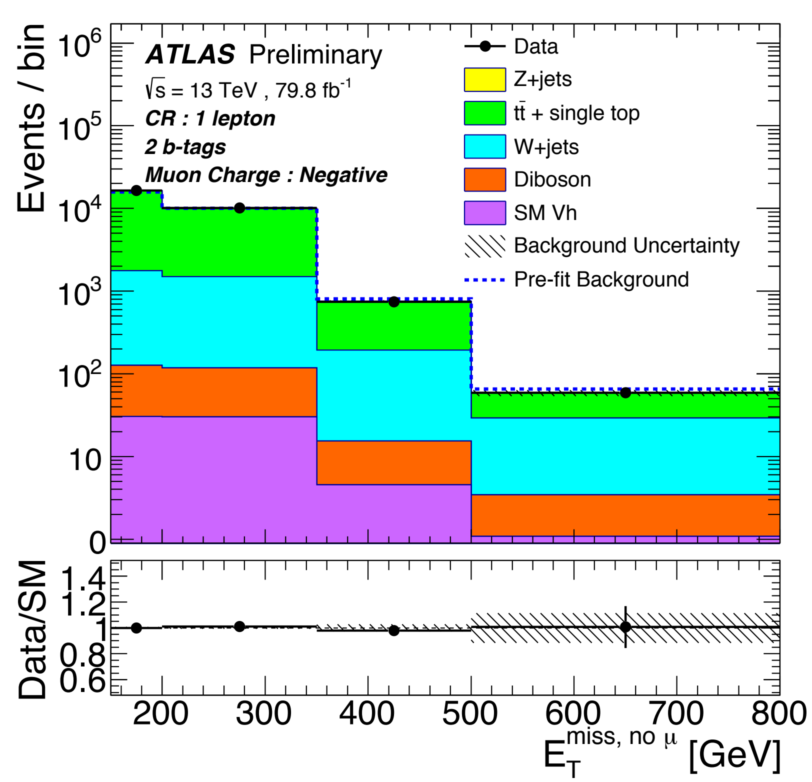
	Resolved: [150,200), [200,350) and [350,500) GeV Merged: Larger than 500 GeV		
Fit variable in each E_T^{miss} bin	m_h	muon charge	Event yield

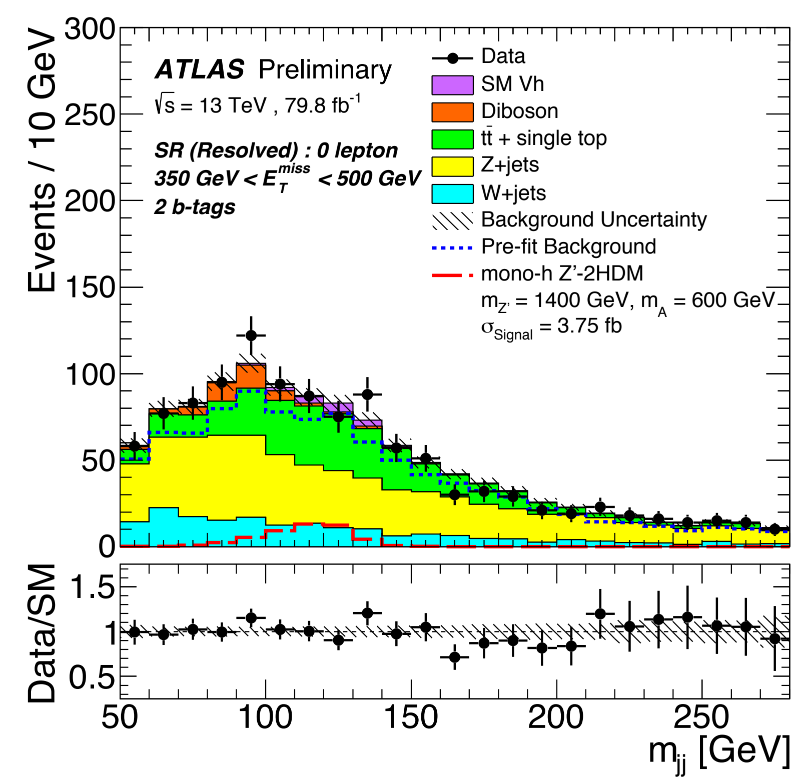
W(lν)+jets and ttbar:

- Single control region (1μ)
- More μ^+ from W+jets, equal in ttbar

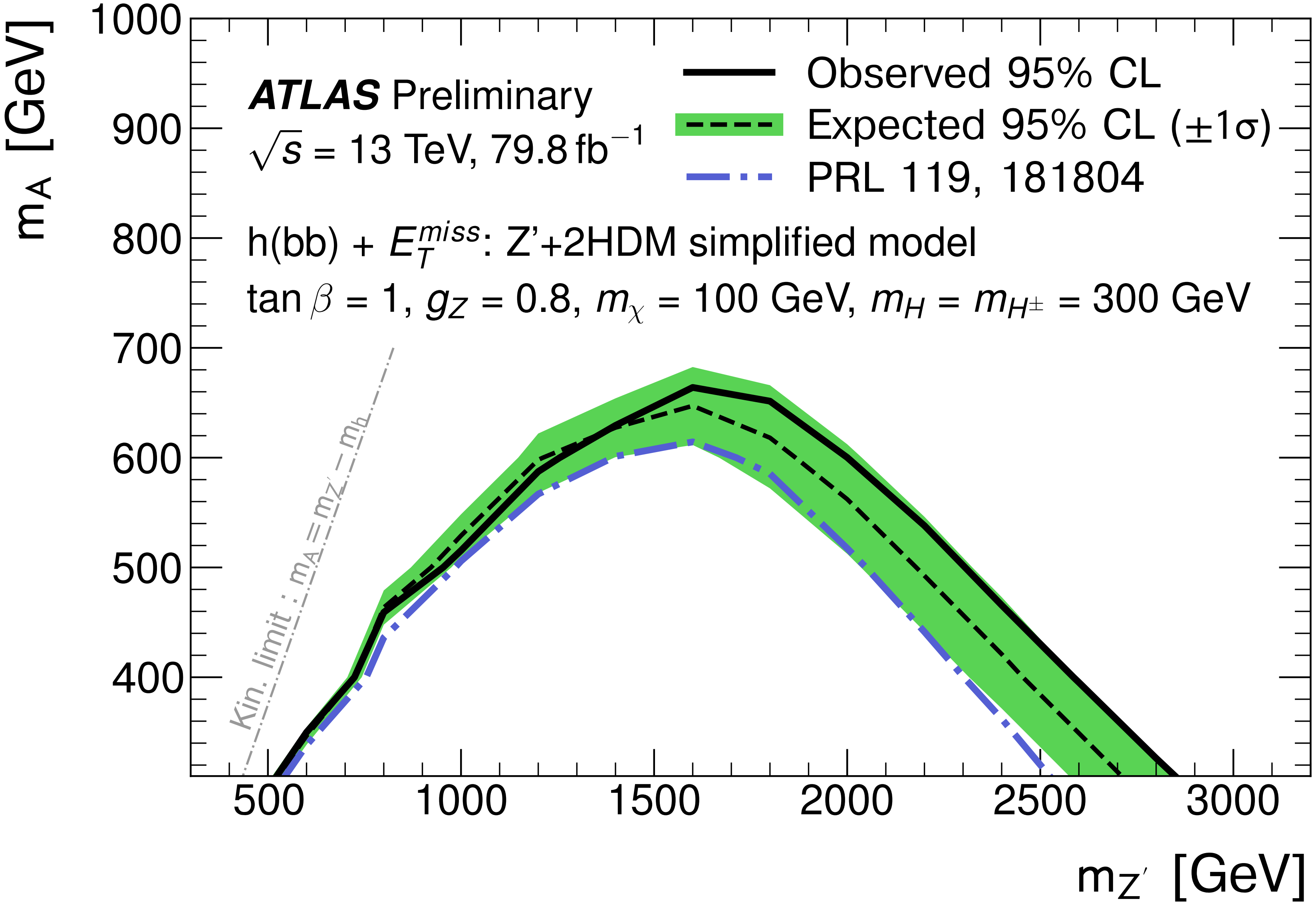
(more $u\bar{d} \rightarrow W^+$ than $d\bar{u} \rightarrow W^-$ in pp collider)

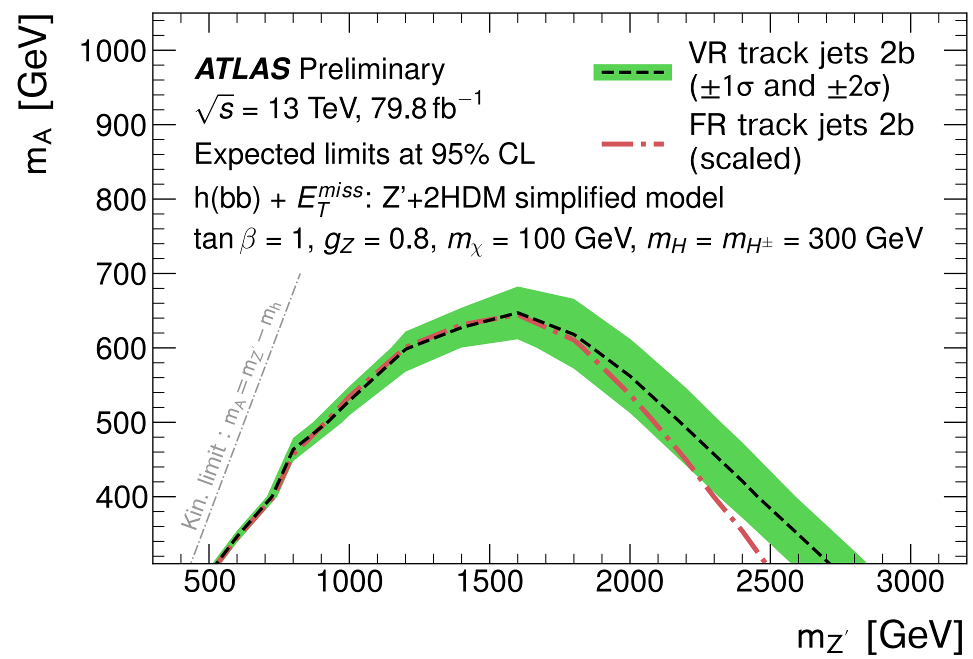




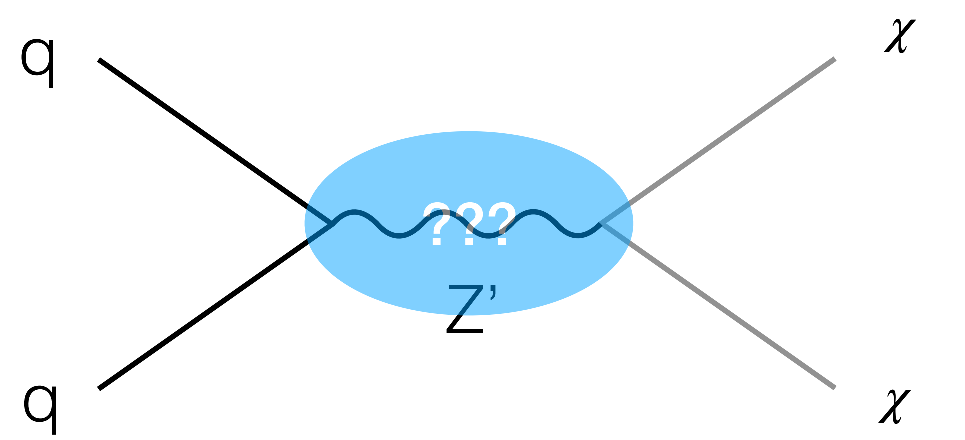


E_T^{miss} + h(bb): results





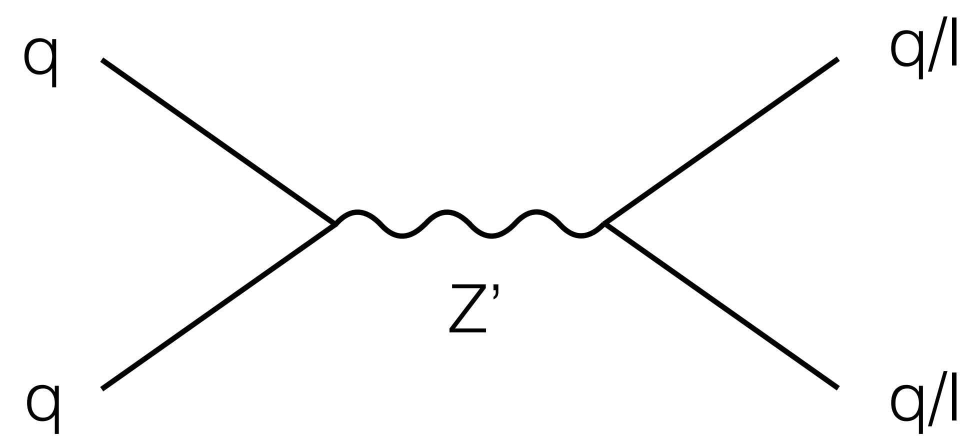
Alternative: dark matter? What dark matter?



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

t-channel → LHC DM WG meeting

s-channel



… then in addition to DM we should look for the mediator

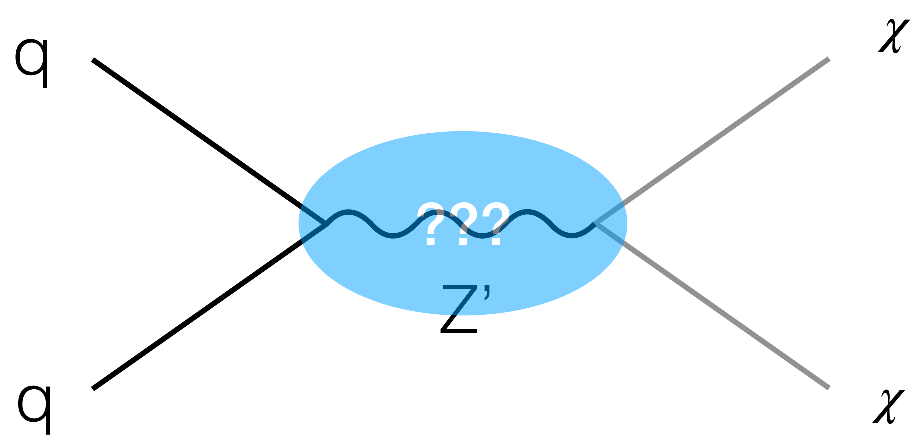
Resonance searches

Heavy resonances, Jennifer Ngadiuba, Tuesday am

CMS hadronic resonances, David Yu, Tuesday pm

Lepton resonances, Noam Tal Hod, this session

Alternative: dark matter? What dark matter?



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

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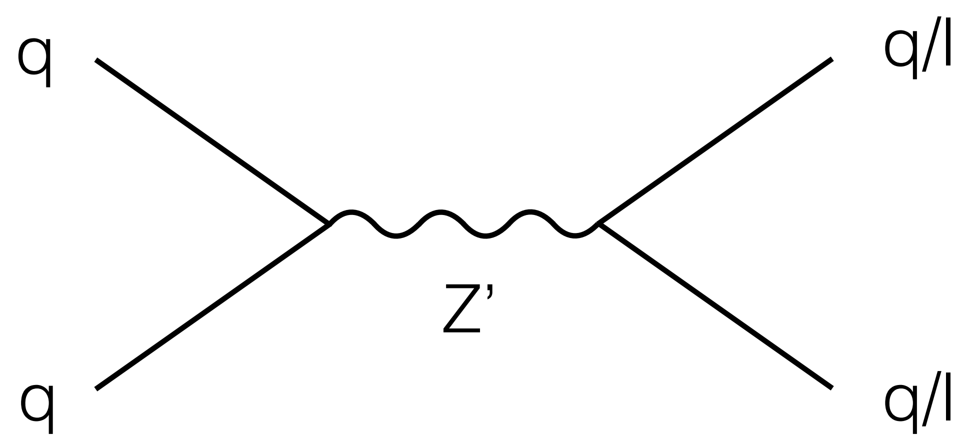
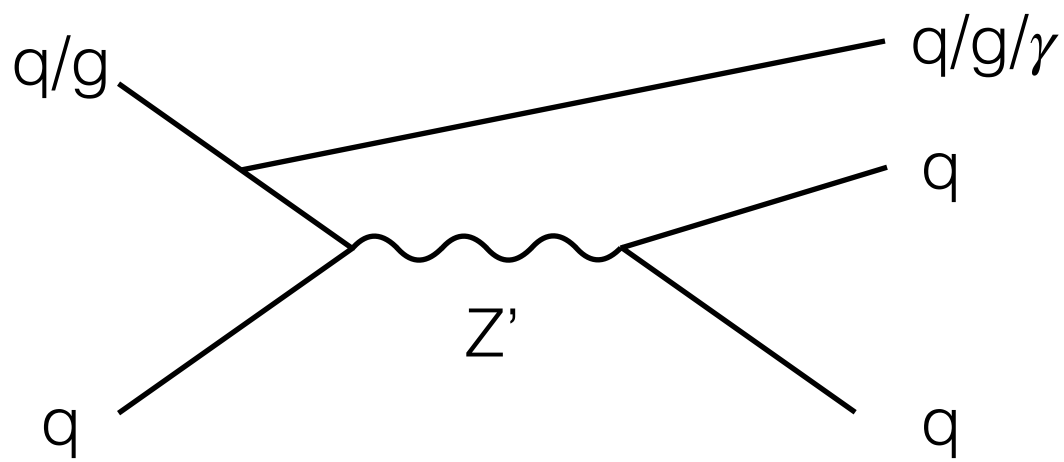


… then in addition to DM we should look for the mediator

Trigger limits this to mediators with masses > 1 TeV (if leptophobic)

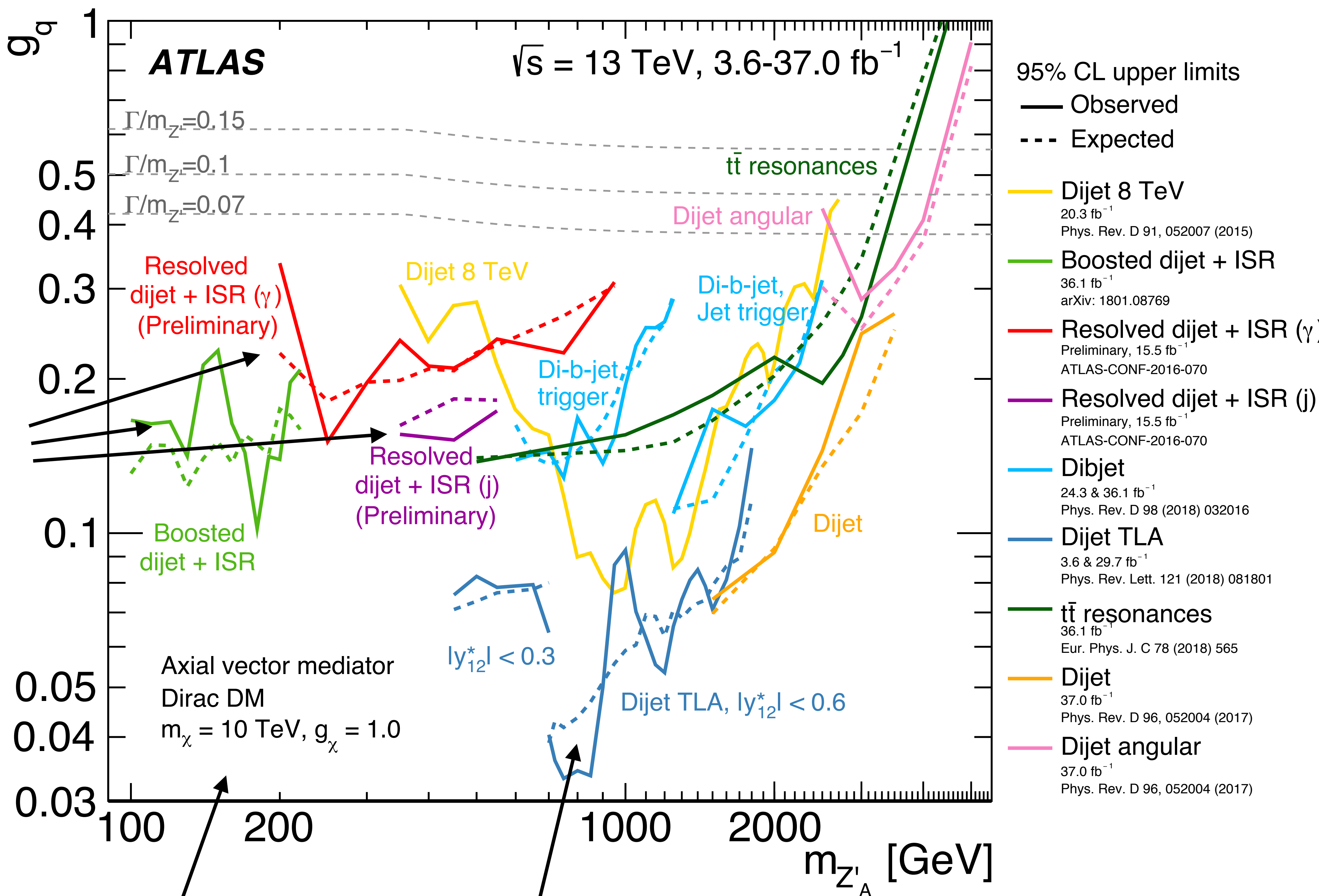


Trigger on ISR to probe lower Z' masses

γ vs jet: lower p_T trigger, easier combinatorics, lower cross-section (α_S vs α_{EM})

Resonance searches summary

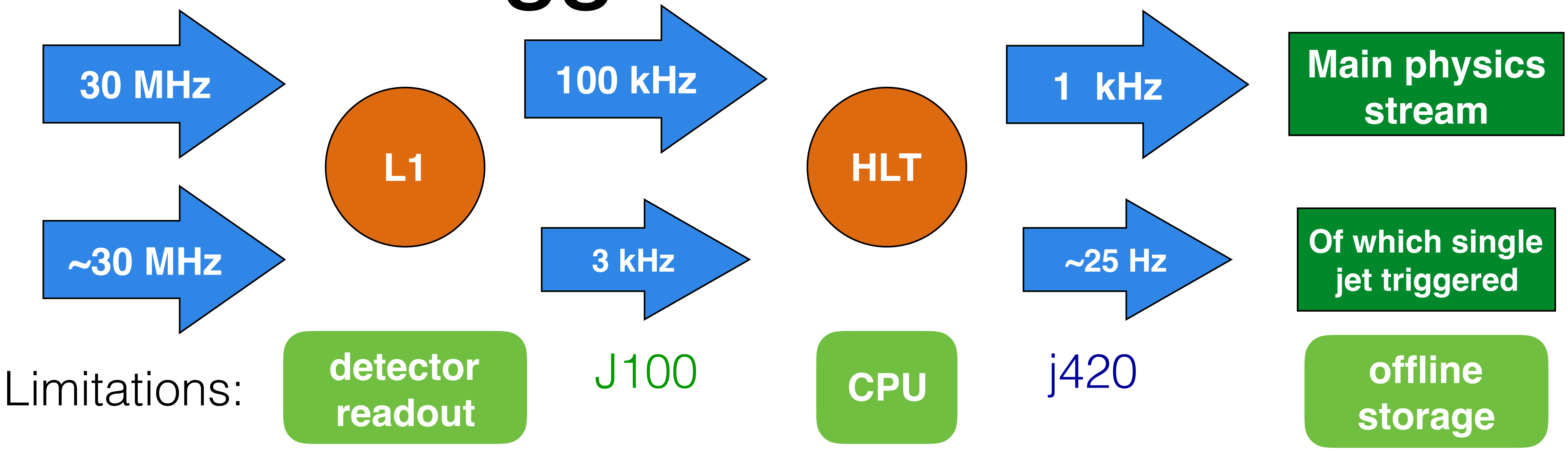
ISR pushes to lower masses, lower sensitivity thanks to acceptance loss



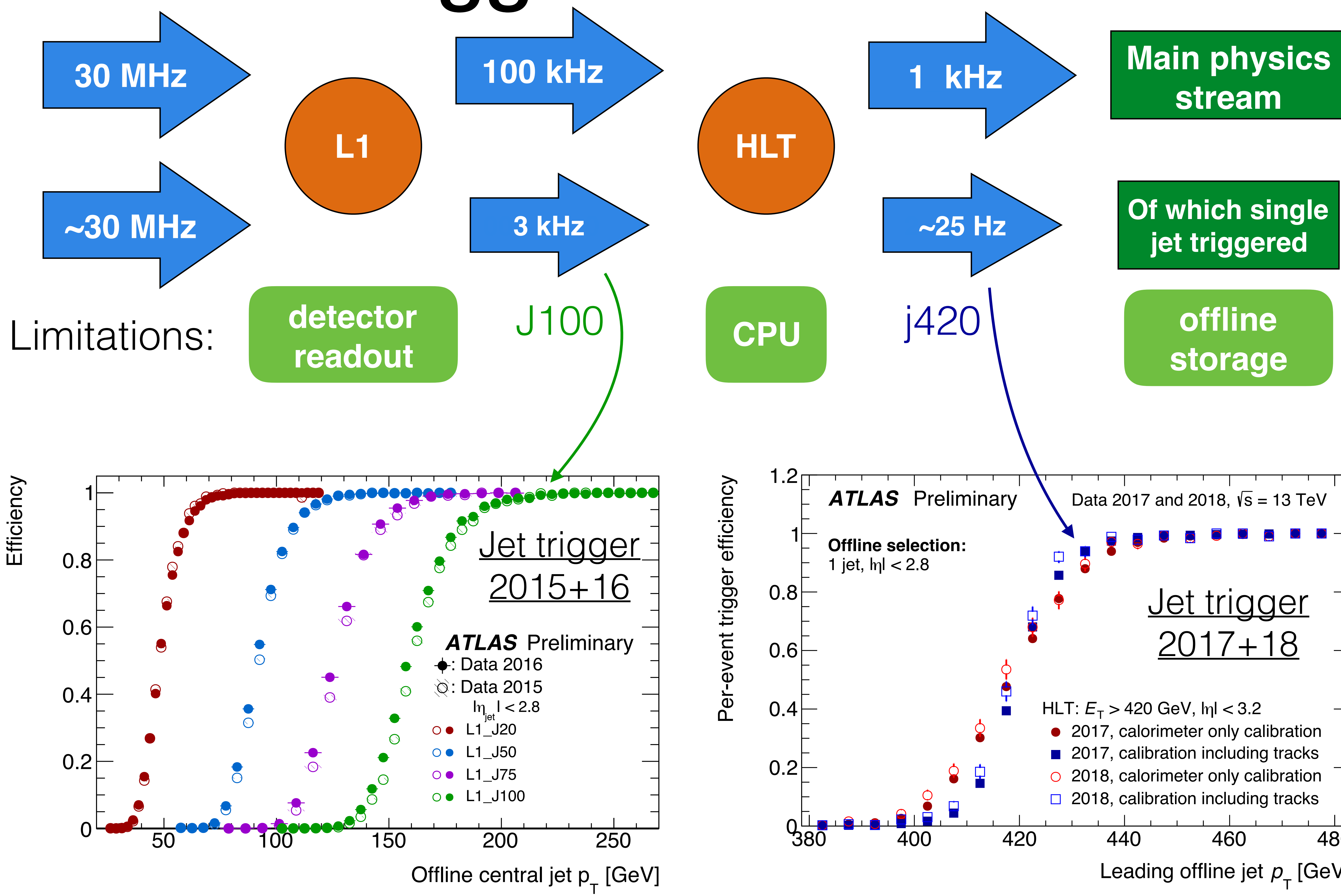
DM set kinematically inaccessible

Trigger-Level Analysis records more data for higher sensitivity than ISR

Trigger limitations

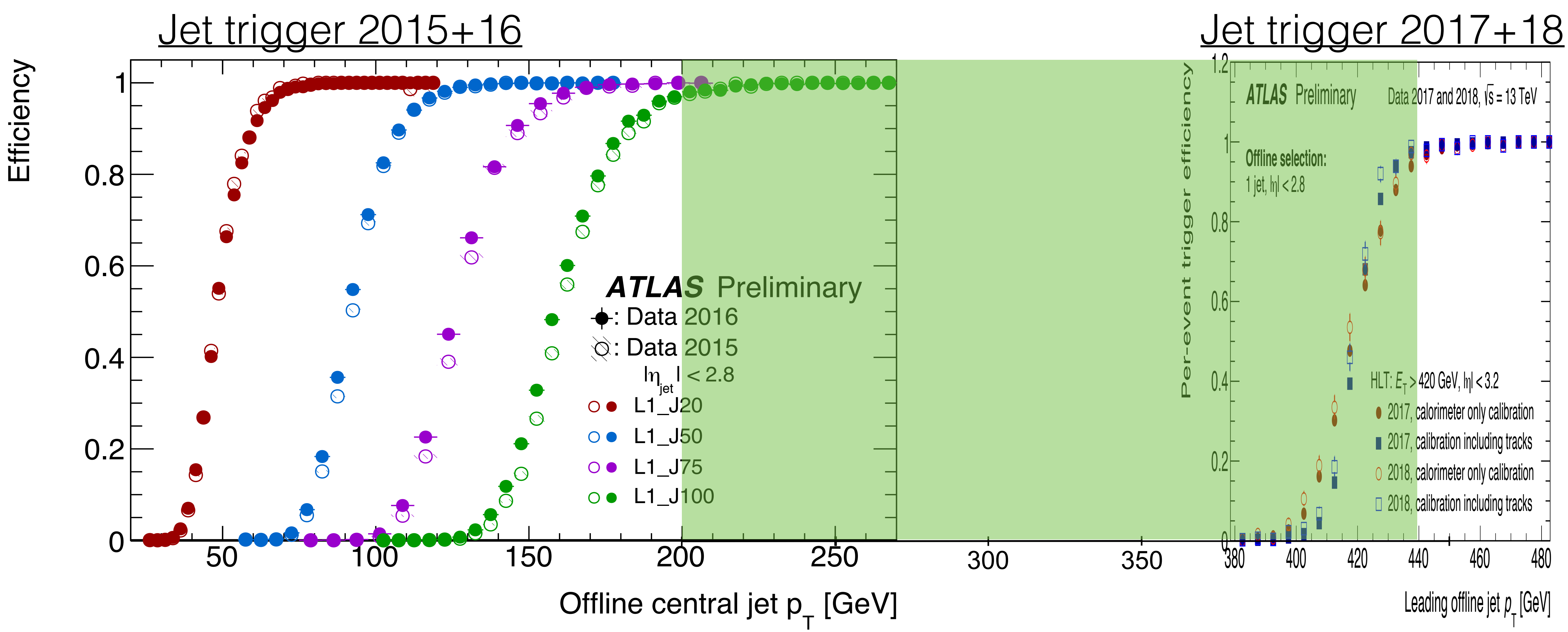


Trigger limitations



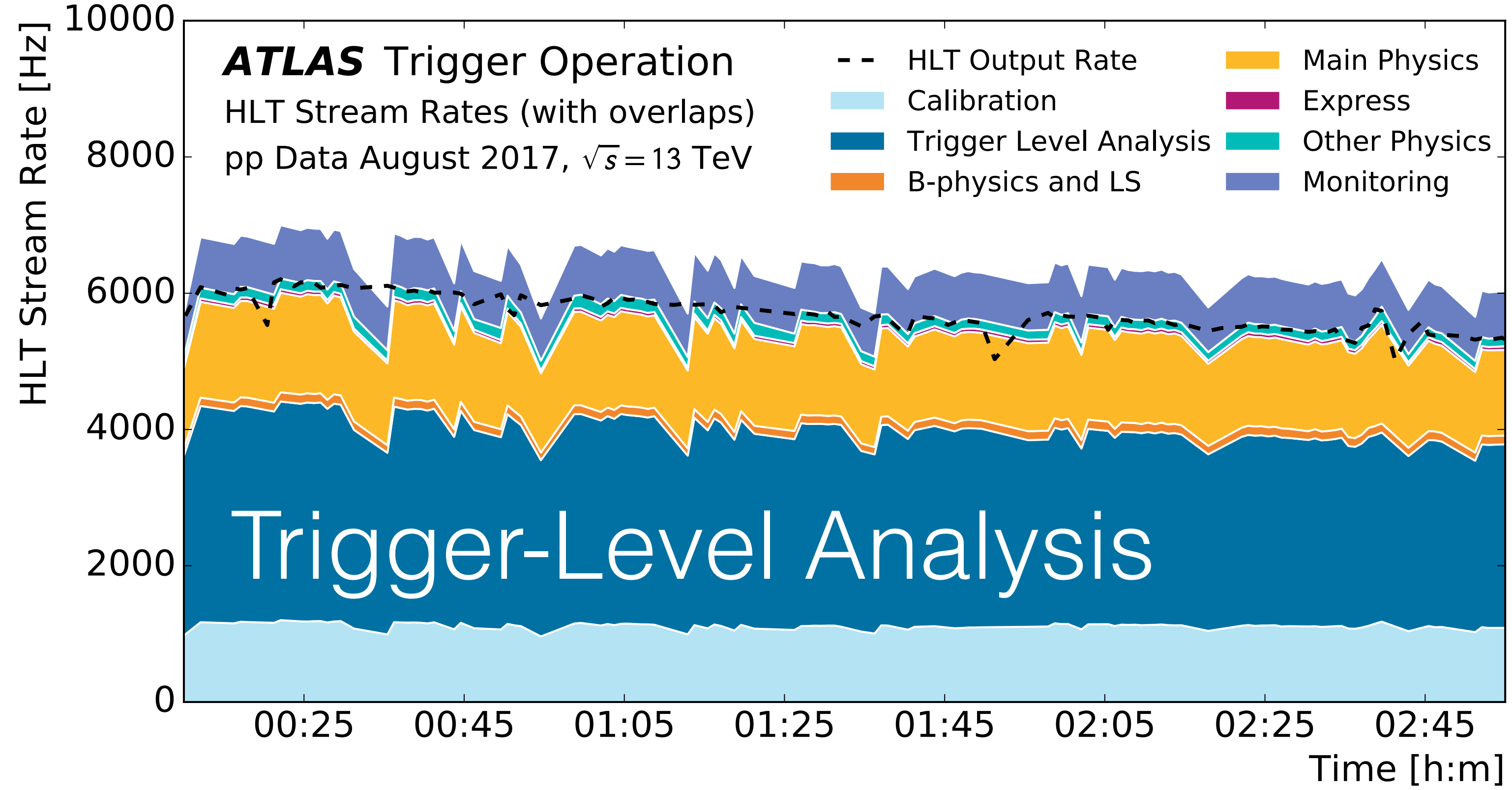
Opportunity

- Now with L1 and HLT turnons on the same x axis scale
- Every event in the green shaded region (~200 - 440 GeV) has full HLT jet reconstruction, but is thrown away because we don't have space to store the full event
- Idea also used (and pioneered) by LHCb and CMS: record partial events

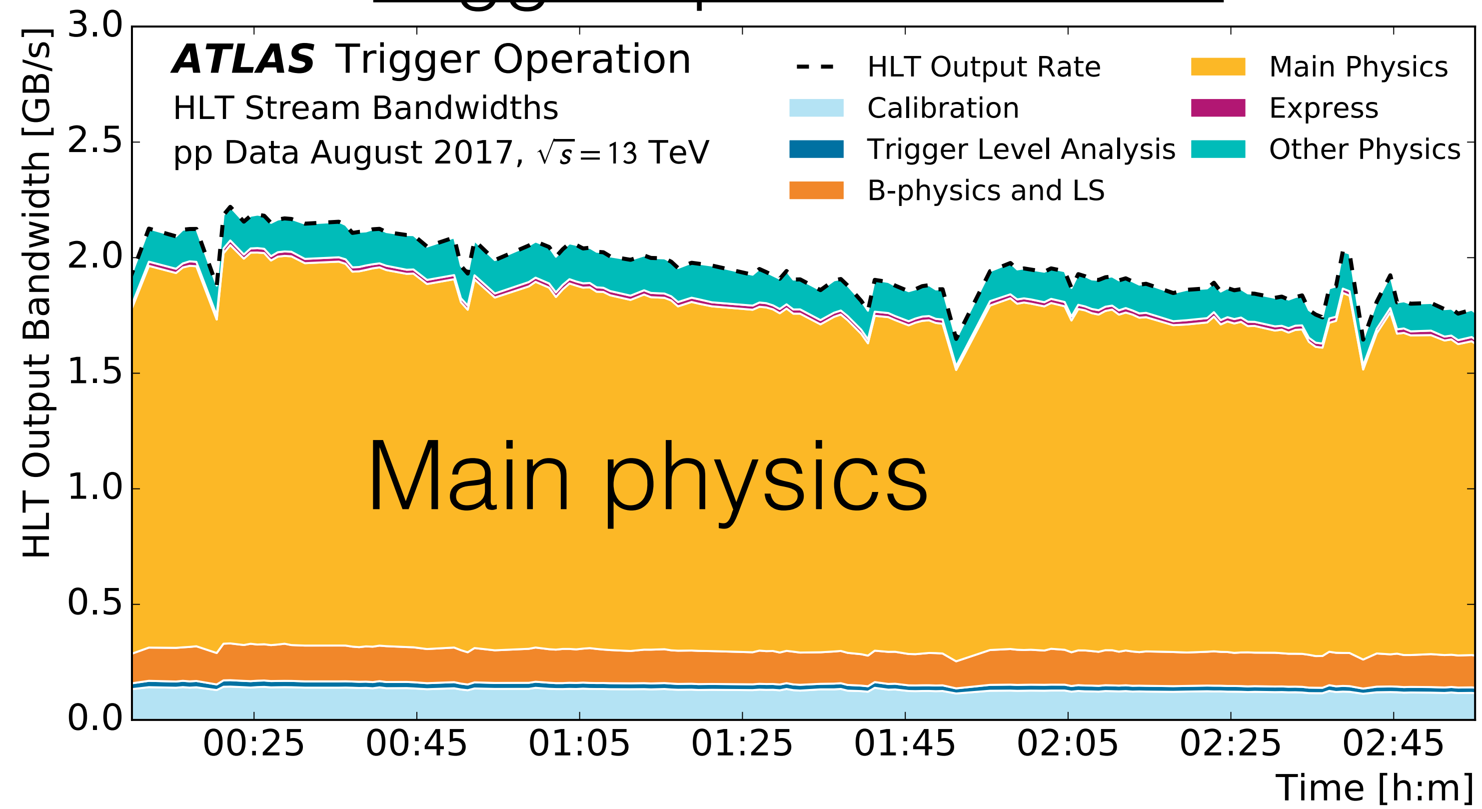


“Trigger-Level Analysis”

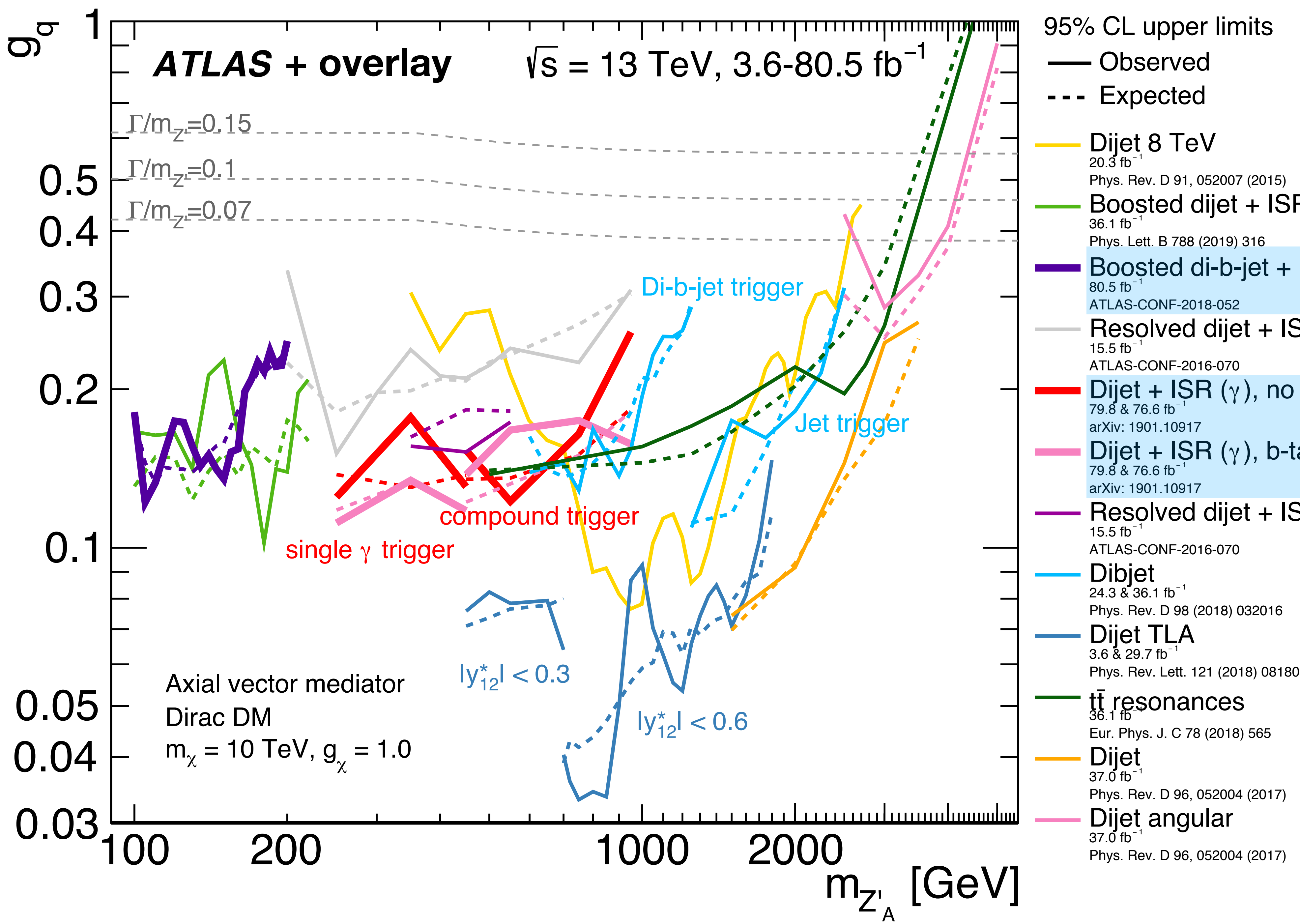
- Store only HLT jet 4-vectors and some summary info
  -> tiny event size (0.5% of full size)
- Allows all events passing unprescaled L1_J100 to be recorded to disk
- Very large event rate, tiny bandwidth impact
- Huge event rates just for dijet resonance search :-)



Trigger operations 2017



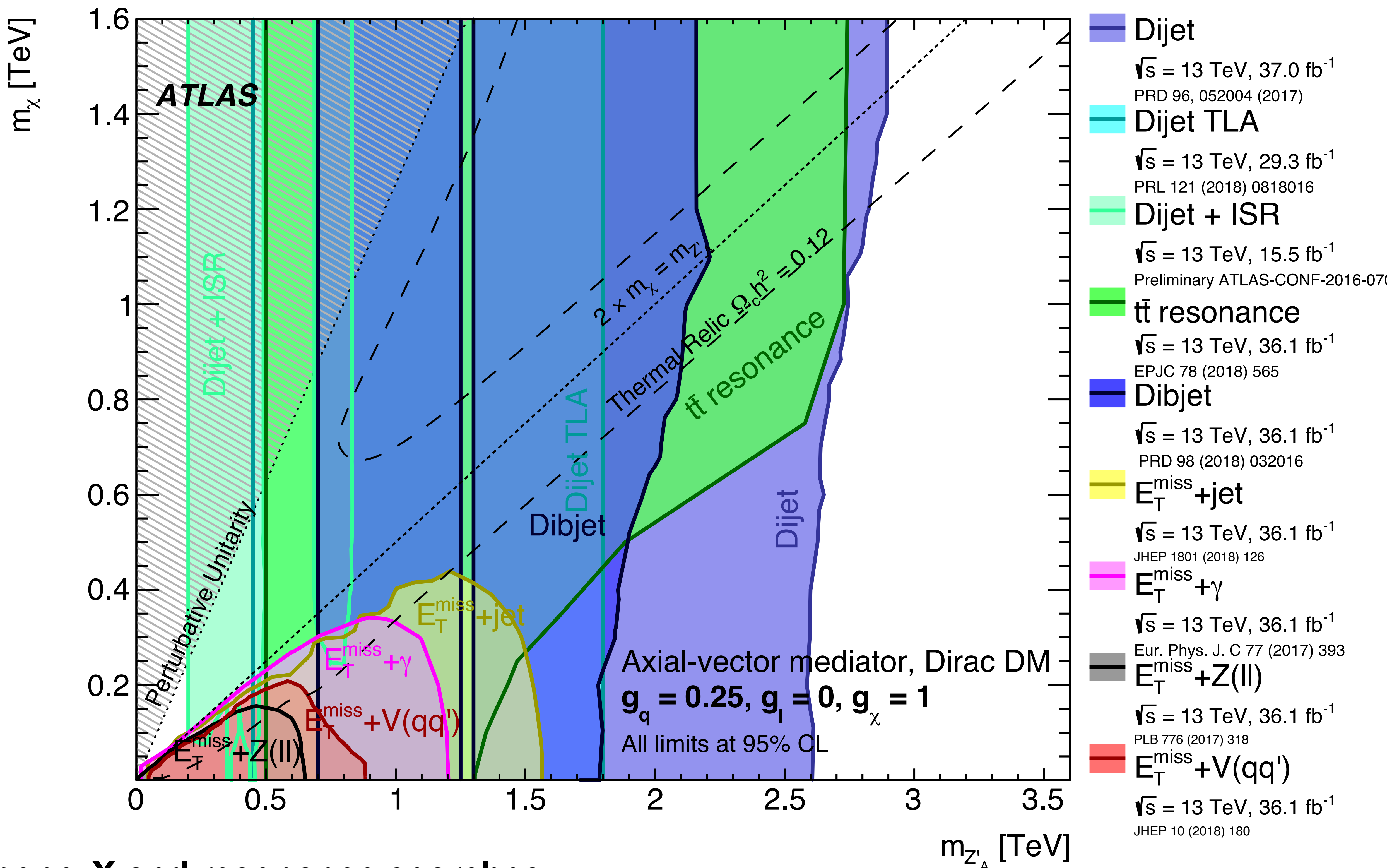
New analyses: add b-tagging



New (80 fb^{-1}) results

- Interesting interplay between b-tagged and inclusive across mass range: dependent on b-tagging performance across p_T range (backup)
  - S *= $\varepsilon_b^2/6$; B *= ε_l^2 $\Longrightarrow$ S/sqrt(B) *= $\varepsilon_b^2 / 6\, \varepsilon_{light}$

Complementarity between DM searches

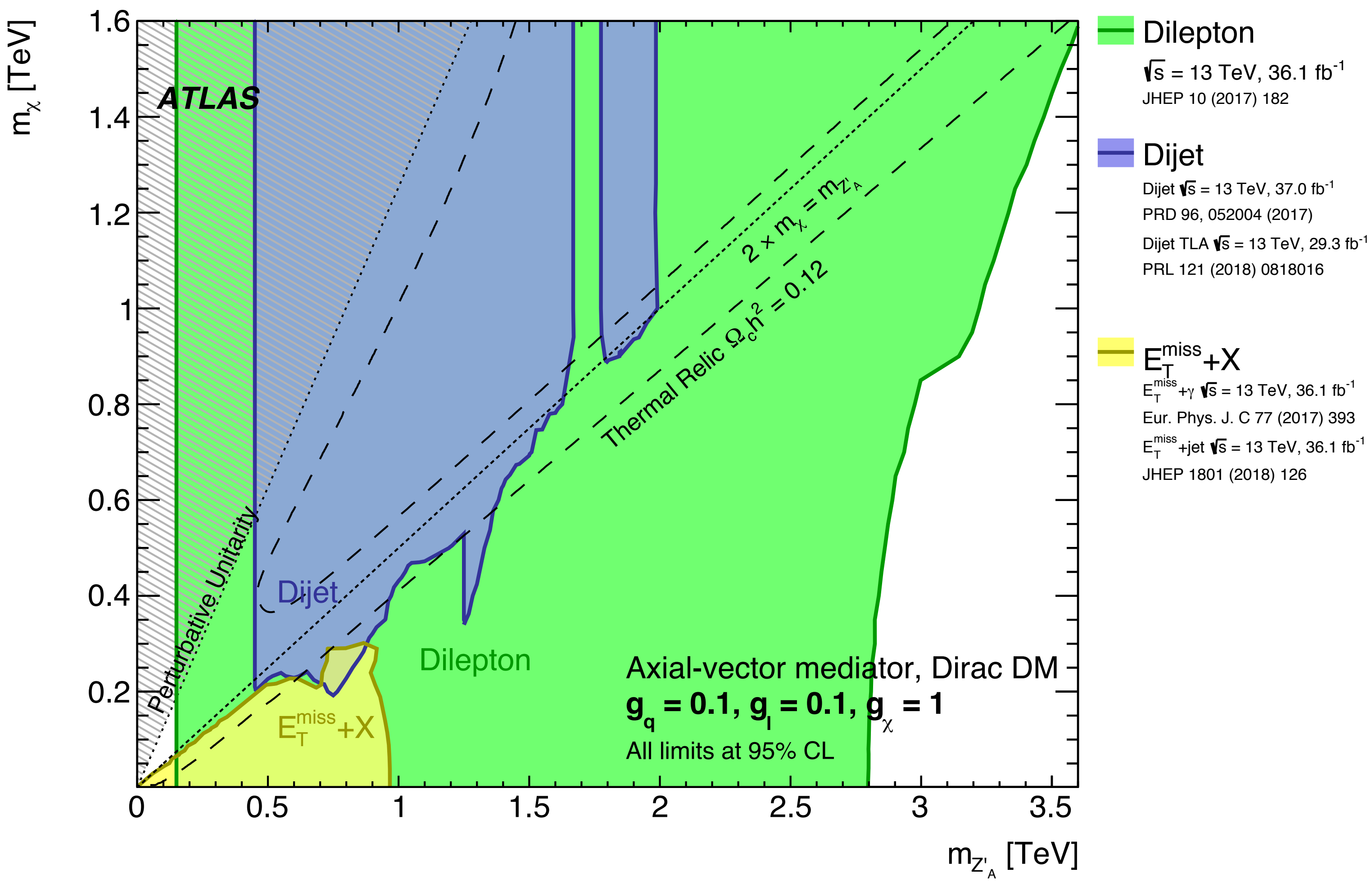


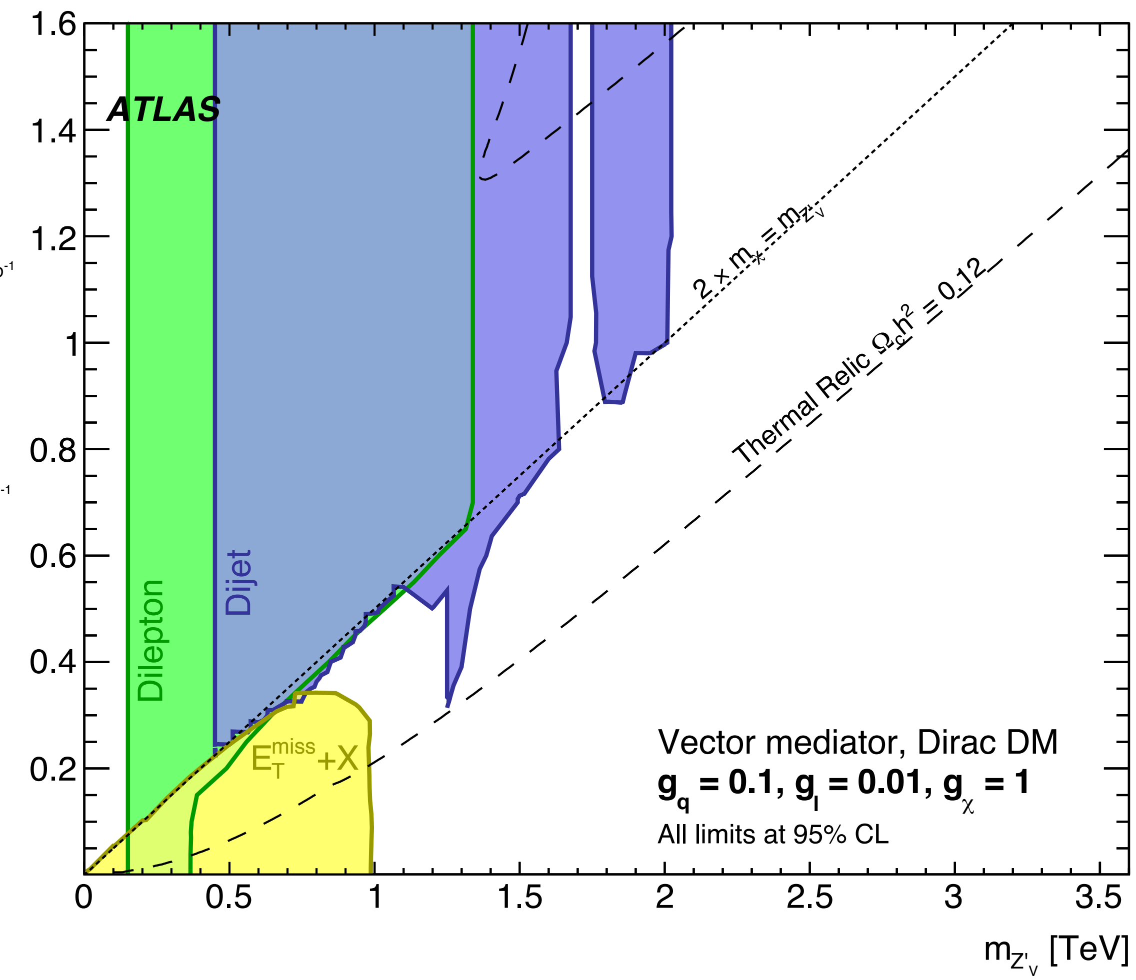
mono-X and resonance searches complement each other in s-channel mediator models

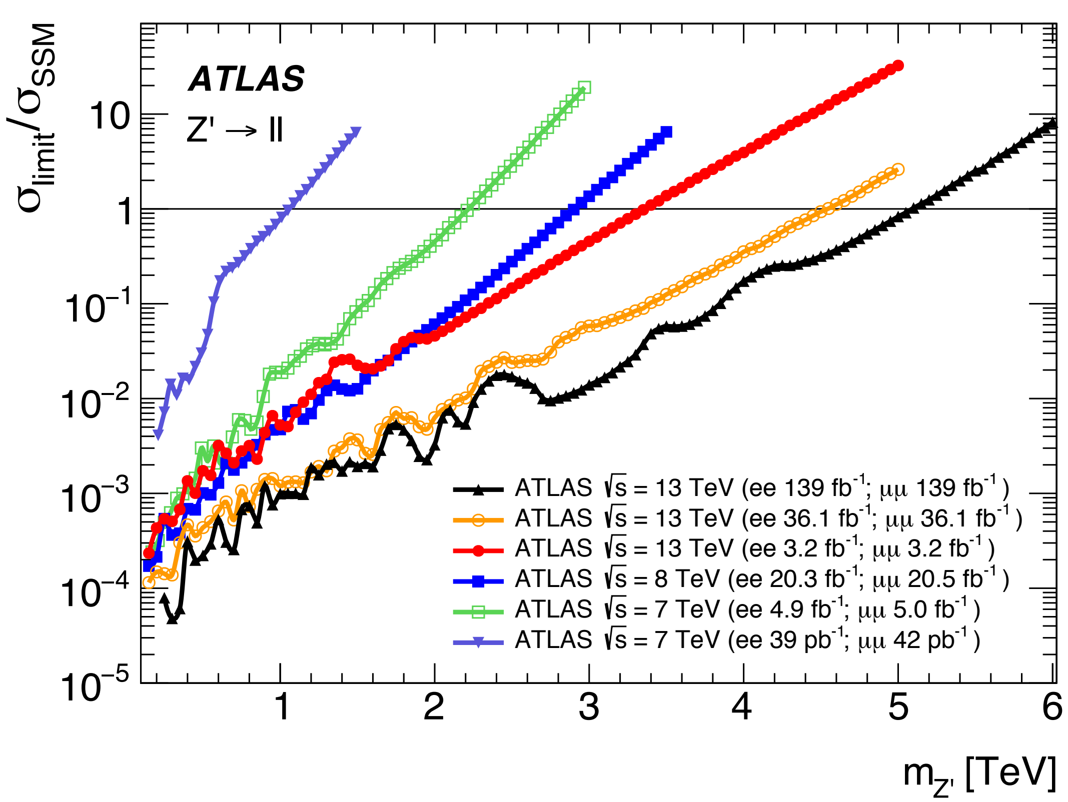
Caveats:

- plot doesn't include merged dijet+ISR or latest dijet / resolved dijet+ISR

Complementarity between DM searches

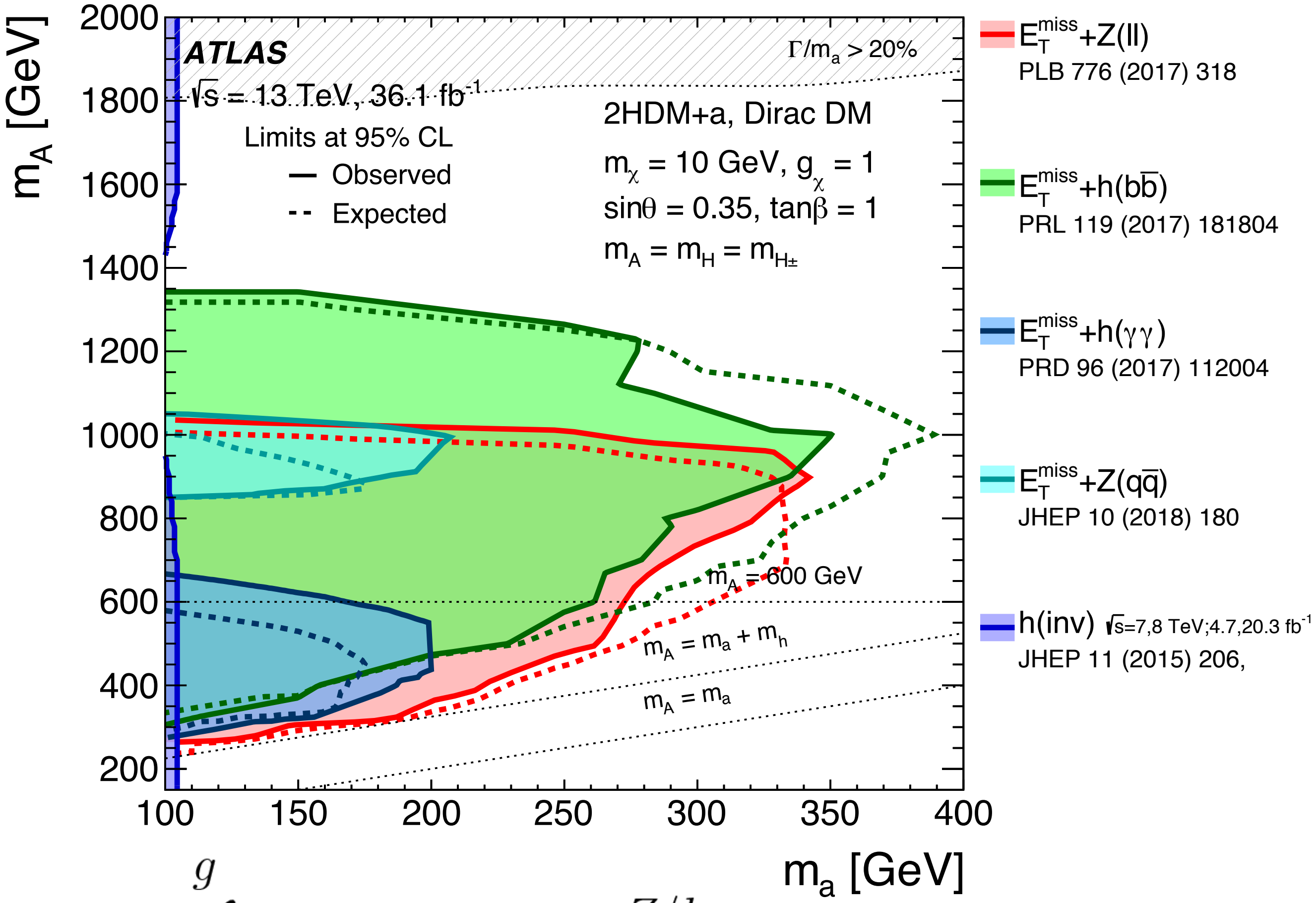


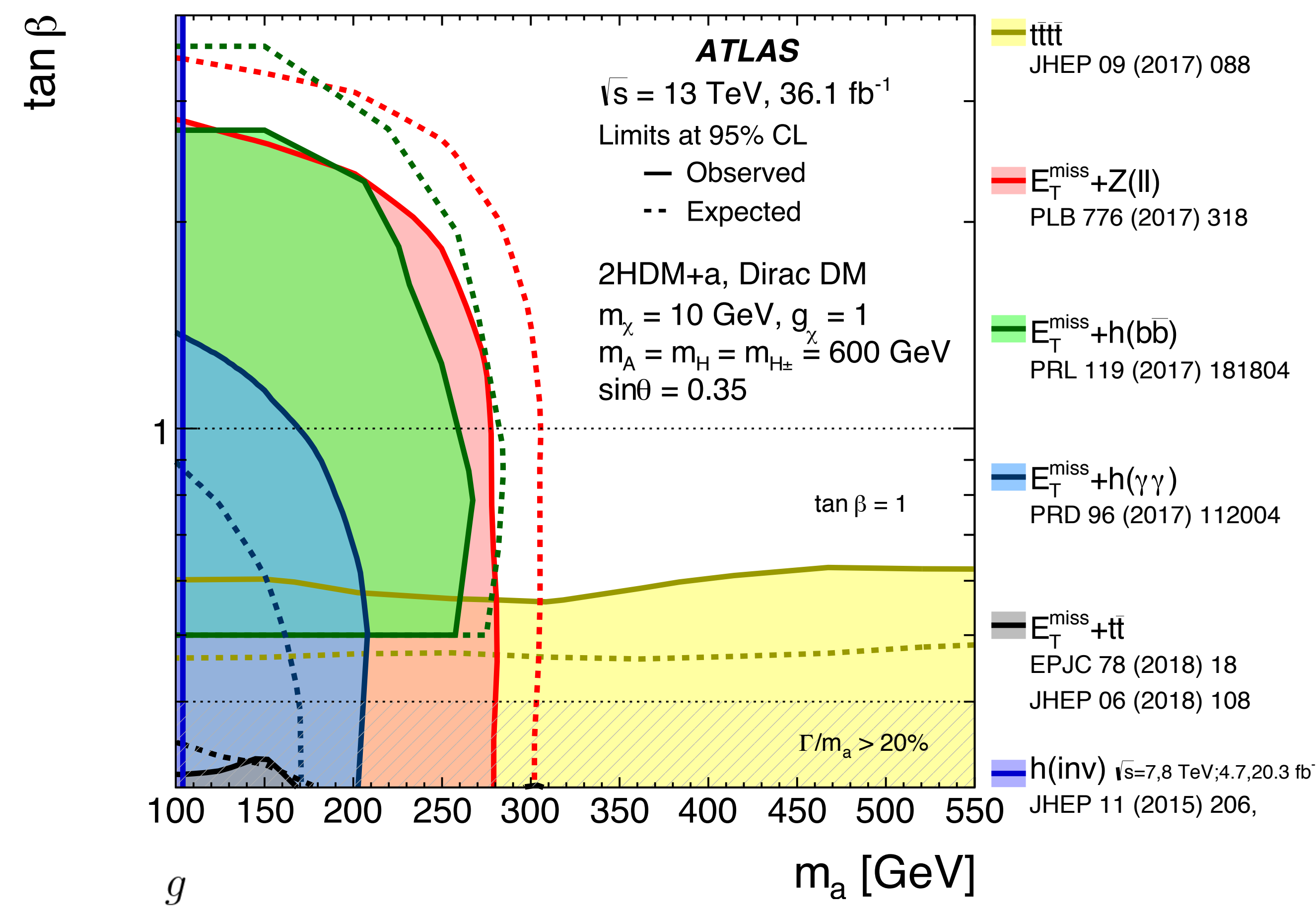


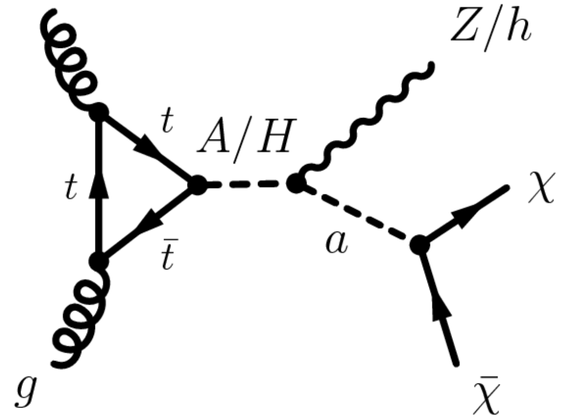


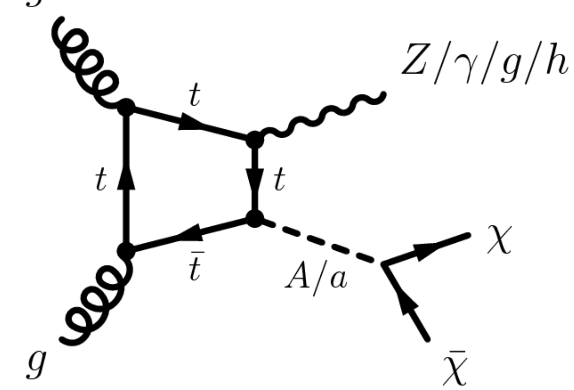
- Very model-dependent, rich parameter space of q,g,χ couplings
- Breadth of searches cover the various model scenarios
- Preview of Noam's talk: new dilepton resonance result (not in summary plots)

Other models



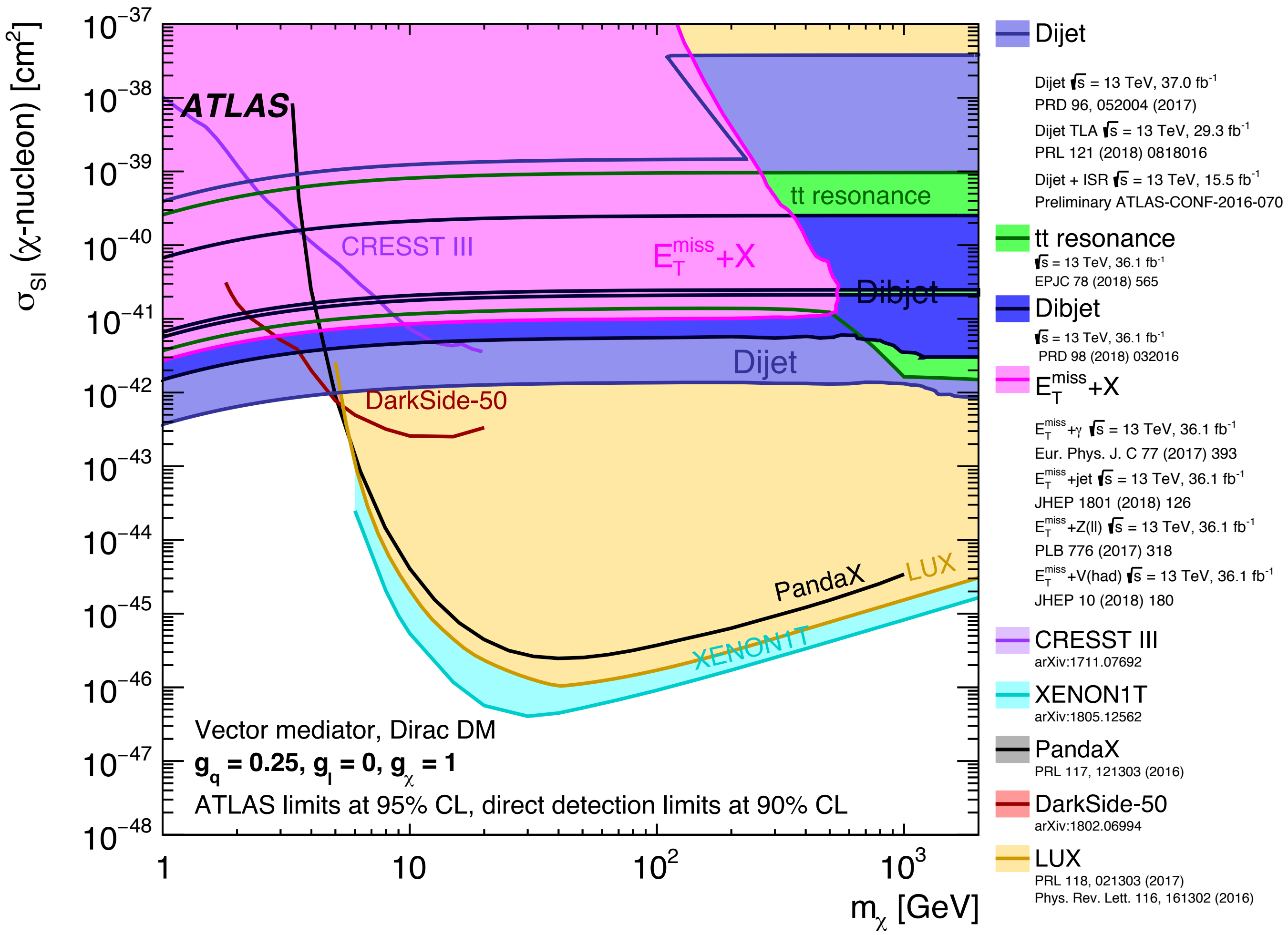


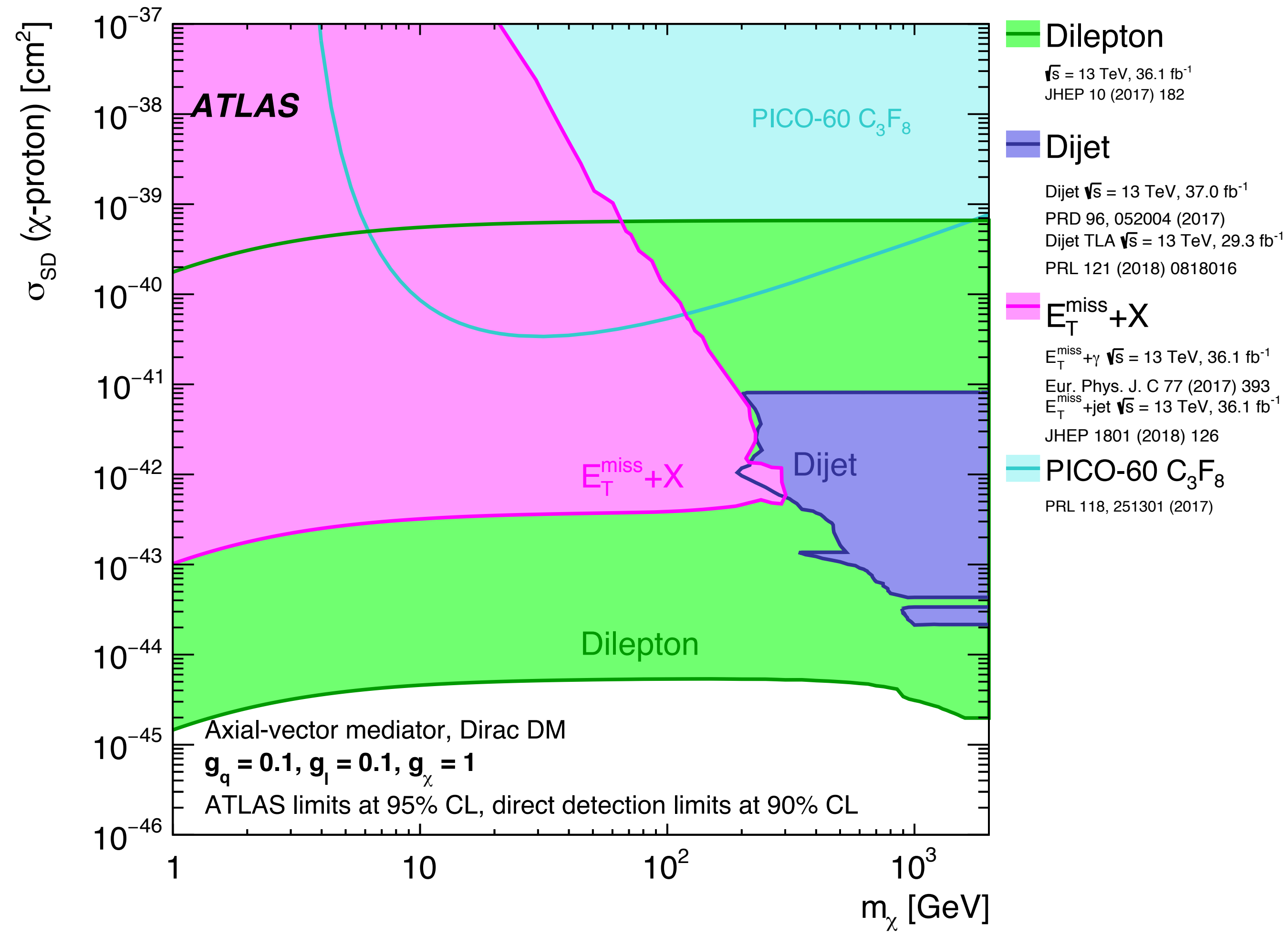




- 2HDM+a: many experimental signatures with non-trivial interplay
- Higgs -> invisible (Higgs portal): see Andres' talk yesterday

Direct detection and collider searches





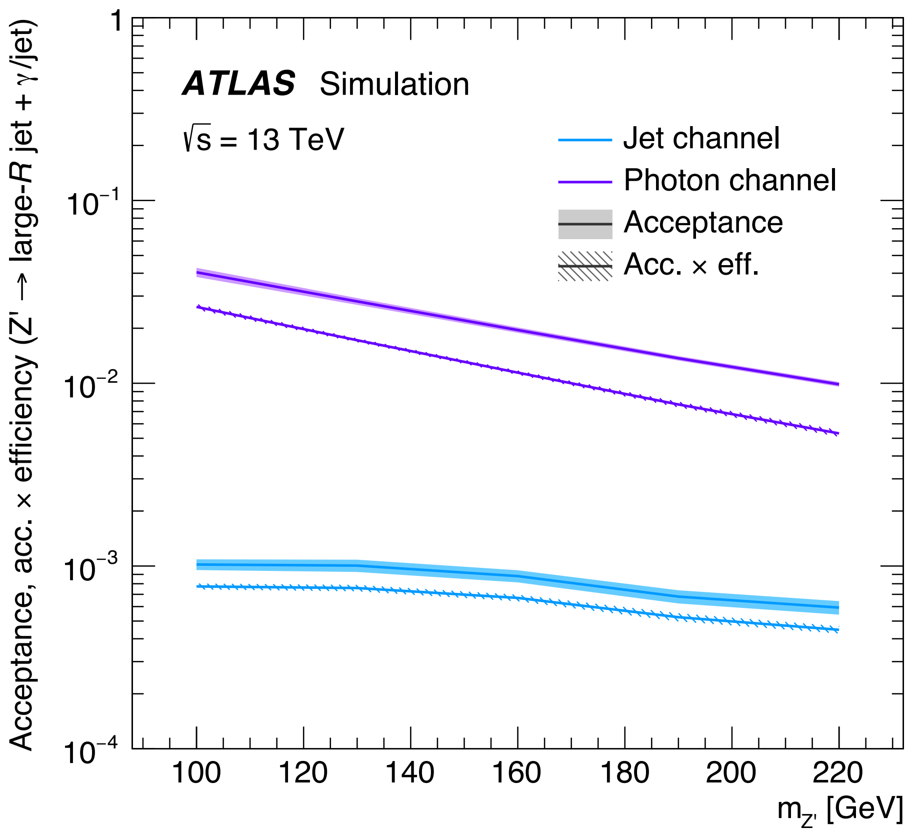
- Also complementarity with direct detection
  - Again, reach of different approaches depends on model and assumptions
- Caveat: direct detection limits 90% CL, collider 95%

Conclusions

- Broad set of approaches to searching for Dark Matter with ATLAS, summarised in recent paper
- Several recent results, more to come with full ~140fb-1 dataset
- Benefitting from improved trigger and performance of ATLAS detector as well as larger dataset
- Outlook bright for run 3: extensive new trigger hardware and software will expand scope of what is possible, coupled with new and maturing analysis techniques and more signatures

Backup

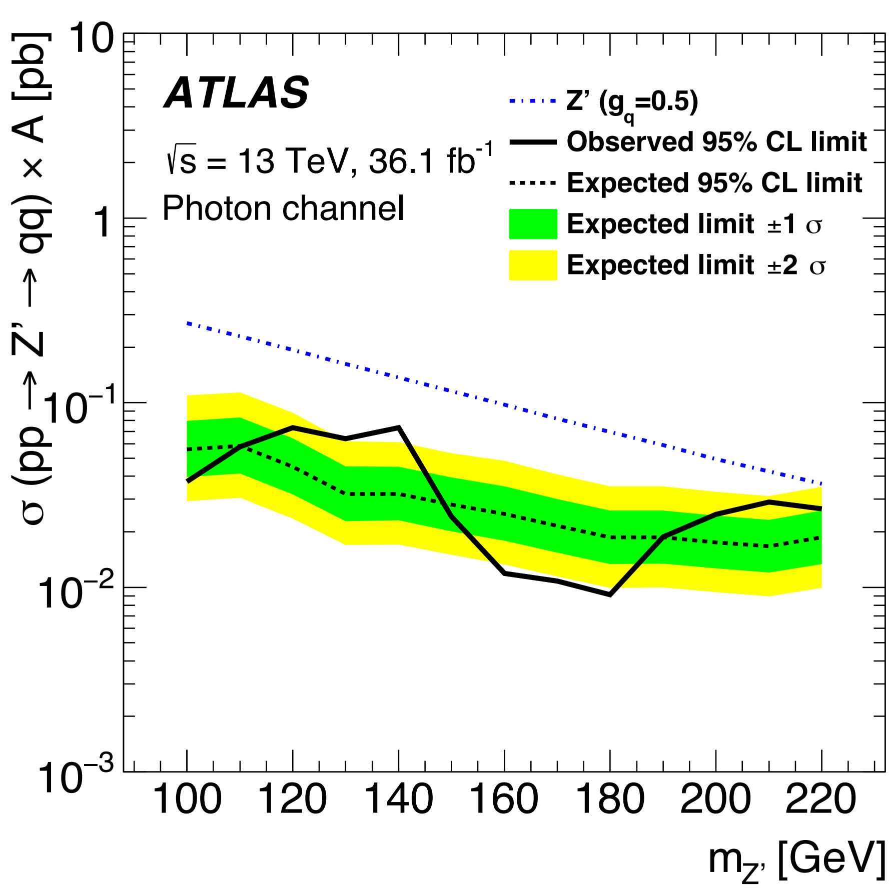
ISR Jet vs Photon

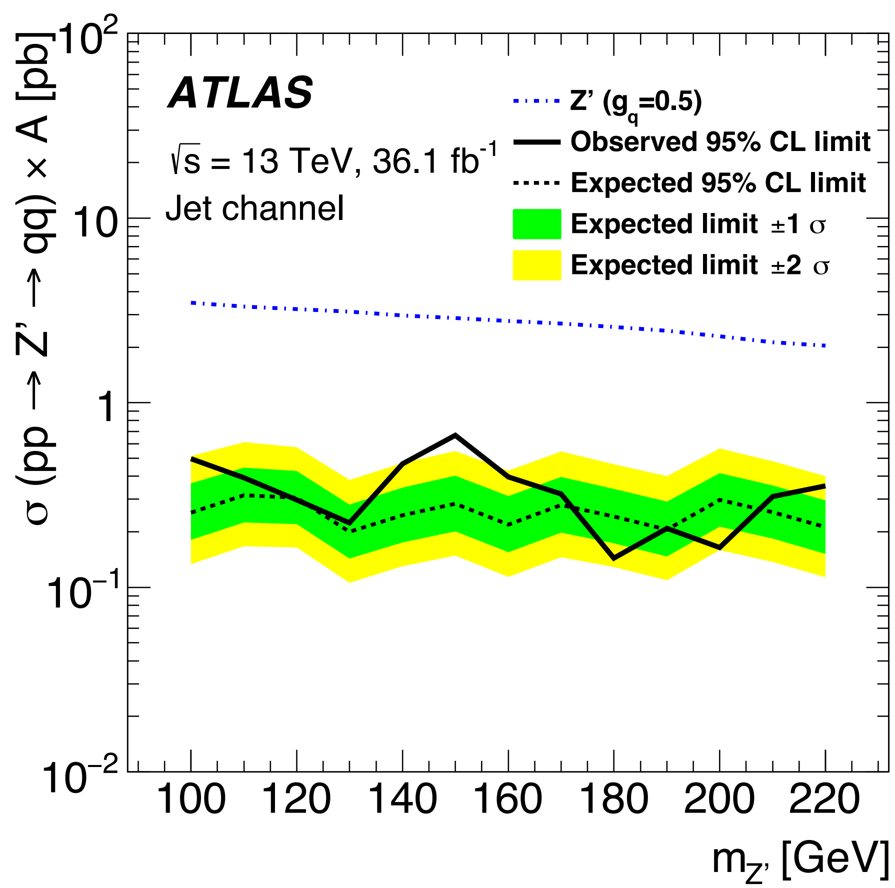


	$m_{Z'}$ = 160 GeV		$m_{Z'}$ = 220 GeV	
ISR jet (ISR γ) selection criterion	ISR jet ϵ [%]	ISR γ ϵ [%]	ISR jet ϵ [%]	ISR γ ϵ [%]
p_T^J > 450 (200) GeV	0.22	5.8	0.17	1.1
ρ^{DDT} > 1.5	0.11	2.4	0.07	0.4
p_T^{ISR} > 420 (155) GeV	0.09	2.4	0.06	0.4
τ_{21}^{DDT} < 0.5	0.07	1.3	0.04	0.3

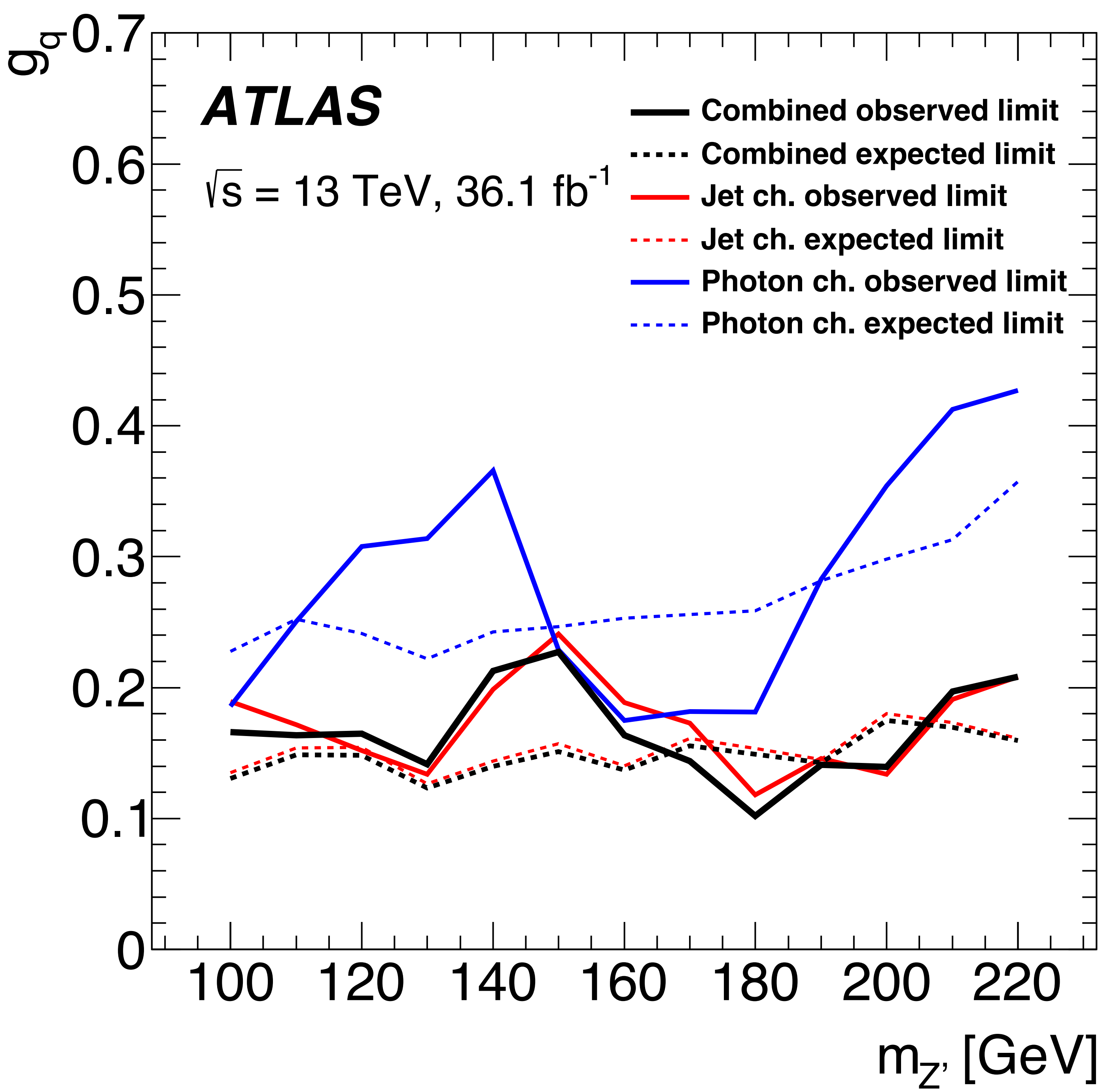
- Jet: lower acceptance due to higher threshold
  - Single jet: E_T > 420 GeV (~30 Hz)
  - Single photon: E_T > 140 GeV (~40 Hz)
- Higher XS thanks to α_S

(Rates from ATL-DAQ-PUB-2018-002)

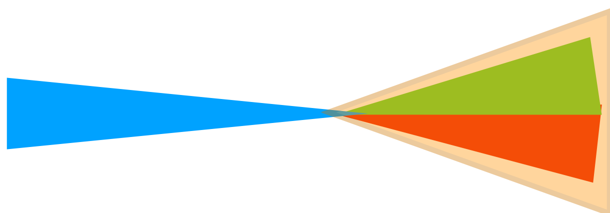




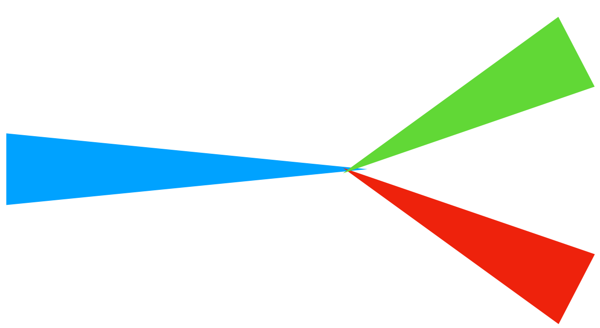
ISR Jet vs Photon



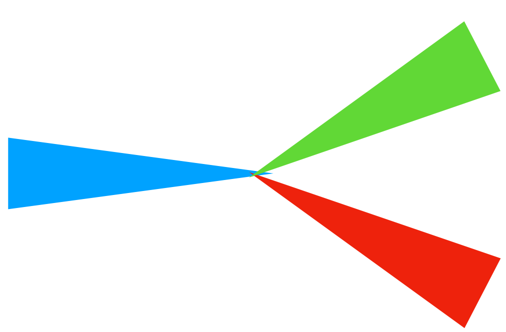
ISR Jet vs Photon: combinatorics



Boosted dijet: easy to group into (ISR, resonance)

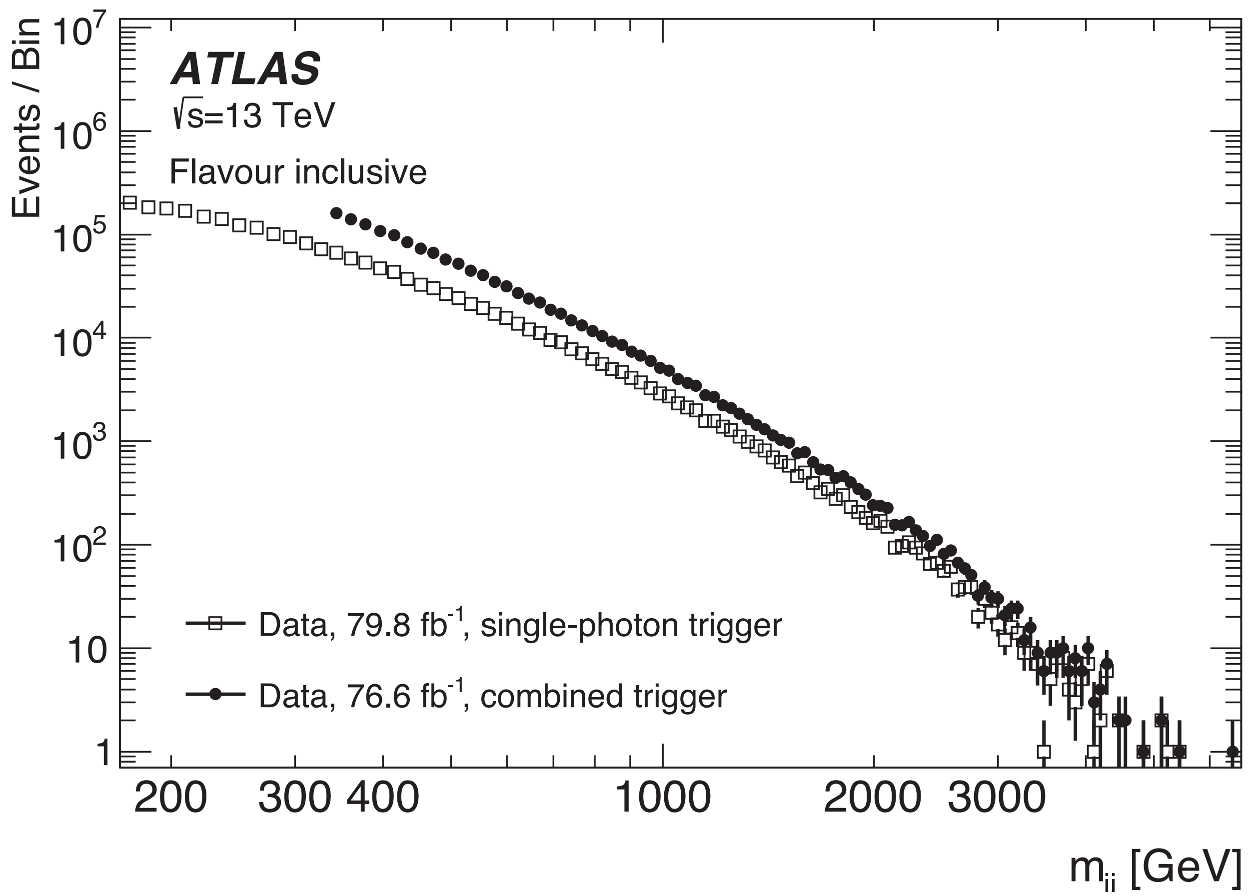


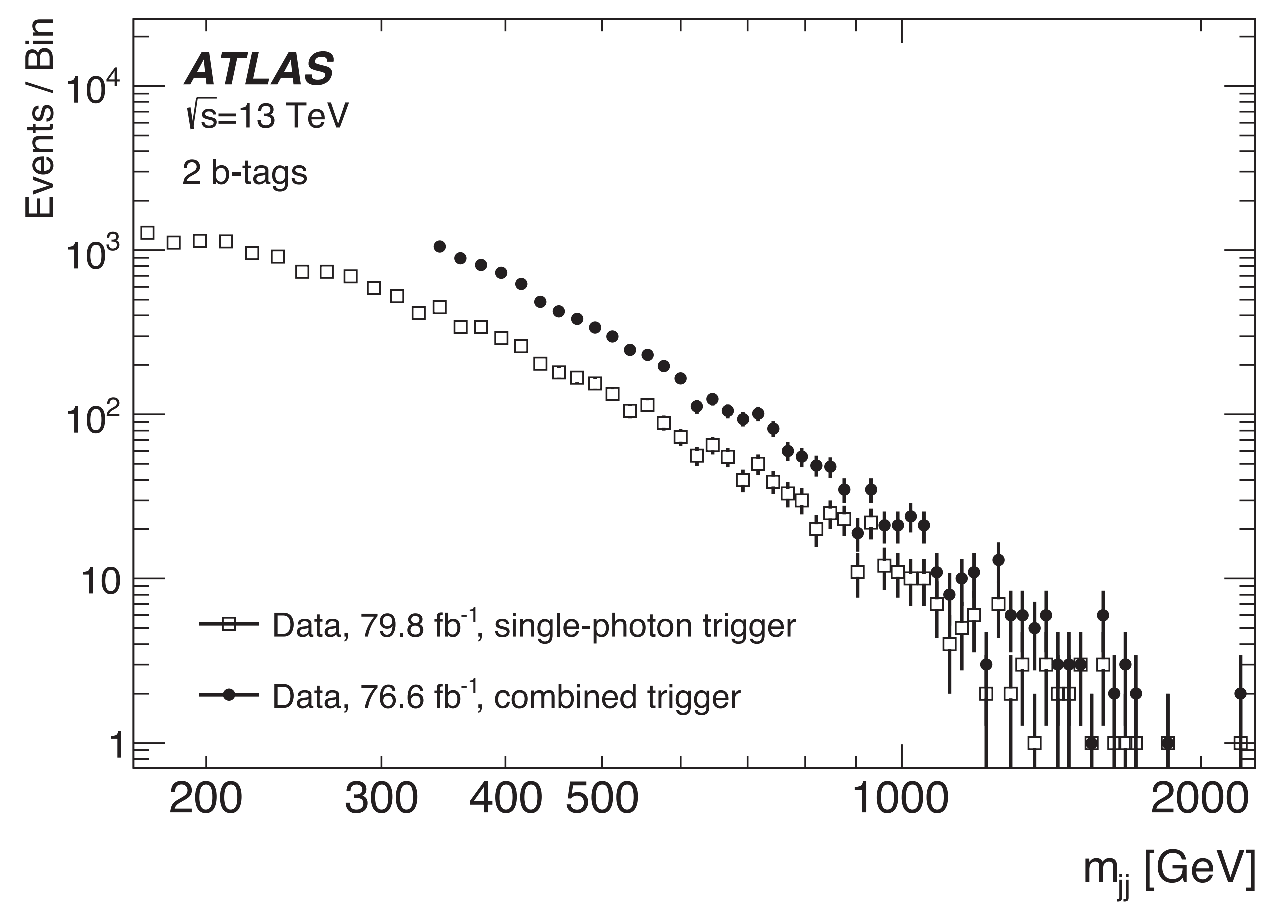
Resolved: take lead jet as ISR, next two as resonance?

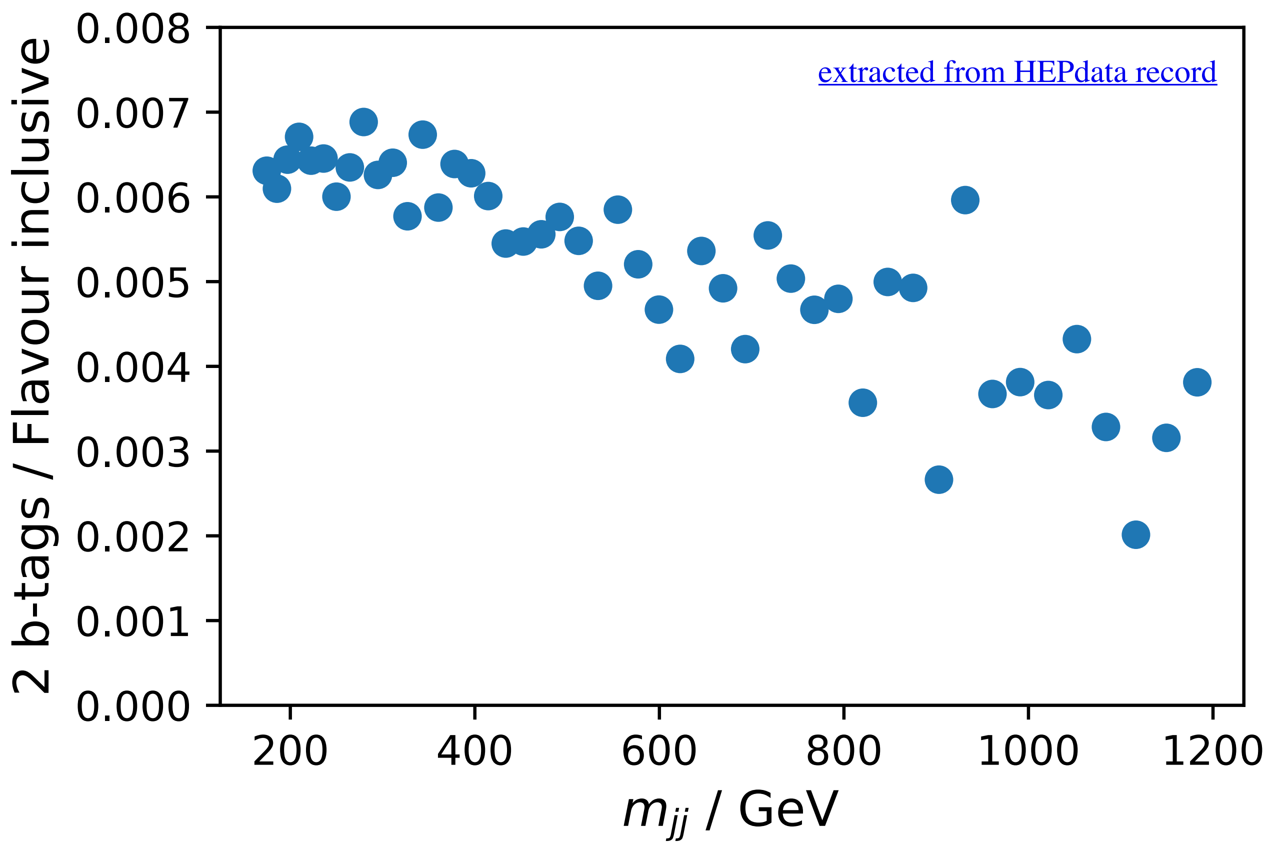


Breaks down for heavier Z’: which to choose?
Smear signal peak

Dijet + ISR: b-tagging

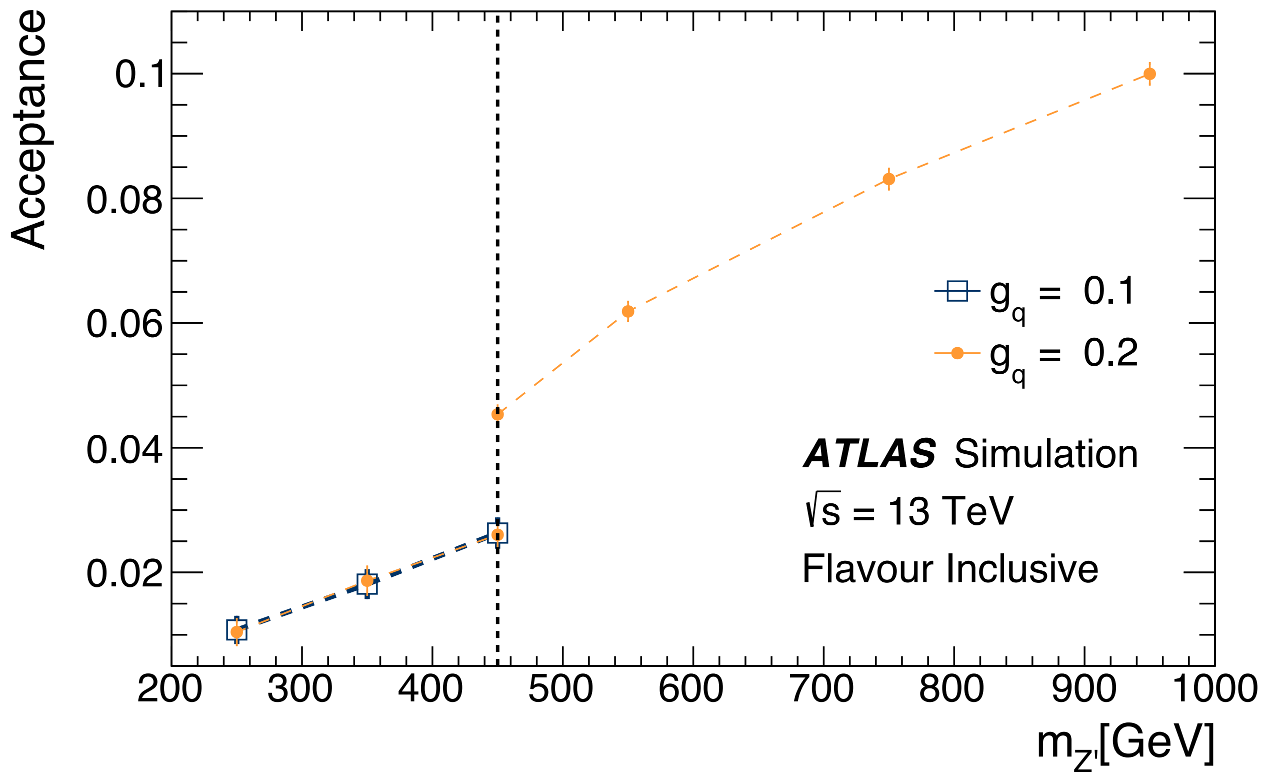


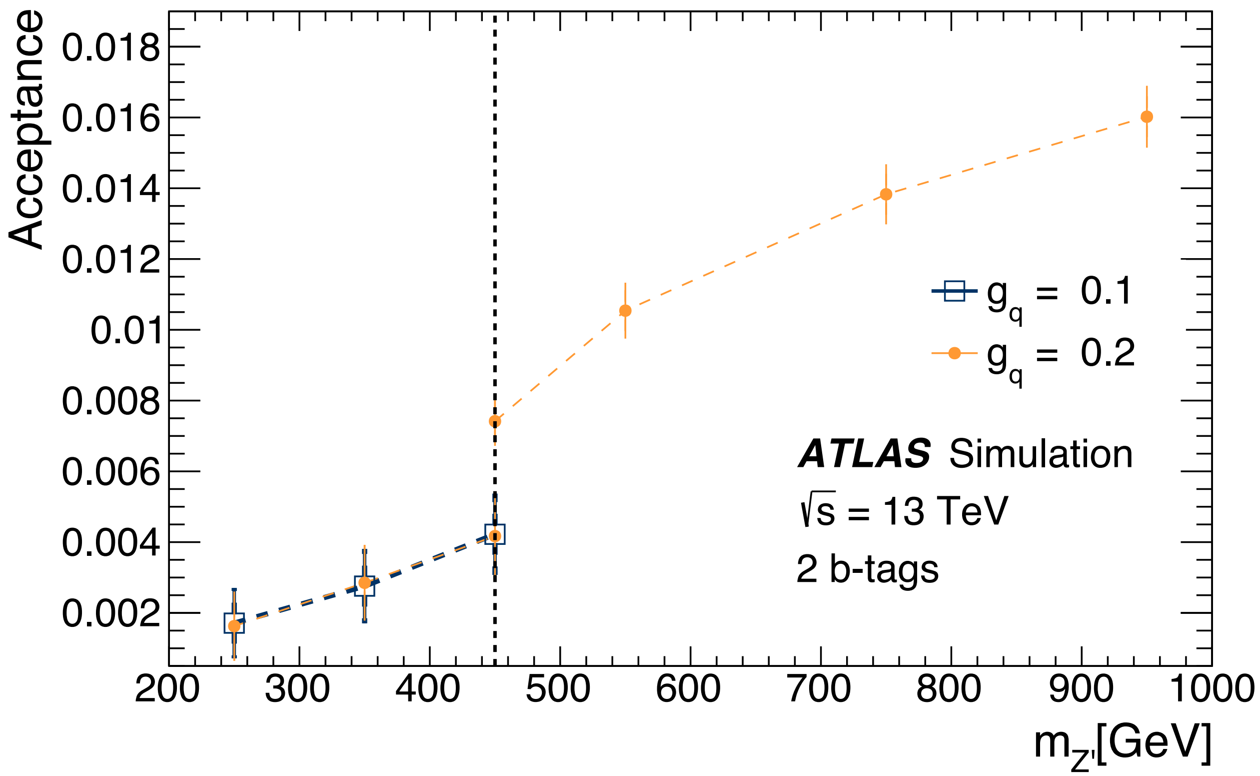


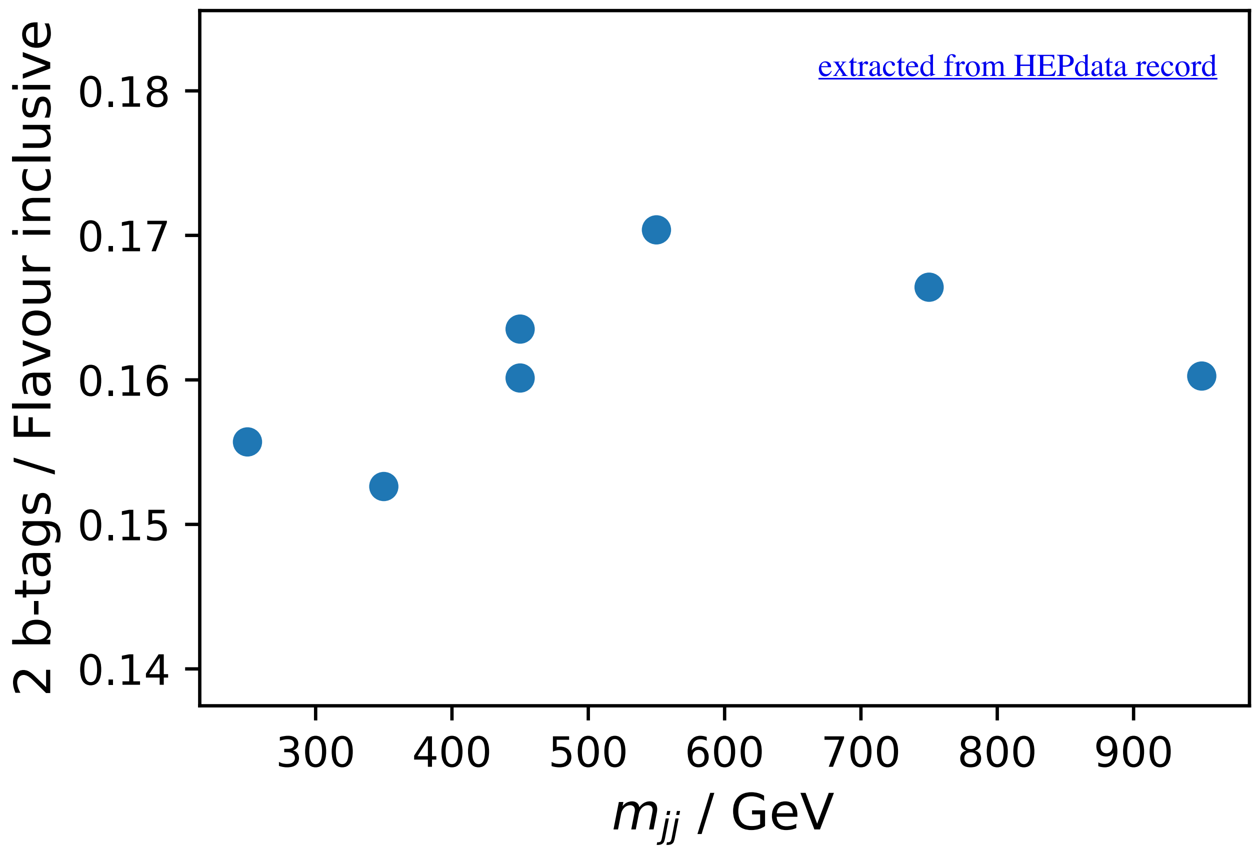


b-tagging accepts 0.3-0.7% of background

Dijet + ISR: b-tagging

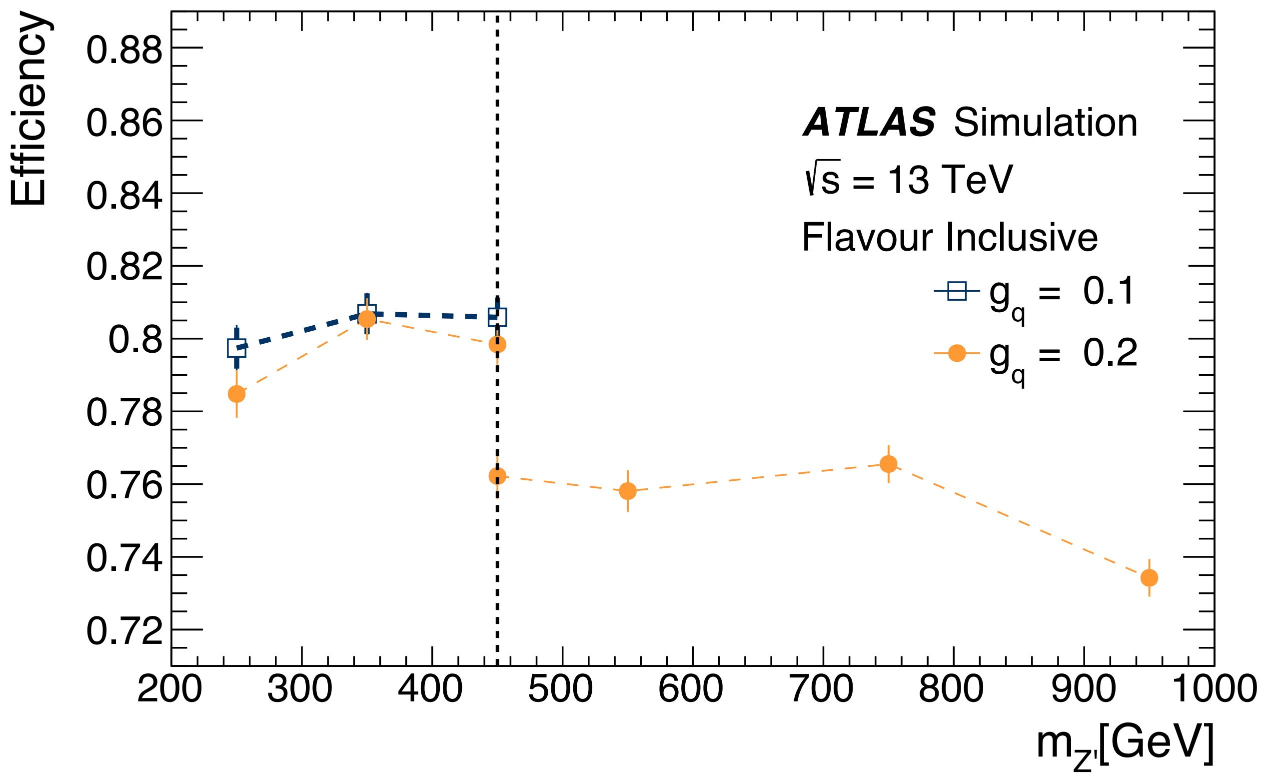


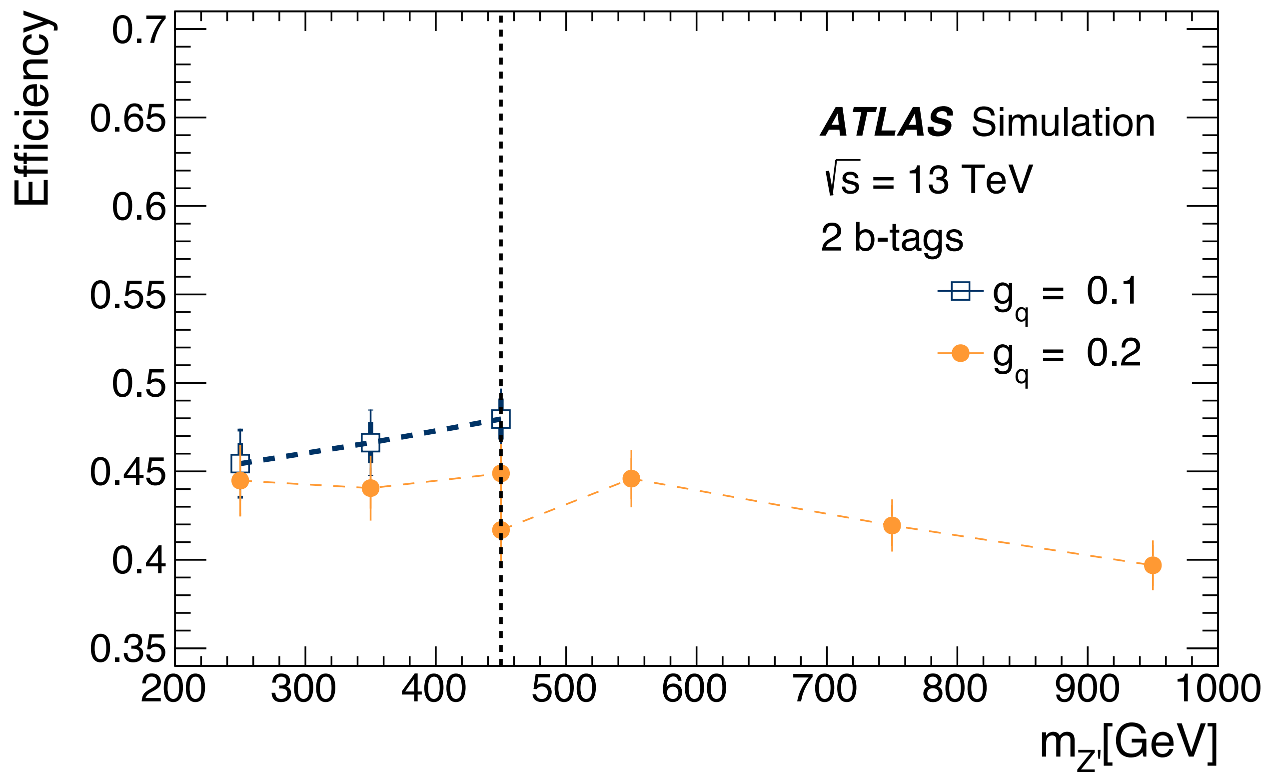


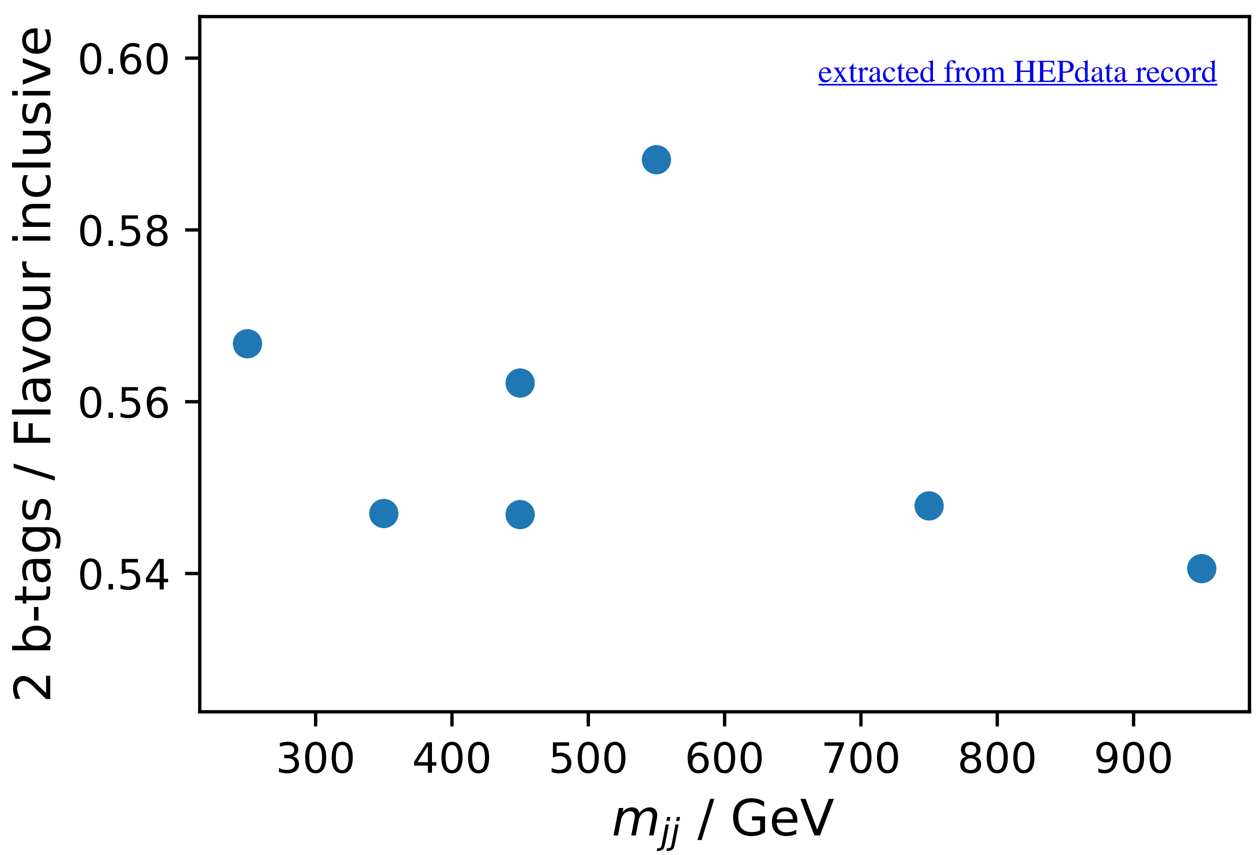


b-tagging accepts 15-17% of background (~1/6)

Dijet + ISR: b-tagging



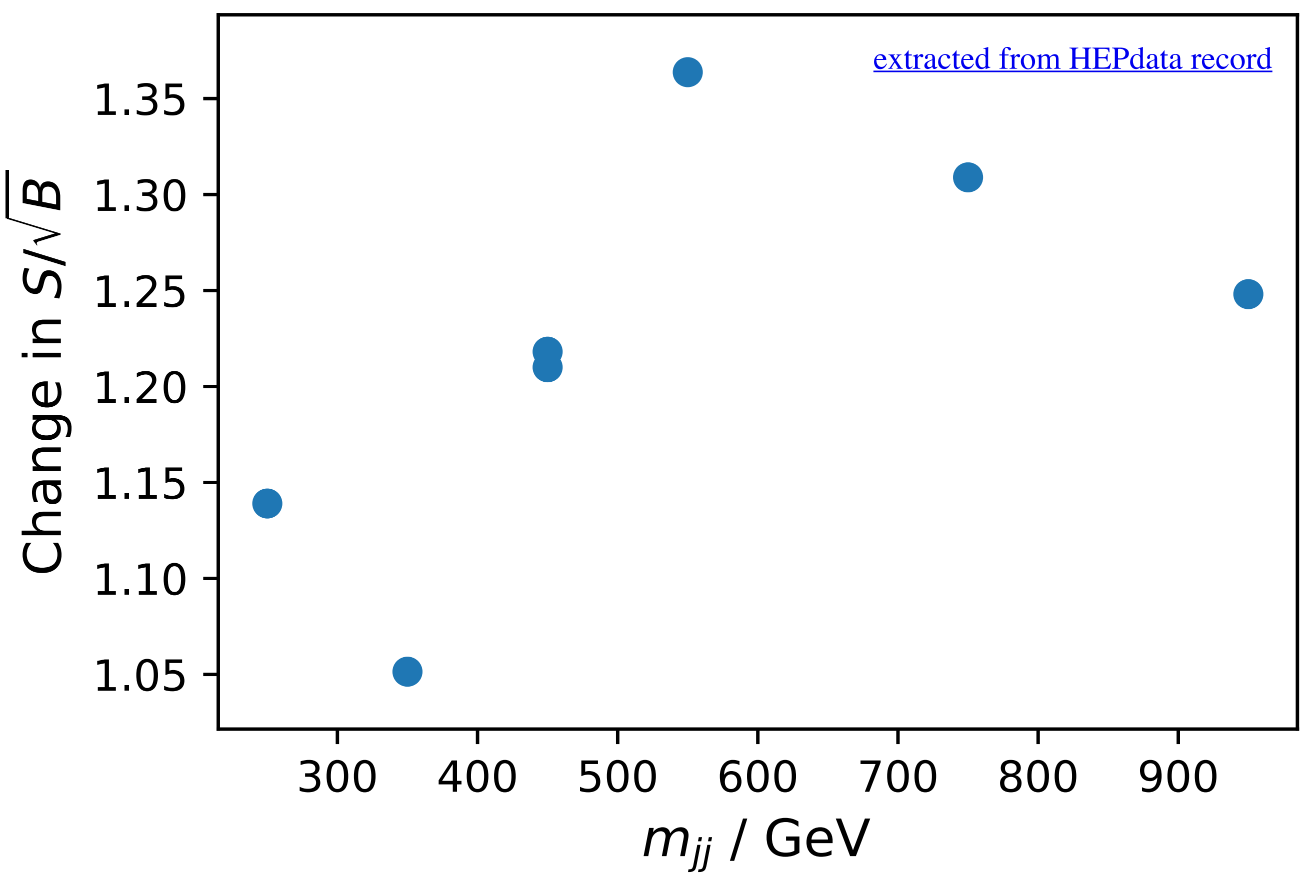


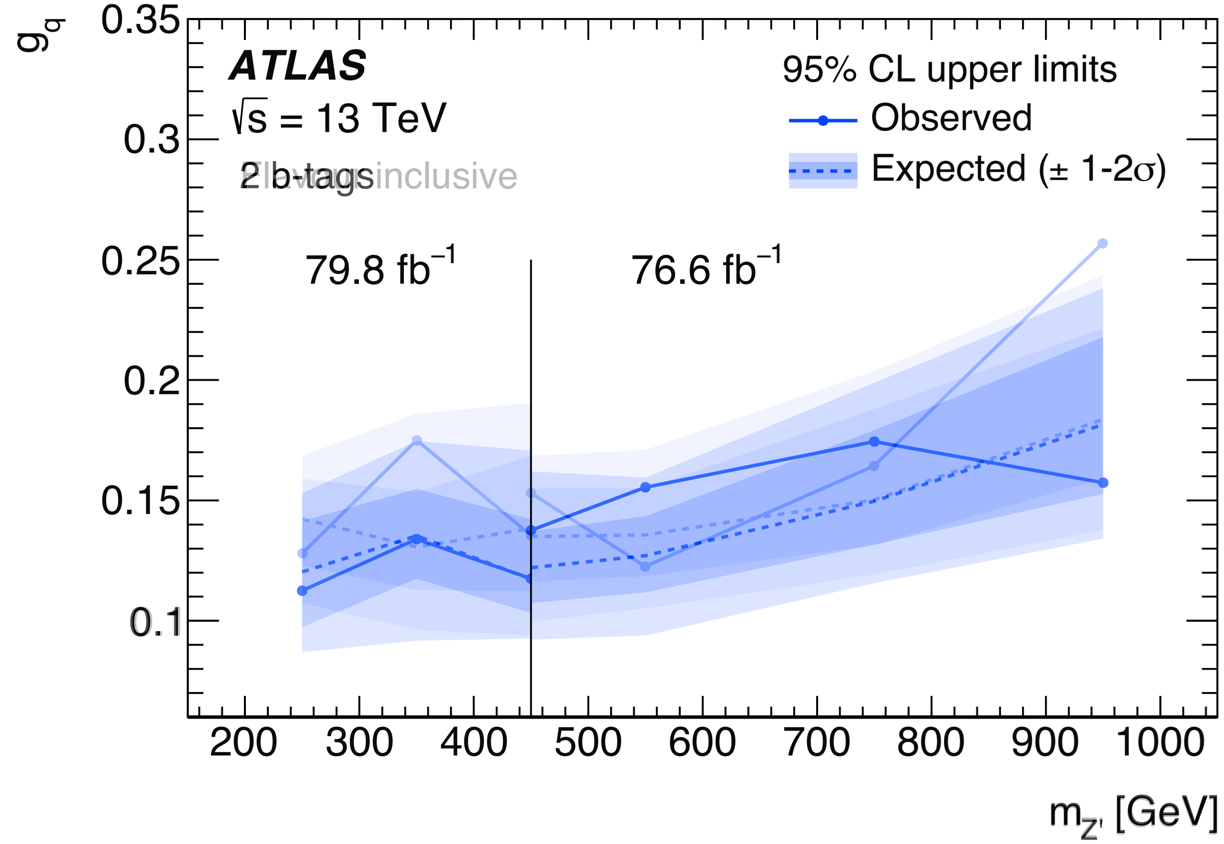


b-tagging accepts 15-17% of background (~1/6)

… but with ~ 50% efficiency

Dijet + ISR: b-tagging





General improvement in S/sqrt(B) thanks to b-tagging

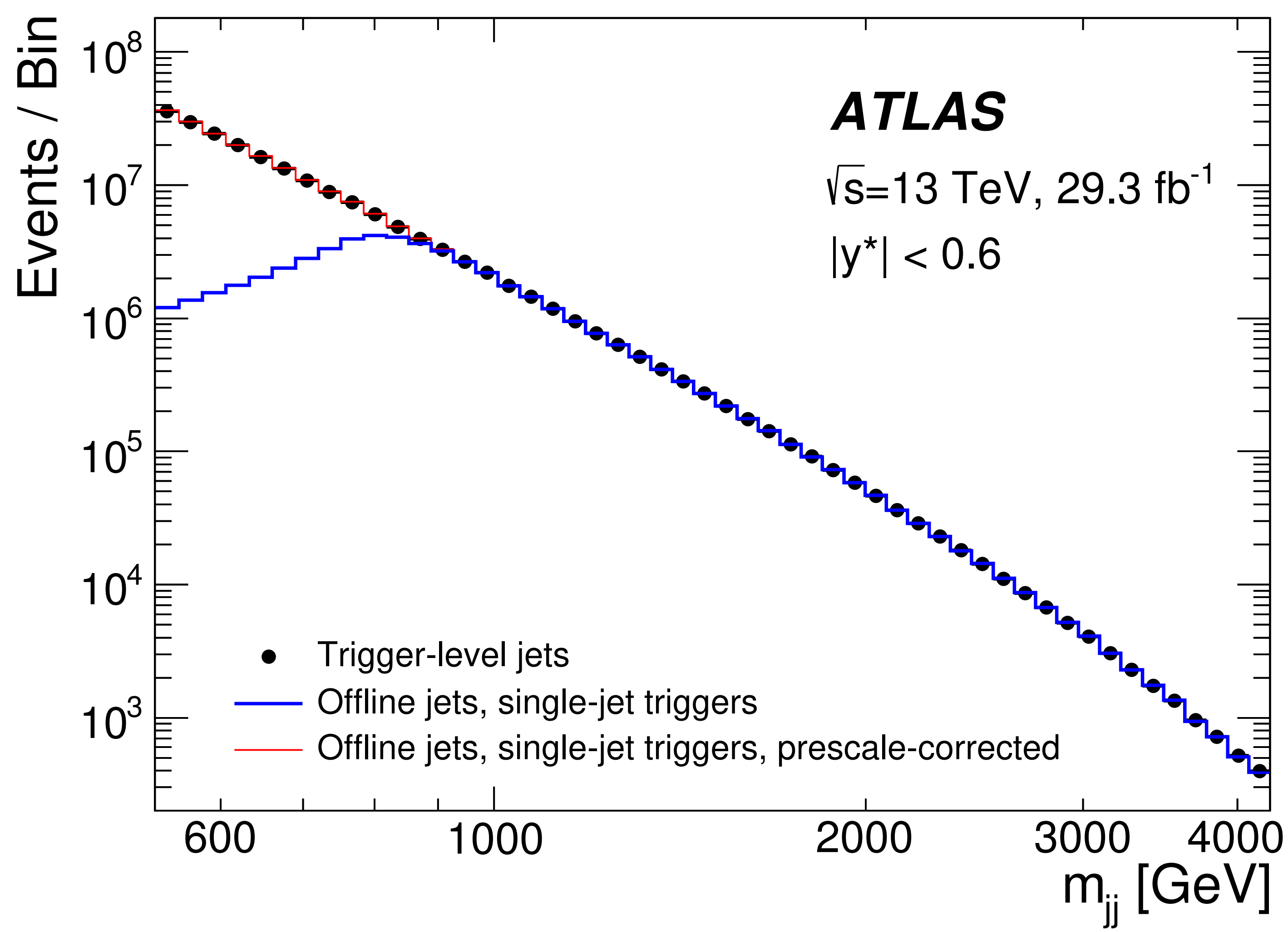
General improvement in expected limit thanks to b-tagging

(Fainter line is inclusive)

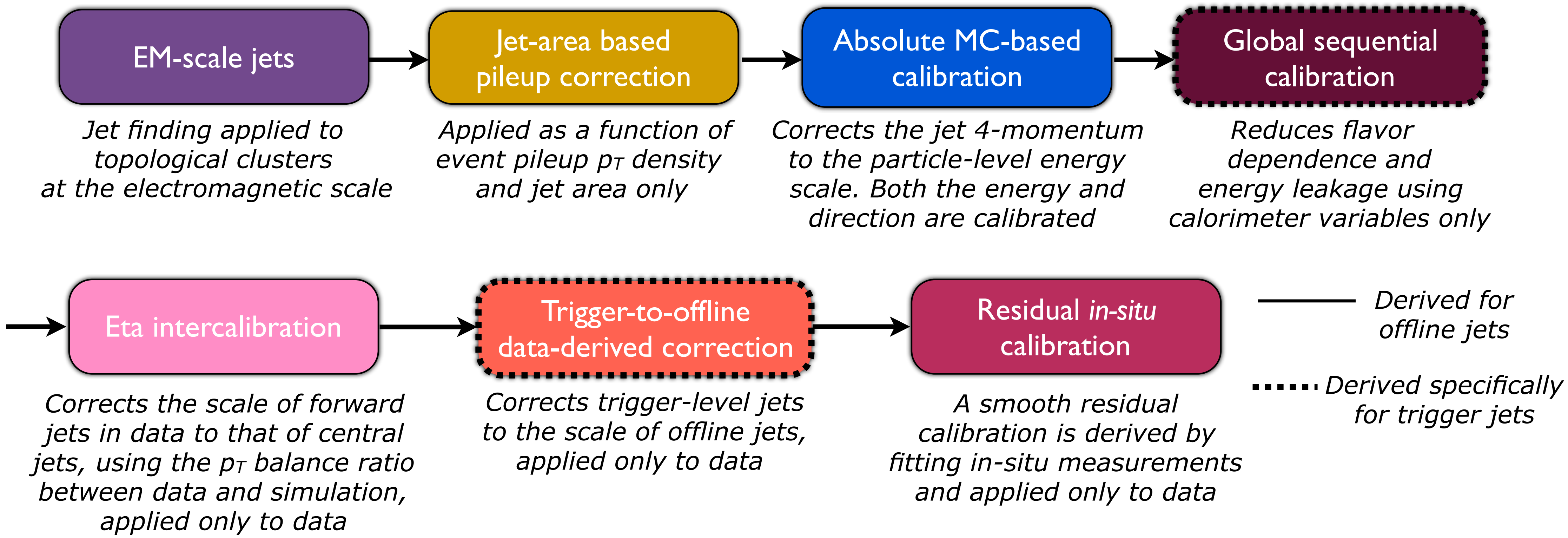
TLA payoff

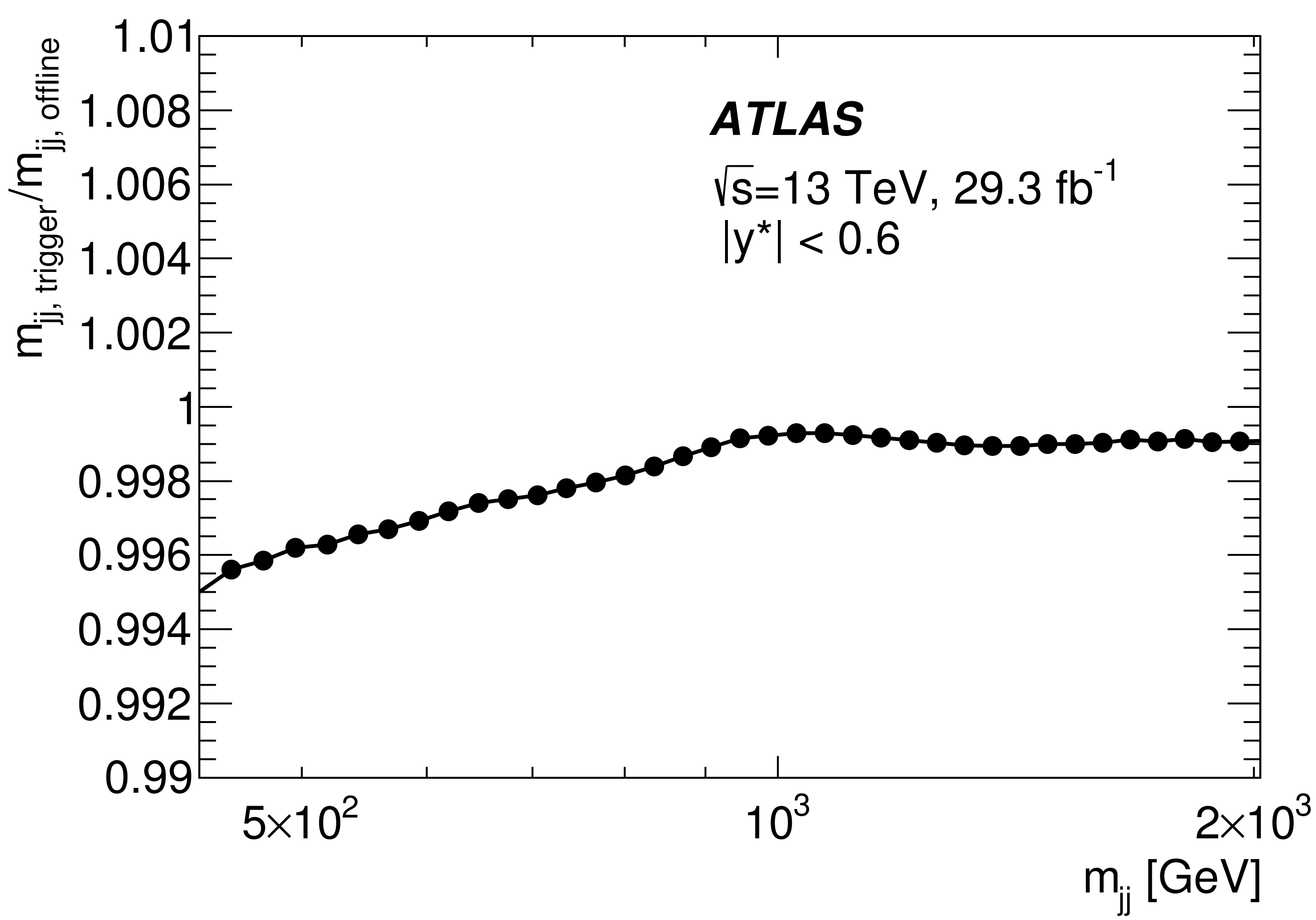
	“‘standard” dijet	TLA
lead jet p_T >	440	220
sublead jet p_T >	60	85
m_{jj} >	1100	520

4×10^7 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 recalibrated 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
  - |y*|<0.3: 27 bins, |y*|<0.6: 19

Functional form
$f(x) = p_1(1-x)^{p_2}x^{p_3}$
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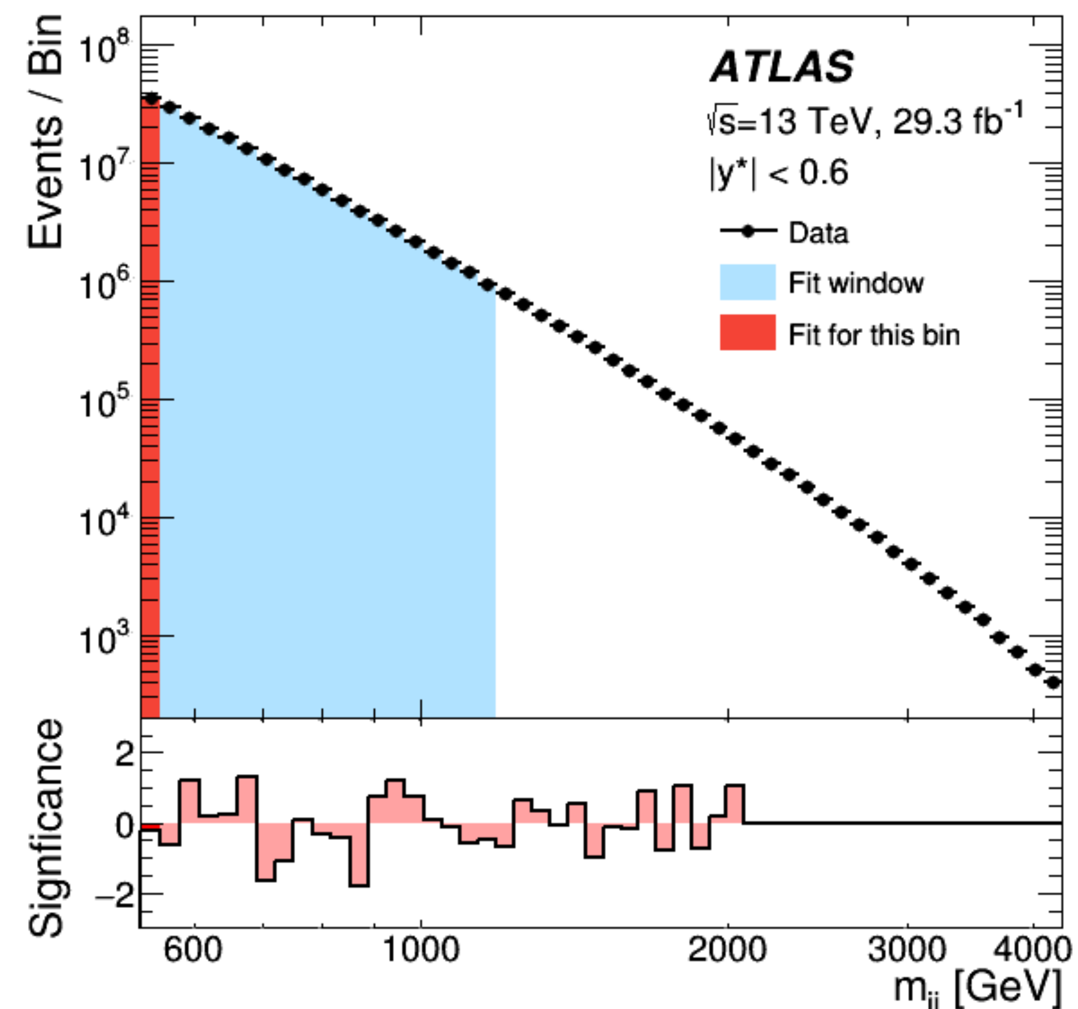

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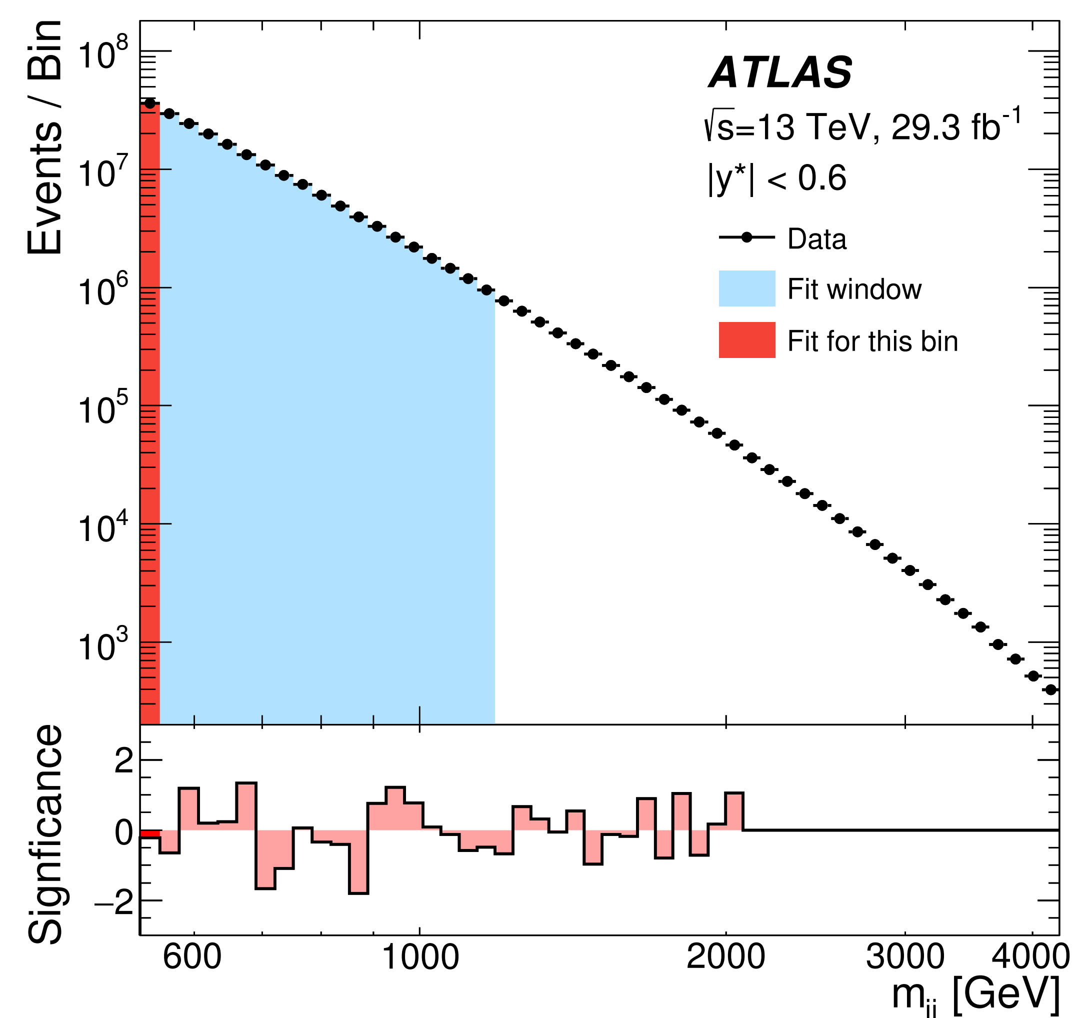

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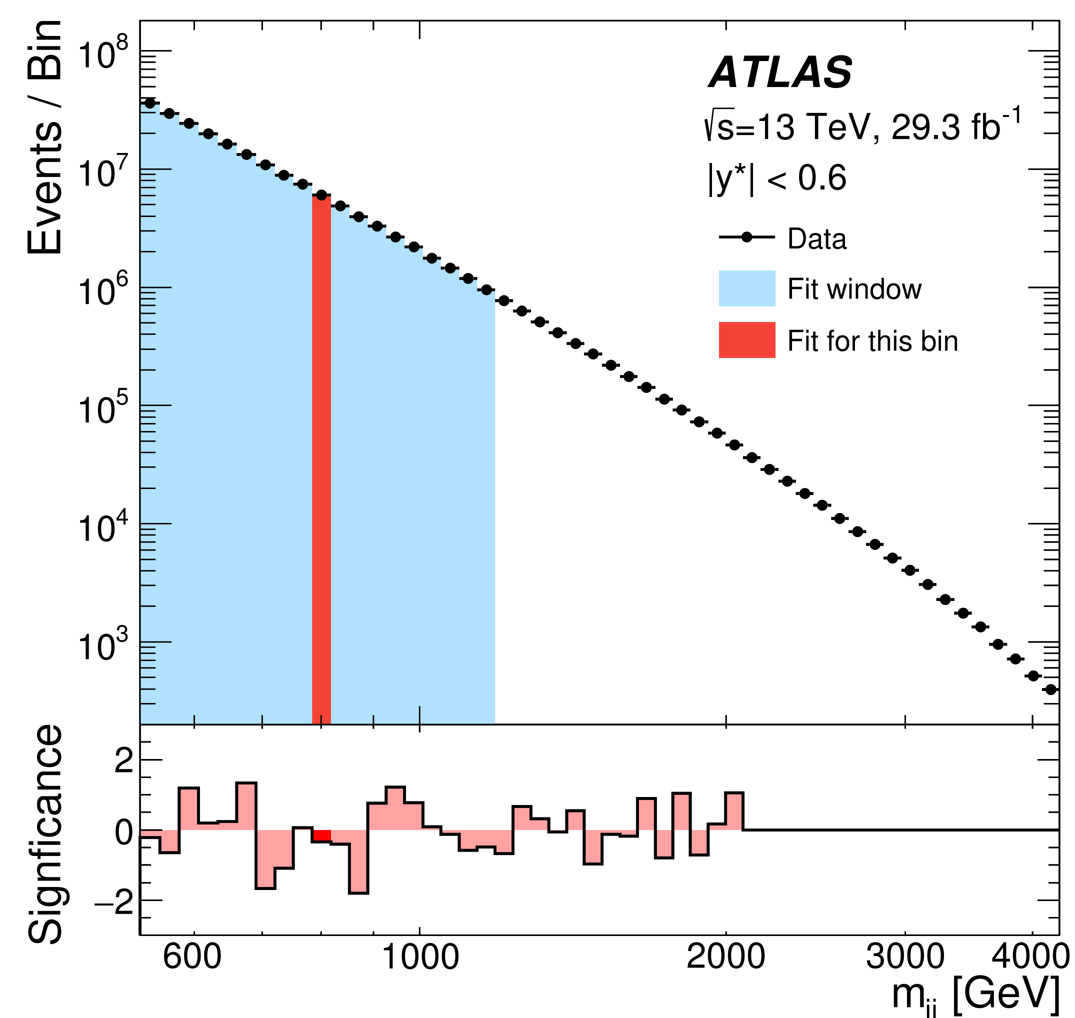

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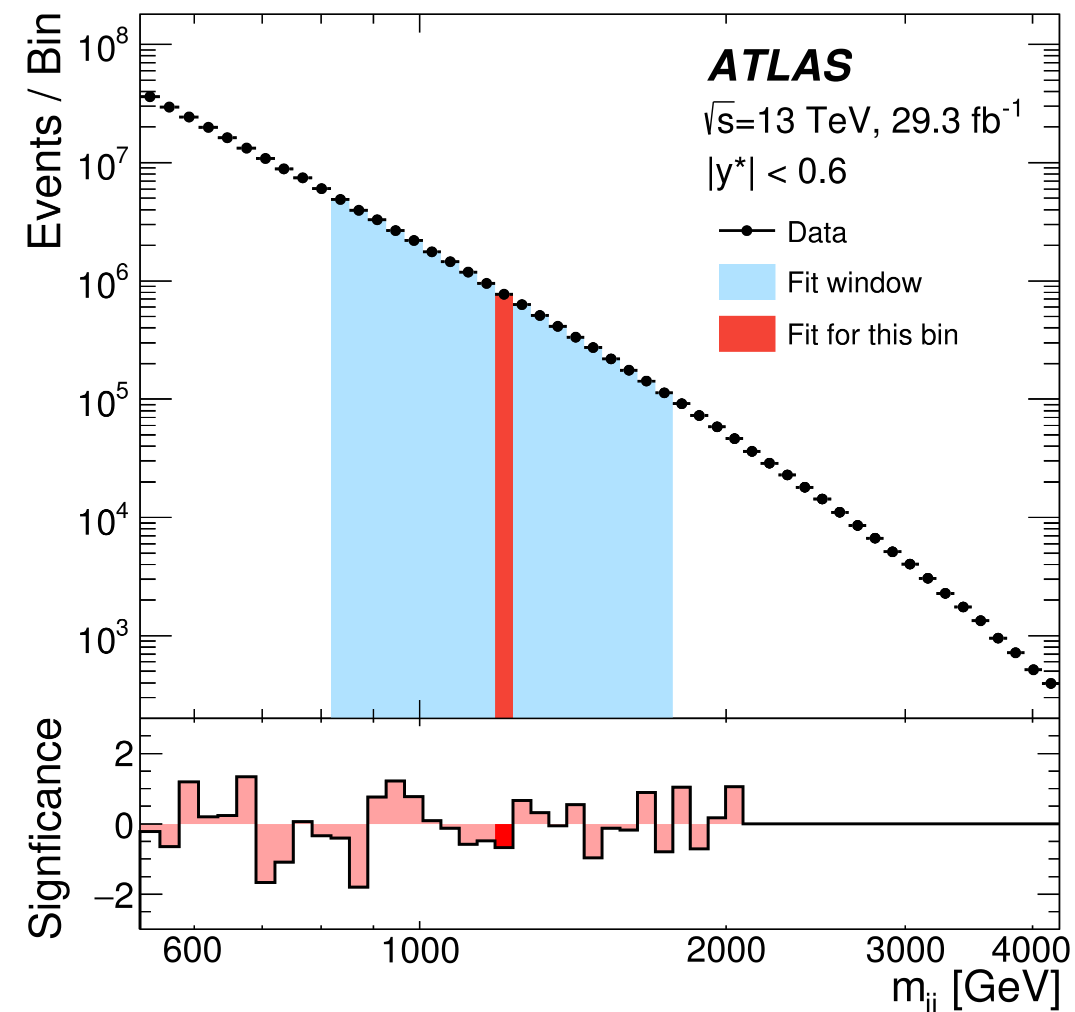

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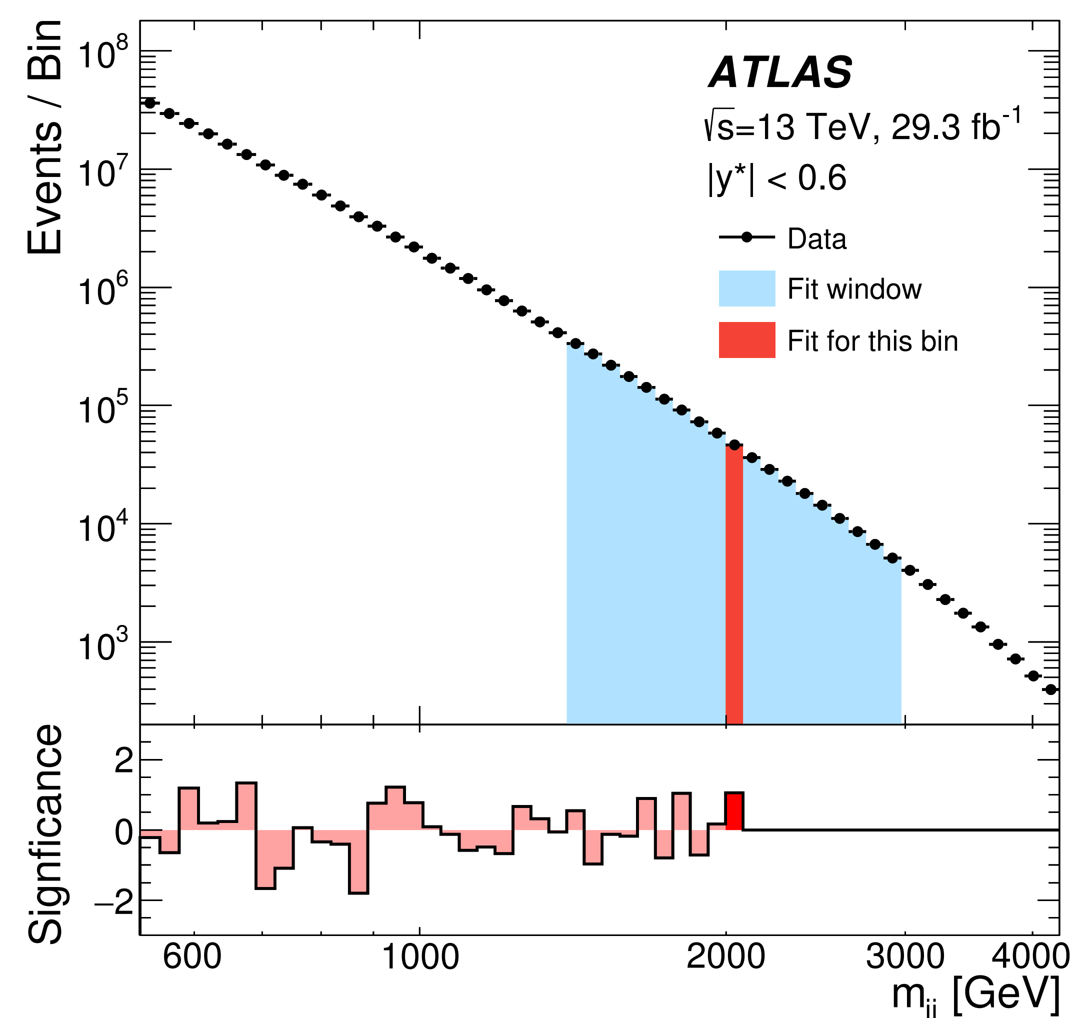

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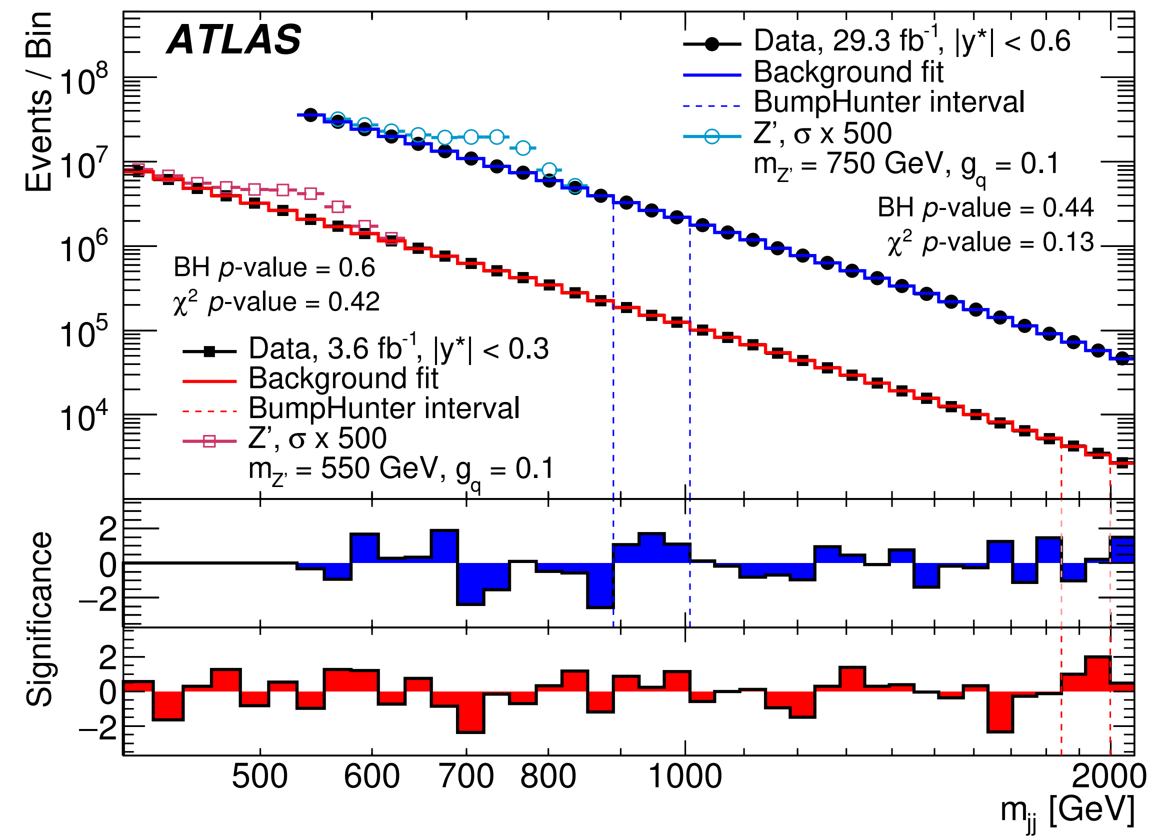
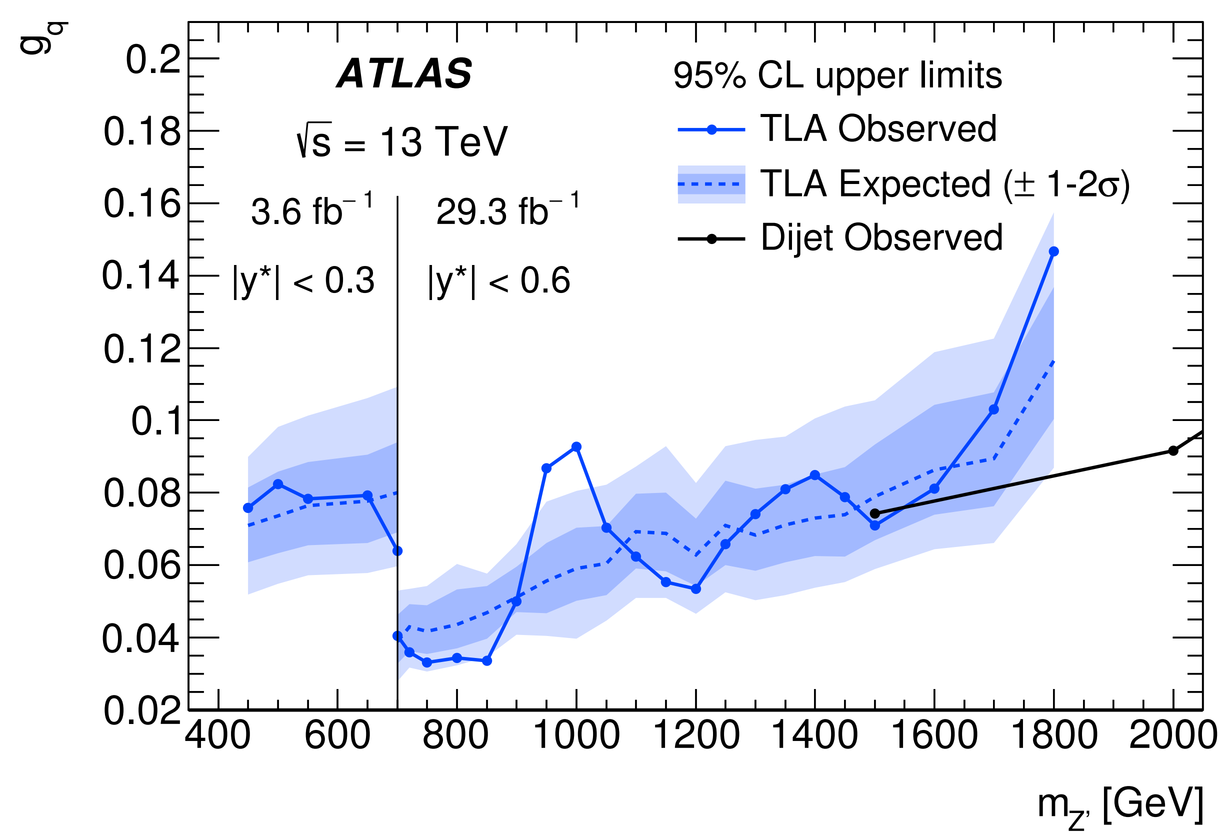
TLA results

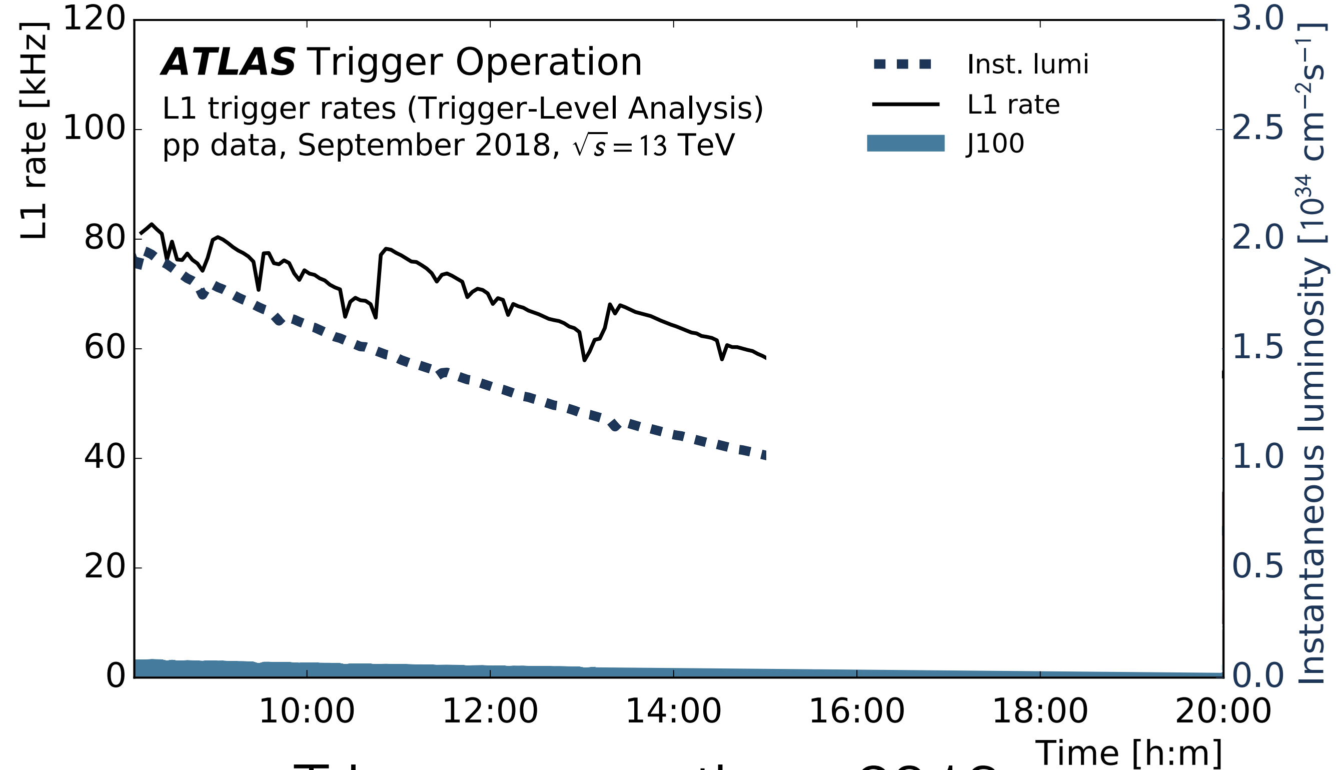
- "BumpHunter" with background-only fit: no significant excesses found
- Signal + Background fit: set limits (areas of flexibility give observed - expected differences)
- Similar sensitivity to conventional dijet resonance search at 1.5 TeV
- Can go much lower in $m_{Z'}$
  - 450-700 GeV using dedicated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





TLA: rest of run 2

- TLA is not a license to ~~print money~~ write out everything
- Most significant limitation is the total L1 rate
- However, this falls significantly over a fill as instantaneous luminosity decreases
- Limited scope for utilisation by other triggers, since they remain bound by the total bandwidth averaged over the fill



Trigger operations 2018

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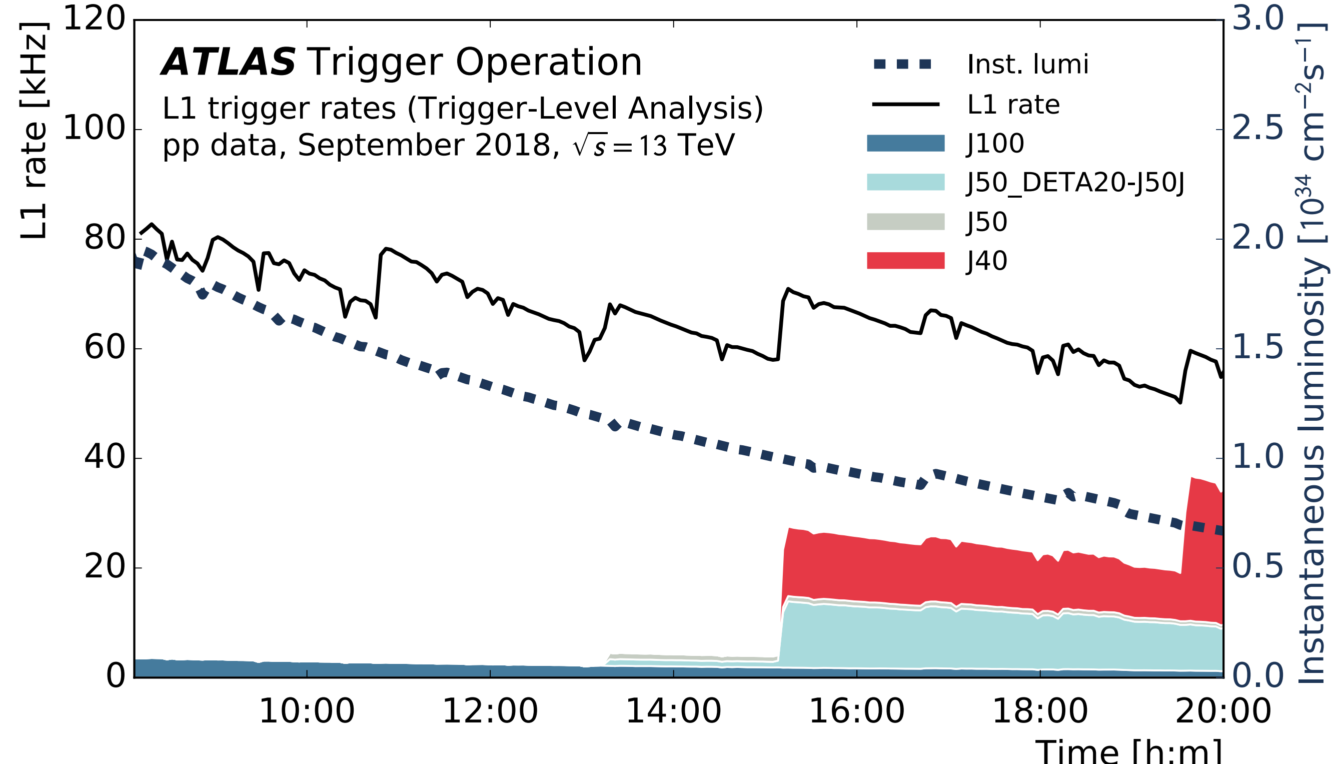
- Can be used for extra TLA triggers (increase random accept rate of lower-threshold L1 triggers and write them out)



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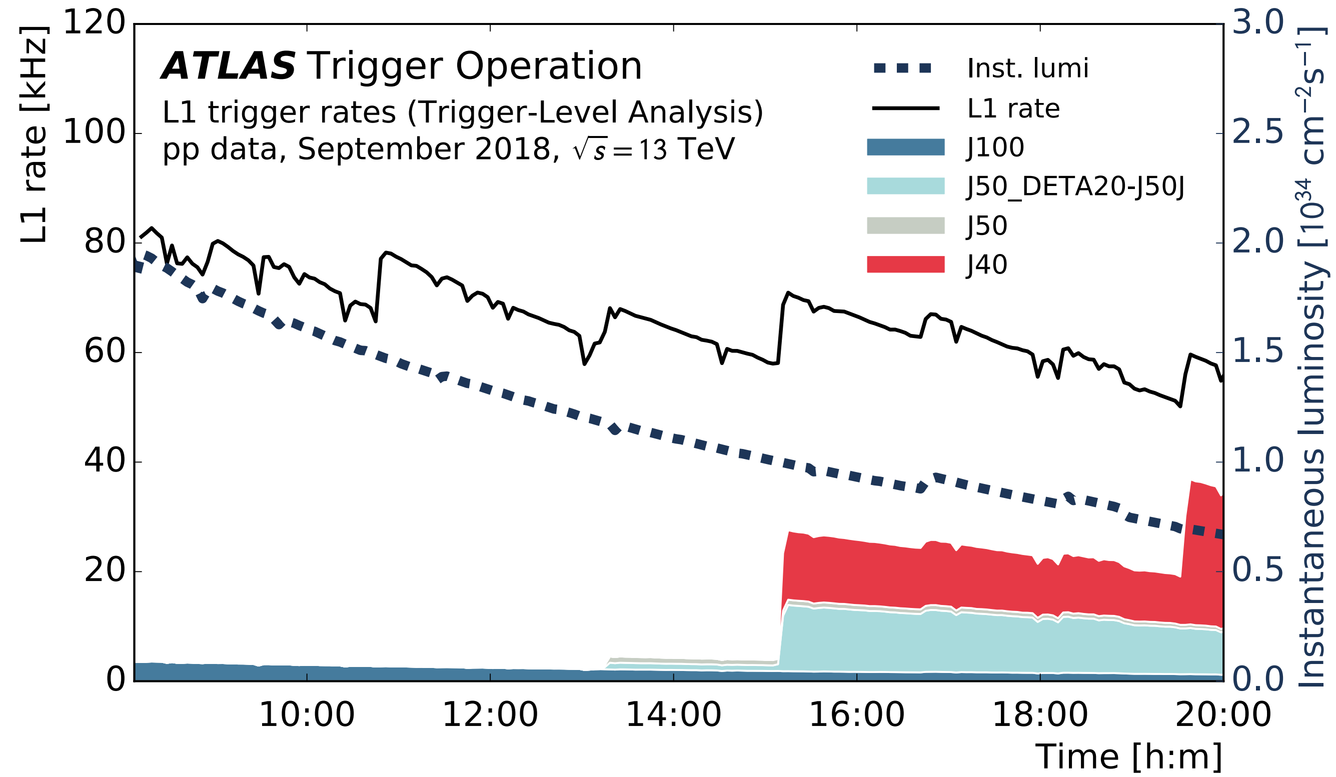

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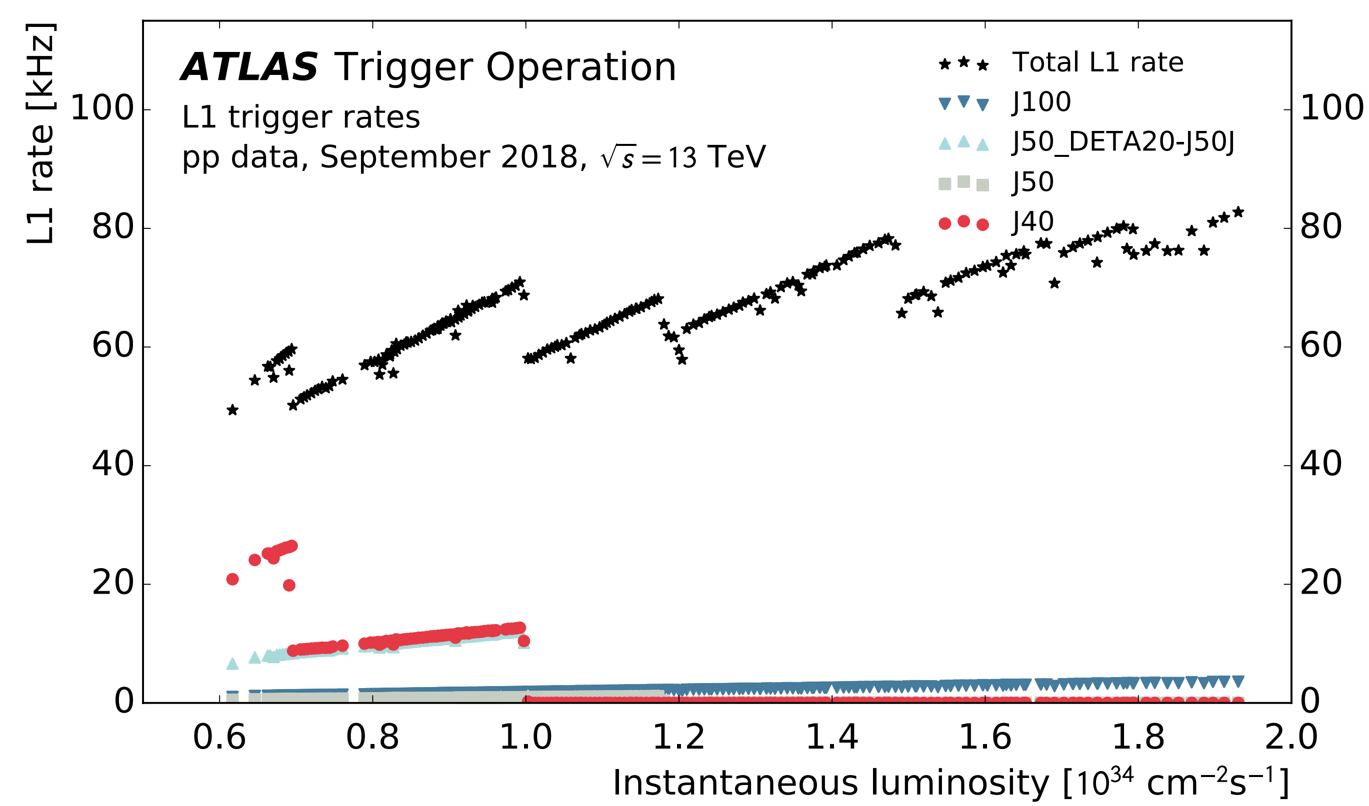
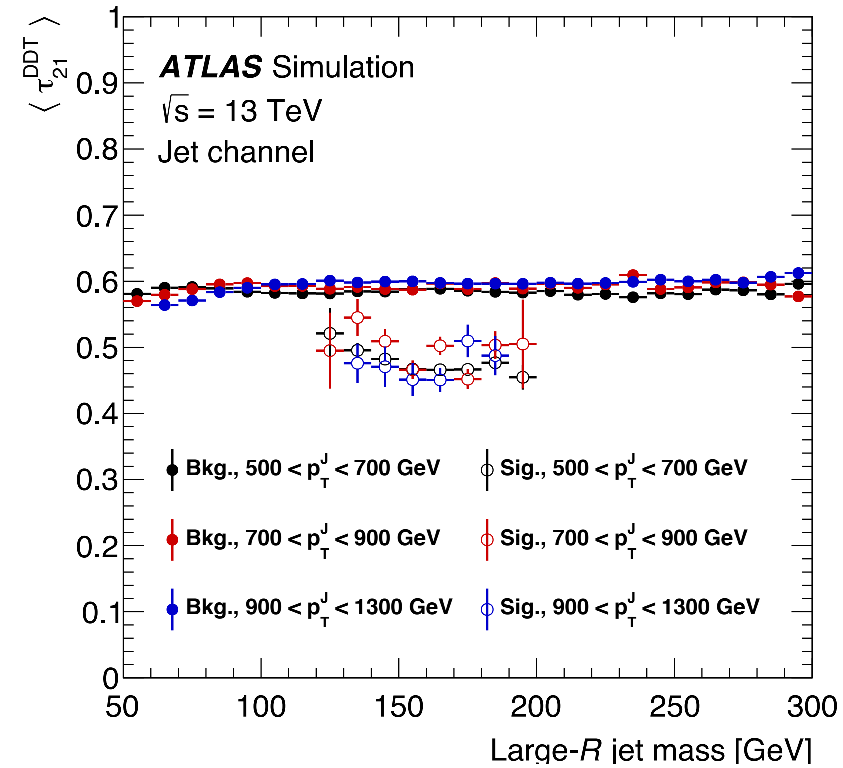
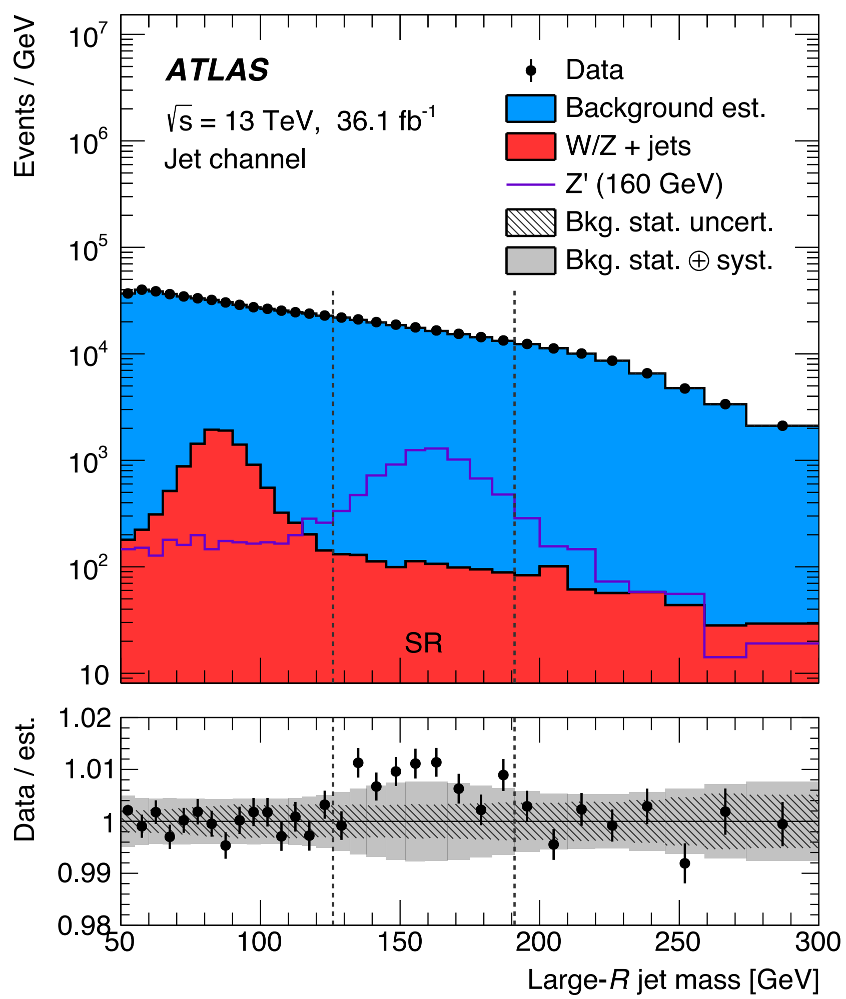


Overview: Large-R + ISR

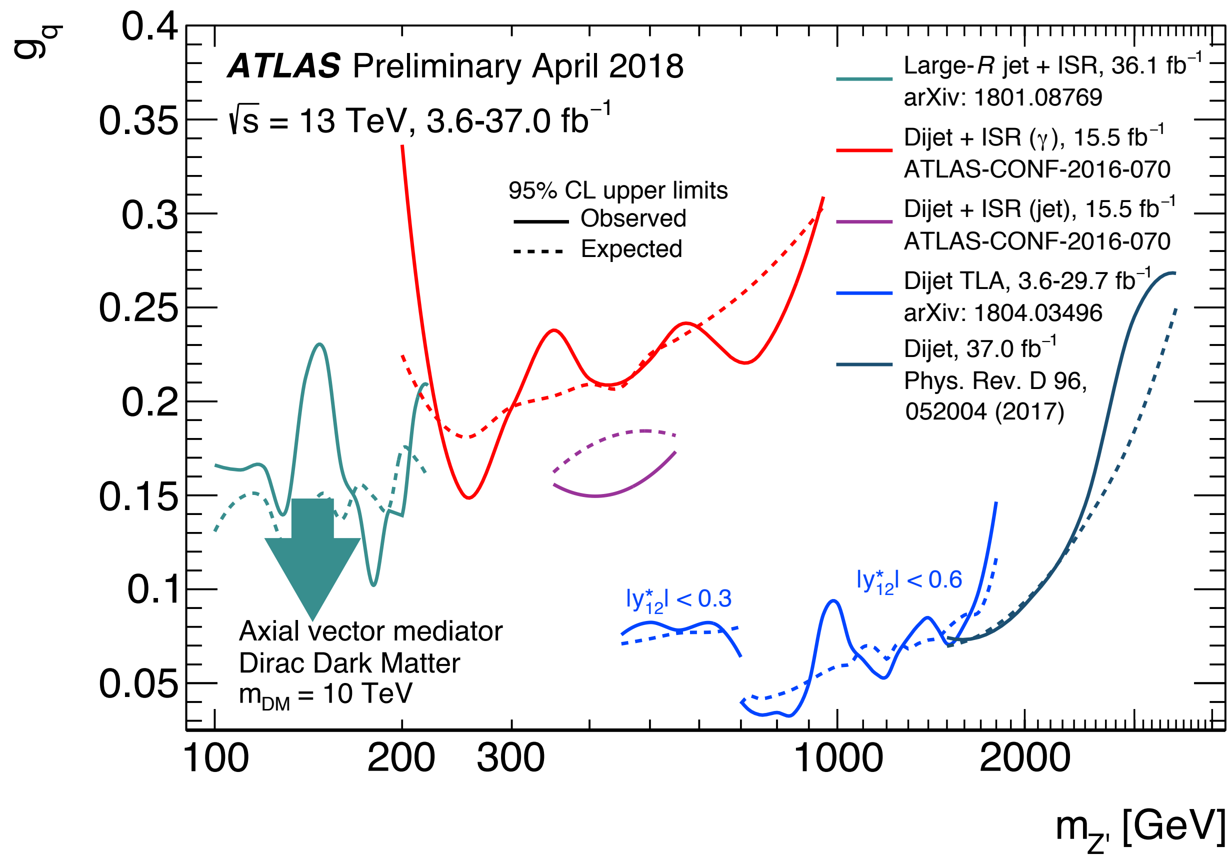


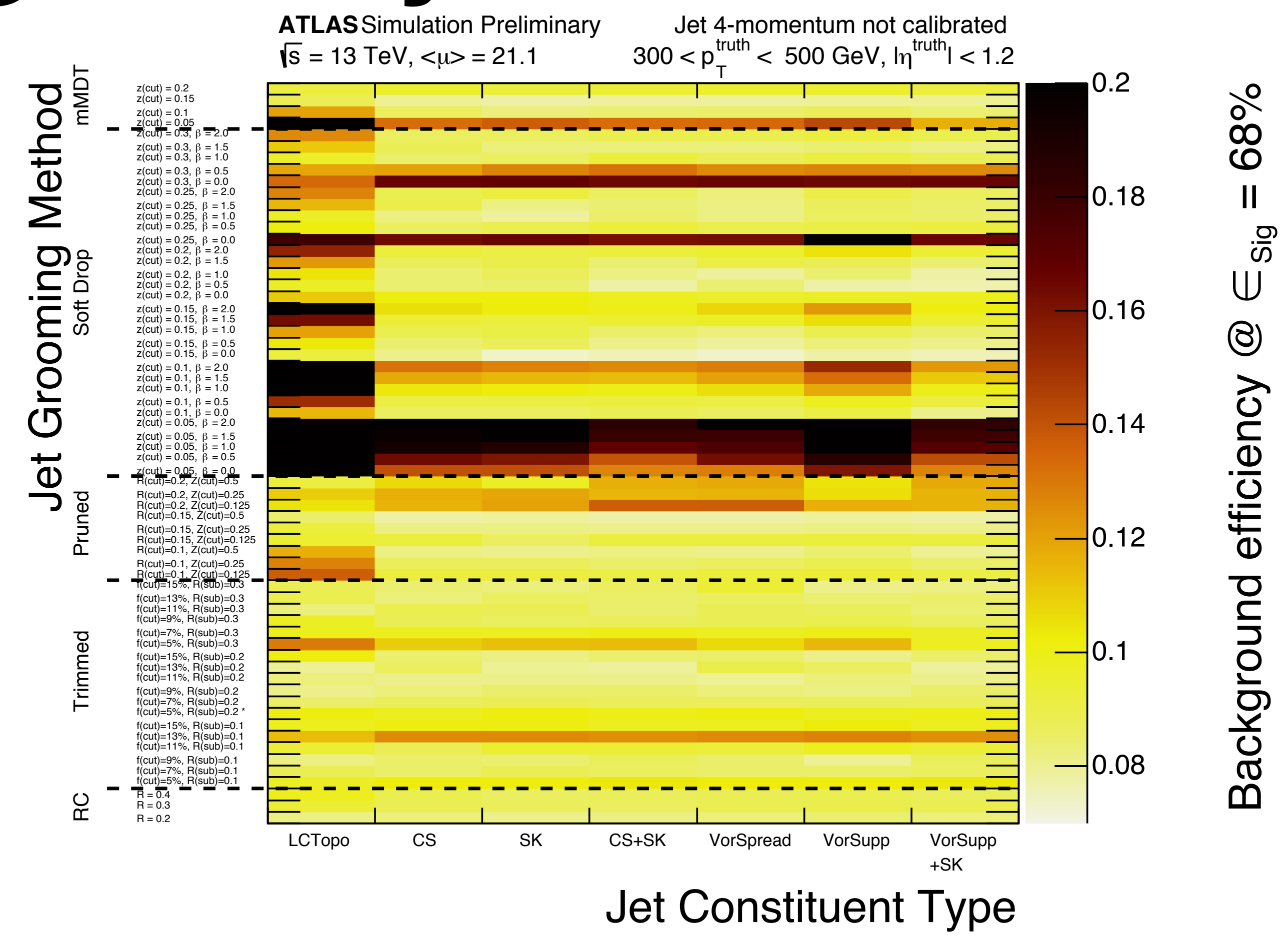


arxiv: 1801.08768, EXOT-2017-01

- 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

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