Searches for Dark Matter in Events with Hadronic Activity at ATLAS - ALPS 2017

19.04.17, Obergurgl

Will Kalderon, Lund University (Sweden)
On behalf of the ATLAS Collaboration

Introduction from S. Lowette and P. Fox

Jets + MET
- cut and count

Jets + more jets
- resonance searches

Overview

- Hadronic + MET:
  - jet+MET [PRD 94 (2016) 032005]
  - bb+MET [ATLAS-CONF-2016-086]
  - tt+MET [ATLAS-CONF-2017-020, ATLAS-CONF-2016-077]*
  - mono-V [Phys. Lett. B 763 (2016) 251]**
  - mono-H(bb) [ATLAS-CONF-2017-028]**

~3fb^{-1} 2015

~13fb^{-1} 2015+2016

~37fb^{-1} 2015+2016

- Resonance searches:
  - Dijet [arXiv: 1703.09127] (+ Karishma)
  - Dijet TLA*** [ATLAS-CONF-2016-030]
  - Dijet+ISR (j/γ) [ATLAS-CONF-2016-070]
  - di-b-jet [ATLAS-CONF-2016-060, 2016-031]

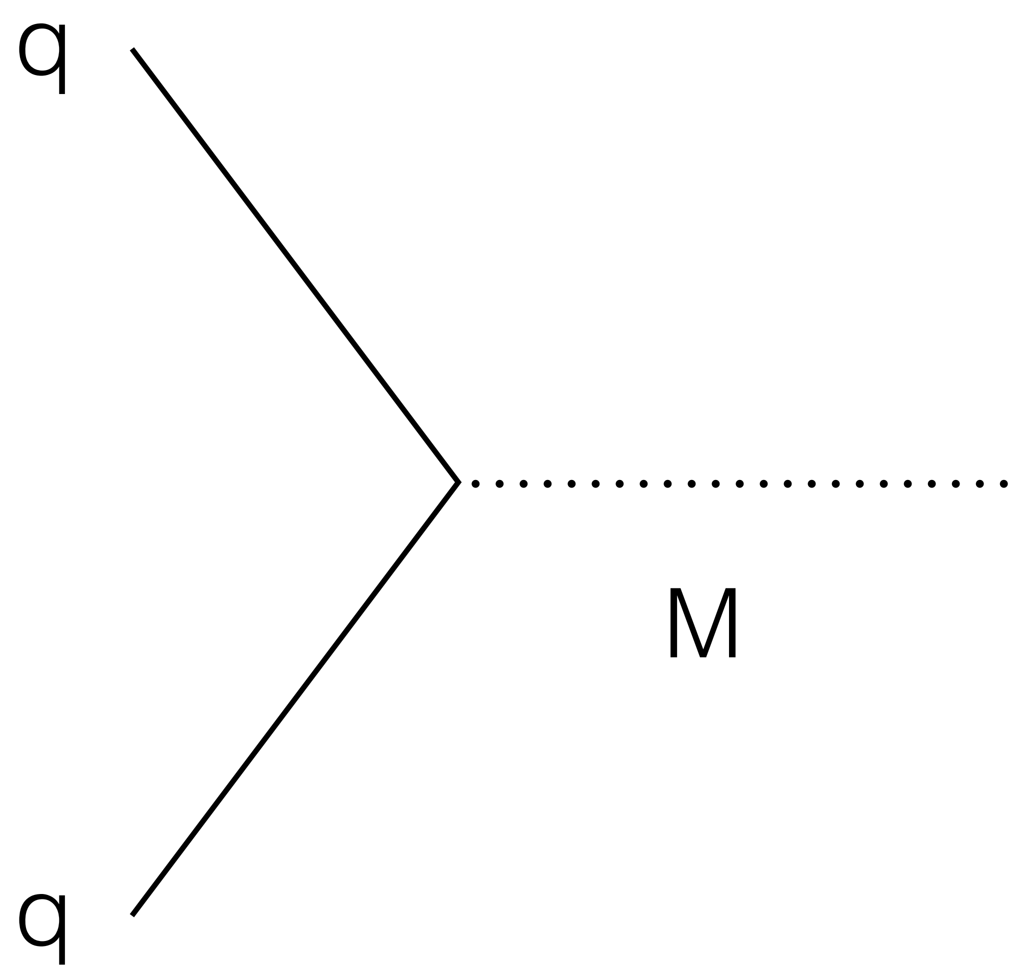
*1 and 2 lepton channels not covered here

**see Hideki's talk

*** Trigger Level Analysis

Start point - mediator connecting quarks and dark matter

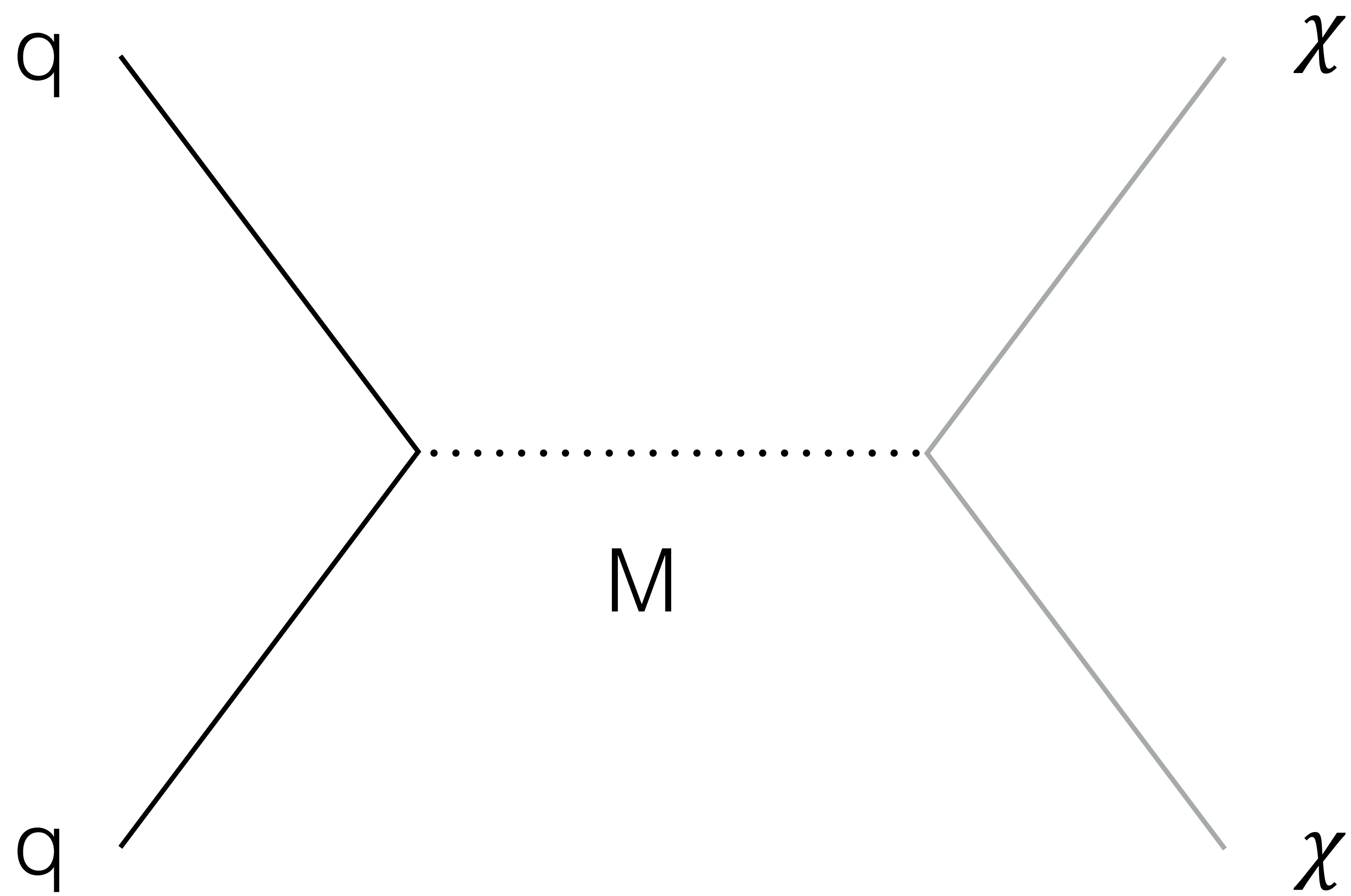
But what can we trigger on?



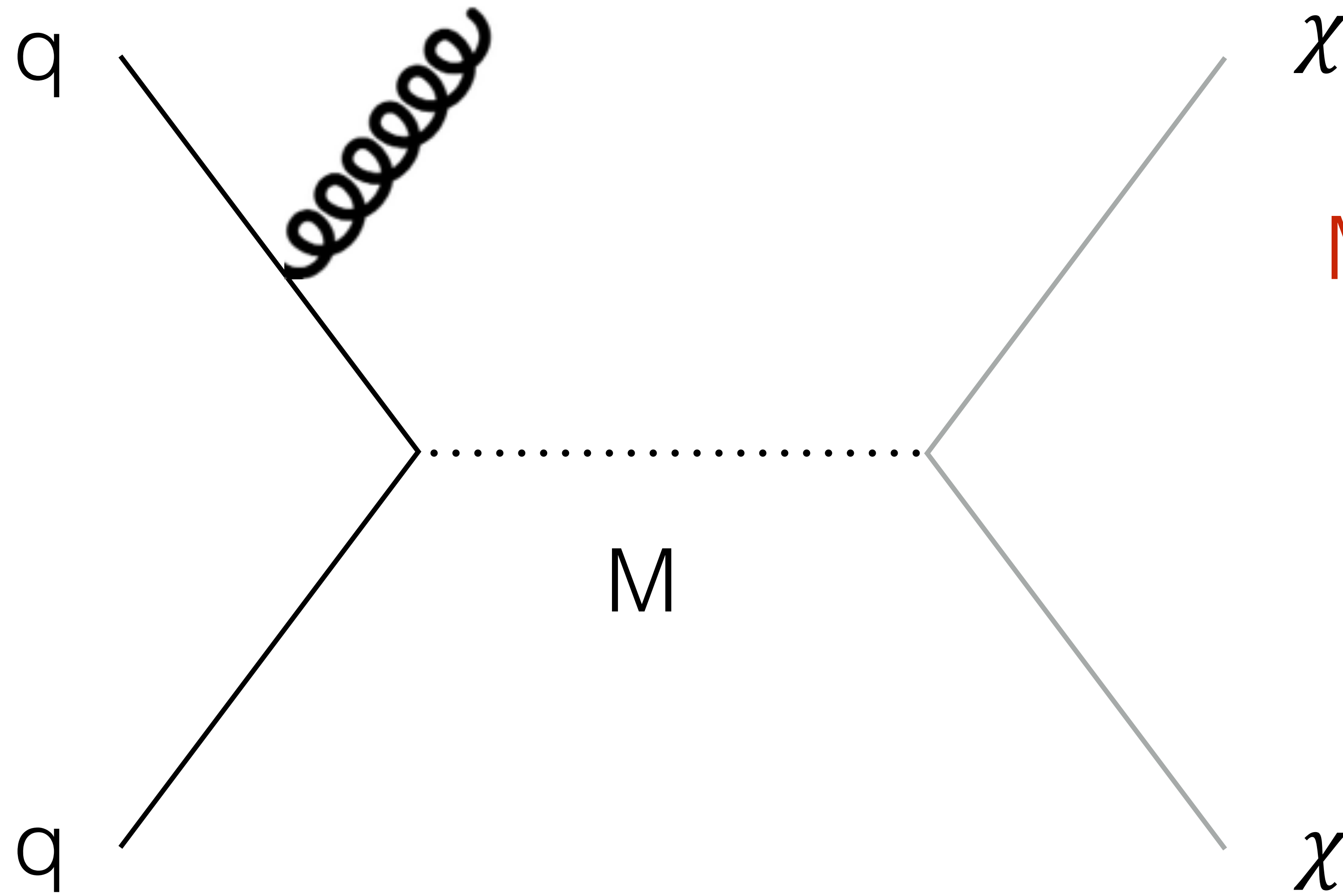
Processes

mediator decays to dark matter - can't see…

no MET since χ back-to-back



Solution 1: ISR -> **jet + MET**

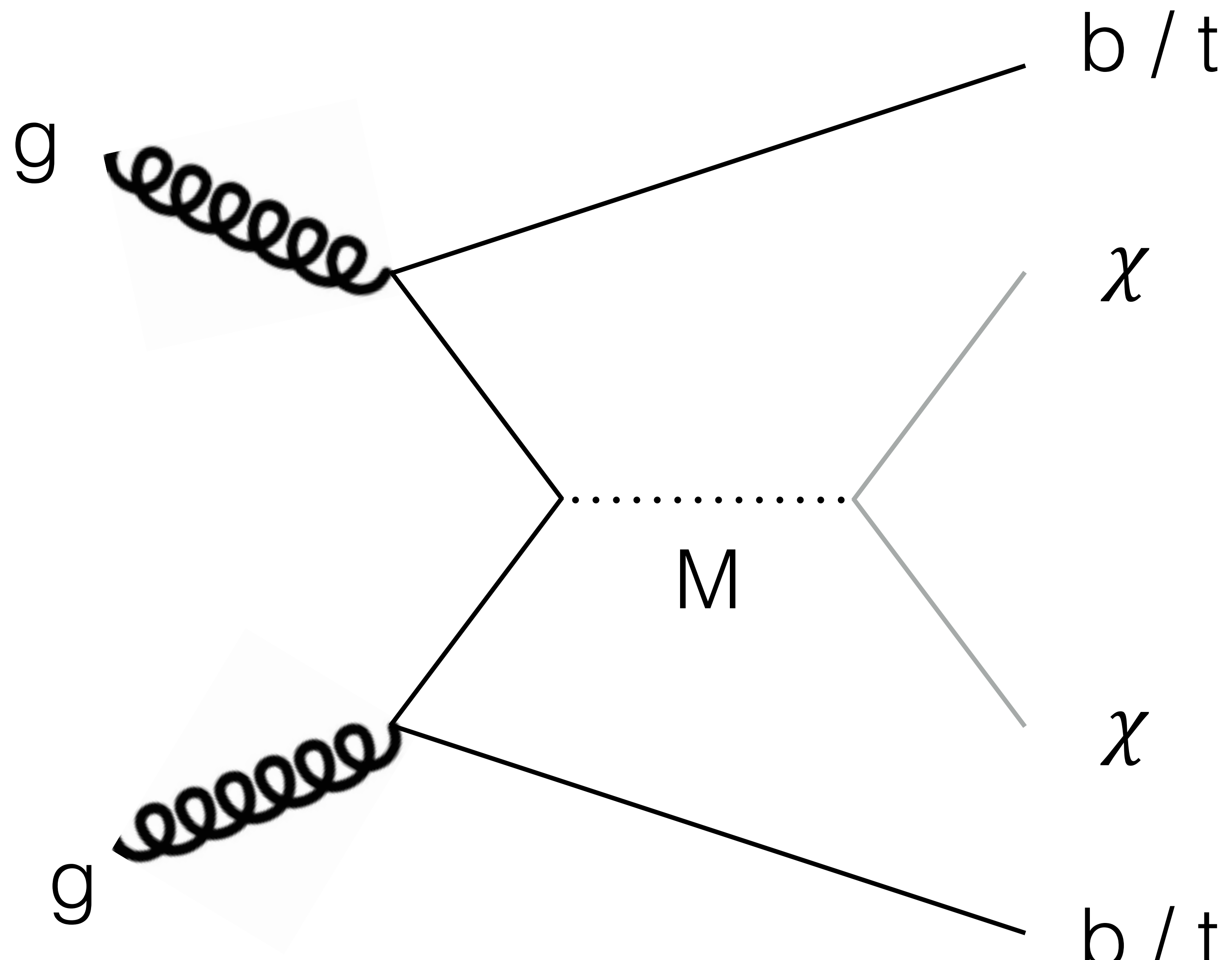


MET from $\chi\chi$ recoiling from ISR

Processes

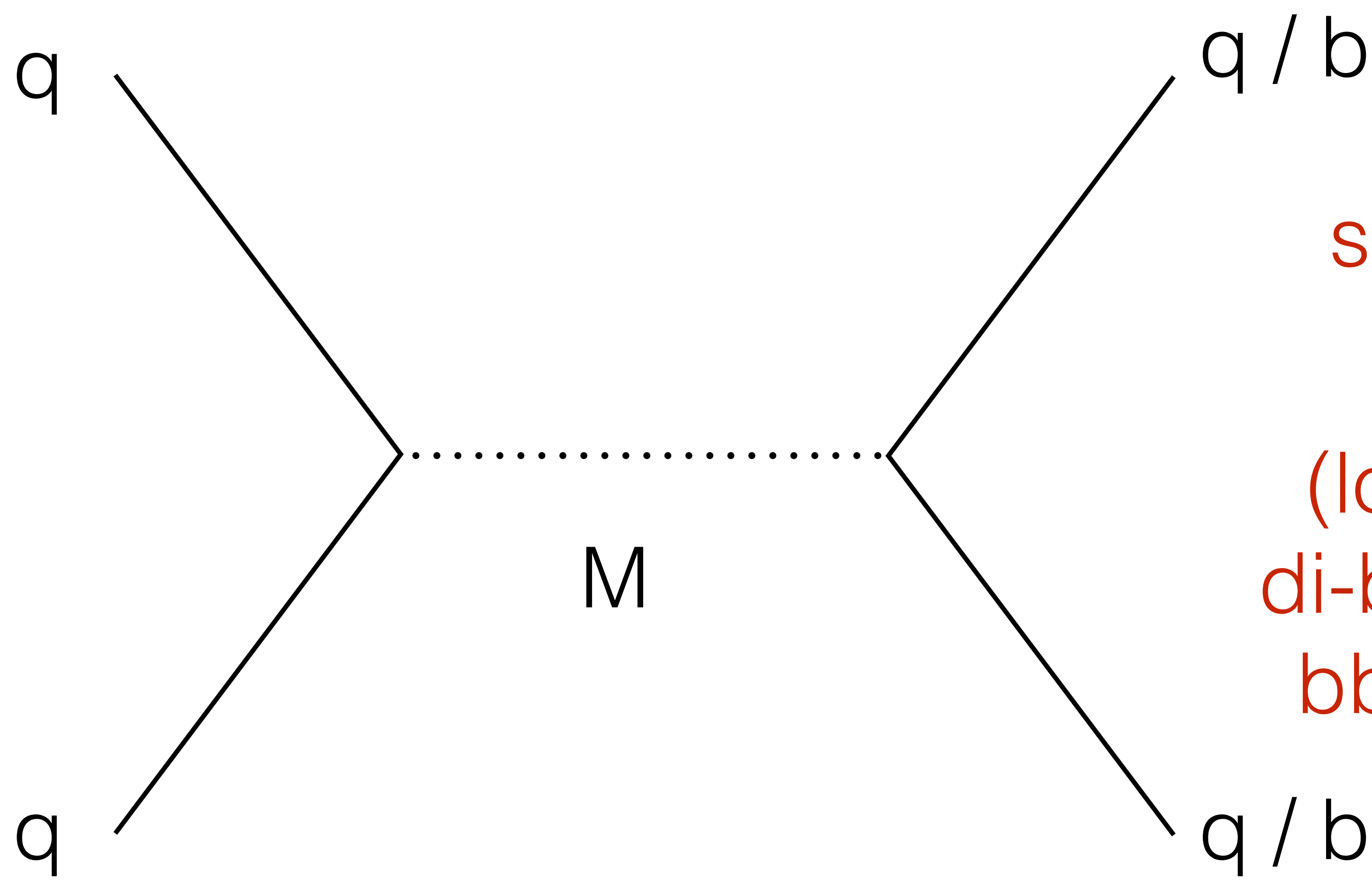
Solution 2: 3rd generation couplings -> **tt / bb + MET**

(especially interesting for (pseudo-)scalar mediators)



MET from $\chi\chi$ recoiling from bb/tt mediator decays back to quarks -> **Dijet (+TLA), di-b-jet**

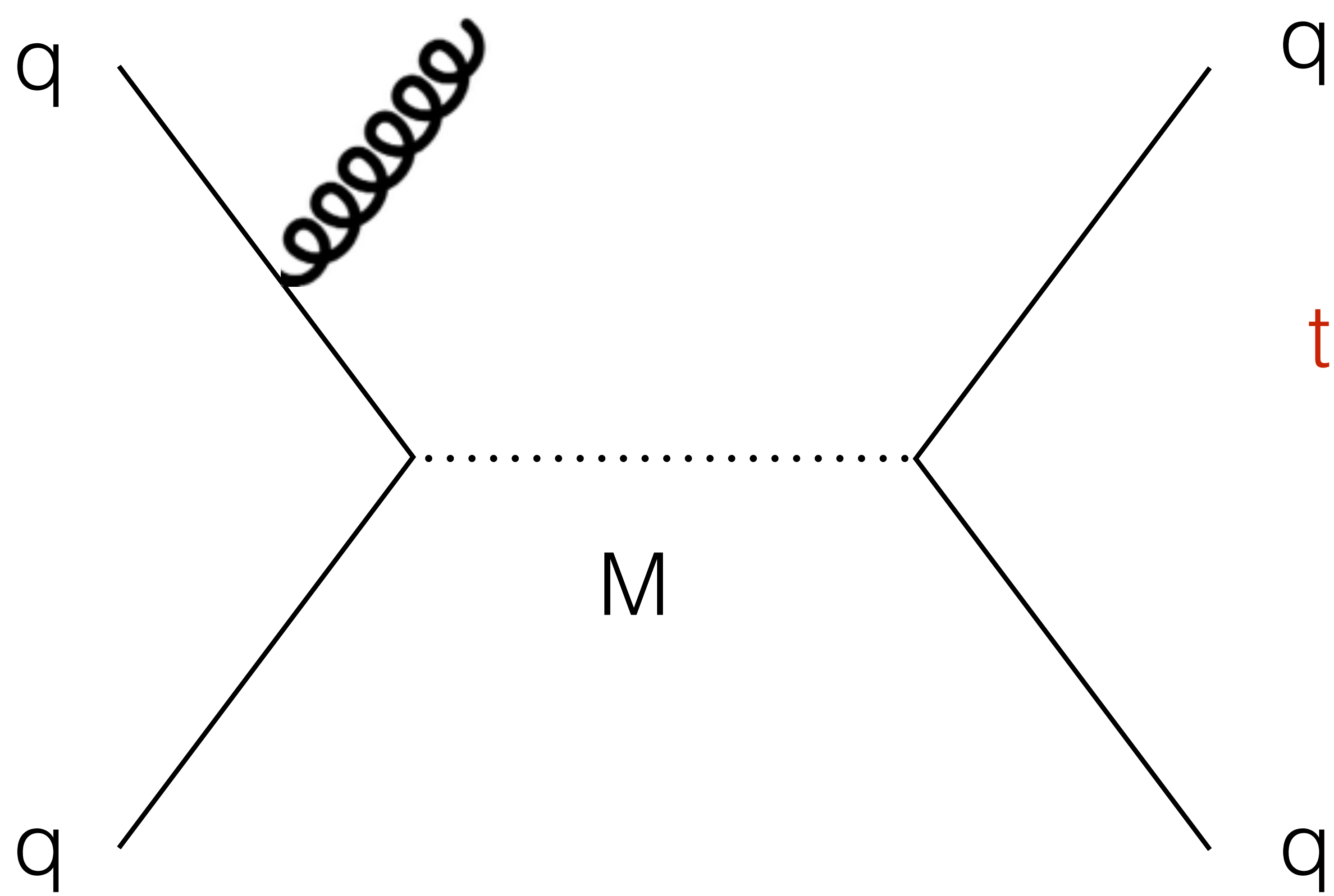
TLA = “Trigger Level Analysis”



single jet trigger

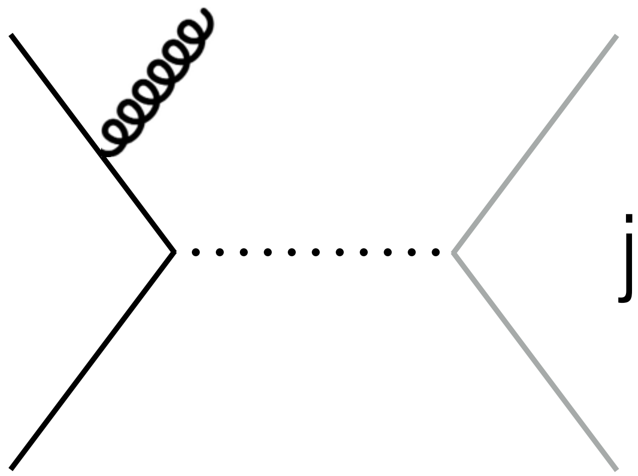
(low-mass di-b requires bb trigger)

Reach lower mass mediators: ISR -> **dijet + ISR**

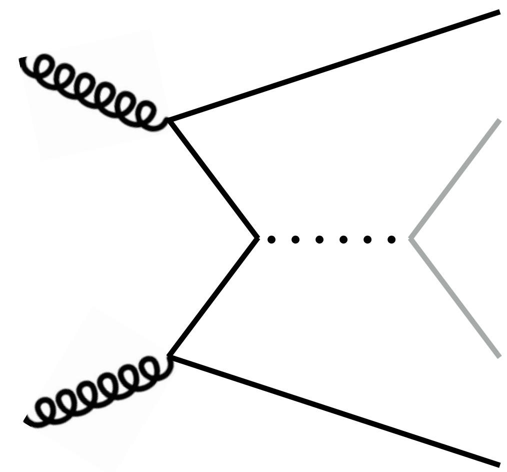


single jet trigger (ISR)

X+MET: trigger and QCD

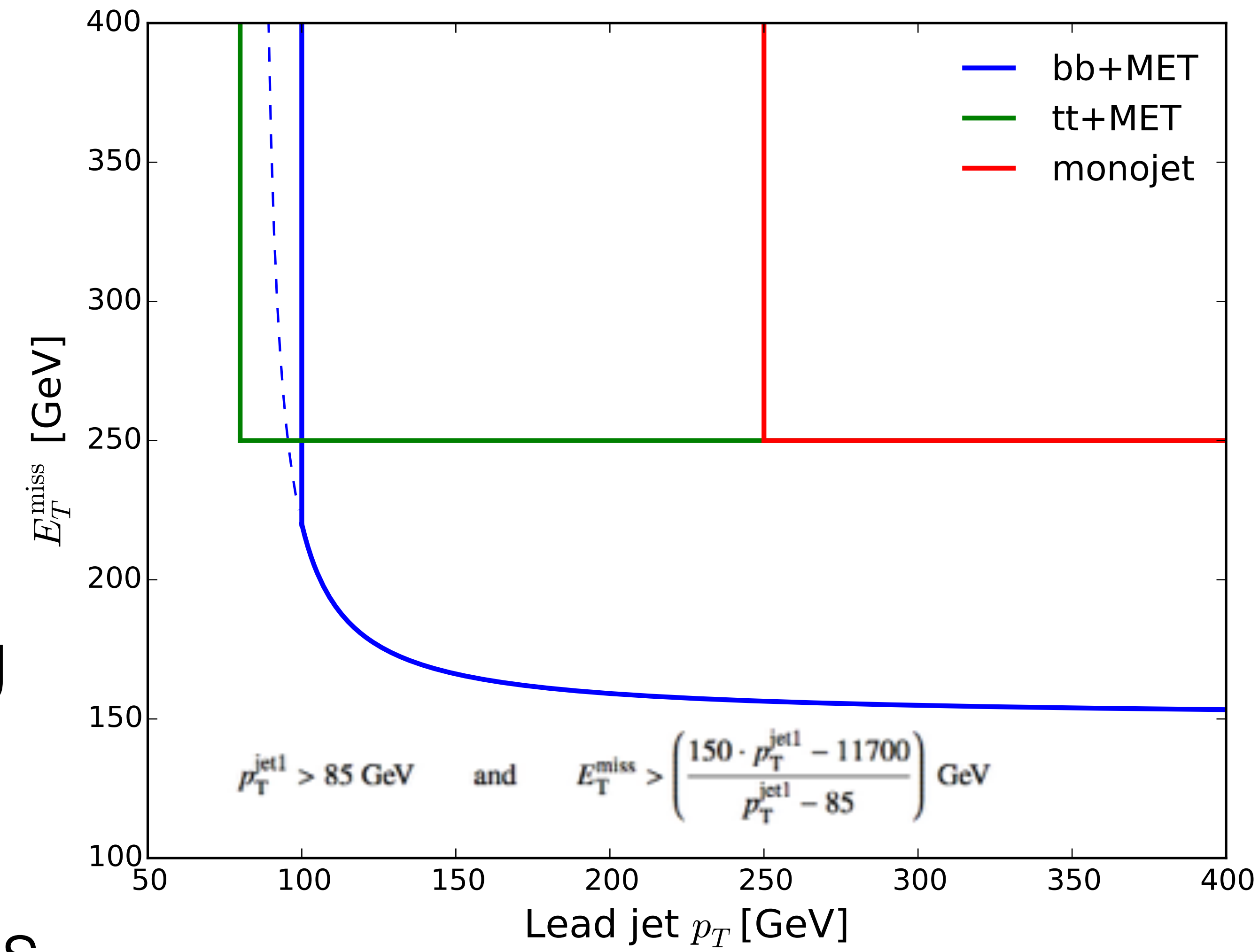


jet + MET



bb/tt + MET

- Trigger on MET
  - Restrict MET (and p_T) due to trigger efficiency
- Reject QCD:
  - $\Delta\phi(\text{jet}, \vec{p}_T^{\,miss}) > 0.4$
  - tighter p_T cut / b-tag / top tag
  - Restrict jet multiplicity
- Reject electroweak: veto leptons

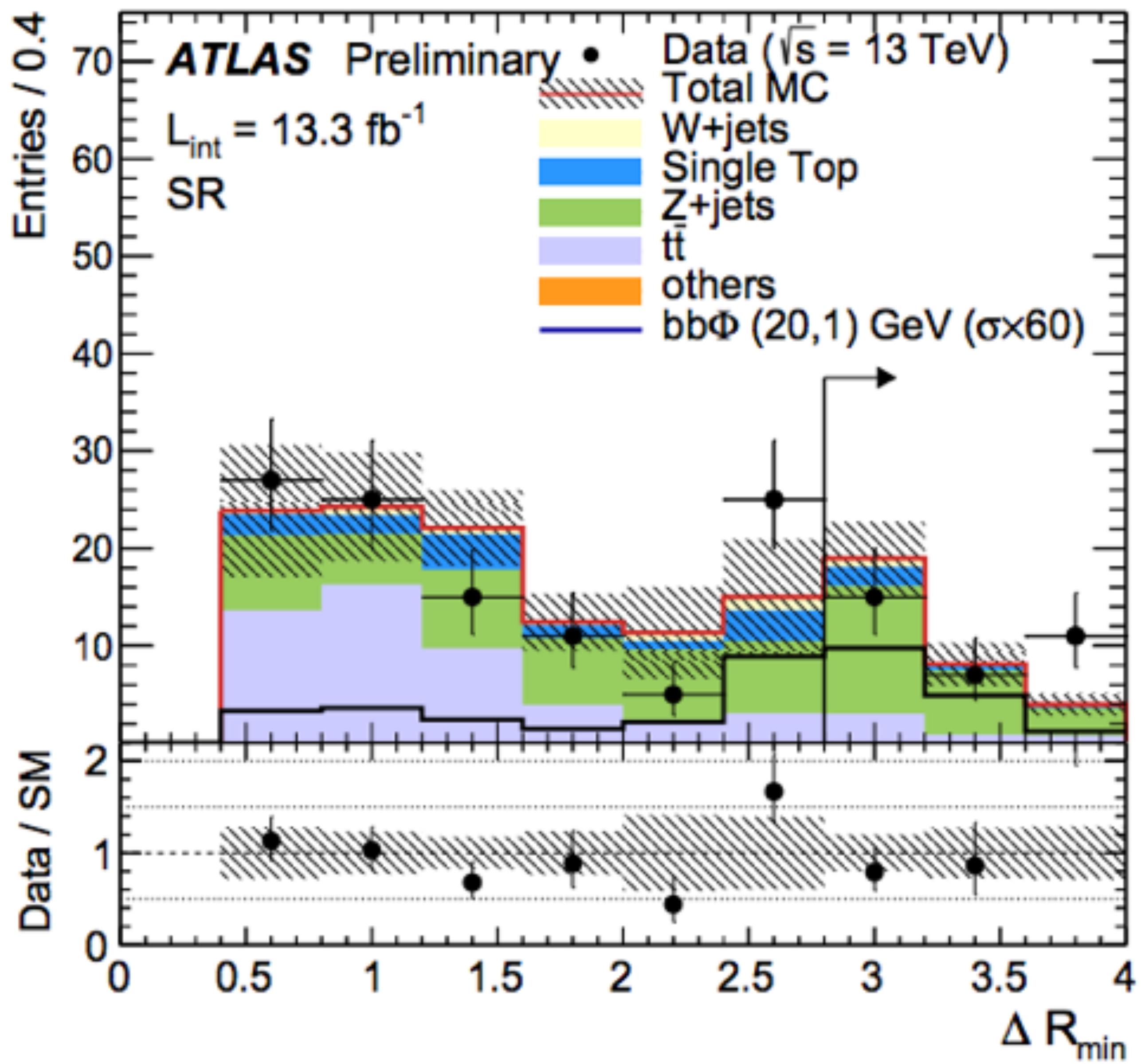


Background rejection

- Specific cuts reject main backgrounds

ATLAS-CONF-2016-086

- **Example: bb+MET**
- Main background $Z(\nu\nu)$ + bb
- Exploit difference in spin and mass of mediator vs Z
- well-separated bb pair (and from third jet if present)
- large b_1-b_2 p_T imbalance



$$\Delta R_{min} = \min(\Delta R(b_1,b_2), \Delta R(b_1,j), \Delta R(b_2,j))$$

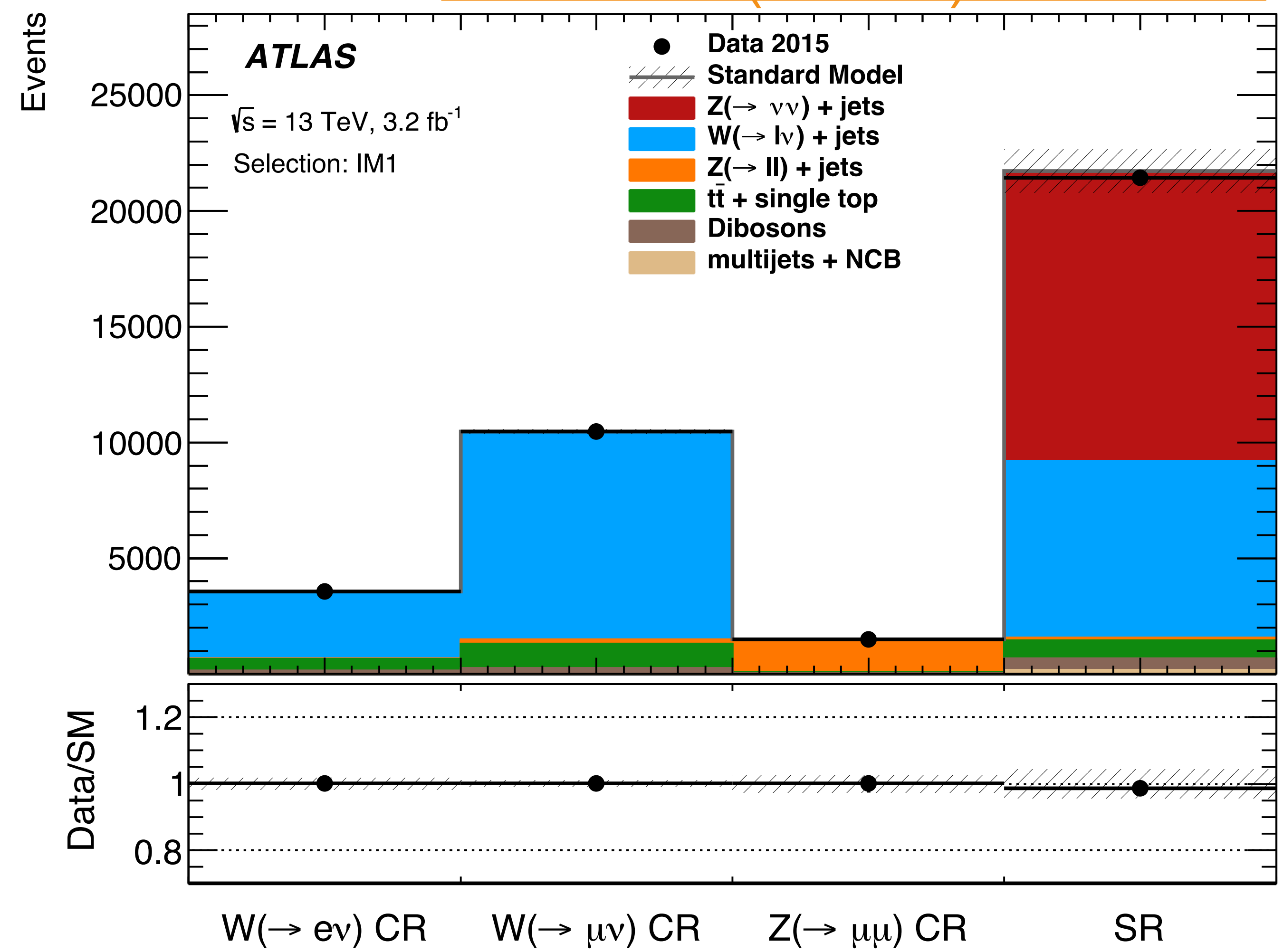
Background estimation

- Estimate background shapes from MC
- Data-driven normalisation from simultaneous fits in control regions - as close as possible to SRs while maintaining acceptable statistics
  - Serves also to reduce uncertainties since CR selections similar to SR -> statistical uncertainties often dominate
- Check background estimate in validation regions

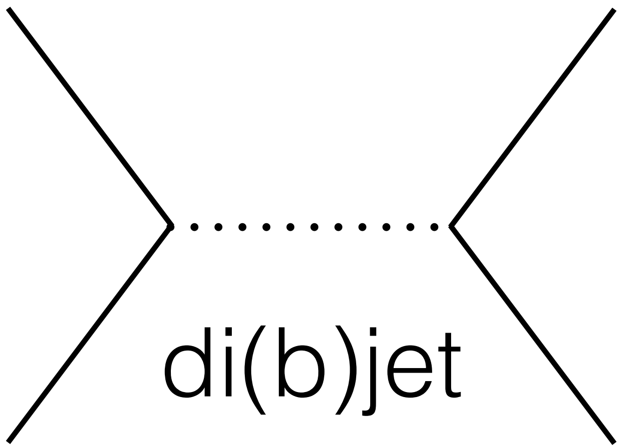
PRD 94 (2016) 032005

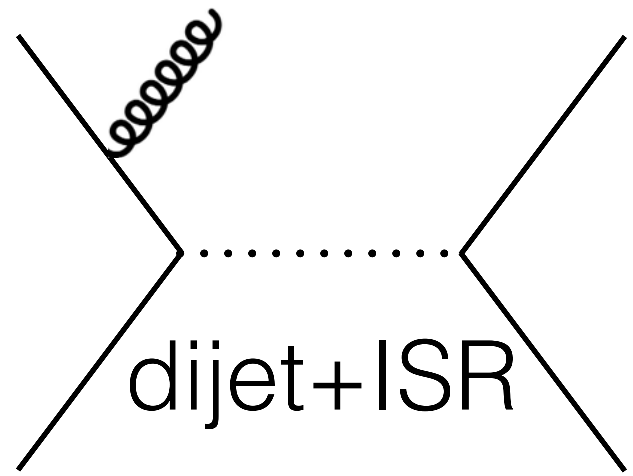
Example: jet+MET

$W\mu\nu$ CR used to constrain dominant $Z\nu\nu$ background since much better stats than kinematically close $Z\mu\mu$ CR



Resonance* searches





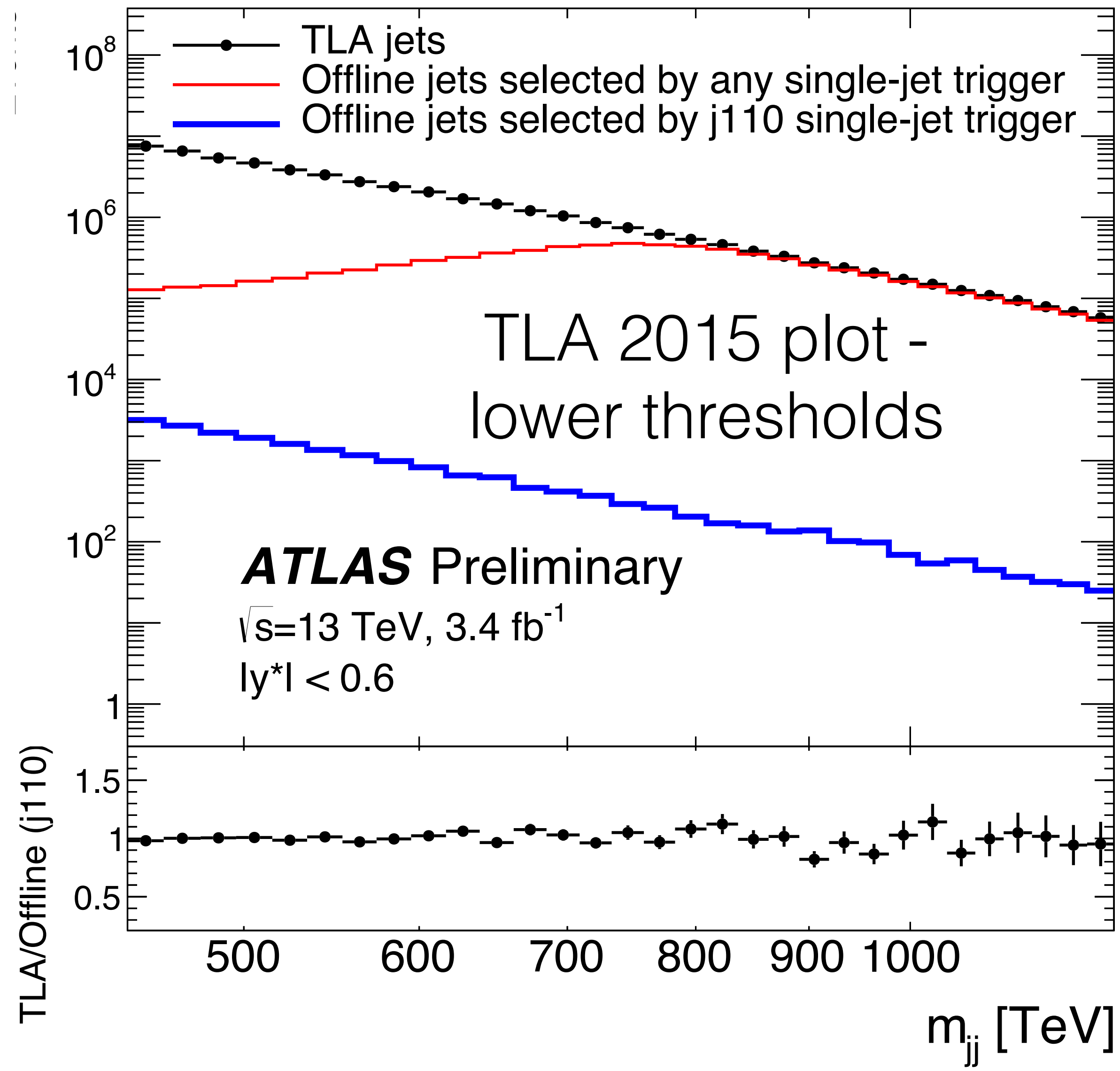
* dijet search also has angular analysis, as Karishma described

- Trigger on single jet
  - (For simplicity - no gain with dijet triggers)
  - Kinematic thresholds define range of sensitivity
- Reject QCD:
  - Restrict $|y^*| = 0.5(y_1 - y_2)$
  - fit to smoothly falling QCD background

Trigger limitations

- Trigger turn-on imposes p_T requirement: 430/440 GeV for unprescaled trigger in 2016
- This equates to m_{jj}>1.1 (1.7) TeV for |y*|<0.6 (1.2)
  - smaller y* -> closer jets -> lower m_{jj} for given p_T
  - Can set limits only a certain distance from the edge of the fit range
- Dijet and di-b-jet: take this as lower bound
- Dijet+ISR: high-pT ISR jet/γ, low p_T pair from resonance

ATLAS-CONF-2016-030

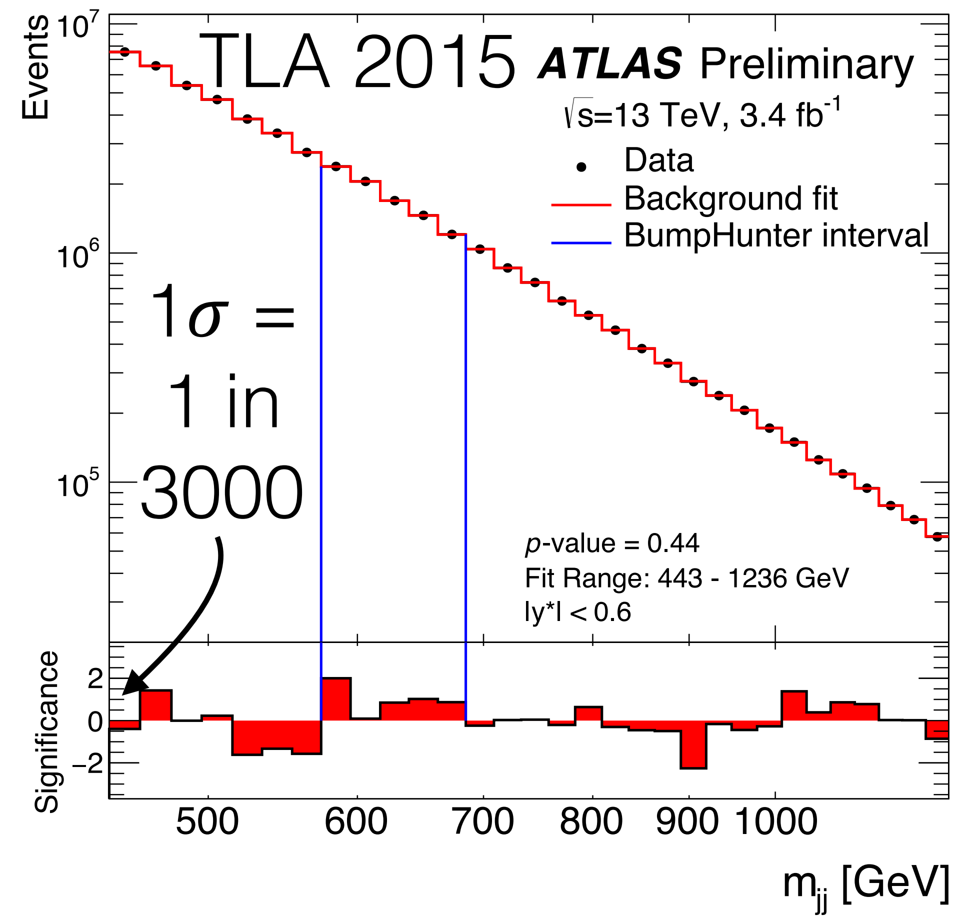


- Dijet TLA: record less information per event -> can record more events -> lower threshold

Background estimate

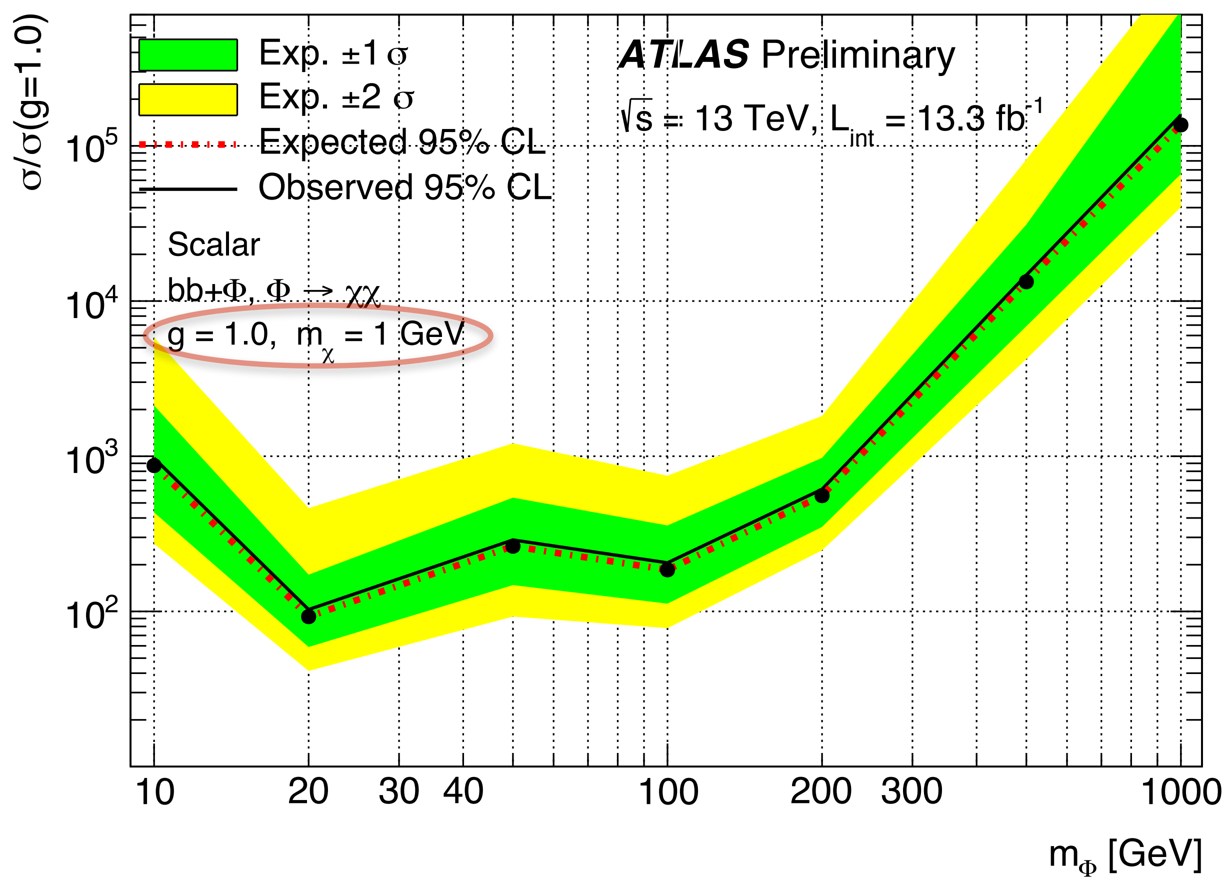
- Dominated by QCD - fit to smooth spectrum $f(z) = c_1(1-z)^{c_2} z^{c_3 + c_4 \ln z}$
- Dijet+ISR, di-b, TLA: “global” fit: single fit spanning whole range
  - Upper range of TLA had to be restricted
- Dijet: set of overlapping fits in smaller windows
- Small (%-level) uncertainties - jet energy scale for signal, pseudo-experiments on background estimate

ATLAS-CONF-2016-030

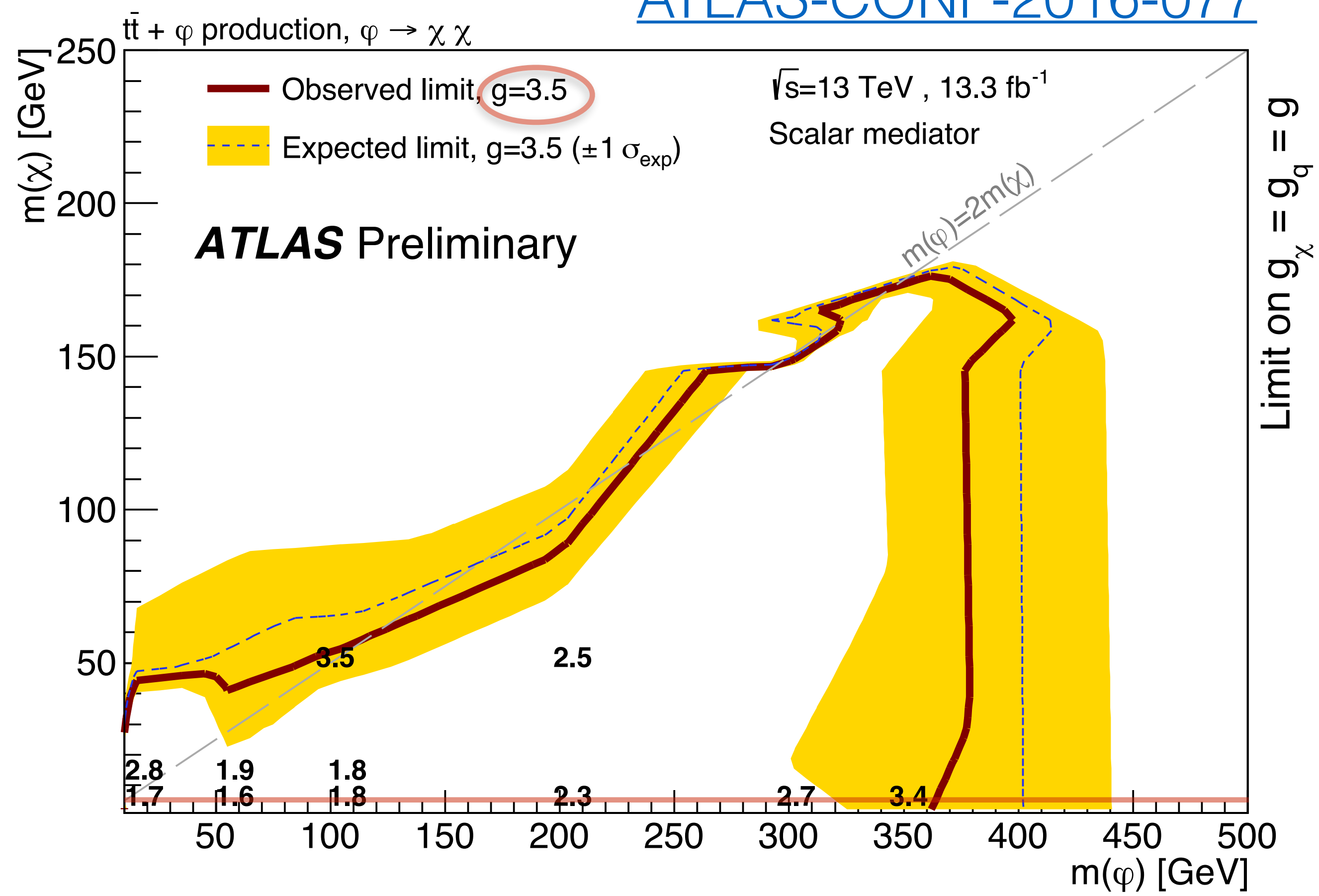


Results - bb/tt + MET

ATLAS-CONF-2016-086



ATLAS-CONF-2016-077

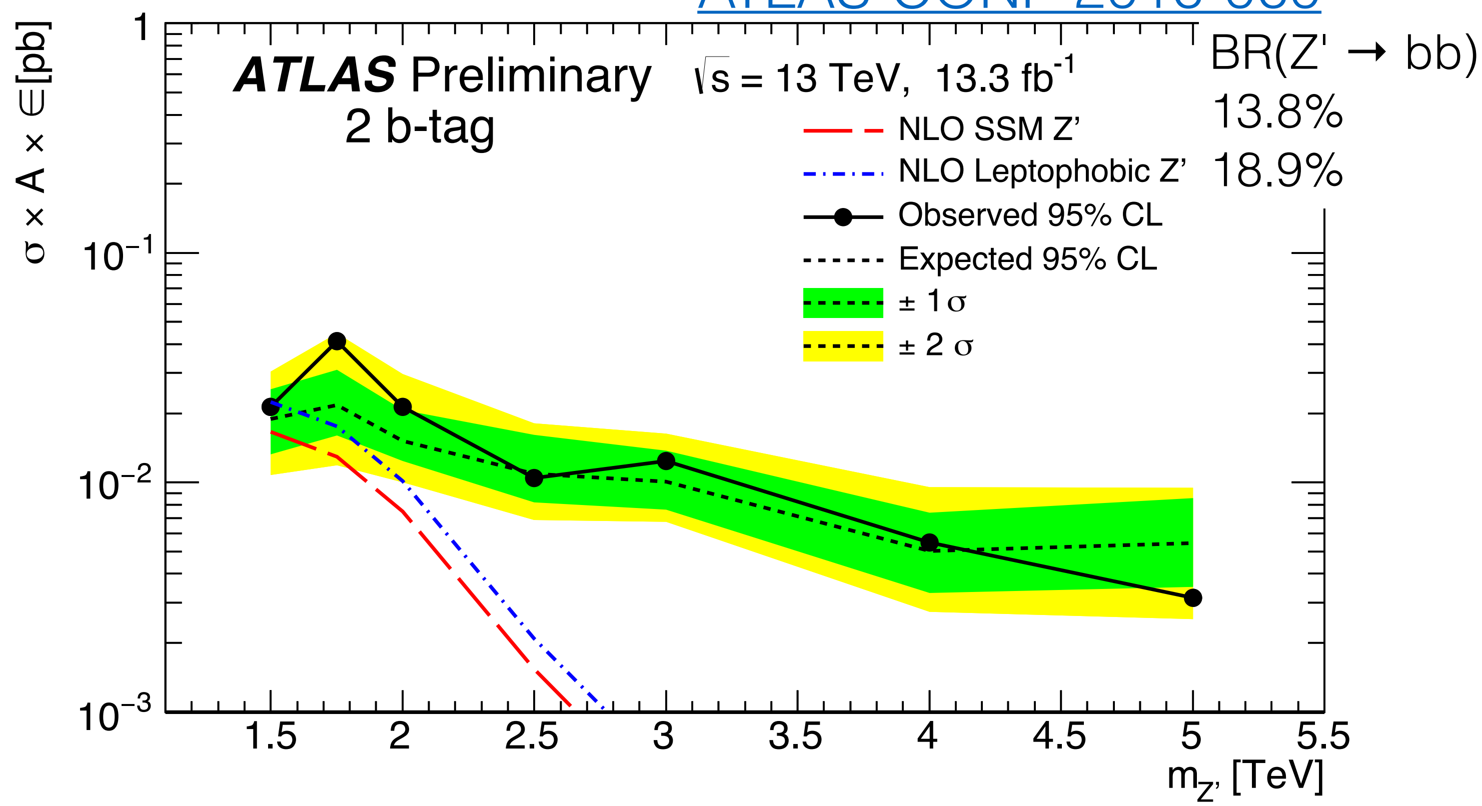


- tt+MET does not provide DM limits in ATLAS-CONF-2017-020
- Pseudoscalar limits in backup
- P. Fox: $\sigma \sim g^2 \Rightarrow \sigma(g=3.5) \sim 10\sigma(g=1.0)$

Results - bb resonances

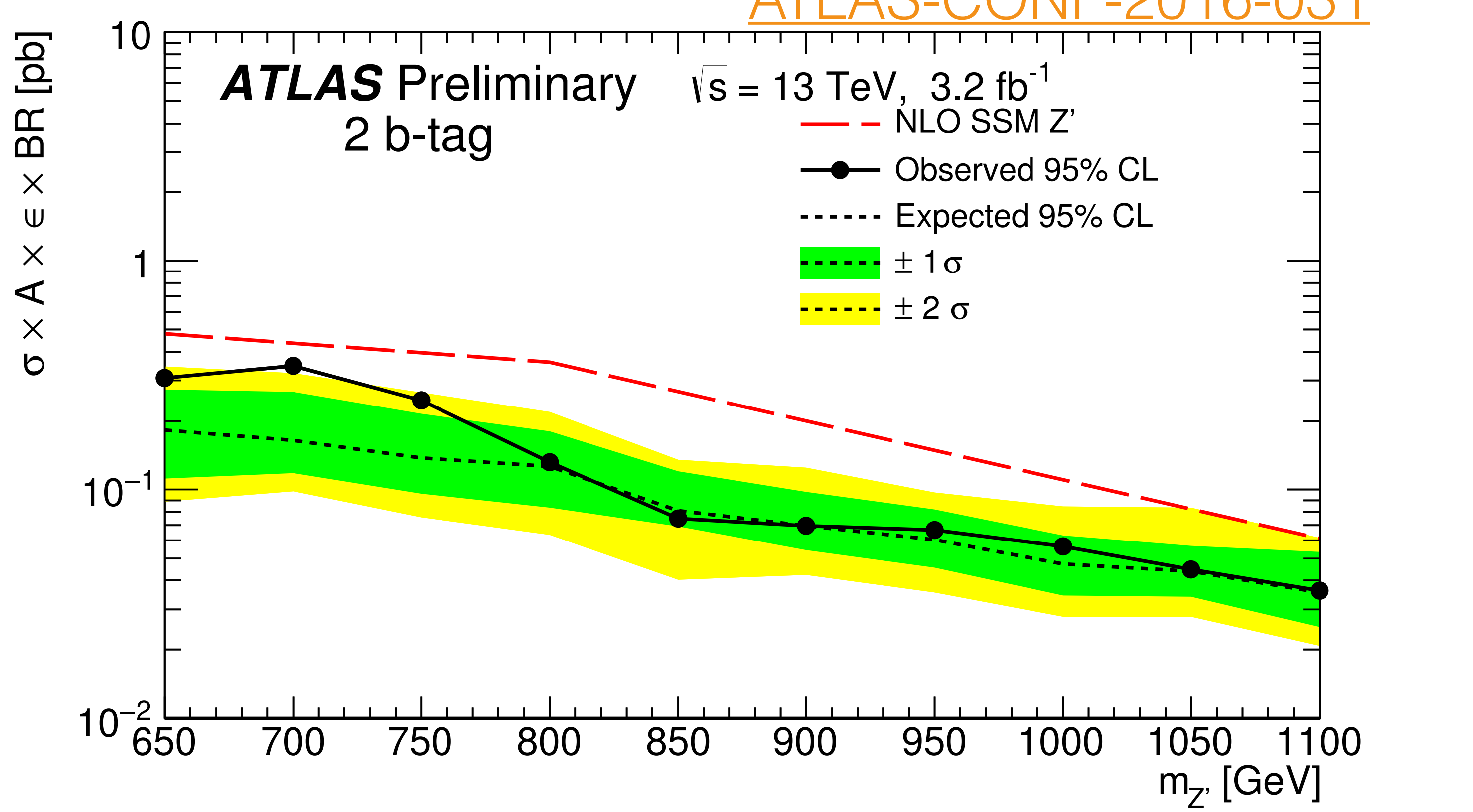
- di-b resonance search: excludes leptophobic Z' at 1.5 TeV

ATLAS-CONF-2016-060



- low-mass di-b resonance search: excludes SSM Z' 0.65-1.1 TeV

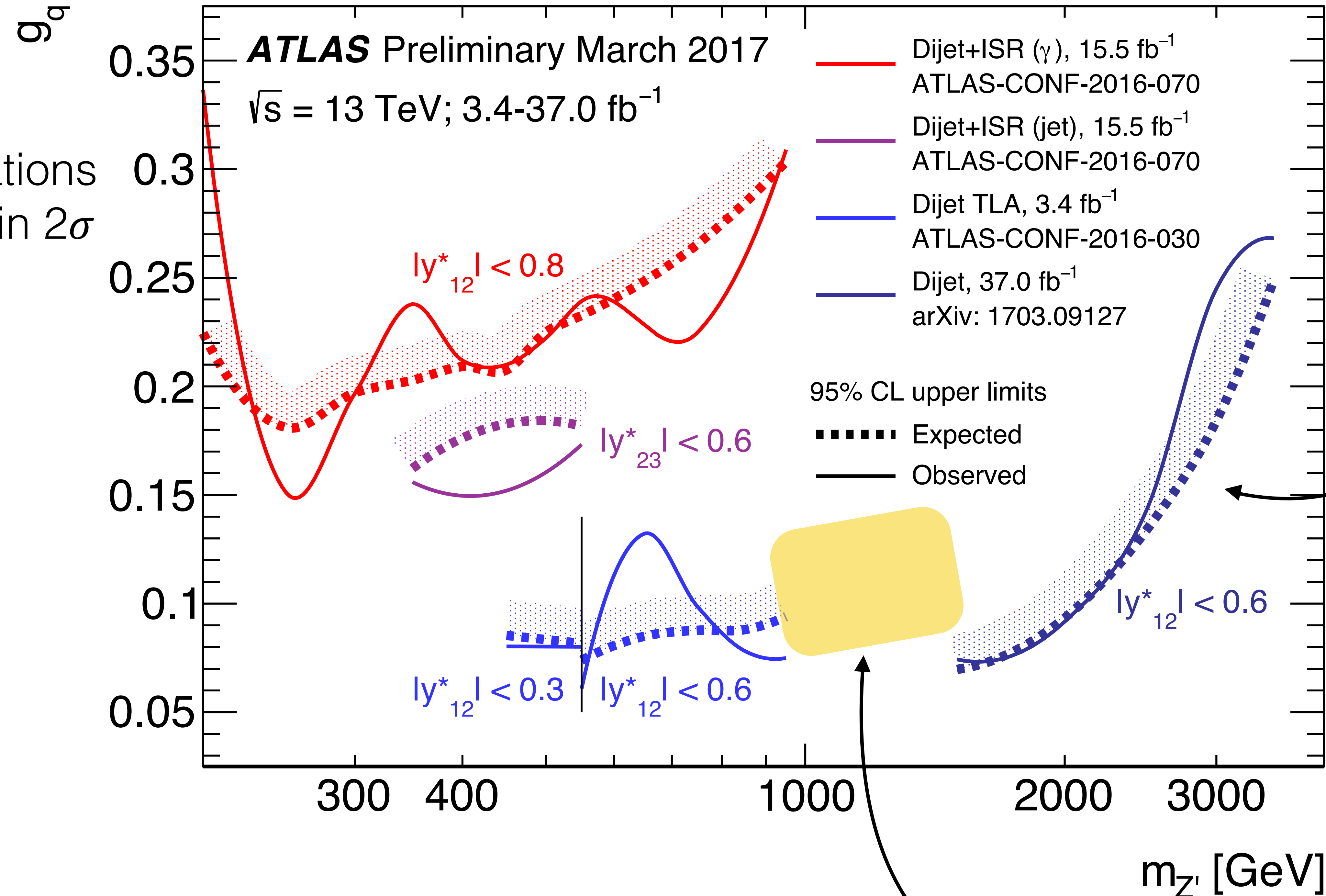
ATLAS-CONF-2016-031



Results - dijet (+X) Z'

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

Fluctuations all within 2σ



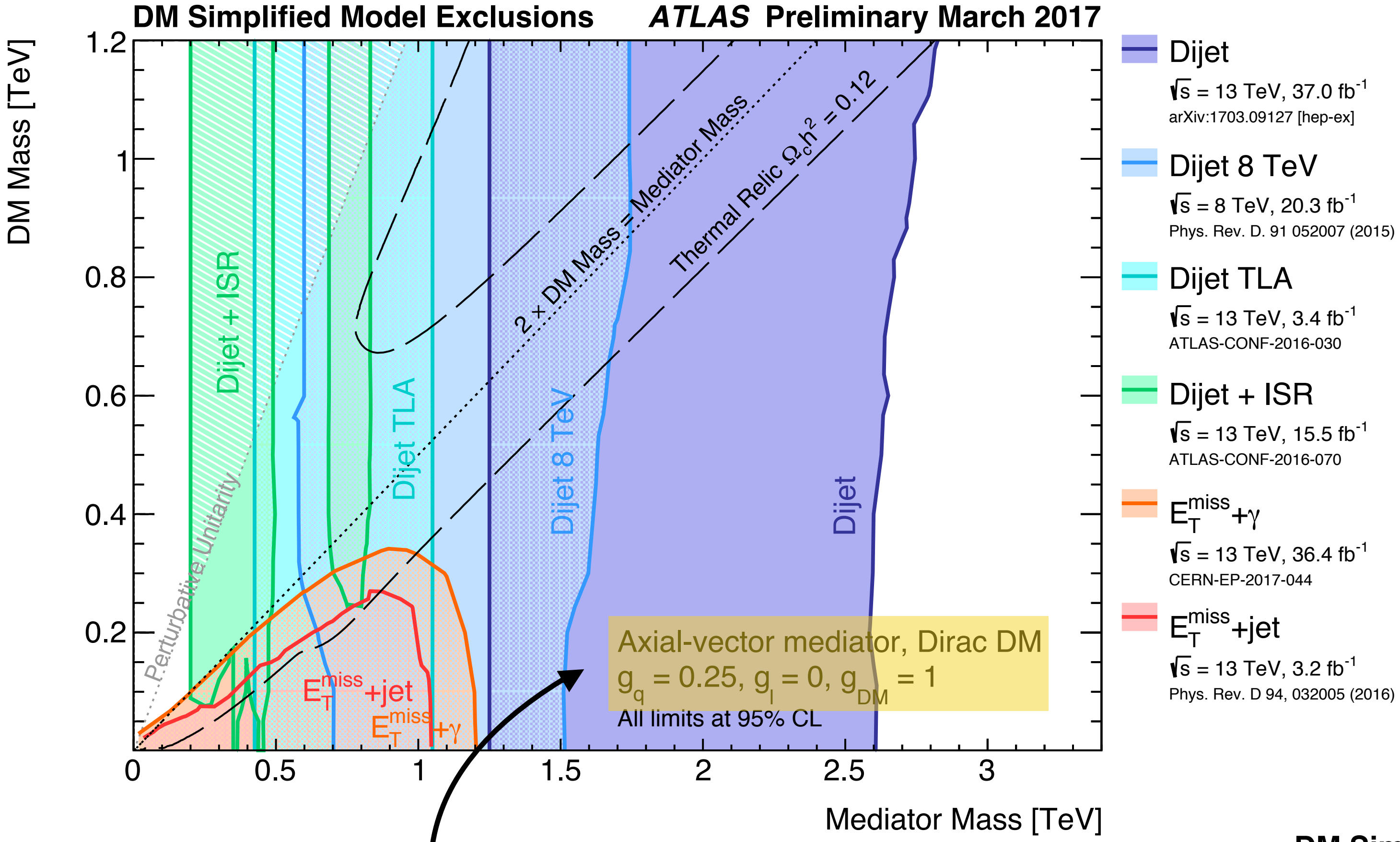
m_{DM}= 10TeV

new!

8TeV dijet

Naive cross-section scaling suggests g_q limit ~ data$^{-1/4}$

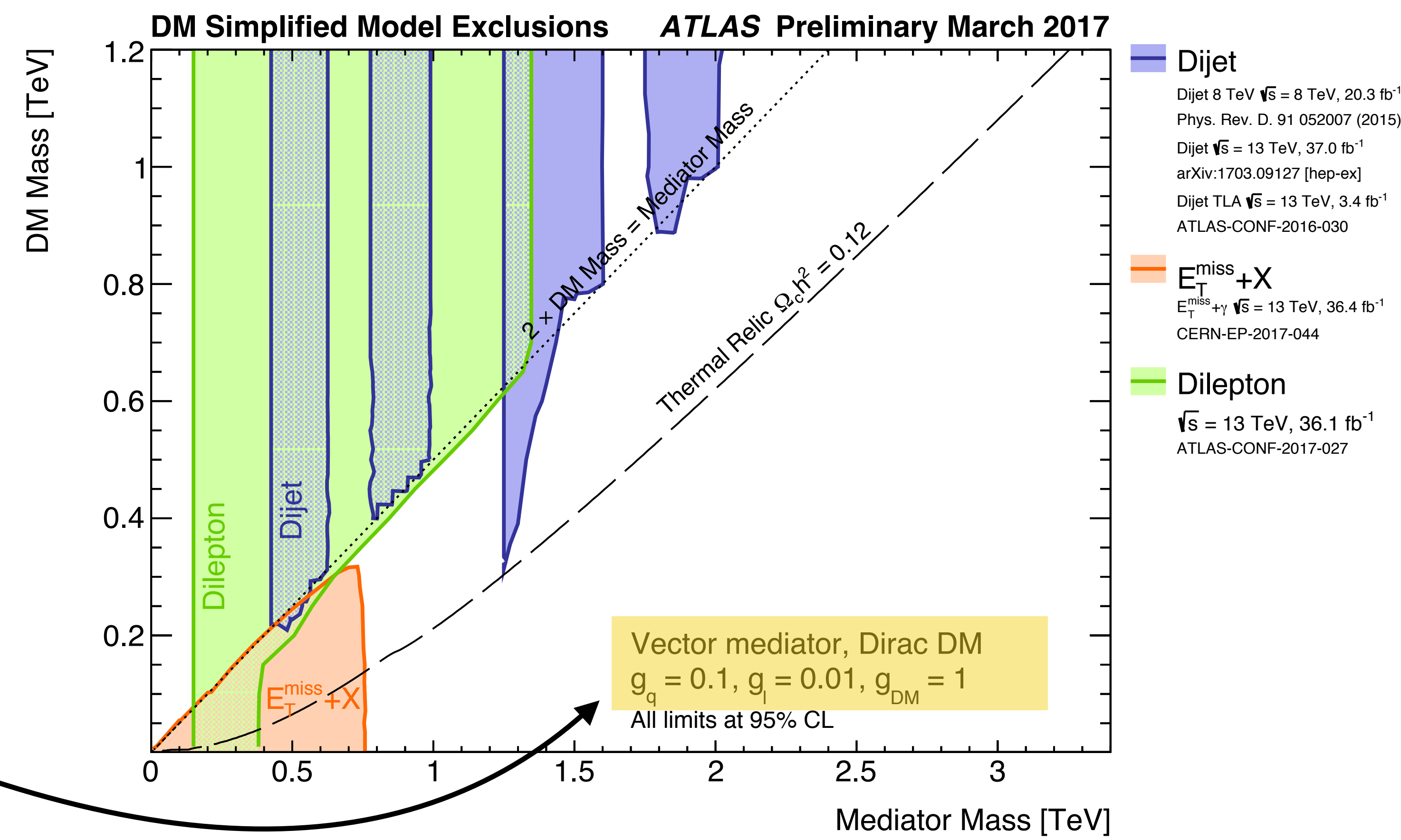
Results and Complementarity



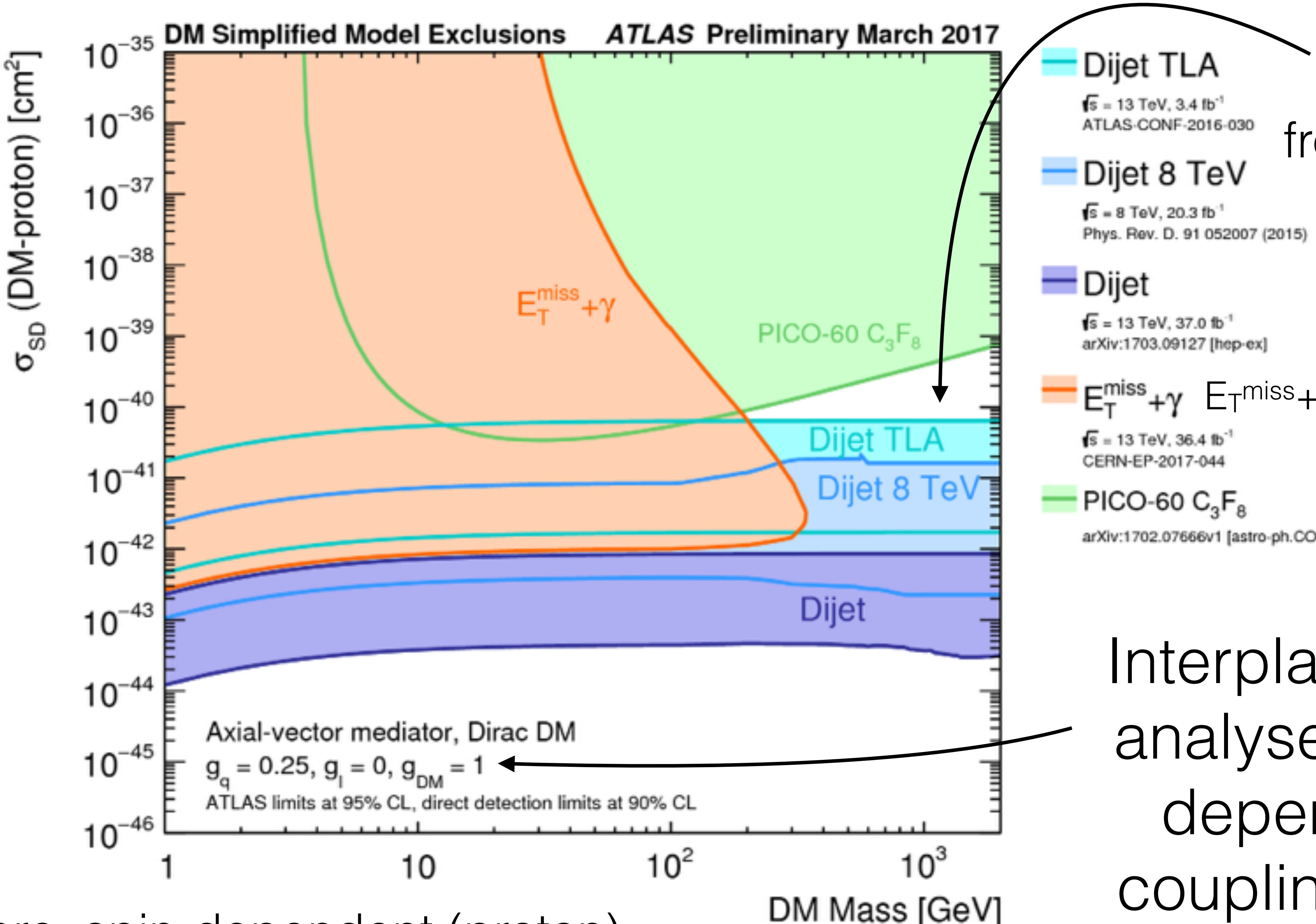
Complementarity between resonance and hadronic+MET searches (and others)

ATLAS Exotics summary plots, following LHC DM Working Group guidelines (arXiv:1703.05703)

Interplay between analyses strongly dependent on coupling choices



Complementarity with Direct Detection experiments



Upper boundary from light mediators

E_T^{miss}+jet v similar

Interplay between analyses strongly dependent on coupling choices

Here: spin-dependent (proton) - see backup for SI and neutron

Summary

- Large number of ways to search for dark matter coupling to quarks at a hadron collider
- Two sets of strategies presented here:
  - qq -> mediator -> MET (+ something to trigger on)
    - "cut and count"
  - qq -> mediator -> qq (+ optional ISR)
    - "fit to smooth background"
- Strong complementarity of results, overlap dependent on model parameters
- Updated results from several searches, plus lots more 13 TeV data, coming soon!

Bonus slides follow from here

Jet+MET signal regions

PRD 94 (2016) 032005

Selection criteria							
Primary vertex							
$E_{\mathrm{T}}^{\mathrm{miss}} > 250\ \mathrm{GeV}$							
Leading jet with $p_{\mathrm{T}} > 250\ \mathrm{GeV}$ and $\lvert\eta\rvert < 2.4$							
At most four jets with $p_{\mathrm{T}} > 30\ \mathrm{GeV}$ and $\lvert\eta\rvert < 2.8$							
$\Delta\phi(\mathrm{jet}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}}) > 0.4$							
Jet quality requirements							
No identified muons with $p_{\mathrm{T}} > 10\ \mathrm{GeV}$ or electrons with $p_{\mathrm{T}} > 20\ \mathrm{GeV}$							
Inclusive signal region	IM1	IM2	IM3	IM4	IM5	IM6	IM7
$E_{\mathrm{T}}^{\mathrm{miss}}$ (GeV)	> 250	> 300	> 350	> 400	> 500	> 600	> 700
Exclusive signal region	EM1	EM2	EM3	EM4	EM5	EM6	
$E_{\mathrm{T}}^{\mathrm{miss}}$ (GeV)	[250–300]	[300–350]	[350–400]	[400–500]	[500–600]	[600–700]	

Jet+MET control regions

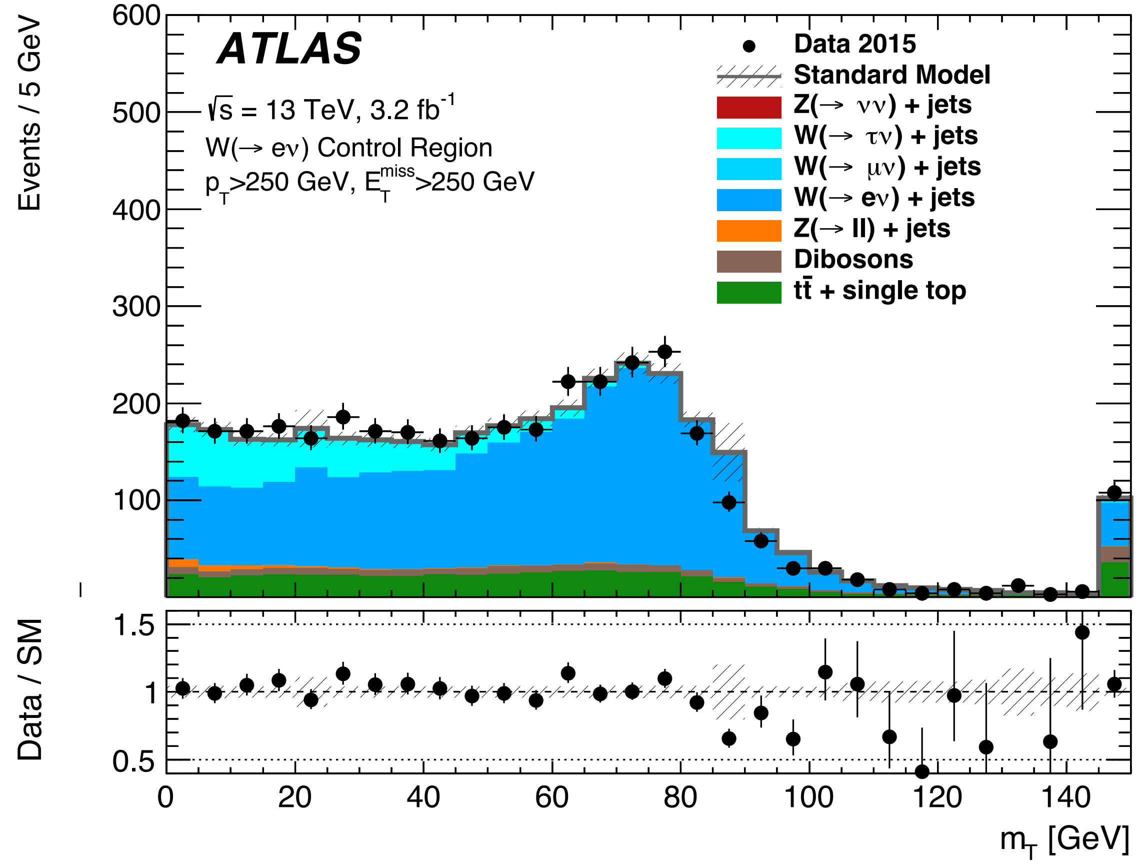
PRD 94 (2016) 032005

Background process	Method	Control sample
$Z(\to \nu\bar{\nu}) + \text{jets}$	MC and control samples in data	$W(\to \mu\nu)$
$W(\to e\nu) + \text{jets}$	MC and control samples in data	$W(\to e\nu)$
$W(\to \tau\nu) + \text{jets}$	MC and control samples in data	$W(\to e\nu)$
$W(\to \mu\nu) + \text{jets}$	MC and control samples in data	$W(\to \mu\nu)$
$Z/\gamma^*(\to \mu^+\mu^-) + \text{jets}$	MC and control samples in data	$Z/\gamma^*(\to \mu^+\mu^-)$
$Z/\gamma^*(\to \tau^+\tau^-) + \text{jets}$	MC and control samples in data	$W(\to e\nu)$
$Z/\gamma^*(\to e^+e^-) + \text{jets}$	MC only	
$t\bar{t}$, single top	MC only	
Diboson	MC only	
Multijets	data driven	
Noncollision	data driven	

W$\mu\nu$ CR has better stats to constrain Z$\nu\nu$

Jet smearing method: MET due to fluctuations in jet response

Jet+MET CR plots



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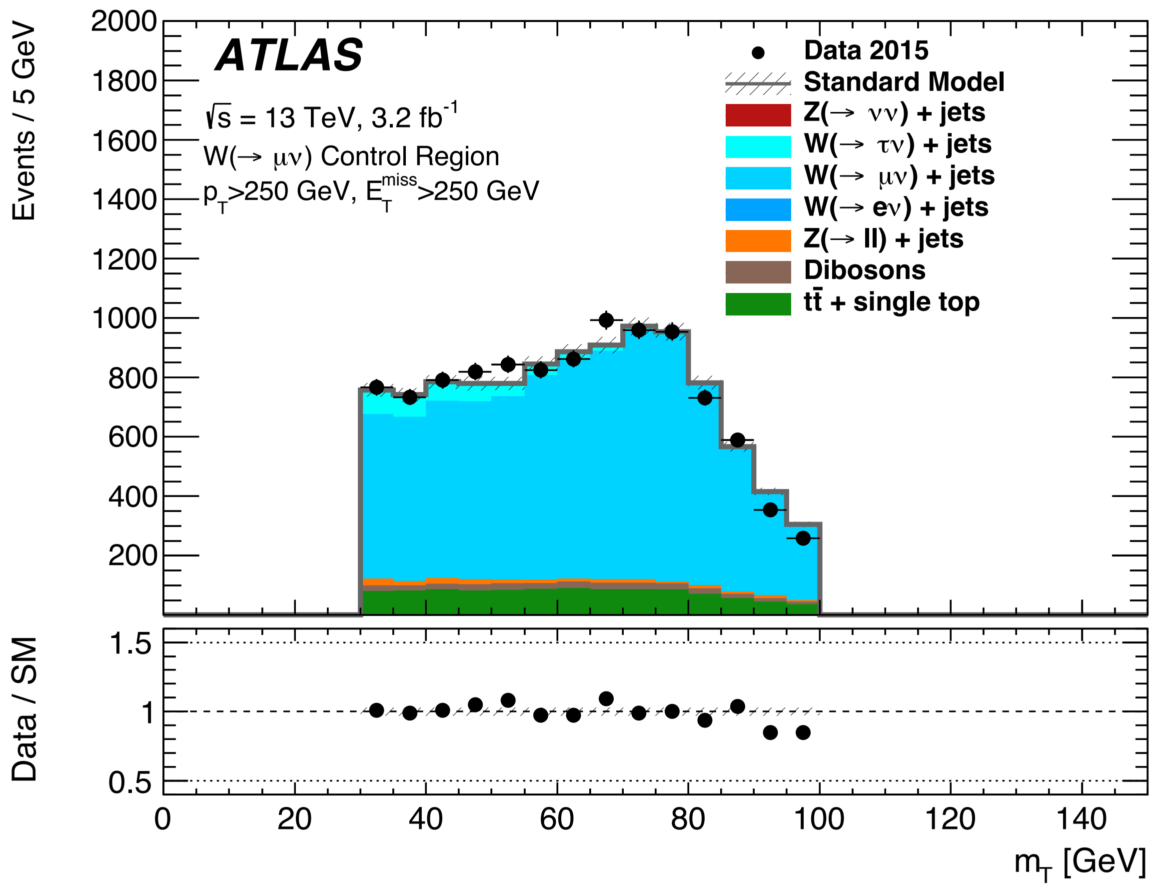

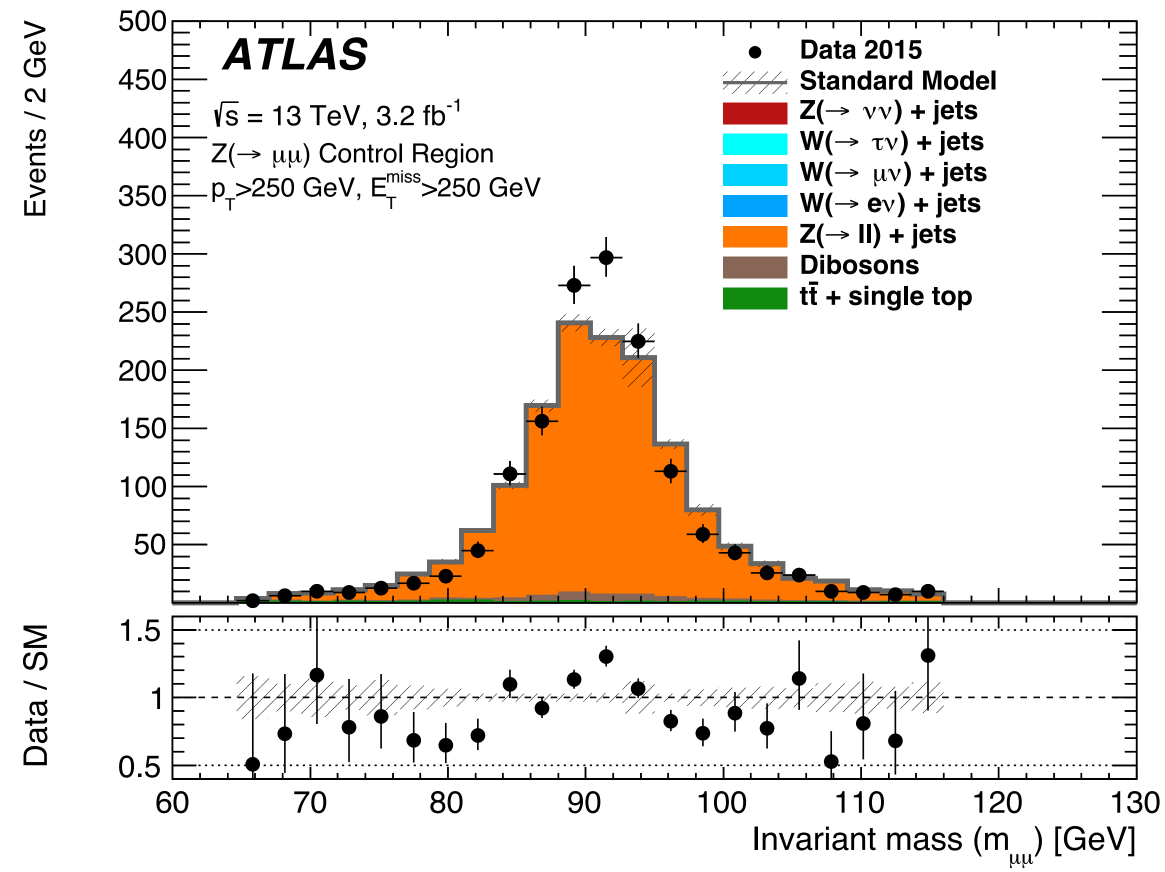

Jet+MET SR plots

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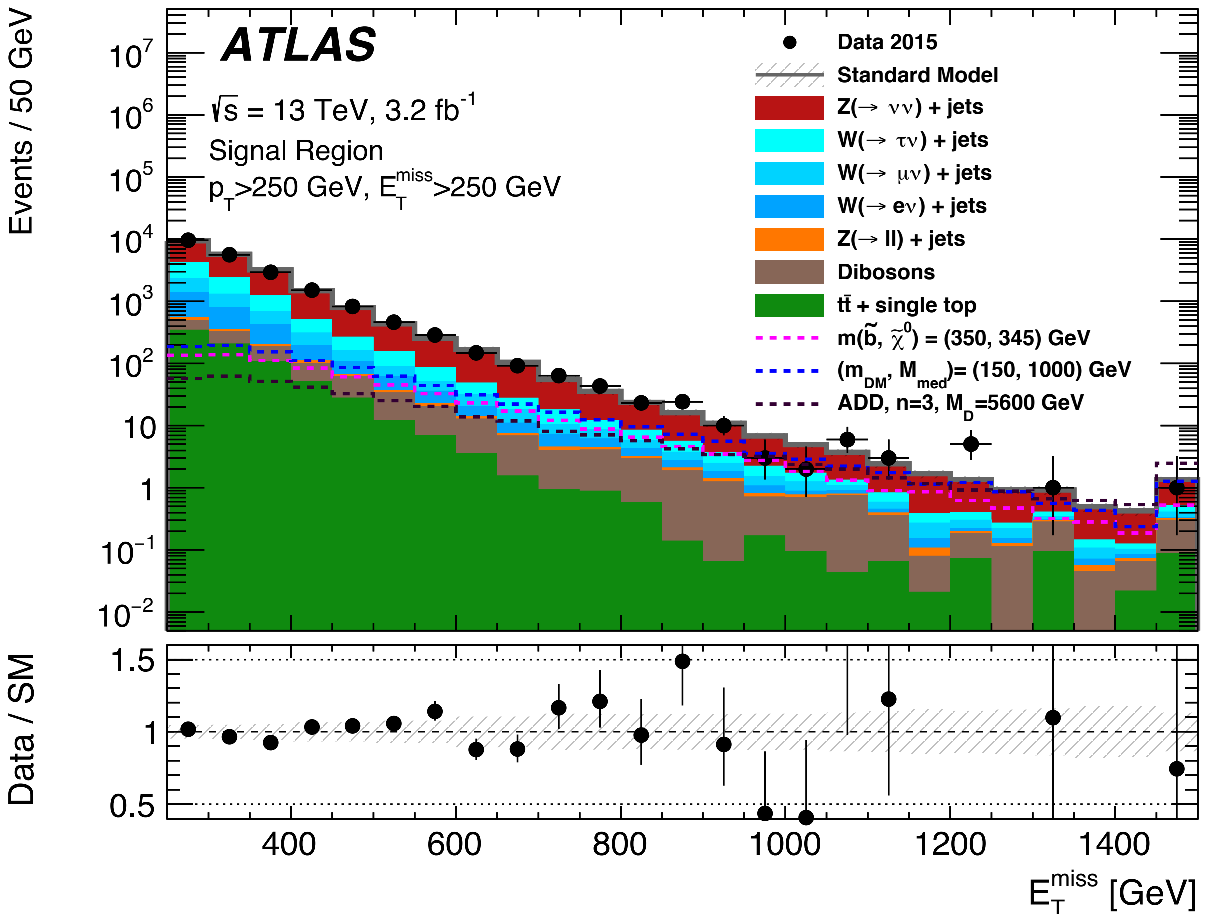
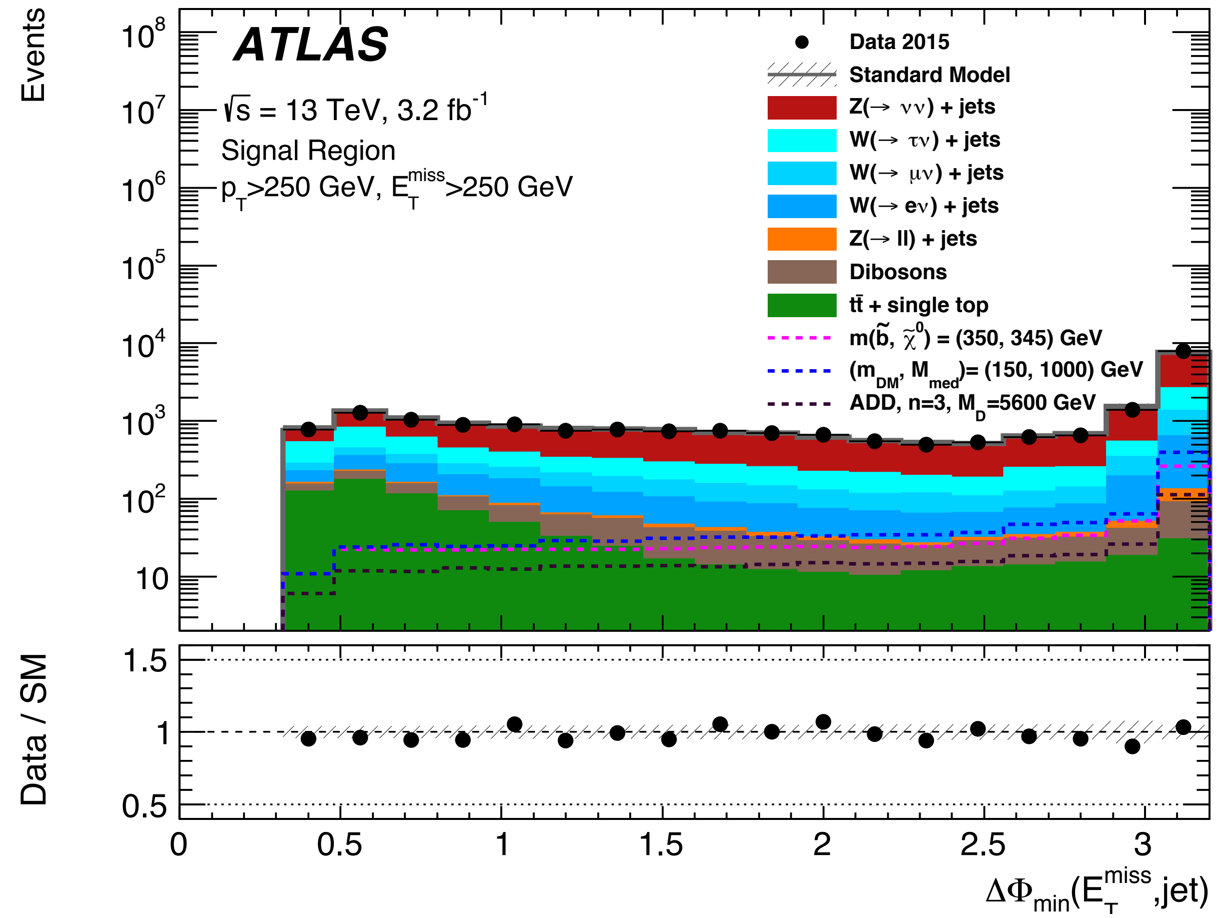




bb+MET SRs & CRs

ATLAS-CONF-2016-086

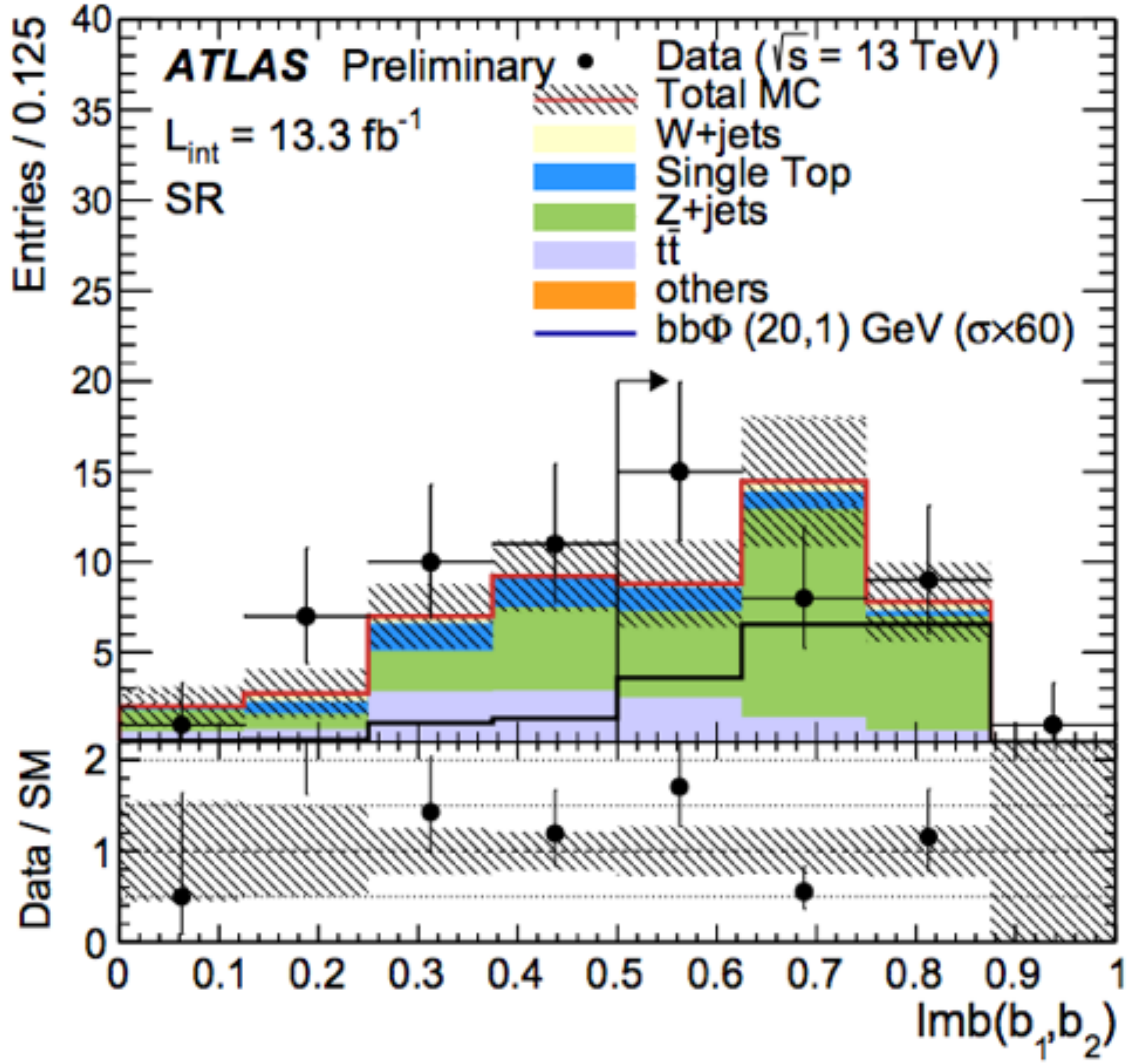
Quantity	SR	CRZ1b	VRZ2b	CRW1b	VRW1b	CRW2b	VRLR
N_{lepton} (baseline)	0	2 (SFOS)	2 (SFOS)	1	1	1	0
N_{lepton} (high-purity)	0	2 (SFOS)	2 (SFOS)	1	1	1	0
$\Delta\phi^{j}_{\mathrm{min}}$	> 0.4	> 0.4	> 0.4	> 0.4	> 0.4	> 0.4	> 0.4
N_{jets}	$2-3$	$2-3$	$2-3$	$2-3$	$2-3$	$2-3$	$2-3$
$N_{\mathrm{b}\,jets}$	$= 2$	$= 1$	$= 2$	$= 1$	$= 1$	$= 2$	$= 2$
jet 1 p_{T} [GeV]	> 100	> 100	> 85	> 100	> 100	> 100	> 100
jet 2 p_{T} [GeV]	> 20	> 20	> 20	> 30	> 30	> 20	> 20
jet 3 p_{T} [GeV]	< 60	< 60	< 60	< 60	< 60	< 60	< 60
$p_{\mathrm{T}}^{\mathrm{b-jet1}}$ [GeV]	> 50	> 50	> 50	> 50	> 50	> 50	> 50
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 150	< 100	< 80	> 130	> 150	> 120	> 150
$E_{\mathrm{T}}^{\mathrm{miss,cor}}$ [GeV]	-	> 120	> 100	-	-	-	-
ΔR_{min}	> 2.8	> 2.8	> 2.8	> 2.5	> 2.8	> 2.8	< 2.5
$\Delta\eta(b_1, b_2)$	> 0.5	-	-	-	> 0.5	-	> 0.5
$Imb(b_1, b_2)$	> 0.5	-	-	-	-	-	> 0.5
m_{T}^{lep}	-	-	-	[30, 100]	[30, 100]	> 30	-
$m_{\ell\ell}$	-	[75, 105]	[80, 100]	-	-	-	-
lepton 1 p_{T} [GeV]	-	> 30	> 30	> 30	> 30	> 30	-
lepton 2 p_{T} [GeV]	-	> 25	> 25	-	-	-	-
$\Delta\phi(b_1, b_2)$	> 2.2	> 2.2	-	[1, 2.2]	> 2.2	> 2.2	> 2.2

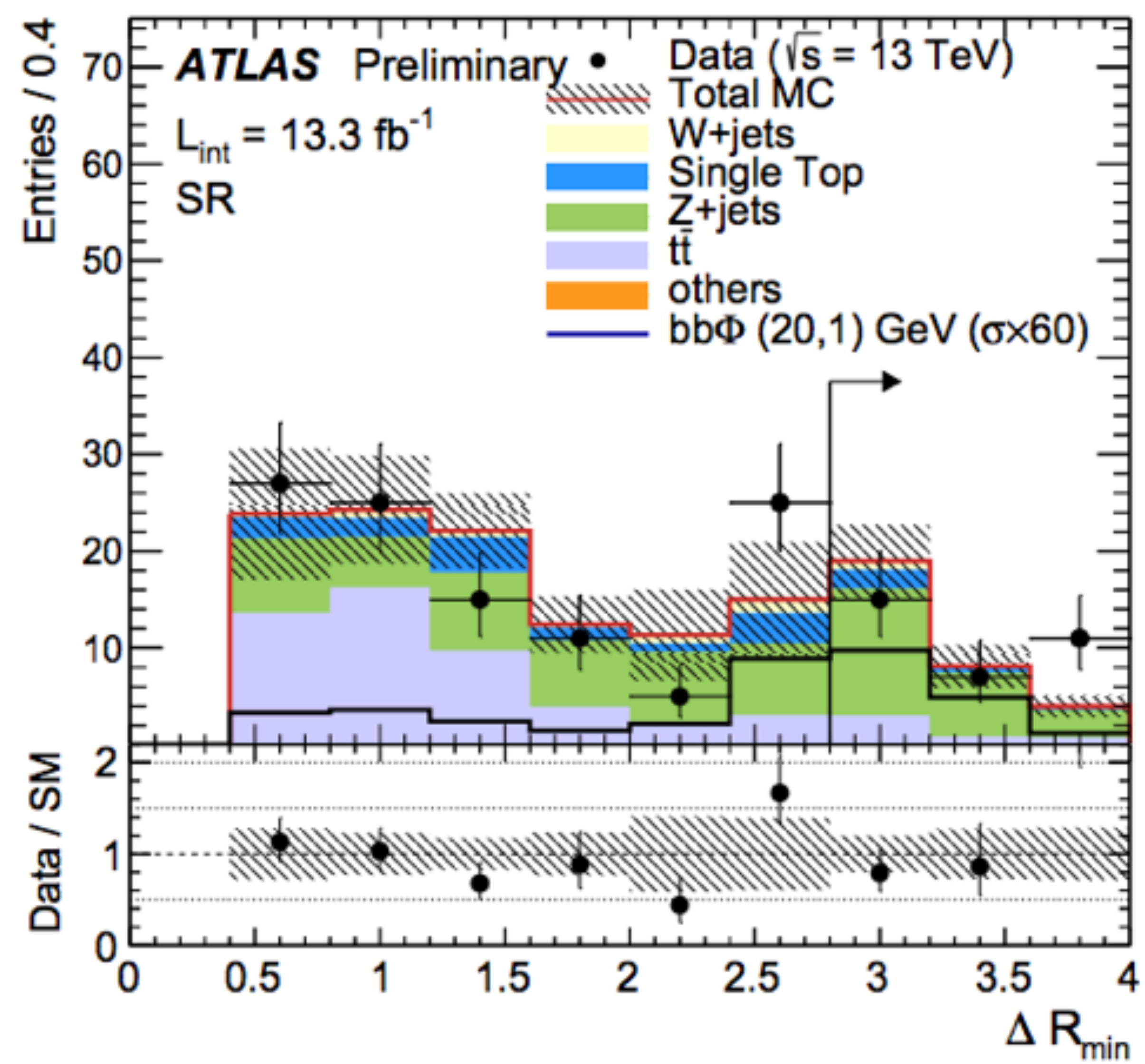
$$Imb(b_1, b_2) = \frac{p_{\mathrm{T}}(b_1) - p_{\mathrm{T}}(b_2)}{p_{\mathrm{T}}(b_1) + p_{\mathrm{T}}(b_2)} > 0.5$$

aka $p_{\mathrm{T}}(b1) > 3 * p_{\mathrm{T}}(b2)$

bb+MET SR plots

ATLAS-CONF-2016-086





bb+MET CR plots

ATLAS-CONF-2016-086

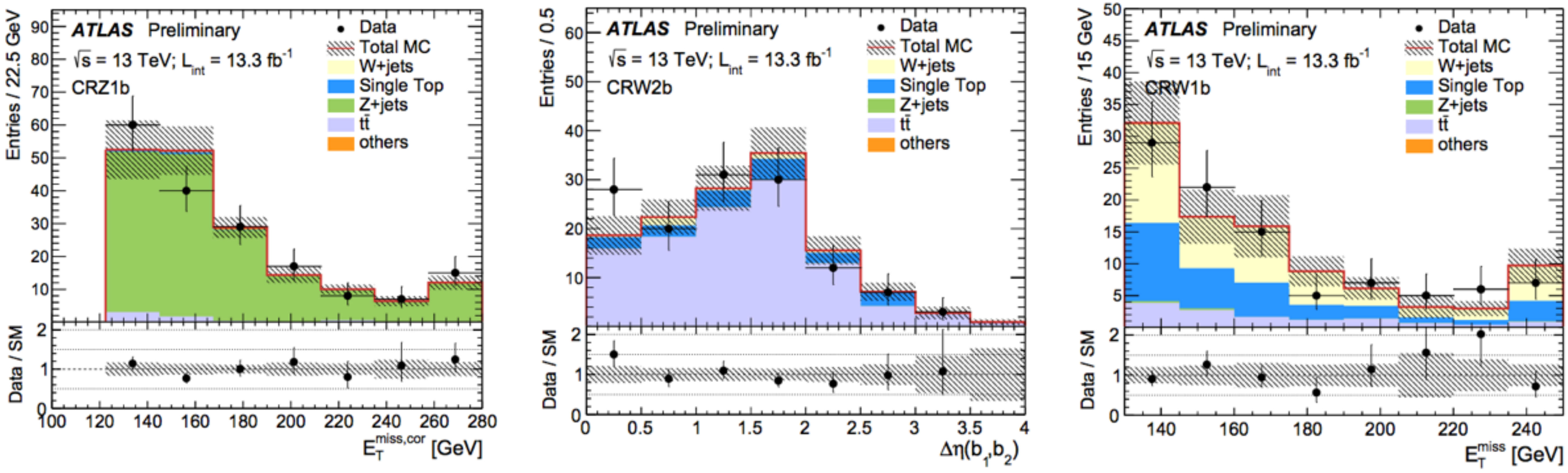
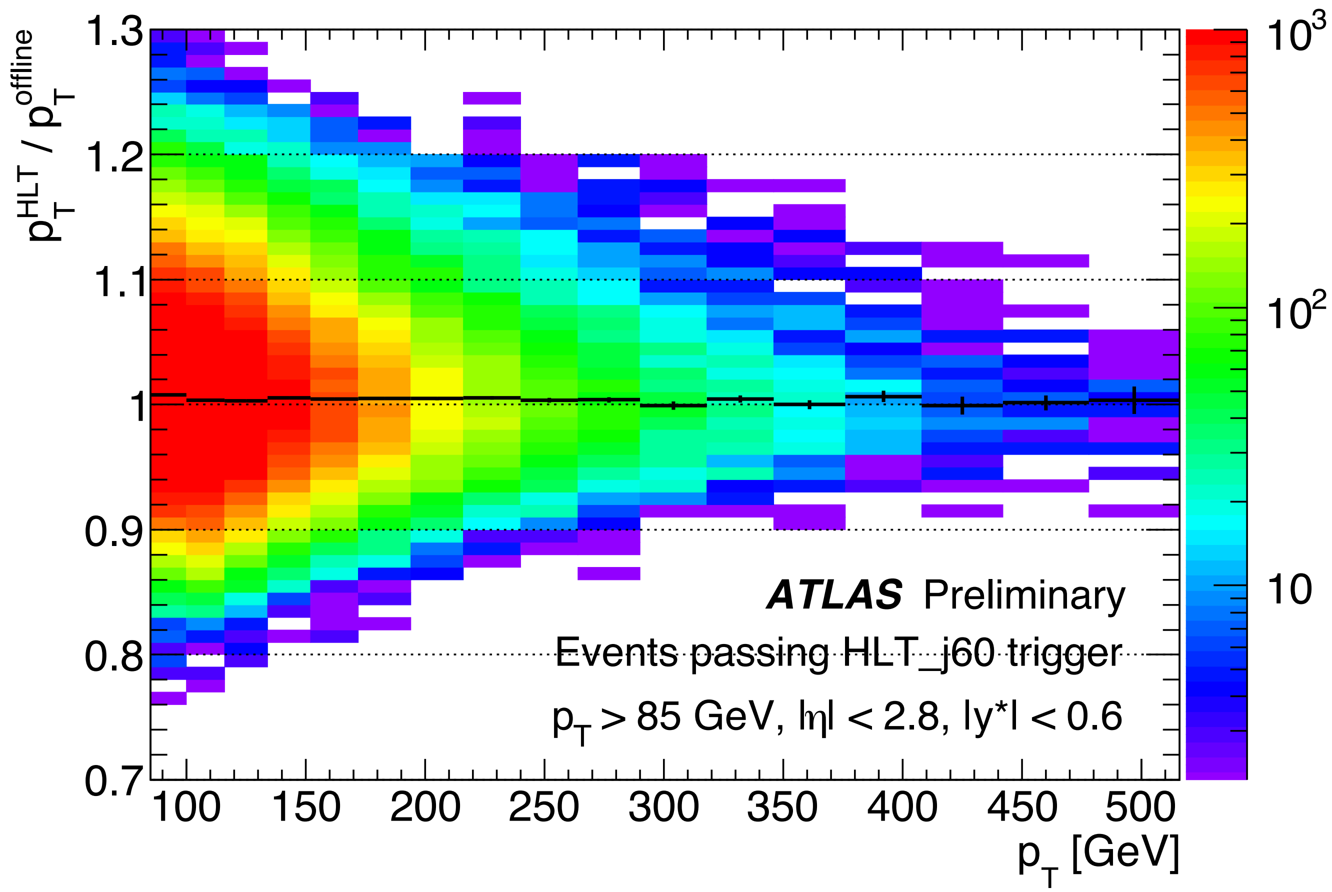


Figure 2: Representative distributions for the three control regions of the analysis. All backgrounds are normalised to the fit results. The dominant post-fit systematic uncertainties are included in the systematic band.

List for all hadronic + MET searches	**Example: tt+MET** ATLAS-CONF-2017-020
• Statistical uncertainty on background estimate	Dominant
• Detector effects:	
• Jet and MET energy scale and resolution	16%
• Tagging efficiencies (where relevant)	9%
• Lepton selection etc in CRs	
• Theoretical uncertainties:	20%
• Scales and generator choice in MC simulation	
• Additional signal uncertainties	
• ISR strength, cross-section	
• Many of these cancel to some degree thanks to closeness of SR and CR	

ATLAS-CONF-2016-030

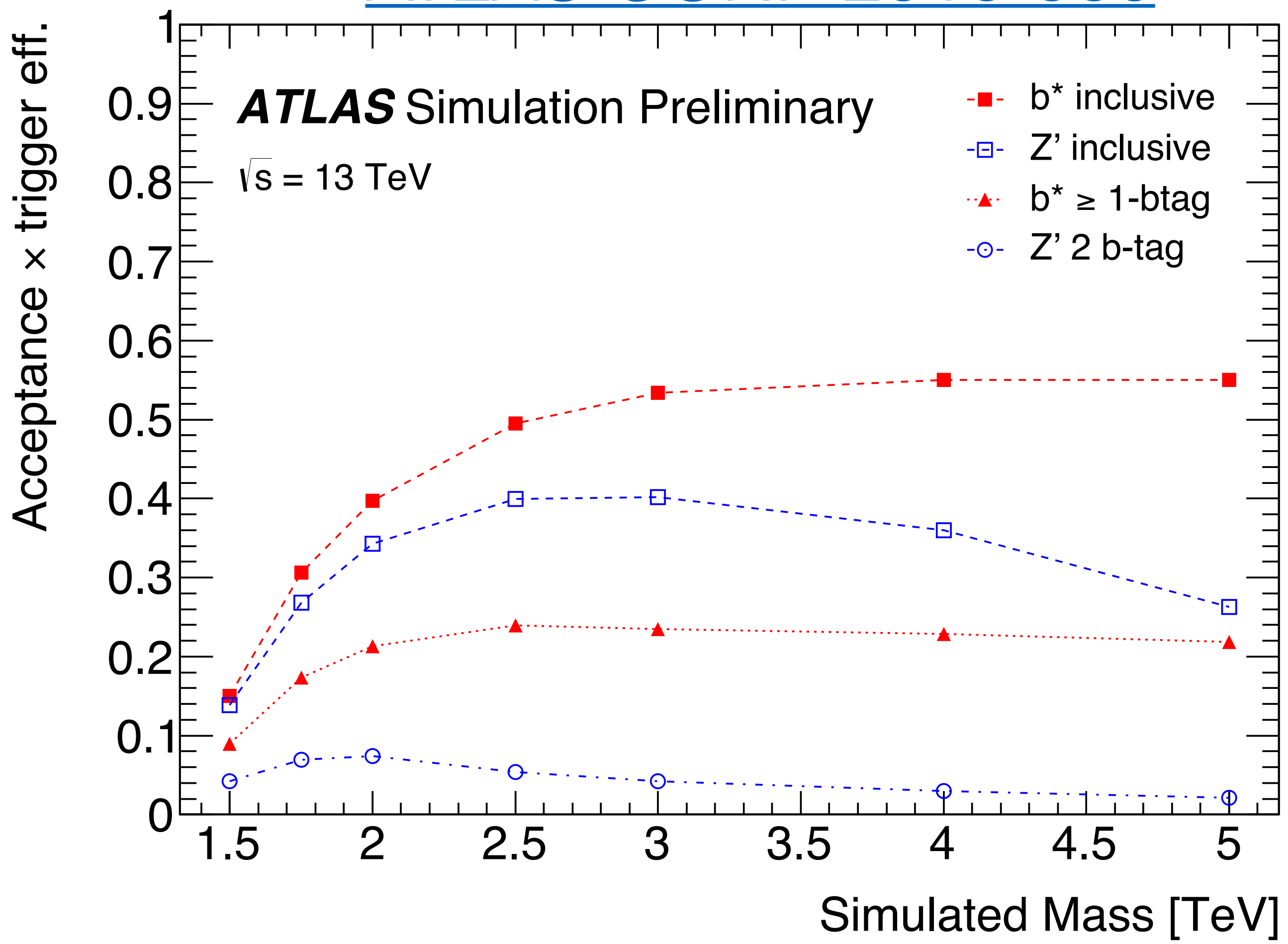


- **Trigger-Level Analysis: custom jet calibration**
- Record events at 2kHz (vs 1kHz for main ATLAS stream) -> no time for tracking to run

Di-b-jet: b-tagging

- **di-b-jet: b-tag jets**
- Gives additional sensitivity to b-quark resonances
- Efficiencies around 60% for 1 TeV jet, with light rejection factor around 30

ATLAS-CONF-2016-060



Resonance uncertainties

- Background uncertainties are purely from the fit:
  - Function choice and parameter uncertainty
  - Evaluated with pseudo-experiments: take nominal background estimate, Poisson fluctuate, refit; take RMS of new estimates
- Detector and theory systematics only relevant for signal simulation. Dominant:
  - Jet energy scale and resolution
  - b-tagging efficiencies (for di-b)

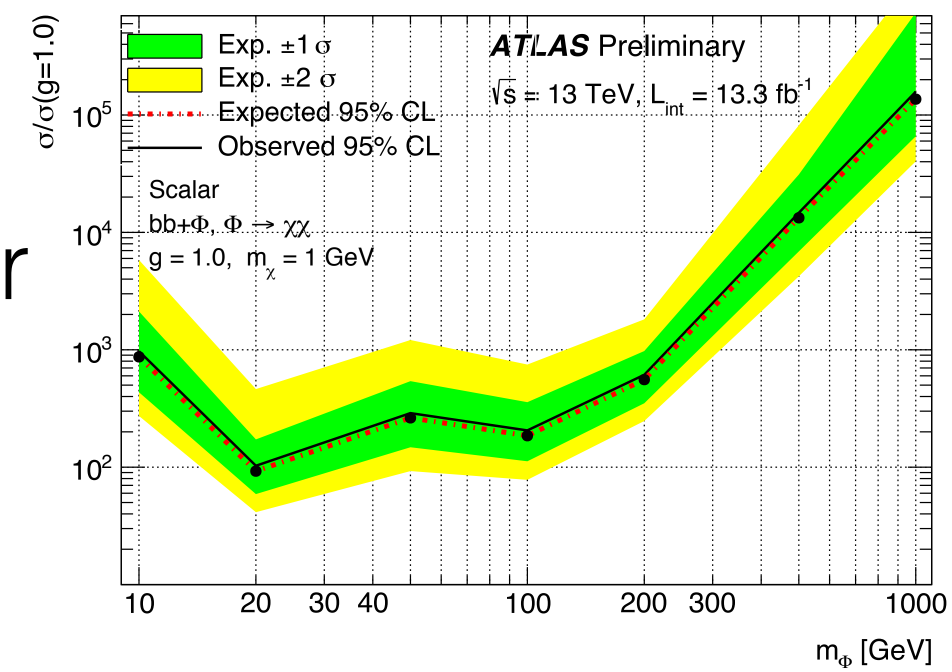
bb+MET

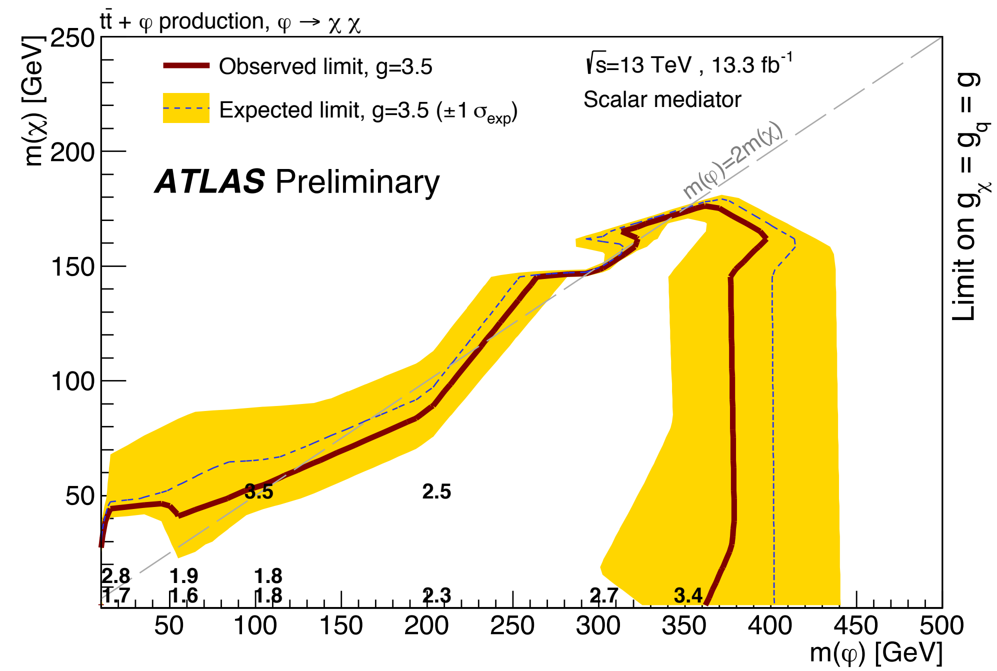
[ATLAS-CONF-2016-086]

tt+MET

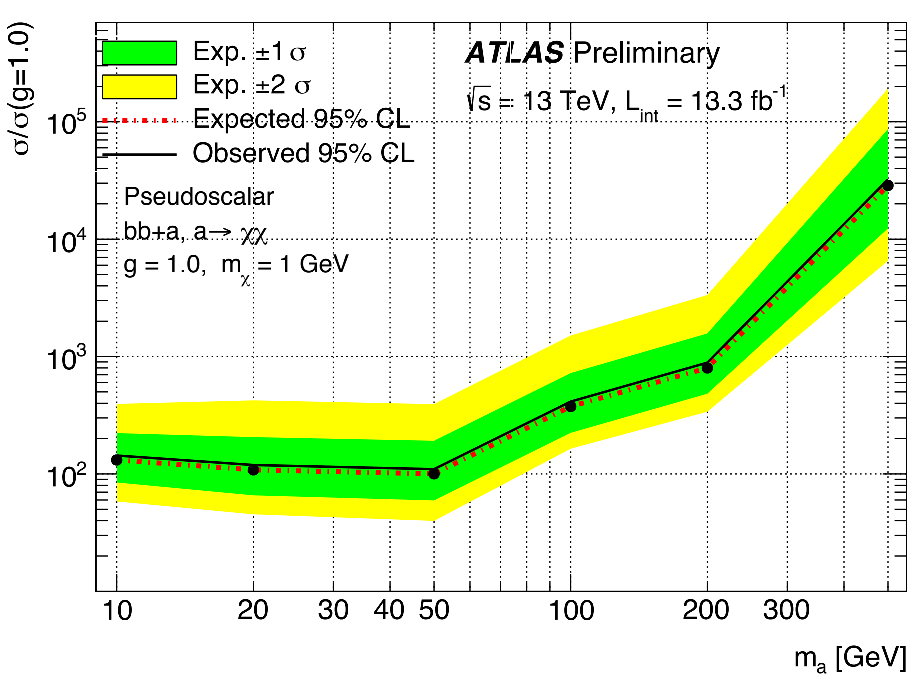
[ATLAS-CONF-2016-077]

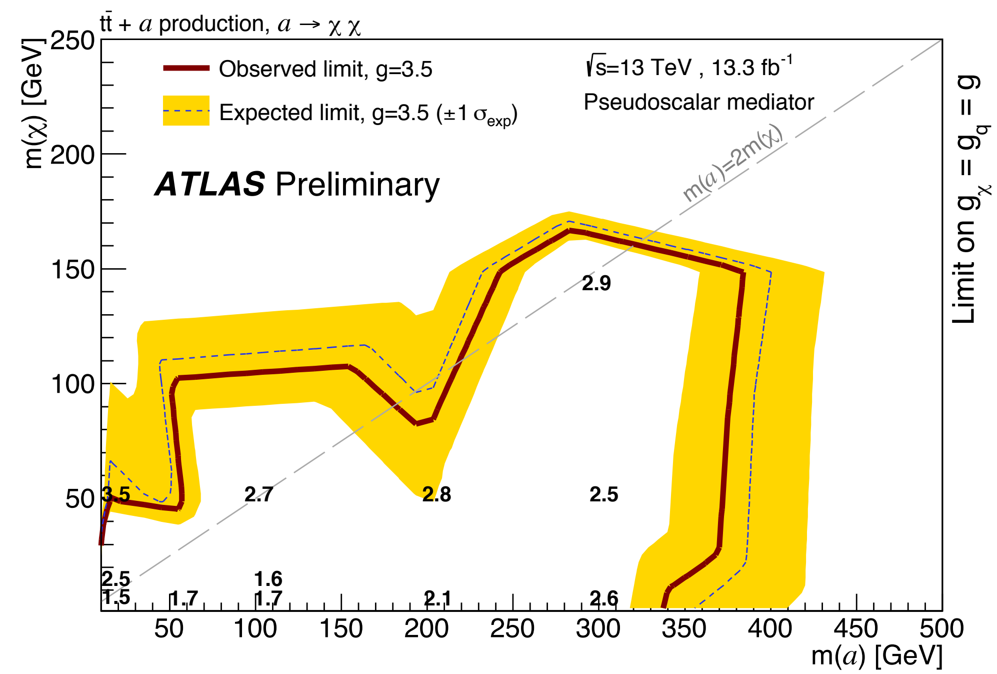
Scalar mediator



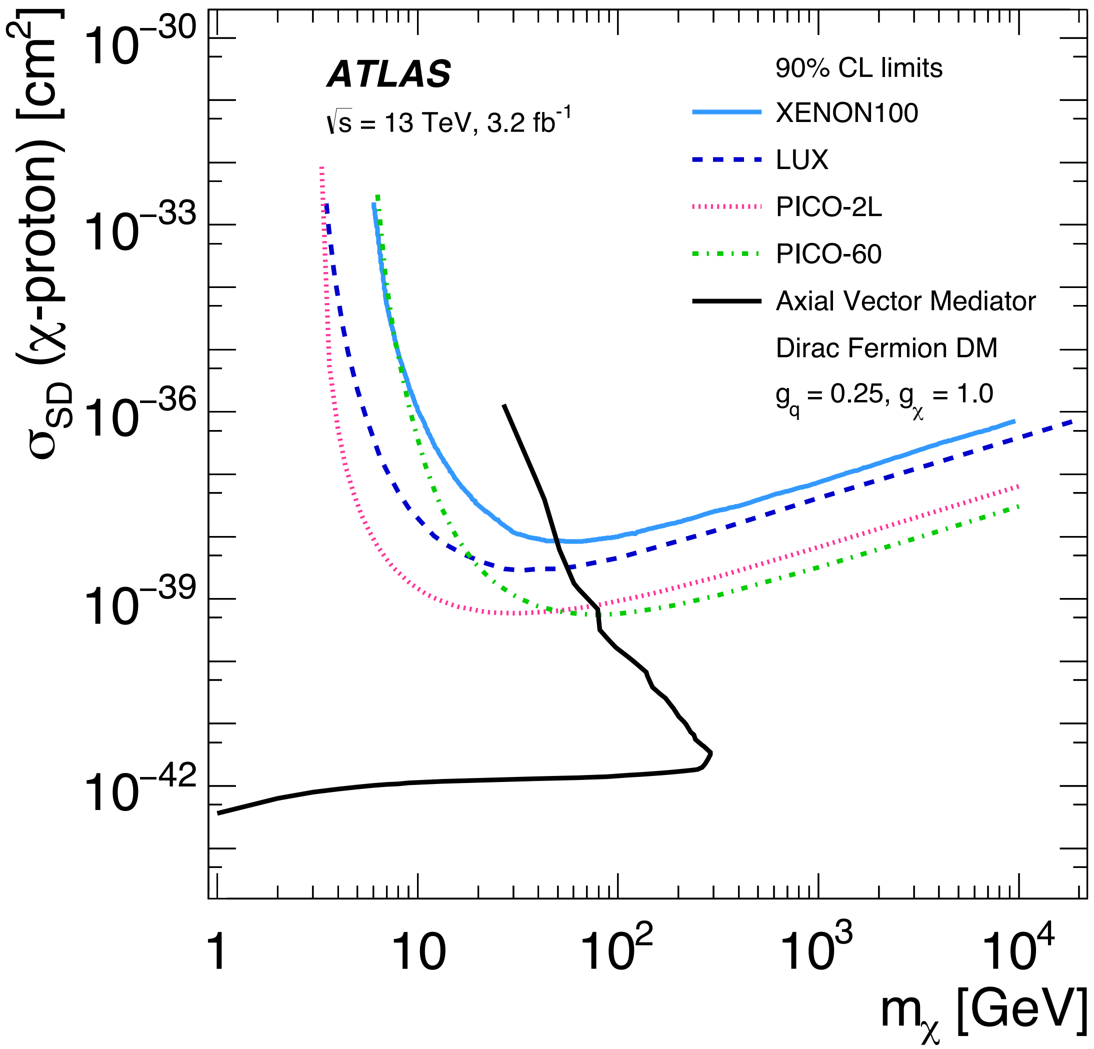


Pseudoscalar mediator

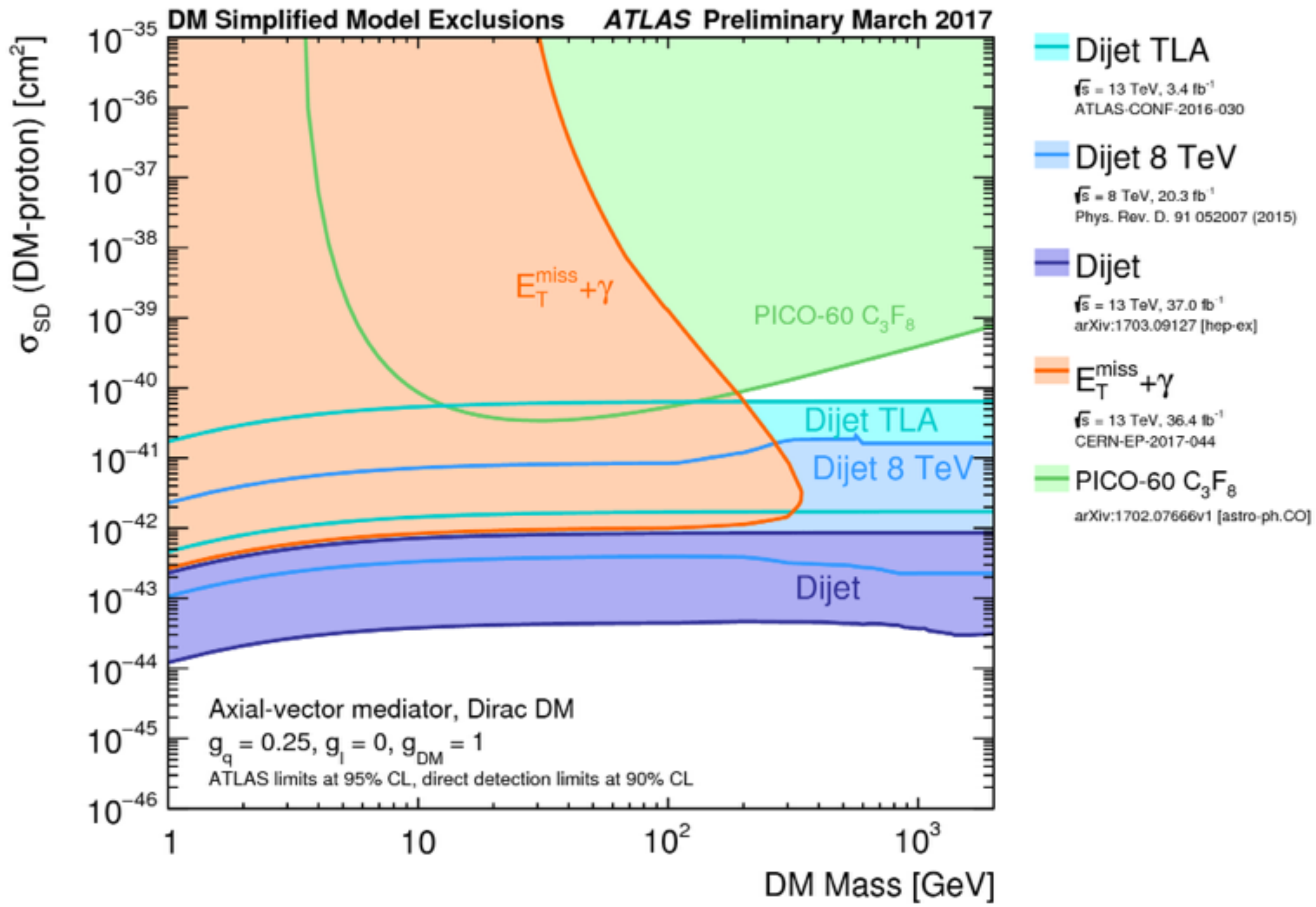




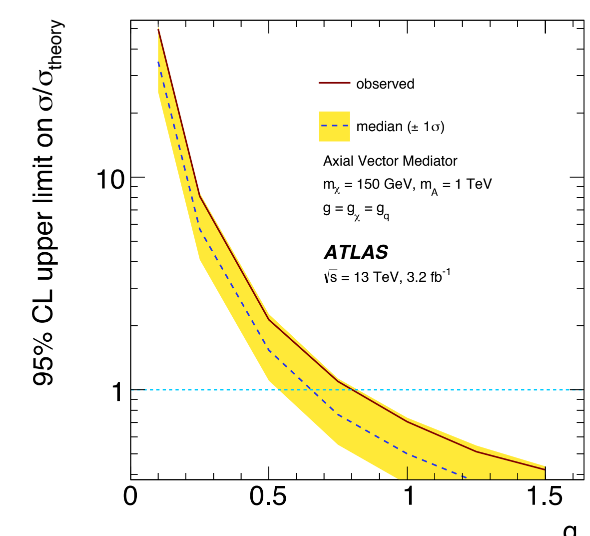
[PRD 94 (2016) 032005](https://doi.org/10.1103/PhysRevD.94.032005)



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

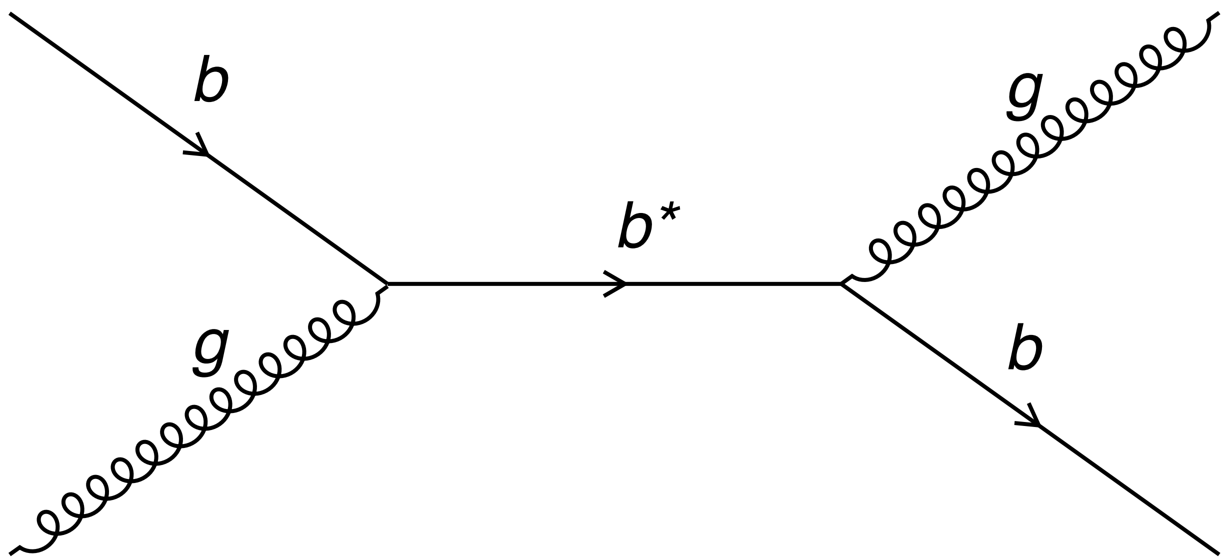


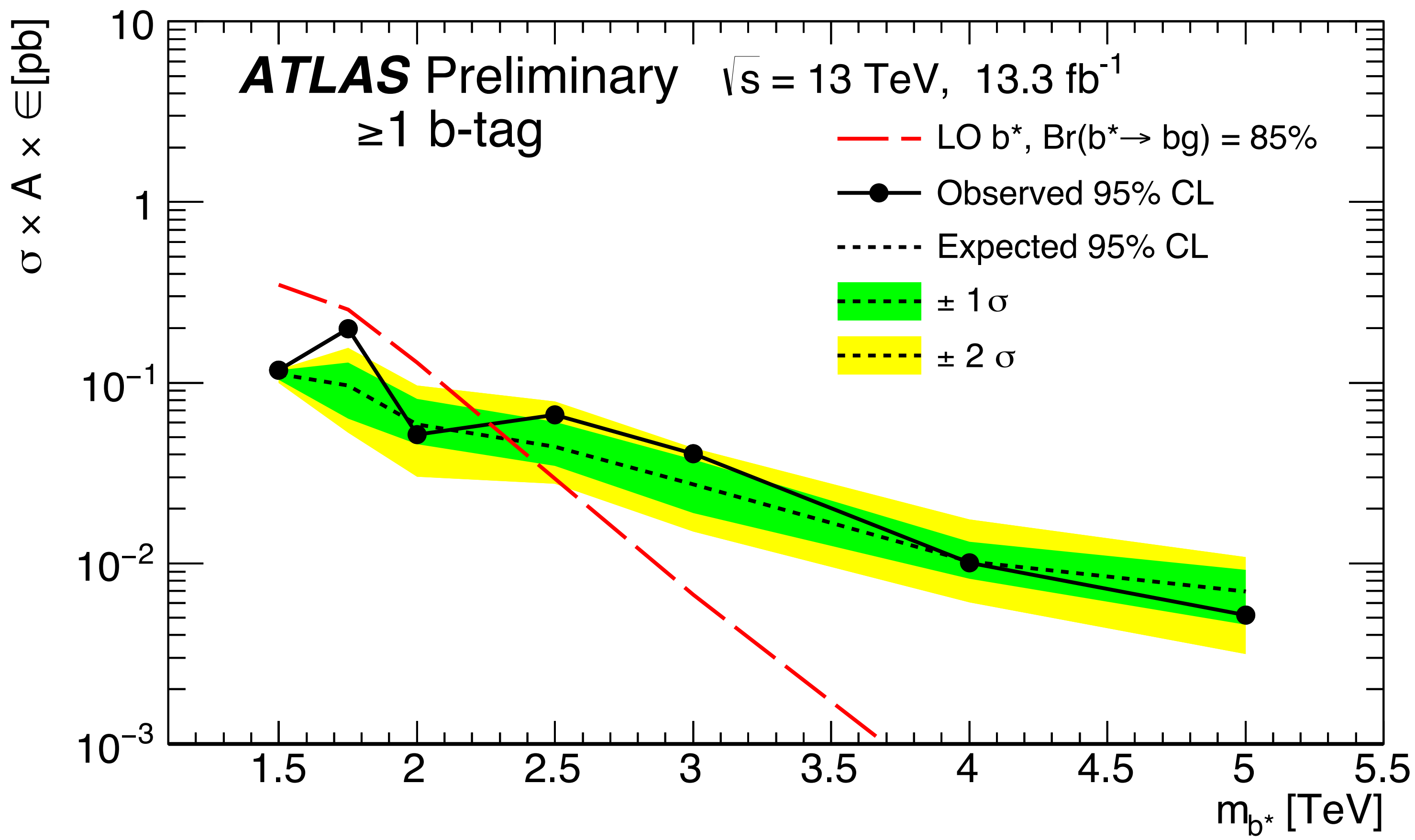
- New PICO-60 result on right
- Jet+MET 3.2 fb^{-1}, γ+MET 36.4 fb-1



di-b-jet b* limits

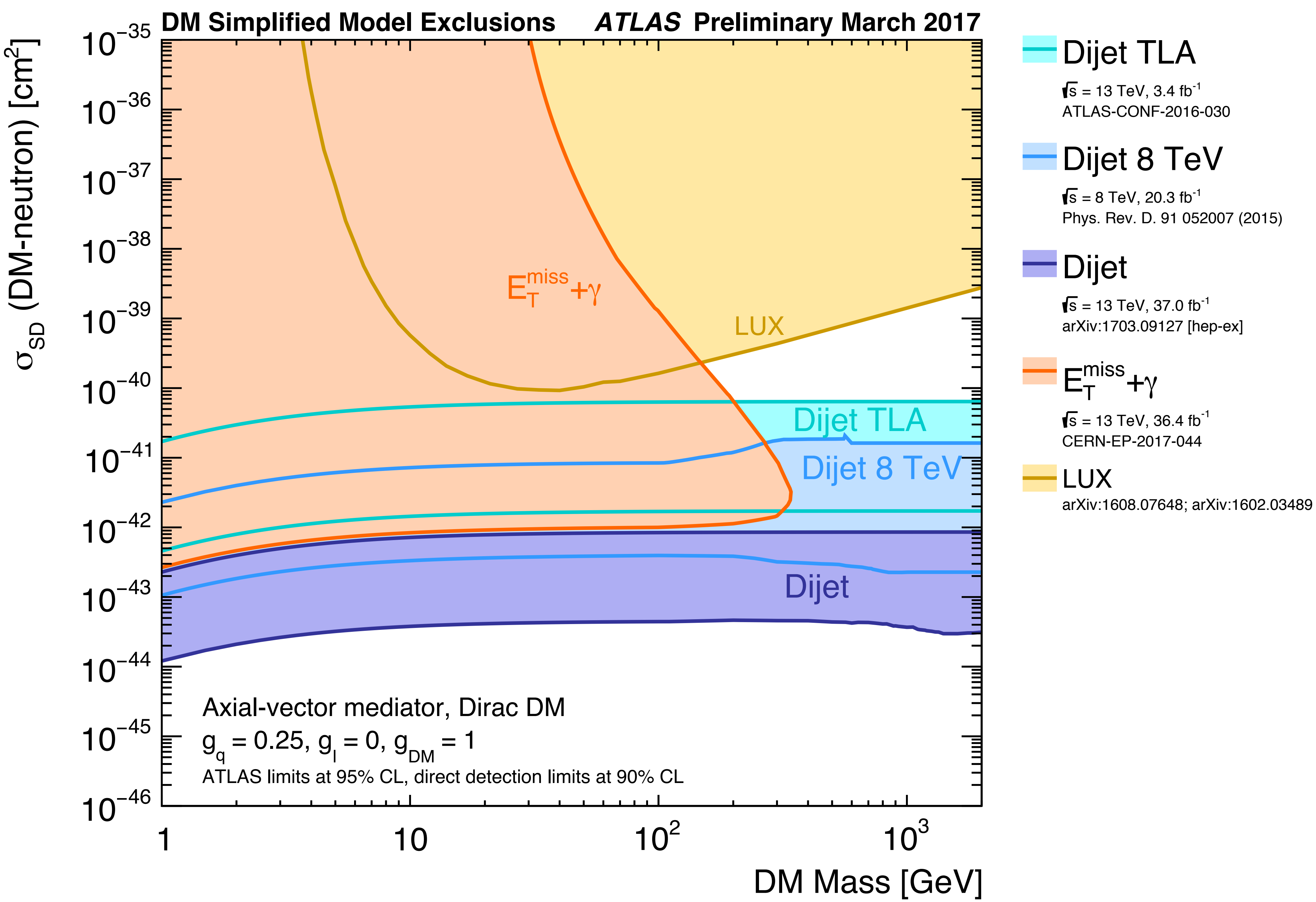
ATLAS-CONF-2016-060





Spin-Dependent, neutron

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



Spin-Independent

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