SEARCHING FOR NEW PHYSICS IN EVENTS WITH AN ENERGETIC JET AND LARGE MISSING TRANSVERSE MOMENTUM WITH THE ATLAS DETECTOR

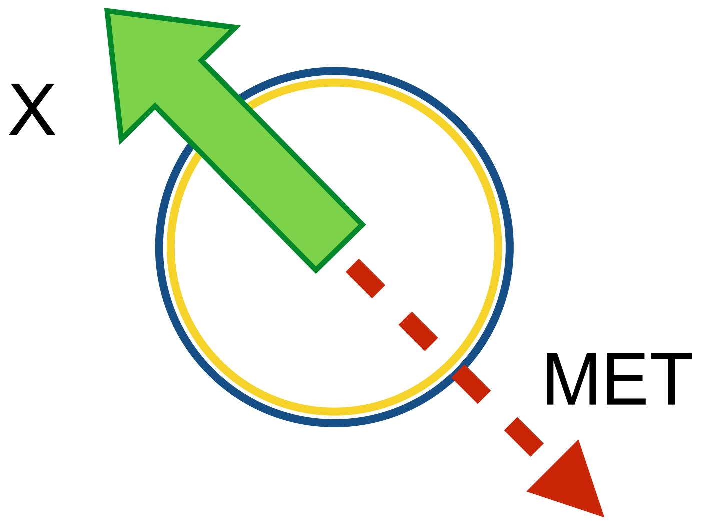
Giuliano Gustavino, on behalf of the ATLAS collaboration

05 April 2018

DM@LHC 2018

DM search with MET+jet

Mono-X signatures

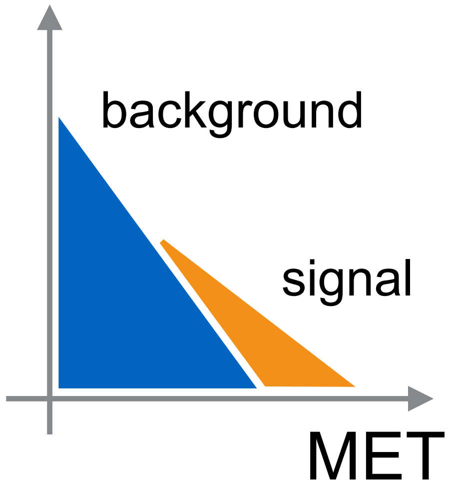


Search for high MET excesses.

General Analysis Strategy:

- Require MET (➡ recoil system p_T)
- Select for X (jet, photon…)
- Veto other objects
- Additional cuts to suppress backgrounds
- Data-driven techniques to estimate background

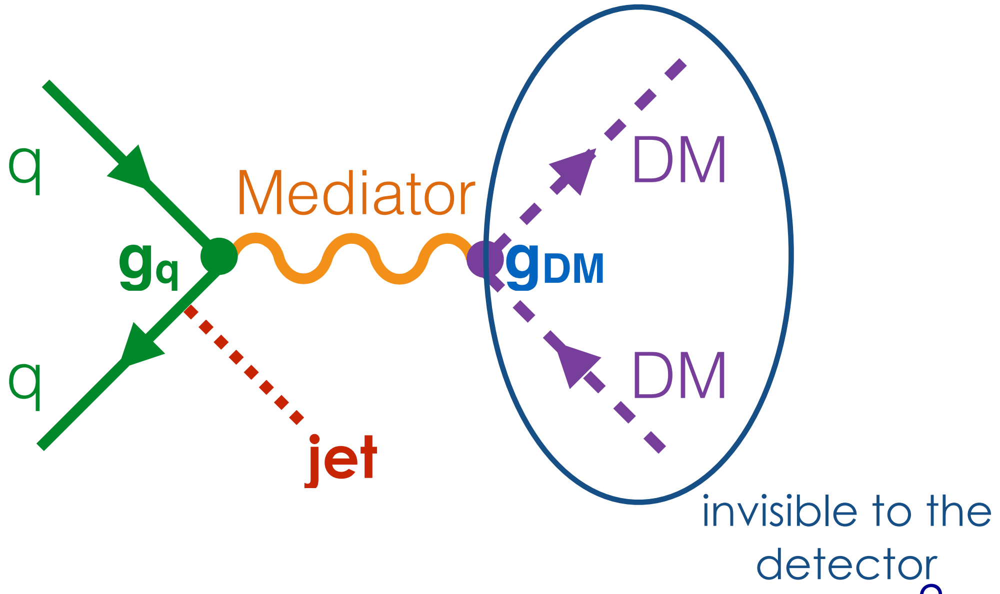
  ➥ control region with inverted vetoes



Why MET+jet signature?

Simple signature and sensitive to many BSM theories.

In ISR+MET processes this channel has more statistics with respect to other mono-X (e.g. mono-photon) final states @LHC ($\alpha_S >> \alpha_{EW}$).



Selection (2015+2016 analysis)

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MET Trigger

MET > 250 GeV

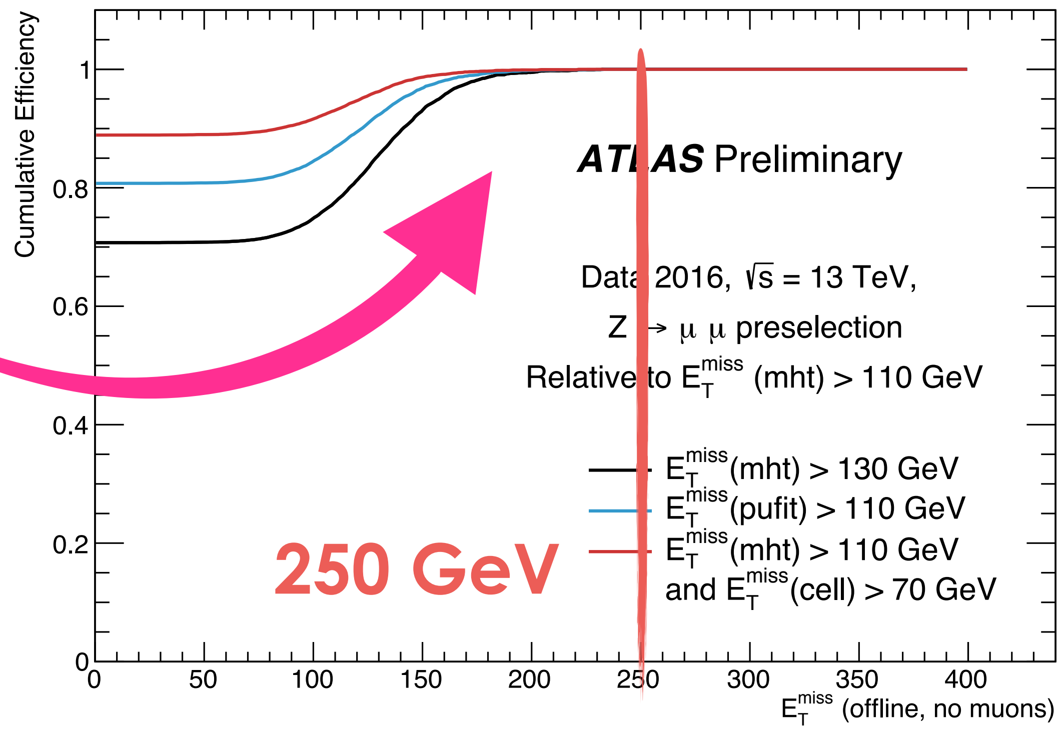
leading jet p_T > 250 GeV , |eta| <2.4,

jet cleaning requirements

n_{jet} (p_T>30 GeV) <= 4

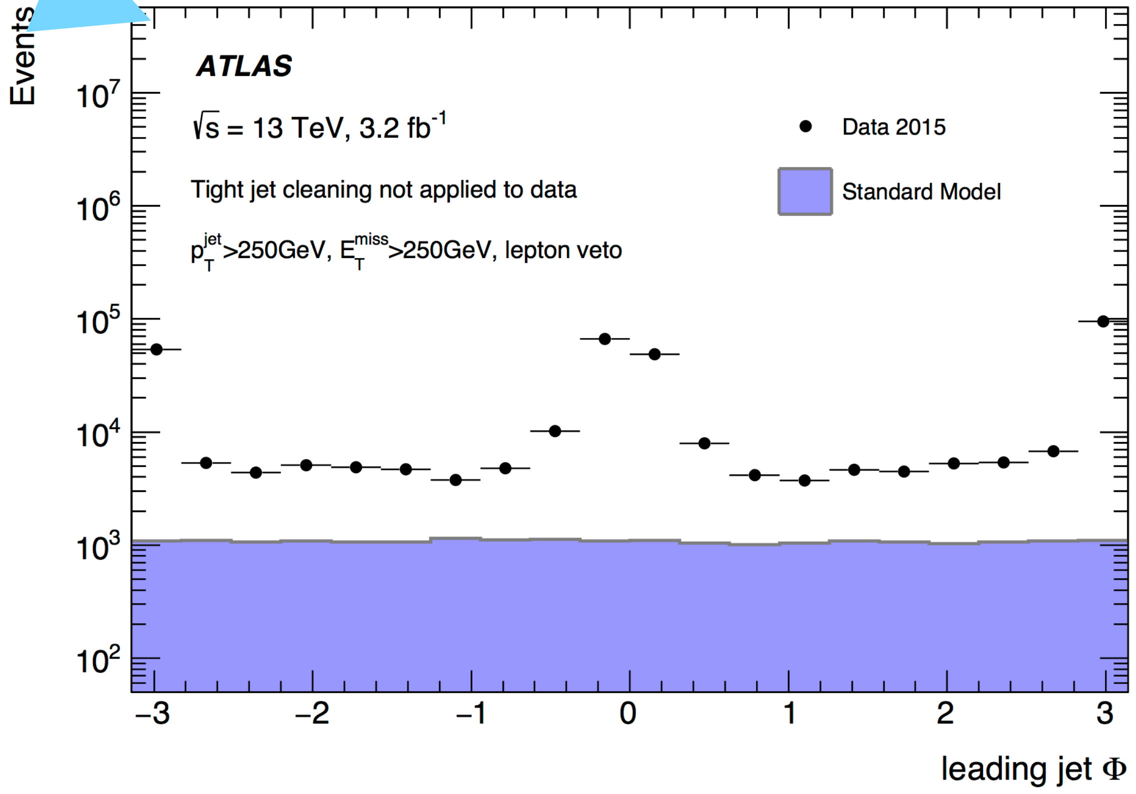
|dϕ(MET, jets)| > 0.4

lepton veto

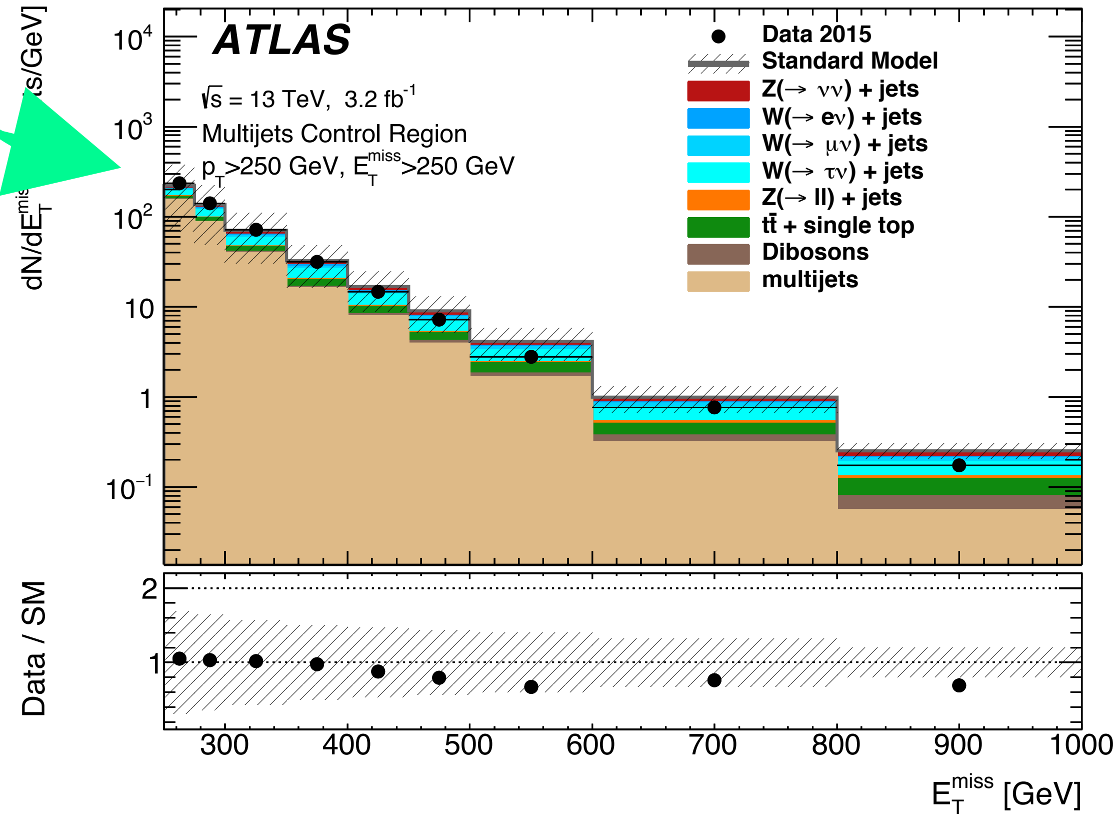


250 GeV

Phys. Rev. D 94 (2016) 032005



Phys. Rev. D 94 (2016) 032005



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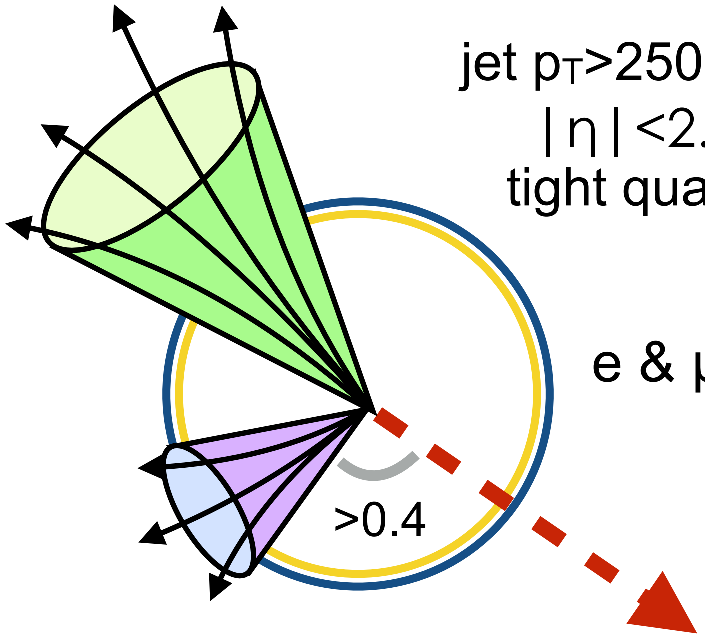


jet p_T>250GeV,
|η|<2.4,
tight quality

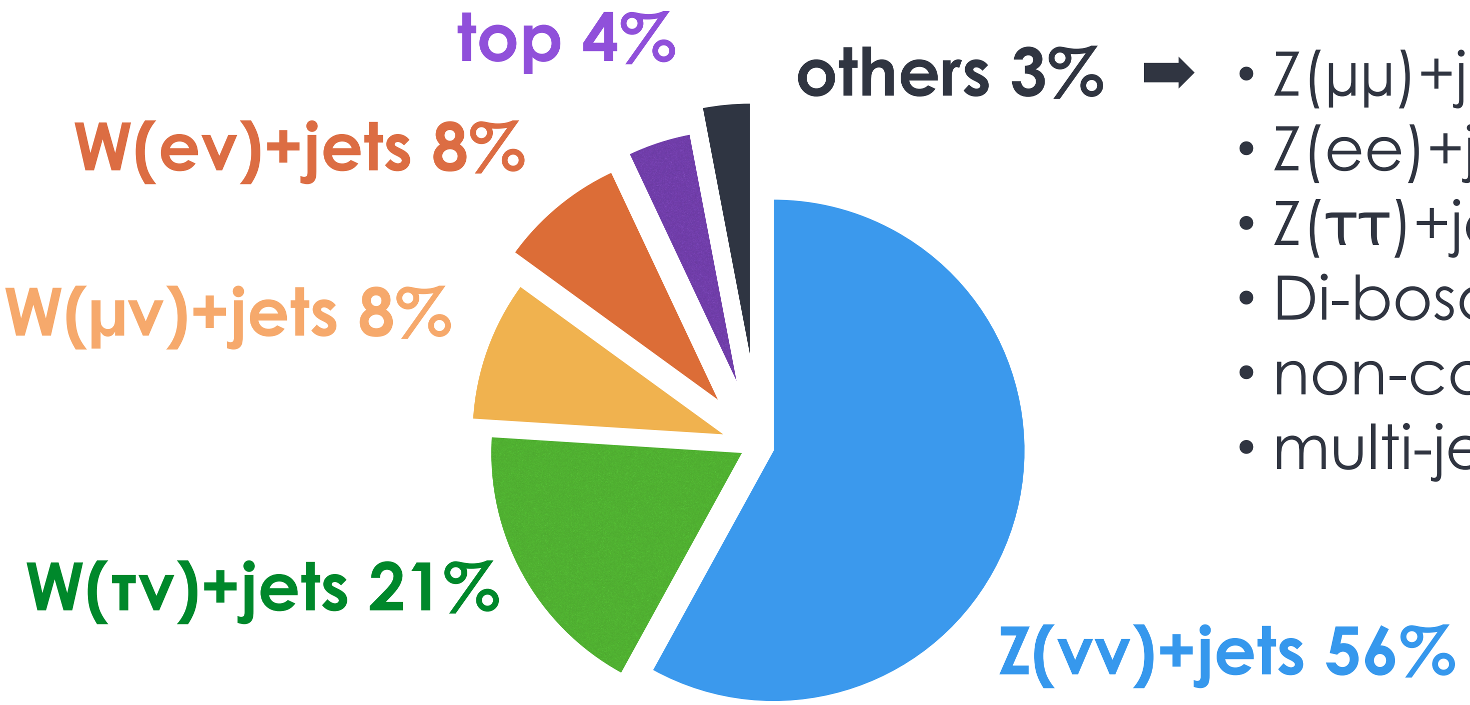
e & μ veto

>0.4

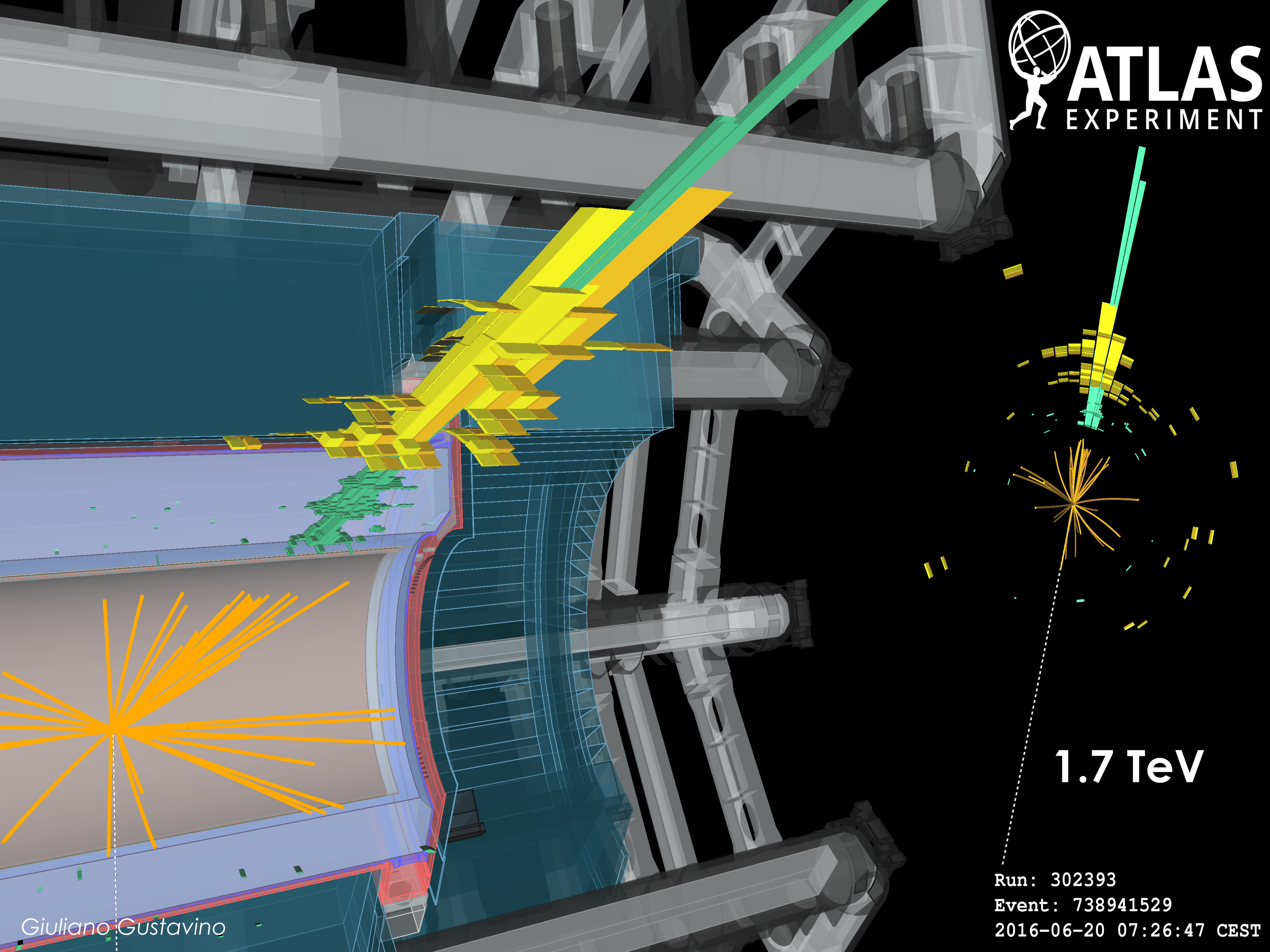
Up to 3 other jets
(p_T>30GeV)

MET>250 GeV

*Residual dominant backgrounds given by the **Z(νν)+jets** and **W(lν)+jets** processes*

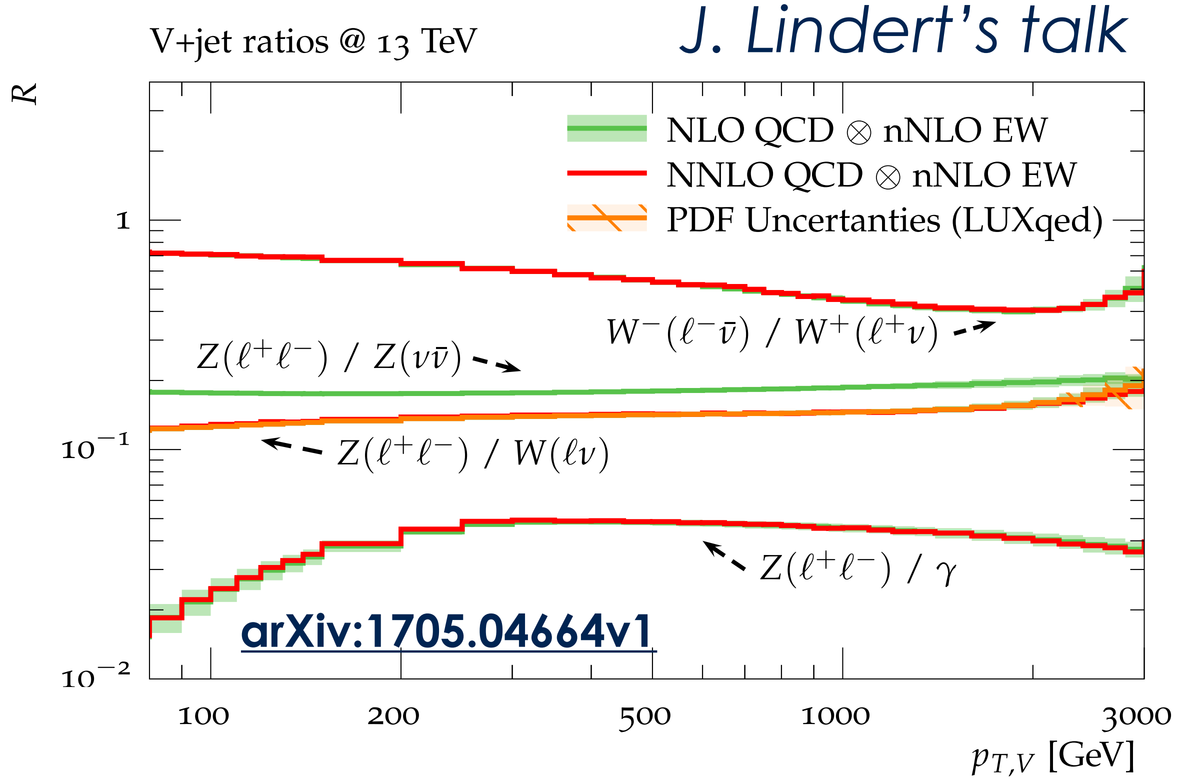


others 3% ➡
- Z(μμ)+jets
- Z(ee)+jets
- Z(ττ)+jets
- Di-bosons (ZZ,WZ,WW)
- non-collision bkg
- multi-jet


ATLAS
EXPERIMENT
1.7 TeV
Run: 302393
Event: 738941529
2016-06-20 07:26:47 CEST
Giuliano Gustavino

Analysis strategy

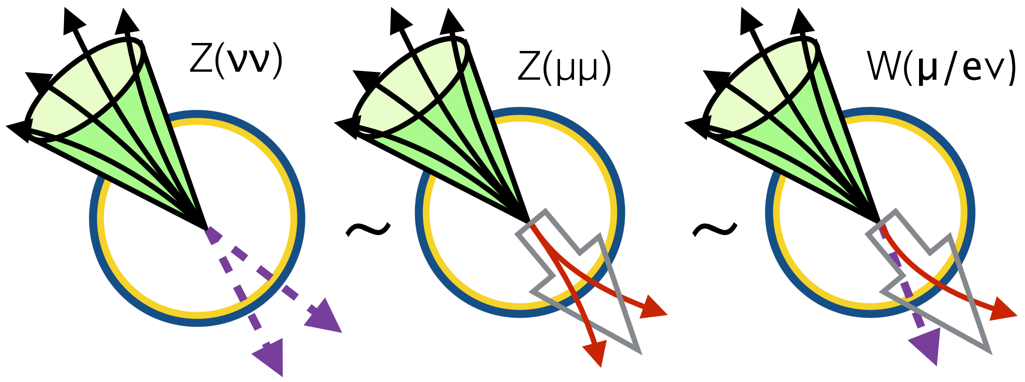
- NLO QCD and EW corrections applied to the V+jets processes (with the related uncertainties)
  - higher MC modelling accuracy (Sherpa multi-leg NLO generator used)



J. Lindert's talk

arXiv:1705.04664v1

- **4 control regions** are defined inverting the lepton veto criteria (1μ, 2μ, 1e) and categorising the events with at least a b-tagged jet in the single muon CR ($1\mu^{0b}$,$1\mu^{b}$):
  - to evaluate the dominant V+jets and top bkgs (ttbar and single top production);
  - to reduce the uncertainties due to the MC modelling;
  - to correct the MC predictions in the SR.



MET ~ boson p_T
charged leptons treated as invisibles in the MET calculation

- Z(ee)+jets and diboson processes evaluated from MC
- NCB and multi-jet backgrounds estimated by data driven techniques (< 1%)

Background estimation

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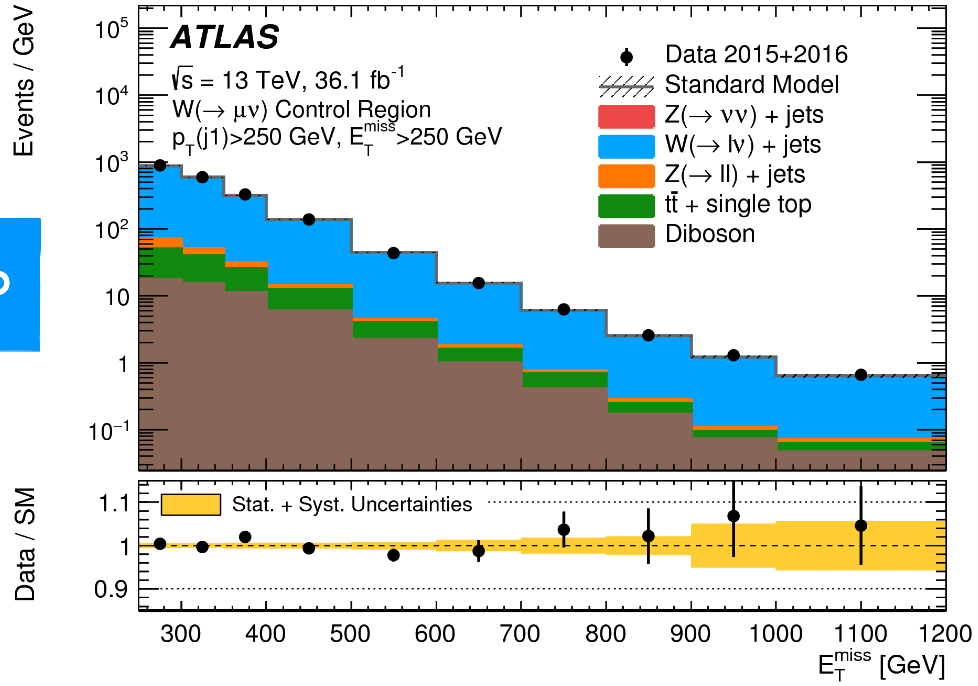
- A **shape fit** is performed on the pTV distribution in order to get a unique normalisation factor for **V+jets** processes and a normalisation factor for the **top** processes.

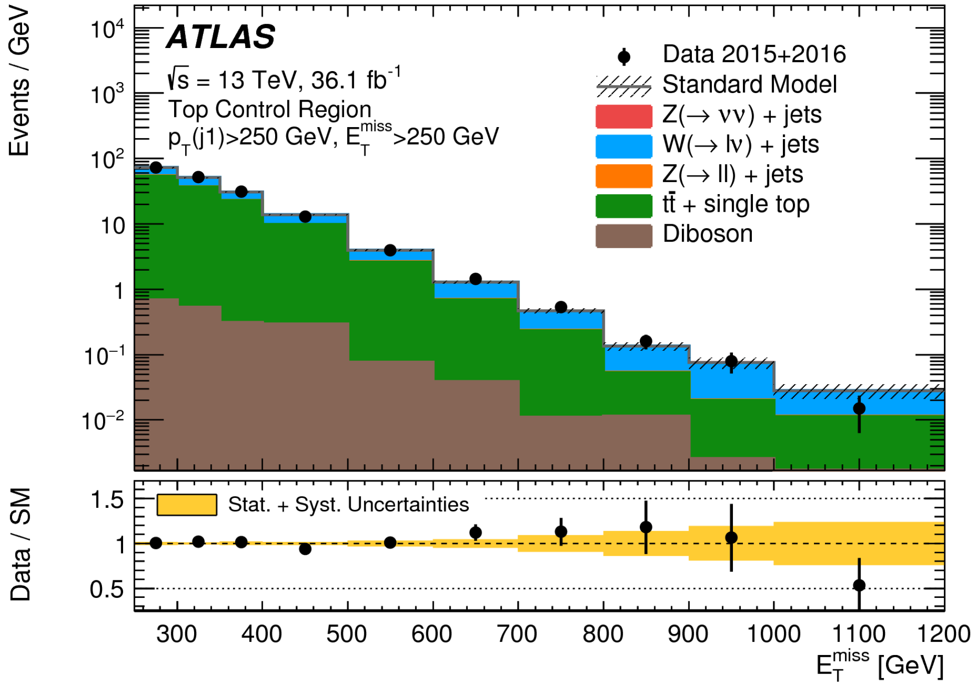
$$\mathcal{L}(\mu, \kappa, \theta) = \prod_r \prod_i \text{Poisson}\left(N_{ri}^{\text{obs}} \mid \mu N_{ri}^{\text{sig}}(\theta) + N_{ri}^{\text{bkg}}(\kappa, \theta)\right) f_{\text{constr}}(\theta)$$

$$\begin{aligned} N_{ri}^{\text{bkg}} = \kappa^{W/Z} (N_{ri}^{Z(\nu\nu)\text{+jets}} &+ N_{ri}^{W(\mu\nu)\text{+jets}} + N_{ri}^{W(e\nu)\text{+jets}} + N_{ri}^{W(\tau\nu)\text{+jets}} \\ &+ N_{ri}^{Z\to\tau\tau\text{+jets}} + N_{ri}^{Z\to\mu\mu\text{+jets}}) \\ &+ \kappa^{t} (N_{ri}^{t\bar{t},\text{single}-t}) \\ &+ N_{ri}^{Z\to ee\text{+jets}} + N_{ri}^{\text{diboson}} + N_{ri}^{\text{multi-jet}} + N_{ri}^{\text{NCB}} \end{aligned}$$

Inclusive (IM)	IM1	IM2	IM3	IM4	IM5	IM6	IM7	IM8	IM9	IM10
$E_{\text{T}}^{\text{miss}}$ [GeV]	>250	>300	>350	>400	>500	>600	>700	>800	>900	>1000
Exclusive (EM)	EM1	EM2	EM3	EM4	EM5	EM6	EM7	EM8	EM9	EM10
$E_{\text{T}}^{\text{miss}}$ [GeV]	250–300	300–350	350–400	400–500	500–600	600–700	700–800	800–900	900–1000	>1000

CR1μ0b





CR1μb

Results

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Dominant shape fit uncertainties (total 2-7%):

- muons 2-5%
- electrons 1-3%
- jets/MET 1-6%
- V+jets theoretical 1-7%

No significance excesses are observed.

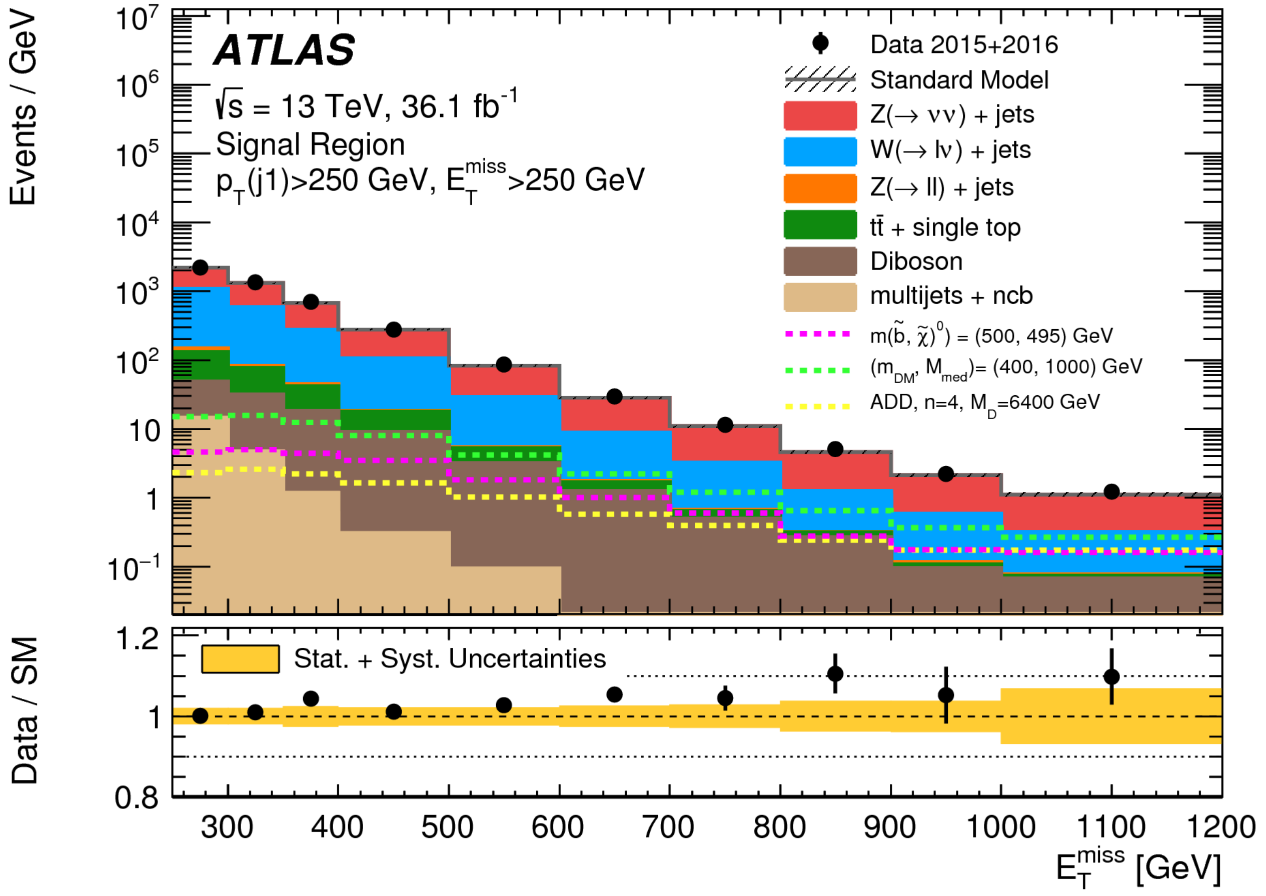
→ Interpret results as limits

Exclusive Signal Region		
Region	Predicted	Observed
EM1	111100 ± 2300	111203
EM2	67100 ± 1400	67475
EM3	33820 ± 940	35285
EM4	27640 ± 610	27843
EM5	8360 ± 190	8583
EM6	2825 ± 78	2975
EM7	1094 ± 33	1142
EM8	463 ± 19	512
EM9	213 ± 9	223
EM10	226 ± 16	245

2%

7%

Selection	$\langle\sigma\rangle_{\text{obs}}^{95}$ [fb]	S_{obs}^{95}	S_{exp}^{95}
IM1	531	19135	11700^{+4400}_{-3300}
IM2	330	11903	7000^{+2600}_{-2600}
IM3	188	6771	4000^{+1400}_{-1100}
IM4	93	3344	2100^{+770}_{-590}
IM5	43	1546	770^{+280}_{-220}
IM6	19	696	360^{+130}_{-100}
IM7	7.7	276	204^{+74}_{-57}
IM8	4.9	178	126^{+47}_{-35}
IM9	2.2	79	76^{+29}_{-21}
IM10	1.6	59	56^{+21}_{-16}



Axial-vector interpretation

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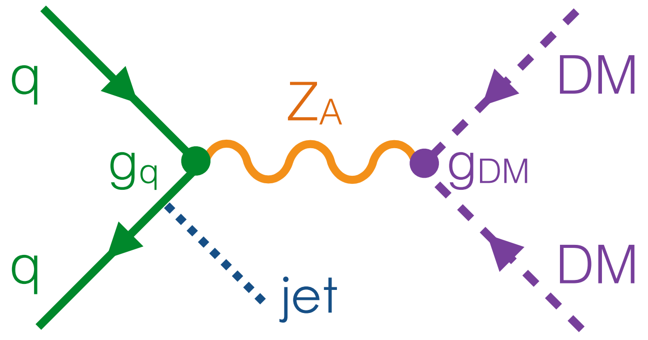
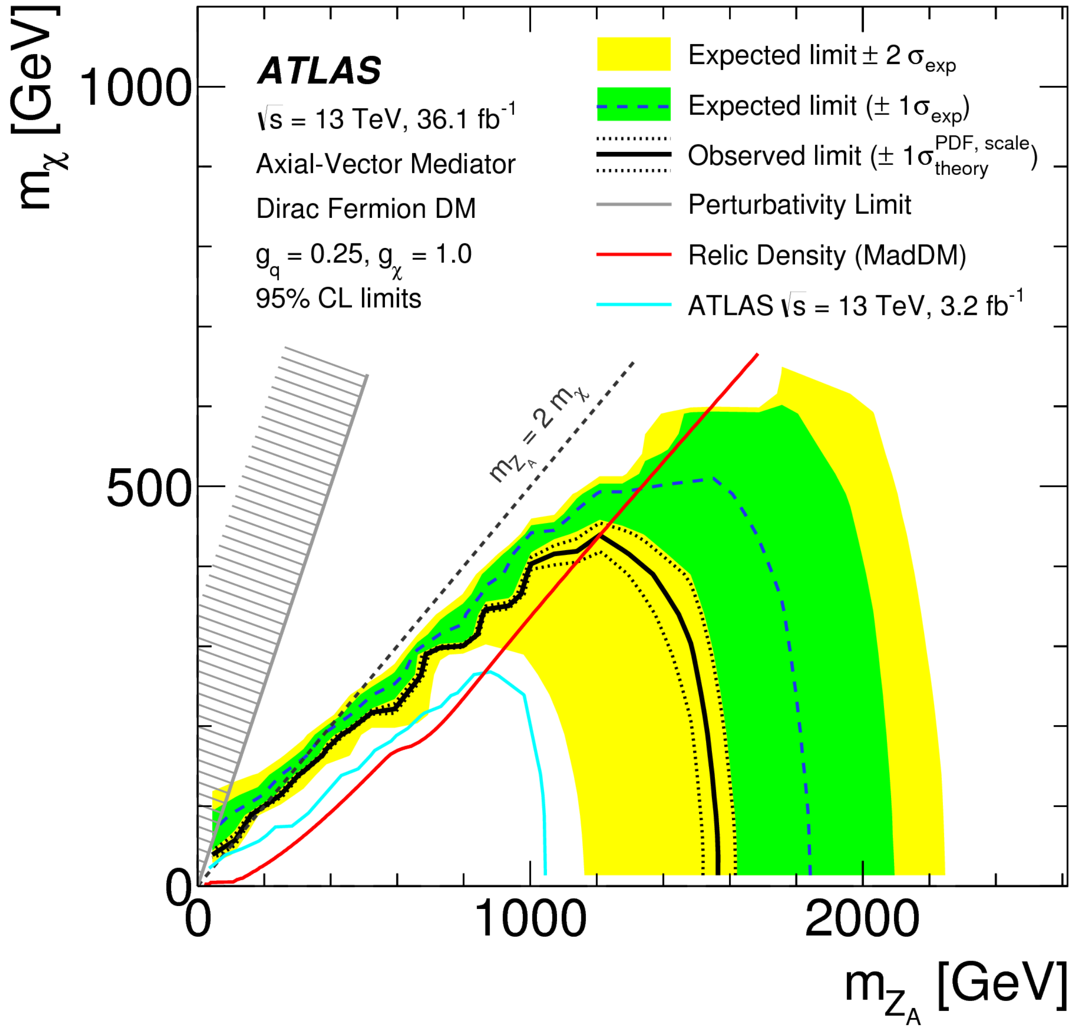
Results interpretation:

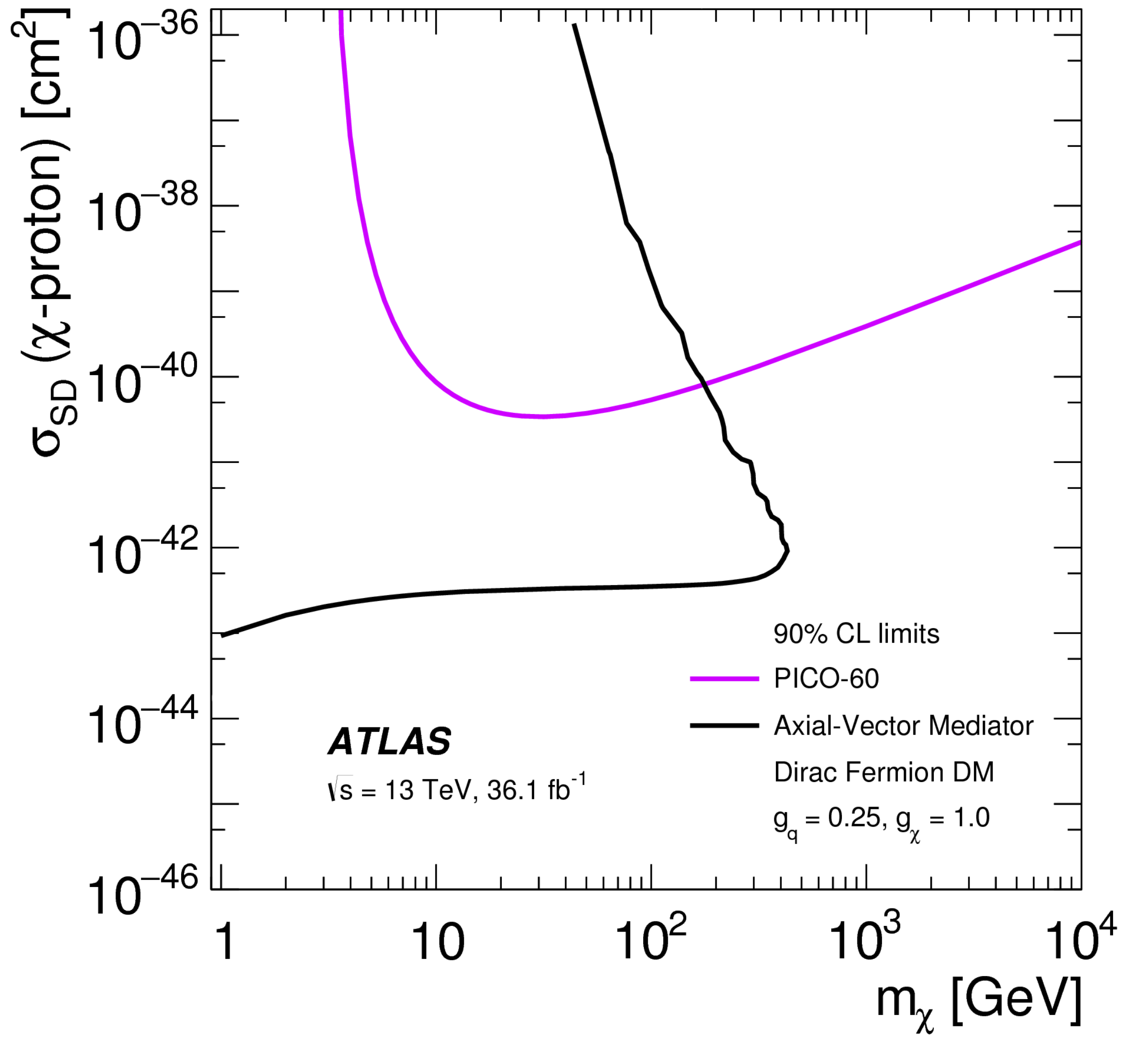
axial vector mediator, g_q=0.25, g_{DM}=1

(as recommended by the LHC Dark Matter Working group arXiv:1603.04156)





Contour Limit in the 2D plane
DM vs Mediator mass



Limit on DM-proton scattering
cross-section.

ATLAS limit gives complementary results wrt direct detection experiments

Axial-vector interpretation

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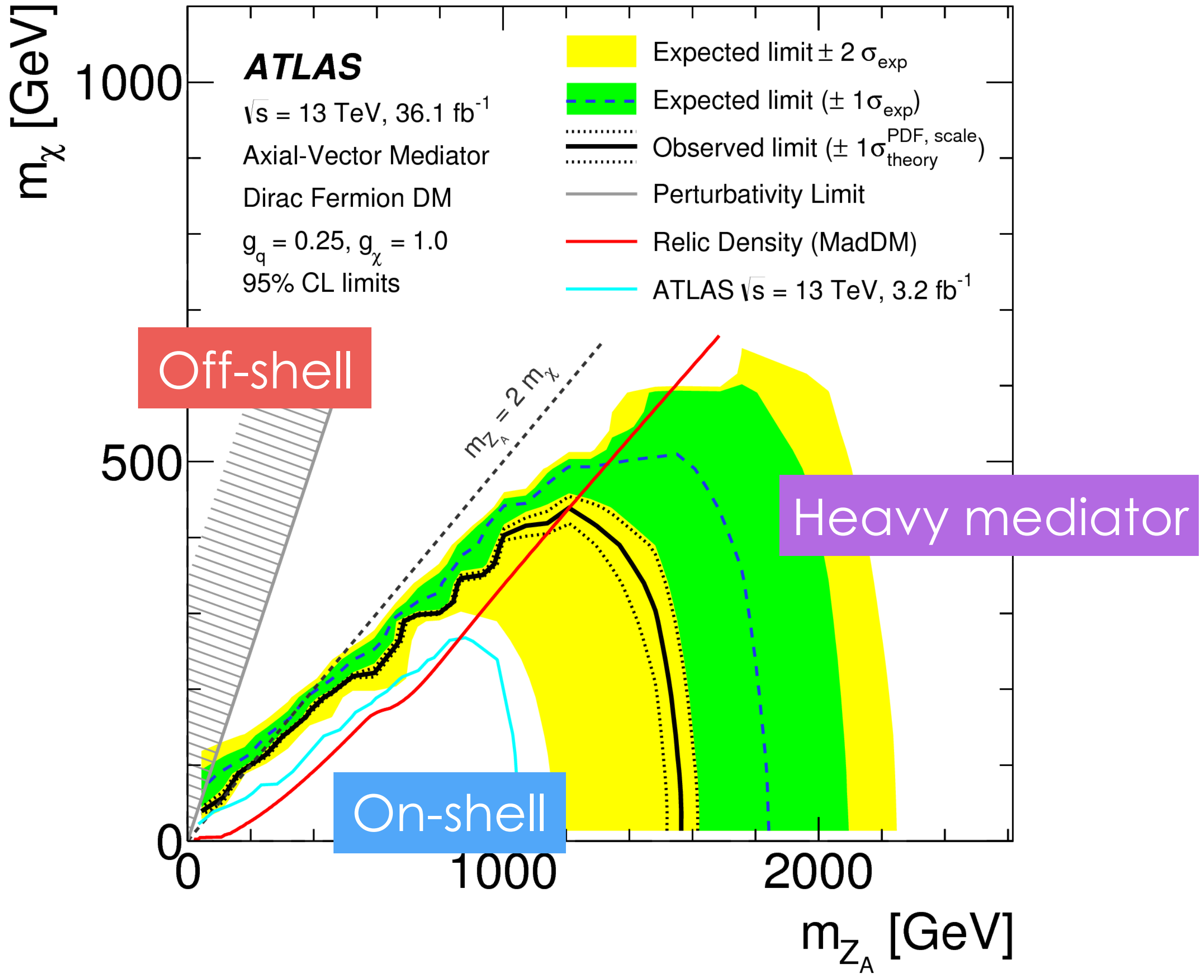
On-shell

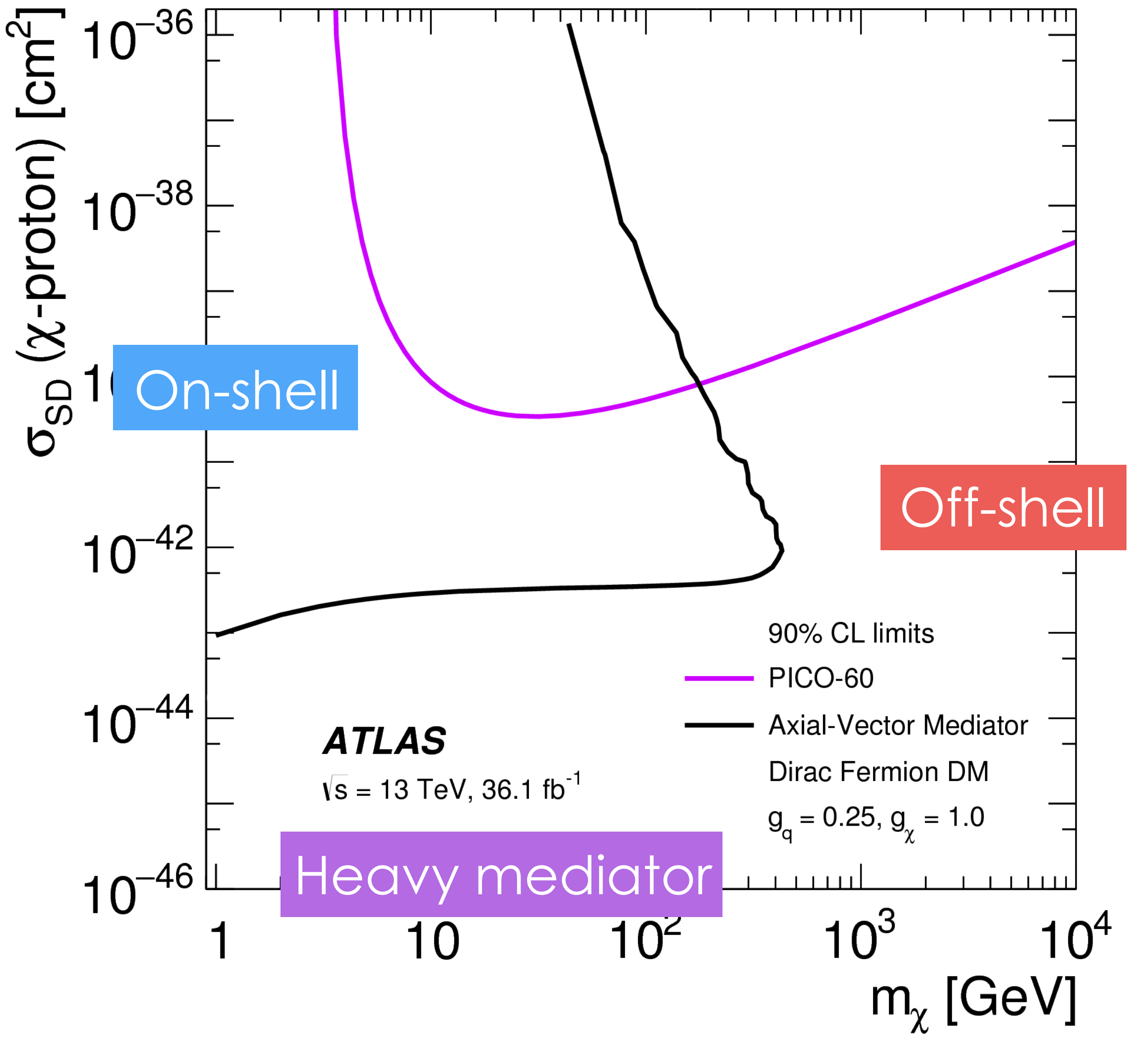
- high xsecs
- LHC exclusion



Off-shell

Heavy mediator

On-shell



On-shell

Off-shell

Heavy mediator

Off-shell

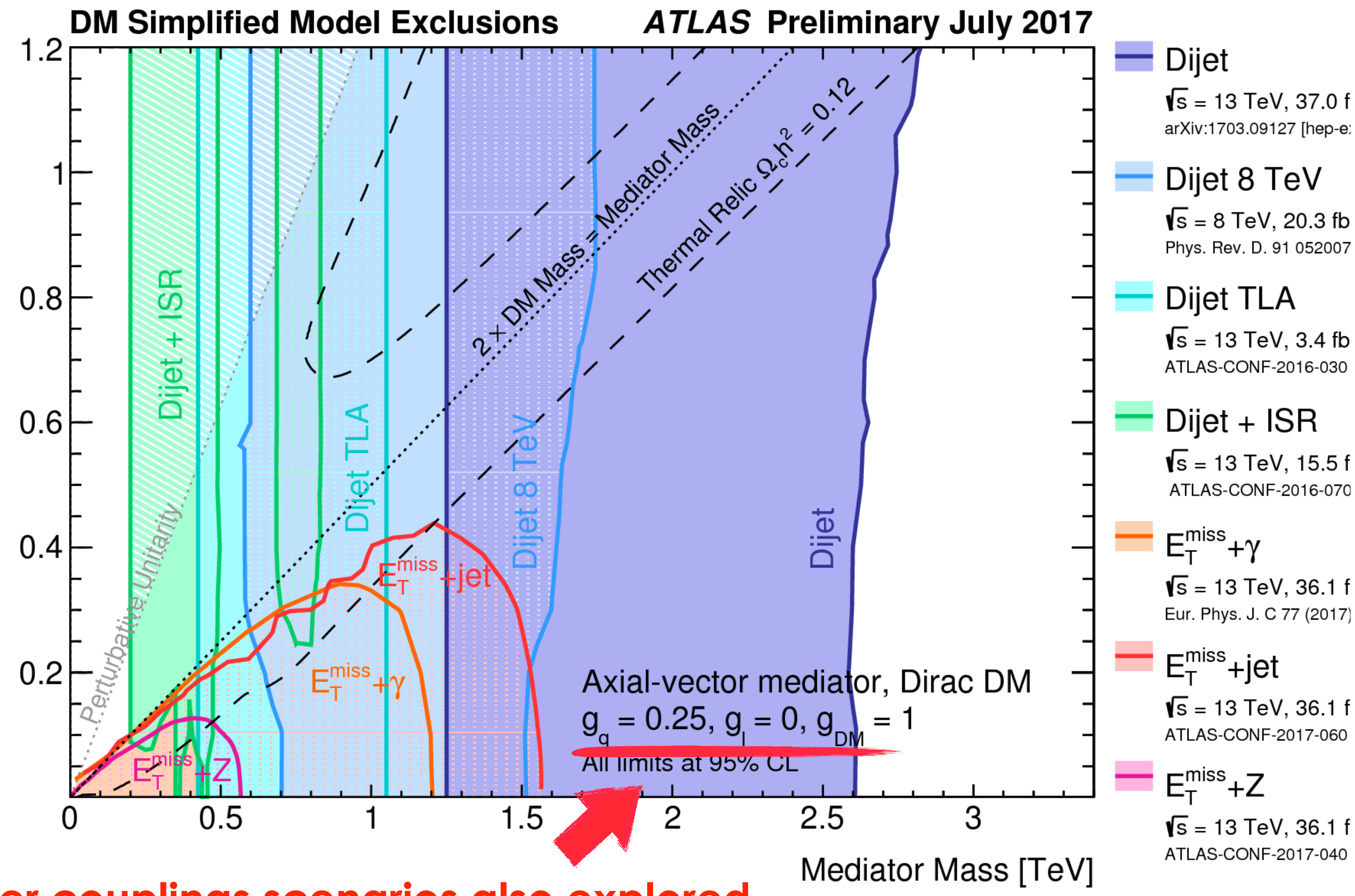
- low xsec
- relic DM underproduced

Heavy mediator

- production suppressed ($\sigma_{SD} \sim M_{med}^{-4}$)
- relic DM overproduced

Summary plot

see also S. Malik's talk



other couplings scenarios also explored

Other interpretations

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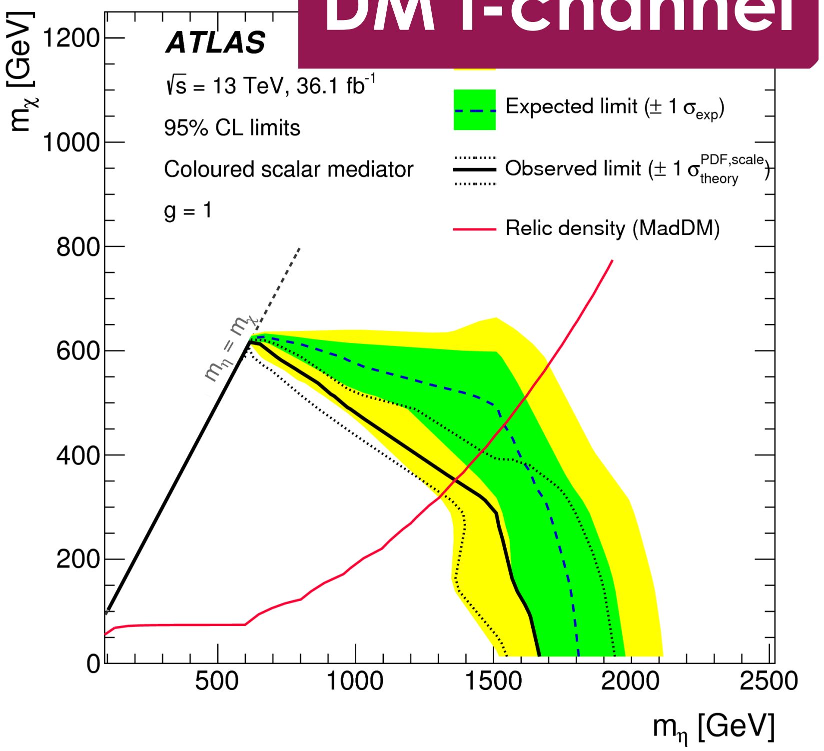
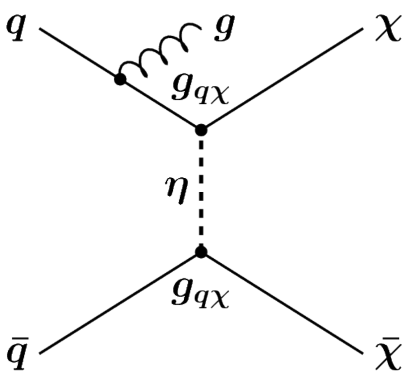
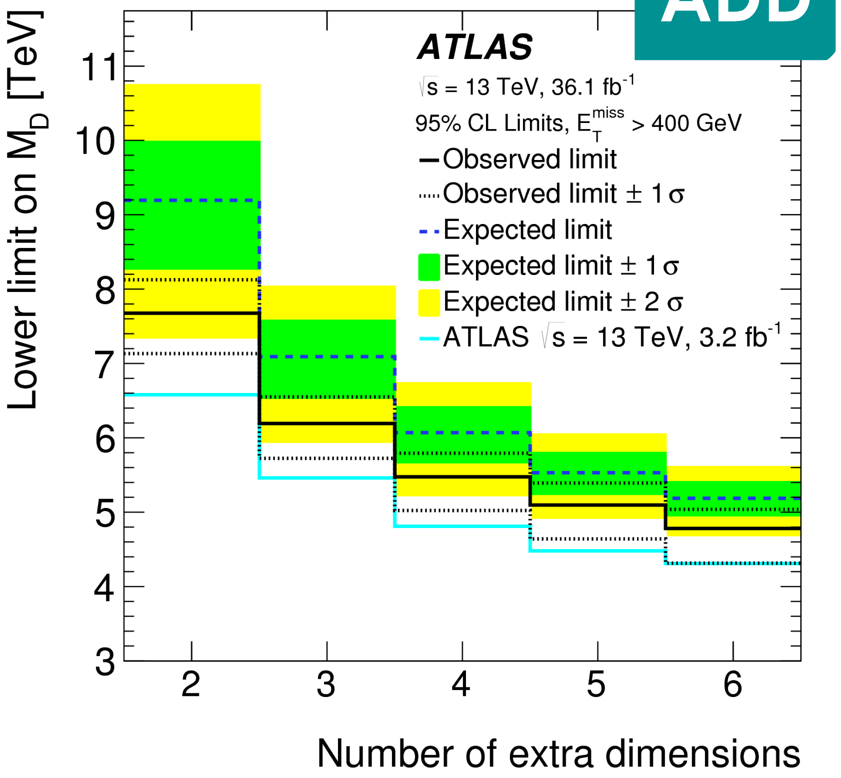
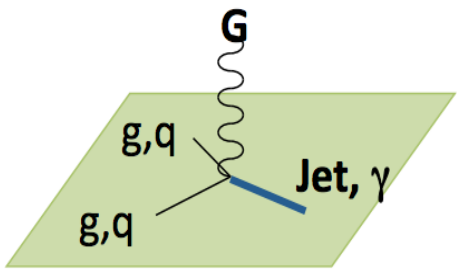
DM t-channel



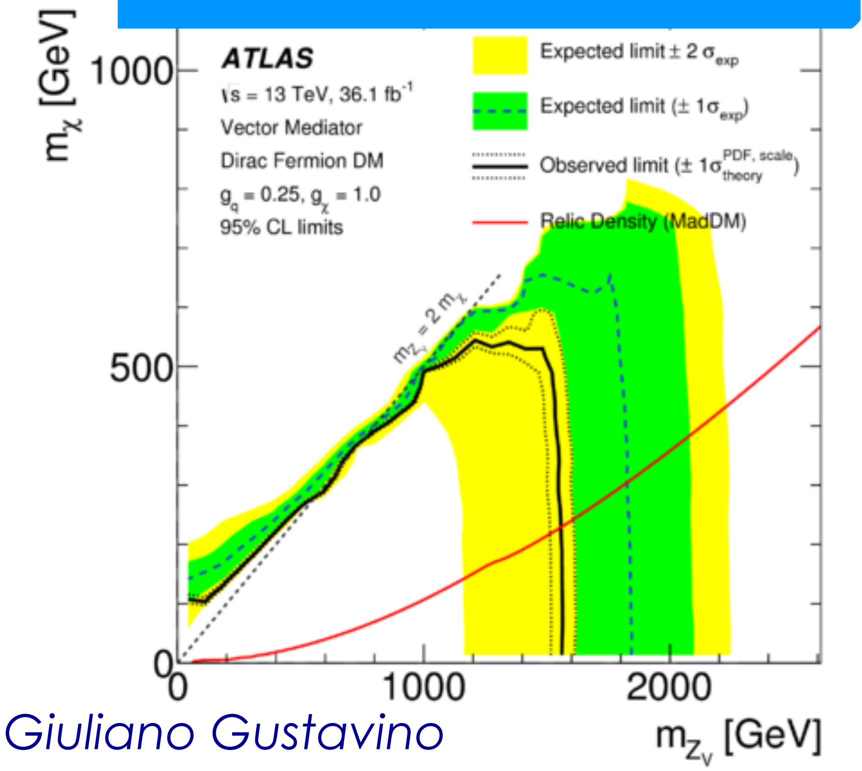


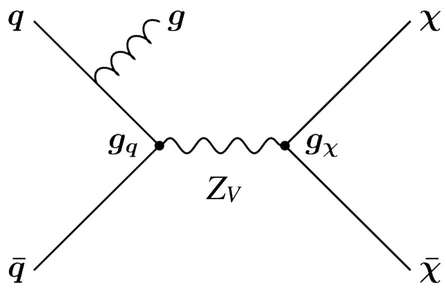
ADD



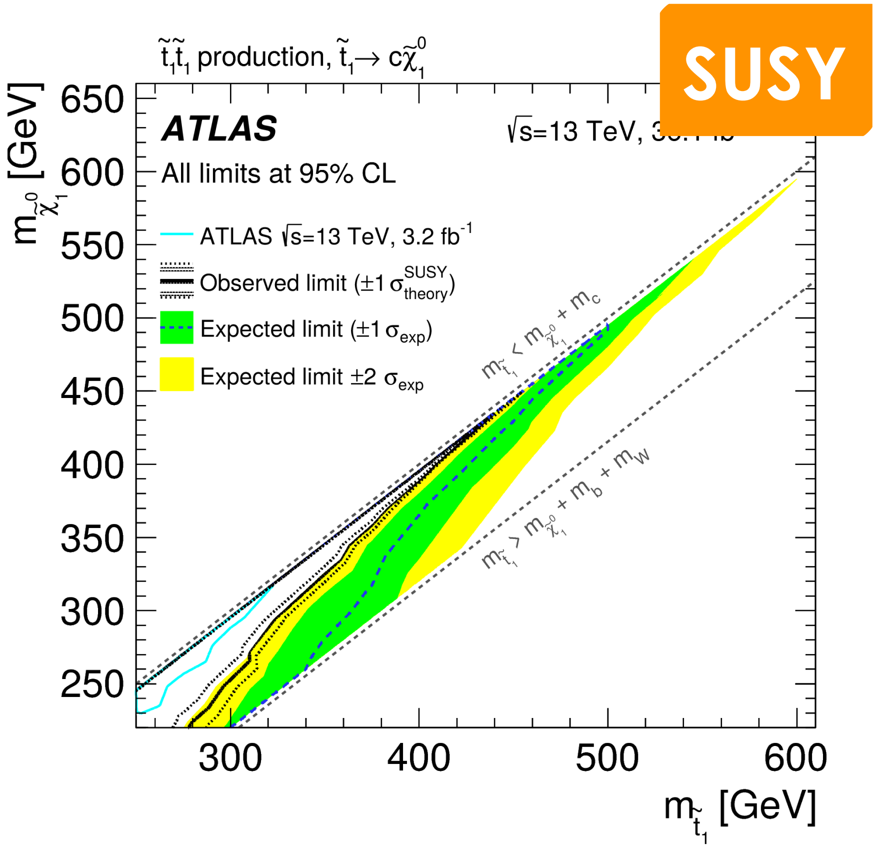


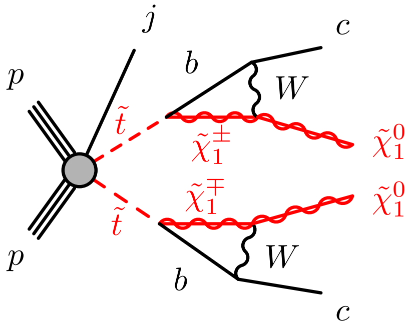
DM vector mediator





SUSY





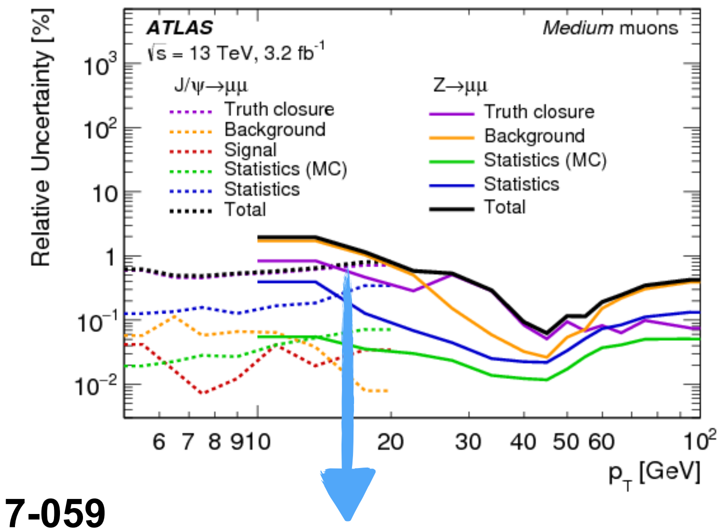
E. Rossi's talk

Thoughts for the future

Experimental improvements challenging:

- reduce background in SR
  - hadronic tau veto
    - reduce the second leading background in the signal region
- reduce the background uncertainty
  - reduce the lepton systematic uncertainties
    - have the major impact on the final background estimation
  - photon control region introduction
    - probe the higher MET spectrum
- other sensitivity enhancements
  - decrease the leading jet and MET threshold
    - probe softer MET spectrum
  - multidimensional fits

Eur.Phys.J. C76 (2016) no.5, 292



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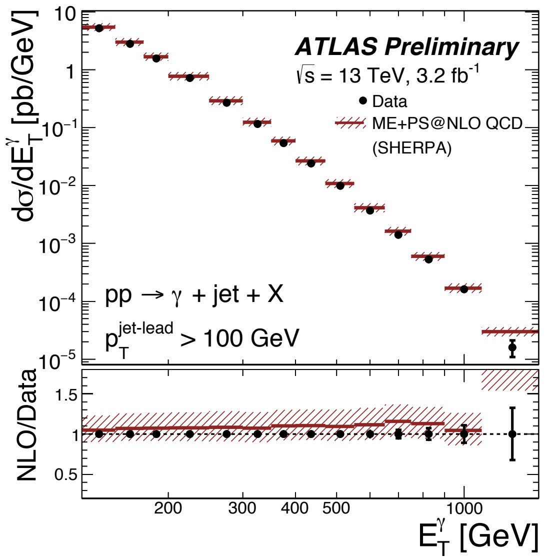
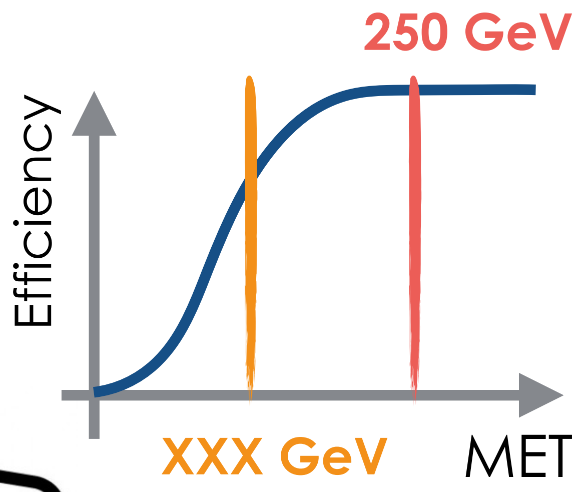
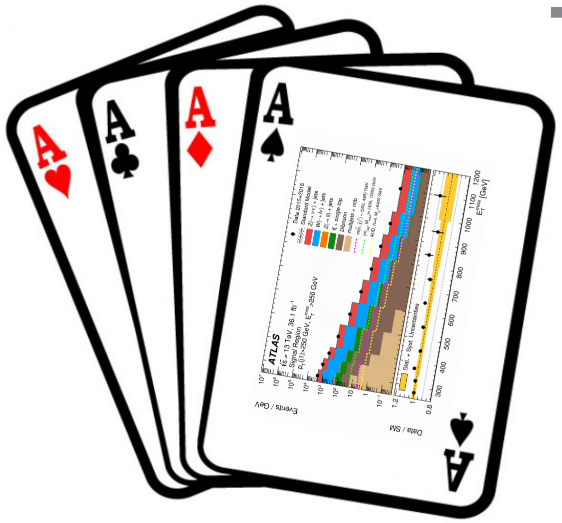


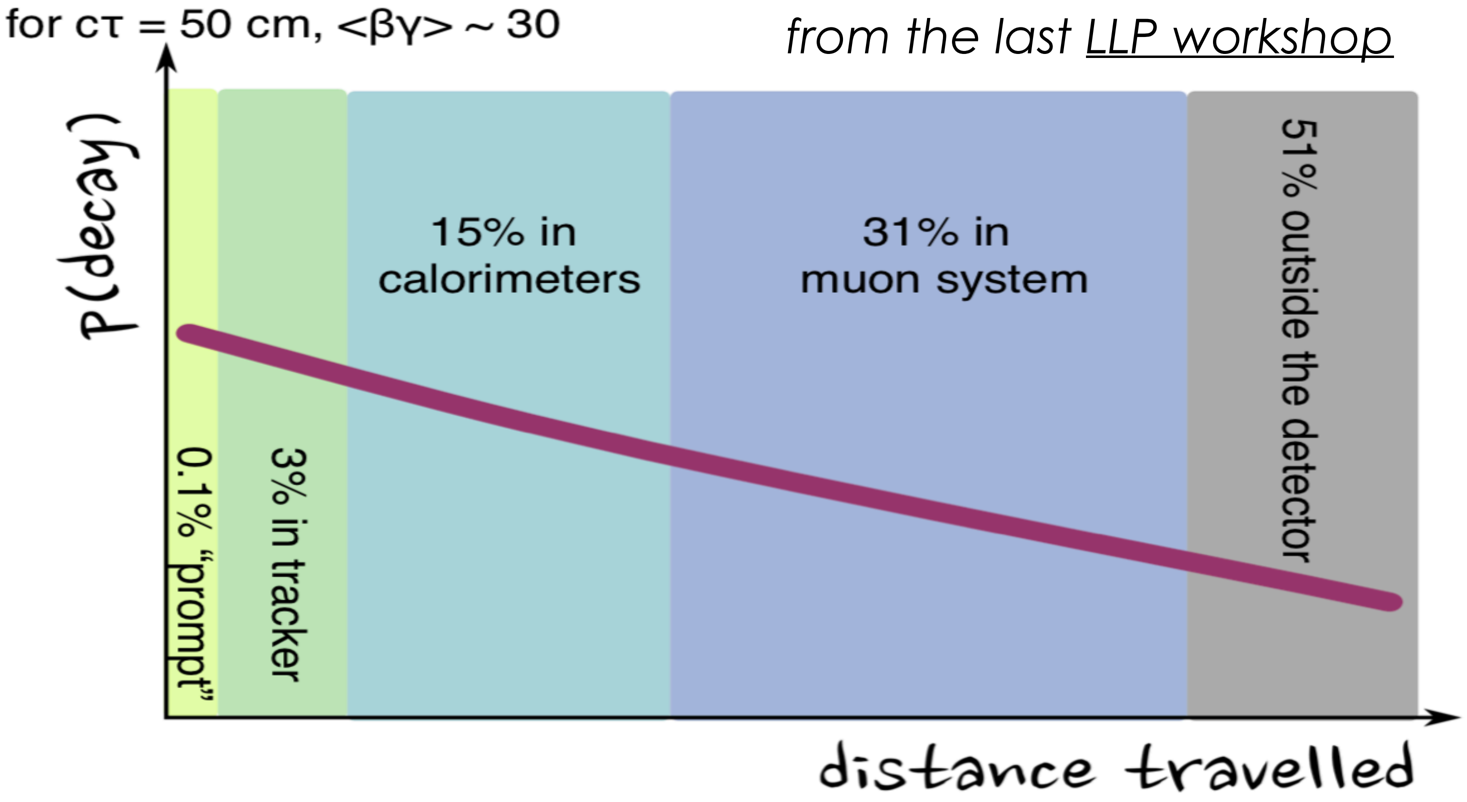




Expand our targets

Exploit the simplicity and the inclusivility of the MET+jet channel

- every new physics model which predicts something invisible to the detector or sufficiently long-lived particles provides a mono-jet signature
- more complex Dark Matter models (e.g. JHEP 1705 (2017) 138 *G. Polesello's talk*)
- Higgs invisible decays (*C. Ohm's talk*)
- Dark Energy (Phys. Rev. D94 (2016) 084054)
- BSM higgs decays in displaced jets (*many talks*)



from the last LLP workshop

Conclusions

MET+jets analysis plays a leading role in the BSM searches in ATLAS.

MET+jets vs ALL

The harmonisation between most of the analyses using a common set of simplified models allows to compare easily:

- mono-X and dijet searches;
- collider, direct and indirect detection experiment's results;
- particle physics and cosmological limits.

What next?

New data collection allows to probe more boosted regimes still unexplored.

New ideas and new strategies to increase the discovery potential.

Not only a Dark Matter search!

Dark Matter → Dark Sector

Backup Slides

Baseline selection

Baseline: overlap removal, lepton veto

Good: final selection

	Baseline	Good
Jets	p_T >30 GeV $\|\eta\| < 2.8$ JVT cut, jet cleaning	$p_T > 30$ GeV tight cleaning on leading jet
Electrons	$E_T > 20$ GeV $\|\eta\| < 2.47$ LooseLLH	$\|d_0/\sigma_{d_0}\| < 5, \|z_0 \sin\theta\| < 0.5$ mm TightLLH MediumLLH for $p_T > 300$ GeV tight isolation
Muons	$p_T > 10$ GeV $\|\eta\| < 2.5$ Combined, medium	$\|d_0/\sigma_{d_0}\| < 3$ $\|z_0 \sin\theta\| < 0.5$ mm

MET: baseline objects, TST, e/μ invisible (depending on CR)

b-tagging: MV2c10, 60% WP (85% WP in OR)

Non-collision bkg (NCB)

The mono-jet signature is dominated by the **non-collision background** (NCB):
beam-induced backgrounds & **cosmic muons**

Jet identification optimized to perform a

- high NCB rejection
- good jet selection efficiency

by using:

- Frac Sampling Max (f_{max})
  Maximum energy fraction deposited in a single layer of the calorimeter
- Charge Fraction (f_{CH})
  Scalar sum of the p_T of tracks associated with the jet divided by the jet p_T

After applying the jet cleaning the NCB consists of only the 0.5% of the total bkg in the SR

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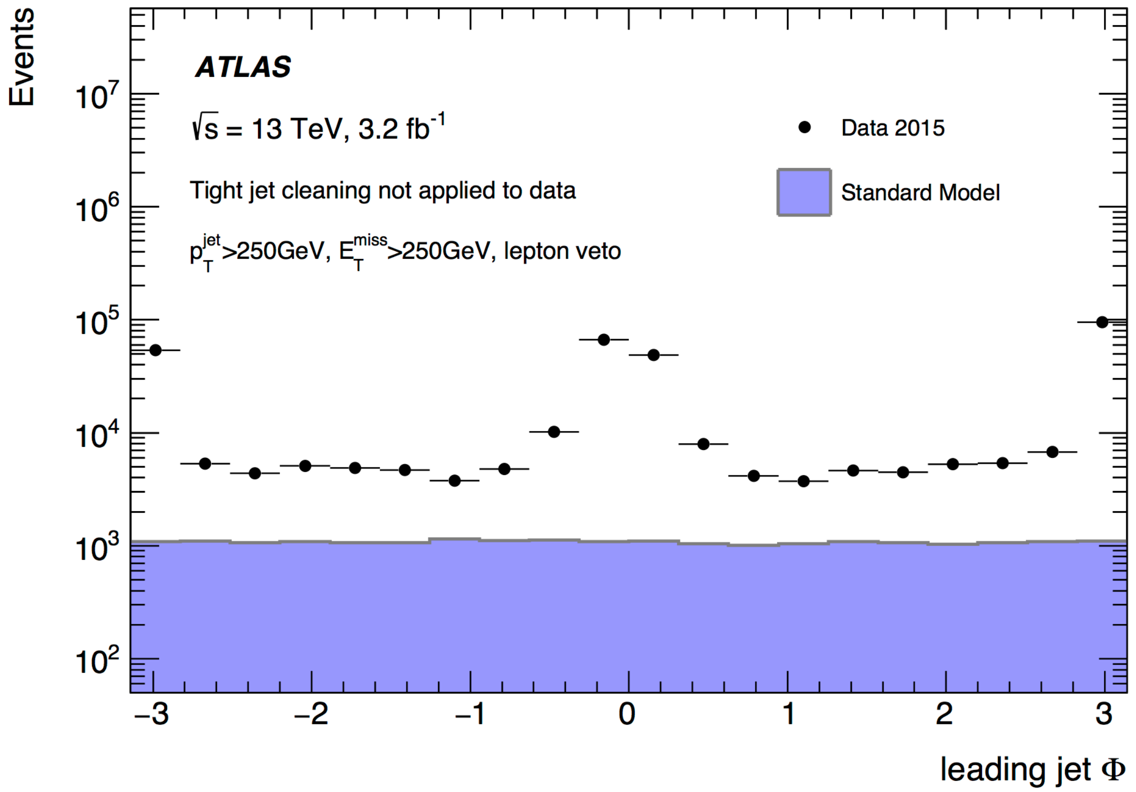


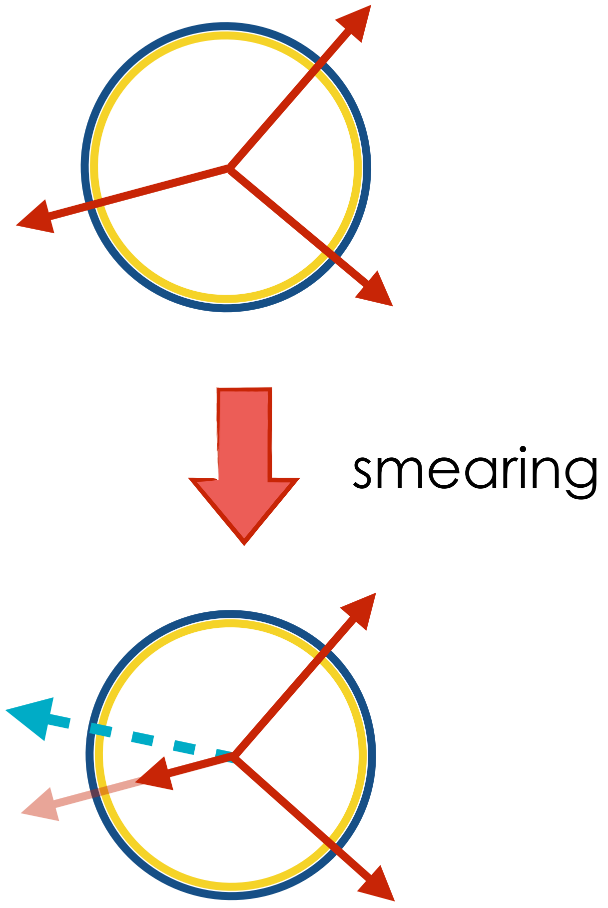
Multi-jet bkg

Coming from QCD processes (high cross sections)

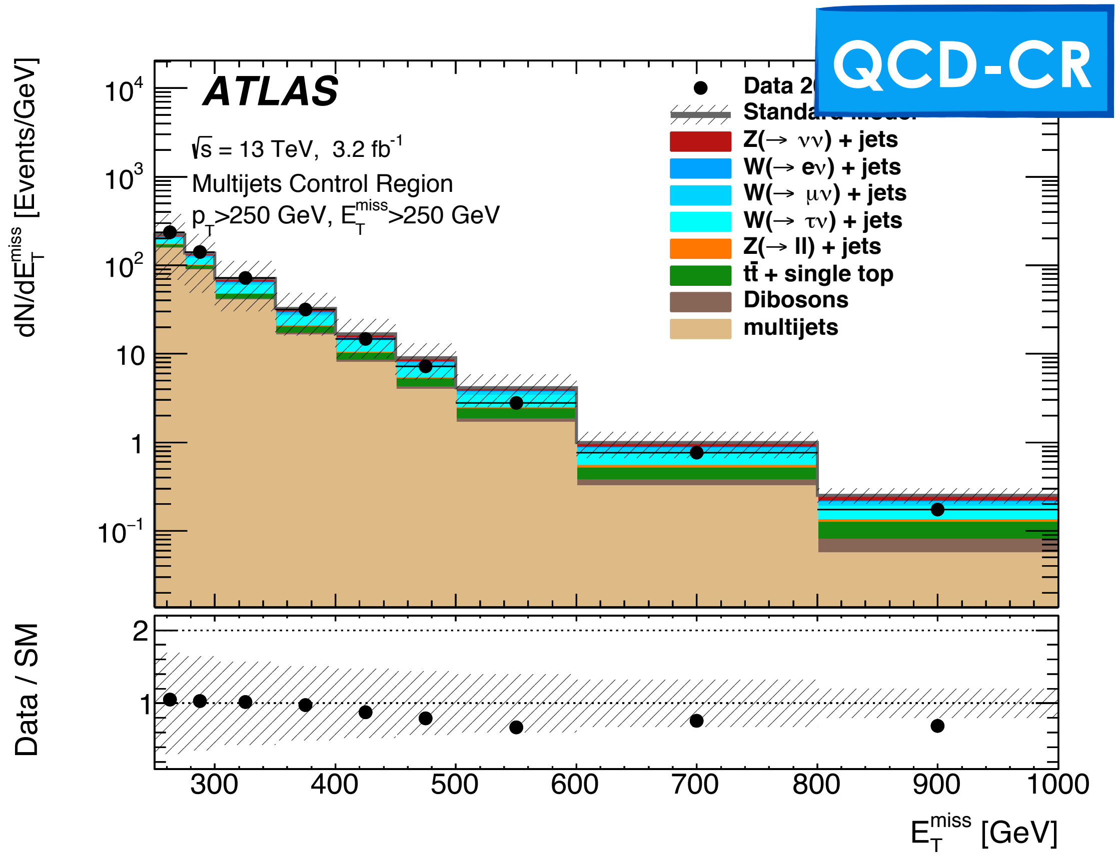
MET arising from misreconstructed jets.

Jet smearing method adopted to estimate the multi-jet bkg:

- Select sample of multi-jet events with *zero*-MET
- Smear these events using the jet response function (creating a new sample with high statistics)
- Normalize the multi-jet bkg from CR defined by inverting the $\Delta\varphi$(jets,MET) cut



The multi-jet bkg evaluated in the SR is of about the 0.2% of the total



Bkg-only fit on CRs

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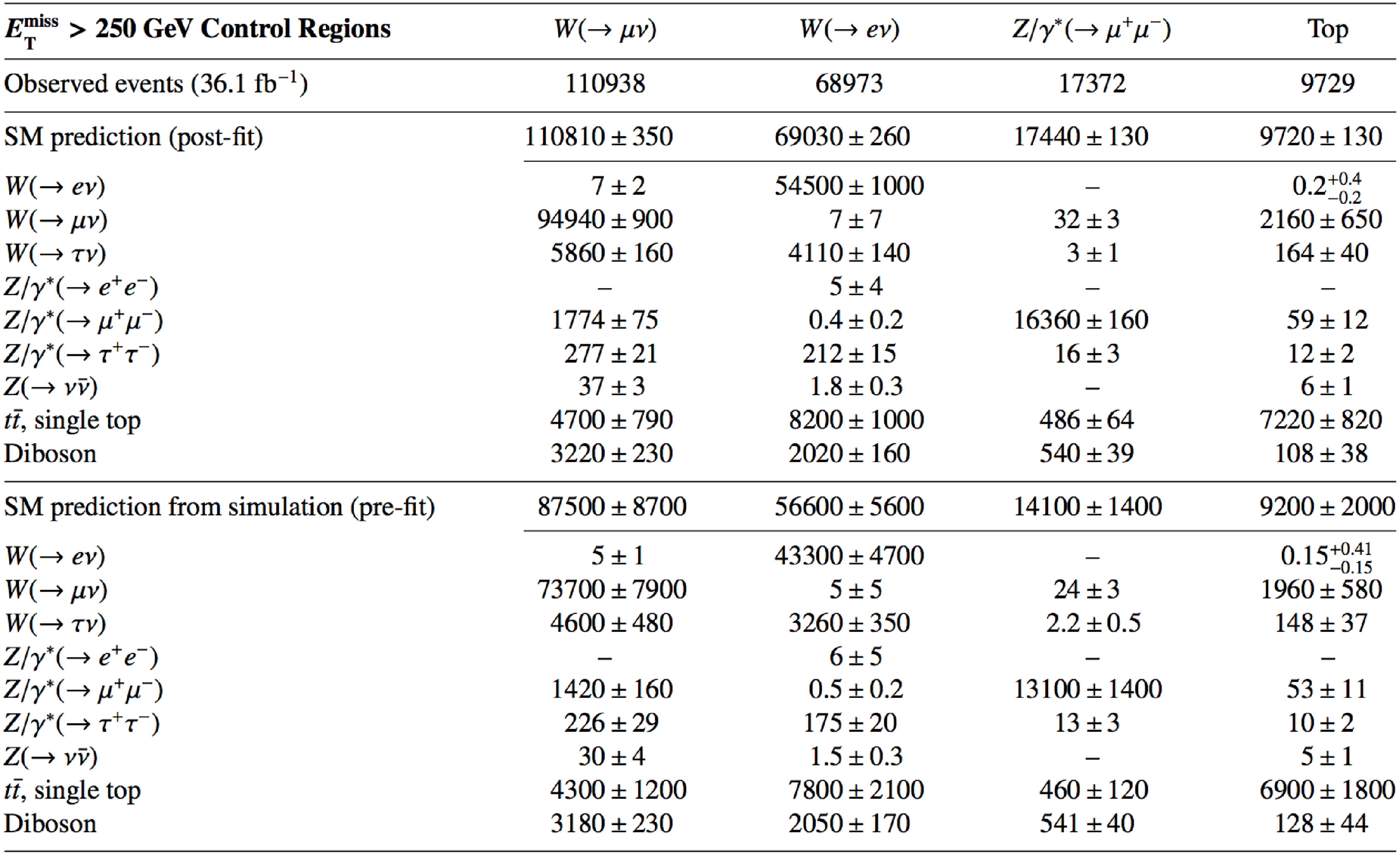

$E_{\mathrm{T}}^{\mathrm{miss}} > 250$ GeV Control Regions	$W(\to \mu\nu)$	$W(\to e\nu)$	$Z/\gamma^*(\to \mu^+\mu^-)$	Top
Observed events (36.1 fb^{-1})	110938	68973	17372	9729
SM prediction (post-fit)	110810 ± 350	69030 ± 260	17440 ± 130	9720 ± 130
$W(\to e\nu)$	7 ± 2	54500 ± 1000	–	$0.2^{+0.4}_{-0.2}$
$W(\to \mu\nu)$	94940 ± 900	7 ± 7	32 ± 3	2160 ± 650
$W(\to \tau\nu)$	5860 ± 160	4110 ± 140	3 ± 1	164 ± 40
$Z/\gamma^*(\to e^+e^-)$	–	5 ± 4	–	–
$Z/\gamma^*(\to \mu^+\mu^-)$	1774 ± 75	0.4 ± 0.2	16360 ± 160	59 ± 12
$Z/\gamma^*(\to \tau^+\tau^-)$	277 ± 21	212 ± 15	16 ± 3	12 ± 2
$Z(\to \nu\bar{\nu})$	37 ± 3	1.8 ± 0.3	–	6 ± 1
$t\bar{t}$, single top	4700 ± 790	8200 ± 1000	486 ± 64	7220 ± 820
Diboson	3220 ± 230	2020 ± 160	540 ± 39	108 ± 38
SM prediction from simulation (pre-fit)	87500 ± 8700	56600 ± 5600	14100 ± 1400	9200 ± 2000
$W(\to e\nu)$	5 ± 1	43300 ± 4700	–	$0.15^{+0.41}_{-0.15}$
$W(\to \mu\nu)$	73700 ± 7900	5 ± 5	24 ± 3	1960 ± 580
$W(\to \tau\nu)$	4600 ± 480	3260 ± 350	2.2 ± 0.5	148 ± 37
$Z/\gamma^*(\to e^+e^-)$	–	6 ± 5	–	–
$Z/\gamma^*(\to \mu^+\mu^-)$	1420 ± 160	0.5 ± 0.2	13100 ± 1400	53 ± 11
$Z/\gamma^*(\to \tau^+\tau^-)$	226 ± 29	175 ± 20	13 ± 3	10 ± 2
$Z(\to \nu\bar{\nu})$	30 ± 4	1.5 ± 0.3	–	5 ± 1
$t\bar{t}$, single top	4300 ± 1200	7800 ± 2100	460 ± 120	6900 ± 1800
Diboson	3180 ± 230	2050 ± 170	541 ± 40	128 ± 44

Monojet Control Regions

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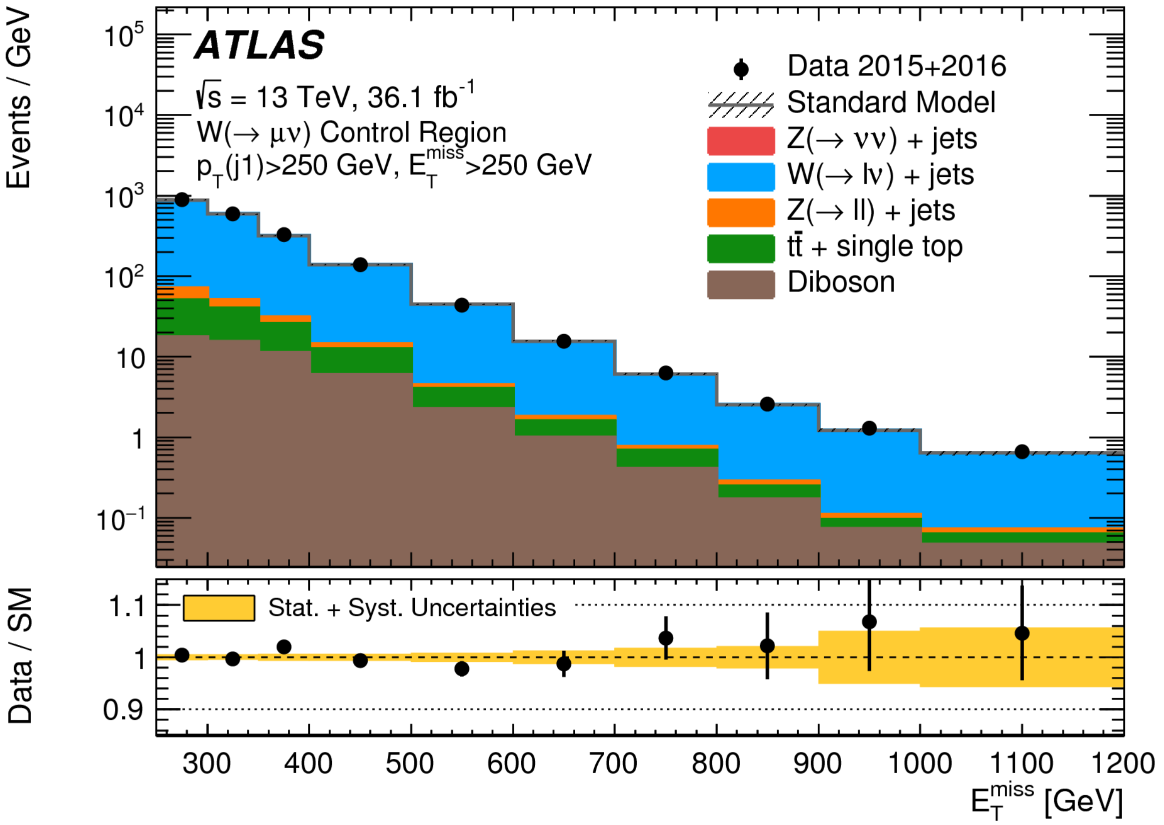

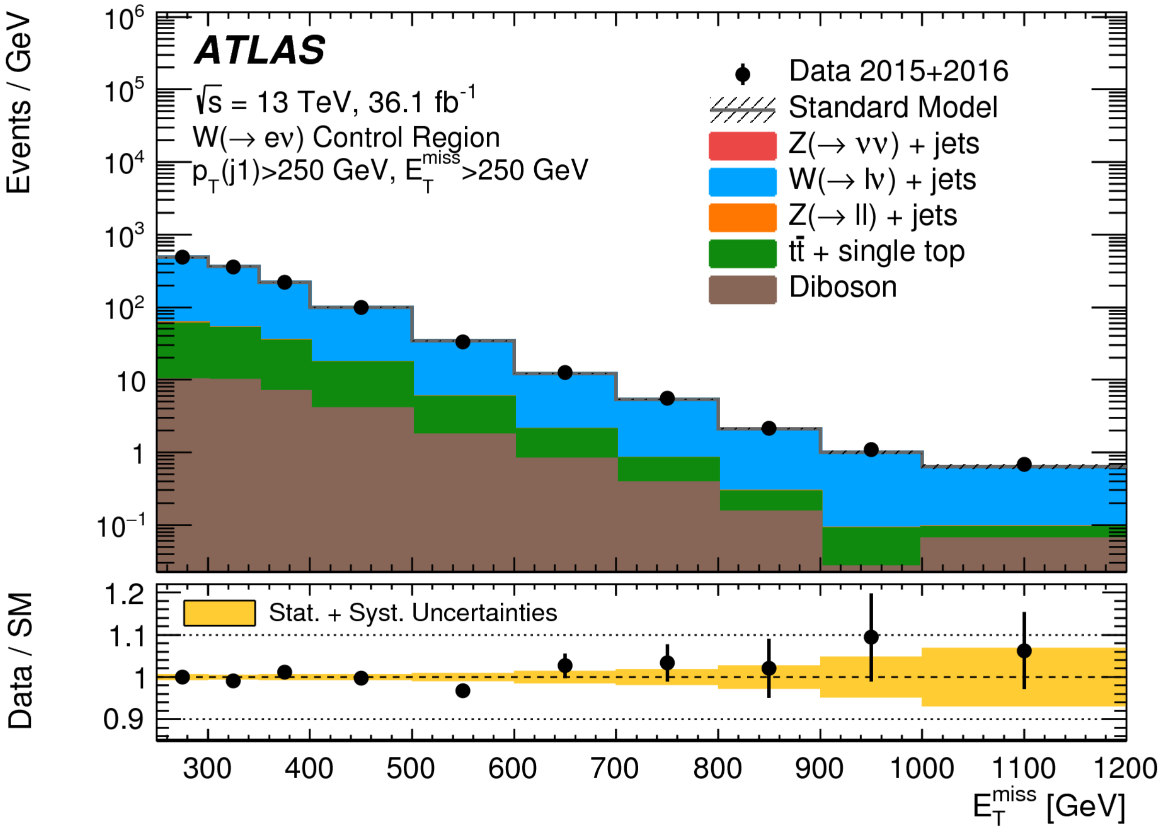

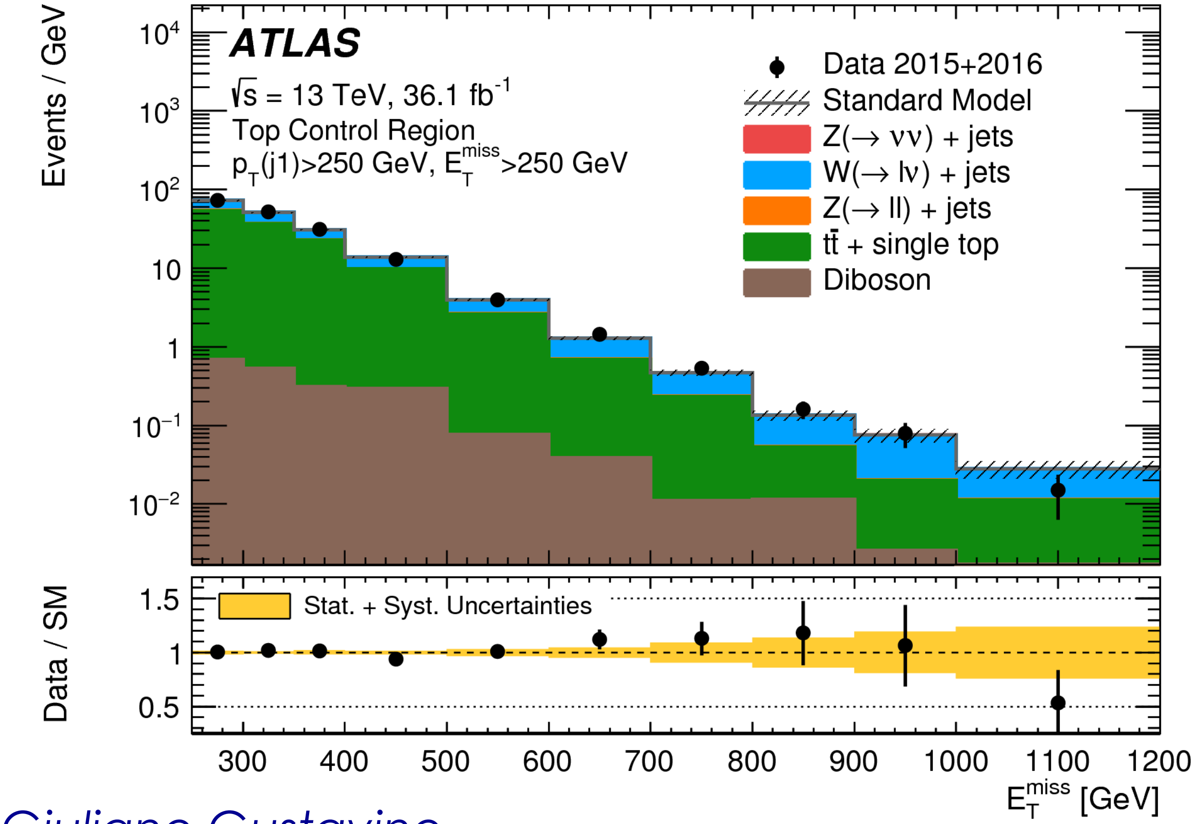

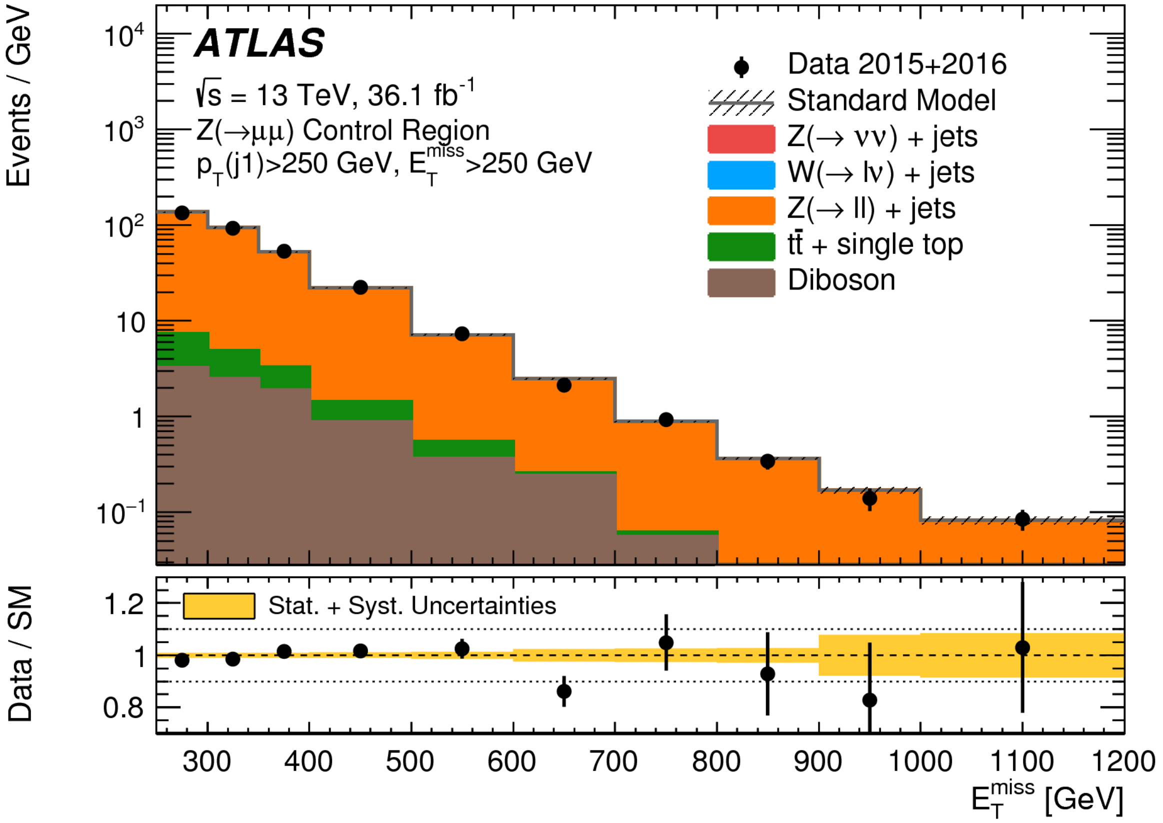

Summary Tables

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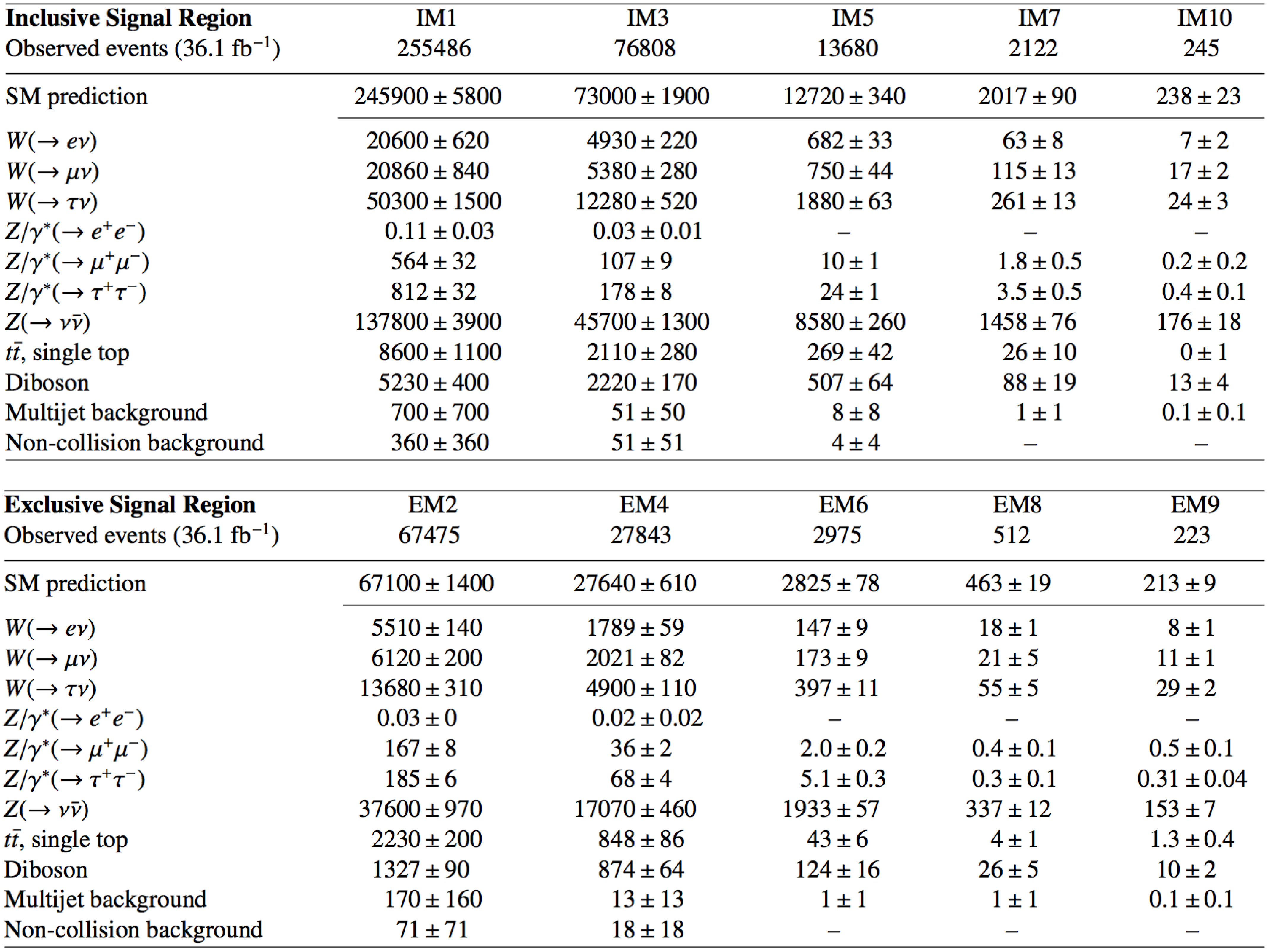

Inclusive Signal Region Observed events (36.1 fb^{-1})	IM1 255486	IM3 76808	IM5 13680	IM7 2122	IM10 245
SM prediction	245900 ± 5800	73000 ± 1900	12720 ± 340	2017 ± 90	238 ± 23
$W(\rightarrow e\nu)$	20600 ± 620	4930 ± 220	682 ± 33	63 ± 8	7 ± 2
$W(\rightarrow \mu\nu)$	20860 ± 840	5380 ± 280	750 ± 44	115 ± 13	17 ± 2
$W(\rightarrow \tau\nu)$	50300 ± 1500	12280 ± 520	1880 ± 63	261 ± 13	24 ± 3
$Z/\gamma^*(\rightarrow e^+e^-)$	0.11 ± 0.03	0.03 ± 0.01	–	–	–
$Z/\gamma^*(\rightarrow \mu^+\mu^-)$	564 ± 32	107 ± 9	10 ± 1	1.8 ± 0.5	0.2 ± 0.2
$Z/\gamma^*(\rightarrow \tau^+\tau^-)$	812 ± 32	178 ± 8	24 ± 1	3.5 ± 0.5	0.4 ± 0.1
$Z(\rightarrow \nu\bar{\nu})$	137800 ± 3900	45700 ± 1300	8580 ± 260	1458 ± 76	176 ± 18
$t\bar{t}$, single top	8600 ± 1100	2110 ± 280	269 ± 42	26 ± 10	0 ± 1
Diboson	5230 ± 400	2220 ± 170	507 ± 64	88 ± 19	13 ± 4
Multijet background	700 ± 700	51 ± 50	8 ± 8	1 ± 1	0.1 ± 0.1
Non-collision background	360 ± 360	51 ± 51	4 ± 4	–	–

Exclusive Signal Region Observed events (36.1 fb^{-1})	EM2 67475	EM4 27843	EM6 2975	EM8 512	EM9 223
SM prediction	67100 ± 1400	27640 ± 610	2825 ± 78	463 ± 19	213 ± 9
$W(\rightarrow e\nu)$	5510 ± 140	1789 ± 59	147 ± 9	18 ± 1	8 ± 1
$W(\rightarrow \mu\nu)$	6120 ± 200	2021 ± 82	173 ± 9	21 ± 5	11 ± 1
$W(\rightarrow \tau\nu)$	13680 ± 310	4900 ± 110	397 ± 11	55 ± 5	29 ± 2
$Z/\gamma^*(\rightarrow e^+e^-)$	0.03 ± 0	0.02 ± 0.02	–	–	–
$Z/\gamma^*(\rightarrow \mu^+\mu^-)$	167 ± 8	36 ± 2	2.0 ± 0.2	0.4 ± 0.1	0.5 ± 0.1
$Z/\gamma^*(\rightarrow \tau^+\tau^-)$	185 ± 6	68 ± 4	5.1 ± 0.3	0.3 ± 0.1	0.31 ± 0.04
$Z(\rightarrow \nu\bar{\nu})$	37600 ± 970	17070 ± 460	1933 ± 57	337 ± 12	153 ± 7
$t\bar{t}$, single top	2230 ± 200	848 ± 86	43 ± 6	4 ± 1	1.3 ± 0.4
Diboson	1327 ± 90	874 ± 64	124 ± 16	26 ± 5	10 ± 2
Multijet background	170 ± 160	13 ± 13	1 ± 1	1 ± 1	0.1 ± 0.1
Non-collision background	71 ± 71	18 ± 18	–	–	–

SUSY interpretation

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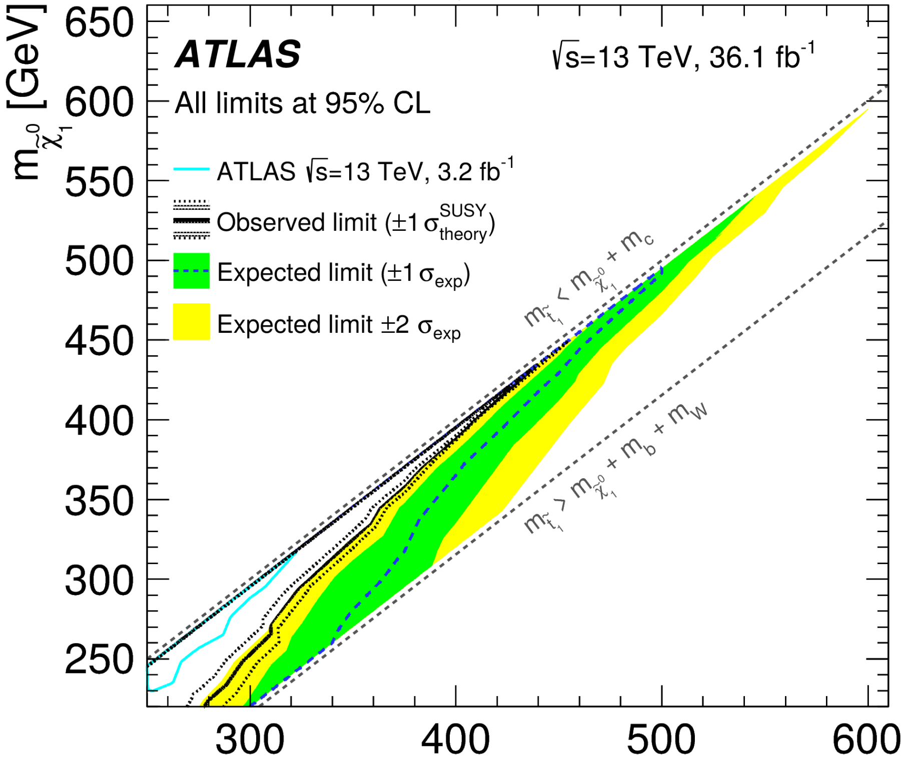
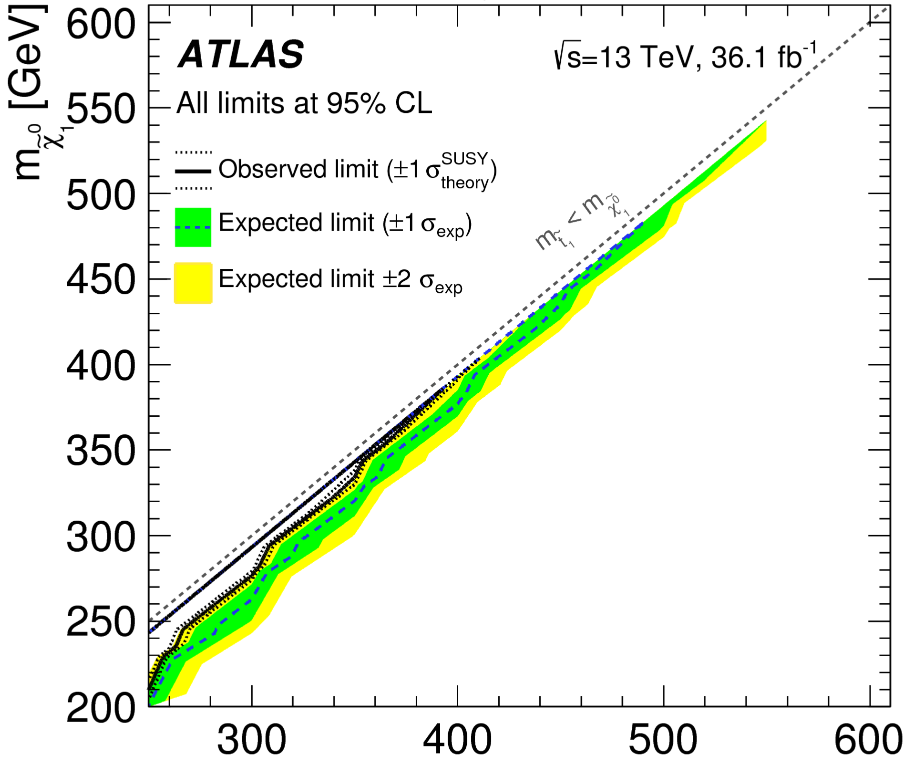
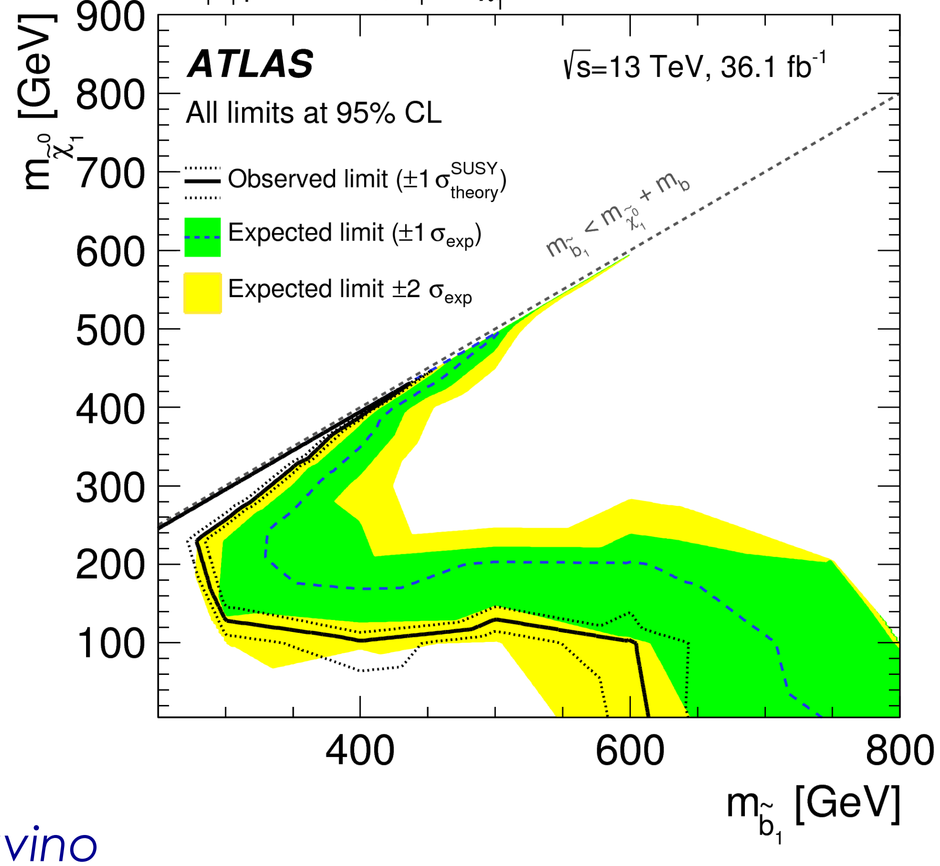
$\tilde{t}_1\tilde{t}_1$ production, $\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$



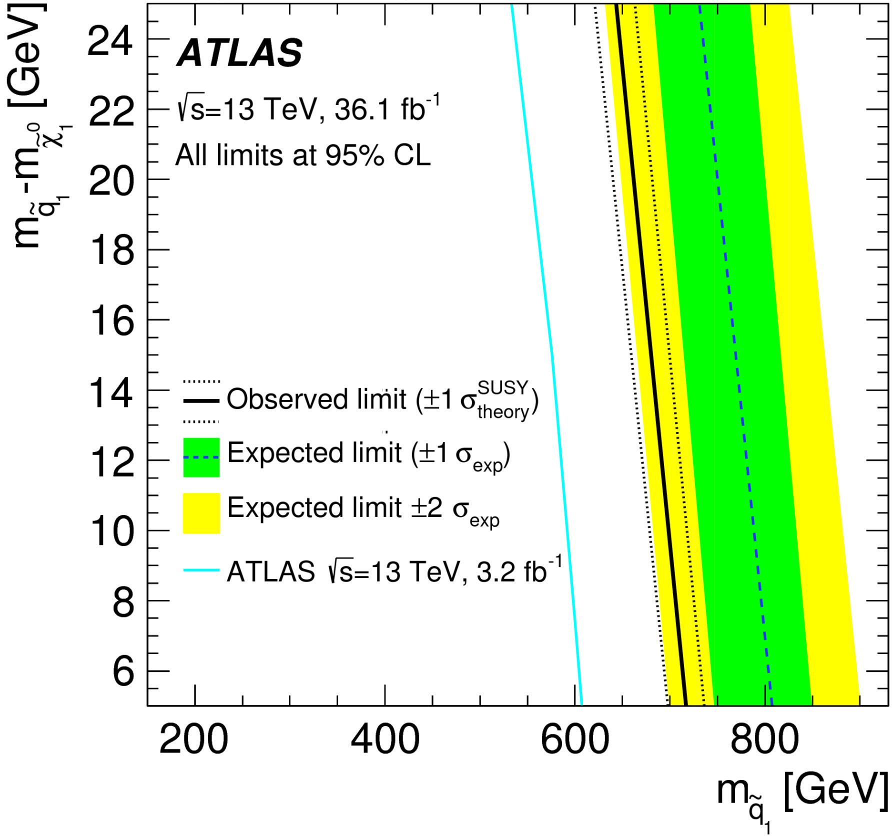
$\tilde{t}_1\tilde{t}_1$ production, $\tilde{t}_1 \rightarrow bff'\tilde{\chi}_1^0$



$\tilde{b}_1\tilde{b}_1$ production, $\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$



$\tilde{q}_1\tilde{q}_1$ production, $\tilde{q}_1 \rightarrow q\tilde{\chi}_1^0$



Pseudo-scalar interpretation

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