Mono-jet searches

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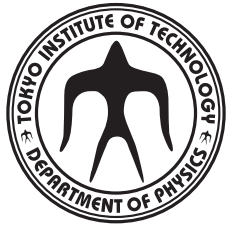
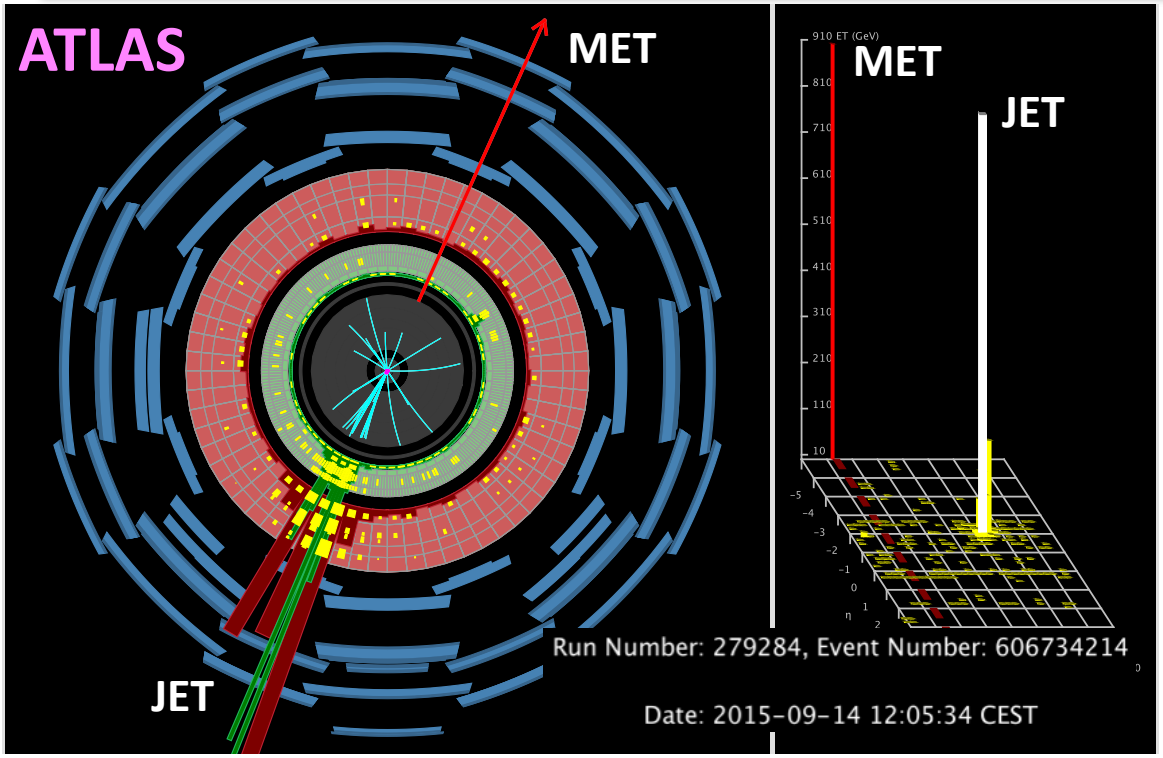
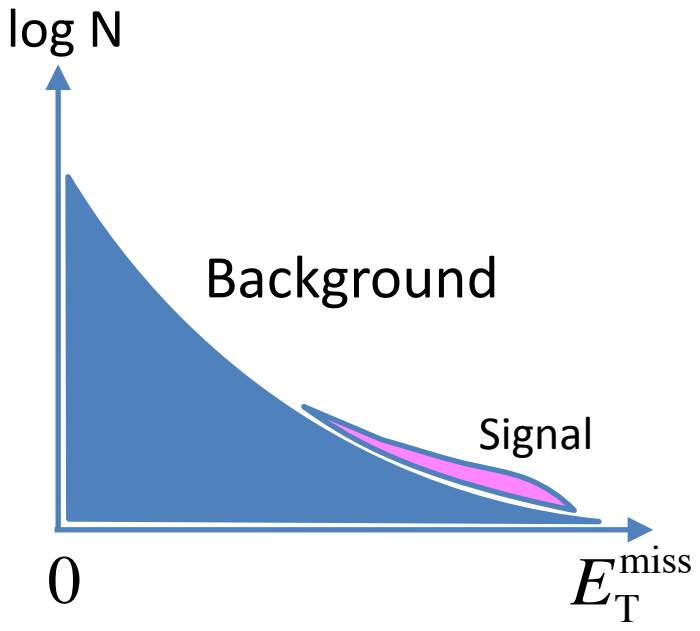


on behalf of ATLAS and CMS Collaborations

2017. 4. 3 DM@LHC2017
University of California Irvine

Mono-jet signature





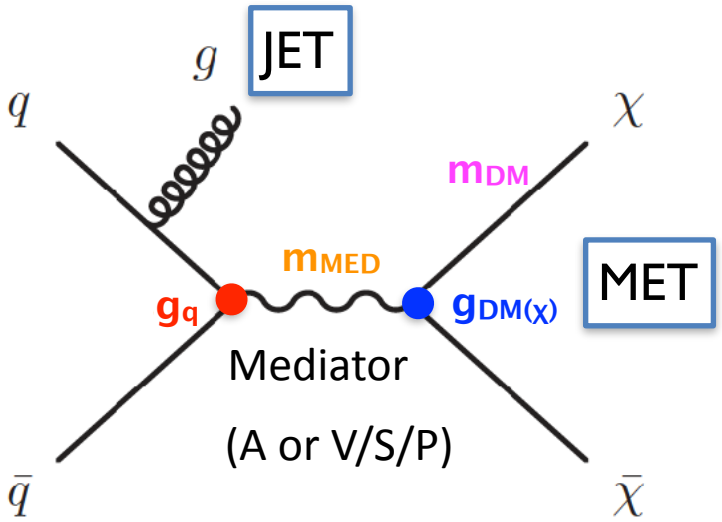
- One of the highest sensitivity signatures for BSM, esp. for DM searches
- Search for (broad) excess in high E_T^{miss} (MET) region
  precise background estimation is vital
  - ATLAS: Phys. Rev. D94 (2016) 032005 13TeV (3.2 fb^{-1} taken in 2015)
  - CMS : PAS EXO-16-037 (submitted to JHEP) 13TeV (12.9 fb^{-1} taken in 2016)

This talk reviews the similarity & difference of the two searches

for mono-V analysis there is a separate paper
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2015-08/

Mono-jet Physics Model for WIMP DM

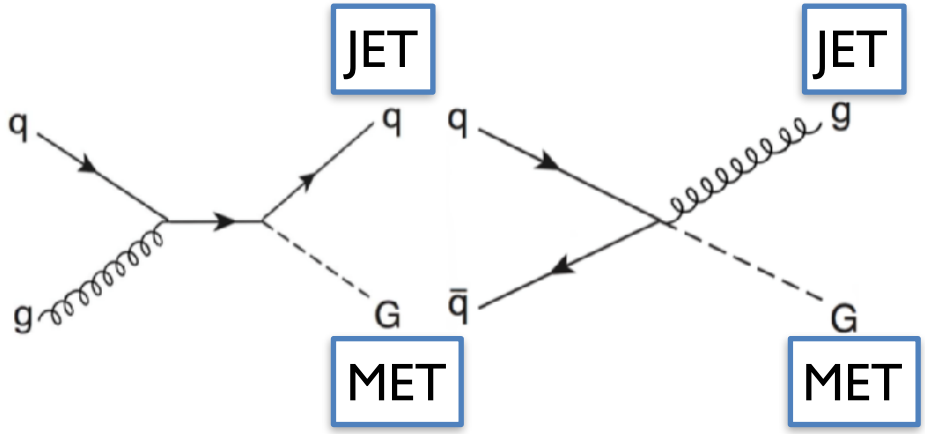
Search for pair produced DM with ISR jet which is used to tag the event



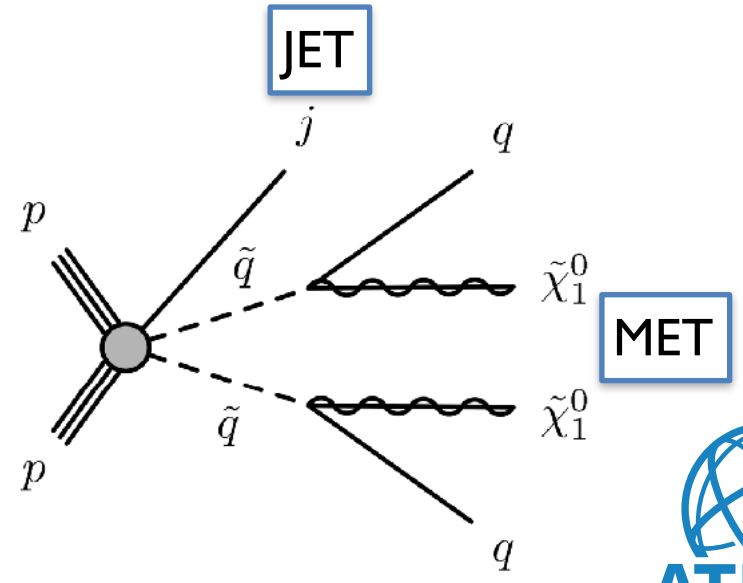
- Both experiments interpret results with Simplified models
  based on the suggestion from DM-Forum/Working Group to harmonize the models
  initial report: https://arxiv.org/abs/1507.00966
  - simplified model described by 4 parameters
    - m_{DM}, m_{MED}, g_q, $g_{DM(\chi)}$
    - minimal mediator width (no other invisible channel)
  - ISR jet + s-channel axial vector mediator (ATLAS)
  - ISR jet + axial-vector/**vector/scalar/pseudo-scalar** mediators (CMS)

Other Physics Model for mono-jet

- **Large Extra dimensions (ADD)**
  - production of KK tower of massive graviton modes
  - escape detection → MET
  - associating with high-p_T jet



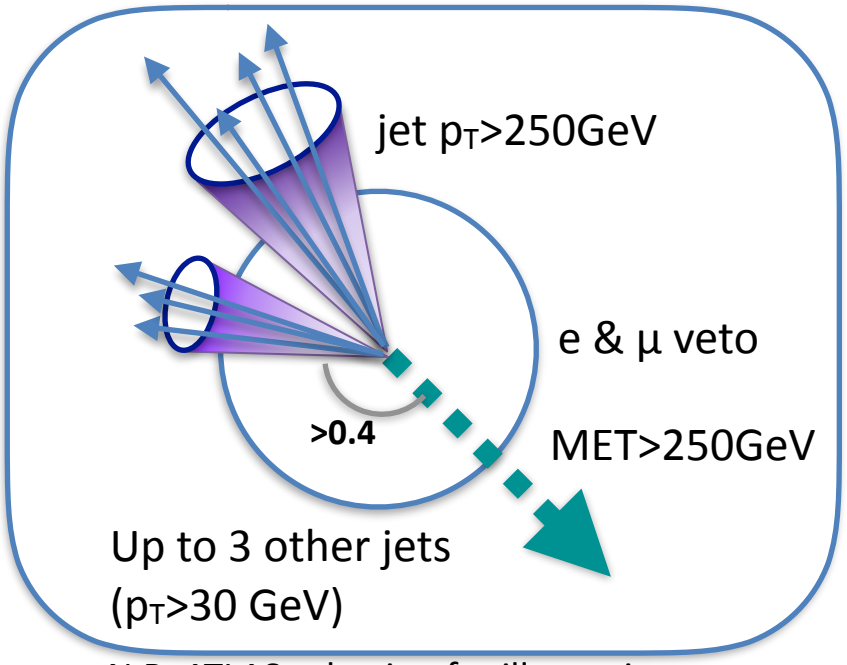
- **Compressed SUSY scenario**
  - squark pair production with relatively small mass gap
  - soft quark jets, MET → hard to detect out of QCD multi-jet BG
  - hard ISR jet + boosted squark pair (large MET)



ATLAS EXPERIMENT

The event selection and backgrounds

Baseline Event Selection Summary



N.B. ATLAS selection for illustration purpose

	ATLAS	CMS
Trigger	E_T^{miss} > 70 GeV	E_T^{miss}, H_T^{miss} >90, 100, 110 GeV
Leading Jet	p_T>250 GeV, |η|<2.4	p_T>100 GeV, |η|<2.5
E_T^{miss}	>250 GeV	>200 GeV
multijet BG rejection	ΔΦ(p_T^{miss}, $jets_{(1,2,3,4)}$) > 0.4 **N_{JETS} (p_T>30 GeV) ≤ 4**	ΔΦ(E_T^{miss}, $jets_{(1,2,3,4)}$) > 0.5 **N_{JETS} could be any**
NCB rejection	Leading jet |η|<2.4 passes tight cleaning	jet energy charged >10%, neutral < 80%

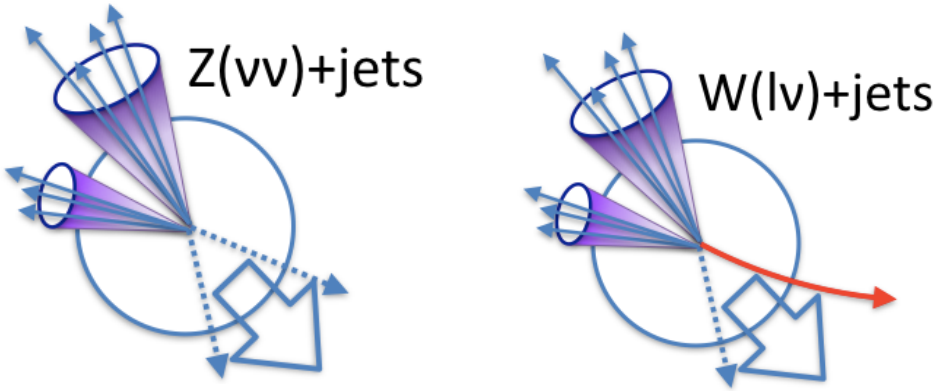
Object definitions

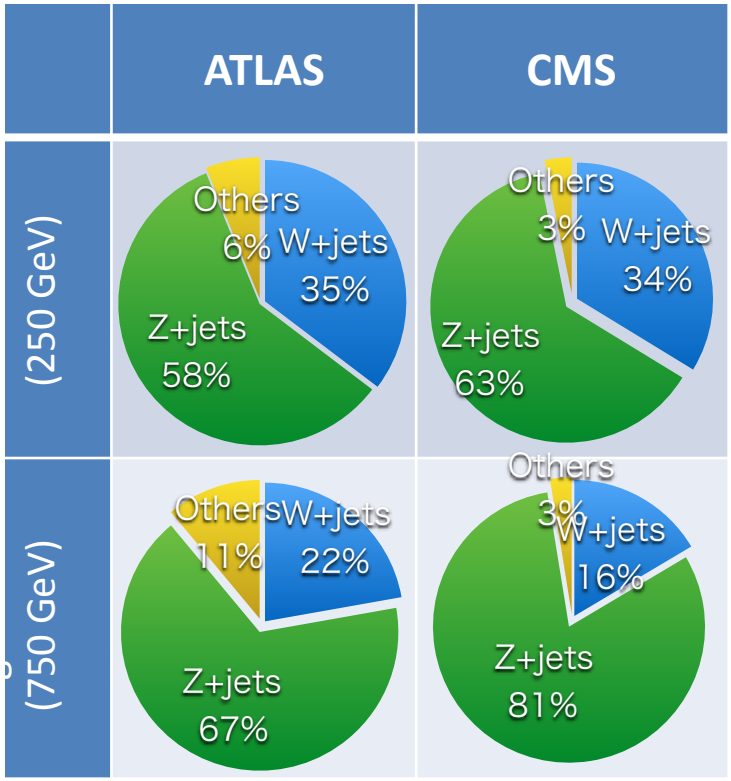
- Jets: baseline : p_T>20 GeV, |η|<2.8, JVT cut(pile up rejection), anti-kT R=0.4 based on topological clusters (ATLAS), particle flow (CMS) signal : p_T>30 GeV
- Electrons : baseline : p_T>20(10) GeV, loose identification, |η|<2.47 (2.5) signal : baseline + tight identification + IP cuts + track based isolation
- Muons : baseline : p_T>10(10) GeV, medium id, |η|<2.5 (2.4) signal : baseline + IP cuts
- (CMS) photon: p_T>15 GeV tau : p_T>18 GeV used for event veto
- E_T^{miss} (H_T^{miss}) : base line objects and track soft term, computed without baseline muons (muons as invisible)

N.B. values in parentheses are ones for CMS

Background composition overview

- Dominant BG: MC + global fit
  - Z (νν) + jets
    - irreducible, dominant esp. in high MET
  - W(lν) + jets
    - irreducible when leptons are out of acceptance or from the detector inefficiency





- Other BG:
  - Z/γ*(ll) + jets : MC+global fit (ATLAS uses MC for Z/γ*(ee))
  - ttbar, single top, di-boson : MC only
  - QCD multi-jet, Non-collision BG : data driven estimate

The Analysis Strategy

Strategy for mono-jet in ATLAS

- Signal Regions **7 exclusive SRs**

Inclusive signal region	IM1	IM2	IM3	IM4	IM5	IM6	IM7
E_T^{miss} (GeV)	> 250	> 300	> 350	> 400	> 500	> 600	> 700
Exclusive signal region	EM1	EM2	EM3	EM4	EM5	EM6	
E_T^{miss} (GeV)	[250–300]	[300–350]	[350–400]	[400–500]	[500–600]	[600–700]	

- SR (7 MET bin) accompany 3 x CR each

SR
veto on baseline leptons

single electron CR
- exactly one isolated e, no μ
- target backgrounds:
  $W(e\nu)$+jets, $W(\tau\nu)$+jets, $Z/\gamma^*(\tau\tau)$+jets

di- muon CR
- exactly two μ, no e
  66 GeV <$M_{\mu\mu}$<116 GeV
- target BG: $Z/\gamma^*(\mu\mu)$+jets

single muon CR
- exactly one μ, no e
  30 GeV <M_T<100GeV
- target BGs: $W(\mu\nu)$+jets, $Z(\nu\nu)$+jets

perform global fit and derive 3 scale factors to normalize EW backgrounds

Analysis strategy in ATLAS (cont'd)

3x E_T^{miss} dependent normalization factors
($f^{bin}_{W\to e}$, $f^{bin}_{W\to \mu}$, $f^{bin}_{Z\to \mu\mu}$) used to constraint the EW backgrounds in each CR

Control Regions	background process	norm. factor
W→eν (single-e)	$W(e\nu)$+jets, $W(\tau\nu)$+jets, $Z/\gamma^*(\tau\tau)$+jets	$f^{bin}_{W\to e}$
W→μν (single-μ)	$W(\mu\nu)$+jets, $Z(\nu\nu)$+jets	$f^{bin}_{W\to \mu}$
Z→μμ (di-muon)	$Z/\gamma^*(\mu\mu)$+jets	$f^{bin}_{Z\to \mu\mu}$

W, Z boson events are generated with Sherpa-2.1.1, up to 2 (4) -parton at NLO (LO)

$Z(\nu\nu)+$ jets

- transfer distribution from W(μν) CR
- statistical power (7x Z(μμ)+jets), partial systematic cancelation

$$N^{Z(\to\nu\bar{\nu})}_{\text{signal}} = (N^{\text{data}}_{W(\to\mu\nu),\text{control}} - N^{\text{non-}W}_{W(\to\mu\nu),\text{control}}) \times \frac{N^{\text{MC}(Z(\to\nu\bar{\nu}))}_{\text{signal}}}{N^{\text{MC}}_{W(\to\mu\nu),\text{control}}}$$

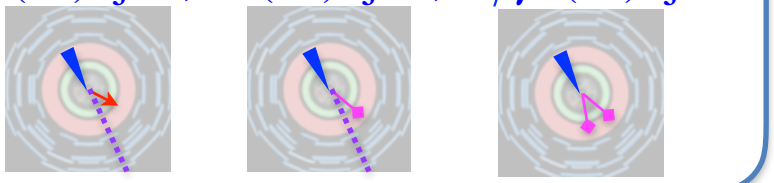
W→μν (single-μ) CR ttbar, etc **MC ratio (Sherpa)**

Single lepton CRs in ATLAS (post fit)

- Objective : performed global fit to derive scale factor for EW backgrounds
- E_T^{miss} calculation includes EM cluster, and not corrected for muon

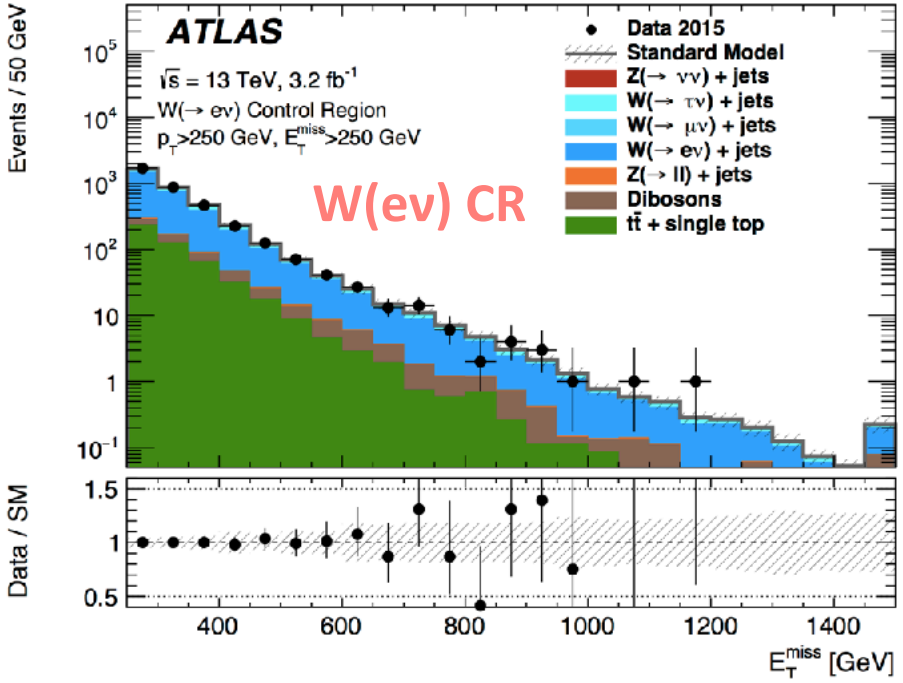
W(eν) CR

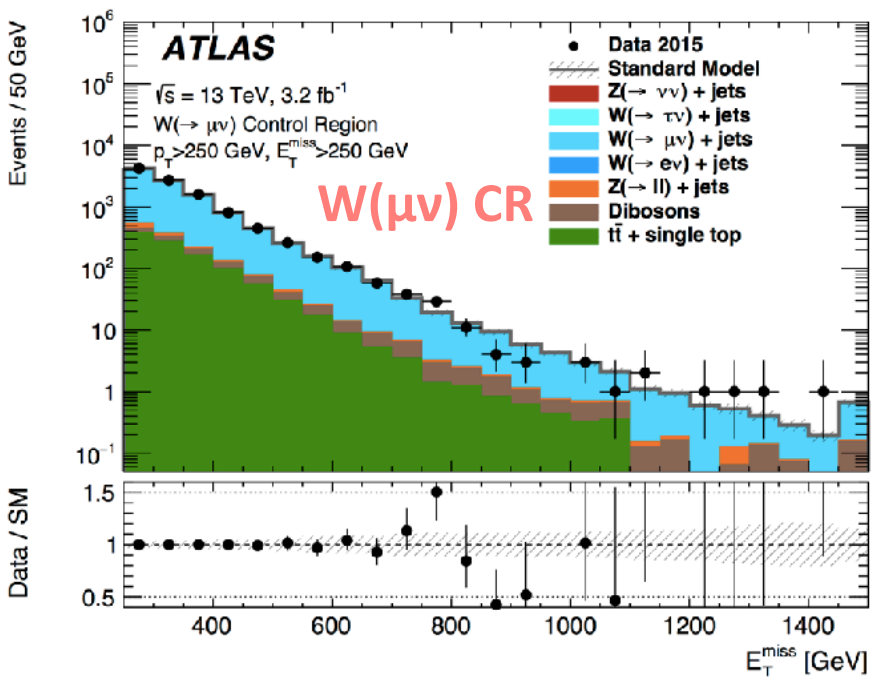
$W(e\nu)$+jets, $W(\tau\nu)$+jets, $Z/\gamma^*(\tau\tau)$+jets



W(μν) CR

$W(\mu\nu)$+jets, $Z(\nu\nu)$+jets





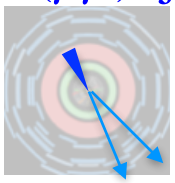
data and prediction for IM1 (MET>250GeV) selection
after the fit in exclusive MET bins, gray band : stat. + syst. errors after the fit

Di-muon CR in ATLAS (post fit)

- objective: estimate Z(μμ)+jets in SR
  E_T^{miss} is not corrected for muons (muons considered as invisible)
- performed global fit to derive scale factor for EW backgrounds

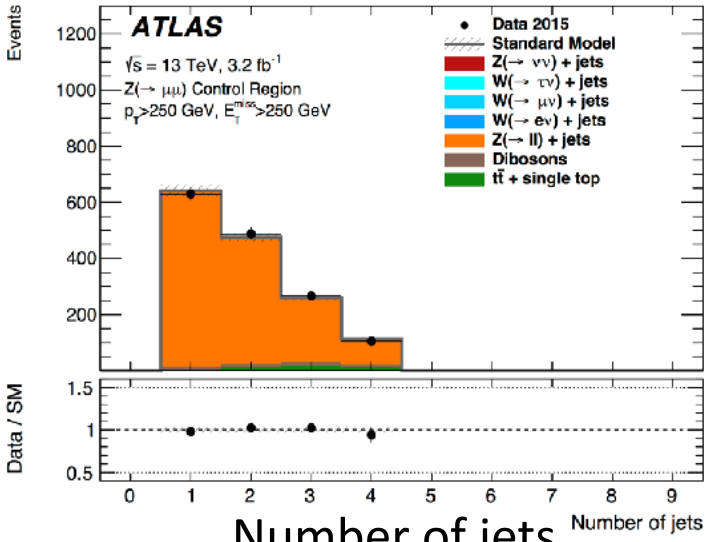
Z(μμ) CR

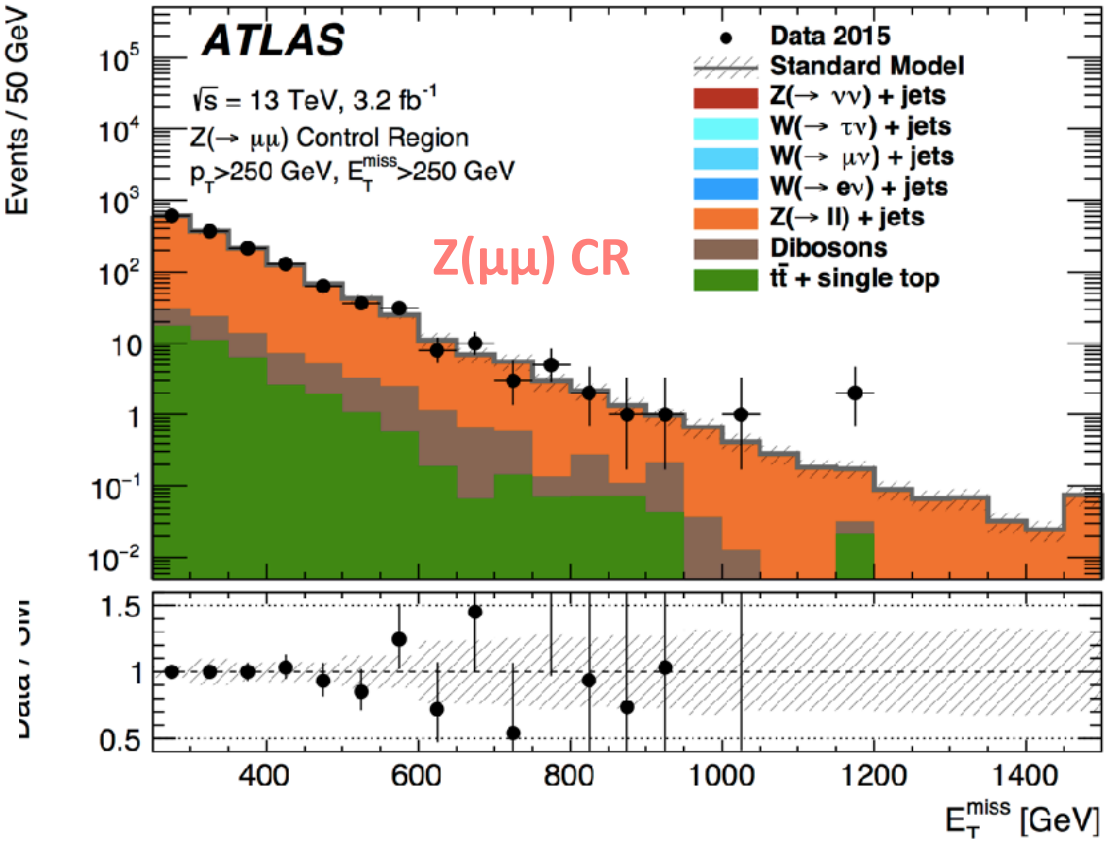
$Z/\gamma^*(\mu\mu)$+jets



N(signal muon)=2, N(base electron)=0

66 GeV < $m_{\mu\mu}$ < 116 GeV





data and prediction for IM1 (MET>250GeV) selection after the fit in exclusive MET bins

gray band : stat. + syst. errors after the fit

Other backgrounds in ATLAS

MC based estimation

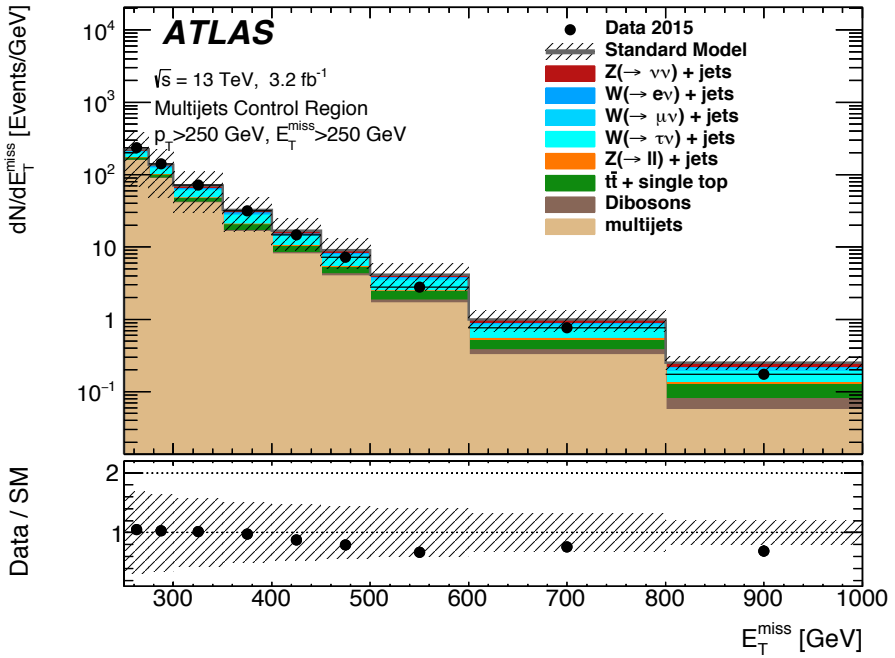
- Z(ee)+jets
- ttbar, single top, di-boson

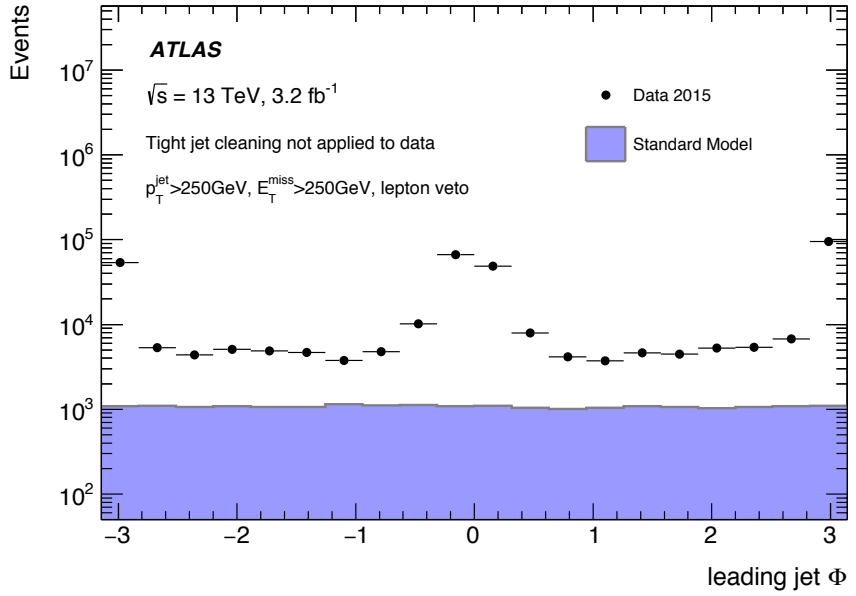
Multi-jet BG

- fake E_T^{miss}, from mis-measured jets
- estimated from jet smearing & inverted dΦ (jet, MET)
- negligible in high MET

NCB (Non Collision BG)

- Cosmic or Beam-induced background
- jet cleaning reduction < 0.1 %
- residual events can be tagged by matching calorimeter and muon segment
- almost negligible contributions in SR

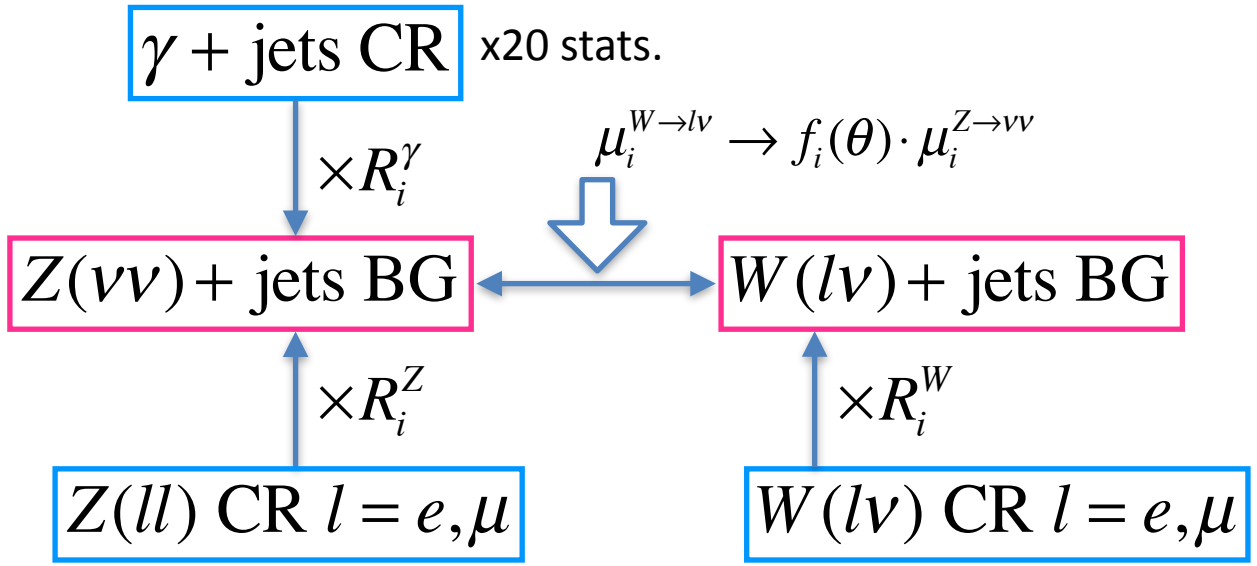




Analysis strategy in CMS

- Signal region
  - mono-jet (& mono-V category)
- 5x Control regions for each SR
  - 5 CRs to constrains 2 major BGs (Z(νν)+jets, W(lν)+jets)

pass the V-tag (AK8, mass, etc)
see backup slide



Analysis strategy in CMS

- Transfer factor to translate recoil (in CR) to missing E_T (in SR)
- Global likelihood fit simultaneously to **SR+5CR** regions in all E_T^{miss} bins

$$\mathcal{L}_k(\mu^{Z(\nu\bar{\nu})}, \mu, \theta) = \prod_i \text{Poisson}\left(d_i^{\gamma} | B_i^{\gamma}(\theta) + \frac{\mu_i^{Z(\nu\bar{\nu})}}{R_i^{\gamma}(\theta)}\right) \quad \gamma + \text{jets CR}$$

$$\times \prod_i \text{Poisson}\left(d_i^{\mu\mu} | B_i^{\mu\mu}(\theta) + \frac{\mu_i^{Z(\nu\bar{\nu})}}{R_i^{\mu\mu}(\theta)}\right)$$

$$\times \prod_i \text{Poisson}\left(d_i^{ee} | B_i^{ee}(\theta) + \frac{\mu_i^{Z(\nu\bar{\nu})}}{R_i^{ee}(\theta)}\right) \quad Z(ll) + \text{jets CR}$$

$$\times \prod_i \text{Poisson}\left(d_i^{\mu} | B_i^{\mu}(\theta) + \frac{f_i(\theta)\mu_i^{Z(\nu\bar{\nu})}}{R_i^{\mu}(\theta)}\right)$$

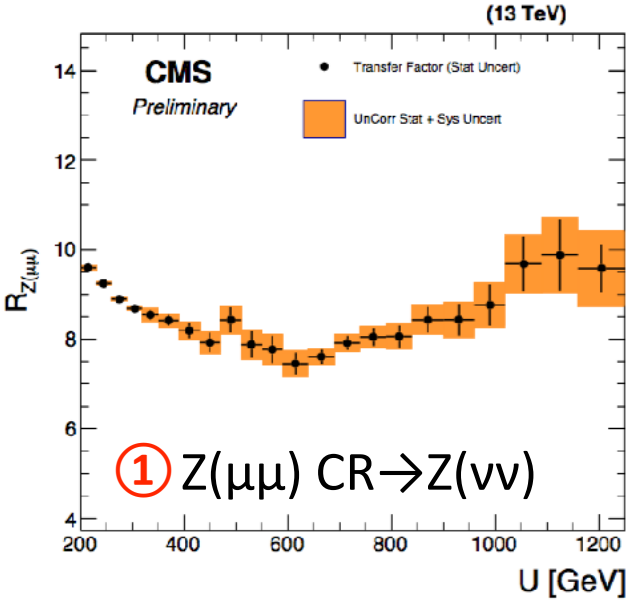
$$\times \prod_i \text{Poisson}\left(d_i^{e} | B_i^{e}(\theta) + \frac{f_i(\theta)\mu_i^{Z(\nu\bar{\nu})}}{R_i^{e}(\theta)}\right) \quad W(l\nu) + \text{jets CR}$$

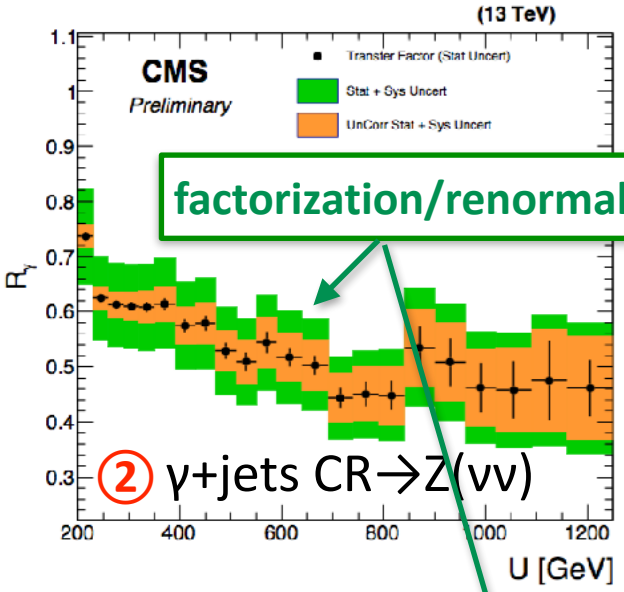
$$\times \prod_i \text{Poisson}\left(d_i | B_i(\theta) + (1 + f_i(\theta))\mu_i^{Z(\nu\bar{\nu})} + \mu S_i(\theta)\right) \quad SR$$

$$\mu_i^{W\to l\nu} \to f_i(\theta) \cdot \mu_i^{Z\to\nu\nu} \qquad \mu_i : \text{yields} \qquad R_i : \text{transfer factor}$$

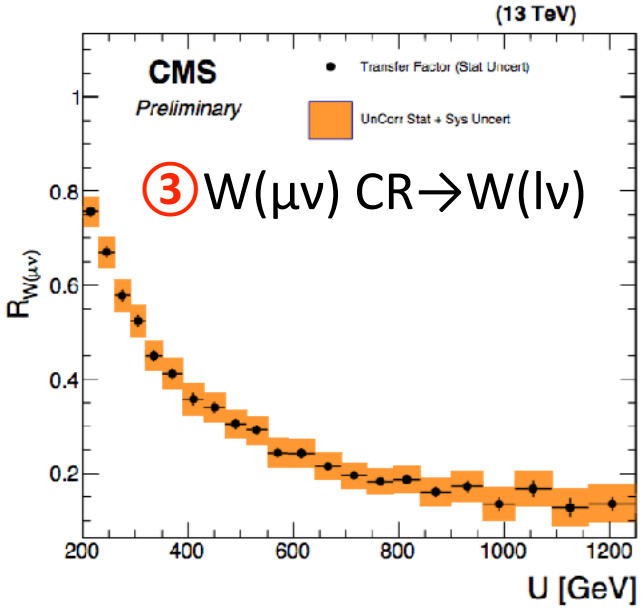
constraints from transfer factors, only one free parameter to fit

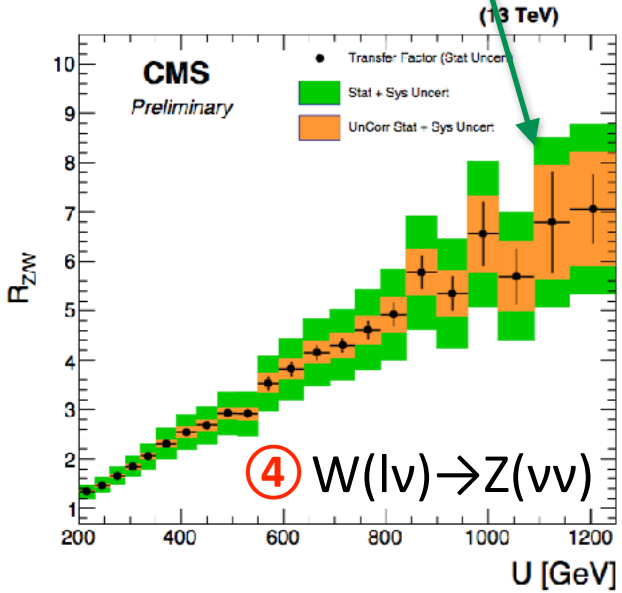
Transfer factors in CMS

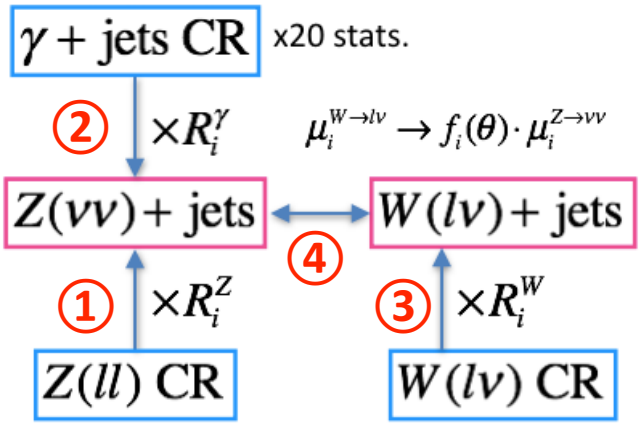




factorization/renormalization scale



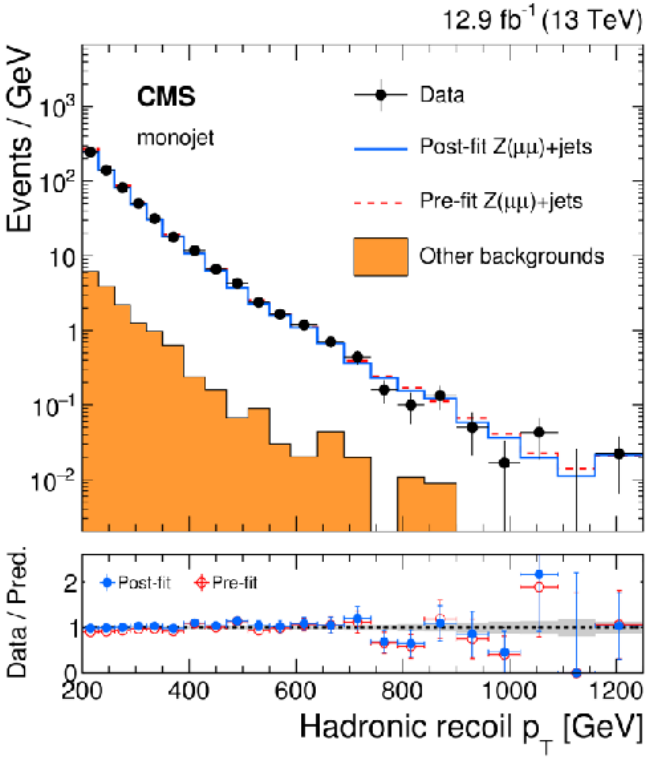




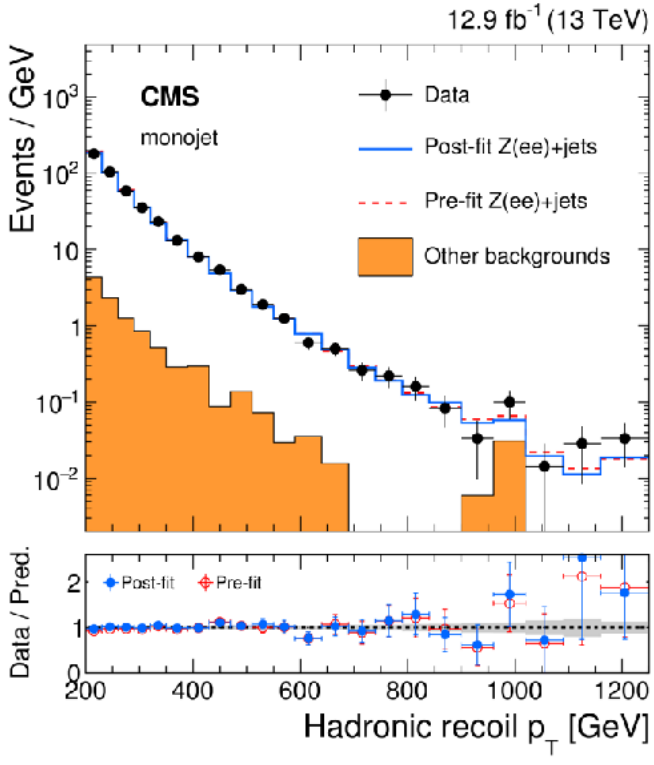
events are generated with MadGraph (LO) and corrected to NLO

from DM WG public meeting 19 Sep 2016

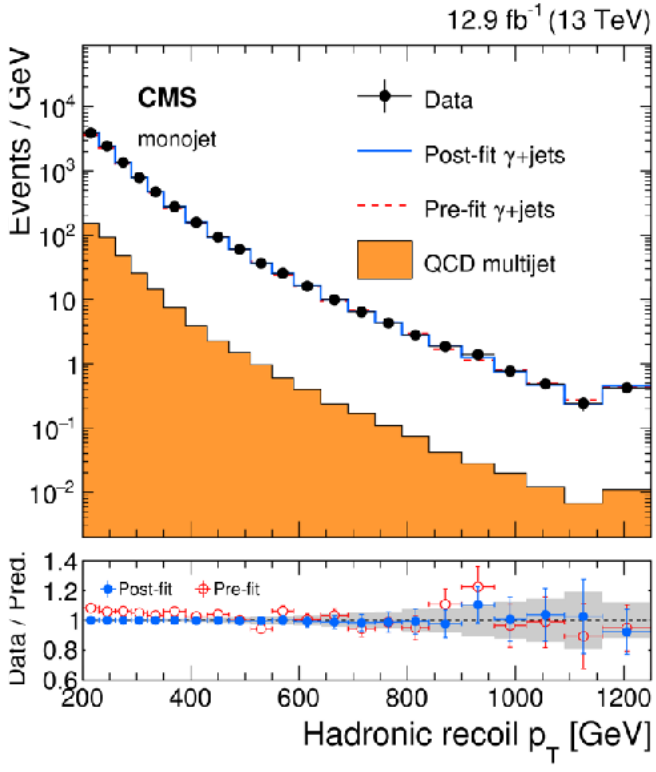
CR distributions in CMS (1)



di-muon CR



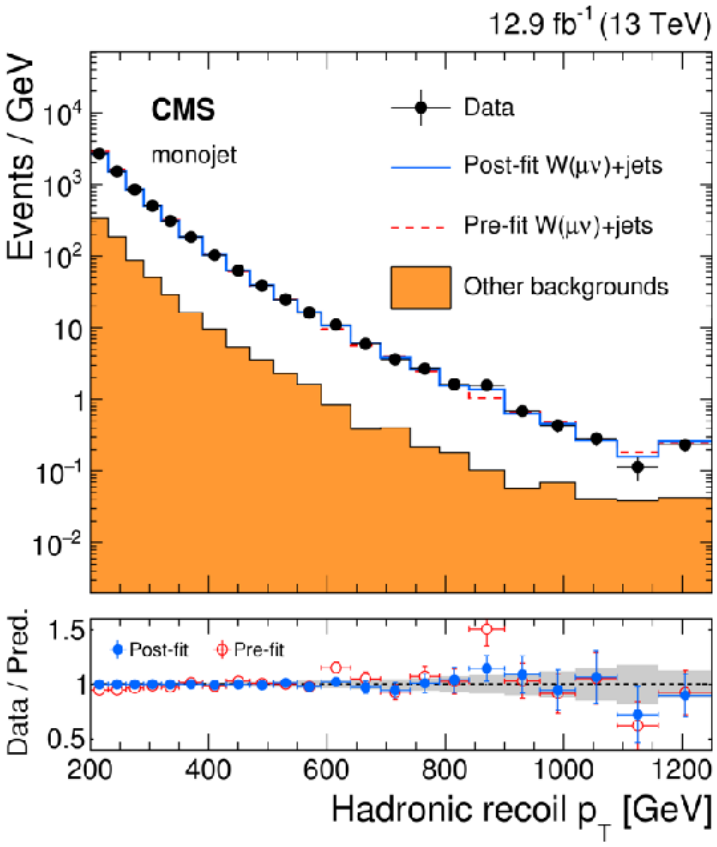
di-electron CR



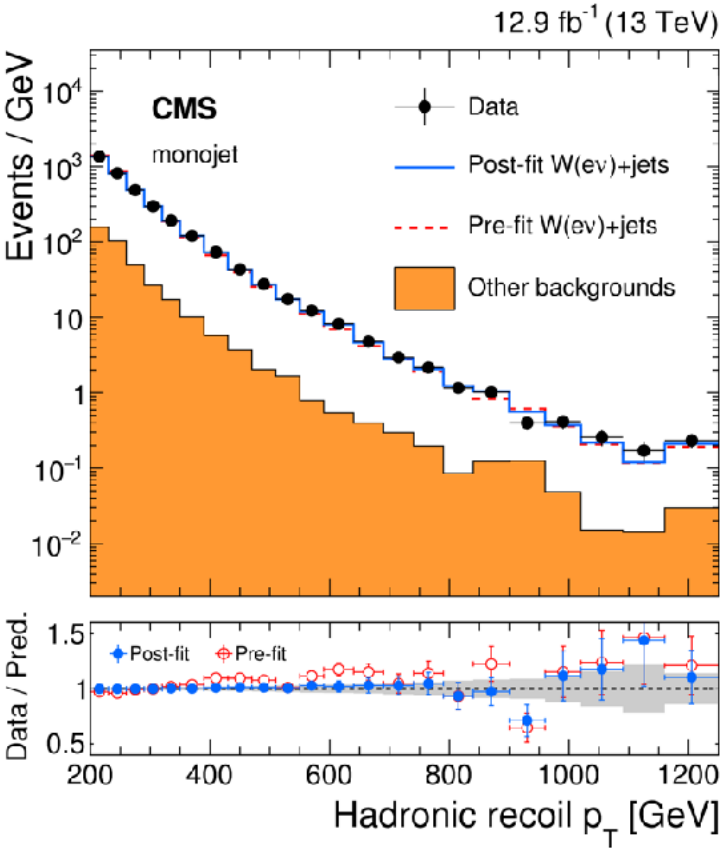
γ+jets CR

- post-fit predictions match well with data in all CRs

CR distributions in CMS (2)



single-muon CR



single-electron CR

- post-fit predictions match well with data in all CRs

Systematics uncertainties in ATLAS

Background theoretical uncertainties

- Normalization, factorization, PS-ME matching scale, PDFs
  - for Sherpa W/Z 1.1 – 1.3 %
  - for top backgrounds 2.7 – 3.3 %
- Diboson generator difference : 0.05 – 0.4%
- Multi-jet background : 0.2 %

W/Z+jets modeling (Z(νν) in SR)

- lepton rec, eff, acceptance
  3% flat uncertainties for all MET bins
- NLO EW radiative corrections :
  1.9 % for IM1, 5.2% for IM7

Experimental uncertainties

- jet, MET scale: 0.5 – 1.6 %
- jet quality requirements, pile-up description/correction to jet/MET : 0.2-0.9%
- lepton ID, reconst Eff., energy scale/ resolutions : 0.1 -2.6 % in IM7
- luminosity : 5 %
- **statistical uncertainties for CRs : 2.5 – 10 %**

Signal uncertainties

- jet/MET reconstruction, energy scale, resolution, luminosity
- gluon radiation model: shower parameters, α_S, renom./factor. scale
- jet quality requirement < 1%

Overall uncertainties (stat. + sys.): 4.0%(IM1), 6.8%(IM5), 12% (IM7)

Systematics uncertainties in CMS

Background theoretical uncertainties

- top backgrounds : relative 10 %
  b-veto : 6%
- Diboson generator difference : relative 20 %
  b-veto : 2%
- Multi-jet background : relative 50-150%

Experimental uncertainties

- luminosity : 6.2 %
- E_T^{miss} modeling (jet energy scale) : 5%
- lepton reconstruction : 1%
  selection : 2%

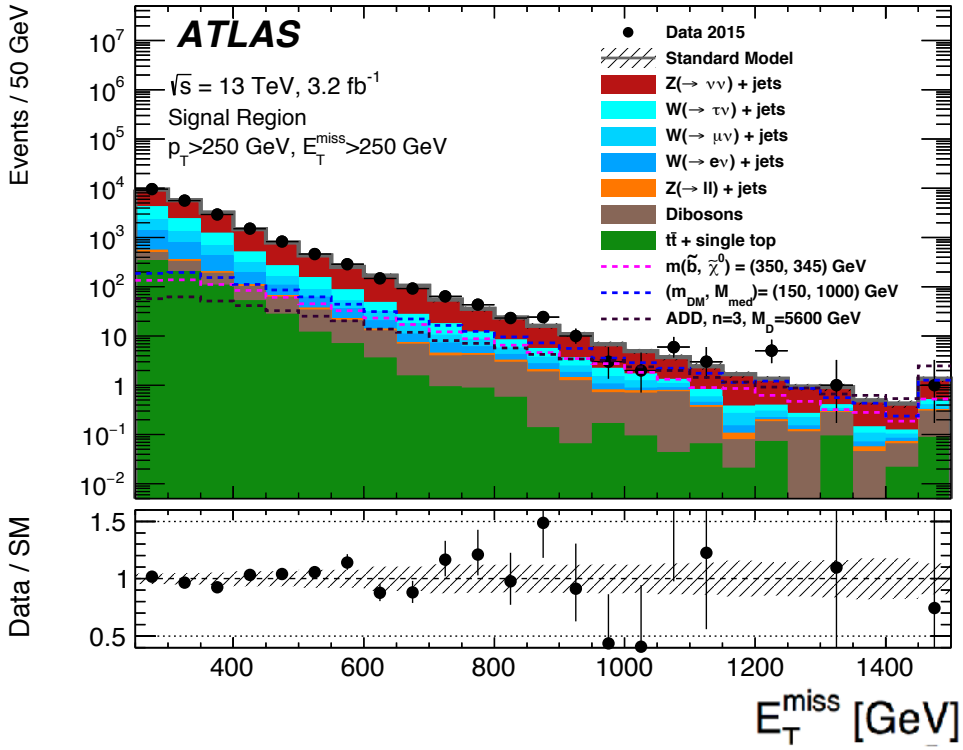
W/Z/γ+jets modeling

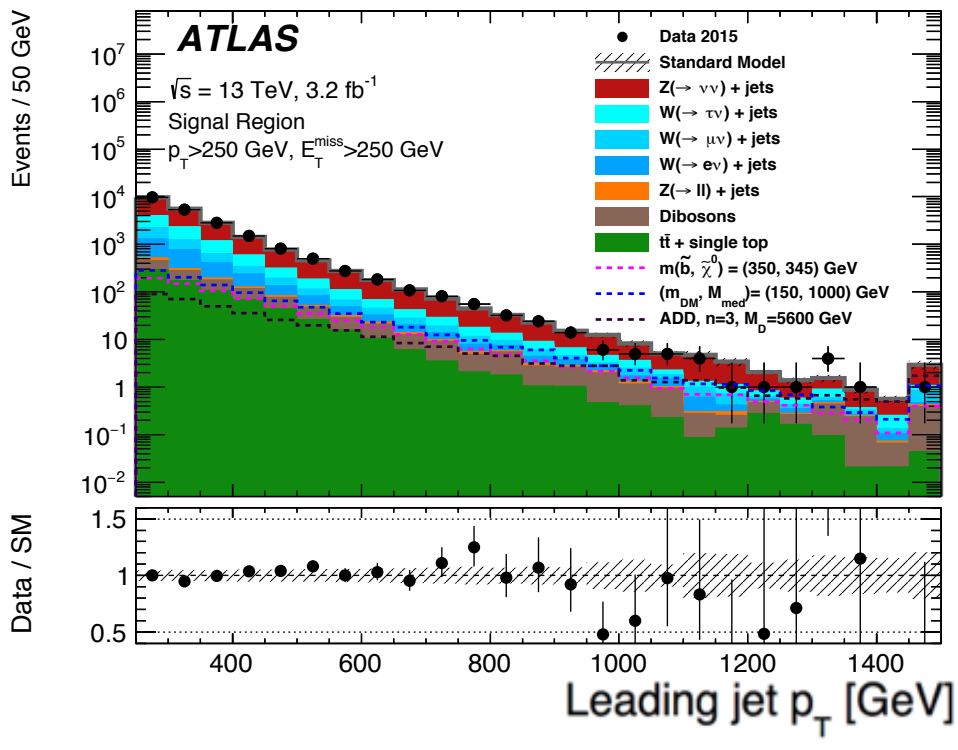
- γ+jets to Z+jets, W+jets to Z+jets differential cross section ratios
  - renormalization (10-15%)
  - factorization (1-10%)
  - PDF (negligible)
- NLO EW corrections
  - γ+jets (2-14%), W+jets (1-9%)

The Results

Results (Signal Region) in ATLAS

no significant excess observed





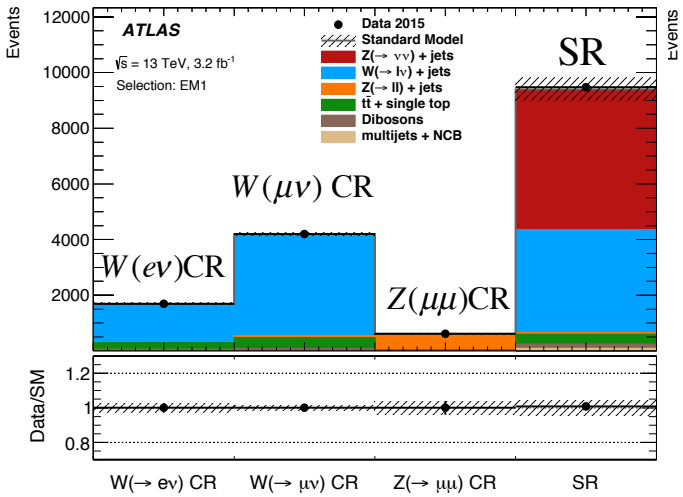
Signal Region	IM1	IM2	IM3	IM4	IM5	IM6	IM7
Observed events (3.2 fb^{-1})	21447	11975	6433	3494	1170	423	185
SM prediction	21730 ± 940	12340 ± 570	6570 ± 340	3390 ± 200	1125 ± 77	441 ± 39	167 ± 20
Signal Region	EM1	EM2	EM3	EM4	EM5	EM6	
Observed events (3.2 fb^{-1})	9472	5542	2939	2324	747	238	
SM prediction	9400 ± 410	5770 ± 260	3210 ± 170	2260 ± 140	686 ± 50	271 ± 28	

Inclusive signal region	IM1	IM2	IM3	IM4	IM5	IM6	IM7
E_T^{miss} (GeV)	> 250	> 300	> 350	> 400	> 500	> 600	> 700
Exclusive signal region	EM1	EM2	EM3	EM4	EM5	EM6	
E_T^{miss} (GeV)	[250–300]	[300–350]	[350–400]	[400–500]	[500–600]	[600–700]	

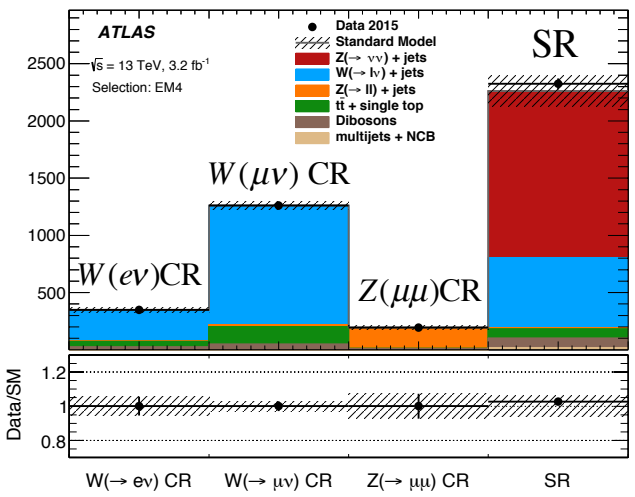
ATLAS EXPERIMENT

Results in ATLAS

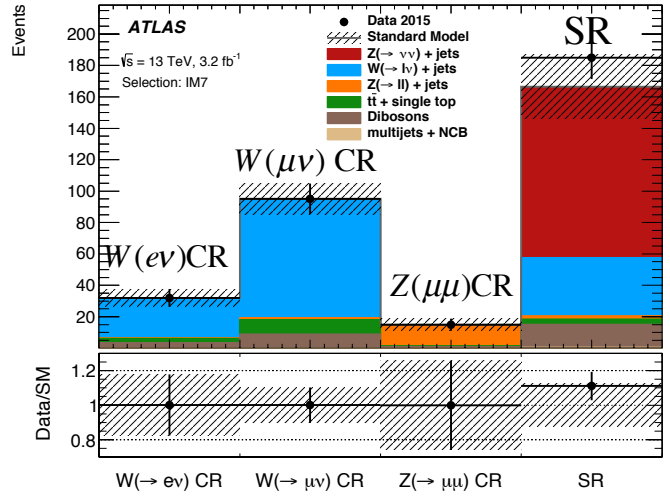
EM1 (E_T^{miss} = 250 – 300 GeV)



EM4 (E_T^{miss} = 400 – 500 GeV)



EM7 (E_T^{miss} > 700 GeV)



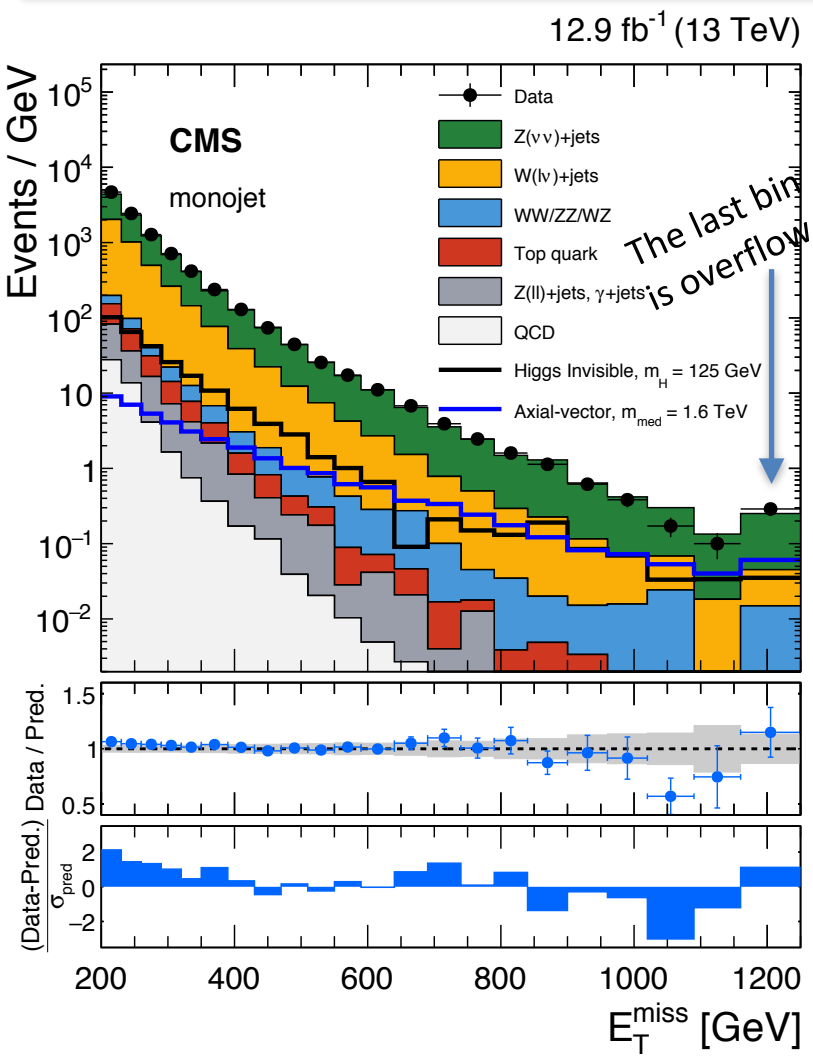
post-fit predictions match well with data in SR/CRs

Signal channel	$\langle\sigma\rangle_{obs}^{95}$ [fb]	S_{obs}^{95}	S_{exp}^{95}
IM1	553	1773	1864^{+829}_{-548}
IM2	308	988	1178^{+541}_{-348}
IM3	196	630	694^{+308}_{-204}
IM4	153	491	401^{+168}_{-113}
IM5	61	196	164^{+63}_{-45}
IM6	23	75	84^{+32}_{-23}
IM7	19	61	48^{+18}_{-13}

- model independent 95% C.L. upper limits on
  - signal events
  - visible cross sections

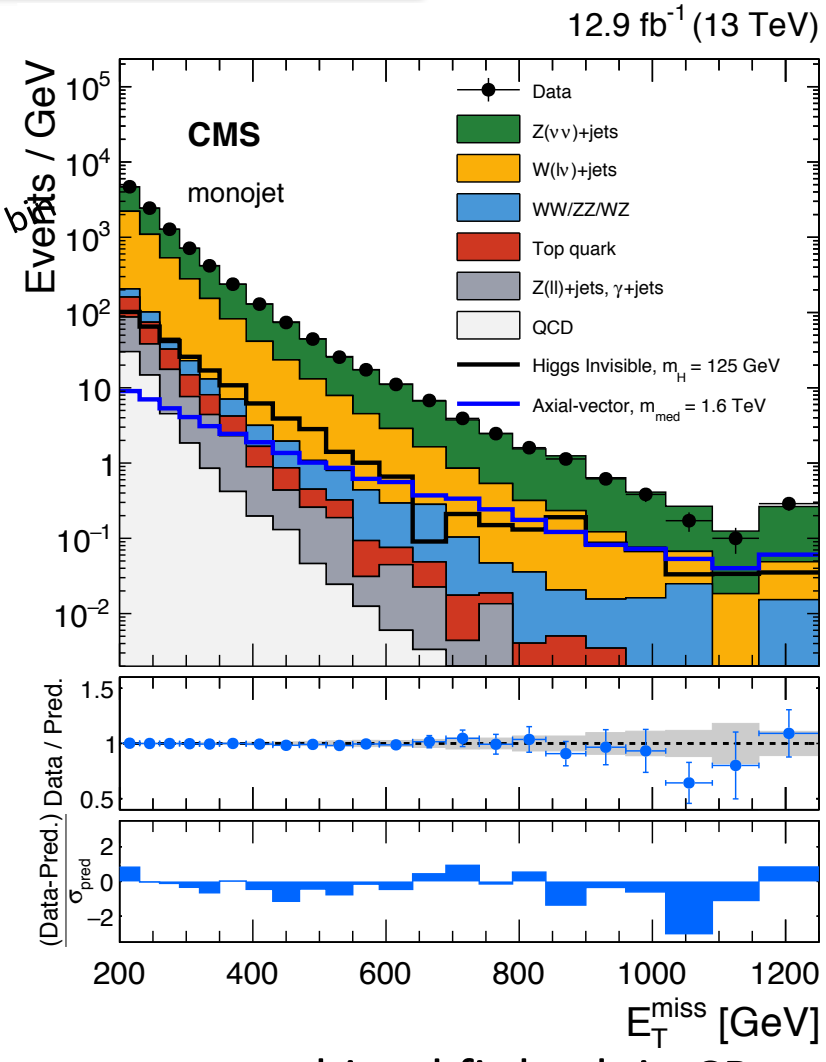
  for each E_T^{miss} bin
- 553 — 19 fb obtained

Results (Signal Region) in CMS



post combined fit only in CRs

gray band: post fit uncertainty



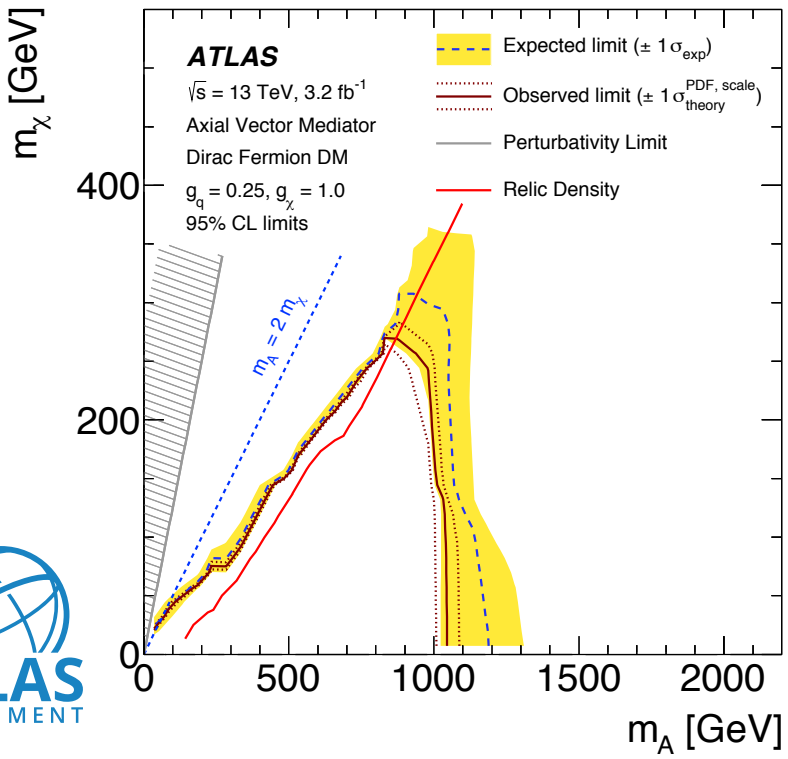
post combined fit both in CRs and SR (assuming no DM signal)

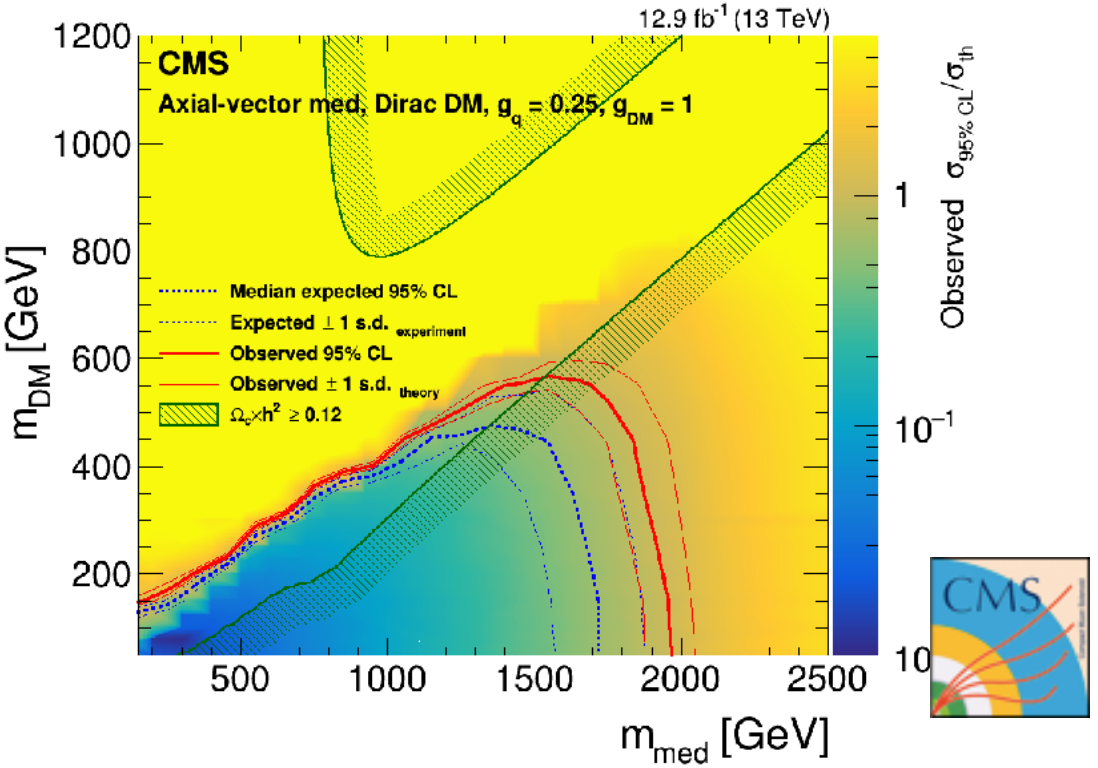
no signal excess (small non-significant deficits)

DM Interpretations

DM interpretation (Mediator mass vs. WIMP (DM) mass)

Axial vector mediator g_q=0.25, g_{DM}=1.0

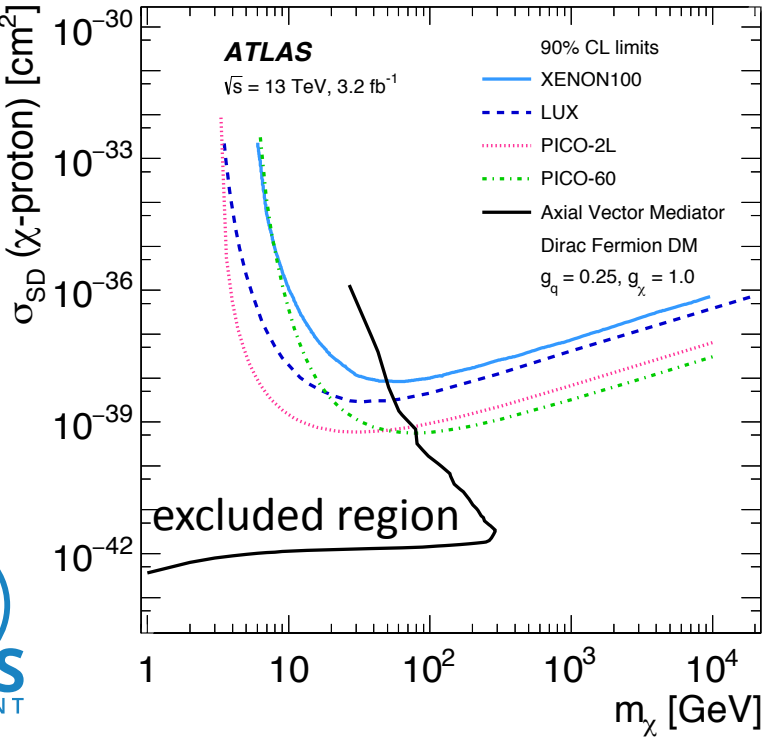


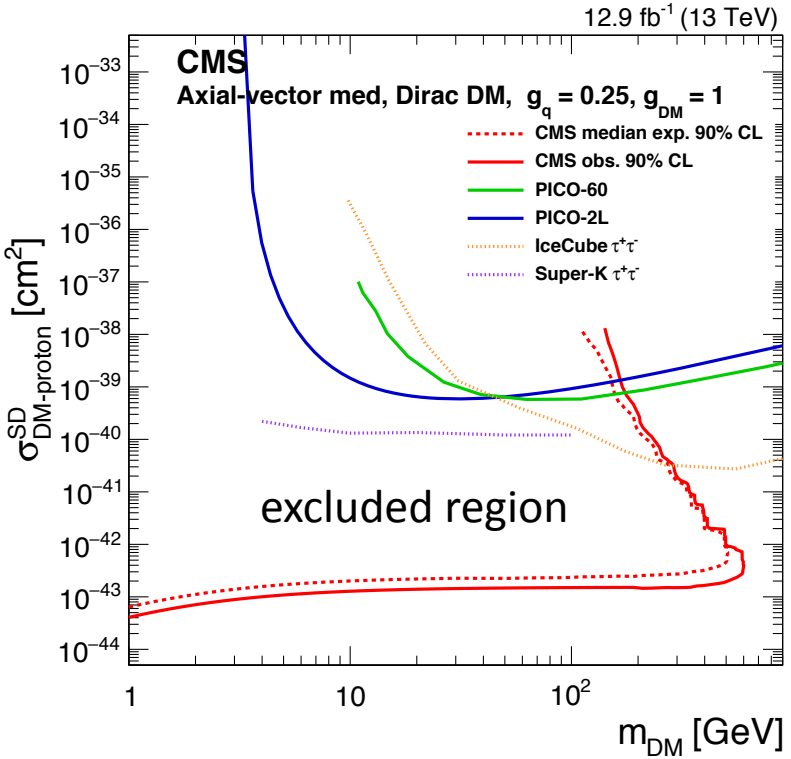


- In ATLAS (L=3.2 fb^{-1}), observed (expected) limit on Mediator mass at **1.0 TeV (1.2 TeV)** for WIMP mass below **250 GeV (300 GeV)** at **95% CL**
- In CMS (L=12.9 fb^{-1}), observed (expected) limit on Mediator mass at **1.95 TeV (1.7 TeV)** for WIMP mass below **450 GeV (600 GeV)** at **95% CL**

DM interpretation (DM–nucleon scattering cross-sections)

Axial vector mediator g_q=0.25, g_{DM}=1.0



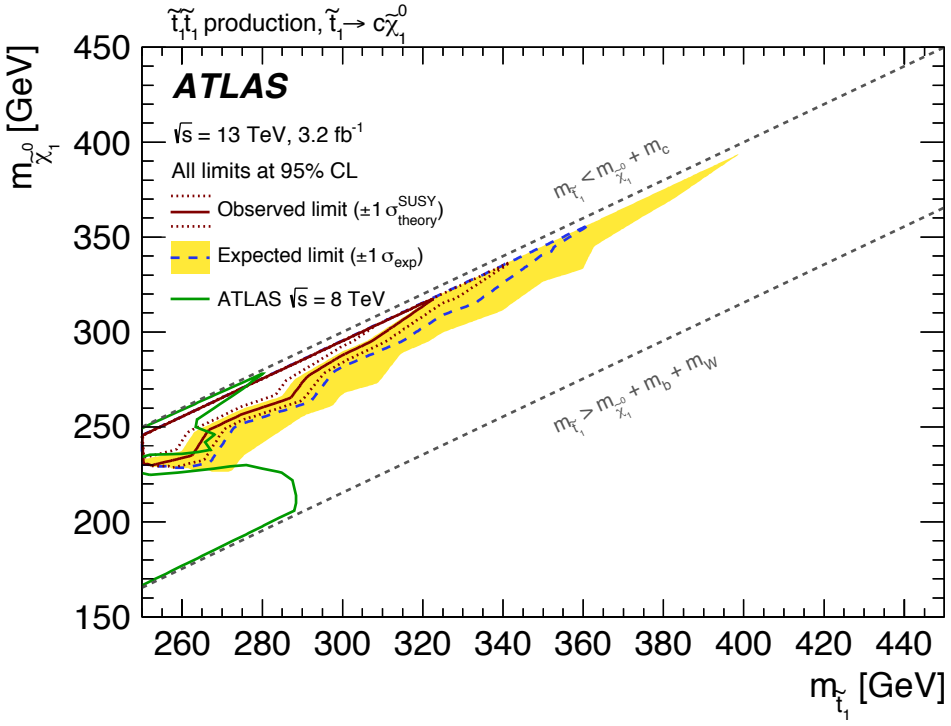


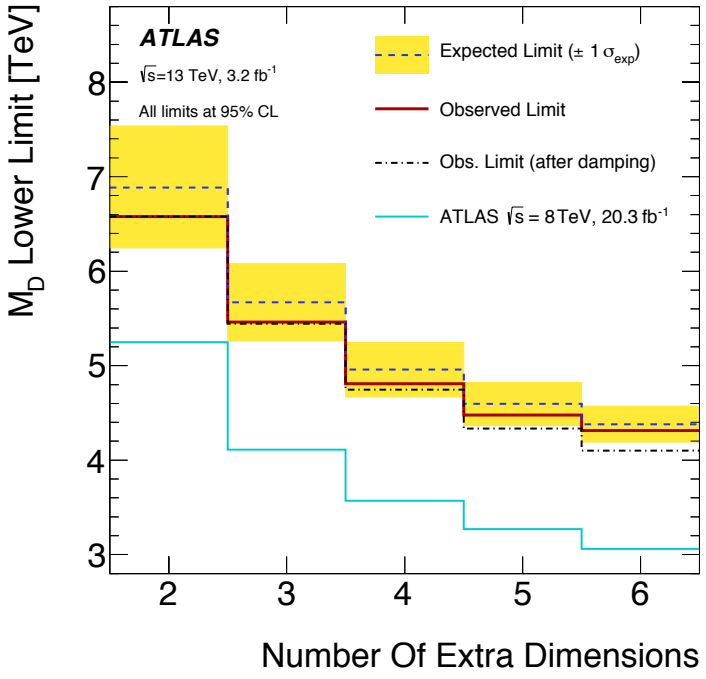
for WIMP masses **below 10 GeV** with **90% CL**,

- In ATLAS, WIMP–nucleon spin dependent cross sections above $\mathbf{10^{-42}cm^2}$ excluded
- In CMS, WIMP–proton spin dependent cross sections above $\mathbf{10^{-43}cm^2}$ excluded

LUX : Phys. Rev. Lett. 116, 161302 (2016), XENON100 : Data, Phys. Rev. Lett. 1110 21301 (2013)
PICO-2L : Phys. Rev. D93 (2016) 061101, PICO-60 : Phys. Rev. D 93, 052014 (2016)
IceCube : JCAP 04 (2016) 022, Super Kamiokande : Phys. Rev. Lett. 114 (2015) 141301

Other interpretations in ATLAS

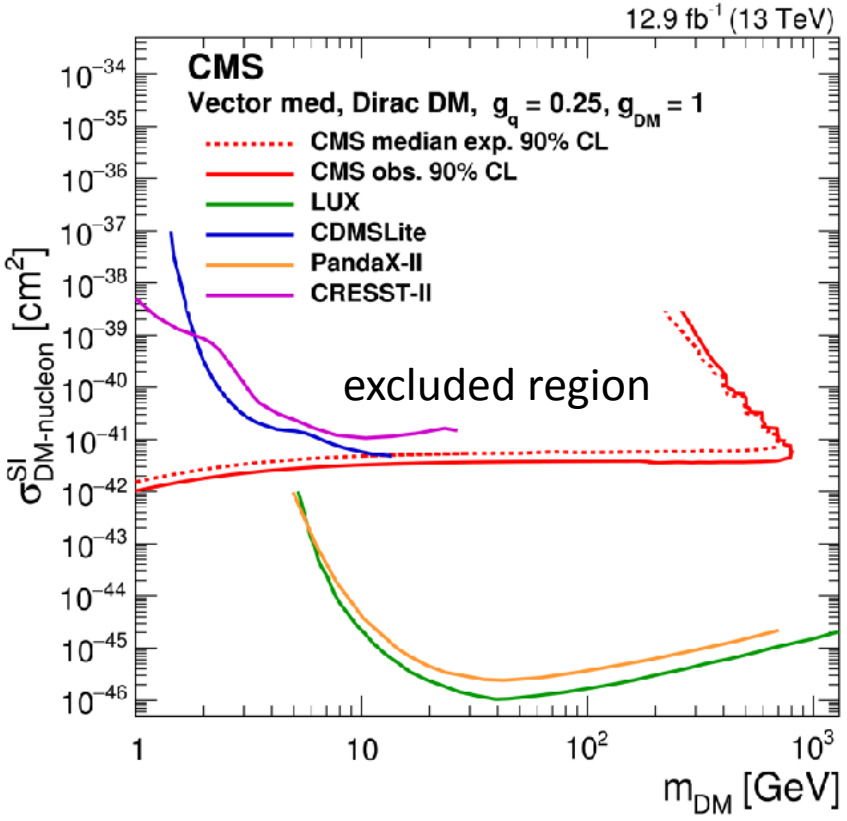




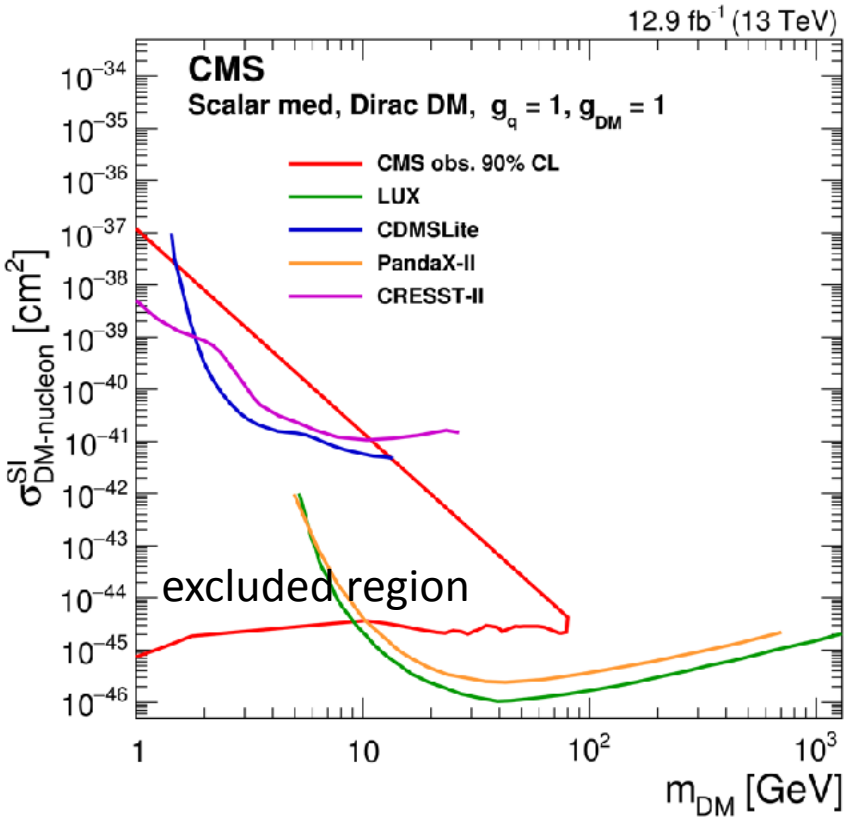
- SUSY: interpreted in terms of stop pair production in a compressed scenarios
  stop masses **below 323 GeV** are excluded in 95% C.L.
  (sbottom/squark mass below 323/608 GeV are excluded in 95% C.L.)
- ADD Large Extra Dimension Model:
  6.58 TeV at n=2 is excluded
- significant improvement against Run-1 result

Other interpretations in CMS

Vector mediator g_q=0.25, g_{DM}=1.0



Scalar mediator g_q=1.0, g_{DM}=1.0



- WIMP–nucleon spin independent cross sections above **10^{-42}cm^2** for WIMP masses below 10 GeV excluded at **90% C.L.** with **Vector type mediator**
- WIMP–nucleon spin independent cross sections above **10^{-45}cm^2** for WIMP masses below 10 GeV excluded at **90% C.L.** with **Scalar type mediator**

Summary of mono-jet searches

- Mono-jet is one of the most powerful channel in searching for DM by collider experiments
- ATLAS and CMS performed searches for mono-jet signature using different approaches
- No excesses were observed, limits were set accordingly
- The results were interpreted with DM models, limits on
  - mediator & DM masses
  - nucleon scattering cross sections, were obtained

Extra materials

V-tagging in CMS

- Events are classified into mono-V or mono-jet
- Mono-V selection:
  - MET > 250 GeV
  - leading AK8 (anti-kT distant parameter 0.8) jet > 250 GeV
  - jet mass between 65 and 105 GeV
    - after pruning
  - τ_N (N sub-jettiness variable) : $\tau_2/\tau_1<0.6$
- Mono-jet
  - the events which failed mono-V selection

Event yields in SRs (ATLAS)

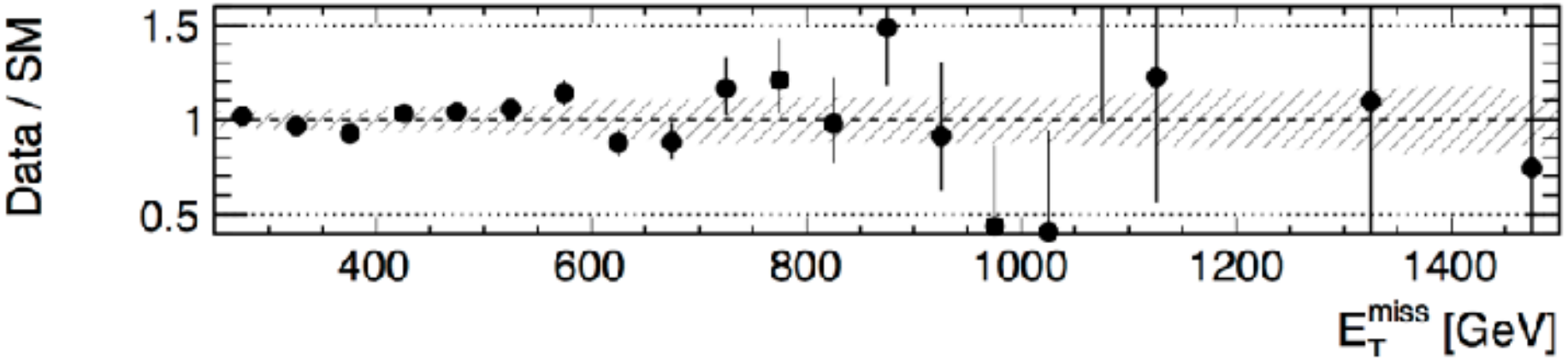
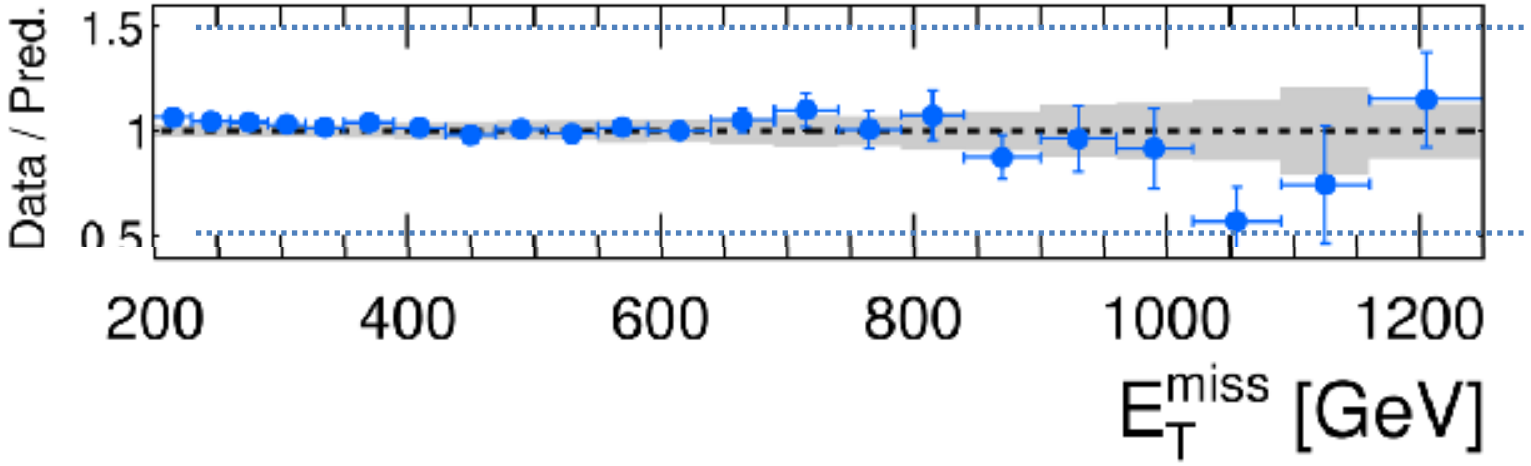
Inclusive signal region	IM1	IM2	IM3	IM4	IM5	IM6	IM7
$E_{\mathrm{T}}^{\mathrm{miss}}$ (GeV)	> 250	> 300	> 350	> 400	> 500	> 600	> 700
Exclusive signal region	EM1	EM2	EM3	EM4	EM5	EM6	
$E_{\mathrm{T}}^{\mathrm{miss}}$ (GeV)	[250–300]	[300–350]	[350–400]	[400–500]	[500–600]	[600–700]	

TABLE VIII. Data and SM background predictions in the signal region for the different selections. For the SM predictions both the statistical and systematic uncertainties are included.

Signal region	IM1	IM2	IM3	IM4	IM5	IM6	IM7
Observed events (3.2 fb^{-1})	21447	11975	6433	3494	1170	423	185
SM prediction	21730 ± 940	12340 ± 570	6570 ± 340	3390 ± 200	1125 ± 77	441 ± 39	167 ± 20
Signal region	EM1	EM2	EM3	EM4	EM5	EM6	
Observed events (3.2 fb^{-1})	9472	5542	2939	2324	747	238	
SM prediction	9400 ± 410	5770 ± 260	3210 ± 170	2260 ± 140	686 ± 50	271 ± 28	

Event yields in SRs (CMS)

Table 1: Expected event yields in each $E_{\mathrm{T}}^{\mathrm{miss}}$ bin for various background processes in the monojet signal region. The background yields and the corresponding uncertainties are obtained after performing a combined fit to data in all the control samples, but excluding data in the signal region. The observed event yields in the monojet signal region are also reported.

$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	$Z(\nu\bar{\nu})$+jets	$W(\ell\nu)$+jets	Top quark	Dibosons	Other	Total bkg.	Observed
200–230	71300 ± 2200	54600 ± 2300	2140 ± 320	1320 ± 220	2470 ± 310	132100 ± 4000	140642
230–260	39500 ± 1300	27500 ± 1200	1060 ± 160	790 ± 130	1090 ± 130	69900 ± 2200	73114
260–290	21900 ± 670	13600 ± 550	440 ± 65	364 ± 61	498 ± 65	36800 ± 1100	38321
290–320	12900 ± 400	7300 ± 290	210 ± 31	235 ± 40	216 ± 30	20780 ± 630	21417
320–350	8000 ± 280	4000 ± 170	107 ± 16	145 ± 24	124 ± 18	12340 ± 400	12525
350–390	6100 ± 220	2800 ± 130	74 ± 11	111 ± 19	87 ± 13	9160 ± 320	9515
390–430	3500 ± 160	1434 ± 66	30.1 ± 4.5	58.4 ± 9.9	33.4 ± 5.3	5100 ± 200	5174
430–470	2100 ± 98	816 ± 37	16.6 ± 2.5	42.4 ± 7.1	16.3 ± 2.7	3000 ± 120	2947
470–510	1300 ± 66	450 ± 20	7.4 ± 1.1	24.6 ± 4.1	9.6 ± 1.6	1763 ± 79	1777
510–550	735 ± 39	266 ± 13	5.2 ± 0.8	18.5 ± 3.1	7.0 ± 1.3	1032 ± 48	1021
550–590	513 ± 31	152 ± 8	2.4 ± 0.4	13.5 ± 2.3	1.1 ± 0.3	683 ± 37	694
590–640	419 ± 23	120 ± 6	1.5 ± 0.2	10.6 ± 1.8	2.1 ± 0.4	554 ± 28	554
640–690	246 ± 16	62.8 ± 3.8	1.3 ± 0.2	11.4 ± 1.9	1.0 ± 0.2	322 ± 19	339
690–740	139 ± 11	34.2 ± 2.4	0.6 ± 0.1	4.2 ± 0.7	0.20 ± 0.07	178 ± 13	196
740–790	97.2 ± 7.2	22.7 ± 1.7	0.22 ± 0.03	1.4 ± 0.2	0.63 ± 0.12	122 ± 8	123
790–840	59.8 ± 5.8	12.9 ± 1.2	0.13 ± 0.02	1.5 ± 0.3	0.05 ± 0.02	74.5 ± 6.6	80
840–900	64.3 ± 6.4	12.3 ± 1.1	0.24 ± 0.04	0.92 ± 0.1	0.03 ± 0.01	77.8 ± 7.2	68
900–960	31.5 ± 4.3	6.0 ± 0.7	0.21 ± 0.03	0.74 ± 0.1	0.01 ± 0.01	38.4 ± 4.8	37
960–1020	20.8 ± 3.0	3.4 ± 0.5	—	0.94 ± 0.2	0.01 ± 0.01	25.1 ± 3.4	23
1020–1090	16.3 ± 2.6	3.1 ± 0.5	0.04 ± 0.01	1.6 ± 0.3	0.01 ± 0.01	21.1 ± 3.0	12
1090–1160	8.1 ± 1.8	1.3 ± 0.3	—	—	—	9.4 ± 1.9	7
>1160	18.6 ± 2.7	2.7 ± 0.4	—	1.3 ± 0.2	—	22.6 ± 3.0	26

Systematic error direct comparison