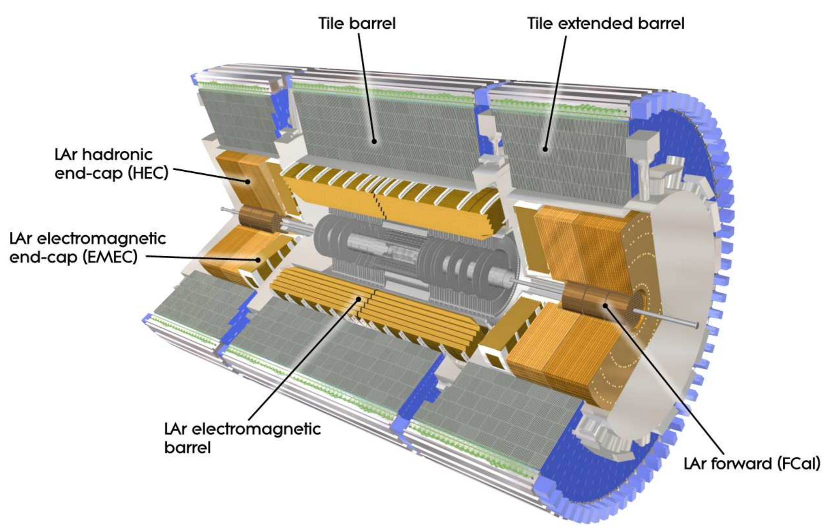
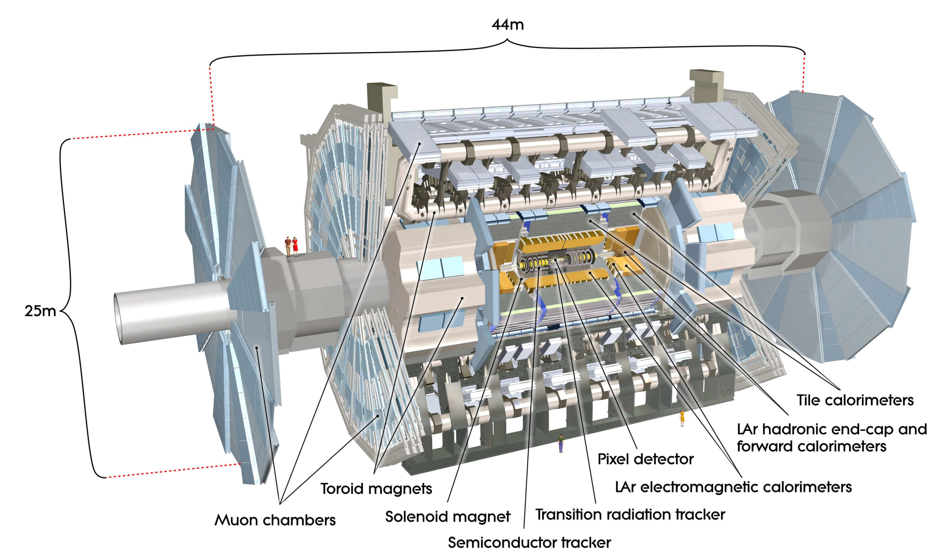
The Higgs and dark matter

On behalf of the ATLAS Collaboration

November 7, 2017

Ben Carlson†





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Outline

Order of physics topics

Most of the physics I will discuss today uses MET to trigger

Mono-Higgs

- $H \rightarrow bb$ + MET
- $H \rightarrow \gamma\gamma$ + MET

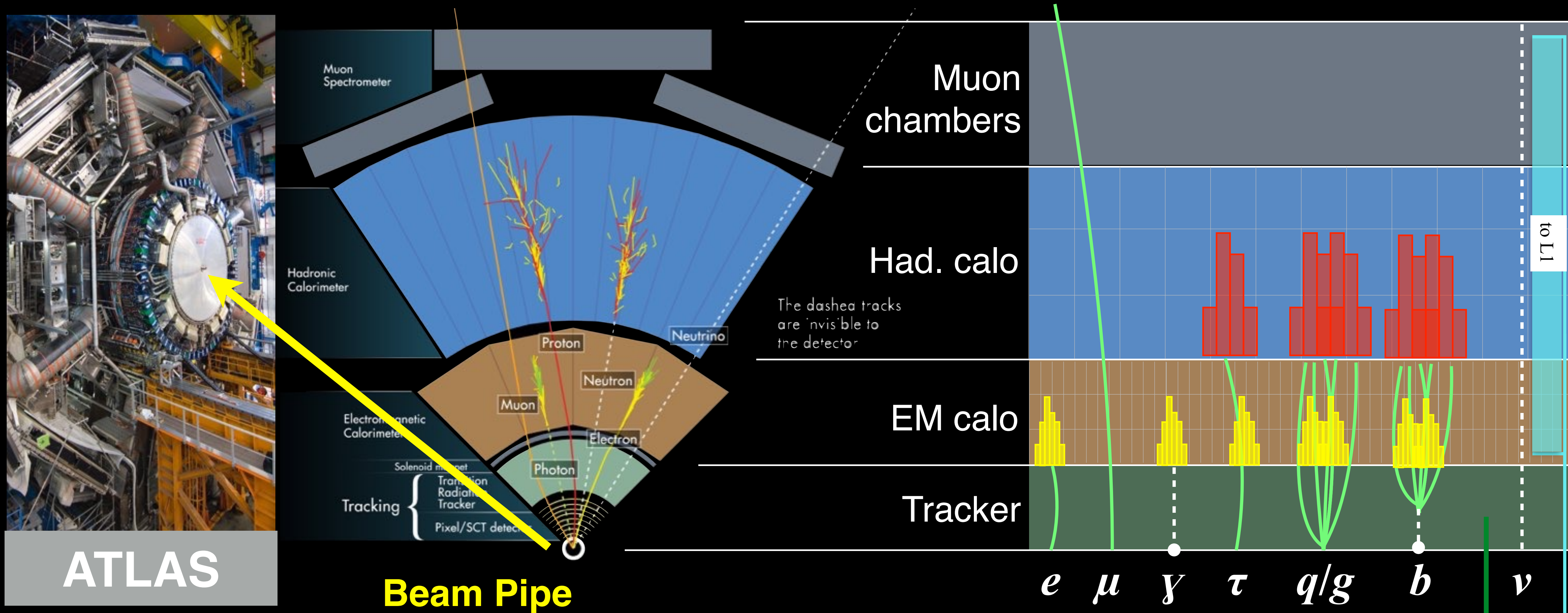
$H \rightarrow$inv searches

- ggF: ISR + MET
- VBF: jets + MET
- $V \rightarrow qq$ *(boosted)*: jet + MET
- $Z \rightarrow \ell\ell$: $\ell\ell$ + MET
- ttH: single lepton, jets + MET

Experimental topics

- MET trigger
- Estimation of invisible backgrounds
- Theory & exp. uncertainties
- Is it sensitive?

ATLAS detector



coarse calorimeter and muon to L1

some tracking to HLT

full calorimeter and muon data to HLT

Hardware trigger (L1): select in 2.2 μs

100 kHz

Software trigger (HLT) select in 0.1 s

1 kHz

Save to permenant storage

MET trigger

Critical for dark matter searches

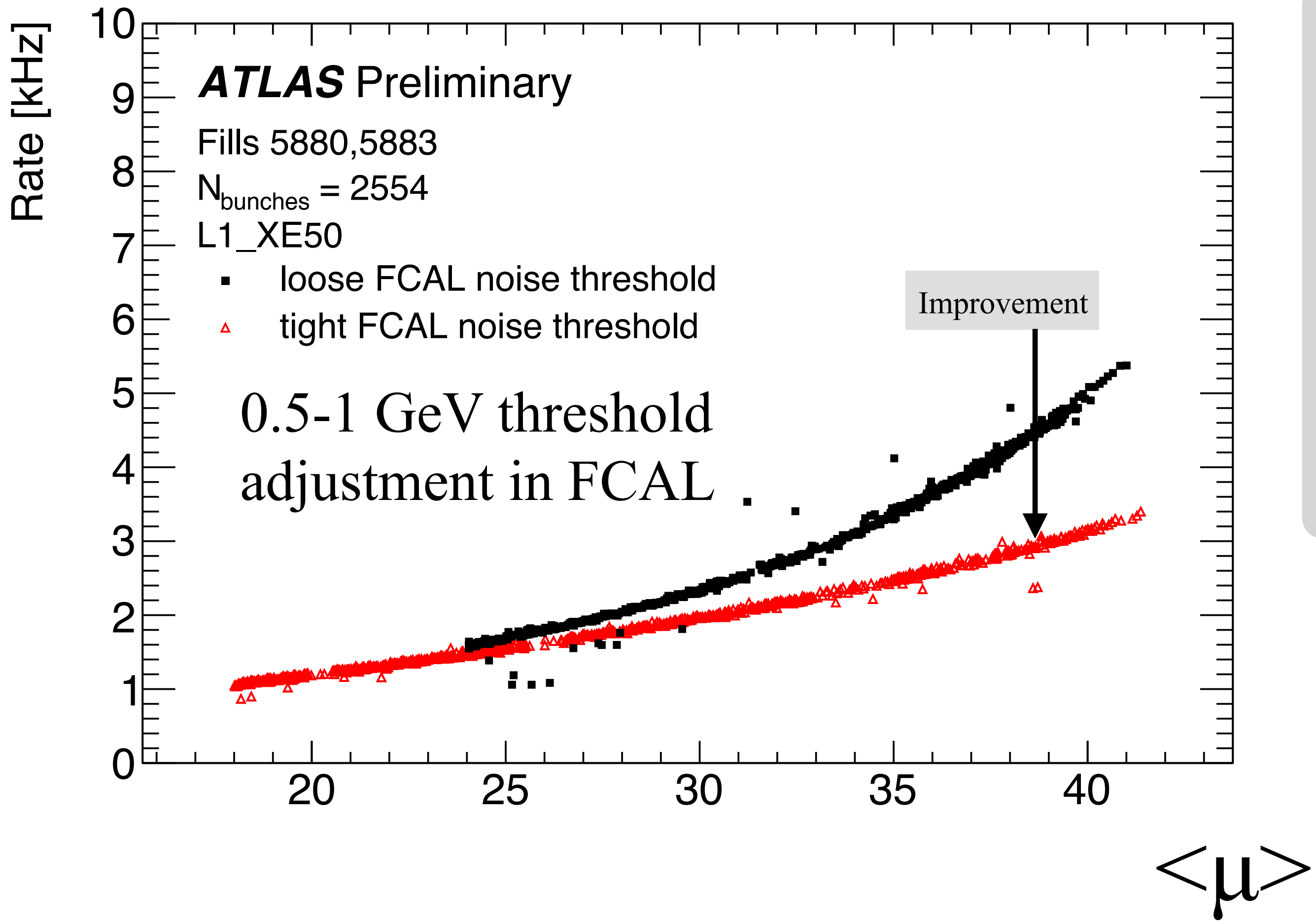
- The trigger rates go up with luminosity, even in the ideal case
- In reality, resolution effects mean the scaling is worse
- Requires tuning (left) and rethinking trigger algorithms (right)

Ideal Rate ~ $k \cdot L_{inst} = k \cdot \langle\mu\rangle$

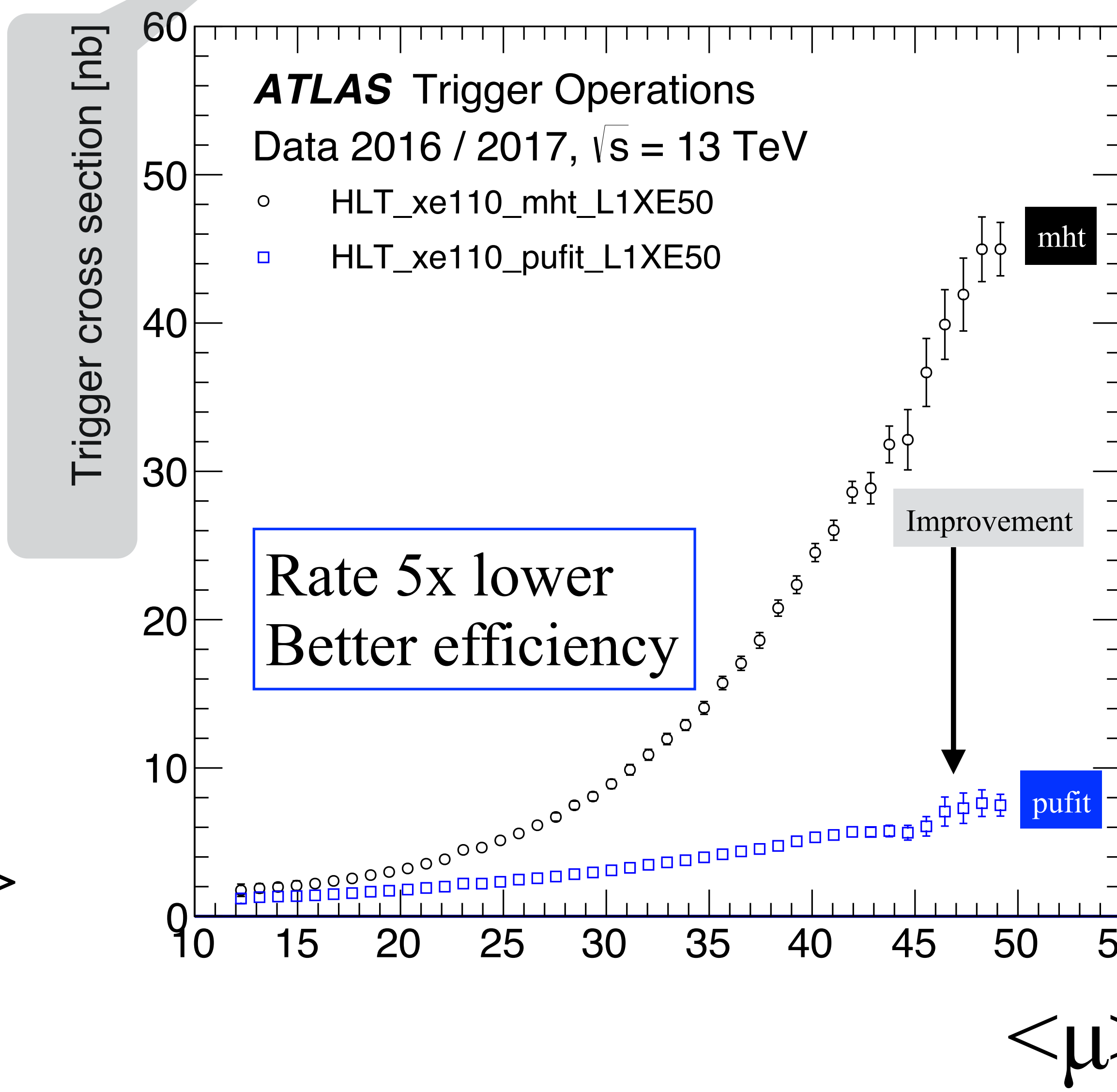
Actual Rate ~ $k \cdot e^{\langle\mu\rangle}$

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/MissingEtTriggerPublicResults

Max L1 rate: 100 kHz



Rate / L_{inst} (flat in the absence of pileup dependence)

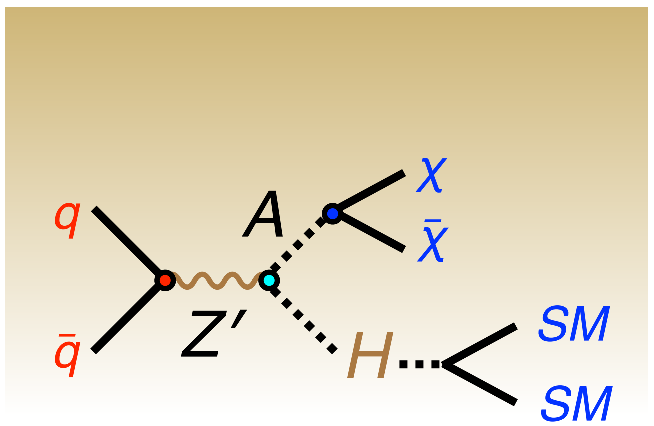


Small adjustments can have a big impact

Algorithm designed to suppress pileup

Using the Higgs to probe dark matter

Mono-Higgs

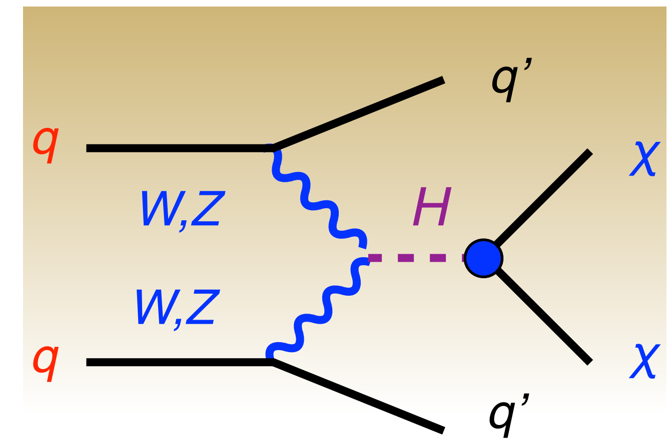


Higgs recoils against DM

Similar to mono-X, but here the Higgs recoils against invisible DM

Decay	Comments
bb	Highest rate
$\gamma\gamma$	Clean signature

Higgs decays to DM

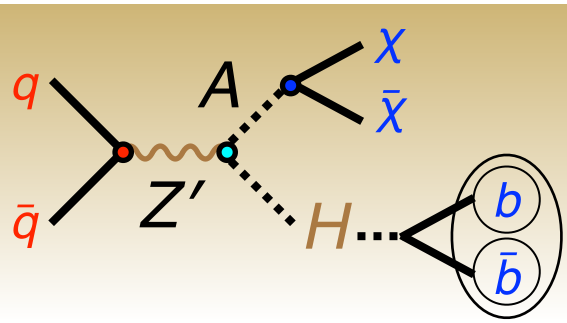


VBF Higgs production

Production modes give something for invisible Higgs to recoil against

Production	objects
ggF + ISR	$P_T \gtrsim 250$ GeV MET $\gtrsim 250$ GeV
VBF	$m_{jj} > 1$ TeV MET >150 GeV
ZH	l^+l^-
WH	$q\bar{q}$
ttH	$t\bar{t}$

Mono-Higgs

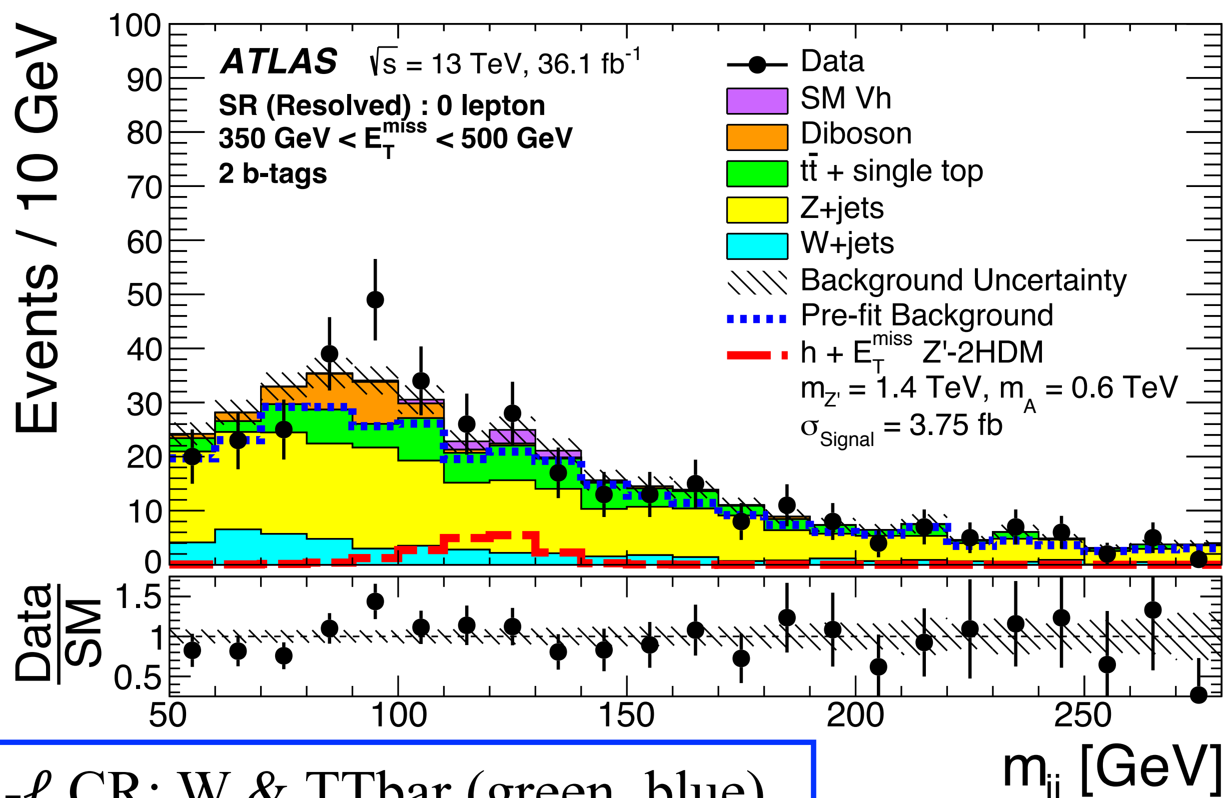


DM recoils against the Higgs

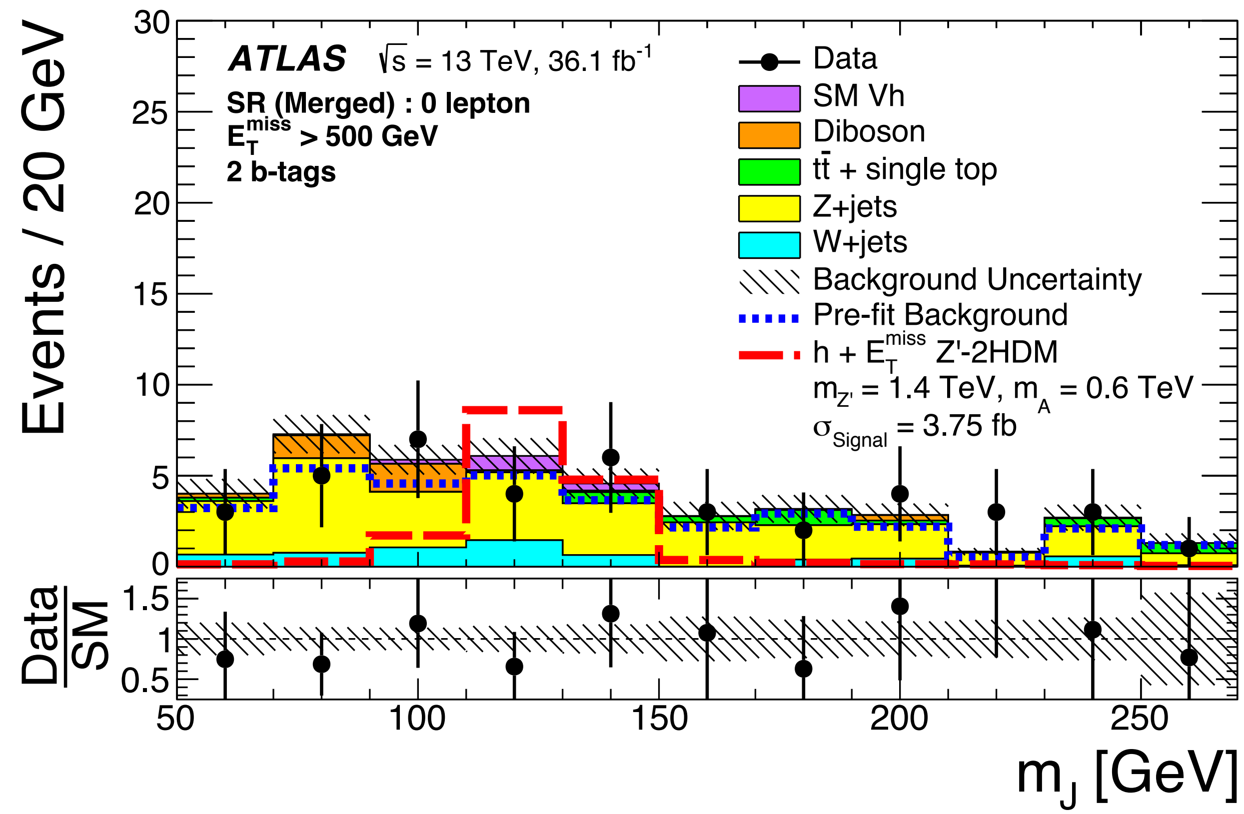
- Largest branching fraction, H → bb
- Resolved (MET < 500 GeV) and boosted (MET > 500 GeV)

Mono-Higgs
CMS bb and $\gamma\gamma$: EXO-16-012
ATLAS H → bb: PRL 119 181804 (2017)
ATLAS H → $\gamma\gamma$: HIGG-2016-18

Resolved, MET < 500 GeV



Boosted, MET > 500 GeV



1-ℓ CR: W & TTbar (green, blue)
$\ell\ell$ CR: Z (yellow)

Systematic uncertainties
MC statistics: 22%
Stat. uncertainty: 62%

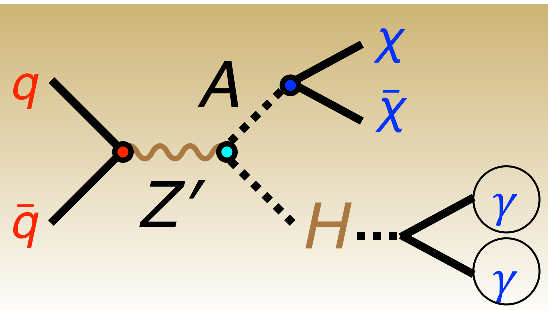
Still mainly statistics limited,
MC is going to be an issue

Most of the sensitivity comes
from the highest MET bins

Range in E_T^{miss} [GeV]	$\sigma^{obs}_{vis,h(b\bar{b})+DM}$ [fb]	$\sigma^{exp}_{vis,h(b\bar{b})+DM}$ [fb]	$\mathcal{A}\times\varepsilon$ [%]
[150, 200)	19.1	$18.3^{+7.2}_{-5.1}$	15
[200, 350)	13.1	$10.5^{+4.1}_{-2.9}$	35
[350, 500)	2.4	$1.7^{+0.7}_{-0.5}$	40
[500, ∞)	1.7	$1.8^{+0.7}_{-0.5}$	55

Mono-Higgs

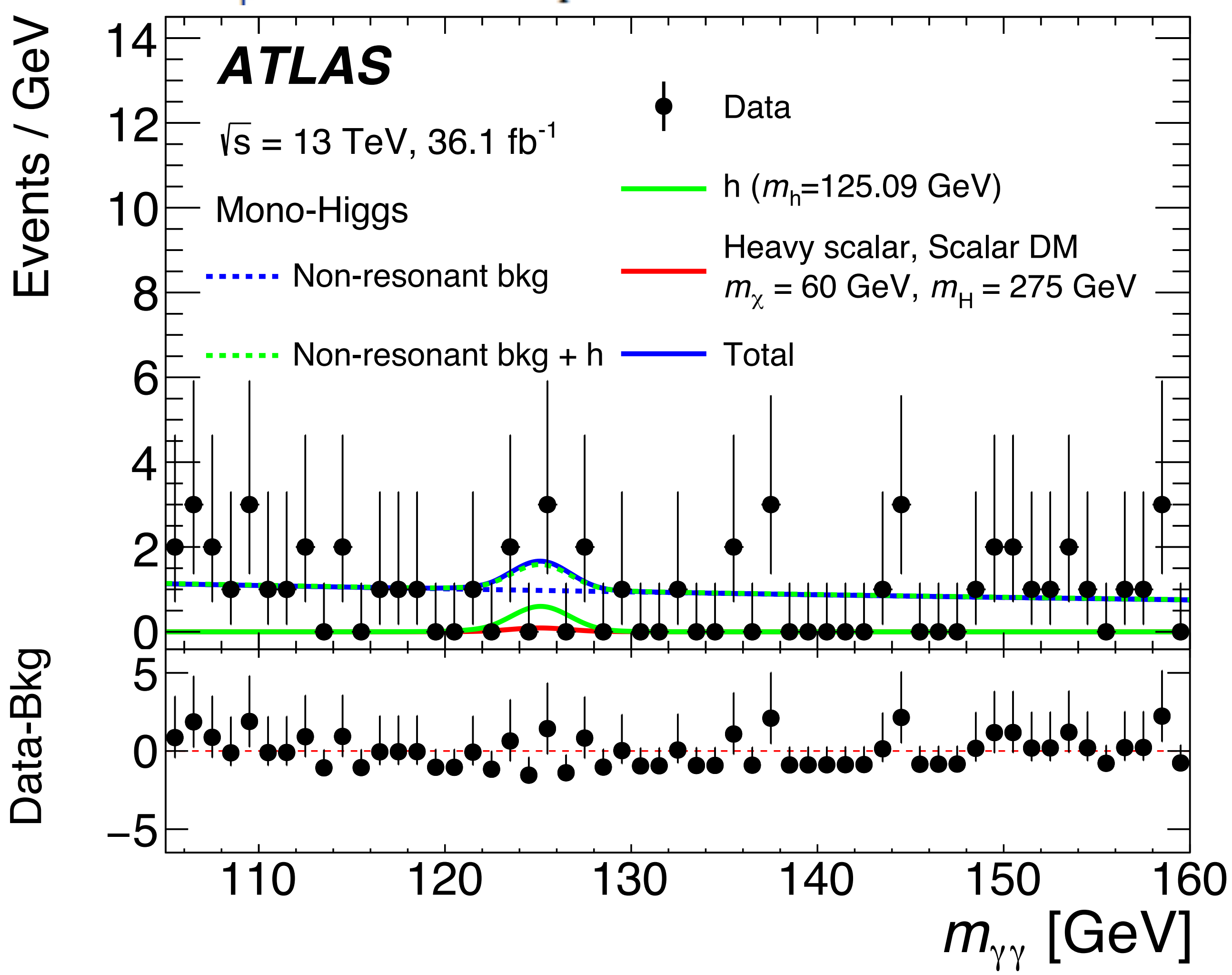
Mono-Higgs
CMS bb and $\gamma\gamma$: EXO-16-012
ATLAS $H \to bb$: PRL 119 181804 (2017)
ATLAS $H \to \gamma\gamma$: HIGG-2016-18

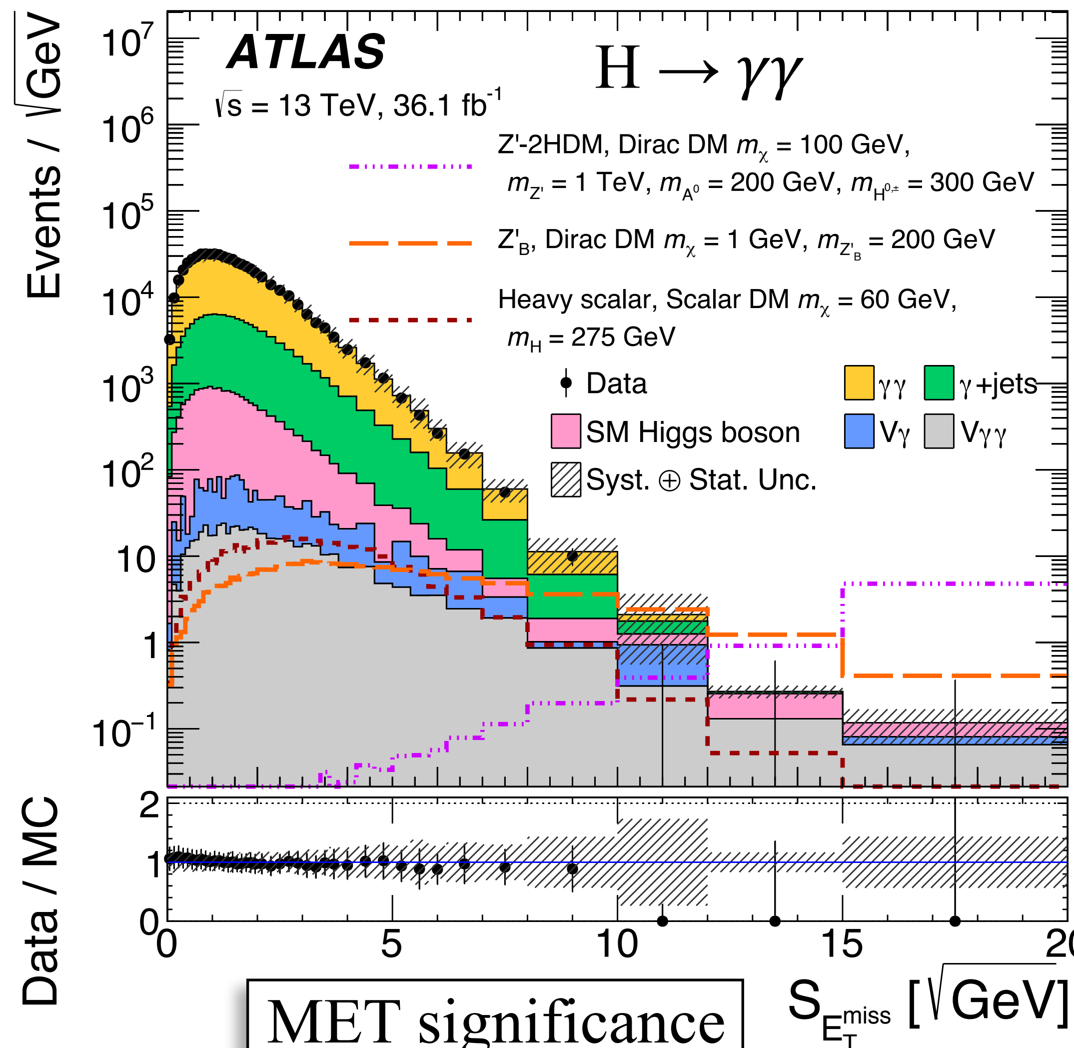


DM recoils against the Higgs

- Boosted (resolved) $H \to bb$
- Resolved $H \to \gamma\gamma$

$S_{E_T^{miss}} > 7\ \sqrt{\text{GeV}}$, $p_T^{\gamma\gamma} > 90$ GeV, lepton veto





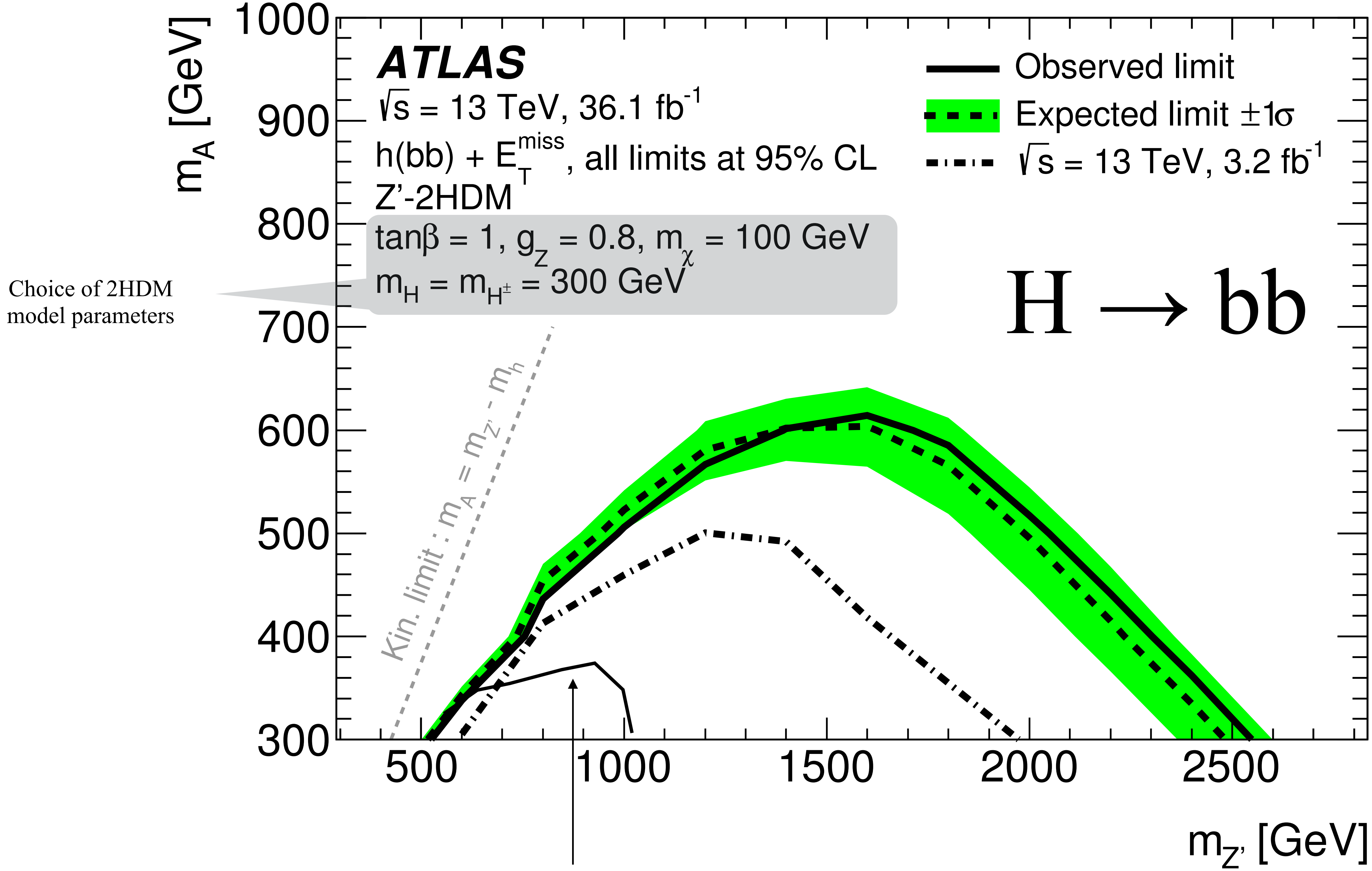
$m_{\gamma\gamma}$

MET significance
$= \text{MET} / \sqrt{E_T}$
(E_T event E_T including jets & γ)

Clean diphoton mass peak

Signal tends to have very high MET

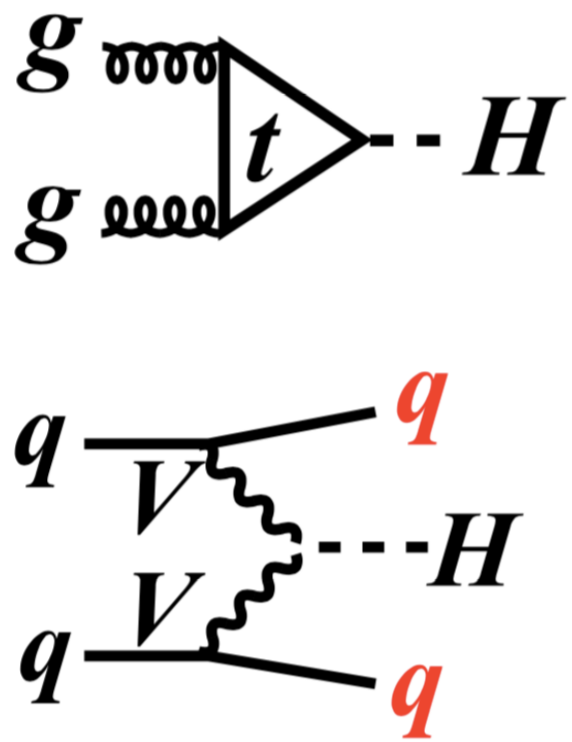
Mono-Higgs interpretation



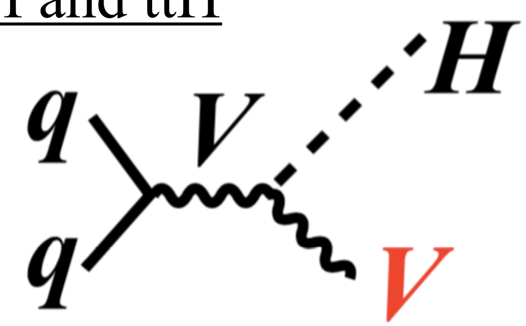
Sketch of H → $\gamma\gamma$ sensitivity

Invisible Higgs searches

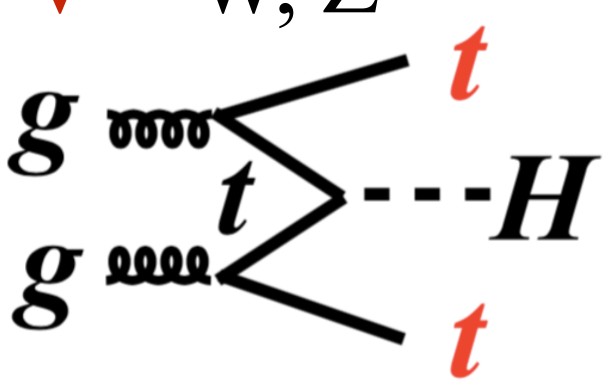
hadron collider production modes

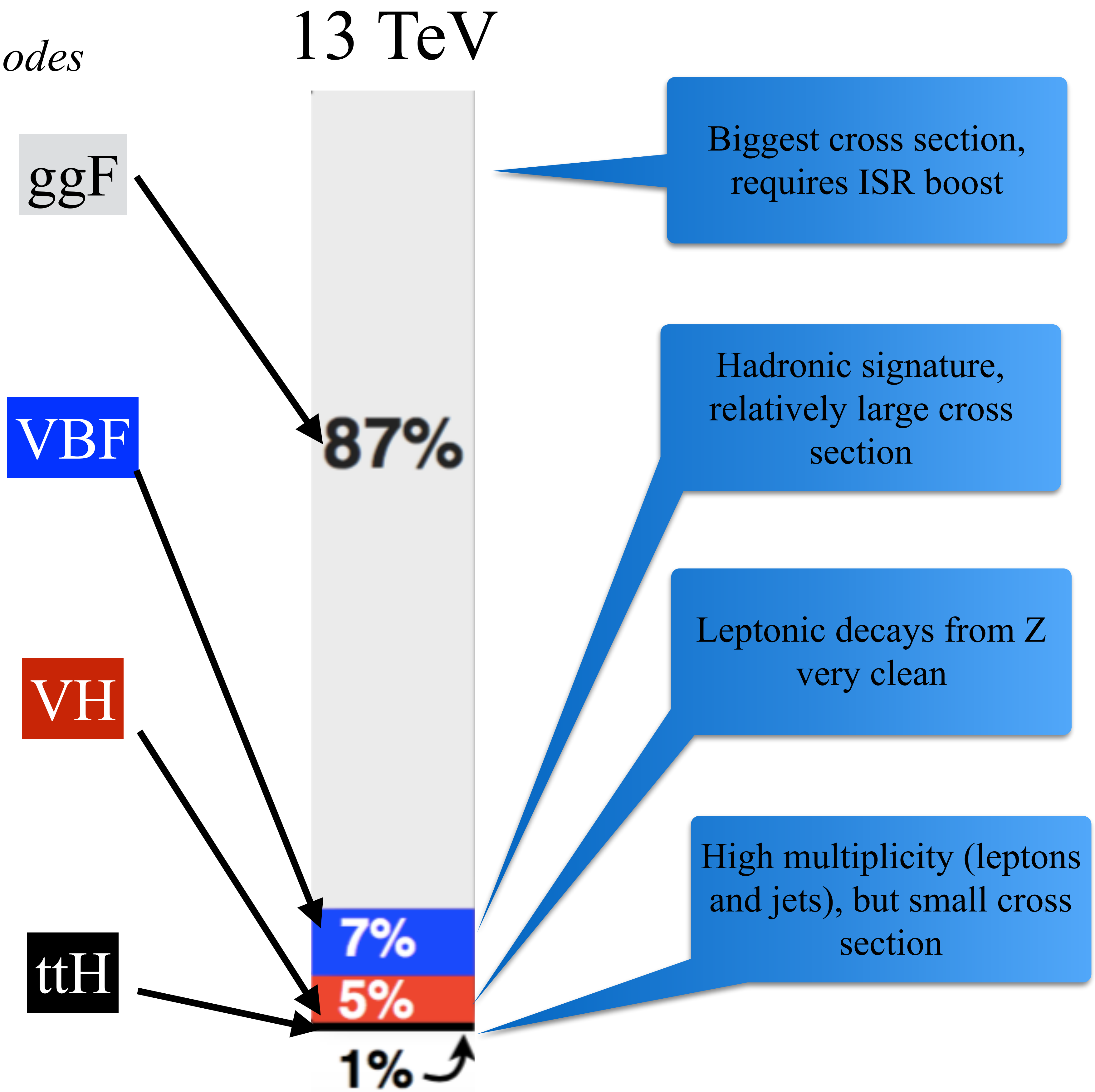


Br hit inVH and ttH



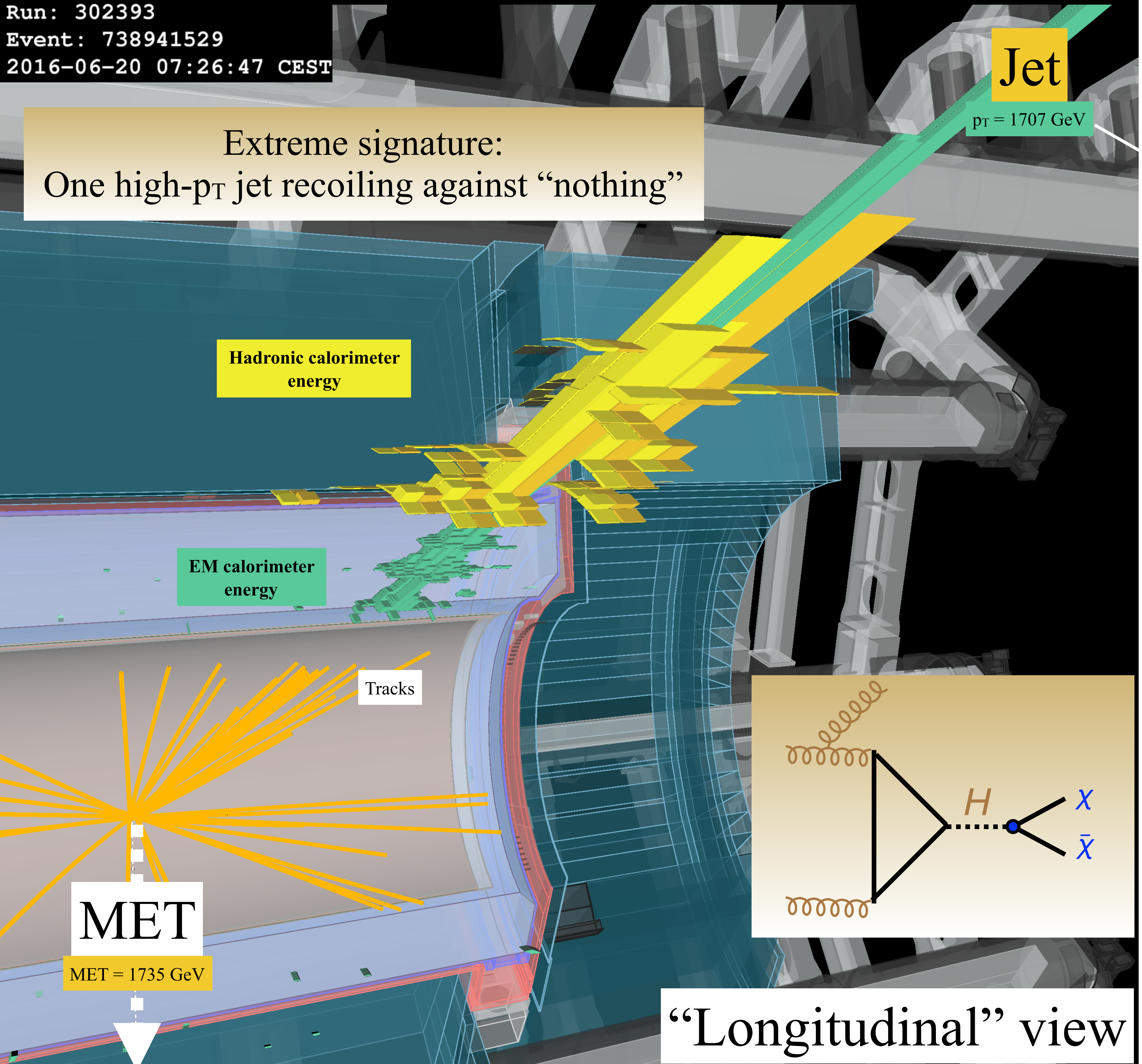
V = W, Z

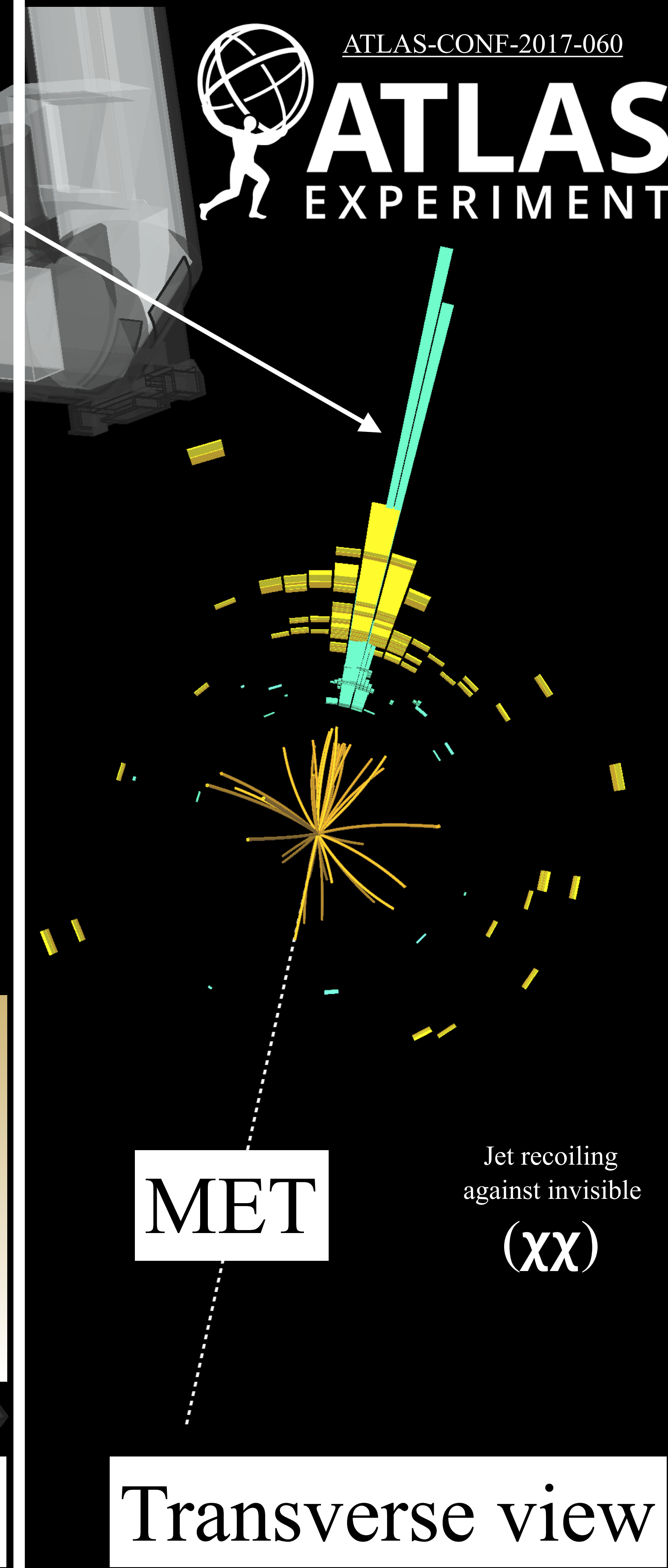




Search for DM “X”: Mono-jet

Extreme signature:
One high-p_T jet recoiling against “nothing”



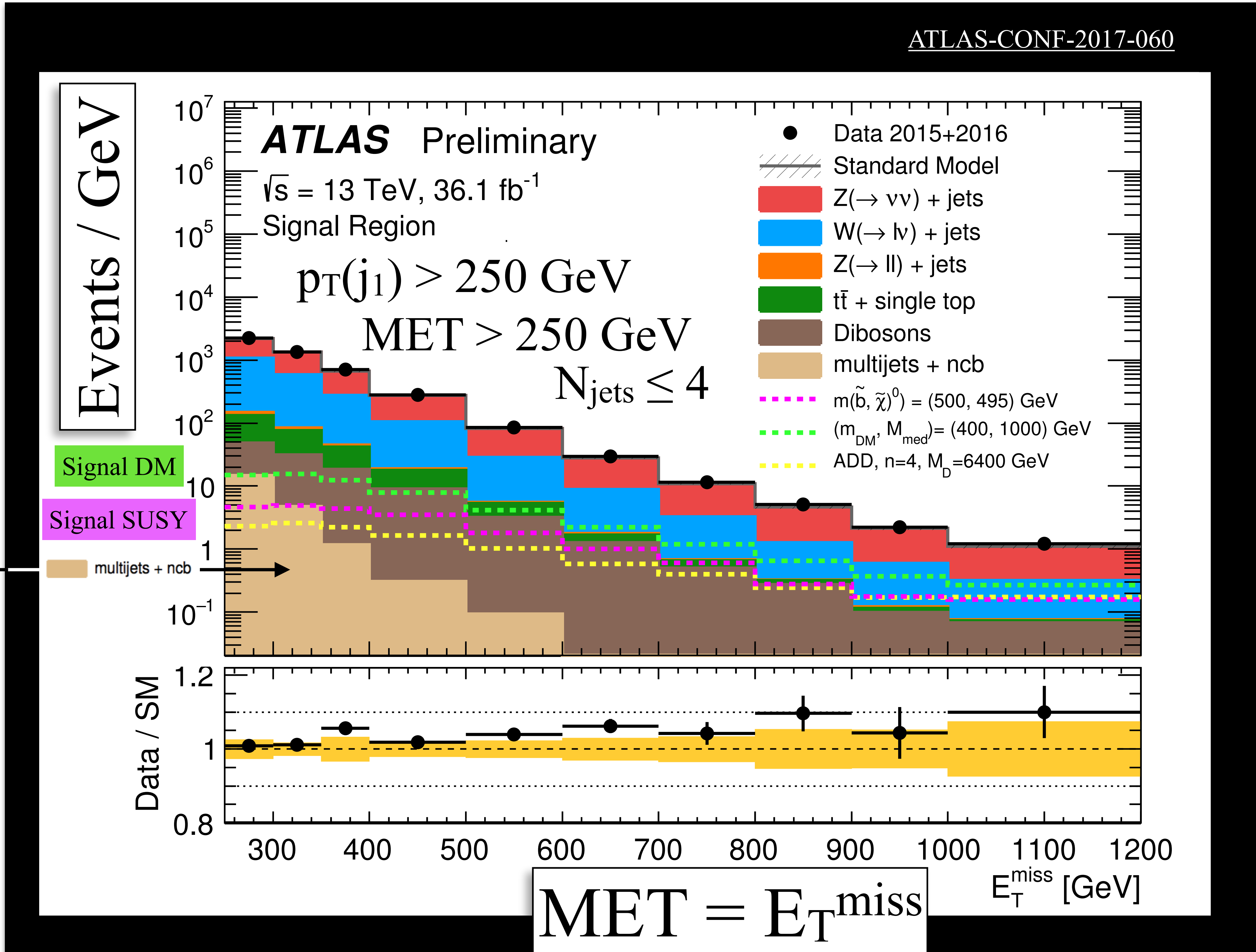


Mono-jet

MET > 250 GeV
- Easy to trigger
- Kills **QCD** (in addition to *Δϕ(j,MET) > 0.4)*

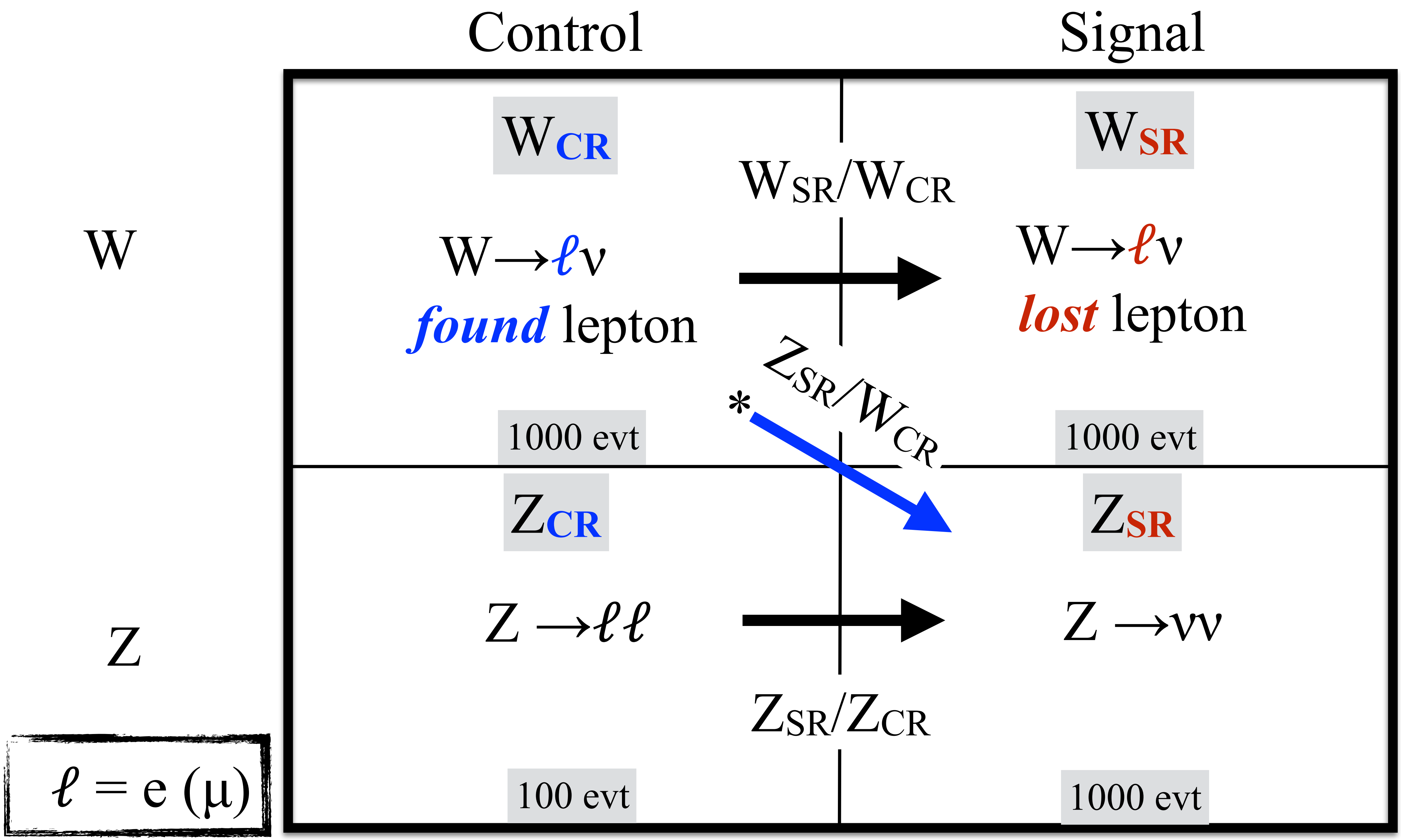
Lepton veto kills
- Top (mostly)
- W→ℓν

Blue background: *ℓ is not reconstructed*



Dominant backgrounds: W→ℓν (lost lepton) and Z→νν

How to estimate invisible backgrounds



- Constrain the W(Z) bkg in SR using CRs with visible leptons
  - W→ℓν: $p_T(\ell)$ + MET
  - Z →ℓℓ: $p_T(\ell\ell)$ + MET

MET in CR corrected to behave like SR

*Technically constrain W(Z) by the same parameter. But in the limit of more W events than Z, it amounts to the blue line.

Background estimation

ATLAS-CONF-2017-060

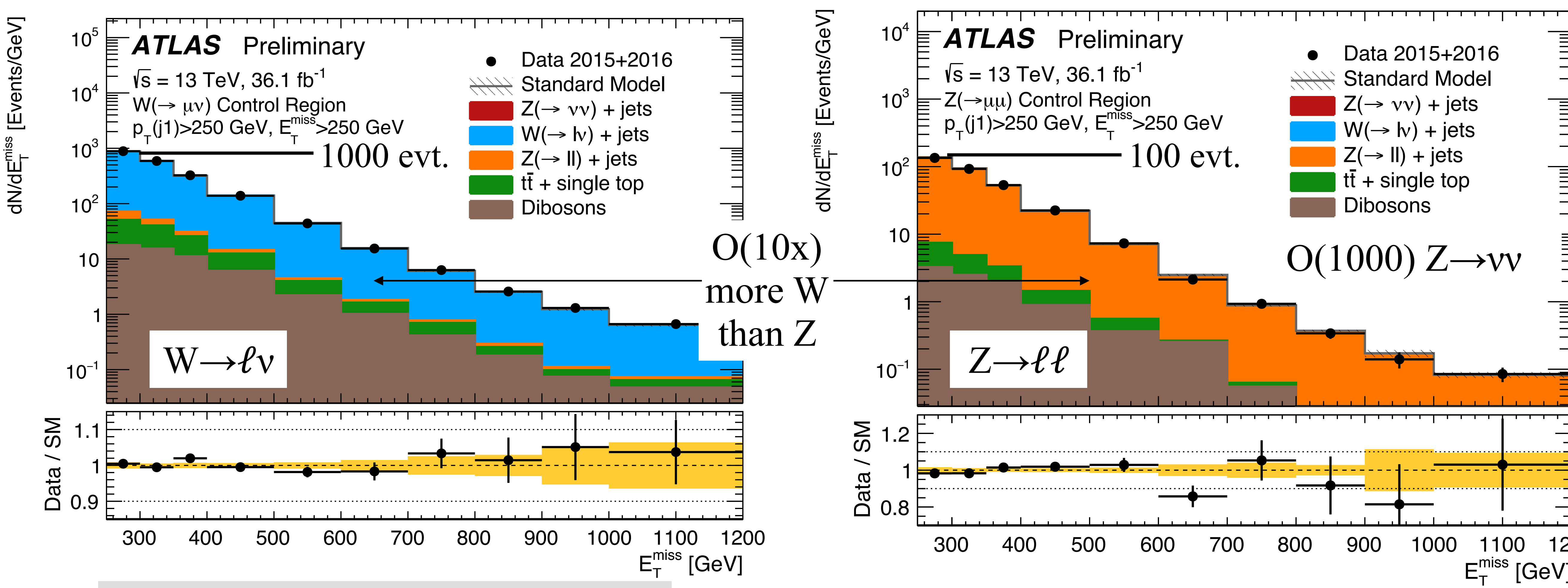
Estimate from CRs using simultaneous fit

- $W \to \ell\nu$
- $Z \to \ell\ell$

More CR stats:
Use $W \to \ell\nu$ to constrain $Z \to \nu\nu$

$W \to \ell\nu$ constraint motivated by branching fractions

- x10 more $W \to \ell\nu$ than $Z \to \ell\ell$
- Requires detailed calculation on correlations between W and Z
- Detailed theory calculation leads to small W→Z uncertainty (J. Lindert et al. 1705.04664)

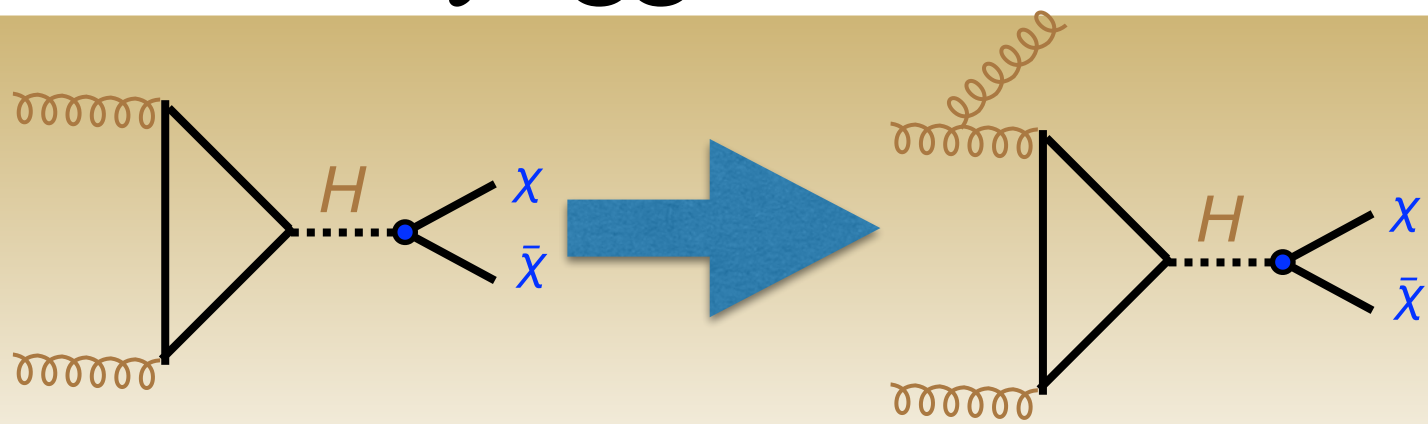


Systematic uncertainties
Jet energy scale (resolution): 0.5-5.0%
Theory: 0.5-2.0%

Slightly lower uncertainties than run 1

Sensitivity: ggF

CMS: JHEP 07 (2017) 014, EXO-16-048
ATLAS: ATLAS-CONF-2017-060



Cannot see this at the LHC *Can see recoil against a jet*

Add an ISR jet

- This is a standard DM search

Discuss the ATLAS analysis details

(but not yet an interpretation, so for that see CMS)

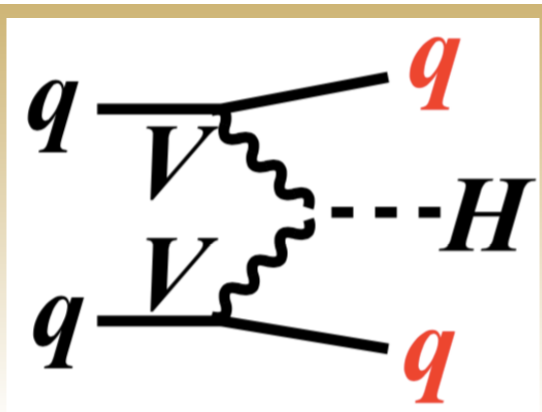
Back of the envelop sensitivity in terms of S/B:

$$\frac{\boldsymbol{\sigma}_{ggF}(H+j)}{\boldsymbol{\sigma}(Z+j) \text{ x } Br(Z \rightarrow \nu\nu)} = \frac{19 \text{ pb}}{6000 \text{ pb}} = \frac{1}{\mathbf{300}}$$

(Doesn't include MET)

Actual S/B: $\frac{1}{\mathbf{100}}$ - $\frac{1}{\mathbf{10}}$

Invisible with VBF



Use the VBF tag jets

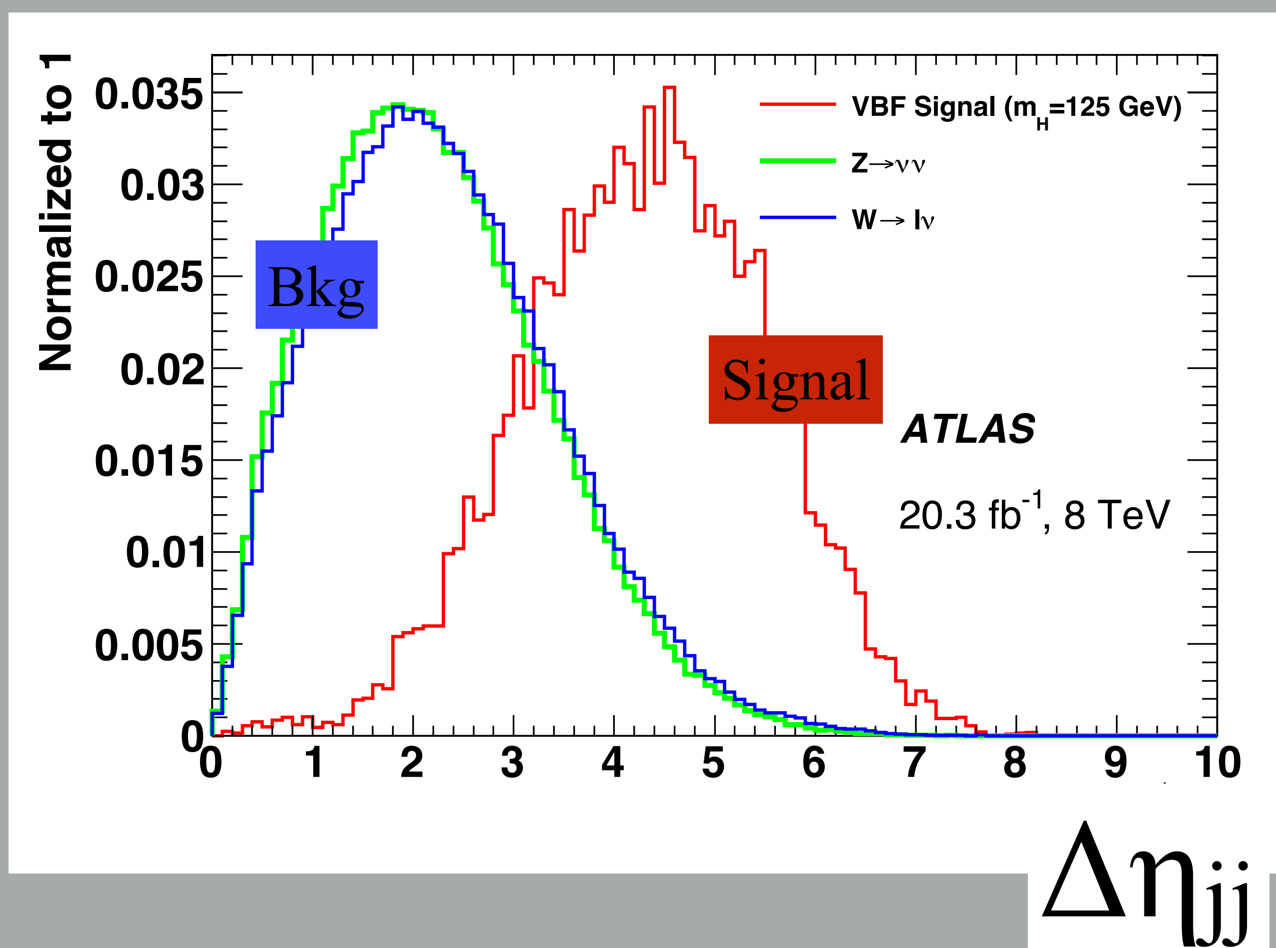
- $m_{jj} > 1.0$ TeV, $\Delta\eta > 4.8$
- MET > 150 GeV

CMS: HIG-16-016
ATLAS: JHEP 01 (2016) 172

No run 2 result from ATLAS yet

VBF: at least one jet at high $|\eta|$, great at killing bkg

Distributions from run 1 analysis



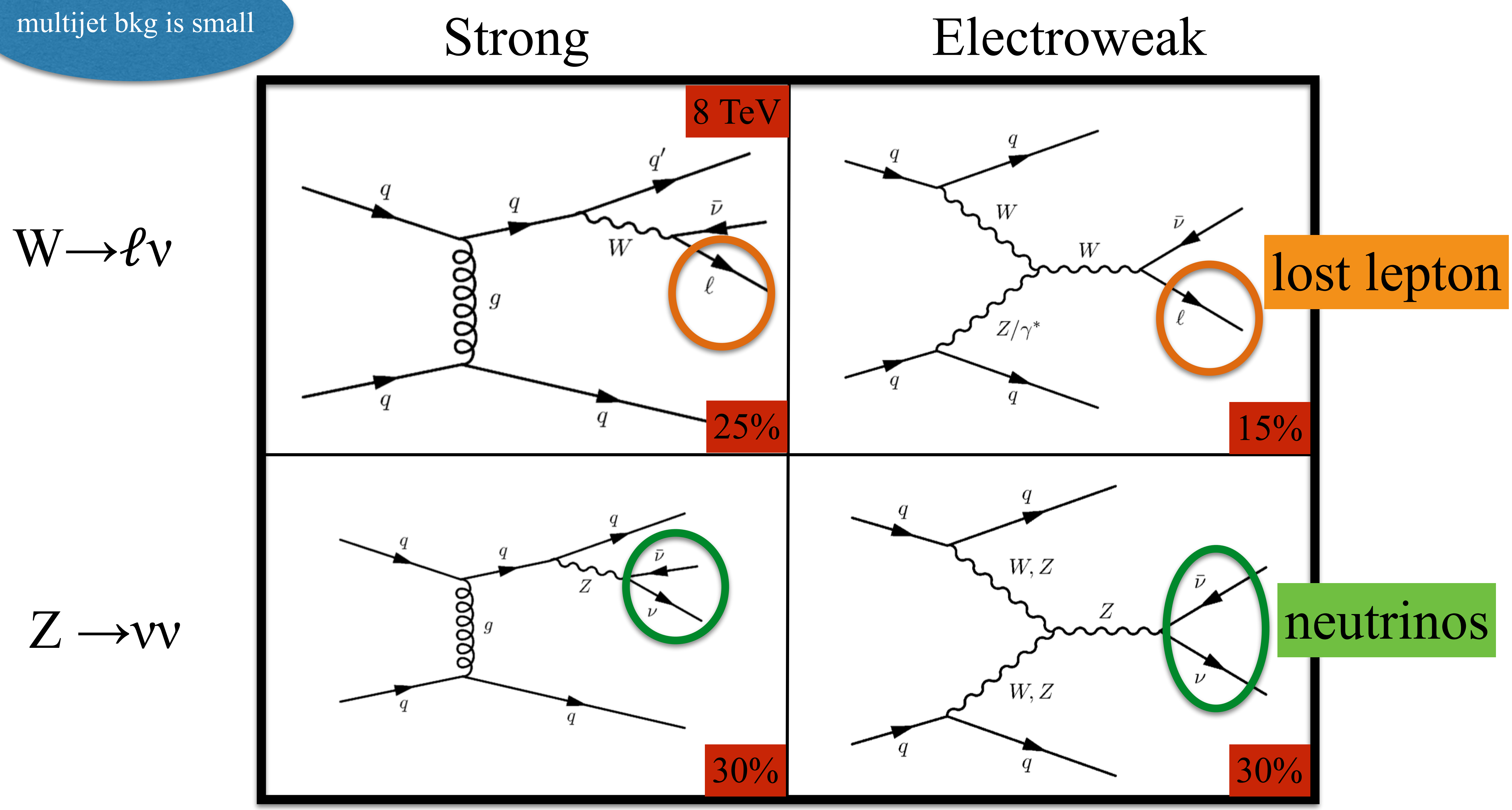
S/B from ATLAS run 1:

$$\frac{S}{\mathbf{B}} = \frac{1}{\mathbf{2}}$$

Systematics matter (more next slide)

Backgrounds for VBF invisible

multijet bkg is small



+ *many more diagrams and interference*

- Backgrounds similar to mono-jet, but EW also starts to contribute at high m_{jj}
- No NNLO W/Z correlation study for VBF though

Identify systematic limitations

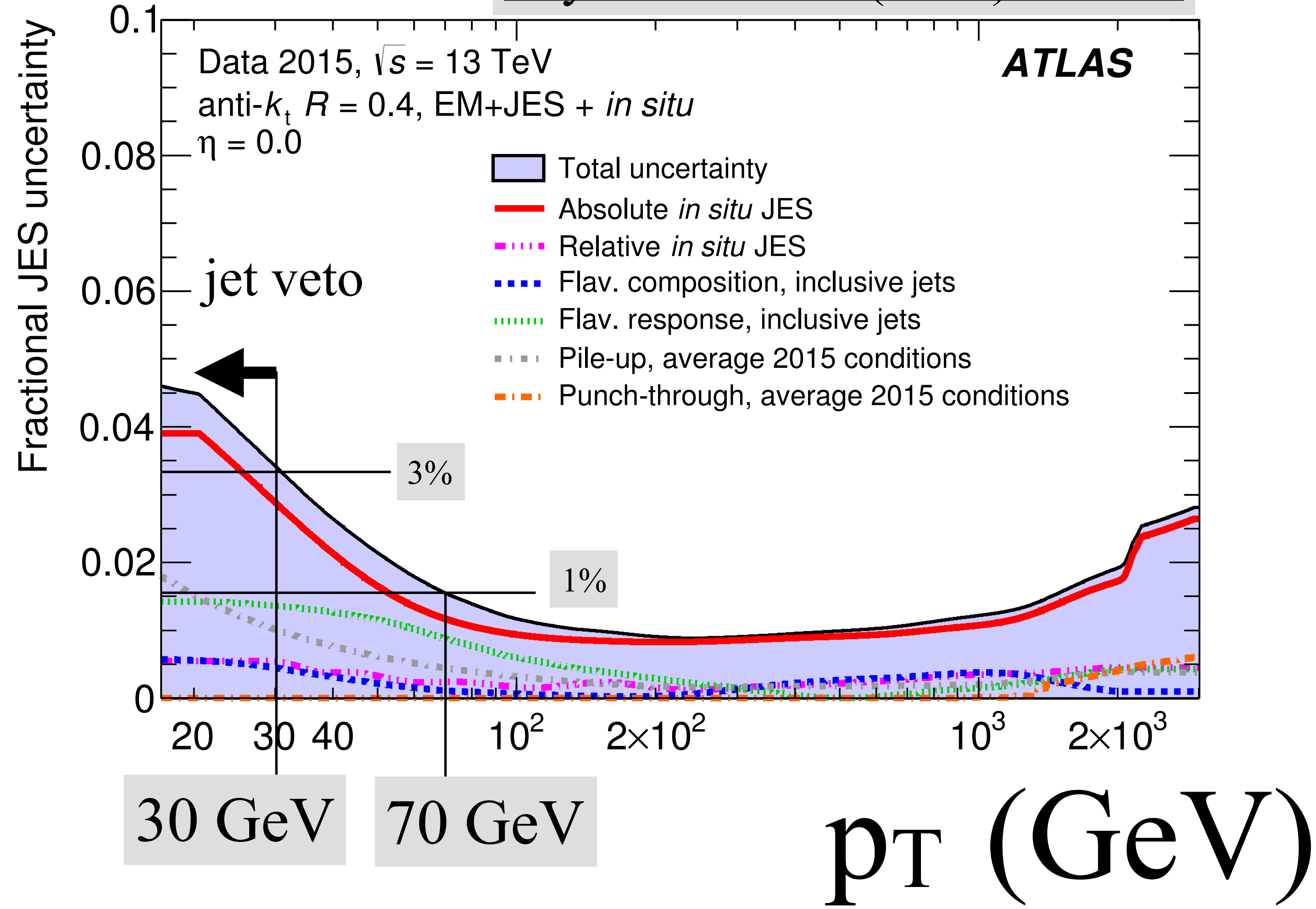
Yields — Cancel in ratio

Uncertainty (%)

Source	W(Z)	W/Z ratio
Jet	17-33	3-5
qcd scale	5-36	7.8-12
W/Z th.	10	
PDF	3-5	1-2

Correlation between W and Z
Unlike mono-jet, there is no detailed NNLO calculation of W/Z correlation.

Phys. Rev. D 96 (2017) 072002



Run 1: 50 $Z\to\ell\ell$ events (15% stat unc.)

If 100 $Z\to\ell\ell$ events (10% stat. unc.),

1. Drop the W→Z extrapolation
2. Reduce theory uncertainties

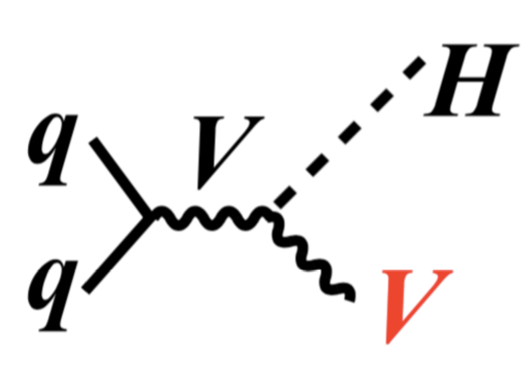
Experimental uncertainties dominated by jet veto

Theory work can make an impact

Experimental work can make an impact

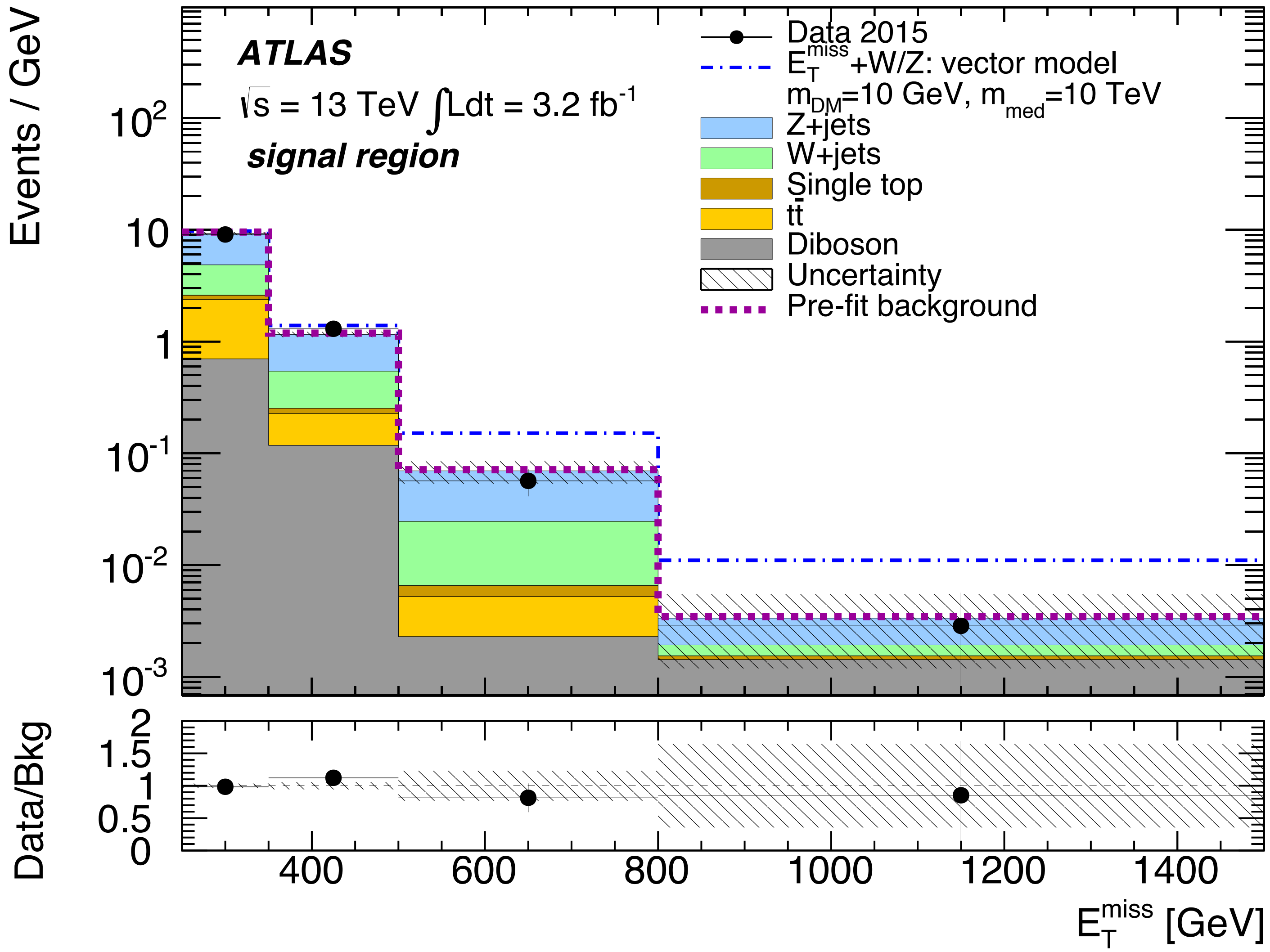
Invisible with VH

ATLAS run 1: Eur. Phys. J. C (2015) 75-337
ATLAS: Phys. Lett. B 763 (2016) 251
CMS: EXO-16-048



$V \to qq$ *(boosted or resolved)*

- MET > 250 GeV
- R = 1.0 jet, p_T > 200 GeV
- Jet mass consistent with W(Z)



Like previous analyses, W and Z are important bkg

(Here top matters too)

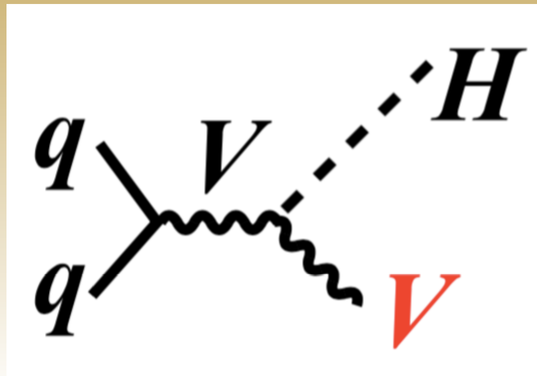
$$\frac{S}{B} = \frac{1}{20} - \frac{1}{2}$$

H→*inv* interpretation not shown

Expected limit ~ 78%
(ATLAS run 1)

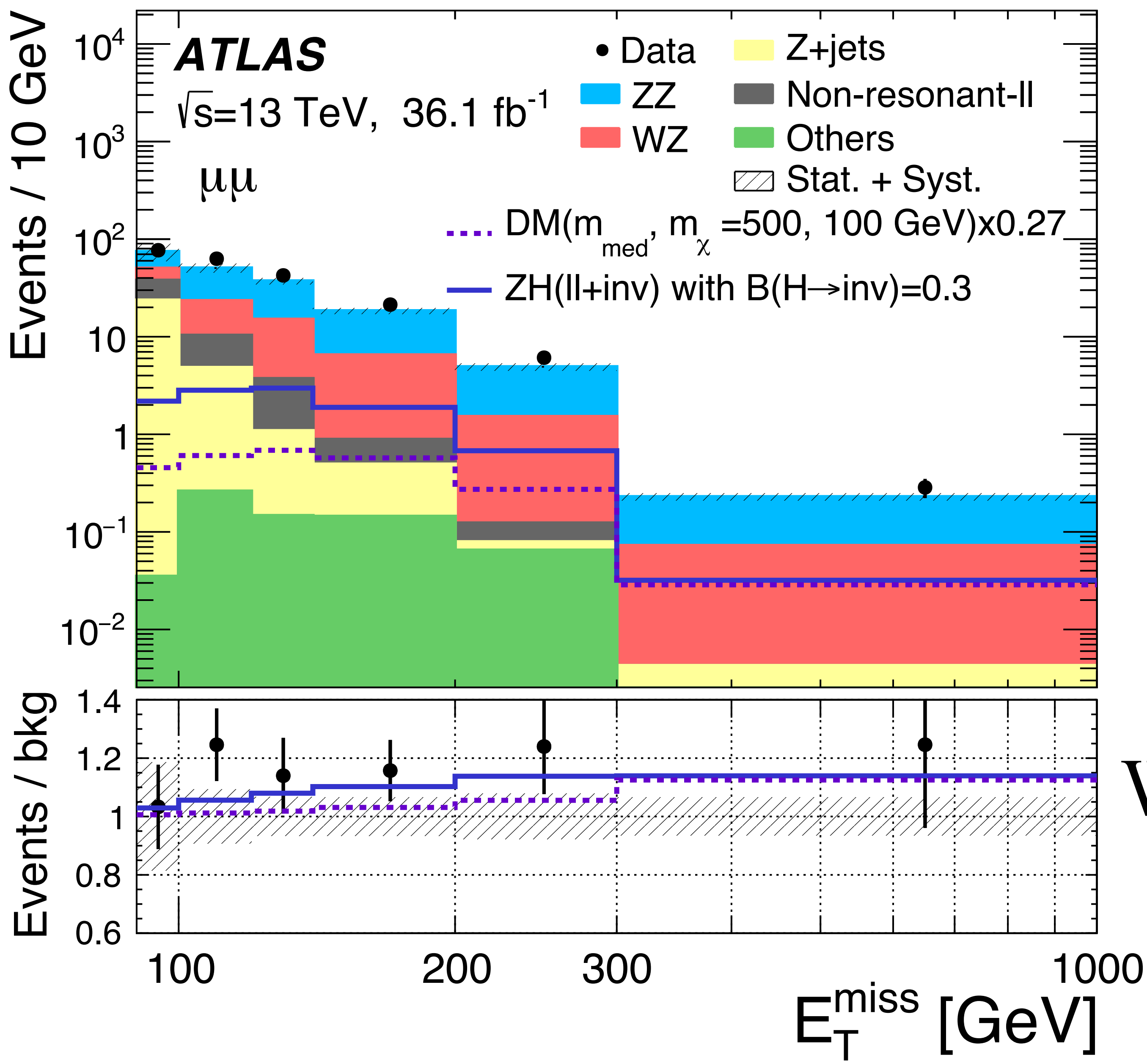
Invisible with ZH

ATLAS: HIGG-2016-28



$Z \to \ell\ell$ ($\ell = e, \mu$)

- Clean signature
- MET > 90 GeV
- ΔΦ(Z,MET) > 2.7 (Higgs recoiling against Z)



$$\frac{S}{B} \sim \frac{1}{3}$$

Expected limit ~ 40%

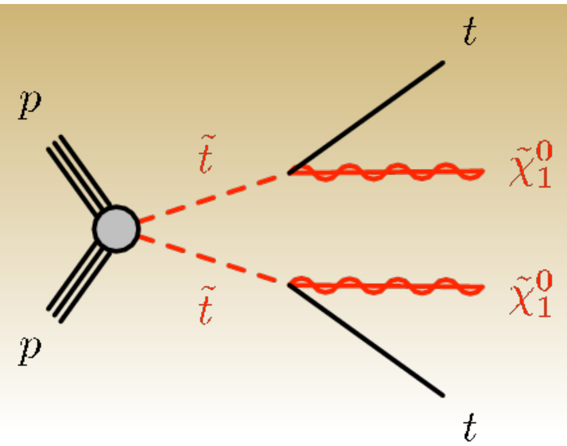
Main background is ZZ (WZ)

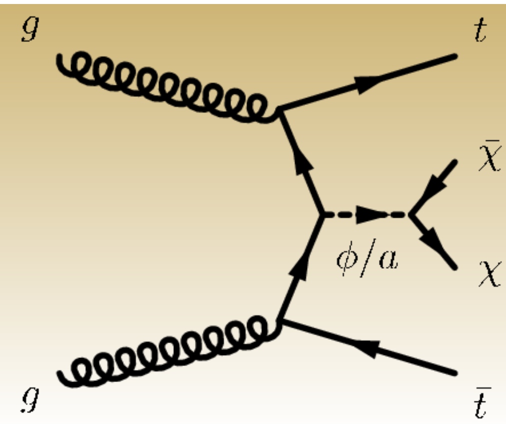
[WZ → lepton out of acceptance]

ZZ control sample is stats. limited
Relies on theory calculation
Approximately equal theory & exp. uno

With lumi, use data to normalize

Invisible with ttH

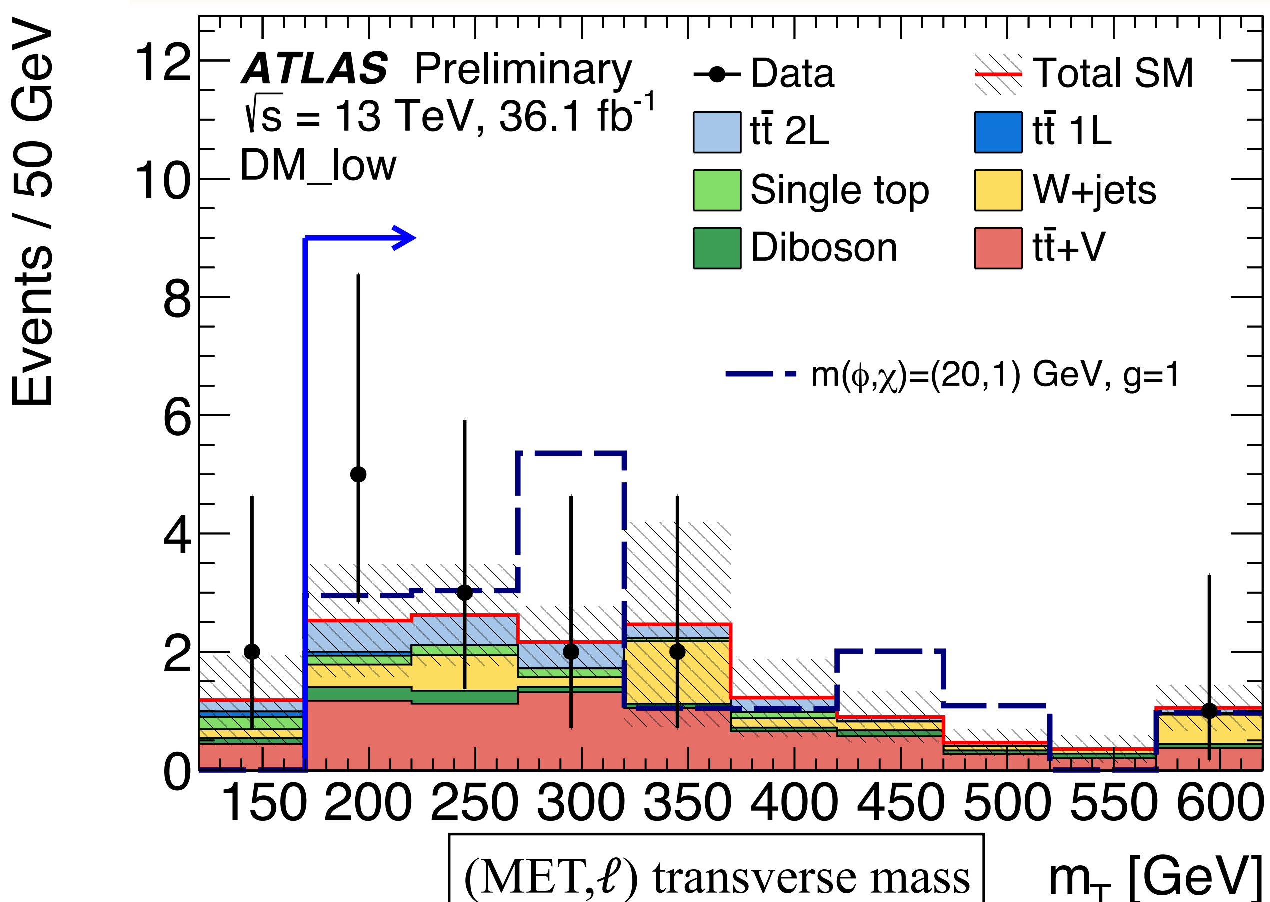




ℓ + jets + MET bin for DM

- SUSY analysis with **13 SR**
- Now includes a bin optimized for DM

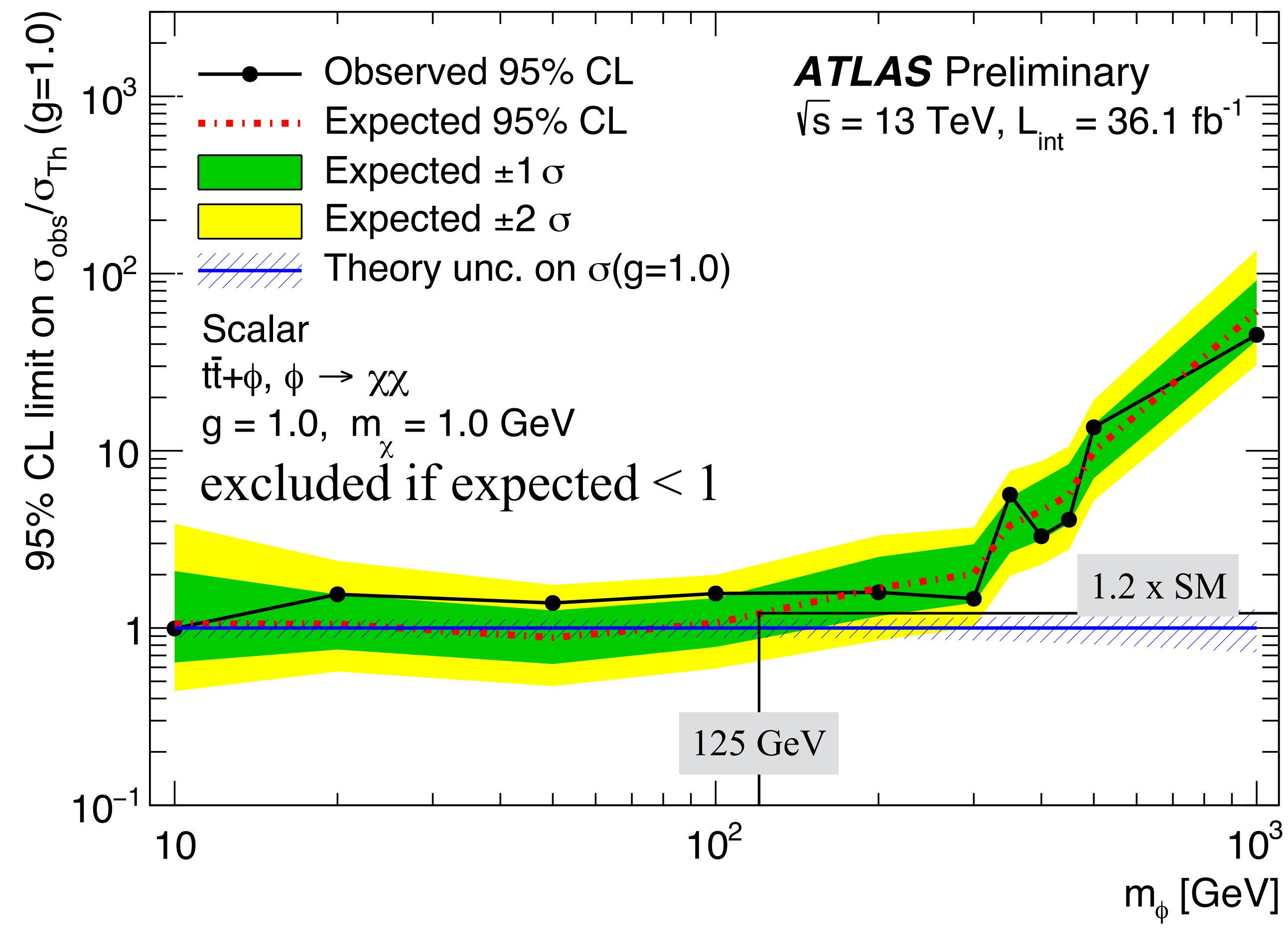
Dedicated bin optimized for DM



(MET,ℓ) transverse mass

$p_T(e)$ or $p_T(\mu)$ > 5 GeV or 4 GeV
MET > 320 GeV
Njets ≥ 4

ATLAS-CONF-2017-037

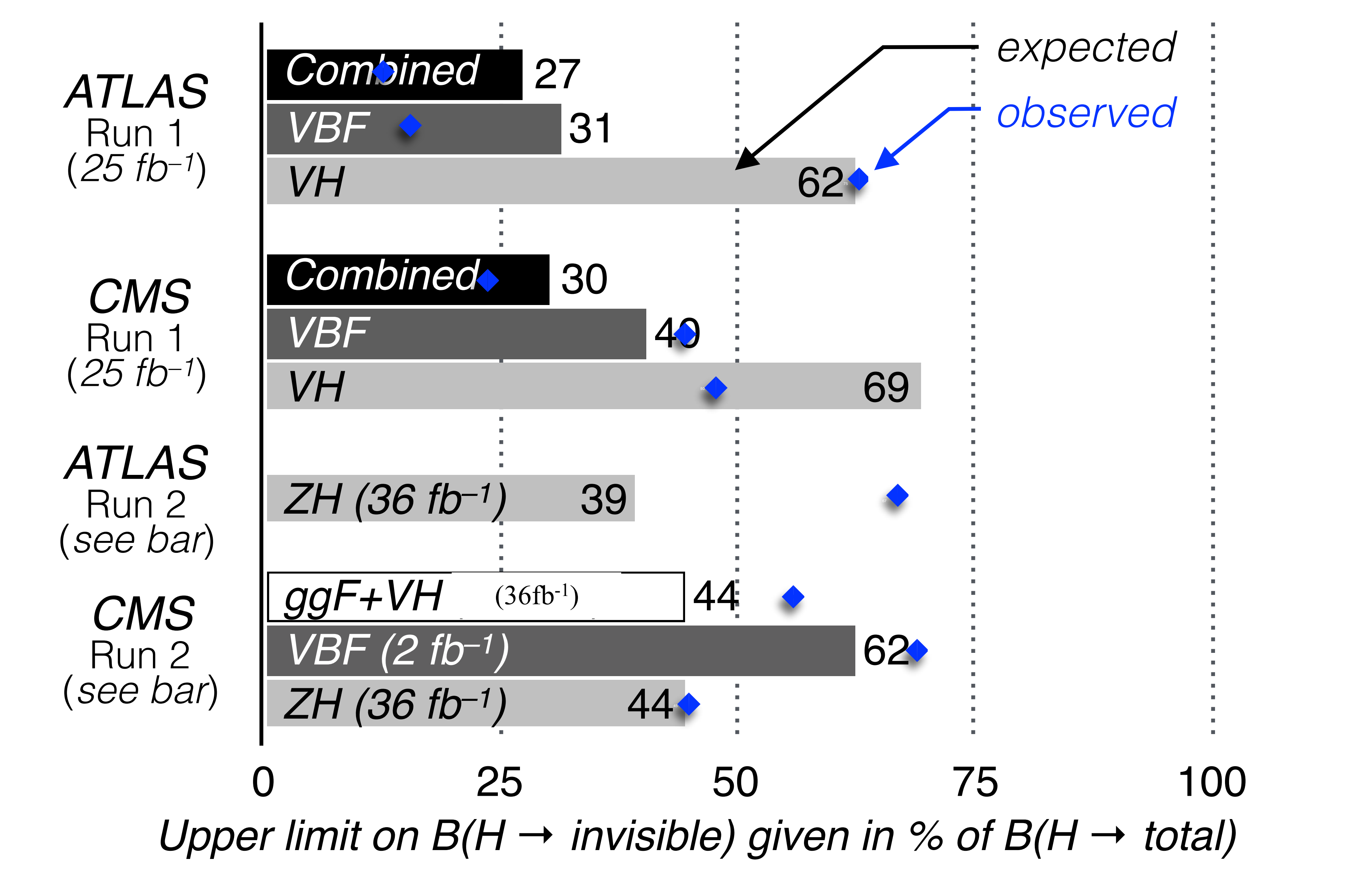


Compare with 3 x SM, reinterpreted using CMS run 1 data
(N. Zhou et al. PRL 113 (2014) 151801)

Invisible Higgs summary

Invisible Higgs decays comparisons

For upper limits, smaller is better. 95% conf. level. Select competitive results are shown.



Sources:

J. High Energy Phys.

11 (2015) 206

01 (2016) 172

02 (2017) 135

ATLAS-EXOT-2015-08

ATLAS-CONF-

2017-040

2017-060

CMS-PAS-

HIG-15-012,

HIG-16-008,

HIG-16-009,

HIG-16-016,

EXO-16-052

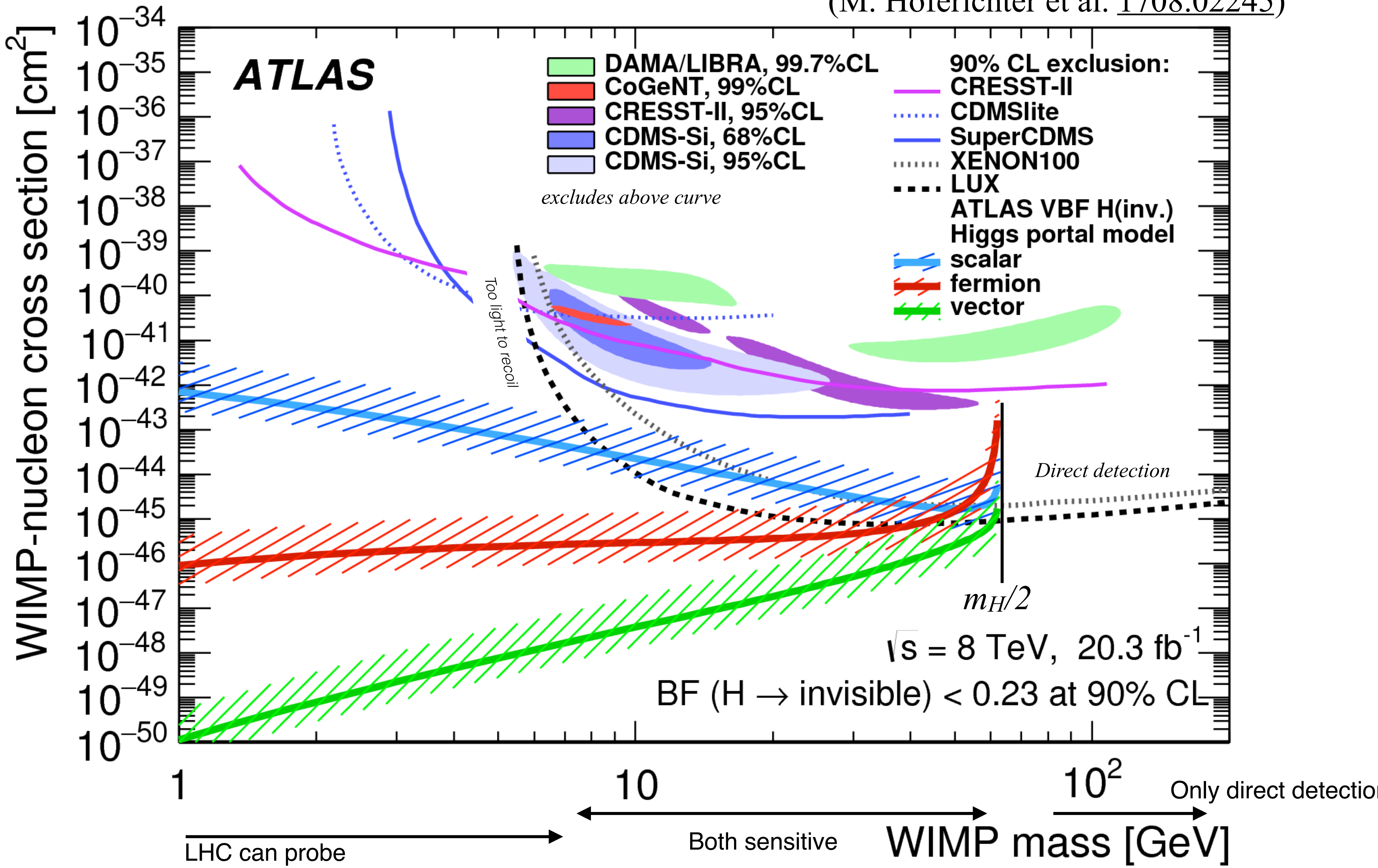
EXO-16-037

More entries on the way

Dark matter interpretation

shaded bands:
Higgs-nucleon form factor uncertainty

Lattice QCD improvements will make experimental improvements more striking (M. Hoferichter et al. 1708.02245)



Conclusions

Higgs recoils against DM

- bb ($\gamma\gamma$) + H→inv

H→inv searches, use production modes

- ggF (mono-jet)
- VBF
- V→qq *(boosted)*
- Z→$\ell\ell$
- ttH

Comparison with direct detection

- LHC sensitive at low mass

The MET trigger is critical for (almost) all these searches

VBF is the most sensitive

- Limitations mainly come from systematic uncertainty
- Theory can improve this
- Experimentalists have work to do too

ZH is a very clean search

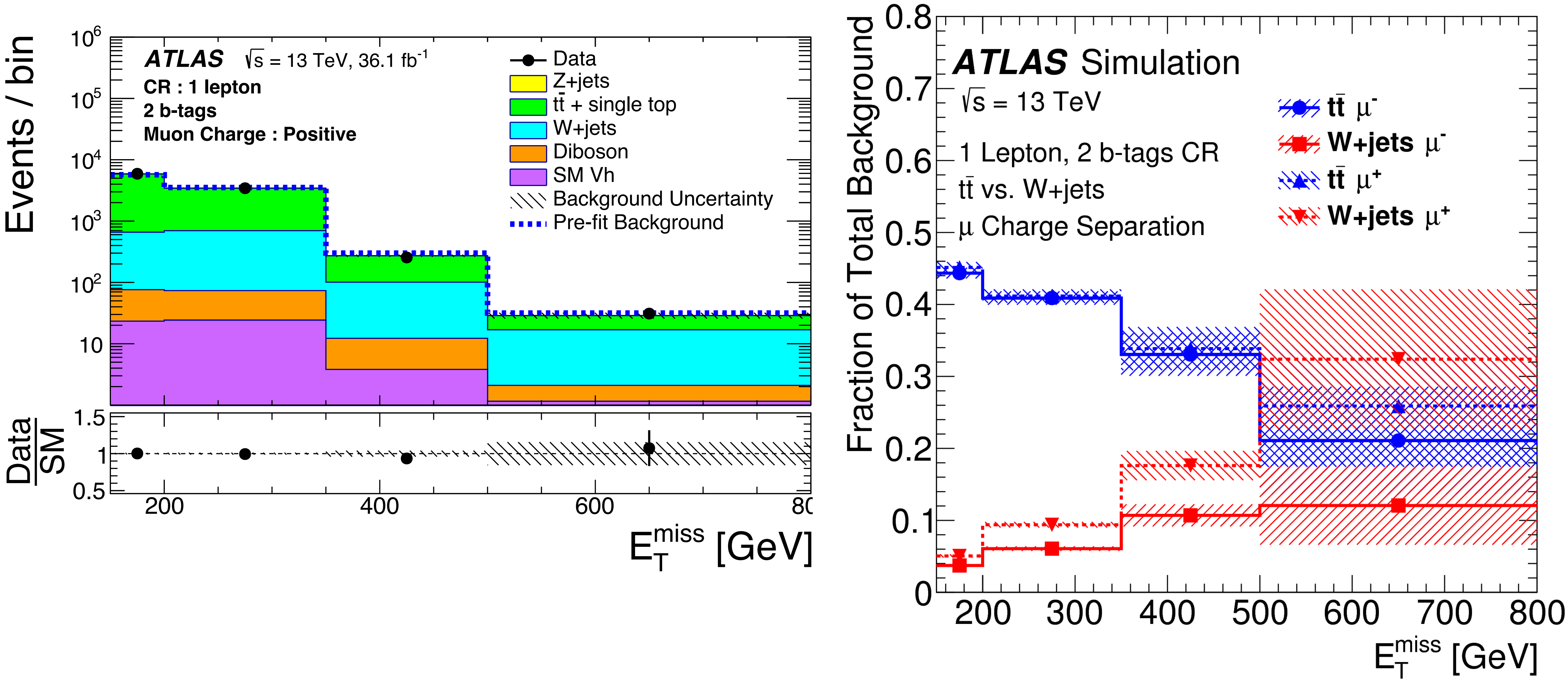
- Control sample stats. get larger with luminosity

Backup

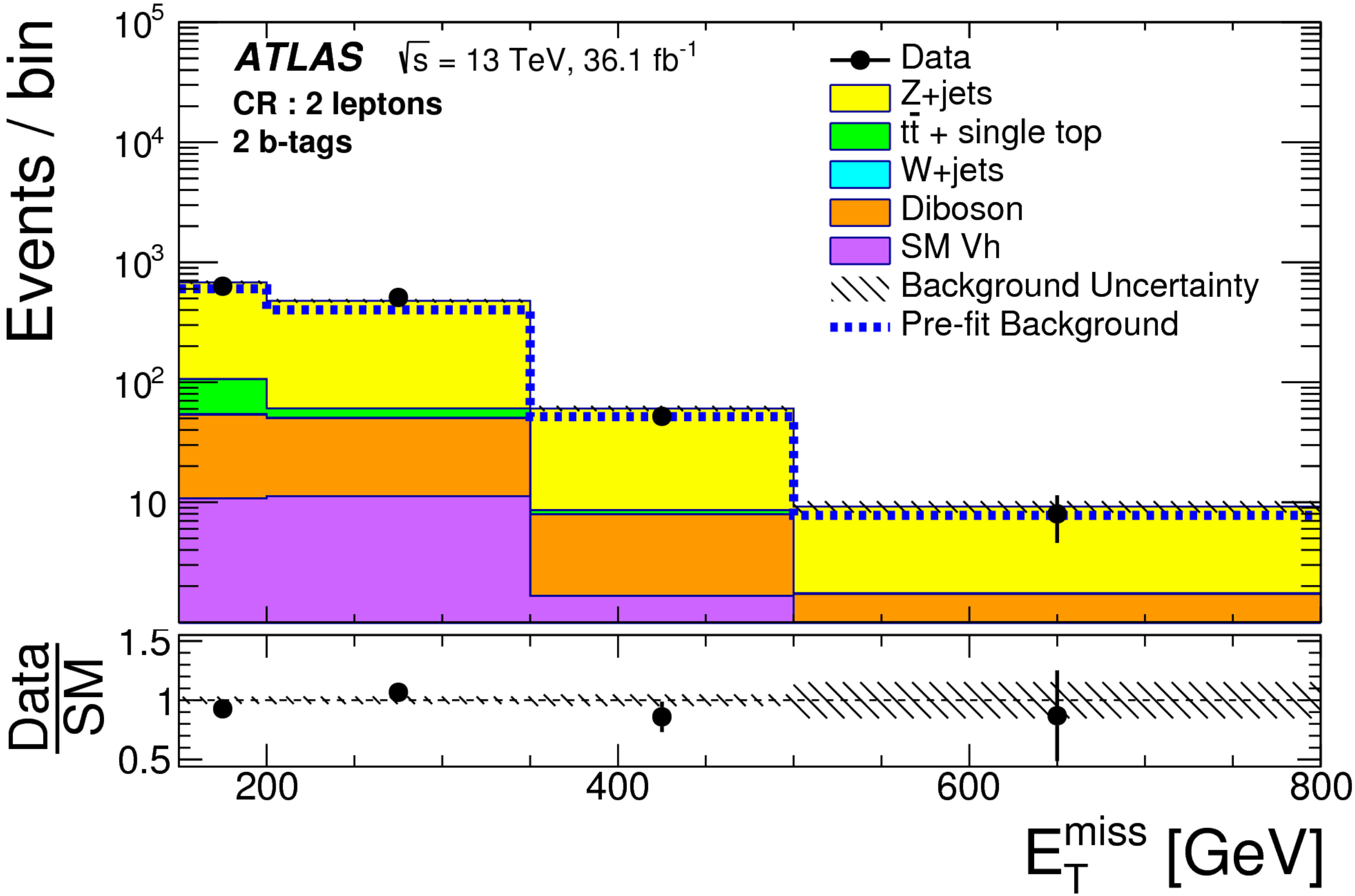
Mono-Higgs: control samples

<table>
<tr><td>Region</td><td>SR</td><td>1μ-CR</td><td>2ℓ-CR</td></tr>
<tr><td>Trigger</td><td>$E_{\mathrm{T}}^{\mathrm{miss}}$</td><td>$E_{\mathrm{T}}^{\mathrm{miss}}$</td><td>Single lepton</td></tr>
<tr><td>Leptons</td><td>No e or μ</td><td>Exactly one μ</td><td>Exactly two e or μ
$83\ \mathrm{GeV} < m_{ee} < 99\ \mathrm{GeV}$
$71\ \mathrm{GeV} < m_{\mu^{\pm}\mu^{\mp}} < 106\ \mathrm{GeV}$</td></tr>
<tr><td rowspan="2">Resolved</td><td>$E_{\mathrm{T}}^{\mathrm{miss}} \in [150, 500)$ GeV
$p_{\mathrm{T}}^{\mathrm{miss,trk}} > 30$ GeV (1 b-tag only)
$\min\left[\Delta\phi\left(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\,j}\right)\right] > \pi/9$
$\Delta\phi\left(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\mathrm{\,miss,trk}}\right) < \pi/2$
–</td><td>$p_{\mathrm{T}}(\mu, E_{\mathrm{T}}^{\mathrm{miss}}) \in [150, 500)$ GeV
$p_{\mathrm{T}}(\mu, \vec{p}_{\mathrm{T}}^{\mathrm{\,miss,trk}}) > 30$ GeV
$\min\left[\Delta\phi\left(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\,j}\right)\right] > \pi/9$
$\Delta\phi\left(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\mathrm{\,miss,trk}}\right) < \pi/2$
–</td><td>$p_{\mathrm{T}}(\ell, \ell) \in [150, 500)$ GeV
–
–
–
$E_{\mathrm{T}}^{\mathrm{miss}} \times \left(\sum_{\mathrm{jets,leptons}} p_{\mathrm{T}}\right)^{-1/2} < 3.5\ \mathrm{GeV}^{1/2}$</td></tr>
<tr><td colspan="3">Number of central small-R jets ≥ 2
Leading Higgs candidate small-R jet $p_{\mathrm{T}} > 45$ GeV
$H_{\mathrm{T},2j} > 120$ GeV for 2 jets, $H_{\mathrm{T},3j} > 150$ GeV for > 2 jets
$\Delta\phi\left(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T},h}\right) > 2\pi/3$
Veto on τ-leptons
$\Delta R\left(\vec{p}_{h}^{\,j_1}, \vec{p}_{h}^{\,j_2}\right) < 1.8$
Veto on events with > 2 b-tags
Sum of p_{T} of two Higgs candidate jets and leading extra jet $> 0.63 \times H_{\mathrm{T,all\,jets}}$
b-tagging : one or two small-R calorimeter jets
Final discriminant = Dijet mass</td></tr>
<tr><td rowspan="2">Merged</td><td>$E_{\mathrm{T}}^{\mathrm{miss}} \geq 500$ GeV
$p_{\mathrm{T}}^{\mathrm{miss,trk}} > 30$ GeV
$\min\left[\Delta\phi\left(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\,j}\right)\right] > \pi/9$
$\Delta\phi\left(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\mathrm{\,miss,trk}}\right) < \pi/2$</td><td>$p_{\mathrm{T}}(\mu, E_{\mathrm{T}}^{\mathrm{miss}}) \geq 500$ GeV
$p_{\mathrm{T}}(\mu, \vec{p}_{\mathrm{T}}^{\mathrm{\,miss,trk}}) > 30$ GeV
$\min\left[\Delta\phi\left(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\,j}\right)\right] > \pi/9$
$\Delta\phi\left(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\mathrm{\,miss,trk}}\right) < \pi/2$</td><td>$p_{\mathrm{T}}(\ell, \ell) \geq 500$ GeV
–
–
–</td></tr>
<tr><td colspan="3">Number of large-R jets ≥ 1
Veto on τ-lepton not associated to large-R jet
Veto on b-jets not associated to large-R jet
H_{T}-ratio selection (<0.57)
b-tagging : one or two ID track jets matched to large-R jet
Final discriminant = Large-R jet mass</td></tr>
</table>

Mono-Higgs: control samples



Mono-Higgs: control samples



ggF H→inv Interpretation of mono-jet (run 1)

EXOT-2013-13

Table 11 The observed and expected 95% CL upper limit on $\sigma \times \mathrm{BR}(H \to \mathrm{invisible})$ as a function of the boson mass, and the expected $\pm 1\sigma$ and $\pm 2\sigma$ ranges of limits in the absence of a signal. The results are expressed in terms of the ratio to the production of an SM Higgs-like boson with $\mathrm{BR}(H \to \mathrm{invisible}) = 1$.

	95% CL limits on $\sigma \times \mathrm{BR}(H \to \mathrm{invisible})/\sigma_{SM}$					
m_H [GeV]	Observed	Expected	-1σ	$+1\sigma$	-2σ	$+2\sigma$
115	1.67	2.01	1.41	2.92	1.04	4.07
120	1.51	1.83	1.27	2.72	0.93	4.03
125	1.59	1.91	1.35	2.77	1.00	3.93
130	1.47	1.77	1.26	2.51	0.93	3.47
150	1.65	1.99	1.39	2.89	1.02	4.14
200	2.04	2.50	1.69	3.96	1.21	6.78
300	2.44	2.94	2.08	4.21	1.54	5.88

Invisible with VBF

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Requirement	SR1	SR2a	SR2b
Leading Jet p_{T}	>75 GeV	>120 GeV	>120 GeV
Leading Jet Charge Fraction	N/A	>10%	>10%
Second Jet p_{T}	>50 GeV	>35 GeV	>35 GeV
m_{jj}	>1 TeV	$0.5 < m_{jj} < 1$ TeV	> 1 TeV
$\eta_{j1} \times \eta_{j2}$		<0	
$\|\Delta\eta_{jj}\|$	>4.8	>3	$3 < \|\Delta\eta_{jj}\| < 4.8$
$\|\Delta\phi_{jj}\|$	<2.5	N/A	
Third Jet Veto p_{T} Threshold	30 GeV		
$\|\Delta\phi_{j,E_{\mathrm{T}}^{\mathrm{miss}}}\|$	>1.6 for j_1, >1 otherwise	>0.5	
$E_{\mathrm{T}}^{\mathrm{miss}}$	>150 GeV	>200 GeV	

Theory improvements help dark matter interpretation

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