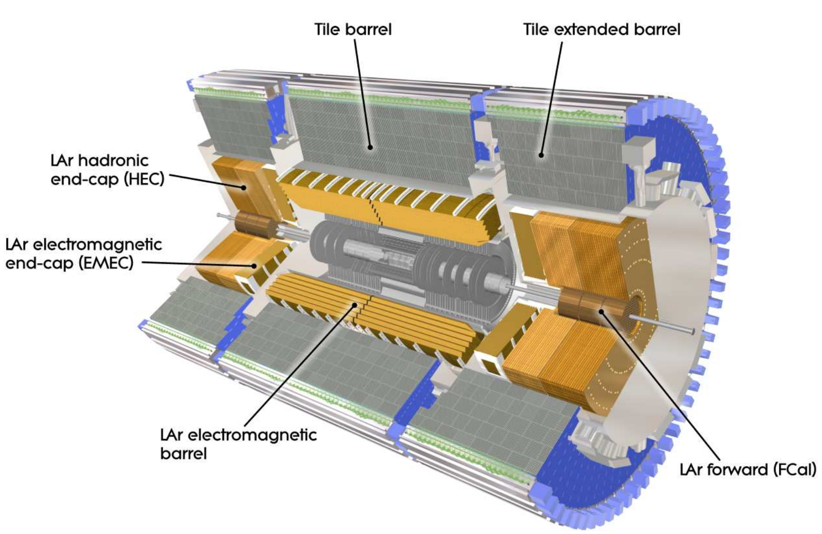
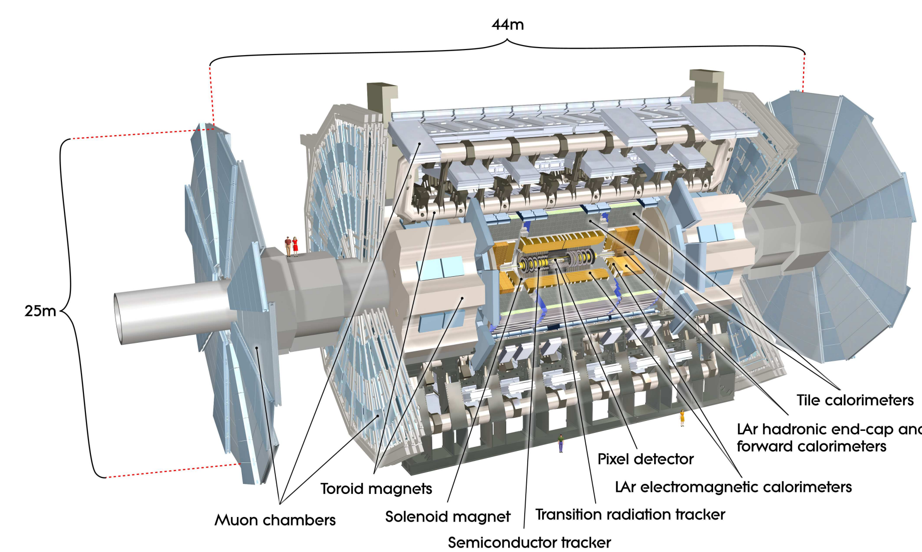
Search for invisible Higgs

With the ATLAS detector

December 11, 2018

Ben Carlson[†]





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https://www.physicsandastronomy.pitt.edu/people/ben-carlson

Outline

Ben Carlson

1. Motivation

- Higgs
- Dark Matter
- Higgs and DM

2. Experiment intro

- The LHC
- ATLAS detector
- ATLAS data

3. SM Higgs constraints

- SM constrain inv.

4. H→inv channels

- Production channels
- MET: searching for inv.
- VBF
- V→qq
- $Z\to\ell\ell$
- ttH
- Combination

5. Implications

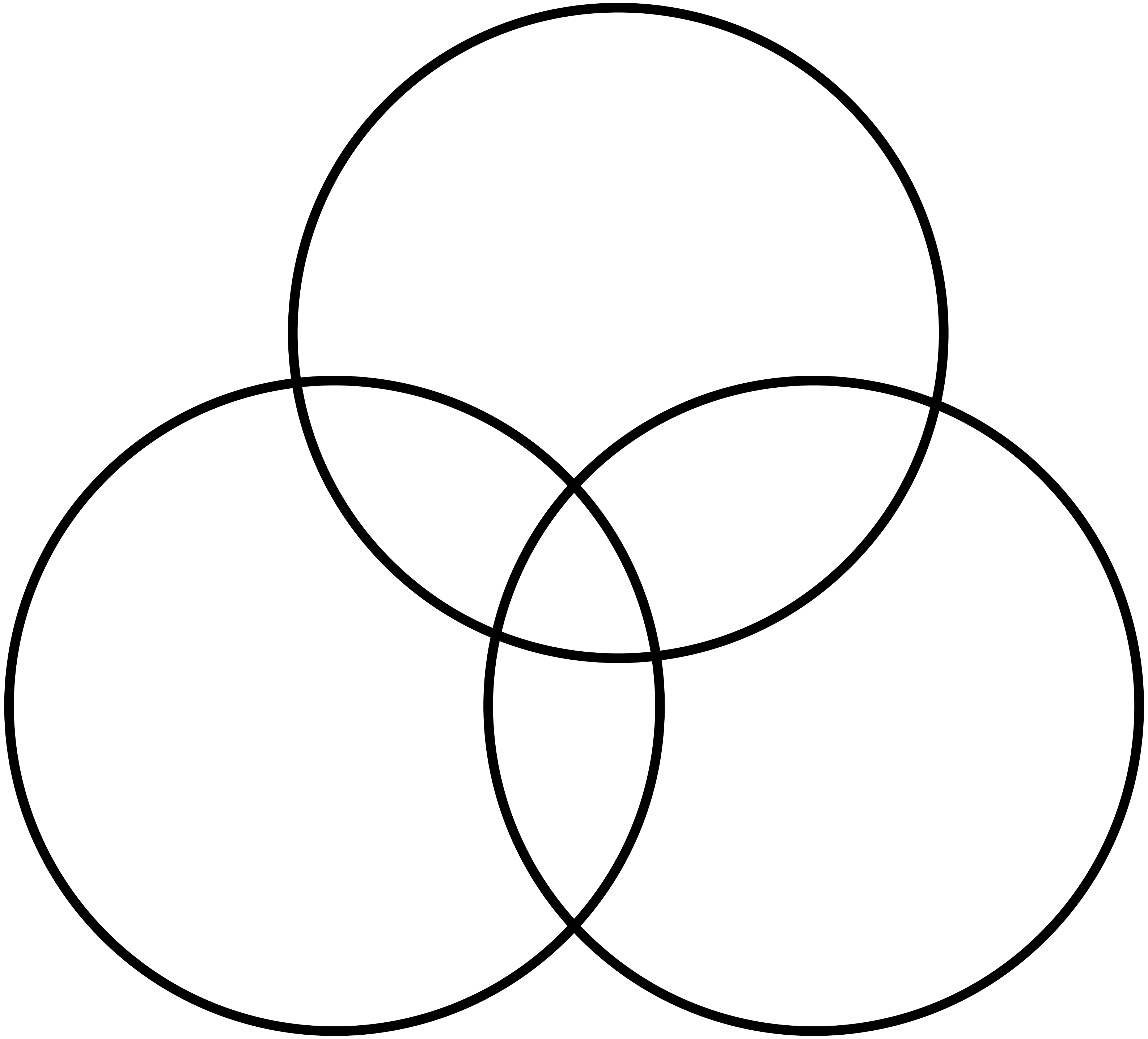
- Limit vs. m_{scalar}
- Comparison to direct detection

6. H→inv next steps

- Monte Carlo
- Trigger for high pileup Run 2

Motivation

Higgs

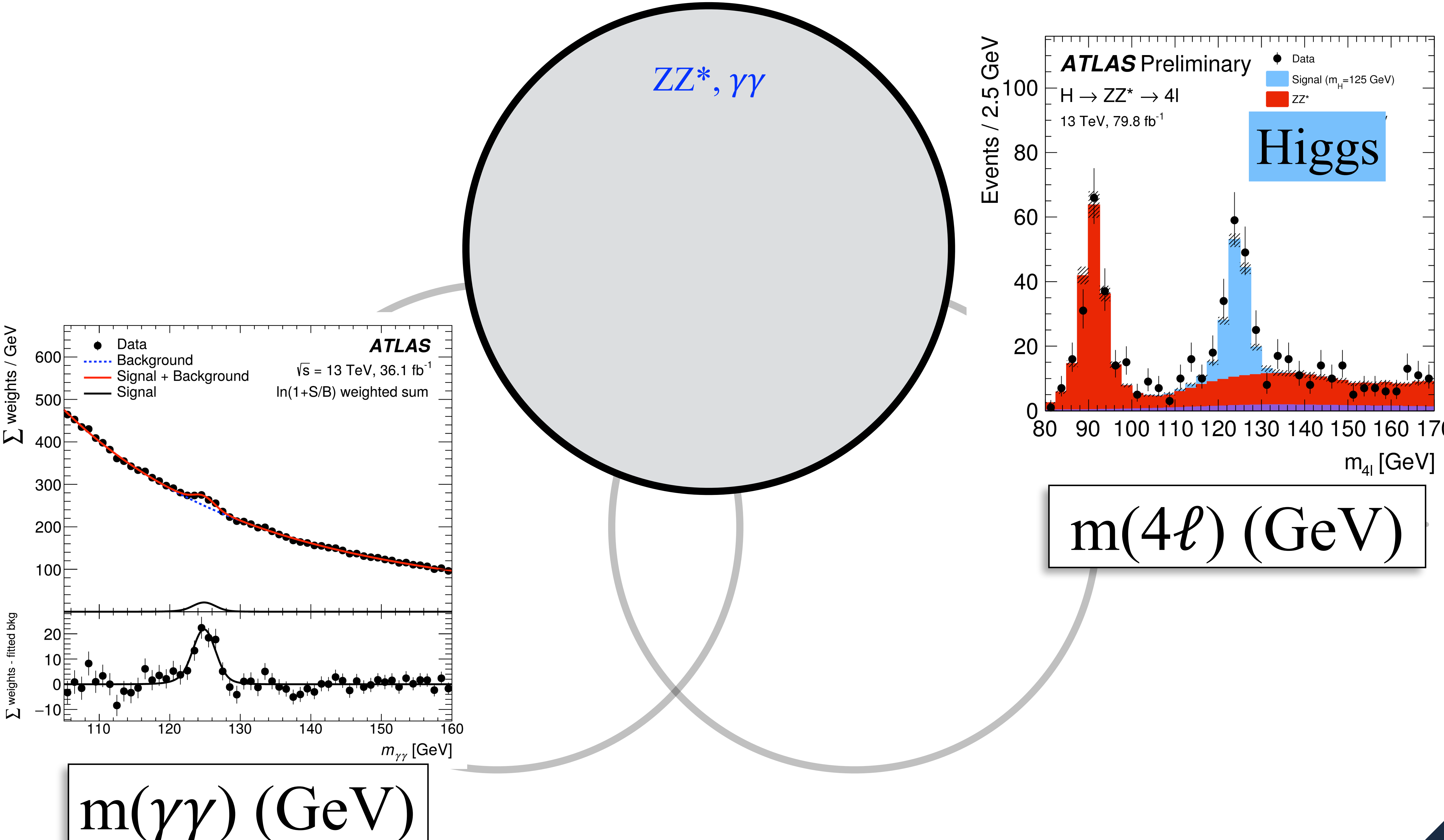


Exotic

Dark Matter

Higgs

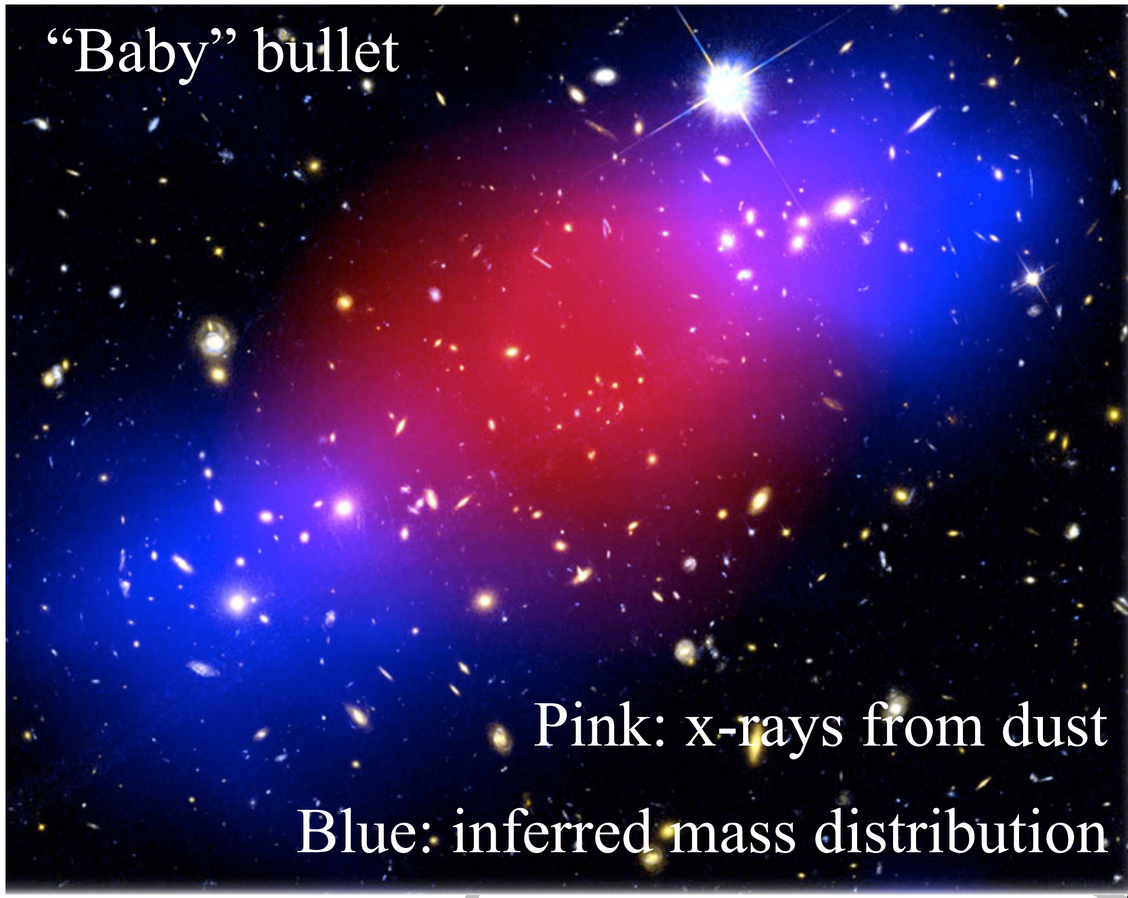
Standard Model

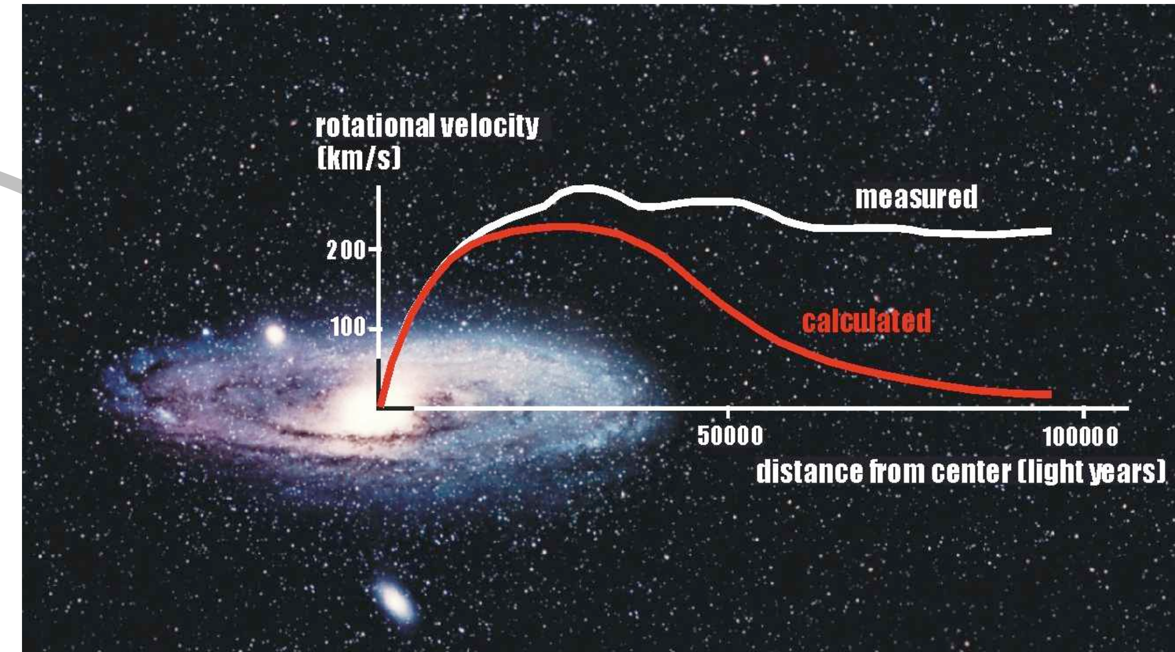


Motivation

Ben Carlson

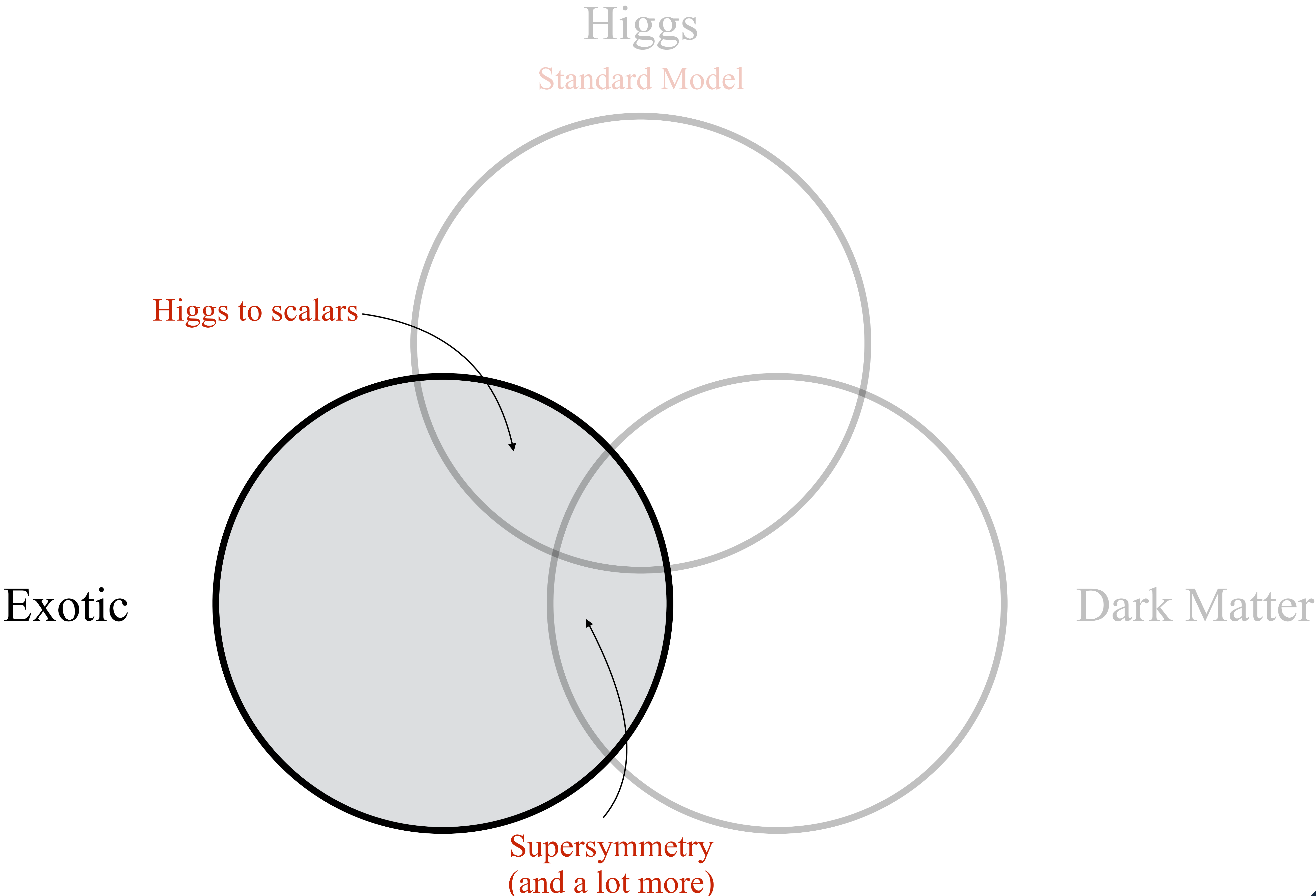
Higgs





Exotic

Dark Matter

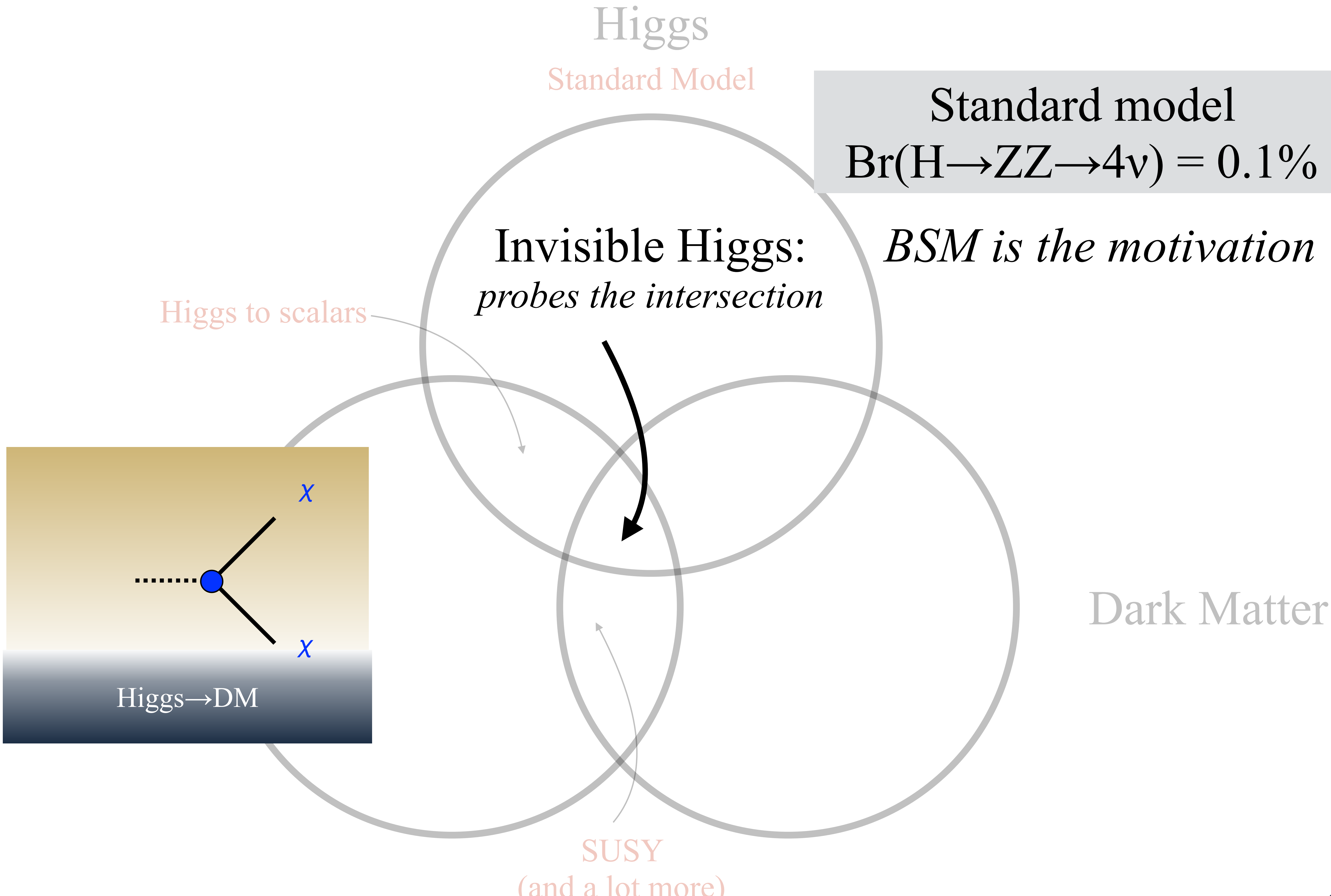

Higgs
Standard Model
Higgs to scalars
Exotic
Dark Matter
Supersymmetry
(and a lot more)

Motivation

Standard model

$Br(H \to ZZ \to 4\nu) = 0.1\%$

BSM is the motivation



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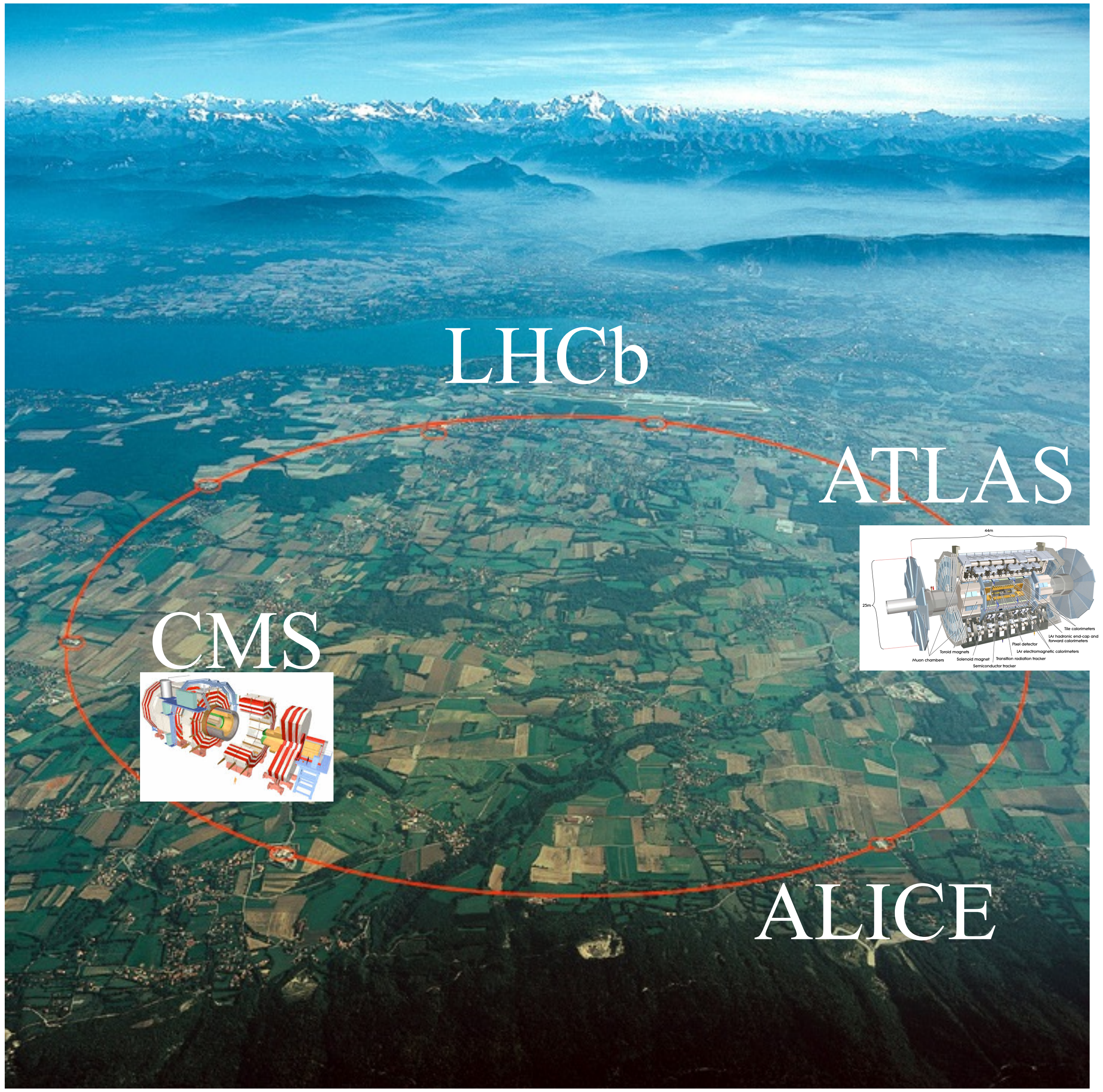
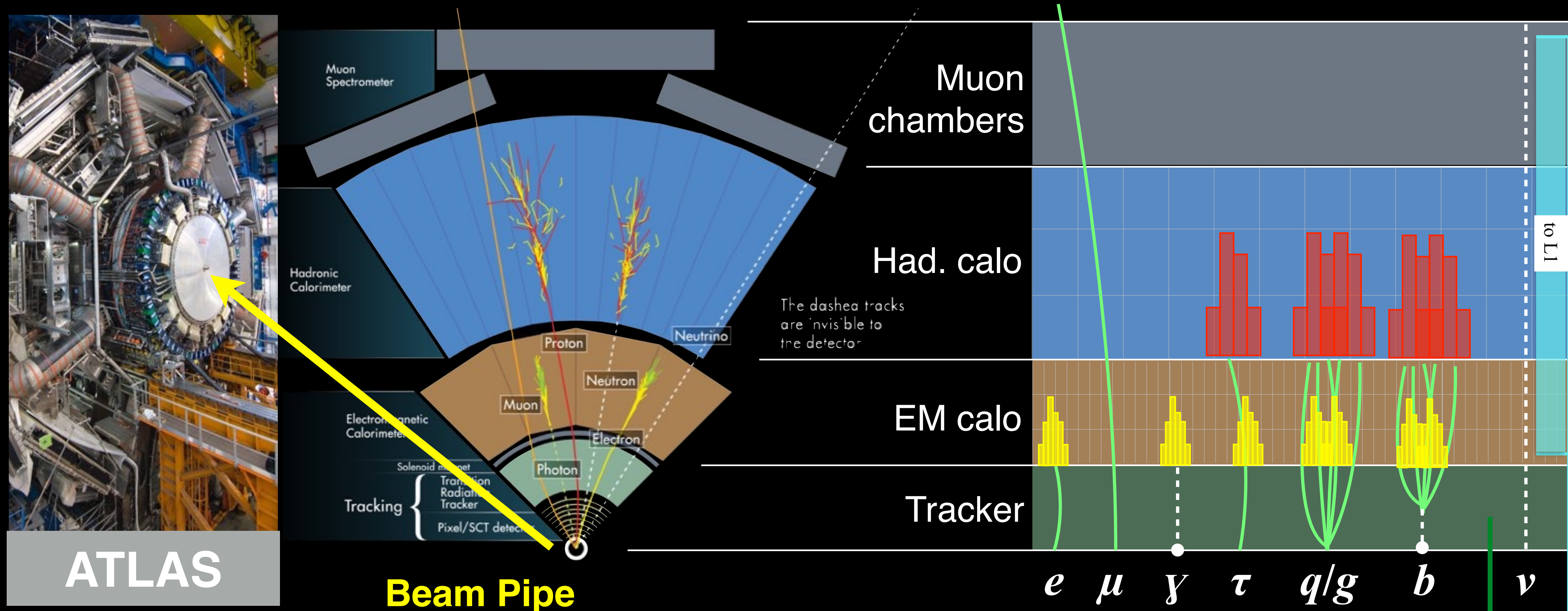
Large Hadron Collider

- The LHC is a pp collider
- Run 1: $\sqrt{s}$ = 7 (8) TeV
- Run 2: $\sqrt{s}$ = 13 TeV



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 permanent storage

ATLAS data

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResultsRun2

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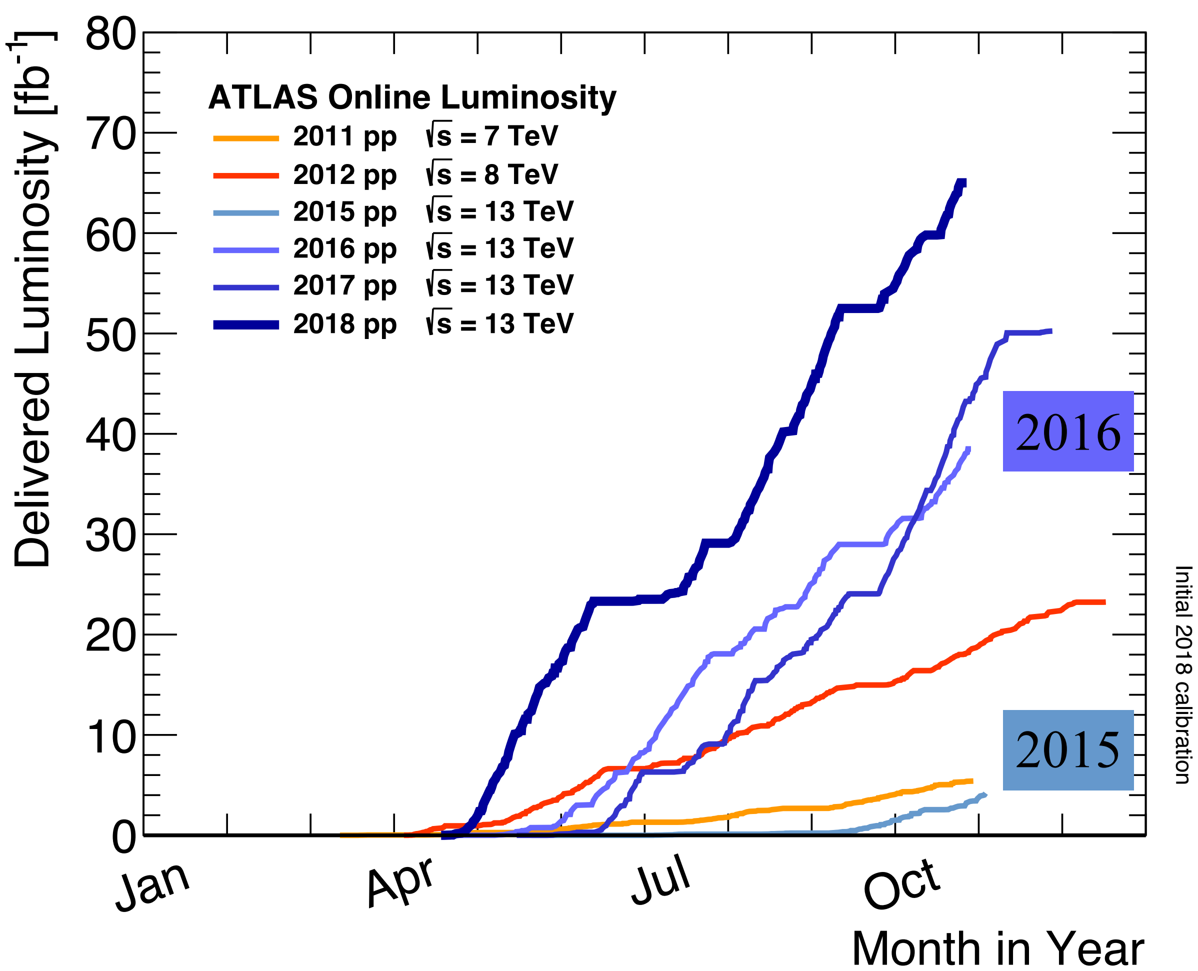
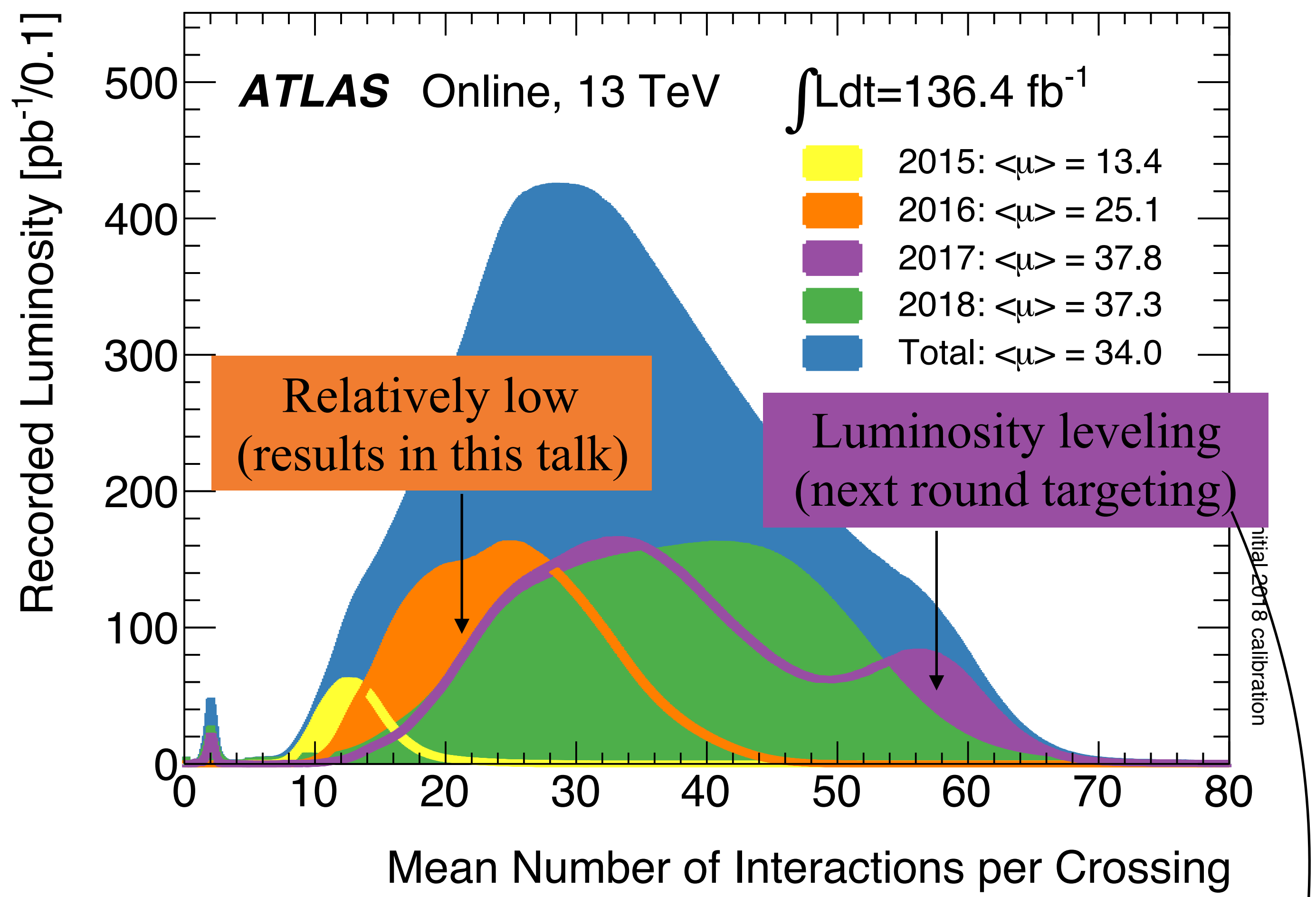
The slope dramatically increased over the seven years plotted

At the cost of increasing pileup

multiple interactions per bunch crossing





This talk is only about 2015 + 2016 data, L = 36.1 fb^{-1}

In total, recorded a total integrated luminosity of **149fb^{-1}**

come back to a few specific challenges related to pileup at the end of the talk

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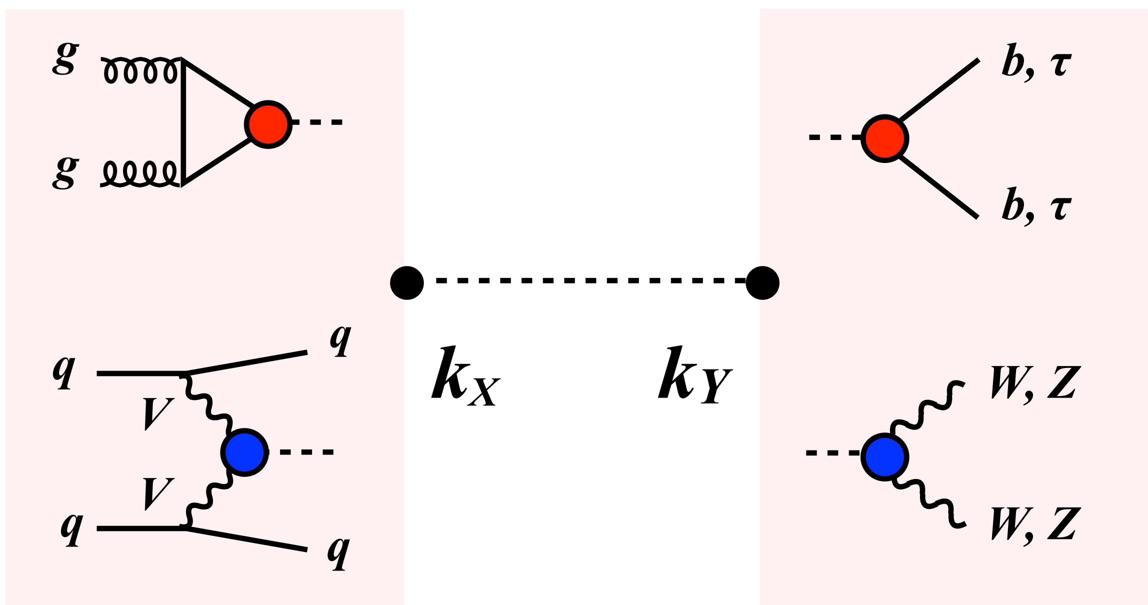


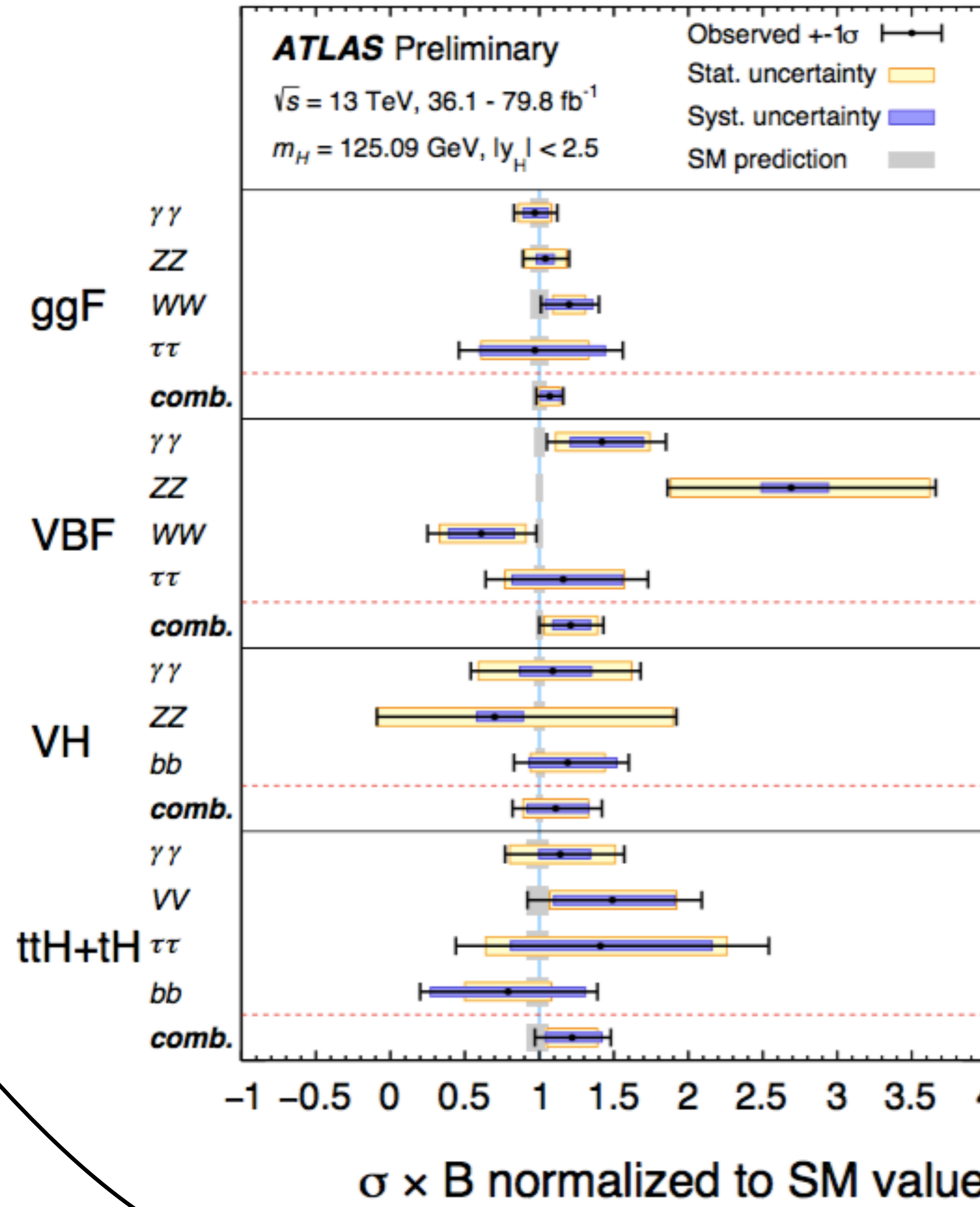
Production X Decay Y

Simultaneous fit of production and decay modes

$$\mu = \frac{N_{\text{observed signal}}}{N_{\text{expected signal}}}$$

Global signal strength

$$\mu = 1.13\ ^{+0.09}_{-0.08}$$



Constraints on undetected

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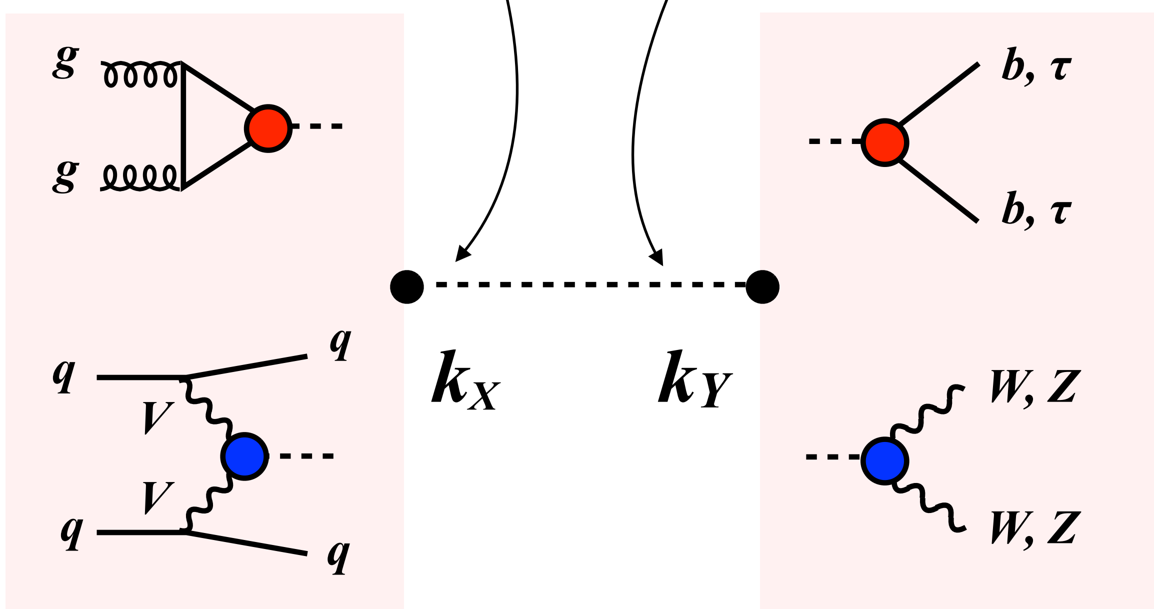
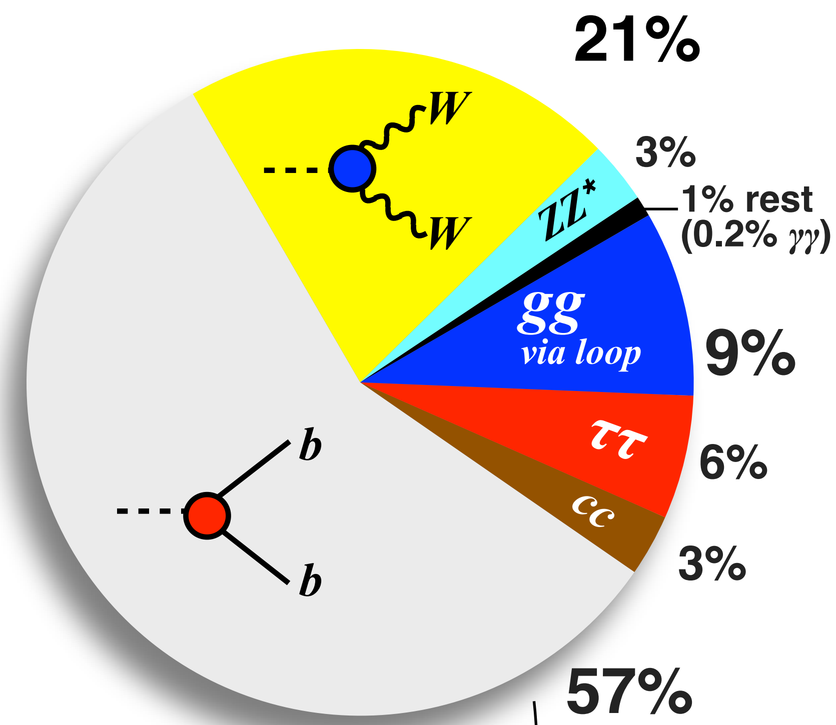
Fix production   Float decays



Production *X*   Decay *Y*

SM Higgs branching fractions



Simultaneous fit of SM couplings undetected

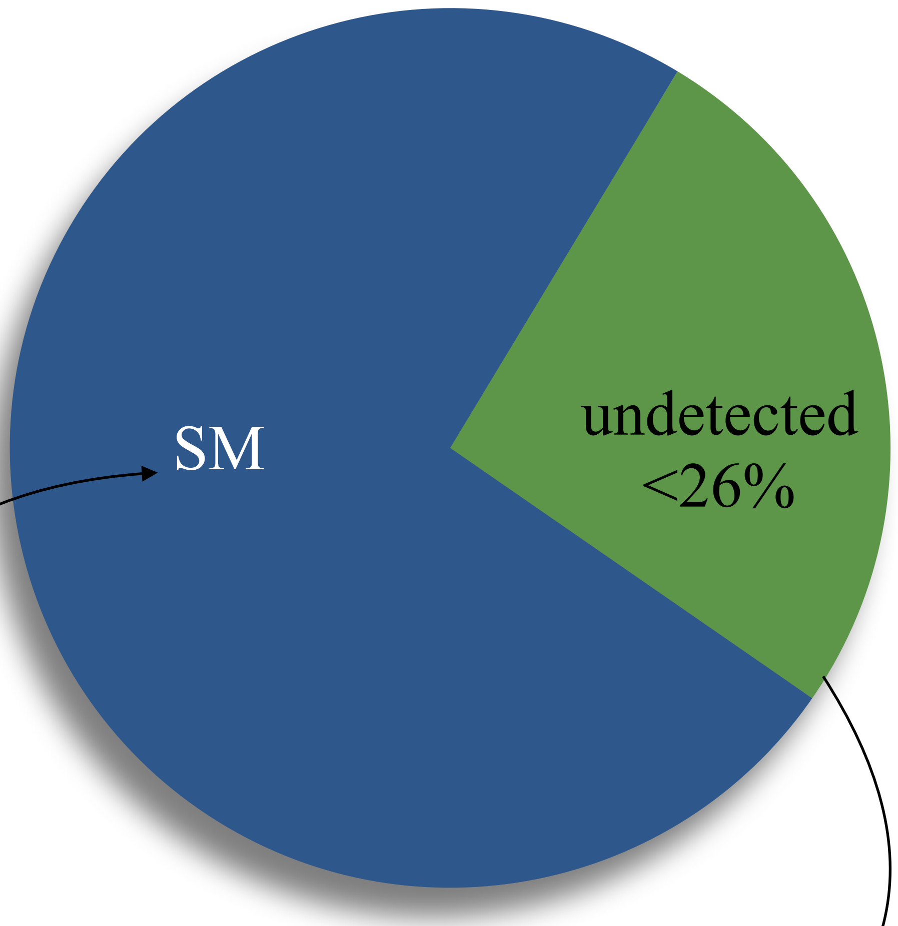
$$k^2{}_{b}\cdot BR_{bb} + k^2{}_{WW}\cdot BR_{WW} + \ldots\ BR_{undetected}$$

Input: Standard Model BR

Fit: k and upper limit on $BR_{undetected}$

Higgs measurements:
Br(undetected) < 26%

Hypothetical branching fraction scenario allowed by Higgs measurements



Allows for BSM including

1. Invisible
2. Not covered by Higgs measurements (4b)
3. Deviations in SM Higgs searches not yet sensitive (cc)

BR to SM processes may decrease

Allowing for more…

Undetected decays

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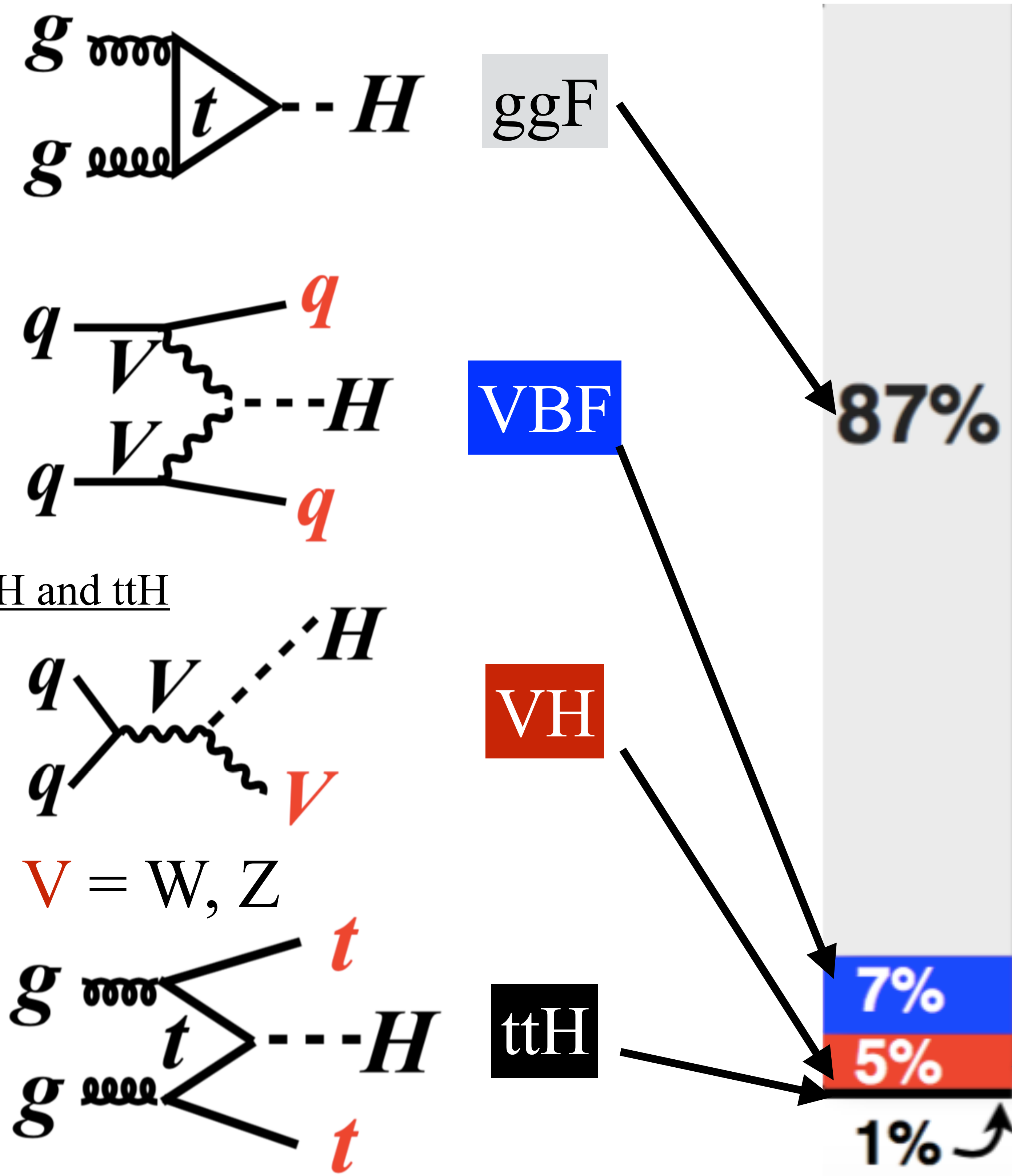
Ben Carlson

hadron collider production modes

Br hit inVH and ttH



Biggest cross section, requires ISR recoil

Hadronic signature, relatively large cross section

Leptonic decays from Z very clean

High multiplicity (leptons and jets), but small cross section

ATLAS-CONF-2018-023

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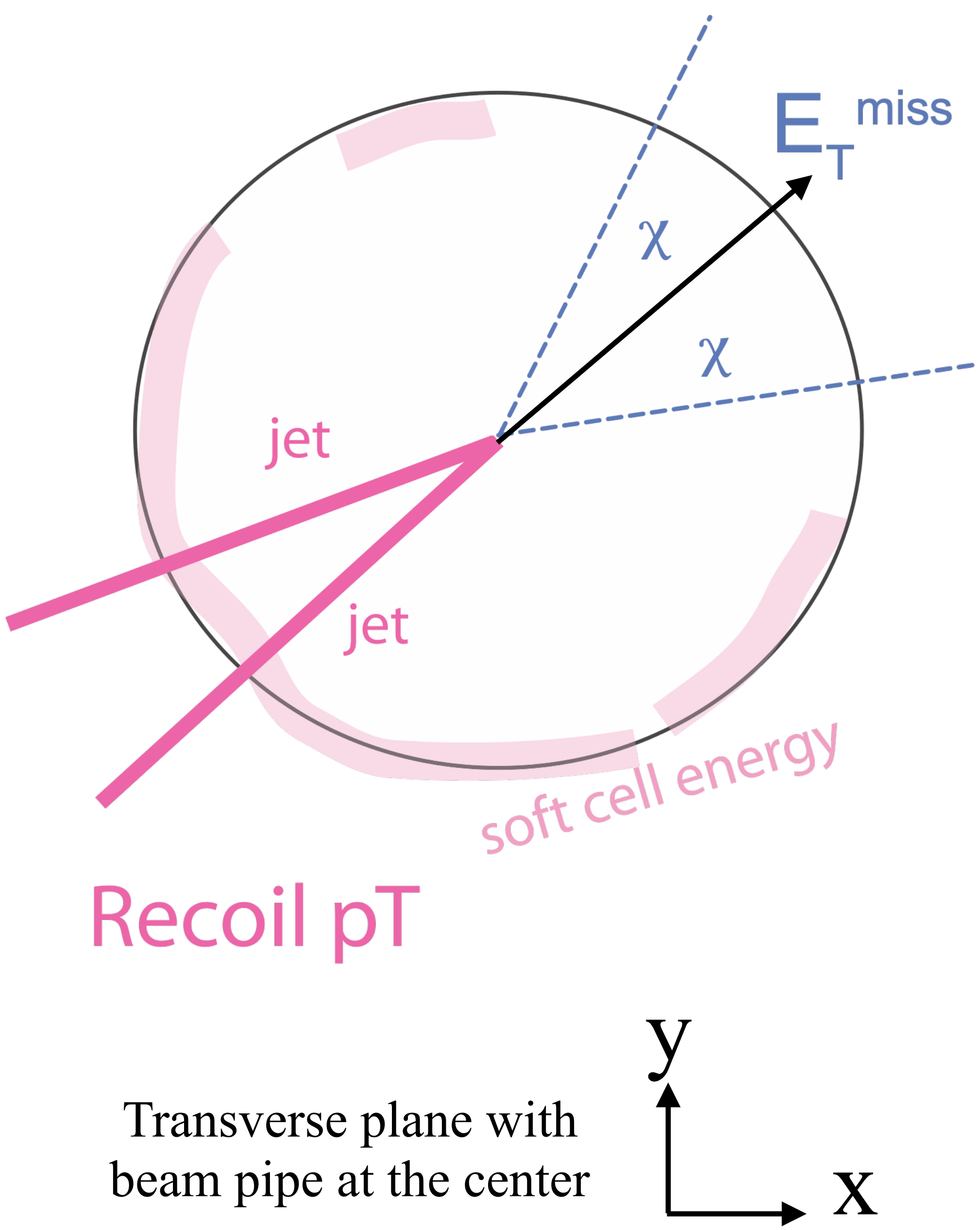
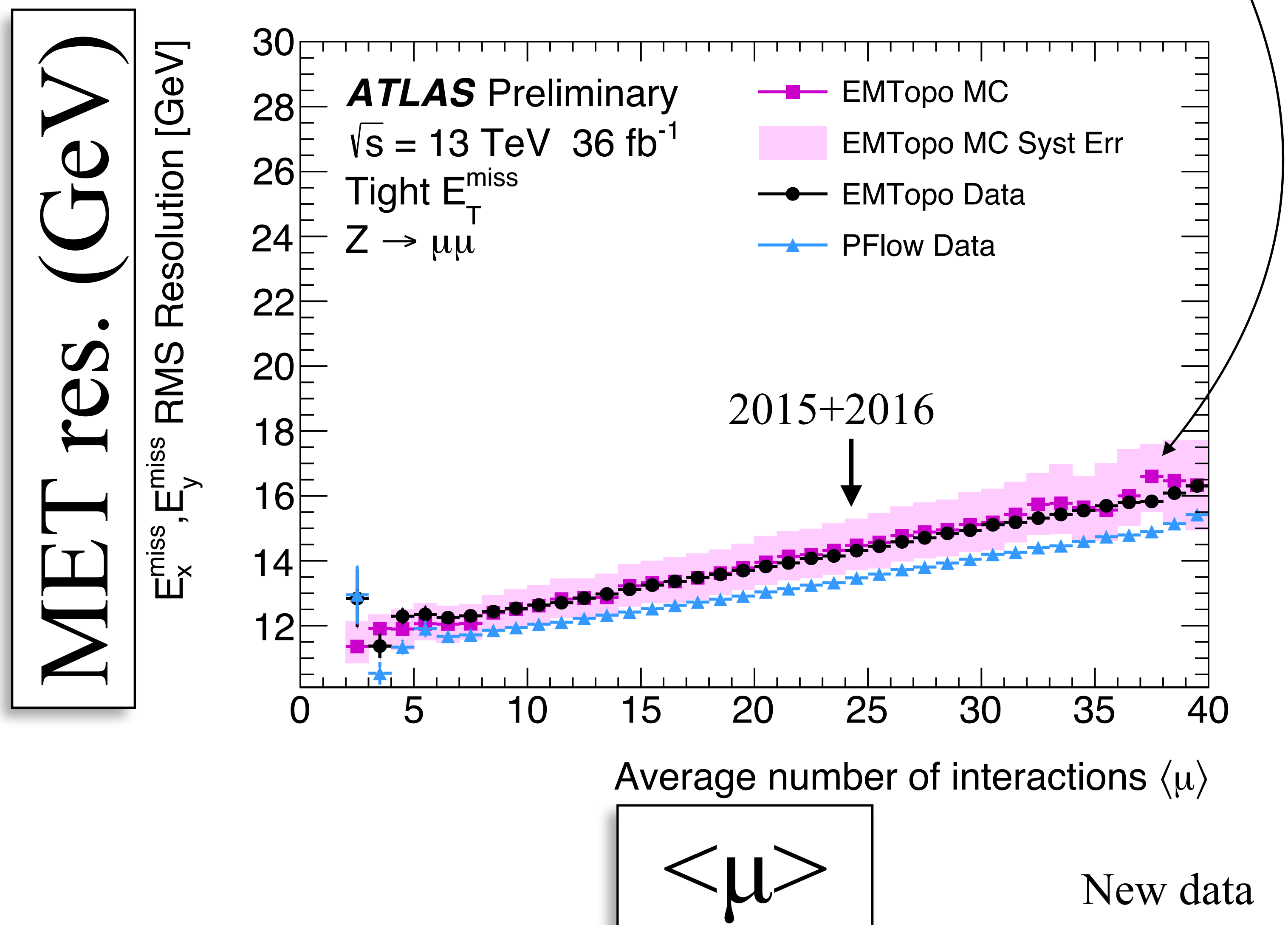
Missing transverse energy

$$\text{MET} = \sum \text{measured } p_T$$
$$= \text{jet} + \text{soft activity}$$



Transverse plane with beam pipe at the center

MET gets more difficult with pileup



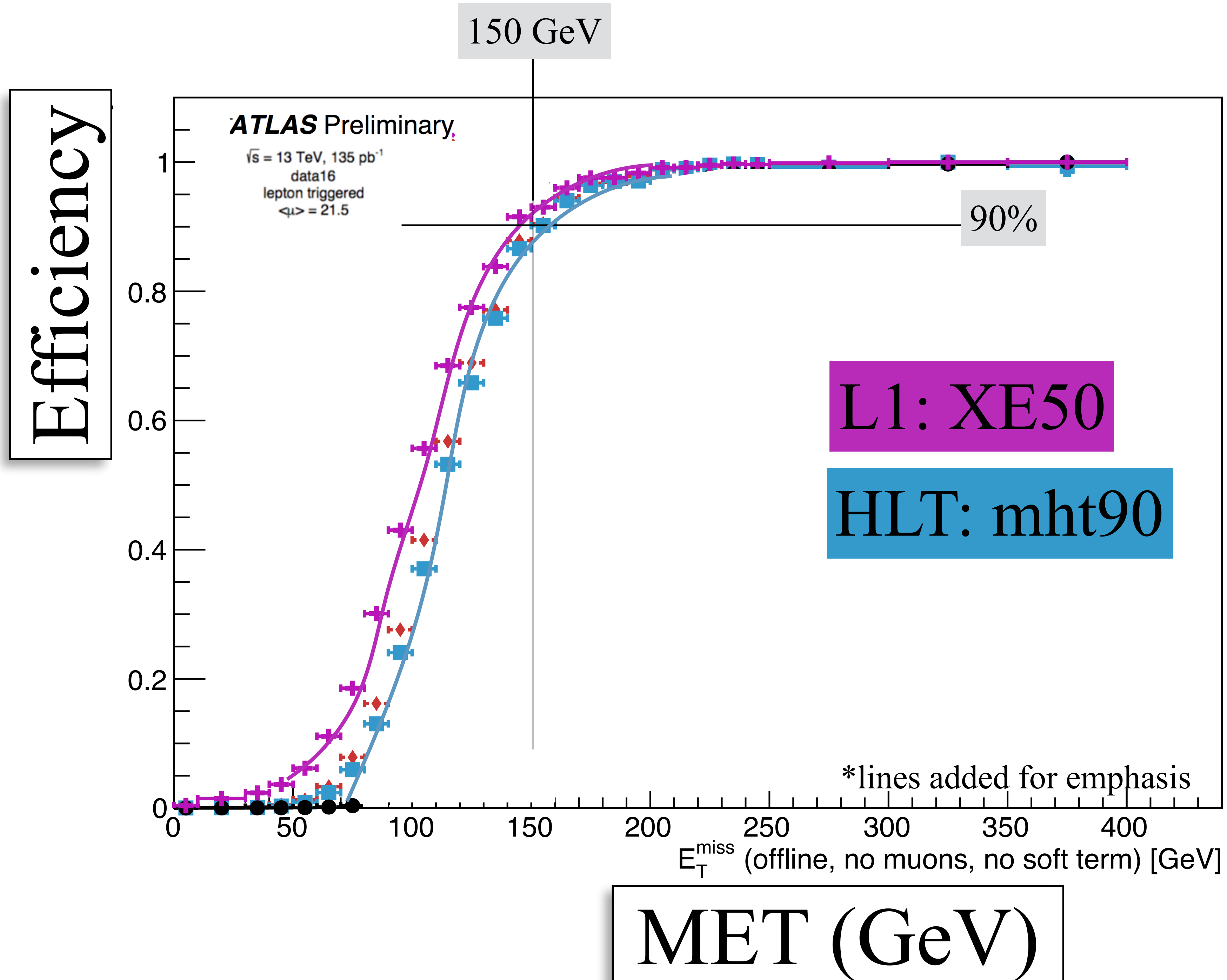
New data out to 55

Trigger

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/MissingEtTriggerPublicResults#13_TeV_data_2016

- Sets the minimum MET value that can be used
- Trigger > 90% efficient for MET = 150 GeV
- Measure efficiency scale factors if not 100% efficient

Measure efficiency using data from muon trigger reference



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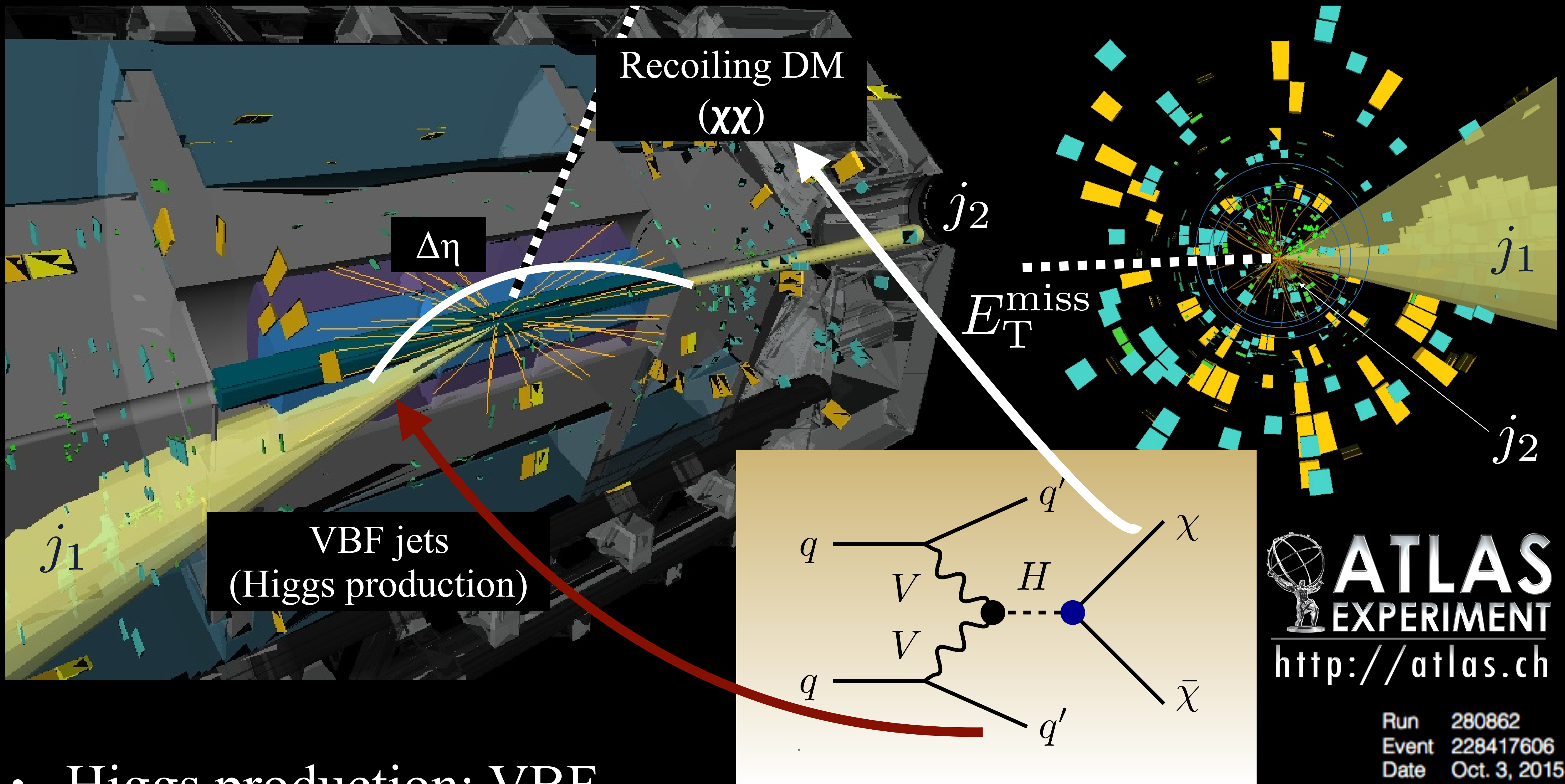
Vector boson fusion



- Higgs production: VBF
- Signature: large MET
- Trigger: MET

Features of VBF

ATLAS: JHEP 01 (2016) 172
Zeppenfeld, Rainwater, PRD 60 (1999) 113004

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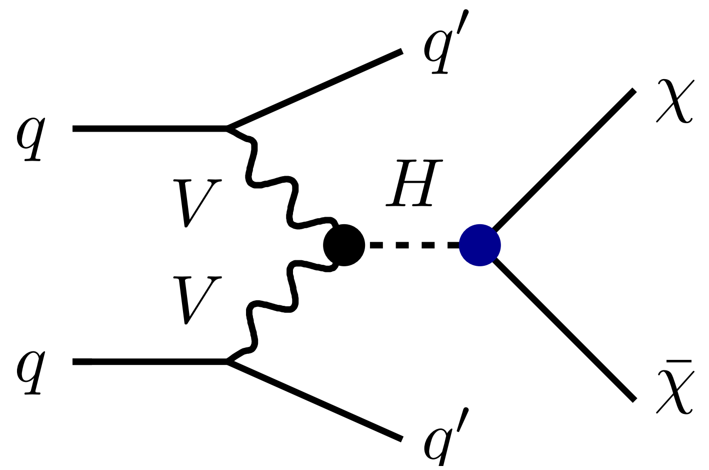
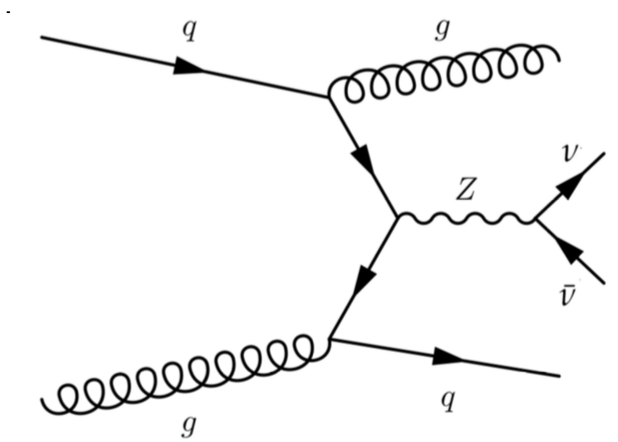


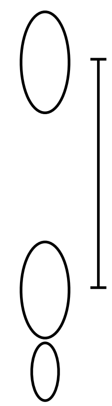


Energy deposits

Invisible decay

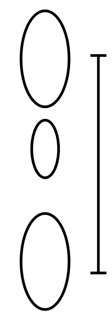
Hadronic activity (addition jets)

Jets



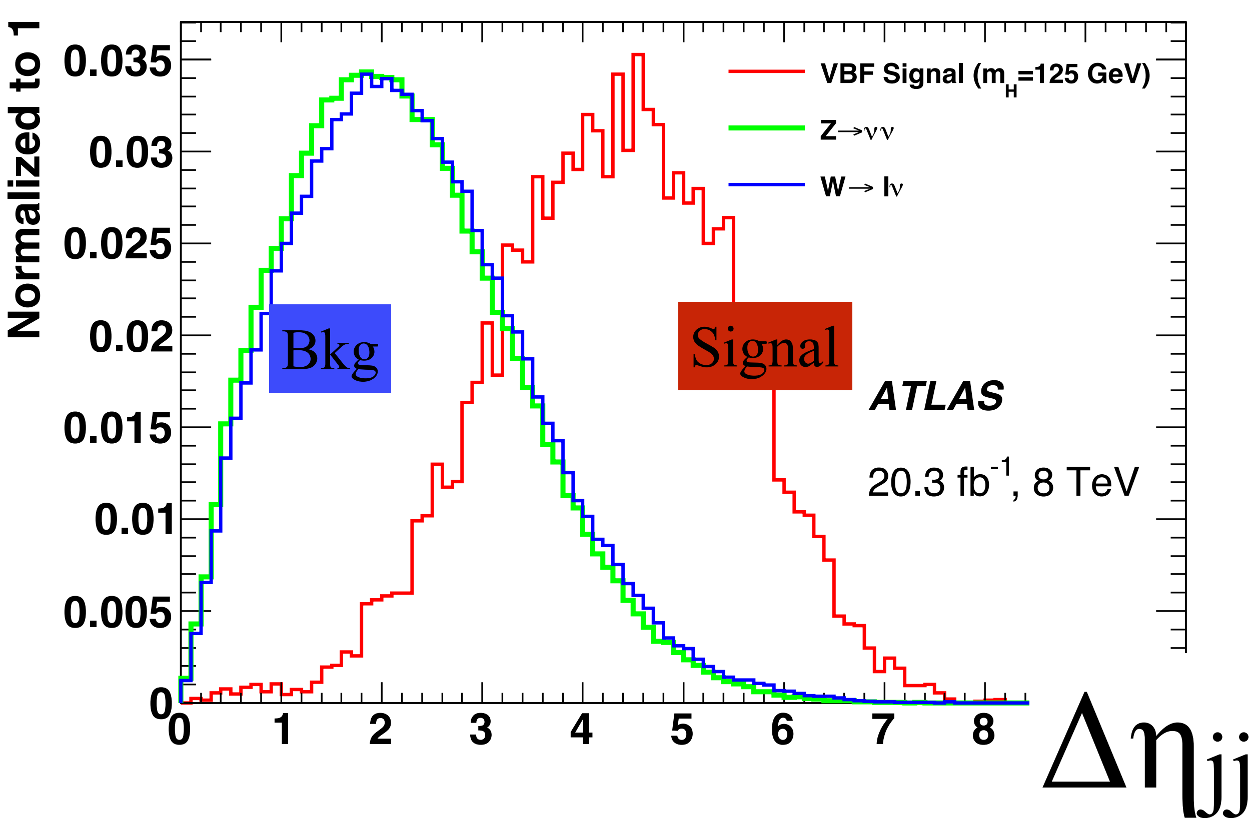
Jets widely separated (η)

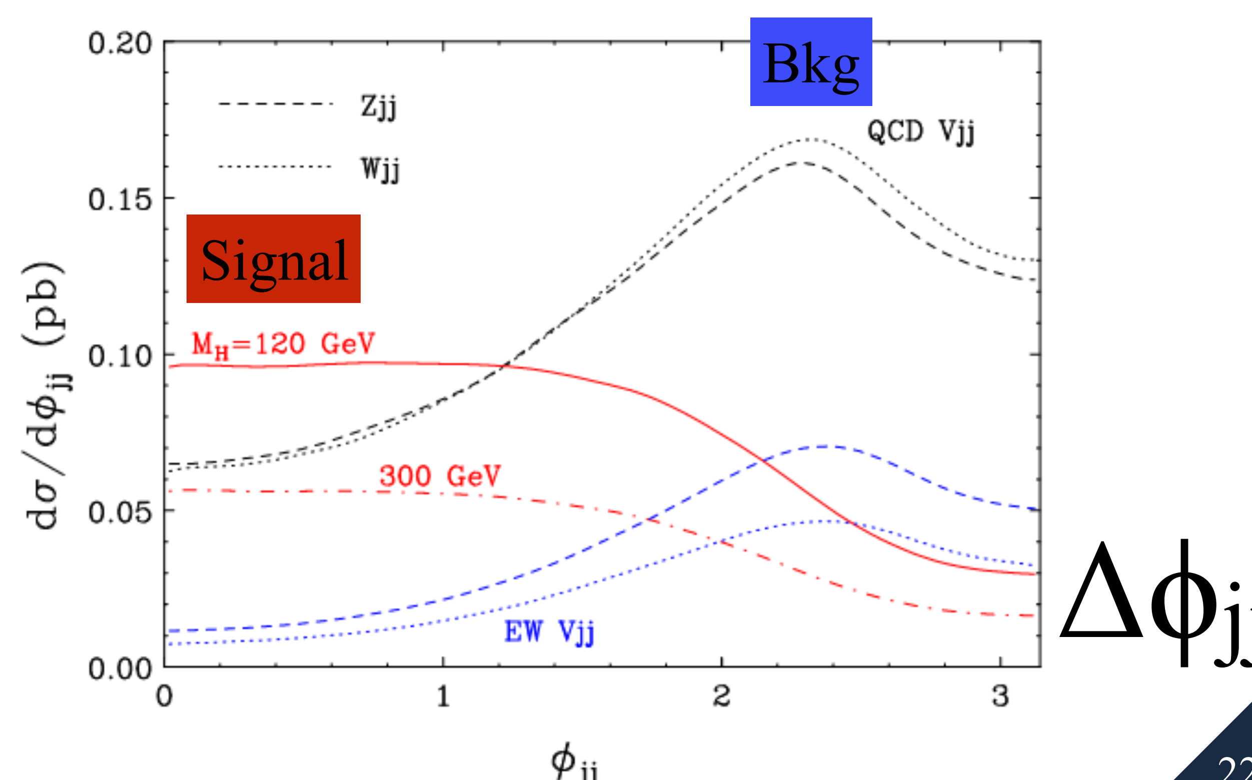
Jets recoil against Higgs (small Δϕ)



Jets not as separated

Jets back to back (ϕ)





Analysis selections

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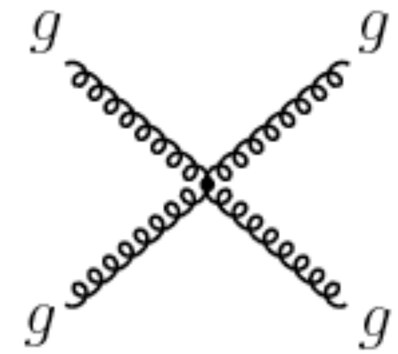
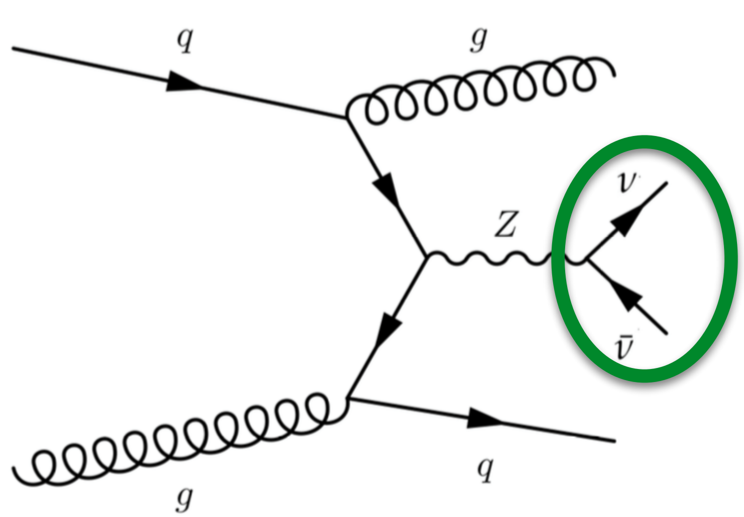
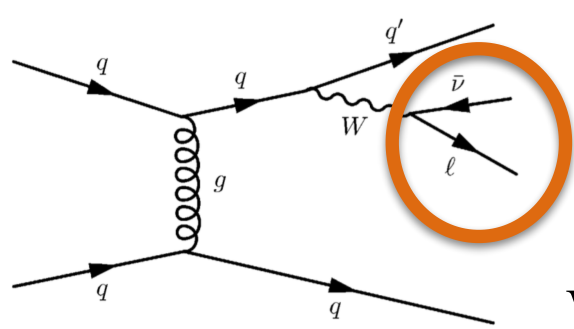
MET	 QCD	MET > 180 GeV
Dijet event	 Z to invisible	Jet p_T > 80, 50 GeV (VBF jets) No other jets with p_T > 25 GeV (Jet veto)
m_{jj}, $\Delta\phi_{jj}$,$\Delta\eta_{jj}$		m_{jj}: 1-1.5, 1.5-2.0, ≥2.0 TeV $\Delta\phi_{jj} < 1.8$ $\Delta\eta_{jj} > 4.8$
Lepton veto	 $W \rightarrow \ell\nu$	No electron (muon) with p_T > 7 GeV

VBF backgrounds

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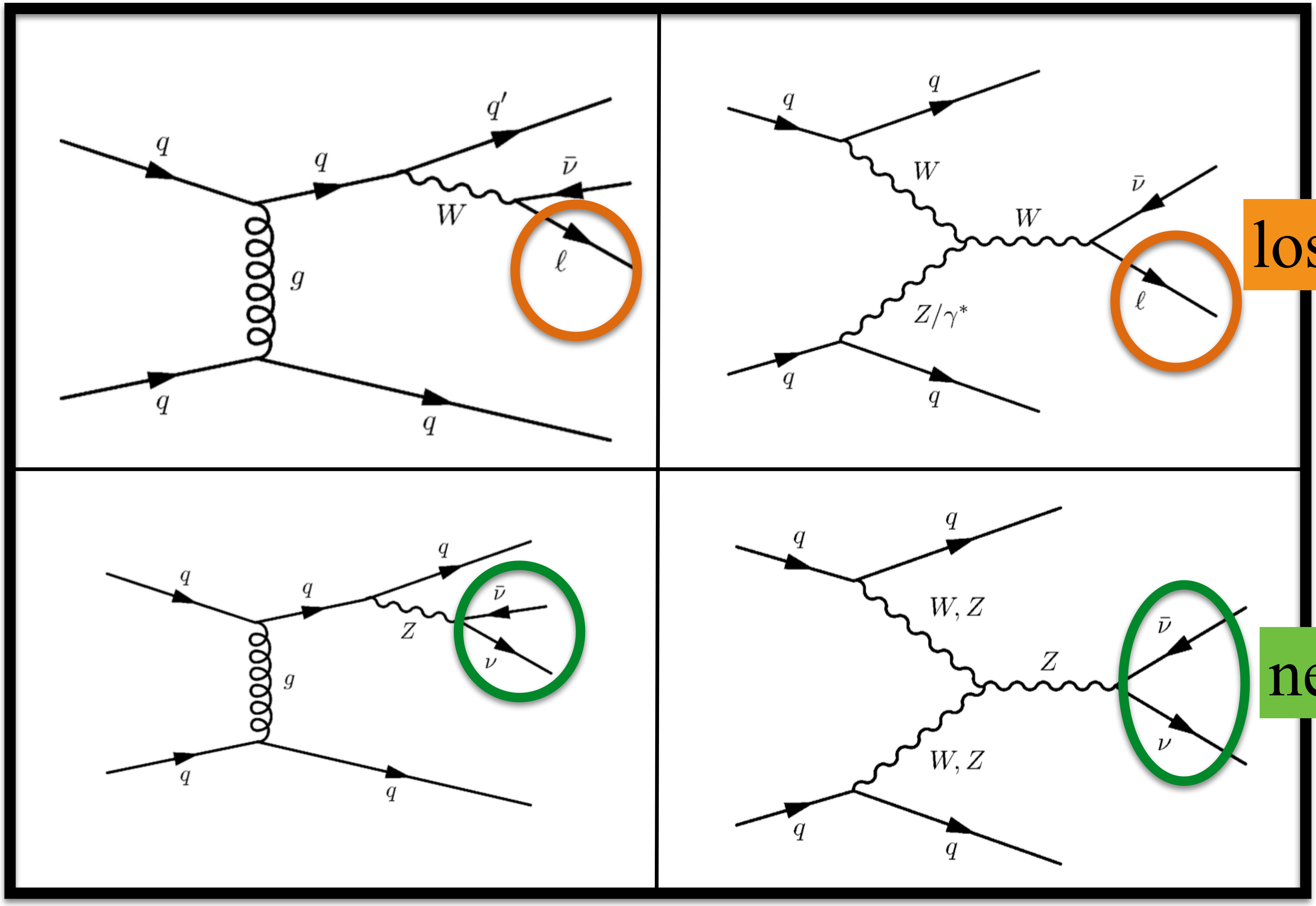
multijet bkg is small

Strong | Electroweak

W→ℓν

Z →νν



lost lepton

neutrinos

+ many more diagrams and interference

Estimating W&Z

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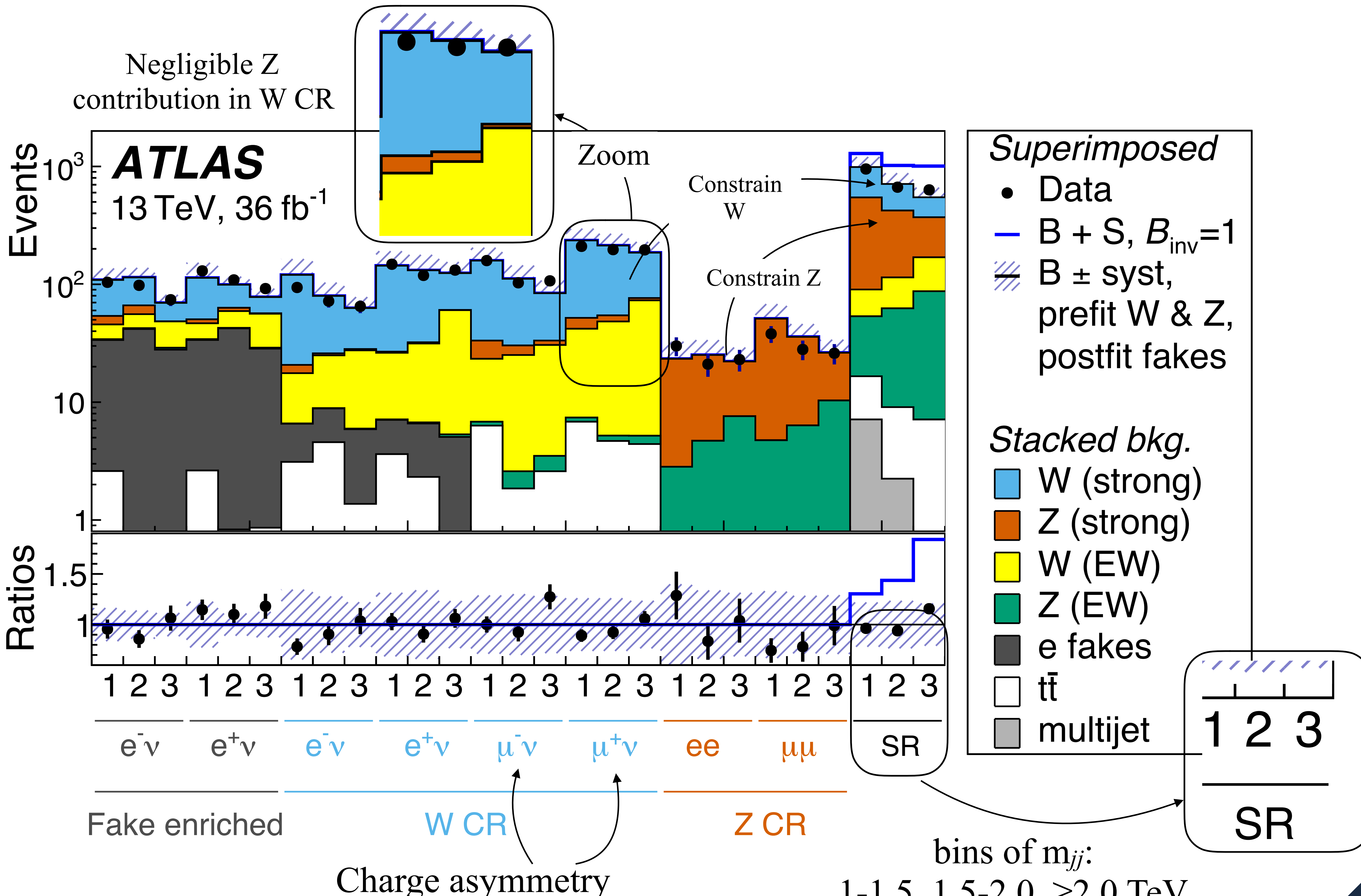
Control sample	Signal sample
$W \rightarrow \ell\nu$ ***found*** lepton	$W \rightarrow \ell\nu$ ***lost*** lepton
$Z \rightarrow \ell\ell$	$Z \rightarrow \nu\nu$

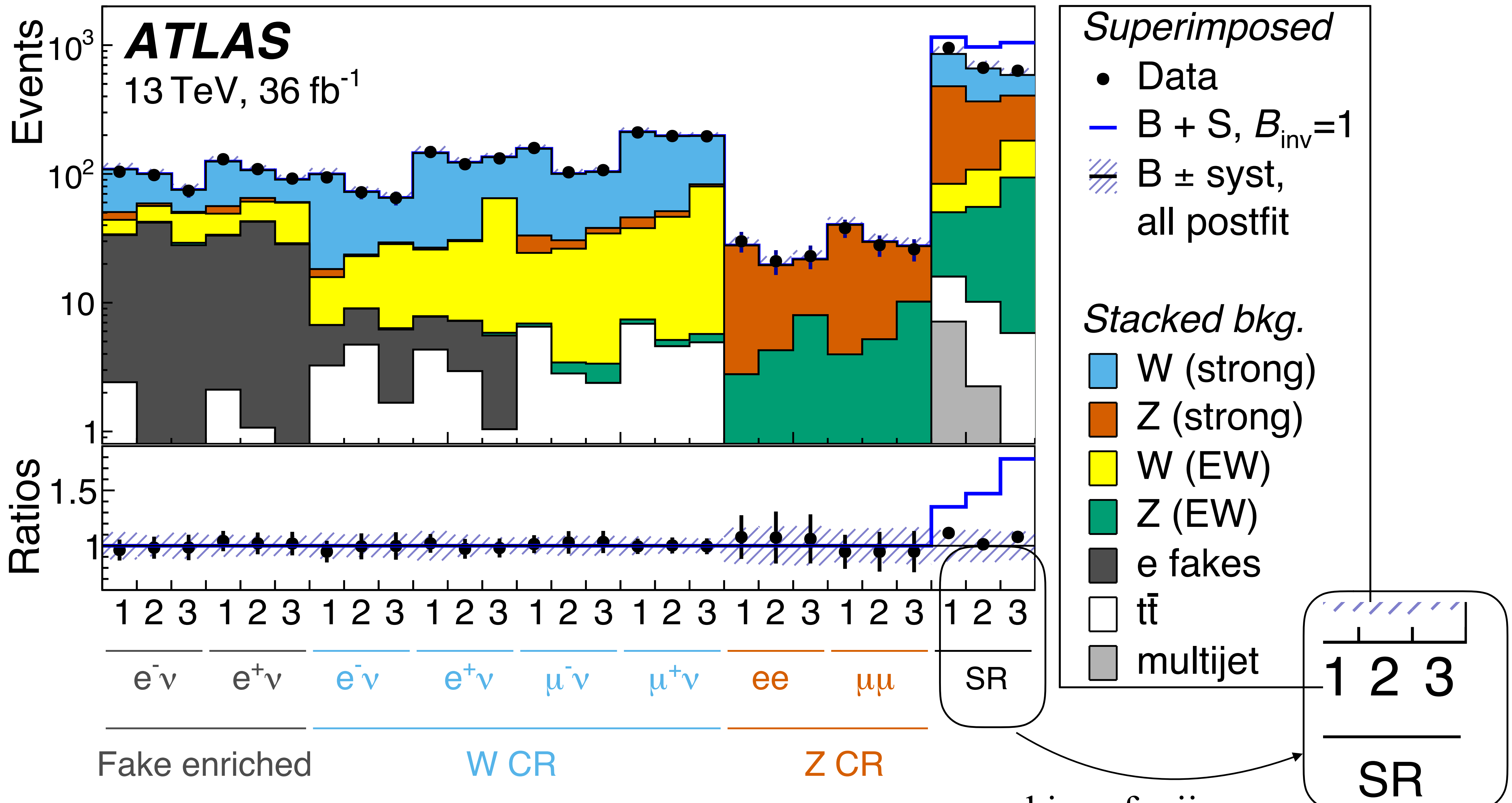
Determine control to signal sample ratio from MC simulation
Normalize to data from control sample

Control sample

Simultaneously will fit all bins shown here (shown here before fit)



Consistency between CRs



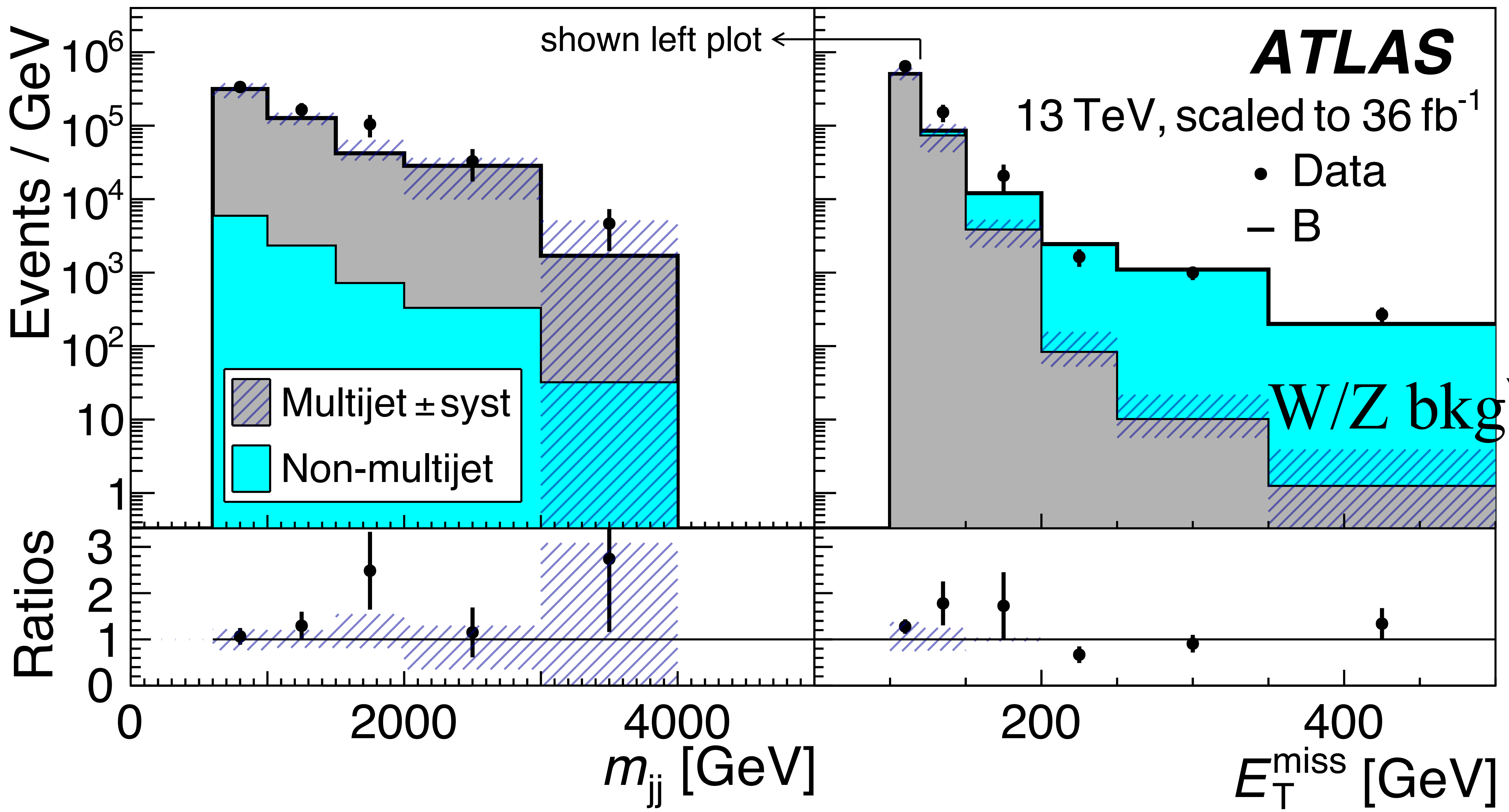
bins of mjj:
1-1.5, 1.5-2.0, ≥2.0 TeV

Estimate using data

Define a dedicated sample, test method

- Good agreement between prediction and data

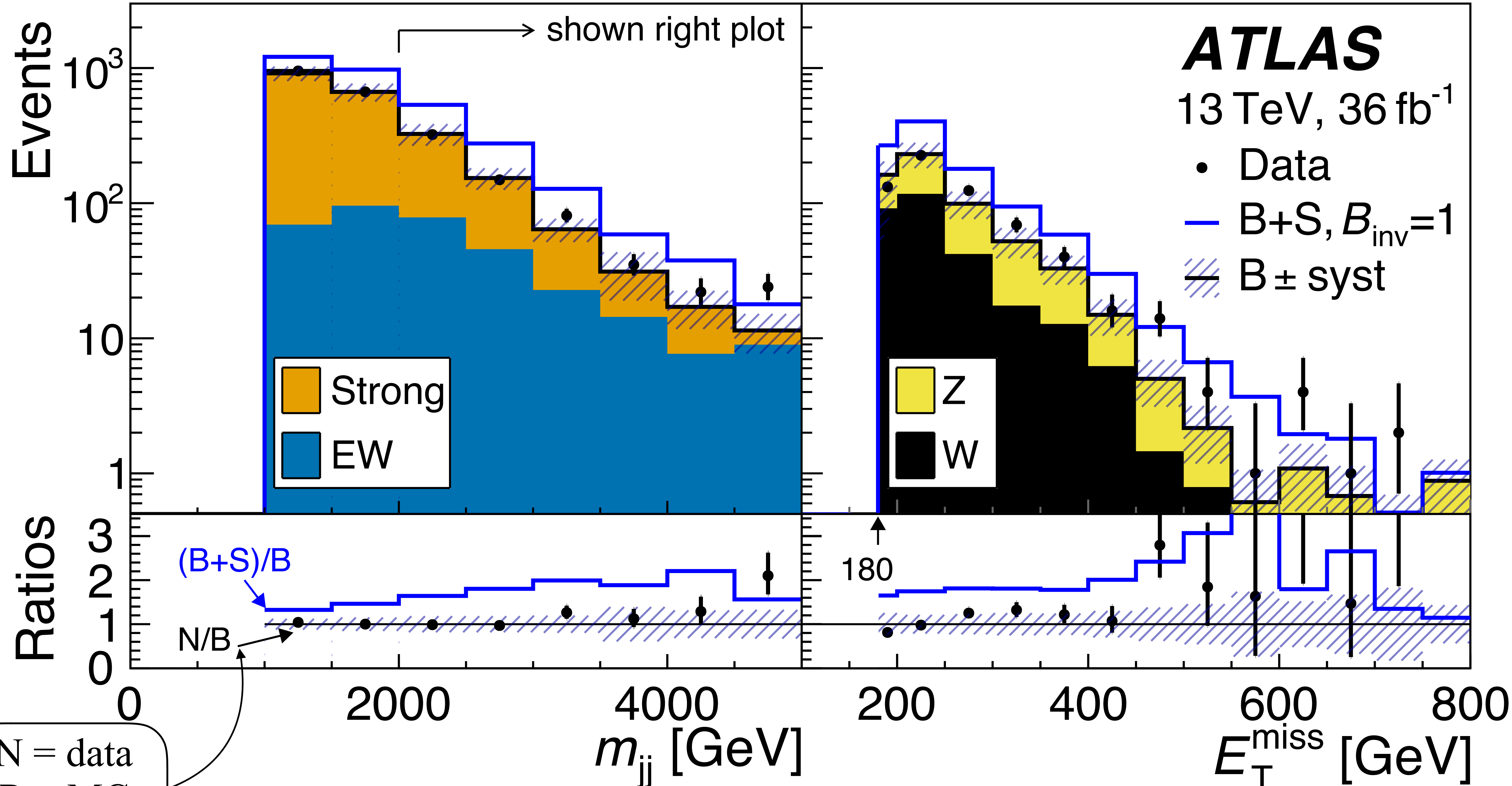
- MET > 100 GeV
- m(jj) > 600 GeV
- |Δη(jj)| > 3.0
- 1.8 < |Δϕ| < 2.7
- j_3 p_T: 25-50, j_4 p_T < 25 GeV



QCD falls off rapidly with MET

Distributions in SR

ATLAS: 1809.06682
(Submitted to PLB)



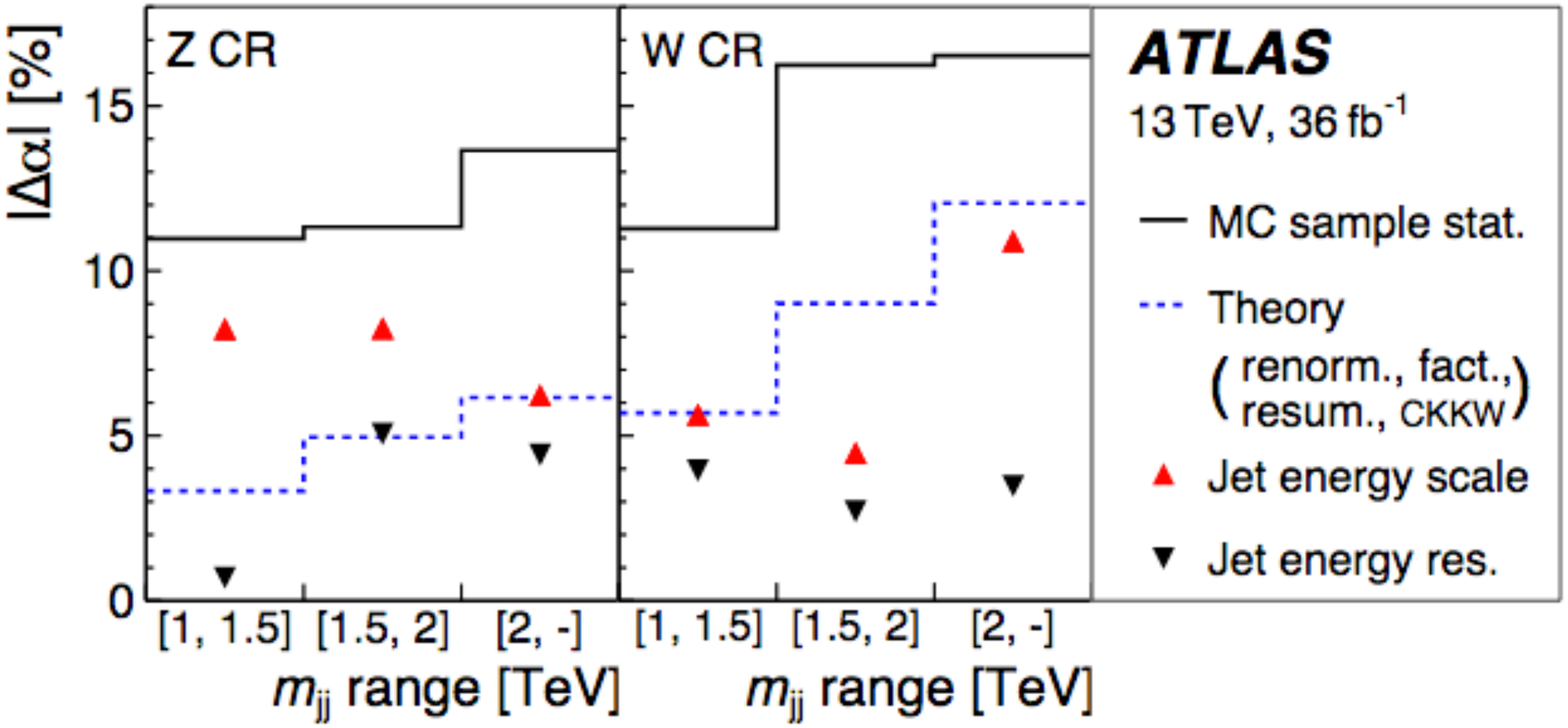
N = data
B = MC

Increasing S/B

Flat S/B

*In fit, use mjj > 2 TeV as a single bin

Uncertainty on SR/CR



Source	ΔB/B
Theory total	10%
Jet scale	10%
Jet resolution	2%
Experiment	17%
MC stats	**12%**
Data stats	**21%**

- Theory
  - Renormalization/factorization: 20% before ratio
  - CKKW jet matching uncertainty dominates
- Experiment
  - Jet scale and resolution: 1-4% in ratio (per term)
  - Total impact of JES significant though (29 terms)
- MC stats: dominant unc.
  - More on how to address this later

- Upper limit, Br(H→inv) assuming SM cross section
- Lower expected limit means the result is more sensitive

Upper limit on Br(H→inv) for ATLAS results in VBF, m_H = 125 GeV

Result	**Expected**	**Observed**	**+1 σ**	**-1 σ**
13 TeV	28%	37%	39%	20%
8 TeV VBF	35%	30%	49%	25%
8 TeV VBF + low m_{jj}	33%	31%	47%	24%

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W/Z→qq H→inv

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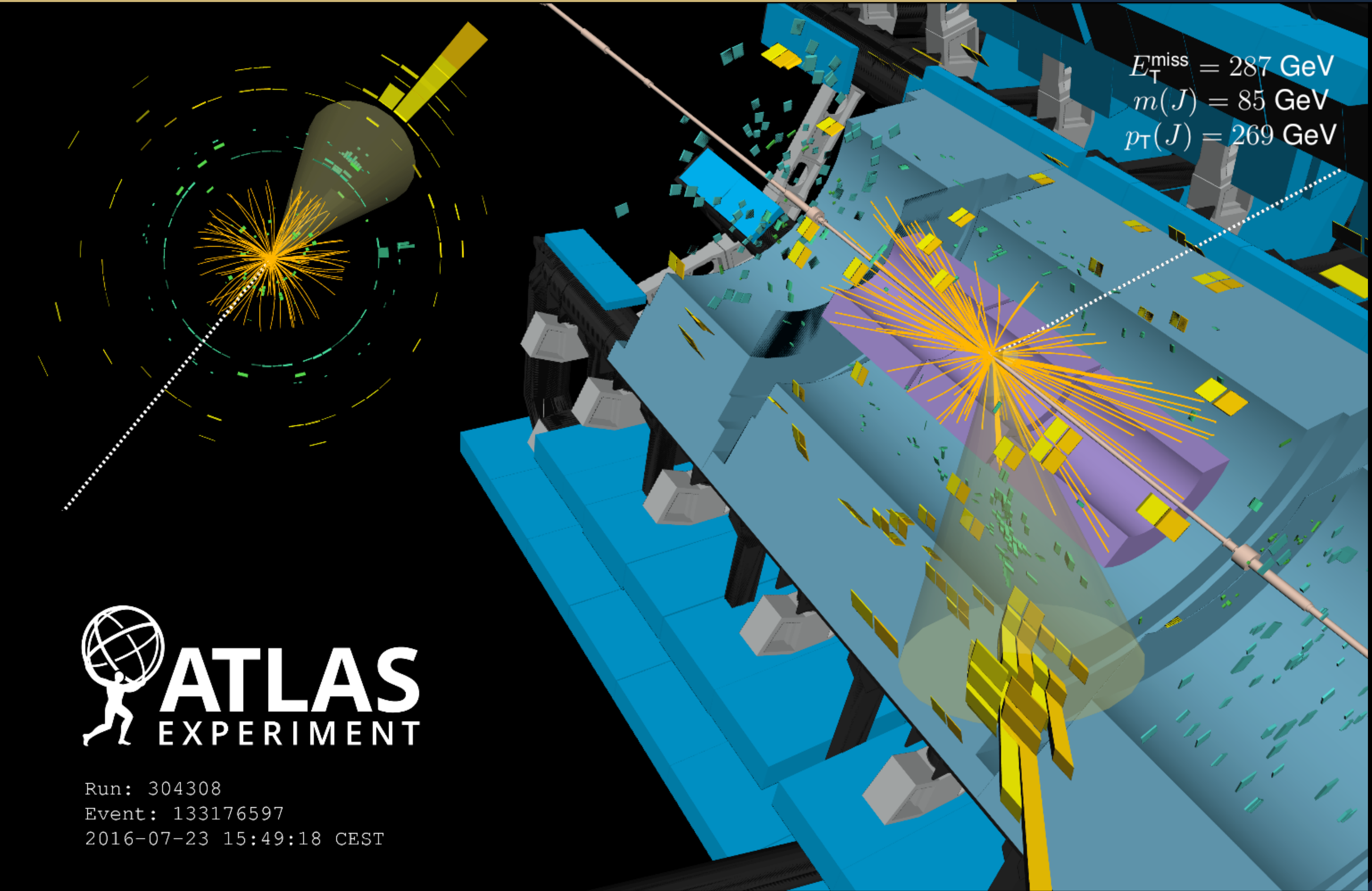

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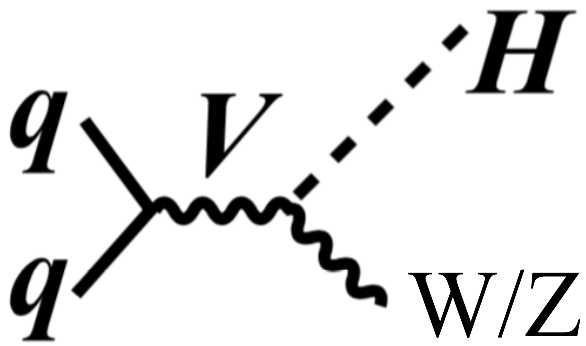
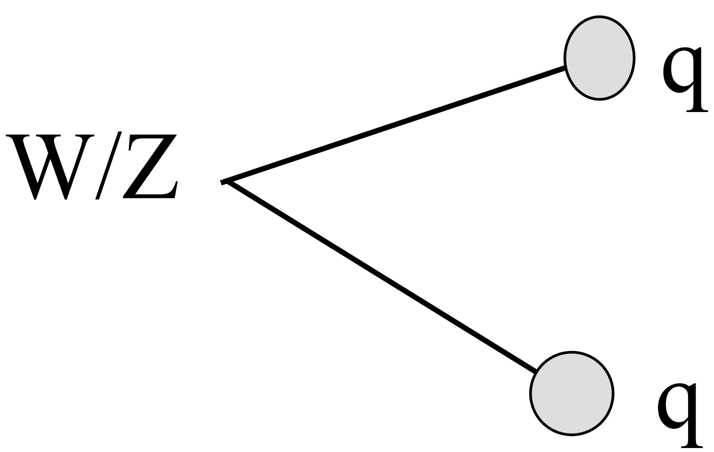


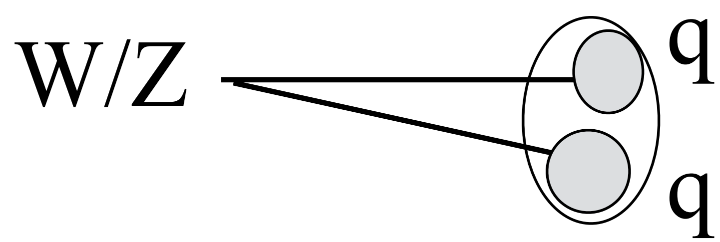
Hadronic W/Z decays

Boosted

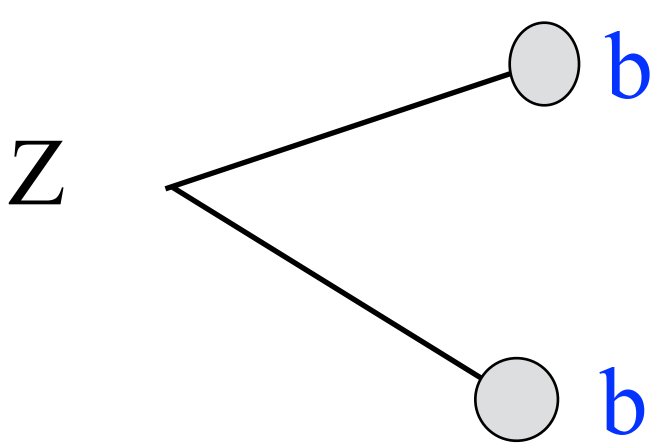
Resolved

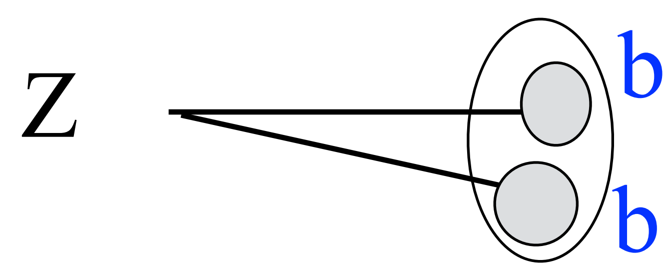
Merged (R ~ $2M/p_T$)





Use b-tagging to target Z→bb





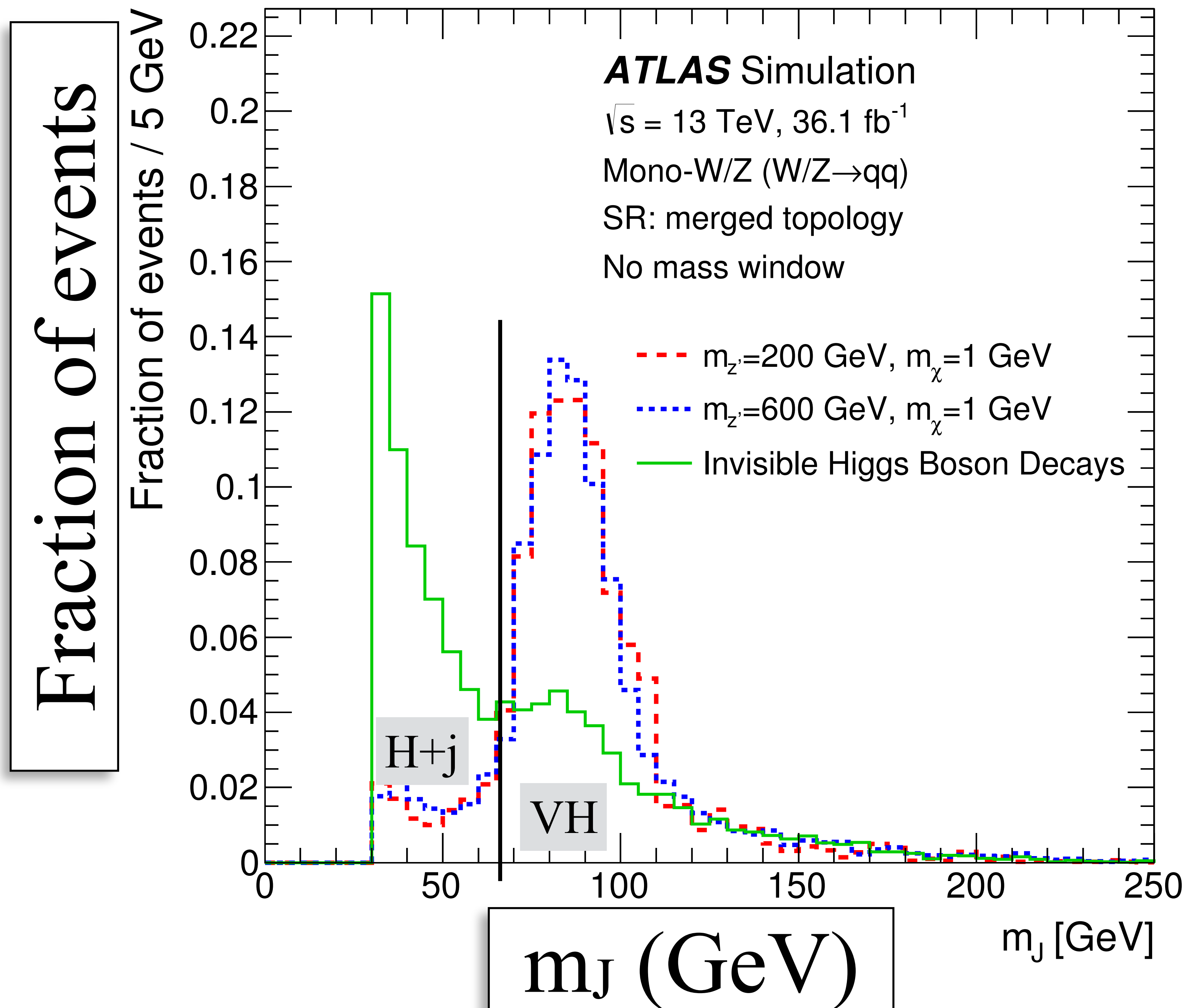
b-tag sub-jets

Merged

- **MET > 250 GeV**
- R = 1.0 jet
- Jet mass M_J: 75-100 GeV
- Binned in $N_{b\text{-tagged}}$ subjets

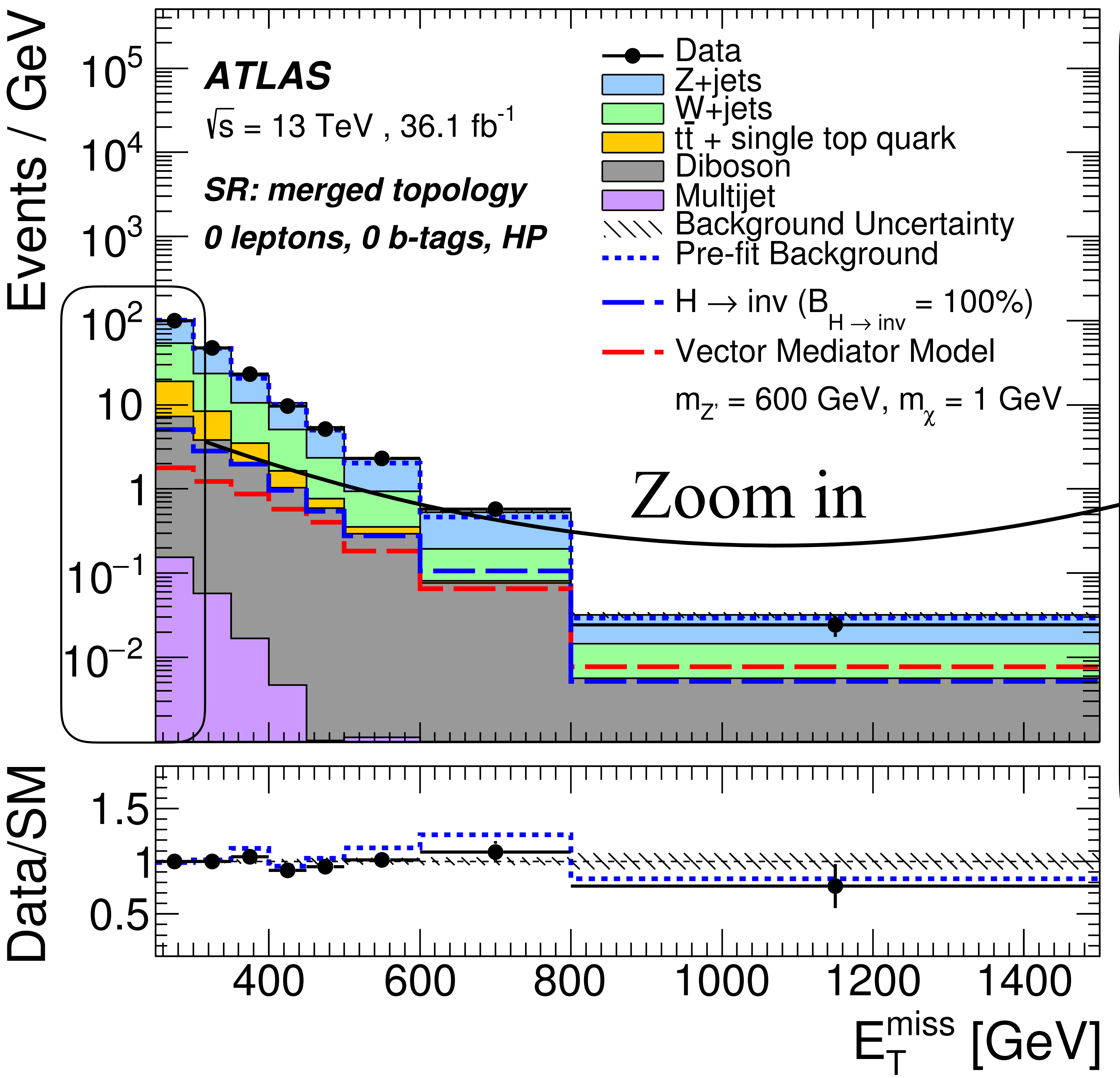
Resolved

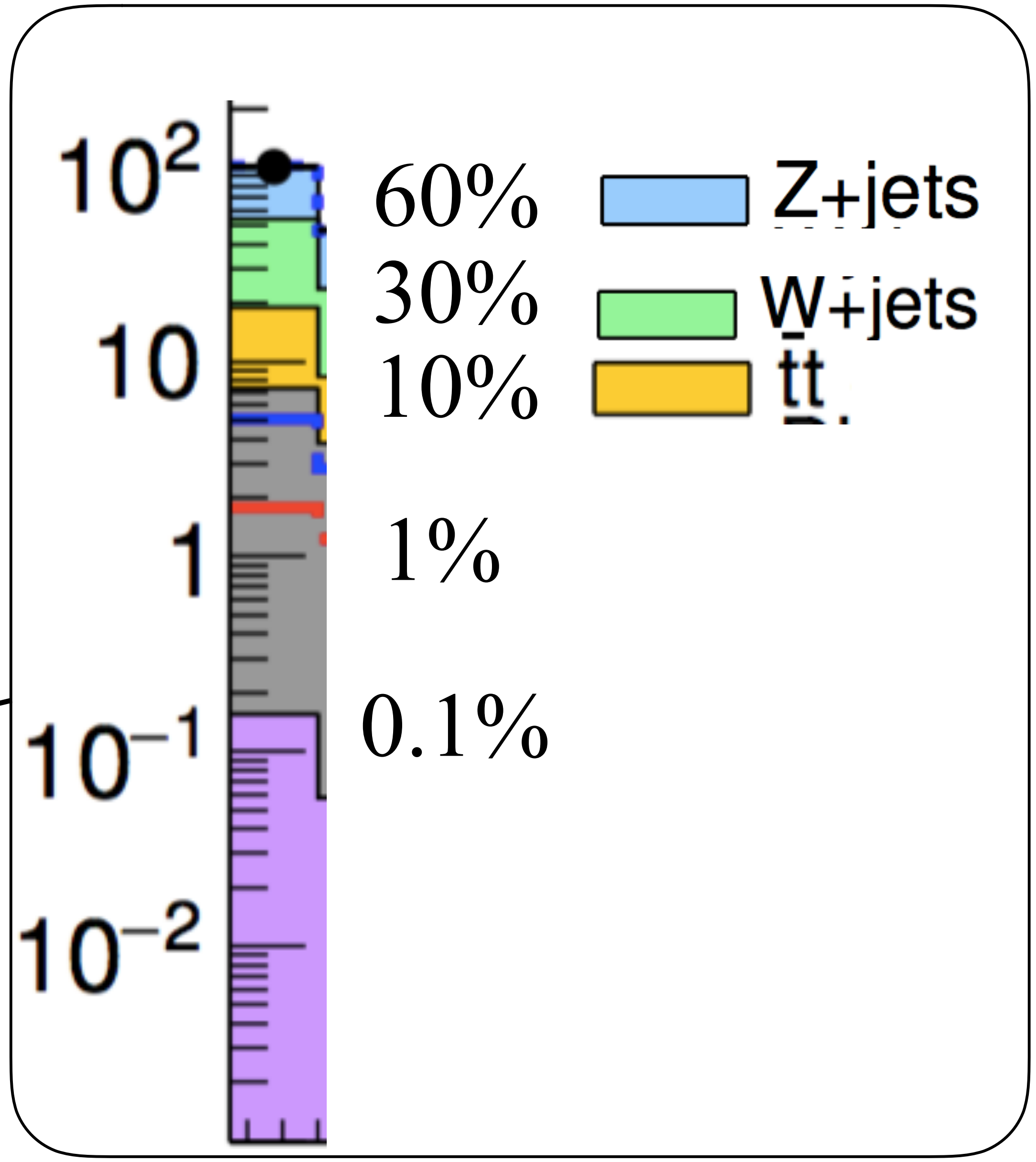
- **MET > 150 GeV**
- Two R = 0.4 jets
- Dijet mass m_{jj}: 65-105 GeV
- Binned in $N_{b\text{-tags}}$



The green line includes ggF and W/Z→qq

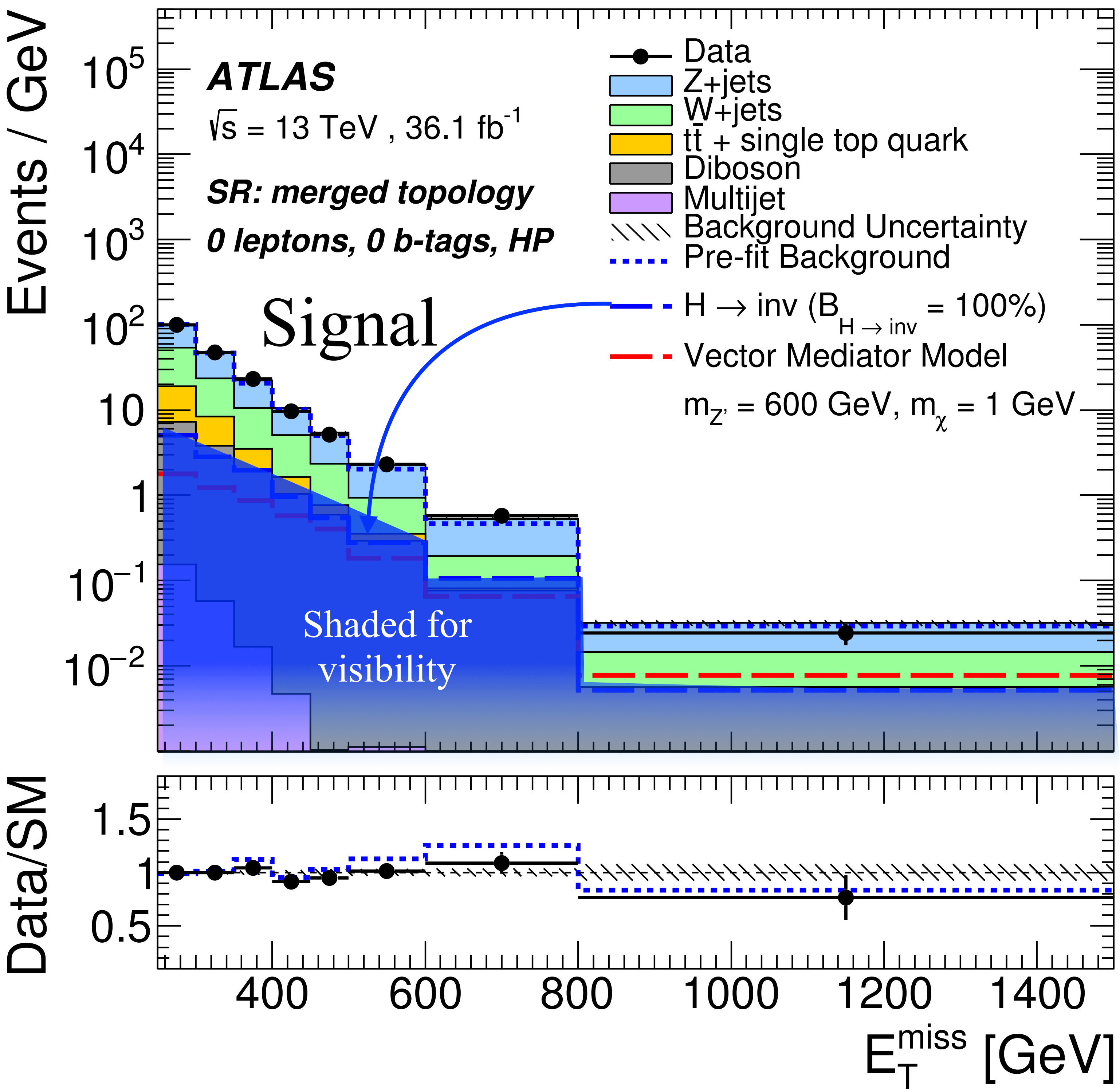
Merged category





Main backgrounds are $Z\to\nu\nu$ and $W\to\ell\nu$

Merged category



Signal to background increases with MET

Combining all bins: Br(H→inv) < 83% (58% expected)

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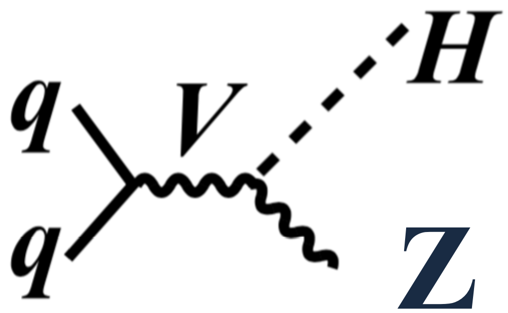
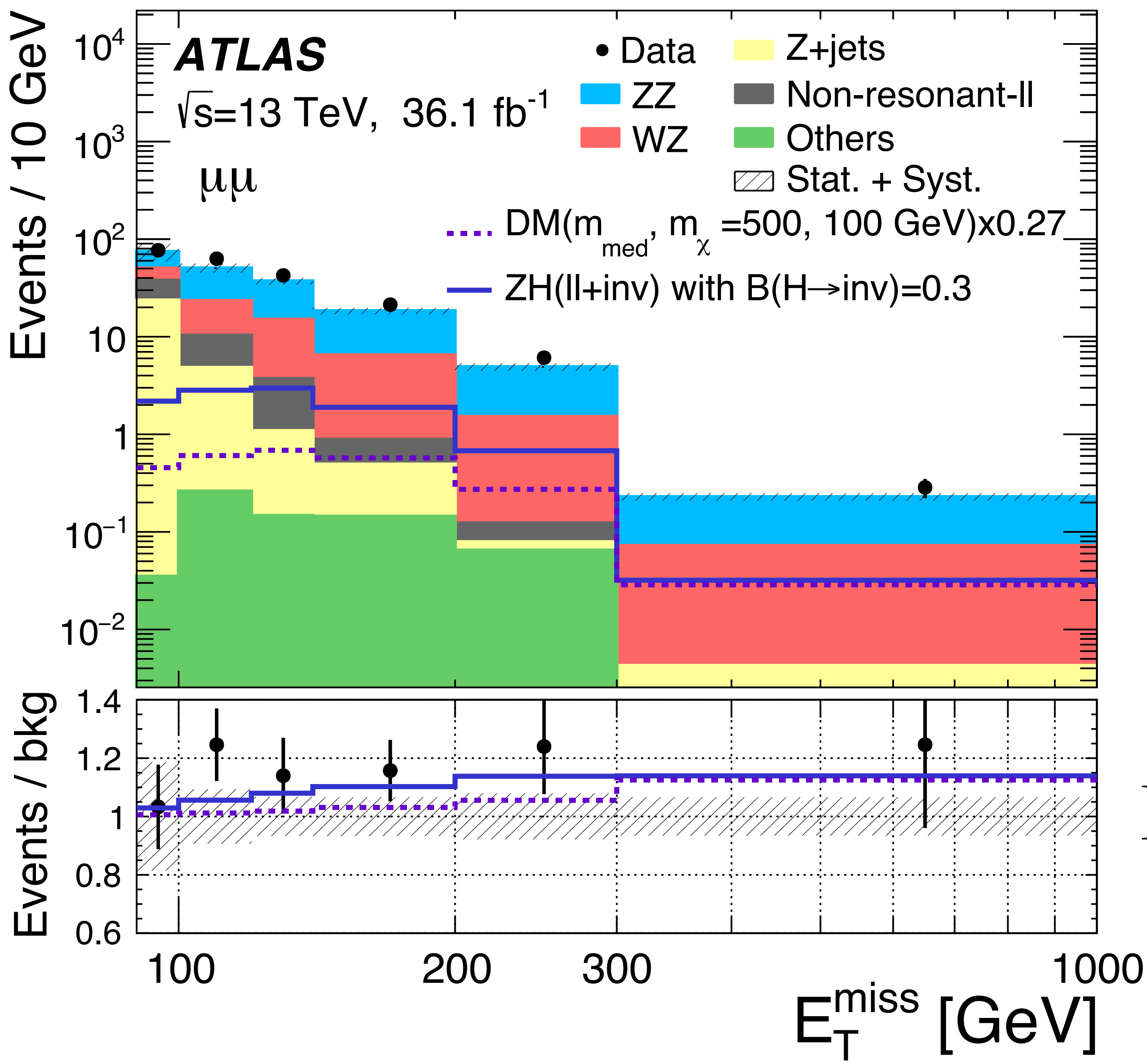
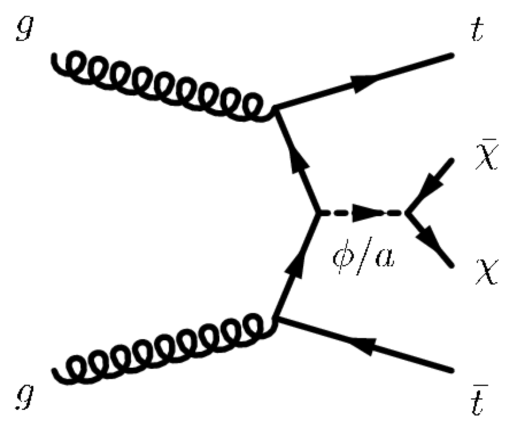


- MET > 90 GeV
- ΔΦ(Z,MET) > 2.7 (Higgs recoiling against Z)

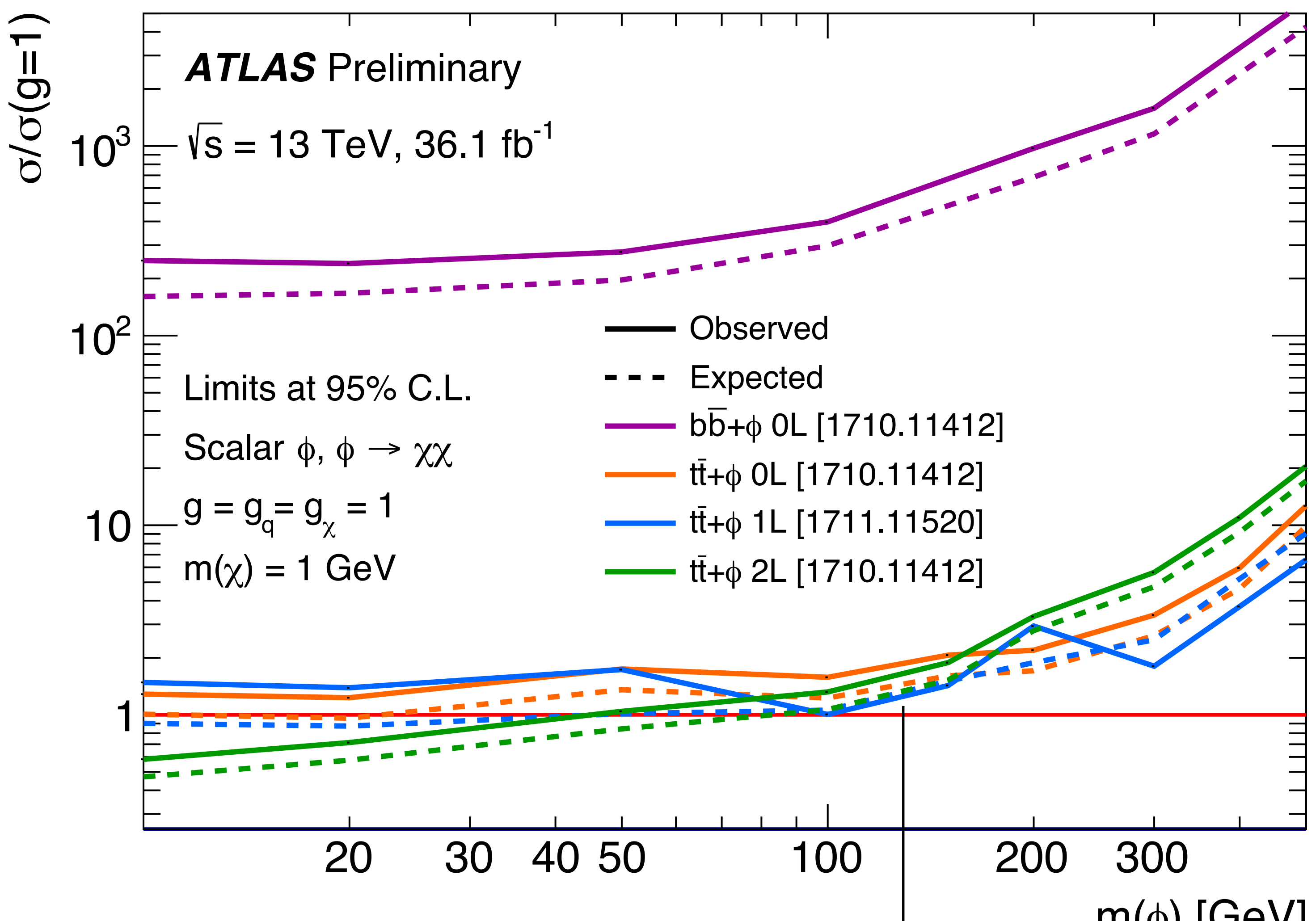


Main background is ZZ (WZ)

Br(H→inv) < 67% (40% exp.)



DM coupling to heavy flavor



Cross section for scalar ϕ same as ttH

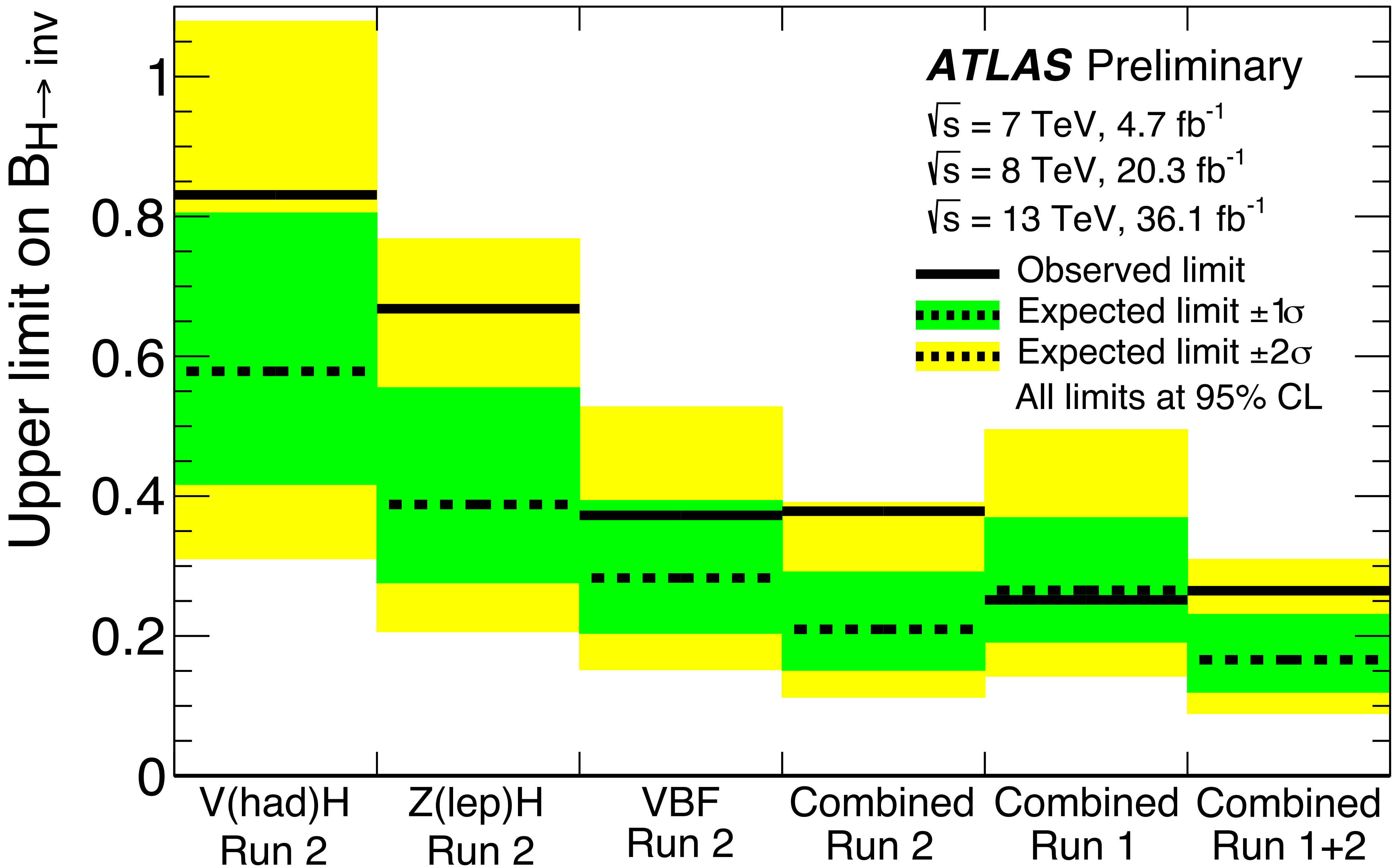
Most channels give:

Br(H→inv) ~ 100%

Compare with 300% reinterpreted using CMS run 1 data (N. Zhou et al. PRL 113 (2014) 151801)

Targeting in lots of top decay channels

Combination



expected: 21%
observed: 38%

expected: 17%
observed: 26%

Uncertainties correlated when possible;
between Run 1 and 2 generally not correlated

Outline

1. Motivation

- Higgs
- Dark Matter
- Higgs and DM

2. Experiment intro

- The LHC
- ATLAS detector
- ATLAS data

3. SM Higgs constraints

- SM constrain inv.

4. H→inv channels

- Production channels
- MET: searching for inv.
- VBF
- V→qq
- Z→ℓℓ
- ttH
- Combination

5. Implications

- Limit vs. m_{scalar}
- Comparison to direct detection

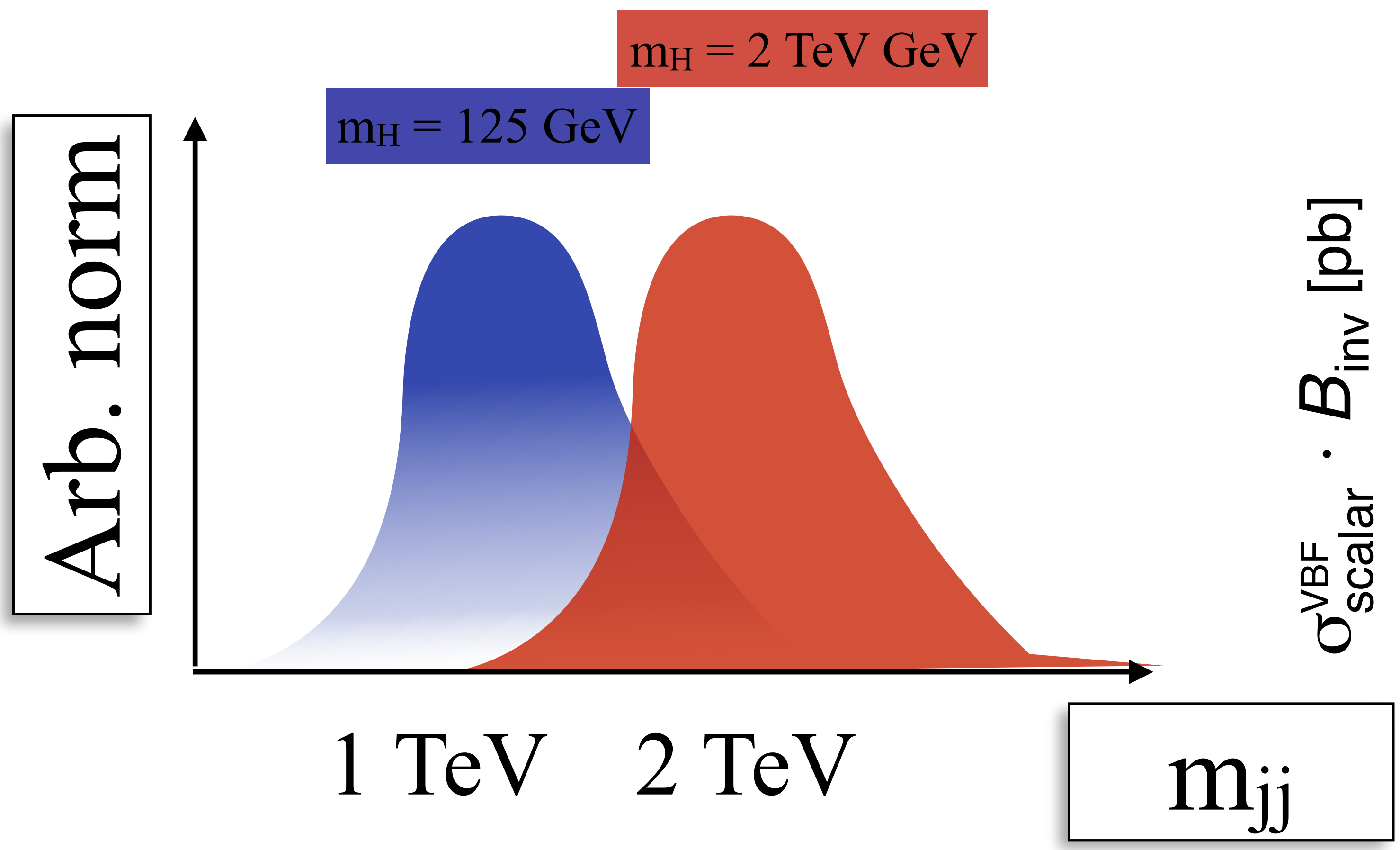
6. H→inv next steps

- Monte Carlo
- Trigger for high pileup Run 2

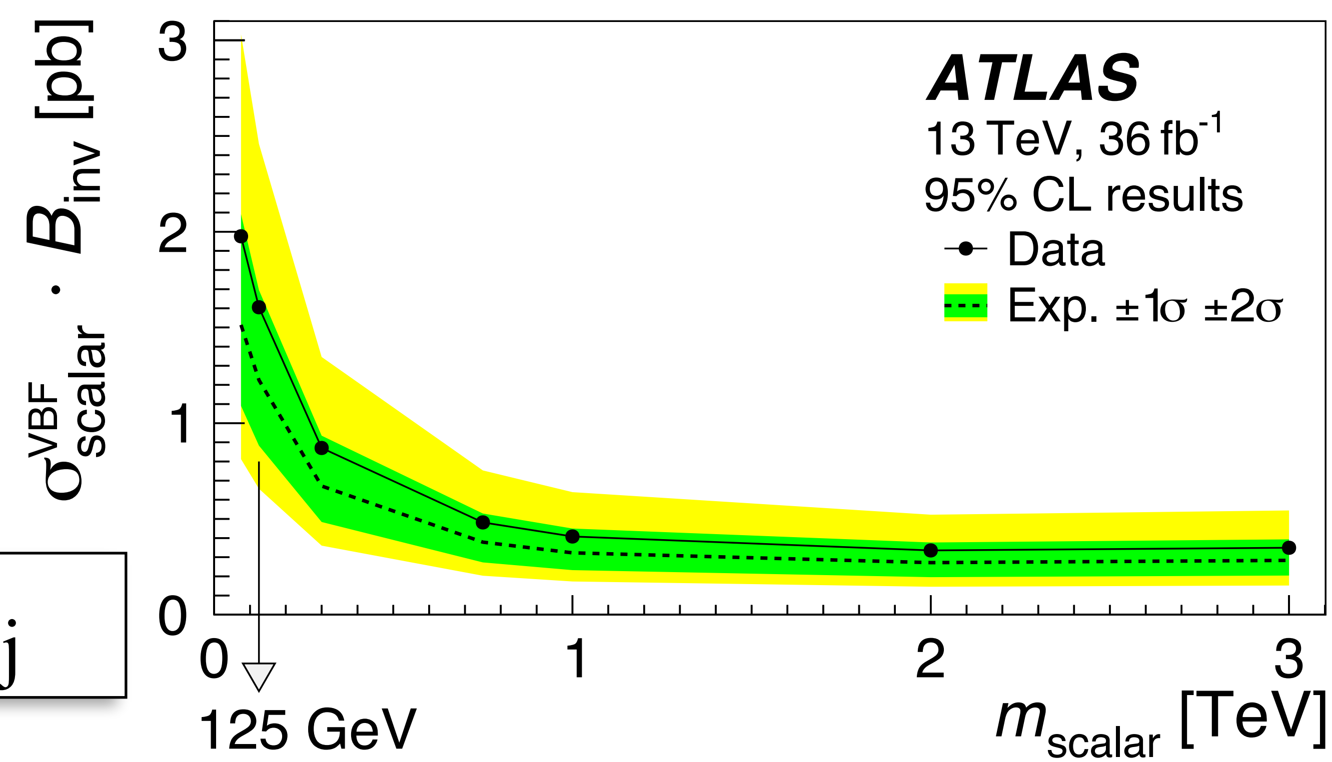
Limit vs. mass

ATLAS: 1809.06682
(Submitted to PLB)

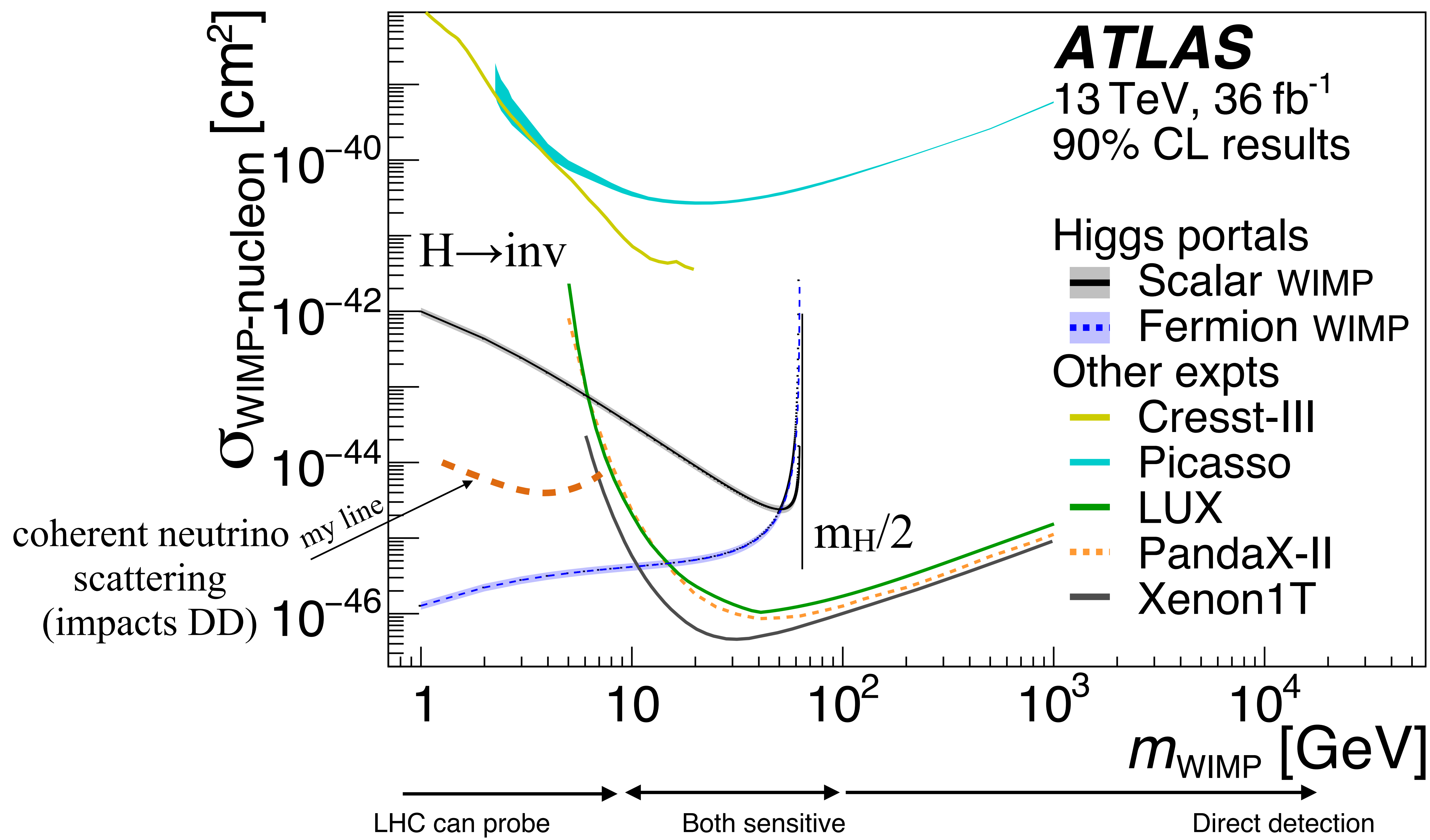
Model independent parameterization of sensitivity in terms of m_H



As m_H increases, jets are more forward, and higher mjj bins contribute more



For the Higgs portal, results complementary with direct detection



Lattice calculations to reduce theory uncertainty on Higgs nucleon form factor
(M. Hoferichter et al. 1708.02245)

Ben Carlson

1. Motivation

- Higgs
- Dark Matter
- Higgs and DM

2. Experiment intro

- The LHC
- ATLAS detector
- ATLAS data

3. SM Higgs constraints

- SM constrain inv.

I worked on both

4. H→inv channels

- Production channels
- MET: searching for inv.
- VBF
- V→qq
- Z→ℓℓ
- ttH
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6. H→inv next steps

- Monte Carlo
- Trigger for high pileup Run 2

Monte Carlo

ATLAS: JHEP 01 (2016) 172

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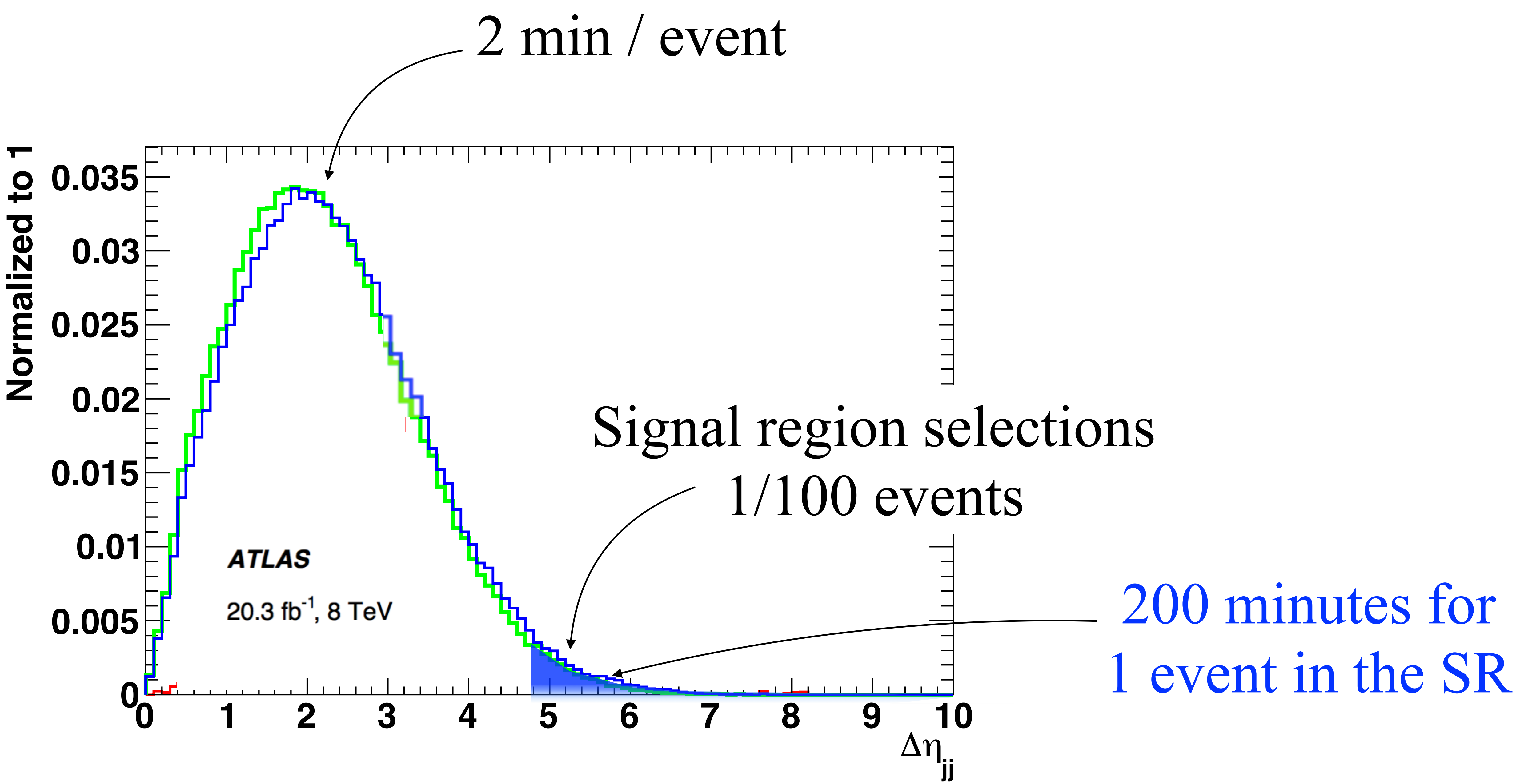
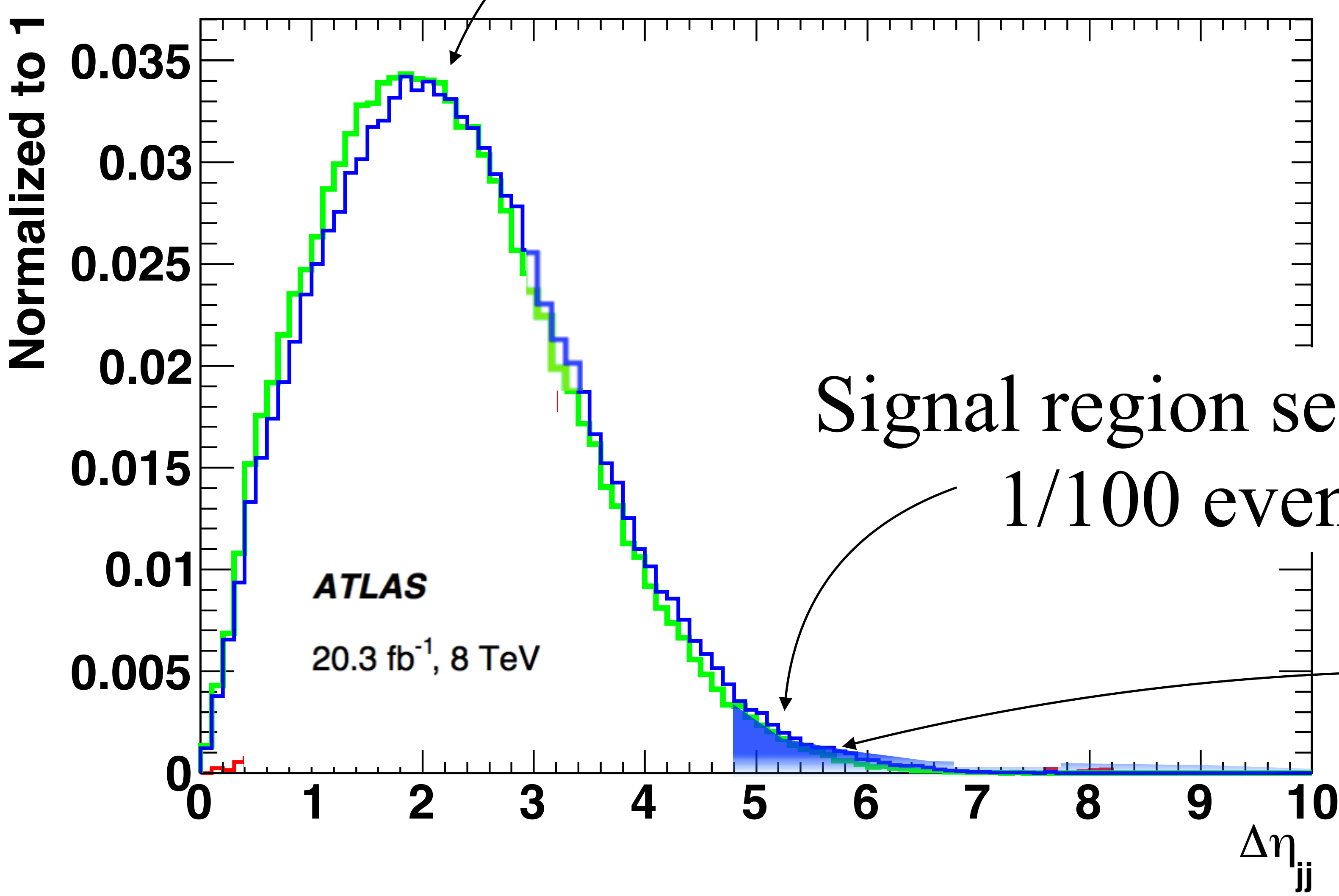
- NLO Sherpa used for strong W/Z + jets background
- Resource limitation from event generation



- Reduce time per event (LO)
- Optimize generator for $\Delta\eta > 4.8$ (or m_{jj})



~~2 min / event~~
10 s / event

Signal region selections
1/100 events

~~200 minutes for 1 event in the SR~~
2 min for 1 event in SR

MET trigger

ATLAS: 1809.06682
(Submitted to PLB)

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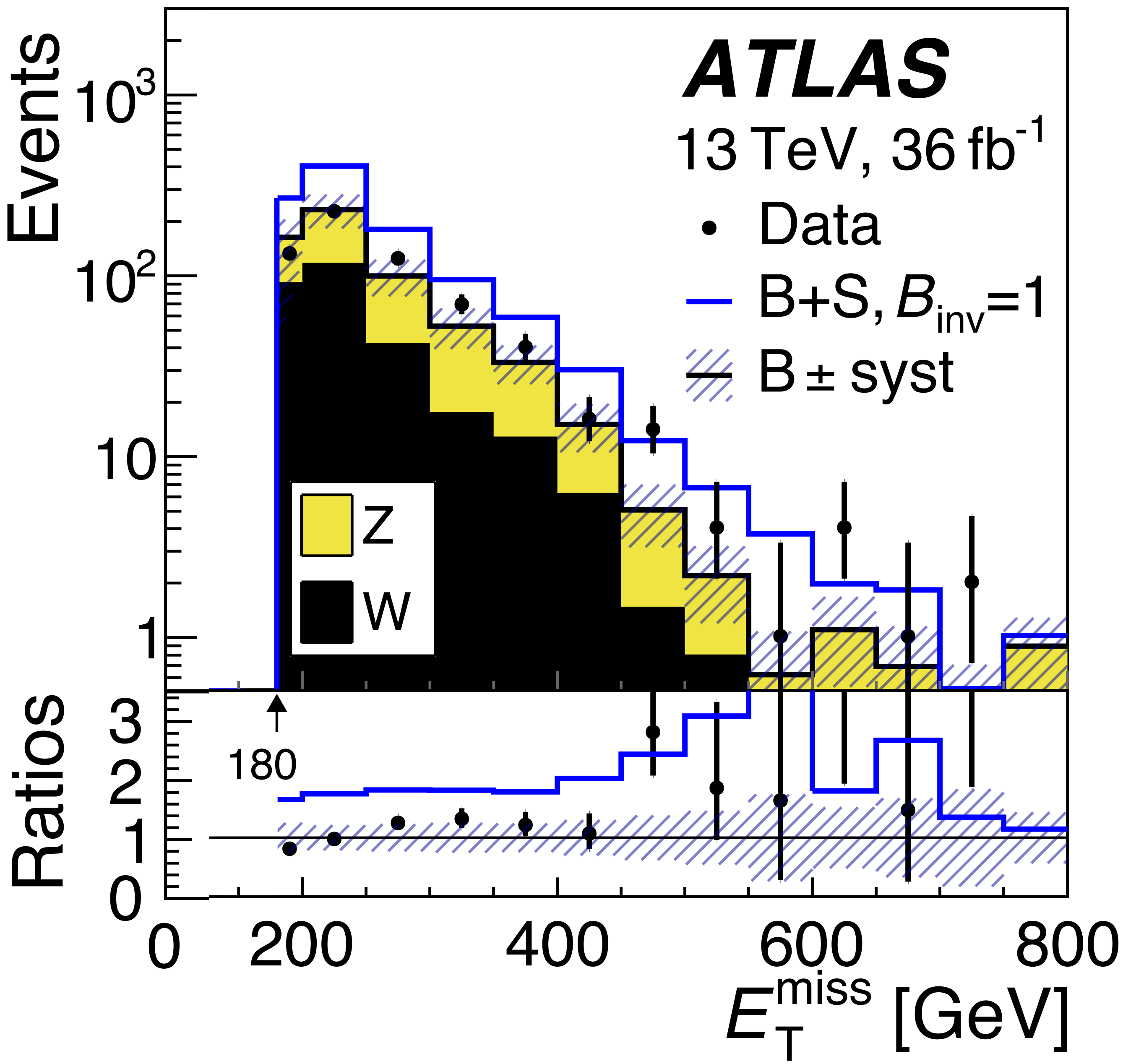
MET trigger important for H→inv searches



Acceptance loss if bins below:
200 GeV: 20%
250 GeV: 60%
are removed

With 2016 trigger,
need to require MET >200 GeV

L1 MET trigger

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

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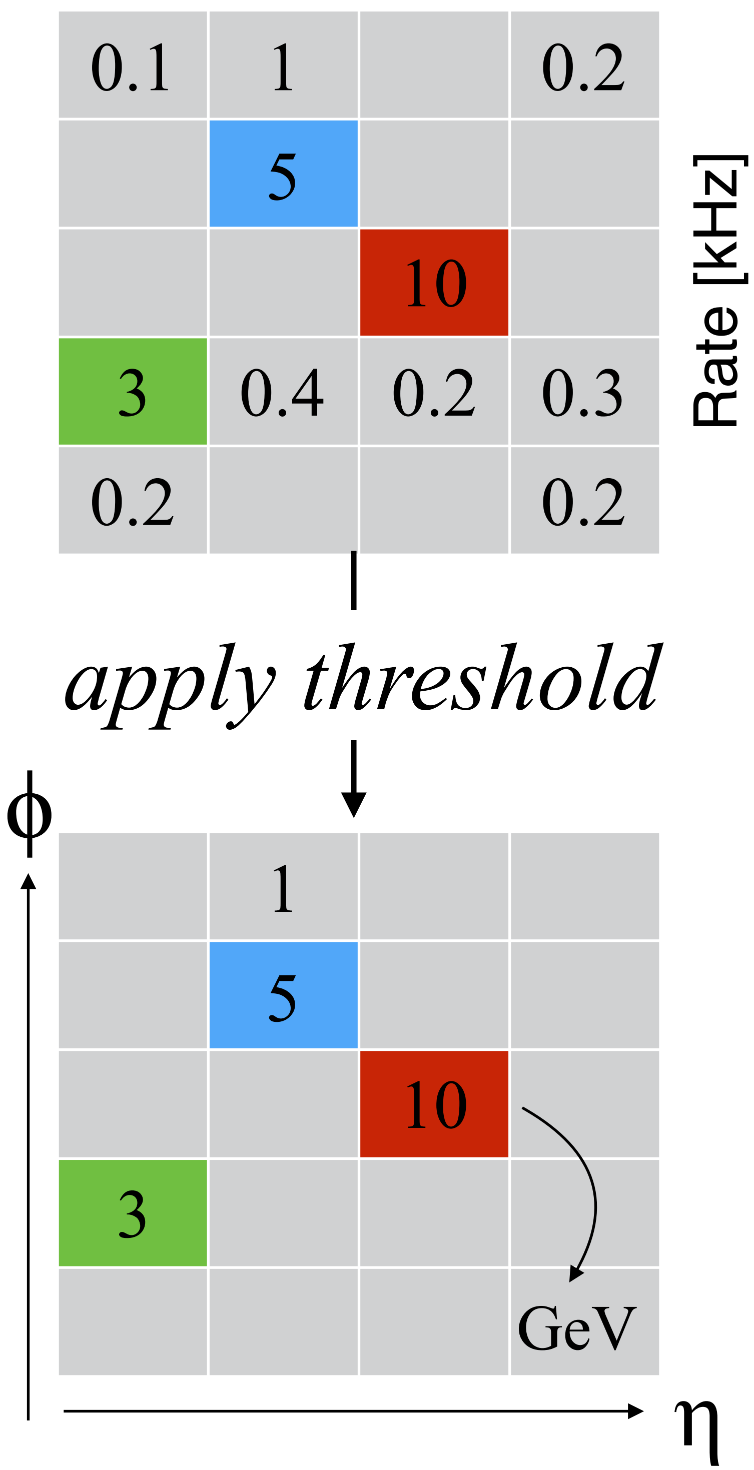
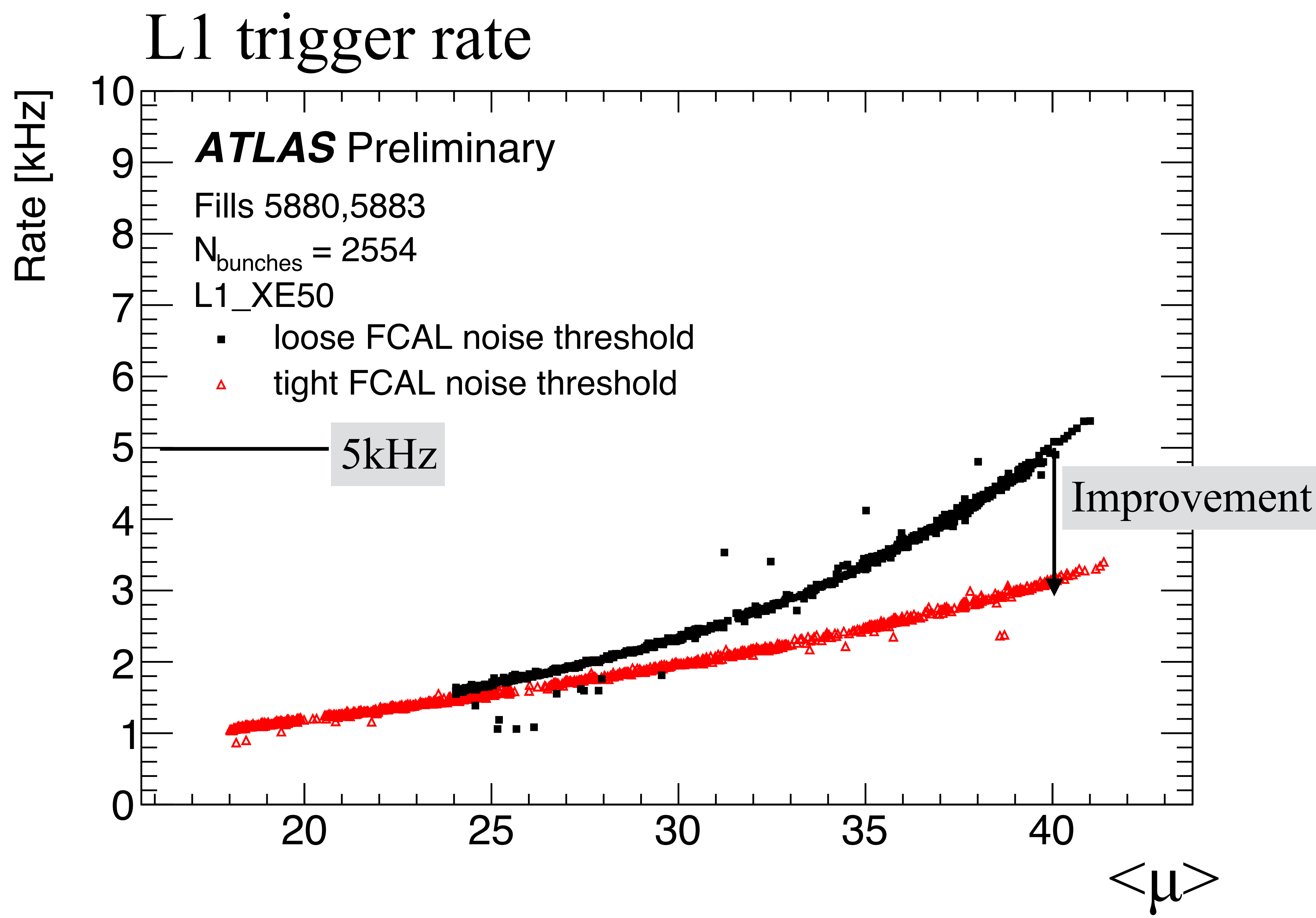
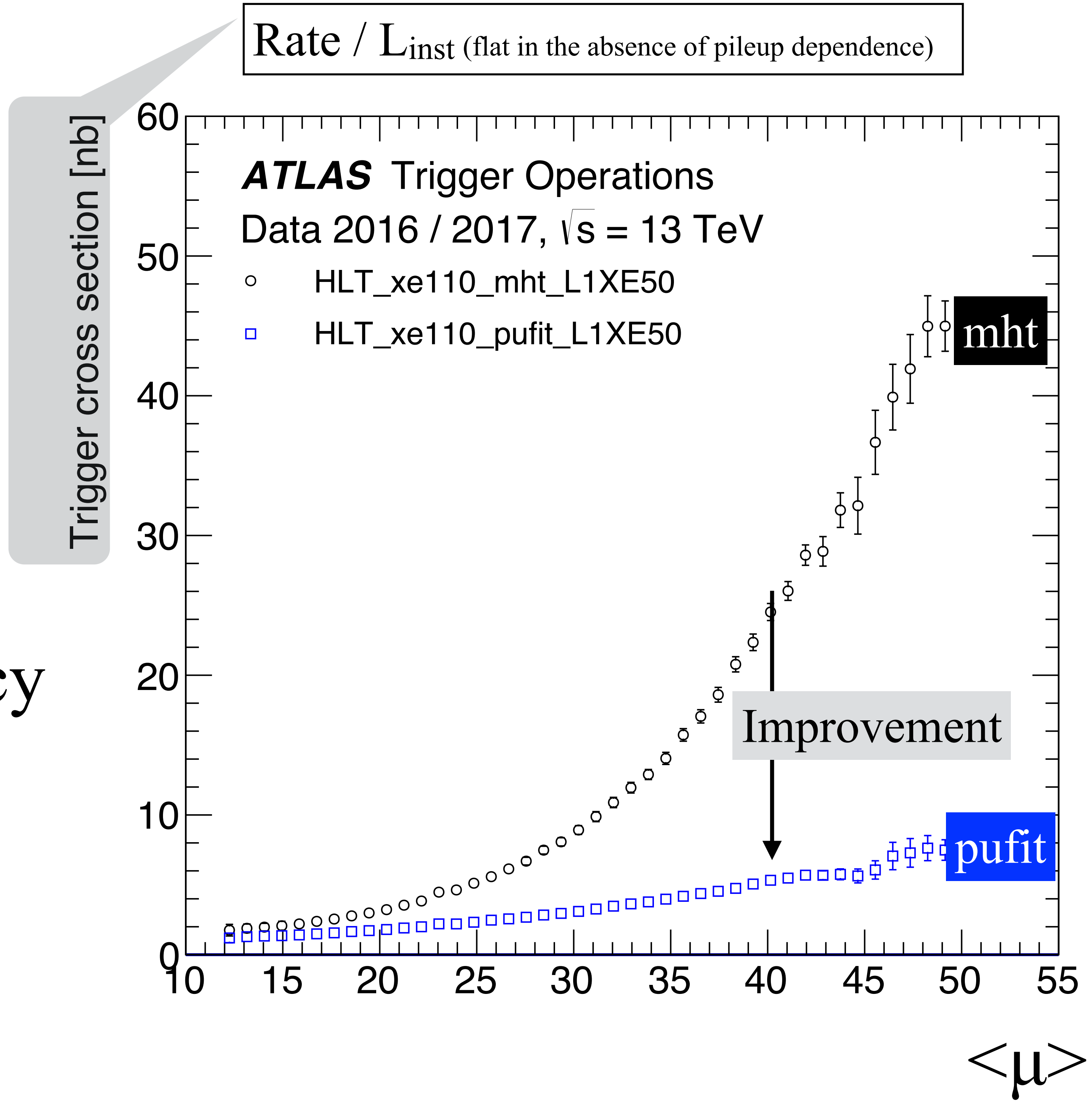
- L1 trigger MET trigger rate is sensitive to pileup
- Reduced by raising the E_T threshold per trigger tower





- HLT (software) trigger rate also sensitive to pileup
- Reduced the rate by developing new algorithm to remove pileup

1/5 the rate; same efficiency



Conclusions

Discussed
- Motivation
- Constraints from SM measurements
- H→inv channels
  - VBF
  - V→qq
  - Z→ℓℓ
  - ttH
  - Combination
- Interpretation: direct detection

Next steps: reduce systematics
- Monte Carlo statistics
- Trigger for Run 2
- 150fb^{-1} of data to analyze

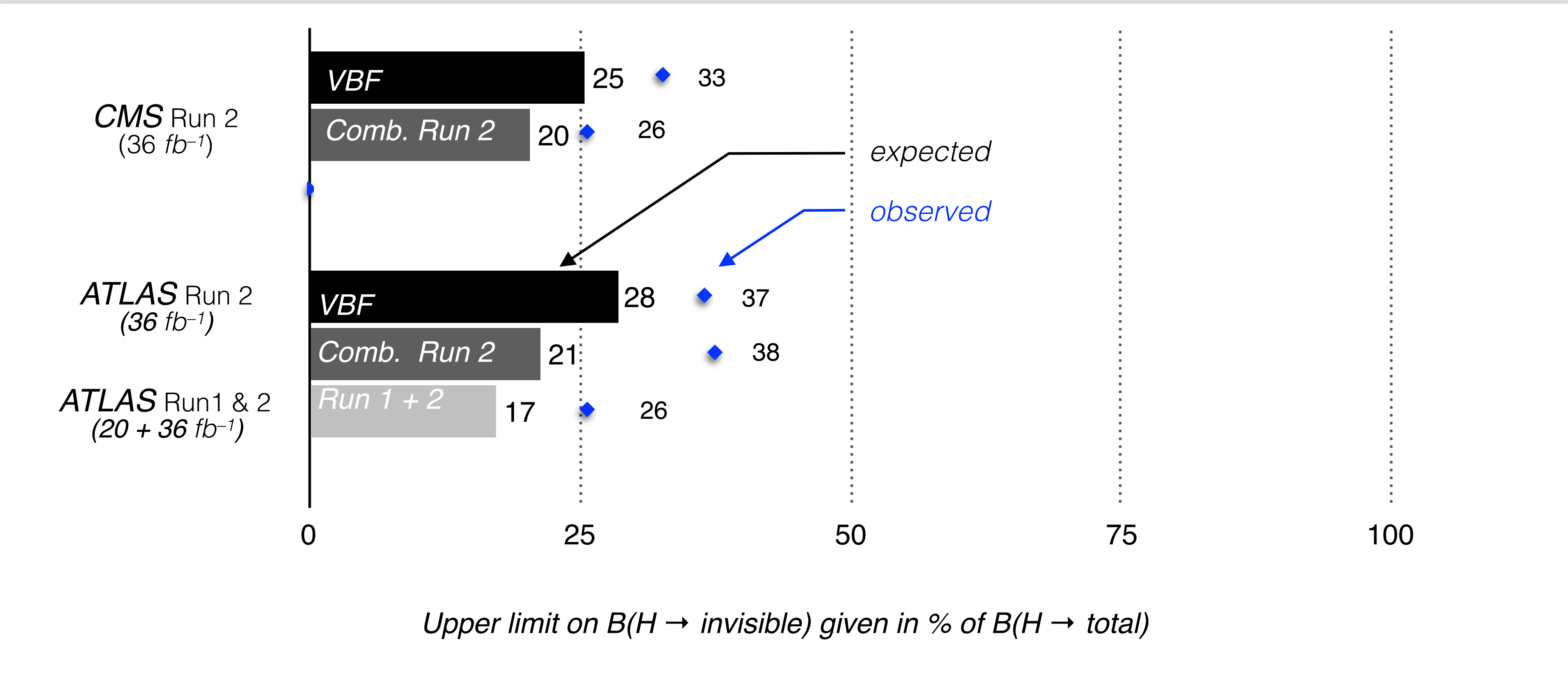
Other topics to ask me about:
- L1 trigger upgrade for Run 3
- VBF trigger

Backup

ATLAS vs. CMS

Ben Carlson

Summary showing driving channels of sensitivity



Sources:

J. High Energy Phys.
- 11 (2015) 206
- 01 (2016) 172
- 02 (2017) 135

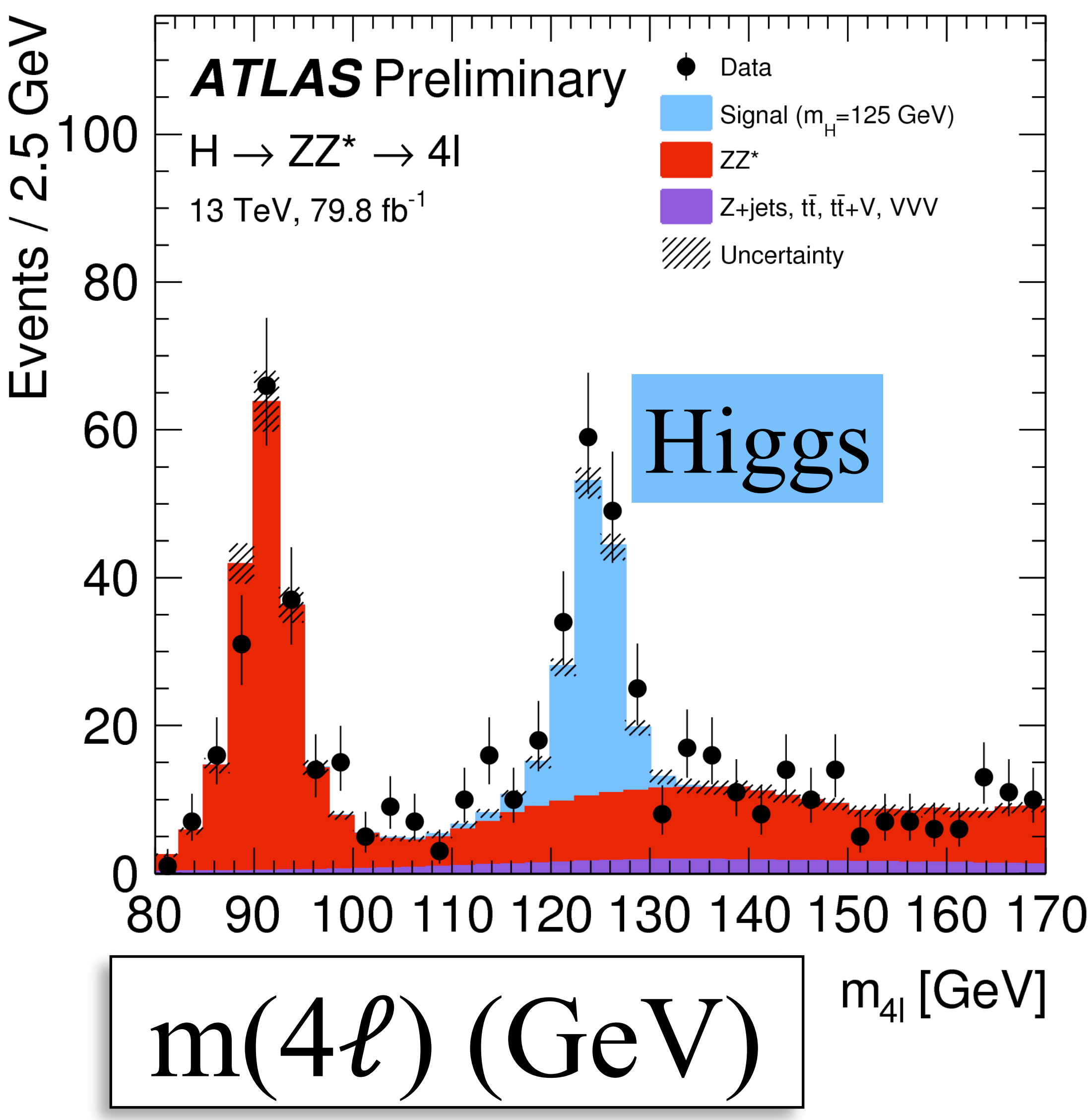
Phys. Letters B
- 776(2018)318–337

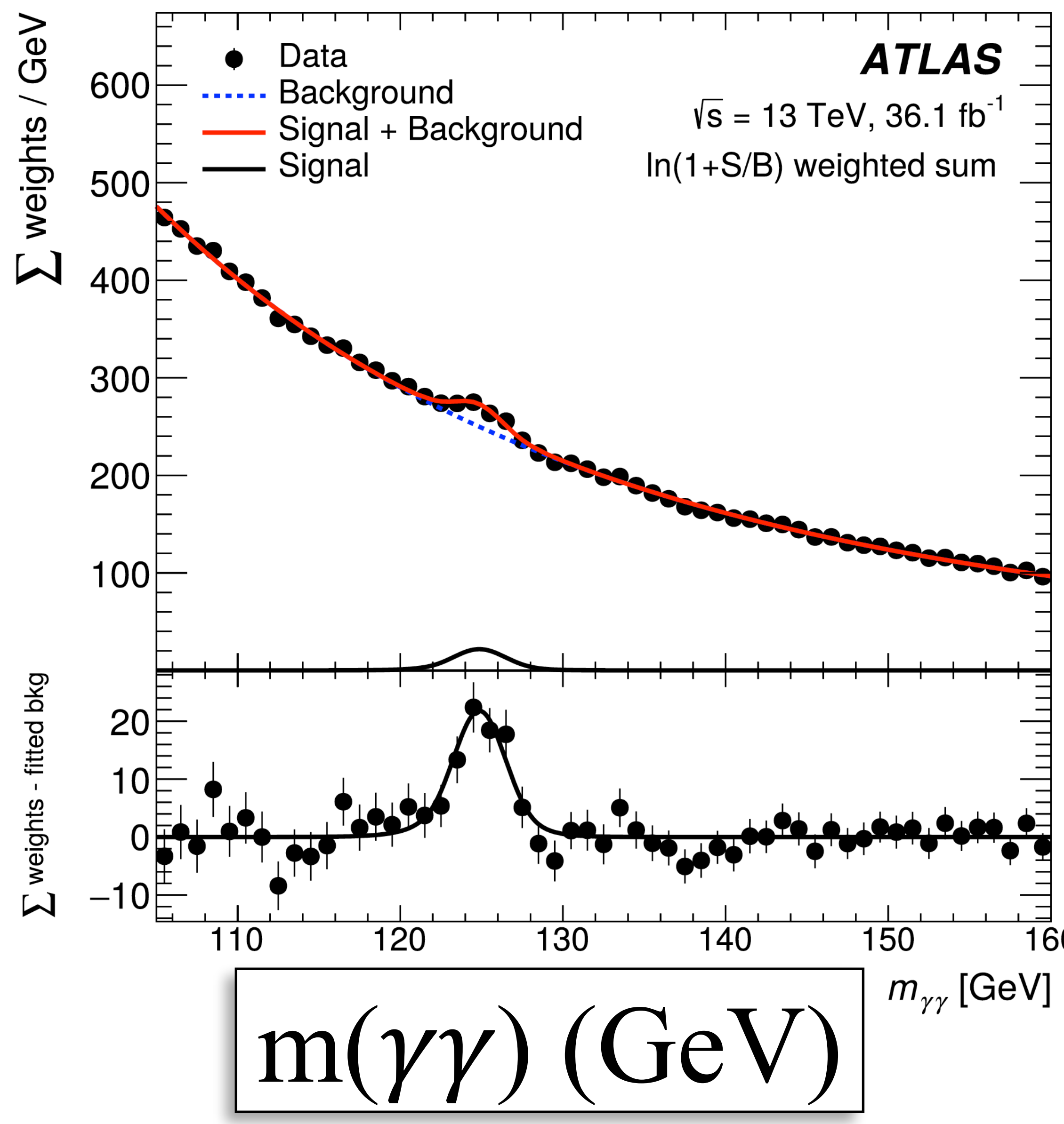
arXiv
- 1809.06682
- 1809.05937

ATLAS-CONF-2018-054

SM Higgs

ATLAS-CONF-2018-018
Phys. Lett. B 784 (2018) 345



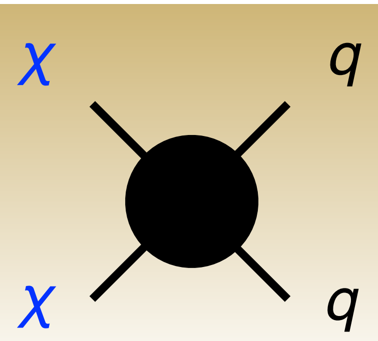


Higgs boson, with $m_H = 124.97 \pm 0.24$ GeV

Finding dark matter

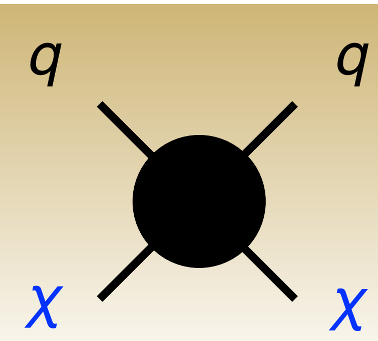
Ben Carlson

Annihilation



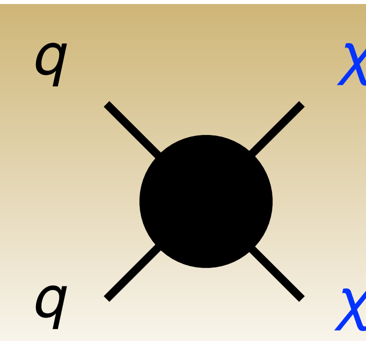
Indirect

Scattering

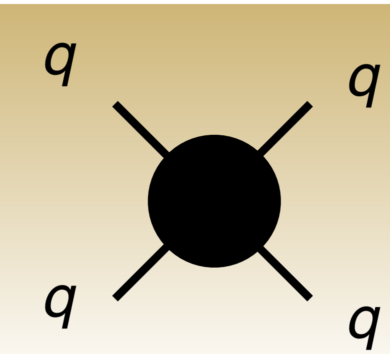


Direct

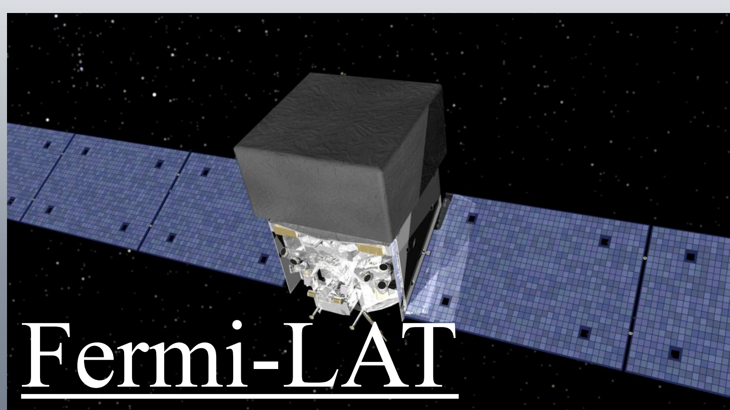
Production



Mediator



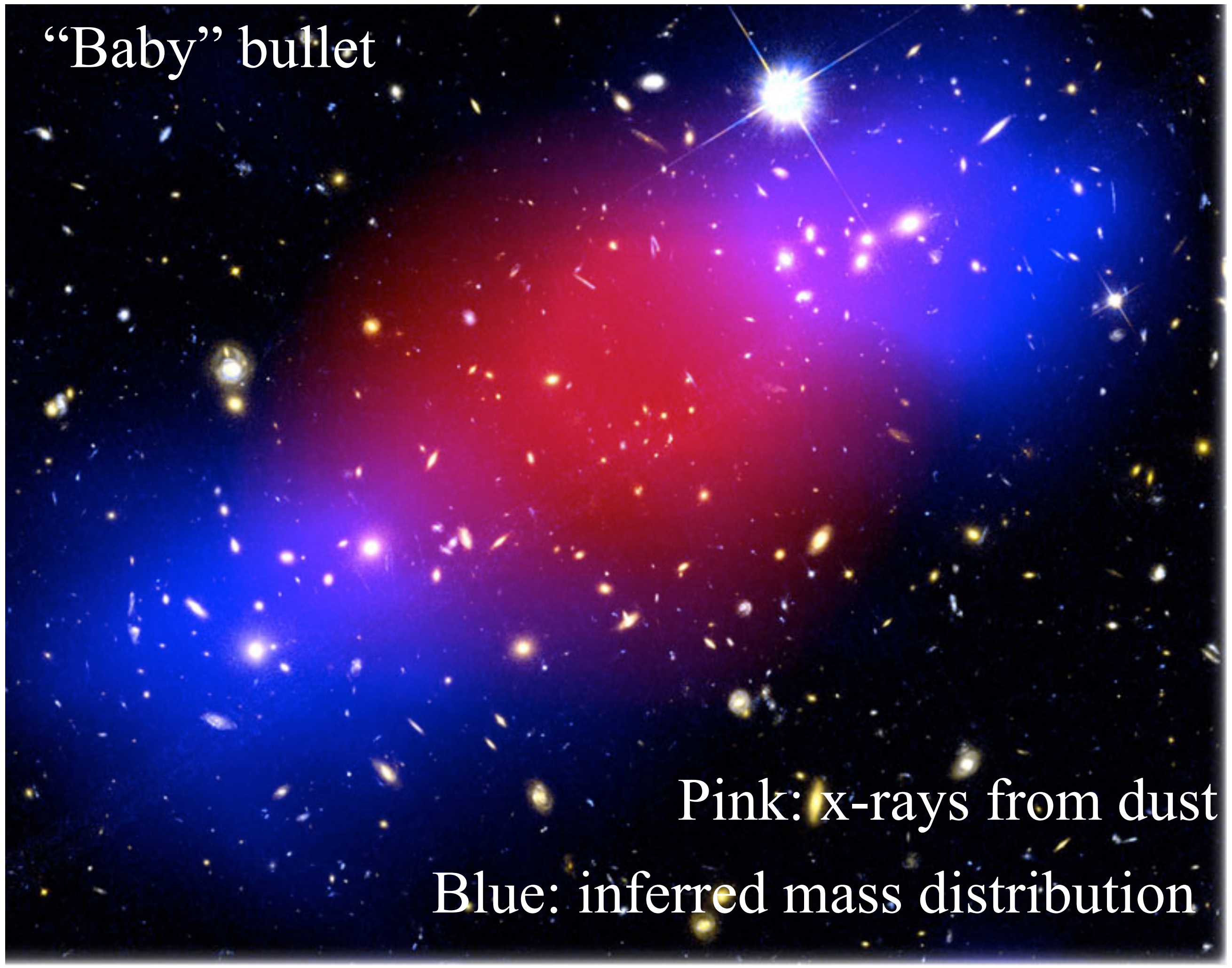
Collider

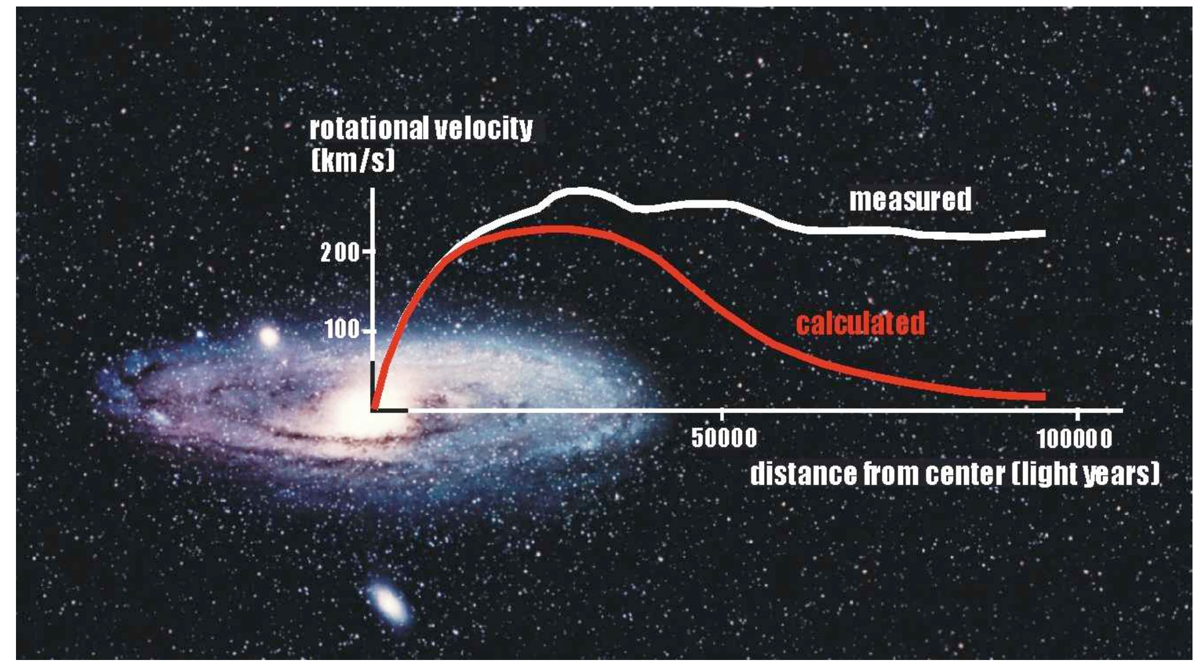


LUX, Panda-X, Picasso…

Dark matter

Evidence for new physics: non-luminous dark matter





Clearly observed gravitational effects
WIMP miracle suggests electroweak scale

Combination tables

ATLAS-CONF-2018-031

Ben Carlson

Analysis	Integrated luminosity (fb^{-1})
$H \to \gamma\gamma$ (including $t\bar{t}H$, $H \to \gamma\gamma$)	79.8
$H \to ZZ^* \to 4\ell$ (including $t\bar{t}H$, $H \to ZZ^* \to 4\ell$)	79.8
$H \to WW^* \to e\nu\mu\nu$	36.1
$H \to \tau\tau$	36.1
VH, $H \to b\bar{b}$	36.1
$H \to \mu\mu$	79.8
$t\bar{t}H$, $H \to b\bar{b}$ and $t\bar{t}H$ multilepton	36.1

Parameter	(a) no BSM	(b) with BSM
κ_Z	1.07 ± 0.10	restricted to $\kappa_Z \leq 1$
κ_W	1.07 ± 0.11	restricted to $\kappa_W \leq 1$
κ_b	$0.97^{+0.24}_{-0.22}$	$0.85^{+0.13}_{-0.14}$
κ_t	$1.09^{+0.15}_{-0.14}$	$1.05^{+0.14}_{-0.13}$
κ_τ	$1.02^{+0.17}_{-0.16}$	0.95 ± 0.13
κ_γ	$1.02^{+0.09}_{-0.12}$	$0.98^{+0.05}_{-0.08}$
κ_g	$1.00^{+0.12}_{-0.11}$	$0.97^{+0.10}_{-0.09}$
B_{BSM}	-	< 0.26 at 95% CL

Improvements in constraints

Run	Experiment	Br(undetected)
1	ATLAS [1]	<48%
1	ATLAS+CMS [2]	<39%
2	ATLAS [3]	<26%

[1] JHEP11(2015)206 (1509.00672)
[2] JHEP08(2016)045 (1606.02266)
[3] ATLAS-CONF-2018-031

Visible + invisible

JHEP08(2016)045 (1606.02266)

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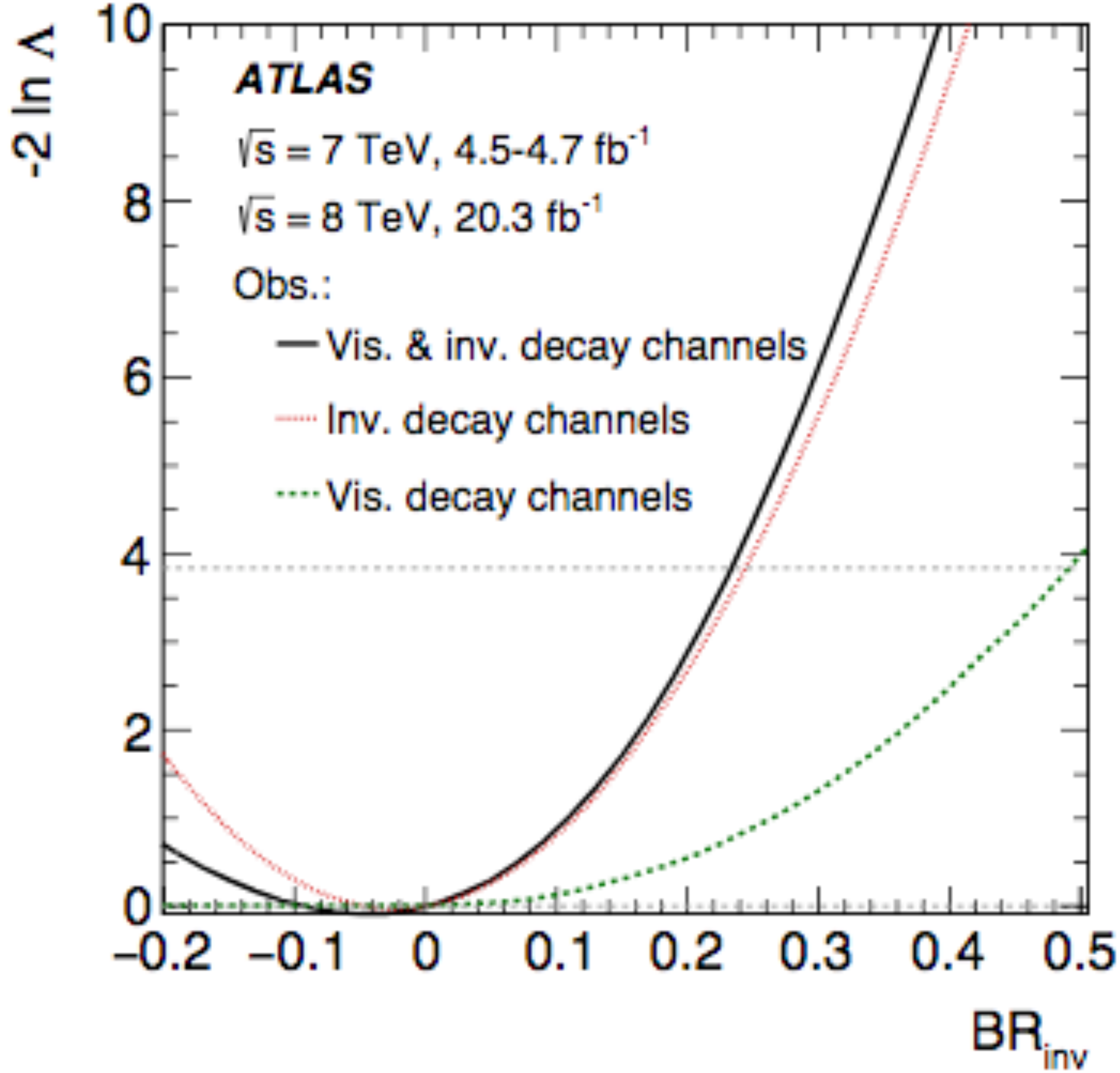
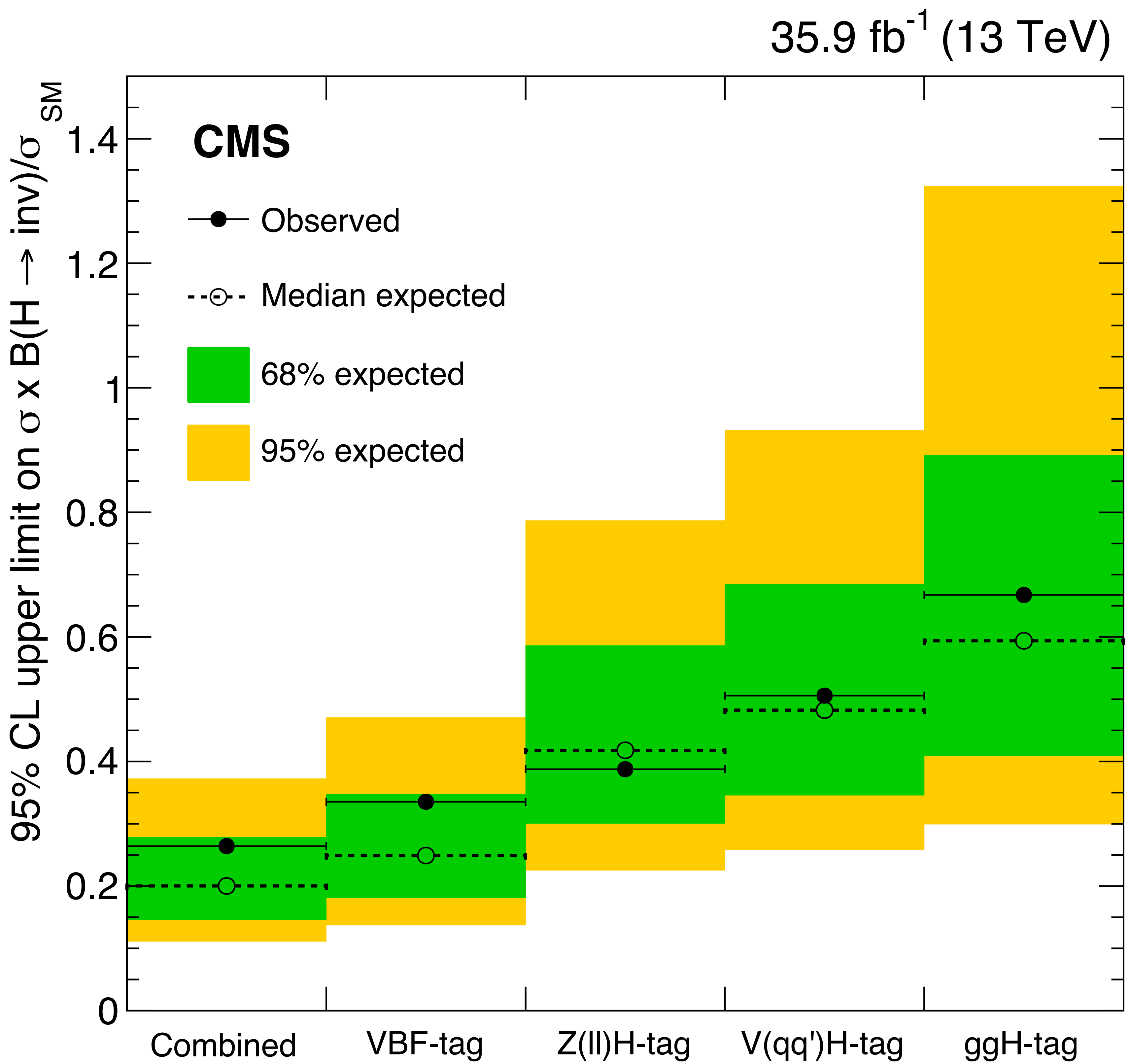
Run 1



CMS result

arXiv: 1809.05937
(submitted to PLB)



CMS background

arXiv: 1809.05937
(submitted to PLB)

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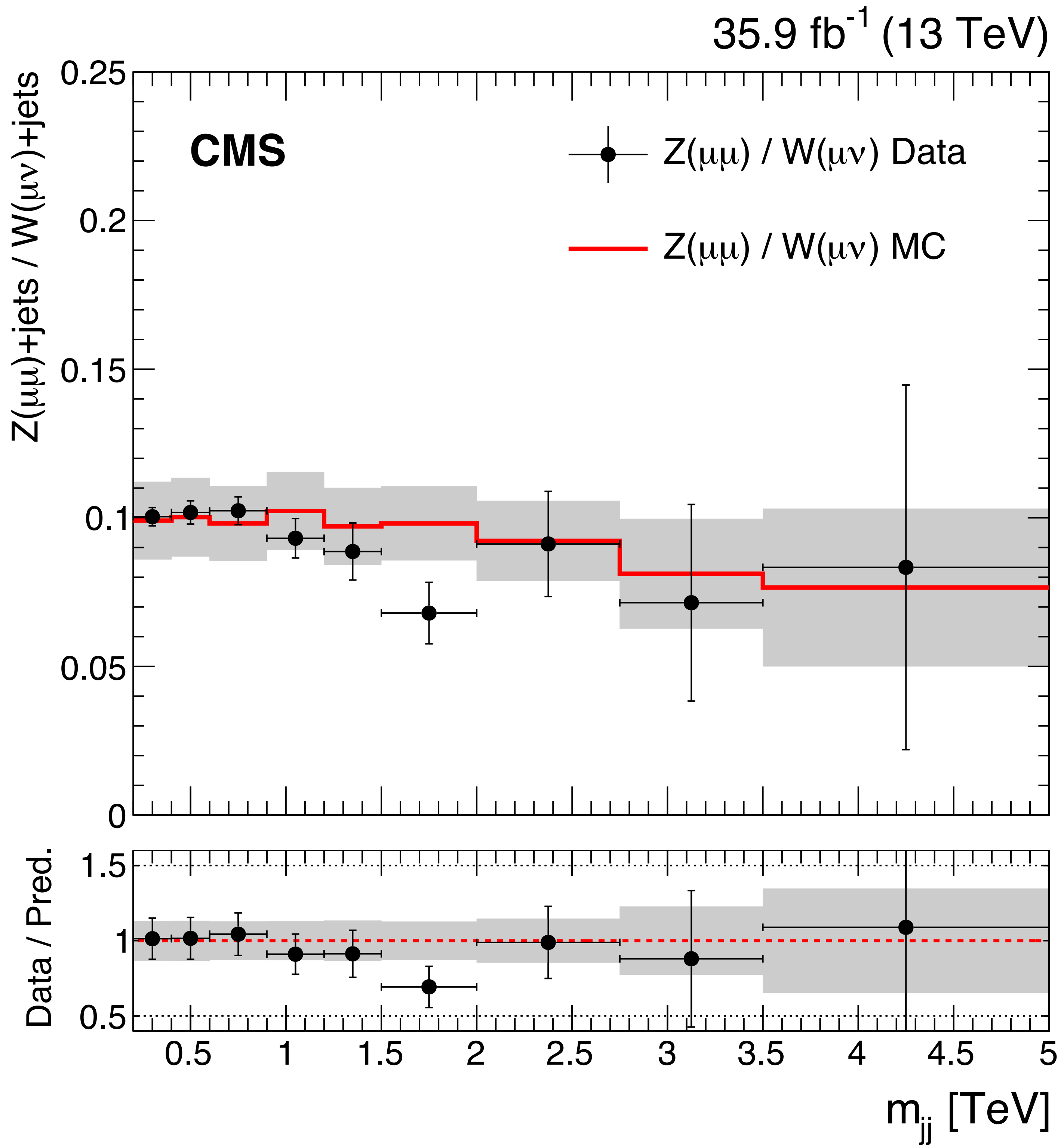
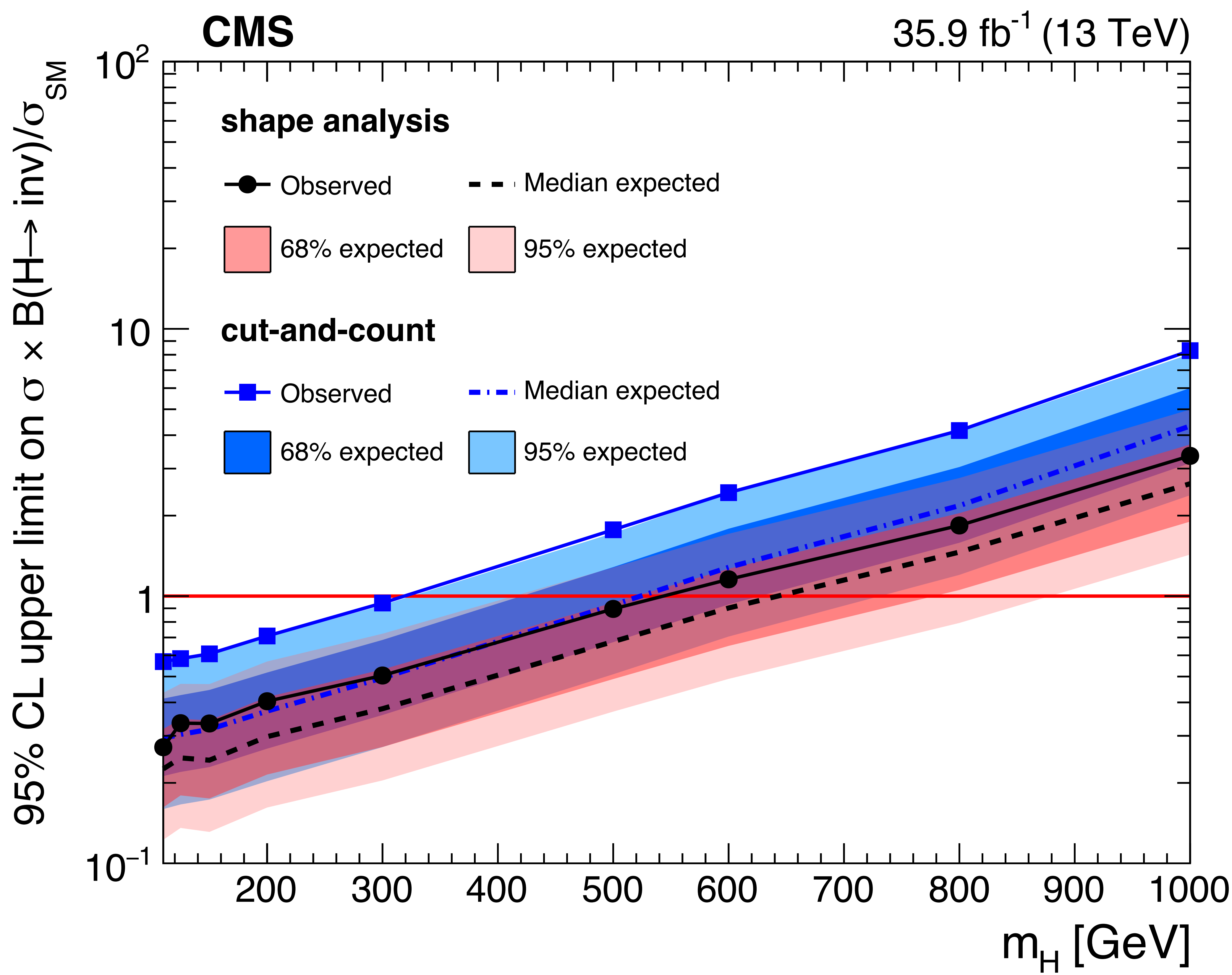


CMS limit vs. mass

arXiv: 1809.05937
(submitted to PLB)

Ben Carlson



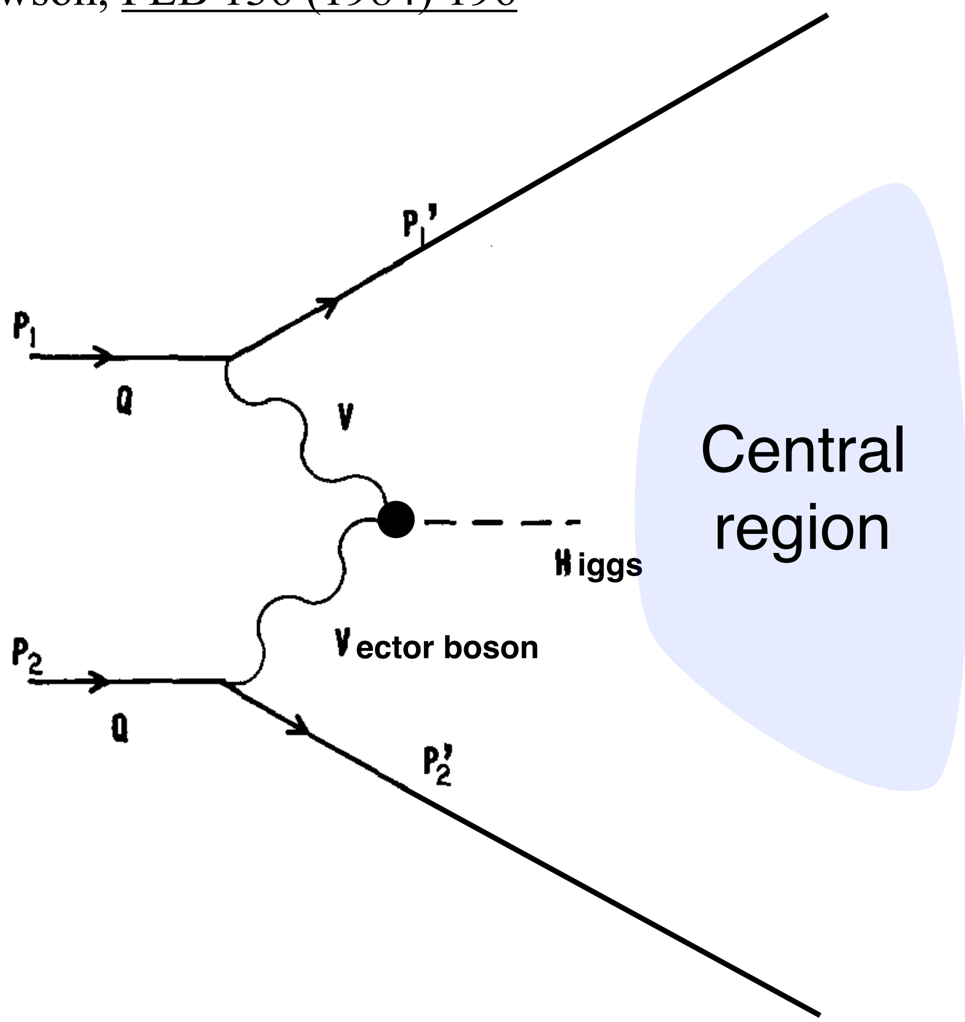
Nr.	Parameter	300 fb^{-1} Theory unc.: All	Half	None	3000 fb^{-1} Theory unc.: All	Half	None
9	κ_g	8.9%	7.1%	6.3%	6.7%	4.1%	2.8%
	κ_γ	4.9%	4.8%	4.7%	2.1%	1.8%	1.7%
	$\kappa_{Z\gamma}$	23%	23%	23%	14%	14%	14%
	$BR_{i,u}$	<22%	<20%	<20%	<14%	<11%	<10%

Upper limit on invisible or undetected

General features of VBF

Vector-boson fusion
Cahn, Dawson, PLB 136 (1984) 196

VBF jet: high-P_T, high-η



Why

- Vector bosons are colorless
- No color between jets

Consequence 1

- Less hadronic activity between jets in VBF

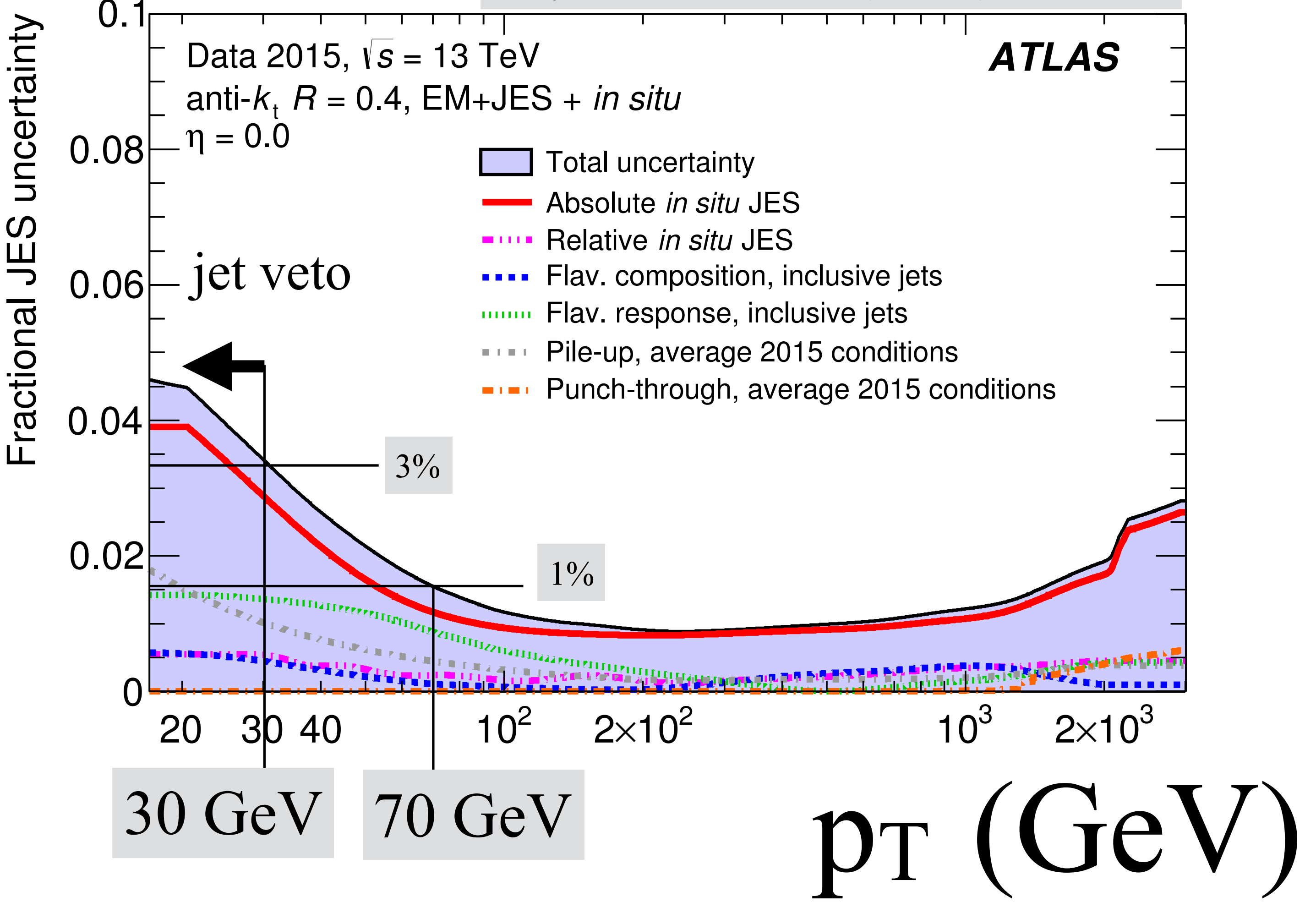
Effective in rejecting non-VBF SM backgrounds

VBF "central region"
Zeppenfeld, Rainwater, PRD 60 (1999) 113004
Barger, Cheung, Han, PRD 42 (1990) 3052

Systematics

Ben Carlson

Phys. Rev. D 96 (2017) 072002



Experimental uncertainties dominated by jet veto

Run 1: 50 $Z\rightarrow\ell\ell$ events (15% stat unc.)
Once we have 100 $Z\rightarrow\ell\ell$ events (10%),

- Dropped the W/Z const.

W/Z→qq H→inv

		0b	2b
Merged	S	620	40
	B	9,640	410
	S/B	0.06	0.10
	S/Sqrt(B)	6	2
Resolved	S	6,750	145
	B	288,000	4600
	S/B	0.02	0.03
	S/Sqrt(B)	13	2

	Merged topology	Resolved topology
General requirements		
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 250 GeV	> 150 GeV
Jets, leptons	$\geq 1J$, 0ℓ	$\geq 2j$, 0ℓ
b-jets	no b-tagged track jets outside of J	≤ 2 b-tagged small-R jets
Multijet suppression	$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, J \text{ or } jj) > 120^{\circ}$ $\min_{i\in\{1,2,3\}}\left[\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, j_i)\right] > 20^{\circ}$ $p_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV or ≥ 2 b-jets $\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}}) < 90^{\circ}$	
Signal properties		$p_{\mathrm{T}}^{j_1} > 45$ GeV $\sum p_{\mathrm{T}}^{j_i} > 120$ (150) GeV for 2 (≥ 3) jets

High purity

Low purity

Mono-W/Z signal regions

	0b HP	0b LP	1b HP	1b LP	2b	0b	1b	2b
ΔR_{jj}	–	–	–	–	–	< 1.4	< 1.4	< 1.25
$D_2^{(\beta=1)}$ p_{T}^{J}-dep.	pass	fail	pass	fail	–	–	–	–
Mass requirement]	m_J W/Z tagger requirement				m_J [75, 100]	m_{jj} [65, 105]		m_{jj} [65, 100]

Jet mass

Dijet mass

Mono-Z' signal regions

	0b HP	0b LP	1b HP	1b LP	2b	0b	1b	2b
$D_2^{(\beta=1)}$ <1.2	pass	fail	pass	fail	–	–	–	–
Mass requirement [GeV]	For $m_{Z'} < 100$ GeV: $[0.85m_{Z'}, m_{Z'} + 10]$ | $[0.75m_{Z'}, m_{Z'} + 10]$ For $m_{Z'} \geq 100$ GeV: no merged-topology selection applied					For $m_{Z'} < 200$ GeV: $[0.85m_{Z'}, m_{Z'} + 10]$ | $[0.75m_{Z'}, m_{Z'} + 10]$ For $m_{Z'} \geq 200$ GeV: $[0.85m_{Z'}, m_{Z'} + 20]$ | $[0.80m_{Z'}, m_{Z'} + 20]$		

Back of envelope ΔB

Ben Carlson

- Consider a simple example case
  - Signal yield S = 200; Background yield B = 560.
  - limit ~ 1/significance, significance ~ $S/\sqrt{B + \delta_1^2 + \delta_2^2}$, where δ_1, δ_2 are uncorrelated syst
  - Say we have B = 560 ± √560 (stat) ± 56 (δ_1) ± 28 (δ_2) = 560 ± 24 (stat) ± 63 (syst)
  - Turning off δ source(s) gives the Δ with respect to the 1st row

	$\sqrt{B}$	δ_1	δ_2	$\sqrt{B+\delta_1^2+\delta_1^2}$	$\Delta_{\sqrt{B}}$
final	24	56	28	67	-
turn off δ_1	24	-	28	37	45%
turn off δ_2	24	56	-	61	9%
turn off δ_1, δ_2	24	-	-	24	64%

Worked out explicitly for the example above

limit	Δ_{limit}
0.33	-
0.18	45% = 1 – 0.18/0.33
0.30	9% = 1 – 0.30/0.33
0.12	64% = 1 – 0.12/0.33

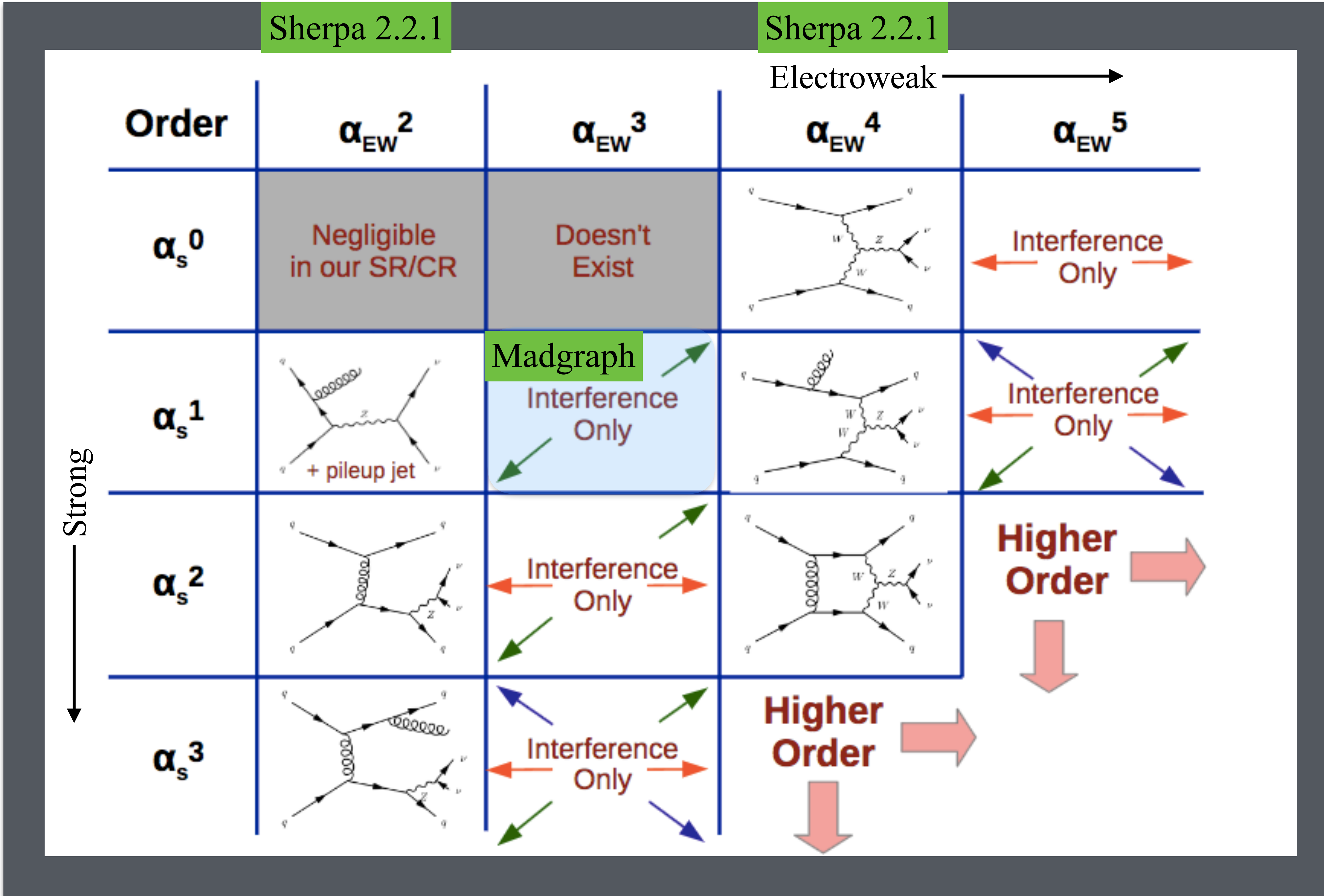
Type of table in the paper

- Observations
  - Notice that turning off δ_1, δ_2 45% and 9% gives us Δ = 64% (true answer)
  - If you tried to add quadratic 45% ⊕ 9% you get 46% « 64% (much much smaller)
  - If you tried to add linearly 45% + 9% you get 54% « 64% (much smaller still)

Background orders

Slide from Bill Balunas

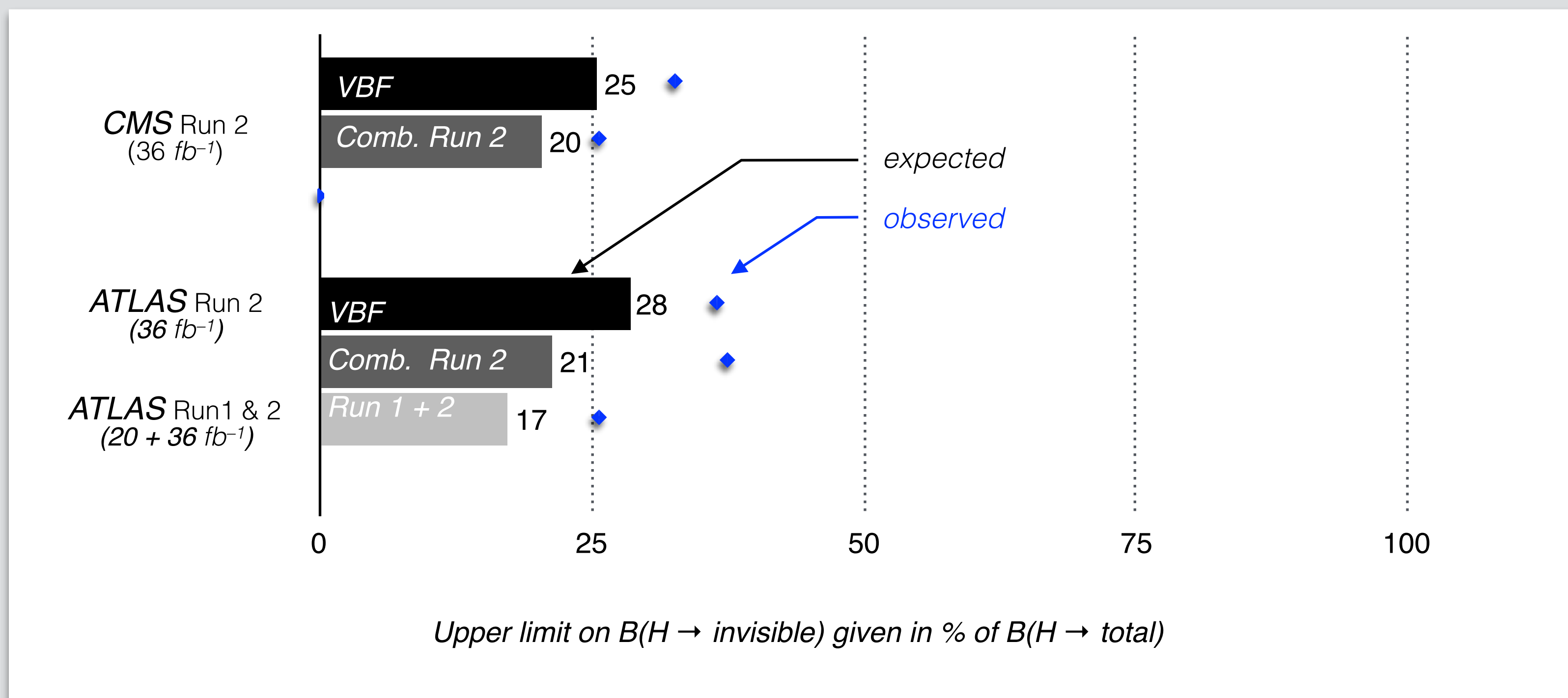
Ben Carlson



Summary showing driving channels of sensitivity

Invisible Higgs decays comparisons

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



Sources:

J. High Energy Phys.
11 (2015) 206
01 (2016) 172
02 (2017) 135

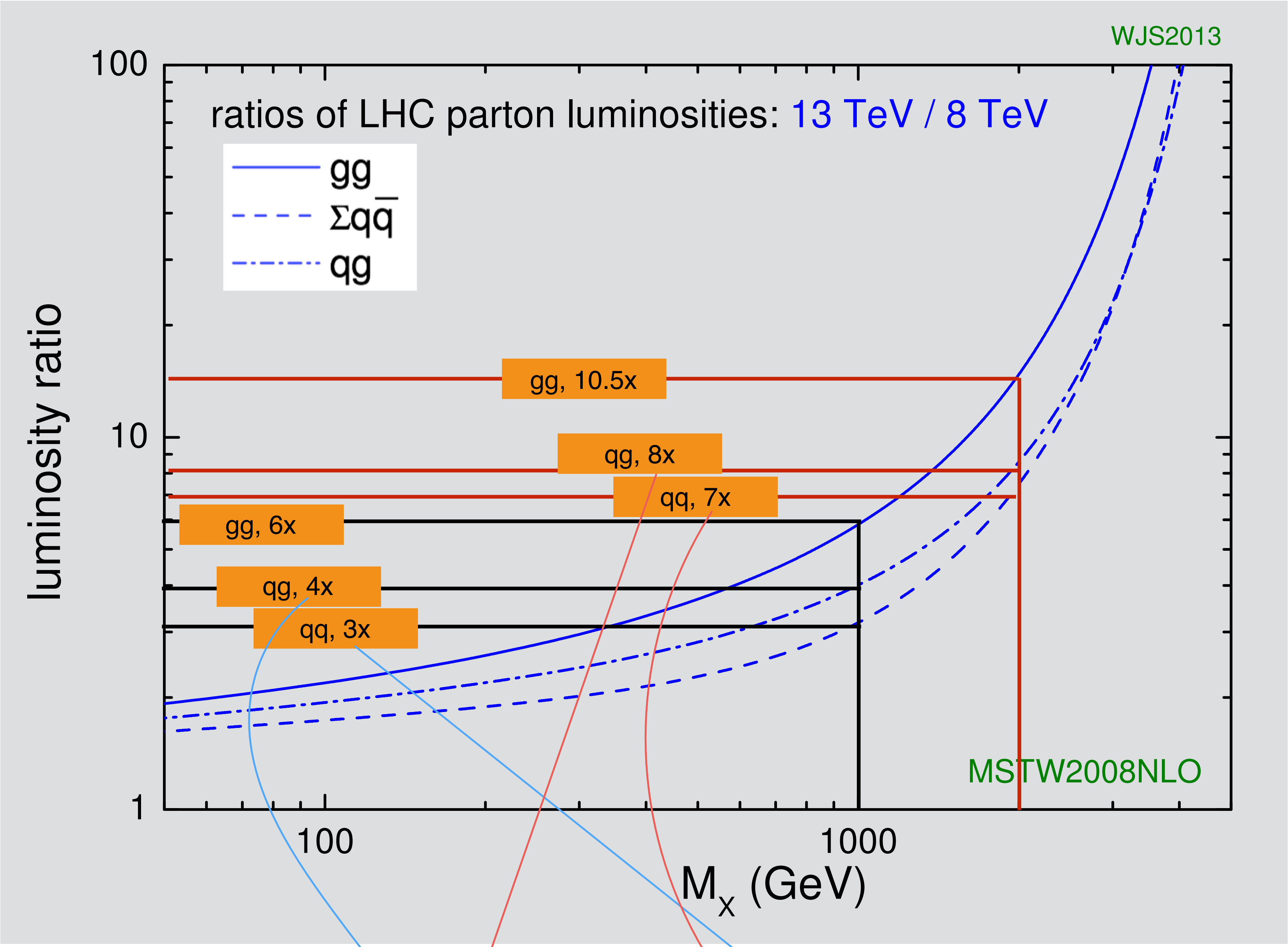
Phys. Letters B
776(2018)318–337

arXiv
1809.06682
1809.05937

ATLAS-CONF-2018-054

Parton luminosity

Both S & B increase as 8 → 13 TeV, but B increased more than S

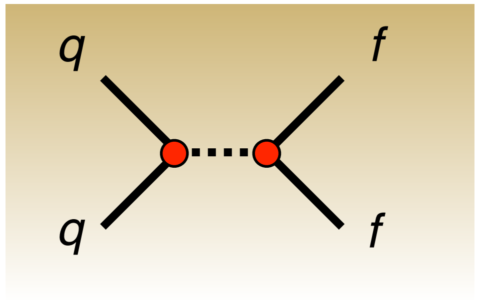


Assume B is qg, S is qq

- For m_{jj} = 1 TeV $\quad B_{13TeV} = 4 * B_{8TeV} \quad S_{13TeV} = 3 * S_{8TeV}$
- For m_{jj} = 2 TeV $\quad B_{13TeV} = 8 * B_{8TeV} \quad S_{13TeV} = 7 * S_{8TeV}$

Dark matter at colliders

Ben Carlson

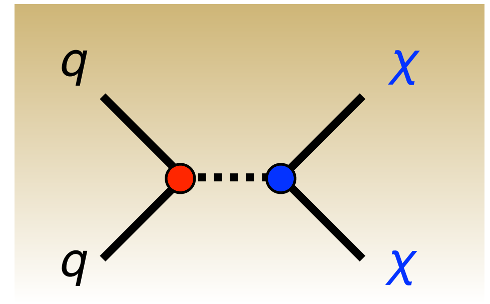


e.g., di-jet

mediator→SM

Direct mediator searches: dijet (dilepton) resonances

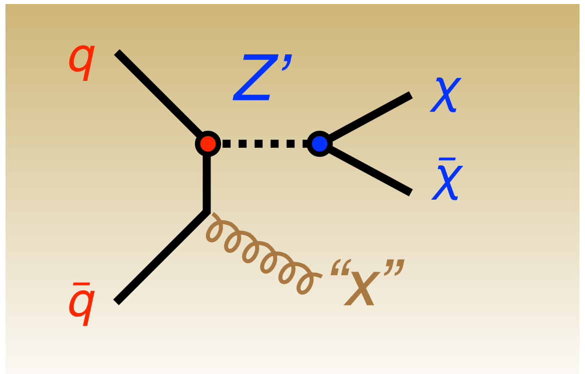
Details, see DM working group recommendations: arXiv 1703.05703



e.g., Z'

mediator→DM

Add "X"



mediator→DM + X

Look for stable dark matter candidate by requiring that the system recoil against a visible "x"

A wide range of models for different "x"

x	objects
Jet	$P_T \gtrsim 250$ GeV MET $\gtrsim 250$ GeV
Photon	$P_T \gtrsim 150$ GeV MET $\gtrsim 150$ GeV
Weak bosons (W/Z)	l^+l^-
	$q\bar{q}$
Higgs boson	$b\bar{b}$
	$\gamma\gamma$
Heavy flavors	b, $b\bar{b}$
	t, $t\bar{t}$

Comparison to run 1

Ben Carlson

Compare to SR1 of run 1
arXiv: 1508.07869

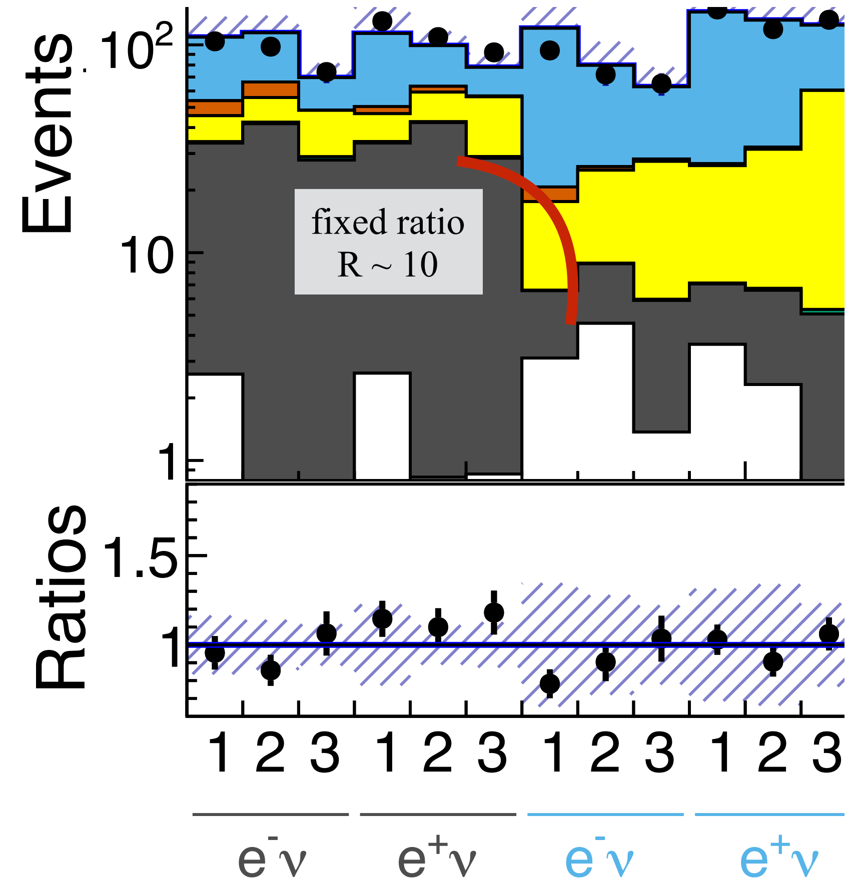
- SR selections optimized for 13 TeV backgrounds

Requirement	Run 1	Run 2	Comment
e(μ)(τ) p_T	< 10 (5) (20) GeV	< 7 (7) (-) GeV	Lepton veto
Jet p_T	> 75 (50) GeV	> 80(50) GeV	
Jet pu removal	JVF > 0.5	JVT > 0.59	
Third jet	< 30 GeV	< 25 GeV	VBF
Δη(jj)	> 4.8	> 4.8	VBF
m(jj)	> 1 TeV	1-1.5, 1.5-2.0, > 2.0 TeV	Binned
Δϕ(jj)	< 2.5	< 1.8	
MET	> 150 GeV	> 180 GeV	Invisible
MHT	-	150 GeV	Cleaning
Δϕ(j,MET)	> 1.6 (1.0)	> 1.0 (1.0)	Cleaning

- Very similar selections to run 1 (though slightly tighter)
- Main differences that impact sensitivity:
  - Bins of *m(jj)*: best sensitivity from m(jj) > 2 TeV
  - Tighter MET: indirectly because of pileup, causes relative ~10% increase in limit

fake enriched fake depleted

- Determine ratio from dedicated fake enriched control sample
- Float normalization in the fit, but fix ratio between bins

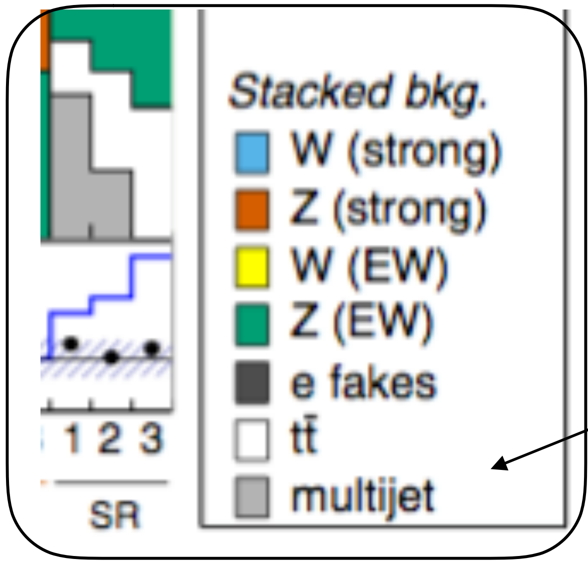


- W^+/W^- cross sections not equal (in pp collisions)
- Non-prompt contribution charge symmetric

Binned in charge (+,-)

QCD background

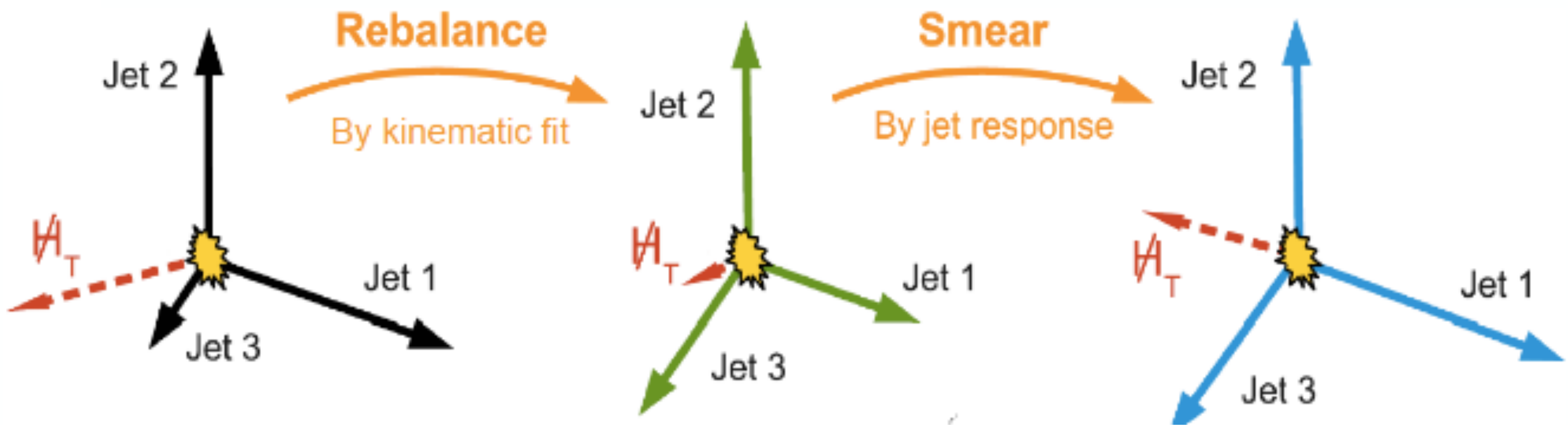
Ben Carlson



Worth mentioning how we get the QCD multi jet component

QCD events reconstructed at high MET due to jet mis-measurement

- Estimate QCD background by randomly varying each jet by resolution

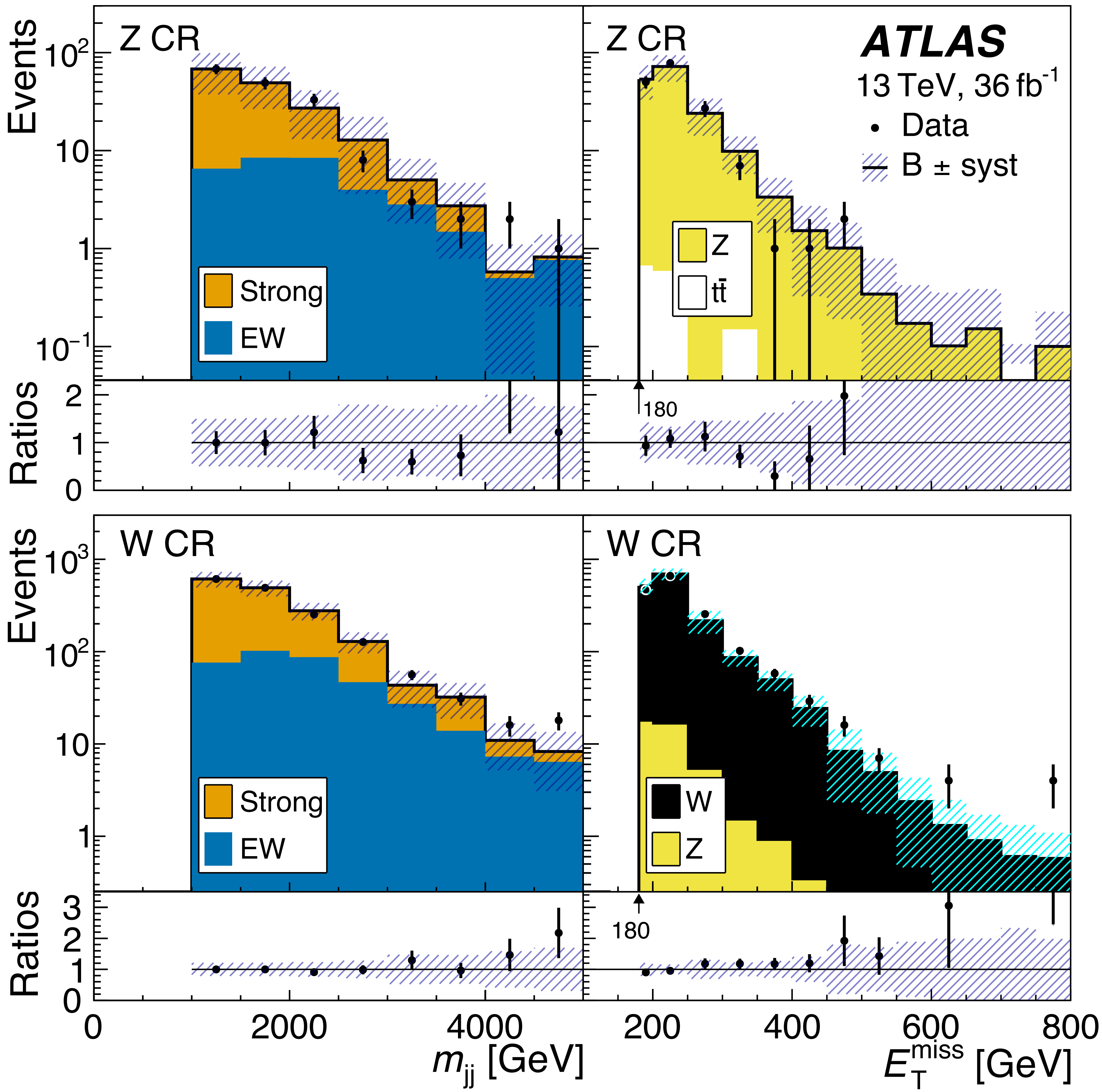


Seed: single jet triggers
prescaled & complete

Vary jet p_T, minimize MET based on jet resolution
Sample of events with no MET

Randomly vary jet p_T according to known resolution:
MET

Distributions



Fit model

Ben Carlson

- Fit model imposes estimates W(Z) separately
  - Normalization of mis-ID electron also constrained by fit
  - Each m(jj) bin is treated independently, e.g., separate normalization factors k_W (k_Z) for each bin
  - Note: essentially the run 1 fit model, except that we replaced M_T with MET sig. bins and have 2 fit parameters, for W(Z) separately

Summary of fit model, each bin of m(jj) is treated separately according to the model shown here.

$$B_{SR} \cdot \underbrace{N_{CR}/B_{CR}}_{\beta \text{ normalization}}$$

Actually binned in charge

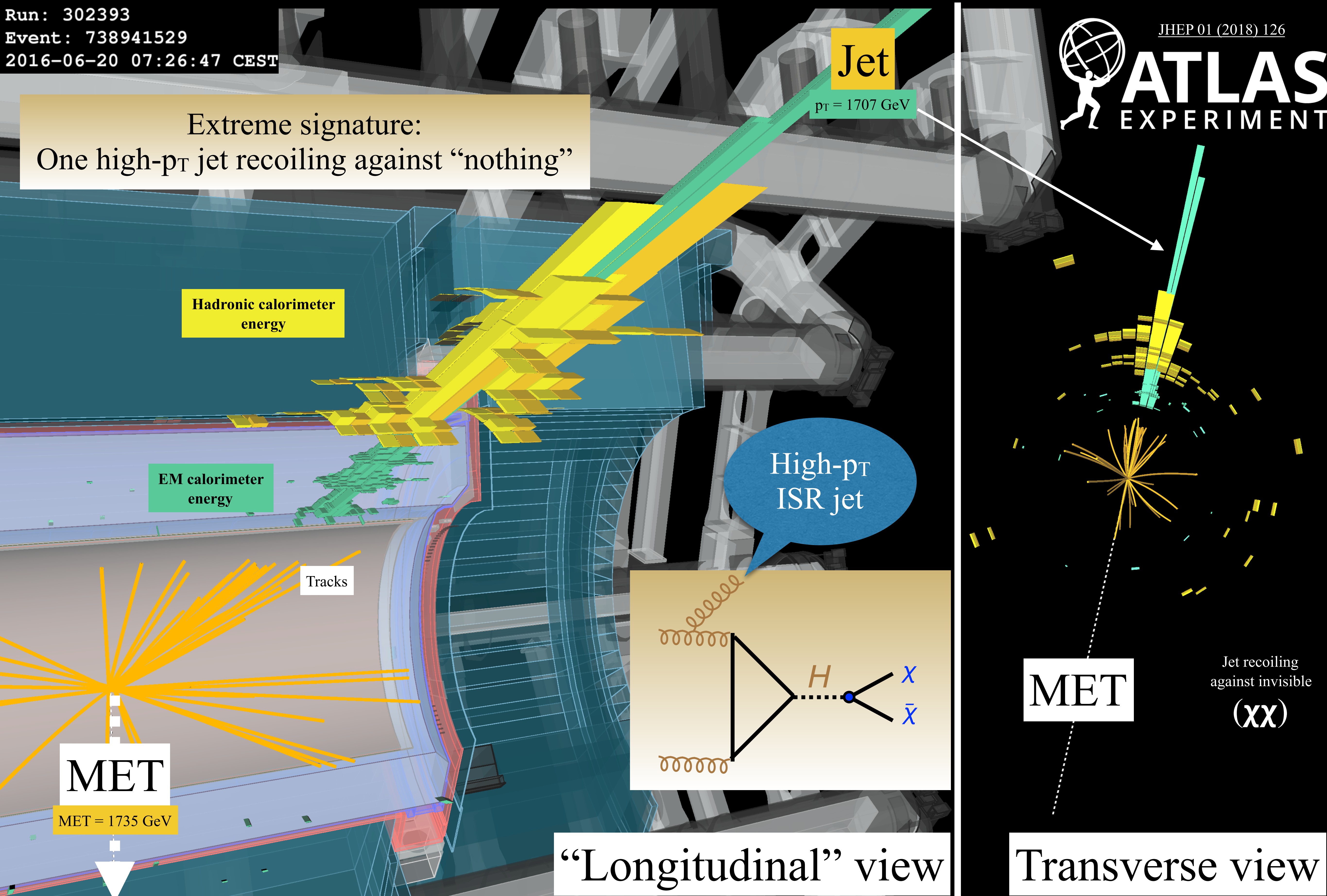
	SR	ee	μμ	e MET sig. > 4	e MET sig. < 4	μ
Signal	μ x S					
Z	k_Z x B_Z	k_Z x B_Z	k_Z x B_Z	k_Z x B_Z	k_Z x B_Z	k_Z x B_Z
W+jets	k_W x B_W	k_W x B_W	k_W x B_W	k_W x B_W	k_W x B_W	k_W x B_W
mis-ID				β	R x β	

$B_{W(Z)}$: prediction from MC

R: ratio from loose not tight (see last slide)

β: normalization of mis-ID component

Mono-jet interpreted as Higgs + 1 jet



Higgs + 1 jet

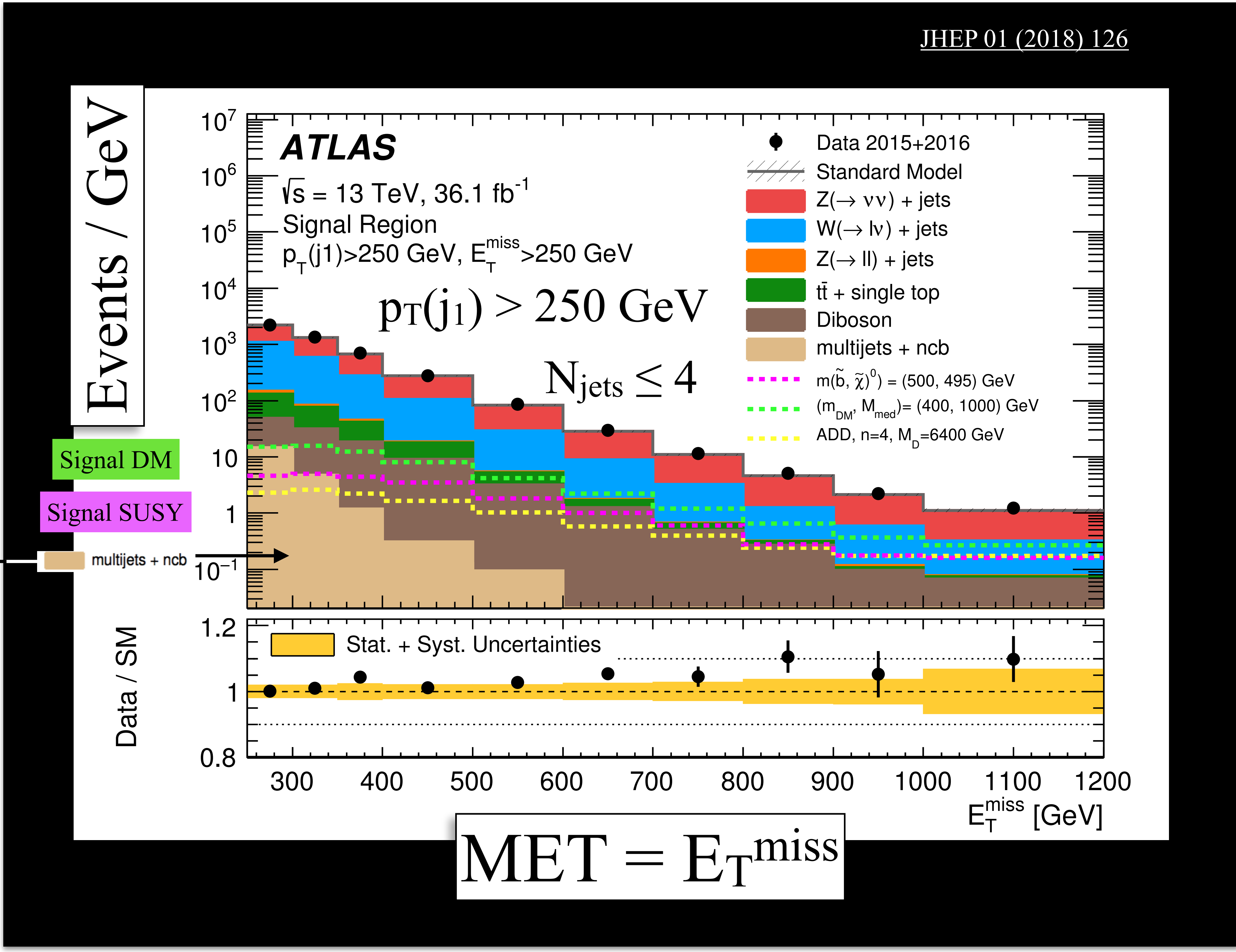
MET > 250 GeV

- Easy to trigger
- Kills **QCD**
  - *$\Delta\phi(j,MET) > 0.4$*

Lepton veto kills

- Top (mostly)
- $W \rightarrow \ell\nu$

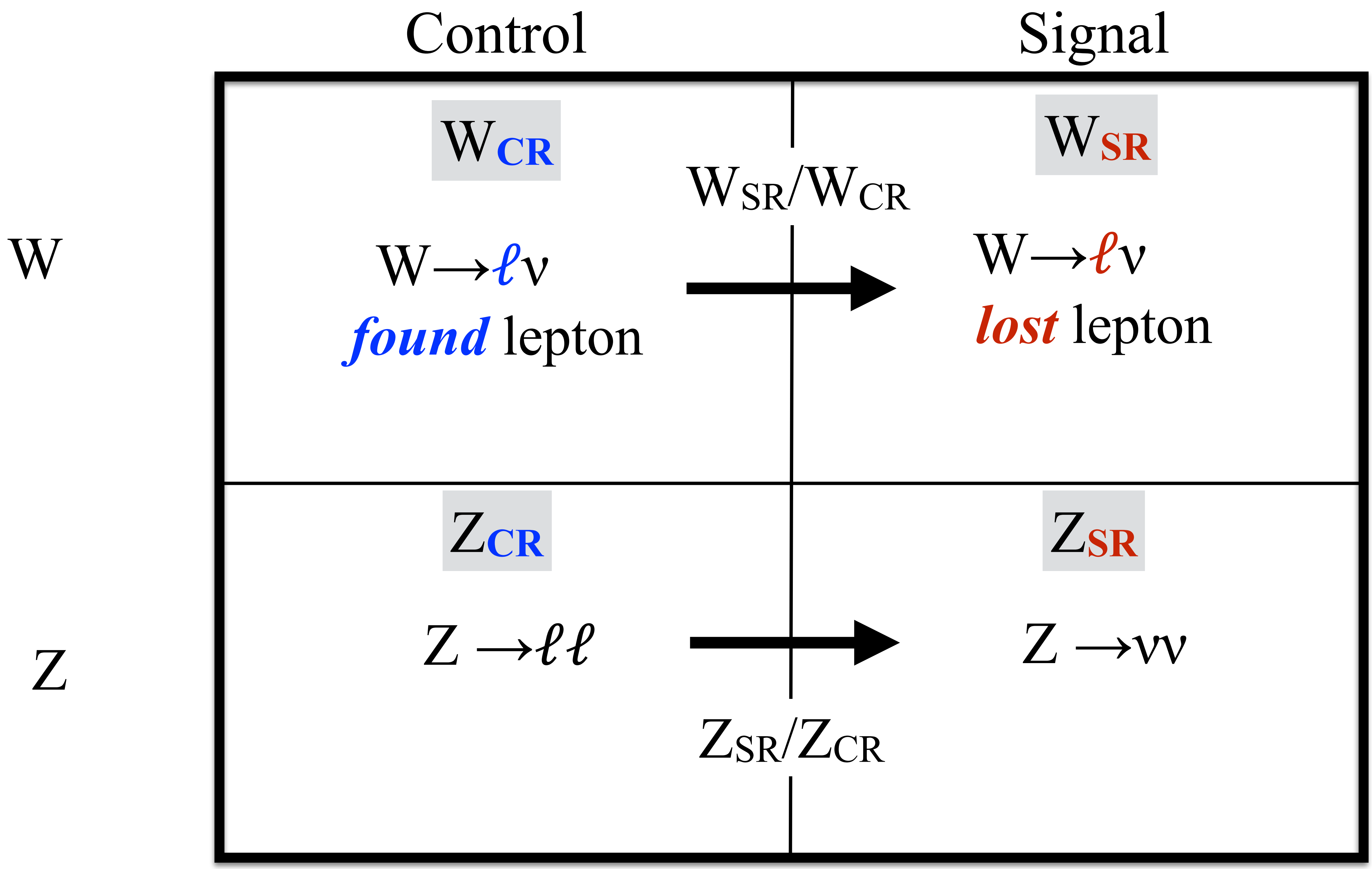
Blue background:
ℓ is not reconstructed



Dominant backgrounds: $W \rightarrow \ell\nu$ (lost lepton) and $Z \rightarrow \nu\nu$

Constraining backgrounds

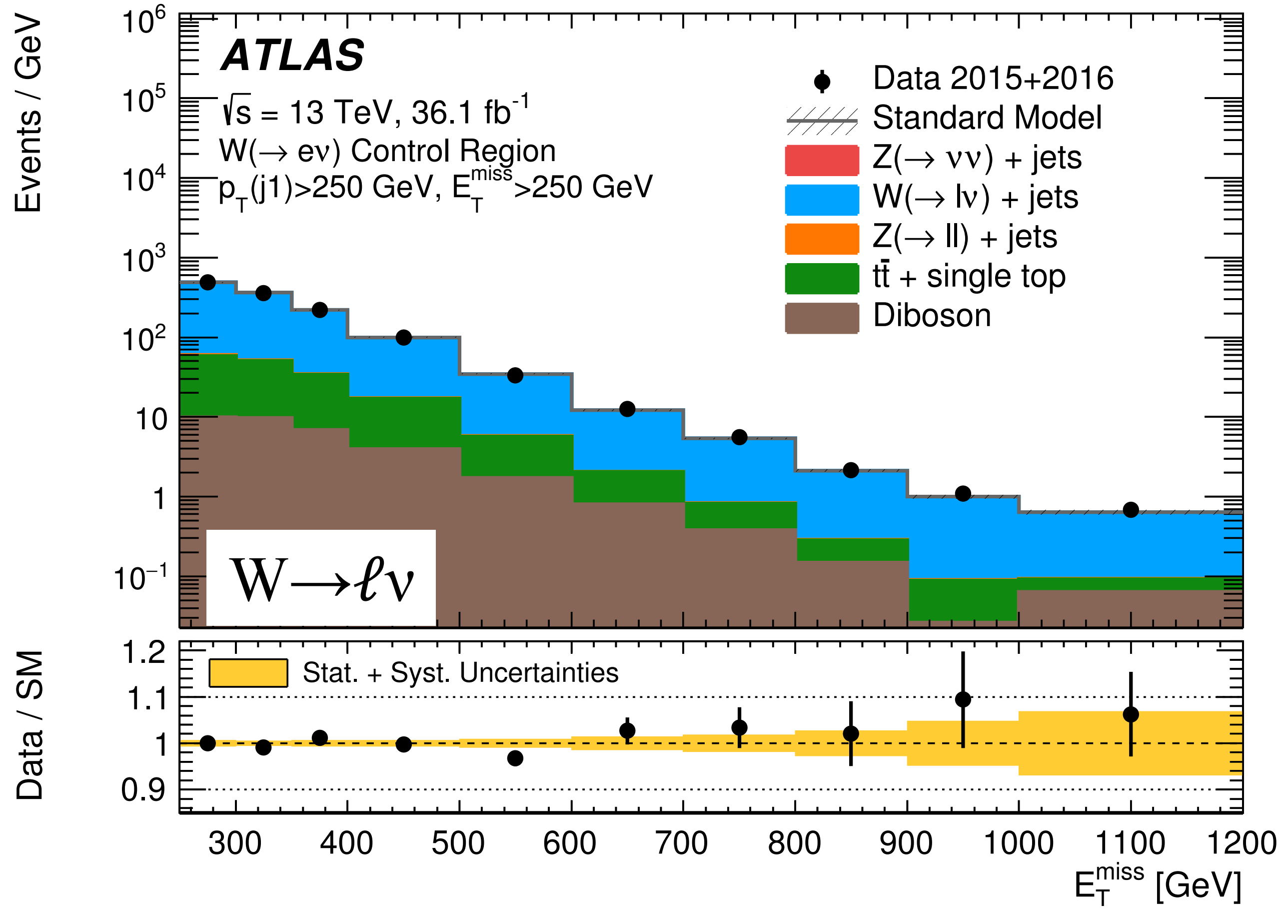
Ben Carlson

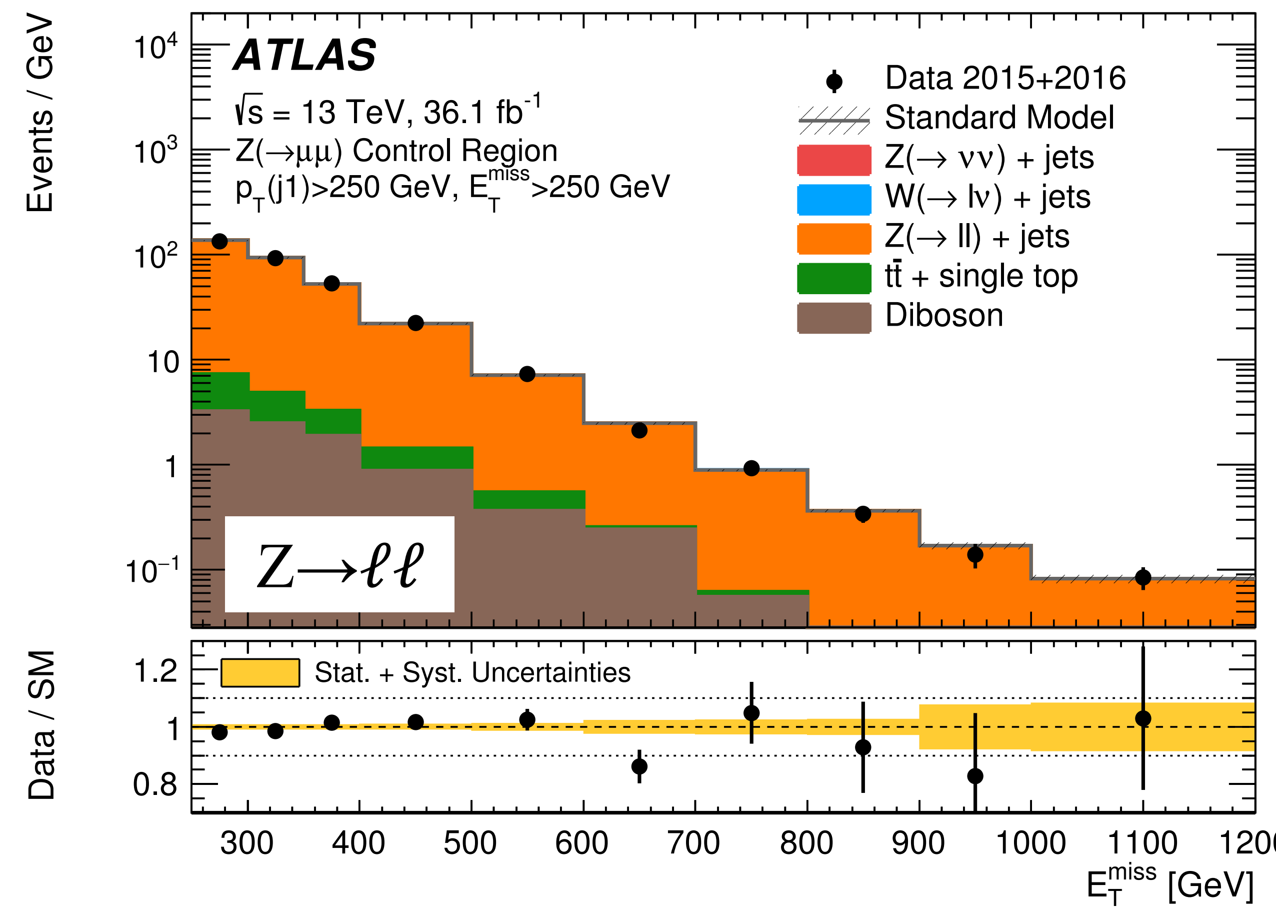


$\ell = e\ (\mu)$

Estimate from CRs using simultaneous fit

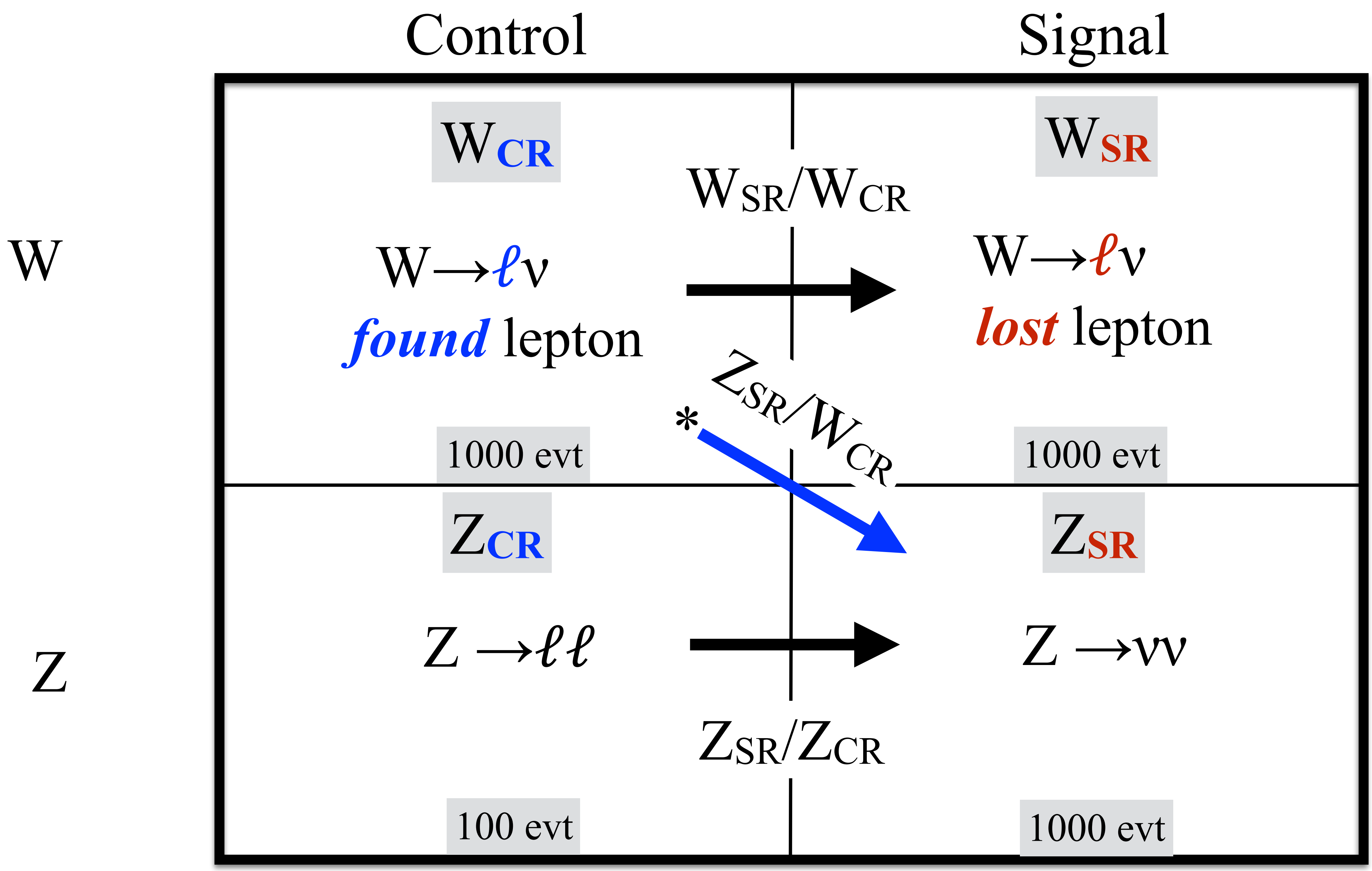
- W→ℓν
- Z→ℓℓ





Constraining backgrounds

Ben Carlson

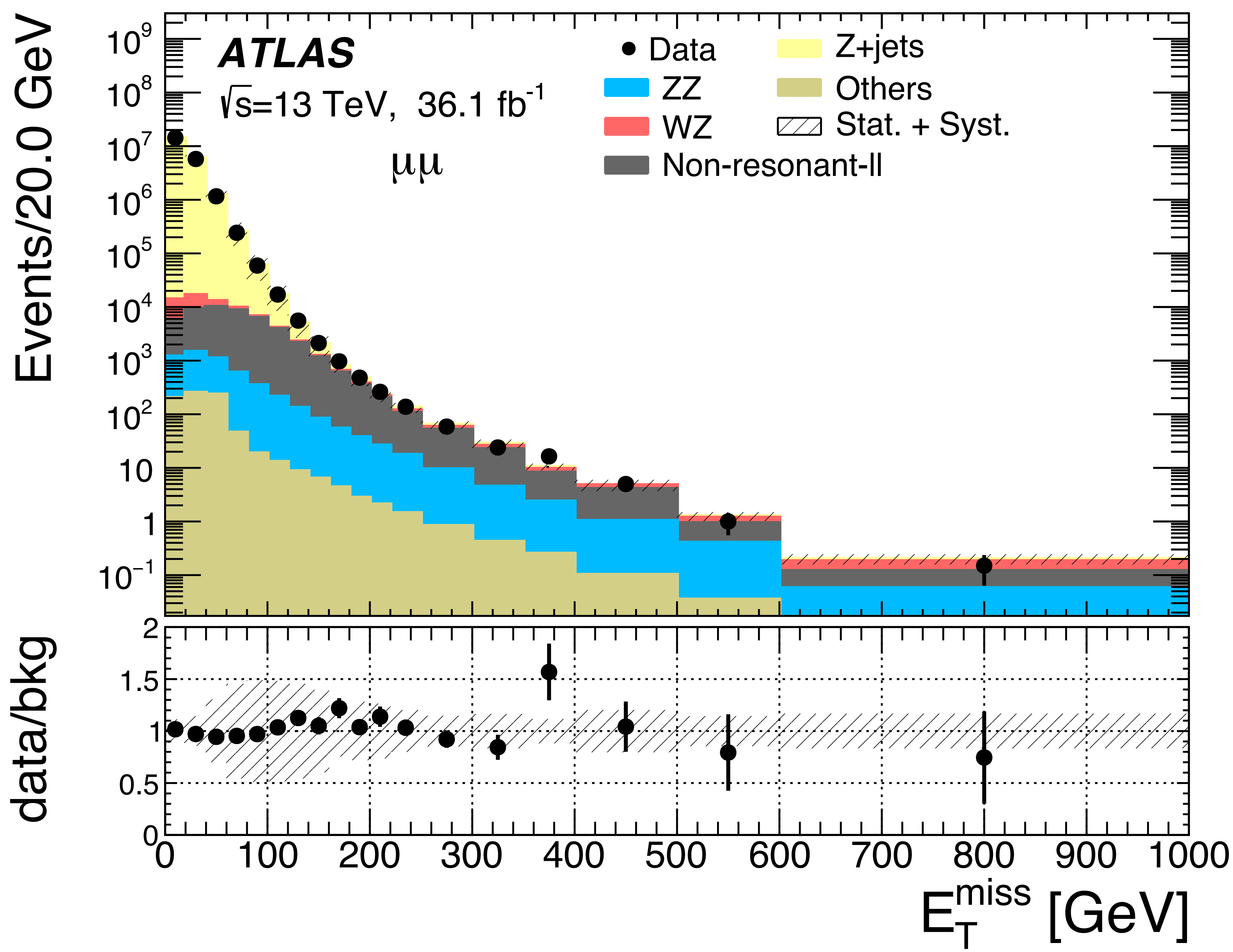


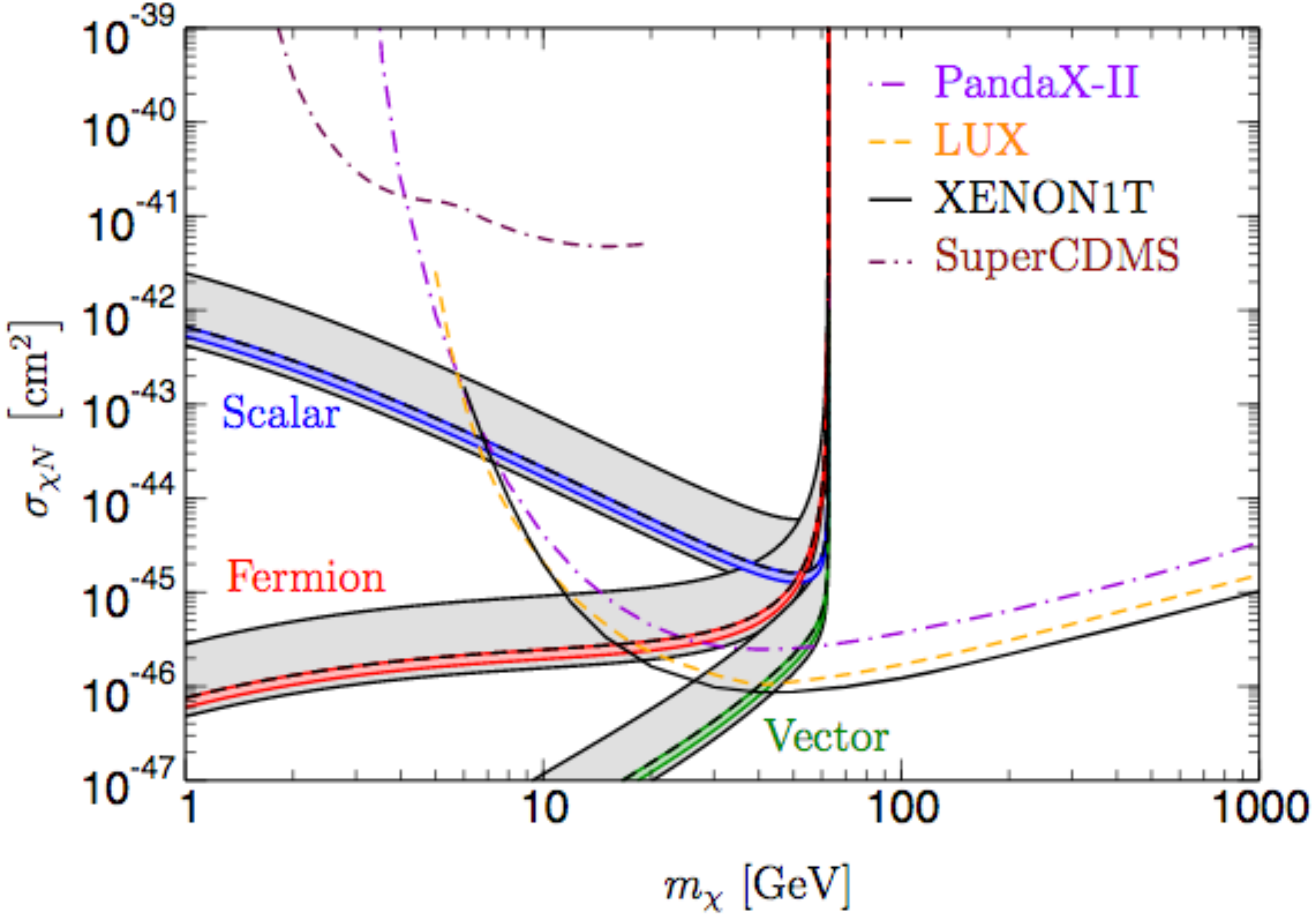
W→ℓν constraint motivated by branching fractions

- x10 more W→ℓν than Z→ℓℓ
- Uses theory calculation leads to small W→Z uncertainty (J. Lindert et al. 1705.04664)

Z→ℓℓ background

Z+jets falls off rapidly with MET




PandaX-II
LUX
XENON1T
SuperCDMS
Scalar
Fermion
Vector
$\sigma_{\chi N}$ [cm^2]
m_χ [GeV]
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
1
10
100
1000

CMS Run-1 paper on VBF and *ZH*, EPJC 74 (2014) 2980

9 Dark matter interactions

We now interpret the experimental upper limit on $\mathcal{B}(\mathrm{H} \to \mathrm{inv})$, under the assumption of SM production cross section, in the context of a Higgs-portal model of DM interactions [7–9]. In these models, a hidden sector can provide viable stable DM particles with direct renormalizable couplings to the Higgs sector of the SM. In direct detection experiments, the elastic interaction between DM and nuclei exchanged through the Higgs boson results in nuclear recoil which can be reinterpreted in terms of DM mass, M_χ, and DM-nucleon cross section. If the DM candidate has a mass below $m_\mathrm{H}/2$, the invisible Higgs boson decay width, Γ_inv, can be directly translated to the spin-independent DM-nucleon elastic cross section, as follows for scalar (S), vector (V), and fermionic (f) DM, respectively [8]:

$$\sigma^{\mathrm{SI}}_{\mathrm{S-N}} = \frac{4\Gamma_{\mathrm{inv}}}{m_\mathrm{H}^3 v^2 \beta} \frac{m_\mathrm{N}^4 f_\mathrm{N}^2}{(M_\chi + m_\mathrm{N})^2}, \quad (8)$$

$$\sigma^{\mathrm{SI}}_{\mathrm{V-N}} = \frac{16\Gamma_{\mathrm{inv}} M_\chi^4}{m_\mathrm{H}^3 v^2 \beta (m_\mathrm{H}^4 - 4M_\chi^2 m_\mathrm{H}^2 + 12 M_\chi^4)} \frac{m_\mathrm{N}^4 f_\mathrm{N}^2}{(M_\chi + m_N)^2}, \quad (9)$$

$$\sigma^{\mathrm{SI}}_{\mathrm{f-N}} = \frac{8\Gamma_{\mathrm{inv}} M_\chi^2}{m_\mathrm{H}^5 v^2 \beta^3} \frac{m_\mathrm{N}^4 f_\mathrm{N}^2}{(M_\chi + m_\mathrm{N})^2}. \quad (10)$$

Here, m_N represents the nucleon mass, taken as the average of proton and neutron masses, 0.939 GeV, while $\sqrt{2}v$ is the Higgs vacuum expectation value of 246 GeV, and $\beta = \sqrt{1 - 4M_\chi^2/m_\mathrm{H}^2}$. The dimensionless quantity f_N [8] parameterizes the Higgs-nucleon coupling; we take the central values of $f_\mathrm{N} = 0.326$ from a lattice calculation [69], while we use results from the MILC Collaboration [70] for the minimum (0.260) and maximum (0.629) values. We convert the invisible branching fraction to the invisible width using $\mathcal{B}(\mathrm{H} \to \mathrm{inv}) = \Gamma_\mathrm{inv}/(\Gamma_\mathrm{SM} + \Gamma_\mathrm{inv})$, where $\Gamma_\mathrm{SM} = 4.07$ MeV.

VBF trigger

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TriggerOperationPublicResults#L1Topo_Operation_VBF_2018

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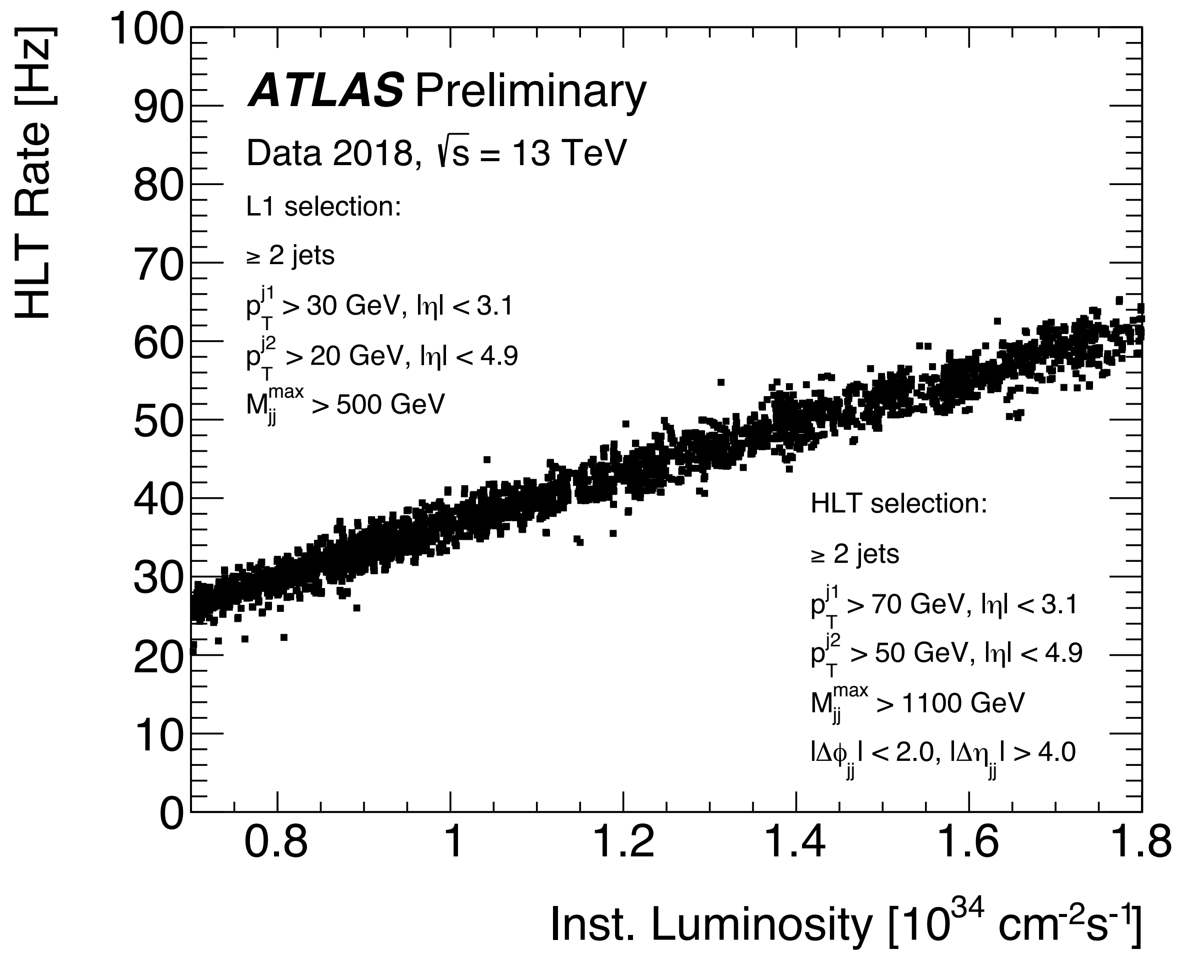
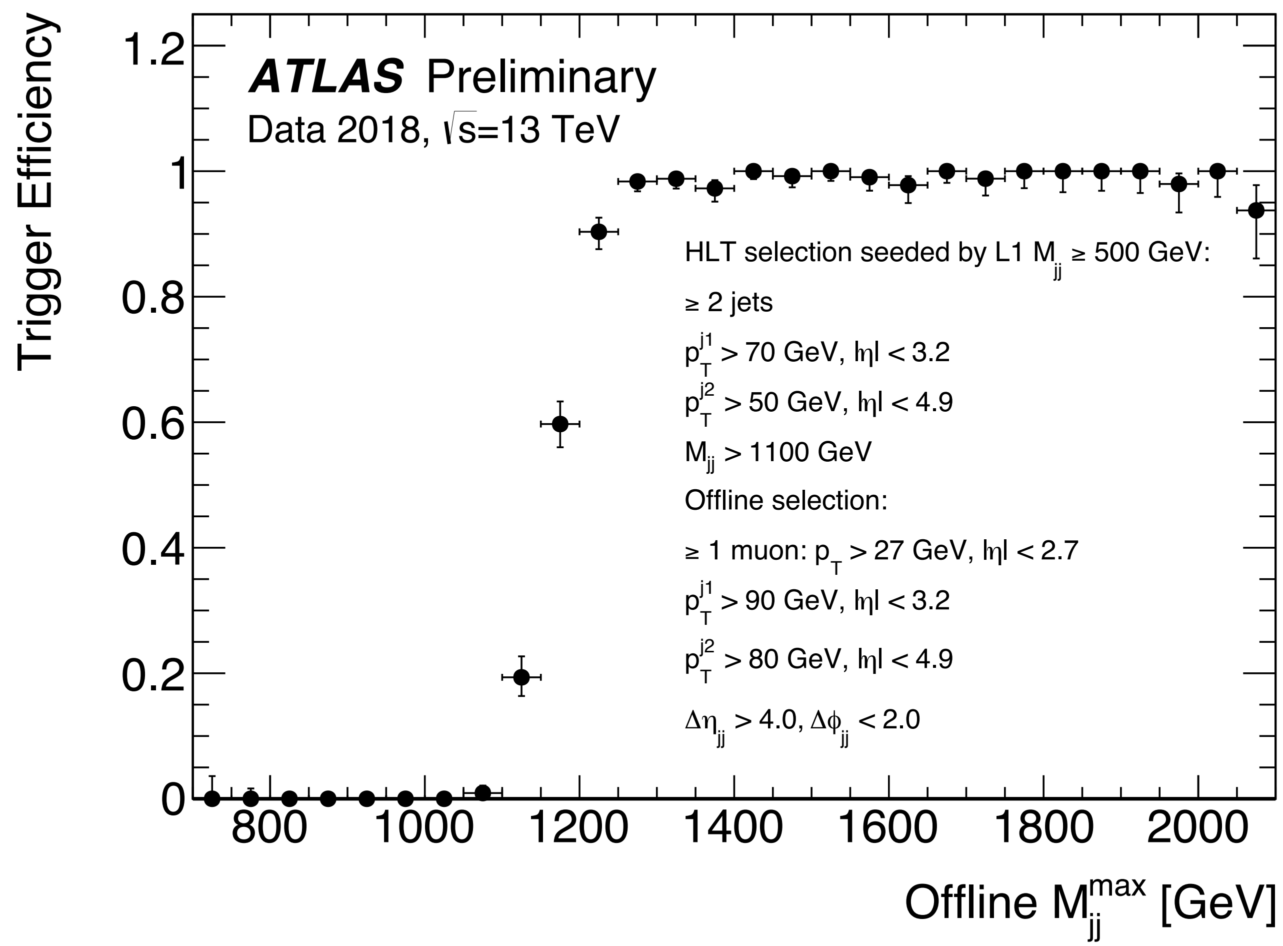
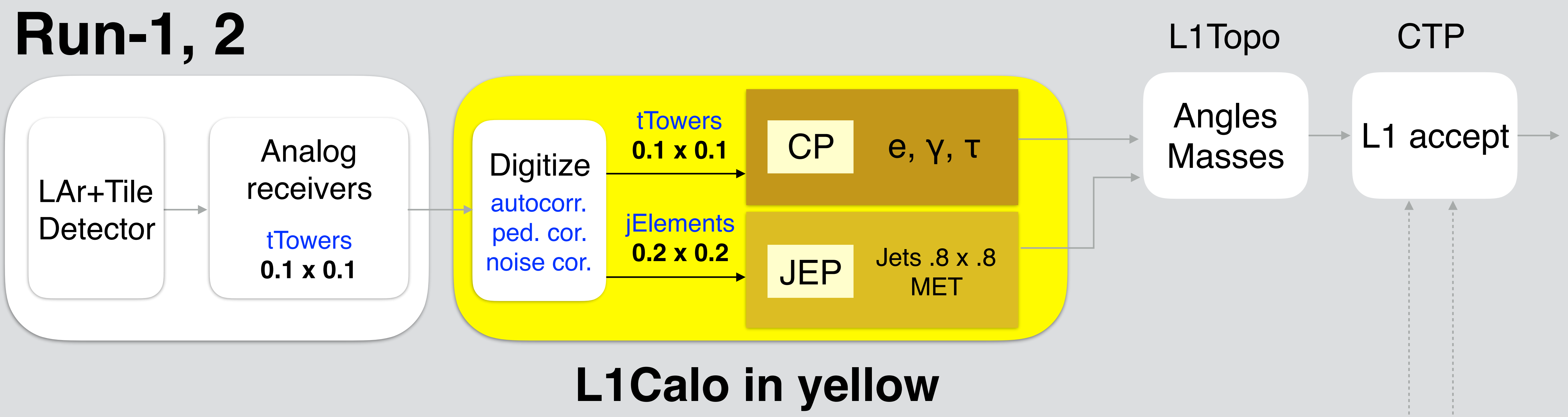
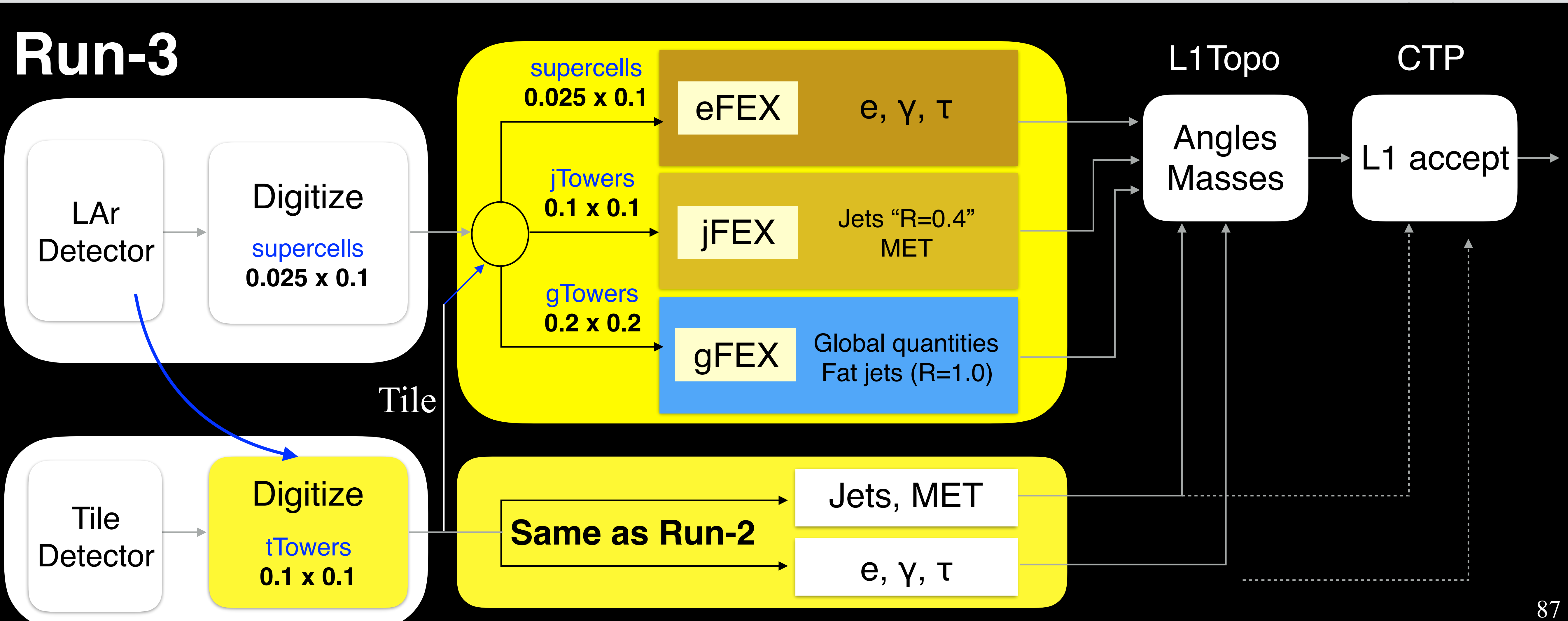




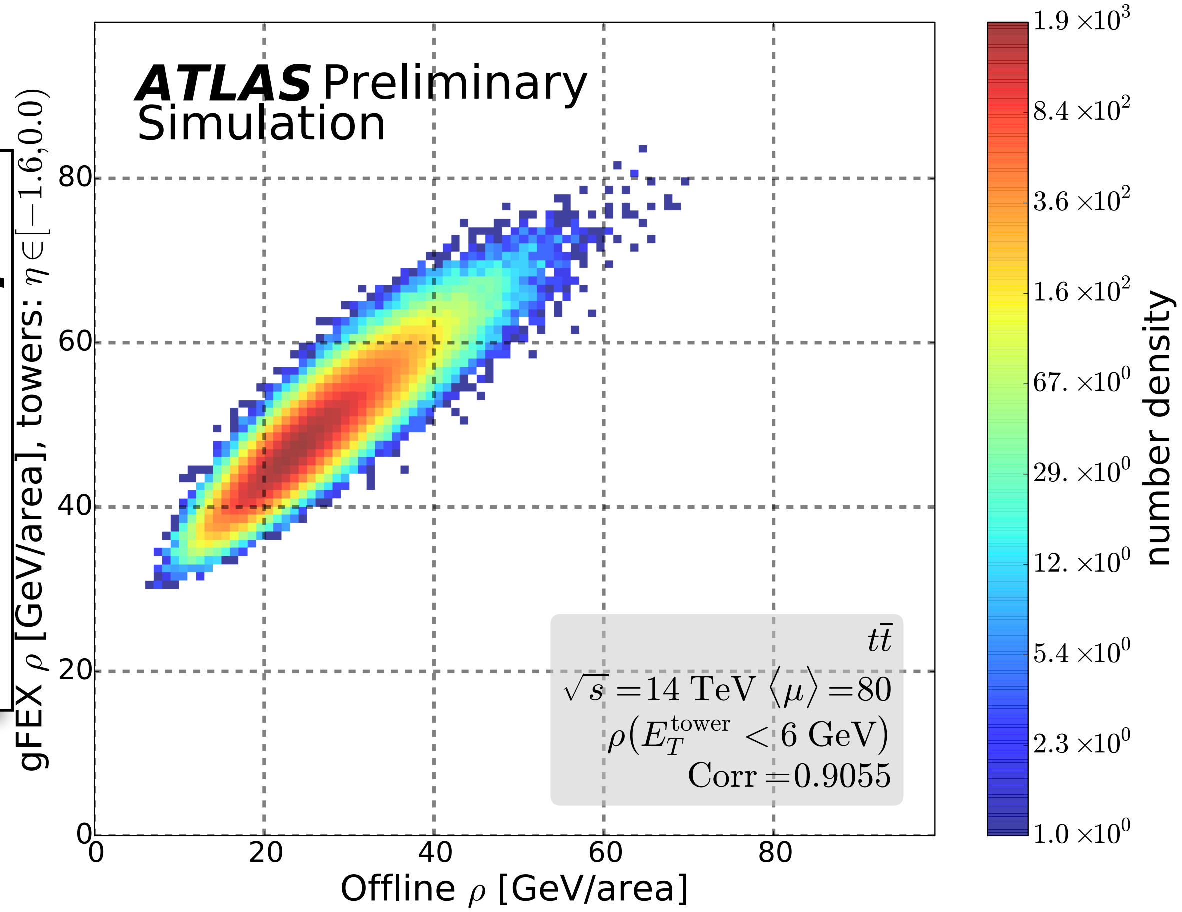
Upgrade (starting now!)





Improving MET

MET is sensitive to pileup
Working on pileup subtraction for L1

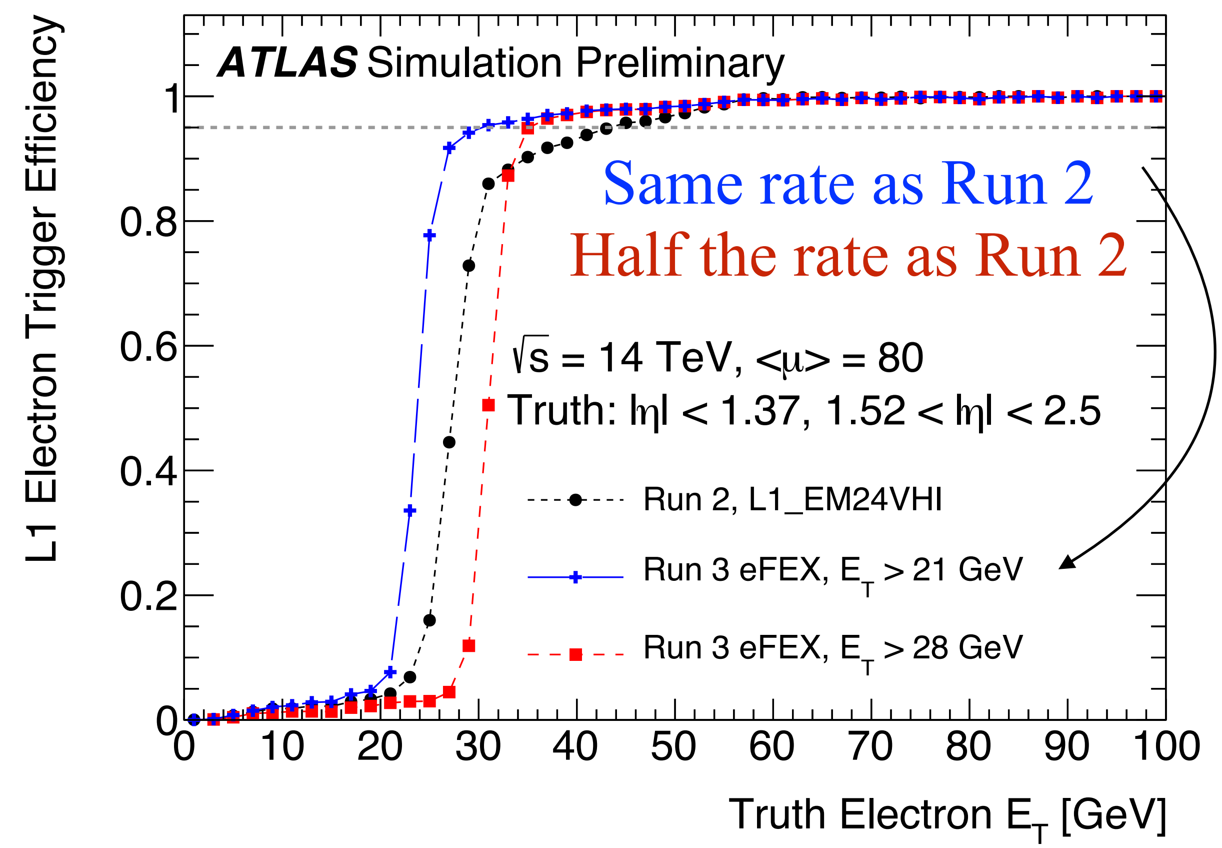


Online ρ

Offline ρ

Dramatic improvement

(Uses additional granularity to target electrons)



Lots of rate saved, use it for DM triggers?

MET comparison

ATLAS (link)
CMS (link)

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