Challenges and plans in search for Higgs decays to Invisible particles via VBF production with the ATLAS detector in Run II

Higgs Couplings 2018

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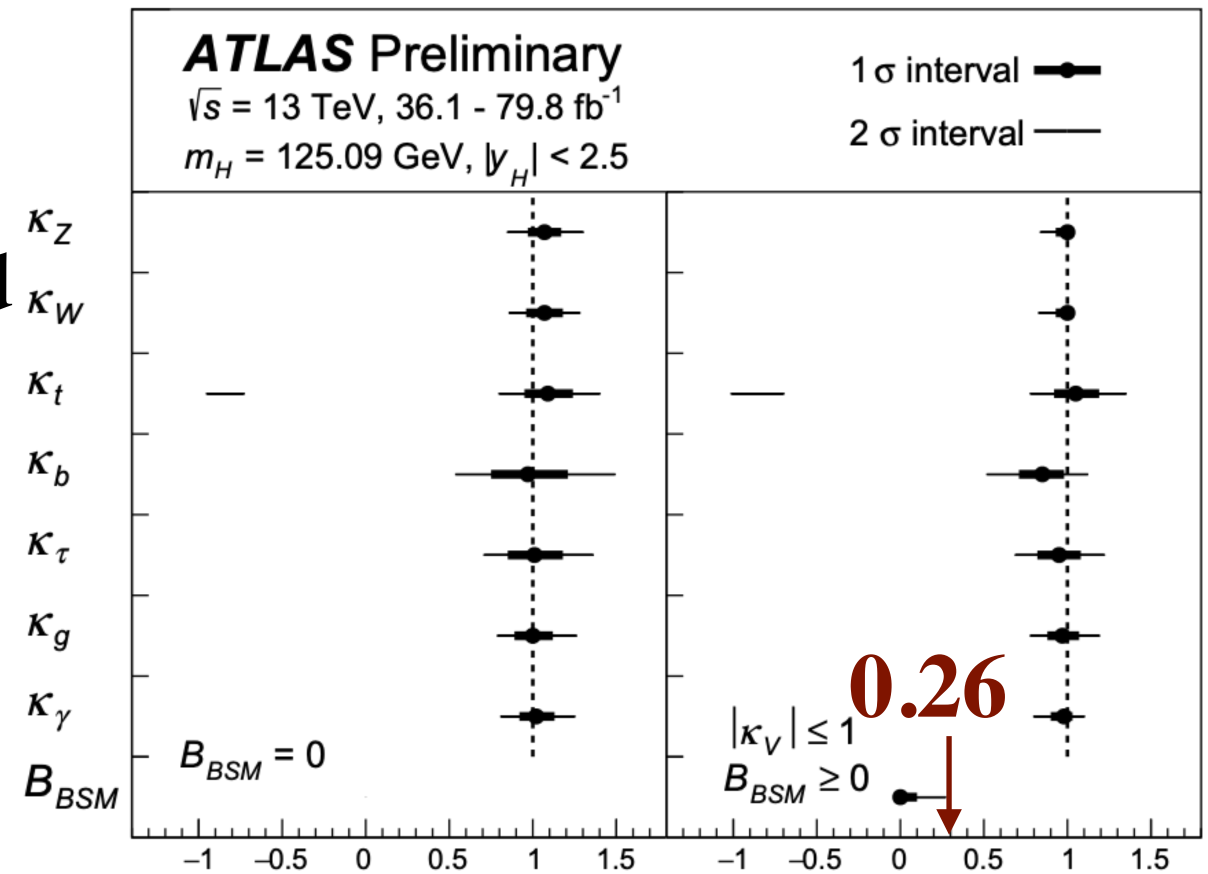
ATLAS
EXPERIMENT

Higgs to Invisible

- Total Higgs decay width not precisely constrained yet
  - ~26% allowed for BSM decays
- Higgs to Invisible final state predicted by lots of BSM theories
- Very rare decay in SM:
  - ~0.1% ($H \to ZZ^* \to 4\nu$)
- VBF H→ Invisible is the strongest constraint



fit assuming no BSM fit floating Br(BSM)

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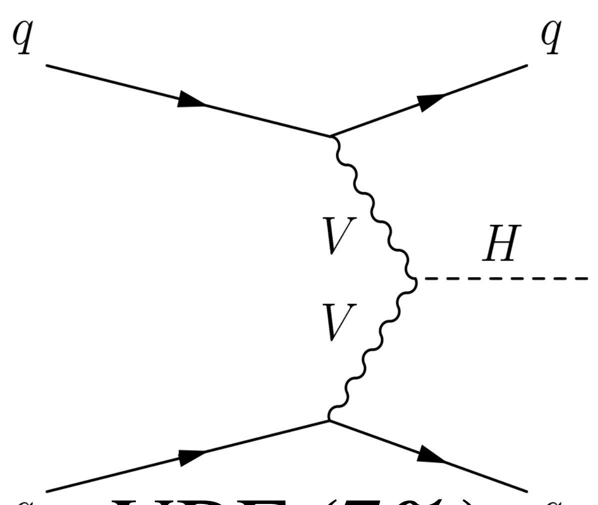
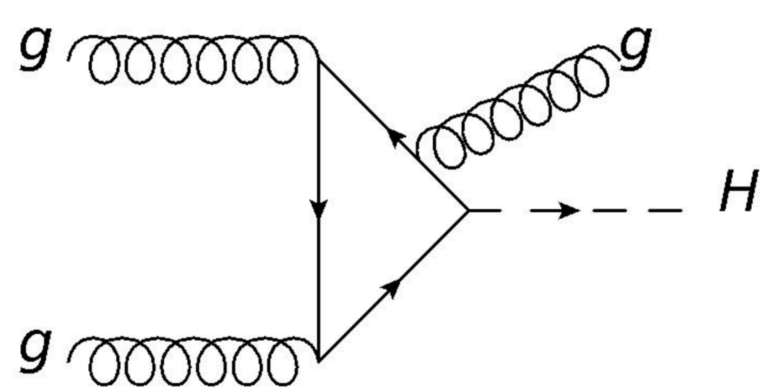
Vector Boson Fusion

Leading sensitivity

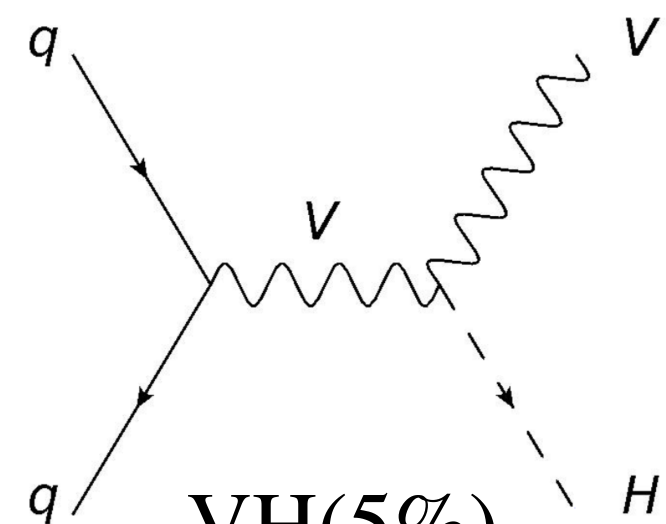


VBF (7%)

See Arely Gonzalez's talk tomorrow for the other channels!



ggF (87%)



VH(5%)

fraction of cross section at 13 TeV

- Vector Boson Fusion (VBF):
  - No color flow
  - Clear signature, easy to reject QCD
- Large MET:
  - Trigger on MET
- Upper limit on Br(H→Invisible) Run 1: 0.28 (0.31)
  - Dominated by theory systematics and data statistics

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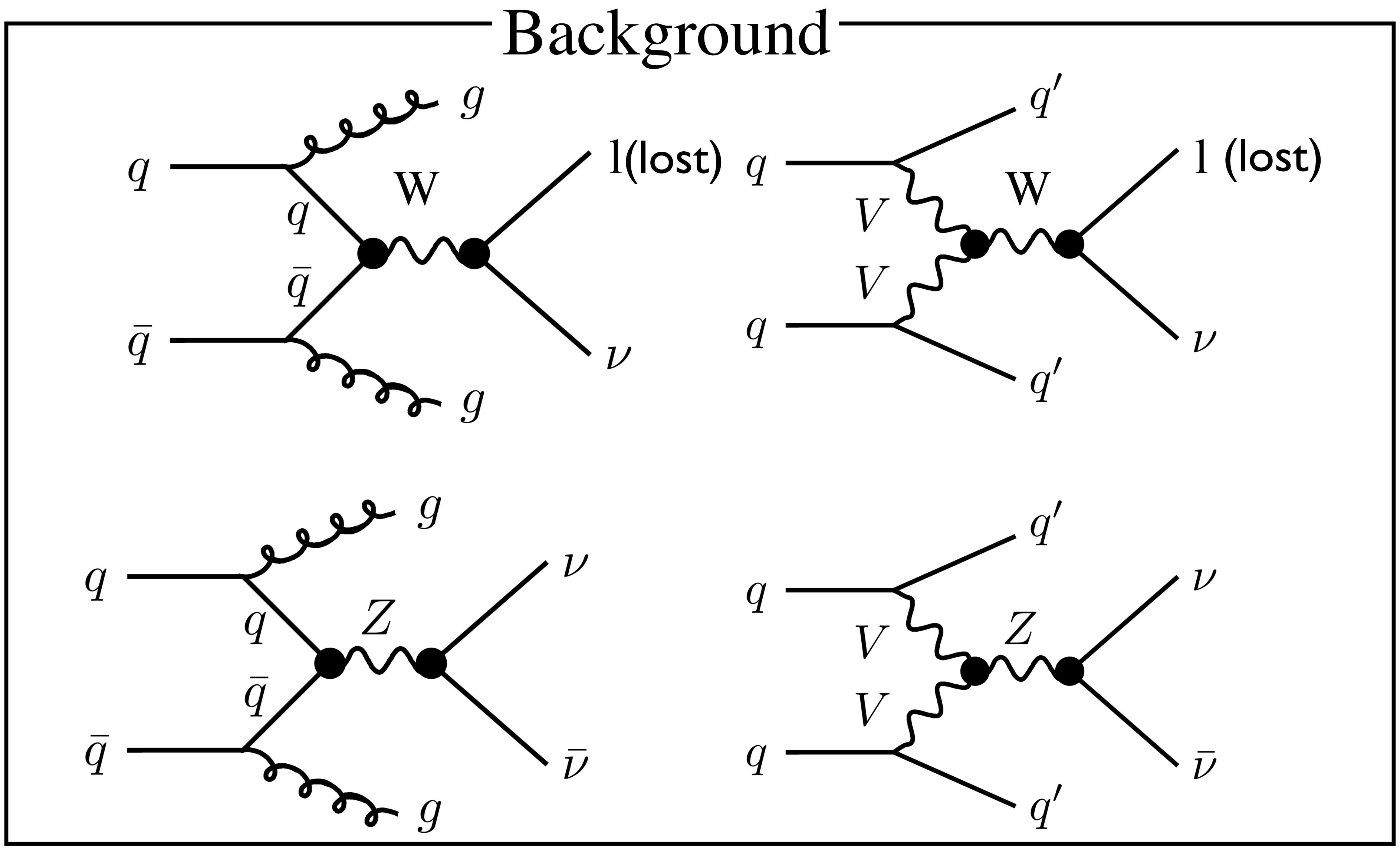
Analysis Strategy



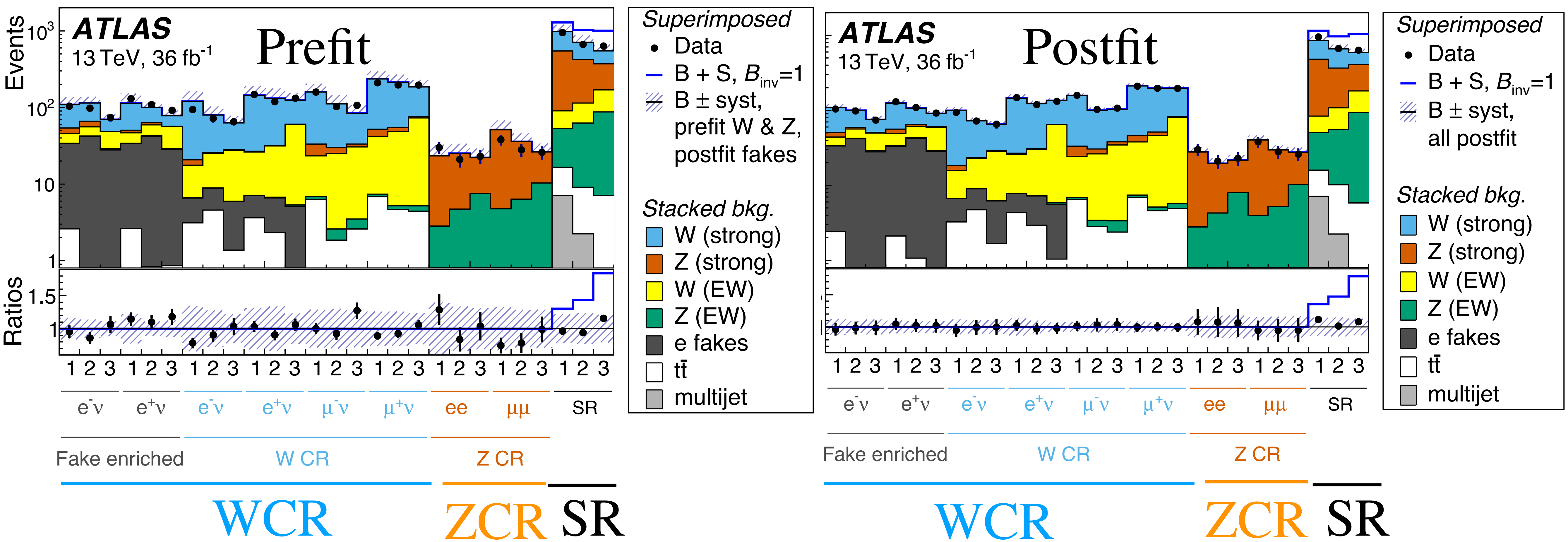
- Use Control Regions with same kinematic selections but different lepton requirement to constrain background in Signal Region
  - W→ lν (found lepton) ⇒ W→lν (lost lepton)
  - Z→ll ⇒ Z→νν

Analysis Selection

Variable	Value	
j_1 (j_2) p_T	> 80 (50) GeV	VBF
j_3 p_T	< 25 GeV	
$\Delta\eta(jj)$	> 4.8	
$\Delta\phi(jj)$	< 1.8	
m_{jj}	> 1 TeV	
e (μ) p_T	< 7 (10) GeV	
MET	> 180 GeV	MET
MHT	> 150 GeV	
$\Delta\phi$(j, MET)	> 1.0	

- Cuts tightened since Run 1 as a result of background changes in 13 TeV
- 3 bins in m_{jj}:
  - 1-1.5 TeV, 1.5-2 TeV, > 2 TeV
  - Most sensitive bin: m_{jj} > 2 TeV
  - Less dependent on MC modeling of m_{jj} shape
- Control Regions:
  - Same cuts with lepton requirements
  - Lepton selection tightened due to trigger
  - $W\rightarrow e\nu$, $W\rightarrow \mu\nu$, $Z\rightarrow\mu\mu$, $Z\rightarrow ee$
- MET cut raised due to offline pileup constraints

Paper with 36.1 fb^{-1} data



- Upper limit assuming SM cross section:
  - Br(H→inv) < 0.37 obs (0.28 exp) at 95% CL

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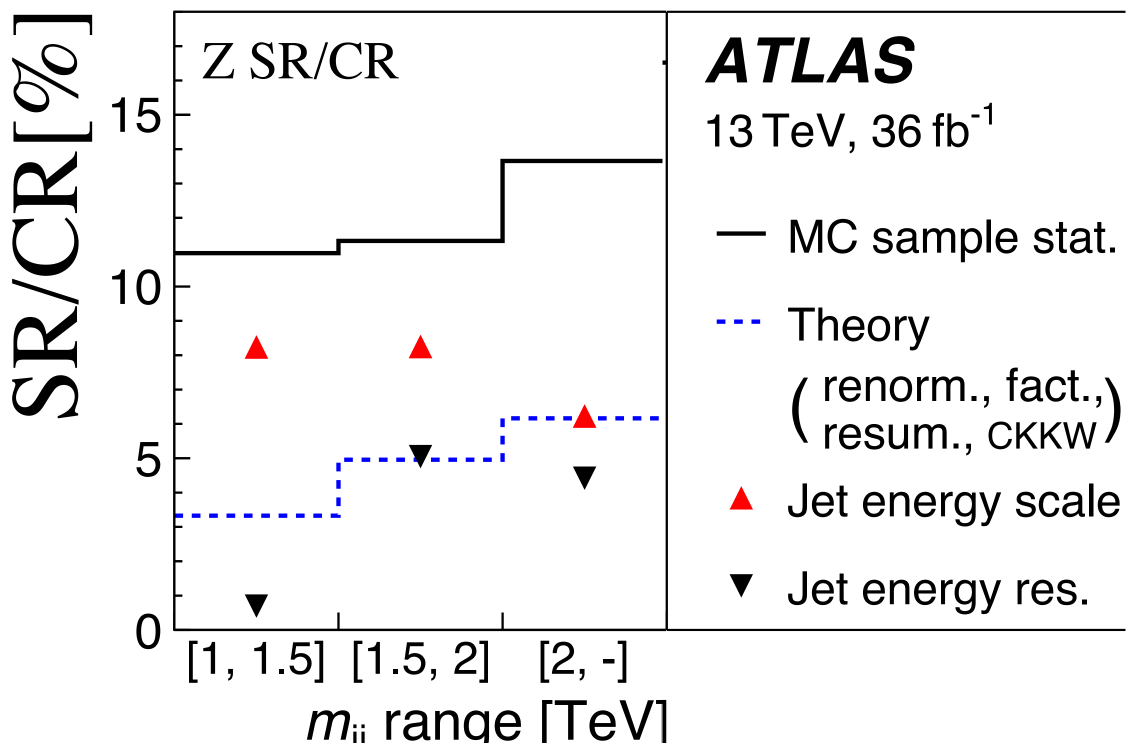
Overall Uncertainties

- MC statistics is big limitation
  - Actively looking for a solution to generate enough MC events in our phase space
  - NLO Sherpa is currently too slow
- Jet systematics:
  - JES: set of 29 nuisance parameters (each 1-4% on the ratio). Are inflated by MC stats.
  - Should cancel in SR/CR ratio



Source	ΔB/B [%]
All Exp	17
JES	10
JER	2
All Theory	10
CKKW	4
Resum	1
Renorm	2
MC statistics	12
Data statistics	21

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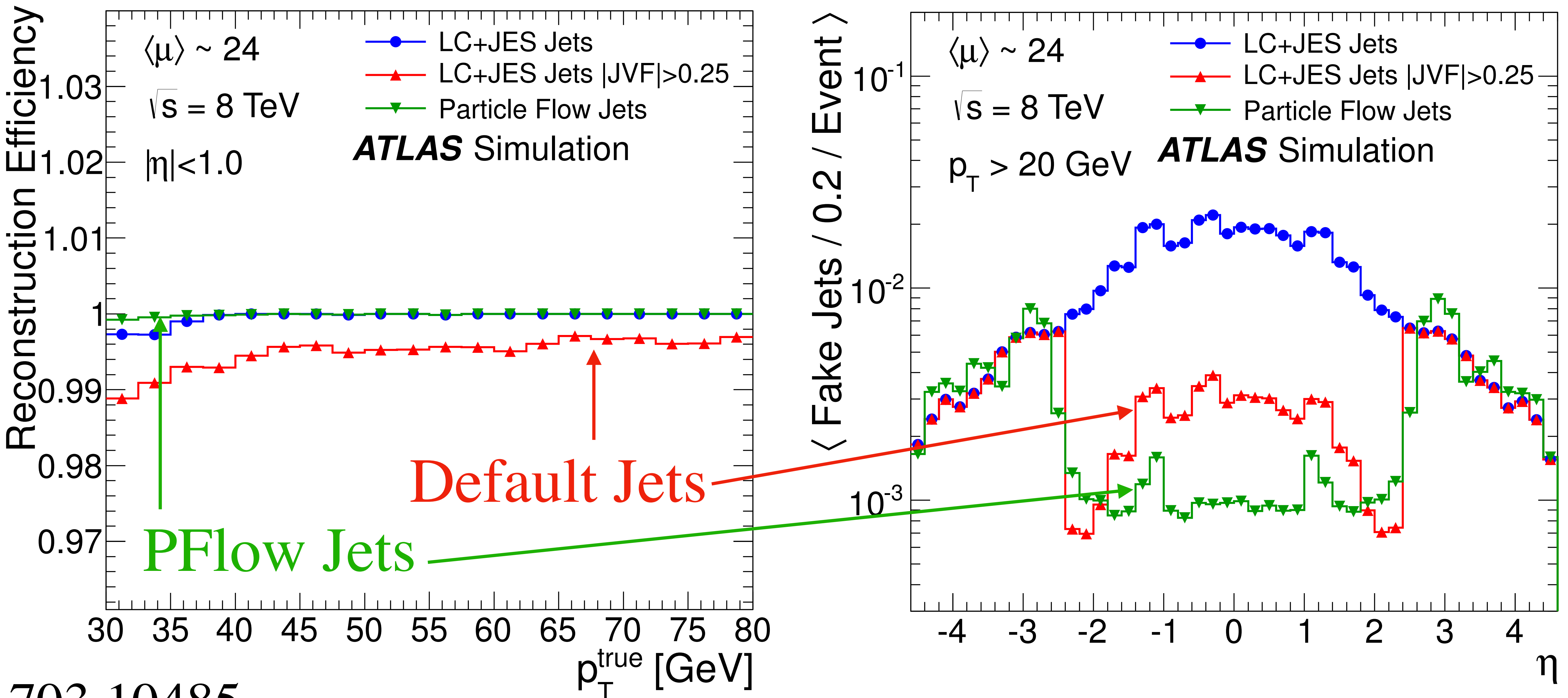
Theory Systematics

- Signal:
  - 3rd jet veto dominates (7%)
    - Plan to try central jet veto to increase signal acceptance and reduce this
- Background:
  - Resummation scale, renormalization+factorization cancels well in SR/CR
  - CKKW dominates
    - Calculated from smaller MC samples
    - Might be inflated by MC stats

	Yields			SR/CR	Br
Source	**S**	$\mathbf{B_{SR}^{Z}}$	$\mathbf{B_{CR}^{Z}}$	$\boldsymbol{\alpha_Z}$	**ΔB/B**
Resum	-	2	3	0	1
Renorm, fact	-	20	19	1	2
CKKW	-	2	3	1	4
PDF	1	1	2	1	0
3rd jet veto	7	-	-	-	-

Particle Flow Jets

- Target improvement for 3rd jet veto
- More efficient reconstruction gives bigger background rejection
- Fake jet reduction improves signal acceptance
- Improvement in JER at low p_T



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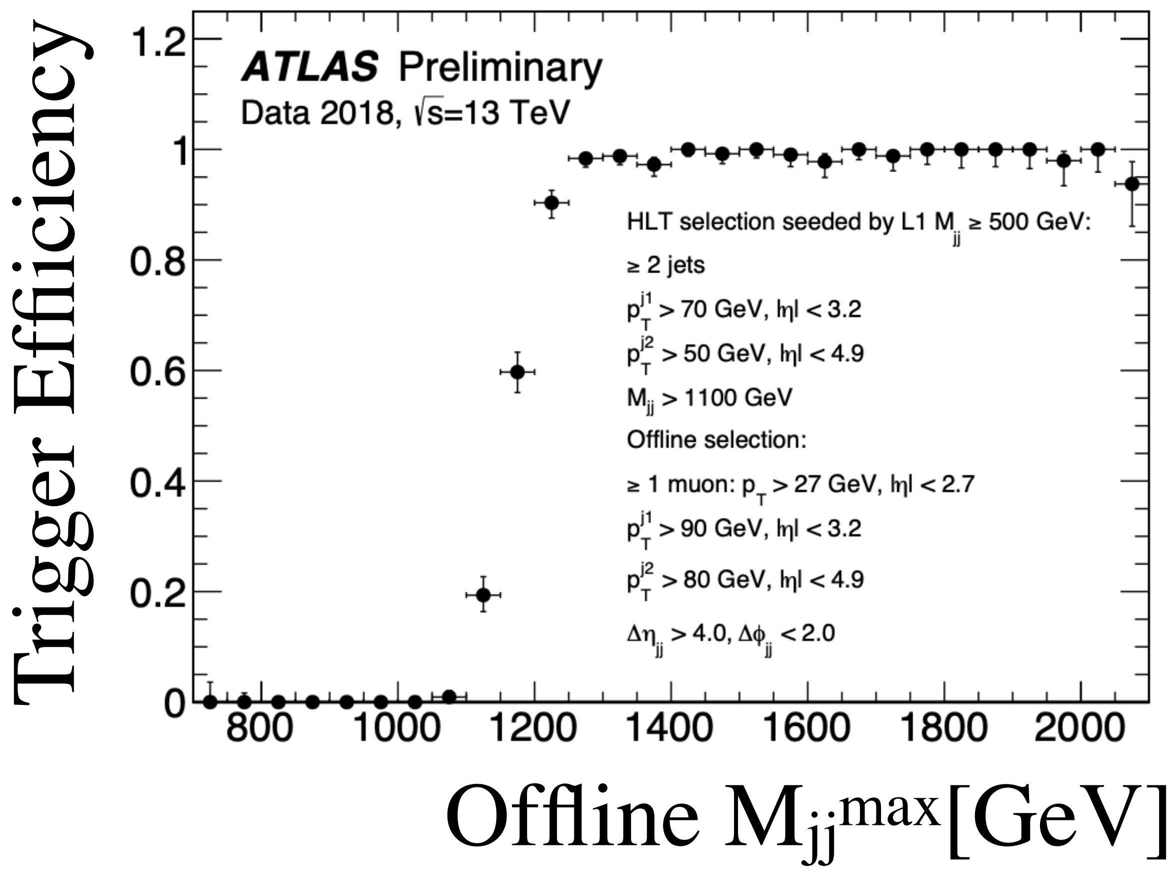
Extend phase space



- New VBF trigger added in 2018 (40.1 fb^{-1}!)
  - L1: $m_{jj} > 0.5$ TeV
  - HLT: pT > 70 (50) GeV, $m_{jj} > 1.1$ TeV
  - Gain additional signal in lower MET with more strict VBF cuts

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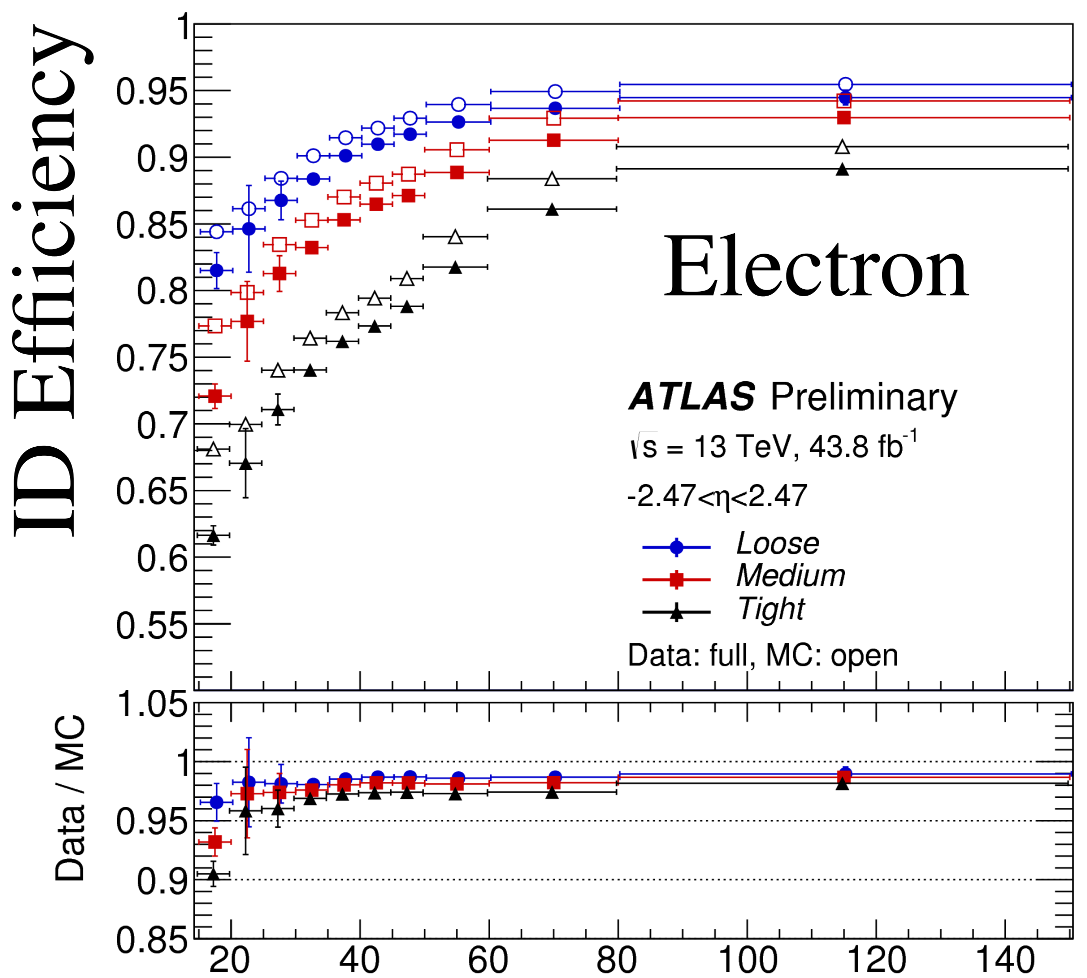
Improve Z CR stats

- Z→ ee: dielectric trigger allows us to move WP from tight to loose for 15% gain in ZCR statistics
- Z→ μμ: moving to loose extend efficiency in wider η range ~ 5%
- Z→ ττ: can add lep+had channel for ~12 % gain in ZCR statistics
- 30% gain in total in ZCR stats! → 13% reduction in stats uncertainty in ZCR!



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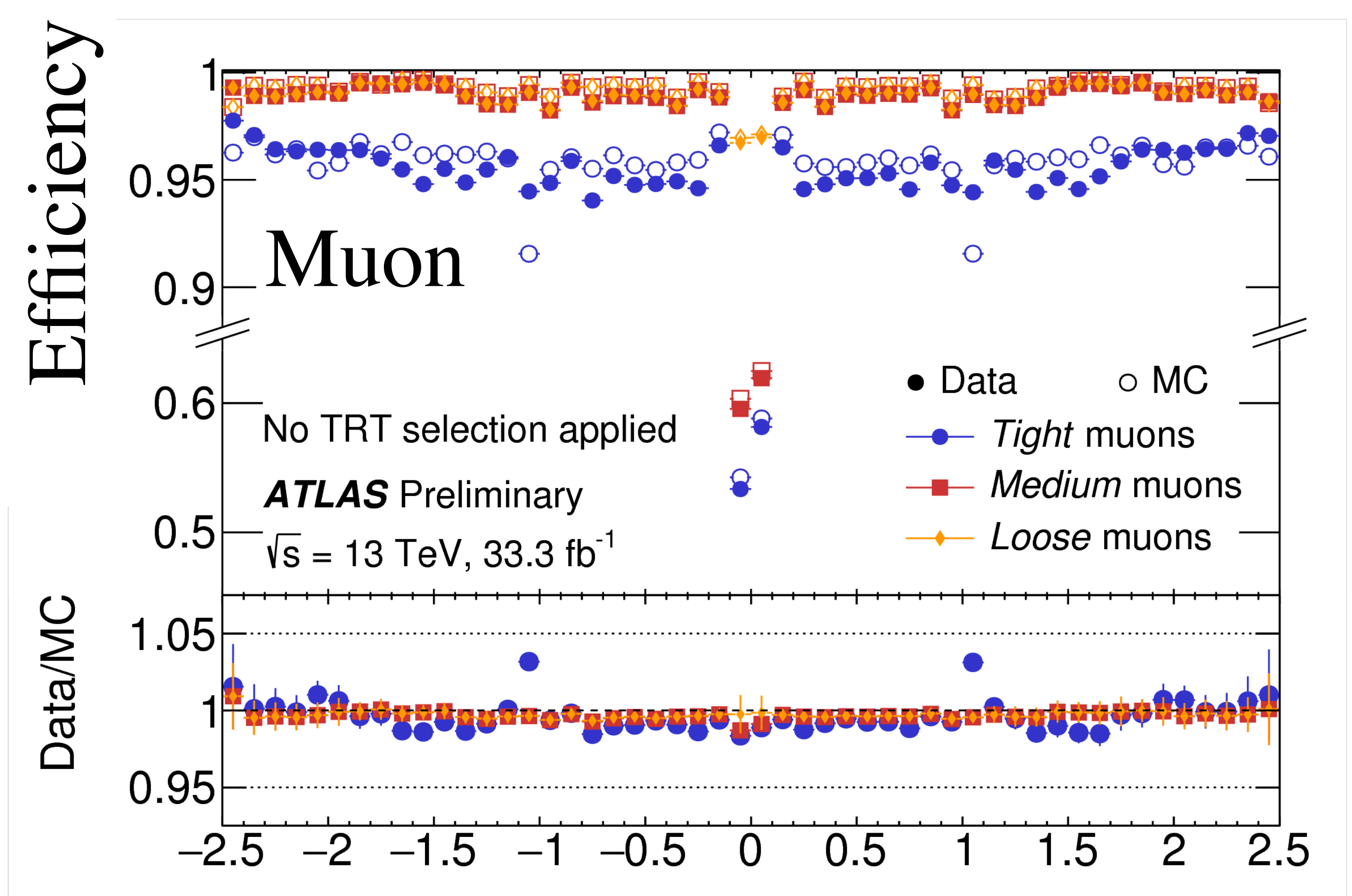

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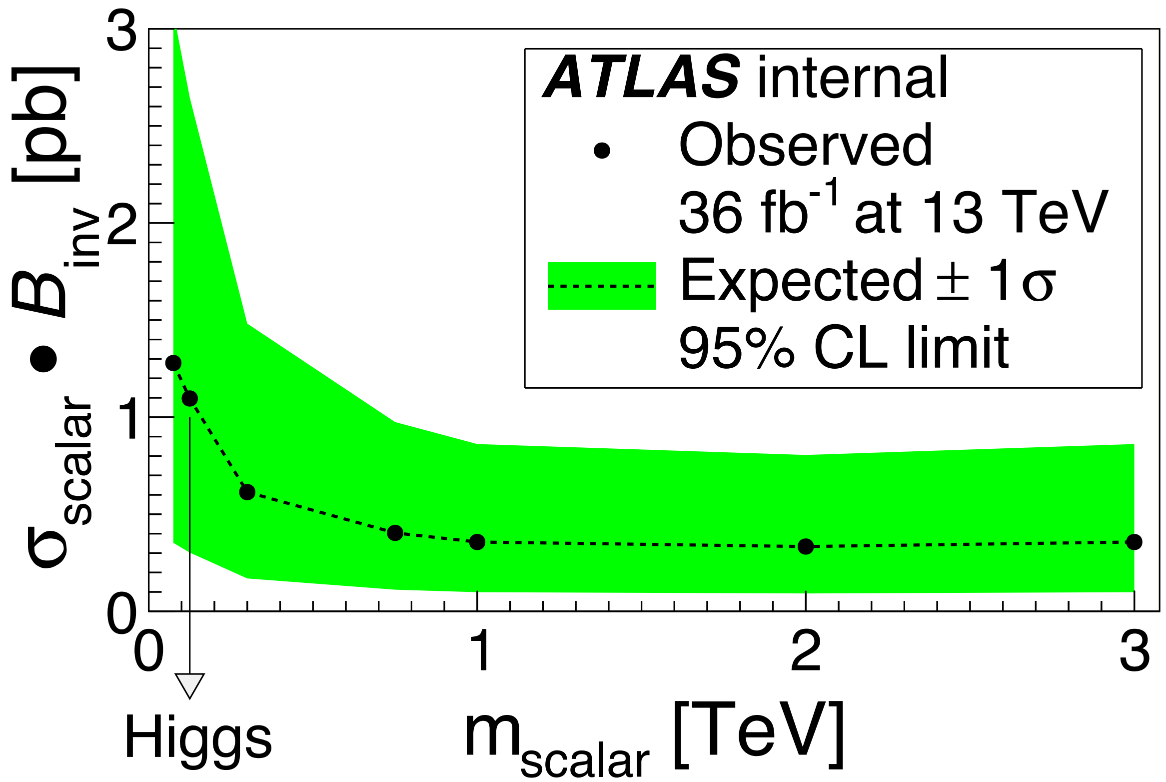
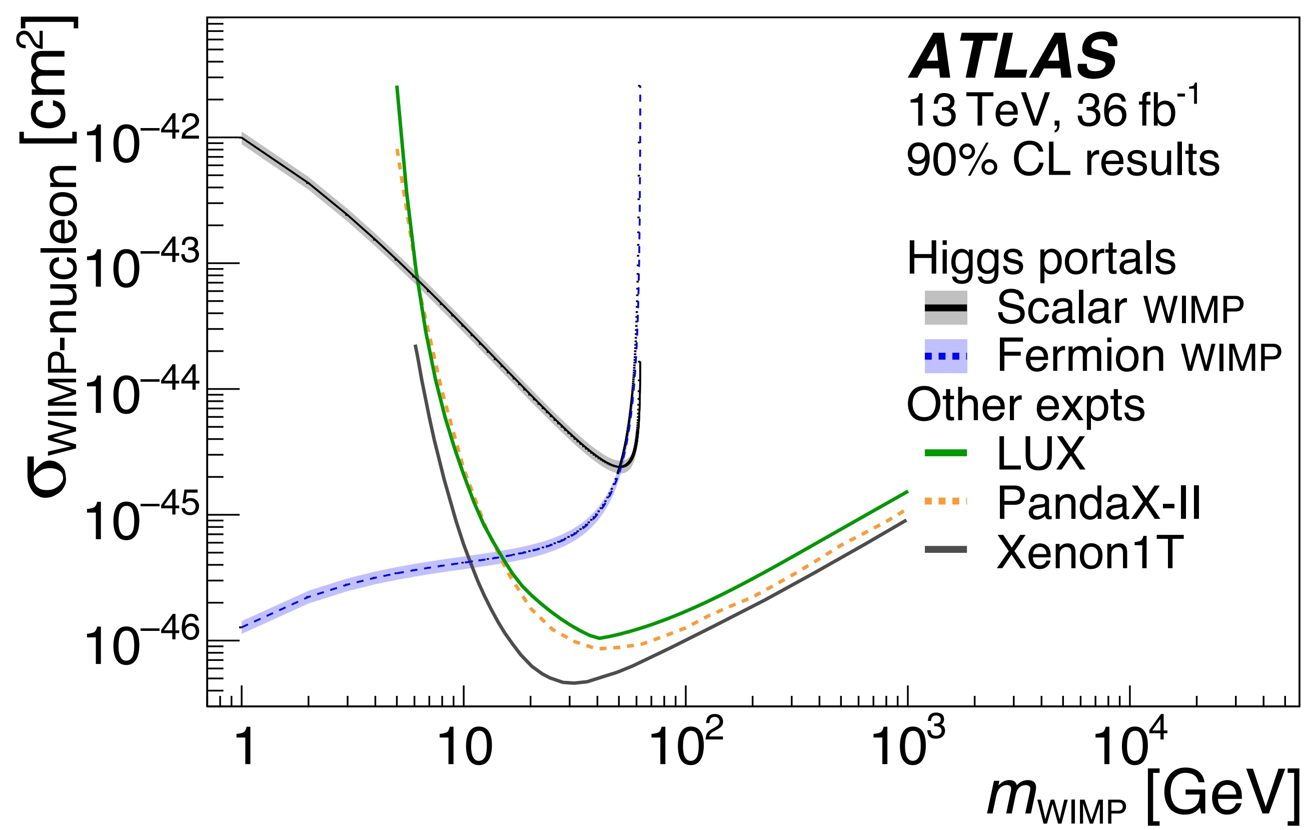
Conclusion

- Run 2 brought new challenges in various aspects
- Lots of room for improvement for full Run 2 analysis:
    - Improvements for jets, MET and lepton identification
    - MC generations
    - Systematics reduction
    - Fit Models
- Combination of $H \rightarrow$ Invisible with 36.1 fb^{-1} and Run 1 coming out

Backup

WIMP interpretations





- Reinterpret with different scalar masses
- Convert to WIMP-nucleon cross section assuming the Higgs portal model
  - Updated nuclear form factor reduces error bands
- Complements direct detection experiments through sensitivity to small WIMP masses

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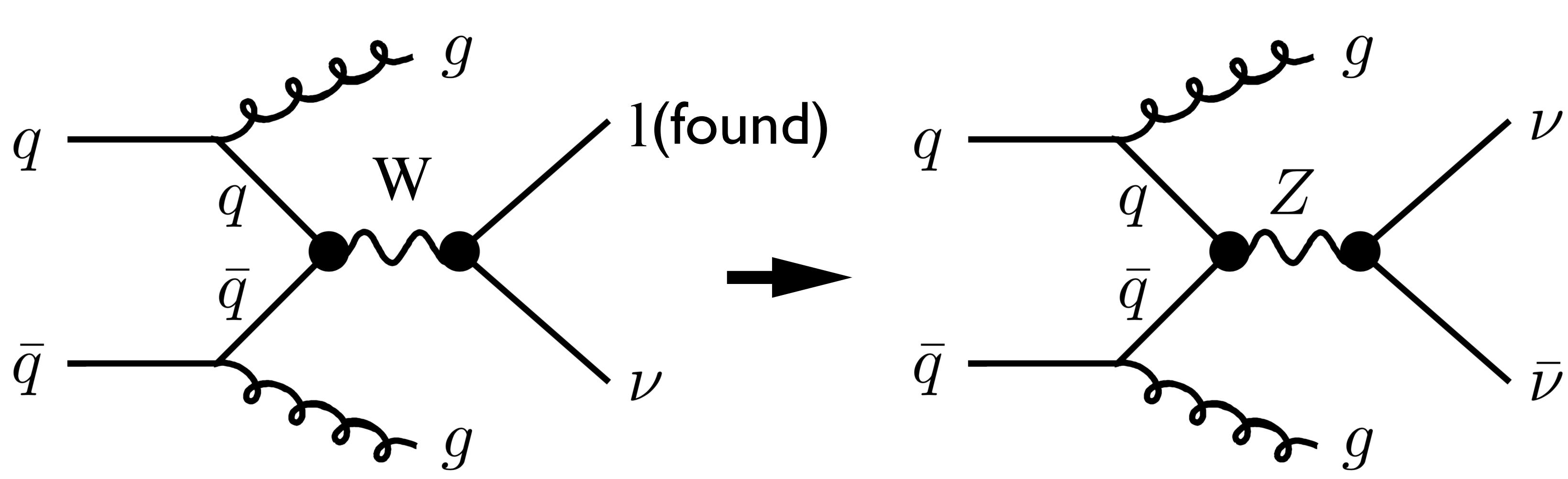
MC stats issues

- Very challenging phase space:
  - ~2 mins/event in Sherpa (total EVNT $\rightarrow$ AOD)
  - To get 500M events: 7 days on 100k cores
    - May still not be enough to cover the phase space
- Three possible solutions:
  - Implement an effective filter for Sherpa NLO
    - Has proven to be very challenging
  - Use Madgraph LO (much faster, CMS method)
    - Much bigger mismodelling
  - Find extra resources to generate MC samples

Use W to Constrain Z

- Statistics limited to constrain Z→ νν (1111) with Z→ ll (181) only
- W→ lν (1400) would be a much stronger constrain for Z→ νν
- Need higher order corrections to the ratio of W/Z
  - Difference in W/Z mass
  - PDFs due to flavor differences
- Z CR will have data stats uncertainty of ~4% with 150 fb^{-1}
  - Need uncertainties on the corrections to be smaller than that
- This was done for the monoJet analysis, more challenging in this phase space

number of events in current paper



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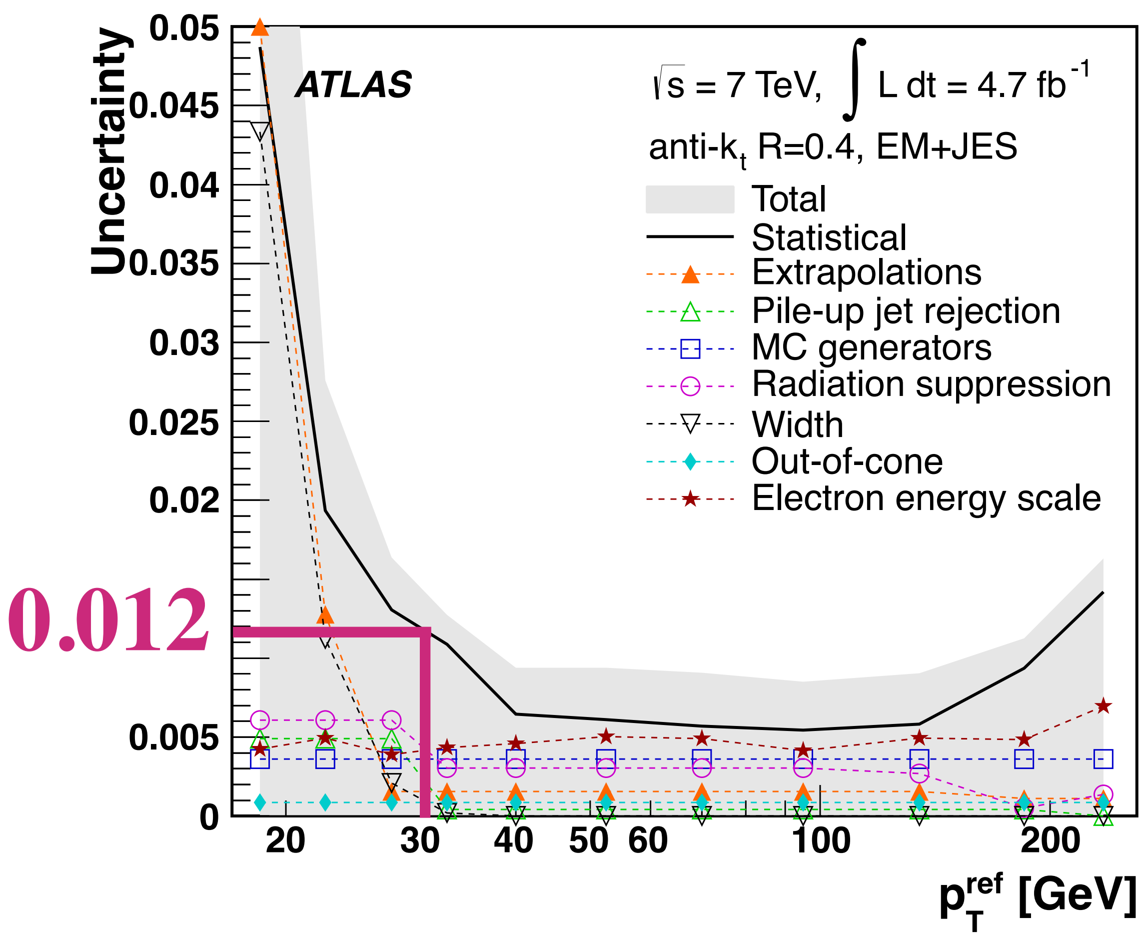
Jet Systematics

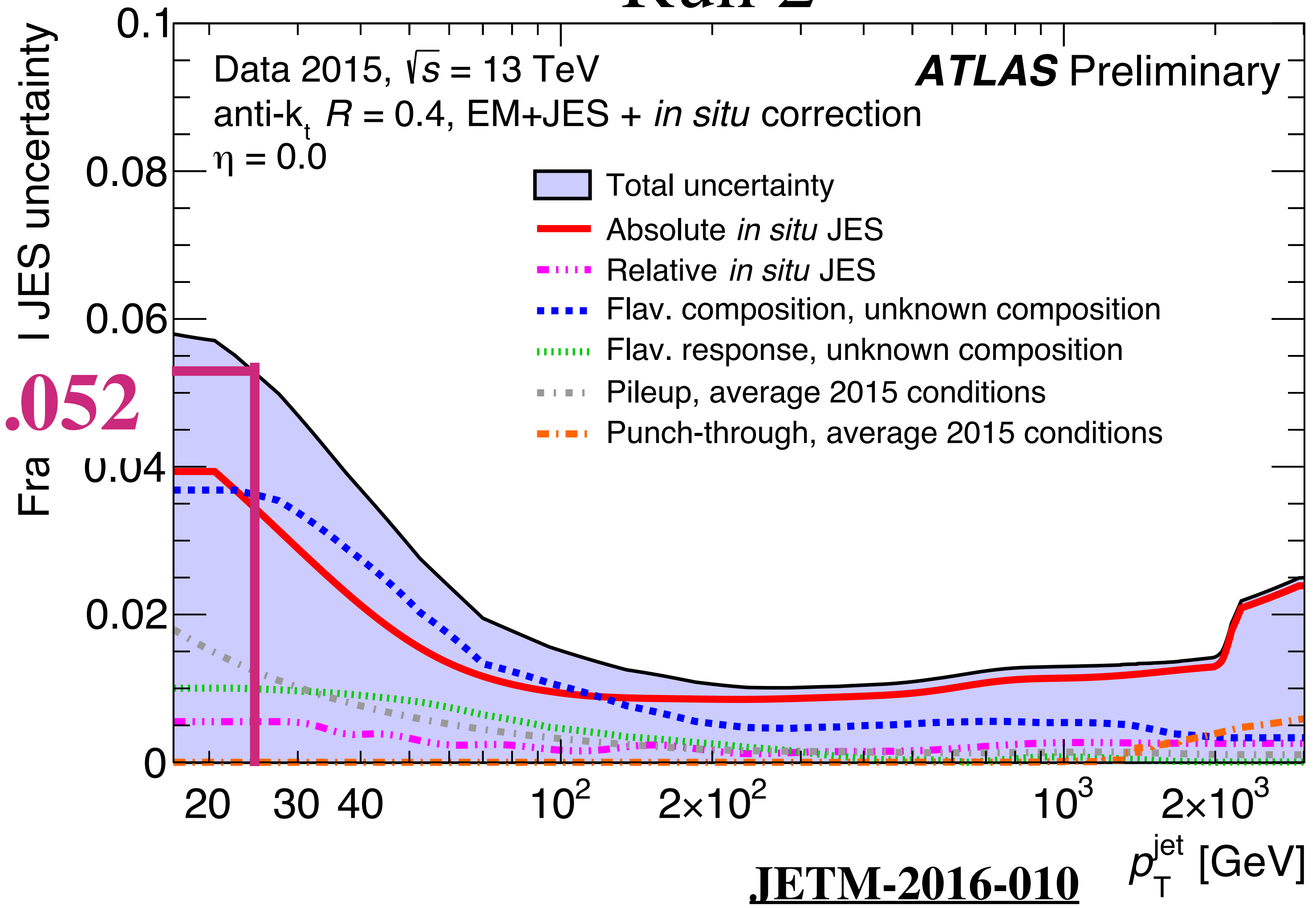
- Jet systematics:
  - Increased greatly overall due to increase in pileup
  - Mainly due to 3rd jet veto at 25 GeV (30 GeV in Run 1)
  - JES uncertainty increased: 0.012 → 0.052

Run 1



arXiv:1406.0076

Run 2



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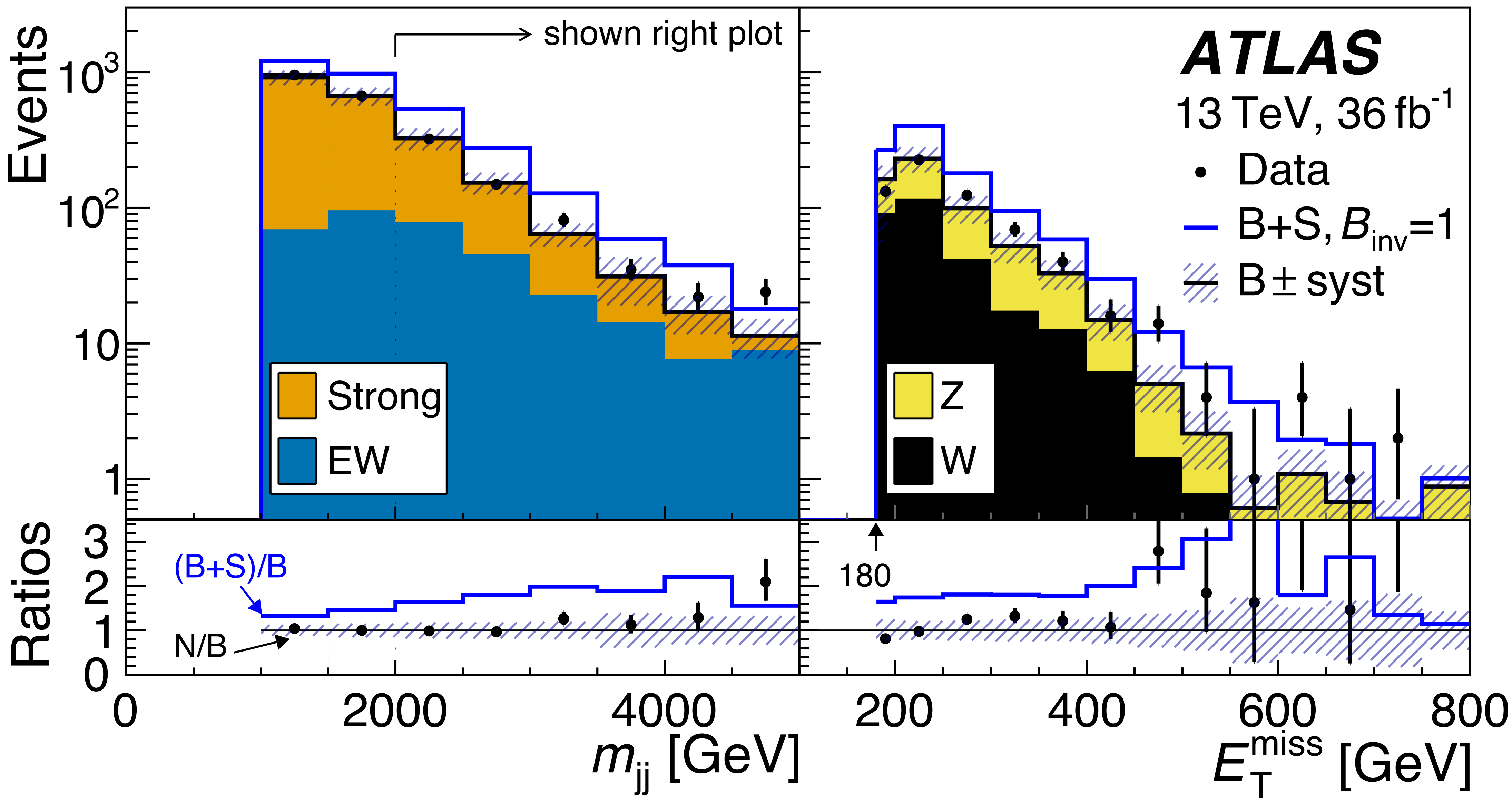
Kinematic Distribution



- S/B increases with m_{jj}, flat with MET

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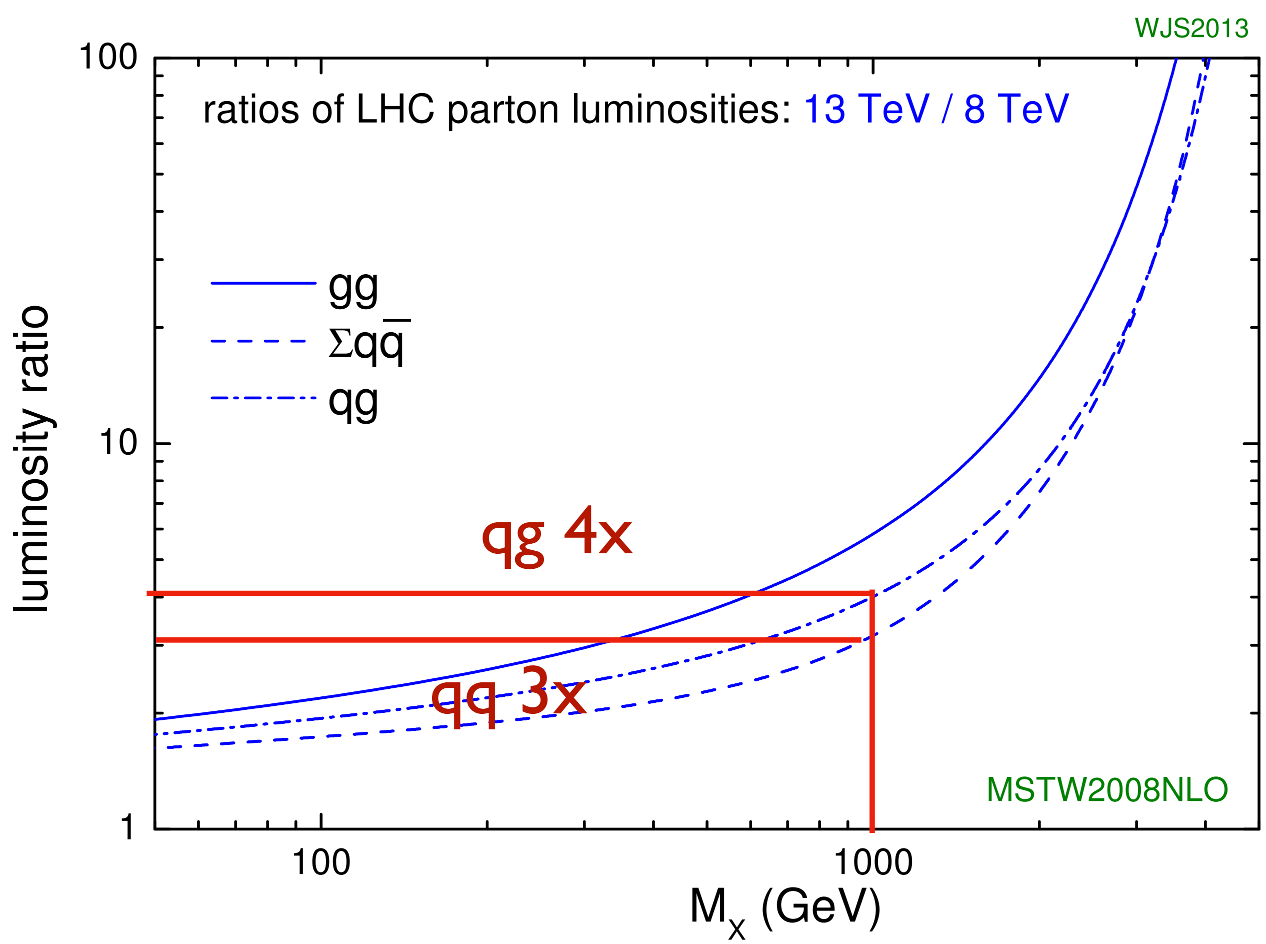
S/B from Run 1 to Run 2

- Most signal events are qq while background events are qg
- Background increased more than signal from Run 1 to Run 2 (8 TeV → 13 TeV)
- Change in background motivates more rigorous kinematic requirements in Run 2

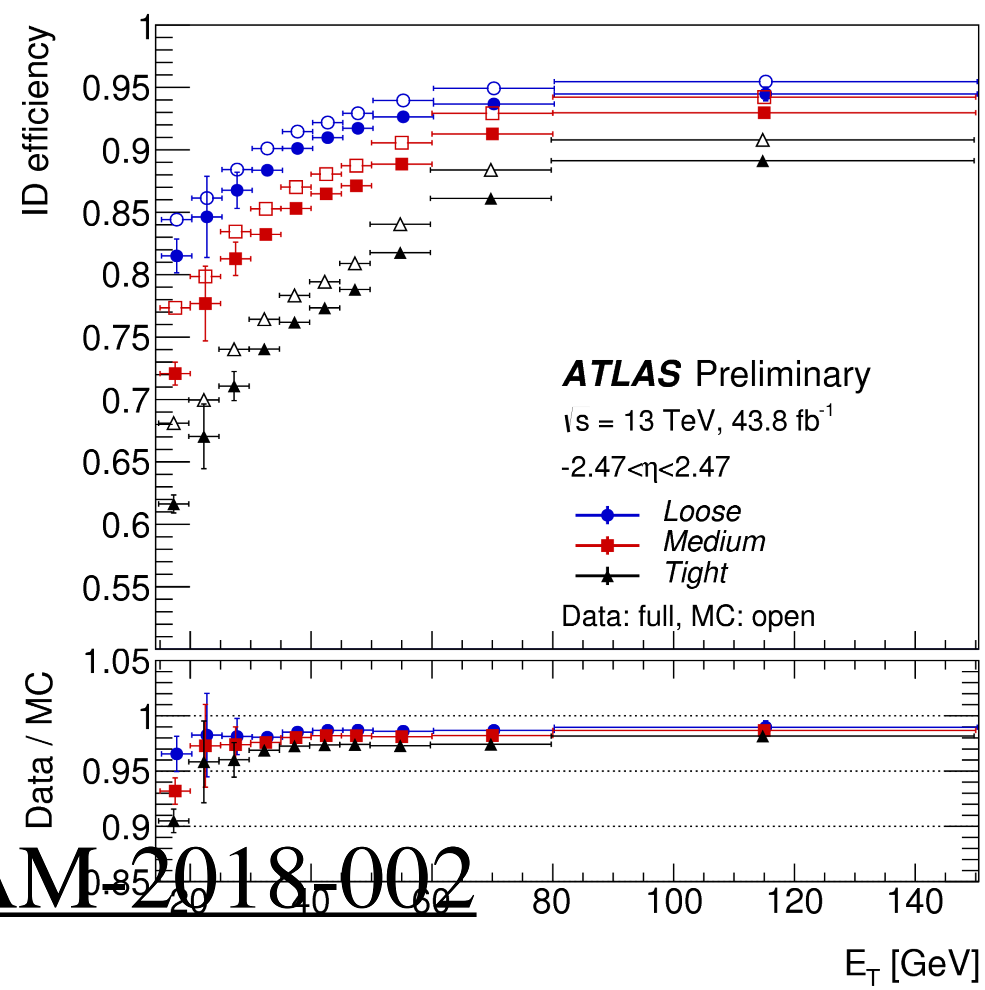
W.J. Stirling



	S	B	S/B	S/√B	σ=S/((0.04B)²+√B)	limit ~ 1/σ
Run 1	306	577	0.53	13	9.2	0.109
Scaled	1652	4154	0.40	26	9.3	0.108

Improve Z CR stats

- Z→ ee
  - Dielectric trigger allows us to move WP from tight to loose for 20% gain in statistic
- Z→ μμ
  - Moving to loose increases efficiency in |η| < 0.1 for 4% gain in statistics
  - Moving to loose will extend η acceptance to 2.7 for ~3%
- Z→ ττ
  - Can add lep+had channel for ~12 % gain in statistics
- 40-50% gain in total in ZCR stats! 17% reduction in stats uncertainty in ZCR!



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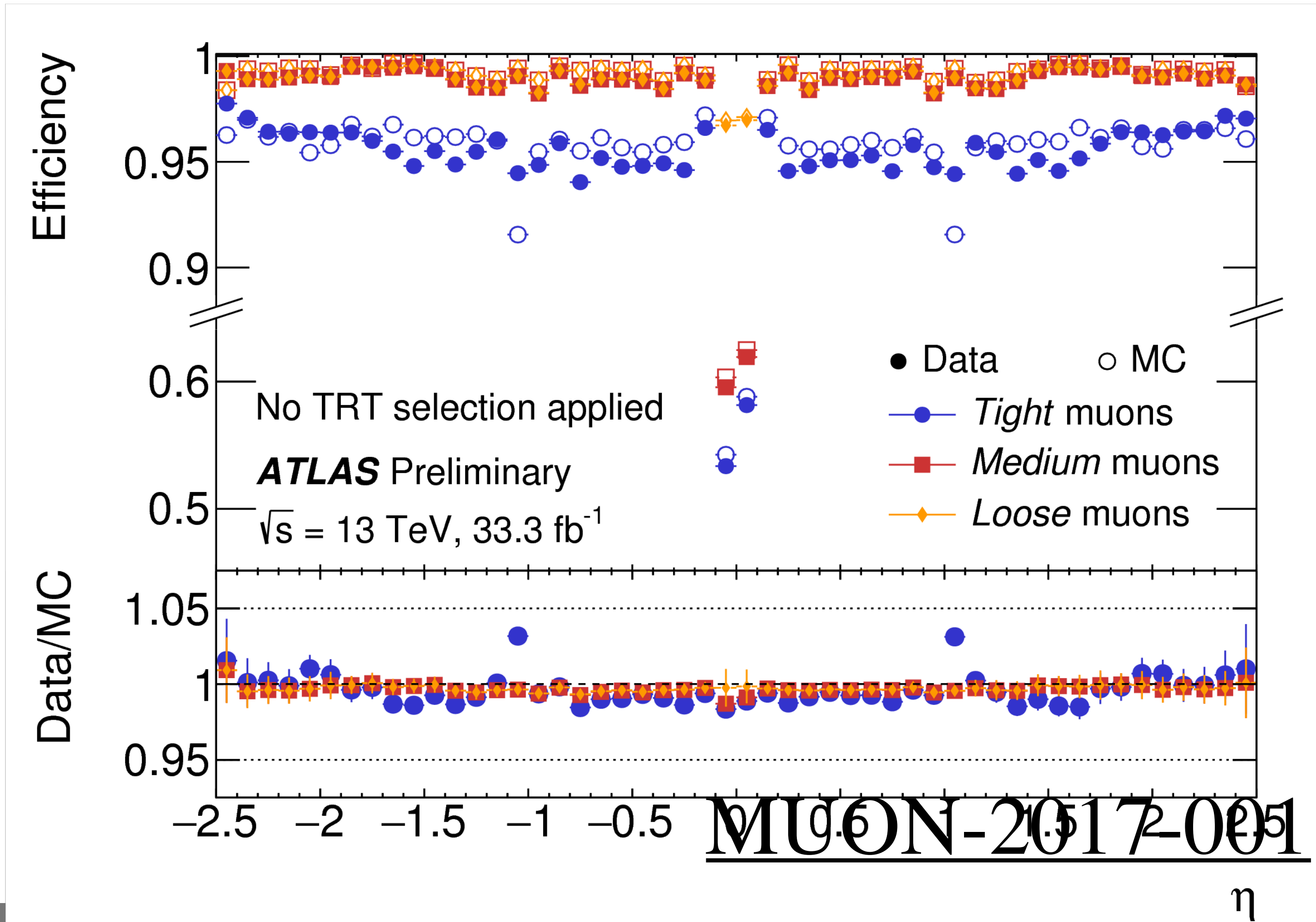

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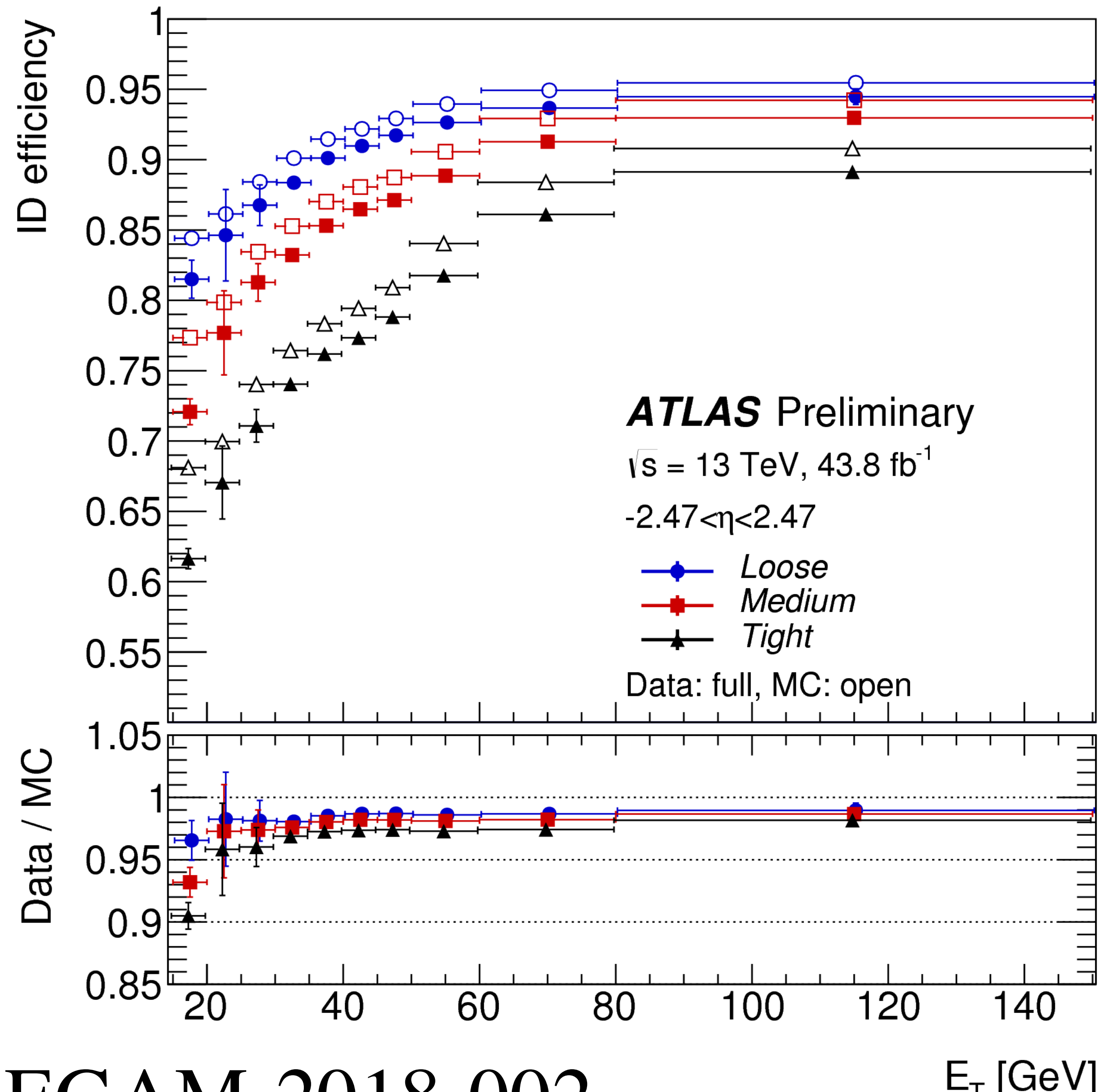
Improve S/B

- Lepton WP for veto:
  - 36.1 paper: electron WP: Tight, muon WP: Medium
  - Veto on loose leptons should reduce W→ lν background



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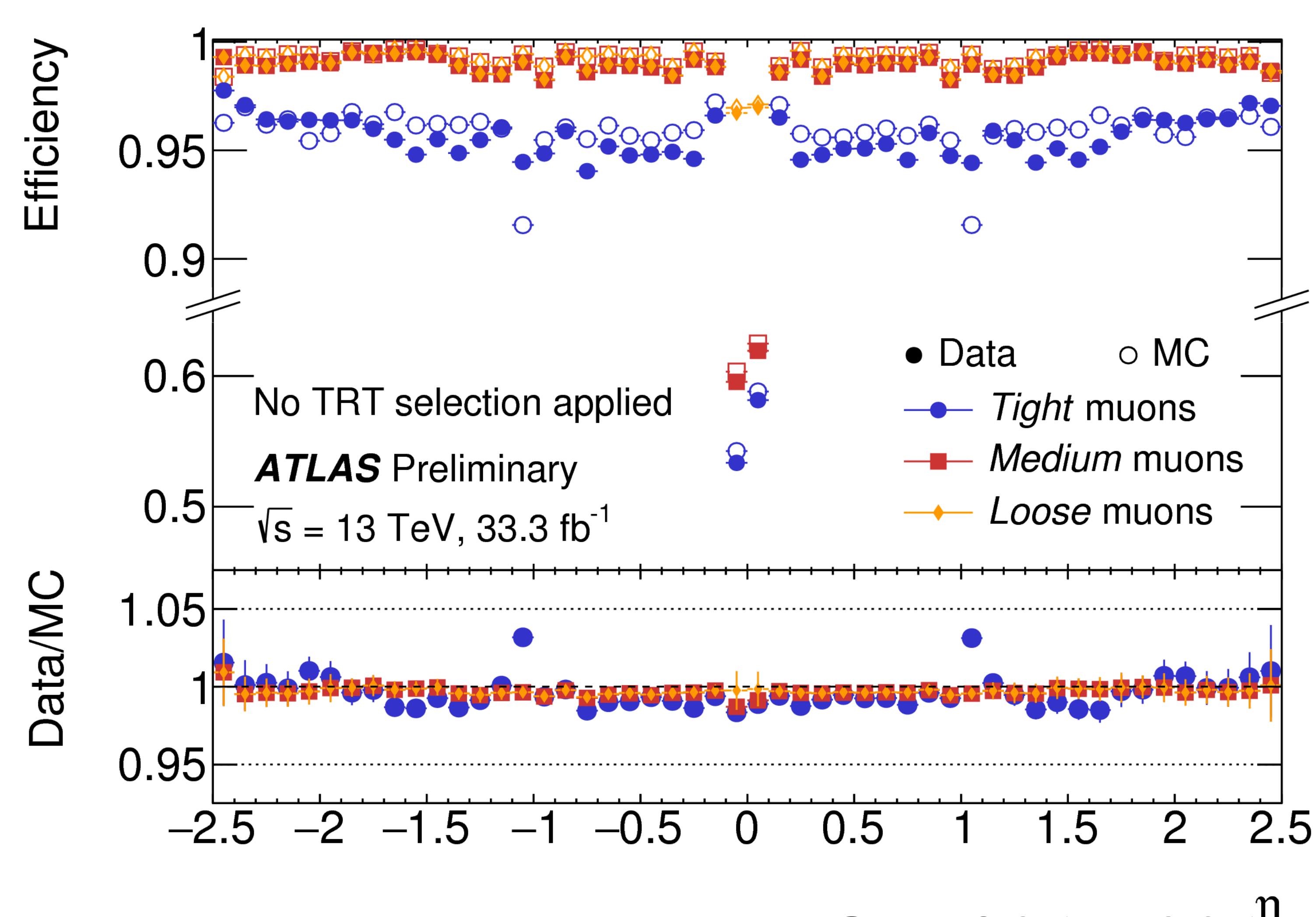

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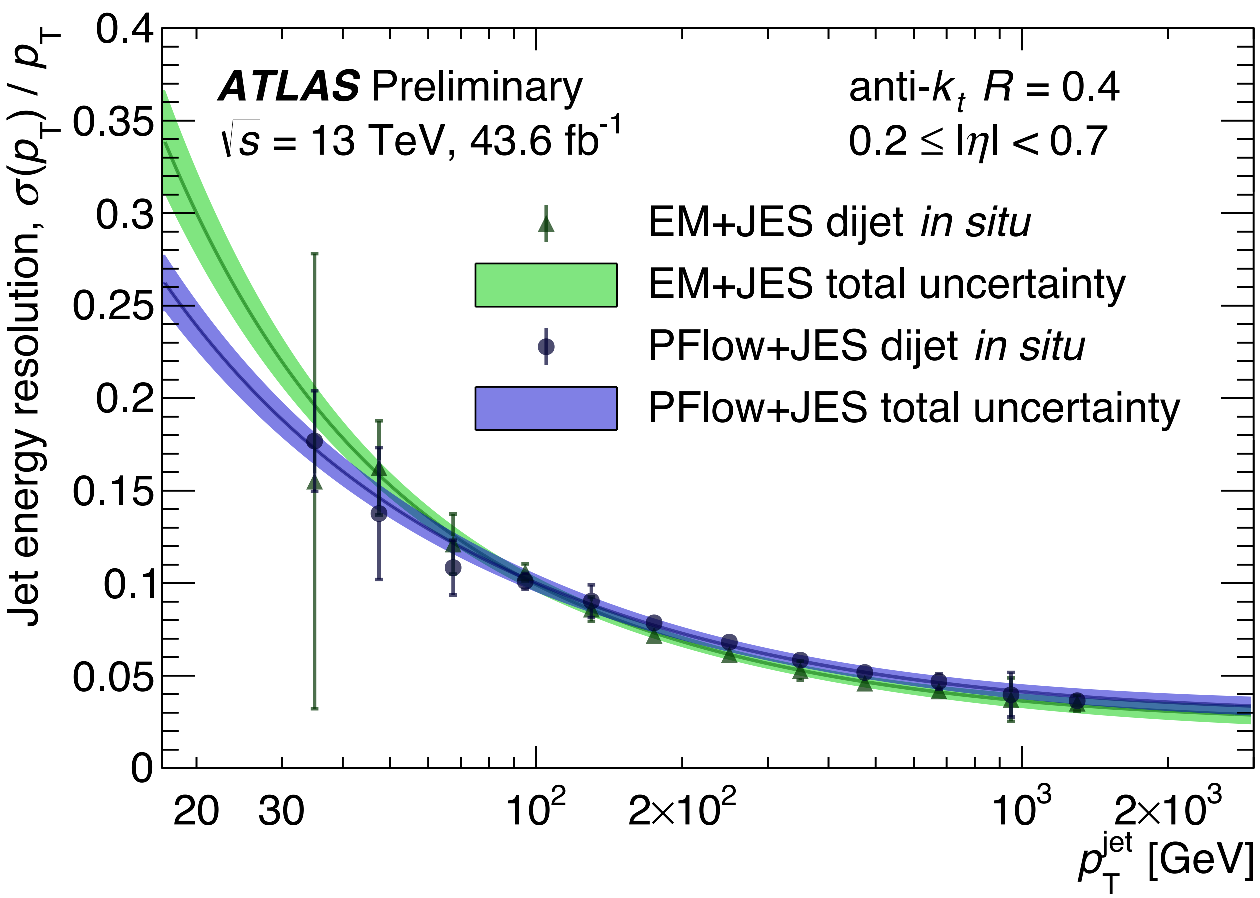
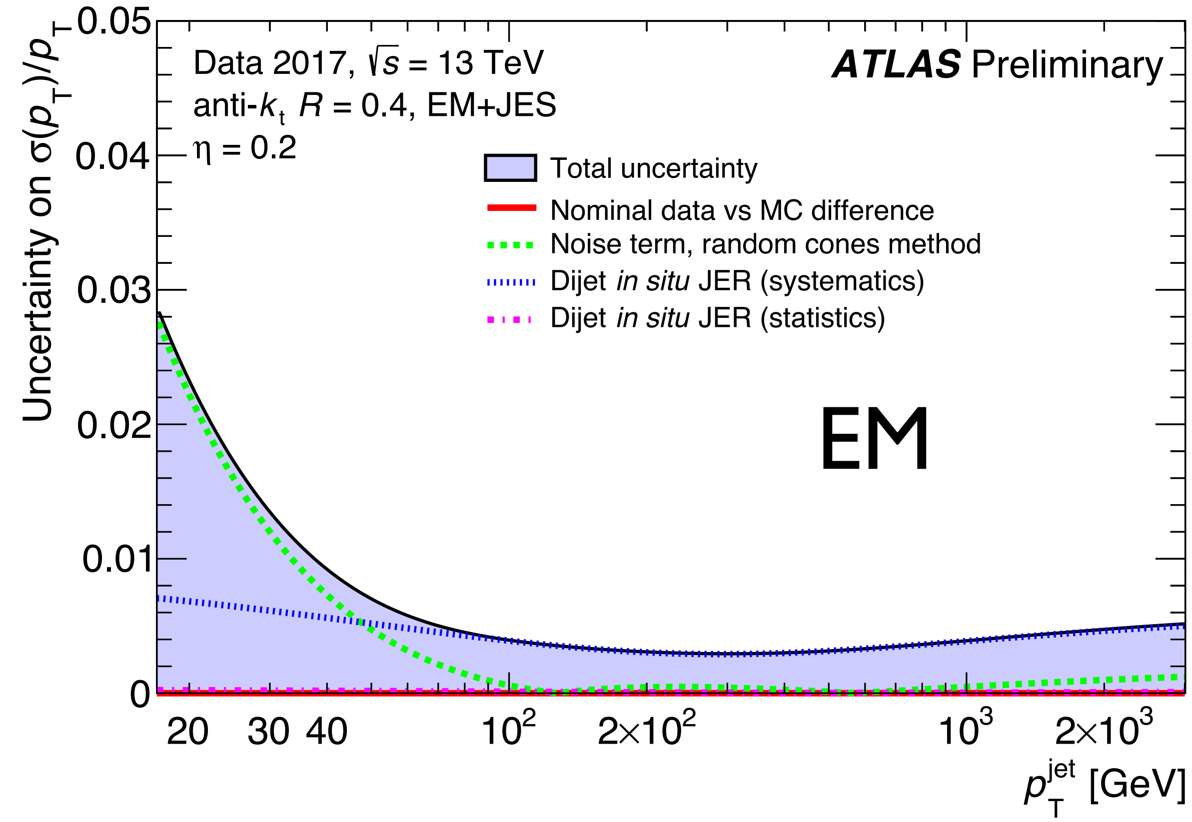
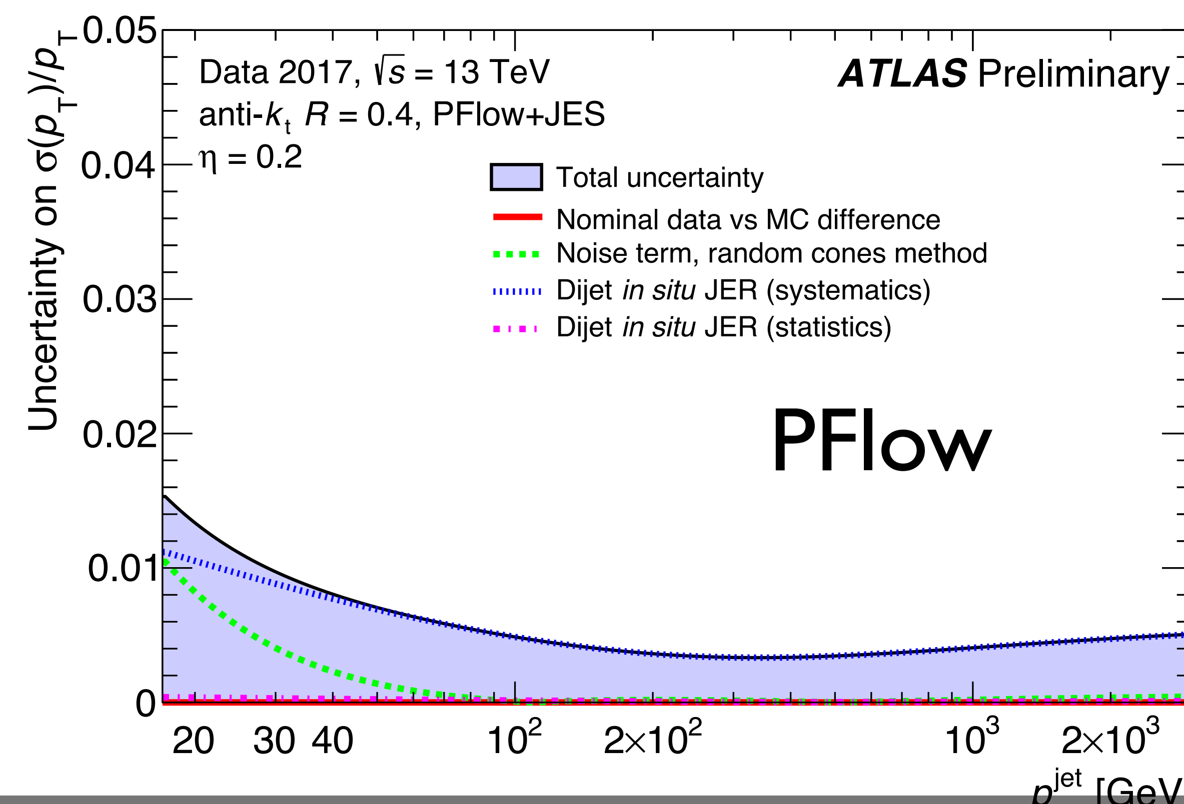
Particle Flow Jets

- Jet energy resolution is better at low p_T for particle flow jet







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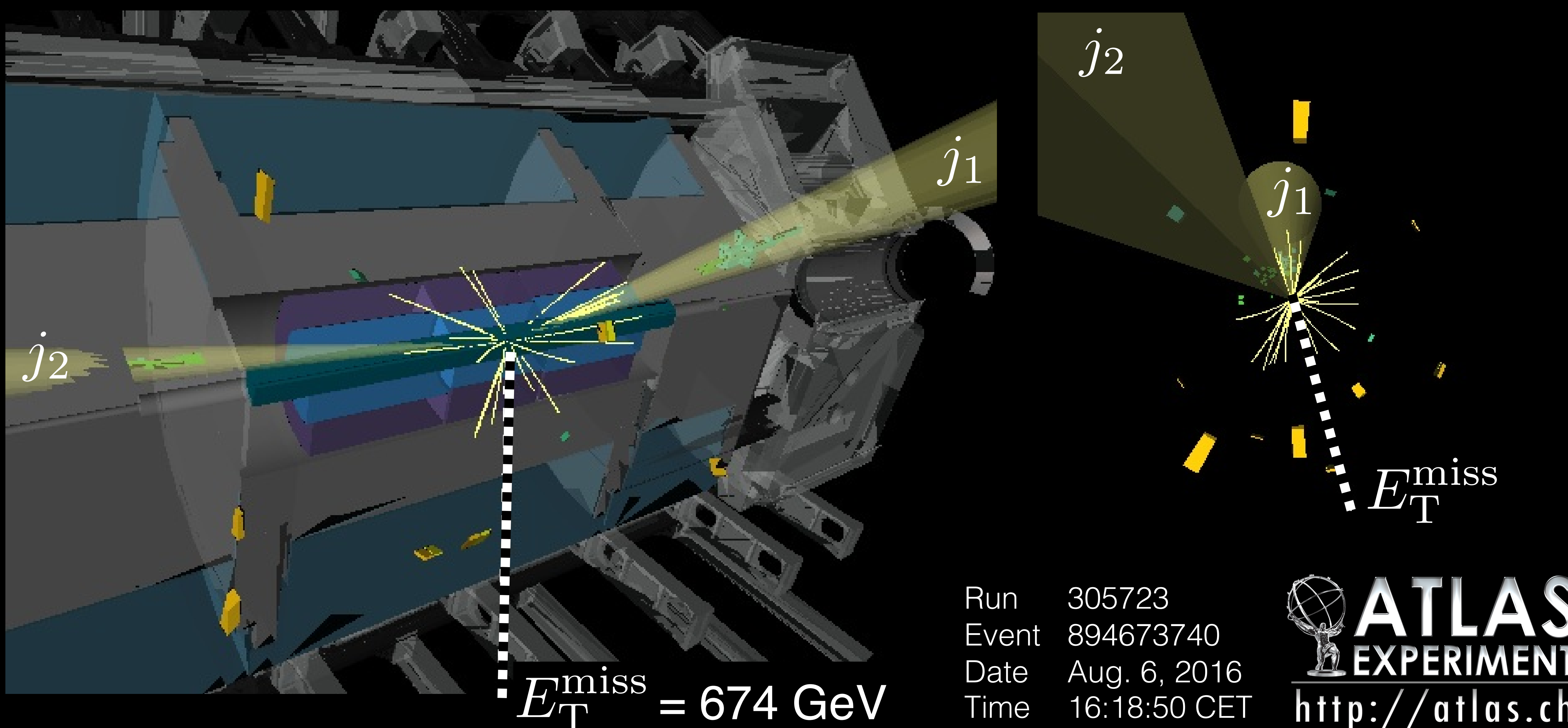
Vector Boson Fusion

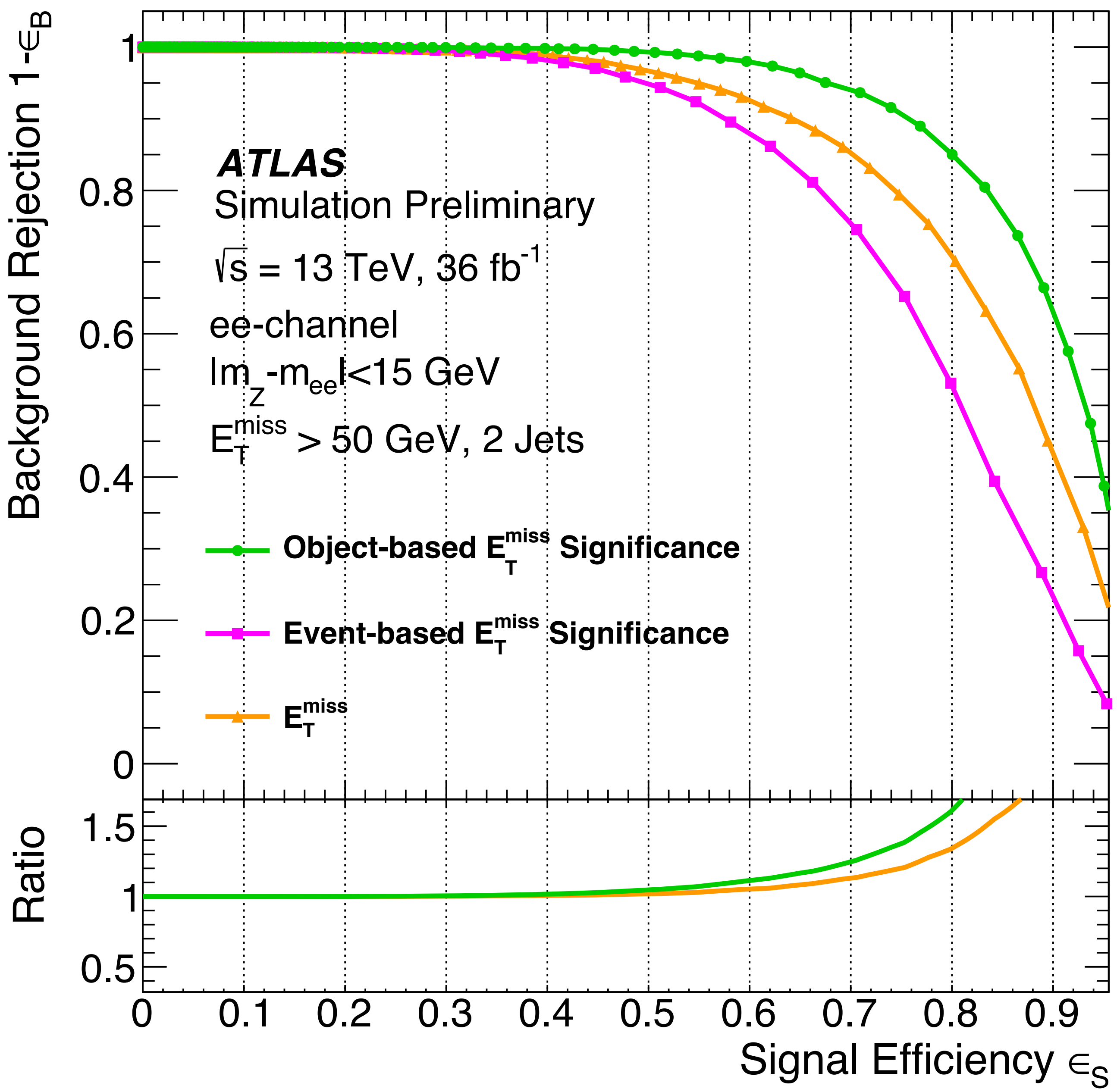
Candidate in signal region of $H \rightarrow \chi\bar{\chi}$ with two VBF jets (m_{jj} = 5.0 TeV)

Longitudinal view *Perspective x-y view*



Improve S/B

- Object based MET significance
- Improved background rejection
- Less pileup background



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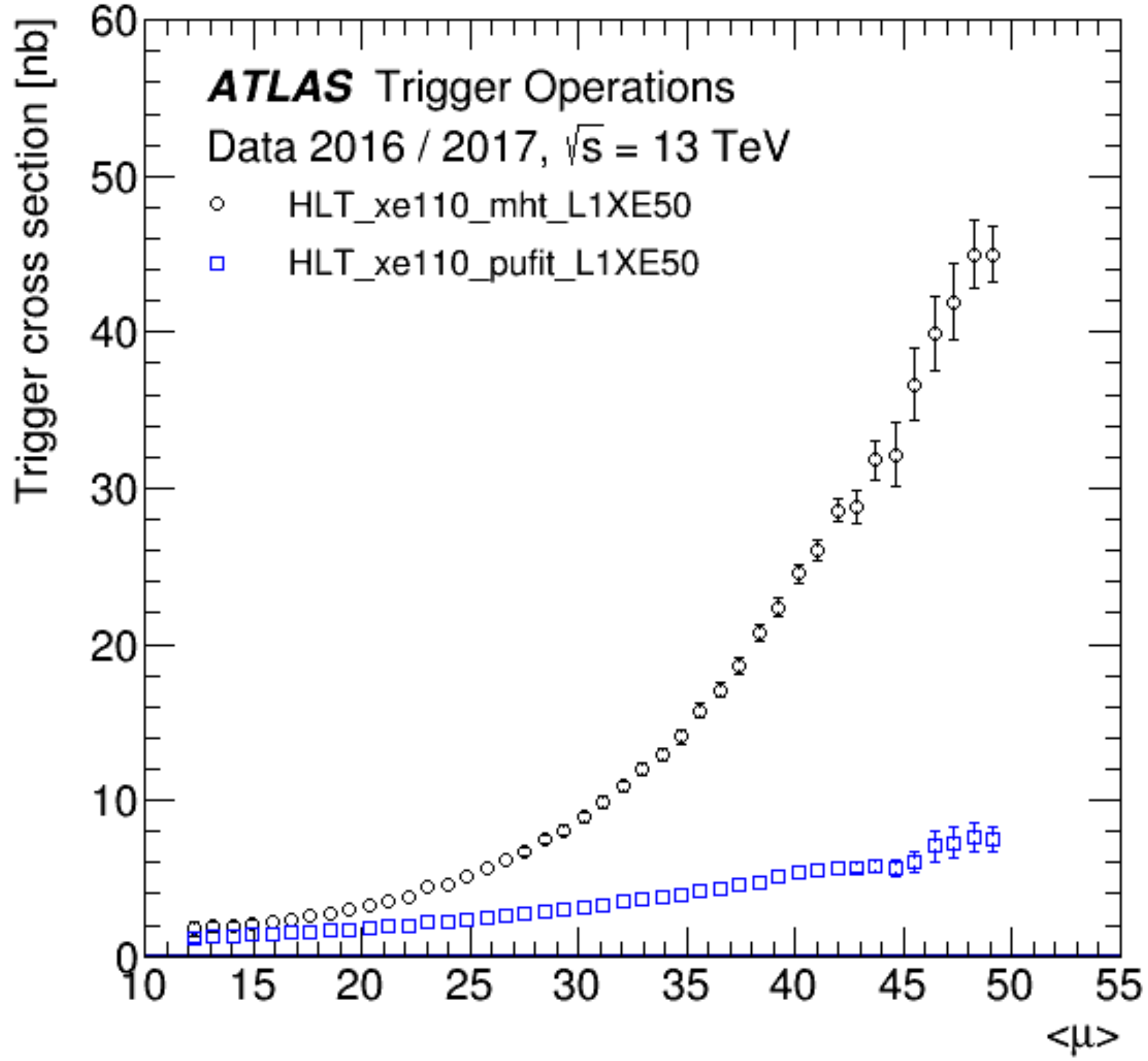
Limiting Factor

Source	$\mathcal{B}_{\rm inv}$ improve. [%] using all m_{jj} bins		Yields, α changes (%) in $1<m_{jj}<1.5$ TeV				
	Δ	visual	S	$B^Z_{\rm SR}$	$B^Z_{\rm CR}$	α_Z	α_W
Experimental (†)							
Jet energy scale	10		12	7	8	8	6
Jet energy resol.	2		2	0	1	1	4
$E_{\rm T}^{\rm miss}$ soft term	1		2	2	2	2	2
Lepton id., veto	2		-	-	-	-	4
Pileup distrib.	1		3	1	2	3	1
Luminosity	0		2	2	2	-	-
Theoretical (‡)							
Resum. scale	1		-	2	3	0	2
Renorm., fact.	2		-	20	19	1	2
CKKW matching	4		-	2	3	1	5
PDF	0		1	1	2	1	1
3rd jet veto	2		7	-	-	-	-
Statistical							
MC sample (★)	12		4	5	9	10	9
Data sample	21		6	5	12	12	6
Combined							
All † sources	17						
All ‡ sources	10						
Combine †, ‡	28						
Combine †, ‡, ★	42						

- MC Statistics
- Jet systematics
- Theory systematics

Trigger Challenge

- mht: vector sum of jet p_T
- pufit: new algorithm developed in 2016



Kinematic argument

- Plots made for qq→ H, works for qq→ VV→ H in limit of Mx > MH