Searches With Jet Substructure

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on behalf of the ATLAS and CMS Collaborations

LHCP 2018
Bologna, June 7, 2018

Overview

Complexity

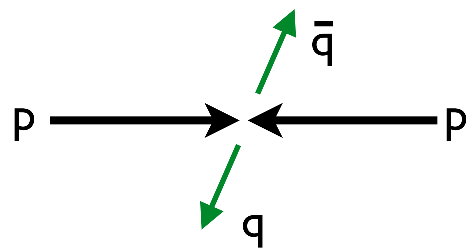
- Methodology
- Diboson resonances
- tb and tt resonances
- Dark matter (MET+X) [Adish Vartak]
- Vector-like quarks [Aurelio Juste]
- SUSY [Brian Petersen, Yu Higuchi]

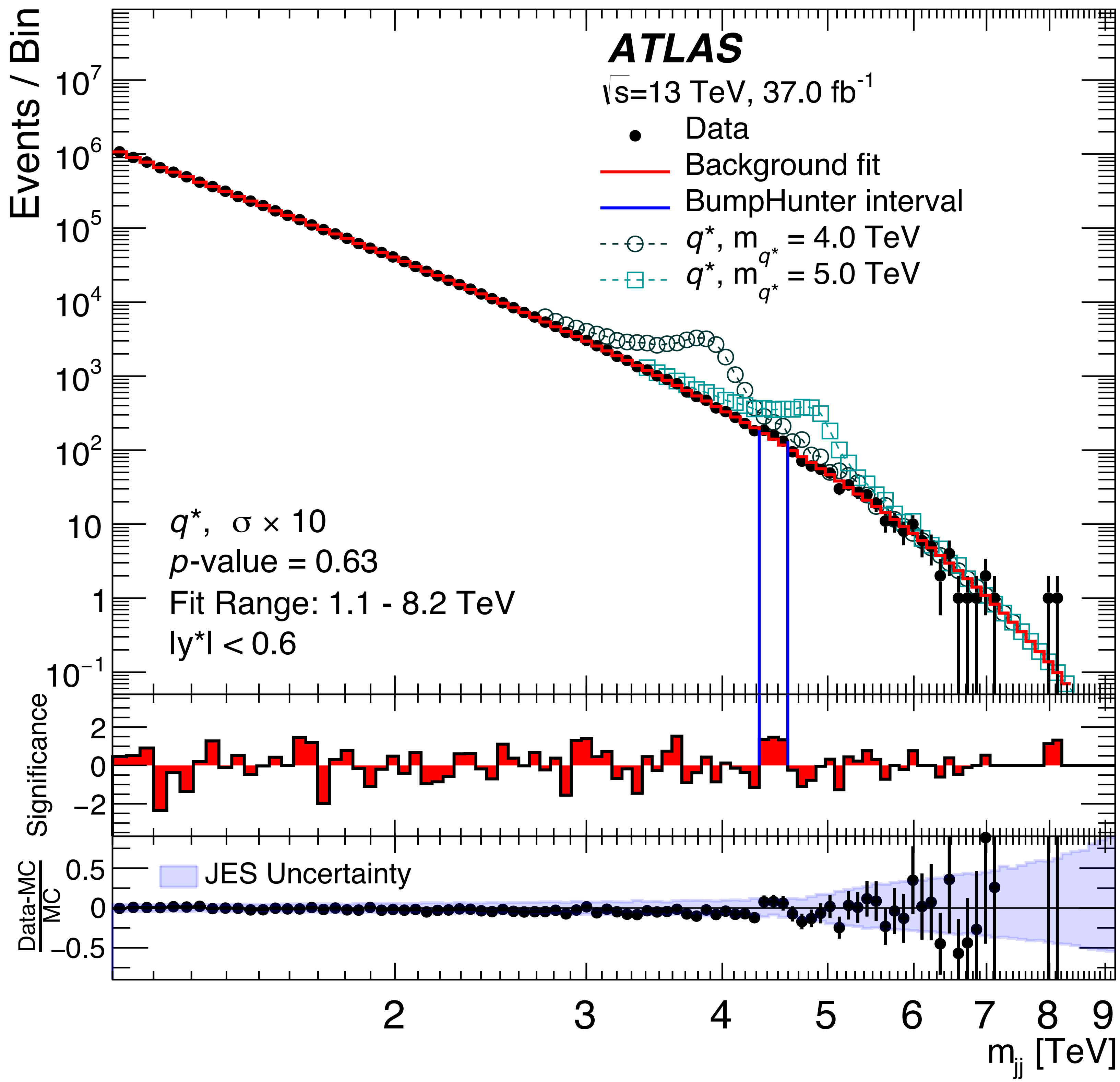
This talk:
new resonances W', Z'

Emphasis on new results, not complete selection

Disclaimer: focus on simple interpretations in benchmark models, more complete interpretations possible and available

qq/gg Resonances



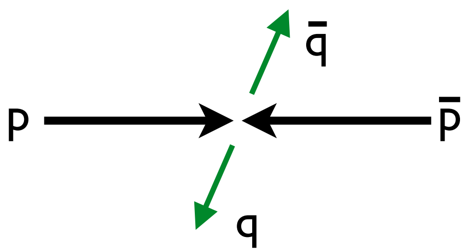


[ATLAS, PRD 96, 052004 (2017)]

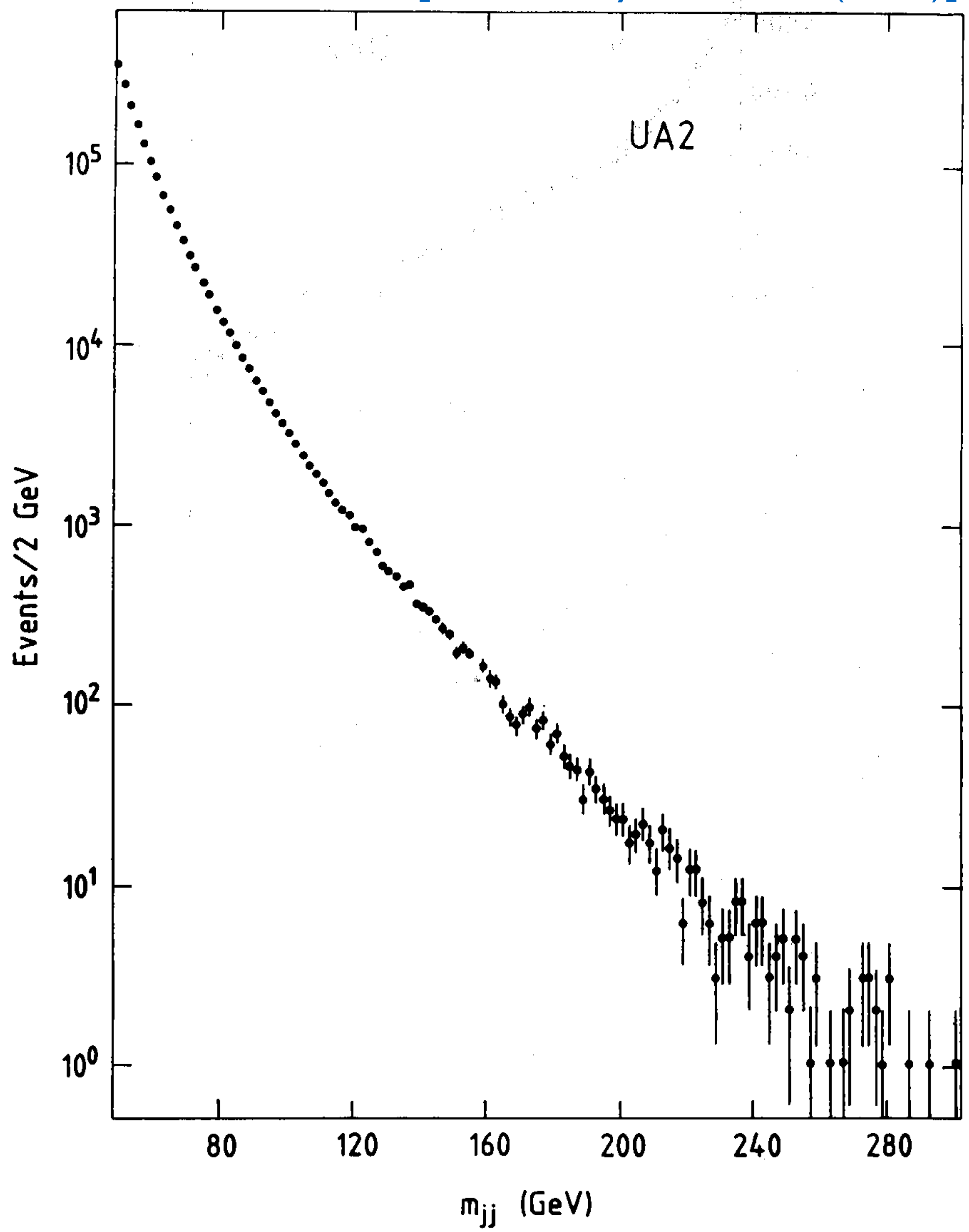
"Inclusive is not conclusive"

[G. Facini]

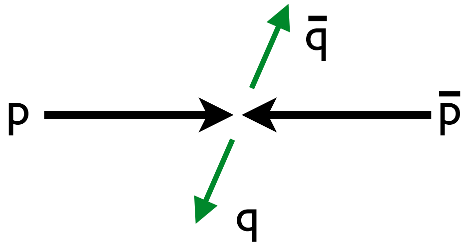
qq/gg Resonances



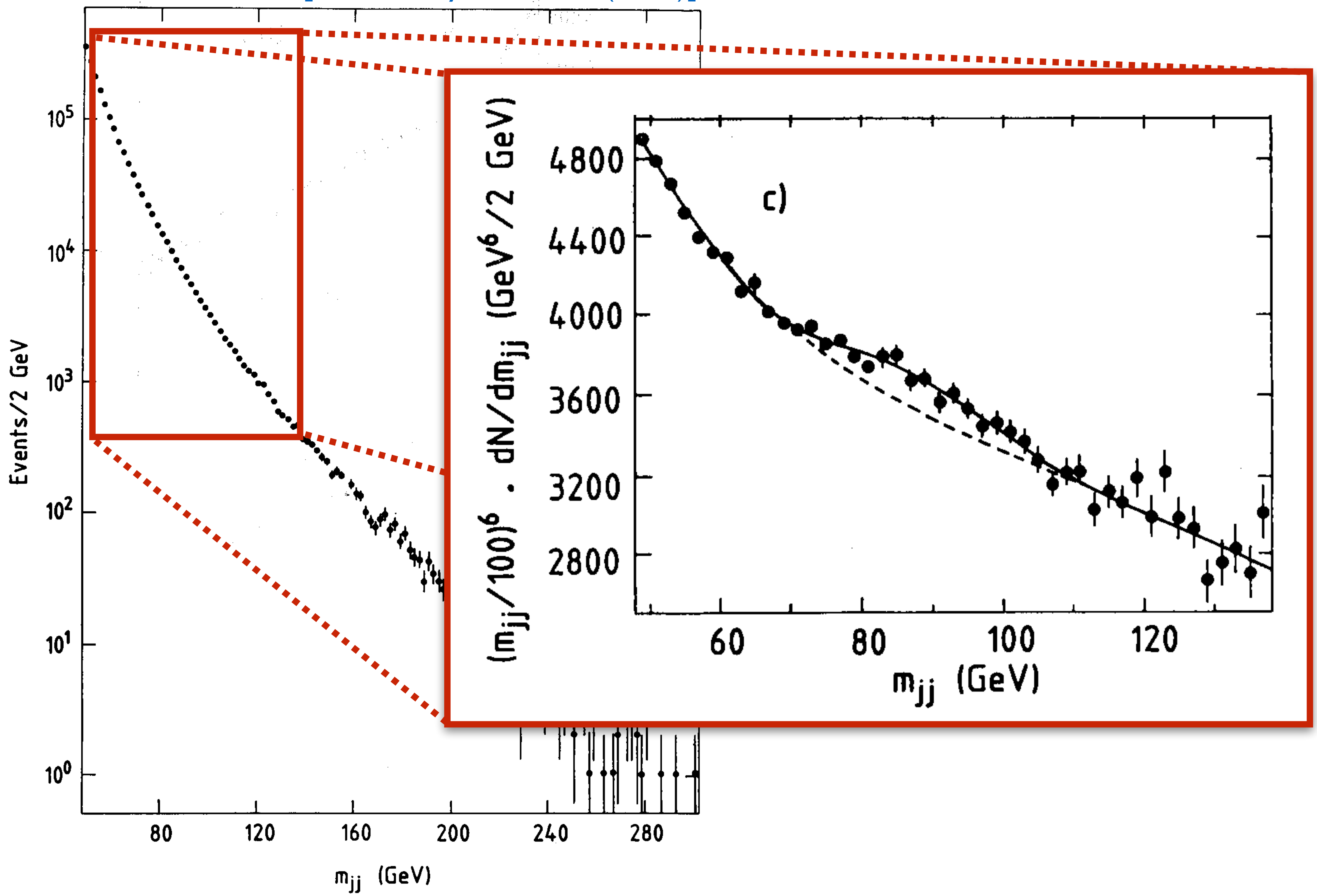
[UA2, Z. Phys. C 49, 17 (1991)]



qq/gg Resonances

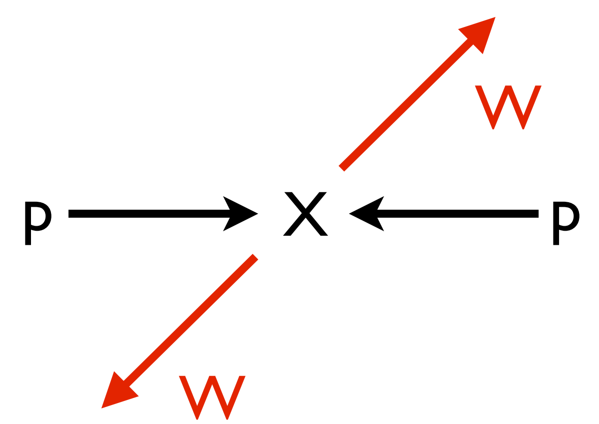


[UA2, Z. Phys. C 49, 17 (1991)]



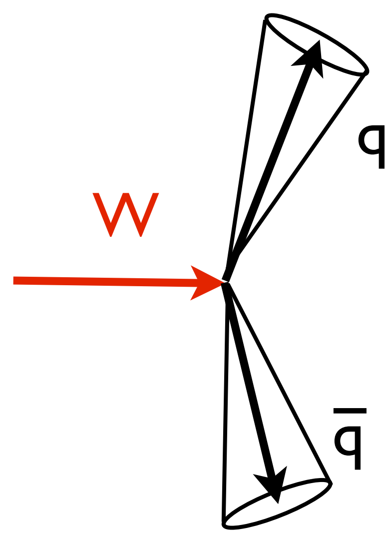
Boost!

$pp \rightarrow X \rightarrow WW \rightarrow Jets$

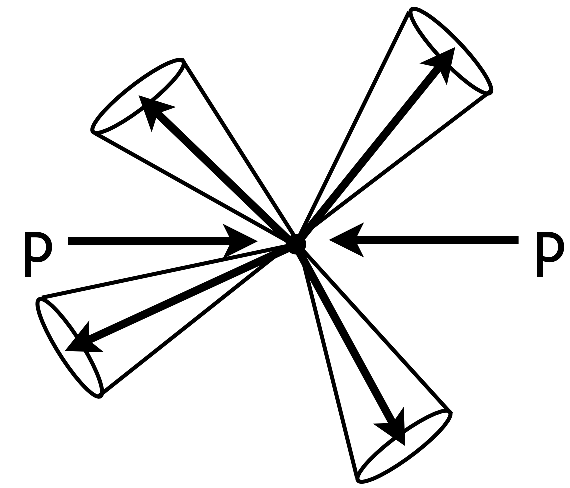


$M_X \sim 2\ M_W$

p_T^W small, $\gamma \lesssim 5$



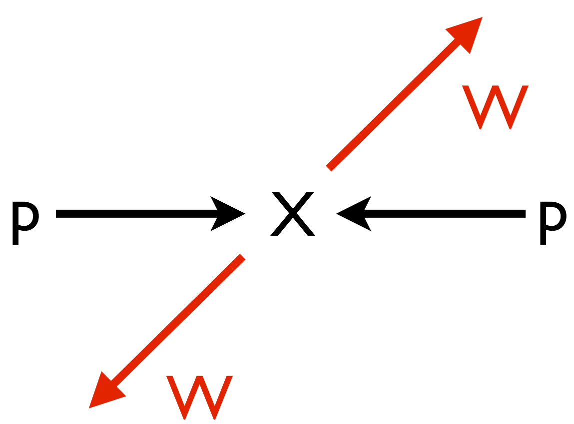
4 jet final state



combinatorics, background!

Boost!

pp→X→WW→Jets



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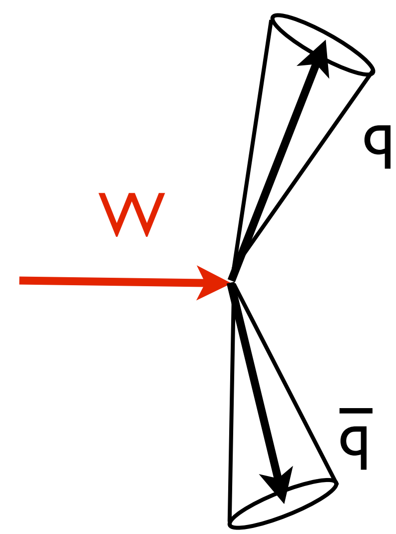
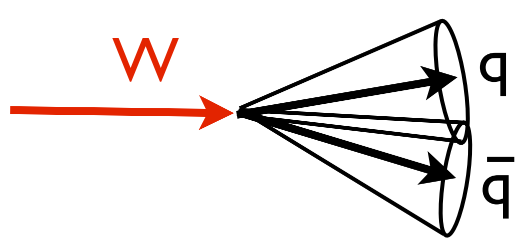
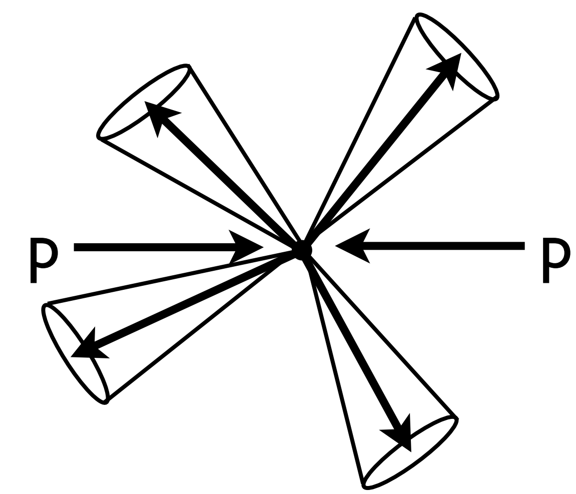


$M_X \gg 2\, M_W$

p_T^W large, $\gamma \gg 5$

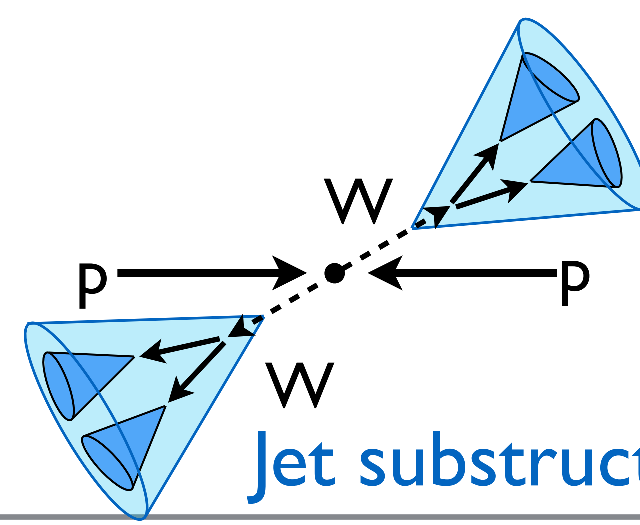


4 jet final state



combinatorics, background!

Dijet final state



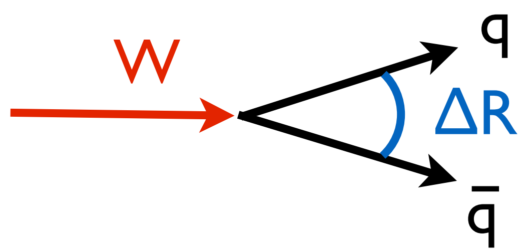
Jet substructure

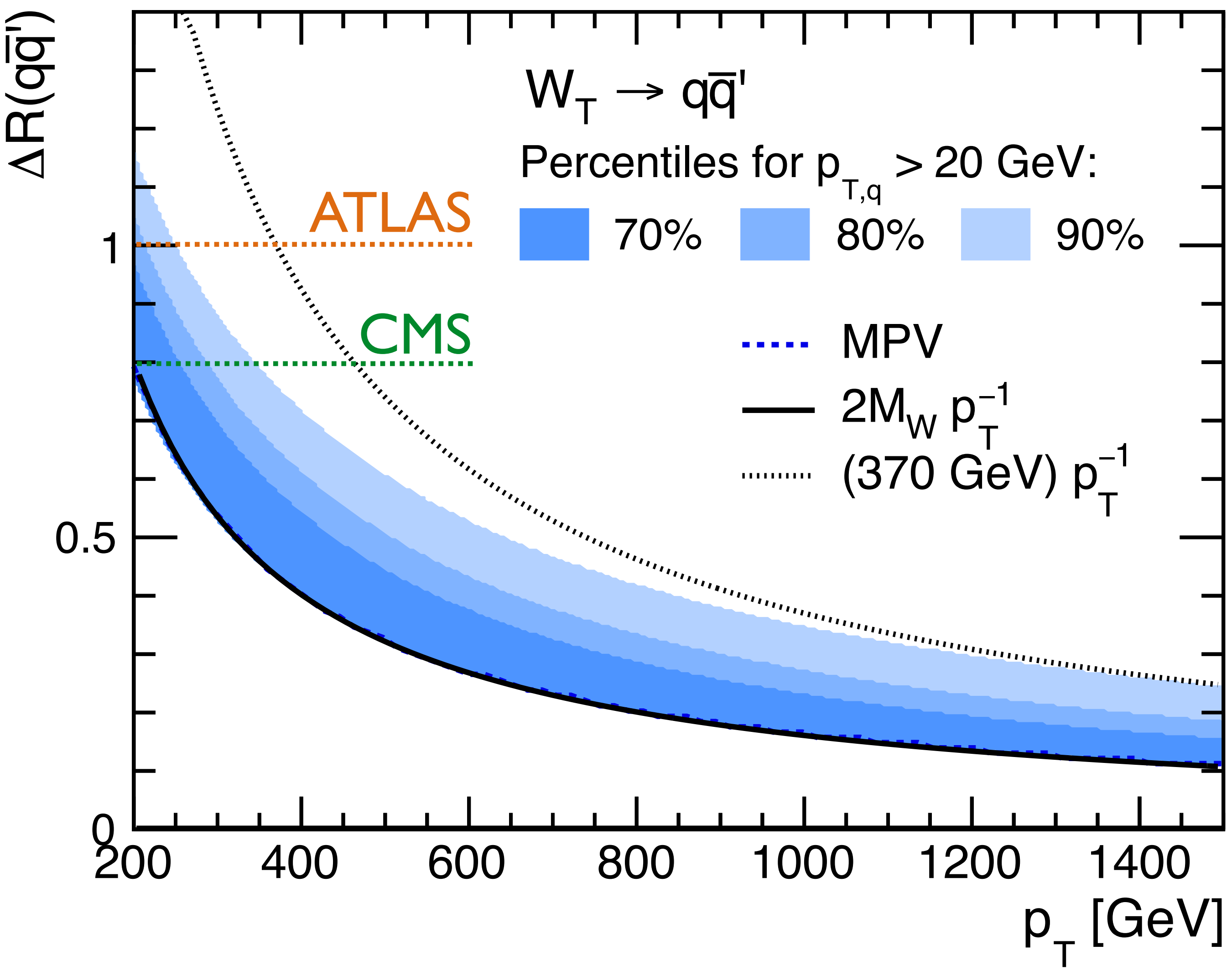
Jet Substructure

Identification of W/Z/H/t → Hadrons

- Collimation depends on p_T

$$\Delta R \approx \frac{2M}{p_T}$$ (rule of thumb)



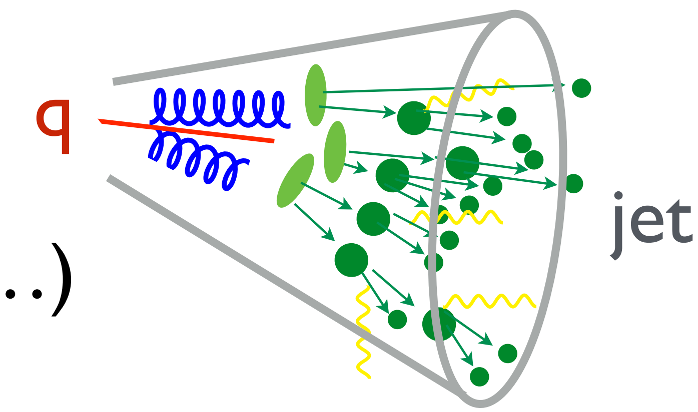


- Ensure high signal efficiency: Jet distance parameter of
  - R = 1.0 (ATLAS)
  - R = 0.8 (CMS)

W/Z/H Boson-Tagging I

Separation of QCD branching and 2-prong structure

1) Jetmass $M_{\text{jet}} = \left(\sum_i p_i\right)^2$



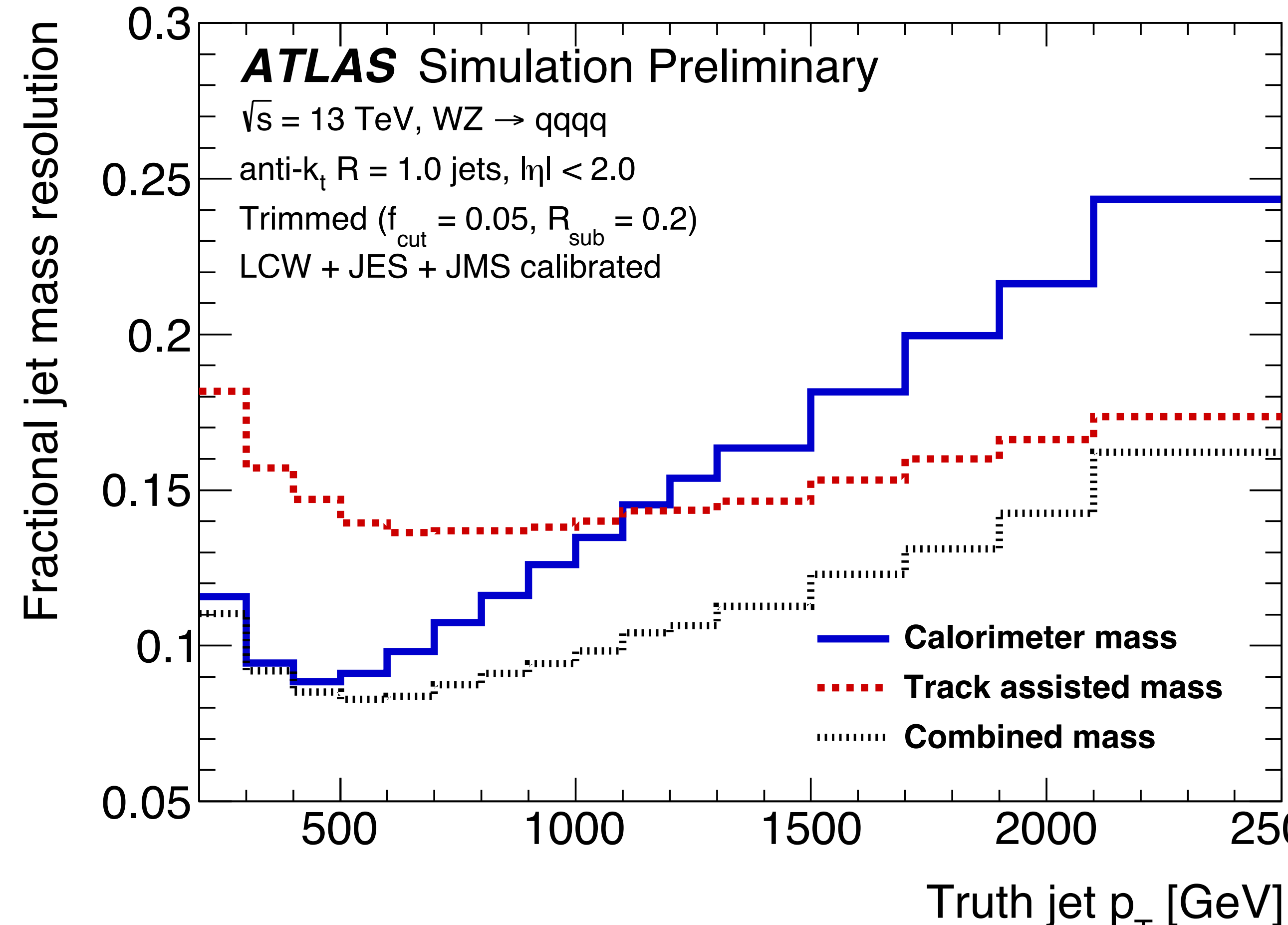
Subject to many systematic sources (rad, had, UE, PU…)

$$\delta M_{\text{UE/PU}} \propto p_T R^4$$

corrections through dedicated algorithms

- PF+PUPPI (cal, PU, CMS)
- Track-assisted jet mass (cal, ATLAS)
- Soft-drop (UE/had, CMS)
- Trimming (PU/UE/had, ATLAS)

10-15% misidentification at 70-80% signal efficiency



[ATLAS-CONF-2016-035]

[talk by C. Delitzsch]

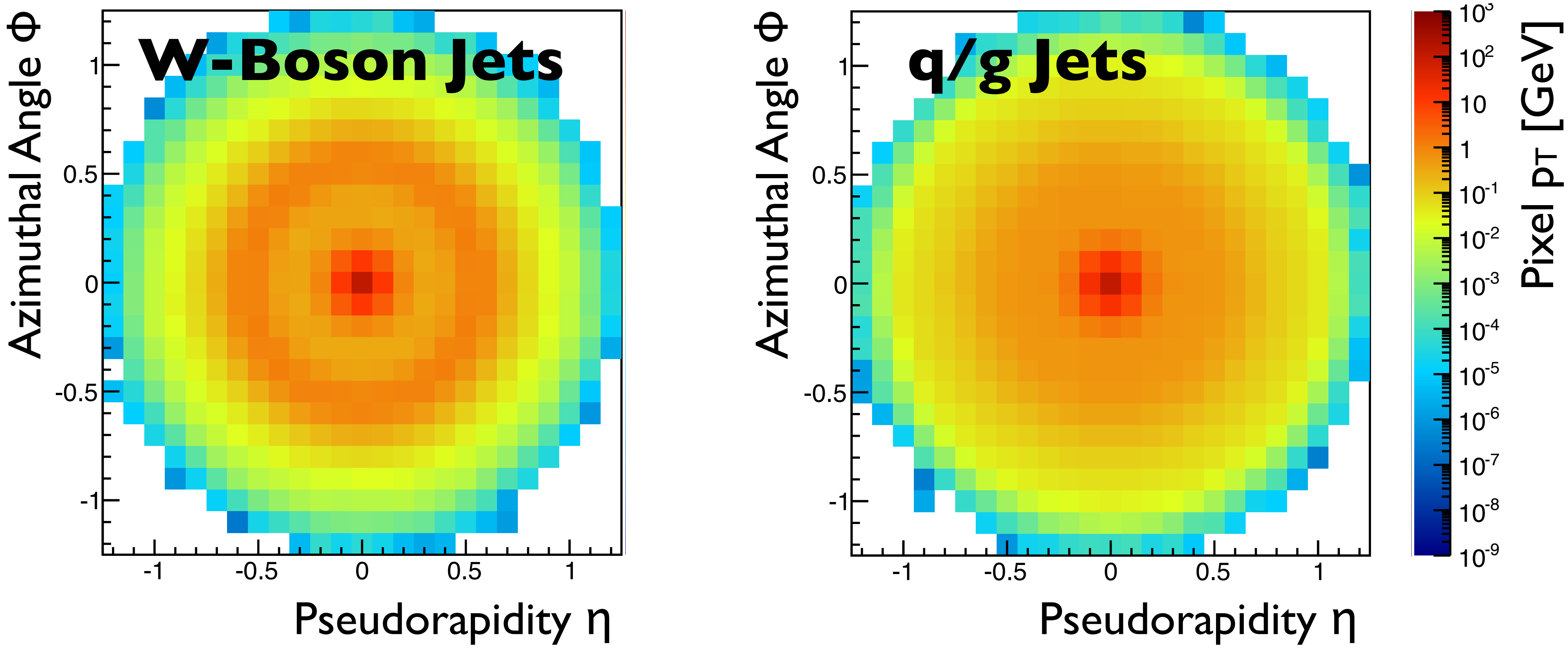
W/Z/H Boson-Tagging 2

2) Substructure

$250 < p_T < 260$ GeV
$65 < M_{jet} < 95$ GeV

$250 < p_T < 260$ GeV
$65 < M_{jet} < 95$ GeV

[Luke de Oliveira et al., JHEP07, 069 (2016)]



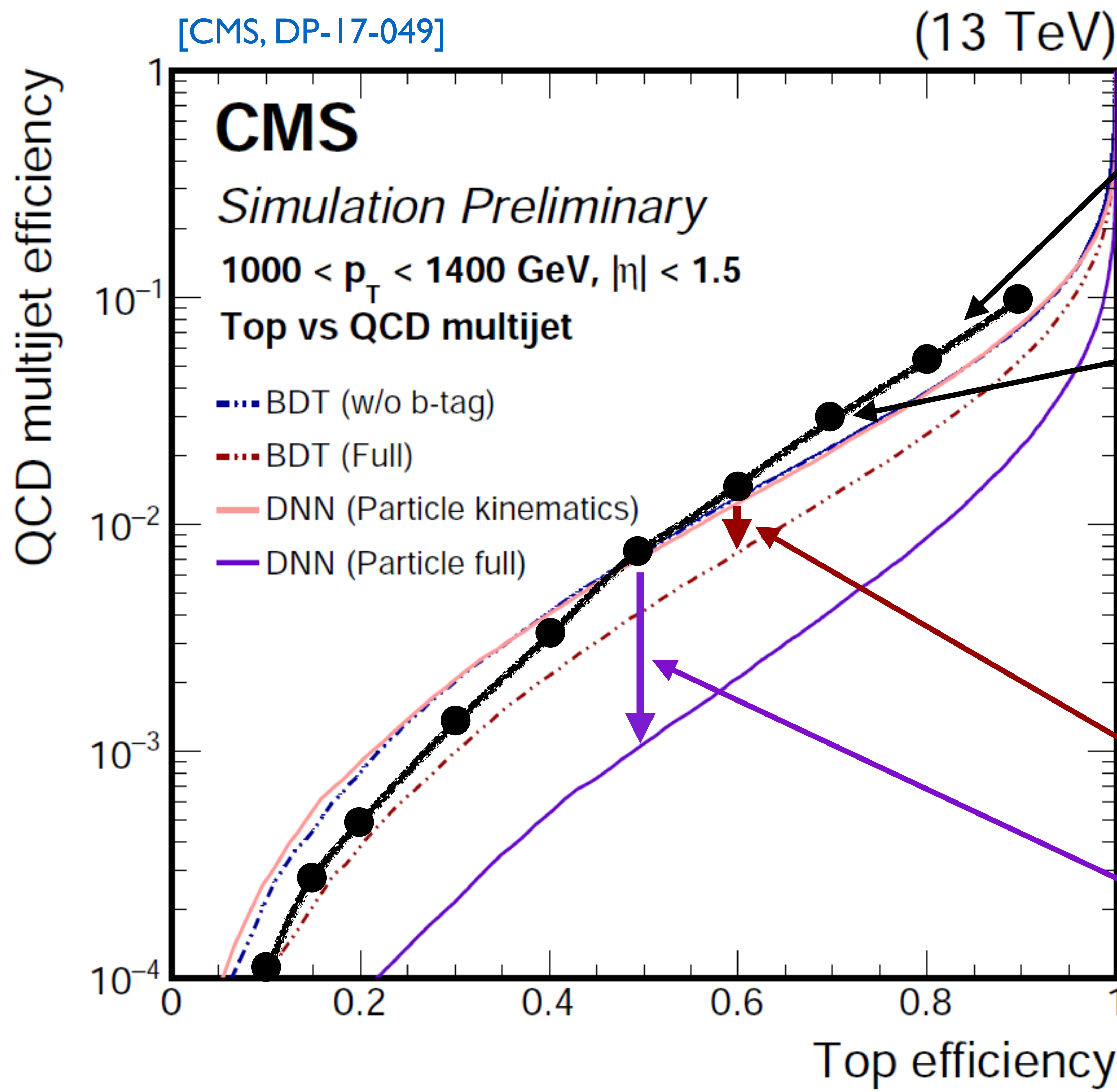
Exploit characteristic radiation pattern

- N-subjettiness ratios τ_2/τ_1 (CMS)
- Energy correlation ratios D_2 (ATLAS)
- Subjet b-tagging for $H \rightarrow bb$ (ATLAS/CMS)

1-5% misidentification at 50-60% signal efficiency

Top Quark Tagging

[CMS, DP-17-049]



soft drop mass, $\tau_{3/2}$, subjet b
[CMS-PAS-JME-15-002]

today's standard

2-3% misidentification at 70% signal efficiency

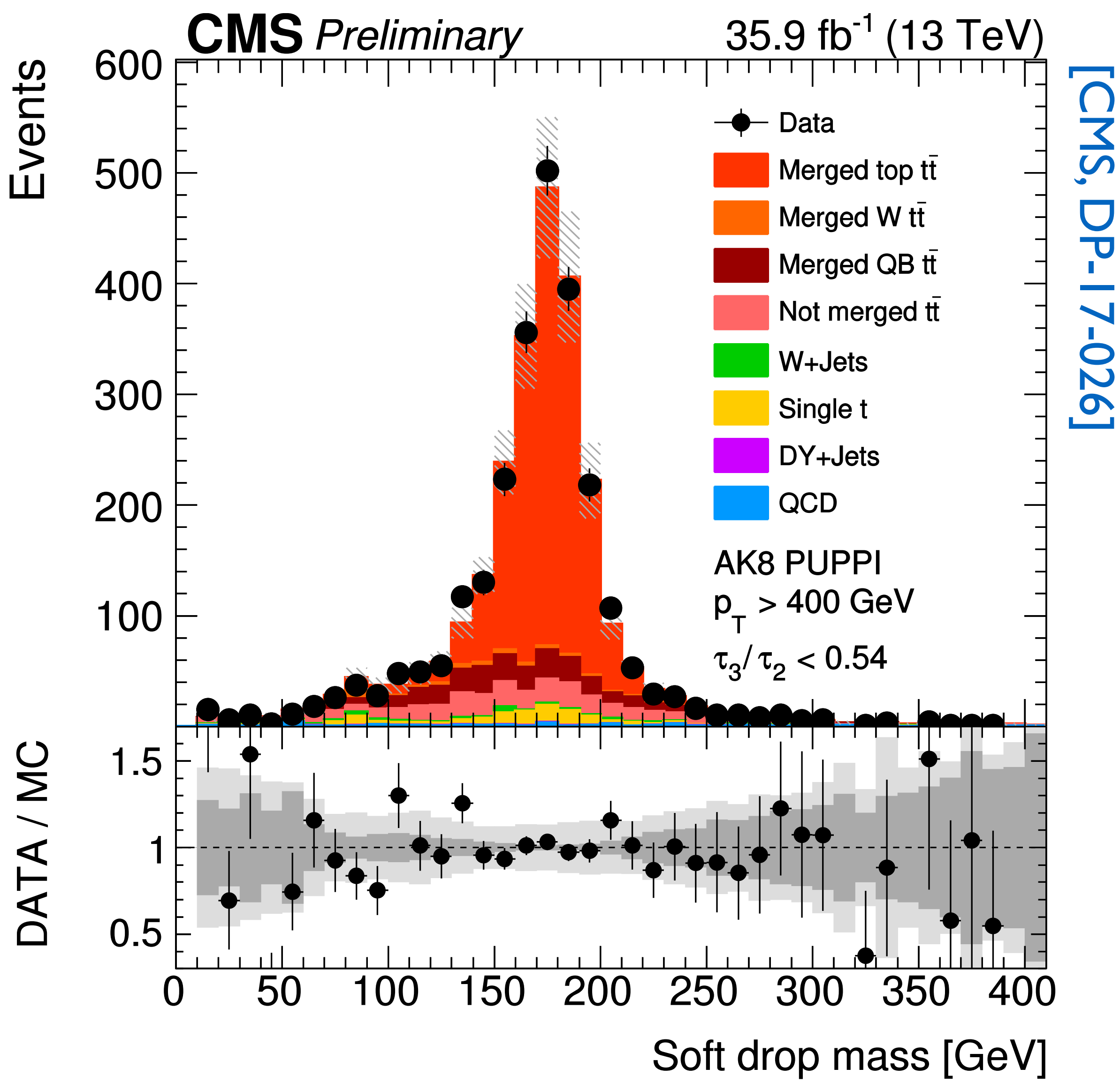
A prime example for machine learning

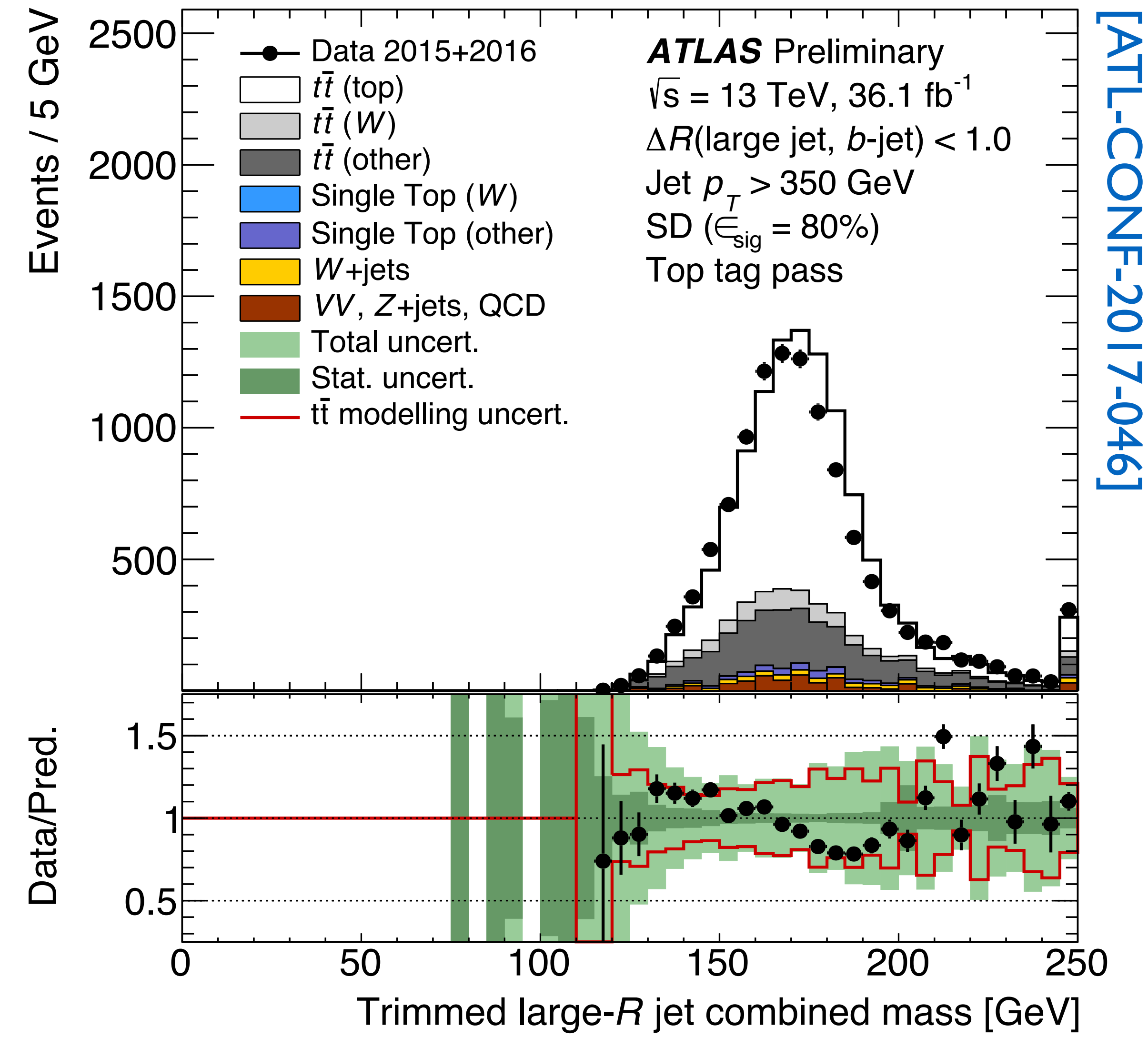
gain from a BDT

gain from a deep neural network

[see also ATL-PHYS-PUB-2017-004]

Top Quark Tagging - Calibration

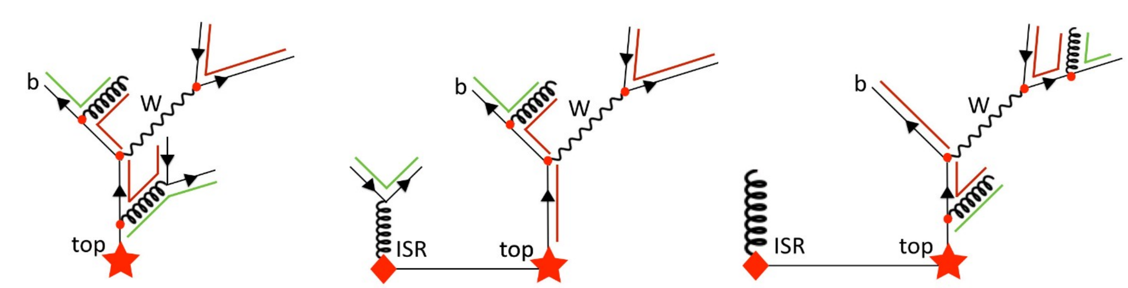




N-subjettiness based tagger

$\tau_{3/2} < 0.54$

Shower deconstruction



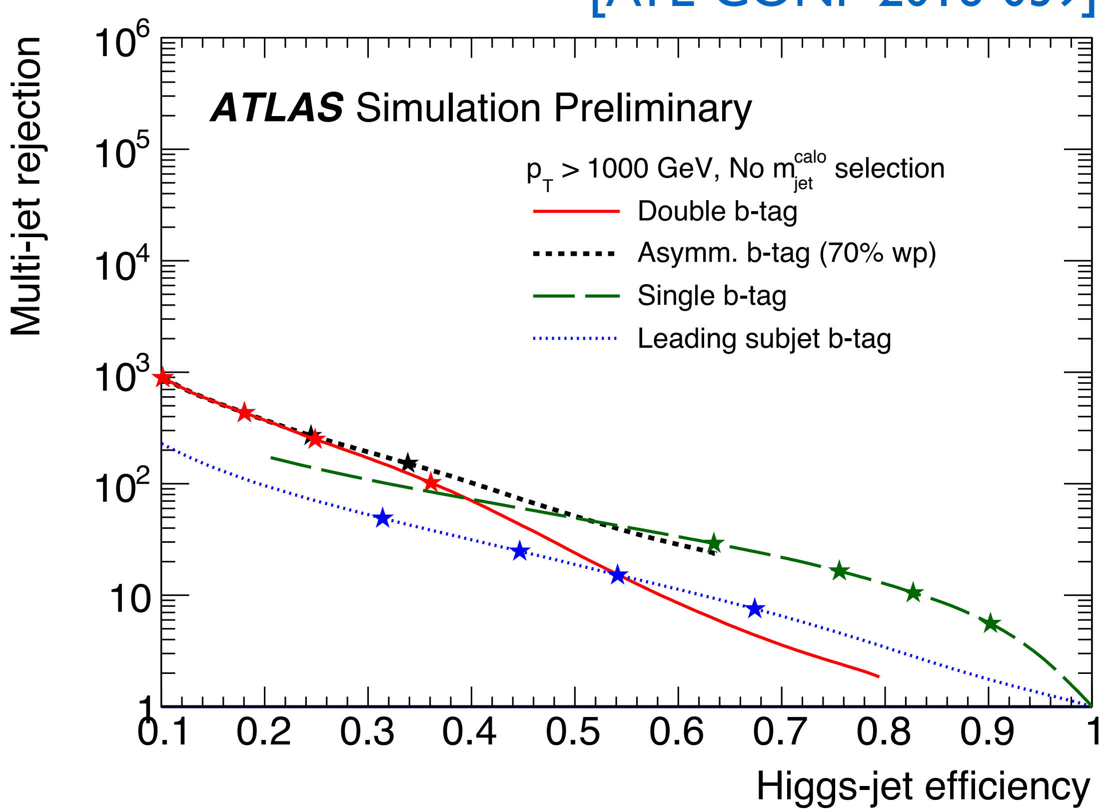
[D. Soper, M. Spannowsky, PRD 87 054012 (2013)] [ATL-CONF-2014-003]

Identifying Boosted H→bb

Subjet b tagging (ATLAS)

Leading track jets with R=0.2 inside a large jet with R=1.0

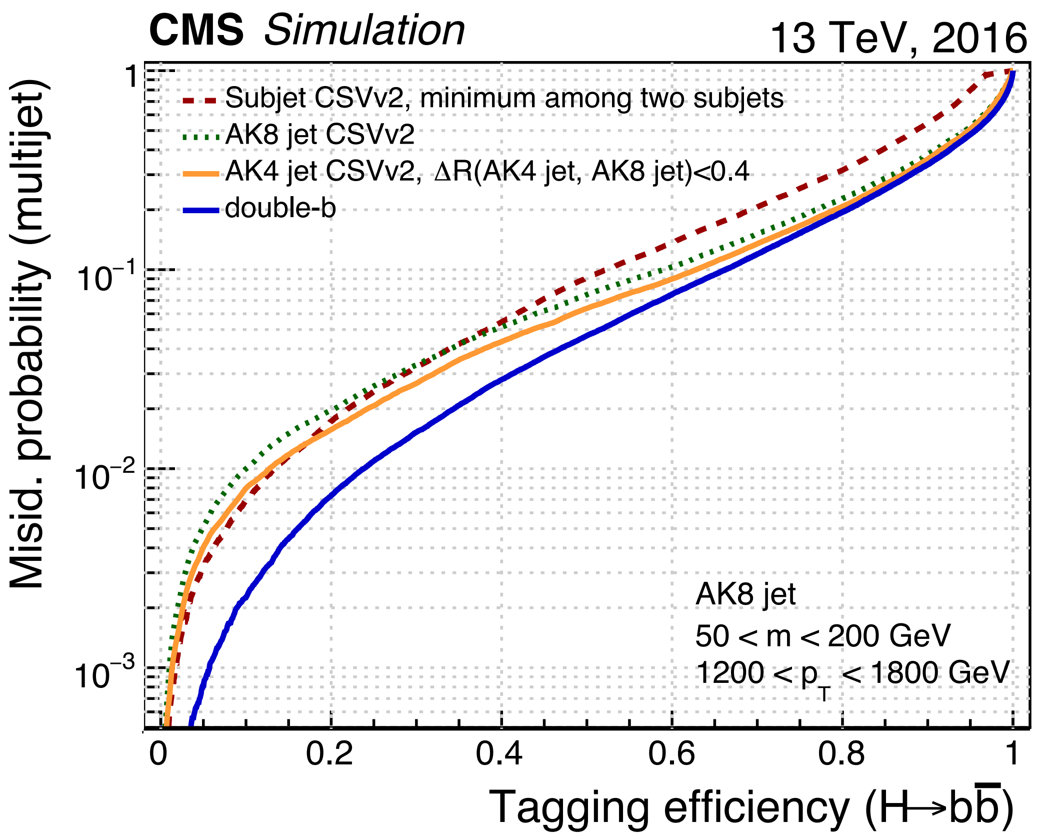
[ATL-CONF-2016-039]



Discrimination against boosted t→bW with double b-tag

Double-b tagger (CMS)

BDT based on track, SV, substructure inputs



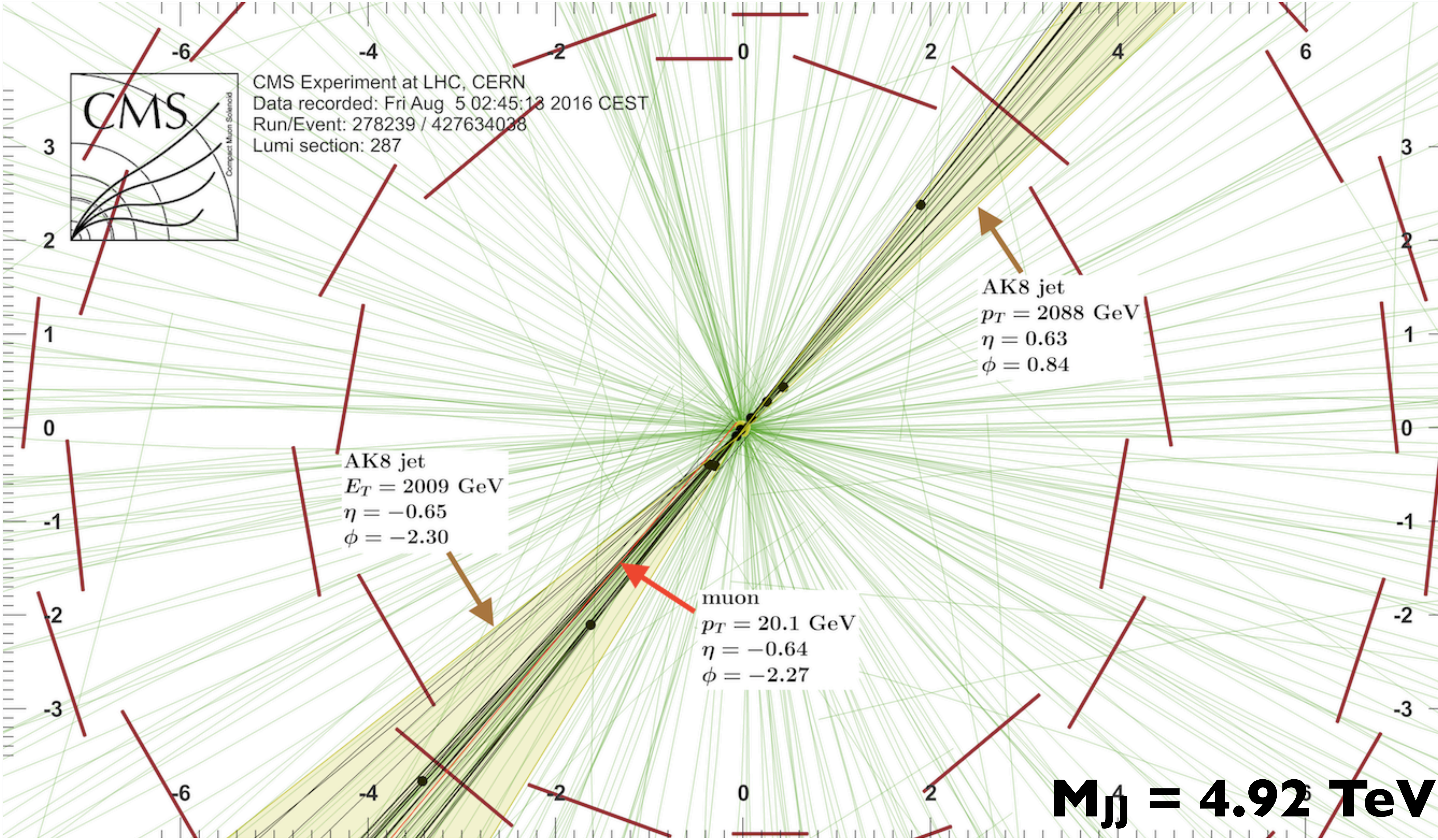
[CMS, JINST 13 (2018) P05011]

Improvement at high p_T, discrimination against g→bb

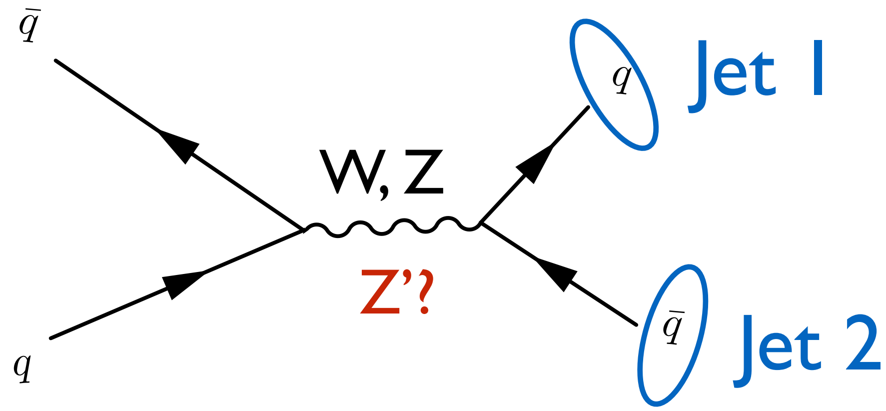
[talk by J. Dolen]

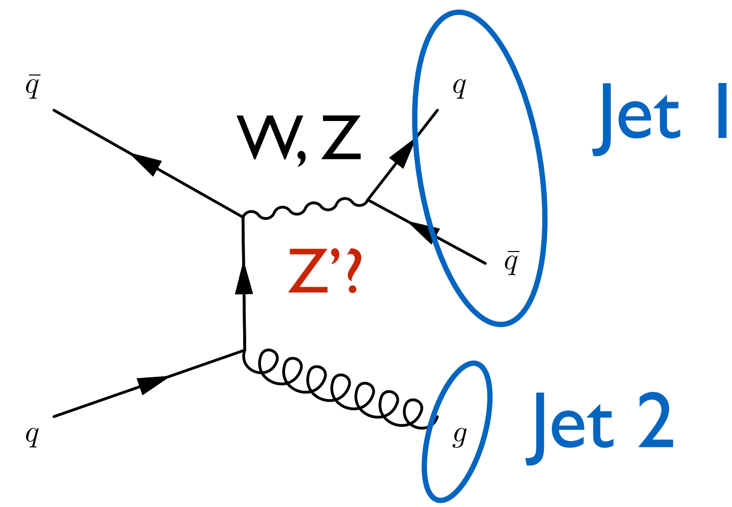
Boosted H→bb Candidate

[CMS, DP-17-032]

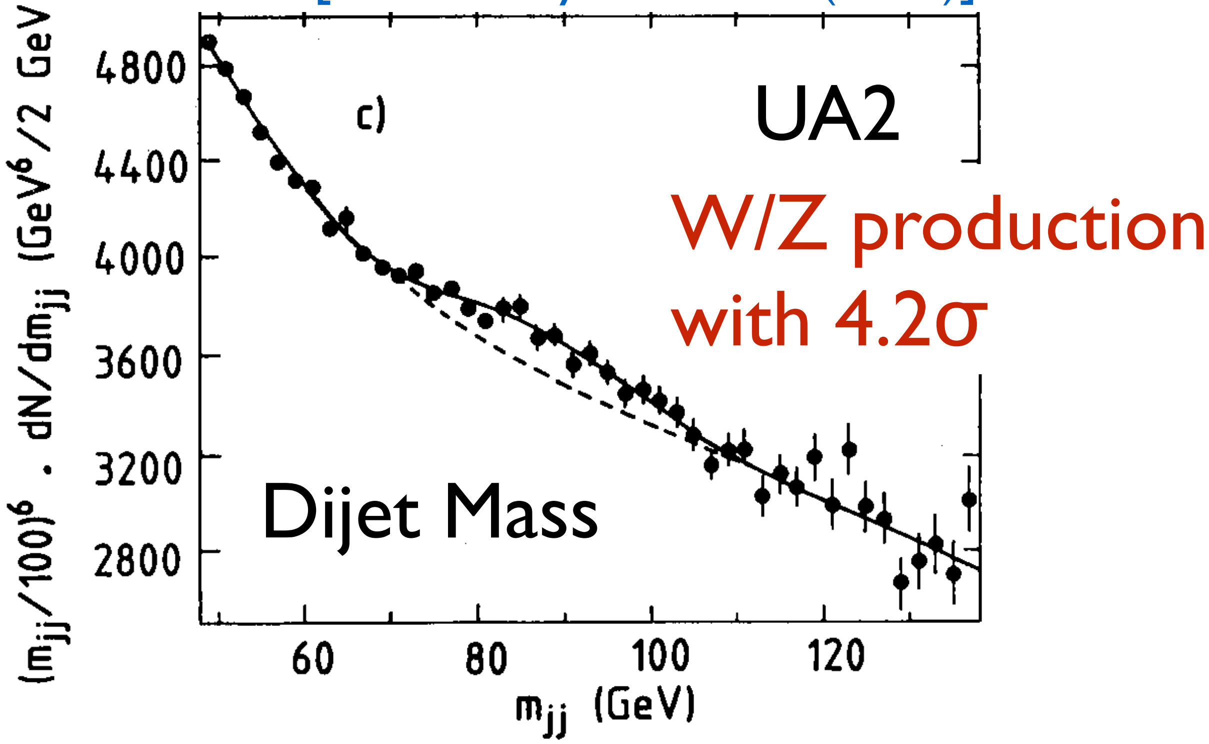


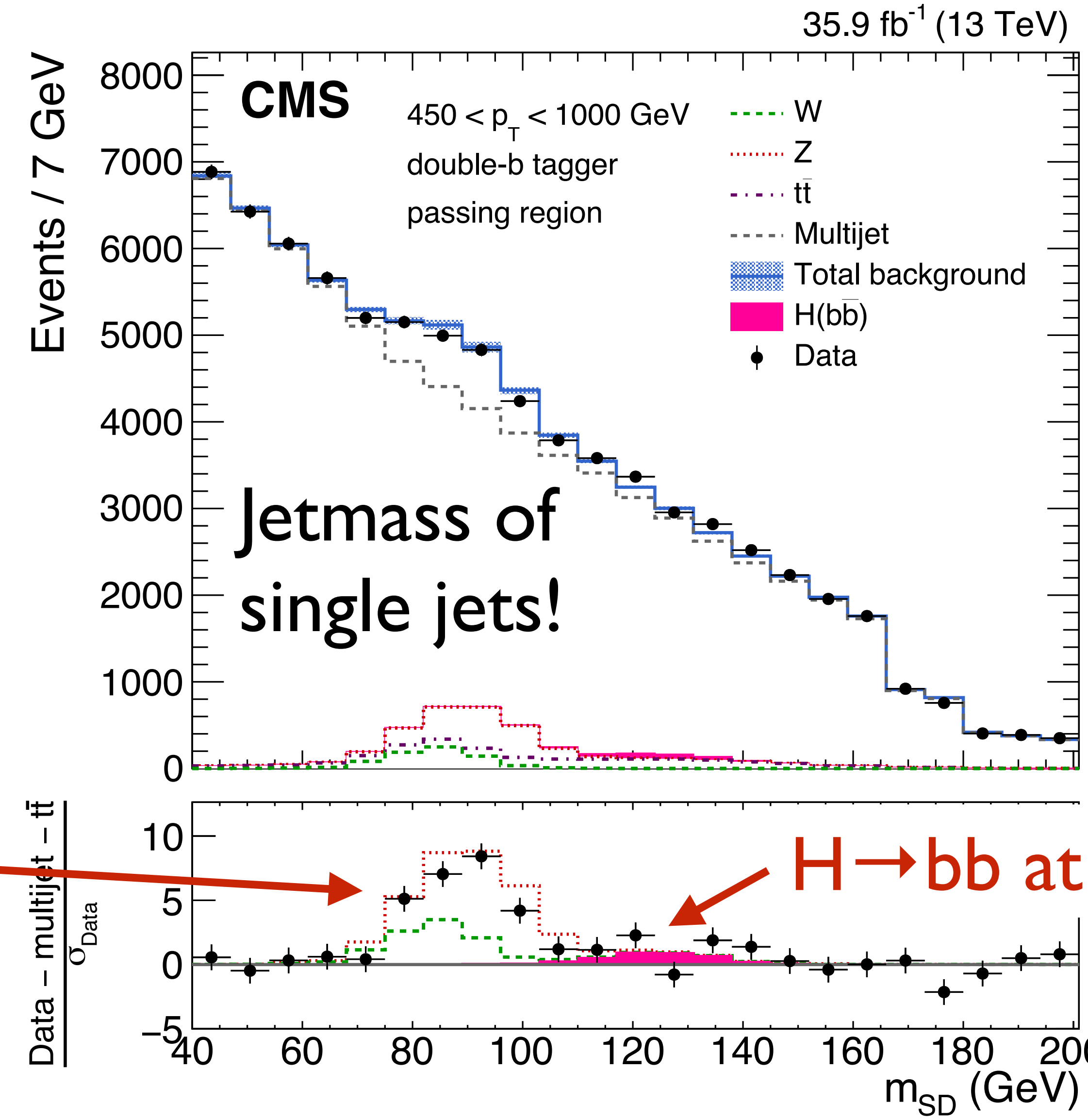
Double-b Tagger at Work





[UA2, Z. Phys. C 49, 17 (1991)]





[CMS, PRL 120, 071802 (2018)]

Amusing fact: signal resolution of ~10 GeV in both measurements

Background Estimates

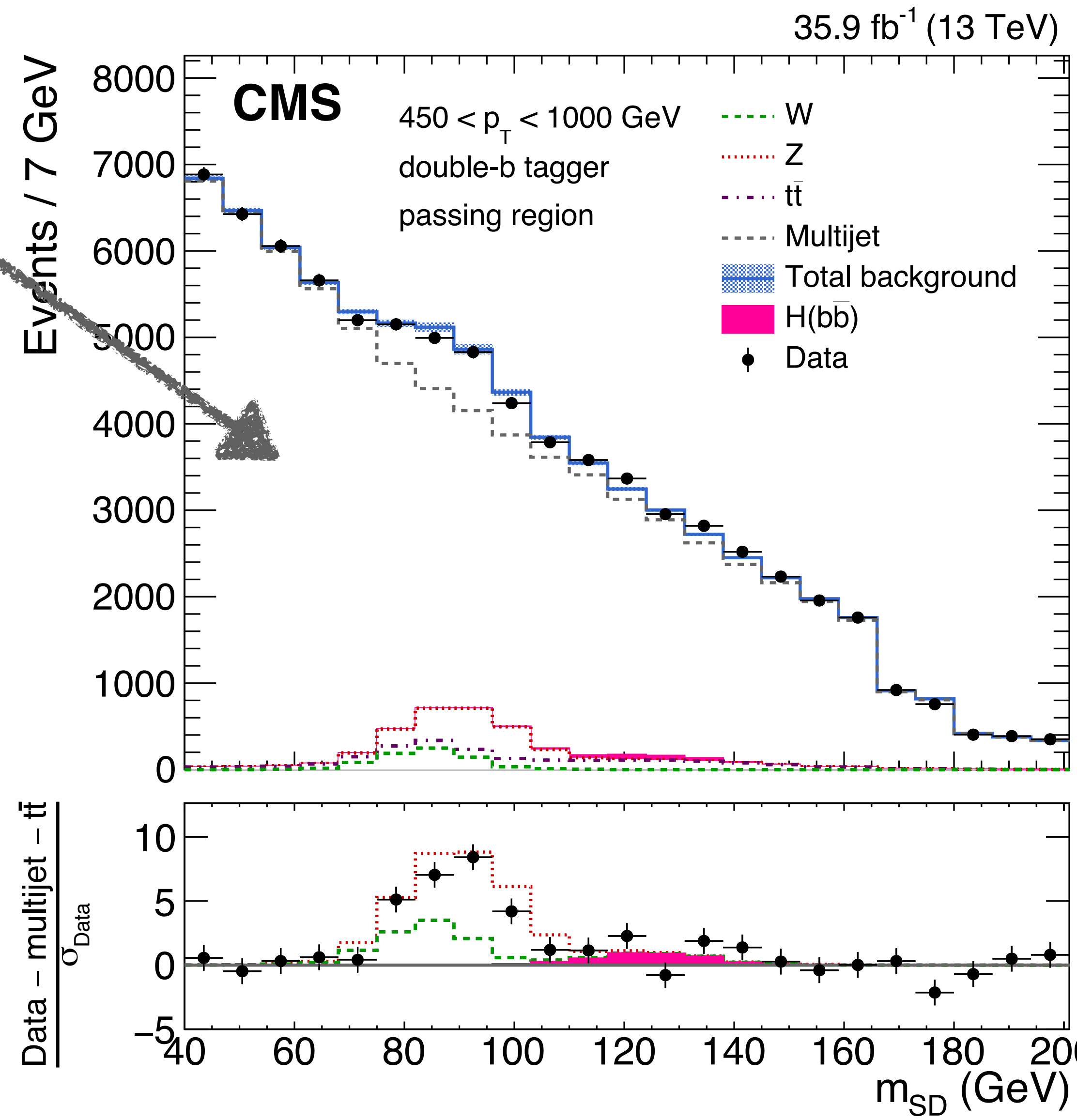
Multi-jet background

A curse

- many orders of magnitude larger than any signal
- modelling very difficult, large uncertainties

and a blessing

- jet mass: opportunity for dedicated control and validation regions
- precise predictions from data possible with in-situ validations



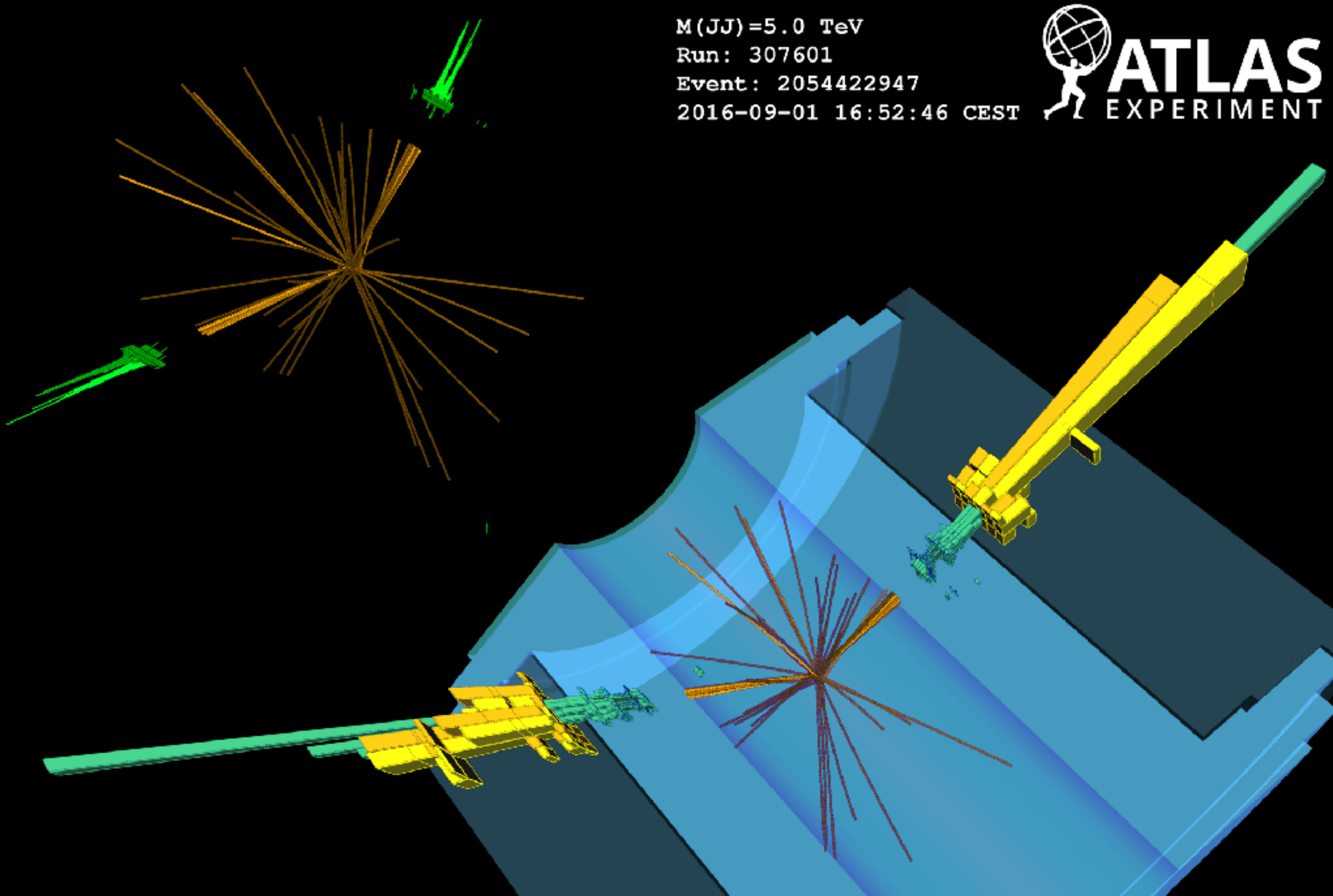
[CMS, PRL 120, 071802 (2018)]

Numerous methods

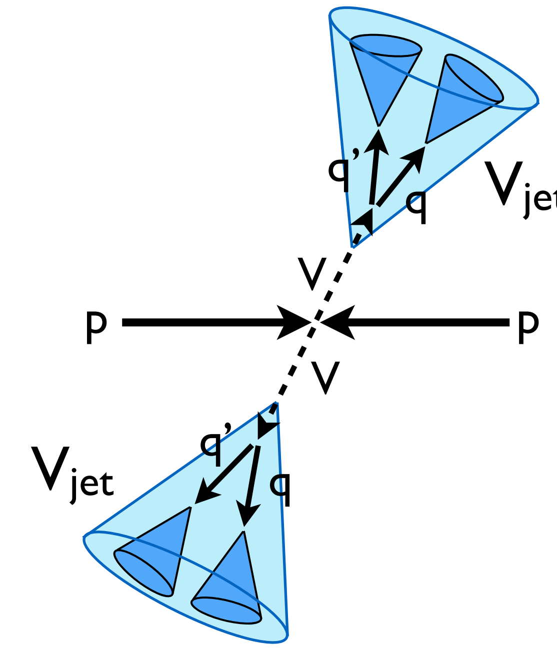
- ABCD extrapolations, $R_{p/f}$, decorrelated taggers, transfer factors…

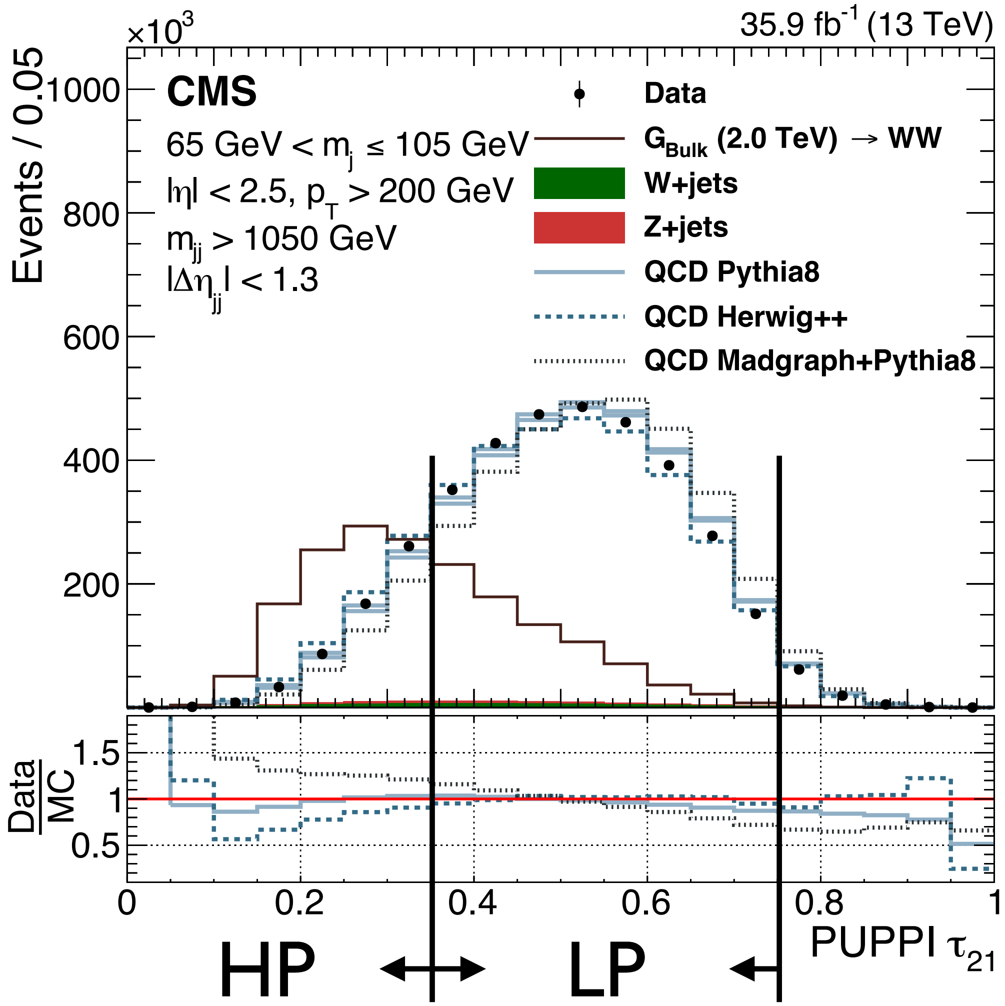
Diboson Resonances

Diboson-tagged dijet event, M_{JJ} = 5.0 TeV

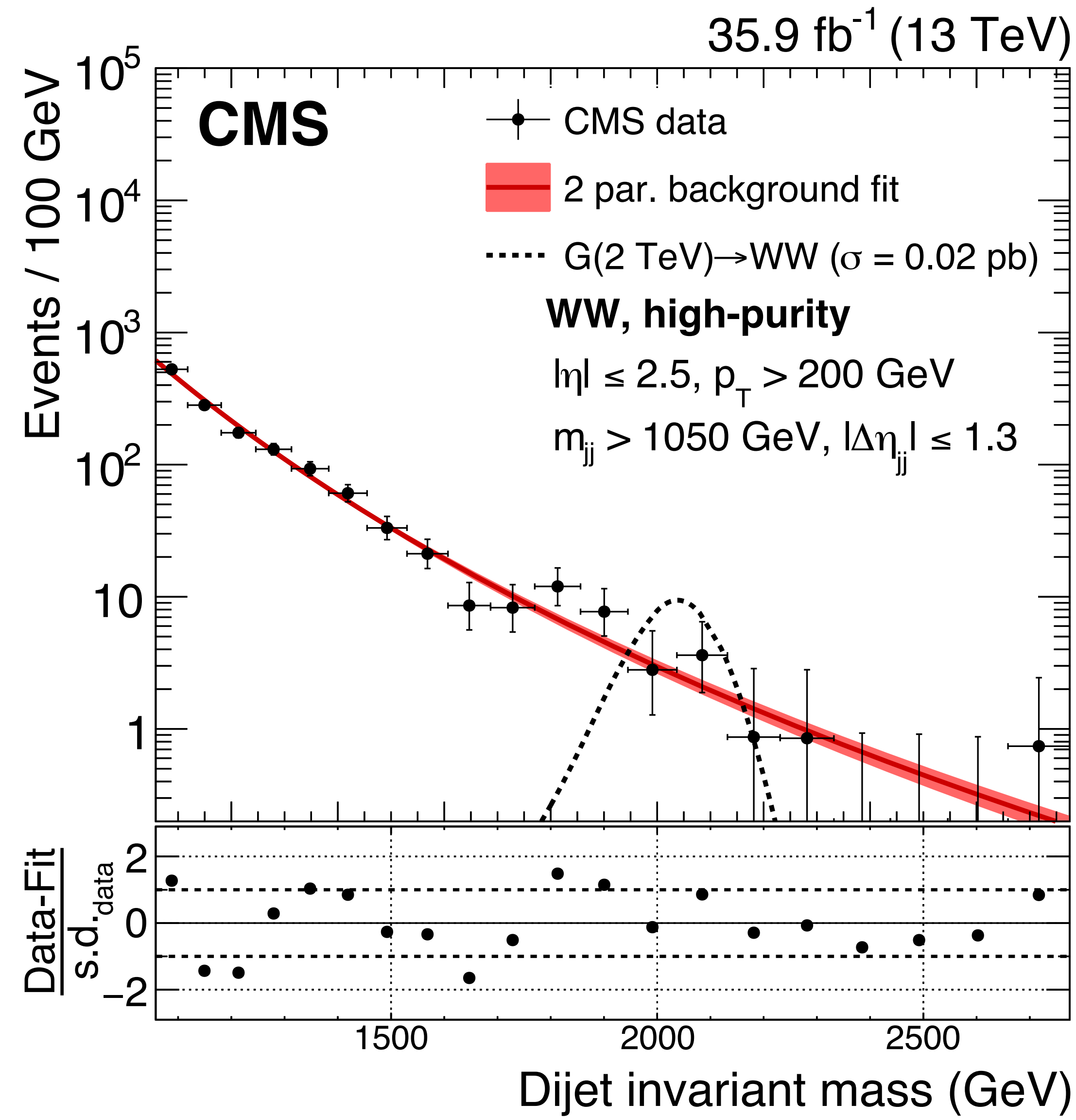


VV Resonances (JJ)





[CMS, PRD 97, 072006 (2018)]



Signal categories

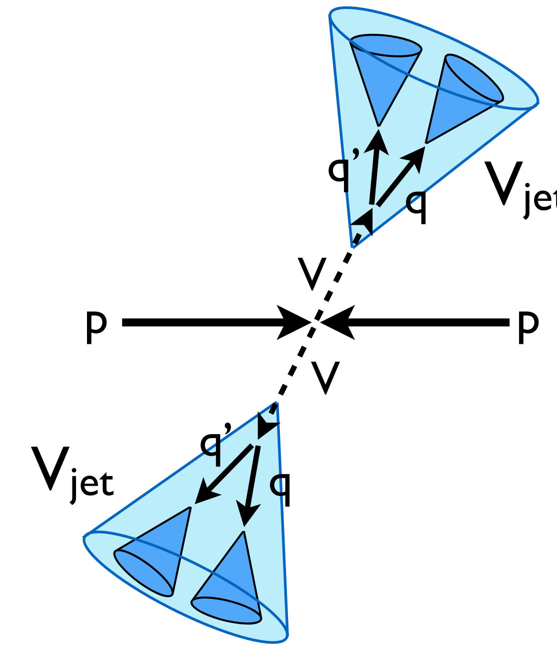
6 for VV: (WW, WZ, ZZ) x (HP, LP)

4 for qV: (W, Z) x (HP, LP)

NEW

80 fb^{-1}

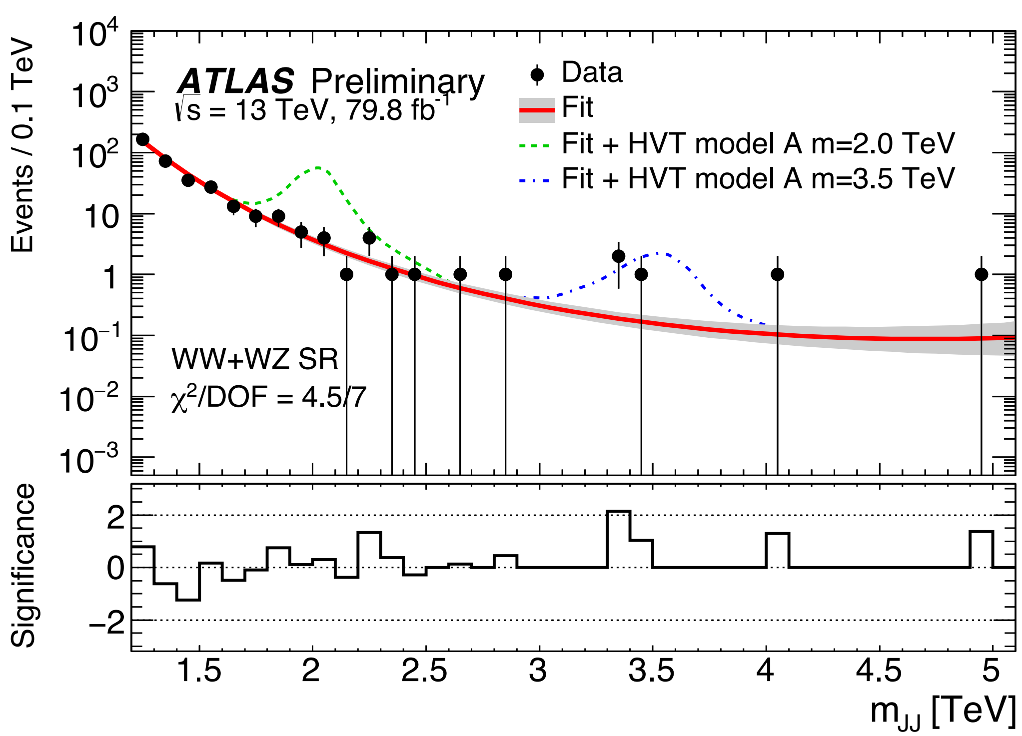
VV Resonances (JJ)

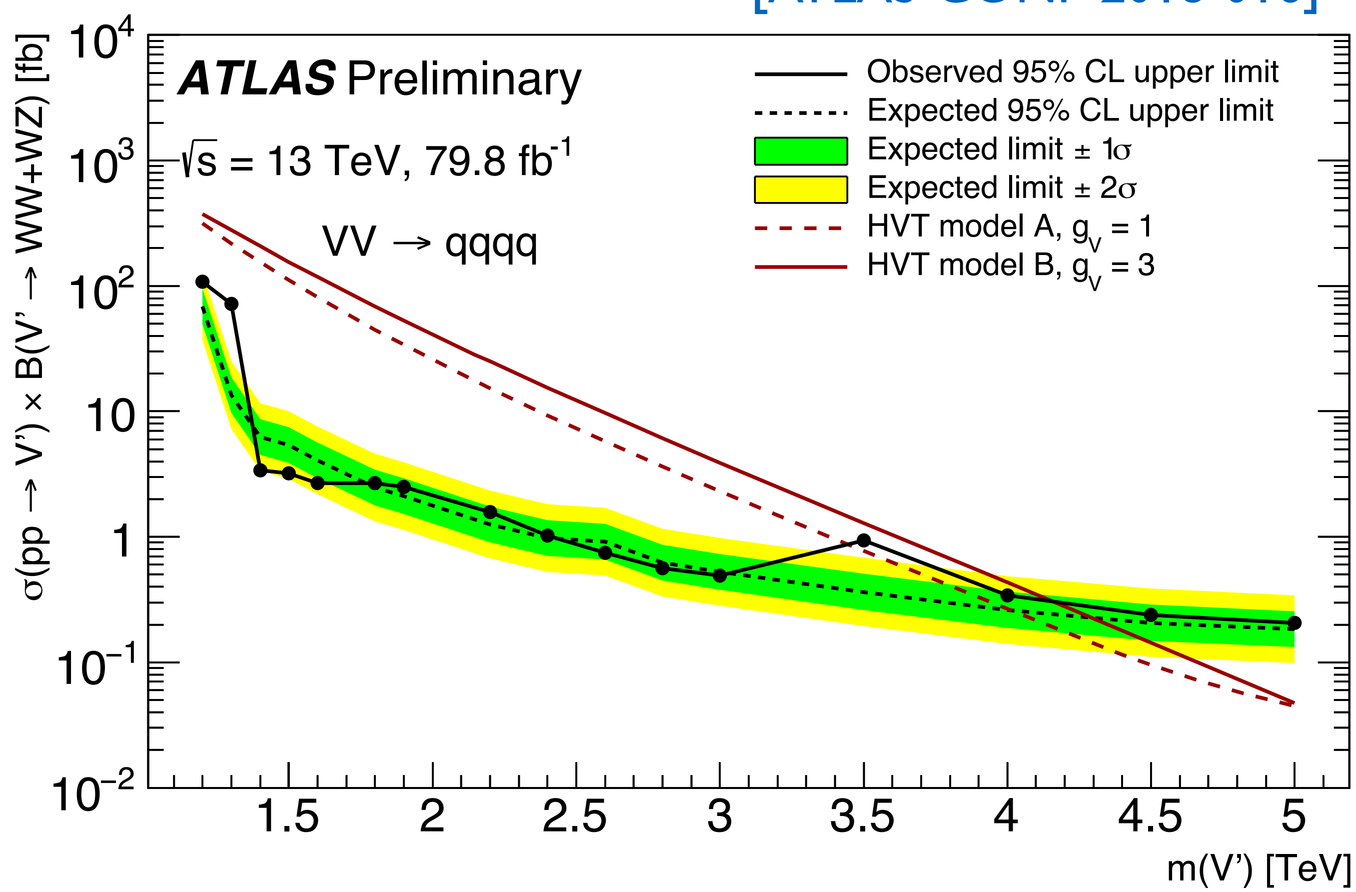


Improved jet substructure resolution with tracking information (TCCs):
50% improvement at high p_T

Optimal S/B with p_T dependent mass and D_2 selections

[ATLAS-CONF-2018-016]



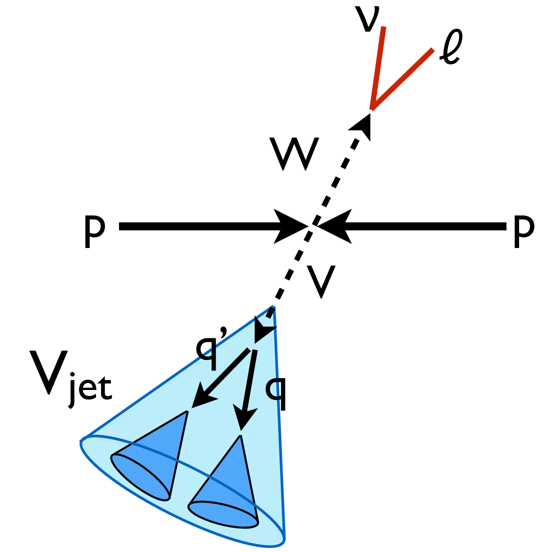


50% improvement w.r.t. expected sensitivity based on 2016 data!

[talk by J. Love]

Extension to 4- and 5-prongs: [CMS, arXiv:1806.01058]

VW Resonances (LJ)

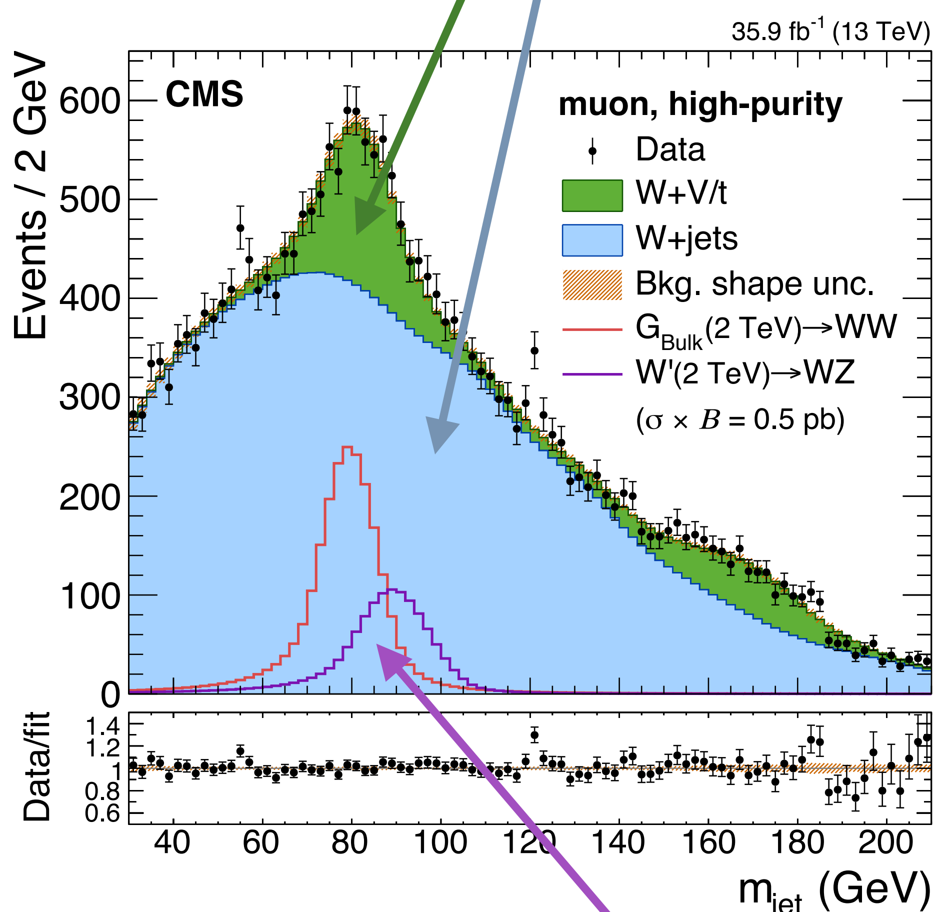


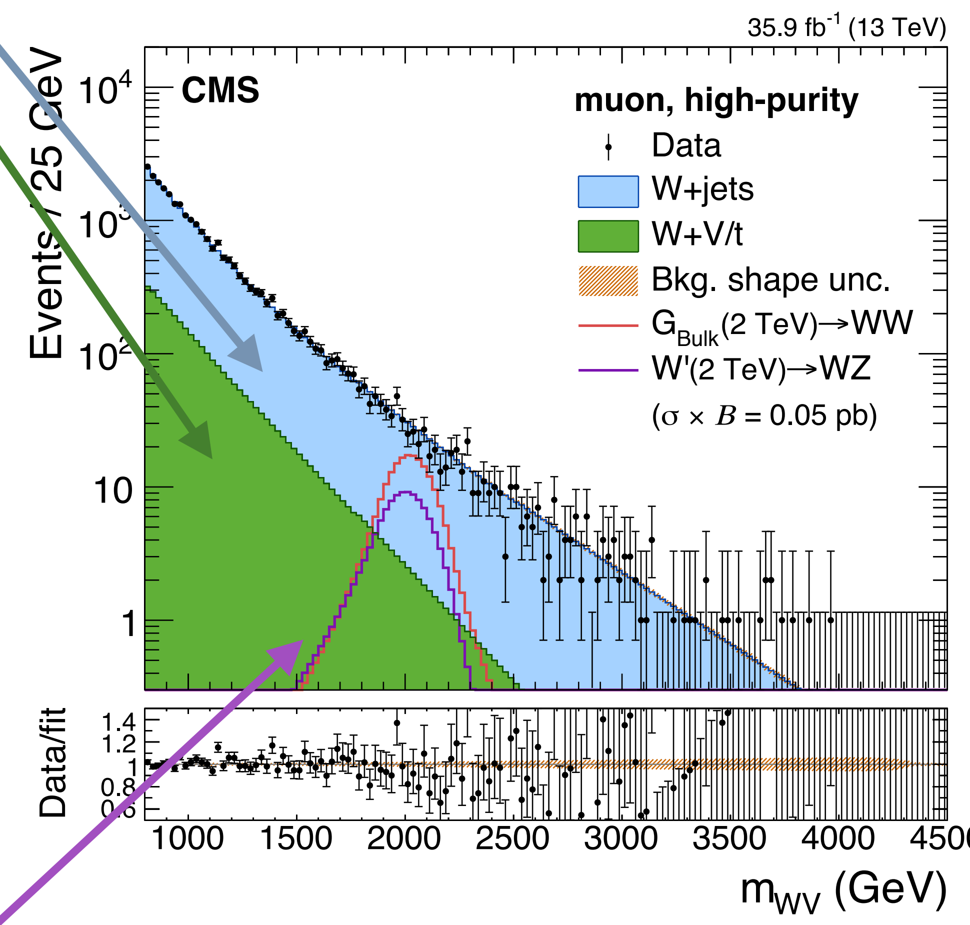
Simultaneous fit to jet mass and resonance mass spectra:

$$P(X \rightarrow WV) = P(m_{\text{jet}}, m_{WV} | m_X, \vec{\theta})$$

SM bkgd: resonant non-resonant non-resonant

[CMS, JHEP 05, 088 (2018)]

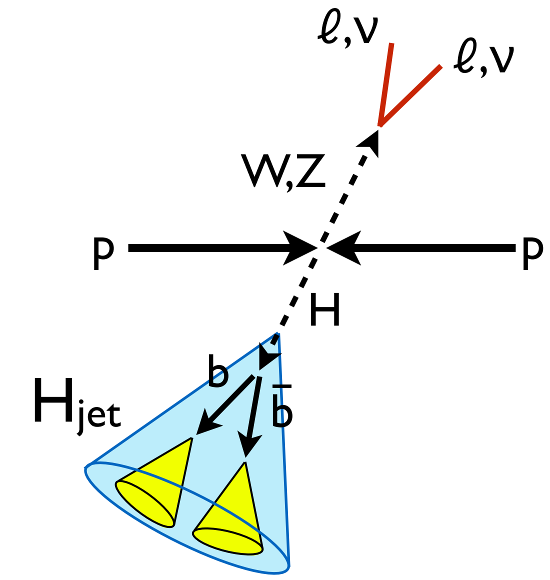




Signal: resonant in m_{jet} and m_{WV}

[see also ATLAS, JHEP 03, 042 (2018)]

VH Resonances

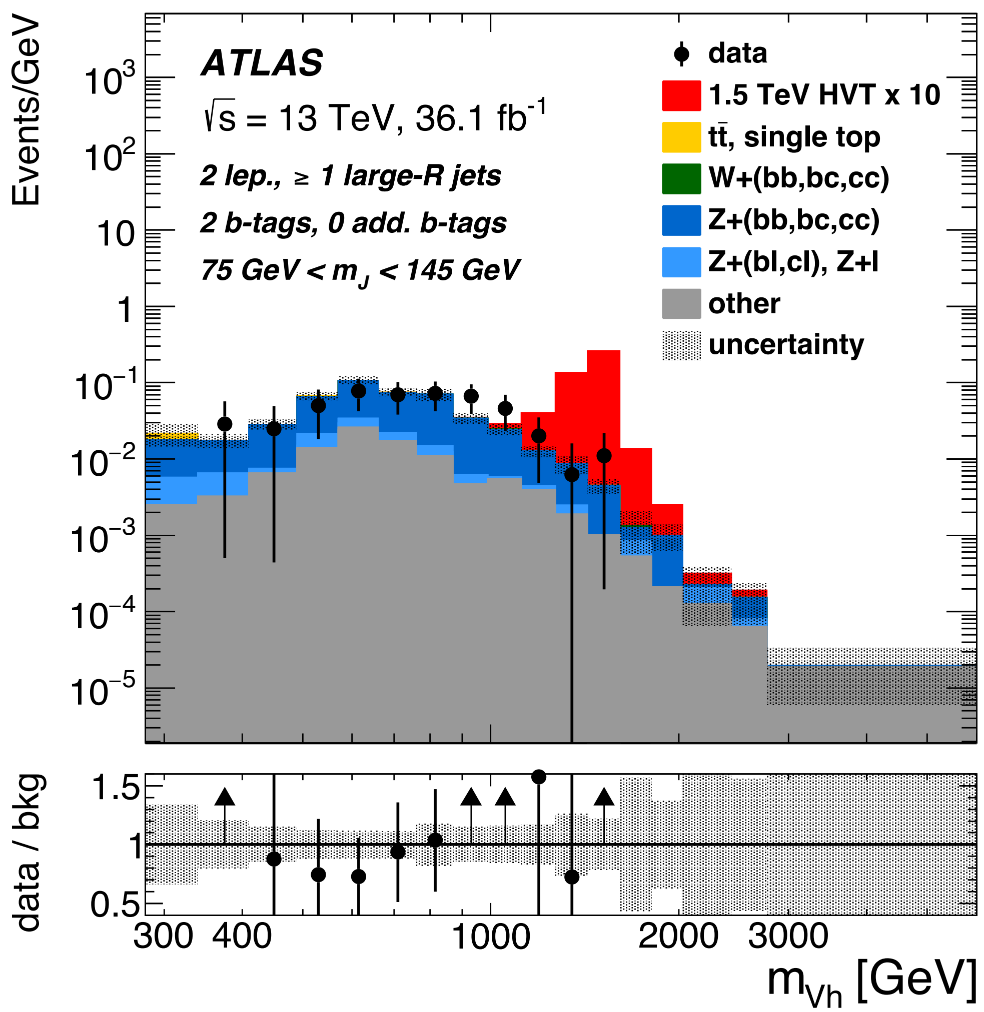


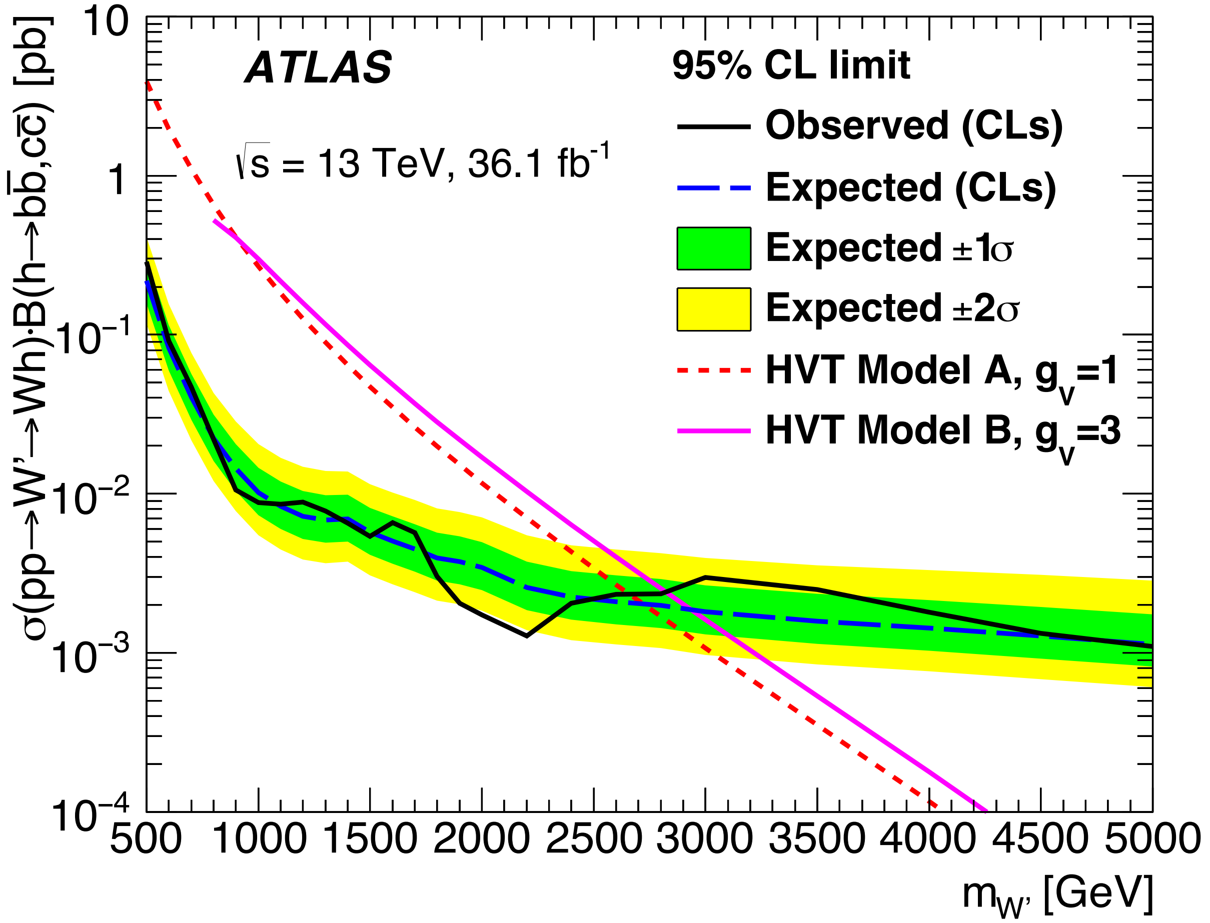
Analysis in 6 categories:

(ννbb, ℓνbb, ℓℓbb) x (resolved H, merged H)

Very different background compositions in each category, relies on modelling of SM backgrounds

[ATLAS, JHEP 03, 174 (2018)]

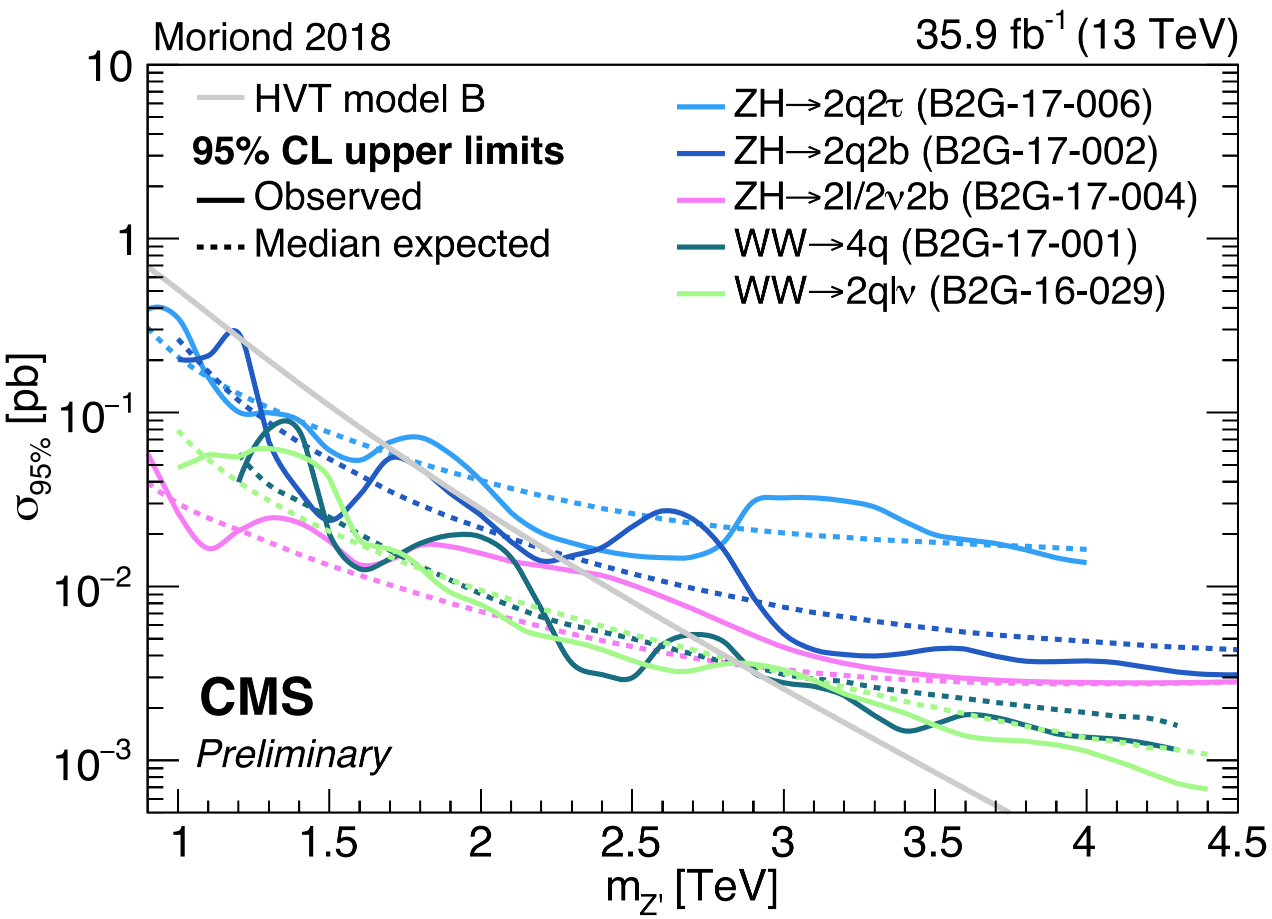




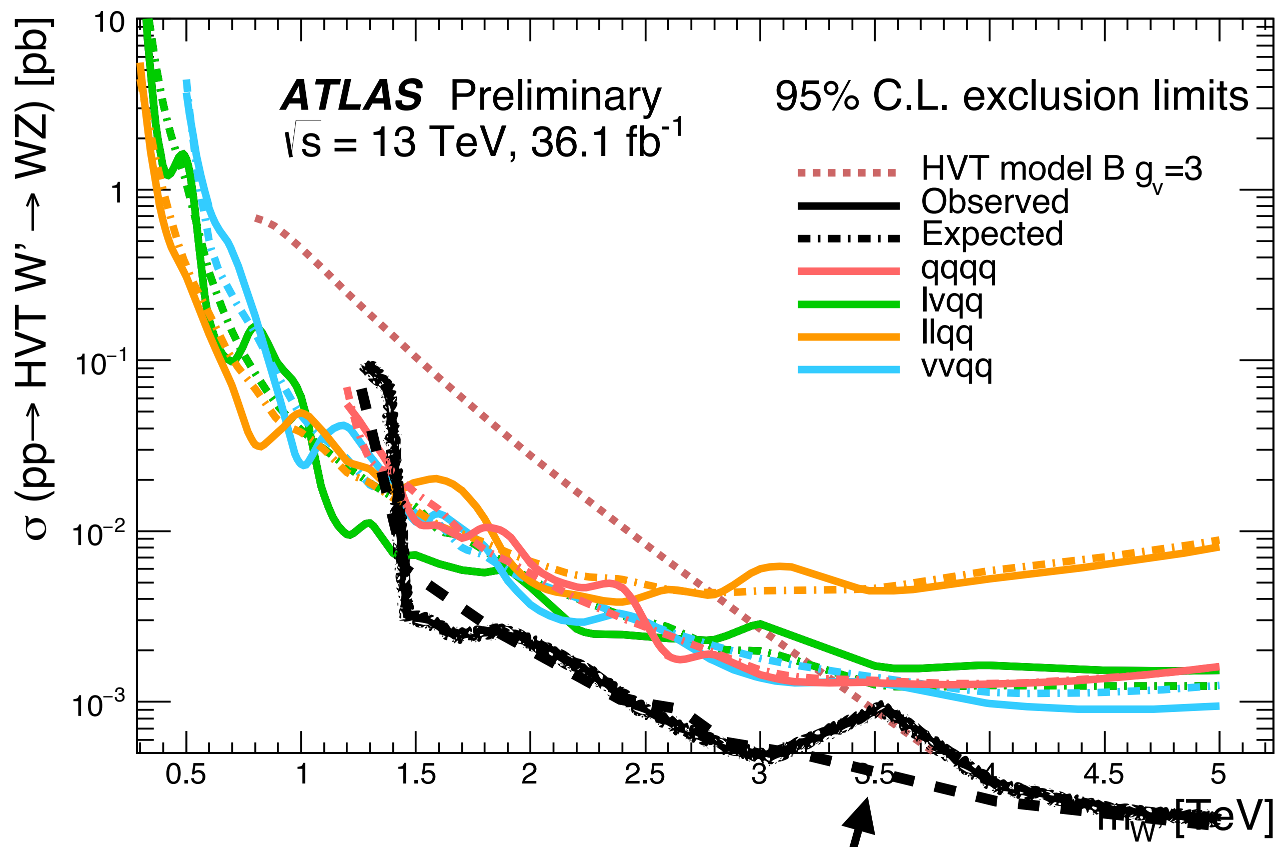
[see also CMS-PAS-17-004]

Diboson Summary

Z'



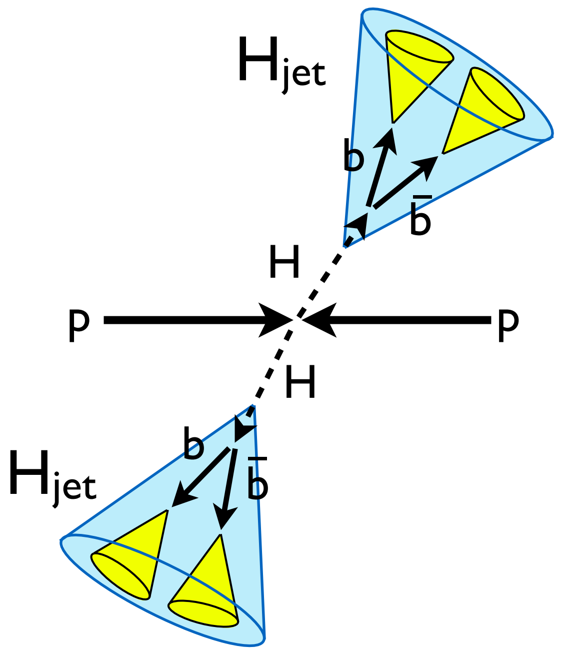
W'



new 80 fb^{-1} result

Complementary search channels, important to look at all of them!

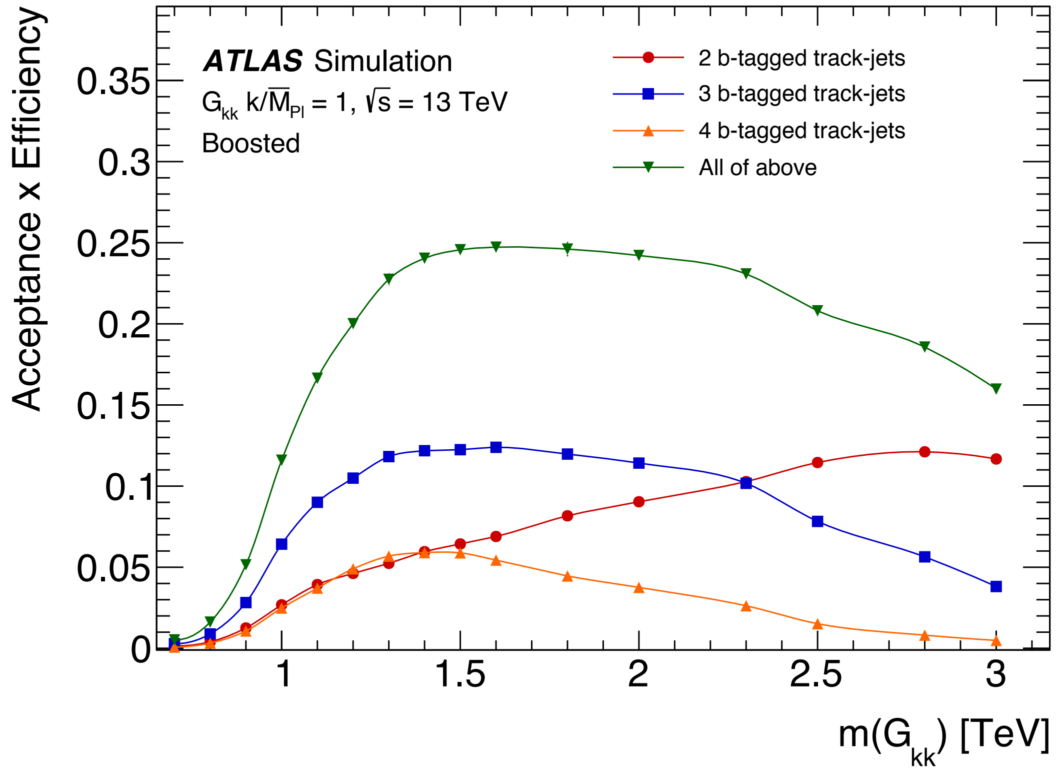
HH → 4b

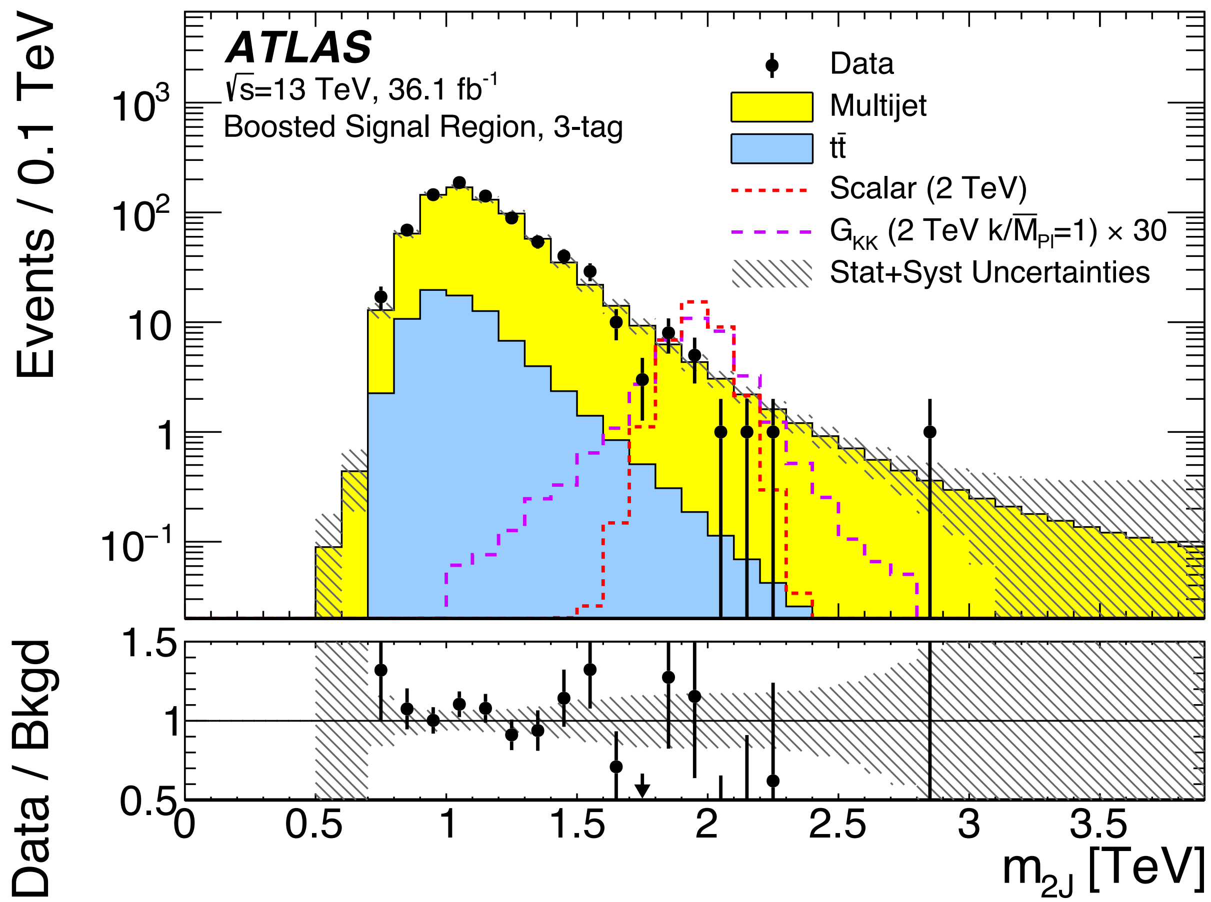


Resonant (BSM) and non-resonant (SM and BSM)

- combination of resolved and fully-merged
- 3 orthogonal signal categories, based on N(b-jets)

[ATLAS, arXiv:1804.06174]





Non-resonant production larger than 13 x SM excluded @ 95% CL

Boosted analysis extends mass range

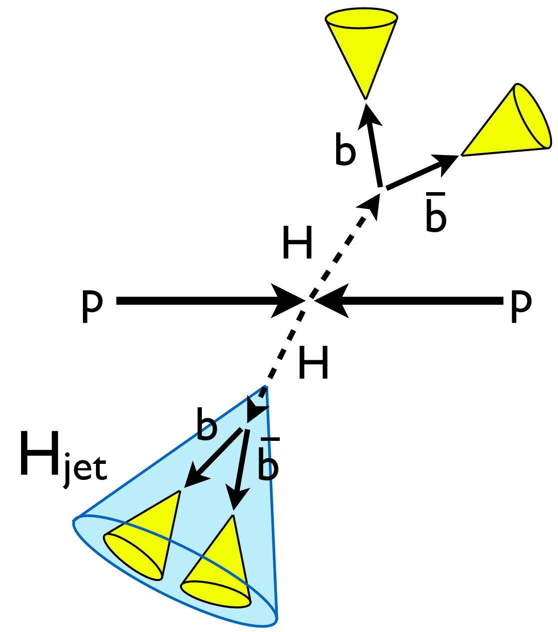
[see also CMS, PLB 781, 244 (2018), CMS-PAS-HIG-17-009]

NEW

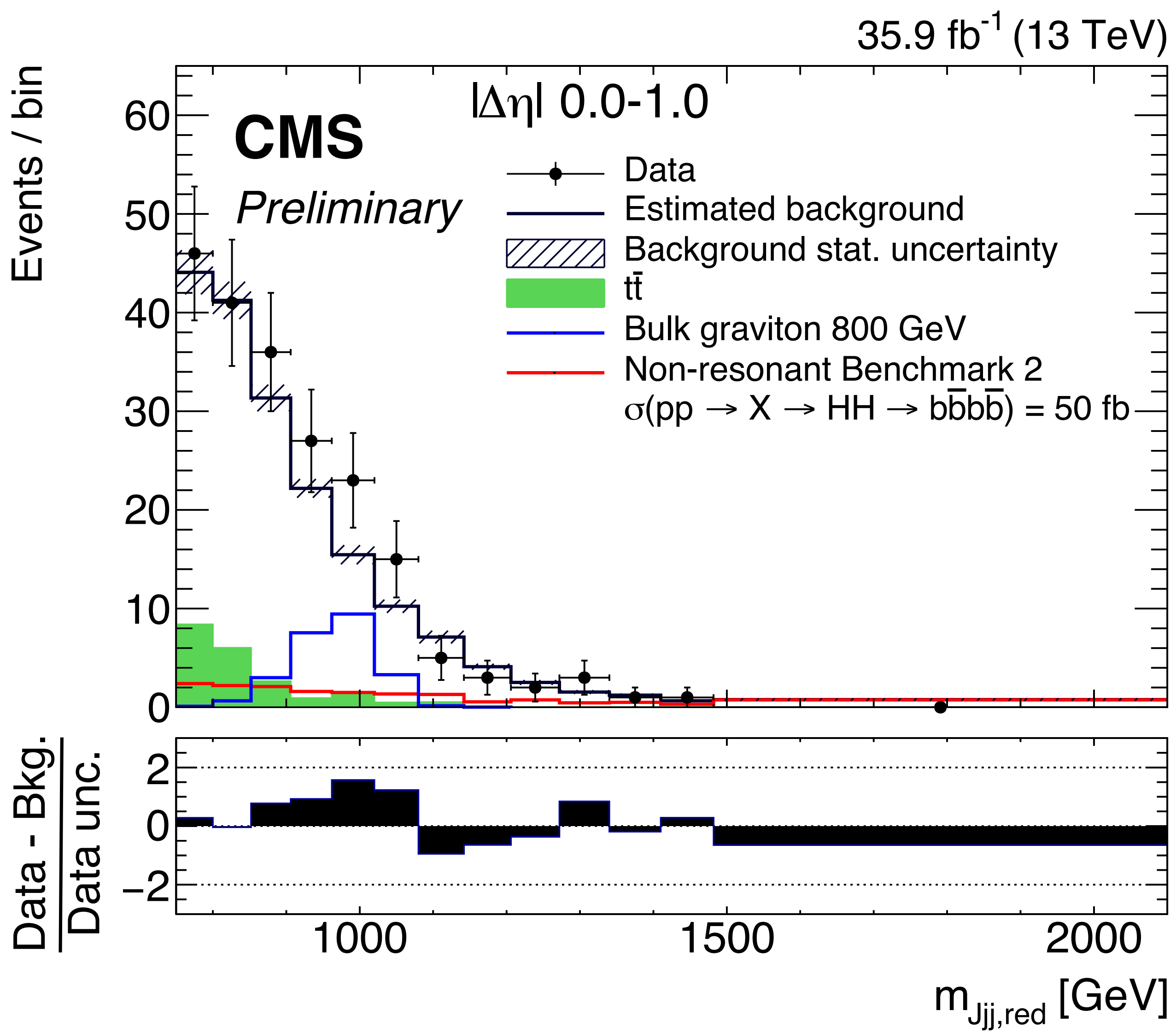
HH → 4b

So far uncovered: semi-resolved

- resolved + merged final state
- orthogonal to fully-merged analysis [CMS, PLB 781, 244 (2018)]



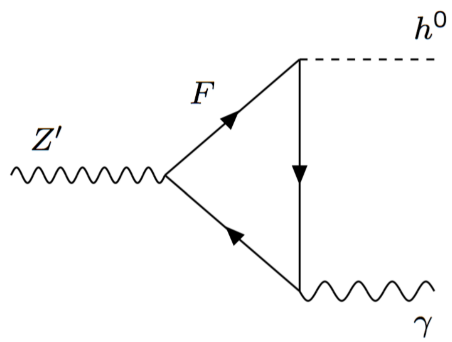
[CMS-PAS-B2G-17-019]



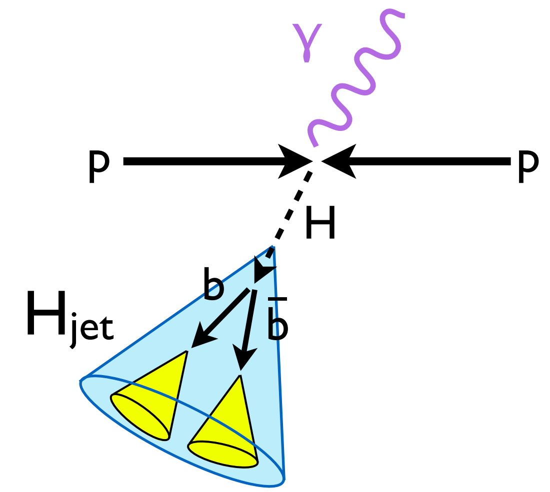
- improves limits on resonant production up to 55%
  - for radion with m = 0.75 - 1.6 TeV
  - above 1.6 - 2 TeV: sensitivity from fully merged analysis
- non-resonant production: better by factors of 2-3 for some benchmarks

NEW

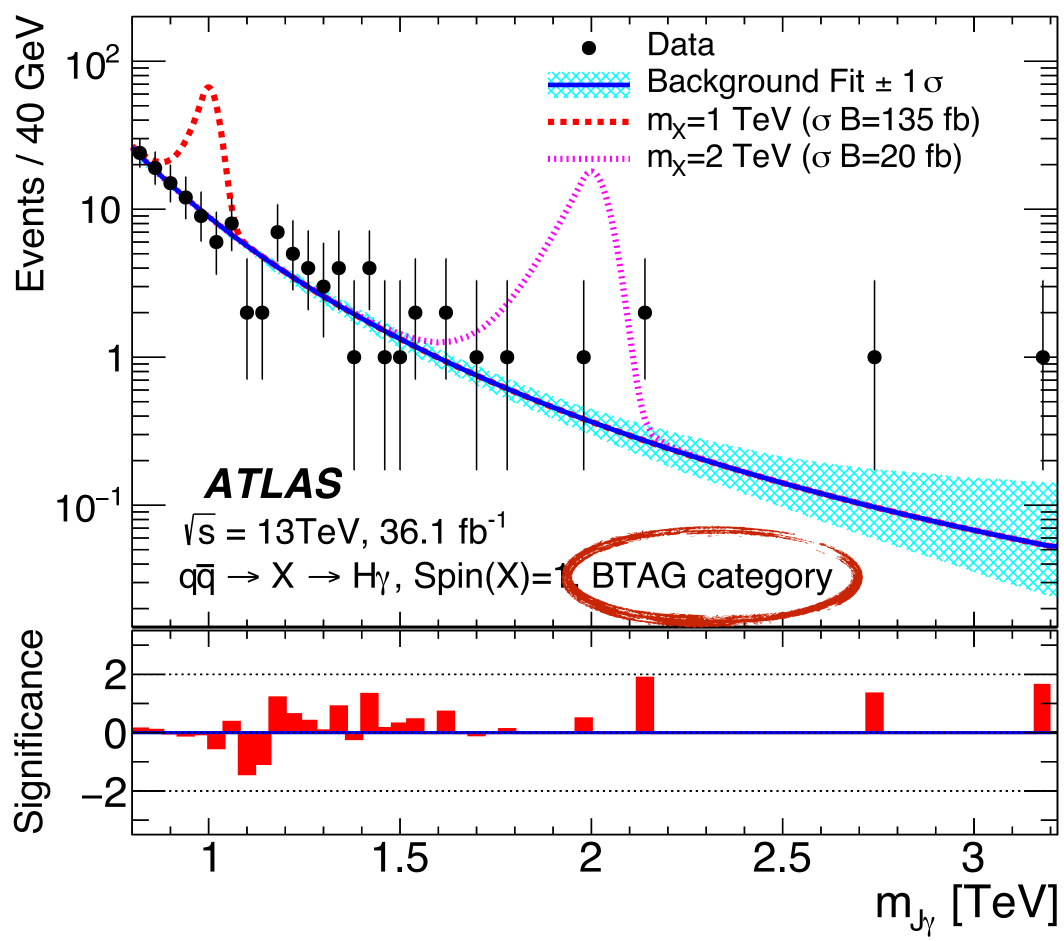
γH Resonances



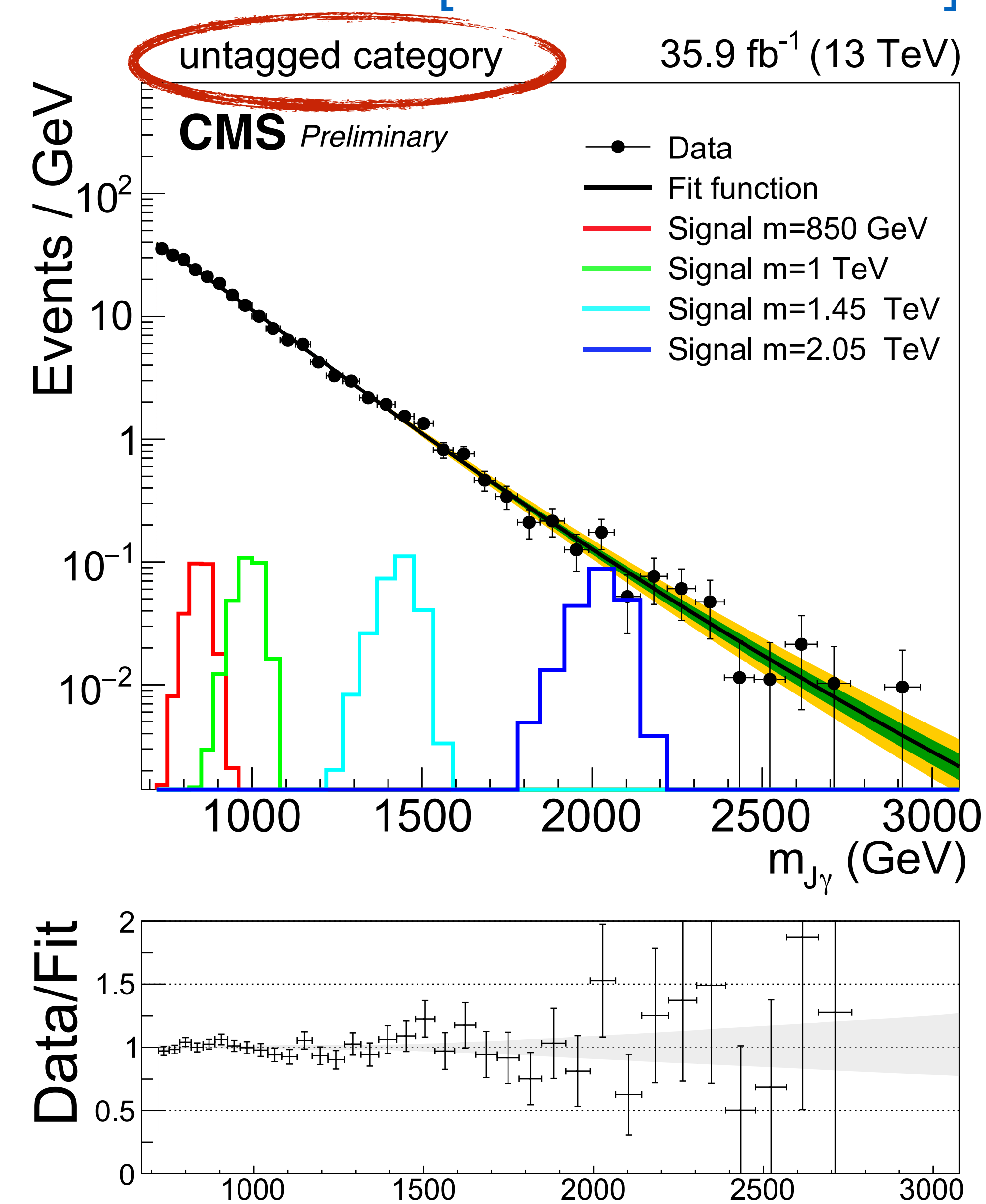
[BA Dobrescu, PJ Fox, J Kearney EPJC77, 704 (2017)]



[ATLAS, arXiv:1805.01908]

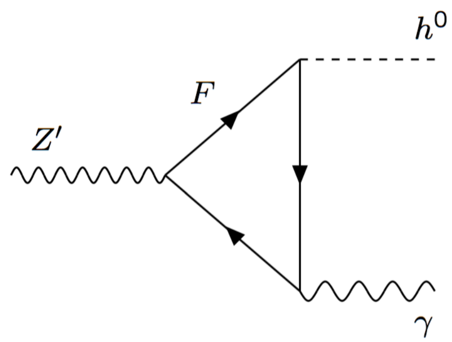


[CMS-PAS-EXO-17-019]

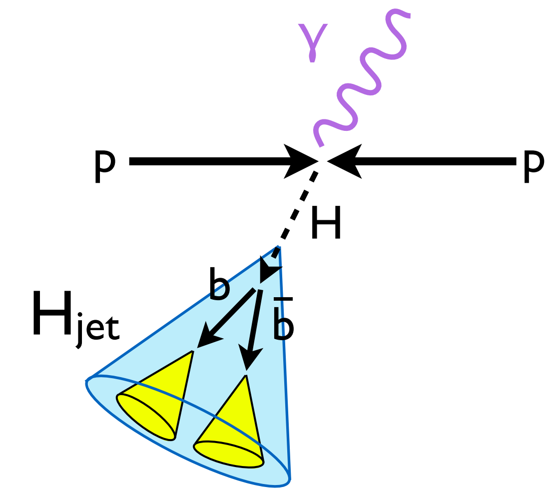


NEW

γH Resonances

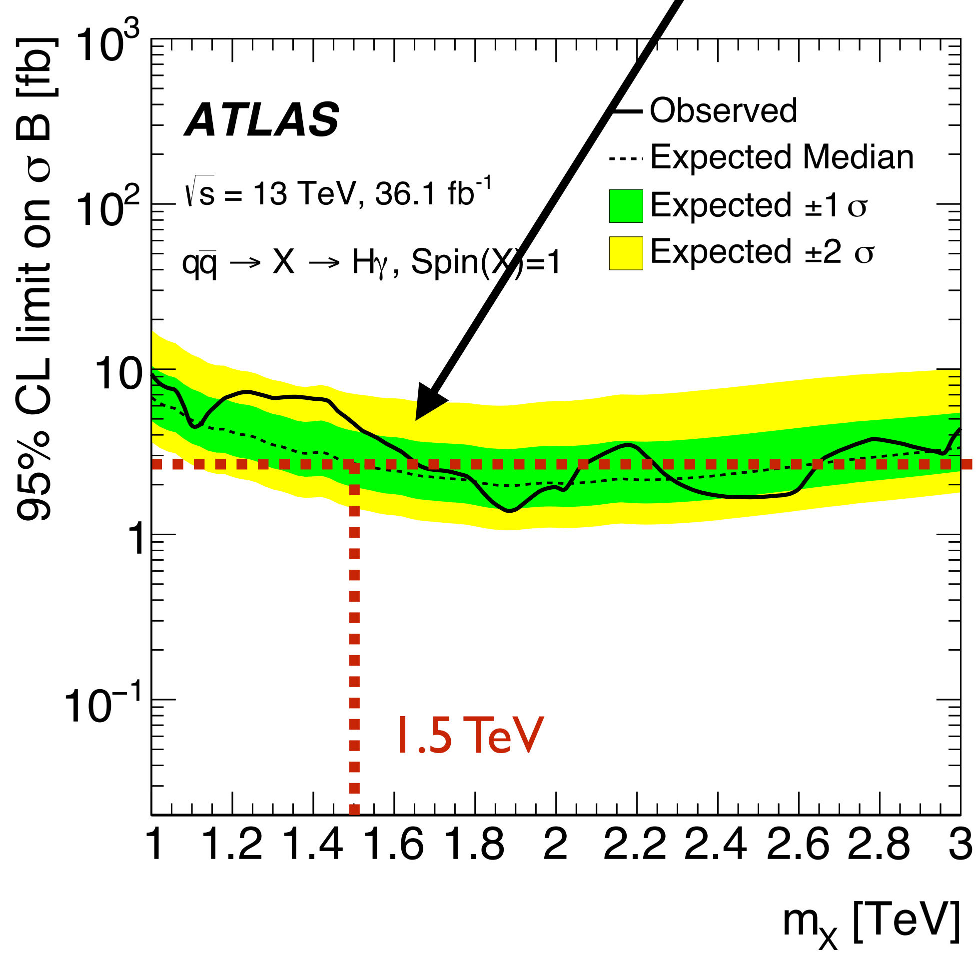


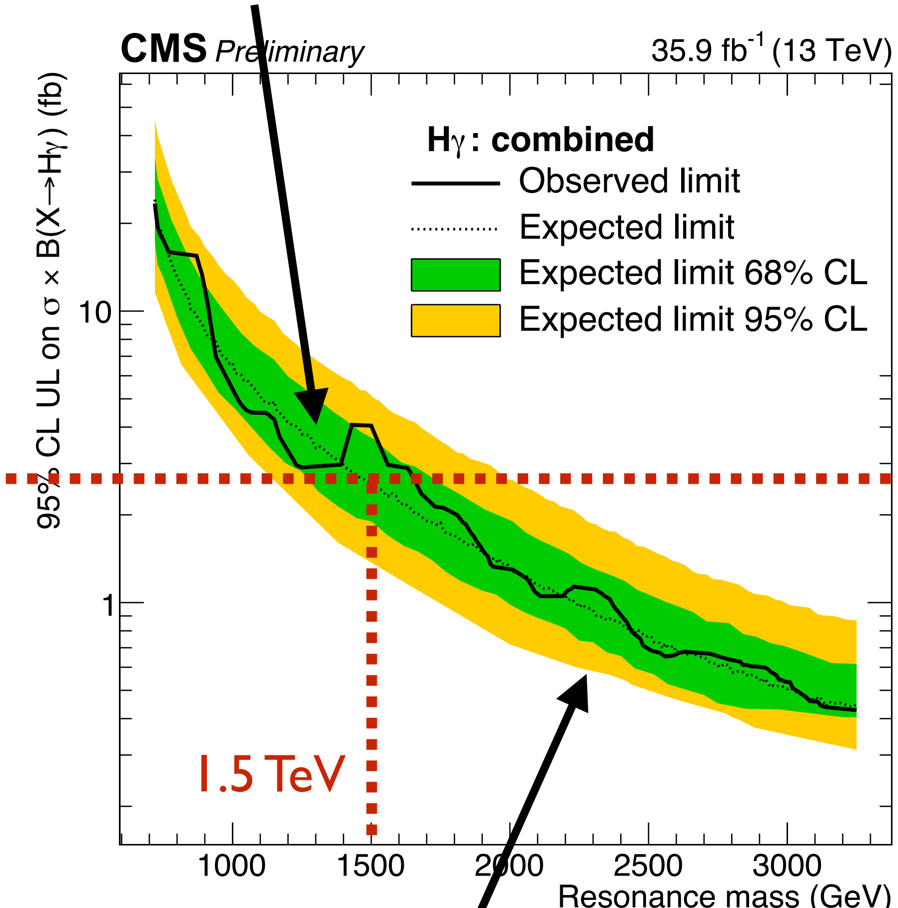
[BA Dobrescu, PJ Fox, J Kearney EPJC77, 704 (2017)]



[CMS-PAS-EXO-17-019]
[ATLAS, arXiv:1805.01908]

Very similar sensitivity up to 1.5 TeV





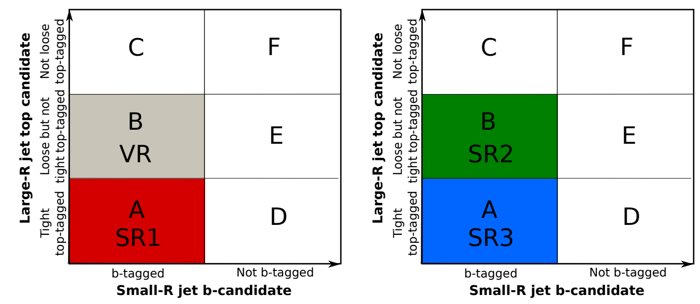
better sensitivity
due to untagged category

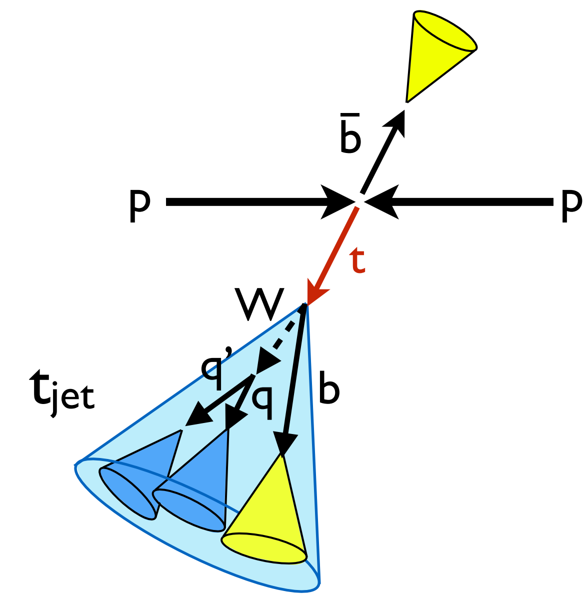
tb and tt Resonances

W’ → tb (JJ)

Shower deconstruction used for the first time in an analysis

Multi-jet backgrounds: sidebands

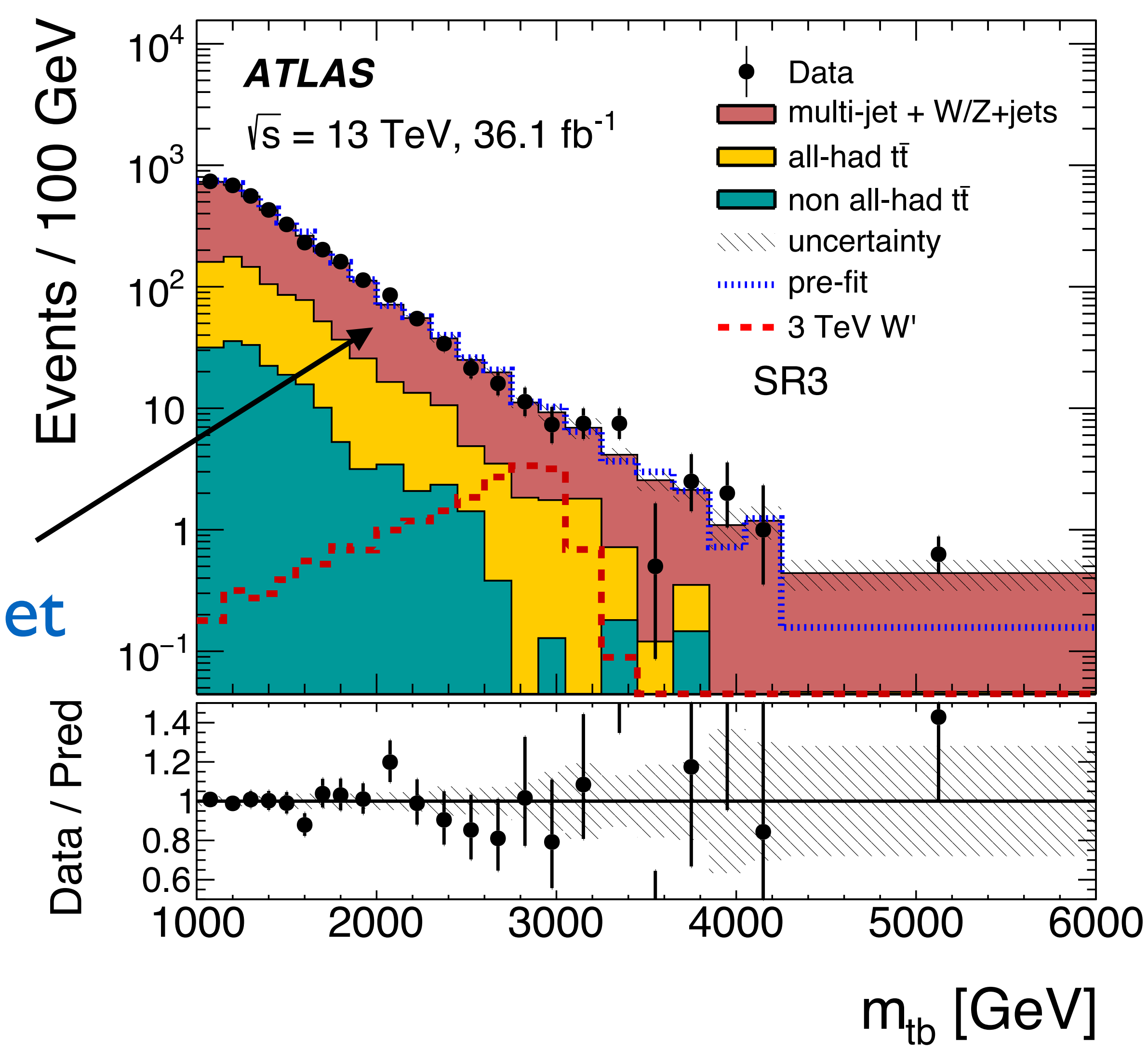


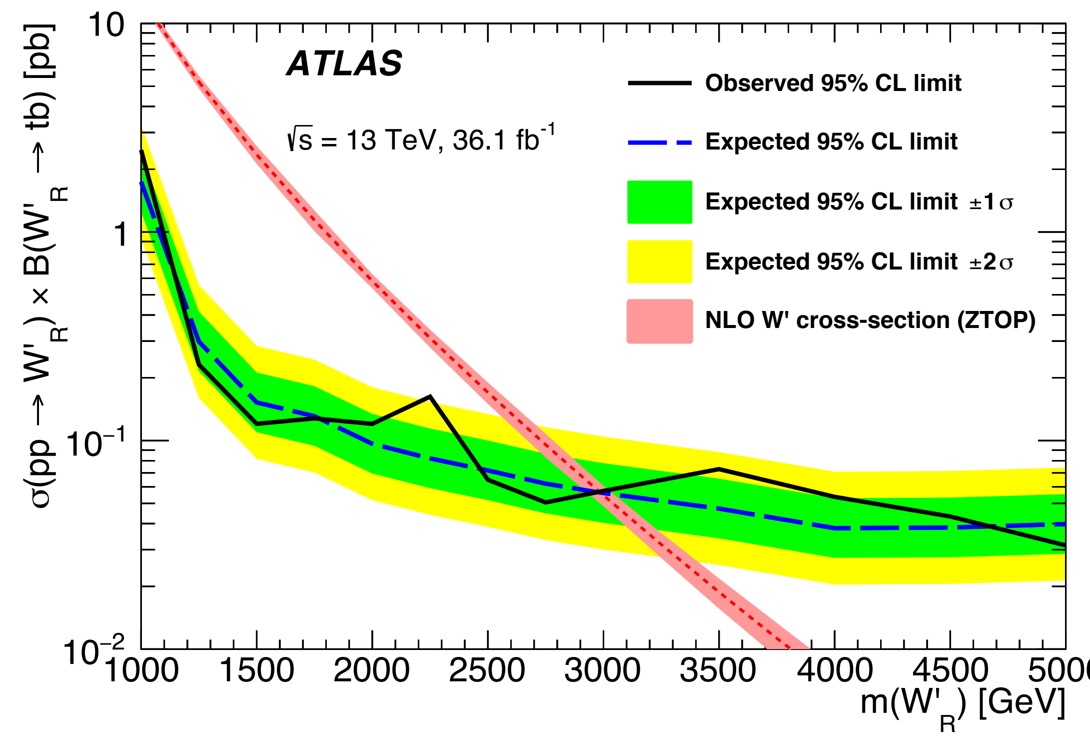


[ATLAS, PLB 781, 327 (2018)]

tight t tag, 2b tags

75% multi-jet bkgd





W_R’ exclusion: 3.0 TeV

LJ (CMS): 3.6 TeV

[see also CMS, PLB 777, 39 (2018)]

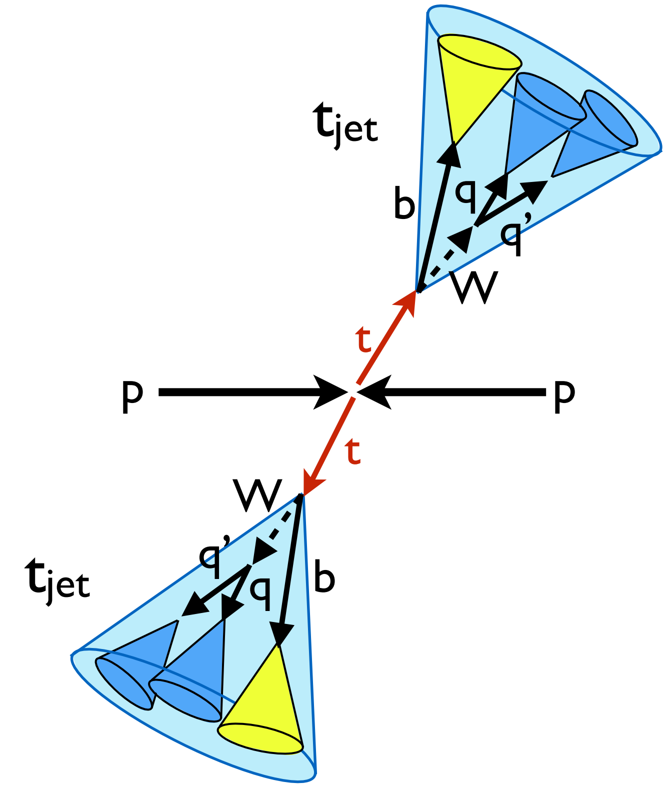
Z’ → tt (LL,LJ,JJ)

NEW

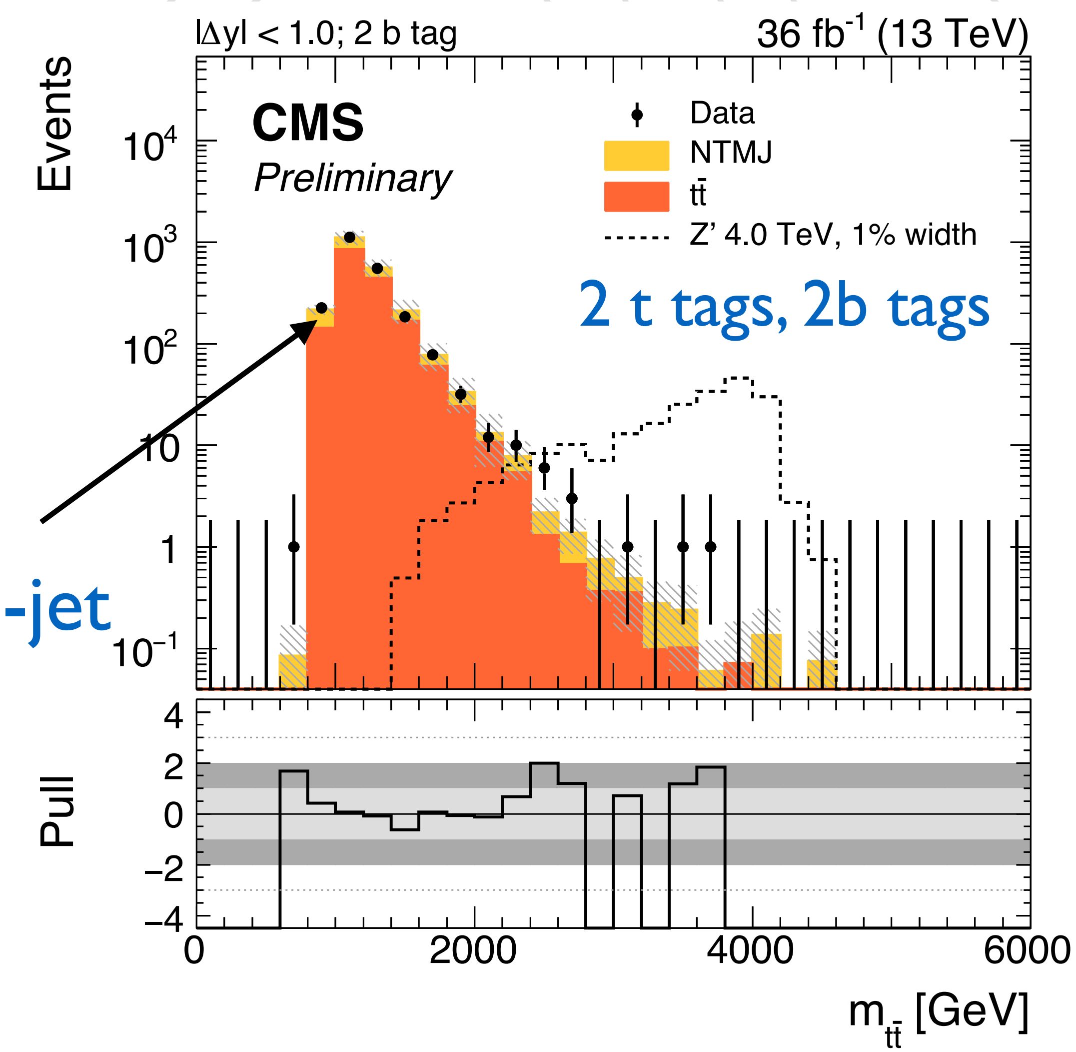
Many improvements since last result

- improved PU mitigation, b-tagging
- BDT for W+jet suppression
- CRs to constrain backgrounds

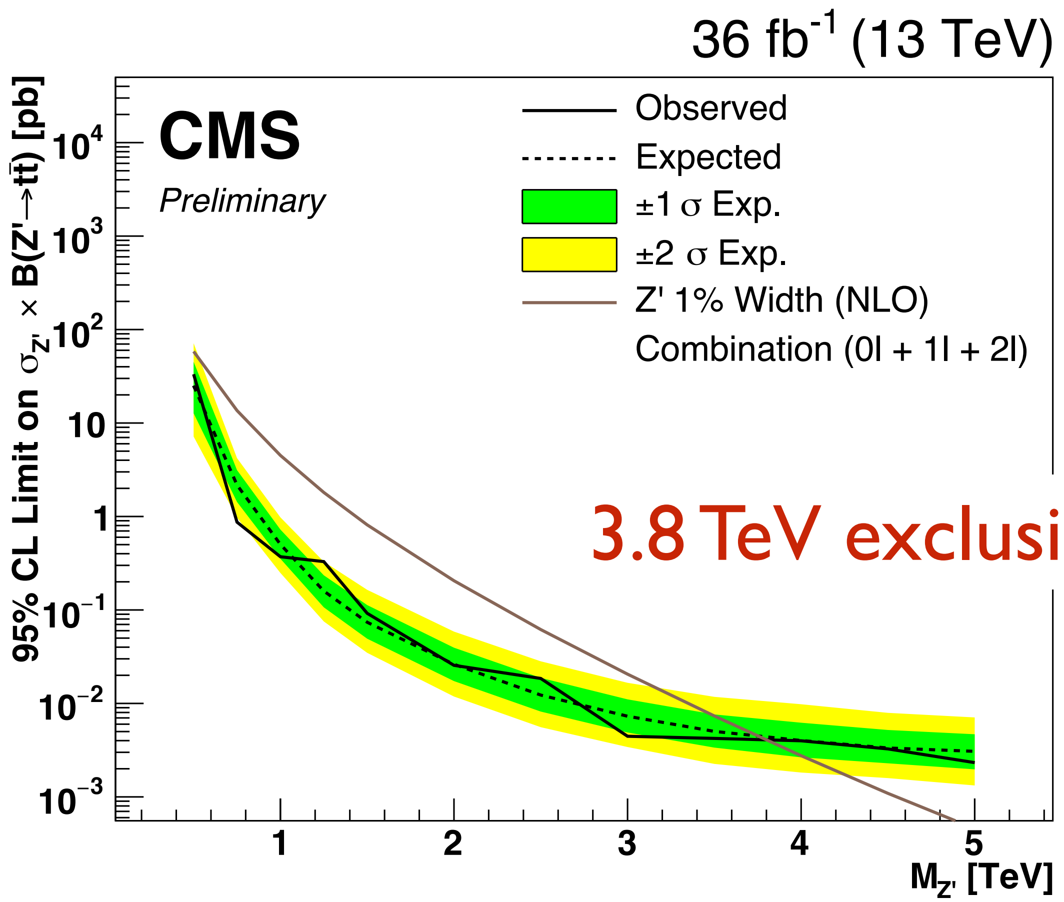
10-40% improvement



[CMS-PAS-17-017]

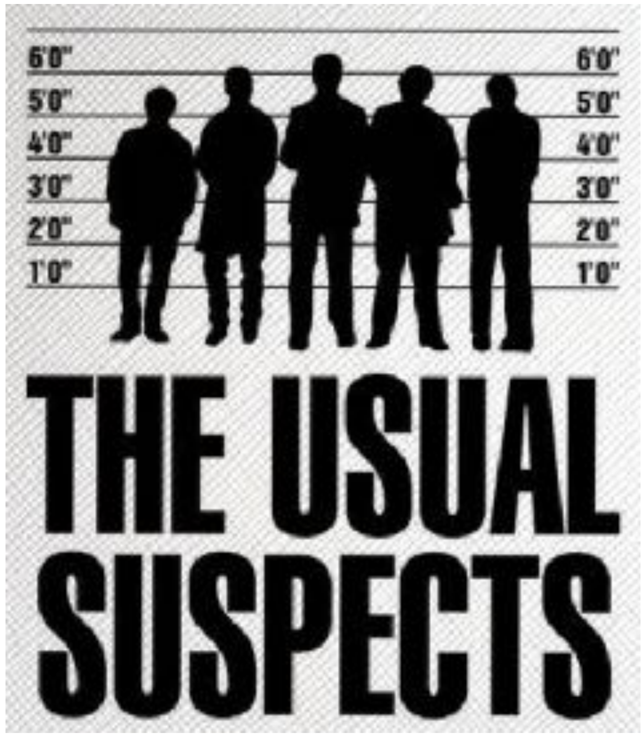


25% multi-jet bkgd



3.8 TeV exclusion

[see also ATLAS, arXiv:1804.10823] [talk by M.Aoki]



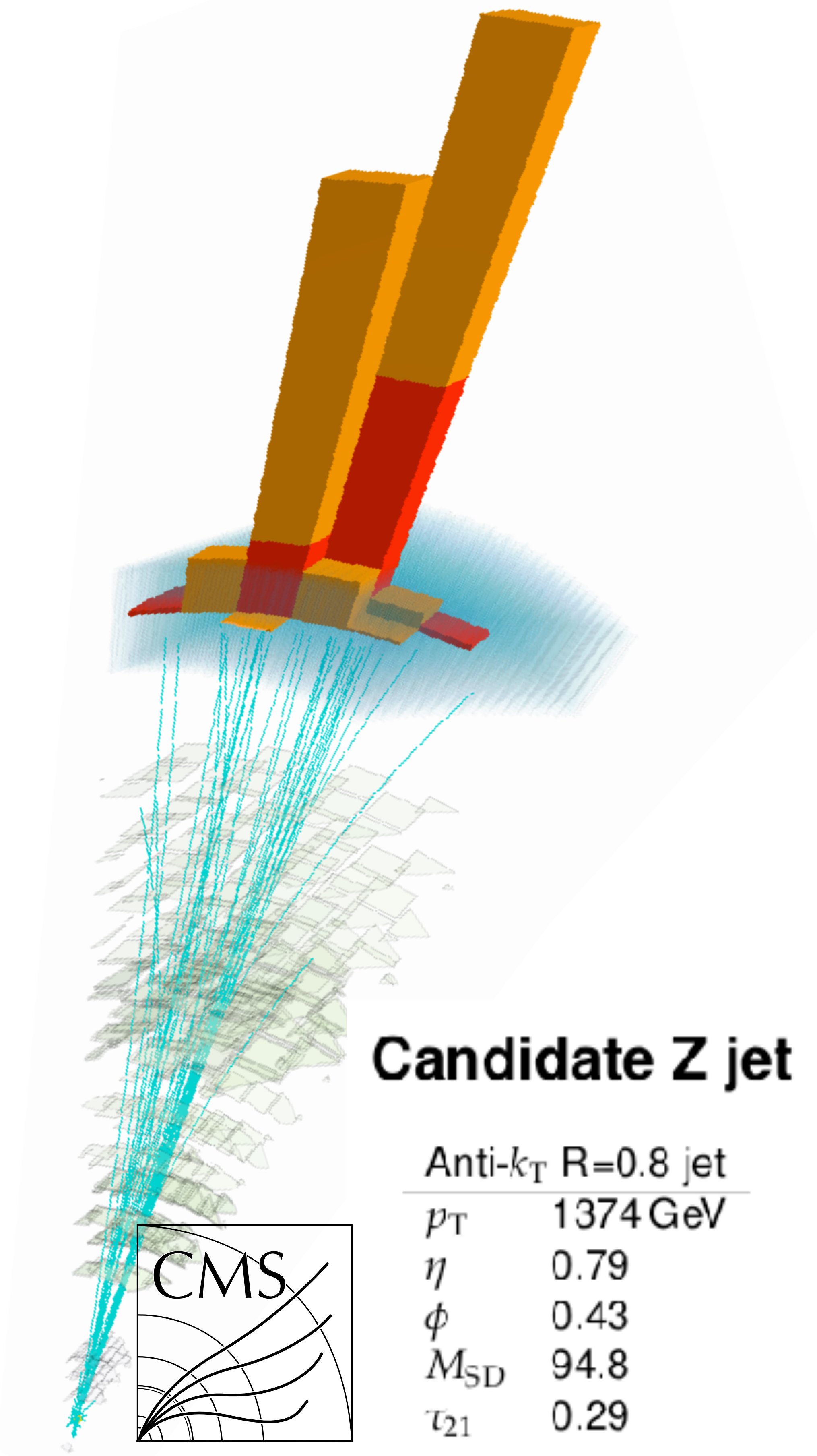
(narrow resonances)

Dijet bump hunts with jet tagging

Improvements on methods and reconstruction essential to achieve ultimate sensitivity

Phase transition in searches: target large widths, contact interactions, cascade decays

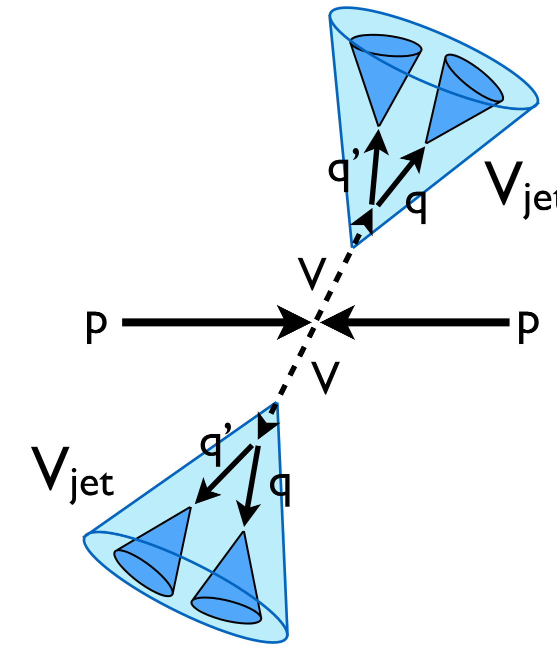
Exciting times ahead!



Additional Material

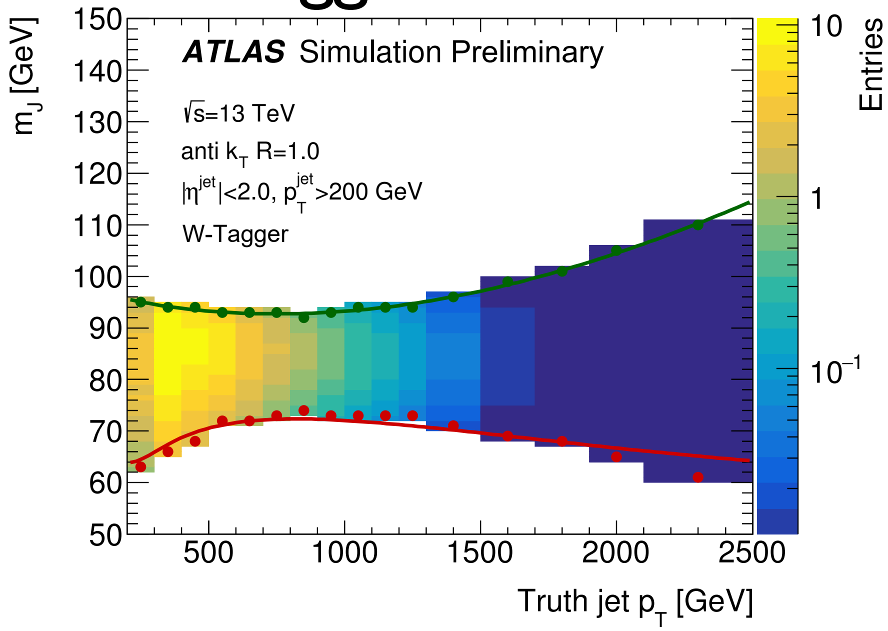
NEW 80 fb^{-1}

VV Resonances (JJ)

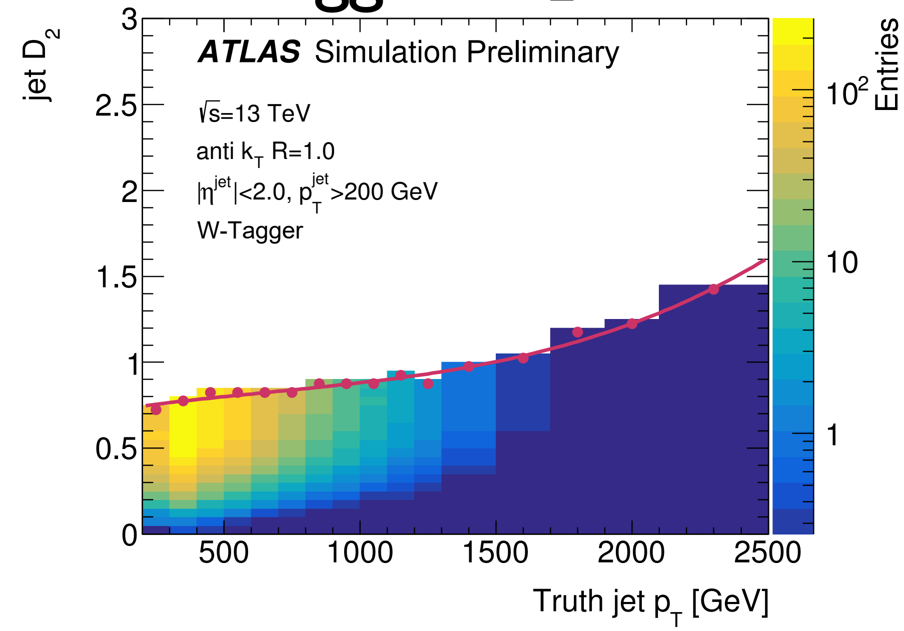


[ATLAS-CONF-2018-016]

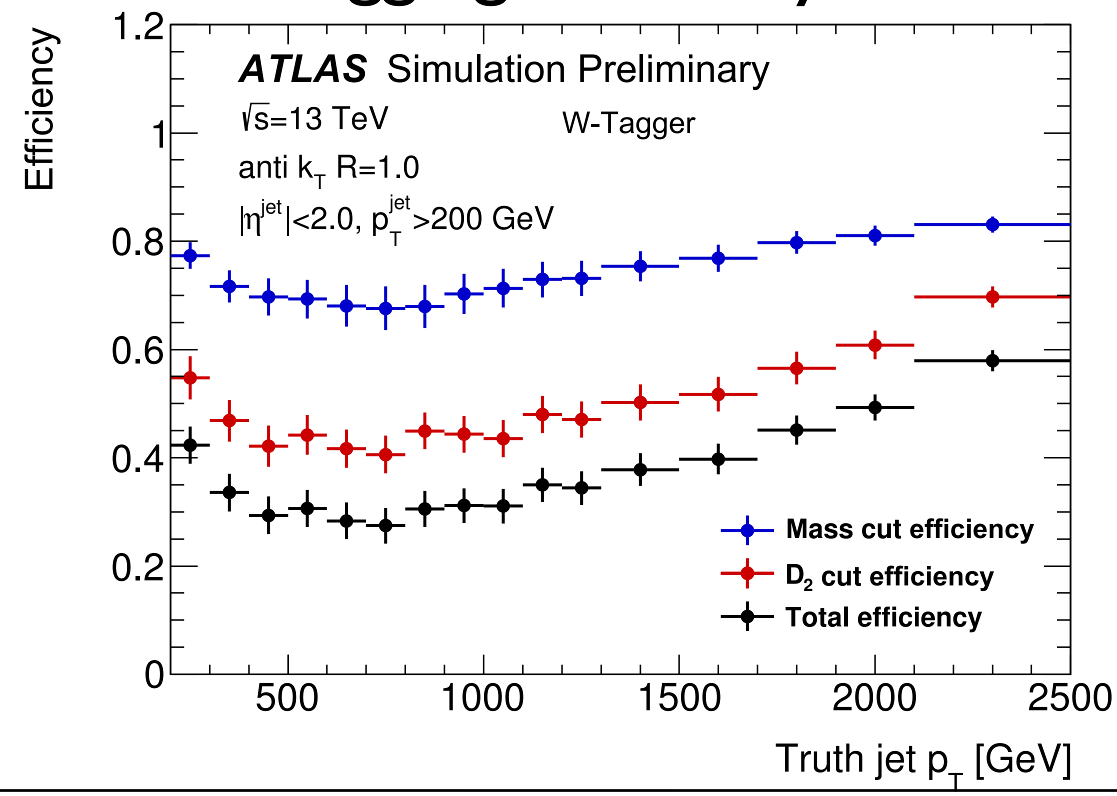
W tagger: mass cuts



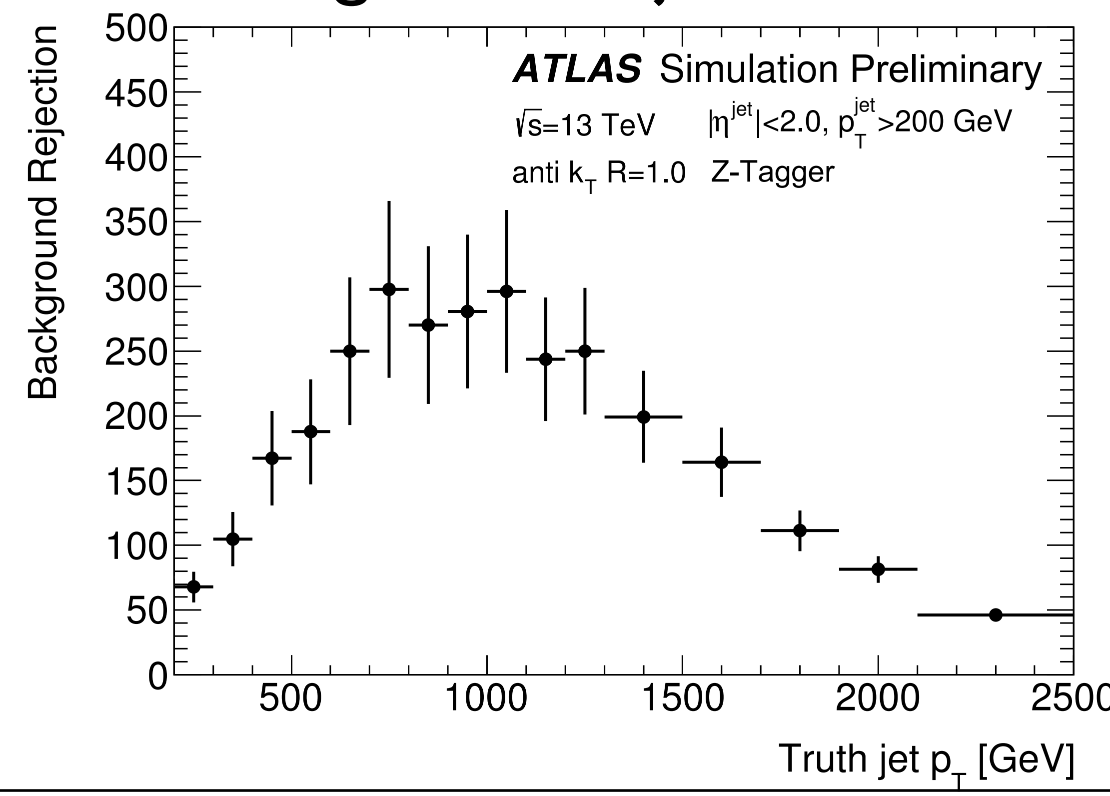
W tagger: D_2 cuts



W tagging efficiency



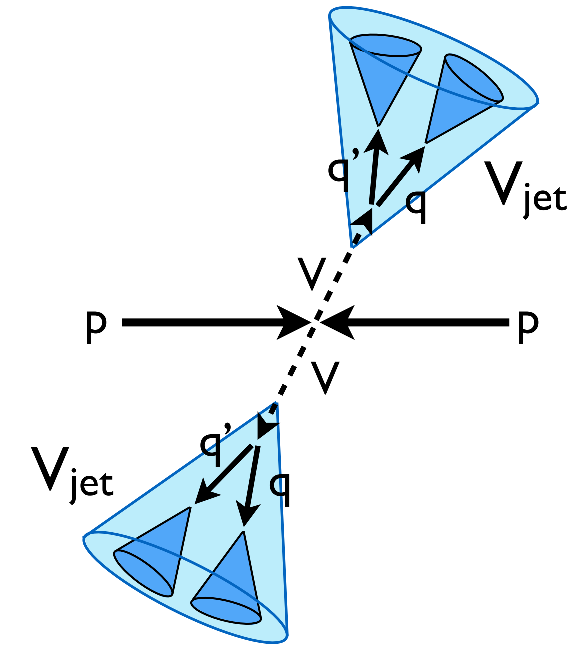
background rejection



NEW

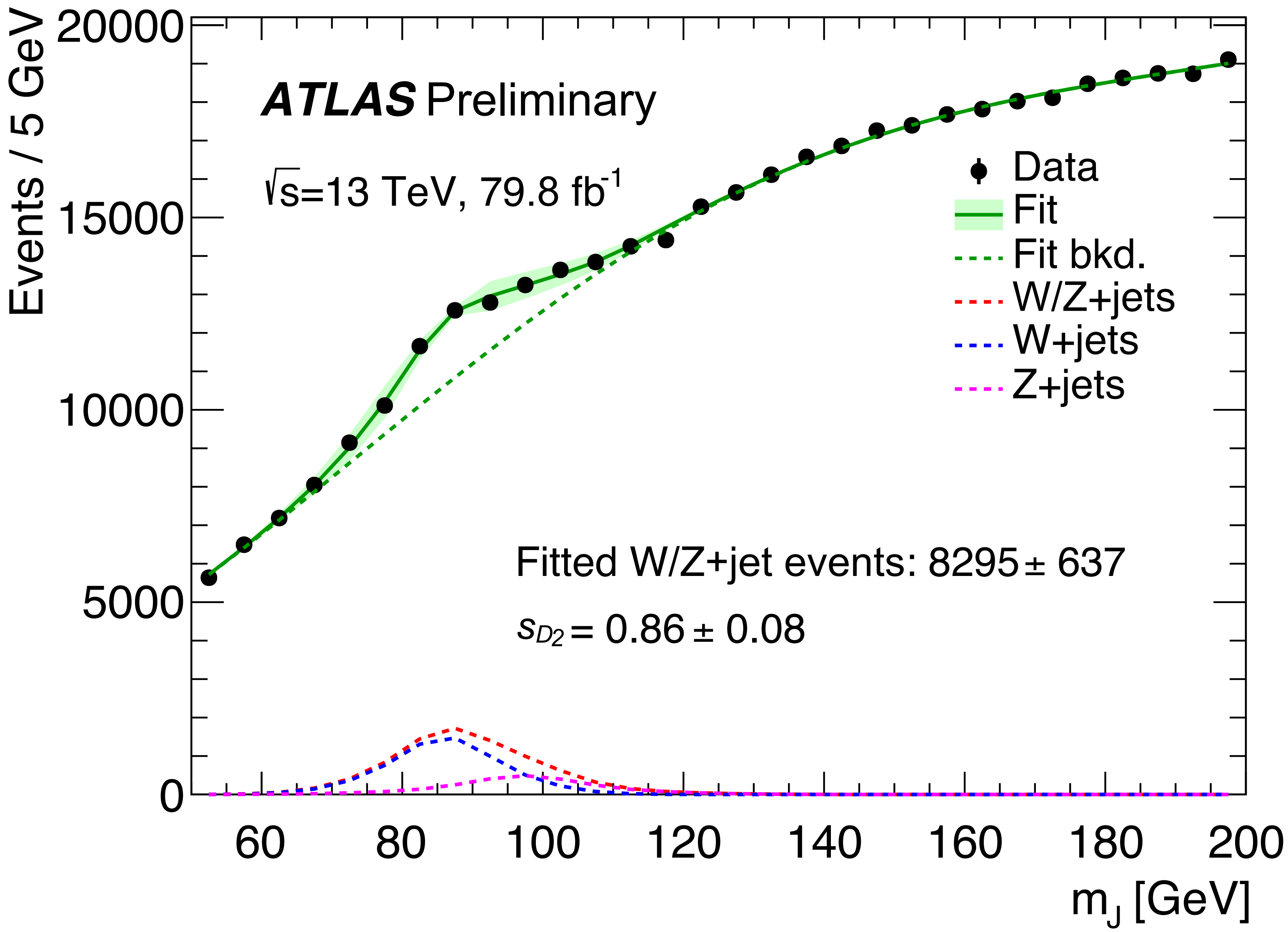
80 fb^{-1}

VV Resonances (JJ)



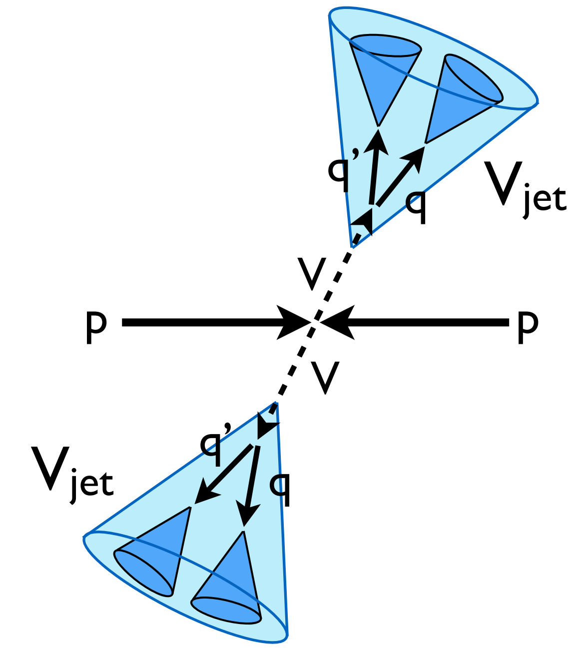
[ATLAS-CONF-2018-016]

W tagger: signal efficiency measurement of D_2 cut



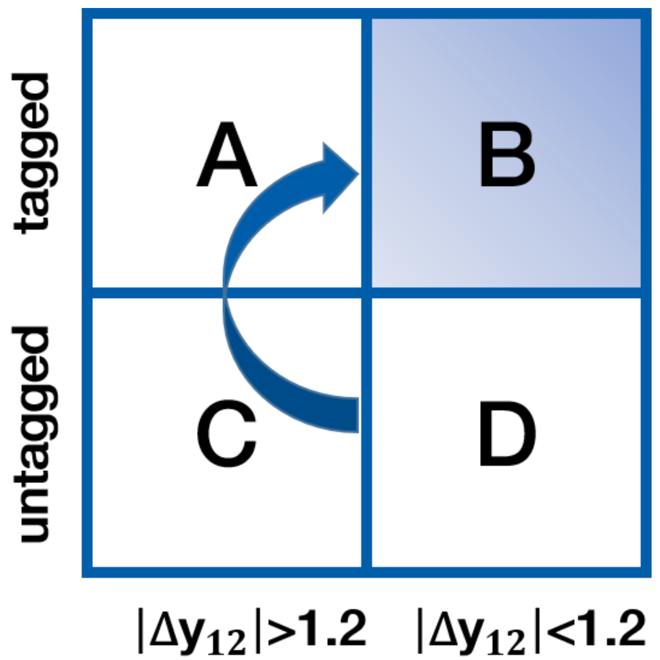
NEW 80 fb^{-1}

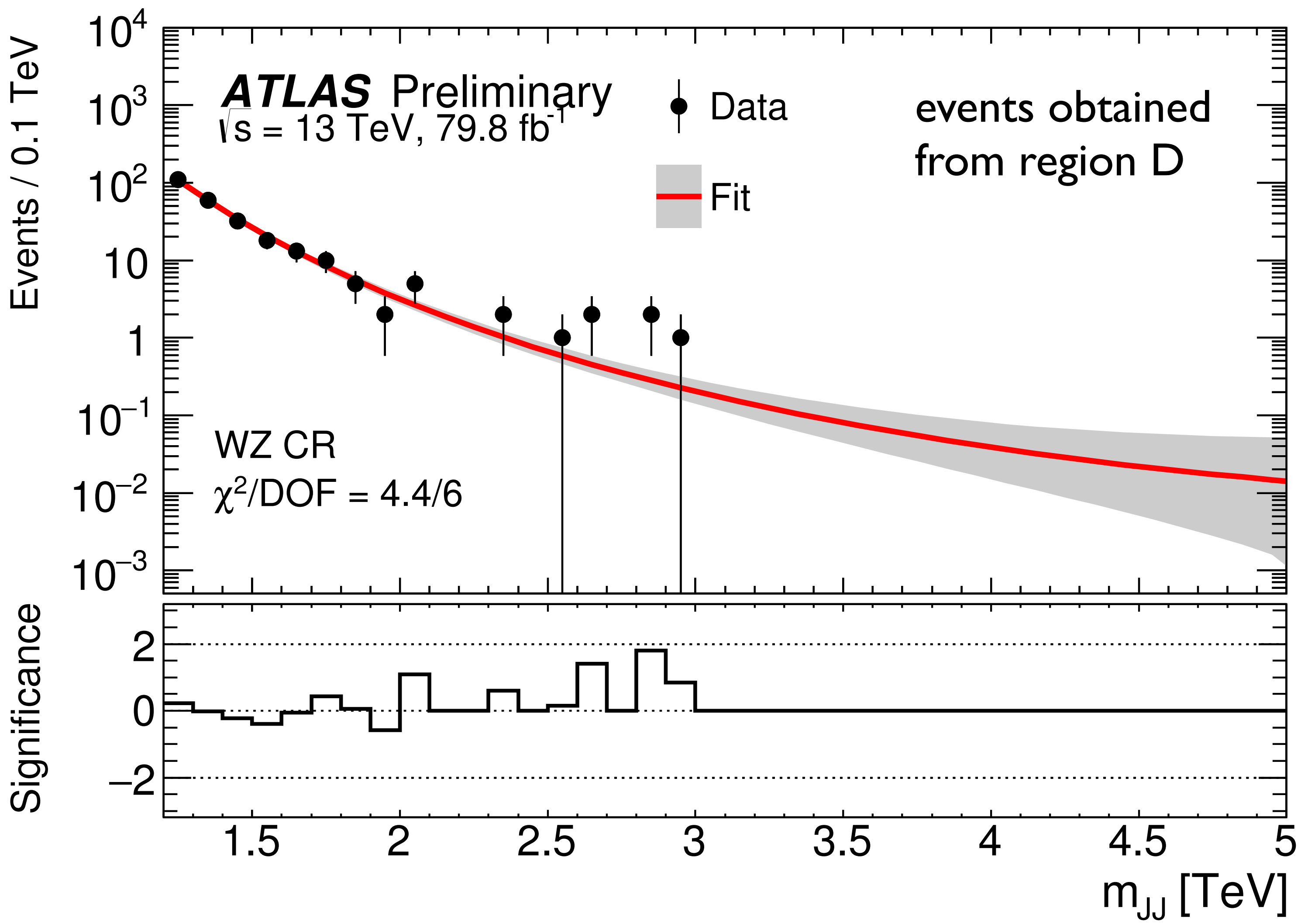
VV Resonances (JJ)



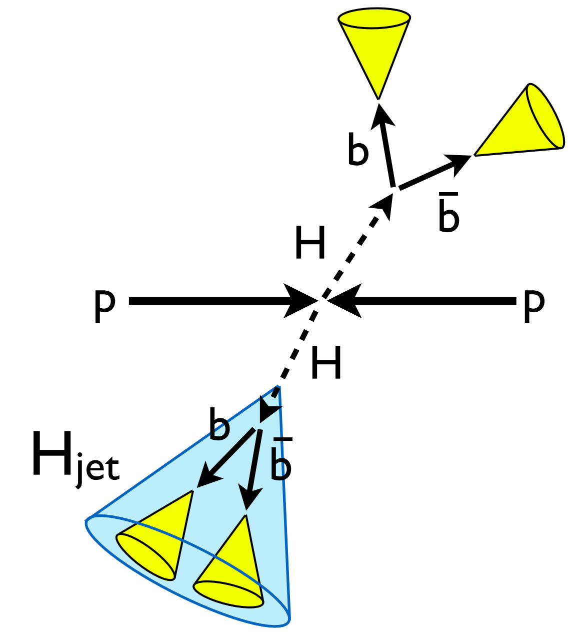
[ATLAS-CONF-2018-016]

Validating the background model

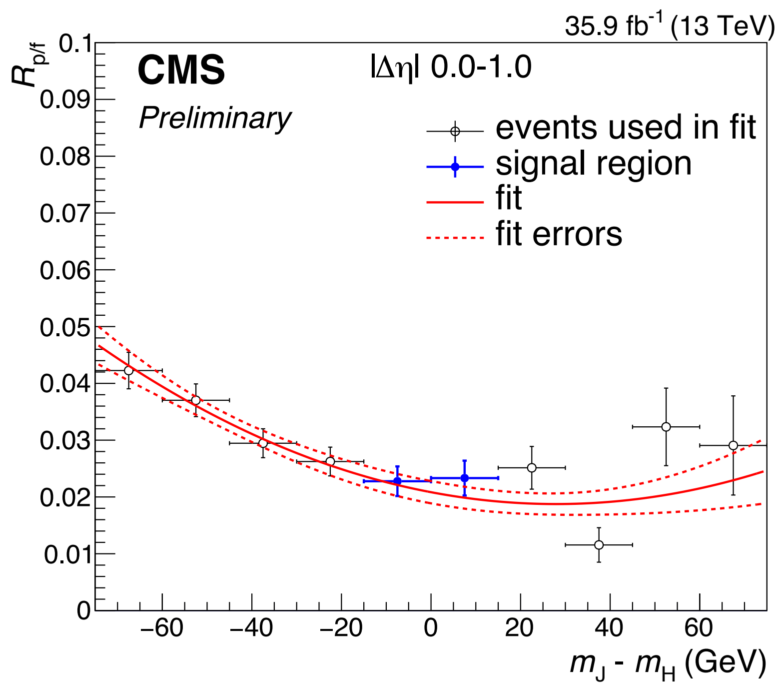


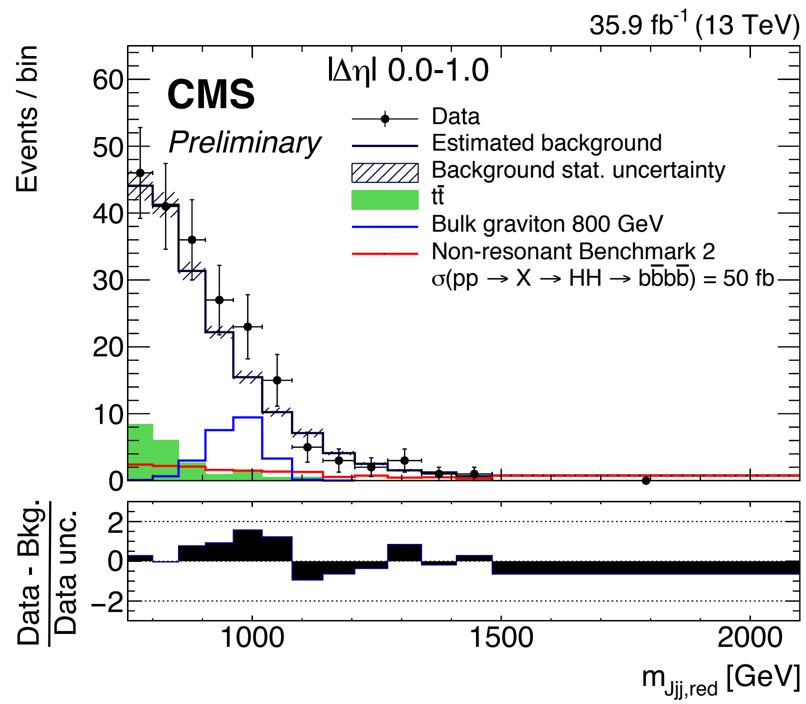


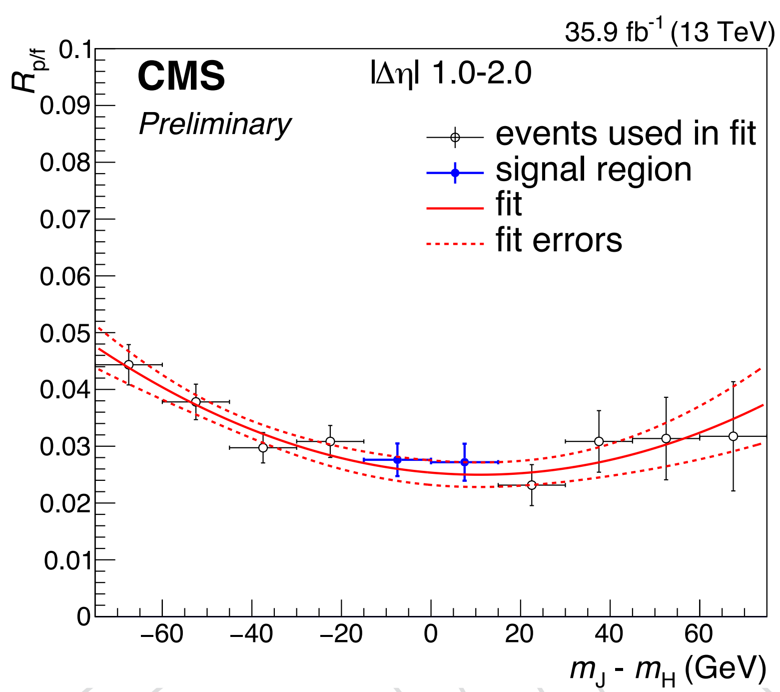
$HH \rightarrow 4b$

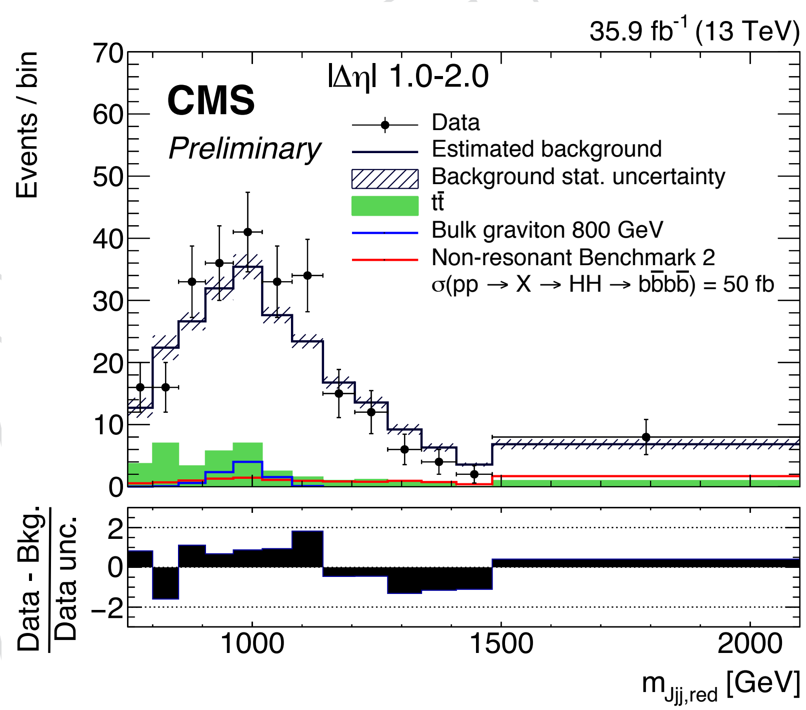


Background estimation through $R_{p/f}$









[CMS-PAS-B2G-17-019]