20.04.2016 **HF-LHC2016**, *Durham*

Top-quark + heavy-flavour measurements at CMS

Results from the **Run I** data

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Outline

1 Top-quark production and decay

2 Inclusive measurements

- dileptonic
- semileptonic

3 Differential measurements

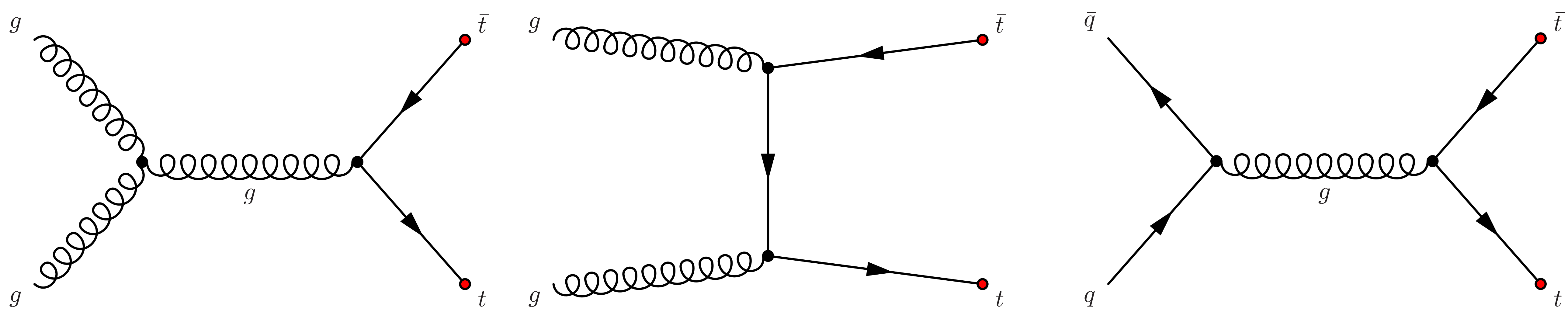
- dileptonic

Top-quark production

The heaviest SM particle: m_t = 172.33 ± 0.49 GeV *(CMS combination)*
arXiv:1509.04044

Life time (10^{-25}s) shorter than hadronisation time scale (10^{-24}s)
bare quark properties accessible: mass, $|V_{tb}|$, spin, charge,...

Top-quark pairs (*tt*): via QCD interactions   dominant at LHC

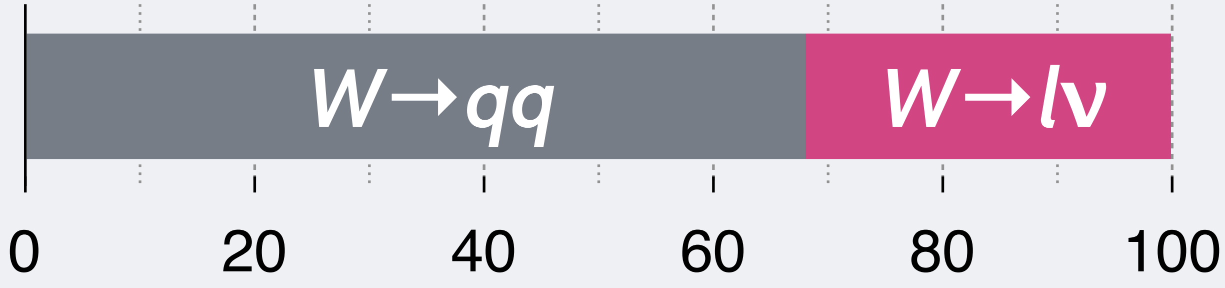


gg fusion *(85%)* $q\bar{q}$ annihilation *(15%)*

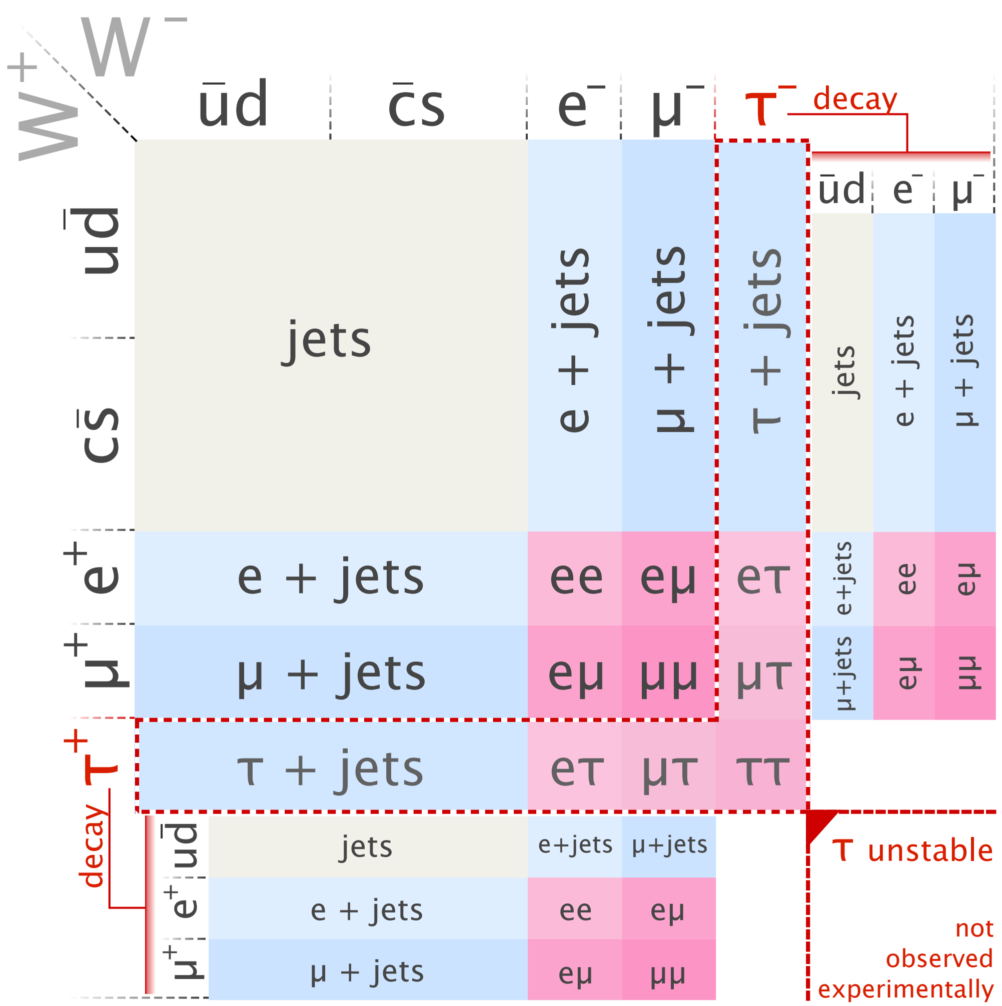
Single top quarks: via EWK interactions   not in this talk

Top-quark decay

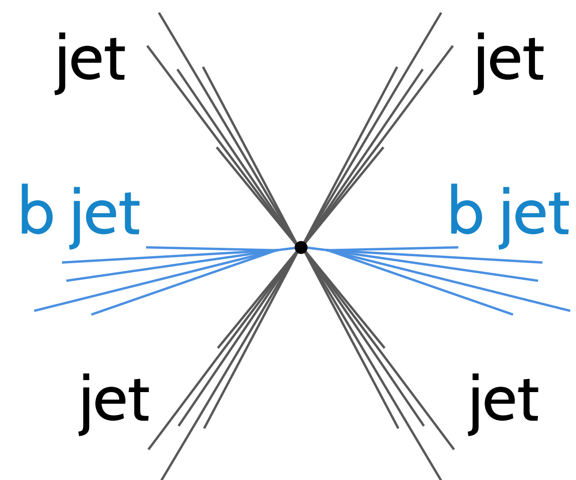
Almost exclusively decays: $t \to bW$



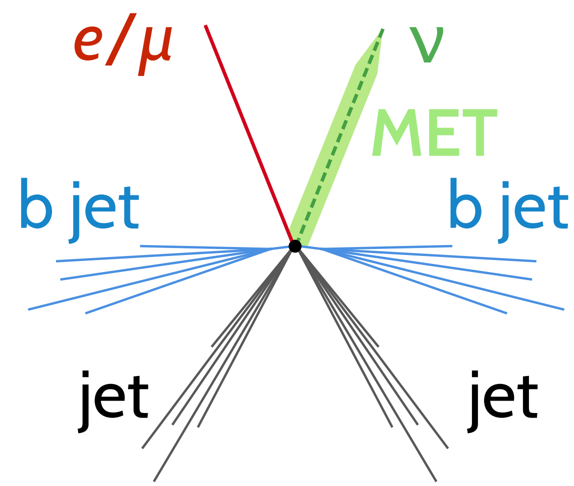
W decay defines the *tt* final state



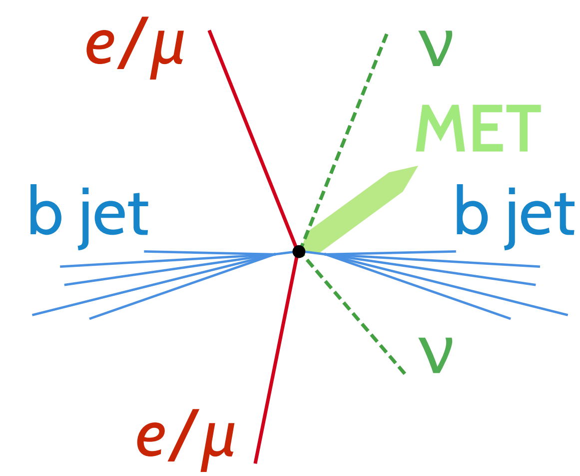
- full hadronic
- semileptonic
- dileptonic



full hadronic BR~56%
Bkg: QCD multijet,.. large



semileptonic BR~37%
Bkg: W+jets,..



dileptonic BR~7%
Bkg: DY+jets,.. small

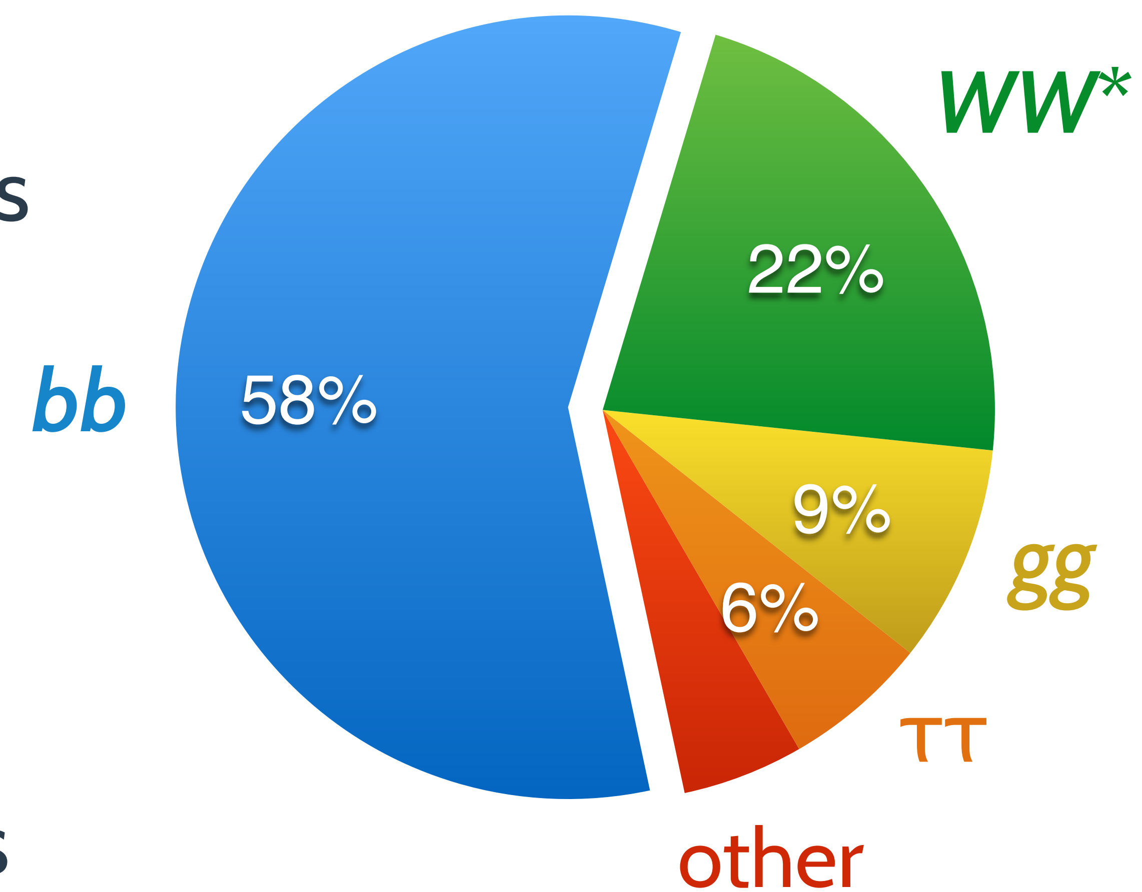
Higgs boson

Gives mass to SM particles via coupling to the ***H*** boson

- fermion coupling proportional to mass: $Y_f \propto m_f$ ‹ to be tested
- couples most to the ***top*** quark

Dominant decay channel: *H*→*bb*

- typical final state in QCD processes
- σ(*pp*→*H*→*bb*) « σ(*pp*→*bb*)
- very challenging to measure



***H*→*bb* associated by *top* quarks (*ttH*)**

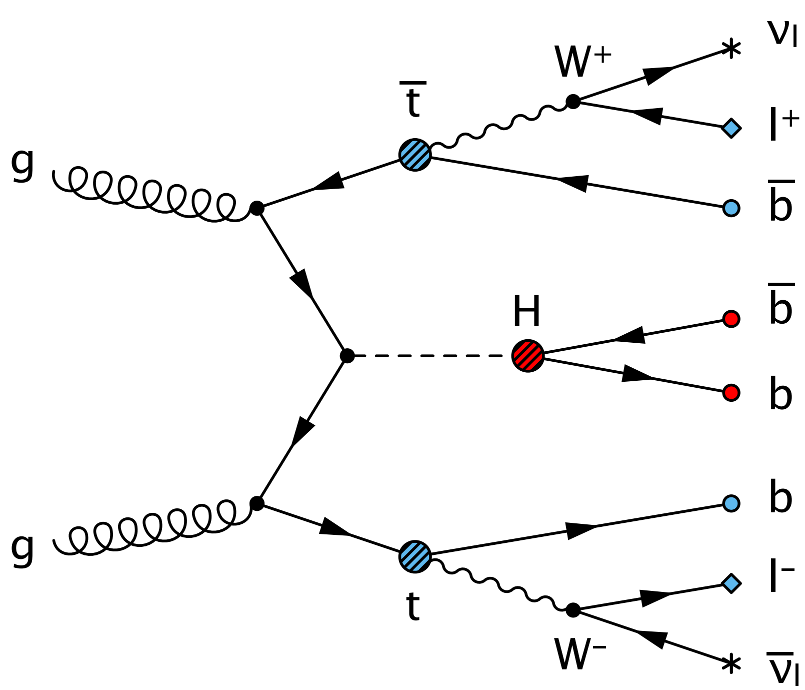
- smaller σ of background processes
- vital test for consistency with SM: $\sigma \propto Y_t^2 Y_b^2$
- **the only direct way to measure *t*-*H* coupling**

tt+bb INCLUSIVE CROSS SECTIONS

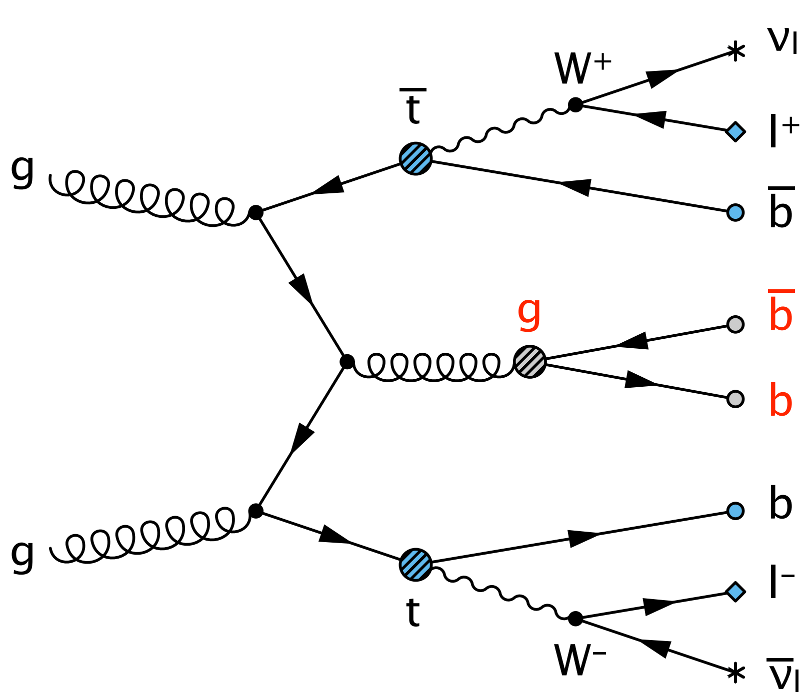
- half of *tt* pairs accompanied by jets *(p_T > 30 GeV)*
- main background to *ttH*(*H*→*bb*) production
  - important for *ttH* searches
- background to new physics

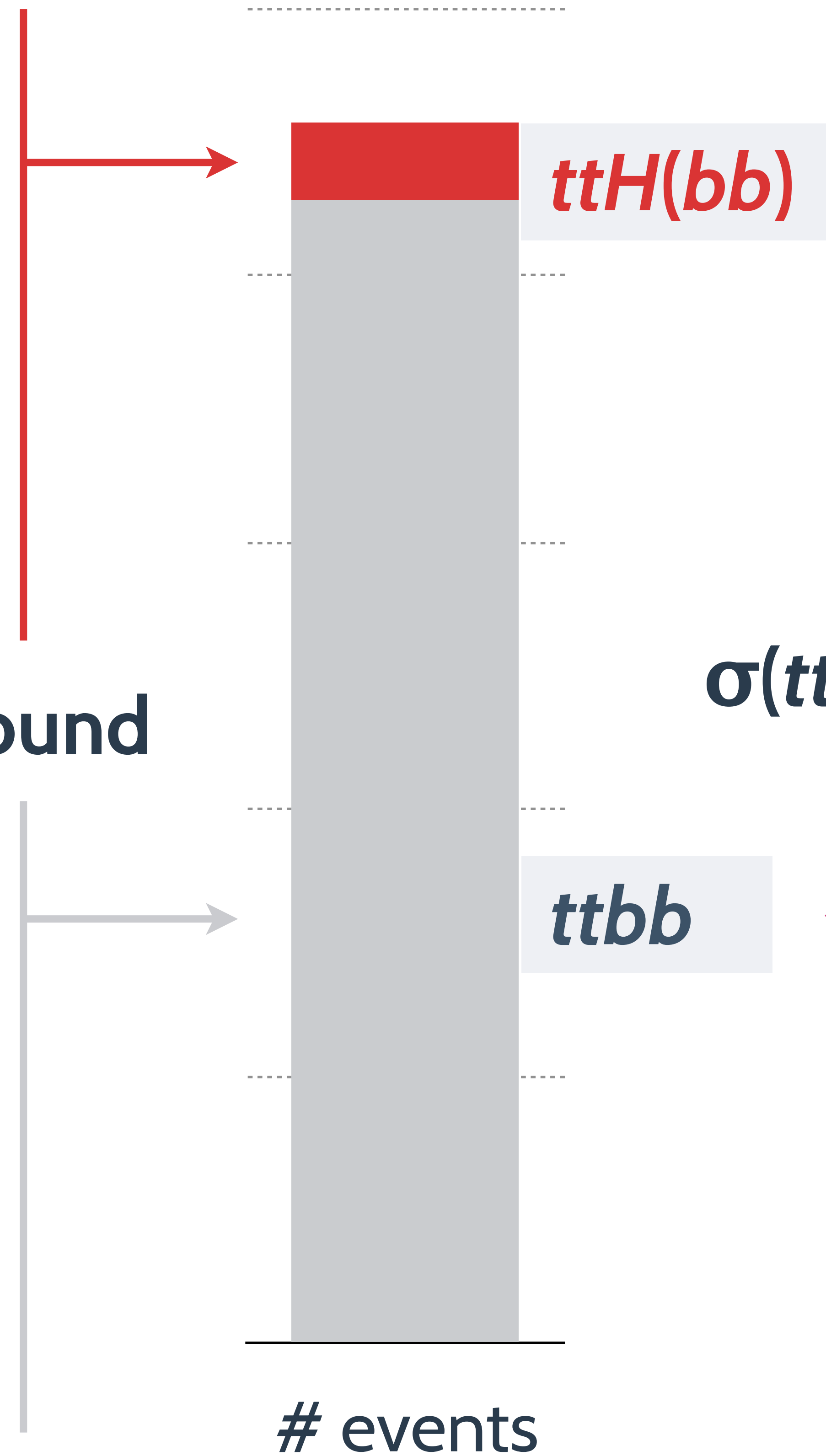
ttbb as background to *ttH*($H \to bb$)

Distinctive and complex final state *(dileptonic channel)*



Large irreducible background





$\sigma(ttbb) \approx 15 \times \sigma(ttH)$

b-jet $p_T > 20$ GeV

← **Must be known precisely**

Inclusive $\sigma_{ttbb}/\sigma_{ttjj}$: *analysis* dileptonic

Absolute σ_{ttjj}, σ_{ttbb}, $\sigma_{ttbb}/\sigma_{ttjj}$: additional (b) jet p_T > 40 GeV, $|\eta| < 2.5$

Dileptonic final states: *ee*, *eμ*, *μμ* including $\tau \rightarrow e/\mu$

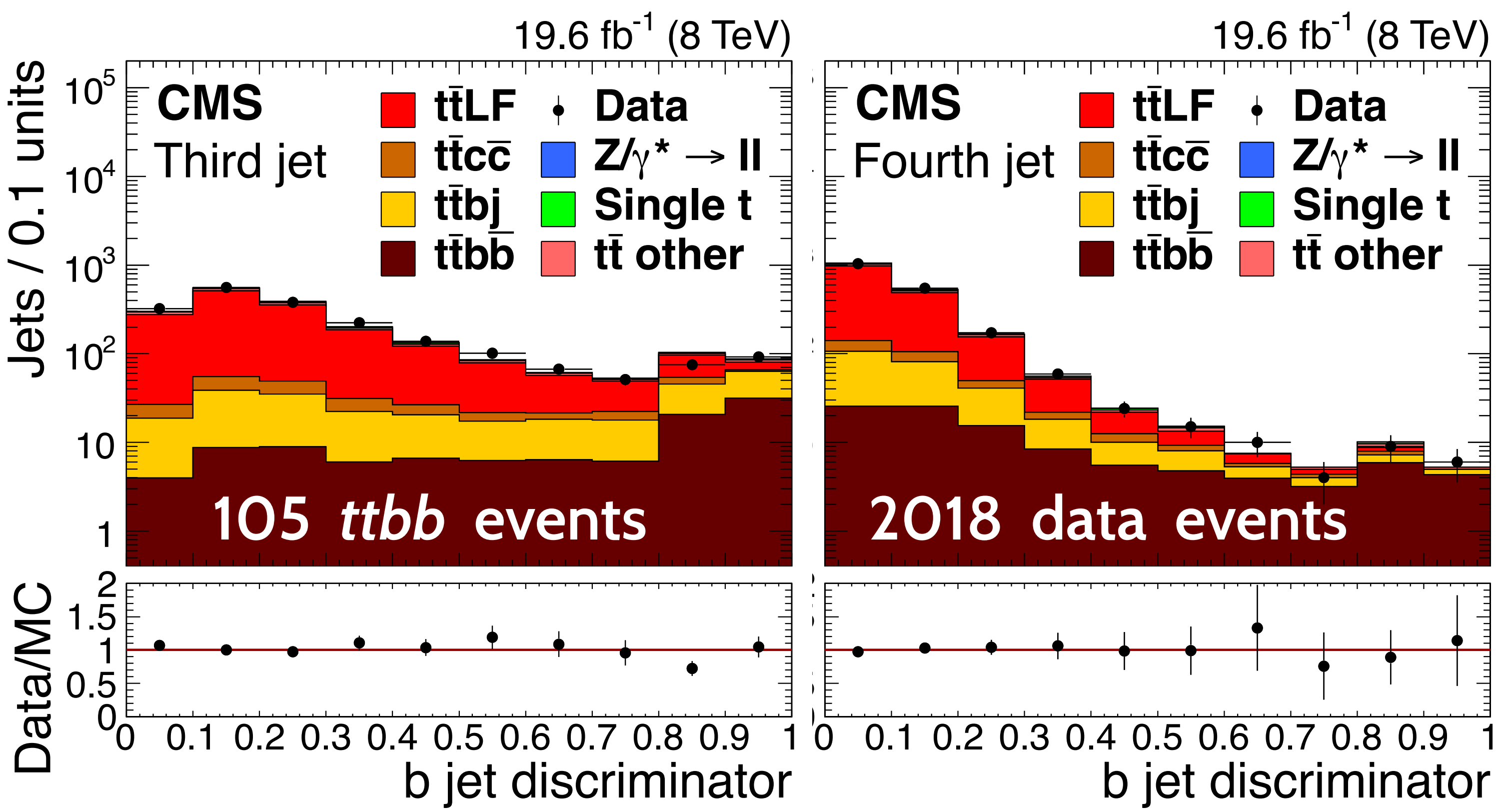
PLB 746 (2015) 132

Stable top quarks. Parton-level additional jets

- **Jet clustering on partons:** *e*, *μ*, τ^{had}, *g*, *u*, *d*, *c*, *s*, *b*

anti-k_T: *R=0.5*

- **Additional b-jets:** ΔR(*b*-quark, jet) < 0.5



- ordered by b-tagging discriminant value
- 2 leading assumed from *top*-quark decay

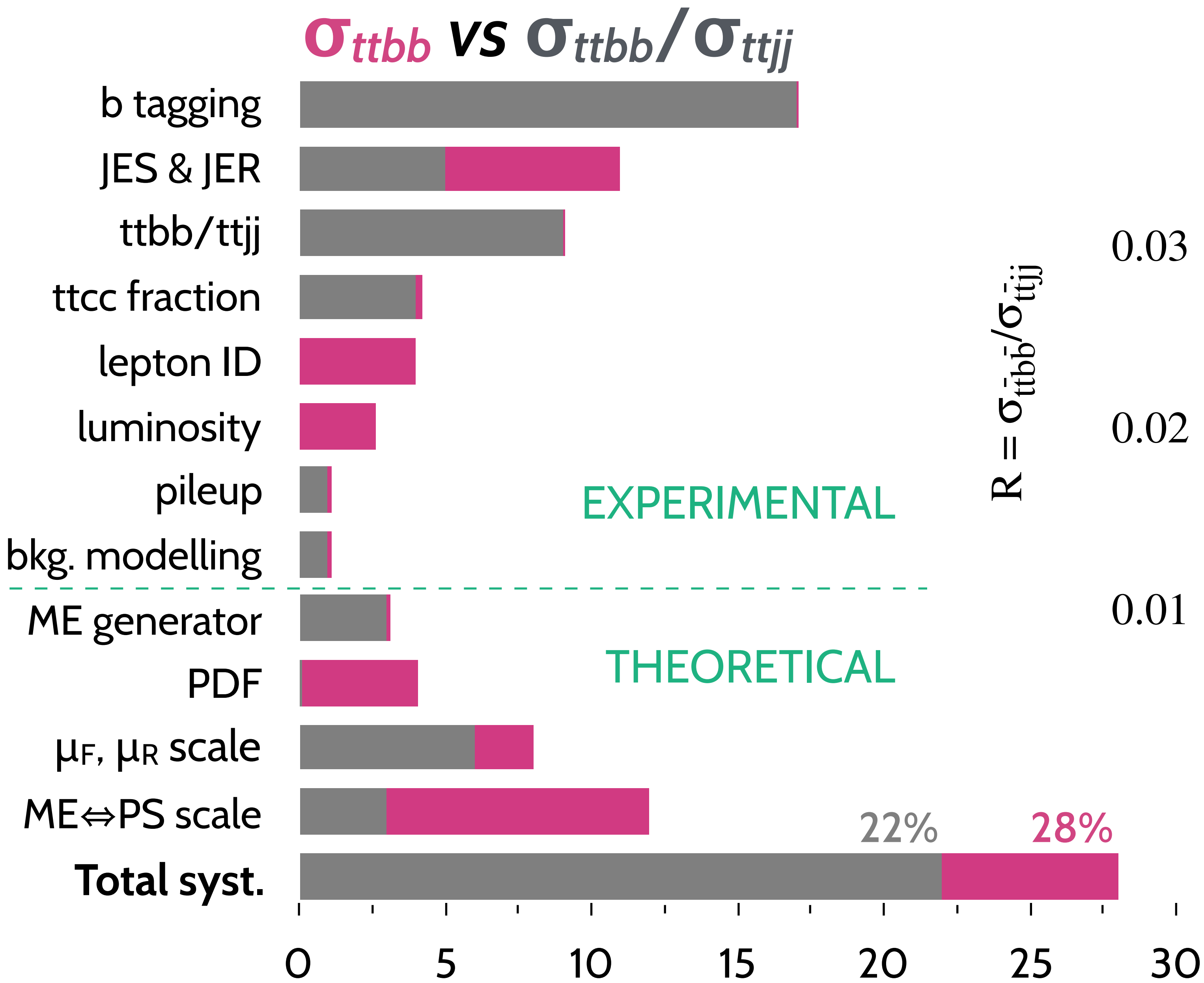
← corrected by fit results

Simultaneous template fit to extract *ttbb/ttjj* cross-section ratio

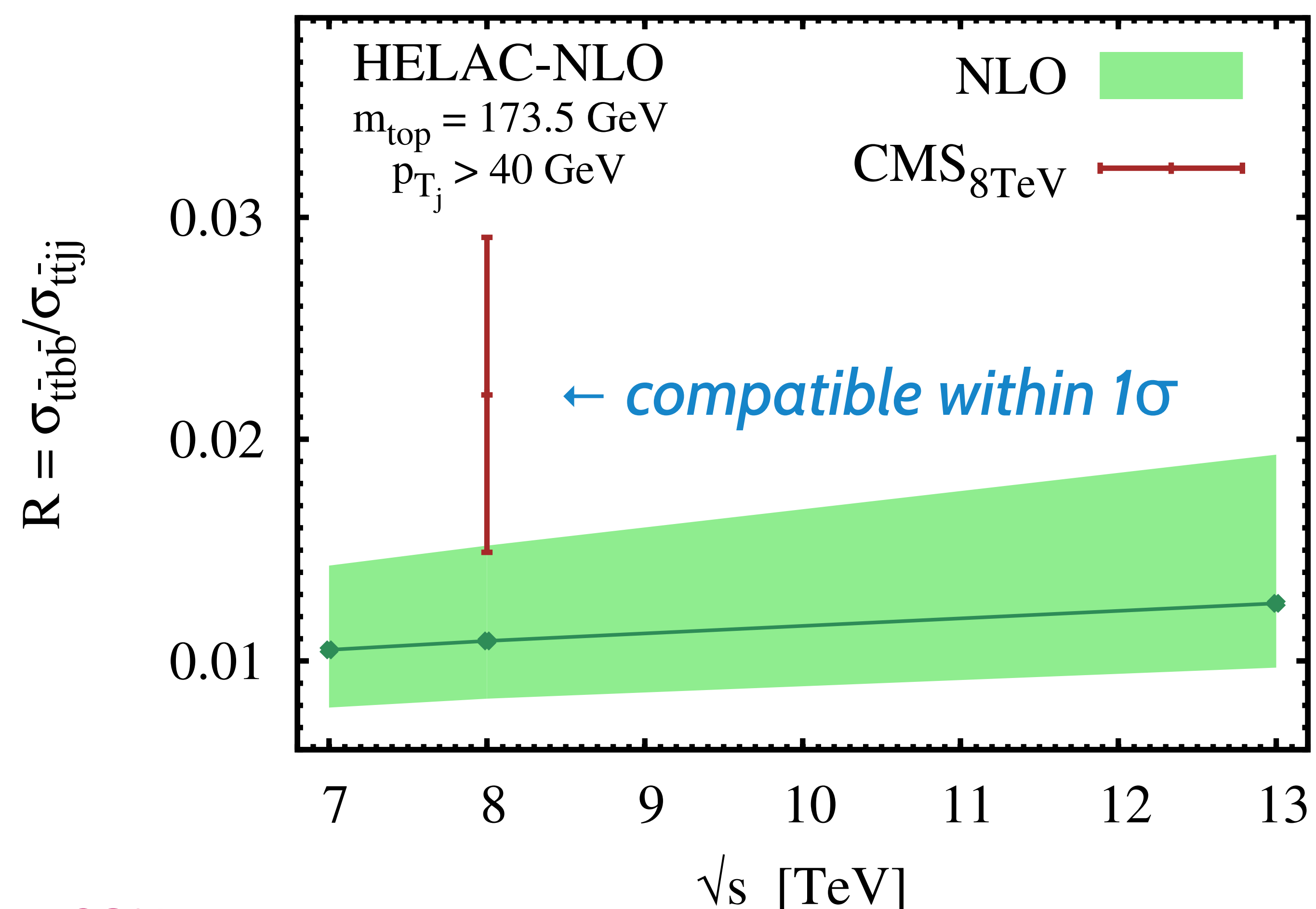
Inclusive $\sigma_{ttbb}/\sigma_{ttjj}$: *results* dileptonic

Additional (b) jet p_T > 40 GeV, $|\eta|$ < 2.5 (full *tt* phase space)

CMS	$\sigma_{ttbb}/\sigma_{ttjj} = 0.022 \pm 0.006^{total}$	$\sigma_{ttbb} = 0.36 \pm 0.13^{total}$ pb
NLO	$\sigma_{ttbb}/\sigma_{ttjj} = 0.011 \pm 0.003^{total}$	$\sigma_{ttbb} = 0.23 \pm 0.05^{total}$ pb



JHEP 1407 (2014) 135



Absolute σ_{ttjj}, σ_{ttbb}, $\sigma_{ttbb}/\sigma_{ttjj}$: additional (b) jet p_T > 40 GeV, $|\eta| < 2.5$

Semileptonic final states: *e/μ* including $\tau \rightarrow e/\mu$

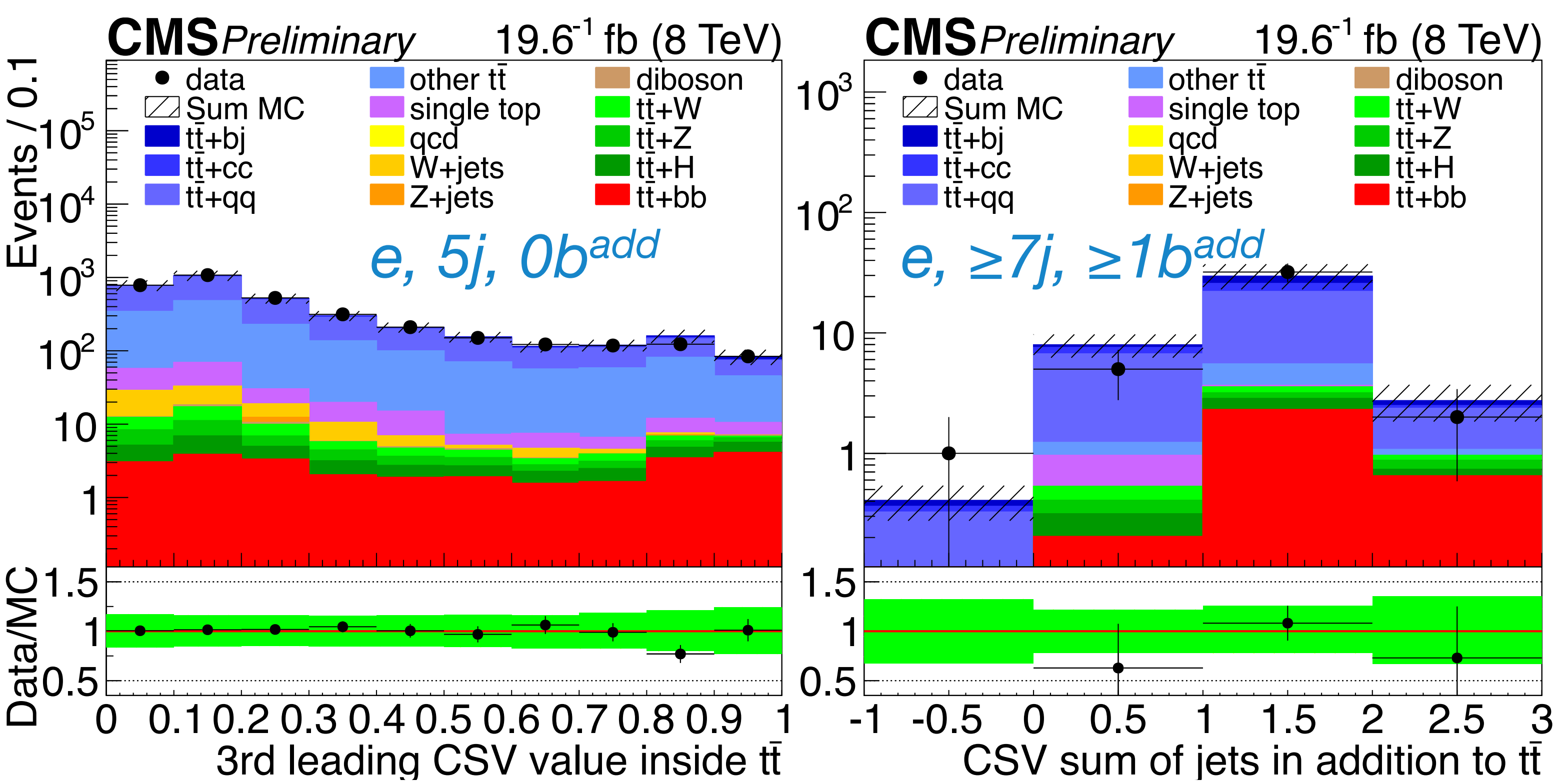
CMS-PAS-TOP-13-016

Jets clustered from stable particles excluding ν

anti-k_T: *R=0.5*

Ghost *b*-hadrons and *b*-quarks clustered for flavour definition:

- hardB: flavour of leading quark
- hadronB: presence of *b* hadron



- Kinematic reconstruction + MVA classifier *($N_j \geq 6$)*
- 14 templates in total: N_j, N_b^{add} × 2 (e, μ)

← corrected by fit results

Simultaneous template fit to extract *ttbb/ttjj* cross-sections ratio

Inclusive $\sigma_{ttbb}/\sigma_{ttjj}$: *results* — lepton+jets

hadronB	$\sigma_{ttbb}/\sigma_{ttjj} = 0.015 \pm 0.005^{total}$	$\sigma_{ttbb} = 0.35 \pm 0.13^{total}$ pb
hardB	$\sigma_{ttbb}/\sigma_{ttjj} = 0.012 \pm 0.004^{total}$	$\sigma_{ttbb} = 0.27 \pm 0.11^{total}$ pb
NLO	$\sigma_{ttbb}/\sigma_{ttjj} = 0.011 \pm 0.003^{total}$	$\sigma_{ttbb} = 0.23 \pm 0.05^{total}$ pb

Effect of parton shower: hardB → hadronB

hadronB results consistent with dileptonic channel:

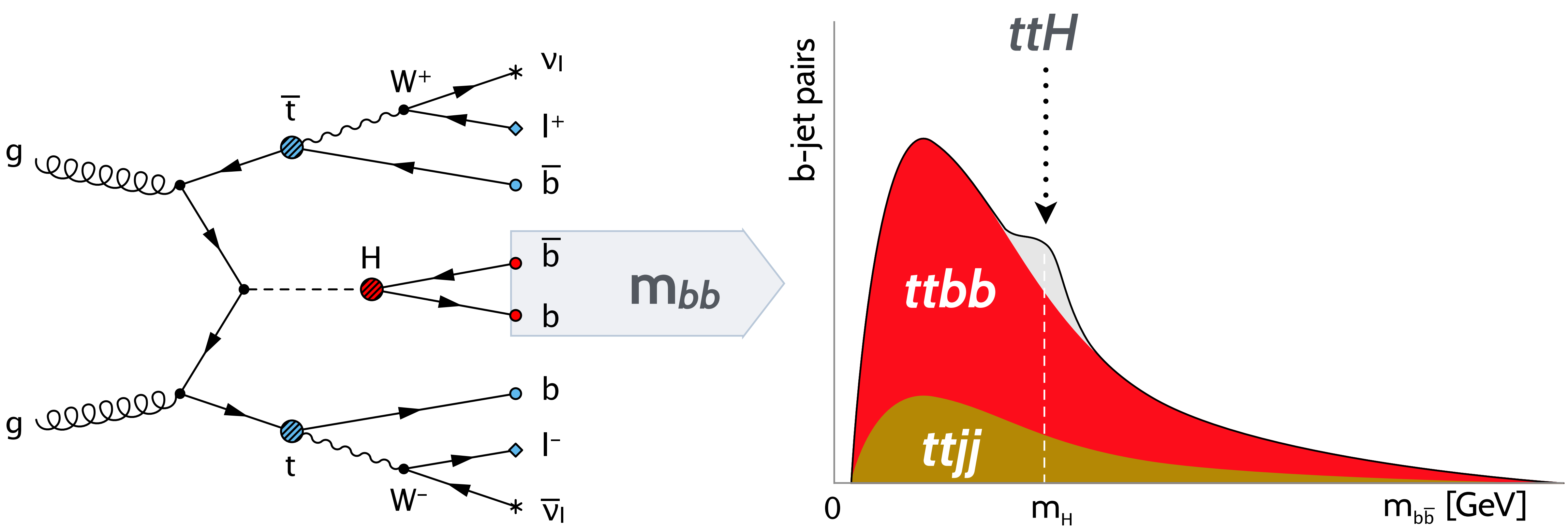
dilep.	$\sigma_{ttbb}/\sigma_{ttjj} = 0.022 \pm 0.006^{total}$	$\sigma_{ttbb} = 0.36 \pm 0.13^{total}$ pb

Dominant systematic uncertainties:

- b-tagging, JES/JER
- *top*-quark p_T reweighting, PDF, MC generators

tt+bb DIFFERENTIAL CROSS SECTIONS

- stringent test of QCD
- better sensitivity to *ttH*(*H*→*bb*)

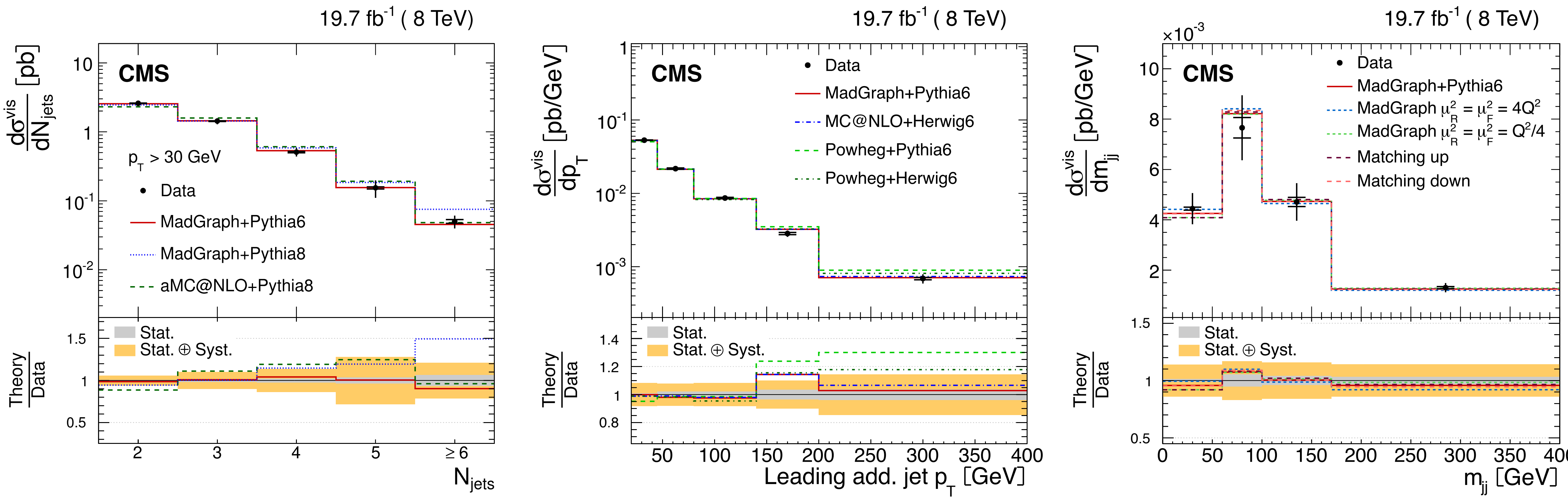


Differential tt + jets: results | dileptonic

Absolute σ_{tt} vs N_{jets}, H_T, m, dR|^{jj}, p_T, |η| |$^{j1, j2}$

arXiv:1510.03072

Kinematic reconstruction of the *tt* sytem: dileptonic channel



Predictions normalised to data: shapes reasonably described

Absolute σ_{tt} underestimated: as seen from inclusive measurements

Dominant uncertainties: JES, μ_R, μ_F, hadronisation model

- model dependence of the measurement needs to be reduced

Differential $t\bar{t}+b\bar{b}$: analysis — dileptonic

Absolute σ_{tt} vs m, $dR|^{bb}$, p_T, $|\eta|\,|^{b1,\,b2}$ — arXiv:1510.03072

B-jet assignment to the *tt* system by a BDT: dileptonic channel

Non-trivial signal definition: many *b* jets in the final state

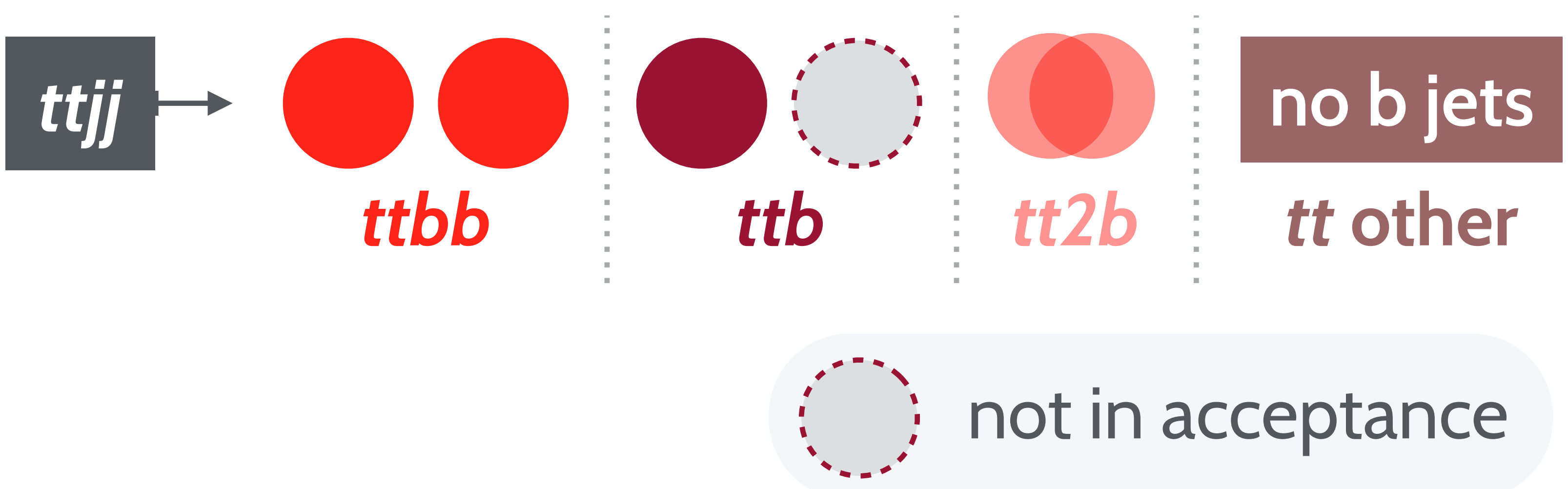
Clustering stable particles to jets: excluding ν, and *e*/*μ* from *W* decay

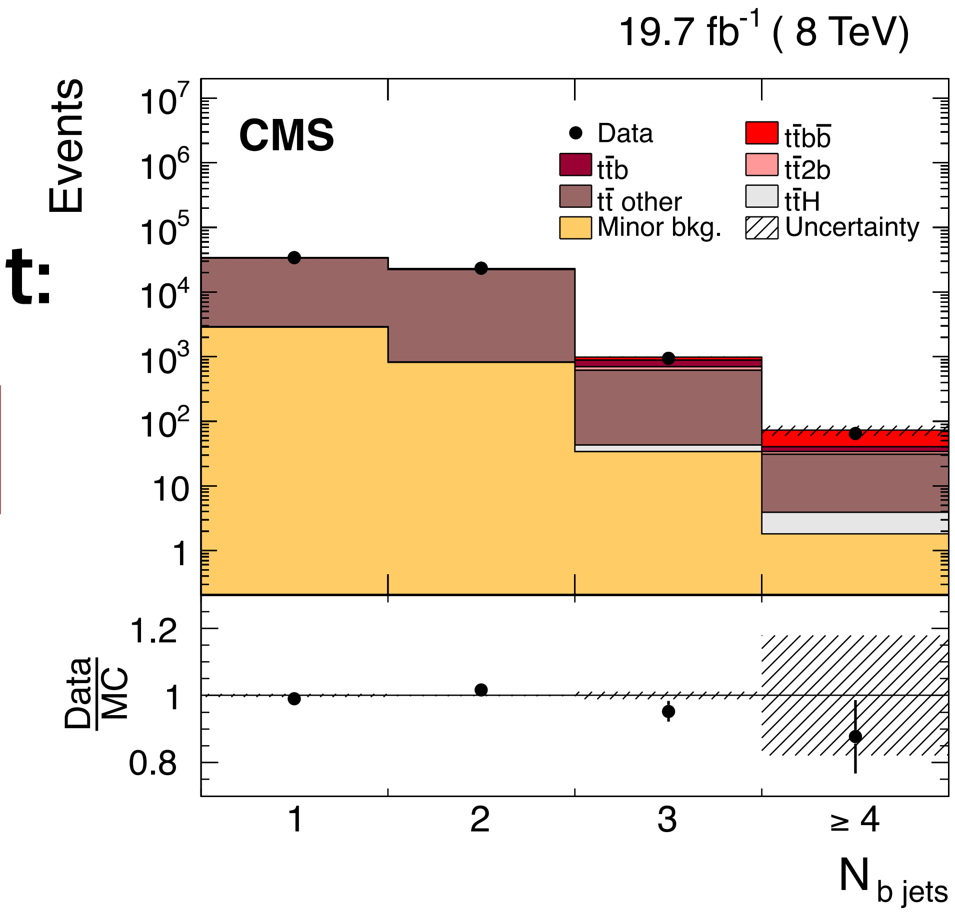
Overlapping *b* jets identified: ≥1 *b* hadron in jet

Jet origin identified by analysing particle chain

- jet → *b* hadron → *b* quark → *g*/*t*/*H*/*Z*

ttjj components constrained by template fit:



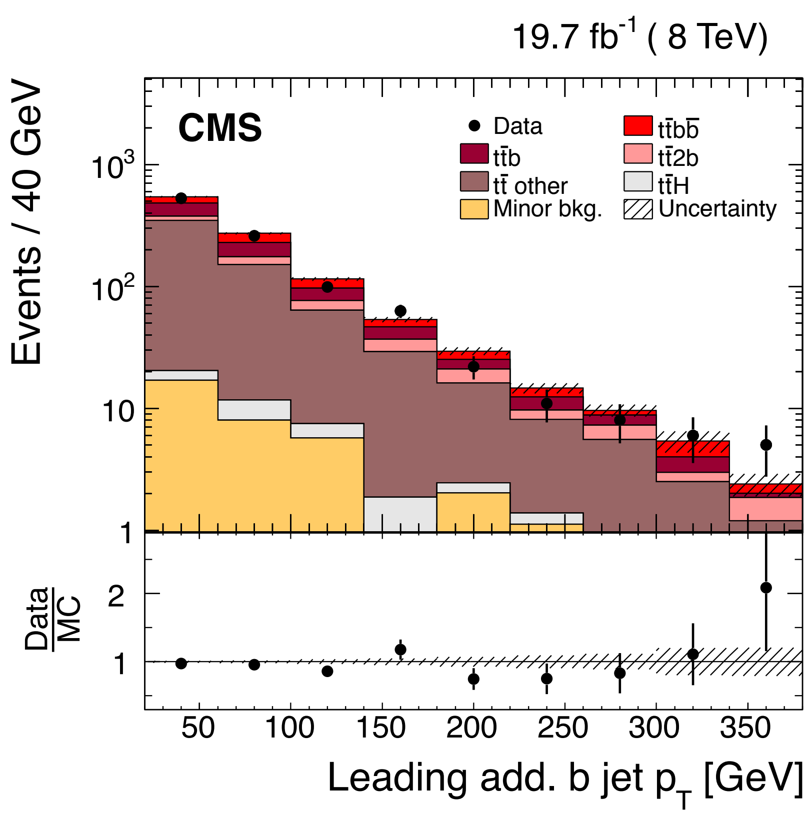


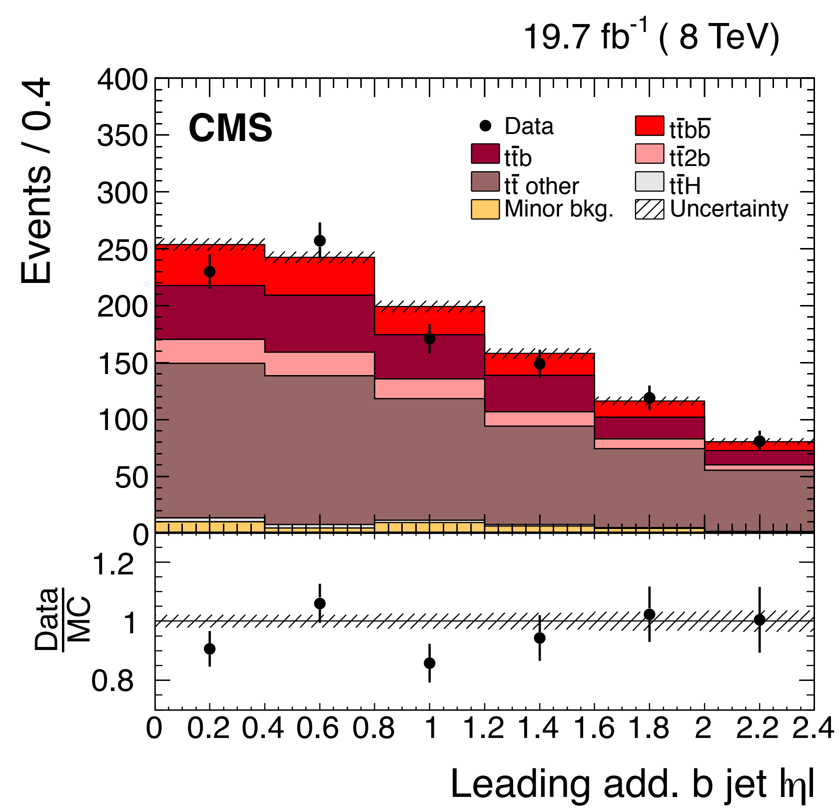
Identification of additional *b* jets at reconstruction level:

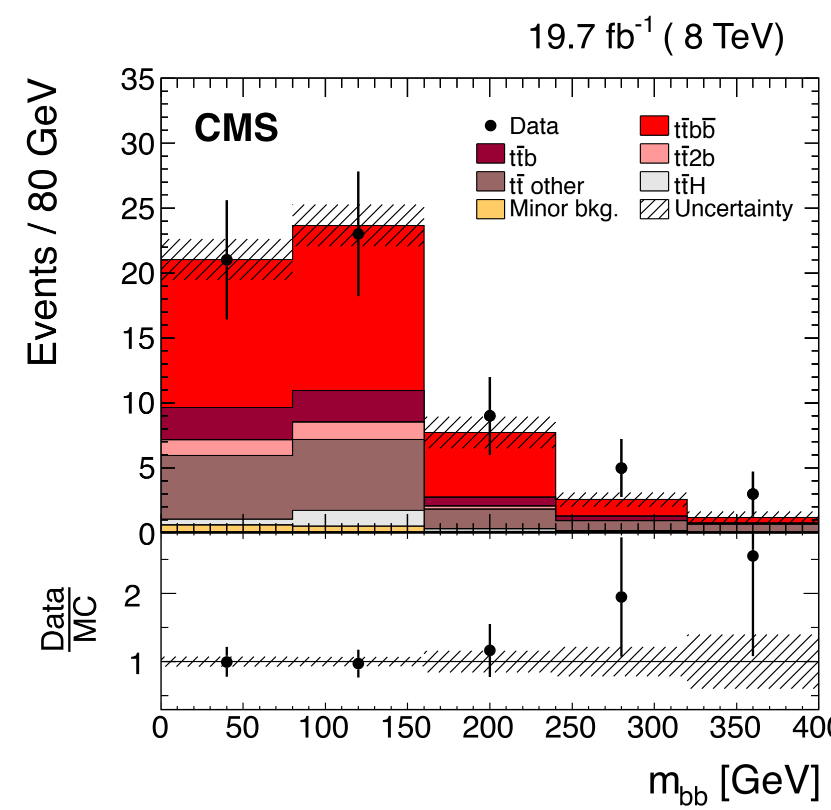
All b-tagged jets - $2 \cdot b^{t\to\underline{b}}$ = additional *b* jets: ordered by ↓p_T

$b^{t\to\underline{b}}$ identified using MVA: based on TMVA BDT

- trained on *ttH*(*H*→*bb*) simulations
- avoiding bias towards *ttH*







correction for migrations

data events

background events

$$\frac{d\sigma}{dX_i} = \frac{\sum_j A_{ij}^{-1}\left[N_j^{\mathrm{data}} - N_j^{\mathrm{bkg}}\right]}{\varepsilon \cdot \mathcal{L} \cdot \Delta x_i}$$

subleading: p_{T} $|\eta|$

2 leading: $\Delta R_{b\bar{b}}$ $m_{b\bar{b}}$

efficiency of event selection

luminosity

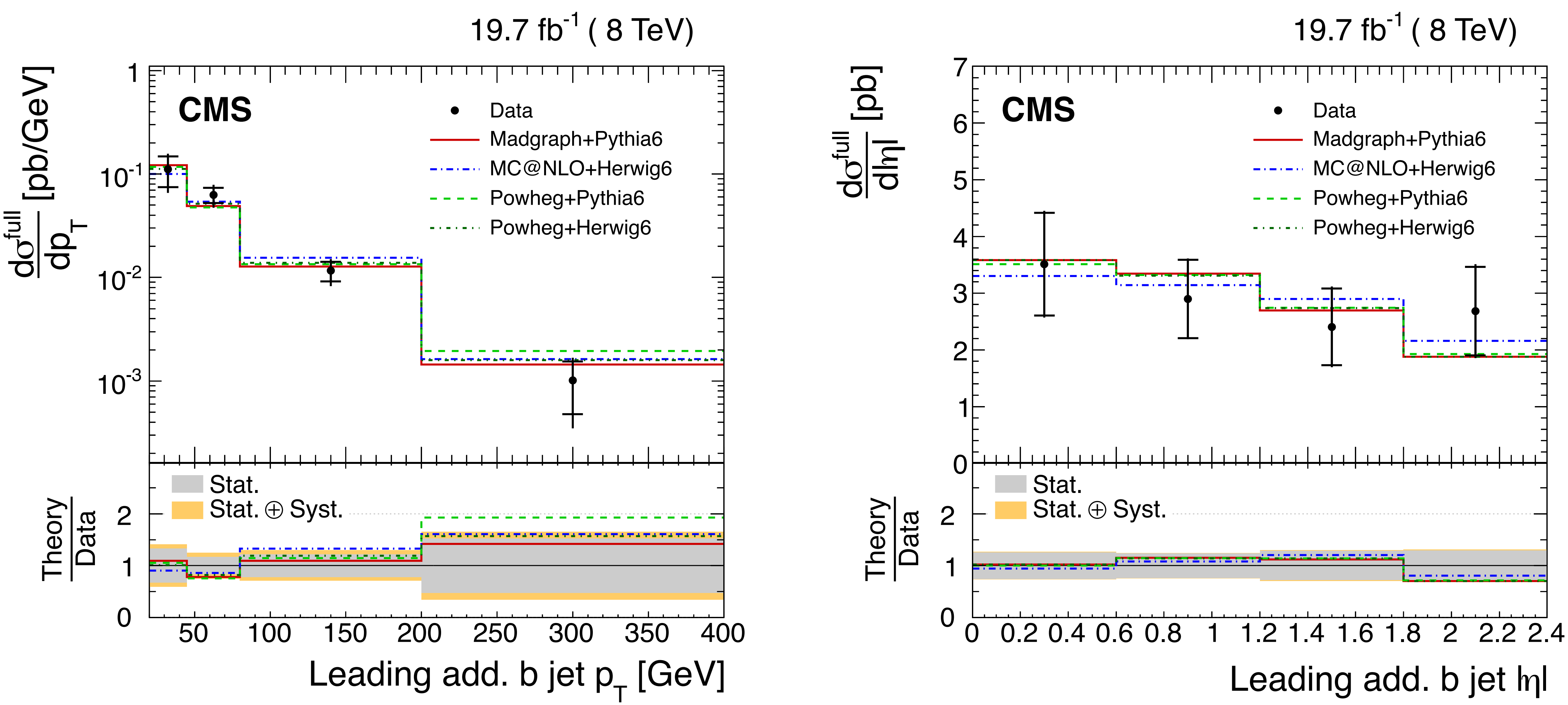
bin width

Regularised SVD unfolding

- binning optimised to have ≥40% events reconstructed in the correct bin

Leading additional *b* jet: p_T > 20 GeV, |η| < 2.4

arXiv:1510.03072



MC predictions normalised to Data

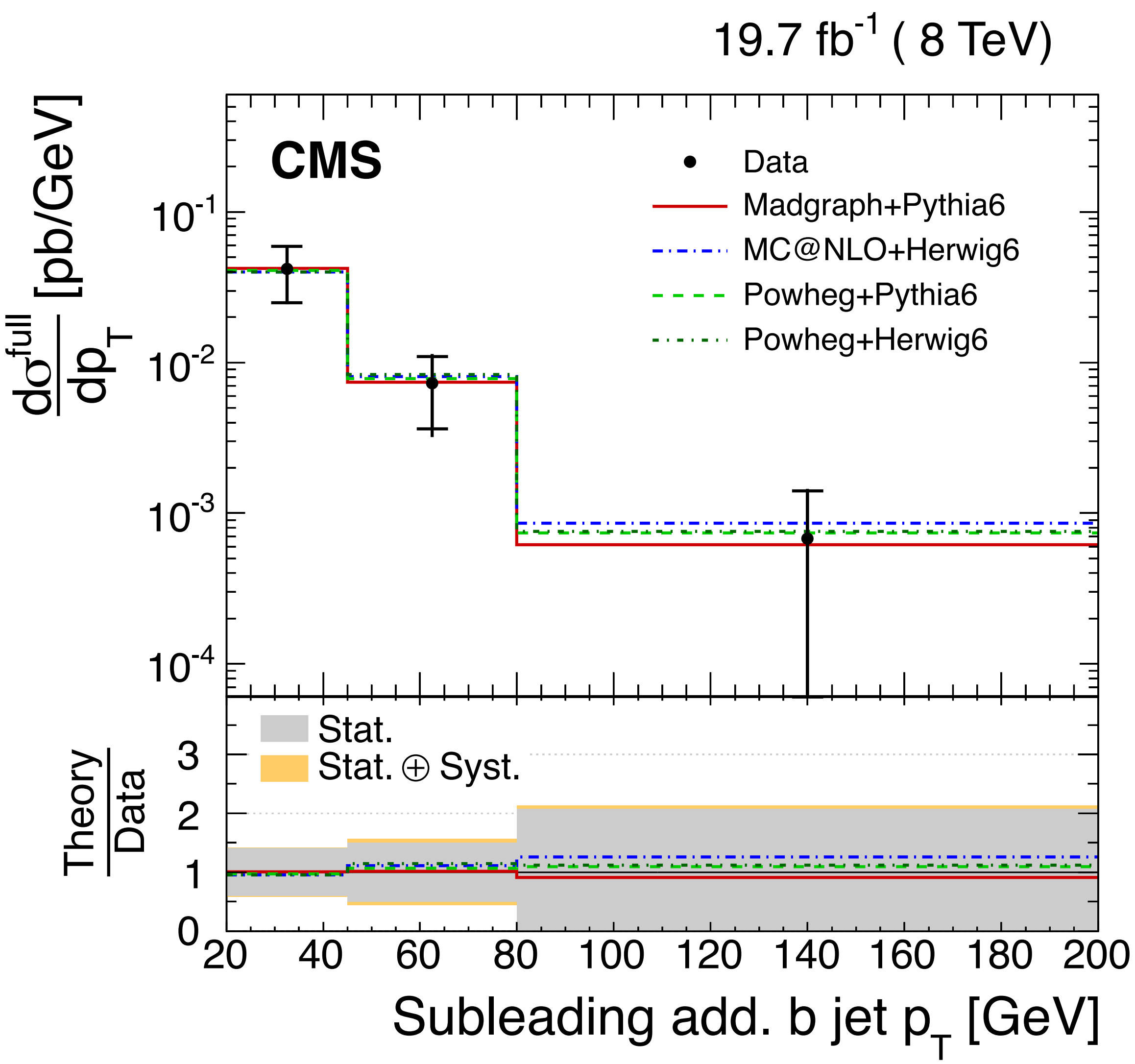
Limited by statistical uncertainty

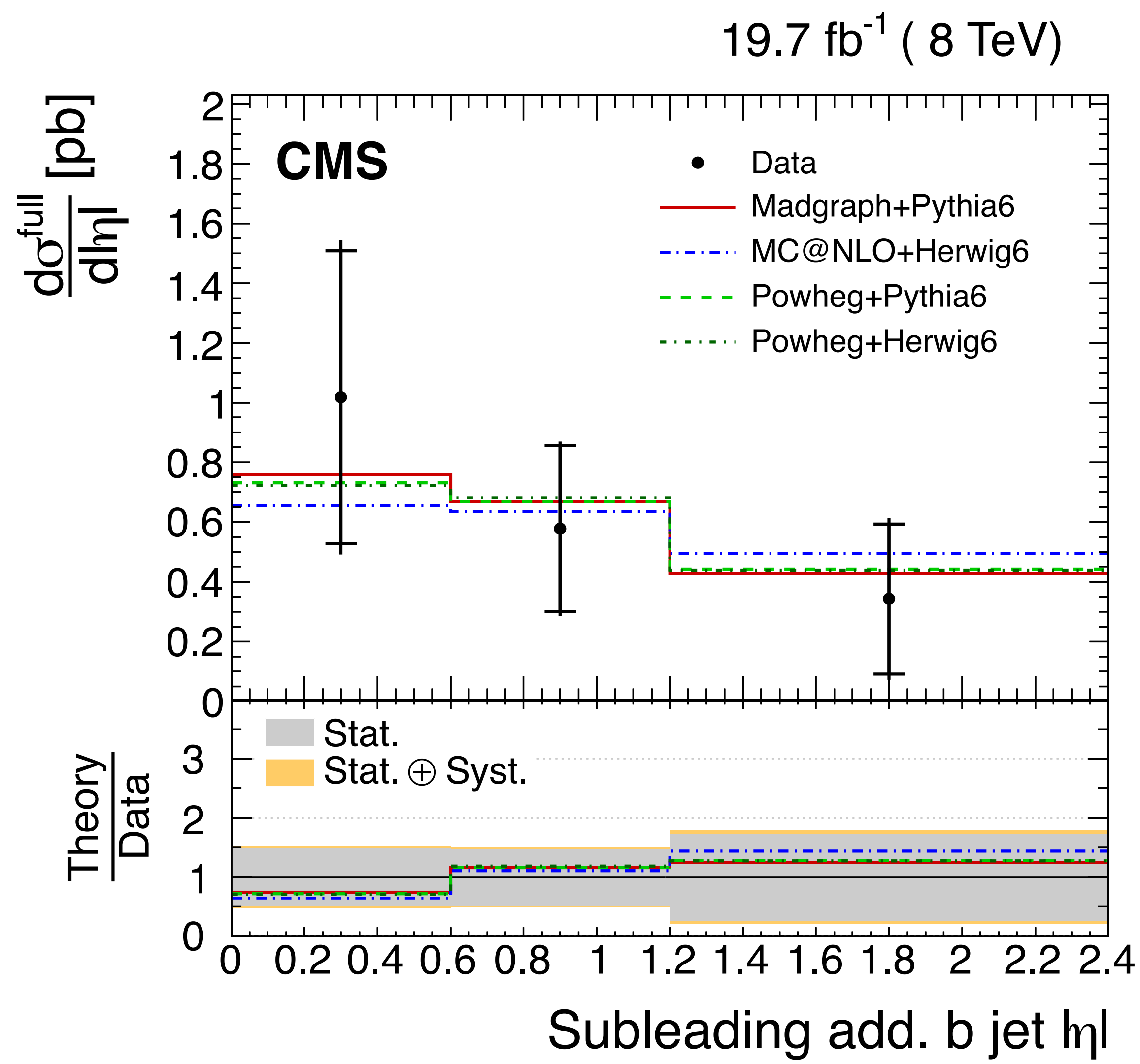
Well described by the considered MC predictions

Differential tt + bb: results dileptonic

Subleading additional *b* jet: $p_T > 20$ GeV, $|\eta| < 2.4$

arXiv:1510.03072





MC predictions normalised to Data

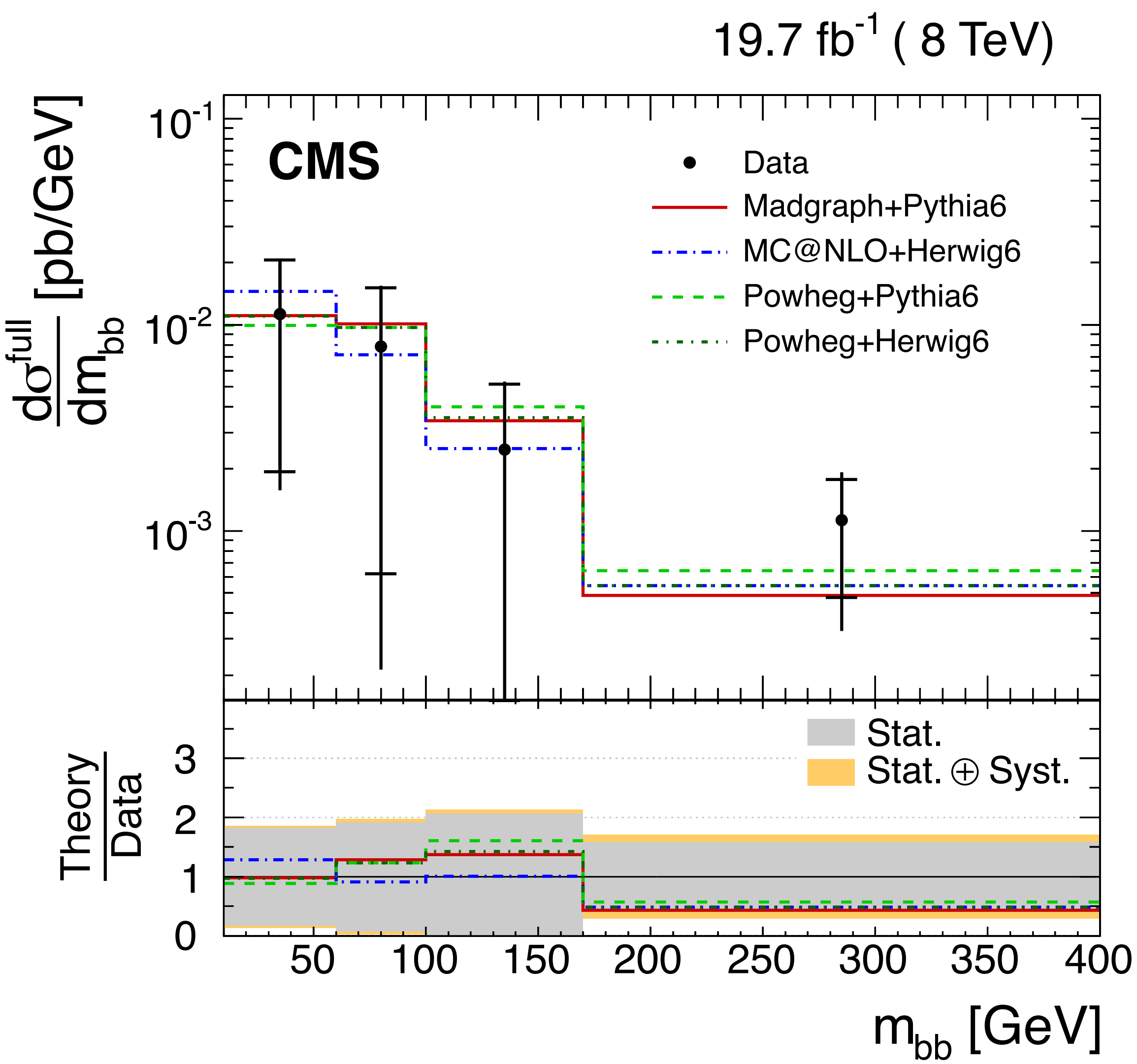
Even larger statistical uncertainty

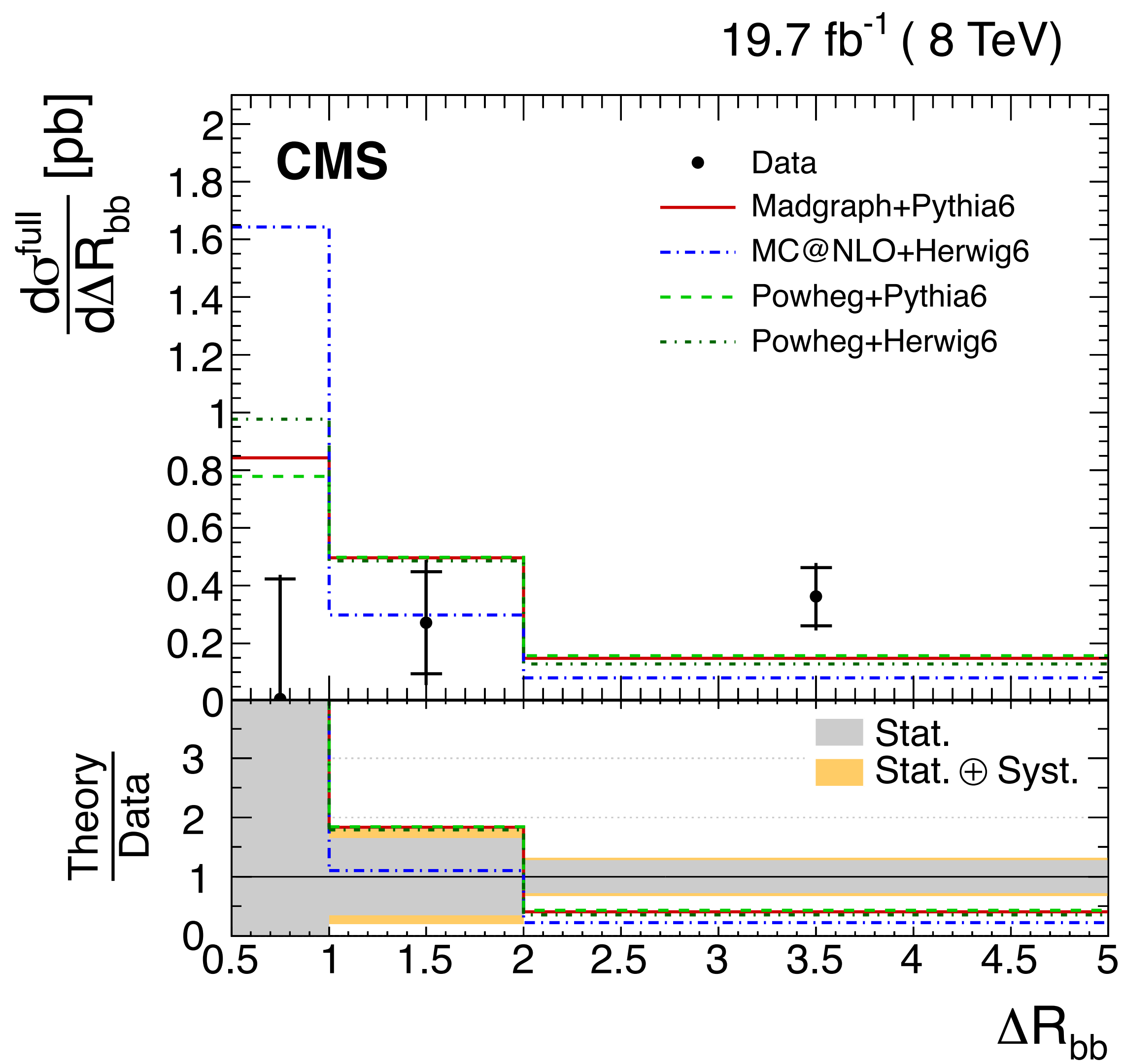
Can't discriminate between different predictions yet

Differential tt + bb: results

Pair of additional *b* jets: $p_T > 20$ GeV, $|\eta| < 2.4$

arXiv:1510.03072





MC predictions normalised to Data

m_{bb} well described. Not much difference between predictions

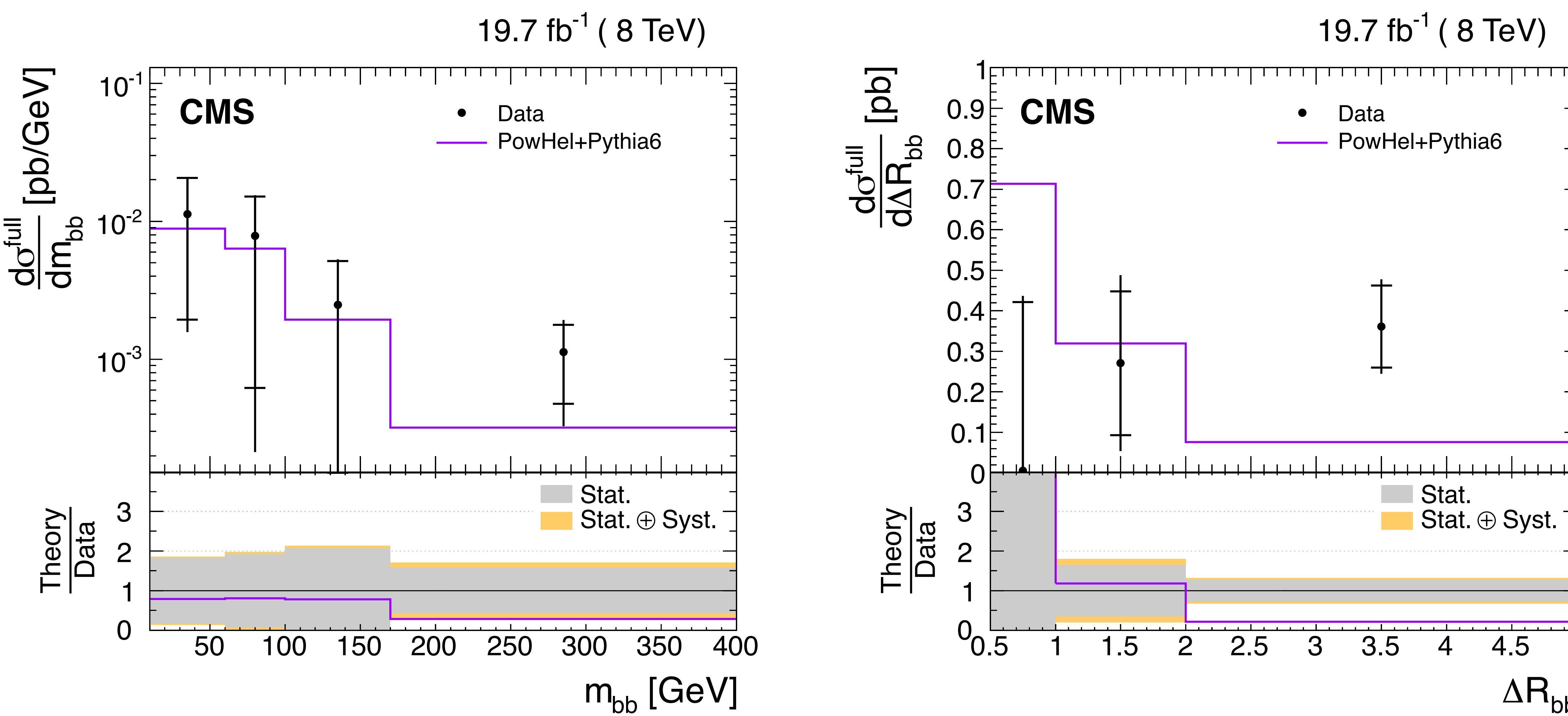
ΔR_{bb} affected by migrations due to wrong *b*-jet assignments

Differential tt + bb: results

dileptonic

Pair of additional *b* jets: $p_T > 20$ GeV, $|\eta| < 2.4$

arXiv:1510.03072



Compared to a full NLO calculation: identical process definitions

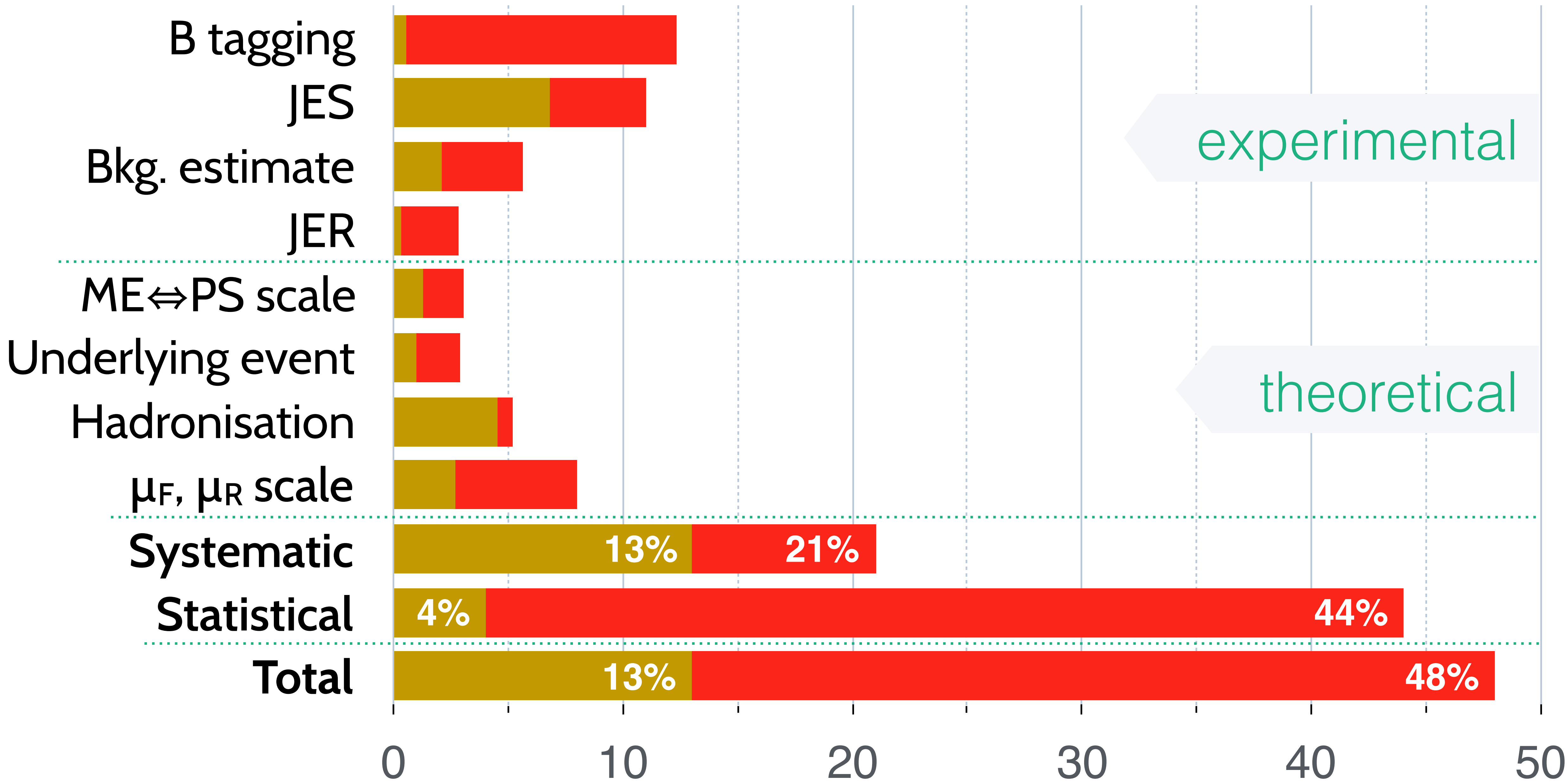
Shapes and normalisations compared

Normalisation uncertainty on the NLO prediction: ~30%

Differential tt + bb: results dileptonic

Precision limited by systematic (statistical) uncertainty in *tt+jj* (*tt+bb*)

Typical uncertainties: median of bins → average over variables



Significant improvement expected with more data from √s=13 TeV

Summary

Top-quark production with heavy-flavour jets is an important process to study, especially in view of *ttH* searches

Inclusive measurements performed in dileptonic and semileptonic decay channels

- consistent results, compatible with NLO predictions
- cross-section increase due to Parton Shower evaluated
- modelling uncertainties comparable to experimental

Differential measurement performed in dileptonic channel

- important side-band region for *ttH*($H \rightarrow bb$) searches
- comparison to NLO *ttbb* calculation shows good agreement
- limited by available statistics from Run I data

Many improvements expected in Run II statistics, b-tag, theory, ...

Thank you

for attention