Top-quark pair production cross-section measurements with the ATLAS detector

Adam Bozson | *Royal Holloway, University of London*
On behalf of the ATLAS Collaboration

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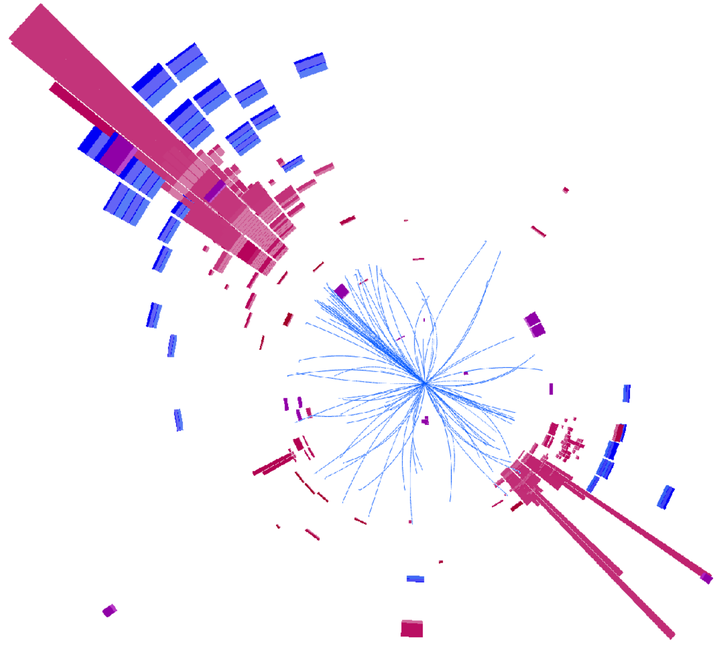
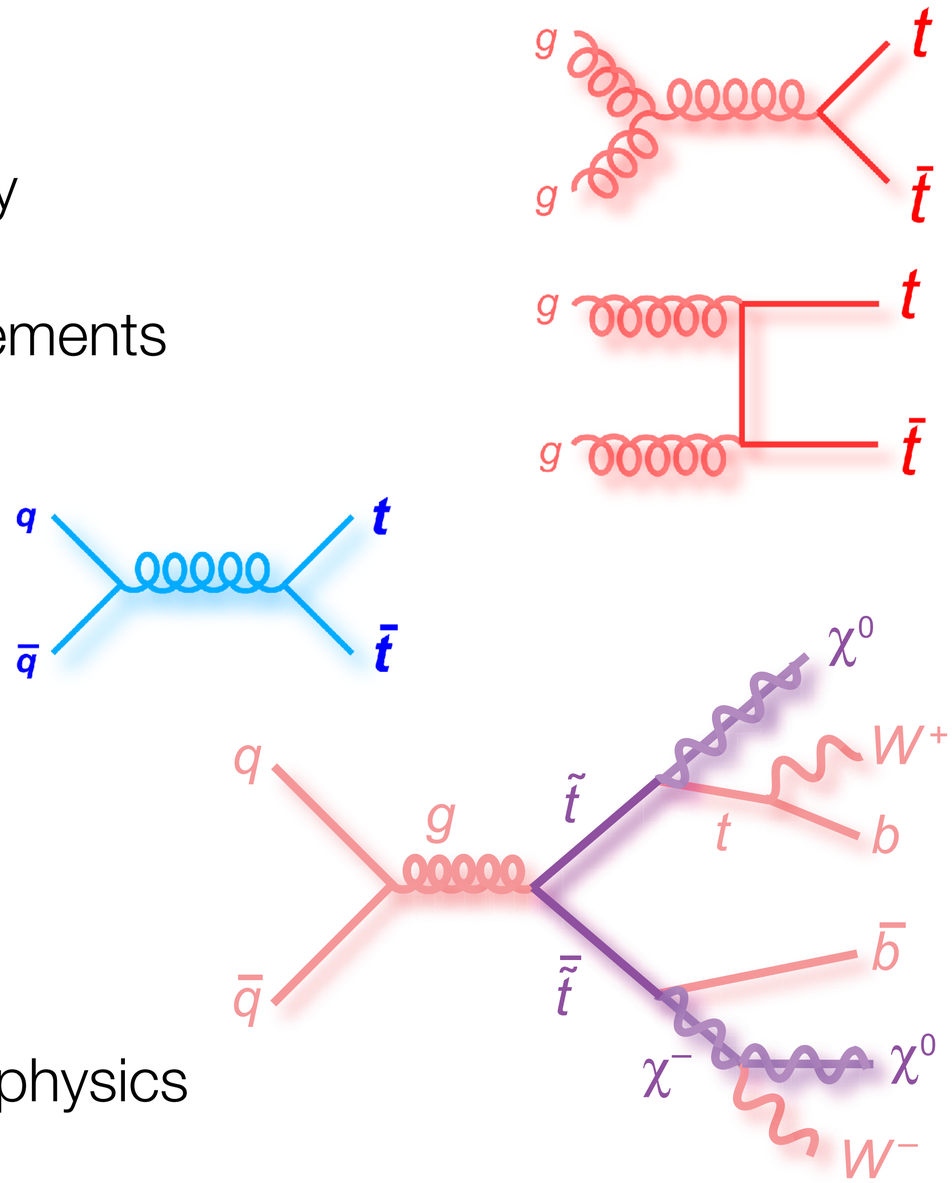


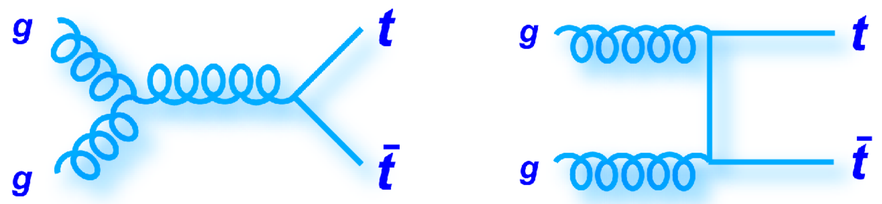
Why study the top quark?

- Heaviest SM particle (172.5 GeV)
  - Role in EW symmetry breaking, vacuum stability
  - Background to exotic searches, Higgs measurements
- Decays before hadronisation ($\tau < 10^{-24}$ s)
  - We can study a ‘bare’ quark
  - Allows precision QCD measurements
- Window into new physics
  - Understanding tt production is crucial for BSM physics

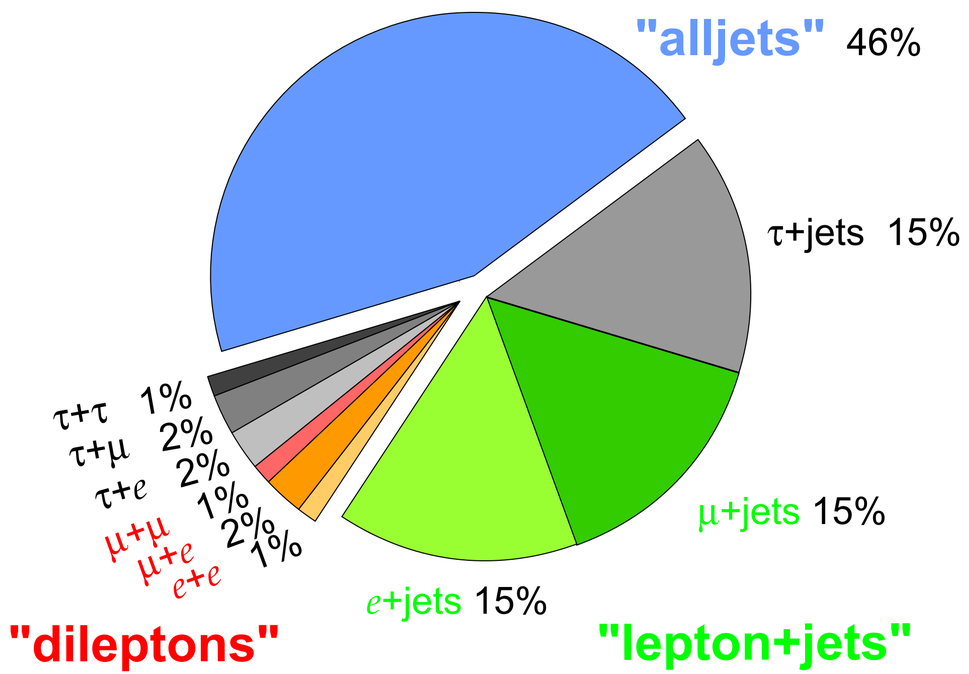


tt cross-sections — motivation

- Cross sections are measured inclusively and differentially
- Theoretical motivation: constraining EFTs, gluon PDF at high x, test predictions at highest precision
- Major background to ttH(bb), exotic, SUSY searches
- Top modelling / MC tuning
  - Top p_T has been poorly described by some generators
- A range of final states separate our analyses



Top Pair Branching Fractions



tt cross sections — analysis channels

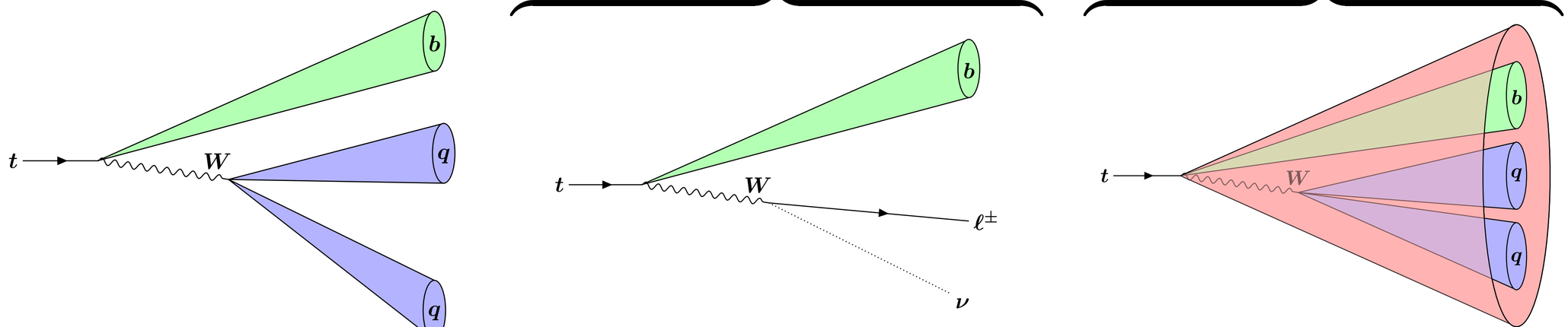
- Top quark decays t→Wb

Dilepton: 2 of these

Reconstruct $t\bar{t}$ system with neutrino weighting

All-Hadronic: 2 of these

Reduce combinatorics by targeting boosted



Lepton+Jets Resolved

Lepton+Jets Boosted

Utilise both reconstruction techniques in same paper

Unfold also in bins of N_{jets} (resolved only)

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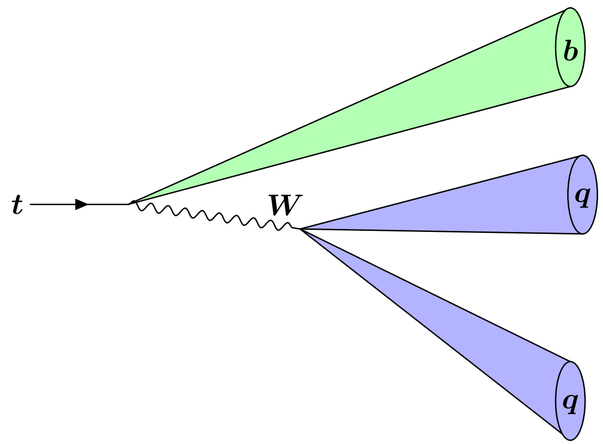

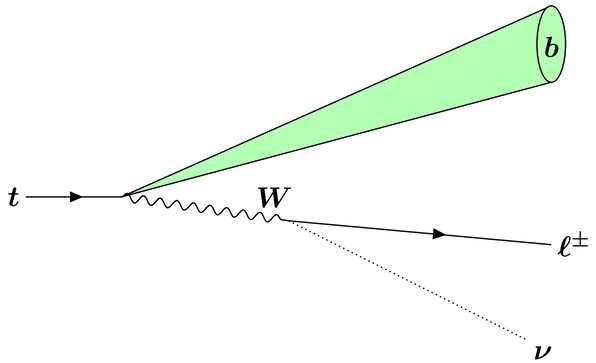

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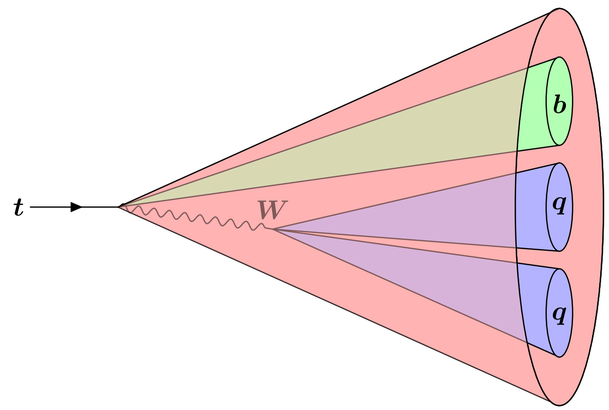


Lepton+Jets Resolved

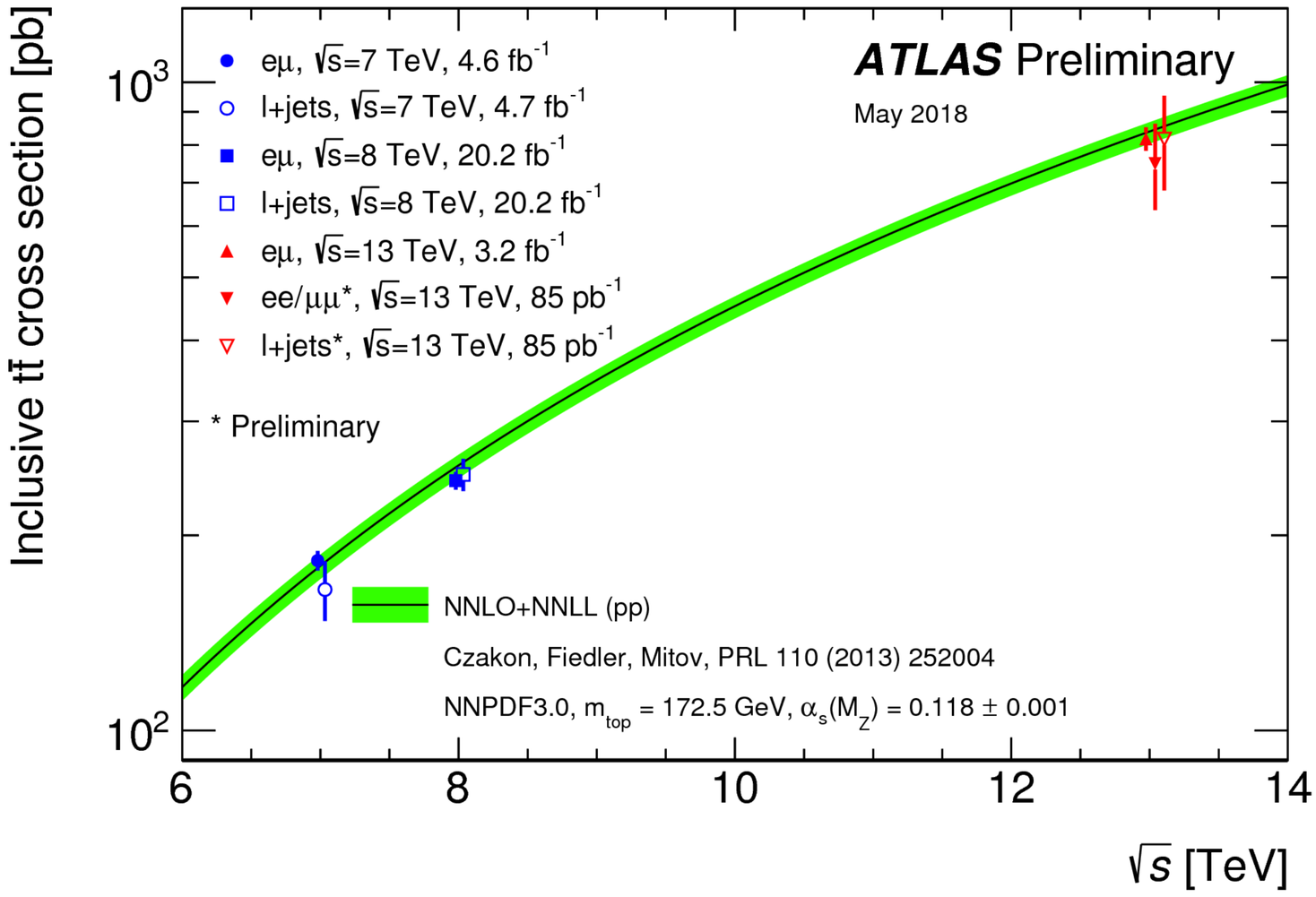
Lepton+Jets Boosted

Utilise both reconstruction techniques in same paper

Unfold also in bins of N_{jets} (resolved only)

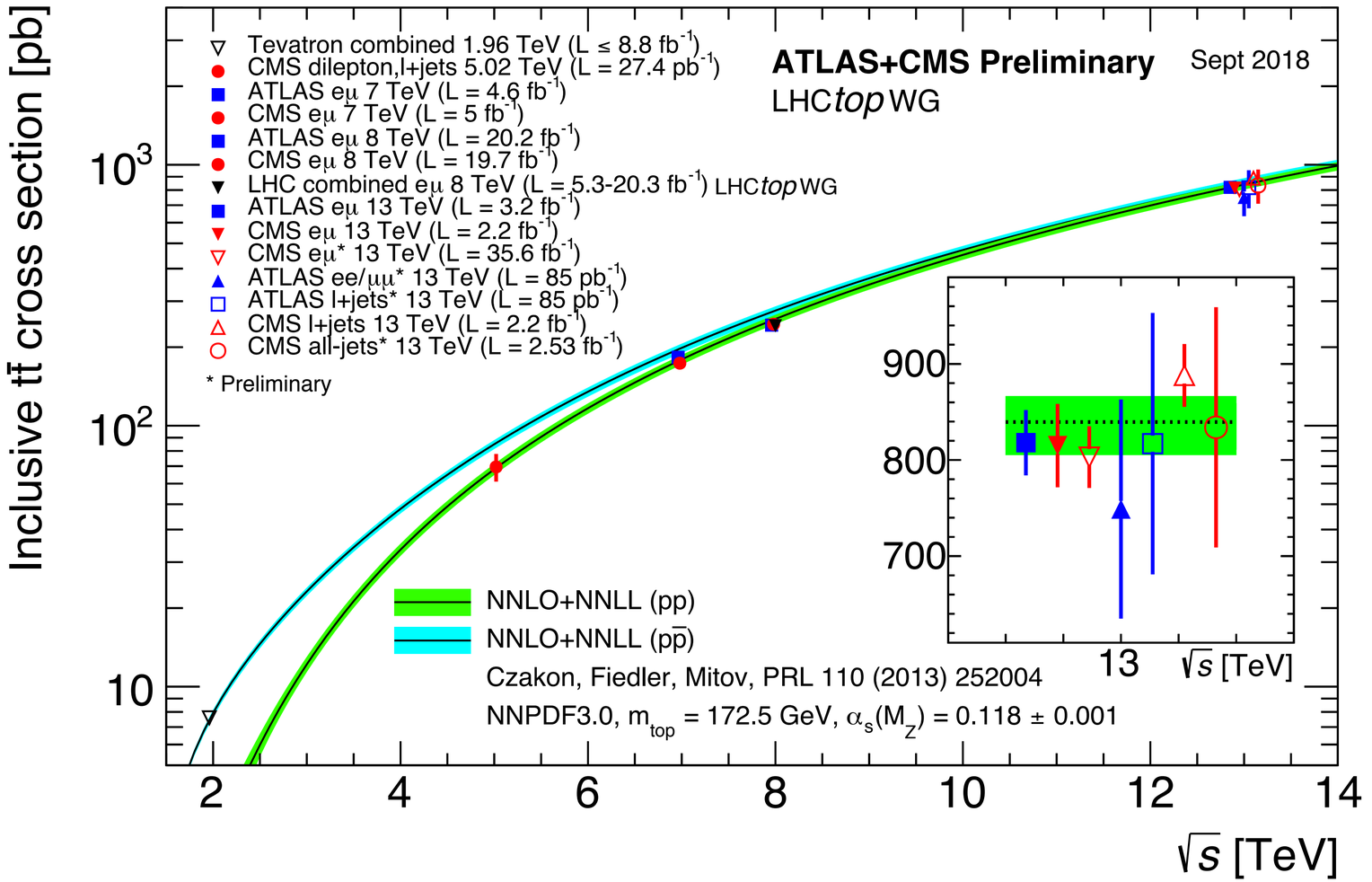
tt inclusive cross-section

- ATLAS has performed measurements at $\sqrt{s}$ = 7, 8, 13 TeV



tt inclusive cross-section

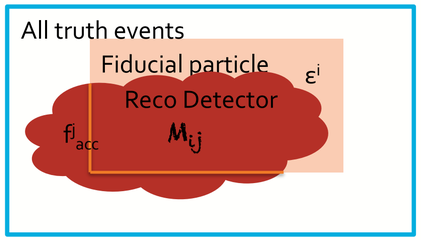
- Combination of Tevatron, ATLAS, CMS measurements over 2–13 TeV



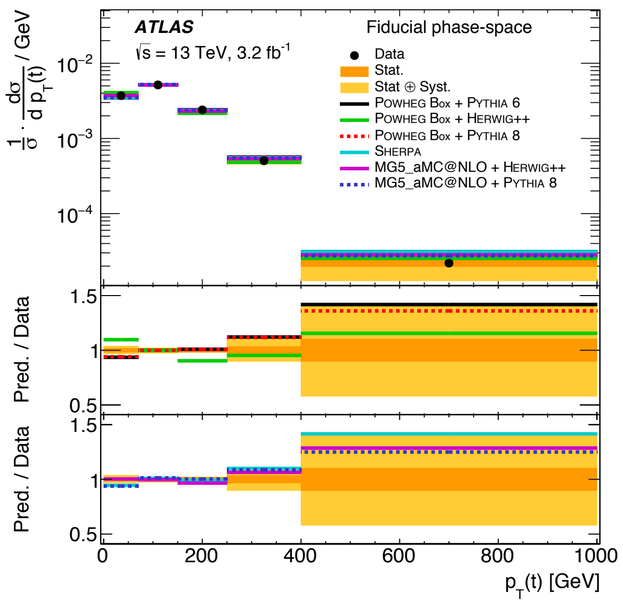
tt differential cross sections — overview

- All analyses share common unfolding strategy to fiducial volume at particle level
  - Some also unfold to parton level
  - 2D unfolding increasingly possible

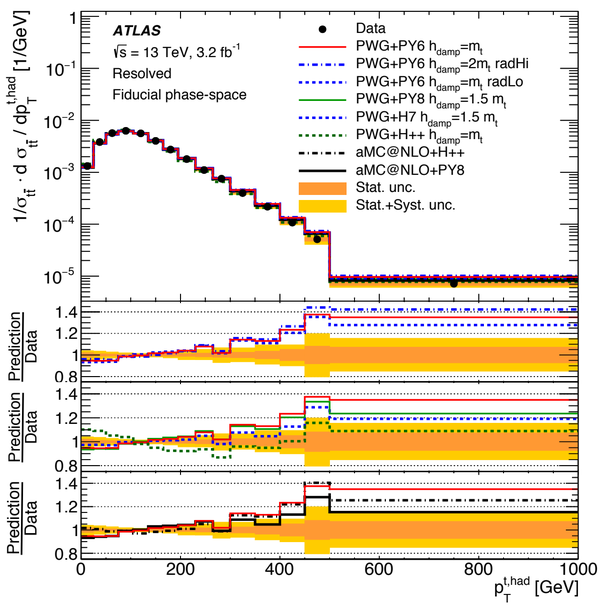
$$\frac{\mathrm{d}\sigma}{\mathrm{d}X_i} \equiv \frac{1}{L \cdot \Delta X_i \cdot \epsilon_i} \sum_j M_{ij}^{-1} f_j^{\mathrm{acc}} \left(N_j^{\mathrm{reco}} - N_j^{\mathrm{bkg}} \right)$$



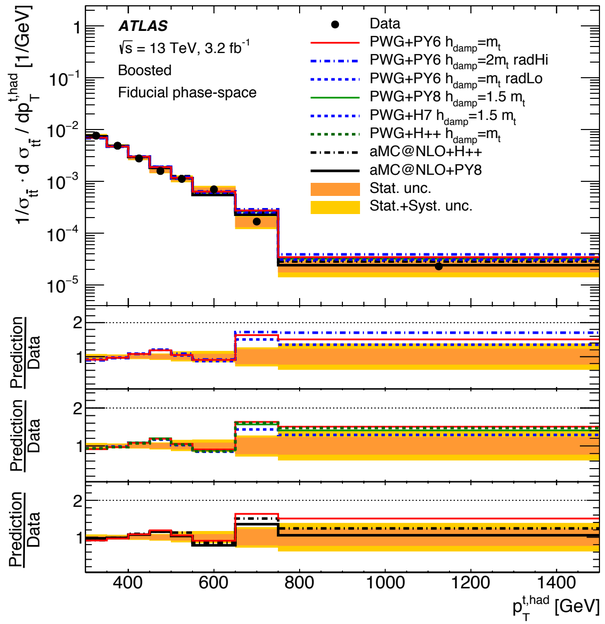
- Systematics dominate uncertainties: top modelling (matrix element, parton shower), jet energy scale/resolution



Dilepton: paper



l+jets resolved: paper



l+jets boosted: paper

tt differentia

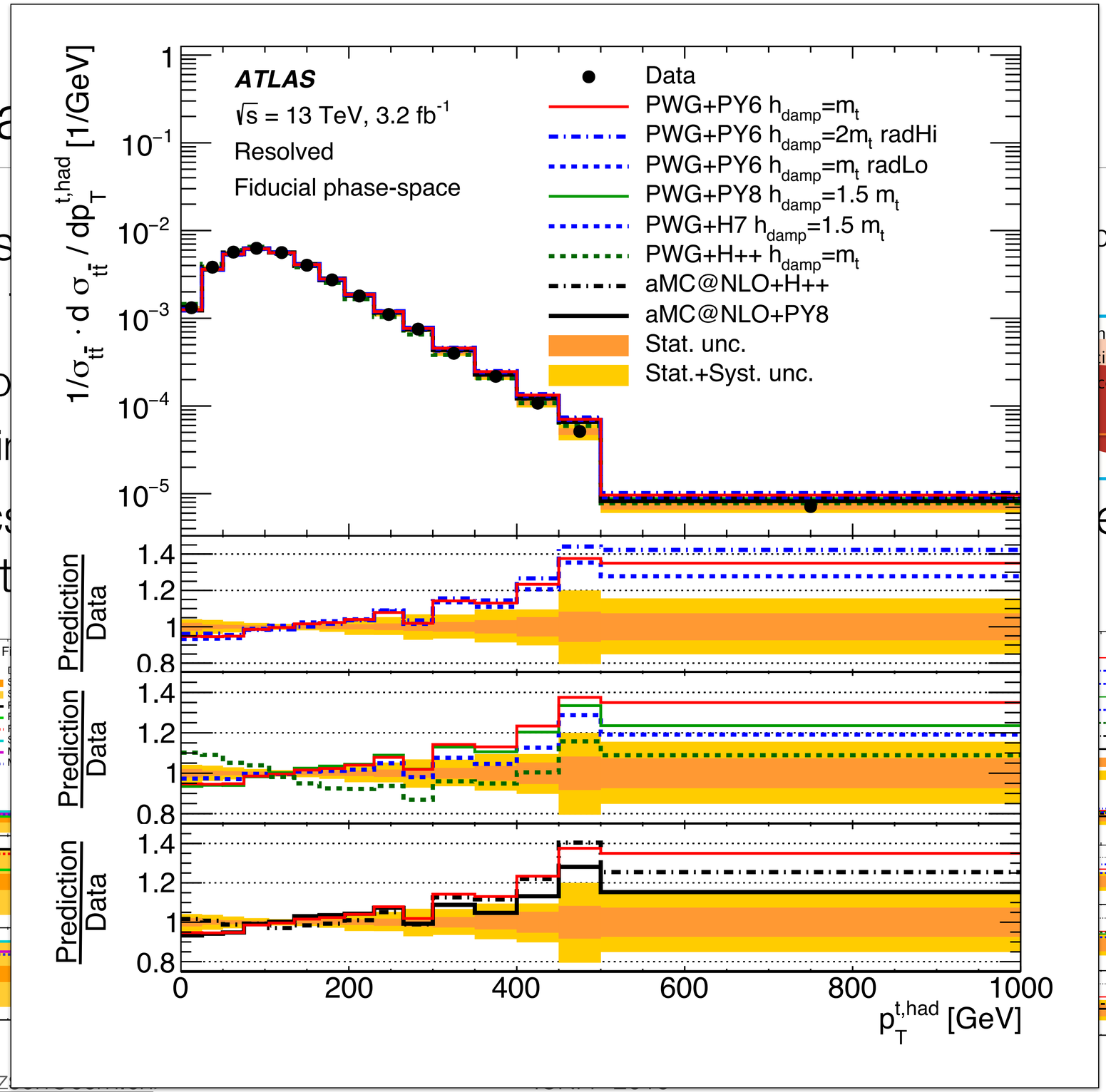
- All analyses
  strategy to
  - Some also
  - 2D unfoldi
- Systematics
  shower), jet

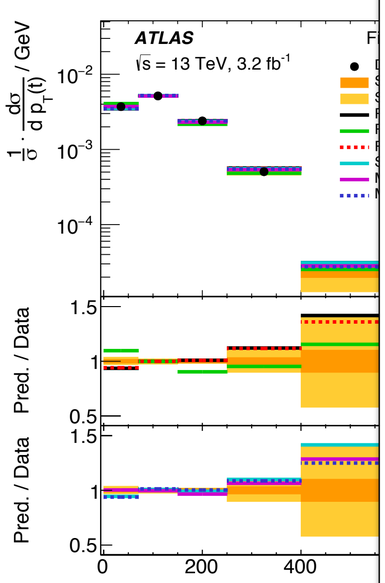
cc $\left(N_j^{\text{reco}} - N_j^{\text{bkg}} \right)$

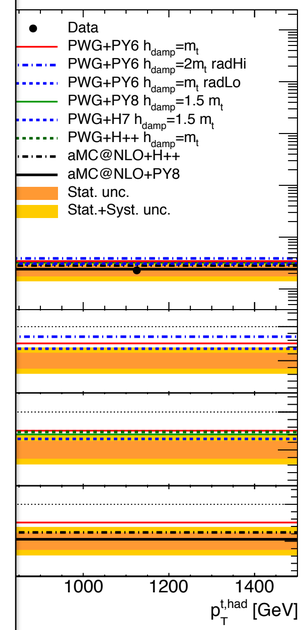
nts
ial particle ε^i
co Detector
$M_{i,j}$

ent, parton

l+jets boosted: paper







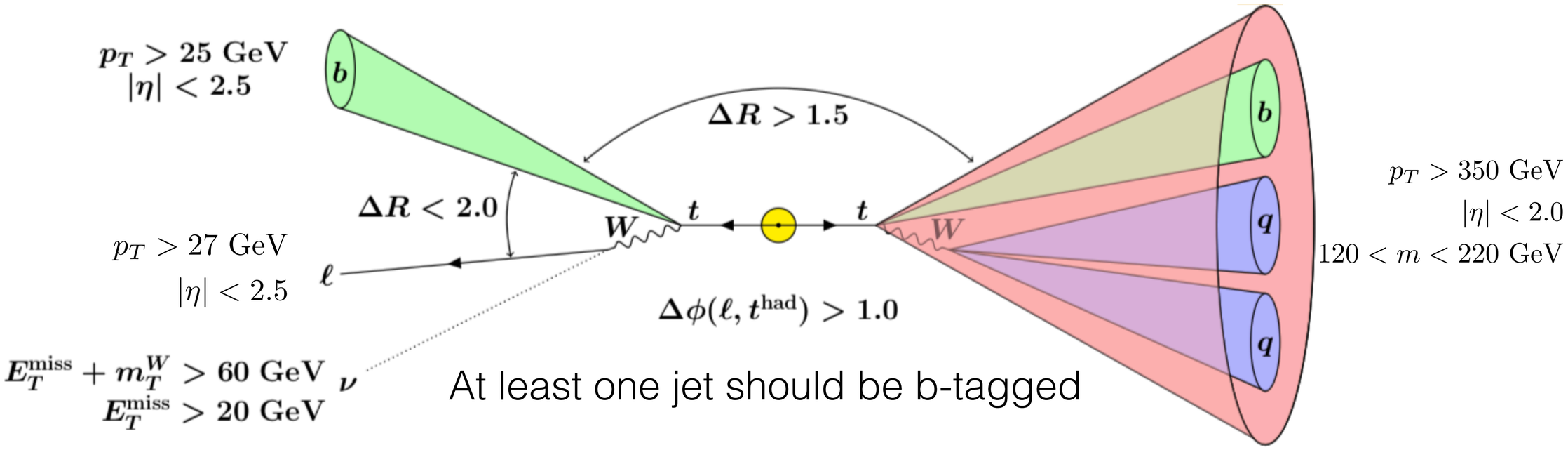
tt differential cross-sections from ATLAS at $\sqrt{s}$ = 13 TeV

- https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults
- **Aug ’19: l+jets boosted differential cross-sections** Submitted to EPJC
- **Nov ’18: tt+bb inclusive and differential cross-sections** JHEP 04 (2019) 046
- Feb ’18: tt+*n* jets differential cross-sections JHEP 10 (2018) 159
- Jan ’18: tt all-hadronic boosted differential cross-sections Phys. Rev. D (2018) 98
- Aug ’17: tt l+jets differential cross-sections JHEP 11 (2017) 191
- Dec ’16: tt *e*+μ differential cross-sections Eur. Phys. J. C77 (2017) 292

Boosted tt l+jets — strategy

Submitted to EPJC

- High p_T tops can probe regions of phase space useful for new physics
- Events with 1 hadronic, 1 leptonic top. Selection:



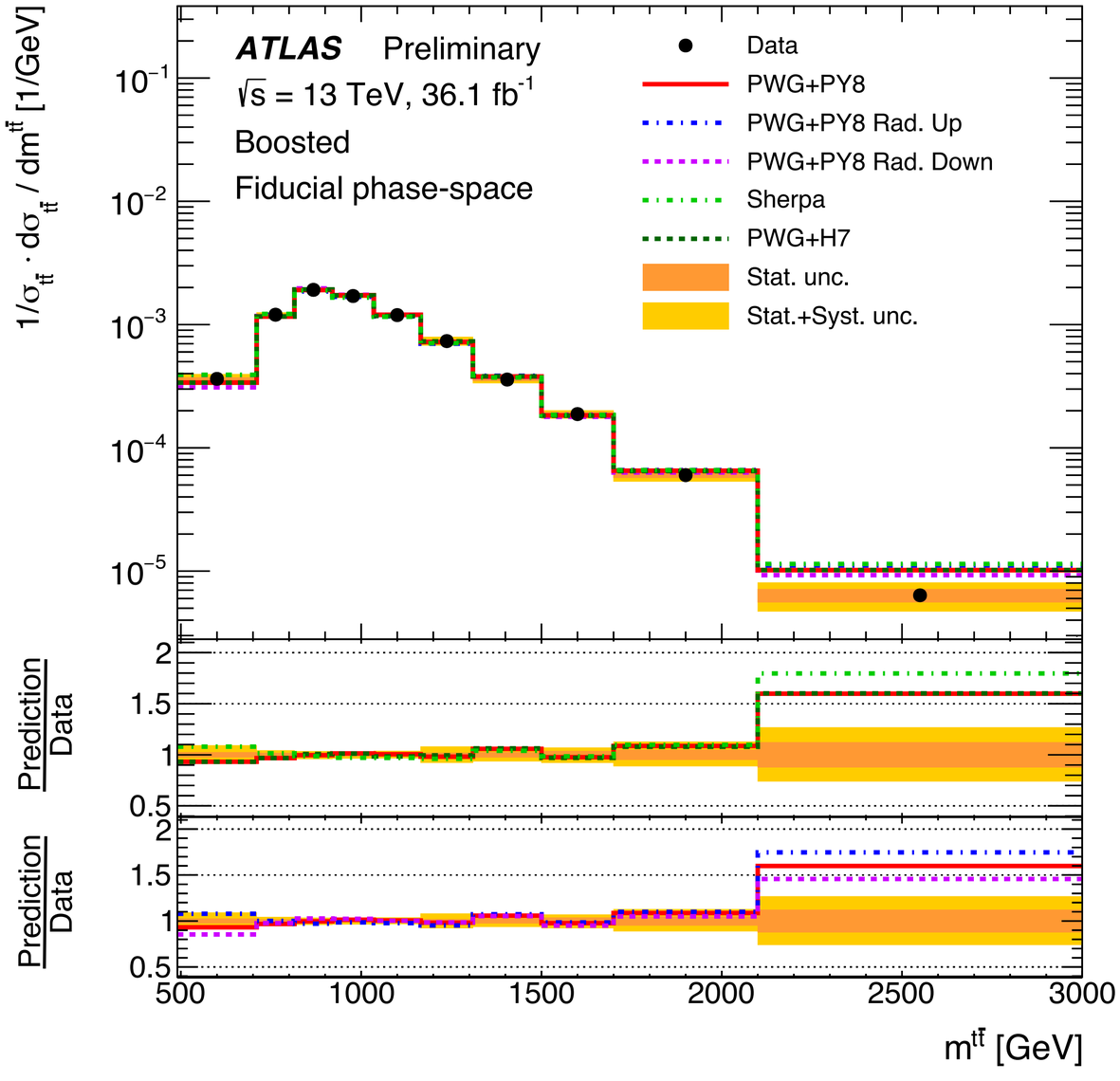
At least one jet should be b-tagged

- R=1.0 reclustered from R=0.4 jets with anti-k_T algorithm
- Generally low background, dominated by W+jets and single top
- Unfold to particle and parton level

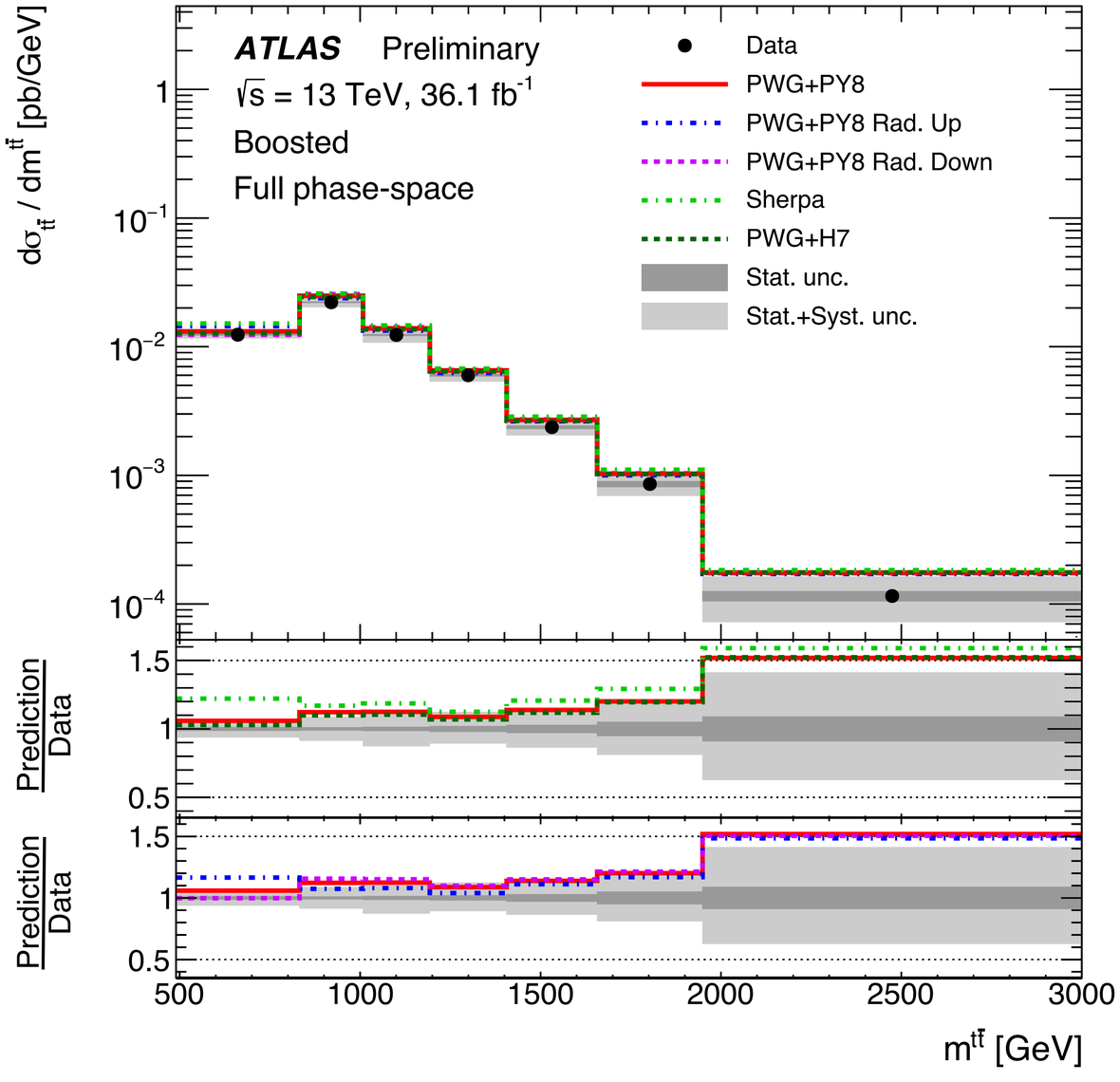
Boosted tt l+jets — results — m_{tt}

Submitted to EPJC

Particle level



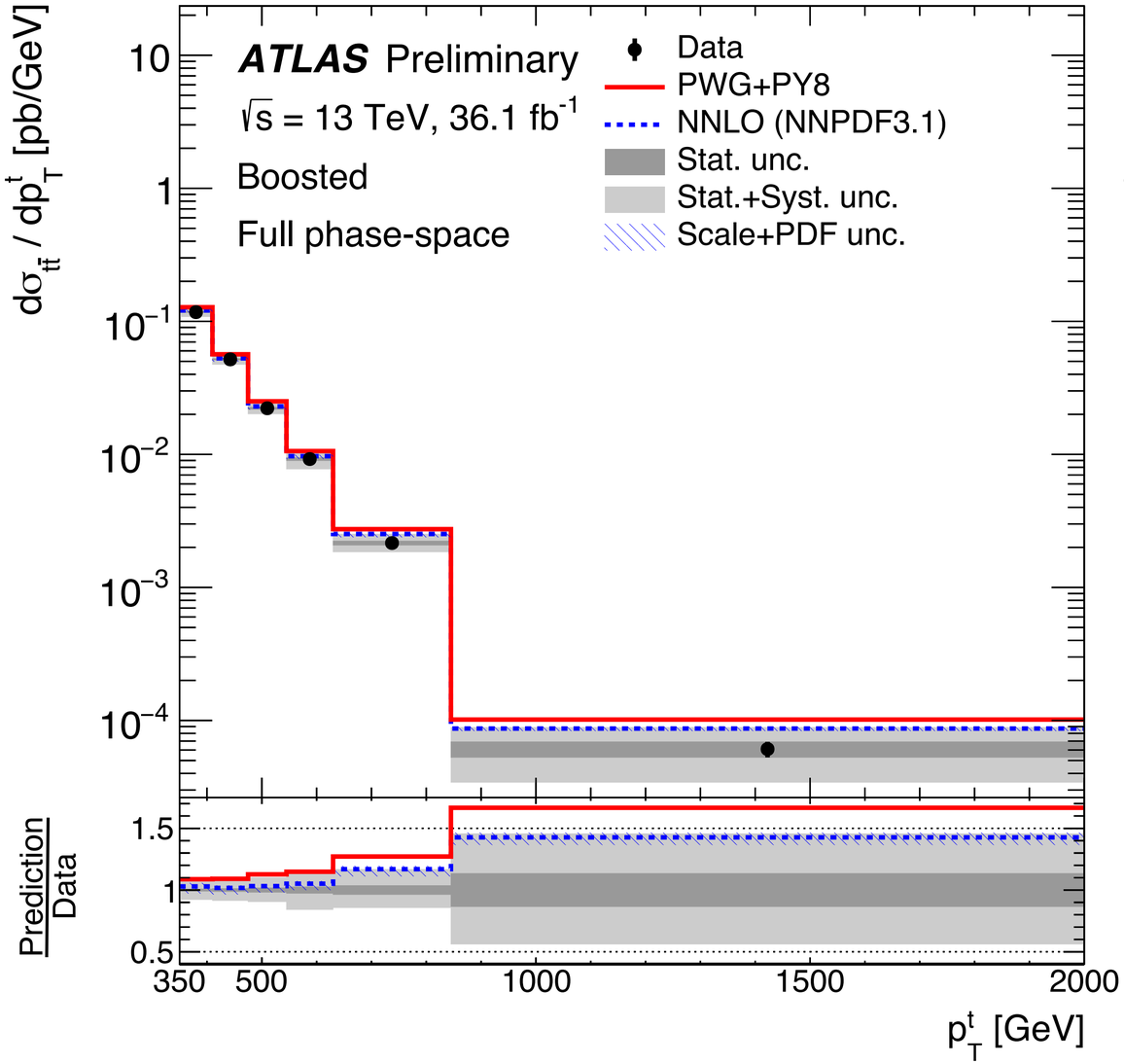
Parton level



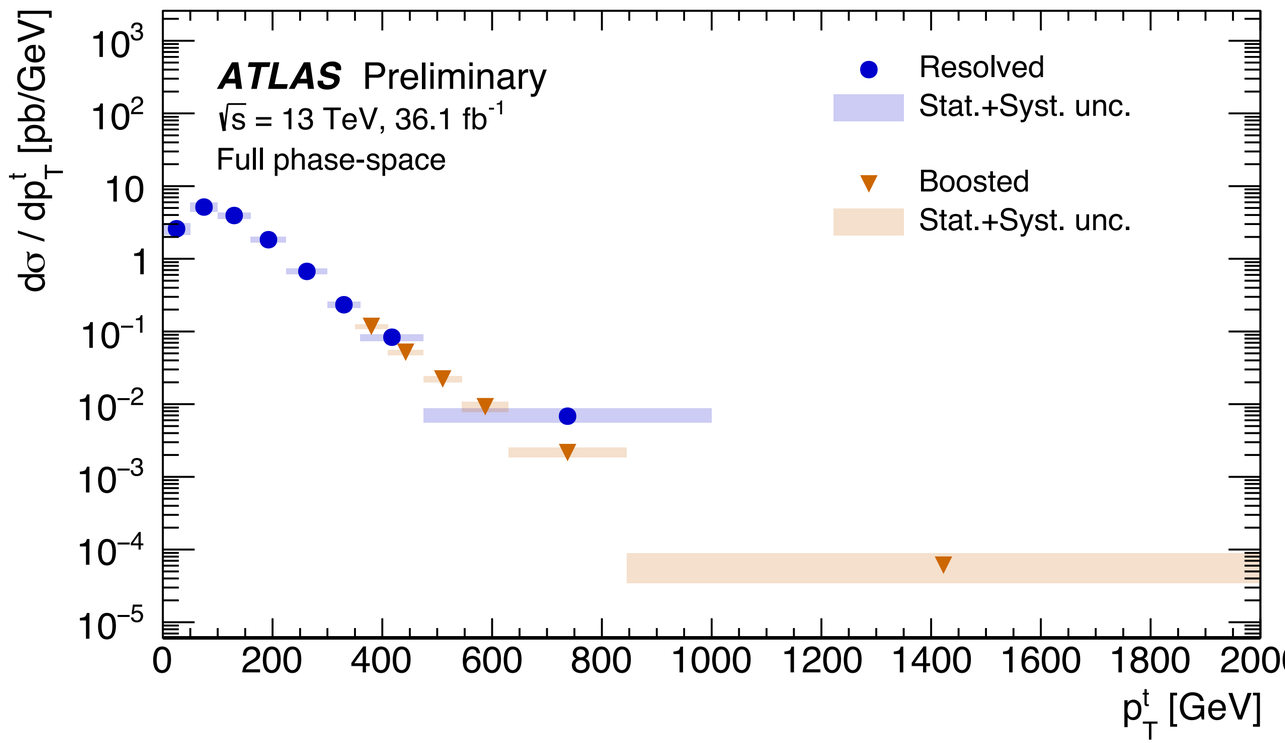
Boosted tt l+jets — results — top p_T

Submitted to EPJC

Parton level

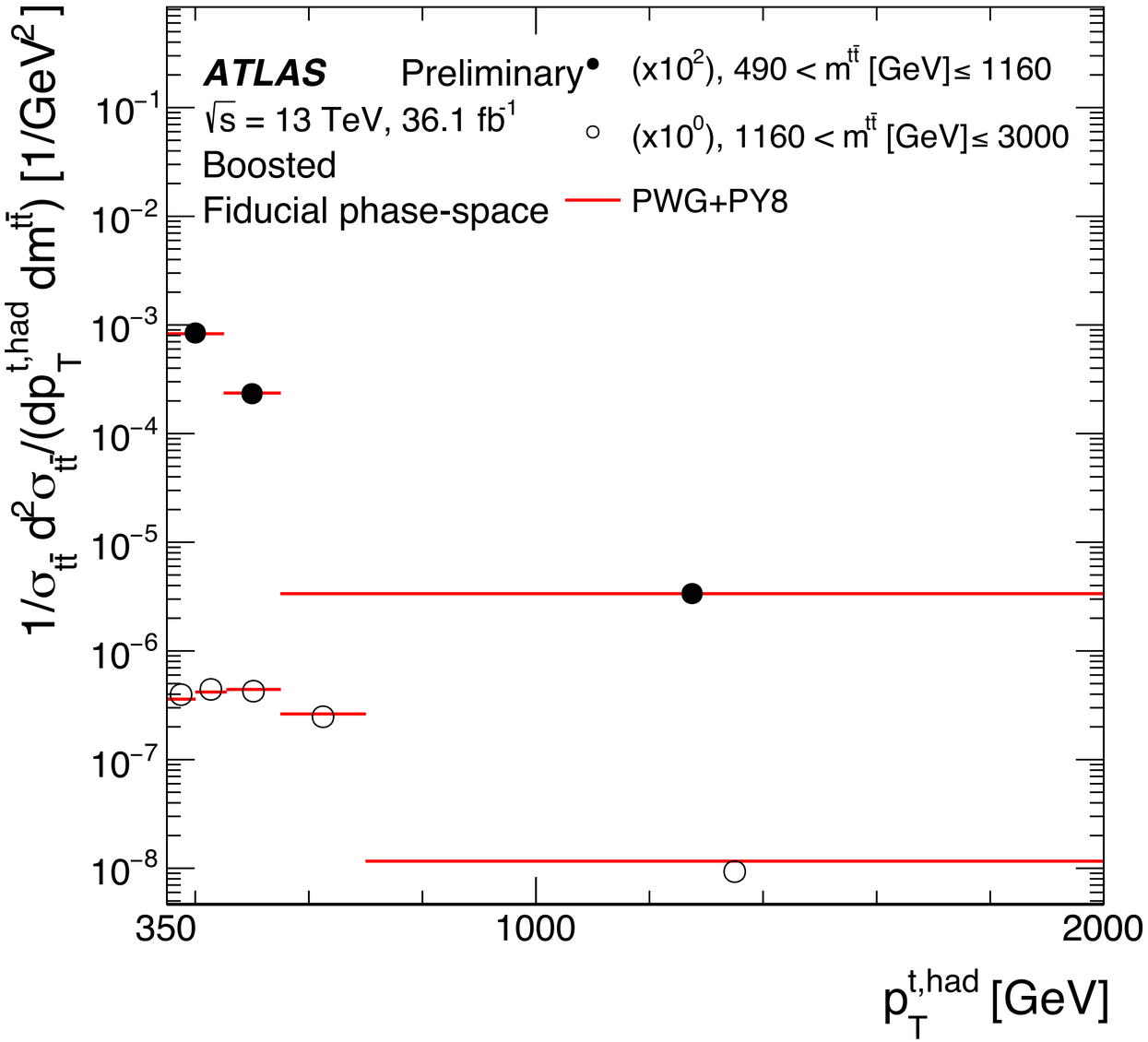


Parton + particle levels



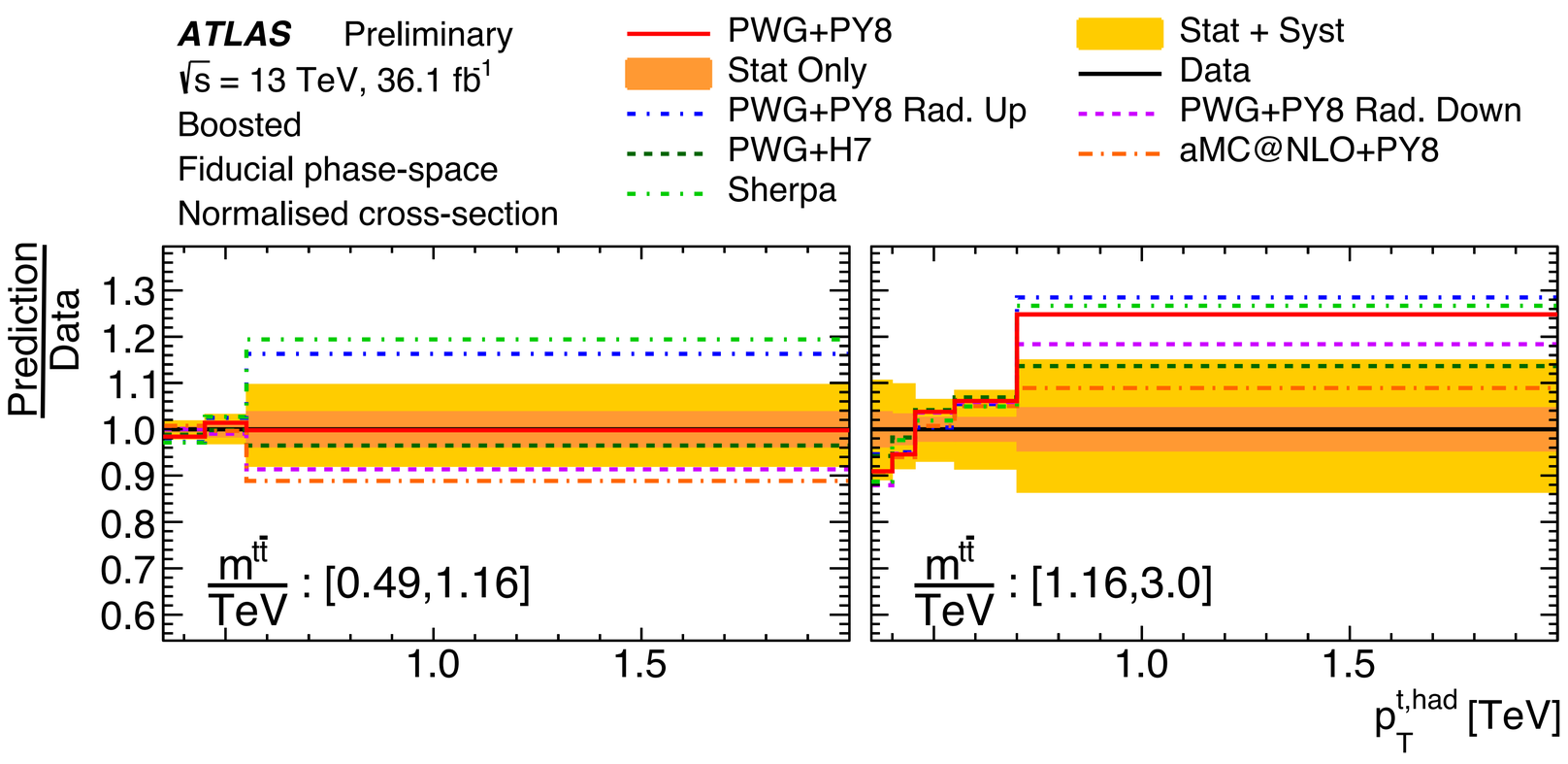
- NNLO improves modelling
- Slope still present
- Resolved+boosted covers large p_T range

Boosted tt l+jets — results — double differential cross-sections



- First double differential cross-sections for boosted tops
- Look at top p_T in bins of m_{tt}
- p_T modelled worse in high-m_{tt} bin
- ~20% difference in MC predictions for low mass bin: data discriminates between the models

Boosted tt l+jets — results — double differential cross-sections



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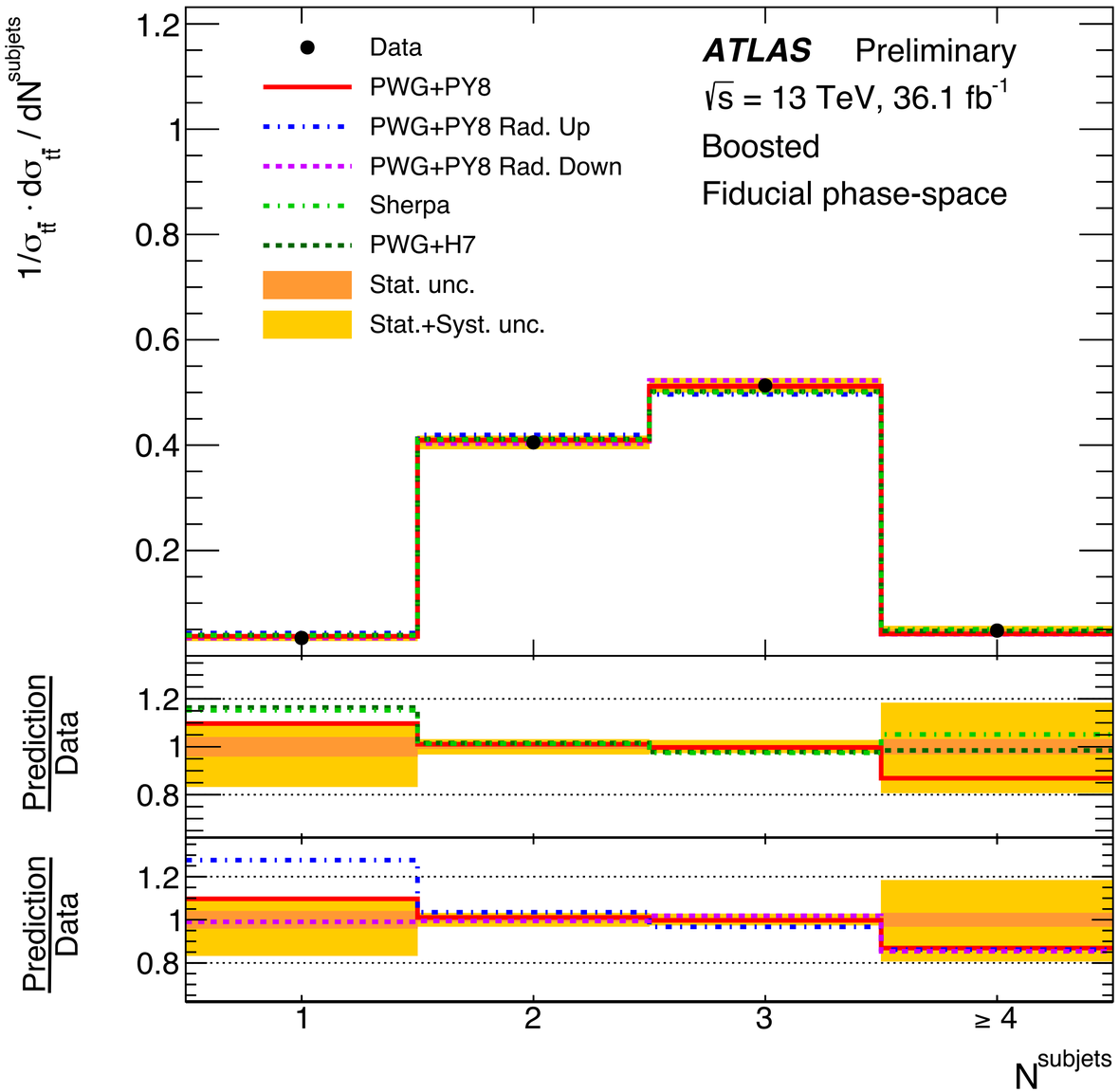
Boosted tt l+jets — results — subjets

Submitted to EPJC

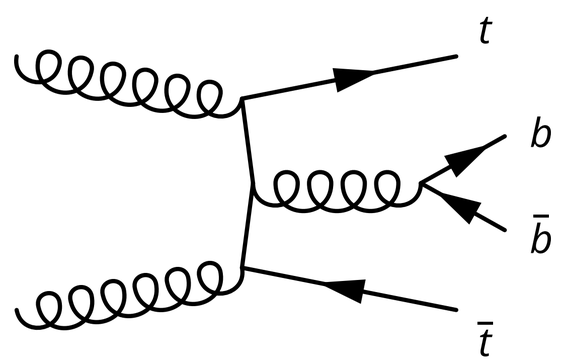
- A peek inside the boosted top
- Number of R=0.4 jets inside R=1.0 boosted top-tagged jet
- Even(ish) distribution of N=2/3 subjets
- N=1 from highly boosted events
- N ≥4 from radiation?



tt+b-jets — strategy

JHEP 04 (2019) 046

- tt+b-jets challenges QCD calculations with the heavy b quark
- tt+bb is a large background (and dominant systematic) for ttH(H→bb). MC can predict to NLO. Let's measure it.
- Analysis done with 36.1 fb^{-1} @ 13 TeV, dilepton, lepton+jets channels
- Data-driven template fit to derive correction factors for flavour composition for tt+X
- Differential cross sections as functions of kinematic variables of b-jet pairs
  - Min ΔR(b,b): expected to be from gluon splitting
  - Highest p_T: dominated by top pair production



tt+b-jets — template fit method

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- tt+{d,u,s,c} contribute backgrounds from mis-tagging b-jets
- Use templates from tt, ttH, ttV Monte Carlo predictions

Category	$e\mu$	lepton + jets
$t\bar{t}b$	$\geq$3 b-jets	$\geq$3 b-jets
$t\bar{t}c$	<3 b-jets and ≥ 1 c-jet	<3 b-jets and ≥ 2 c-jets
$t\bar{t}l$	events that do not meet above criteria	events that do not meet above criteria

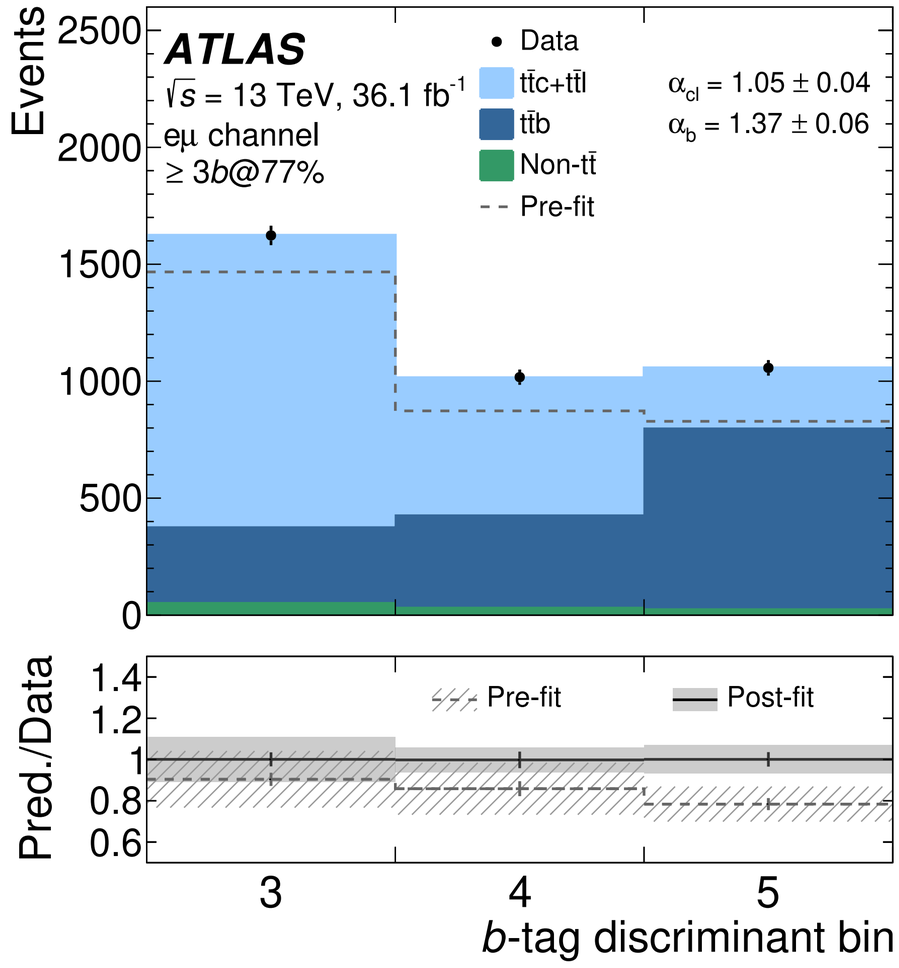
- Perform binned maximum-likelihood fit to data

$$\mathcal{L}(\vec{\alpha}|x_1,\ldots,x_n) = \prod_k^n \frac{\mathrm{e}^{-\nu_k(\vec{\alpha})}\nu_k(\vec{\alpha})^{x_k}}{x_k!}, \qquad \nu_k(\alpha_b,\alpha_c,\alpha_l) = \alpha_b N^k_{t\bar{t}b} + \alpha_c N^k_{t\bar{t}c} + \alpha_l N^k_{t\bar{t}l} + N^k_{\text{non-}t\bar{t}}$$

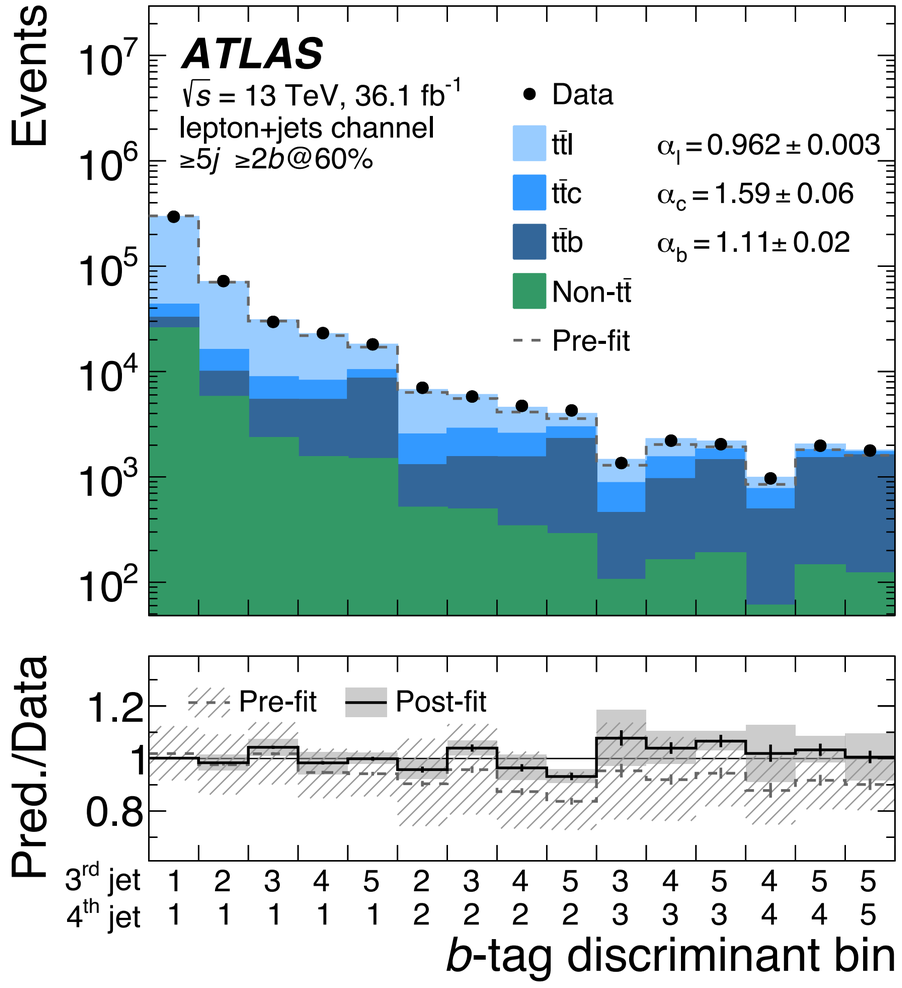
tt+bb — template fit results

JHEP 04 (2019) 046

Dilepton



l+jets



tt+bb — inclusive fiducial cross section results

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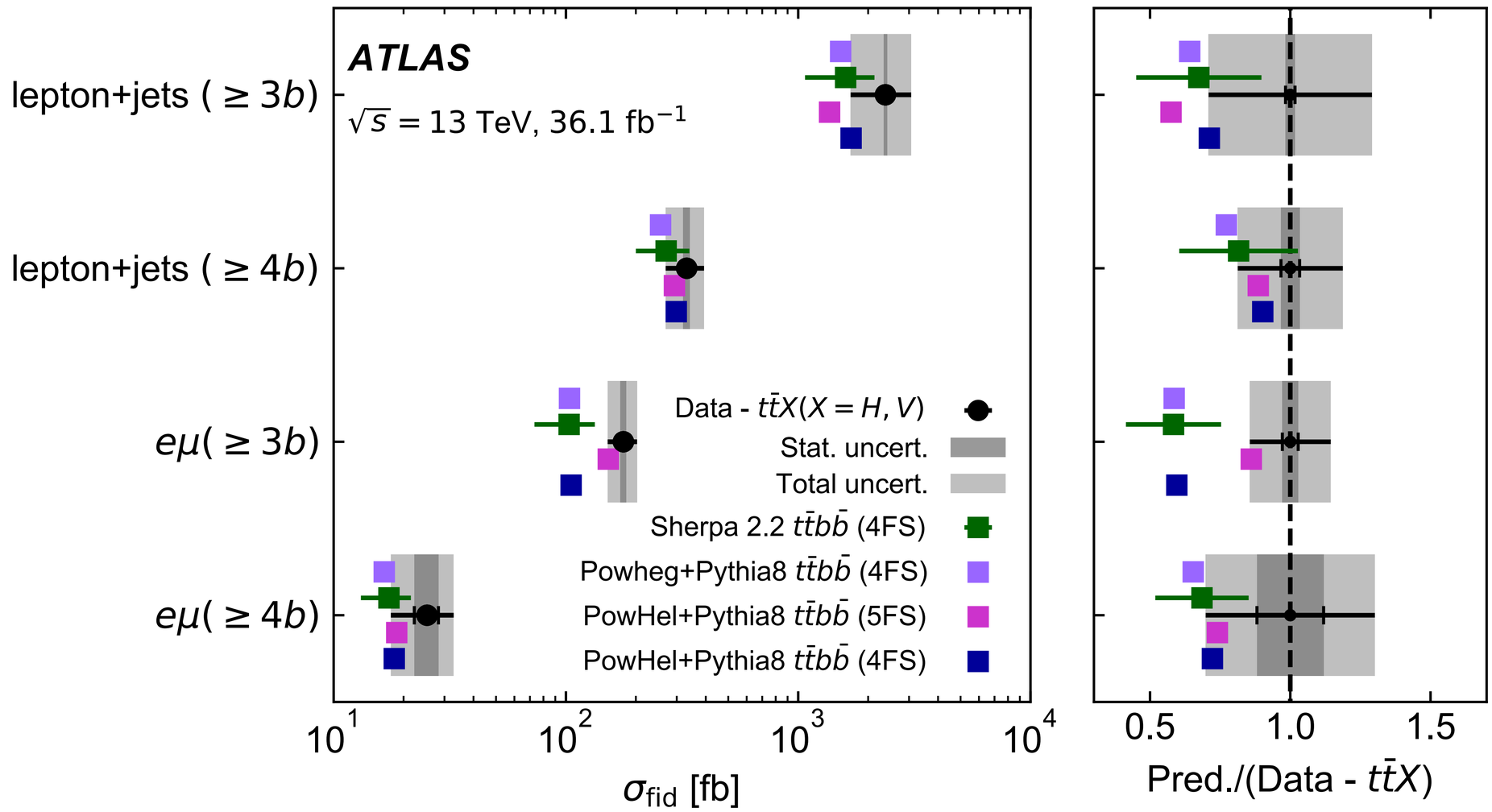
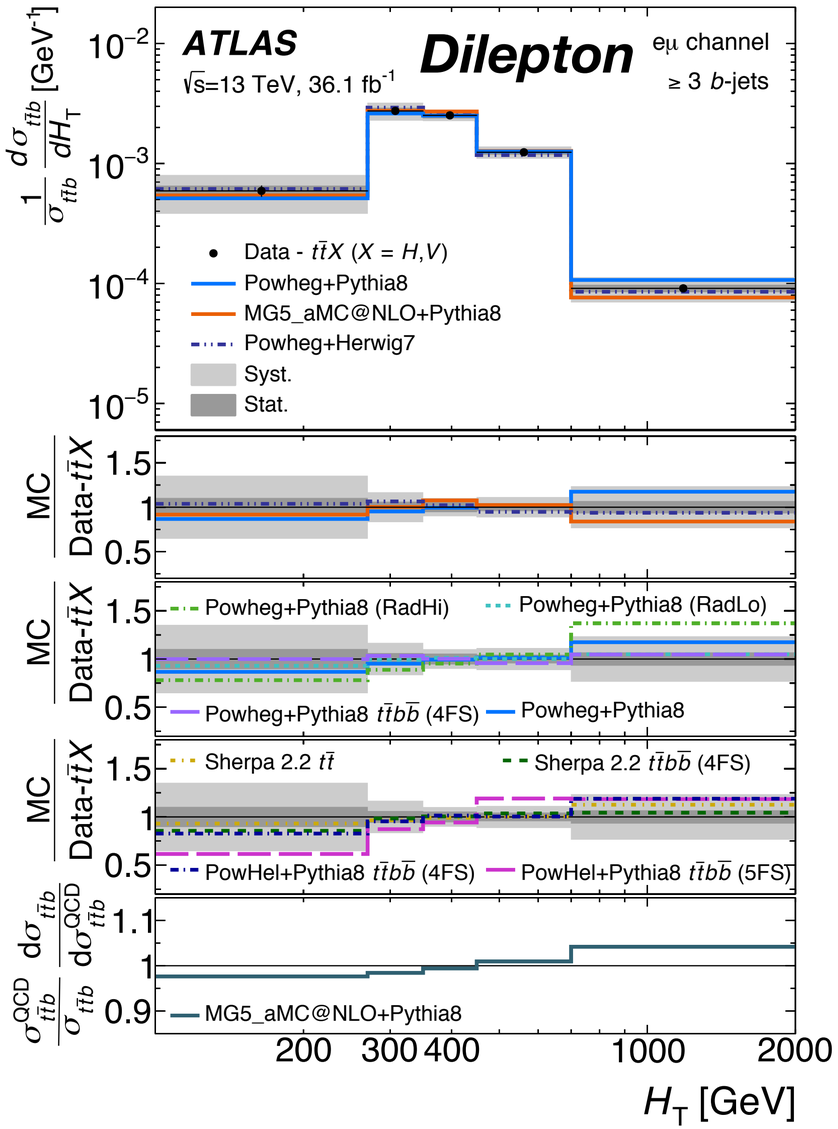
- Generally exceed NLO predictions, but compatible within uncertainties

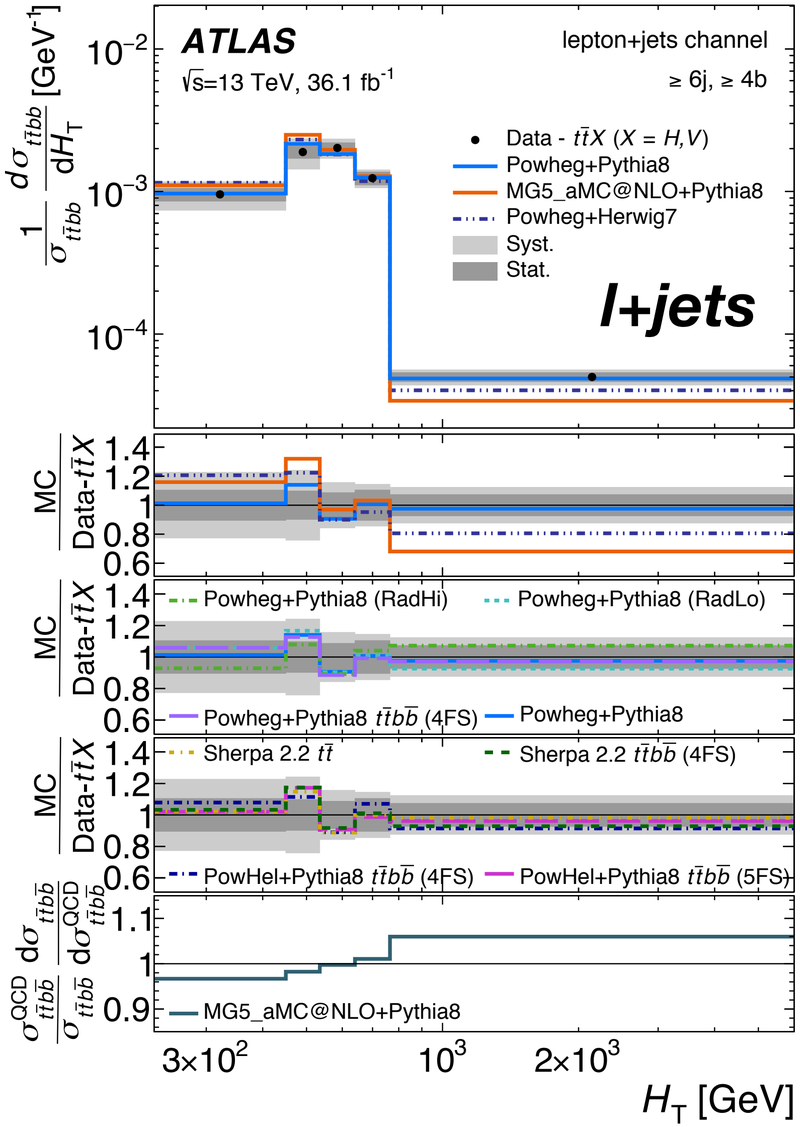


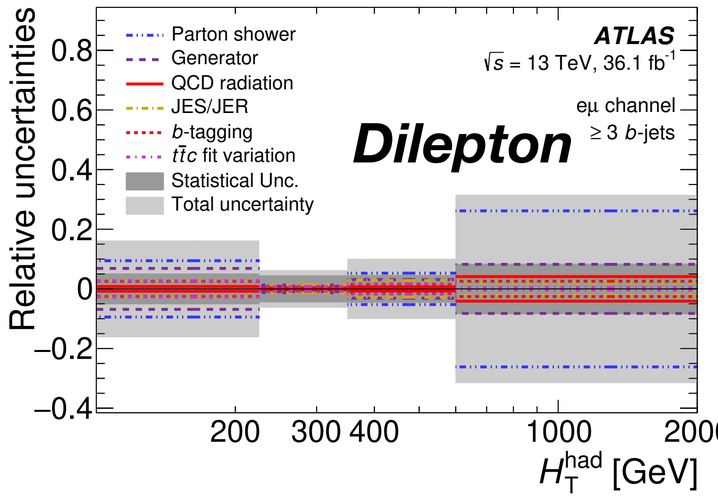
tt+bb — differential cross section results

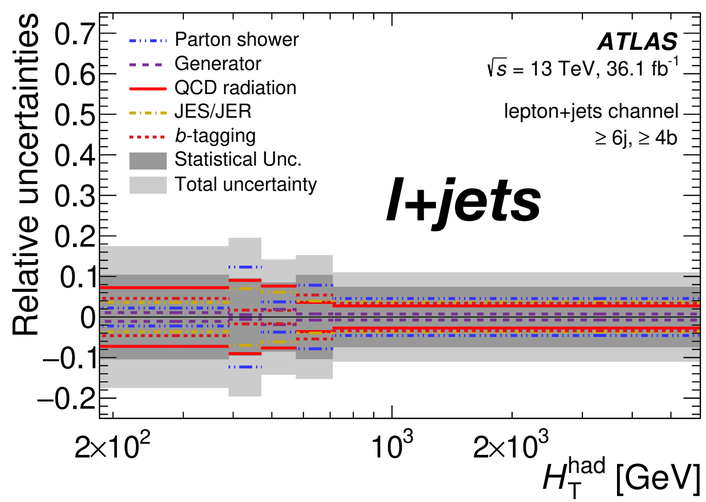
JHEP 04 (2019) 046

- Systematic modelling uncertainties dominate experimental uncertainties









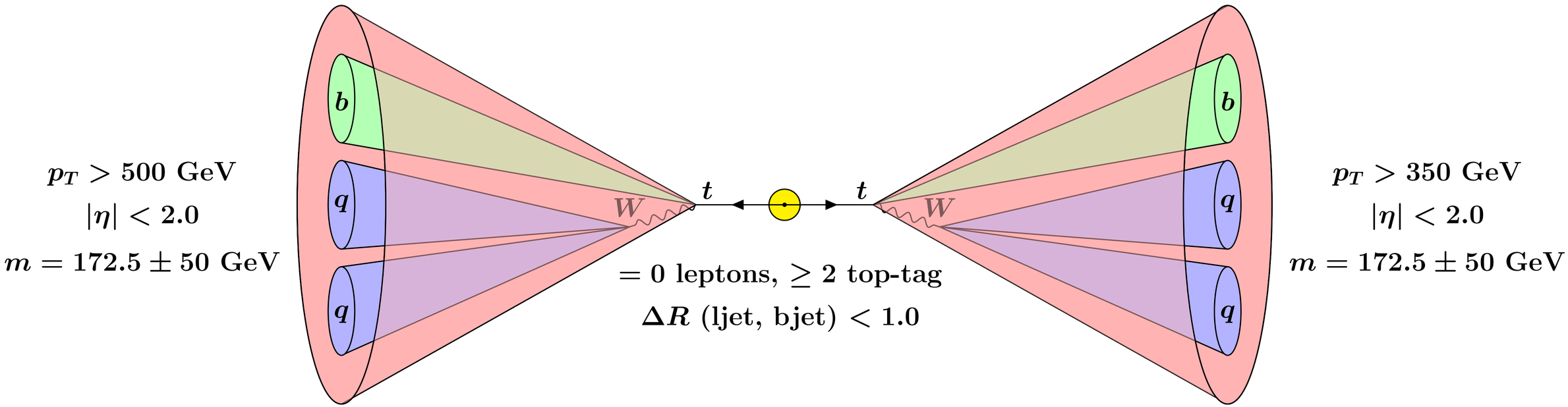
Summary

- The top quark is interesting and unique. The LHC is a top factory.
- Provides a laboratory for testing theory predictions and performing high-precision measurements
- Window into BSM physics, possible future directions
- A significant part of ATLAS research programme
- Lots of recent activity with interesting results (tt, tt+bb)
- First double differential boosted top measurements probe the details of top kinematics
- More data brings more results from 2017/18

Backup

tt all-hadronic differential cross sections

Phys. Rev. D (2018) 98



- Both large-*R* jets contain an associated small-*R* b-tagged jet
- Multijet background suppressed by top tagging algorithm: uses jet mass and τ_{32} (prefers 3-pronged jets) (Link to top tagging note)
- Remaining background estimated using ABCD method with 16 regions

ABCD(EFGHIJKLMNOS) method

Phys. Rev. D (2018) 98

- Used in all-hadronic analysis
- Extends ABCD method to account for correlations in background-dominated regions

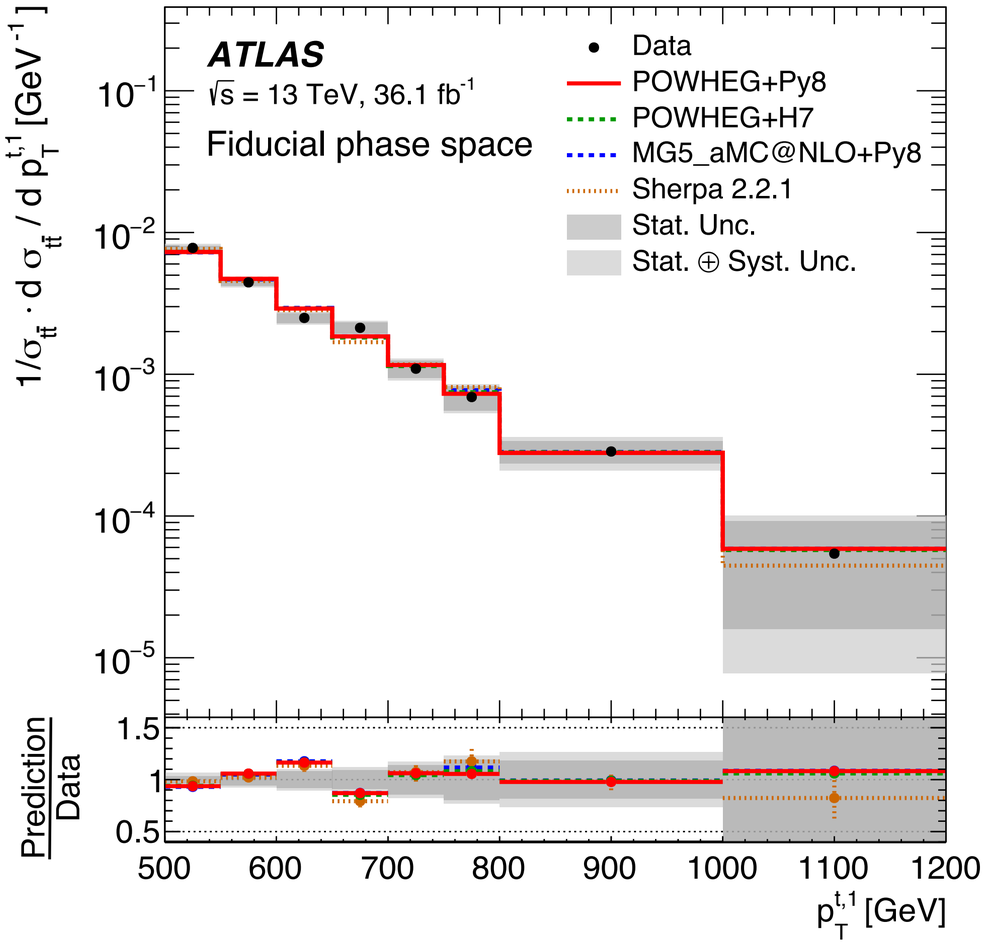
2nd large-R jet \ Leading large-R jet	0t0b	1t0b	0t1b	1t1b
1t1b	A (0.2%)	C (0.8%)	I (2.2%)	O (11%)
0t1b	B (2.2%)	D (5.8%)	H (13%)	N (47%)
1t0b	E (0.7%)	F (2.4%)	G (6.4%)	M (30%)
0t0b	J (7.6%)	K (21%)	L (42%)	S

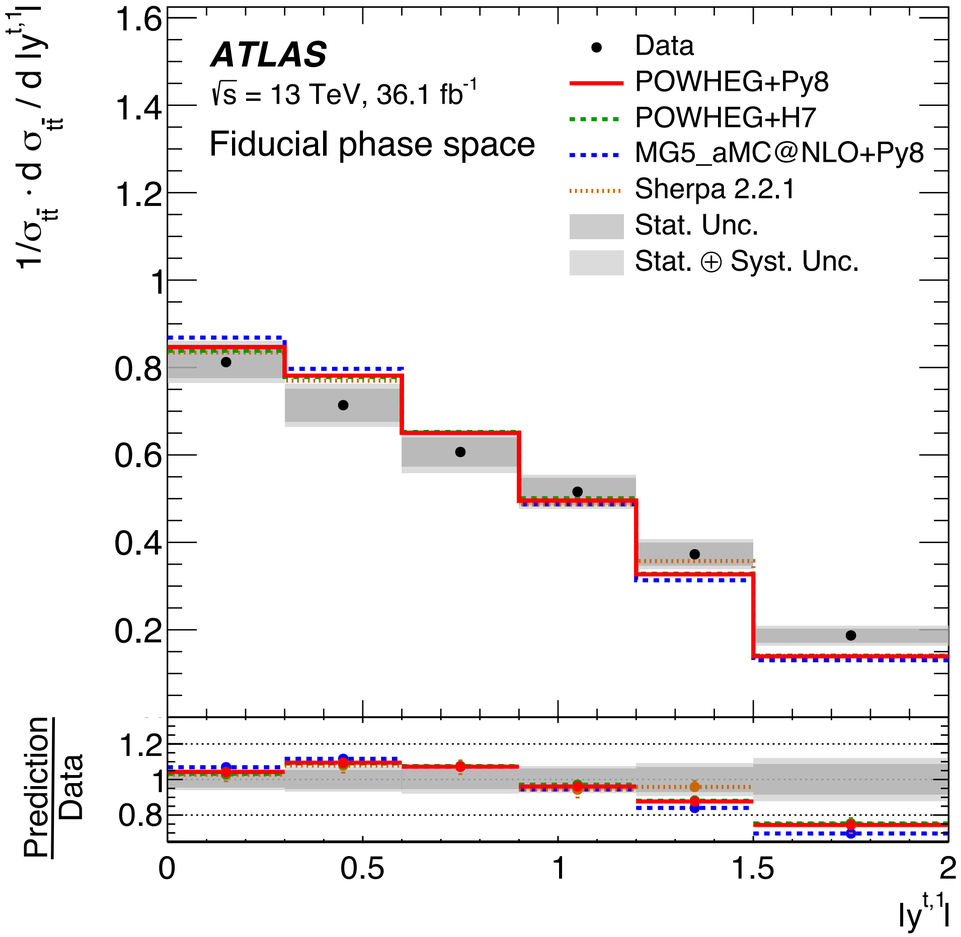
$$S = \frac{J \times O}{A} \cdot \frac{D \times A}{B \times C} \cdot \frac{G \times A}{E \times I} \cdot \frac{F \times A}{E \times C} \cdot \frac{H \times A}{B \times I}$$
$$= \frac{J \times O \times H \times F \times D \times G \times A^3}{(B \times E \times C \times I)^2},$$

tt all-hadronic differential cross sections — results

Phys. Rev. D (2018) 98

- Unfolded cross-section in particle level leading top p_T and |rapidity|





tt all-hadronic differential cross sections — results

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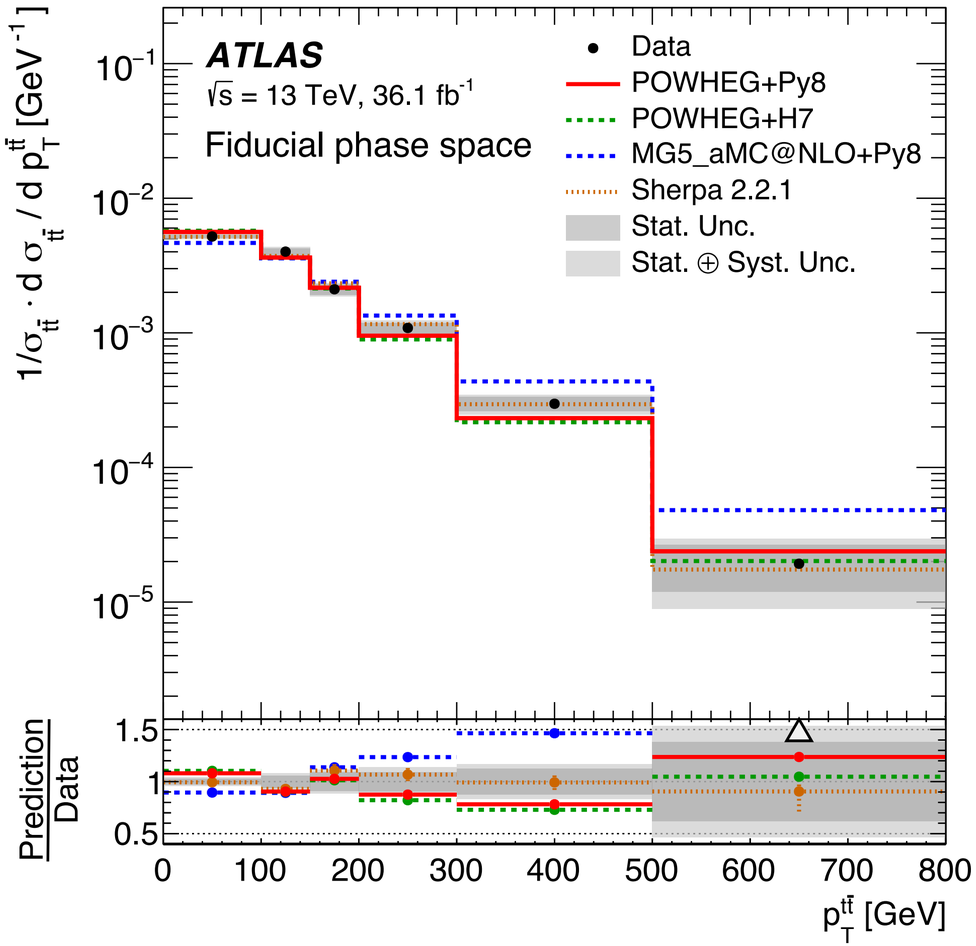
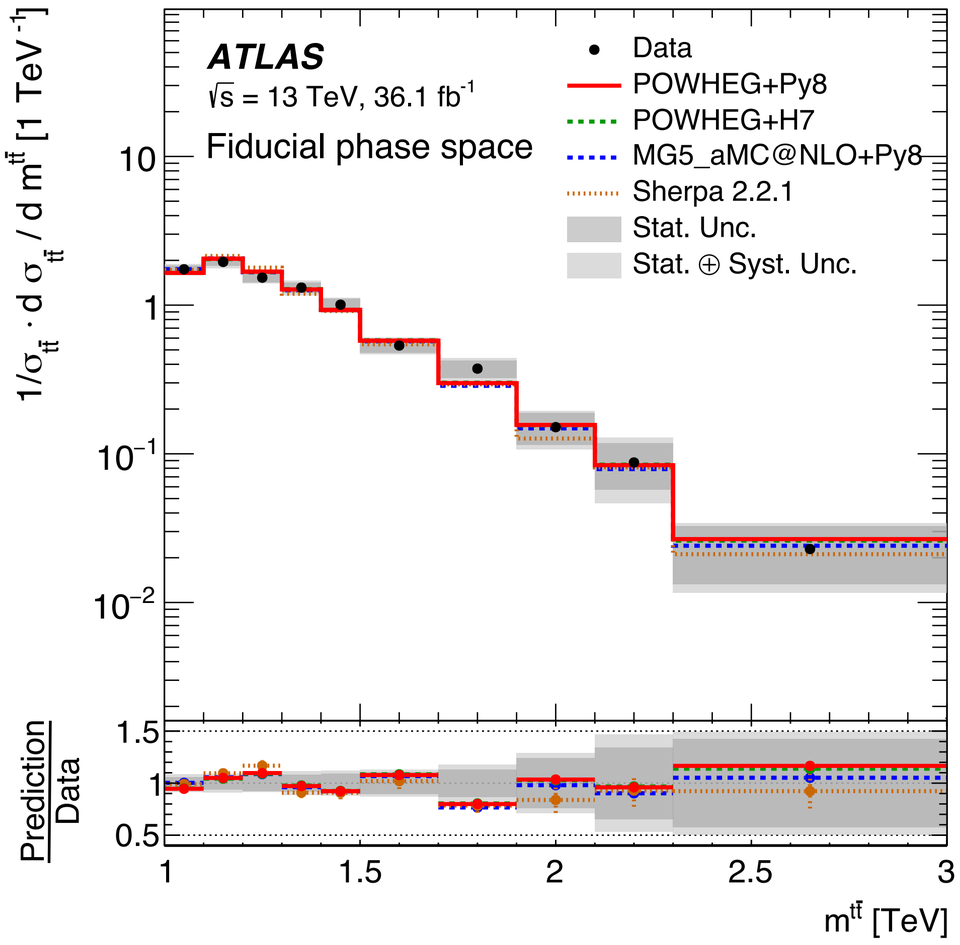
- Unfolded cross-section in particle level tt system p_T and invariant mass

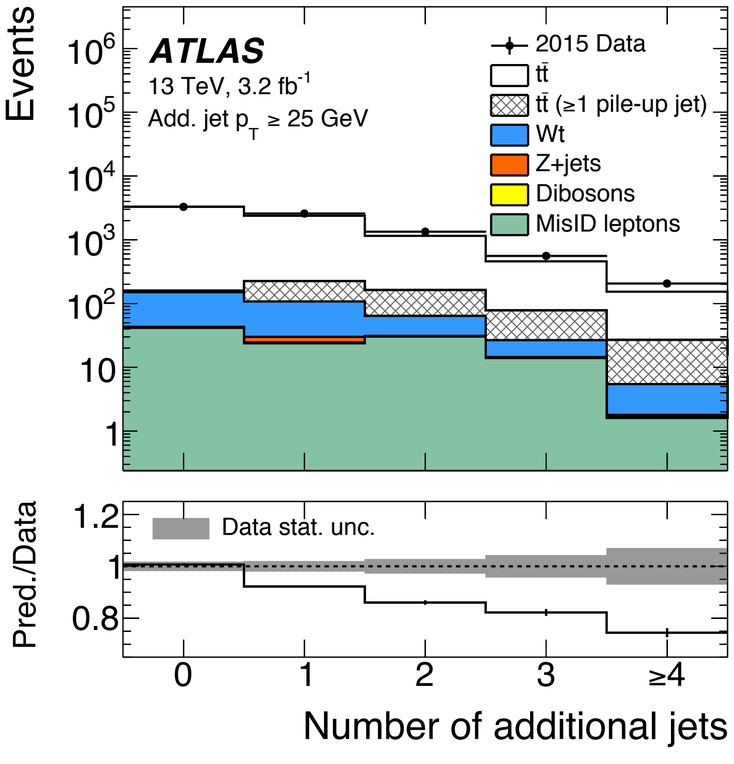


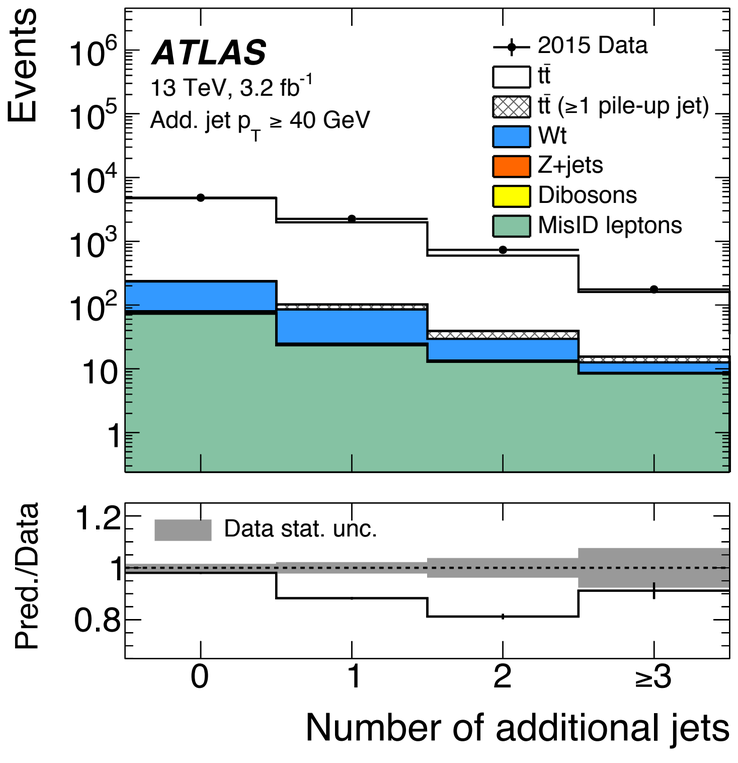


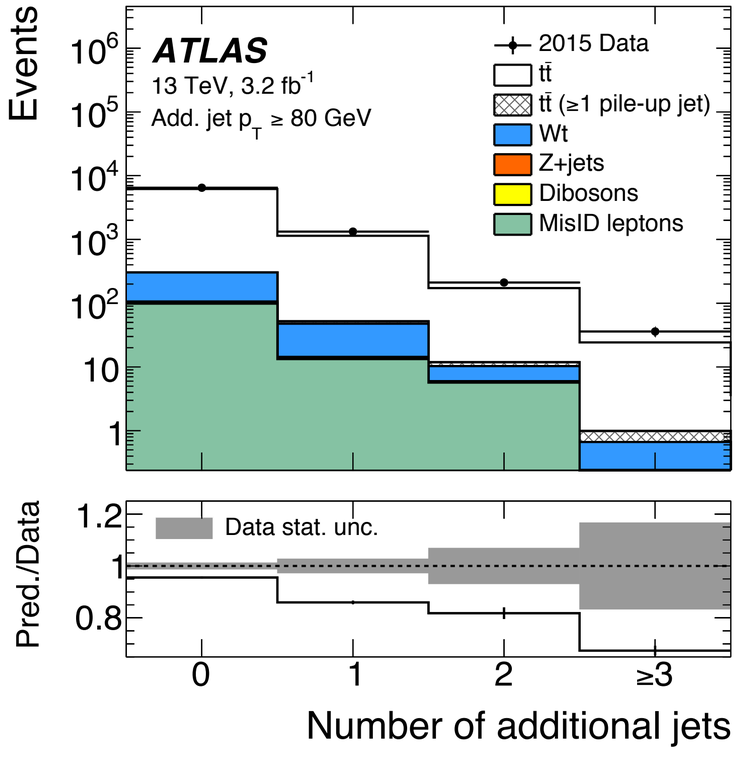
tt + additional jets ($e\mu$+jets channel)

JHEP 10 (2018) 159

- Channel (2 b-tags) gives a pure sample of tt







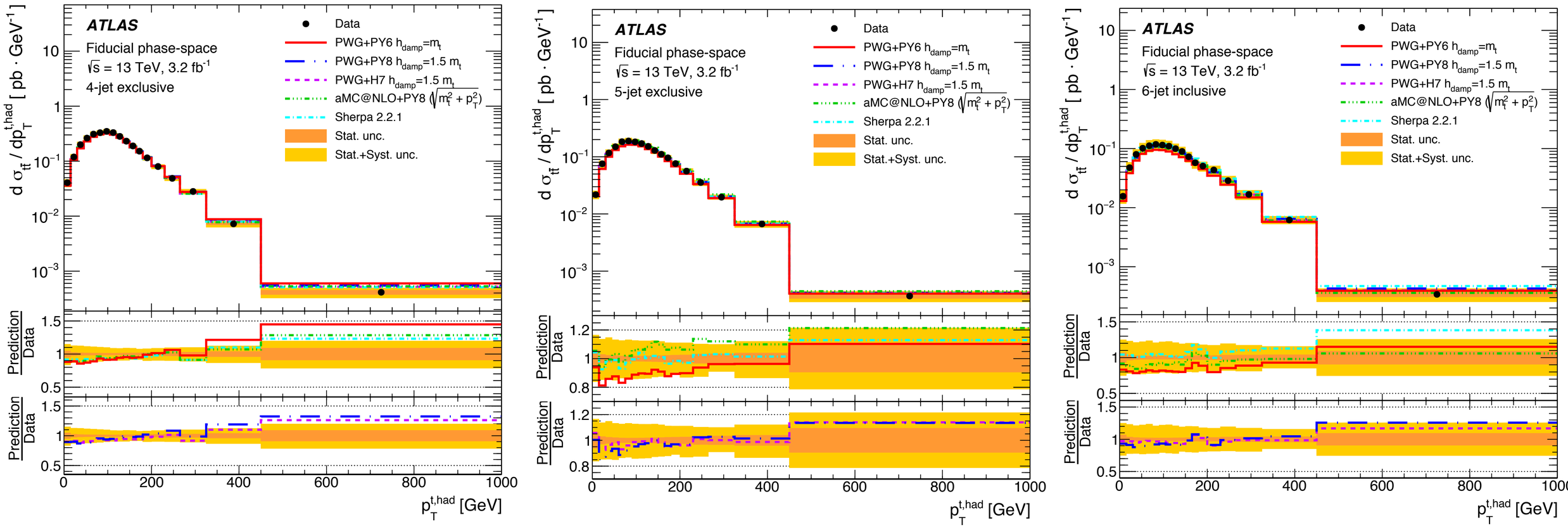
- Generally more jets in data than predicted by Powheg+Pythia6

tt + additional jets (l+jets channel)

JHEP 10 (2018) 159

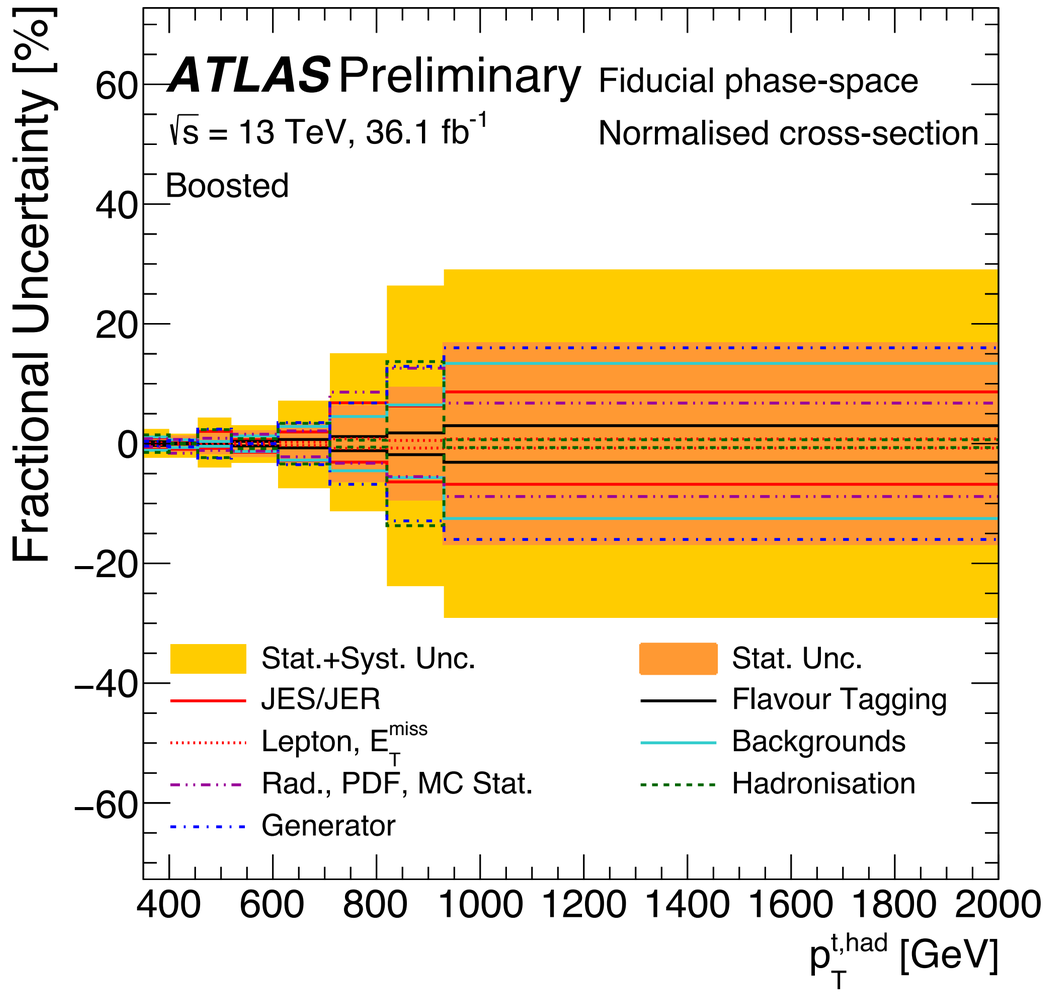
- Differential cross-sections in *n*-jet regions. e.g. hadronic top p_T

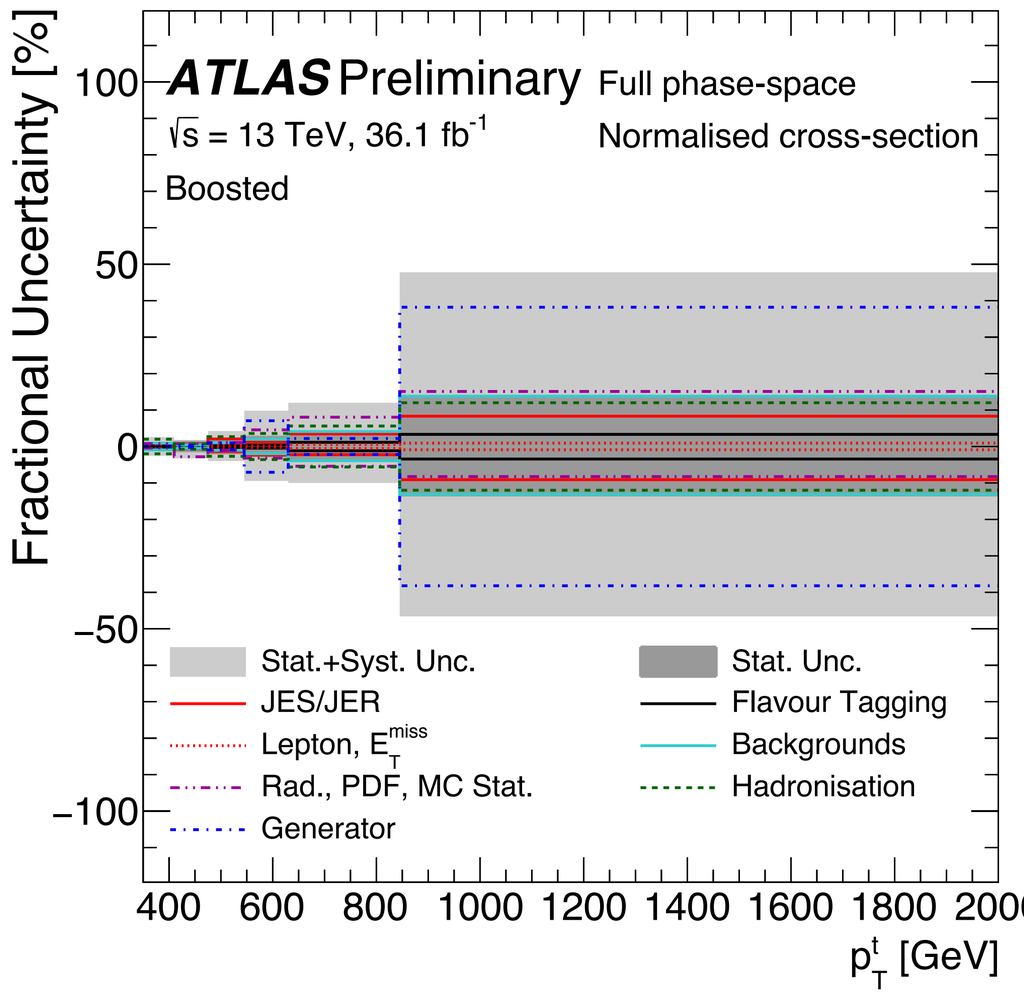
=4 jets **=5 jets** **≥6 jets**



- Slope in p_T: top is softer than predicted (most evident in =4 jets)

Boosted tt l+jets — uncertainties

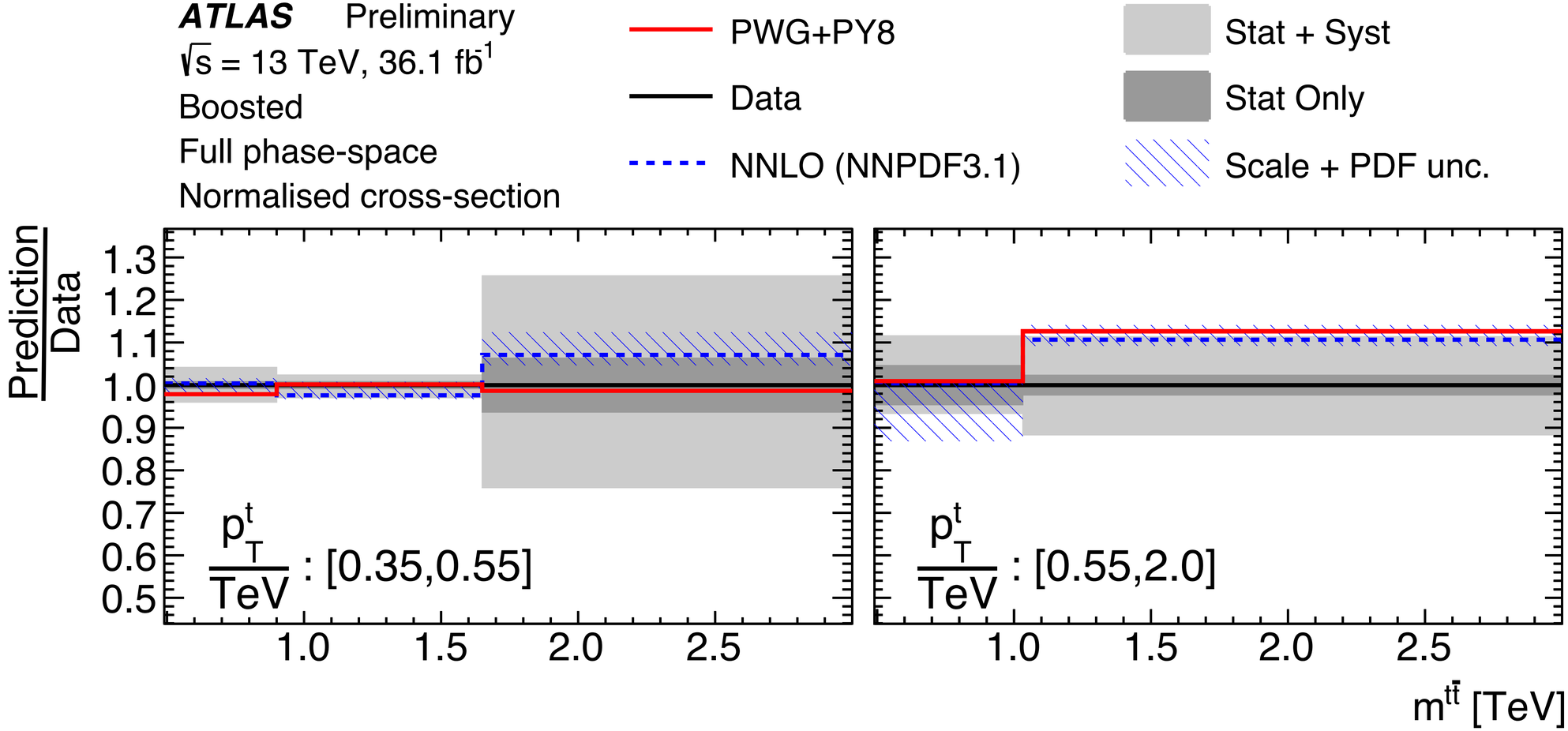




- Main sources: JES, tt modelling, b-tagging, backgrounds

Boosted tt l+jets — double differential cross-section

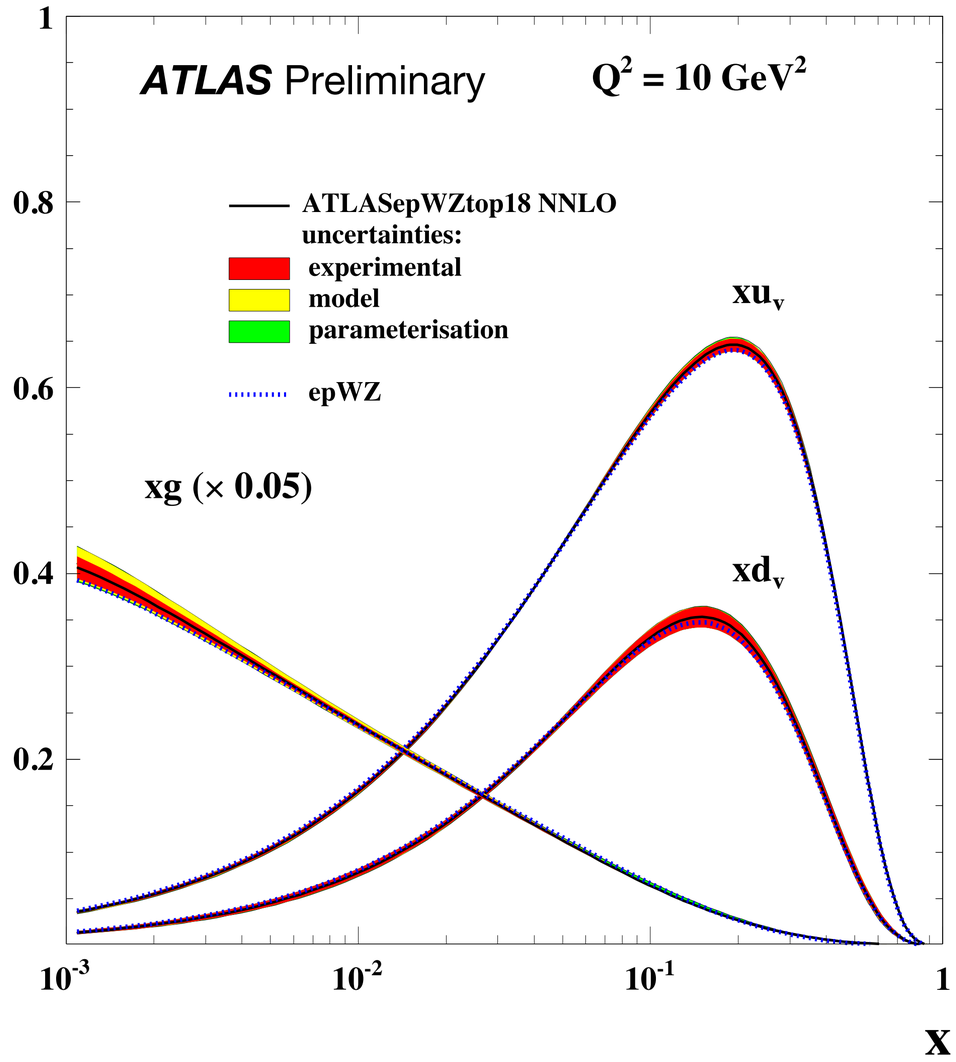
- Double differential cross section in m_{tt} vs top p_T at parton level



PDF fits

- Goal: fit ATLAS W, Z/γ^* cross sections (7 TeV), **tt p_T+m_{tt}+y_{tt}** distributions (8 TeV), HERA $e^{\pm}p$ DIS data to produce new PDF set ATLASepWZtop18

Link to note



- Use full correlation information to perform simultaneous fit — increases impact of tt data

- After including tt data gluon PDF is slightly harder, lower uncertainty at high x

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