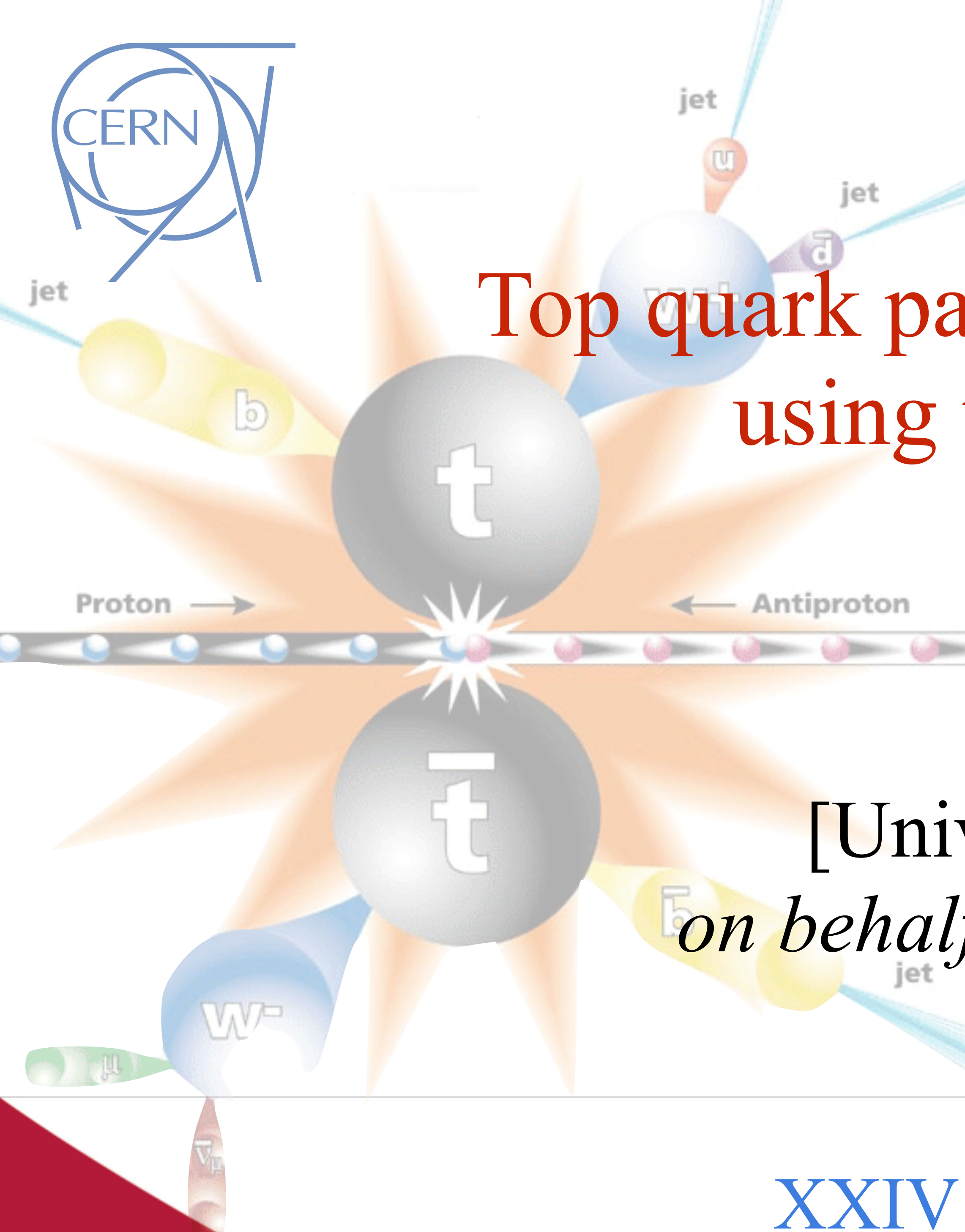

Top quark pair production cross section using the ATLAS detector

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on behalf of ATLAS collaboration

XXIV International Workshop
Deep-Inelastic Scattering
April 13th 2016

The University *of* Oklahoma

Overview

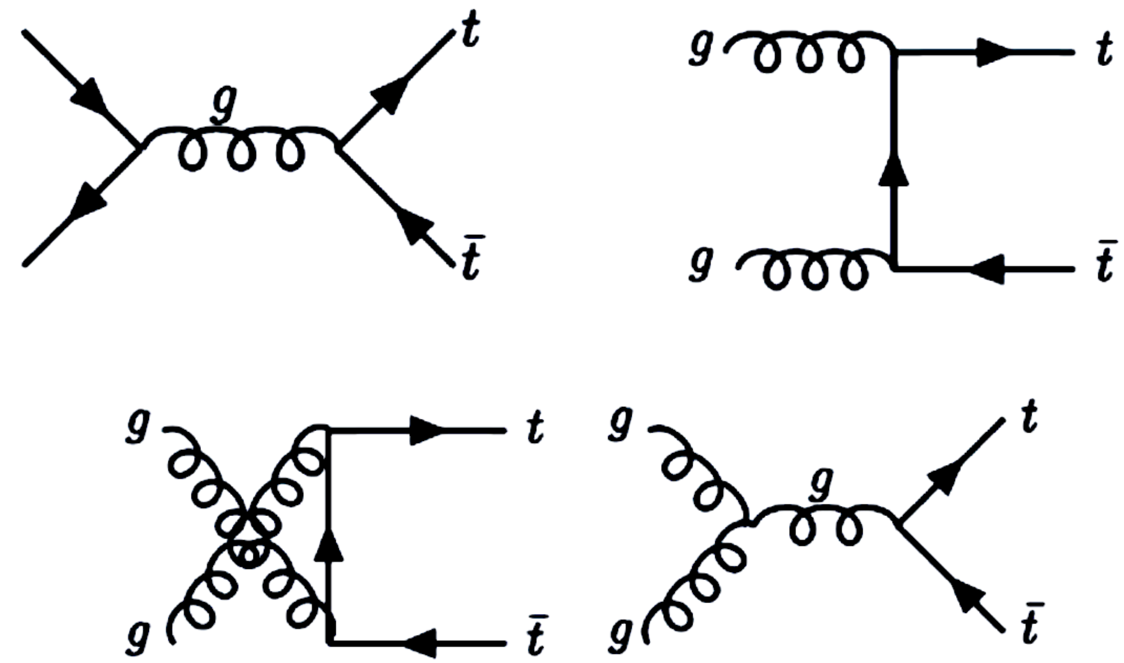
- Top quark pair production and decay
- Inclusive cross section:
  - ✦ eμ events at 7,8 and 13 TeV
  - ✦ e/μ +jets events at 13 TeV
  - ✦ ee/μμ events at 13 TeV
- Differential cross section:
  - ✤ Resolved top quark pair in e/μ events at 8 TeV
  - ✤ Boosted top quark pair in e/μ events at 8 TeV

For tt+X: See the talk by Alexander Khanov

More results: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults

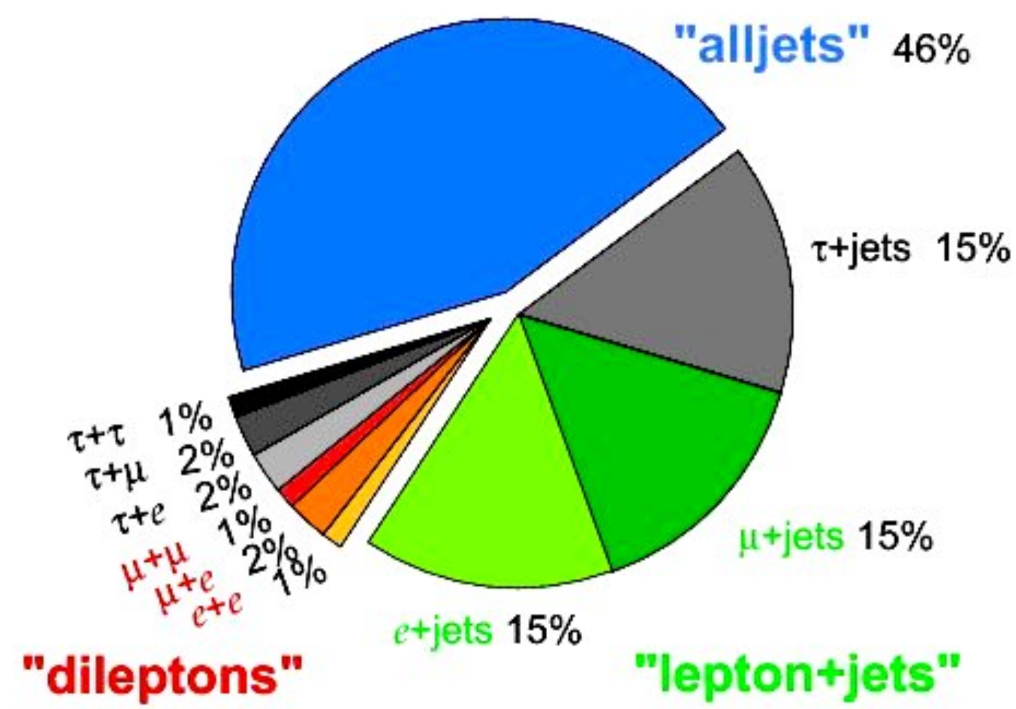
Top quark pair production and decay

- LHC is a top quark factory
- Pair production through:
  - gluon-gluon fusion ~ 87%
  - quark-quark interaction ~ 13%



- Top quark pair decay
  - $t \rightarrow Wb \approx 100\%$

- Final state categorized by the W decays:
  - dilepton (ee/μμ/eμ) ~5%
  - lepton (e/μ) + jets ~ 30%
  - all jets and τ-lepton decay modes



Inclusive cross section σ(tt)

- Provides precision test of the Standard Model :
  - perturbative QCD and NNLO calculations
- Sensitive to fundamental parameters : $\hat{\sigma} \propto (\alpha_s/m_t)^2 f(\alpha_s, \beta)$
- Sensitive to Beyond SM physics

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots

Assuming m_t = 172.5 GeV

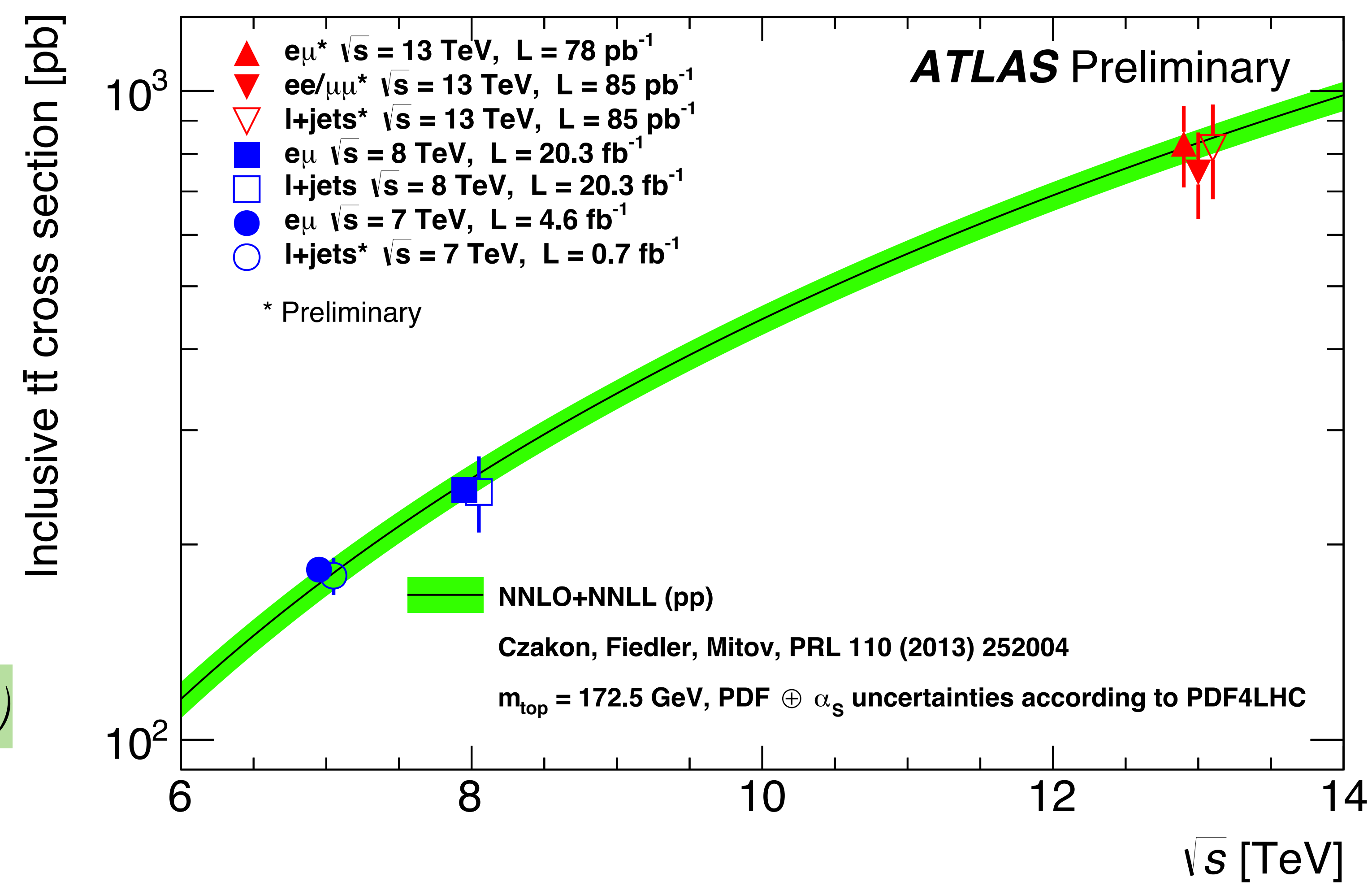
σ (7 TeV) = 177 pb ± 7%

σ (8 TeV) = 253 pb ± 6%

σ (13 TeV) = 832 pb ± 5%

$R_{13/8}$ = 3.28

NNLO+NNLL predictions (arXiv:1112.5675)

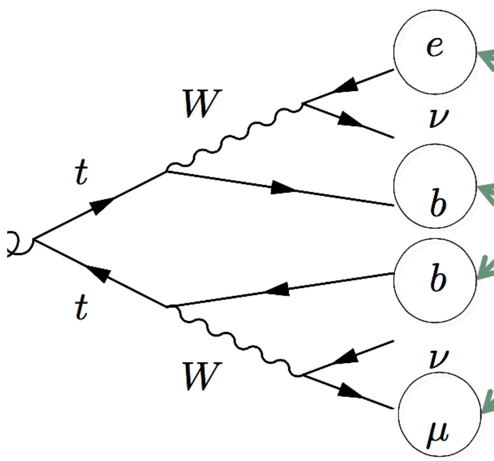


Will focus on the most recent results …

Inclusive σ(tt): eμ events at 7 & 8 TeV

Eur.Phys. J. C74 (2014) 3109

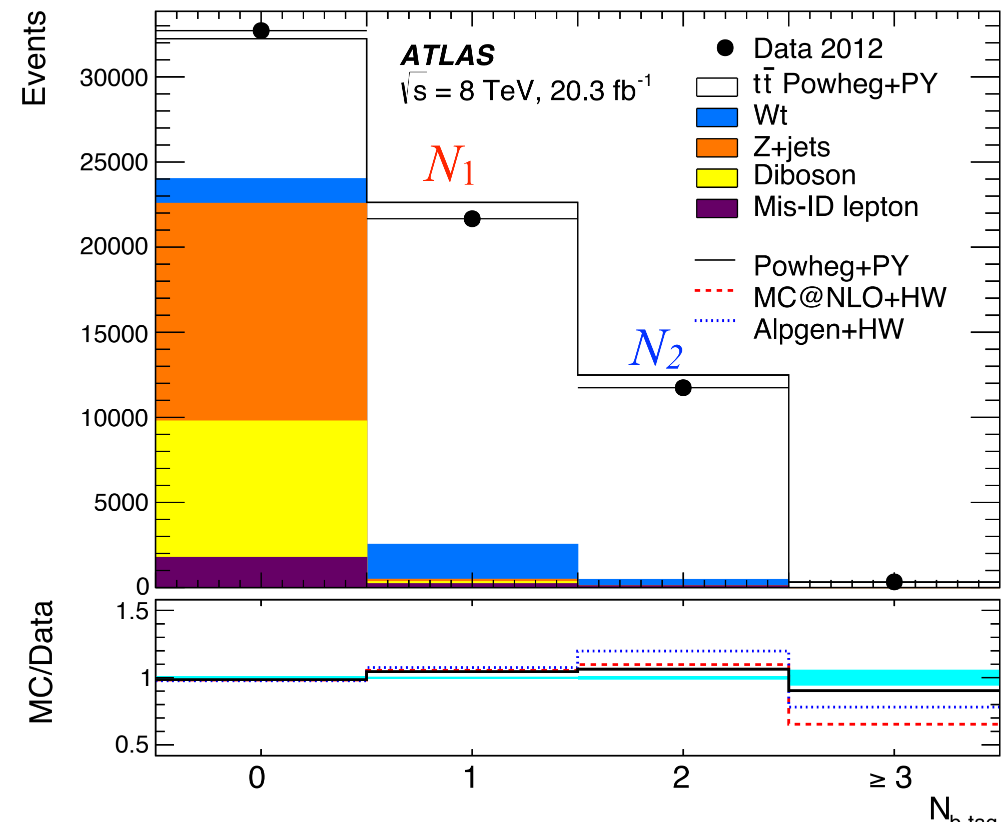
Most precise results, more precise than theory!



Large b-tag uncertainties → determine efficiency from data

Likelihood fit to simultaneously determine:

- inclusive cross section
- b-tag efficiency



$$N_1 = L\sigma_{t\bar{t}}\epsilon_{e\mu}2\epsilon_b\left(1 - C_b\epsilon_b\right) + N_1^{\rm bkg}$$

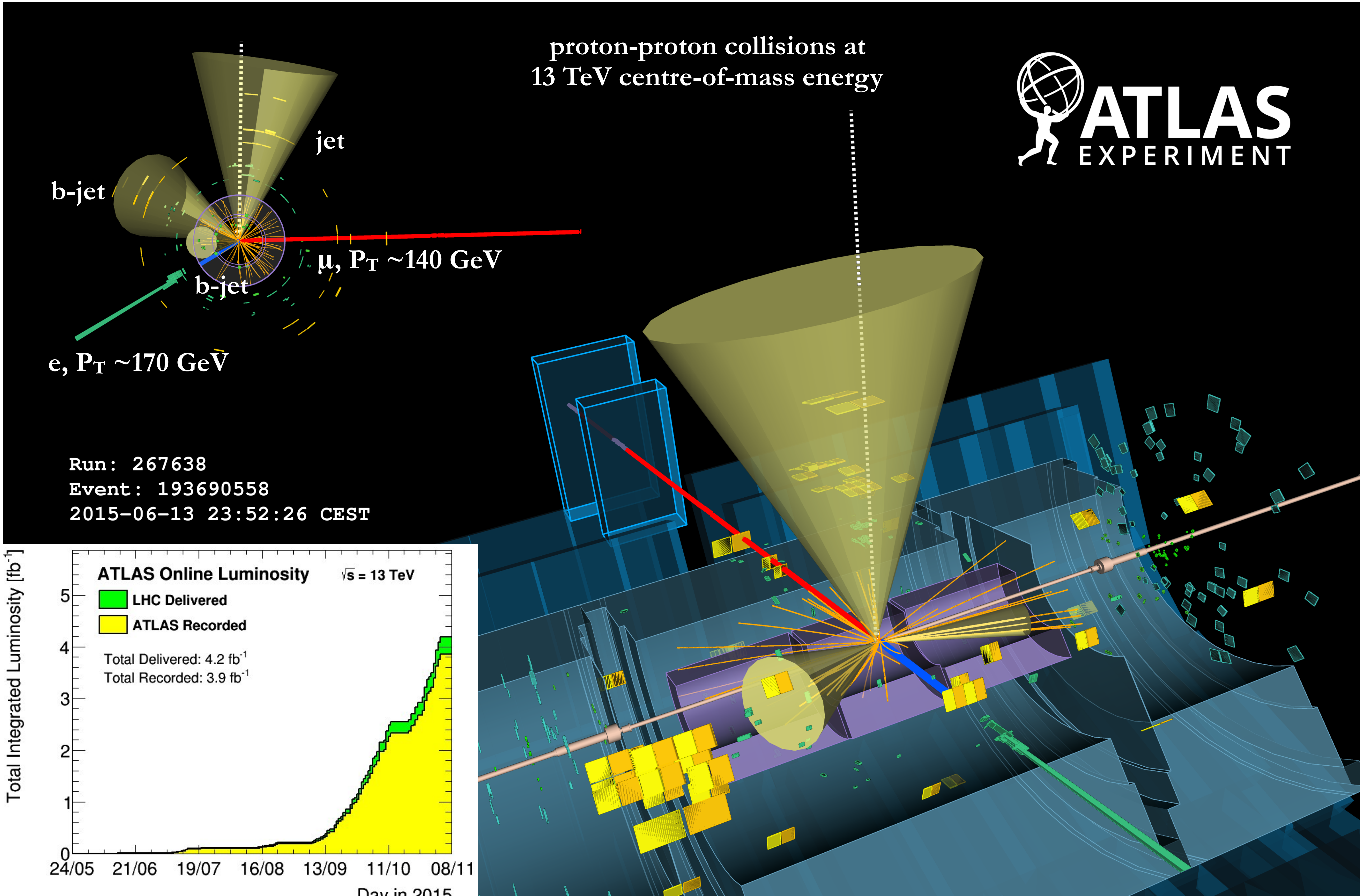
$$N_2 = L\sigma_{t\bar{t}}\epsilon_{e\mu}C_b\epsilon_b^2 + N_2^{\rm bkg}$$

$\varepsilon_{e\mu}$: selection efficiency for events with eμ pairs
ε_b : efficiency to identify and b-tag a jet
C_b : correlation between 1 or 2 b-tag (= 1.007)

σ(tt) = 182.9 ±3.1(stat) ± 4.2(syst) ± 3.6(lumi) ± 3.3(beam) pb (7 TeV, 4.6 fb^{-1}) ~ 3.9%
σ(tt) = 242.4 ±1.7(stat) ± 5.5(syst) ± 7.5(lumi) ± 4.2(beam) pb (8 TeV, 20.3 fb^{-1}) ~ 4.3%

Top quark pair at 13 TeV!

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

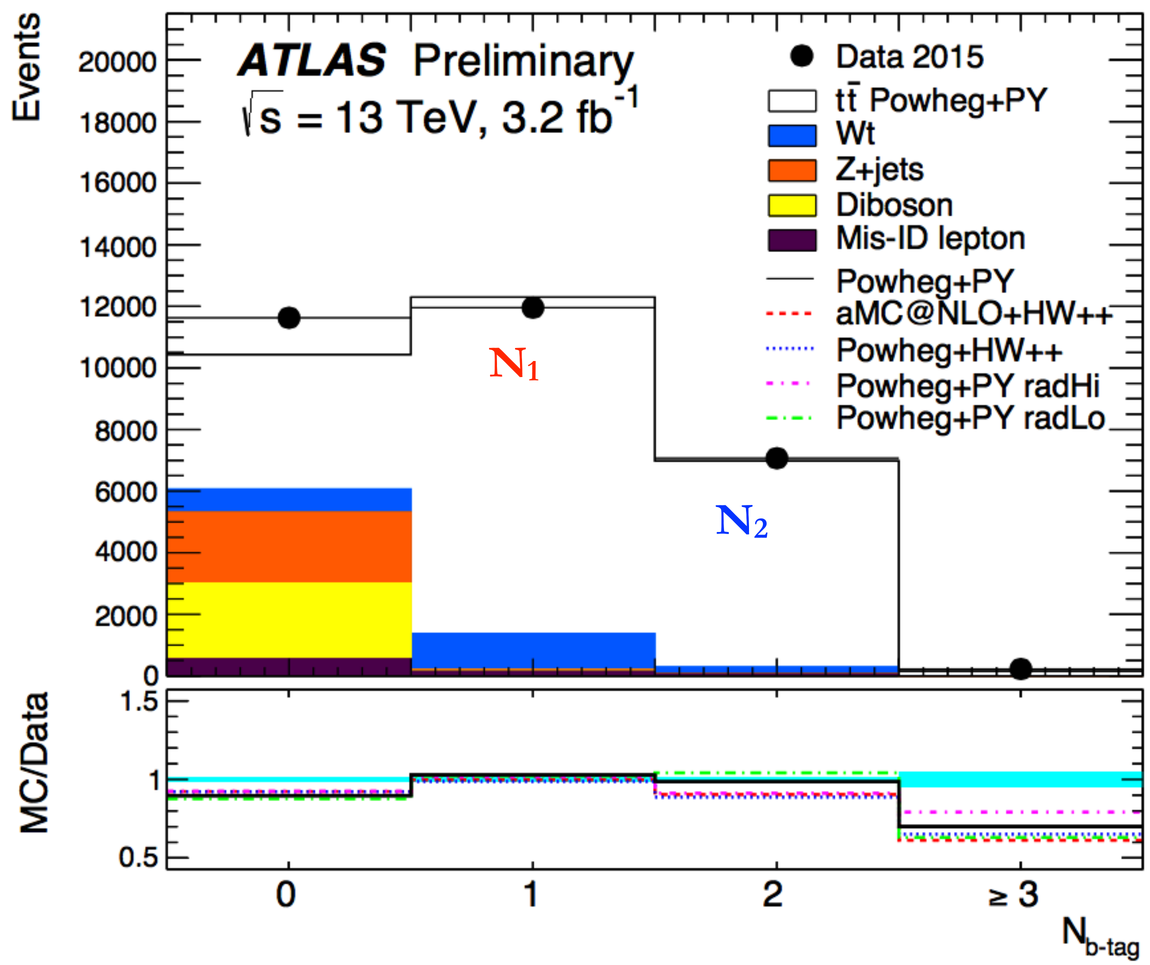


Inclusive σ(tt): eμ events at 13 TeV

$\int \mathcal{L}\,dt = 3.2\ fb^{-1}$
Full 2015 dataset!

ATLAS-CONF-2016-005

Same method as 7 & 8 TeV measurements



Event Count	N_1	N_2	Estimation
Data	11958	7069	—
Single top	1160±120	224±70	simulation
Dibosons	34±12	1±0	simulation
Z(➛ττ➛eμ)+ jets	37±16	2±1	simulation+data
Misidentified leptons	165±65	116±55	simulation+ data
Total background	1390±140	343±89	—
Signal purity	**89%**	**96%**	—

- Oppositely charged eμ events:
  - lepton $p_T > 25$ GeV, $|\eta| < 2.5$
- Dominant background:
  - single top (Wt-channel) estimated in simulation
- Large theory uncertainty for Z+jets cross section:
  - measure the rates of Z ➛ ee and Z ➛ μμ in both data and simulation
  - scale the simulated Z ➛ ττ+jets with the ratio
- Large uncertainty on ttbar modeling :
  - due to lepton isolation efficiency
  - measured in-situ
- Misidentified lepton:
  - measured in data with same sign charged eμ events
- The cross section is measured both in full phase space volume and fiducial volume.

Inclusive σ(tt): eμ events at 13 TeV

$\int \mathcal{L}\, dt = 3.2\ fb^{-1}$

ATLAS-CONF-2016-005

Uncertainty	Δσ/σ [inclusive]	Δσ/σ [fiducial]
Data statistics	0.9%	
NLO modeling Compare MadGraph+Herwig++ and Powheg+Herwig++	0.8%	0.6%
Hadronization Compare Powheg+Pythia6 and Powheg+Herwig++	2.8%	1.9%
PDF Compare CT10 and NNPDF 3.0	0.5%	0.1%
Integrated luminosity	5.5%	
LHC beam energy	1.5%	
Experimental	1.5%	
Total uncertainty	**6.7%**	**6.3%**

Extrapolation to full phase space volume:

σ(tt) = 803 ± 7 (stat) ± 27 (syst) ± 45 (lumi) ± 12 (beam) pb

0.8% 3.3% 5.5% 1.5% Δσ/σ = 6.7%

Measurement in the fiducial volume:

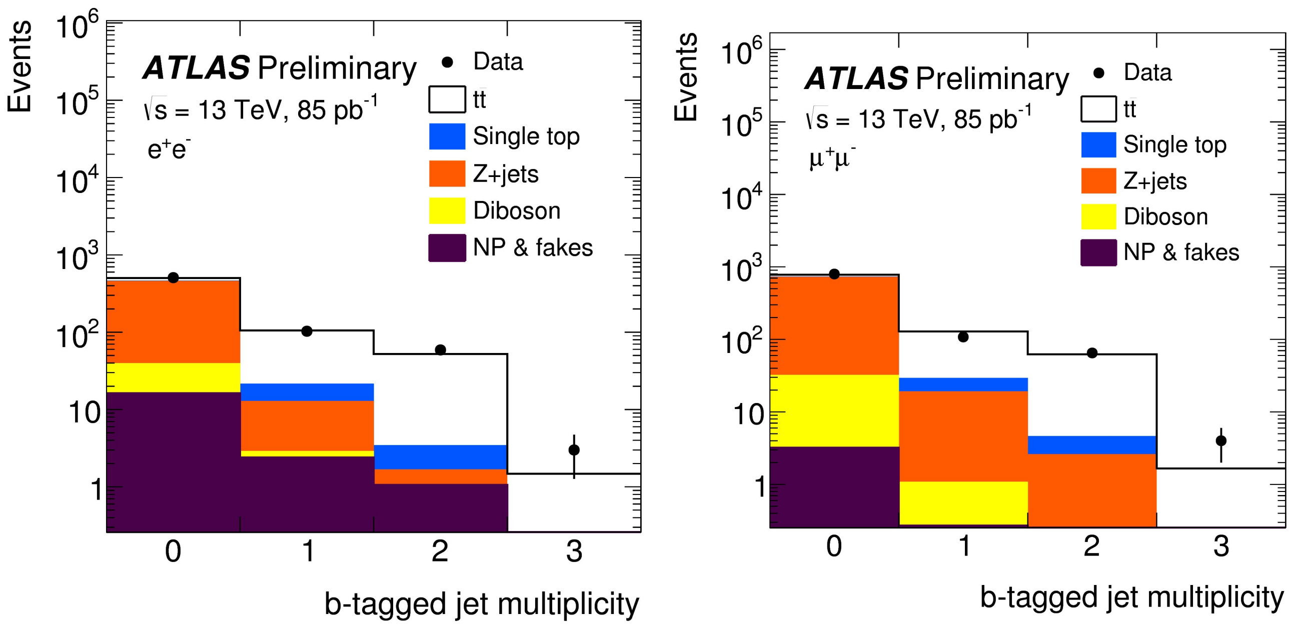
σ^{fid}(tt) = 11.12 ± 0.10 (stat) ± 0.28 (syst) ± 0.62 (lumi) ± 0.17 (beam) pb

Inclusive σ(tt): ee/μμ and e/μ+jets events at 13 TeV

$\int \mathcal{L}\,dt = 85\ pb^{-1}$

ATLAS-CONF-2015-049

- Oppositely charged ee or μ μ events:
  - lepton $p_T > 25$ GeV, $|\eta| < 2.5$
- Same method as eμ analysis:



- Dominant background Z+jets:
  - suppressed by vetoing Z mass
  - normalized in data region with high purity Z+jets events

ATLAS-CONF-2015-049

- Exactly one e/μ events:
  - lepton $p_T > 25$ GeV, $|\eta| < 2.5$
- Cross section measured by counting number of events:

$$\sigma = (N_{data} - N_{background})/\varepsilon L$$

- Non-prompt/fake background estimated in data
- Dominant background W+jets:
  - suppressed by requiring at least 4 jets at least 1 b-tag
  - normalized in data using W boson charge asymmetry measurement

σ(tt) = 749 ± 57 (stat) ± 79 (syst) ± 74 (lumi) pb
8% 11% 10%
$\Delta\sigma/\sigma = 16\%$ (ee/μμ)

σ(tt) = 817 ± 13 (stat) ± 103 (syst) ± 88 (lumi) pb
2% 13% 11%
$\Delta\sigma/\sigma = 17\%$ (e/μ+jets)

Ratio of σ(tt) and σ(Z)

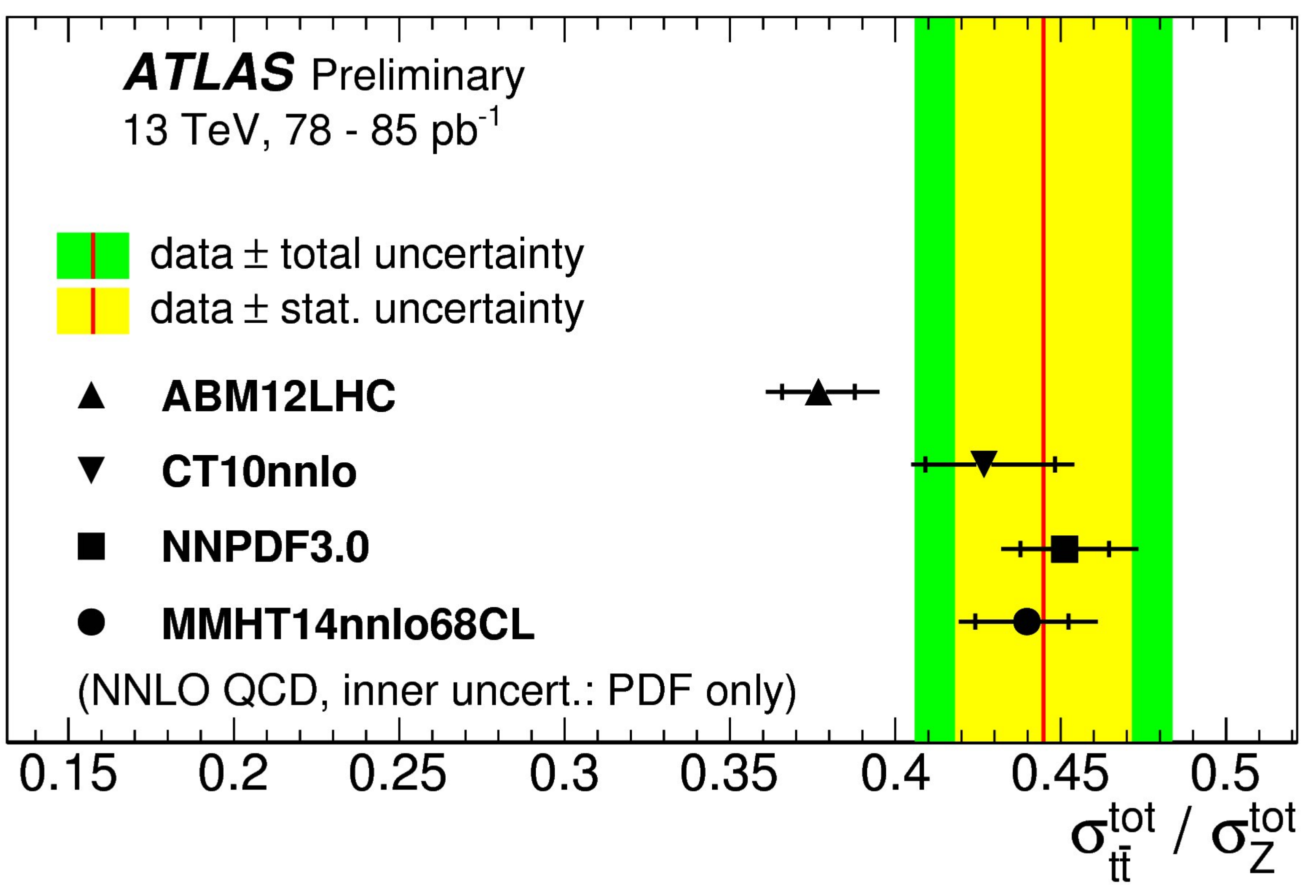
$\int \mathcal{L}\, dt = 78 - 85\ pb^{-1}$

ATLAS-CONF-2015-049

- Expected to cancel the large uncertainty from integrated luminosity
- Significant constraint on the qq/gg ratio in protons
- σ(tt) measured in eμ events and σ(Z) is measured in Z➛ee and Z ➛μμ events

$$R_{t\bar{t}/Z} = 0.445 \pm 0.027\ (\text{stat}) \pm 0.028\ (\text{syst})$$

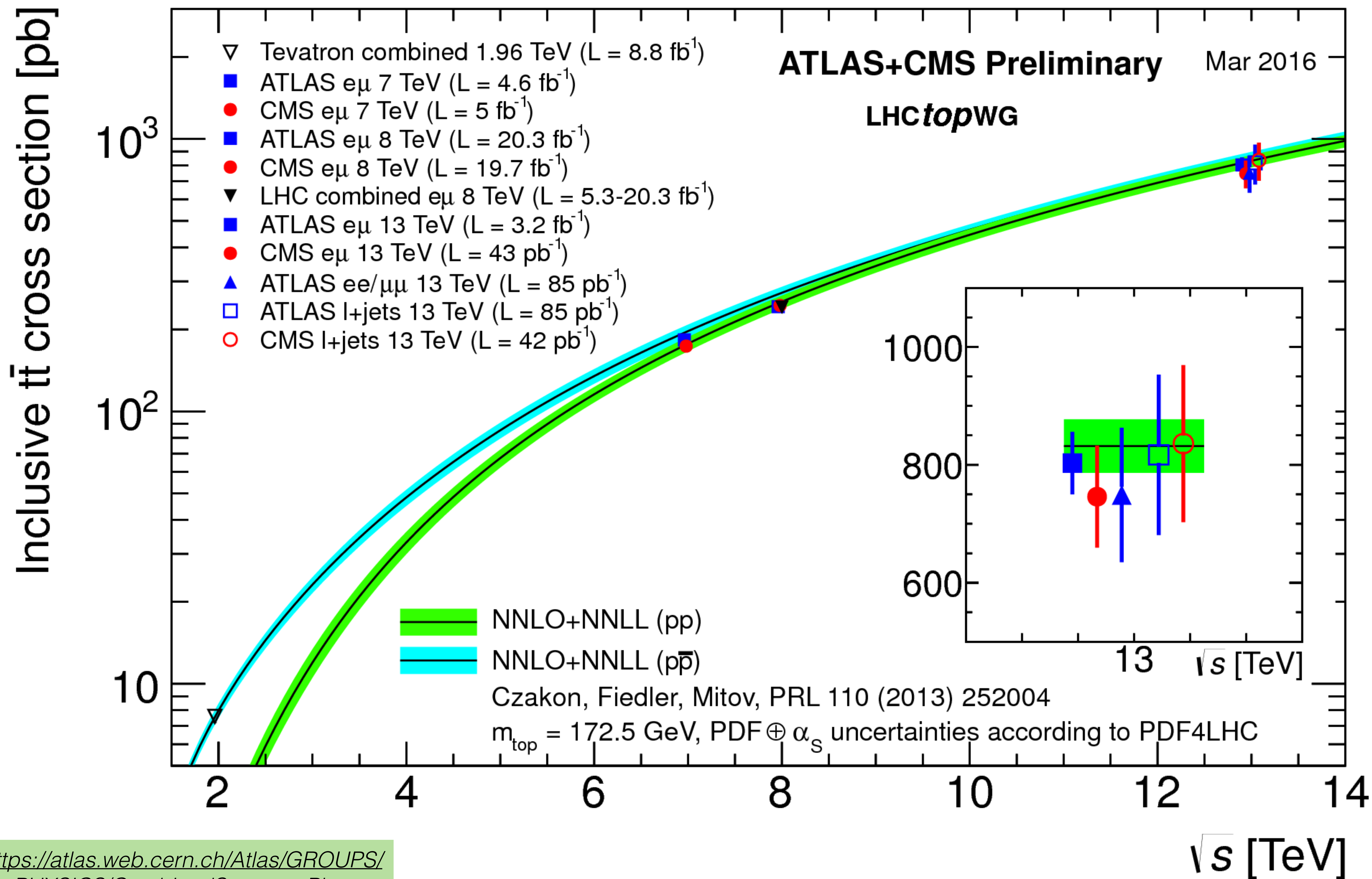
Uncertainty	σ(Z➛ee)	σ(Z ➛μμ)	σ(tt)	Ratio
Data statistics	0.5%	0.5%	6.0%	6.0%
Analysis systematics	4.4%	2.3%	6.7%	6.3%
Luminosity	9.0%	9.0%	10.0%	1.0%
Total	10.0%	9.3%	13.5%	8.8%



- Result is compared to prediction:
  - FEWZ for Z production
  - top++ for top pair production
- PDF predictions tested mostly compatible with data
- Some tension with ABM12LHC PDF set
  ➛ predicts 12% smaller σ(tt)

Further room to explore different ratios in Run 2 !

Inclusive σ(tt): The big picture

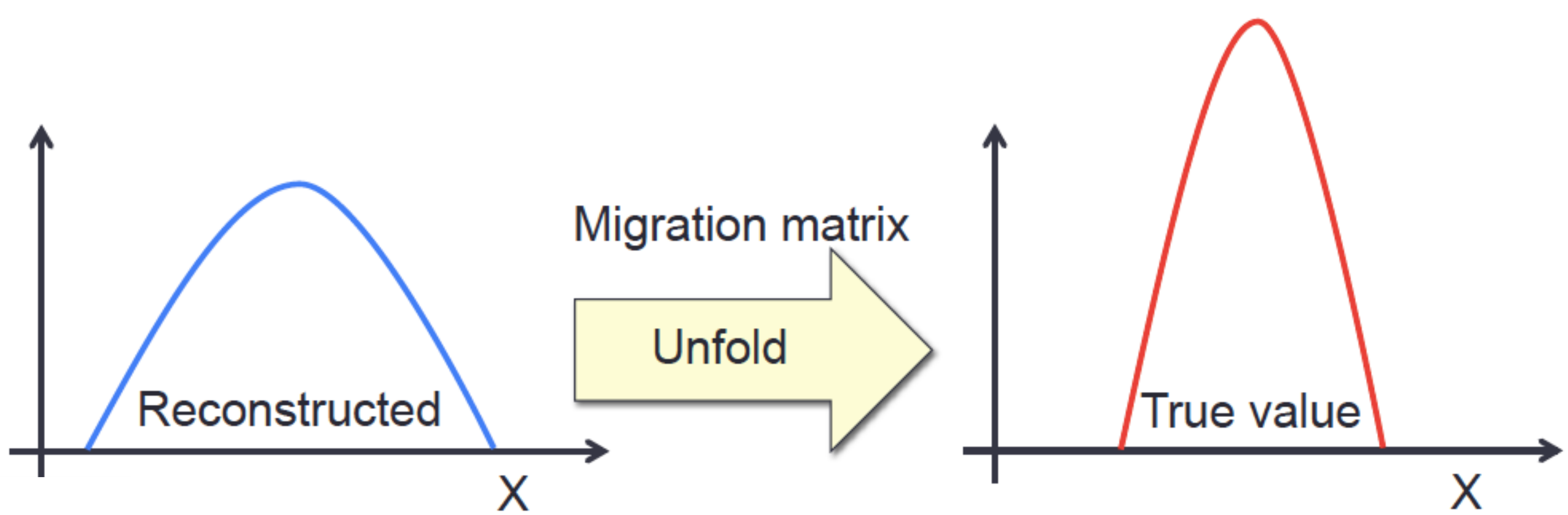


https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots

Remarkable agreement with theory!

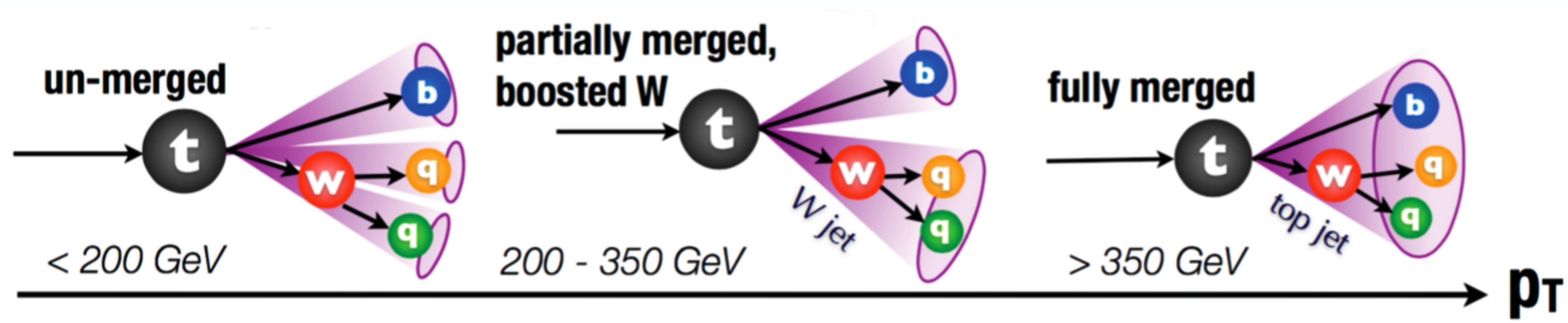
Differential measurements

- Large statistics of top quark pair at the LHC allows for precise differential measurements:
    - additional constraints on m_t, α_s, PDF, pQCD, new physics
    - compare theory to data corrected for reconstruction, resolution, parton shower effects
- Reconstruct variable X from selected events. X is corrected for detector effects ("unfolding" technique) to parton- and particle-level
- Parton-level: easier comparison with theoretical prediction
    - look at simulated decay chain and select the top quark. Usually before it decays to b-quark and W-boson (after radiation)
- Particle-level(pseudo-top): less model dependance
    - directly measurable quantities. No extrapolation to full phase space



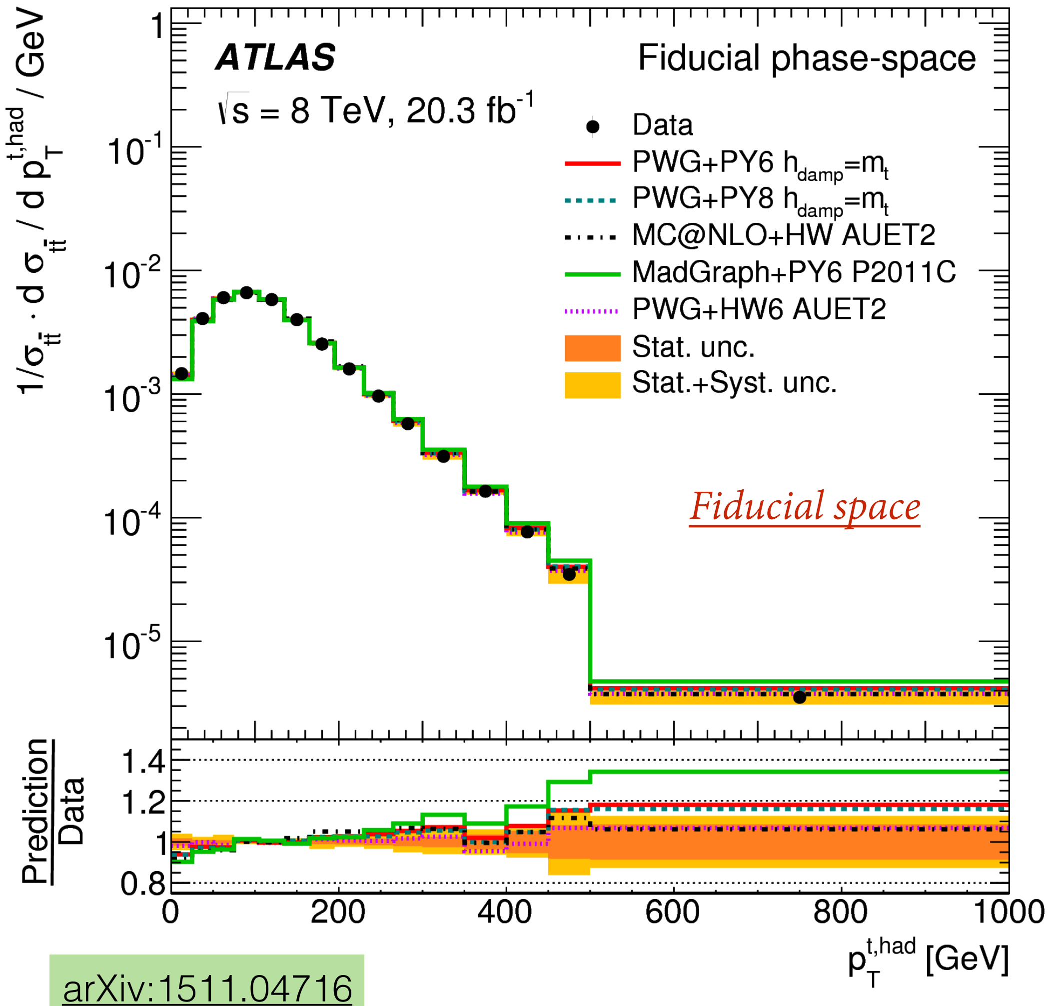
Differential measurements $d\sigma(tt)/dX$:

- Measure σ as a function of different observables: $p_T(t)$, $y(tt)$, M_{tt}, N_{jets}
- Both in the
  - resolved topology: top quark produced almost at rest- isolated leptons, not overlapping jet cones
  - boosted topology: form "large fat" jets+W bosons, leptons non-isolated
- Observables are sensitive to effects of ISR/FSR, PDF, non-resonant processes and higher order corrections



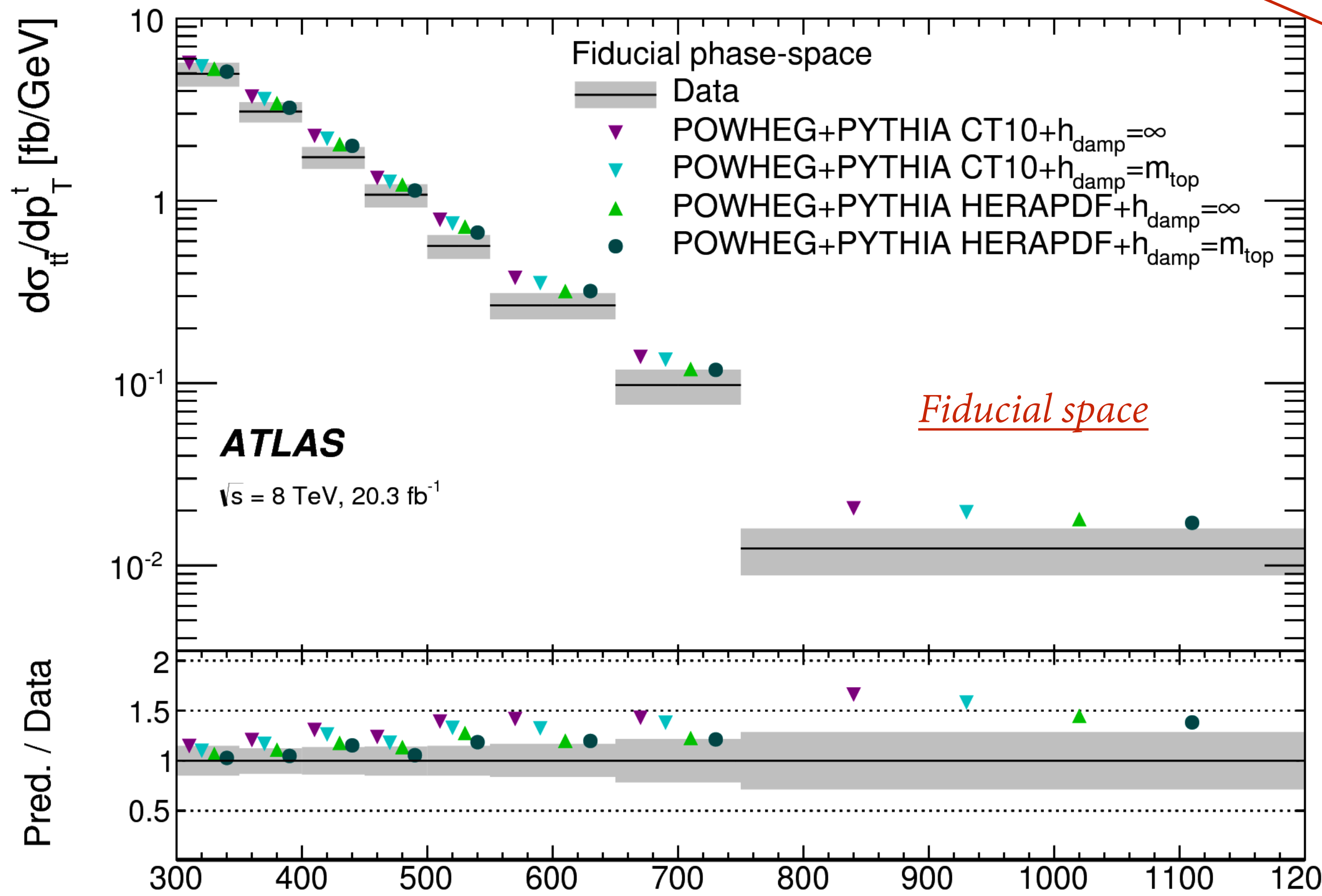
$d\sigma(tt)/dp_T(t)$: e/μ + jets at 8 TeV

$\int \mathcal{L}\, dt = 20.3\ \text{fb}^{-1}$



arXiv:1511.04716

Resolved



arXiv:1510.03818

Particle top-jet candidate p_T [GeV]

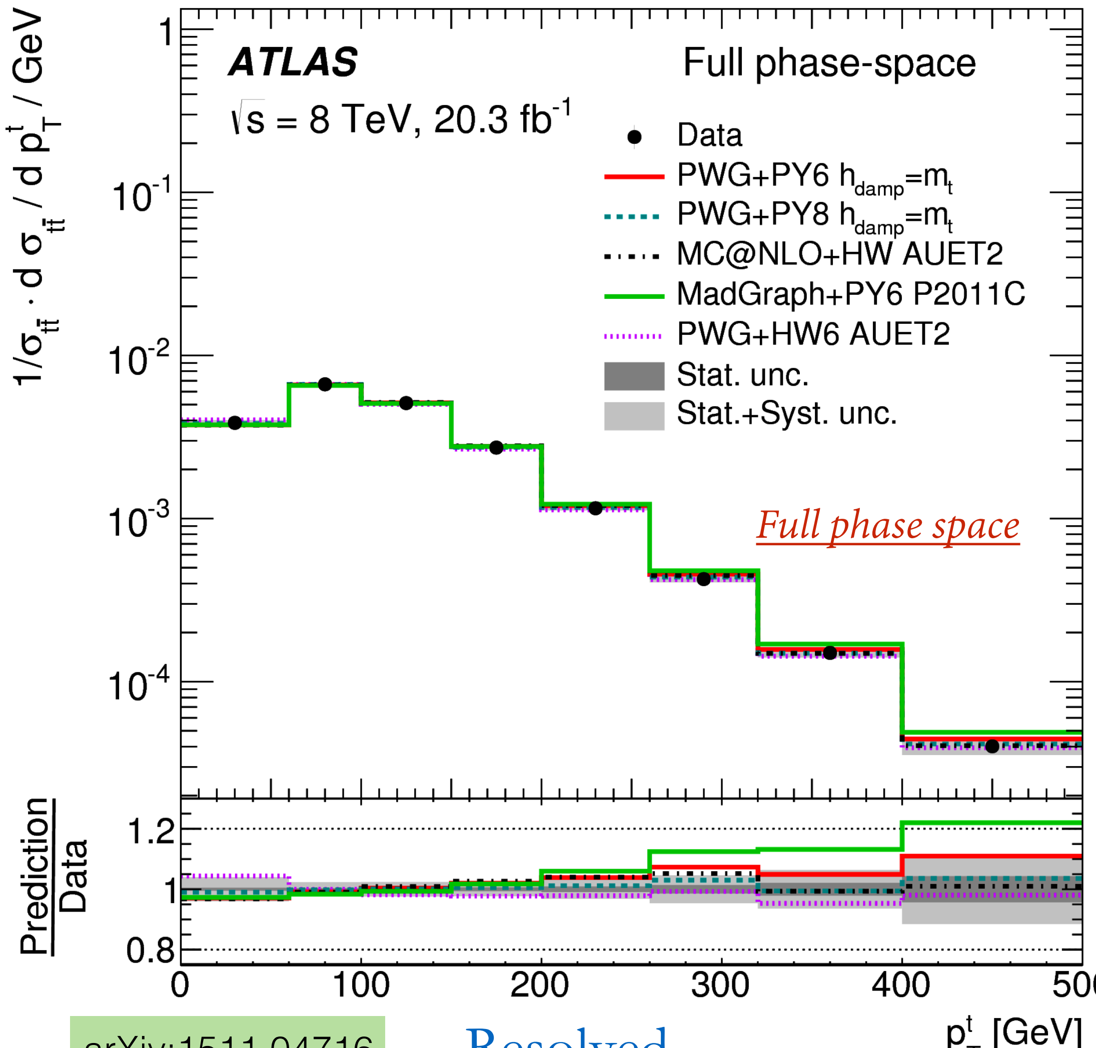
Boosted

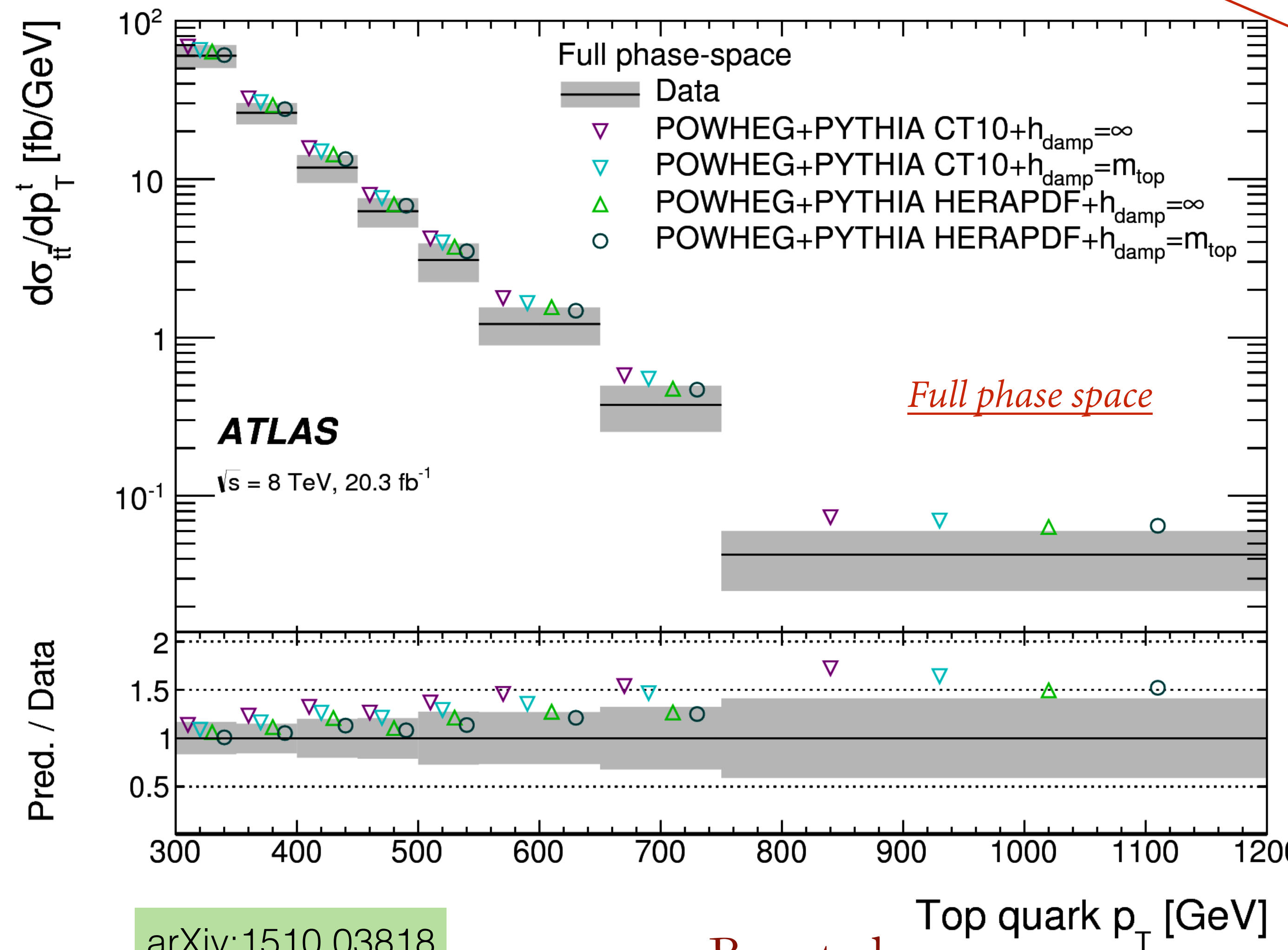
- Unfolded to top-jet particle level, i.e. jets built of stable truth-level particles
- p_T spectrum harder in simulation than data esp. for $p_T > 400$ GeV
- Same trend is observed in the boosted topology

p-value	PWG+PY8 CT10 $h_{damp} = m_t$	MC@NLO +HW CT10 AUET2	PWG+PY6 CT10 $h_{damp} = m_t$	PWG+HW6 CT10 $h_{damp} = \infty$	MadGraph+PY6 MadGraph+PY6 P2011C	PWG+PY6 HERAPDF $h_{damp} = m_t$	PWG+PY6 HERAPDF $h_{damp} = \infty$
resolved	0.72	0.04	0.59	1.00	< 0.01	-	0.05
boosted	-	0.14	0.11	0.41	-	0.31	0.21

$d\sigma(t\bar{t})/dp_T(t)$: e/μ + jets at 8 TeV

$\int \mathcal{L}\, dt = 20.3\ fb^{-1}$





arXiv:1511.04716 Resolved

arXiv:1510.03818 Boosted

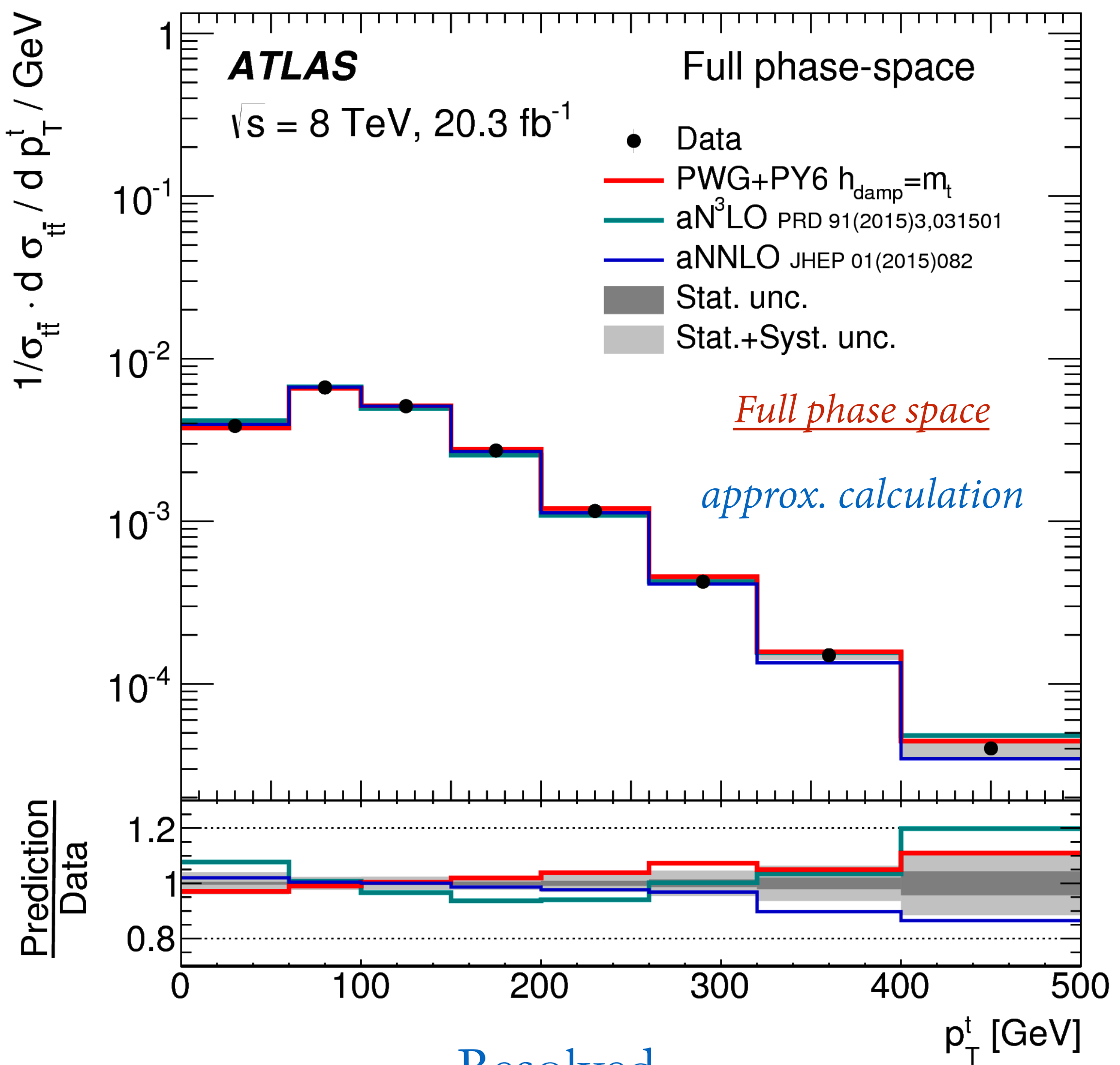
- Unfolded to parton level and extrapolated to full phase space using Powheg+Pythia
- Better agreement in simulation and data at the parton level both in resolved and boosted topology
- Mostly due to the large uncertainty compared to particle level

p-value	PWG+PY8 CT10 $h_{damp} = m_t$	MC@NLO +HW CT10 AUET2	PWG+PY6 CT10 $h_{damp} = m_t$	PWG+HW6 CT10 $h_{damp} = \infty$	MadGraph+PY6 MadGraph+PY6 P2011C
resolved	1.0	0.65	0.56	0.80	0.03

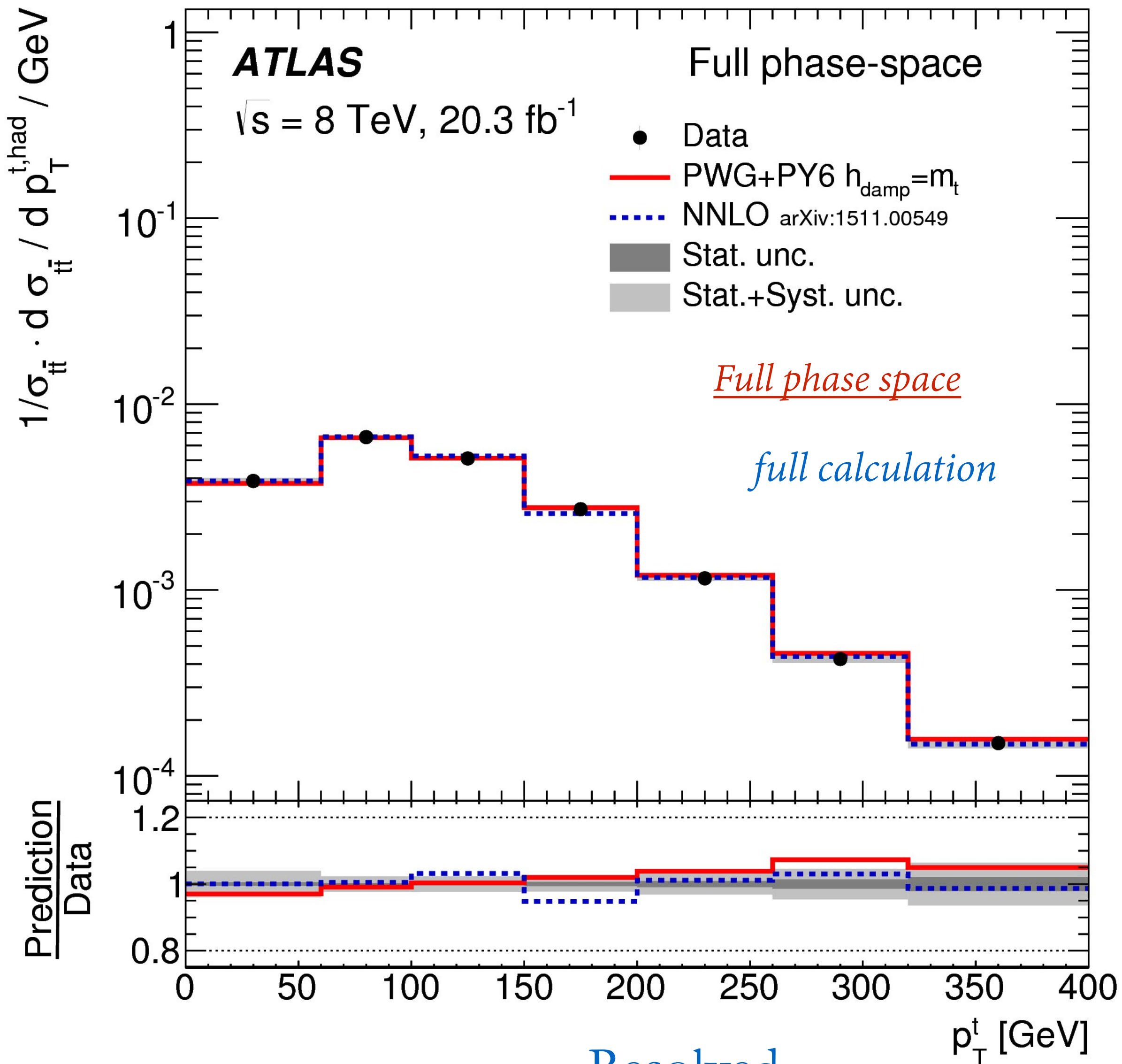
$d\sigma(tt)/dp_T(t)$: e/μ + jets at 8 TeV

$\int \mathcal{L}\, dt = 20.3\ fb^{-1}$

arXiv:1511.04716



Resolved

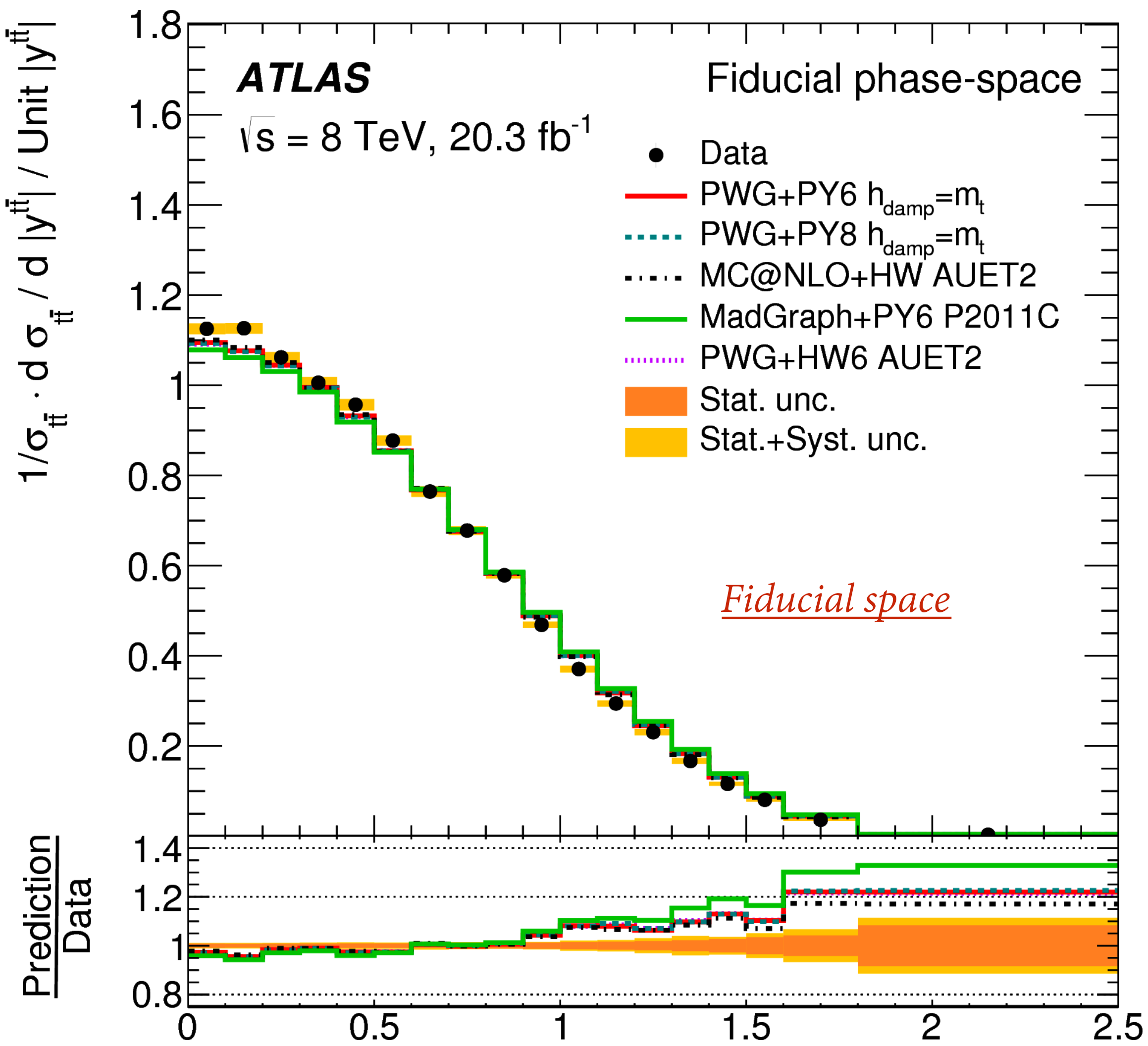


Resolved

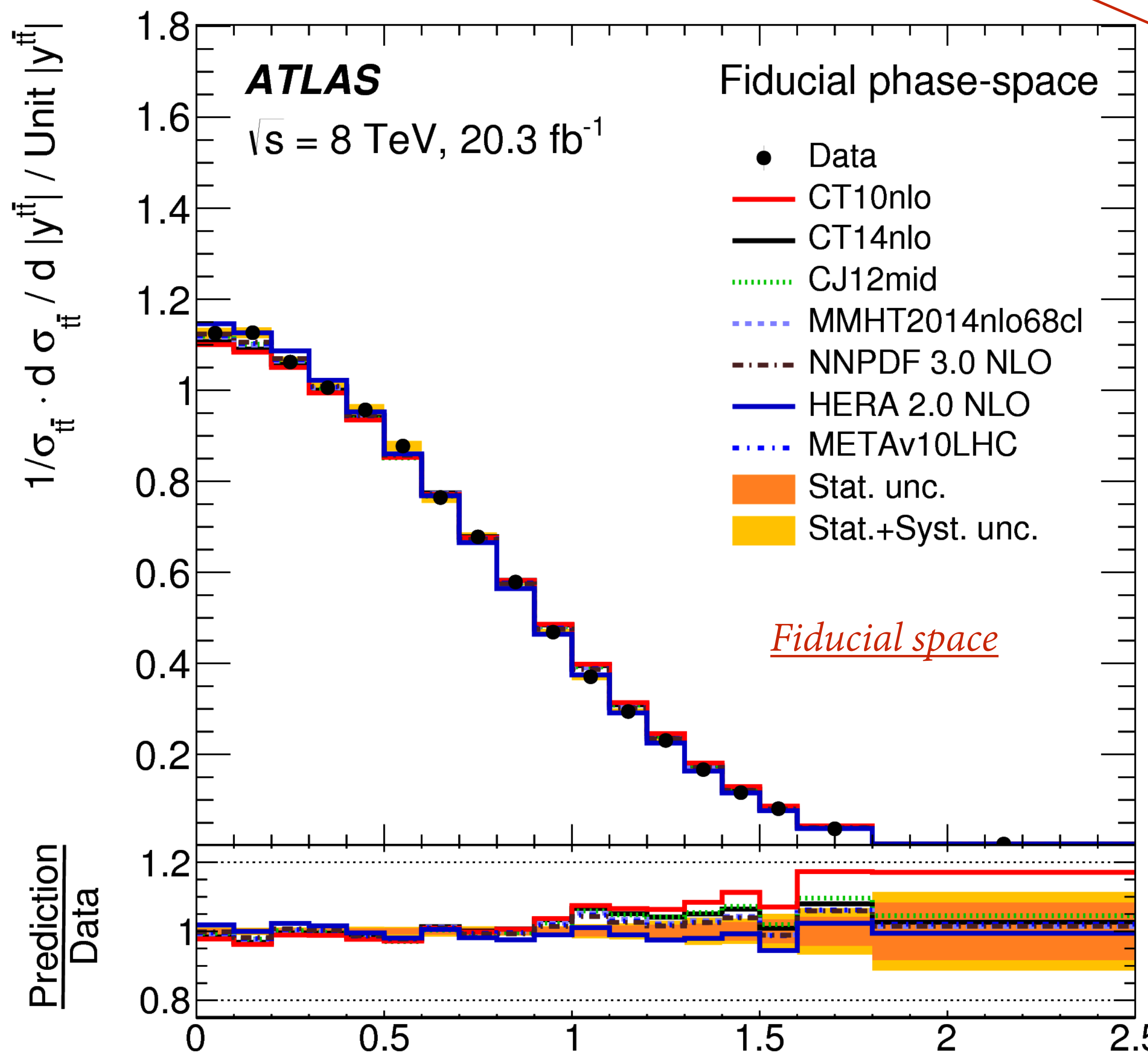
- In resolved topology, theoretical predictions with higher order QCD calculations also used
  - aN^3LO: apprx. next-to-next-to-next-to-leading order
  - aNNLO: apprx. next-to-next-to-leading order
  - NNLO: full next-to-next-to-leading order
- A full NNLO QCD calculation gives the best agreement with data

$d\sigma(tt)/dy(tt)$: e/μ + jets at 8 TeV

$\int \mathcal{L}\, dt = 20.3\ \text{fb}^{-1}$



Resolved



Resolved

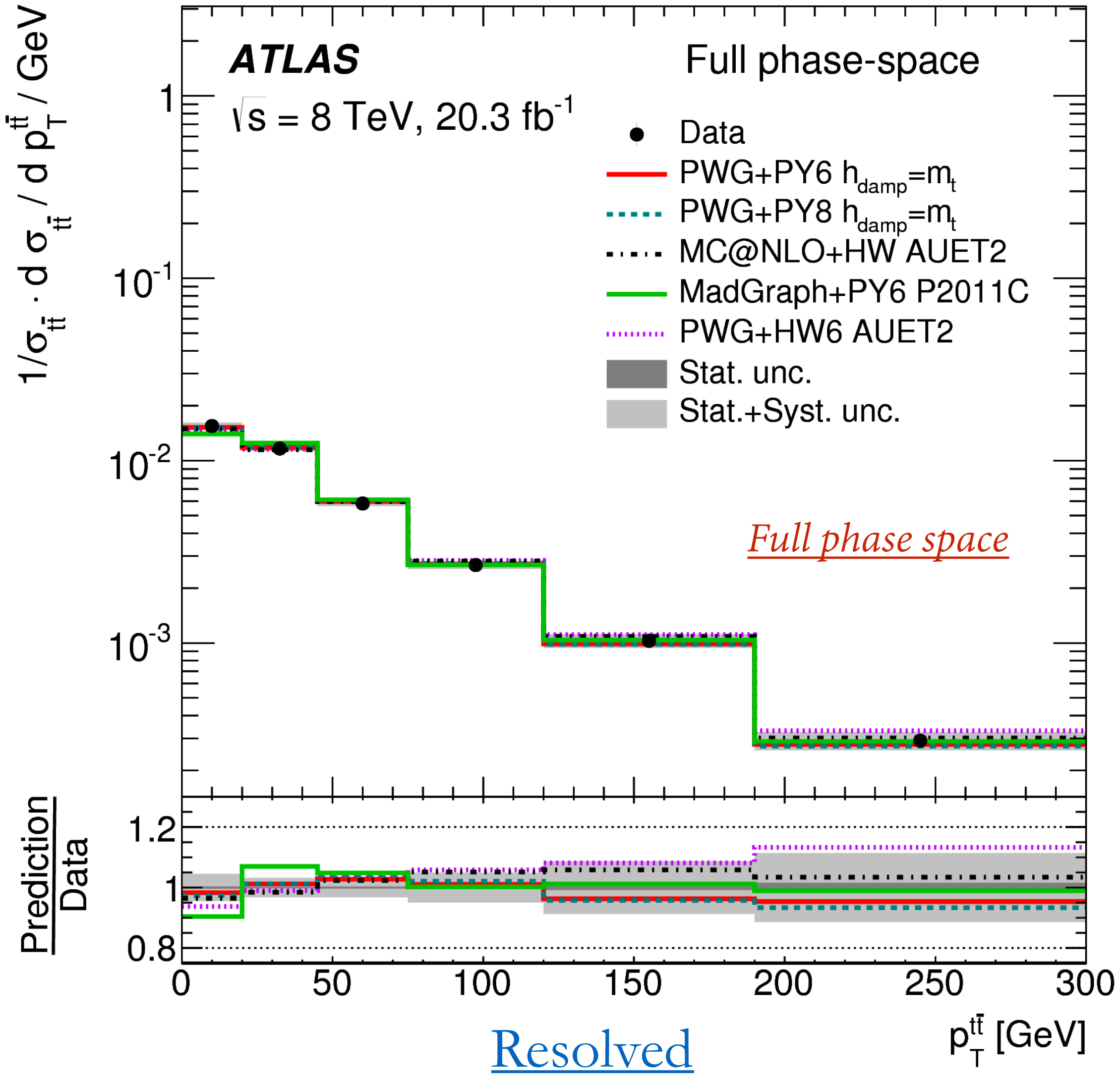
- Unfolded to parton level and extrapolated to full phase space using Powheg+Pythia6 with CT10 PDF
- Sensitive to (gluon) PDF, especially in the forward region
- *p*-value for all generators < 0.01
- Direct comparison among different PDF sets for Powheg+Pythia6

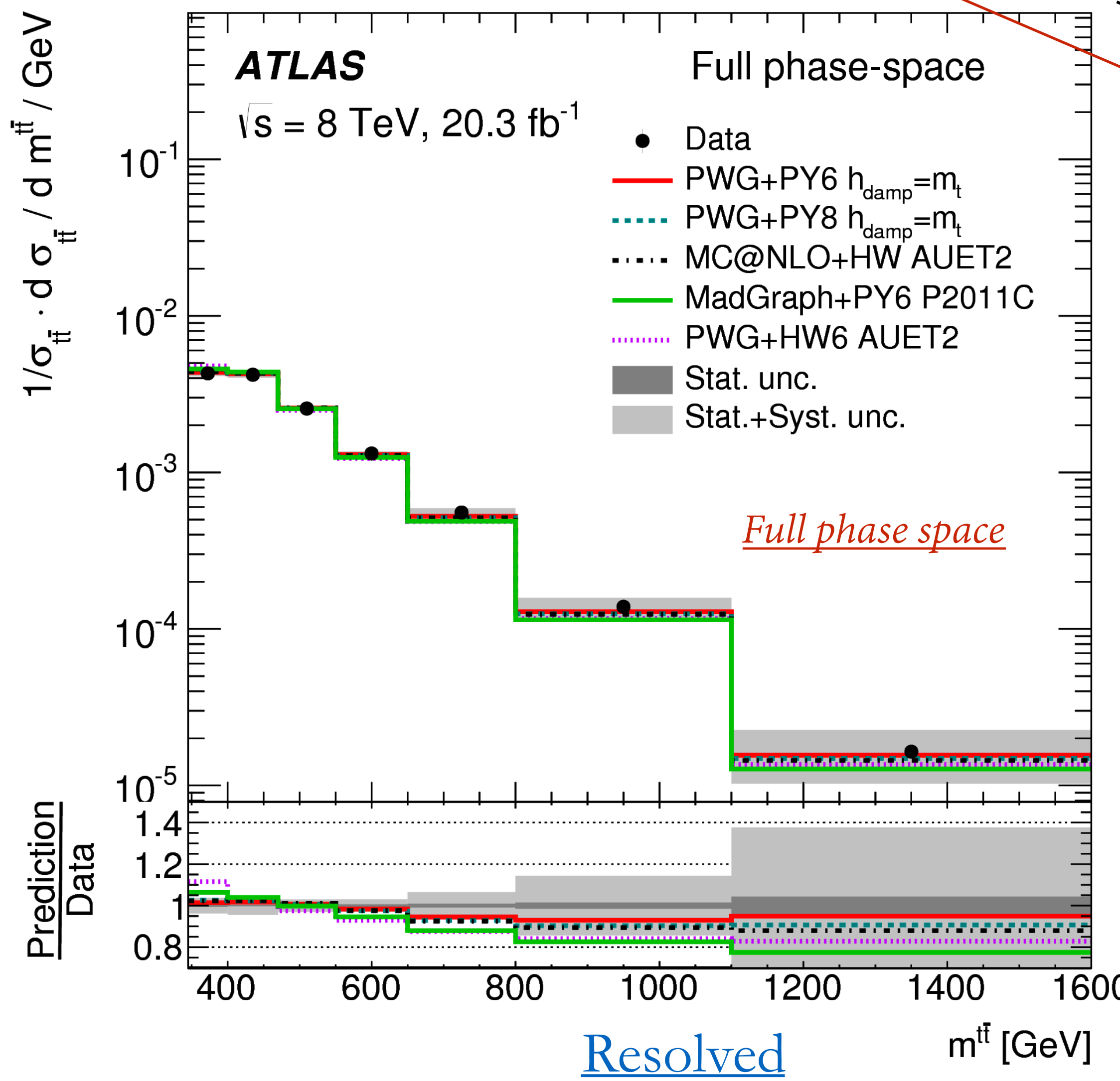
arXiv:1511.04716

p-value	CT14nlo	CJ12mid	MMHT 2014nlo68cl	NNPDF30nlo	CT10nlo	METAv10LHC	HERA20NLO
resolved	< 0.01	<0.01	0.10	0.40	<0.01	0.27	0.22

$d\sigma(tt)/dp_T(tt), d\sigma(tt)/dm(tt)$: e/μ + jets at 8 TeV

$\int \mathcal{L}\, dt = 20.3\ fb^{-1}$





- Unfolded to parton level and extrapolated to full phase space using Powheg+Pythia6 with CT10 PDF
- Sensitive to new, large width, particles decaying to top quark pair
- Important to tune simulation well

arXiv:1511.04716

p-value	PWG+PY8 CT10 $h_{damp} = m_t$	MC@NLO +HW CT10 AUET2	PWG+PY6 CT10 $h_{damp} = m_t$	PWG+HW6 CT10 $h_{damp} = \infty$	MadGraph+PY6 MadGraph+PY6 P2011C
$p_T(tt)$	0.75	0.72	0.94	0.41	0.05
$m(tt)$	0.73	0.71	0.93	<0.01	0.04

Summary

- ATLAS performed inclusive top quark pair production cross section in single lepton, dilepton and all hadronic decay modes
- All measurements are in agreement with NNLO+NNLL calculations
- Final states with eμ events provide the most precise measurements
- Experimental accuracy has reached the theoretical calculations
- Further precision tests performed through differential cross section measurements
- Unfolding techniques to particle and parton level provides a variety of interface with theory.
- Softer $p_T(t)$ spectrum is observed in data, full NNLO calculation describes data better than NLO, aNNLO and aN^{3}LO calculations.

A wealth of measurements to follow with high statistics and never before achieved precision!

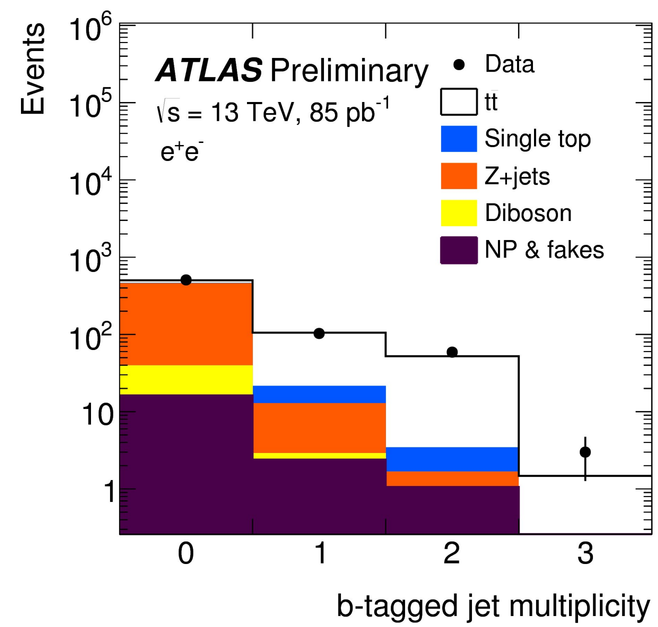
BACKUP

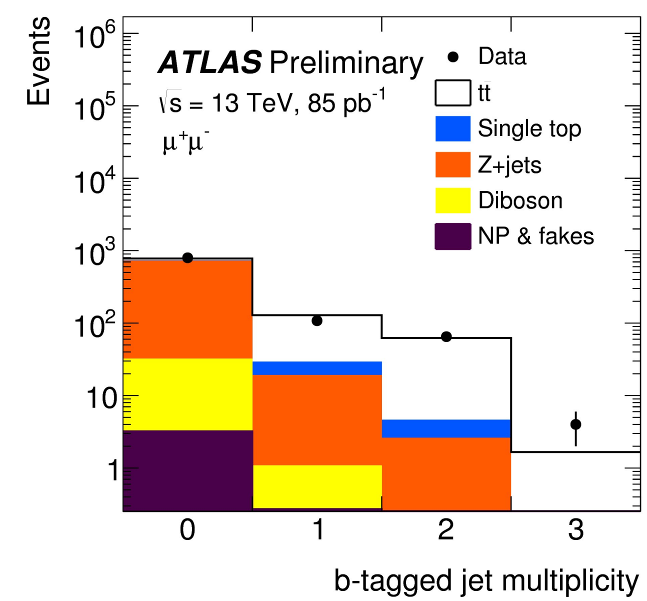
Inclusive σ(tt): ee/μμ events at 13 TeV

$\int \mathcal{L}\, dt = 85\ \mathrm{pb}^{-1}$

ATLAS-CONF-2015-049

- Oppositely charged ee or μ μ events:
  - lepton $p_T > 25$ GeV, $|\eta| < 2.5$
- Z+jets background is suppressed :
  - $101 < M(\ell\ell)$ (GeV) < 81
  - missing $E_T > 30$ GeV
- Dominant background Z+jets:
  - normalized using a high purity Z+jets control region $81 < M(\ell\ell)$ (GeV) < 101





$$N_1^{ee} = L\sigma_{t\bar{t}}\,\epsilon^{ee}_{\mathrm{presel}} 2\epsilon_b^{ee}(1 - C_b^{ee}\epsilon_b^{ee}) + N_1^{\mathrm{bkg},ee}$$
$$N_2^{ee} = L\sigma_{t\bar{t}}\,\epsilon^{ee}_{\mathrm{presel}} C_b^{ee}\epsilon_b^{ee}\epsilon_b^{ee} + N_2^{\mathrm{bkg},ee}$$

$$N_1^{\mu\mu} = L\sigma_{t\bar{t}}\,\epsilon^{\mu\mu}_{\mathrm{presel}} 2\epsilon_b^{\mu\mu}(1 - C_b^{\mu\mu}\epsilon_b^{\mu\mu}) + N_1^{\mathrm{bkg},\mu\mu}$$
$$N_2^{\mu\mu} = L\sigma_{t\bar{t}}\,\epsilon^{\mu\mu}_{\mathrm{presel}} C_b^{\mu\mu}\epsilon_b^{\mu\mu}\epsilon_b^{\mu\mu} + N_2^{\mathrm{bkg},\mu\mu},$$

Event Count	N_1(ee)	N_2(ee)	N_1(μμ)	N_2(μμ)	Estimation
Data	103	59	108	65	—
Z(→ℓℓ)+ jets	9.9±2.3	0.6±0.7	18±6	2.5±2.0	sim.+data
Z(→ττ→ℓℓ)+ jets	0.14±0.1	< 0.01	0.11±0.1	0.02±0.1	sim.+data
Dibosons	0.5±0.4	0.02±0.1	0.8±0.6	0.07±0.1	simulation
Non prompt/Fakes	2.4±0.5	1.1±0.4	0.27±0.2	0.08±0.2	simulation
Single top	8.7±1.6	1.8±0.9	10.3±1.6	2.0±0.9	simulation
Total background	21.6±2.8	3.4±1.8	29.4±3.0	4.6±1.8	—
Signal purity	80%	93%	80%	96%	—

σ(tt) = 749 ± 57 (stat) ± 79 (syst) ± 74 (lumi) pb
8% 11% 10% Δσ/σ = 16%

Inclusive σ(tt): e/μ+jets events at 13 TeV

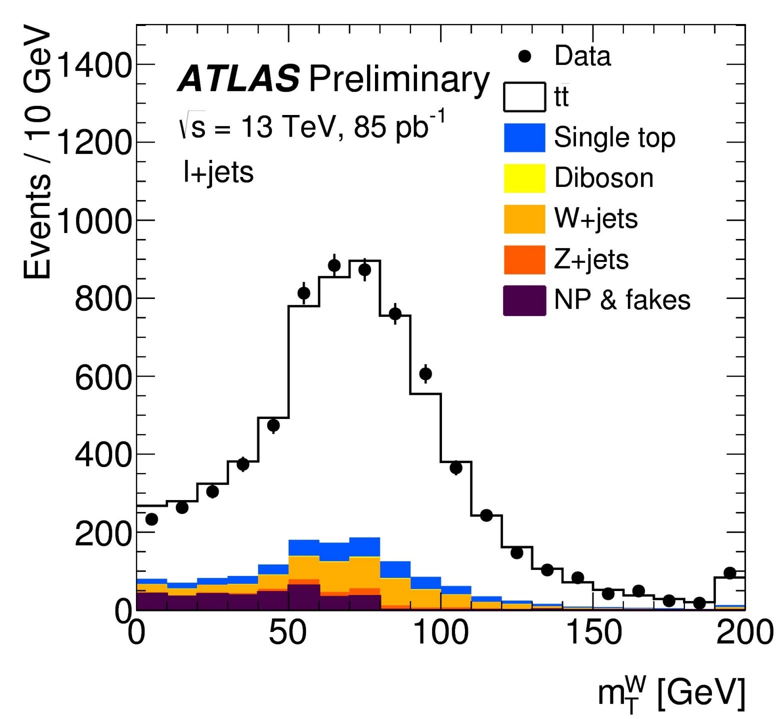
$\int \mathcal{L}\, dt = 85\ pb^{-1}$

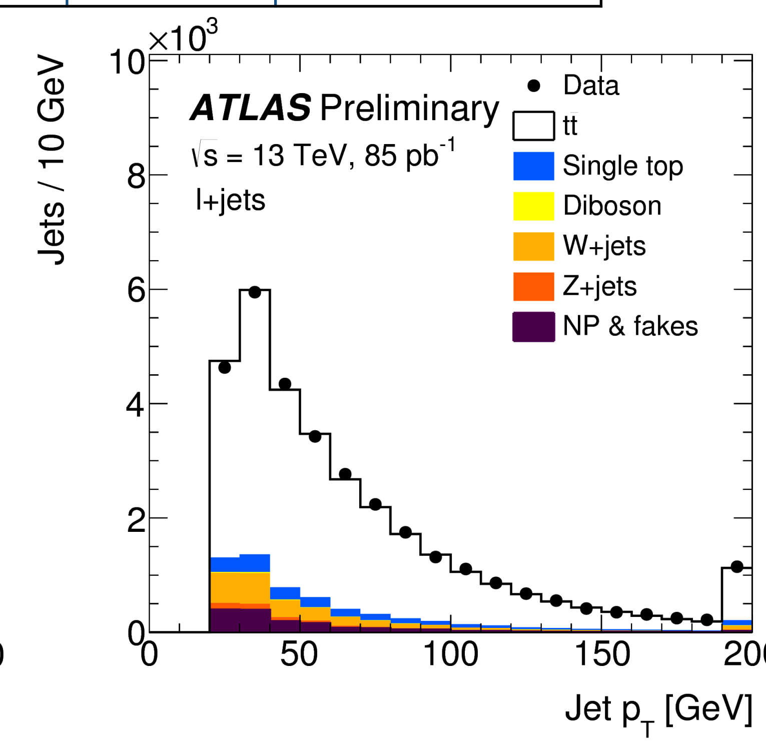
ATLAS-CONF-2015-049

- Exactly one e/μ events:
  - lepton $p_T > 25$ GeV, $|\eta| < 2.5$
- Suppress W+jets background:
  - at least 4 jets
  - at least 1 jet is b-tagged
- Suppress non-prompt/fake background:
  - missing $E_T > 40$ GeV
  - W transverse mass, $m_T > 50$ GeV
- Dominant background W+jets:
  - normalized in data using W boson charge asymmetry measurement
- Cross section measured using counting number of events:

$$\sigma = (N_{data} - N_{background})/\varepsilon L$$

Event Count	e+jets	μ+jets	Estimation
Data	3439	3314	—
W+jets	340±100	230±60	data
Single top	192±34	180±30	simulation
Dibosons	10±5	10±5	simulation
Z+ jets	71±35	45±22	simulation
Fakes	200±70	130±60	data
Total background	820±130	600±100	—
Signal purity	80%	80%	—





σ(tt) = 817 ± 13 (stat) ± 103 (syst) ± 88 (lumi) pb

2% 13% 11% $\Delta\sigma/\sigma = 17\%$

$d\sigma(tt)/dN_{jets}$: ee/μμ/eμ events at 13 TeV

$\int \mathcal{L}\, dt = 3.2\ \mathrm{fb}^{-1}$

ATLAS-CONF-2015-065

- Production of additional jets is sensitive to higher order pQCD effects
- Expected to be independent of the lepton flavor from W decay
- The modeling of these jets contribute to significant source of uncertainty in precision measurement
- Dominant background in searches for new physics
- Dilepton events are considered:
  - oppositely charged ee/μμ/eμ pairs
  - at least 2 b-tagged jets
  - Z mass veto
- Any other accompanying jets are considered to be additional
- Data is unfolded to particle level i.e. fiducial region using Powheg+Pythia6

$d\sigma(tt)/dN_{jets}$: ee/μμ/eμ events at 13 TeV

$\int \mathcal{L}\, dt = 3.2\ fb^{-1}$

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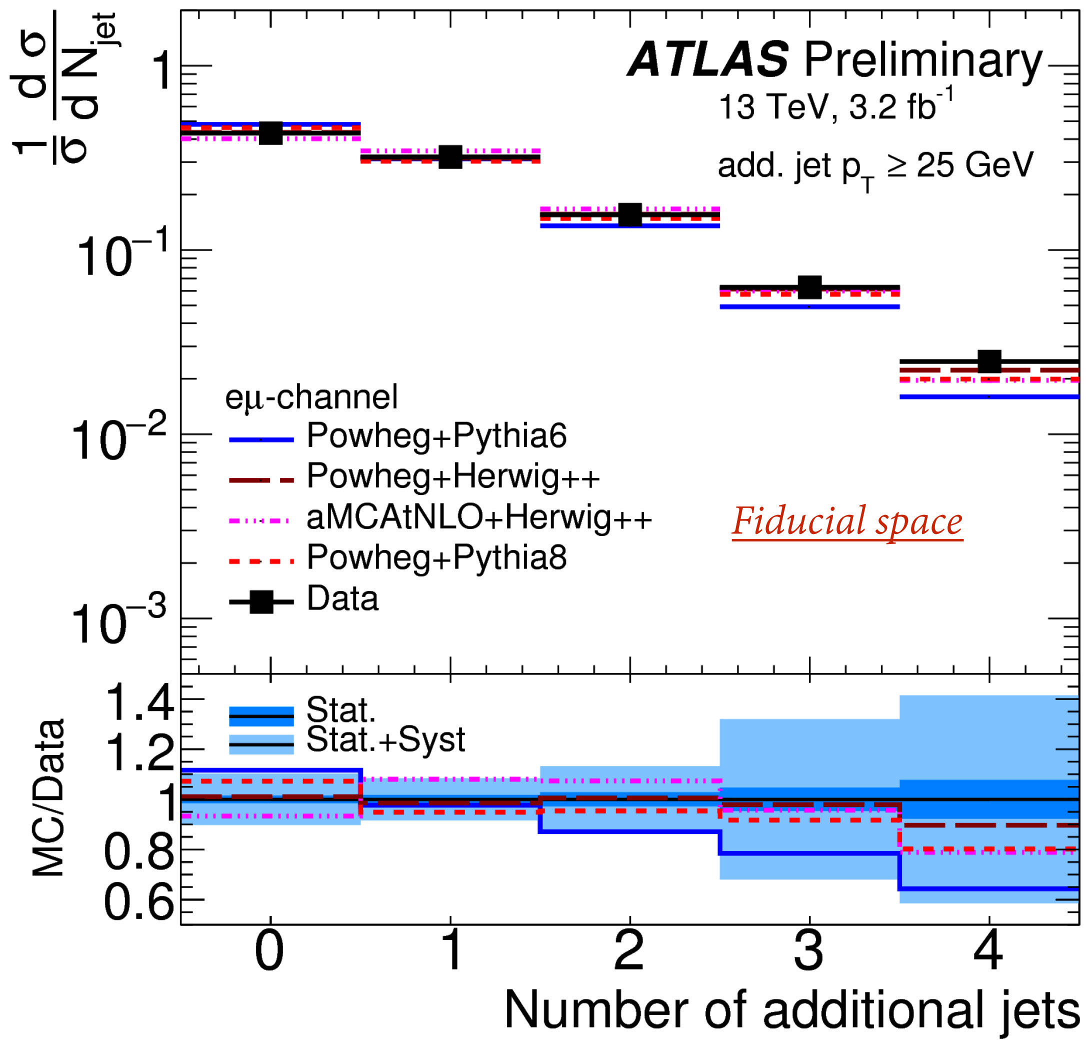

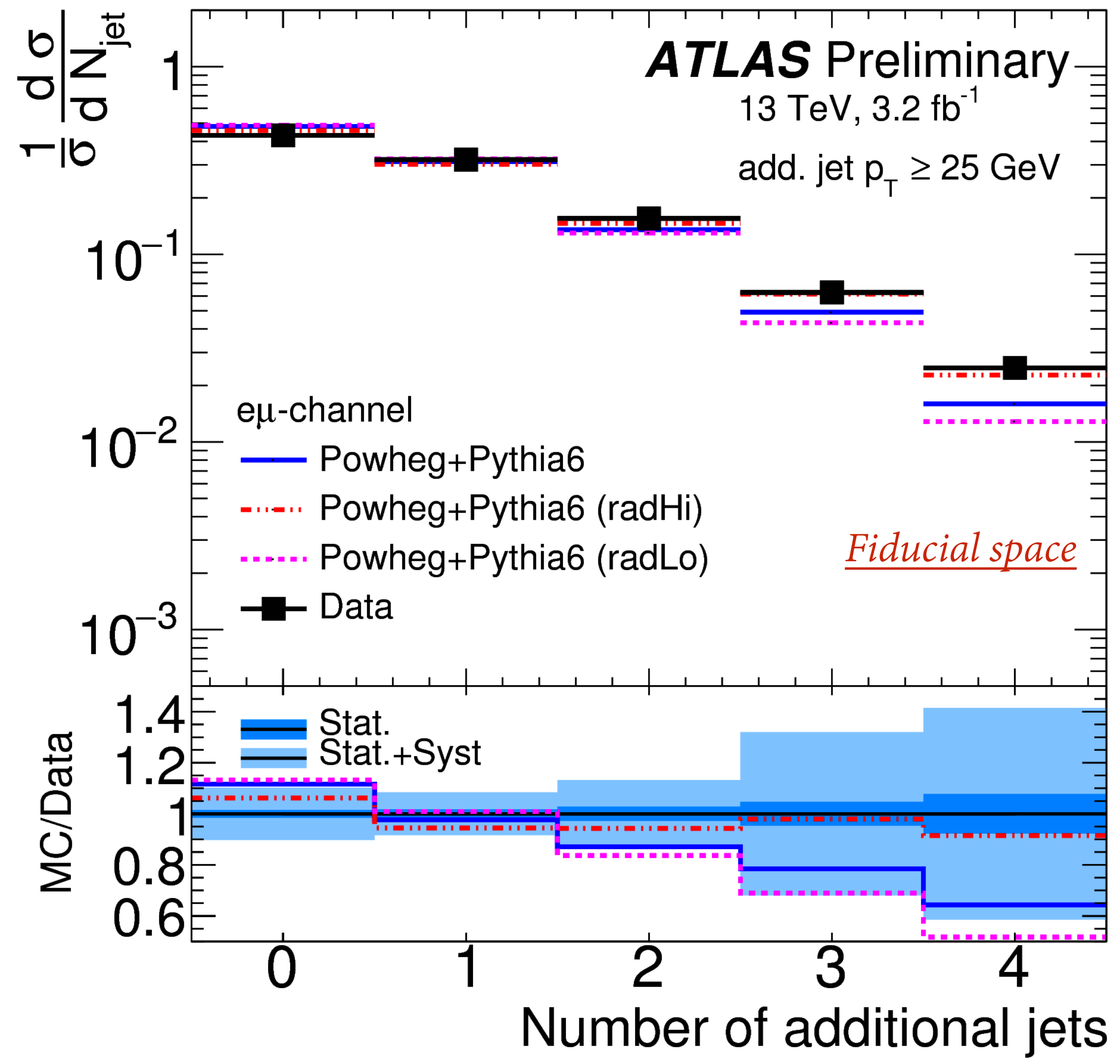

Syst (%)	0-jet	1-jet	2-jets	3-jets	4-jets
Statistics	1.5	1.8	2.8	4.6	7.7
Signal modelling	6.3	7.3	5.1	22.0	32.8
Jets	6.7	3.9	11.3	22.2	21.5
Other	0.3	1.4	1.3	3.3	9.5
Total	**9.3**	**8.6**	**12.7**	**31.8**	**41.1**