Latest results on top production from the CMS and ATLAS collaborations: inclusive and differential measurements

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On behalf of the CMS and ATLAS Collaborations

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Wildbad Kreuth 4-9 October 2015

Outline

- Top quark pair production cross sections at the LHC (7, 8 and 13 TeV)
  - Total inclusive
  - Differential (resolved and boosted regimes)

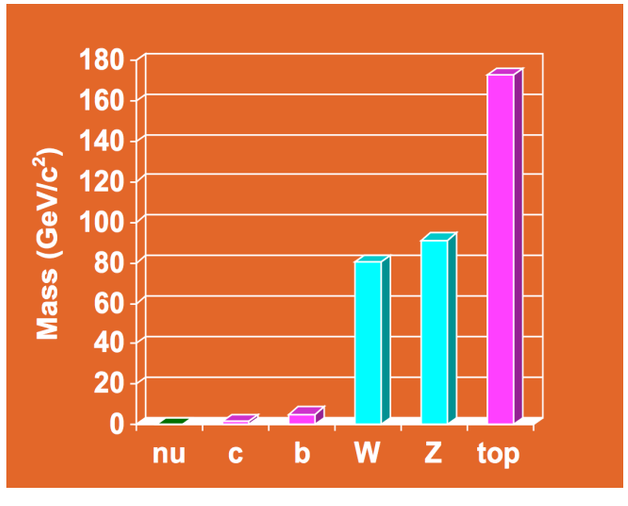
- Associated production of top quarks with a gauge boson
  - $t\bar{t}+W$, $t\bar{t}+Z$

- Single top production
  - t-channel
  - Wt channel
  - s-channel

Introduction

20 years after its discovery top quark remains an intriguing particle

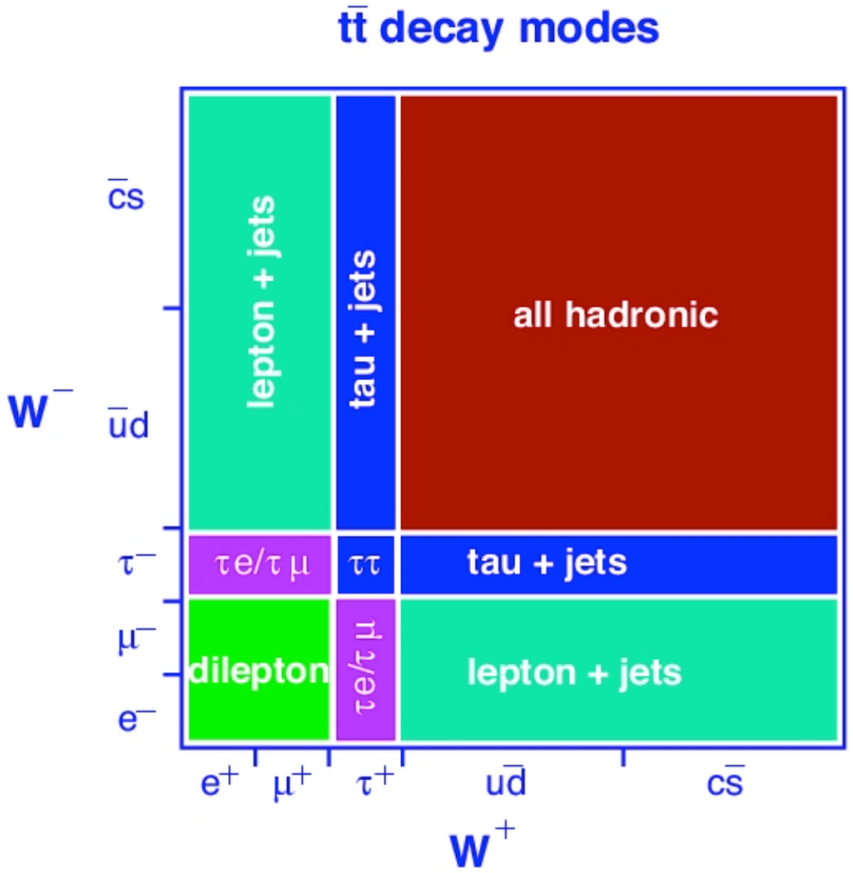
- The most massive elementary particle
- Decays before hadronising
- Could play a role in EWSB

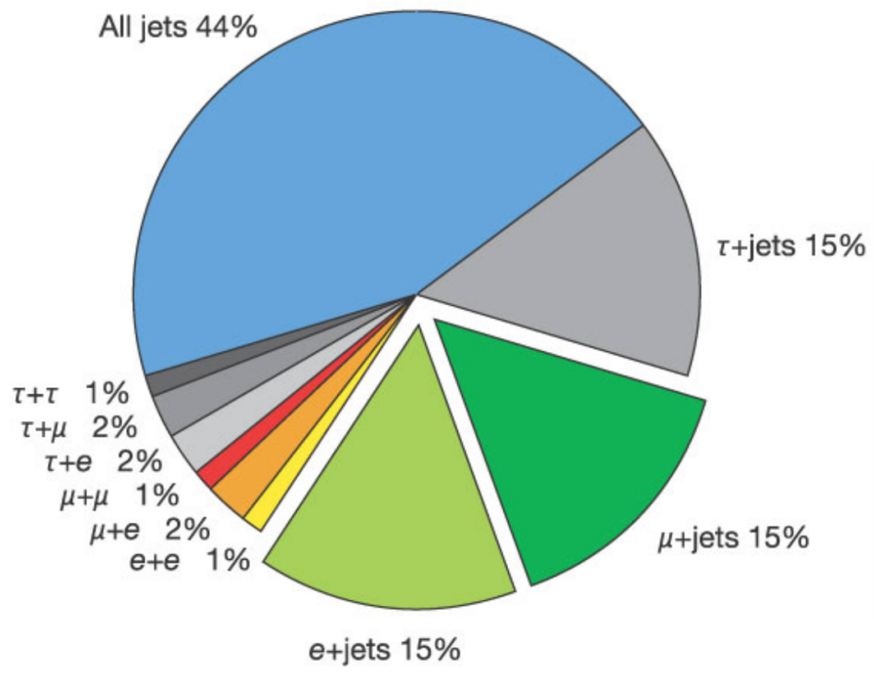


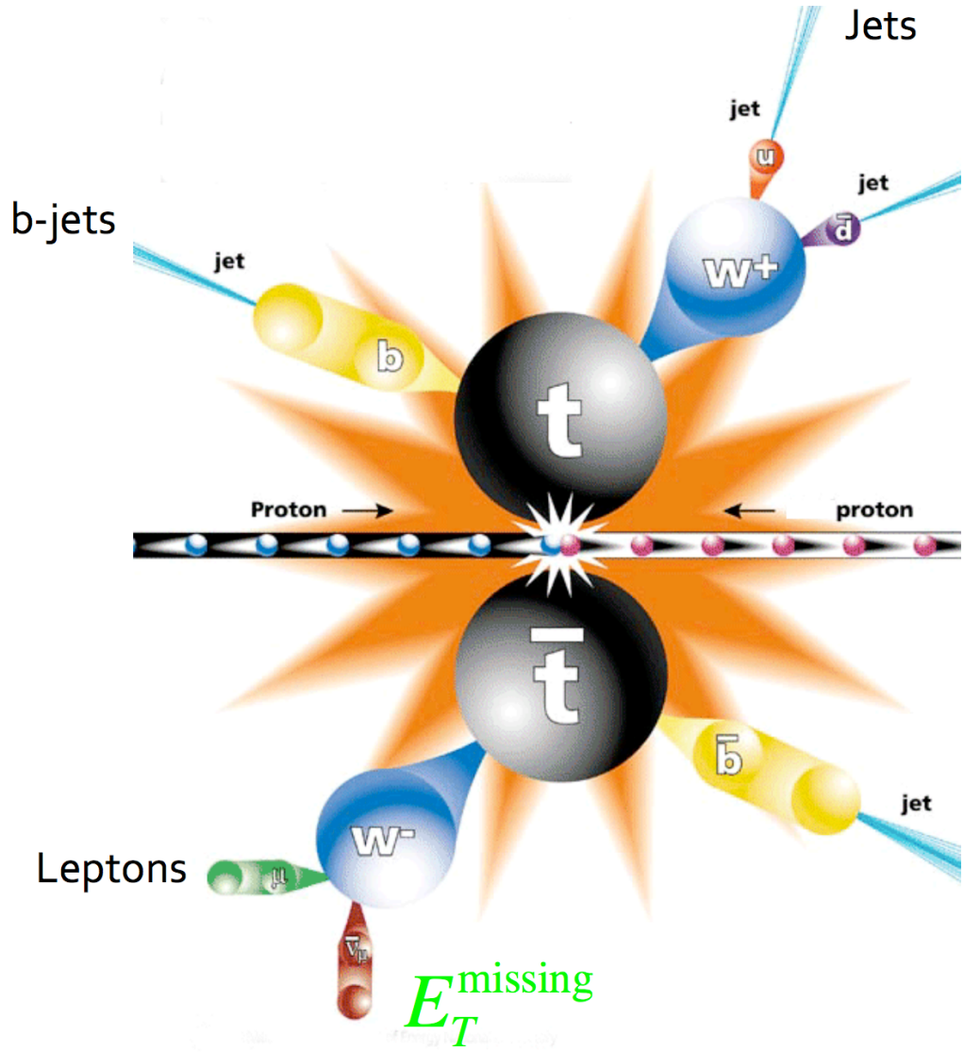
With its large top production rates, LHC is a top factory. This makes it possible to carry out a very important Top Physics programme:

- Production and decay processes: test pQCD and EW
- Probe couplings to H and Z
- Significant background to Higgs and New Physics searches

Top pair decays







$$BR(t \to b + W) \cong 100\%$$

The leptonic/hadronic decays of the W fully characterise the final state signature

$t\bar{t}$ production - pQCD

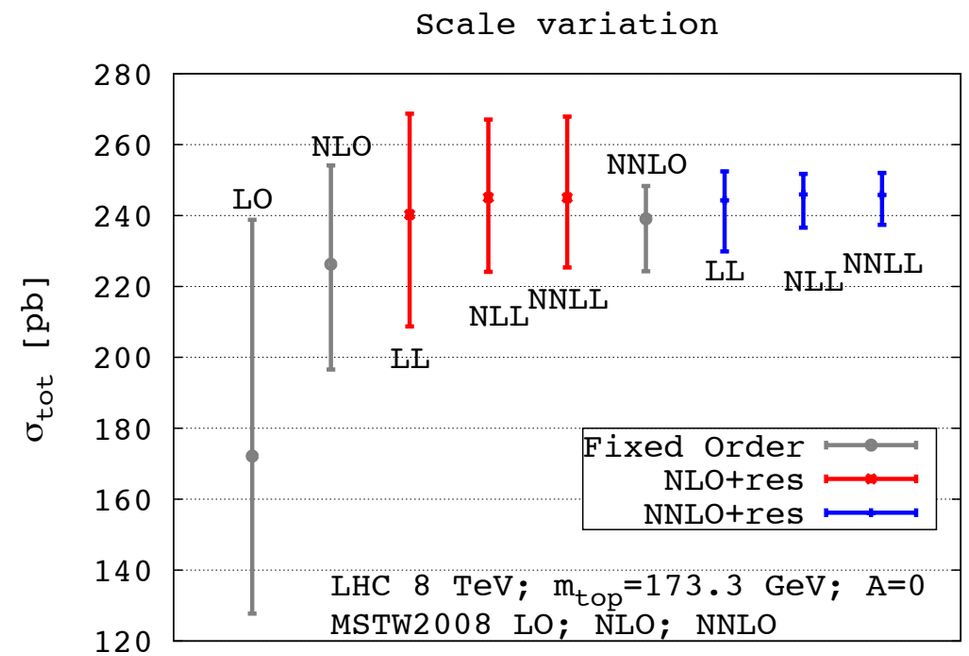
arXiv:1305.3892

Test of pQCD

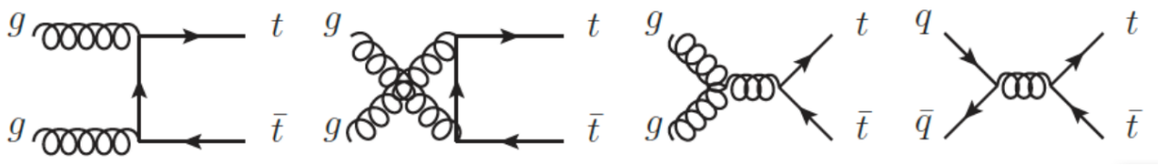
The total cross section for top pair production process

$$\sigma_{\rm tot}(p+p \to t+\bar{t}+X)$$

is known with very high theoretical precision (NNLO +NNLL)



Leading order terms:



Gluon-initiated: 90% Quark initiated: 10% (@14 TeV)

PRL 110,252004 (2013)

Collider	$\sigma_{\rm tot}$ [pb]	scales [pb]	PDF [pb]
Tevatron	7.164	$^{+0.110(1.5\%)}_{-0.200(2.8\%)}$	$^{+0.169(2.4\%)}_{-0.122(1.7\%)}$
LHC 7 TeV	172.0	$^{+4.4(2.6\%)}_{-5.8(3.4\%)}$	$^{+4.7(2.7\%)}_{-4.8(2.8\%)}$
LHC 8 TeV	245.8	$^{+6.2(2.5\%)}_{-8.4(3.4\%)}$	$^{+6.2(2.5\%)}_{-6.4(2.6\%)}$
LHC 14 TeV	953.6	$^{+22.7(2.4\%)}_{-33.9(3.6\%)}$	$^{+16.2(1.7\%)}_{-17.8(1.9\%)}$

$t\bar{t}$ production - pQCD

arXiv:1305.3892

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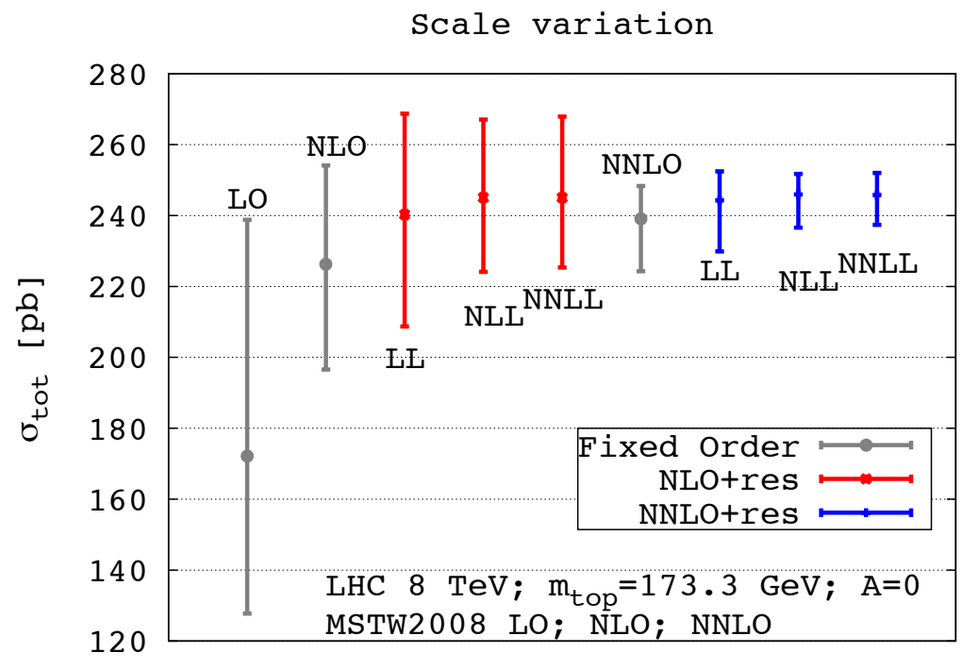
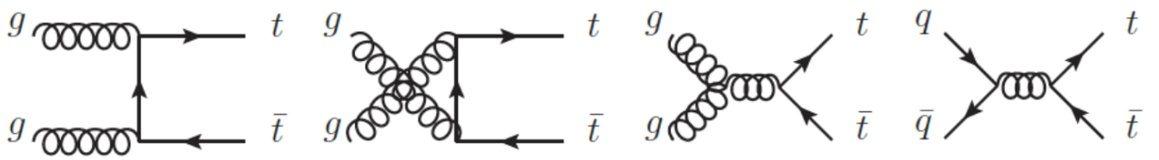


Leading order terms:



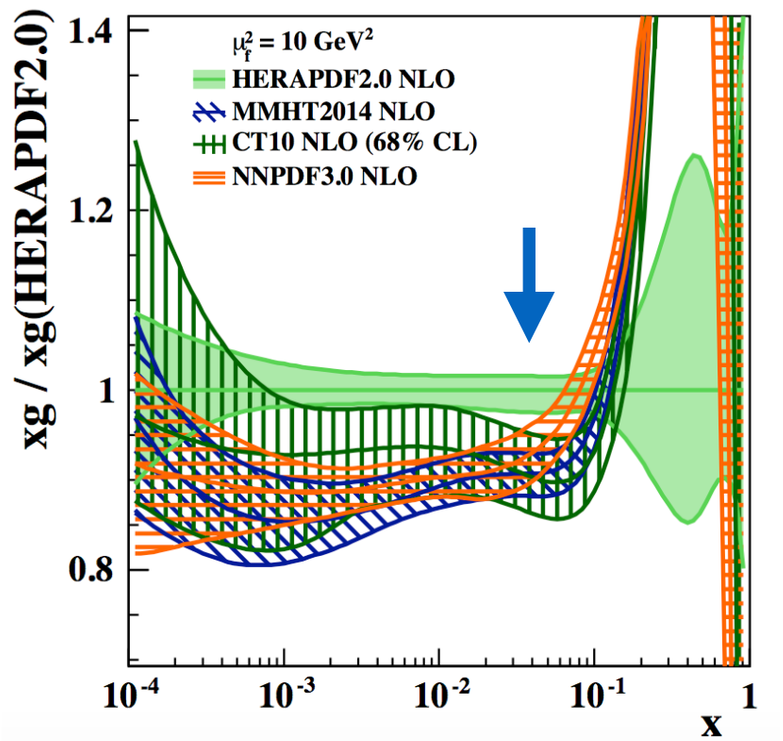
Gluon-initiated: 90% Quark initiated: 10% (@14 TeV)

arXiv:1506.06042

Gluon density

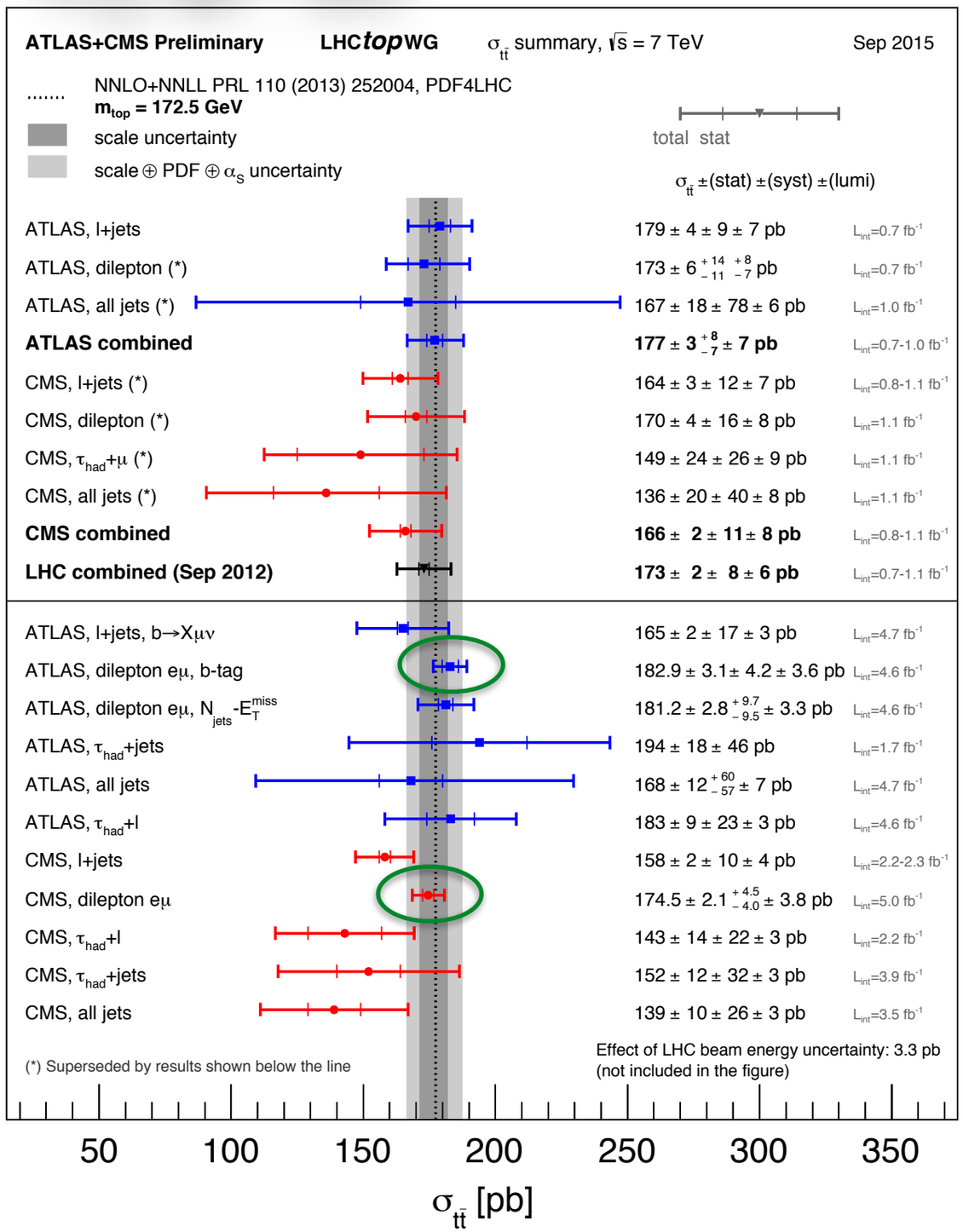
typical x-Bjorken values of the initial partons:

$$x \sim \frac{2m_t}{\sqrt{s}} \sim 4 \cdot 10^{-2} \quad @\ 8\ \mathrm{TeV}$$



Total inclusive cross sections for top pair production

$\sigma_{t\bar{t}}$ @7 TeV



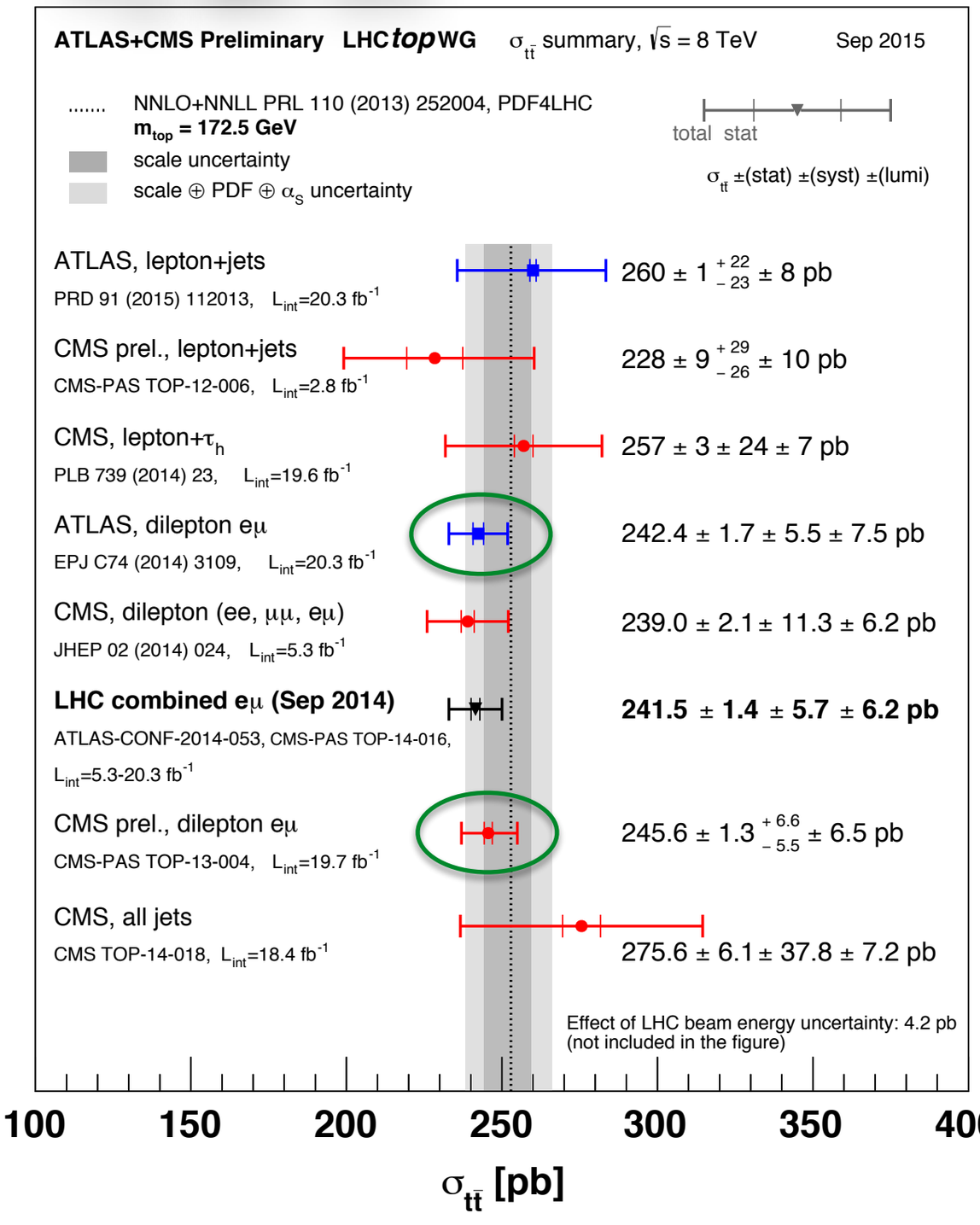
The ATLAS and CMS collaborations have measured the total inclusive cross sections for top pair production at 7, 8 and 13 TeV

All channels (di-lepton, l+jet and full had) have been exploited using diverse experimental approaches.

Table presents a summary of the results at:
- 7 TeV Run (based on ~ 2-5 fb^{-1})

Total inclusive cross sections for top pair production

$\sigma_{t\bar{t}}$ @8 TeV



The ATLAS and CMS collaborations have measured the total inclusive cross sections for top pair production at 7, 8 and 13 TeV

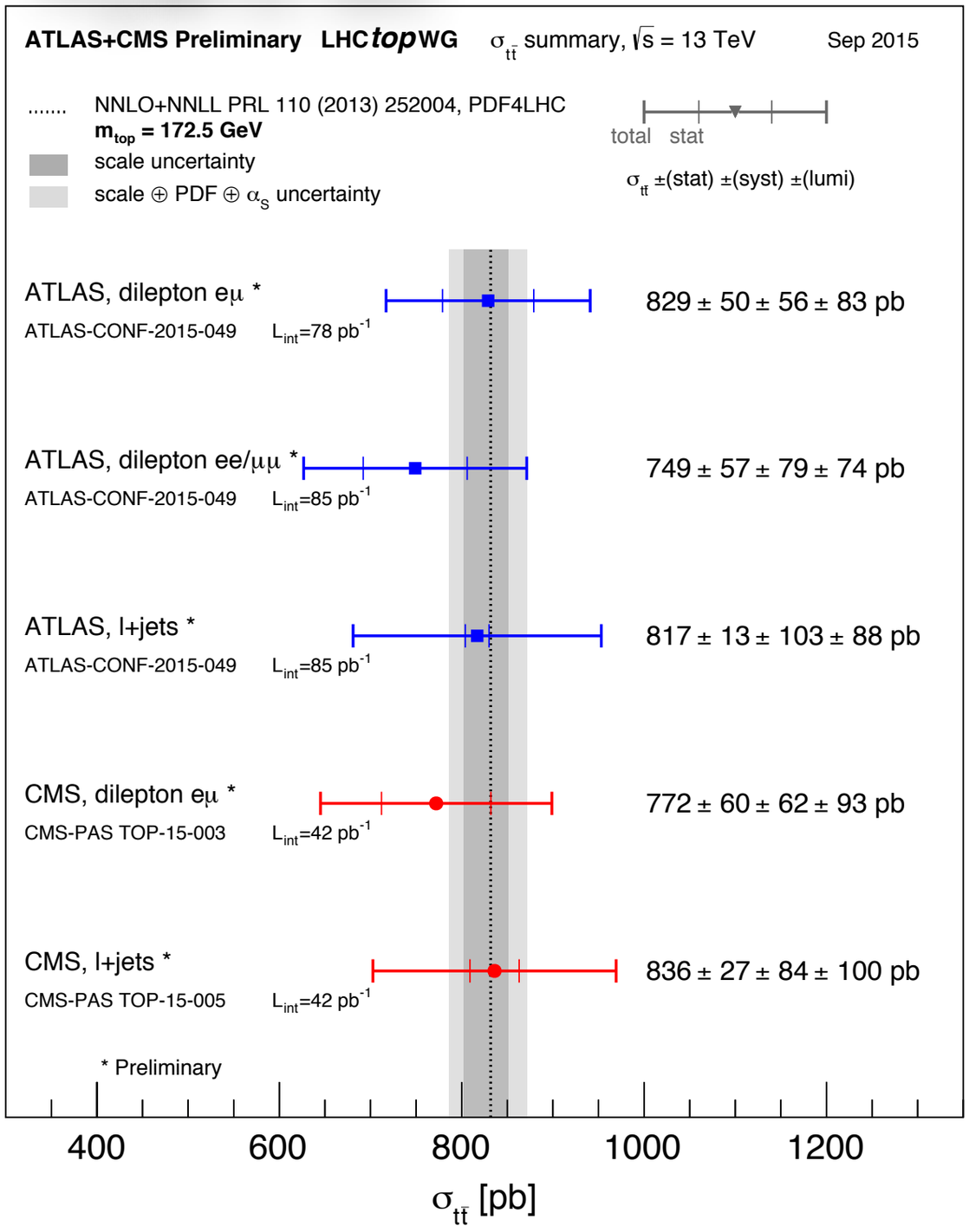
All channels (di-lepton, l+jet and full had) have been exploited using diverse experimental approaches.

Table presents a summary of the results(*) at:
- 7 TeV Run (based on ~ 2-5 fb^{-1})
- 8 TeV Run (based on ~ 20 fb^{-1})

(*)For additional precise CMS results presently not included in the tables see also CMS TOP-13-004

Total inclusive cross sections for top pair production

$\sigma_{t\bar{t}}$@13 TeV



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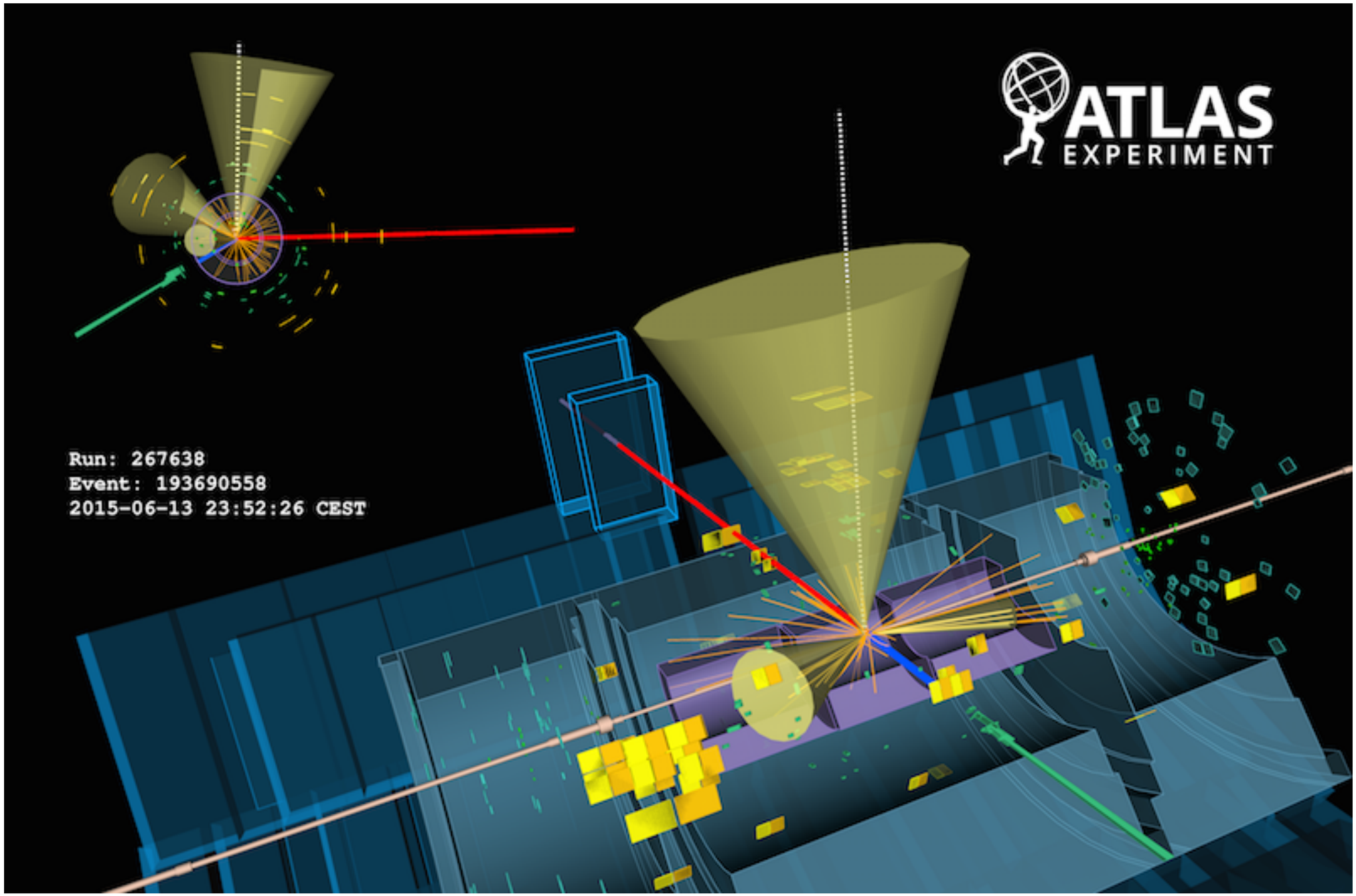
All channels (di-lepton, l+jet and full had) have been exploited using diverse experimental approaches.

Table presents a summary of the results at:
- 7 TeV Run (based on ~ 2-5 fb^{-1})
- 8 TeV Run (based on ~ 20 fb^{-1})
- 13 TeV Run 2 (based on 40-80 pb^{-1})

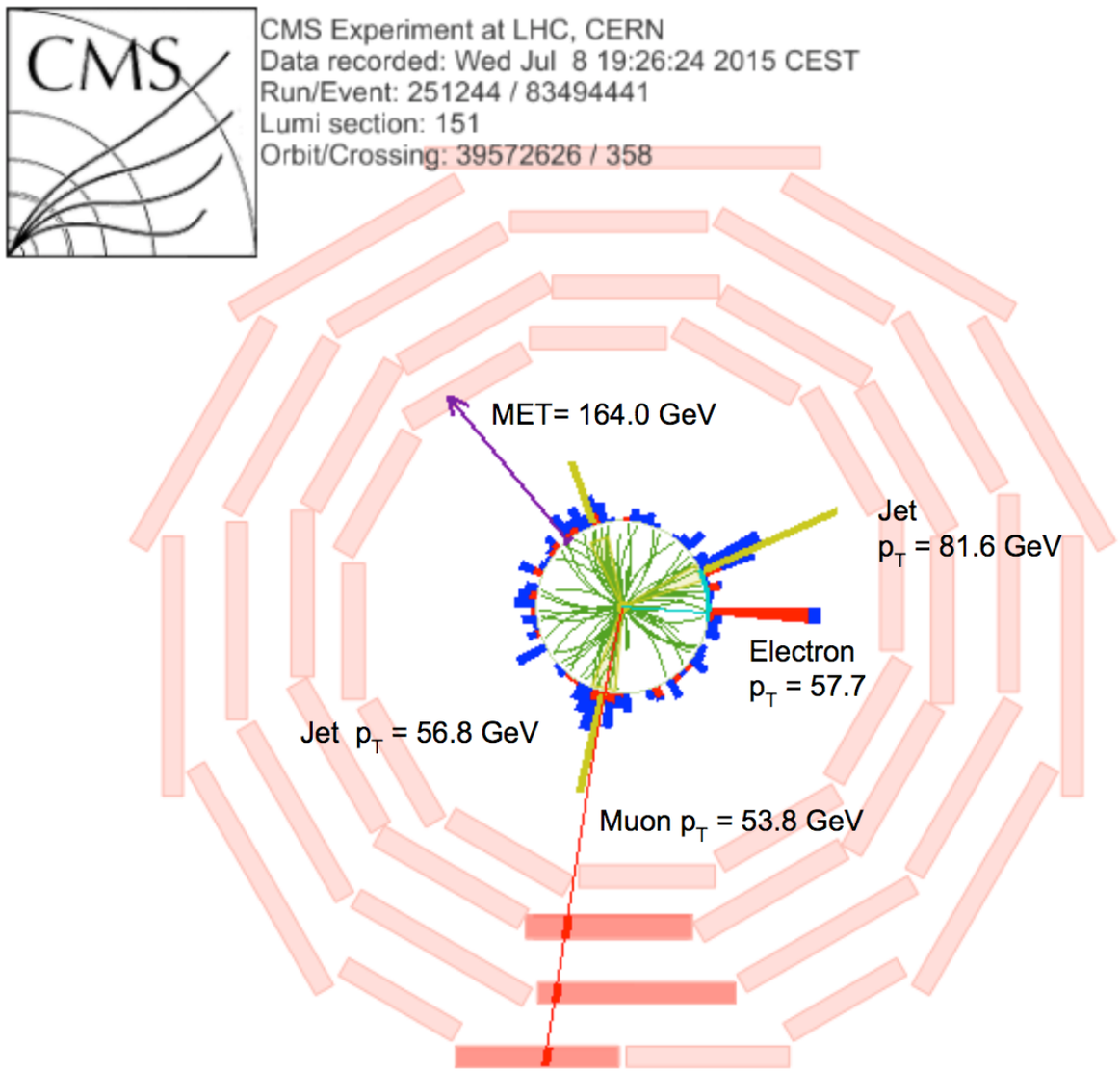
Best precision achieved so far on $\sigma_{t\bar{t}}$:

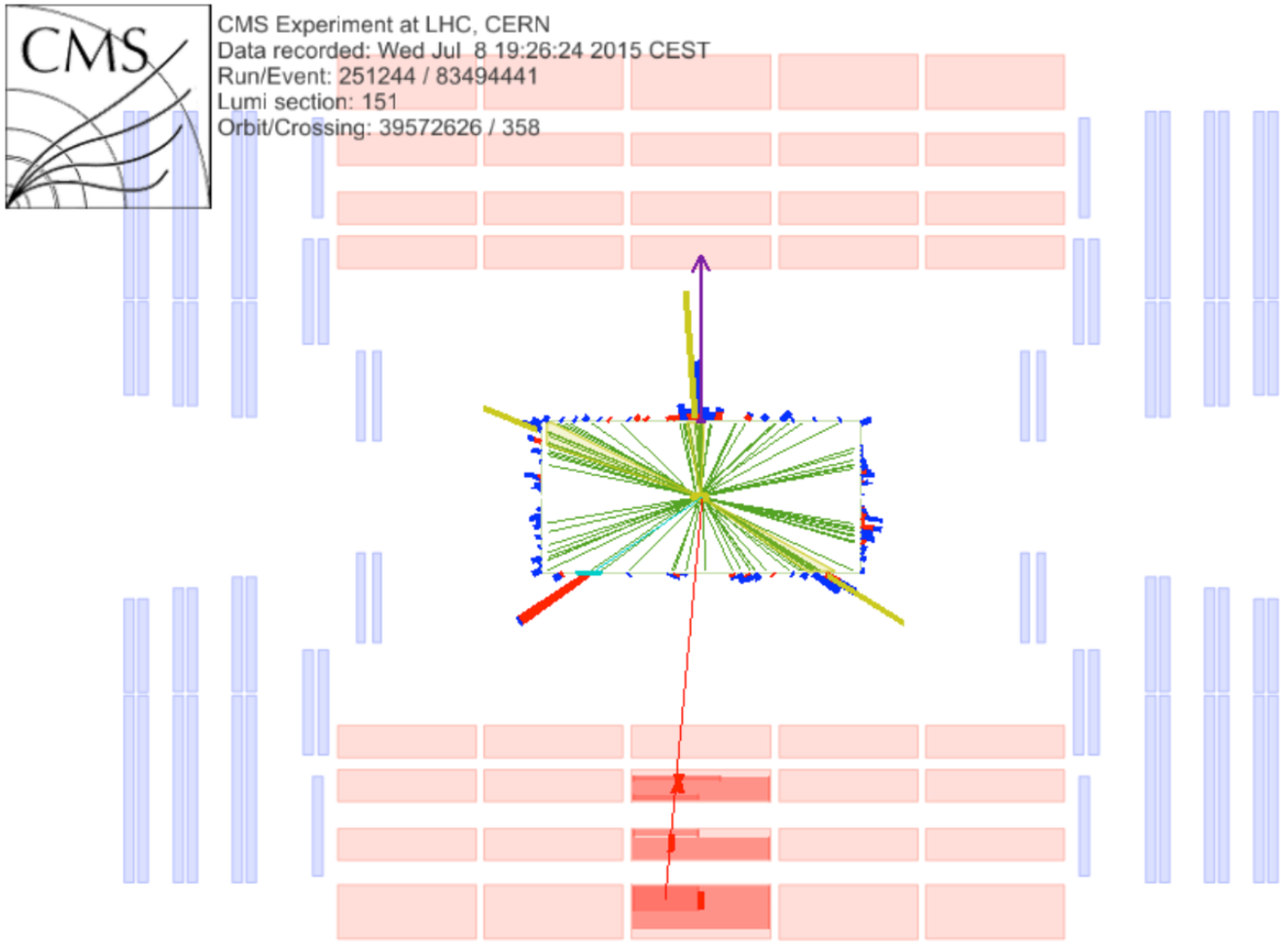
- 3.5% at 7 and 8 TeV
- 13.5% at 13 TeV

Candidate top-pair event at 13 TeV



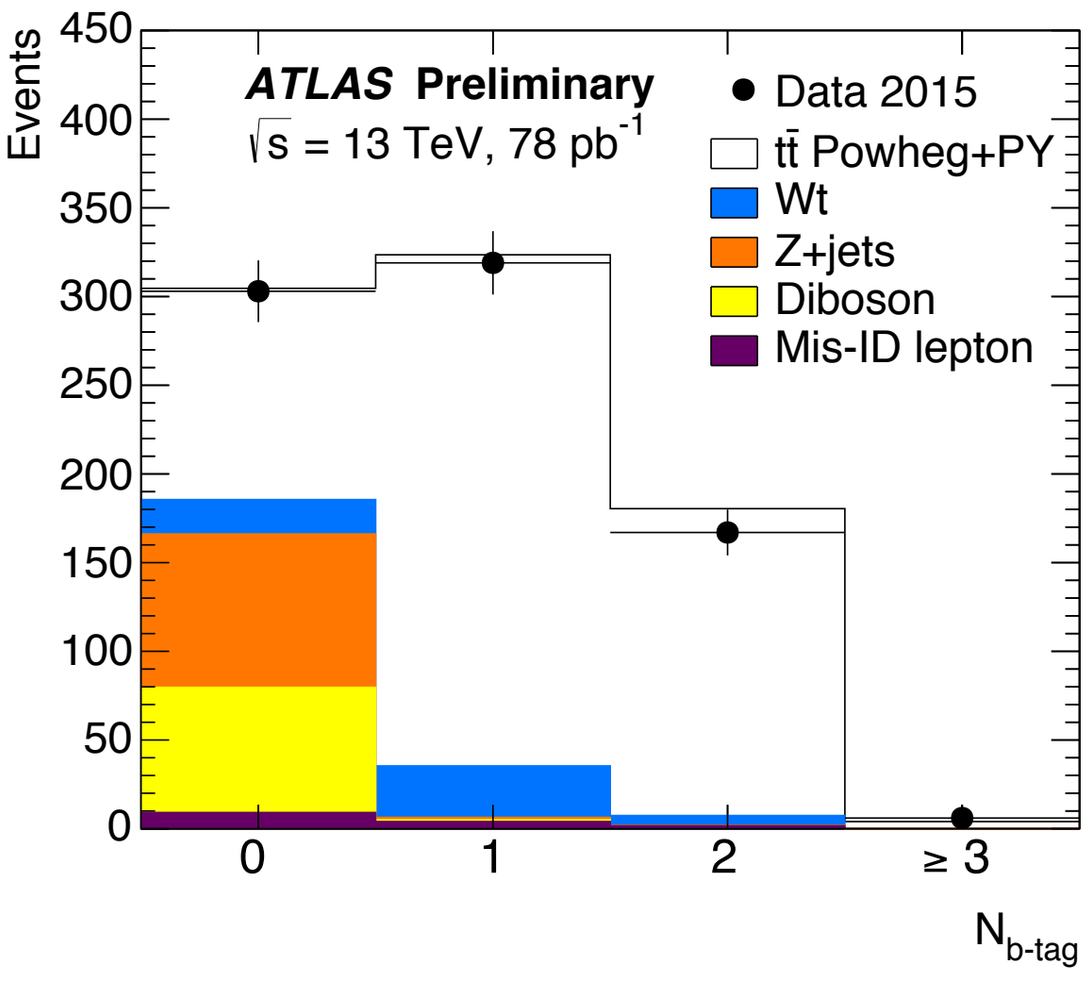
Candidate top-pair event at 13 TeV



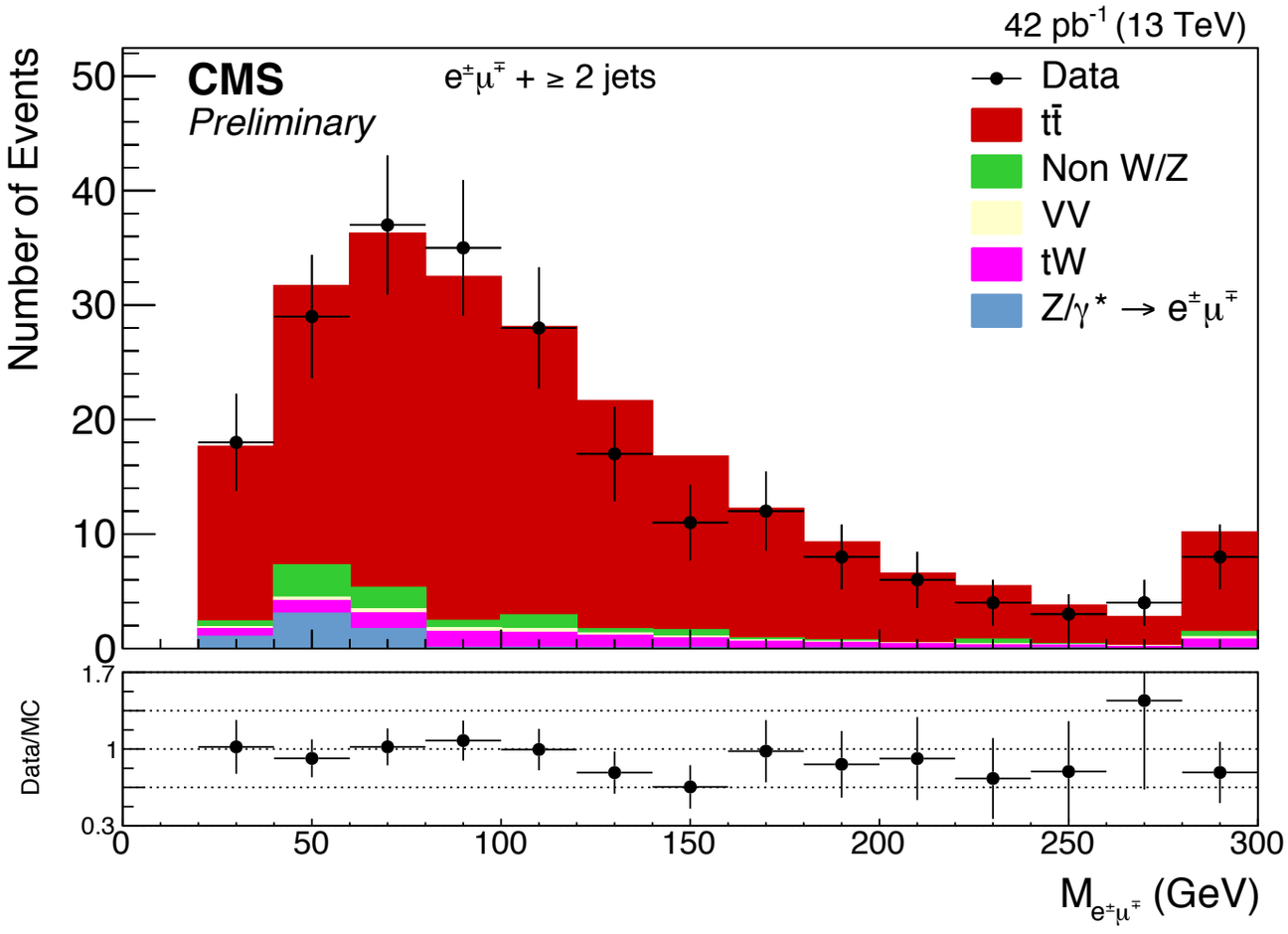


Total inclusive cross sections for top pair production @ 13 TeV

ATLAS
ATLAS-CONF-2015-033
78 pb^{-1}



CMS
CMS PAS TOP-15-003
42 pb^{-1}



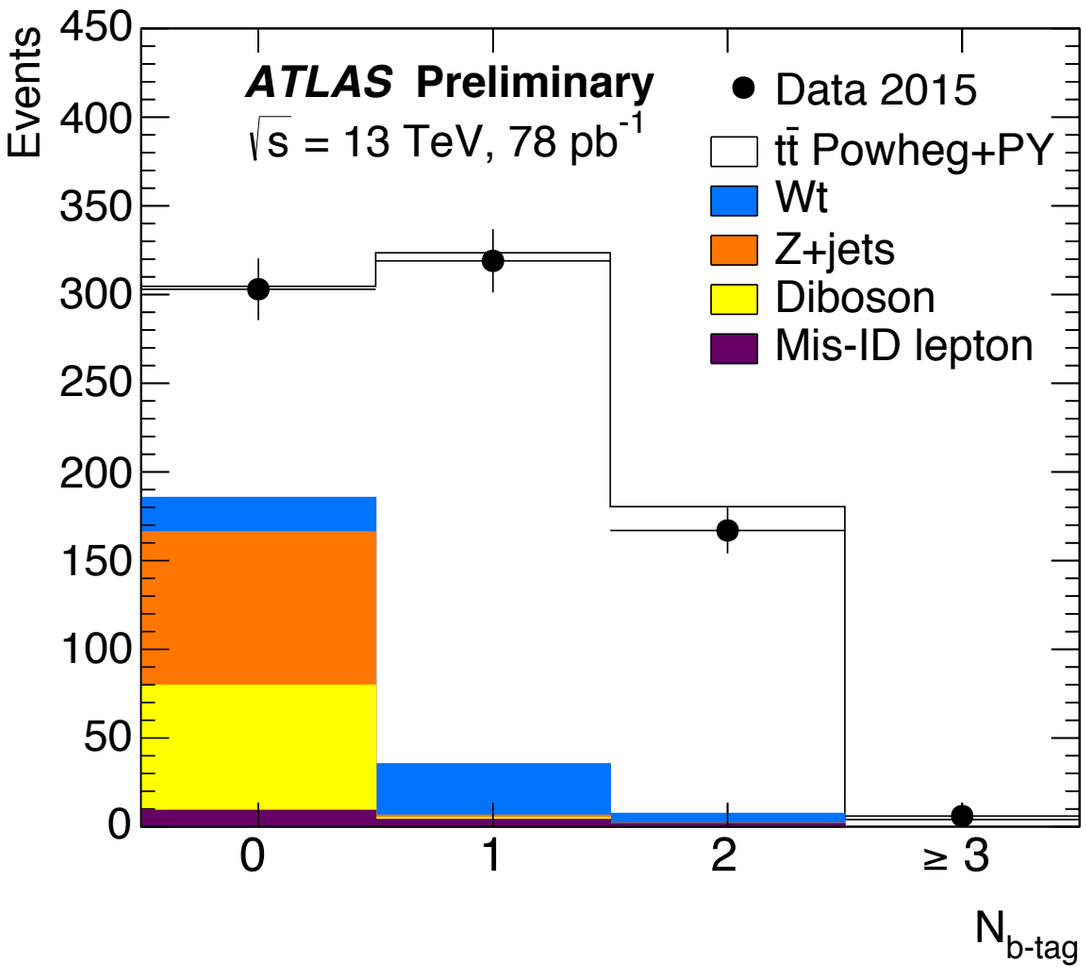
- Di-lepton channel (eμ) (gives slightly more precise results w.r.t the lepton+jet channel).
- Very good description of the 13 TeV data by MC generators.

Total inclusive cross sections for top pair production @ 13 TeV

ATLAS

ATLAS-CONF-2015-033

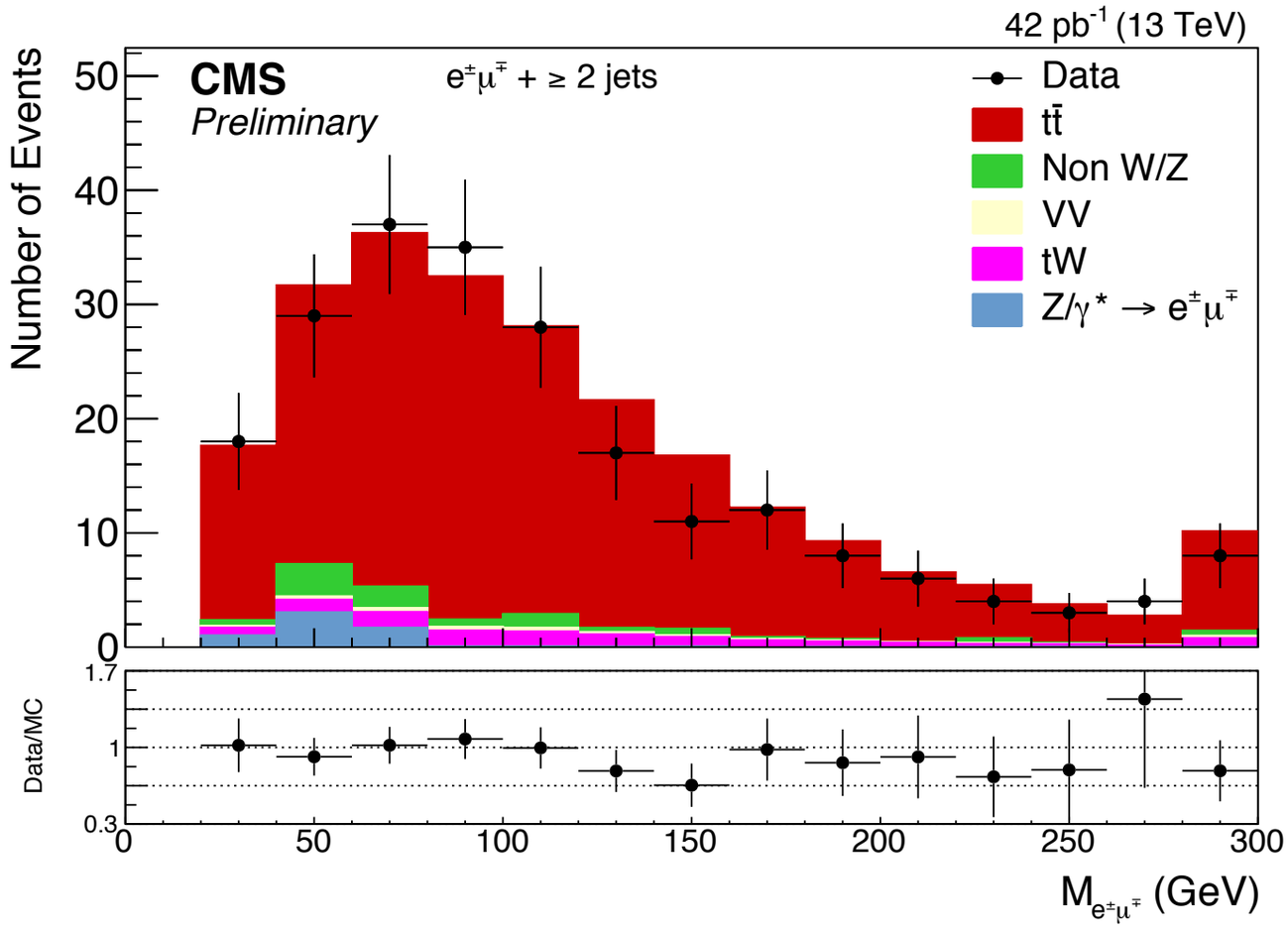
78 pb^{-1}



CMS

CMS PAS TOP-15-003

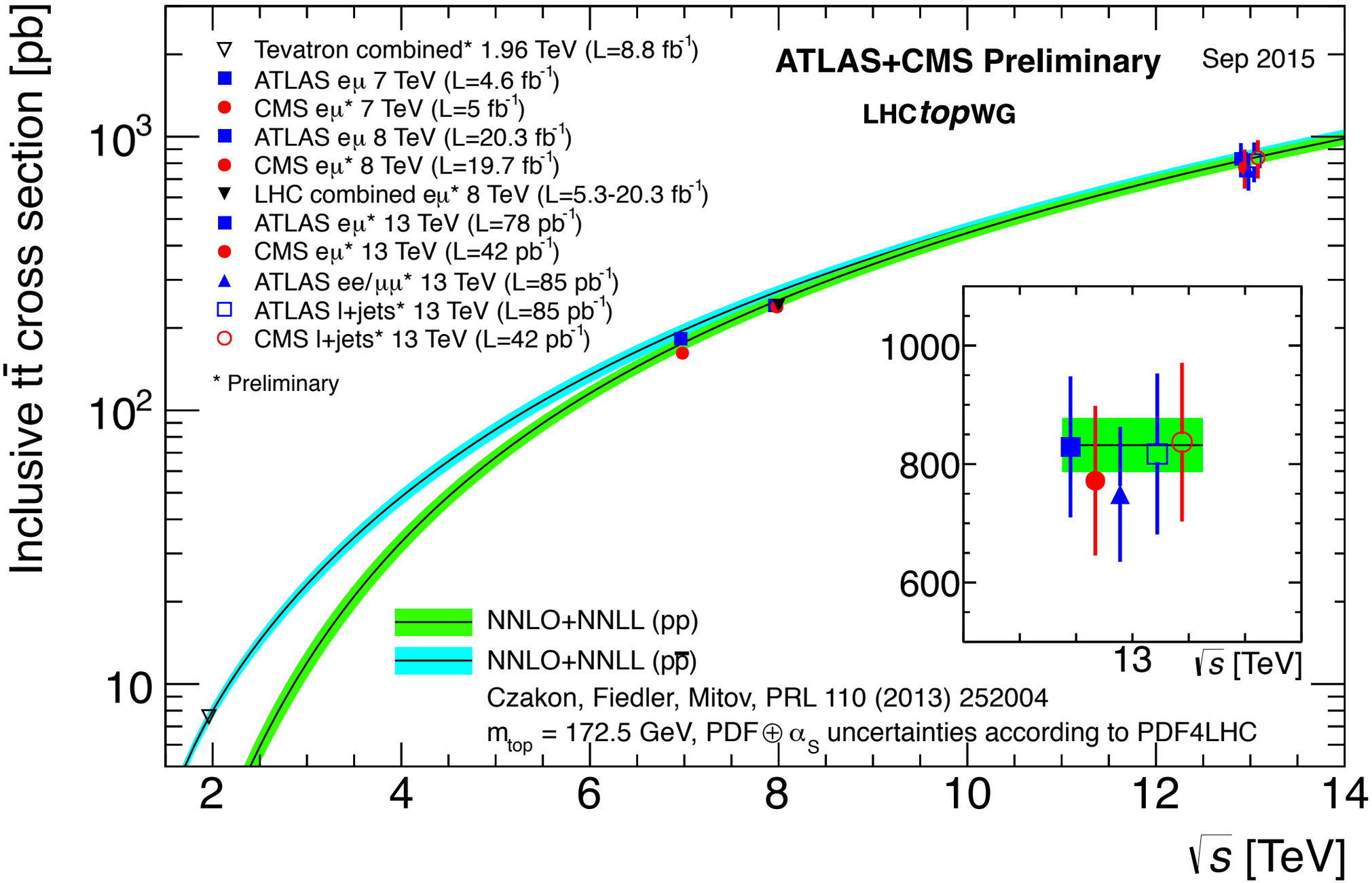
42 pb^{-1}



ATLAS: $\sigma_{\mathrm{tt}} = 825 \pm 49\ (\mathrm{stat}) \pm 60\ (\mathrm{syst}) \pm 83\ (\mathrm{lumi})\ \mathrm{pb}$

CMS: $\sigma_{\mathrm{tt}} = 772 \pm 60\ (\mathrm{stat}) \pm 62\ (\mathrm{syst}) \pm 93\ (\mathrm{lumi})\ \mathrm{pb}$

Total inclusive cross sections for top pair production



Measurements, as a function of √s, in excellent agreement with NNLO+NNLL pQCD predictions

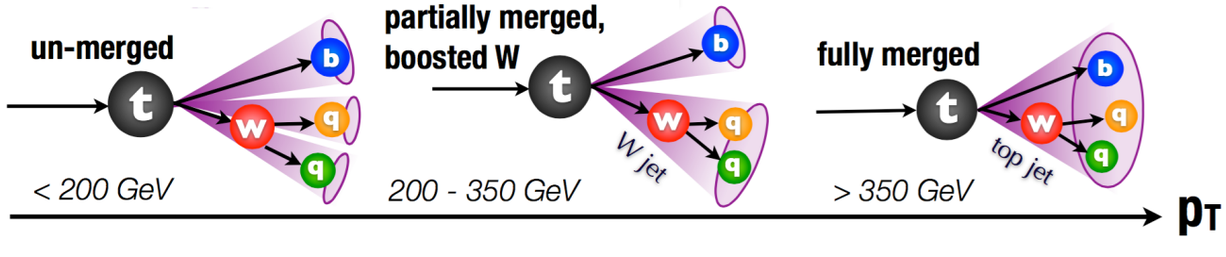
Top pair differential cross sections

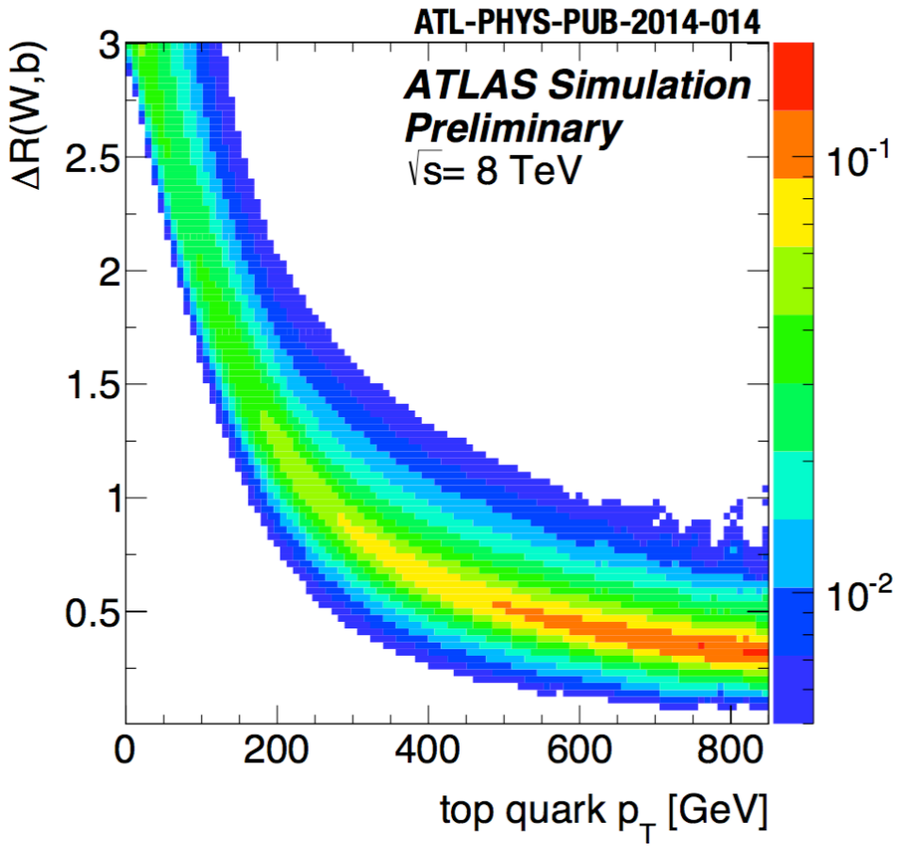
The measurement of single differential top pair cross sections allows one:
- to perform particularly stringent test of pQCD
- to improve on the determination of the gluon density
- to test MC programs

Will present new results at 8 and 13 TeV (resolved and boosted regimes)

Resolved regime:
- well separated jets
- isolated leptons

Boosted regime:
- overlapping decay products
- non isolated leptons

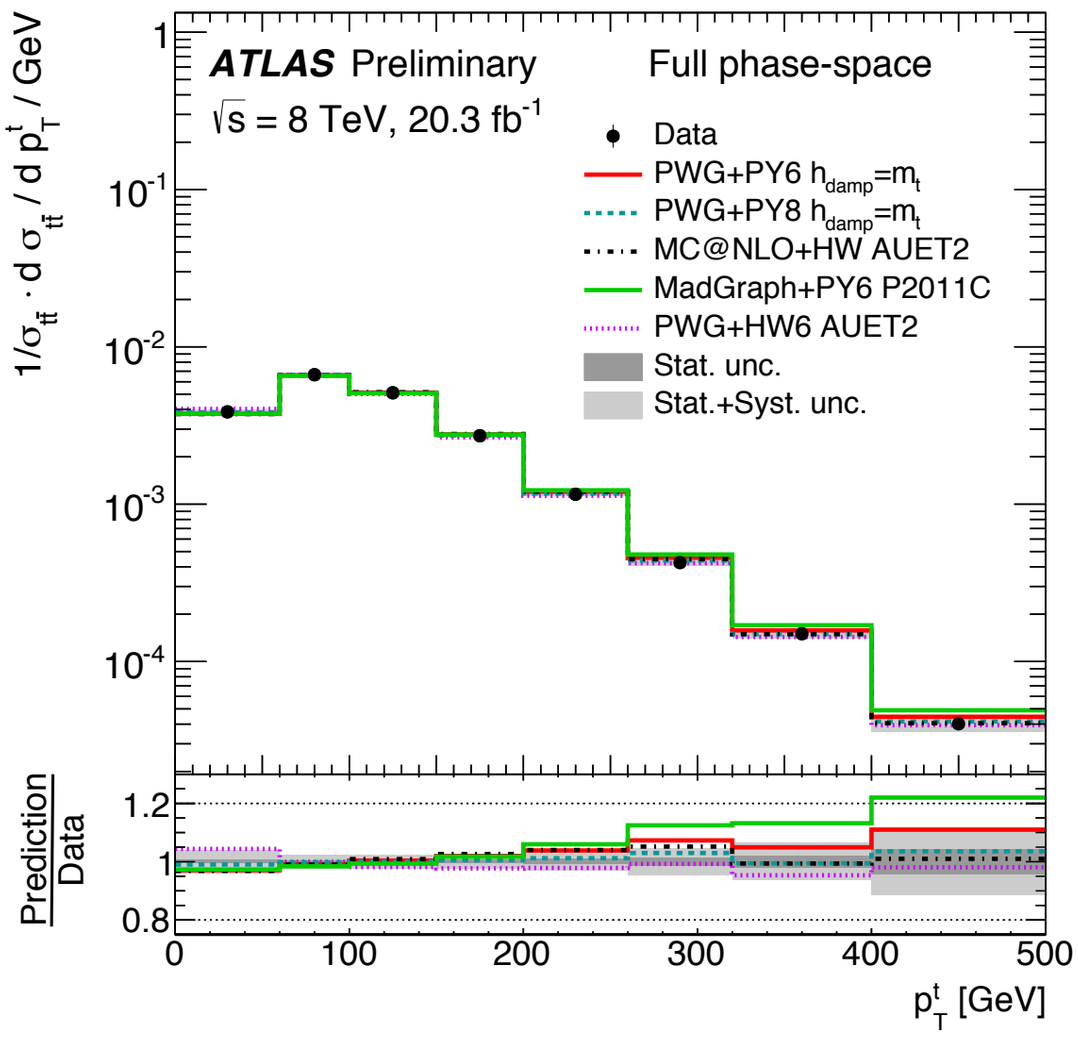




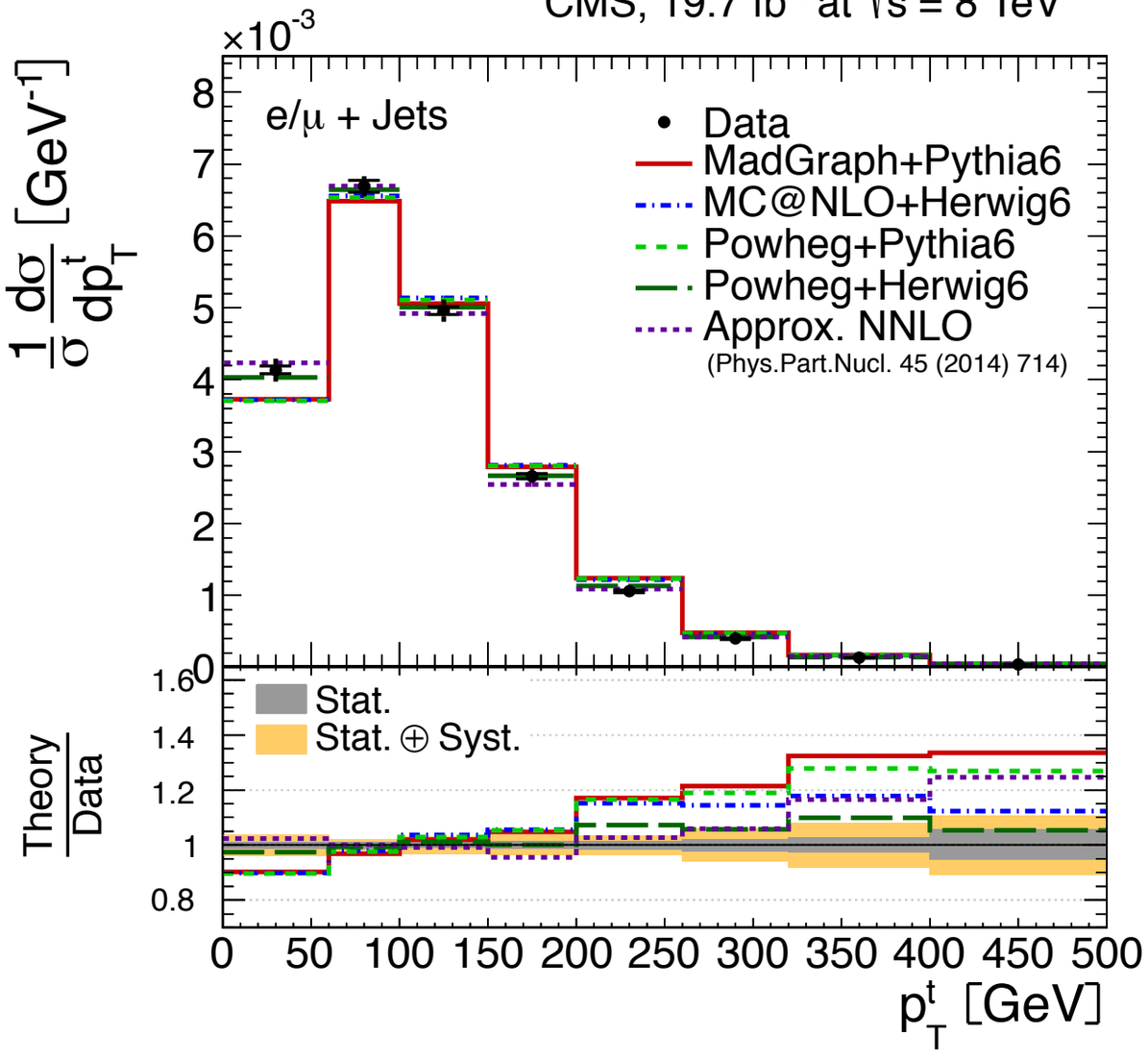
Top pair differential cross sections @8 TeV

TOPQ-2015-06

lepton +jet



arXiv:1505.04480

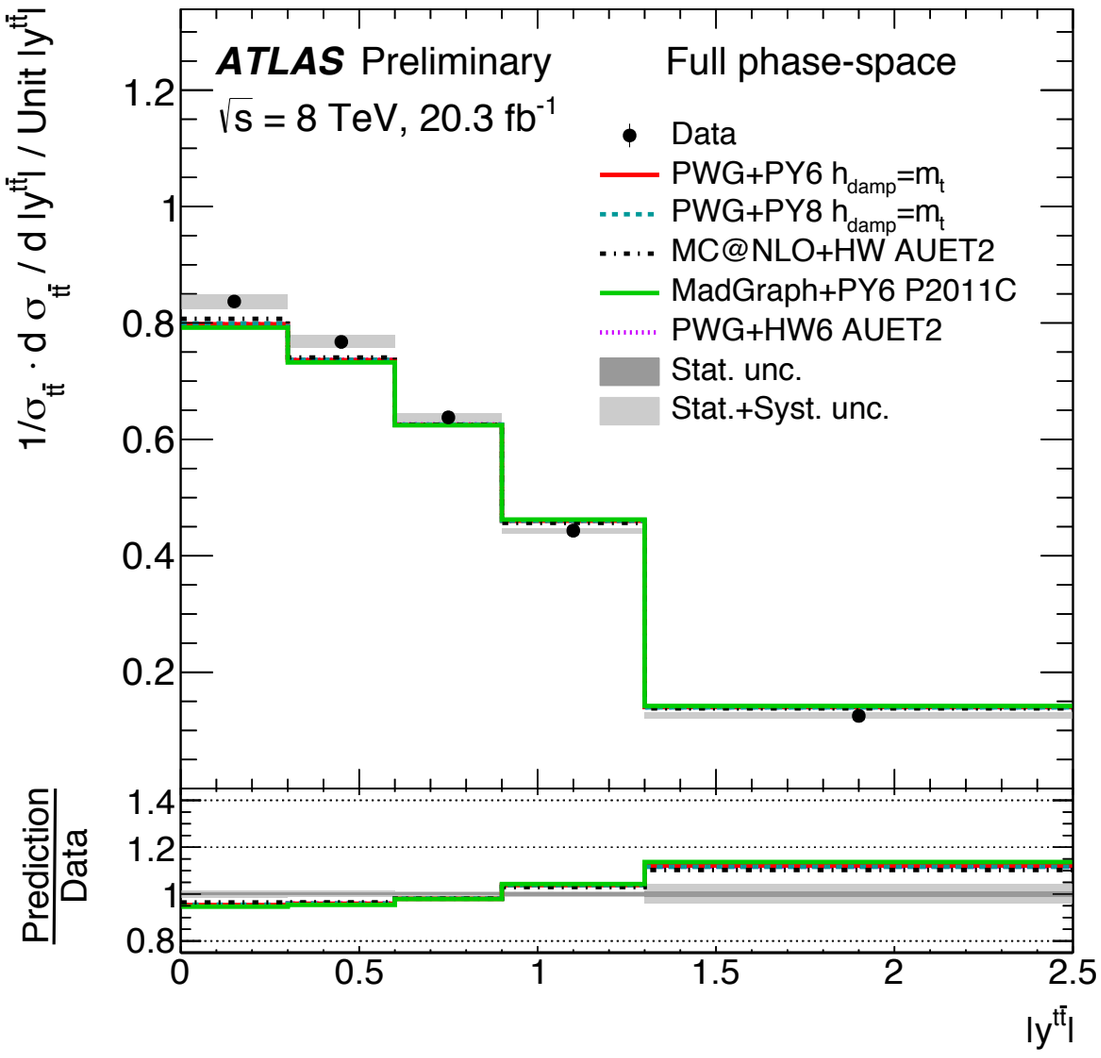


- Full phase-space normalised parton-level cross sections (same binning for CMS and ATLAS).
- MC predictions, at high top p_T, show a harder spectrum than the data (Madgraph gives the worse description for both ATLAS and CMS).

Top pair differential cross sections @8 TeV

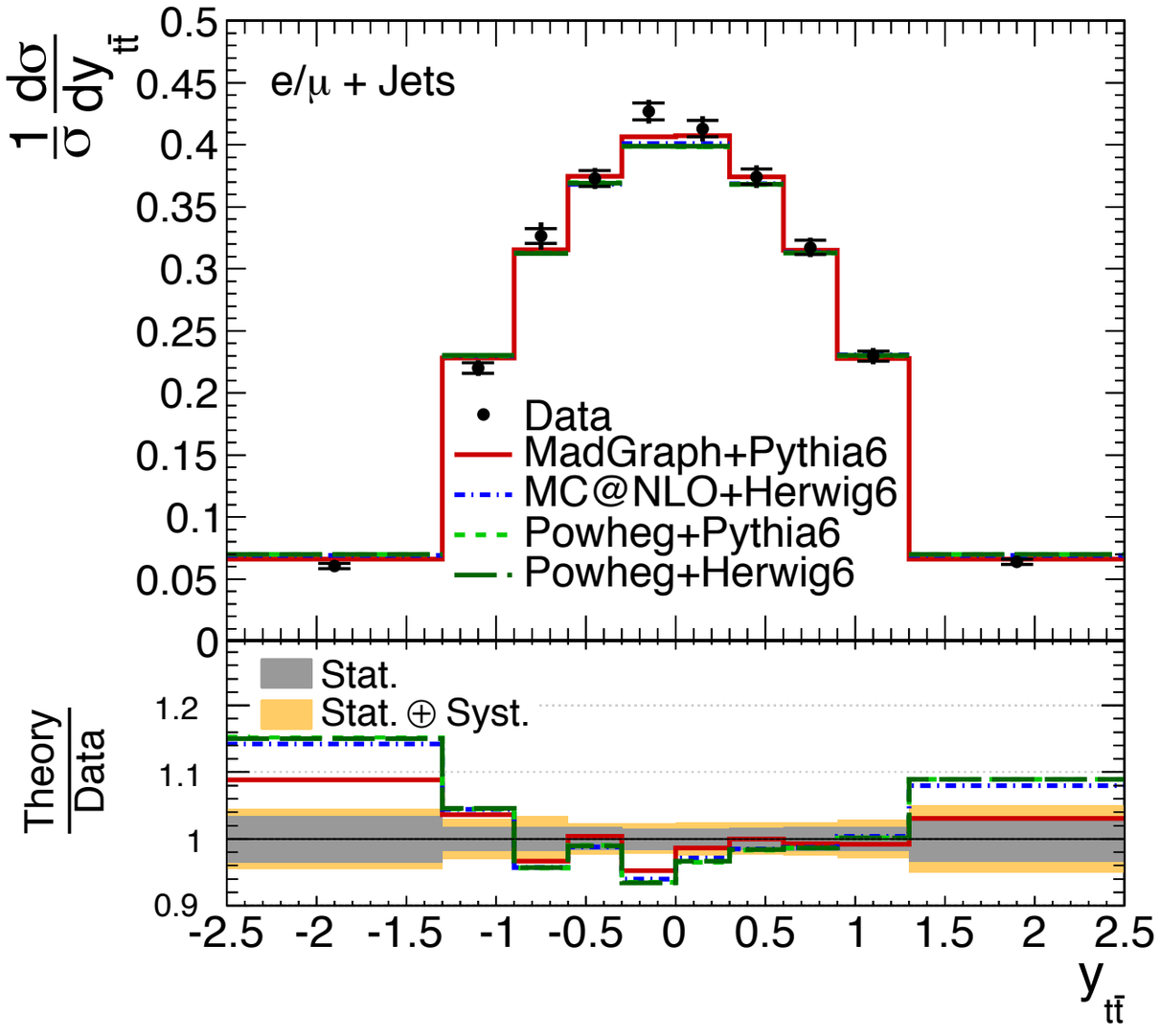
TOPQ-2015-06

lepton +jet



arXiv:1505.04480

CMS, 19.7 fb^{-1} at $\sqrt{s}$ = 8 TeV

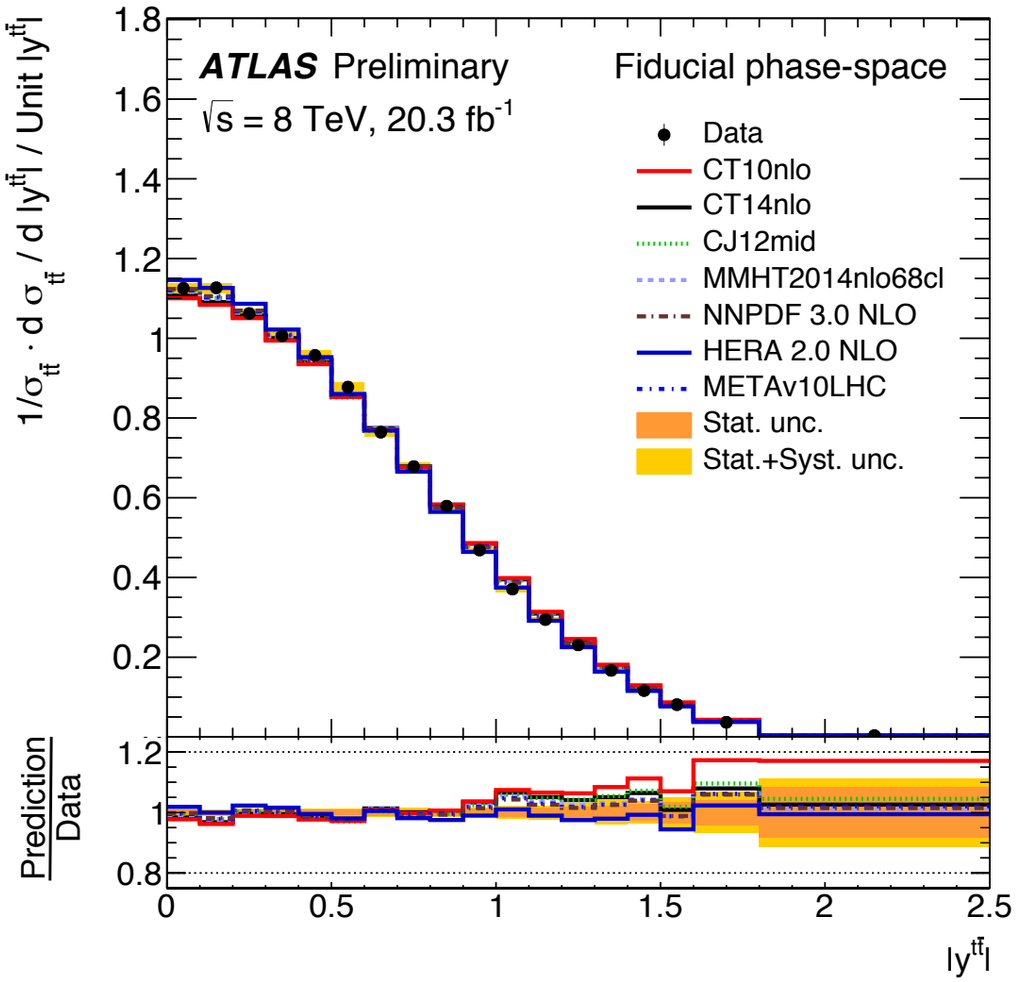


- Full phase-space normalised parton-level cross sections (same binning for CMS and ATLAS).
- Data/MC comparison show similar trends for both ATLAS and CMS.

Top pair differential cross sections @8 TeV

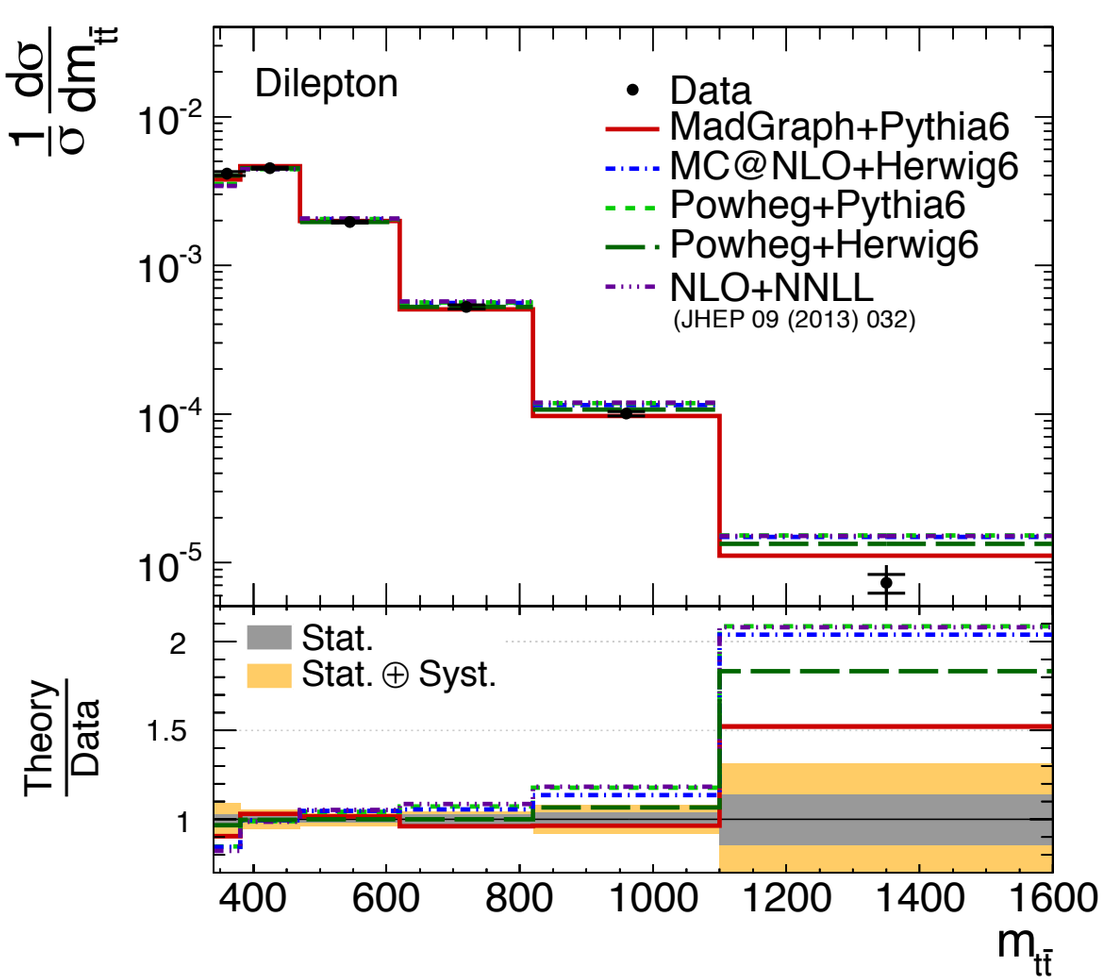
TOPQ-2015-06

lepton +jet



arXiv:1505.04480

di-lepton



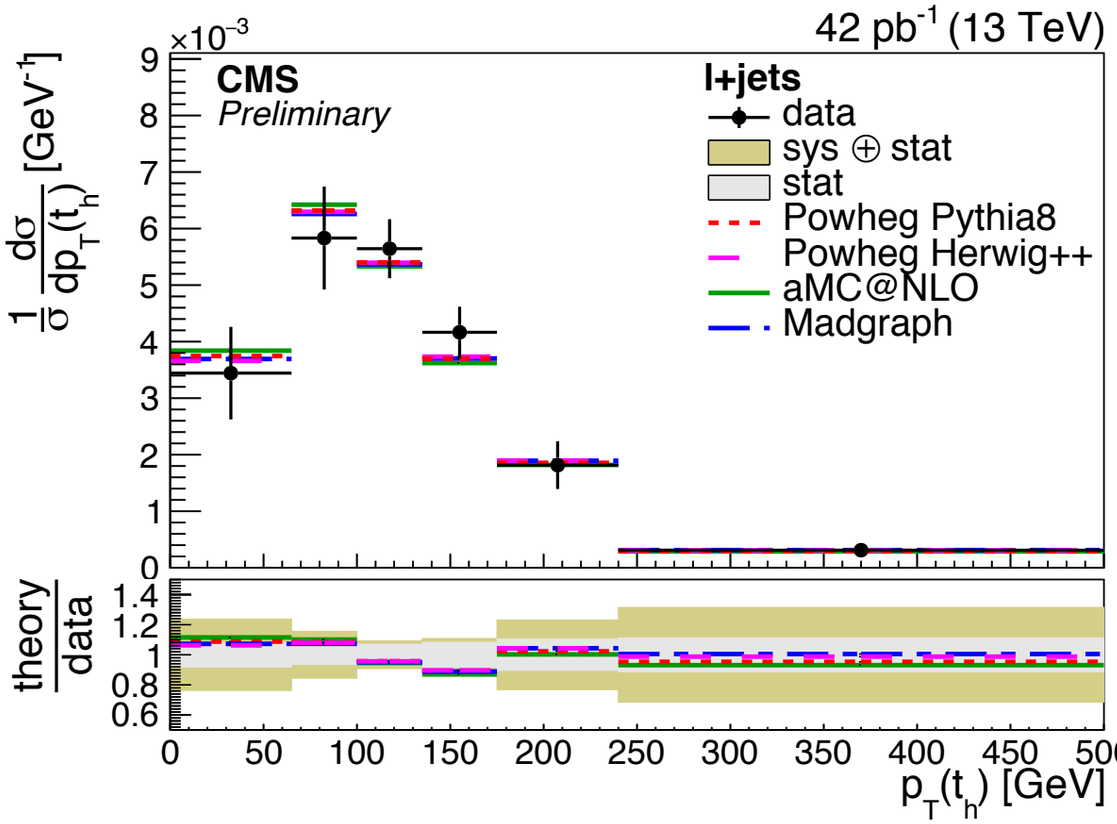
ATLAS: visible (particle level) normalised differential cross sections are measured and compared to predictions based on recent PDF sets.

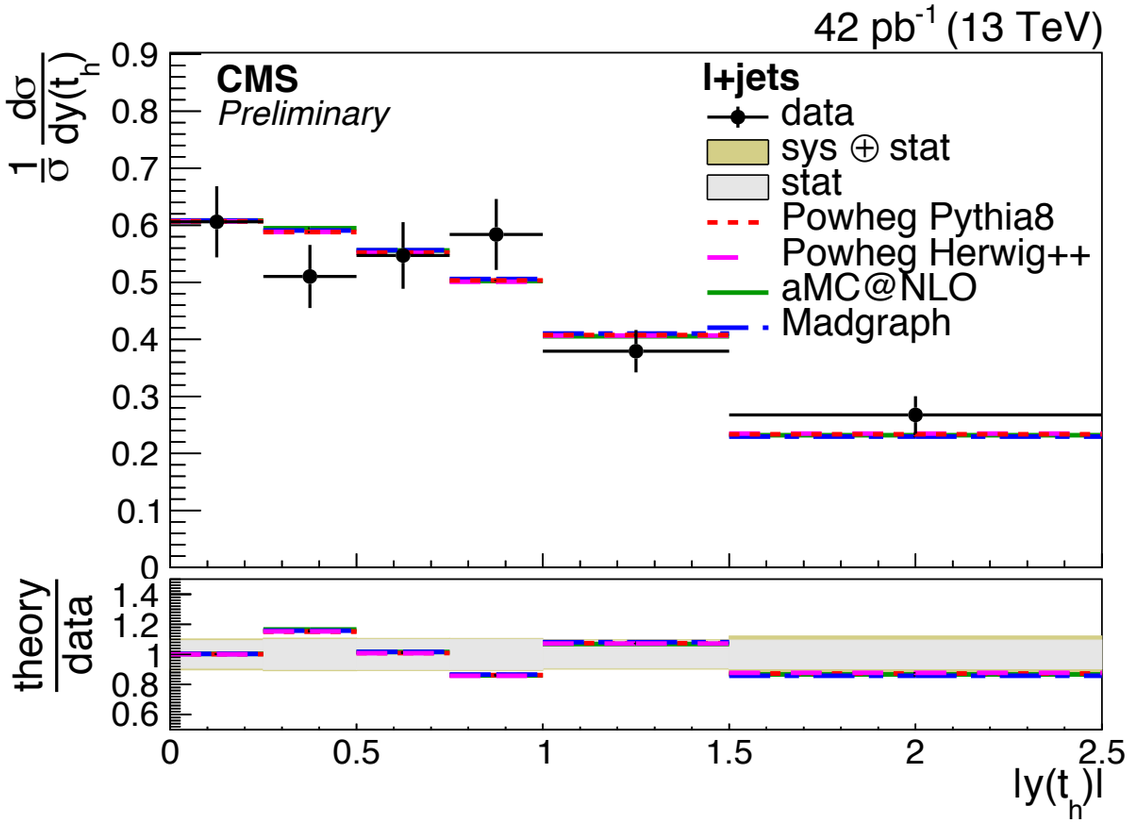
→ reduced extrapolation uncertainties

CMS: also measures fiducial normalised cross sections.
Results are presented in addition in the di-lepton channel.

Top pair differential cross sections @13 TeV

CMS PAS-TOP-15-005





- First measurements of the normalised differential cross sections at 13 TeV
- All MC give a fair description of the measurements
- Total cross section at 13 TeV:

$$\sigma_{t\bar{t}} = 836 \pm 27\ (stat) \pm 88\ (sys) \pm 100\ (lumi)\ pb$$

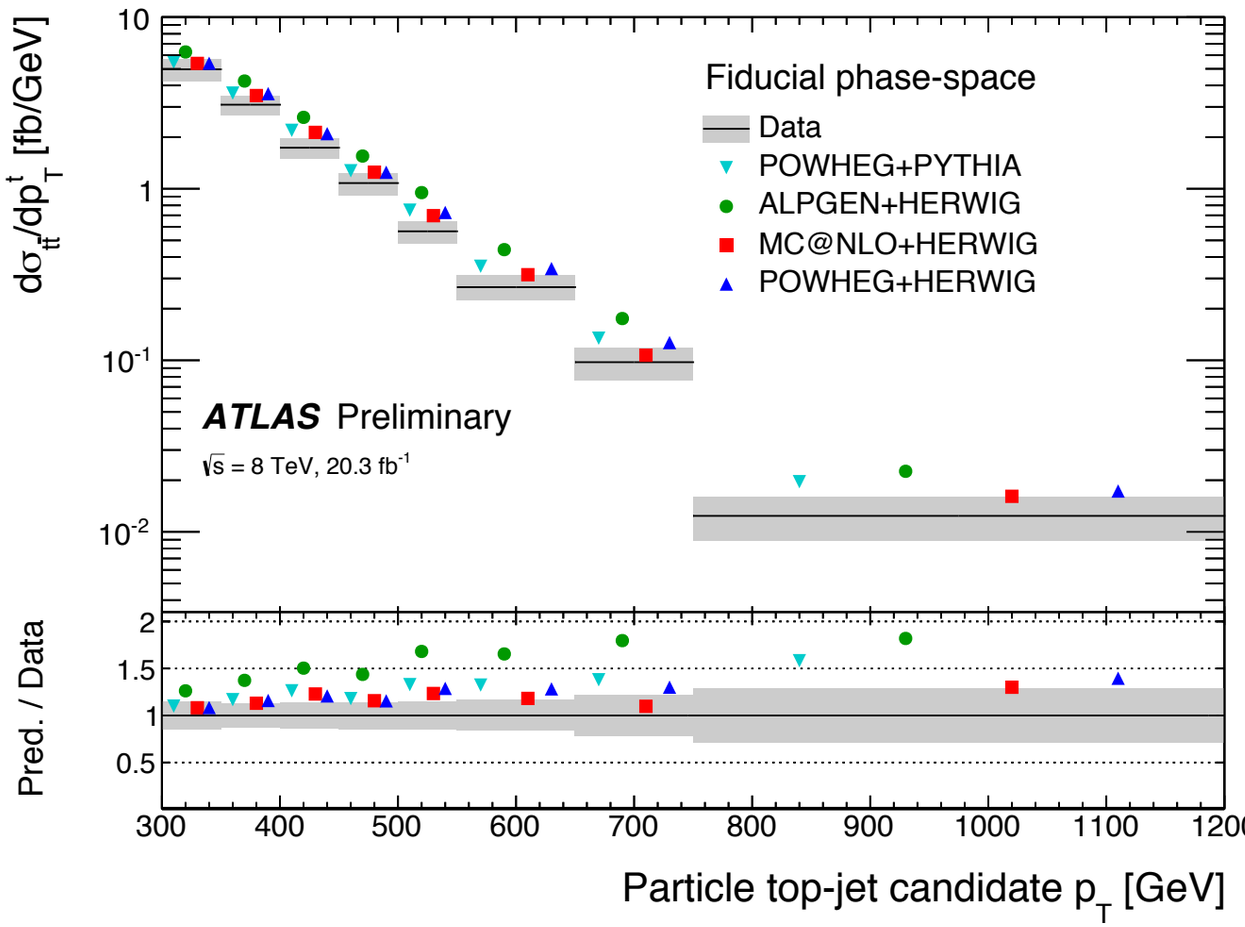
in good agreement with NNLO predictions.

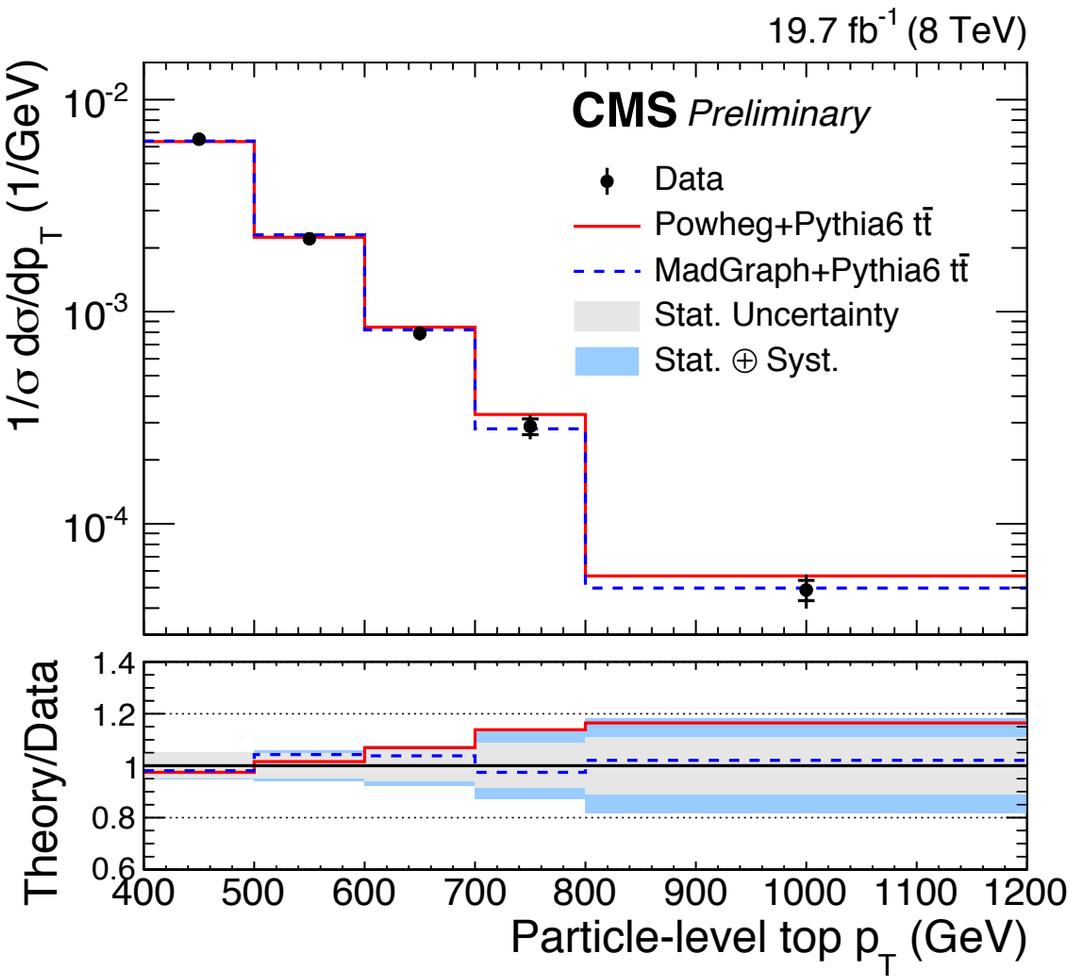
Top pair differential cross sections 8 TeV boosted regime

TOPQ-2014-15

Particle Level

CMS PAS-TOP-14-012





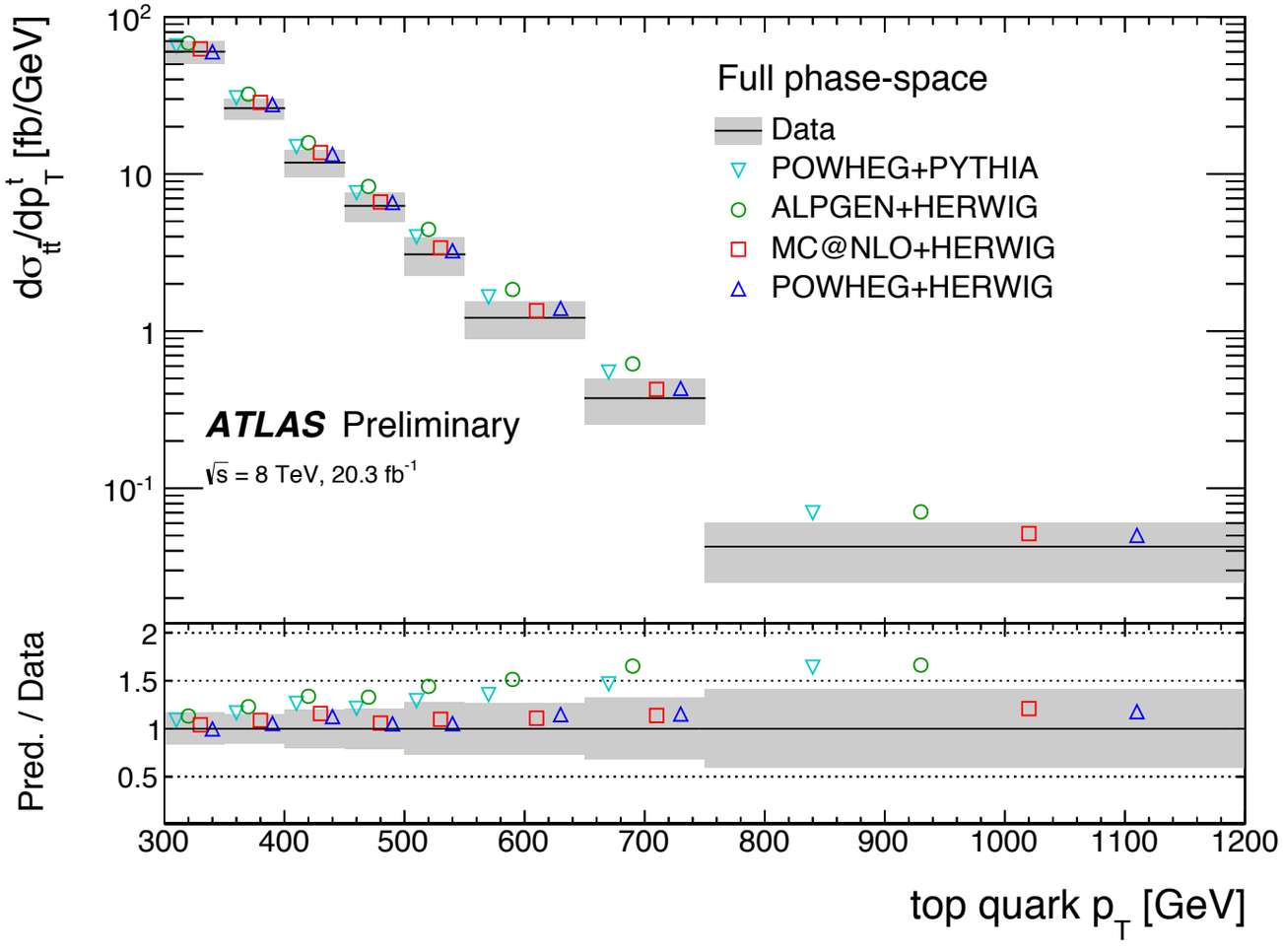
As for the results in the resolved regime, the MC predictions, at high-p_T show a harder spectrum than the data. Both at particle…

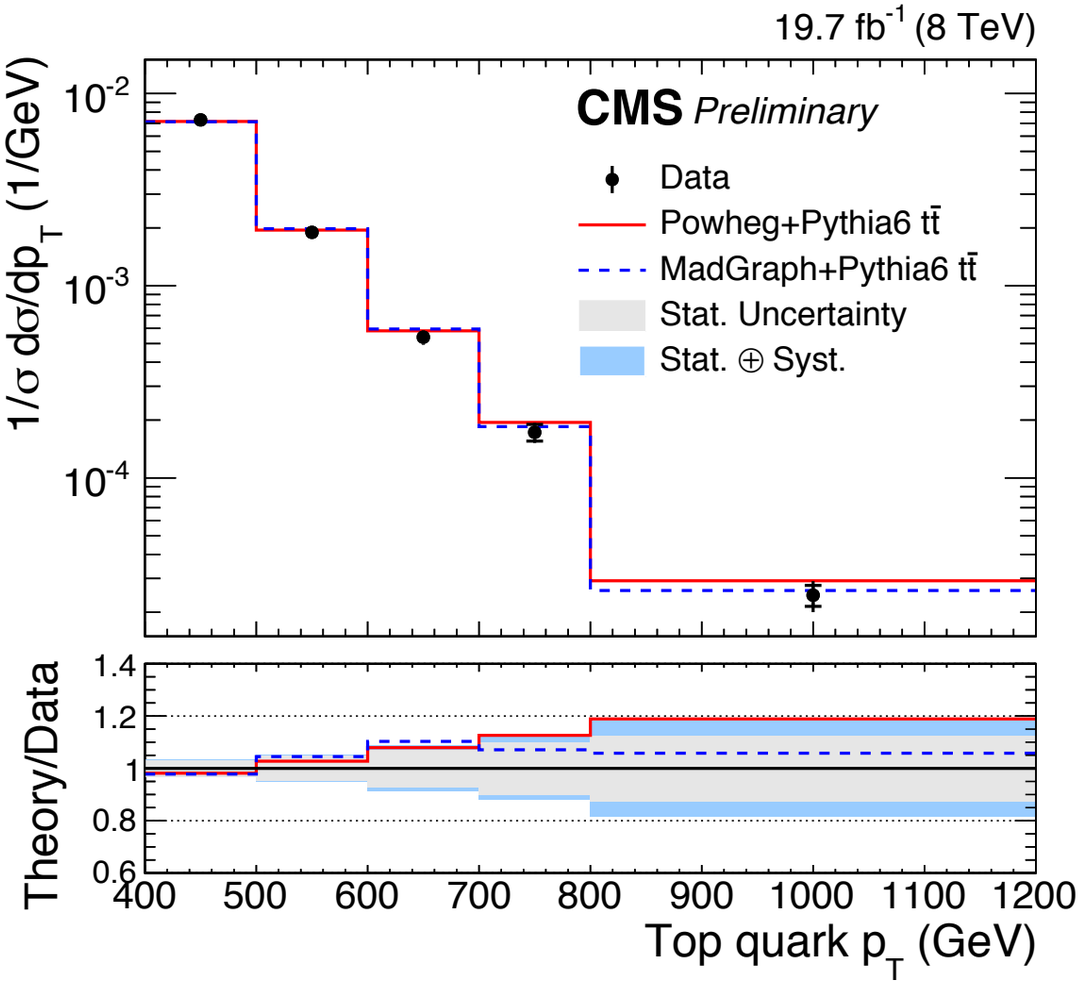
Top pair differential cross sections 8 TeV boosted regime

Parton Level

TOPQ-2014-15

CMS PAS-TOP-14-012

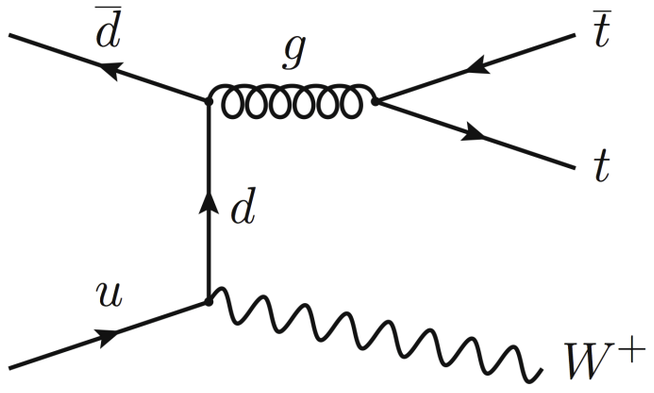


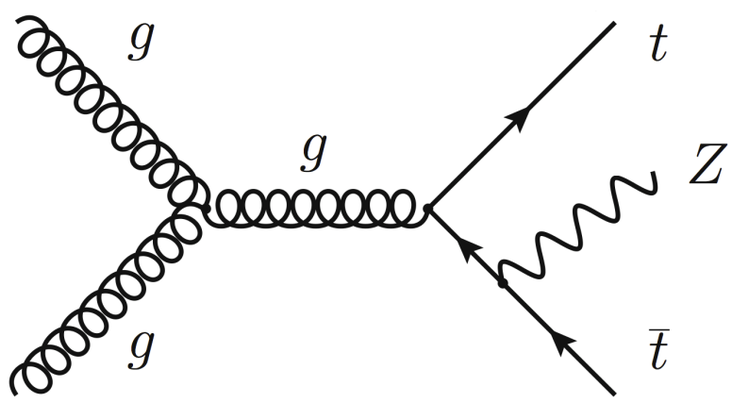


As for the results in the resolved regime, the MC predictions, at high-p_T show a harder spectrum than the data. Both at particle and parton level.

$t\bar{t}$ production in association with W or Z @ 8 TeV

Dominant production modes:





- $t\bar{t}W$ and $t\bar{t}Z$ small expected cross sections (~200 fb @ 8TeV)

- $t\bar{t}Z$ production cross section provide most accessible direct measurement to the coupling of the top quark to the Z

- Both $\sigma(t\bar{t}W)$ and $\sigma(t\bar{t}Z)$ expected to be altered in new physics models

ttW, ttZ cross sections @ 8 TeV

CMS PAS-TOP-14-021

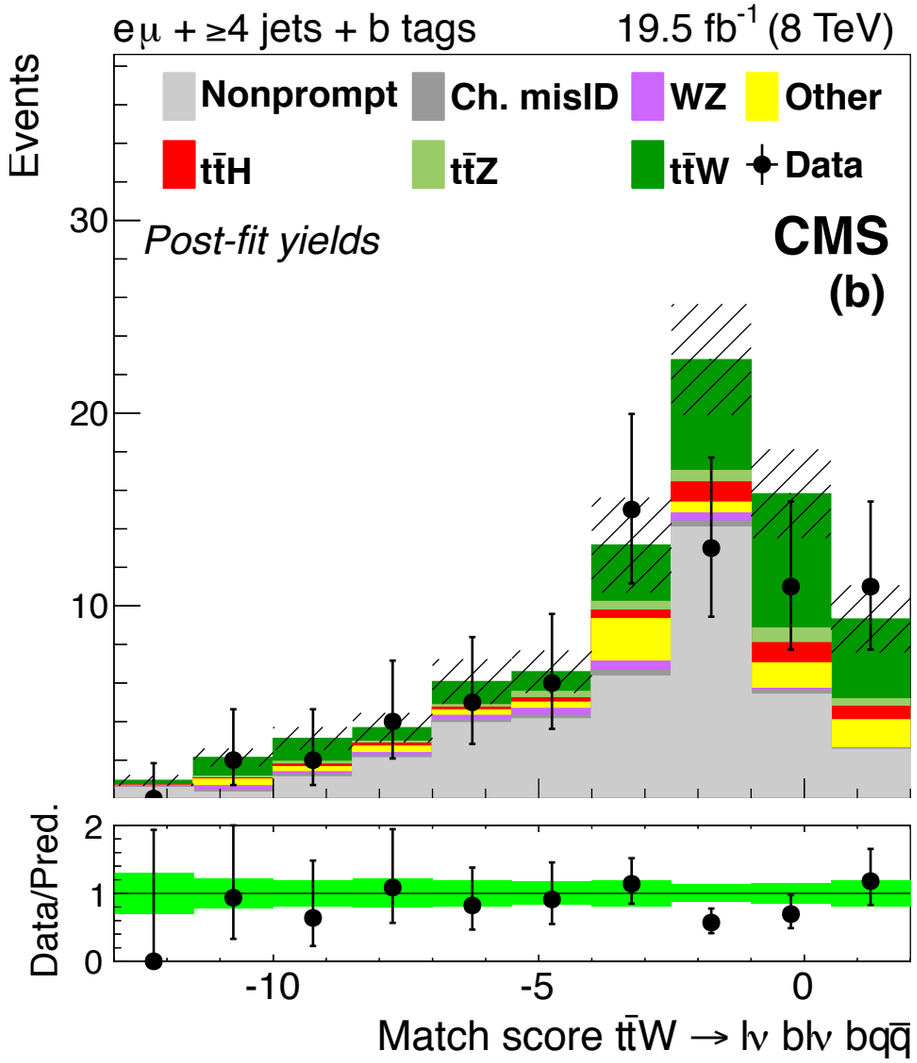
- 5 mutually exclusive signal channels
  - at least 1 lepton with p_T > 20 GeV
  - p_T > 10 GeV for additional leptons

- Even after selection final signal categories are background dominated

- Use full reconstruction and linear discriminant to match $t\bar{t}$ system

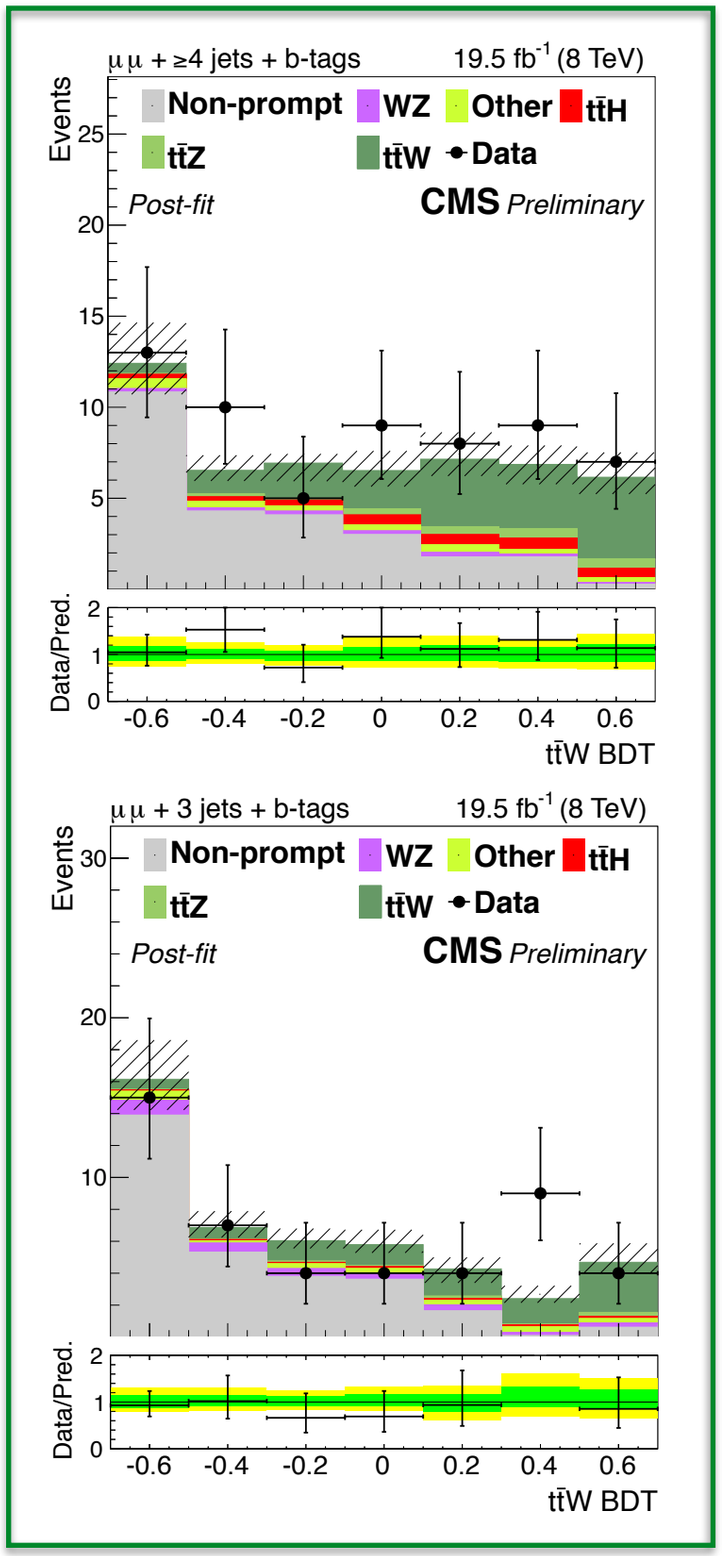
- Match scores and other rec. variables into a Boosted Decision Tree (BDT)

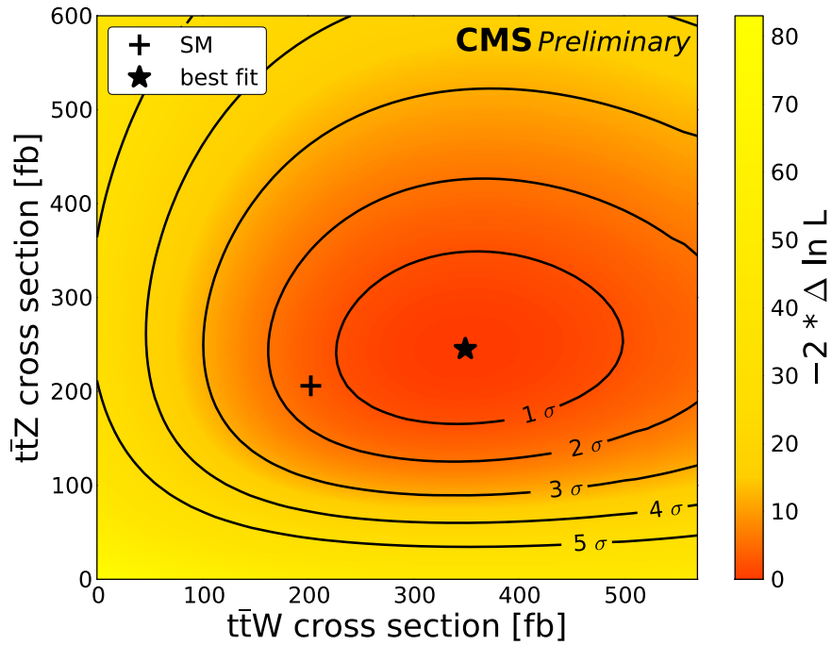
- Cross sections extracted from binned likelihood fit

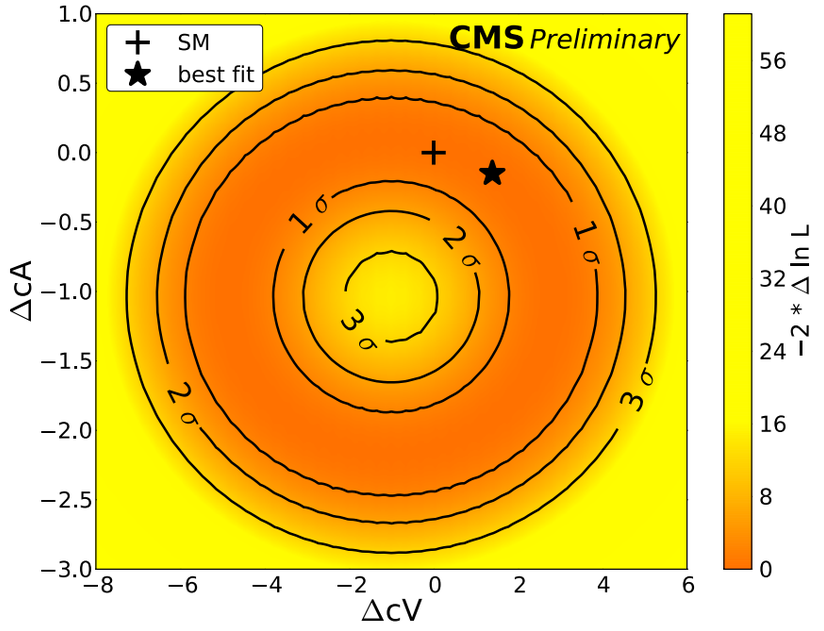


ttW, ttZ cross sections @ 8 TeV

CMS PAS-TOP-14-021







Cross section measurements:

$$\sigma_{t\bar{t}Z} = 242^{+65}_{-55}\ \text{fb}$$

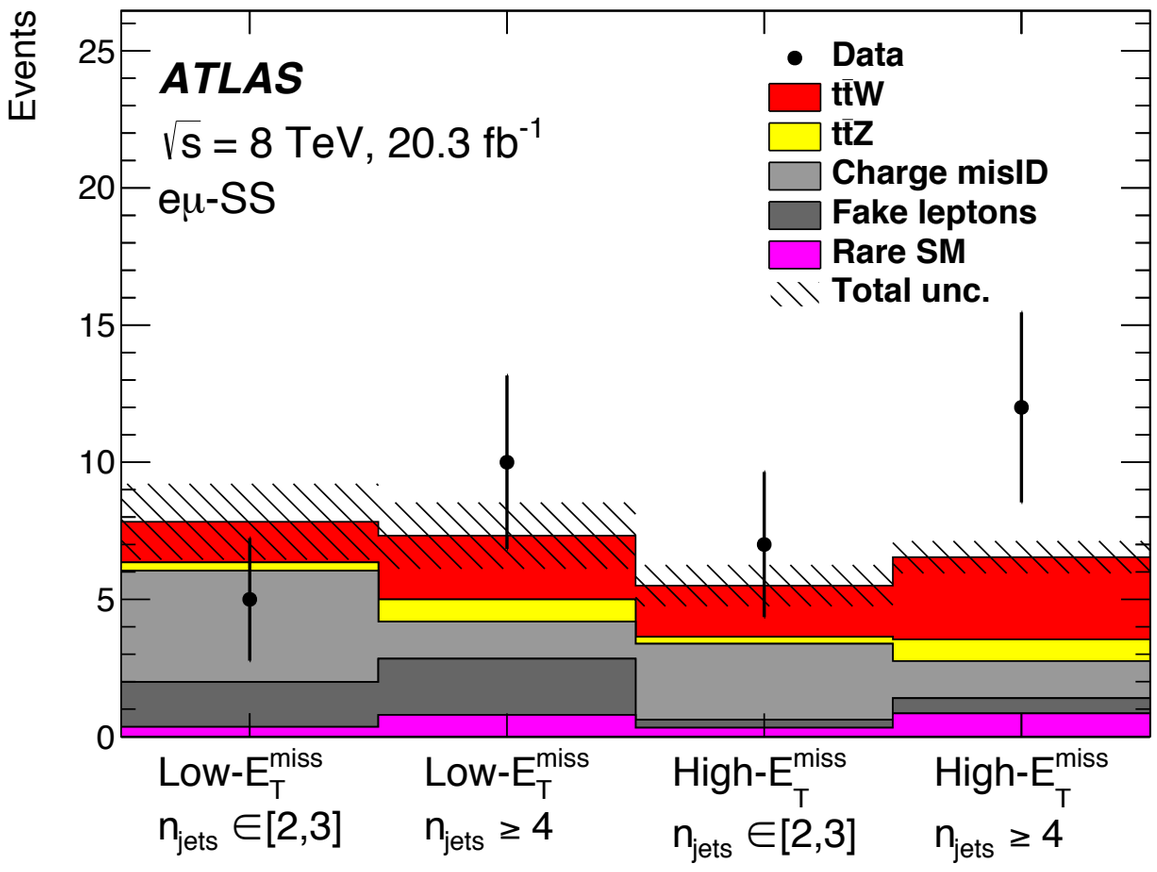
$$\sigma_{t\bar{t}W} = 382^{+117}_{-102}\ \text{fb}$$

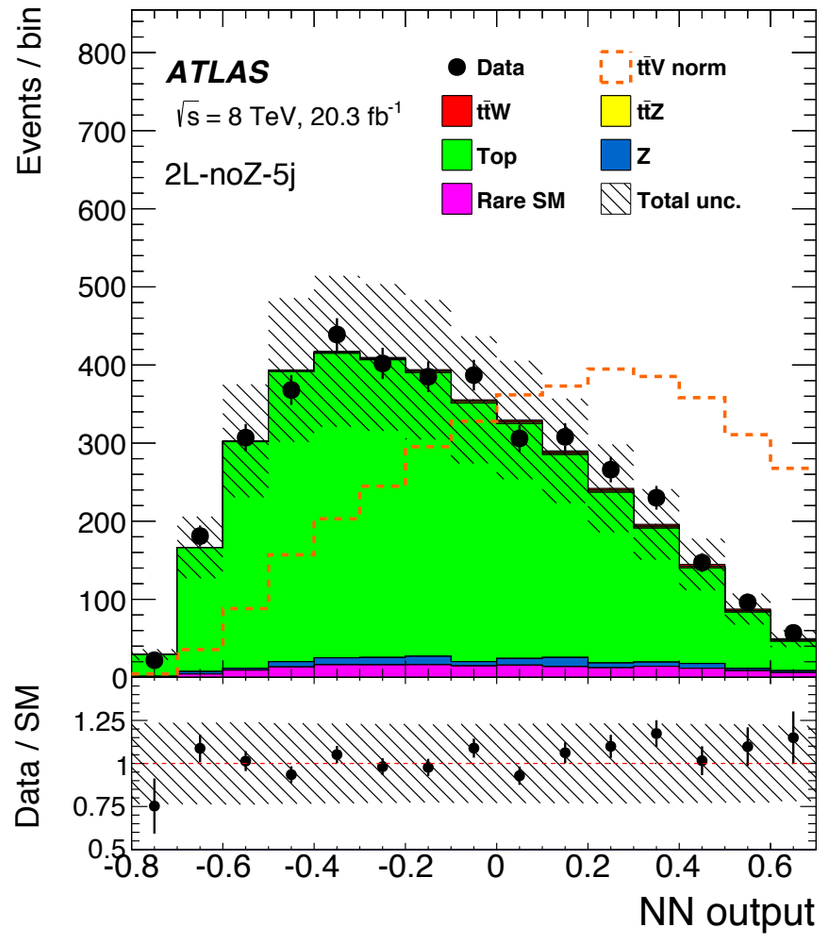
Source of slight excess in ttW, consistent with CMS excess in ttH

ttW, ttZ cross sections @ 8 TeV

ATLAS, arXiv:1509.05276

- Final results
- 15 signal regions and 5 control regions
  - at least 1 lepton with p_T > 20 GeV
  - p_T> 15 or 7 GeV for additional leptons
- 2 OS leptons: NN used to separate ttW and ttZ from the background



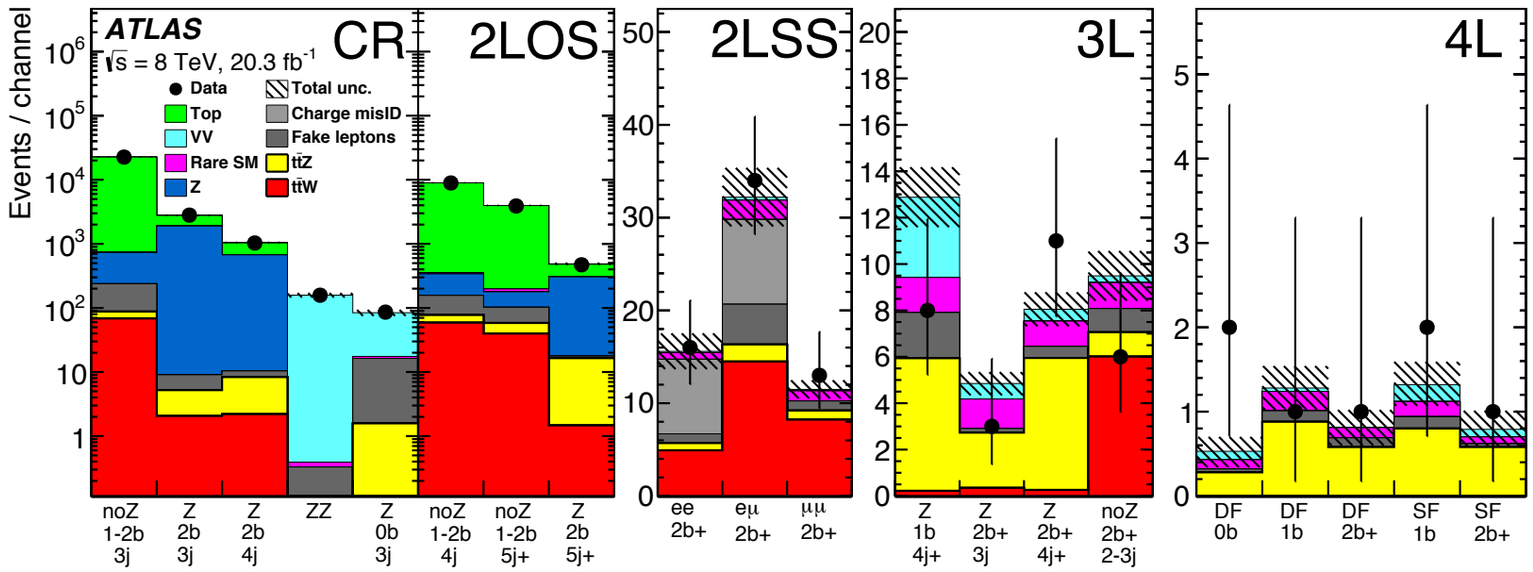


All signal and control regions are combined in a profile likelihood fit with σ(ttZ) and σ(ttW) as free parameters.

ttW, ttZ cross sections @ 8 TeV

ATLAS, arXiv:1509.05276

Post fit results (per region):



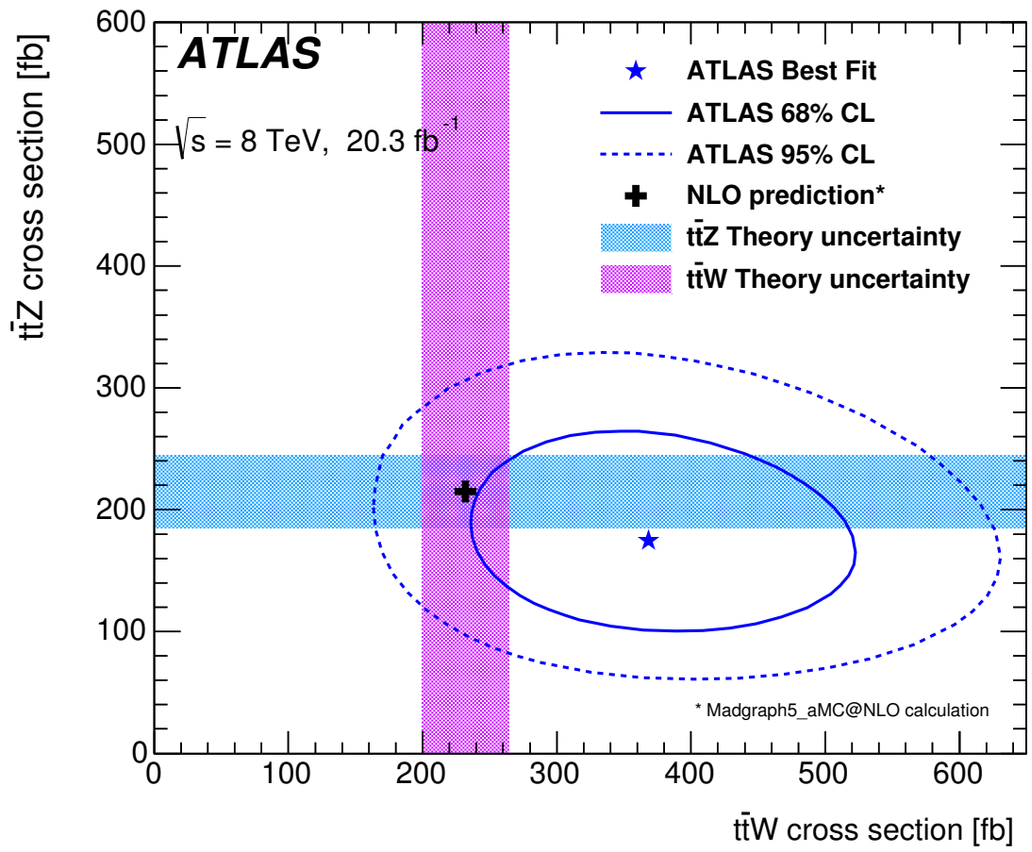
Measured cross sections:

$$\sigma_{t\bar{t}W} = 369^{+86}_{-79}\ (\text{stat}) \pm 44\ (\text{syst})\ \text{fb}$$

$$\sigma_{t\bar{t}Z} = 176^{+52}_{-48}\ (\text{stat}) \pm 24\ (\text{syst})\ \text{fb}$$

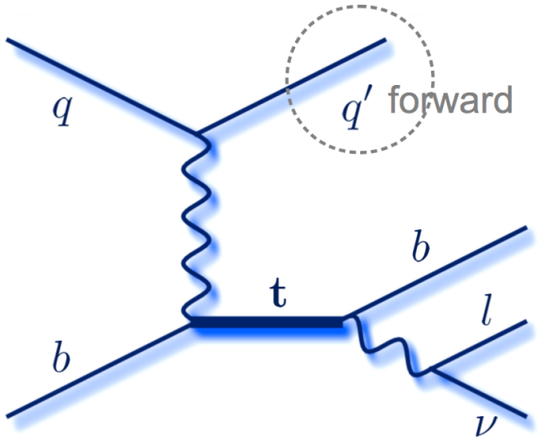
The observed (expected) significance of:

- ttW is 5.0σ (3.2σ)
- ttZ is 4.2σ (4.5σ)



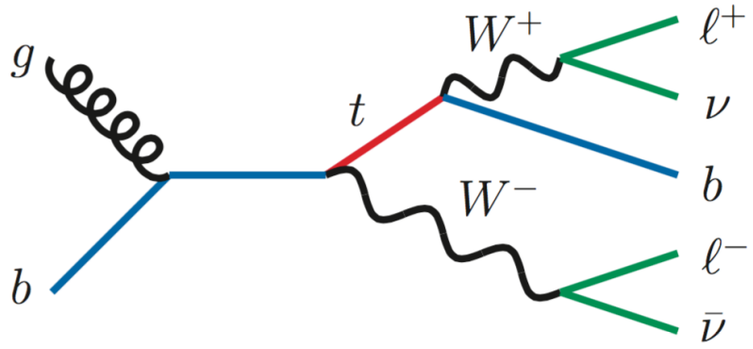
Single top production

t-channel



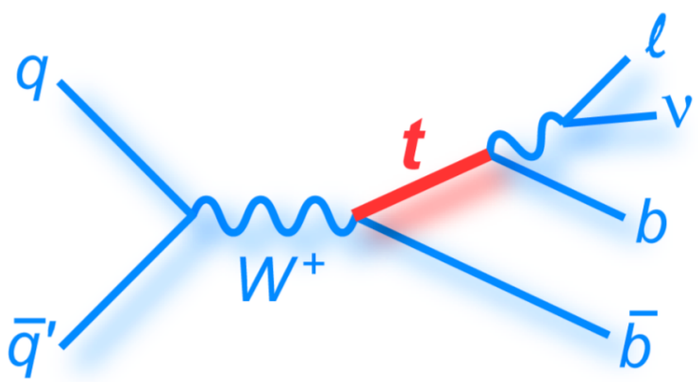
- One forward jet
- One lepton
- One b-jet
- Missing transverse energy

Wt-channel



- Two oppositely charged leptons
- One high-pT and central b-jet
- Missing transverse energy

s-channel



- One isolated and high-pT lepton
- Two b-jets with high-pT
- Missing transverse energy

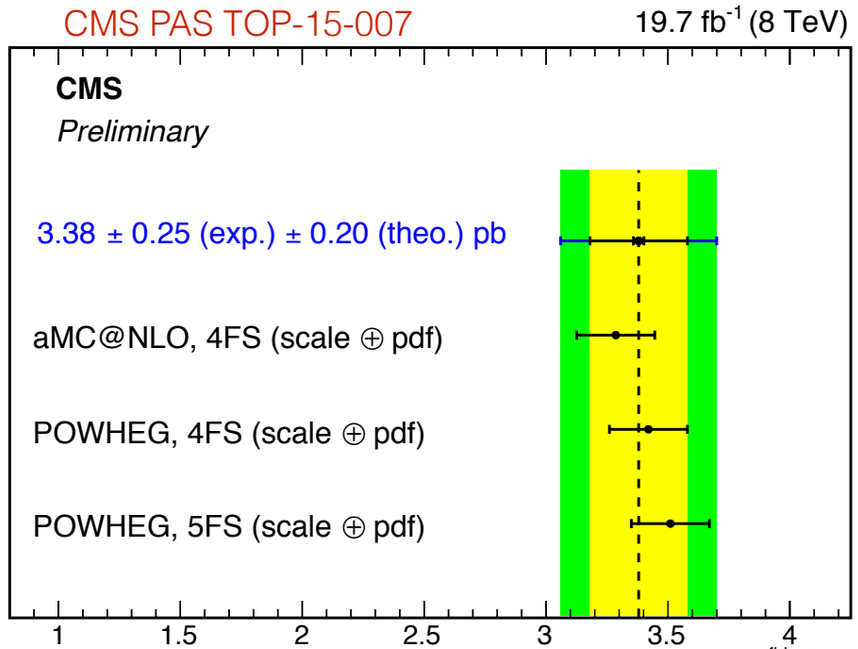
t-channel single top @ 8 TeV

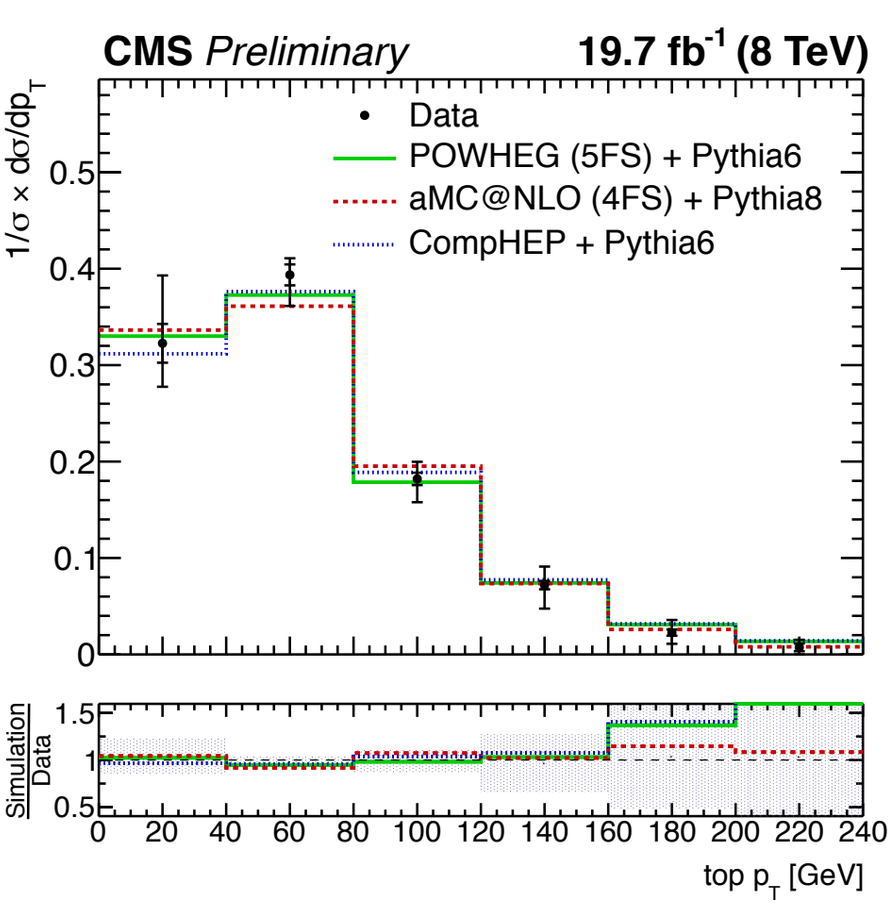
CMS PAS TOP-14-004

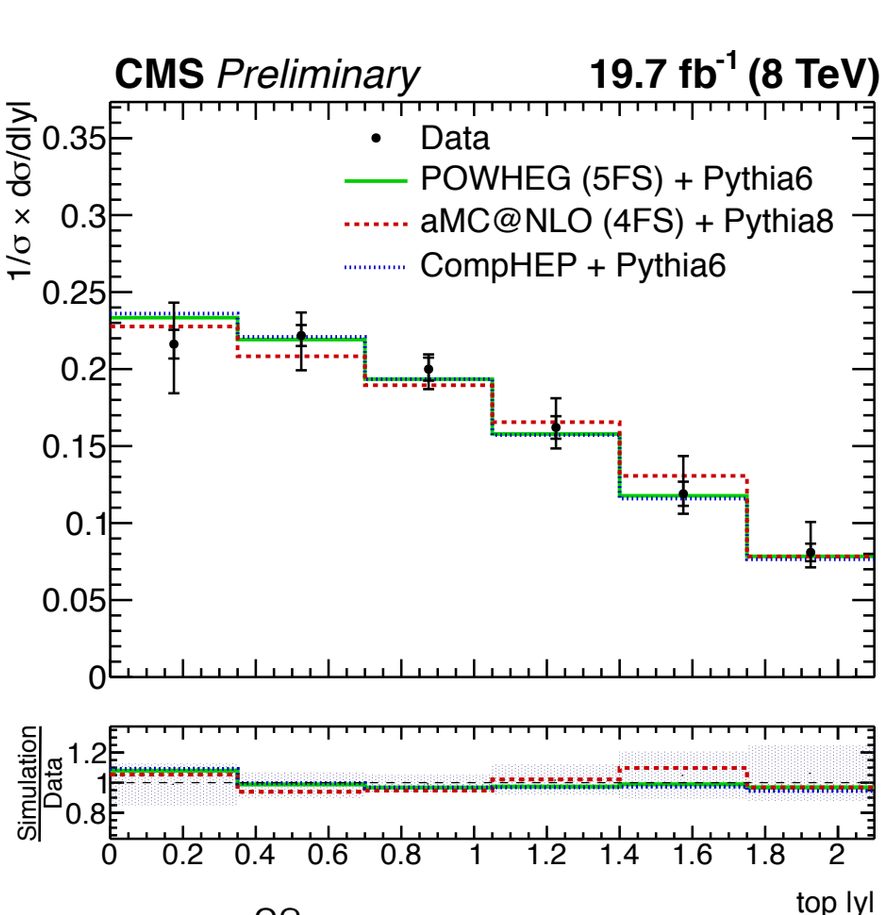
- One electron (muon) with pT > 30 GeV (26 GeV)
- jet pT > 40 GeV
- ETmiss > 45 GeV , mT(W) > 50 GeV
- Measure differential cross sections

CMS PAS TOP-15-007

Fiducial cross section measurement recently released



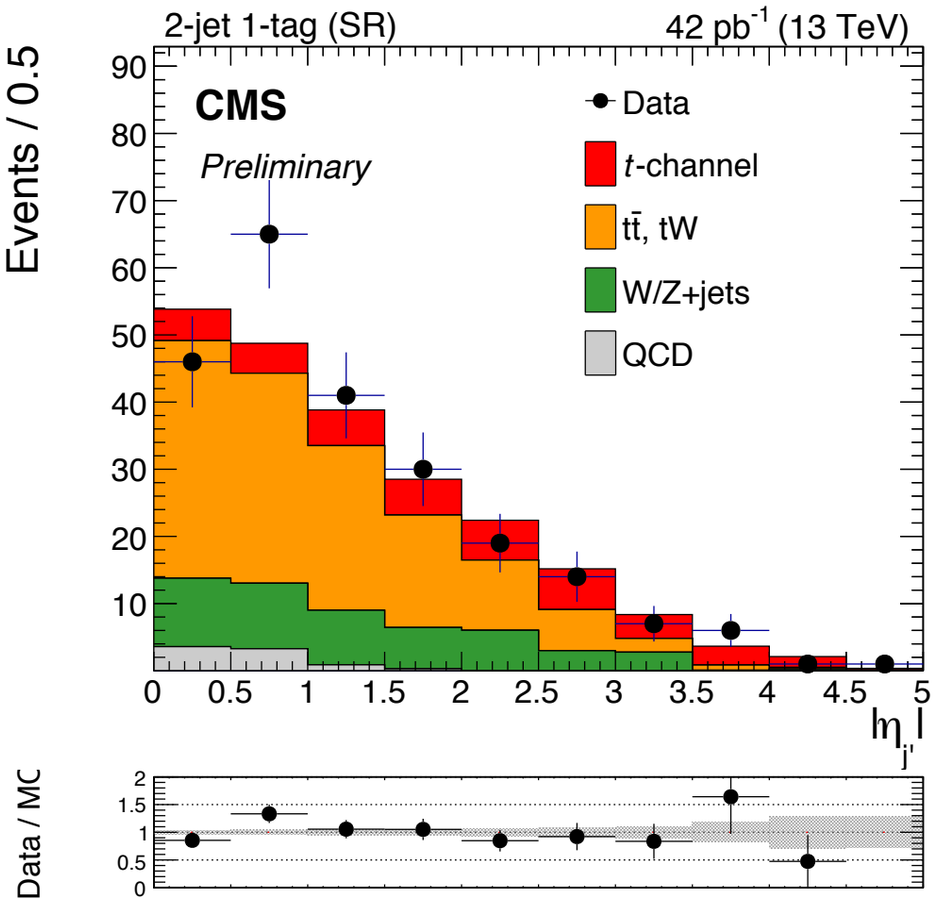


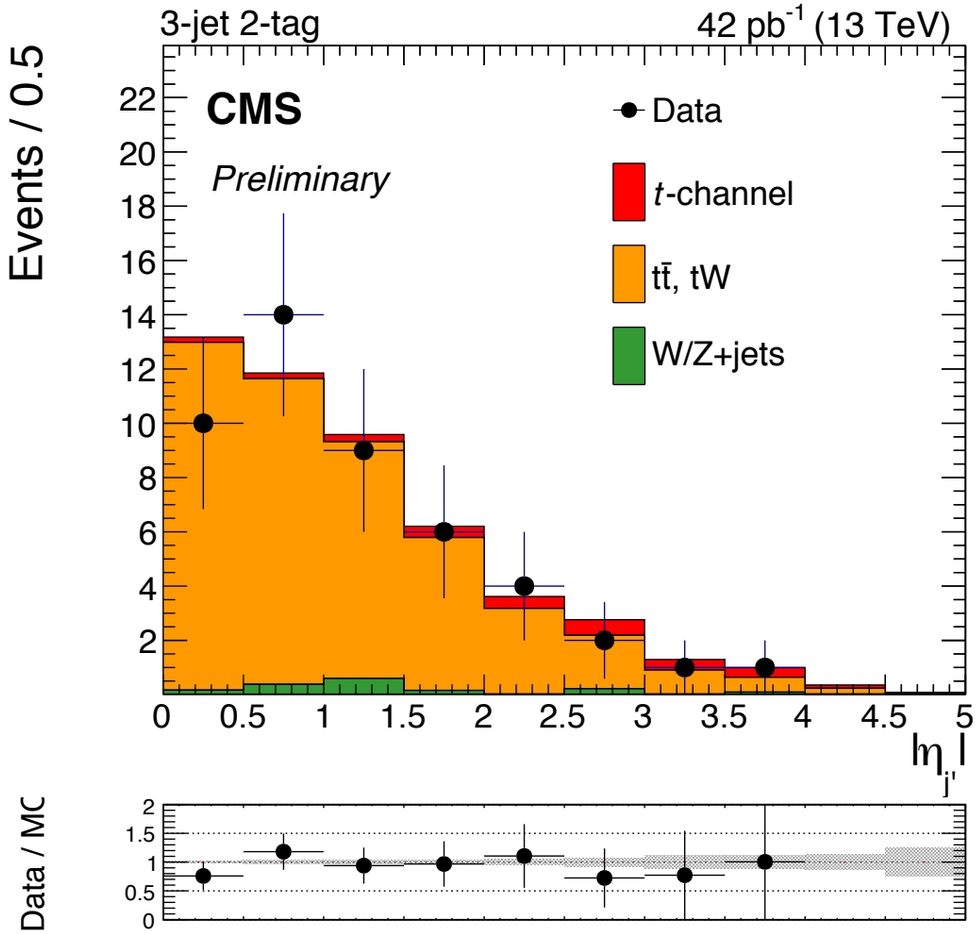


CMS PAS TOP-14-004

t-channel single top @ 13 TeV

CMS PAS-TOP-15-004





Measured cross section: $\sigma_{\mathrm{t-ch}} = 274\ \mathrm{pb} \pm 42\%$

Observed (expected) significance: $3.5\sigma(2.7\sigma)$

Theory: $\sigma^{\mathrm{theo}}_{\mathrm{t-ch}} = 218 \pm 7\ \mathrm{pb}$

tW single top @ 8 TeV

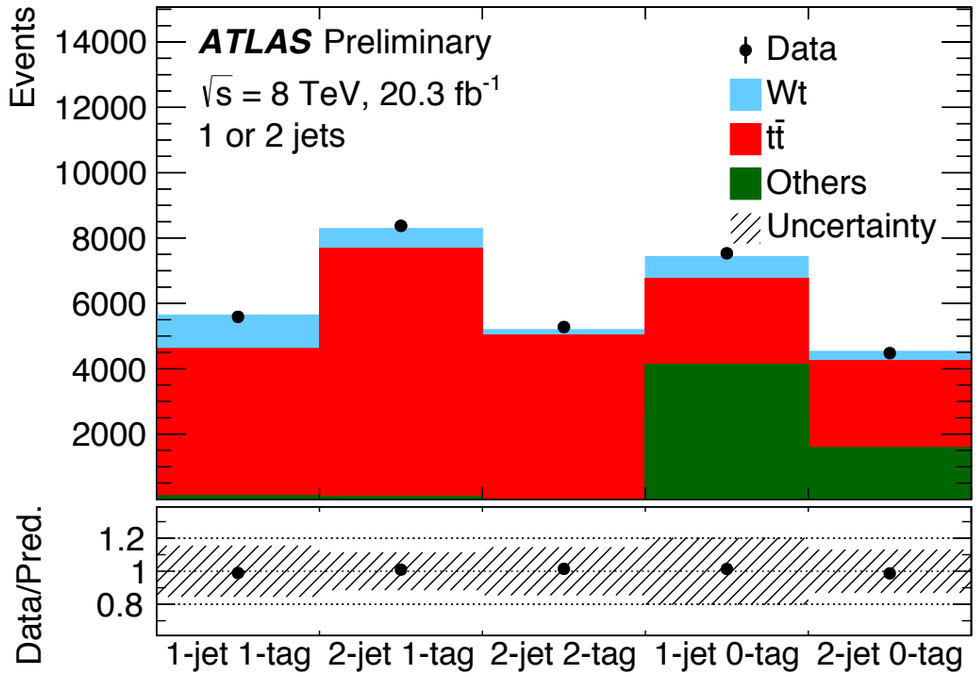
TOPQ-2012-20

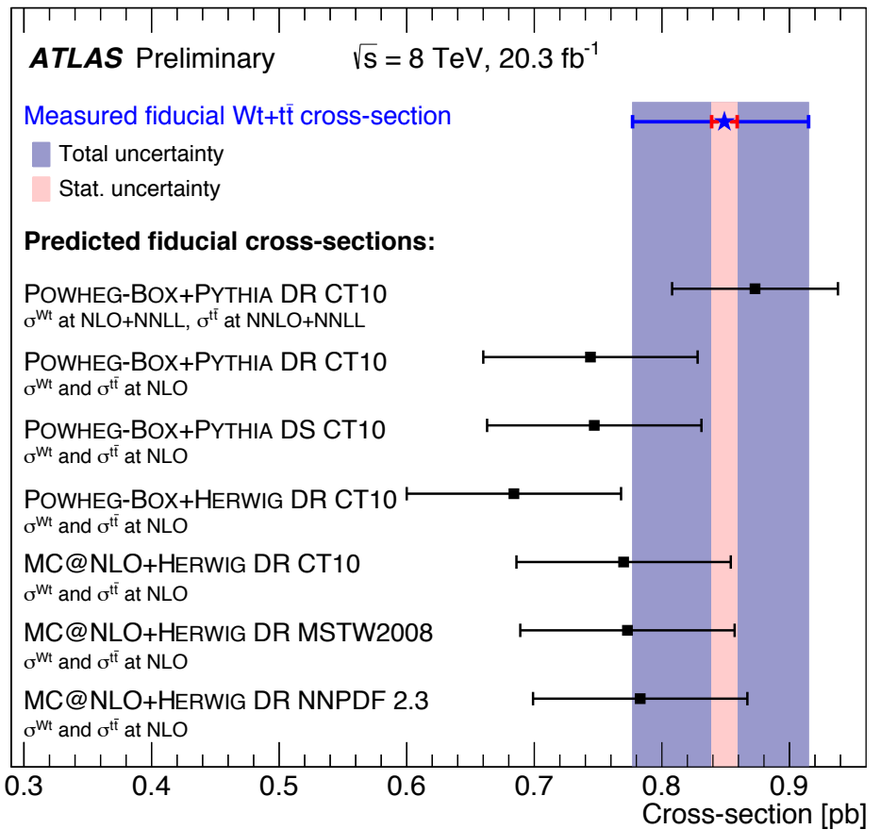
- Di-lepton selection with 1 or 2 jets (0,1 or 2 b-tag)
- BDT to separate signal from tt
- Wt inclusive cross section:

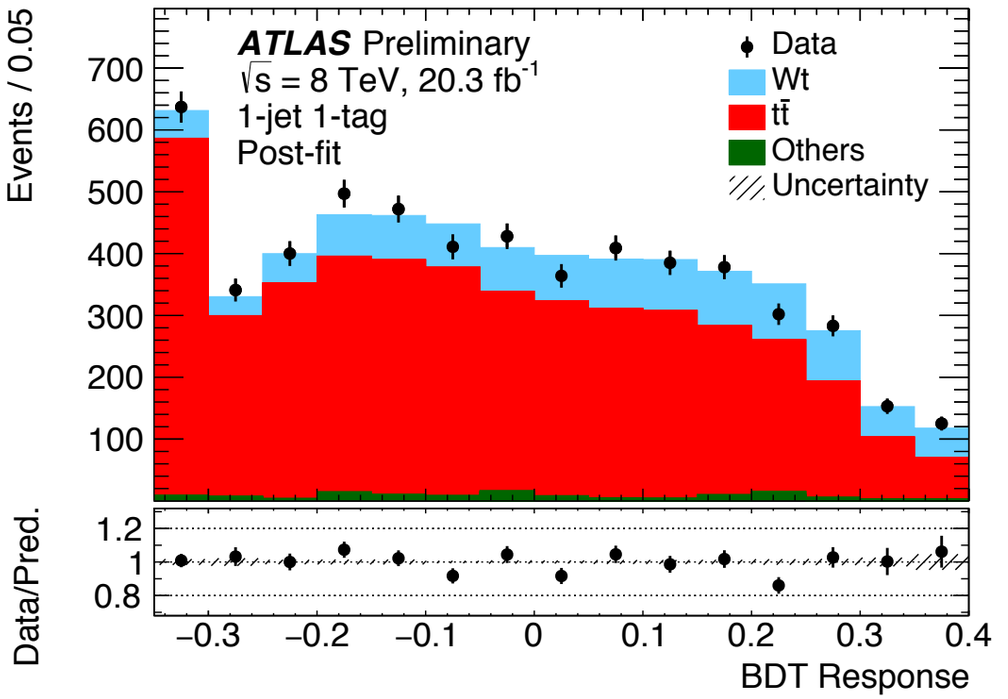
$$\sigma_{\mathrm{tW}} = 23.0 \pm 1.3(\mathrm{stat})\ ^{+3.2}_{-3.5}(\mathrm{syst}) \pm 1.1(\mathrm{lumi})\ \mathrm{pb}$$

- Wt +$t\bar{t}$ fiducial cross section measured by fitting the sum of the Wt and $t\bar{t}$ contributions to data in the 1-jet 1-tag region:

$$\sigma_{\mathrm{fid}} = 0.85 \pm 0.01\ (\mathrm{stat})^{+0.06}_{-0.07}\ (\mathrm{syst}) \pm 0.02\ (\mathrm{lumi})\ \mathrm{pb}$$







s-channel single top

ATLAS-CONF-2015-047

Selection:
One lepton + 2 b-jets and ETmiss

Discriminant:
- Build Matrix Element discriminant for each selected event
- s-channel vs t-channel, $t\bar{t}$, W+jets
- Template fit in signal and control region

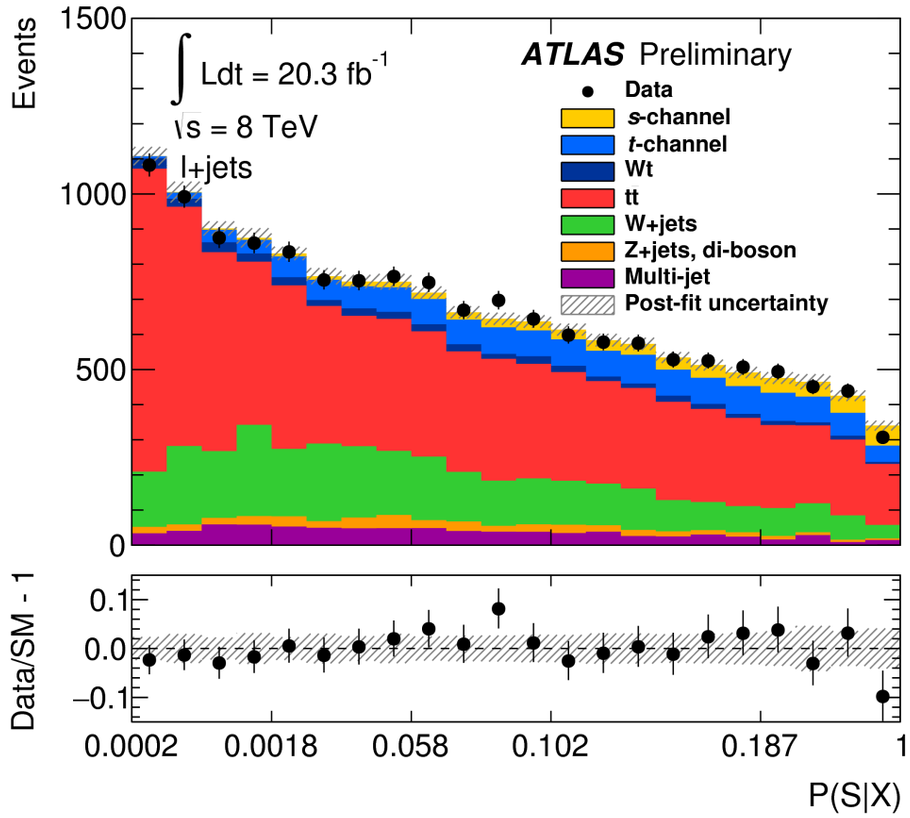
$$P(S|X) = \frac{\sum_i \alpha_{S_i} P(X|S_i)}{\sum_i \alpha_{S_i} P(X|S_i) + \sum_j \alpha_{B_j} P(X|B_j)}$$

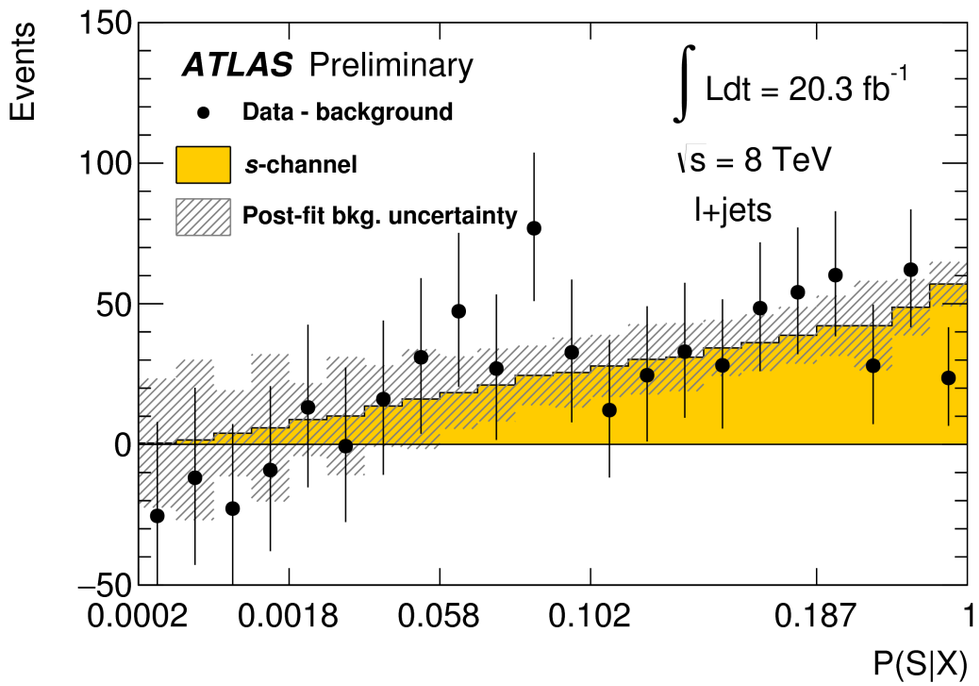
Cross section:

$$\sigma_s = 4.8 \pm 1.1(\text{stat}) \; ^{+2.2}_{-2.0}(\text{syst+lumi}) \text{ pb}$$

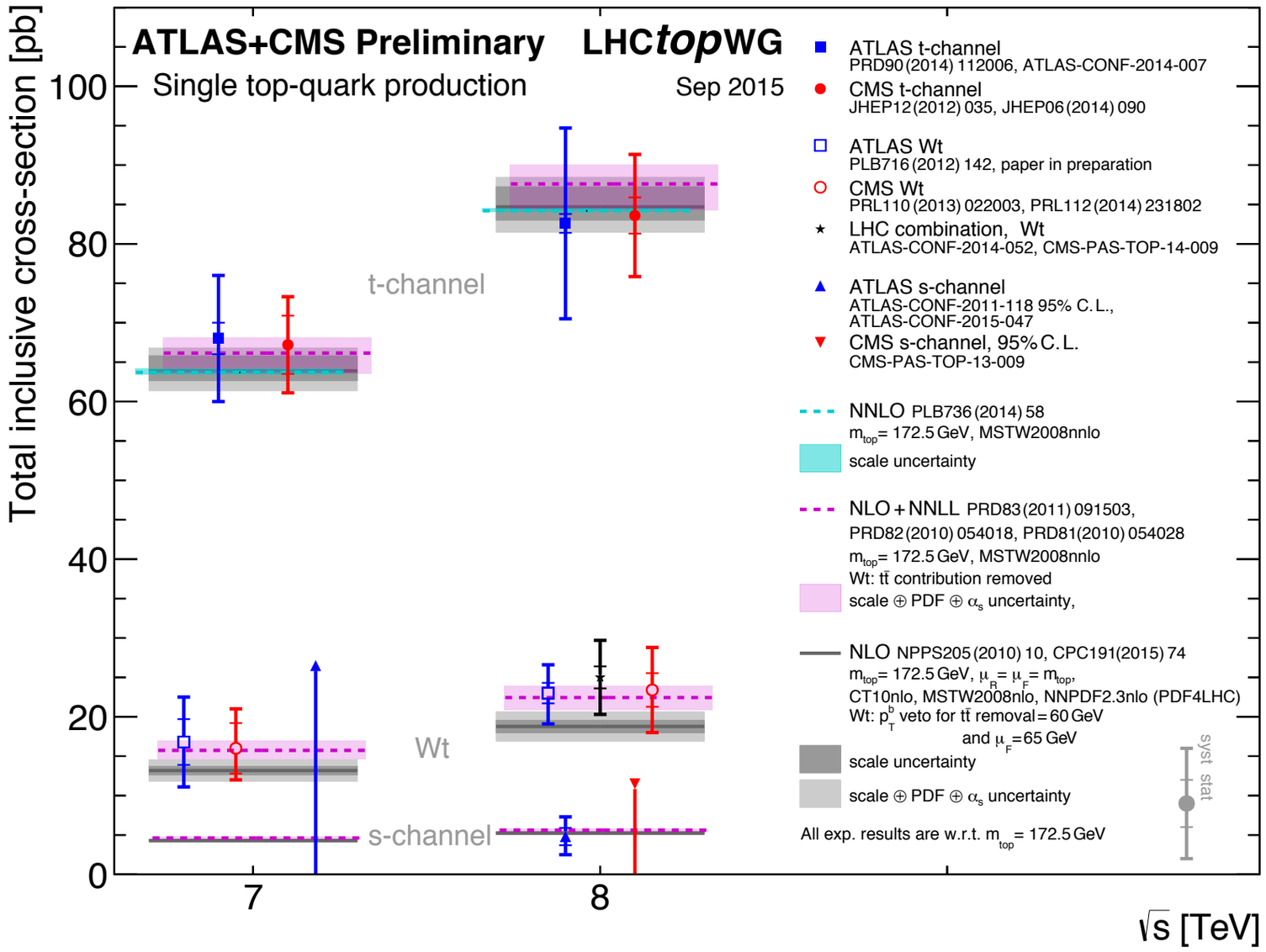
Observed (expected) significance: 3.2σ (3.9σ)

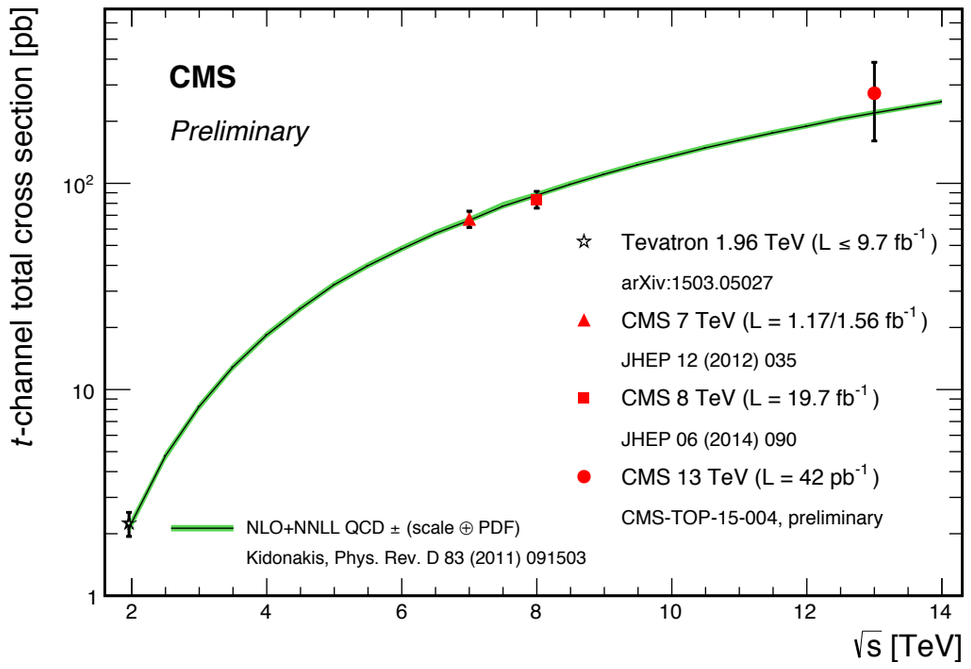
First evidence of the s-channel production at LHC





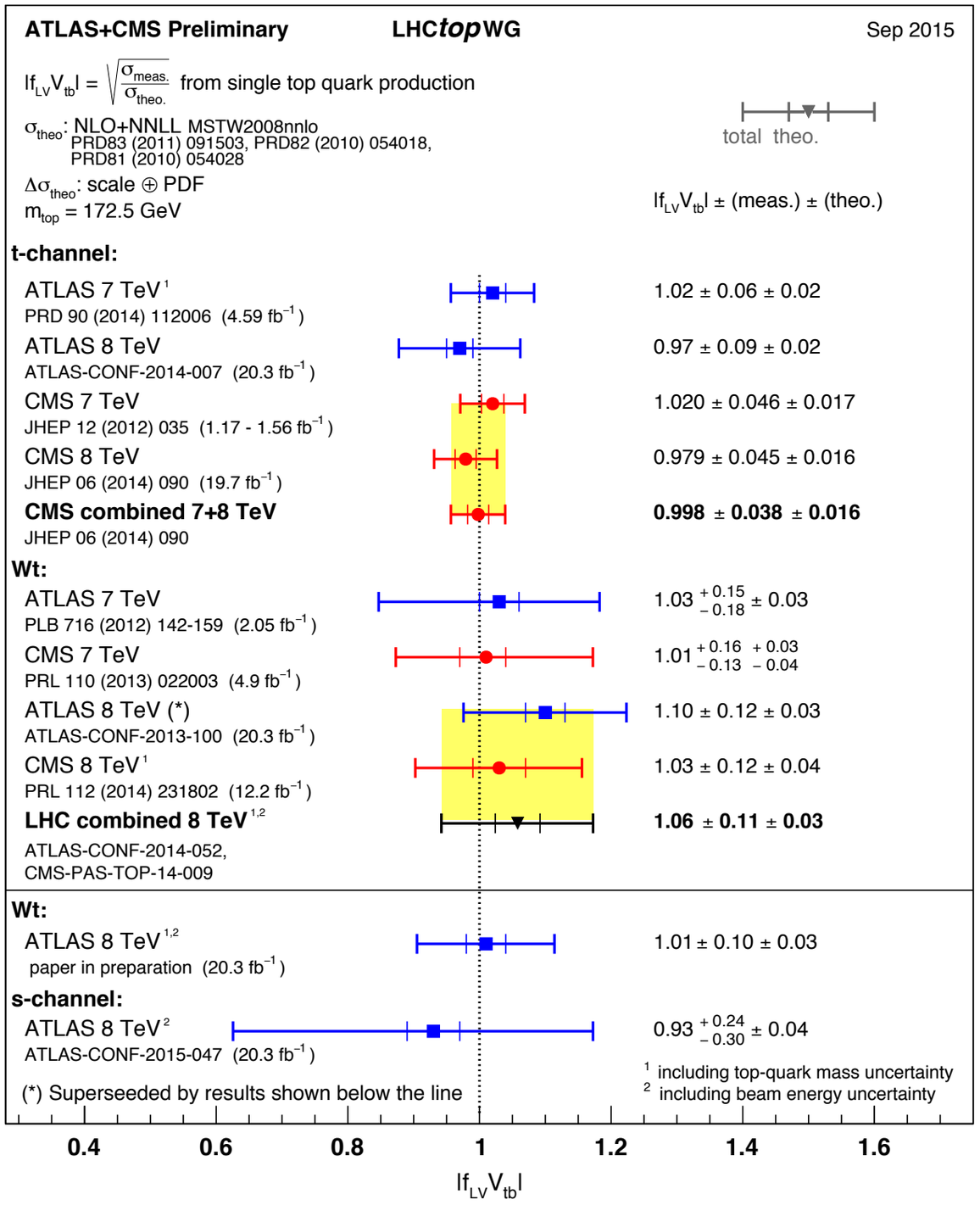
Summary of Single top measurements





All the measurements are so far consistent with the SM predictions

Summary of $|V_{tb}|$ determinations at 7 and 8 TeV



Direct determination of the matrix element $|V_{tb}|$:

- Test the unitary of the CKM Matrix
- Sensitivity to new physics

Measure $|V_{tb}|$ assuming left-handed SM-like W-t-b coupling (and $|V_{tb}| >> |V_{ts}|, |V_{td}|$):

$$|V_{\mathrm{tb}} \cdot f_{\mathrm{LV}}| = \sqrt{\frac{\sigma_{\mathrm{obs}}}{\sigma_{\mathrm{theory}}}}$$

with $f_{\mathrm{LV}} = 1$ in the SM.

Summary

- Top quark pair production cross sections at the LHC (7, 8 and 13 TeV)
  - inclusive cross sections:
    - new 8 and 13 TeV results from ATLAS and CMS
    - excellent agreement with pQCD (NNLO+NNLL)
  - Differential cross sections:
    - new 8 TeV (resolved and boosted regimes) and 13 TeV results
    - 8 TeV measurements have discriminating power (MC generators, PDFs)

- Associated production of top quarks with a gauge boson
  - ttZ and ttW: improved cross sections measurements

- Single top production
  - t-channel:
    - new 13 TeV result from CMS
  - Wt channel:
    - Wt cross sections has been measured with a precision of 23% in CMS and 17% in ATLAS
    - First Wt + $t\bar{t}$ fiducial cross section measurement by ATLAS
  - s-channel:
    - First evidence of the s-channel by ATLAS

- …a rich Top Physics Programme ahead of us with the ongoing Run 2