University of Bologna & INFN

Top Quark Production Measurements with ATLAS

Matteo Franchini
(On behalf of the ATLAS collaboration)

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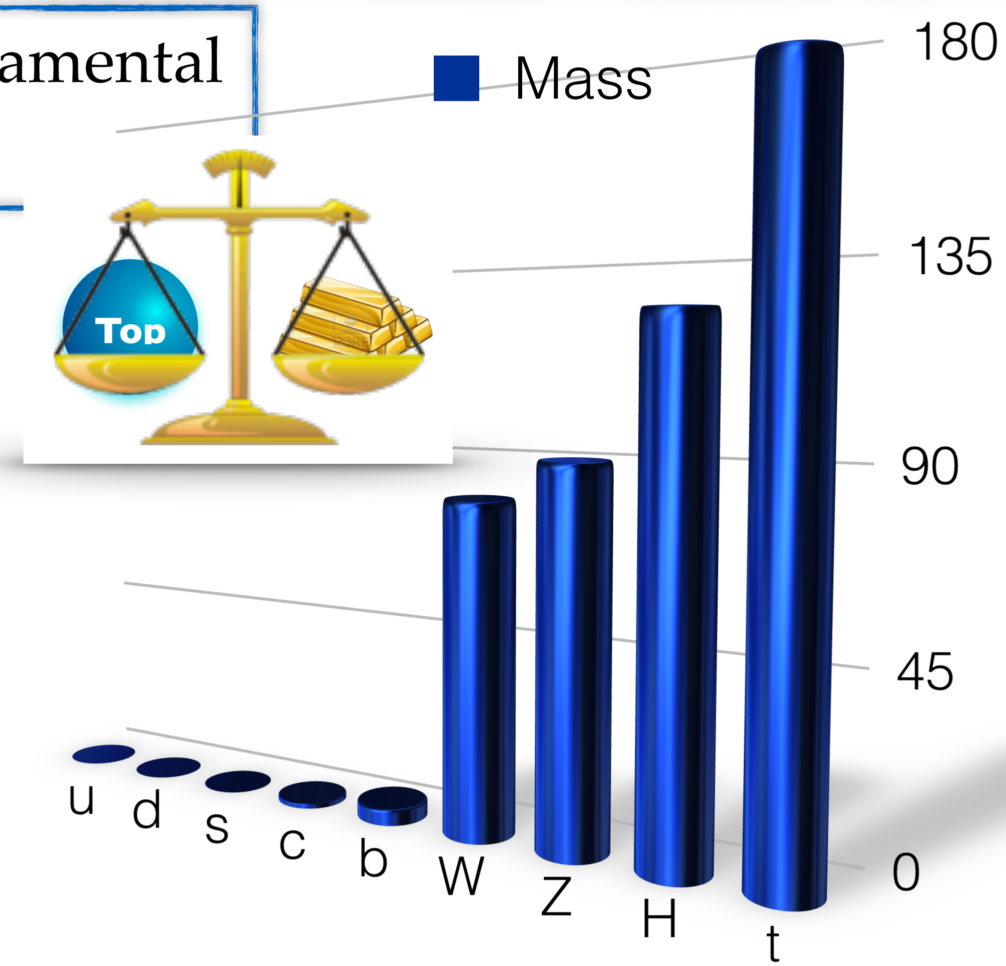
matteo.franchini@cern.ch

The top quark

The **most massive** known fundamental particle (172.3 ± 0.9 GeV)



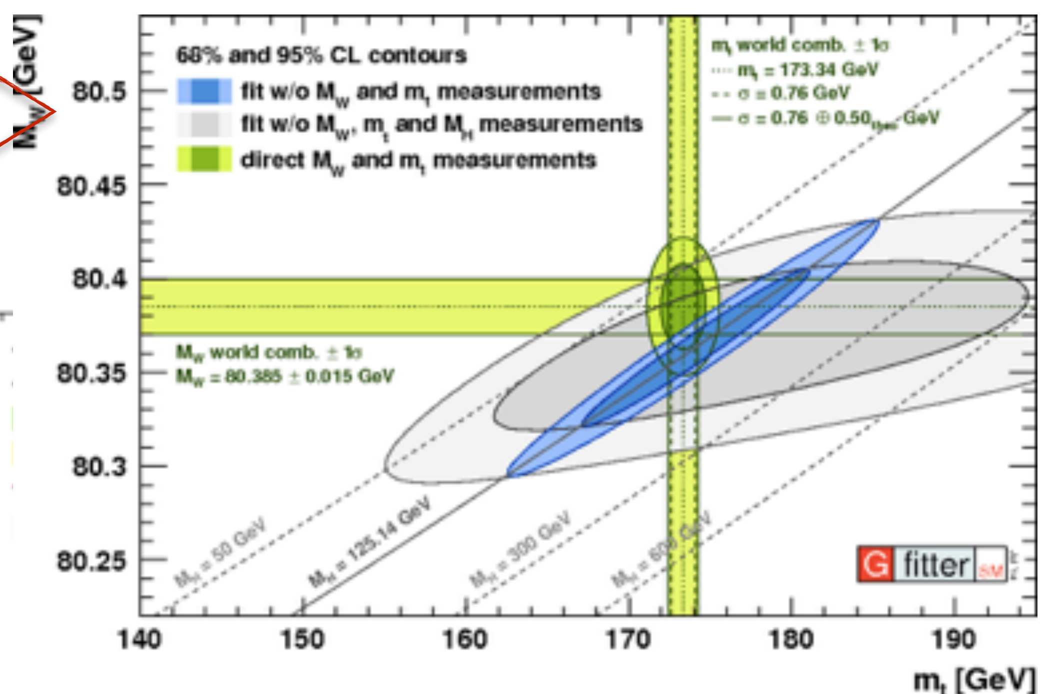
Top quark decays **faster** than its hadronization time. Unique possibility to study a **bare quark**.

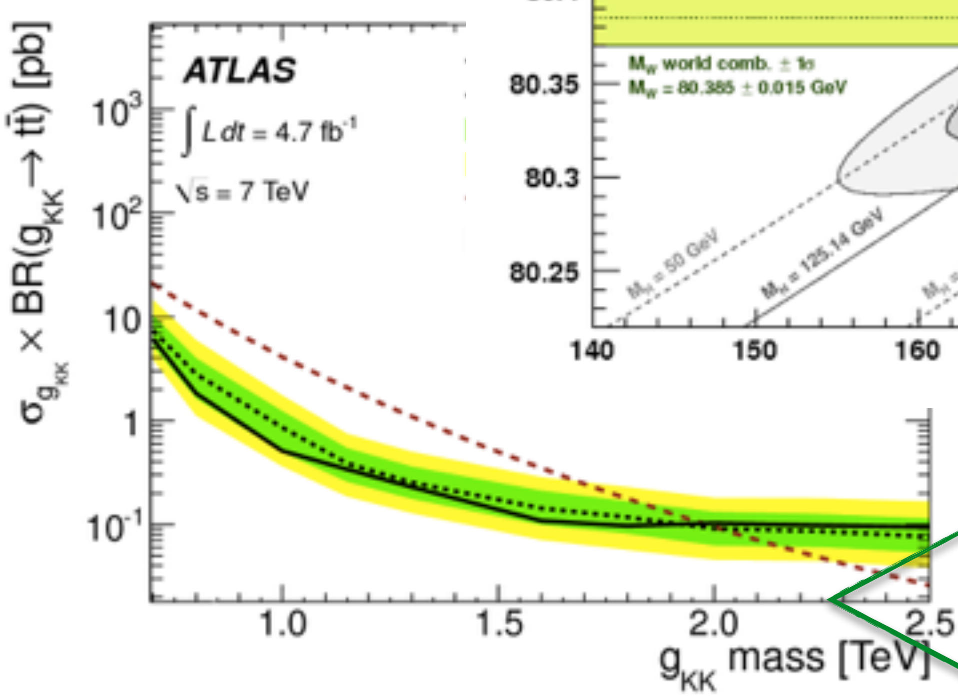
$\tau_{decay} = \sim 3 \cdot 10^{-25}$s

VS

$\tau_{had} = \sim 3 \cdot 10^{-24}$s

Constrain the SM





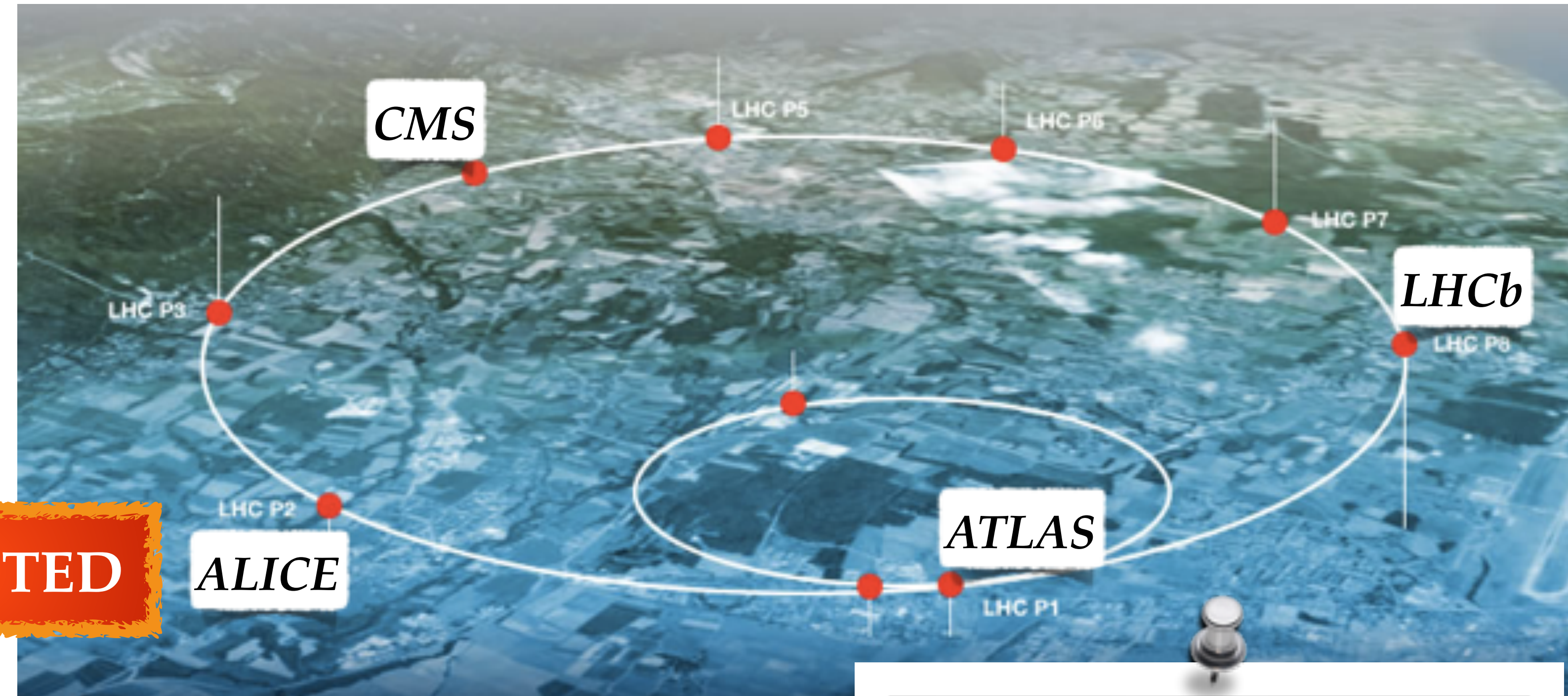
Principal background to many new physics models and most of the Higgs final states.

Gate for **new physics** (Z′, kk gluons and many more)

LHC & ATLAS

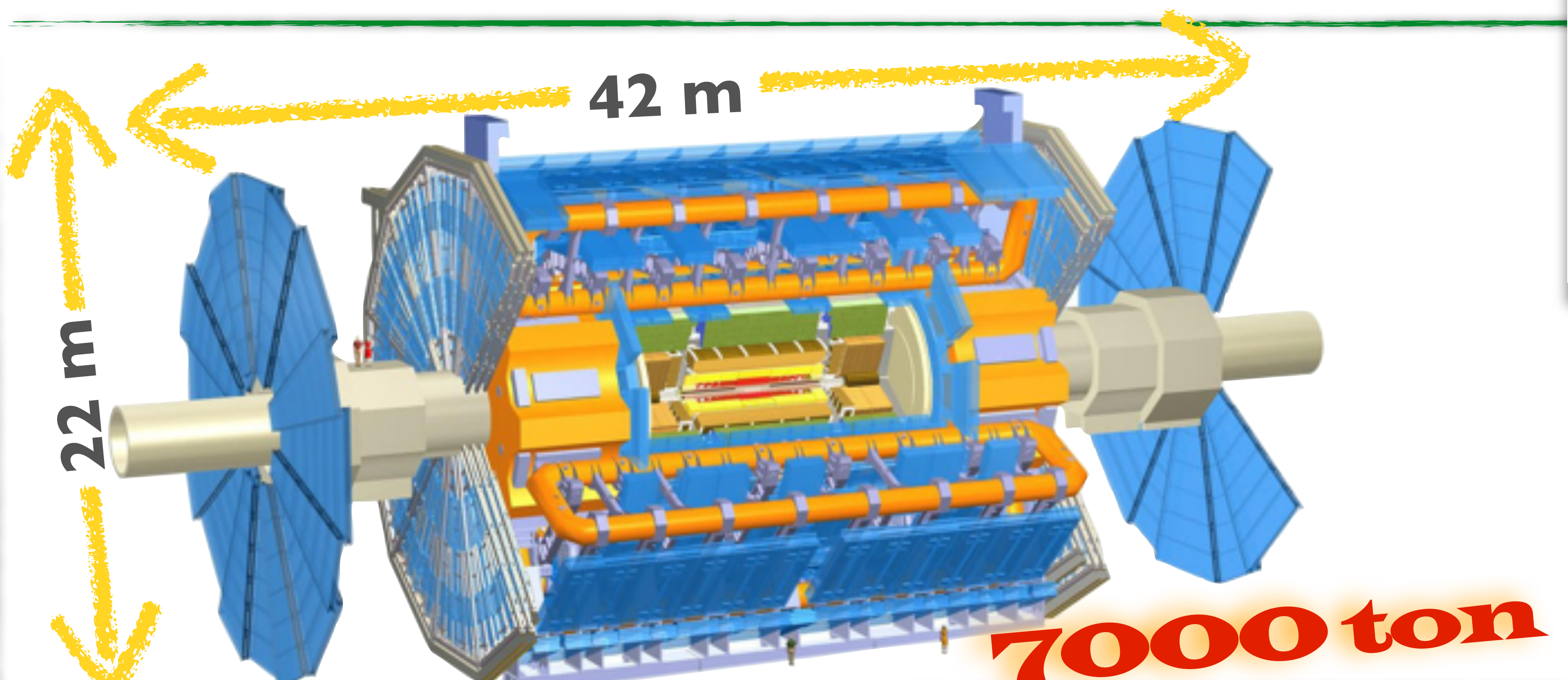
- **2011**: $\sqrt{s} = 7$ TeV
  $\int L \cdot dt \approx 4.6\ fb^{-1}$
  $L_{max} = 7.7 \cdot 10^{33}\ cm^{-2}\ s^{-1}$
- **2012**: $\sqrt{s} = 8$ TeV
  $\int L \cdot dt \approx 20.3\ fb^{-1}$
  $L_{max} = 2 \cdot 10^{33}\ cm^{-2}\ s^{-1}$
- **2015**: $\sqrt{s} = 13$ TeV
  $\int L \cdot dt \approx 10\ fb^{-1}$
  $L_{max} = 1.2 \cdot 10^{34}\ cm^{-2}\ s^{-1}$

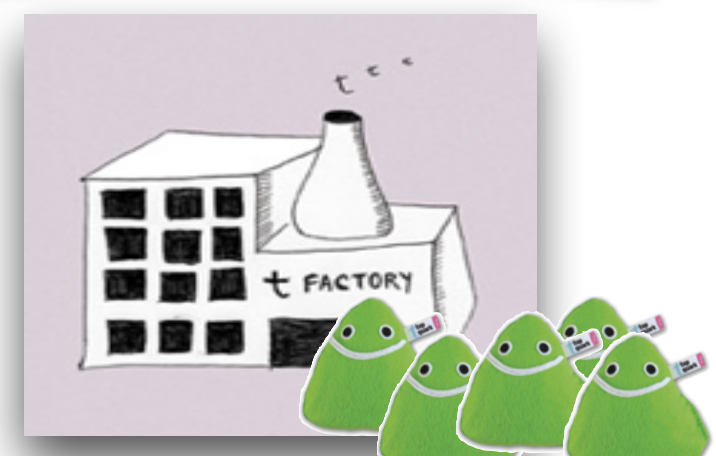
EXPECTED



<u>At LHC</u> 5.5 x10^6 $t\bar{t}$ produced (2011+2012) and ~9 x10^6 expected (2015)

<u>At Tevatron</u> ~35 x10^3.

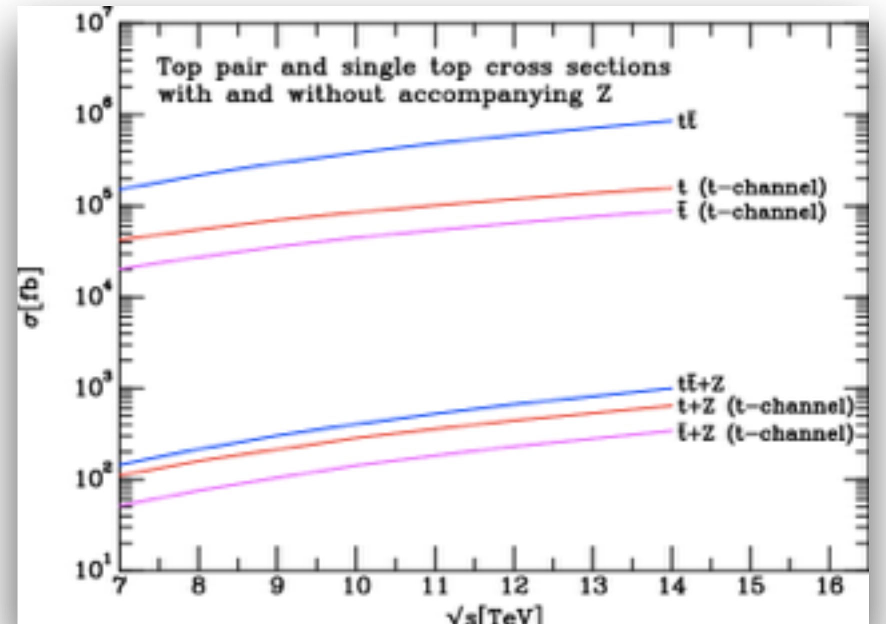




Production at LHC

Top pairs

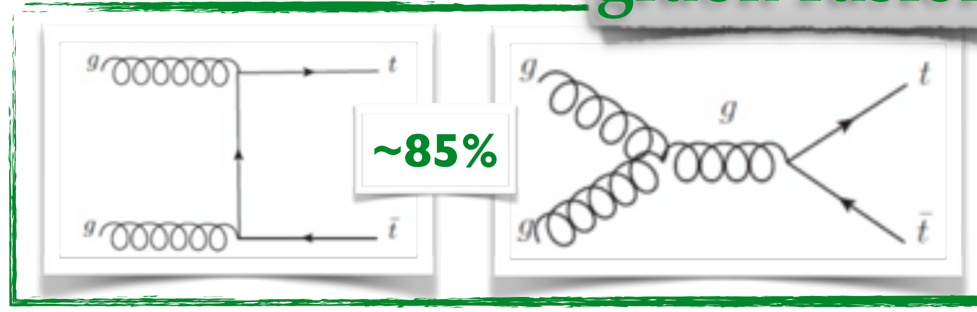
Strong interaction.



Production channels

	gg	qq
Tevatron	~10%	~90%
LHC(7-8)	~85%	~15%
LHC(13)	~90%	~10%

gluon fusion

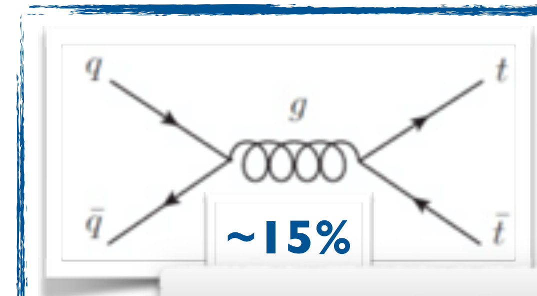


$t\bar{t}$ cross section

NNLO+NNLL

σ_{7TeV} (pb)	177.3 ± 11.4
σ_{8TeV} (pb)	252.8 ± 15.4
σ_{13TeV} (pb)	831.8 ± 48.8

Phys. Rev. Lett. 110 (2013) 252004



qq annihilation

Single top

Electroweak interaction.

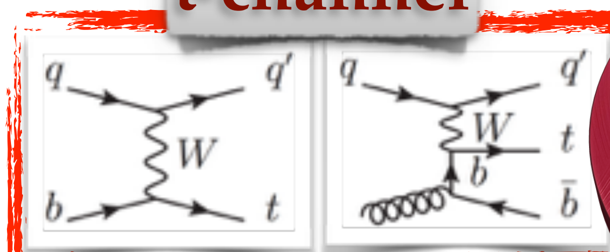
top cross section

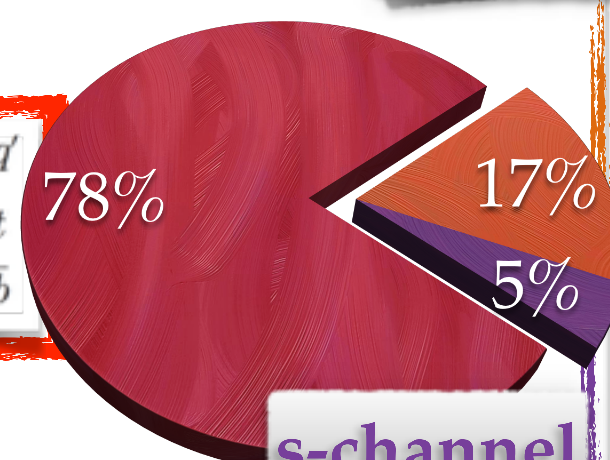
Hathor

	t-chan (pb)
LHC(7)	63.9 ± 3.8
LHC(8)	84.7 ± 4.9
LHC(13)	217.0 ± 11.7

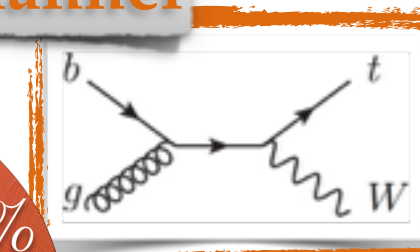
arXiv:1406.4403

t-channel

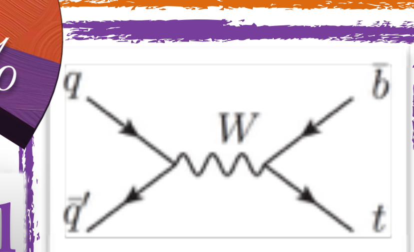




Wt-channel



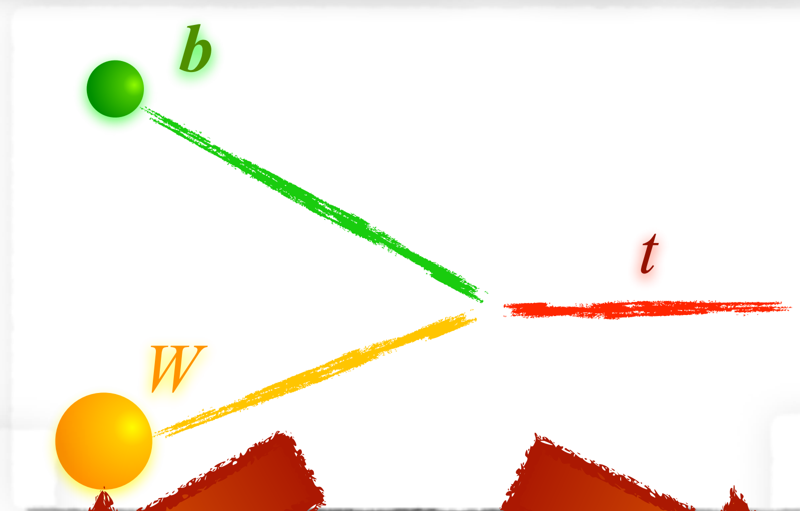
s-channel

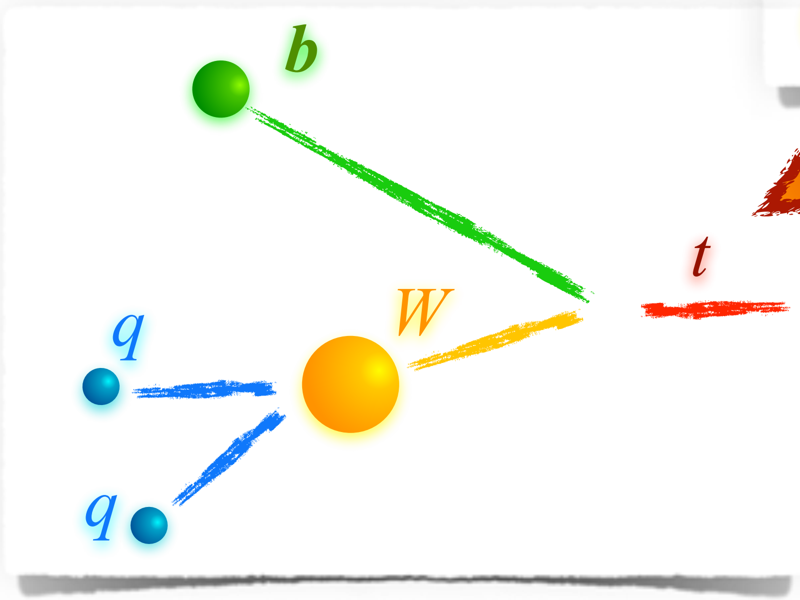


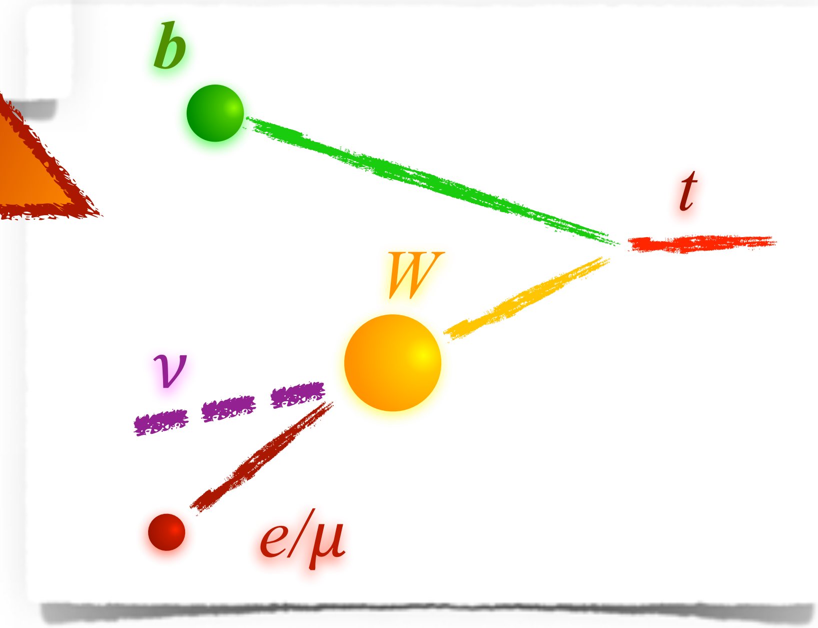
Top Decay

top quarks decay almost 100% in Wb

W decays had. or lep.



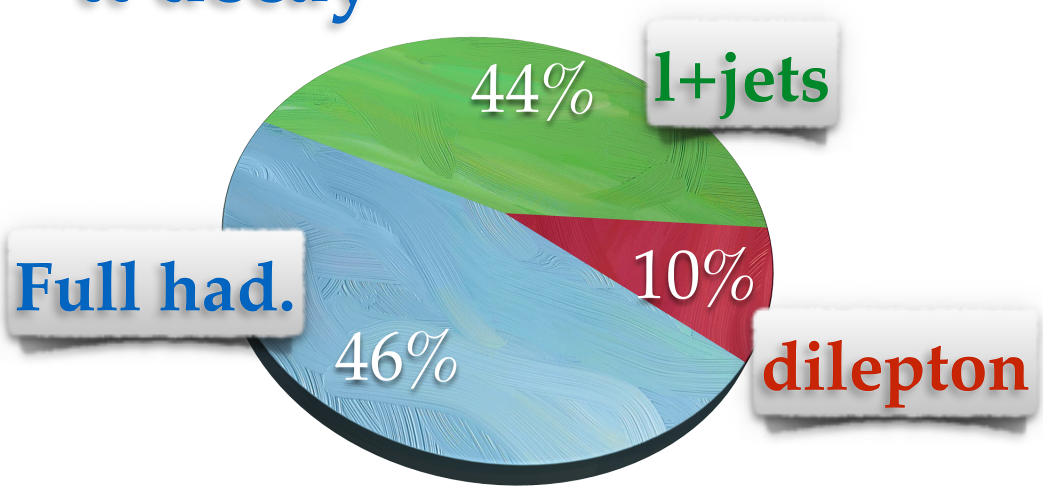




Signature

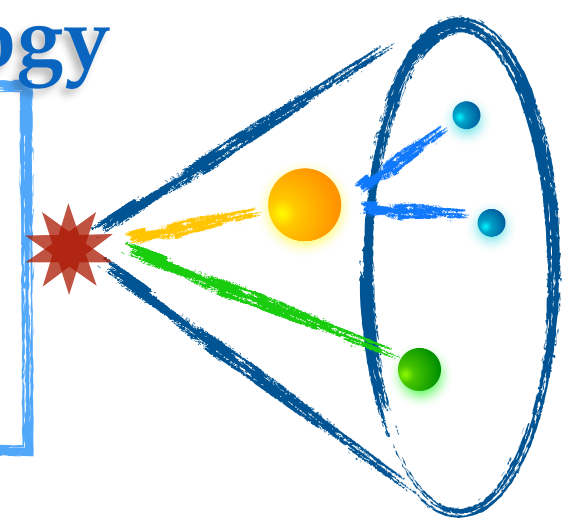
High p_T jets,
b-jets,
High p_T leptons,
Missing energy.

$t\bar{t}$ decay



Boosted Topology

Very high p_T top quarks decays cannot be separated in single jets;
Peculiar topology needs specific algorithms.



Top Pairs ($t\bar{t}$)

$t\bar{t}$ Inclusive Cross Section - Dilepton

$\sigma_{t\bar{t}}$ -> *lvlvbb*

$\sqrt{s} = 7$ TeV
$\sqrt{s} = 8$ TeV

∫L·dt ≃ **4.6 fb^{-1}** (2011)
∫L·dt ≃ **20.3 fb^{-1}** (2012)

Selection: opposite sign(OS) $e\mu$ + 1 or 2 b-tag jets;

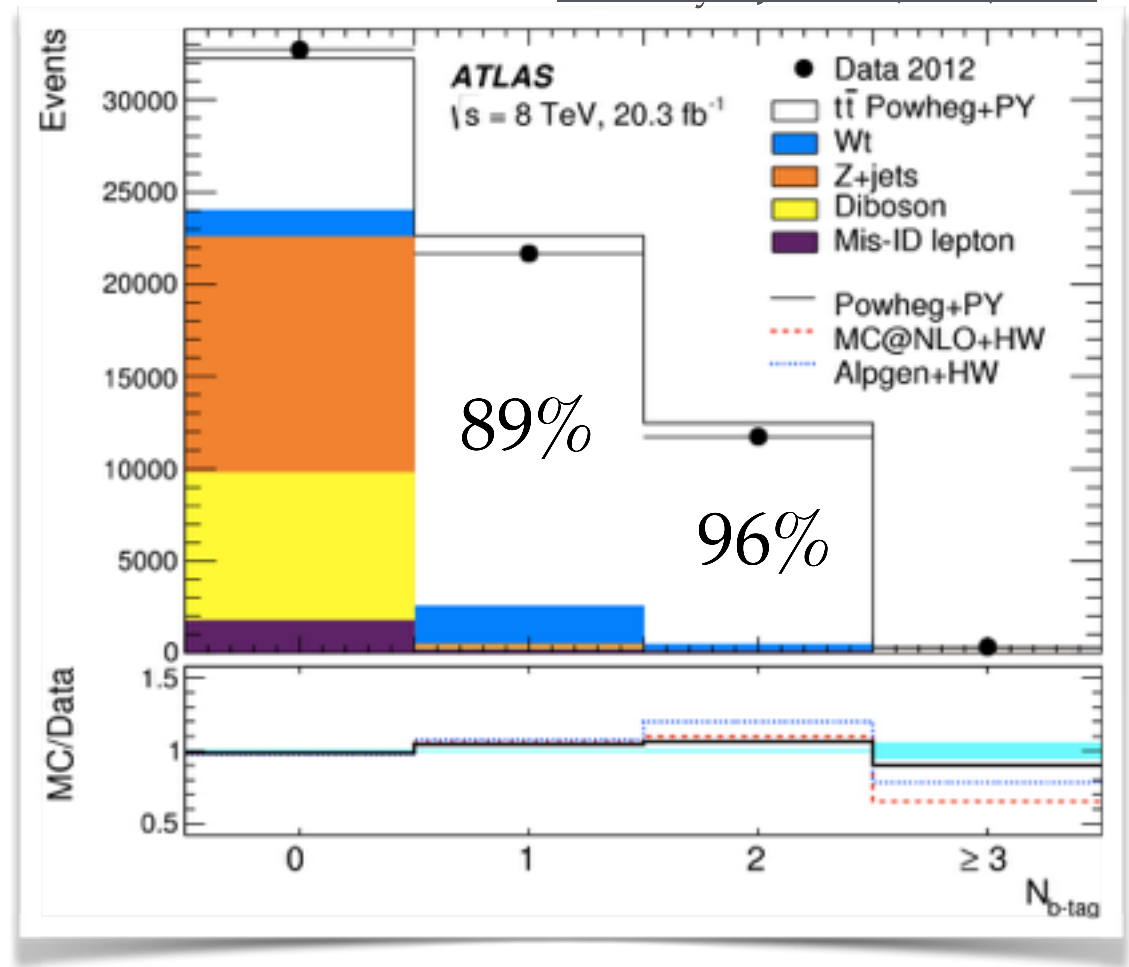
Bkg: W-t single top (**main**, from MC), Z+jets(from MC + data driven Z->ll scaling), fake leptons(data driven extrapolation from same sign(SS) sample);

Cross Section strategy: directly from cross section equations in both the cases of exactly 1 or 2 b-tag:

$$N_1 = L\sigma_{t\bar{t}}\ \epsilon_{e\mu} 2\epsilon_b (1 - C_b \epsilon_b) + N_1^{\mathrm{bkg}}$$
$$N_2 = L\sigma_{t\bar{t}}\ \epsilon_{e\mu} C_b {\epsilon_b}^2 + N_2^{\mathrm{bkg}}$$

Systematics: Lumi(2-3%), beam energy(2%), tt modelling(~1.3%), PDF(~1.1%).

Eur. Phys. J. C 74 (2014) 3109



$$\sigma_{t\bar{t}} = 182.9 \pm 3.1 \pm 4.2 \pm 3.6 \pm 3.3\,\mathrm{pb}\ (\sqrt{s} = 7\,\mathrm{TeV})$$
$$\sigma_{t\bar{t}} = 242.4 \pm 1.7 \pm 5.5 \pm 7.5 \pm 4.2\,\mathrm{pb}\ (\sqrt{s} = 8\,\mathrm{TeV})$$

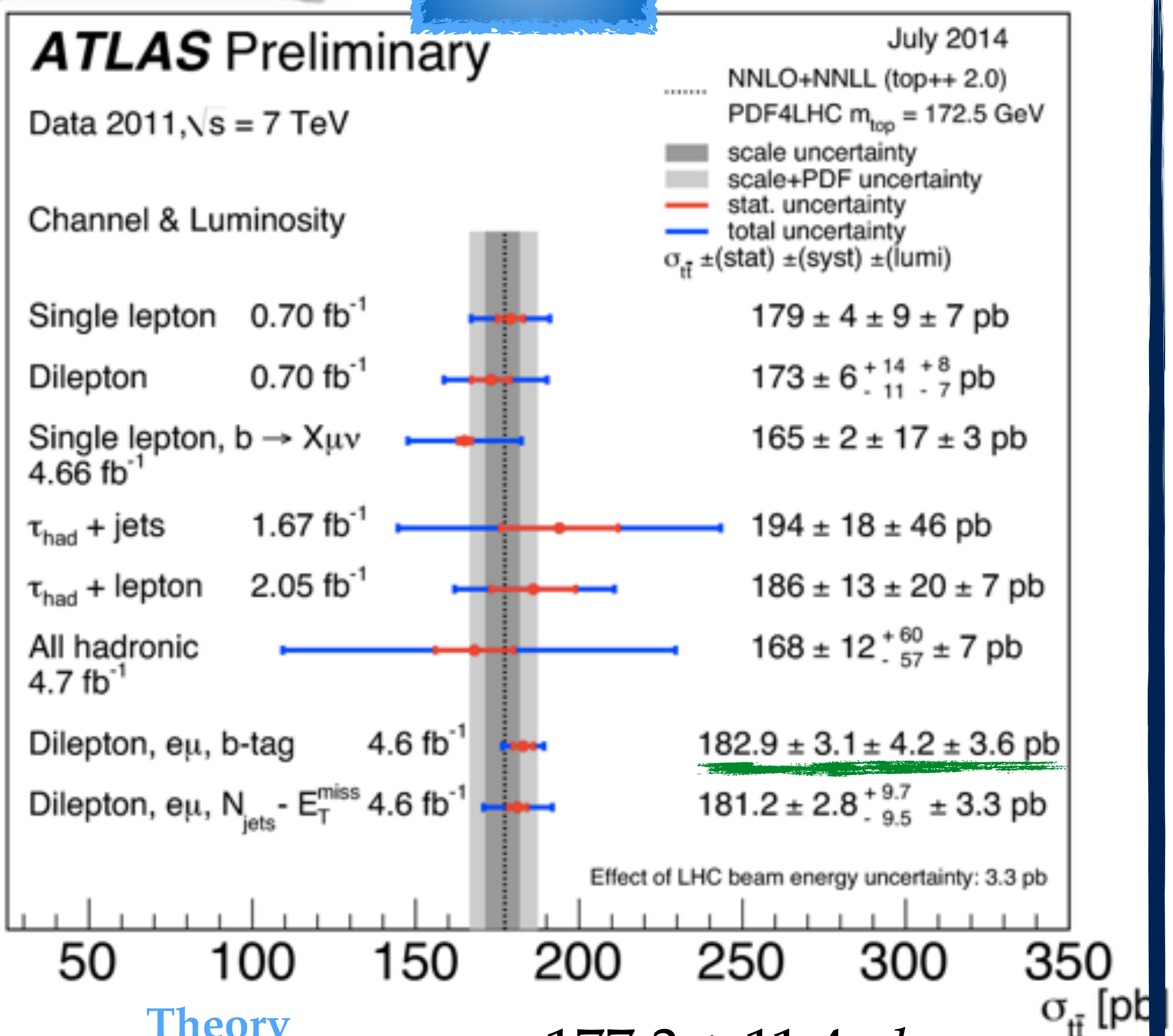
stat. + syst. + lumi + beam energy

$$\frac{\Delta\sigma_{tt}}{\sigma_{tt}} = 4\%$$

$t\bar{t}$ Inclusive Cross Section - Combination

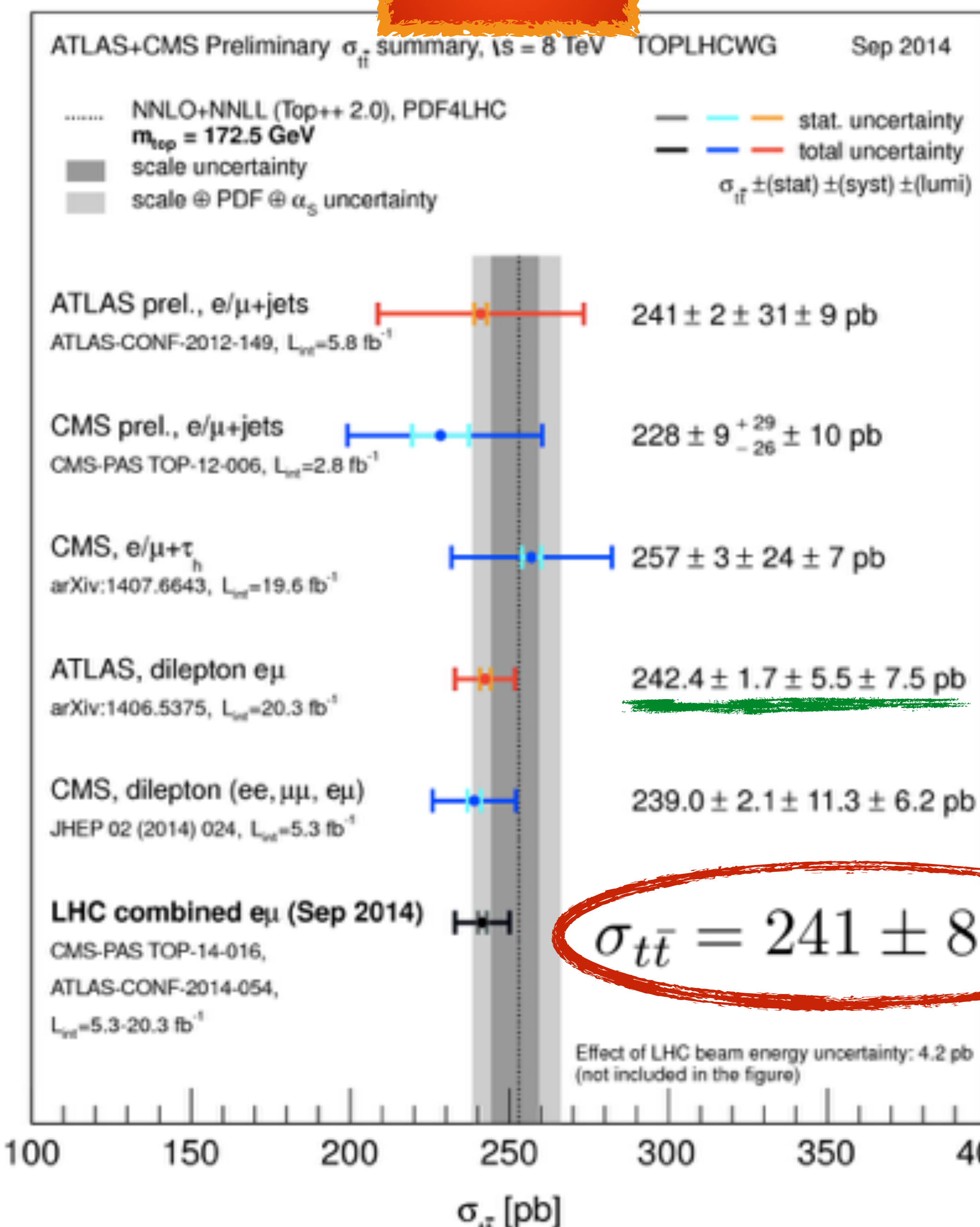
m_{top} = 172.5 GeV

7 TeV



Theory NNLO+NNLL $\sigma_{t\bar{t}} = 177.3 \pm 11.4\ pb$

8 TeV



$\sigma_{t\bar{t}} = 241 \pm 8.5 pb$

Theory NNLO+NNLL $\sigma_{t\bar{t}} = 253 \pm 15\ pb$

- ☑ Dilepton golden channel;
- ☑ Experimental unc. even smaller than theory ones;
- ☑ Dominated by systematic uncertainties;

Combination improves sensitivity on the most precise result (ATLAS dilepton) by about **10%**.

Oct. '14

$t\bar{t}$ Differential Cross Section - *l+jets*

Sept. '14

$\sigma_{t\bar{t}}$ -> *qqlvbb*

Resolved

$$\frac{d\sigma_{t\bar{t}}}{dX}$$

X = $p_T(t)$, $p_T(tt)$, m(tt), *y*(tt)

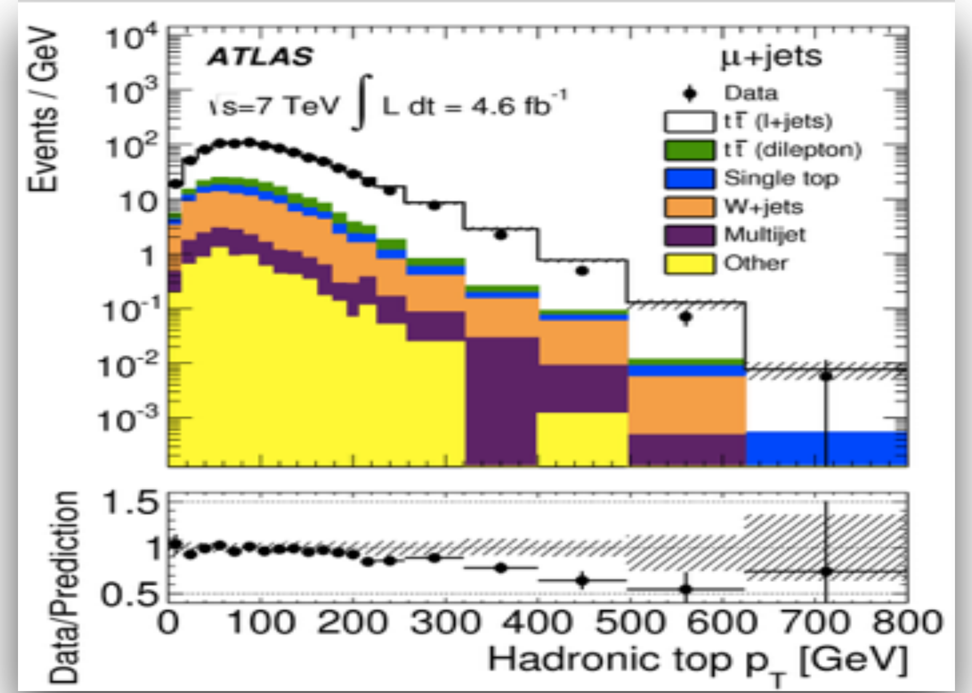
$\sqrt{s}$ = 7 TeV

$\int L\cdot dt$ ≃ **4.6 fb^{-1}** (2011)

Phys. Rev. D 90, 072004

- **Selection:** one isolated *e*/*μ*, symmetric missing E_T and m_T^W, ≥ **4 anti-k_T R=0.4 jets**, ≥ 1 b-tag;

- **Analysis strategy:** $\sigma_{t\bar{t}}$ as a function of different kinematic variables. **Unfold** N-N_{bkg} kinematic distributions (**SVD** method, bin-per-bin correction for migrations and eff.), scale for luminosity and BR;



Boosted

First!

$$\frac{d\sigma_{t\bar{t}}}{dp_T(top)}$$

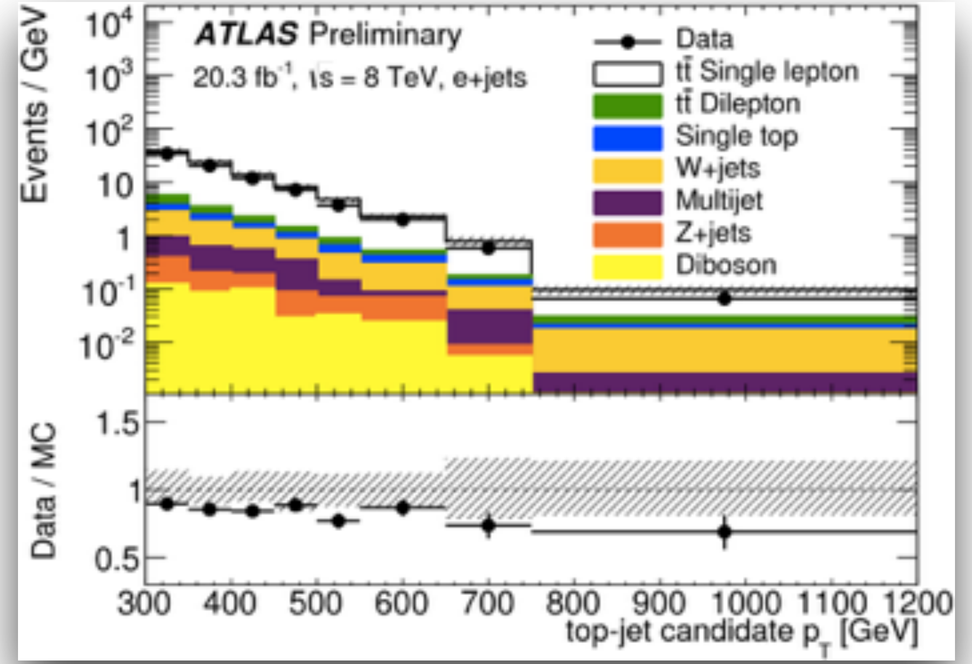
$\sqrt{s}$ = 8 TeV

$\int L\cdot dt$ ≃ **20.3 fb^{-1}** (2012)

ATLAS-CONF-2014-057

- **Selection:** one isolated *e*/*μ*, symmetric missing E_T and m_T^W, **≥ 1 high-p_T anti-k_T R=1.0** jet, ≥ 1 b-tag (had. or lep. side);

- **Analysis strategy: unfold** (**SVD** method) N-N_{bkg} to fiducial phase-space (**particle level**) and extended at full phase-space (parton level), scale for luminosity and BR;

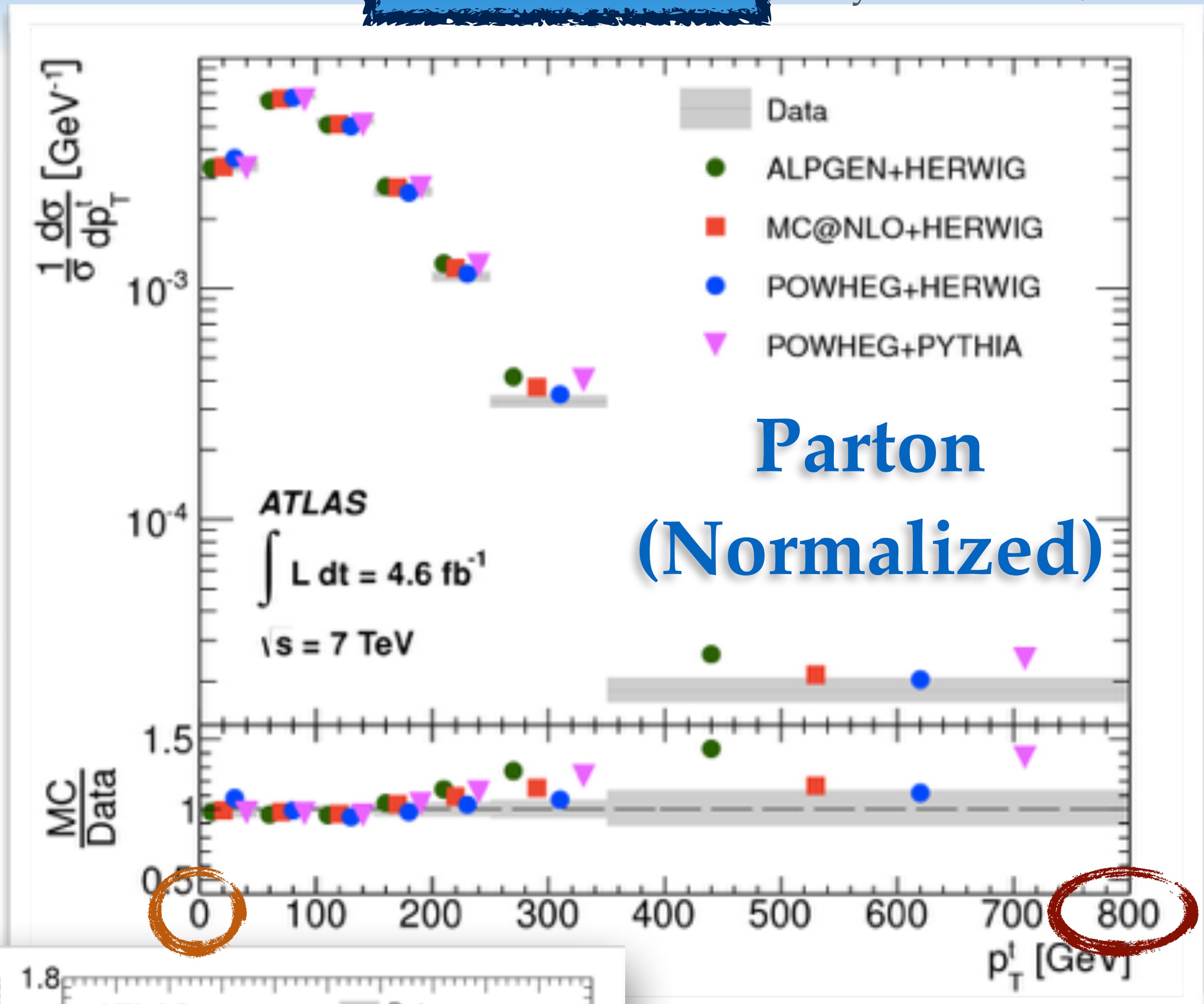


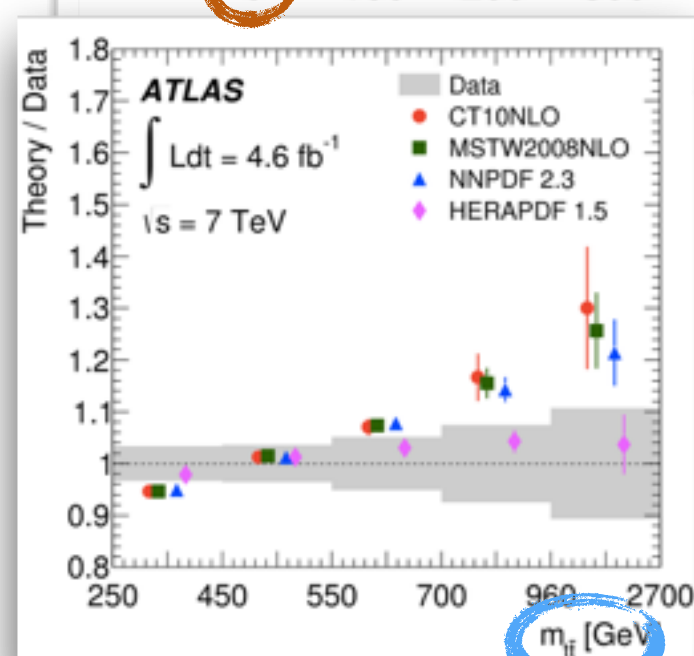
W+jets: main bkg

$t\bar{t}$ Differential Cross Section - *l+jets*

Resolved

Phys. Rev. D 90, 072004

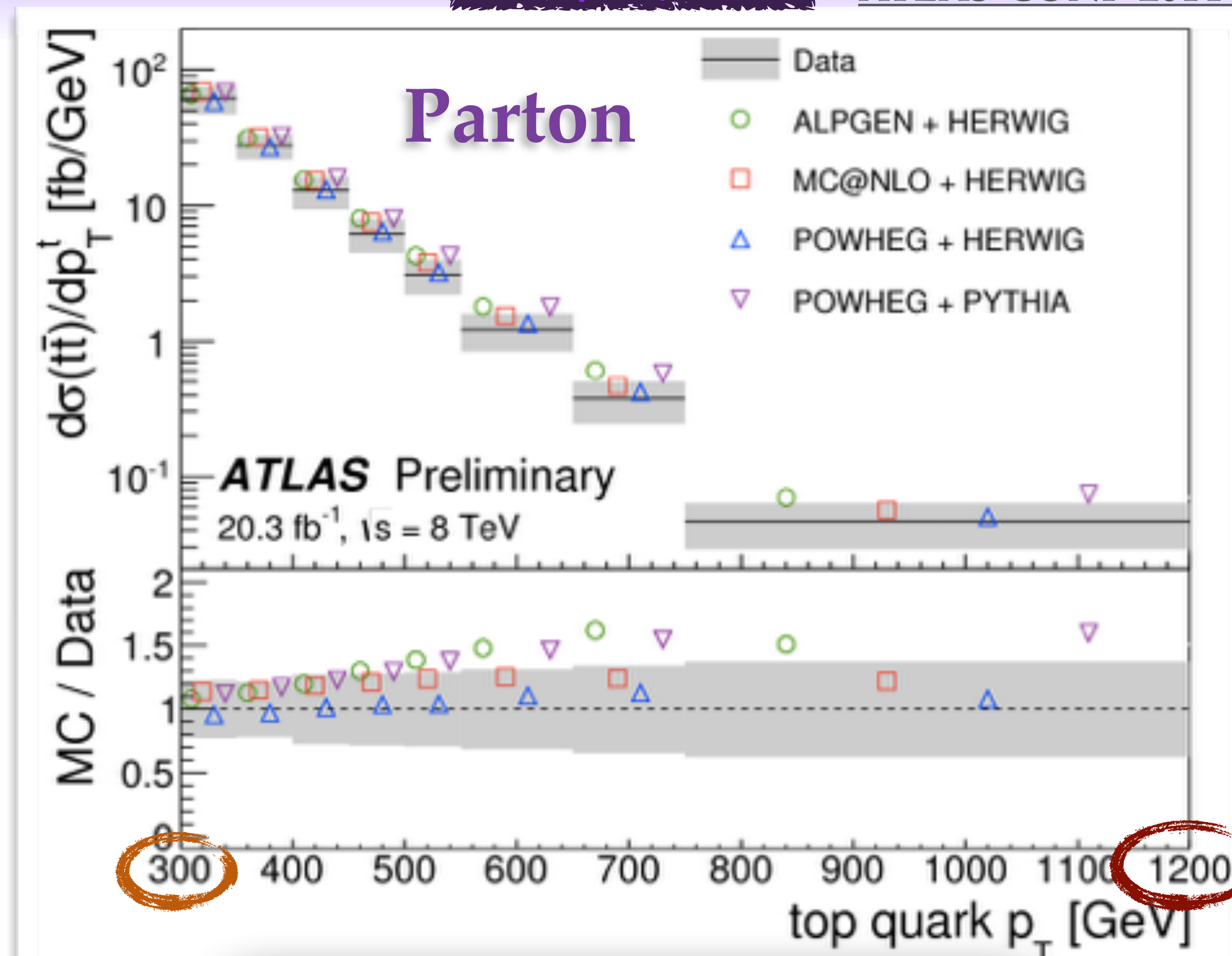


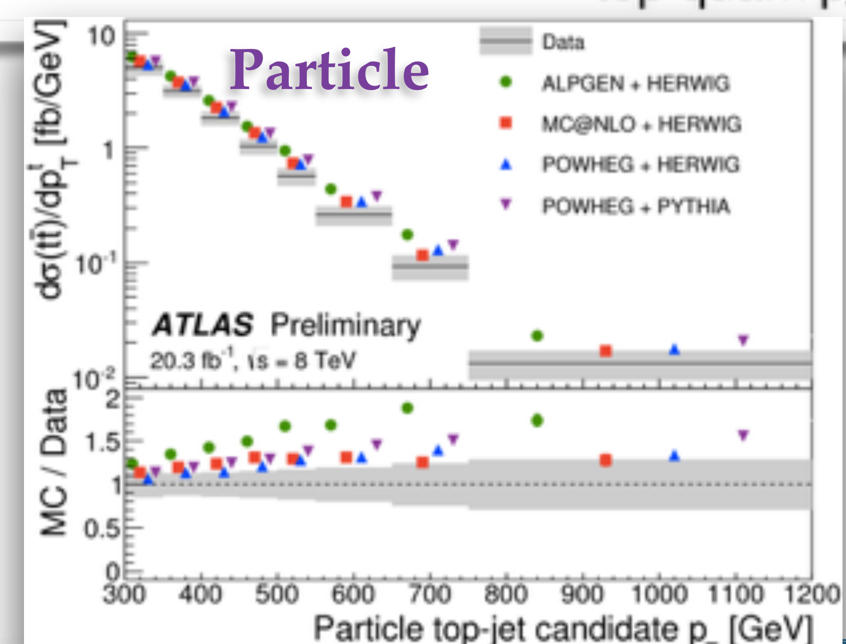


- ✦ Tested with different PDFs;
- ✦ **Included in PDF** parametrisation (HERApdf, CT10).

Boosted

ATLAS-CONF-2014-057





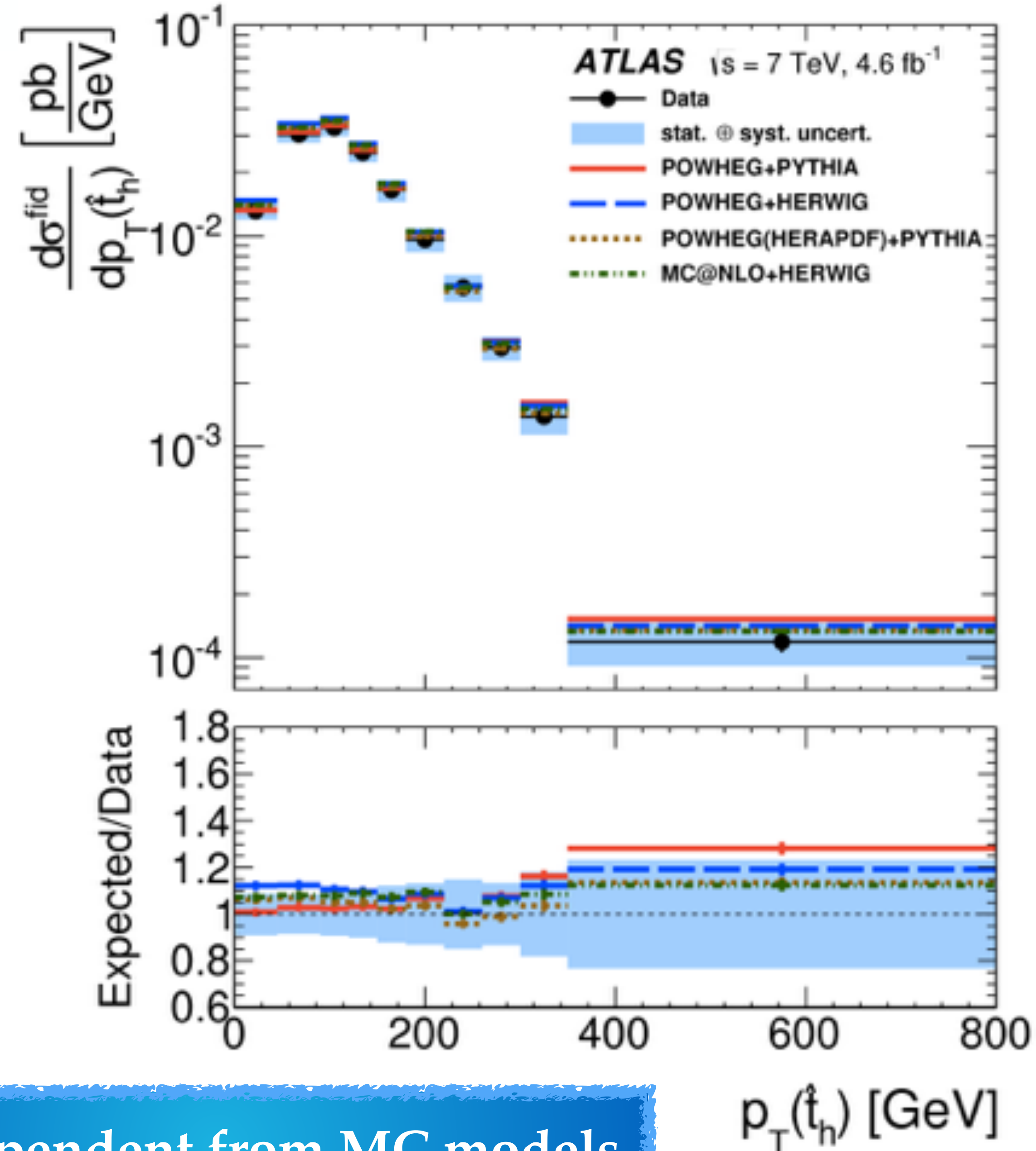
Pseudo-top differential Cross Section

$\sigma_{t\bar{t}}$ -> $qql\nu bb$ $\sqrt{s} = 7$ TeV $\int L \cdot dt \simeq$ **4.6 fb-1** (2011)

arXiv:1502.05923

Same strategy as in the **resolved diff. cross section** at 7 TeV;

Measured in a **fiducial phase-space** (particle level) as a function of hadronic and leptonic ***pseudo-top*** p_T and ***pseudo-$t\bar{t}$*** p_T, m, y (**particle-objects**).



Particle object definition

- **Leptons:** adding the photons around a cone of R=0.1;
- **E_T^{miss}**: sum of all neutrinos;
- **Jets:** include all stable particles but μ, e and γ not from hadrons;
- **b-tag:** ghost-matching.

Less dependent from MC models

$t\bar{t}$ + *jets* differential Cross Section

Feb. '15

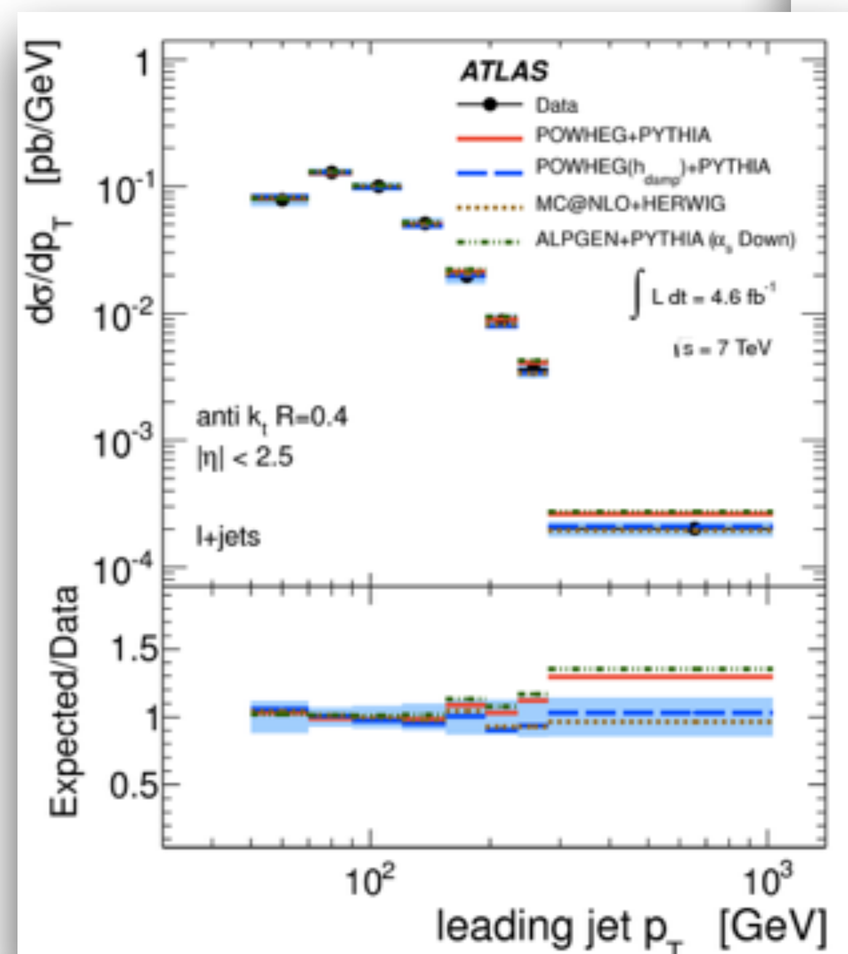
$\sigma_{t\bar{t}+\gamma}$ -> *qqlvbb* $\sqrt{s} = 7$ TeV $\int L \cdot dt \simeq$ **4.6 fb^{-1}** (2011)

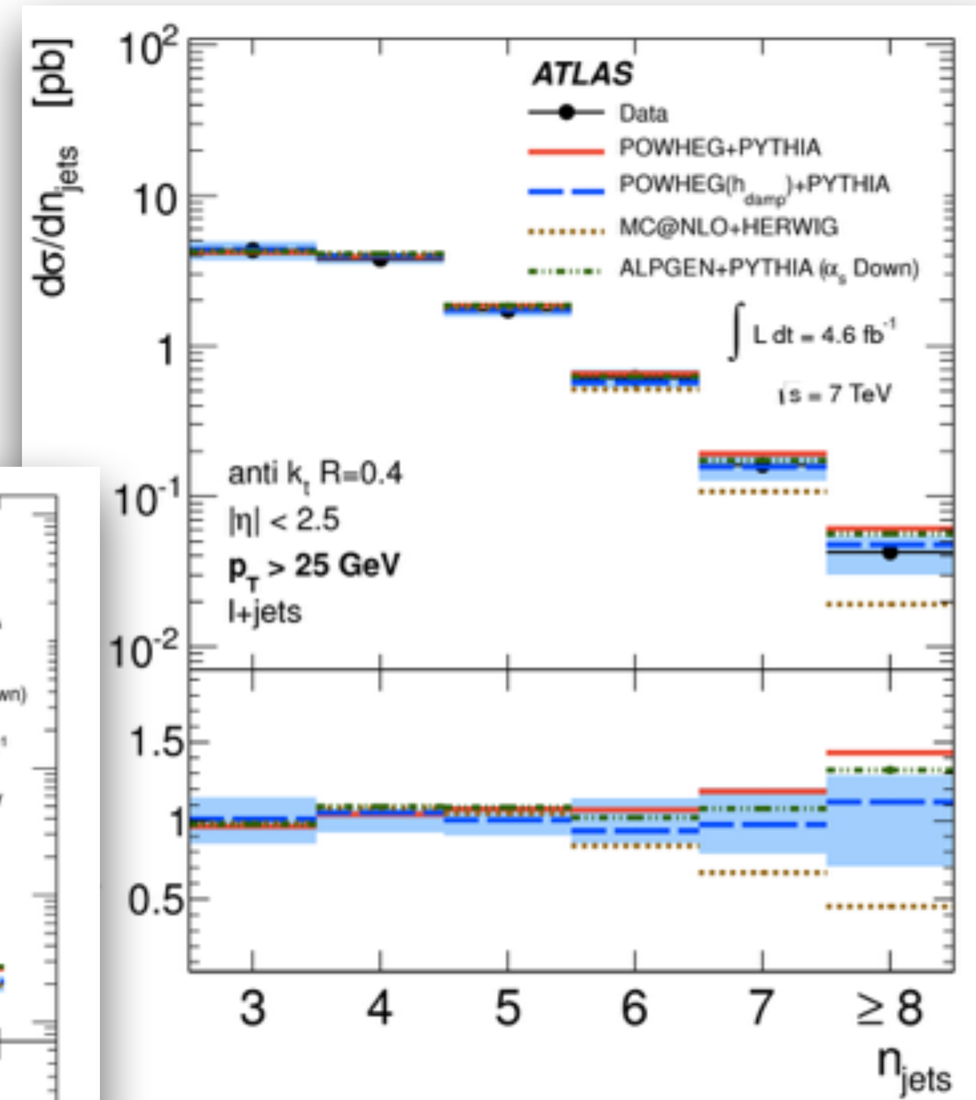
JHEP01(2015)020
arXiv:1407.0891

Selection: 1 lepton (e/μ), ≥ 3 jets, ≥ 1 b-tag, E_T^{miss};

Cross Section strategy: measured in a fiducial phase-space as a function of ***n jets*** (3 to 8) and of the p_T of the ***5 leading p_T* jets**;

- **Jet multiplicity** (>4) correlated to *n hard jets* in QCD bremsstrahlung;
- As a **function of jets p_T** is particularly *sensitive to higher order QCD effects* in modelling MC;
- As function of **leading p_T** jet complement other cross section measurements.





POWHEG with reduced hard radiation gives the **best overall agreement.**

$t\bar{t} + \gamma$ Inclusive Cross Section

$\sigma_{t\bar{t}+\gamma}$ -> $qql\nu bb\gamma$ $\sqrt{s} = 7$ TeV $\int L \cdot dt \simeq$ **4.6 fb^{-1}** (2011)

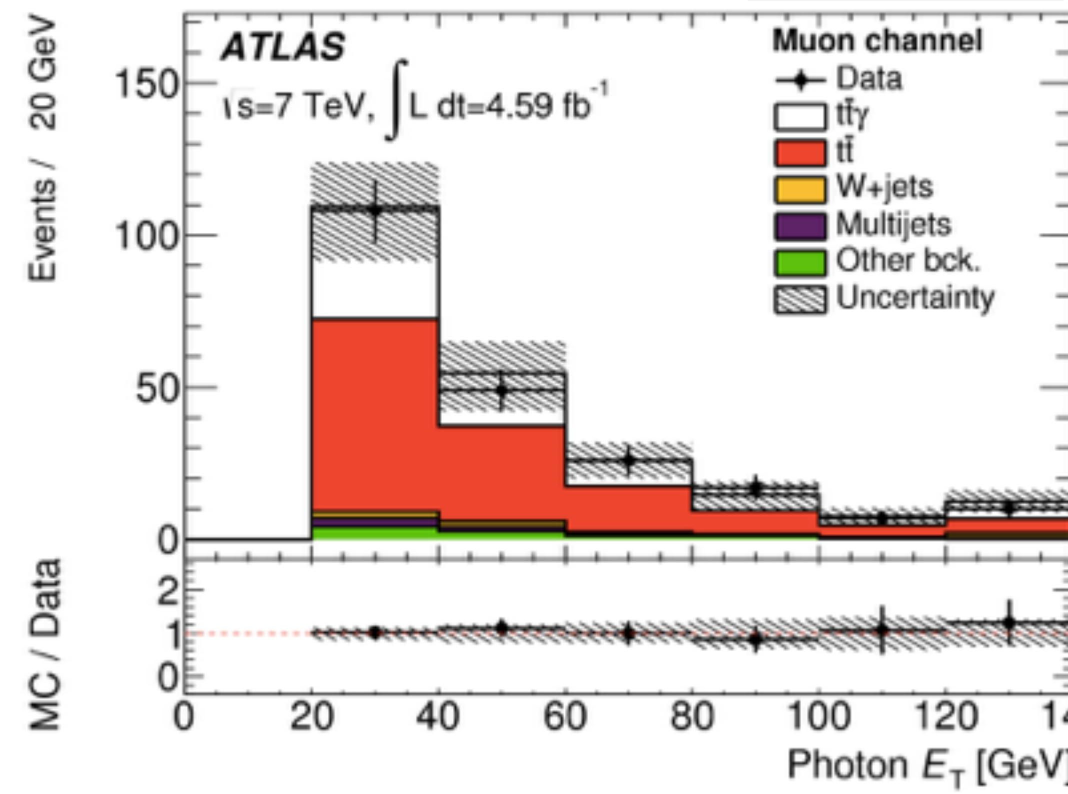
Selection: 1 lepton (e/μ), ≥ 4 jets, ≥ 1 b-tag, E_T^{miss}, 1 γ;

Bkg: prompt-photons(various DD methods), $t\bar{t}$, W +jets(MC+DD normalization), fake leptons;

Cross Section strategy: via binned template maximum likelihood fit, measurement in a **fiducial phase-space**;

Systematics: Systematics: Jet modelling(16.6%), photon modelling(8.8%), b-tag(8.2%).

arXiv:1502.00586



$$\sigma_{t\bar{t}+\gamma} \times BR = 63 \; {+19}/{-16} \text{ fb}$$

$$\sigma_{t\bar{t}+\gamma}\,(theory) = 48 \pm 10 \text{ fb}$$

Prediction from MadGraph and WHIZARD.

Observed with a significance of **5.3σ** away from the *no-signal hypothesis*.

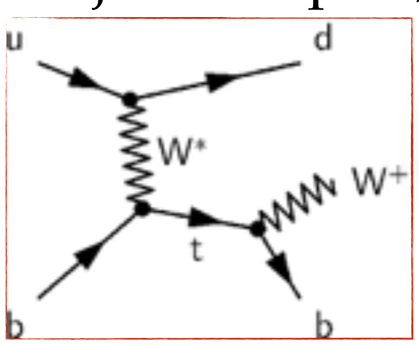
Single Top

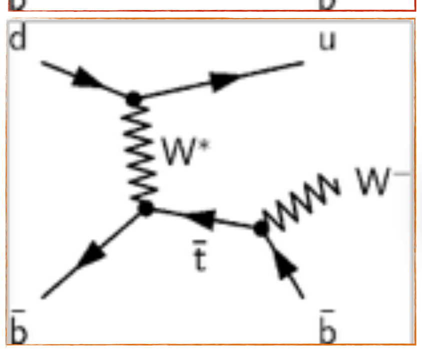
Single top Cross Section - t-channel

σ_t & $\sigma_{\bar{t}}$ -> $ql\nu b$ $\sqrt{s} = 7$ TeV $\int L \cdot dt \simeq$ **4.6 fb^{-1}** (2011)

Phys. Rev. D. 90, 112006 (2014)

- **Selection:** one isolated e/μ, E_T^{miss}, 2 or 3 jets, ≥ 1 b-tag;
- **Bkg:** W+jets (**main**), fake lepton, $t\bar{t}$ and diboson+jets (MC);
- **Analysis strategy:** binned maximum-likelihood fit to the **Neural Network(NN)** discriminant distributions in 2 and 3 jets samples;

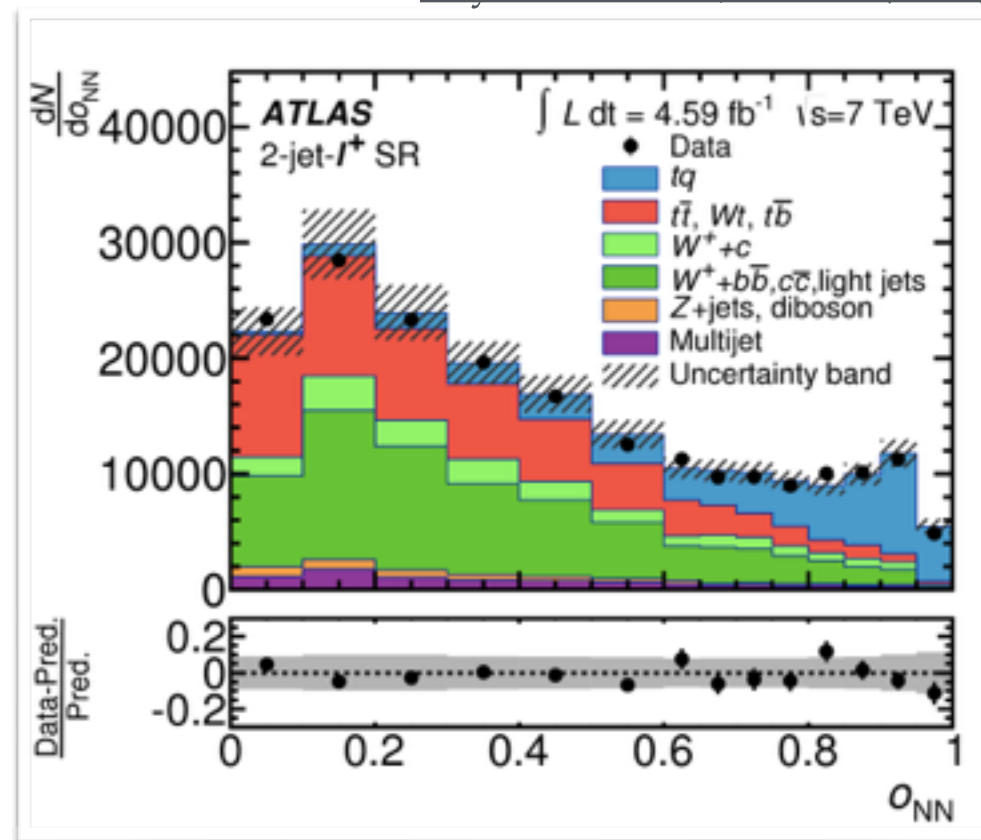




$$\sigma(tq) = 46 \pm 1\,(\text{stat.}) \pm 6\,(\text{syst.})\,\text{pb}$$

Extend PDFs sensitivity to u-quark and d-quark

$$\sigma(\bar{t}q) = 23 \pm 1\,(\text{stat.}) \pm 3\,(\text{syst.})\,\text{pb}$$



Relative t-ch top xSec.

$$R_t = 2.04 \pm 0.13\,(\text{stat.}) \pm 0.12\,(\text{syst.})$$

$R_t = \sigma(t)/\sigma(\bar{t})$ $dR_t/R_t = 8\%$

Decrease the syst. uncertainty (stat. dominates).
Still constraining PDFs.

Total t-ch top xSec. $d\sigma/\sigma = 12\%$

$$\sigma_t(tq + \bar{t}q) = 68 \pm 2\,(\text{stat.}) \pm 8\,(\text{syst.})\,\text{pb}$$

Systematics:
JES(~9-16%), IFSR (~7%), b-tag.

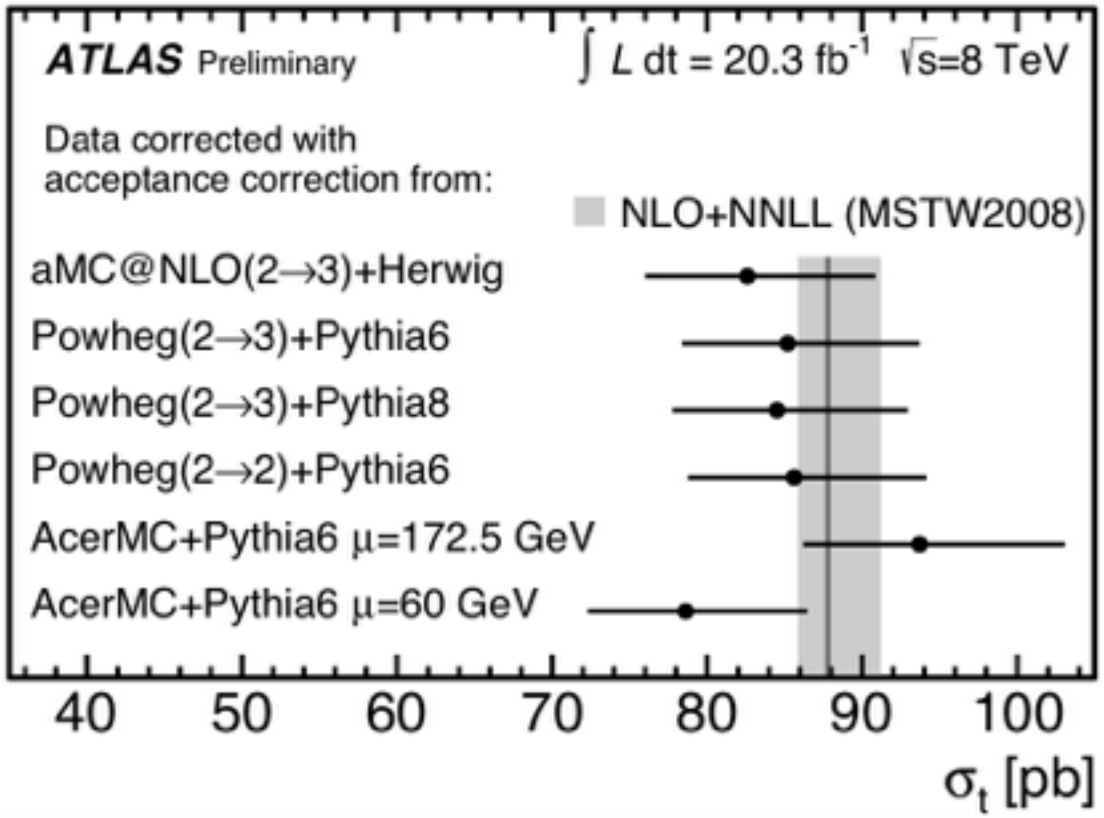
Single top Cross Section - t-channel

t-channel single top cross section

$\sqrt{s} = 8$ TeV $\int L \cdot dt \simeq$ **20.3 fb^{-1}** (2012)

ATLAS-CONF-2014-007

Same strategy as in 7TeV but cross section first measured in a **fiducial phase-space** then **extrapolated** to full phase-space.



First!

Fiducial phase-space

$\sigma_t = 3.4 \pm 0.5\ pb$

$\frac{\Delta\sigma_{t\text{-}ch}}{\sigma_{t\text{-}ch}} = 14\%$

Full phase-space

aMC@NLO extrapolation

$\sigma_t = 82.6 \pm 11.8\ pb$

$\sigma_{theory} = 78.8 \pm 2.8\ pb$

$\frac{\Delta\sigma_{t\text{-}ch}}{\sigma_{t\text{-}ch}} = 17\%$

- **POWHEG** and **aMC@NLO** in agreement (1.7% difference)
- **AcerMC** and **aMC@NLO** quite different (9%)

Single top Cross Section - s-channel

s-channel single top cross section

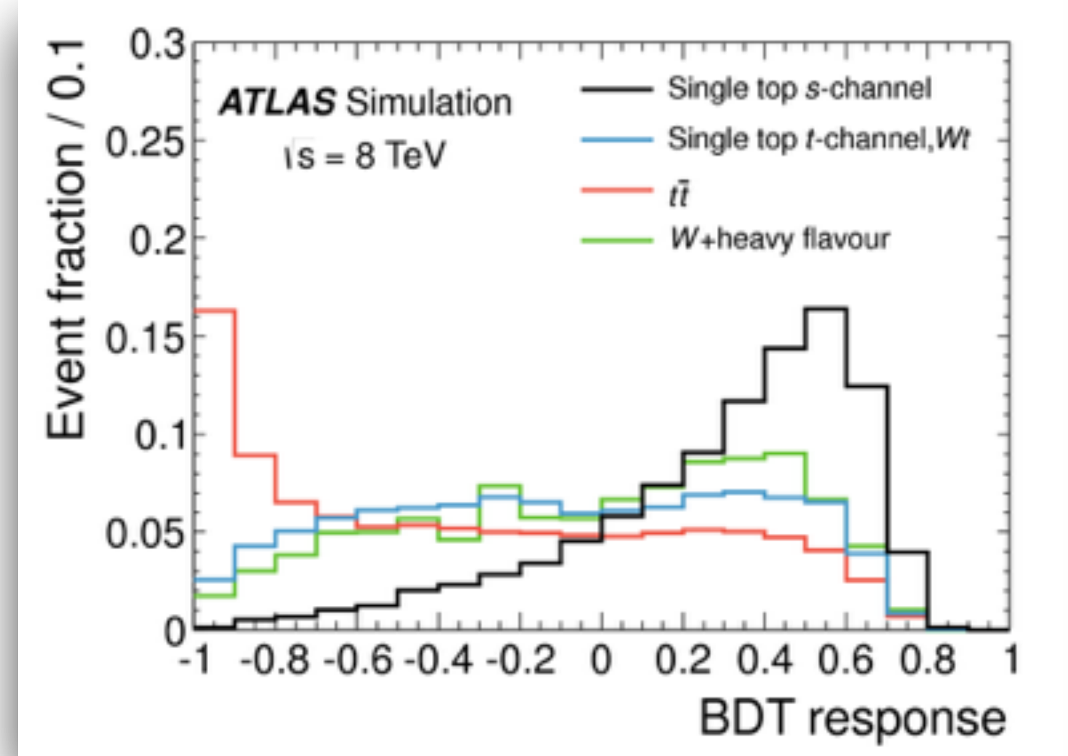
$\sqrt{s} = 8$ TeV $\int L \cdot dt \simeq$ **20.3 fb^{-1}** (2012)

Phys.Lett. B740 (2015) 118

Selection: one lepton (e/μ), large E_T^{miss}, 2 b-tag jets;

Bkg: $t\bar{t}$ (**main**), single top t-ch, W+jets;

Analysis strategy: bkg discrimination via Boosted Decision Tree (**BDT**) and *signal extraction* using binned maximum likelihood fit.



$\sigma_s = 5.0 \pm 4.3\ pb$

$\sigma_{theory} = 5.61 \pm 0.22\ pb$

$$\frac{\Delta\sigma_{s\text{-}ch}}{\sigma_{s\text{-}ch}} = 86\%$$

Upper limit fixed at 14.6 pb with CL = 95%.

Main Uncertainties: E_T^{miss} scale (54%), JES(39%), stat. (35%);

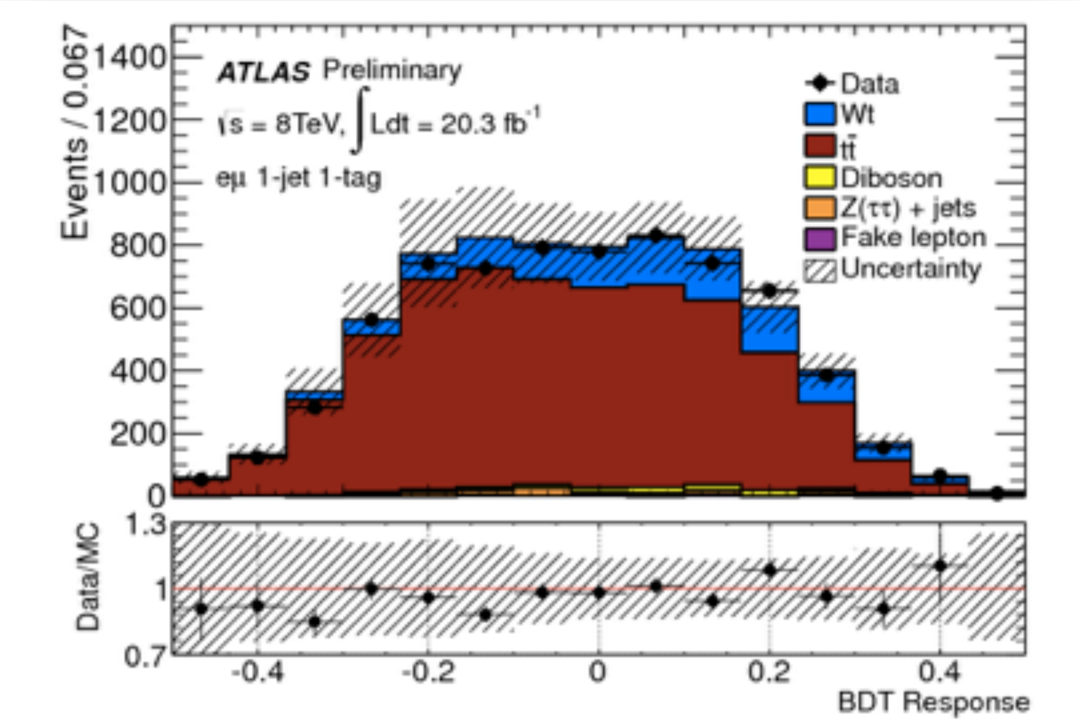
Sept. '14

Single top Cross Section - Wt-channel

σ_{Wt} ->$l\nu l\nu b$ $\sqrt{s}$ = 8 TeV ∫L·dt ≃ **20.3 fb^{-1}** (2012)

ATLAS-CONF-2013-100

- **Selection:** **one *e* + one *μ*** (isolated and opposite sign), missing E_T, 1 or 2 jets, ≥ 1 b-tag;
- **Bkg:** Z+jets, $t\bar{t}$, diboson (MC), fake lepton (data driven via matrix method);
- **Analysis strategy:** **Boosted Decision Tree (BDT)** for signal/bkg selection; cross section from a maximum likelihood fit of both 1 and 2 jets samples;



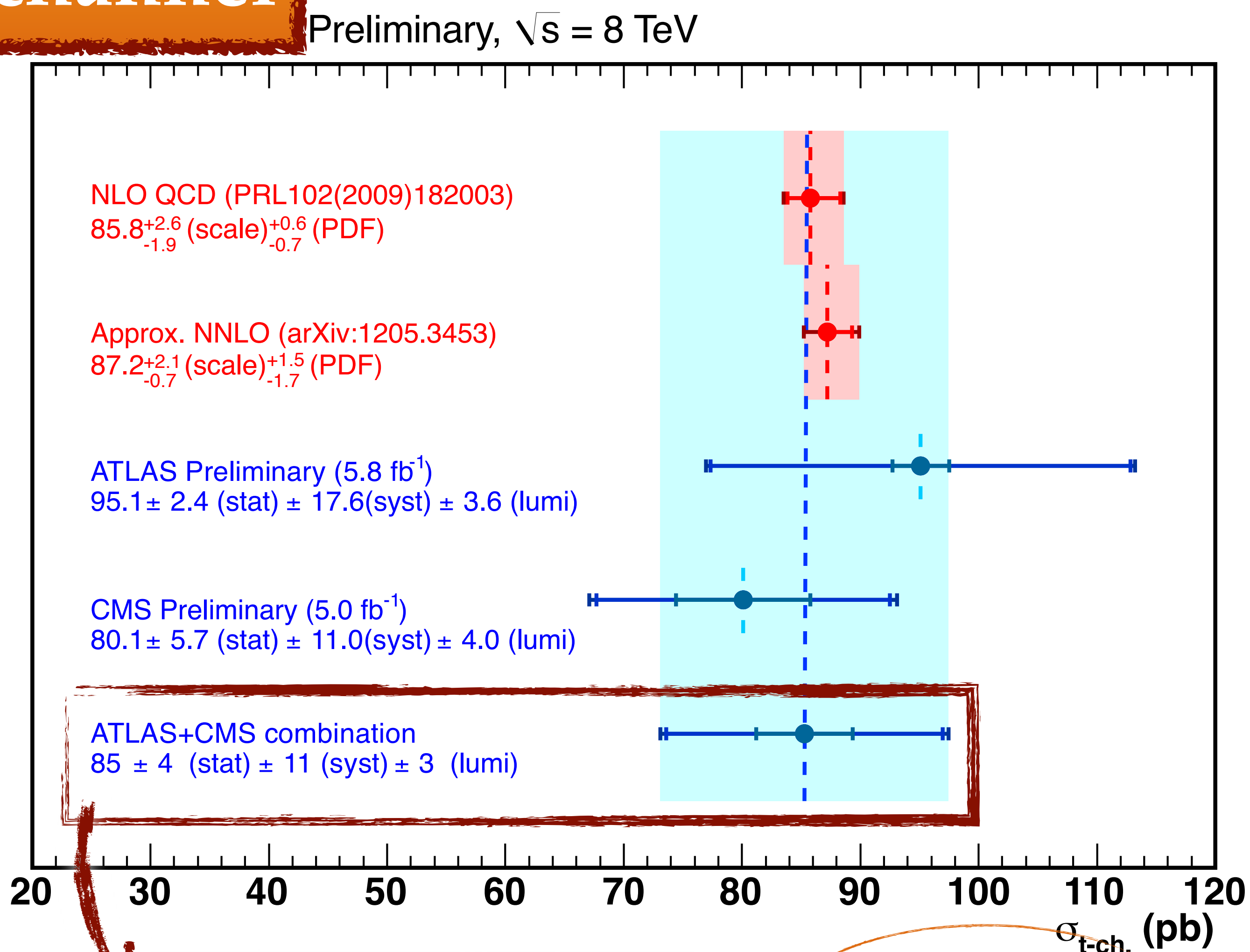
$$\sigma(pp \to Wt + X) = 27.2 \pm 2.8\,(\text{stat}) \pm 5.4\,(\text{syst})\ \text{pb}$$

$$\sigma_{Wt}^{\text{theory}} = 22.4 \pm 1.5\ \text{pb}$$

Systematics evaluated from pseudo-experiments;
Breakdown obtained by subtraction one sys. contribution at a time;
Main impact from JES(10%) and b-tag(8.4%).

Single top Cross Section - Combination

t-channel



$$\sigma_{\text{t-ch.}} = 85 \pm 12\,\text{pb}$$

$$\frac{\Delta\sigma_{t\text{-}ch}}{\sigma_{t\text{-}ch}} = 14\%$$

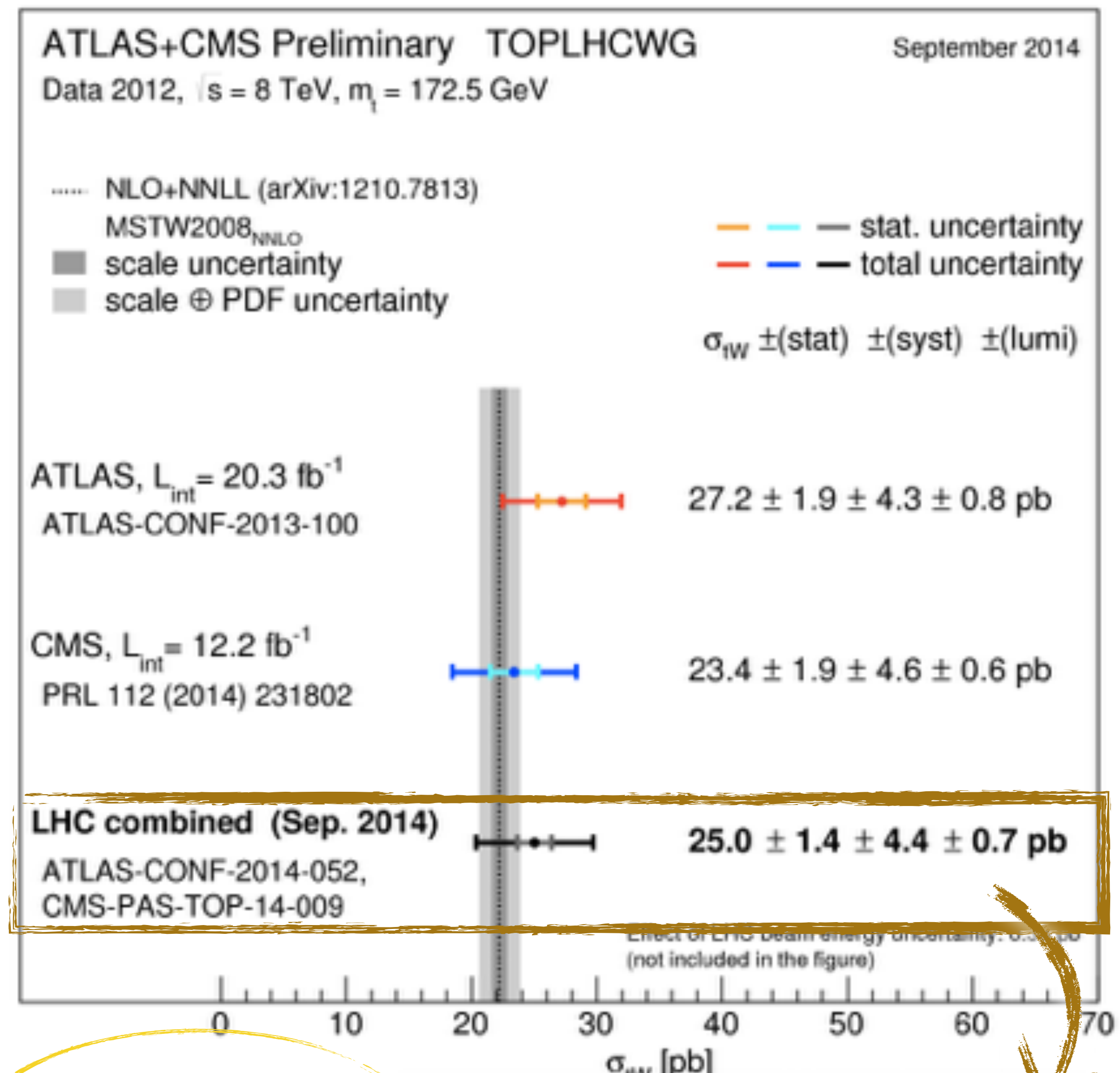
$$\sigma^{\text{th}}_{\text{t-ch.}} = 87.2^{+2.1}_{-0.7}\,(\text{scale})^{+1.5}_{-1.7}\,(\text{PDF})$$

NNLO theory

Limited luminosity, waiting for updated combination.

ATLAS-CONF-2013-098

Wt-channel



$$\frac{\Delta\sigma_{Wt}}{\sigma_{Wt}} = 19\%$$

$$\sigma_{tW} = 25.0 \pm 4.7\ \text{pb}$$

$$\sigma^{\text{th.}}_{tW} = 22.2 \pm 0.6 \pm 1.4\ \text{pb}$$

NLO + NNLL

ATLAS-CONF-2014-052

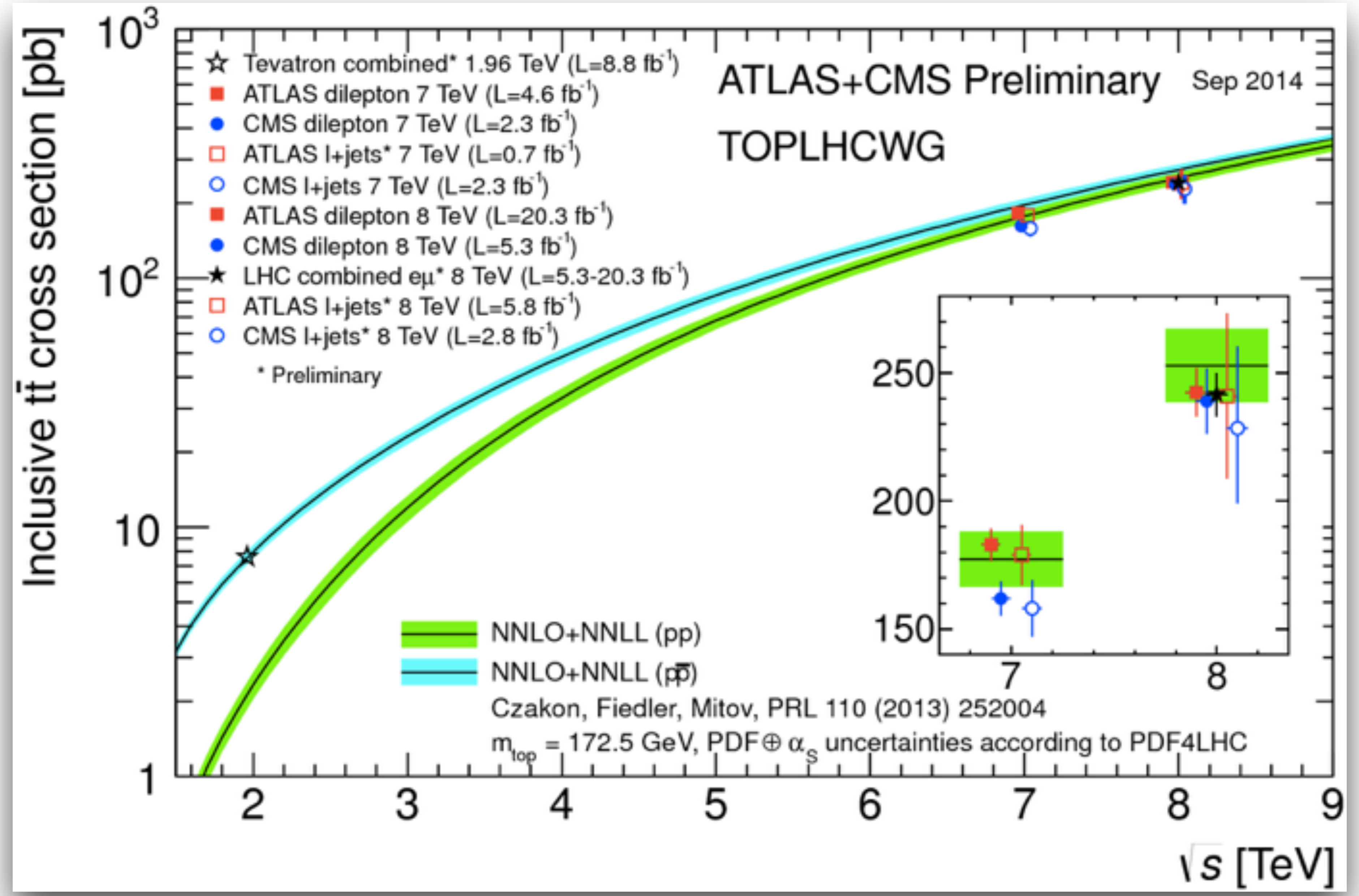
Conclusion

- First measurements in **fiducial phase-spaces** and in **boosted regime**;
  - **Boosted** approach will be fundamental in runII allowing to study the top quark up to the **TeV scale** thanks to greater statistics and higher energy;
- **Inclusive measurements** in agreement with the theoretical predictions;
  - Inclusive $t\bar{t}$ cross section (ATLAS deletion & ATLAS+CMS combination) surpassed the precision of theoretical predictions;
- **Differential measurements** disagree at high p_T values;
  - now sensitive enough to tune the MCs;
- Some ***runI* analysis** still ongoing: stay tuned;
- TopLHC Working Group is in the process of discussing **harmonising** ATLAS and CMS top analyses systematics and MC generators in order to **decrease combination uncertainties.**


Thanks
for the attention

Back-up

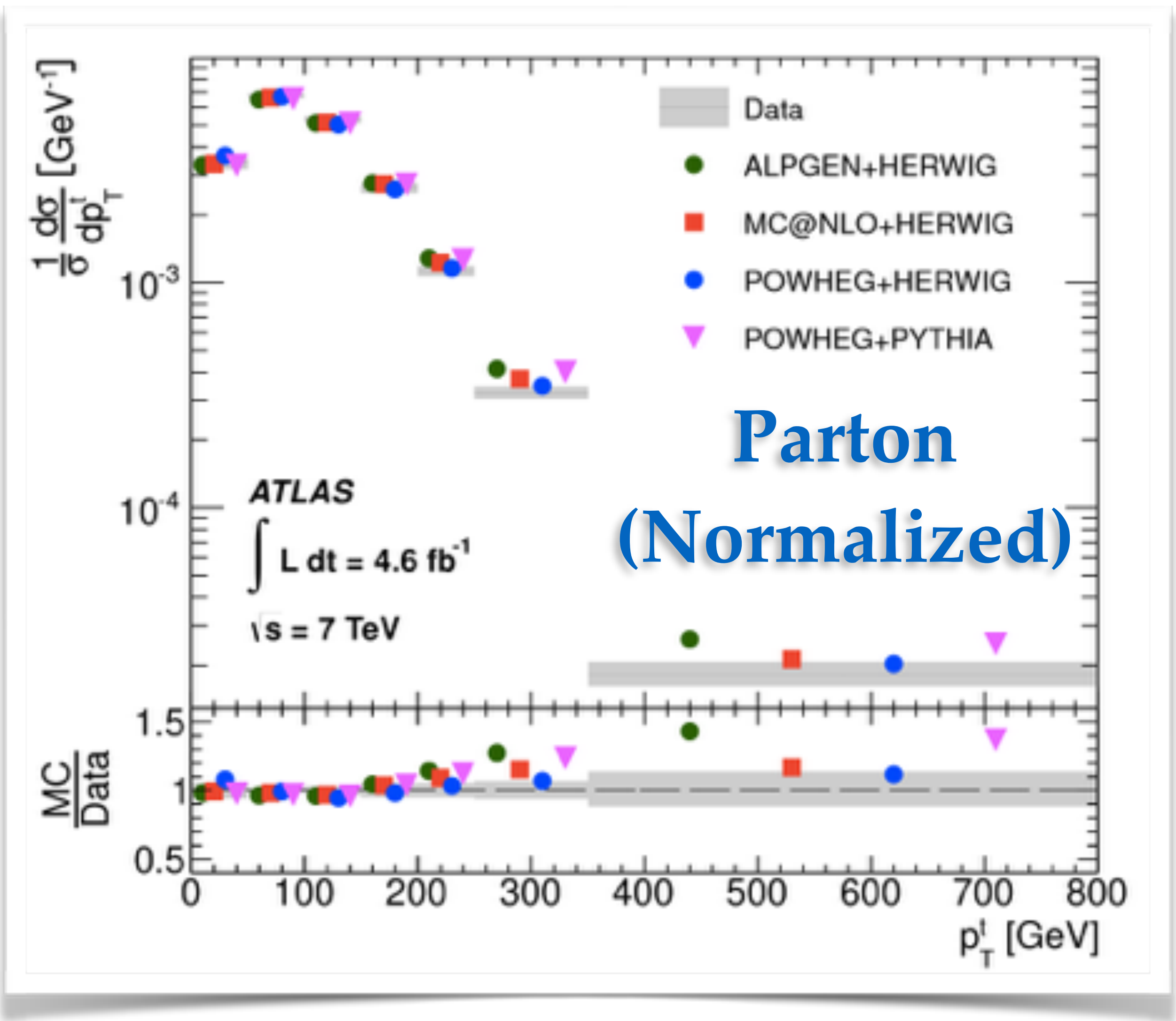
Top Pairs Cross Section

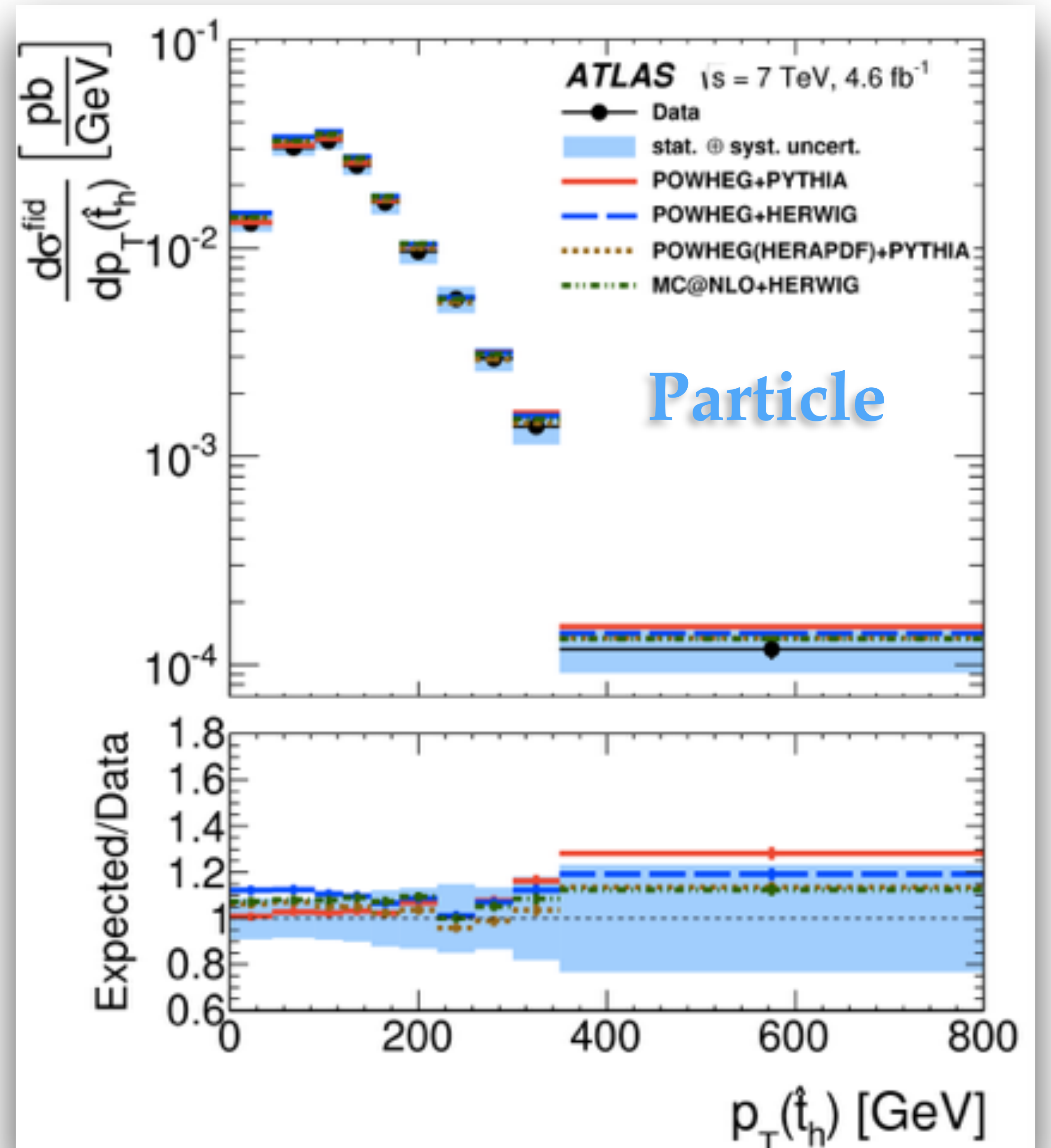


- All measurements in agreement with theory;
- The dilepton channel has smaller uncertainty with respect to the l+jets one;

$t\bar{t}$ Differential Cross Section - *l+jets*

Resolved





$t\bar{t}$ Differential Cross Section - *l+jets*

Boosted