Inclusive and differential top anti-top cross-section measurements with the ATLAS and CMS experiments

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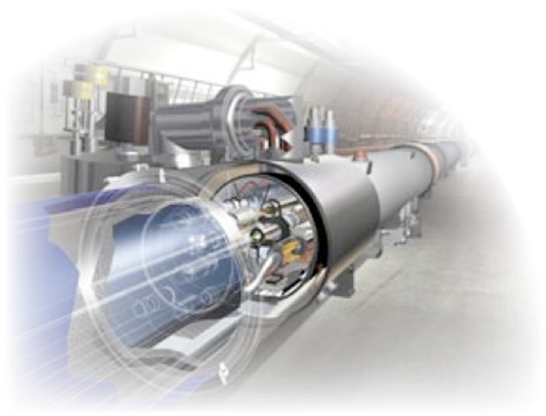
on behalf of the ATLAS and CMS Collaborations



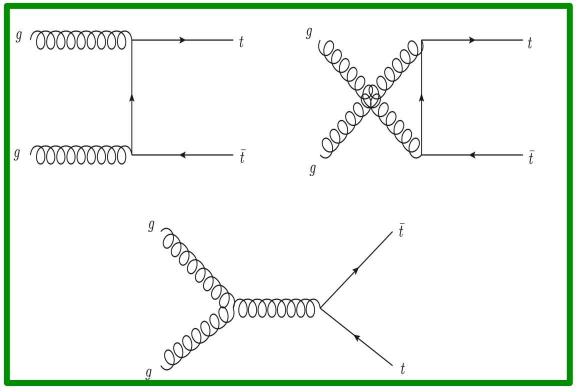
Top Quark Pair Production at the LHC : Theoretical references

- **ATLAS and CMS adopted full NNLO calculations including the resummation of NNLL soft gluon terms, obtained with Top++v2.0.**
- **M. Czakon, A. Mitov, Comput. Phys. Commun. 185, 2930 (2014). arXiv:1112.5675.**
- **Theoretical predictions of $\sigma_{t\bar{t}}$ assuming m_{top} = 172.5 GeV.**

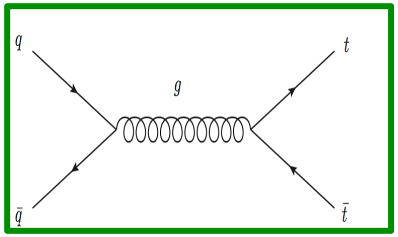
$$\sigma_{t\bar{t}}^{theor}(\sqrt{s}=7\,\text{TeV}) = 177.3\,^{+10.1}_{+10.8}\,\text{pb} \quad \delta\sigma_{t\bar{t}}^{theor} = ^{+5.7\%}_{+6.1\%}$$

$$\sigma_{t\bar{t}}^{theor}(\sqrt{s}=8\,\text{TeV}) = 252.9\,^{+13.3}_{+14.5}\,\text{pb} \quad \delta\sigma_{t\bar{t}}^{theor} = ^{+5.3\%}_{+5.7\%}$$

$$\sigma_{t\bar{t}}^{theor}(\sqrt{s}=13\,\text{TeV}) = 831.8\,^{+40.3}_{+45.6}\,\text{pb} \quad \delta\sigma_{t\bar{t}}^{theor} = ^{+4.8\%}_{+5.5\%}$$

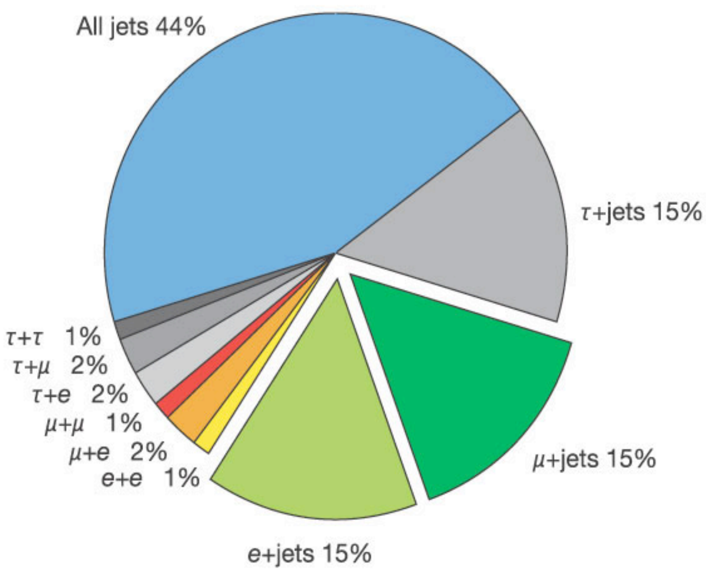


> 80%



< 20%

~100% BR(t→W⁺b)

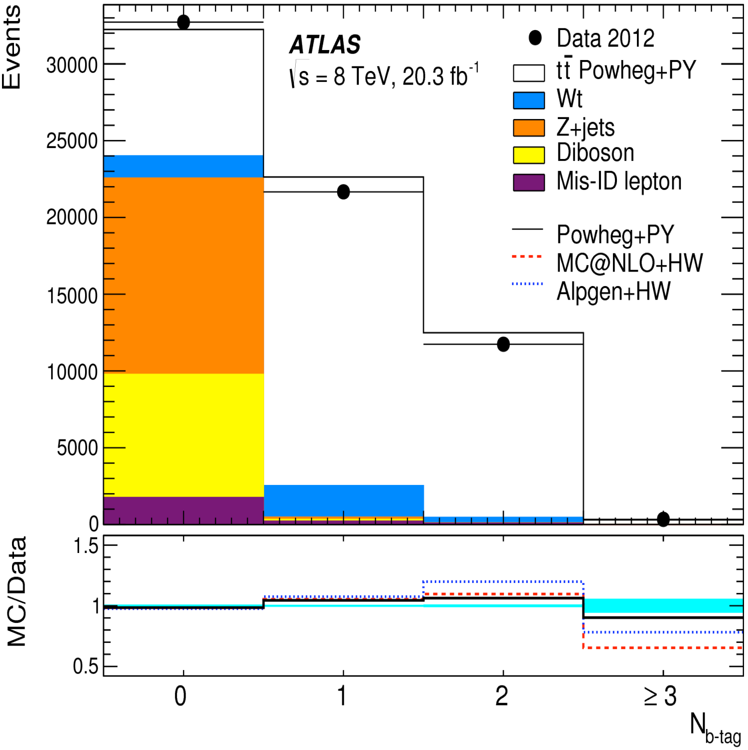


Motivations:

- Test perturbative QCD theoretical calculations of $\sigma_{t\bar{t}}$.
- $t\bar{t}$ is the primary background in many searches.

L_{int} =4.6 fb^{-1} @ 7 TeV L_{int} =20.3 fb^{-1} @ 8 TeV

- **Dilepton eμ pre-selection:**
  - One high Pt isolated electron and one high Pt isolated muon, oppositely charged.
- **Backgrounds:**
  - With two real prompt leptons from W & Z decays: MC driven.
  - With one real and one misidentified lepton: SS data & Scale Factors (OS/SS) MC driven.
- **Analysis technique:**
  - Simultaneous determination of $\sigma_{t\bar{t}}$ and ε_b .
  - ε_b efficiency to reconstruct and b-tag a jet from a top quark decay.



$$N_1 = L \cdot \sigma_{t\bar{t}} \cdot \varepsilon_{e\mu} \cdot 2\varepsilon_b (1 - C_b \cdot \varepsilon_b) + N_1^{bkg}$$

$$N_2 = L \cdot \sigma_{t\bar{t}} \cdot \varepsilon_{e\mu} \cdot C_b \cdot \varepsilon_b^2 + N_2^{bkg}$$

$$C_b = 4 N_{e\mu}^{t\bar{t}} N_2^{t\bar{t}} / (N_1^{t\bar{t}} + 2 N_2^{t\bar{t}})^2$$

$$\sigma_{t\bar{t}} = 182.9 \pm 3.1(\text{stat.}) \pm 4.2(\text{syst.}) \pm 3.6(\text{lumi.}) \pm 3.3(\text{beam.})\text{pb.}$$
$$\delta\sigma_{t\bar{t}}^{\text{exp}} = 7.2\text{pb } (3.9\%)$$

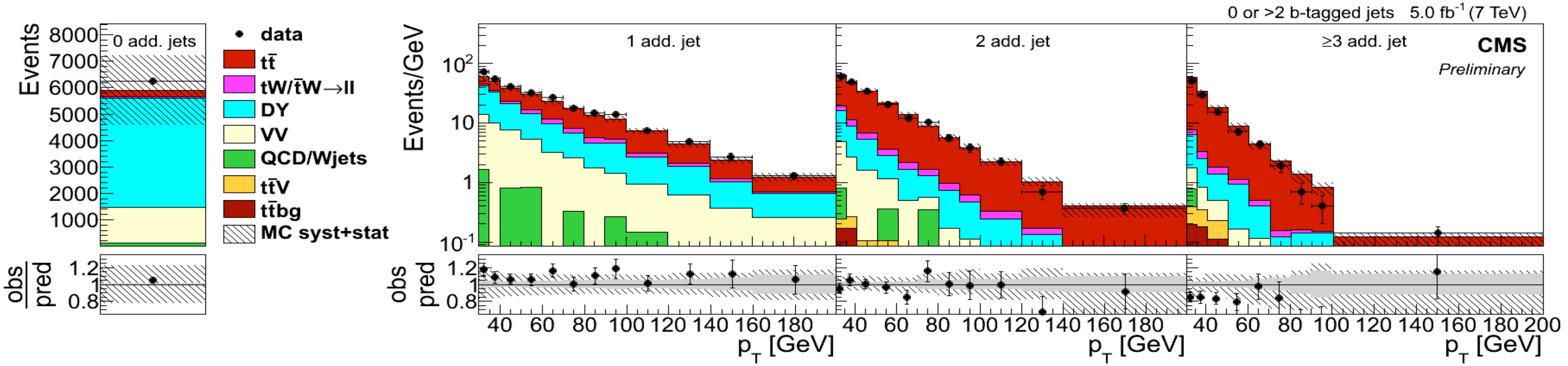
$$\sigma_{t\bar{t}} = 242.4 \pm 1.7(\text{stat.}) \pm 5.5(\text{syst.}) \pm 7.5(\text{lumi.}) \pm 4.2(\text{beam.})\text{pb.}$$
$$\delta\sigma_{t\bar{t}}^{\text{exp}} = 10.4\text{pb } (4.2\%)$$

- At 7 TeV, biggest uncertainty from systematic:
  - Main systematics: $t\bar{t}$ modeling and QCD scale: 1.5%.
- At 8 TeV, biggest uncertainty from L_{int}
  - Main systematics: $t\bar{t}$ modeling and QCD scale: 1.3%.

Inclusive $\sigma_{t\bar{t}}$ $\sqrt{s}$= 7/8 TeV eμ-Channel CMS PAS TOP-13-004 NEW

L_{int} =5.0 fb^{-1} @ 7 TeV L_{int} =19.7 fb^{-1} @ 8 TeV

- Dilepton eμ pre-selection:
  - Two opposite charged leptons, $M_{e\mu} > 20$ GeV
- Backgrounds:
  - tW,VV: MC driven; DY: MC normalization, Scale Factors data/MC from Z peak in data.
  - Non-W/Z lepton: SS data & Scale Factors (OS/SS) MC driven.
- Analysis technique:
  - Simultaneous 7 & 8 TeV template fit: N_{evts}, p_T^{lead}, $p_T^{sublead}$, p_T^{lowest} for N_b =1,2 and 0 or ≥3
  - Template fit to lowest light jet p_T allows the extraction of ε_b and constraining of syst. unc.



$$\sigma_{t\bar{t}} = \sigma_{t\bar{t}}^{vis} / A_{e\mu}$$

$$N_1 = L \cdot \sigma_{t\bar{t}} \cdot \varepsilon_{e\mu} \cdot 2\varepsilon_b (1 - C_b \cdot \varepsilon_b) + N_1^{bkg}$$

$$N_2 = L \cdot \sigma_{t\bar{t}} \cdot \varepsilon_{e\mu} \cdot C_b \cdot \varepsilon_b^2 + N_2^{bkg}$$

$$N_{0,3+} = L \cdot \sigma_{t\bar{t}} \cdot \varepsilon_{e\mu} \cdot (1 - 2 \cdot \varepsilon_b (1 - C_b \cdot \varepsilon_b) - C_b \cdot \varepsilon_b^2) + N_{0,3+}^{bkg}$$

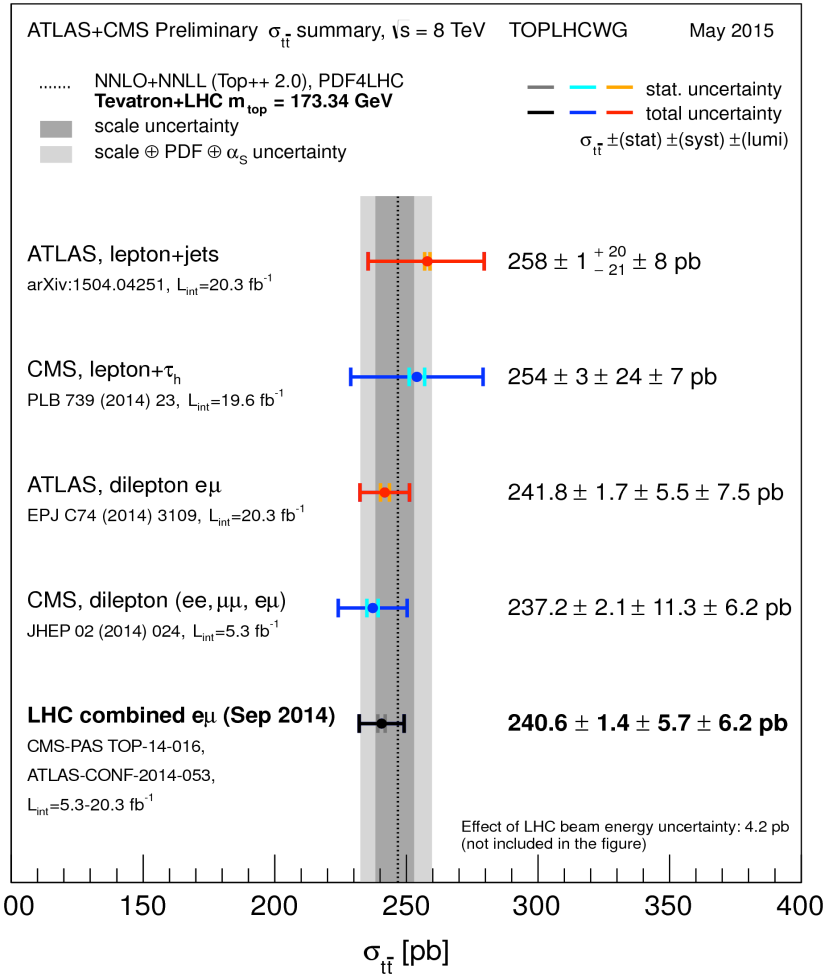
$$\sigma_{t\bar{t}} = 174.5 \pm 2.1(\text{stat.})^{+4.5}_{-4.0}(\text{syst.}) \pm 3.8(\text{lumi.})\text{pb.}$$

$$\delta\sigma_{t\bar{t}}^{exp} = ^{6.3}_{5.9} \text{ pb} = ^{+3.6\%}_{-3.4\%}$$

$$\sigma_{t\bar{t}} = 245.6 \pm 1.3(\text{stat.})^{+6.6}_{-5.5}(\text{syst.}) \pm 6.5(\text{lumi.}) \text{ pb.}$$

$$\delta\sigma_{t\bar{t}}^{exp} = ^{9.4}_{8.6} \text{ pb} = ^{+3.8\%}_{-3.5\%}$$

- Main systematics: lepton ID/Isolation 1.4%/ 1.5%



	$\sigma_{t\bar{t}}$ (pb)	$\delta\sigma_{t\bar{t}}$ (pb)	$\delta\sigma_{t\bar{t}}$ (%)
Eur.Phys.J.C (2014) 74:3109 (eμ+jets Channel) ATLAS L_{int} =20.3 fb^{-1}	242.4	± 9.5	± 3.9%
JHEP 02 (2014) 024 (eμ+jets Channel) CMS L_{int} = 2.4 fb^{-1}	239.0	± 13.7	± 5.7%
ATLAS-CONF-2014-054 CMS PAS TOP-14-016	241.5	± 8.5	± 3.5%

$$\sigma^{theor}_{t\bar{t}}(\sqrt{s} = 8\,\text{TeV}, m_{top}=172.5\,\text{GeV}) = 252.89\,^{+13.30}_{+14.52}\,\text{pb}$$

$$\delta\sigma^{theor}_{t\bar{t}} = ^{+5.26\%}_{+5.74\%}$$

NNLO+NNLL: Top++v2.0 M. Czakon, A. Mitov, Comput. Phys. Commun. 185, 2930 (2014). arXiv:1112.5675

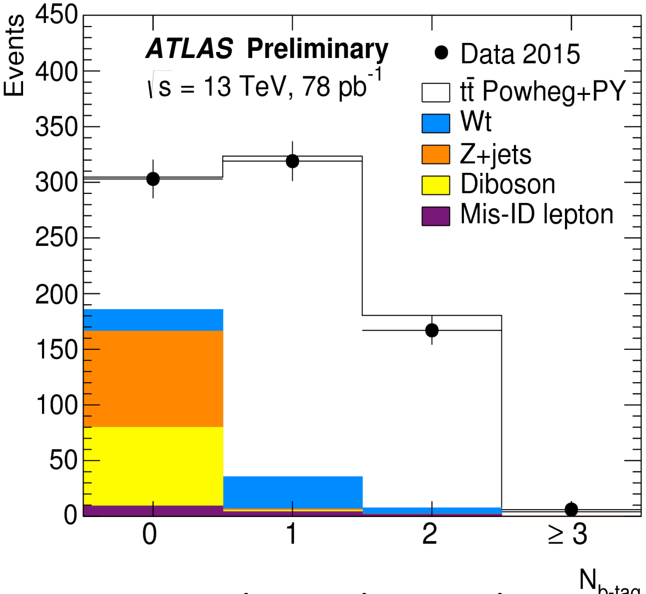
- Dominant systematics: Signal Model (1.6%) & JES (1.3%).
- Additional uncertainty due to LHC beam energy calibration: 4.2 pb (1.7%).
- Dependence with the top mass around reference value:

$$1/\sigma_{t\bar{t}} * d\sigma_{t\bar{t}}/dm_{top} = -0.46\%/\text{GeV}$$

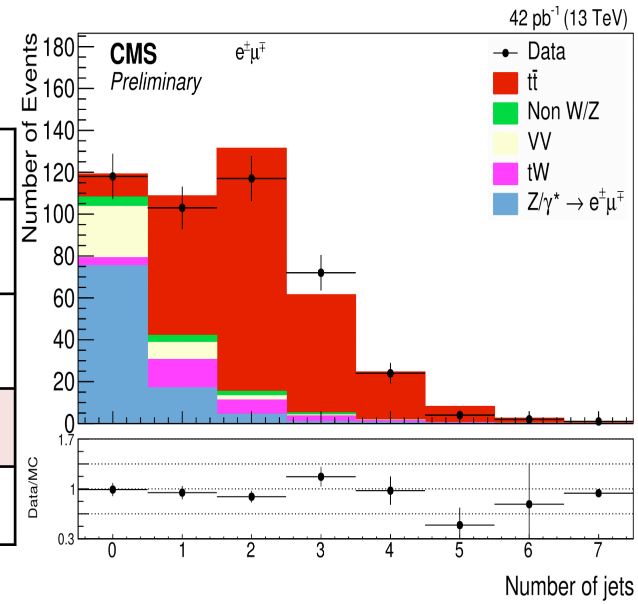
Inclusive $\sigma_{t\bar{t}}$ $\sqrt{s}$= 13 TeV eμ-Channel

ATLAS-CONF-2015-033 — L_{int} =78 pb^{-1}

CMS PAS TOP-15-003 — L_{int} = 42 pb^{-1}



	ATLAS		CMS
	N_1	N_2	
	=1 b-jet	=2 b-jets	≥ 2 jets
Data	319	167	220
Bkgr	37.3±5.5	8.5±3.5	28.1 ±5.7



- Very similar analysis technique as in Eur.Phys.J.C. (2014) 74:3109 .
- Integrated luminosity error dominates, main systematics form ttbar modeling (hadronization) (4.5%) and electron ID (4%).

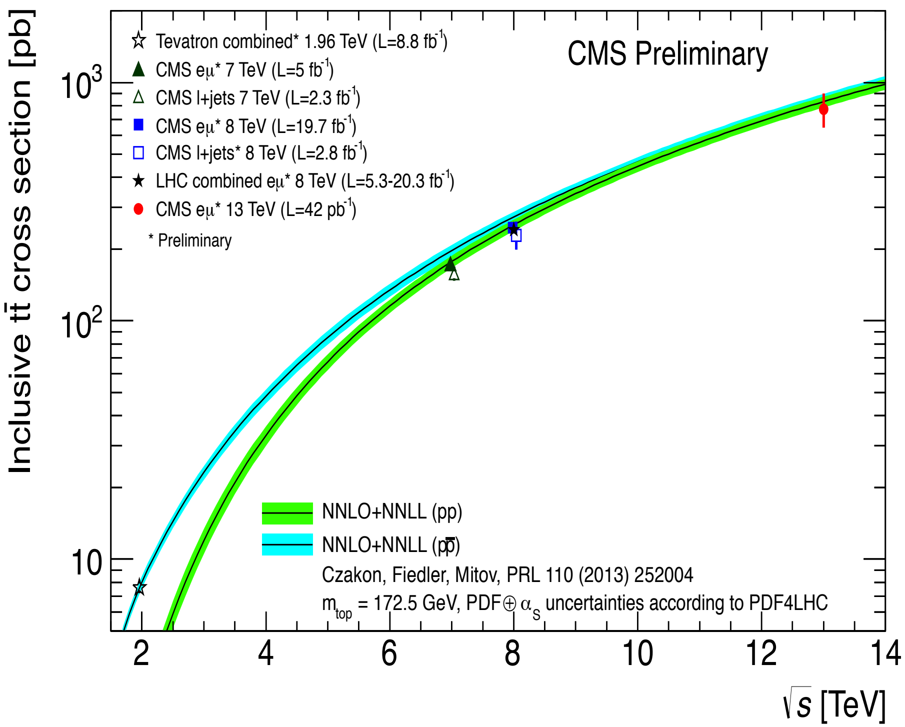
$$\sigma_{t\bar{t}} = 825 \pm 49(\text{stat.}) \pm 60(\text{syst.}) \pm 83(\text{lumi.})\ \text{pb.}$$
$$\delta\sigma_{t\bar{t}}^{exp} = 114\text{pb}\ (14\%)$$

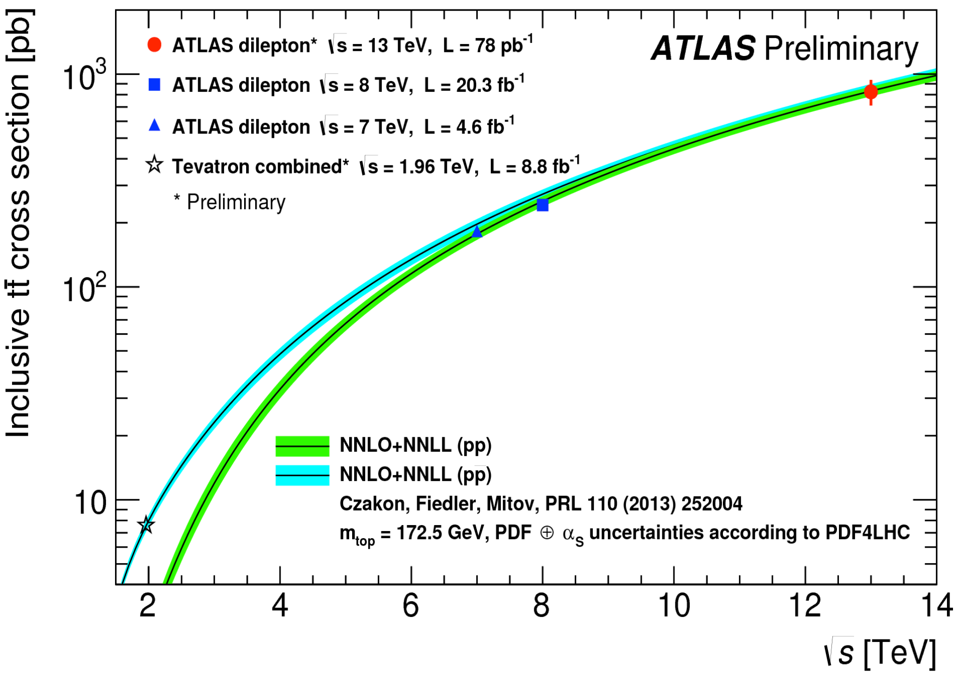
- eμ selection: $M_{e\mu}$ >20, ≥2 high E_T jets.
- Integrated luminosity error dominates, main systematics form trigger (5.5%) and lepton efficiencies (4.3%).

$$\sigma_{t\bar{t}} = 772 \pm 60(\text{stat.}) \pm 62(\text{syst.}) \pm 93(\text{lumi.})\ \text{pb.}$$
$$\delta\sigma_{t\bar{t}}^{exp} = 127\text{pb}\ (17\%)$$

$$\sigma_{t\bar{t}}^{theor}(\sqrt{s} = 13\,\text{TeV}, m_{top} = 172.5\,\text{GeV}) = 831.8\,^{+40.3}_{+45.6}\ \text{pb} \quad \delta\sigma_{t\bar{t}}^{theor} = ^{+4.8\%}_{+5.5\%}$$

$\sigma_{t\bar{t}}$ evolution with √s



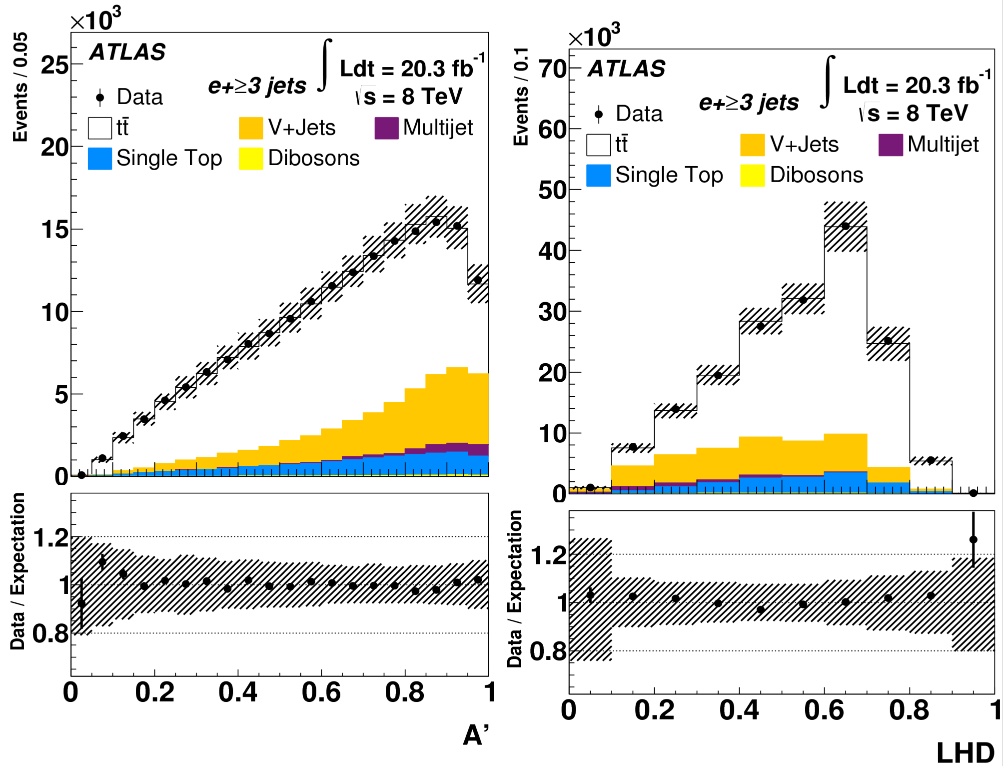


- New measurements at 7,8 and 13 TeV by CMS and ATLAS :
  - Evolution with √s in good agreement with the SM.

L_{int} =20.3 fb^{-1} @ 8 TeV

- **Motivations:**
  - Independent sample to dilepton measurement: different background conditions, different systematics.
  - Important to probe new physics that modify the top branching fractions, e.g. charged Higgs: tt→$H^{\pm}$(→$\tau\upsilon_{\tau}$)bWb.

- **Lepton+jets selection:** (S/B≈2.3)
  - 1 lepton, ≥1 btag, ≥3 jets
  - $m_T(W)$, E_t^{miss} > 30 geV
- **Backgrounds:**
  - Real leptons (MC driven).
  - Fake leptons (data driven, Matrix Method).
- **Analysis technique:**
  - V+jets normalization from data fit.
  - Projective lilelihood discriminant LHD(η_l,A') exploits kinematic properties of ttbar signal and W+jets.
  - Binned likelihood fit of LHD(η_l,A') templates of signal and each background to data → Ntt→



$$\sigma_{t\bar{t}} = \frac{N_{t\bar{t}}}{L \times BR \times \varepsilon_{sig}}$$

$$\sigma_{t\bar{t}} = 260 \pm 1(\text{stat.})^{+22}_{-23}(\text{syst.}) \pm 8(\text{lumi.}) \pm 4(\text{beam.})\ \text{pb.}$$

$$\delta\sigma^{exp}_{t\bar{t}} = 25\text{pb}\ (10\%)$$

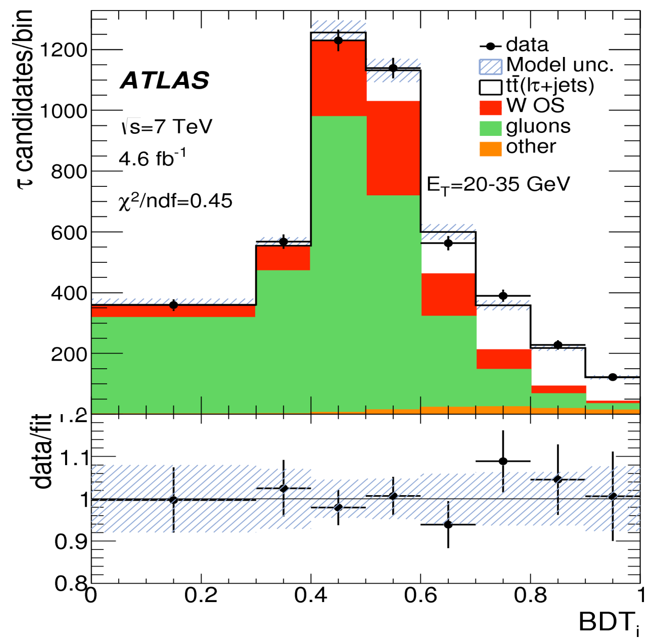
$$\sigma^{theor}_{t\bar{t}}(\sqrt{s} = 8\,\text{TeV}) = 252.9\ ^{+13.3}_{+14.5}\ \text{pb} \quad \delta\sigma^{theor}_{t\bar{t}} = ^{+5.3\%}_{+5.7\%}$$

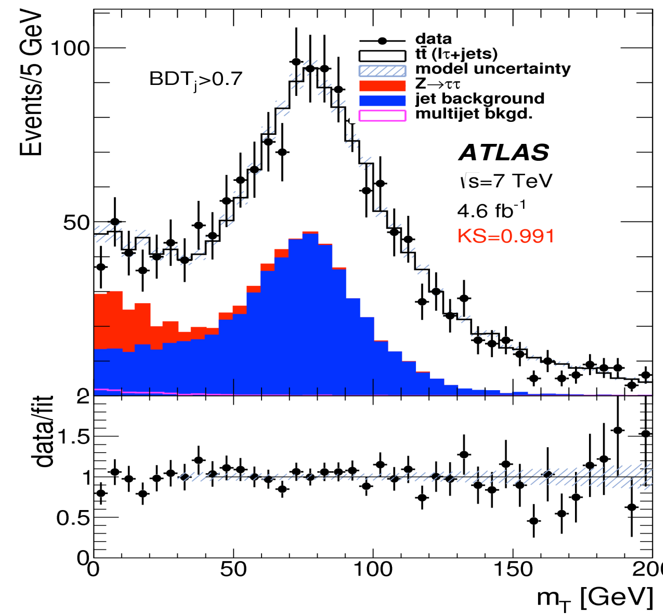
- **Main systematic:**
  - ttbar modelling: PDF, MC generator, PS and fragmentation, IFSR, PDF: +7.5% -7.5%.

- **Motivation:**
  - Sensitive to new Physics:
    - Charged Higgs: tt→H±(→τυ_τ)bWb.
    - SUSY: stop pair production, decaying to staus.
- **Tau reco & ID:**
  - Calorimeter jets as seeds, identification via BDT.
- **l+τ_{had}+jets selection:**
  - Exactly one high Pt isolated lepton, at least two high Et jets, at least one of them b-tagged, high E_t^{miss}.
  - 1 τ-jet candidate OS w.r.t lepton.
- **Analysis technique:**
  - Signal extraction by χ^2 fit to BDT_j shape.
  - (I) Dominant background: Jet→τ fakes background
    - Modeled with differentiated templates: light-quark jet & gluon jet τ fakes from enriched W+jets data samples.
  - (II) Backgrounds with real taus.
  - (III) Backgrounds with e/μ→τ.
  - (II) and (III) MC driven.
- **Systematics:**
  - MC generator (5%), ISR/FSR (6.7%), b-tag SF (5.4%), τID (4.3%).

$$\sigma_{t\bar{t}} = 183 \pm 9\,(\text{stat.}) \pm 23\,(\text{syst.}) \pm 3\,(\text{lumi.})\ \text{pb.}$$

$$\sigma_{t\bar{t}}^{theor}(\sqrt{s} = 7\,\text{TeV},\ m_{top} = 172.5\,\text{GeV}) = 177.31^{+10.06}_{+10.75}\ \text{pb}\quad \delta\sigma_{t\bar{t}}^{theor} = ^{+5.67\%}_{+6.06\%}$$





Normalized $t\bar{t}$ Differential Cross Section   CMS-TOP-12-028   arXiv:1505.04480

L_{int} =19.7 fb^{-1} @ 8 TeV

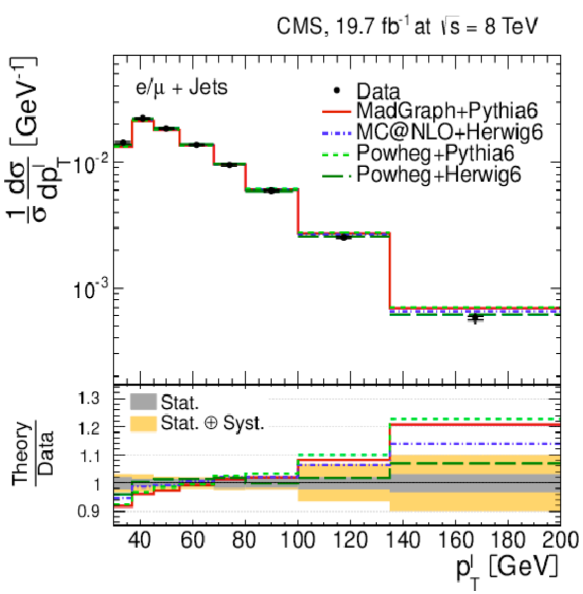
- Motivation:
  - Test pQCD predictions in different kinematic regions.
  - Provide direct information on the gluon PDF at large momentum fractions:
    - M.Czakon, M.L.Mangano, A.Mitov & J.Rojo J. High Energy Phys. 1307 (2013) 167.
  - $m_{t\bar{t}}$ sensitive to the resonant production of new particles, e.g. massive Z-like bosons.
    - R. Frederix, F. Maltoni J. High Energy Phys. 0901, 047 (2009).
    - C.T Hill, Phys. Lett. B 345,483 (1995).

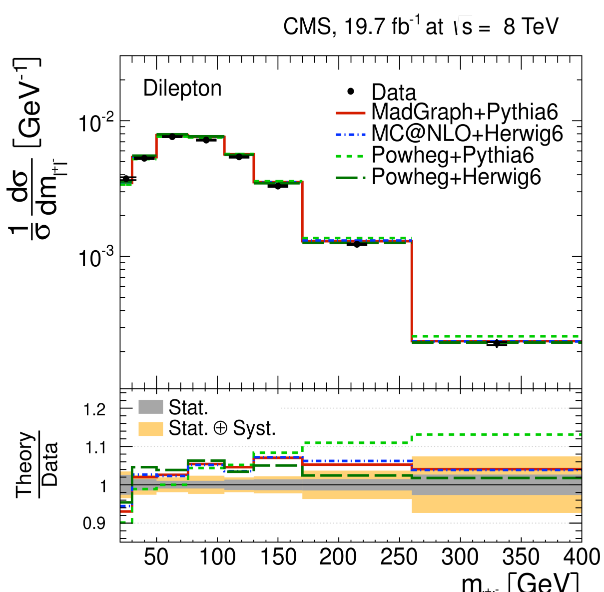
$$\frac{1}{\sigma}\cdot\frac{d\sigma}{dX_j}\equiv\frac{1}{\sigma}\cdot\frac{1}{\Delta X_j}\cdot\frac{\sum_i M_{ji}^{-1}\left[D_i-B_i\right]}{BR\cdot L\cdot\varepsilon_j}$$

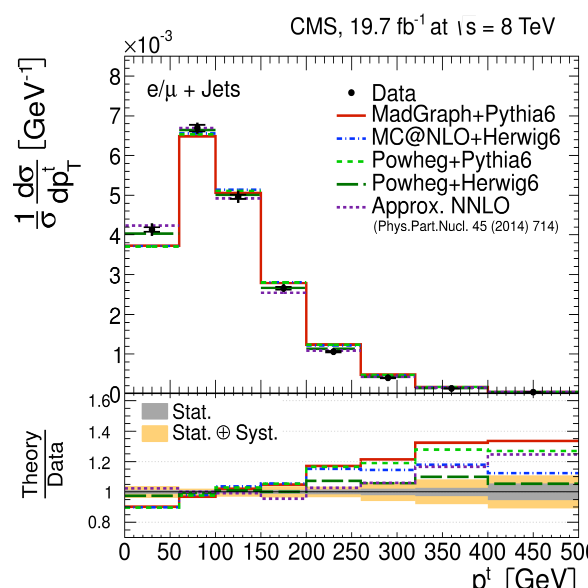
- Kinematic properties of top decay products:
  - Final charged leptons and b-quark jets → measured in fiducial phase space.
- Main systematics: JES 2.3% and hadronization 2.7% (l+jets) hadronization 1.4% (dileptons)

•Conclusions:

- Only POWHEG+HERWIG6 provide a good description of data for all measured distributions.
- In general, p_T (lepton,b,ll,bb) and M_{ll} slightly softer in data.





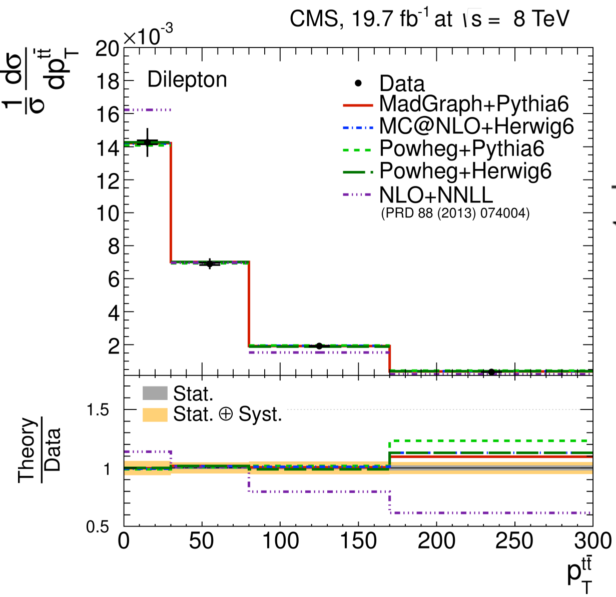


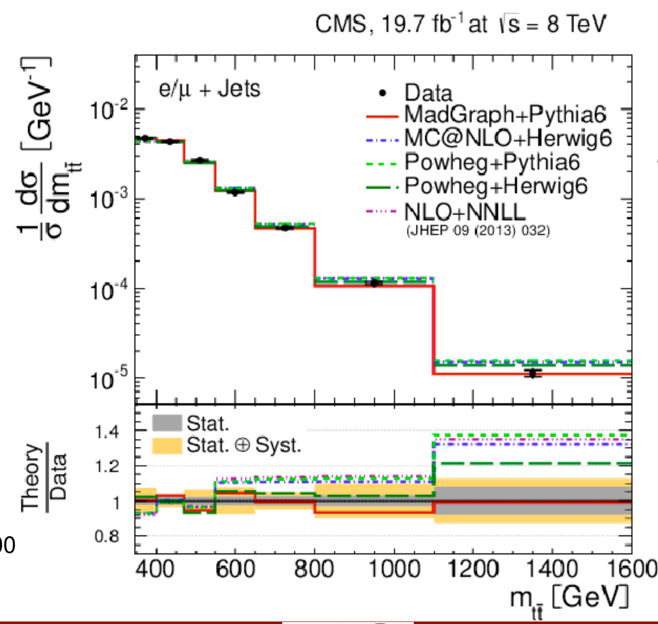
L_{int} =19.7 fb^{-1} @ 8 TeV

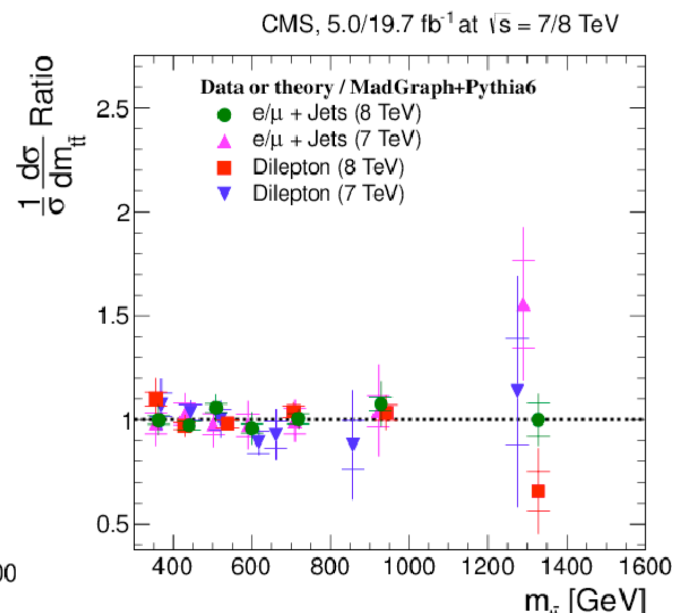
- Kinematic properties of top quarks and $t\bar{t}$ system
  - Corrected to parton level, before decay and extrapolated to full phase space using MADGRAPH+PYTHIA6. Compared with theory: fixed-order NLO+NNLL.
- Main systematics: Hadronization 1.9% (l+jets) Fact/renorm.scale 1.2% (dileptons).

•Conclusions:

- Top quark kinematics:
  - POWHEG+HERWIG6 and NLO+NNLL calculation provide a good description of data for all measured distributions.
  - $p_{T,t}$ spectrum softer in data.
- $t\bar{t}$ Kinematics:
  - $p_{T,t\bar{t}}$ well described by MC, not by NLO+NNLL calculation.
  - $M_{t\bar{t}}$ high tail lower in data than predictions.
- Consistency of results among dilepton and lepton+jets channel, 7 and 8 TeV.



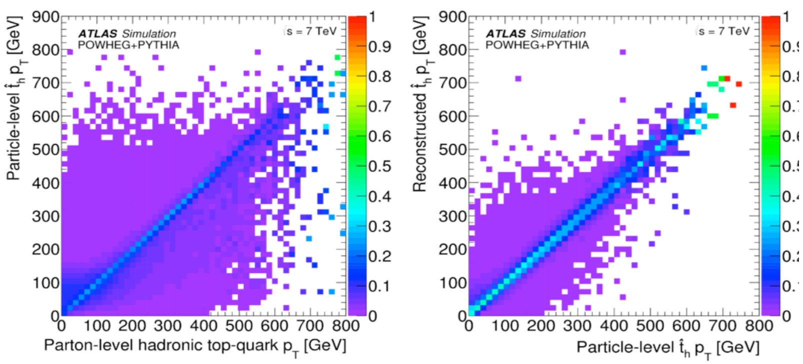


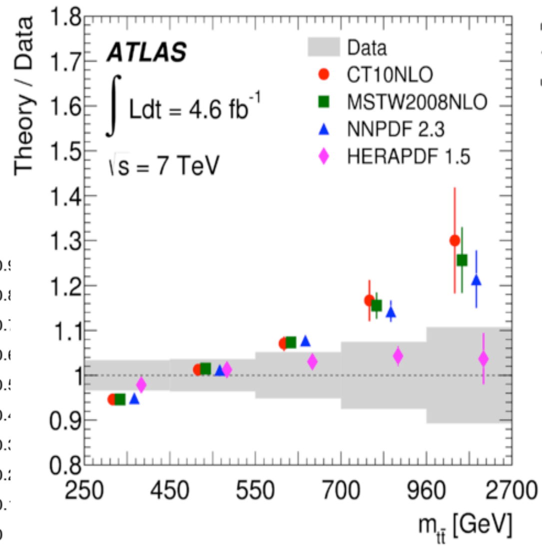


L_{int} =4.6 fb^{-1} @ 7 TeV

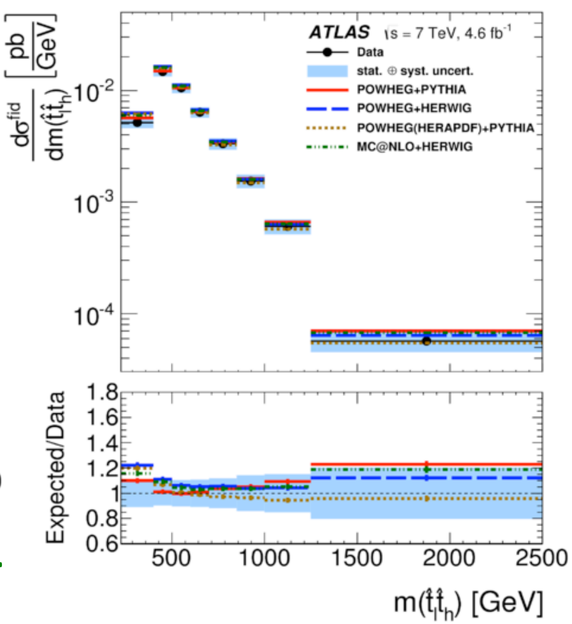
- Motivation:
  - Measure differential cross sections using a definition: "pseudo-top-quark" built from "particle" objects.
  - Avoid large model-dependent extrapolation corrections to parton-level top-quarks.
- Analysis technique:
  - Event selection: lepton+jets selection with at least two b-jets. Leptonic pseudo-top from lepton, E_t^{miss} and closest b-jet, hadronic pseudo-top from remaining b-jet and two highest Et jets.
  - "particle-level" measurements in the "fiducial region", with high reconstruction efficiency for detector-level physics objects.

$$N^i_{part} = f^i_{part!reco} \cdot \sum_j M^{part,i}_{reco,j} \cdot f^j_{misassign} \cdot f^j_{reco!part} \cdot (N^j_{reco} - N^j_{bgnd})$$





Phys. Rev. D 90, 072004



- Main systematics: b-tagging, JES and ISR/FSR modelling.

•Conclusions:

- POWHEG(HERAPDF)+PYTHIA provided the best representation of data, except at low $M_{t\bar{t}}$.

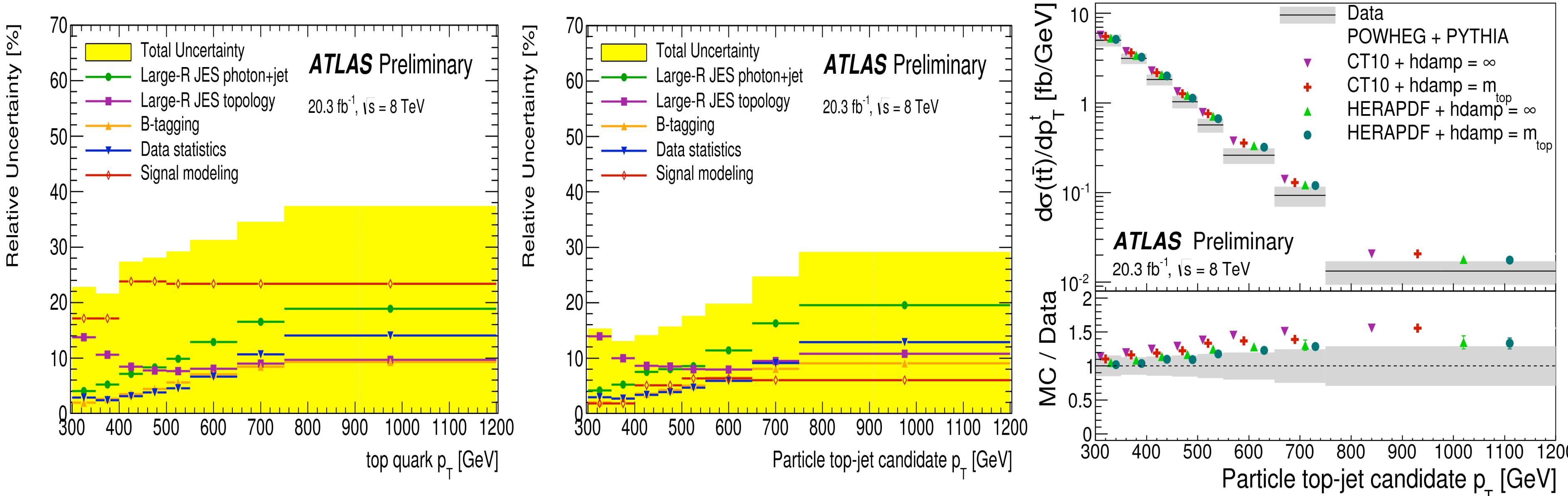
L_{int} =20.3 fb^{-1} @ 8 TeV

•Motivation:

- Boosted top final states enhance the $t\bar{t} \rightarrow q\bar{q}$ contribution, sensitive to the intrinsic structure of top-quarks: top radius Rt.
  - •C.Englert, A.Freitas, M.Spira and P.M.Zerwas, Phys.Lett.B721(2013)261-268.
- •Top pT spectrum may be distorted at high pT by potential anomalous chromomagnetic moment of the top quark, window to new physics (compositeness and technicolor scenarios).
  - •D.Atwood, A.Kagan and T.Rizzo, Phys.Rev.D52(1995) 6264-6270.

•Analysis technique highlights:

- $t\bar{t}$ differential cross section measured versus pT of hadronic top quark with p_T> 300 GeV:



•Systematic uncertainty dominates: large-R jets energy scale (15%-29% for particle-level measurement).

•Conclusions:

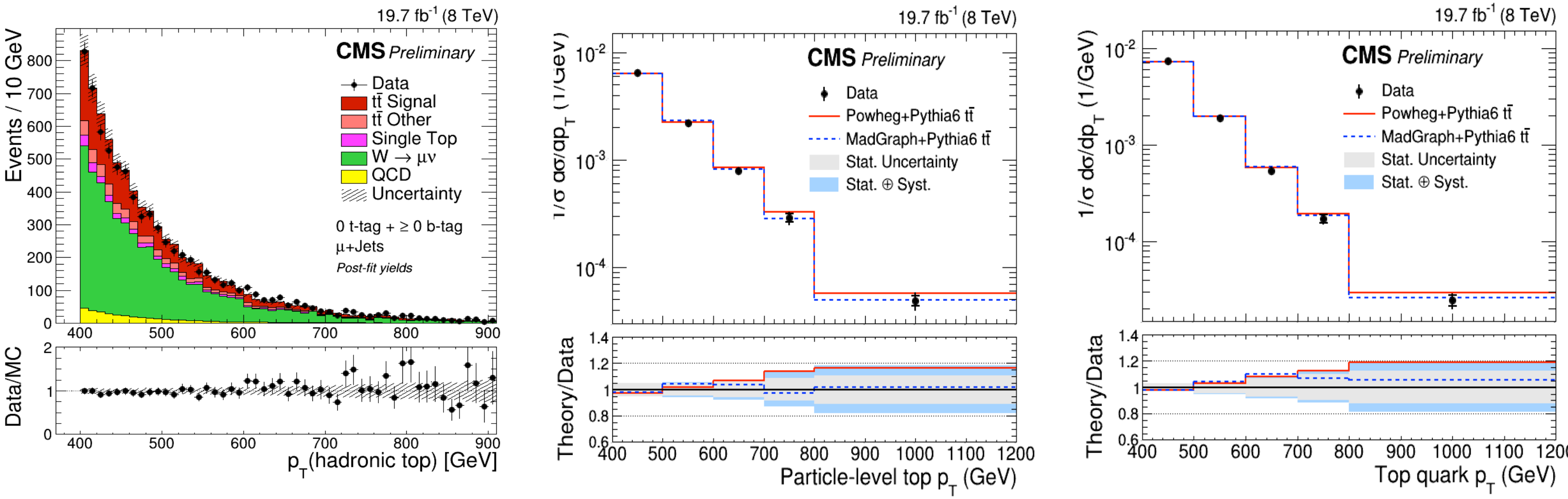
- •Measured cross sections lower than NLO and LO+PS MC generators.
- •Discrepancy increases with hadronic top quark p_T, up to 30-70% in the highest p_T bin depending on MC.

$t\bar{t}$ Differential Cross Section of boosted tops

CMS PAS TOP-14-012

$L_{int} = 19.7\ fb^{-1}$ @ 8 TeV

- Analysis technique highlights:
  - Normalized $t\bar{t}$ differential cross section measured versus p_T of hadronic top quark with $p_T > 400$ GeV.
  - Inclusive cross section in the high p_T region ($p_T^{top} > 400$ GeV) extracted using a likelihood template fit to different kinematic variables in 3 orthogonal regions: 0t, 1t+0b and 1t+1b



- Uncertainties: statistical (5-12%) , systematic (2-15%) dominated by top tagging efficiency and Q^2 scale.

Conclusions:

- Fiducial cross section in the high p_T region ($p_T^{top} > 400$ GeV) is measured to be overestimated by 14% in the POWHEG $t\bar{t}$ simulation.

$$\sigma_{t\bar{t}}(\text{particle level}) = 1.28 \pm 0.09(\text{stat.+syst.}) \pm 0.10(\text{PDF}) \pm 0.09(Q^2) \pm 0.03(\text{lumi.})\ \text{pb} \qquad \sigma_{t\bar{t}}^{POWHEG} = 1.49\ \text{pb}$$

$$\sigma_{t\bar{t}}(\text{parton level}) = 1.44 \pm 0.10(\text{stat.+syst.}) \pm 0.13(\text{PDF}) \pm 0.15(Q^2) \pm 0.04(\text{lumi.})\ \text{pb} \qquad \sigma_{t\bar{t}}^{POWHEG} = 1.67\ \text{pb}$$

- POWHEG+PYTHIA6 and MADGRAPH+PYTHIA6 $t\bar{t}$ MC are observed to overestimate the differential cross section, especially at high top quark p_T.

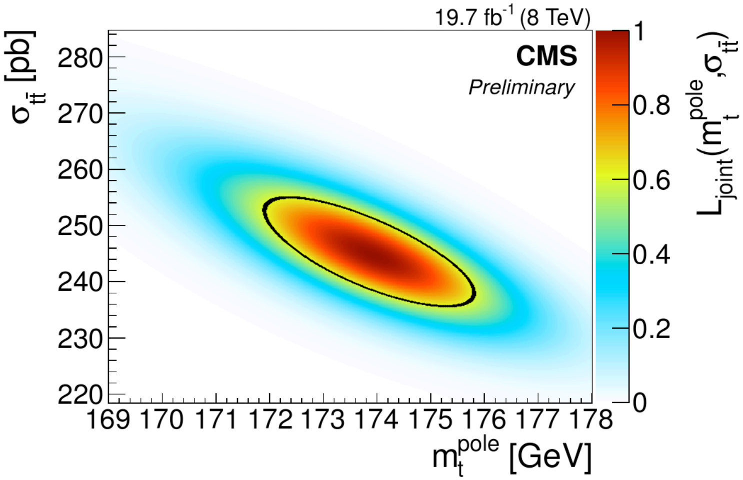
CONCLUSIONS

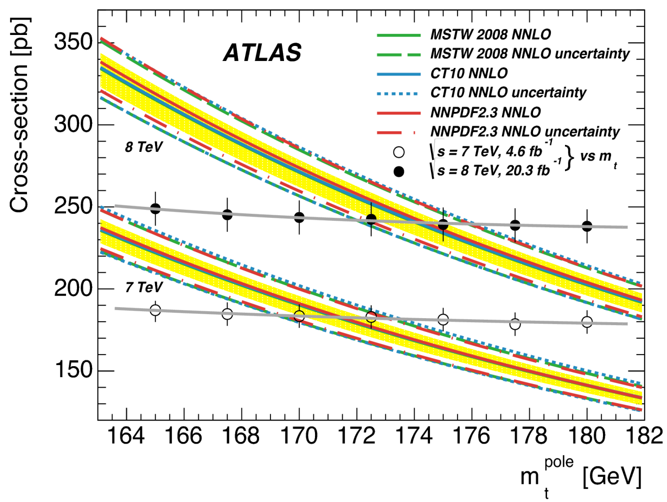
- CMS+ATLAS $\sigma_{t\bar{t}}$ combination at 8 TeV: experimental accuracy (3.5%) have reached the precision of the theoretical calculations (+5.3%-5.7%).
  - Combined measurement in agreement with the SM.
- Best single $\sigma_{t\bar{t}}$ measurements by CMS and ATLAS in the eμ + b-jets channel at 7 and 8 TeV.
  - Experimental accuracy ≈ 4%
- New $\sigma_{t\bar{t}}$ measurements at 13 TeV by CMS and ATLAS :
  - Evolution with √s in good agreement with the SM.

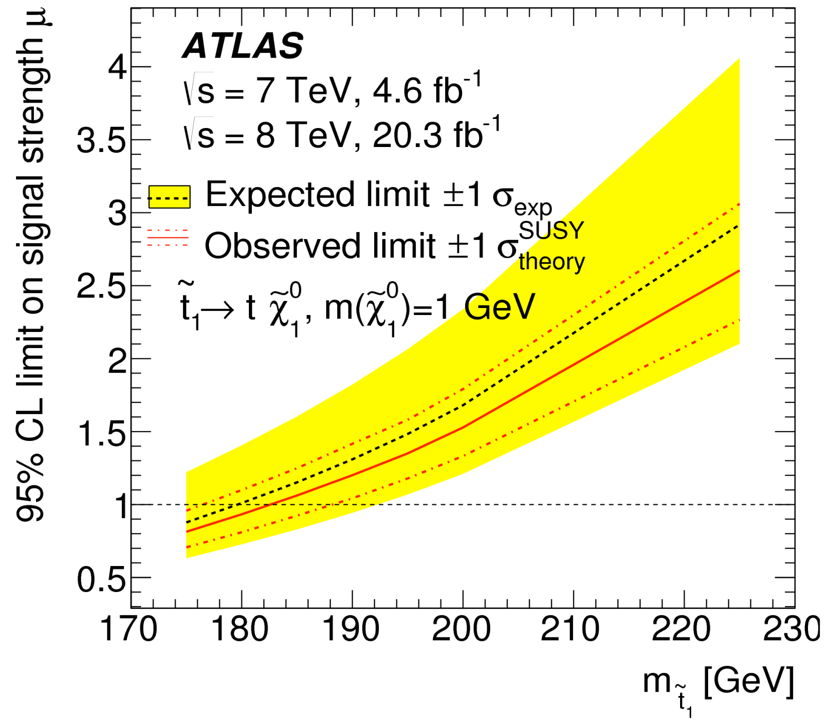
- Different definitions for differential cross section measurements as a function of kinematic properties of top quarks and $t\bar{t}$ system.
  - Parton-level cross section extrapolated to full kinematic region.
  - Particle-level cross section measured in the fiducial region, with significantly lower systematics, especially signal modeling.
  - CMS: POWHEG+HERWIG6 and NLO+NNLL calculation provide a good description of data for all measured distributions.
  - ATLAS: POWHEG(HERAPDF)+PYTHIA provided the best representation of data.
  - Data are slightly softer than NLO+NNLL predictions in the tail of the $p_{T,t}$, $M_{t\bar{t}}$ and $p_{T,t\bar{t}}$.
  - No significant deviations from SM predictions.

- High statistics in 8 TeV data samples have allowed measurements with boosted tops:
  - ATLAS and CMS : Measured cross sections as a function of top quark p_T lower than NLO and LO+PS MC generators, especially at high p_T .

BACKUP SLIDES







- Top quark pole mass determined via the theoretical dependence of $\sigma_{t\bar{t}}$ on m_t^{pole}

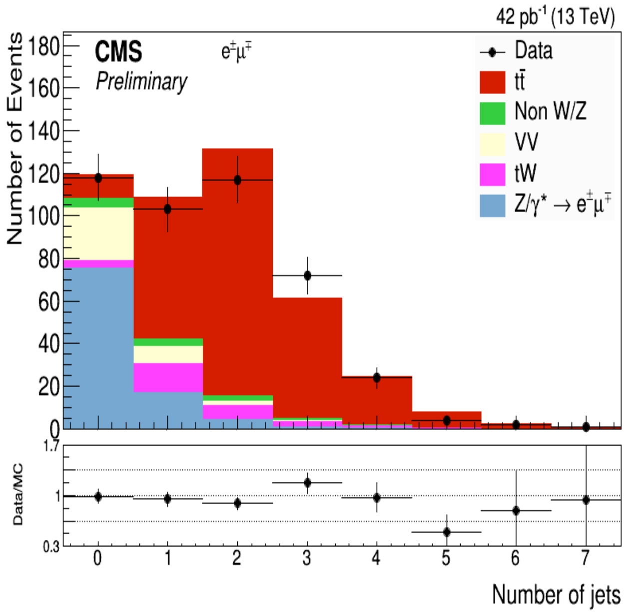
$$m_t^{pole}(\mathrm{CMS}) = 173.6^{+1.7}_{-1.8}\,\mathrm{GeV}$$

$$m_t^{pole}(\mathrm{ATLAS}) = 172.9^{+2.5}_{-2.6}\,\mathrm{GeV}$$

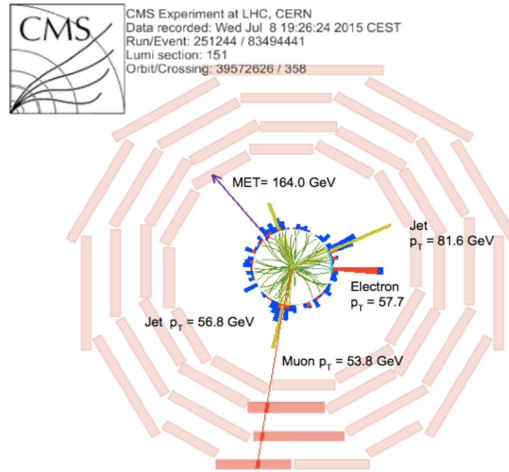
- By looking for an excess of $\sigma_{t\bar{t}}$ w.r.t pQCD prediction:
  - Stop quarks decaying with masses below 189 GeV (177 GeV) are excluded @95% C.L by CMS (ATLAS)

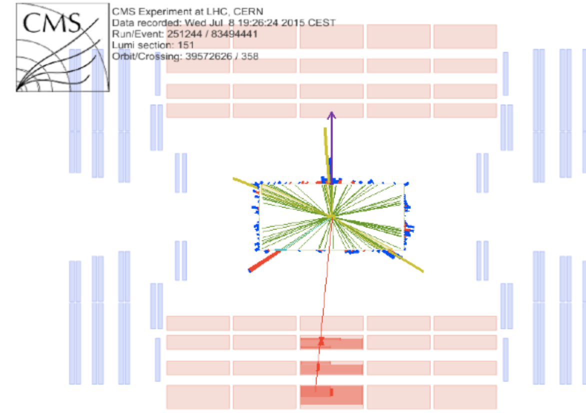
Early $t\bar{t}$ studies of kinematic distributions CMS DP-2015/01

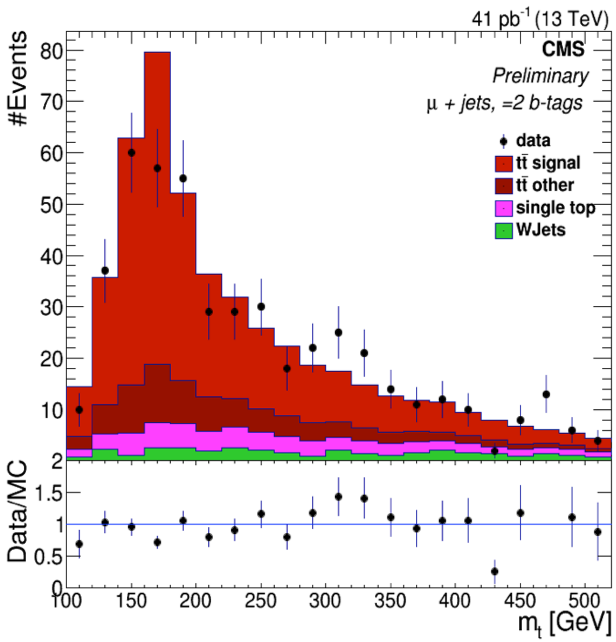
L_{int} = 41 pb^{-1} @ 13 TeV



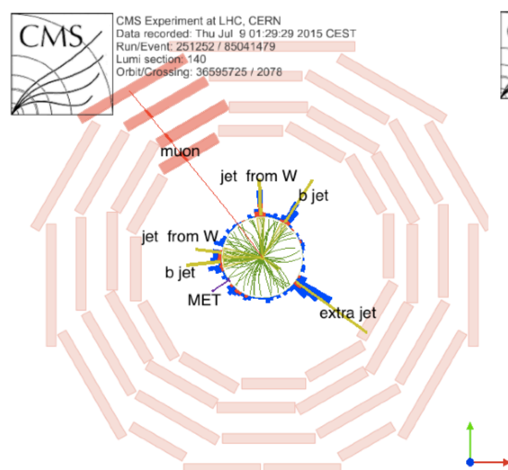
- $t\bar{t}$ dilepton candidates:
  - 1 electron and 1 muon high p_T and isolated, OS, $M_{e\mu}$ > 50 GeV

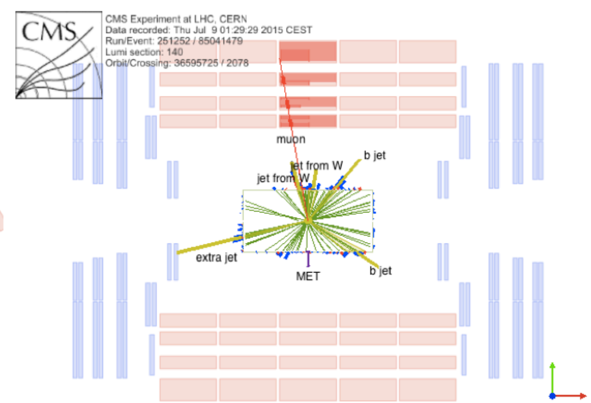


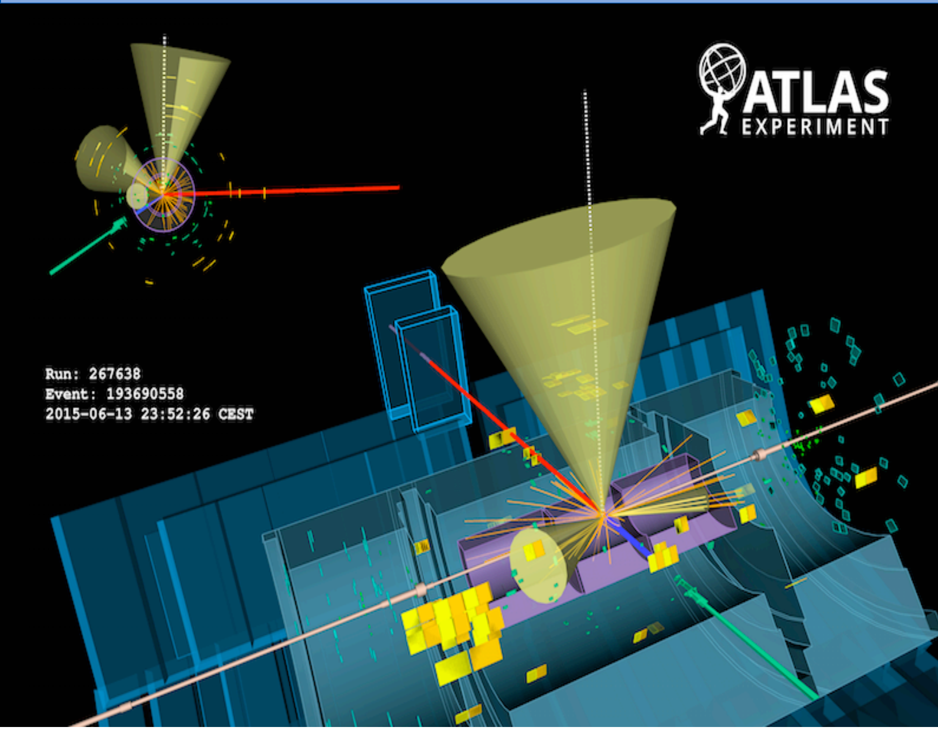




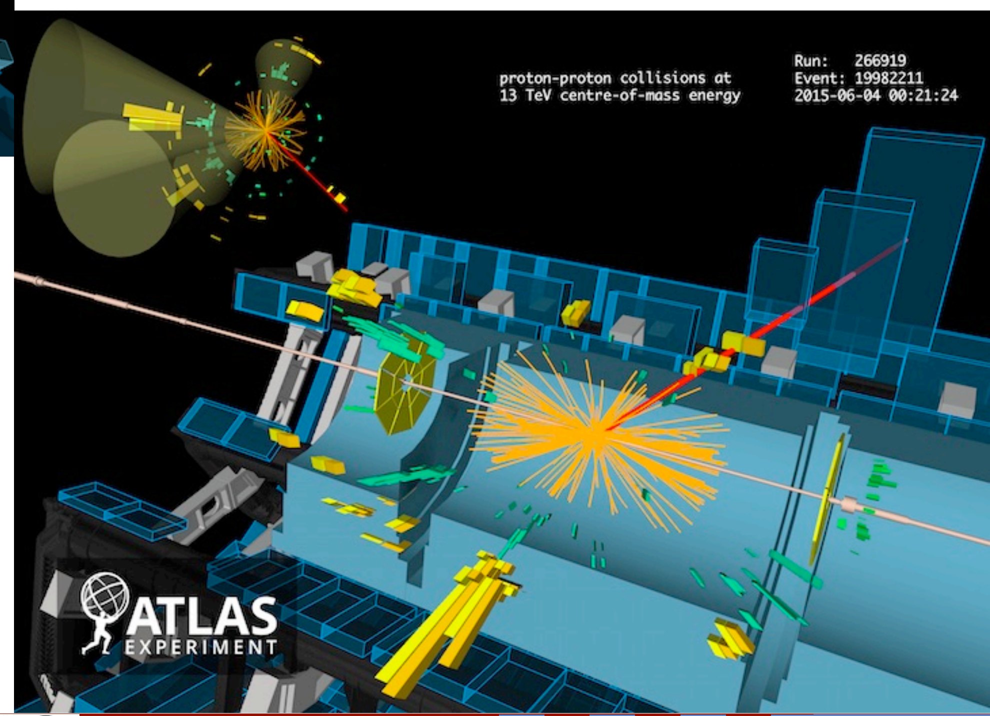
- $t\bar{t}$ l+jets candidates:
  - 1 isolated and high p_T muon/electron, ≥4 high E_T jets, ≥2 b-jets







- $t\bar{t}$ dilepton candidate:
  - 1 electron with p_T = 170 GeV
  - 1 muon with p_T = 140 GeV
  - 3 jets with 30 < E_T < 80 GeV
  - 2 b-jets



- $t\bar{t}$ lepton+jets candidate:
  - 1 muon with p_T = 35 GeV
  - 4 jets with 25 < E_T < 80 GeV