Recent results on top quark physics

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for the ATLAS, LHCb, and CMS collaborations

28th Rencontres de Blois on Particle Physics and Cosmology
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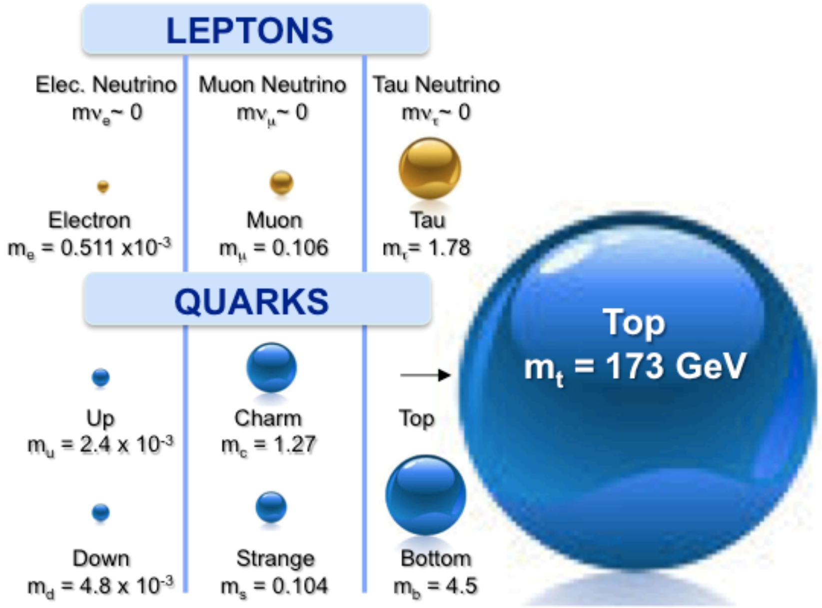
Why is the top quark still interesting?



- Heaviest elementary particle known
  - top: largest Yukawa coupling to Higgs
- Several open questions:
  - Is the top mass generated by the Higgs mechanism?
  - Role in EW symmetry breaking?
  - Role in beyond SM (BSM) physics?
- Only quark that decays before hadronizing:

  $\tau(\text{had}) \sim 1/\Lambda_{QCD} \sim 2 \times 10^{-24}$ s

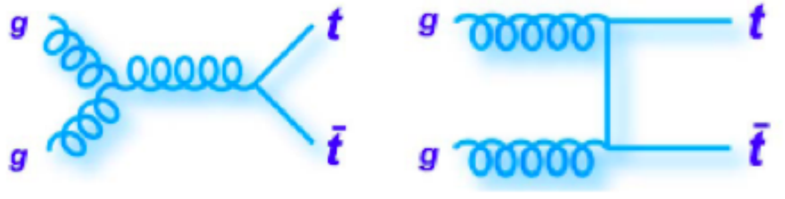
  $\tau(\text{top}) \sim 5 \times 10^{-25}$ s $< 1/\Lambda_{QCD}$

  → No bound states, spin information propagated to decay products
- Main background for Higgs and many searches for BSM physics

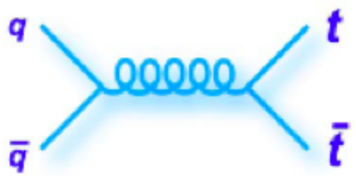
Precise understanding of top quark production and properties is crucial

Top quark pairs

- Strong top pair ($t\bar{t}$) production: sensitive to α_s and PDFs



~ 90% (13 TeV)



~ 10% (13 TeV)

σ(tt) at NNLO+NNLL: [PRL 110 (2013) 252004]

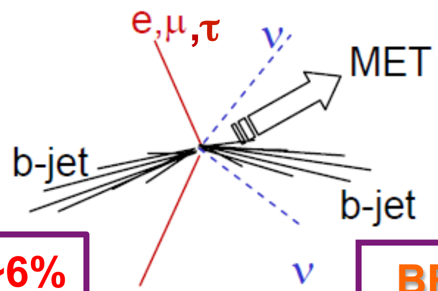
@13 TeV	832 +- 40 pb
@8 TeV	252 +- 12 pb
@7 TeV	178 +- 10 pb

x 3

All with top mass = 172.5 GeV

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/TtbarNNLO

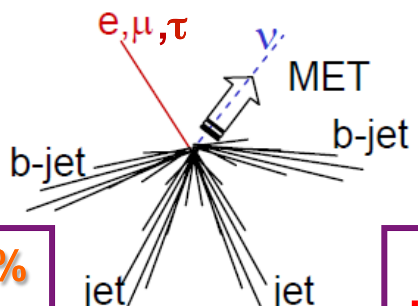
- In SM, t → Wb (~100%) ➔ W decay defines final states



BR(μ,e)~6%
Low bg:
Z+jets

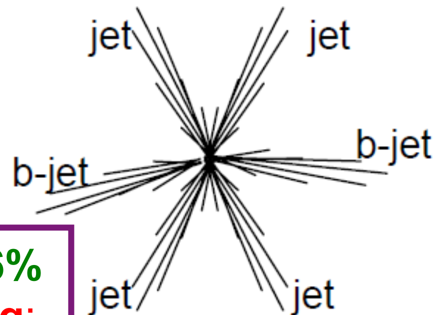
dileptons

BR(μ,e)~34%
Moderate bg:
W+jets



lepton + jets

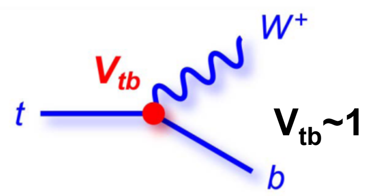
BR~46%
Huge bg:
QCD

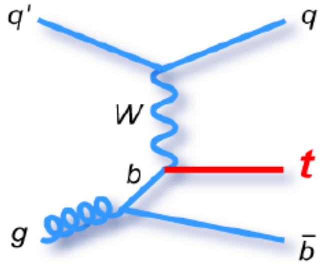


all hadronic

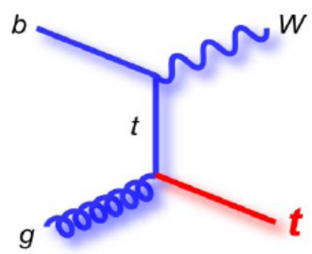
Single top

- Electroweak single top production: tWb vertex in production, sensitive to Vtb

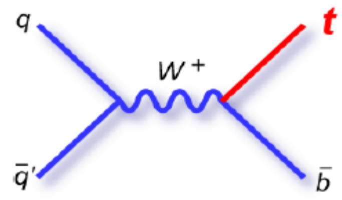




t-channel



tW-channel

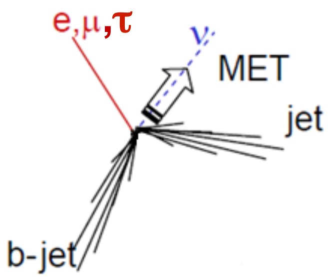


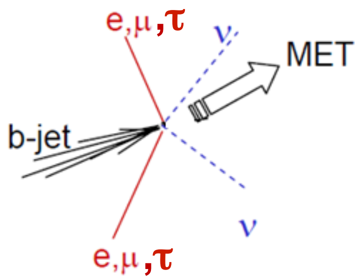
s-channel

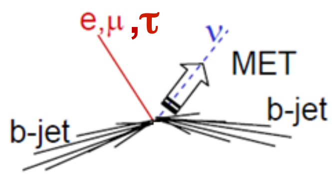
	t-channel	tW-channel	s-channel
@7 TeV[(1)(2)]	63.9±2.7 pb	15.7±1.2 pb	4.29±0.18 pb
@8 TeV[(1)(2)]	85.2±2.2 pb[(3)]	22.4±1.5 pb	5.24±0.21 pb
@13 TeV[(1)(2)]	217.0±8.4 pb	71.7±3.8 pb	10.32±0.38pb
	(NLO)	(Approx. NNLO)	(NLO)

(1): LHCTopWG: calculations with HATOR, see also https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SingleTopRefXsec (2): N. Kidonakis Phys. arXiv:1205.3453
(3): M. Burcherseifer, F.Caola, K. Melnikov: arXiv:1404.7116 All with top mass = 172.5 GeV

- Final states:

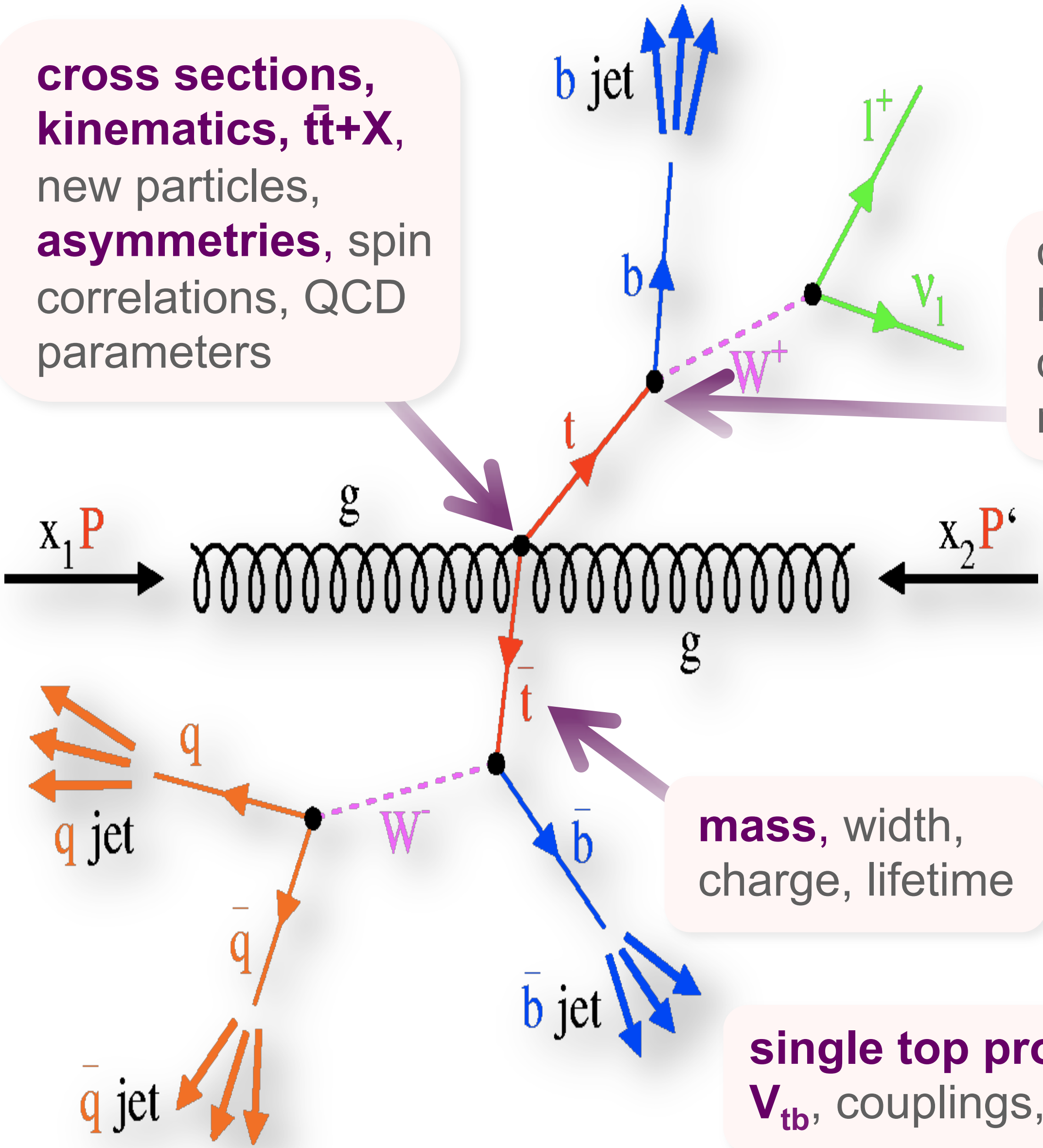






- Large backgrounds: W/Z+jets, $t\bar{t}$, QCD

Top quark properties in production and decay



cross sections, kinematics, $t\bar{t}$+X, new particles, **asymmetries**, spin correlations, QCD parameters

couplings, FCNC, branching ratios, rare decays, **W-helicity**, new particles

mass, width, charge, lifetime

single top production, **V_{tb}**, couplings, PDFs

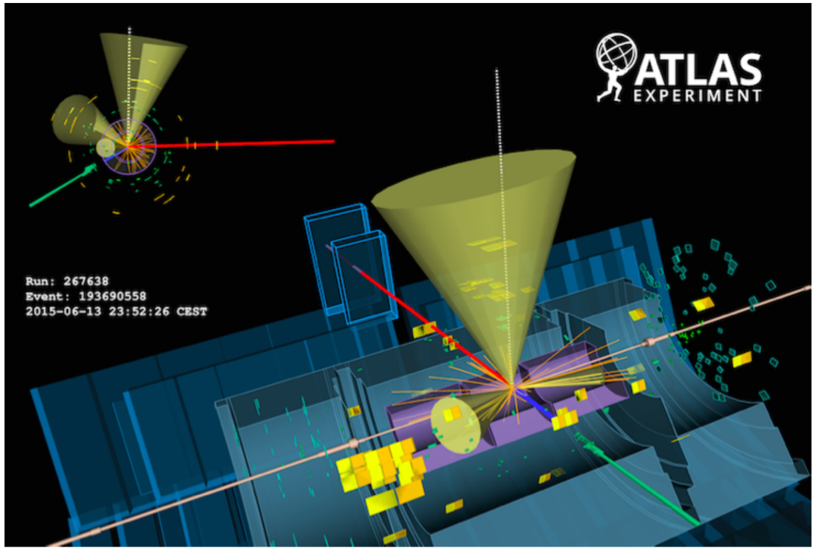
Today's talk

Selection of:

Latest Run-I results

13 TeV results

13 TeV candidate:
eμ + 2 b-tags



Top quark production (differential) cross sections

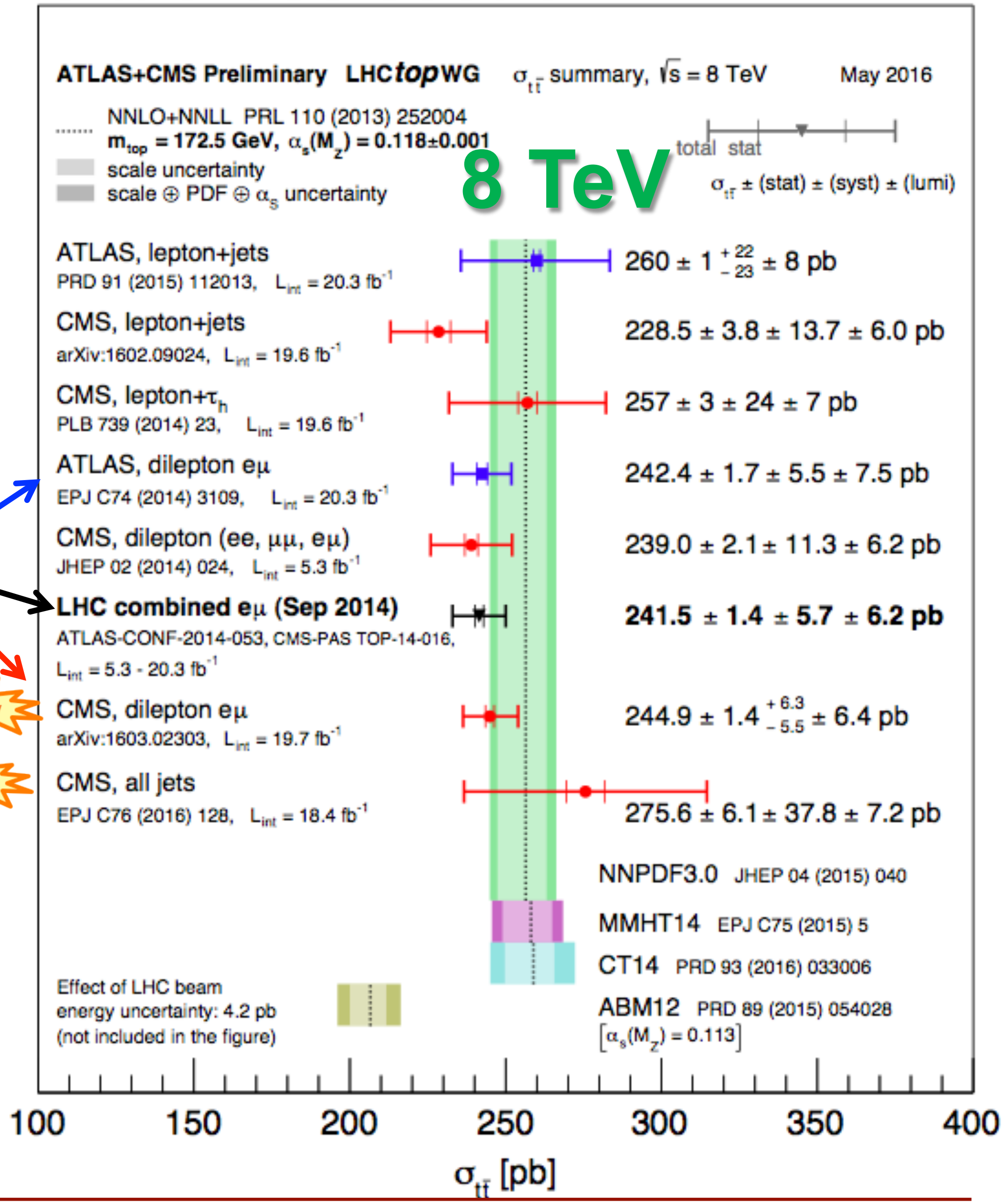
- First step in understanding top physics
- Test of QCD calculations and search for new physics

→ More in talk by A. Sidoti

Run-I inclusive $t\bar{t}$ cross section

All channels measured at 7 & 8 TeV
to look for the unexpected

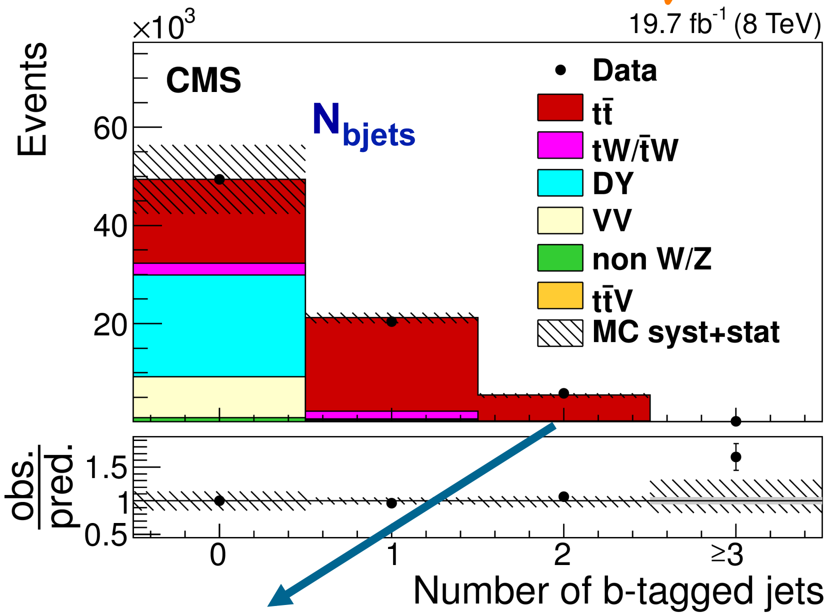
- Good agreement with NNLO+NNLL
- Highest precision: dilepton channels ~4%, similar to theory prediction
  - High purity (~90%)
  - Also used to set limits to stop quark production (for stop mass ~ top mass)



$t\bar{t}$ cross section in eμ at 7 & 8 TeV

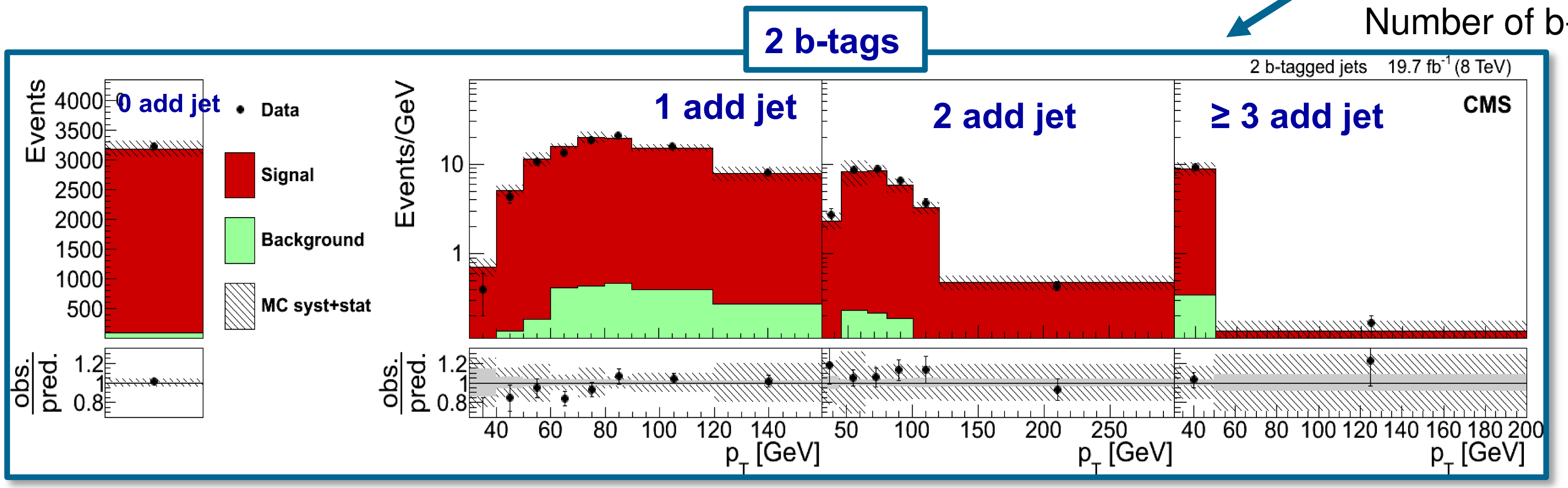
CMS, arXiv:1603.02303 — New

Last word from Run-I in dileptons at CMS



Selection: opp.-sign isolated eμ pair, jets, b-tags

- Template fit in different Nbjets and additional Njets categories
  - Fit to p_T of softest jet in each category
  - Constrain backgrounds and main systematic uncertainties



7 TeV: $\sigma_{t\bar{t}} = 173.6 \pm 2.1\,(\text{stat})^{+4.5}_{-4.0}\,(\text{syst}) \pm 3.8\,(\text{lumi})\,\text{pb}$

8 TeV: $\sigma_{t\bar{t}} = 244.9 \pm 1.4\,(\text{stat})^{+6.3}_{-5.5}\,(\text{syst}) \pm 6.4\,(\text{lumi})\,\text{pb}$

(3.7%)

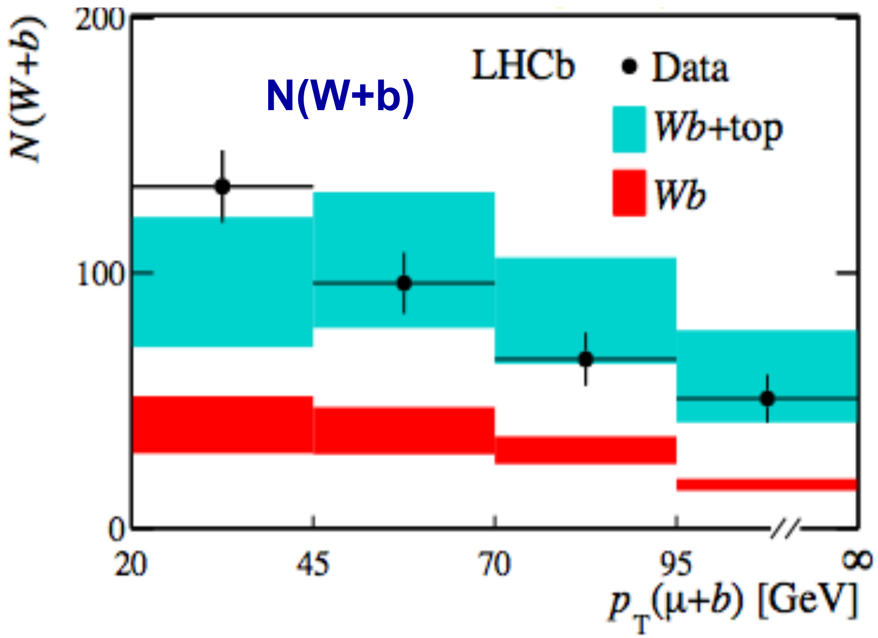
Main syst: luminosity, trigger, lepton selection

Top production in forward rapidities

LHCb, PRL 115 (2015) 112001

First observation of top quarks at LHCb !

- Forward region: enhanced sensitivity to BSM, can constrain gluon PDF at larger x
- Combined measurement of $t\bar{t}$ (75%) and single top (25%) in events with
  1 top → Wb → $\mu\nu$b:
  - 1 μ: p_T > 25 GeV, η in (2.0, 4.5)
  - ≥ 1 jet: p_T in (50, 100) GeV, η in (2.2, 4.2)
  - Jet must be b-tagged



- Extract top content from likelihood fit:

$$\sigma(\mathrm{top})[7\,\mathrm{TeV}] = 239 \pm 53\,(\mathrm{stat}) \pm 33\,(\mathrm{syst}) \pm 24\,(\mathrm{theory})\ \mathrm{fb}$$
$$\sigma(\mathrm{top})[8\,\mathrm{TeV}] = 289 \pm 43\,(\mathrm{stat}) \pm 40\,(\mathrm{syst}) \pm 29\,(\mathrm{theory})\ \mathrm{fb}$$

NLO using MCFM predicts

$$\sigma(\mathrm{top})[7\mathrm{TeV}] = 180^{+51}_{-41}$$
$$\sigma(\mathrm{top})[8\mathrm{TeV}] = 312^{+83}_{-68}$$

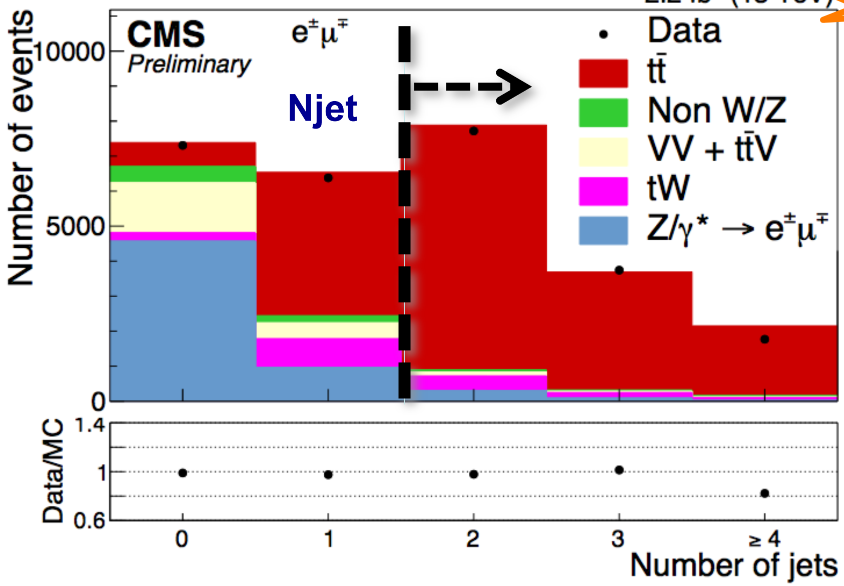
- Consistent with SM prediction, significance of 5.4 standard deviations

Main syst: b-tagging, theory

$t\bar{t}$ cross section in eμ at 13 TeV

CMS-PAS TOP-16-005

New



- CMS: focus on counting high-purity eμ events

  Selection: eμ pair, ≥ 2 jets, ≥1 b-tag

(~6%)

σ_{tt} = 793 ± 8 (stat) ± 38 (syst) ± 21 (lumi) pb

Main syst: luminosity, trigger

- ATLAS: already constraining some systematic uncertainties with data !
  - Simultaneous fit to σ_{tt} & efficiency to select, reconstruct and b-tag a jet

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

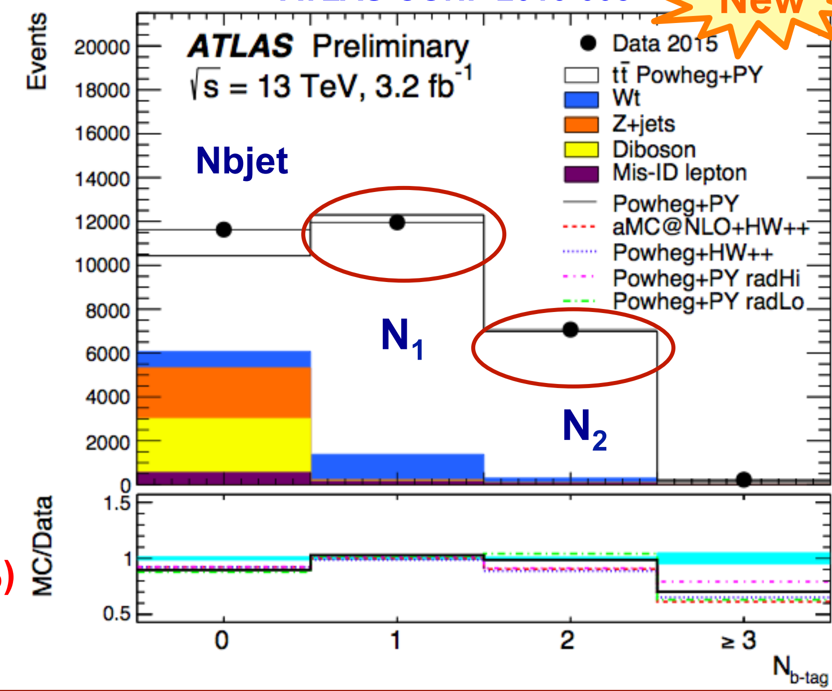
$$N_2 = \mathcal{L}\sigma_{t\bar{t}}\epsilon_{e\mu}C_b\epsilon_b^2 + N_2^{bkg}$$

σ_{tt} = 803 ± 7 (stat) ± 27 (syst) ± 45 (lumi) pb (~7%)

Main syst: luminosity, tt modelling

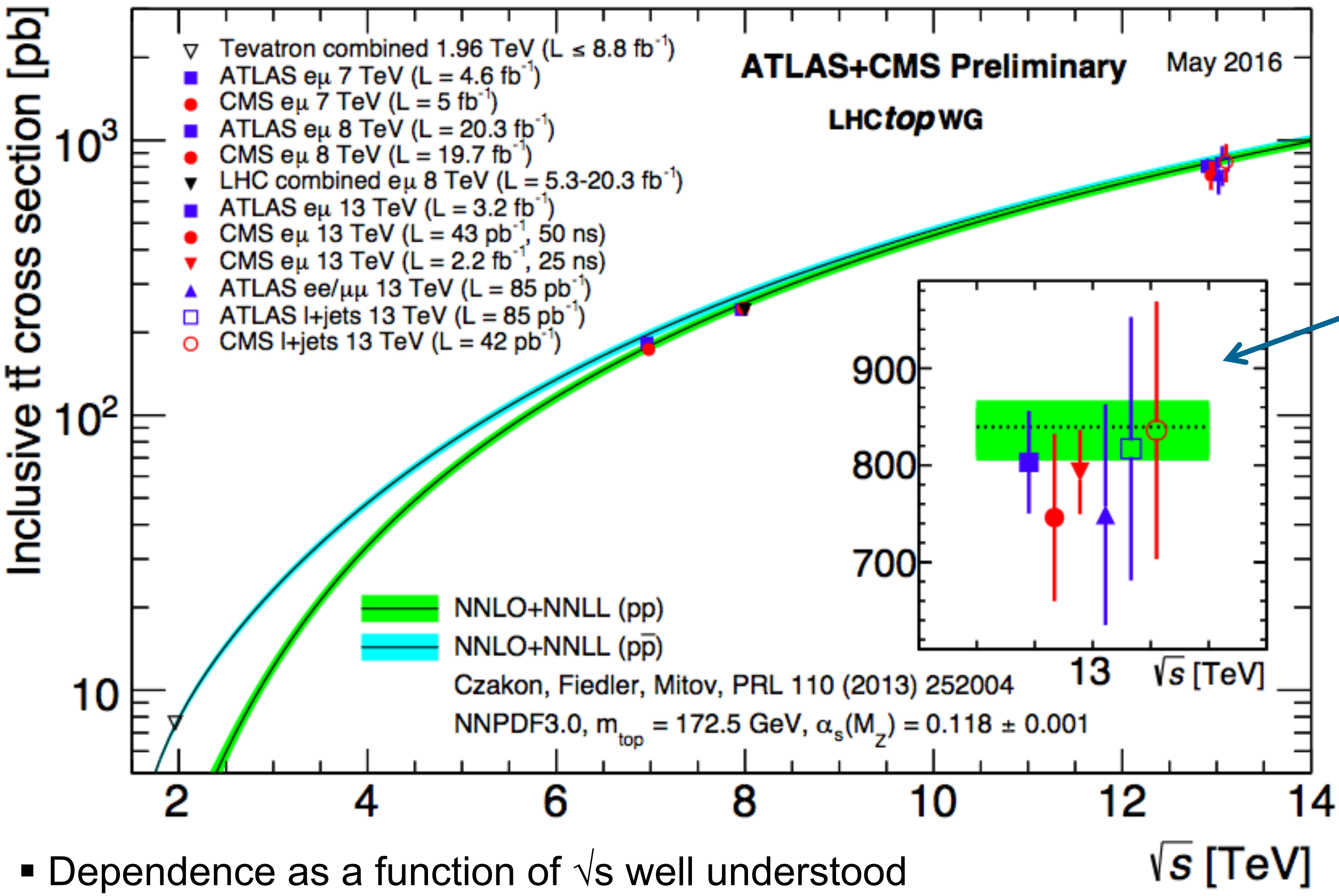
ATLAS-CONF-2016-005

New



$t\bar{t}$ cross section measured at all energies

Re-established $t\bar{t}$ production at 13 TeV with very early data (< 100 pb^{-1})



13 TeV results:
Already limited by syst. uncertainties

→ Starting to use data to constrain them

- Dependence as a function of √s well understood
- ATLAS: $t\bar{t}$/Z ratio (13 TeV): 0.445 ± 0.039 → test gg/qq ratio, cancel some syst. (lumi) **ATLAS-CONF -2015-049**

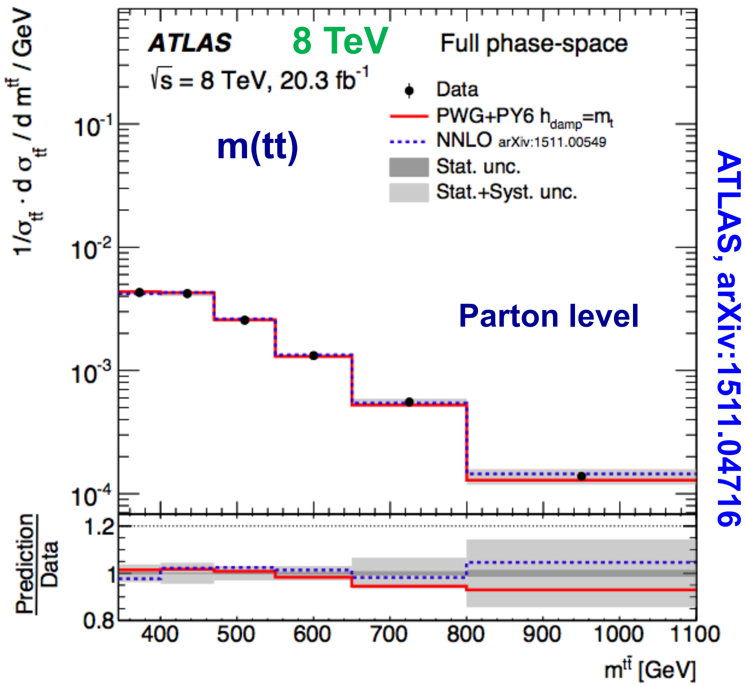
$t\bar{t}$ differential cross sections

Scrutinize $t\bar{t}$ production in many channels as a function of many kinematic observables

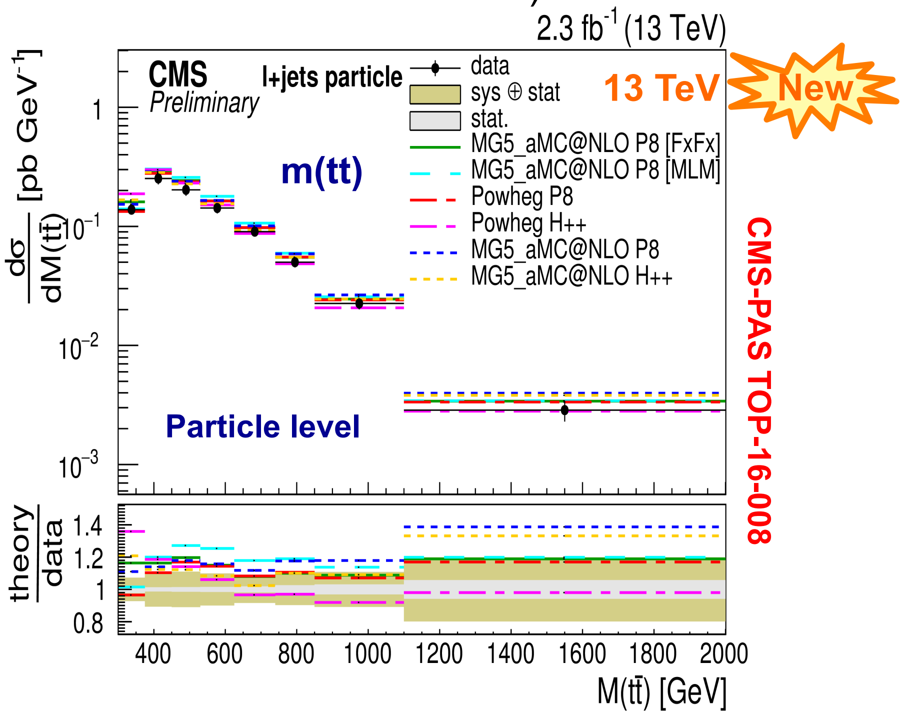
→ Precision tests of pQCD in different regions of phase space, window to BSM physics

- Use final-state products to reconstruct top quark candidates
- Correct for detector effects & acceptance → unfolding

  - Parton level: allows comparison with fixed-order calculations
  - Particle level: mimic detector-level selections and reconstruction algorithms (closer to what is measured in the detector)

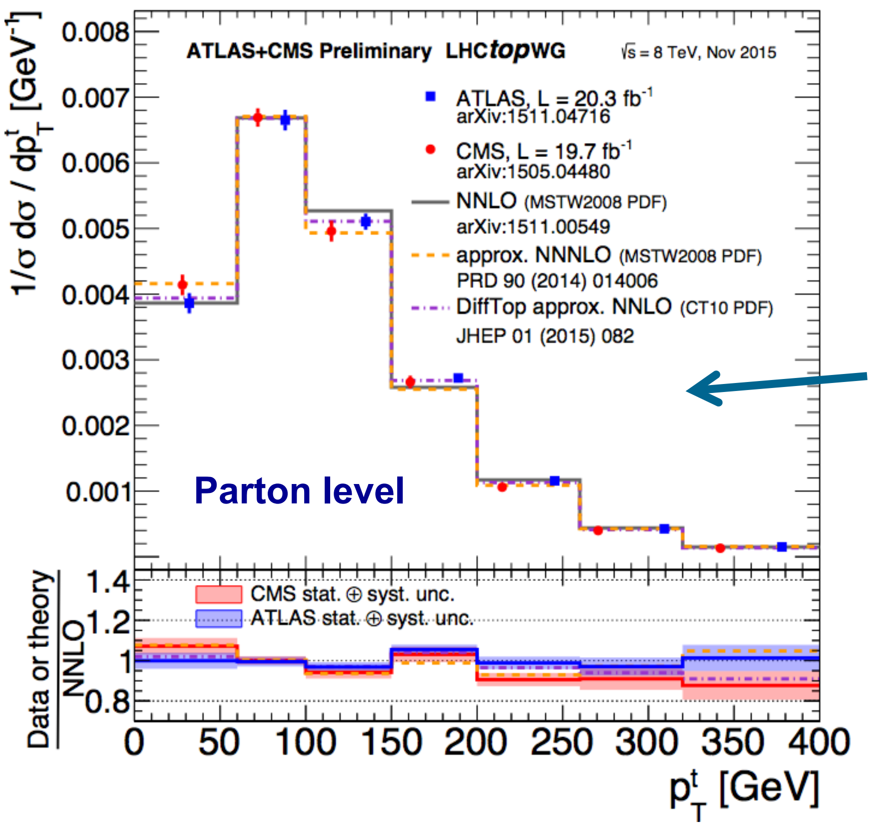


ATLAS, arXiv:1511.04716



CMS-PAS TOP-16-008

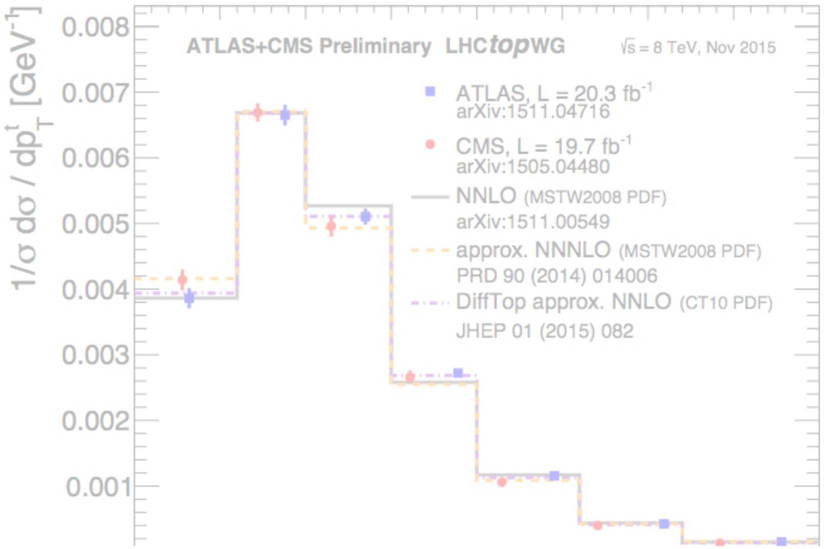
The p_T(top) distribution



Run-I 'discovery': top-p_T spectrum not well described by (most) matrix element + parton shower simulations

Fair agreement between ATLAS and CMS data at 8 TeV, better described by NNLO QCD calculations

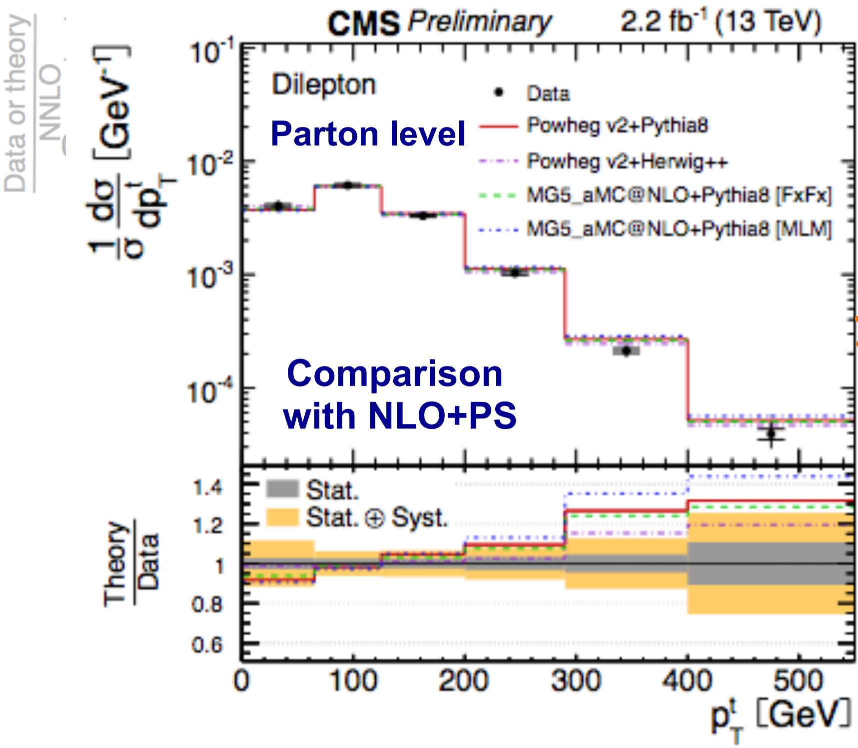
The p_T(top) distribution



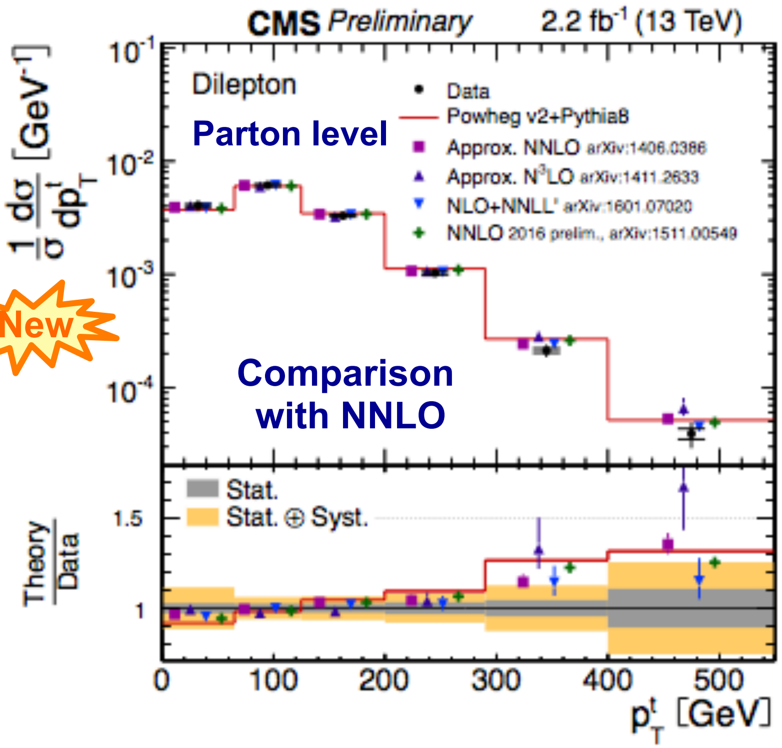
Run-I 'discovery': top-p_T spectrum not well described by (most) matrix element + parton shower simulations

Fair agreement between ATLAS and CMS data at 8 TeV, better described by NNLO QCD calculations

First results at 13 TeV



New

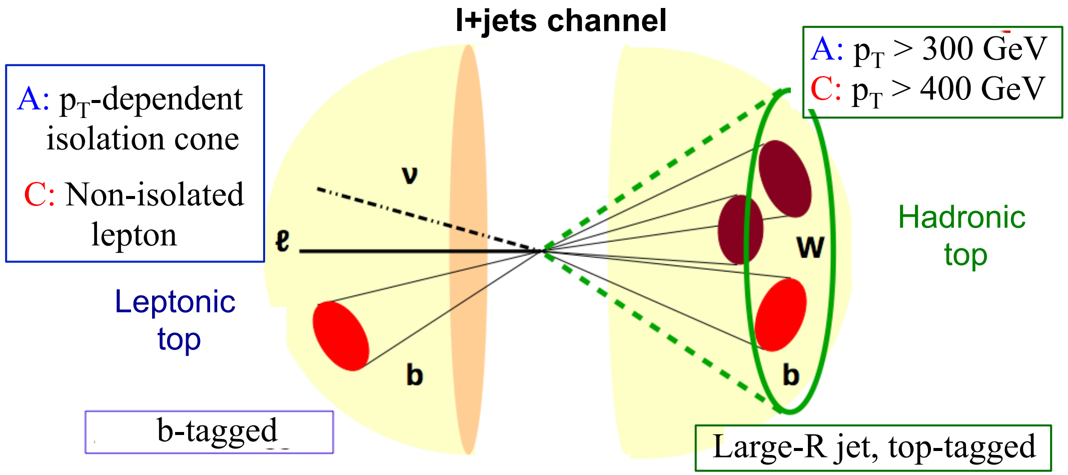


CMS-PAS TOP-16-011

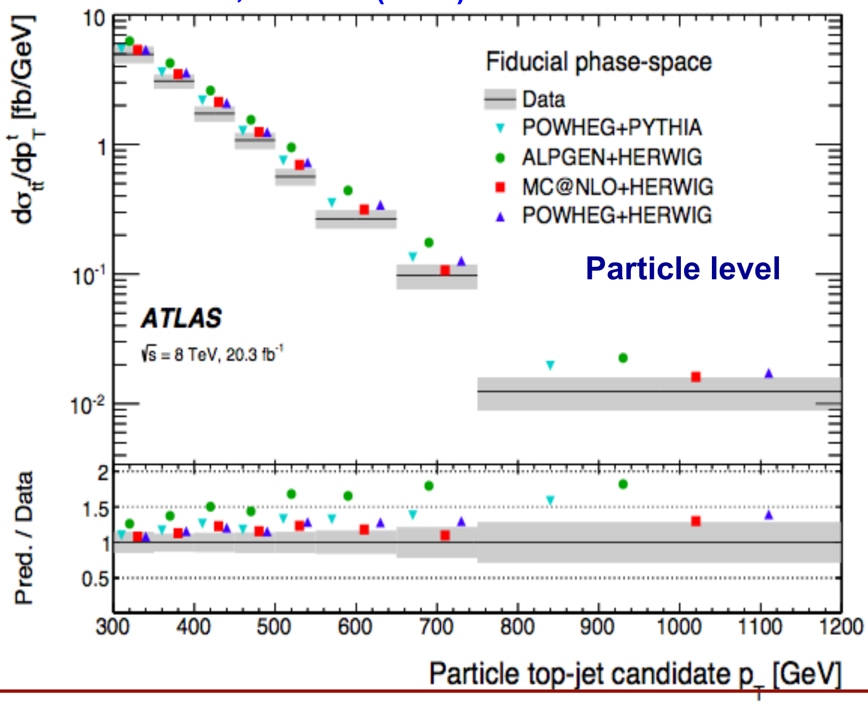
High p_T tops: entering boosted regime in Run-I

Measure top quarks at high p_T using optimized event selection & reconstruction up to TeV range !

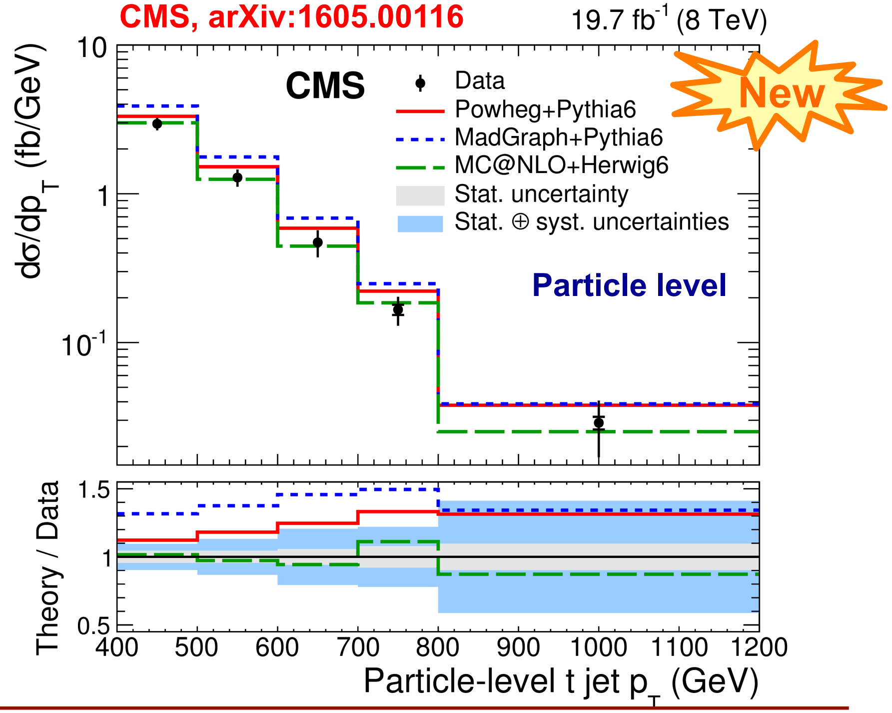
- Parton and particle level
- Slightly softer p_T spectrum in data for both ATLAS & CMS



ATLAS, PRD 93 (2016) 032009



CMS, arXiv:1605.00116



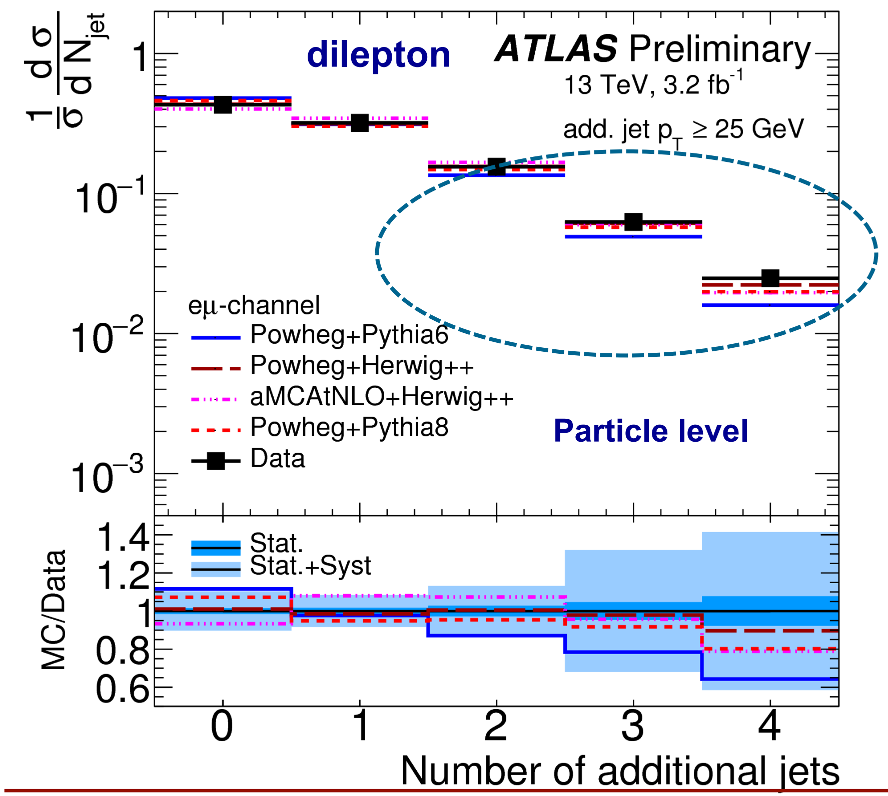
tt production + “friends”

$t\bar{t}$+jets associated production at 13 TeV

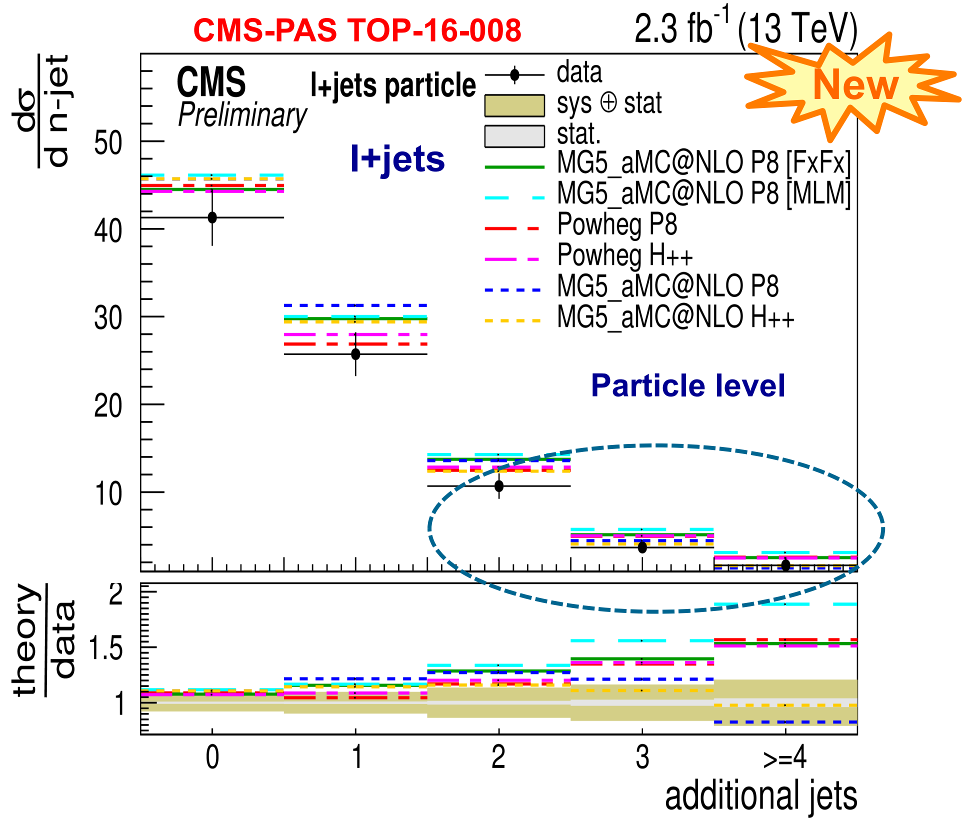
Large fraction of $t\bar{t}$ events have extra hard jets from initial or final state radiation

- Sensitive to matching of matrix element to parton shower
- Reveal presence of new physics in $t\bar{t}$+jets final states, bg for $t\bar{t}$+H
- High jet multiplicity dominated by parton shower, further tuning ongoing to improve description of data (CMS, see backup)

ATLAS-CONF-2015-065



CMS-PAS TOP-16-008



$t\bar{t}$ with veto on extra jets: "gap fraction"

ATLAS, to be sub. to JHEP

New

Quantify additional jet activity from quark and gluon radiation with a jet veto

- Use dilepton eμ events

  eμ pair, ≥ 2 b-tags

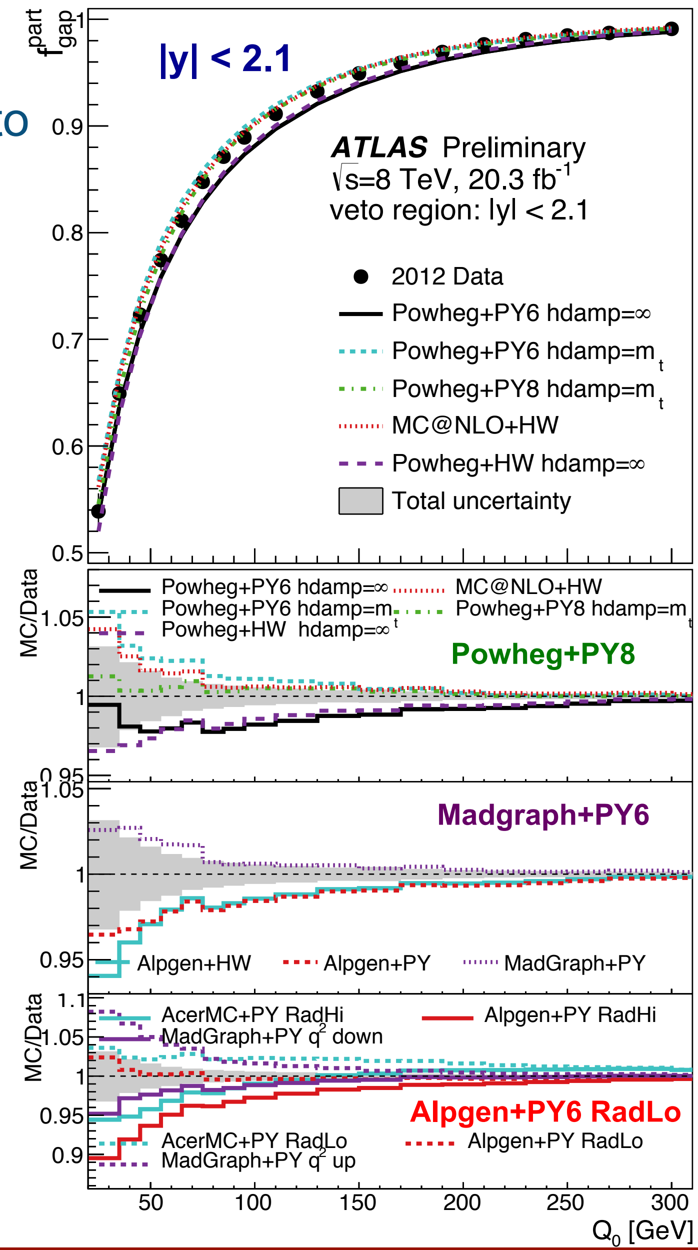
- Fraction of events with **no** extra jet above a given p_T (Q_0) for |y| < 2.1

  → sensitive to leading-p_T add. jet

- Comparison to different (N)LO + PS MC generators, also with varied PS radiation

Overall good agreement between data and predictions

- Can help constraining QCD radiation uncertainty



Compare to NLO+PS

Compare to LO multileg+PS

Compare to LO multileg+PS with varied PS radiation

$t\bar{t}$+Z and $t\bar{t}$+W at 13 TeV

ATLAS-CONF-2016-003
CMS-PAS TOP-16-009

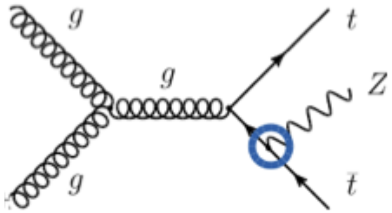
Very rare processes in SM

- Measure coupling of top to Z boson, important backgrounds for BSM and $t\bar{t}$+H

- Established at 8 TeV (also $t\bar{t}+\gamma$), first results at 13 TeV !
- $t\bar{t}$+Z (ATLAS & CMS):

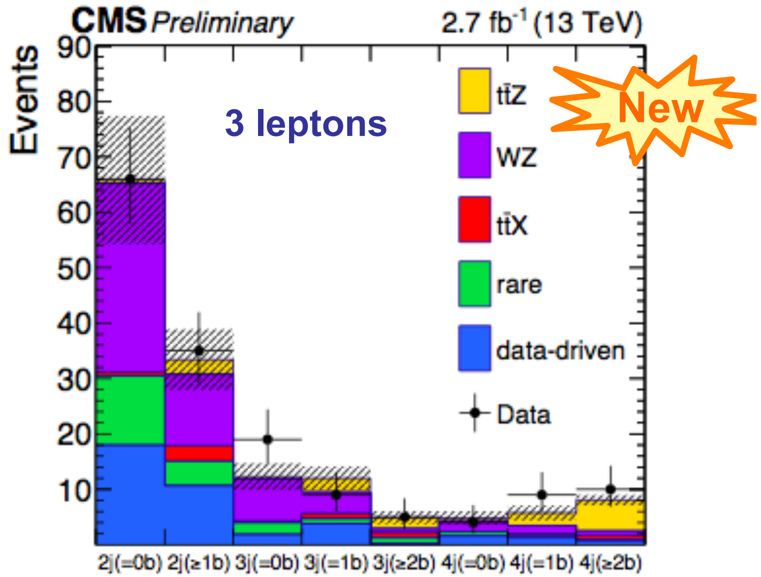
  3-4 leptons, > 2 jets in different (b) jet categories

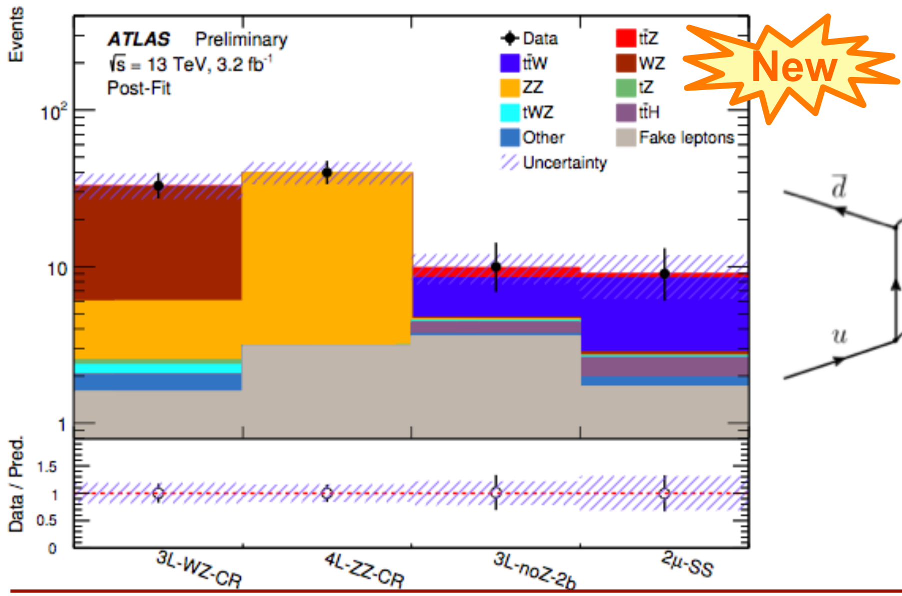
  - Extract $t\bar{t}$+Z from likelihood fit

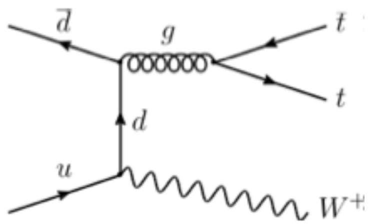


ATLAS: $\sigma(t\bar{t}+Z) = 0.9 \pm 0.3$ pb
CMS: $\sigma(t\bar{t}+Z) = 1.1 \pm 0.4$ pb

Theory (aMC@NLO) $= 0.76 \pm 0.08$ pb







- $t\bar{t}$+W (ATLAS):

  2-3 leptons (one same-sign pair) and > 2 jets in different categories

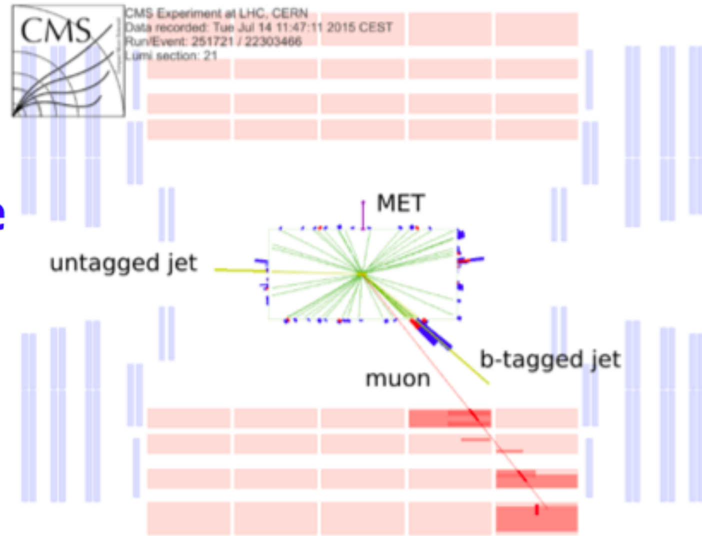
  - Extract $t\bar{t}$+W from likelihood fit

$\sigma(t\bar{t}+W) = 1.4 \pm 0.8$ pb

Theory (aMC@NLO) $= 0.57 \pm 0.06$ pb

13 TeV

single top candidate

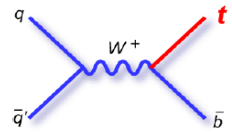


Single top quark

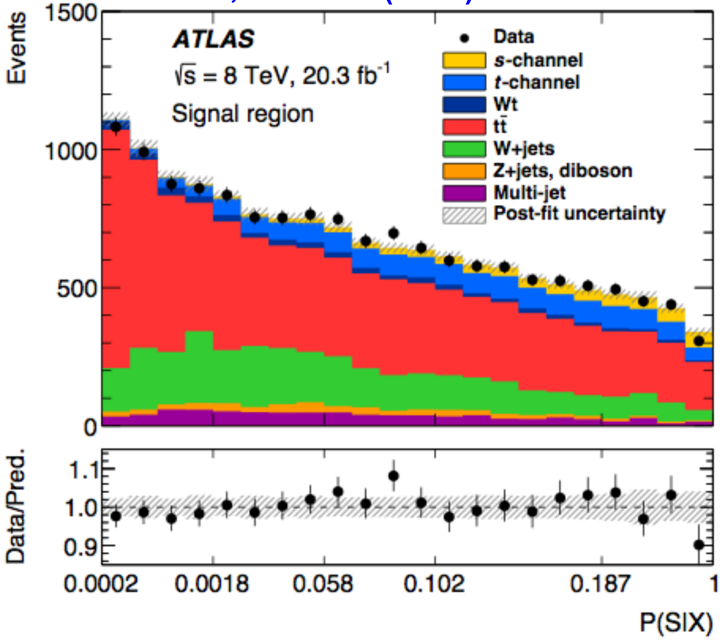
- Probe CKM matrix element $|V_{tb}|$, EWK coupling structure
- Probe alternative production mechanisms (e.g heavy bosons, FCNC)
- Sensitive to b-PDF and u/d-PDFs

→ More in talk by J. Andrea

Single top s-channel at 8 TeV



ATLAS, PLB 756 (2016) 228



- **ATLAS**: First evidence of s-channel at LHC !

  Selection: 1 lepton and 2 b-tagged jets

  - Use matrix element approach to discriminate signal
  - Profile likelihood fit including systematics

$$\sigma_s = 4.8 \pm 0.8(\text{stat.})^{+1.6}_{-1.3}(\text{syst.})\ \text{pb}$$ **(34%)**

3.2σ obs (3.9σ exp)

- **CMS**: s-channel at 7+8 TeV **New**

  Selection: 1 lepton, 2-3 jets, 1-2 b-tags

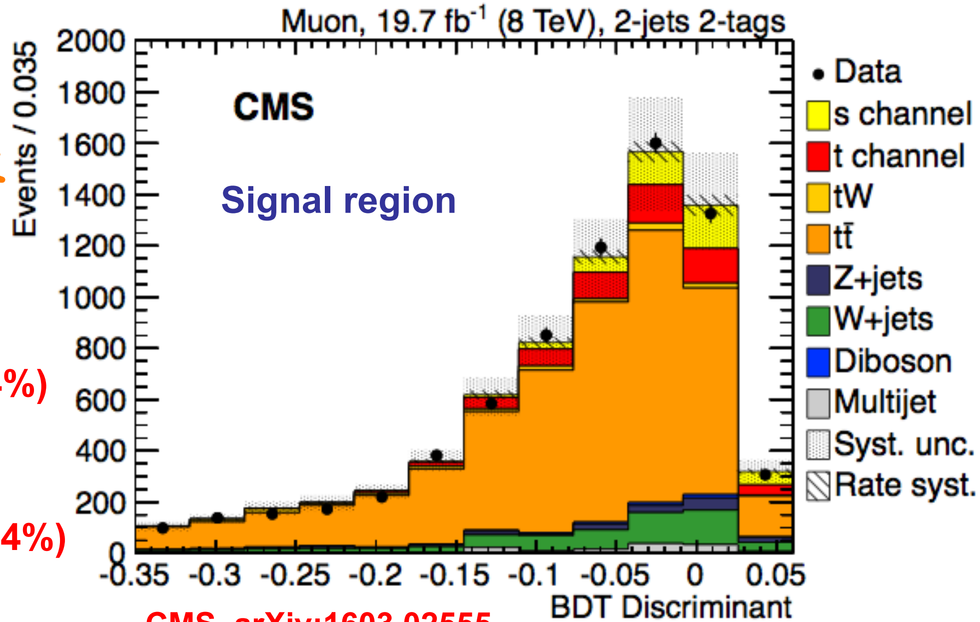
  - Use MVA approach to discriminate signal

8 TeV: $\sigma_s = 13.4 \pm 7.3\,(\text{stat} + \text{syst})\,\text{pb}$ **(54%)**

2.3σ obs (0.8σ exp)

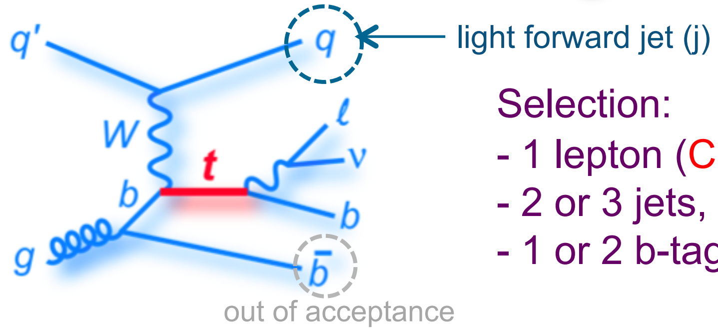
7 TeV: $\sigma_s = 7.1 \pm 8.1\,(\text{stat} + \text{syst})\,\text{pb}$ **(114%)**

0.9σ obs (0.5σ exp)

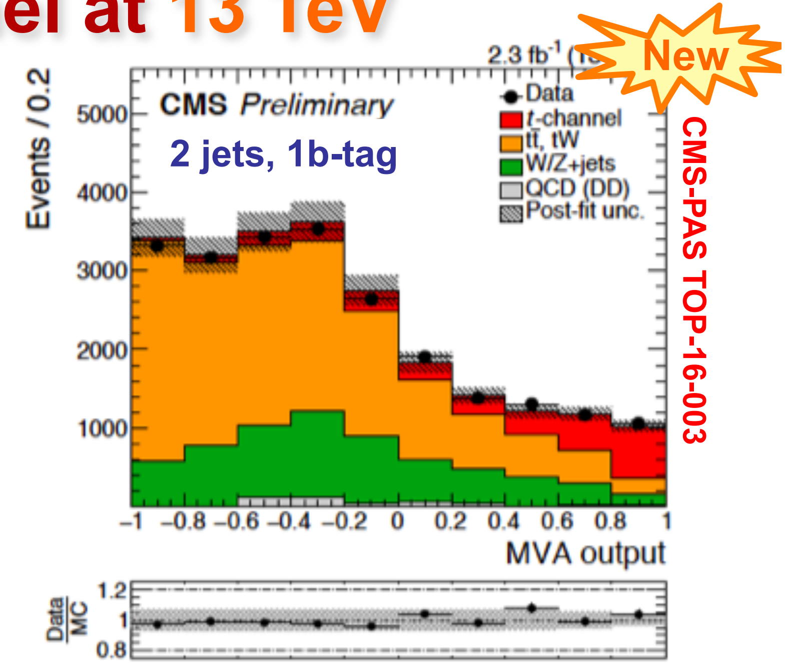


CMS, arXiv:1603.02555

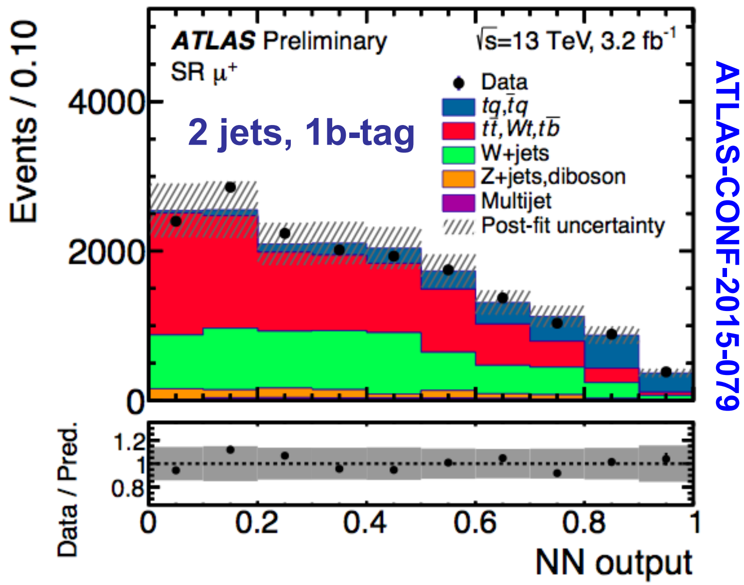
Single top t-channel at 13 TeV



Selection:
- 1 lepton (CMS: μ; ATLAS: μ/e)
- 2 or 3 jets,
- 1 or 2 b-tags



- Control regions for main backgrounds
- Extract signal from fit to MVA discriminator optimized to maximize background rejection
  - Most relevant variables: $\eta(j)$, m_t, $m_{l\nu b}$, m_{jb}, $m_T(W)$



- Cross sections:

ATLAS: $\sigma(t+\bar{t}) = 229 \pm 48$ pb	**(21%)**
CMS: $\sigma(t+\bar{t}) = 228 \pm 33$ pb	**(15%)**

Main syst for both: signal model, JES

- CKM matrix element $|V_{tb}| = \sqrt{(\sigma^{obs.}_{t\text{-}ch.} / \sigma^{theo.}_{t\text{-}ch})}$:

ATLAS: $|V_{tb}| = 1.03 \pm 0.11$
CMS: $|V_{tb}| = 1.02 \pm 0.07$

(for $|V_{ts}|$, $|V_{td}| << |V_{tb}|$)

t-channel differential at 13 TeV

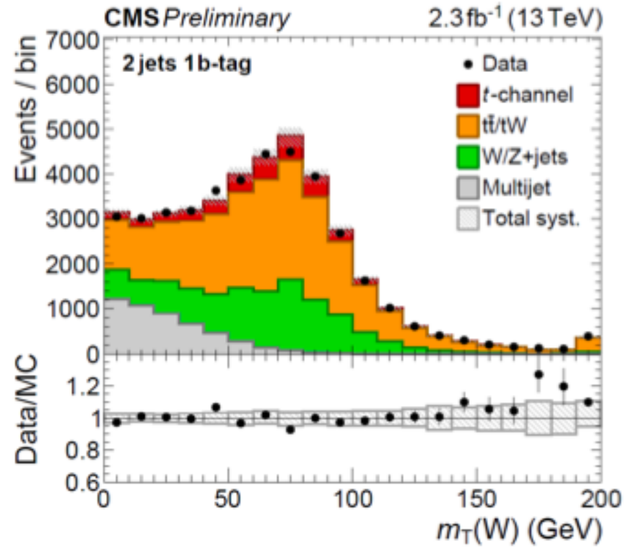
CMS-PAS TOP-16-004

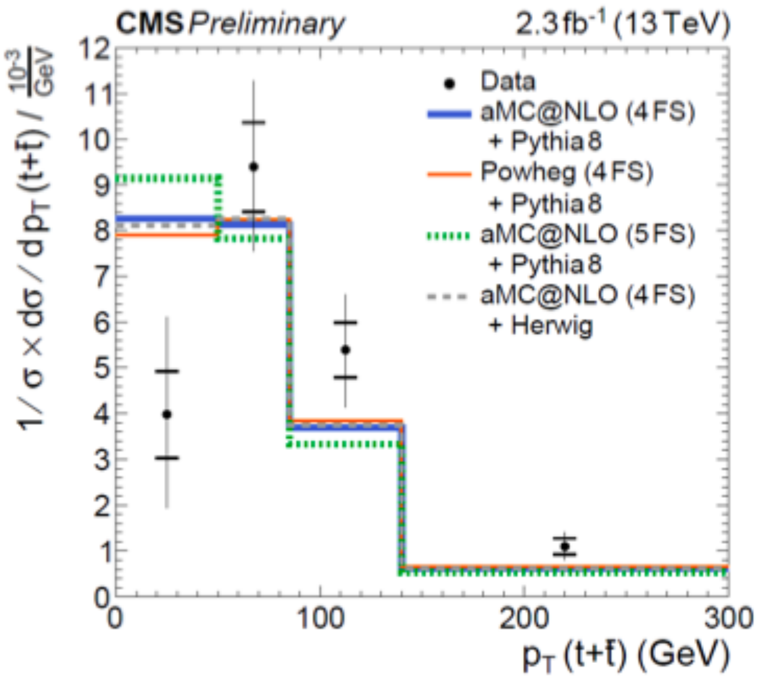
New

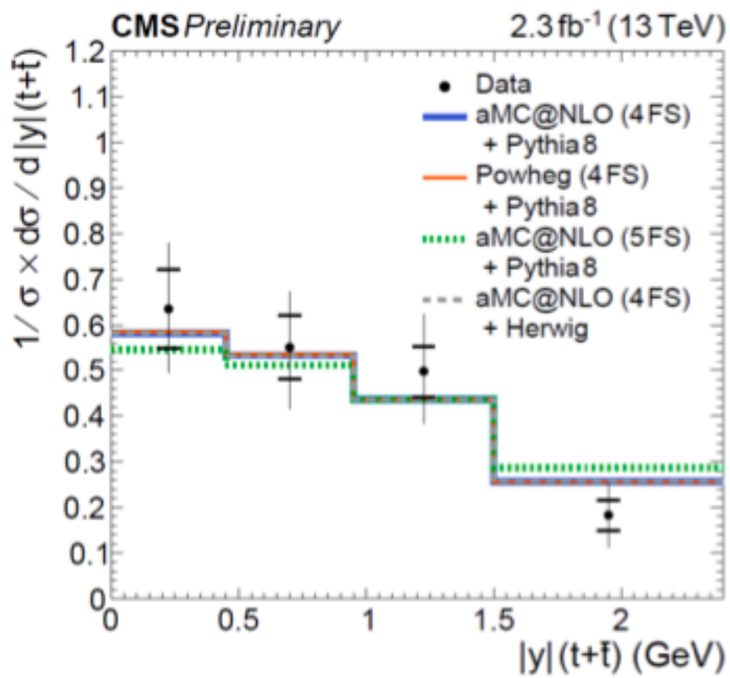
First single top differential cross sections at 13 TeV !

1 isolated μ, 2 or 3 jets, 1 or 2 b-tags

- Maximum likelihood fit to $m_T(W)$ (for $m_T(W) < 50$ GeV) and MVA discriminant (for $m_T(W) > 50$ GeV)
  - Observables in the discriminant selected to have minimum correlation with top p_T and y
- Data described by predictions within large uncertainties







Single top production: the big picture

All single top processes
studied in Run-I

New

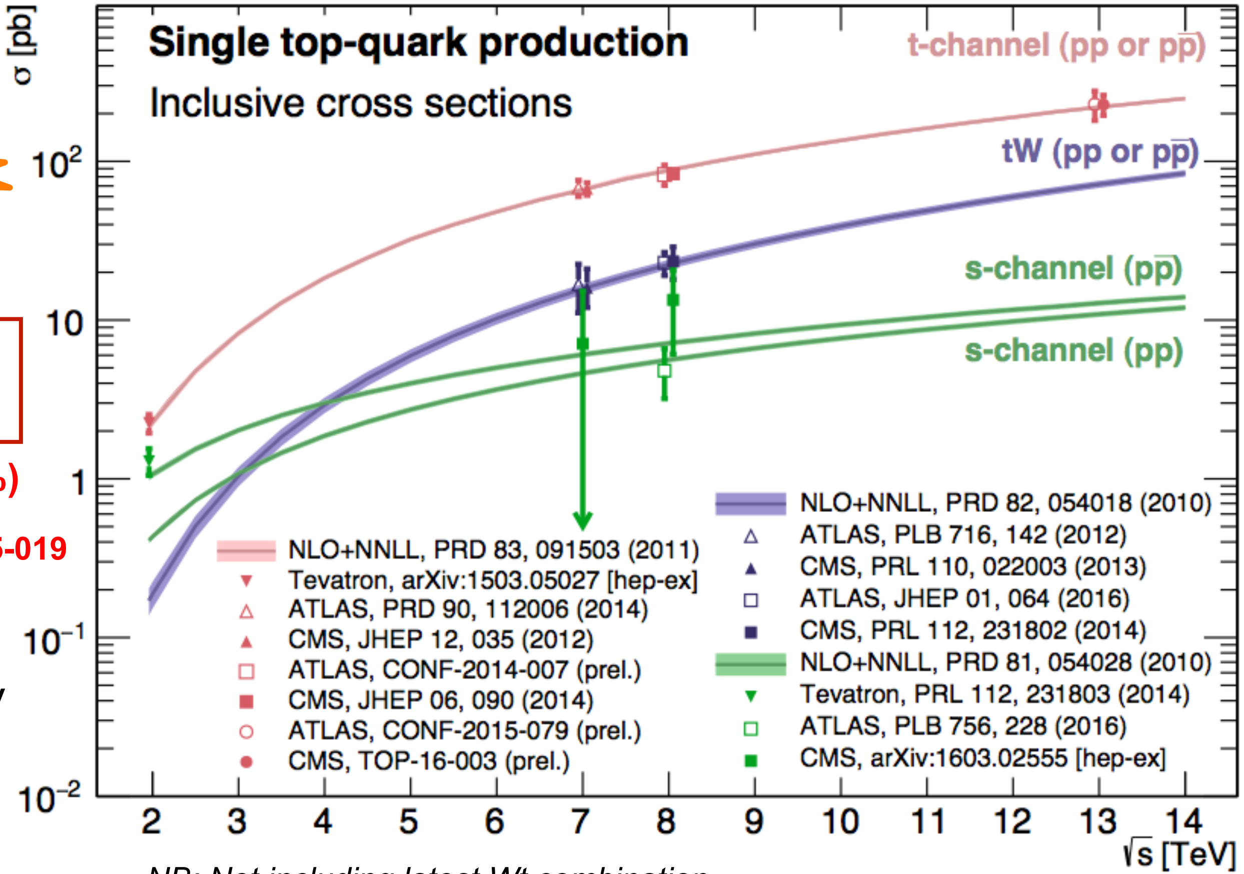
- Final ATLAS & CMS combination of Wt at 8 TeV:

$\sigma(Wt) = 23.1 \pm 1.1\ (stat) \pm 3.3\ (syst) \pm 0.8\ (lumi)$ pb

(15.6%)

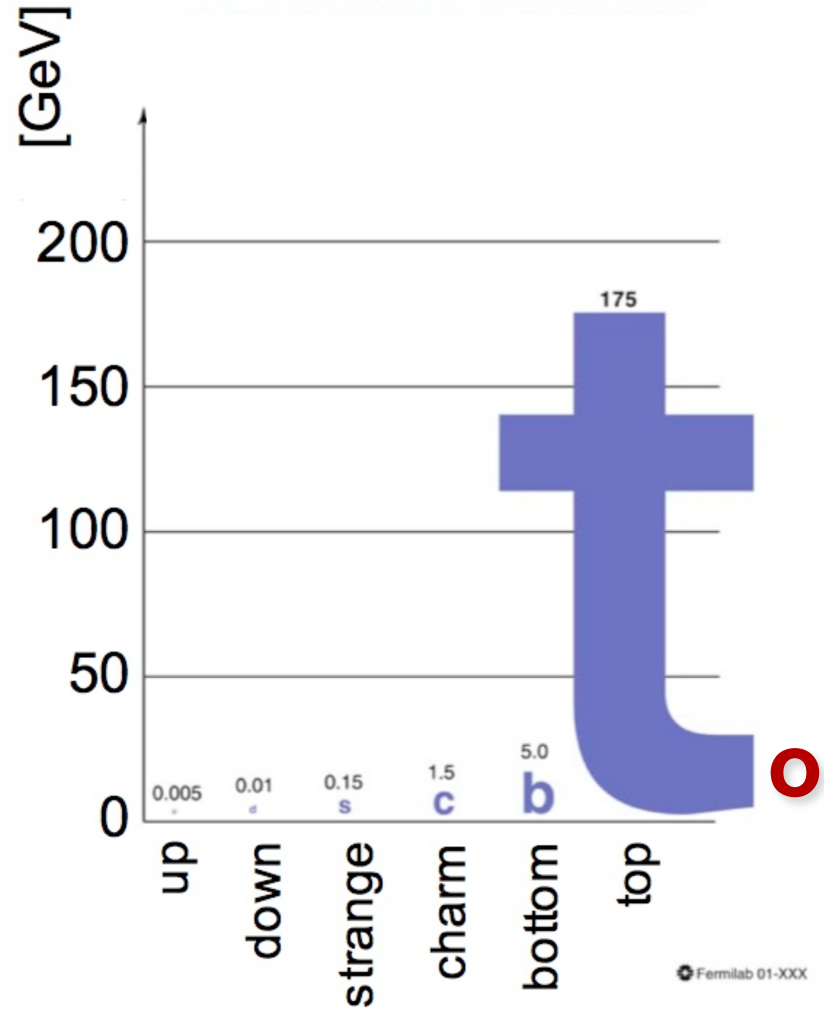
ATLAS-CONF-2016-023 / **CMS-PAS TOP-15-019**

- First t-channel results at 13 TeV by ATLAS and CMS



NB: Not including latest Wt combination

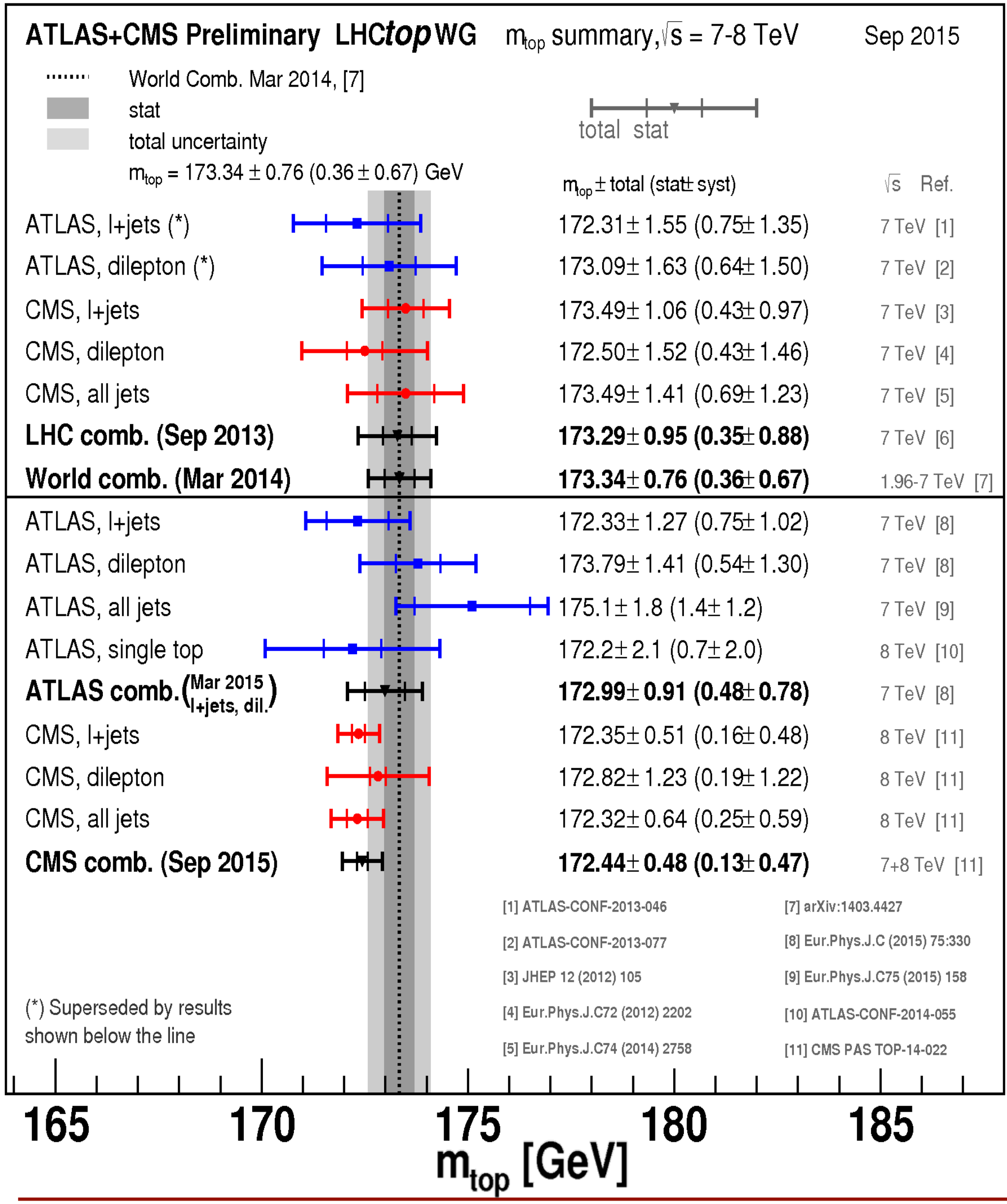
Ramping up towards new era of high-precision in single top



op quark properties

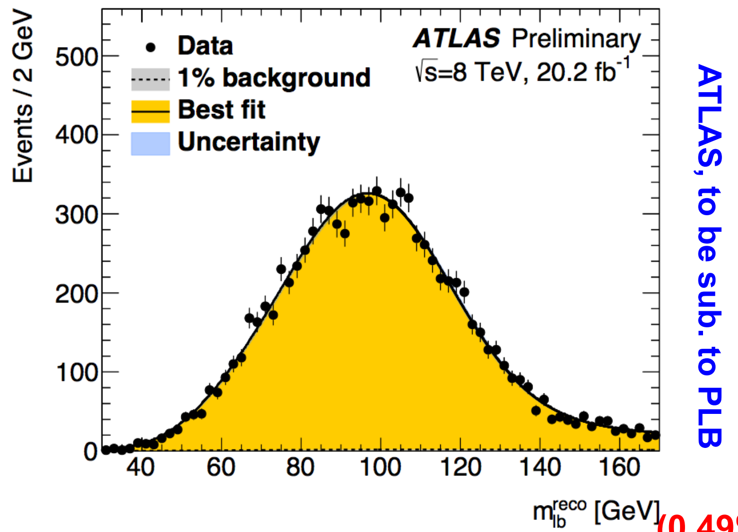
→ More in talks by J. Piedra, I. Brock

"Standard" top quark mass



- Latest result from ATLAS: New
  - Likelihood fit to mlb distribution in dilepton events

2 leptons, ≥ 2 jets, b-tagged jets, cut on p_T of the lepton-b-jet systems ($p_T$lb)



(0.49%)

$$m_{top} = 172.99 \pm 0.41\,(\text{stat.}) \pm 0.74\,(\text{syst.})\,\text{GeV}$$

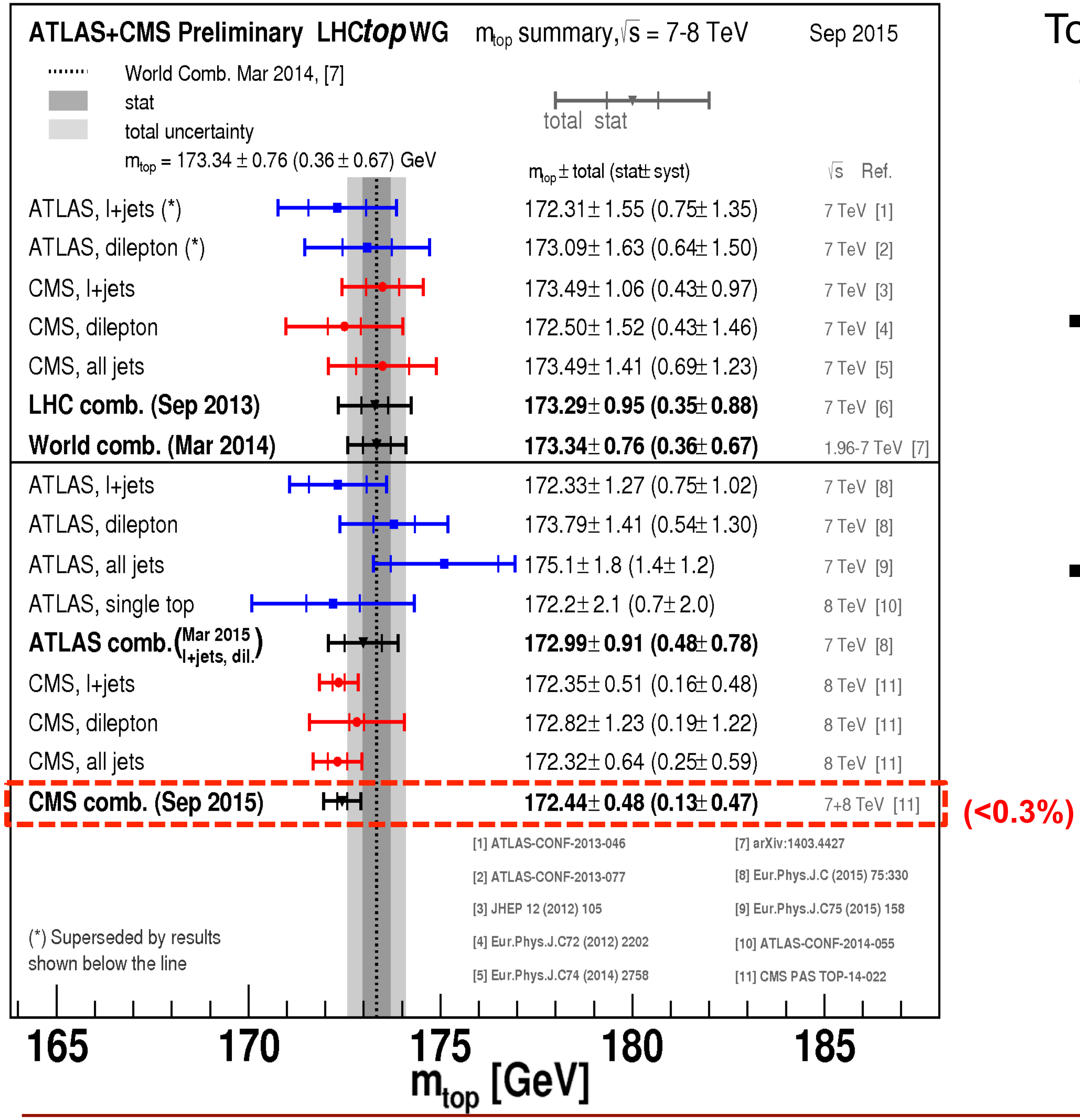
Main syst: (b)JES, hadronization, ISR/FSR

- Combine with best ATLAS result:

$$m_{top}^{comb} = 172.84 \pm 0.34\,(\text{stat.}) \pm 0.61\,(\text{syst.})\,\text{GeV}$$

(0.40%)

"Standard" top quark mass



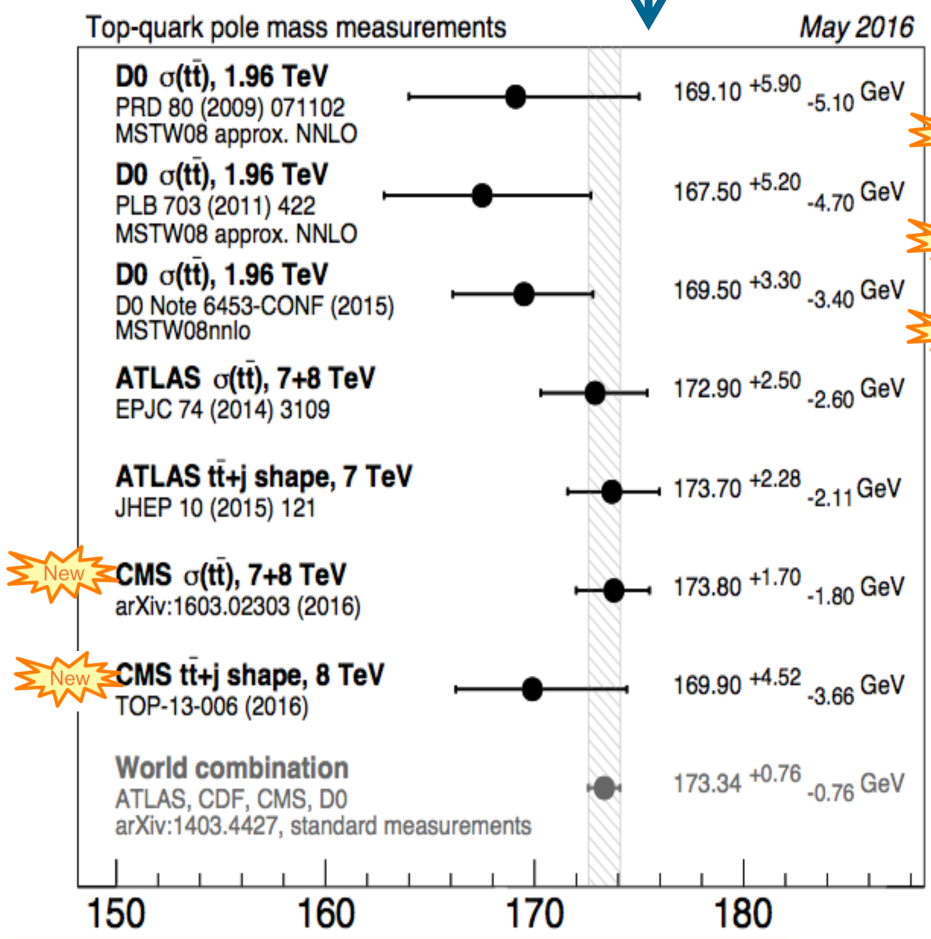
Top mass results using standard (i.e, most sensitive) methods are reaching a precision of **order 500 MeV** (< 0.3%)

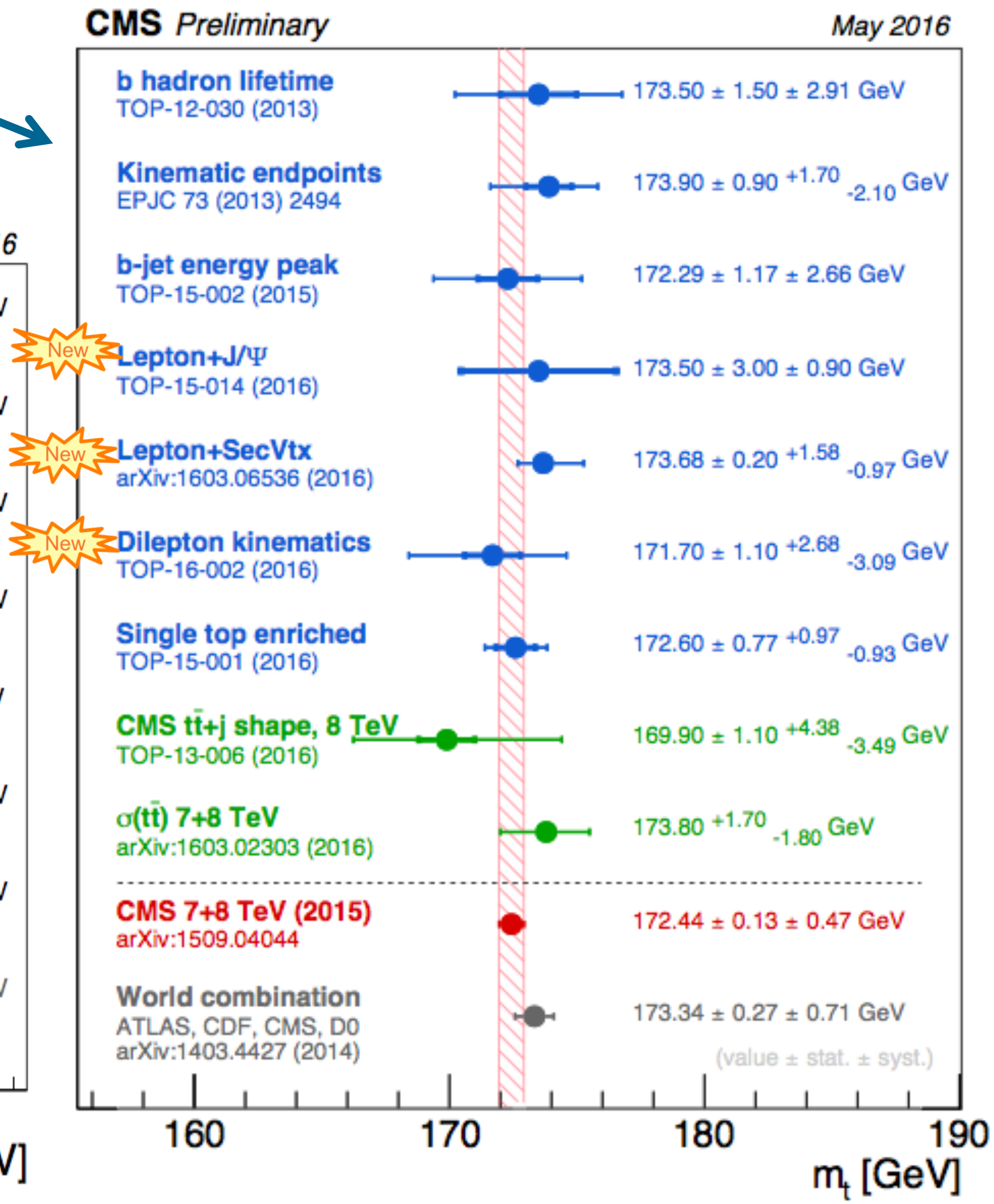
- Dominant uncertainties:
  - Jet energy response calibration
  - Hadronization modelling
- Continuous efforts to:
  - Improve current techniques
  - Develop new methods
  - Combine results

→ More in talk by J. Piedra

Pole mass and other alternative methods

- Exploit other ("cleaner") observables
- Extract pole mass from cross sections



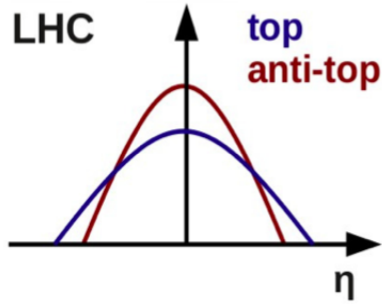


Pole mass reaching < 2 GeV precision

$t\bar{t}$ charge asymmetry

Top-pair angular production asymmetries may indicate BSM top production interfering with SM

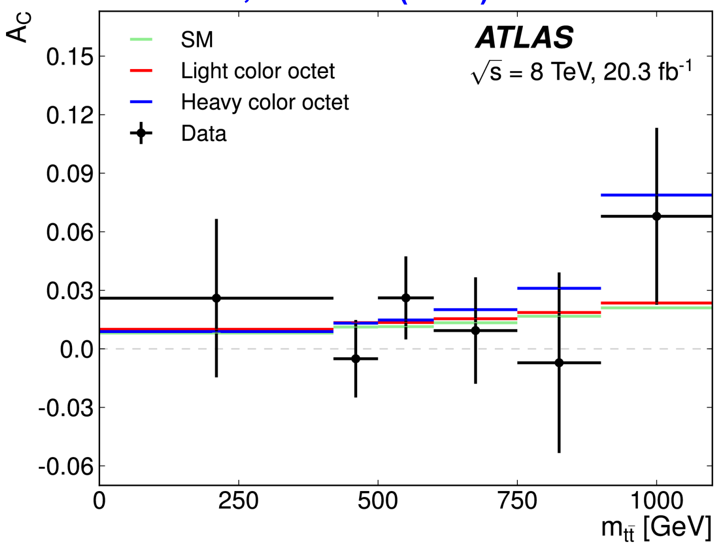
- NLO effect originating from interference of $q\bar{q} \rightarrow t\bar{t}$ diagrams, can be enhanced by BSM physics (e.g, W', axigluon)
- LHC: top is more forward than antitop
- Several channels exploited in Run-I, also boosted top regime
- Investigate regions of phase space where charge asymmetry can be enhanced (differentially in, e.g, m(tt), p_T(tt), |y(tt)|)



$$A_C = \frac{N(\Delta|y|>0) - N(\Delta|y|<0)}{N(\Delta|y|>0) + N(\Delta|y|<0)}$$

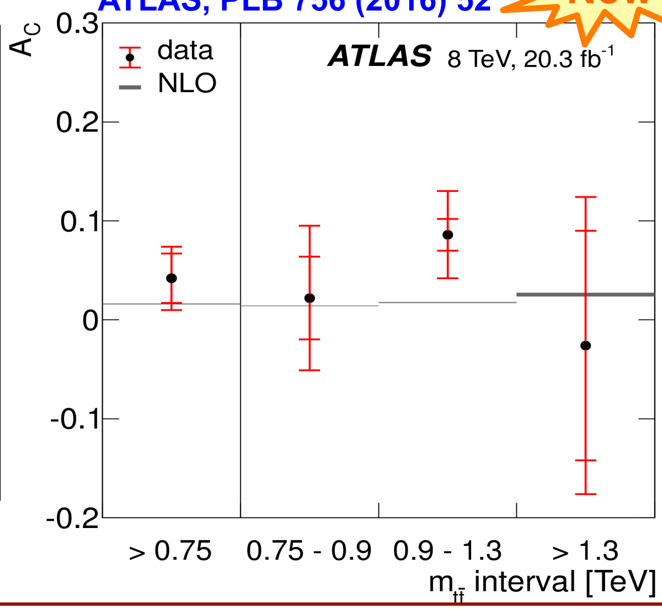
$$\Delta|y| = |y_{top}| - |y_{antitop}|$$

ATLAS, EPJC 76 (2016) 87



ATLAS, PLB 756 (2016) 52

New



$t\bar{t}$ charge asymmetry

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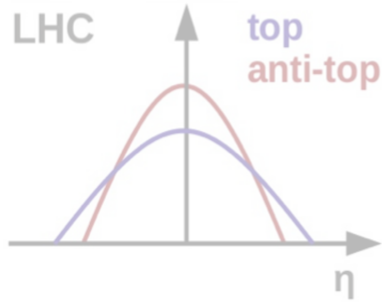

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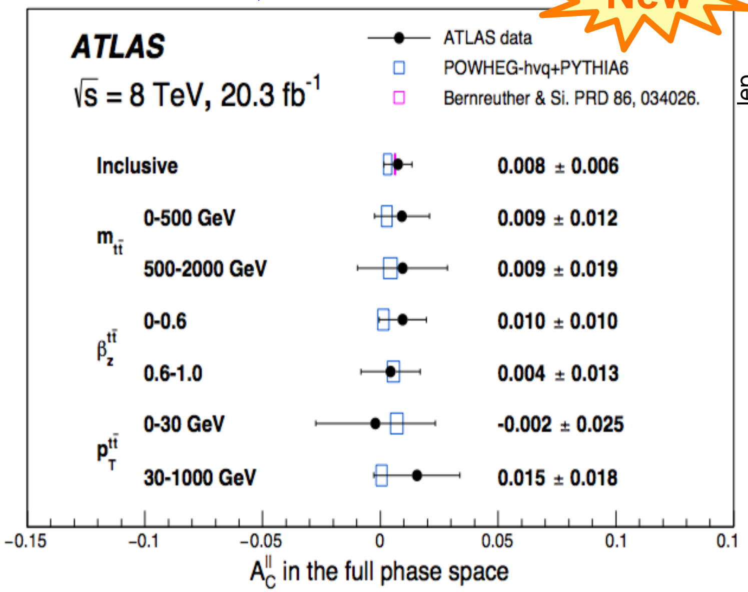
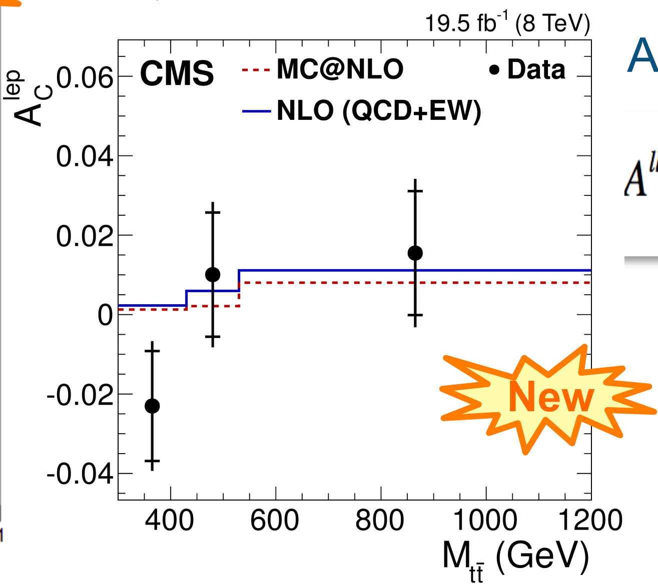
ATLAS, arXiv:1604.05538 New



CMS, arXiv:1603.06221



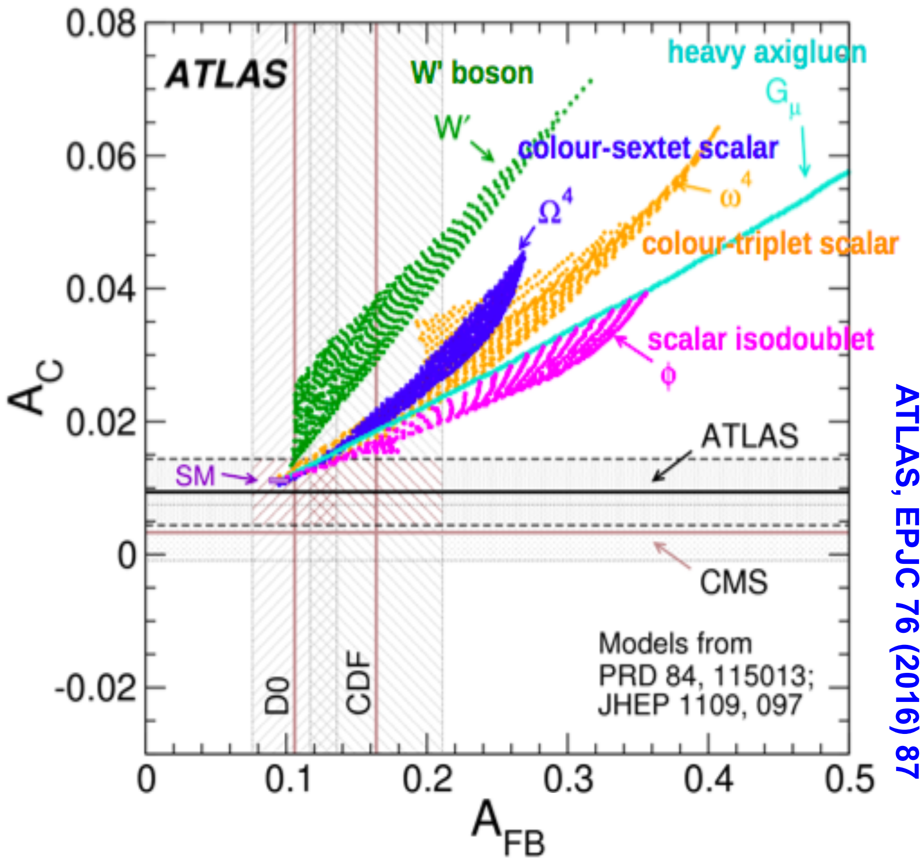
Also: lepton asymmetry

$$A^{ll}_C = \frac{N(\Delta|\eta|>0) - N(\Delta|\eta|<0)}{N(\Delta|\eta|>0) + N(\Delta|\eta|<0)}$$

$$\Delta|\eta| = |\eta_{l+}| - |\eta_{l-}|$$

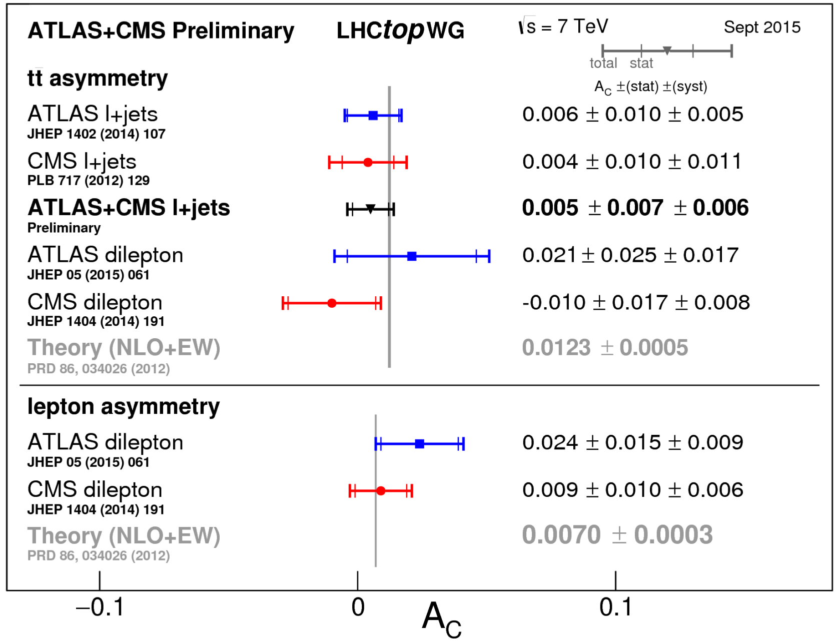
$t\bar{t}$ charge asymmetry: summary

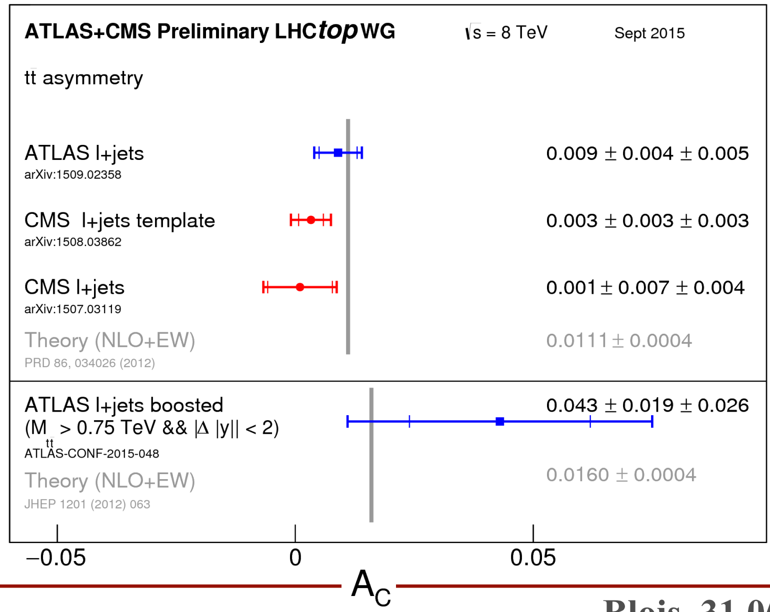
- Plethora of results from ATLAS and CMS
- No significant deviation from SM
- Several BSM models can be excluded



ATLAS, EPJC 76 (2016) 87

→ More in talk by I. Brock





Not including latest lepton asym. results

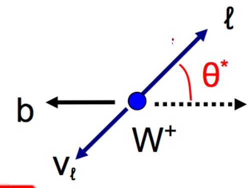
W helicity in top decays in Run-I

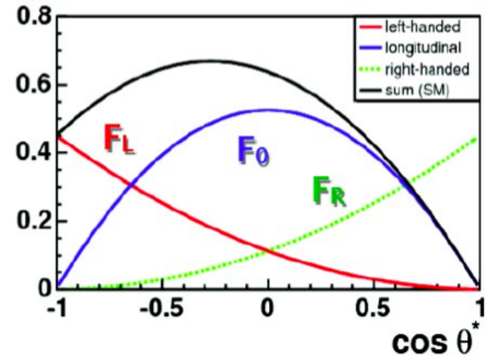
CMS, to be sub. to PLB

New

Anomalous contributions to the tWb vertex change the probabilities of the W helicity states

- In SM: 3 possible W helicity states ($F_R+F_L+F_0 = 1$):

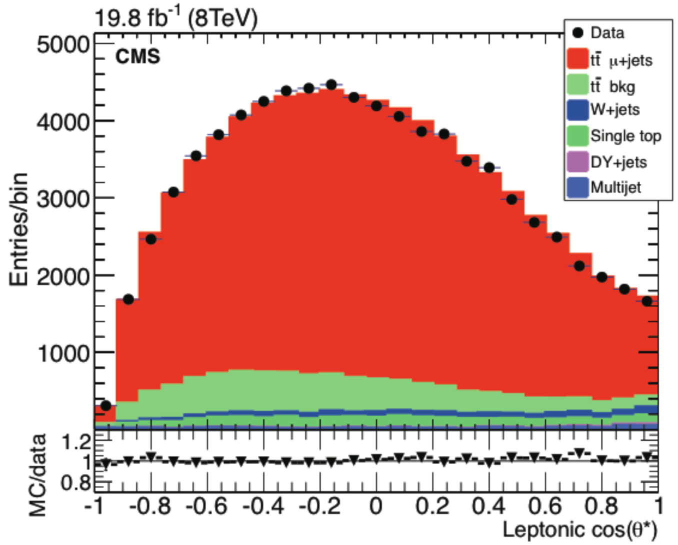




$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*} = \frac{3}{8}(1+\cos\theta^*)^2 F_R + \frac{3}{8}(1-\cos\theta^*)^2 F_L + \frac{3}{4}\sin^2\theta^* F_0$$

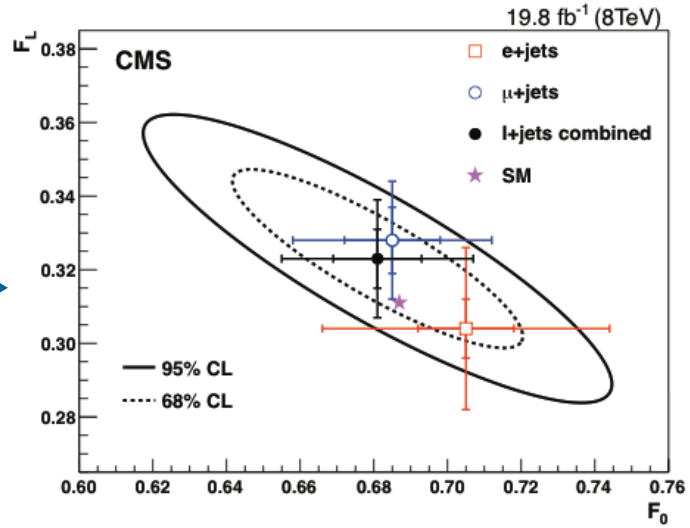
SM: ~0% ~30% ~70%

- Measure sensitive variable cos(θ*) in events with e/μ + 4 jets (2 b-tags):



Most precise F_0 and F_L results so far !

(< 5%)



$F_0 = 0.681 \pm 0.012$ (stat) ± 0.023 (syst)
$F_L = 0.323 \pm 0.008$ (stat) ± 0.014 (syst)
$F_R = -0.004 \pm 0.005$ (stat) ± 0.014 (syst)

Also used to place limits on anomalous couplings

Summary & outlook

- **Top physics: key to QCD, electroweak and New Physics**
- **In Run-I, the LHC became a real "top factory"**
  - **Top quark production & properties measurements entered precision regime**
  - **First measurements of associated $t\bar{t}$+X production**
  - **Started to challenge theory predictions in many respects**
- **First 13 TeV cross section results !**
- **So far, good agreement with SM predictions**
- **Run-II: expect 100 fb^{-1} by end of 2018: ~80M $t\bar{t}$, ~20M single top, ~80000 $t\bar{t}Z$ and tZ events**
  - **Trade off statistics for systematics**
  - **Improvements in MC models and theory calculations**
  - **Access to new physics in the top environment**

Exciting times ahead !

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

CMS: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP

Additional information

CP asymmetry in $t\bar{t}$ events at 8 TeV

CMS-PAS TOP-16-001 New

Probing CP violation for the first time in $t\bar{t}$ production

- Use observables that show asymmetry in presence of CP violation

$$A_{CP}(O_i) = \frac{N_{events}(O_i > 0) - N_{events}(O_i < 0)}{N_{events}(O_i > 0) + N_{events}(O_i < 0)}$$

$$O_2 = \epsilon(P, p_b + p_{\bar{b}}, p_\ell, p_{j1}) \xrightarrow{lab} \propto (\vec{p}_b + \vec{p}_{\bar{b}}) \cdot (\vec{p}_\ell \times \vec{p}_{j1})$$

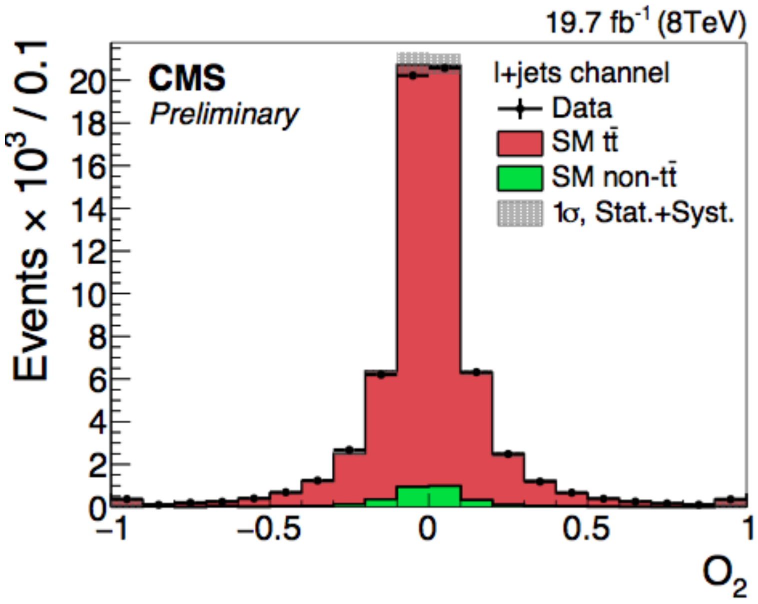
$$O_3 = Q_\ell \epsilon(p_b, p_{\bar{b}}, p_\ell, p_{j1}) \xrightarrow{b\bar{b}\ CM} \propto Q_\ell \vec{p}_b \cdot (\vec{p}_\ell \times \vec{p}_{j1})$$

$$O_4 = Q_\ell \epsilon(P, p_b - p_{\bar{b}}, p_\ell, p_{j1}) \xrightarrow{lab} \propto Q_\ell (\vec{p}_b - \vec{p}_{\bar{b}}) \cdot (\vec{p}_\ell \times \vec{p}_{j1})$$

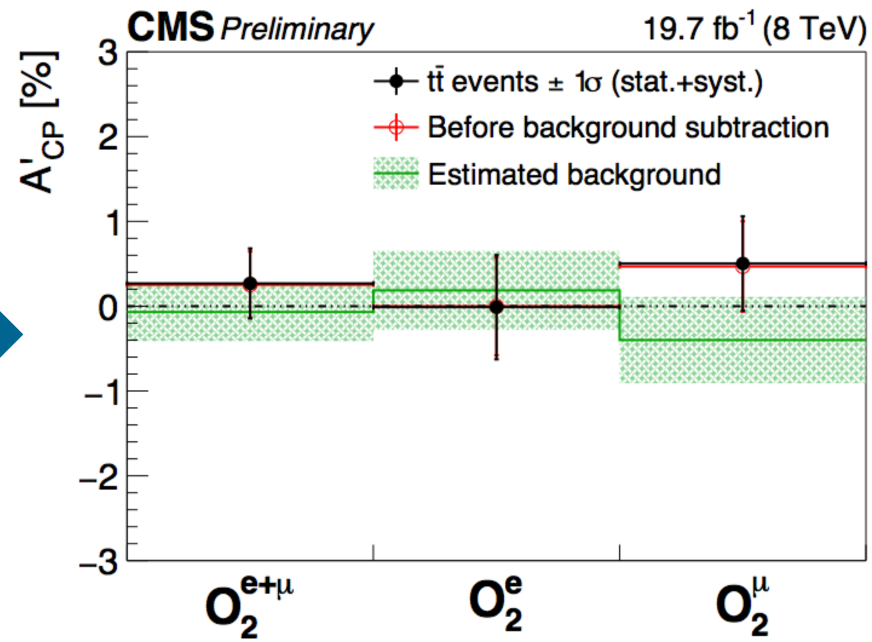
$$O_7 = q \cdot (p_b - p_{\bar{b}})\, \epsilon(P, q, p_b, p_{\bar{b}}) \xrightarrow{lab} \propto (\vec{p}_b - \vec{p}_{\bar{b}})_z (\vec{p}_b \times \vec{p}_{\bar{b}})_z$$

- Measurement in the l+jets channel

Selection: 1 e/μ, ≥ 4 jets, 2 b-tags



No deviation from SM expectation:



$t\bar{t}$ cross section ratios

ATLAS-CONF-2015-049

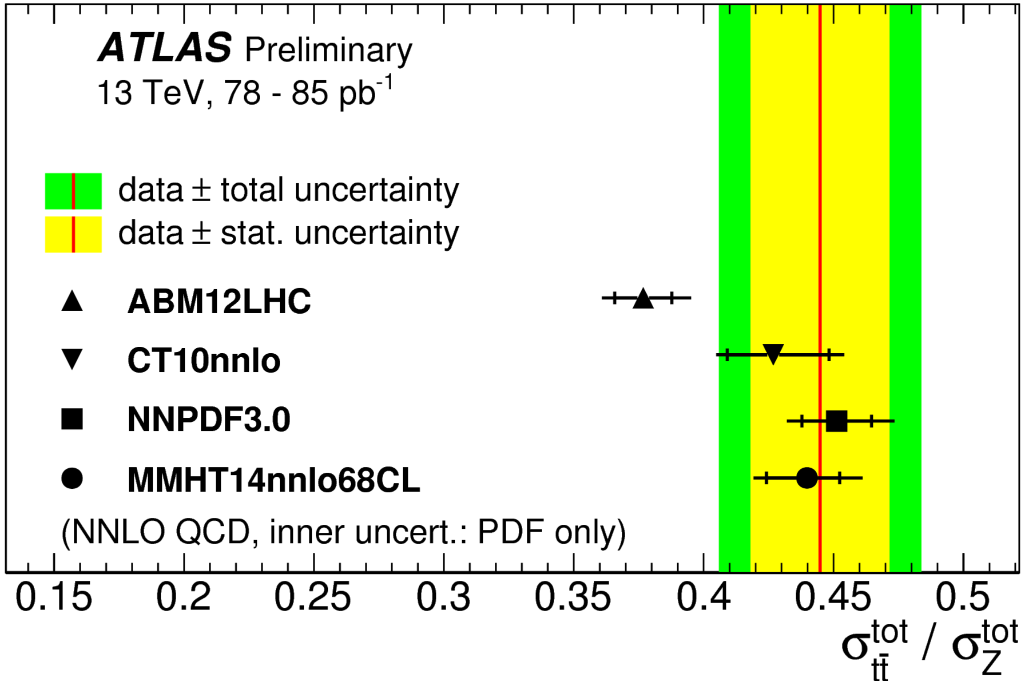
Sep'15

Ratios of cross sections are expected to cancel out some of the systematic uncertainties

→ Comparison to theory: potential to constrain PDFs, sensitive to BSM effects

- $t\bar{t}$/Z ratio: testing the gg/qq ratio
  - Reduces luminosity uncertainty (10% → 1%), electron ID (3.2% → 1.3%)

$$R_{t\bar{t}/Z} = 0.445 \pm 0.027\ (\text{stat}) \pm 0.028\ (\text{syst}) = 0.445 \pm 0.039$$



- General good agreement between data and different PDF
  - ABM12LHC uses smaller gluon density

Run-II: potential to explore different ratios, also at different energies, to constrain further PDFs

Differential cross sections: fixed order calculations

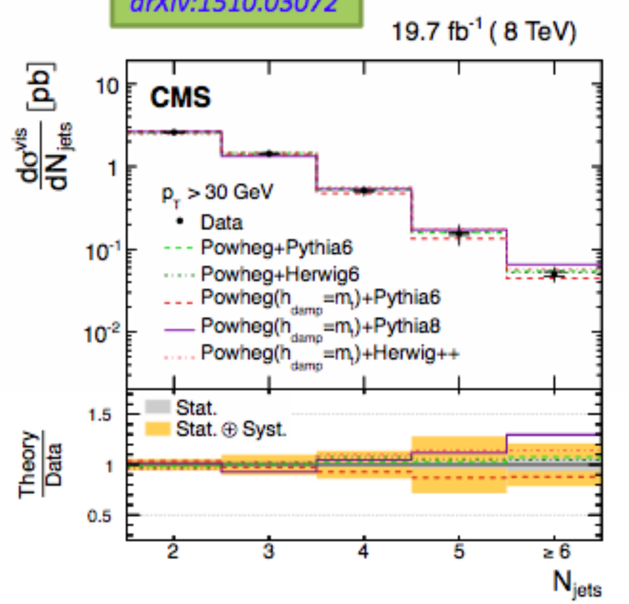
- **approx. NNLO - DiffTop,** *S.Moch et al*
  - the uncertainty is the full theory uncertainty, obtained by adding in quadrature PDF and α_S uncertainties
  - scale uncertainty (simultaneous variation of ren. and fact. scales by factors 2 and 0.5; the scale is set to m_t= 172.5 GeV)
  - variation of m_t by +-1 GeV
- **approx. N^{3}LO** *N.Kidonakis*
  - the uncertainty is only the scale uncertainty - simultaneous variation of ren. and fact. scales by factors 2 and 0.5
  - the scale is set to m_t = 172.5 GeV).
- **NLO+NNLL'** , *B.Pecjak et al.*
  - the uncertainty is only the scale uncert, where the factorization scale μ_F is:
  - for pT(top): $\mu_F = m_T = \mathrm{sqrt}(m_t^2 + p_T(top)^2)$, and it is varied by factors 2 and 0.5
  - for m(ttbar): μ_F = m(ttbar)/2, and it is varied by factors 2 and 0.5
- **NNLO,** *A.Mitov et al.*
  - the uncertainty is only the scale uncertainty. The scale (dynamic) is:
  - for p_T(top): $\mu = m_T/2$ (varied by factors 2 and 0.5)
  - for y(top), pT(ttbar), m(ttbar), y(ttbar): $\mu = H_T/4$

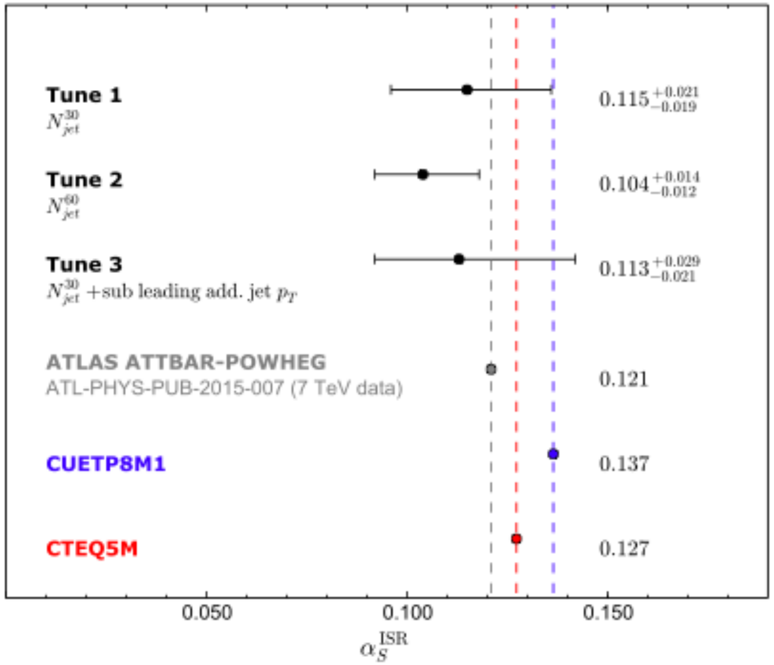
Shower α_S tuning

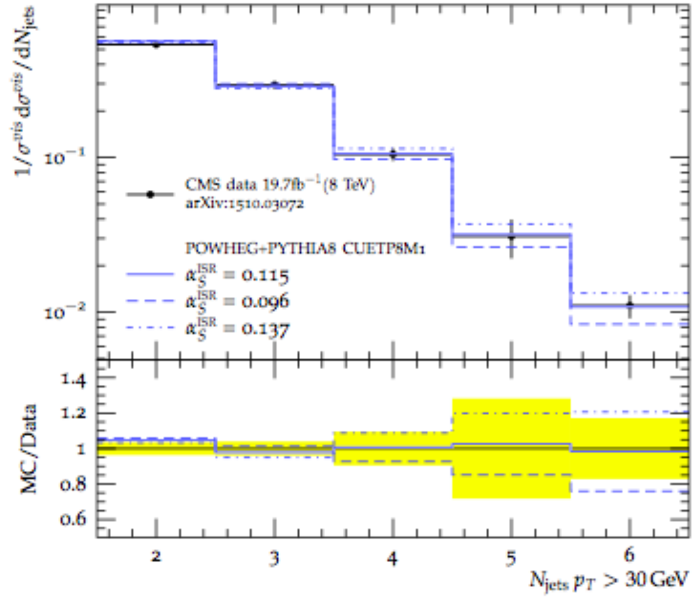
- Discrepancies at high Njets → e.g. non-optimal parton shower α_s.
- Use N_{jets} > 3 where jets predominantly originate from the parton shower.

Rivet routine: CMS_2015_I1397174

arXiv:1510.03072





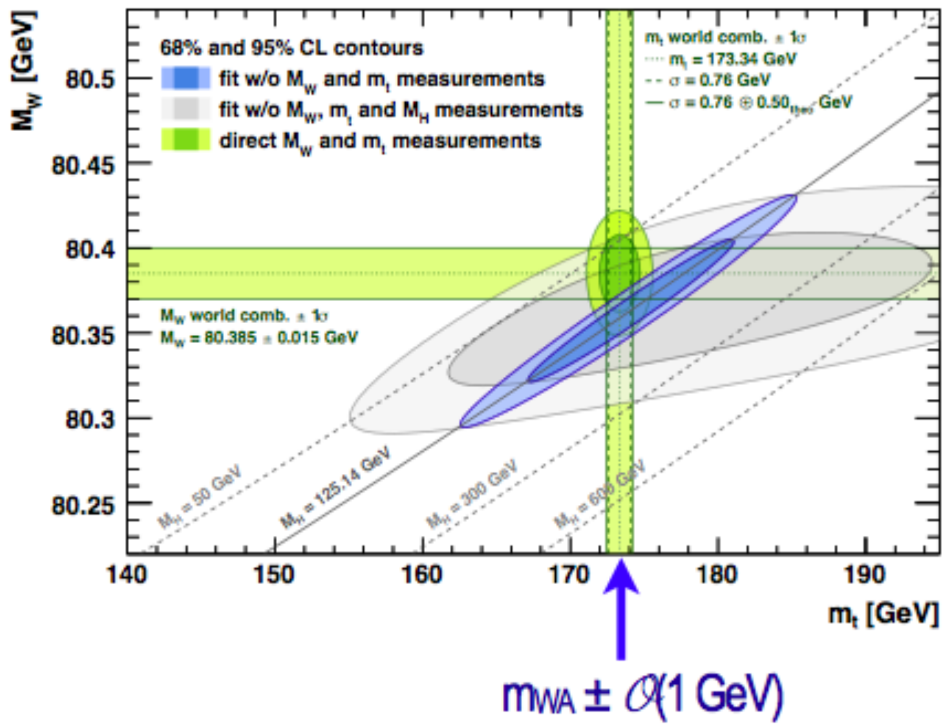


Top quark mass

Fundamental parameter in the SM, not an observable
→ scheme-dependent

- Pole mass: top quark as free parton
- Other schemes, e.g, running mass
- MC mass (mass as defined in MC)

[arXiv:1407.3792]



- Difference between 'direct' MC mass and pole mass estimated to be O(1) GeV

- 'Direct' mass measurements:
  - Reconstruct m_{top}(rec) and extract m_{top}(MC)
  - Experimentally most precise, limited by
    - flavour-dependent jet energy uncertainties
    - modelling of hadronization

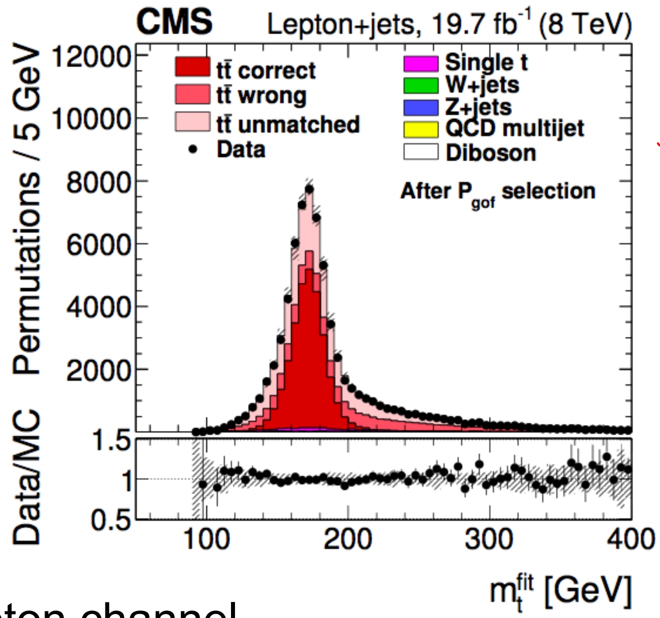
- 'Alternative' methods:
  - Use experimentally cleaner observables (i.e, no jets)
  - Use theoretically calculable observables with some sensitivity to the top mass

High precision top mass measurements

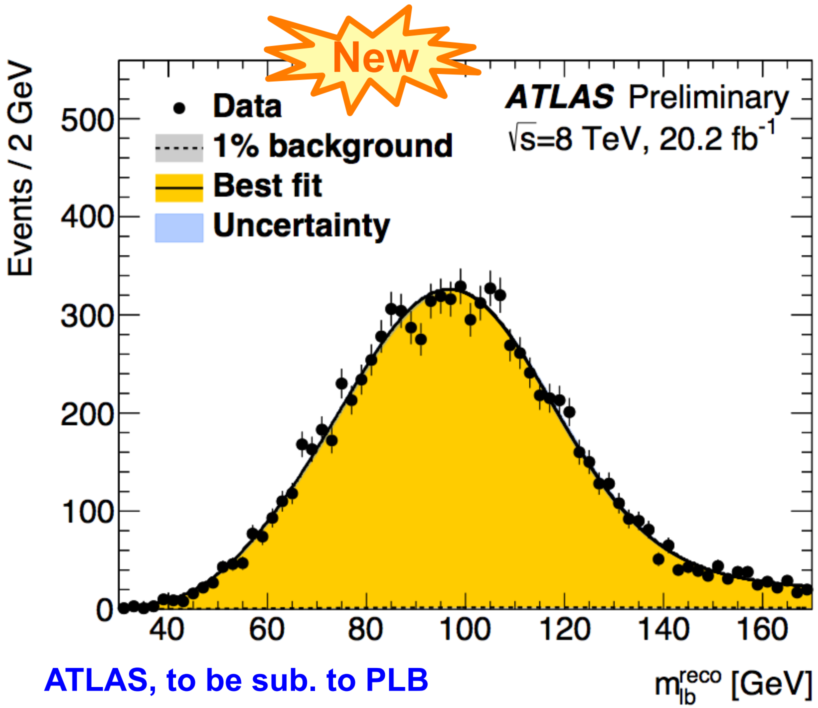
- CMS: l+jets channel: 1 μ/e, ≥ 4 jets, 2 b-tags
  - 2D likelihood fit to extract m_{top} and light-quark jet energy scale from W-mass constraint
  - All different jet permutations are taken into account

$$m_t^{hyb} = 172.35 \pm 0.16\,(\text{stat+JSF}) \pm 0.48\,(\text{syst})\,\text{GeV}$$ (0.29%)

Main syst: bJES, b hadron decay modelling



CMS, arXiv:1509.04044



ATLAS, to be sub. to PLB

- ATLAS: dilepton channel

  2 leptons, ≥ 2 jets, b-tagged jets, cut on p_T of the lepton-b-jet systems ($p_T$lb)
  - Likelihood fit to mlb distribution

$$m_{top} = 172.99 \pm 0.41\,(\text{stat.}) \pm 0.74\,(\text{syst.})\,\text{GeV}$$ (0.49%)

Main syst: (b)JES, hadronization, ISR/FSR

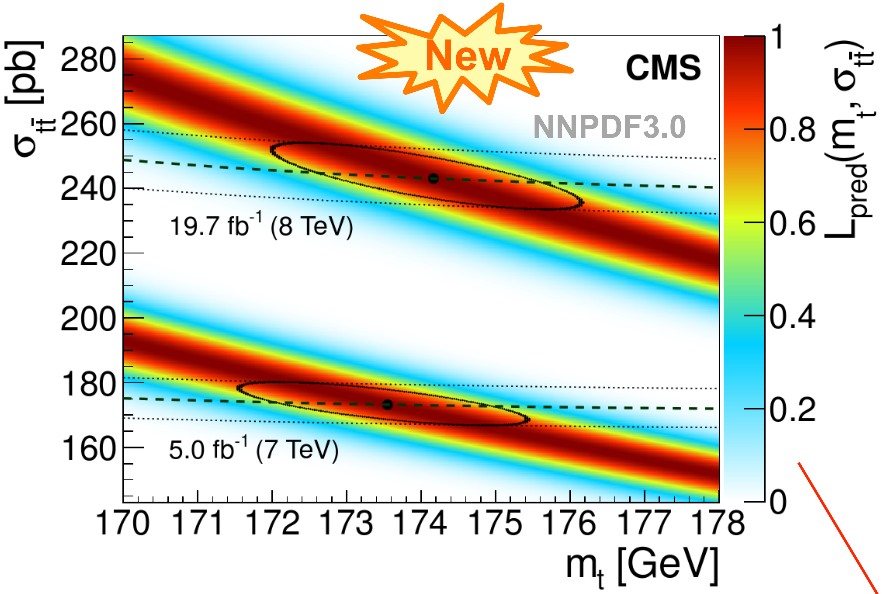
- Combine with 7 TeV result (l+jets,dileptons): ATLAS, EPJC 75 (2015) 330

$$m_{top}^{comb} = 172.84 \pm 0.34\,(\text{stat.}) \pm 0.61\,(\text{syst.})\,\text{GeV}$$ (0.40%)

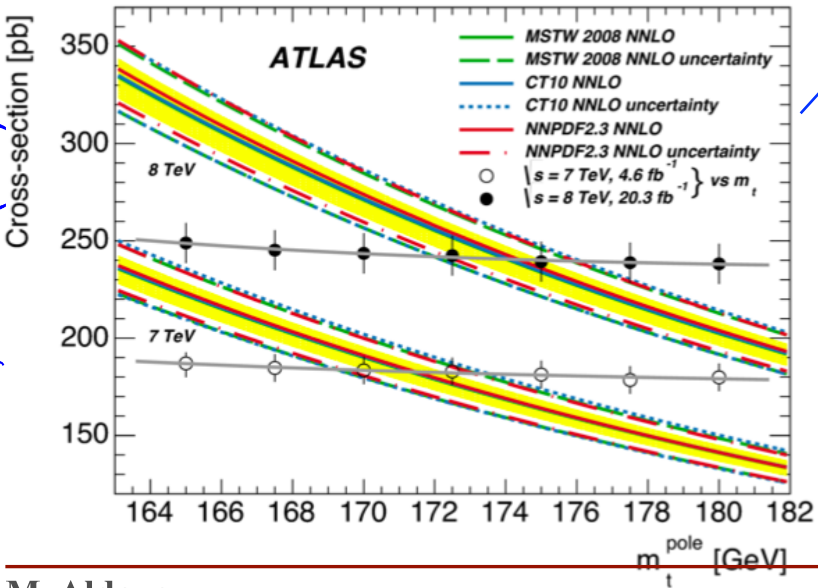
Top pole mass from $\sigma(t\bar{t})$

Mass dependence of predicted cross section allows determining m_t from measured $\sigma(tt)$

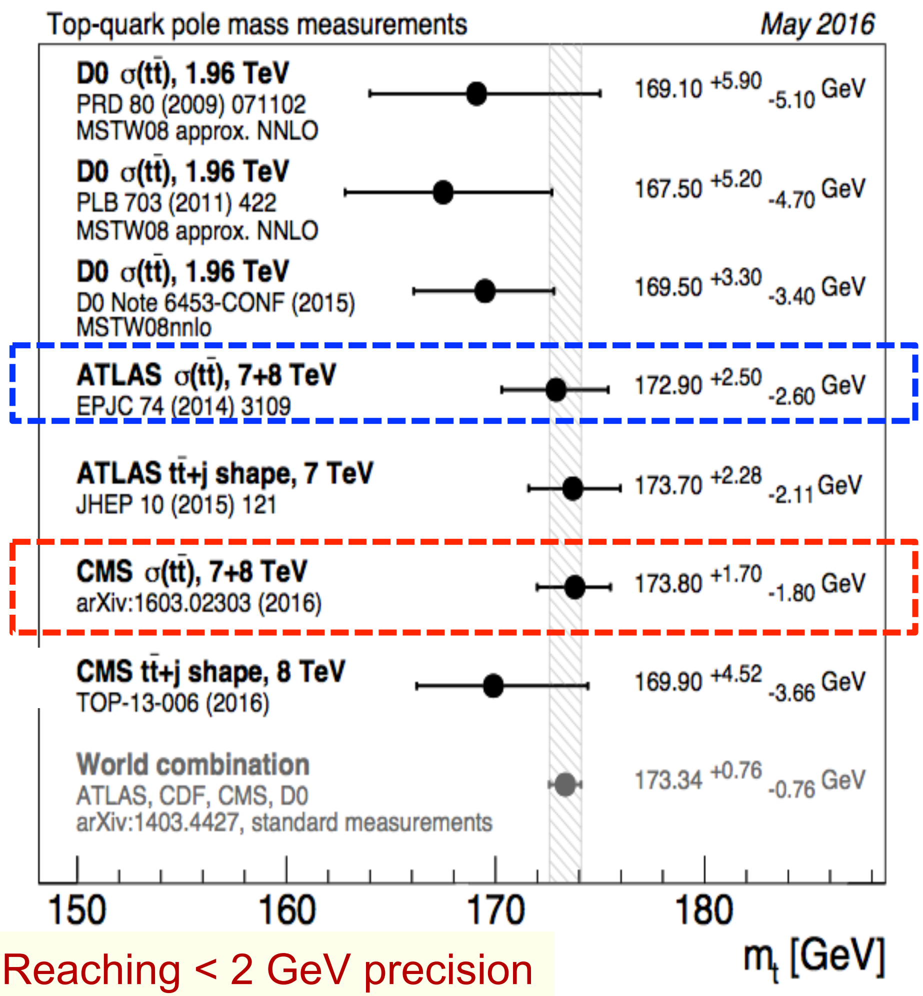
CMS, arXiv:1603.02303



ATLAS, EPJC 74 (2014) 3109



Use most precise theory (NNLO) and measurements to extract m_t (for fixed α_s and PDF)



Reaching < 2 GeV precision

Asymmetry in dileptons at 8 TeV

ATLAS, arXiv:1604.05538

New

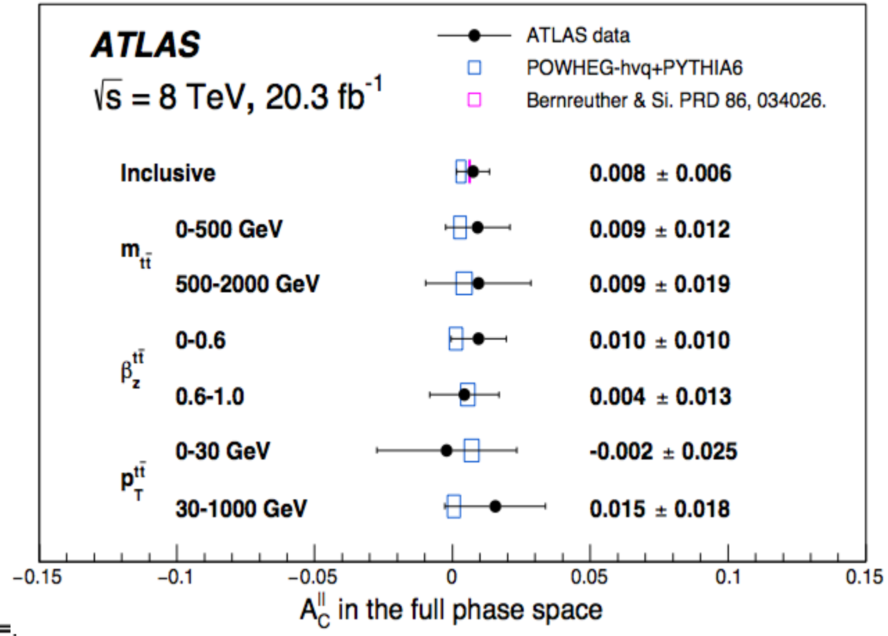
Alternative approach: lepton asymmetry

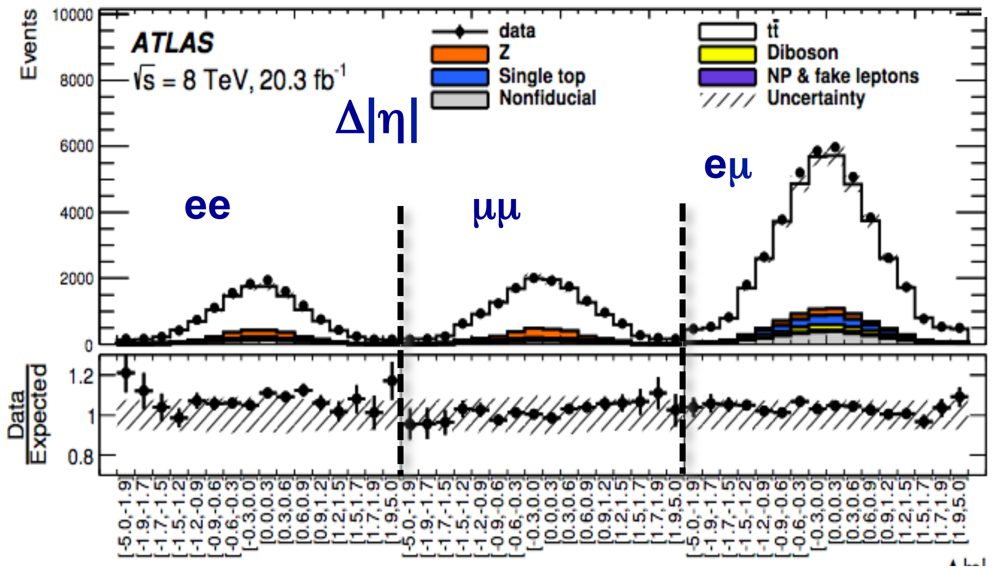
- Sensitive to top polarization, no tt kinematic reconstruction needed

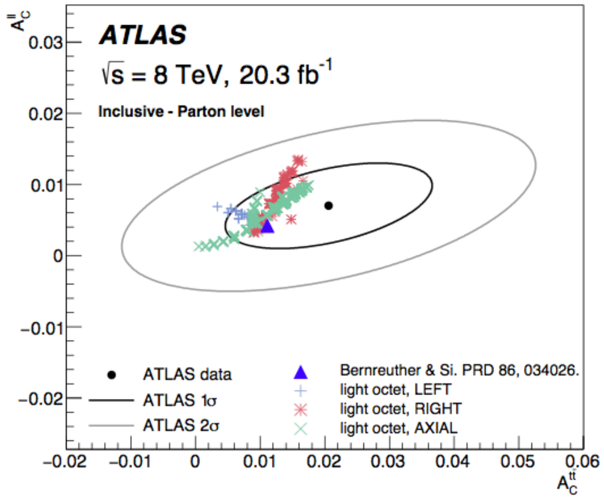
$$A^{ll}_{C} = \frac{N(\Delta|\eta| > 0) - N(\Delta|\eta| < 0)}{N(\Delta|\eta| > 0) + N(\Delta|\eta| < 0)}$$

$$\Delta|\eta| = |\eta_{l+}| - |\eta_{l-}|$$

Selection: 2 leptons, ≥ 2 jets &
≥1 b-tag (ee,μμ) or large H_T (eμ)







Consistent with SM, limited by stat. uncertainties

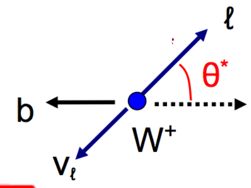
W helicity in top decays in Run-I

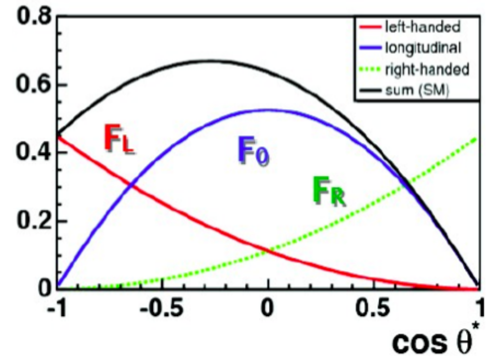
CMS, to be sub. to PLB

New

Anomalous contributions to the tWb vertex change the probabilities of the W helicity states

- In SM: 3 possible W helicity states ($F_R+F_L+F_0 = 1$):

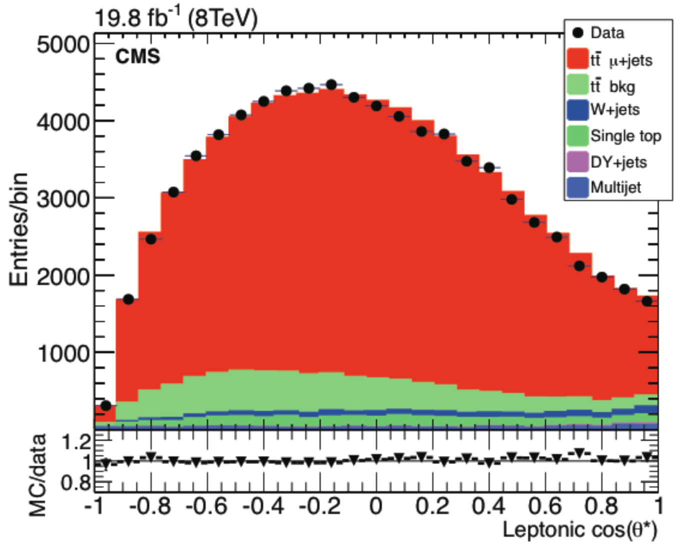




$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*} = \frac{3}{8}(1+\cos\theta^*)^2 F_R + \frac{3}{8}(1-\cos\theta^*)^2 F_L + \frac{3}{4}\sin^2\theta^* F_0$$

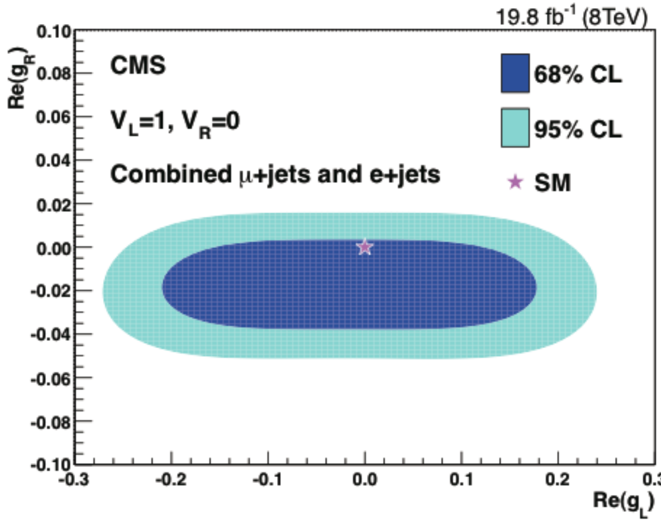
SM: ~0% ~30% ~70%

- Measure sensitive variable cos(θ*) in events with e/μ + 4 jets (2 b-tags):



Exclusion limits on anomalous tWb couplings

Most precise F_0 and F_L results so far !
(< 5%)



$F_0 = \; 0.681 \pm 0.012\,(\text{stat}) \pm 0.023\,(\text{syst})$
$F_L = \; 0.323 \pm 0.008\,(\text{stat}) \pm 0.014\,(\text{syst})$
$F_R = -0.004 \pm 0.005\,(\text{stat}) \pm 0.014\,(\text{syst})$

0 in the SM

$$\mathcal{L}_{tWb} = \mathcal{L}_{tWb}^{SM} - \frac{g}{\sqrt{2}}\bar{b}\left[(V_L P_L + V_R P_R)\gamma^\mu + \frac{i\sigma^{\mu\nu}q_\nu}{m_W}(G_L P_L + G_R P_R)\right] t W_\mu$$

W helicity in top decays in Run-I

CMS, to be sub. to PLB

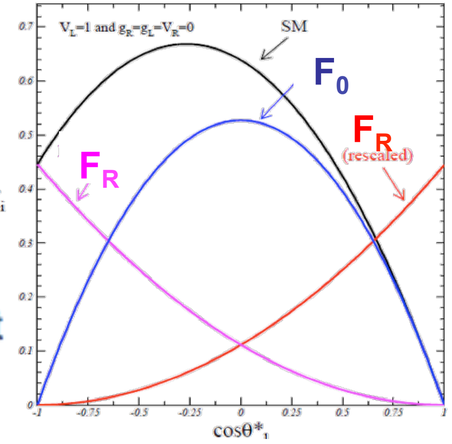
New

- Measurement is **affected by two aspects**:
  - Distortions due to detector effects: resolution, acceptance, ...
  - Generalizing the generator level polarization to any scenario

- Weighting procedure is used:

$$w_{\text{lep/had/single-t}}(\cos\theta^*_{\text{gen}};\vec{F}) \equiv \frac{\frac{3}{8}F_L(1-\cos\theta^*_{\text{gen}})^2 + \frac{3}{4}F_0\sin^2\theta^*_{\text{gen}} + \frac{3}{8}F_R(1+\cos\theta^*_{\text{gen}})^2}{\frac{3}{8}F_L^{SM}(1-\cos\theta^*_{\text{gen}})^2 + \frac{3}{4}F_0^{SM}\sin^2\theta^*_{\text{gen}} + \frac{3}{8}F_R^{SM}(1+\cos\theta^*_{\text{gen}})^2},\ F_i$$

SM prediction used at generator level ▶



- The fractions F_0, F_L and F_R are extracted using a binned likelihod fit to cos θ*

$$\mathcal{L}(\vec{F}) = \prod_{bin\ i} \frac{N_{MC}(i;\vec{F})^{N_{data}(i)}}{(N_{data}(i))!}\exp\left(-N_{MC}(i;\vec{F})\right)$$

$$N_{MC}(i,\vec{F}) = N_{BKG}(i) + N_{t\bar{t}}(i;\vec{F})$$

$$N_{t\bar{t}}(i;\vec{F}) = \mathcal{F}_{t\bar{t}}\left[\sum_{t\bar{t}\ \text{events, bin}\ i} W(\cos\theta^*_{gen};\vec{F})\right]$$