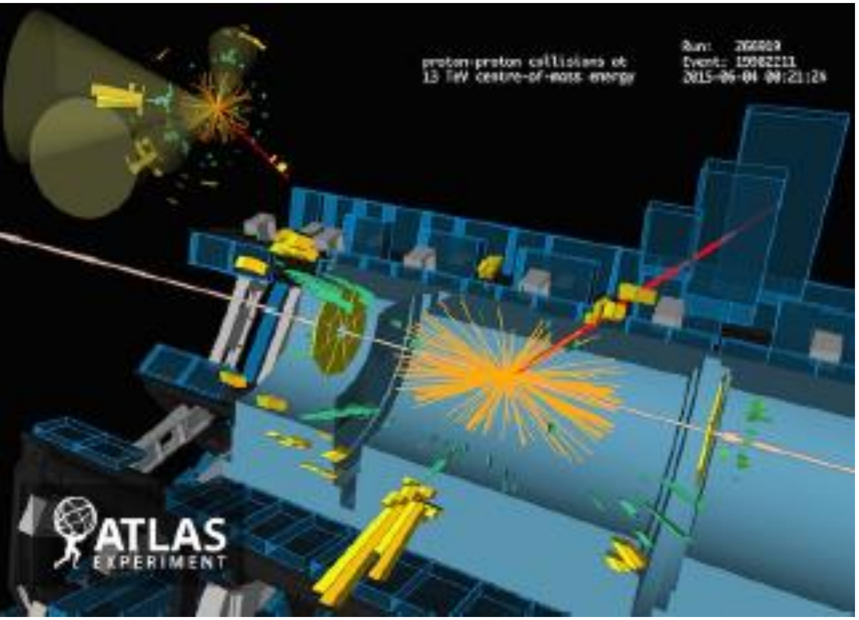
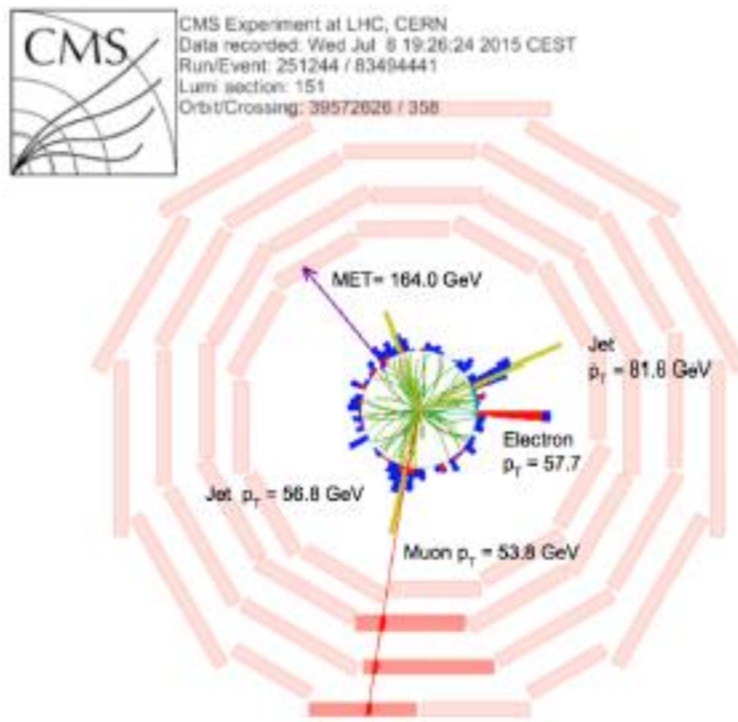


SM and BSM: experimental techniques and results

top quark physics



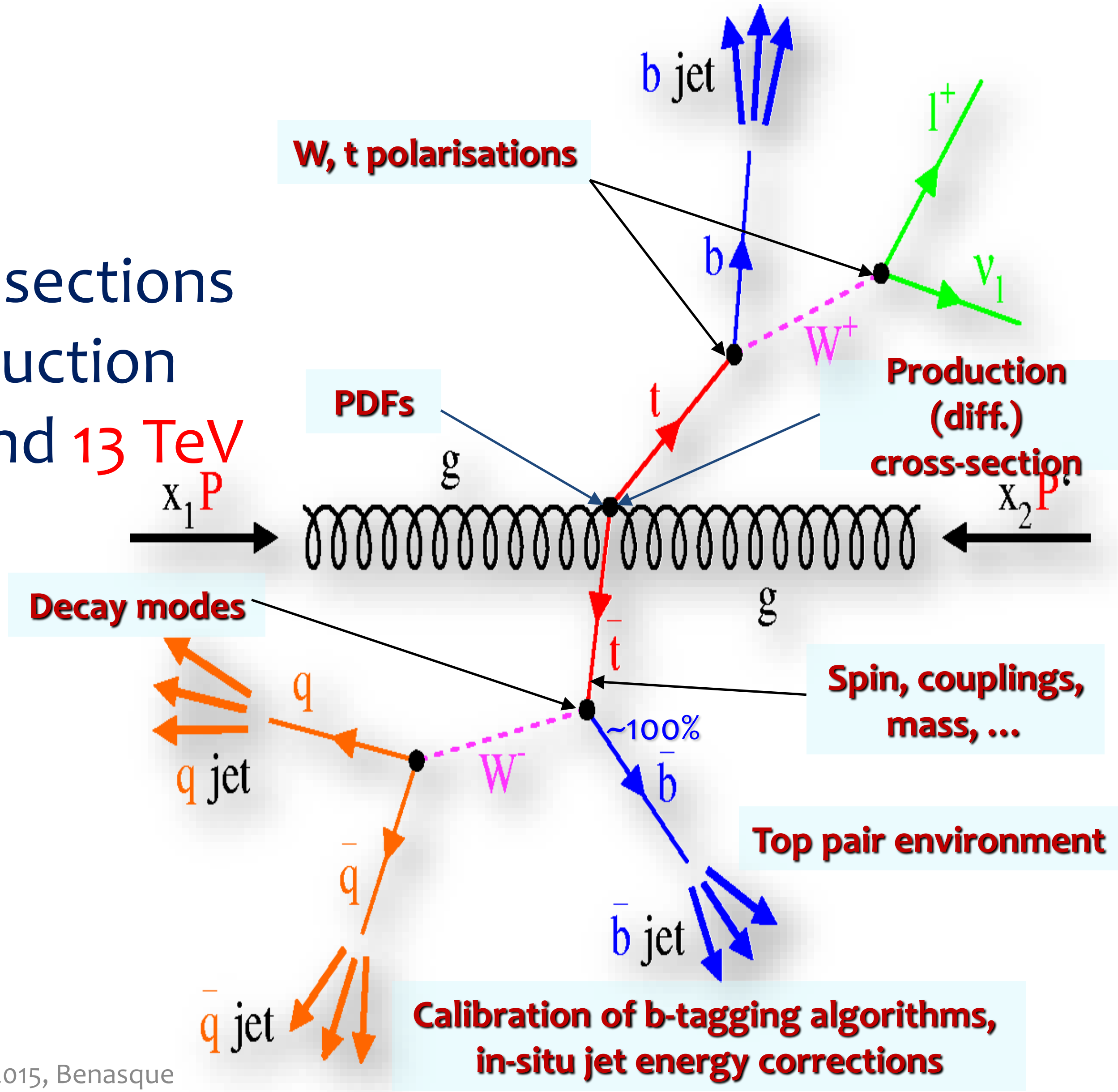
J. Cuevas
U. Oviedo (Spain)

TAE 2015,
22[th] – 26[th] Sep 2015, Benasque

top quark

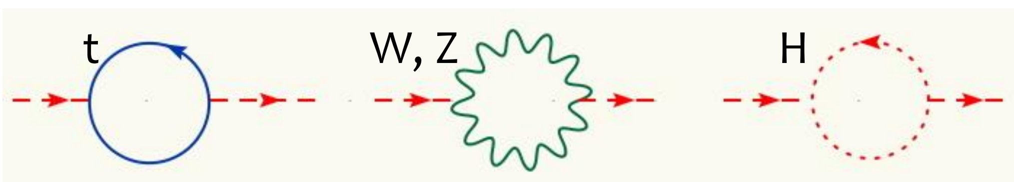
- Top pair cross sections measurements
  - Inclusive
  - Differential
- Single top cross sections
- Associated production
- Results on 7,8 and 13 TeV data

  - Top mass
  - Looking for new physics



A particle with unique characteristics

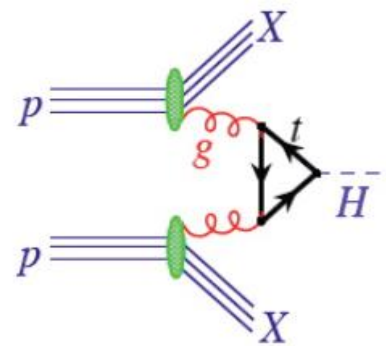
- Special because of its enormous mass: heaviest known particle
  - Still a point-like particle in our understanding
  - **The top and the Higgs are "strongly" coupled** $y_t \approx 1$ $m_t = y_t \mathrm{v}/\sqrt{2}$
  - The top mass dramatically affects the stability of the Higgs mass
    - If we consider the SM valid up to a certain scale Λ



$$\Gamma(H \to f\bar{f}) = \frac{N_c g^2 m_f^2}{32\pi m_W^2}\beta^3 m_H$$

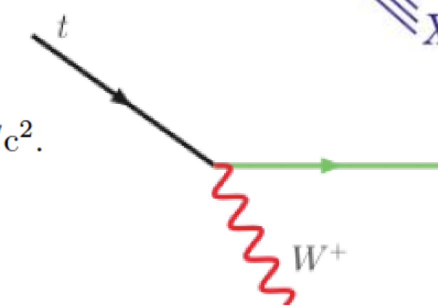
$$m_H^2 = m_{H0}^2 - \frac{3}{8\pi^2} y_t \Lambda^2 + \frac{1}{16\pi^2} g^2 \Lambda^2 + \frac{1}{16\pi^2}\lambda^2\Lambda^2$$

$$(125\,\mathrm{GeV})^2 = m_{H0}^2 + \left[-(2\,\mathrm{TeV})^2 + (700\,\mathrm{GeV})^2 + (500\,\mathrm{GeV})^2\right]\left(\frac{\Lambda}{10\mathrm{TeV}}\right)^2$$



- It is the only quark that does not hadronise
  - ○ $\tau(\mathrm{had}) \sim h/\Lambda_{QCD} \sim 2\ 10^{-24}$ s
  - ○ $\tau(\mathrm{top}) \sim h/\Gamma_{top} \sim 5\ 10^{-25}$ s
  - ○ Compare with $\tau(b) \sim 10^{-12}$ s

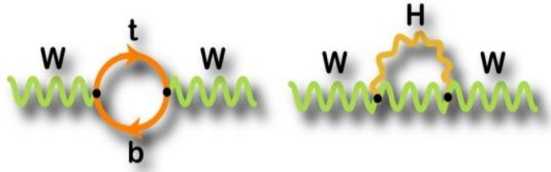
$$\Gamma(t \to bW) = \frac{G_F}{8\pi\sqrt{(2)}} m_t^3 |V_{tb}|^2 \approx 1.5\,\mathrm{GeV/c^2}.$$



  - ➢ Decays before forming a "dressed" top quarks
  - ➢ No bound tq states, its spin properties are directly passed to its decay products
  - ➢ QCD, Flavor and EWK physics at their best !

Constraining the SM

- Can use the fact that m_t, m_W, m_H are linked at loop level to constrain the SM
  - **The Higgs/symmetry breaking sector can be explored with more insights coming from top physics**



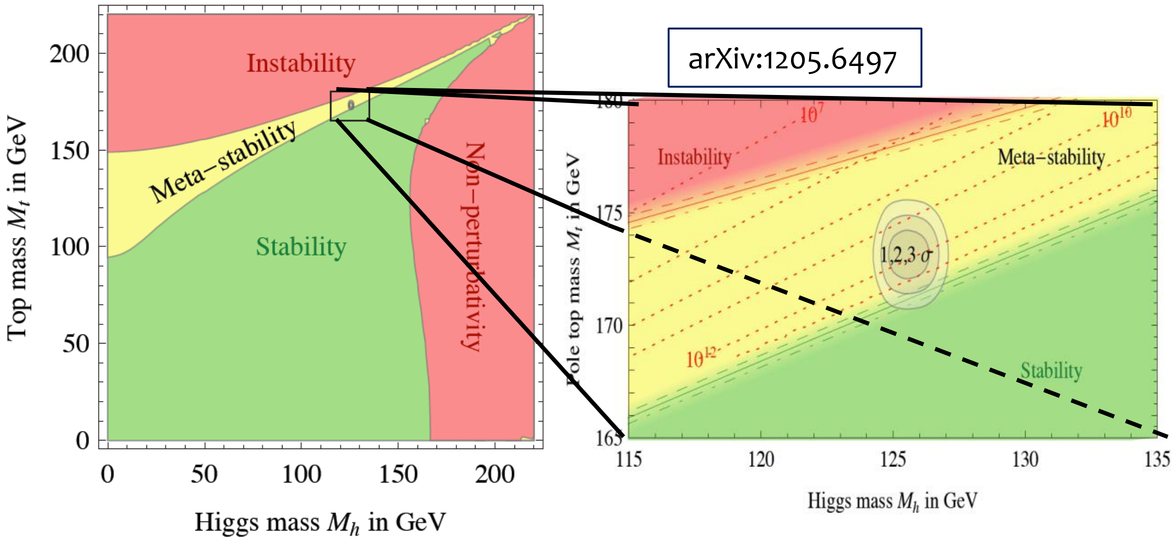
$\propto m_t^2$ $\propto ln(m_H)$

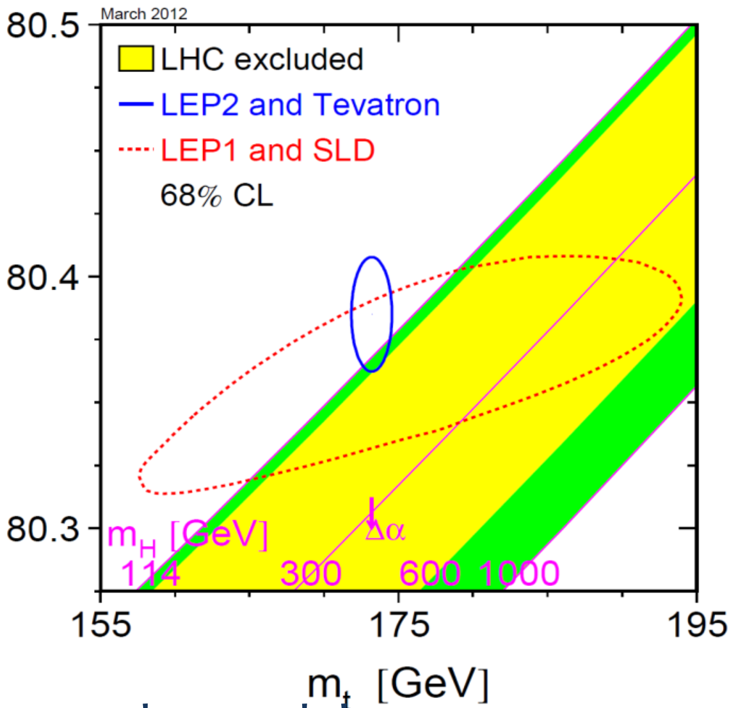
$$m_W = m_W(m_t^2, \log(m_H))$$

$$V(\phi) = -\mu^2 \phi^+\phi + \lambda (\phi^+\phi)^2 + Y^{ij} \psi_L^{\ i} \psi_R^{\ j} \phi$$

λ now known at NNLO QCD. Vacuum meta-stability when the minimum of $V(\Phi)$ is just local

arXiv:1205.6497



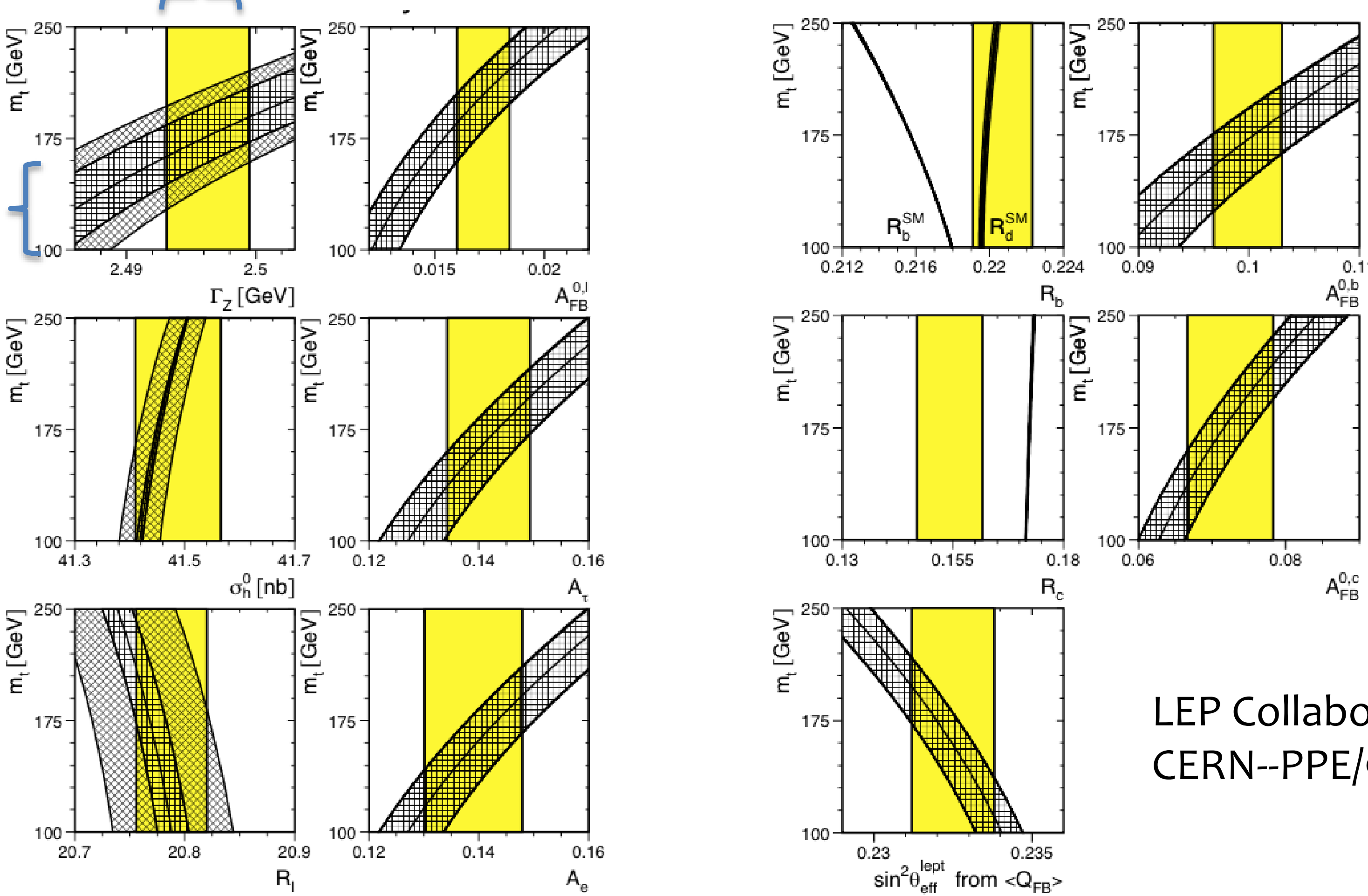


- The top quark also provide other direct constraints to the model
  - Direct access to parameters of the SM (m_t, V_{tb})
  - Other stringent tests of SM (QCD in $d\sigma/dX$, couplings, CPT invariance,…)

LEP (1995) vs SM predictions

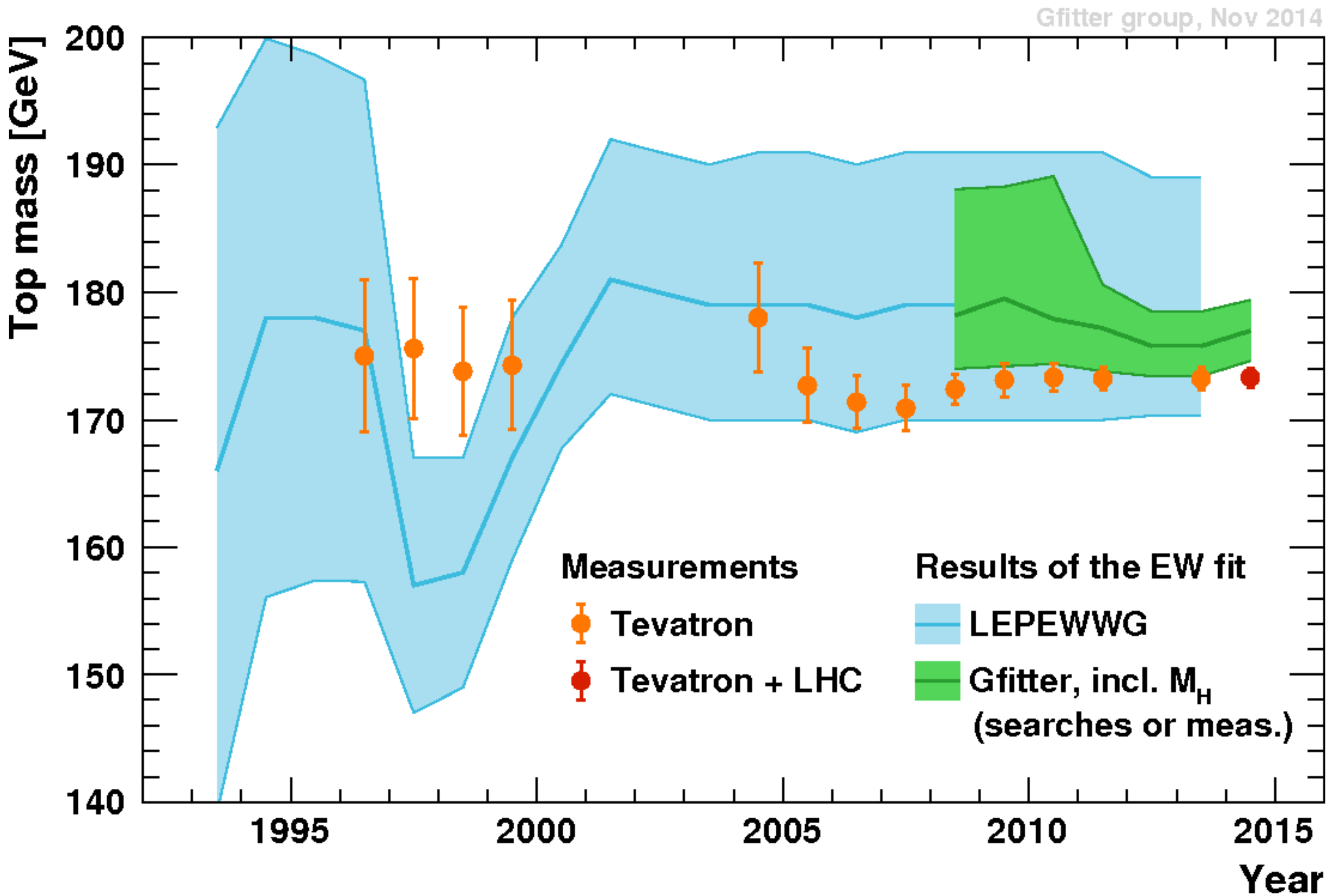
m_H=60-1000 GeV $\sqrt{s} = 100\ GeV < mtop$

α_S & m_H variations



LEP Collaborations
CERN--PPE/95-172

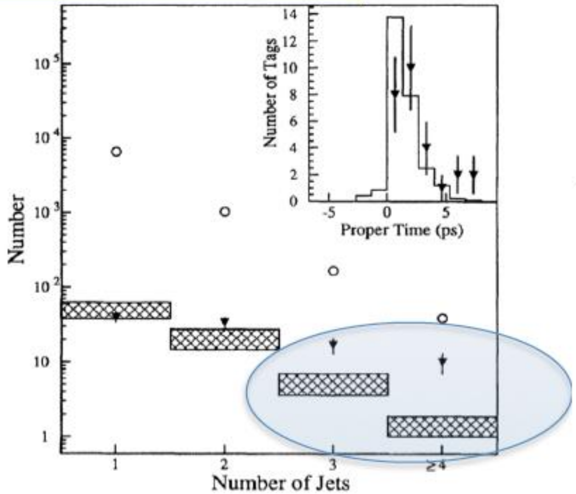
- Z boson line shape and asymmetries compared to SM measurements vs. top mass
- LEP 1 prediction: **m_{top} = 173 + 13 – 10 GeV**

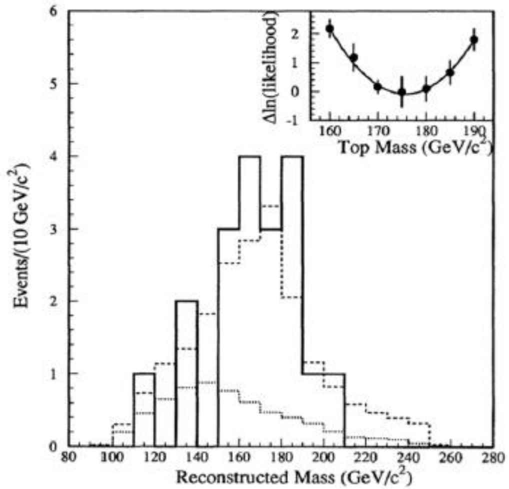


- Quantum fluctuations showed the existence of the top quark and predicted its mass precisely before it was discovered. **-> Triumph of the SM.**

The Discovery of the Top Quark

CDF, PRL 74, 2626 (1995)





Discovery at the Tevatron with O(10) events.

Signal consistent with

$$t\bar{t} \rightarrow W^{+}bW^{-}\bar{b}$$

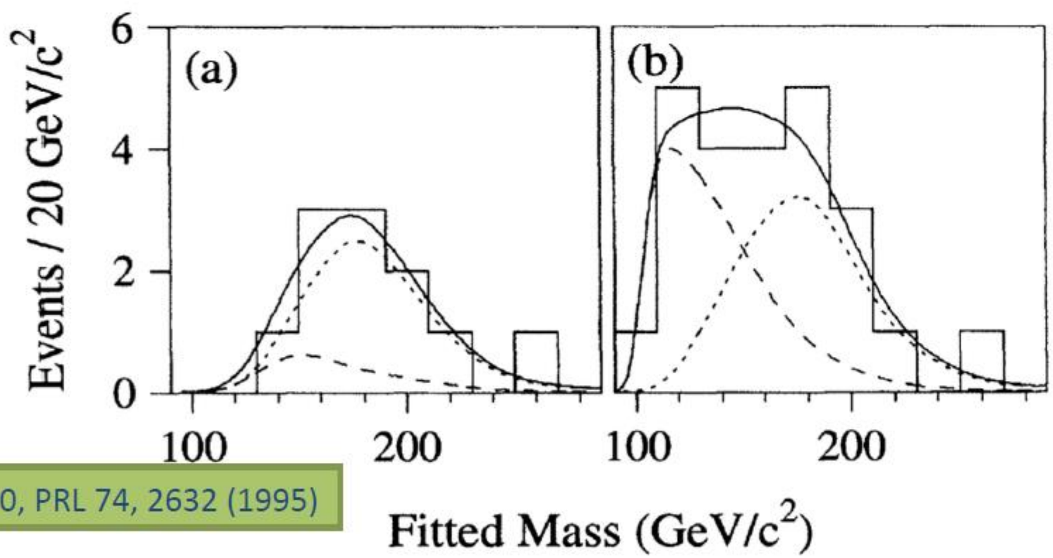
and inconsistent w/ the background prediction.

$$\sigma_{t\bar{t}}^{CDF} = 6.8_{-2.4}^{+3.6}\,pb$$

$$\sigma_{t\bar{t}}^{D0} = 6.4 \pm 2.2\,pb$$

$$m_t^{CDF} = 176 \pm 8(stat.) \pm 10(syst.)\ GeV$$

$$m_t^{D0} = 199_{-21}^{+19}(stat.) \pm 22(syst.)\ GeV$$

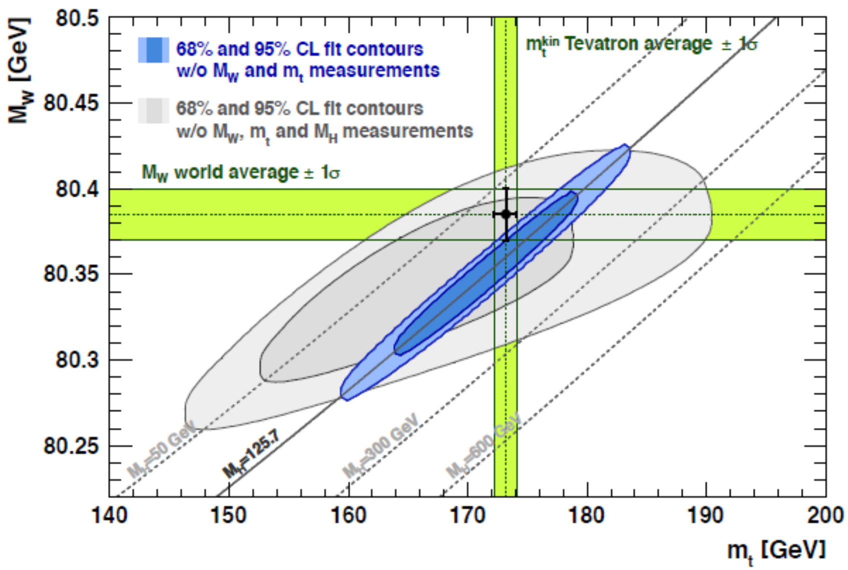


D0, PRL 74, 2632 (1995)

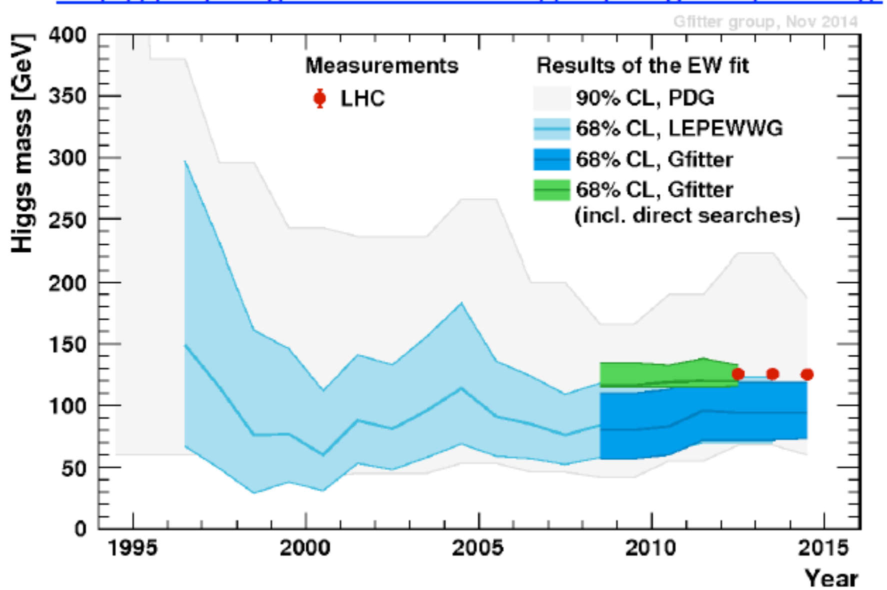
The Top Quark Mass

Electroweak fit before Higgs discovery: $m_H = 94^{+25}_{-22}\, GeV$ consistent with measured m_H within 1.3σ.

The Gfitter Group, M. Baak et al., EPJC 72, 2205 (2012)

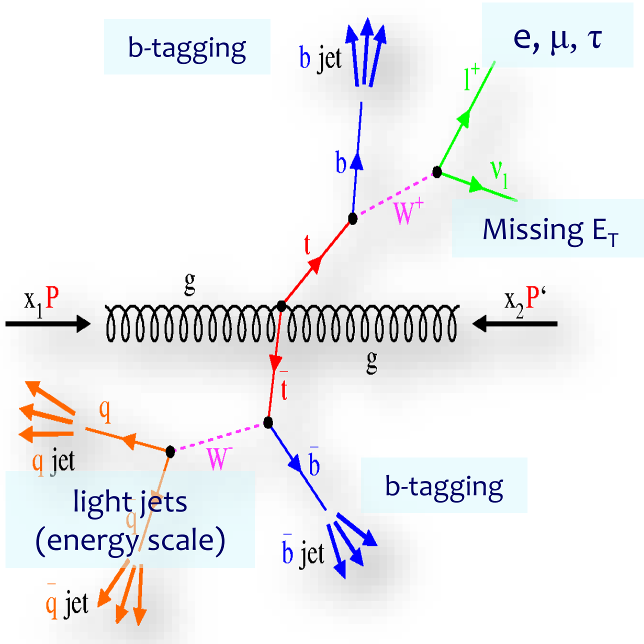


http://project-gfitter.web.cern.ch/project-gfitter/History/

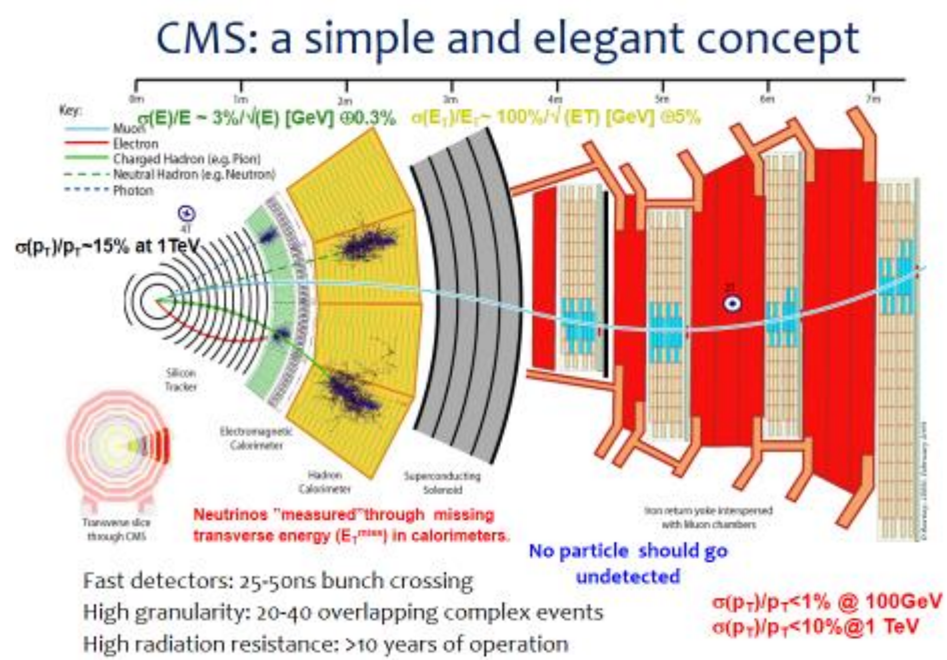


Quantum fluctuations showed the existence of the Higgs boson and predicted its mass precisely before it was discovered. → One of the most critical tests of the standard model!

Experimental challenges



- Top quark studies require **all** components and capabilities of the **CMS** detector to work:
  - Trigger
  - Charged lepton reconstruction, identification and isolation
  - Jet reconstruction
  - Missing transverse energy
  - b-tagging
- important to consider PU conditions at 8 TeV.



- **Optimal use of the detectors…**
  - ➢ Particle Flow reconstruction in CMS
    - ○ Combine all sub-detector information to reconstruct and identify particles, after pile-up substraction
- … and sophisticated analysis tools:
  - ➢ B-tagging, τ reconstruction, kinematic fitting

Jets

PRODUCTION:

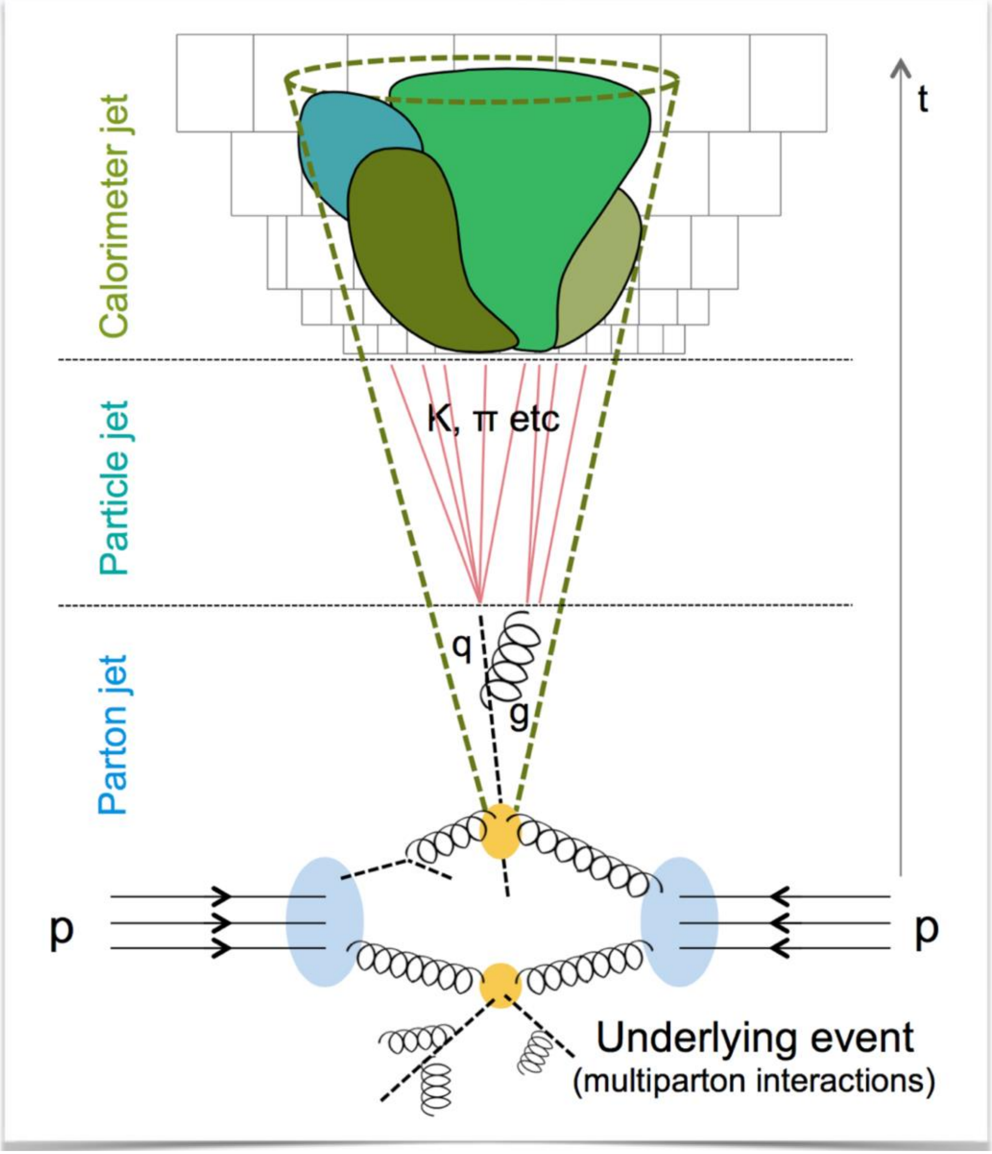
- by fragmentation of gluons and (light) quarks in QCD scattering

RECONSTRUCTION:

- Need to satisfy requirements:
  - theoretical requirements (infrared and collinear safety)
  - experimental requirements (detector & environment independent, easily implementable, etc.)
- Commonly used in ATLAS and CMS
  - 'anti-kt' algorithm (typical cone sizes: R=0.4/0.5)

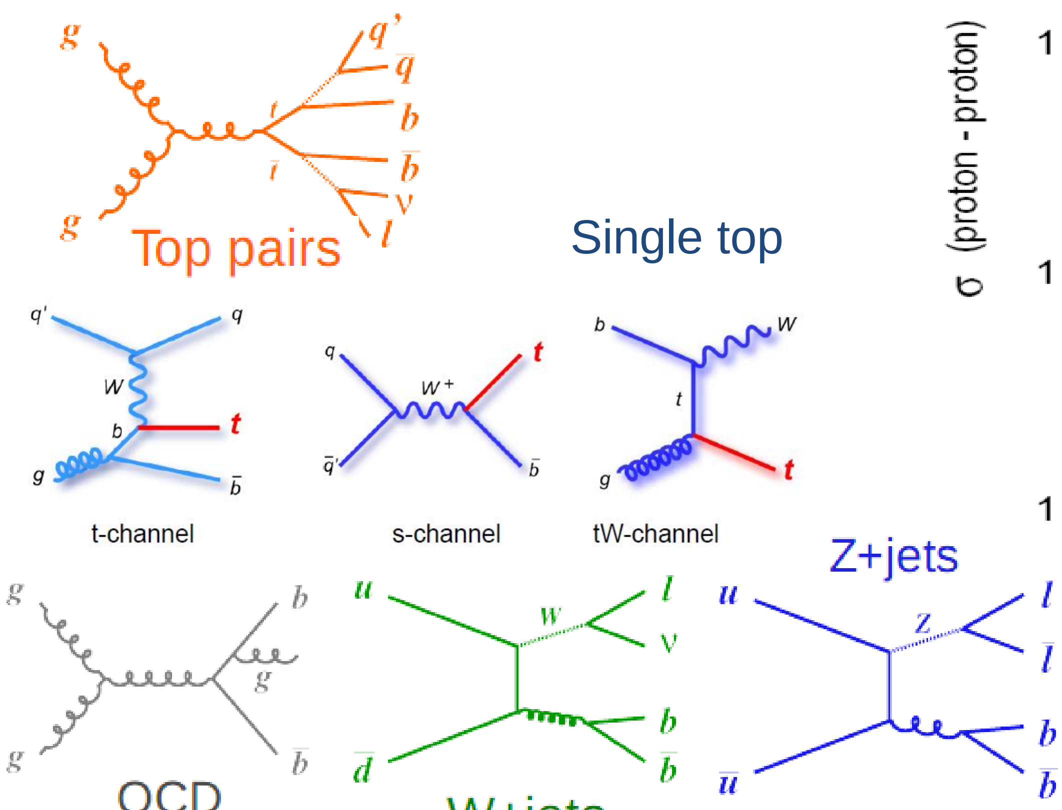
CALIBRATION:

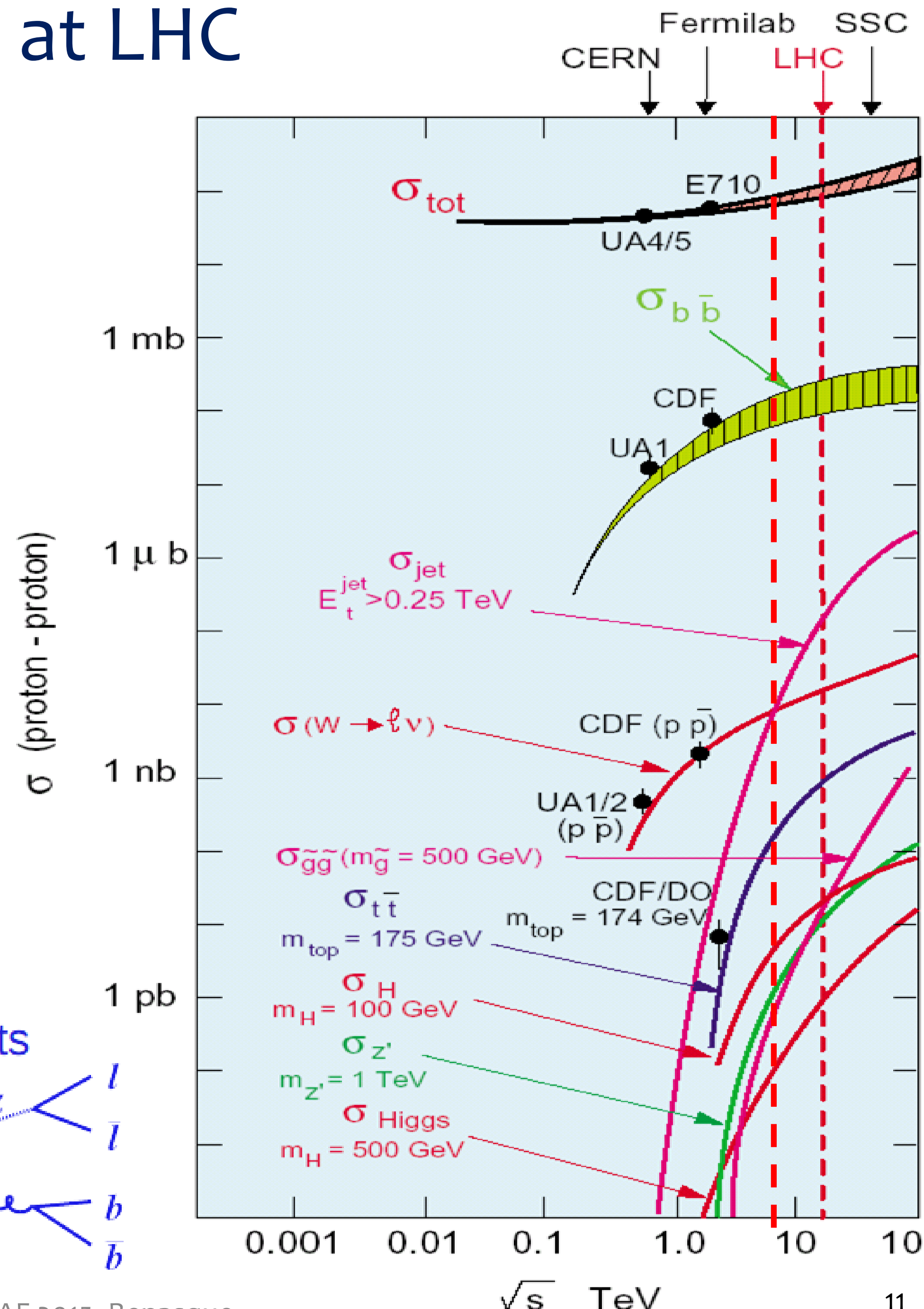
- Correct the energy and position measurement, and the resolution.
- Correct for instrumental & physics effects



Top quark production at LHC

process	Events/s 8 TeV, peak lumi	Events/y 8 TeV, 25/fb
bb	~10^6	~3 10^{12}
W→ℓν	~70	~2.5 10^8
Z→ℓℓ	~6	~25 10^6
tt	~1.5	~6 10^6





Number of events with 20 fb^{-1} at 8 TeV

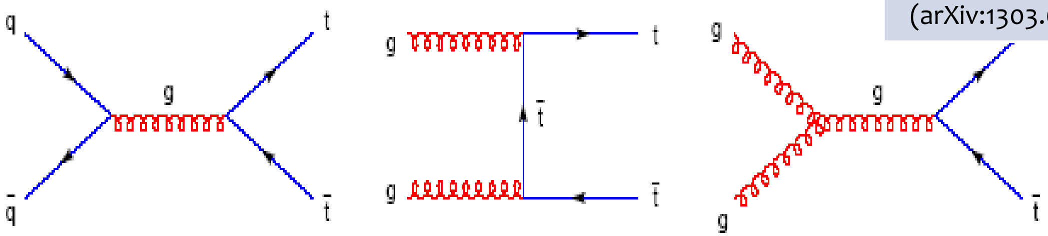
Channel	σ (NLO)	BR	Trigger eff	# Events
ttbar SL e mu	232	0.3	0.8	1 090 000
ttbar SL tau	232	0.15	0.5	340 000
ttbar DL (e, mu)	232	0.053	0.9	220 000
ttbar DL 1 tau	232	0.053	0.8	200 000
single top t-ch e mu	83	0.22	0.7	250 000
single top s-ch e mu	45.5	0.22	0.7	17 000
single top tW e mu	23	0.22	0.7	70 000

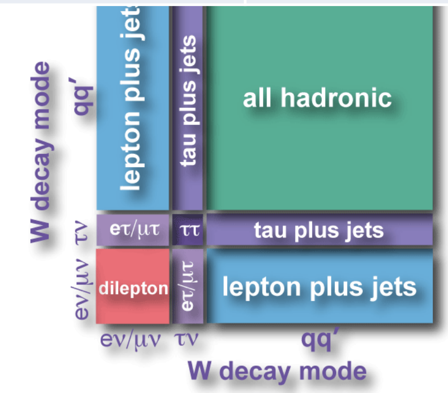
- Typically two orders of magnitude more than final amount at Tevatron.
- selection eff. not included
- trigger efficiencies, average

Top (pair) production at the LHC

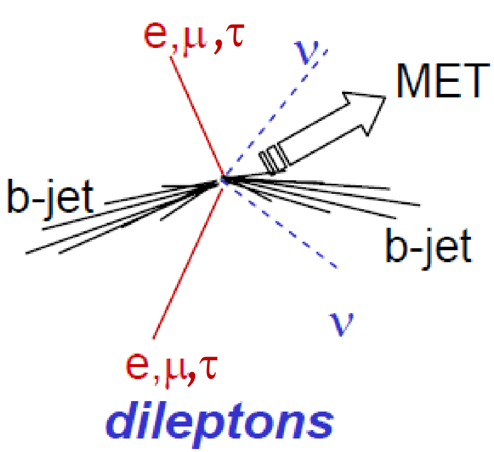
- Top pair QCD production happens mainly via gluon fusion

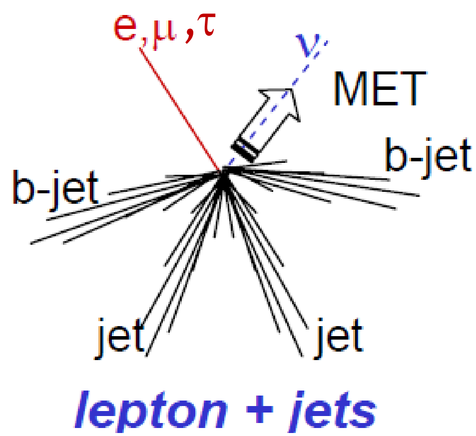
σ(NNLO+NNLL) ± scales ± PDFs [pb]		
	7 TeV	8 TeV
Czakon, Fiedler, Mitov (arXiv:1303.6254)	$172.0^{+4.4}_{-5.8}\ ^{+4.7}_{-4.8}$	$245.8^{+6.2}_{-8.4}\ ^{+6.2}_{-6.4}$

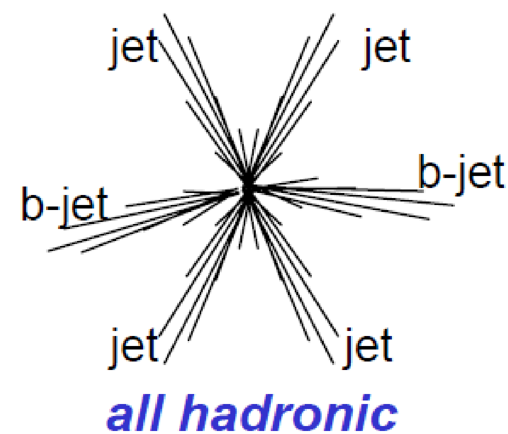




- Final states depend on the decay of the W bosons





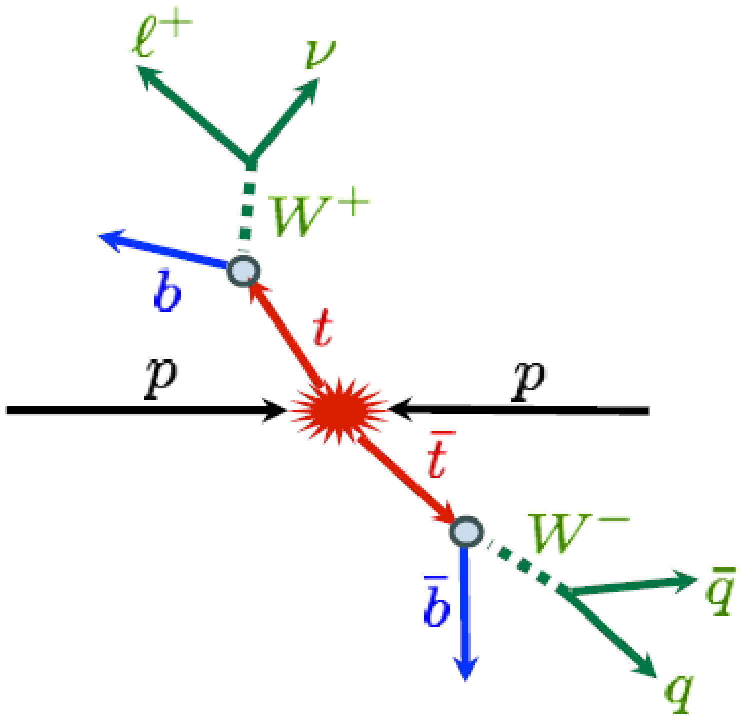


- BR~10%
- BR~44%
- BR~46%

- Backgrounds coming from: W/Z+jets, single top (tW), QCD, di-boson

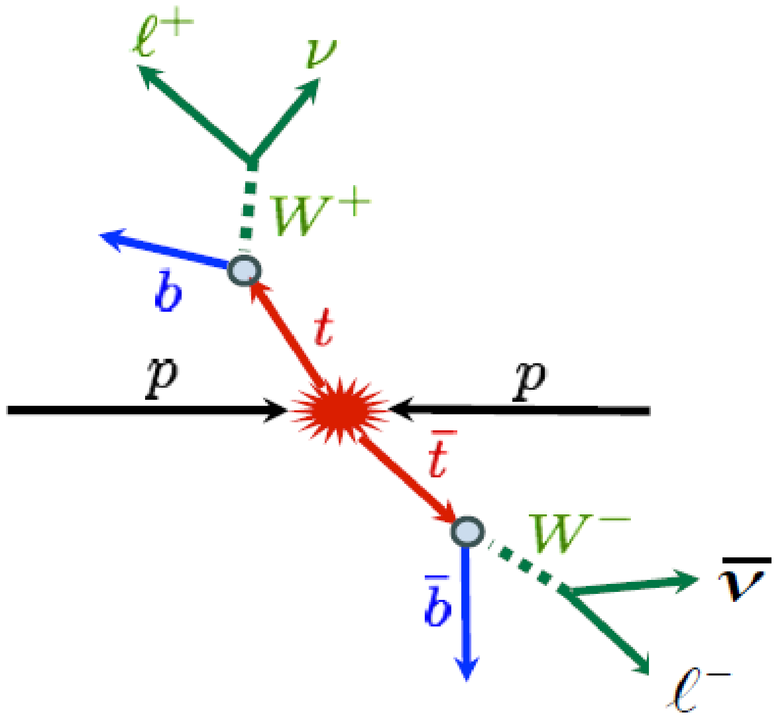
Top Quark Signatures and Backgrounds

- Lepton+jets channel
  - A high pT lepton
  - ≥ 4 high pT jets (2 of which are jets from b-decays)
  - Missing transverse energy
- Main backgrounds:
  - tt other, Single top, W+jets



Top Quark Signatures and Backgrounds

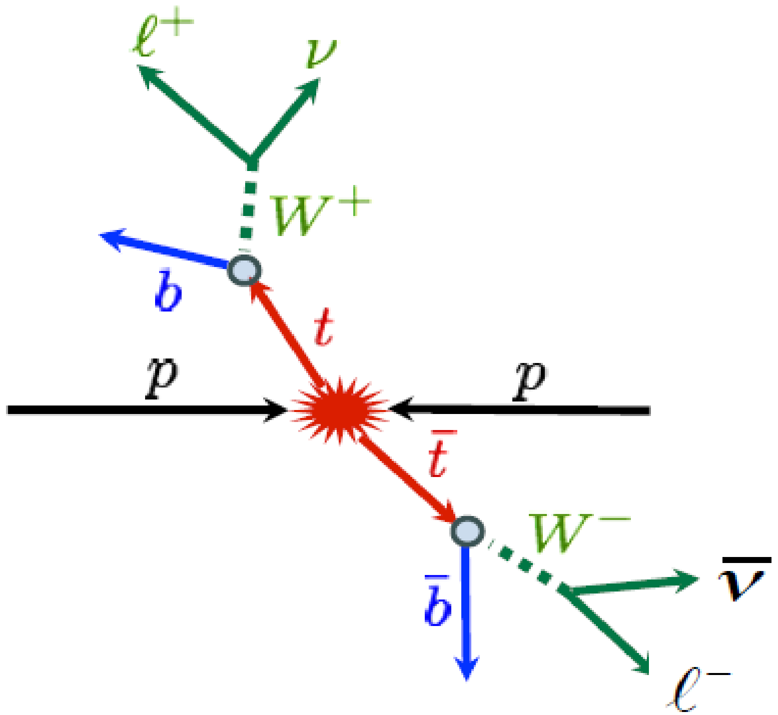
- Dilepton channel
  - Two high p_T leptons
  - ≥ 2 high p_T jets (2 of which are jets from b-decays)
  - Missing transverse energy
- Main backgrounds:
  - tt other, Single top, W/Z+jets



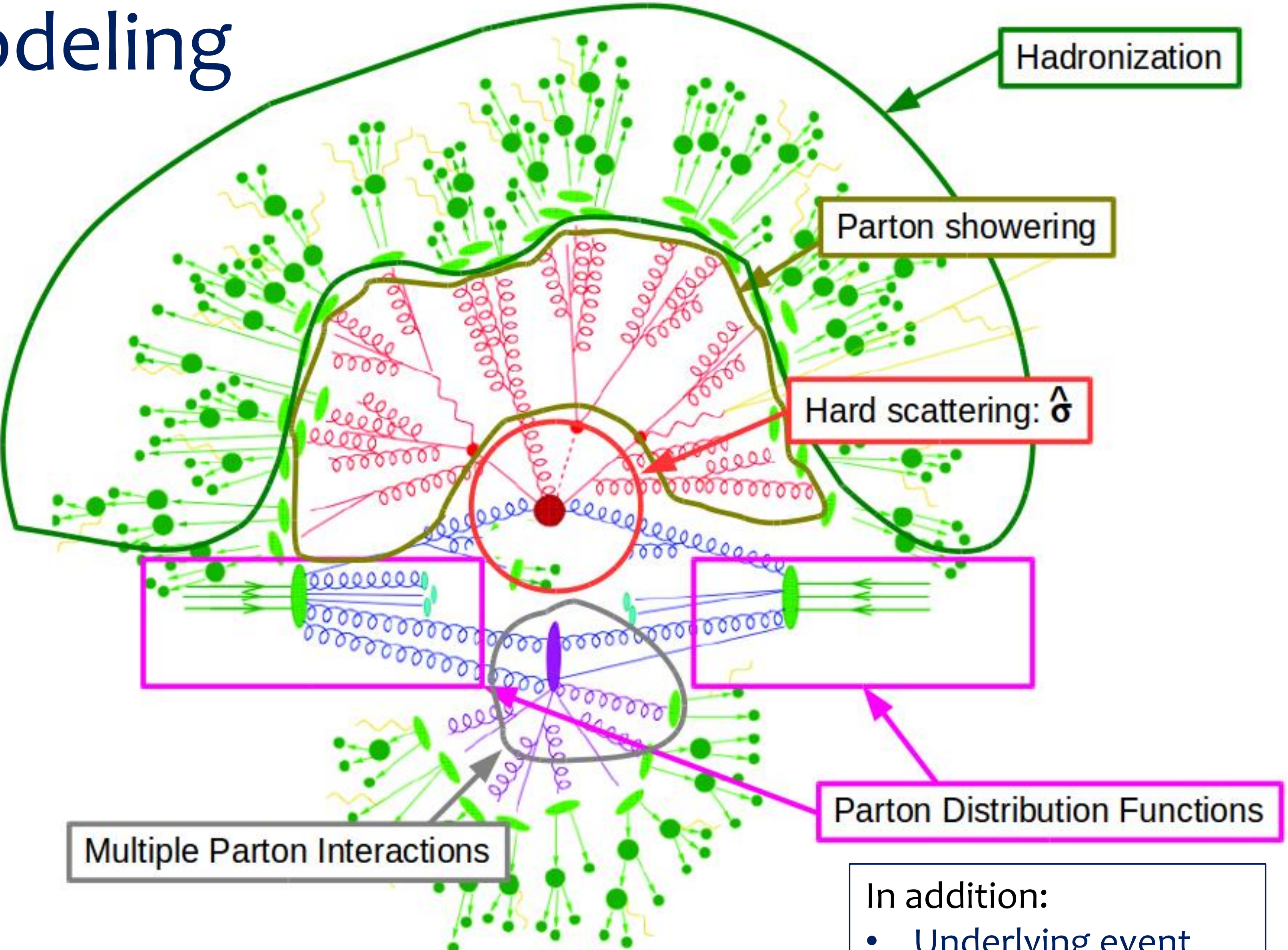
Fewer number of events, more pure, best channel **eμ**

Top Quark Signatures and Backgrounds

- All-hadronicchannel
  - ≥ 6 high p_T jets (2 of which are jets from b-decays)
- Main backgrounds:
  - QCD multijets
- Possible fully reconstruction of the event (no neutrinos)
- Larger uncertainties compared to other channels due to multiple jets
  - Jet energy scale and b-tagging



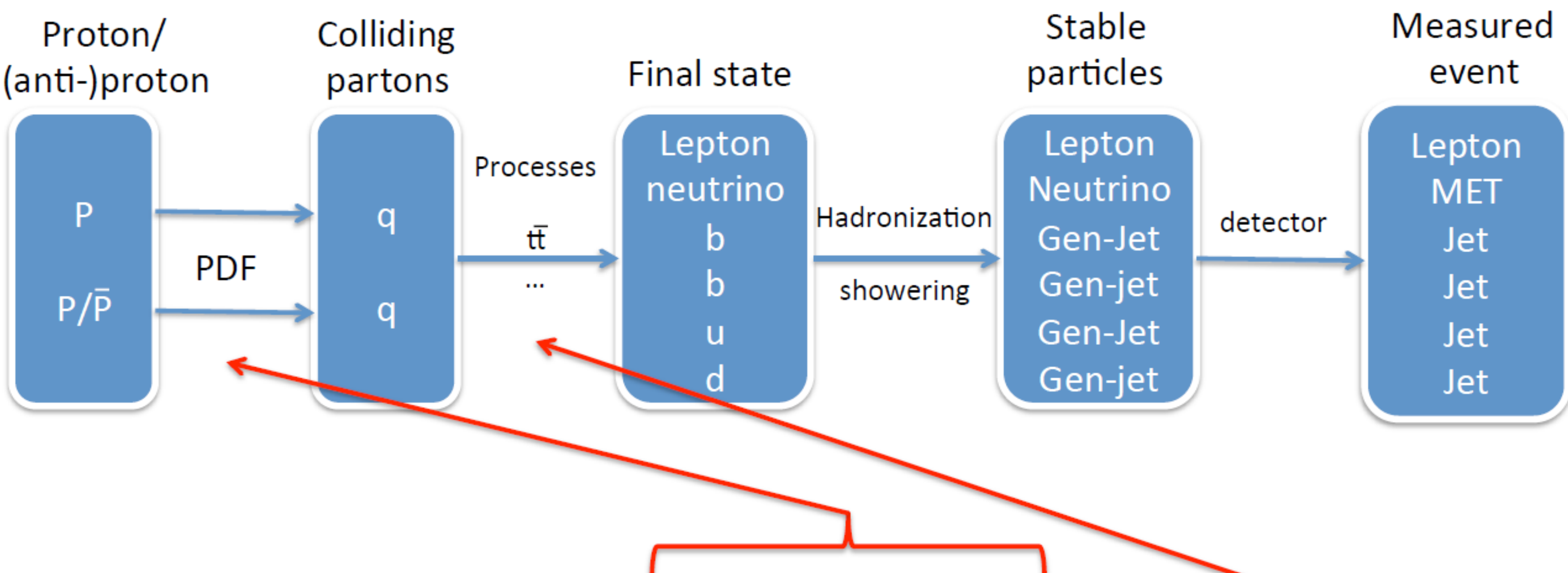
Top Quark event modeling



In addition:

- Underlying event
- Initial state radiation

Top Quark event modeling



$$\sigma_{pp\to t\bar{t}}(s,m_t) = \sum_{i,j=partons} \int dx_1\, dx_2\, f_i^{pdf}(x_1,\mu_f^2)\, f_j^{pdf}(x_2,\mu_f^2)\, \hat{\sigma}_{ij\to t\bar{t}}(\hat{s},m_t,\mu_f,\mu_r,\alpha_s(\mu_r))$$

Top Quark event modeling

$$\sigma_{pp\to t\bar{t}}(s,m_t) = \sum_{i,j=partons} \int dx_1\, dx_2\, f_i^{pdf}(x_1,\mu_f^2)\, f_j^{pdf}(x_2,\mu_f^2)\, \hat{\sigma}_{ij\to t\bar{t}}(\hat{s},m_t,\mu_f,\mu_r,\alpha_s(\mu_r))$$

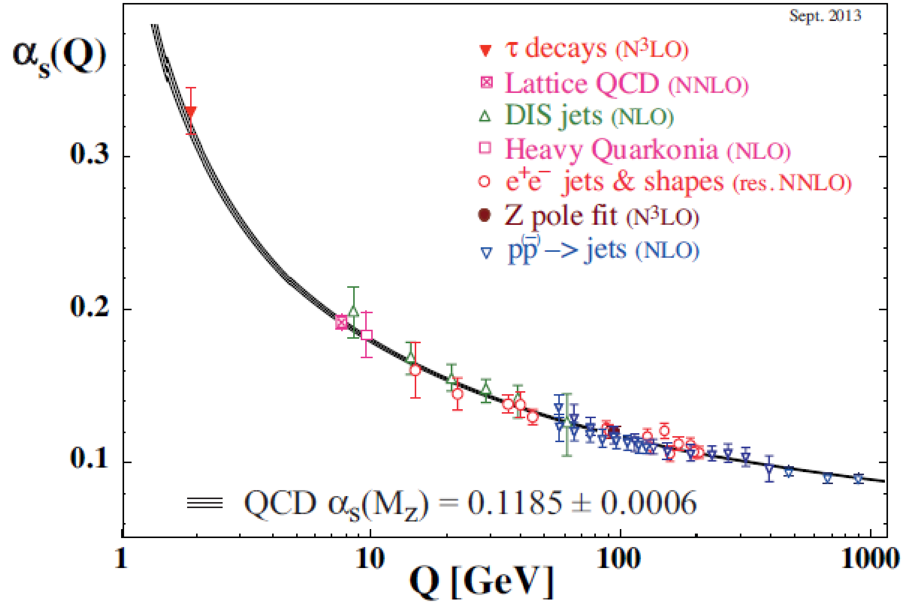
$\oplus$ showering/ & hadronization

Non-perturbative | *Perturbative in α_s*

factorization → $PDFs(x,\mu_f^2) \otimes \hat{\sigma}(\hat{s},m_t,\mu_f,\mu_r,\alpha_s(\mu_r))$

$p_T^{parton} < \mu_F$ | $p_T^{parton} > \mu_F$

$\mu_f \sim Q \sim \sqrt{\hat{s}} \sim \sqrt{x_1 x_2 s}$ *(Q: energy scale of the hard process)*



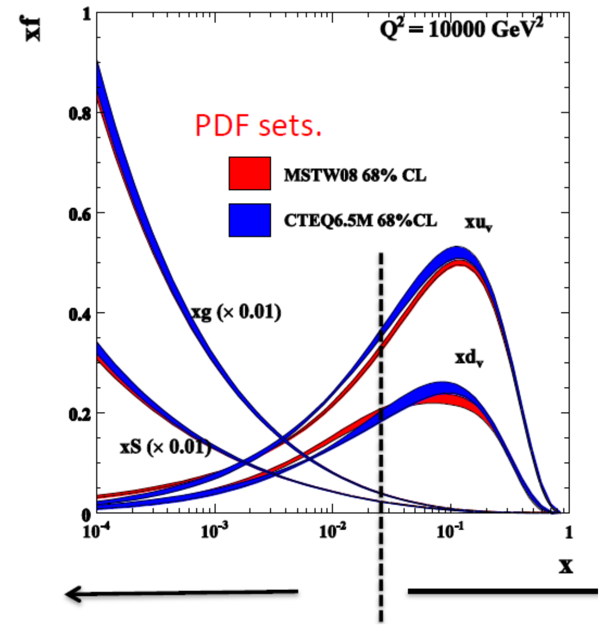
→ inputs: m_t, α_s, and PDFs

Total cross section measurements

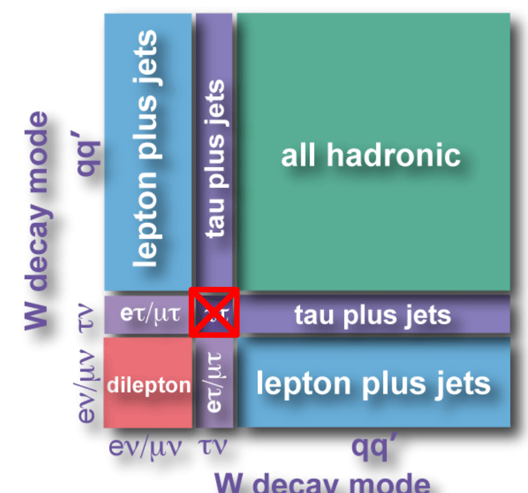
- Monitoring the total production cross section is the first fundamental step for understanding top physics at the LHC
  - Test the presence of new production mechanisms
  - In the frame of the SM, test QCD predictions and help constraining the PDFs (especially gluons)
    - Important for Higgs production

$$\sigma_{t\bar{t}}(m_t) = \sum_{i,j} \int_0^1 dx_1 dx_2\, f_i(x_1) f_j(x_2)\, \hat{\sigma}_{ij}(m_t)$$

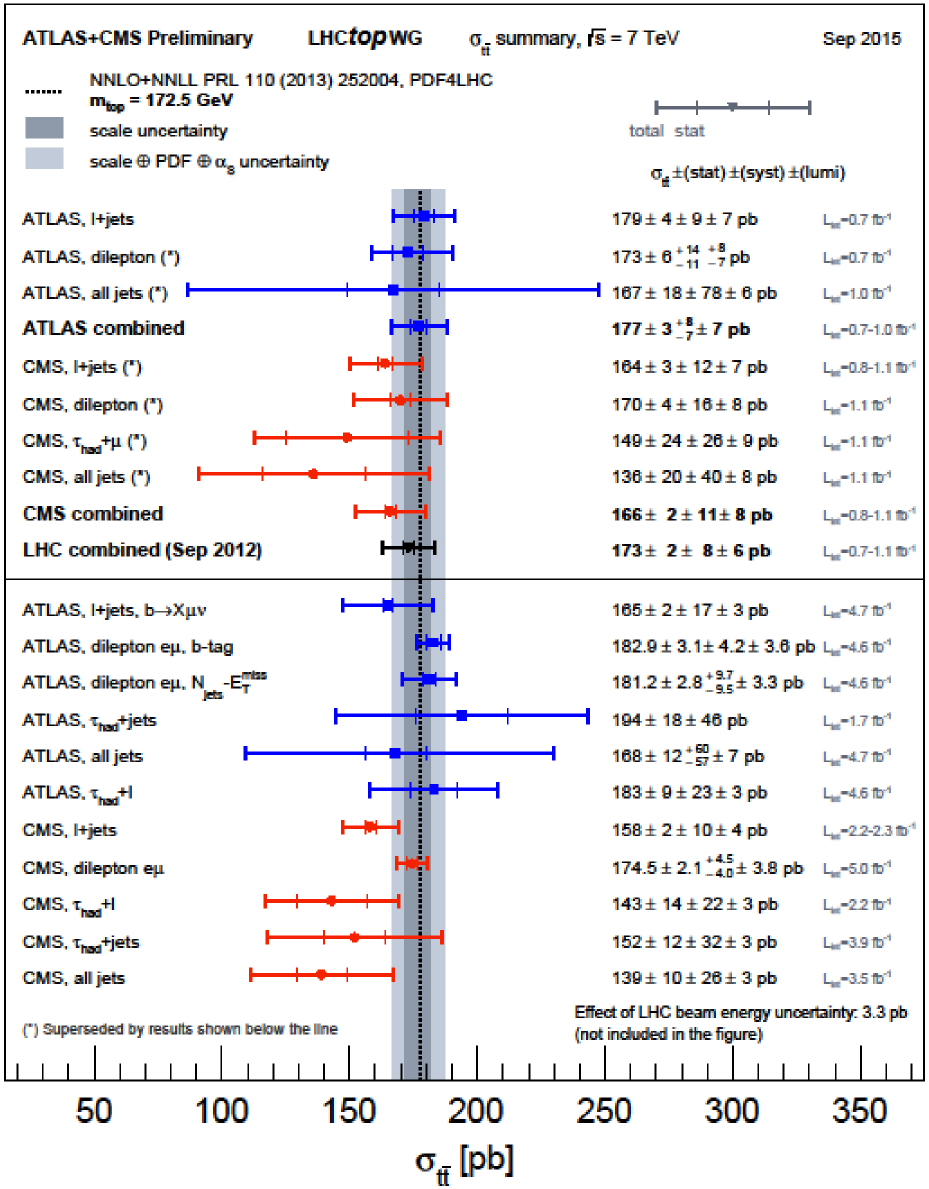
  - Indirect determination of m_t or α_S.
  - Constrain a very important background for many searches at the LHC

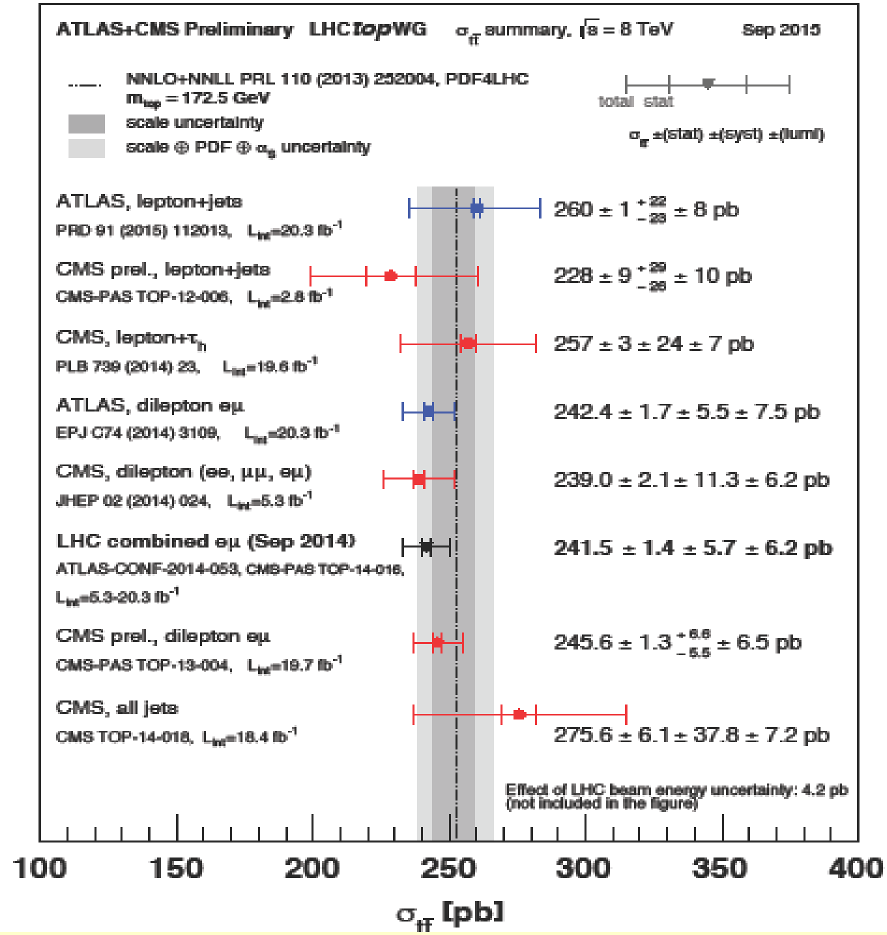


- **Almost all decay modes are investigated at the LHC**
- The measurements are performed at different level of complexity:
  - ➢ Counting experiment in acceptance $\sigma = \dfrac{N_{data} - N_{BG}}{\epsilon_{t\bar{t}} \int \mathcal{L}dt}$
  - ➢ Fit to data in several portions of phase space with in situ constraining of various backgrounds
  - ➢ Multivariate analyses
  - ➢ Selections defined for inclusive cross sections are in general used for the rest of the measurements in that final state



CMS + ATLAS inclusive cross section combination

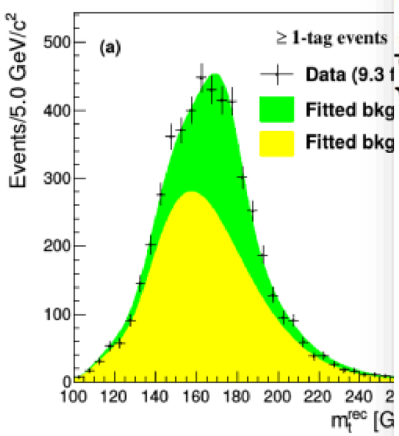




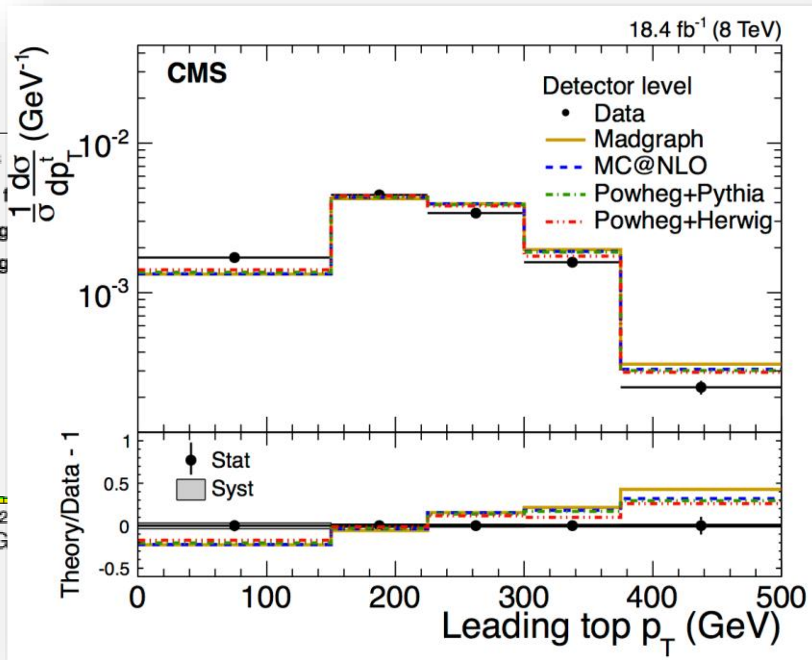
- All channels covered and consistent with SM
- Good agreement with NNLO+NNLL
- **Precision of ~4% (di-lepton channel), similar to theoretical prediction**

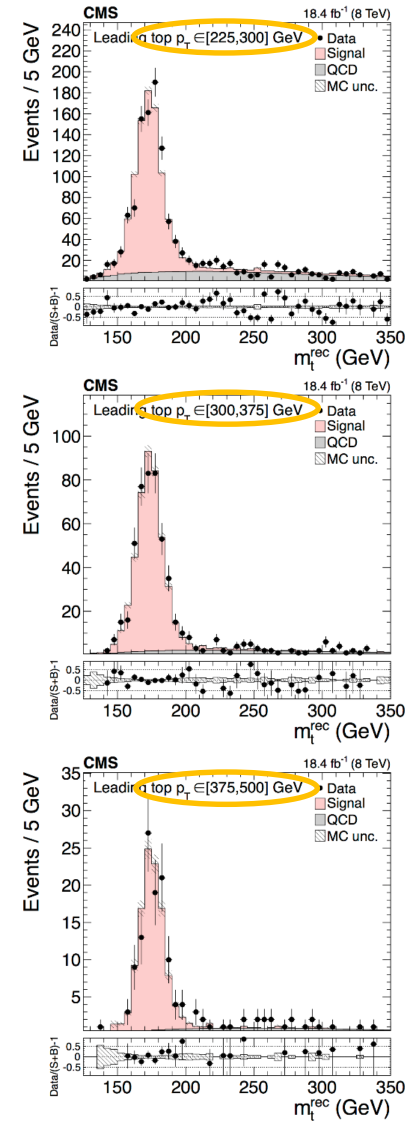
The all-jets channel

- Traditionally the most challenging final state (backgrounds!)
- But: large branching fraction
- No neutrinos = superior kinematic information + resolution
- At 8 TeV CMS used "parked data" to afford trigger rate
- S/B improves with higher top pT, and with higher √s

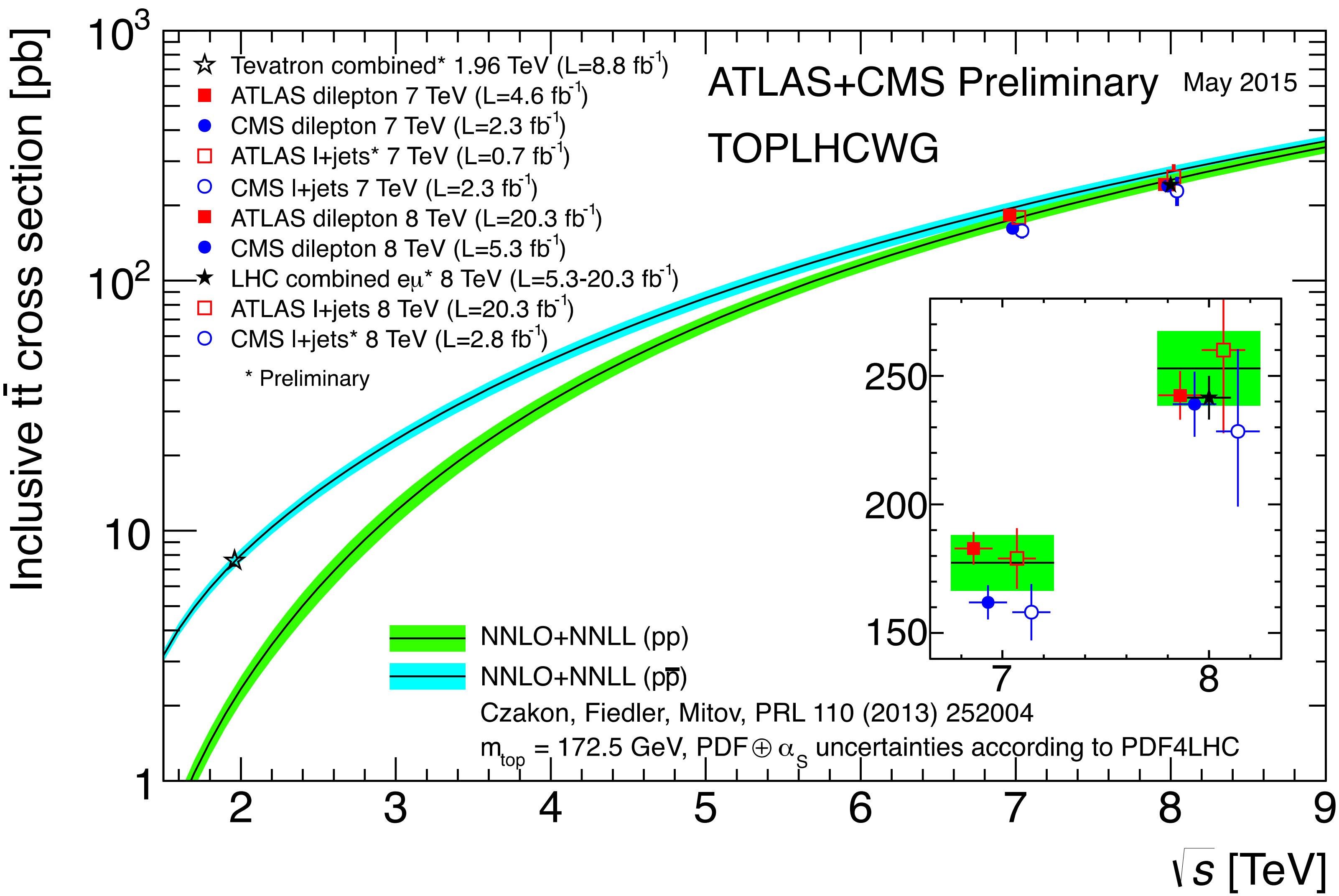


CDF
→ Deterre





$t\bar{t}$ inclusive cross section production

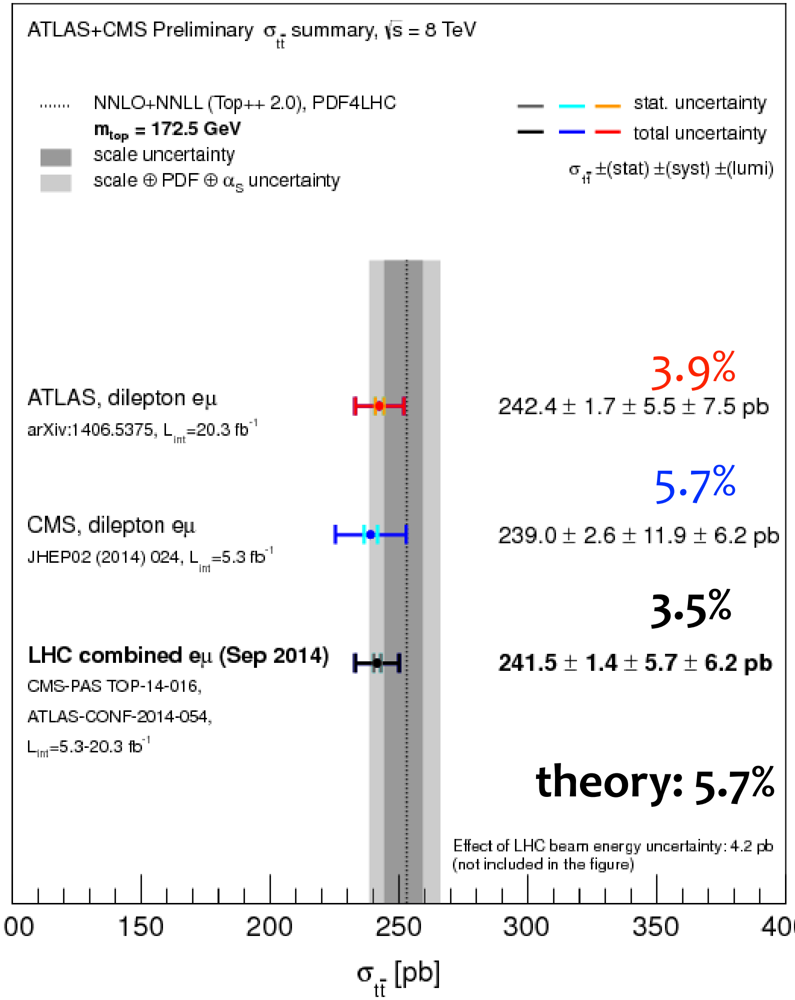


tt cross section inclusive combination

CMS-PAS TOP-14-016
ATLAS-CONF-2014-054

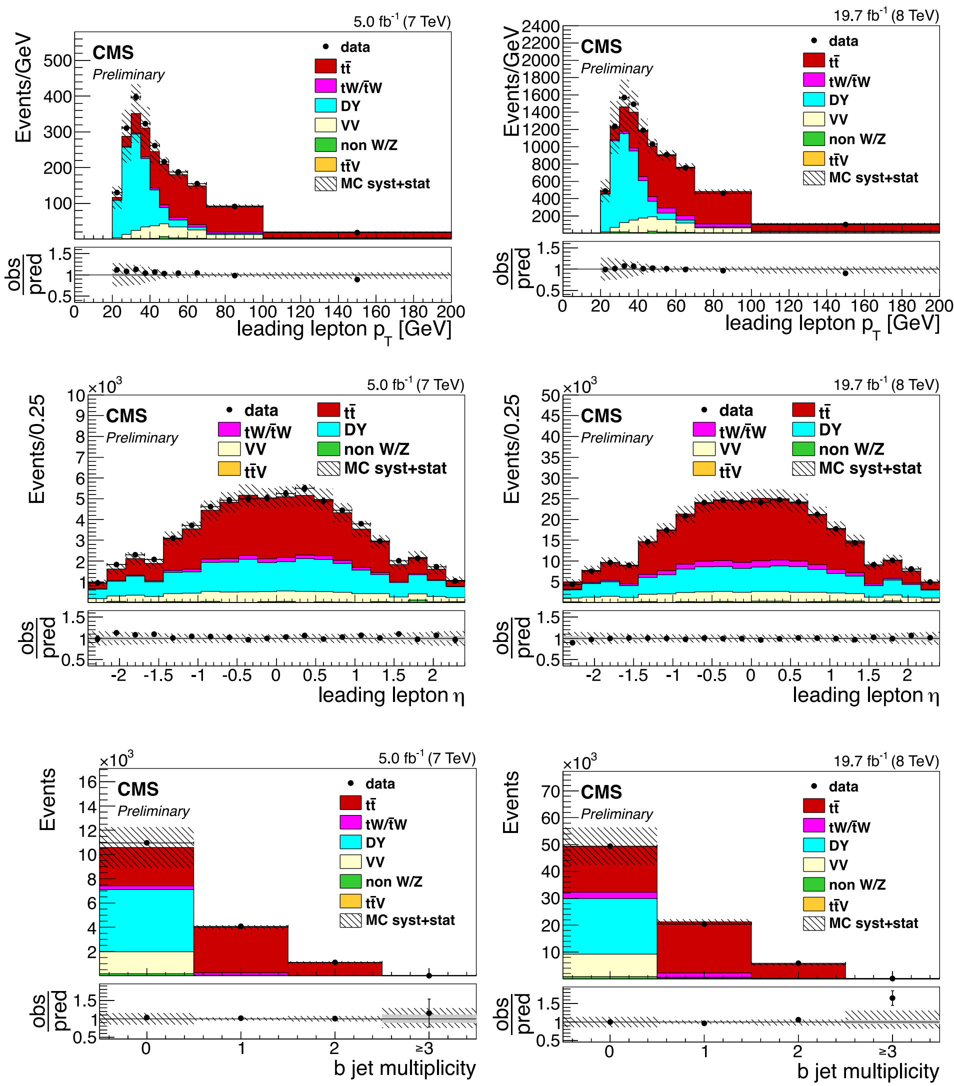
TOPLHCWG combination of best σ_{tt} measurements

	ATLAS	CMS	Correlation	LHC combination
Cross section [pb]	242.4	239.0		241.5
Uncertainty [pb]				
Statistical	1.7	2.6	0	1.4
Detector model				
Trigger	0.4	3.6	0	1.0
Lepton scale and resolution	1.2	0.2	0	0.9
Lepton identification	1.7	4.0	0	1.6
Jet resolution	1.2	3.0	0	1.2
Jet identification	0.1	–	–	0.1
b-tagging	1.0	1.7	0	0.8
Pileup	–	2.0	–	0.5
Non-JES subtotal	2.6	6.7	0	2.6
UncorrJES	0.6	4.3	0	1.2
InsituJES	0.6	0.6	0	0.5
IntercalibJES	0.3	0.1	0.5	0.2
FlavourJES	0.9	2.9	1	1.4
bJES	0.1	–	–	0.1
JES subtotal	1.3	5.2	0.4	1.9
Class subtotal	2.9	8.5		3.2
Signal model				
Scale	0.7	5.6	0.5	1.9
Radiation	–	3.8	–	1.0
Generator and parton shower	3.0	3.3	0.5	2.7
PDF	2.7	0.5	1	2.1
Class subtotal	4.1	7.5	0.3	4.0
Background from data				
Z+jets	<0.1	1.5	0	0.4
Lepton misidentification	0.8	1.9	0	0.8
Class subtotal	0.8	2.4	0	0.9
Background from simulation				
Dibosons	0.3	0.5	1	0.4
Single top quark	2.0	2.3	1	2.1
Class subtotal	2.0	2.4	1	2.1
Luminosity				
Beam modelling	2.9	5.0	1	3.5
Luminosity determination	6.9	3.6	0	5.1
Class subtotal	7.5	6.2	0.3	6.2
Total systematic	9.3	13.4		8.4
Total	9.4	13.6		8.5



CMS $t\bar{t}$ inclusive cross section in the eμ channel at 7/8 TeV (New) Top-13-004

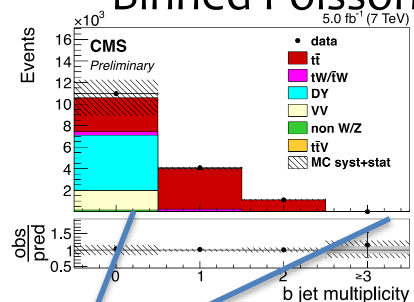
- **Measure the production cross sections at particle level in a fiducial range, defined within the kinematic acceptance of the ttbar decay particles that are directly visible in the detector.**
- **Visible cross section** is defined for events at particle level containing a true opposite charge electron-muon pair from the decay chain t → W → l (including W → τ → l) and with both leptons with $p_T > 20$ GeV and $|\eta| < 2.4$
- Extrapolate visible cross section to obtain the cross section for ttbar production at parton level in the full phase space using MC $A_{e\mu}$ (Signal acceptance is taken from simulation assuming a top mass of 172.5 GeV.)

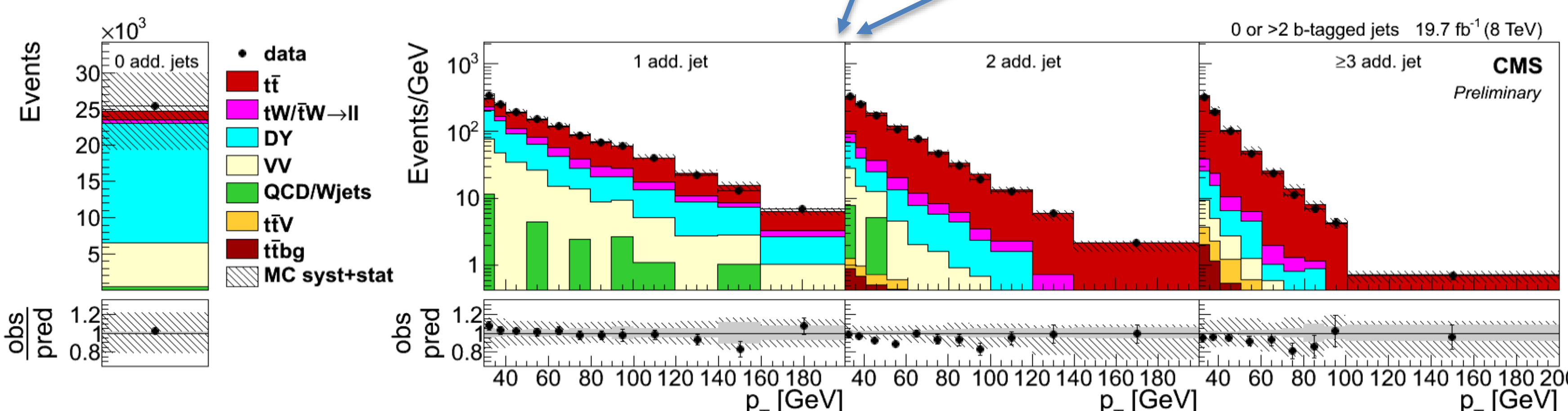


CMS: Method:

- Jet variables used in order to constrain uncertainty from b-tagging, JES
- First divide events into three bins by number of b-jets: N_b = 1, 2 and 0 or ≥3, then, each category is divided in 4 bins, as a function on the number of non b jets.
- For each of these N_{events}, p_T^{lead}, $p_T^{sublead}$ and p_T^{lowest} for events with 0, 1, 2 or 3 non b jets, respectively are taken (12 distributions in total)

- Template fit to lowest light jet p_T for each category (N_{events} if there are no light jets)
  - **Allows the extraction of the b-tagging efficiency and constraining of syst. unc.**
- Signal and background templates taken from MC, fitted to data.
  - Templates normalized to luminosity (depending on the cross section)
  - Templates depend on systematic variations λ_i
  - Binned Poisson Likelihood used for fitting





CMS Method and results:

- **Allow to derive b-jet acceptance ε_b from data (Eur.Phys.J. C74 (2014) 3109)**

$$s_1 = \mathcal{L} \cdot \epsilon_{e\mu} \cdot \sigma_{t\bar{t}}^{\text{vis}} \cdot 2\epsilon_b(1 - C_b\epsilon_b)$$

$$s_2 = \mathcal{L} \cdot \epsilon_{e\mu} \cdot \sigma_{t\bar{t}}^{\text{vis}} \cdot 2\epsilon_b^2 C_b$$

$$s_0 = \mathcal{L} \cdot \epsilon_{e\mu} \cdot \sigma_{t\bar{t}}^{\text{vis}} \cdot (1 - 2\epsilon_b^2 C_b - 2\epsilon_b(1 - \epsilon_b C_b))$$

- Implementation in the fit
  - Use equations for signal contribution:
  - Derive C_b, ε_b and $\varepsilon_{e\mu}$ parameters from MC
  - Parametrize them in terms of λ_i
- Each systematic source is treated individually by suitable variations of the MC simulations or varying parameter values within their estimated uncertainties
- Each source is finally represented by a nuisance parameter which is fitted together with the visible cross section
- **Fit simultaneously 7 and 8 TeV, using as many constraints as possible, we can lower uncertainties, Need to take into account correlations between sources at 7 and 8 TeV**

Source	Uncertainty [%]	
	7 TeV	8 TeV
Trigger	1.2	1.2
Lepton ID/isolation	1.4	1.5
Lepton energy scale	0.1	0.1
Jet energy scale	0.7	0.9
Jet energy resolution	0.1	0.1
Single top	0.9	0.6
DY	1.2	1.2
$t\bar{t}$ other	0.1	0.1
$t\bar{t} + V$	0.0	0.1
Diboson	0.2	0.6
W+jets	0.0	0.0
QCD	0.0	0.0
B-tag	0.5	0.5
Mistag	0.2	0.1
Pileup	0.3	0.3
Q^2 scale	0.3	0.3
ME/PS matching	0.2	0.1
MG+PY $\rightarrow$ PH+PY	0.2	0.4
Hadronization (JES)	0.6	0.8
Top p_T	0.3	0.3
Color reconnection	0.1	0.0
Underlying event	0.0	0.1
PDF	0.2	0.7
Luminosity	2.2	2.6
Statistical	1.2	0.6

σ_{vis}(7 TeV) = 3.05 $^{+0.11}_{-0.10}$ pb (+3.5% -3.4%)

σ_{vis}(8 TeV) = 4.24 $^{+0.16}_{-0.14}$ pb (+3.7% -3.4%)

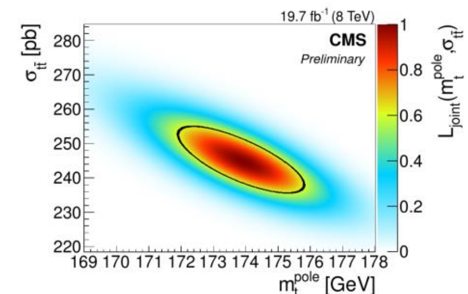
CMS Results: cross section, pole mass, limit on stop production

$\sigma(7\ \text{TeV}) = 174.5 \pm 2.1(\text{stat})\ ^{+4.5}_{-4.0}(\text{syst}) \pm 3.8(\text{lumi})\ \text{pb}\ (+3.6\%\ -3.4\%)$

$\sigma(8\ \text{TeV}) = 245.6 \pm 1.3(\text{stat})\ ^{+6.6}_{-5.5}(\text{syst}) \pm 6.5(\text{lumi})\ \text{pb}\ (+3.8\%\ -3.5\%)$

R (8/7 TeV) = 1.41 ± 0.06 (stat+syst)

R(7/8 TeV, NNLO) = 1.430



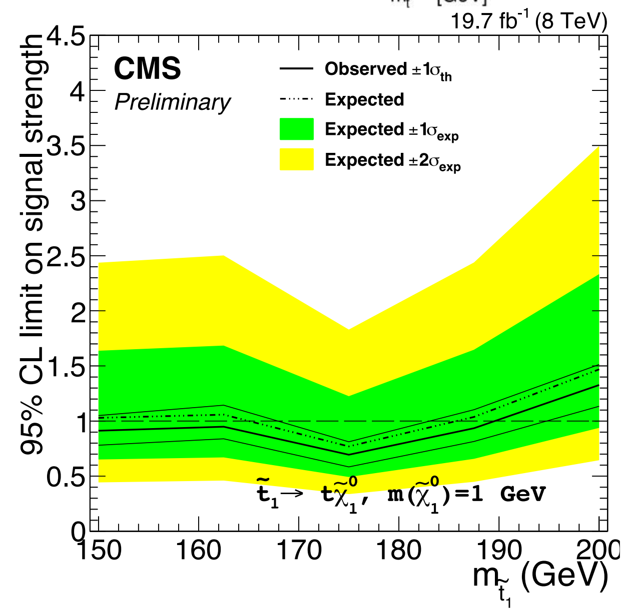
Top pole mass: $m_t = 173.6\ ^{+1.7}_{-1.8}$ GeV

SUSY Constraints from

ttbar Cross Section:

Stop quarks with masses below 189 GeV are excluded (for light neutralinos)

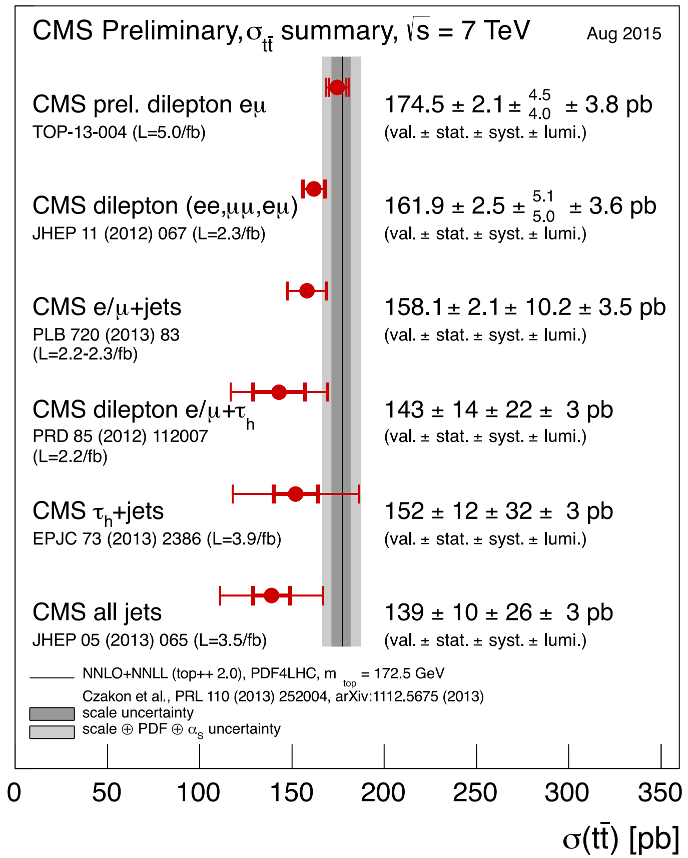
Similar level of exclusion by ATLAS

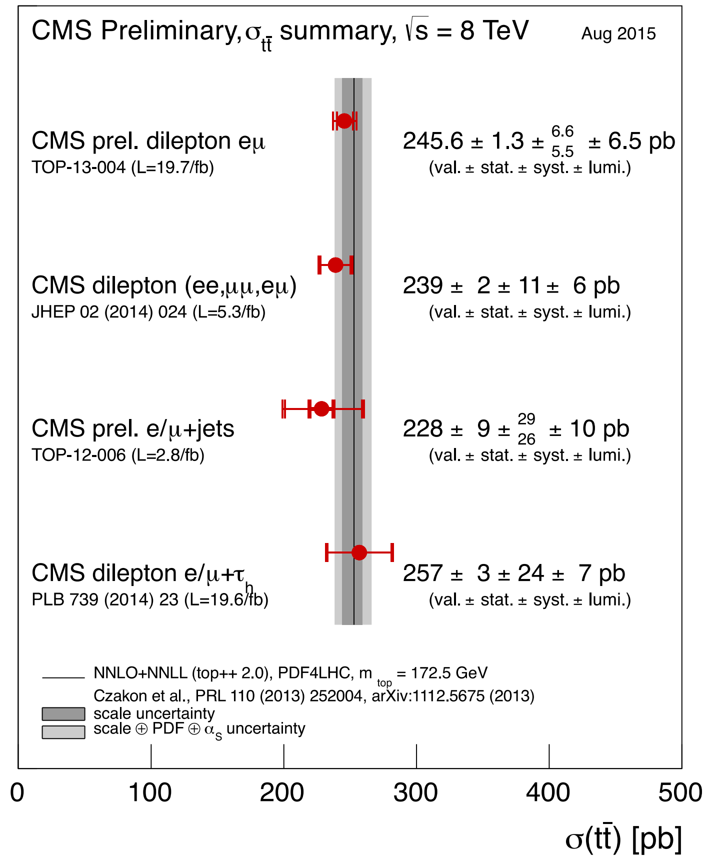


CMS new cross section inclusive combination

Most top pair final states investigated

- $\ell(e,\mu,\tau)$+jets, $\ell\ell$ (all but $\tau\tau$)+jets and fully hadronic final states in the combination.
- Highest precision reached in the di-lepton channels
- **All results consistent**





ATLAS Top pair cross section in the eμ channel at 13 TeV

ATLAS-CONF-2015-033

- Analysis strategy follows Run1 best measurement
  - select OS eμ, pT(ℓ)>25 GeV, jets (25 GeV),≥1 btag,

    no MET required
- Count number of eμ events with
  - exactly one (N1) and exactly two (N2) b-tagged jets
  - extract $\sigma_{t\bar{t}}$ and prob. to b-tag q from t⟶ Wq(ε_b)

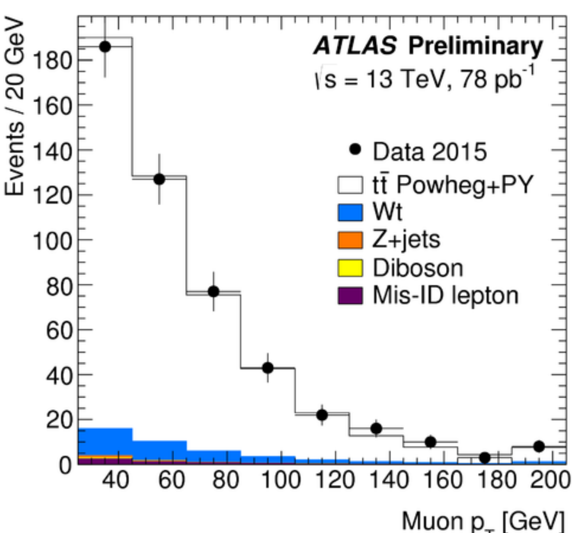
$$N_1 = L\sigma_{t\bar{t}}\ \epsilon_{e\mu} 2\epsilon_b(1 - C_b\epsilon_b) + N_1^{\rm bkg}$$

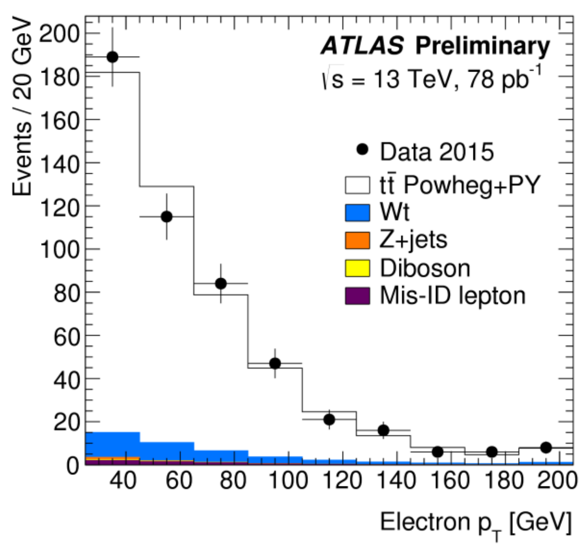
$$N_2 = L\sigma_{t\bar{t}}\ \epsilon_{e\mu} C_b{\epsilon_b}^2 + N_2^{\rm bkg}$$

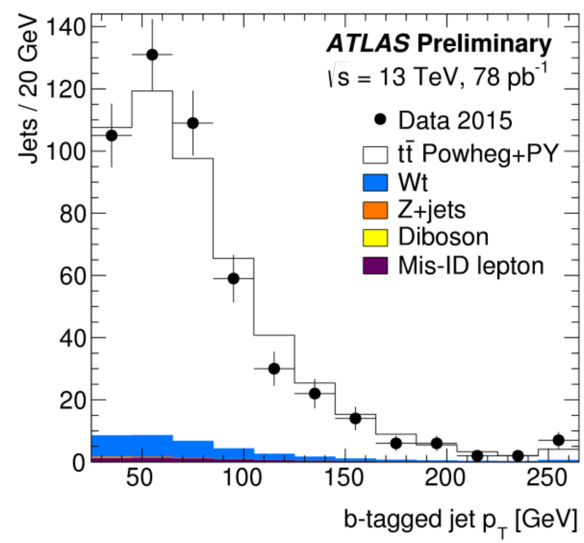
luminosity of data sample

sel. eff.+acc. incl. BR (0.9%)

non-factorisation correction from MC $\varepsilon_{bb}/\varepsilon_b^2 = 1.005 \pm 0.006$

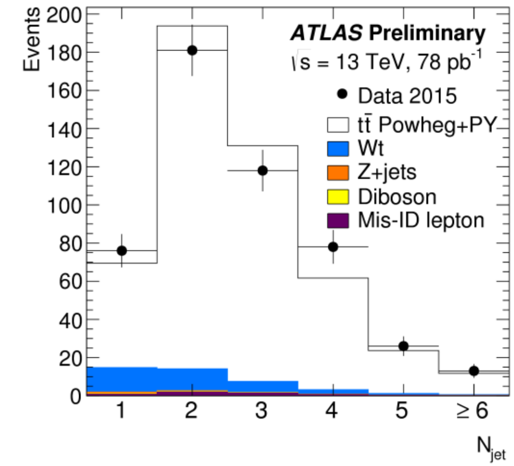






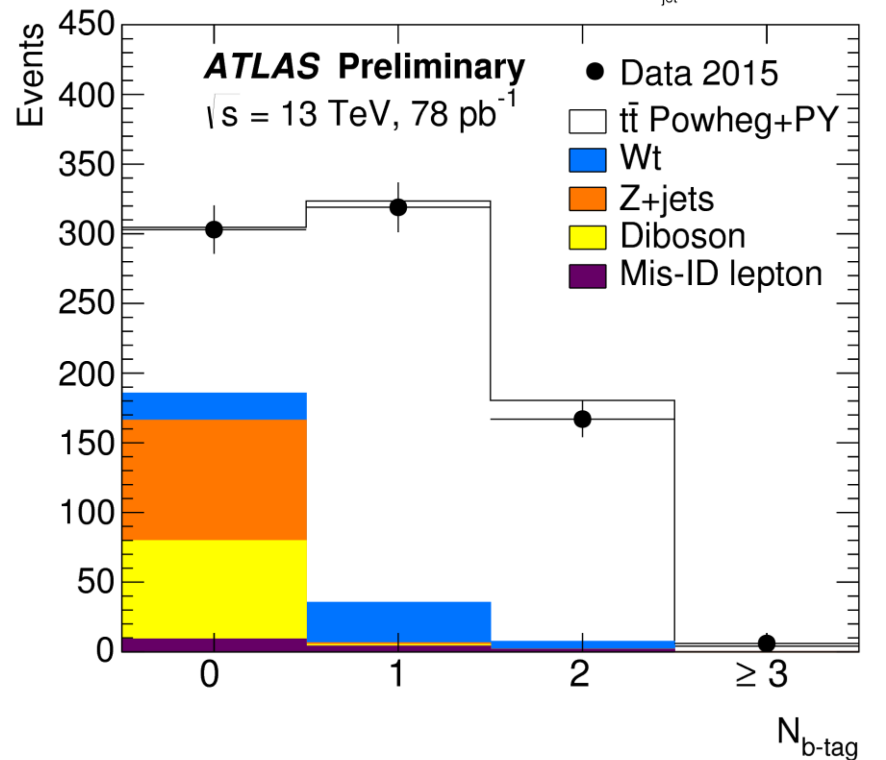
ATLAS Top pair cross section in the eμ channel at 13 TeV

Event counts	N_1	N_2
Data	319	167
Wt single top	29.0 ± 3.8	5.6 ± 2.0
Dibosons	1.1 ± 0.2	0.0 ± 0.0
$Z(\to \tau\tau \to e\mu)$+jets	1.3 ± 0.7	0.1 ± 0.1
Misidentified leptons	6.0 ± 3.9	2.8 ± 2.9
Total background	37.3 ± 5.5	8.5 ± 3.5



ε_b=0.527 ± 0.026$_{stat}$ ± 0.006$_{syst}$

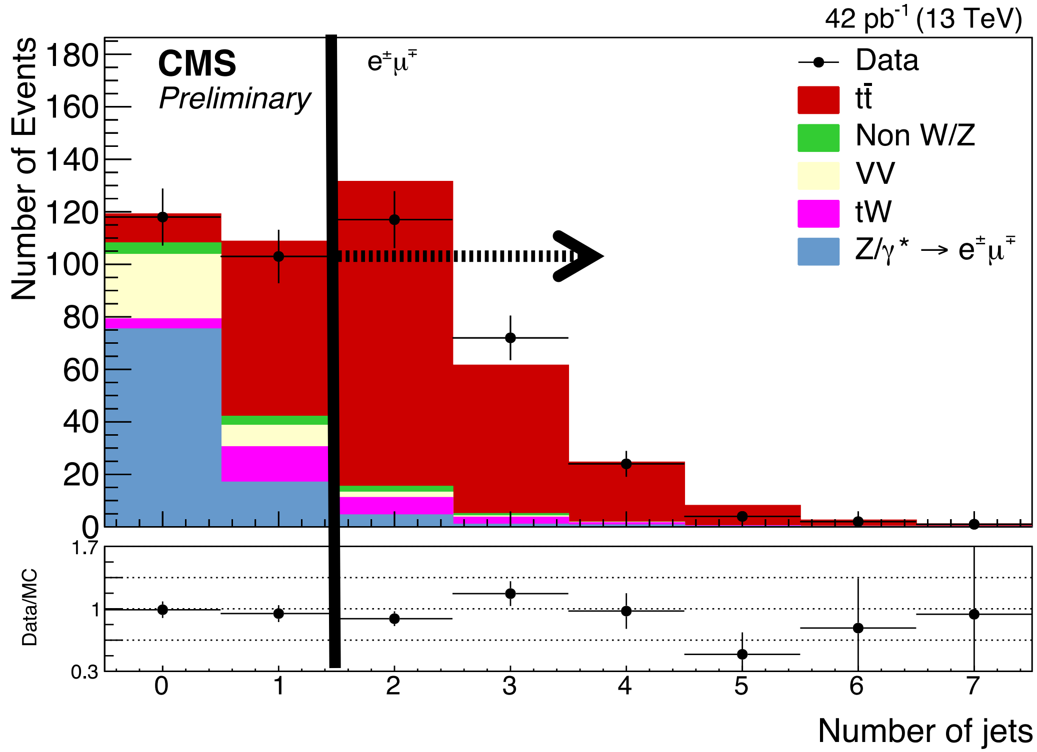
In **good agreement with simulation** (0.543), includes jet acceptance



σ_{tt} (13 TeV) = 825 ± 49$_{stat}$ ± 60$_{syst}$ ± 83$_{lumi}$ pb

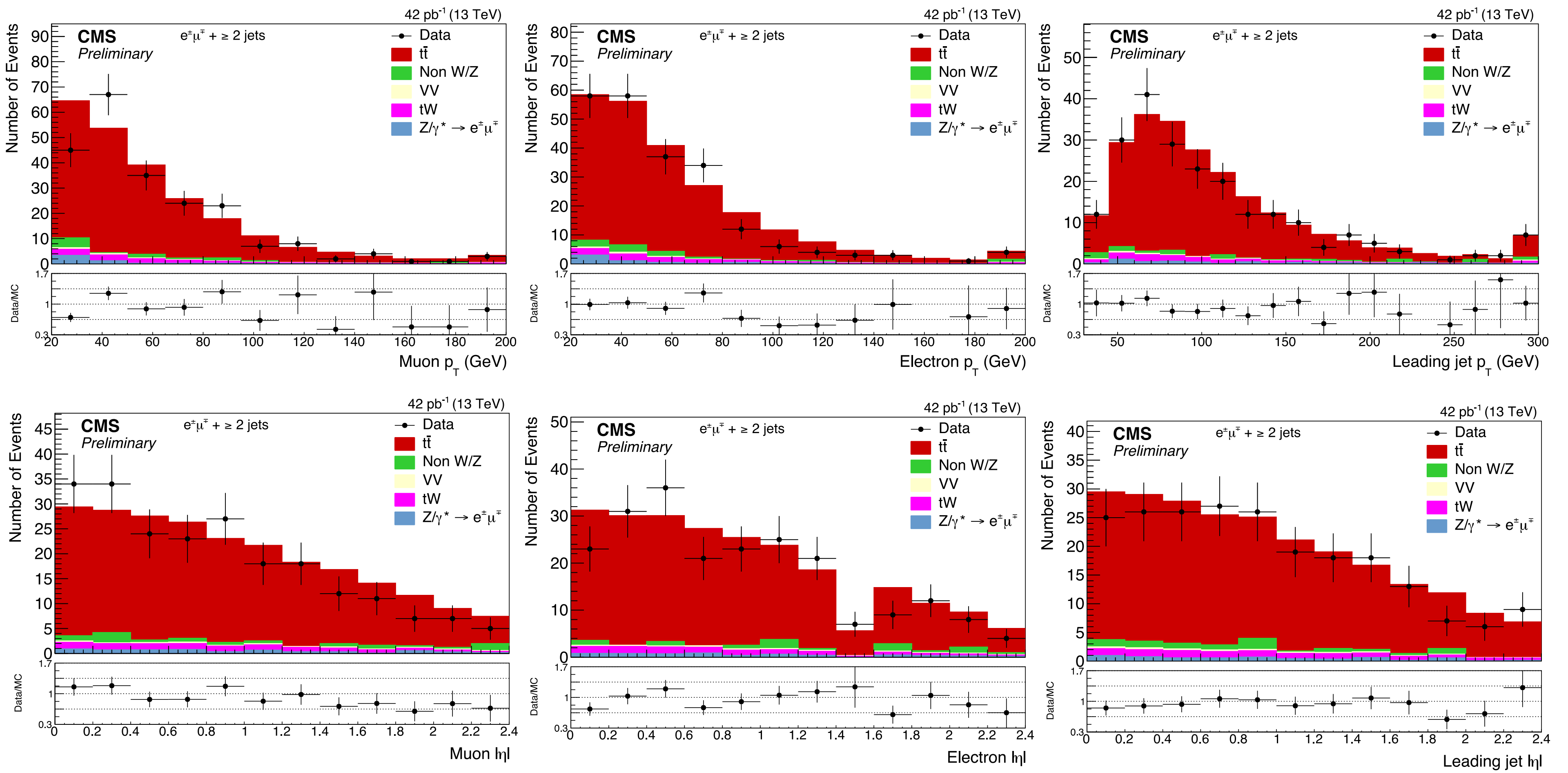
CMS Top pair cross section in the eμ channel at 13 TeV

- **Same Cut and Count technique as in Run I (TOP-11-005, TOP-12-007, TOP-13-004) is used for the measurement**
- **Luminosity:** 42 pb^{-1}
- **Event selection**
  - ≥ 2 (OS) leptons (1 e, 1 μ), p_T> 20 GeV and |η|< 2.4, and invariant mass > 20 GeV
  - ≥ 2 jets with p_T> 30 GeV and |η|< 2.4
- **Background estimation**
  - Drell Yan normalized to MC prediction by a data/MC SF (from Z peak in data)
  - Non W/Z: fully data driven technique
  - Single top (tW) and diboson are taken from MC



Source	Number of events $e^{\pm}\mu^{\mp}$
Drell–Yan	6.4 ± 1.2
Non-W/Z leptons	8.5 ± 4.3
Single top quark	10.6 ± 3.4
VV (V = W or Z)	2.6 ± 0.9
Total background	28.1 ± 5.7
$t\bar{t}$ dilepton signal	207 ± 16
Data	220

Kinematic distributions (normalized to NNLO+NNLL)



Comparison of ATLAS and CMS syst. uncertainties

- **luminosity uncertainty dominates (9%, 12%)**
  - will be reduced with dedicated VdM scans (performed weekend August 23th)
- ***$t\bar{t}$* modeling**
  - $t\bar{t}$ hadronisation (4.5%, 1.8%)
  - $t\bar{t}$ NLO modeling, ISR/FSR radiation & PDF (2.9%, 2.4%)
- **detector-related**
  - lepton triggers (1.3%, 5.0%)
  - electron ID and isolation (4.2%), muon ID and isolation (1.6%); lepton efficiency (4.3%)
  - lepton mis-ID (1.3%, 1.0%)
  - jet energy scale (0.3%, 2.6%)
- **statistical uncertainty**
  - ATLAS analysed 78 pb^{-1} (6.0%), CMS 42 pb^{-1} (7.7%)

- **Cross section measurements (essentially same systematic uncertainty)**

$\sigma_{t\bar{t}} = 825 \pm 49_{stat} \pm 60_{syst} \pm 83_{lumi}$ pb , $\Delta\sigma_{t\bar{t}} / \sigma_{t\bar{t}} = 14\%$ (**ATLAS**)

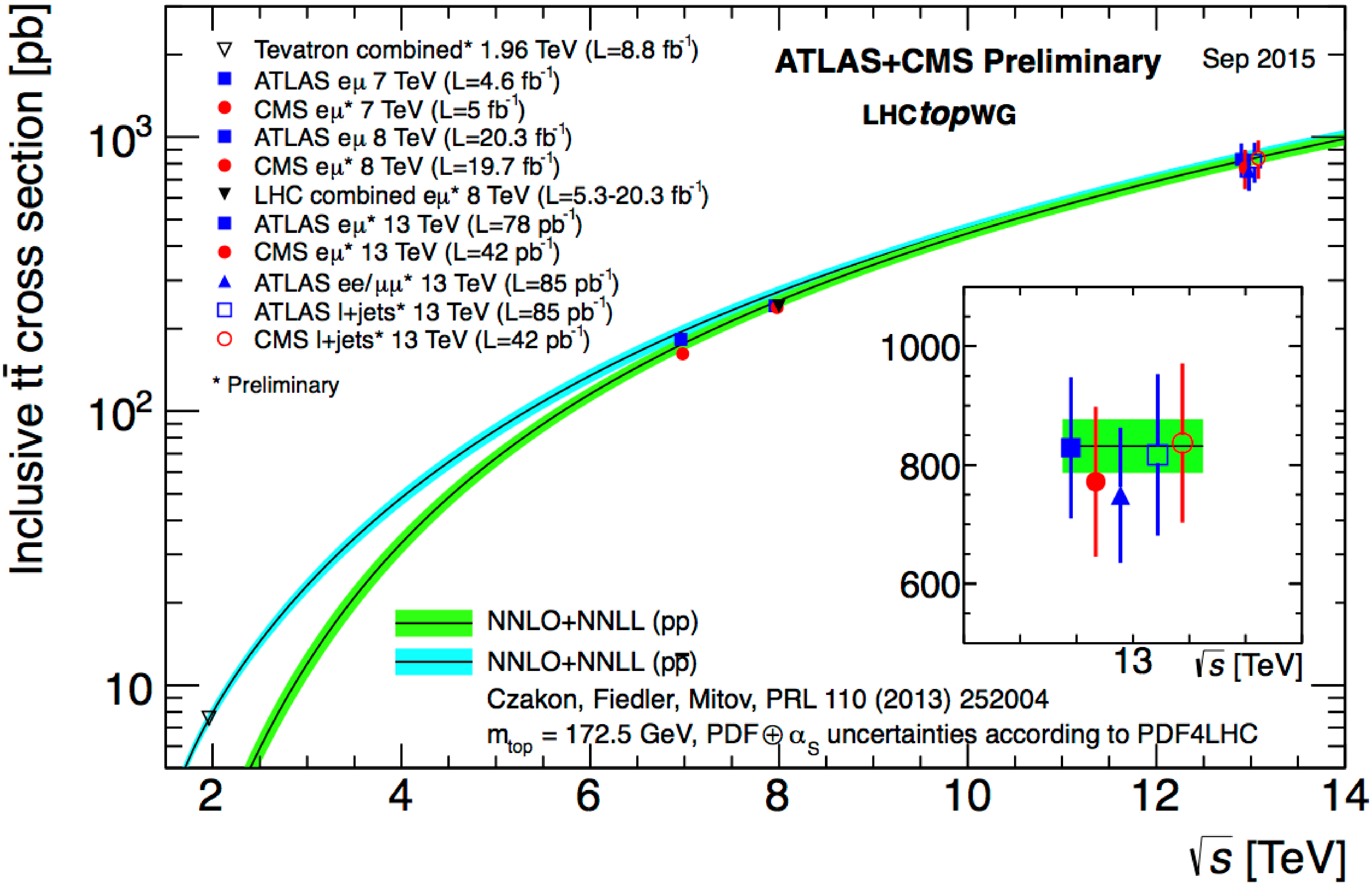
$\sigma_{t\bar{t}} = 772 \pm 60_{stat} \pm 62_{syst} \pm 93_{lumi}$ pb , $\Delta\sigma_{t\bar{t}} / \sigma_{t\bar{t}} = 16\%$ (**CMS**)

Comparison of ATLAS and CMS results at different CM energies

- Good agreement in central values, similar overall systematic uncertainty, but some differences in the estimates

		σ(pb)		Stat (%)	Syst (%)	Lumi (%)
		NNLO	Meas.			
7 TeV	CMS	177.3	**174.5**	1.2	**2.5**	2.2
	ATLAS[1]		**182.9**	1.7	**2.3**	2.0
8 TeV	CMS	252.9	**245.6**	0.5	**2.4**	2.6
	ATLAS[1]		**242.4**	0.7	**2.3**	3.1
13 TeV	CMS	831.7	**772**	7.7	**8.0**	12
	ATLAS		**825**	5.9	**7.2**	10

[1] Eur. Phys. J C74 (2014) 3109


Inclusive tt̄ cross section [pb]
Tevatron combined* 1.96 TeV (L=8.8 fb-1)
ATLAS eμ 7 TeV (L=4.6 fb-1)
CMS eμ* 7 TeV (L=5 fb-1)
ATLAS eμ 8 TeV (L=20.3 fb-1)
CMS eμ* 8 TeV (L=19.7 fb-1)
LHC combined eμ* 8 TeV (L=5.3-20.3 fb-1)
ATLAS eμ* 13 TeV (L=78 pb-1)
CMS eμ* 13 TeV (L=42 pb-1)
ATLAS ee/μμ* 13 TeV (L=85 pb-1)
ATLAS l+jets* 13 TeV (L=85 pb-1)
CMS l+jets* 13 TeV (L=42 pb-1)
* Preliminary
ATLAS+CMS Preliminary
Sep 2015
LHCtopWG
NNLO+NNLL (pp)
NNLO+NNLL (pp̄)
Czakon, Fiedler, Mitov, PRL 110 (2013) 252004
m_top = 172.5 GeV, PDF ⊕ α_S uncertainties according to PDF4LHC
√s [TeV]

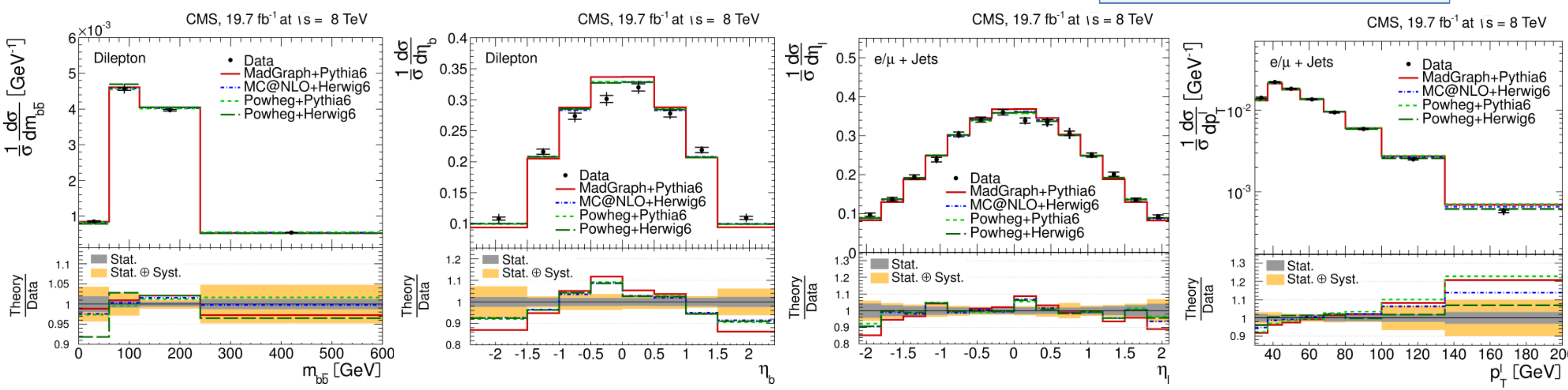
CMS Top pair differential cross sections

- Test top physics in different portions of the phase space

$$\frac{1}{\sigma}\frac{d\sigma^i}{dX} = \frac{1}{\sigma}\frac{N^i_{\rm Data} - N^i_{\rm BG}}{\Delta^i_{\rm X}\epsilon^i L}$$

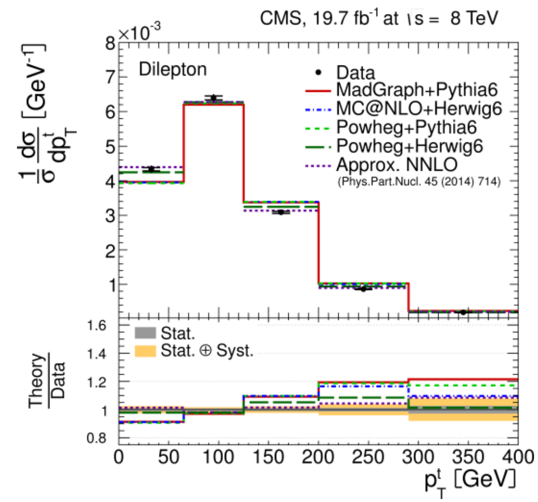
  - Test of perturbative QCD, constrain of different generators, theory uncertainties, systematic effects. Window to new physics
  - Use unfolding techniques on background-subtracted reconstructed distributions for a direct comparison to theory predictions
  - Propagation of the systematic errors (only shape errors important)
    - Most relevant coming from background knowledge, radiation and hadronization
- Look at lepton, jets, and to more complex variables in top quark final states
  - Need a full reconstruction of top kinematics
  - Compare to reference generators and predictions on differential distribution from theory
  - No significant deviations from SM predictions.

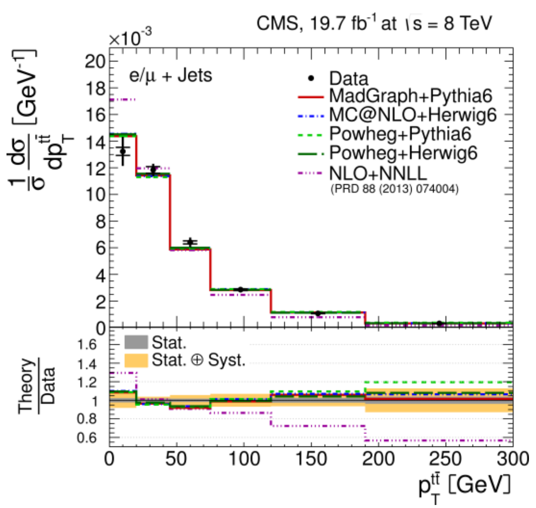
visible phase space

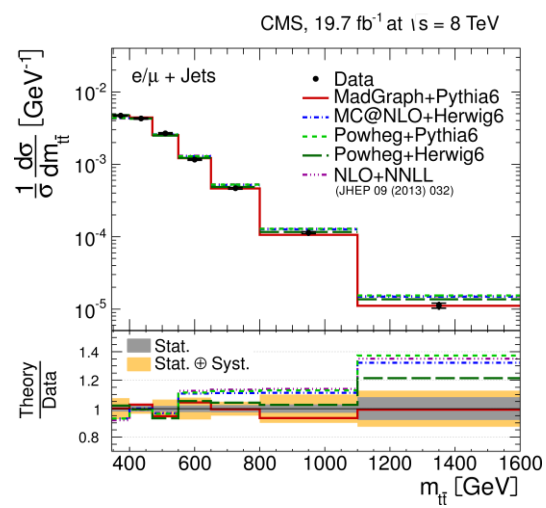


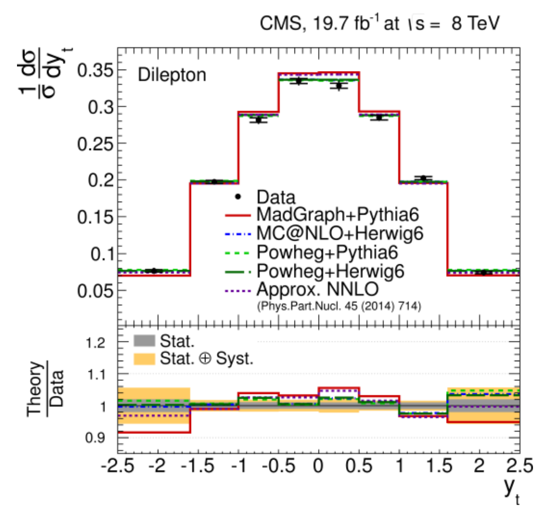
CMS Top pair differential in full phase space

- Differential cross section measured as a function of the top quarks and the tt system at parton level in full phase space
- Good agreement with SM predictions.
  - Observed top p_T softer than most MC predictions.
  - $p_T(tt)$ in general well described
  - m(tt) has tail in data lower than prediction.





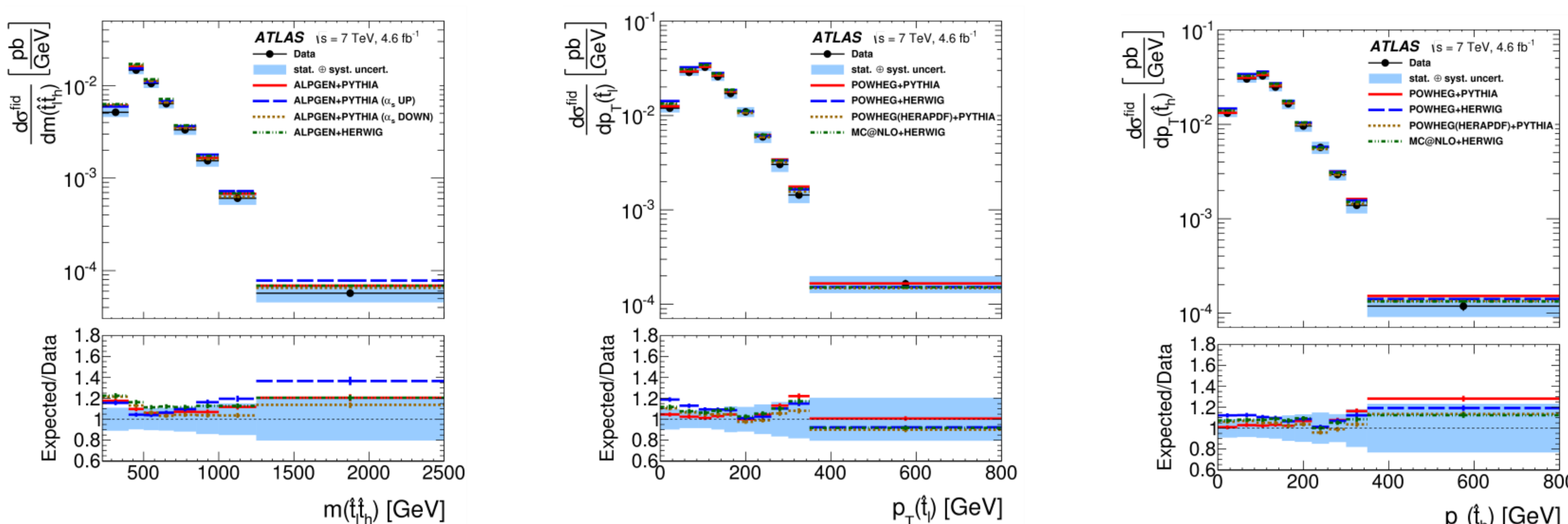




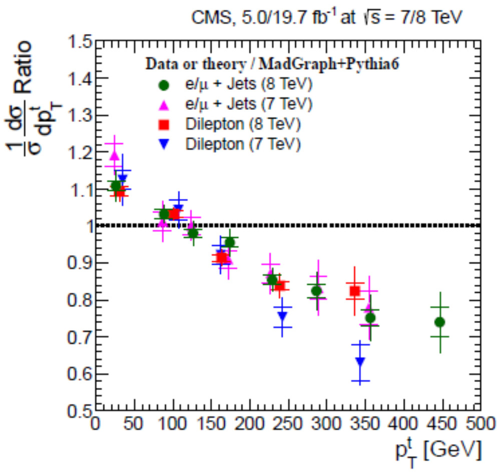
ATLAS tt differential: particle level top

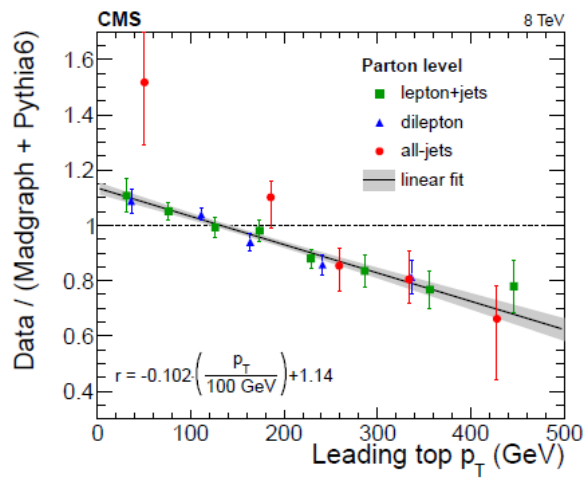
- Use well defined top definition at particle level
  - (LHCTOPWG recommendation)
  - fully fiducial, differential measurement
  - Top quark proxy constructed from stable particles/detector level observables
- Cut based analysis in ℓ+jets channel
  - data well described by models
  - Discrepancy at low $m_{t\bar{t}}$
  - Main uncertainties: b-tagging, JES and JER

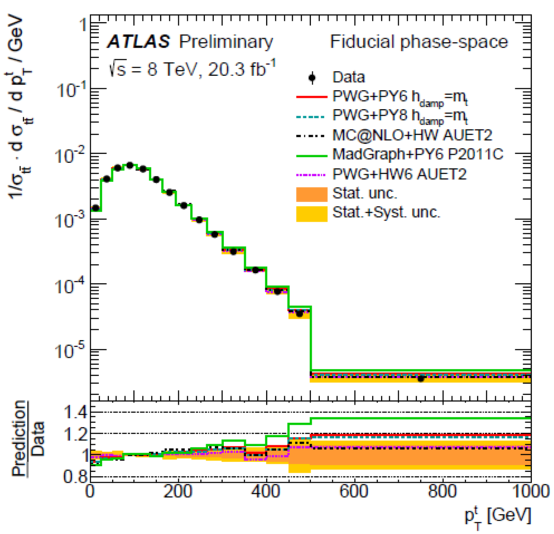
JHEP06 (2015) 100

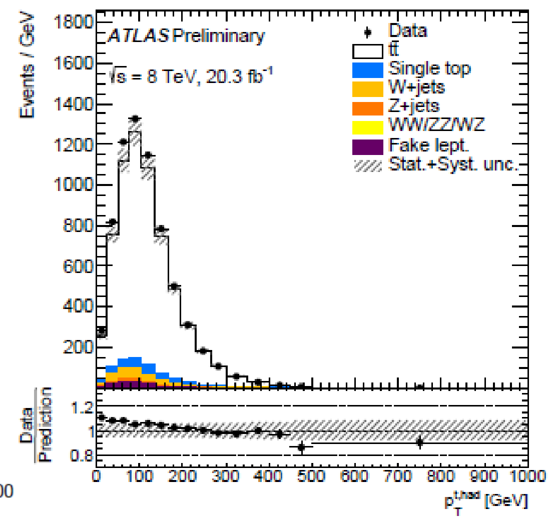


Top p_T differential distribution









My observations:

CMS – consistent slope between data and default MG+PY6 in all channels, 7 and 8 TeV

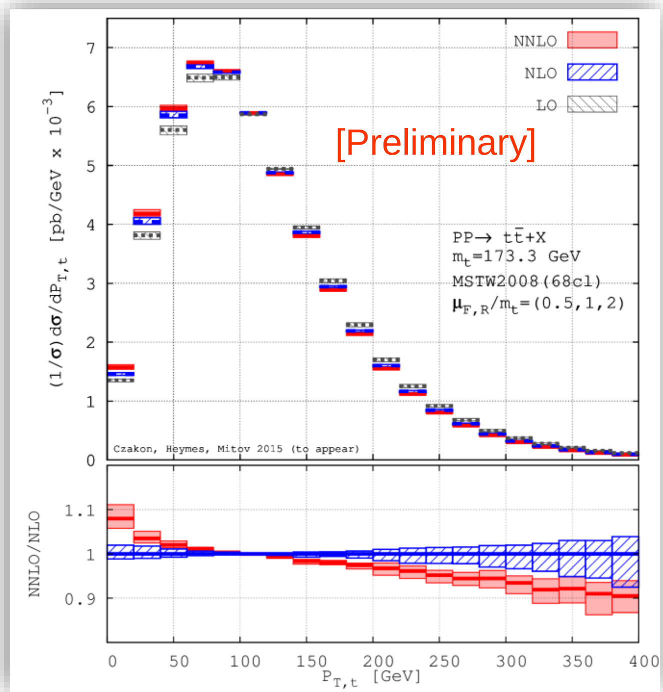
Full difference counted as additional systematic effect (also for Searches, eg ttH)

= = =

ATLAS and CMS data appear in good agreement at 8 TeV

ATLAS PWG+PY (hdamp=mt) and other MCs do better than MG+PY

Top p_T modeling



Full NNLO/NLO k-factor vs top pT : a slope!

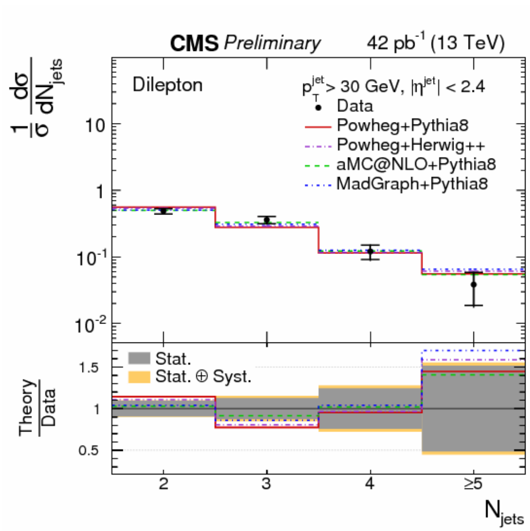
- Full NNLO correction "confirms" observed slope, in direction closer to the data
- Use k-factors to reweight NLO+PS MCs ?
- Ultimately NNLO+PS would be great ☺

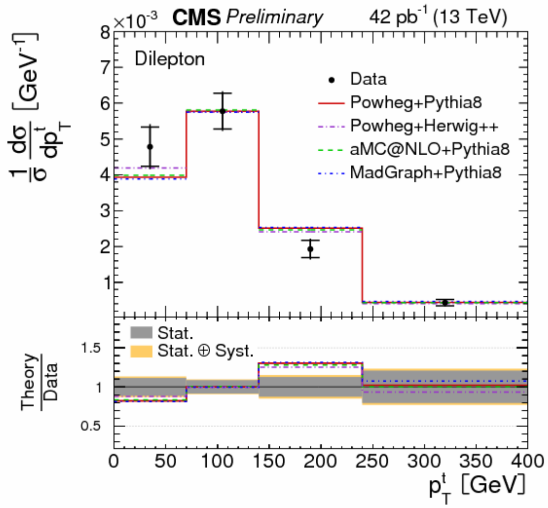
➔ Great to see this dialogue between LHC precision measurements and state-of-the art theory calculations

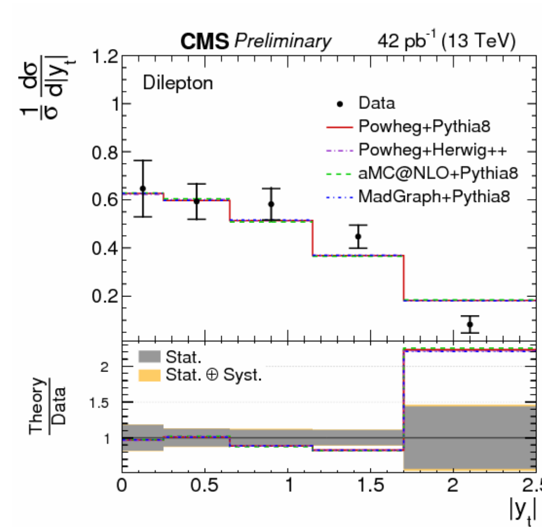
➔ Important step forward in our understanding of Top production !!

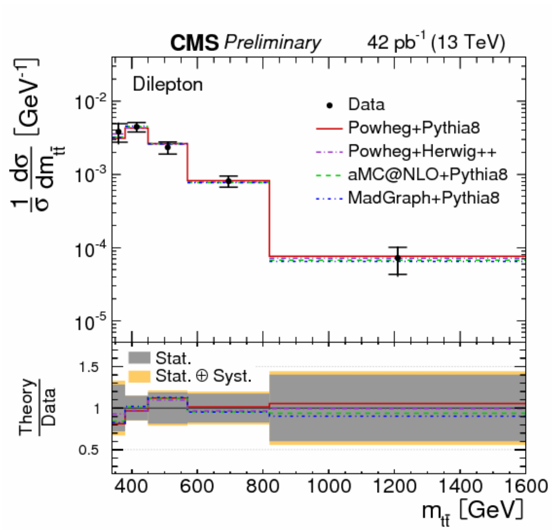
CMS Top pair differential cross section at 13 TeV

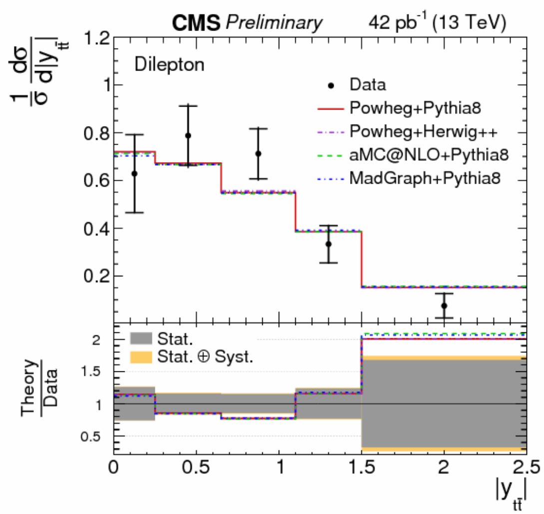
CMS PAS TOP-15-010

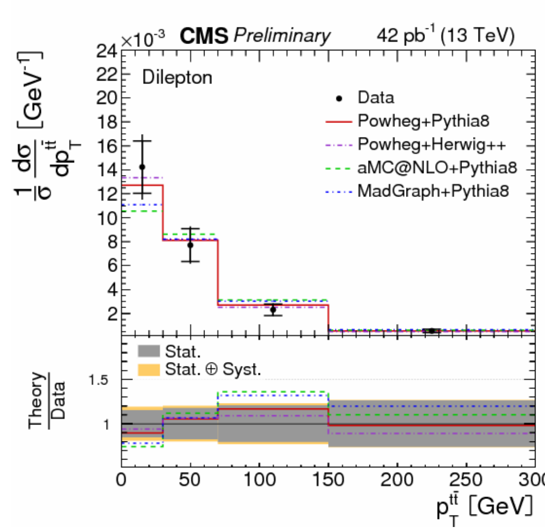








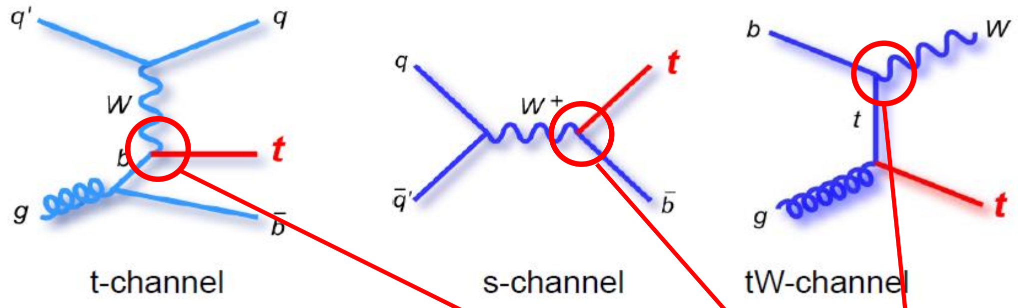




Single top quark production

Top quarks produced singly via electroweak interaction

- **The production cross section gives direct access to the CKM matrix element $|V|_{tb}$**
  - May also test the presence of a possible 4th generation quark
  - Check for presence of FCNC
  - Important background for Higgs searches in associated production W/ZH→qqbb



	LHC [pb] √s=7 TeV	LHC [pb] √s=8 TeV
s-channel	5	6
t-channel	65	87
tW	16	22

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

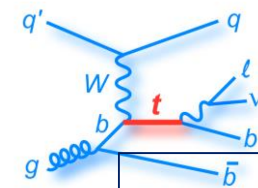
Kidonakis, NLO+NNLL
t-channel: PRD 83 (2011) 091503
s-channel: PRD 81 (2010) 054028
tW-channel: PRD 82 (2010) 054018

- **Investigate t-channel and tW production**
  - ➢ s-channel still out of range for an observation
  - ➢ **t-channel:** 1 isolated e or μ, one b-tagged jet, one forward jet, missing E_T
  - ➢ **tW channel:** 2 isolated charged leptons (e, μ), one b-tagged jet, missing E_T

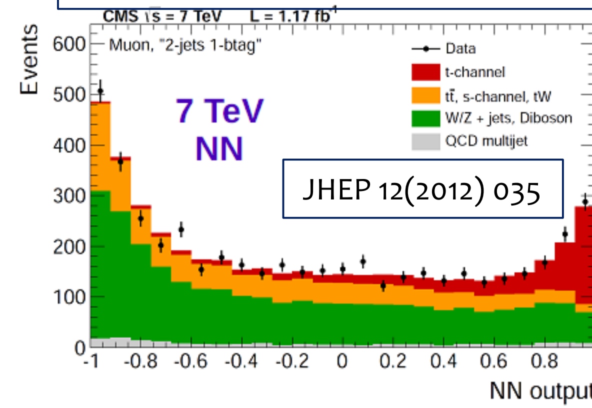
Kidonakis NNLO
arxiv 1311.0283

- **Main backgrounds** from top-pair production (both semileptonic and di-leptonic topologies), Z(ll)/W(lν)+jets, Multijet QCD (reduced to extreme kinematic regions by selection cuts)
  - ➢ Use data whenever possible to constrain the backgrounds

Single top t-channel



$\sigma_{(t\text{-ch.},7\ \text{TeV})}$ = 67.2 ± 6.1 pb (total)



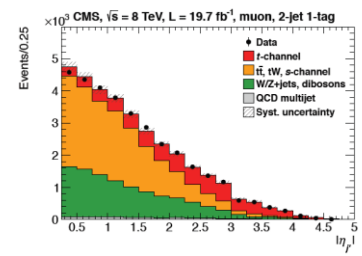
JHEP 12(2012) 035

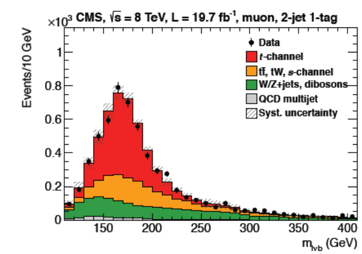
- Robust analysis based on data-driven methods
- Use of multivariate techniques (NN, BDT)
  - Optimize S/B separation using full event properties, constrain systematic effects by simultaneously analyzing signal and background dominated regions
- Cross sections in agreement with the SM expectations, $|V_{tb}|$ can be derived $|V_{td}|, |V_{ts}| << |V_{tb}|$

$$|V_{\text{tb}}| = \sqrt{\frac{\sigma_{t-\text{ch.}}}{\sigma^{\text{th}}_{t-\text{ch.}}}} = 1.020 \pm 0.046\ (\text{exp.}) \pm 0.017\ (\text{theor.})$$

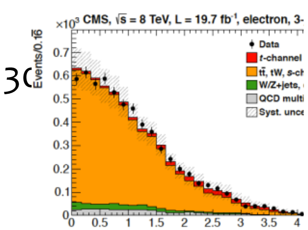
$0.92 < |V_{\text{tb}}| \leq 1$ @ 95% C.L.

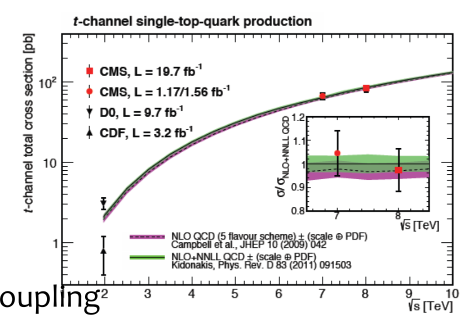
JHEP06(2014) 090





- Analysis ported to 8 TeV (template fit to $|\eta_j|$)
  - fit to the pseudorapidity of the recoil jet in the signal region 130 < m_{top} < 220 GeV
  - **W/Z+jets** and **tt** background shapes are estimated from data (from top mass sidebands and 3 jets 2 b-tags event category, respectively)
  - **QCD multijet** background is fixed with a fit to the W transverse mass (muon channel) / transverse missing energy (electron channel)





f_{LV}, anomalous form factor in the Wtb coupling

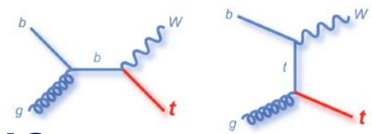
$|f_{LV}\ V_{tb}|$ = **0.979 ± 0.045(exp.) ± 0.016(theo.)**

$\sigma_{(t\text{-ch.},8\ \text{TeV})}$ = 83.6 ± 2.3 (stat) ± 7.4 (syst) pb

Single top tW channel

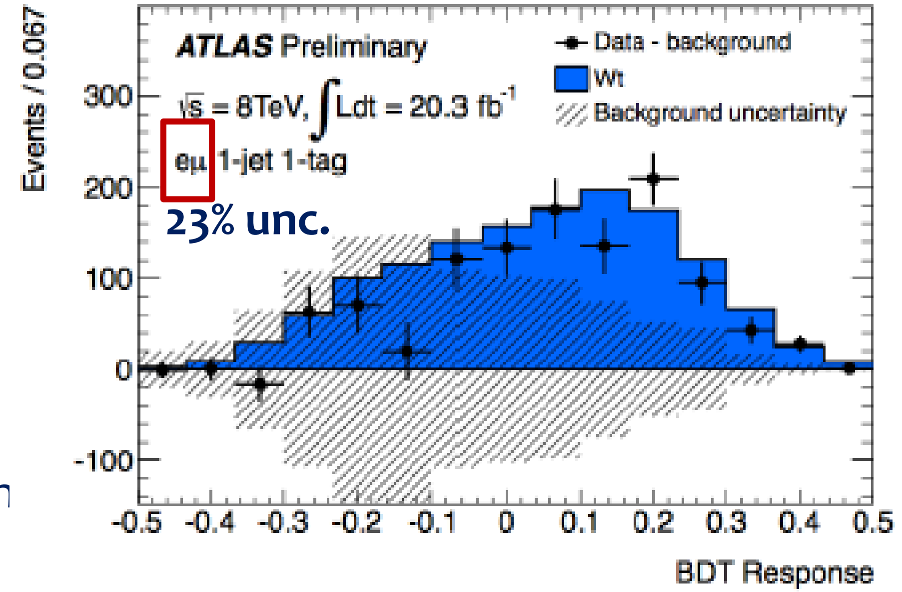
ATLAS-CONF-2014-052
CMS PAS TOP-14-009

First evidence at 7 TeV, PRL 110, 022003 (2013)



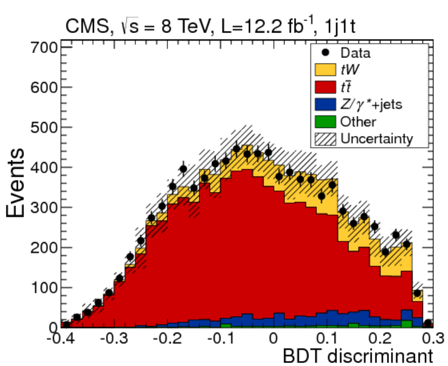
tW production observed at LHC

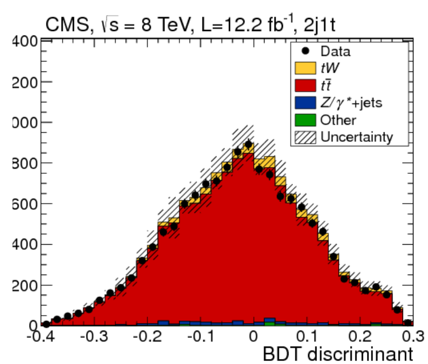
- Interesting topology (background to Higgs->WW searches), only leptonic (e, μ) decays of W considered
- In the dilepton topology: two isolated leptons, MET and one b-jet, main backgrounds: Top pairs and Z+jets, all other processes easily reducible
- tW mixing with top pair at NLO: Diagram Removal vs. Diagram Subtraction (DR/DS)

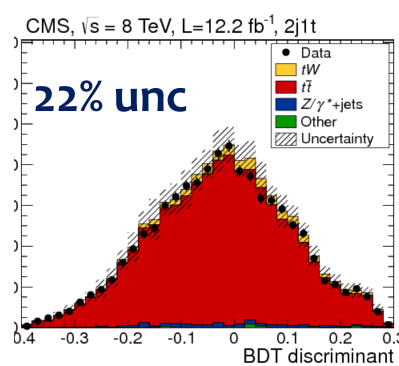


BDT based on 13 kinematic input variables chosen based on signal/background separation, data/MC in several control regions (2j1b, 2j2b, 2j0b,1j0b)

Systematic Uncertainty	$\Delta\sigma$ (pb)	$\frac{\Delta\sigma}{\sigma}$
ME/PS matching thresholds	3.25	14%
Q^2 scale	2.68	11%
Top quark mass	2.28	10%
Statistical	2.13	9%
Luminosity	1.13	5%
JES	0.91	4%







the choice of the control regions allows also to constrain b-tag efficiency in situ in the same likelihood fit, and reduce that systematic that would be overwhelming otherwise

- Observed significance **6.1 σ**/Expected significance: **5.4 ± 1.4σ.**
- Cross-section estimated using profile likelihood: **σ_{tW} = 23.4 ± 5.4 pb at 8TeV,** for (m_{top}=173GeV): $\sigma_{tW(th)}$ = 22.2 ± 0.6(scale) ±1.4(PDF) pb

PRL 112, 231802 (2014)

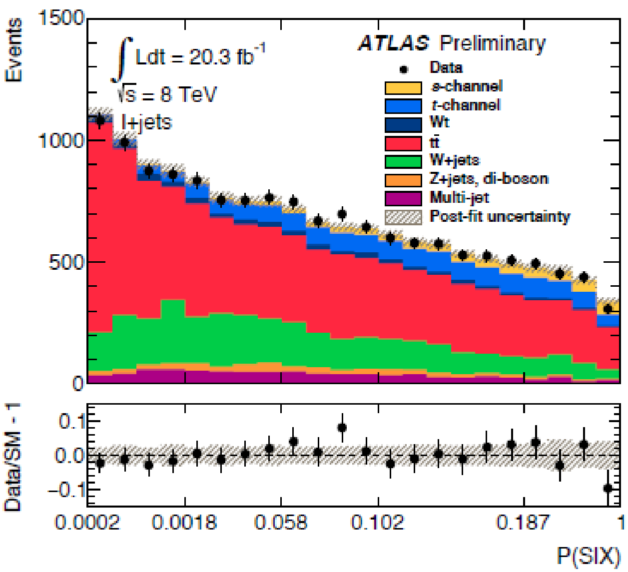
Single top s-channel evidence

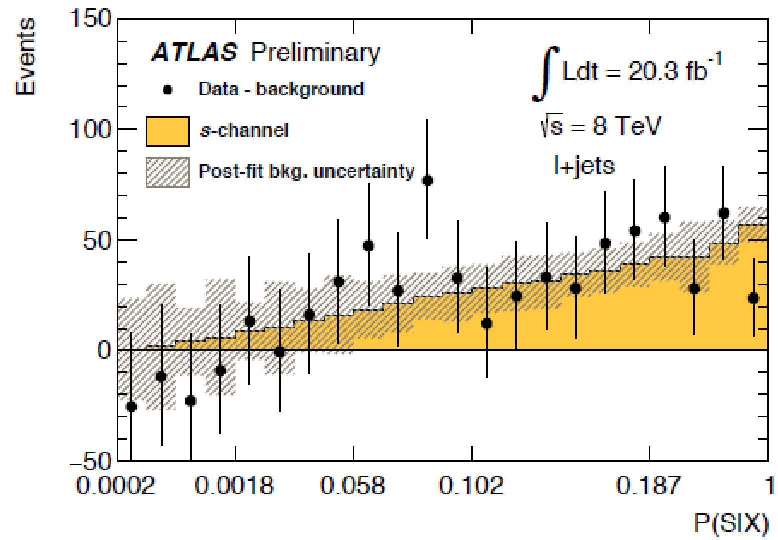
$\sigma_s = 4.8 \pm 1.1\ (\text{stat.})^{+2.2}_{-2.0}\ (\text{syst.})\text{pb}$
Significance: 3.2σ (exp. 3.9σ)

→ Consistent with SM expectation:
$\sigma^{theory}_{s-ch.} = 5.61 \pm 0.22$ pb

Uses the Matrix Element method to squeeze out optimal sensitivity…

2-jet 2-tag ($\sim$ 4.3% of s-channel)

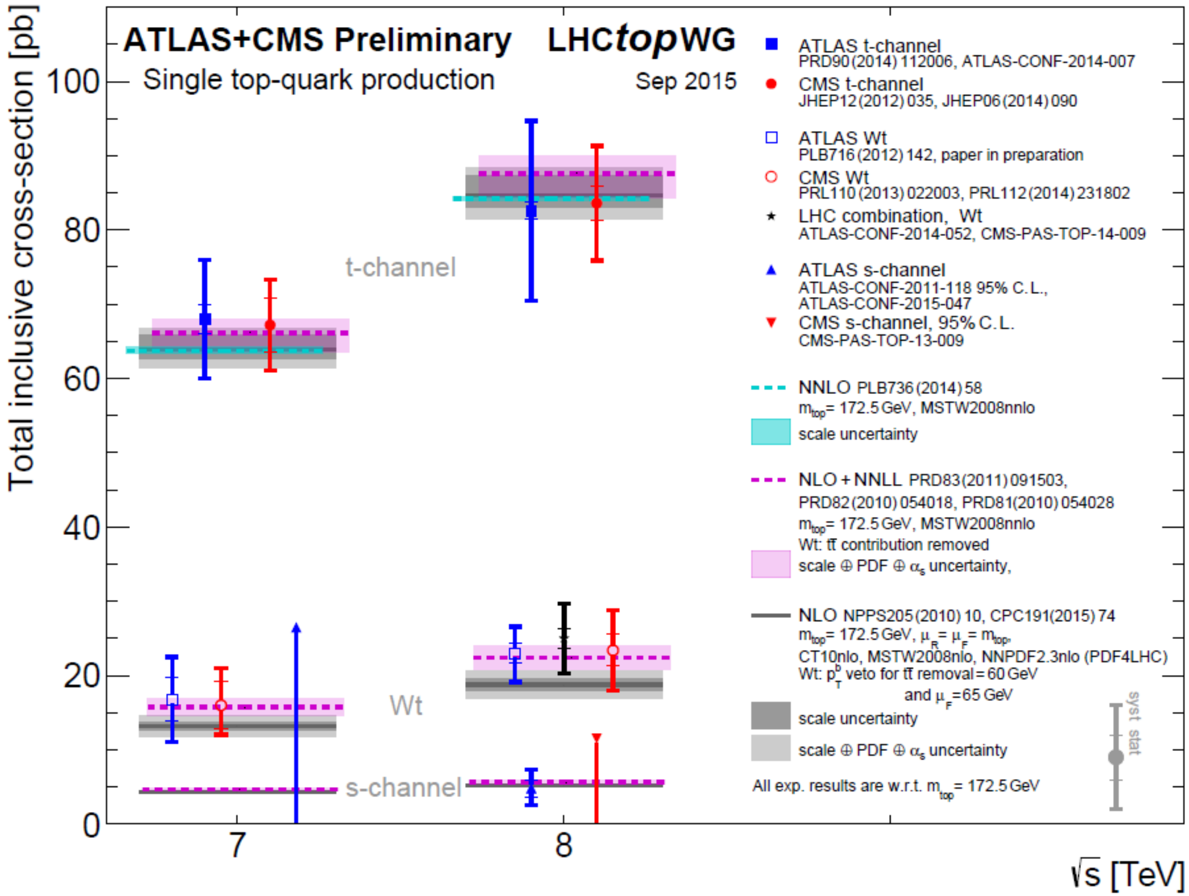




First EVIDENCE
of the s-channel production at LHC

Note: this will *not* get easier at 13 TeV!

Single top at LHC



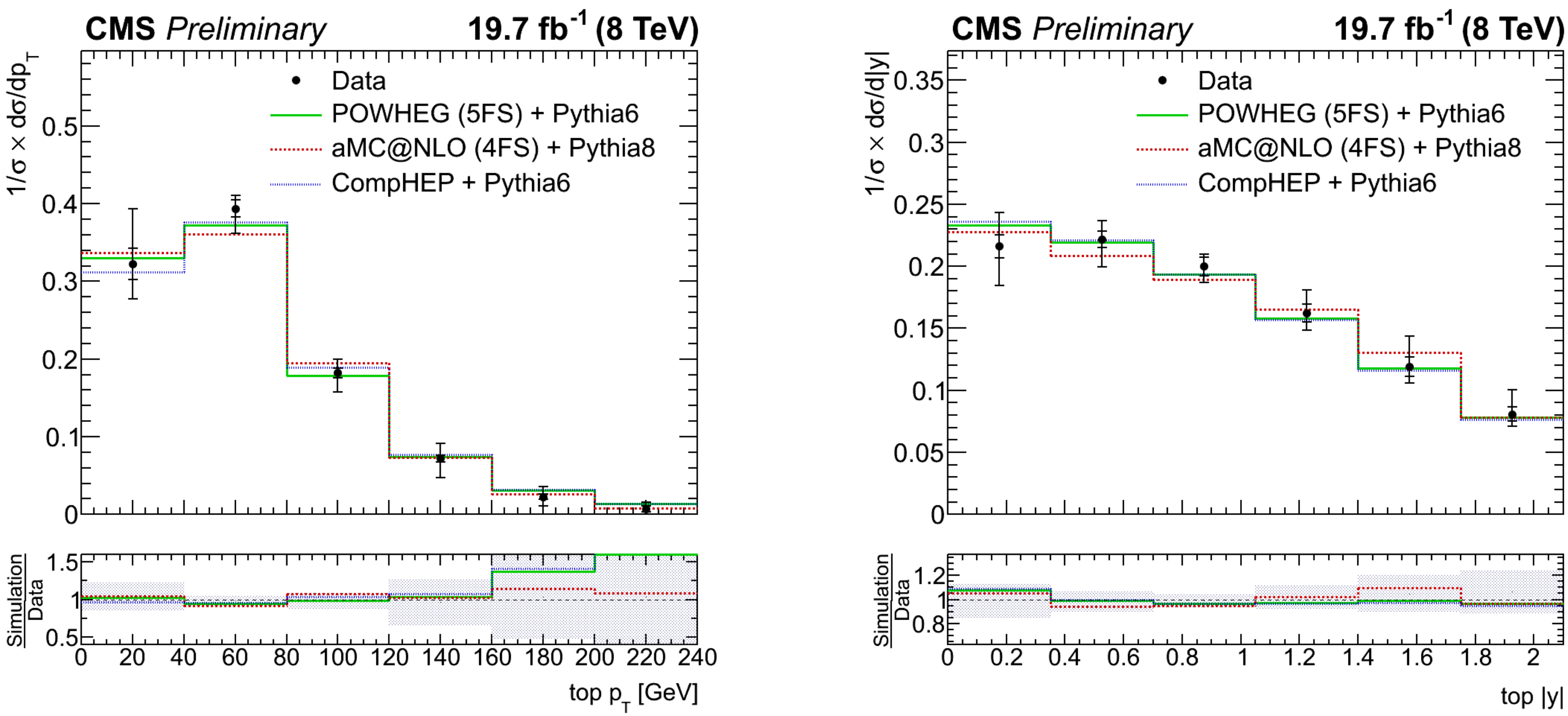
Summary of **ATLAS** and **CMS** measurements of the single top production cross-sections in various channels as a function of the center of mass energy. For the s-channel only an upper limit is shown. The measurements are compared to theoretical calculations based on: NLO QCD, NLO QCD complemented with NNLL resummation and NNLO QCD (t-channel only).

$|V\ |^{\text{CMS 7+8 TeV}}_{t\text{-channel}} = 1.00 \pm 0.04$ $|V\ |^{\text{Tevatron}}_{s+t\text{-channel}} = 1.02\ {}^{+0.06}_{-0.05}$

$|V\ |^{\text{LHC 8 TeV}}_{Wt\text{-channel}} = 1.06 \pm 0.11$

in good agreement with $|Vtb|_{\text{global SM fit}} = 0.99914 \pm 0.00005$

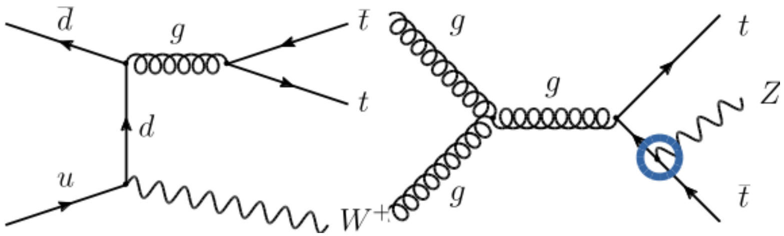
Differential measurement of the cross section of single top-quark production in the t-channel at 8 TeV

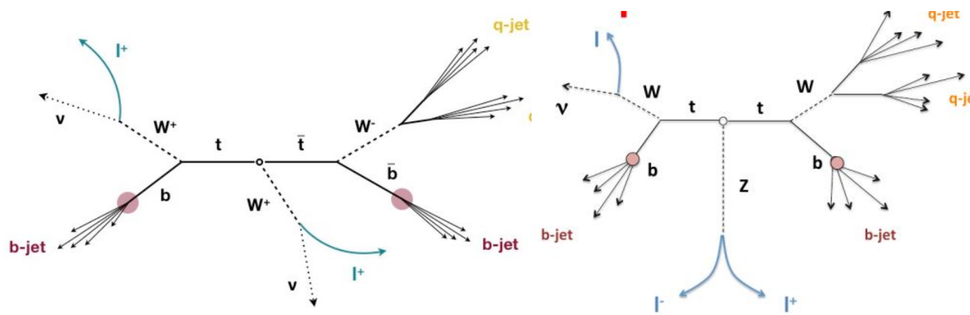


Unfolded p_T and abs(y) spectrum of the top quarks in the combined lepton+jets channel compared with the predictions from PowHeg+Pythia (solid), aMC@NLO+Pythia (dotted), and CompHEP (dashed). The inner error bars indicate the statistical uncertainty while the outer error bars indicate the full (stat. + syst.) uncertainty

Associated production of top and bosons at 8 TeV

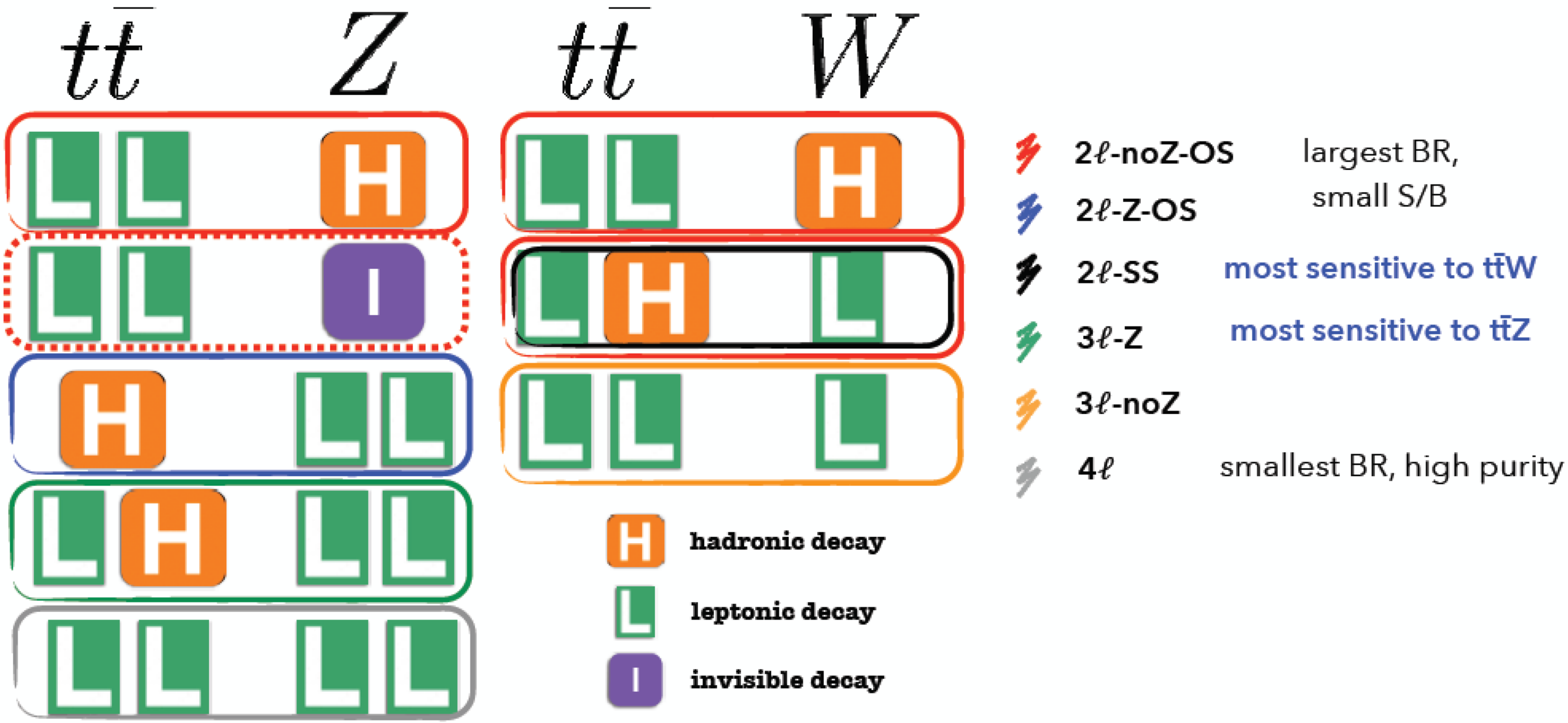
- Measure couplings to bosons
- Important background for BSM searches
- Analyses are performed in bins of the number of selected leptons (2,3,4)
- Different number of leptons → different admixture of ttW and ttZ processes
  - **Same-sign** dilepton analysis: tt+W
  - **Trilepton** and **Four-lepton** analysis: tt+Z process





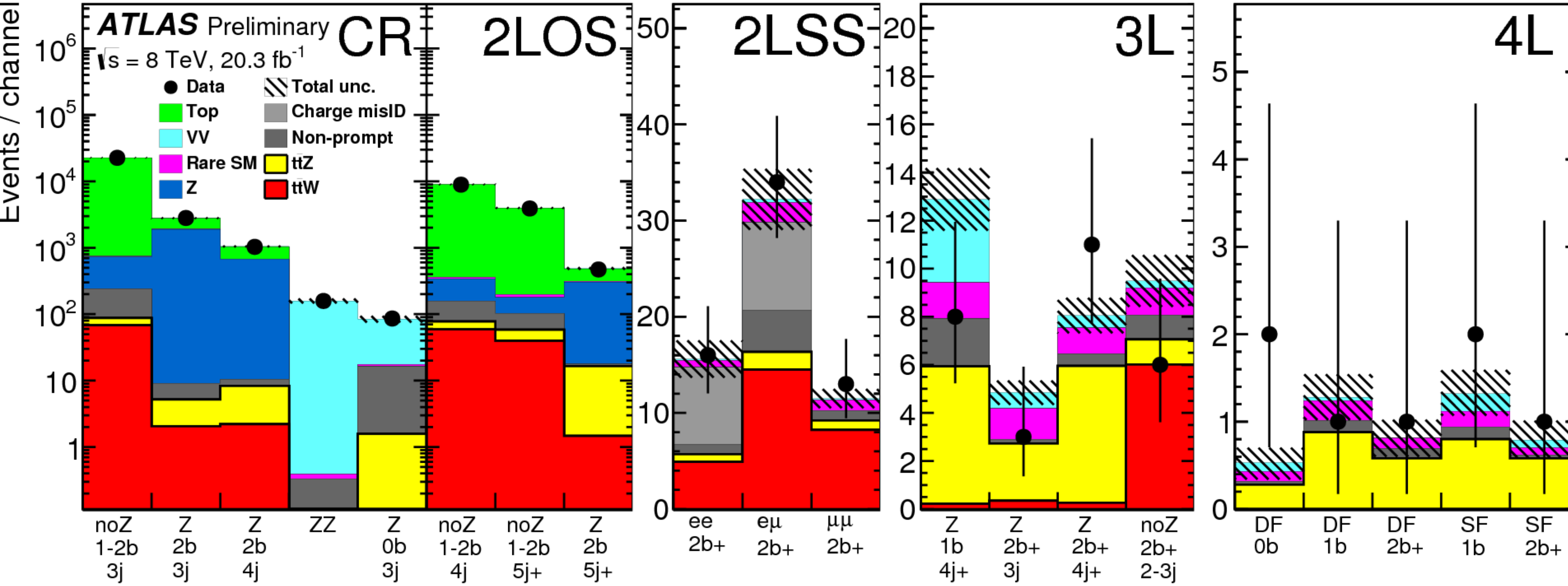
- **tt+W/Z [ATLAS-CONF-2015-032]**
  - Four signal regions: opposite sign (OS) dilepton, same sign (SS) dilepton, 3 and 4 lepton.
  - Fit for ttZ and ttW simultaneously in a binned likelihood t
  - Further split into categories depending on jet multiplicity, number of b-tagged jets and EmissT , optimised individually to increase sensitivity.
- **tt+W/Z [CMS PAS TOP-14-021 (2015)]**
  - Also performed in many channels with different numbers of leptons, jets and b tags
  - Additionally: perform event reconstruction by matching jets and leptons to W/Z bosons and top
    - Combine into linear discriminant
    - Choose best permutation
  - Combine resulting match scores with kinematic quantities in BDTs

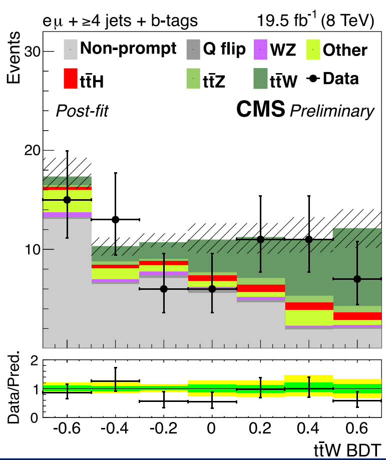
ttV: signatures and analysis

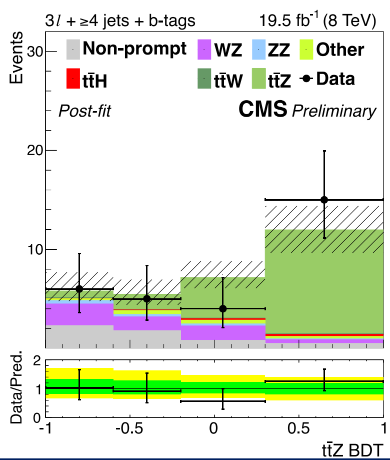


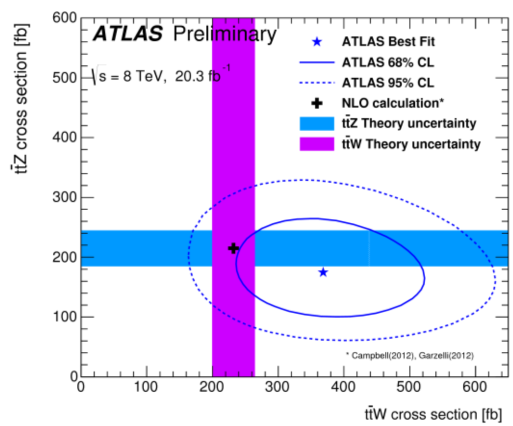
Signal region	Main cuts	Main background	Background treatment
OS dilepton	$\geq$ 3jets, $\geq$ 1b-tag	$t\bar{t}$, Z	Neural networks
SS dilepton	$\geq 2b$-tags	Fake leptons	Fake factor method
Trilepton	≥ 1 b-tag	Fake leptons, WZ	Matrix method, fit WZ in CR
Tetralepton	1-2 OSSF pairs[1]	ZZ	Fit ZZ in CR

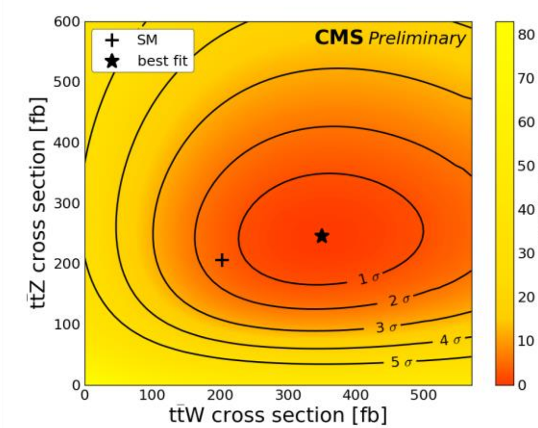
Asociated tt+W/Z production established











- σ(ttW) = 369 $^{+100}_{-91}$ fb - 5.0 obs. (3.2 exp)
- σ(ttZ) = 176 $^{+58}_{-52}$ fb - 4.2 obs. (4.5 exp)

- σ(ttW) = 382 $^{+117}_{-102}$ fb - 4.8 obs. (3.2 exp)
- σ(ttZ) = 242 $^{+65}_{-55}$ fb - 6.0 obs. (5.7 exp)

tt̄H associated production

Search in different Higgs decay modes.
Very different signatures and analysis related issues

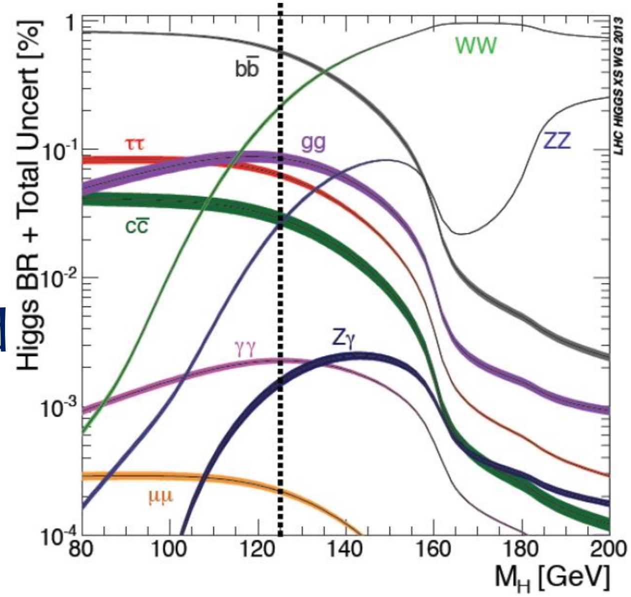
H -> bb

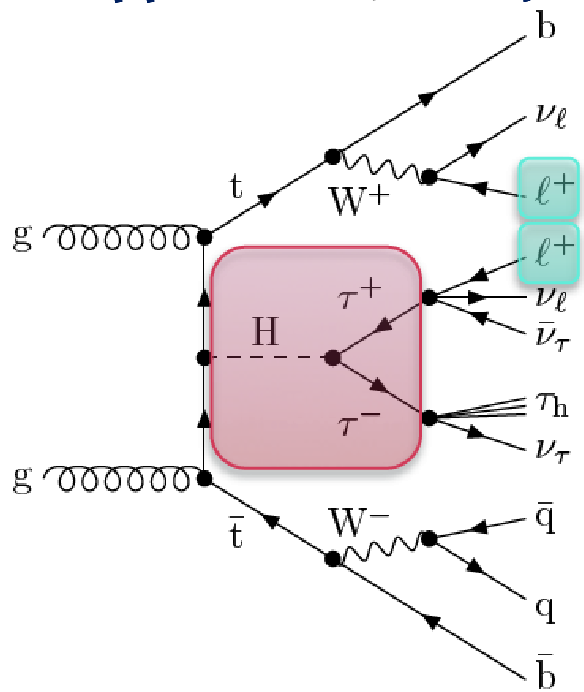
BR=58% dominant mode but large background

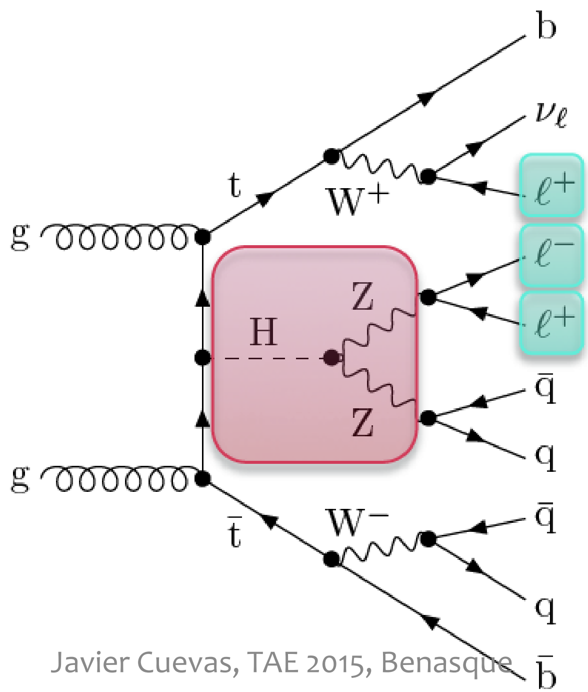
H -> WW, ZZ, ττ

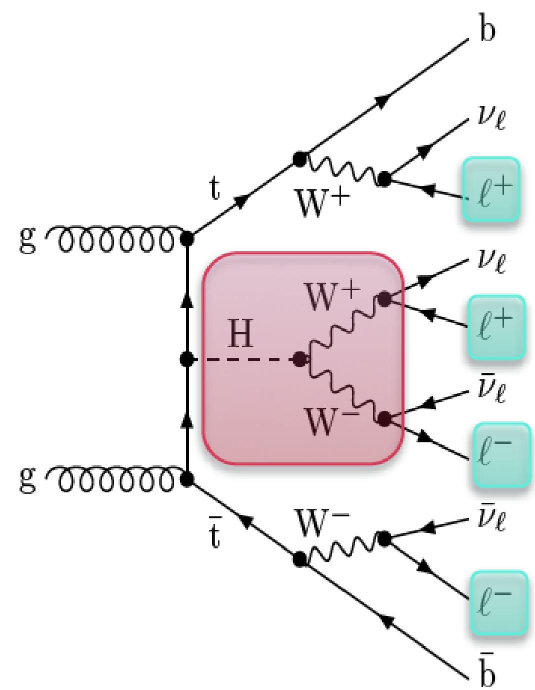
BR=30% multilepton final state

H -> γγ BR<0.23% tiny but clean signature

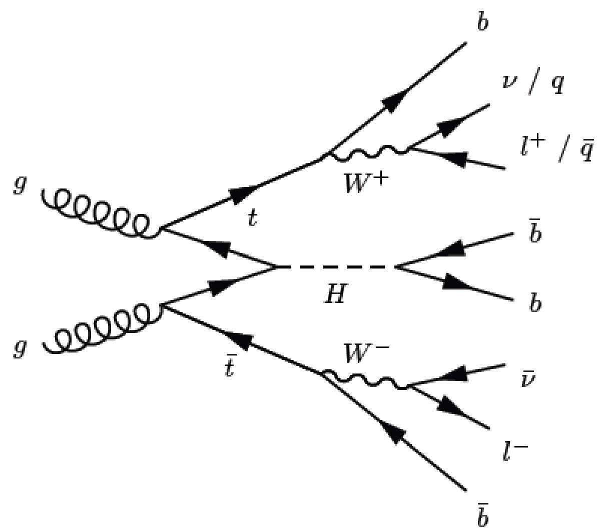




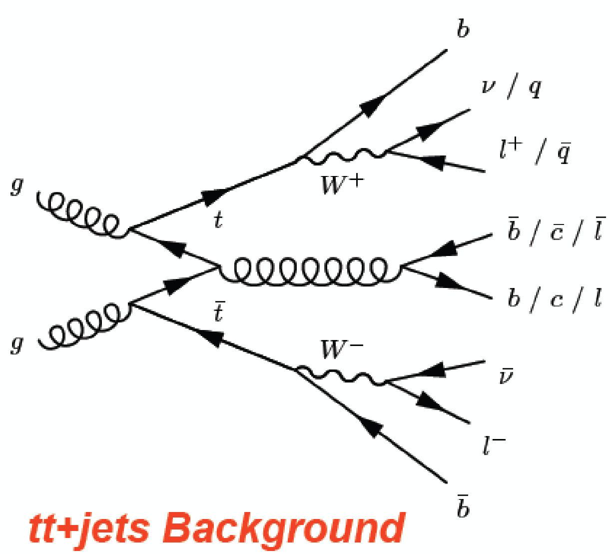


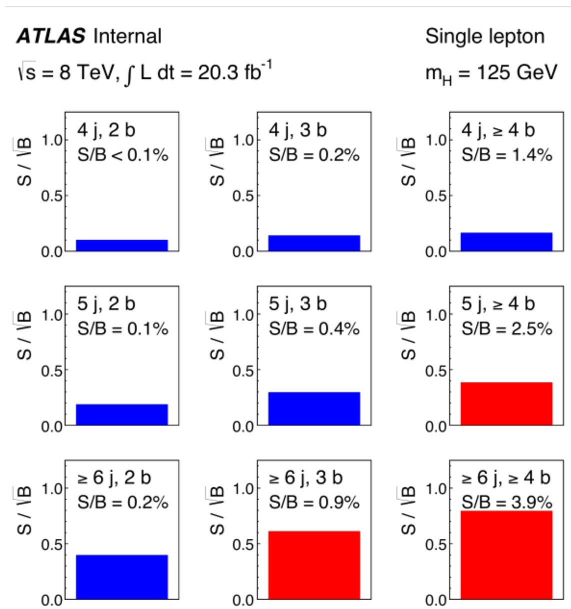


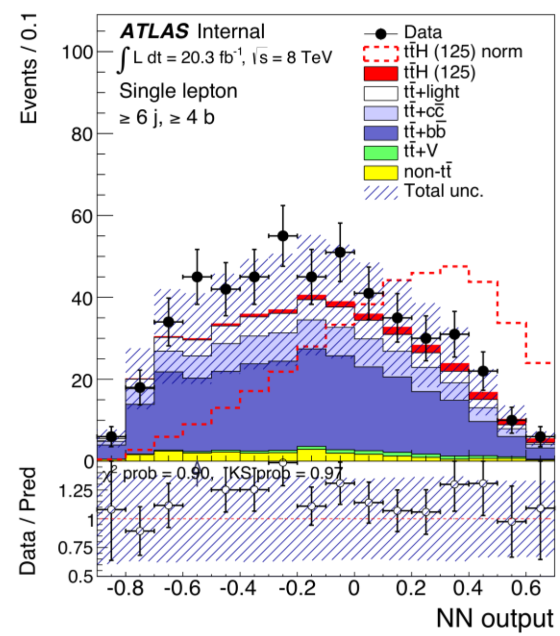
tt̄H(->bb) associated production



- Categorize events according to the # jets and b-jets
  - control and signal regions.
- Build multivariate discriminant in signal regions.
- A simultaneous fit is performed in all regions to limit the systematic uncertainties in the signal regions.

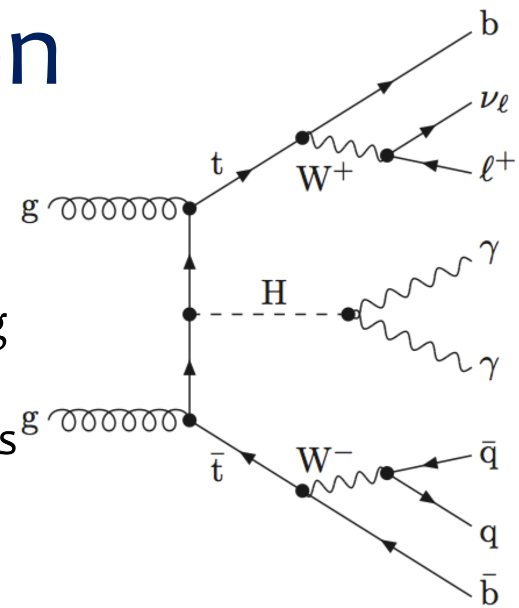


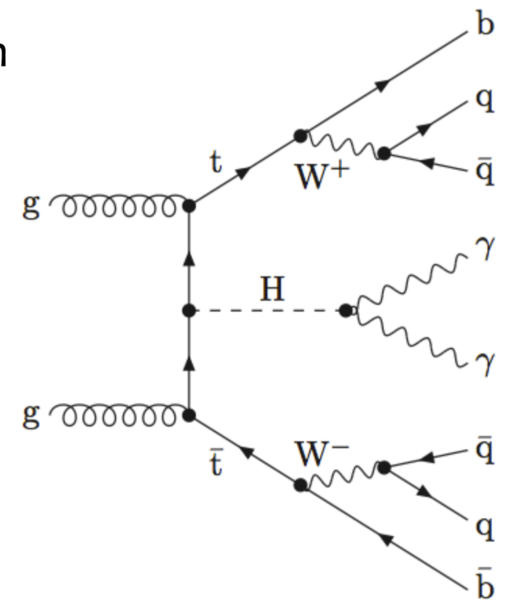


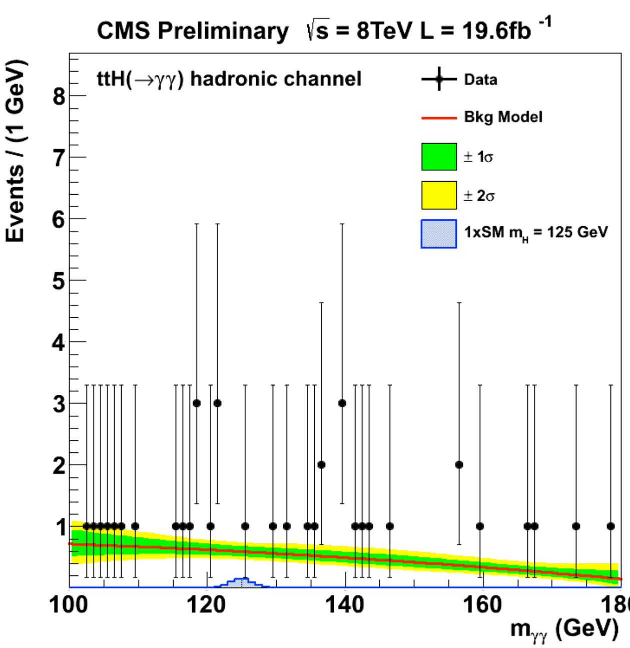


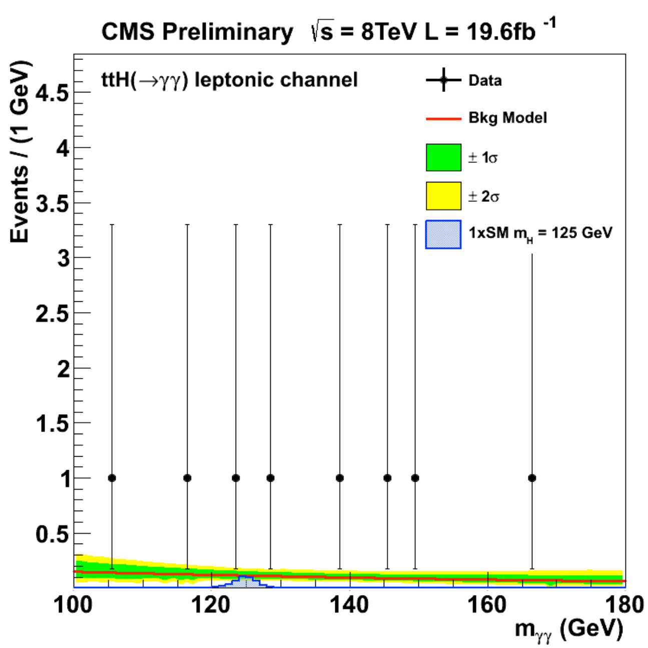
$t\bar{t}H(\rightarrow\gamma\gamma)$ associated production

- Analysis limited by statistic (low BR $H\rightarrow\gamma\gamma$) but distinctive signature:
  - two energetic photons, narrow Higgs peak over falling bkg in $M_{\gamma\gamma}$ distribution
  - the only channel that can eventually confirm that an excess is due to h(126)
- Strategy: fit the $M_{\gamma\gamma}$ distribution using the diphoton spectrum sidebands to fit the bkg
- Data fitted with simple exponential (second order polinomial) in the leptonic (hadronic) channel



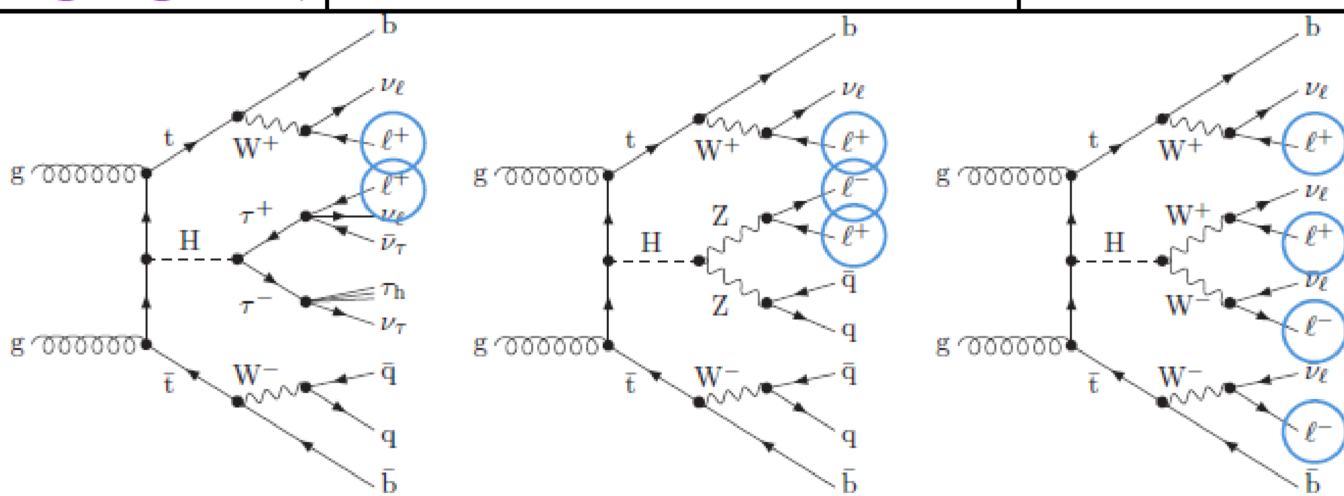






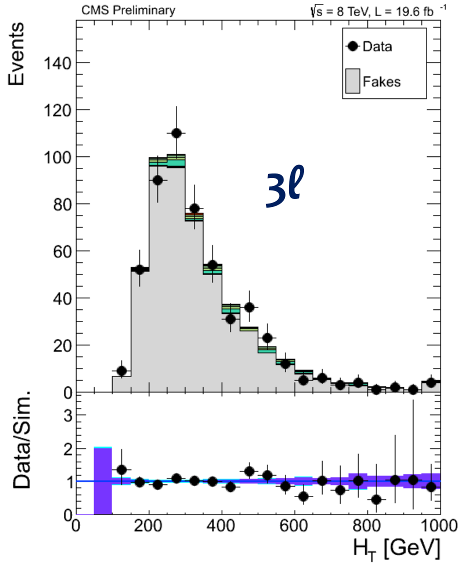
$t\bar{t}H$(->leptons) associated production

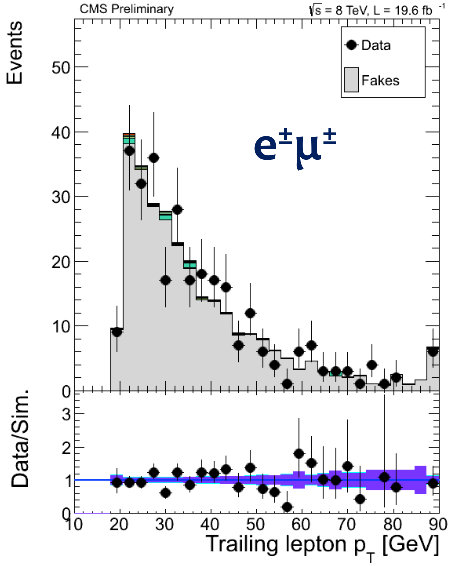
H decay	top pair decay	trigger
WW, ZZ, ττ	semileptonic or dileptonic	double lepton (p_T >17,8 GeV)
signature		
2 same-sign leptons (ee,em,mm) 2 e/μ, p_T>20 GeV ≥4 jets (≥1b-jet), p_T>25 GeV **(#sig~8 sig/bkg~0.08)**	**3 leptons** 1 e/μ, p_T>20 GeV 1 e/μ, p_T>10 GeV 1 e(μ), p_T>7(5) GeV ≥2 jets (≥1b-jet), p_T>25 GeV no resonant Z->ll **(#sig~4 sig/bkg~0.07)**	**4 leptons** 1 e/μ, p_T>20 GeV 1 e/μ, p_T>10 GeV 2 e(μ), p_T>7(5) GeV ≥2 jets (≥1b-jet), p_T>25 GeV no resonant Z->ll **(#sig~0.5 sig/bkg~0.2)**



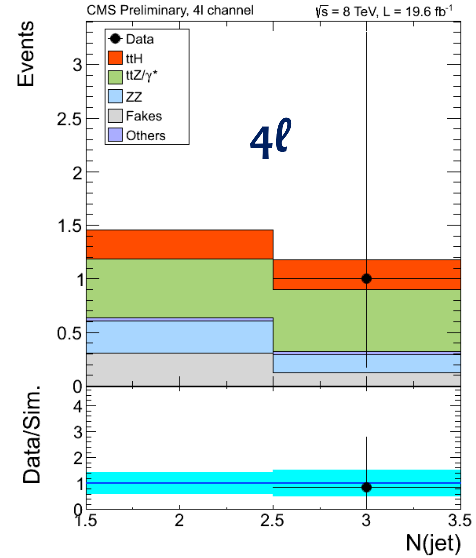
tt̄H(->leptons)

- Main focus: suppress and control reducible background (~up to 2/3 of the total bkg after selection)
  - tt with fake ℓ from b--jets
    - Dedicated lepton ID (MVA) developed to suppress it.
  - data--driven estimate: measurement of the probability for a lepton from b--jet to pass the MVA ID requirement
- Inclusive selection to preserve signal efficiency.
- Full event kinematic cannot be reconstructed
  - to improve sensitivity:
  - categorize events (for 2ℓ, 3ℓ) in positive and negative total lepton charge (ttW, WZ and Wjets are asymmetric),
    - 5% gain in sensitivity
  - combine partial kinematic variables in a BDT (for 2ℓ, 3ℓ),
    - 10% gain in sensitivity

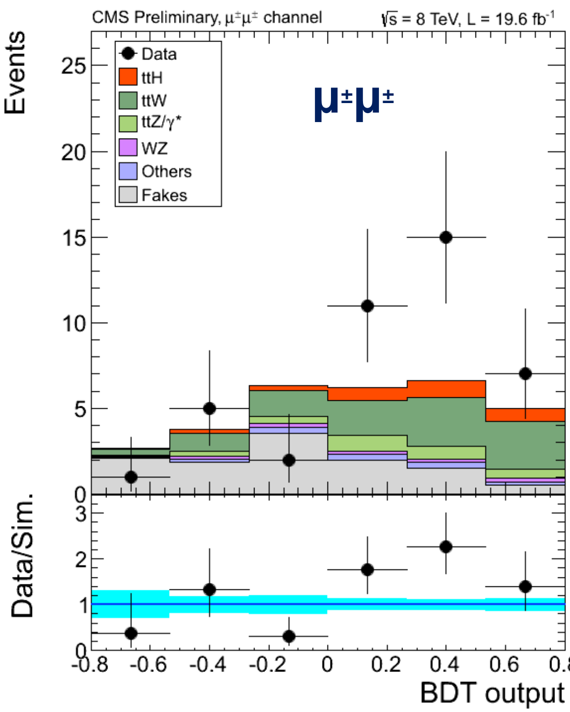


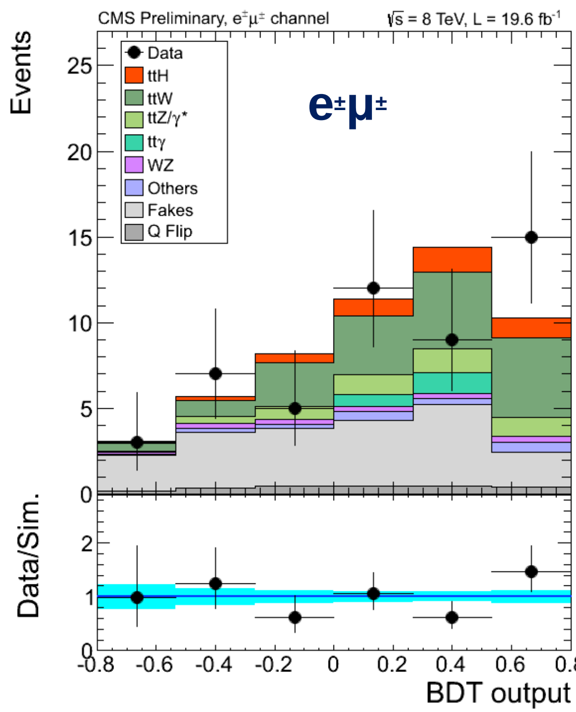


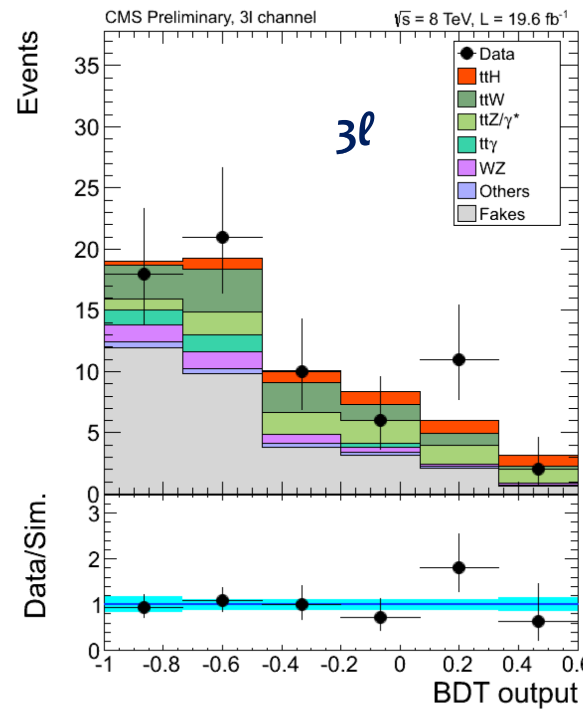
tt̄H(->leptons)



- signal extraction, in each category:
- **2ℓ, 3ℓ: simple BDT** with few kinematic variables
- **4ℓ:** just use N(jet), since yields are small.
- N(jet) used also as cross-check in 2ℓ, 3ℓ







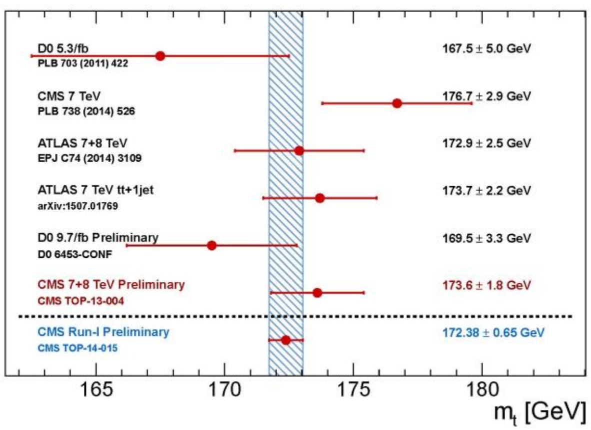
$t\bar{t}H$ associated production: combination

- ttH production not yet discovered at the LHC
- ATLAS and CMS working on LHC combination, expected to be close to SM sensitivity
  - **Discovery of ttH is expected in Run II of the LHC**

Higgs Decay	Channel	Expected (Observed) Limit	
		ATLAS	CMS
$H \to b\bar{b}$	single lepton	2.6 (3.6)	4.2 (5.5)*
	dilepton	4.1 (6.7)	6.7 (7.0)
	combined	2.2 (3.4)	3.5 (4.1)
$H \to \gamma\gamma$	leptonic	6.6 (10.7)	6.8 (8.2)
	hadronic	10.1 (9.0)	10.7 (8.0)
	combined	4.9 (6.7)	4.7 (7.4)
$H \to WW/ZZ/\tau\tau$	2ℓ	3.9 (6.7)	3.4 (9.0)
	3ℓ	3.8 (6.8)	4.1 (7.5)
	4ℓ	15 (18)	8.8 (6.8)
	$2\tau_{\rm had}$	18 (13)	14.2 (13.0)
	$2\ell 1\tau_{\rm had}$	8.4 (7.5)	-
	combined	2.4 (4.7)	2.4 (6.6)
Combination		1.4 (3.2)	1.7 (4.5)

Constraining the SM with the **top mass**

- **The top mass, the W mass and the Higgs mass depend on each other**
- **Direct mass measurement at Tevatron** m(top) = 173.18 ± 0.94 GeV
- **Not an observable, i.e. scheme-dependent**
  - **Pole-mass: viewing top quark as a free parton**
    - **inclusive cross section (NNLO) dependent on top-quark pole mass**



  - MS scheme (“running mass”):
    - “MC mass”: (N)LO+PS yet different from pole or MS mass
- **Colour Reconnection:**
  - Soft interactions not calculable in pQCD
  - Present model uncertainties: 0.5 … 1 GeV

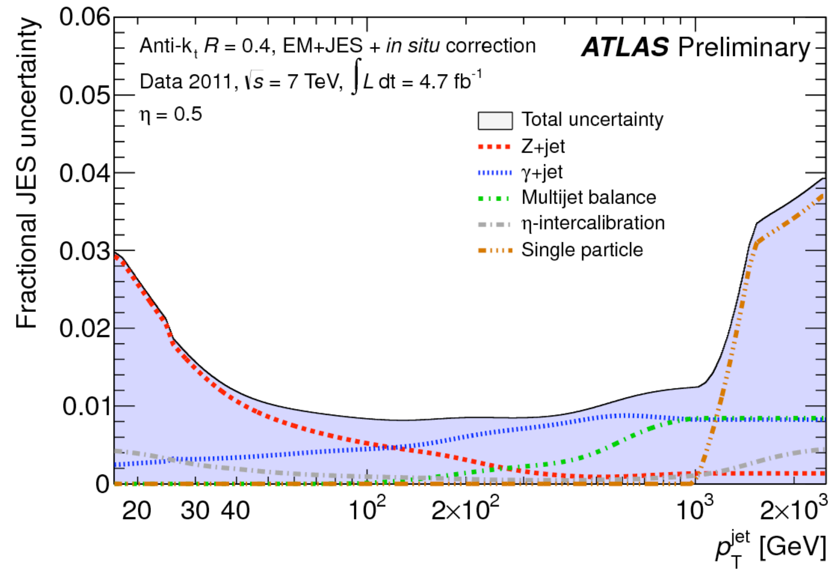
- Direct reconstruction methods
  - ➢ Full reconstruction by resolving the pairing ambiguities (all channels studied)
  - ➢ Use kinematic constrained fitting to improve the mass resolution
    - o Constrain the light jet energy scale in situ by using the W mass constraint
  - ➢ Fit the mass with MC template fits or event by event likelihood fits
    - o Methods very sensitive to the description of radiation and JES uncertainties
- Indirect methods
  - Use the dependence on the top mass on other variables
    - o Top pair cross section
    - o Lepton p_T and end-point methods
    - o Invariant mass of the system J/Ψ+lepton from W
    - o Decay length of the b hadron
  - ➢ Main issue: need of a lot of statistics

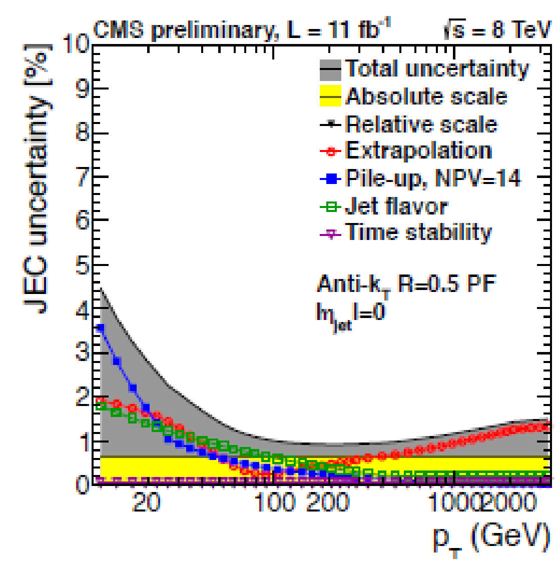
Full mass reconstruction

- **General features**:
  - Assign each jet to a top decay product (constrained kinematic fits)
  - Calibration of the method based on $m_t^{MC} = m_t^{meas}$
  - Determination of m_t (and JES simultaneously) from data
  - Main challenge: jet reconstruction, jet energy scale uncertainties, modelling.
- **Template method**: Simple and relatively fast:
  - Compare data to MC distributions with different top mass values
- **Matrix element method**: Most powerful, only LO
  - Event likelihood calculated from tt ME integrated in the full phase space using the full event information.
- **Ideogram method** (lepton+jets and all-hadronic)
  - Combine the ME in an approx. way and template
  - Analytical event likelihoods based on templates from simulation.
- **Dilepton channel**:
  - Solve the underconstrained tt system

Jet energy scale uncertainties

- JES calibration with dijets and γ/Z+jet events -> 1-3%
- < 1% when complemented with in-situ JES calibration
  - 2D method (Tevatron, CMS): fit JES factor using W->jj (remaining unc. from different jet-flavors)
  - 3D method (ATLAS): 2D + fit relative b-to-light-jet scale (bJSF)



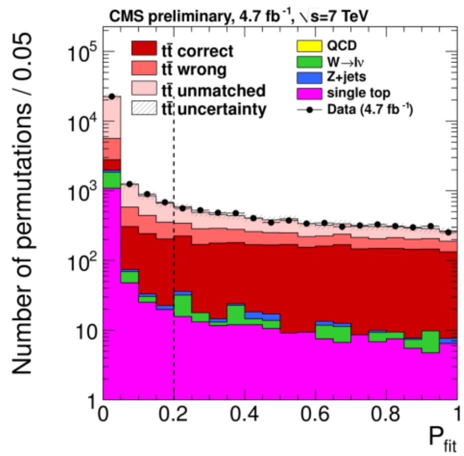


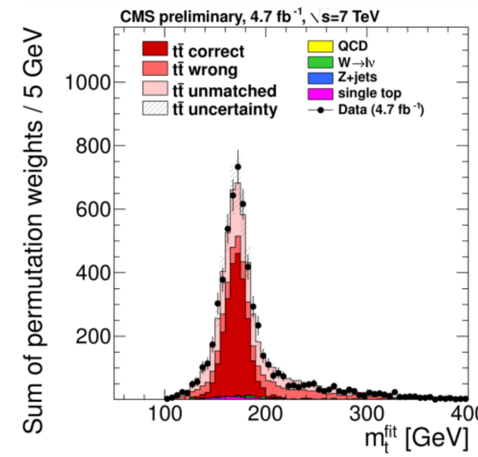
Systematic uncertainties (CMS PAS-TOP-14-001)

	δm_t^{2D} (GeV)	δJSF	δm_t^{1D} (GeV)
Experimental uncertainties			
Fit calibration	0.10	0.001	0.06
p_T- and η-dependent JES	0.18	0.007	1.17
Lepton energy scale	0.03	$<$0.001	0.03
MET	0.09	0.001	0.01
Jet energy resolution	0.26	0.004	0.07
b tagging	0.02	$<$0.001	0.01
Pileup	0.27	0.005	0.17
Non-$t\bar{t}$ background	0.11	0.001	0.01
Modeling of hadronization			
Flavor-dependent JSF	0.41	0.004	0.32
b fragmentation	0.06	0.001	0.04
Semi-leptonic B hadron decays	0.16	$<$0.001	0.15
Modeling of the hard scattering process			
PDF	0.09	0.001	0.05
Renormalization and factorization scales	0.12$\pm$0.13	0.004$\pm$0.001	0.25$\pm$0.08
ME-PS matching threshold	0.15$\pm$0.13	0.003$\pm$0.001	0.07$\pm$0.08
ME generator	0.23$\pm$0.14	0.003$\pm$0.001	0.20$\pm$0.08
Modeling of non-perturbative QCD			
Underlying event	0.14$\pm$0.17	0.002$\pm$0.002	0.06$\pm$0.10
Color reconnection modeling	0.08$\pm$0.15	0.002$\pm$0.001	0.07$\pm$0.09
Total	0.75	0.012	1.29

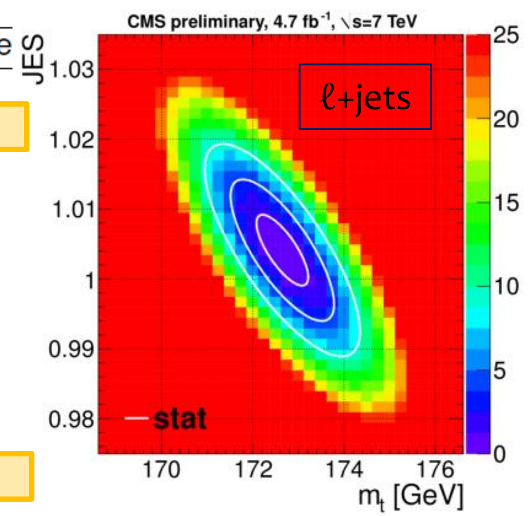
Top mass direct reconstruction, ℓ+jets:

- **ℓ+jets**: 90% tt , 3% W+jets, 4% single top, 3% other
- Kinematic fit:
  - two untagged jets: m_{jj} = 80.4 GeV
- lepton and neutrino (MET)
  - $m_{l\nu}$= 80.4 GeV
- combine with two b-tagged jets:
  - $m_{Pjjb1} = m_{l\nu b2}$
- **Ideogram method:**
- fitting JES in situ and constraining radiation from data, simultaneous measurement of the top quark mass and JES
  - no dependence on $m_{t,gen}$
- Dominated by systematic errors
  - Dominant sources are JES and TH uncertainties (scale, color rec.)
- **Single most precise top mass measurement to date at this energy.**





Lepton + Jets	
Systematic Source	Δm_t (Ge
Calibration	0.06
b-JES	0.61
p_T and η dependent JES	0.28
Lepton energy scale	0.02
Missing transverse energy	0.06
Jet energy resolution	0.23
b-tagging	0.12
Pile-up	0.07
Non-$t\bar{t}$ background	0.13
PDF	0.07
μ_R, μ_F	0.24
ME-PS matching threshold	0.18
Underlying event	0.15
Color reconnections	0.54

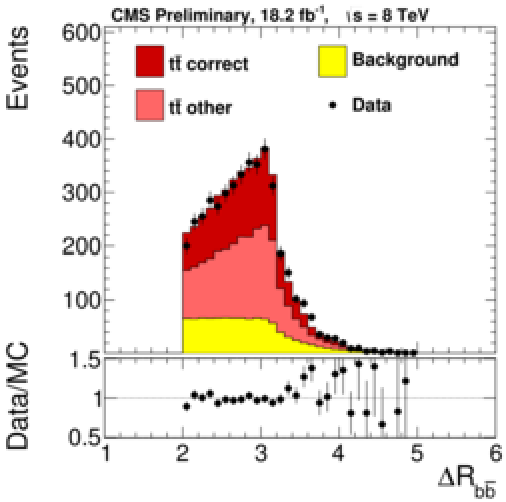


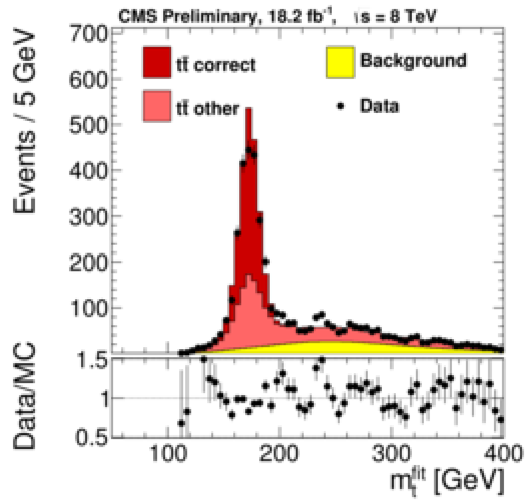
JHEP **12**, 105 (2012)

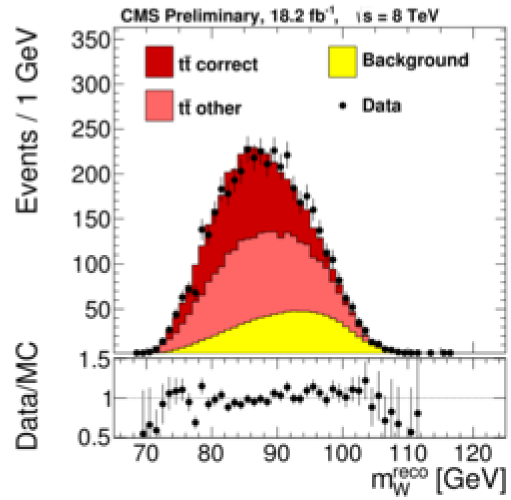
m_t = 173.49 ± 0.43 (stat.+JES) ± 0.98 (syst.) GeV
JES = 0.994 ± 0.003 (stat.) ± 0.008 (syst.)

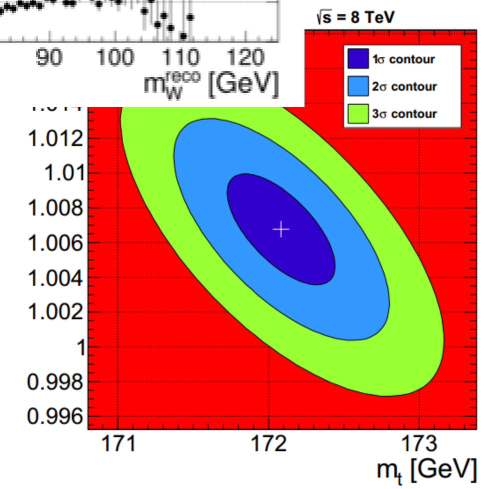
Top mass all hadronic, 8TeV

Enhanced 7 TeV analysis
2D Ideogram
TOP-14-002









	δm_t^{2D} (GeV)	δJSF	δm_t^{1D} (GeV)
Experimental uncertainties			
Fit calibration	0.06	<0.001	0.06
p_T- and η-dependent JES	0.28	0.006	0.86
Jet energy resolution	0.10	0.001	0.01
b tagging	0.02	<0.001	<0.01
Pileup	0.31	0.001	0.30
Calorimeter JES of trigger confirmation	0.18	0.003	0.07
Non-$t\bar{t}$ background	0.22	0.002	0.08
Modeling of hadronization			
Flavor-dependent JSF	0.36	0.004	0.30
b fragmentation	0.07	0.001	0.03
Semi-leptonic B hadron decays	0.12	<0.001	0.12
Modeling of the hard scattering process			
PDF	0.02	<0.001	0.01
Renormalization and factorization scales	0.19±0.19	0.004±0.002	0.18±0.14
ME-PS matching threshold	0.20±0.19	0.002±0.002	0.09±0.14
ME generator	0.09±0.21	0.003±0.002	0.17±0.15
Modeling of non-perturbative QCD			
Underlying event	0.13±0.28	0.000±0.002	0.11±0.20
Color reconnection modeling	0.00±0.25	0.000±0.002	0.03±0.18
Total	0.83	0.011	1.05

all-hadronic channel competitive with lepton+jets channel

high statistics → tighter selecti
no neutrinos in final state
full kinematics available

2D

m_t = 172.08 ± 0.36 (stat+JSF) ± 0.83 (syst) GeV
JSF = 1.007 ± 0.003 (stat) ± 0.011 (syst)

1D

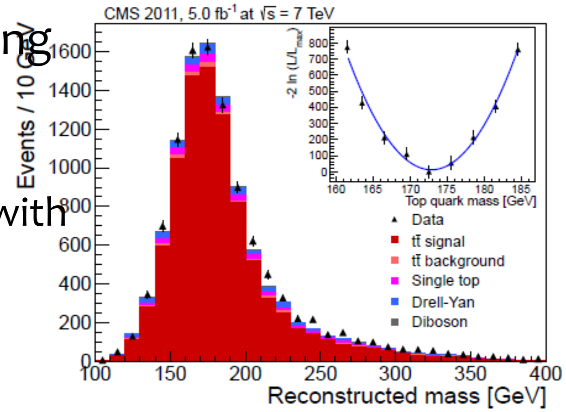
m_t = 172.59 ± 0.27 (stat) ± 1.05 (syst) GeV

Top mass, other channels, 7/8 TeV

Eur. Phys. J. C72 (2012) 2202

Dilepton channel: Analytical Matrix Weighting Technique:

- scan different m_t hypotheses: smear jets and solve kin. equations of tt system, hypothesis with maximum weight -> reconstructed mass



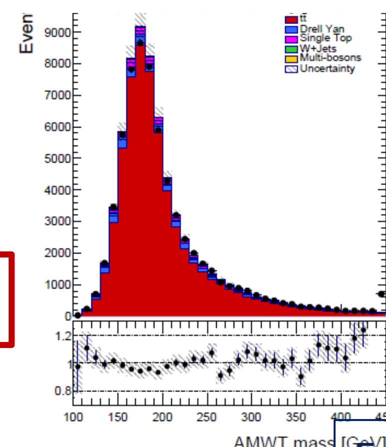
Source	δ_{m_t} (GeV)
Fit calibration	$\pm$0.40
Jet energy scale	**+0.90 −0.97**
b-JES	**+0.76 −0.66**
Lepton energy scale	$\pm$0.14
Unclustered E_T	$\pm$0.12
Jet energy resolution	$\pm$0.14
b-tagging	$\pm$0.09
Pileup	$\pm$0.11
Background normalization	$\pm$0.05
Parton distribution functions	$\pm$0.09
μ_R and μ_F scales	$\pm$0.55
ME-PS matching threshold	$\pm$0.19
Underlying event	$\pm$0.26
Color reconnection effects	$\pm$0.13
Monte Carlo generator	$\pm$0.04
Total	+1.48

At 7 TeV:

- m_t = 172.5 ± 0.4 (stat.) ± 1.5 (syst.) GeV

At 8 TeV NEW (TOP-14-010):

m_t =172.47 ± 0.17 (stat) ± 1.4 (syst) GeV



Source of uncertainty	δm_t(GeV)
Experimental uncertainties	
Fit calibration	0.03
p_T- and η-dependent JES	0.61
Lepton energy scale	0.12
Unclustered E_T	0.07
Jet energy resolution	0.09
b tagging	0.04
Pile-up	0.15
Non-$t\bar{t}$ background	0.02
Modeling of hadronization	
Flavor-dependent jet energy scale	0.28
b fragmentation	0.67
Semi-leptonic b hadron decays	0.18
Modeling of the hard scattering process	
PDF	0.18
Renormalization and factorization scales	0.87
ME-PS matching threshold	0.13
ME generator	0.37
Modeling of non-perturbative QCD	
Underlying event	0.04
Color reconnection modeling	0.16
Total	1.40

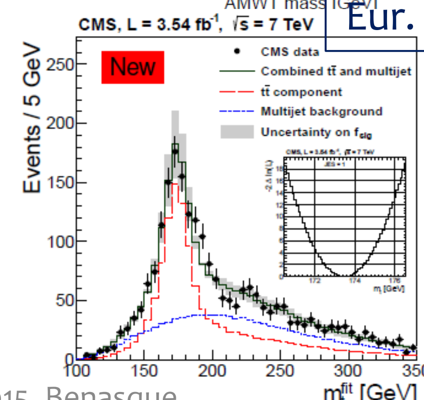
All jets channel:

2 x 2 untagged jets: m_{jj} = 80.4 GeV combine with two b-tagged jets: m_{jjb1} = m $_{jjb2}$

Background modeled by mixing jets from selected data events

- m_t = 173.49 ± 0.69 (stat.) ± 1.21 (syst.) GeV

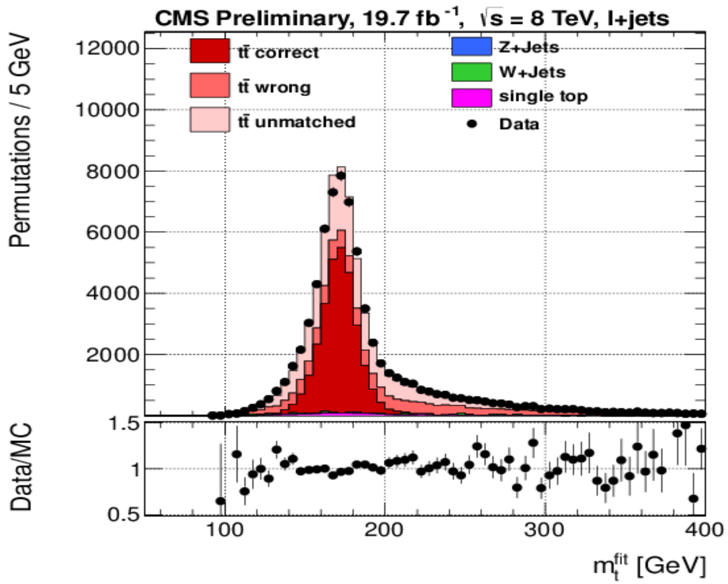
Eur. Phys. J. C74 (2014) 2758

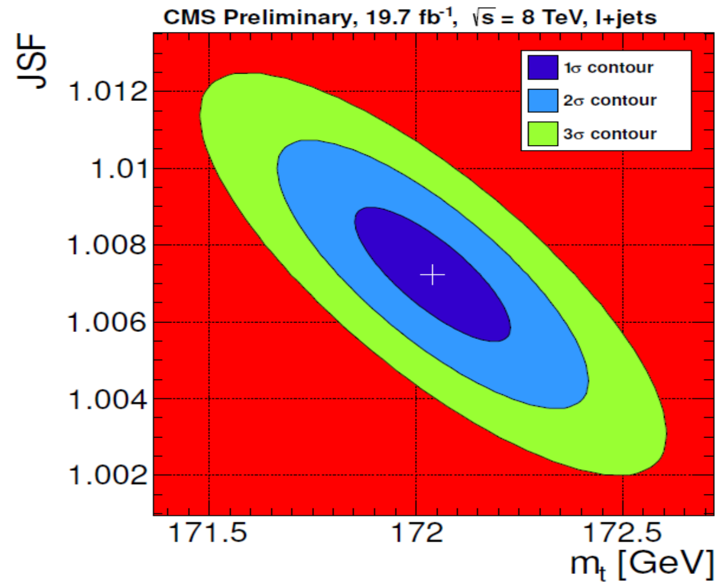


	δ_{m_t} (GeV)
Fit calibration	0.13
Jet energy scale	**0.97**
b-JES	**0.49**
Jet energy resolution	0.15
b tagging	0.06
Trigger	0.24
Pileup	0.06
Parton distribution functions	0.06
μ_R and μ_F scales	0.22
ME-PS matching threshold	0.24
Underlying event	0.20
Color reconnection effects	0.15
Multijet background	0.13
Total	1.21

CMS (MC) Top mass with lepton+jets events, 8TeV

TOP-14-001





	δm_t^{2D} (GeV)	δJSF	δm_t^{1D} (GeV)
Experimental uncertainties			
Fit calibration	0.10	0.001	0.06
p_T- and η-dependent JES	0.18	0.007	1.17
Lepton energy scale	0.03	<0.001	0.03
MET	0.09	0.001	0.01
Jet energy resolution	0.26	0.004	0.07
b tagging	0.02	<0.001	0.01
Pileup	0.27	0.005	0.17
Non-tt̄ background	0.11	0.001	0.01
Modeling of hadronization			
Flavor-dependent JSF	0.41	0.004	0.32
b fragmentation	0.06	0.001	0.04
Semi-leptonic B hadron decays	0.16	<0.001	0.15
Modeling of the hard scattering process			
PDF	0.09	0.001	0.05
Renormalization and factorization scales	0.12±0.13	0.004±0.001	0.25±0.08
ME-PS matching threshold	0.15±0.13	0.003±0.001	0.07±0.08
ME generator	0.23±0.14	0.003±0.001	0.20±0.08
Modeling of non-perturbative QCD			
Underlying event	0.14±0.17	0.002±0.002	0.06±0.10
Color reconnection modeling	0.08±0.15	0.002±0.001	0.07±0.09
Total	0.75	0.012	1.29

$$m_t = 172.04 \pm 0.19\,(\text{stat.+JSF}) \pm 0.75\,(\text{syst.})\ \text{GeV},$$
$$\text{JSF} = 1.007 \pm 0.002\,(\text{stat.}) \pm 0.012\,(\text{syst.}).$$

σ_{tot}= 0.77 GeV

2D fit uncertainty comparable to world average

1D m_t =172.66 ± 0.11 (stat) ± 1.29 (syst) GeV

ATLAS (MC) top mass lepton+jets channel, 7 TeV

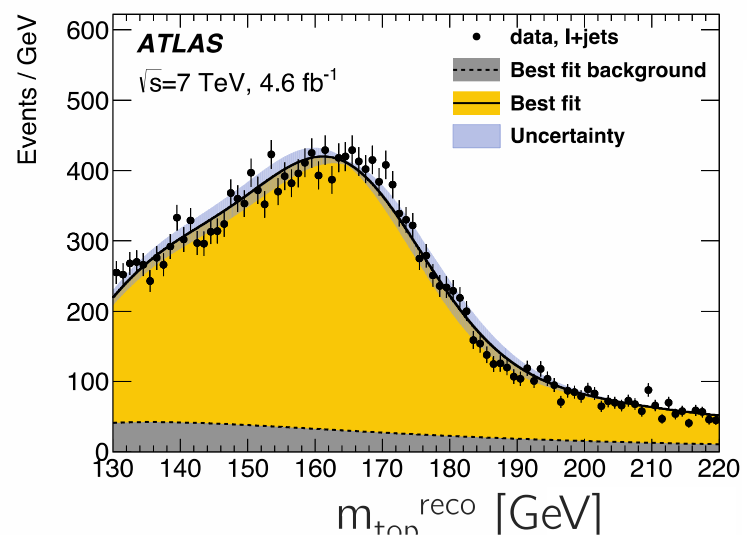
Eur. Phys. J. C (2015) 75:330

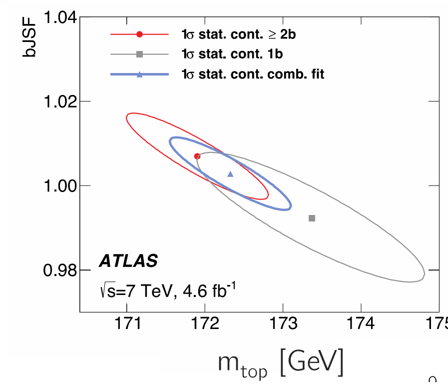
- Event selection similar to CMS lepton+jets result.
  - Separate events into 1 b tag and ≥2 b tags.
- Reconstruct ttbar system with kinematic likelihood fit.
  - Improves purity and assignment of reconstructed jets to partons.
- **Template-based approach with observabes: m_{top}^{reco}, m_W^{reco} and R_{bq} (ratio of $p_T^{b\,had}$ and $p_T^{b\,lep}$ over $p_T^{Wjet1+2}$)**
  - In-situ calibration of JES (m_W^{reco}) and bJES (Rbq), relative to udsg.

m_t = 172.33 ± 0.75 (stat+JSF+bJSF) ± 1.02 (syst) GeV
JSF = 1.019 ± 0.003 (stat) ± 0.027 (syst)
bJSF = 1.003 ± 0.008 (stat) ± 0.023 (syst)

Systematic uncertainties	Δm_t (GeV)
Jet energy scale	0.58
b jet energy scale	0.06
Pile up	0.02
Detector modeling	0.58
Method and backgrounds	0.33
Signal modeling	0.53
Total	**1.22**

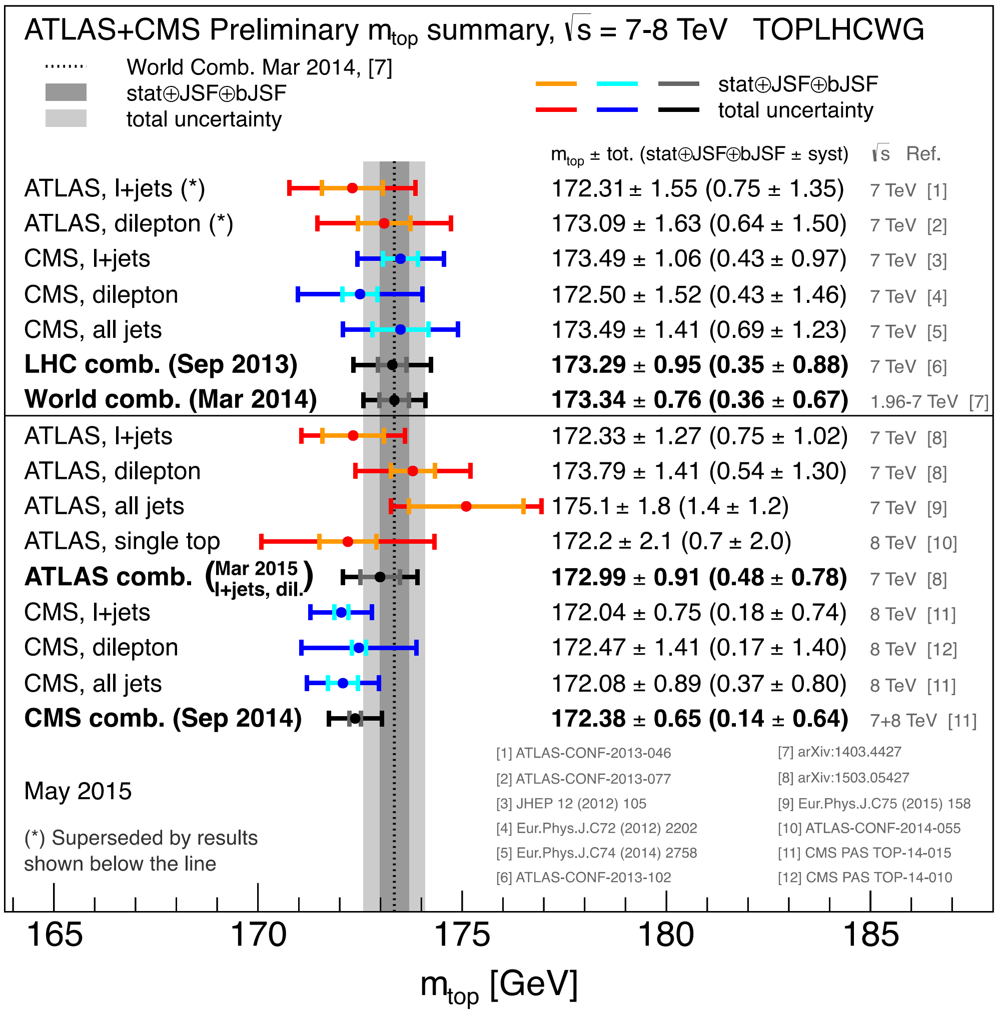
Signal + background fit to data





CMS + ATLAS m_{top} (MC)

LHCTOPWG



Analysis combined using BLUE, accounts for correlations between all uncertainties.

CMS combination

m_{top} = 172.38 ± 0.65 (syst) GeV

ATLAS combination

m_{top} = 172.99 ± 0.91 (syst) GeV

Tevatron combination

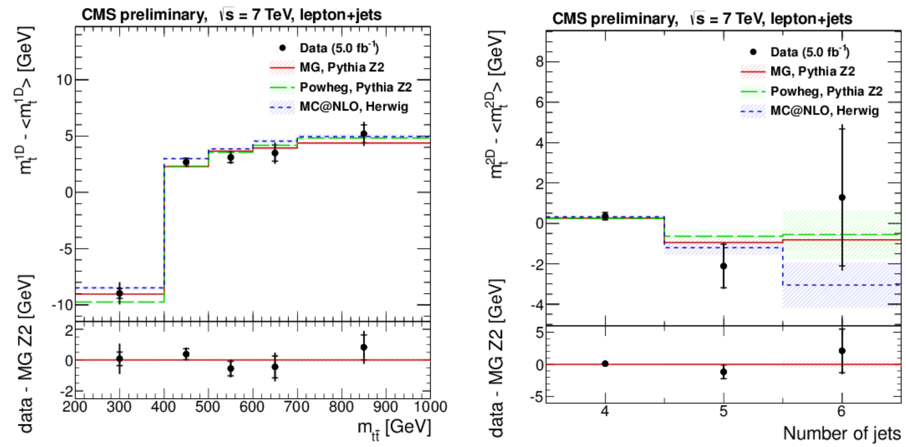
m_{top} = 174.34 ± 0.64 syst GeV

Total uncertainty is now below 1 GeV

m_t^{obs} and event kinematics

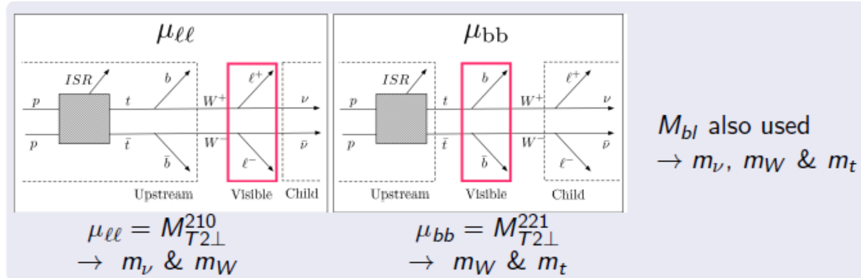
CMS-PAS-TOP-12-029

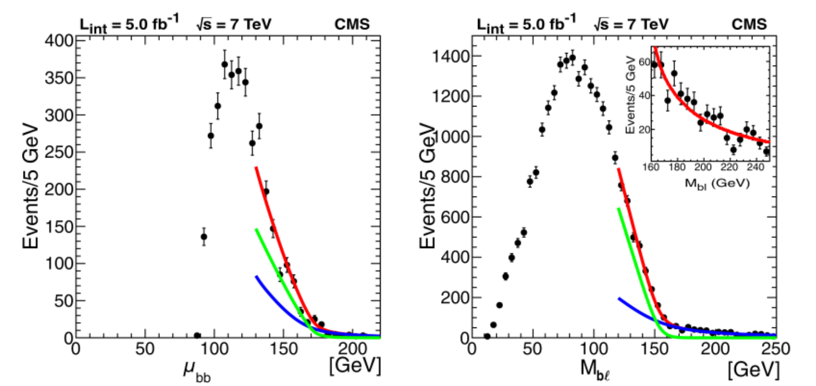
- Measure m_t^{1D} , m_t^{2D}, JES (stat syst) in bins of kinematic variables
  - Results for 14 kinematic variables
  - First binned m_t^{obs} measurement
  - Good agreement between Data and 'standard' MadGraph TuneZ2
  - m_t^{obs} not heavily affected by diferent tunes / generators
  - Precision does not yet allow to distinguish between different models



Eur. Phys. J. C73 (2013) 2494

- $m_t^{endpoint}$ via kinematic endpoints
  - M_{T2}-type variables designed to measure SUSY masses via endpoints.
  - Exploit analytic relations between $M_{T2}^{endpoint}$ and underlying masses
  - Independent of assumptions on shapes, measurement independent of m_t^{MC}
  - Doubly-constrained fit (m_ν = 0,m_W = 80.4 GeV)
    - **$m_t^{endpoint}$ = 173.9 ± 0.9(stat) $^{+1.6}_{-2.0}$ (syst) GeV**
    - In agreement with other measurements





- m_t^{MC} via b-hadron lifetime

CMS-PAS-TOP-12-030

  - Diferent sensitivity to systematics, Decay length $L_{b\text{-}hadron}$ correlated with m_t Use Lxy : transverse decay length of secondary vertex (same as in CDF)

m_t^{MC} = 173.5 ± 1.5(stat) ± 1.3 (syst) ± 2.6 (p_T^{top}) GeV

$\alpha_S(m_Z)$ and m_t^{pole} extraction from $\sigma(t\bar{t})$ at 7 TeV

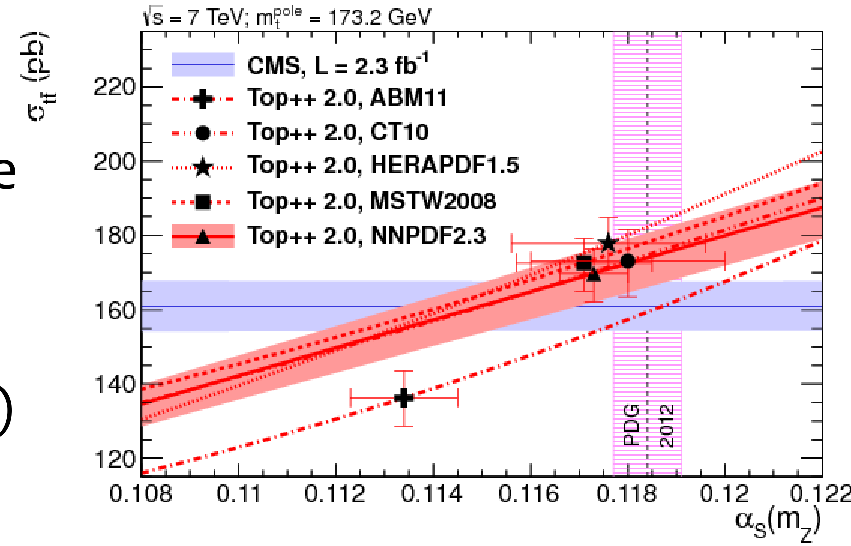
- Cross section prediction depends on α_S and m_t^{pole}
  - Turning this into measurements
- Constrain either α_S or m_t^{pole} and measure the other one
  - m_t^{pole} = 173.2 ± 1.4 GeV (Tevatron average)
  - $\alpha_S(m_Z)$ = 0.1184 ± 0.0007 (world average)
  - Using the most precise CMS σ_{tt} measurement (dilepton)
- Compare to **NNLO** predictions as function m_t^{pole} or α_S
- Most probable result from joint likelihood theory ⊗ experiment (using NNPDF2.3)

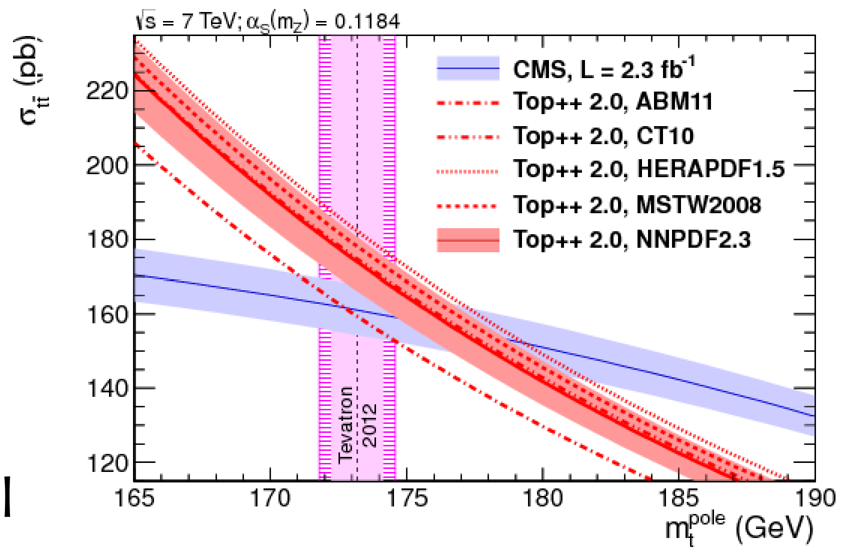
$\mathbf{m_t^{pole} = 176.7\ ^{+3.0}_{-2.8}\ GeV}$

- First determination of α_S from σ_{tt}:

$\mathbf{\alpha_S(m_Z) = 0.1151\ ^{+0.0028}_{-0.0027}}$

- High precision due to small experimental uncertainty and available **NNLO predictions**



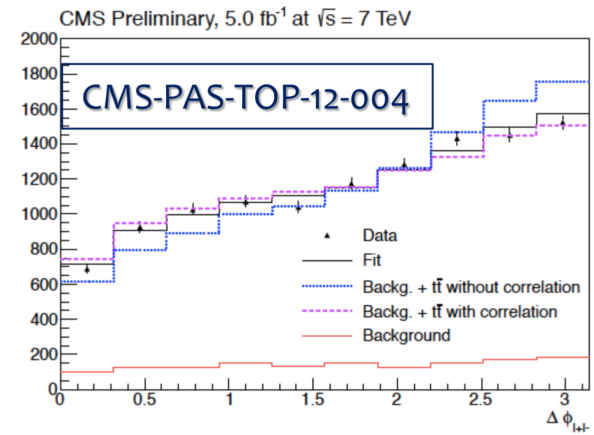


Top polarization and spin correlations

- The decay time of the top is short so that the decay products should contain information about the spin of the top quark. Can be measured from angular distributions of the top decay products
  - A: correlation strength at production
  - α_i: amount of spin information from each probe
  - Measuring the difference in the azimuthal angle between the leptons in the lab frame gives information about spin correlation
    - Just the lepton information is needed
    - No full reconstruction and associated error!
    - Compared with the SM expectation $A^{SM}_{hel} = 0.31$

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_1\, d\cos\theta_2} = \frac{1}{4}(1 - C\cos\theta_1\cos\theta_2)$$

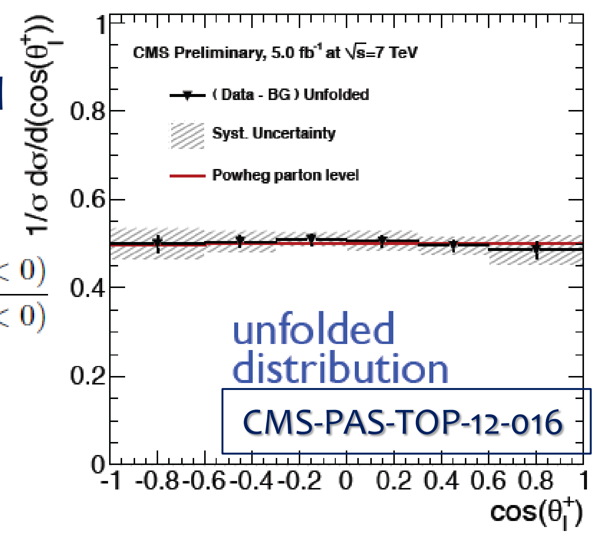
$$\text{where } C = A\alpha_1\alpha_2$$



$A^{meas}_{hel} = 0.24 \pm 0.02(\text{stat.}) \pm 0.08(\text{syst})$

- Similarly the polarization of the top quark can be measured with the daughter particles

$$\frac{1}{\Gamma}\frac{d\Gamma}{\cos\theta_{l,n}} = \frac{1}{2}(1 + 2\alpha_l P_n \cos\theta_{l,n}) \quad P_n = \frac{N(\cos(\theta_l^+) > 0) - N(\cos(\theta_l^+) < 0)}{N(\cos(\theta_l^+) > 0) + N(\cos(\theta_l^+) < 0)}$$

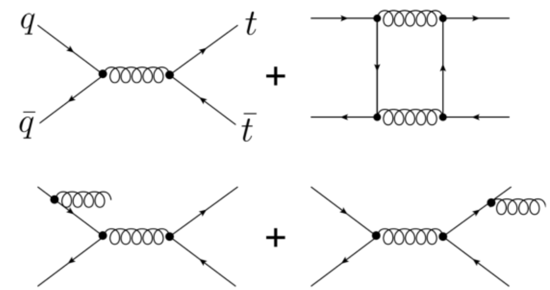


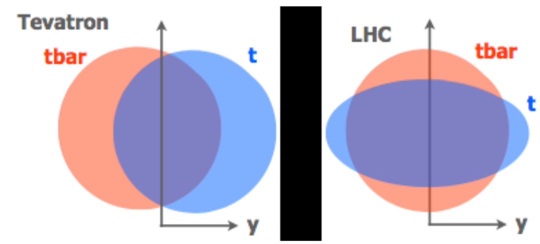
- From QCD, top pairs unpolarized, but EWK corrections provide small polarization that is **enhanced by new physics**

$P_n = 0.009 \pm 0.029(\text{stat}) \pm 0.041(\text{syst})$

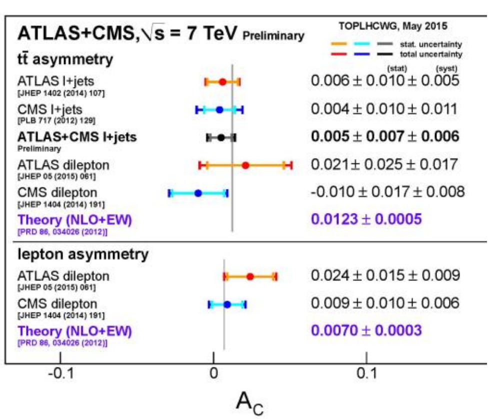
Charge asymmetry

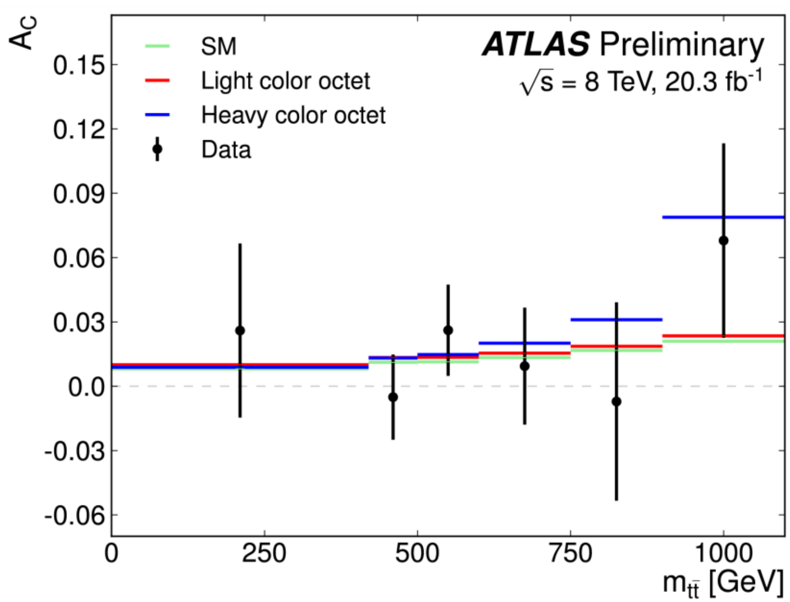
- NLO effect originating from the interference of q--qbar diagrams producing top pairs. Could be enhanced if new physics present like with W'.
  - LHC has symmetric initial state (pp):
  - Quarks are mostly valence and anti---quarks are sea quarks
  - PDF's are not symmetric, quarks carry more momentum than anti-quarks
- Rapidity distribution of tops is broader
- A_C studied e.g. in l+jets using a template method
- Charge asymmetries in data are background subtracted and unfolded to parton level to allow comparison with theory
- **Differential distributions (m_{tt}, y_{tt}, $p^T{}_{tt}$) sensitive to BSM physics**
- **New ATLAS measurement: ATLAS-TOP-2014-016 (to be submitted to EPJC)**

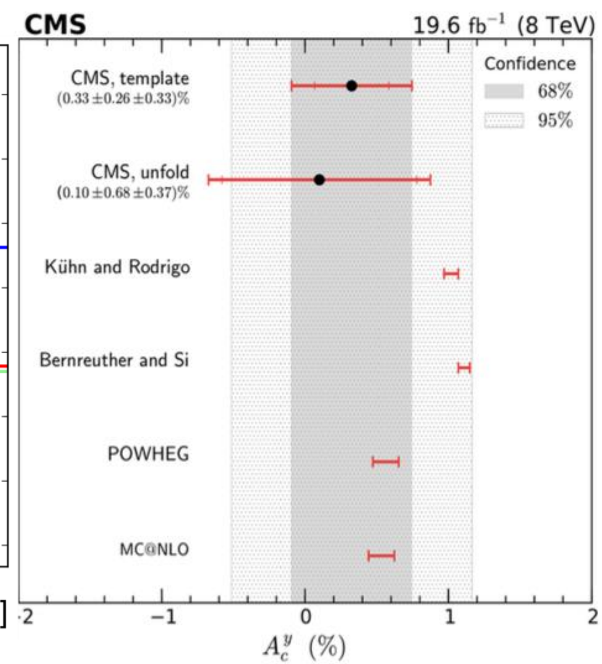




$$A_C = \frac{N(|y_t| > |y_{\bar{t}}|) - N(|y_t| < |y_{\bar{t}}|)}{N(|y_t| > |y_{\bar{t}}|) + N(|y_t| < |y_{\bar{t}}|)}$$







Summary

- **Top quark physics is a pillar of the current research program in HEP and provide stringent tests of pQCD . Both the CMS and ATLAS collaborations cover a wide range of top-related topics**
- Key to QCD, electro-weak and New Physics
  - Ideal probe for constraining (directly + indirectly) the symmetry breaking of the SM
    - The top is way heavy → the Higgs scalar mostly couples to tops
  - Ideal probe for looking for new physics beyond the model itself
    - Via precision measurements
    - Via direct searches for new signals
- **Results in agreement with SM predictions**
  - $t\bar{t}$ production
    - **Precision regime: σ_{tt} < 4%,** m(top) $\lesssim$1 GeV.
    - First measurements at 13 TeV
  - Single top production:
    - t-channel large enough to investigate properties
    - tW channel observed at LHC. s-channel observed at Tevatron
  - Associated production, observation of tt+γ , tt+W/Z, important to study top-Higgs couplings.