Top Quark Physics at CMS

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DESY

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Outline

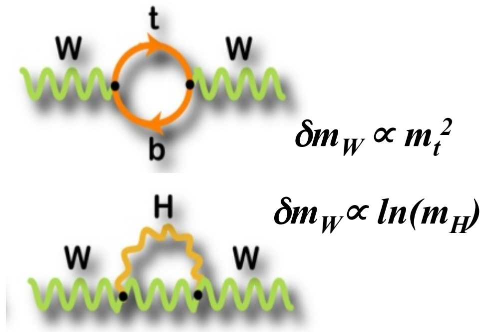
- Introduction
- Detecting top quark signatures at CMS
- Selected top quark physics results from CMS

I will only show today a personal selection of CMS results on top physics
The state of the art of CMS top quark results is available here:
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP

What's special about top?

- Special role in the electroweak (EWK) sector and in QCD
  - Heaviest elementary particle known
    - The Higgs couples preferentially to top

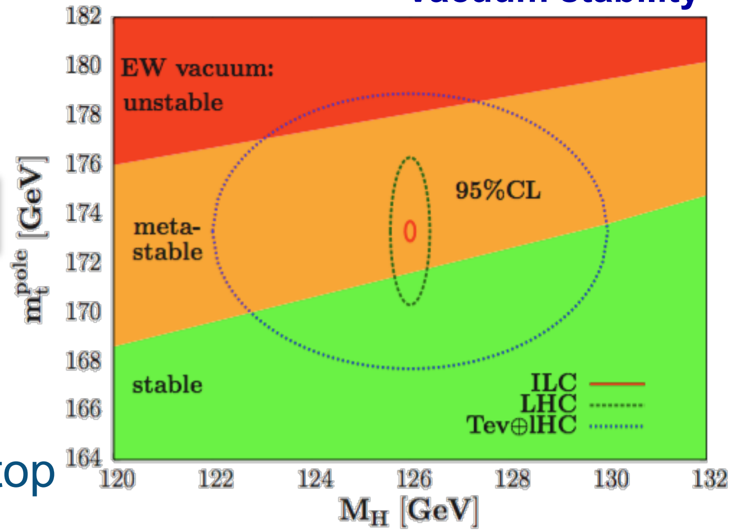
$$y_t = \frac{\sqrt{2} m_t}{v} \approx 1$$



  - Sensitive to Higgs mass through EWK loop corrections
    - Top mass is related to the fate of the Universe
  - Decays before hadronising: "bare" quark
    $\tau \sim 5 \times 10^{-25}$ s << $1/\Lambda_{QCD}$

➔ A tool for precise tests of Standard Model (SM)

Vacuum stability

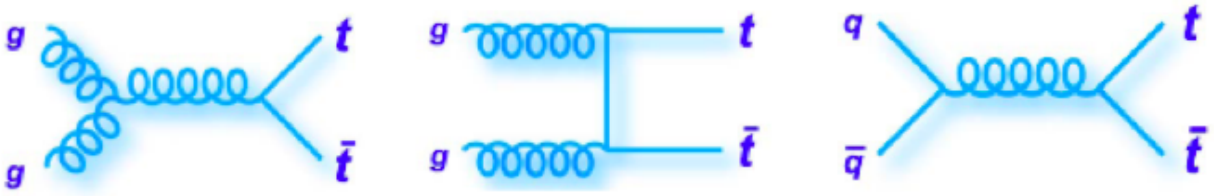


- Special role in various beyond SM extensions
  - New physics may preferentially couple/decay to top
  - Major source of background for many searches

➔ A sensitive probe to New Physics

Top quark production …

- $t\bar{t}$ production dominated by gluon fusion at LHC (~90%)



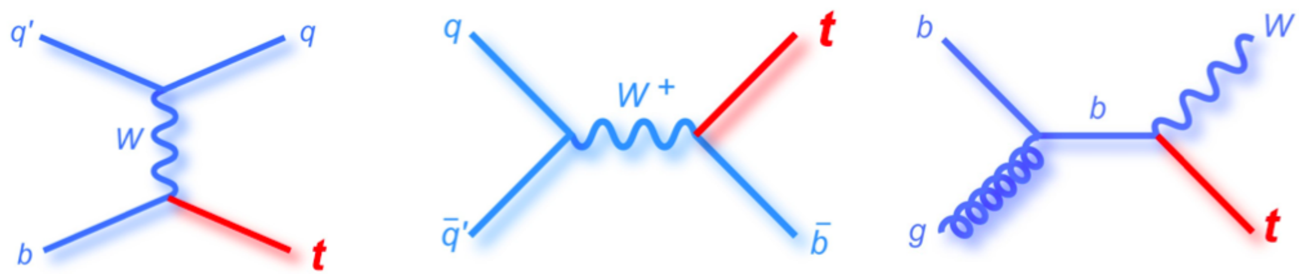
	LHC (7TeV)	Tevatron
gg	~80%	~15%
$q\bar{q}$	~20%	~85%

- Uncertainties ~ 5 %
- Full NNLO for $qq \rightarrow t\bar{t}$ available
- NNLO $gg \rightarrow t\bar{t}$ just came out !

[Beneke et al. arXiv:1208.5578]

σ_{tt}[pb]	Tevatron	LHC (7 TeV)	LHC (8 TeV)
NLO	$6.68^{+0.36+0.23}_{-0.75-0.22}$	$158.1^{+19.5+6.8}_{-21.2-6.2}$	$226.2^{+27.8+9.2}_{-29.7-8.3}$
NNLO	$7.00^{+0.21+0.29}_{-0.31-0.25}$	$160.9^{+11.1+7.2}_{-11.5-6.7}$	$229.8^{+16.5+9.7}_{-16.7-9.0}$
NNLL	$7.15^{+0.21+0.30}_{-0.20-0.25}$	$162.4^{+6.7+7.3}_{-6.9-6.8}$	$231.8^{+9.6+9.8}_{-9.9-9.1}$

- Production of single top via electroweak force

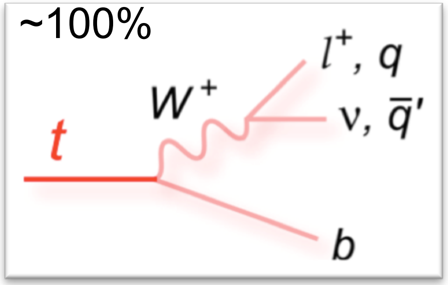


Predictions	t-channel (σ_{tqb})	s-channel (σ_{tb})	tW-channel
Tevatron	**2.26 pb**	**1.04 pb**	**0.28 pb**
LHC (7 TeV)	**64.6 pb**	**4.6 pb**	**15.7 pb**

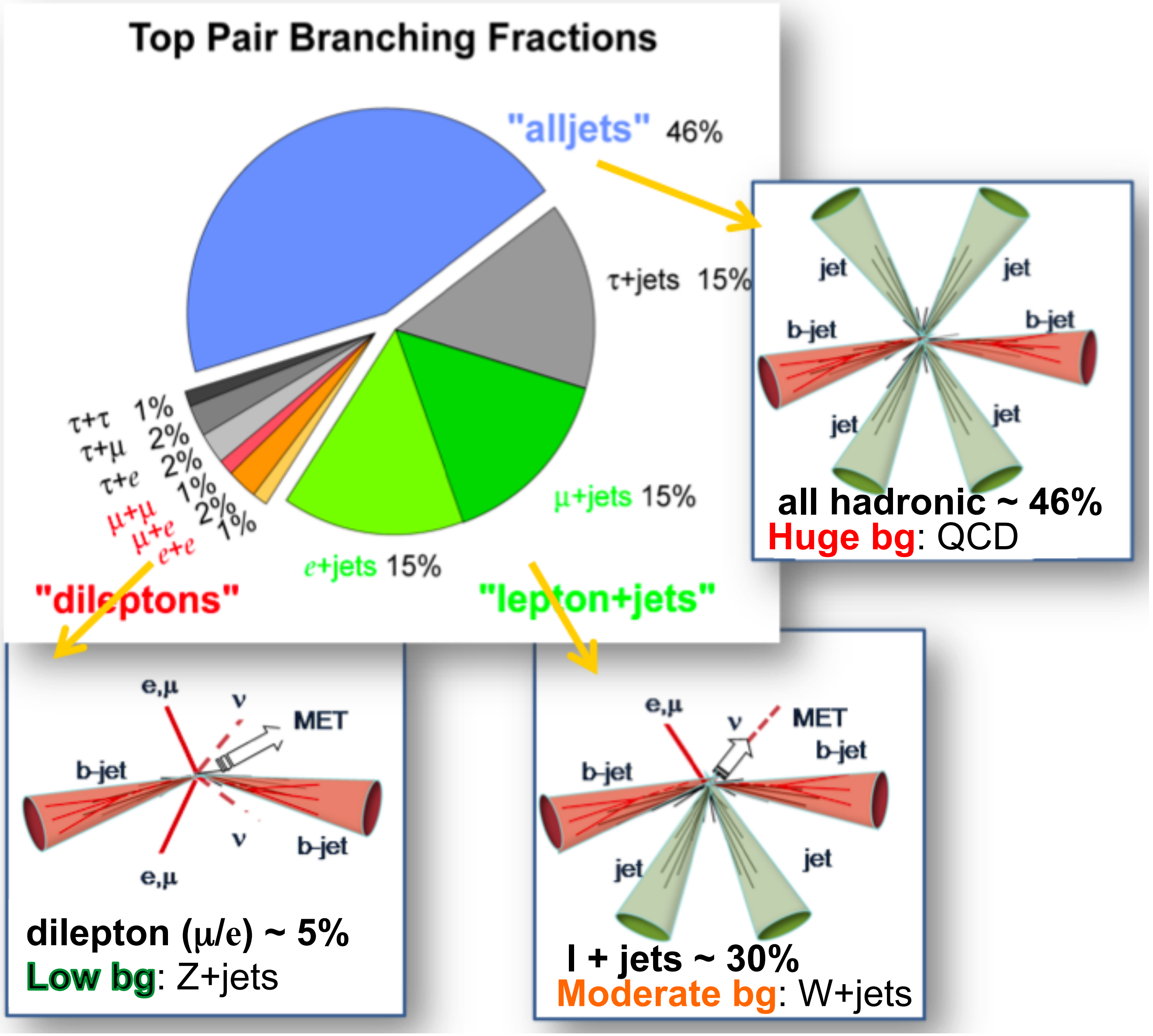
N. Kidonakis, Phys. Rev. D 83, 091503(R) (2011); Phys. Rev. D 81, 054028 (2010); Phys. Rev. D 82, 054018 (2010)

… and decay

In Standard Model:

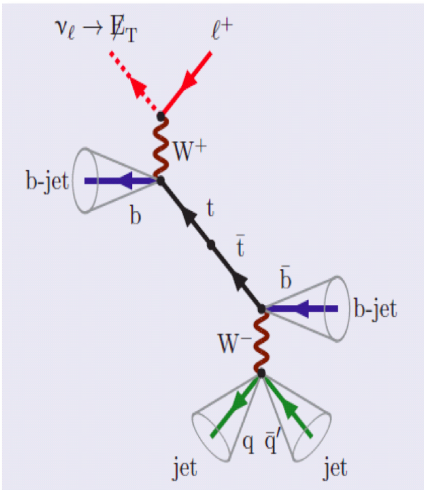


W decay modes
define
top final states

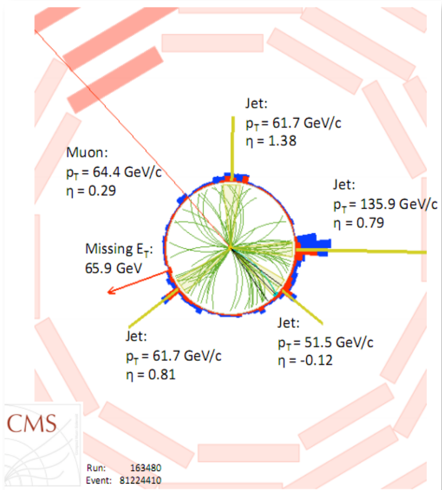


Detecting top quark signatures at CMS

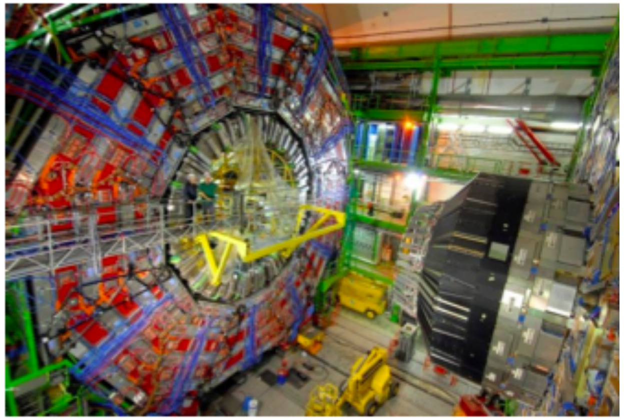
In theory …



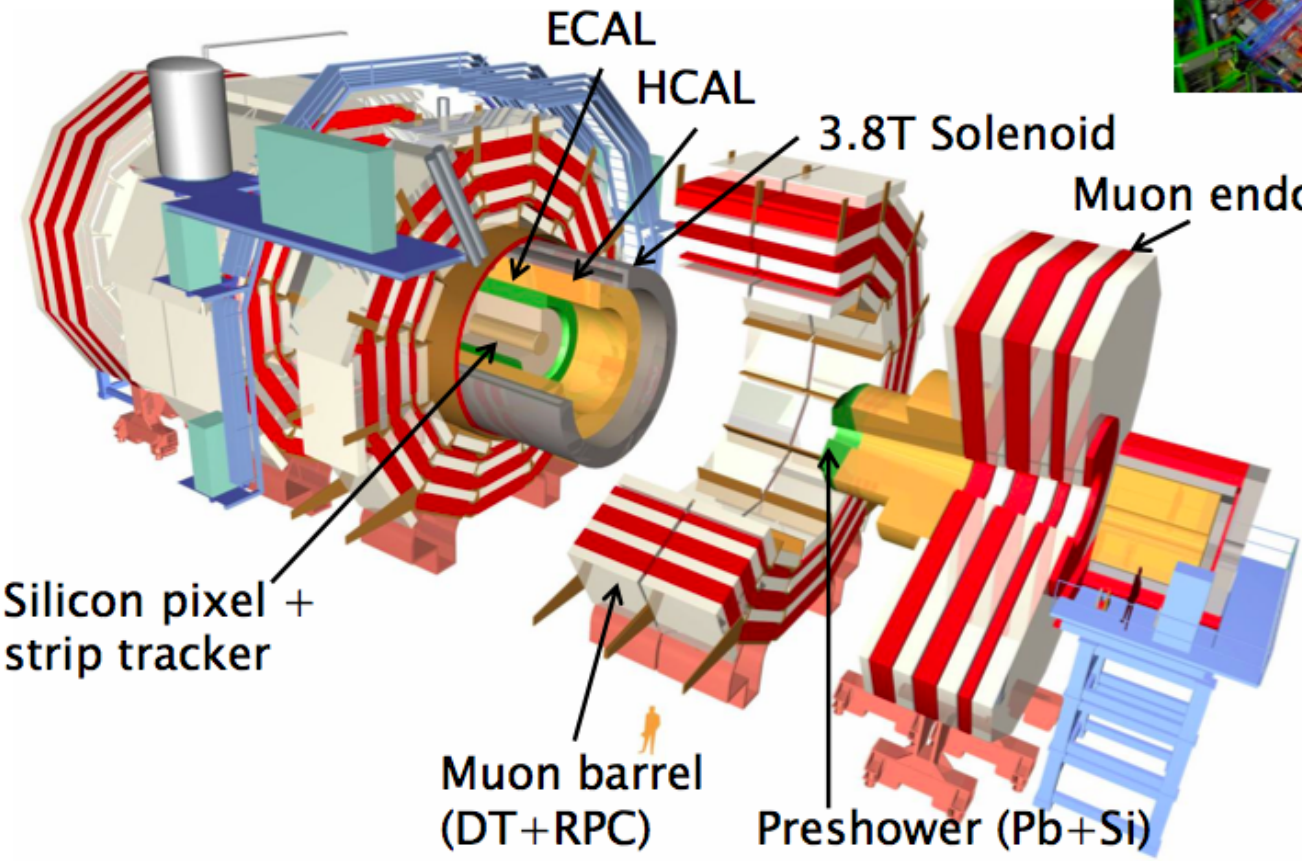
… in detector



The Compact Muon Solenoid detector

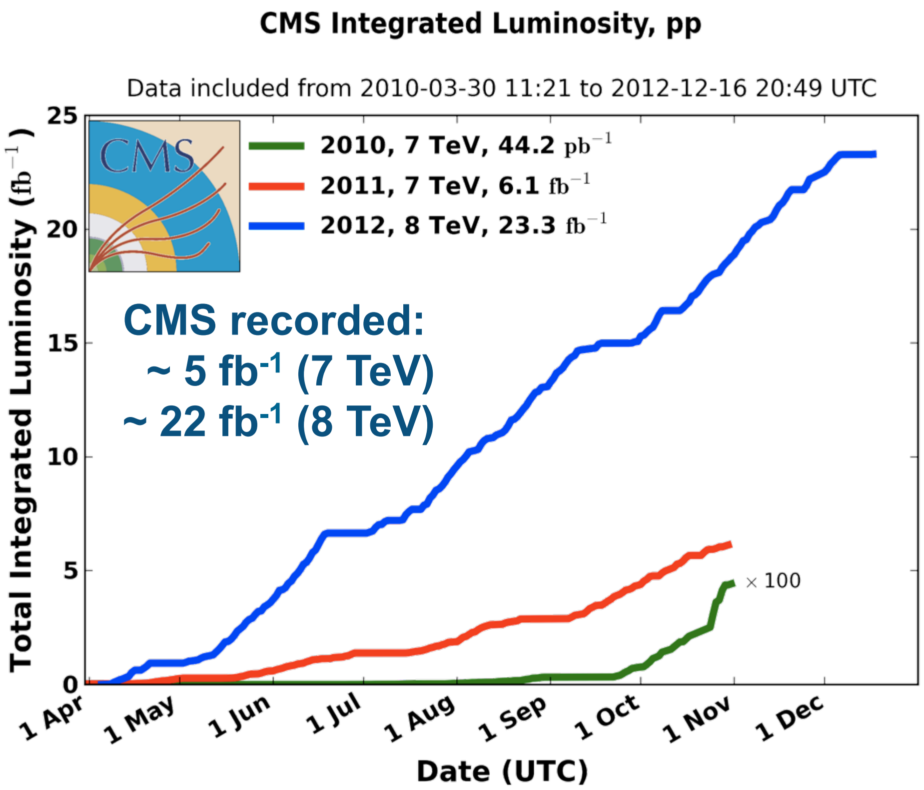


- 21m long, 15m in diameter
- 14000 tons



CMS Collaboration:
- *~2500 scientists + engineers*
- *~850 students*
- *173 institutes*
- *40 countries*

CMS in the inverse femtobarn era



- Excellent performance of LHC and CMS at 7 TeV (2010-2011) and 8 TeV (2012)

- Subdetector efficiencies from 97.1% - 99.9%, at design performance or better

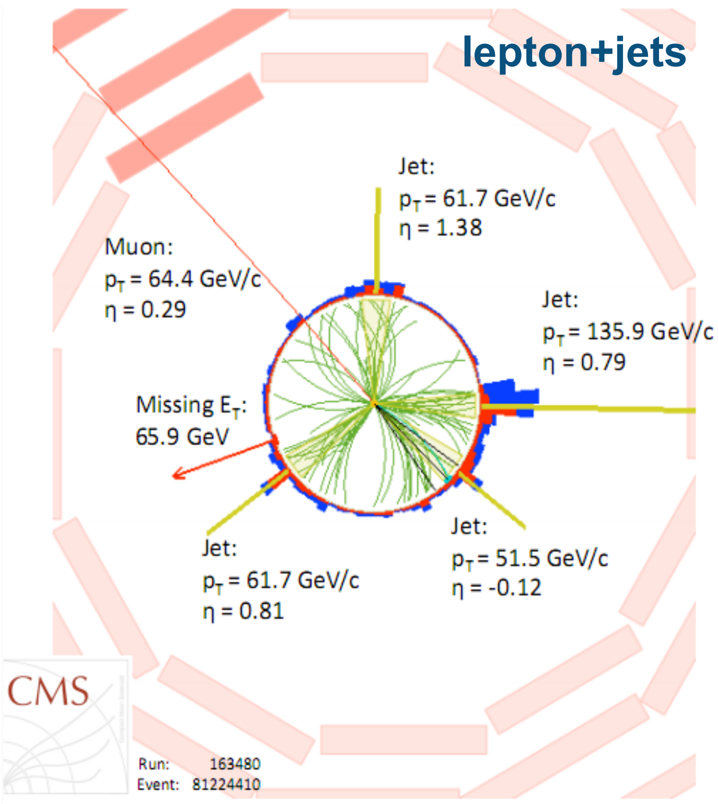
- Coping successfully with challenges of high luminosity in all fronts
  trigger, computing, reconstruction

- Luminosity uncertainty is 2.2% (7 TeV) and 4.4% (8TeV)

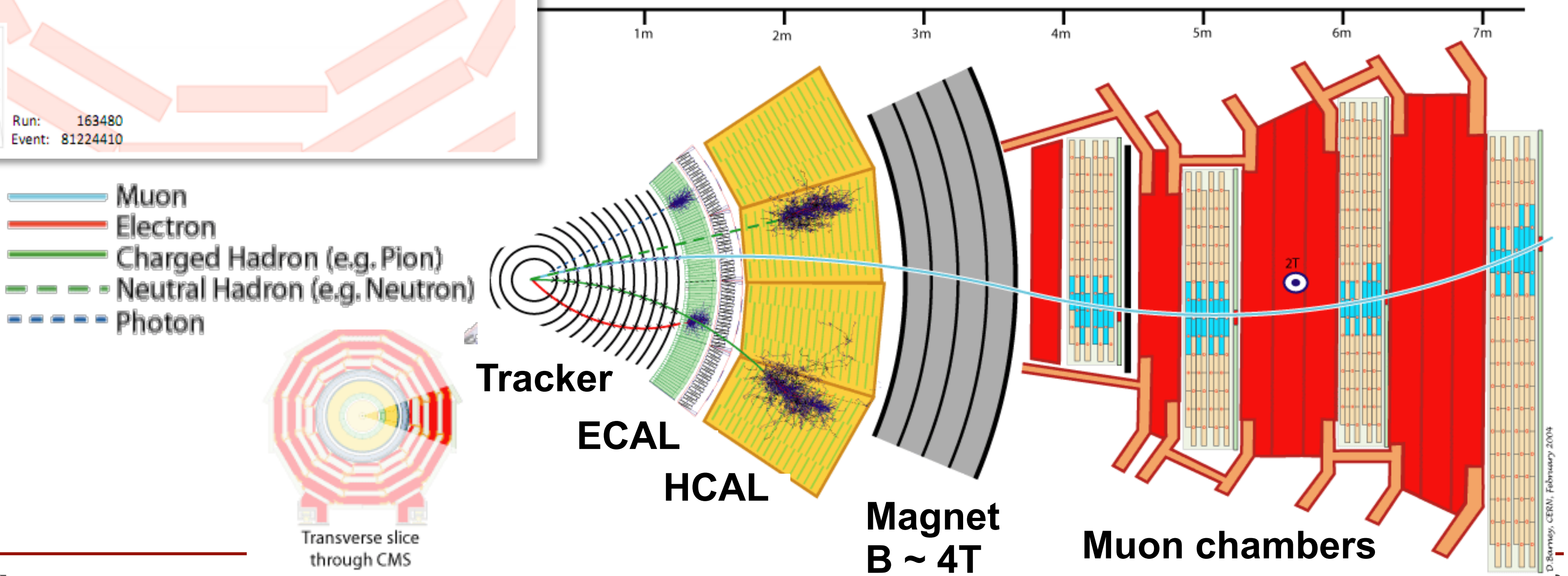
LHC is a 'top factory': ~ 1M $t\bar{t}$ events at 7 TeV and ~ 10M at 8 TeV !!

- Entering the era of precision measurements: cross sections, …
- Entering the top properties domain: mass, asymmetries, couplings, spin structure, V_{tb} …

Detecting top quarks at CMS



- All physics objects are essential for top physics
  - Charged leptons, (b)-jets, E_T^{miss}
- Needs optimal object reconstruction
  - 'Particle flow' combines information from all subdetectors to reconstruct and identify particles
- Needs sophisticated analysis tools
  - b-tagging, tau reconstruction, kinematic fitting

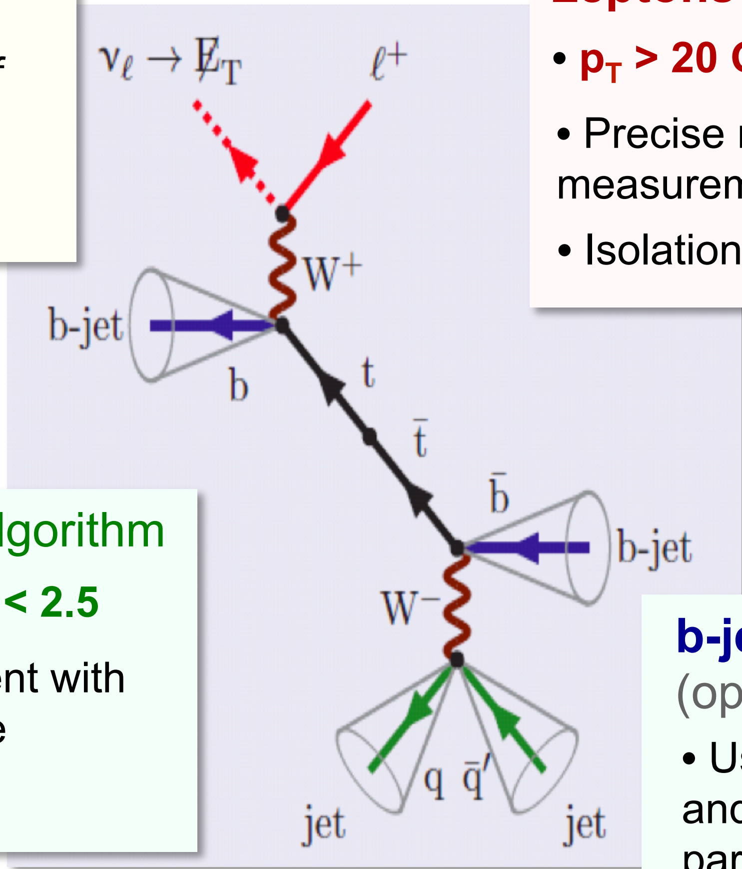


Selecting top quarks at CMS

Trigger: Single / double (isolated) leptons, or based on hadronic activity

Missing transverse energy (E_T^{miss}) (optional)

- Negative vectorial sum p_T of reconstructed particles
- **E_T^{miss} > 20 – 60 GeV**



Leptons (μ, e, τ)

- **p_T > 20 GeV, $|\eta|$ < 2.1 – 2.5**
- Precise momentum measurement, excellent ID
- Isolation

Jets, with anti-k_T algorithm

- **p_T > 20-30 GeV, $|\eta|$ < 2.5**
- Precise measurement with small jet energy scale uncertainty

b-jet ID (b-tagging) (optional)

- Using secondary vertices and/or track impact parameter information

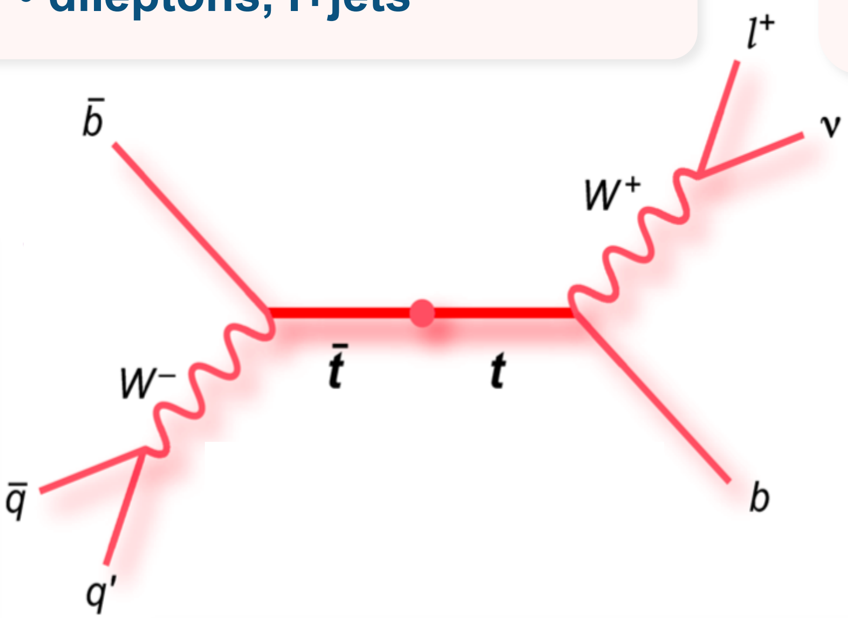
CMS top quark measurements in a nutshell

Top-pair production cross section:
- **dileptons, l+jets,** all hadronic, taus

Top-pair differential cross sections:
- **dileptons, l+jets**

Searches:
- resonances
- search for FCNC

Other properties:
- **mass**
- **charge asymmetry**
- W helicity
- Spin correlations
- Charge
- Polarisation
- Rare decays



Single top t-, s-, tW channel production, properties, couplings

Top-quark pair (differential) cross section measurements

$$\boxed{\sigma = \frac{N_{data} - N_{BG}}{\epsilon_{t\bar{t}} \int \mathcal{L} dt}}$$

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

Top-pair production cross sections

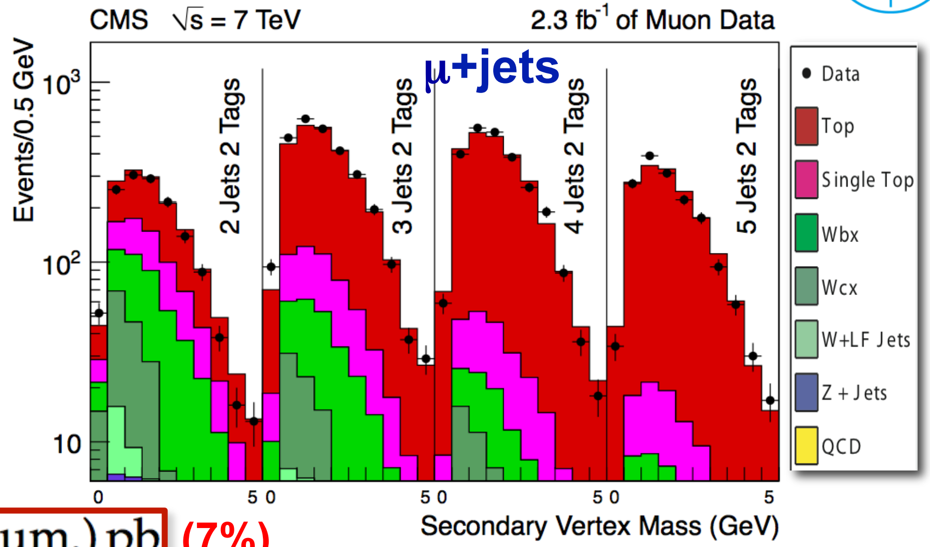
Lepton+jets channels:

arXiv:1212.6682 (accepted PLB)

1 isolated high-p_T μ/e, veto on additional leptons, ≥ 4 jets, ≥ 1 b-tagged jet

- Fit to secondary-vertex mass in different jet and b-tag categories

Main syst.: jet energy scale (JES), b-tagging

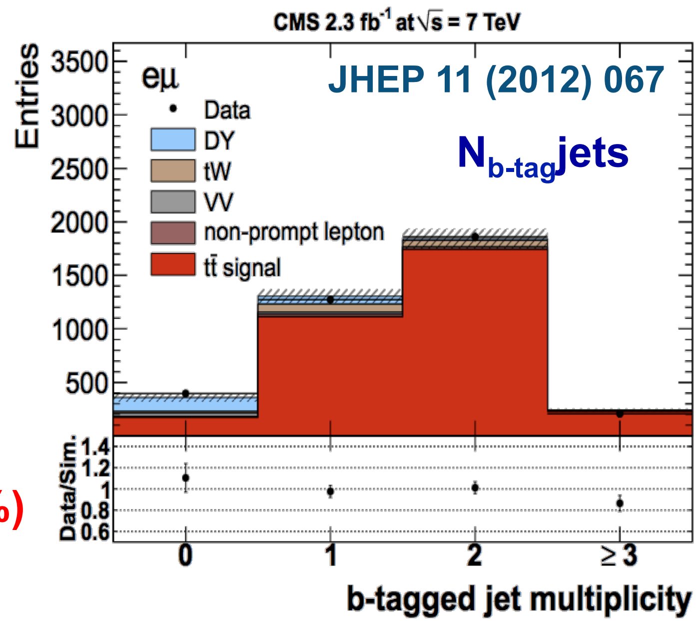


$$\boxed{\sigma_{t\bar{t}} = 158.1 \pm 2.1\,(\text{stat.}) \pm 10.2\,(\text{syst.}) \pm 3.5\,(\text{lum.})\,\text{pb}}$$ **(7%)**

Dilepton ee, μμ, μe channels:

2 opposite-sign isolated, high-p_T leptons, ≥ 2 jets, ≥ 1 b-tagged jet

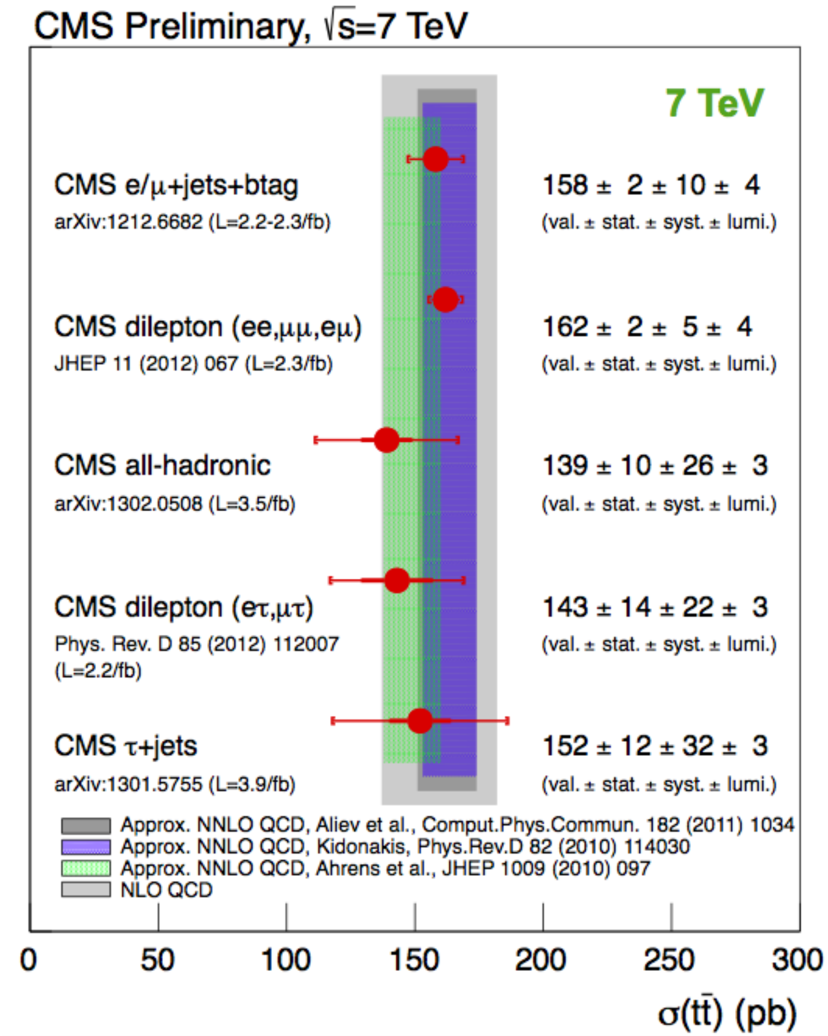
- E_T^{miss} for ee, μμ; veto Z-mass region
- Almost background-free
- Profile likelihood ratio in different jet & b-tag categories

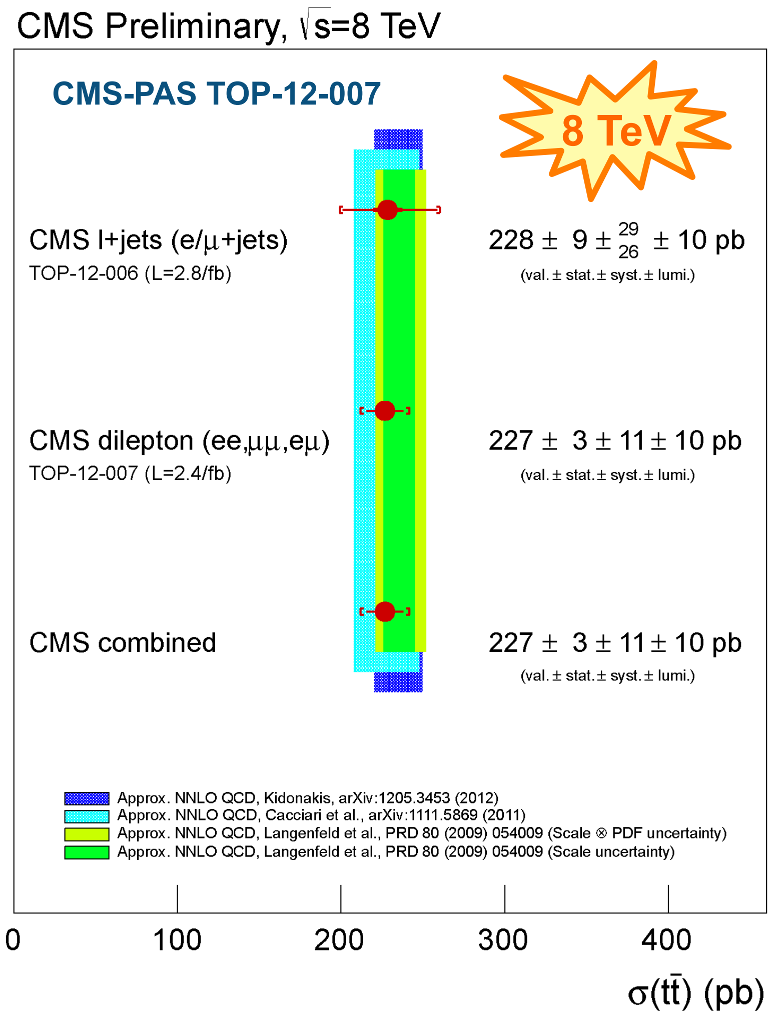


$$\boxed{\sigma_{t\bar{t}} = 161.9 \pm 2.5\,(\text{stat.})\,^{+5.1}_{-5.0}\,(\text{syst.}) \pm 3.6\,(\text{lumi.})\,\text{pb}}$$ **(4%)**

Main systematics: JES, lepton selection

Summary of σ(tt̄) results



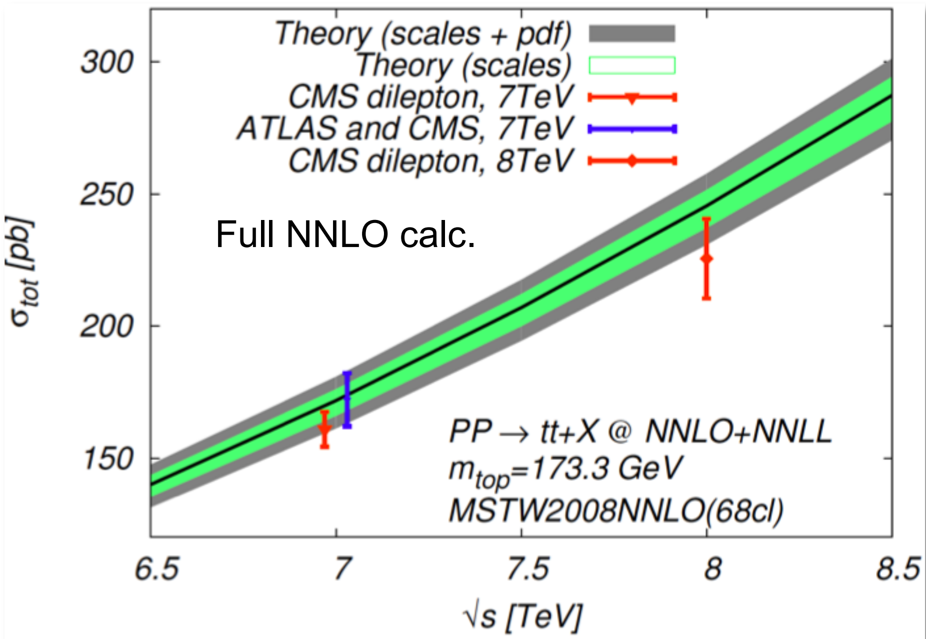


Excellent agreement between different channels at 7 and 8 TeV

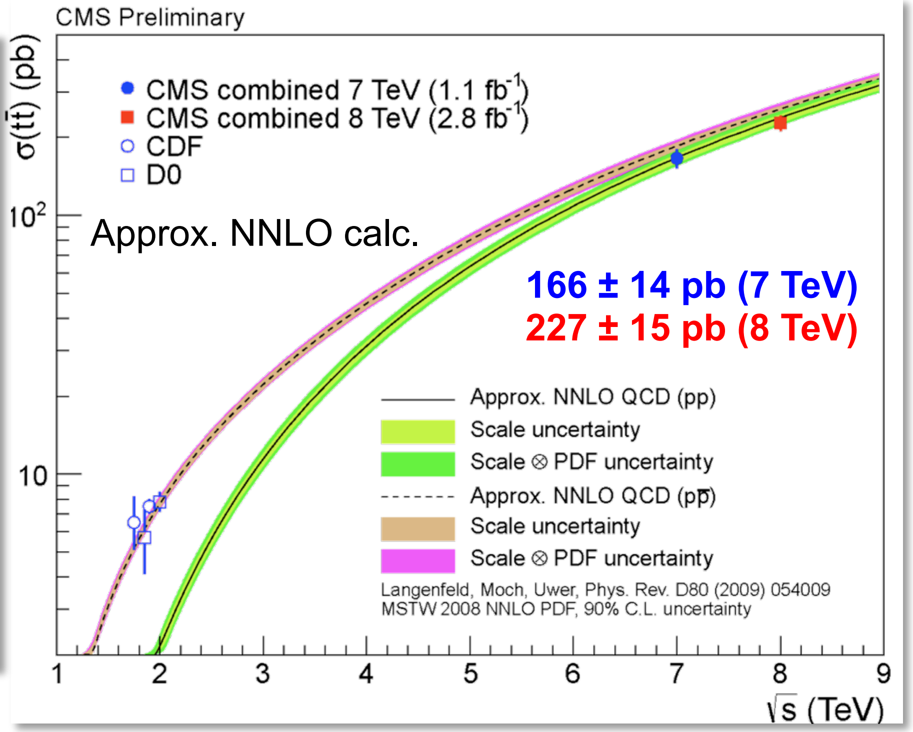
Experimental uncertainties < 5 – 15 % → approaching theory precision

Summary of $\sigma(t\bar{t})$ results

A. Mitov, La Thuile'13



[Czakon, Fiedler, Mitov (to appear)]



Experimental precision: 6 – 8 %

- Full NNLO calculation for gg available since last Thursday !

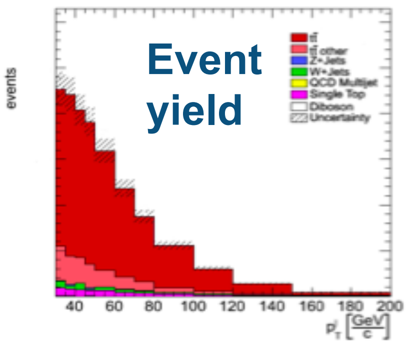
Good agreement between measurements and full NNLO calculation

Top-pair differential cross sections

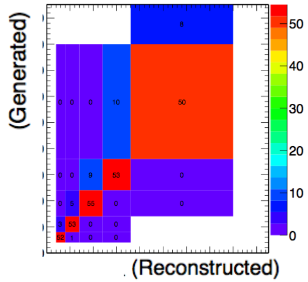
Precise tests of pQCD, tuning & validation of MC models, constrains on BSM effects

- Measure $\sigma(t\bar{t})$ as a function of several kinematic variables for different observables
  top, top pairs, (b)-jets, leptons, lepton pairs, E_T^{miss}, …

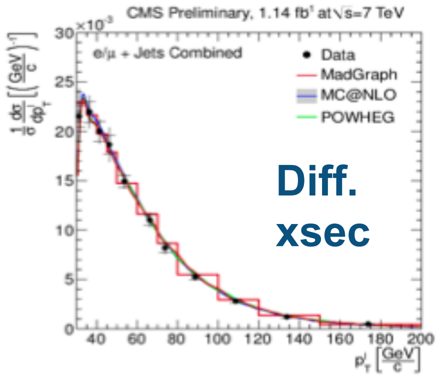
Event yield



Response matrix



Diff. xsec



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

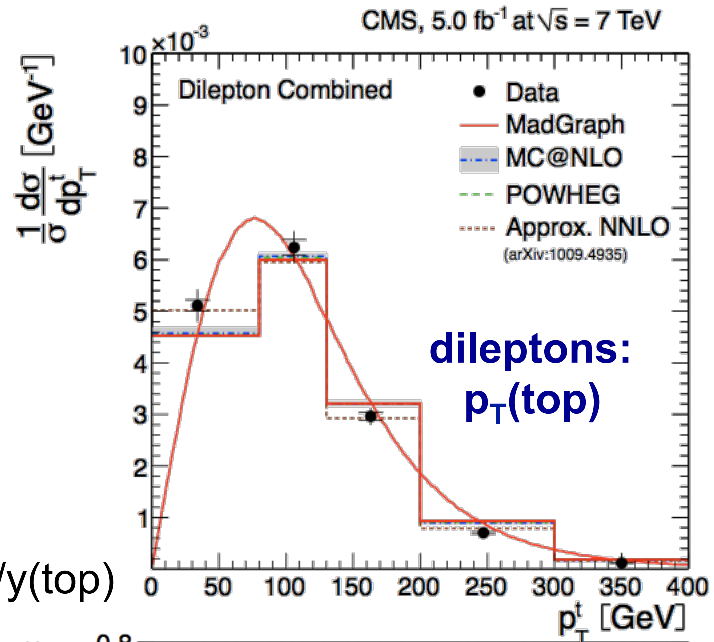
L = integrated luminosity
Δ^i_X = bin width for variable X
ε^i = efficiency and acceptance

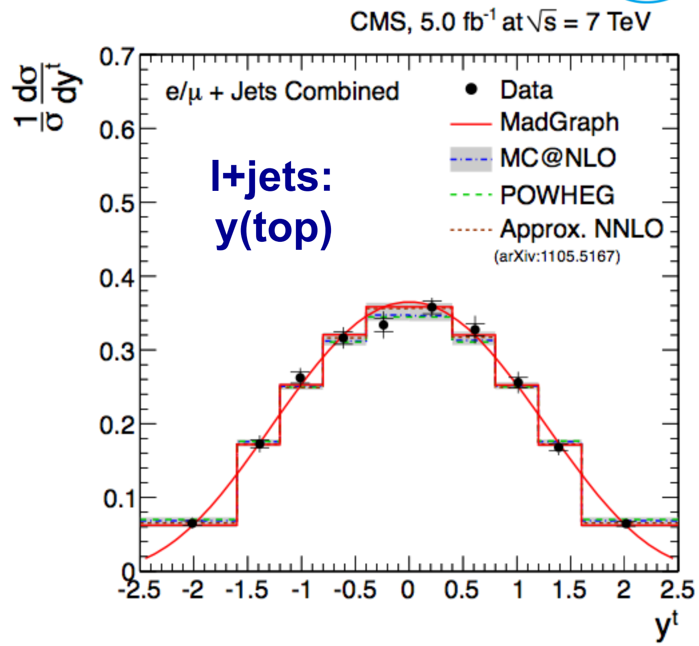
- Corrected for detector effects (finite experimental resolution)
- Visible phase space or extrapolated to full phase space for comparison with theory
- Normalized to inclusive cross section in corresponding phase space
  - Only shape uncertainties contribute

Top-pair differential cross sections

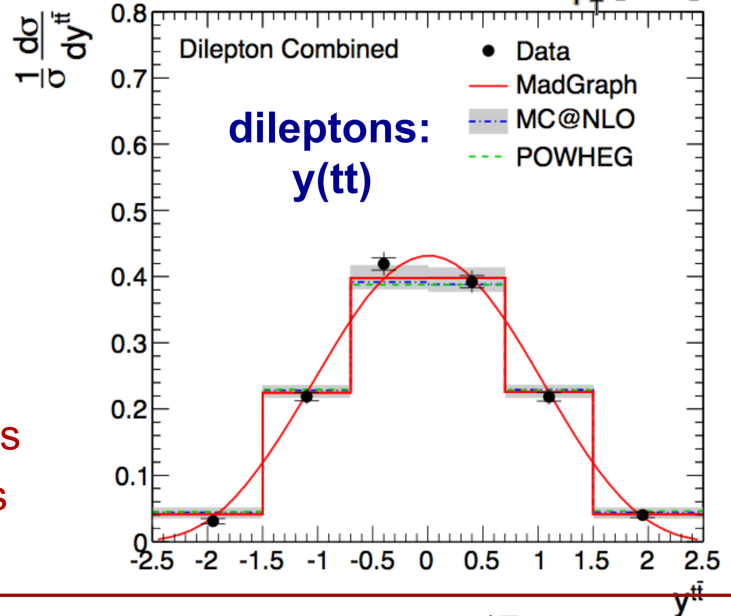
arXiv:1211.2220 (accepted EPJC)

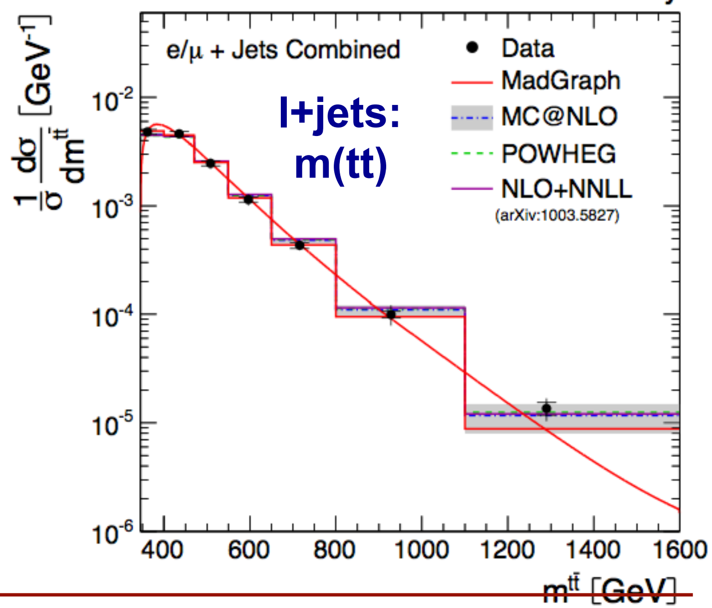
- Full kinematic reco. of the $t\bar{t}$ system
- Comparison to different predictions:
  - MadGraph+Pythia
  - MC@NLO+Herwig
  - POWHEG+Pythia
  - NLO+NNLL → $m(t\bar{t})$
  - approx. NNLO → p_T/y(top)





Softer top p_T in data, better described by approx. NNLO



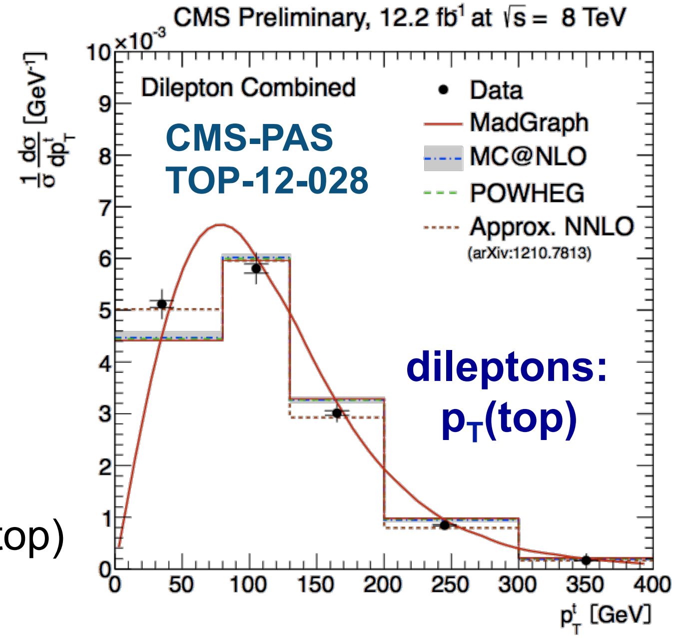


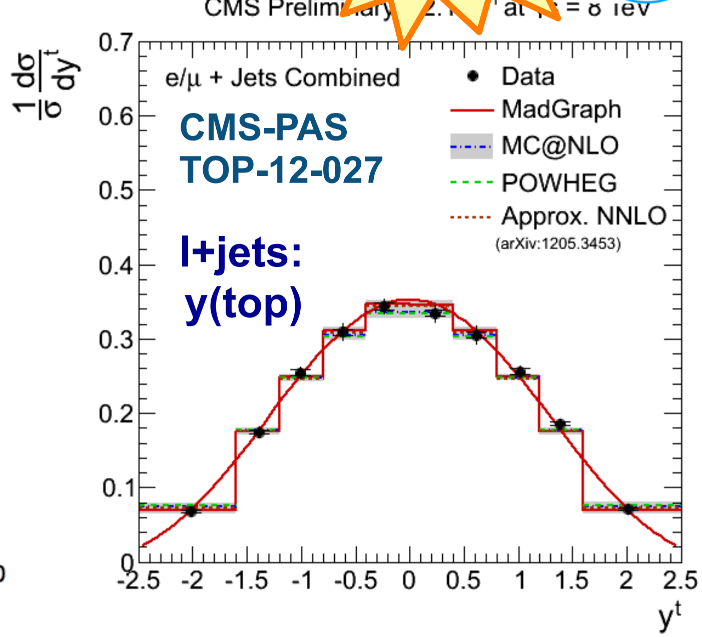
In general, good agreement btw:
- data and predictions
- different predictions

Top-pair differential cross sections

8 TeV New

- Full kinematic reco. of the tt system
- Comparison to different predictions:
  - MadGraph+Pythia
  - MC@NLO+Herwig
  - POWHEG+Pythia
  - approx. NNLO → p_T/y(top)





Softer top p_T in data, better described by approx. NNLO

In general, good agreement btw:
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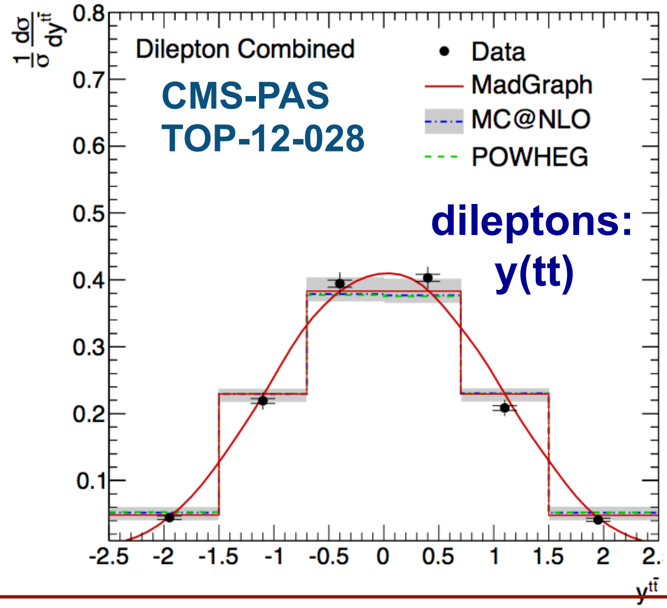
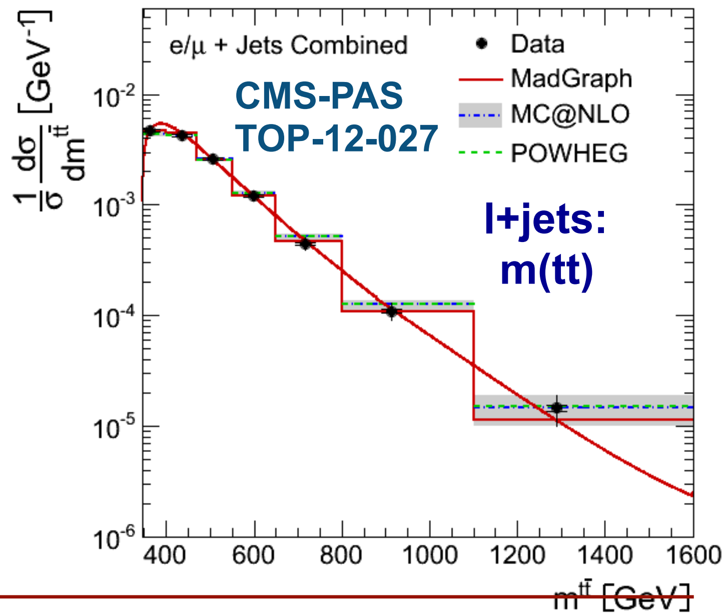
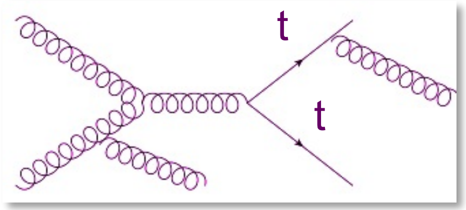


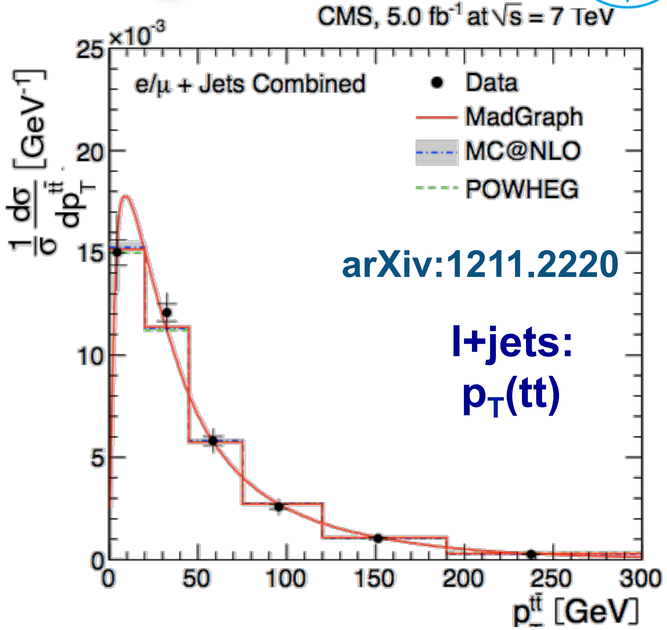


Constraining QCD radiation using $t\bar{t}$ events

At LHC, the fraction of $t\bar{t}$ events produced with additional hard jets from initial (final) state radiation is high

- Typically, large uncertainty due to radiation modelling in MC
  - Help tuning MC models with measurements

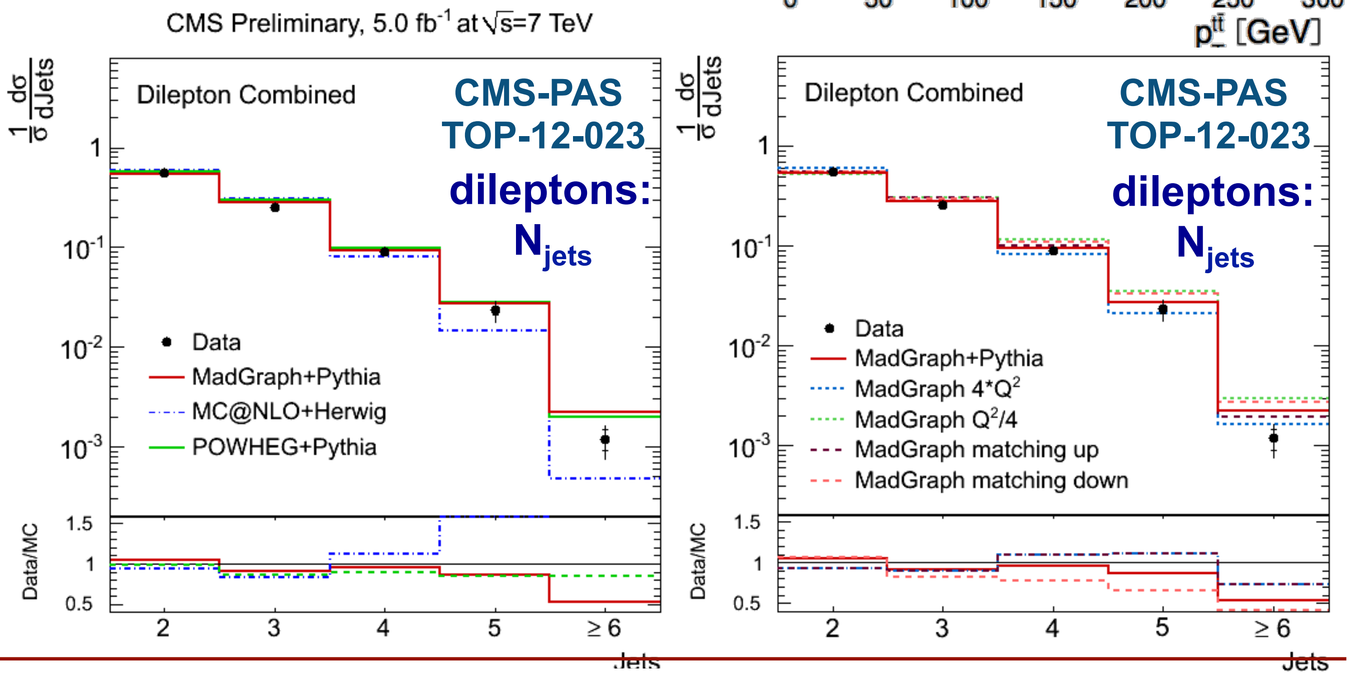




- Anomalous production of $t\bar{t}$+jets could reveal new physics
- Background for $t\bar{t}$+H and many BSM searches

In general, good agreement between data and predictions

N(jets) sensitive to modelling of radiation in MadGraph: data better described by larger scales



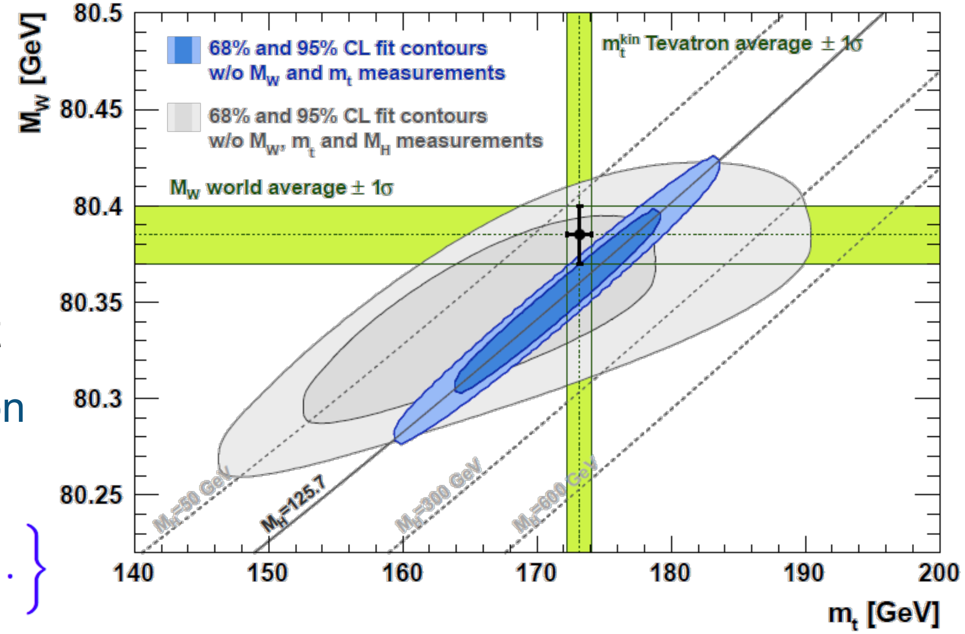
Top-quark properties

Top quark mass

- Current measurements of the top mass are very precise
  - Tevatron: m_t = 173.18 ± 0.94 GeV
- Fundamental parameter in the SM, not an observable → scheme-dependent
  - Pole mass: viewing top quark as free parton
  - $\overline{\text{MS}}$ mass ('running mass'):

$$m^{\text{pole}} = m(\mu)\left\{1 + \frac{\alpha_s(\mu)}{4\pi}\left(\frac{4}{3} + \ln\left(\frac{\mu^2}{m(\mu)^2}\right)\right) + \ldots\right\}$$

  - 'MC mass': (N)LO+PS, different from pole or $\overline{\text{MS}}$ mass

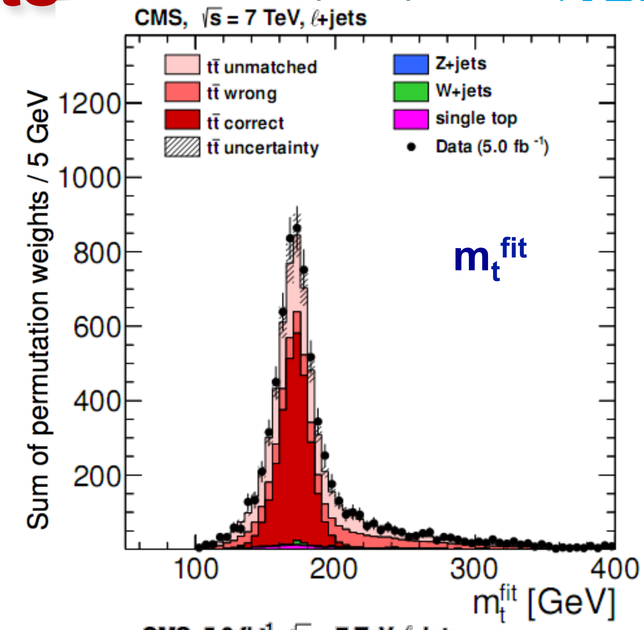


- Determining the top mass:
  - Direct methods: full reconstruction of $t\bar{t}$ events, depend on MC
  - Indirect methods: use the dependence of the top mass on other variables

NB: relation of measured m_{top} to well-defined mass not straightforward

Top mass in l+jets

JHEP 12 (2012) 105



Simultaneous measurement of top mass and JES:

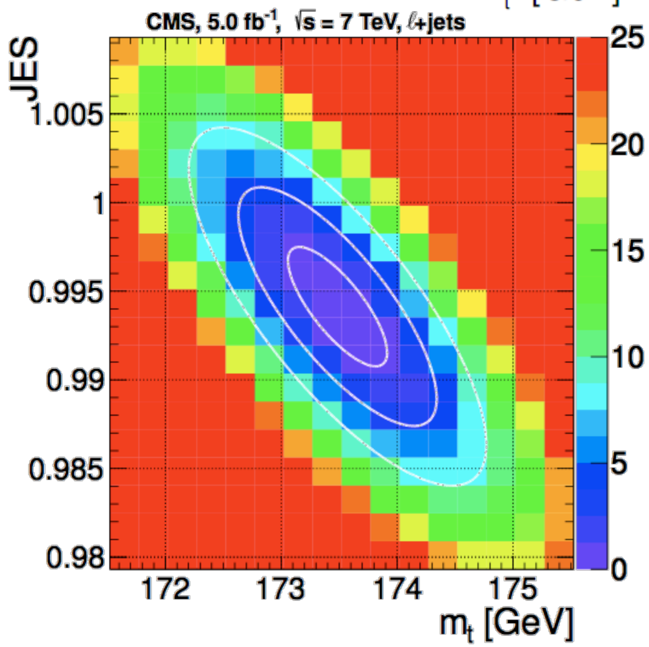
1 isolated μ/e, ≥ 4 jets, 2 b-tagged jets

- Reconstruct top mass from kinematic fit → m_t^{fit}
- W from reconstructed 2-jet invariant mass (handle on JES) → m_W^{reco}
- For each event, calculate the likelihood that m_t^{fit} and m_W^{reco} are consistent with a given top mass and JES factor
- 2D fit over all events to extract the top mass and JES:

(< 1% precision !)

$$\boxed{m_t = 173.49 \pm 0.43\,(\text{stat.+JES}) \pm 0.98\,(\text{syst.})\,\text{GeV}}$$

$$\text{JES} = 0.994 \pm 0.003\,(\text{stat.}) \pm 0.008\,(\text{syst.})$$



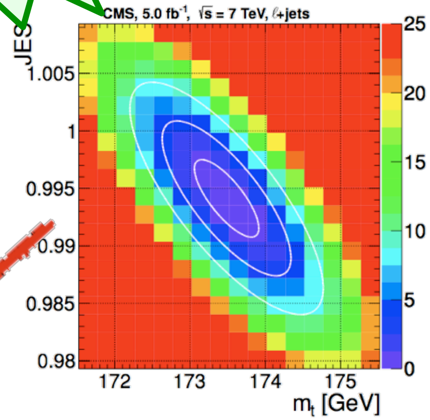
- Most precise individual mass measurement ever !
- Consistent with world average

Main systematics: b-JES, colour reconnection

m_t dependence on kinematics

7 TeV New

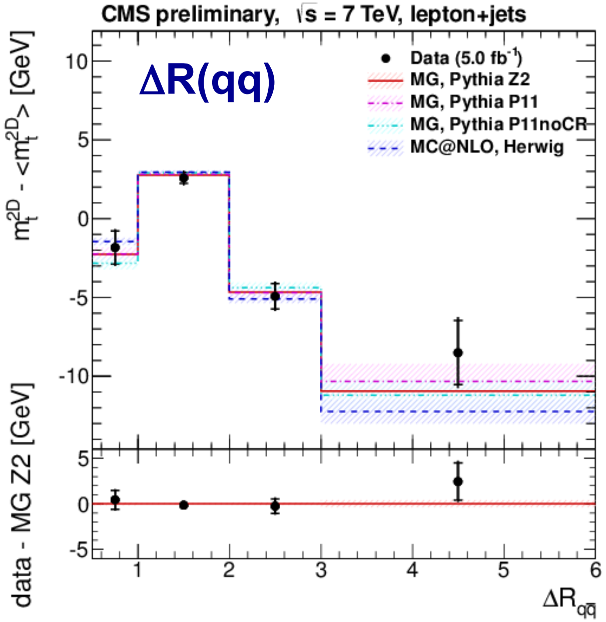
CMS-PAS TOP-12-029



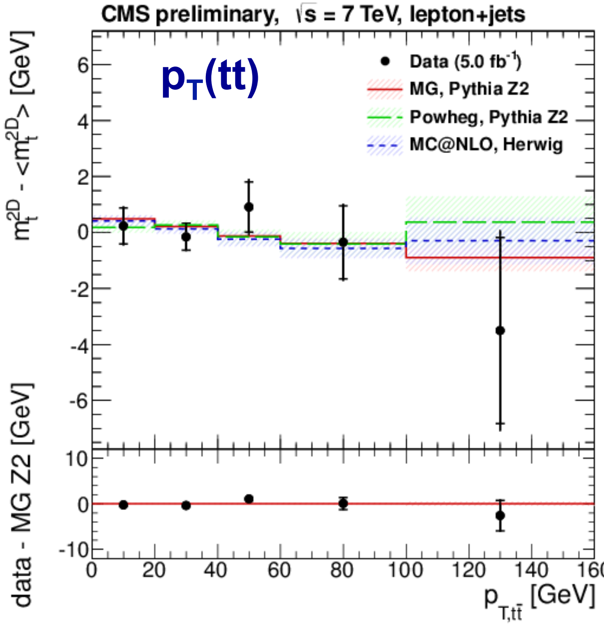
How does the measured m_t relate to the one needed for theoretical calculations ?

- Relation contains (non)perturbative corrections, expected to depend on event kinematics
  - Colour reconnection (CR), ISR/FSR radiation, …
- Is this kinematic dependence properly modelled in simulation?

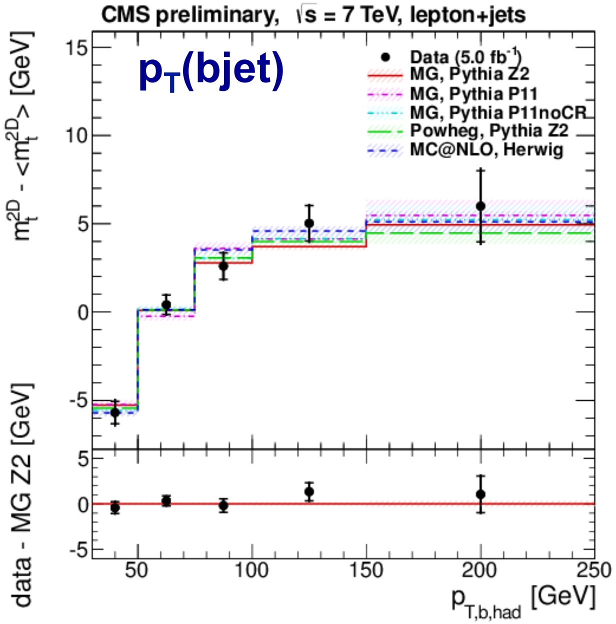
Sensitive to CR



Sensitive to ISR/FSR



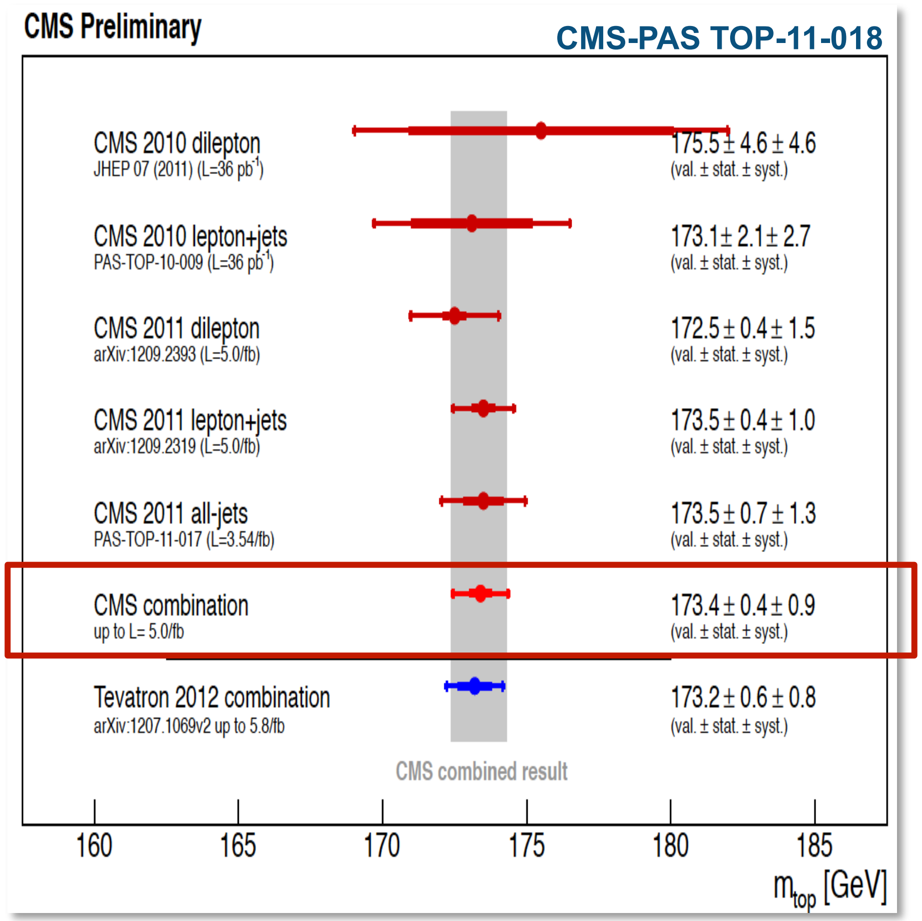
b-quark kinematics



Good agreement between data and predictions; more data needed !

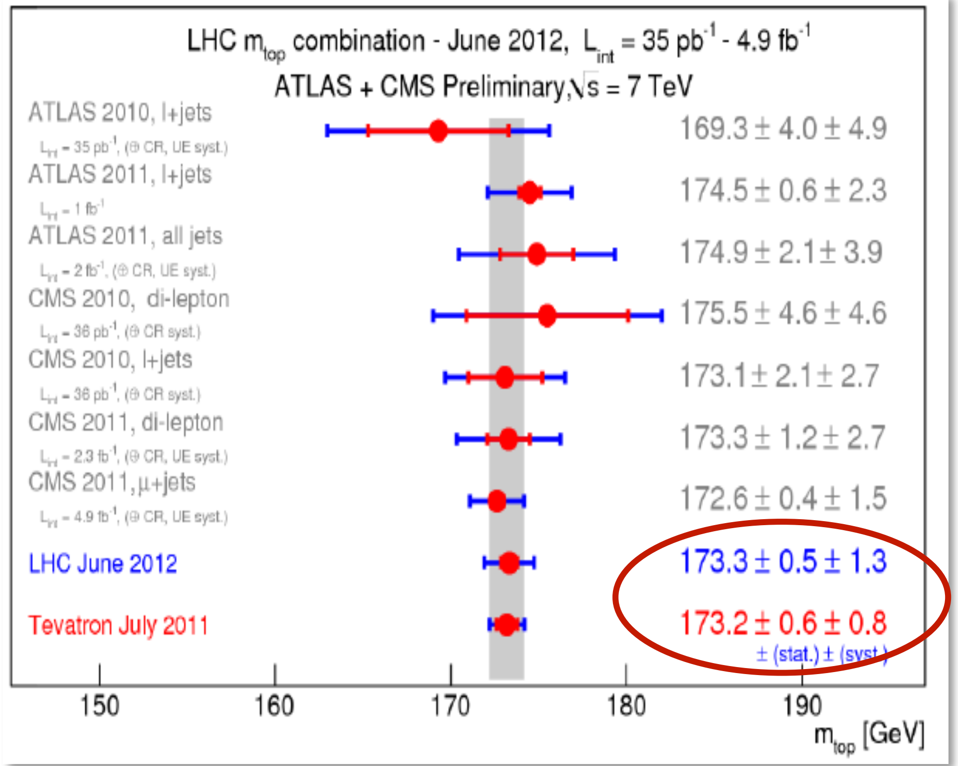
Summary of top mass results

CMS-PAS TOP-11-018



LHC combination

CMS-PAS TOP-12-001
CONF-ATLAS-2012-095



Missing most up-to-date CMS and ATLAS results

Measurements in l+jets and dilepton channels now competitive with the corresponding ones at Tevatron

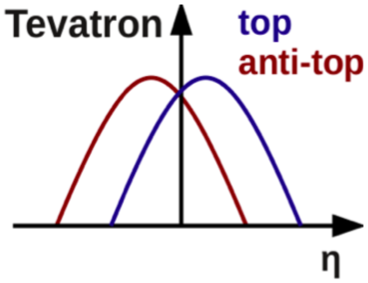
Precision of combination similar to Tevatron combination

$t\bar{t}$ charge asymmetries

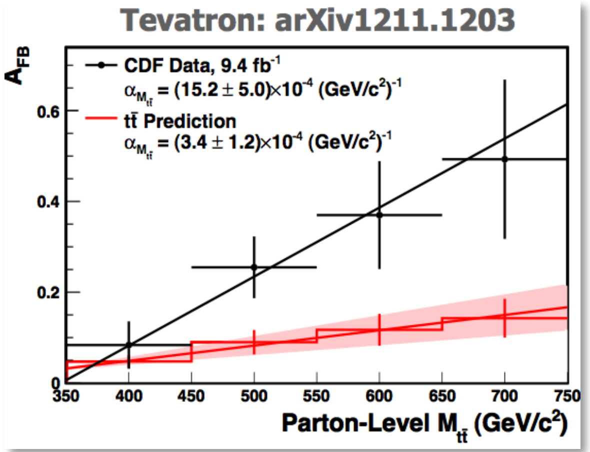
Asymmetries in angular distributions between top and antitop may indicate BSM top production interfering with SM production

- Tevatron ($p\bar{p}$): (anti)top quarks preferably emitted in the direction of the incoming (anti)quarks
  - Small $q\bar{q} \rightarrow t\bar{t}$ NLO effect, not present at LO or in $gg \rightarrow t\bar{t}$

→ Forward-backward asymmetry

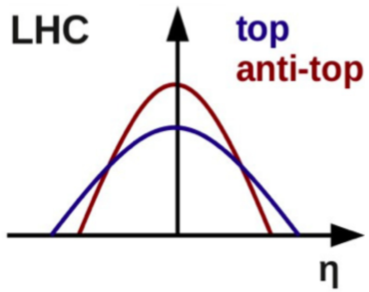


Tevatron: A_{FB} higher than predicted by SM



- LHC (pp): gg symmetric → SM asymmetries more diluted
  - No valence antiquarks, quarks have higher momentum on average

→ Asymmetry in width of (pseudo)rapidity distribution



Sensitive variable: $\Delta|y| = |y_t| - |y_{tbar}|$

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

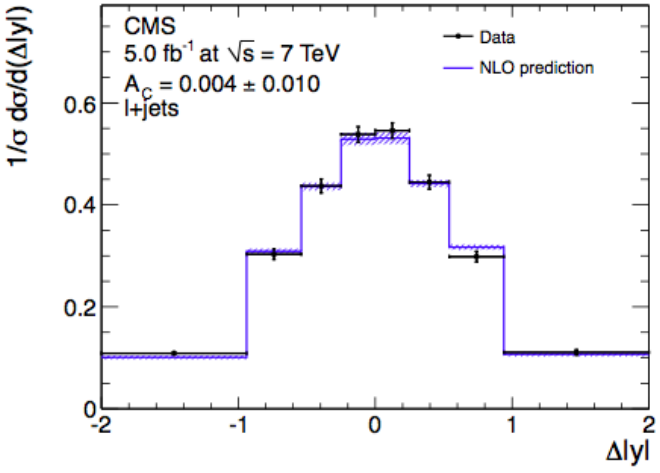
In dileptons, also lepton charge asymmetry: $\Delta|\eta| = |\eta_{l+}| - |\eta_{l-}|$

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

Measuring $t\bar{t}$ charge asymmetries

Phys. Lett. B717 (2012) 129

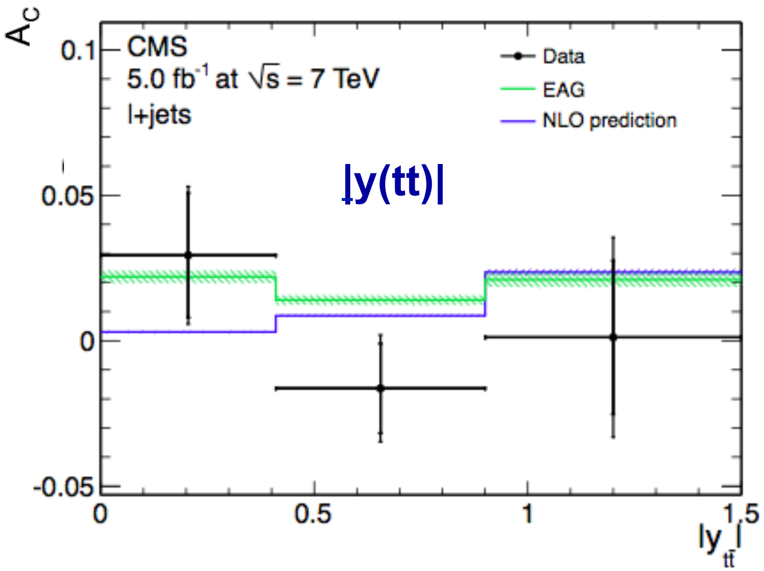
- Inclusive and differential A_C measurements in l+jets:

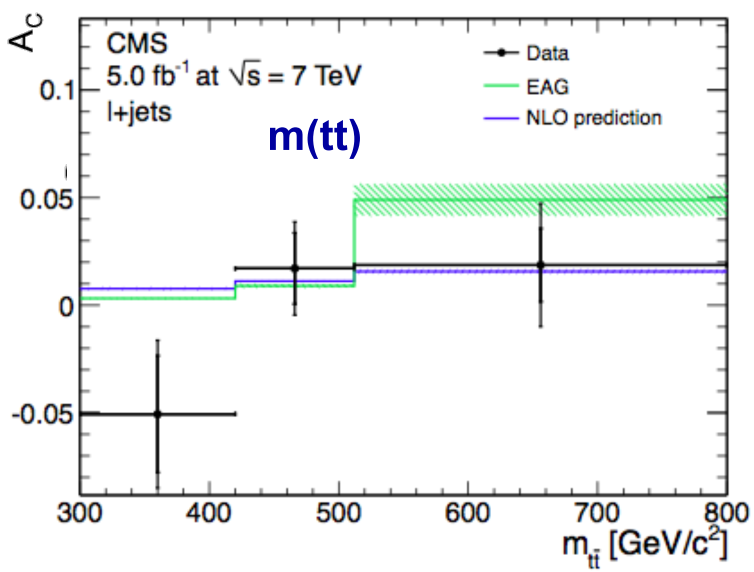


- Kinematic reconstruction of the $t\bar{t}$ system
- Corrected for background and detector effects
- SM prediction: $A_C^{thy} = 0.015 \pm 0.0006$ [Kühn, Rodrigo arXiv:1209.6830]

$$A_C = 0.004 \pm 0.010\,(\text{stat.}) \pm 0.011\,(\text{syst.})$$

- Comparison to NLO and to effective axial-vector gluon BSM model (EAG) [Gabrielli, et al. PRD 85 (2012) 074201]





No significant deviation from SM observed so far; more data needed !

Summary & outlook

- Top physics: key to QCD, electroweak and new physics
- In the last years, the LHC has become a real "top factory"
  - Precision regime: $\sigma(tt) < 5\%$, $m_{top} \sim 1$ GeV
  - Experimental precision challenging the theory
- CMS has a huge physics program for top quark physics
  - Cross sections, mass & other properties, searches
- So far, good agreement with SM predictions
- More results expected soon with up to ~20 fb^{-1} of data at 8 TeV

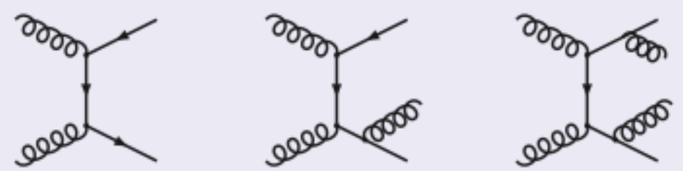
Stay tuned !

Additional information

Generator setups for $t\bar{t}$ at CMS

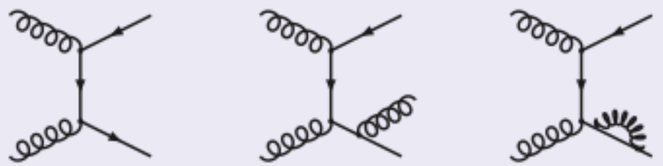
process	ME	PS	method	PDF	Tune
$t\bar{t}$ + jets	MadGraph v5.x	Pythia v6.42x	ME+PS	CTEQ6L1	Z2(*)
$t\bar{t}$	POWHEG-box 1.0	Pythia v6.42x	NLO	CTEQ6M	Z2(*)
$t\bar{t}$	MC@NLO v3.41	Herwig v6.520	NLO	CTEQ6M	

- Matrix Element + Parton Shower generators
  - Better description of high multiplicities
  - ISR/FSR modelling via ME from assumed Q^2 variation
  - Matching procedure to remove double counting between partons produced by ME and PS



tree level diagrams with up to 3 partons

- Next to Leading Order generators
  - More accurate in normalization
  - Smaller uncertainty on Q^2

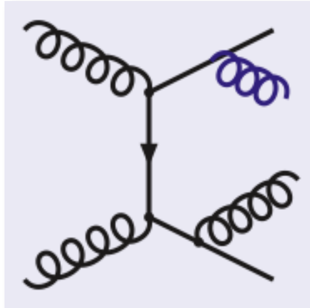


real + virtual corrections

- MadGraph(+Pythia) is the default for most of the analyses
  - Uncertainty on radiation covered by variations of Q^2 and ME-PS matching

Radiative corrections

- The ‘Q^2 scale’ variation addresses 2 aspects:
  - renormalisation and factorisation scale (ME)
  - amount of initial and final state radiation (ISR/FSR)



- For each event, Q^2 is defined as:

$$Q^2 = m_t^2 + \sum p_T^2 \text{ (MadGraph)}$$

$$Q^2 = m_t^2 \text{ (POWHEG/MC@NLO)}$$

  - Q^2 varied up (down) by a factor 4.0 (0.25)

- Parton showering:
  - p_T-ordered evolution scale of ISR/FSR
  - shares Q^2 factor α_S scale with ME
  - implicitly: starting scale changes with ΔQ^2

- MadGraph uses:
  - tree-level diagrams for hard radiation and interferences (up to 3 final-state partons for ttbar)
  - parton showering for soft and collinear region (with Pythia 6.42X)
  - matching via ktMLM, thresholds varied by factor 0.5 to 2.0 (nominal = 20 GeV)

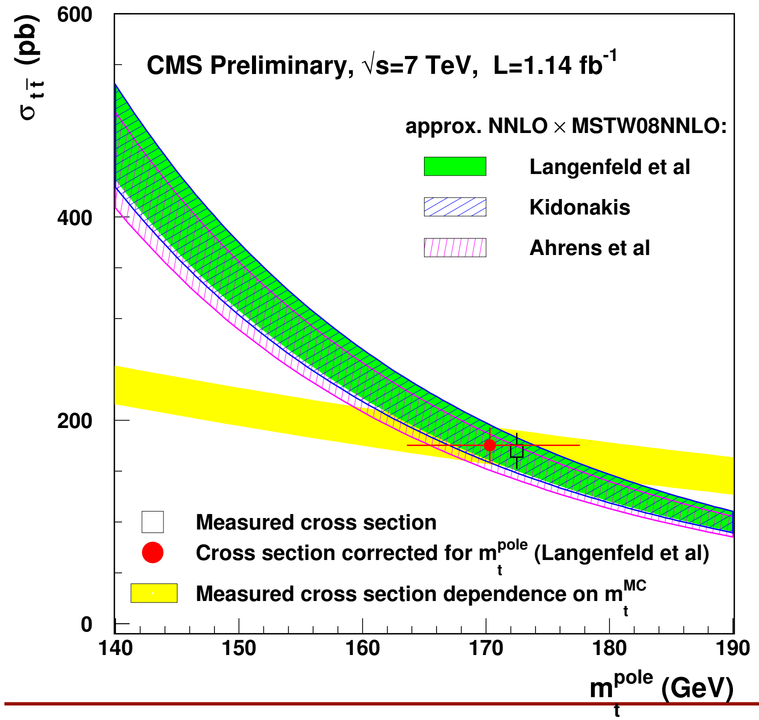
Top quark mass from $\sigma(t\bar{t})$

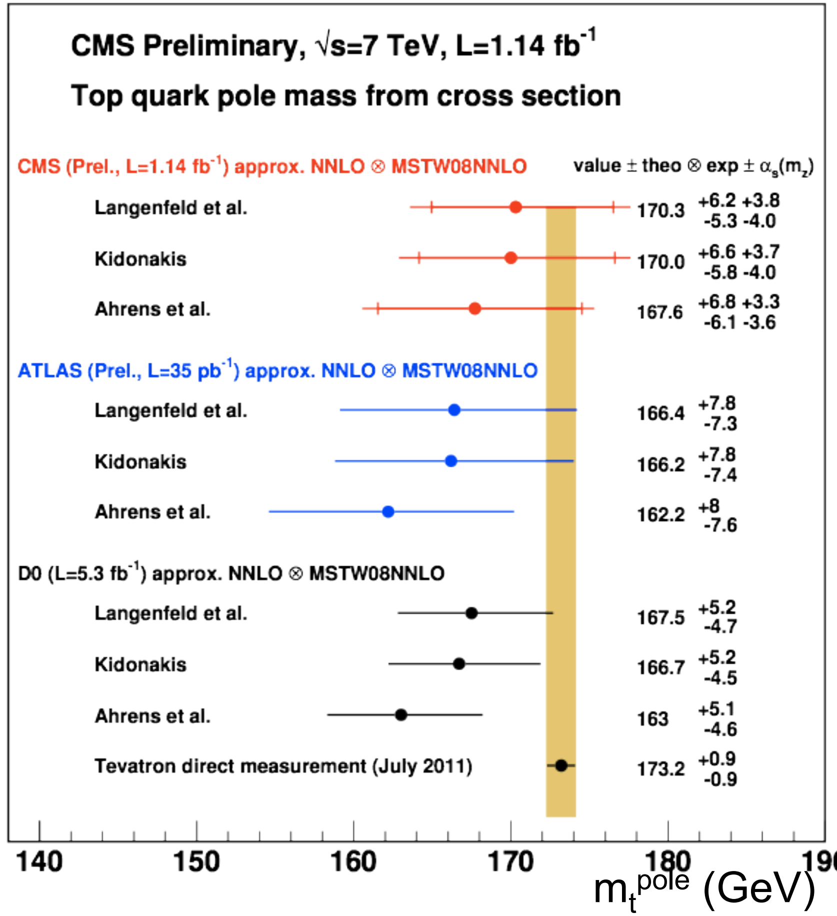
CMS-PAS
TOP-11-008

Mass dependence of predicted cross section allows determining m_t from measured σ_{tt}

→ provides top mass in unambiguous definition

- Extract **pole** and $\overline{\textbf{MS}}$ **mass** from measured cross section in dileptons
- Most probable mass results from joint likelihood: theory $\otimes$ experiment



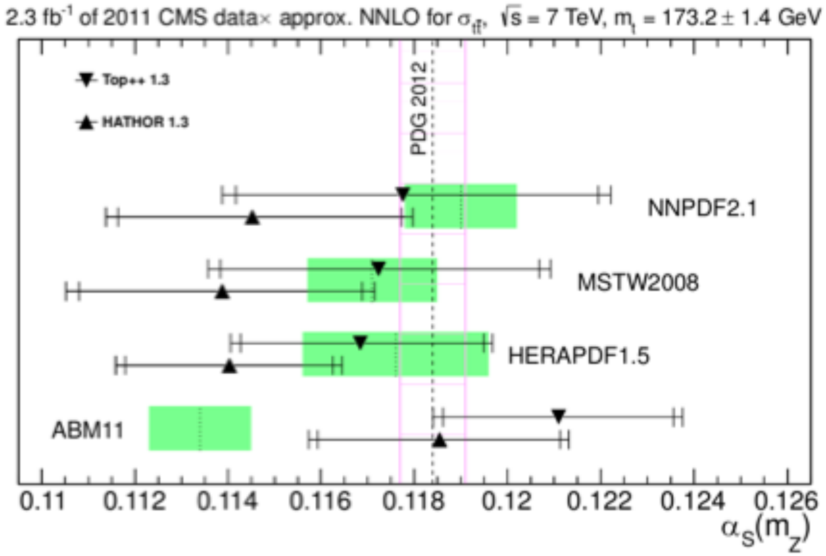


Good agreement between different calculations
Results consistent also with other experiments

Precision limitations:
- Systematic uncert. of the measurement
- PDF uncert. + α_S uncert. in the PDF

α_s from σ(tt)

Using arXiv:1208.2671		Most likely value	Uncertainty Total	Uncertainty From δm_t
Top++ 1.3	with NNPDF2.1	0.1178	$^{+0.0045}_{-0.0039}$	$^{+0.0015}_{-0.0015}$
HATHOR 1.3		0.1145	$^{+0.0034}_{-0.0031}$	$^{+0.0013}_{-0.0013}$
Top++ 1.3	with MSTW2008	0.1172	$^{+0.0037}_{-0.0037}$	$^{+0.0013}_{-0.0014}$
HATHOR 1.3		0.1139	$^{+0.0033}_{-0.0034}$	$^{+0.0013}_{-0.0013}$
Top++ 1.3	with HERAPDF1.5	0.1168	$^{+0.0028}_{-0.0028}$	$^{+0.0010}_{-0.0011}$
HATHOR 1.3		0.1140	$^{+0.0024}_{-0.0024}$	$^{+0.0010}_{-0.0010}$
Top++ 1.3	with ABM11	0.1211	$^{+0.0027}_{-0.0027}$	$^{+0.0010}_{-0.0010}$
HATHOR 1.3		0.1185	$^{+0.0028}_{-0.0028}$	$^{+0.0010}_{-0.0010}$



New CMS PAS TOP-12-022

- High precision measurement of the top pair cross section can be used to determine the strong coupling constant $\alpha_s(m_Z)$.

- Dependence of the $t\bar{t}$ cross section on α_s and correlations with m_t determined with Top++ and HATHOR and for various PDF sets.

- α_s determined from the maximization of a likelihood function :

$$L(\alpha_S) = \int \boxed{f_{\mathrm{exp}}(\sigma_{t\bar{t}}|\alpha_S)} \boxed{f_{\mathrm{th}}(\sigma_{t\bar{t}}|\alpha_S)} \, d\sigma_{t\bar{t}}.$$

Gaussian term, experimental measurement

Convolution of a Gaussian (PDF) and a rectangular function (ren./fact. scales)

Top-antitop mass difference

JHEP 06 (2012) 109

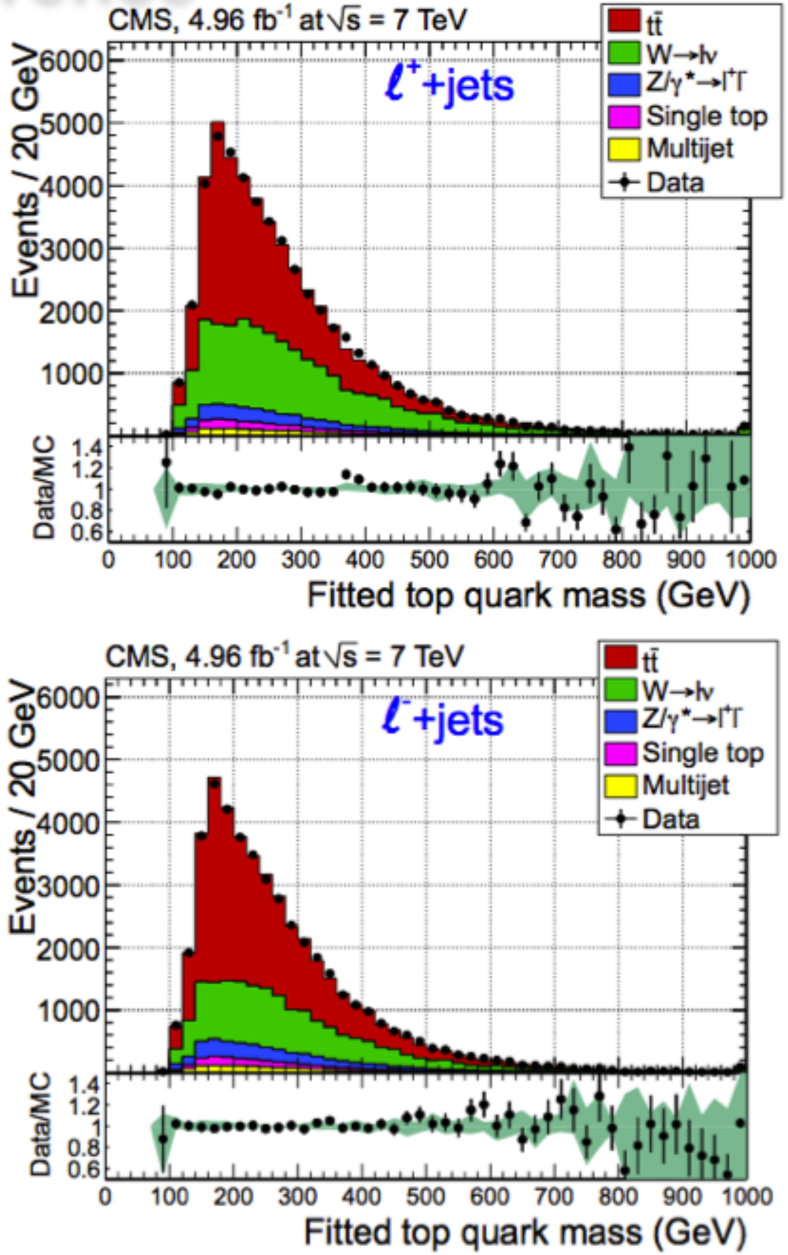
Test of CPT invariance: particle and anti-particle must have the same mass

- Compare l^++jets vs. l^-+jets samples
  - 1 isolated high-p_T μ/e, $\geq$ 4 jets
- Mass reconstructed from hadronic t, tbar decay
  - Kinematic fit from the jet combination with lowest χ^2
- Event-by-event likelihood for l^+ and l^- separately
- World's best measurement so far!

$$\boxed{\Delta m_t = -0.44 \pm 0.46\ \text{(stat.)} \pm 0.27\ \text{(syst.)}\ \text{GeV}}$$

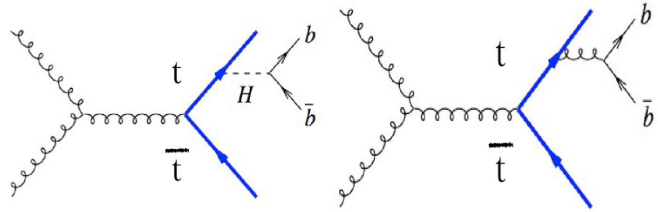
- Consistent with SM ($\Delta m = 0$) and between the e and μ channels
- Still statistically limited

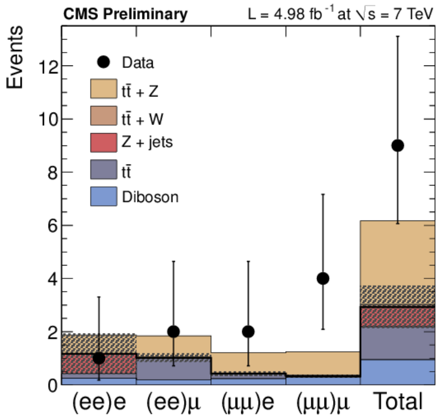
JES uncertainty largely cancelled in the mass difference



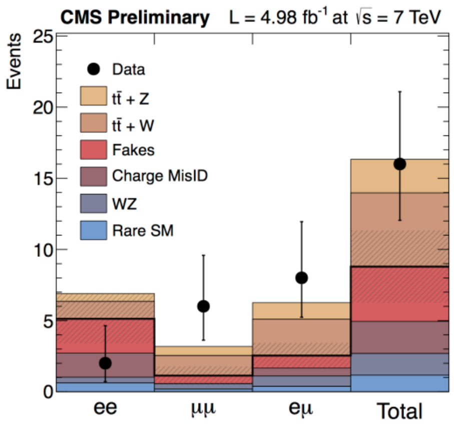
Associated production of top and W/Z, bb

- ttbar+W/Z are rare processes in SM
  - Access to top-vector-boson coupling
  - Important background for BSM searches





Trileptons

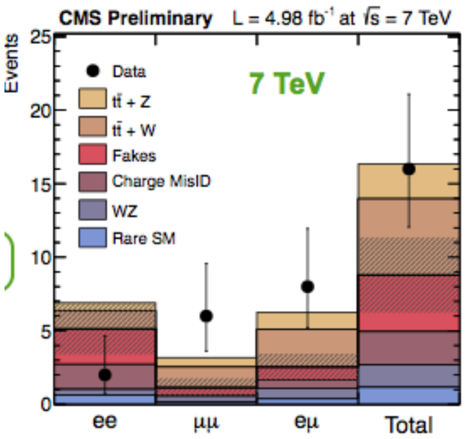


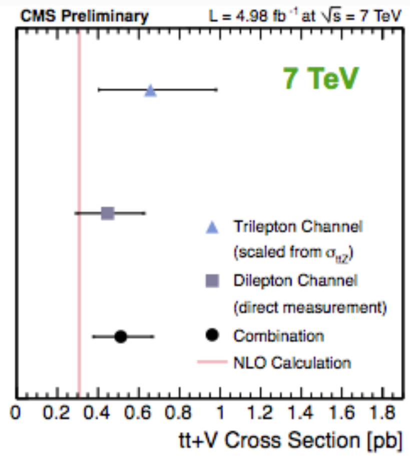
Dileptons

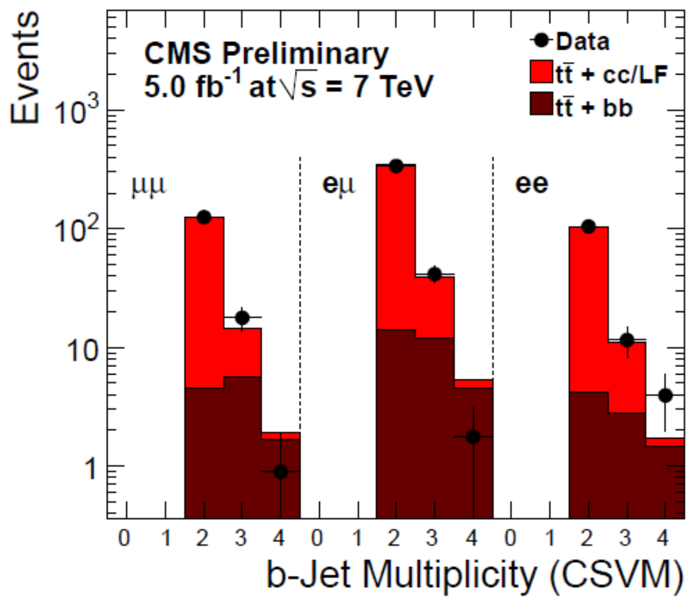
$t\bar{t}$+$b\bar{b}$: Ratio of light flavor to b-flavored jets (dilepton final state)

- important background to $t\bar{t}$H search

$$\boxed{\frac{\sigma(t\bar{t}b\bar{b})}{\sigma(t\bar{t}jj)} = 3.6 \pm 1.1_{stat} \pm 0.9_{syst}\%}$$



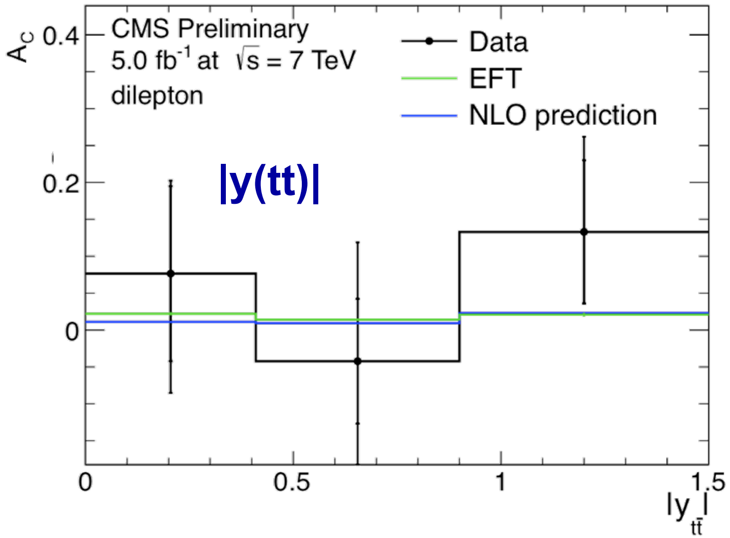




Measuring $t\bar{t}$ charge asymmetries

CMS-PAS TOP-12-010

- A_C measurement in **dileptons** (ee, μμ, μe):



2 OS isolated, high-p_T leptons, ≥ 2 jets, ≥ 1 b-tagged jet; E_T^{miss} for ee, μμ; veto Z-mass region

- Kinematic reconstruction of the ttbar system
- Correct for background and detector effects
- Compare to different theory predictions

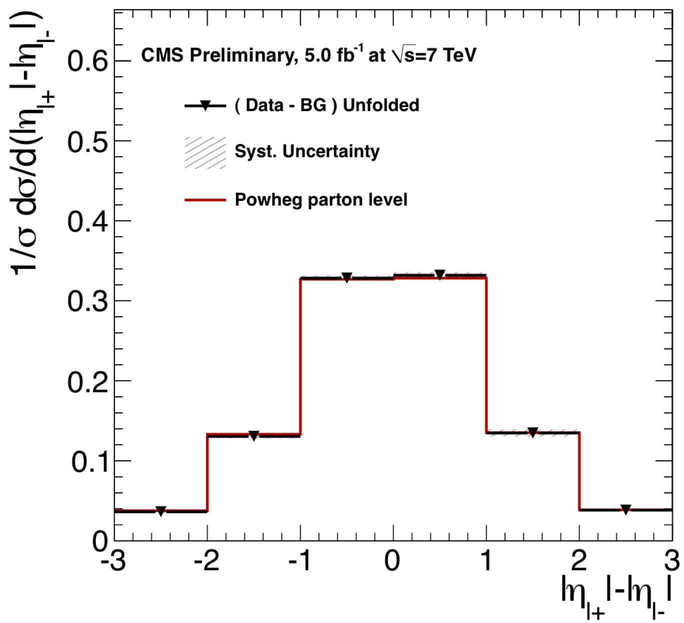
Inclusive: $A_C = 0.050 \pm 0.043\,(\text{stat.})\,^{+0.010}_{-0.039}\,(\text{syst.})$

- Alternative approach: lepton charge asymmetry

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

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

$A_{lepC} = 0.010 \pm 0.015\,(\text{stat.}) \pm 0.006\,(\text{syst.})$



Compatible with SM; more data needed !