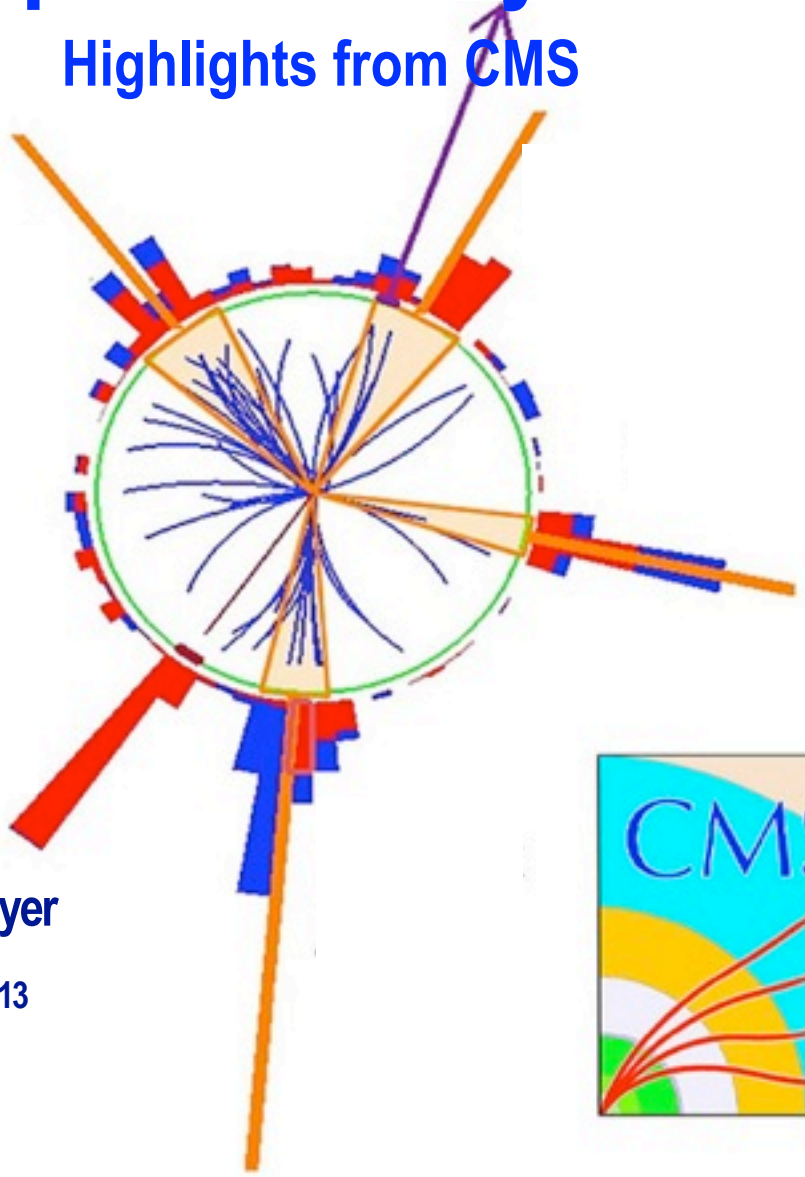
Top Quark Physics

Highlights from CMS



Andreas B. Meyer
DESY

LC2013, 28 May 2013

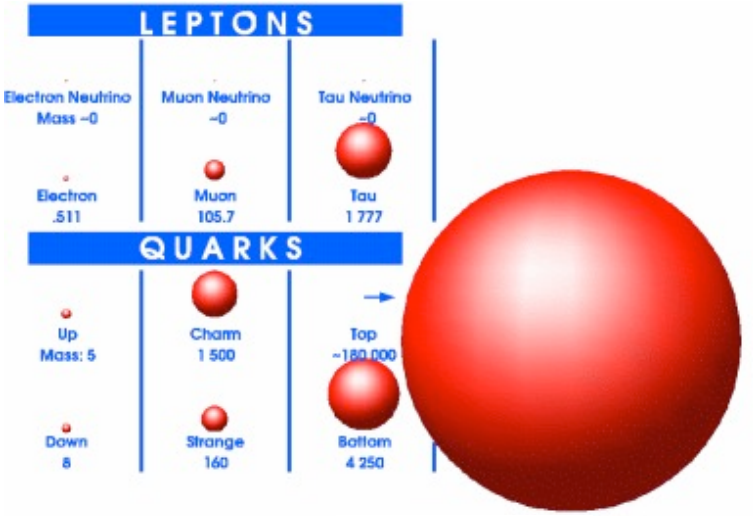
Motivation

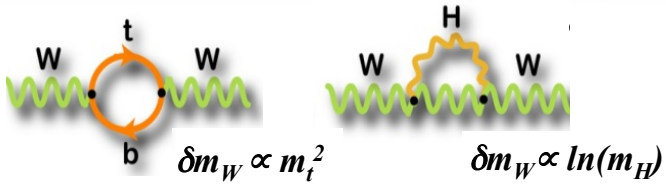
- **Top Quark is special**
  - Heaviest known particle
  - Maximum sensitivity to Higgs (EWK loops, gg ⟶ H)
  - $\tau \sim 5\times10^{-25}$ s: decay before hadronization: "bare quark"
  - Direct access to spin and charge

- **Search for New Physics**
  - New physics might preferentially couple / decay to top
  - Non-standard couplings ?

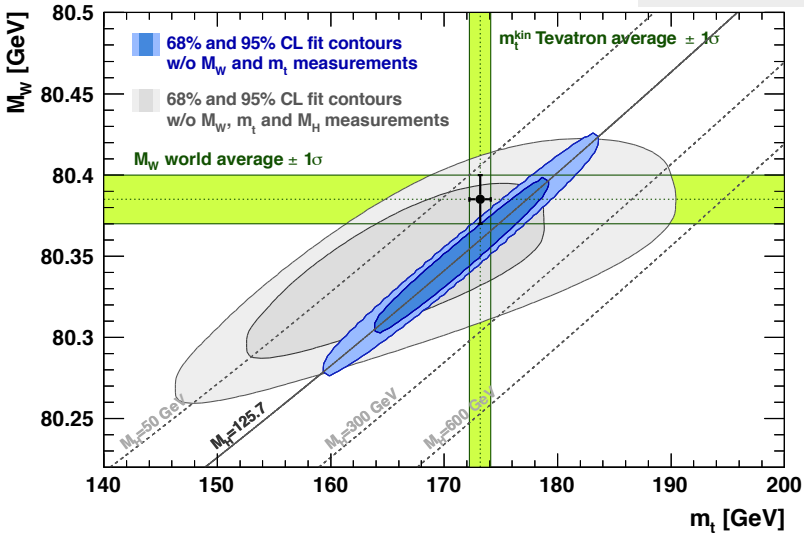
- **Precision measurements of SM parameters**
  - Total cross sections, differential distributions
  - Properties (mass, spin structure, asymmetries, V_{tb} …)

Precise top quark measurements
⟶ tighten constraints on standard model parameters
⟶ sensitivity to New Physics



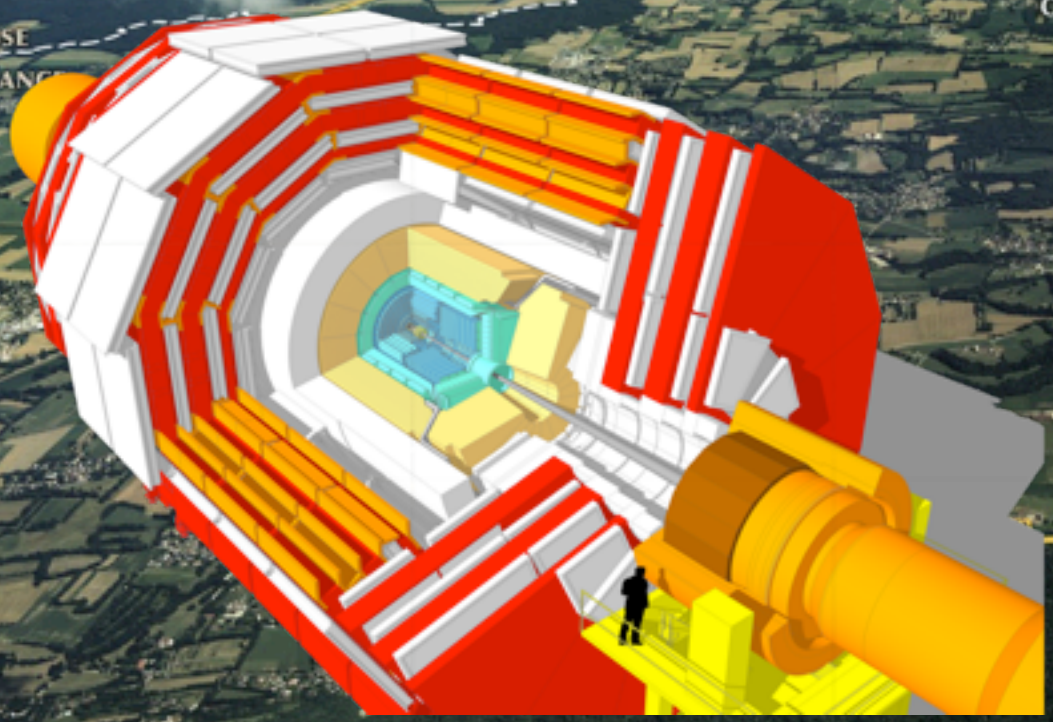


arXiv:1209.2716



The CMS Experiment at the LHC

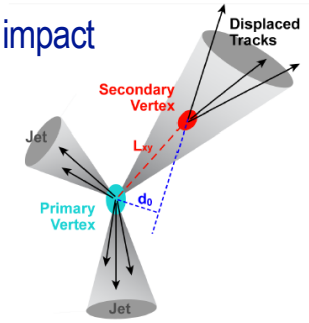
- Total Weight 14000 t
- Diameter 15 m
- Magnetic Field 3.8 T
- Silicon Pixel and Strip Trackers
- Crystal ECal, Brass HCal
- Muon Chambers, DT, RPC, CSC
- Trigger L1: 100kHz, ~500 Hz to tape



- **LHC 2010-2012: Top Quark Factory**
  - peak inst. luminosity: 8 x 10^{33} $cm^{-2}s^{-1}$
    ➔ 7000 top quark pairs per hour (8 TeV)
  - > 25 fb^{-1} recorded
    ➔ > 5,000,000 top each CMS and ATLAS

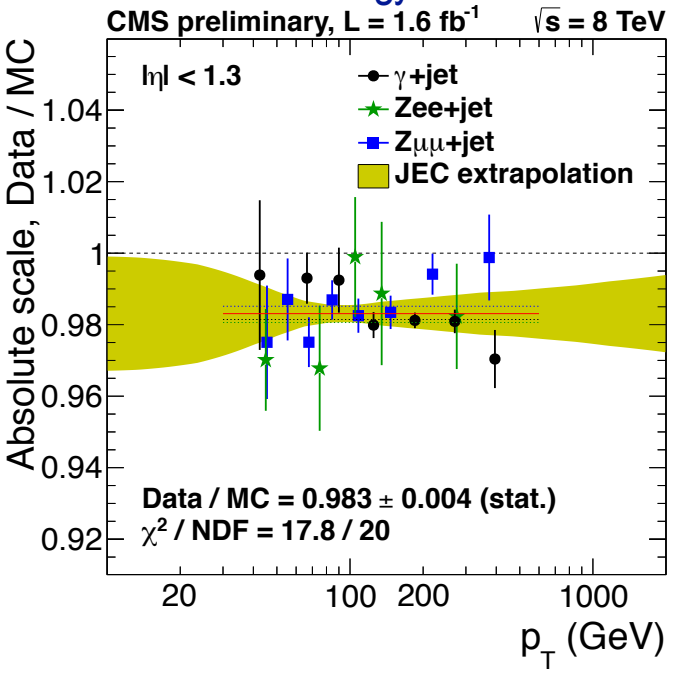
Experimental Ingredients

- **Isolated Leptons (e, μ or τ)**
  - isolation cuts against QCD backgrounds
- **Jet (and E_T^{miss})**
  - particle flow (track/calo combination)
  - optimal resolution and scale uncertainties,
  - minimal flavour response differences
- **Pile-up subtraction**
  - based on charged component
- **b-tagging**
  - combination of several techniques (vertex, impact parameter, track distributions within jets)



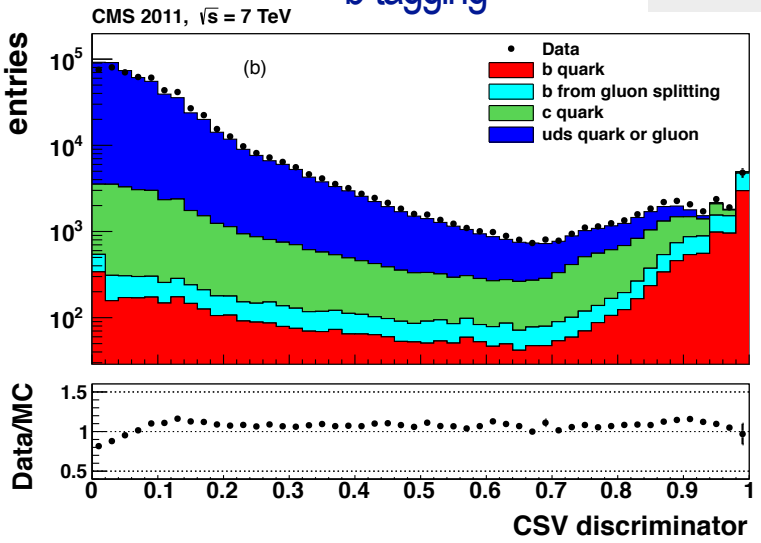
CMS-DP-2012/012

Jet energy scale

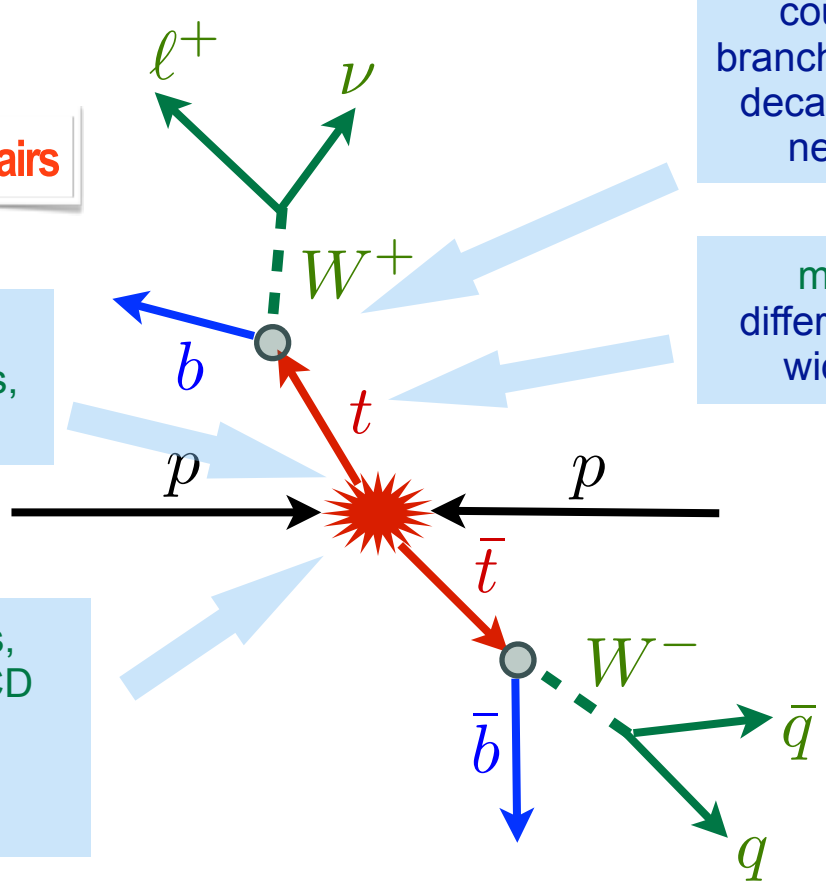


b-tagging

BTV-12-001



Top Quark Properties in Production and Decay



Top Quark Pairs

couplings, V_{tb}, branching ratios, rare decays, W-helicity, new particles

mass, mass difference, charge, width, lifetime

asymmetries, spin correlations, color flow

cross sections, kinematics, QCD parameters, resonances, new particles

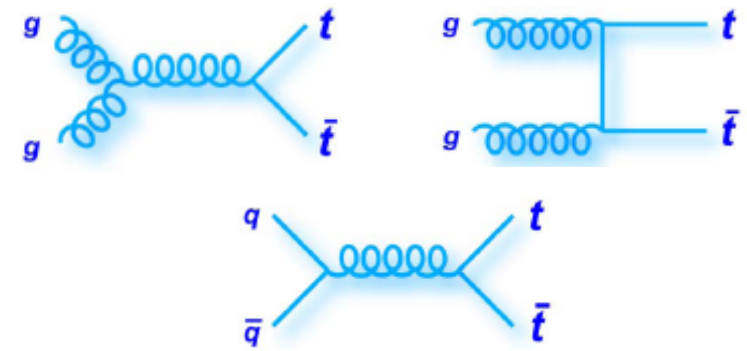
- **Production**
- **Properties**
- **Single Top**

EWK Single-Top Production

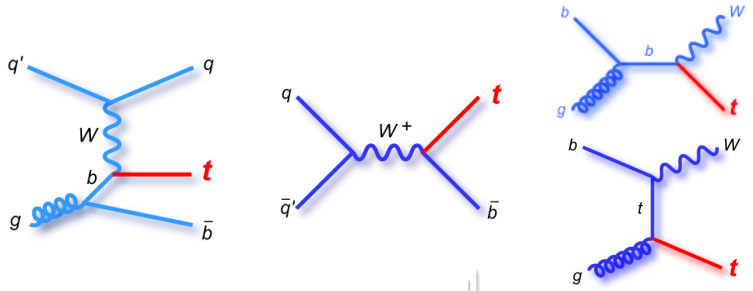
cross sections properties, couplings, QCD parameters

Top Quark Production

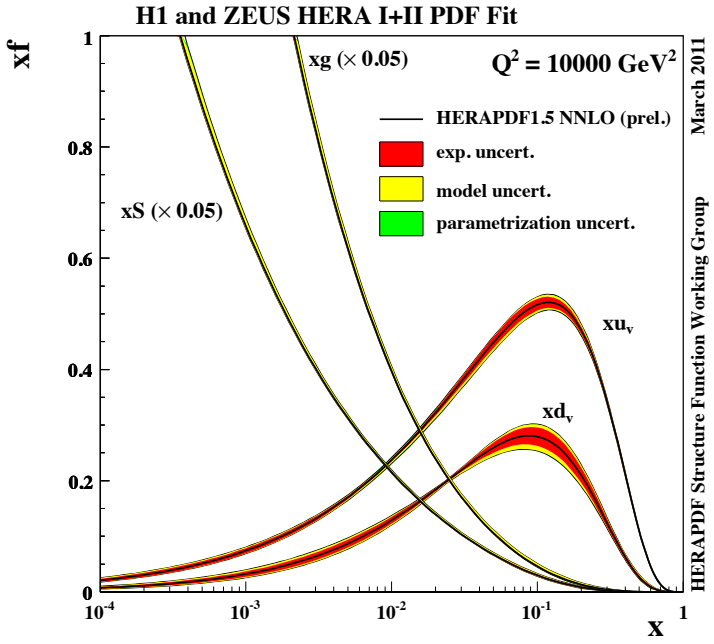
Top Quark Pairs



EWK Single-Top Production



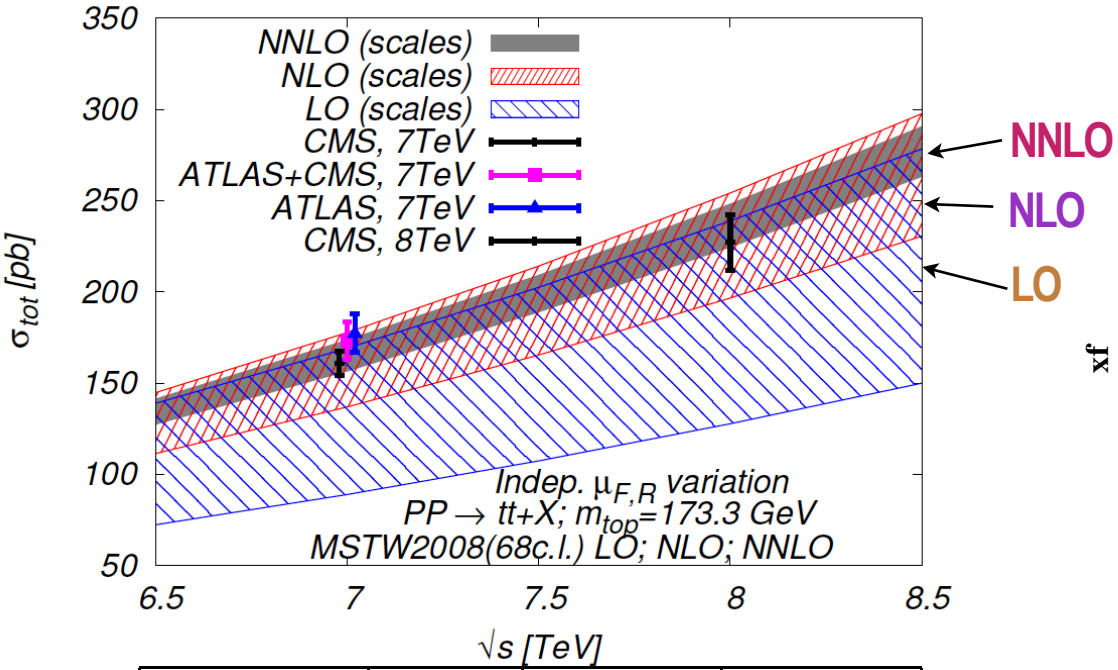
	LHC (7TeV)	Tevatron
gg	~80%	~15%
$q\bar{q}$	~20%	~85%



LHC (gg→tt) and Tevatron ($q\bar{q}$→tt): complementary production

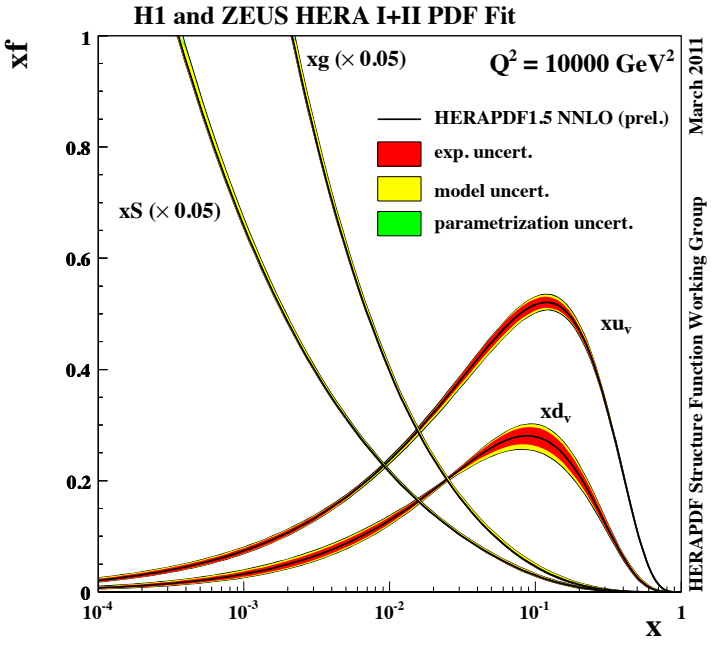
Top Quark Pair Production

Czakon, Fiedler, Mitov 1303.6254 [hep-ph]



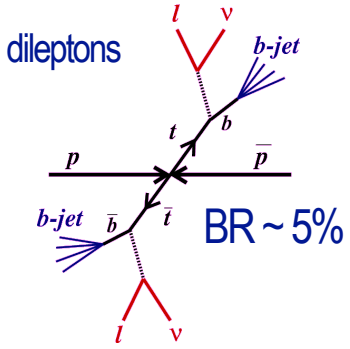
Collider	$\sigma_{\rm tot}$ [pb]	scales [pb]	pdf [pb]
Tevatron	7.164	$^{+0.110(1.5\%)}_{-0.200(2.8\%)}$	$^{+0.169(2.4\%)}_{-0.122(1.7\%)}$
LHC 7 TeV	172.0	$^{+4.4(2.6\%)}_{-5.8(3.4\%)}$	$^{+4.7(2.7\%)}_{-4.8(2.8\%)}$
LHC 8 TeV	245.8	$^{+6.2(2.5\%)}_{-8.4(3.4\%)}$	$^{+6.2(2.5\%)}_{-6.4(2.6\%)}$
LHC 14 TeV	953.6	$^{+22.7(2.4\%)}_{-33.9(3.6\%)}$	$^{+16.2(1.7\%)}_{-17.8(1.9\%)}$

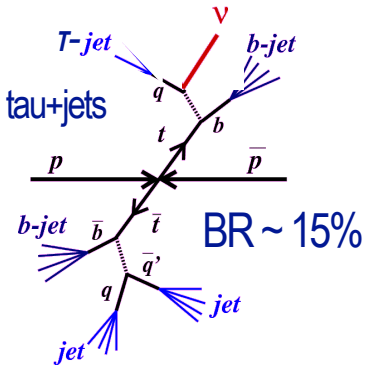
	LHC (7TeV)	Tevatron
gg	~80%	~15%
$q\bar{q}$	~20%	~85%

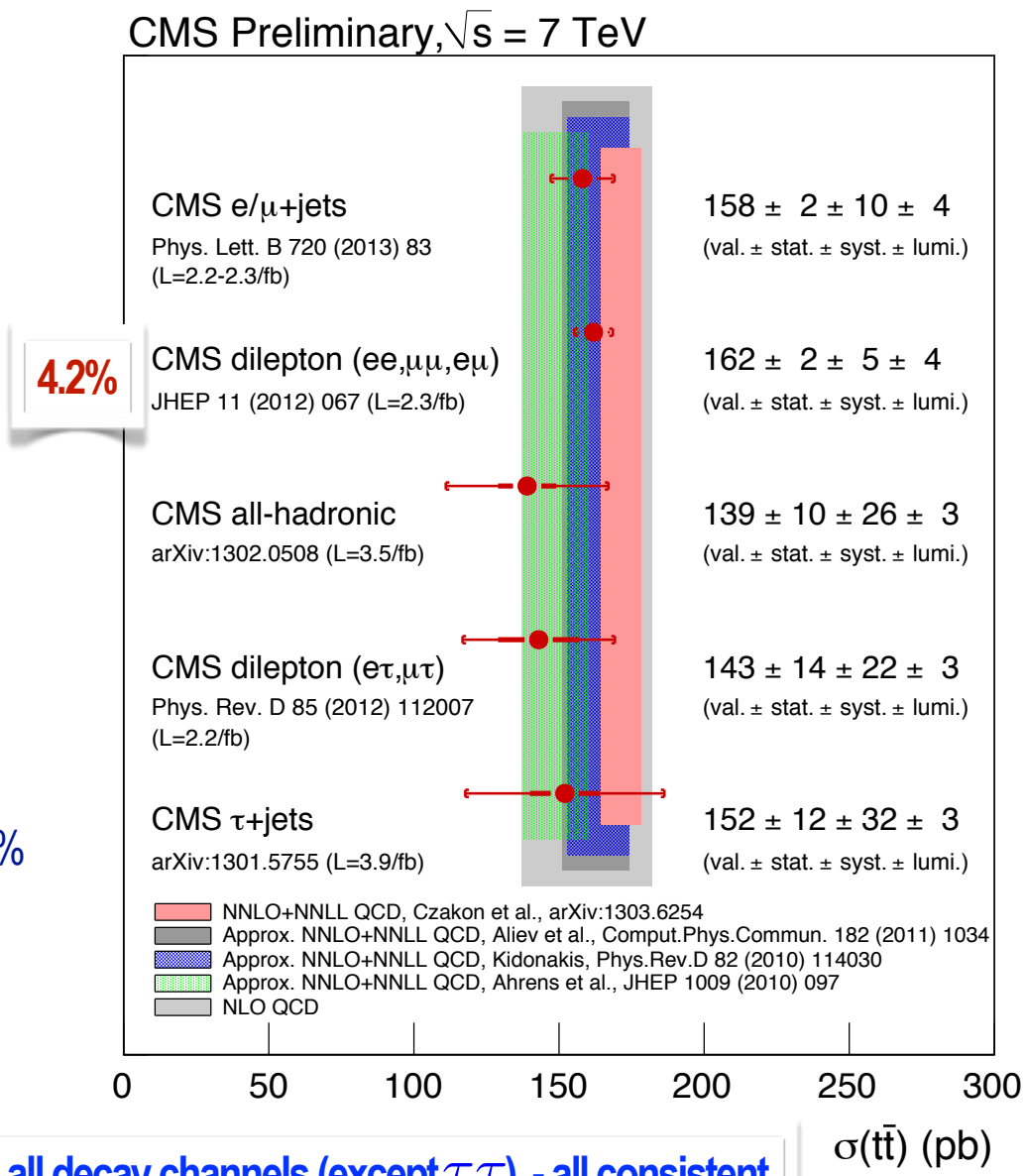


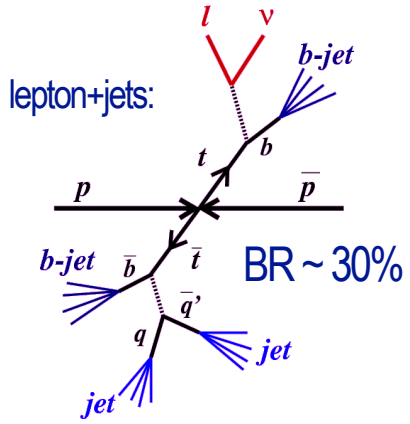
full NNLO available since very recently - scale and pdf uncertainties 2-3%

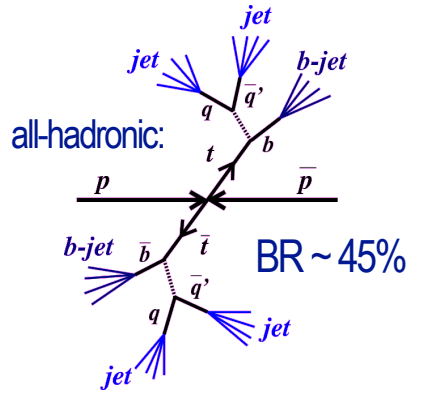
Total $t\bar{t}$ Cross Section at 7 TeV











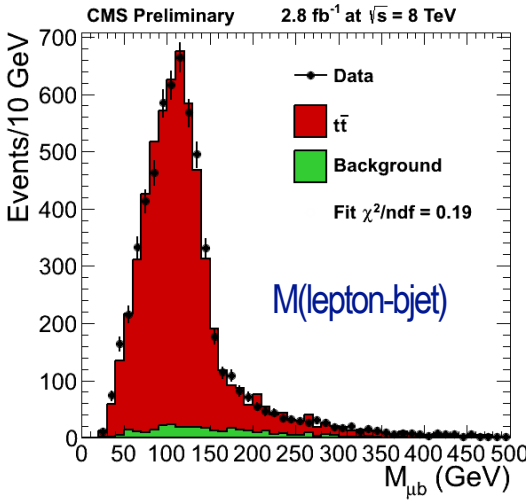
$t\bar{t}$ measured in all decay channels (except $\tau\tau$) - all consistent

Total $t\bar{t}$ Cross Section at 8 TeV

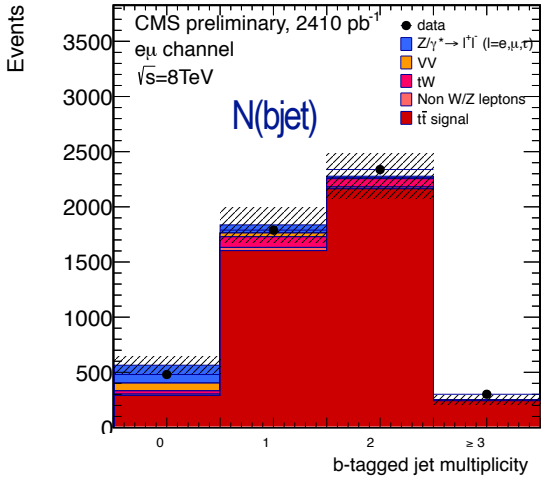
2.4/2.8 fb^{-1}

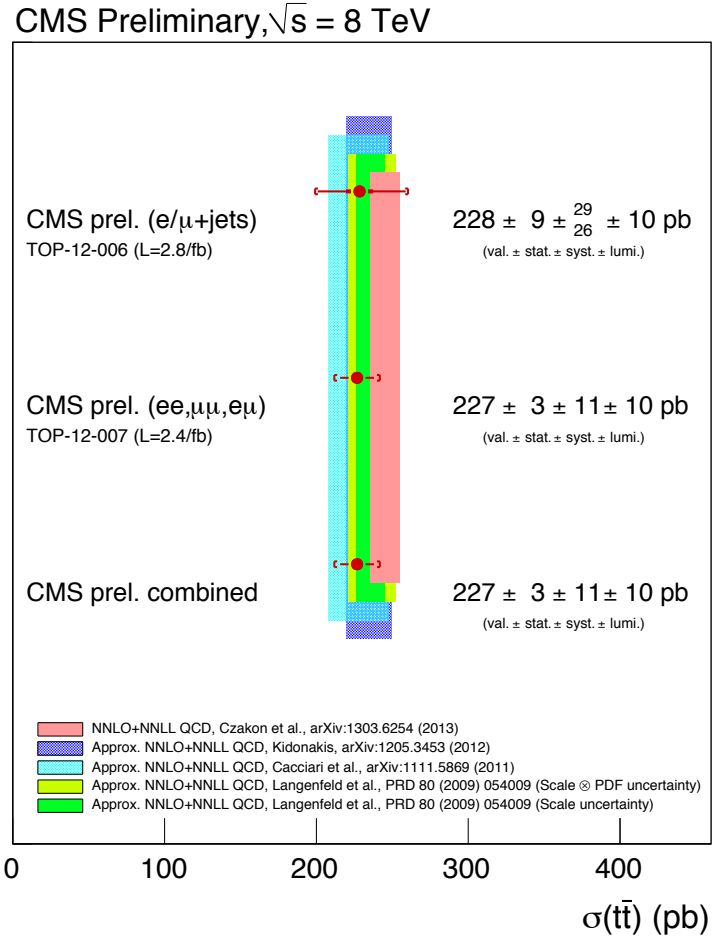
TOP-12-006
TOP-12-007

- **e/μ+jets channel**
  - Template fit to M_{lb}
  - QCD bg shape from data
  - Systematics:
    - b-tagging
    - jet-energy scale



- **dilepton channel**
  - Cut-and-count
  - High purity, high statistics
  - Systematics:
    - lepton-ID
    - jet-energy scale



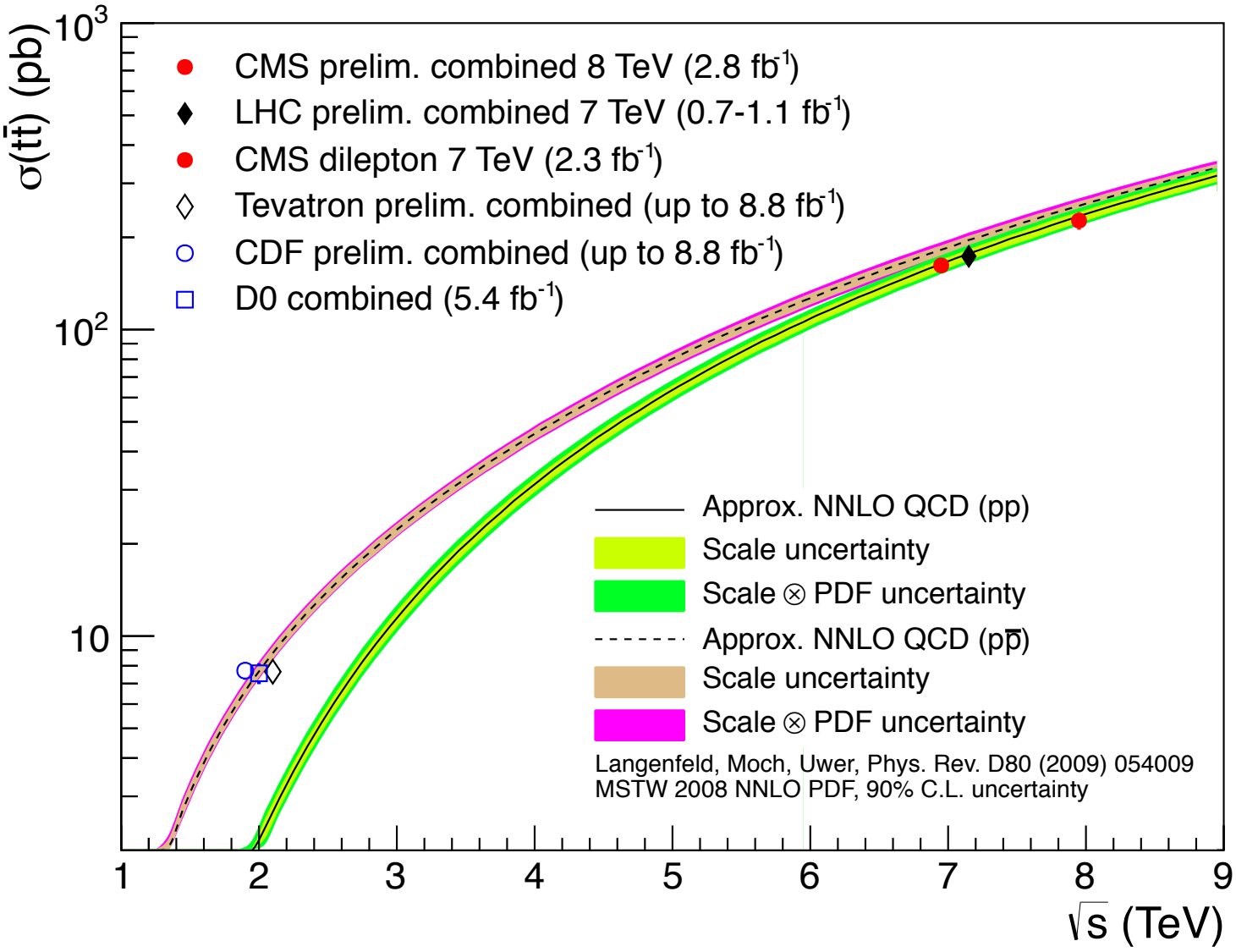


$$\frac{\sigma_{t\bar{t}}(8\ \mathrm{TeV})}{\sigma_{t\bar{t}}(7\ \mathrm{TeV})} = 1.41 \pm 0.11$$

$\sigma_{tt} = 227 \pm 3_{stat} \pm 11_{syst} \pm 10_{lumi}$ pb

6.6%

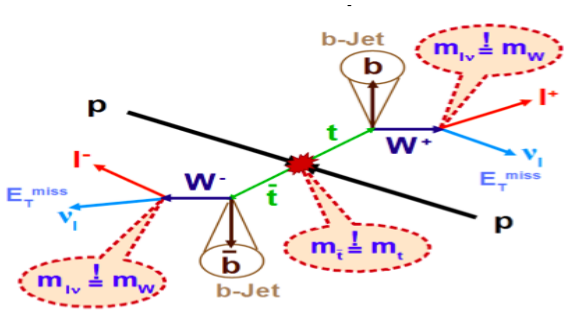
Total $t\bar{t}$ Cross Section



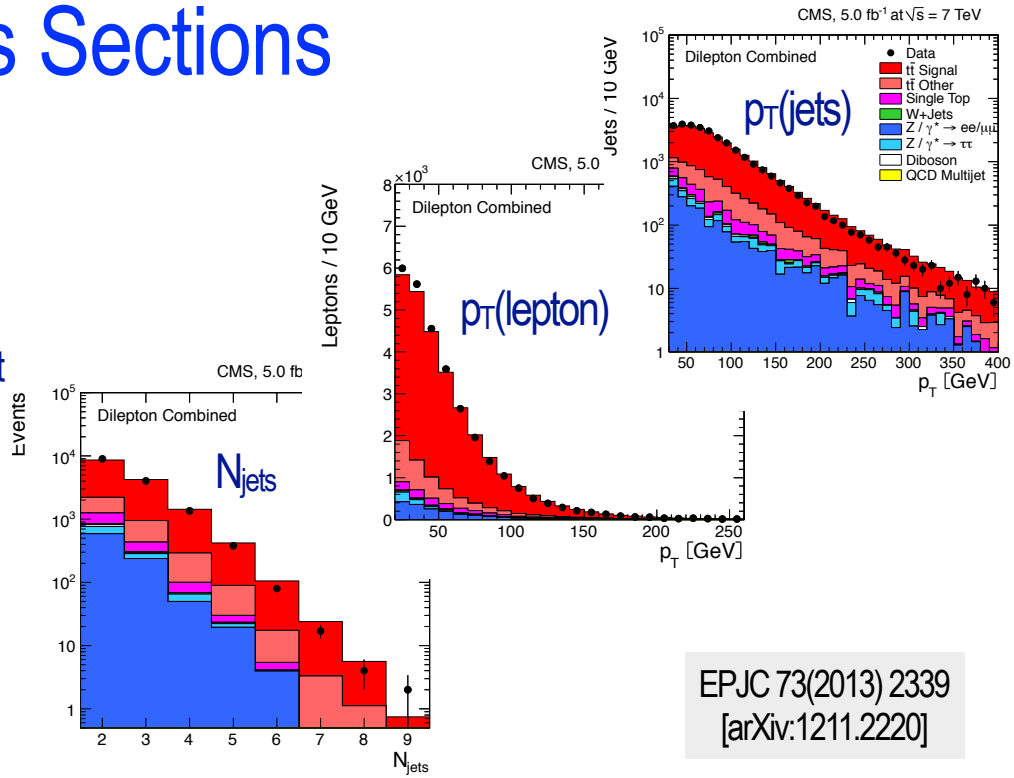
Differential $t\bar{t}$ Cross Sections

- **Measure top quark kinematic distributions**
  - Scrutinize theory predictions and models
  - Ensure that acceptances, efficiencies are correct
  - Enhance sensitivity to new physics
  - Extract / use for PDF-fits (future)

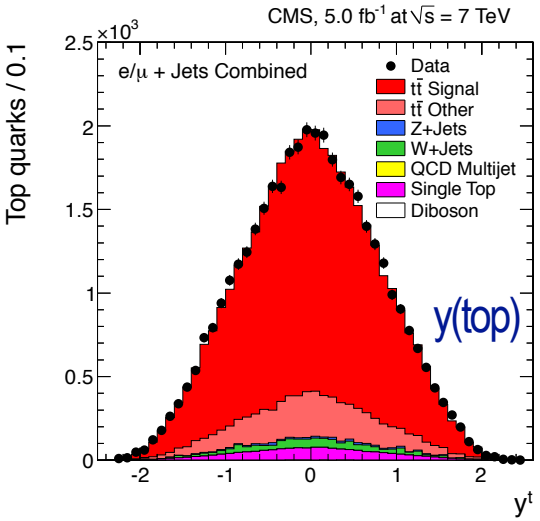
- **Main analysis ingredients:**
  - Kinematic reconstruction

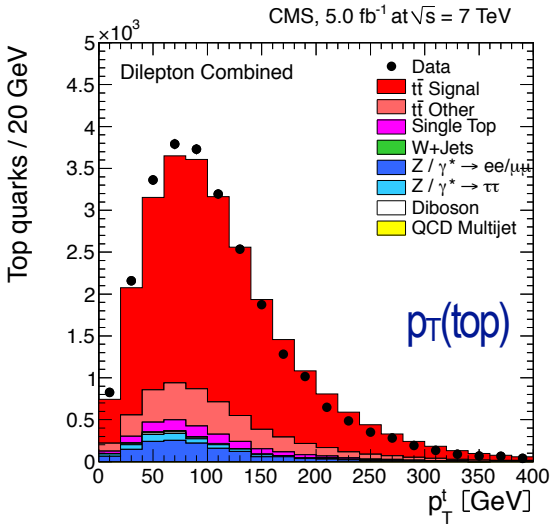


  - Bin-wise cross section analysis
  - Regularized unfolding



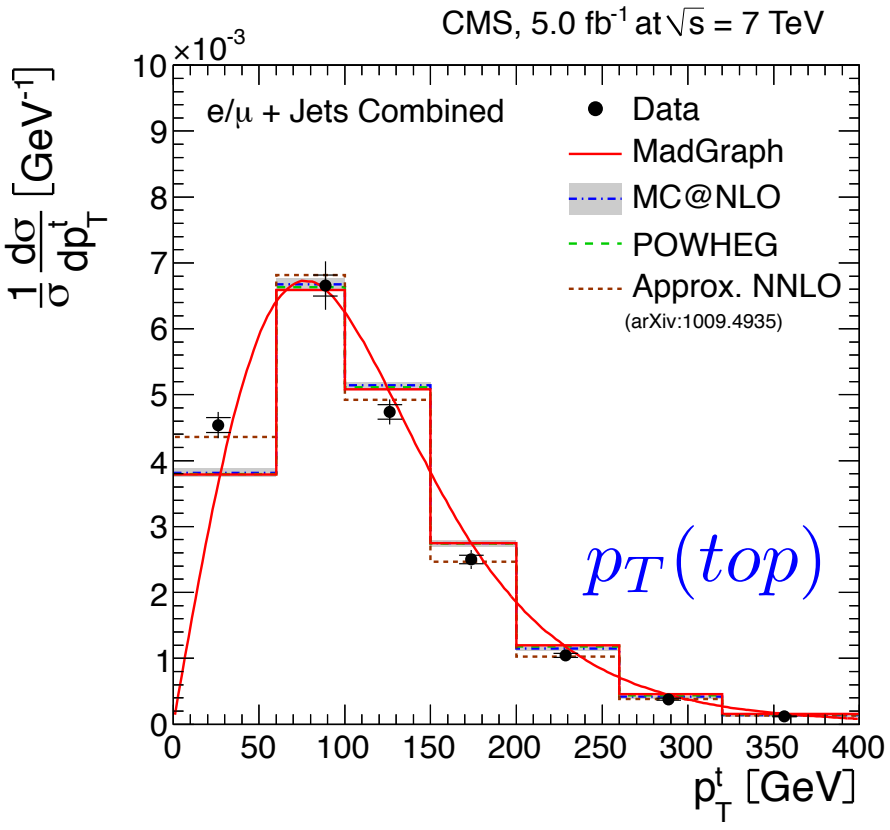
EPJC 73(2013) 2339
[arXiv:1211.2220]

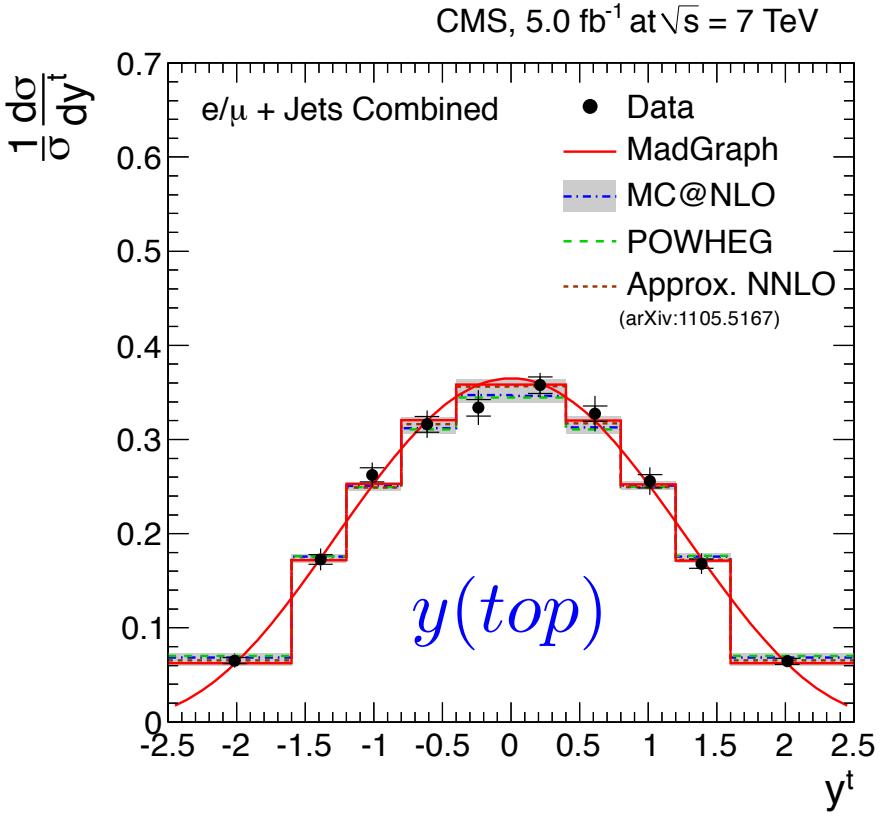




Top Quark Distributions at 7 TeV

EPJC 73(2013) 2339
[arXiv:1211.2220]

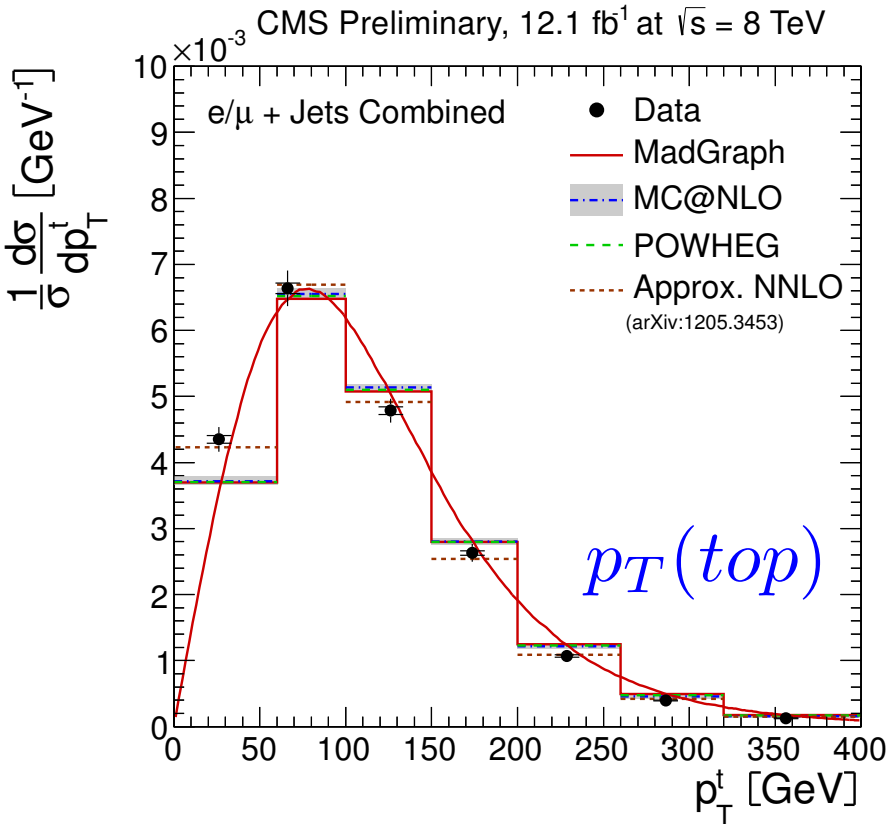


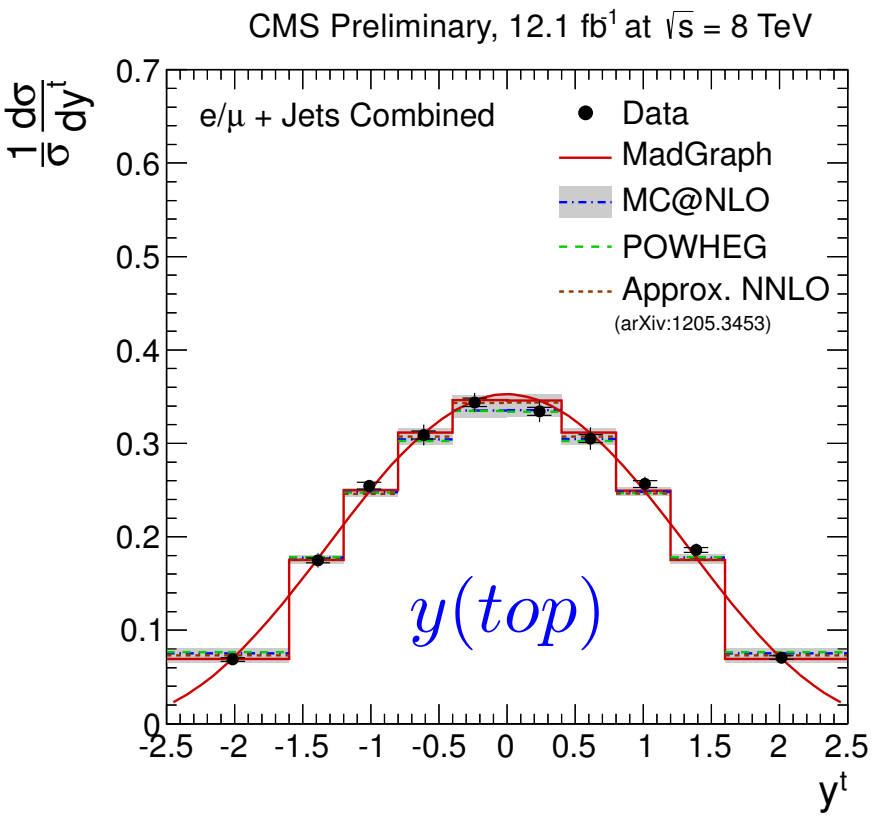


Generally good description by all predictions - approx. NNLO better than MC (NLO and multi-leg)

Top Quark Distributions at 8 TeV

CMS-12-027
CMS-12-028

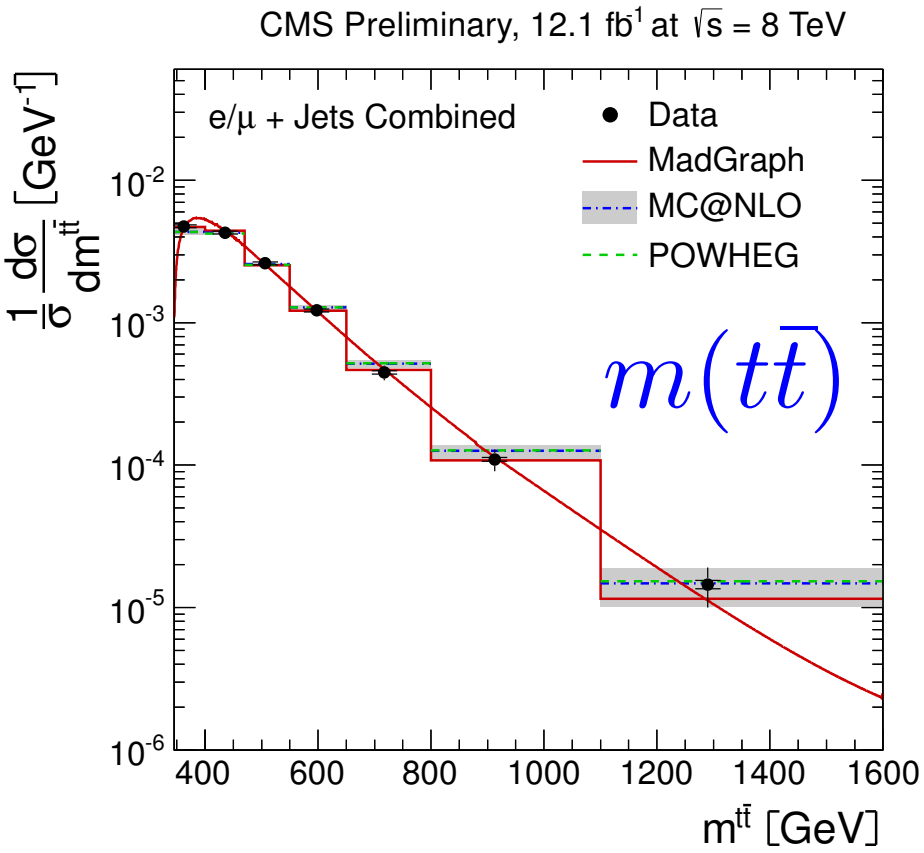




Generally good description by all predictions - approx. NNLO better than MC (NLO and multi-leg)

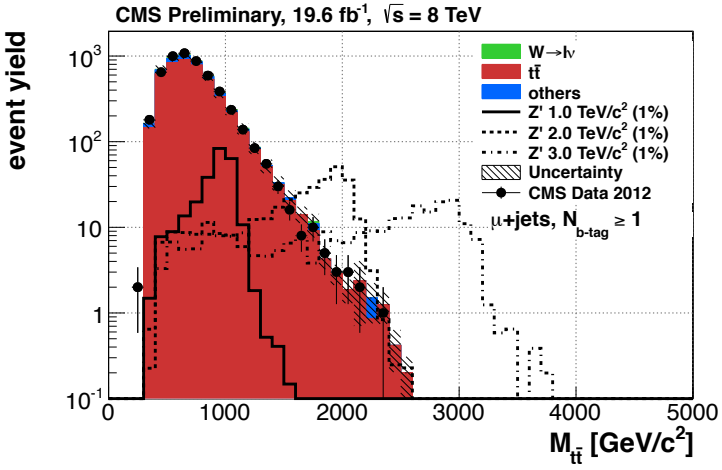
Top Quark Pair Distributions

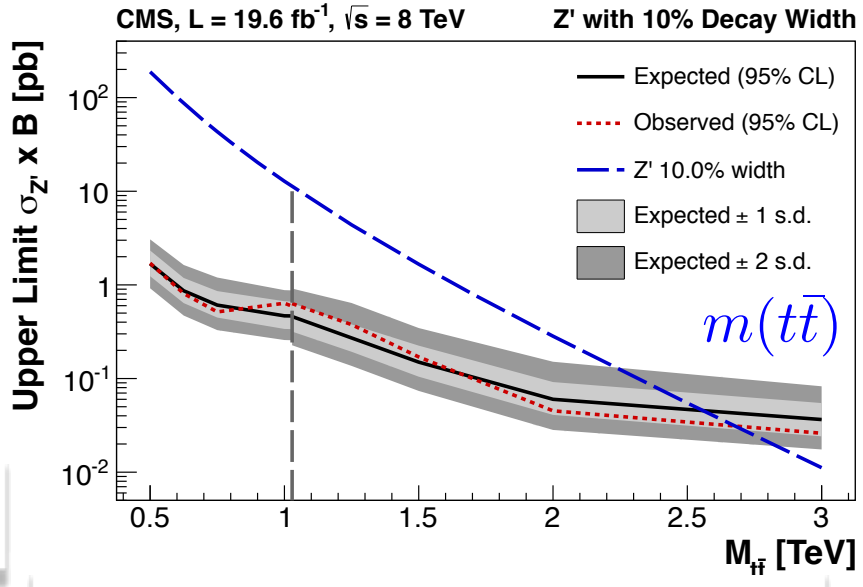
CMS-12-027
CMS-12-028



high m_{tt}: increasing theory uncs. due to PDF

CMS B2G-12-006



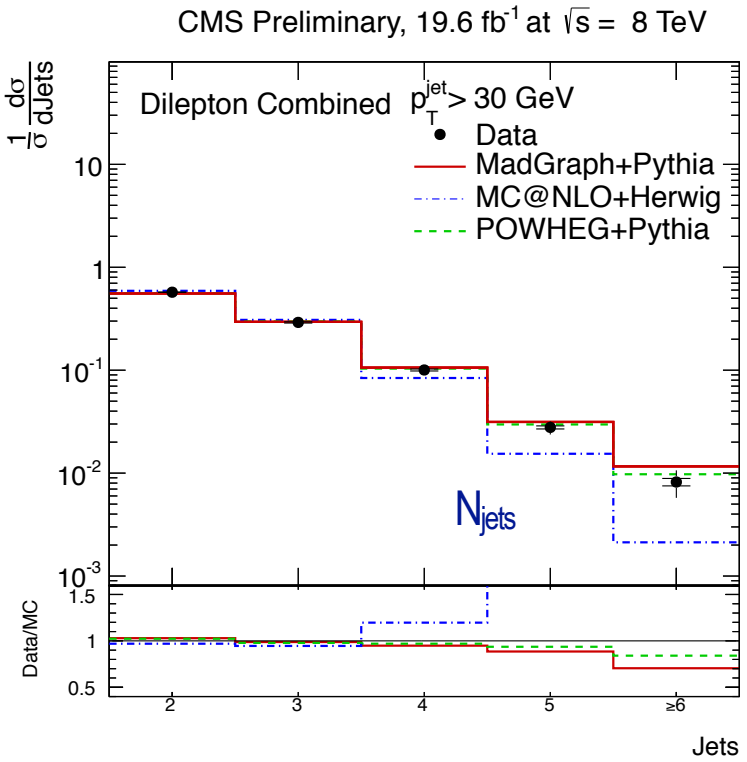


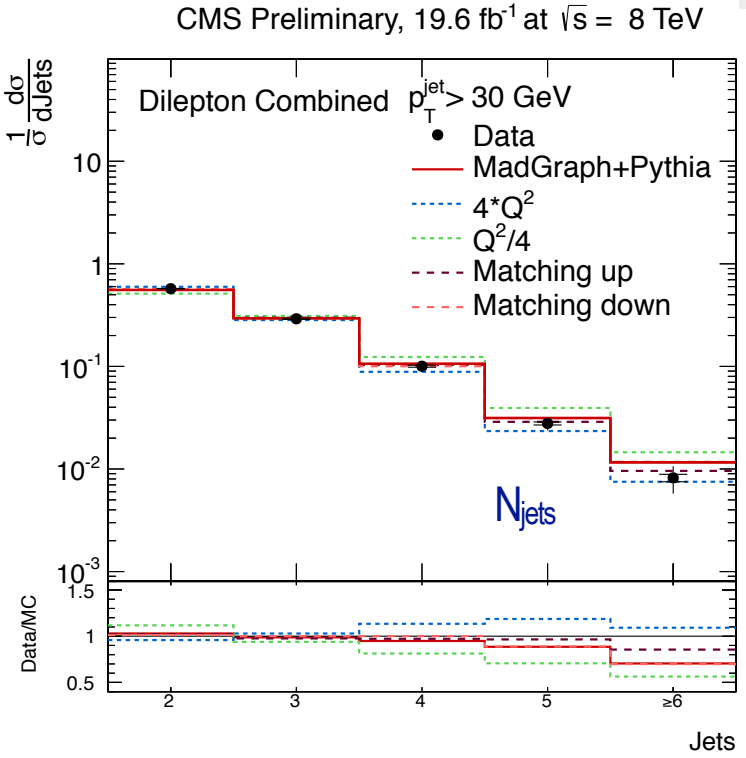
(resonant or non-resonant) new physics ?
Z' → tt typically excluded up to 2.5 TeV

$t\bar{t}$+jets

Differential cross section as function of jet multiplicity

TOP-12-018
TOP-12-023
TOP-12-041





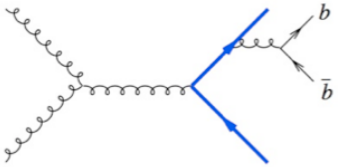
- Also measured (not shown here):
  - Jet Veto distributions
  - Distributions of 1st and 2nd additional jets

test of event generators, final state model and QCD scales

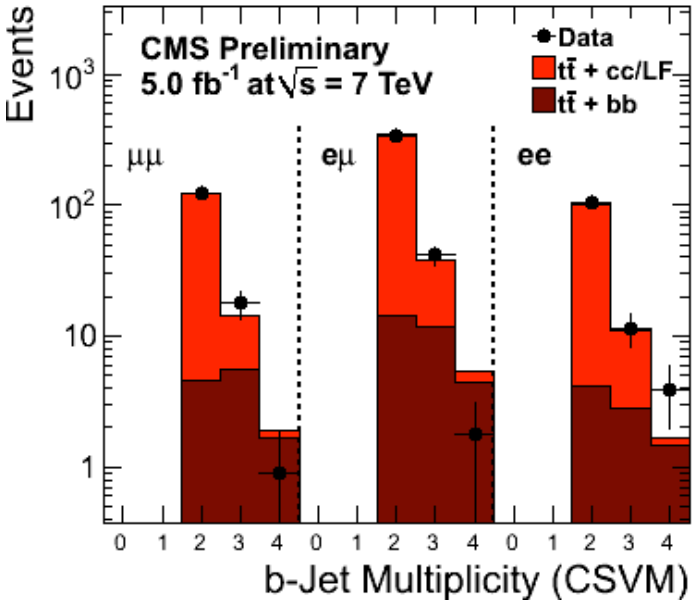
$t\bar{t}$+bb and $t\bar{t}$H

- **tt+bb**
  - Dilepton Channel
- **Analysis**
  - Fit to b-tag multiplicity
- **Dominant Uncertainty**
  - fake b-fraction
- **MC predictions ttbb/ttjj:**
  - 1.2% (MADGRAPH), 1.3% (POWHEG)

ttbb: first measurement available



TOP-12-024

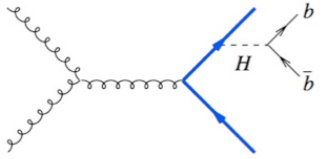


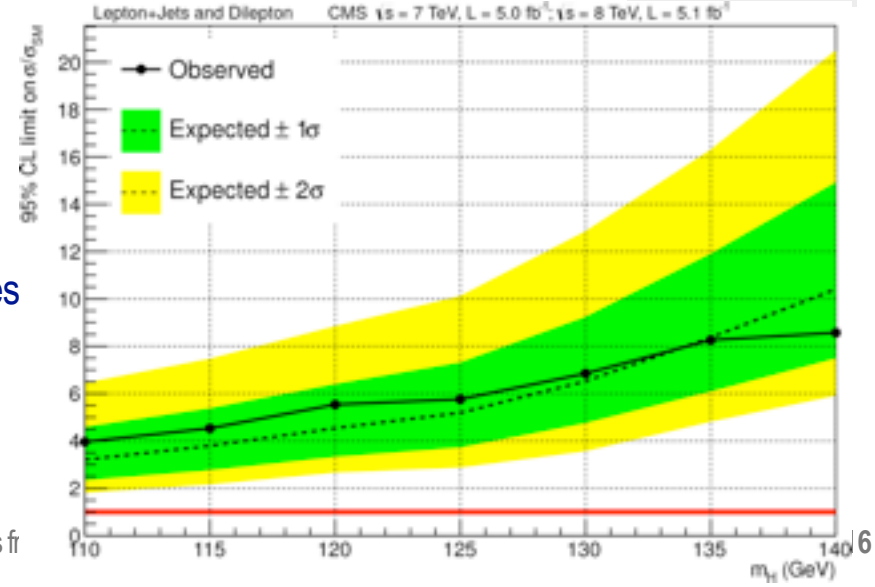
$$\frac{\sigma(t\bar{t}b\bar{b})}{\sigma(t\bar{t}jj)} = 3.6 \pm 1.1_{stat} \pm 0.9_{syst}\%$$

arXiv:1303.0763

- **tt-Higgs**
  - tt enriched sample
  - Neural Network using variables in jet and b-tag categories

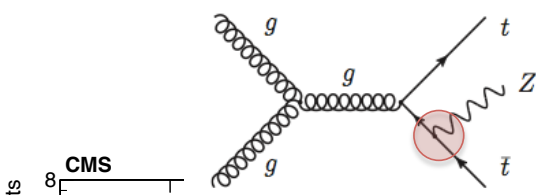
ttH limits based on 5+5 fb^{-1}(2011+2012)

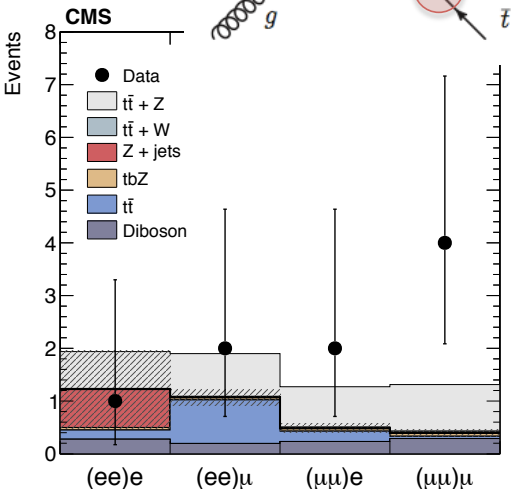


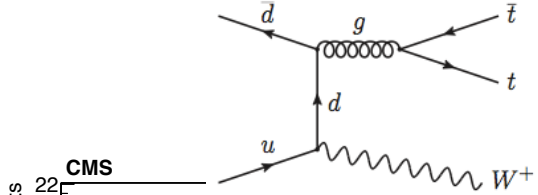


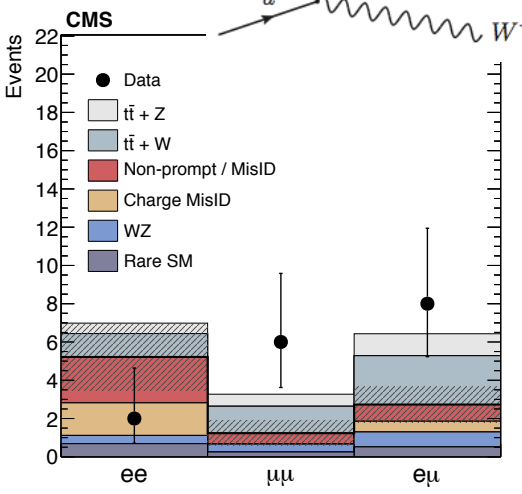
ttZ and ttW

- **3-Lepton Analysis**
  - 1 lepton (e or μ) from tt
  - 2 opposite-charge same-flavour from Z
  - 3 jets, 2 b-tags, H_T>120 GeV
- **2-Lepton Analysis**
  - 1 lepton from tt
  - 1 lepton from W (same-charge to remove tt dilepton and DY)
  - 3 jets, 1 b-tag, H_T>100 GeV
  - contamination from ttZ due to detector acceptance





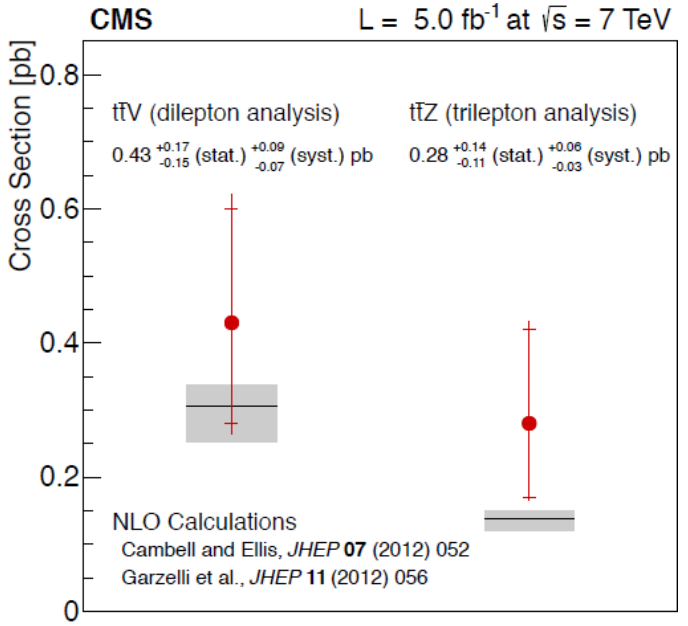




PRL 110 (2013) 172002
[arXiv: 1303.3239]

ttV signal established at 4.7σ
first measurement of ttZ
rate consistent with SM

$\sigma_{ttZ} = 0.28\ ^{+0.14}_{-0.11}\,_{stat}\ ^{+0.06}_{-0.03}\,_{syst}$ pb



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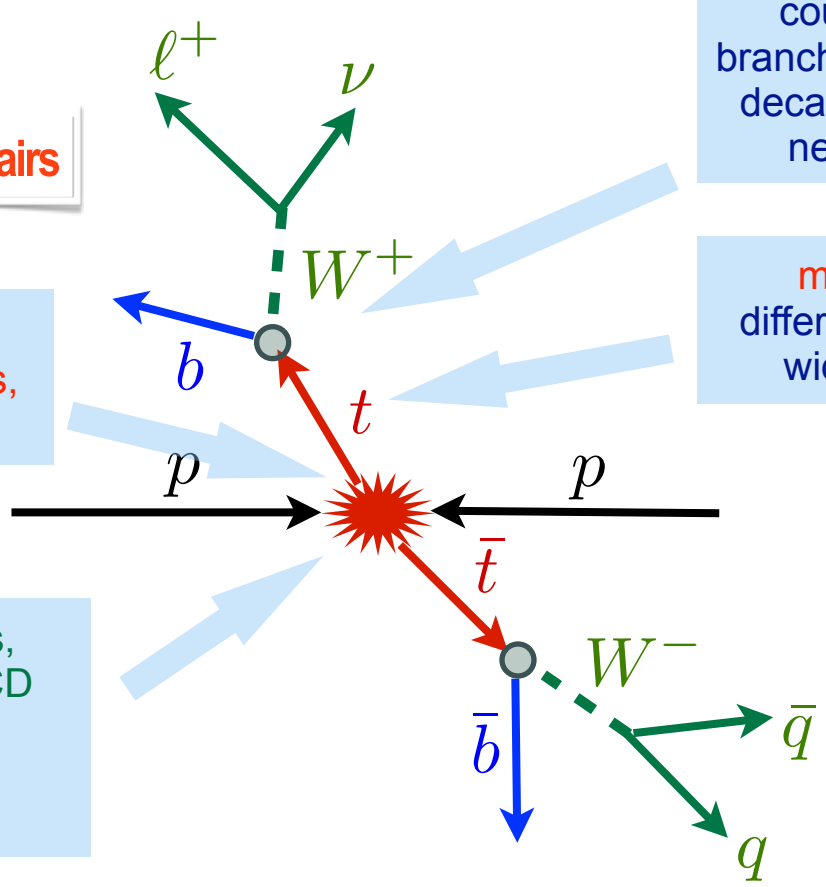


Top Quark Pairs

couplings, V_{tb}, branching ratios, rare decays, W-helicity, new particles

mass, mass difference, charge, width, lifetime

asymmetries, spin correlations, color flow

cross sections, kinematics, QCD parameters, resonances, new particles

- **Production**
- **Properties**
- **Single Top**

EWK Single-Top Production

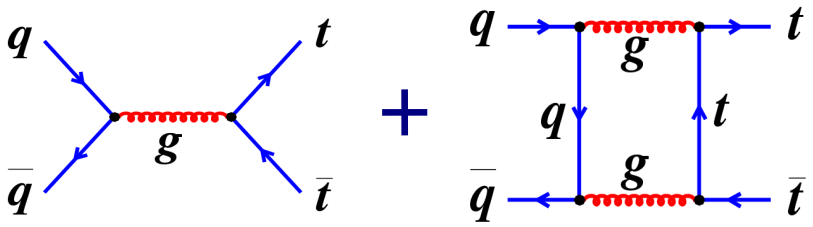
cross sections properties, couplings, QCD parameters

FB and Charge-Asymmetry

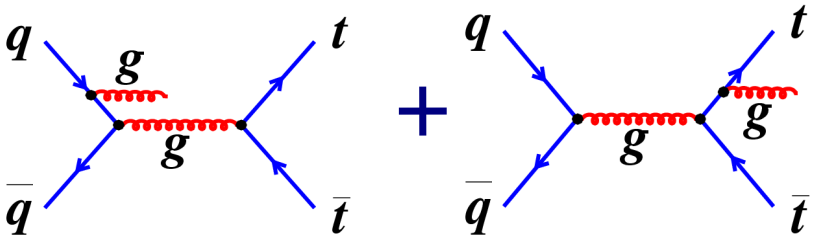
- Contribution from qq̄ only
- LO: No charge asymmetry expected
- NLO: Interference between qq̄ diagrams
  - diluted at LHC due to large gg

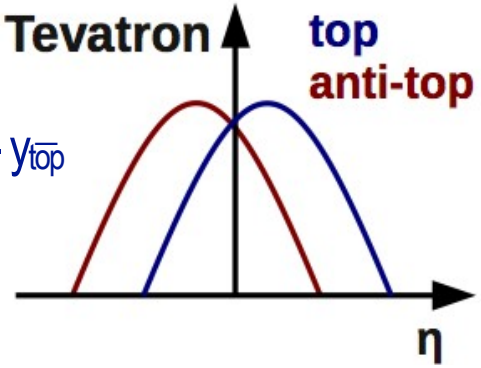
All available asymmetry calculations are effectively leading order

tree-level and box diagrams: positive asymmetry



ISR/FSR: negative asymmetry

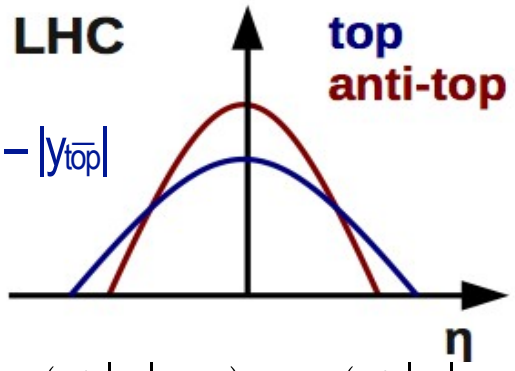




$\Delta y = y_{top} - y_{\bar{top}}$

A_{FB}

$$A_{FB}^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$



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

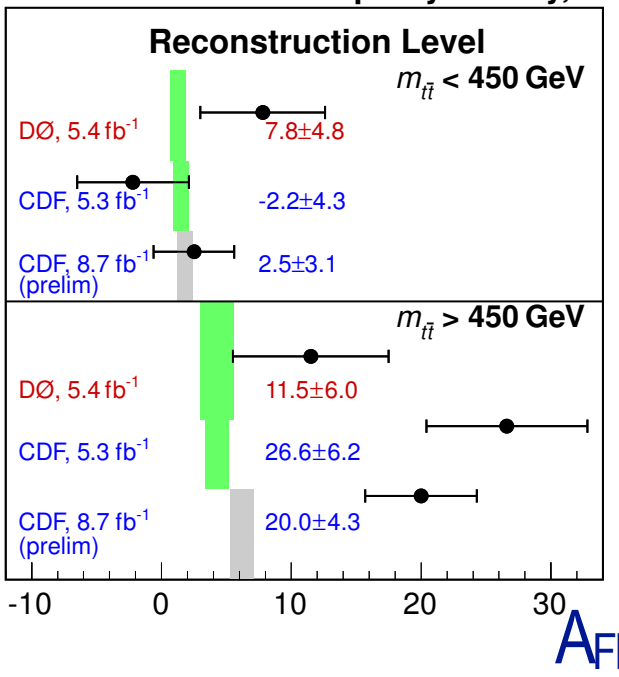
A_C

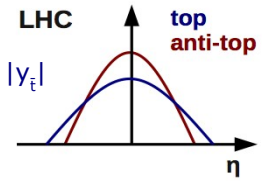
$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

FB vs. Charge-Asymmetry

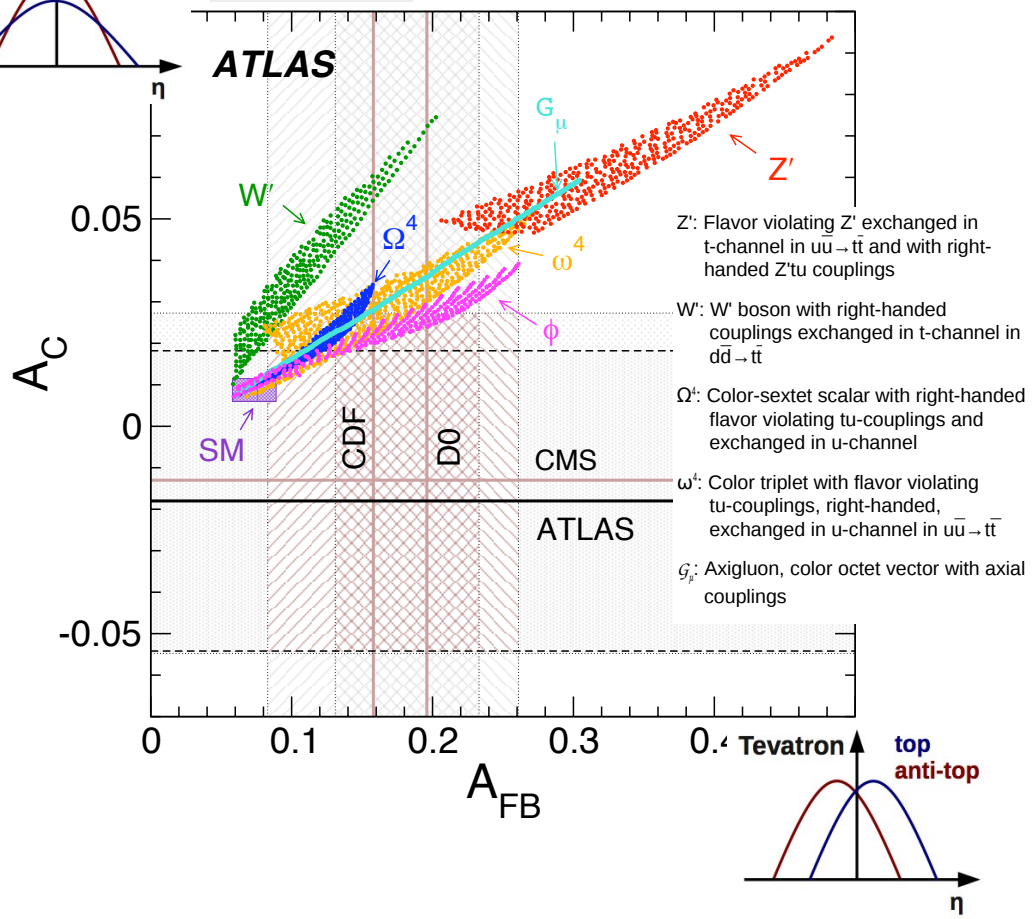
CDF 10807

arXiv:1207.0364





arXiv:1203.4211



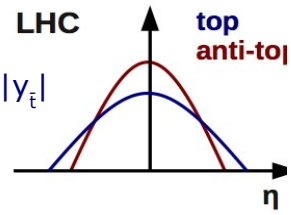
FB-asymmetry at Tevatron:
CDF: ~3 σ excess for m_{tt} > 450 GeV

Combination of Tevatron and LHC (1 fb^{-1}):
Several New Physics models disfavoured

Charge-Asymmetry

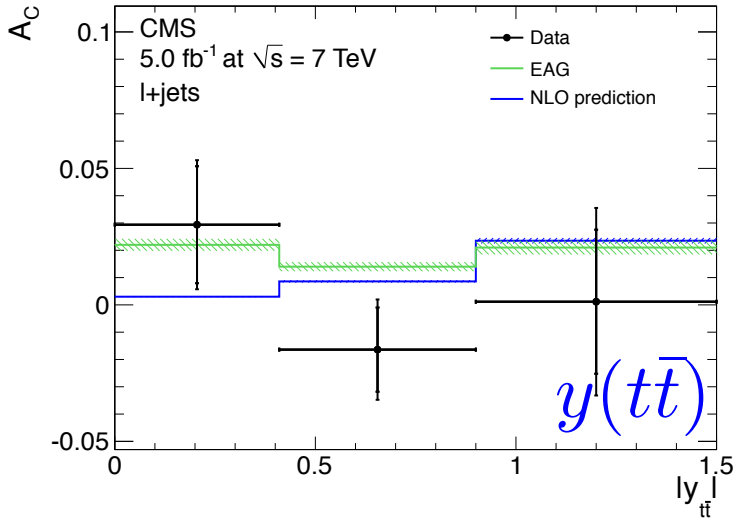
PLB 717 (2012) 129
[arXiv:1207.0065]

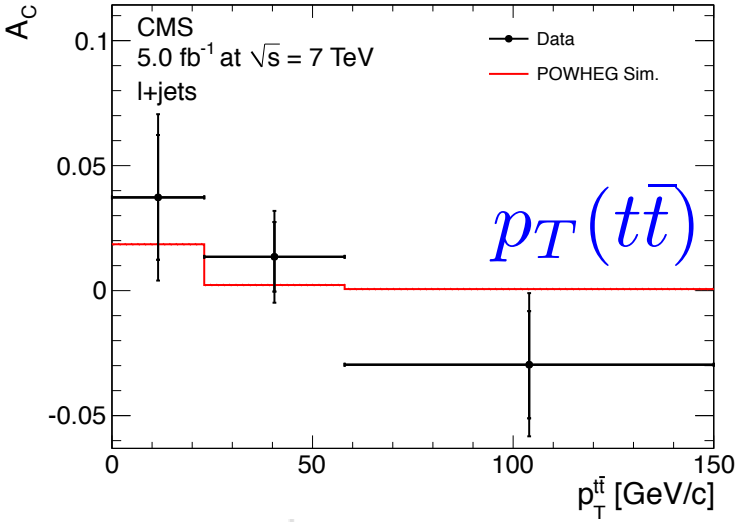
- **Measure kinematic dependency**



$A_{C,top} = 0.004 \pm 0.010_{stat} \pm 0.012_{syst}$

QCD: $A_{C,top} = 0.012 \pm 0.001$ Kühn, Rodrigo arXiv:1209.6830

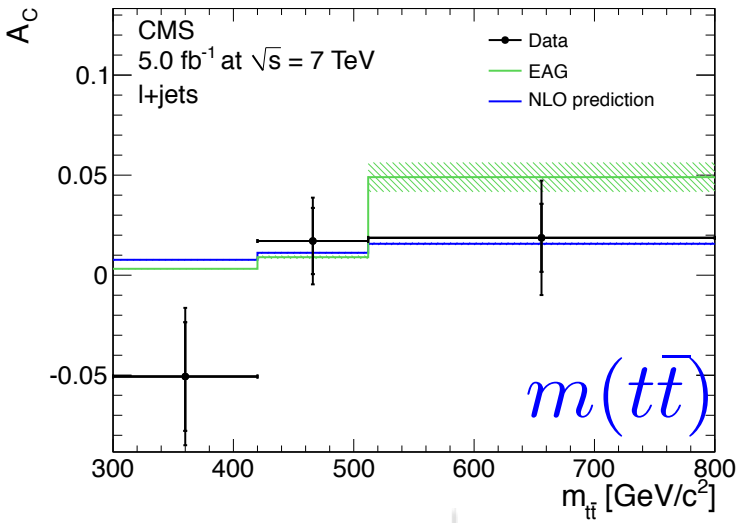




Green:
effective axial-vector
coupling of gluon (EAG)

Blue:
NLO QCD

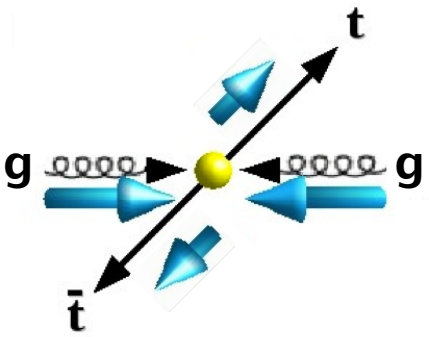
Red
POWHEG



No significant deviation from QCD prediction - more statistics needed

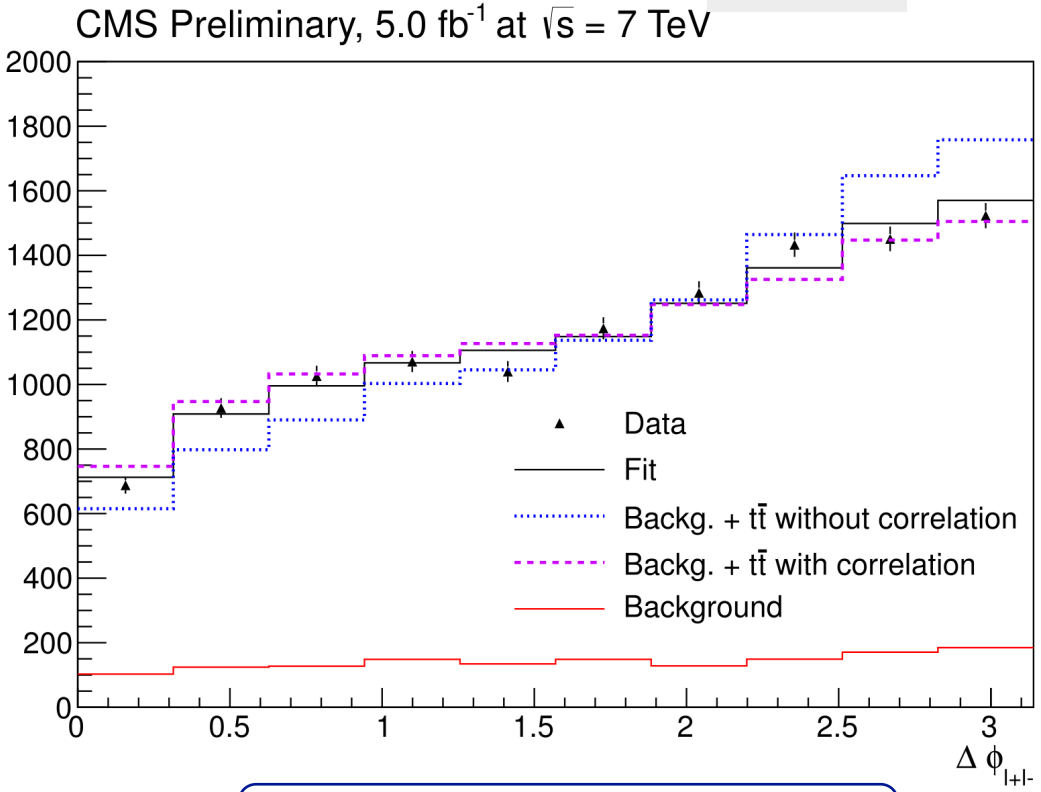
Spin Correlations

TOP-12-004 5.0 fb^{-1}



$$A = \frac{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} - N_{\uparrow\downarrow} - N_{\downarrow\uparrow}}{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} + N_{\uparrow\downarrow} + N_{\downarrow\uparrow}}$$

Top quarks decay before hadronization: spin information in decay products



$A_{helicity} = 0.24 \pm 0.02_{stat} \pm 0.08_{syst}$

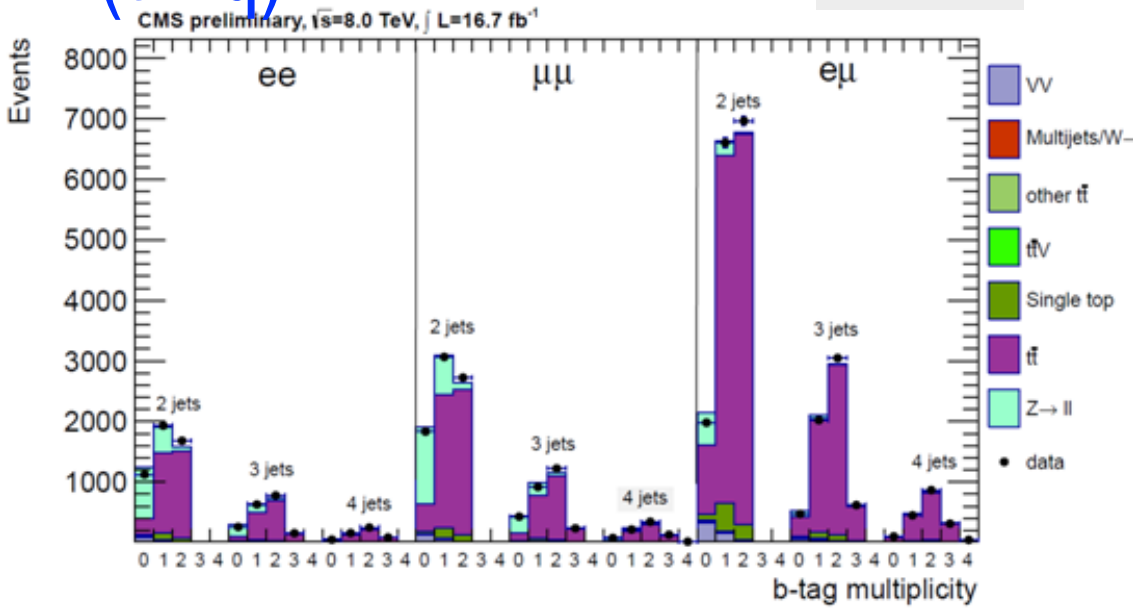
- Measure spin correlation (asymmetry in helicity basis) from Δφ of leptons in dilepton channel
- SM prediction: $A_{helicity} = 0.31$ Bernreuther et al, Nucl.Phys B837, 90 (2010) Mahlon, Parke, PRD D81, 074024 (2010)

data in agreement with QCD-production of spin-½ tops

R = BR (tWb) / BR (tWq)

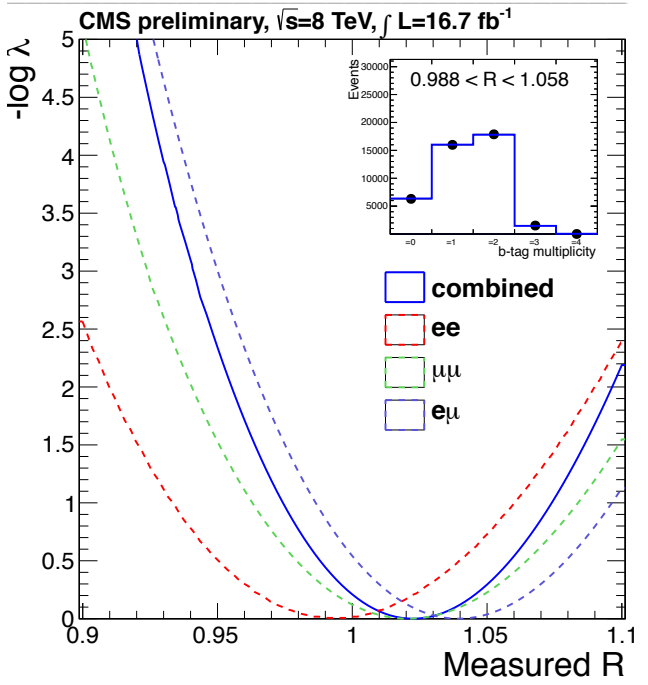
TOP-12-035

- **dilepton channel**
  - 2 leptons, 2 jets, MET
- **extract R from profile likelihood to b-tag multiplicity distribution**
  - including signal and background
  - correct jet assignment
  - b-tag efficiency and misidentification
- **V_{tb} from R assuming 3-family CKM**



R	unconstrained	$1.023 + {}^{0.036}_{-0.034}$
R	constrained < 1 95% C.L	> 0.945
$\|V_{tb}\|$	unconstrained	$1.011 \pm {}^{0.018}_{-0.017}$
$\|V_{tb}\|$	constrained < 1 95% C.L	> 0.972

Most precise measurement of R



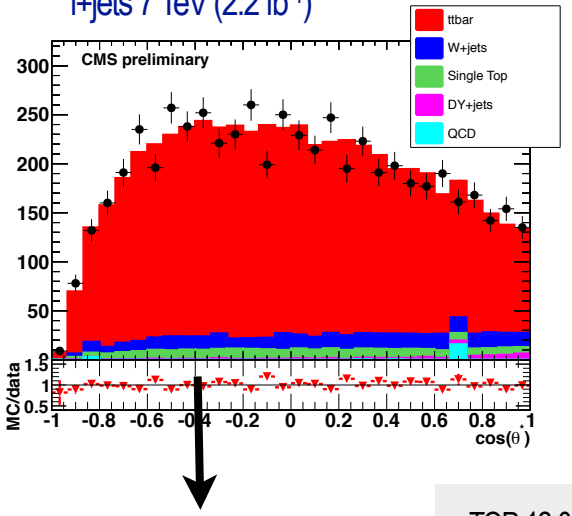
W Polarization

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

- **θ* distribution (angle between the p(fermion) in W rest-frame and p(W))**
- **Test V-A structure of tWb-vertex, possible BSM contributions modify helicity fractions F_L, F_R, F_0**

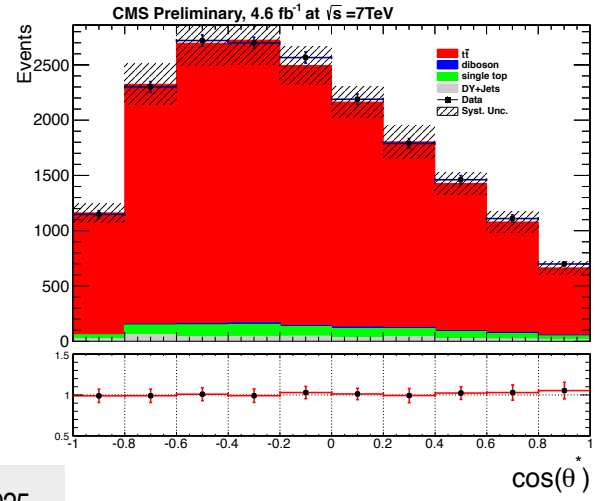
TOP-11-020

l+jets 7 TeV (2.2 fb^{-1})



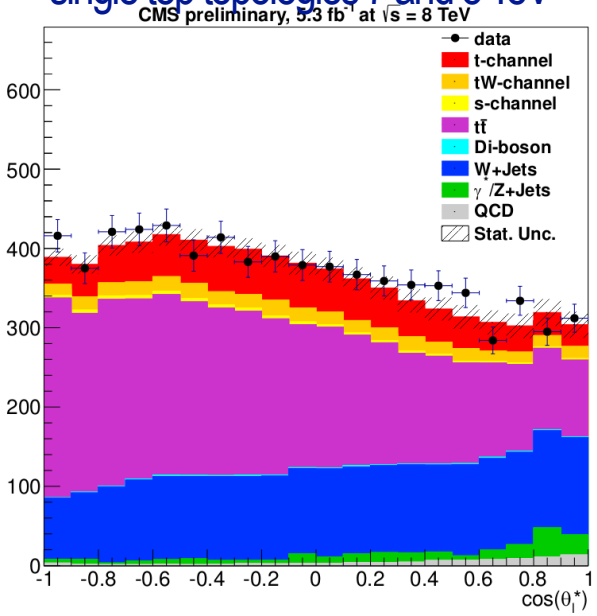
TOP-12-015

dilepton 7 TeV (4.6 fb^{-1})



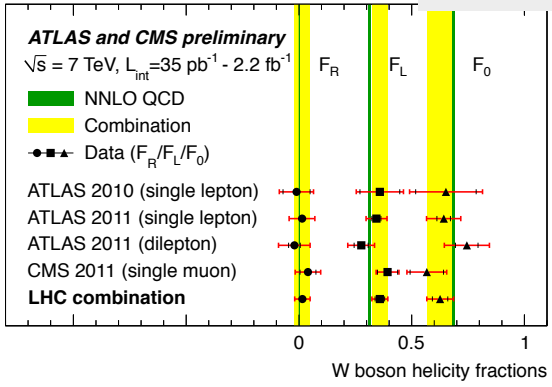
TOP-12-020

single top topologies 7 and 8 TeV



CMS-ATLAS combination

TOP-12-025



$$F_L = 0.288 \pm 0.035(\text{stat}) \pm 0.040(\text{syst})$$
$$F_0 = 0.698 \pm 0.057(\text{stat}) \pm 0.063(\text{syst})$$
$$F_R = 0.014 \pm 0.027(\text{stat}) \pm 0.042(\text{syst})$$

$$F_L = 0.293 \pm 0.069(\text{stat.}) \pm 0.030(\text{syst.}),$$
$$F_0 = 0.713 \pm 0.114(\text{stat.}) \pm 0.023(\text{syst.}),$$
$$F_R = -0.006 \pm 0.057(\text{stat.}) \pm 0.027(\text{syst.}).$$

Several measurements: All consistent with left-handed charged current

Top Quark Mass

- **Direct mass measurement at Tevatron**
  - m(top) = 173.20 ± 0.51$_{stat}$ ± 0.71$_{sys}$ GeV

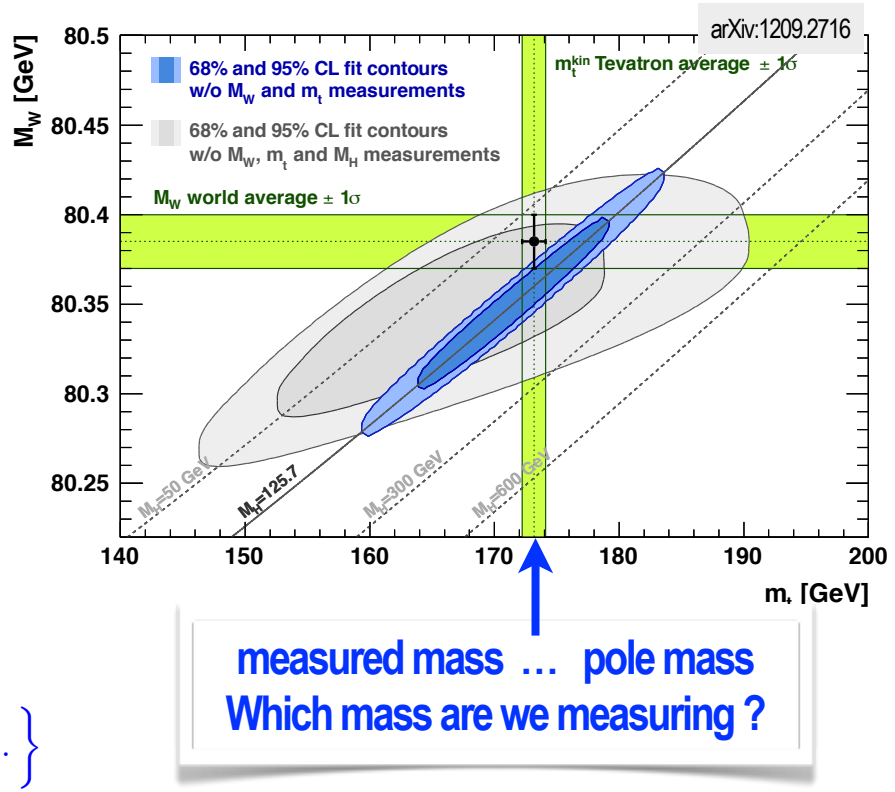
CDF:10976, D0:6381

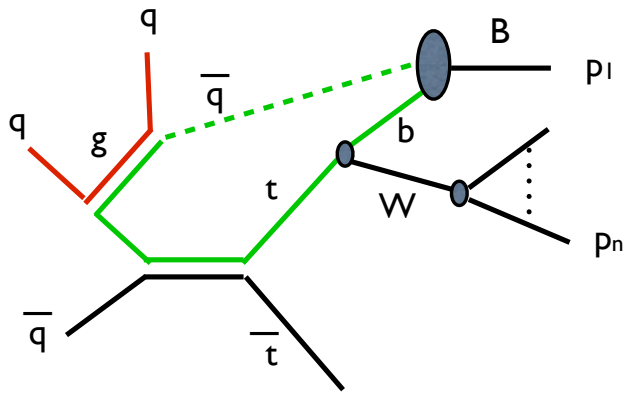
- **Quark mass is scheme-dependent**
  - Pole-mass: viewing top quark as a free parton
  - $\overline{\text{MS}}$ scheme ('running mass'):

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

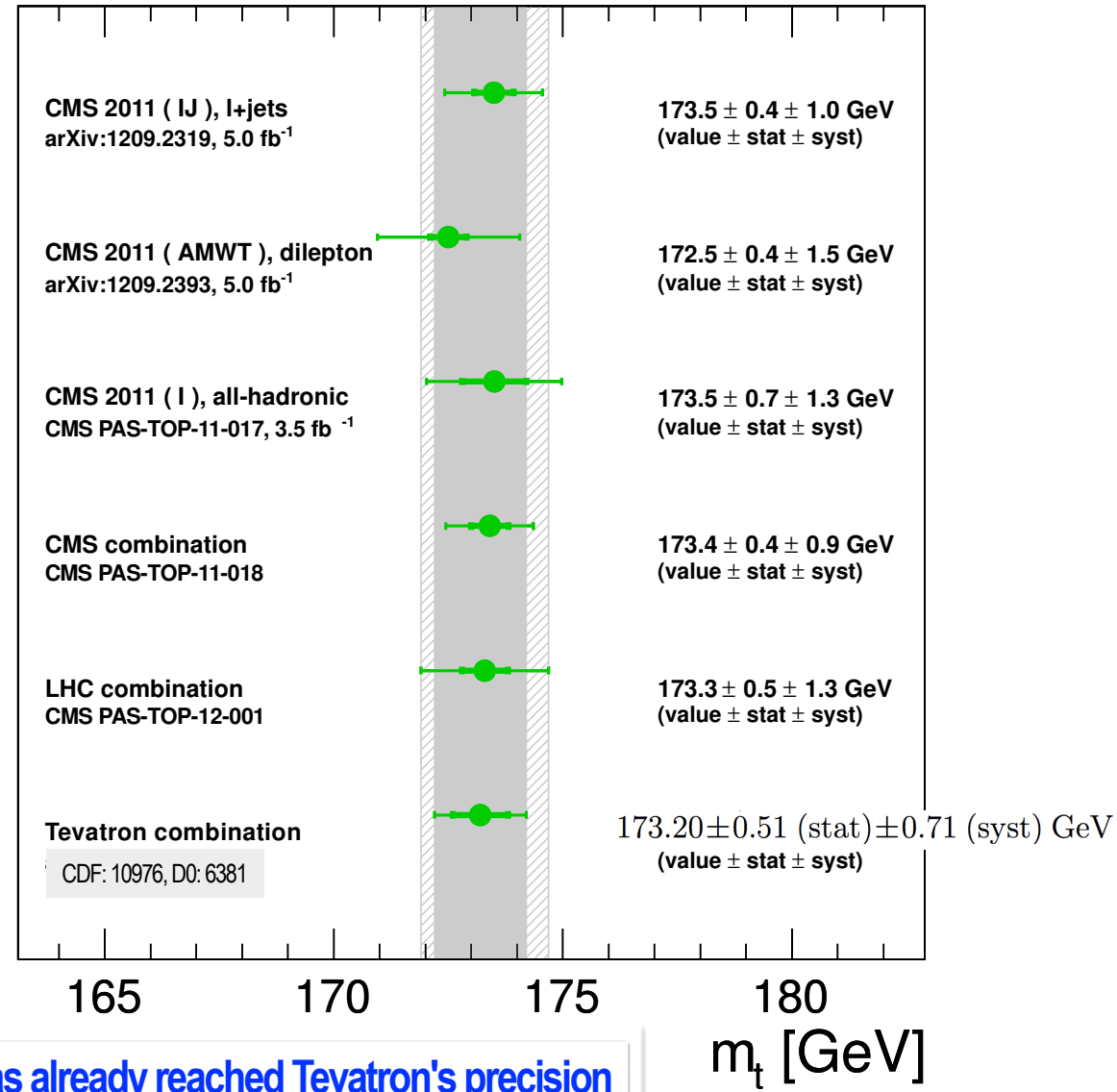
  - 'MC mass': (N)LO+PS yet different from pole or $\overline{\text{MS}}$ mass

- **Colour Reconnection:**
  - Soft interactions not calculable in pQCD
  - Present model uncertainties: estimated to be 0.5 … 1 GeV





Top Quark Direct Mass Combination

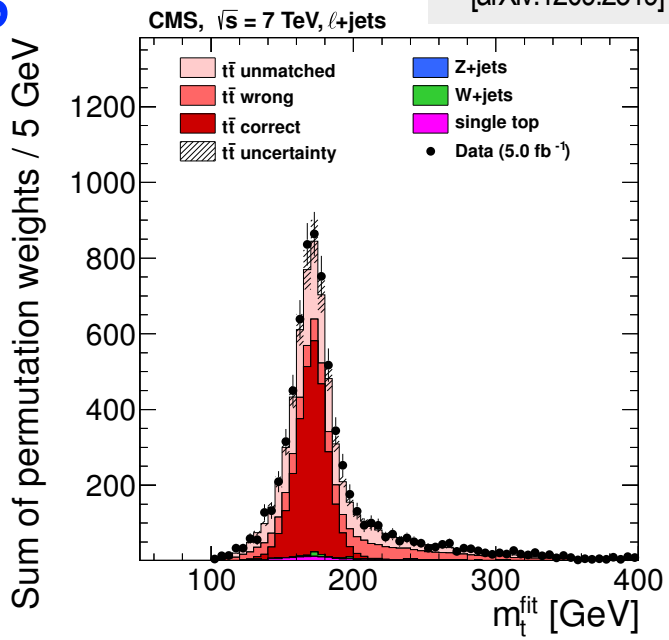


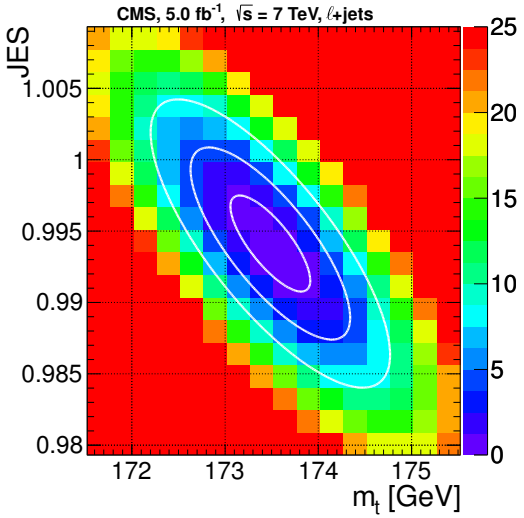
LHC has already reached Tevatron's precision

Direct Mass: Lepton+Jets

JHEP 12(2012) 105
[arXiv:1209.2319]

- **Signature**
  - 1 e or μ
  - 4 jets, 2 b-tags (high purity selection)
- **Analysis ('2D-ideogram')**
  - Reconstruct top mass from kinematic fit ($P_{gof} > 0.2$)
  - 2D fit of mass and jet energy scale (JES) using W-mass constraint
  - Weight each fit solution by P_{gof}
  - Measurement from max.likelihood in mass-JES plane
  - Calibration using pseudo-experiments for different input m(top) and JES (→ small corrections)
- **Dominant Uncertainties**
  - Color reconnection (0.54 GeV)
  - b-jet energy scale (0.61 GeV)





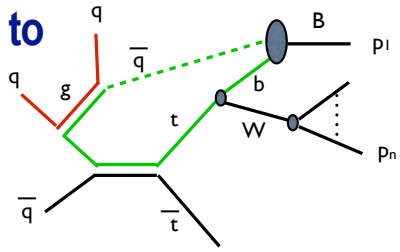
Single most precise top mass measurement to date

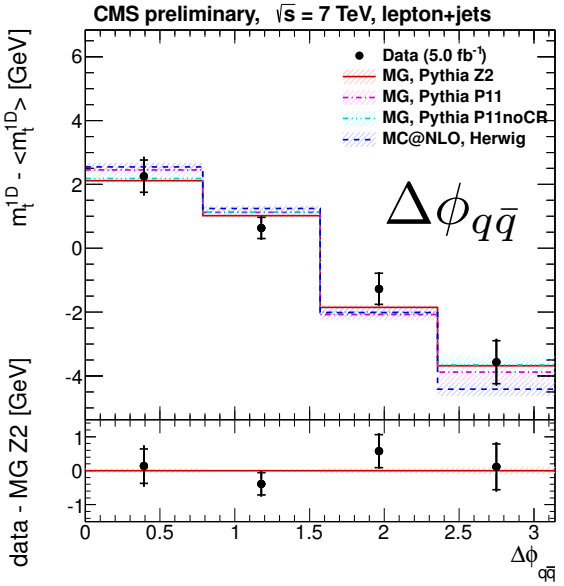
$m_{top} = 173.5 \pm 0.4_{stat+JES} \pm 1.0_{syst}$ GeV

Kinematic Dependence

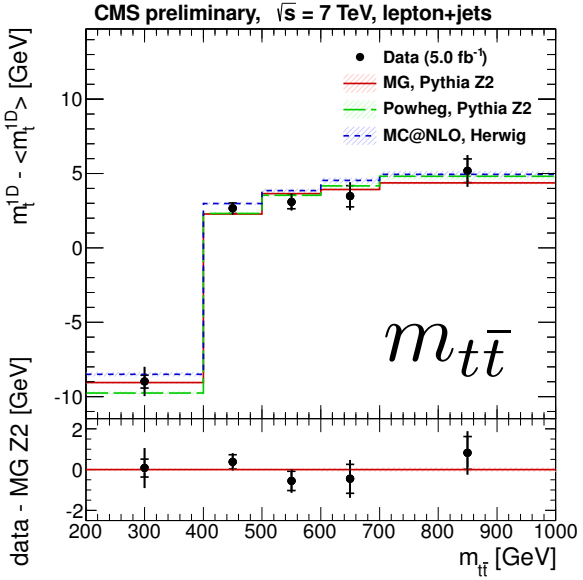
TOP-12-029

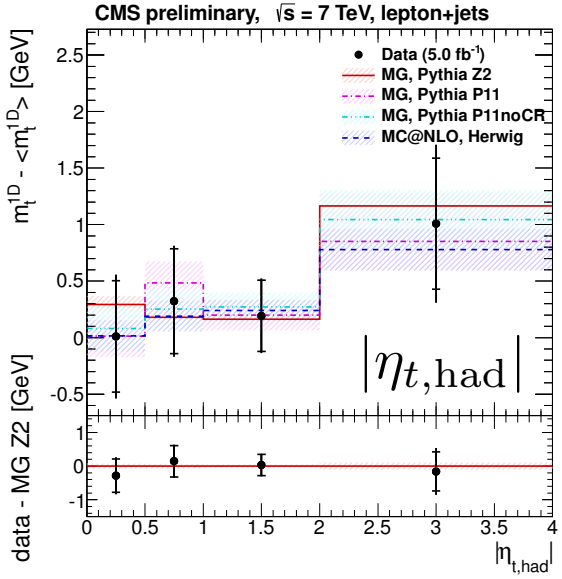
- **Investigate model uncertainty: various (non-)perturbative corrections are different in their kinematic dependence**
- **Investigate distributions with sensitivity to**
  - Color reconnection
  - ISR/FSR
  - b-quark kinematics
- **Figures:** m_{top} - $\langle m_{top} \rangle$





#	Observable	m_t^{2D} χ^2	Ndf
1	$\Delta R_{q\bar{q}}$	1.49	3
2	$\Delta\phi_{q\bar{q}}$	2.89	3
3	$p_{T,t,had}$	2.41	4
4	$\lvert\eta_{t,had}\rvert$	3.17	3
5	H_T	2.24	4
6	$m_{t\bar{t}}$	2.25	4
7	$p_{t\bar{t}}$	2.18	4
8	# Jets	1.56	2
9	$p_{T,b,had}$	2.17	4
10	$\lvert\eta_{b,had}\rvert$	0.48	2
11	$\Delta R_{b\bar{b}}$	8.01	3
12	$\Delta\phi_{b\bar{b}}$	6.86	3



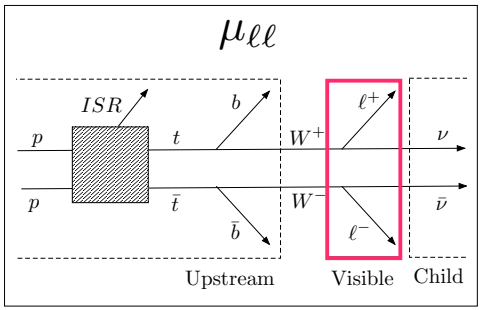


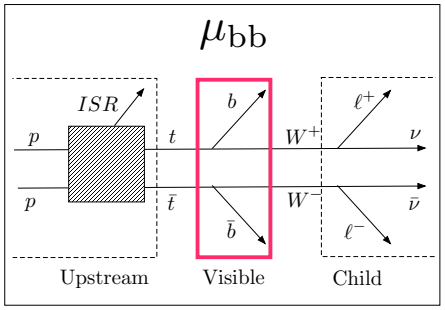
No significant deviations between data and various models w.r.t their kinematic dependence

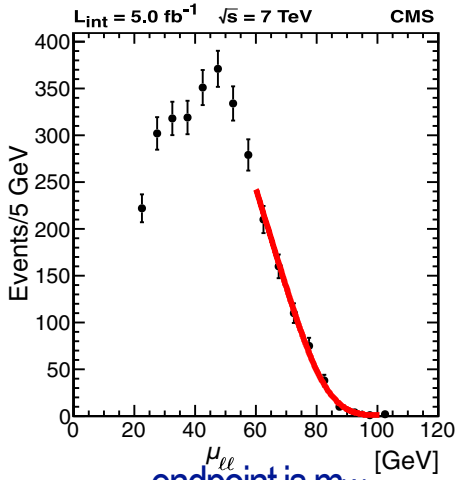
Mass from Endpoint Analysis

arXiv:1304.5783

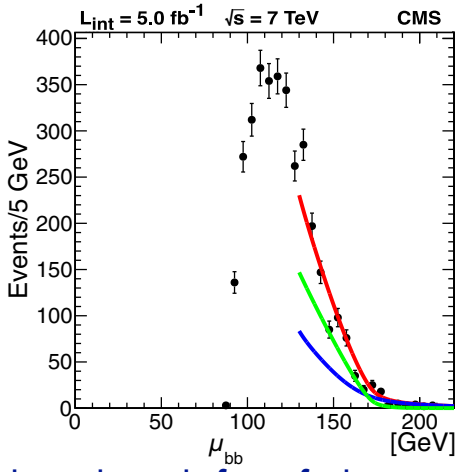
- Endpoint analysis: independent of assumptions on shapes (no templates or transfer functions)
- M_{T2}: minimum parent mass consistent with observed final state
- $M_{T2\perp}$: remove production dynamics, keep only momentum components perpendicular to 2-parent p_T
- Three $M_{T2\perp}$ subsystem variables: measure top, W- and neutrino masses simultaneously



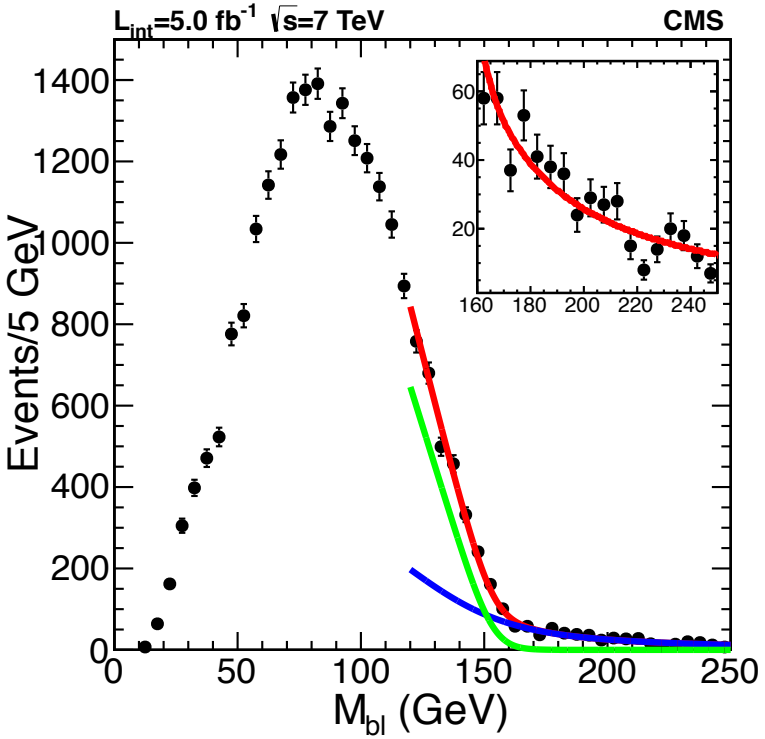




endpoint is m_W



lower bound of m_{top} for known m_W

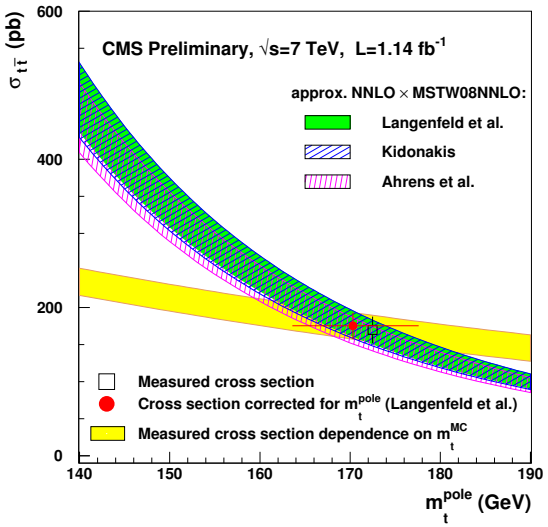


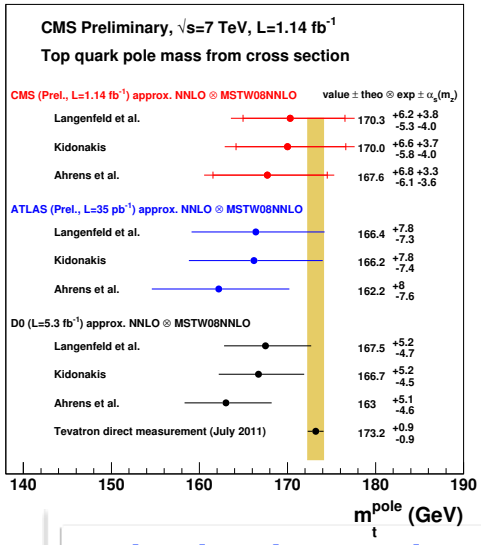
m_{top} = 173.9 ± 0.9$_{stat}$ + 1.6-2.0$_{syst}$ GeV

Top Mass or α_S from Inclusive Cross Section

CMS TOP-11-008

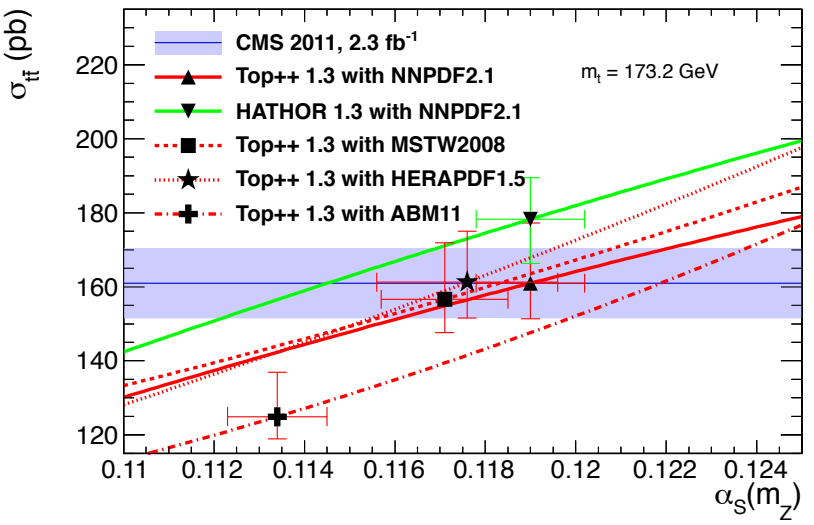
- Mass from cross section (for fixed α_S)



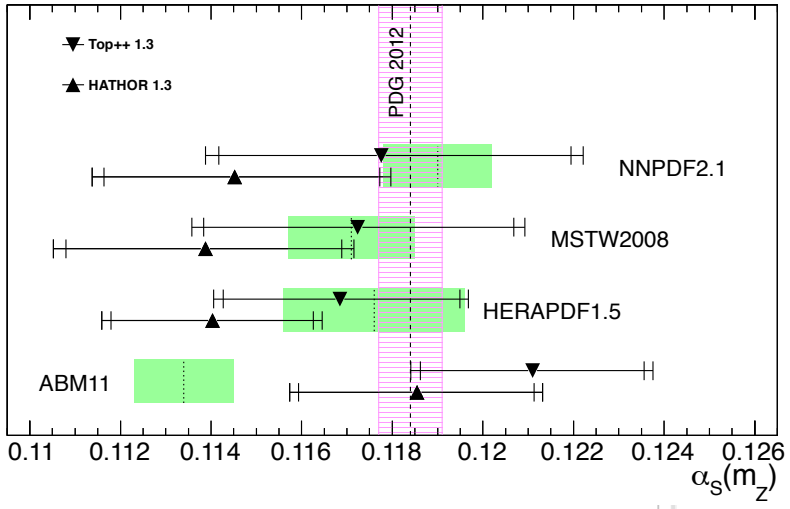


CMS TOP-12-022

- Strong coupling constant (for fixed mass)



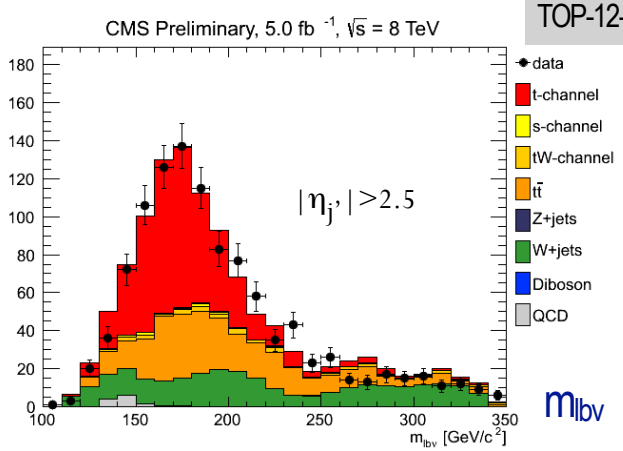
2.3 fb^{-1} of 2011 CMS data × approx. NNLO for $\sigma_{t\bar{t}}$, $\sqrt{s}$ = 7 TeV, m_t = 173.2 ± 1.4 GeV



update imminent, using published inclusive cross section and full NNLO calculation

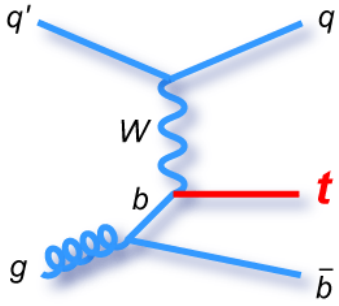
Single Top Production

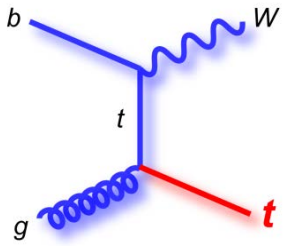
TOP-12-011

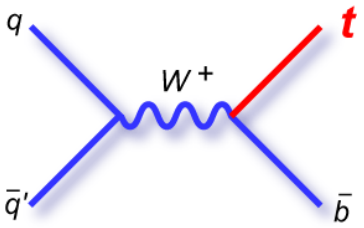


- Test of EW interactions, probe for new physics (4th gen., FCNC)
- Sensitivity to b-PDF and u/d-PDF
- Large backgrounds (W+jets, tt, QCD)

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







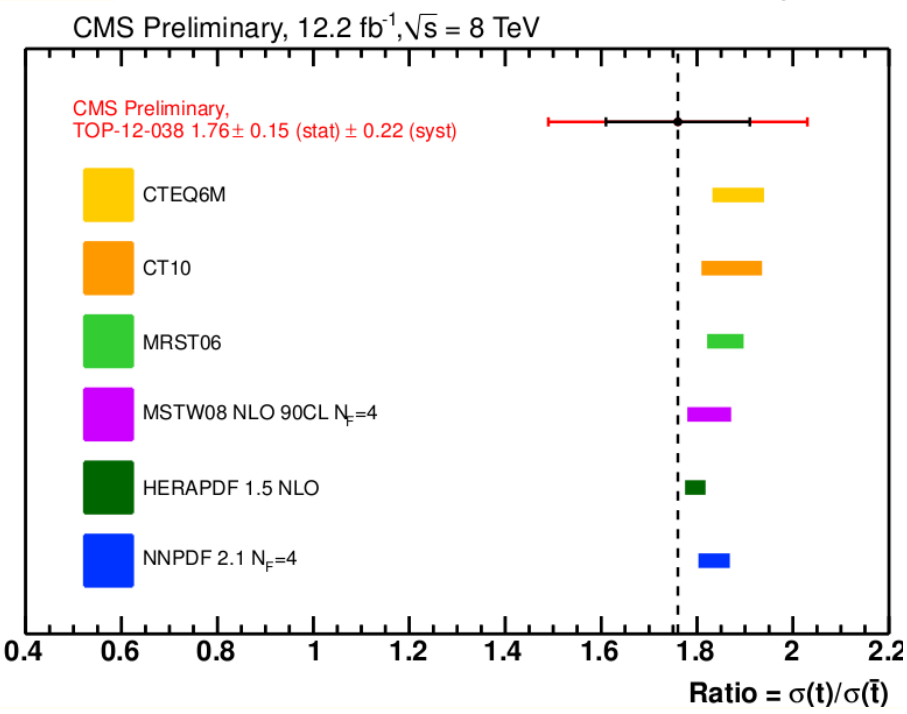
		t-channel [pb]	tW-channel [pb]	s-channel [pb]
7 TeV	prediction	64.6 pb arXiv:1209.4533	15.7 pb	4.6 pb
	CMS σ	67.2 ±6.1$_{stat+syst}$ pb $\|V_{tb}\|$ = 1.020± 0.046$_{exp}$± 0.017$_{theo}$	15.6 ±0.4$_{stat}$ +1.0-1.2$_{sys}$ pb arXiv:1209.3489	-
8 TeV	prediction	87.8 pb TOP-12-011	22.4 pb	5.6 pb
	CMS σ	80.1 ±5.7$_{stat}$ ±11.0$_{syst}$±4.0$_{lumi}$ pb	-	-

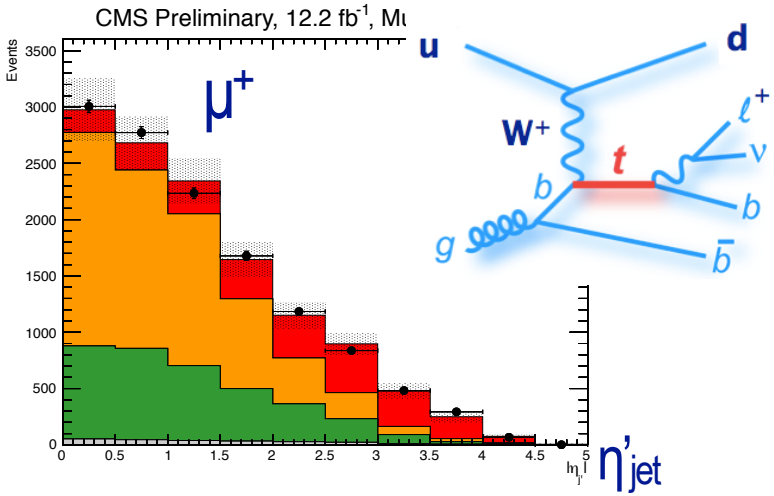
Precise results in t channel - evidence for tW

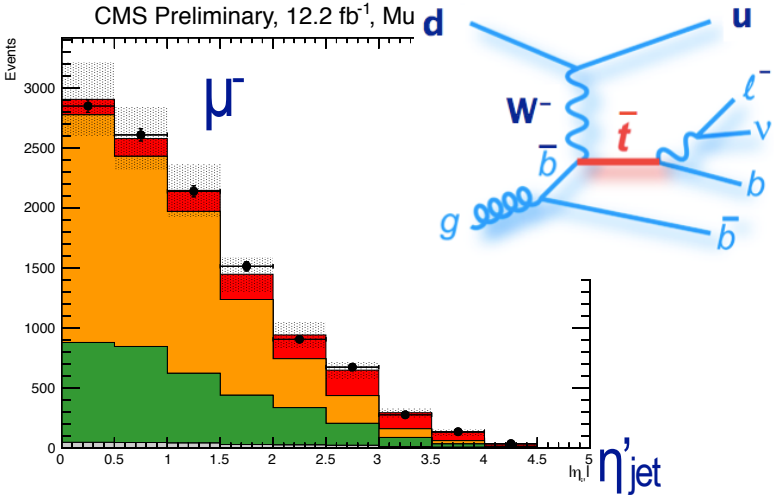
σ(t)/σ(t̄) in t-channel

TOP-12-038

- pp collision: expect u-density ~2 × d-density
- Simultaneous fit to η'-distributions of positive and negative lepton







$$R_{t\text{-ch.}} = 1.76 \pm 0.15(\text{stat.}) \pm 0.22(\text{syst.})$$

Consistent with all PDF - errors still large

Conclusions

- **Top quark physics: Key to QCD, electro-weak and New Physics**

- **Precision regime: σ_{tt} < 5%, m(top) ≲ 1 GeV, …**
- **Inclusive cross section prediction available up to full NNLO, same precision as data**

- **Top Top-Topics:**
  - Diff.dists, high m_{tt}, tt+jets, ttbb, ttH, ttW/Z, A_C, spin-correlations, W-helicity, V_{tb}, mass, α_S, PDF
  - Many results not shown: polarization, mass, mass difference, charge, tW, FCNC, searches, ...

- **All results so far in agreement with SM predictions**

- **Many more measurements underway**
- **Statistics → systematics: with 2012 data, another leap in precision and reach**