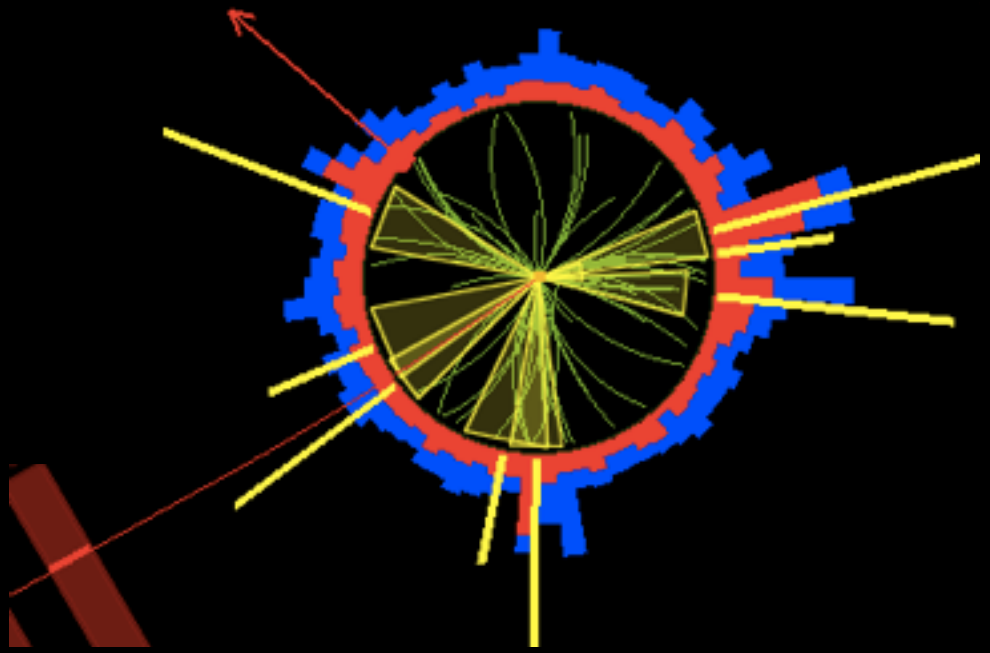
Top Quark Physics at CMS



Andreas B. Meyer

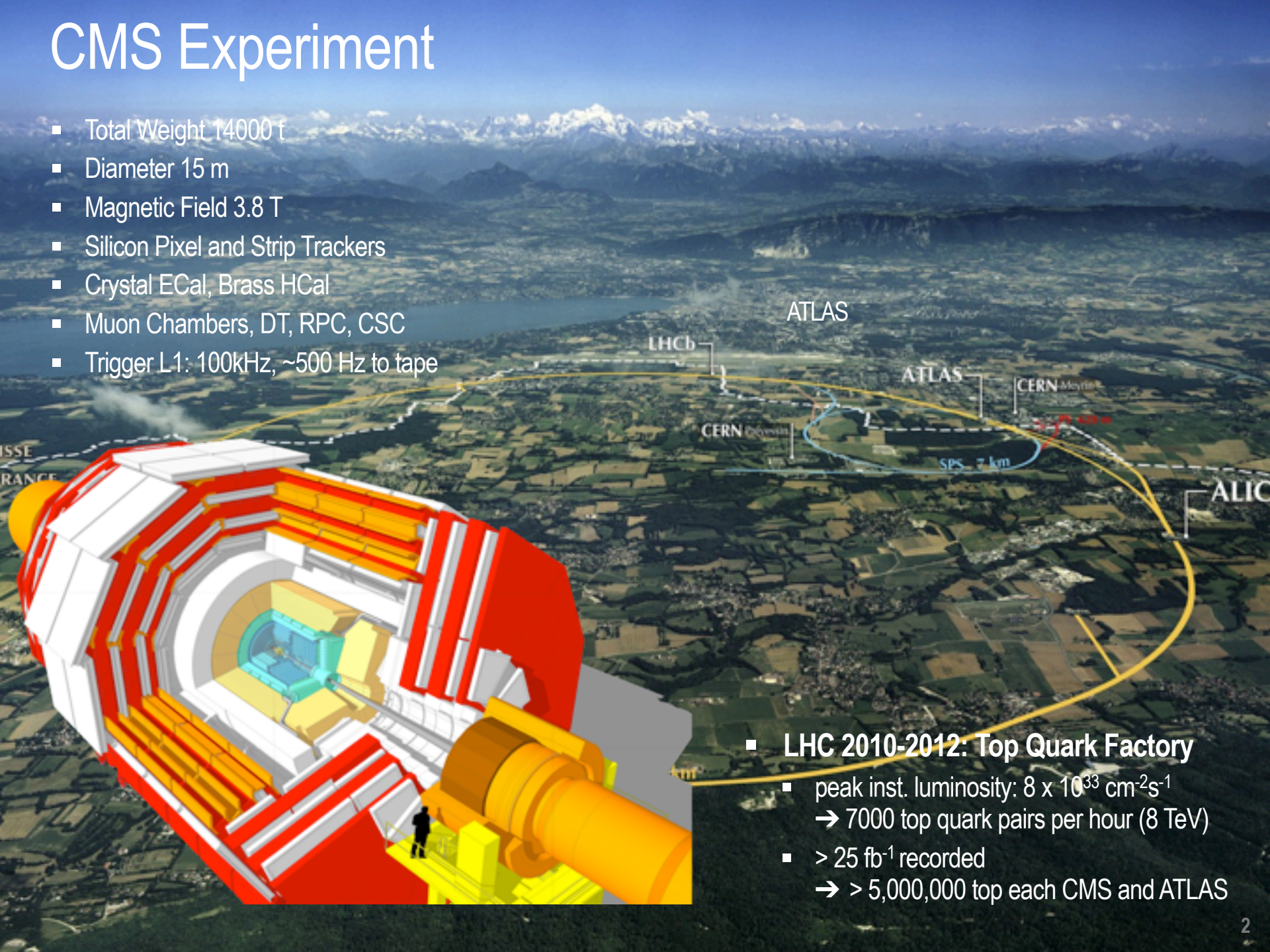
XIIth International Conference on

Heavy Quarks and Leptons

Waldthausen Castle, Mainz, August 25-29, 2014

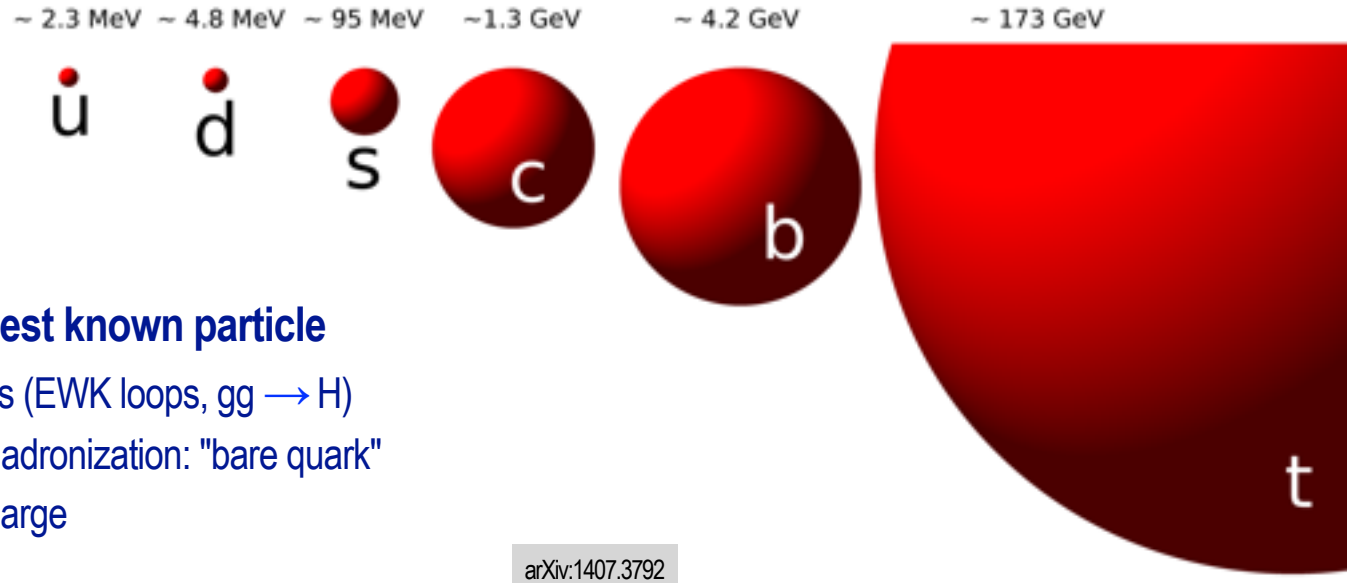
CMS Experiment

- 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

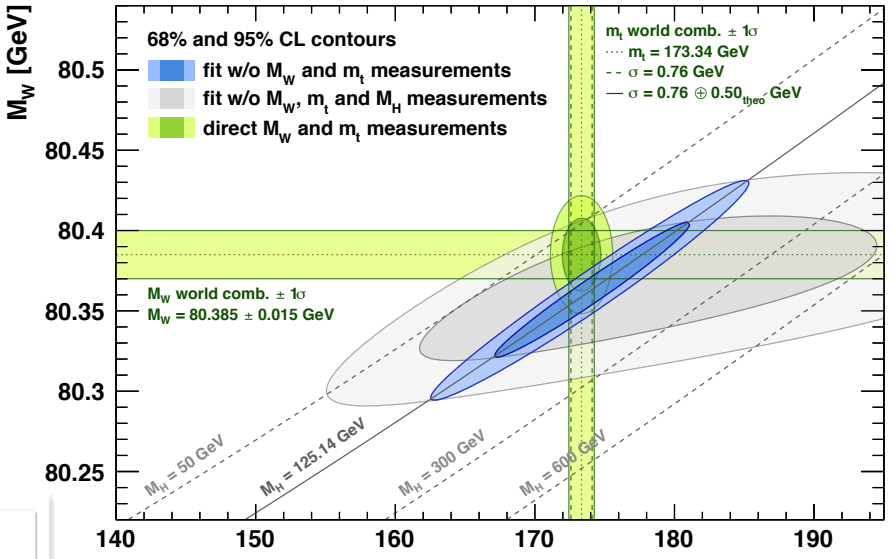
Top Quarks

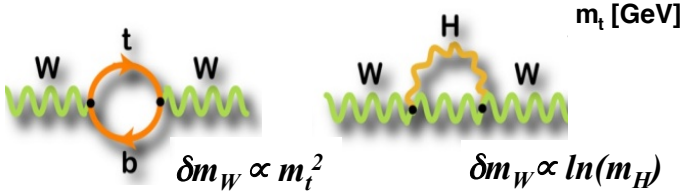


- **The top quark is the heaviest known particle**
  - Maximum sensitivity to Higgs (EWK loops, gg ⟶ H)
  - $\tau \sim 5 \times 10^{-25}$ s: decay before hadronization: "bare quark"
  - Direct access to spin and charge
- **Search for New Physics**
  - New physics might preferentially couple / decay to top
  - Measure standard (and non-standard) couplings
- **Precision measurement of SM parameters**
  - Total cross sections, differential distributions
  - Properties (mass, spin structure, asymmetries, V_{tb} …)

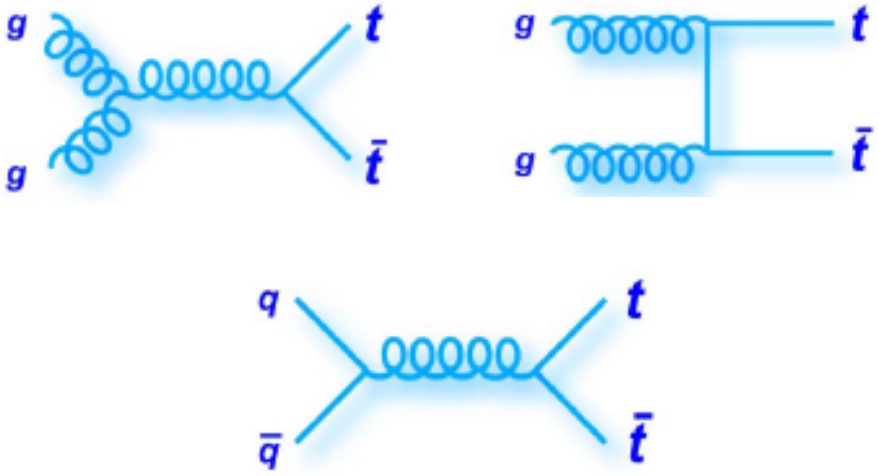
Precise top quark measurements
⟶ tighten constraints on standard model parameters
⟶ sensitivity to New Physics

arXiv:1407.3792





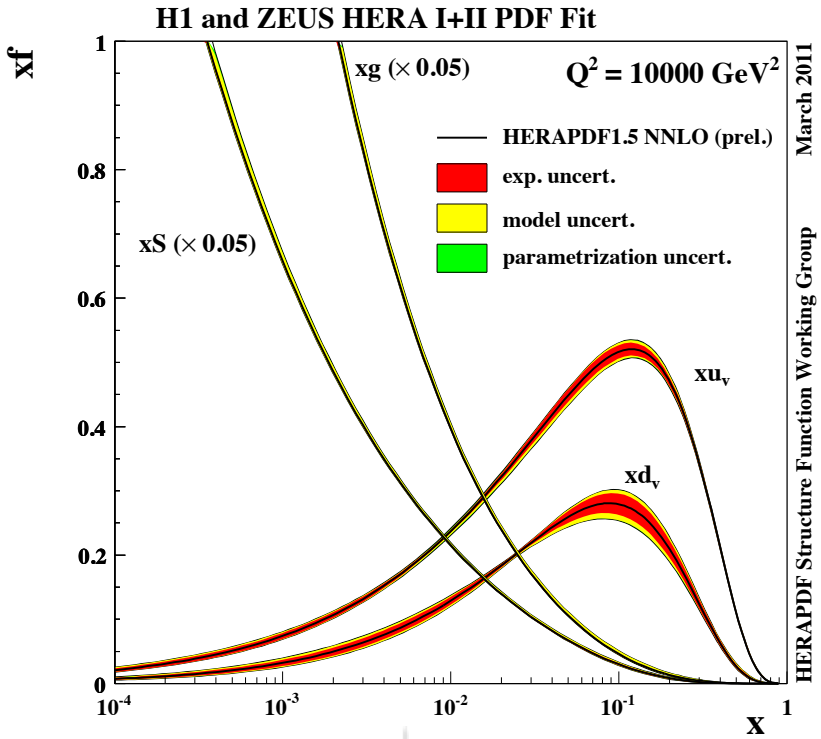
Top Quark Pair Production



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

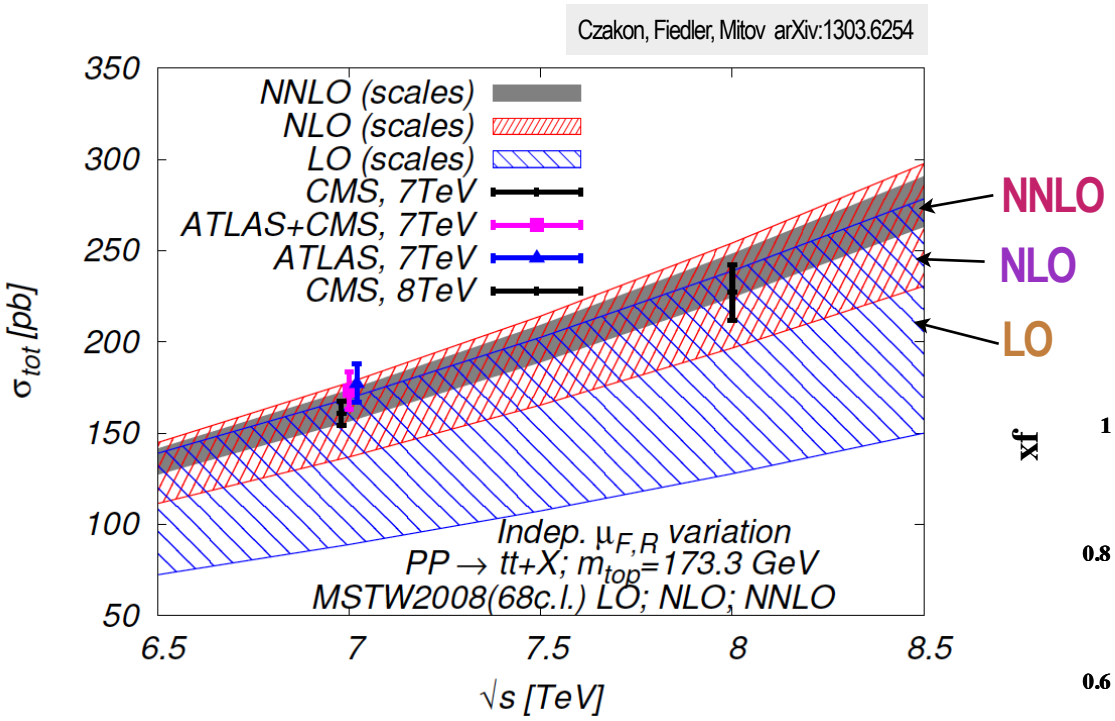
Czakon, Fiedler, Mitov arXiv:1303.6254

Collider	σ_{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 ($gg \to t\bar{t}$) complementary to Tevatron ($q\bar{q} \to t\bar{t}$)

Top Quark Pair Production



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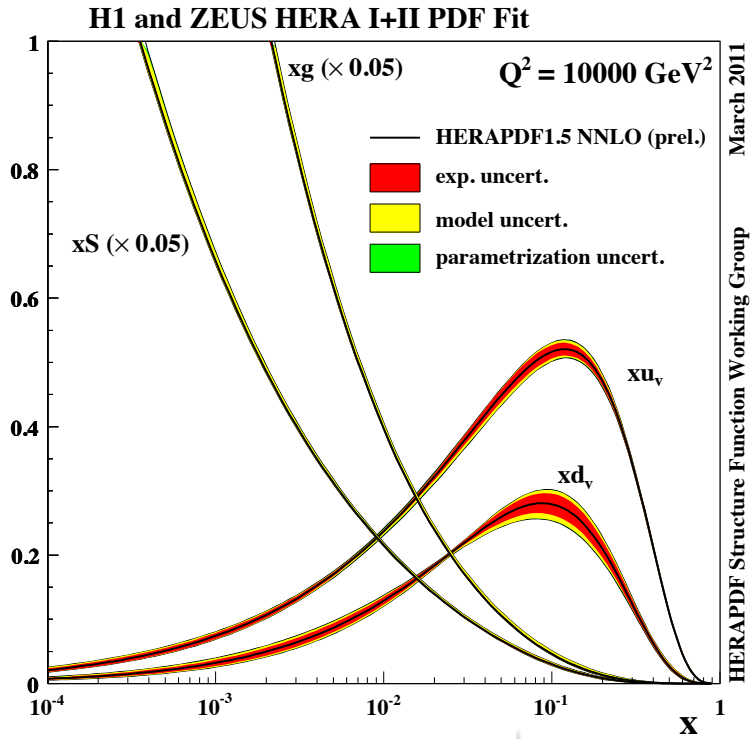

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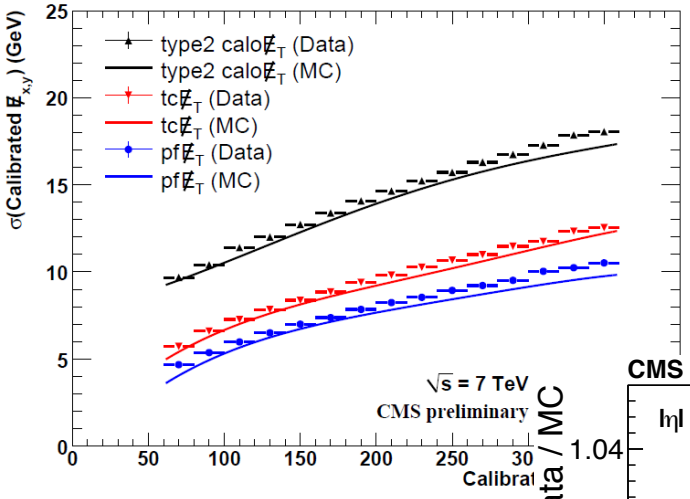
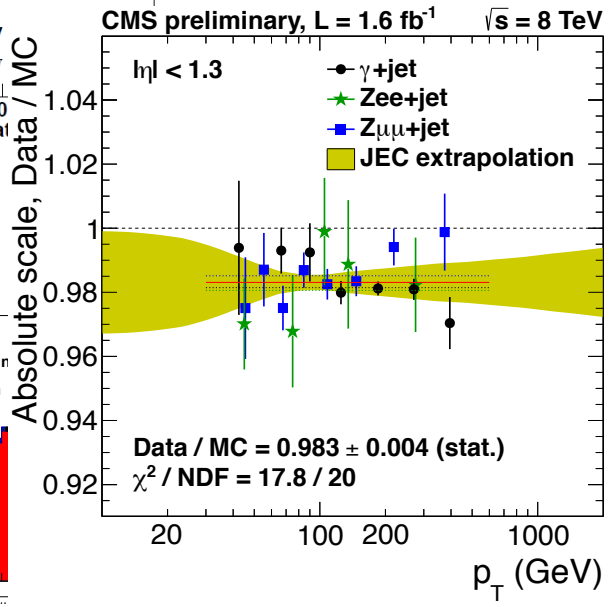
full NNLO available since early 2013 - scale and PDF uncertainties 2-3%

Experimental Ingredients

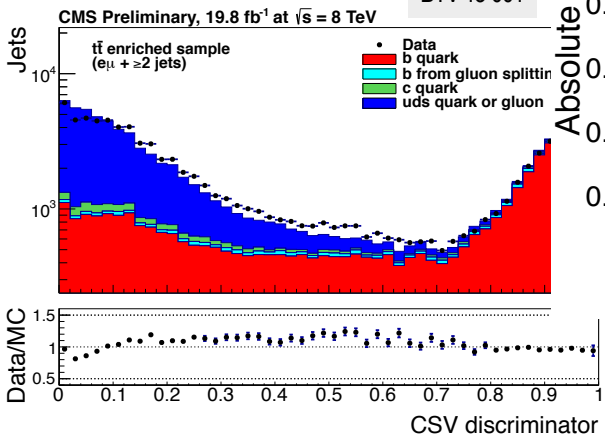
- **Particle Flow**
  - Holistic view of all detector information
  - Combination of tracker and calorimeter to obtain list of identified particles
- **Isolated Leptons (e, μ or τ)**
  - Isolation (including PU subtraction)
  - Calibrations and efficiencies from dilepton resonances (Z, ϒ, J/ψ)
- **Jet (and E_T^{miss})**
  - Optimal resolution and scale
  - Pile-up subtraction based on charged component
- **b-tagging**
  - Combination of several techniques (vertex, impact parameter, track distributions within jets)



CMS-DP-2012/012



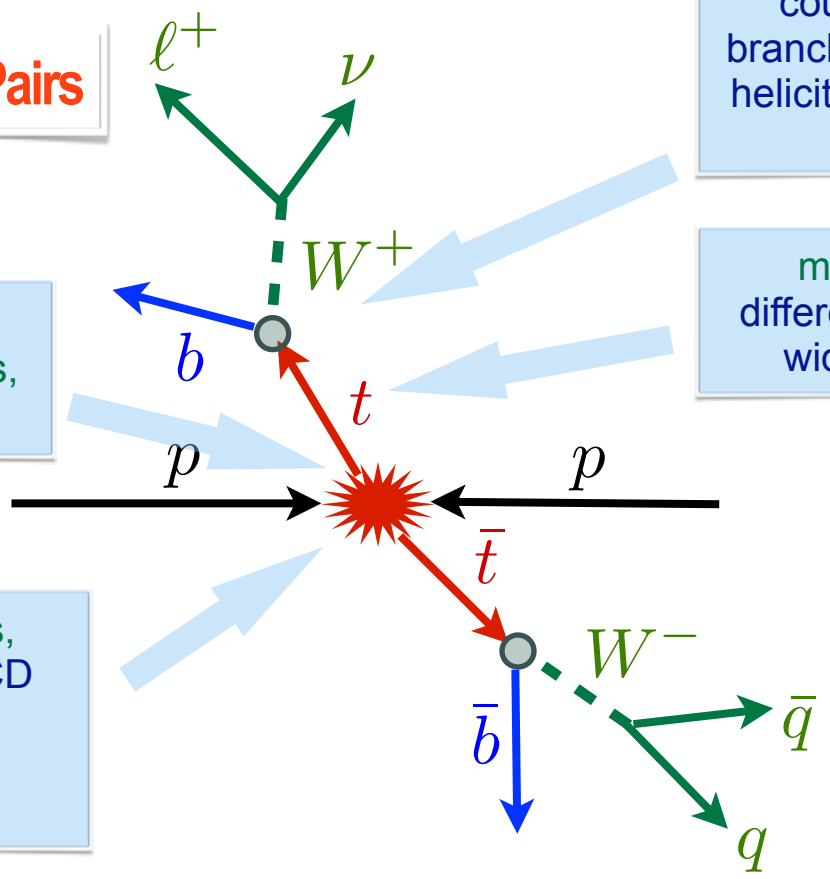
BTV-13-001



Top quark physics: require high-precision leptons, jets and b-tagging

Physics from Top Quark Production and Decay

Top Quark Pairs



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

mass, mass difference, charge, width, lifetime

asymmetries, spin correlations, color flow

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

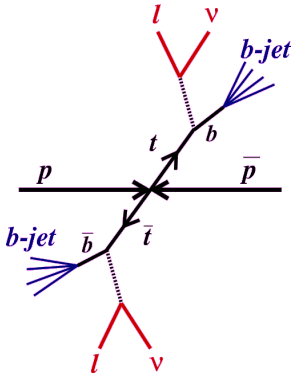
Menu:

- **Production**
- **Properties**
- **Couplings**
- **Mass**
- **Outlook**

EWK Single-Top Production

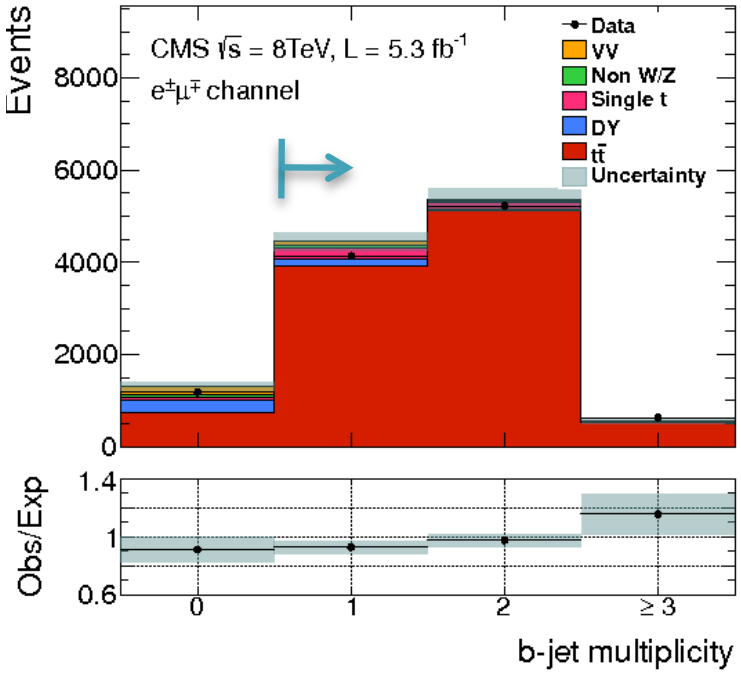
s,t,tW channel production, properties, couplings

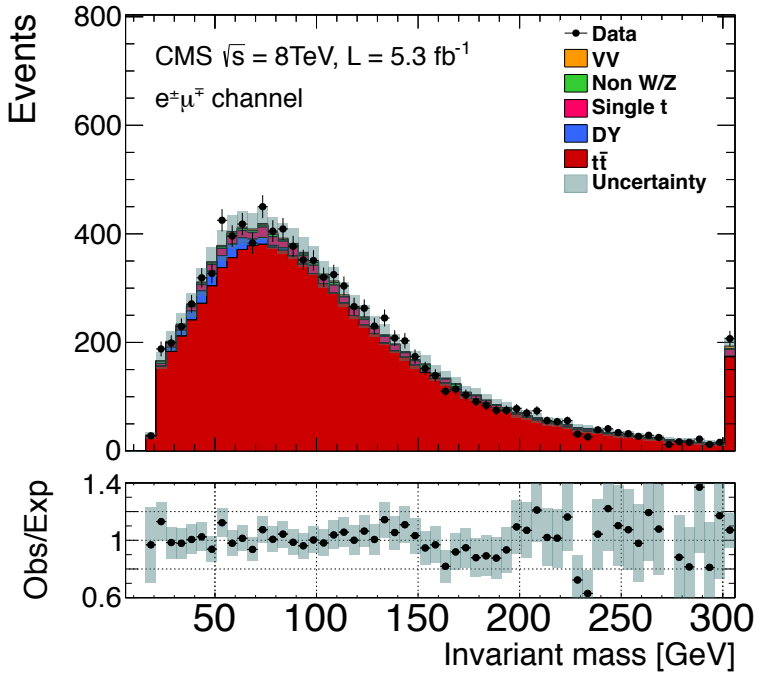
Inclusive $t\bar{t}$ Cross Sections (8 TeV)



JHEP 02 (2014) 024

- **dilepton channel: 1e+1μ+2jets (1b-tag)**
  - Almost background-free, remaining backgrounds estimated from data
  - Systematics: Q^2, matching, jet energy scale





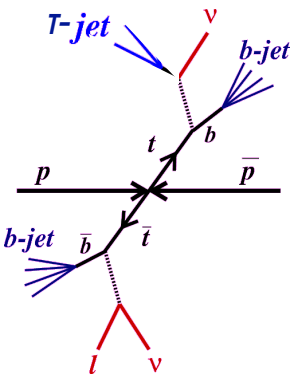
$\sigma_{t\bar{t}} = 239 \pm 2_{stat} \pm 11_{syst} \pm 6_{lumi}$ pb

5.3%

First LHC cross section measurement at 8 TeV, still room for improvement

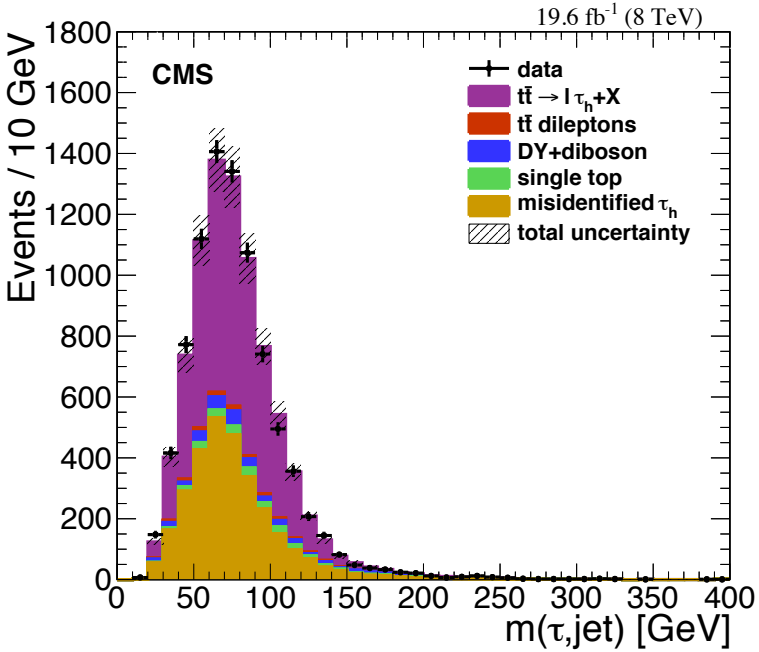
→ update CMS Run1

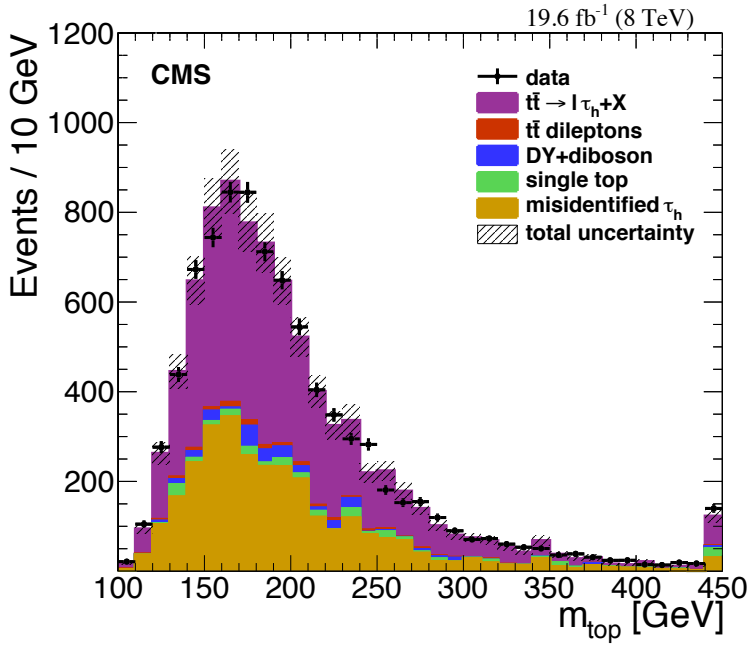
Inclusive $t\bar{t}$ Cross Sections (8 TeV)



arXiv:1407.6643

- **e/μ-tau channel: 1e or μ + 1 τ-lepton (1b-tag)**
  - Dominant systematics: tau-ID and tau-mis-ID



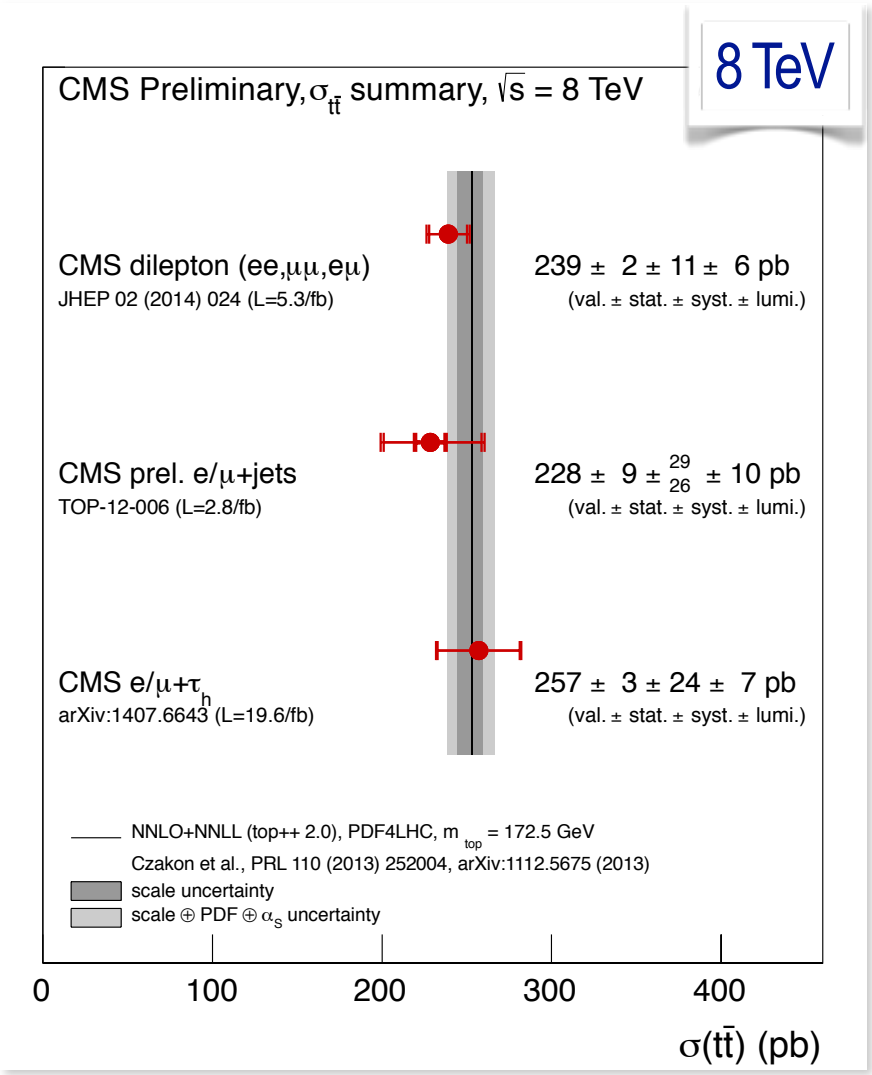


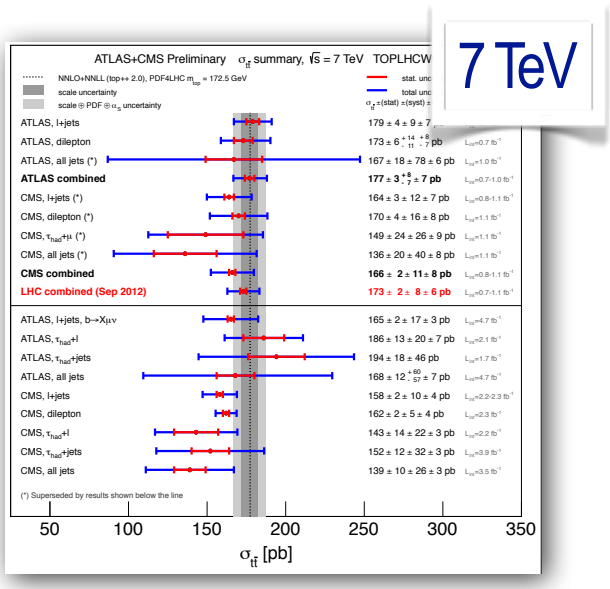
$\sigma_{tt} = 257 \pm 3_{stat} \pm 24_{syst} \pm 7_{lumi}$ pb

9.5%

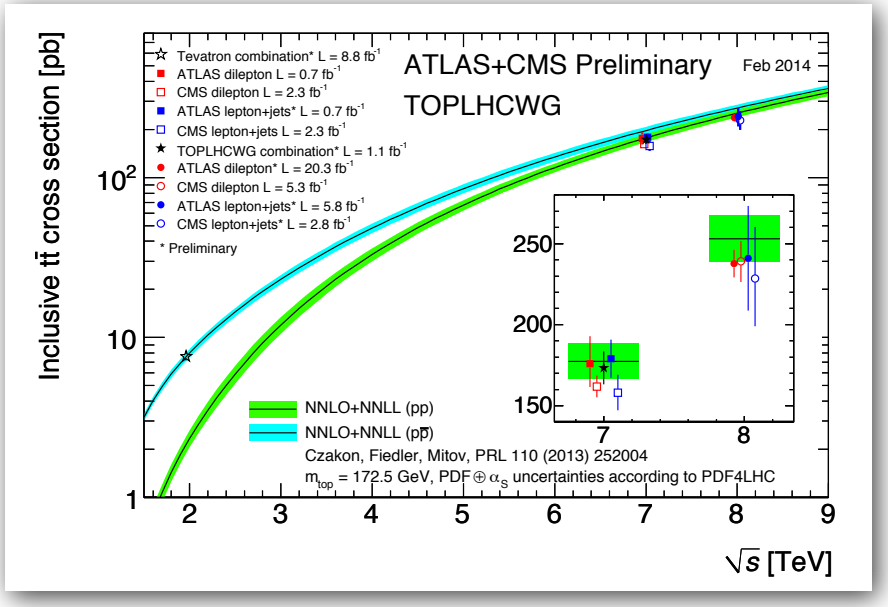
Precision dominated by tau-ID

Inclusive $t\bar{t}$ Cross Sections





TOPLHCWG

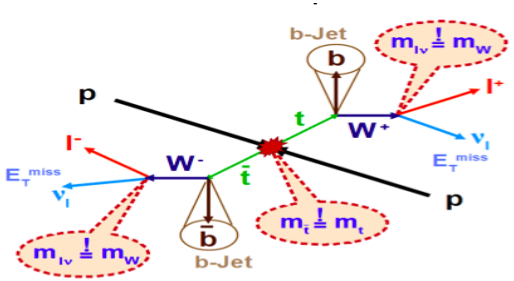


ATLAS and CMS have measured the inclusive tt cross section in all decay channels (except ττ)

Differential $t\bar{t}$ Cross Sections

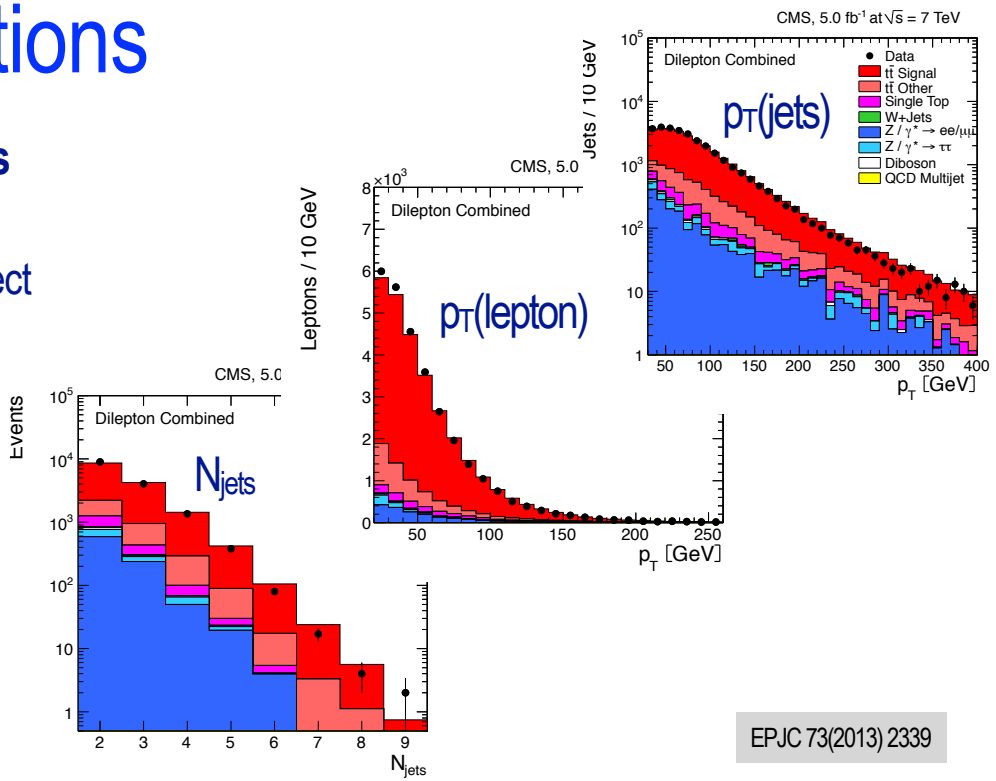
- **Measure top quark kinematic distributions**
  - Scrutinize theory predictions and models
  - Ensure that acceptances, efficiencies are correct
  - Enhance sensitivity to new physics
  - Extract / use for PDF-fits (future)

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

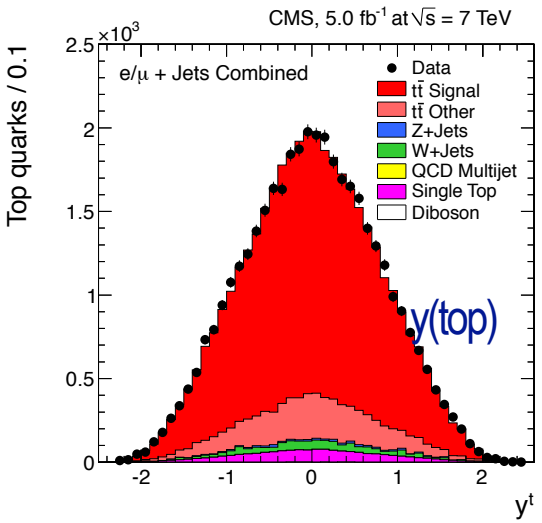


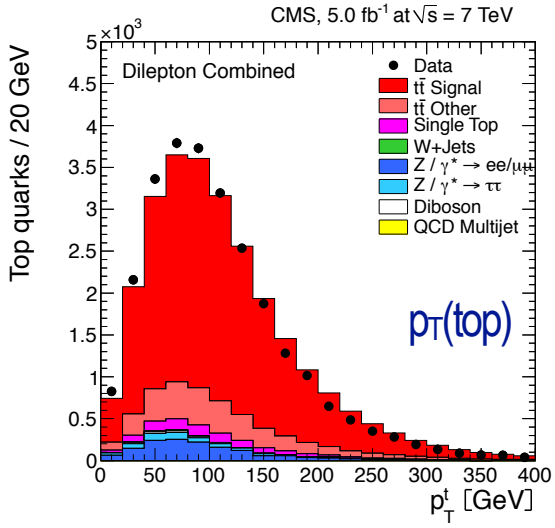
  - Bin-wise cross section analysis
  - Regularized unfolding

CMS results for 7 and 8 TeV for both l+jets and dileptons



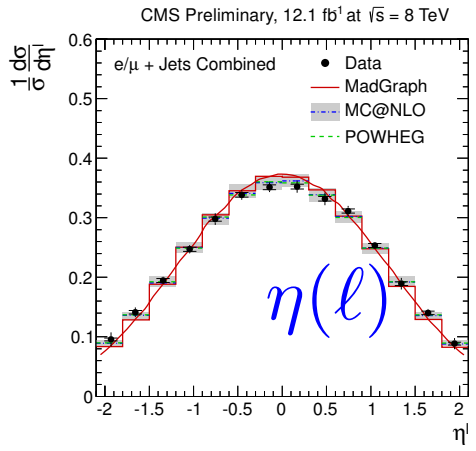
EPJC 73(2013) 2339

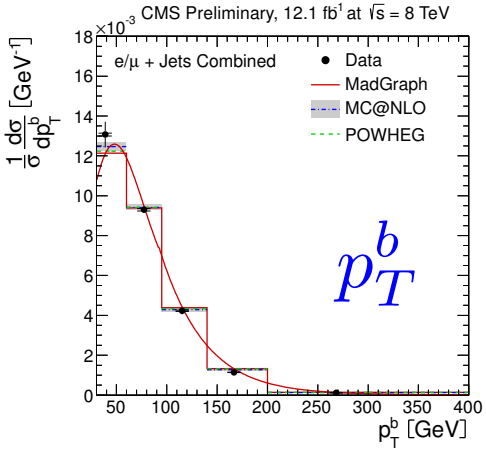


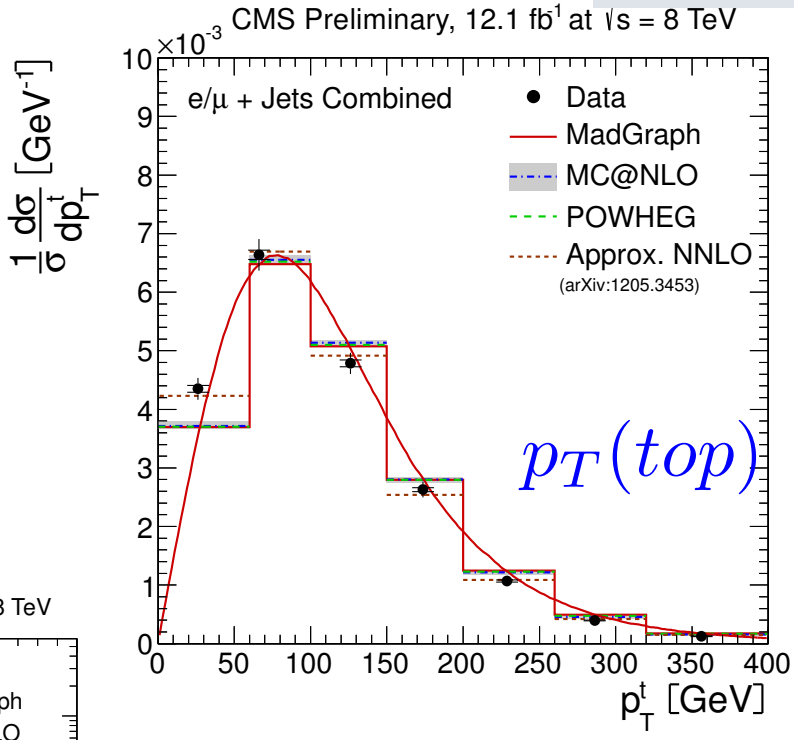


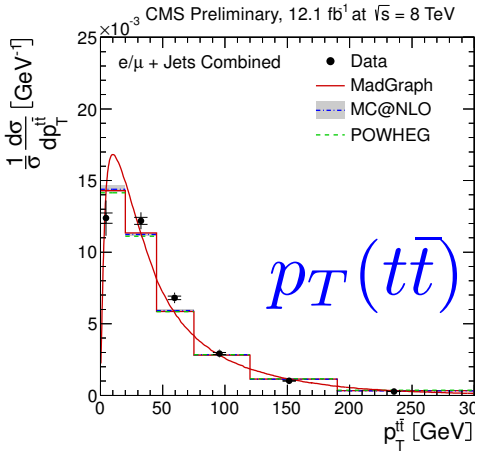
Differential $t\bar{t}$ Cross Sections

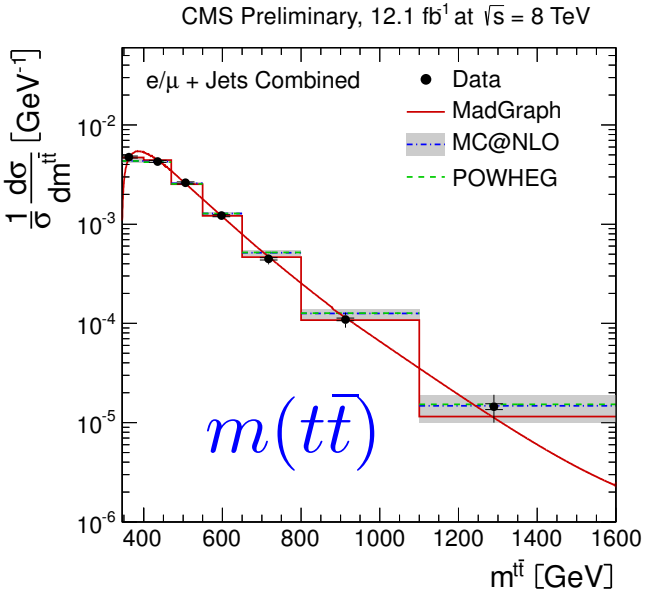
TOP-12-027,TOP-12-028



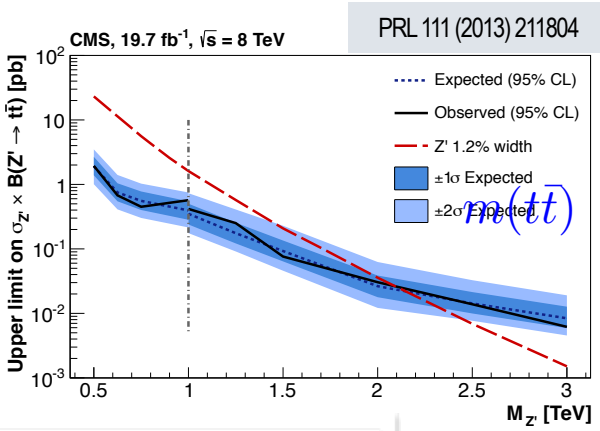






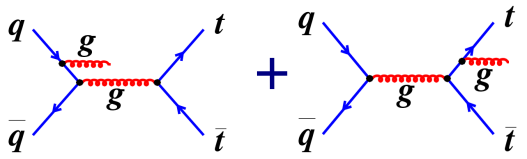


PRL 111 (2013) 211804

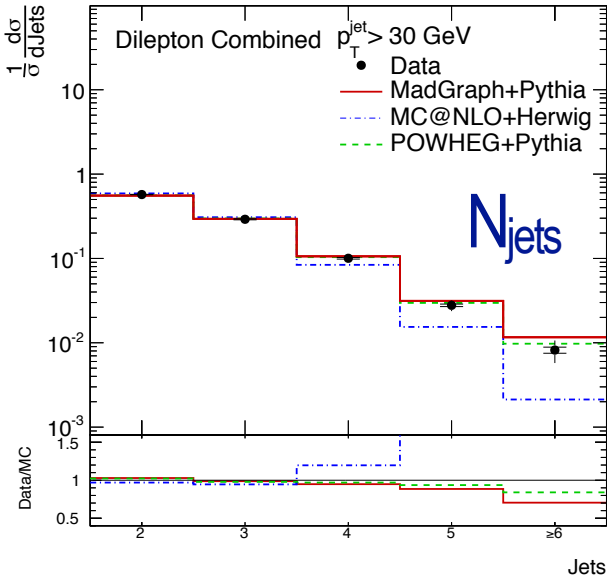


pt(top): Approx. NNLO better than MC - Narrow Z' resonance excluded up to 2 TeV

$t\bar{t}$ + jets, $t\bar{t}$+$b\bar{b}$, $t\bar{t}$+$t\bar{t}$



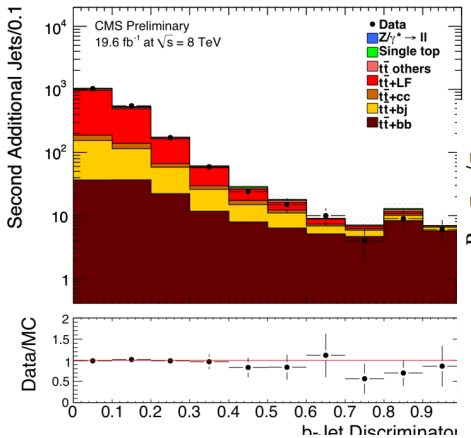
arXiv:1404.3171
TOP-12-041

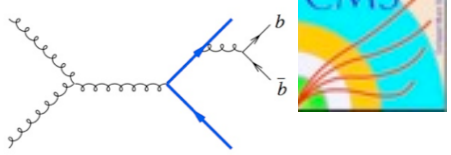


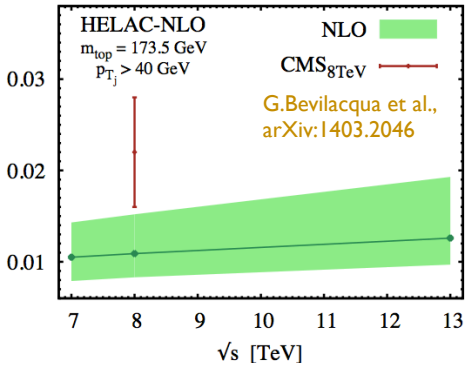
Probing radiation and parton shower modelling

ttbb: important background to ttH

TOP-12-024, TOP-13-010



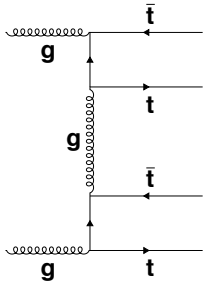


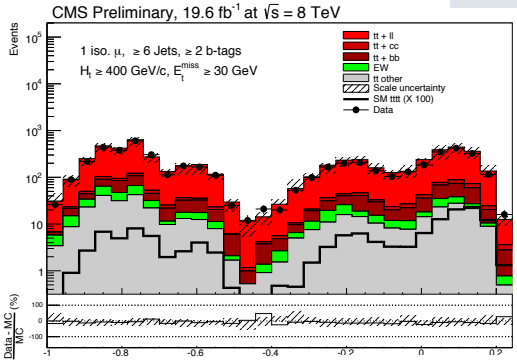


Fit to b-tag discriminator distribution

$\sigma(ttbb)/\sigma(ttjj) = 2.2 \pm 0.4_{stat} \pm 0.5_{syst}$ %

TOP-13-012



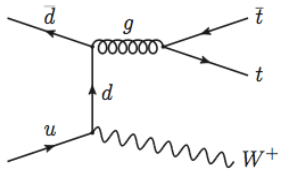


Boosted decision tree

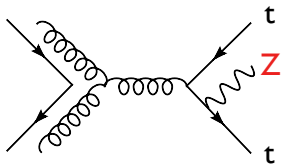
multitopness

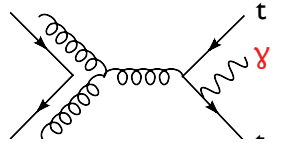
$\sigma(tttt) < 63$ fb at 95% CL (obs), 42+18-13 fb (exp)

$t\bar{t}$ + W,Z,γ

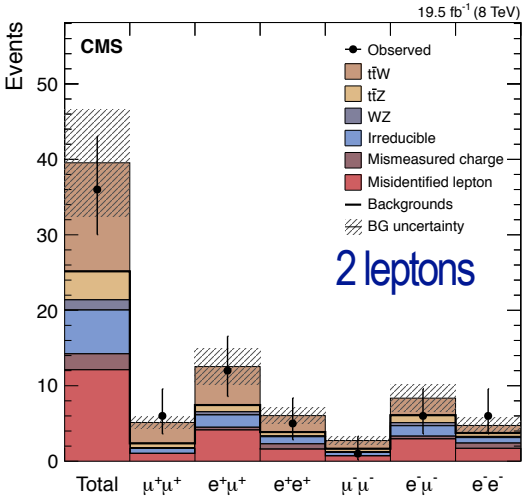


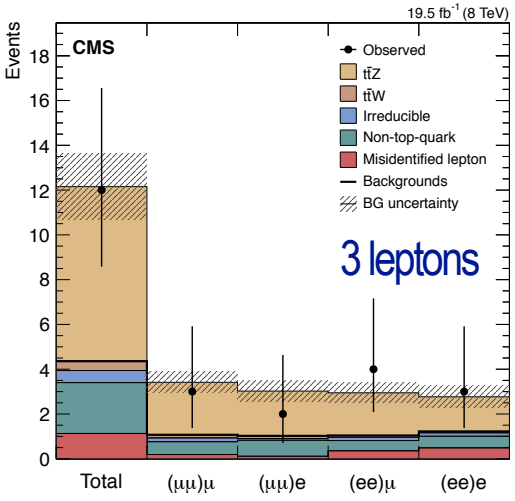
arXiv:1406.7830

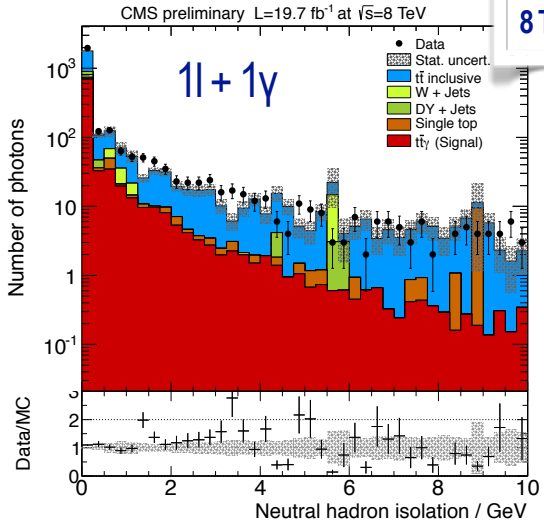




TOP-13-011

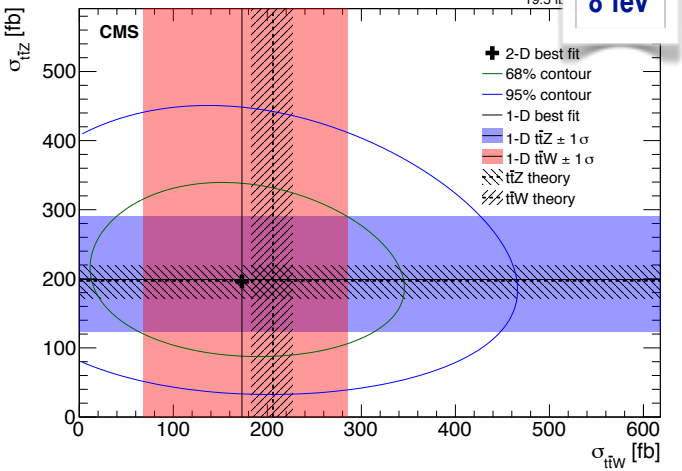






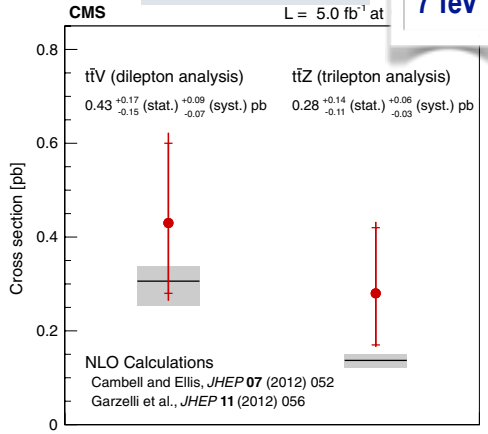
arXiv:1406.7830

8 TeV



PRL 110 (2013) 172002

7 TeV



$\sigma_{tt+\gamma} = 2.4 \pm 0.2_{stat} \pm 0.6_{syst}$ pb

$$\sigma^{SM}_{t\bar{t}+\gamma} = 1.8 \pm 0.5\,\text{pb}$$

Consistent with SM
Uncertainties statistically limited

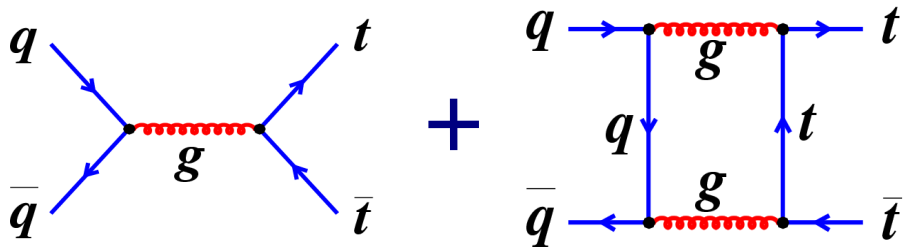
→ CMS Run 2

Charge/FB-Asymmetry

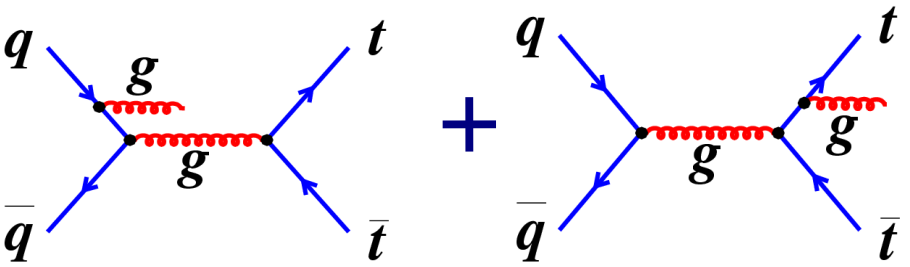
- **LO: No charge asymmetry expected**
- **NLO: Interferences between $q\bar{q}$ diagrams**
  - diluted at LHC due to large gg and unknown quark direction

Available asymmetry calculations are effectively leading order

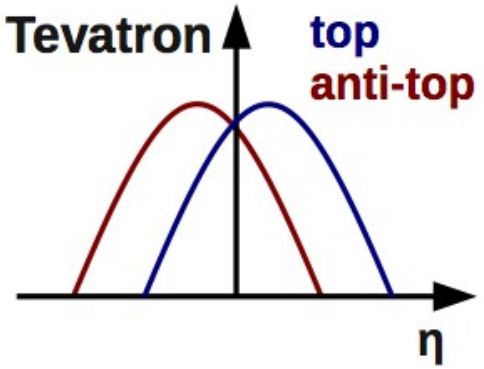
tree-level and box diagrams: positive asymmetry



ISR/FSR: negative asymmetry

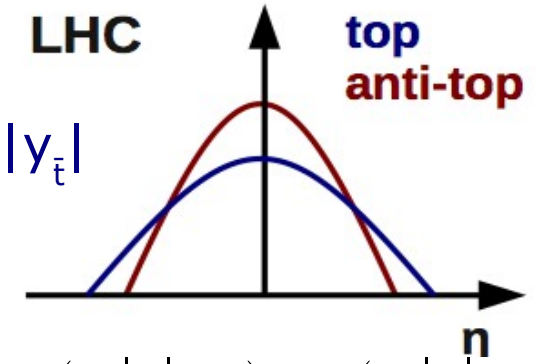


A_{FB}



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

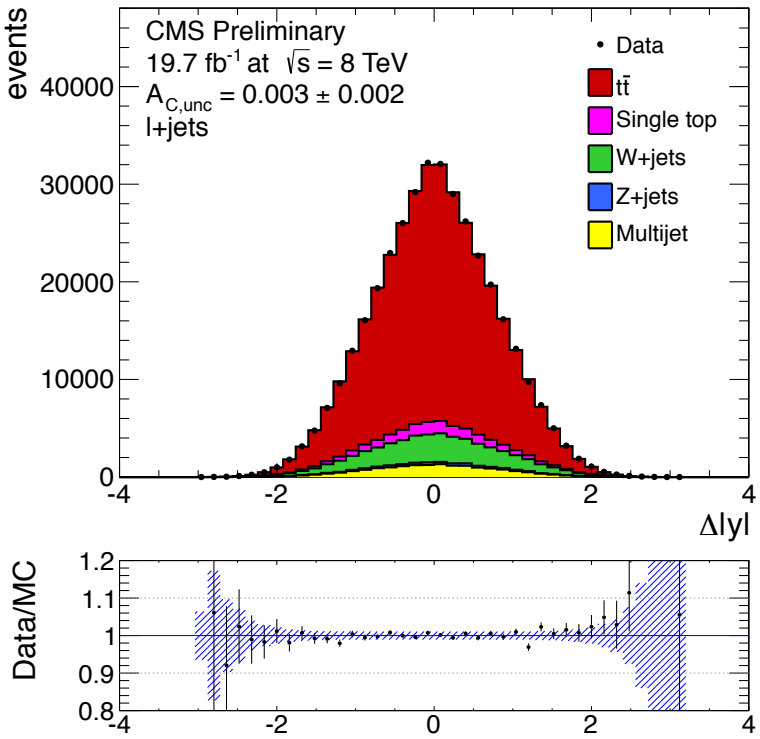
A_C



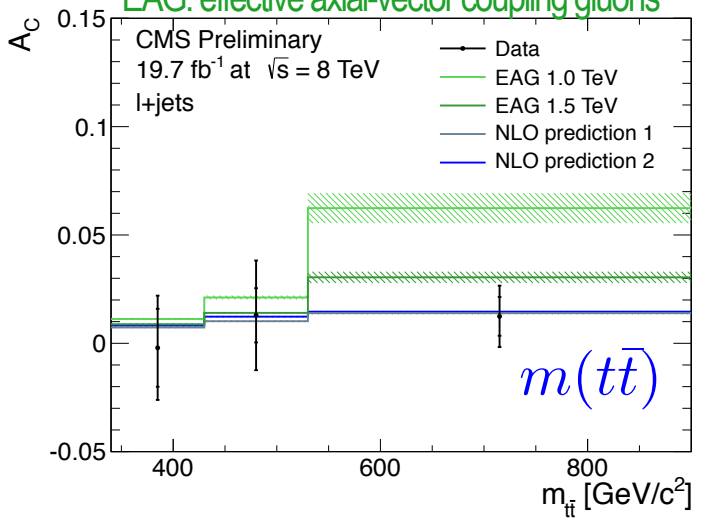
$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

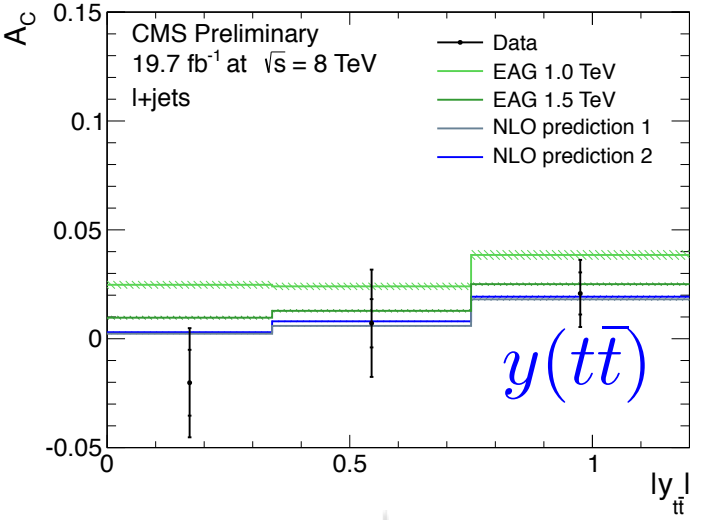
Charge-Asymmetry

TOP-12-033



EAG: effective axial-vector coupling gluons





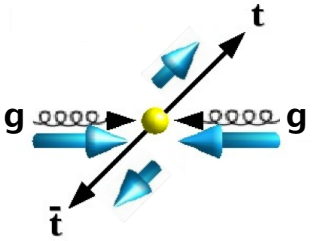
$A_{C,top} = 0.4 \pm 1.0_{stat} \pm 1.1_{syst}$ % PLB 717 (2012) 129

$A_{C,top} = 0.5 \pm 0.7_{stat} \pm 0.6_{syst}$ % TOP-12-033

QCD: $A_{C,top} = 1.23 \pm 0.05$ % Bernreuther, Si arXiv:1205.6580

NNLO prediction underway
Differential distributions give additional sensitivity

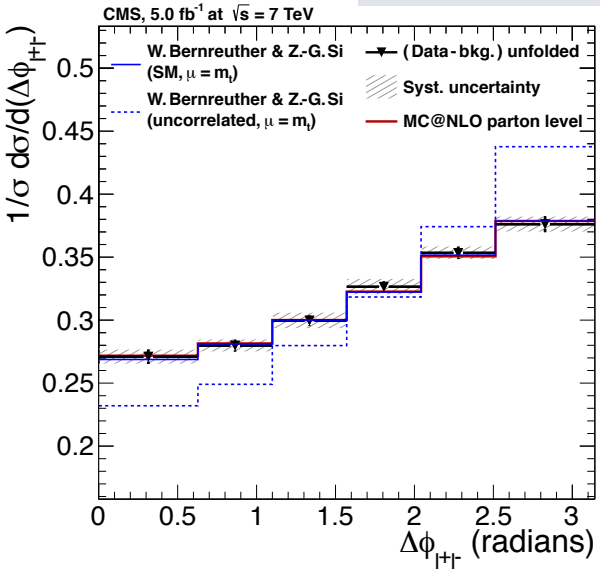
Spin Correlations



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

Top quarks decay before spins can flip → measure

PRL 112 (2014) 182001



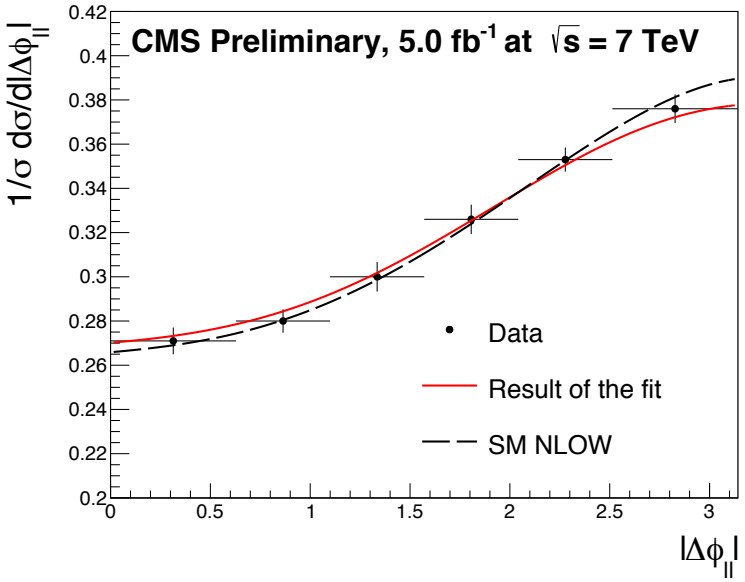
$$A_{\Delta\phi} = \frac{N(\Delta\phi_{\ell^+\ell^-} > \pi/2) - N(\Delta\phi_{\ell^+\ell^-} < \pi/2)}{N(\Delta\phi_{\ell^+\ell^-} > \pi/2) + N(\Delta\phi_{\ell^+\ell^-} < \pi/2)}$$

$A_{helicity} = 0.113 \pm 0.010_{stat} \pm 0.007_{syst} \pm 0.012_{syst}$

$A_{SM} = 0.115 \pm 0.015$ $A_{uncorr} = 0.210$

$\Rightarrow f_{CMS} \sim 1.02$

TOP-14-005



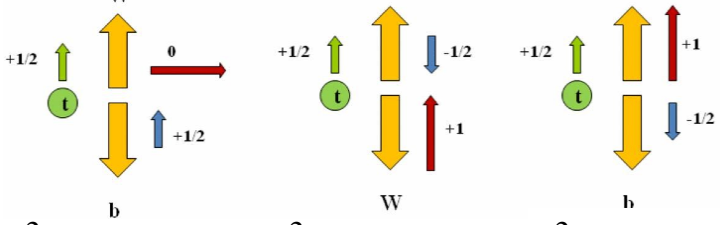
$$\mathcal{L}_{eff} = -\frac{\tilde{\mu}_t}{2}\bar{t}\sigma^{\mu\nu}T^a t G^a_{\mu\nu} - \frac{\tilde{d}_t}{2}i\sigma^{\mu\nu}\gamma_5 T^a t G^a_{\mu\nu},$$

Search for chromomagnetic dipole-moments

$-0.043 < Re(\mu) < 0.117$ at 95% CL

Limited by scale uncertainties

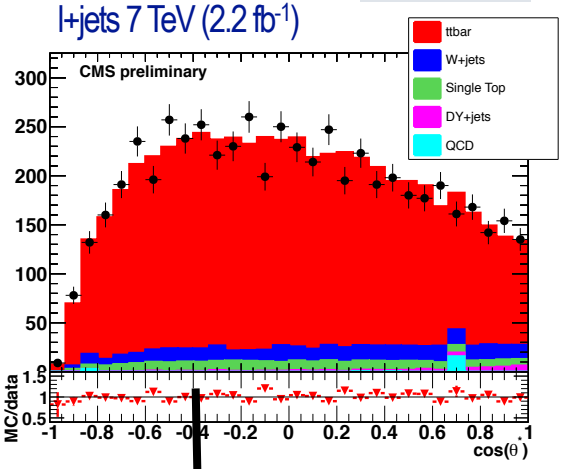
W Polarization



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

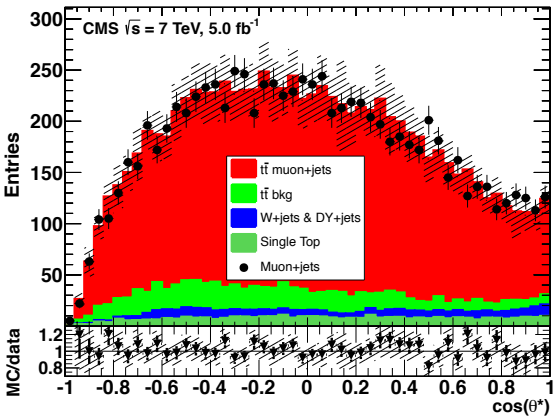
TOP-11-020

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



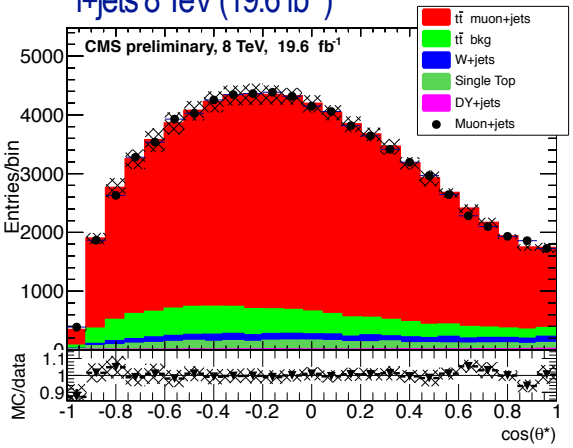
JHEP 10 (2013) 167

l+jets 7 TeV (5.0 fb^{-1})



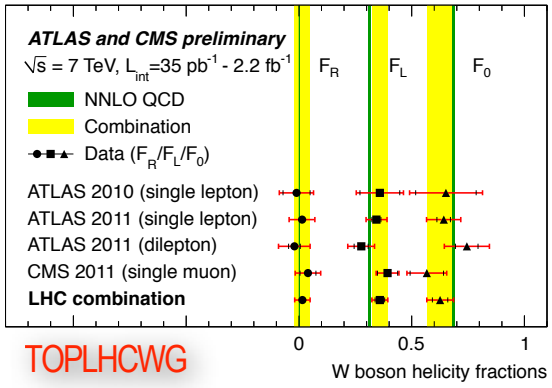
TOP-13-008

l+jets 8 TeV (19.6 fb^{-1})



TOP-12-025

CMS-ATLAS combination



TOPLHCWG

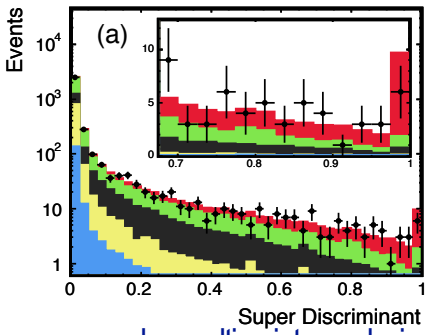
- **Also available from CMS: dileptons (7 TeV) and single-top topologies (7 and 8 TeV)** TOP-12-020 TOP-12-015

All measurements consistent with left-handed charged currents
Used to set limits on anomalous couplings

Single Top Production

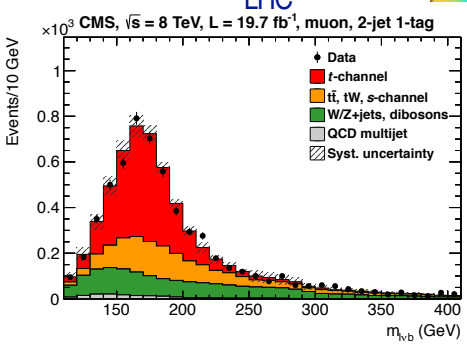
- Test of EW interactions
- V_{tb} / 4th generation / FCNC
- Sensitivity to b-PDF and u/d-PDF

CDF: 2009

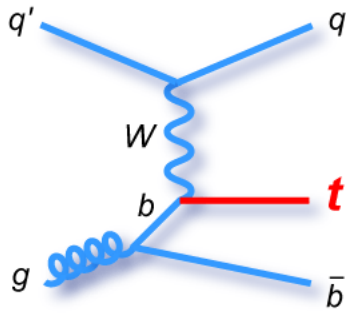


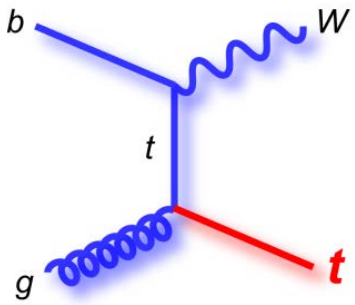
complex multivariate analysis

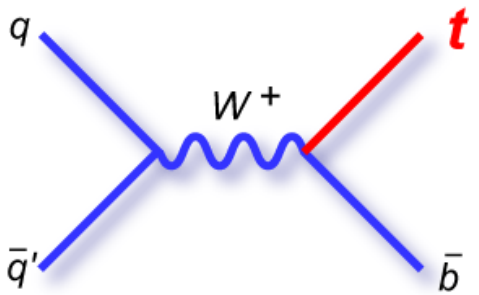
LHC



simple kinematic analysis



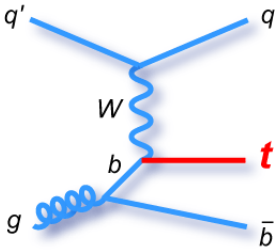




		t ch.	tW ch.	s ch.	$t\bar{t}$
Tevatron ($p\bar{p}$)	2 TeV	2.08pb	0.25pb	1.05pb	7.08pb
LHC (pp)	7 TeV	64.6pb	15.6pb	4.59pb	172pb
	8 TeV	87.6pb	22.2pb	5.55pb	249pb
	14 TeV	248pb (×3.2)	84.8pb (×3.8)	11.9pb (×2.1)	954pb (×3.9)

LHC: much more gluons, leading to very different relative contributions

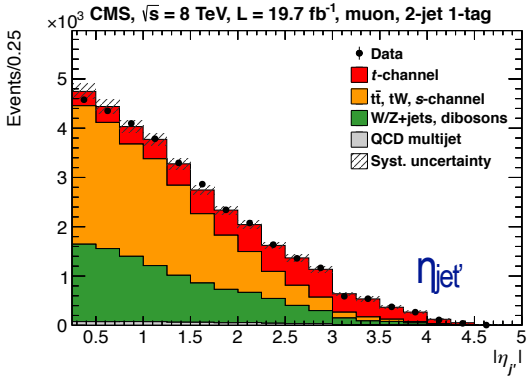
t-Channel

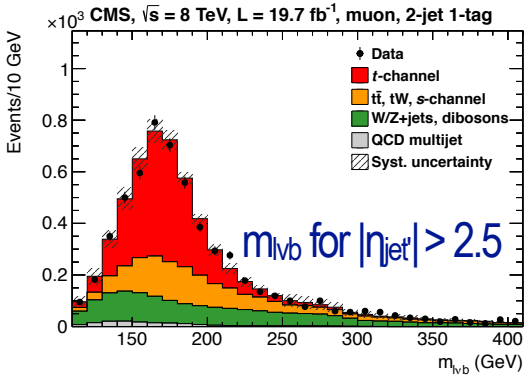


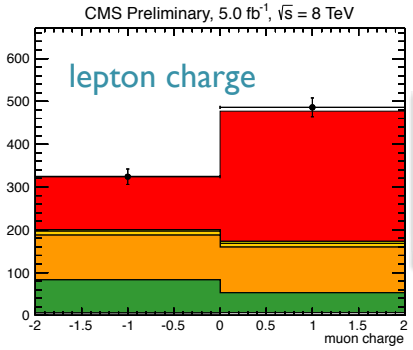
JHEP 06 (2014) 090

- Cut-based analysis
- One e or μ, 2jets-1b-tag events in reco'd top mass window
- Backgrounds determined from fit to $\eta_{jet'}$ distribution
- Total cross-section

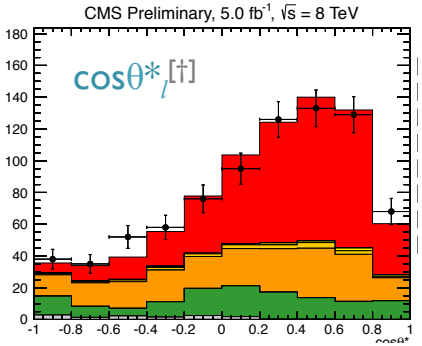
σ_t (8 TeV):	$83.6 \pm 2.3_{stat} \pm 7.4_{syst}$ pb
$V_{td}, V_{ts} \ll V_{tb}$, unconstrained:	0.979 ± 0.045 (exp.) ± 0.016 (theo)
constrained < 1 @ 95% CL:	> 0.92







Top/Anti-top cross-section ratio



Single-top polarization — TOP-13-001

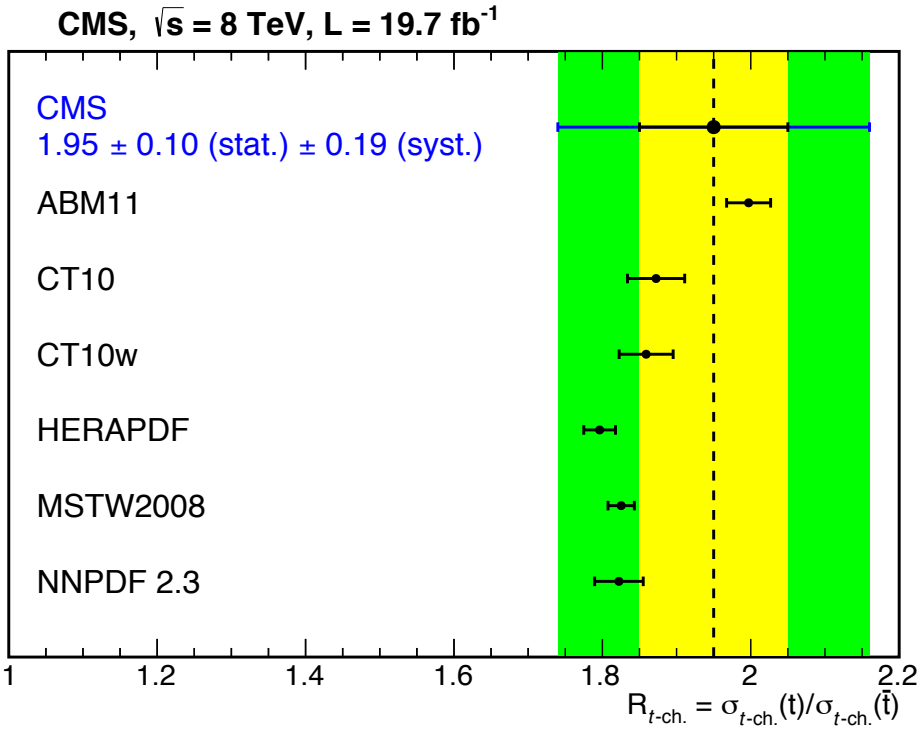
W-helicity — TOP-12-020

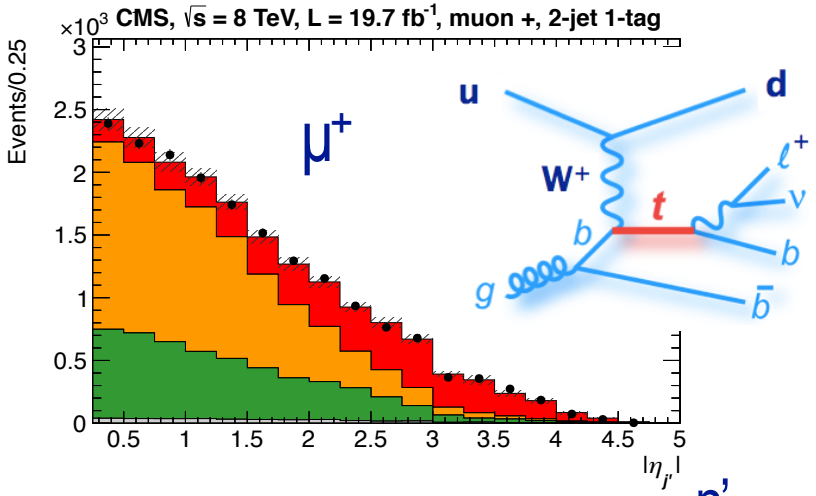
Large program of detailed studies (diff. distributions, properties, couplings, QCD studies) → CMS Runs 1 and 2

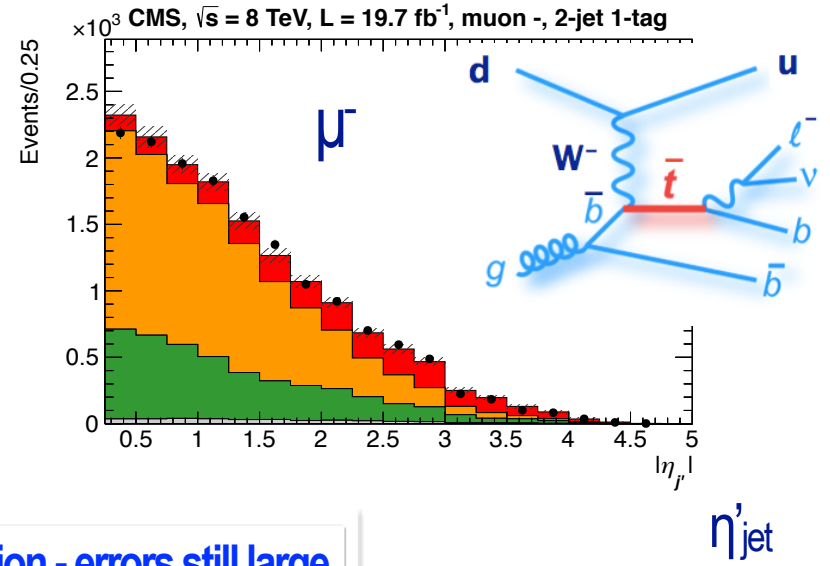
t-Channel: PDF from $\sigma_t/\sigma_{\bar{t}}$

JHEP 06 (2014) 090

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

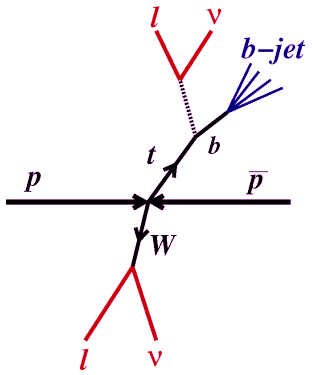






Consistent with expectation - errors still large

tW-Channel



- **Event Signature**
  - 2 e or μ, 1 jet (b-tagged)
- **Analysis**
  - Binned likelihood fit to BDT
- **Dominant uncertainties:**
  - statistics, b-tagging, tt bg-model

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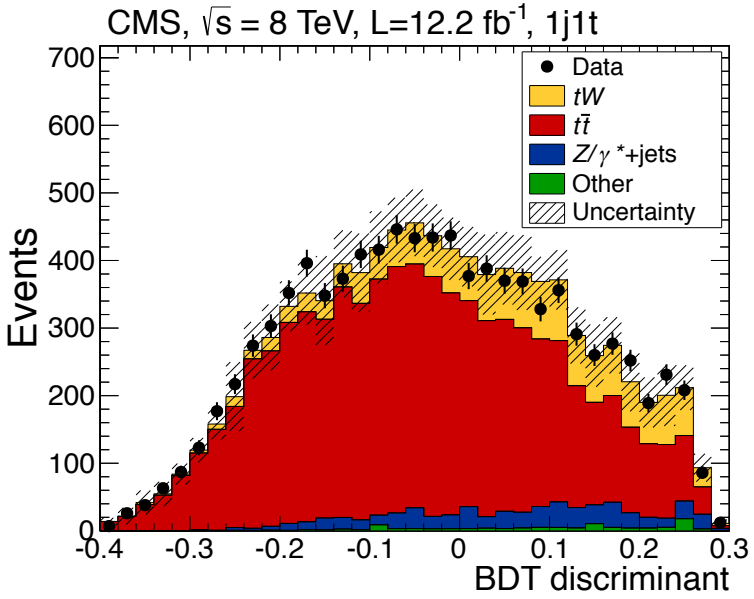
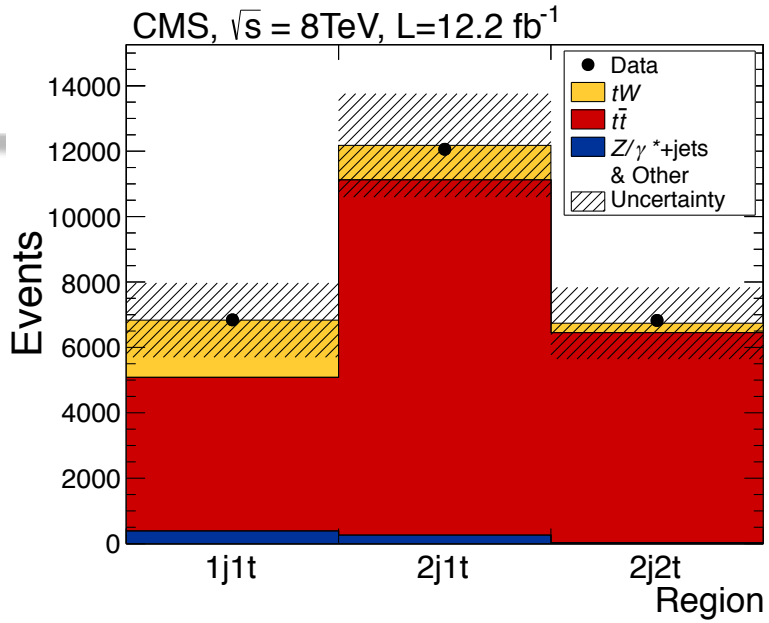


6.1σ obs. (5.4σ exp.)

σ_{tW} (8 TeV):	23.4 + 5.5-5.4$_{stat+syst}$ pb
$V_{td}, V_{ts} \ll V_{tb}$, unconstrained:	1.03 ± 0.12 (exp.) ± 0.04 (theo)
constrained < 1 @ 95% CL:	> 0.78

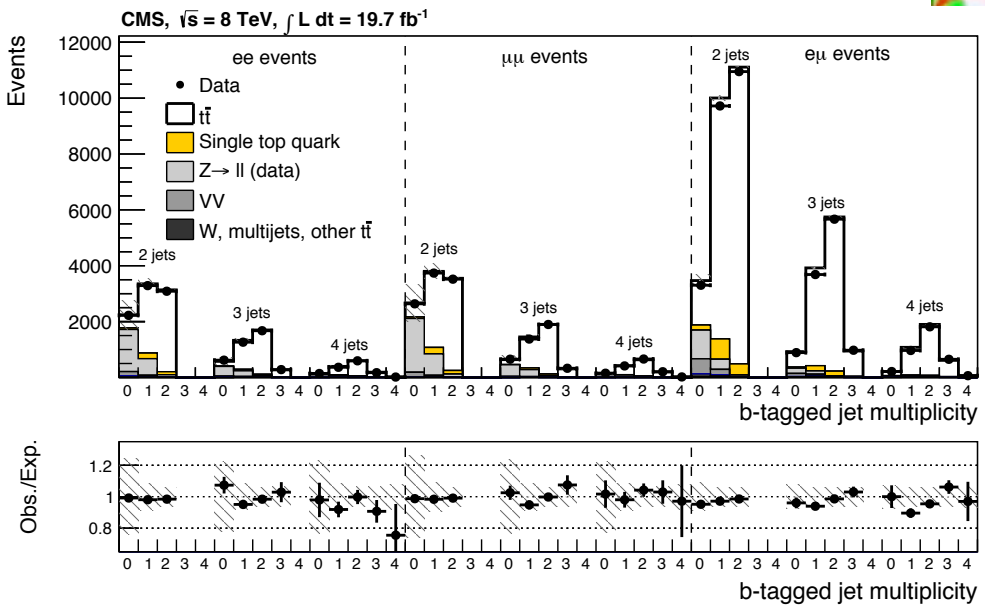
Observation! Agrees with SM



R_B = BR (tWb) / BR (tWq)

PLB 736 (2014) 33

- 2 leptons, 2 jets, MET
- R_B from fit to b-tag multiplicity
  - data-driven determination of correct jet-assignment fraction, b-tag efficiency and misidentification
- Dominant systematics: b-tag and m_{top}
- $|V_{tb}|$ from R_B assuming unitary CKM
- Total width Γ_{top} from R_B and t-channel single top cross section



measured t-channel (7 TeV)

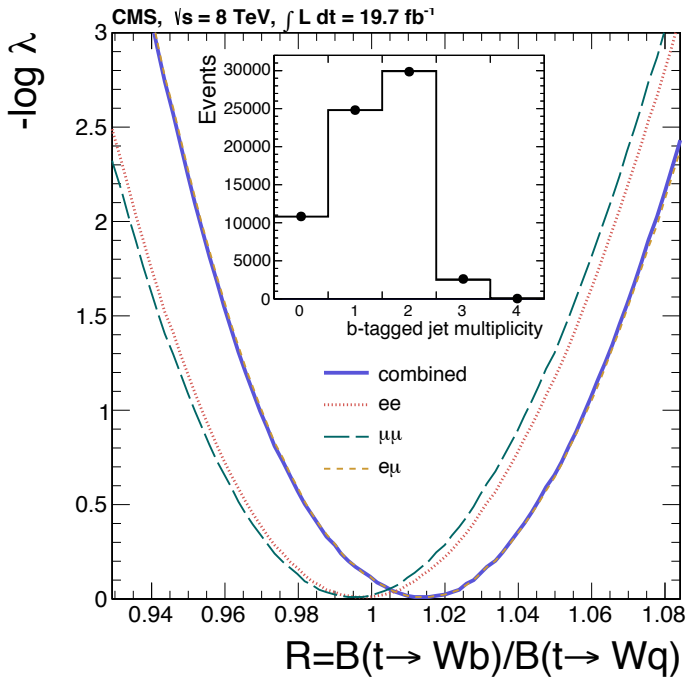
$$\Gamma_t = \frac{\sigma_{t\text{-ch.}}}{\mathcal{B}(t \to Wb)} \cdot \frac{\Gamma(t \to Wb)}{\sigma^{\text{theor.}}_{t\text{-ch.}}}$$

measured R

theory

R	unconstrained	1.014 ± 0.003 ± 0.032
$\|V_{tb}\|$	constrained < 1 @ 95% CL	> 0.972
Γ_{top}		1.36 ± 0.02$_{stat}$ + 0.14$_{syst}$ - 0.11$_{syst}$ GeV

Most precise direct measurement of $|V_{tb}|$



Wtb-Couplings: $|V_{tb}|$ Summary

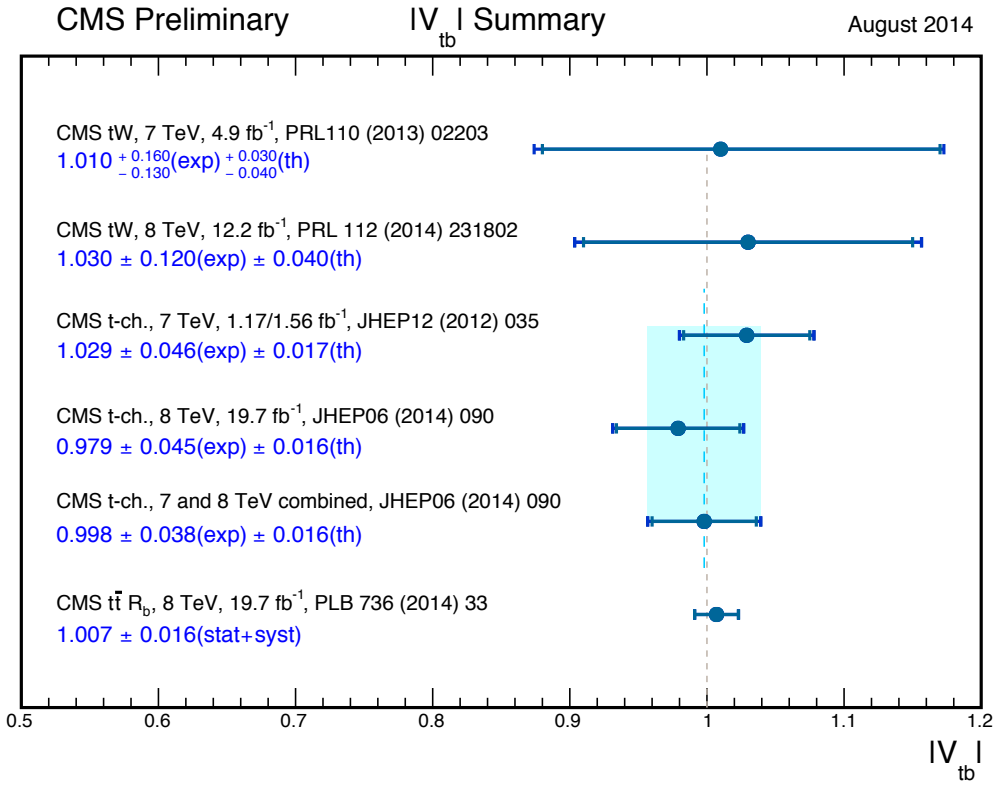
$$\mathfrak{L} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}\left(f_V^L P_L + f_V^R P_R\right) tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}\partial_{\nu}W_{\mu}^{-}}{M_W}\left(f_T^L P_L + f_T^R P_R\right) t + h.c.$$

vector operators

tensor operators

$$|V_{td}|, |V_{ts}| << |V_{tb}|, Br \cong 1 \rightarrow |f_V^L V_{tb}| = \sqrt{\frac{\sigma_{t-ch.}}{\sigma_{t-ch.}^{theo.}}}$$

$$SM: \; f_V^L = V_{tb}, \; f_V^R = f_T^L = f_V^R = 0 \text{ (at tree level)}$$



tW (7 TeV)	$1.01^{+0.16}_{-0.13}{}_{exp}{}^{+0.03}_{-0.04}{}_{theo}$
tW (8 TeV)	$1.03 \pm 0.12_{exp} \pm 0.04_{theo}$
t (7 TeV)	$1.020 \pm 0.046_{exp} \pm 0.017_{theo}$
t (8 TeV)	$0.979 \pm 0.045_{exp} \pm 0.016_{theo}$
t (7+8 TeV)	$0.998 \pm 0.038_{exp} \pm 0.016_{theo}$
R	1.007±0.016 (stat+syst.)

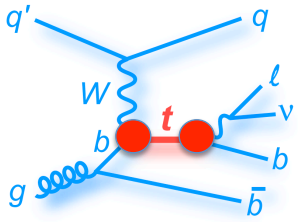
Anomalous Wtb-Couplings

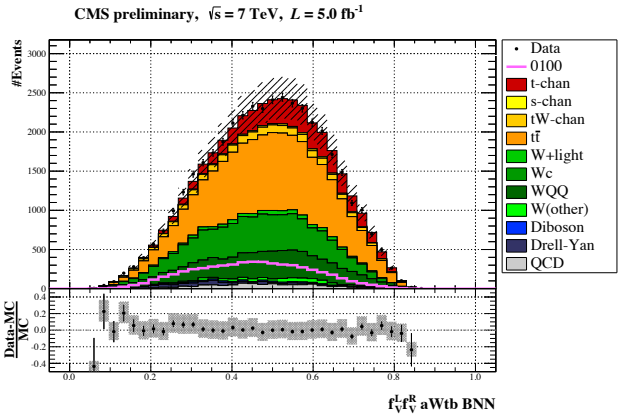
$$\mathfrak{L} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}\left(f_V^L P_L + f_V^R P_R\right) tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}\partial_{\nu}W_{\mu}^{-}}{M_W}\left(f_T^L P_L + f_T^R P_R\right) t + h.c.$$

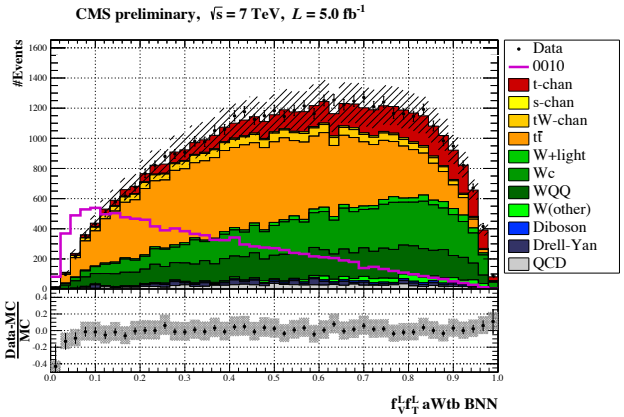
vector operators

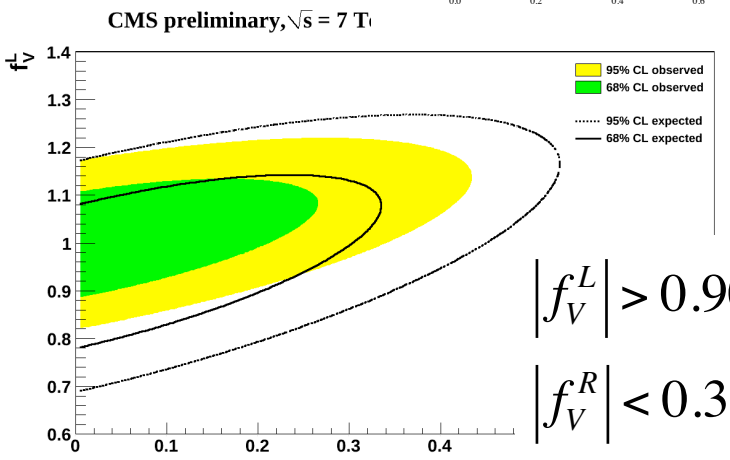
tensor operators

TOP-14-007



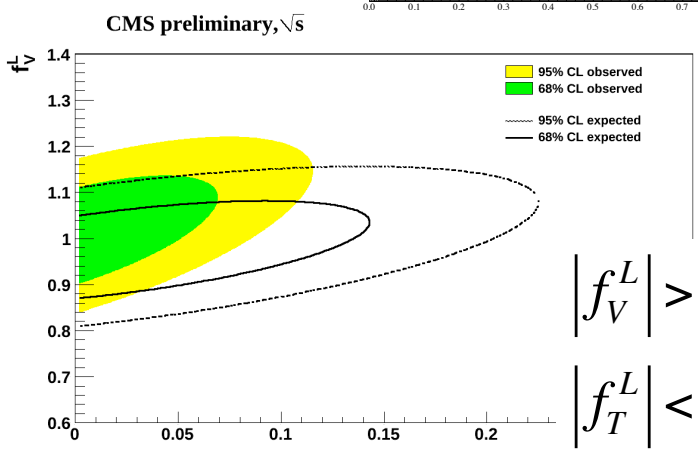






$$\left|f_V^L\right| > 0.90\,(0.88)$$

$$\left|f_V^R\right| < 0.34\,(0.39)$$

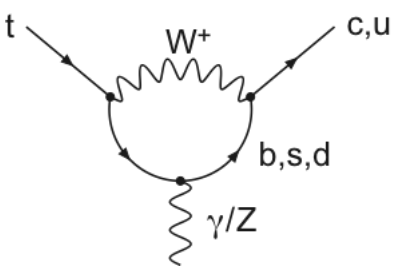


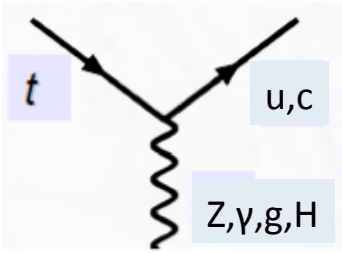
$$\left|f_V^L\right| > 0.92\,(0.88)$$

$$\left|f_T^L\right| < 0.09\,(0.16)$$

Update using full Run-I statistics underway

Rare Top decays: FCNC





ACTA Phys. Pol. B 35 (2004)

PRL 112(2014) 171802
PLB 718 (2013) 1252
TOP-12-021

< 0.05% (u)
< 11% (c)

TOP-14-007
PLB 712 (2012) 351

< 0.035% (*u*)
< 0.34% (*c*)

TOP-14-003

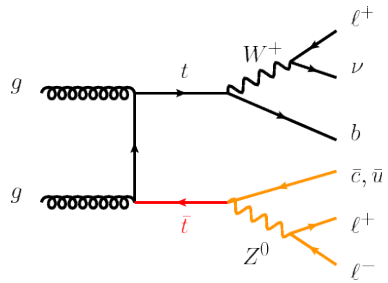
< 0.01% (*u*)
< 0.13% (*c*)

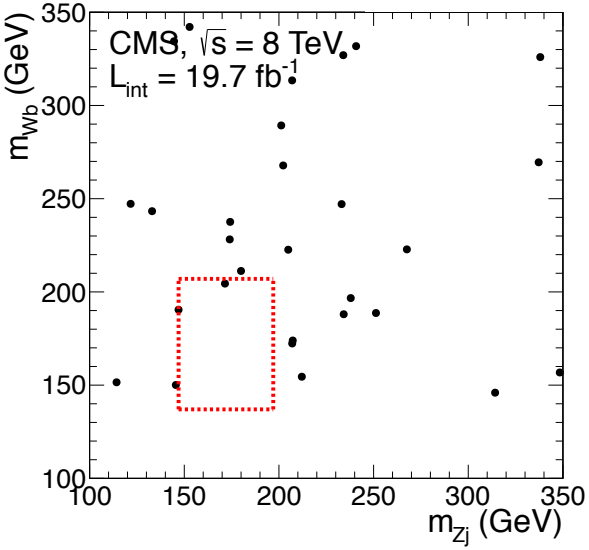
Process	SM	2HDM(FV)	2HDM(FC)	MSSM
$t \to Zu$	7×10^{-17}	–	–	$\leq 10^{-7}$
$t \to Zc$	1×10^{-14}	$\leq 10^{-6}$	$\leq 10^{-10}$	$\leq 10^{-7}$
$t \to gu$	4×10^{-14}	–	–	$\leq 10^{-7}$
$t \to gc$	5×10^{-12}	$\leq 10^{-4}$	$\leq 10^{-8}$	$\leq 10^{-7}$
$t \to \gamma u$	4×10^{-16}	–	–	$\leq 10^{-8}$
$t \to \gamma c$	5×10^{-14}	$\leq 10^{-7}$	$\leq 10^{-9}$	$\leq 10^{-8}$
$t \to hu$	2×10^{-17}	6×10^{-6}	–	$\leq 10^{-5}$
$t \to hc$	3×10^{-15}	2×10^{-3}	$\leq 10^{-5}$	$\leq 10^{-5}$

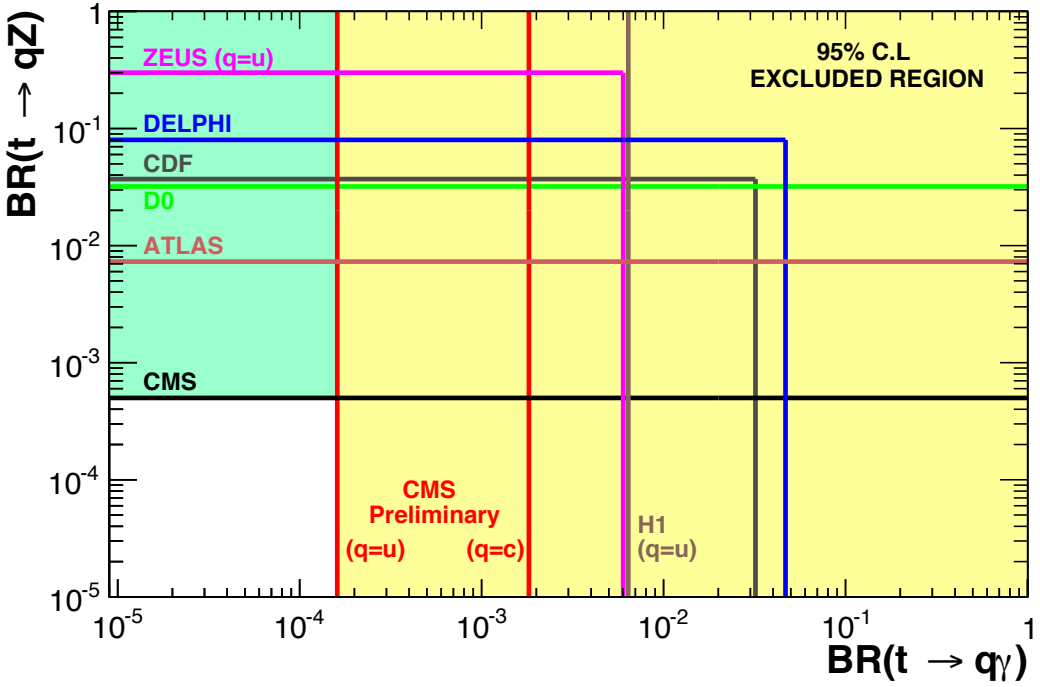
FCNC couplings can be probed in production (single top) and decay of top quarks

Rare Top decays: FCNC

PRL 112 (2014) 171802

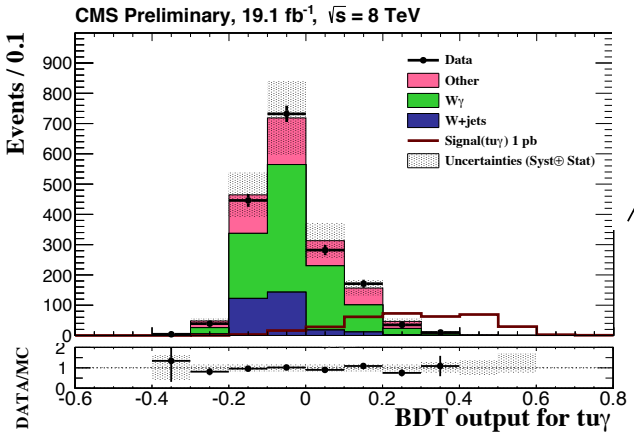


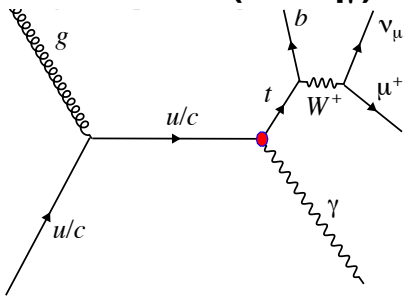




- tqZ: select 3-lepton events and look for Zj-resonance in top-mass window

- tqγ: Use BDT to separate tγ from Wγ (and other backgrounds)

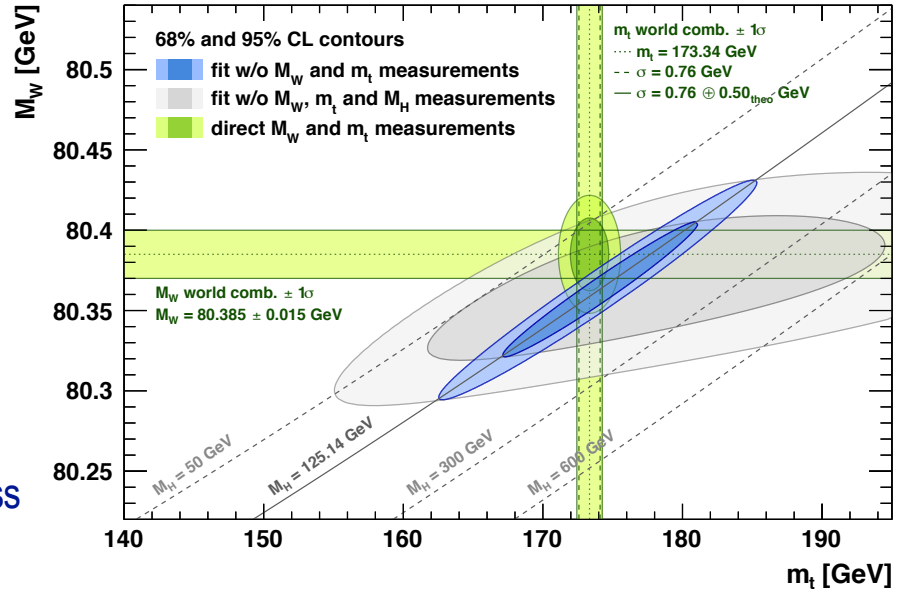




TOP-14-003

Top-Quark Mass

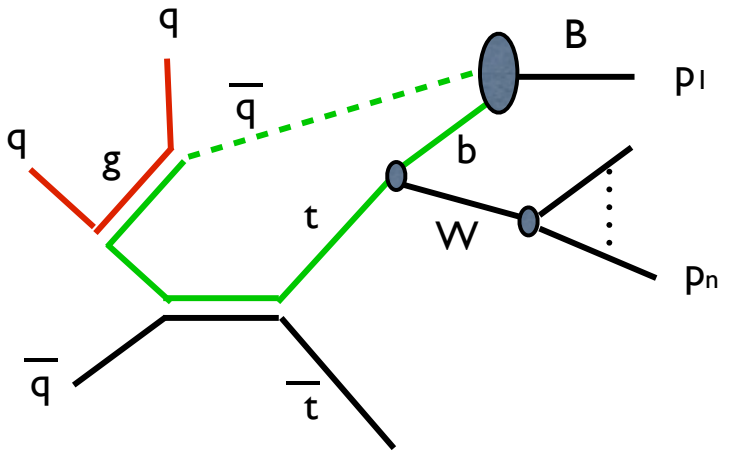
arXiv:1407.3792



- **Not an observable, i.e. scheme-dependent**
  - Pole-mass: viewing top quark as a free parton
  - $\overline{\text{MS}}$ scheme ('running mass'):

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

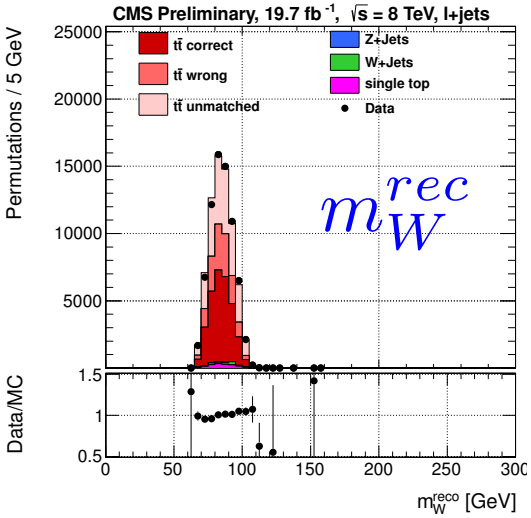
  - 'MC mass': (N)LO+PS yet different from pole or $\overline{\text{MS}}$ mass
- **MC mass believed to be close to pole mass within 0.5 GeV**
- **Experimental uncertainties due to final state modeling**
  - Hadronization
  - Fragmentation
  - Colour Reconnection
  - Flavour-dependent jet energy response

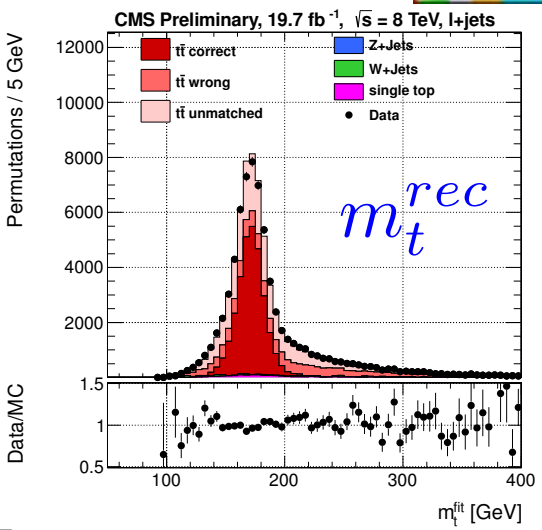


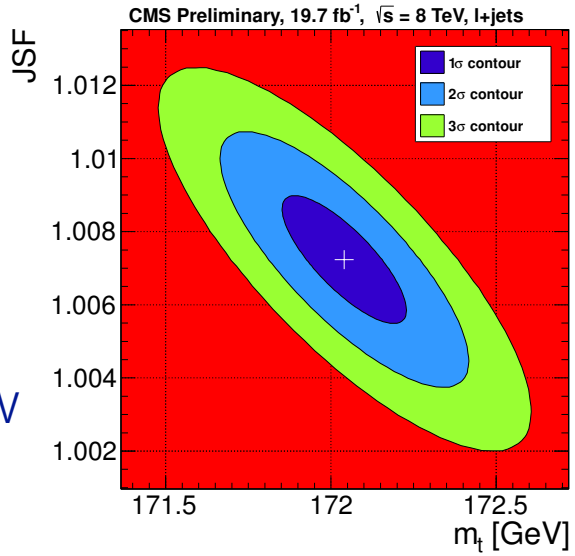
Top-Quark Mass in l+jets channel

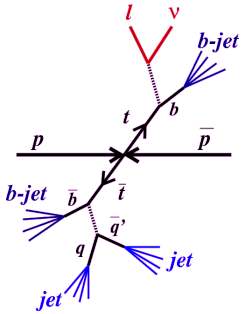
TOP-14-001

- **Signature**
  - e/μ + 4 jets, 2 b-tags (high purity selection)
- **Analysis ('2D-Ideogram')**
  - Reconstruct top mass from kin.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
- **Dominant Uncertainties**
  - Jet energy resolution: 0.26 GeV
  - Pile-up: 0.27 GeV
  - Flavour-dependent jet energy scale, includes hadronization (PYTHIA vs HERWIG) 0.41 GeV
  - ME-generator: 0.23 GeV









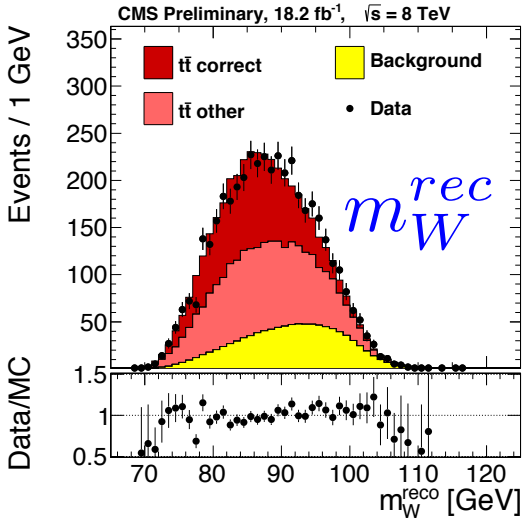
As precise as World Average

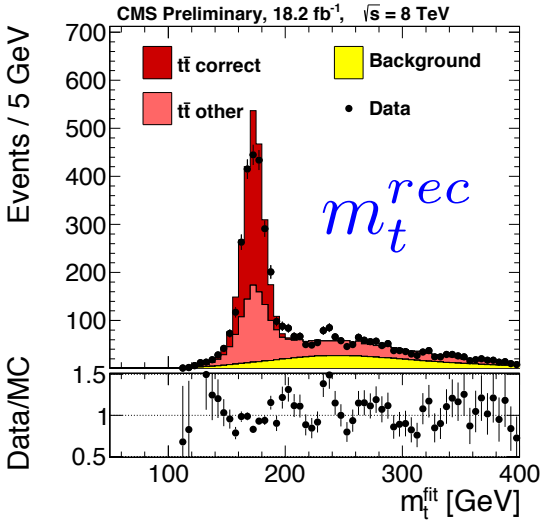
$m_{top} = 172.04 \pm 0.19_{stat+JES} \pm 0.75_{syst}$ GeV

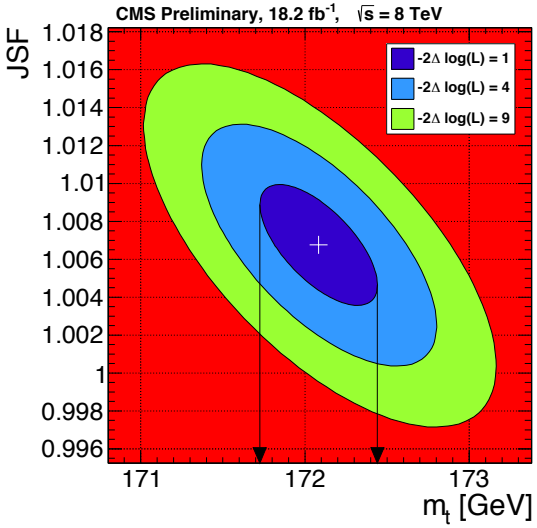
Top-Quark Mass in fully hadronic channel

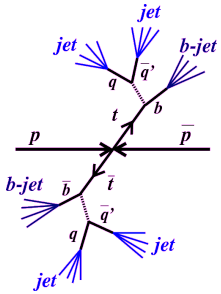
TOP-14-002

- **Signature**
  - 6 jets, 2 b-tags (high purity selection)
- **Analysis ('2D-Ideogram')**
  - Reconstruct top mass from kin.fit ($P_{gof} > 0.1$)
  - 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
- **Dominant Uncertainties**
  - p_T and η-dependent JES: 0.28 GeV
  - Pile-up: 0.31 GeV
  - Flavour-dependent jet energy scale, includes hadronization (PYTHIA vs HERWIG) 0.36 GeV
  - ME-generator: 0.21 GeV







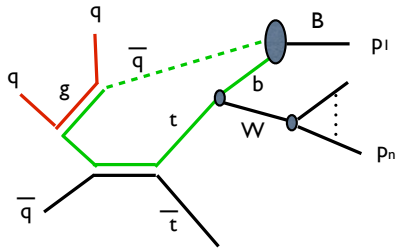


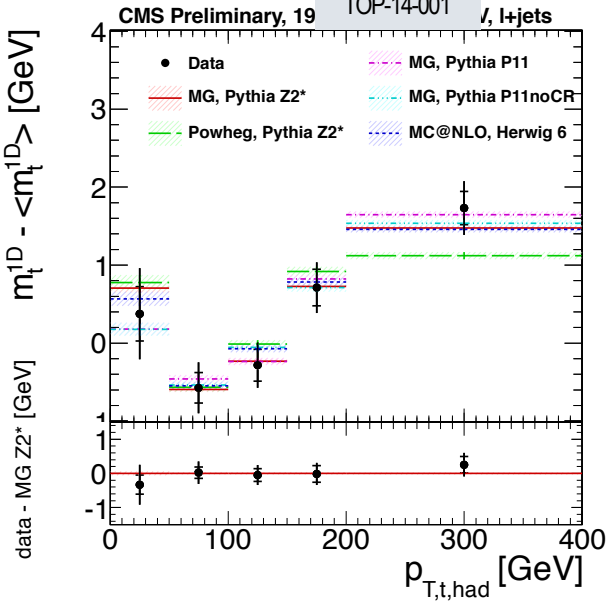
As precise as World Average

$m_{top} = 172.08 \pm 0.36_{stat+JES} \pm 0.83_{syst}$ GeV

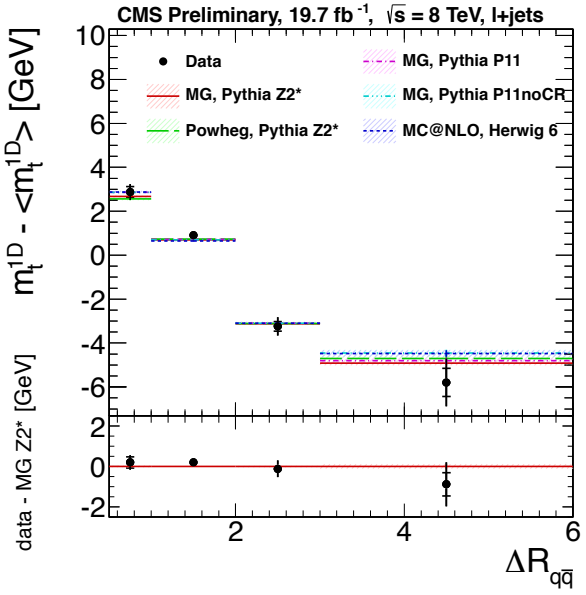
Top Mass: Kinematic Dependence

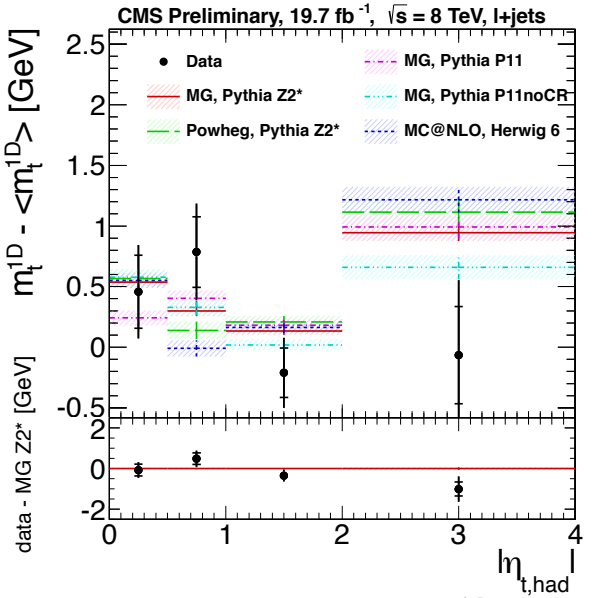
- **Investigate modelling issues: various (non-)perturbative corrections are different in their kinematic dependence**
- **Investigate distributions with sensitivity to**
  - Color reconnection
  - ISR/FSR
  - b-quark kinematics
- **Figures:** $m_{top} - \langle m_{top} \rangle$





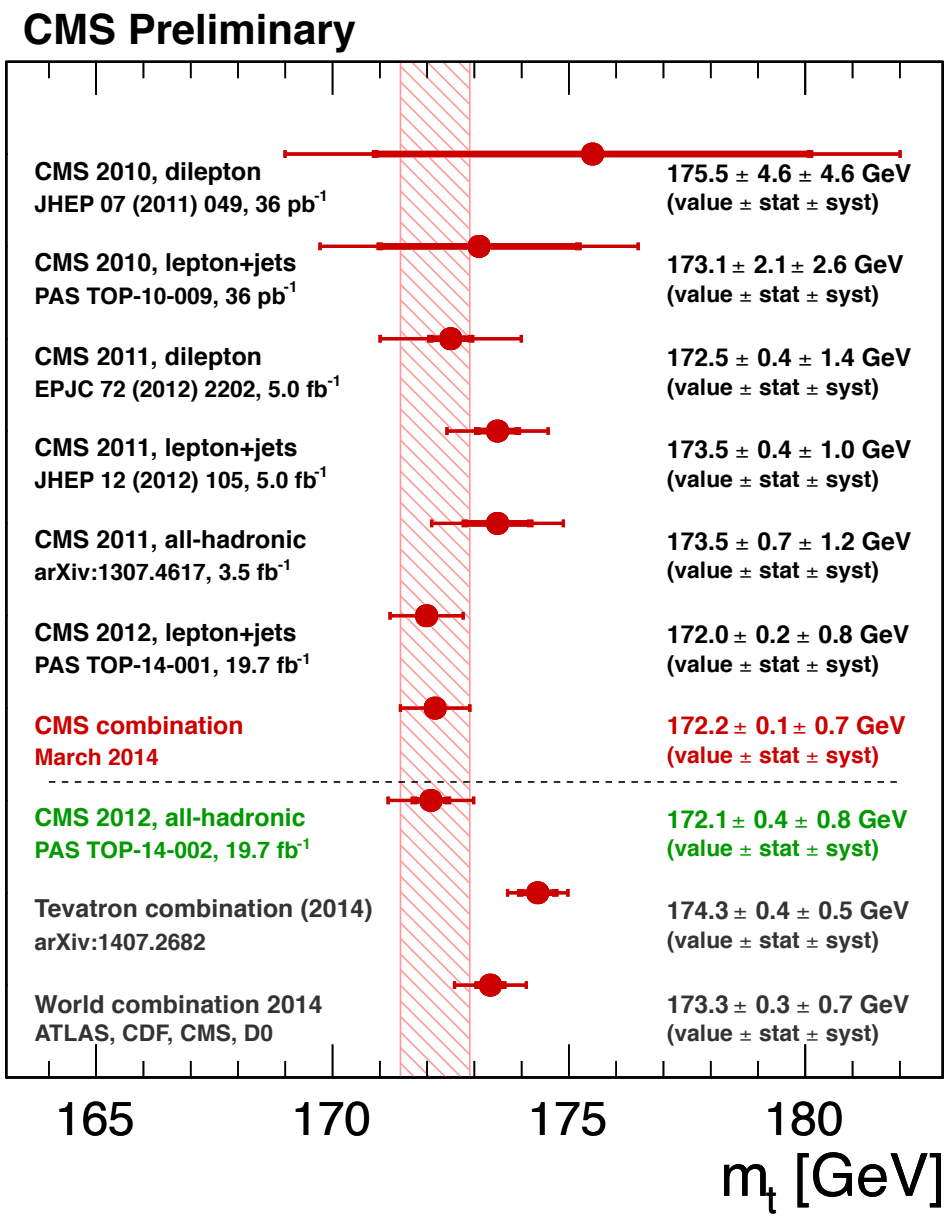
Observable	m_t^{1D} χ^2	JSF χ^2	m_t^{2D} χ^2	Ndf
$\Delta R_{q\bar{q}}$	2.87	3.66	0.83	3
$p_{T,t,had}$	0.89	12.03	5.76	4
$\lvert\eta_{t,had}\rvert$	5.56	1.22	1.14	3
H_T^4	6.19	9.18	7.54	4
$m_{t\bar{t}}$	2.16	4.69	4.22	5
$p_{T,t\bar{t}}$	1.02	1.22	1.33	4
Jet multiplicity	4.24	0.10	1.16	2
$p_{T,b,had}$	2.57	5.80	2.17	4
$\lvert\eta_{b,had}\rvert$	1.15	0.08	0.72	2
$\Delta R_{b\bar{b}}$	0.37	1.63	1.77	3
$p_{T,q,had}^1$	4.04	8.39	1.28	4
$\lvert\eta_{q,had}^1\rvert$	3.36	3.79	6.27	2
$p_{T,W,had}$	1.59	8.06	1.60	4
$\lvert\eta_{W,had}\rvert$	1.41	1.09	1.35	3
Total	37.43	60.94	37.15	47





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

Top Quark Mass Summary



Results using alternative methods not included in this summary

m(top), α_S and PDF from tt Cross Section

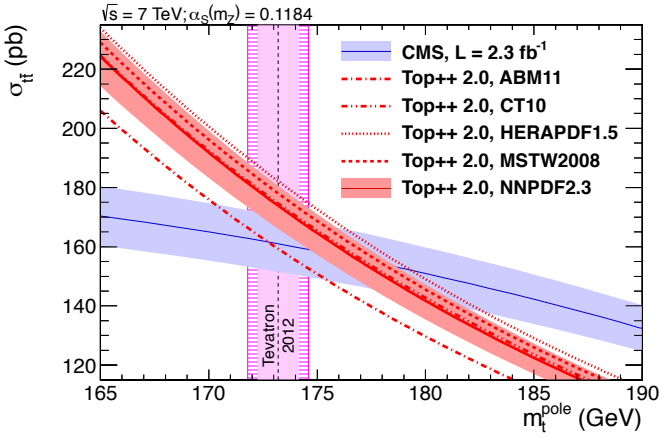
- **NNLO calculation: precise relation between cross section, pole mass, α_S and PDF**
- **Compare to most precise CMS-cross section measurement: dilepton at 7 TeV**
- **Blue band: $m_{MC}(top) = m_{pole}(top) \pm 1$ GeV**

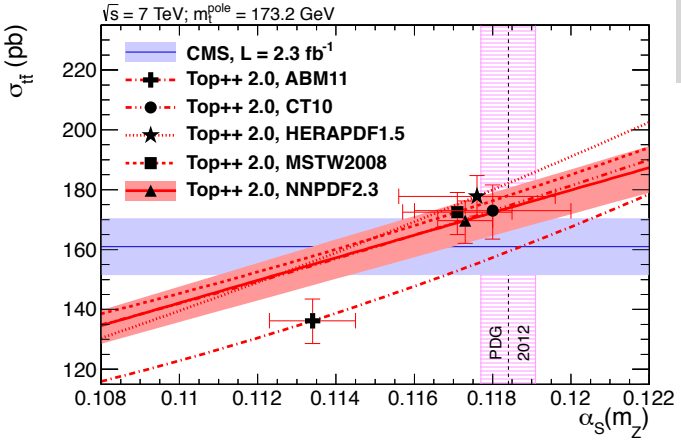
$$m_t = 176.7^{+3.0}_{-2.8}\,\text{GeV}$$

for fixed $\alpha_S = 0.1151$ and NNPDF2.3

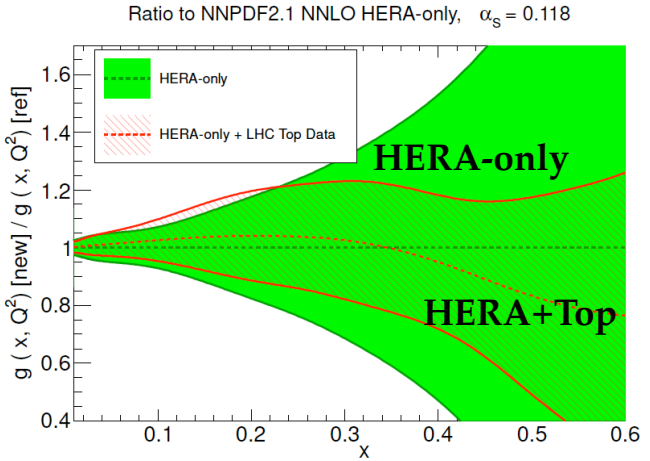
$$\alpha_S(m_Z) = 0.1151^{+0.0028}_{-0.0027}$$

for fixed $m_{top} = 173.2 \pm 1.4$ GeV and NNPDF2.3





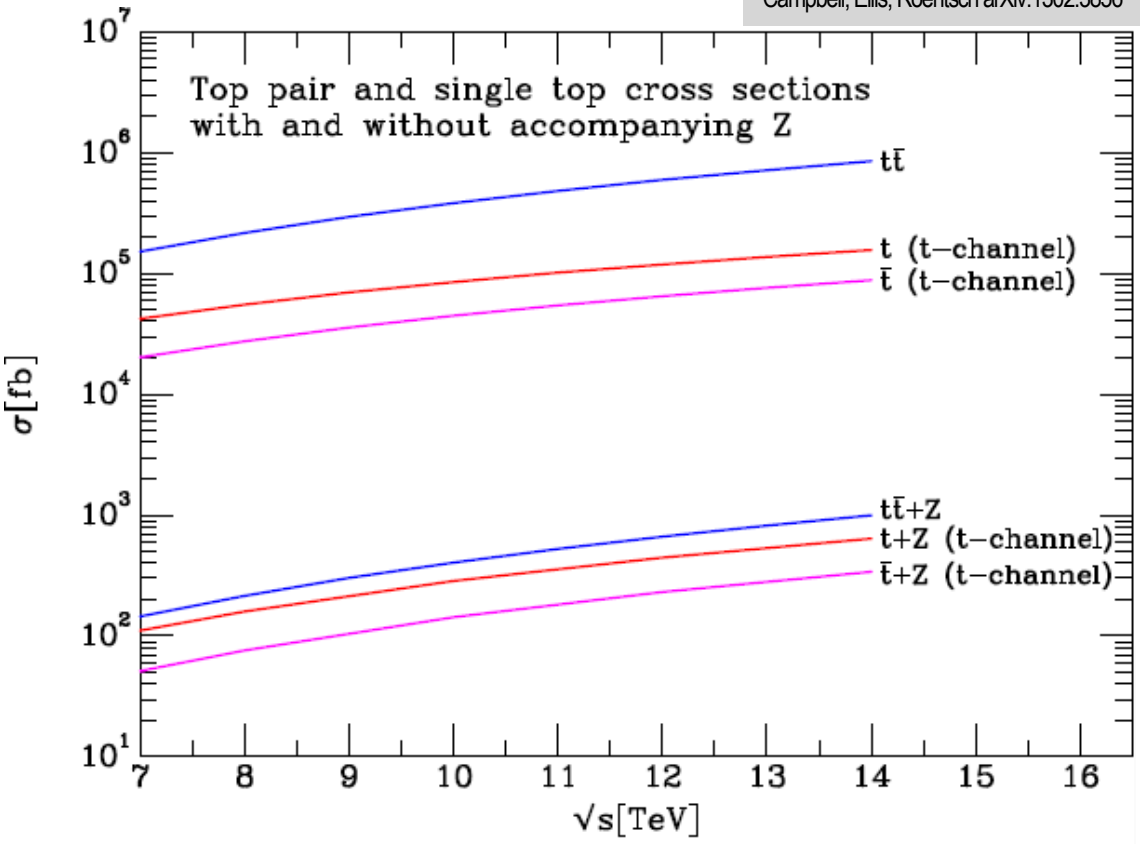
arXiv:1307.1907



J.Rojo et al arXiv 1303.7215

Outlook: Top at 13 TeV

Campbell, Ellis, Roentsch arXiv:1302.3856



10 Hz (at 10^{34})

2 Hz (at 10^{34})

0.01Hz (at 10^{34})

13/8 TeV tt and single top cross sections: factors ~4 and ~2.5 resp.

FTR-13-016

300 fb^{-1}: 3σ-evidence if B(t→Zq)>0.03%

Mangano, Rojo arXiv:1206.3557

14/8 Ratio

	$R^{\rm nnpdf}$	$\delta_{\rm PDF}(\%)$
$t\bar{t}/Z$	2.12	1.3
$t\bar{t}$	3.90	1.1
Z	1.84	0.7
W^+	1.75	0.7
W^-	1.86	0.6
W^+/W^-	0.94	0.3
W/Z	0.98	0.1
ggH	2.56	0.6
$t\bar{t}(M_{tt} \geq 1$ TeV)	8.18	2.5
$t\bar{t}(M_{\rm tt} \geq 2$ TeV)	24.9	6.3
$\sigma_{\rm jet}(p_T \geq 1$ TeV)	15.1	2.1
$\sigma_{\rm jet}(p_T \geq 2$ TeV)	181.6	7.7

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:**
  - tt and single-top production including differential distributions, tt+jets, ttbb, tttt
  - tt+W,Z,γ, charge-asymmetry, spin-correlations, W-helicity, V_{tb}, FCNC
  - mass, α_S, PDF

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

- **Run-1: CMS working on Run-1 Legacy measurements**
- **Run-2: A new regime of precision measurements and searches with top quarks**

Backup

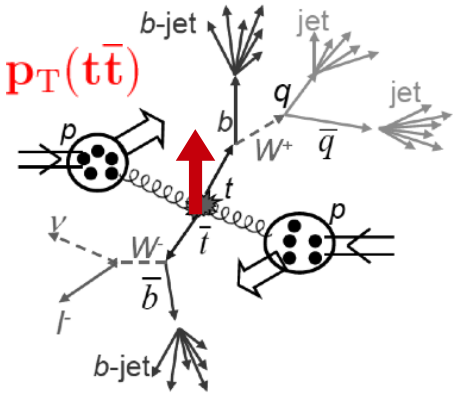
Systematics Top-Quark Mass

Channel	ℓ+jets δm_t (GeV)	ℓ+jets δJSF	All jets δm_t (GeV)	All jets δJSF
Experimental uncertainties				
Fit calibration	0.10	0.001	0.06	<0.001
p_T- and η-dependent JES	0.18	0.007	0.28	0.006
Lepton energy scale	0.03	<0.001		
Missing transverse energy	0.09	0.001		
Jet energy resolution	0.26	0.004	0.10	<0.001
b-tagging	0.02	<0.001	0.02	<0.001
Pileup	0.27	0.005	0.31	0.001
Trigger			0.18	0.003
Background	0.11	0.001	0.22	0.002
Hadronization model				
Flavor-dependent JSF	0.41	0.004	0.36	0.004
b-fragmentation	0.06	0.001	0.07	0.001
Semi-leptonic B hadron decays	0.16	<0.001	0.12	<0.001
Hard scattering process model				
PDF	0.09	0.001	0.02	<0.001
Renormalization/factorization scales	0.12±0.13	0.004±0.001	0.19±0.19	0.004±0.002
ME-PS matching threshold	0.15±0.13	0.003±0.001	0.20±0.19	0.002±0.002
ME generator	0.23±0.14	0.003±0.001	0.09±0.21	0.003±0.002
Non-perturbative QCD model				
Underlying event	0.14±0.17	0.002±0.002	0.13±0.28	0.000±0.002
Colour reconnection	0.08±0.15	0.002±0.001	0.00±0.25	0.000±0.002
Total	**0.75**	**0.012**	**0.83**	**0.011**

- Similar treatment as for 7 TeV but larger statistics (data + MC) help refining syst. assessments
- JES uncertainty component due to pileup + $\Delta\sigma_{\text{min.bias}}$
- **Signal modelling is added**
  Madgraph vs Powheg +
  modeling of top p_T estimated after re-weigthing simulation to observed top p_T
- **Hadronization** is the dominant uncertainty
  Pythia-based JES extrapolation: from calibrated jet flavour to other flavours
  Pythia vs Herwig differences are evaluated separately for light, gluon and b-jets
  b-fragmentation: default vs LEP
  Semi-leptonic B rates: from PDG

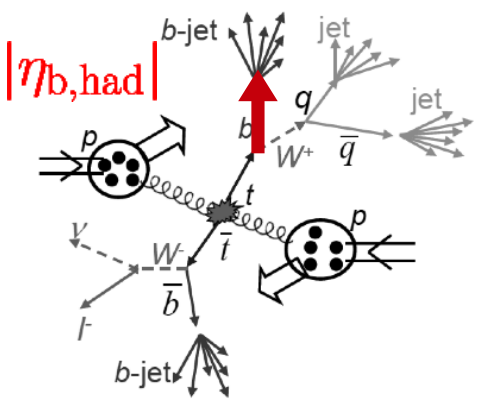
Systematics Top-Quark Mass

Radiation effects



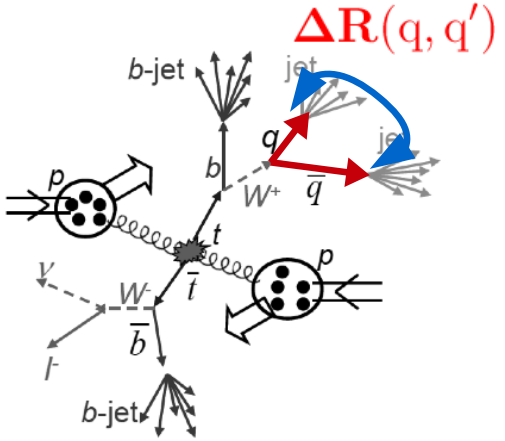
H_T $m_{t\bar{t}}$ $p_{T,t\bar{t}}$
Jet multiplicity

b-quark kinematics



$p_{T,b,had}$ $|\eta_{b,had}|$
$\Delta R_{b\bar{b}}$ $\Delta\phi_{b\bar{b}}$

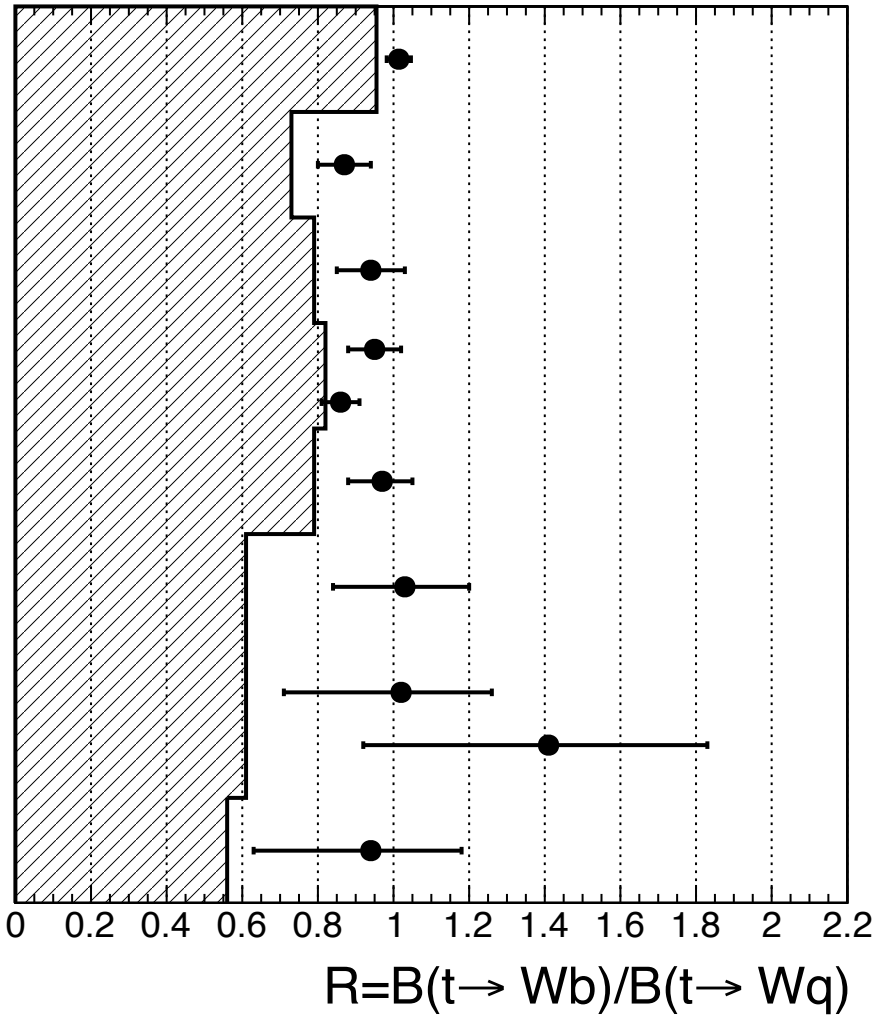
Colour reconnection



$\Delta R_{q\bar{q}}$ $\Delta\phi_{q\bar{q}}$
$p_{T,t,had}$ $|\eta_{t,had}|$

R = BR (tWb) / BR (tWq)

PLB 736 (2014) 33



ll: $1.014^{+0.032}_{-0.032}$ *CMS TOP-12-035 (2014)*

ll: **0.87±0.07** *CDF arXiv:1404.3392*

lj: $0.94^{+0.09}_{-0.09}$ *CDF PRD 87, 111101 (2014)*

lj: $0.95^{+0.07}_{-0.07}$
ll: $0.86^{+0.05}_{-0.05}$ *DØ PRL 107, 121802 (2011)*

lj: $0.97^{+0.09}_{-0.08}$ *DØ PRL 100, 192003 (2008)*

lj: $1.03^{+0.19}_{-0.17}$ *DØ PLB 639, 616 (2006)*

lj: $1.02^{+0.31}_{-0.24}$
ll: $1.41^{+0.49}_{-0.42}$ *CDF PRL 95, 102002 (2005)*

lj+ll: $0.94^{+0.31}_{-0.24}$ *CDF PRL 86, 3233 (2001)*

Chronological summary of measurements of R_B performed so far