Status of Top Quark Physics

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on behalf of
the ATLAS, CDF, CMS, and D0 Collaborations

Top Quarks at hadron colliders

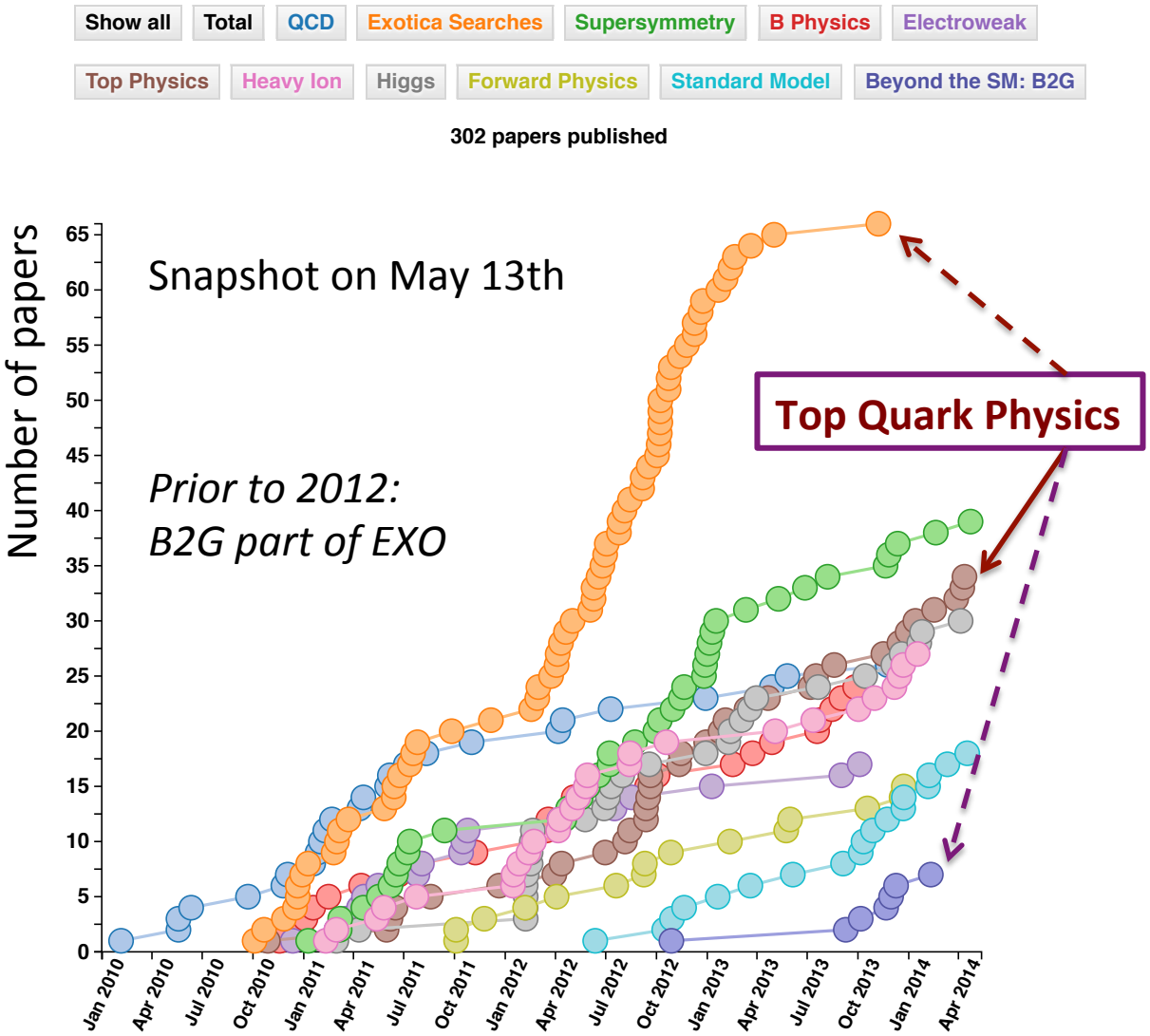
A hot topic at colliders, example from CMS.

Related talks this week:

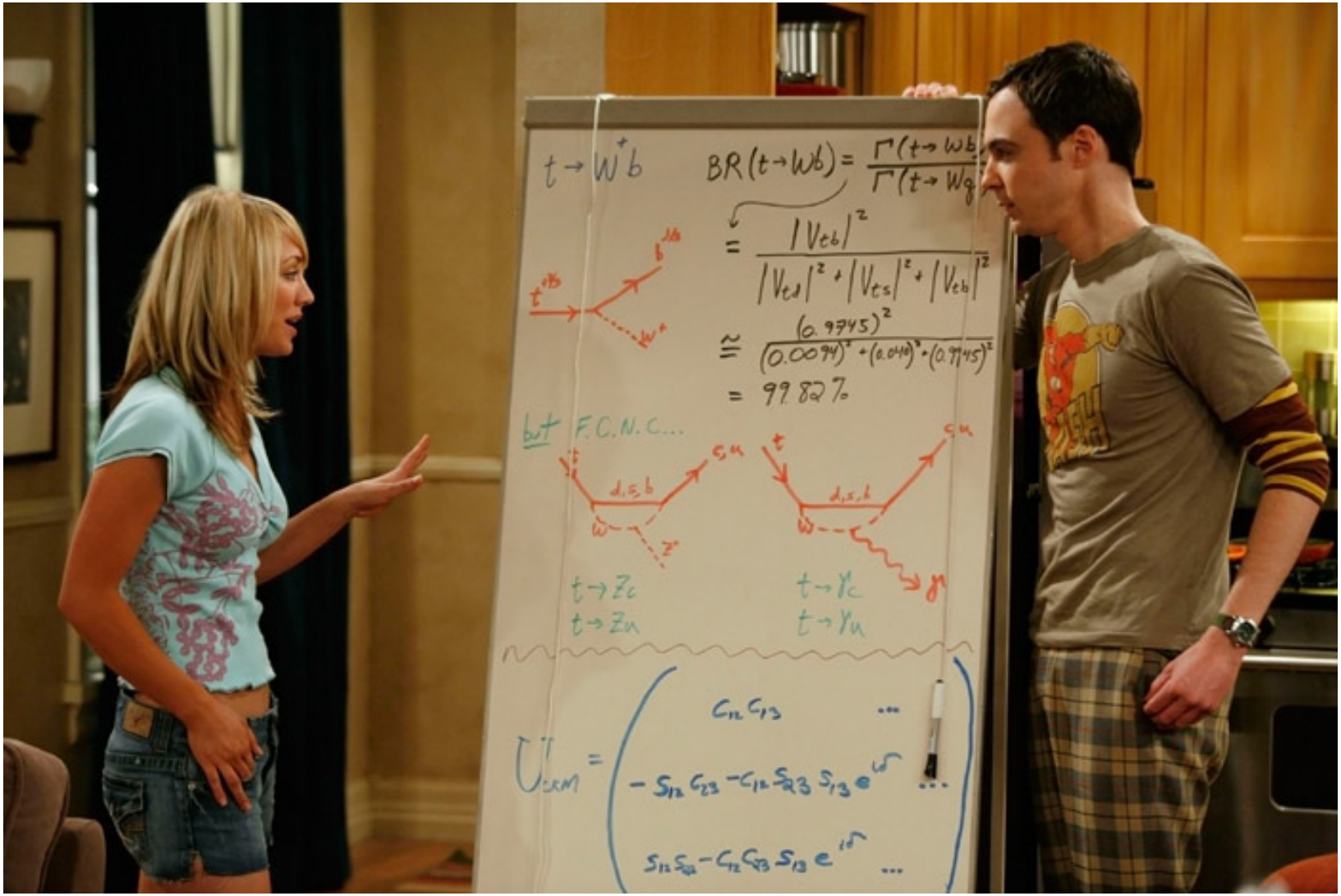
Top Quark Theory – P. Uwer

Searches w. t/b – F. Blekman

9 (!) talks in parallel session

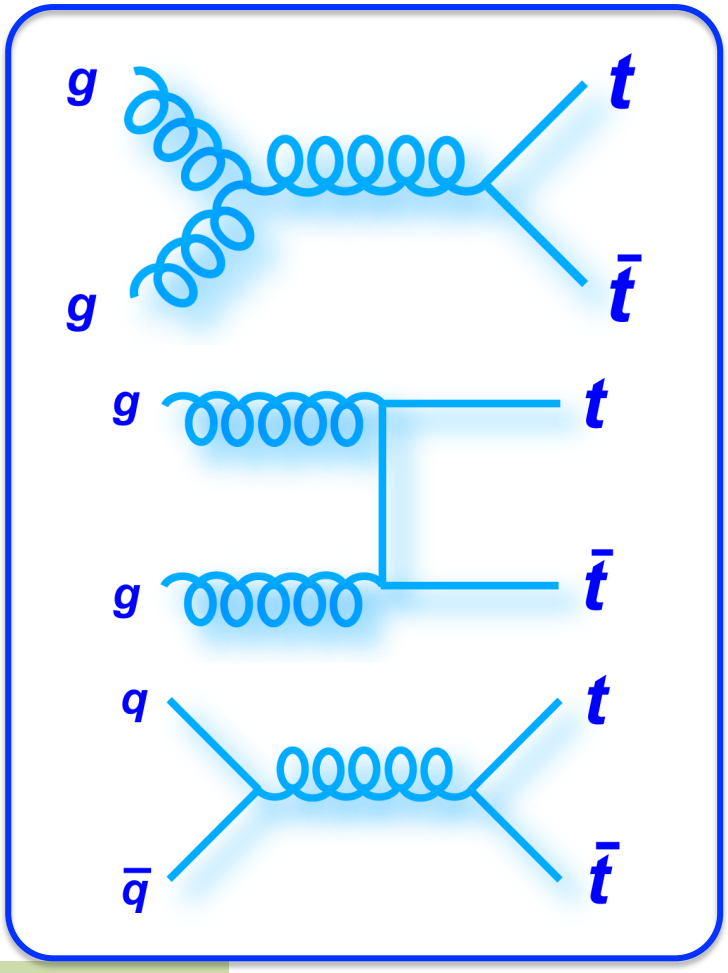


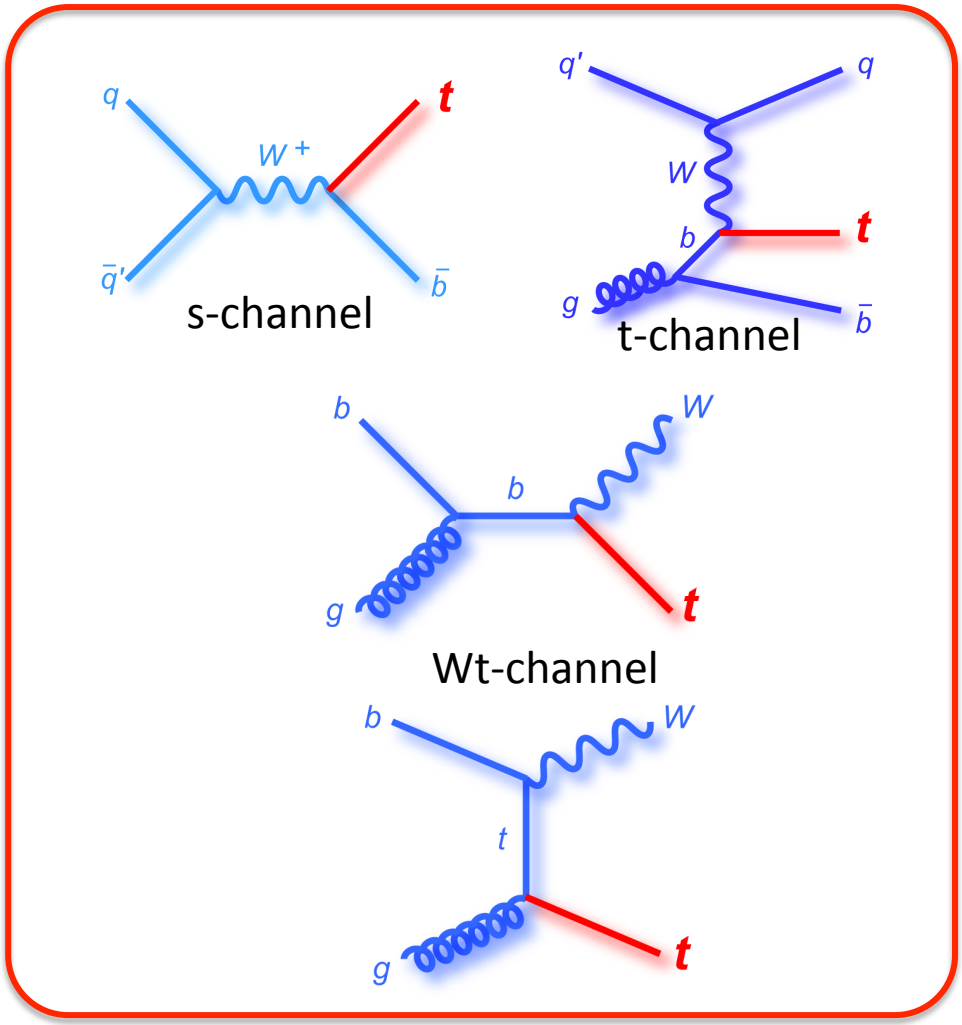
Top Quarks: a hot topic



Top Quarks at hadron colliders

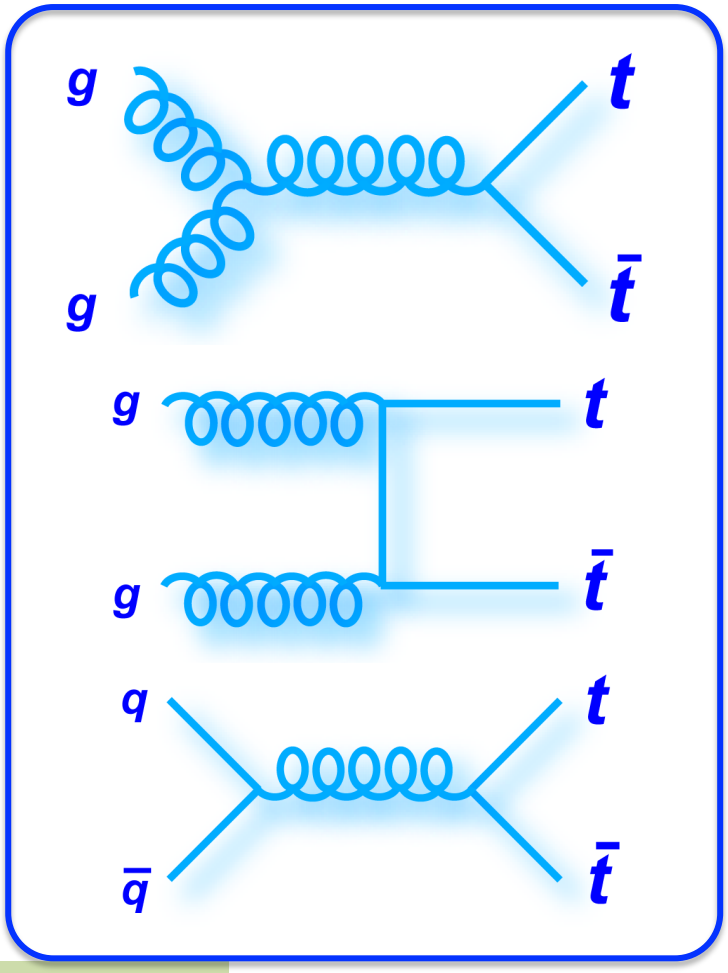
- Both strong and electroweak production

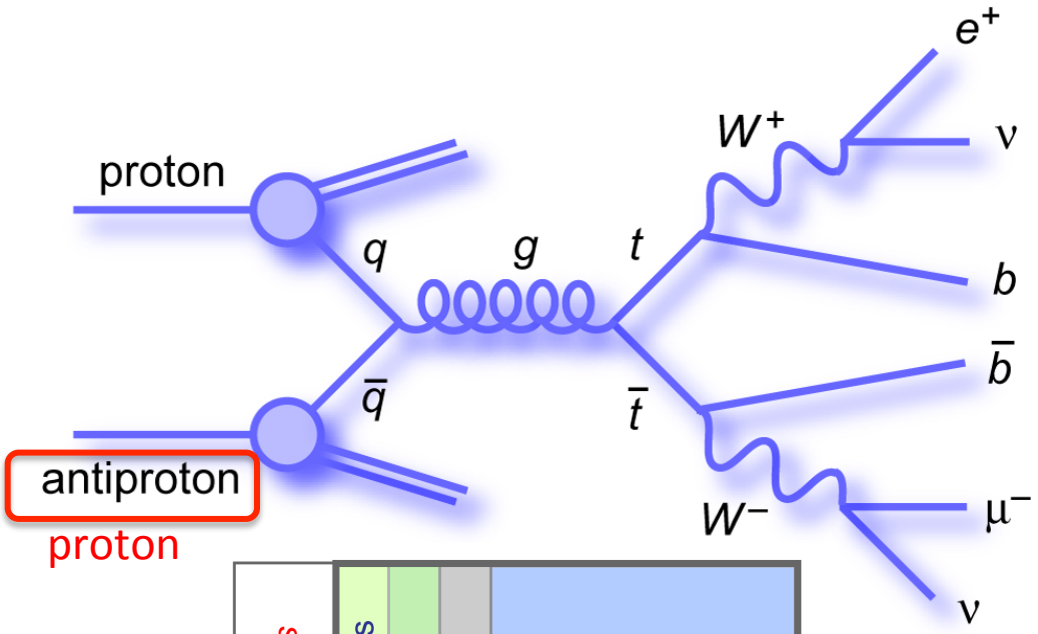




Top Quarks at hadron colliders

The strong pair production



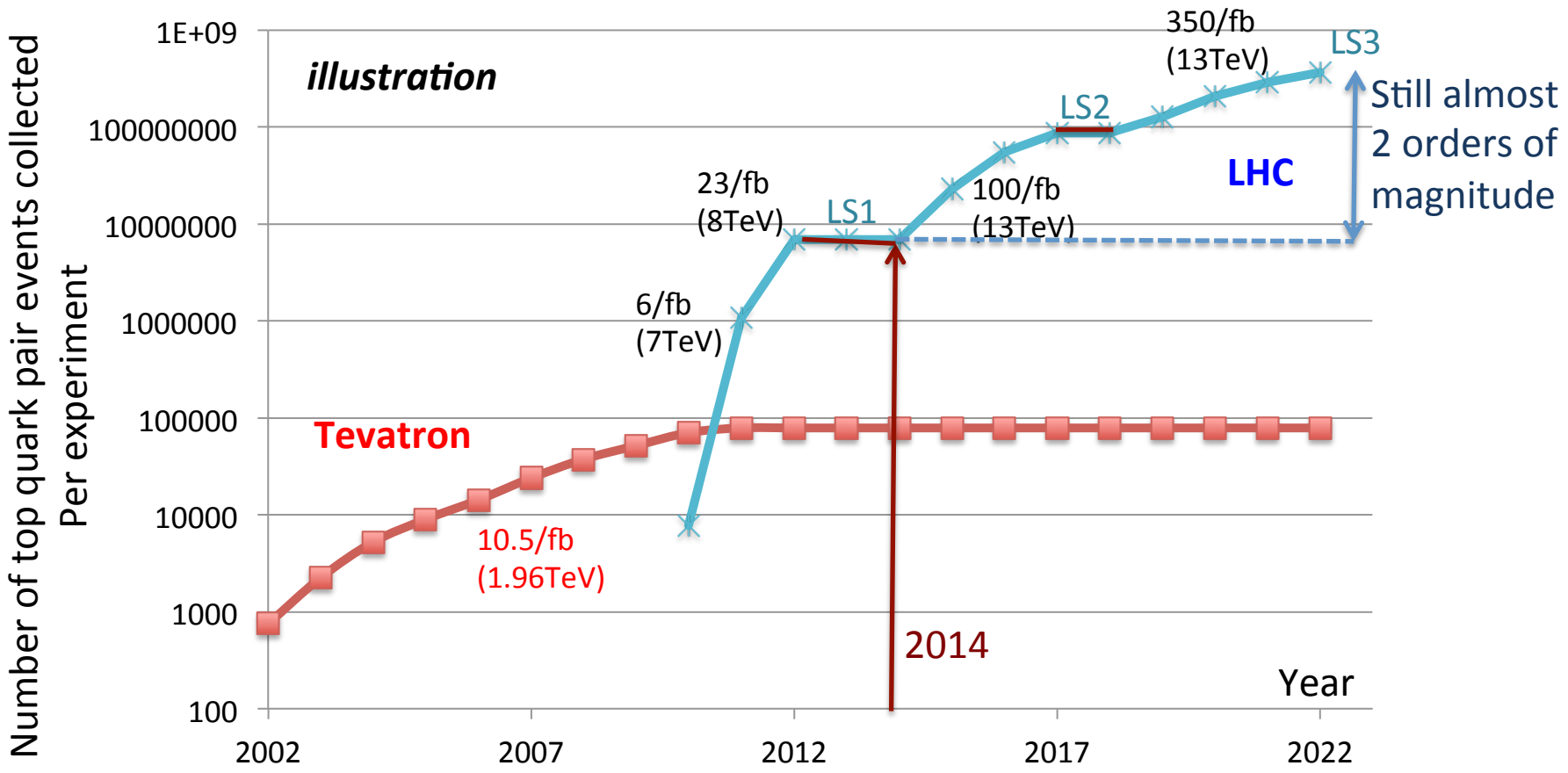


W decay	e^+	μ^+	τ^+	$u\bar{d}$	$c\bar{s}$
e^-	$e\mu$	$e\mu$	$e\tau$	electron+jets	
μ^-	$e\mu$	$\mu\mu$	$\mu\tau$	muon+jets	
τ^-	$e\tau$	$\mu\tau$	$\tau\tau$	tau+jets	
$\bar{u}d$	electron+jets	muon+jets	tau+jets	all-hadronic	
$\bar{c}s$					

dileptons

Production at Tevatron and LHC

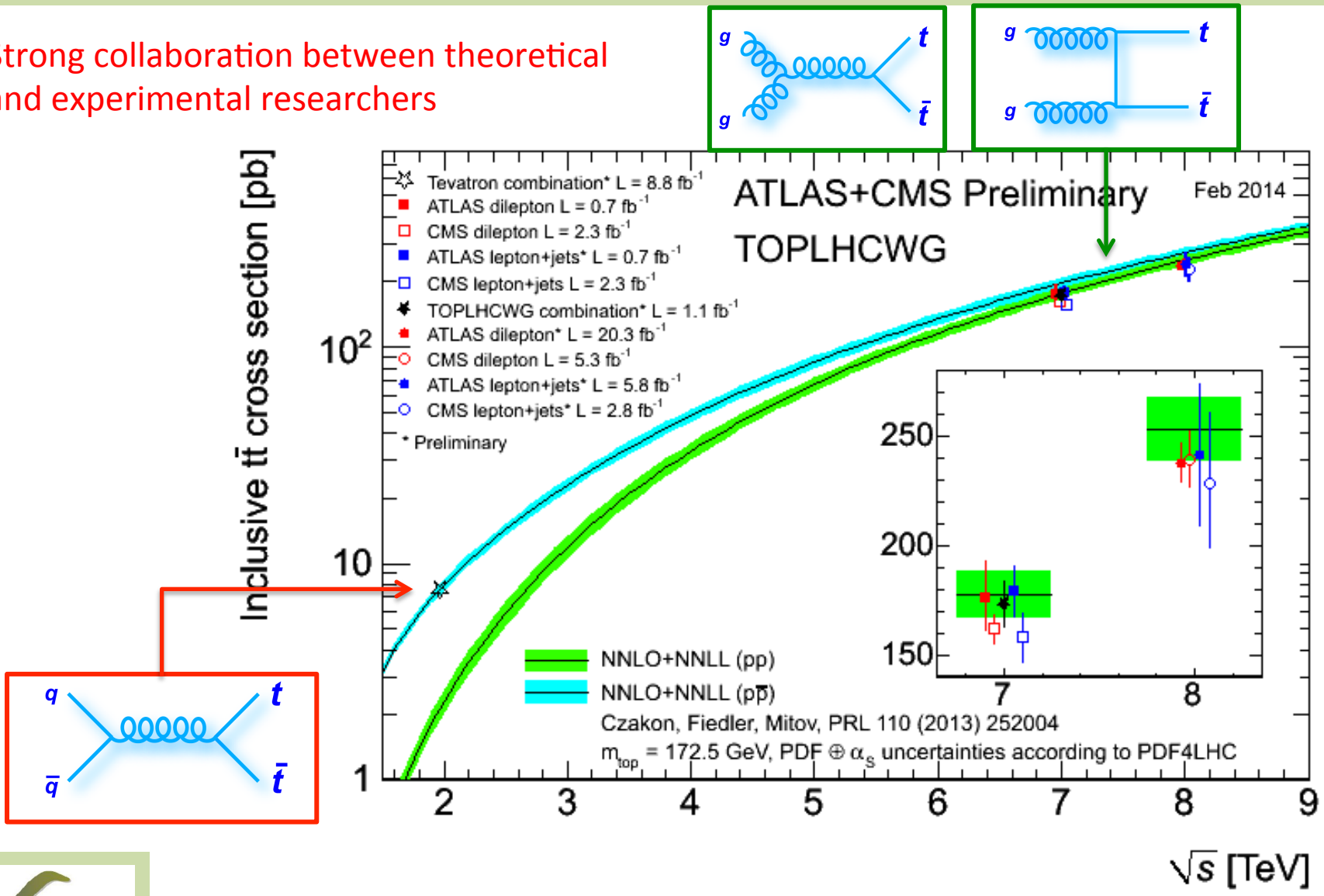
20 years for almost 6 orders of magnitude → the Top Quark era



(caveat: assumed 13 TeV collisions with a cross section of 800 pb)

Cross-section – pair production

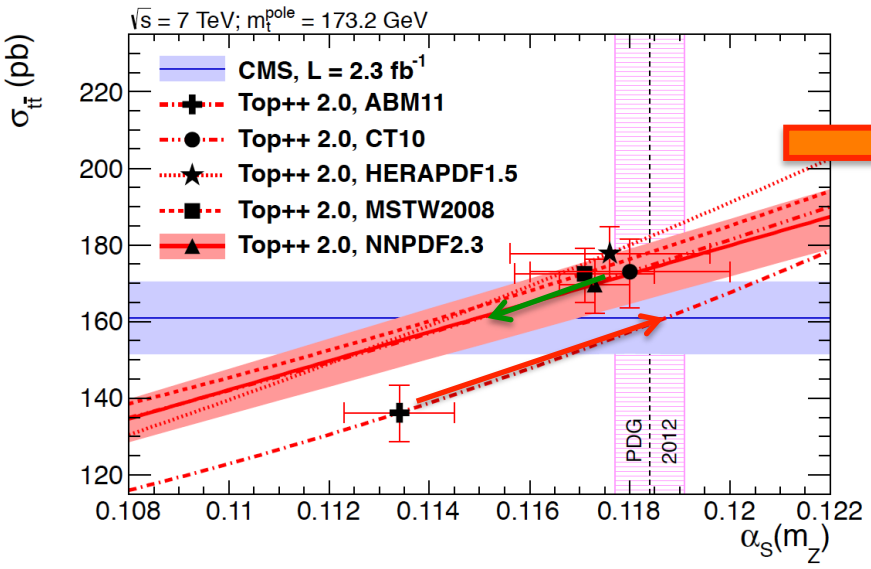
Strong collaboration between theoretical and experimental researchers

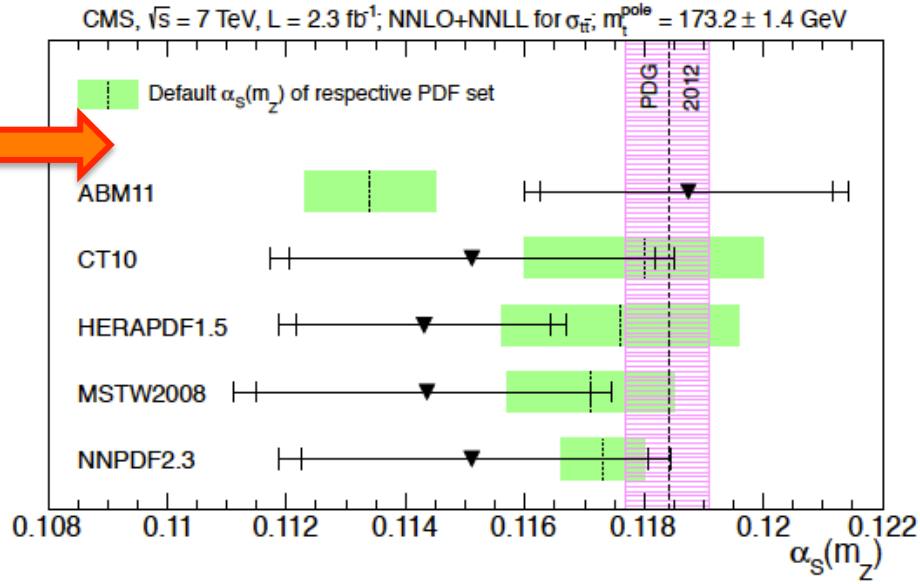


CMS Phys. Lett. B 728 (2013) 496

Cross-section and PDF's

- PDF's from the measured top quark pair cross-sections
  (soon also single-top & differential cross-sections)
- Assume the top quark pole mass to be 173.2 ± 1.4 GeV



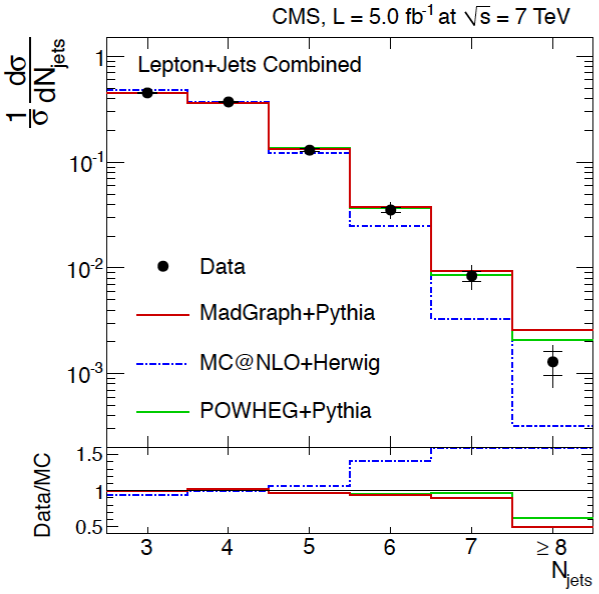


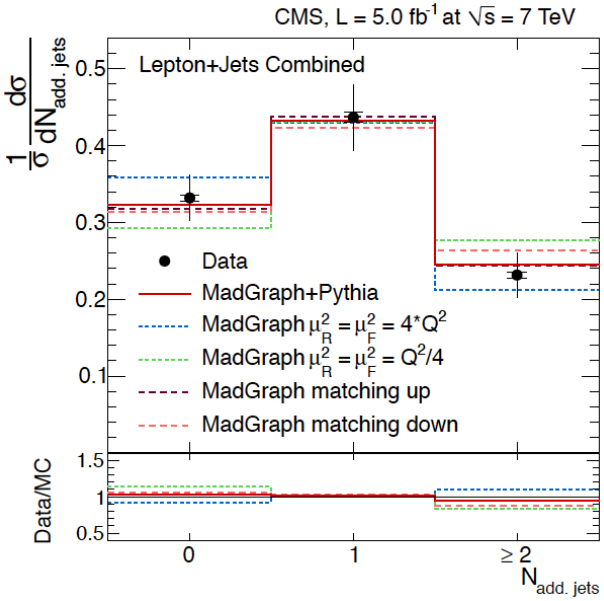
$$\alpha_S(M_Z) = 0.1151^{+0.0033}_{-0.0032}$$

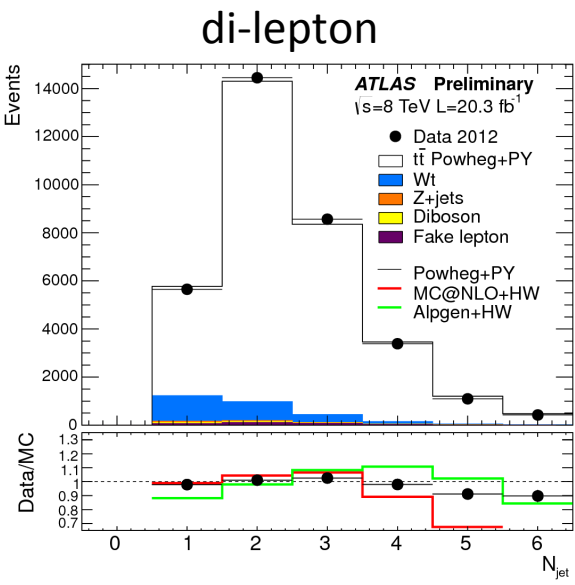
CMS arXiv:1404.3171; ATLAS CONF-2013-097

Cross-section – Jet Multiplicity

Differential cross-section as a function of the jet multiplicity (testing higher order QCD and an important background for ttH), measurement in visible phase-space.



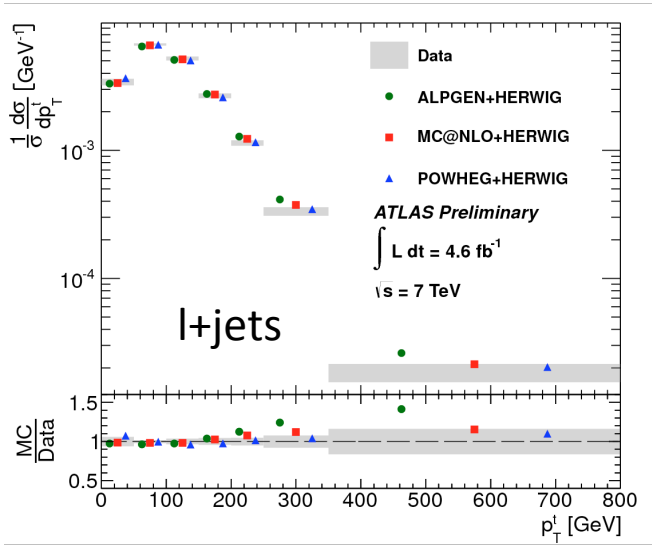


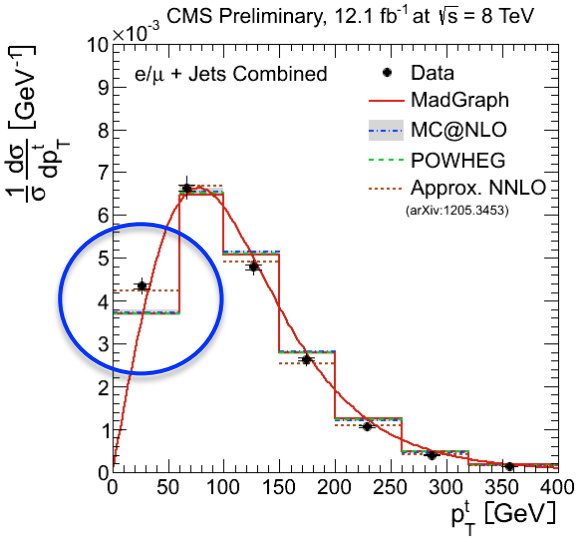


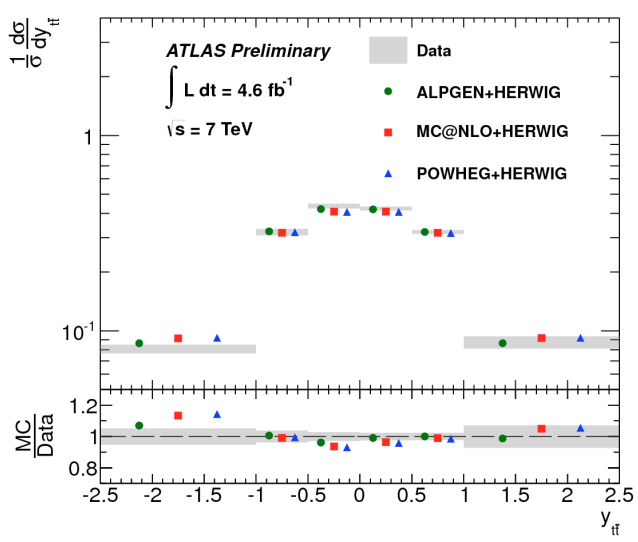
Differential cross-sections

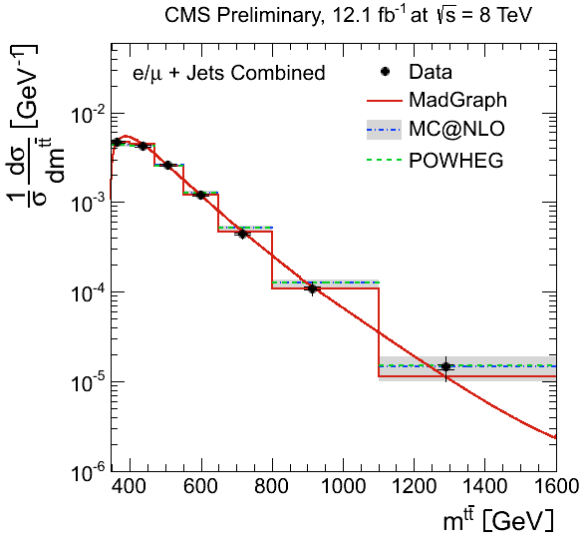
Measured distributions are unfolded to correct for experimental effects.

Possible discrepancies with NLO generators are to be taken into account when estimating systematic uncertainties in measurement/ searches.



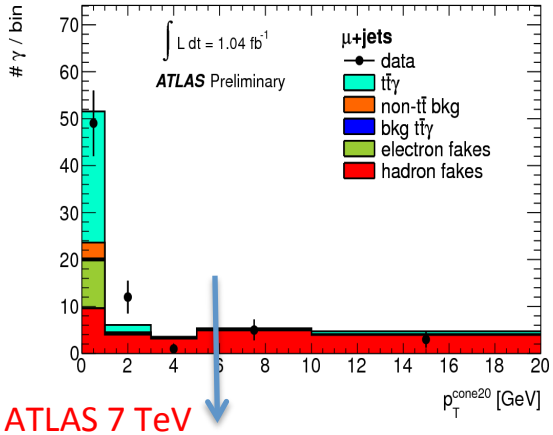




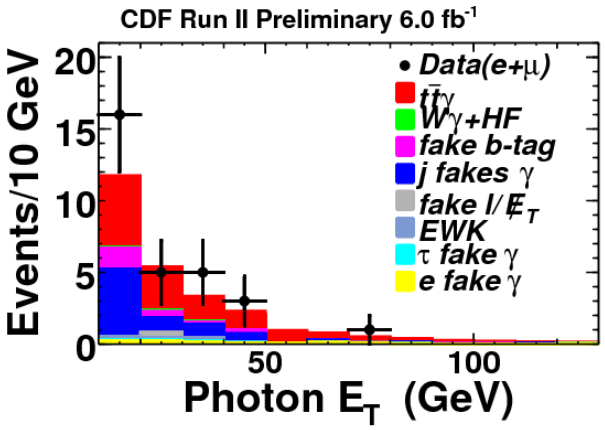


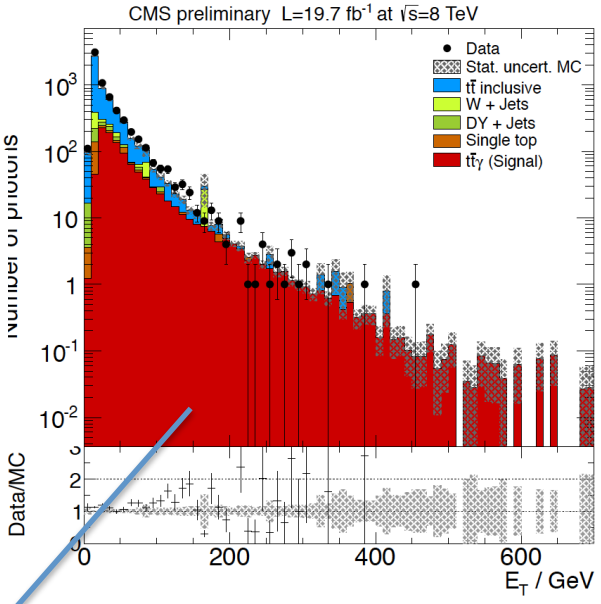
Cross-section – tt + photon

Top quark pairs with a photon



ATLAS 7 TeV





$\sigma(tt\gamma) = 2.0 \pm 0.5\,(stat.) \pm 0.7\,(syst.) \pm 0.08\,(lumi.)\,pb$

Data-driven treatment of mis-identification rate of hadronic.

$E_T^{photon} > 20$ GeV

$\Delta R(photon, b\text{-}quarks) > 0.1$

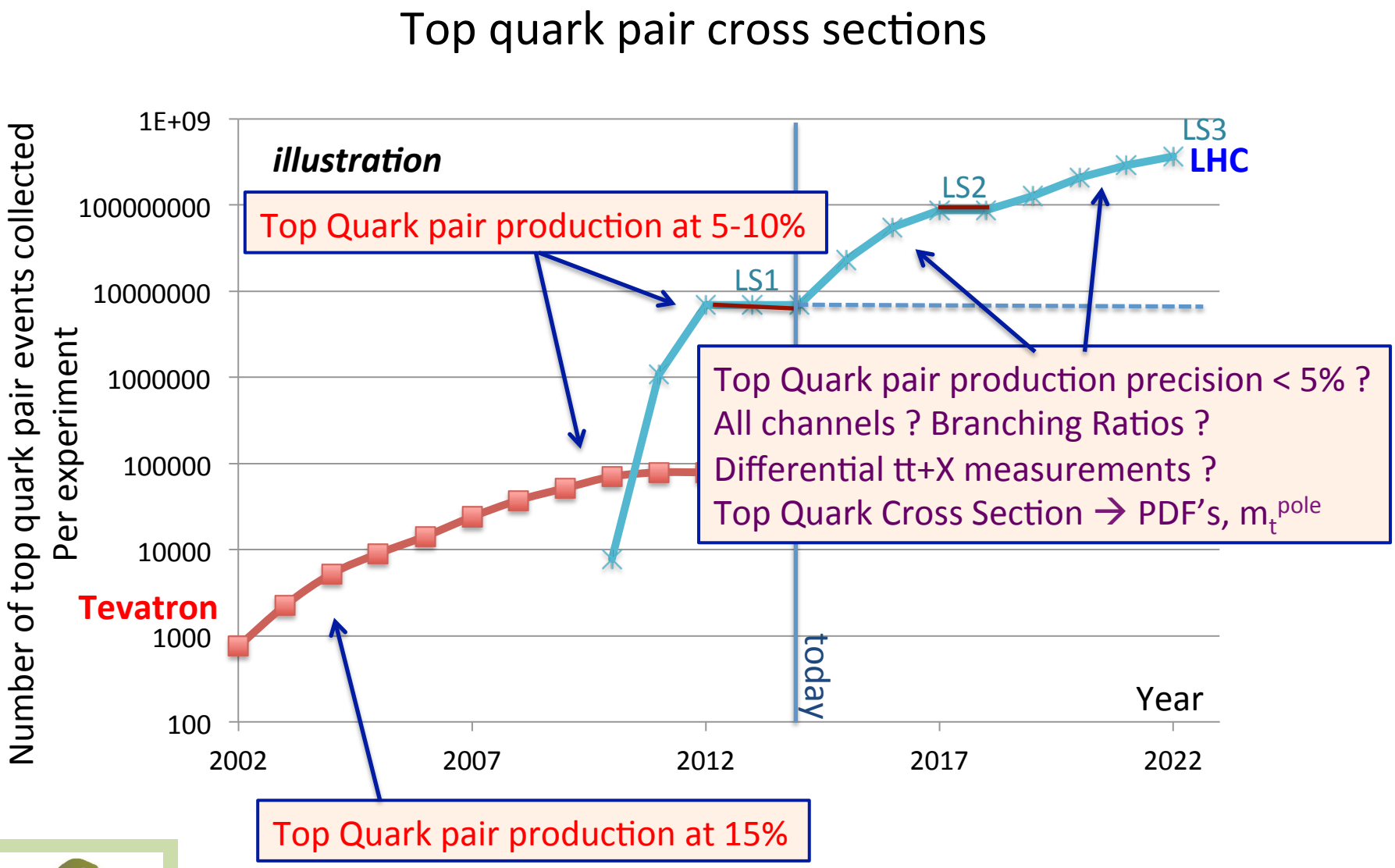
modeling bck

CMS 8 TeV

$$\sigma_{t\bar{t}+\gamma} = 2.4 \pm 0.2(stat.) \pm 0.6(syst.)\,pb$$

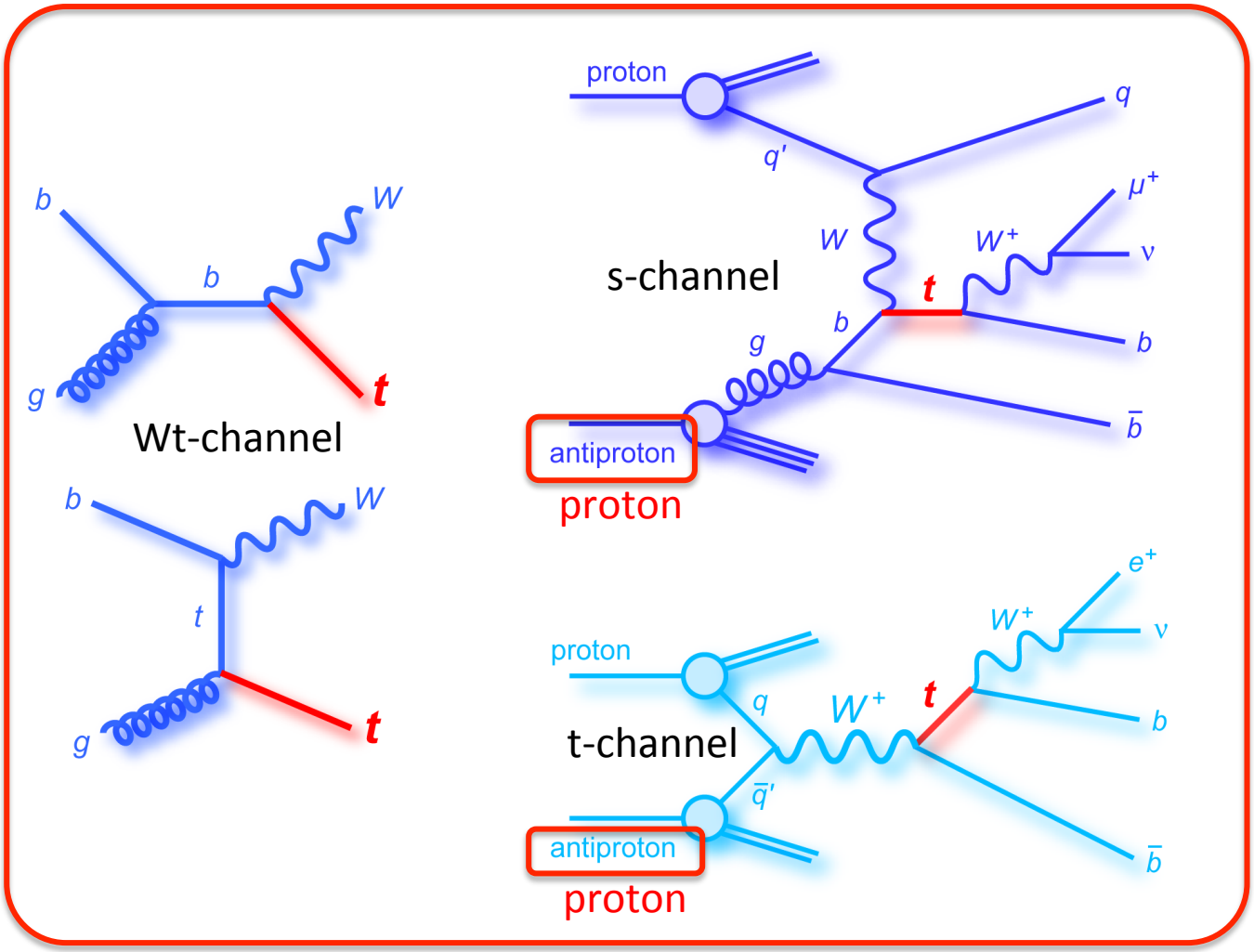
$$\sigma^{SM}_{\bar{t}t+\gamma} = 1.8 \pm 0.5\,pb$$

The status of Top Quark Physics



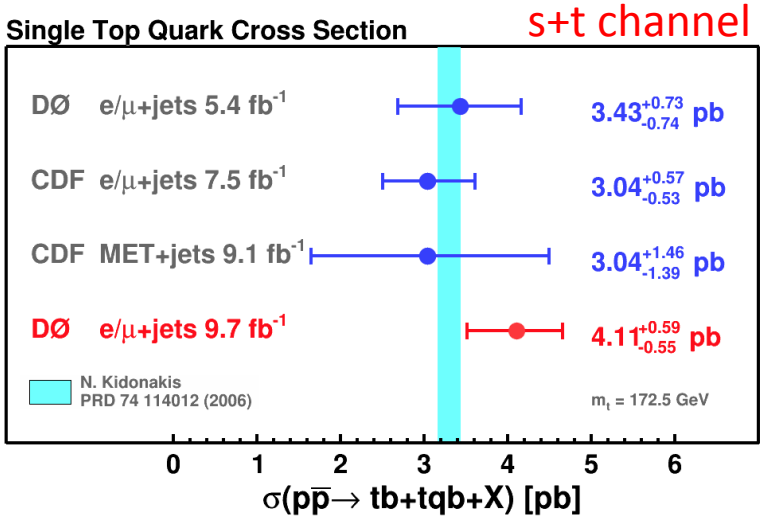
Cross-section – single-top production

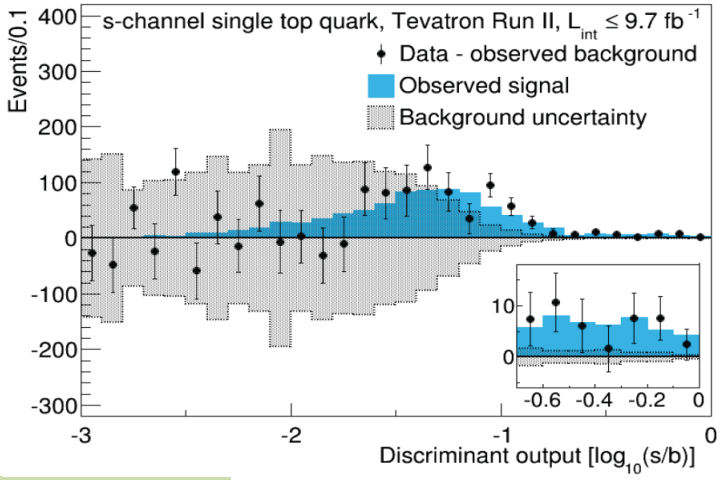
Electroweak single-top production



arXiv:1402.5126

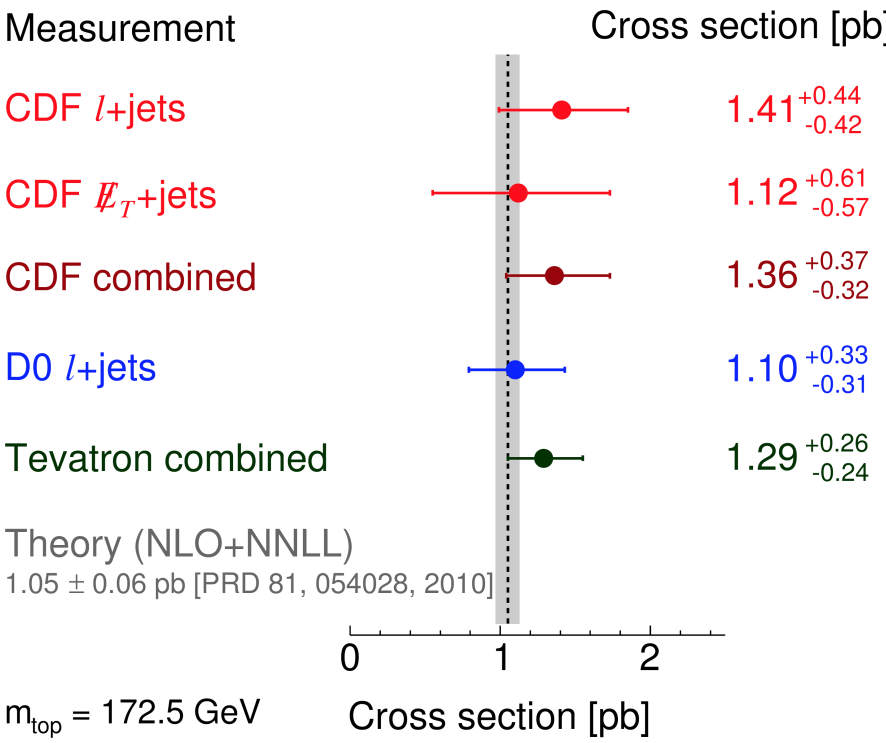
Cross-section – single-top Tevatron





Tevatron's legacy

s-channel single top quark, Tevatron Run II, $L_{int} \leq 9.7$ fb^{-1}

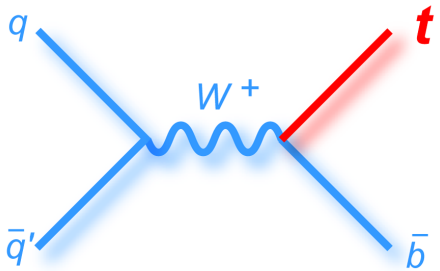


m_{top} = 172.5 GeV

Observed significance is 6.3 σ

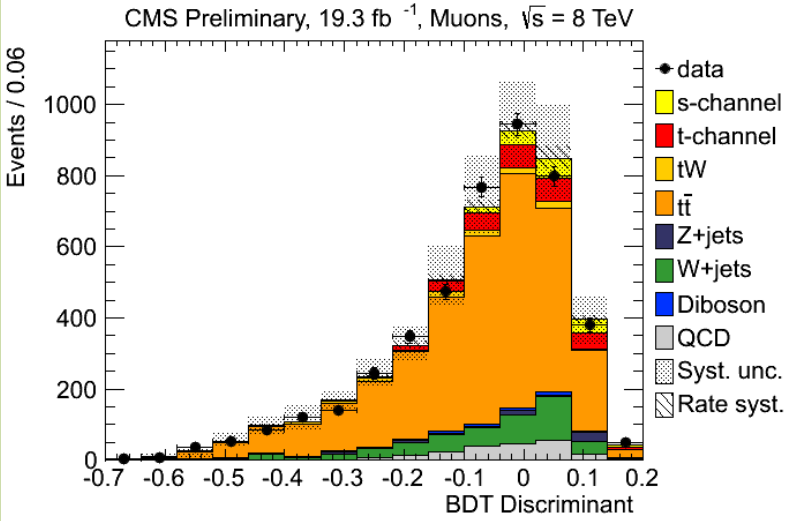
Cross-section – s-channel

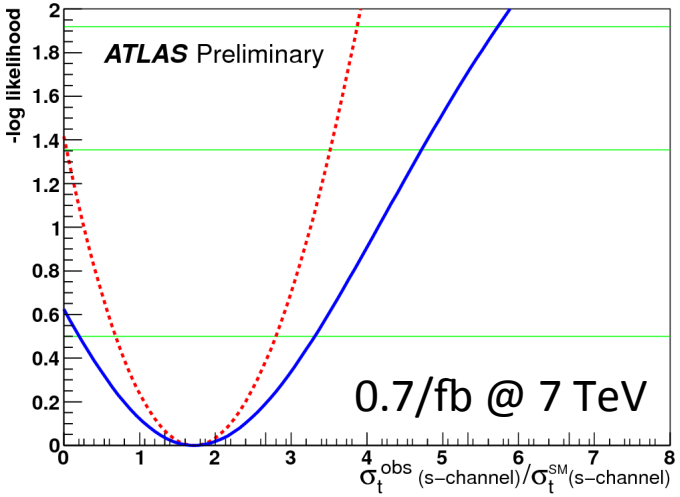
- Multivariate analyses are developed, and sensitivity limited by theoretical uncertainties
- **ATLAS** (7 TeV): $\sigma_{s\text{-ch}} < 26.5$ pb (= 5.8 x σ^{SM})
- **CMS** (8 TeV): $\sigma_{s\text{-ch}} < 11.5$ pb (= 2.1 x σ^{SM})



Assuming signal ($\sigma > 0$)
(Feldman-Cousins 68% CI)

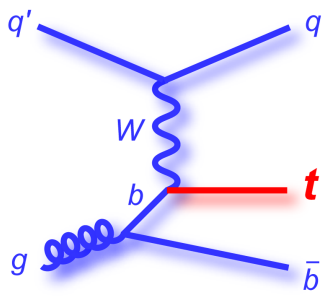
$$\sigma_{s\text{-ch.}} = 5.9^{+8.6}_{-5.1}\ \text{pb}\ \text{muon channel}$$
$$\sigma_{s\text{-ch.}} = 6.9^{+8.7}_{-5.7}\ \text{pb}\ \text{electron channel}$$
$$\sigma_{s\text{-ch.}} = 6.2^{+8.0}_{-5.1}\ \text{pb}\ \text{combined}$$



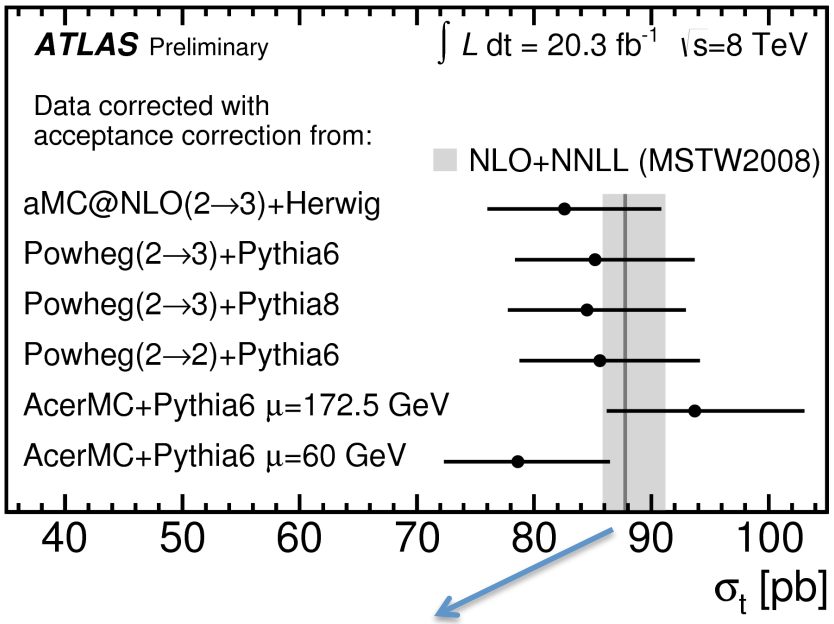


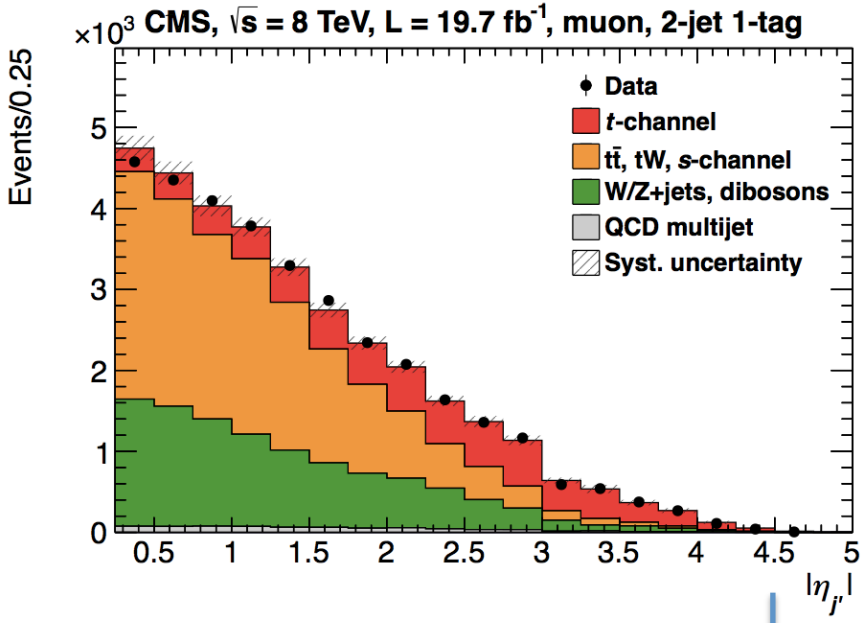
Cross-section – t-channel

- **ATLAS**: Multivariate analyses to measure fiducial cross-section in detector acceptance and extrapolate to full phase space
- **CMS**: fitting on $|\eta_j|$ distribution
- Systematic uncertainties dominate



First top-quark measurement of visible cross section





$\sigma_{t\text{-ch}}$ (aMC@NLO + Herwig)= 82.6 ± 1.2(stat) ± 11.4(syst) ± 3.1(PDF) ± 2.3(lumi) pb

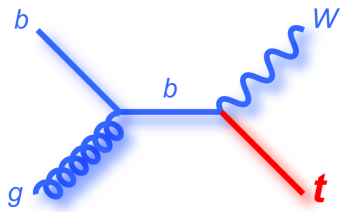
$\sigma_{t\text{-ch}}$ = 83.6 ± 2.3(stat) ± 7.4(syst) pb

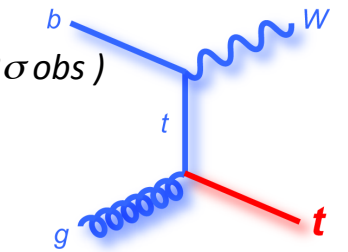
CMS arXiv:1401.2942; CMS Phys. Rev. Lett. 110 (2013) 022003; ATLAS CONF-2013-100; ATLAS Phys. Lett. B716 (2012) 142-159

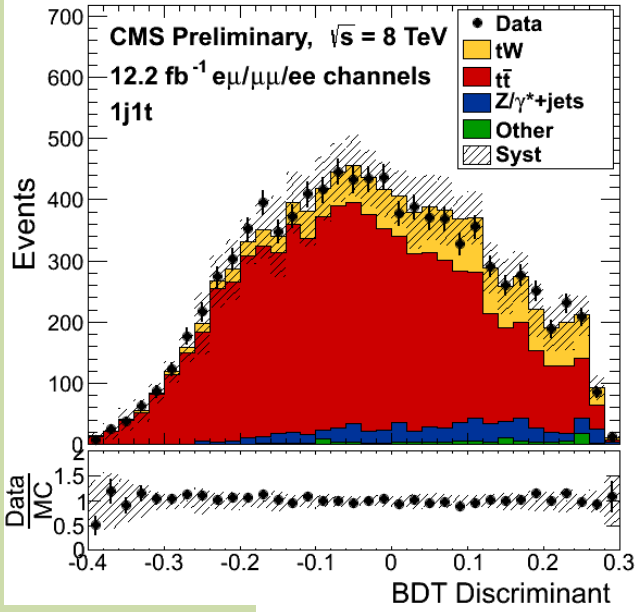
Cross-section – Wt-channel

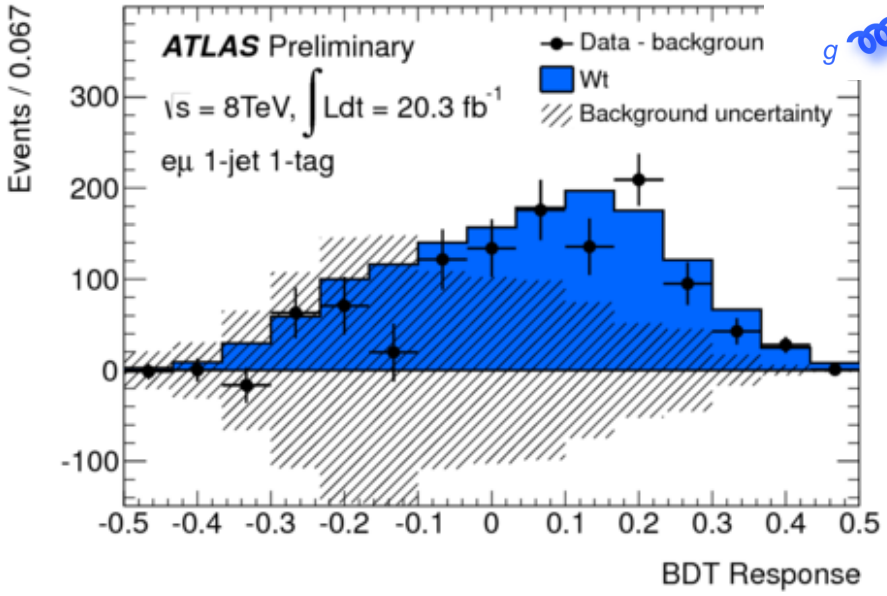
BDT analyses have observed the Wt-channel at 8 TeV

- **CMS** (12.2/fb): $\sigma_{tW} = 23.4\ ^{+5.5}_{-5.4}$ pb
  - (6.1σ obs, 5.4σ exp.) *(CMS 7 TeV evidence: $16\ ^{+5}_{-4}$ pb, 4σ obs)*
- **ATLAS** (20.3/fb): $\sigma_{tW} = 27.2 \pm 2.8(\text{stat}) \pm 5.4(\text{syst})$ pb
  - (4.2σ obs, 4.0σ exp.) *(ATLAS 7 TeV evidence: 16.8 ± 2.9 (stat) ± 4.9 (syst) pb, 3.3σ obs)*

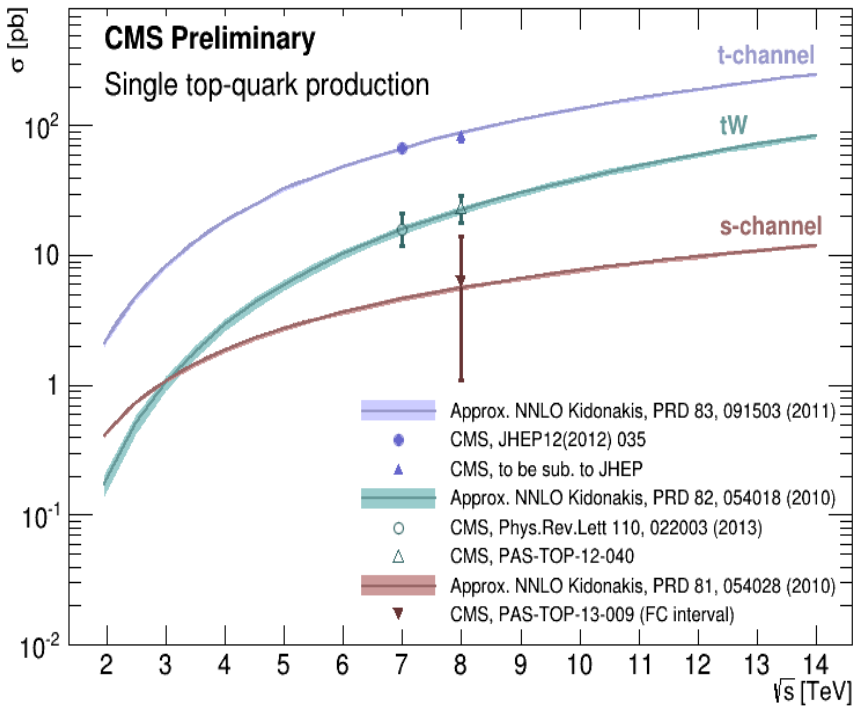


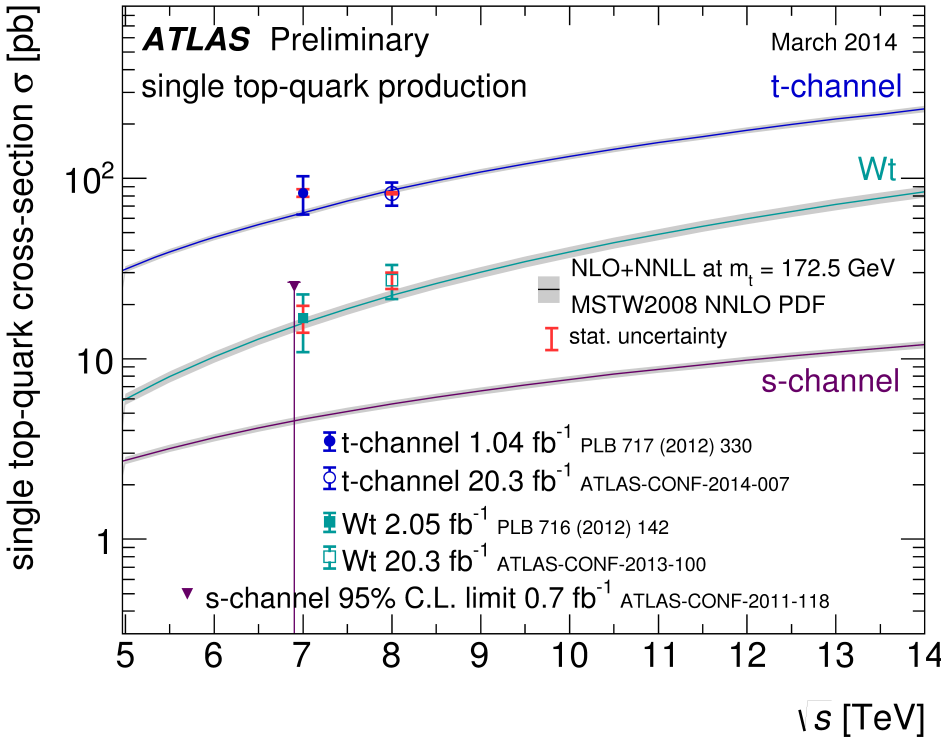






Cross-section – single-top production





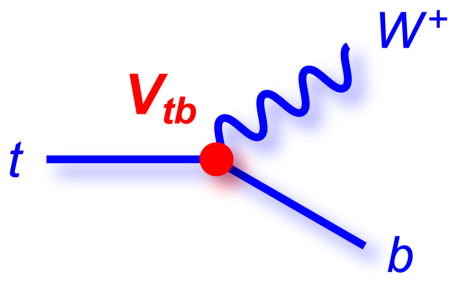
Agreement with SM

V_{tb} in single-top production

Direct measurement of $|V_{tb}|$, *assuming BR(t→Wb)=1*:

$$|V_{tb}|^2 = \sigma/\sigma_{th}(|V_{tb}|=1)$$

Measurements at 4-5% precision, and limited by the statistical uncertainty and more data will come.

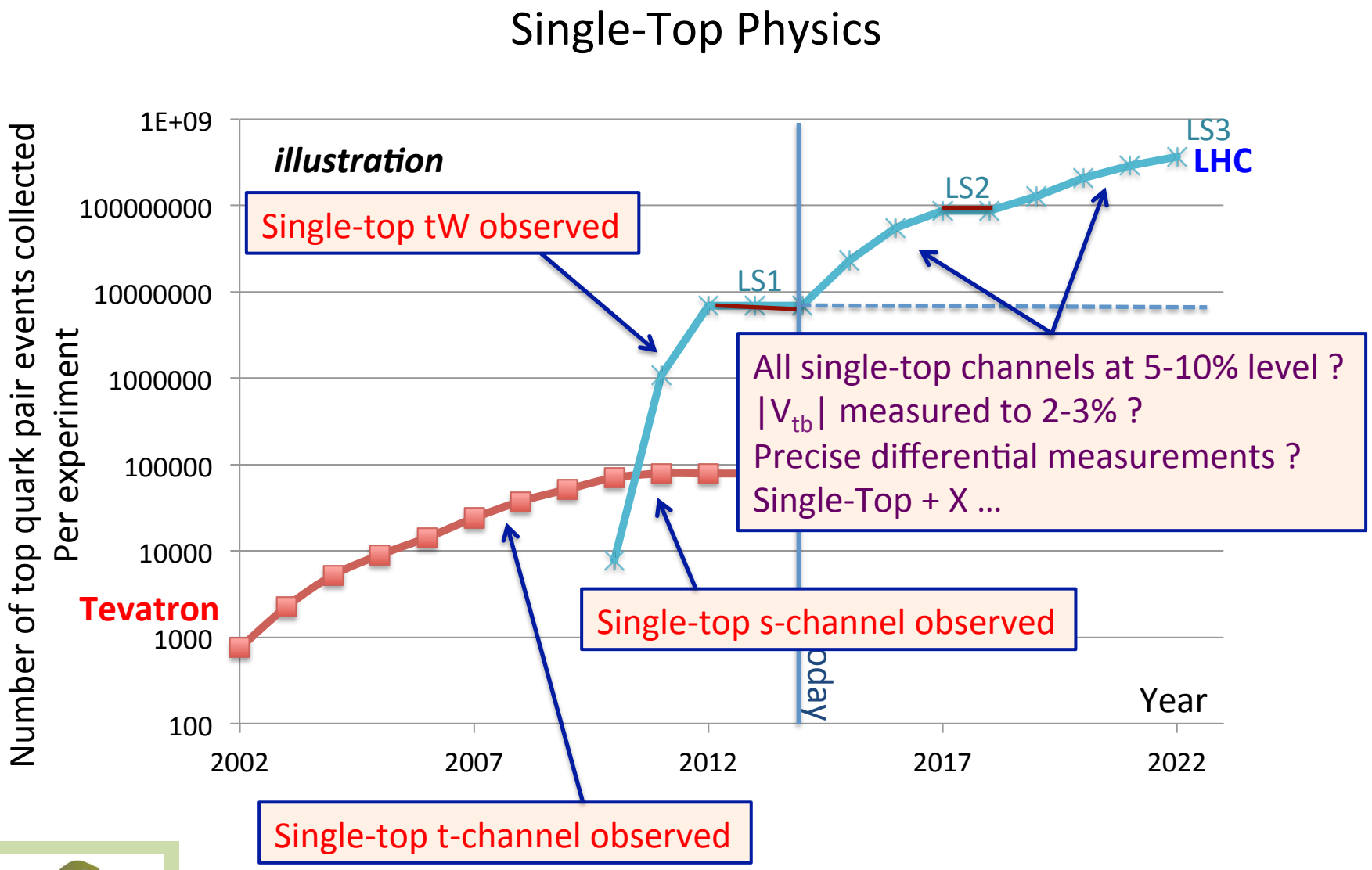


Luca Lista @ Moriond EW 2014

- **ATLAS:**
  - 7 TeV: $|V_{tb}| = 1.13^{+0.14}_{-0.13}$ (t-ch., 11.9%)
    $|V_{tb}| = 1.03^{+0.16}_{-0.19}$ (tW, 17.0%)
  - 8 TeV: $|V_{tb}| = 0.97 \pm 0.01(\text{stat})^{+0.06}_{-0.07}(\text{syst}) \pm 0.06(\text{gen+PDF})\ ^{+0.02}_{-0.01}(\text{th}) \pm 0.01(\text{lumi})$ NEW
    $= 0.97^{+0.09}_{-0.10}$ (t-ch., 9.8%)
    $|V_{tb}| = 1.10 \pm 0.12(\text{exp}) \pm 0.03(\text{th})$ (tW, 11.2%)
- **CMS:** NEW
  - 7 TeV: $|V_{tb}| = 1.020 \pm 0.046(\text{exp}) \pm 0.017(\text{th})$ (t-ch. 4.8%)
    $|V_{tb}| = 1.01^{+0.16}_{-0.13}(\text{exp})^{+0.03}_{-0.04}(\text{th})$ (tW, 14.8%)
  - 8 TeV: $|V_{tb}| = 0.979 \pm 0.045(\text{exp}) \pm 0.016(\text{th})$ (t-ch. 4.9%)
    $|V_{tb}| = 1.03 \pm 0.12(\text{exp}) \pm 0.04(\text{th})$ (tW 12.3%)

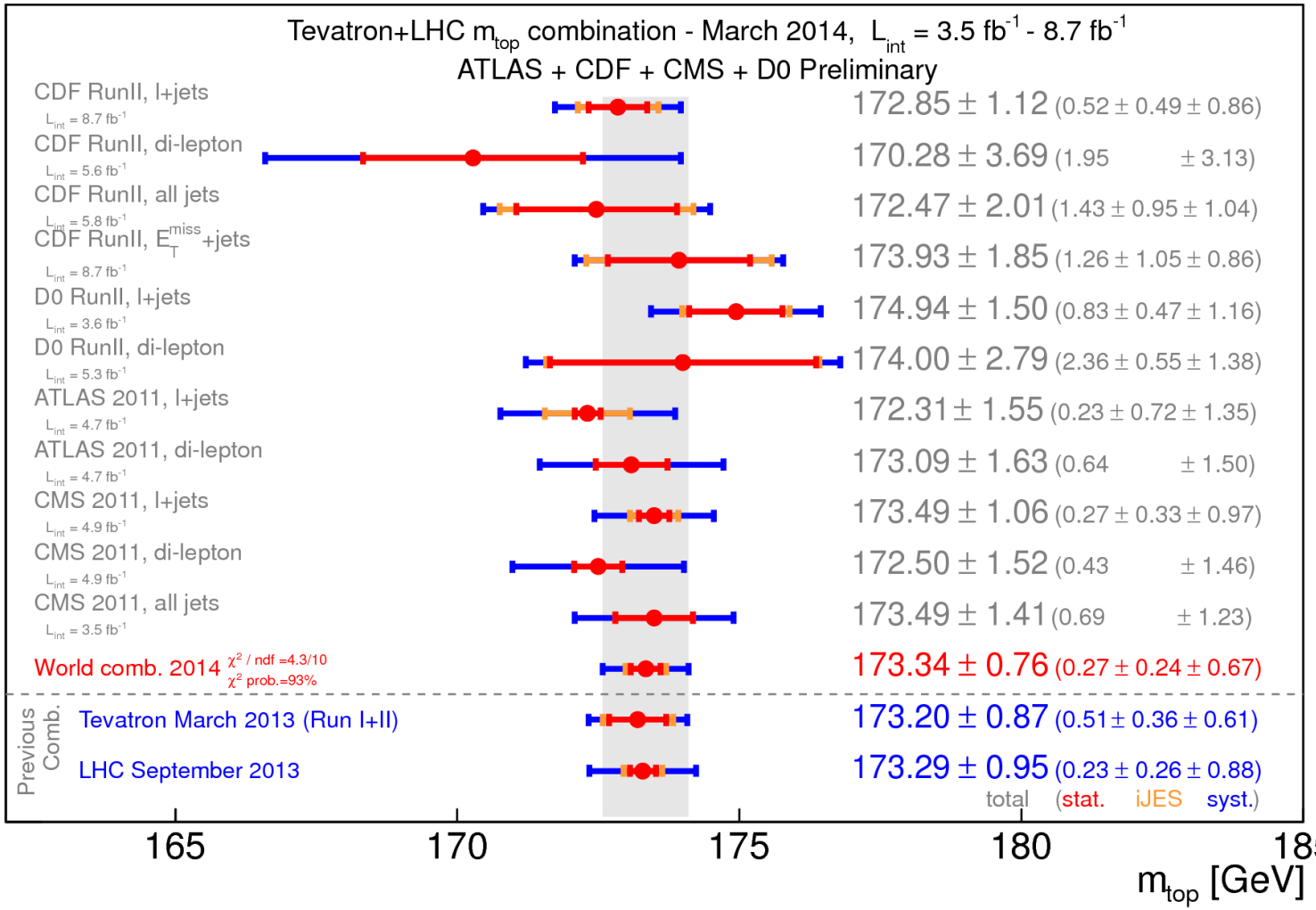
$|V_{tb}| = 0.998 \pm 0.038(\text{exp}) \pm 0.016(\text{th})$
(7+8 TeV t-ch., comb.: 4.1%)

The status of Top Quark Physics



The Top Quark Mass

First LHC + Tevatron combination (11 measurements, 93% fit probability)



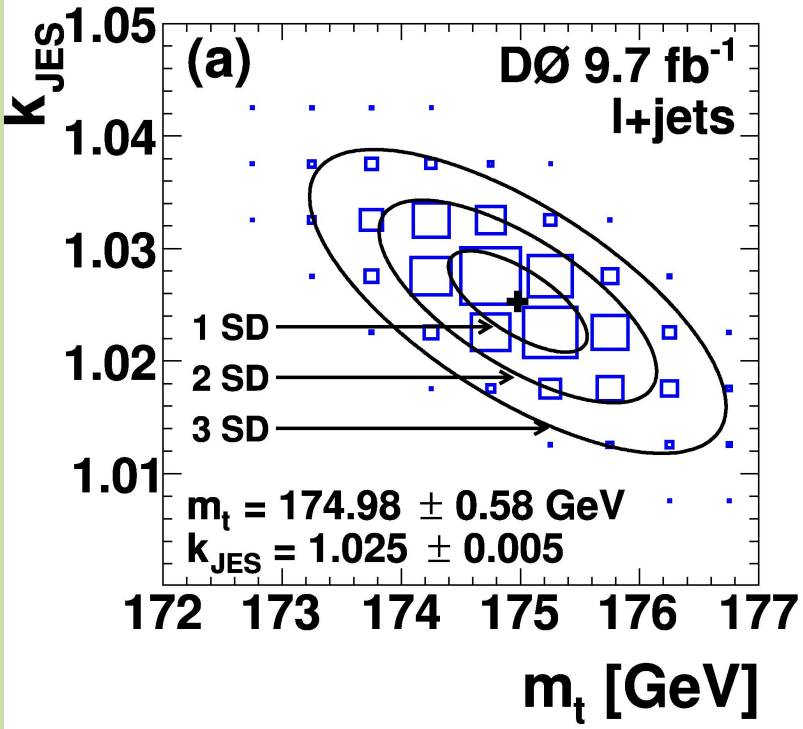
arXiv:1405.1756

The Top Quark Mass – update D0

Applying the Matrix Element technique in the lepton+jet final state on the full Run-II dataset

$$m_t = 174.98 \pm 0.58\,(\text{stat} + \text{JES}) \pm 0.49\,(\text{syst})\ \text{GeV}$$

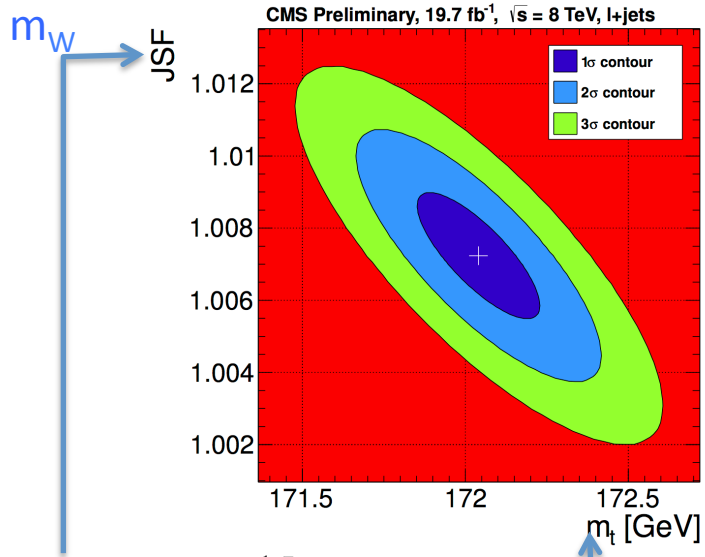
$$m_t = 174.98 \pm 0.76\ \text{GeV},$$

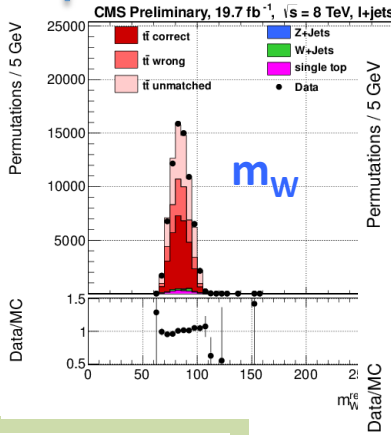


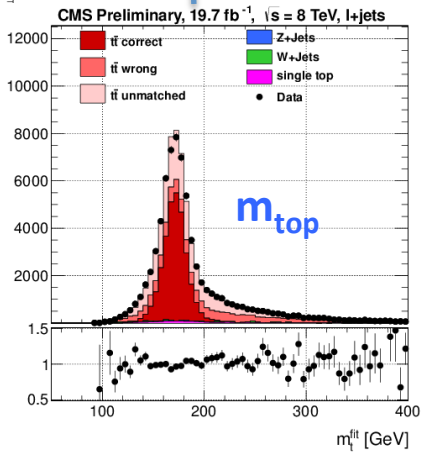
Source of uncertainty	Effect on m_t (GeV)
Signal and background modeling:	
Higher order corrections	$+0.15$
Initial/final state radiation	± 0.09
Hadronization and UE	$+0.26$
Color reconnection	$+0.10$
Multiple $p\bar{p}$ interactions	-0.06
Heavy flavor scale factor	± 0.06
b-jet modeling	$+0.09$
PDF uncertainty	± 0.11
Detector modeling:	
Residual jet energy scale	± 0.21
Flavor-dependent response to jets	± 0.16
b tagging	± 0.10
Trigger	± 0.01
Lepton momentum scale	± 0.01
Jet energy resolution	± 0.07
Jet ID efficiency	-0.01
Method:	
Modeling of multijet events	$+0.04$
Signal fraction	± 0.08
MC calibration	± 0.07
Total systematic uncertainty	± 0.49
Total statistical uncertainty	± 0.58
Total uncertainty	± 0.76

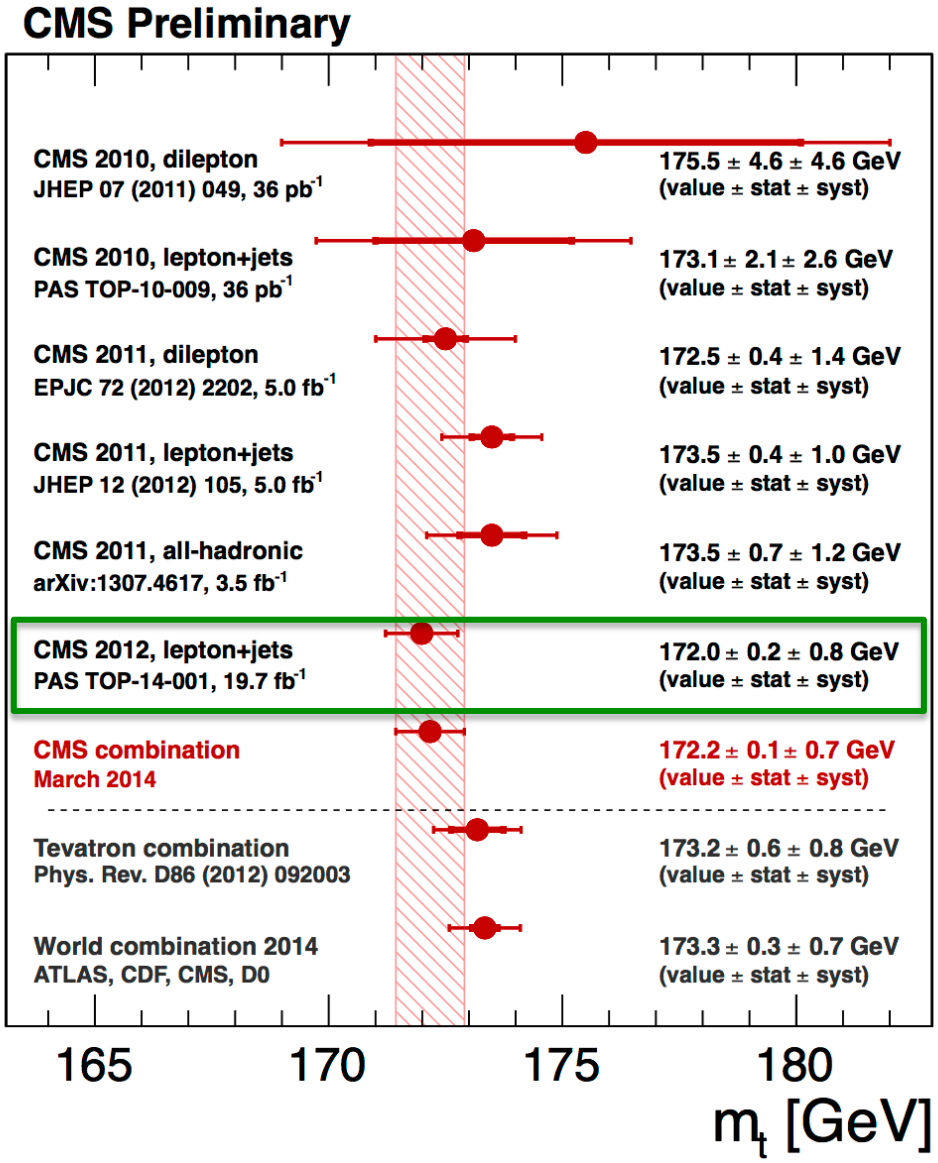
The Top Quark Mass – update CMS

2D measurement with the Jet energy Scale Factor (using kinematic fit)



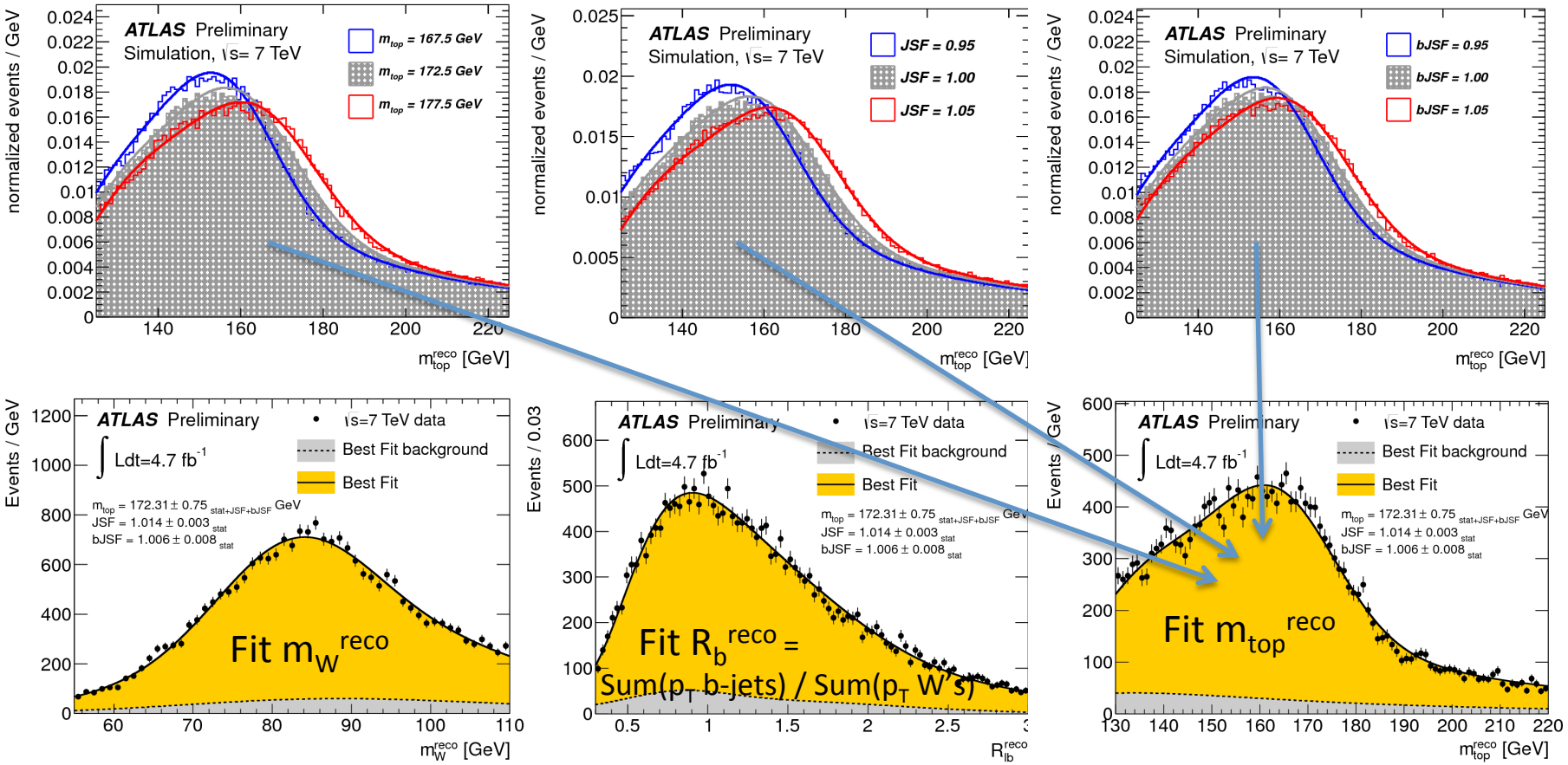






Top Quark Mass - alternatives

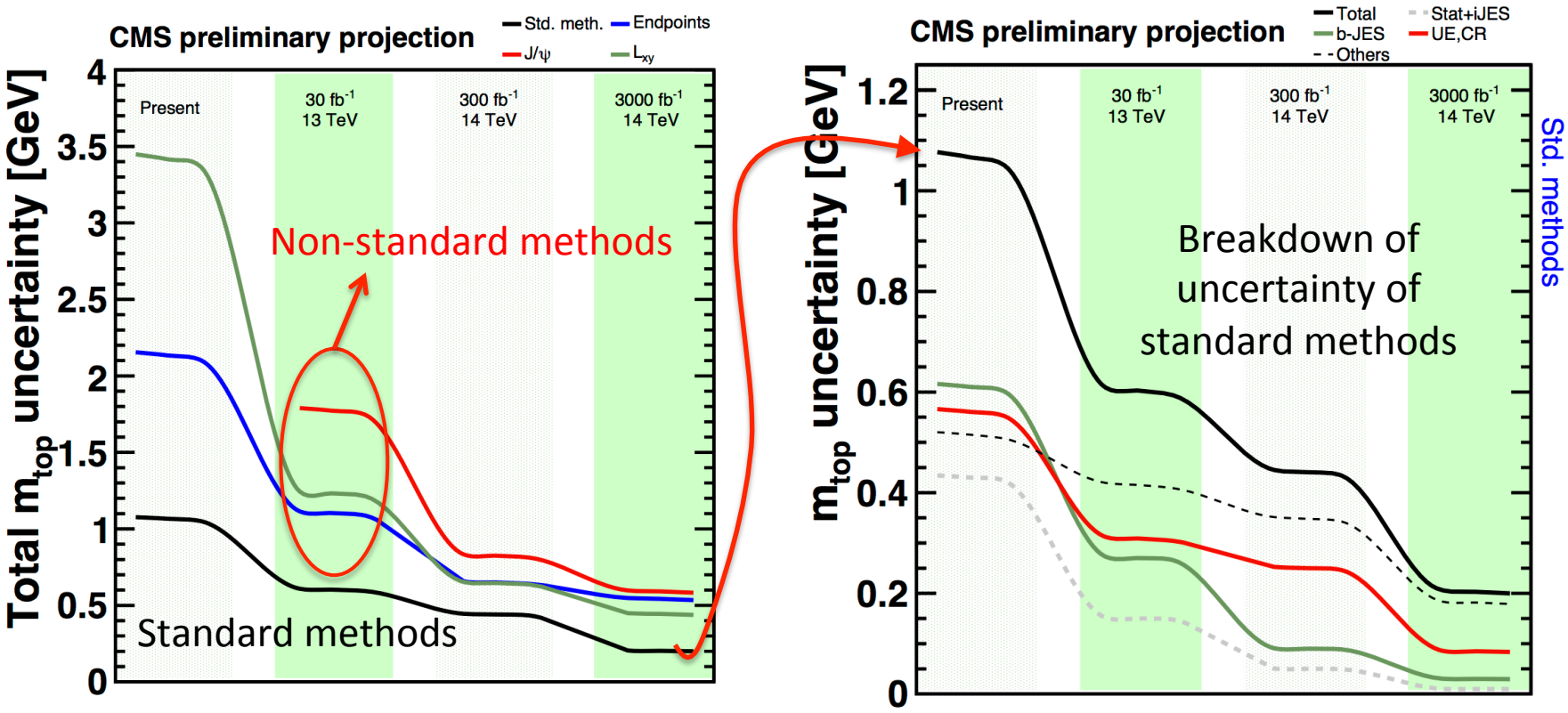
From 2-dim to 3-dimensional template fitting (7 TeV)



Fitting m_{top}, global Jet Energy Scale and b-jet-to-light Jet Energy Scale on distributions.

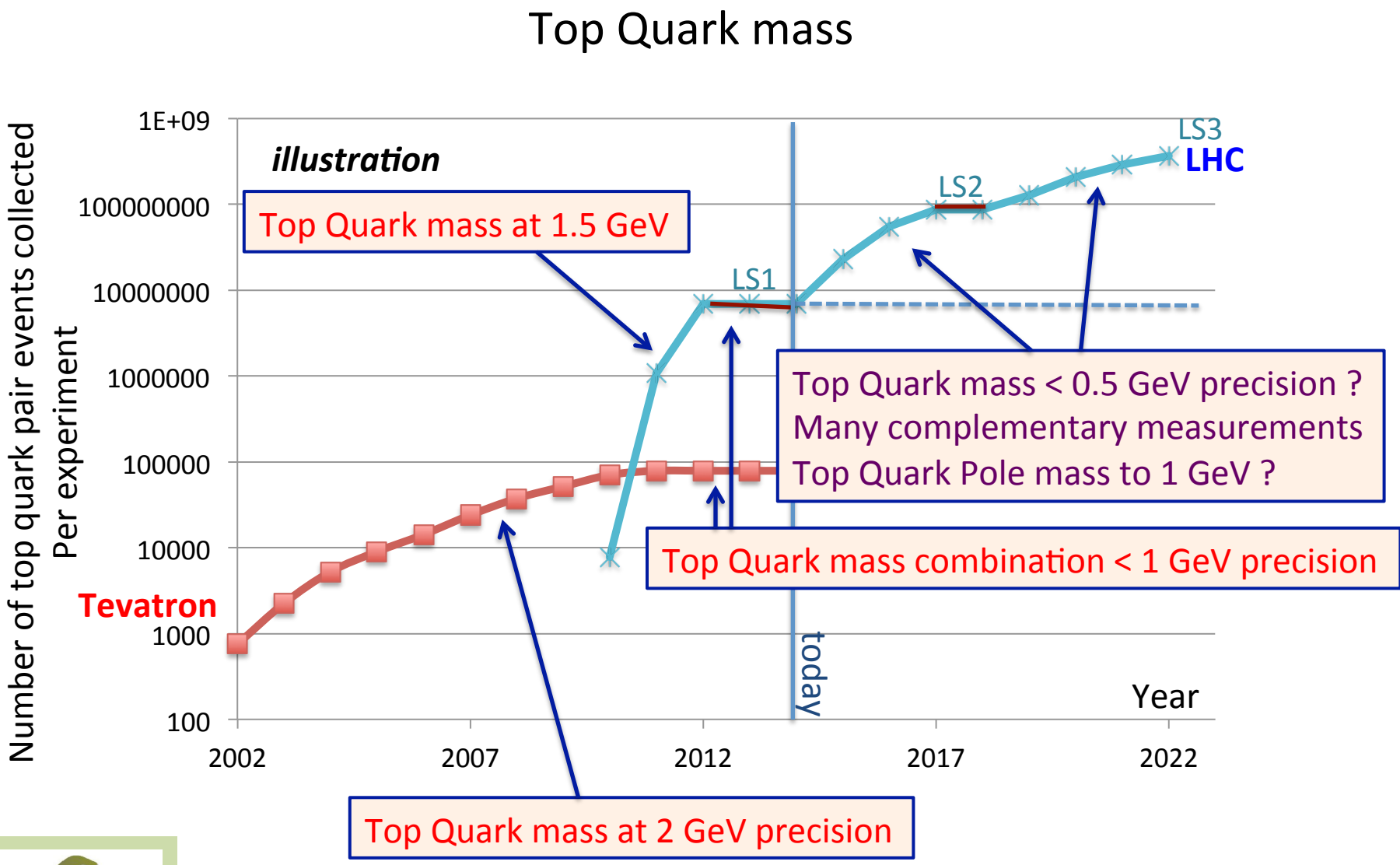
m_t = 172.31 ± 0.75 (stat + JSF + bJSF) ± 1.35 (syst) GeV *in-situ*

Top Quark Mass - future



Top Quark sample size increase by a factor 10-100,
but it will require lots of work to reduce the uncertainty by a factor 3-5.

The status of Top Quark Physics

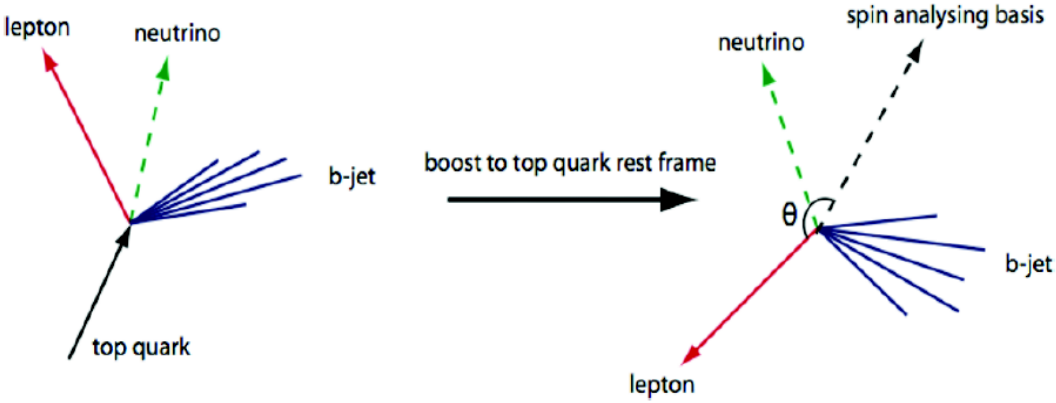


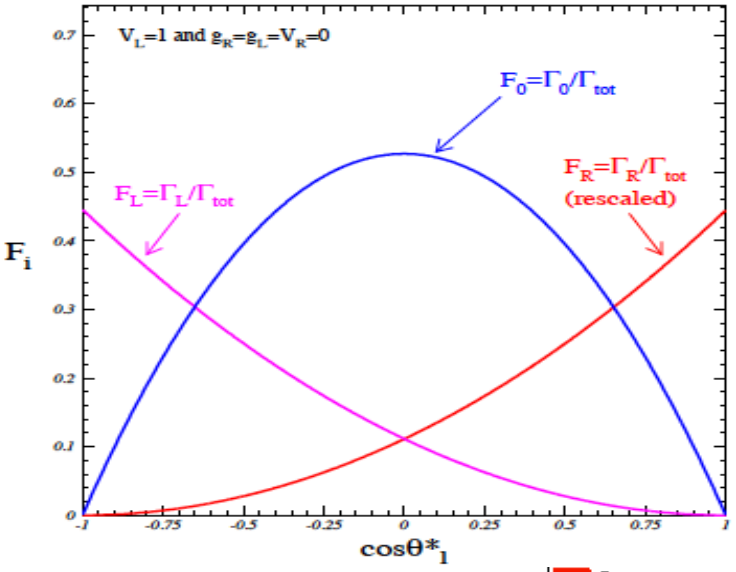
W helicity in Top Quark Decay

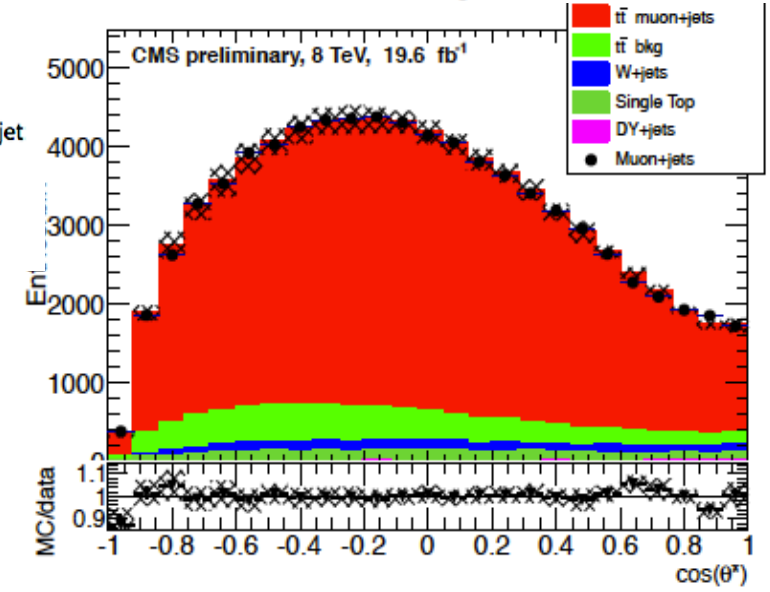
Reweighting method to fit the cosθ distribution with 2 free parameters (F_L and F_0)

Theoretical uncertainties dominate and the MET shape

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







$$F_0 = 0.659 \pm 0.015(\text{stat.}) \pm 0.023(\text{syst.}),$$
$$F_L = 0.350 \pm 0.010(\text{stat.}) \pm 0.024(\text{syst.}),$$

3-5% precision, agreement with SM

Top Quark polarization

Parity conservation in the strong production of top quark pair events implies zero longitudinal polarization of the to quarks.

	b	ℓ	d	u
α (NLO)	-0.39	0.998	0.93	-0.31

$P_{SM} = 0.003 \pm 0.001$ [PLB 725 (2013) 115]

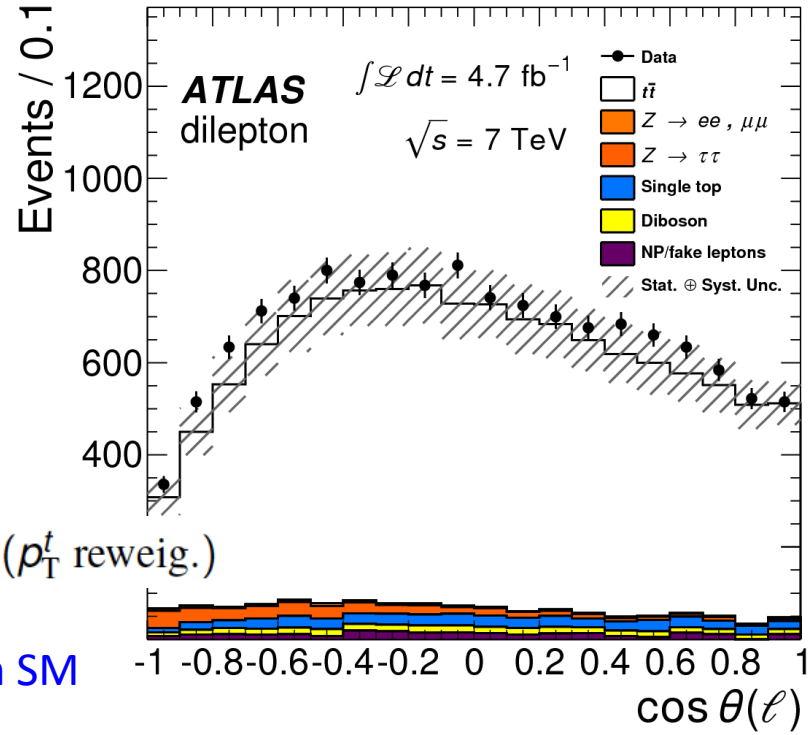
$$\frac{1}{\sigma}\frac{d^2\sigma}{d[\cos(\theta_i)]d[\cos(\theta_j)]} = \frac{1}{4}[P\alpha_i \cos(\theta_i) + P\alpha_j \cos(\theta_j) + A\alpha_i\alpha_j \cos(\theta_i)\cos(\theta_j)]$$

$$P = 2A_P$$

$$A_P = \frac{N(\cos\theta_\ell)>0 - N(\cos\theta_\ell)<0}{N(\cos\theta_\ell)>0 + N(\cos\theta_\ell)<0}$$

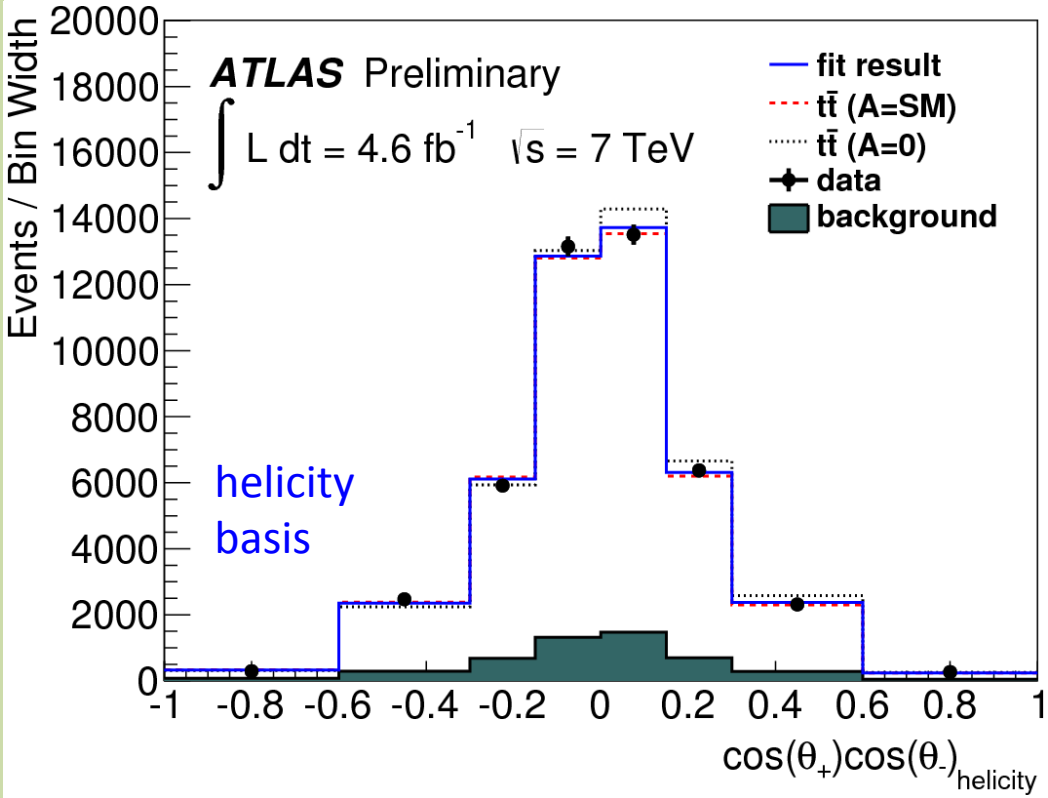
$$A_P = 0.005 \pm 0.013\ (\text{stat.}) \pm 0.020\ (\text{syst.}) \pm 0.008(p_T^t\ \text{reweig.})$$

~5% precision on P, agreement with SM



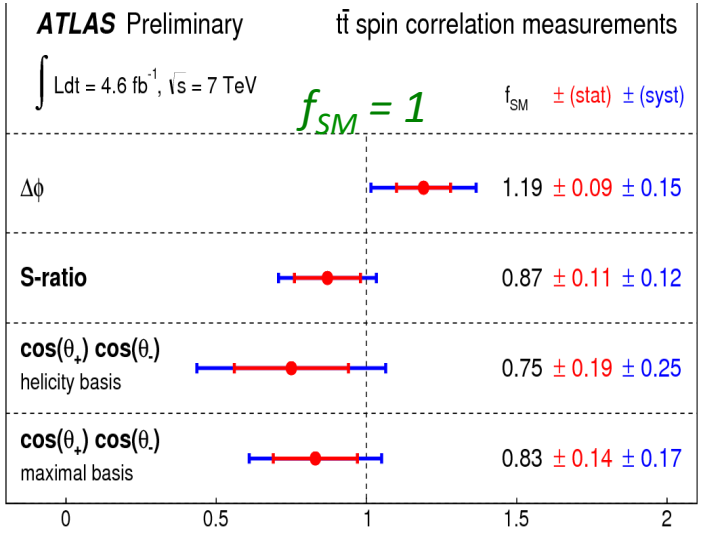
Top Quark spin correlations

$$\frac{1}{\sigma}\frac{d^2\sigma}{d[\cos(\theta_i)]d[\cos(\theta_j)]} = \frac{1}{4}[P\alpha_i \cos(\theta_i) + P\alpha_j \cos(\theta_j) + A\alpha_i\alpha_j \cos(\theta_i)\cos(\theta_j)]$$



Fit fraction of top quark pair events with spin correlations

$$f_{SM} = N_{A=SM}/(N_{A=SM} + N_{A=0})$$



Asymmetry	Data (unfolded)	NLO (SM, correlated)	NLO (uncorrelated)
$A_{\Delta\phi}$	$0.113 \pm 0.010 \pm 0.006 \pm 0.012$	$0.115^{+0.014}_{-0.016}$	$0.210^{+0.013}_{-0.008}$
$A_{c_1c_2}$	$-0.021 \pm 0.023 \pm 0.025 \pm 0.010$	-0.078 ± 0.006	0

CMS 7 TeV

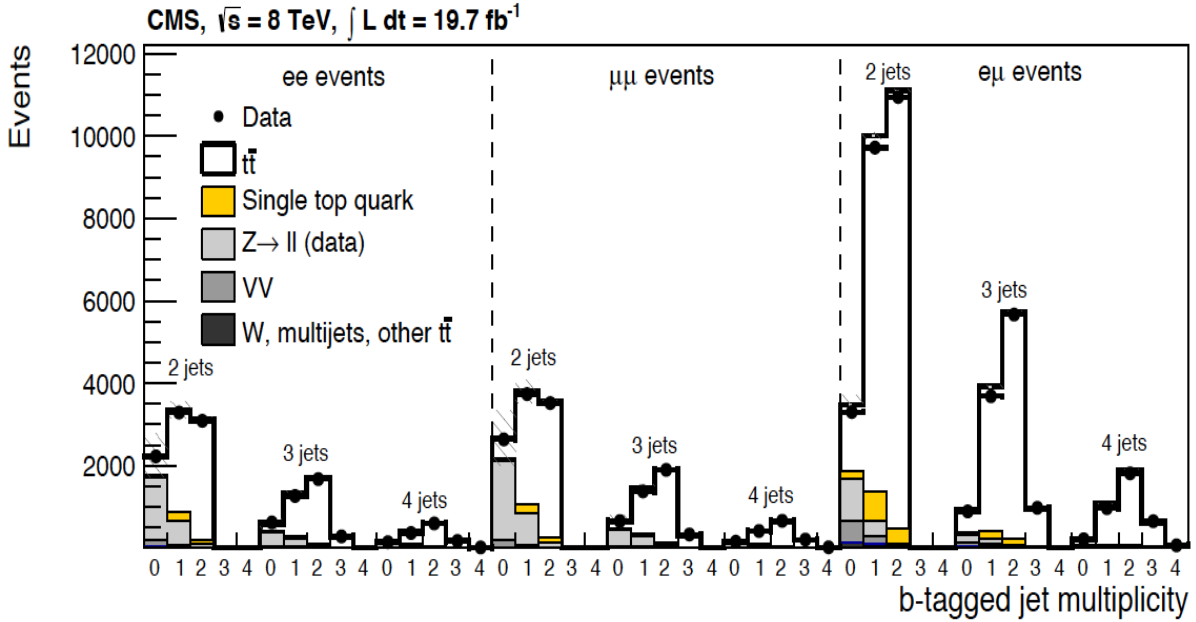
Dominated by systematic modeling uncertainties

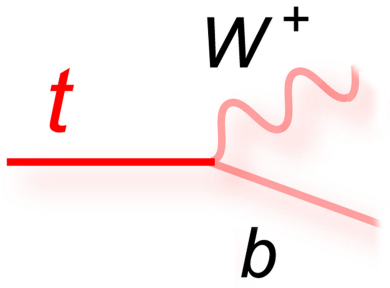
CMS arXiv:1404.2292

Top Quark Decay

Branching to other quarks t→Wq : **R = BR(t→Wb) / BR(t→Wq, all q flavors)**

- Typically measured by counting b-jets in the event.
- Mis-reconstructions taken into account in a large likelihood fit (eg. jet assignment & flavor tagging matching).
- No $|V_{tb}|$ assumption made.





Also indirect Top Quark width:

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

$$\sum_q \mathcal{B}(t \to Wq) = 1$$

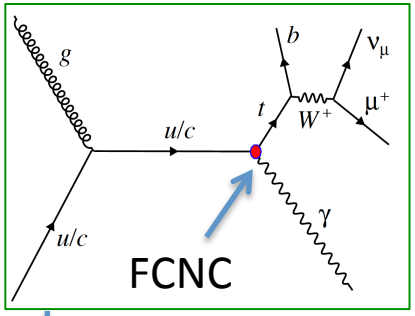
$$\mathcal{R} = 1.014 \pm 0.003\,(\text{stat.}) \pm 0.032\,(\text{syst.})$$

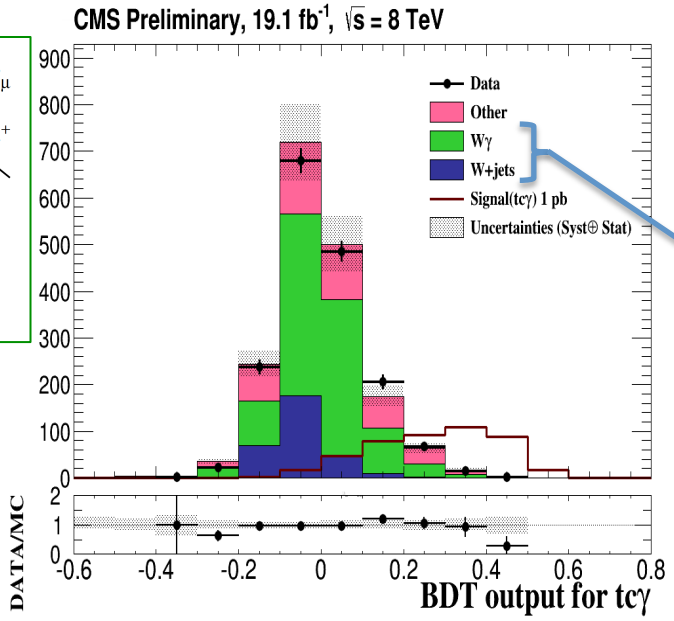
$$\mathcal{R} > 0.955 \text{ at } 95\% \text{ CL}$$

$$\Gamma_t = 1.36 \pm 0.02\,(\text{stat.})^{+0.14}_{-0.11}\,(\text{syst.})\,\text{GeV}$$

Top Quark Rare Decays – FCNC

BDT analysis combining for example kinematic variables of the photon, lepton and jets in the single-top event



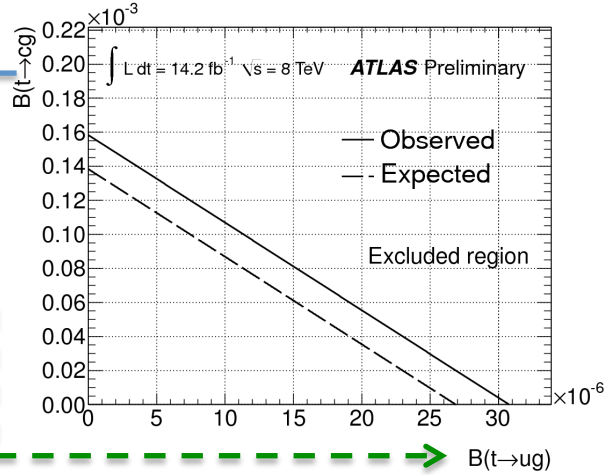


data driven

SM typically at 10^{-13} %

ATLAS and CMS best limits:

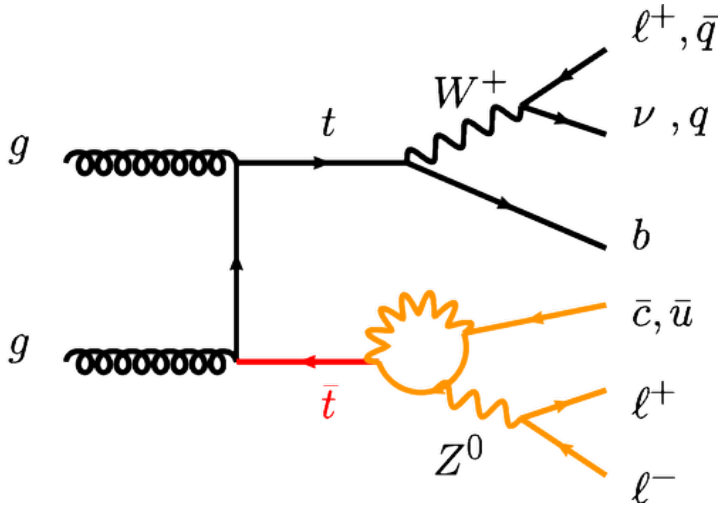
ATLAS	BR(t->ug)	< 0.0031%
ATLAS	BR(t->cg)	< 0.016%
CMS	BR(t->Zq)	< 0.05%
CMS	BR(t->uγ)	< 0.016%
CMS	BR(t->cγ)	< 0.18%



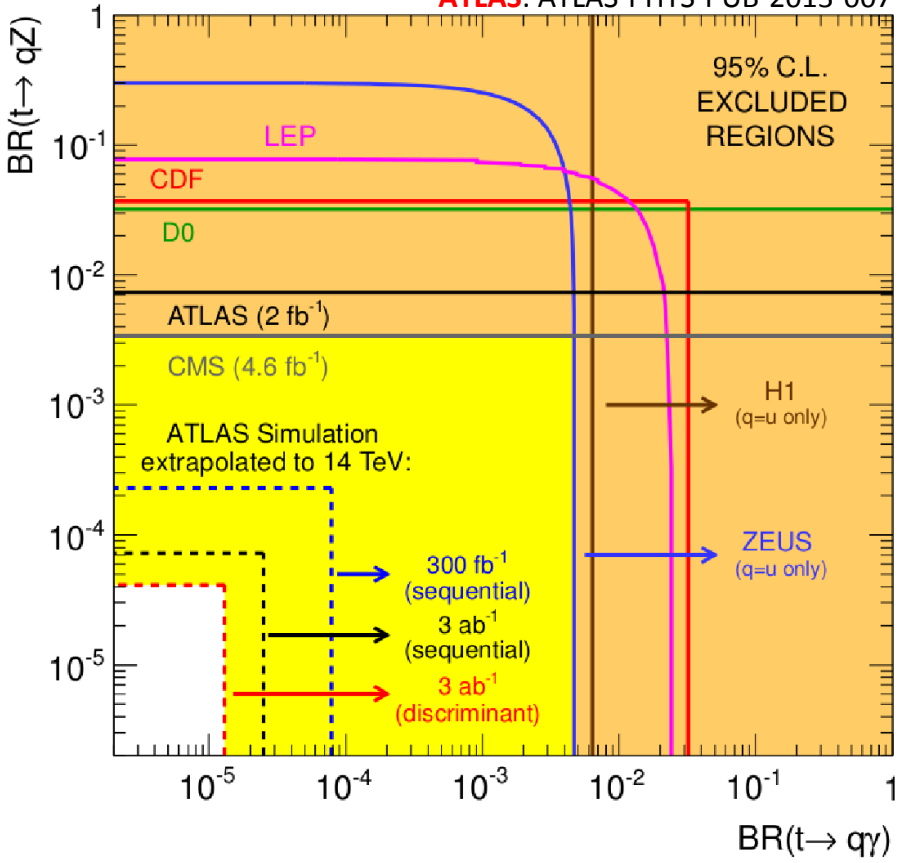
Towards inclusive EFT analyses collecting info from pair & single top production

Top Quark Rare Decays – FCNC

The limit for FCNC is reduced by orders of magnitude, and this will continue



ATLAS: ATLAS-PHYS-PUB-2013-007



CMS, projection using the selection efficiencies for signal and background

$\mathcal{B}(t \to Zq)$	19.5 fb^{-1} @ 8 TeV	300 fb^{-1} @ 14 TeV	3000 fb^{-1} @ 14 TeV
Exp. bkg. yield	3.2	184	1841
Expected limit	$< 0.10\%$	$< 0.011\%$	$< 0.007\%$

CMS SUS-13-002; ATLAS arXiv:1403.6293

Top Quark Rare Decays – FCHC

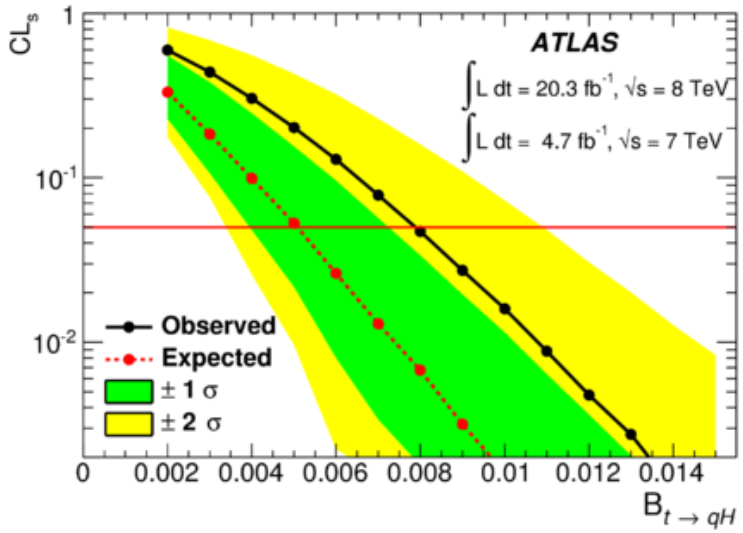
CMS (8 TeV) re-interpretation of SUSY multi-lepton analyses
Limits at 95% CL
BR(t→cH) < 1.28%

Higgs Decay Mode		obs	exp	1σ range
$h \to WW^*$	(BR = 23.1 %)	1.58 %	1.57 %	(1.02–2.22) %
$h \to \tau\tau$	(BR = 6.15 %)	7.01 %	4.99 %	(3.53–7.74) %
$h \to ZZ^*$	(BR = 2.89 %)	5.31 %	4.11 %	(2.85–6.45) %
combined		1.28 %	1.17 %	(0.85–1.73) %

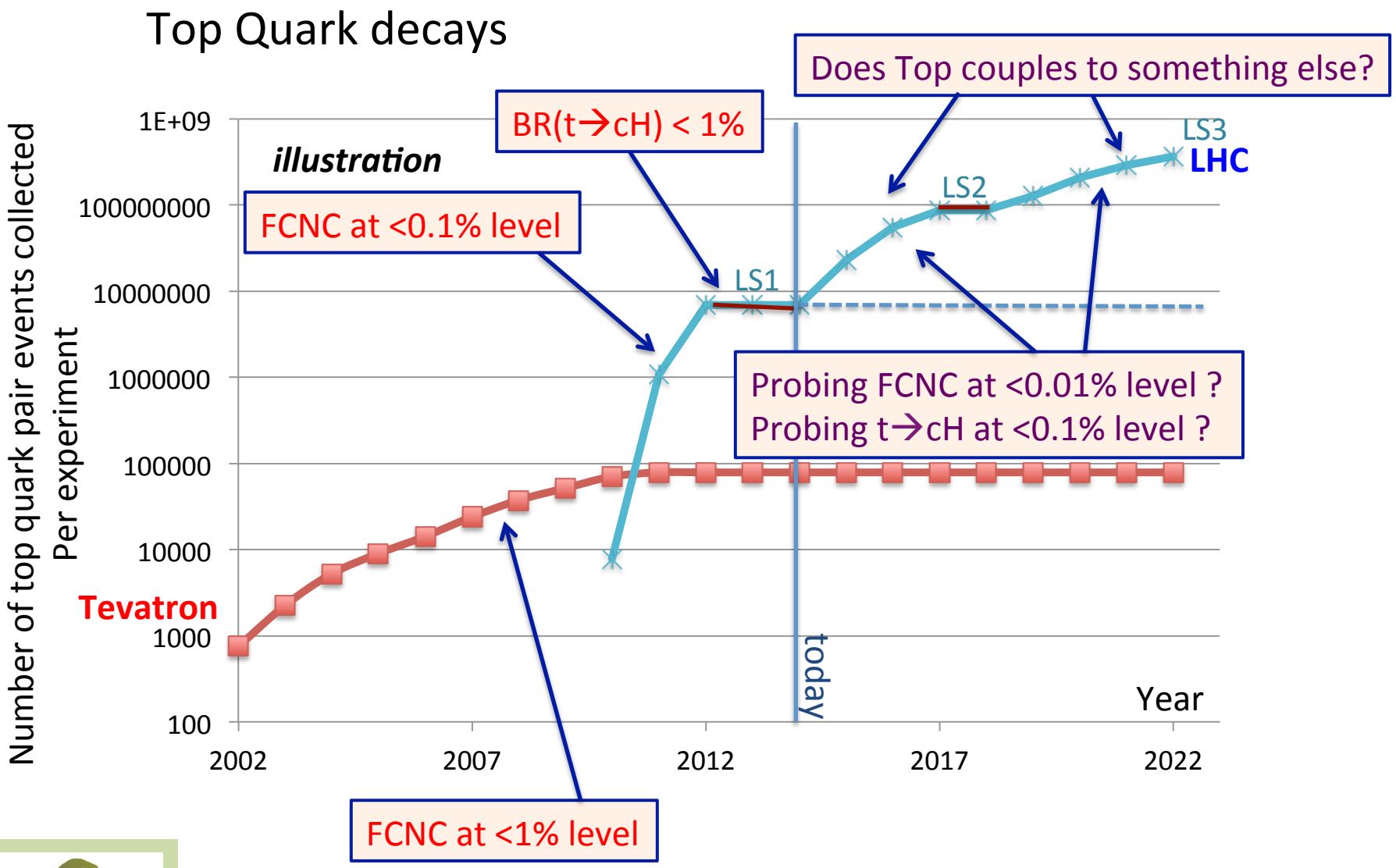
top-charm flavor violating Higgs Yukawa couplings of $\sqrt{|\lambda^h_{tc}|^2 + |\lambda^h_{ct}|^2} < 0.21$

ATLAS (7-8 TeV)
using H→γγ
Limits at 95% CL
BR(t→qH) < 0.79%
$\sqrt{|\lambda^h_{tc}|^2 + |\lambda^h_{ct}|^2} < 0.17$

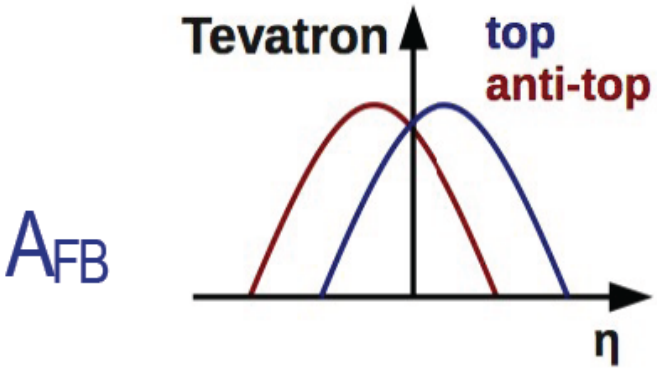
Expectation in SM: BR(t→cH) ≈ 3 . 10^{-15}
arXiv:hep-ph/0409342



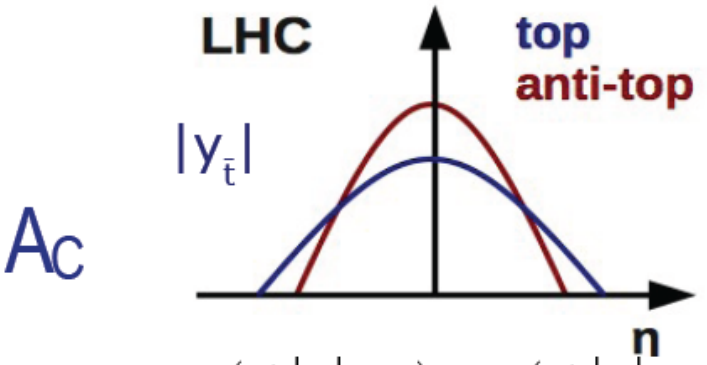
The status of Top Quark Physics



Top Quark Event Variables – Asymmetries

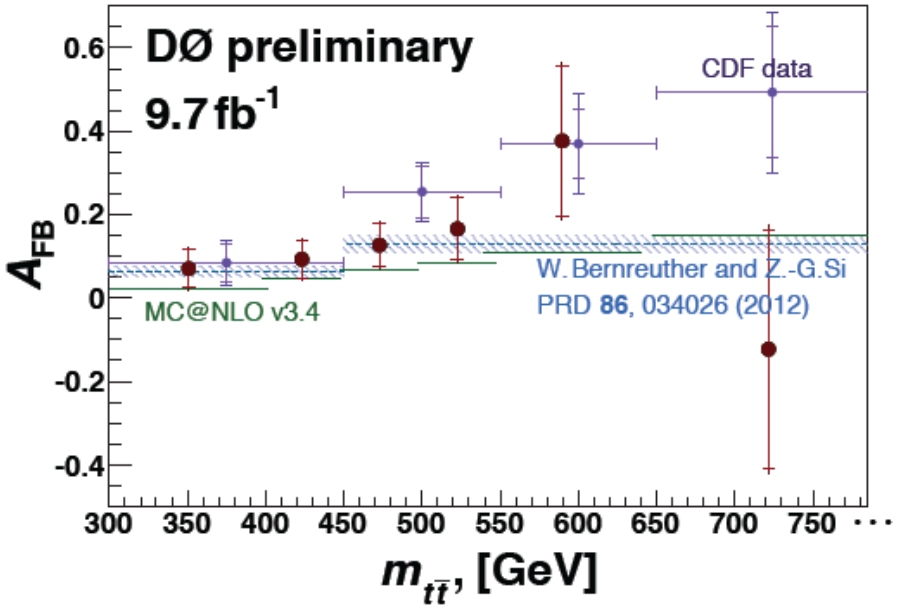


$$A_{FB}^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$



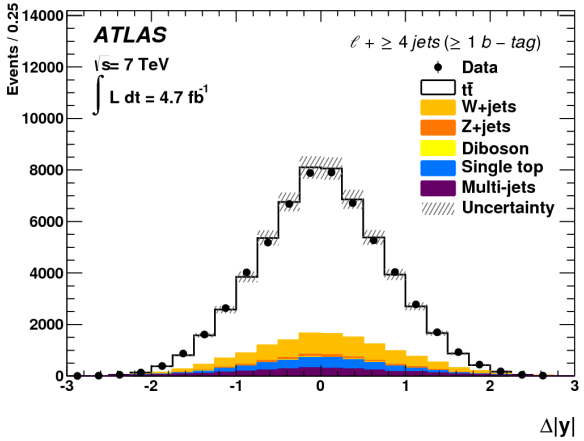
$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

- New A_{FB} measurement from D0
- Agrees with SM expectations
- CDF result with ~2σ deviation is shown



ATLAS JHEP11(2014)107, CMS Phys. Lett. B 717 (2012) 129

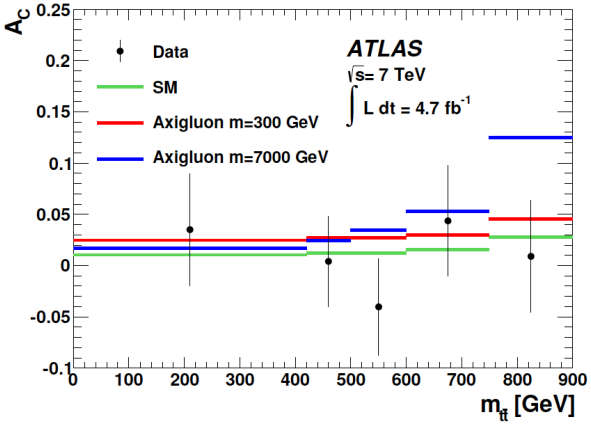
Top Quark Event Variables – Charge Asymmetry

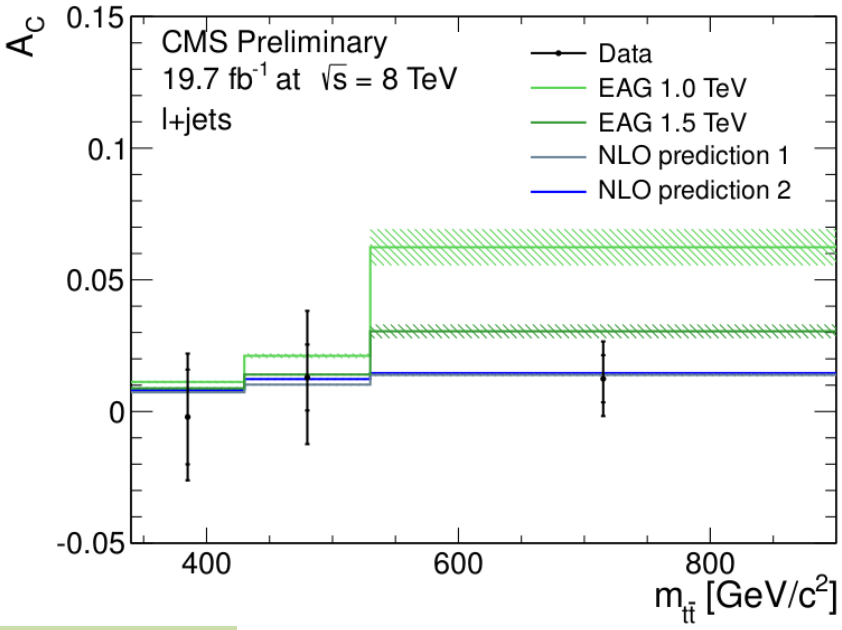


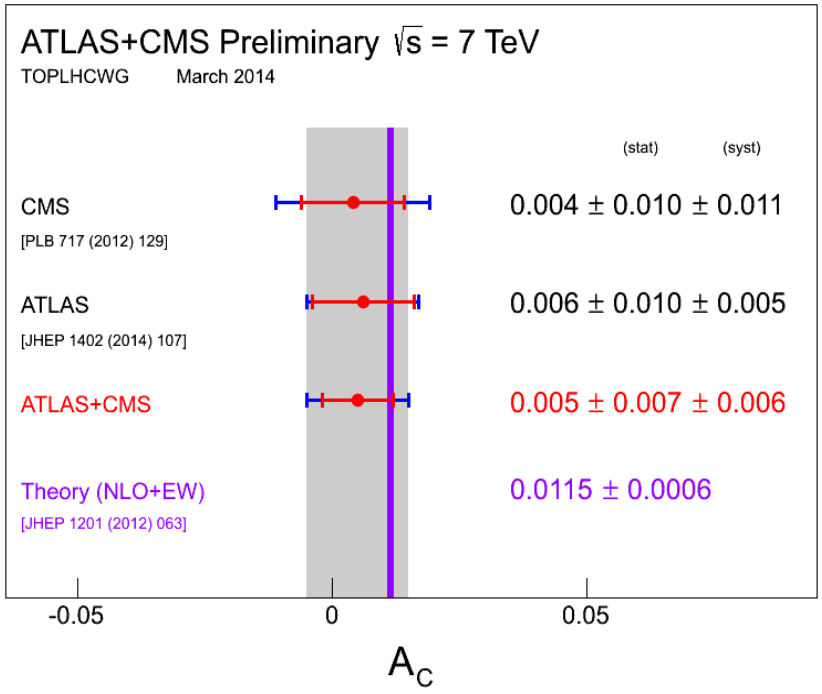
$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

$$\Delta|y| \equiv |y_t| - |y_{\bar{t}}|$$

After unfolding of acceptance and detector effects, hence a parton-level A_C measurement





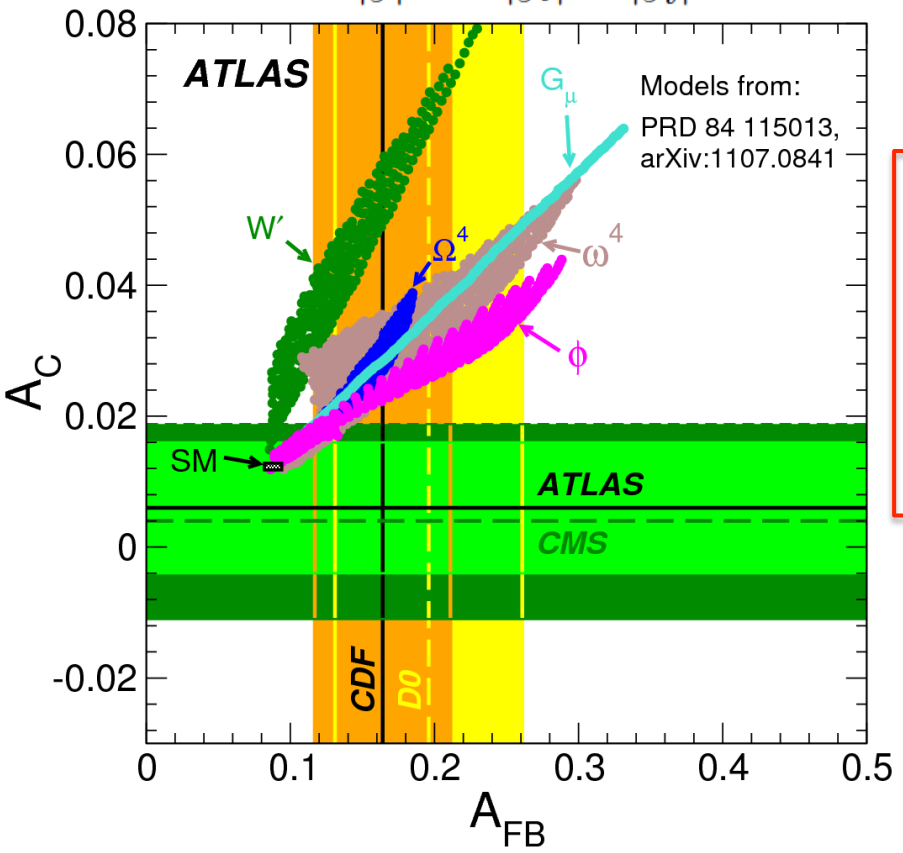


Top Quark Event Variables – Asymmetries

LHC (proton-proton)

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

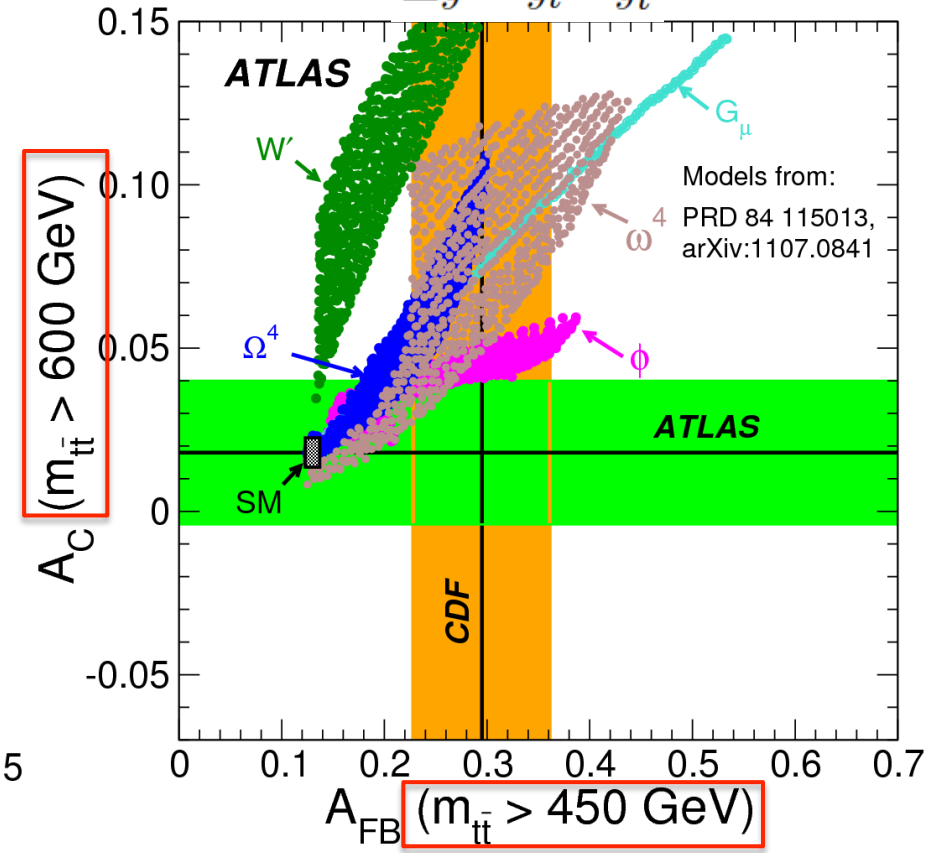
$$\Delta|y| \equiv |y_t| - |y_{\bar{t}}|$$



Tevatron (antiproton-proton)

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

$$\Delta y \equiv y_t - y_{\bar{t}}$$



The Top Quark stronghold

① Measured at the brick level !

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② Survived many attacks (eg. A_{FB})

The Top Quark stronghold

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③ Ready to measure at the sub-brick level

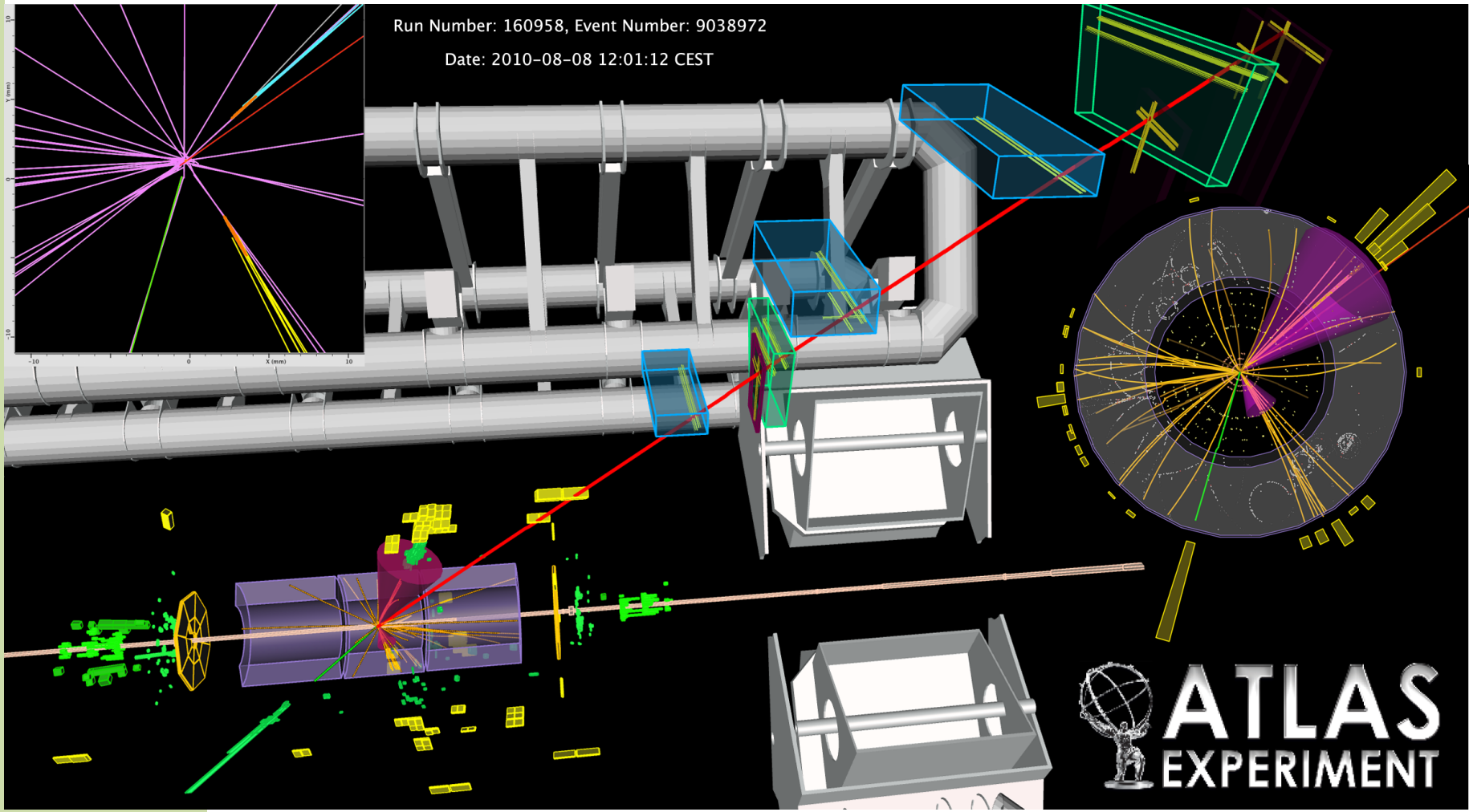
The Top Quark stronghold

① Measured at the brick level !
② Survived many attacks (eg. A_{FB})
③ Ready to measure at the sub-brick level
④ Excellent portal to Physics Beyond the SM
(tt+X, non-SM couplings, DM, CP-violation, …)

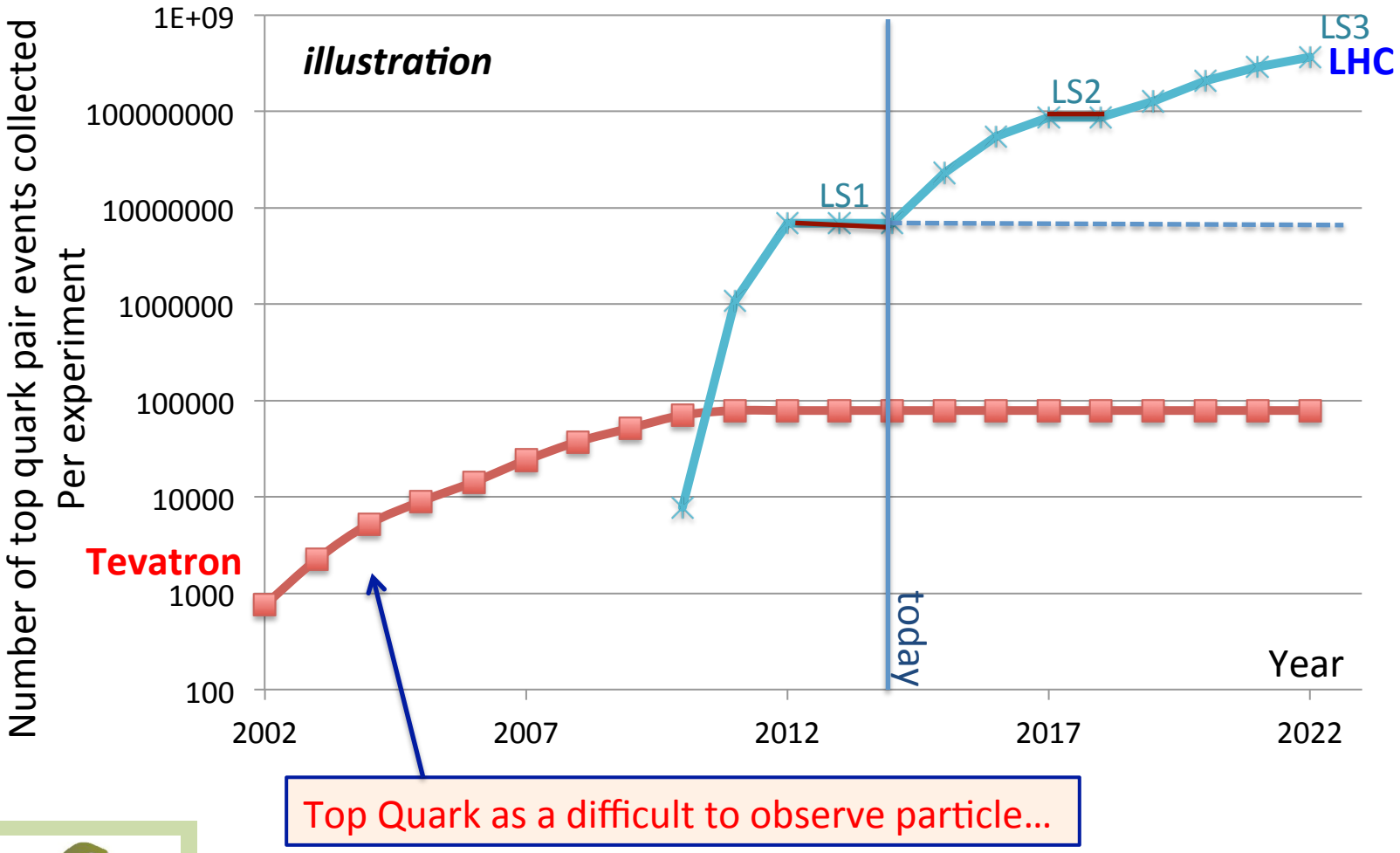
Back-up

Observing t → b W at colliders

jets, b-jets, charged leptons, neutrino's → need the full functionality of the detector



The status of Top Quark Physics



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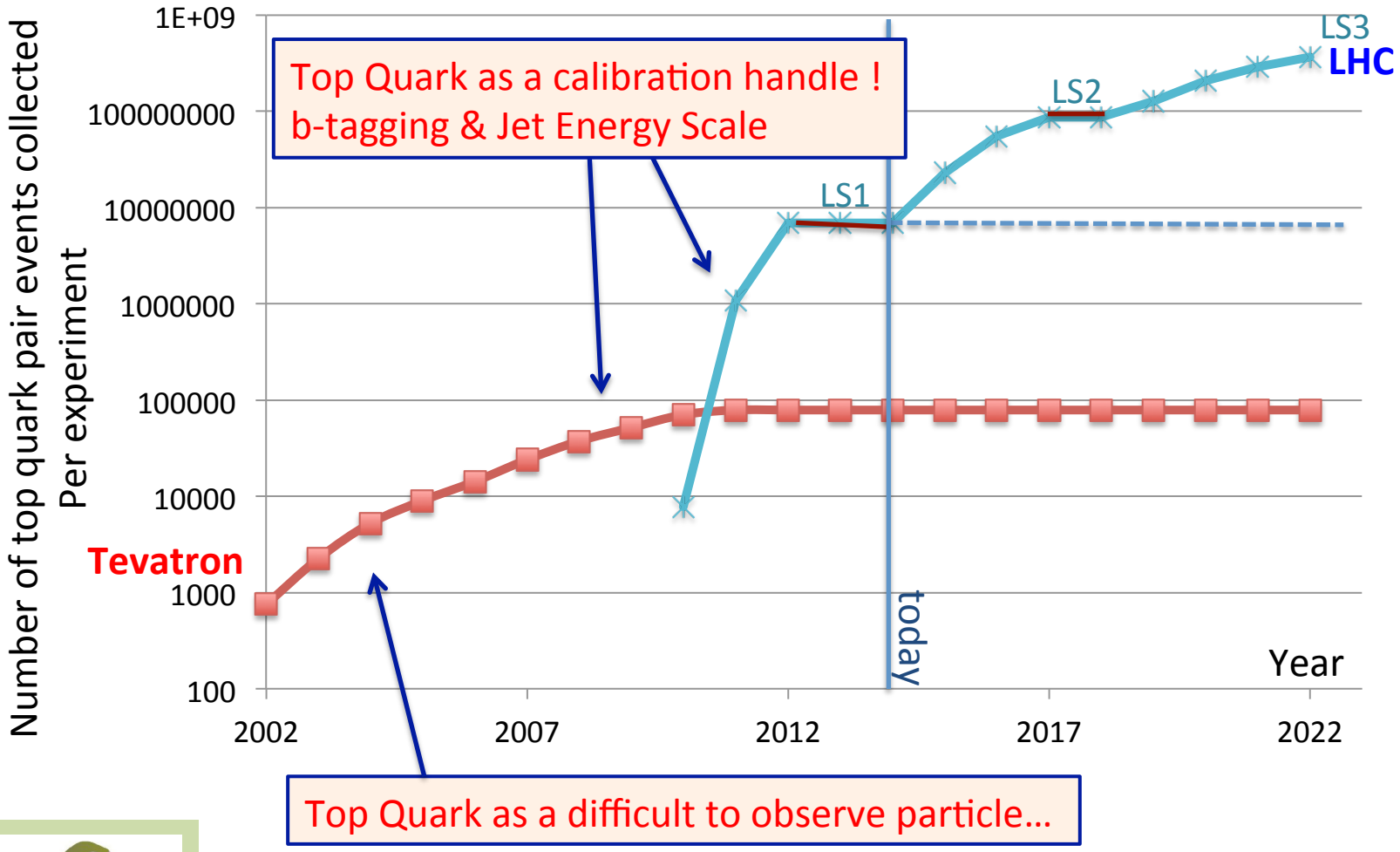
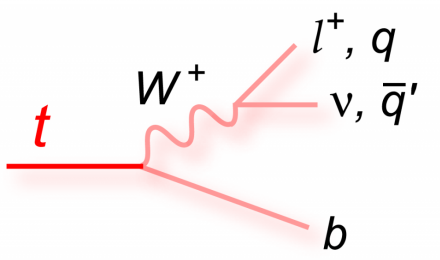
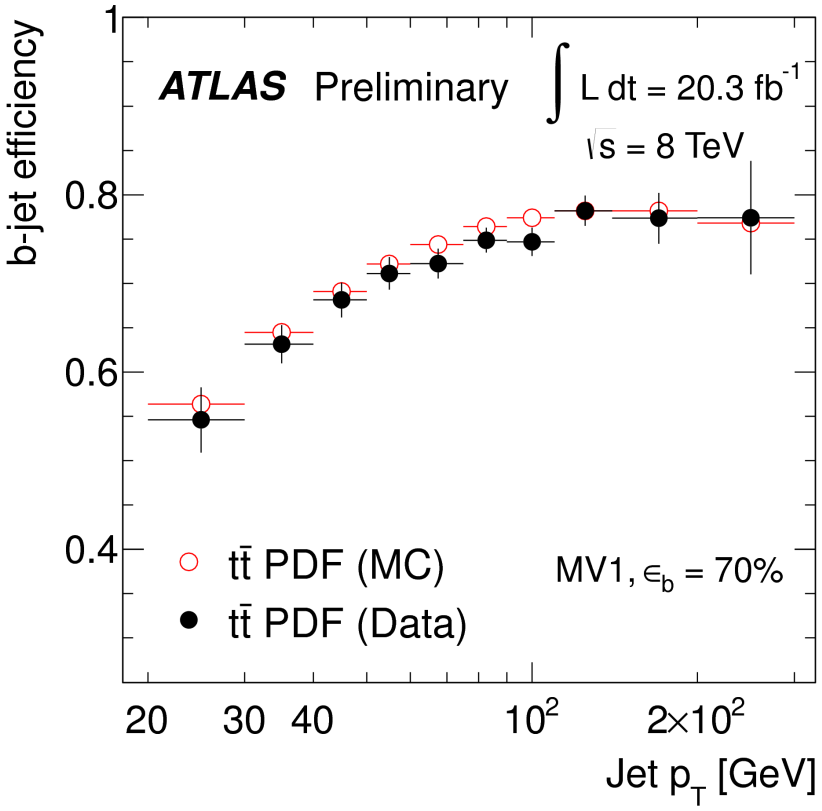


Using t → b W for calibration

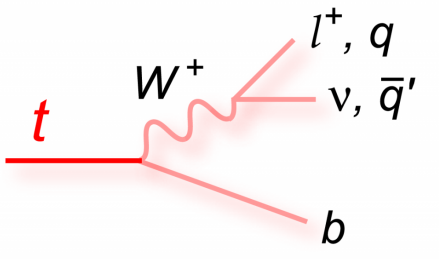


Top quark events useful for the calibration of the Jet Energy Scale as well as for the b-tagging performance.

- assume $|V_{tb}|=1$
- limited by systematic uncertainties



Using t → b W for calibration



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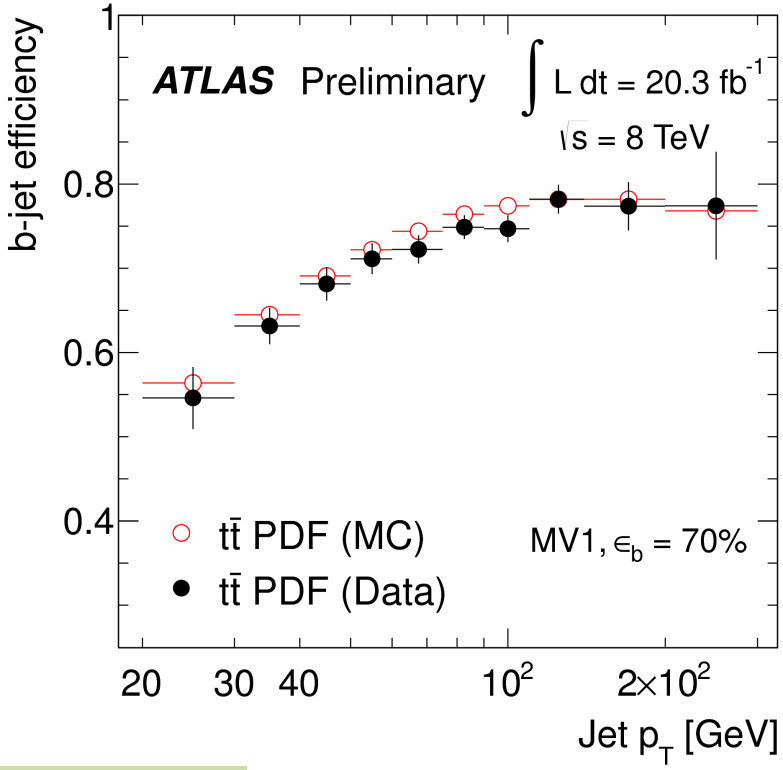
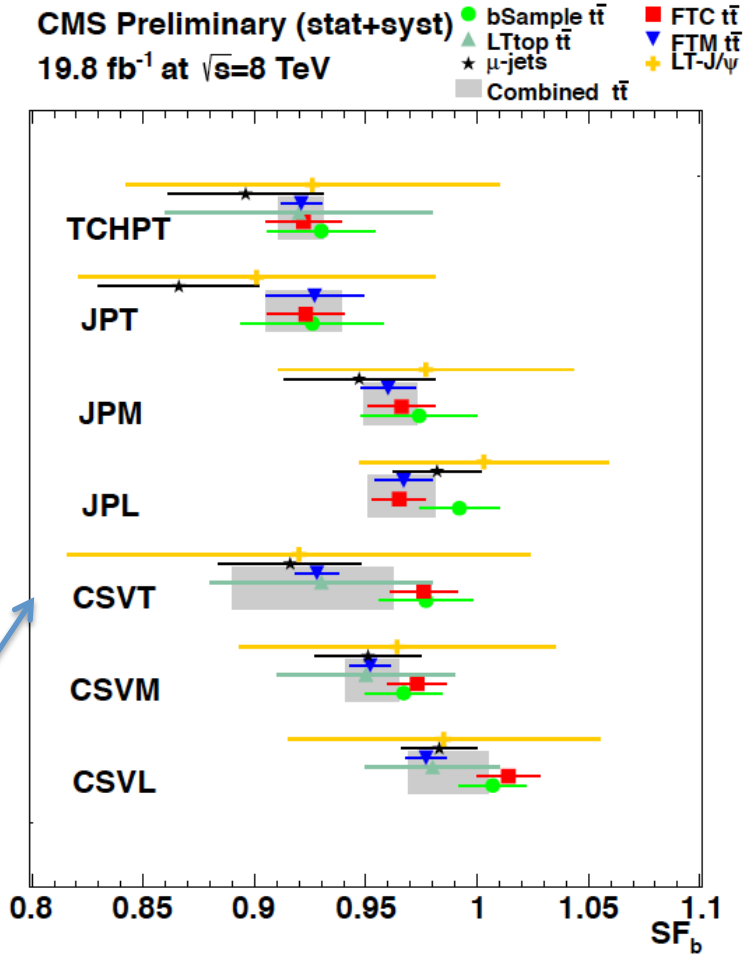
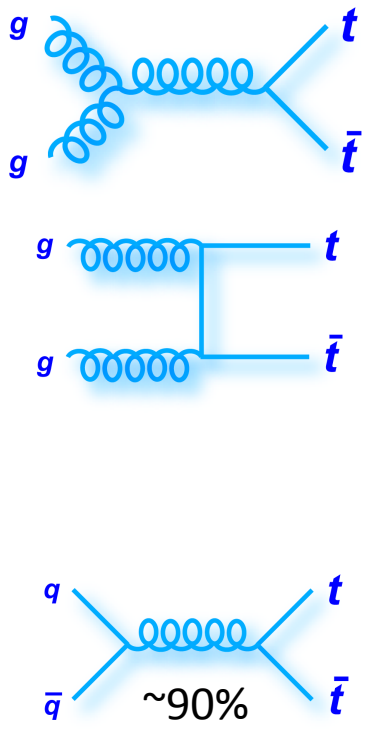


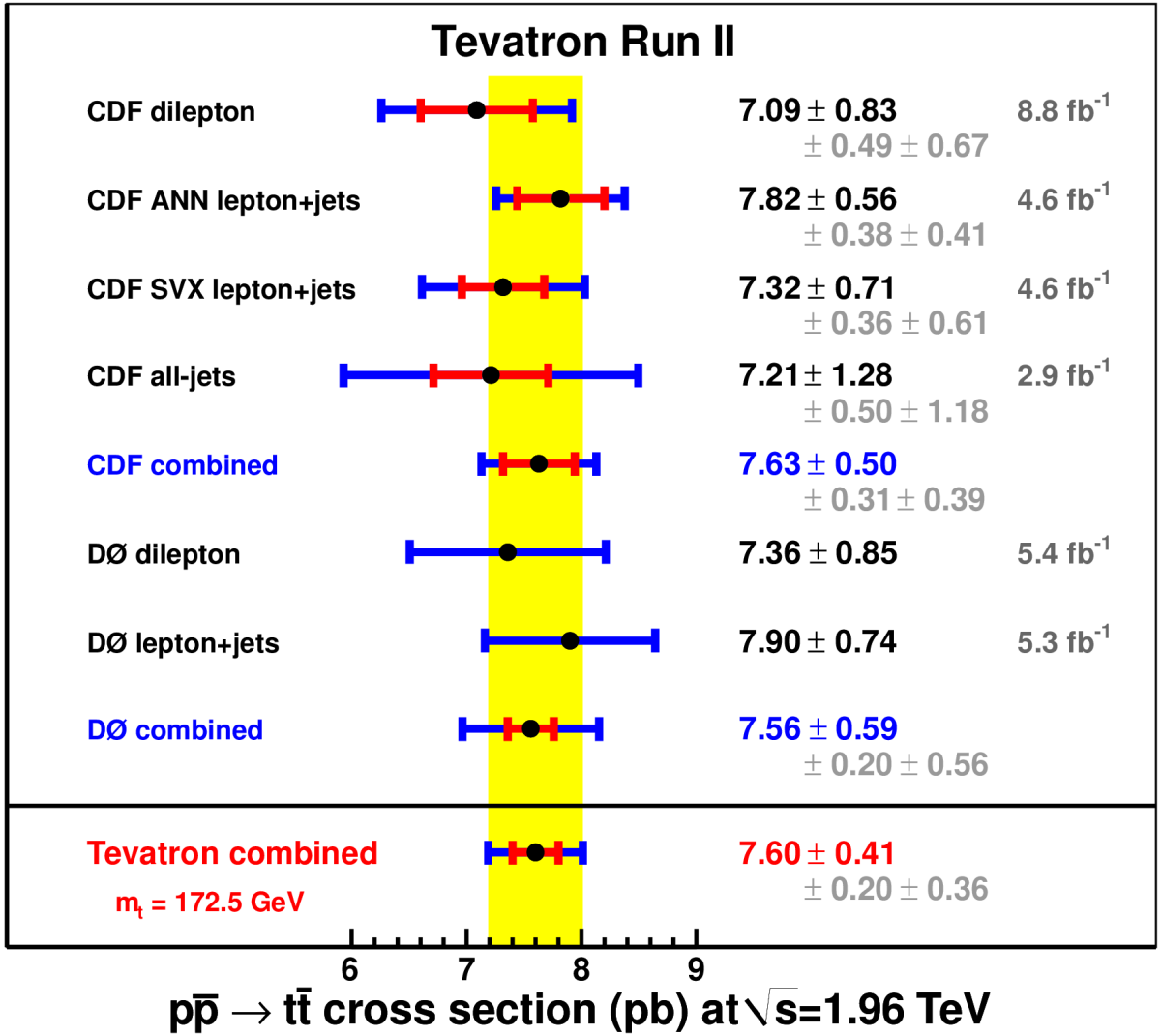


Diversity of methods in CMS

arXiv:1309.7570

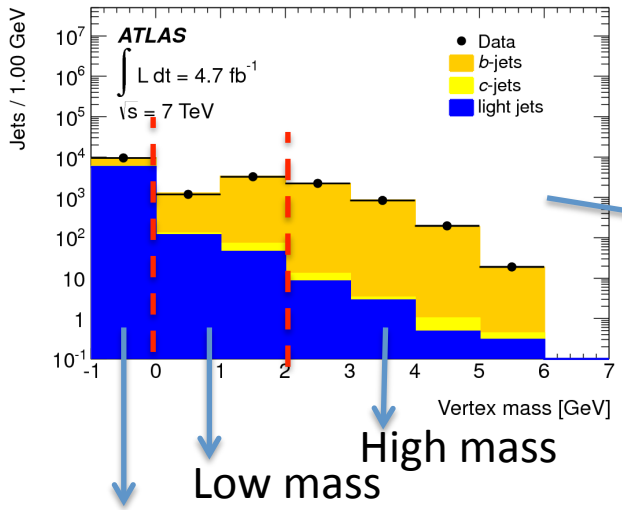
Cross-section – Tevatron

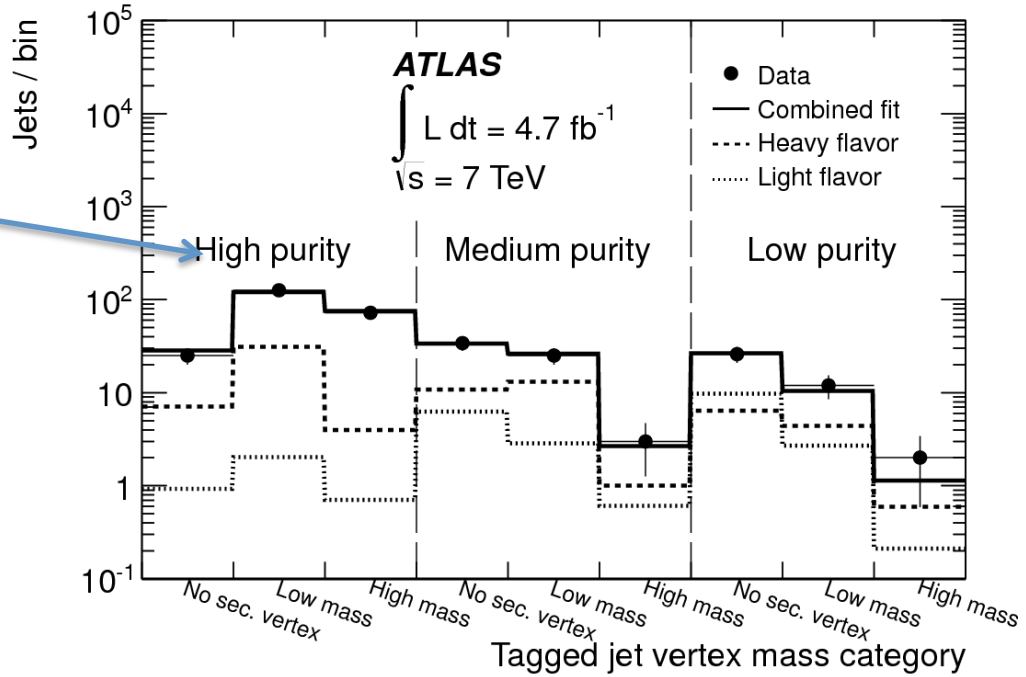




Cross-section – tt + Heavy Flavor

- Top quarks in association with heavy-flavor quarks (b or c) are important background events for several searches, eg. tt+H (H→bb).
- Selected di-lepton sample with at least 3 b-tagged jets.





$$R_{\mathrm{HF}} = \frac{\sigma_{\mathrm{fid}}(t\bar{t}+\mathrm{HF})}{\sigma_{\mathrm{fid}}(t\bar{t}+j)}$$

→ Fitted fraction of Heavy-Flavour is 6.2 ± 1.1(stat) ± 1.8(syst) %.

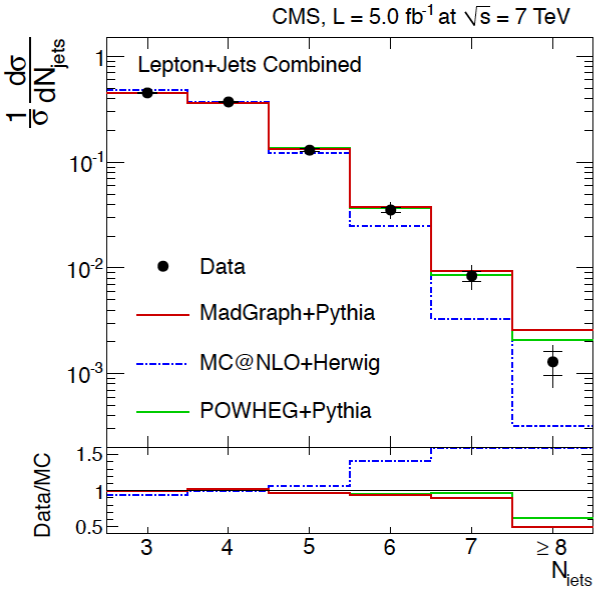
CMS (8 TeV): $\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj) = 0.023 \pm 0.003(stat.) \pm 0.005(syst.)$ at 20 GeV

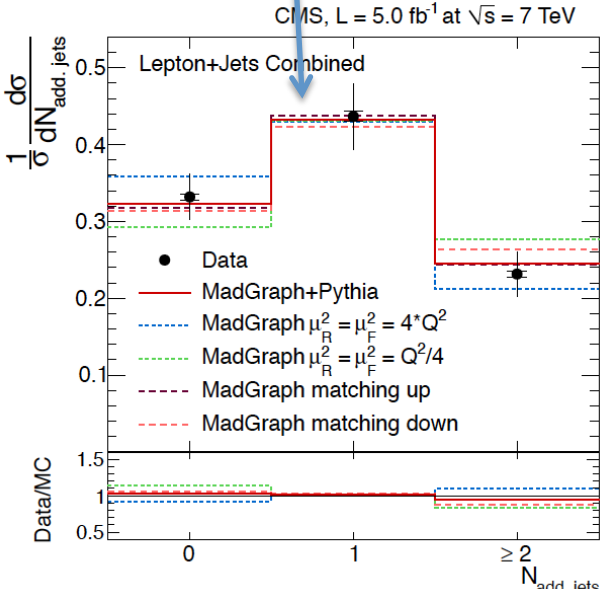
CMS arXiv:1404.3171; ATLAS CONF-2013-097

Cross-section – Jet Multiplicity

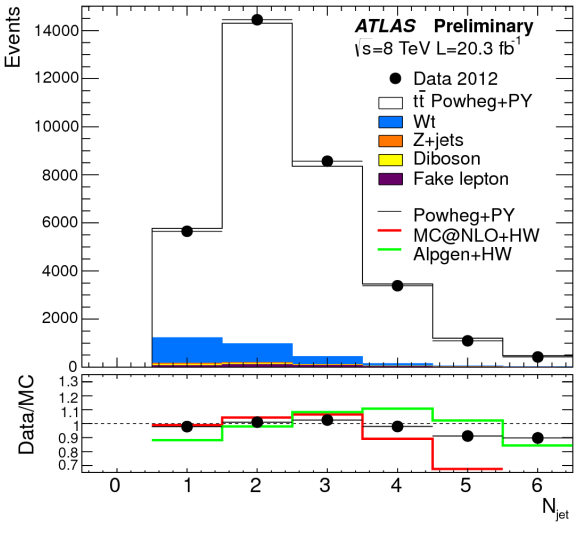
Differential cross-section as a function of the jet multiplicity (testing higher order QCD and an important background for ttH), measurement in visible phase-space.

The fractions with 0, 1, ≥2 jets are fitted to data histograms of a χ^2 variable including the observed kinematics of the event (m_W and m_{top})





di-lepton

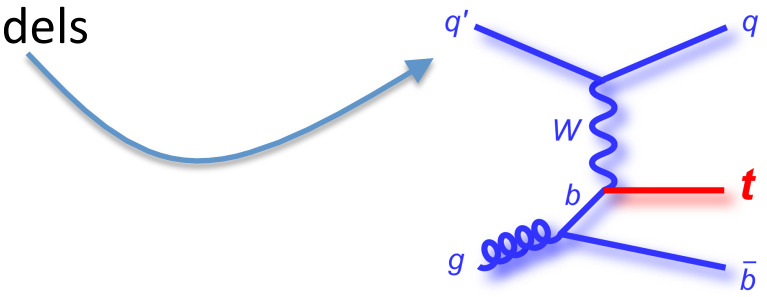


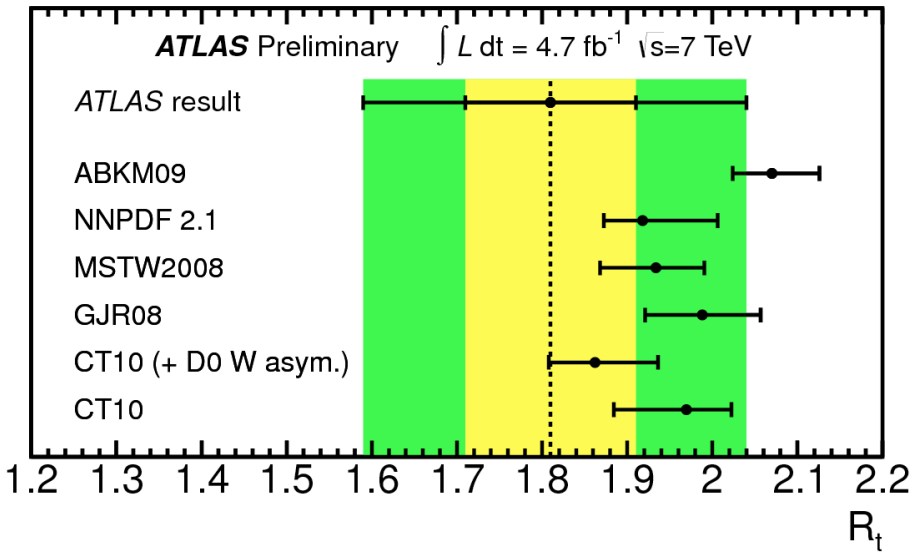
CMS 7 TeV

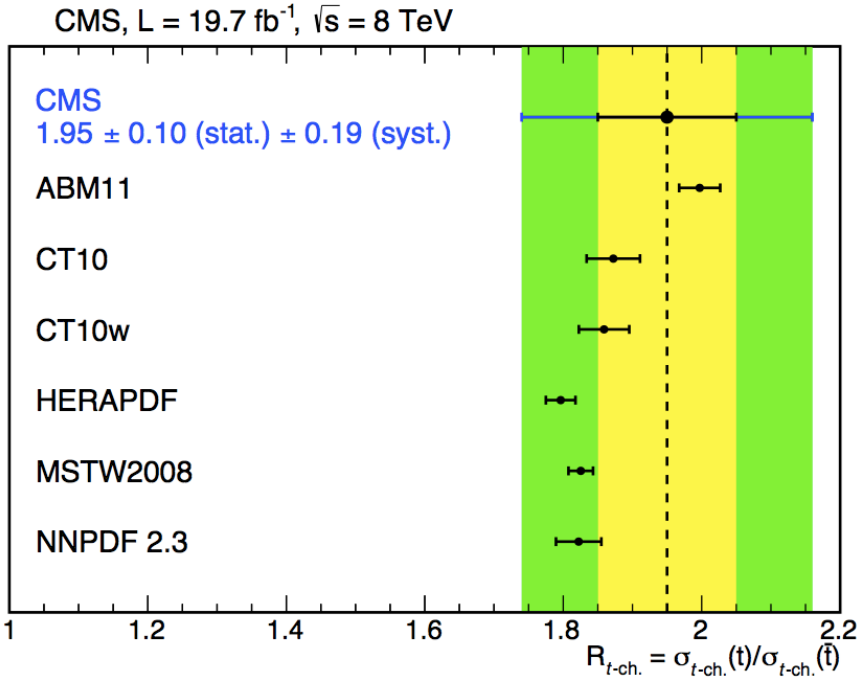
N_{jets}	$1/\sigma\, d\sigma/dN_{add.\ jets}$	Exp. Syst. (%) JES	Exp. Syst. (%) Other	Model Syst. (%) Q^2/Match./Had.	Model Syst. (%) Other	Total (%)
$t\bar{t}$ + 0 add. Jets	0.332	4.2	1.4	7.5	1.6	9.0
$t\bar{t}$ + 1 add. Jet	0.436	0.9	1.0	9.5	1.3	9.8
$t\bar{t}$ + ≥2 add. Jets	0.232	7.2	1.5	9.6	2.6	12.5

Lepton Charge Ratio – t-channel

- Lepton charge ratio is sensitive to PDF models

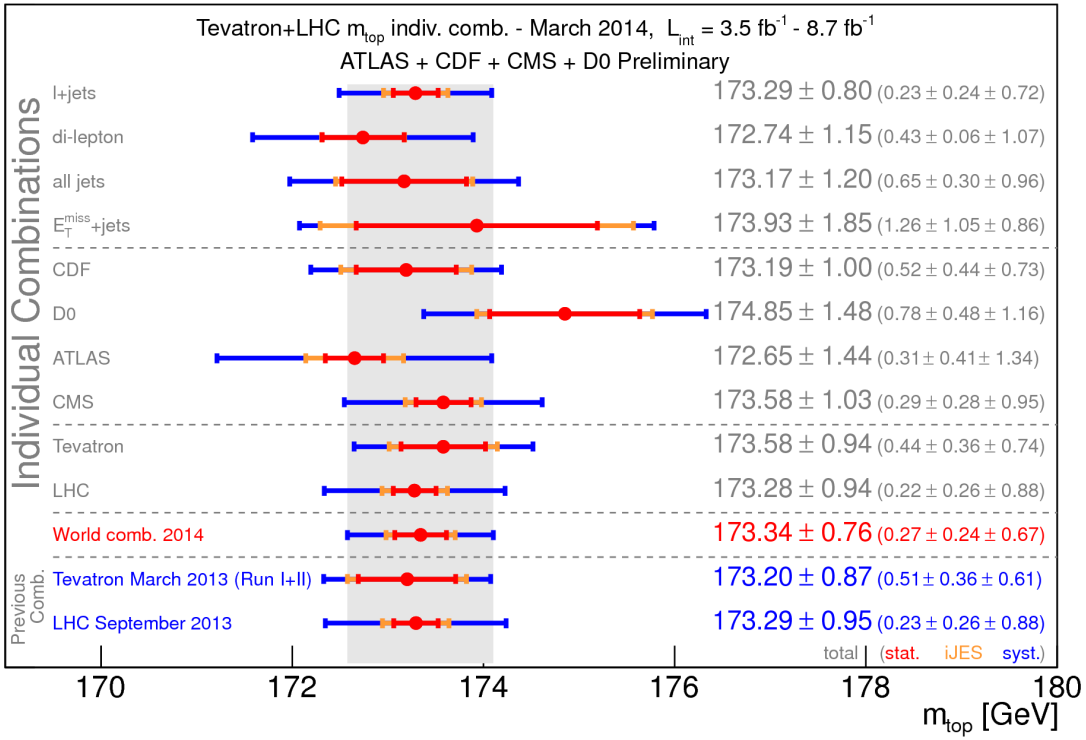


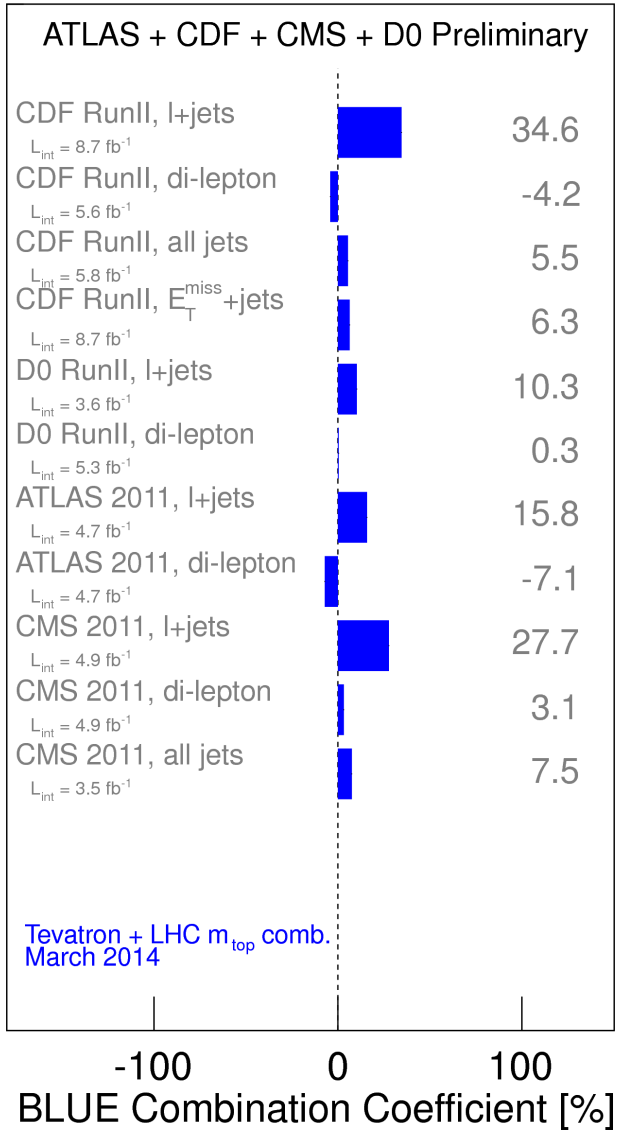




The Top Quark Mass

- Impact of the different measurements in the BLUE combination
- Comparing decay channels, experiments, colliders





The Top Quark Mass – update CMS

Measuring the key systematic uncertainties together with the top quark mass improves the precision.

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

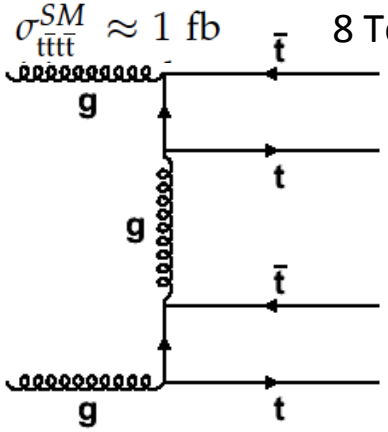
Top Quark Mass - alternatives

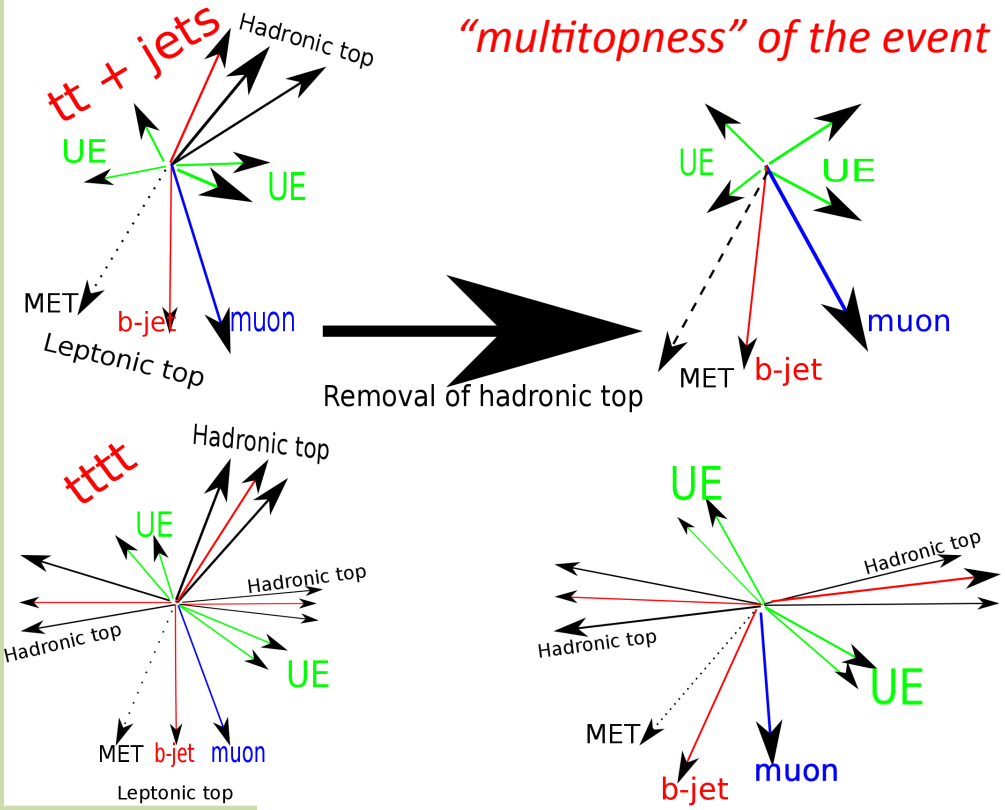
Measuring the key systematic uncertainties together with the top quark mass improves the precision.

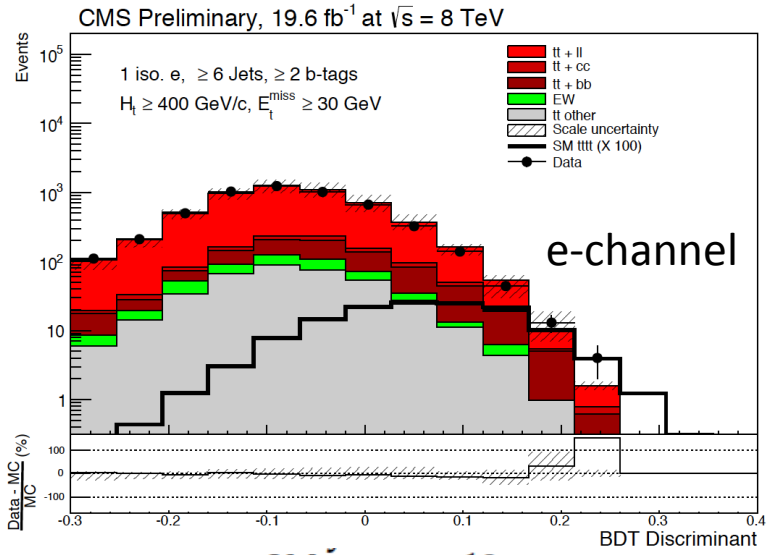
	2d-analysis		3d-analysis		
	m_{top} [GeV]	JSF	m_{top} [GeV]	JSF	bJSF
Measured value	172.80	1.014	172.31	1.014	1.006
Data statistics	0.23	0.003	0.23	0.003	0.008
Jet energy scale factor (stat. comp.)	0.27	n/a	0.27	n/a	n/a
bJet energy scale factor (stat. comp.)	n/a	n/a	0.67	n/a	n/a
Method calibration	0.13	0.002	0.13	0.002	0.003
Signal MC generator	0.36	0.005	0.19	0.005	0.002
Hadronisation	1.30	~~0.008~~	0.27	0.008	0.013
Underlying event	0.02	0.001	0.12	0.001	0.002
Colour reconnection	0.03	0.001	0.32	0.001	0.004
ISR and FSR (signal only)	0.96	0.017	0.45	0.017	0.006
Proton PDF	0.09	0.000	0.17	0.000	0.001
single top normalisation	0.00	0.000	0.00	0.000	0.000
W+jets background	0.02	0.000	0.03	0.000	0.000
QCD multijet background	0.04	0.000	0.10	0.000	0.001
Jet energy scale	0.60	0.005	0.79	0.004	0.007
b-jet energy scale	0.92	0.000	0.08	0.000	0.002
Jet energy resolution	0.22	0.006	0.22	0.006	0.000
Jet reconstruction efficiency	0.03	0.000	0.05	0.000	0.000
b-tagging efficiency and mistag rate	0.17	0.001	0.81	0.001	0.011
Lepton energy scale	0.03	0.000	0.04	0.000	0.000
Missing transverse momentum	0.01	0.000	0.03	0.000	0.000
Pile-up	0.03	0.000	0.03	0.000	0.001
Total systematic uncertainty	2.02	0.021	1.35	0.021	0.020
Total uncertainty	2.05	0.021	1.55	0.021	0.022

Hunting for multi-top production

A combination of kinematic reconstruction and multivariate techniques is used to distinguish between signal and backgrounds.







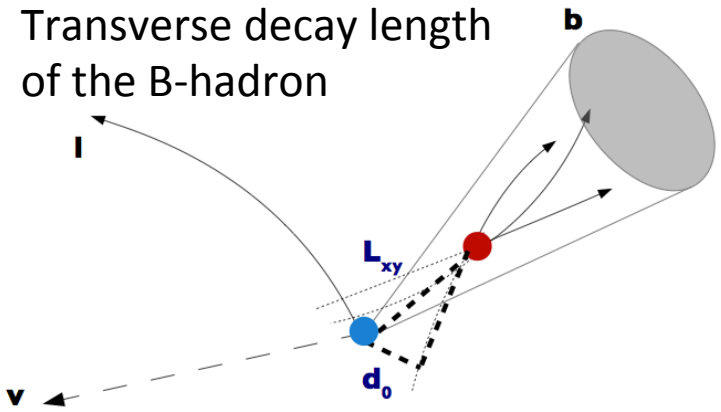
upper limit: $\sigma^{SM}_{t\bar{t}t\bar{t}}$ of 42^{+18}_{-13} fb (expected)

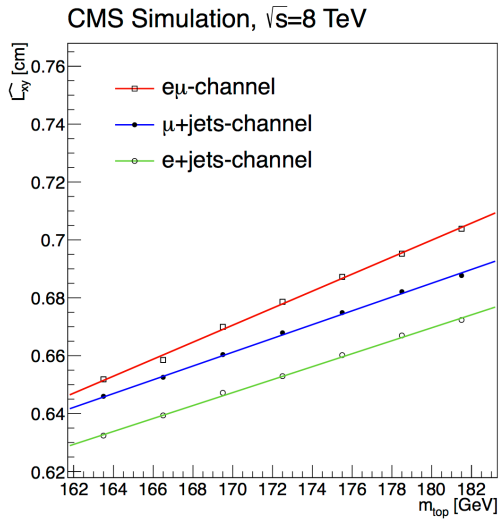
63 fb (observed)

Top Quark Mass - alternatives

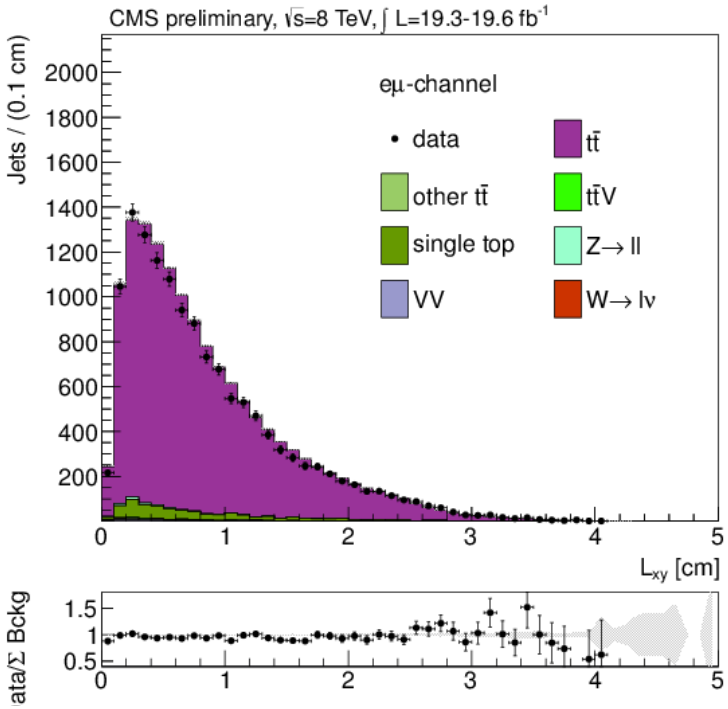
example: using the B-hadron lifetime technique (8 TeV)

Transverse decay length of the B-hadron





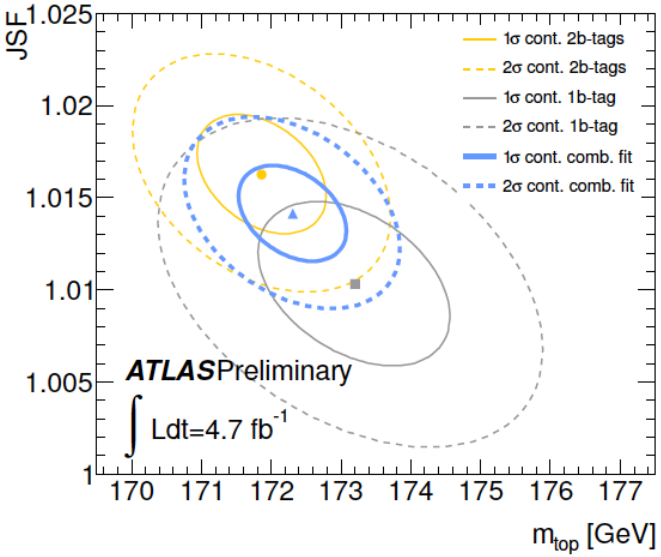
Main uncertainty is the modeling of the top quark p_T

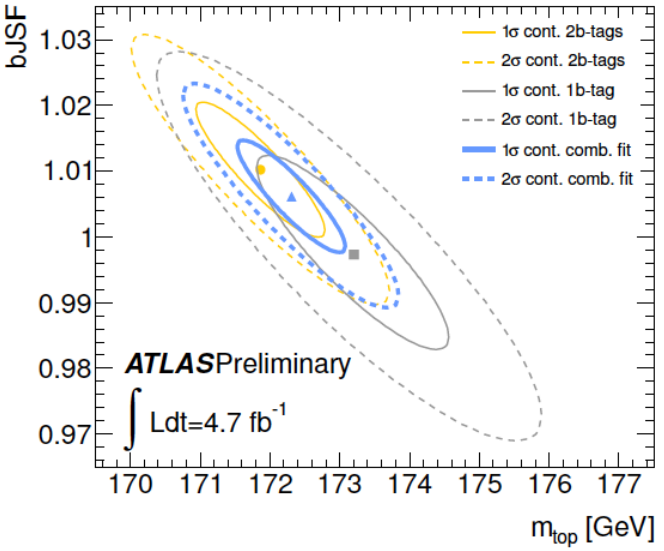


Channel	m_t [GeV]
muon+jets	$173.2 \pm 1.0_{stat} \pm 1.6_{syst} \pm 3.3_{p_T(t)}$
electron+jets	$172.8 \pm 1.0_{stat} \pm 1.7_{syst} \pm 3.1_{p_T(t)}$
electron-muon	$173.7 \pm 2.0_{stat} \pm 1.4_{syst} \pm 2.4_{p_T(t)}$

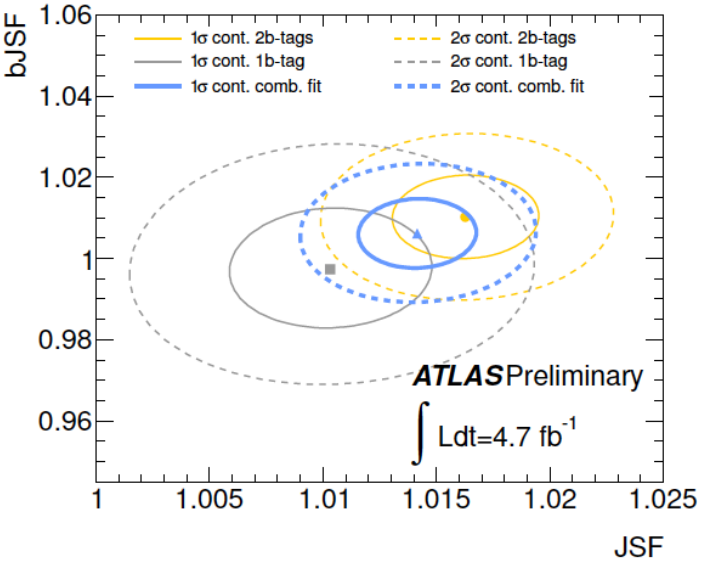
$m_t = 173.5 \pm 1.5_{stat} \pm 1.3_{syst} \pm 2.6_{pt(t)}$ GeV

Top Quark Mass - alternatives



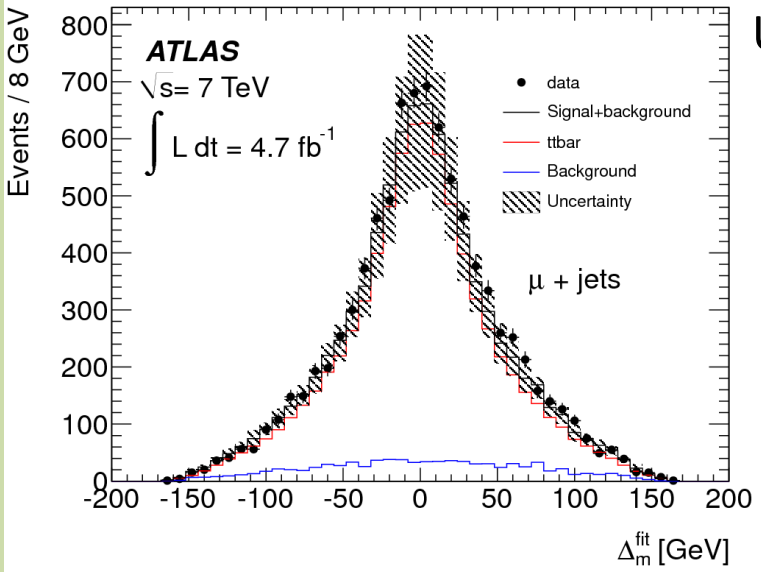


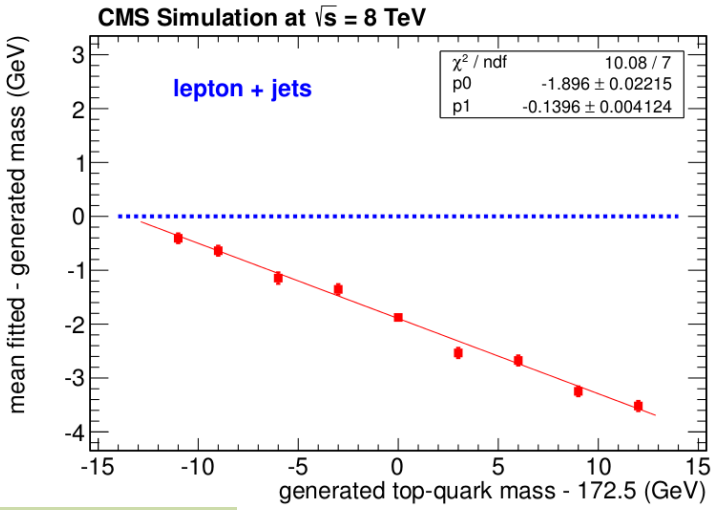
$$
\begin{aligned}
m_{\text{top}} &= 172.31 \pm 0.75\ (\text{stat} + \text{JSF} + \text{bJSF}) \pm 1.35\ (\text{syst})\ \text{GeV}, \\
\text{JSF} &= 1.014 \pm 0.003\ (\text{stat}) \pm 0.021\ (\text{syst}), \\
\text{bJSF} &= 1.006 \pm 0.008\ (\text{stat}) \pm 0.020\ (\text{syst}).
\end{aligned}
$$



ATLAS Phys. Lett. B 728C (2014); pp.363-379, CMS JHEP 06(2012)109; CMS TOP-12-031

Top Quark Mass – top versus anti-top





Unique testing of CPT invariance on bare quarks

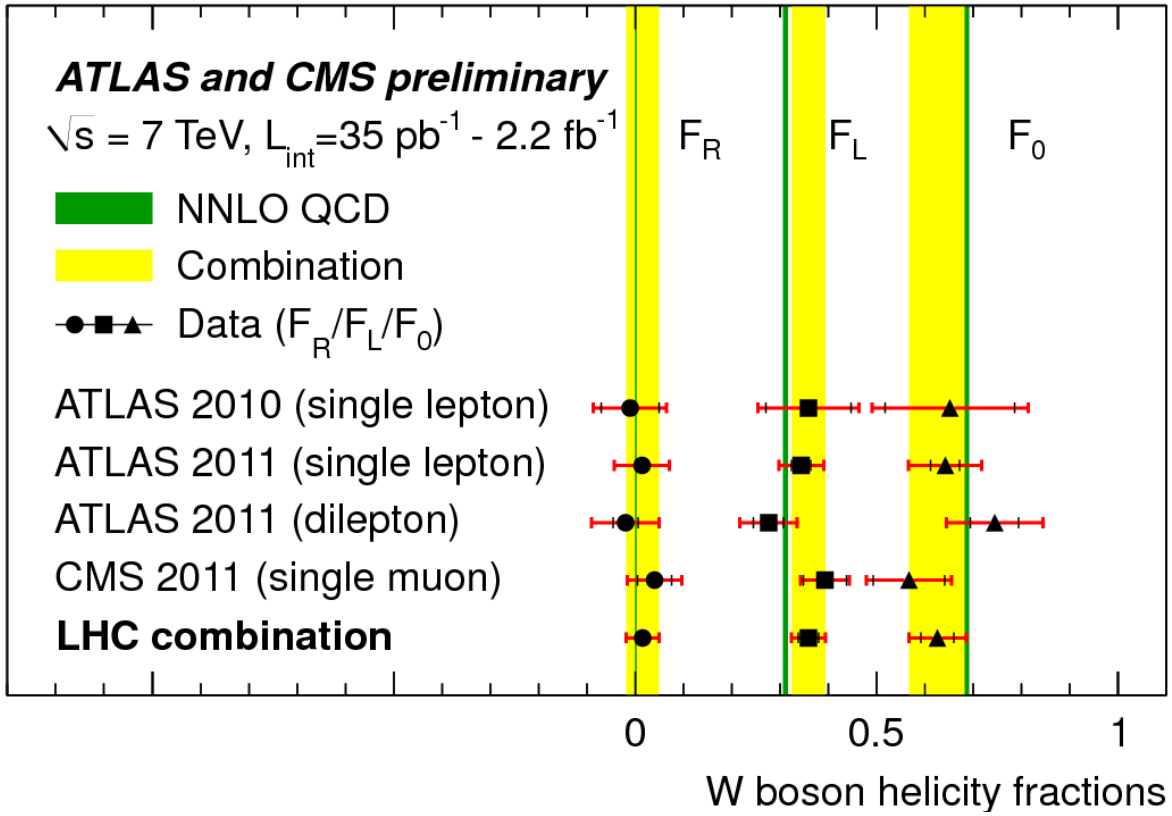
Source (CMS TOP-12-031)	Estimated effect (MeV)
Jet energy scale	$\mathbf{17} \pm 15$
Jet energy resolution	$8 \pm \mathbf{11}$
b vs. $\bar{b}$ jet response	$\mathbf{64} \pm 7$
Signal fraction	$\mathbf{45} \pm 2$
Background charge asymmetry	$\mathbf{12.43} \pm 0.03$
Background composition	$\mathbf{50} \pm 1$
Pileup	$\mathbf{17.4} \pm 0.4$
b-tagging efficiency	$\mathbf{20} \pm 8$
b vs. $\bar{b}$ tagging efficiency	$\mathbf{43} \pm 6$
Method calibration	$15 \pm \mathbf{54}$
Parton distribution functions	$\mathbf{12} \pm 3$
Total	122

Results (in GeV), still statistics dominated

CMS	7 TeV	-0.44 +- 0.46 (stat) +- 0.27 (syst)
CMS	8 TeV	-0.27 +- 0.20 (stat) +- 0.12 (syst)
ATLAS	7 TeV	0.67 +- 0.61 (stat) +- 0.41 (syst)

b vs anti-b systematic: comparing EvtGen & Pythia (ATLAS), difference of 0.1% in simulated jet response (CMS)

W helicity in Top Quark Decay



$$F_0 = 0.626 \pm 0.034\ (\text{stat.}) \pm 0.048\ (\text{syst.})$$

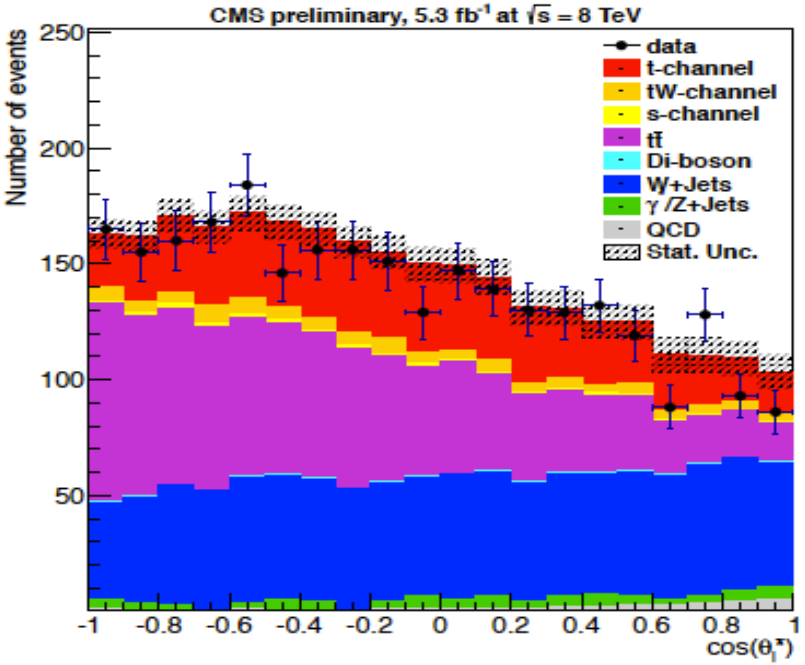
$$F_L = 0.359 \pm 0.021\ (\text{stat.}) \pm 0.028\ (\text{syst.})$$

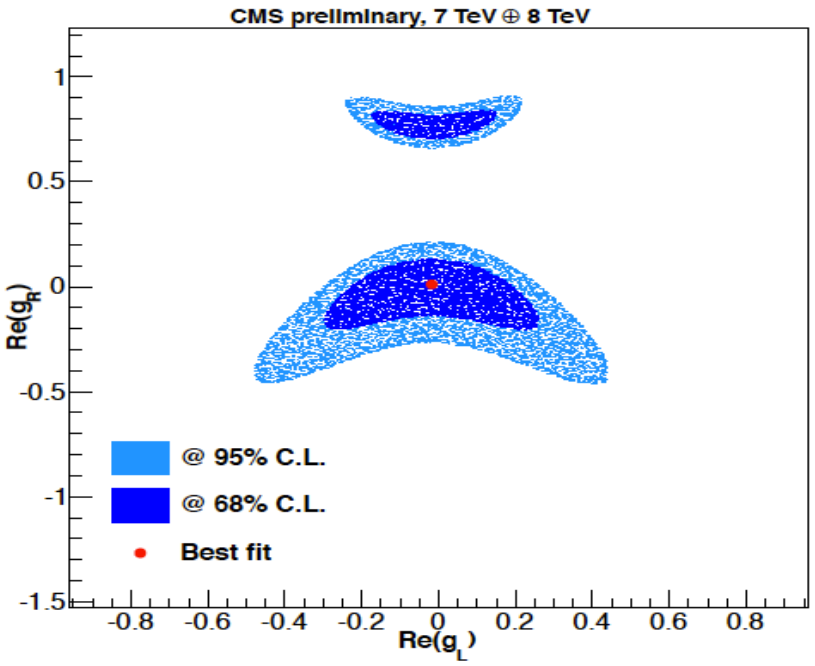
Assuming unity sum: $F_R = 0.015 \pm 0.034$

W helicity in Top Quark Decay

Also measured this distribution in single-top events

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





$$\mathcal{L}_{tWb}^{anom.} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}(V_L P_L + V_R P_R)tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{m_W}(g_L P_L + g_R P_R)tW_{\mu}^{-} + H.C,$$

Top Quark Decay – polarization

Also polarization measurement using Single-Top

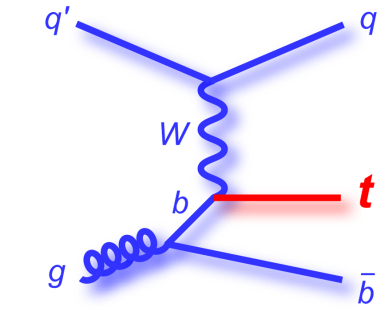
$$\frac{d\Gamma}{d\cos\theta_X} = \frac{\Gamma}{2}(1 + P_t\alpha_X\cos\theta_X) \equiv \Gamma(\frac{1}{2} + A_X\cos\theta_X)$$

(angle between the charged lepton and the untagged jet)

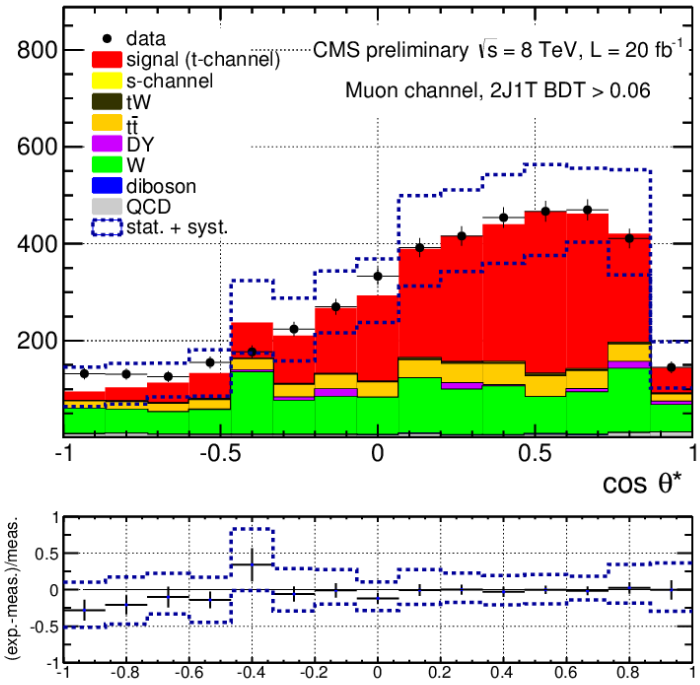
$$P_t = 0.82 \pm 0.12(stat.) \pm 0.32(syst.) = 0.82 \pm 0.34(tot.)$$

(with $\alpha_l = 1$)

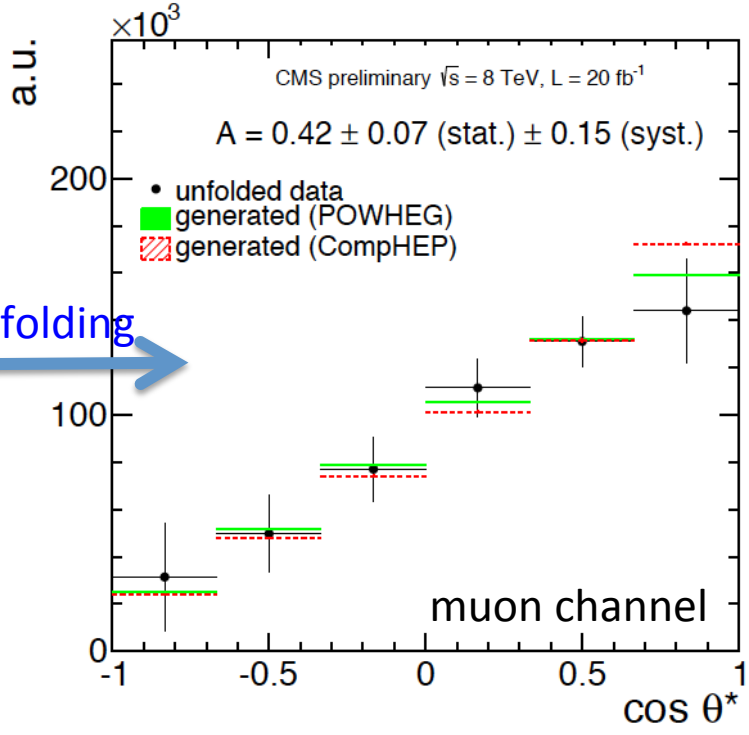
Should be 100% polarized due to V-A coupling



$$A_l \equiv \frac{1}{2}\cdot P_t \cdot \alpha_l = \frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)}$$



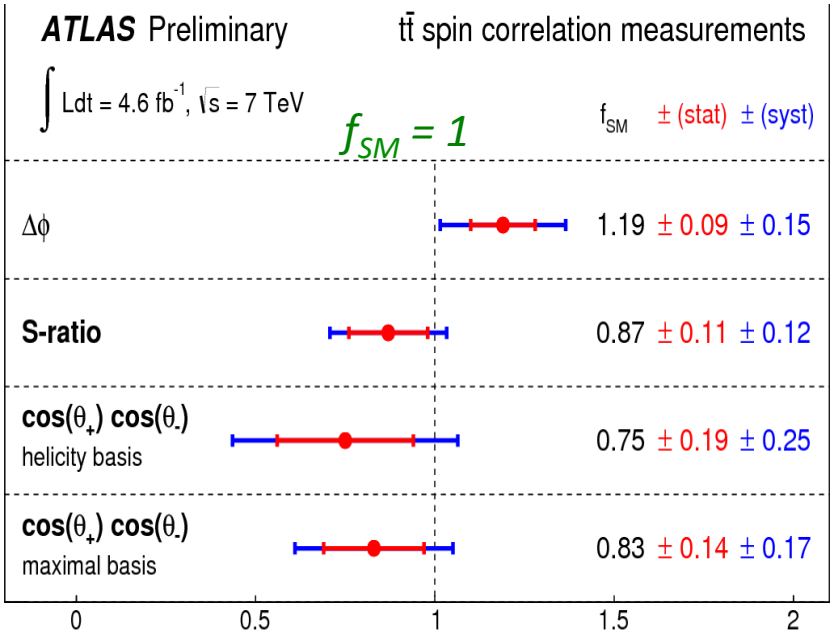
unfolding

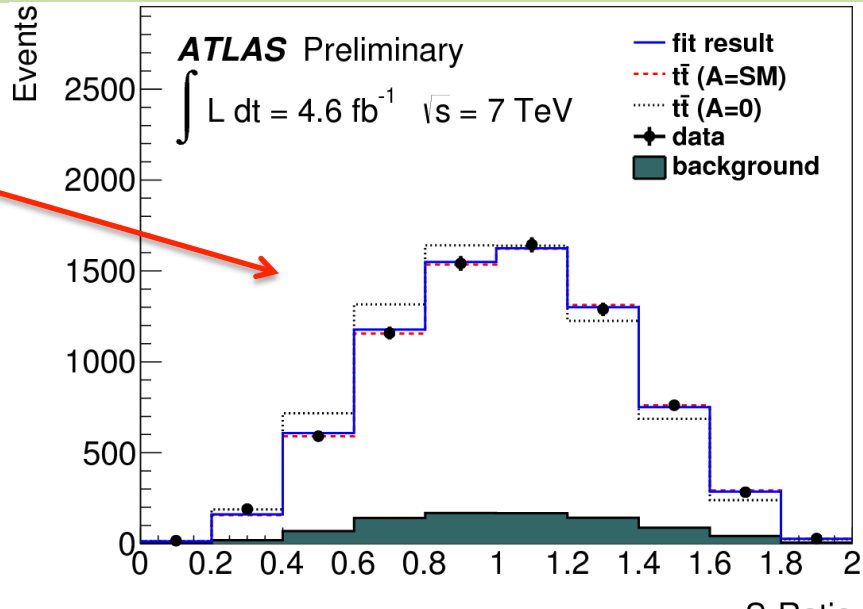


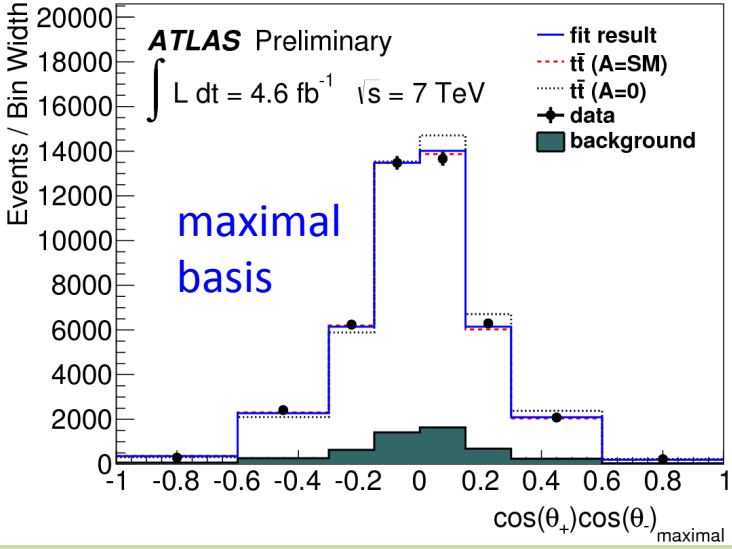
Top Quark spin correlations

$$S = \frac{(|\mathcal{M}|^2_{RR} + |\mathcal{M}|^2_{LL})_{corr}}{(|\mathcal{M}|^2_{RR} + |\mathcal{M}|^2_{LL})_{uncorr}} = \frac{m_t^2\{(t\cdot l^+)(t\cdot l^-) + (\bar{t}\cdot l^+)(\bar{t}\cdot l^-) - m_t^2(l^+\cdot l^-)\}}{(t\cdot l^+)(\bar{t}\cdot l^-)(t\cdot\bar{t})}$$

$$f_{SM} = N_{A=SM}/(N_{A=SM} + N_{A=0})$$

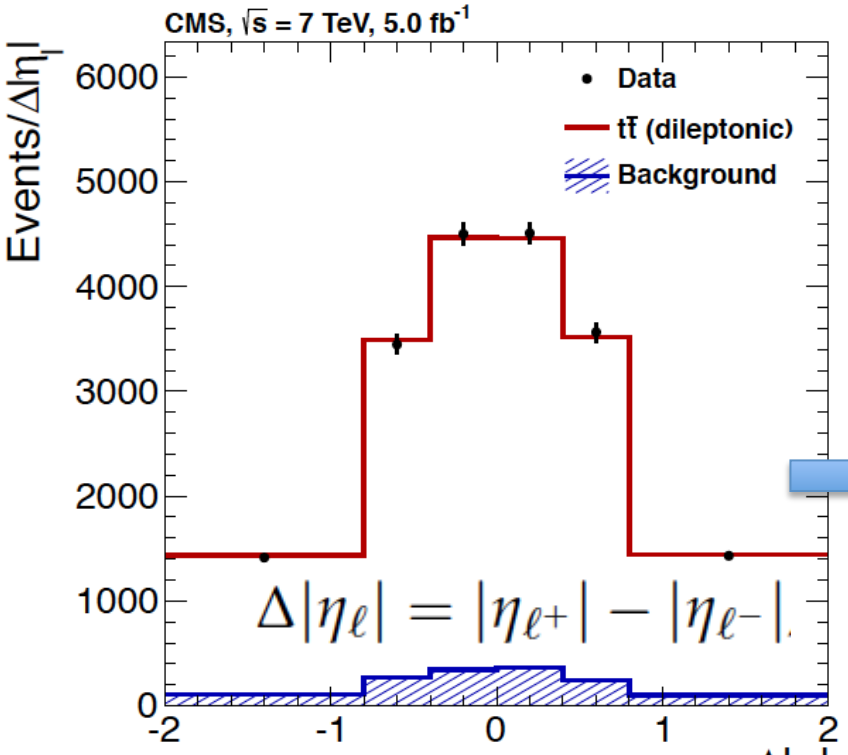






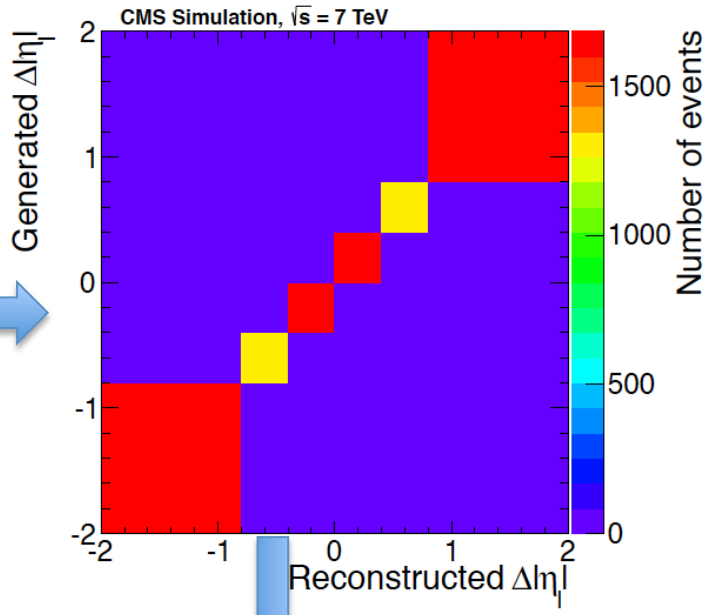
Top Quark Event Variables – Charge Asymmetry

Measurement in the di-lepton channel of the lepton charge asymmetry



$$A_C^{\text{lep}} = \frac{N(\Delta|\eta_\ell| > 0) - N(\Delta|\eta_\ell| < 0)}{N(\Delta|\eta_\ell| > 0) + N(\Delta|\eta_\ell| < 0)}$$

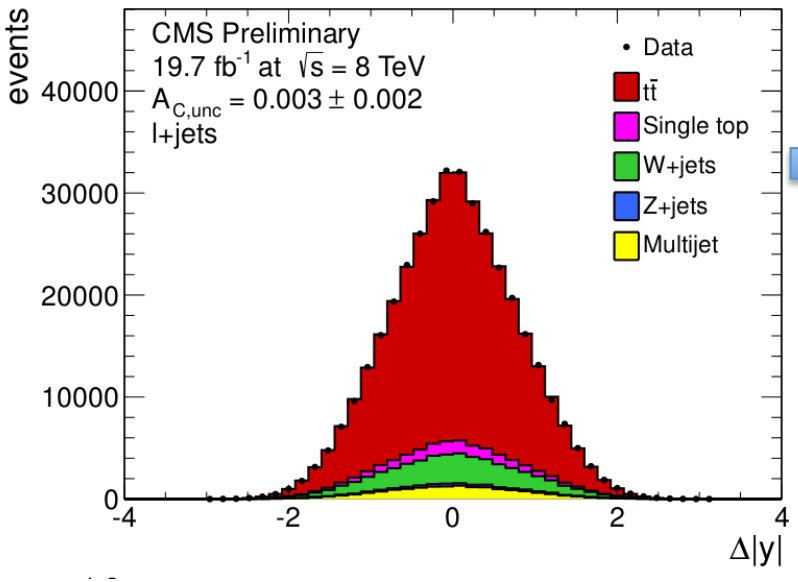
Unfolding to correct the data for acceptance, selection and resolution.

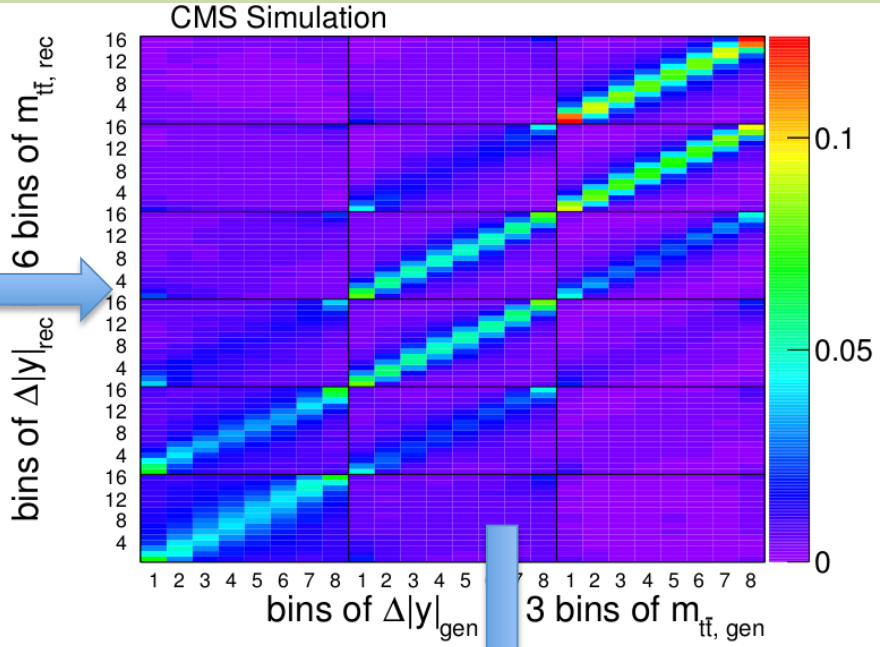


Variable	Data (unfolded)	MC@NLO prediction	NLO theory
A_C	$-0.010 \pm 0.017 \pm 0.008$	0.004 ± 0.001	0.0123 ± 0.0005
A_C^{lep}	$0.009 \pm 0.010 \pm 0.006$	0.004 ± 0.001	0.0070 ± 0.0003

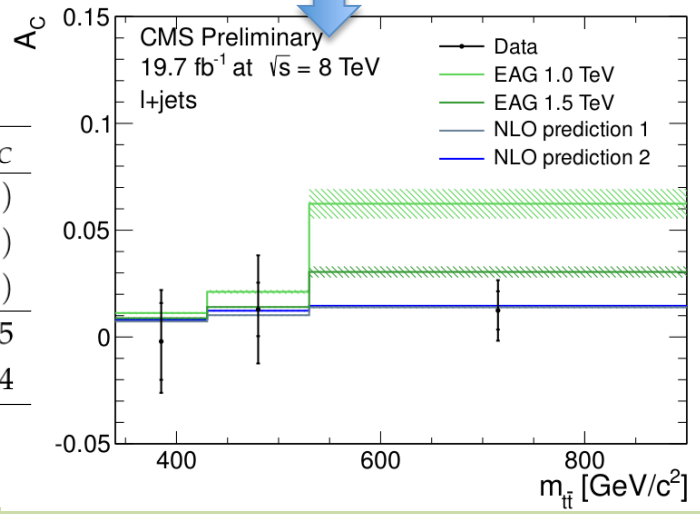
Top Quark Event Variables – Charge Asymmetry

Measurement in the lepton+jet channel





Asymmetry	A_C
Reconstructed	0.003 ± 0.002 (stat.)
BG-subtracted	0.002 ± 0.002 (stat.)
Unfolded	0.005 ± 0.007 (stat.) ± 0.006 (syst.)
Theory prediction [Kühn, Rodrigo] [9, 33]	0.0102 ± 0.0005
Theory prediction [Bernreuther, Si] [34, 35]	0.0111 ± 0.0004



Top Quark Charge

Event-by-event reconstruction of the b-quark charge and combine with the measured lepton charge:

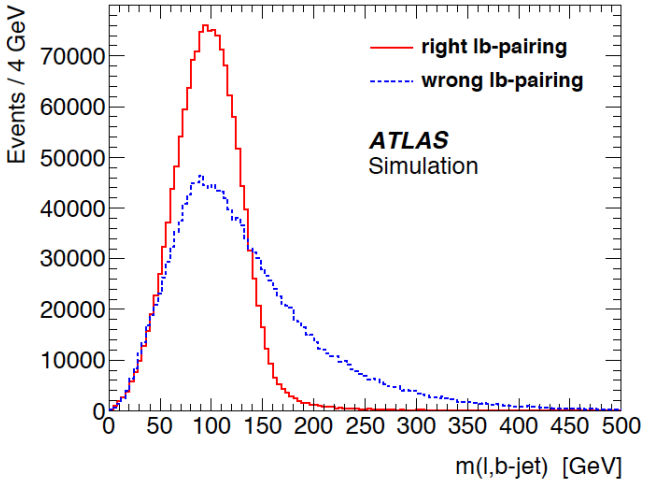
κ=0.5

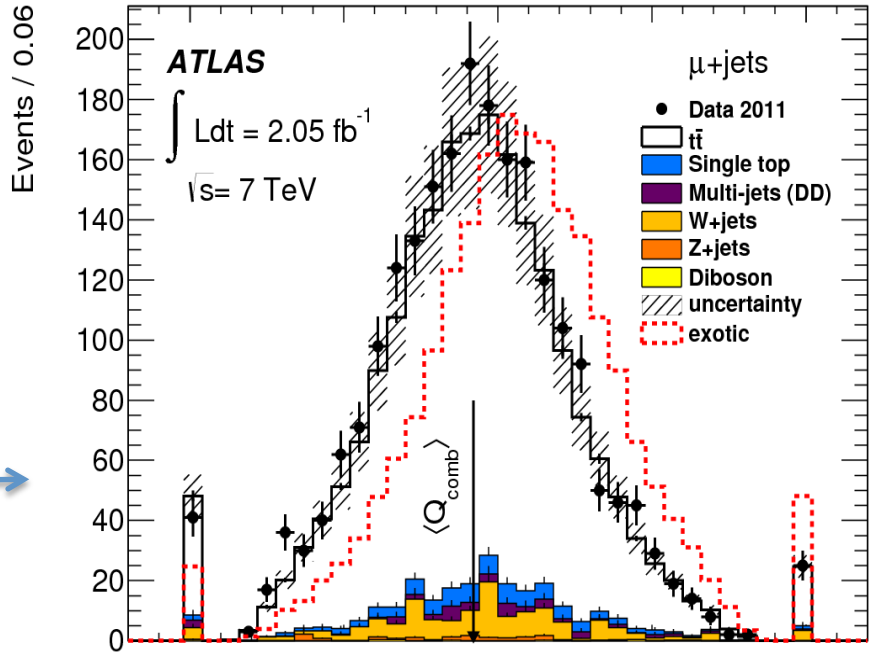
$$Q_{b-\text{jet}} = \frac{\sum_i Q_i |\vec{j}\cdot\vec{p}_i|^\kappa}{\sum_i |\vec{j}\cdot\vec{p}_i|^\kappa}$$

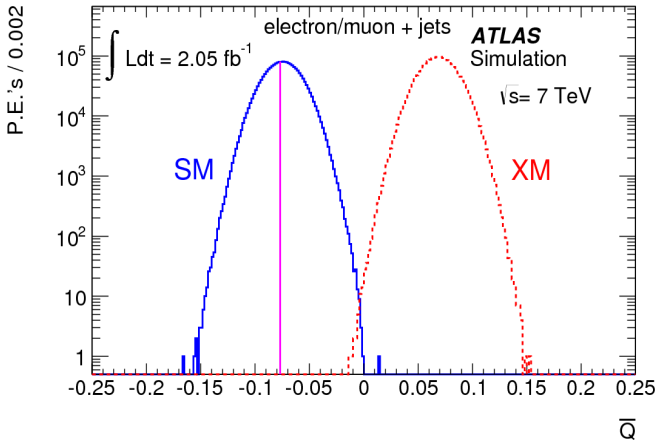
Weighted sum of track charges

Lepton and b-quark pairing using the mass of the "b+l" system.

$$Q_{\text{comb}} = Q^{\ell}_{b-\text{jet}} \cdot Q_{\ell}$$







Charge -4/3 excluded by >8σ

$$0.64 \pm 0.02\,(\text{stat.}) \pm 0.08\,(\text{syst.})$$