Determination of Top-Quark Properties

Yuji Yamazaki (Kobe University)
on behalf of the ATLAS, CMS and LHCb Collaborations

The 28th International Symposium
on Lepton Photon Interactions at High Energies

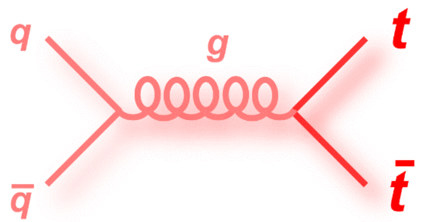
8 August 2017

Sun Yat-Sen University, Guangzhou, China

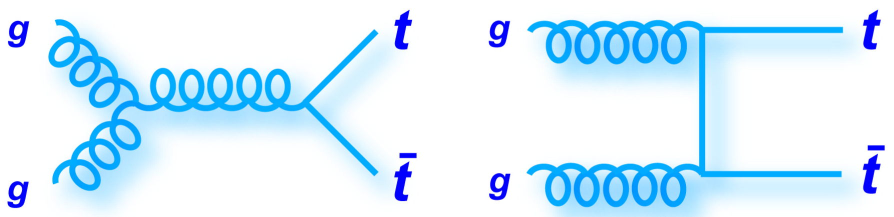
Contents

Top production in hadron colliders

- The only quark heavier than EW scale: $\boldsymbol{m_t \simeq 173}$ **GeV**
- **pair production:**
  thru **strong** interaction



$p\bar{p}$ @ Tevatron: 7.2 pb
mostly $q\bar{q} \to t\bar{t}$

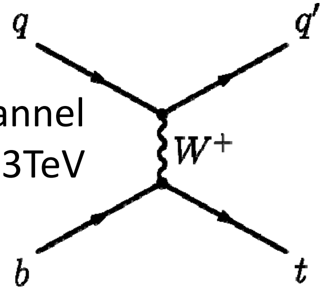


pp @ LHC: mostly from $gg \to t\bar{t}$

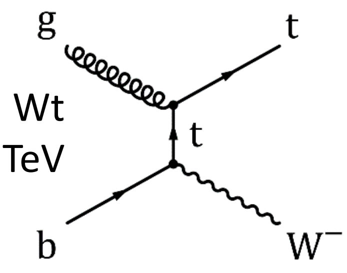
~ 820 pb @ 13 TeV
> 40 millions of top pairs already produced
cf. Belle > 772 millions of $\Upsilon(4s)$

- **single-top** production: **weak** processes
  - Quite large cross sections at the LHC

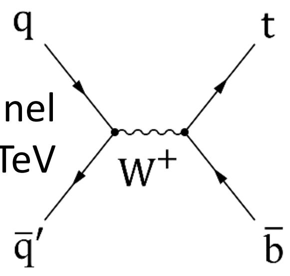
t-channel
210pb @13TeV



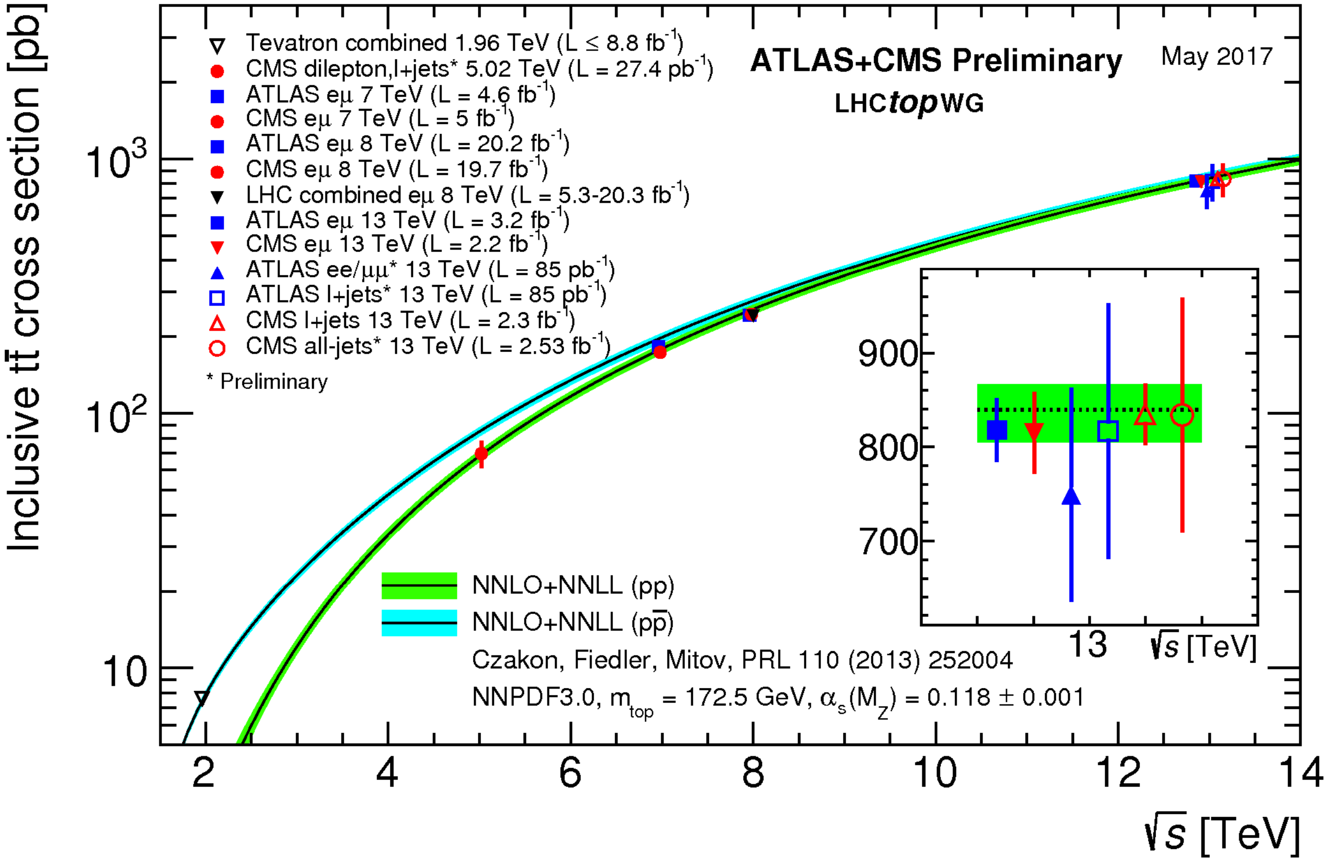
Wt
72pb @13TeV



s-channel
11pb @13TeV



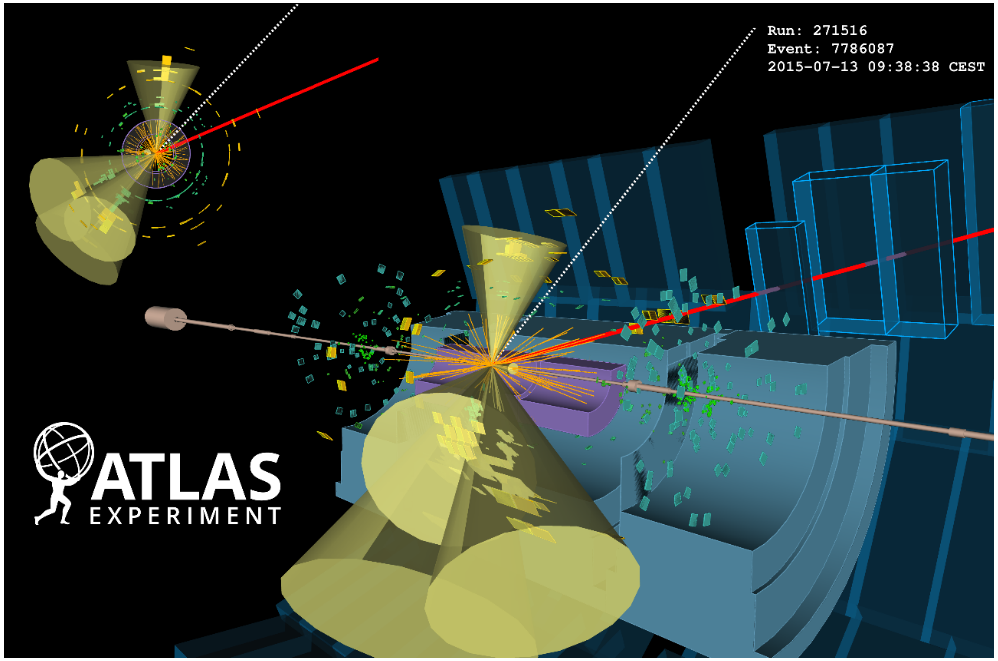
Inclusive cross section behaviour



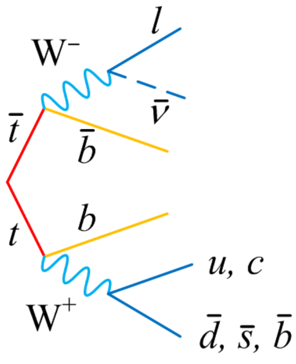
- Rapid rise: reflecting the gluon density
- 5 TeV data from CMS from 2015 data (reference *pp* run for heavy ions)

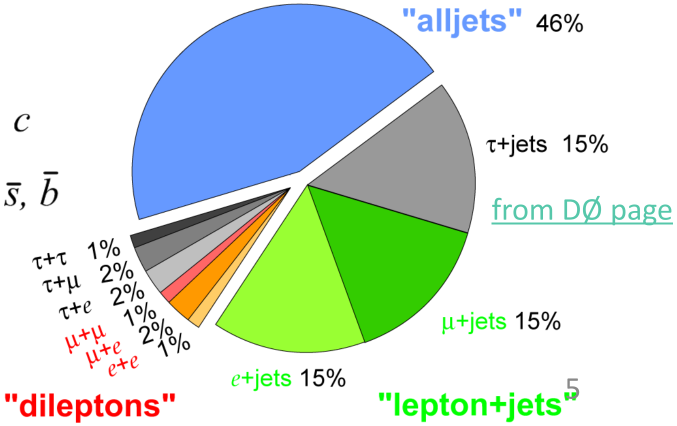
New result not included here: ATLAS 8TeV l+jets (±13pb) ATLAS-CONF-2017-054

Top decay and reconstruction



- $t \to b + W \sim 100\%$
  - Helicity transferred to W
  - short lifetime ($\Gamma \sim 1.3$ GeV)
    The only quark that **decays before hadronisation**
  - pure b-quark:
    best **source for b-calibration** i.e. b-tag & b-jet energy
- Top pair reconstruction
  - single lepton: “$\ell + \text{jets}$”
  - dilepton (2ℓ)
    - one or two neutrinos in final state solution by mass constraints: $m_{\ell\nu} = m_W$, $m_{\ell\nu b} = m_t$
  - all-hadronic (all jets)



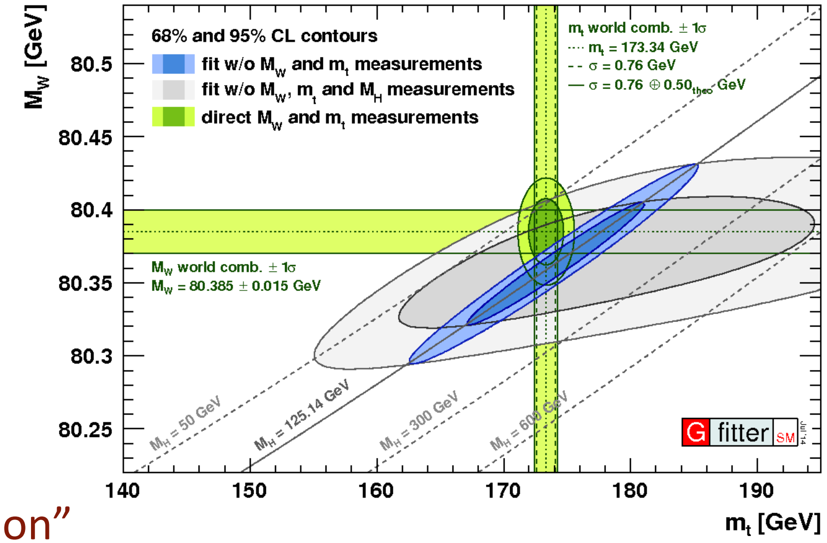


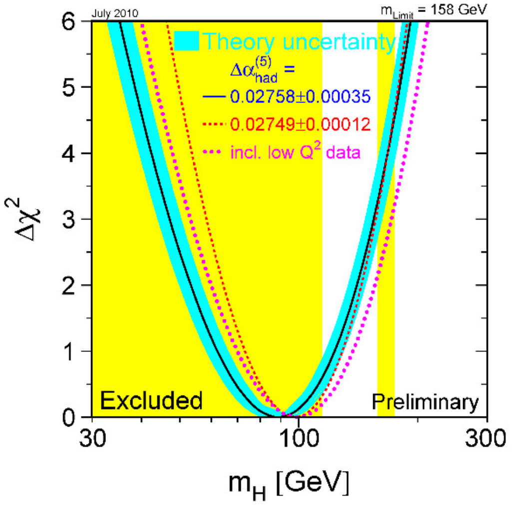
from DØ page

from http://project-gfitter.web.cern.ch/project-gfitter/Standard_Model/

Why do we measure top?

- LHC is a top factory
  - Precision measurement of mass
  - Couplings
- Precise measurements: gateway to new physics
  - Remember LEP/SLC Higgs mass “prediction”
- Today’s signal is tomorrow’s background
  - Precise understanding of cross section behavior
  - Studying rare processes (e.g. ttZ for ttH)
- It cannot be measured elsewhere for next 10+ years!





arXiv:1012.2367
(LEP-SLD EW WGs)

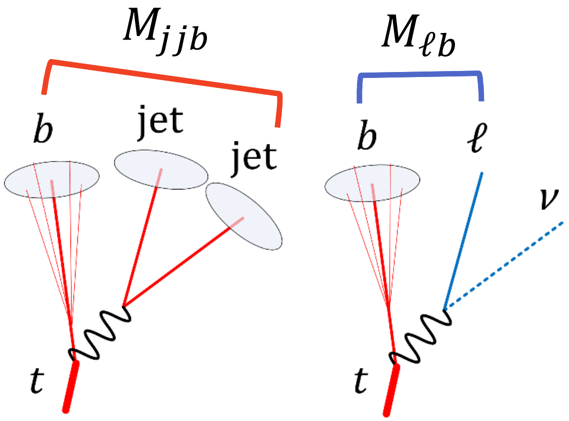
precision measurement should come from the LHC

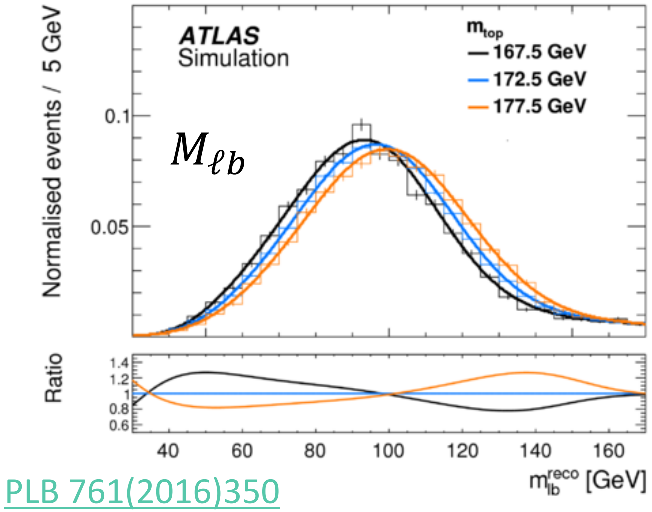
TOP MASS

Top mass measurements: methods

"Direct mass"

- Measuring **the 4-momentum of decay product**



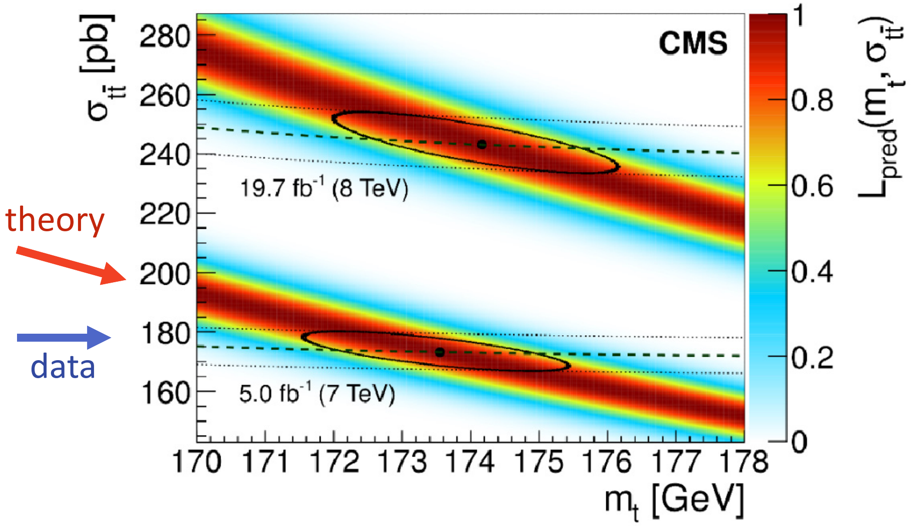


PLB 761(2016)350

"Pole mass"

- Through **cross section** or cross section shapes
  - propagator appears in cross section calculations

JHEP 08(2016)029



Inclusive $t\bar{t}$ cross section in comparison TOP++ (NNLO+NNLL)

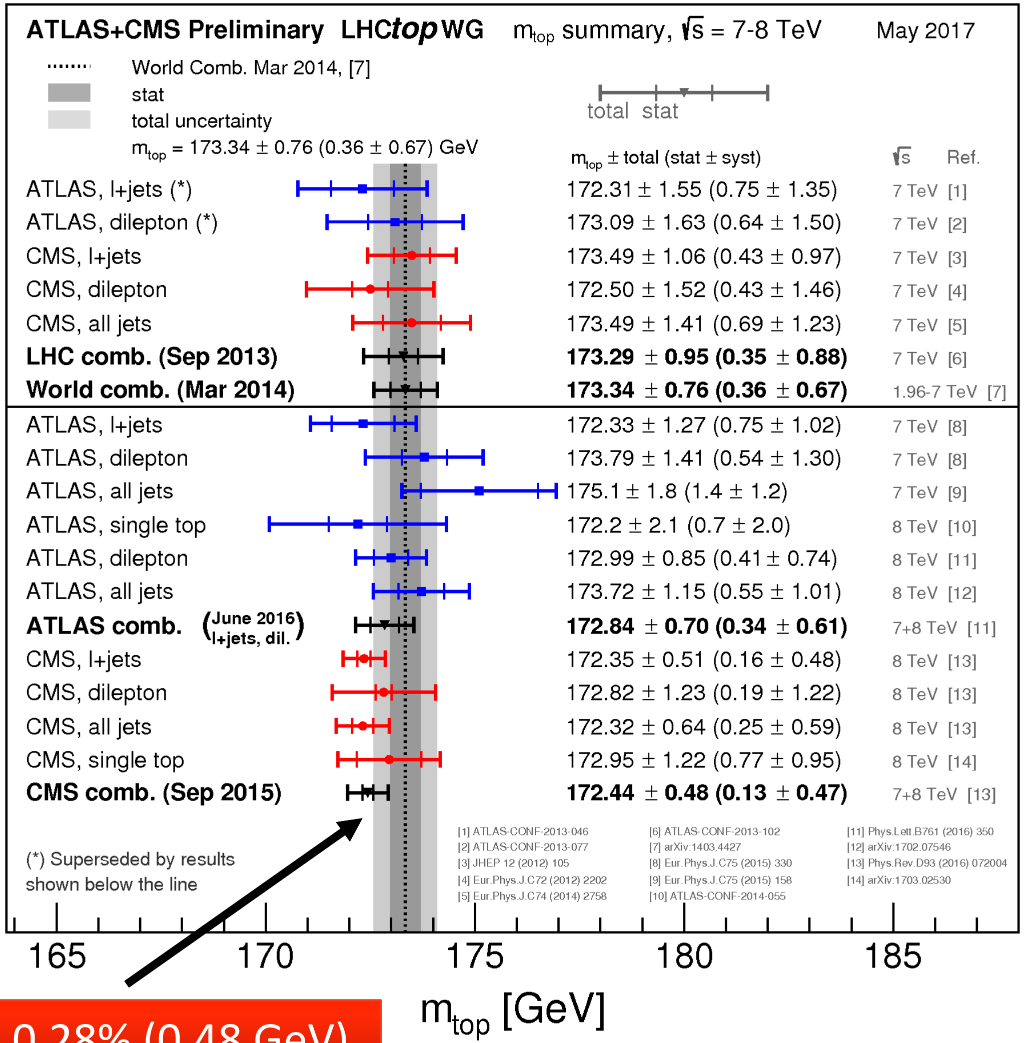
"Direct mass" measurements

Best measurements are from "mature" 8TeV data, (being) published in 2016-17

- World combination (2014)
  173.34 ± 0.76 GeV (0.44%)

ATLAS best results:
jets and dilepton
Combination: 0.40%

CMS best results
l+jets, all jets
and dilepton

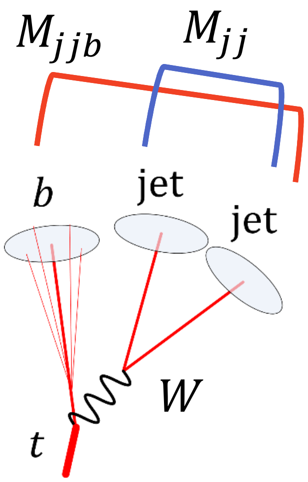


	m_{top} ± total (stat ± syst)	$\sqrt{s}$	Ref.
ATLAS, l+jets (*)	172.31 ± 1.55 (0.75 ± 1.35)	7 TeV	[1]
ATLAS, dilepton (*)	173.09 ± 1.63 (0.64 ± 1.50)	7 TeV	[2]
CMS, l+jets	173.49 ± 1.06 (0.43 ± 0.97)	7 TeV	[3]
CMS, dilepton	172.50 ± 1.52 (0.43 ± 1.46)	7 TeV	[4]
CMS, all jets	173.49 ± 1.41 (0.69 ± 1.23)	7 TeV	[5]
LHC comb. (Sep 2013)	**173.29 ± 0.95 (0.35 ± 0.88)**	7 TeV	[6]
World comb. (Mar 2014)	**173.34 ± 0.76 (0.36 ± 0.67)**	1.96-7 TeV	[7]
ATLAS, l+jets	172.33 ± 1.27 (0.75 ± 1.02)	7 TeV	[8]
ATLAS, dilepton	173.79 ± 1.41 (0.54 ± 1.30)	7 TeV	[8]
ATLAS, all jets	175.1 ± 1.8 (1.4 ± 1.2)	7 TeV	[9]
ATLAS, single top	172.2 ± 2.1 (0.7 ± 2.0)	8 TeV	[10]
ATLAS, dilepton	172.99 ± 0.85 (0.41 ± 0.74)	8 TeV	[11]
ATLAS, all jets	173.72 ± 1.15 (0.55 ± 1.01)	8 TeV	[12]
ATLAS comb. (June 2016 l+jets, dil.)	**172.84 ± 0.70 (0.34 ± 0.61)**	7+8 TeV	[11]
CMS, l+jets	172.35 ± 0.51 (0.16 ± 0.48)	8 TeV	[13]
CMS, dilepton	172.82 ± 1.23 (0.19 ± 1.22)	8 TeV	[13]
CMS, all jets	172.32 ± 0.64 (0.25 ± 0.59)	8 TeV	[13]
CMS, single top	172.95 ± 1.22 (0.77 ± 0.95)	8 TeV	[14]
CMS comb. (Sep 2015)	**172.44 ± 0.48 (0.13 ± 0.47)**	7+8 TeV	[13]

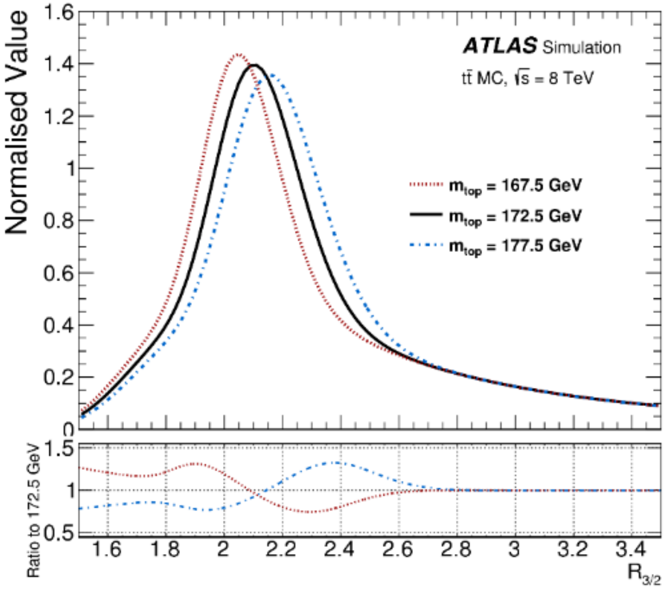
[1] ATLAS-CONF-2013-046
[2] ATLAS-CONF-2013-077
[3] JHEP 12 (2012) 105
[4] Eur.Phys.J.C72 (2012) 2202
[5] Eur.Phys.J.C74 (2014) 2758
[6] ATLAS-CONF-2013-102
[7] arXiv:1403.4427
[8] Eur.Phys.J.C75 (2015) 330
[9] Eur.Phys.J.C75 (2015) 158
[10] ATLAS-CONF-2014-055
[11] Phys.Lett.B761 (2016) 350
[12] arXiv:1702.07546
[13] Phys.Rev.D93 (2016) 072004
[14] arXiv:1703.02530

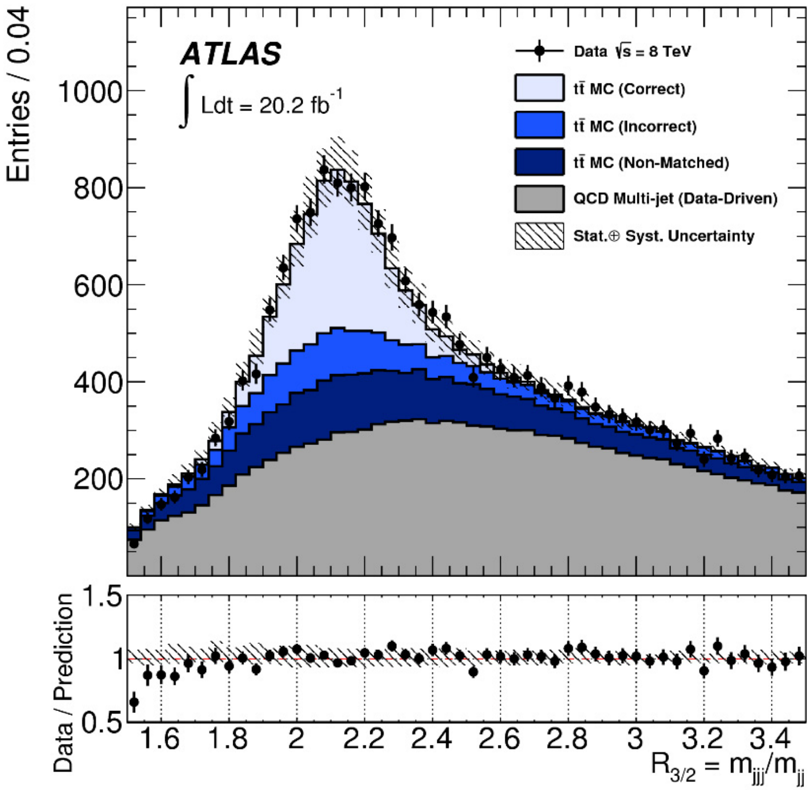
World best result from CMS combination: 0.28% (0.48 GeV)

Direct mass through hadronic decay



- hadronic channel: using $R_{3/2} = \frac{m_{jjb}}{m_{jj}} \simeq \frac{m_t}{m_W}$
  - reducing jet energy scale sensitivity
- 173.72 $\pm$ 0.55 (stat.) $\pm$ 1.01 (syst.) GeV
  - Jet energy scale (0.64 GeV)
  - Hadronisation modelling (0.60 GeV)

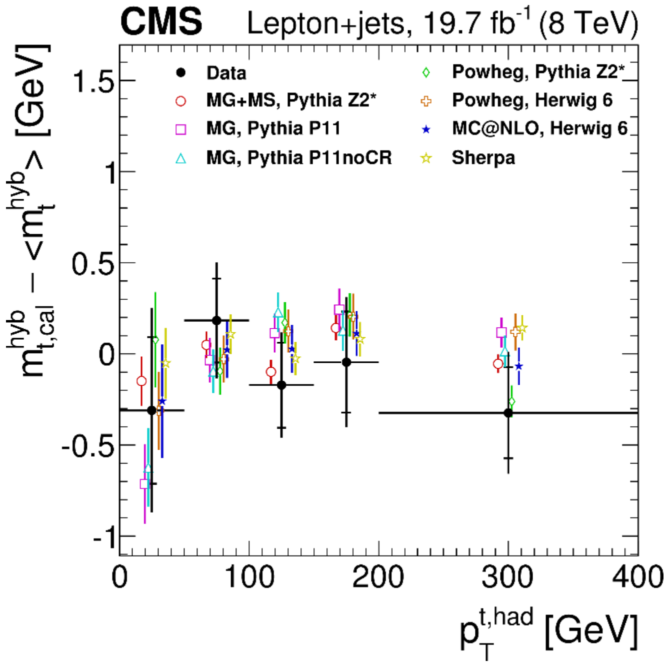




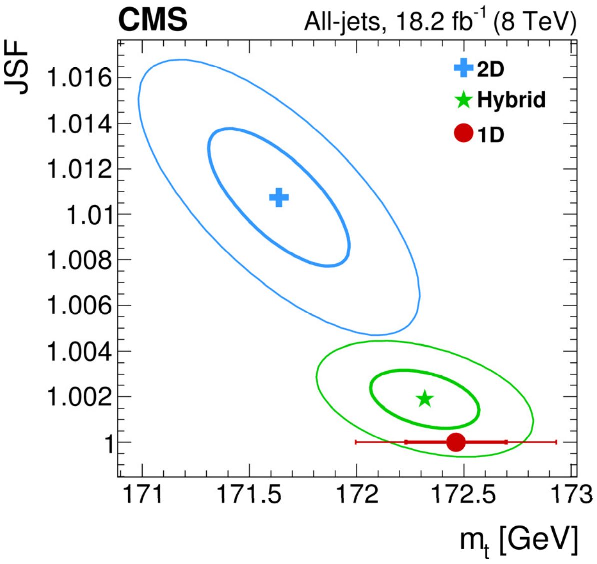
arXiv: 1702.07546

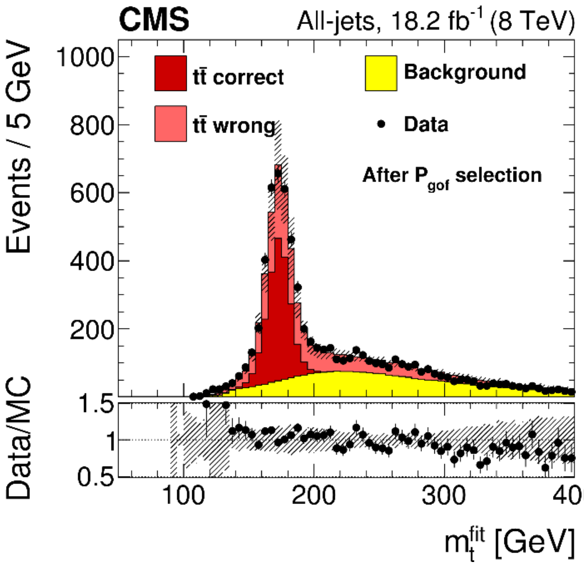
Most precise measurements from CMS

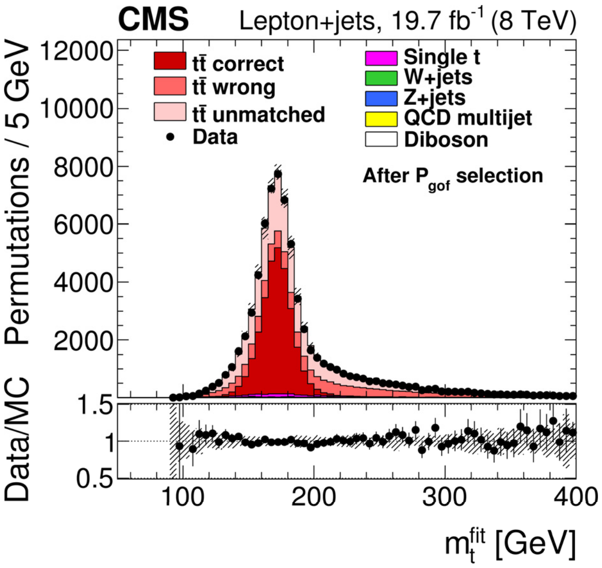
PRD 93 (2016) 072004



- Mass from kinematic fits: controlling kinematic dependence on the mass reconstruction → good resolution
- Jet energy scale factor (JSF) was constrained by either
  - simultaneous determination of JSF and m_{top}
  - or external knowledge from W reconstruction and the data-driven determination are given equal weight (hybrid method)







Road to < 0.3 GeV precision

Best record: 0.49 GeV

Analysis (syst. error)	1st source (error)	2nd source (error)	3rd source (error)
ATLAS dilepton (0.74) PLB 761(2016)350	Jet energy scale (0.54)	b-jet energy scale (0.30)	ISR and FSR (0.23)
ATLAS all hadron (1.01) arXiv: 1702.07546	Hadronisation modelling (0.64)	Jet energy scale (0.60)	b-jet energy scale (0.34)
CMS lepton+jets (0.49) PRD 93(2016)072004	b-jet energy scale (0.32)	Matrix element generator (0.12)	Jet energy correction (0.12)
CMS dilepton (1.22) PRD 93(2016)072004	μ_R, μ_F (0.75)	b-fragmentation (0.69)	b-jet energy scale (0.34)
CMS all hadron (0.59) PRD 93(2016)072004	b-jet energy scale (0.29)	Background estimation (0.20)	In situ jet energy scale (0.19)

🟦 experimental 🟧 model dependence

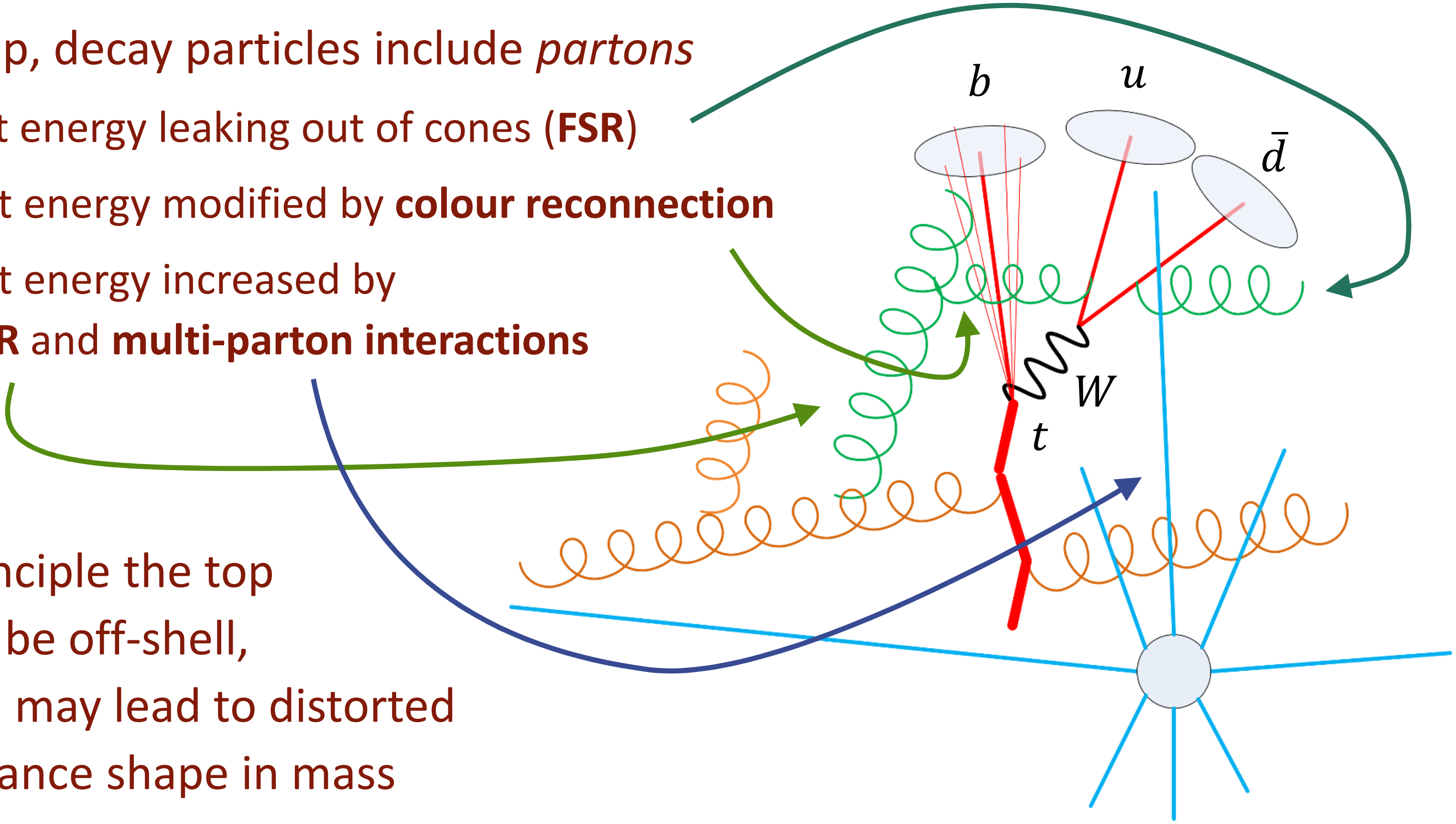
(Experimental uncertainties) ≈ (model uncertainties)

- Worthwhile trying **other mass reconstruction methods** than direct mass
- Need more **control to event generators**
  - **e.g. parton shower, hadronisation …**

Could direct mass have some bias?

Net effect would be
(a factor) × Λ_{QCD}
Could be ~ GeV

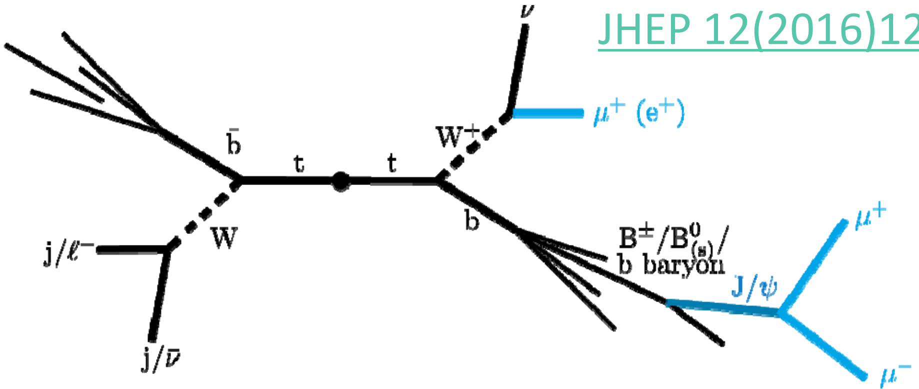
- Meson mass (e.g. J/ψ mass) well defined
  - decay particles are well defined
  - radiation (e.g. $\mathrm{J}/\psi \to \mu\mu\gamma$) well understood
- For top, decay particles include *partons*
  - jet energy leaking out of cones (**FSR**)
  - Jet energy modified by **colour reconnection**
  - Jet energy increased by **ISR** and **multi-parton interactions**



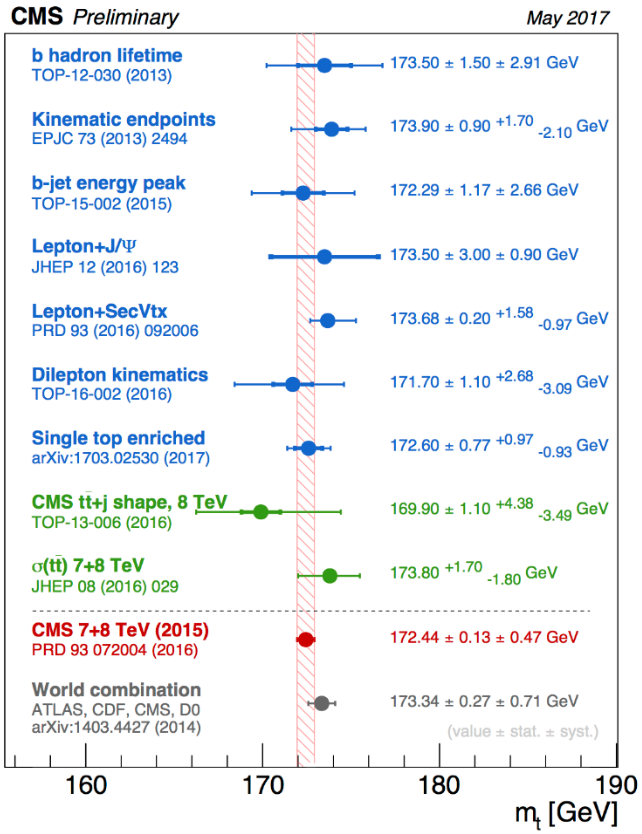
- In principle the top could be off-shell, which may lead to distorted resonance shape in mass

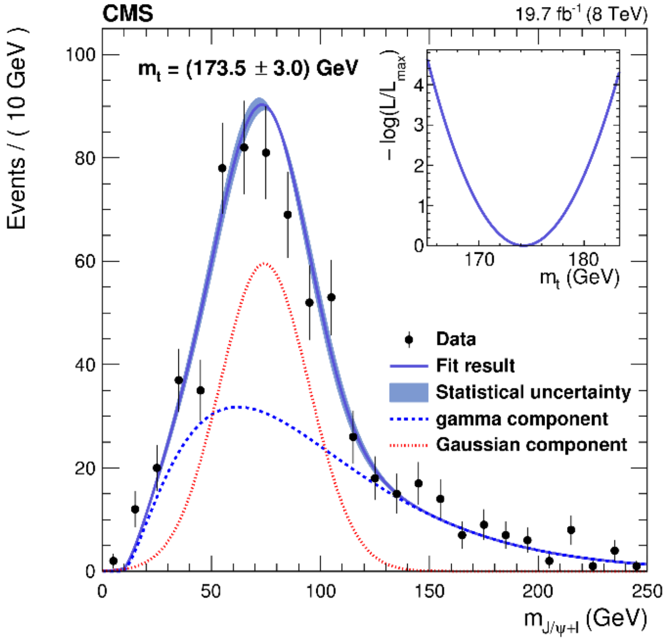
JHEP 12(2016)123

"Alternative method": Mass reconstructed from lepton + J/ψ from b-jet



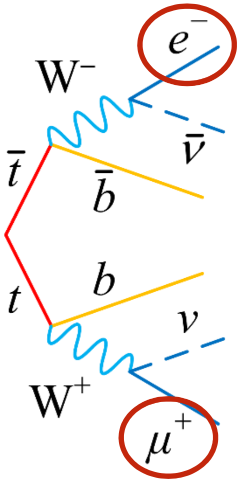
Using J/ψ momentum to represent b-jet

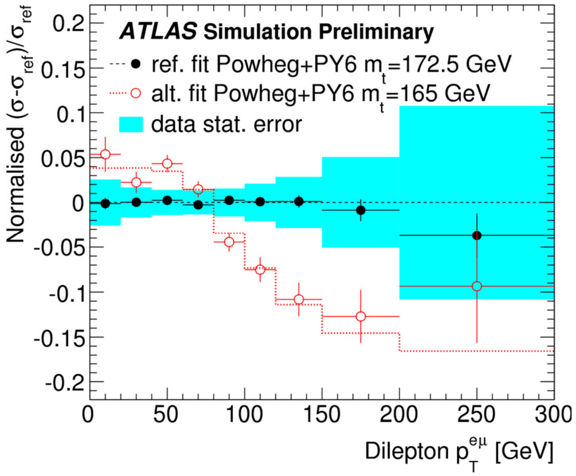


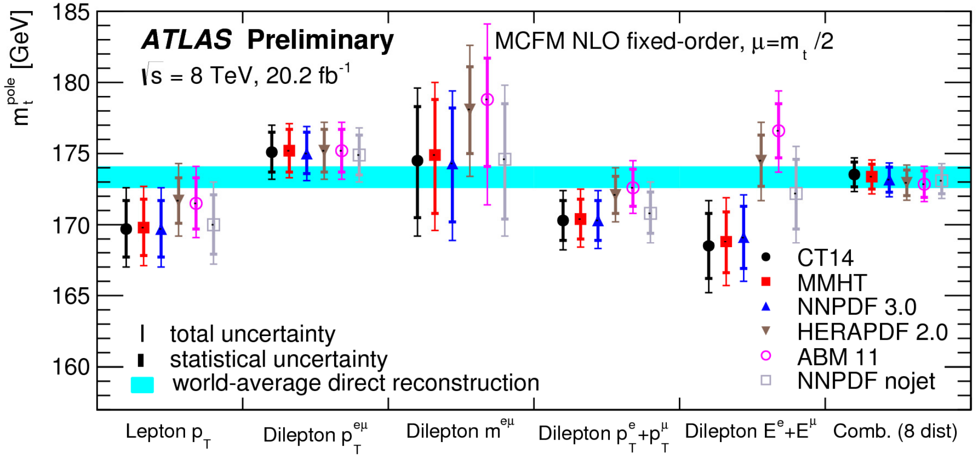


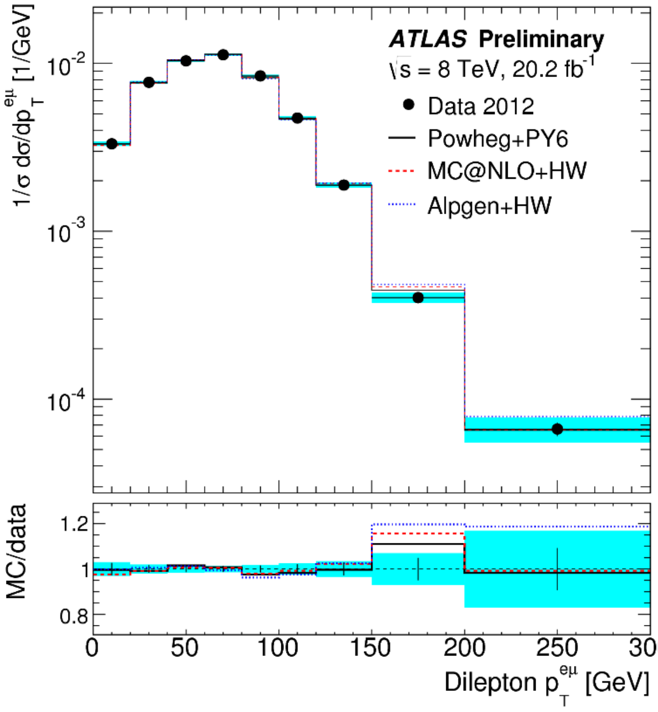
- Well-defined **leptonic** observable
- syst. error 0.9 GeV only
  - **top p_T modelling (0.64)**
  - b-fragmentation (0.37)

“Pole mass” by σ shapes: lepton kinematics









ATLAS-CONF-2017-044

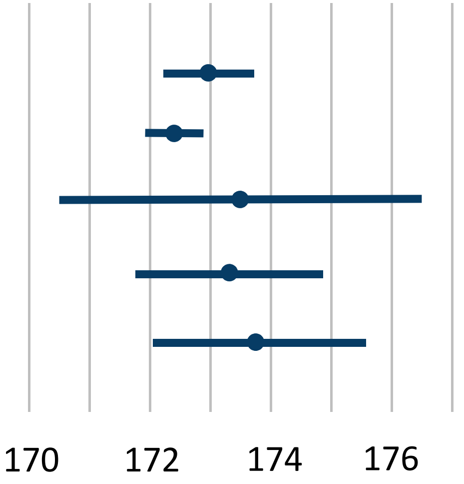
- **Kinematic distribution of leptons** $(e\mu)$
  - 8 distributions: $p_T(e \text{ or } \mu)$, $|\eta|$, dilepton $p_T^{e\mu}$, $m^{e\mu}, |y^{e\mu}|, \Delta\phi^{e\mu}, p_T^e + p_T^\mu, E^e + E^\mu$
- Insensitive to detail of modelling the hadronic part of the decay
- $m_t = 173.2 \pm 0.9(stat.) \pm 0.8(exp.) \pm 1.2(theo.)$
  - **dominated by μ_R, μ_F uncertainties**

Summary and prospects in top mass measurements

Direct mass has been cross-checked by alternative methods

- Consistent within large errors

ATLAS **direct** (dilepton)	172.99 ± 0.85
CMS **direct** (l+jets)	172.35 ± 0.51
CMS J/ψ	$173.5 \pm 3.0 \pm 0.9$
ATLAS dilepton σ shape	173.2 ± 1.6
CMS $\sigma(t\bar{t})$	$173.8^{+1.7}_{-1.8}$



Plot by hand
for illustration purpose only

Ways to improve further

- direct mass: **jet/b-jet energy measurement**
- track mass: **top kinematics modelling**, b-fragmentation
- through cross sections: scale uncertainties $\simeq$ **higher order calculation**

Understanding the top events is crucial for future mass measurements with <0.3 GeV precision

DIFFERENTIAL CROSS SECTIONS

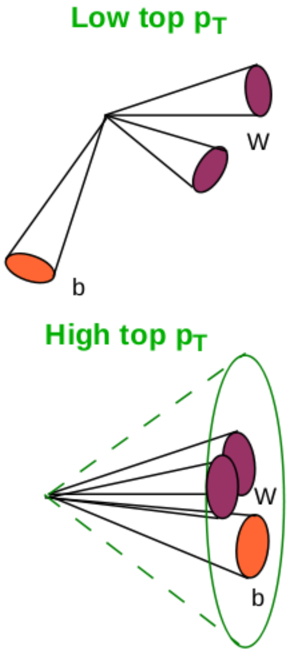
Motivation for differential cross sections

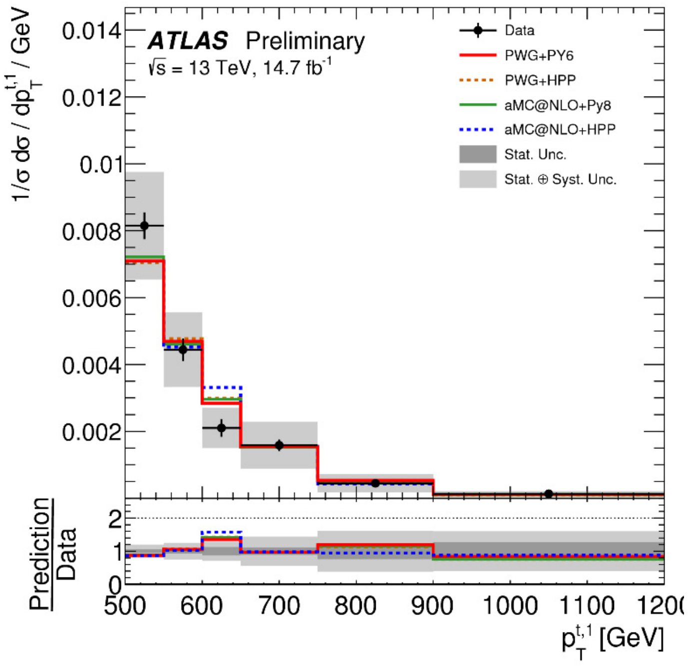
- Better to **link data** and **theoretical models**
  - unfolded data: direct comparison to higher-order models
    i.e. to discriminate parton shower models,
    generator tuning and PDFs (parton density functions)
  - also for controlling systematics for other measurements

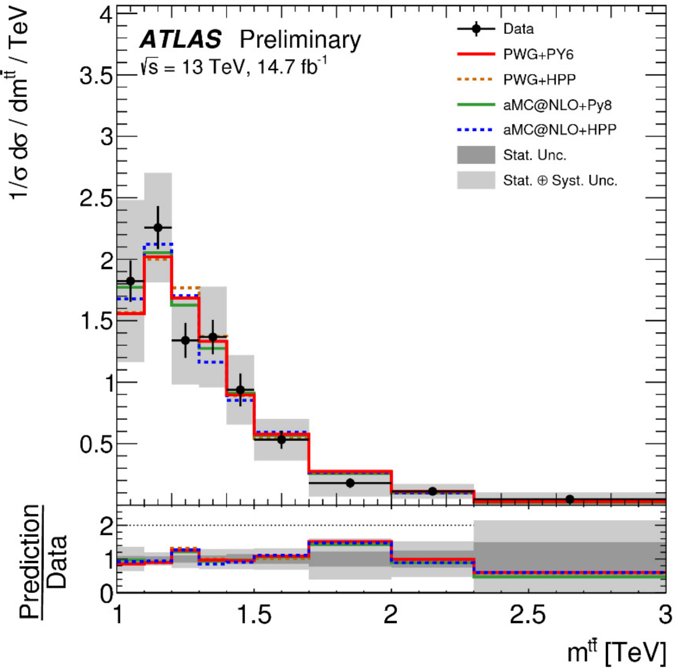
- Sensitivity **to BSM** by comparison with predictions
  - in particular **highly-boosted** high-p_T production
- To understand top as a “standard candle”
  - as it appears as decay particle of new states
    as well background for BSM searches

ATLAS-CONF-2016-100

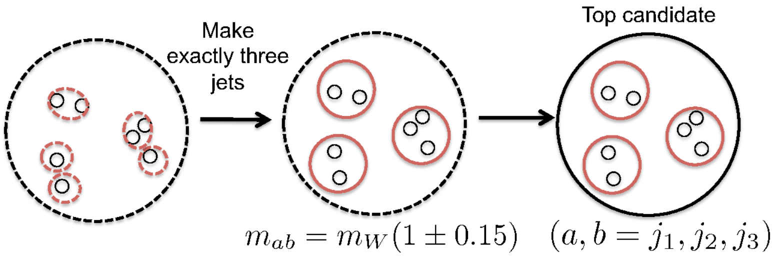
Recent 13 TeV measurements (1)







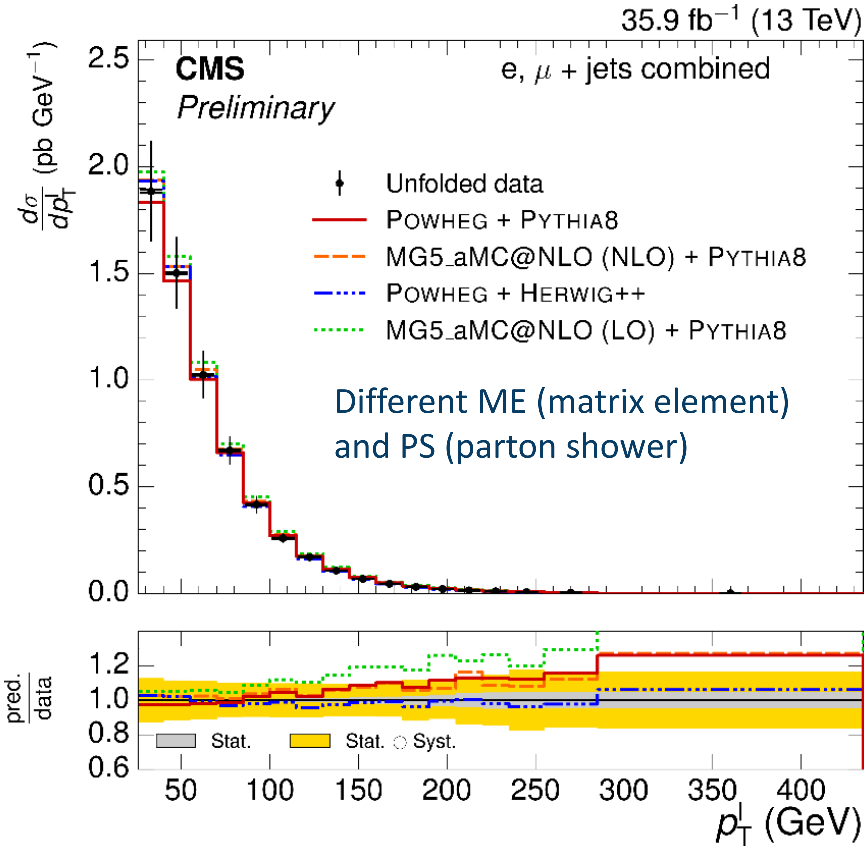
- All-hadronic channels (14.7 fb^{-1}), normalised cross sections
- Boosted topology: colliimiated decay products into "fat" jet
- Internal 3-jet structure to tag top
- $p_T^{top} \sim 1$ TeV, $m_{tt} > 2$ TeV



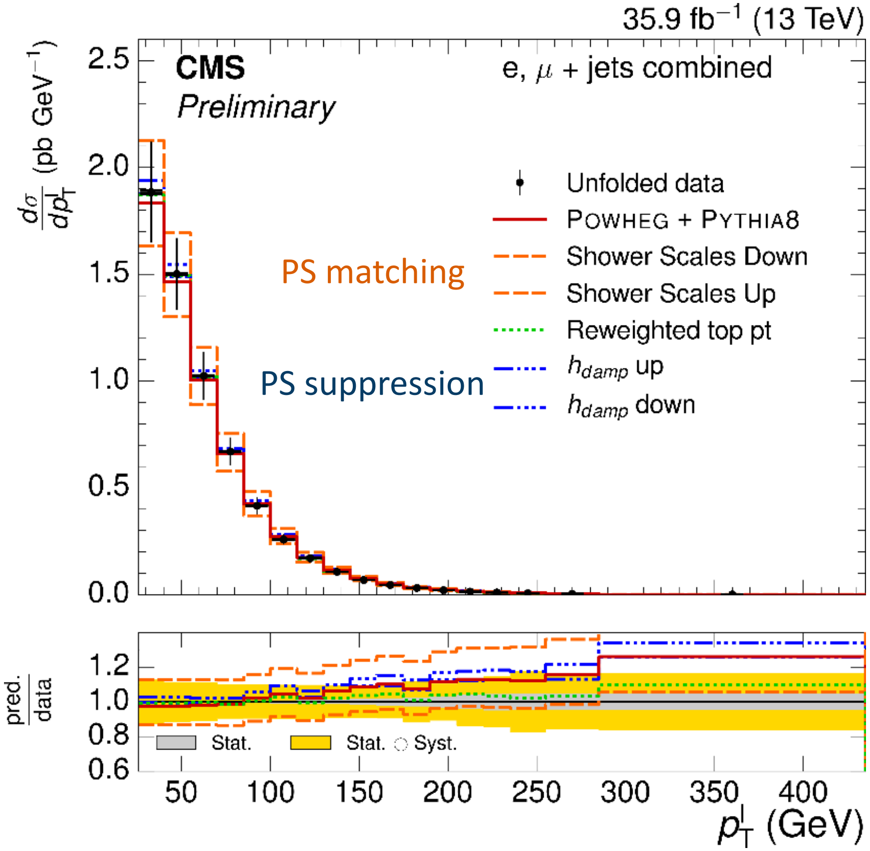
(from JHEP09(2013)076: note that this analysis does somewhat differently to tag boosted top)

13 TeV result (2) closer look

CMS-PAS-TOP-16-014



Different ME (matrix element) and PS (parton shower)



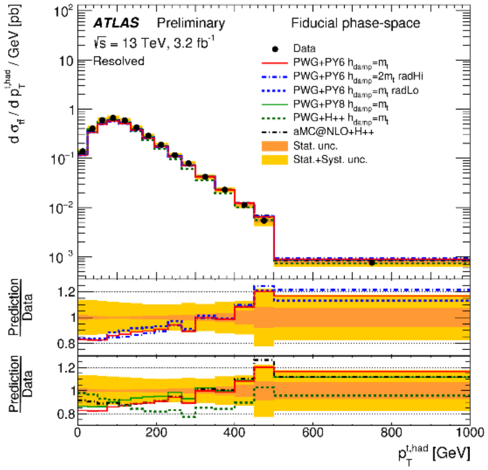
PS matching

PS suppression

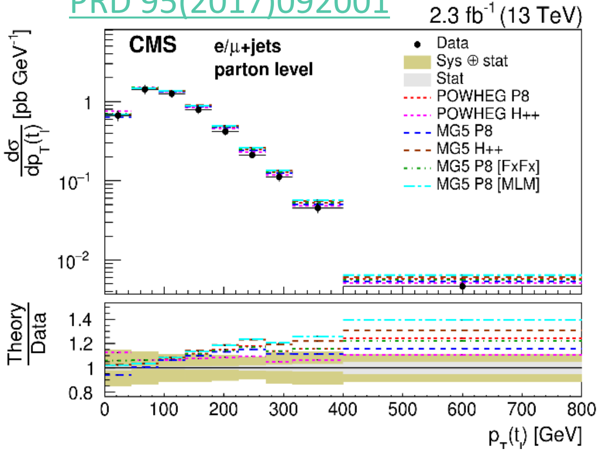
- Cross section vs event variables, not top quark kinematics
  - avoiding theoretical uncertainties in correction / reconstructing top
- high sensitivity to models and their parameters
- Data tend to be softer than NLO calculations →

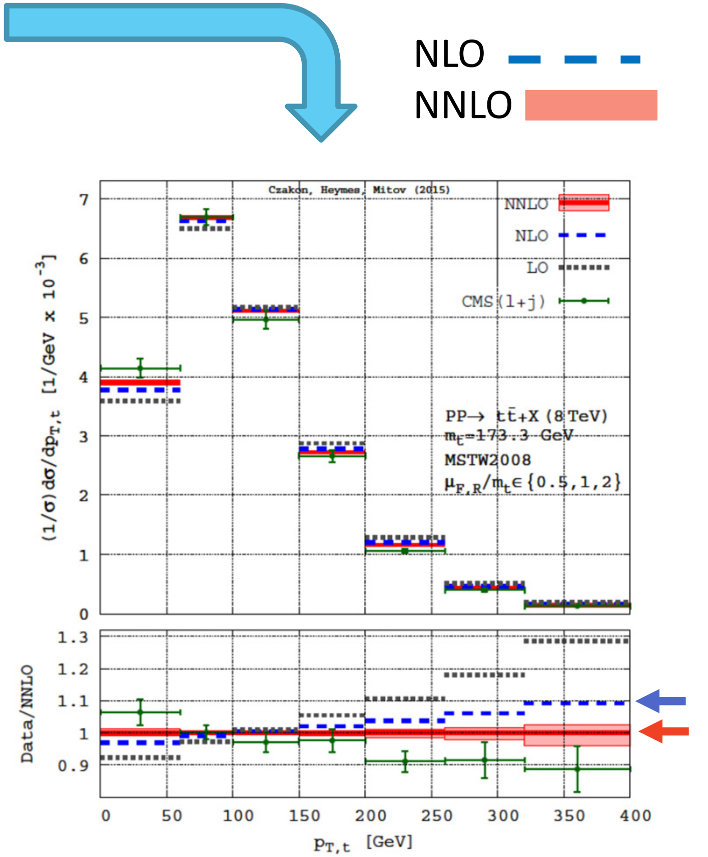
That was not the only one … other 13TeV data

ATLAS-CONF-2016-040

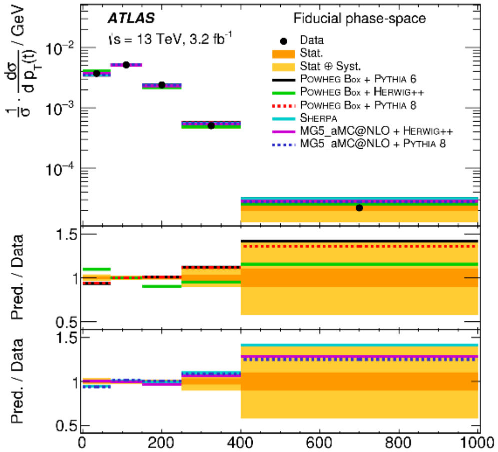


PRD 95(2017)092001

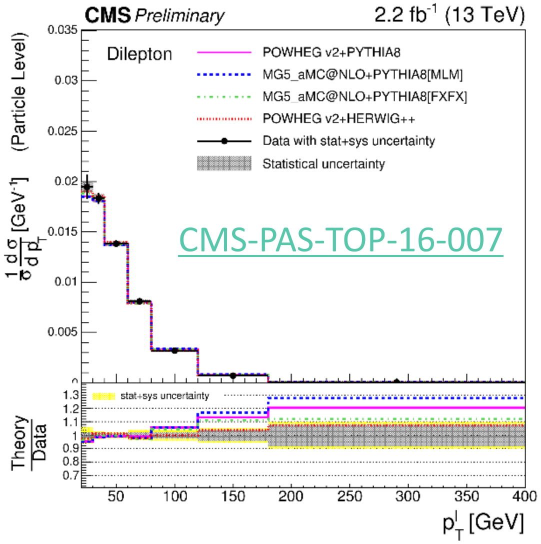




M. Czakon, D. Heymes and A. Mitov,
PRL 116, 082003



EPJC 77(2017)292

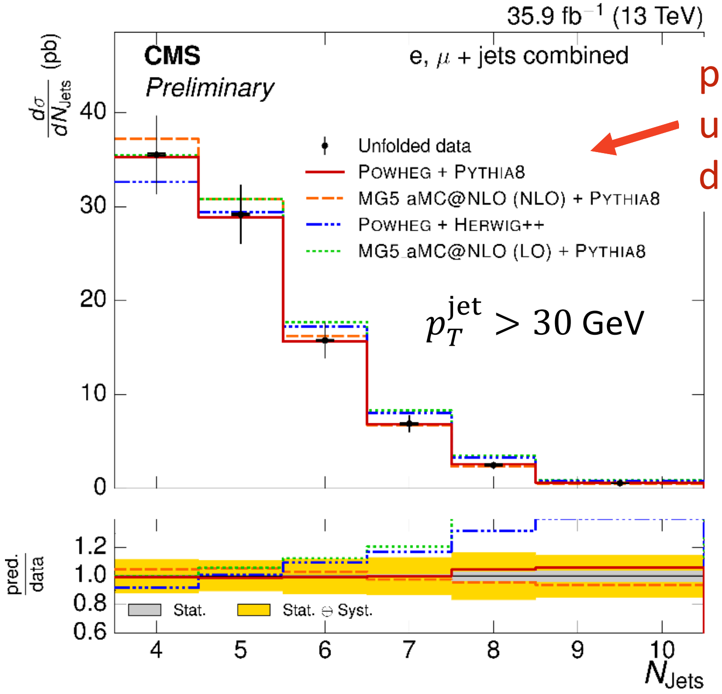


CMS-PAS-TOP-16-007

- p_T of the top quarks tend to be softer than NLO calculations
  - **NNLO gives better description**
  - **wishing to have higher order event generators!**

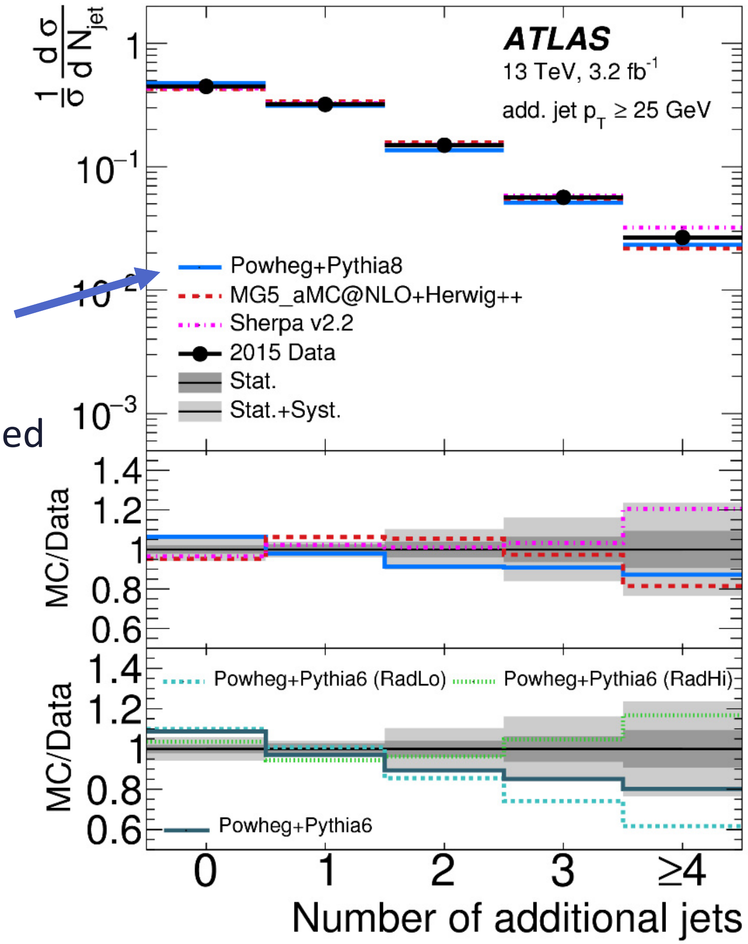
EPJC 77(2017)220

$t\bar{t}$ + jets @ 13 TeV



parameters tuned using 8 TeV top XS data by CMS

Hard radiation parameters are not optimised

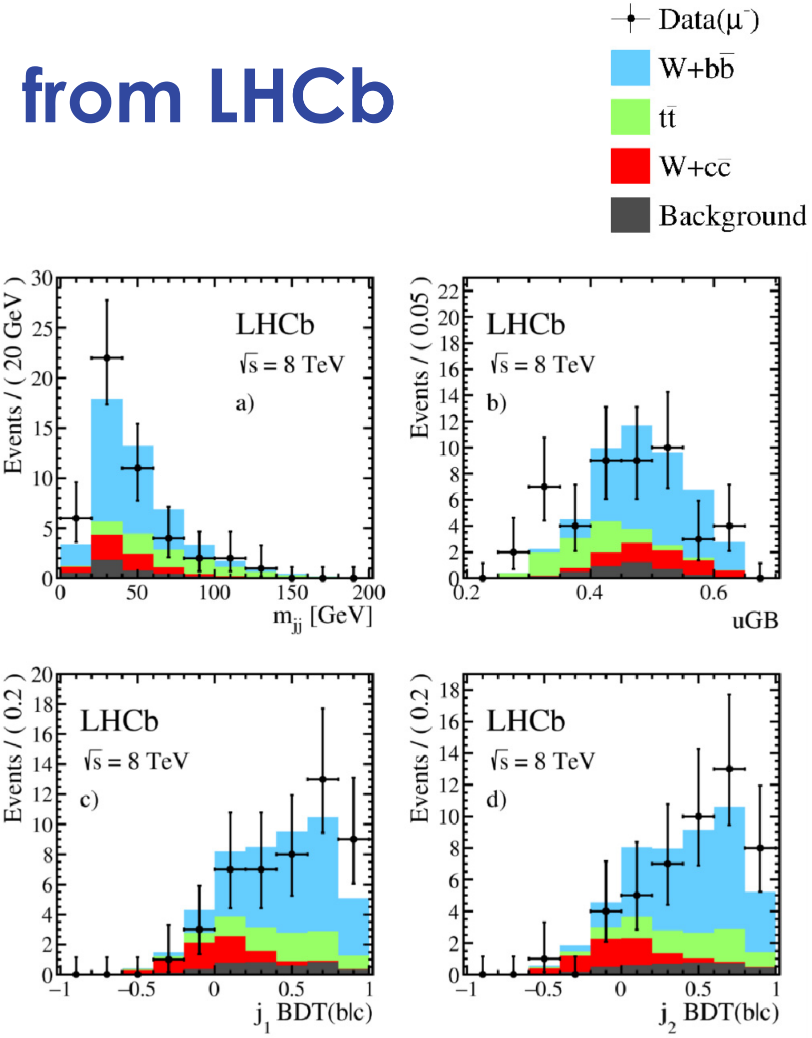


- Very sensitive to the models, especially the **parton shower models**
  - Used for tuning parameters to reduce model dependence

We continue to measure differential cross sections for further improving models

Top in very forward rapidity from LHCb

- Asymmetric configuration: small mass $m_{partons} = \sqrt{s x_1 x_2}$ is small when x_1 or x_2 is small
  - Top production cross section at the LHCb rapidity range $(2 < \eta \lesssim 4.5)$ is tiny
- Main BG: $W + b\bar{b}$
- Fiducial $\sigma \sim 0.045$ pb
  Observed:
  $0.05^{+0.02}_{-0.01}(stat.)^{+0.02}_{-0.01}(syst.)$ pb
  4.9σ significance
- Higher statistics for constraining high/low-x gluons



Selection:
1 lepton with $p_T > 20$ GeV
and $2.0 < \eta < 4.5(4.25)$ for $\mu(e)$
2 b-tagged jets with $p_T > 12.5$ GeV
and $2.2 < \eta < 4.2$

PLB 767(2017)110

Enough QCD? Need EW?

TOP COUPLINGS AND SPIN

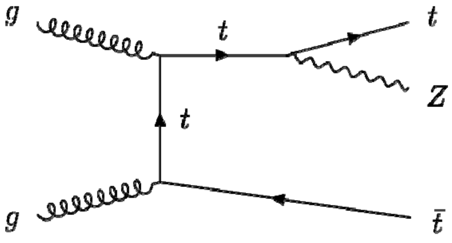
Extracting couplings and spin

- Cross section to $t\bar{t} + W, Z,\ t\bar{t} + \gamma$: **EW coupling**
- **Decay to unknowns**? → Top width
- Angular distributions of the leptons from top
  - spin correlation of top quarks
  - $\boldsymbol{Wtb}$ **vertex** (V-A structure etc.)

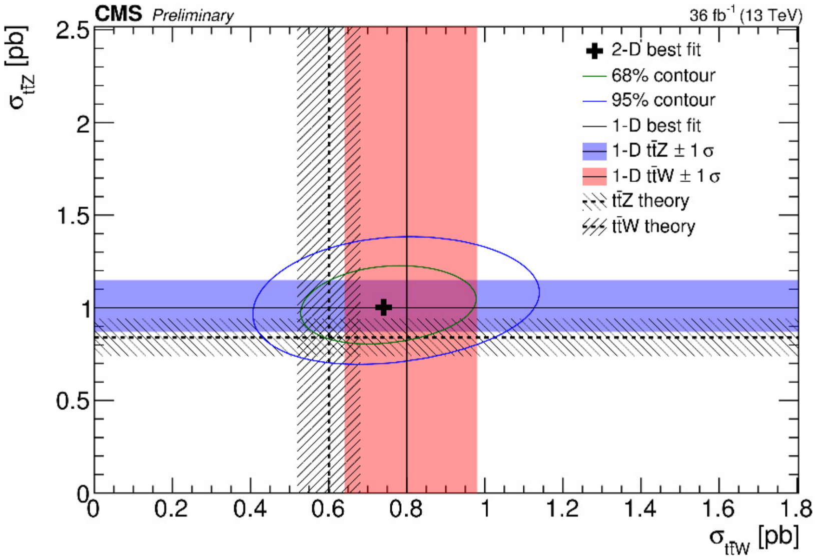
  → now also from **single-top** production (slides later)

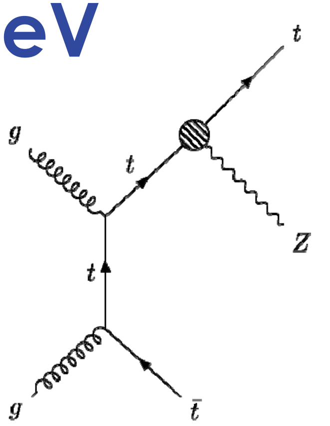
CMS-PAS-TOP-17-005

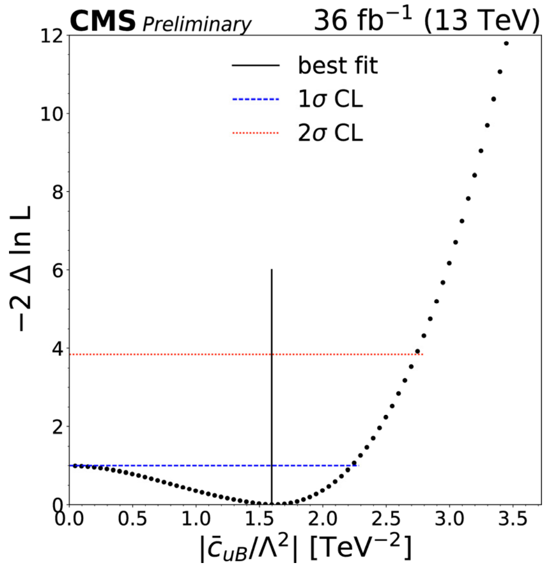
First $t\bar{t}W$ and $t\bar{t}Z$ cross sections at 13 TeV



$t\bar{t}Z$ vs $t\bar{t}W$ both >5σ observation with 36fb^{-1}







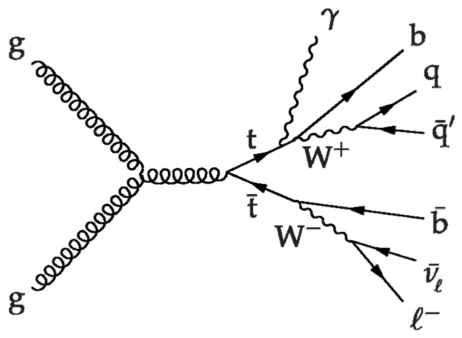
- Z^0's are radiated partially from top quarks
  - Anomalous coupling to the 3rd generation are much less constrained so far
- Also for understanding $t\bar{t}H$
- Very good precision – e.g. for $t\bar{t}Z$,

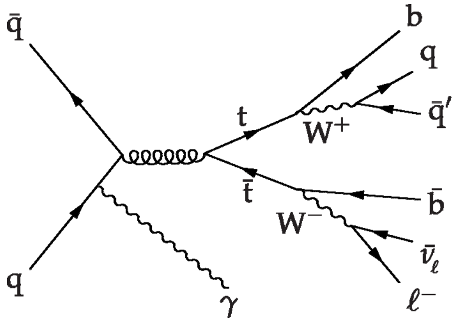
$\sigma(stat.) \simeq 10\%, \sigma(stat.) \simeq 12\%, \sigma(theo.) \simeq 10\%$

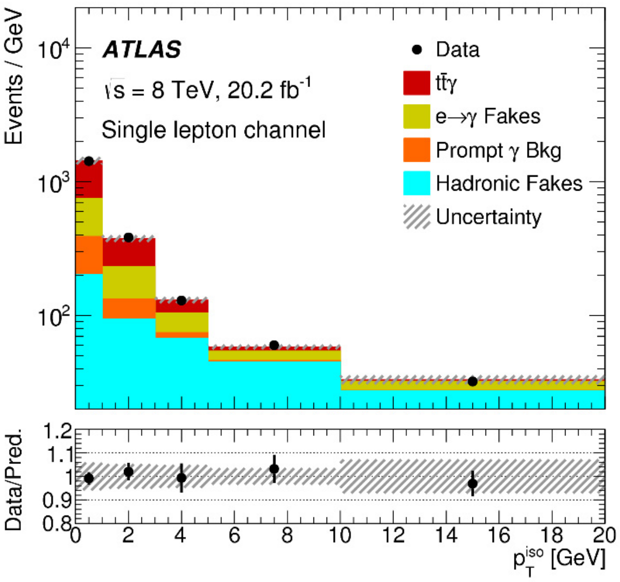
- Interpreted in terms of effective field theory $\mathcal{L} \mathrel{+}= \frac{1}{\Lambda^2}\sum_j c_j\, O_j$

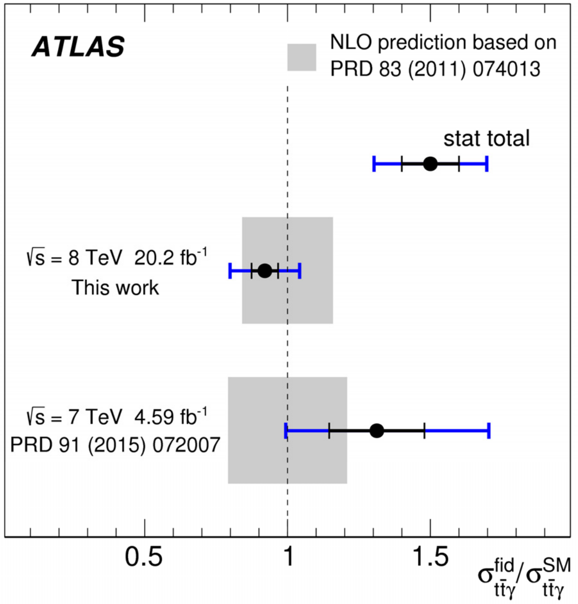
$t\bar{t}\gamma$ cross sections

arXiv: 1706.03046

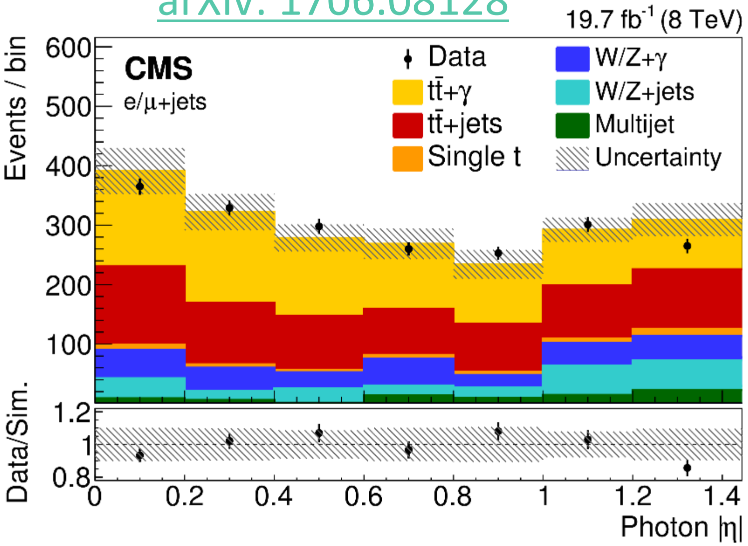








arXiv: 1706.08128

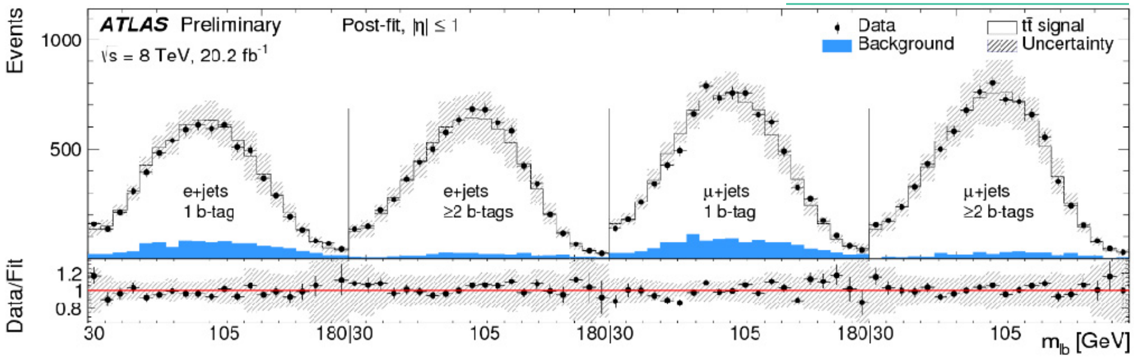


- Probing $tt\gamma$ vertex
- Good agreement with SM

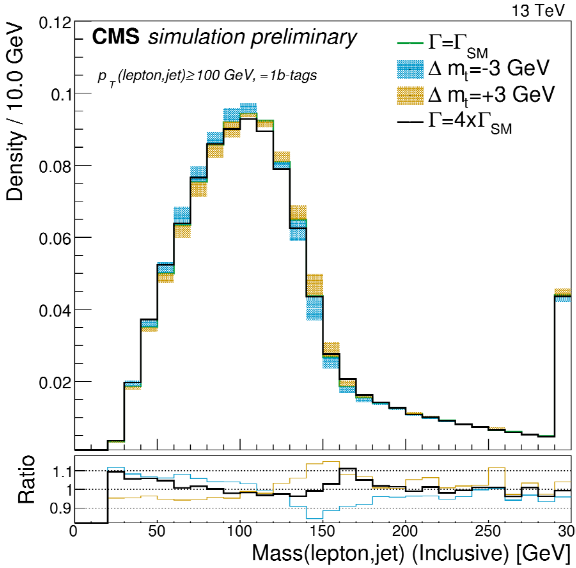
Category	R	$\sigma^{\text{fid}}_{t\bar{t}+\gamma}$ (fb)	$\sigma_{t\bar{t}+\gamma}\,\mathcal{B}$ (fb)
e+jets	$(5.7 \pm 1.8) \times 10^{-4}$	138 ± 45	582 ± 187
μ+jets	$(4.7 \pm 1.3) \times 10^{-4}$	115 ± 32	453 ± 124
Combination	$(5.2 \pm 1.1) \times 10^{-4}$	127 ± 27	515 ± 108
Theory	—	—	592 ± 71 (scales) ± 30 (PDFs)

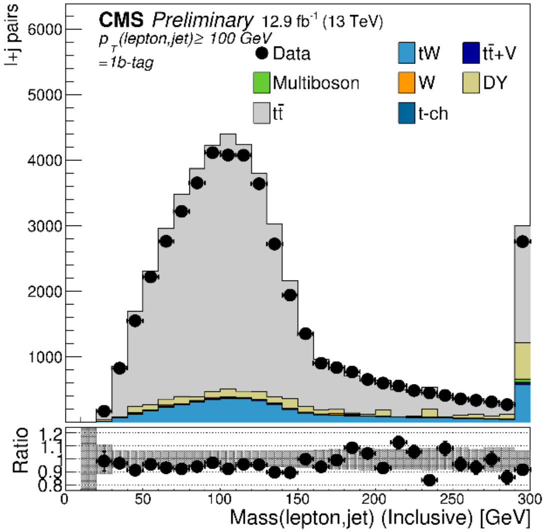
Decay to unknowns?
⇨ Top width

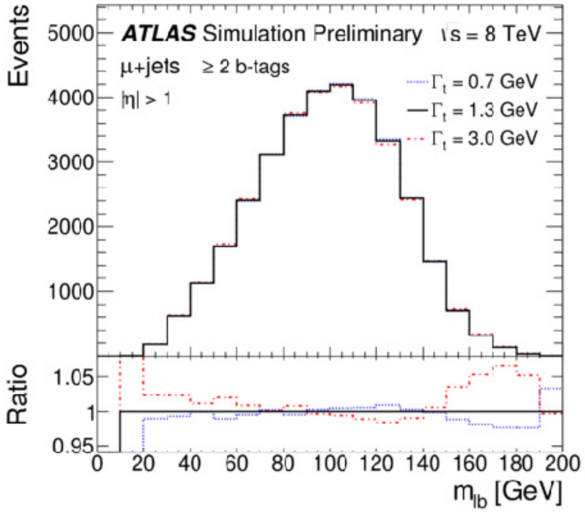
ATLAS-CONF-2017-056



CMS-PAS-TOP-16-019



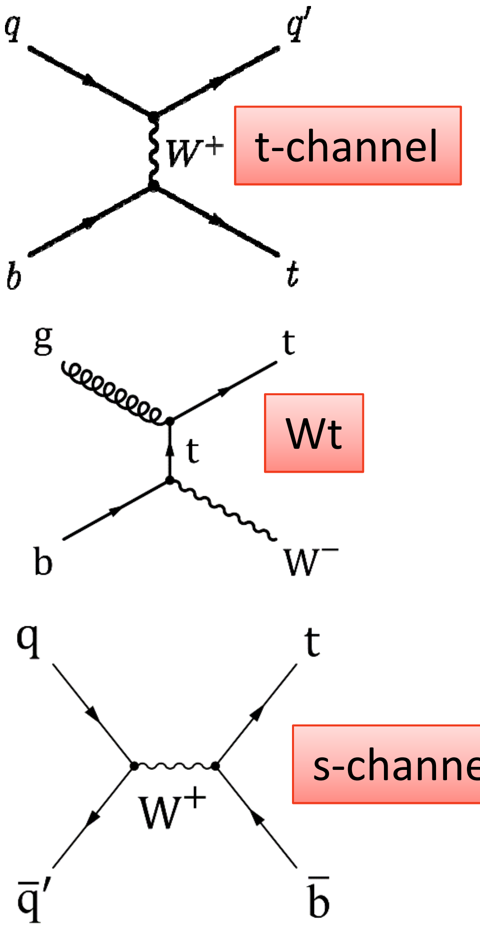


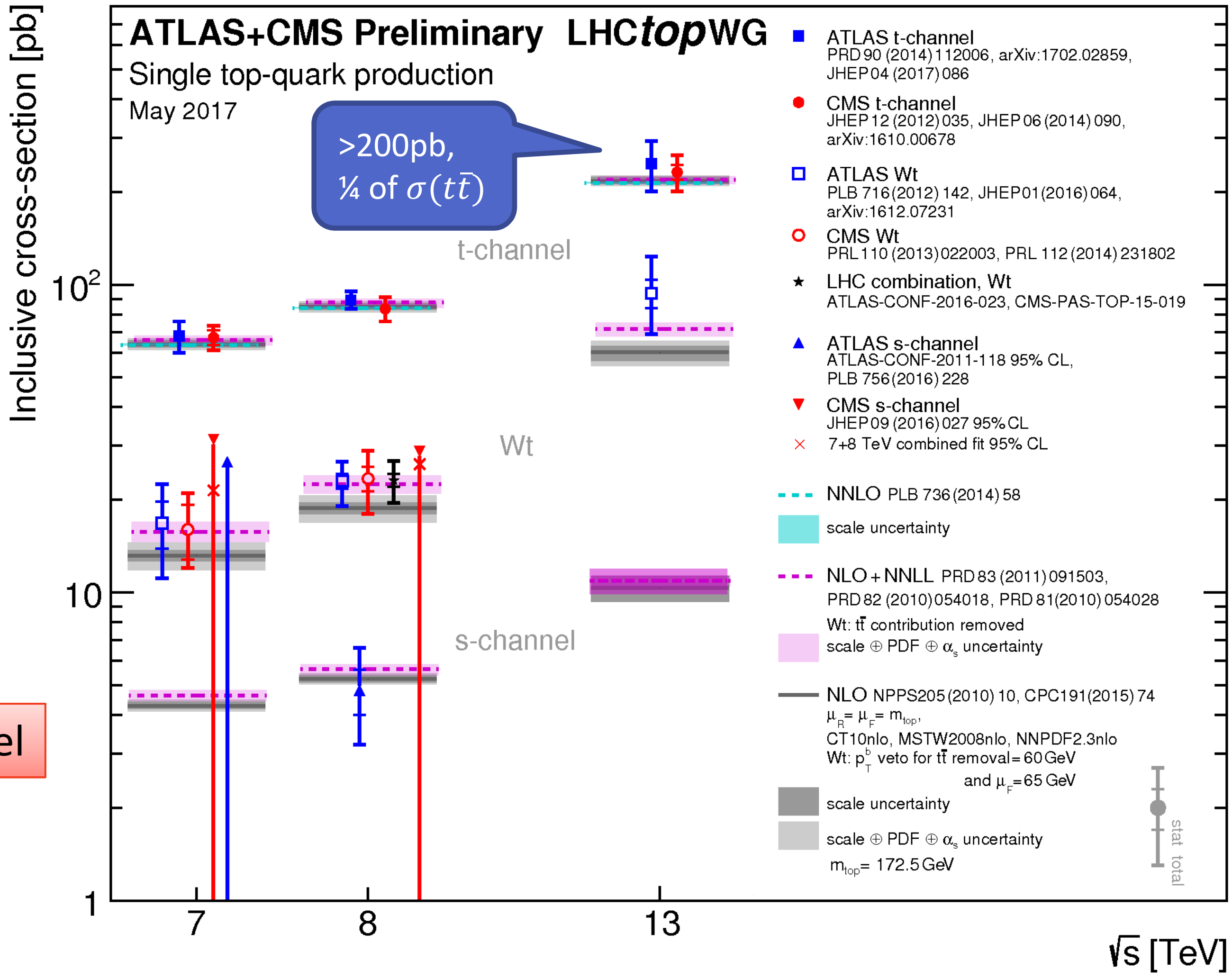


- SM prediction: 1.322 GeV (for 172.5 GeV top)
- Tiny deviation in mass shape in m_{lb} for leptonic decay, still sensitive
  - CMS: 0.6 < Γ < 2.5 GeV (95% CL)
  - ATLAS: $\Gamma = 1.76 \pm 0.33(\text{stat.})^{+0.79}_{-0.68}(\text{syst.})$

SINGLE-TOP PRODUCTION

Single-top: overview

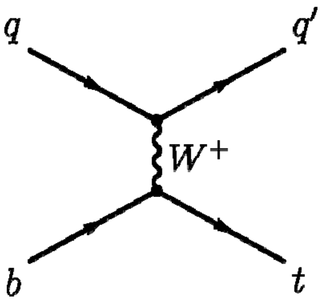




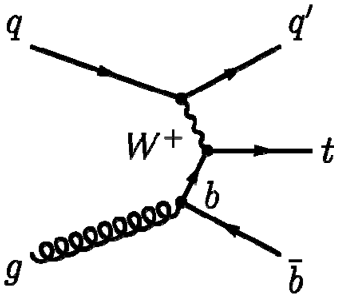
>200pb, ¼ of $\sigma(t\bar{t})$

- No longer statistically limited for inclusive σ
- Can measure t-channel without multi-variate analysis (and soon Wt as well)

t-channel: differential XS and flavour scheme

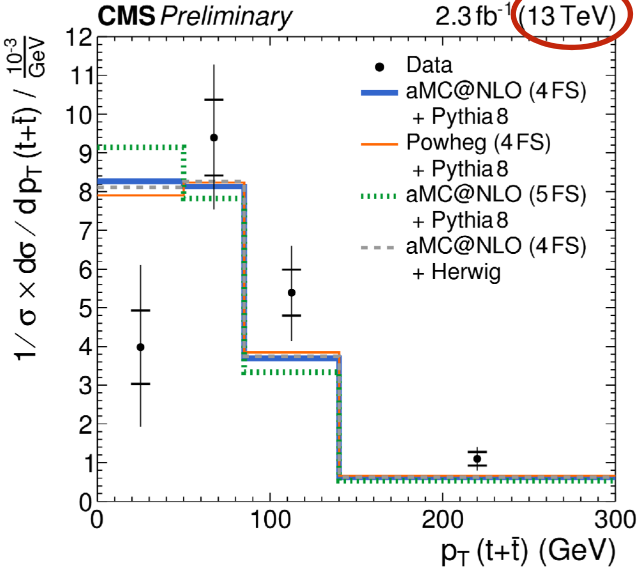


5-flavour scheme

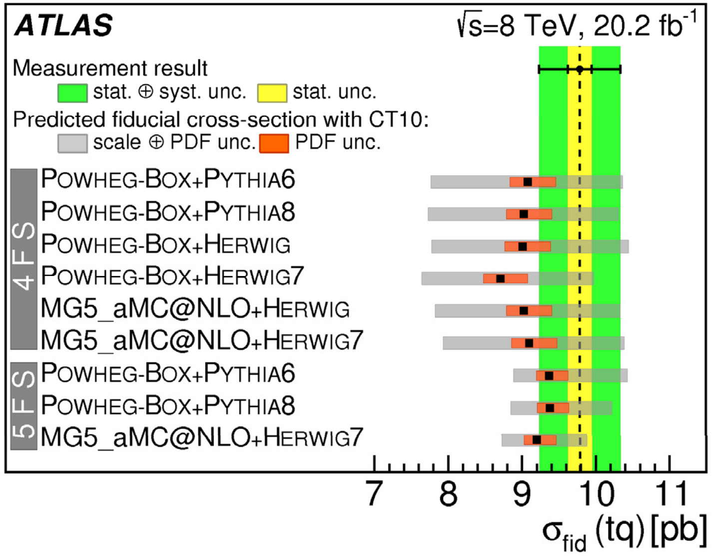


4-flavour scheme

CMS-PAS-TOP-16-004



arXiv: 1702.02859



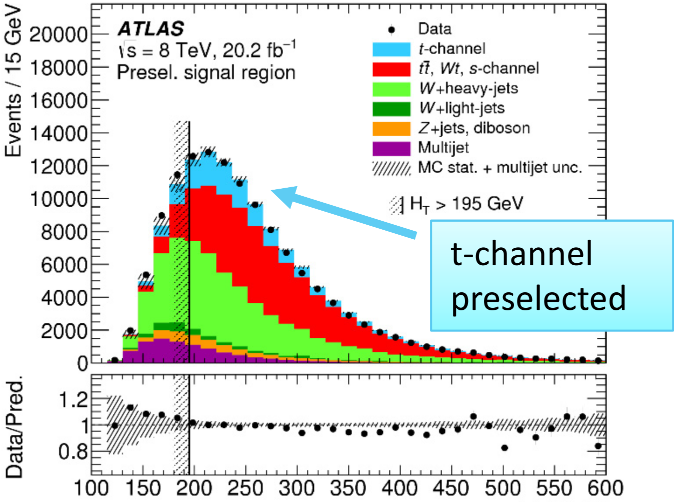
- t-channel needs b-quark in/around the initial state
  - Intrinsic b-quark in the proton (5-Flavour Scheme, 5FS)?
    Or all should be produced dynamically from gluons (4FS)?
    Need to factorise the two diagrams properly
- $p_T(t \text{ or } \bar{t})$ might imply some model improvement in the future

Helicity studies

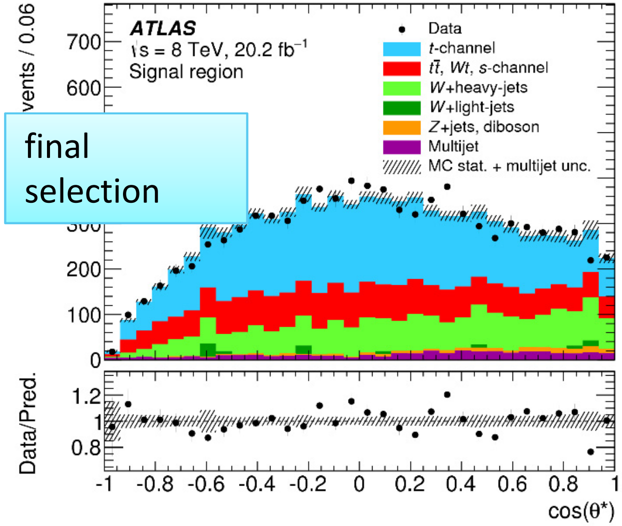
$$\mathcal{L} = \frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}(V_L P_L + V_R P_R)tW_\mu^- - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_\nu}{m_W}(g_L P_L + g_R P_R)tW_\mu^- + h.c.$$

$$\mathcal{L} = \frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}(f_L^V P_L + f_R^V P_R)tW_\mu^- - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_\nu}{m_W}(f_T^L P_L + f_T^R P_R)tW_\mu^- + h.c.$$

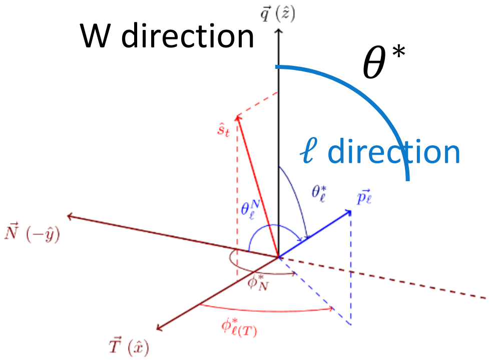
arXiv: 1707.05393



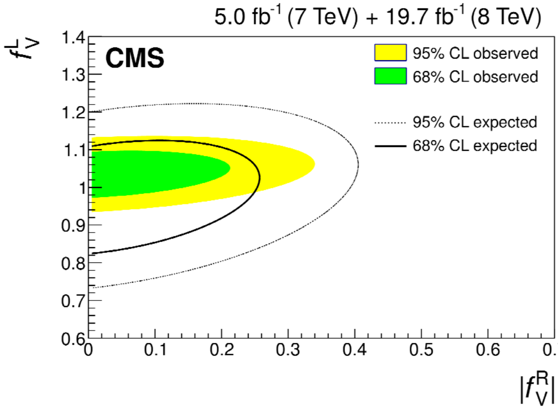
t-channel preselected



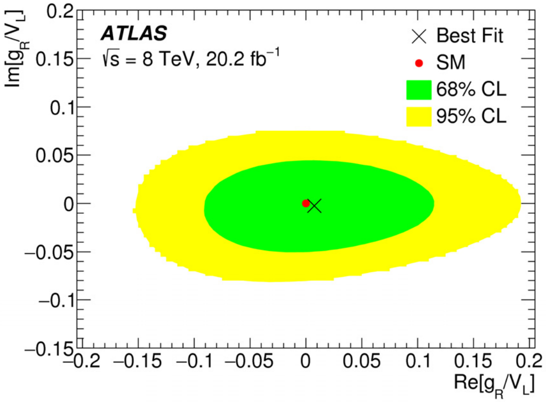
final selection

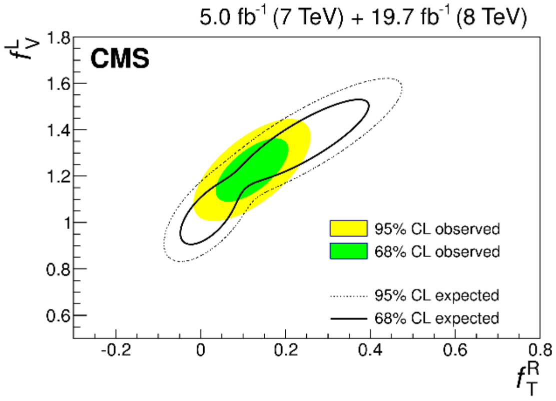


arXiv: 1610.03545



arXiv: 1707.05393

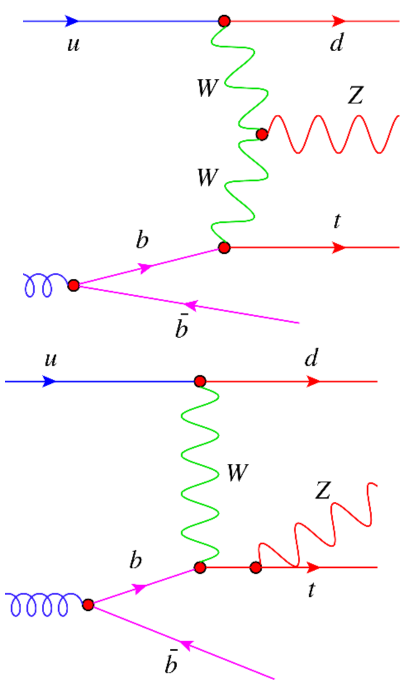




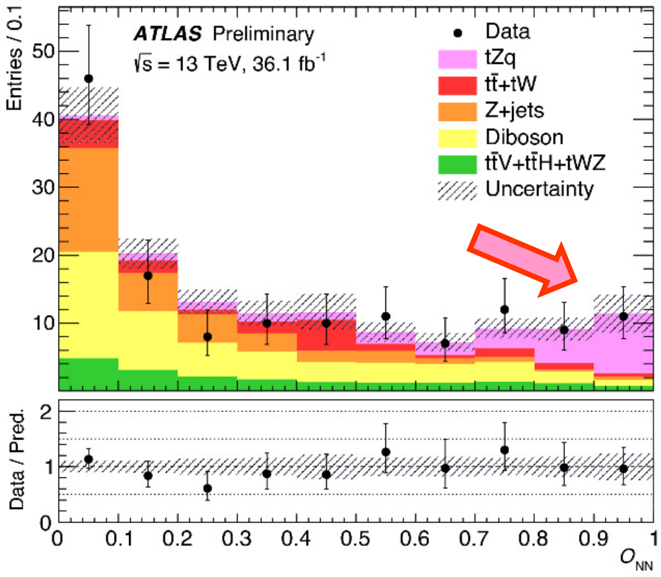
- Event selection: as simple as cut-based (ATLAS)
  - Full analysis with azimuthal angle

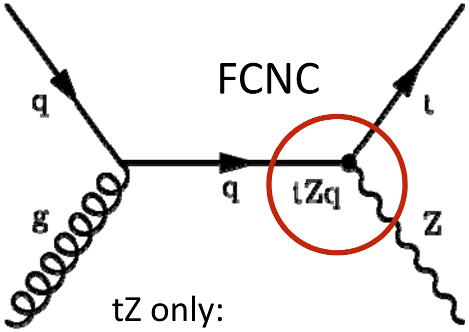
similar precision to $t\bar{t}$-based analyses

Evidence for tZq production + FCNC search

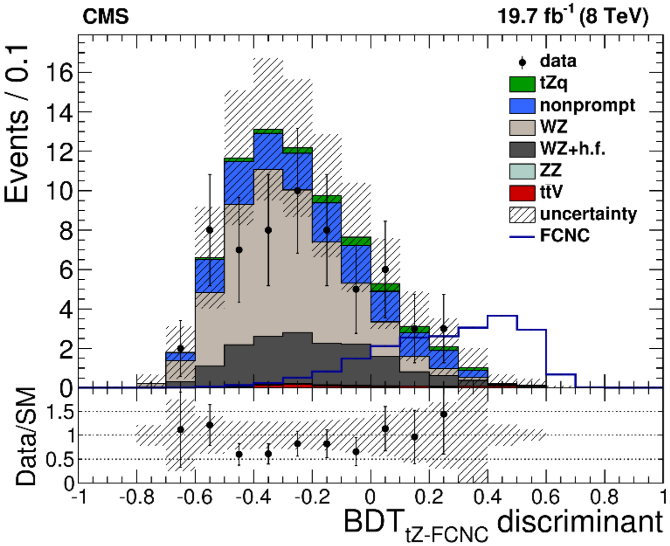


ATLAS-CONF-2017-052





tZ only:
no b-quark radiated



- Sensitive to both WWZ and tZ vertices
  - EW physics via single top!
- First evidence with 36/fb for tZq (4.2σ)
  - 600 fb (obs.) 800 fb (expected)
- FCNC upper limit by tZ final state (no additional b-quark)
  - Br($t \rightarrow Zu$) < 0.022%, Br($t \rightarrow Zc$) < 0.049% @95% CL

Summary

Top physics: towards very high precision in **mass, properties**

through $t\bar{t}$ and **single-top** production

Need to control experimental and theoretical systematics

- Interaction between experiments and theory
  through **cross section measurements**

Higher luminosity – extension to unexplored regime

3x more statistics by the end of 2018

- **new processes** (ttZ, tZq…) for **EW** and **BSM couplings**
- **higher p_T** for **new physics**

BACKUP

Why do we measure top? (2)

Top quark is a probe to new physics

through huge Yukawa coupling to Higgs

$y_t \sim 1$

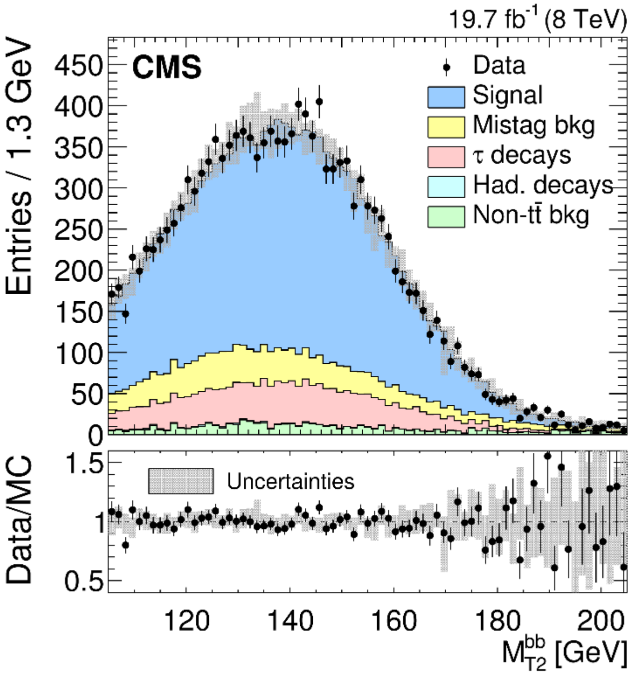
- top is by far heavier than other quarks, beyond EW scale

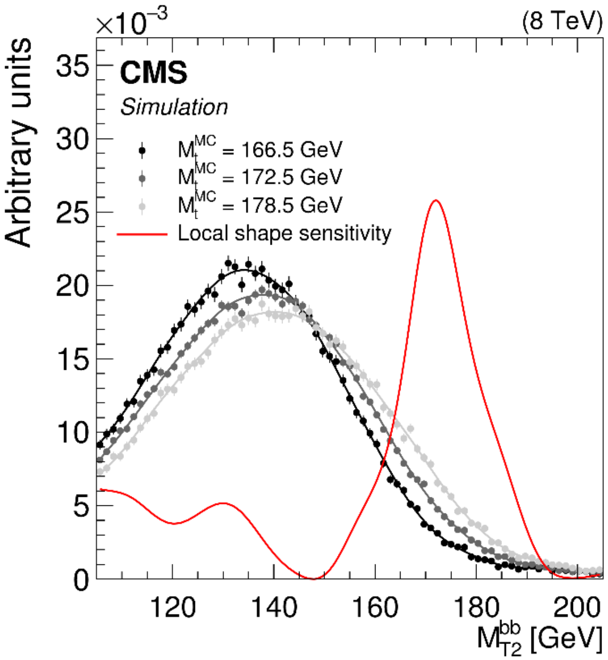
	$m_f/(\sqrt{2}\phi_0)$
e	2.0×10^{-6}
μ	4.1×10^{-4}
τ	7.0×10^{-3}
u	2×10^{-5}
d	3×10^{-5}
s	5×10^{-4}
c	5.2×10^{-3}
b	1.7×10^{-2}
t	0.7

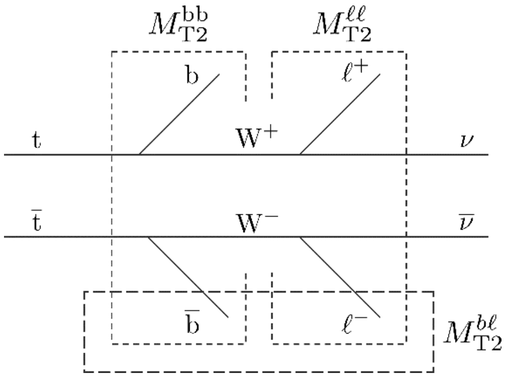
If new physics contains unknown Higgs-like sector, top quarks should know about it, hopefully at a reachable energy

*Alternative kinematic reconstruction (1)

- Kinematic endpoint by “M_{T2}” reconstruction (CMS arXiv: 1704.06142)
  - maximum mass of either t or $\bar{t}$ is minimised to find optimum distribution of missing momentum to two neutrinos: $M_{T2}^{bb} = \min_{p_{Tmiss}}(\max\{m_{T,b1}, m_{T,b2}\})$
- Best fit from “hybrid” method: $172.22 \pm 0.18^{+0.89}_{-0.93}$ GeV
  - syst. from jet energy scale, b-fragmentation, scale uncertainties



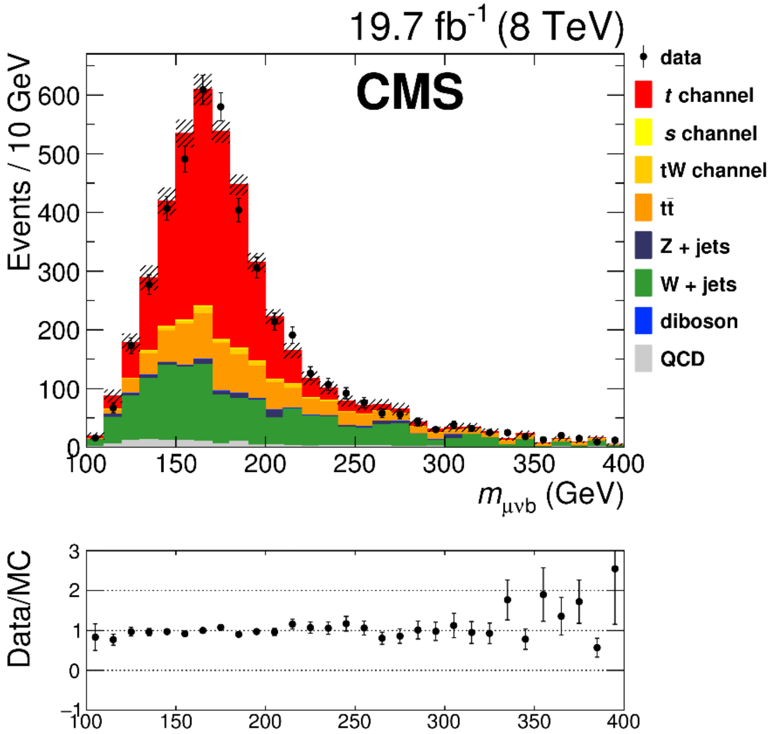


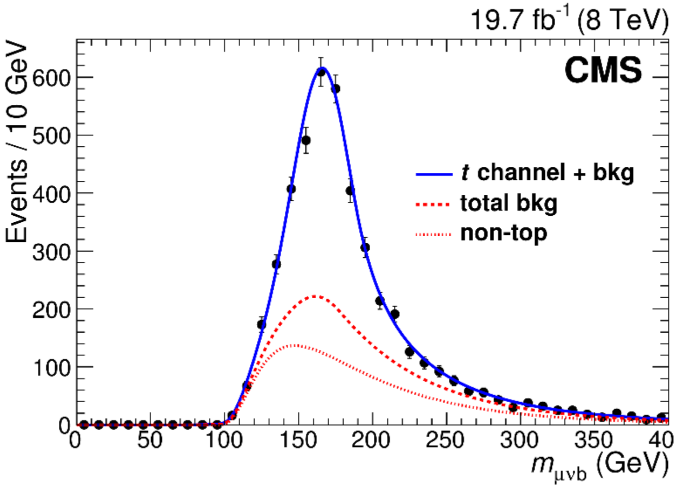


Single-top enriched mass

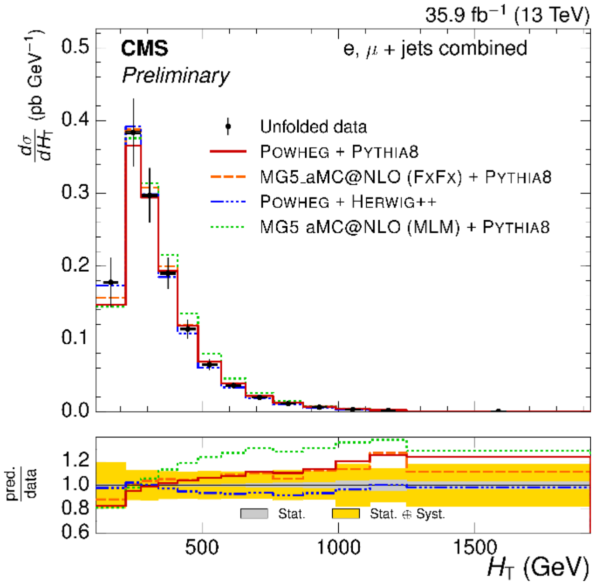
- Weak production:
  different influences from QCD effects
  i.e. ISR/FSR, colour reconnection
  - less partons involved in the interaction
- Reflected to the systematic errors
  - Jet energy scale: 0.6-0.7 GeV
  - **Model dependence ≲ 0.4 GeV**

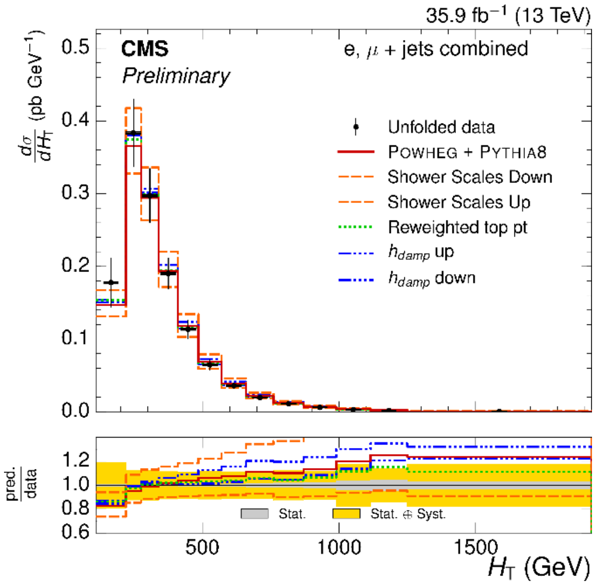
$$m_t = 172.95 \pm 0.77(stat.)^{+0.97}_{-0.93}(syst.)$$





*Recent 13 TeV measuremnts (2a)

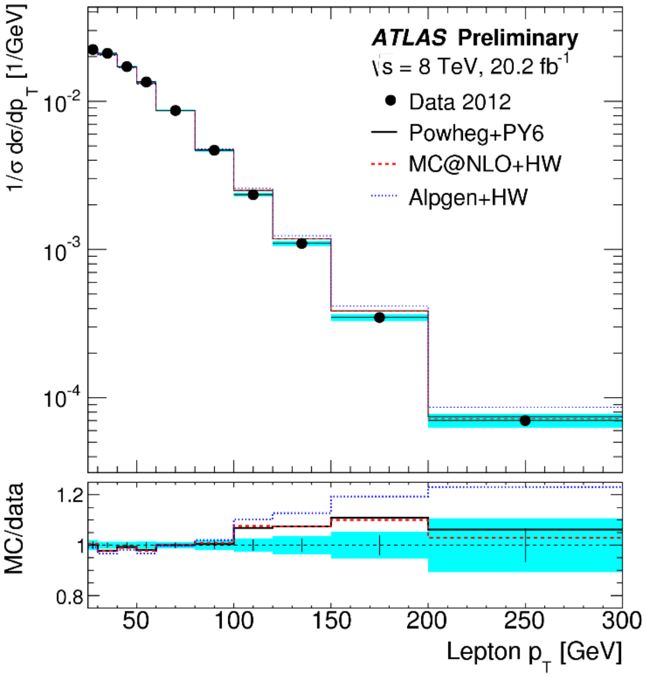




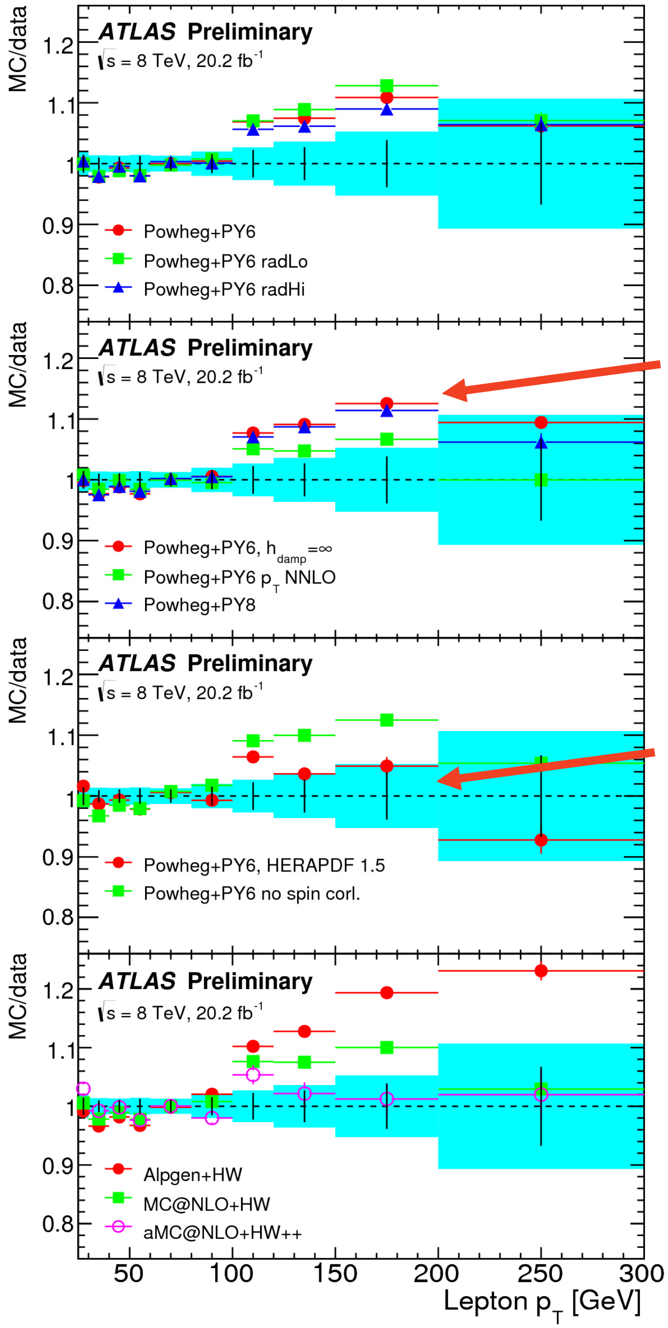
- Comparison to different models
  - matrix elements calculation @ NLO
  - parton shower simulation
  - matching scheme between matrix element and parton shower
  - parton shower phenomenological parameters
- You see why it is important to understand the models!

*Event kinematics result @ 8 TeV from ATLAS

ATLAS-CONF-2017-044



- many of generators tend to predict harder p_T spectrum
- ISR/FSR, parton shower matching parameters would change behaviour



Changing parton shower (less, more) parameters from previous tuning

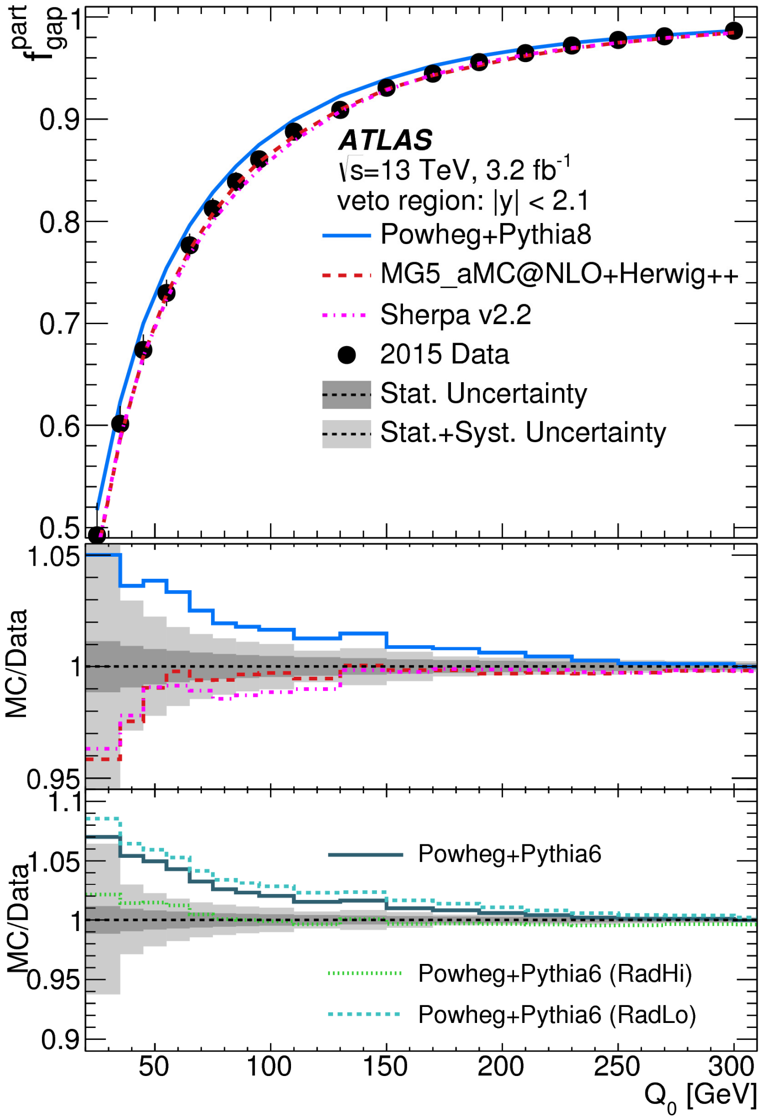
Without PS suppression

PDF to HERA-only fit

Different generator models

EPJC 77(2017)220

*Gap fraction @ 13 TeV



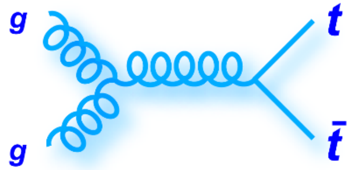
- Fraction of events without any jet with

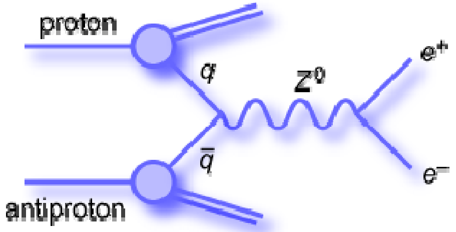
$$p_T(jet) > Q_0$$

in addition to the b-jet from the top decay

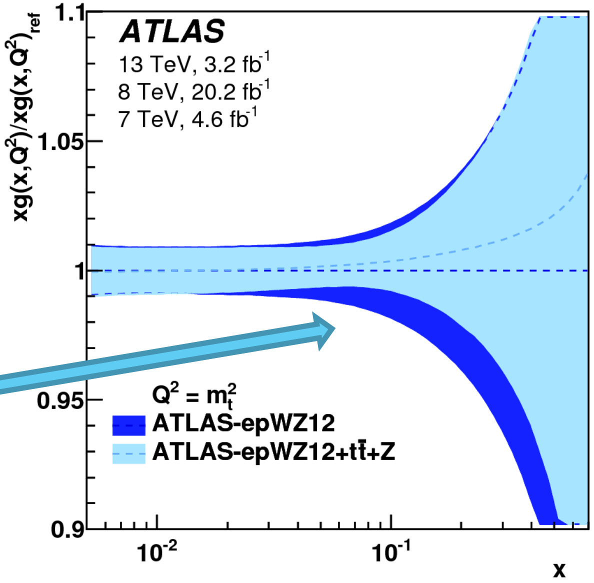
- Sensitive to hard radiation in I/FSR, parton shower due to colour connection

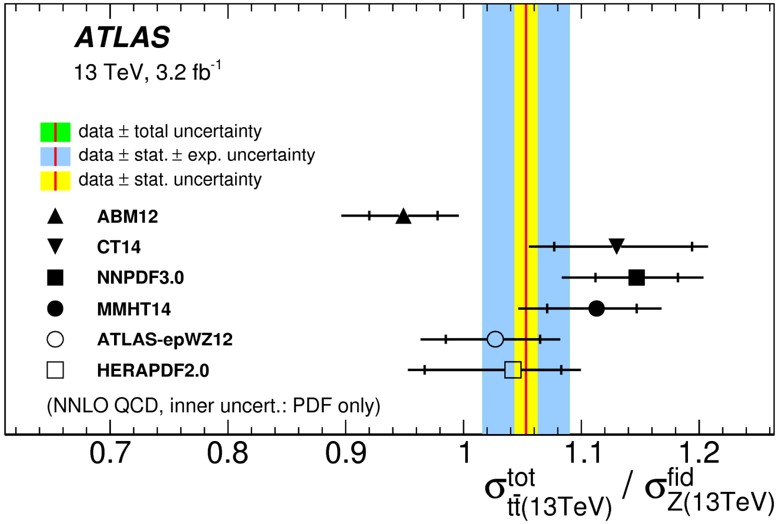
*Sensitivity to PDF(1): ratio to Z, lepton kinematics





JHEP02(2017)117





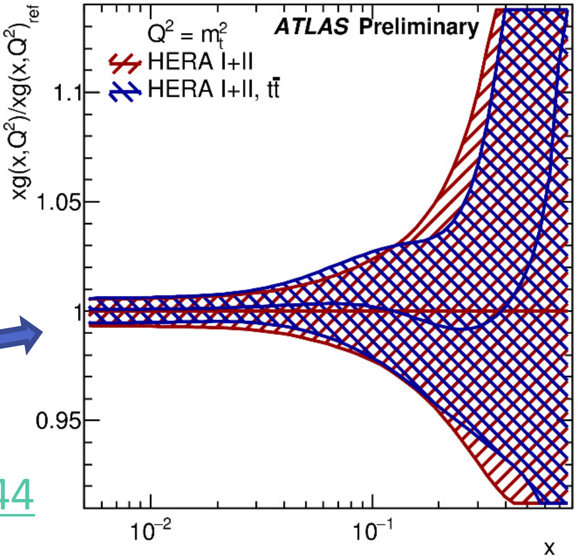
$$R^{tot/fid}_{t\bar{t}/Z} = \sigma^{tot}(t\bar{t})/\sigma^{fid}(Z)$$

- ∝ gluon / quark

Lepton kinematics

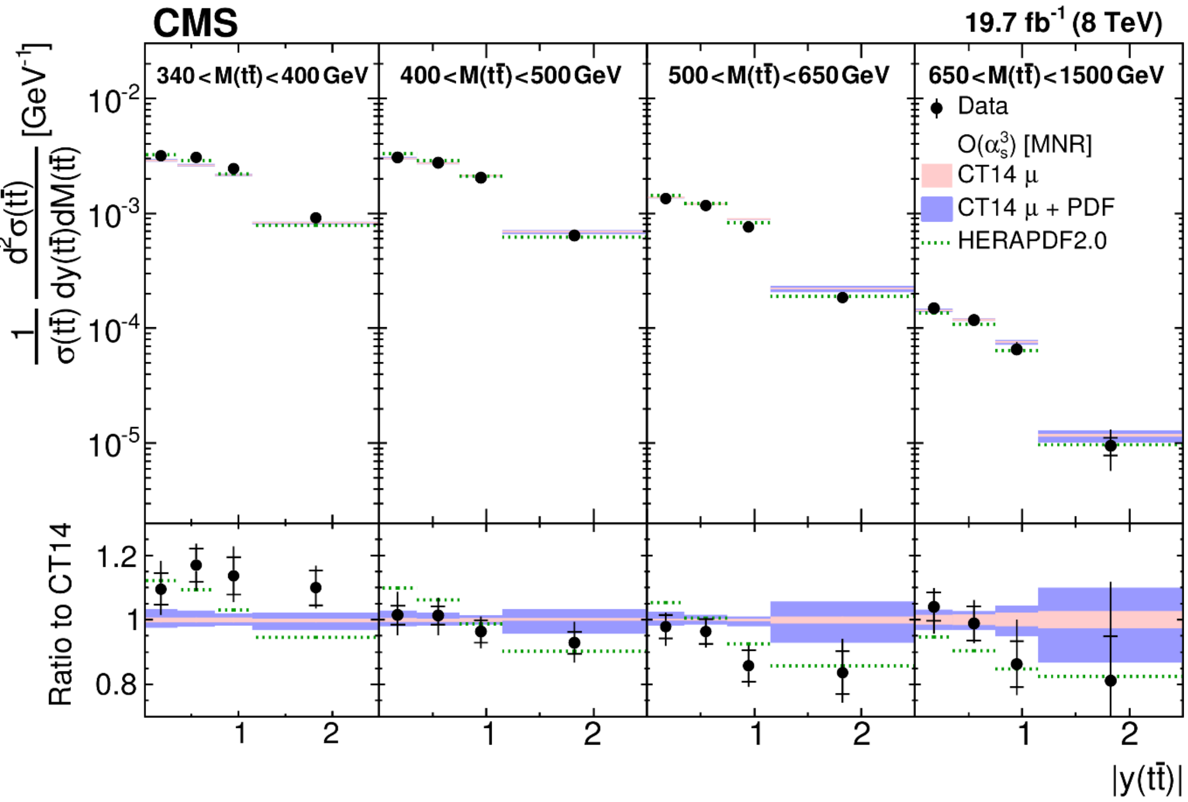
- shape of gluons

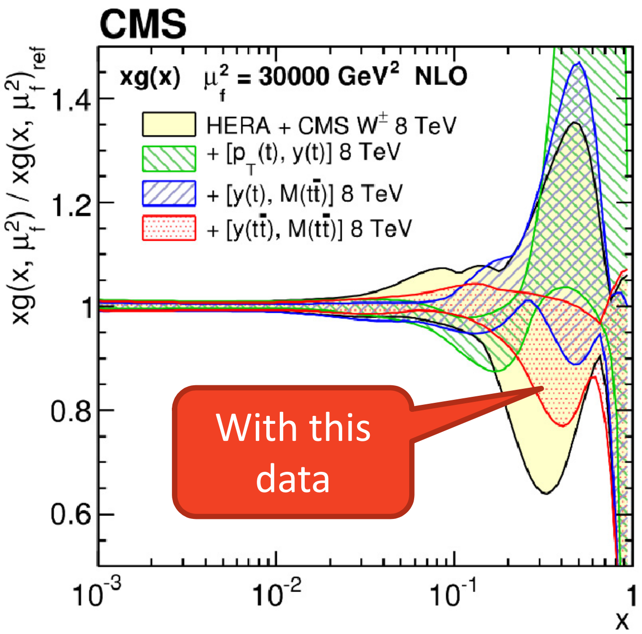
ATLAS-CONF-2017-044



EPJC 77(2017)459

*Cross sections sensitive to PDFs (2)





With this data

PDF fit with HERA data only

CMS Double-differential cross section

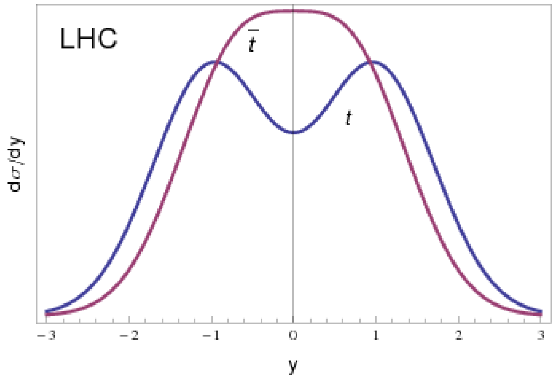
- More direct correspondence to q or $g(x, Q^2)$ through

$$x \simeq \frac{E_{T1}e^{-\eta_1} + E_{T2}e^{-\eta_2}}{E_p}, \qquad Q^2 \simeq E_T^2$$

- Better constraining gluons by adding $t\bar{t}$ data to HERA DIS data

Charge Asymmetry

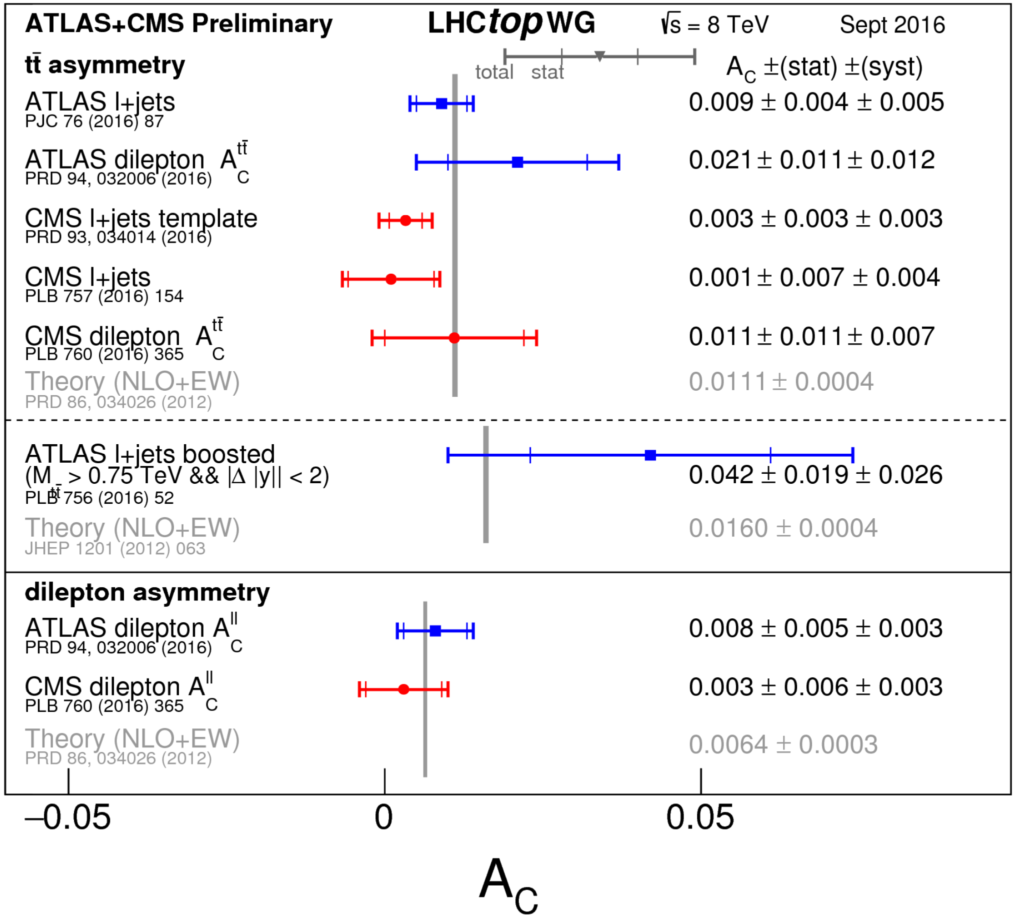
from arXiv: 1207:0331 by G. Rodorigo
Moriond EW 2012 proceedings



A_C gives which of t and $\bar{t}$
is produced in more forward direction

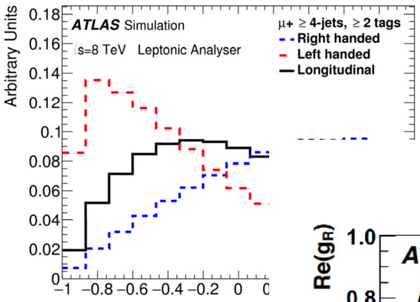
$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$

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

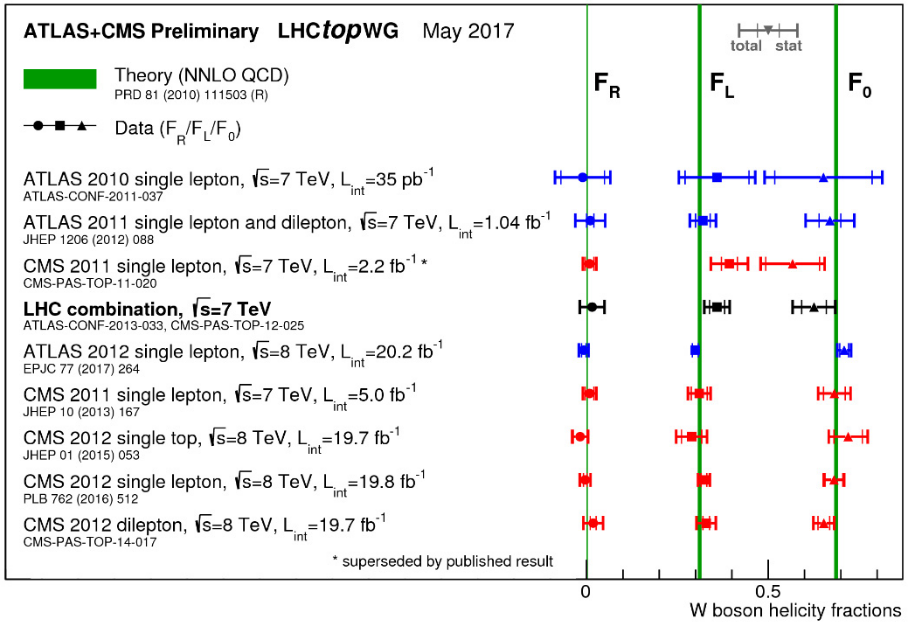


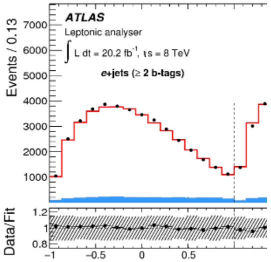
*W polarisation from $t\bar{t}$ decays

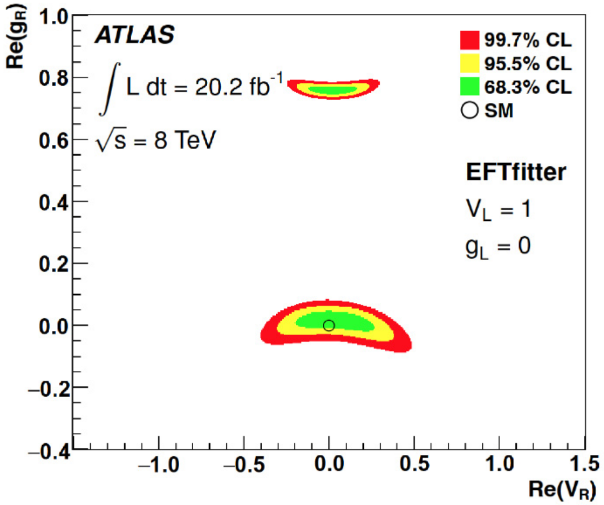
$$\mathcal{L} = \frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}(V_L P_L + V_R P_R)tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{m_W}(g_L P_L + g_R P_R)tW_{\mu}^{-} + h.c.$$

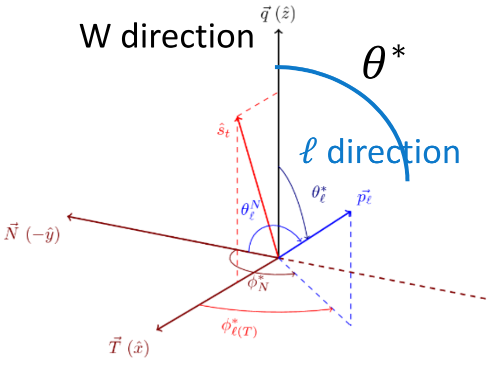


EPJC 77(2017)264



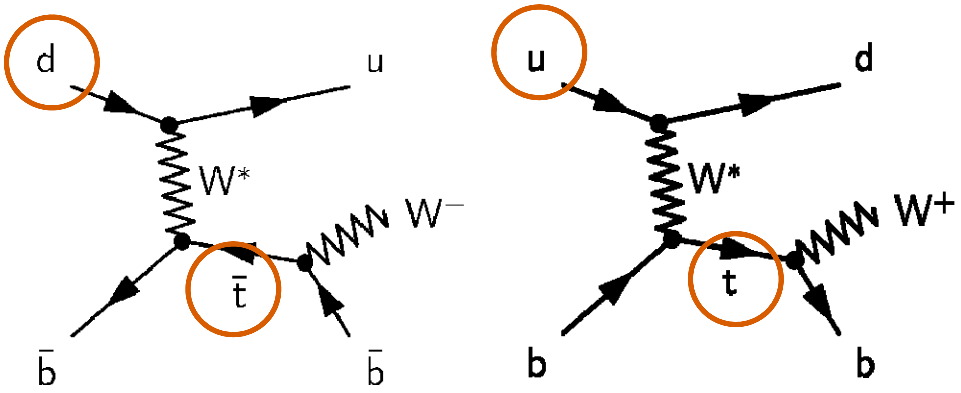




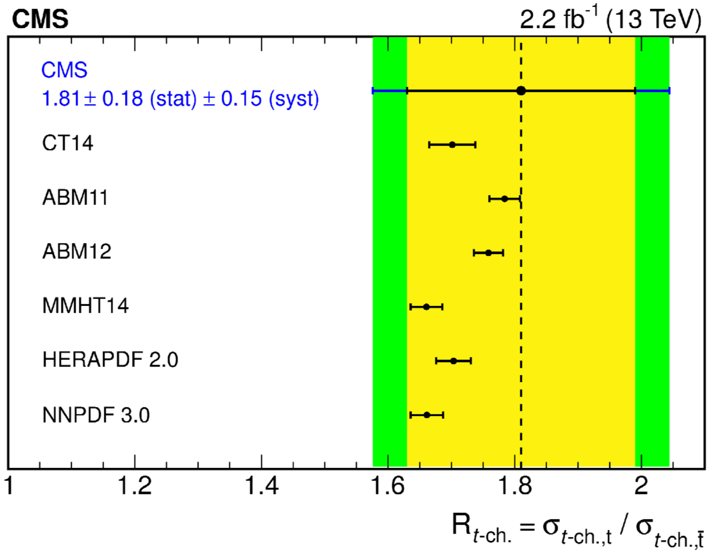


- Wtb vertex: $V - A$ type coupling (V_L)
  - W polarisation: F_L (Left-polarised W) 31.1%, $F_R \sim$ 0.1%, F_0 68.7%
  - Deviation in polarisation may suggest additional term in coupling (V_R or g_L, g_R: tensor couplings)
- Polarisation obtained from ℓ^+ (ℓ^-) or c-quark from $W \rightarrow cs$ decay

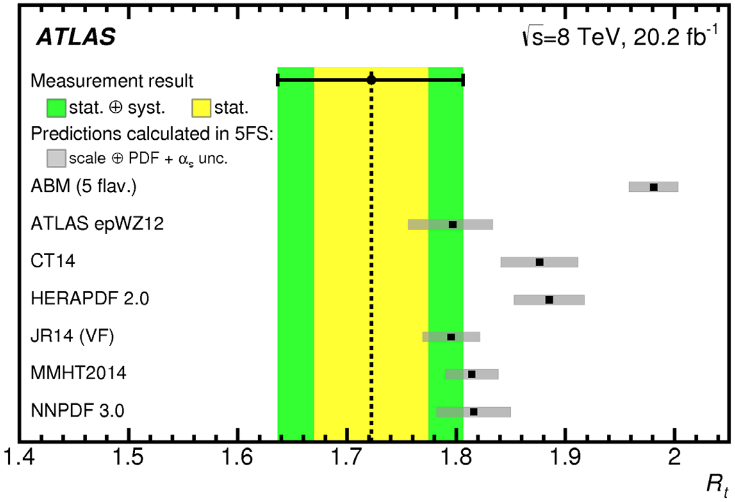
t-channel t and $\bar{t}$ ratio for singlet PDF

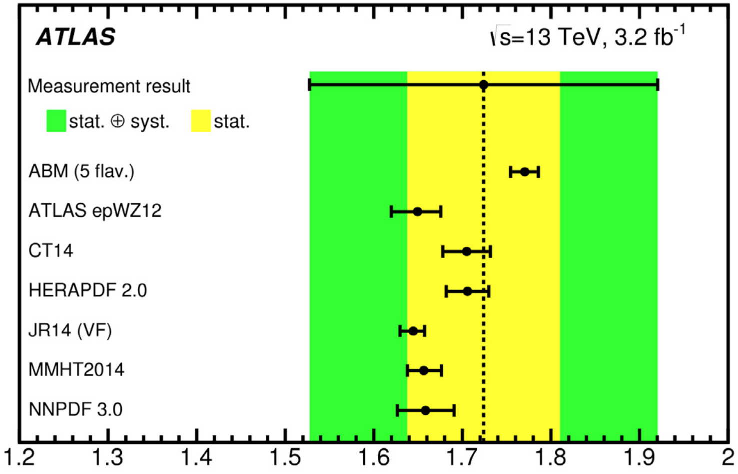


arXiv: 1610.00678



arXiv: 1702.02859

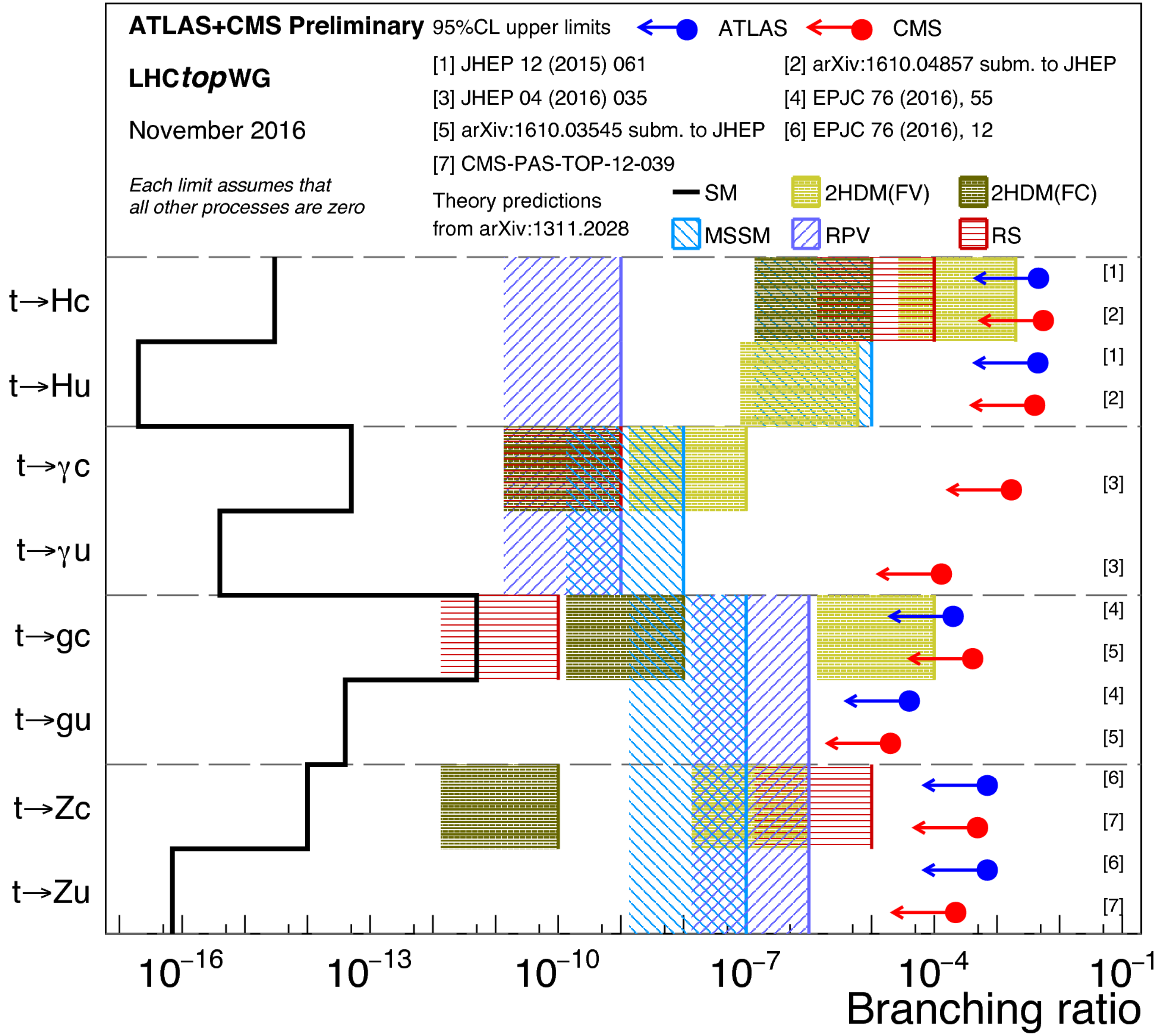




JHEP 04(2017)086

- Sensitive to the isospin of the valence quark PDFs (e.g. u/d)
- Further statistics should help

FCNC limits


ATLAS+CMS Preliminary
95%CL upper limits
ATLAS
CMS
LHCtopWG
November 2016
[1] JHEP 12 (2015) 061
[2] arXiv:1610.04857 subm. to JHEP
[3] JHEP 04 (2016) 035
[4] EPJC 76 (2016), 55
[5] arXiv:1610.03545 subm. to JHEP
[6] EPJC 76 (2016), 12
[7] CMS-PAS-TOP-12-039
Each limit assumes that all other processes are zero
Theory predictions from arXiv:1311.2028
SM
2HDM(FV)
2HDM(FC)
MSSM
RPV
RS
t→Hc
t→Hu
t→γc
t→γu
t→gc
t→gu
t→Zc
t→Zu
[1]
[2]
[1]
[2]
[3]
[3]
[4]
[5]
[4]
[5]
[6]
[7]
[6]
[7]
10^{-16}
10^{-13}
10^{-10}
10^{-7}
10^{-4}
10^{-1}
Branching ratio