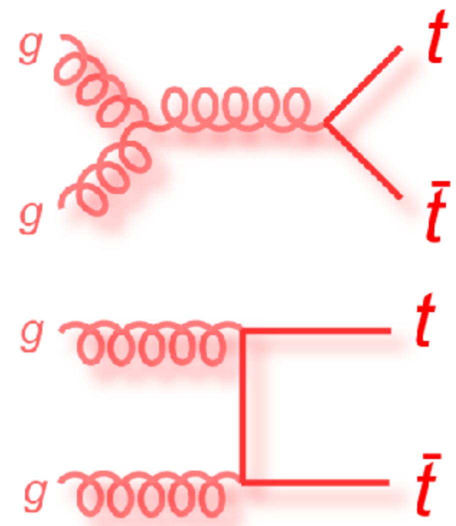
Top quark pair properties & top mass measurements at the LHC

DIS'2019 / Heavy Flavour WG
Tuesday, 9th April 2019

Baptiste Ravina
University of Sheffield

on behalf of the ATLAS & CMS collaborations

Overview

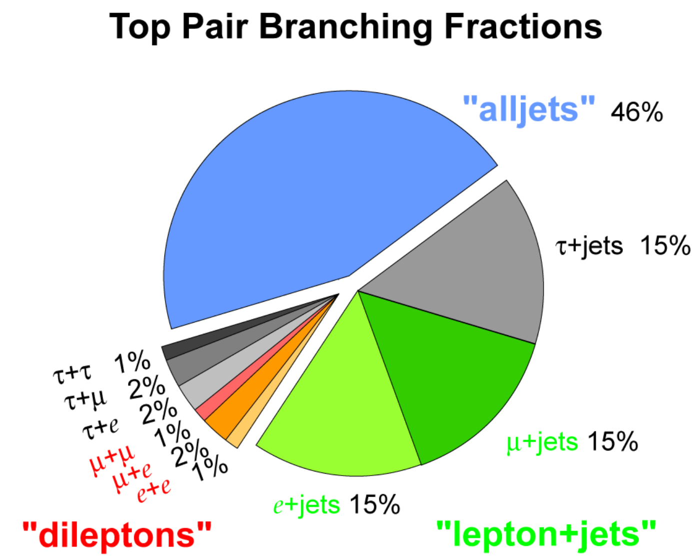


Some top quark facts to get you started…

14 $t\bar{t}$ events produced per second @13 TeV

80-90% through gluon-gluon processes

O(10^5) dilepton / O(10^6) l+jets @8TeV



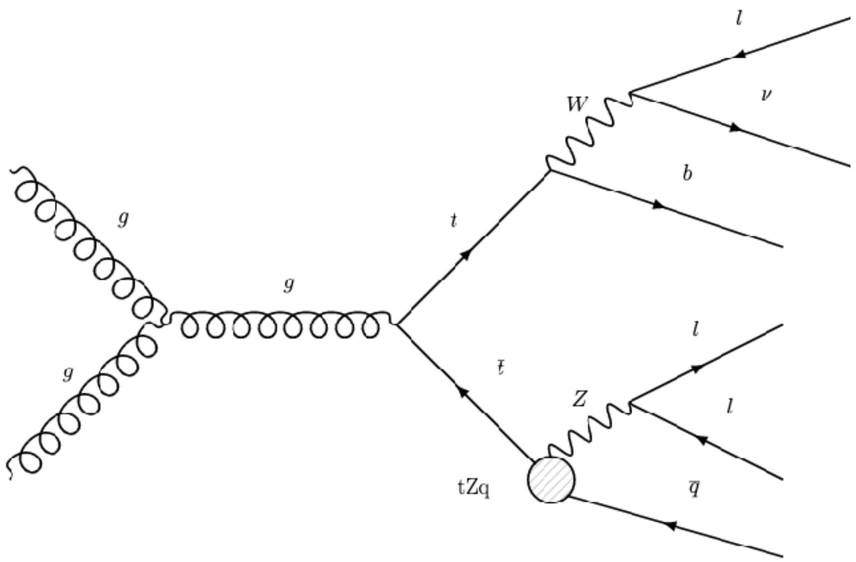
I will cover a mix of ATLAS & CMS measurements on:

- Searches for FCNCs @13 TeV
  - tqZ
  - tqH and combination
- Top properties @13 TeV
  - Spin correlation
  - Charge asymmetries
  - Top Yukawa
  - Colour flow
- Top mass @8 TeV and @13 TeV
  - Indirect: dileptonic, l+jets+1jet
  - Direct: dileptonic, l+jets, combinations
  - Extraction of α_s

Flavour-Changing Neutral Currents

Search for t→qZ FCNC: multilepton

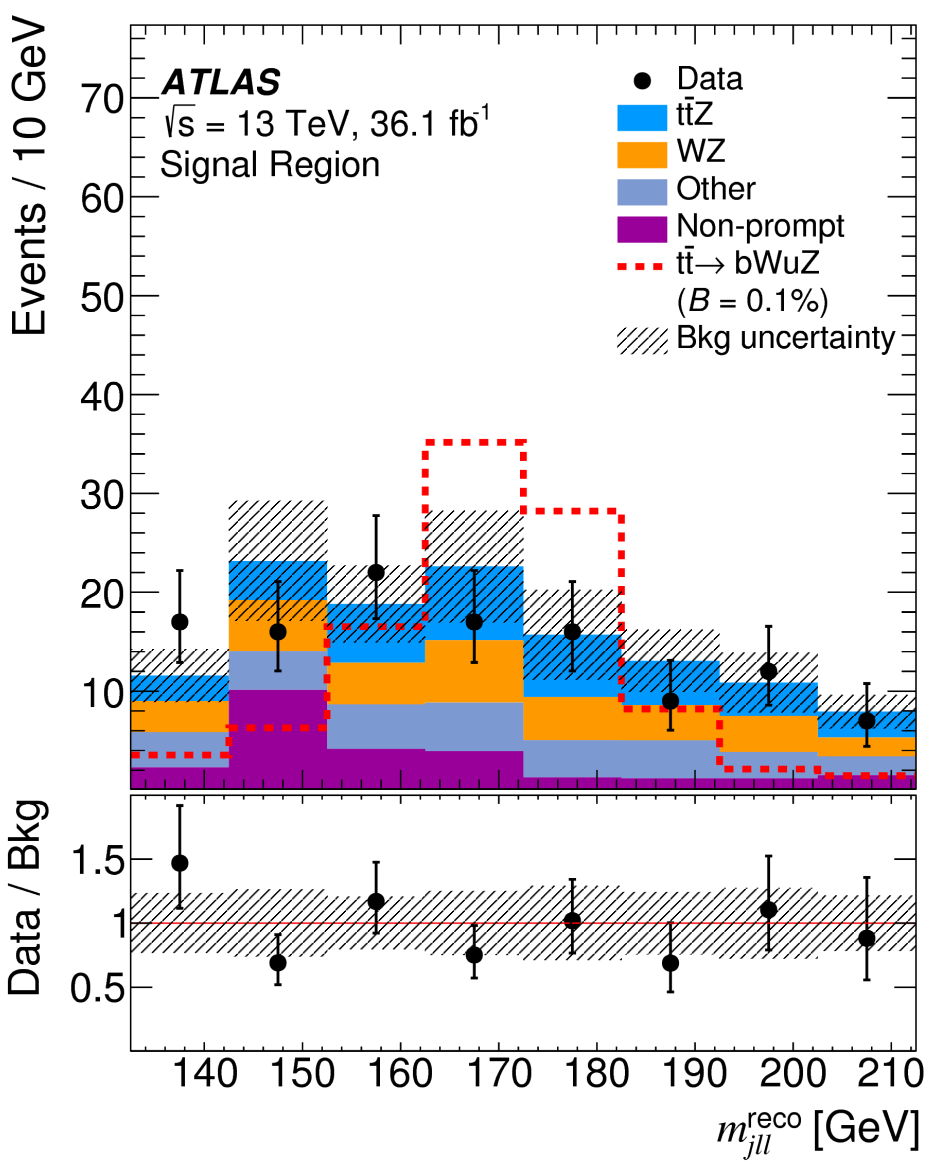
JHEP 07 (2018) 176



Heavily suppressed in the SM (GIM) with **BR~10^{-14}**, but signature of several potential BSM scenarios (e.g. SUSY, BR up to ~10^{-4})

Selection: =3 leptons, ≥2 jets, =1 b-tag, Z candidate

Reconstruct SM top (ε~58%) and FCNC top (ε~80%) by minimising mass-χ^2, apply 40 GeV mass window on both tops.

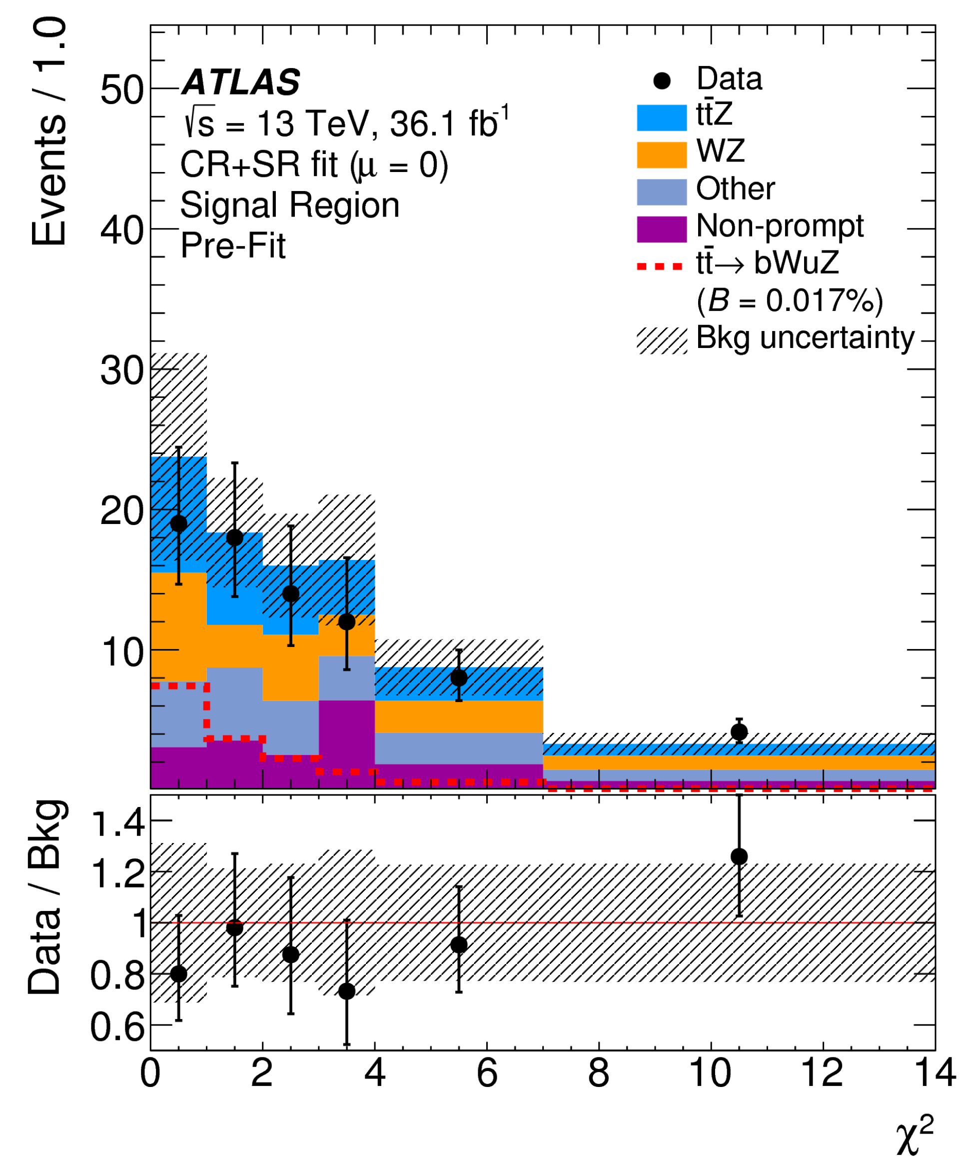


Backgrounds: VV, tZ, tt̄Z, non-prompt leptons estimated in 5 CRs

Leading uncertainties: bkg modelling + theory normalisation for rare processes (tZ, tWZ, tt̄Z)

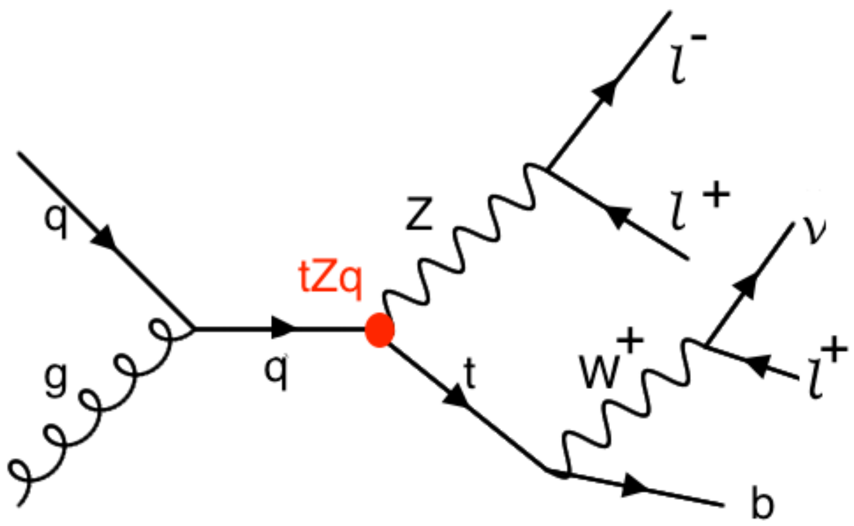
Maximum LH fit to kinematic variables:

- χ^2 in SR
- lepton p_T, $m_T(W)$ and m(llll) in CRs



Search for t→qZ FCNC: multilepton

CMS PAS TOP-17-017

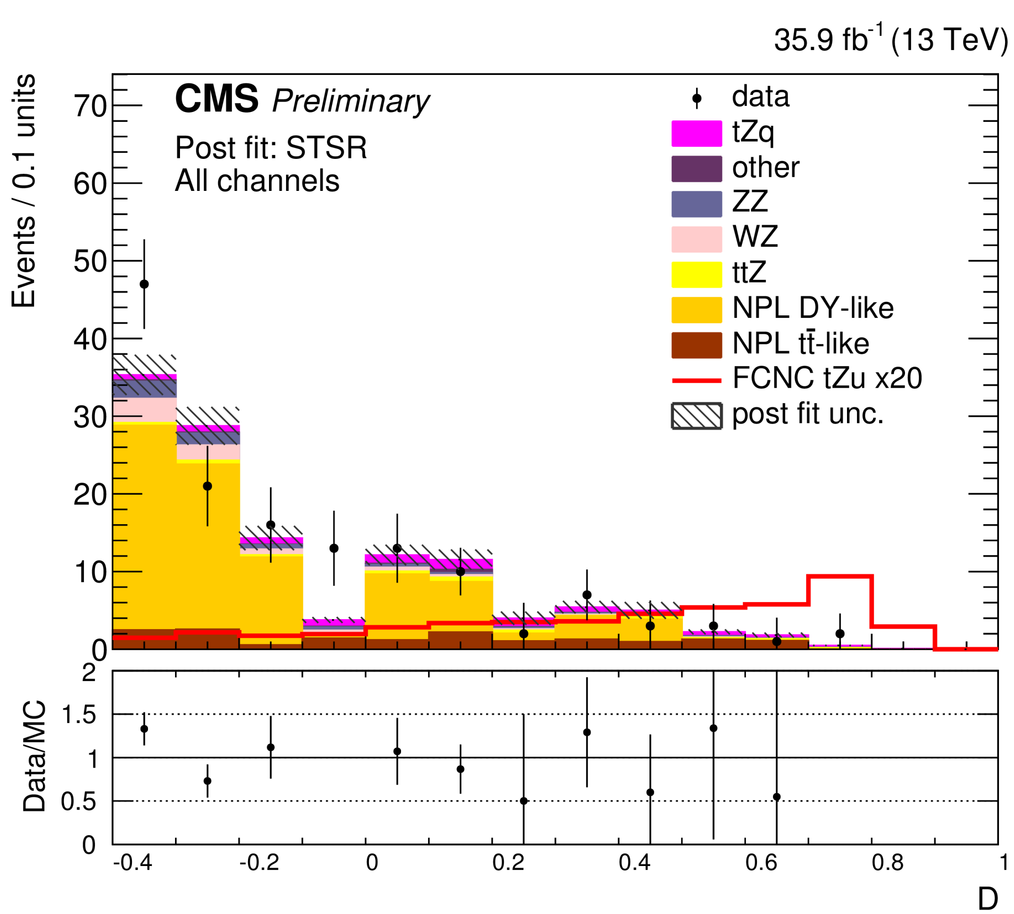


CMS also looking for production mode (single top)

Selection: =3 leptons, [1-3] jets, $m_T(W)$<300 GeV

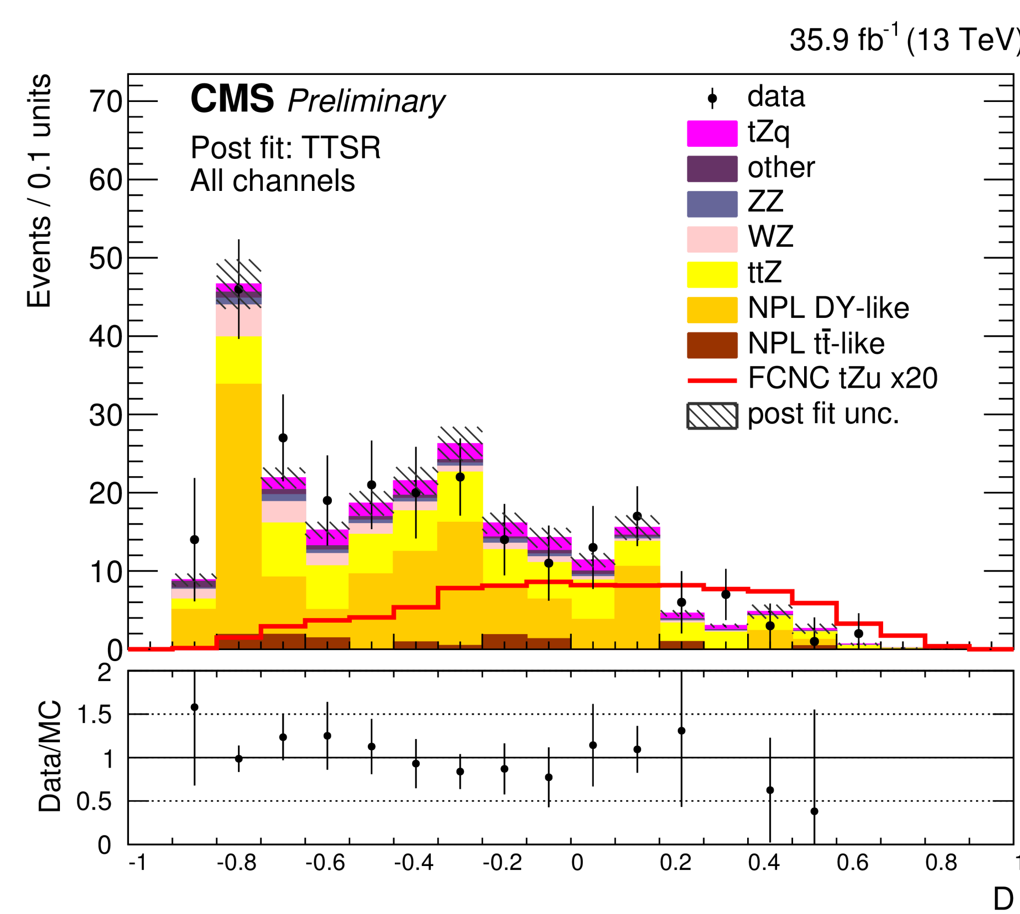
	WZ control region (WZCR)	single top quark signal region (STSR)	top quark pair signal region (TTSR)	single top quark control region (STCR)	top quark pair control region (TTCR)
Number of jets	$\geq 1, \leq 3$	1	$\geq 2, \leq 3$	1	$\geq 2, \leq 3$
Number of b jets	0	1	≥ 1	1	≥ 1
$\lvert M(Z_{reco}) - M_Z \rvert < 7.5$ GeV	Yes	Yes	Yes	No	No

+ ***BDT*** *using basic kinematics and b-tagging information*



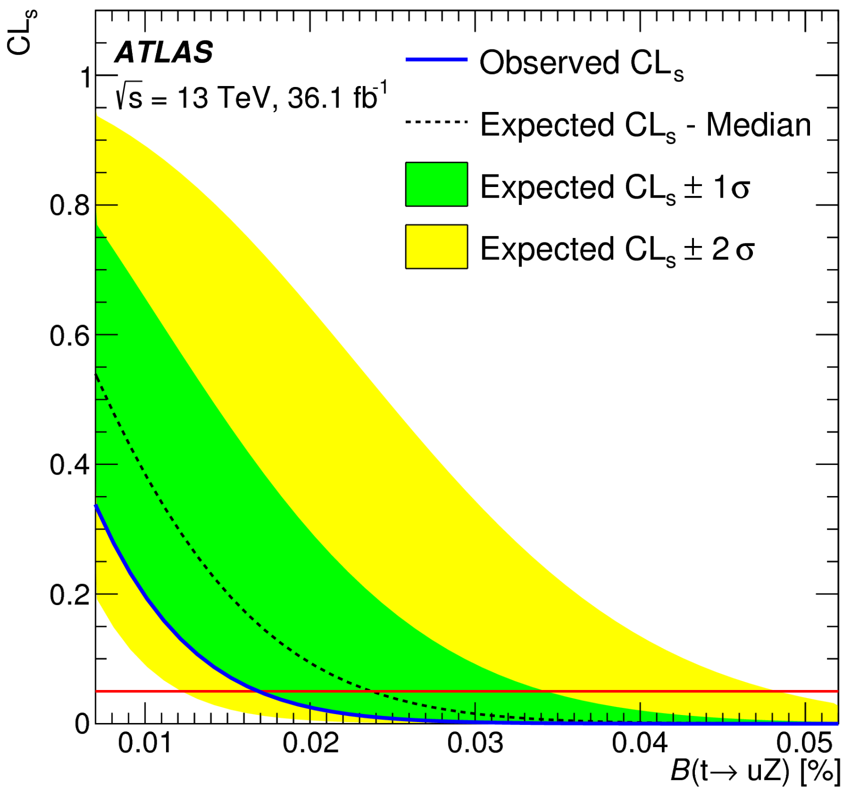
Conservative uncertainties on fakes (50%) and main backgrounds (30%)

Simultaneous fit to 5 regions x 4 channels (lepton flavour)

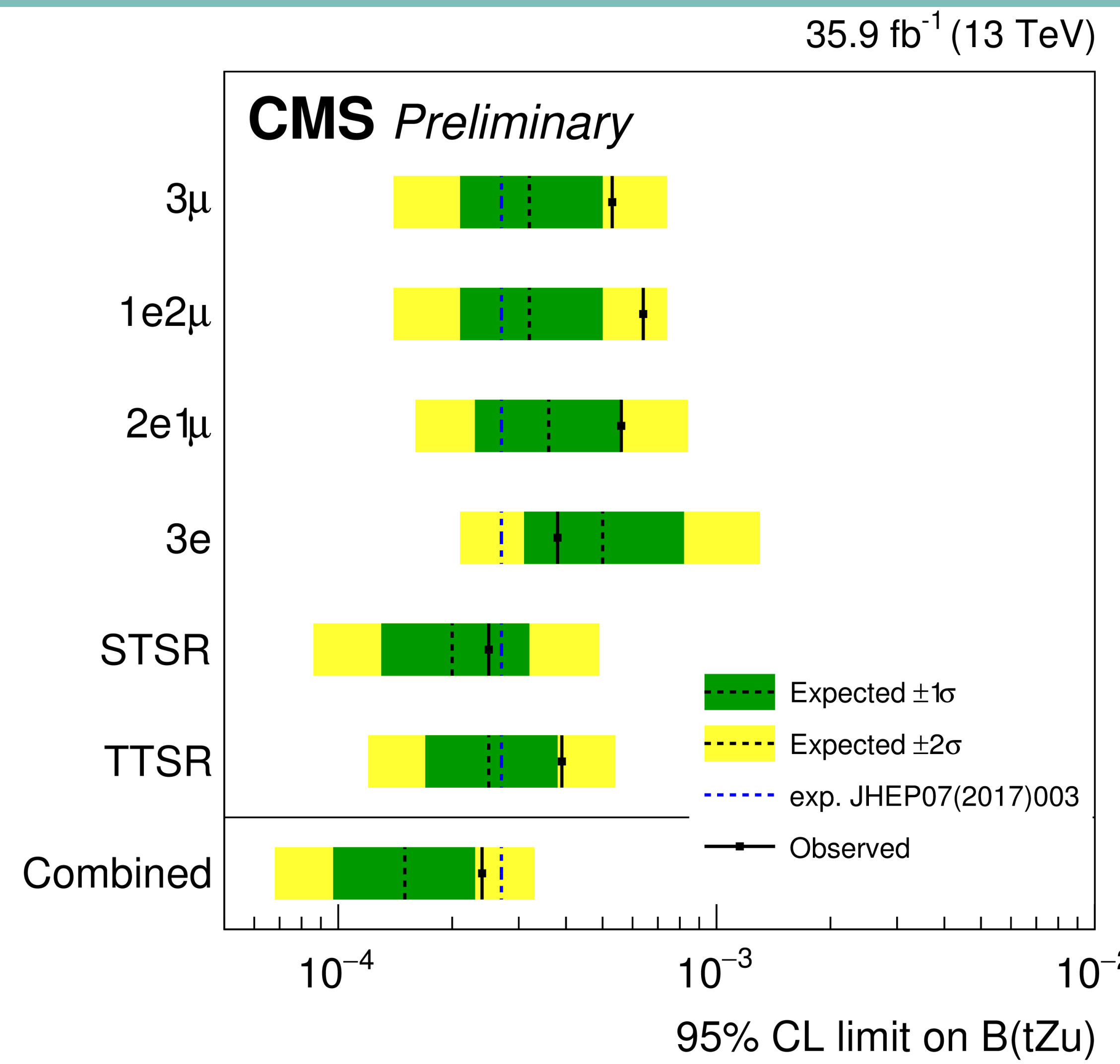


Search for t→qZ FCNC: results

JHEP 07 (2018) 176
CMS PAS TOP-17-017



95% CL upper limits



EFT interpretation
(Λ=1 TeV)

Operator	Observed	Expected
$\|C_{uB}^{(31)}\|$	0.25	0.30
$\|C_{uW}^{(31)}\|$	0.25	0.30
$\|C_{uB}^{(32)}\|$	0.30	0.34
$\|C_{uW}^{(32)}\|$	0.30	0.34

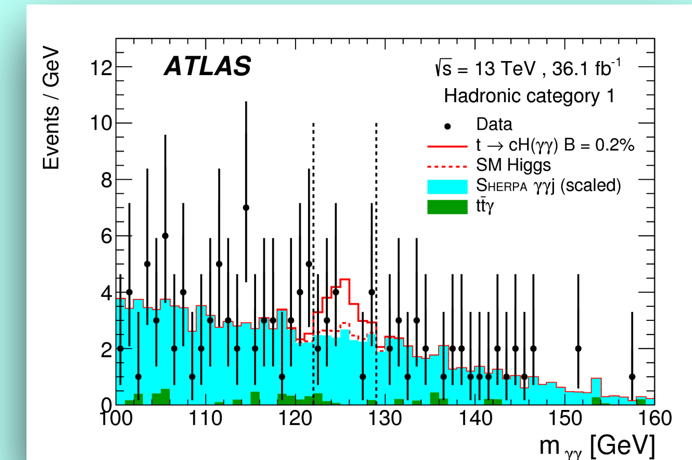
95% CL upper limits	BR(t→uZ) x 10^{-4}	BR(t→cZ) x 10^{-4}
ATLAS	1.7 (exp. 2.4)	2.4 (exp. 3.2)
CMS	2.4 (exp. 1.5)	4.5 (exp. 3.7)

Search for t→qH FCNC: overview

Di-photon

JHEP 10 (2017) 129

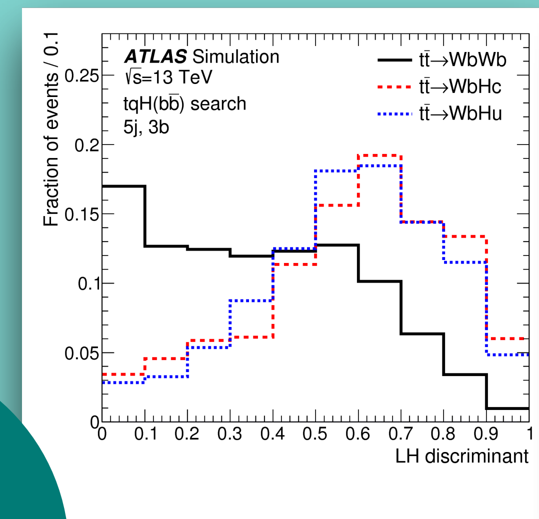
- all-had/1 lepton + Higgs candidate
- dominated by statistical uncertainties

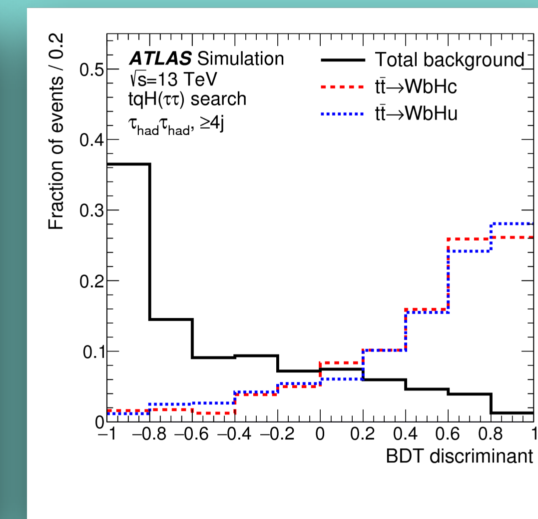


$b\bar{b}/\tau\tau$

arXiv:1812.11568 (submitted to JHEP)

- LH discriminant: WbHq vs WbWb
- BDT trained on di-tau kinematics



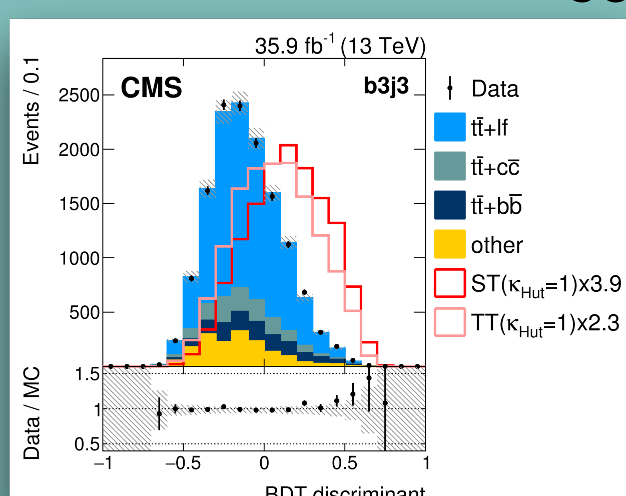


t→qH

$b\bar{b}$

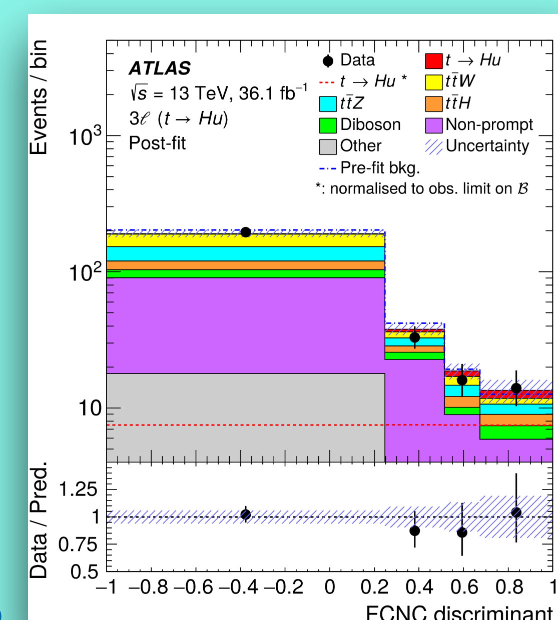
JHEP 06 (2018) 102

- 5 SRs in 1L channel
- BDT to discriminate between: production vs decay mode, signal vs background
- largest uncertainties from b-tagging



Multi-lepton

- 2LSS + 3L selections
- mostly targeting WW*
- use 2 BDTs to reject background and boost sensitivity to tHu



Phys. Rev. D 98 (2018) 032002

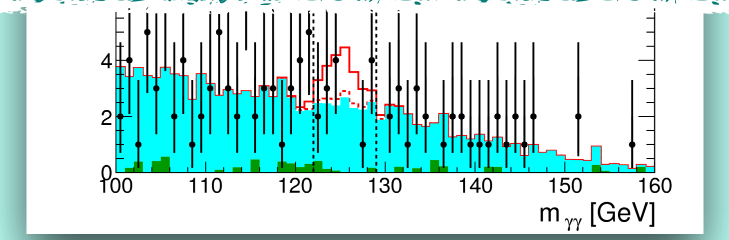
t→qH

Di-photon

JHEP 10 (2017) 129

- all-had/1 lepton + Higgs candidate
- dominated by $t\bar{t}$ production and modelling systematics

BR(t→cH)<2.2x10^{-3} (95% CL)
BR(t→uH)<2.4x10^{-3} (95% CL)



$b\bar{b}/\tau\tau$

arXiv:1812.11568 (submitted to JHEP)

BR(t→cH)<4.2x10^{-3} (95% CL)
BR(t→uH)<5.2x10^{-3} (95% CL)

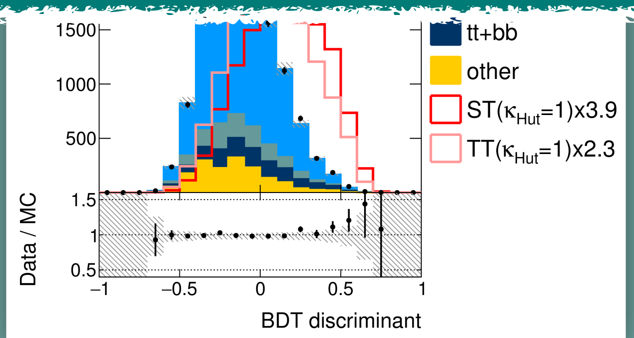
BR(t→cH)<1.9x10^{-3} (95% CL)
BR(t→uH)<1.7x10^{-3} (95% CL)

$b\bar{b}$

JHEP 06 (2018) 102

- 5 SRs in 1L channel
- BDT to discriminate between: production vs decay mode, signal vs background

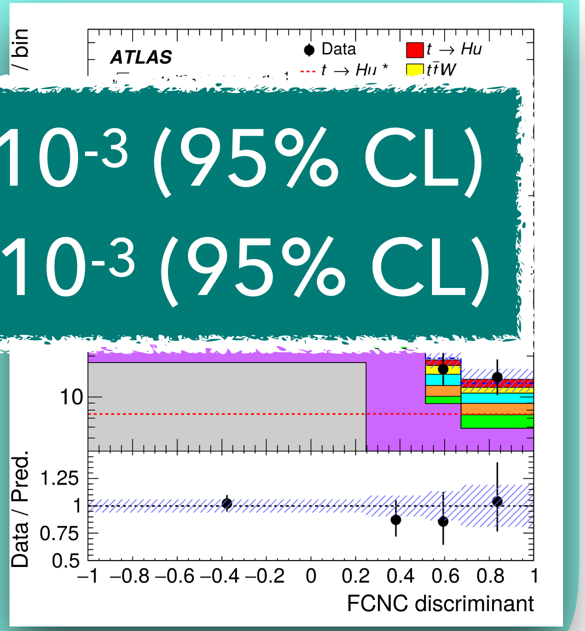
BR(t→cH)<4.7x10^{-3} (95% CL)
BR(t→uH)<4.7x10^{-3} (95% CL)



Multi-lepton

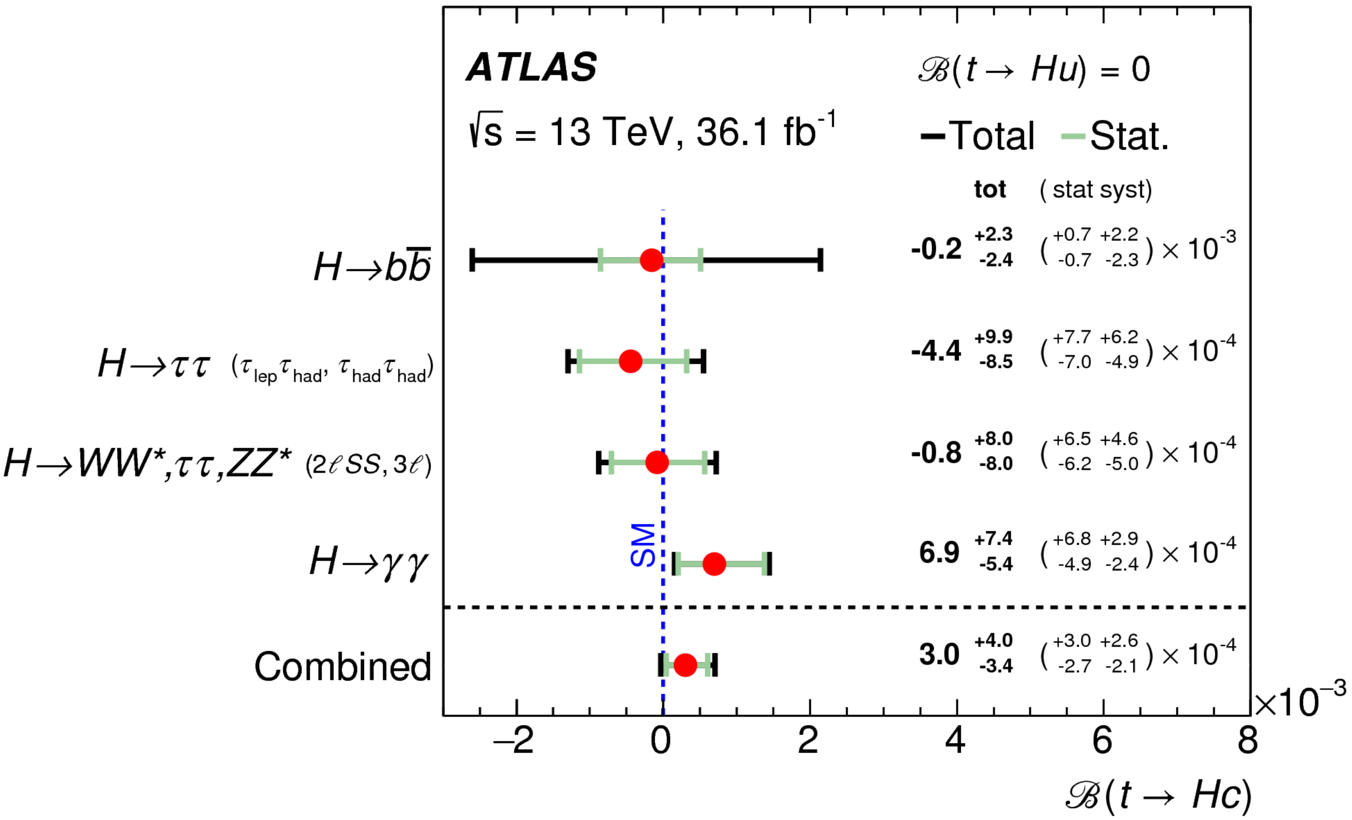
- 2LSS + 3L selections
- mostly targeting WW*
- use 2 BDTs to reject

BR(t→cH)<1.6x10^{-3} (95% CL)
BR(t→uH)<1.9x10^{-3} (95% CL)



Phys. Rev. D 98 (2018) 032002

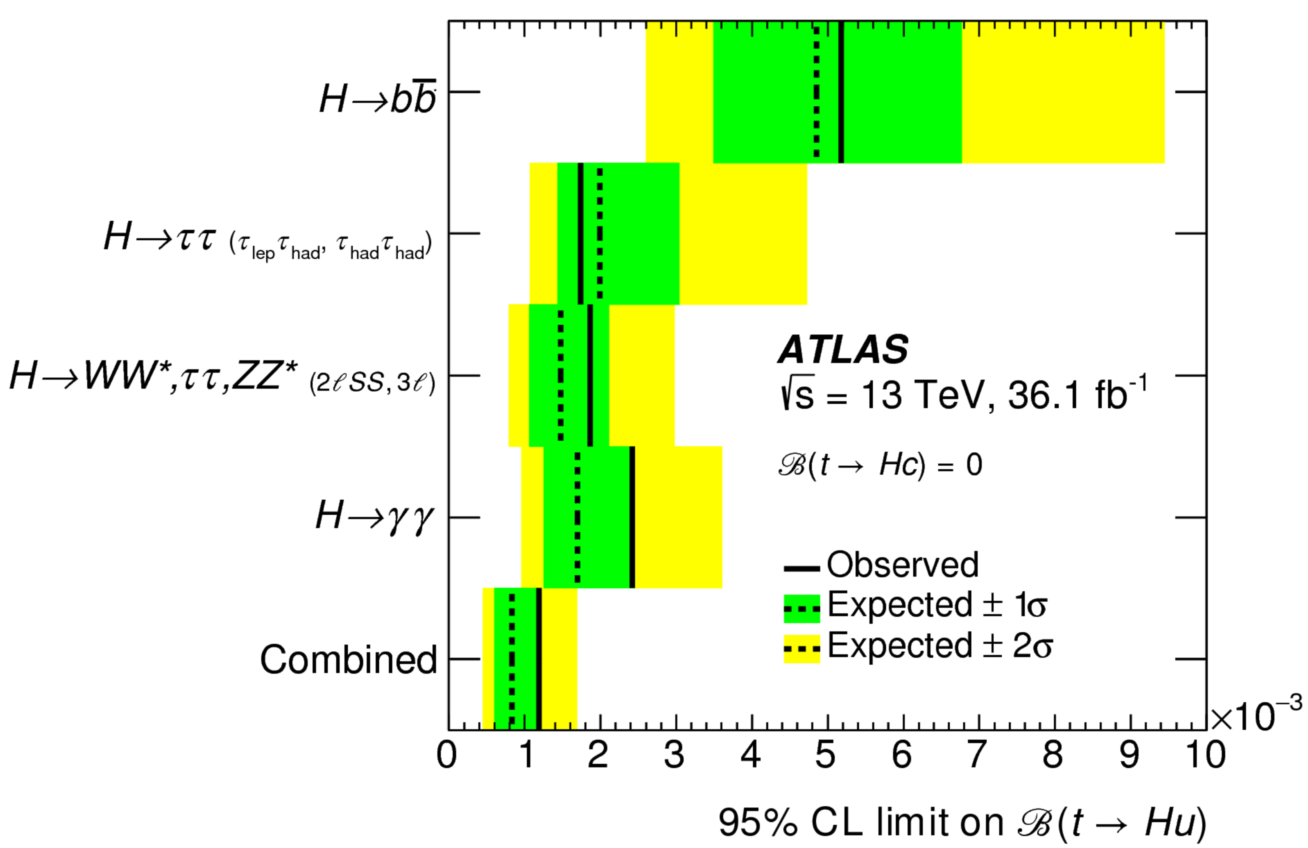
arXiv:1812.11568 (submitted to JHEP)

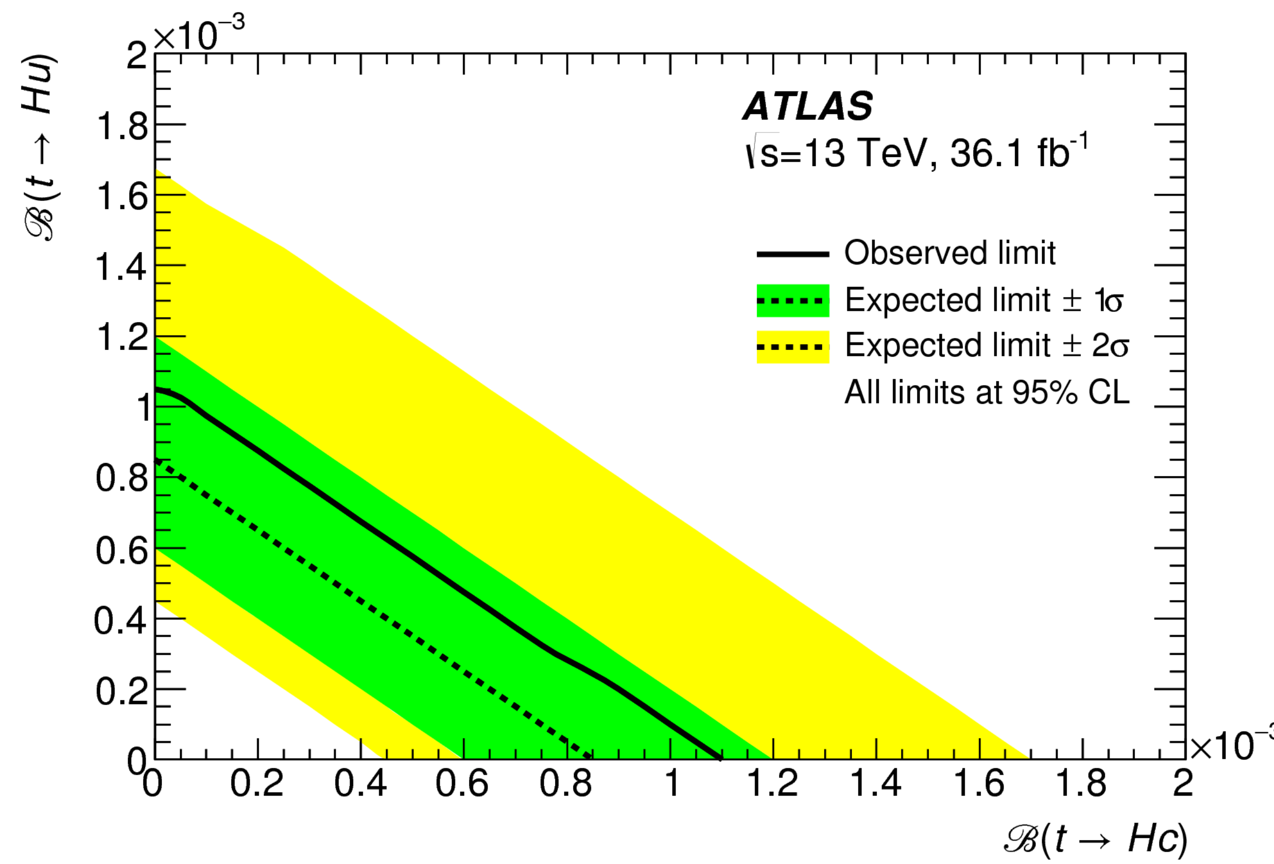


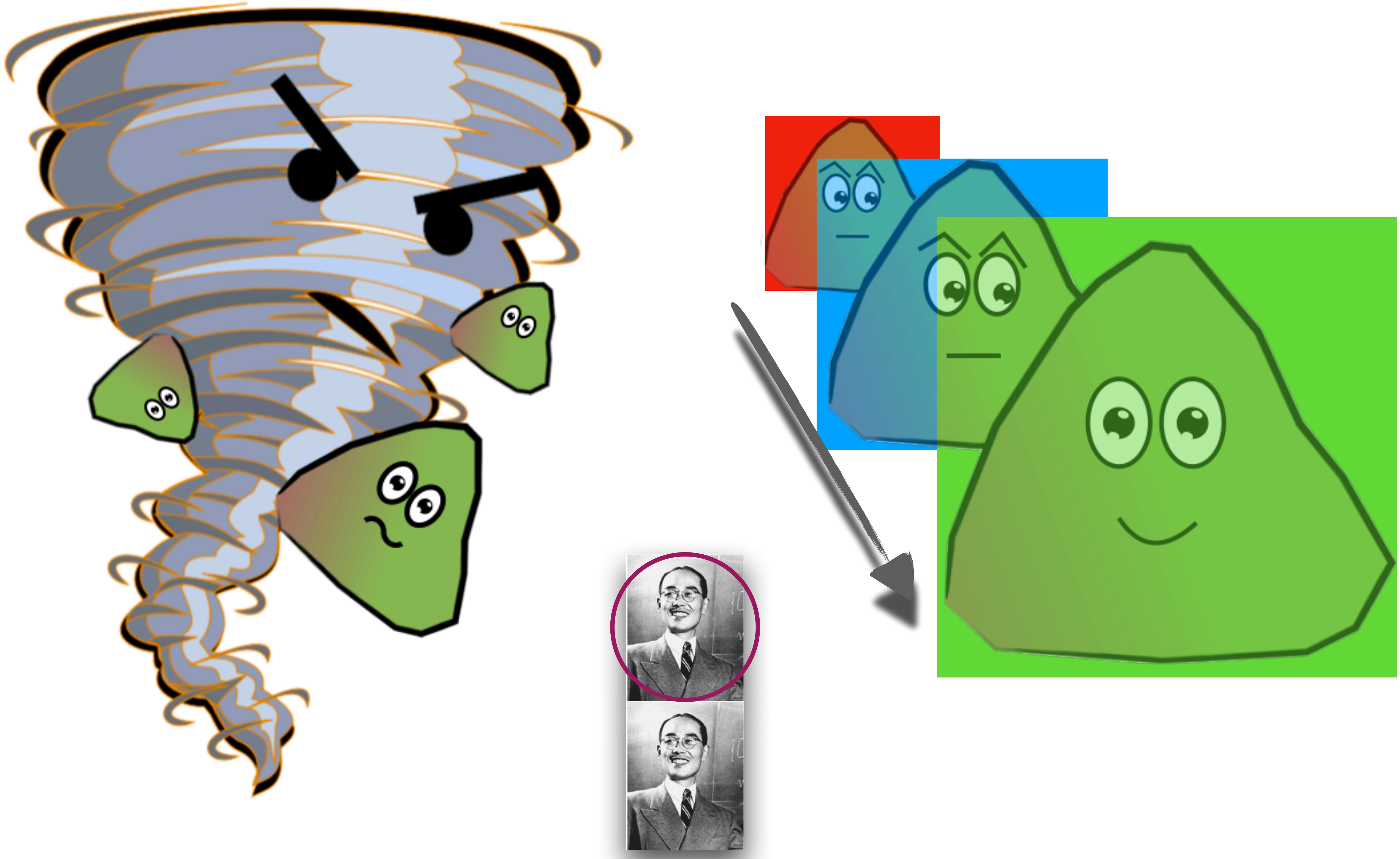
Different leading systematics: combination insensitive to assumed correlations.

Only **fully correlated systs** are: lumi, $t\bar{t}$ cross-section, signal modelling, jet energy resolution (JER) / jet vertex tagger (JVT) and some Higgs BRs.

	95% CL upper limits on $\mathcal{B}(t \to Hc)$ Observed (Expected)	95% CL upper limits on $\mathcal{B}(t \to Hu)$ Observed (Expected)
$H \to b\bar{b}$	4.2×10^{-3} (4.0×10^{-3})	5.2×10^{-3} (4.9×10^{-3})
$H \to \tau\tau$ ($\tau_{\rm lep}\tau_{\rm had}$, $\tau_{\rm had}\tau_{\rm had}$)	1.9×10^{-3} (2.1×10^{-3})	1.7×10^{-3} (2.0×10^{-3})
$H \to WW^*, \tau\tau, ZZ^*$ (2ℓSS, 3ℓ) [22]	1.6×10^{-3} (1.5×10^{-3})	1.9×10^{-3} (1.5×10^{-3})
$H \to \gamma\gamma$ [21]	2.2×10^{-3} (1.6×10^{-3})	2.4×10^{-3} (1.7×10^{-3})
Combination	1.1×10^{-3} (8.3×10^{-4})	1.2×10^{-3} (8.3×10^{-4})







Top quark pair properties

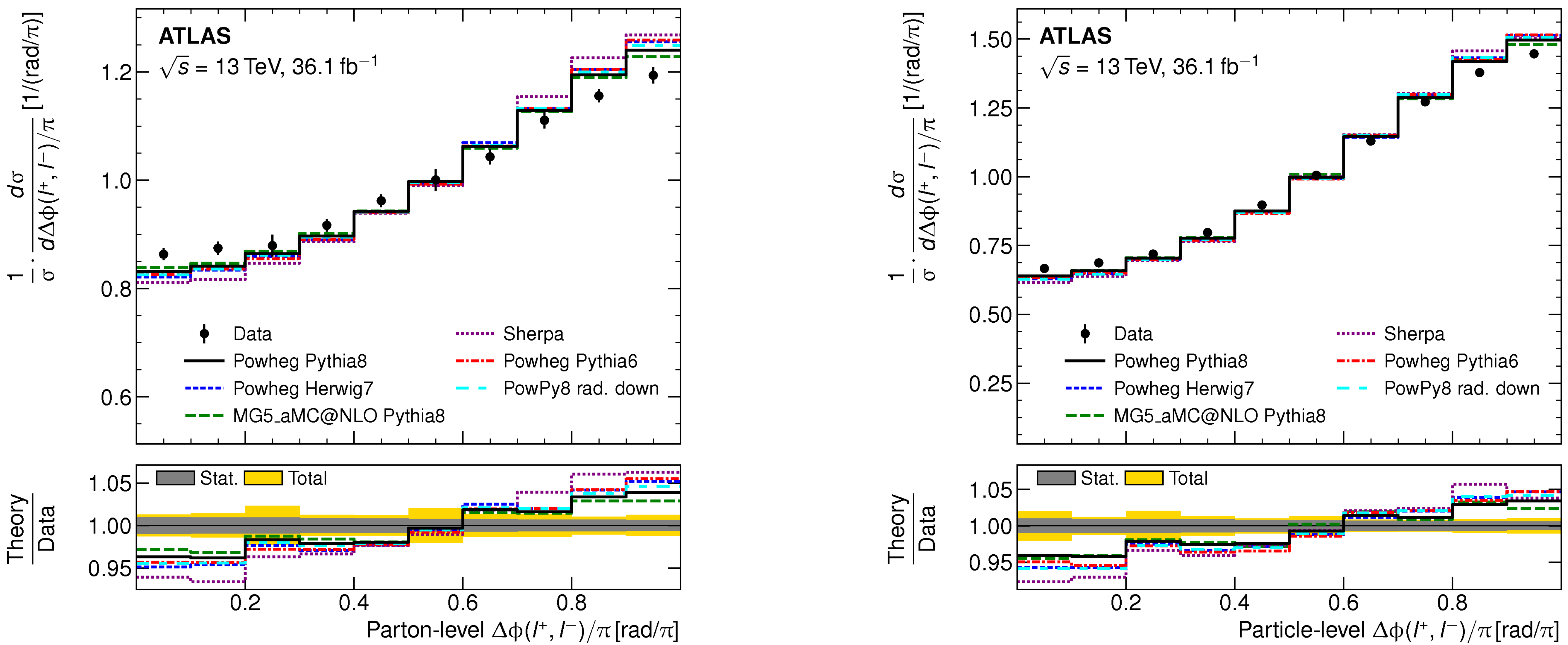
Spin correlation: dilepton (eμ)

arXiv:1903.07570 (submitted to EPJC)

- **Top decays before hadronising:** spin information transferred to decay products (lepton most sensitive).
- Sensitivity to BSM mediators and most 6D EFT operators.
- **Previous results:** slightly stronger spin correlation than SM, but within experimental uncertainties.
- ✓ *Run 2 = more data and improved MC generators!*

Differential in Δη, Δφ; doubly in M(tt̄).

Δφ: tops produced *preferentially back-to-back* → relative enhancement at low Δφ due to spin corr.
~3σ discrepancy at parton-level, also in fiducial volume (lower extrapolation)

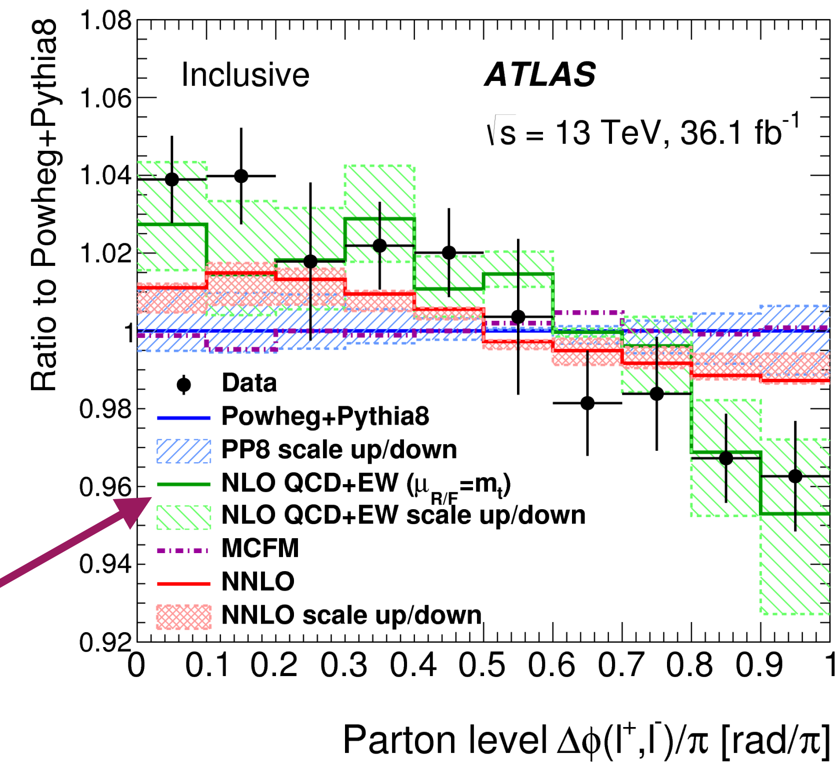


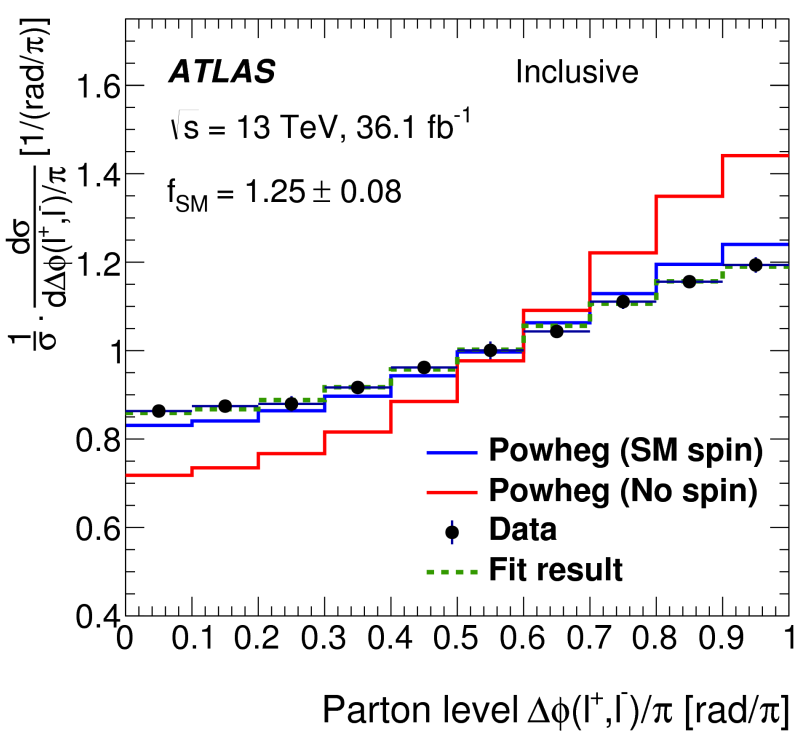
Region	f_{SM} ± (stat.,syst.,theory)	Significance (excl. theory uncertainties)
Inclusive	$1.249 \pm 0.024 \pm 0.061 \pm 0.040$	3.2 (3.8)
$m_{t\bar{t}} < 450$ GeV	$1.12 \pm 0.04 ^{+0.12}_{-0.13} \pm 0.02$	0.86 (0.87)
$450 \leq m_{t\bar{t}} < 550$ GeV	$1.18 \pm 0.08 ^{+0.13}_{-0.14} \pm 0.08$	1.0 (1.1)
$550 \leq m_{t\bar{t}} < 800$ GeV	$1.65 \pm 0.19 ^{+0.31}_{-0.41} \pm 0.22$	1.3 (1.4)
$m_{t\bar{t}} \geq 800$ GeV	$2.2 \pm 0.9 ^{+2.5}_{-1.7} \pm 0.7$	0.58 (0.61)

arXiv:1903.07570 (submitted to EPJC)
CMS PAS TOP-18-006

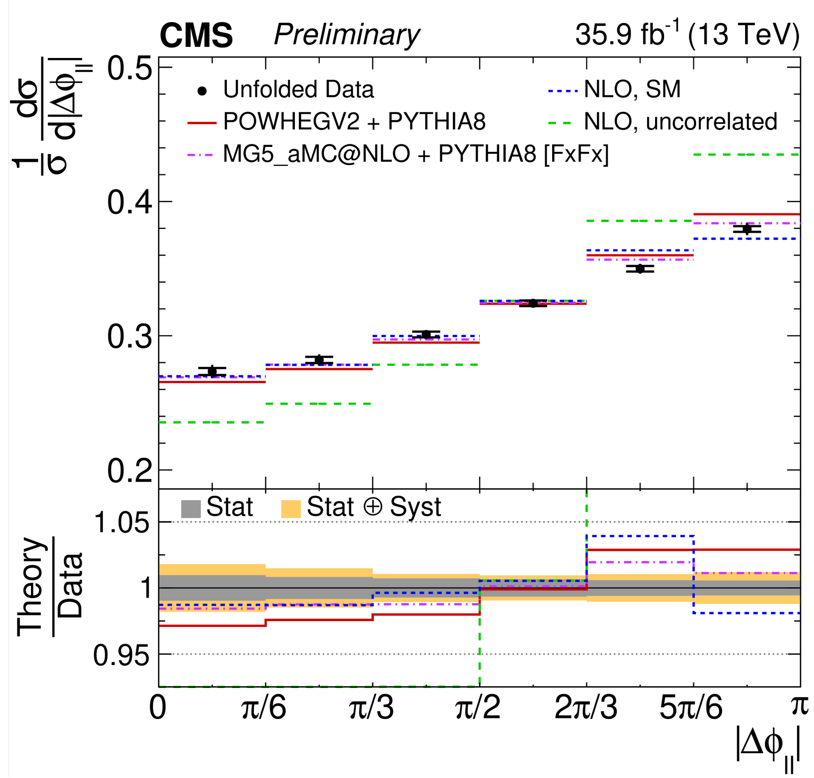
Larger uncertainties in M($t\bar{t}$) bins due to $t\bar{t}$ reco.
Dominant syst: generator radiation and scale, theory uncert. on fit templates.

Alternative template: fixed $\mu_R=\mu_F=m_t$, expansion at NLO in QCD+EW → $f_{SM}=1.03 \pm 0.13$ (significant scale uncert.!)



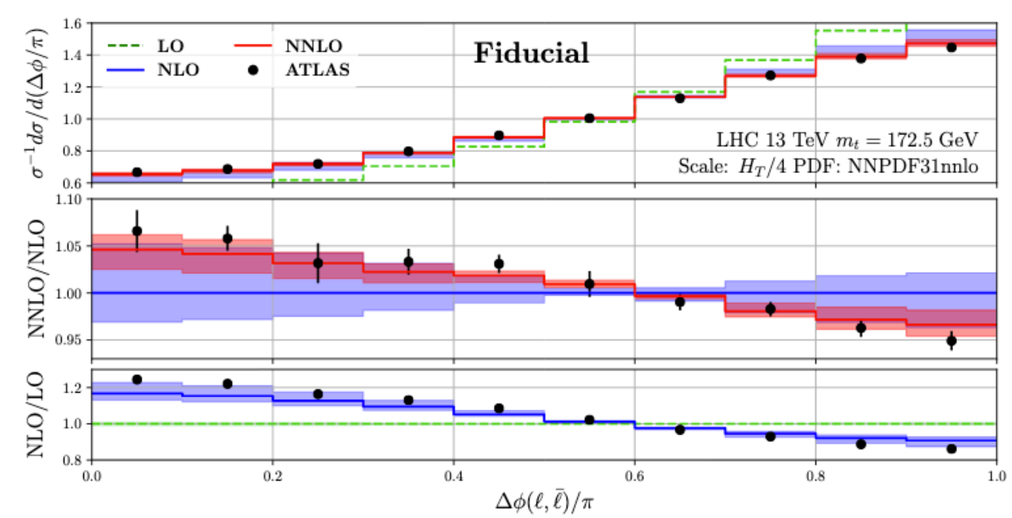


$f_{SM}=1.25 \pm 0.06$



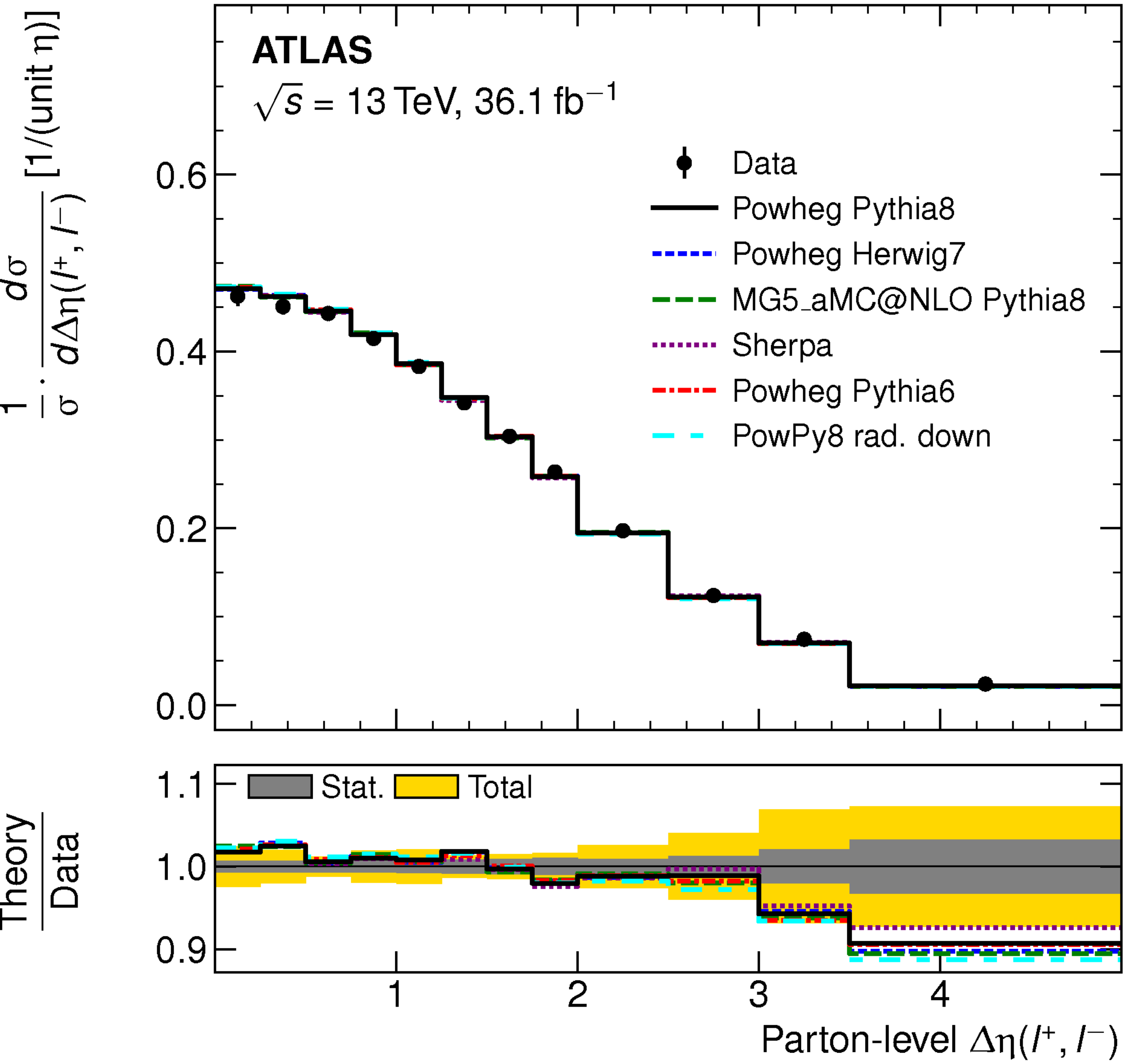
Recent work (Behrig et. al) suggests NNLO corrections are important:

arXiv:1901.05407

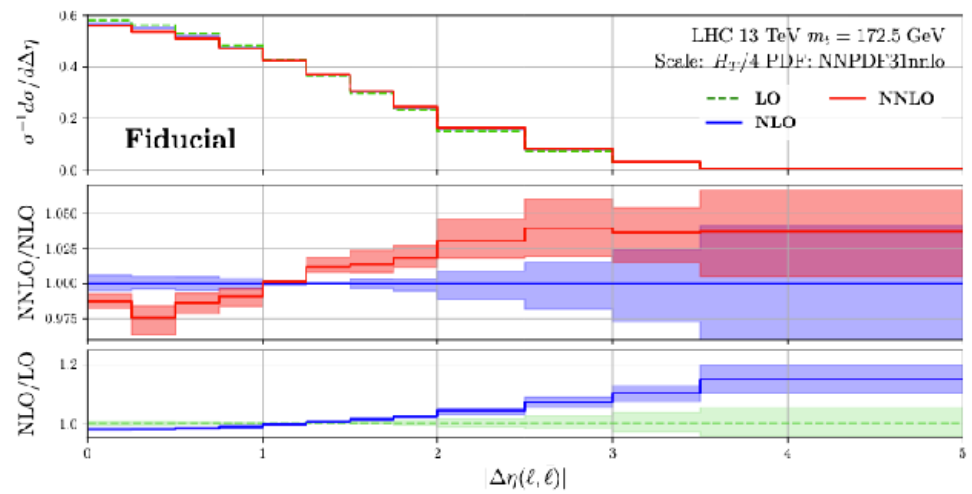


Spin correlation: results in $\Delta\eta$

arXiv:1903.07570 (submitted to EPJC)



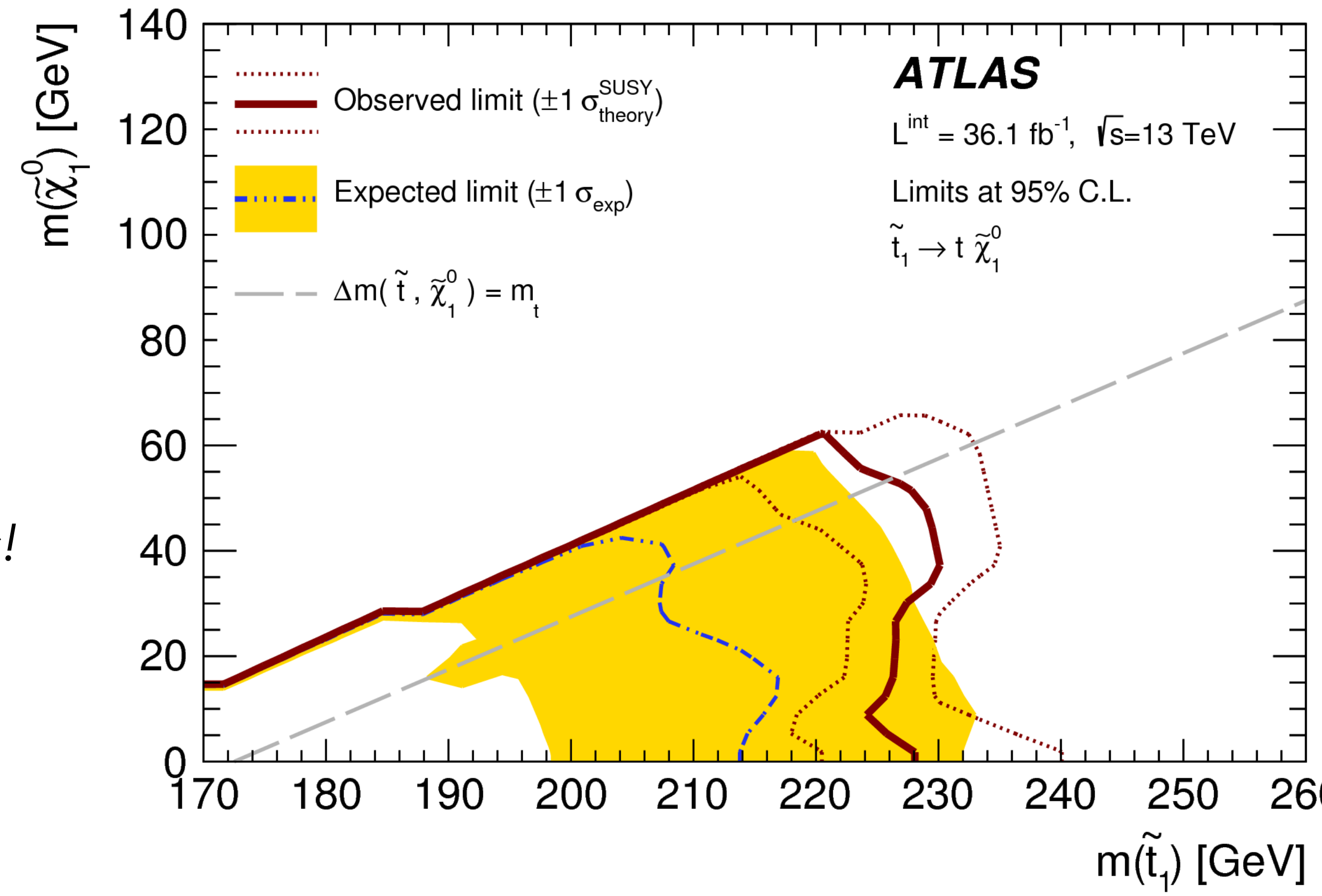
$\Delta\eta$: consistent within uncertainties, but *hint of deviation in the tail* (could be partly explained by NNLO corrections).



arXiv:1901.05407

Stop quark pair production look similar to uncorrelated $t\bar{t}$, and scalar production is typically more central: *use results in $\Delta\eta$ and $\Delta\varphi$ to set limits!*

Exclusion beyond direct search for $\Delta m = m_t$.



Spin correlation: full spin density matrix

[CMS PAS TOP-18-006](#)

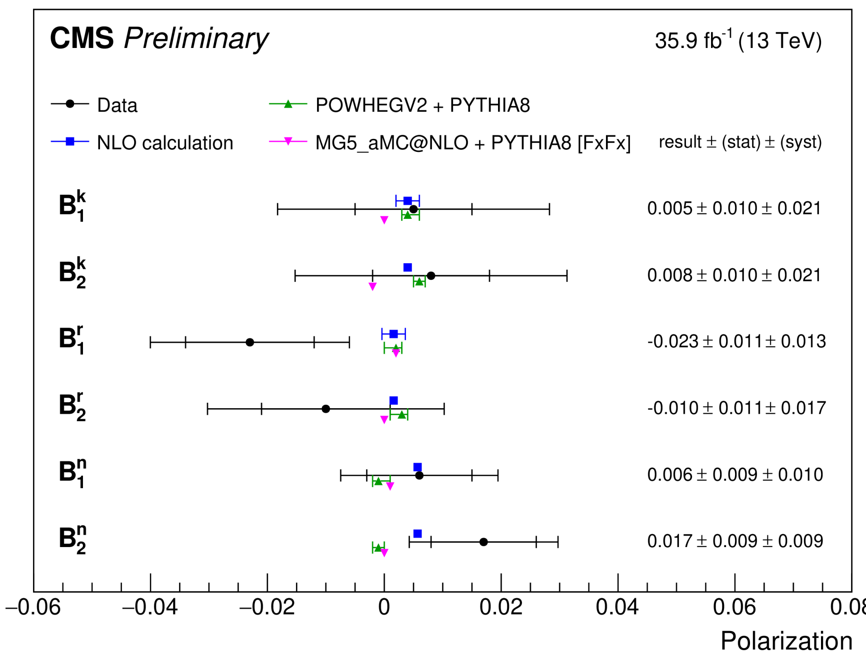
See [Brieuc's talk](#) for the EFT measurement!

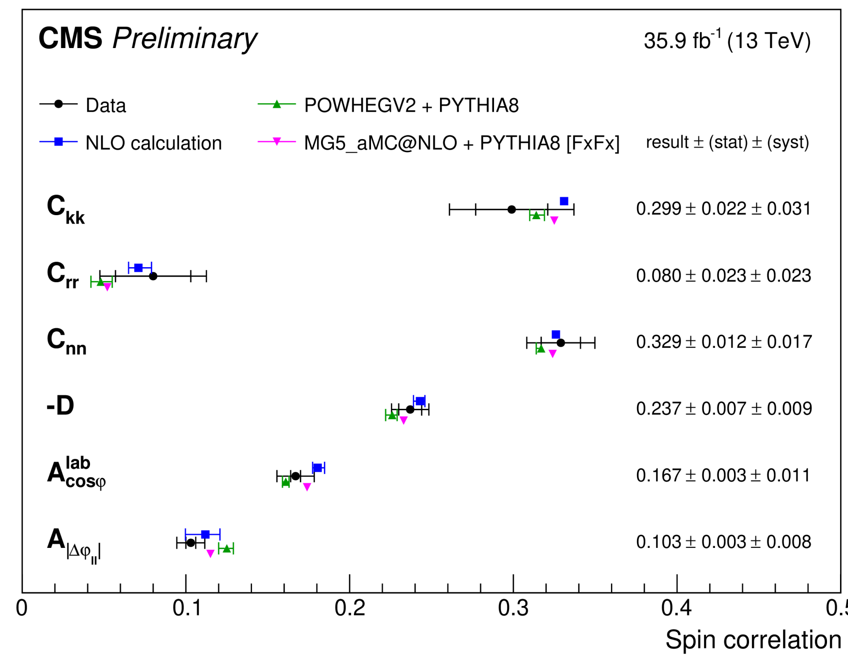
First time done @13 TeV! Measure all 15 coefficients:

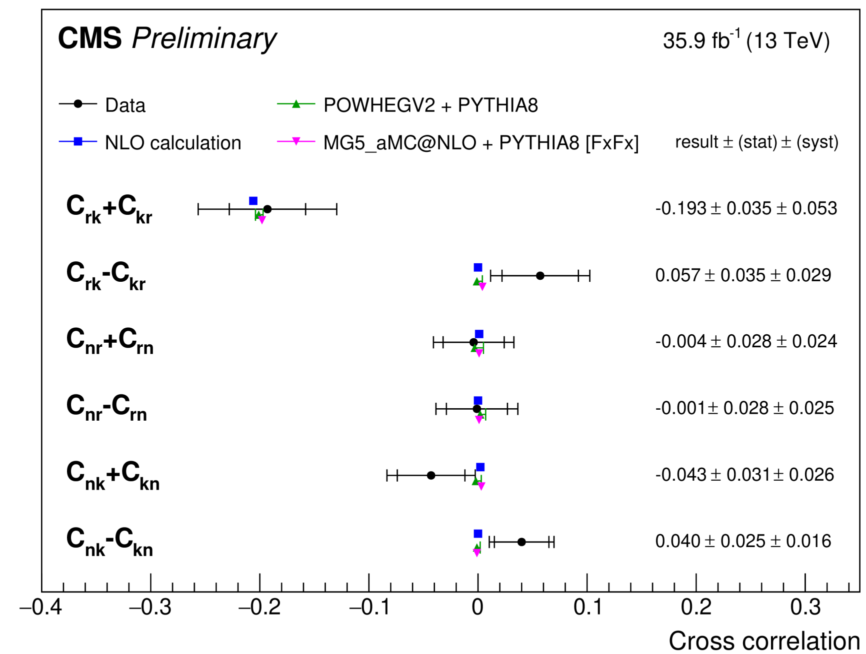
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_1^i d\cos\theta_2^j} = \frac{1}{4}\left(1 + B_1^i\cos\theta_1^i + B_2^j\cos\theta_2^j - C_{ij}\cos\theta_1^i\cos\theta_2^j\right)$$

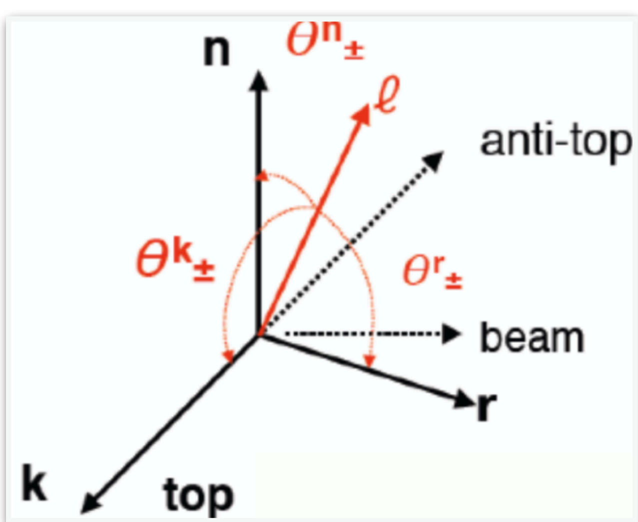
Can be reduced to individual 1D distributions of the form:

$$\frac{1}{\sigma}\frac{d\sigma}{dx} = \frac{1}{2}\left(1 + [\mathbf{Coef.}]\, x\right) f(x)$$









All agree with SM within uncertainties!

- *Top polarisation (B) consistent with 0* for each axis, but not yet sensitive enough.
- D (linear combination of spin correlations) **most sensitive ~5%**
- only 2 off-diagonal elements of C are not small in the SM: *first 3σ evidence of spin correlation between r and k axes*

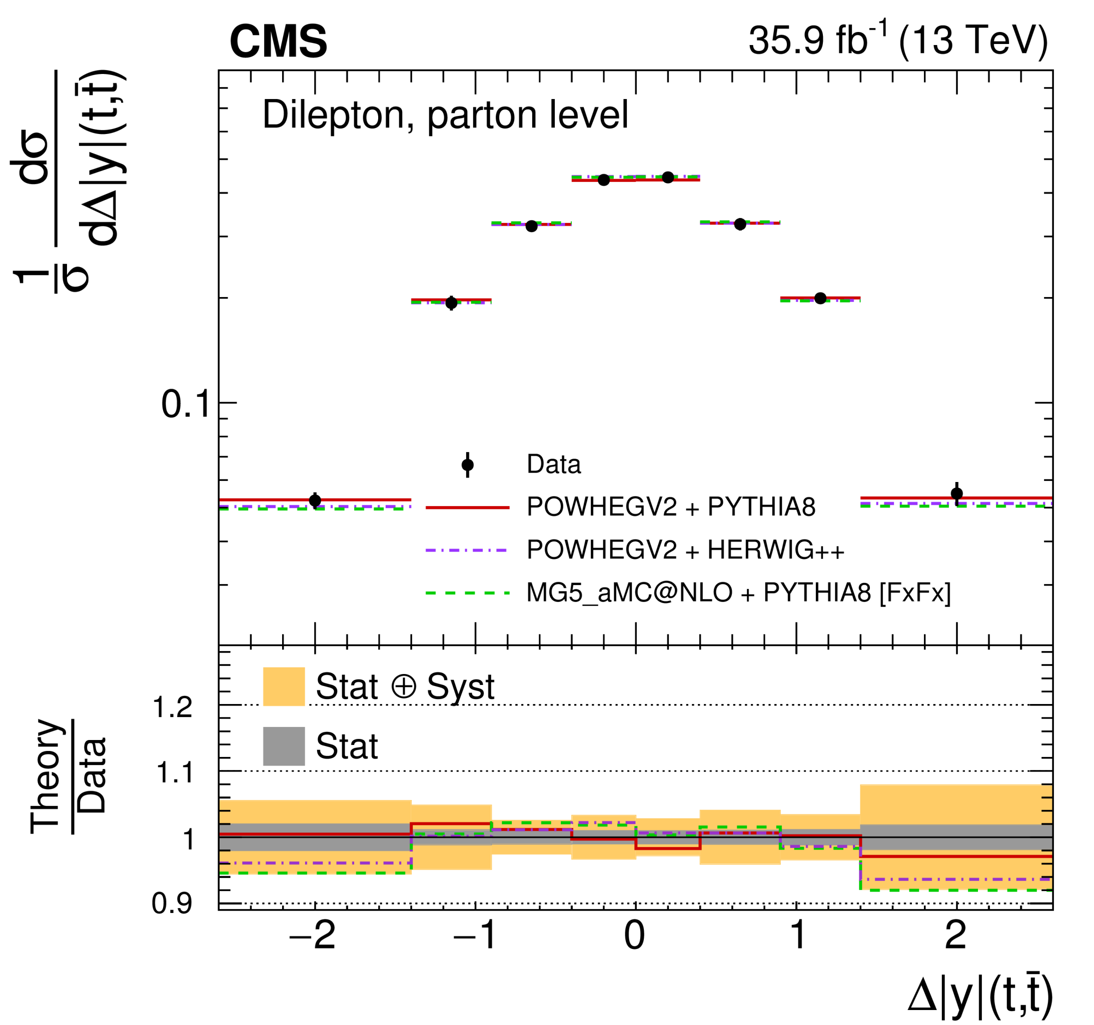
JHEP 02 (2019) 149

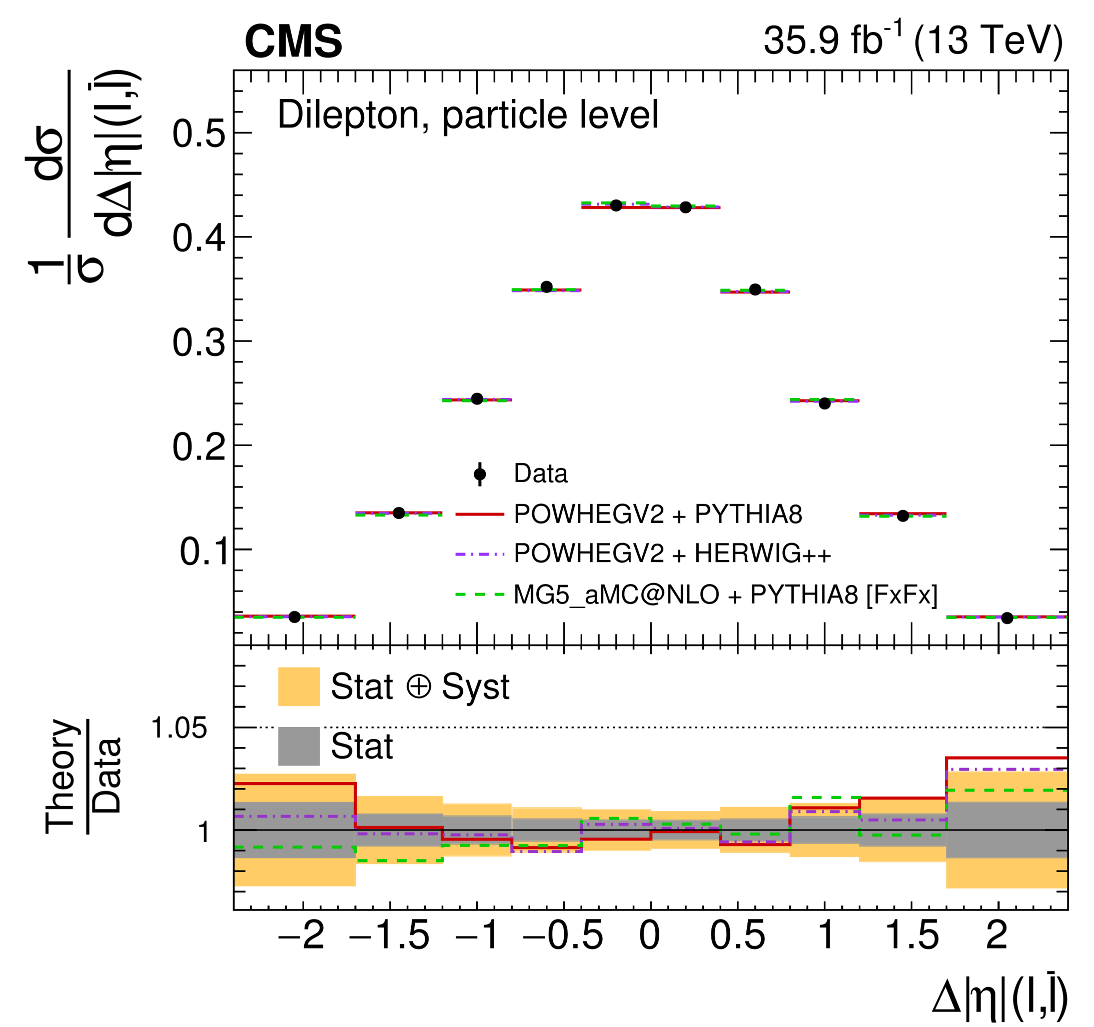
First time done @13 TeV! Extracted from differential distributions:

See Sergio G.'s talk for the cross-section measurement!

$$A_c^{t\bar{t}} = \frac{\sigma_{t\bar{t}}\left(\Delta|y|(t,\bar{t}) > 0\right) - \sigma_{t\bar{t}}\left(\Delta|y|(t,\bar{t}) < 0\right)}{\sigma_{t\bar{t}}\left(\Delta|y|(t,\bar{t}) > 0\right) + \sigma_{t\bar{t}}\left(\Delta|y|(t,\bar{t}) < 0\right)}$$

$$A_c^{\ell\bar{\ell}} = \frac{\sigma_{\ell\bar{\ell}}\left(\Delta|\eta|(\ell,\bar{\ell}) > 0\right) - \sigma_{\ell\bar{\ell}}\left(\Delta|\eta|(\ell,\bar{\ell}) < 0\right)}{\sigma_{\ell\bar{\ell}}\left(\Delta|\eta|(\ell,\bar{\ell}) > 0\right) + \sigma_{\ell\bar{\ell}}\left(\Delta|\eta|(\ell,\bar{\ell}) < 0\right)}$$





Good agreement with the SM!

A_c($t\bar{t}$, parton) = 0.01 ± 0.009

A_c($t\bar{t}$, particle) = 0.008 ± 0.009

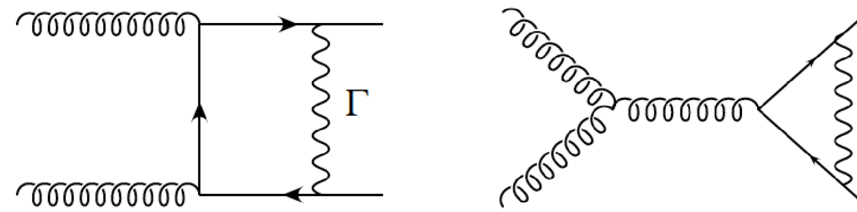
A_c(ll, particle) = -0.005 ± 0.004

Top Yukawa from l+jets $t\bar{t}$ cross-section

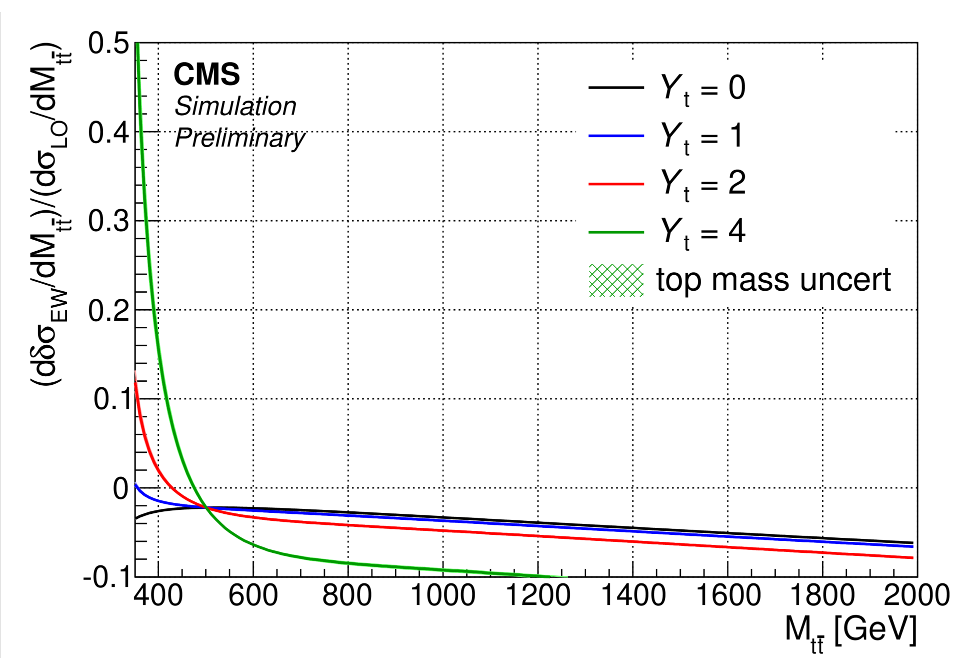
NEW

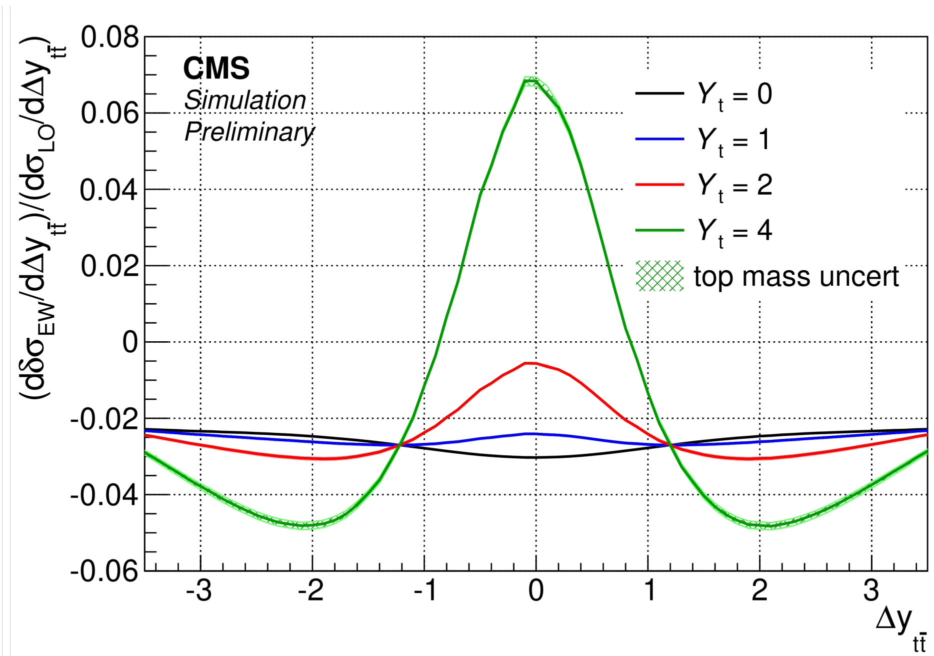
CMS-PAS-TOP-17-004

Idea: EWK corrections larger near $t\bar{t}$ production threshold, enhanced sensitivity to top Yukawa

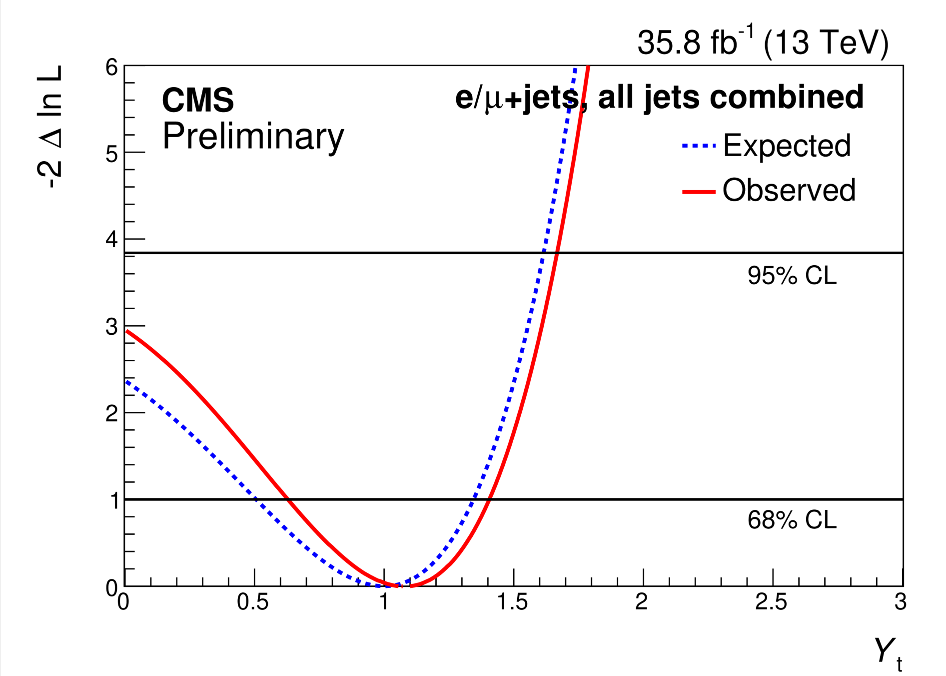


See Sergio G.'s talk for the cross-section measurement!





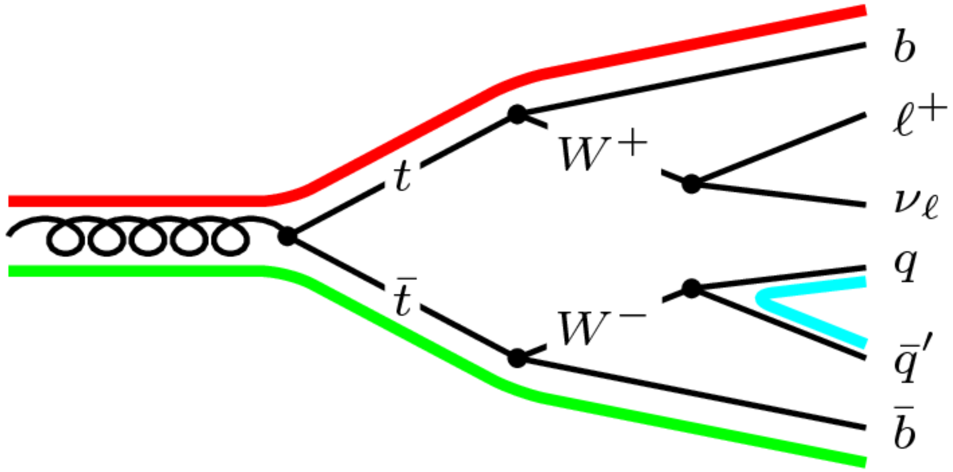
Strategy: reweight generator distributions of $M(t\bar{t})$ and $\Delta|y|(t\bar{t})$ for various value of Y_t



Results: 57-bin profile likelihood scan yields $Y_t<1.67$

Channel	Expected 95% CL	Observed 95% CL
3 jets	$Y_t < 2.17$	$Y_t < 2.59$
4 jets	$Y_t < 1.88$	$Y_t < 1.77$
5 jets	$Y_t < 2.03$	$Y_t < 2.23$
Combined	$Y_t < 1.62$	$Y_t < 1.67$

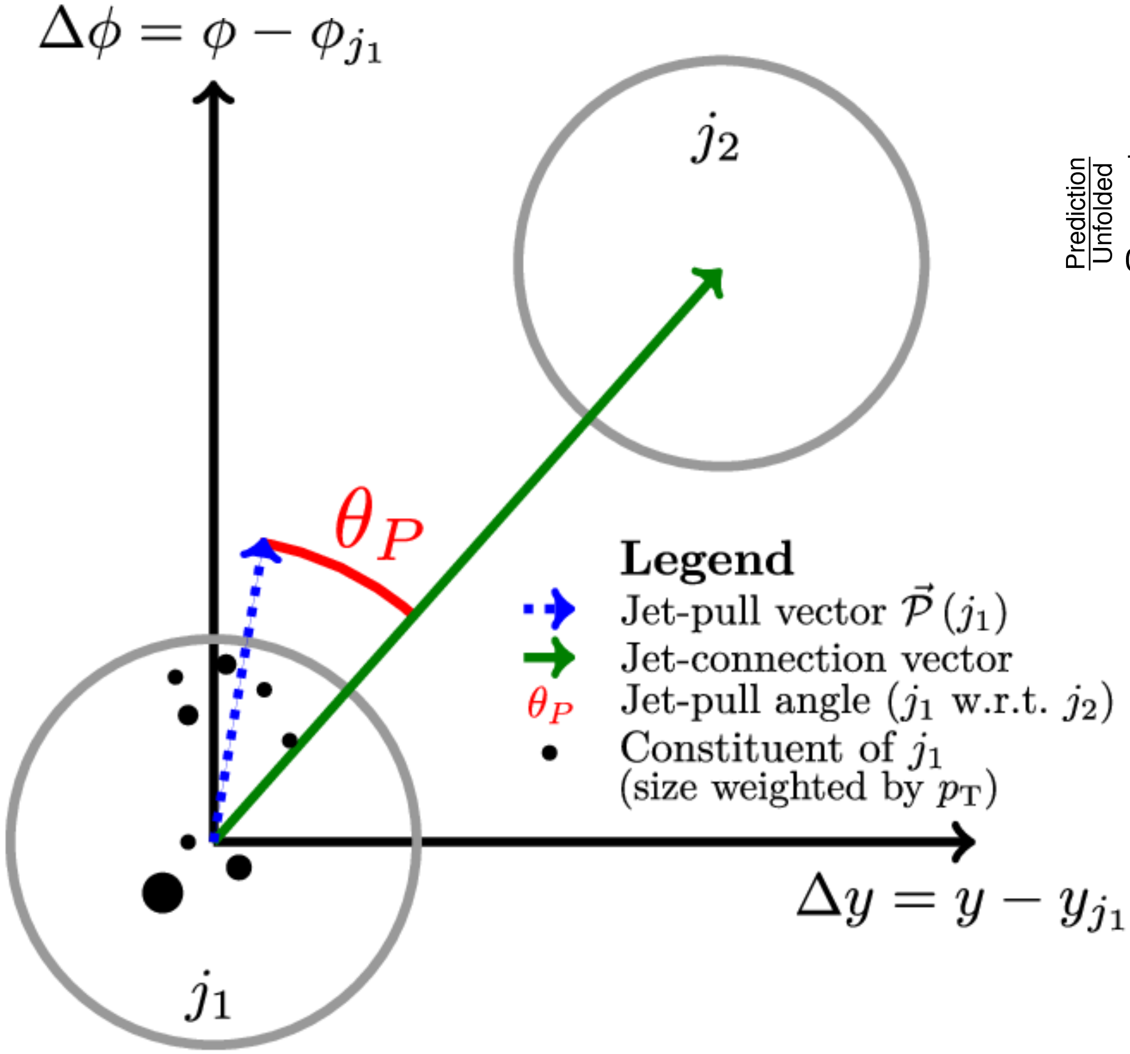
[Eur. Phys. J. C 78 (2018) 847]

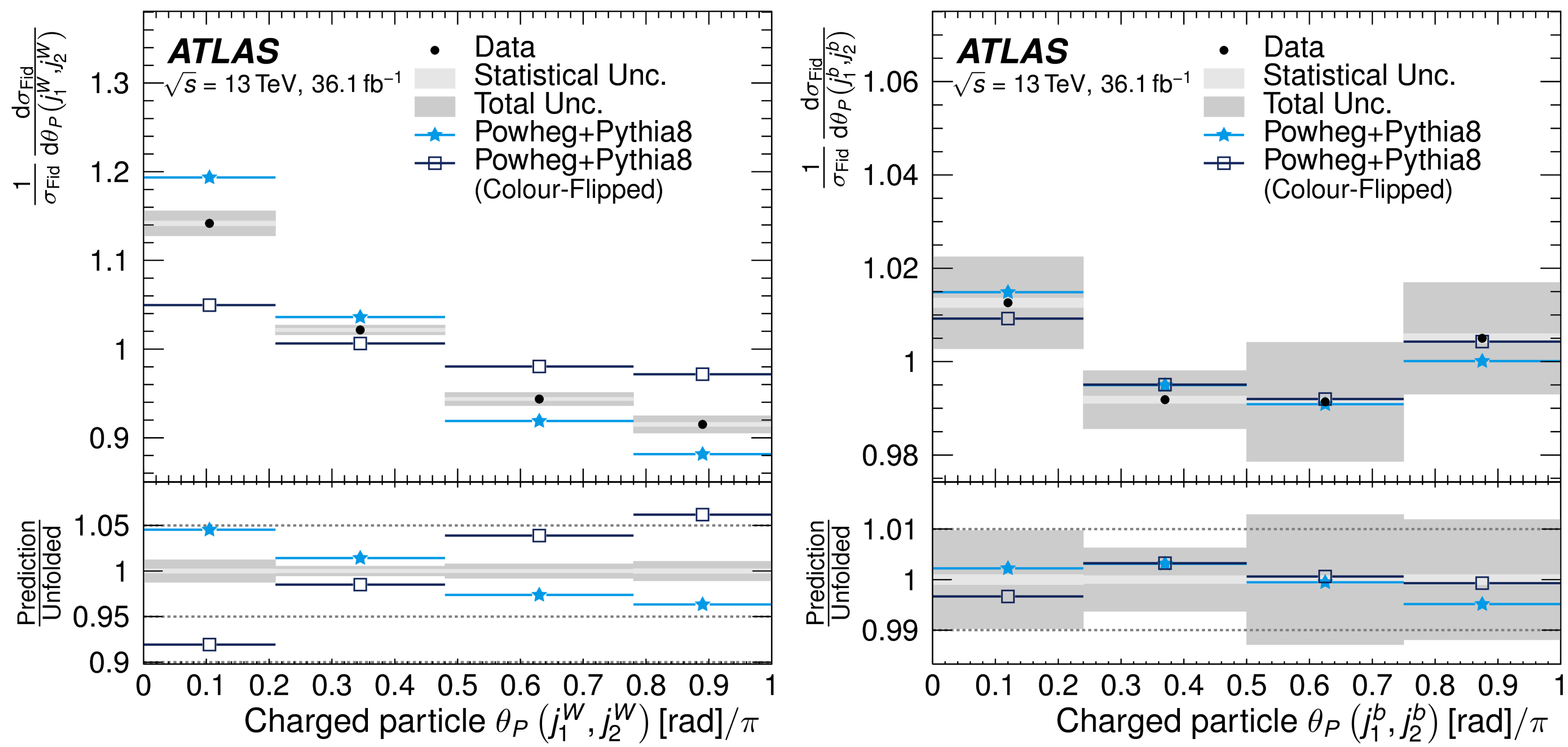


Direct applications, e.g. $t\bar{t}H(b\bar{b})$!

Selection: =1 lepton, ≥4 jets, ≥2 b-tags

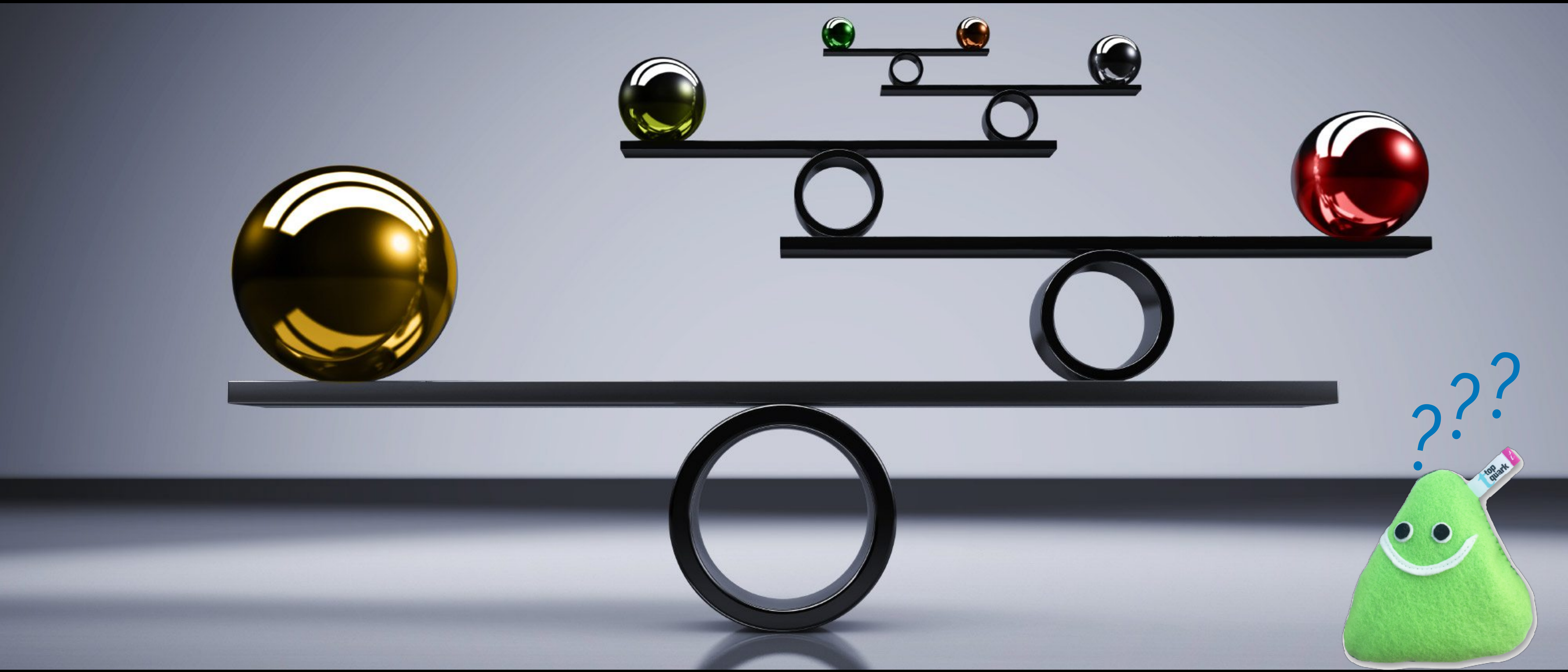
$$\vec{\mathcal{P}}(j) = \sum_{i \in j} \frac{\left|\vec{\Delta r}_i\right| \cdot p_T^i}{p_T^j} \vec{\Delta r}_i$$





No single MC model to describe all distributions: e.g. Powheg+Herwig7 *best* for W pull-angle, *worst* for b-jets…

Test **"colour-flipped" model** (W as colour-octet): *data prefers the SM!*



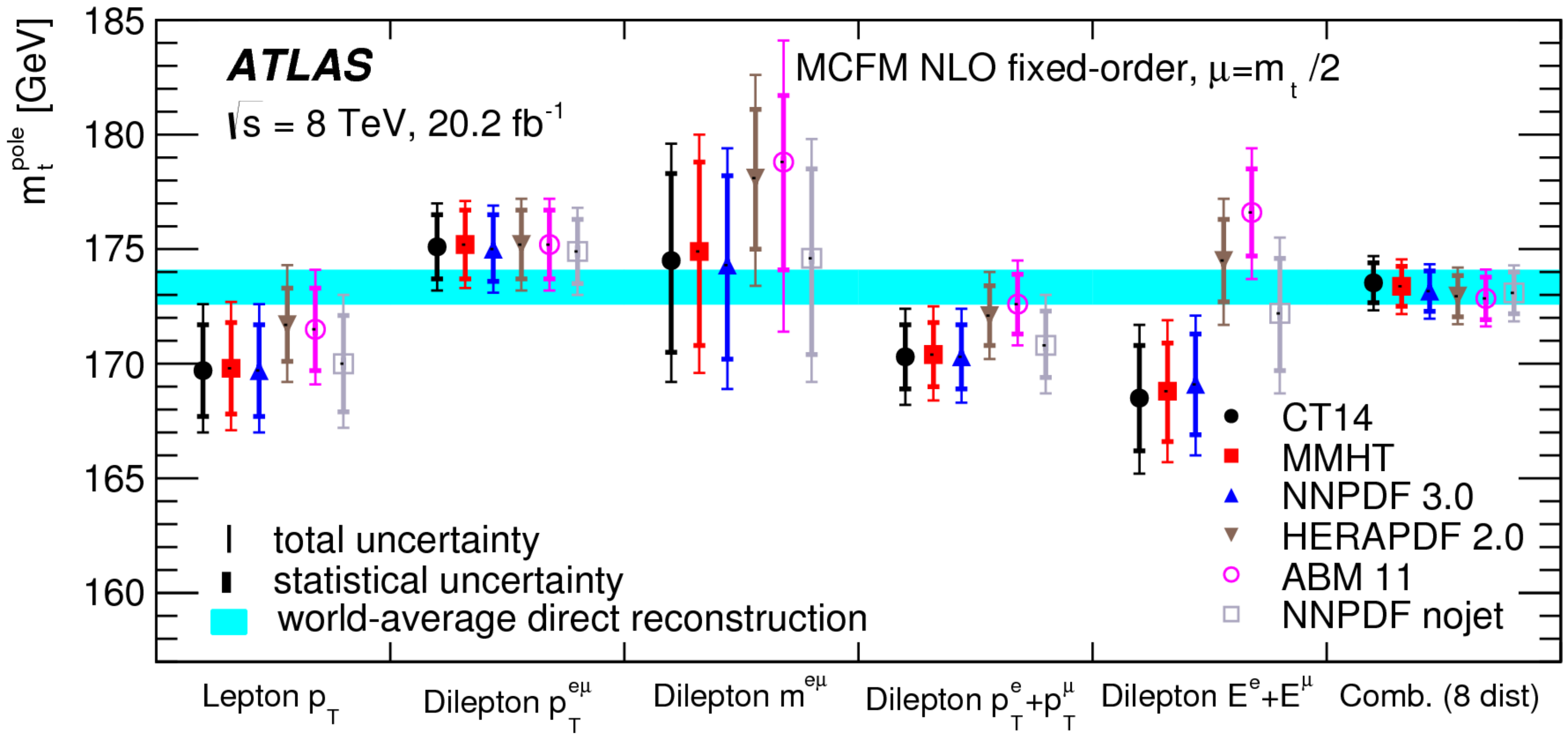
Top quark mass

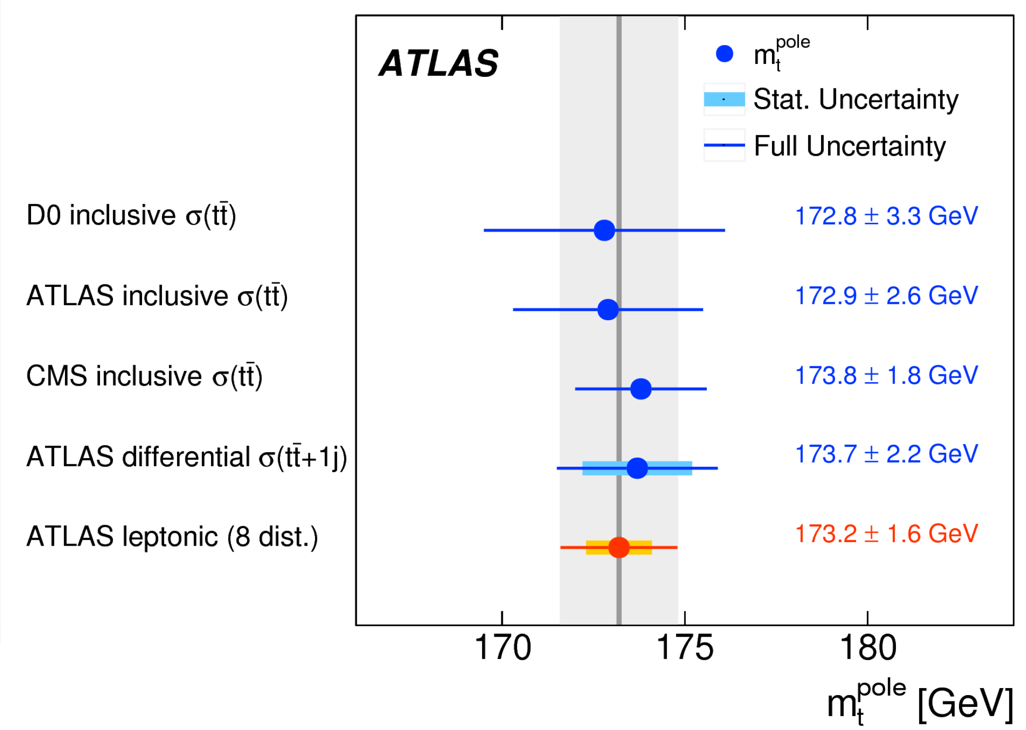
Indirect: dilepton (eμ) @8 TeV

Eur. Phys. J. C 77 (2017) 804

Selection: OS eμ, =1 or 2 b-tags

Leptonic observables → correct to particle-level (fiducial) → absolute+normalised cross-section = **comparison to fixed-order NLO QCD calculation** to explore sensitivity to gluon PDF (not covered here) and **top quark pole mass**

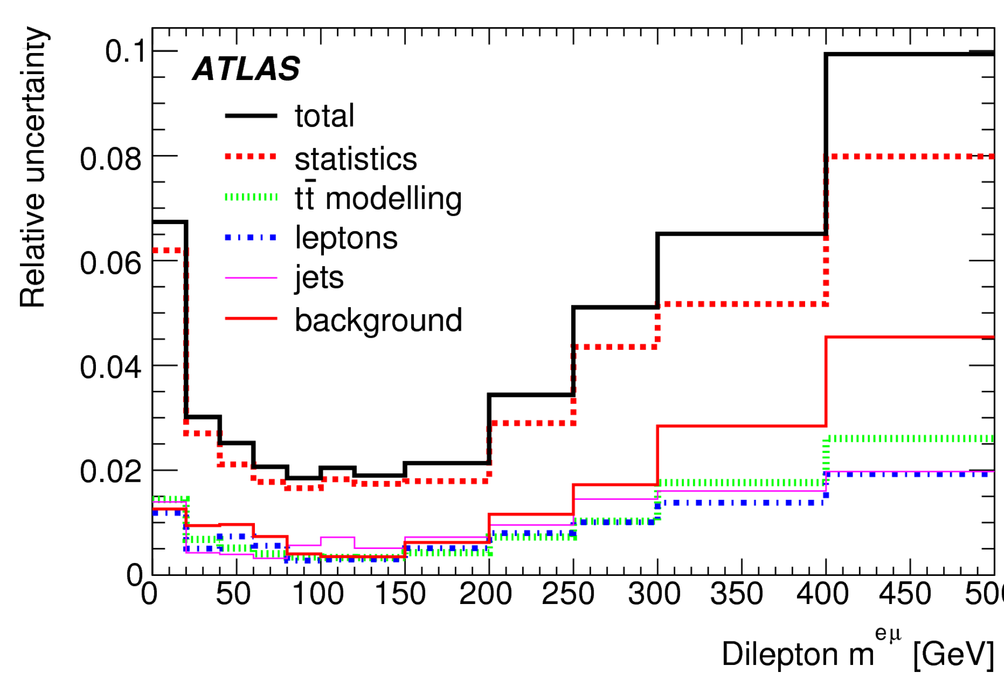




m_t=173.2 ± 0.9 (stat.) ± 0.8 (syst.) ± 1.2 (theo.) GeV, Δ=0.98%

Dominated by QCD scale choice!

Systematic uncertainties in normalised measurement **usually ~% level**, except in some bins



Top quark pole mass dependence of the $t\bar{t}$+1jet cross-section ***enhanced*** wrt. $t\bar{t}$ (but ~25% cross-section).

ATL-COM-PHYS-2018-1242

$$\frac{\Delta\sigma_{t\bar{t}+1\text{-jet}}}{\sigma_{t\bar{t}+1\text{-jet}}} \approx -5\,\frac{\Delta m_t^{\text{pole}}}{m_t^{\text{pole}}}$$

Extracted from normalised differential distribution:

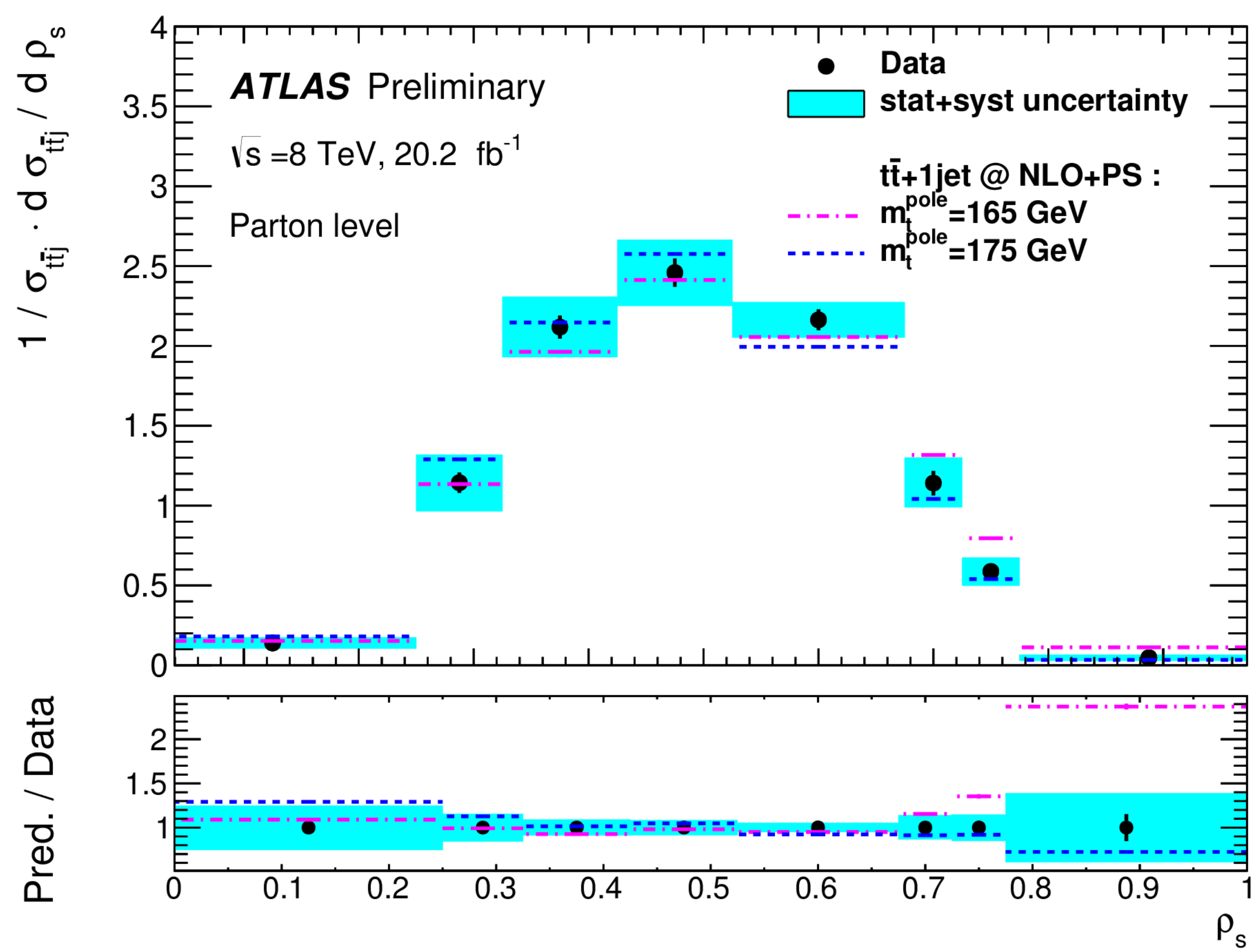
$$\mathcal{R}(\rho_s, m_t) = \frac{1}{\sigma_{t\bar{t}+1\text{-jet}}} \times \frac{d\sigma_{t\bar{t}+1\text{-jet}}}{d\rho_s}\,, \text{ with } \rho_s = \frac{340\text{ GeV}}{\sqrt{s_{t\bar{t}+1\text{-jet}}}}$$

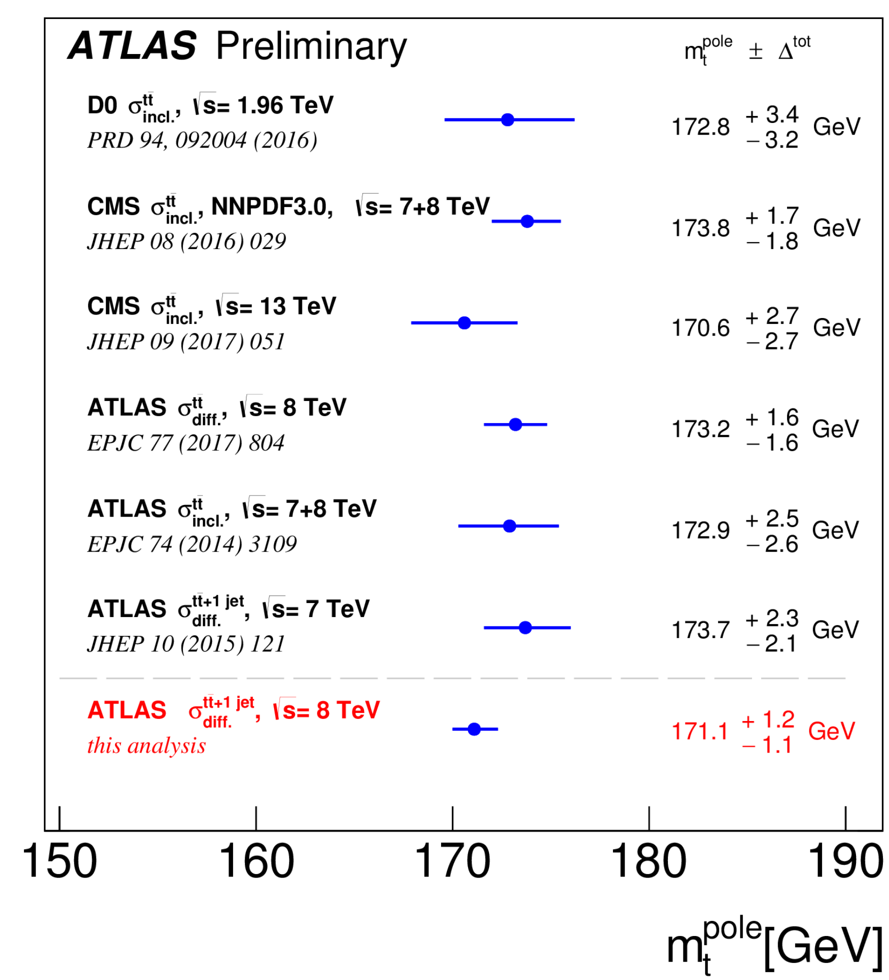
Leading p_T jet not used in $t\bar{t}$ reconstruction = "associated hard jet".
Unfolded to parton-level and **compared to fixed-order calculation** (χ^2).

m_t=171.1 ± 0.4 (stat.) ± 0.9 (syst.) +0.7/-0.3 (theo.) GeV, Δ=0.7%

Factor 2 improvement wrt. previous measurement @7 TeV!

Leading uncertainties: $t\bar{t}$ modelling (scale variations)





Direct: l+jets @8 TeV

arXiv:1810.01772 (accepted in EPJC)

Selection: =1 lepton, ≥4 jets, =2 b-tags

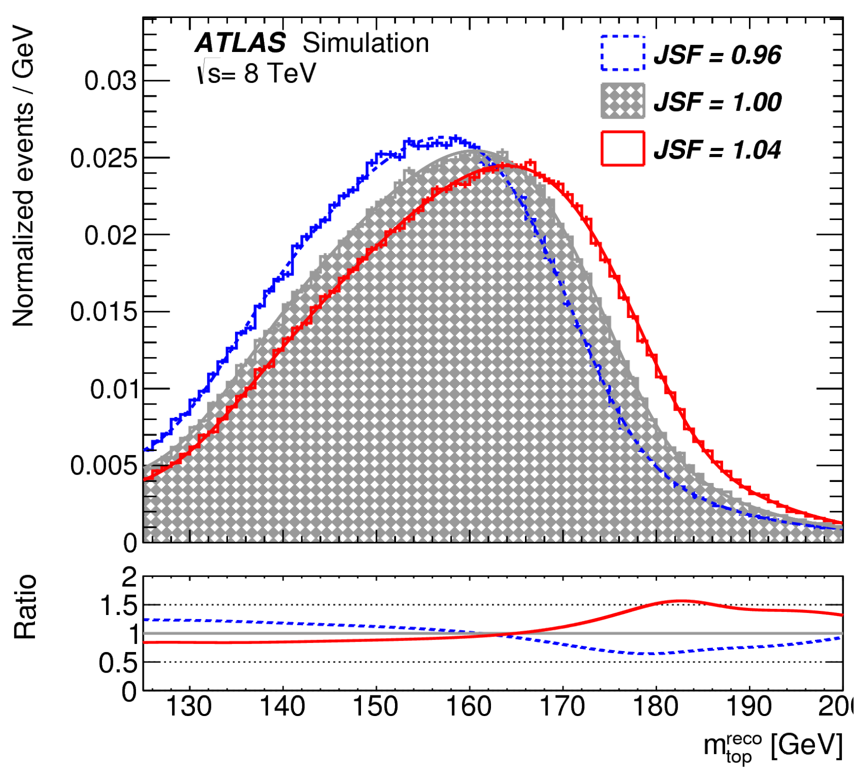
- **e-channel:** $\not{E}_T$>30 GeV, $m_T(W)$>30 GeV (reduce fake bkg.)
- **μ-channel:** $\not{E}_T$>20 GeV, $m_T(W)+\not{E}_T$>60 GeV
- **optimisation with BDT (13 variables):** from 4% bkg contamination down to 1%. (Most powerful variable is event log likelihood from KLFitter top reconstruction)

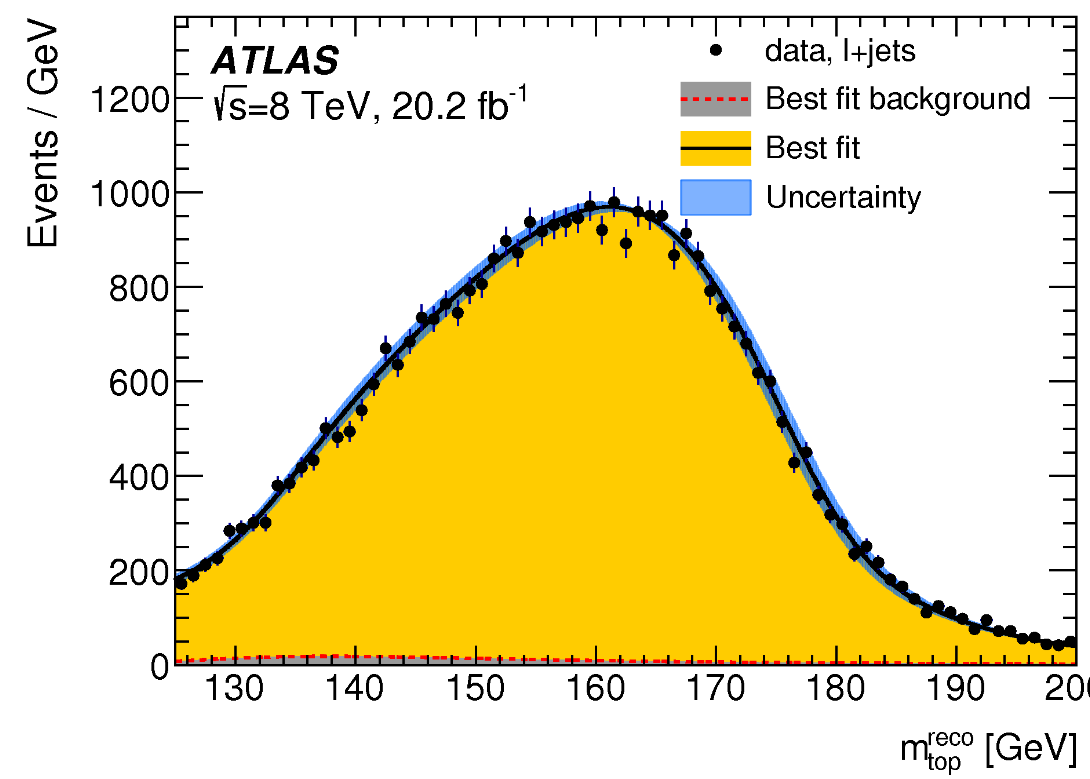
3 observables: m_{reco}(top), m_{reco}(had. W) and R_{reco}(bq) ← sensitive to JES and bJES

$$R_{bq}^{\text{reco}} = \frac{p_T^{b_{\text{had}}} + p_T^{b_{\text{lep}}}}{p_T^{q_1} + p_T^{q_2}}$$

Further selection: 125≤m_{reco}(top)≤200 GeV, 55≤m_{reco}(had. W)≤110 GeV, 0.3≤ R_{reco}(bq)≤3.

3D template fit: extract m_t, JSF and bJSF (these transform partially the b/JES uncertainties into statistical ones on m_t, which can be reduced with enough data)





m_t=172.08 ± 0.39 (stat.) ± 0.82 (syst.) GeV, Δ=0.53%

29% improvement wrt. previous analysis @7 TeV!

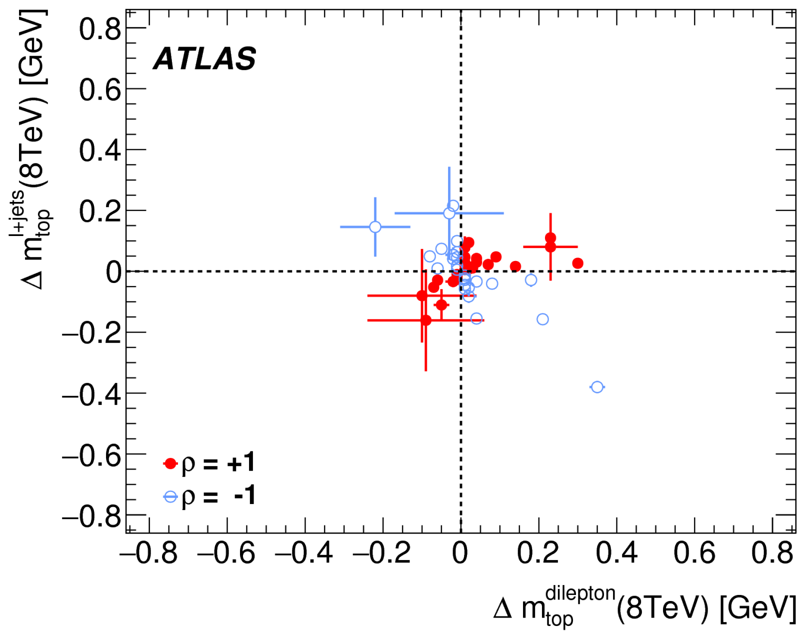
Direct: combination @7-8 TeV

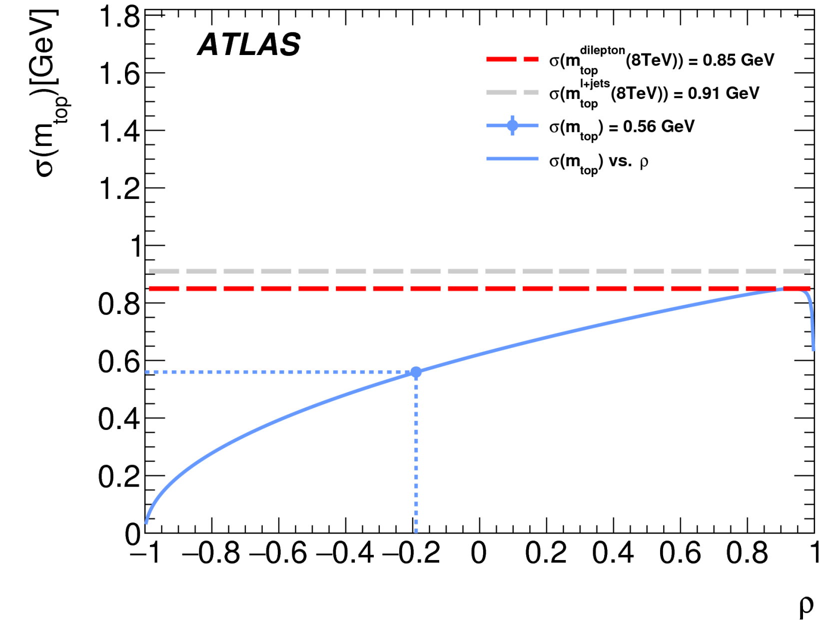
arXiv:1810.01772 (accepted in EPJC)

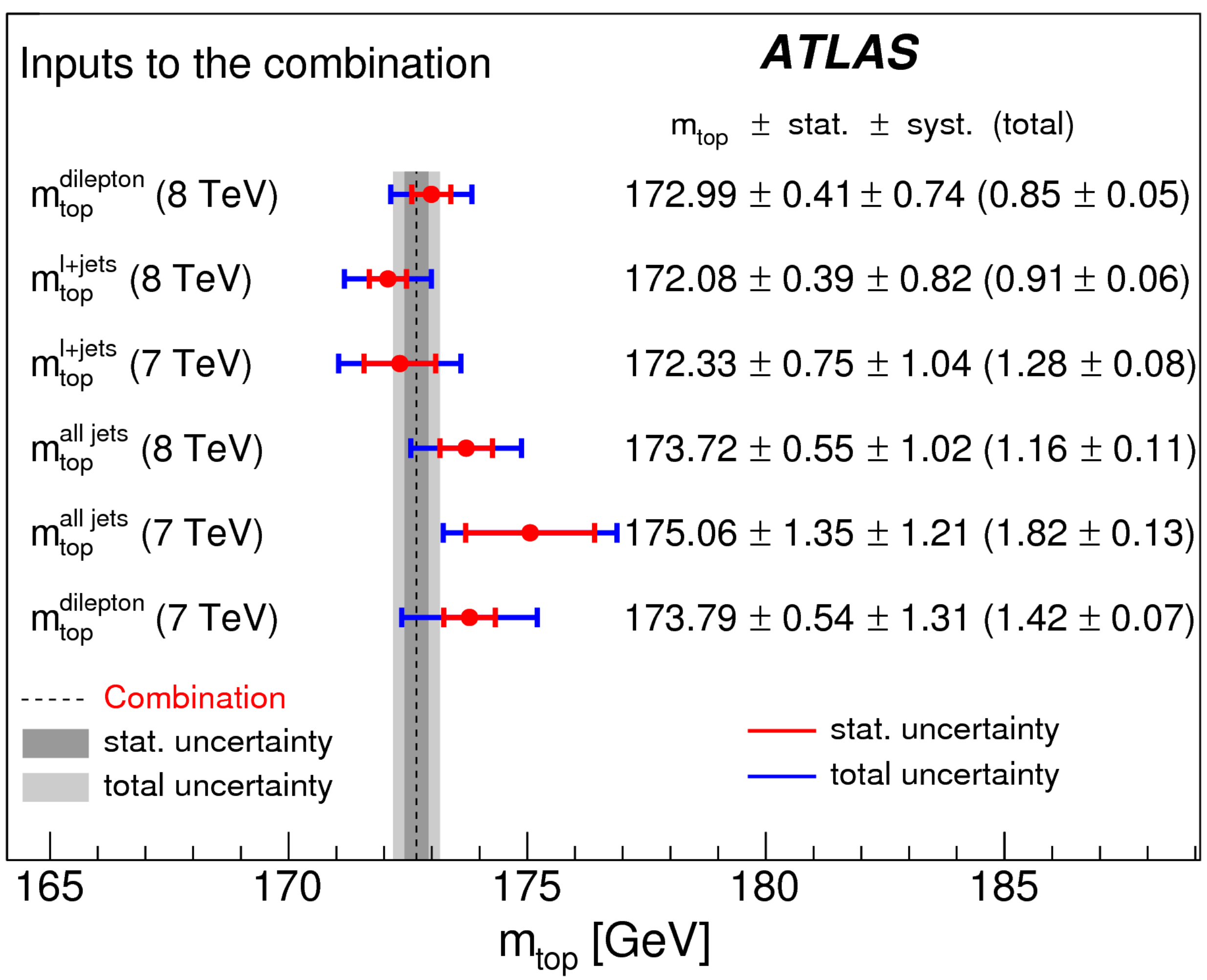
m_t=172.69 ± 0.25 (stat.) ± 0.41 (syst.) GeV, Δ=0.28%

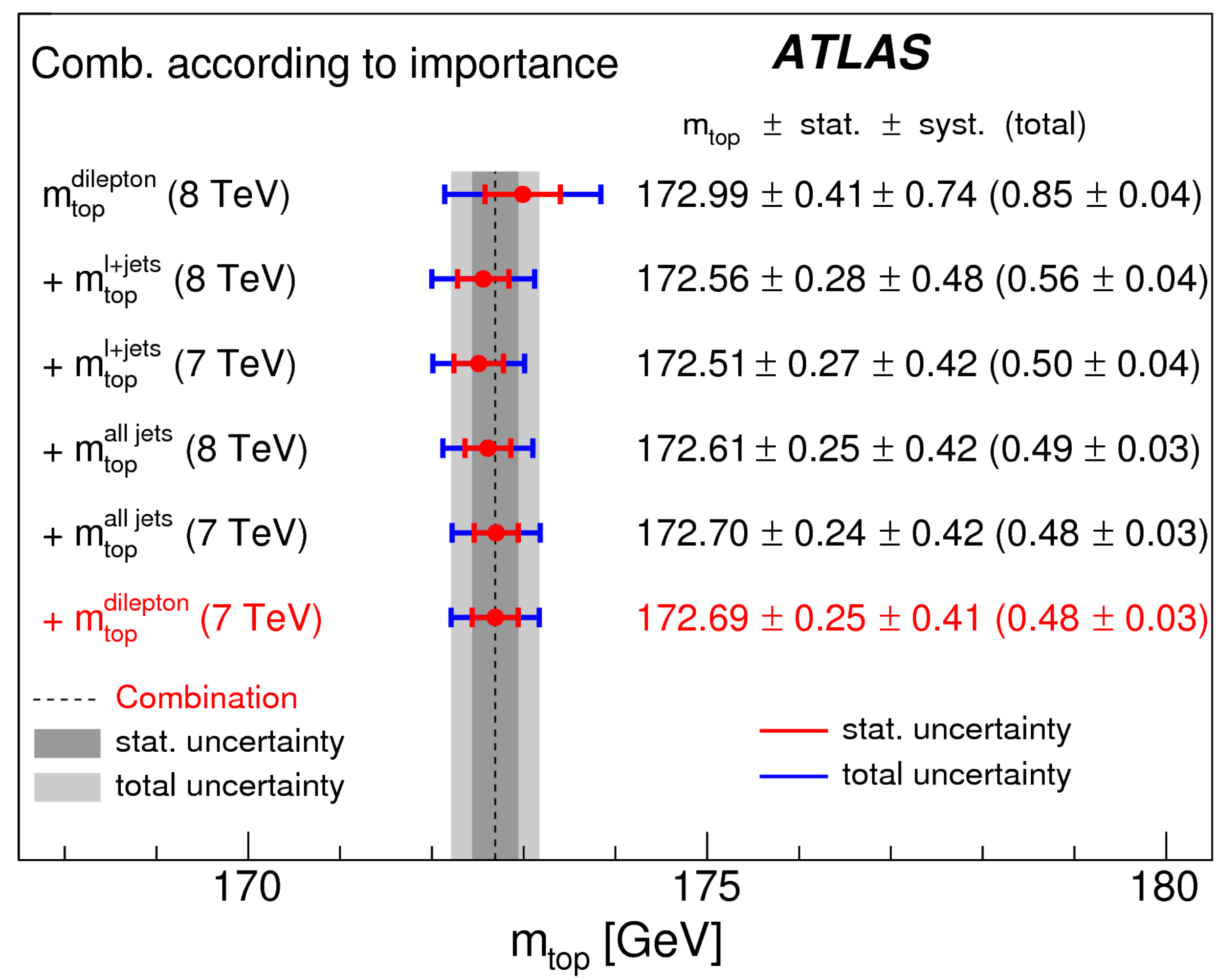
Combine all-hadronic, l+jets, and dileptonic channels at 7 & 8 TeV

- using "best linear unbiased estimate" (BLUE) framework
- all (anti-)correlations of uncertainties properly accounted for





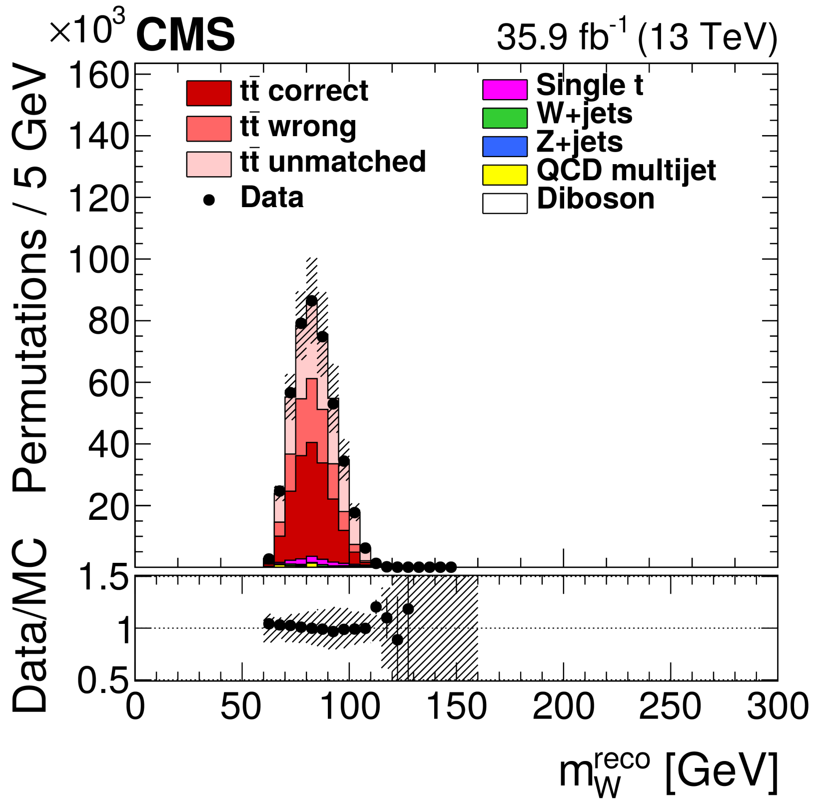


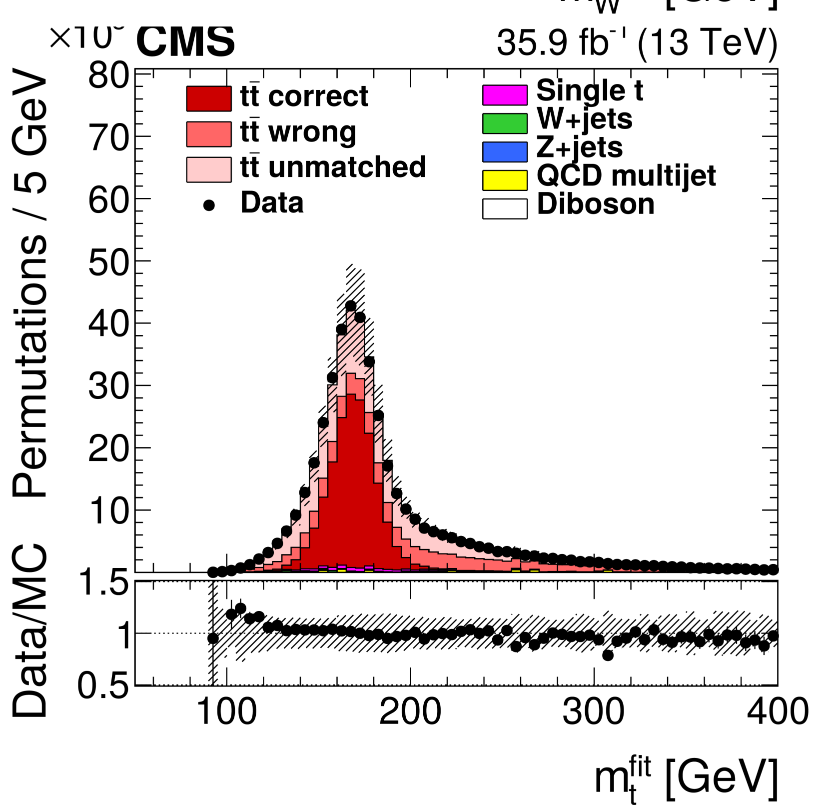


Selection: =1 lepton, ≥4 jets, =2 b-tags

Eur. Phys. J. C 78 (2018) 891

Ideogram method: joint maximum LH fit to determine m_{fit}(top) and JSF after kinematic fit. Additionally use m_{reco}(had. W) to constrain JES.





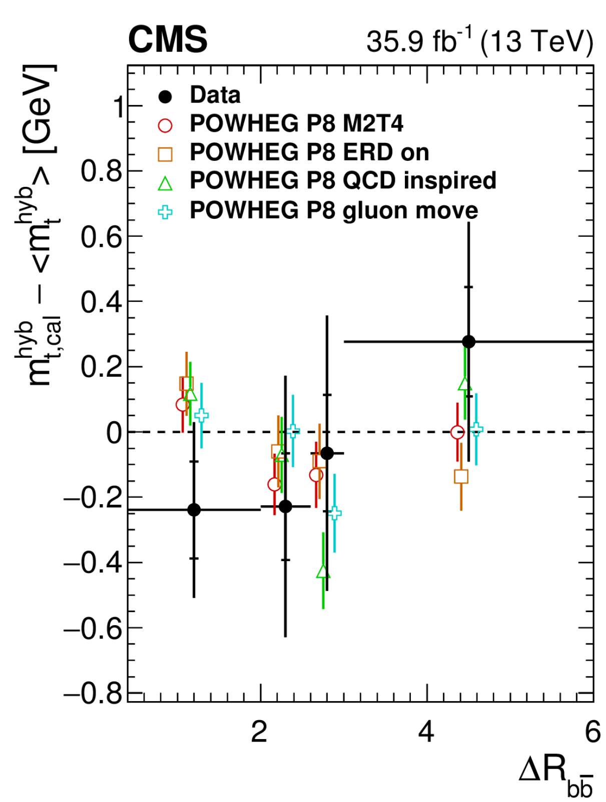
2 fits are performed (1D & 2D in m_t and JSF) + **"hybrid" (1D with prior on JES)**

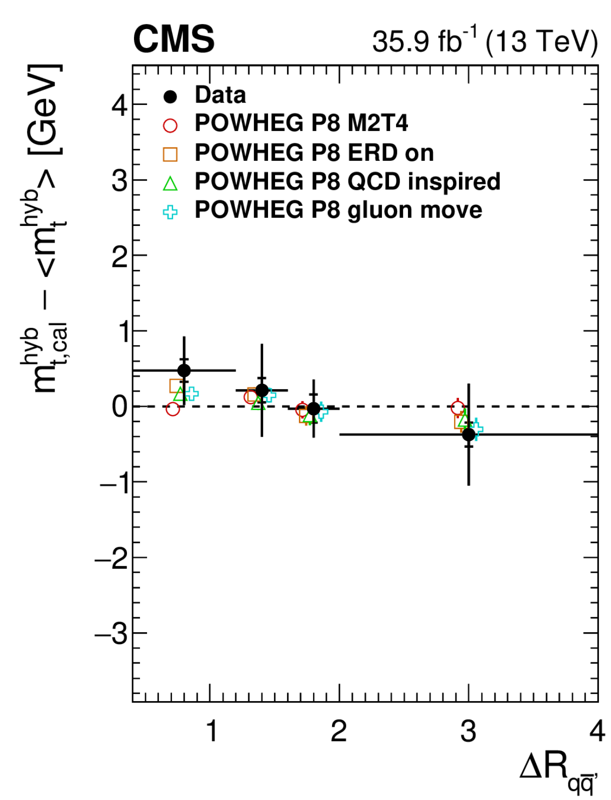
$$m_t^{hyb} = 172.25 \pm 0.08\,(\text{stat+JSF}) \pm 0.62\,(\text{syst})\,\text{GeV},$$
$$\text{JSF}^{hyb} = 0.996 \pm 0.001\,(\text{stat}) \pm 0.008\,(\text{syst}).$$

Δ=0.37% → half the Run 1 stat. uncert.!

New color reconnection models all with "early resonance decays" (ERD):

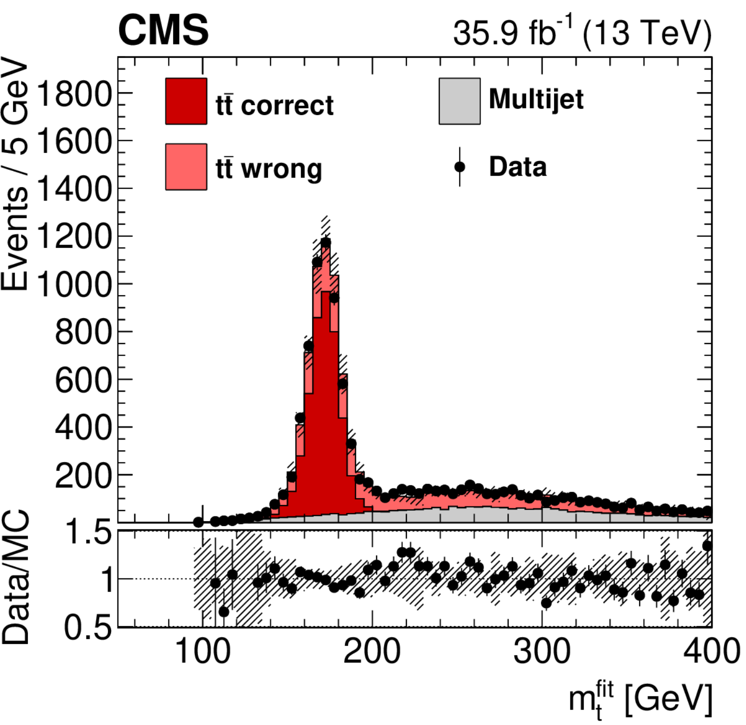
- Default setup ("ERD on")
- String formation beyond leading color ("QCD inspired") JHEP 08 (2015) 003
- Gluons can be moved to another string ("gluon move") JHEP 11 (2014) 043

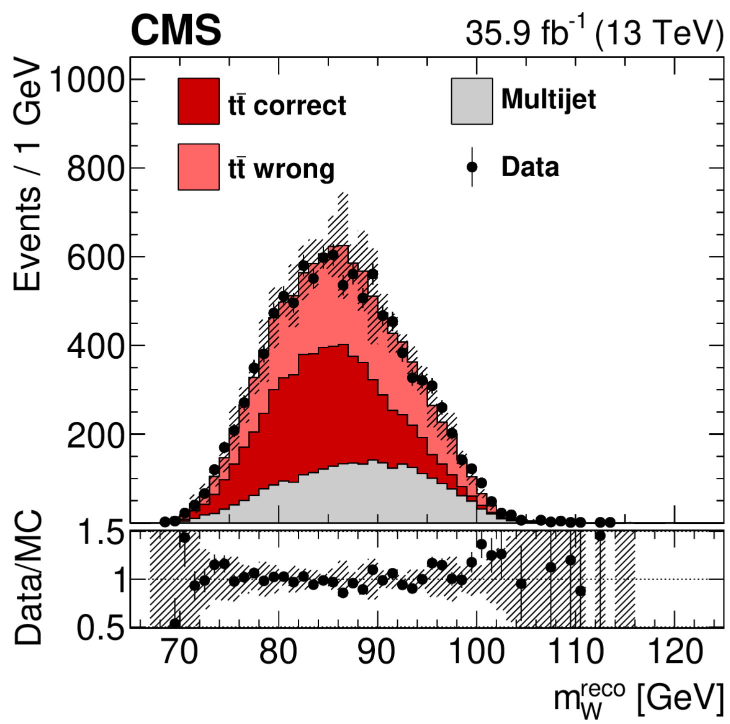




All-hadronic selection: =0 lepton, ≥6 jets, ≥2 b-tags, H_T>450 GeV CMS TOP-17-008 (accepted in EPJC)

Similarly, use **Ideogram method** (after χ^2 reconstruction of the W jets), with 2+1 fits:

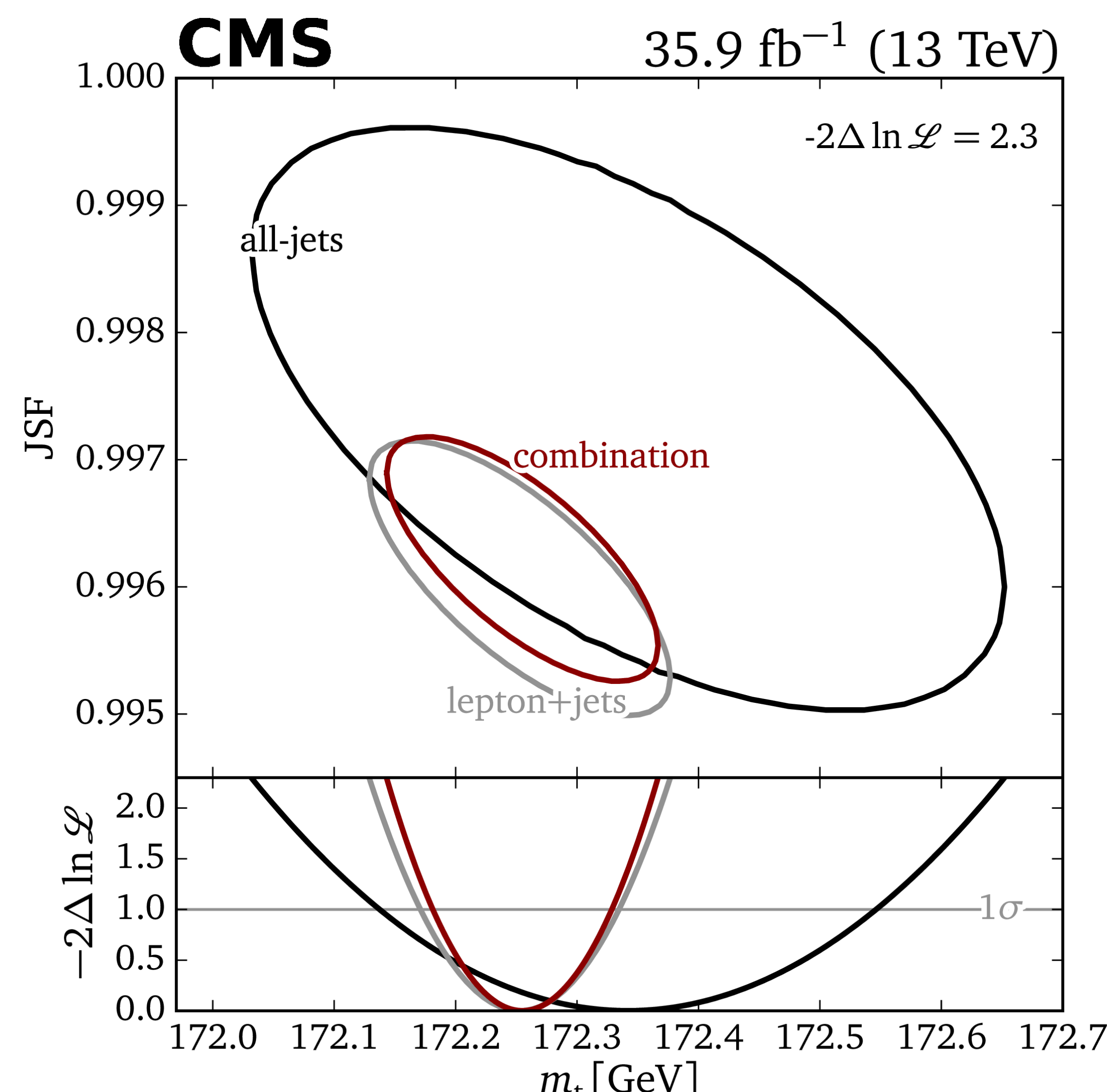




Systematics dominated by JES, ME generator and colour reconnection

$$m_t^{hyb} = 172.34 \pm 0.20\,(\text{stat+JSF}) \pm 0.70\,(\text{syst})\ \text{GeV, and}$$
$$\text{JSF}^{hyb} = 0.997 \pm 0.002\,(\text{stat}) \pm 0.007\,(\text{syst}).$$

Δ=0.41%



Then, perform simultaneous fit to all-had/l+jets @13 TeV:

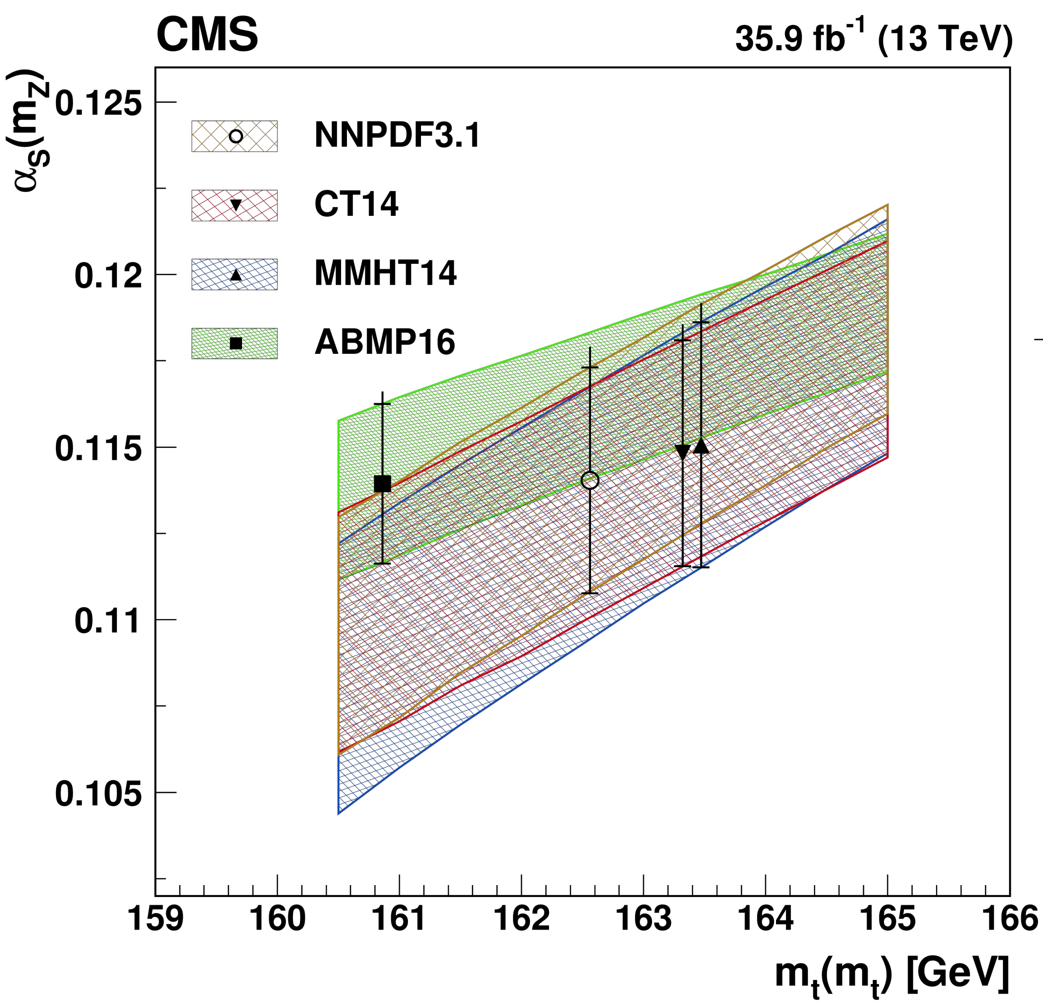
$$m_t^{hyb} = 172.26 \pm 0.07\,(\text{stat+JSF}) \pm 0.61\,(\text{syst})\ \text{GeV, and}$$
$$\text{JSF}^{hyb} = 0.996 \pm 0.001\,(\text{stat}) \pm 0.007\,(\text{syst})$$

Δ=0.35%

CMS TOP-17-001 (submitted to EPJC)
CMS PAS TOP-18-004

α_s and m_t **cannot** be measured simultaneously (opposite variations in cross-section) → values individually fixed according to PDF choice

See Sergio G.'s talk for the cross-section measurement, and Olaf's for the PDF interpretations!



Observe **linear dependence** between extracted α_s and m_t

PDF set	$\alpha_S(m_Z)$
ABMP16	0.1139 ± 0.0023 (fit + PDF) $^{+0.0014}_{-0.0001}$ (scale)
NNPDF3.1	0.1140 ± 0.0033 (fit + PDF) $^{+0.0021}_{-0.0002}$ (scale)
CT14	0.1148 ± 0.0032 (fit + PDF) $^{+0.0018}_{-0.0002}$ (scale)
MMHT14	0.1151 ± 0.0035 (fit + PDF) $^{+0.0020}_{-0.0002}$ (scale)

PDF set	m_t^{pole} [GeV]
ABMP16	169.9 ± 1.8 (fit + PDF + α_S) $^{+0.8}_{-1.2}$ (scale)
NNPDF3.1	173.2 ± 1.9 (fit + PDF + α_S) $^{+0.9}_{-1.3}$ (scale)
CT14	173.7 ± 2.0 (fit + PDF + α_S) $^{+0.9}_{-1.4}$ (scale)
MMHT14	173.6 ± 1.9 (fit + PDF + α_S) $^{+0.9}_{-1.4}$ (scale)

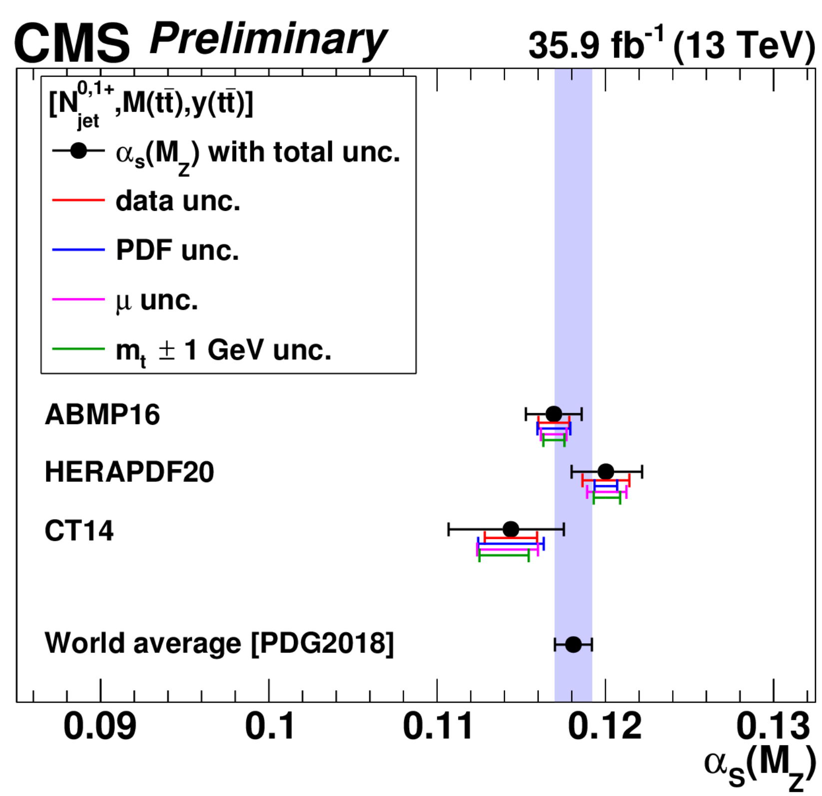
Systematics: from the inclusive cross-section measurement, choice of PDFs, μ_R/μ_F variations

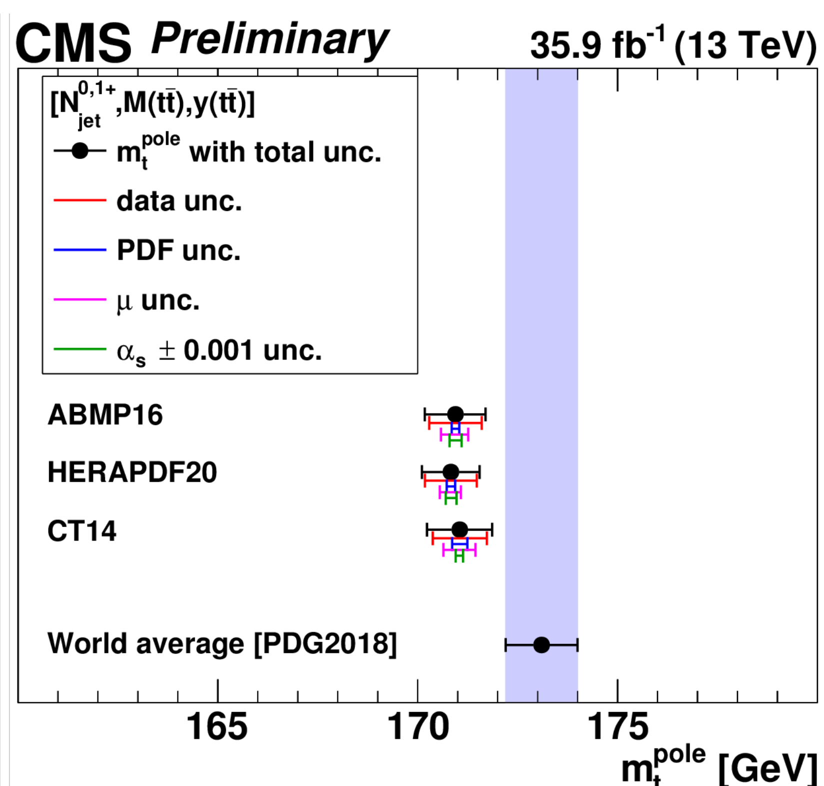
Next step: perform **differential measurement** to investigate relation further…

Triply-differential cross-section measurement: nJets, $M(t\bar{t})$ and $y(t\bar{t})$
→ **simultaneous extraction of α_s, m_t and PDFs**
(+using HERA data)

$$\alpha_s(M_Z) = 0.1135^{+0.0021}_{-0.0017}\,(\text{total}),$$

$$m_t^{\text{pole}} = 170.5 \pm 0.8\,(\text{total})\,\text{GeV}$$

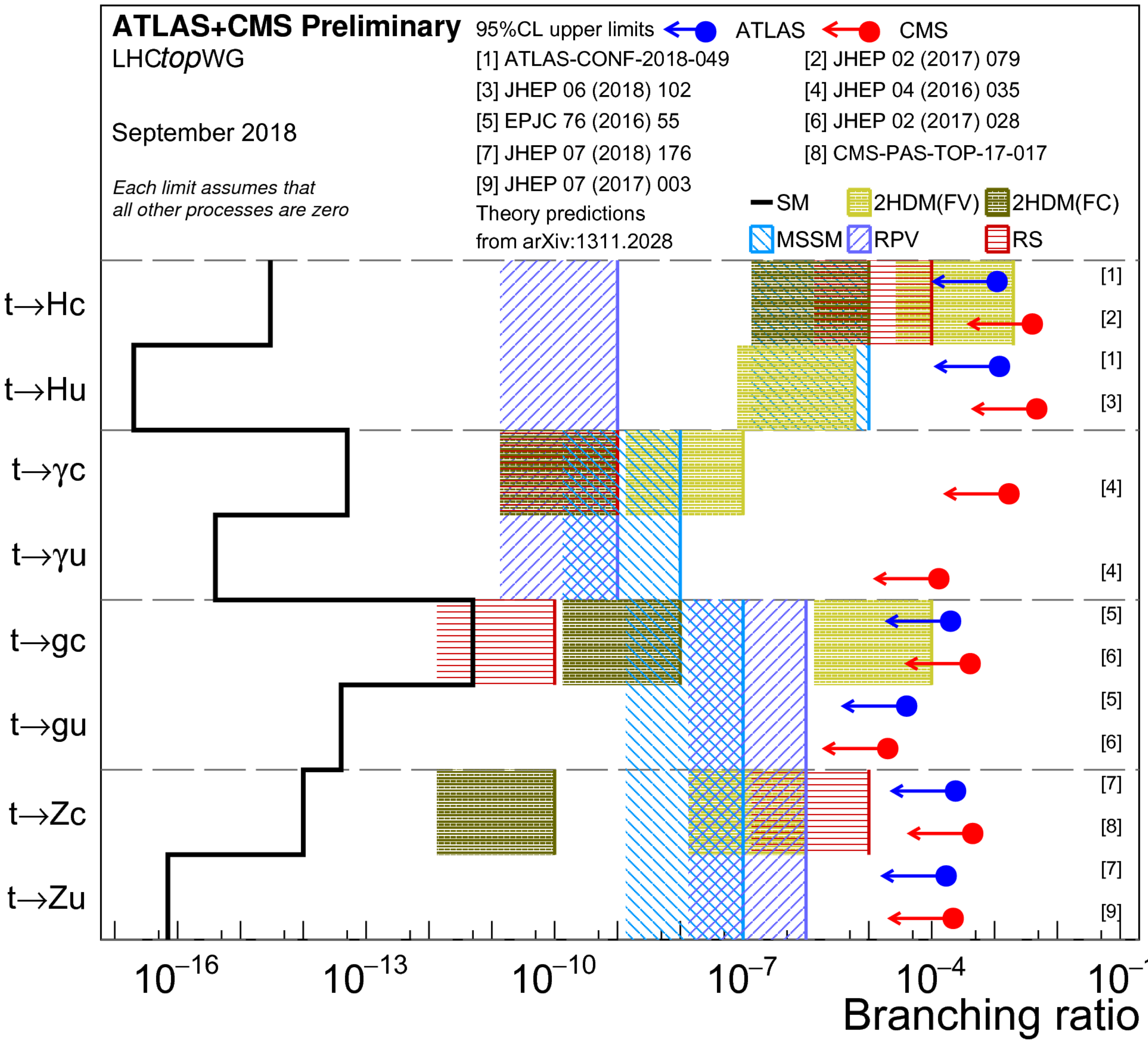


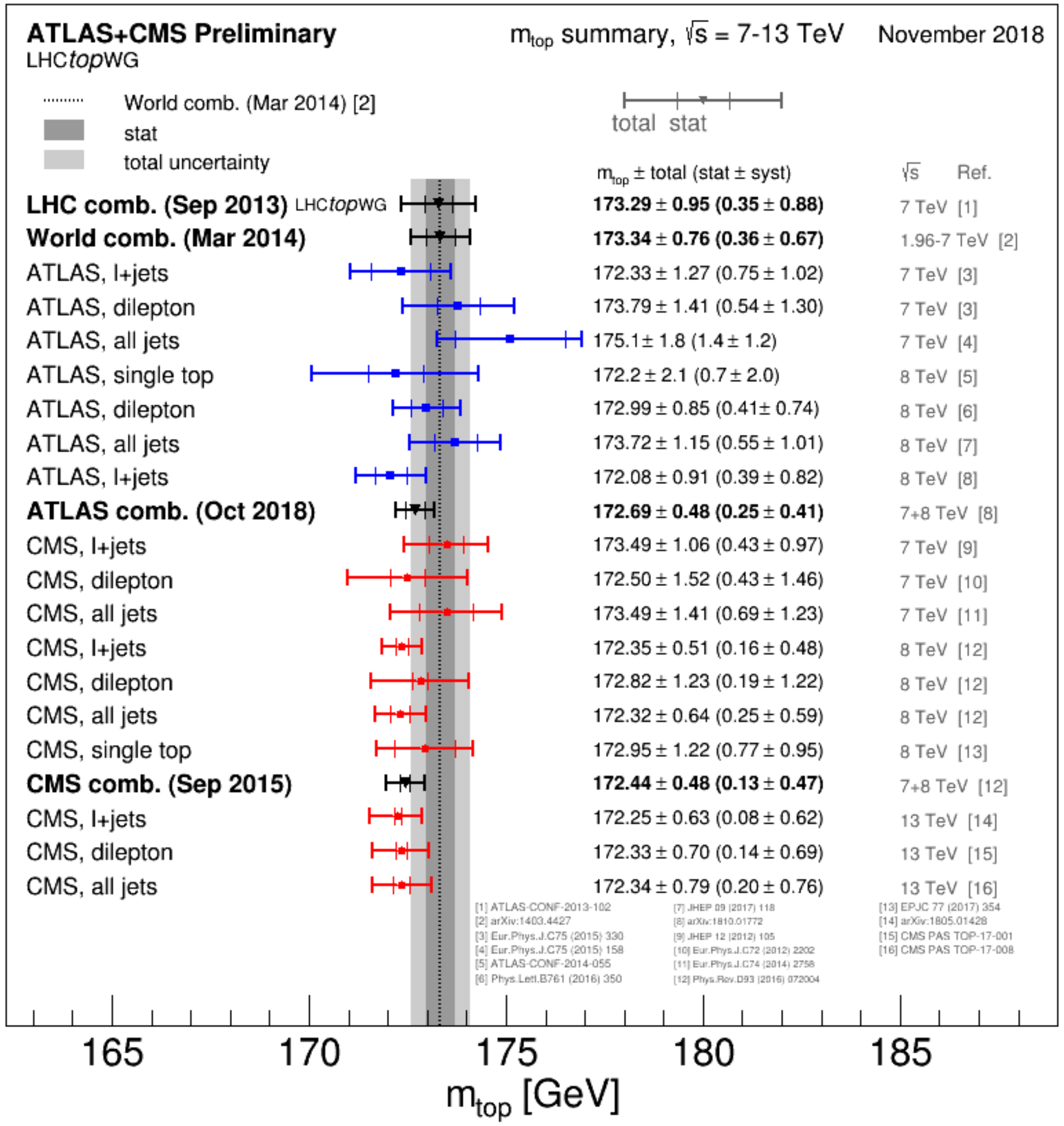


Closing statement: towards Run 2 combinations!

- The hunt for FCNC continues – top sector promising for BSM!
- Precision spin correlation measurements *are* telling us something (either NP or improve theory)
- Top mass now known to high precision (~0.3% / 0.5 GeV)

With thanks to the LHC machine and injector teams for the excellent performance of the LHC and a successful Run 2!





+ exciting Top Properties measurements!

Backup

Search for t→qH FCNC: di-photon

JHEP 10 (2017) 129

Heavily suppressed in the SM (GIM) with **BR~10^{-15}**, but signature of several potential BSM scenarios (e.g. 2HDM, BR up to ~10^{-3}).

Pre-selection: Higgs candidate (100<m($\gamma\gamma$)<160 GeV)

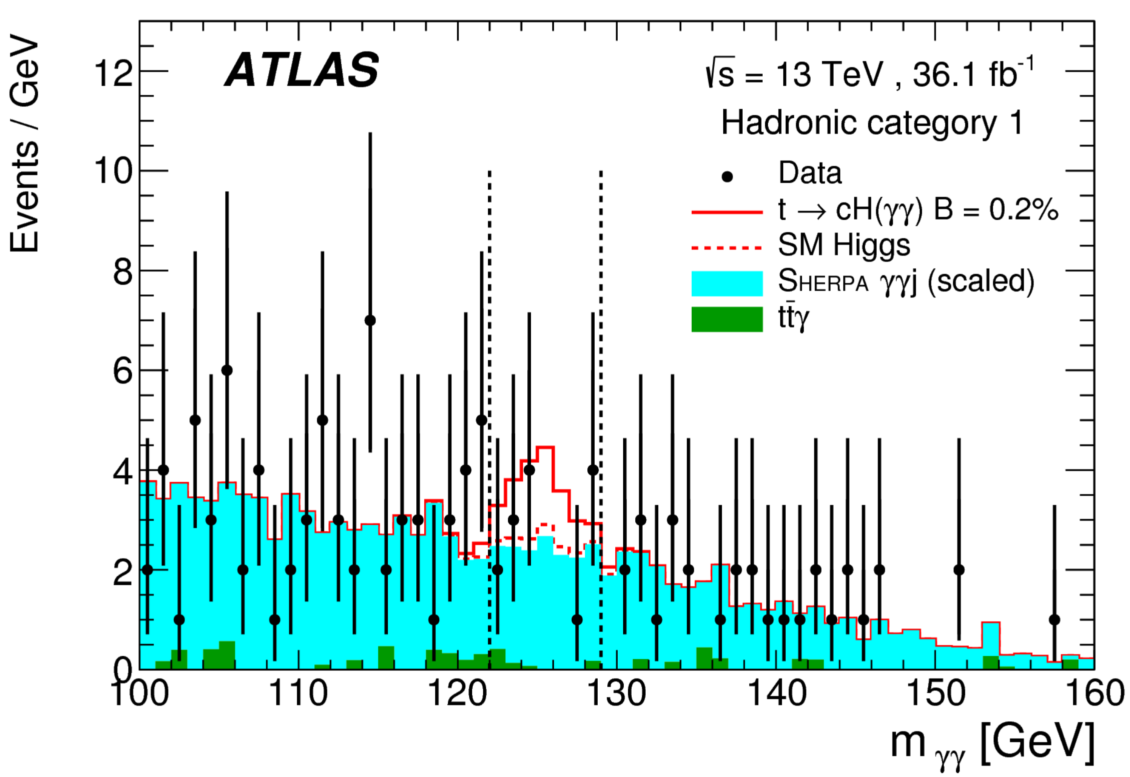
Hadronic:

=0 lepton, ≥4 jets, ≥1 b-tag

m(j$\gamma\gamma$) and m(jjj) for all jjjj permutations

152<m(j$\gamma\gamma$)<190 GeV

120<m(jjj)<220 GeV



Uncertainties: tt̄ production cross-section, JES, BR(H→$\gamma\gamma$), modelling of hadronisation and underlying event.

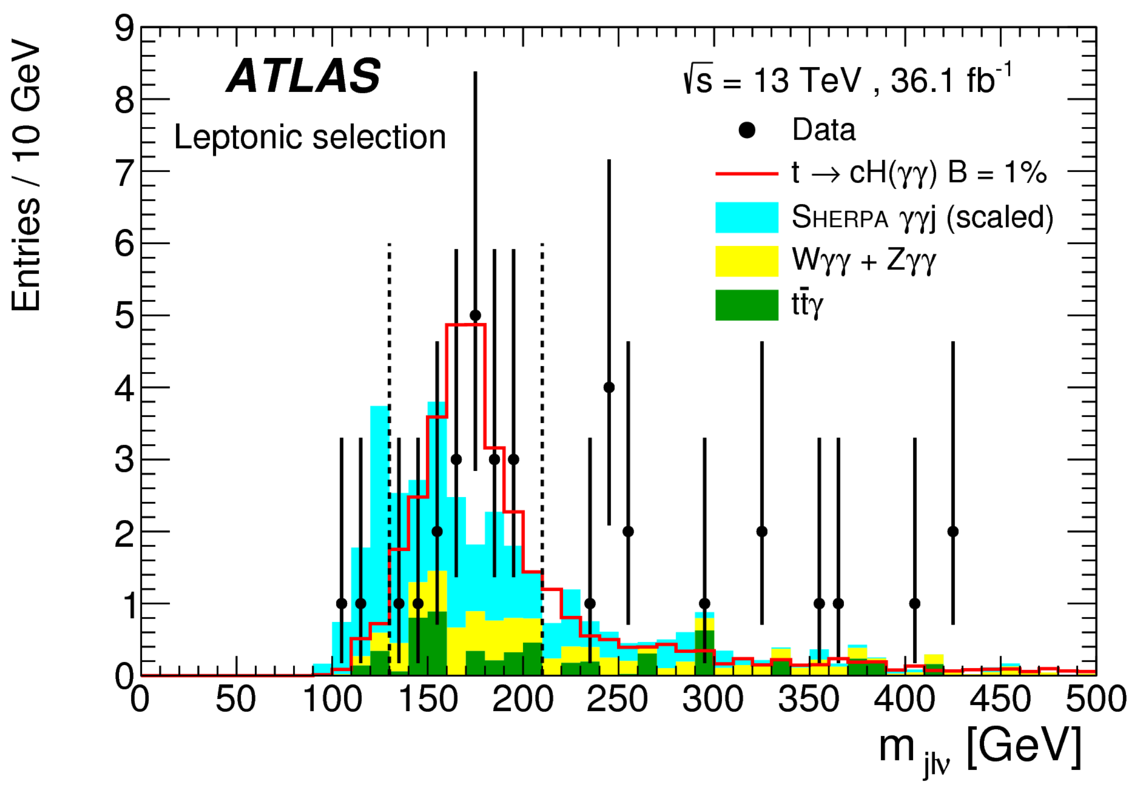
Leptonic:

=1 lepton, ≥2 jets, m_T(W)>30 GeV

m(j$\gamma\gamma$) and m(jlν) for all jj permutations

152<m(j$\gamma\gamma$)<190 GeV

130<m(jlν)<210 GeV



BR(t→cH)<2.2x10^{-3} (95% CL)

(almost equally sensitive to t→uH; acceptance is 8% lower due to b-tagging)

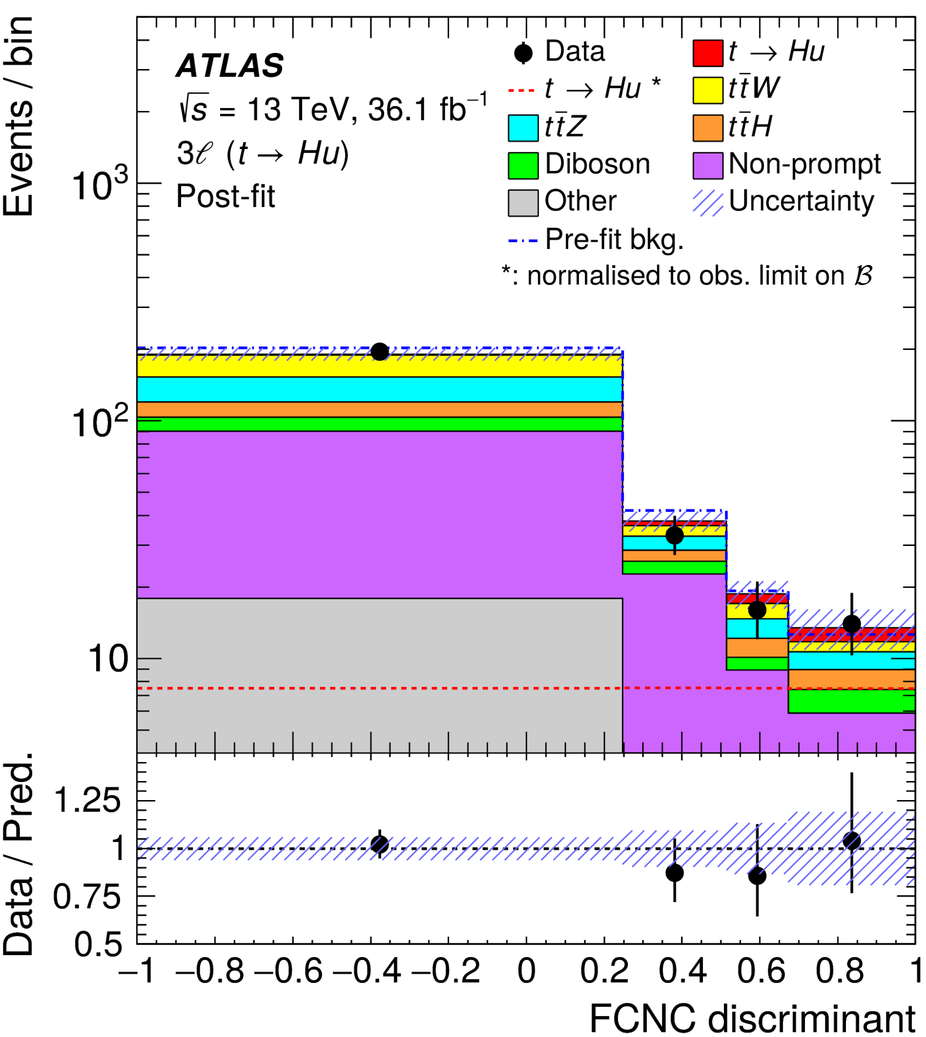
Search for t→qH FCNC: multilepton

Phys. Rev. D 98 (2018) 032002

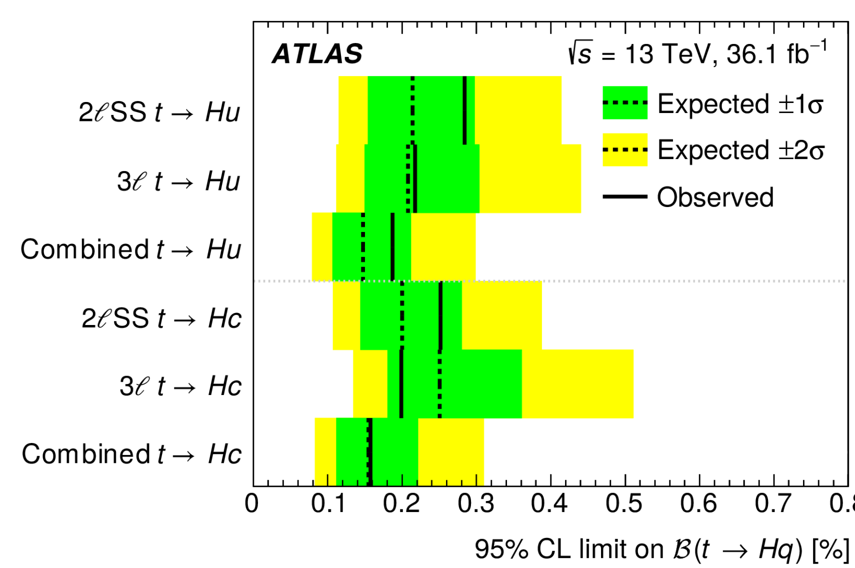
2LSS: ≥4 jets, =1 or 2 b-tags
3L: ≥2 jets, ≥1 b-tag, Z veto (reduces tt̄Z contamination!)

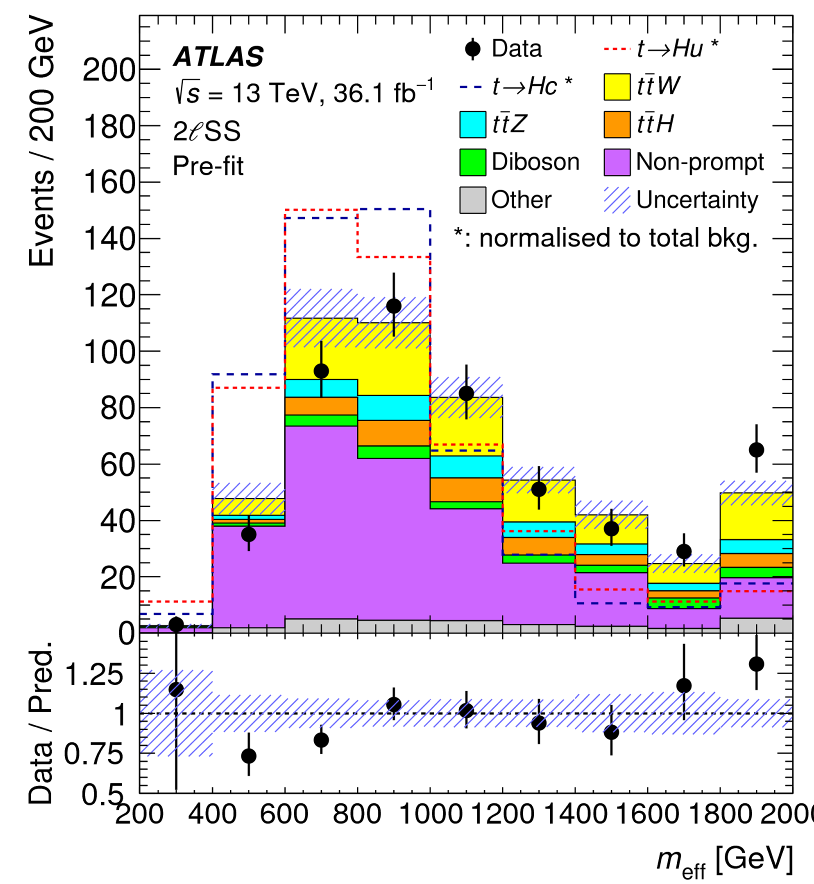
% of tHq	2LSS	3L
H→WW*	85%	71%
H→ττ	12%	16%
H→ZZ*	2%	9%

Backgrounds: fakes/tt̄, tt̄V → 2 BDTs trained on kinematics, combined linearly.
Signal event characterised by =1 b-tag and low H_T and E_T^{miss}: better separation for tHu as tHc is more likely to carry a second b-tag.



2 fits are performed, *fixing either BR to 0.*
Leading systematics: tt̄ modelling (BDT response variation), fake estimation (stat.), VV+HF norm.

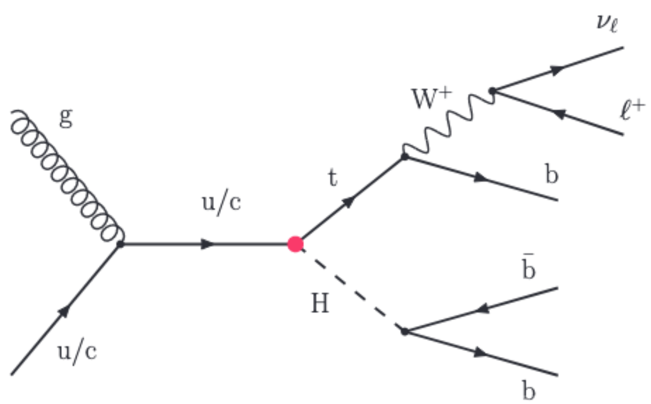




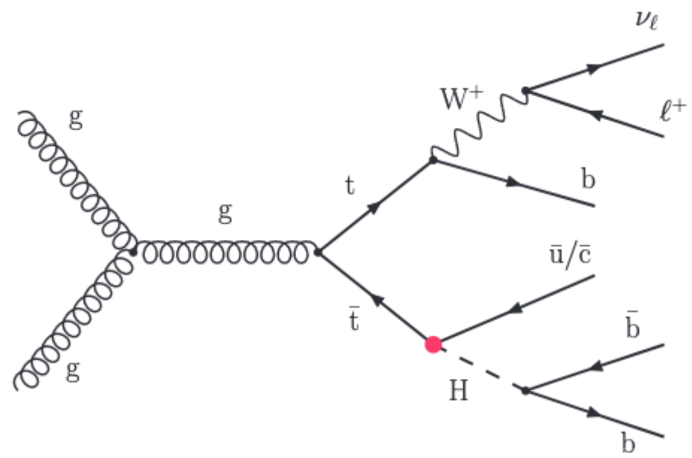
BR(t→cH)<1.6x10⁻³ (95% CL)
BR(t→uH)<1.9x10⁻³ (95% CL)

Again, CMS considering both production (single top) and decay ($t\bar{t}$) modes

JHEP 06 (2018) 102



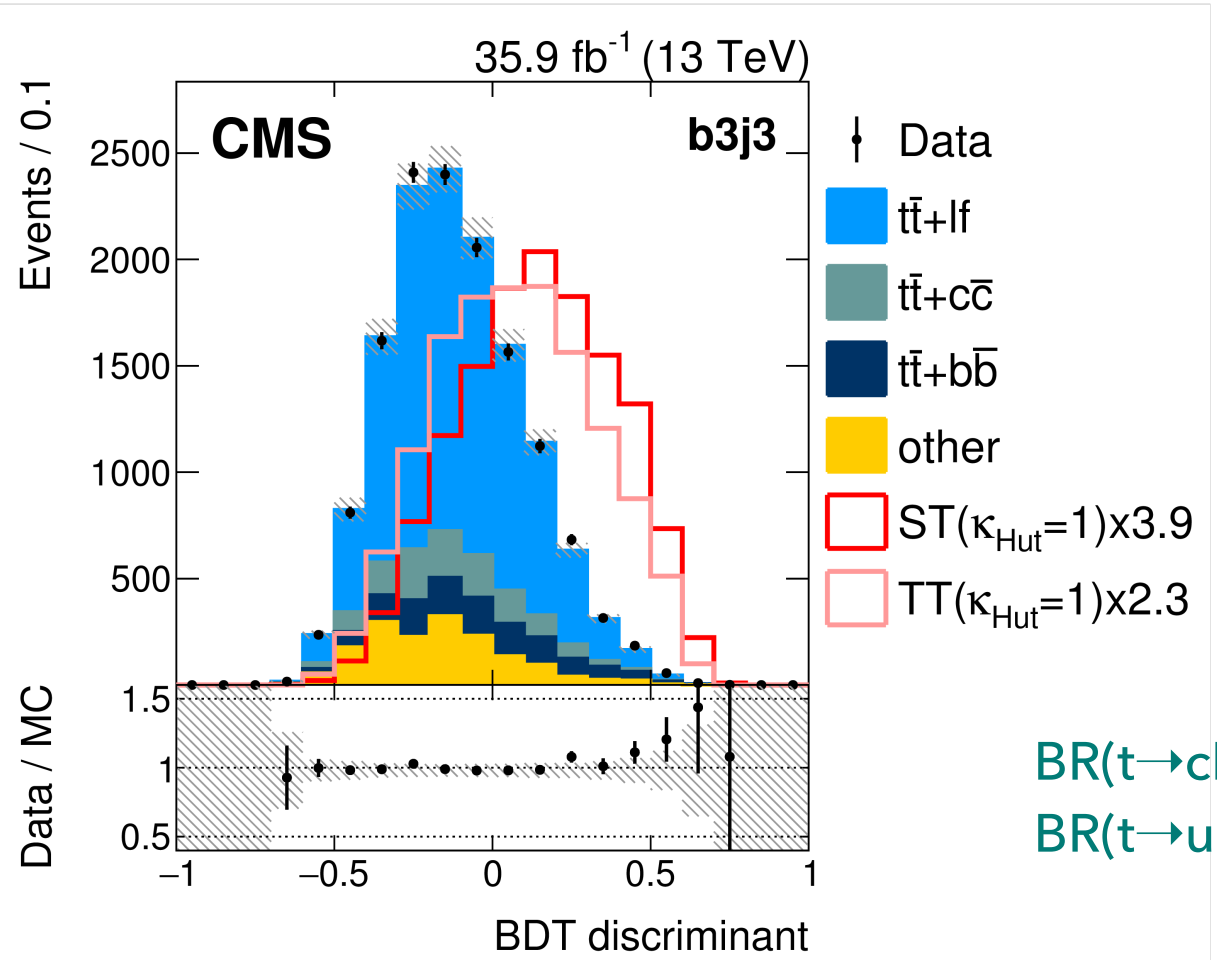
Selection: ≥3 jets, ≥2 b-tags, =1 lepton
→ 5 SRs based on (b)jet multiplicity



BDT trained to discriminate between 3 hypotheses: single top production, $t\bar{t}$ decay, and background $t\bar{t}$.

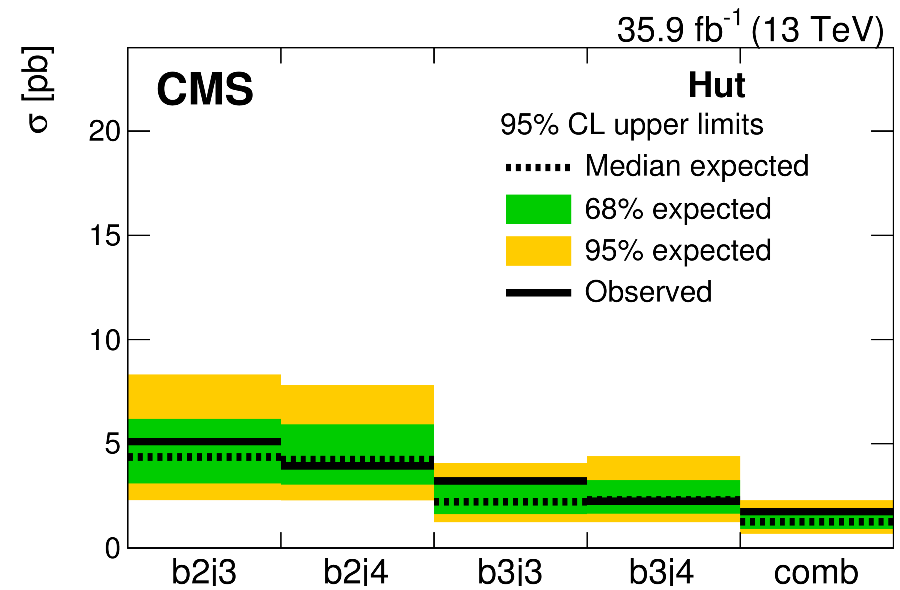
Input variables: reconstructed quantities *for all jet permutations.*

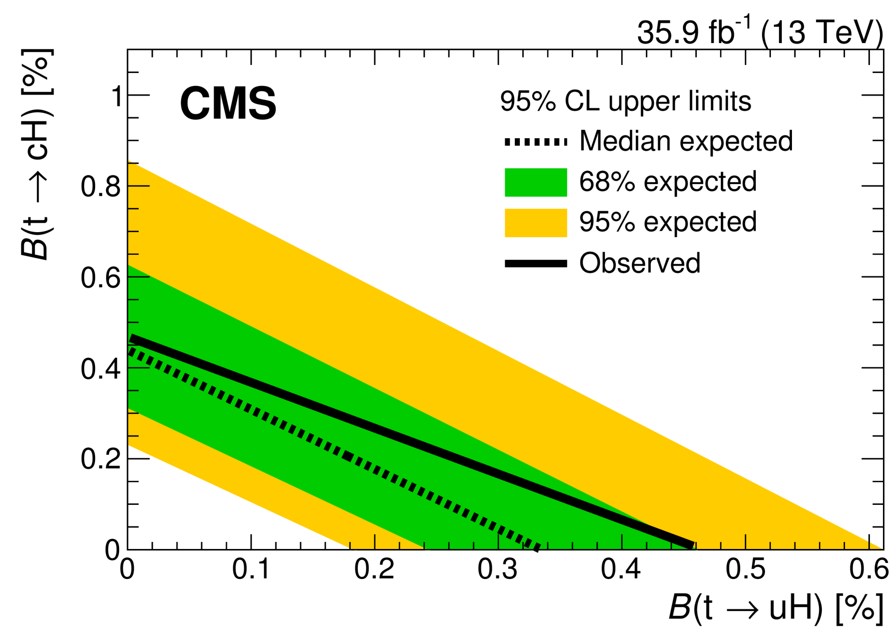
Largest uncertainties from b-tagging: ~8-30%.



BR(t→cH)<4.7x10^{-3} (95% CL)

BR(t→uH)<4.7x10^{-3} (95% CL)



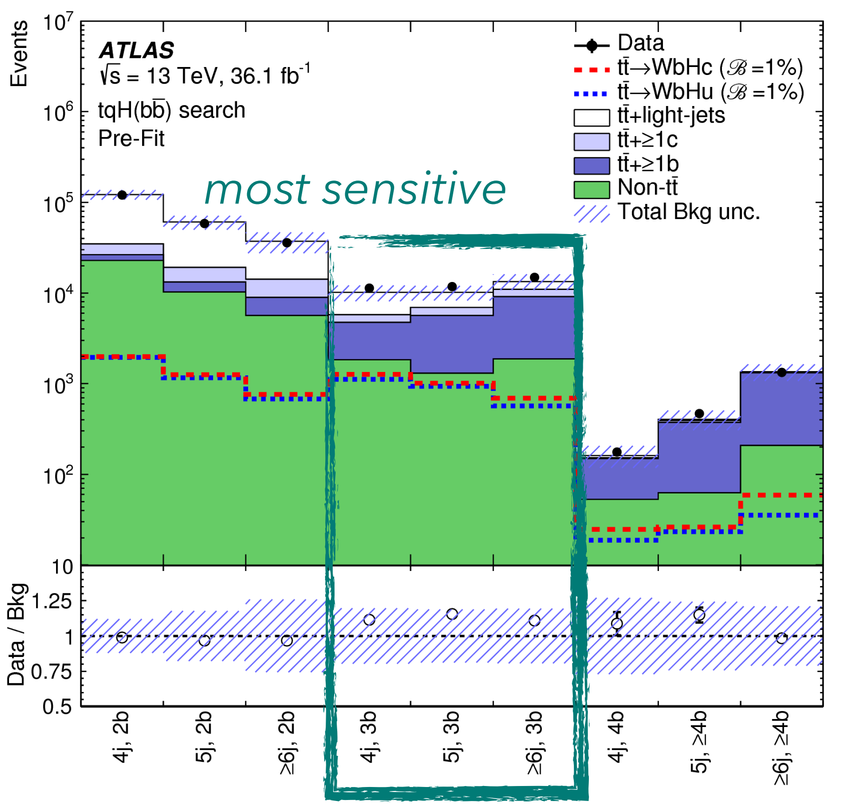


[arXiv:1812.11568](https://arxiv.org/abs/1812.11568) (submitted to JHEP)

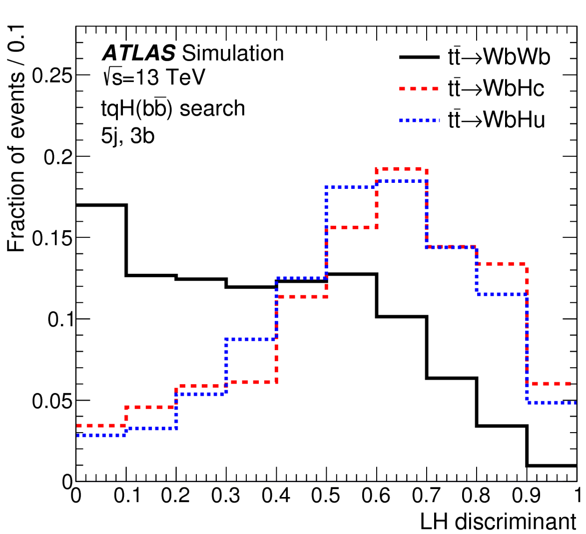
$H\to b\bar{b}$: ≥4 jets, ≥2 b-tags, =1 lepton

$H\to\tau\tau$: ≥3 jets, =1 b-tag, either $\tau_{lep}\tau_{had}$ (lepton trigger) or $\tau_{had}\tau_{had}$ (di-τ trigger)

$H\to b\bar{b}$: 9 SRs based on (b)jet multiplicity



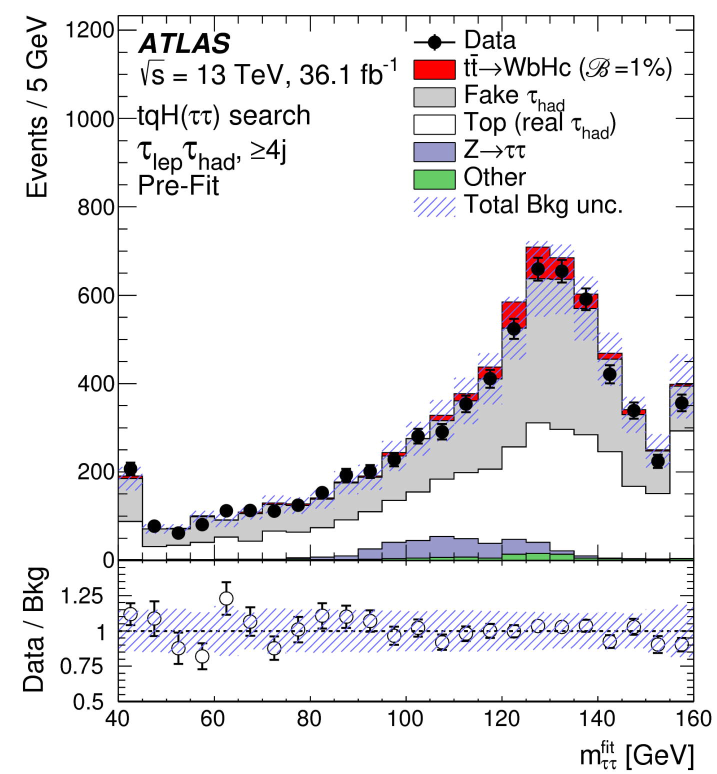
LH discriminant: WbHq vs WbWb

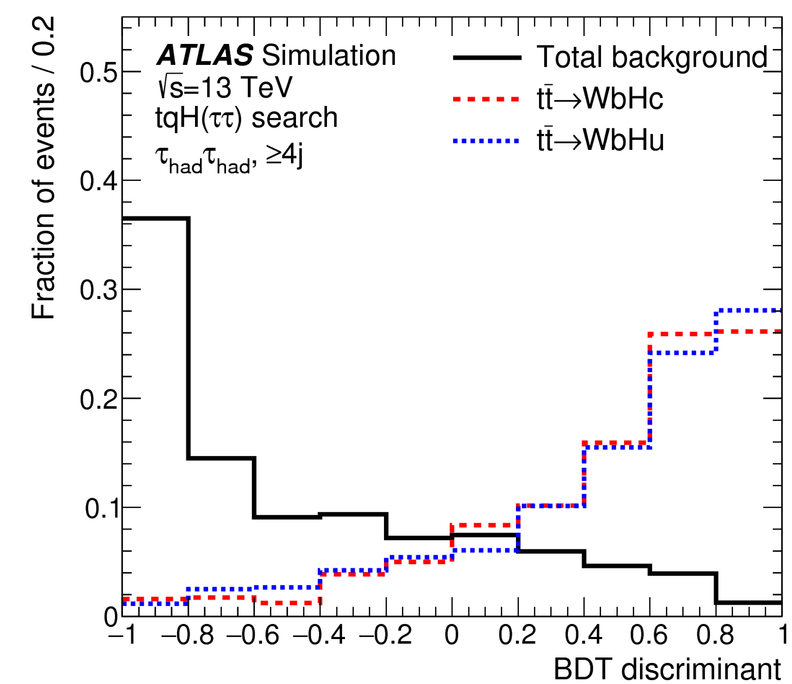


BR(t→cH)<4.2x10⁻³ (95% CL)
BR(t→uH)<5.2x10⁻³ (95% CL)

only tqH result *not dominated by stats!*

$H\to\tau\tau$: 4 SRs, (τ_{had}/τ_{lep}) x (=3/≥4) jets





BDT based on mass/p_T of reco objects.
Most discriminating: m(ττ) and x_1, x_2 (momentum fractions from visible decay τ products after χ^2 fit).

BR(t→cH)<1.9x10⁻³ (95% CL)
BR(t→uH)<1.7x10⁻³ (95% CL)

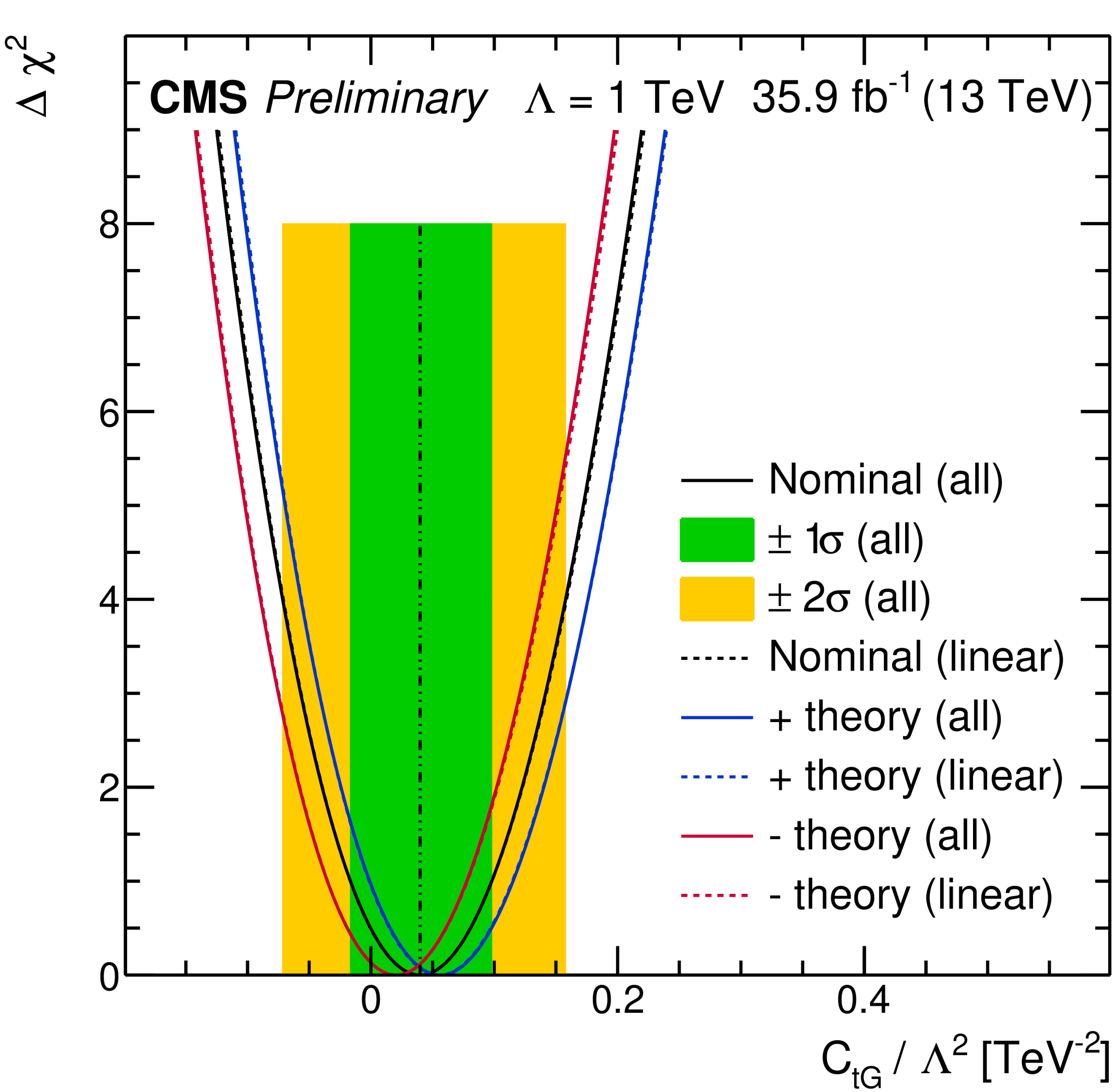
- ✓ large number of regions
- ✓ different bkg composition allows more constraining
- ✓ many-b events effectively reduce c-tagging uncert. by factor 2

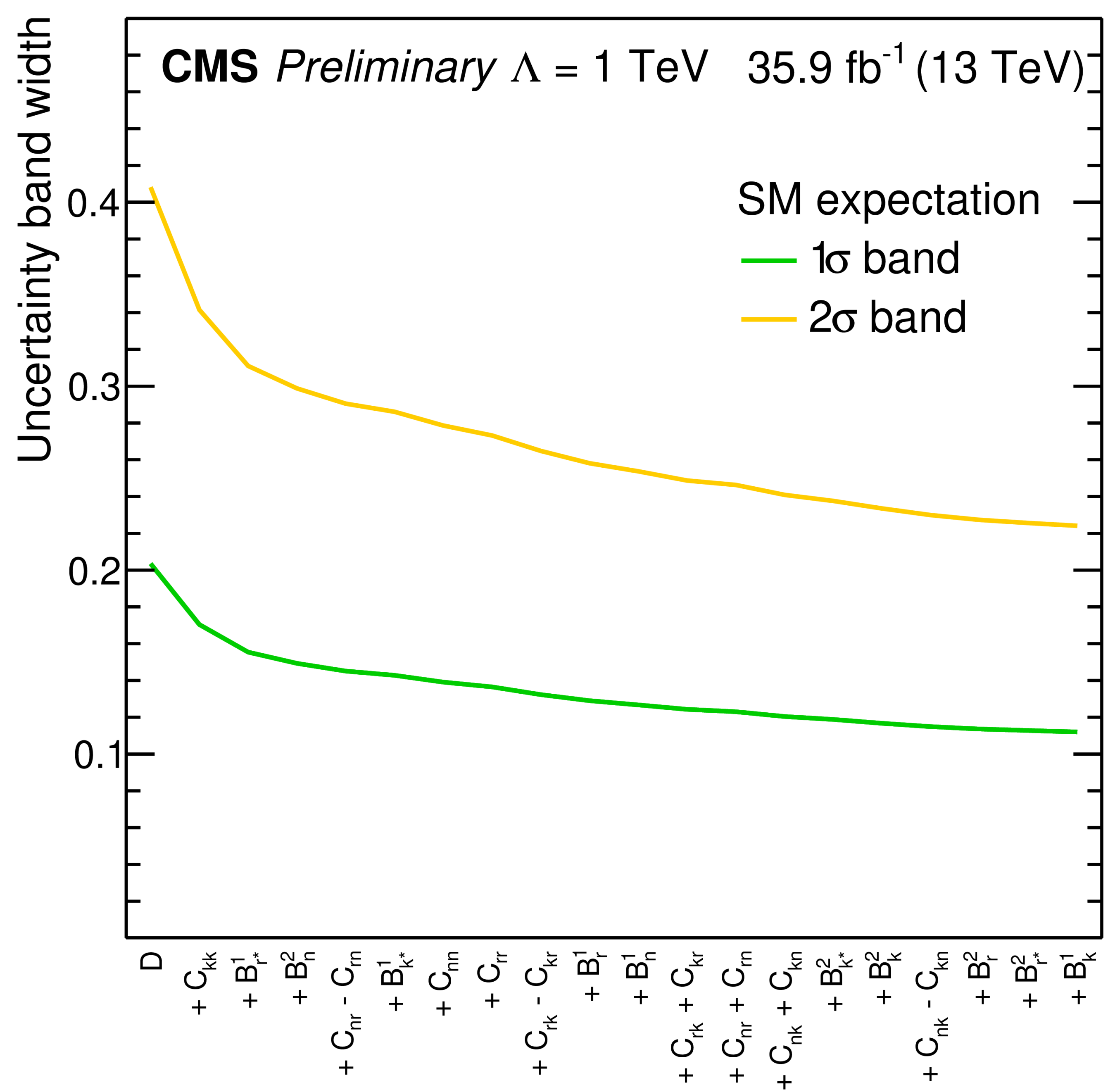
Constrain top chromo-magnetic dipole moment (CMDM) operator: $O_{tG} = y_t g_s \left(\bar{Q}\sigma^{\mu\nu}T^a t\right)\tilde{\phi}G^a_{\mu\nu}$

CMS PAS TOP-18-006

$-0.07 < C_{tG}/\Lambda^2 < 0.16\ \mathrm{TeV}^{-2}$

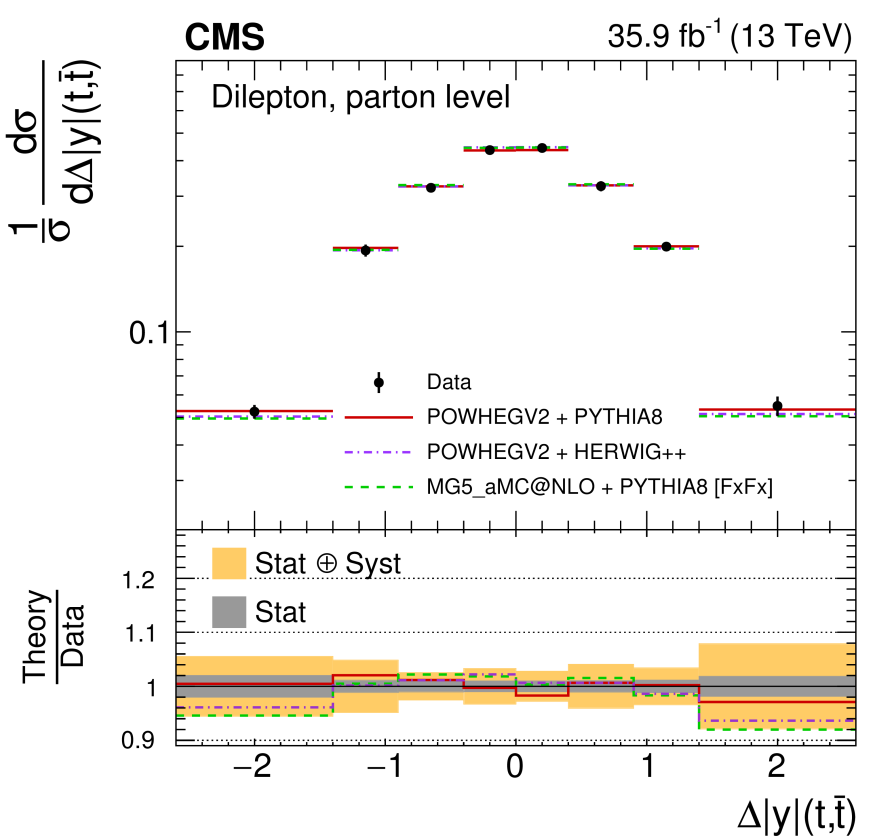
Strongest constraints to date! *(factor 2 improvement)*

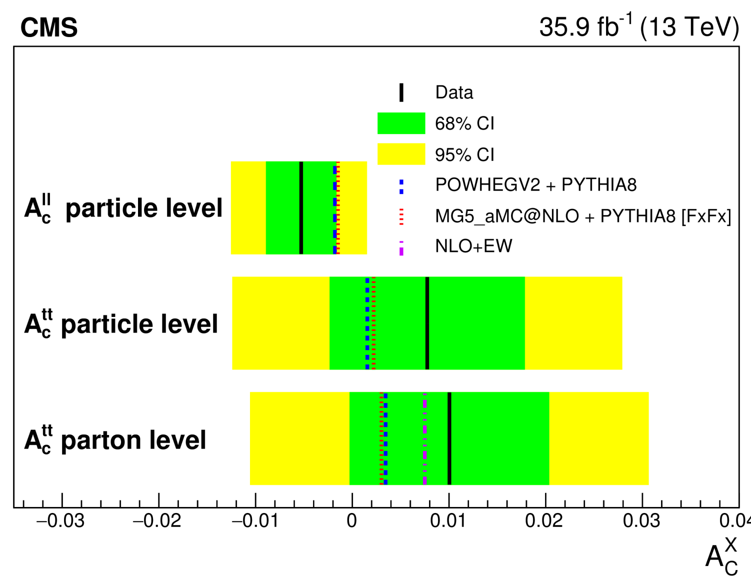


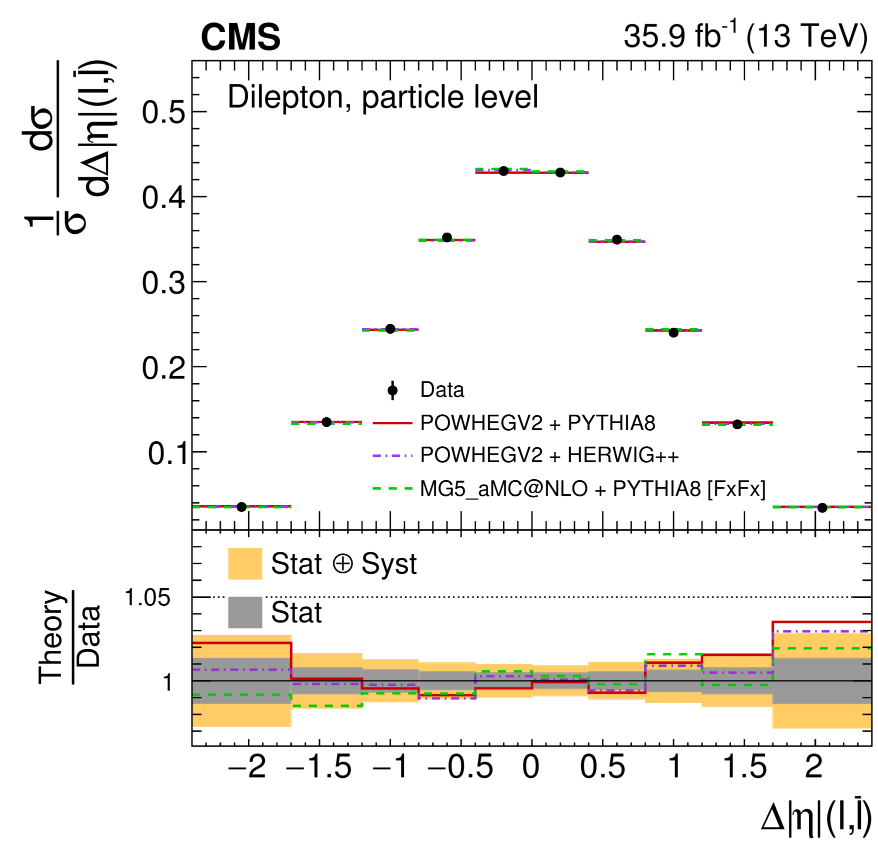


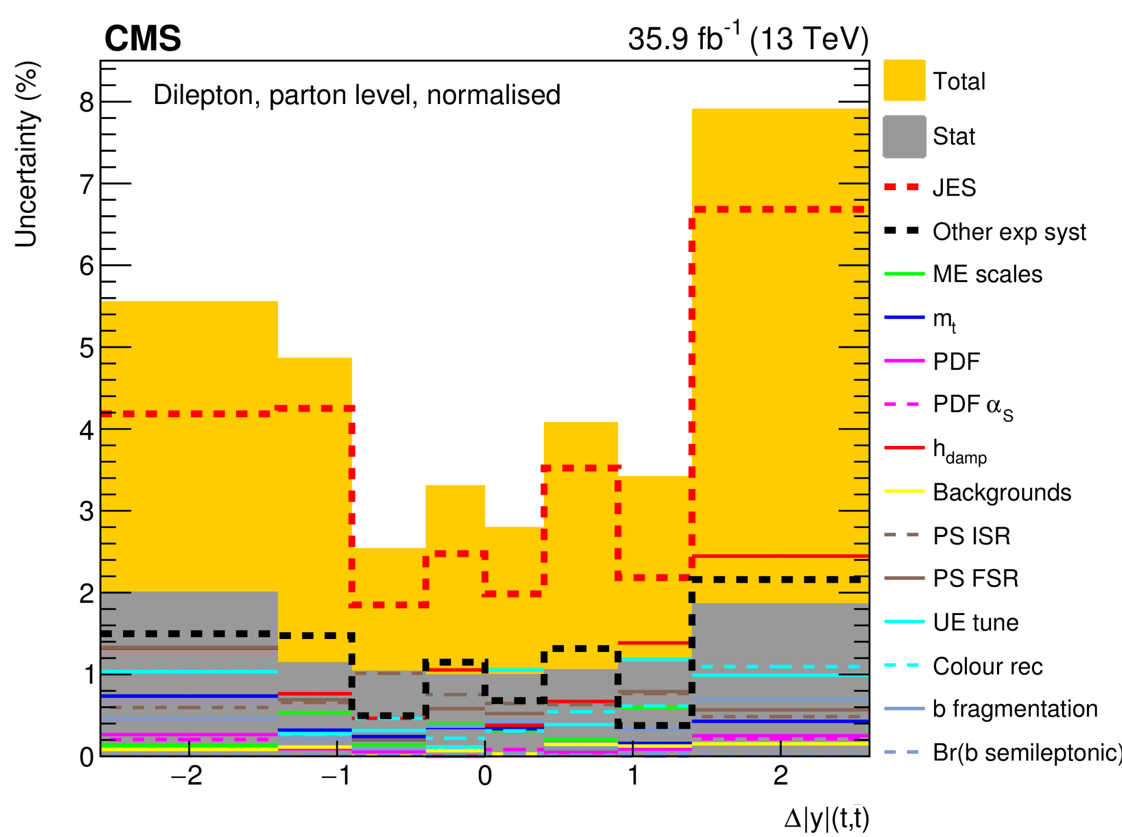
Charge asymmetries from dileptonic $t\bar{t}$ cross-section

JHEP 02 (2019) 149









Good agreement with the SM!

$A_c(t\bar{t}, \text{parton}) = 0.01 \pm 0.009$

$A_c(t\bar{t}, \text{particle}) = 0.008 \pm 0.009$

$A_c(ll, \text{particle}) = -0.005 \pm 0.004$

Top quark pole mass dependence of the $t\bar{t}$+1jet cross-section *enhanced* wrt. $t\bar{t}$ (but ~25% cross-section).

JHEP 10 (2015) 121

$$\frac{\Delta\sigma_{t\bar{t}+1-\mathrm{jet}}}{\sigma_{t\bar{t}+1-\mathrm{jet}}} \approx -5\frac{\Delta m_t^{\mathrm{pole}}}{m_t^{\mathrm{pole}}}$$

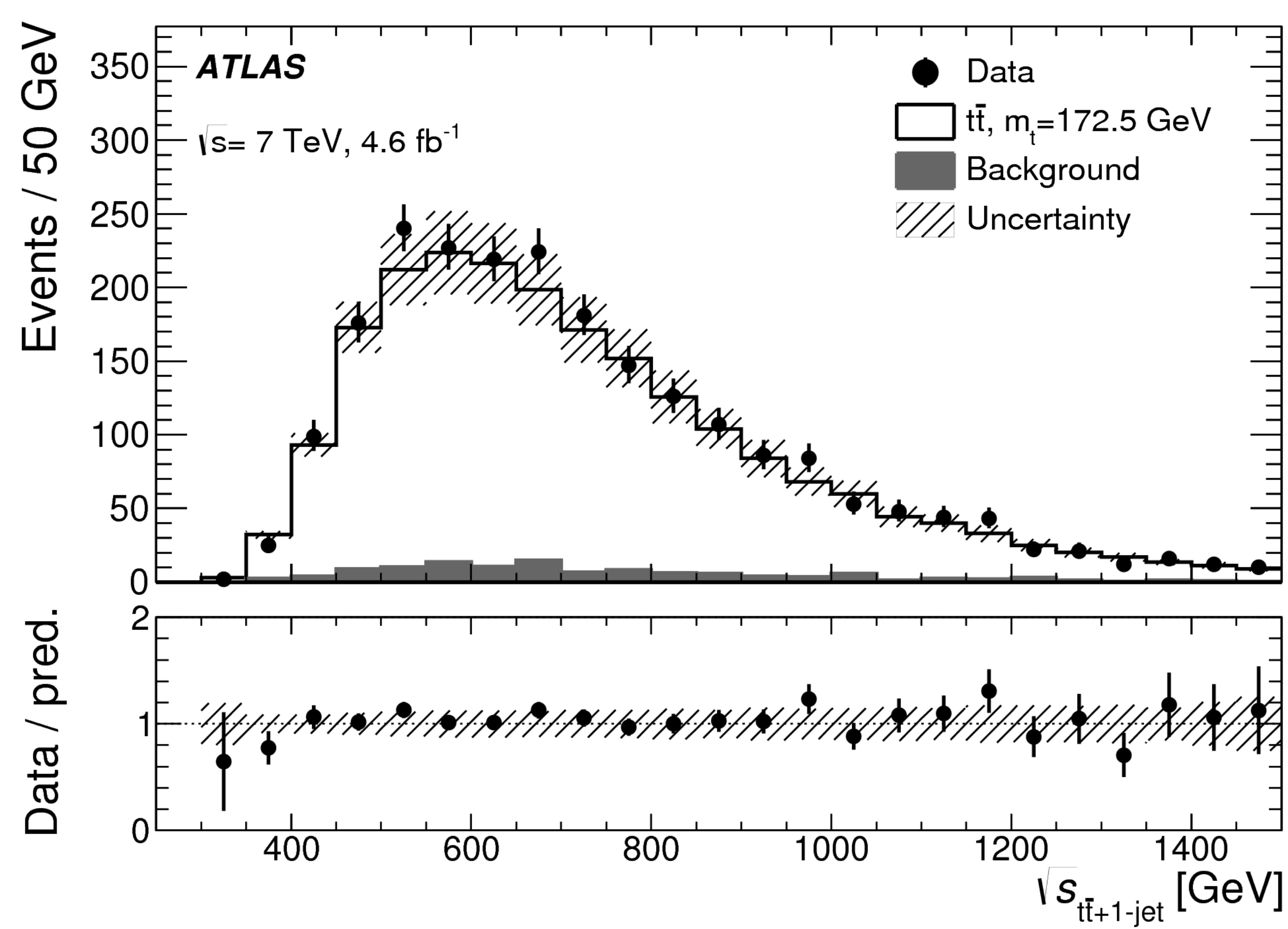
Extracted from normalised differential distribution:

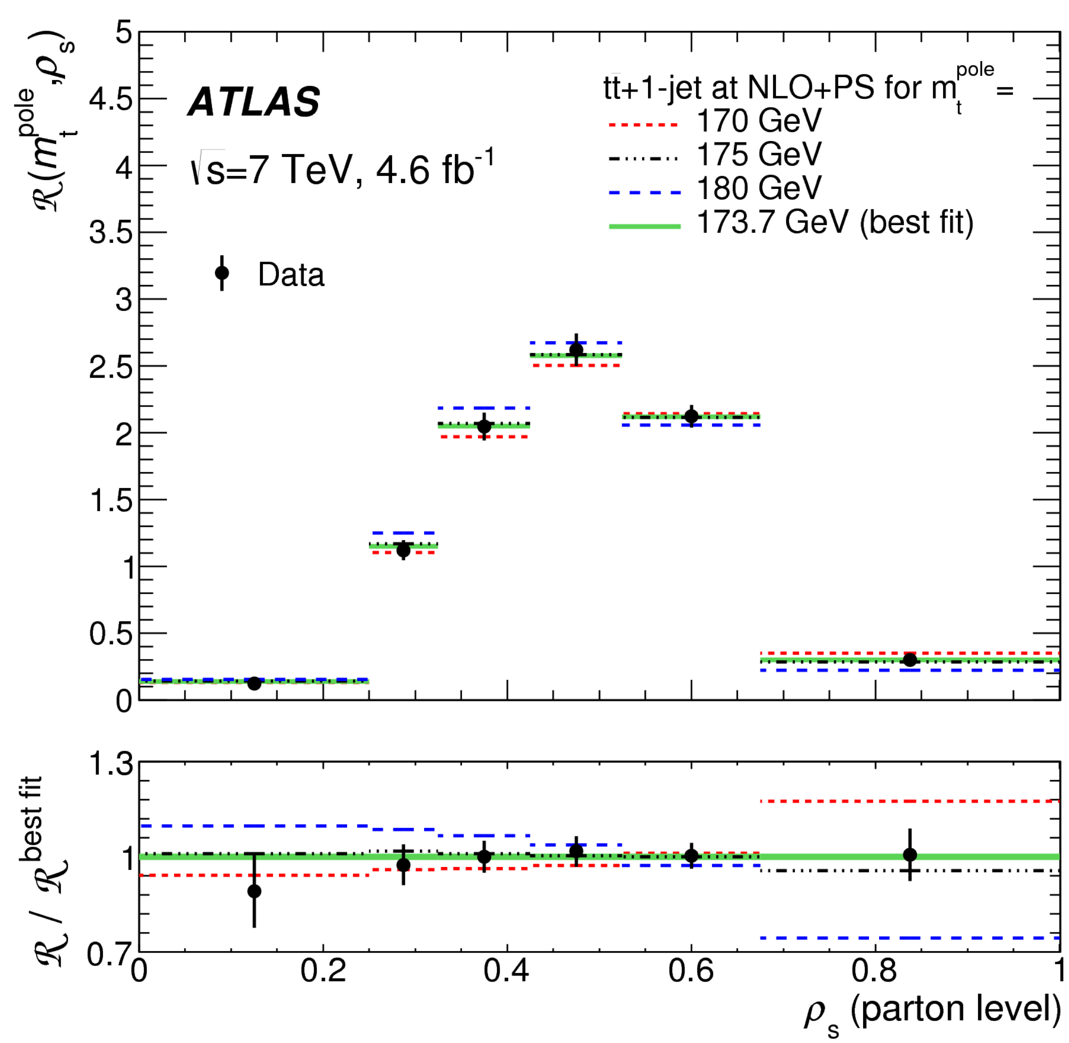
$$\mathscr{R}(\rho_s, m_t) = \frac{1}{\sigma_{t\bar{t}+1-\mathrm{jet}}} \times \frac{d\sigma_{t\bar{t}+1-\mathrm{jet}}}{d\rho_s}, \text{with } \rho_s = \frac{340\,\mathrm{GeV}}{\sqrt{s_{t\bar{t}+1-\mathrm{jet}}}}$$

Leading p_T jet not used in $t\bar{t}$ reconstruction = "associated hard jet".
Unfolded to parton-level and **compared to fixed-order calculation** (χ^2).

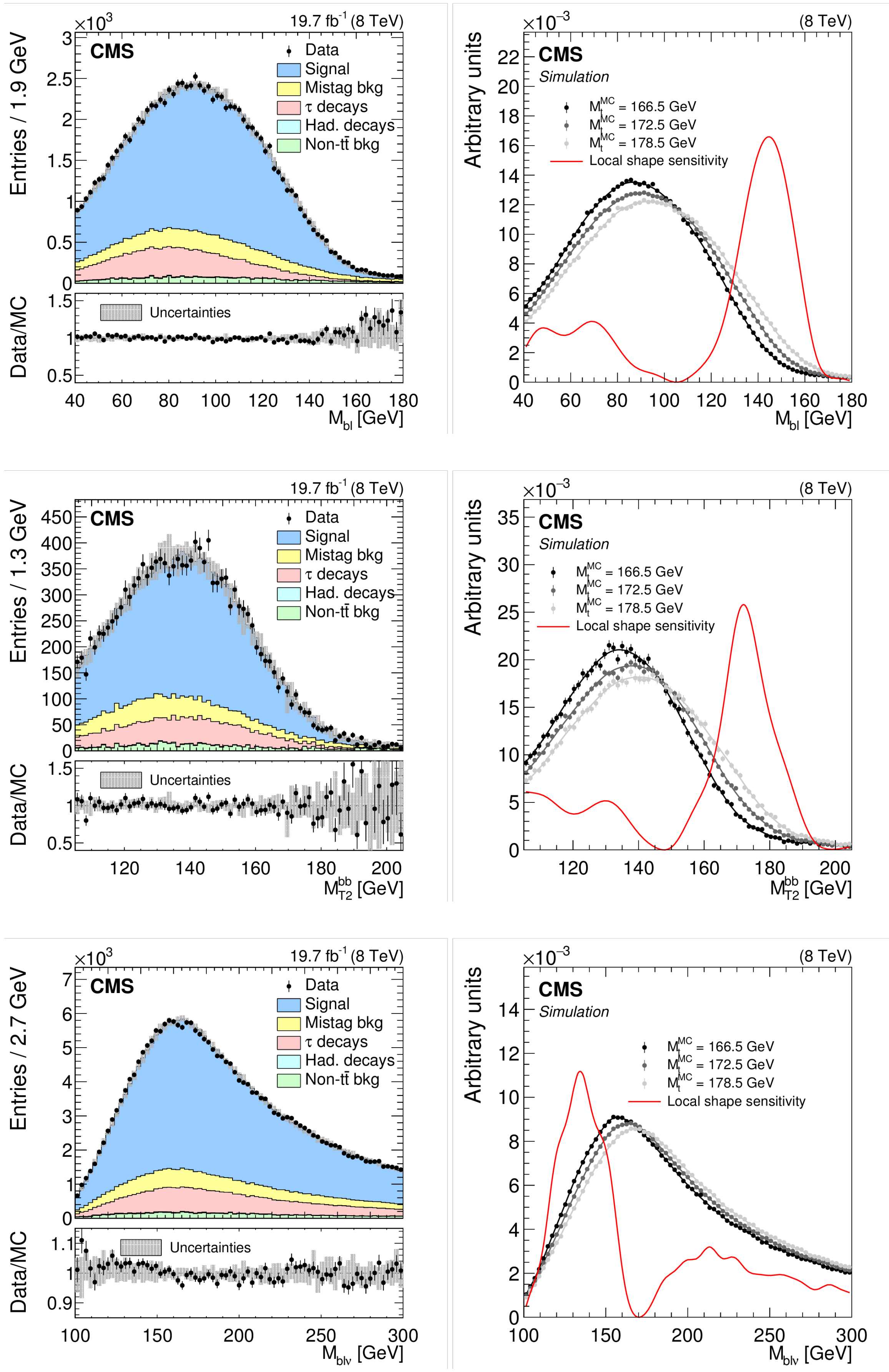
m_t=173.7 ± 1.5 (stat.) ± 1.4 (syst.) +1.0/-0.5 (theo.) GeV, Δ=1.2%

Leading uncertainties: $t\bar{t}$ modelling, JES





Direct: dilepton (eμ) @8 TeV



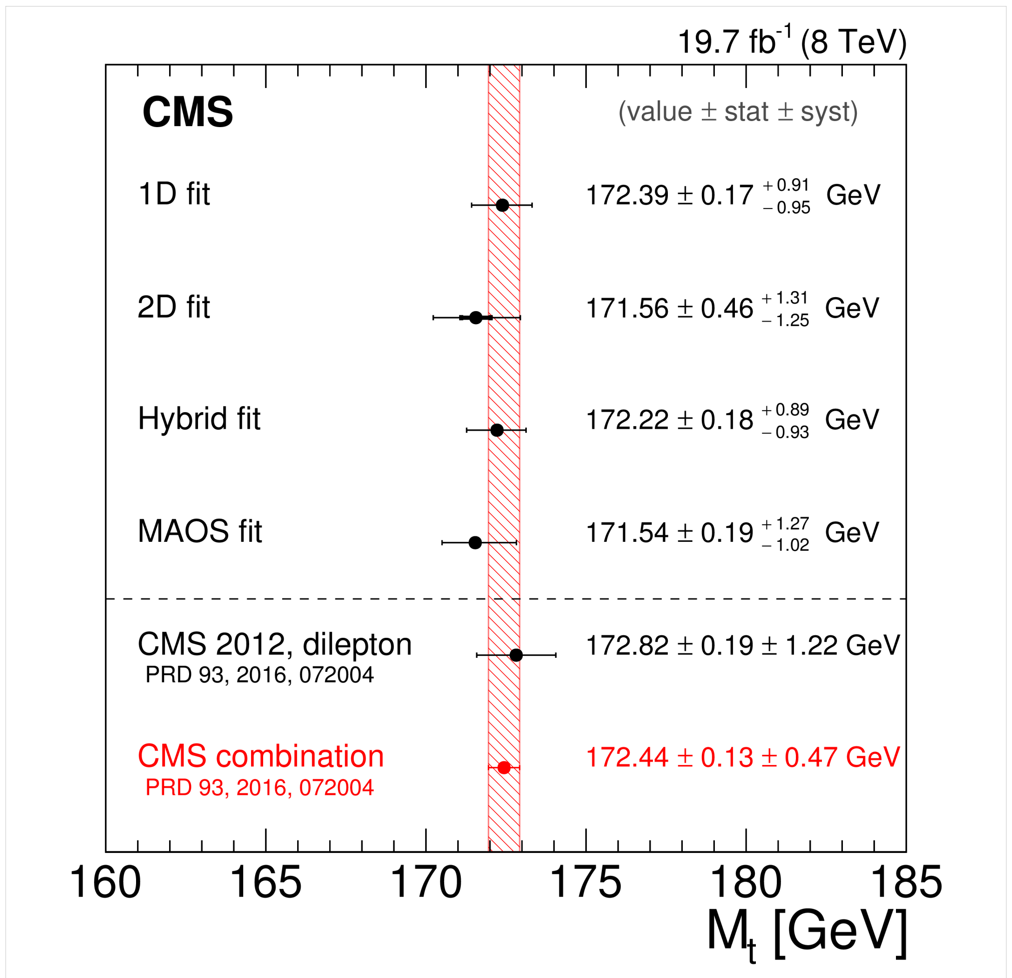
[Phys. Rev. D 96 (2017) 032002]

Selection: OS eμ, ≥2 b-tags, $\not{E}_T$>40 GeV

3 observables: M(bl), $M_T{}^2$ (stransverse mass), M(blν)

Dominated by JES, b-tagging and tt̄ modelling uncertainties

3 fits are performed (1D & 2D in m_t and JSF, 1D in m_t using M(blν)) + **"hybrid" (1D+2D combination)**

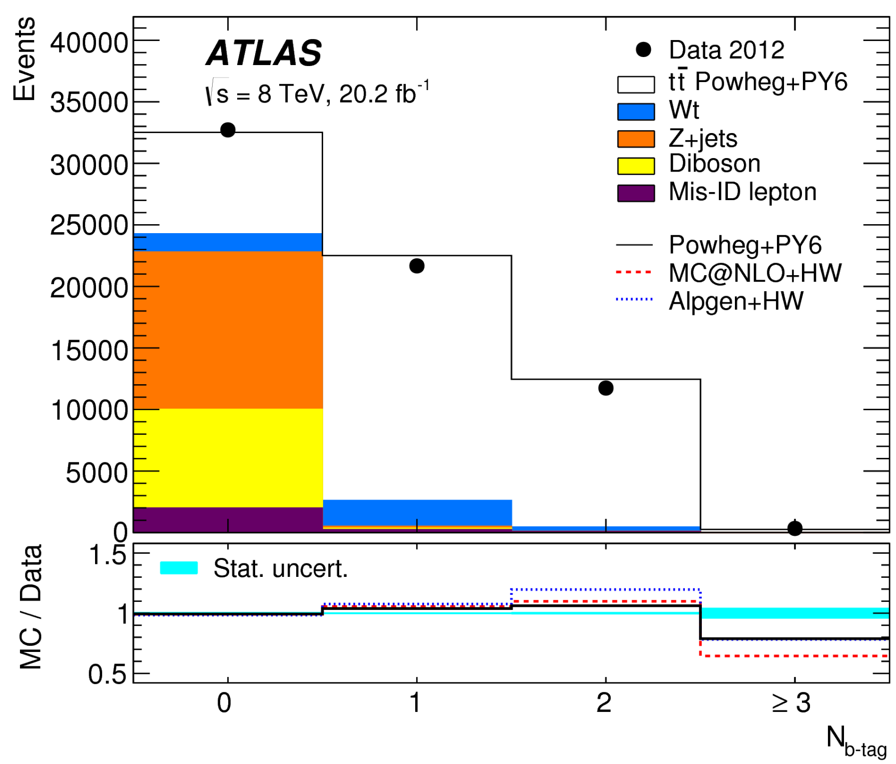


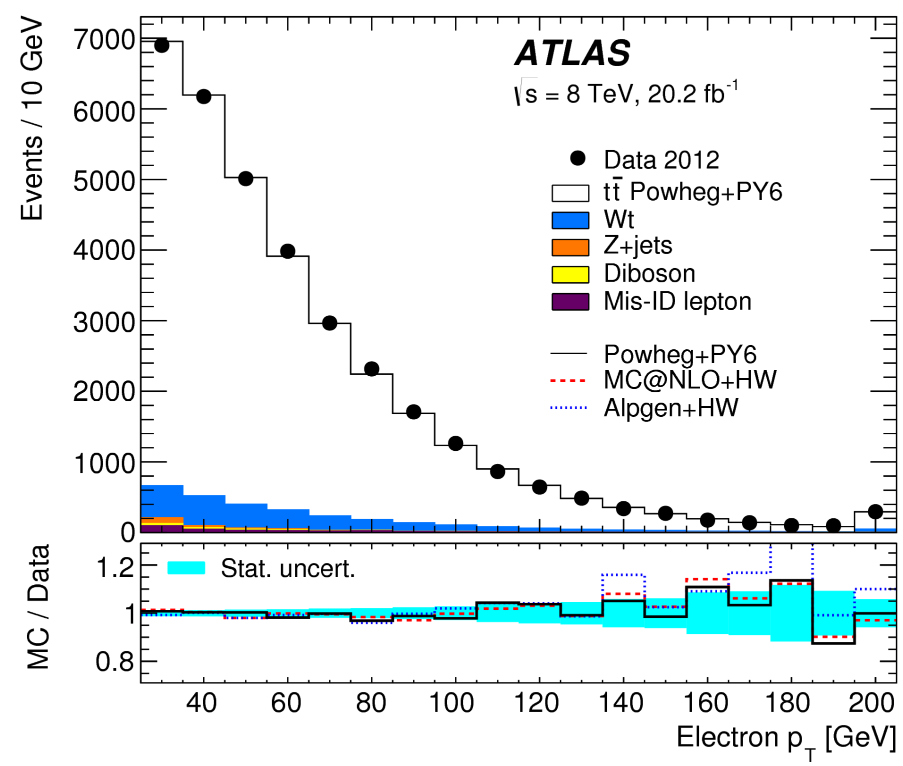
m_t=172.22 ± 0.18 (stat.) +0.89/-0.93 (theo.) GeV, Δ=0.5%

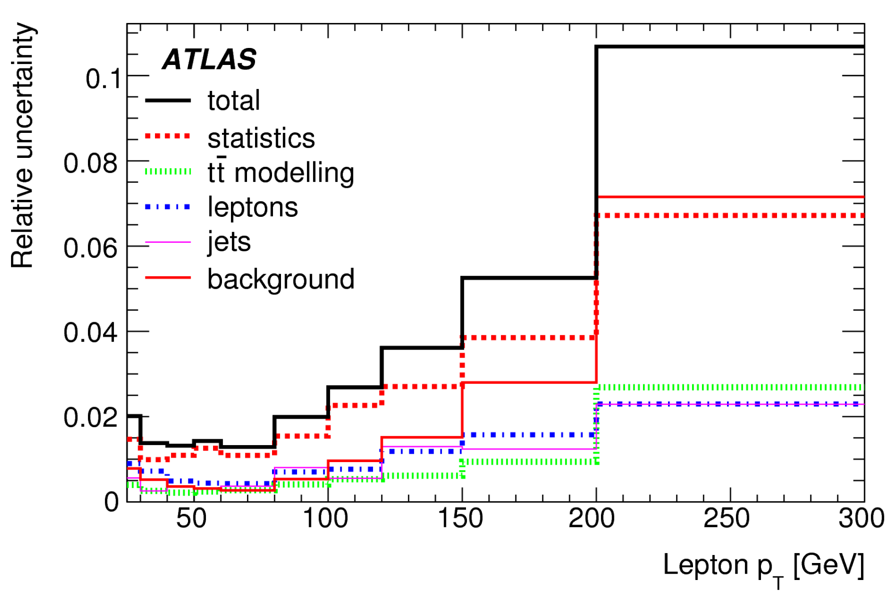
Selection: OS eμ, =1 or 2 b-tags

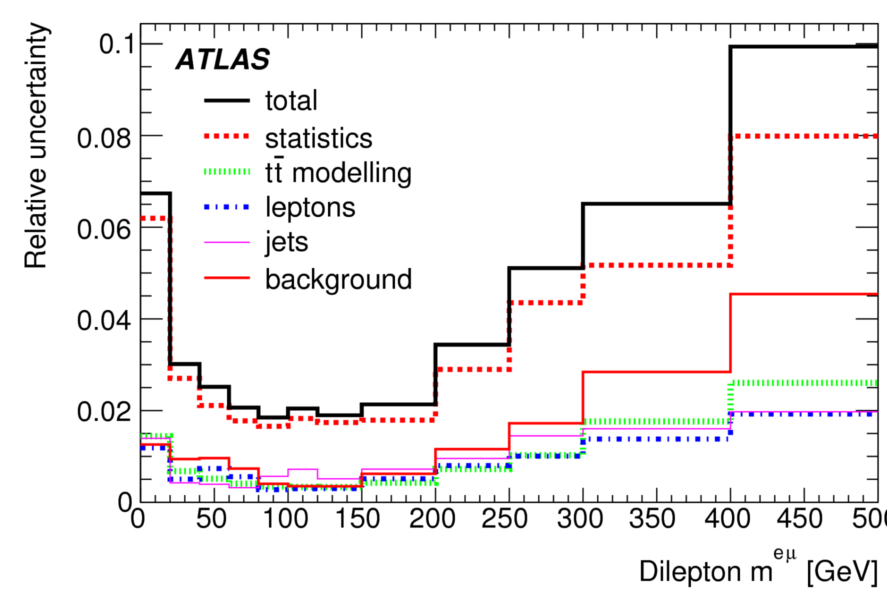
Eur. Phys. J. C 77 (2017) 804

Leptonic observables → correct to particle-level (fiducial) → absolute+normalised cross-section = **comparison to fixed-order QCD calculation** to explore sensitivity to gluon PDF (not covered here) and top quark pole mass









Systematic uncertainties in normalised measurement **usually ~% level**, except in some bins

Eur. Phys. J. C 77 (2017) 804

From normalised distributions: $p_T(e/\mu)$, $p_T(e\mu)$, $m(e\mu)$, $E(e)+E(\mu)$, $p_T(e)+p_T(\mu)$

✓ double-tagging technique and lack of $t\bar{t}$ reco **reduce exposure to QCD modelling uncert.**

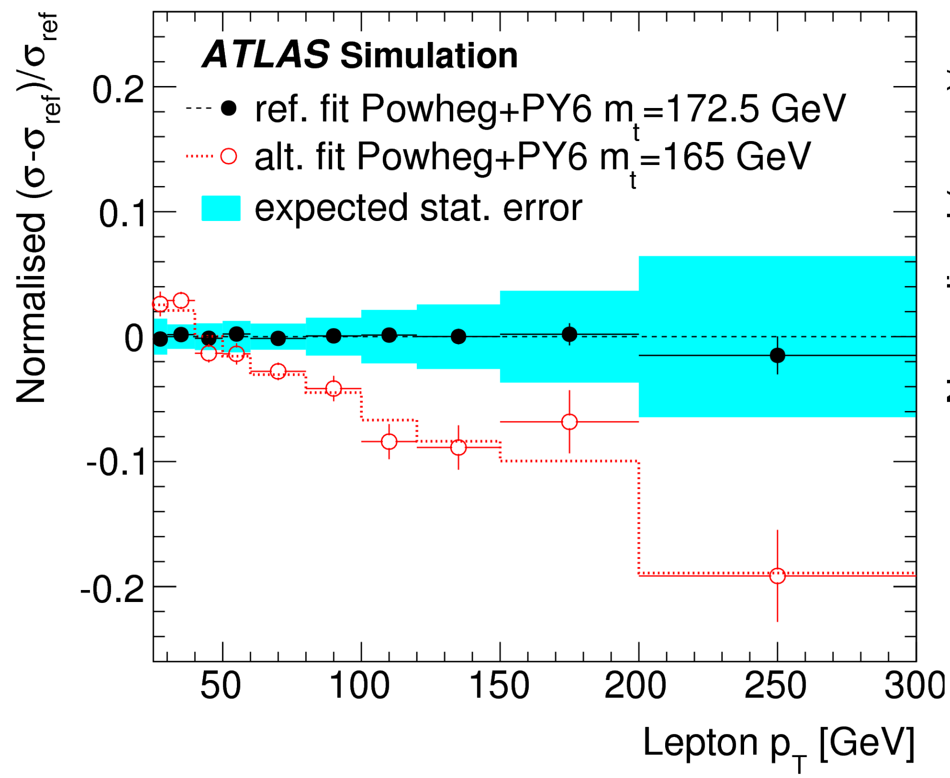
✓ number of leptonic variables **reduces generator bias in extraction**

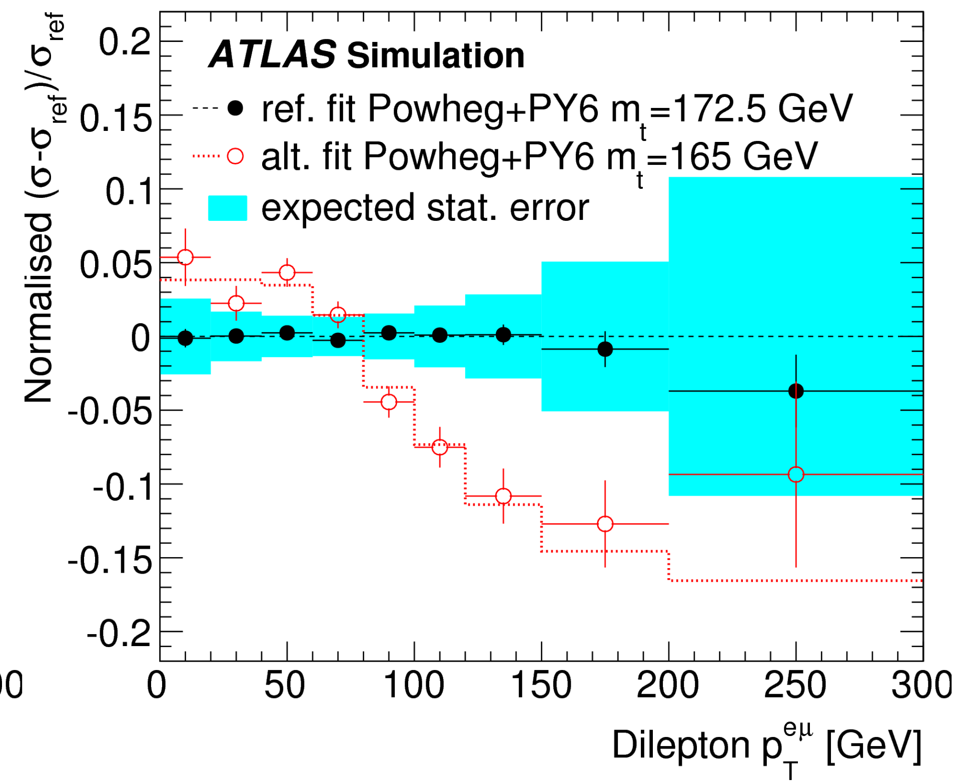
2 methods:

- **template fits:** minimise χ^2 by varying m_t in the calculation
- **Mellin moments:** can be fitted to second order polynomials in m_t

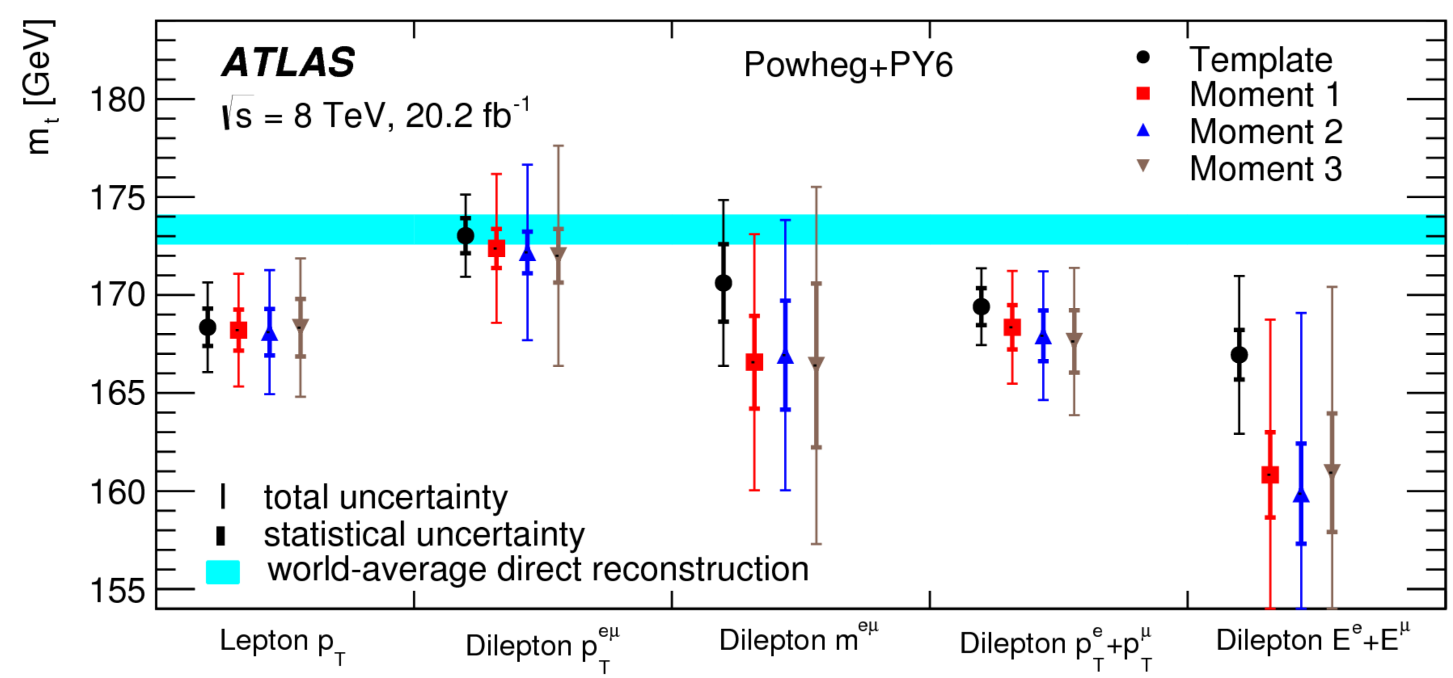
$$\mu^{(k)} = \frac{1}{\sigma_{\text{fid}}} \int x^k D(x)\, \mathrm{d}x$$

$$D(x) \equiv \mathrm{d}\sigma/\mathrm{d}x$$



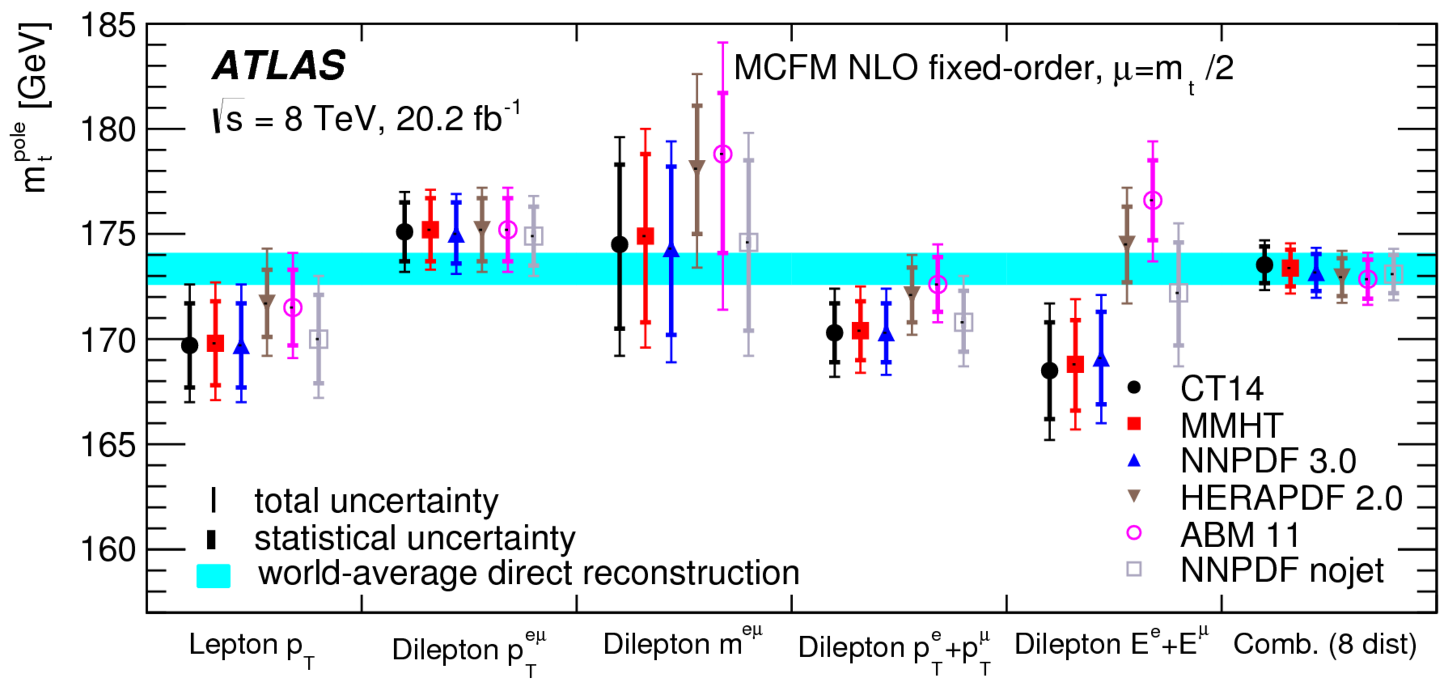


Results limited by missing NNLO corrections and PDF uncertainty ($\Delta m_t \sim 2$ GeV)



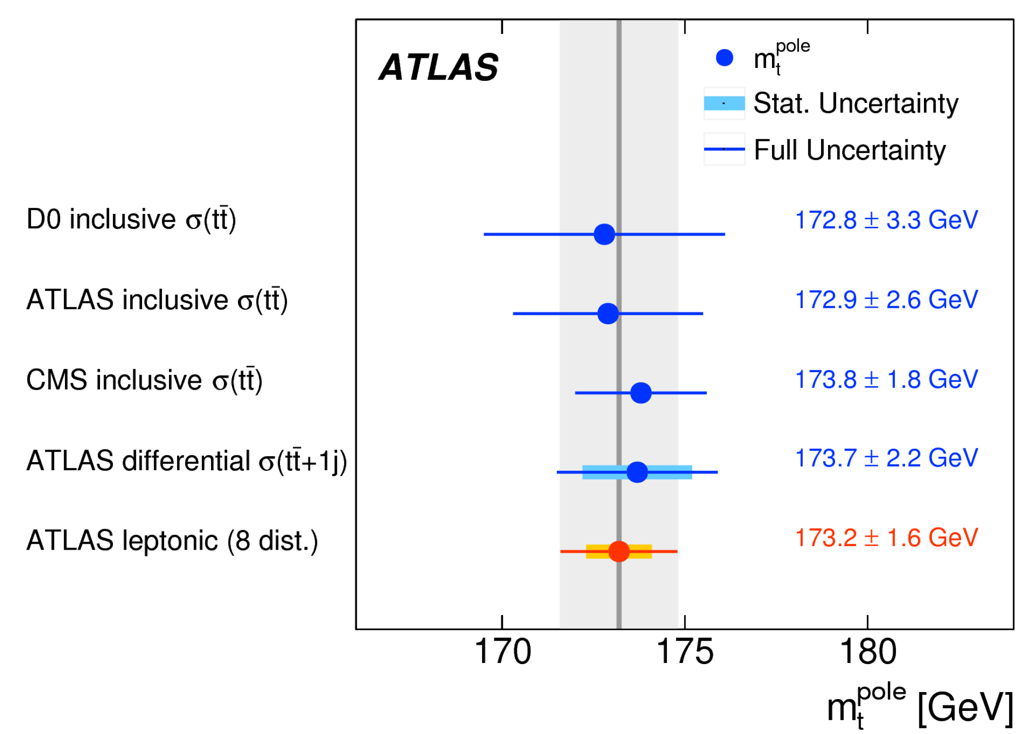
Eur. Phys. J. C 77 (2017) 804

Instead, **comparison with NLO QCD fixed-order predictions (from MCFM):** can either extract per distribution, or with simultaneous combination.
Here, combine 5 previous distributions + |η| of lepton, |y| of dilepton system and Δφ between the leptons.



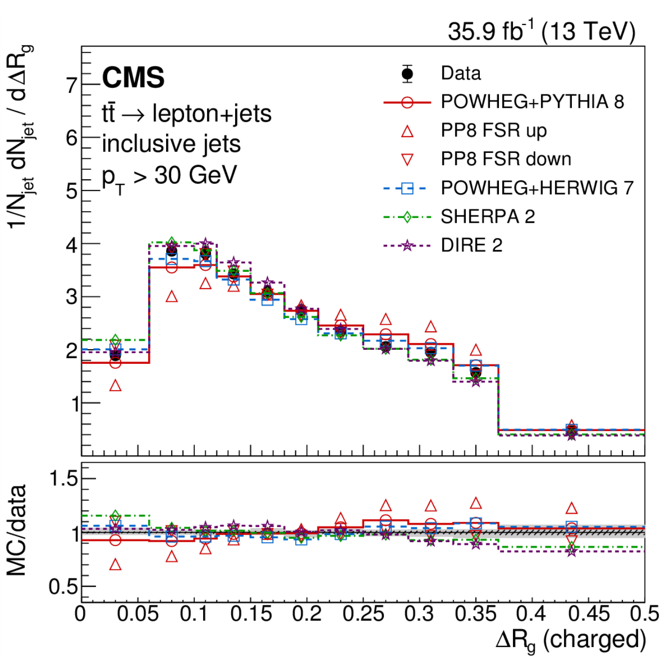
m_t=173.2 ± 0.9 (stat.) ± 0.8 (syst.) ± 1.2 (theo.) GeV, Δ=0.98%

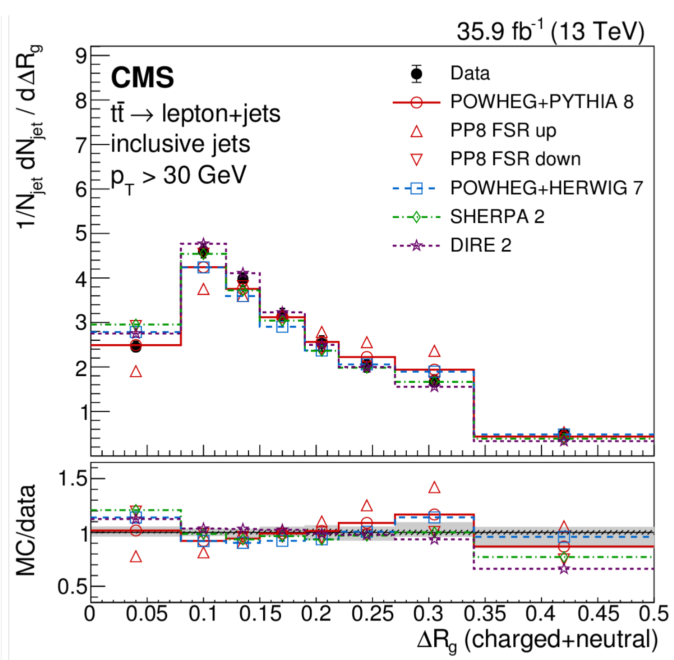
Dominated by QCD scale choice!

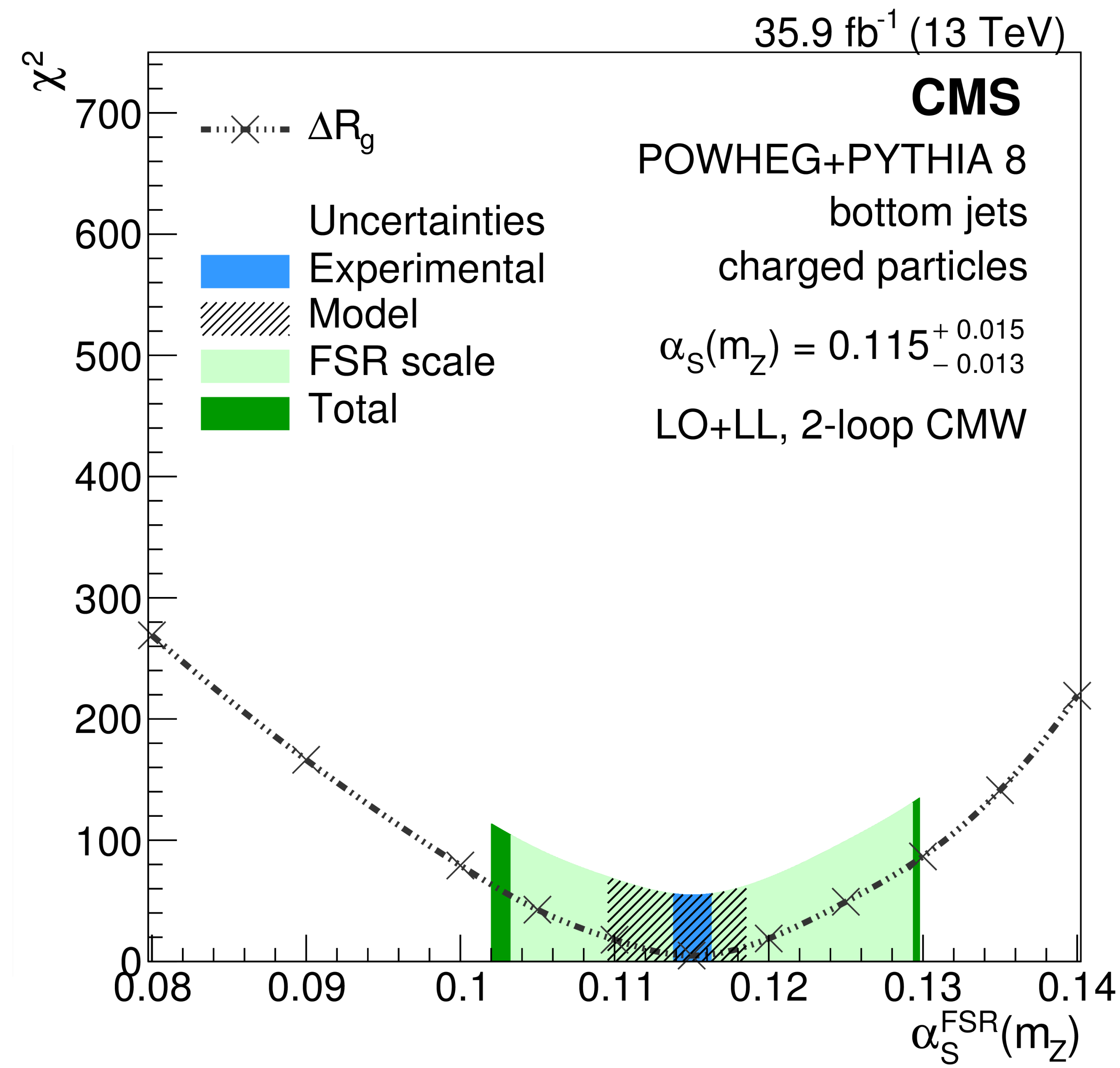


[Phys. Rev. D 98 (2018) 092014](https://doi.org/10.1103/PhysRevD.98.092014)

Use “soft-drop” algorithm to remove soft, wide-angle radiation from the jet.
The angle between two groomed subjets, ΔR_g, is then strongly dependent on the amount of FSR: sensitive to α_s!







$$\alpha_s(M_Z) = 0.115^{+0.015}_{-0.013}\ (\text{total})$$

- Compare observed distribution in b-quark sample (44% of total) to **Powheg+Pythia8 with variations of α_s**
- Systematics largely dominated by **FSR scale uncertainties**
- Measurement can be improved once **next-leading-log accuracy parton showers** for top quark decays are available