Top Quark Physics
Summary & Discussion

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SM@LHC-2019, Zürich, April 26, 2019

Outline of Session

- Top as background (to Higgs)
- Top cross sections and distributions
- Top properties
- Rare processes

In the following, few highlights linked to each other to some extent.

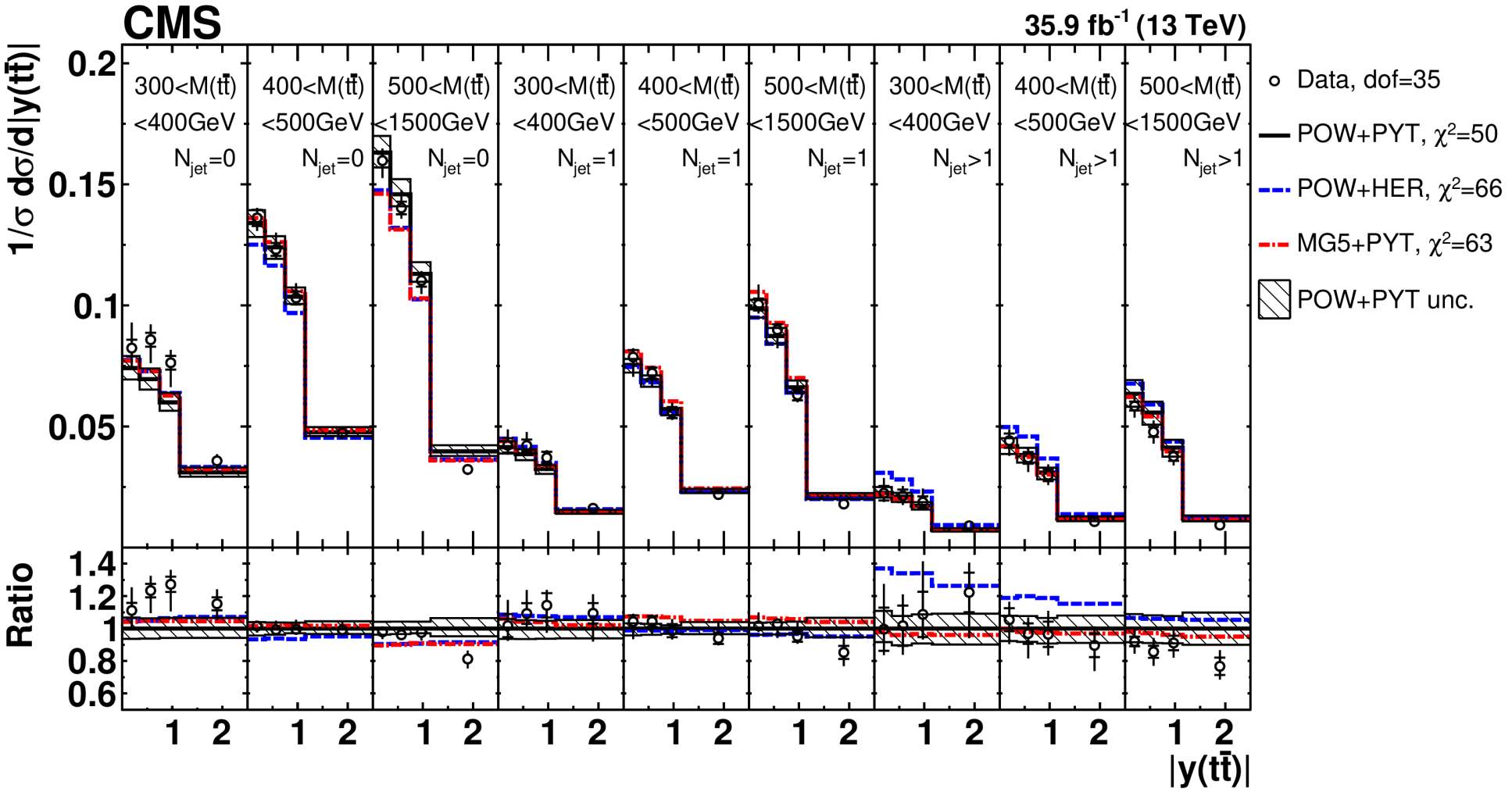
Cross Sections and properties

The status of Top cross section measurements (Dell'Asta), in comparison with theoretical calculations (Czakon, Zaro, Siegert) is a good example of progress interplay in the experimental and theoretical aspects.

- Differential distributions in $t\bar{t}$ production are being constantly refined
- Differential distributions in single top begin to appear.
- NNLO calculation now extended to include top decay!
- Also new, from the theory side: NNLO $t\bar{t}$ in q_t subtraction, Catani,Devoto,Grazzini,Kallweit,Mazzitelli,2019
- Investigation of top properties rely now upon very accurate calculations of cross sections.

$t\bar{t}$ (dilepton) multi-differential cross section

New



⟶ See talk by Lucio Cerrito

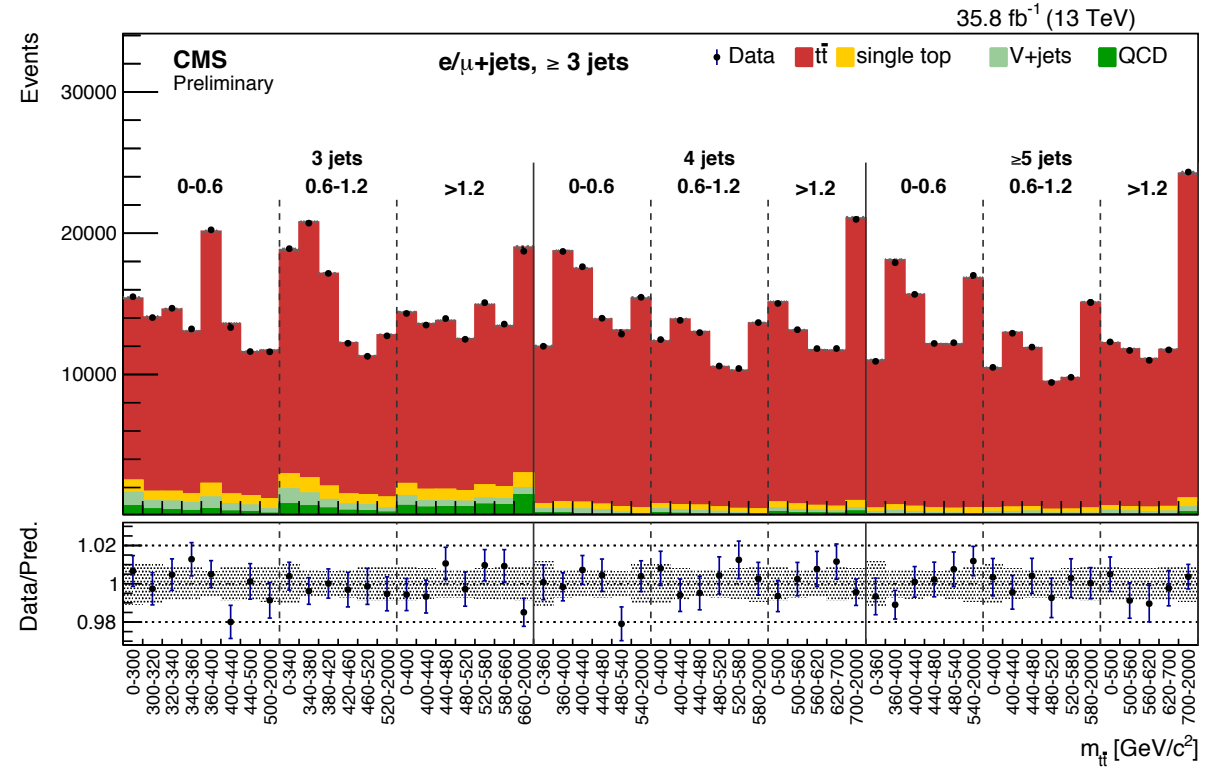
TOP-YUKAWA COUPLING

NEW

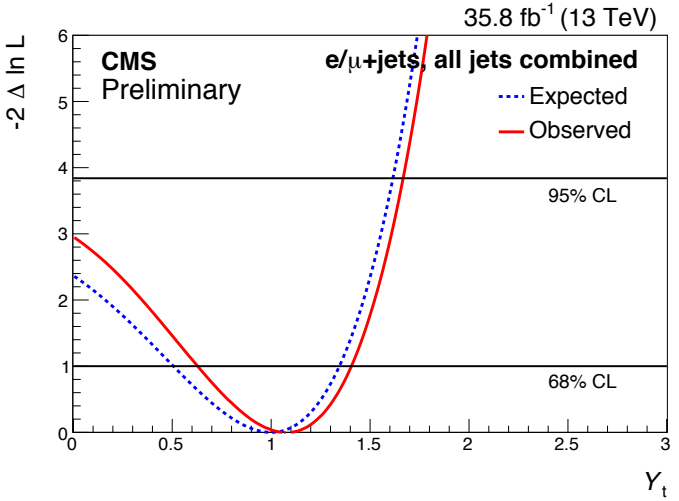
CMS-PAS-TOP-17-004

13 TeV, 35.8 fb^{-1}

Separate N_{jet} Regions: M_{tt} distribution in Δy bins



Combined fit. Best Y_{top}



Ratio to predicted value: $Y_{top} < 1.67$ (95% C.L.)

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	$Y_t < 1.62$	$Y_t < 1.67$

SPIN CORRELATION

Previous ATLAS and CMS measurements have shown slighly stronger spin correlation in $\Delta\varphi$ than expected in, but still consistent with, the Standard Model

Signature: 2 isolated OS e/μ & ≥2 jets (≥1 *b or* ≥2 *b*).

Method: Inclusive (≥1 *b*) and *tt*-reconstructed (≥2 *b*) selections.

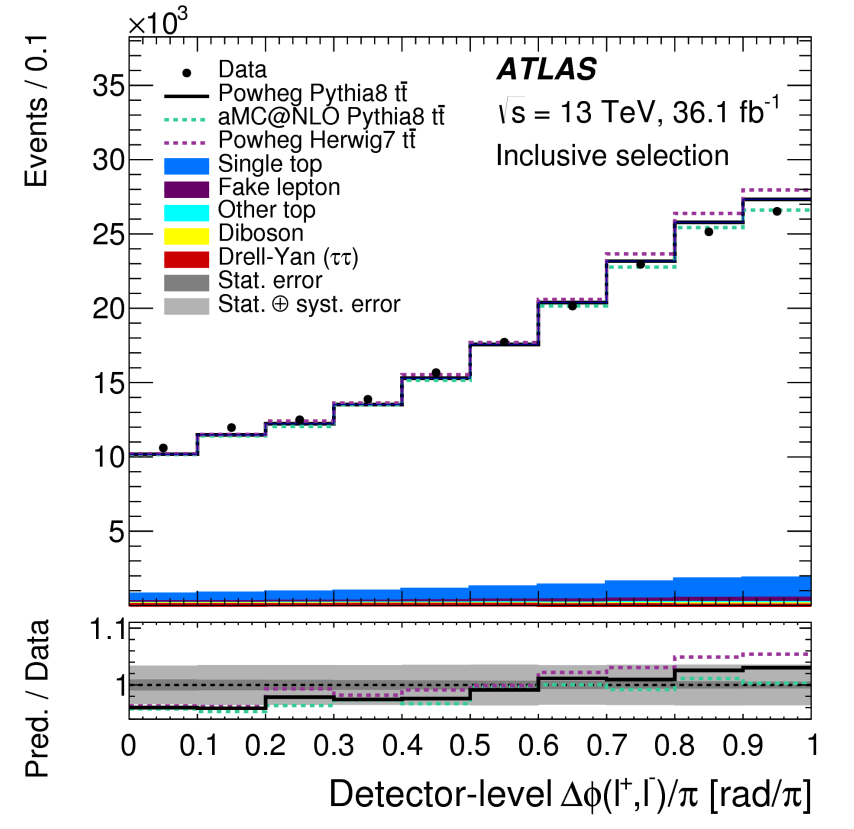
Differential in M_{tt}, Parton and Particle Level

NEW

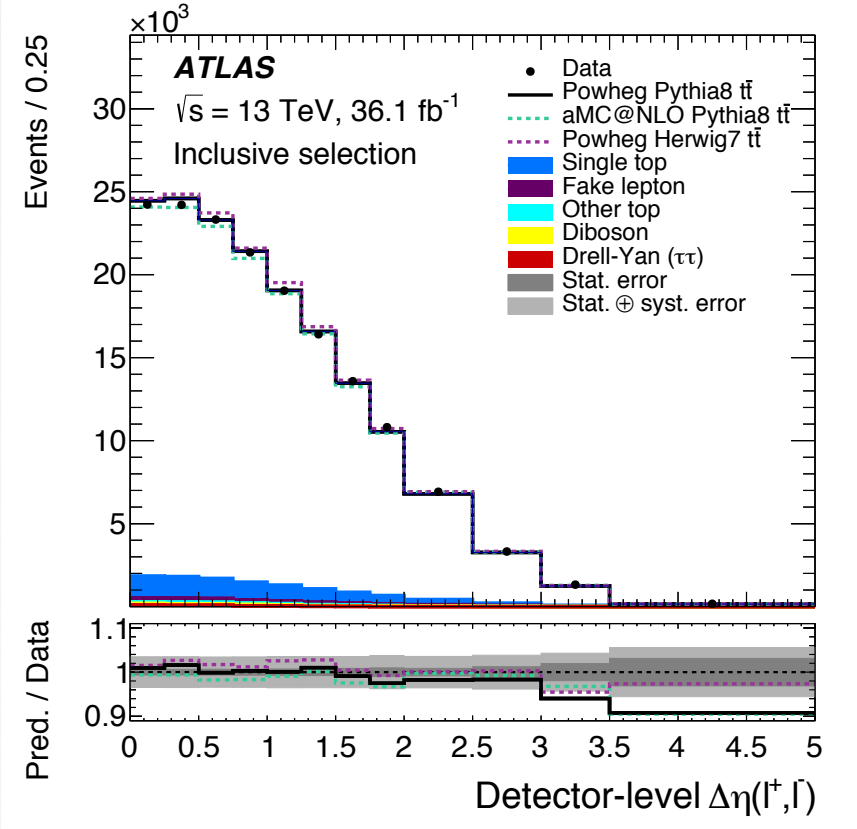
Submitted to EPJC 18th March 2019:
arXiv:1903.07570 (2019)
Follows 5 previous publications.

13 TeV, 36.1 fb^{-1}

Azimuthal opening angle (detector level) - Inclusive Selection



Pseudorapidity separation (det. level) - Inclusive Selection



Systematic Bands: uncertainties excluding PDFs and signal modelling

Not self-normalised (NNLO scaling)

POLARISATION & SPIN CORRELATION

NEW

CMS-PAS-TOP-18-006
Released December 2018

13 TeV, 35.9 fb^{-1}

Signature: 2 isolated OS e/μ (incl. same flav.) & ≥2 jets (≥1 *b*).
Method: Normalised differential cross sections. Parton-level to full phase space.

$$|\mathcal{M}(q\bar{q}/gg \to t\bar{t} \to (\ell^+\nu b)(\ell^-\bar{\nu}\bar{b}))|^2 \sim Tr[\rho R \bar{\rho}].$$

R: spin density matrix for on-shell ttbar production

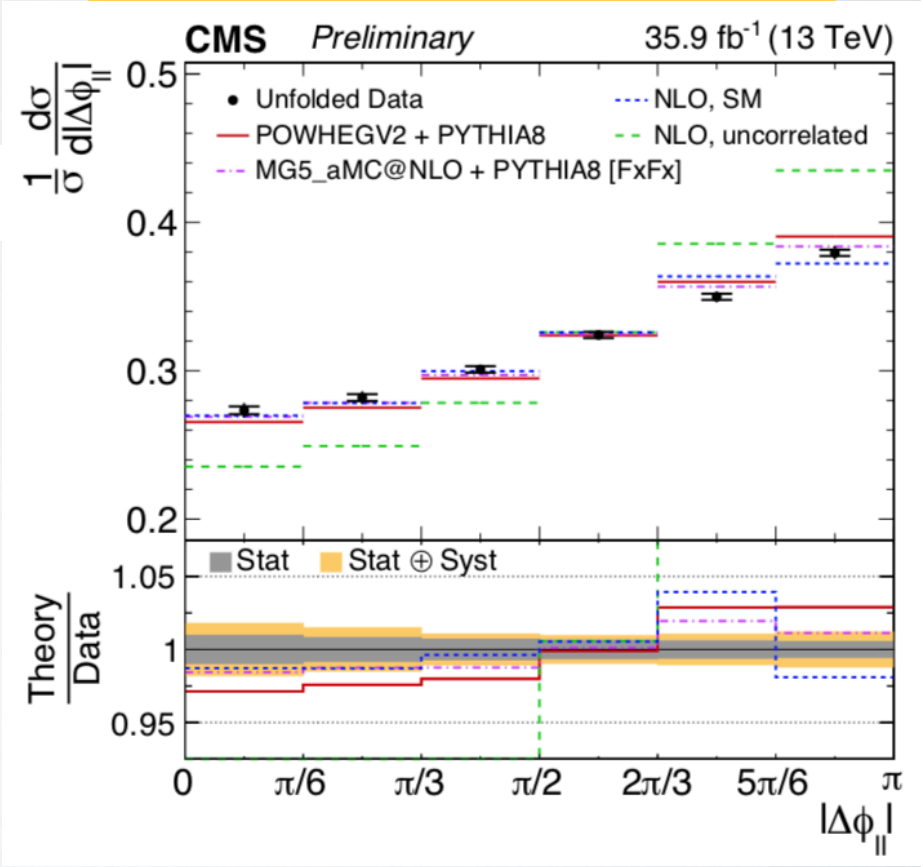
Production Density Matrix as described in: W. Bernreuther, D. Heisler, and Z.-G. Si, JHEP 12 (2015) 026, doi:10.1007/JHEP12(2015)026, arXiv:1508.05271.

$$R \propto \tilde{A}\mathbb{1}\otimes\mathbb{1} + \tilde{B}_i^+\sigma^i\otimes\mathbb{1} + \tilde{B}_i^-\mathbb{1}\otimes\sigma^i + \tilde{C}_{ij}\sigma^i\otimes\sigma^j,$$

polarisations spin correlations

- Each of the 15 coefficients extracted from normalised differential cross sections at parton level
- Also measured: $|\Delta\varphi_{\ell\ell}|$,the difference in azimuthal angle φ between the two leptons in the laboratory frame

Parton Cross Section, Azimuthal opening angle

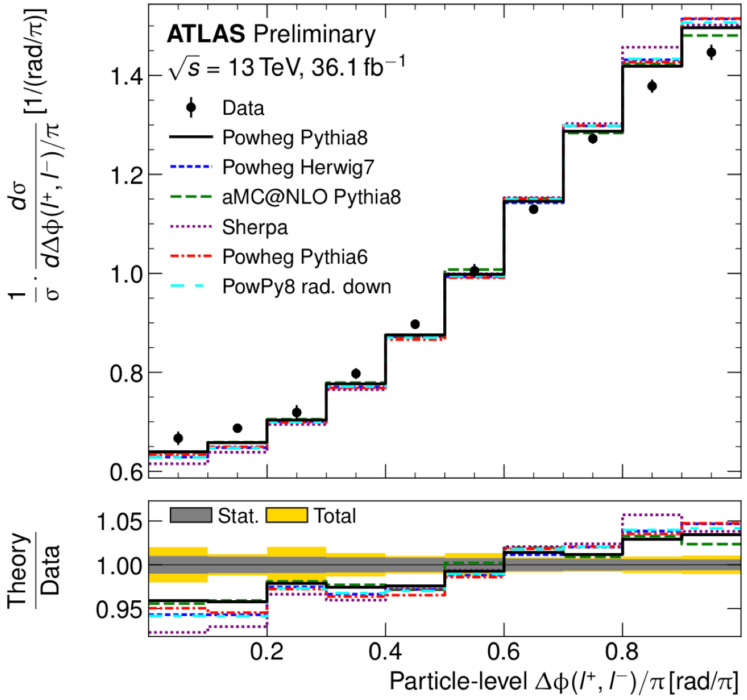


Normalised Cross section

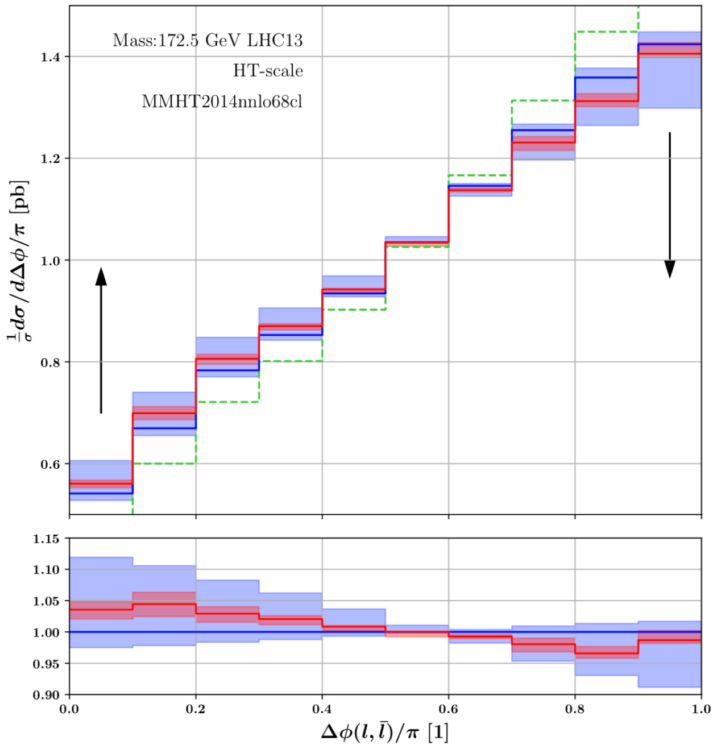
Exact NWA results @ NNLO

- Application in case of data/theory discrepancies

ATLAS-CONF-2018-027



NWA @ NNLO predictions



Behring, MC, Mitov, Papanastasiou, Poncelet `18

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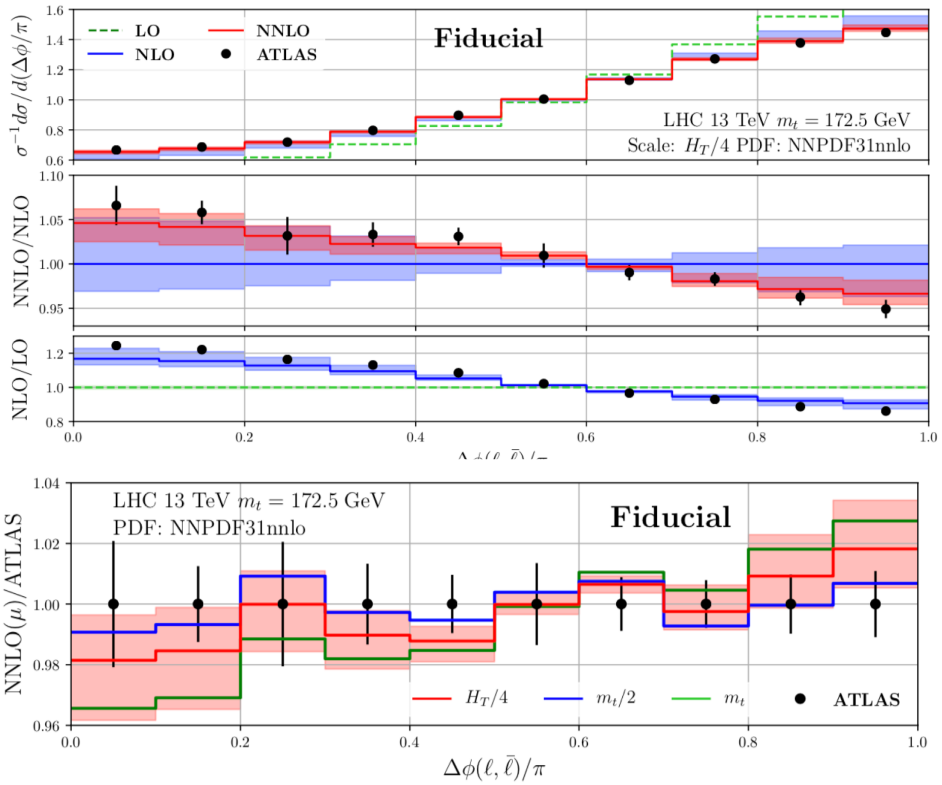
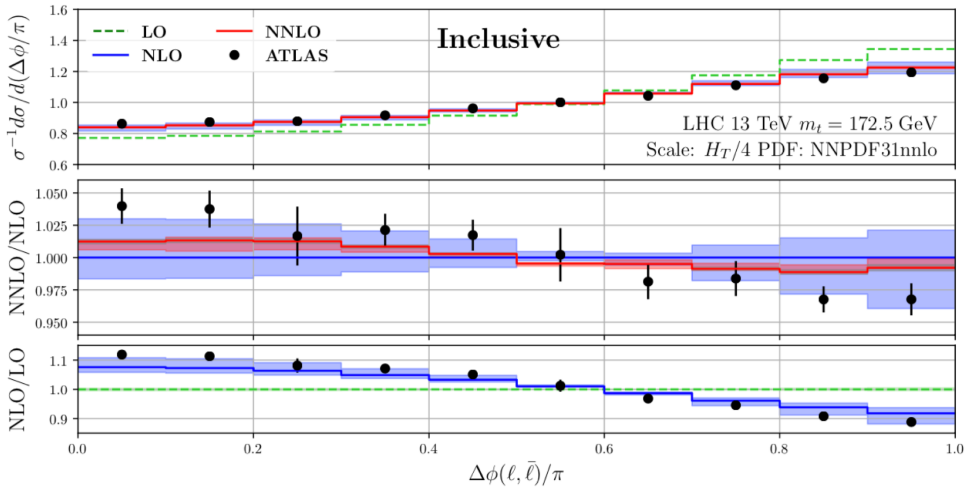
Exact NWA results @ NNLO

- Fine-tuned analysis reveals shortcomings in full phase space extrapolation



Negligible sensitivity to:

1. Top quark mass
2. Parton Distribution Functions
3. Electroweak effects
4. Radiation in the decay



Behring, MC, Mitov, Papanastasiou, Poncelet `19

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Spin Correlations

Deviation of the order of few percent from predictions!

Theoretical NNLO results indicate that comparable variations in prediction are obtained by alternative choices of central scales.

Establishing-dismissing deviations linked to the choice of an "optimal" scale.

A question for everybody: where do we draw the line?
What is our error?

Karlsruher Institut für Technologie

TRR 257 - Particle Physics Phenomenology after the Higgs Discovery

KIRILL MELNIKOV (TTP KIT)

TOP MASS: THE WORDS OF WISDOM

SM@LHC 2019

The Top Mass

My favourite words of wisdom from Kirill's talk:

A mass parameter extracted from a measurement depends mostly on an observable rather than a simulation tool

Other things that we get out:

- Things seem difficult because they are!
- Don't say: we just measure the Monte Carlo mass, let the theorists sort it out ...
- Don't be afraid to think!

TOP QUARK MASS: INDIRECT

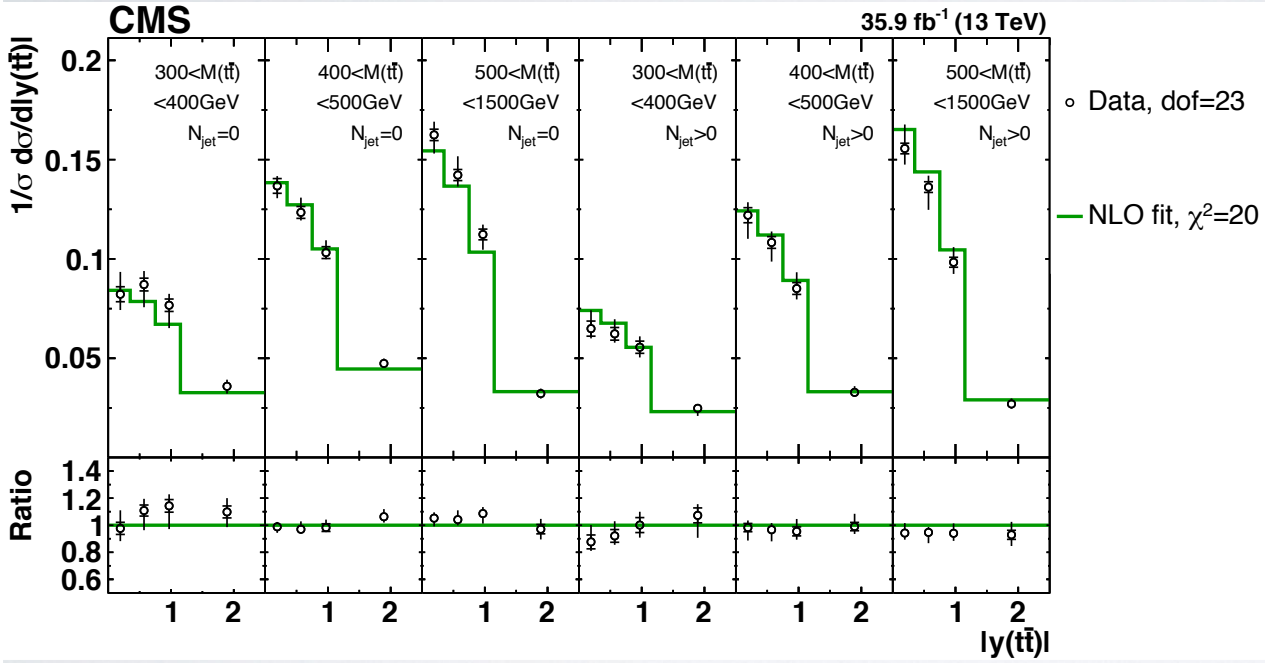
NEW

arXiv:1904.05237 (2019)

13 TeV, 35.9 fb^{-1}

- Final values determined from a simultaneous fit to m_{top}, PDF, α_S in XFITTER

Triple-differential cross section and NLO prediction with best-fit m_{top}, $\alpha_S(m_Z)$, PDFs



Parameter	Variation	$\alpha_S(m_Z)$	m_t^{pole} [GeV]
	Fit uncertainty		
Total	$\Delta\chi^2 = 1$	±0.0016	±0.7
	Model uncertainty		
f_s	$f_s = 0.5$	$+0.0001$	0.0
f_s	$f_s = 0.3$	0.0000	0.0
Q^2_{min}	$Q^2_{min} = 5.0\,GeV^2$	$+0.0002$	$+0.1$
Q^2_{min}	$Q^2_{min} = 2.5\,GeV^2$	-0.0004	-0.1
M_c	$M_c = 1.49\,GeV$	$+0.0001$	0.0
M_c	$M_c = 1.37\,GeV$	0.0000	0.0
Total		$^{+0.0002}_{-0.0004}$	$^{+0.1}_{-0.1}$
	PDF parametrisation uncertainty		
$\mu^2_{f,0}$	$\mu^2_{f,0} = 2.2\,GeV^2$	-0.0001	0.0
$\mu^2_{f,0}$	$\mu^2_{f,0} = 1.6\,GeV^2$	$+0.0002$	0.0
A'_g	set to 0	$+0.0002$	-0.1
E_g	set to 0	$+0.0008$	0.0
Total		$^{+0.0008}_{-0.0001}$	-0.1
	Scale uncertainty		
μ_r variation	$\mu_r = H$	$+0.0004$	-0.2
μ_r variation	$\mu_r = H/4$	$+0.0007$	$+0.1$
μ_f variation	$\mu_f = H$	-0.0002	$+0.3$
μ_f variation	$\mu_f = H/4$	$+0.0001$	-0.3
$\mu_{r,f}$ variation	$\mu_{r,f} = H$	$+0.0004$	$+0.1$
$\mu_{r,f}$ variation	$\mu_{r,f} = H/4$	$+0.0011$	-0.2
alternative $\mu_{r,f}$	$\mu_{r,f} = H/2$	-0.0005	$+0.1$
Total		$^{+0.0011}_{-0.0005}$	$^{+0.3}_{-0.3}$

$$\alpha_S(m_Z) = 0.1135 \pm 0.0016(\text{fit})^{+0.0002}_{-0.0004}(\text{model})^{+0.0008}_{-0.0001}(\text{param})^{+0.0011}_{-0.0005}(\text{scale}) = 0.1135^{+0.0021}_{-0.0017}(\text{total}),$$

$$m_t^{pole} = 170.5 \pm 0.7(\text{fit}) \pm 0.1(\text{model})^{+0.0}_{-0.1}(\text{param}) \pm 0.3(\text{scale})\,\text{GeV} = 170.5 \pm 0.8(\text{total})\,\text{GeV}.$$

TOP QUARK MASS: DIRECT/INDIRECT

NEW

arXiv:1812.10505 (2018)
Accepted by EPJC

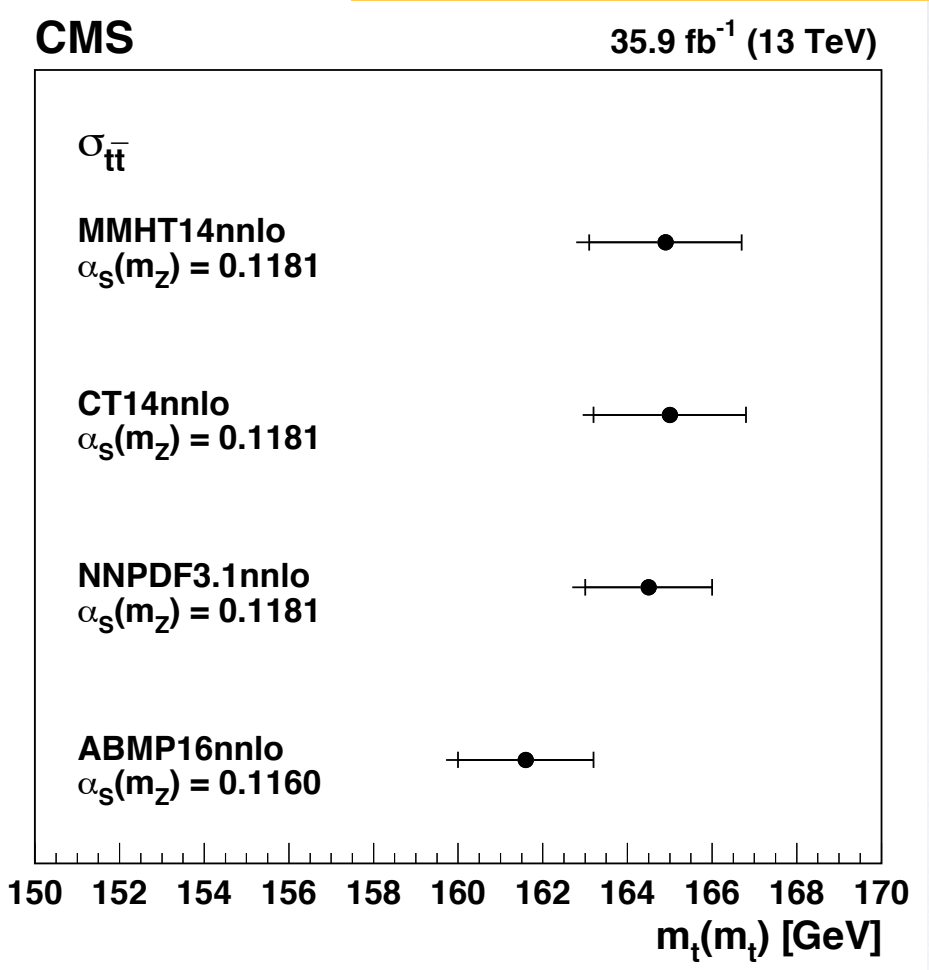
13 TeV, 35.9 fb^{-1}

Signature: 2 isolated OS e/μ & ≥2 jets (≥1 *b*). Multi-categories

Method: (1) Fit to multi differential distributions for the direct top mass via dependence in the signal acceptance, efficiency and m_{lb}^{min}.
(2) Use theoretical calculation of the absolute cross section to determine the indirect top mass (MSbar- and pole- schemes) and α_S (M_Z)

See dedicated talk by M. Defranchis, on 25 April !!

Extraction in the MSBar scheme



Direct top mass from the acceptance/ efficiency dependence, and m_{lb}^{min}:

$$172.33 \pm 0.14\,(\text{stat})\,^{+0.66}_{-0.72}\,(\text{syst})\,\text{GeV}$$

Fit for the indirect MSbar mass, then converted to the pole mass scheme:

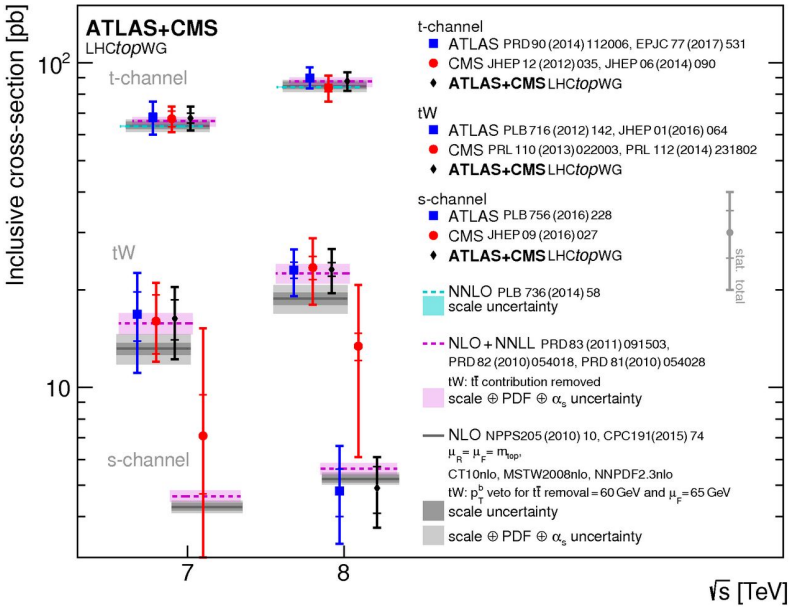
PDF set	m_t^{pole} [GeV]
ABMP16	$169.9 \pm 1.8\,(\text{fit} + \text{PDF} + \alpha_S)\,^{+0.8}_{-1.2}\,(\text{scale})$
NNPDF3.1	$173.2 \pm 1.9\,(\text{fit} + \text{PDF} + \alpha_S)\,^{+0.9}_{-1.3}\,(\text{scale})$
CT14	$173.7 \pm 2.0\,(\text{fit} + \text{PDF} + \alpha_S)\,^{+0.9}_{-1.4}\,(\text{scale})$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

Top Mass: Indirect

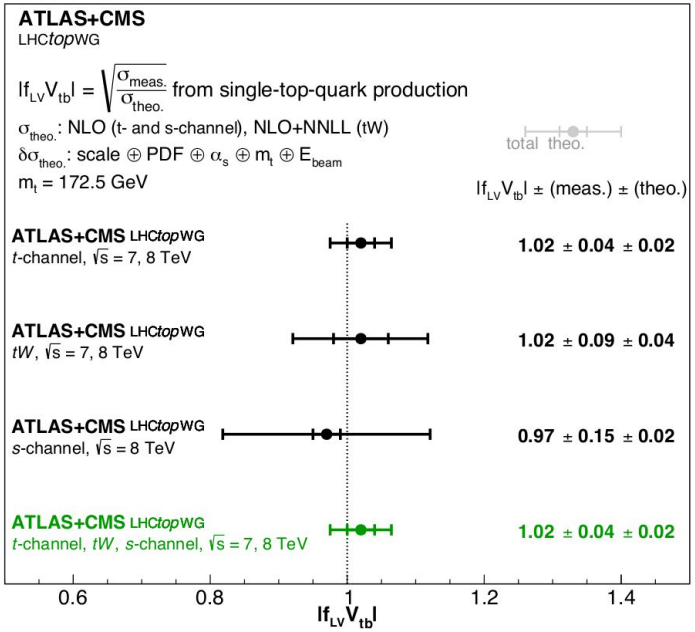
Multidifferential: Is NLO really enough for that precision?

What is driving the error so small? Where does the mass come from?

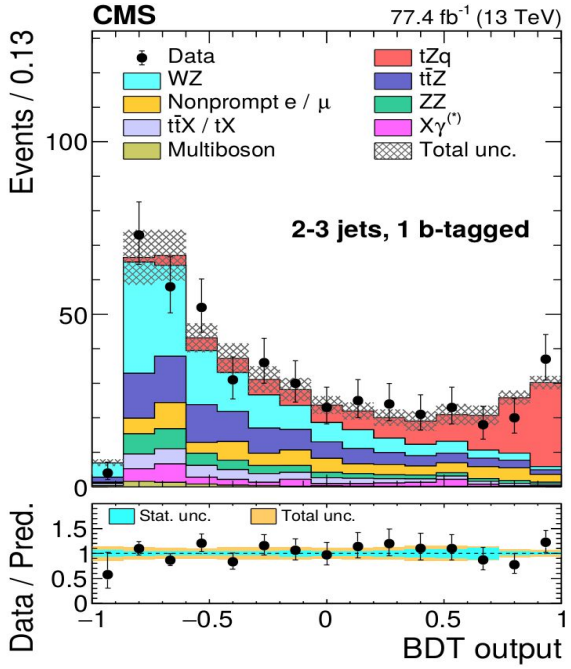
Single Top and more!



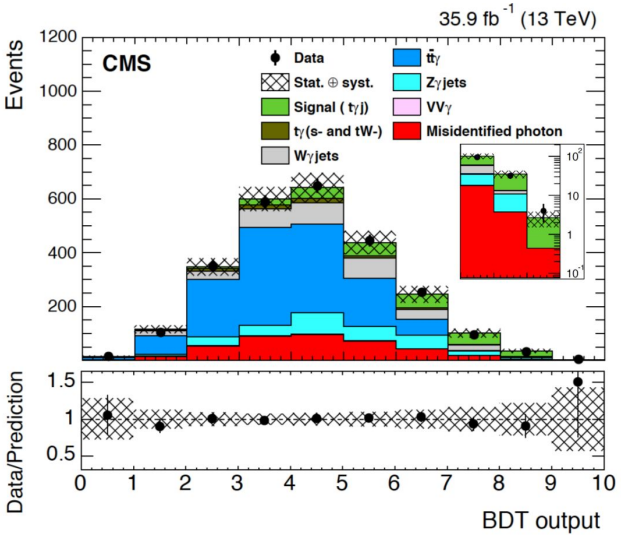
Dominant modes precisely measured, $|V_{tb}|$ determined



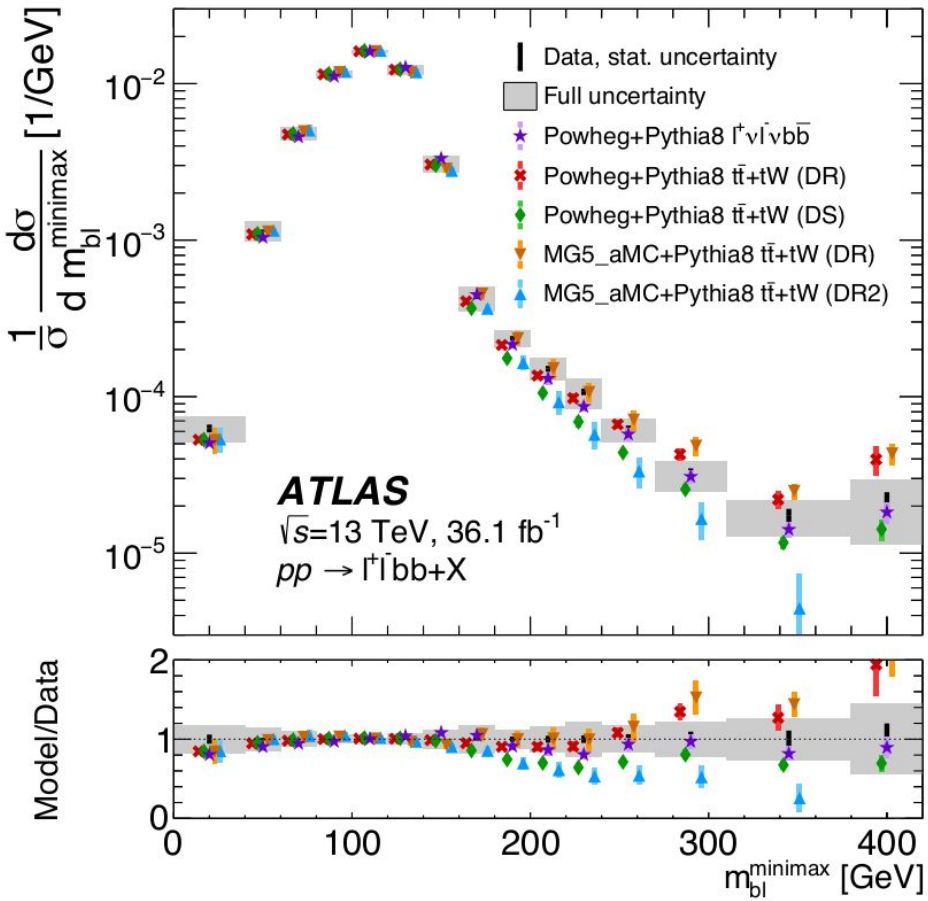
Rare t + Z: Obs by CMS >5σ!



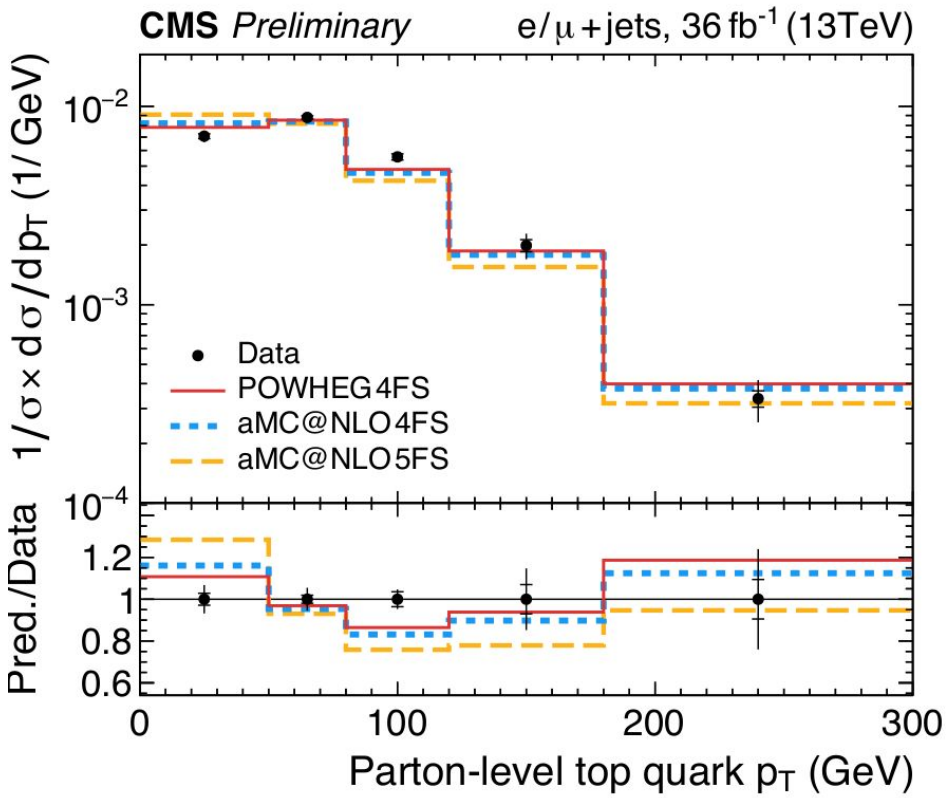
Rare t + γ: Evidence!



Single Top and more!

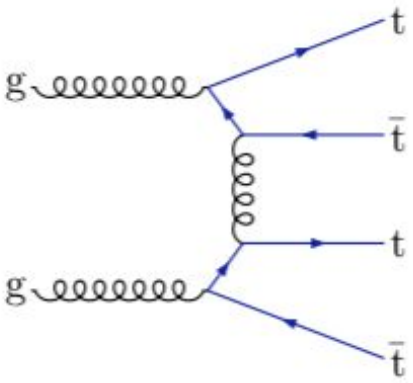


tt-tW interference



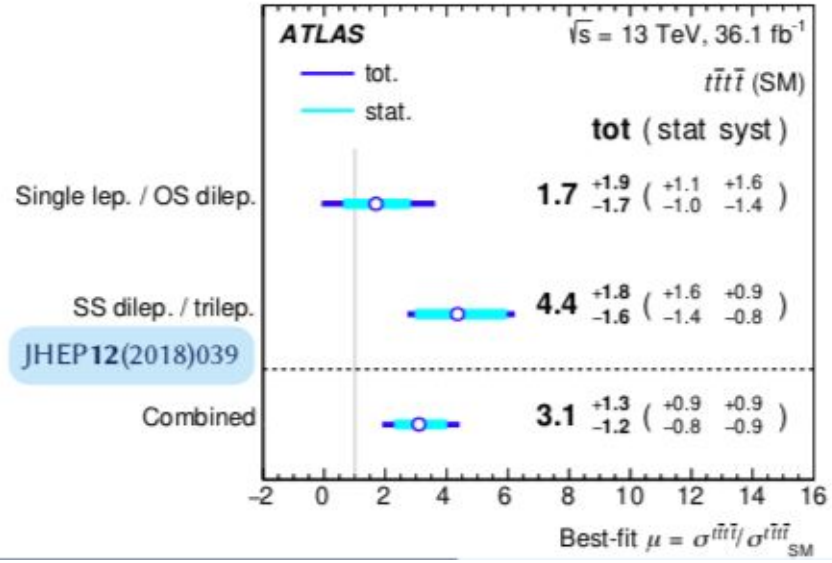
top pT test in another phase space

Tops! Tops! Tops!



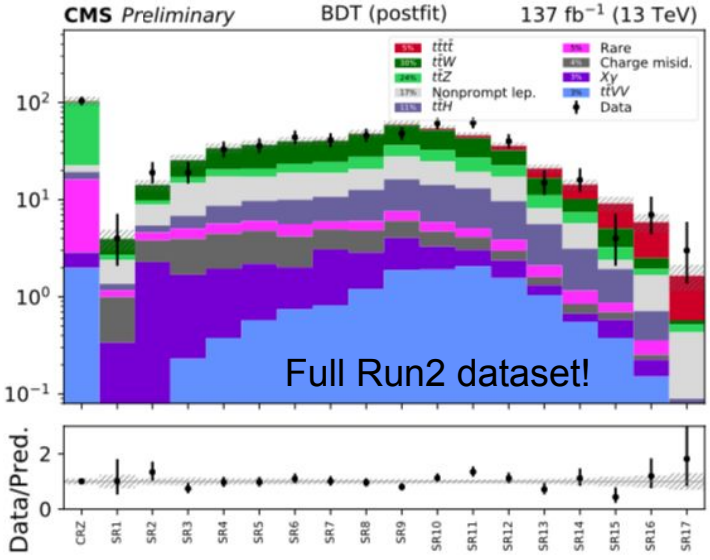
Four-tops production: complex topology, background to ttH, possibly enhanced by BSM

Observed (expected) upper limit:
47(33) fb, i.e. $5.1(3.6^{+2.9}_{-1.8}) \times$ SM



Observed (expected) upper limit:
22.5 fb ($8.4^{+3.9}_{-2.6}$) (BDT)

Best-fit: $12.6^{+5.8}_{-5.2}$ fb, $2.6(2.7)\sigma$ from zero



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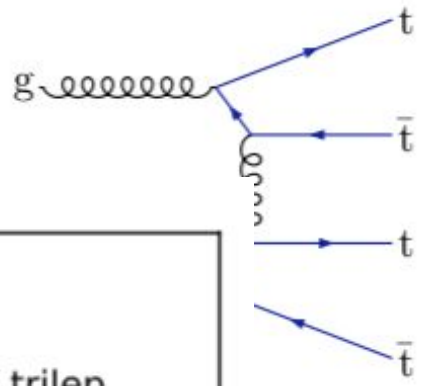
Tops! Tops! Tops!



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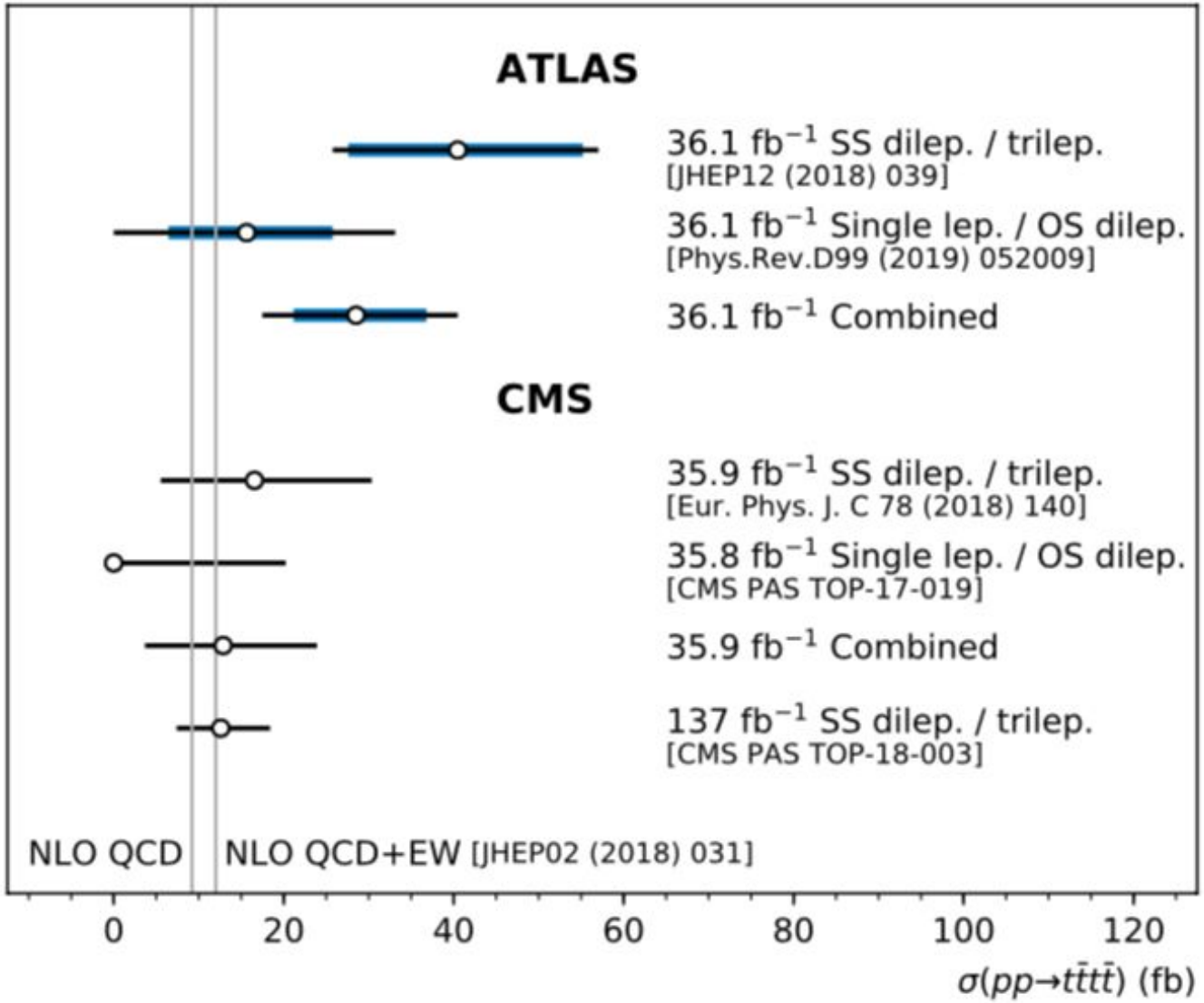

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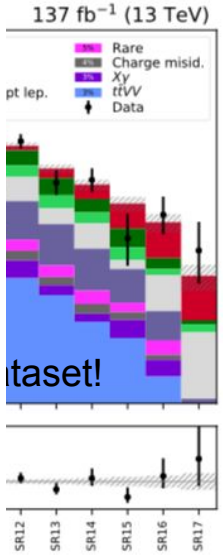
σ from zero



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Summary

- Many interesting new results, both in rare proesses and in the most common ones.
- Most debatable issues in very well measured ones (precision is hunting us?).
- Spin correlations: 5% effect! Is theory that accurate? What attitude should we have towards theory errors? Does EFT interpretation help in using theoretical progress in the most productive way?
- Top mass: what attitude? The traditional one (MC mass vs Pole or MSbar mass) is not very productive ... (see also Hang,P.N.,Corcella,Yokoya in the High Luminosity-High Energy workshop report).
- Fiducial phase-space differential cross sections combination a la Higgs?