Top physics at LHC
[ATLAS-biased]

Fellini
Fellowship for Innovation at INFN

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Outline

1. Top physics at the Large Hadron Collider (LHC)

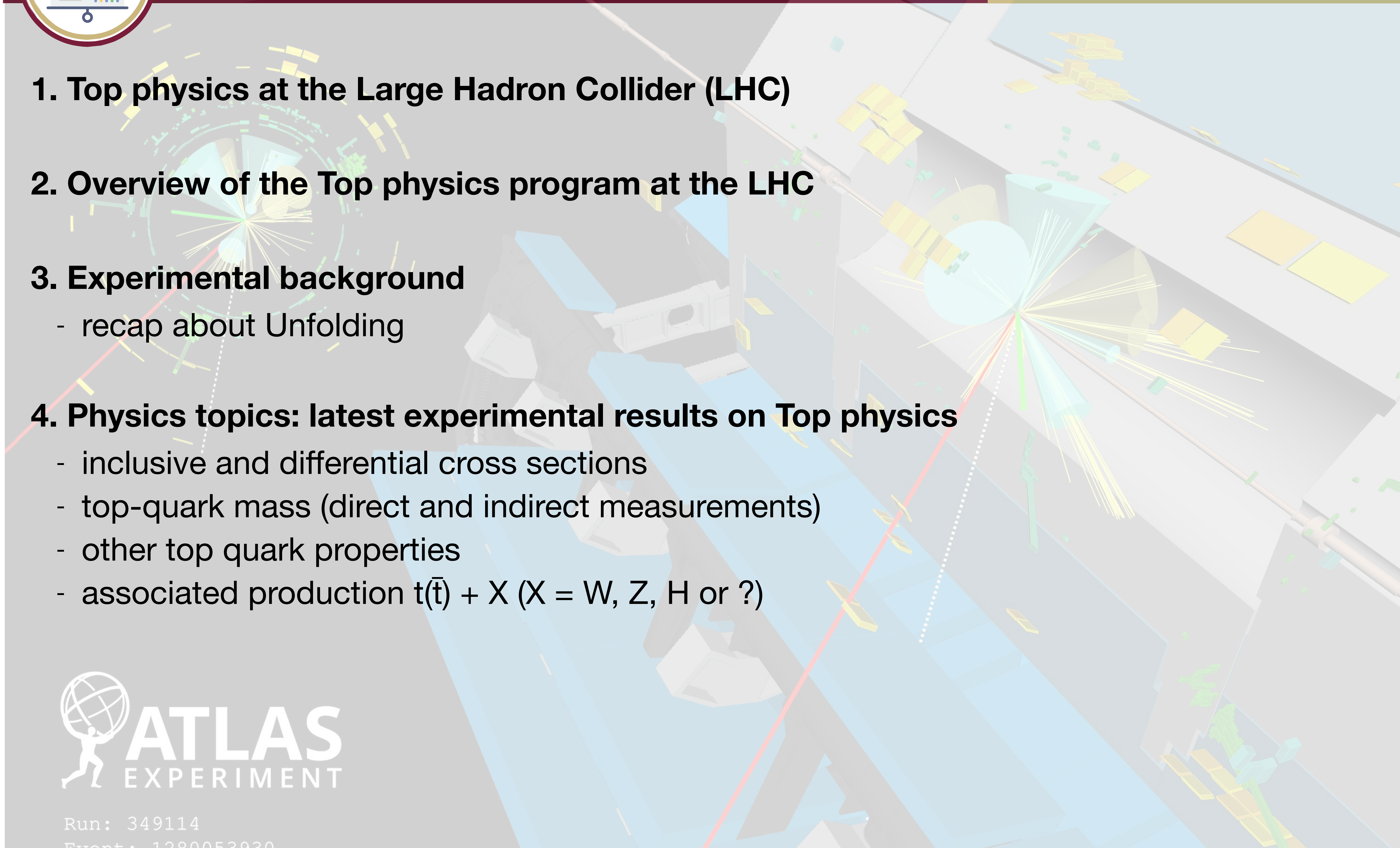
2. Overview of the Top physics program at the LHC

3. Experimental background

- recap about Unfolding

4. Physics topics: latest experimental results on Top physics

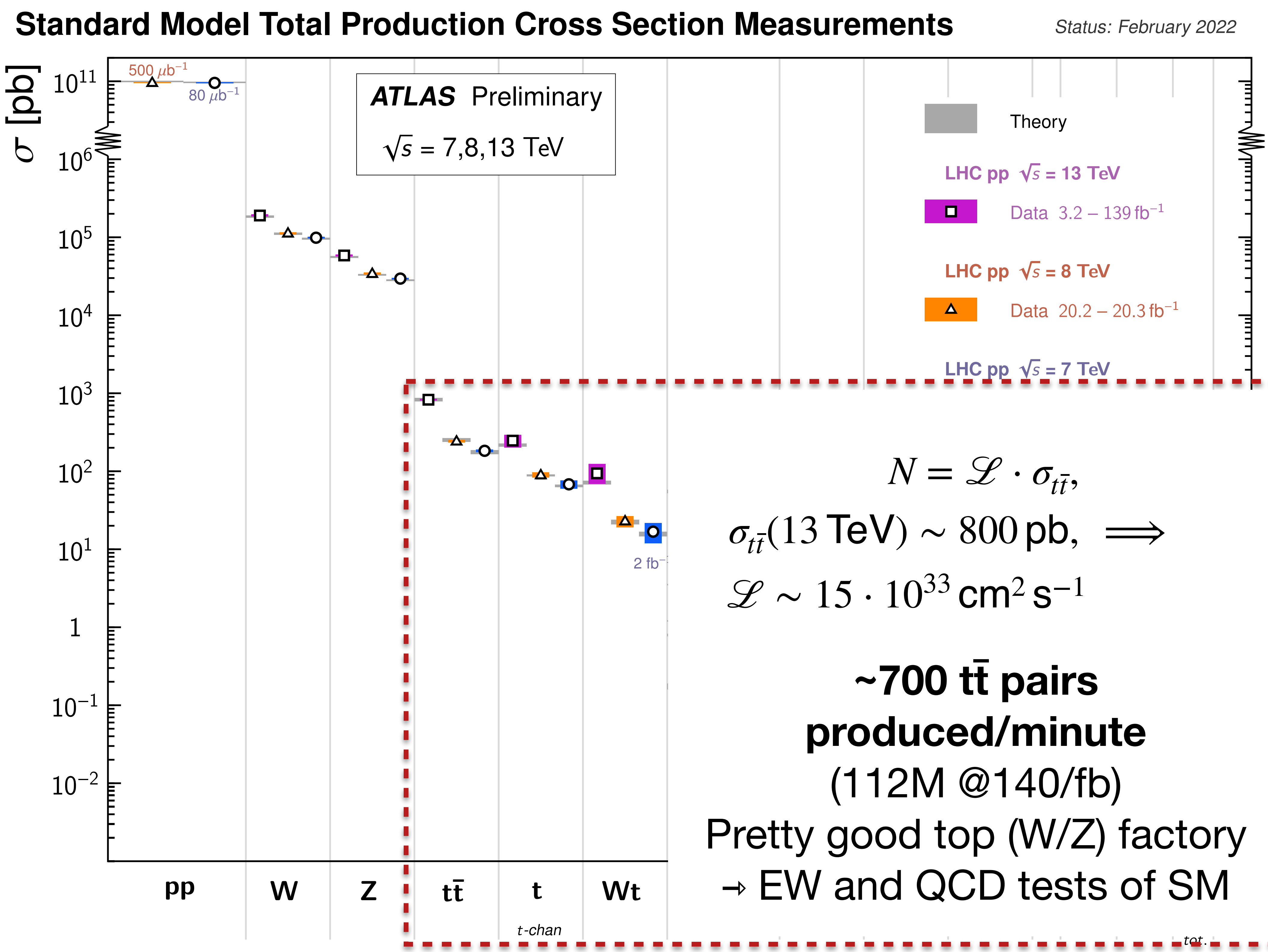
- inclusive and differential cross sections
- top-quark mass (direct and indirect measurements)
- other top quark properties
- associated production $t(\bar{t})$ + X (X = W, Z, H or ?)



About the event display: Four-top candidate from 2018. Event display of a candidate four-top-quark event (Run 349114, Event 1280053930) with seven jets (four of them are b-tagged); two of the top quarks decay leptonically (one with a resulting muon, shown in red, and one with an electron, shown in green), and two top quarks decay hadronically. Green rectangles correspond to energy deposits in cells of the electromagnetic calorimeter, while yellow rectangles correspond to energy deposits in cells of the hadron calorimeter. The jets (b-tagged jets) are shown as yellow (blue) cones. The direction of the missing transverse momentum is indicated by a dotted line. (Image: ATLAS Collaboration/CERN)

LHC as top factory?

Rate at which process happen



$$N = \mathscr{L} \cdot \sigma_{t\bar{t}},$$
$$\sigma_{t\bar{t}}(13\,\text{TeV}) \sim 800\,\text{pb}, \implies$$
$$\mathscr{L} \sim 15 \cdot 10^{33}\,\text{cm}^2\,\text{s}^{-1}$$

~700 tt̄ pairs produced/minute

(112M @140/fb)

Pretty good top (W/Z) factory

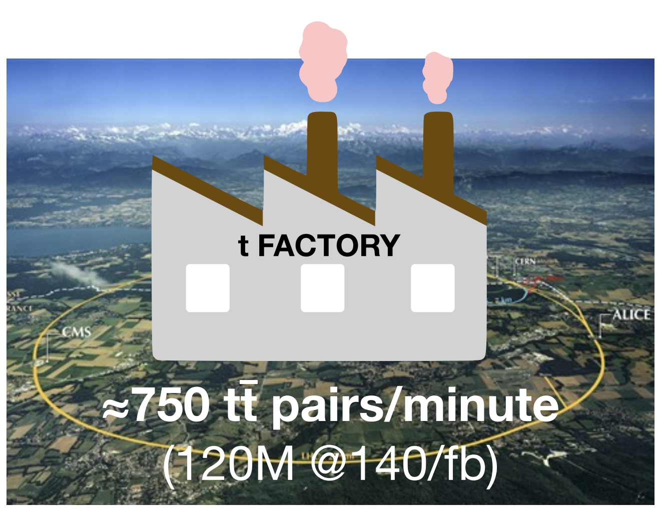
→ EW and QCD tests of SM

The last quark!

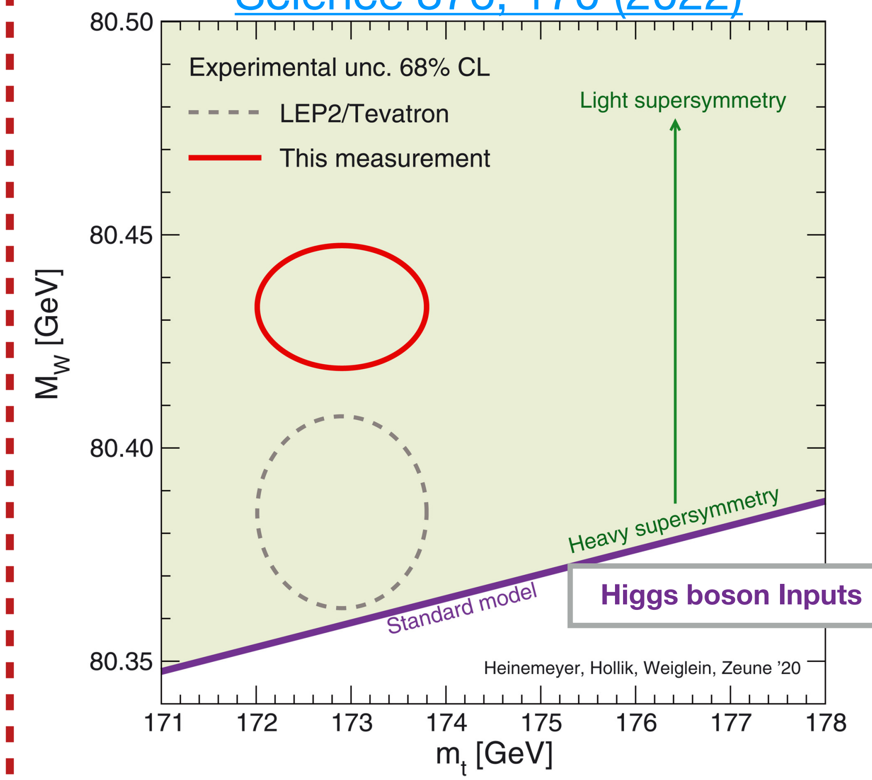
Production time		Decay time		Hadronisation time		Spin-Decorr. time
$\frac{1}{m_t}$	$<$	$\frac{1}{\Gamma_t}$	$<$	$\frac{1}{\Lambda_{QCD}}$	$<$	$\frac{m_t}{\Lambda^2_{QCD}}$
$\sim 10^{-27}$ s		$\sim 10^{-25}$ s		$\sim 10^{-24}$ s		$\sim 10^{-21}$ s

Why top quarks?

- heaviest known particle with unique features: decay time is orders of magnitude shorter than hadronisation or spin de-correlation times → top acts like “bare” quark
- copious production at LHC (top-factory) allows precision tests and search for new physics (Effective Field Theory frameworks)



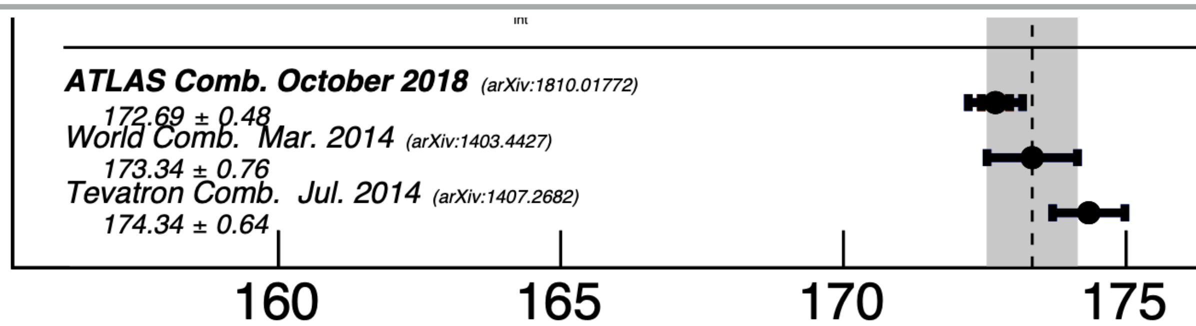
Science 376, 170 (2022)



ATLAS Physics Briefing

Top quark at LHC

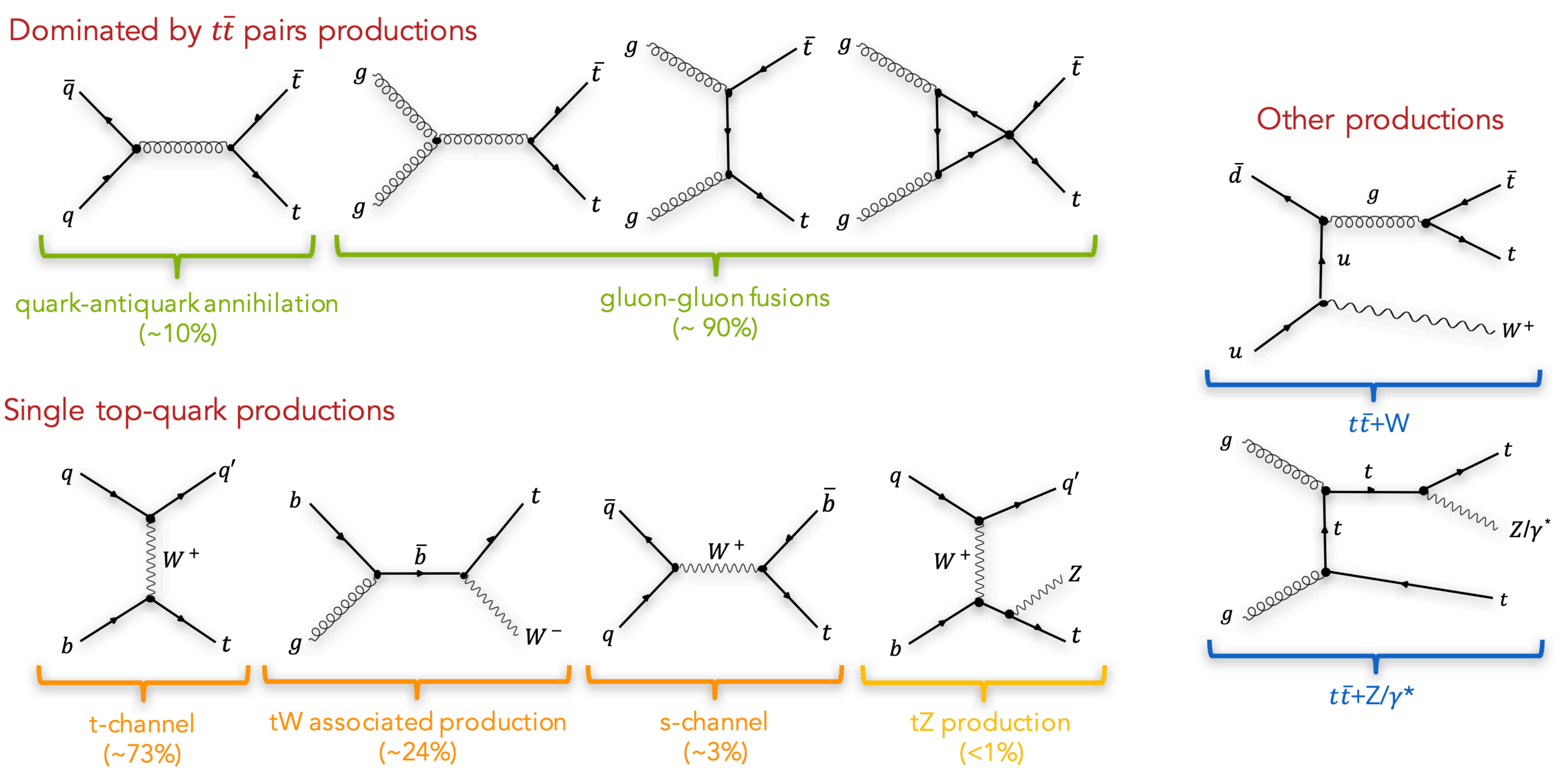
[Top quark on PDG]



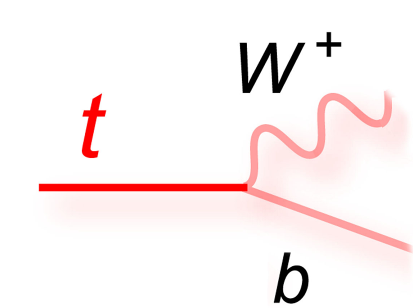
World combination (Tevatron + LHC)

Direct m_t = 173.34± 0.27(stat) ±0.71(syst) GeV

Production modes at pp collider



top decay modes



BR(t → Wb) ≈ 100%
(W on-shell)
Very clear signature

$t\bar{t}$ + jets at LHC

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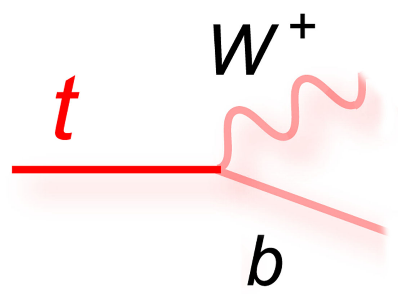

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$$\Gamma_W = \Gamma_{\rm lep} + \Gamma_{\rm had} = (2N_C + 3)\Gamma(W \to \ell\,\nu) = 9\,\Gamma(W \to \ell\,\nu)$$

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~Universality of charged current coupling to fermions → **BR(W → eν) ≈ 10%**

$t\bar{t}$ + jets at LHC

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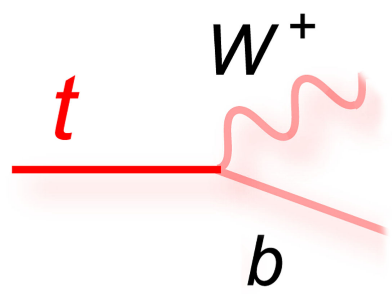

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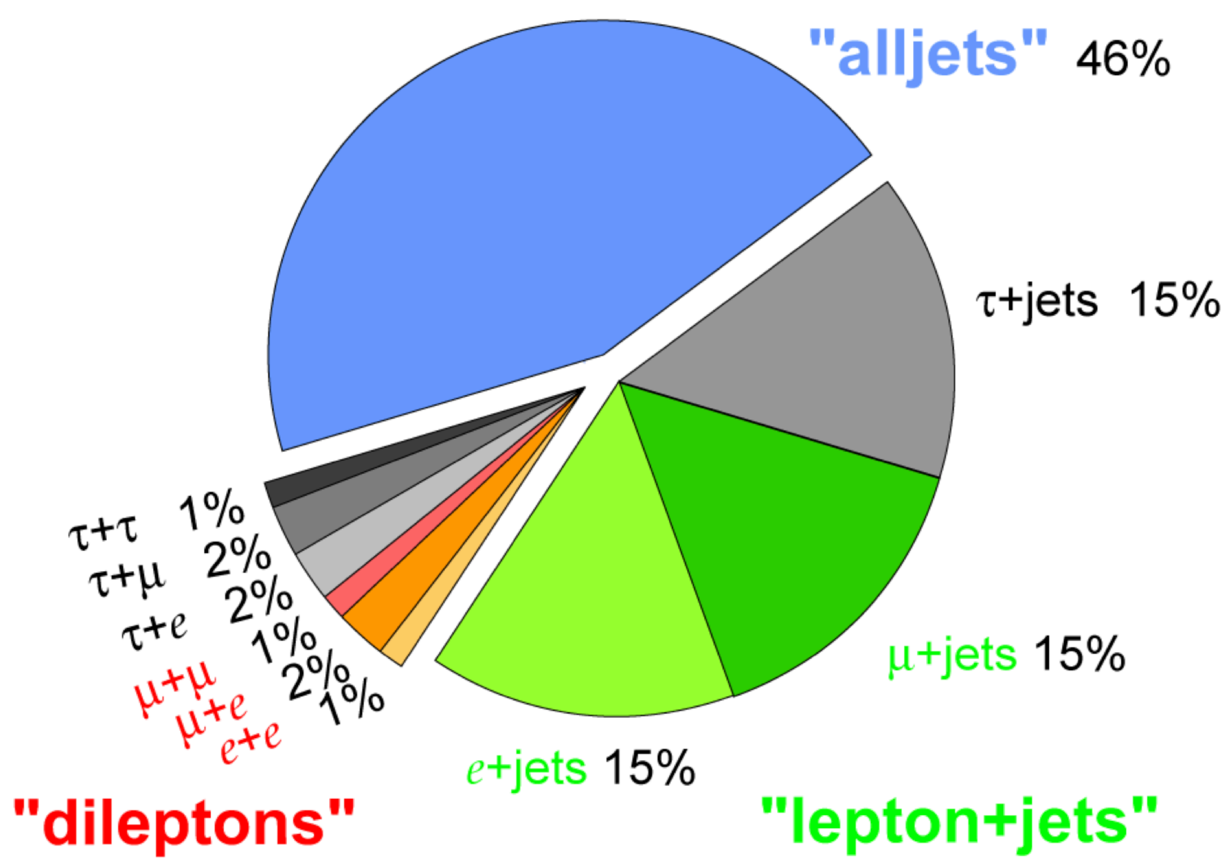
Top-pair branching ratios



$t\bar{t}$ + jets at LHC

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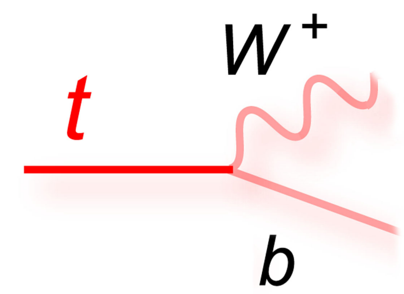

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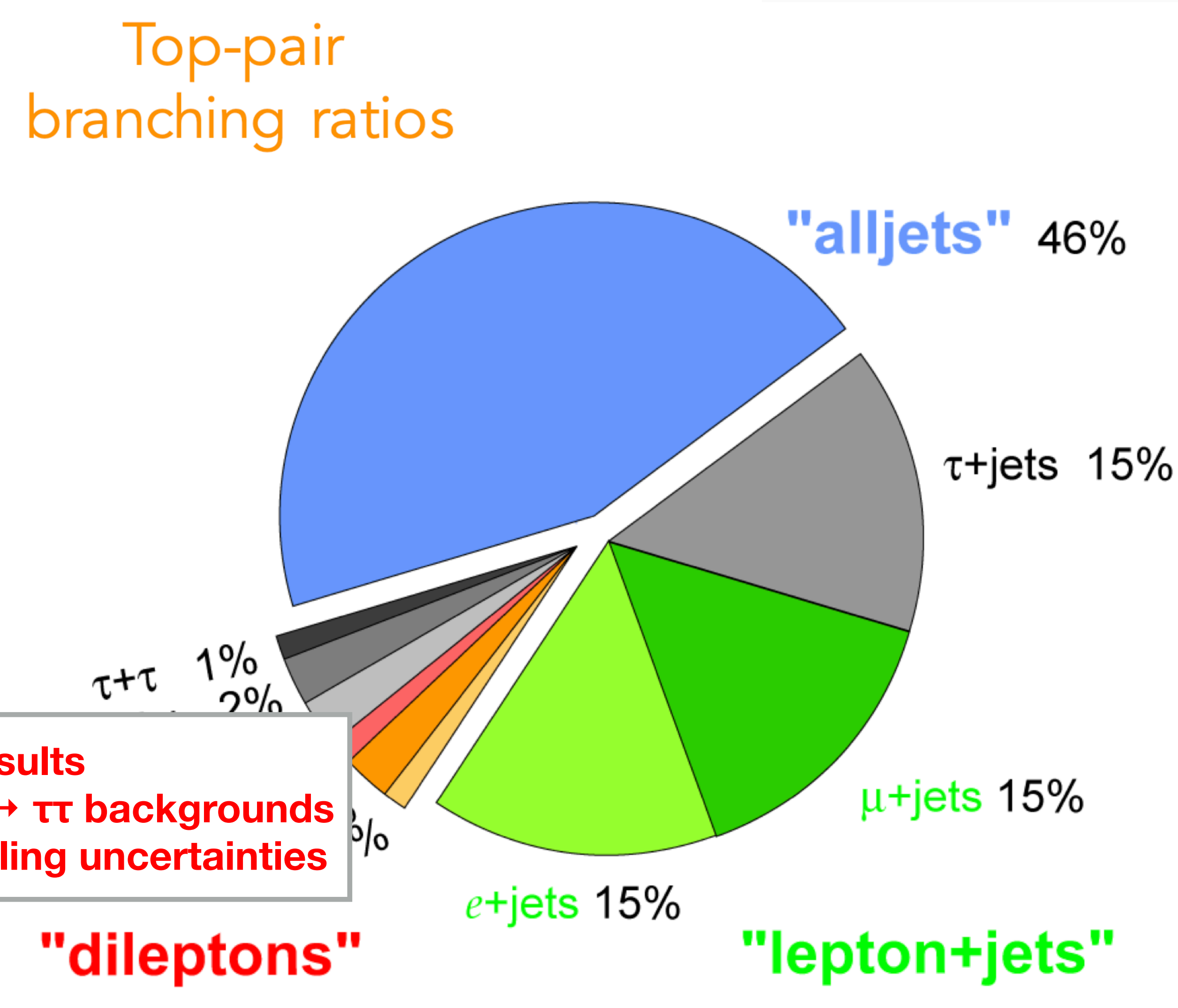

Most precise results
Wt, fake leptons, diboson, Z→ ττ backgrounds
Limited constrains on modelling uncertainties

$t\bar{t}$ + jets at LHC

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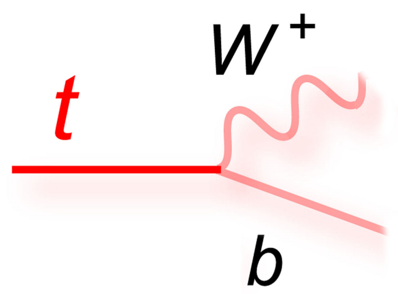

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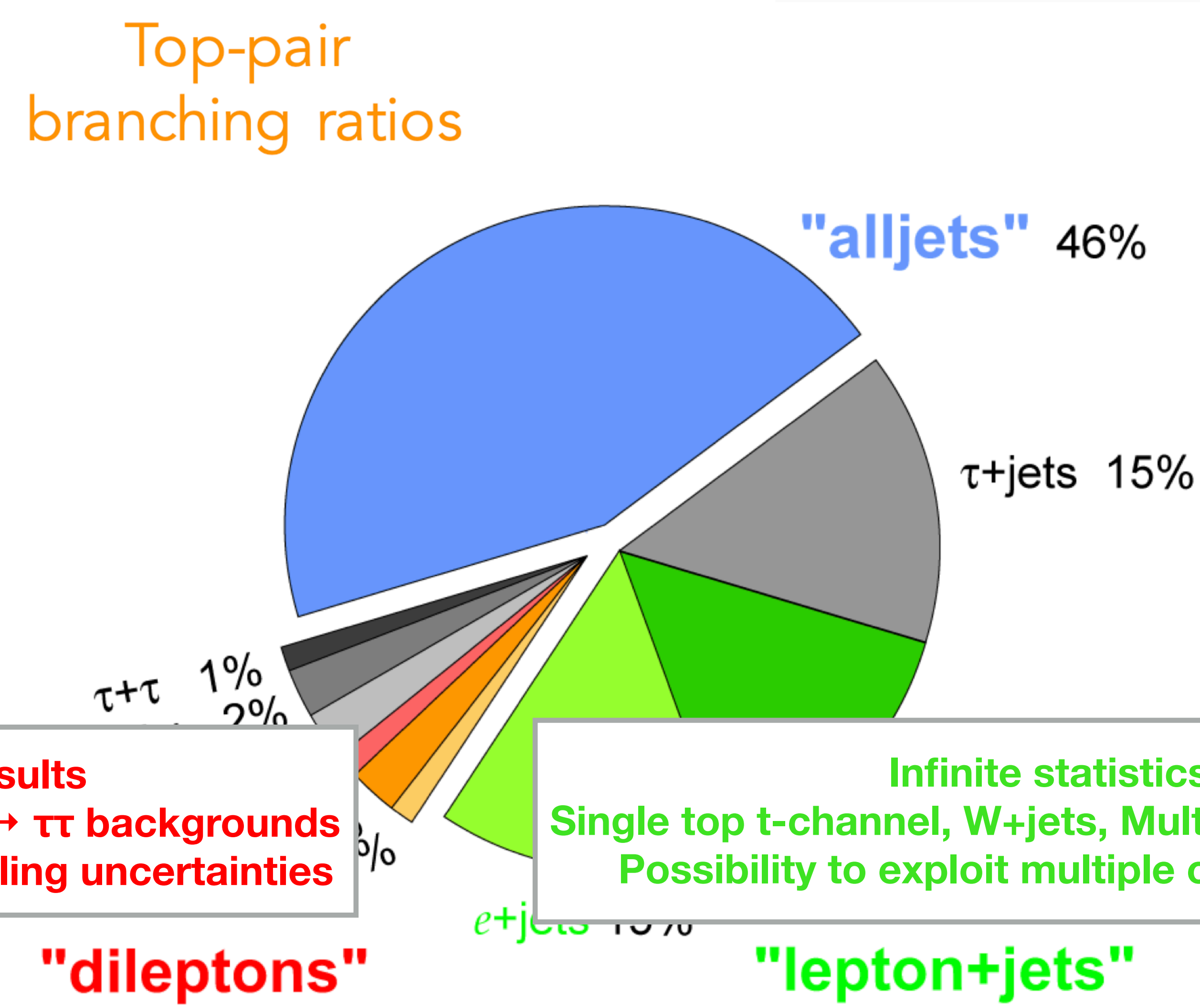

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Infinite statistics
Single top t-channel, W+jets, Multi-jet backgrounds
Possibility to exploit multiple control regions

$t\bar{t}$ + jets at LHC

[Top quark on PDG](#)

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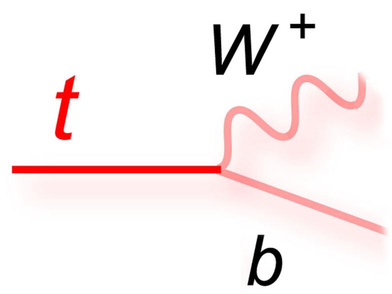

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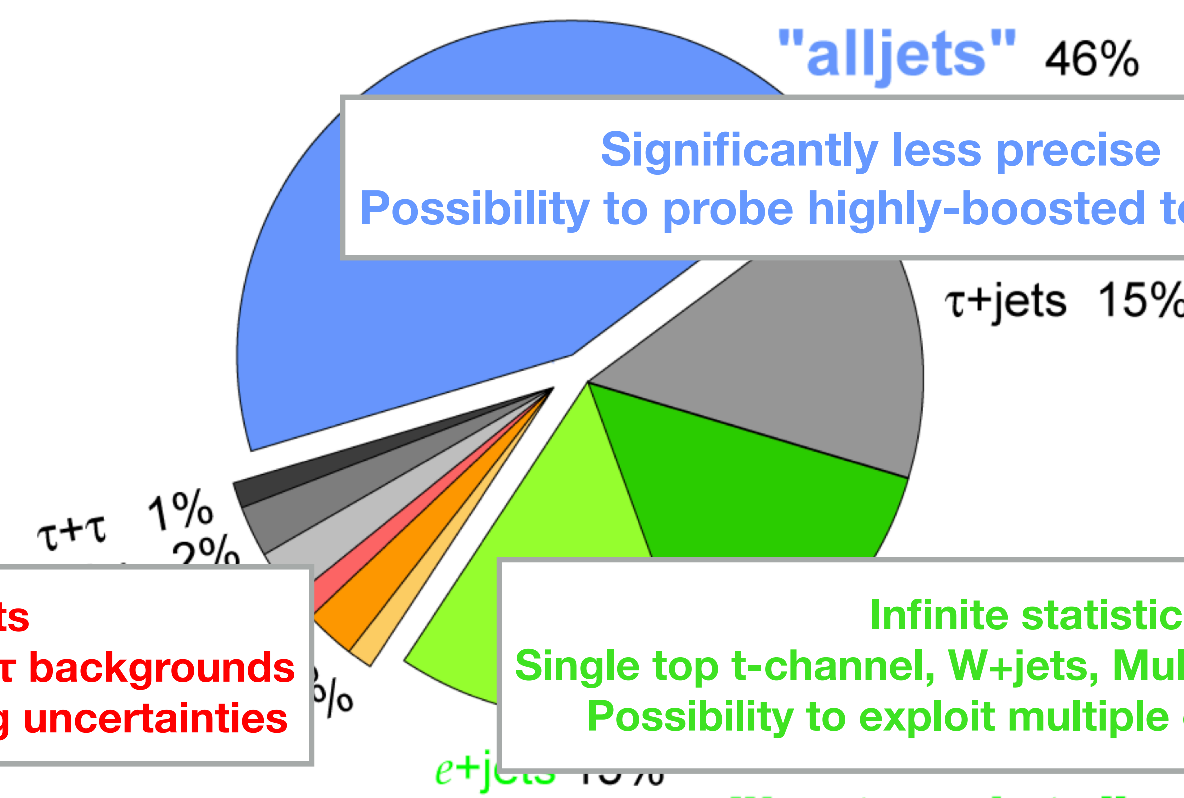

Significantly less precise
Possibility to probe highly-boosted top quarks

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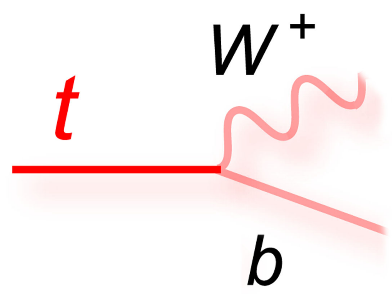

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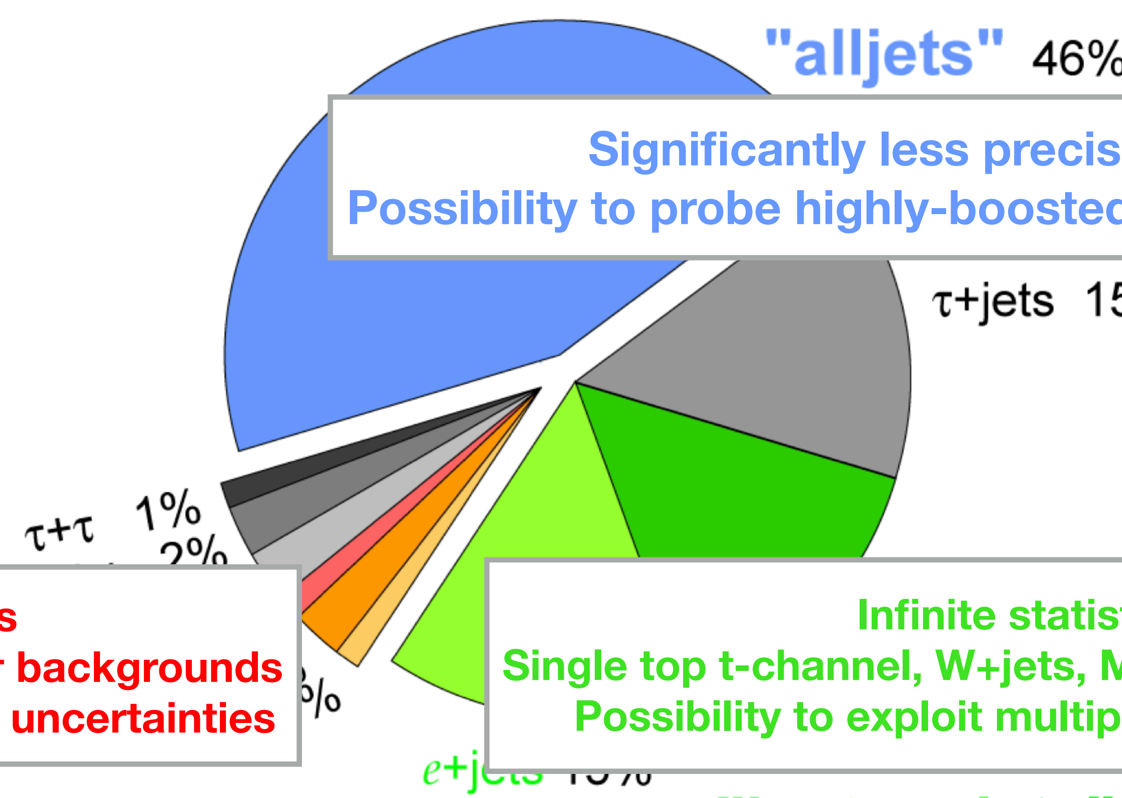

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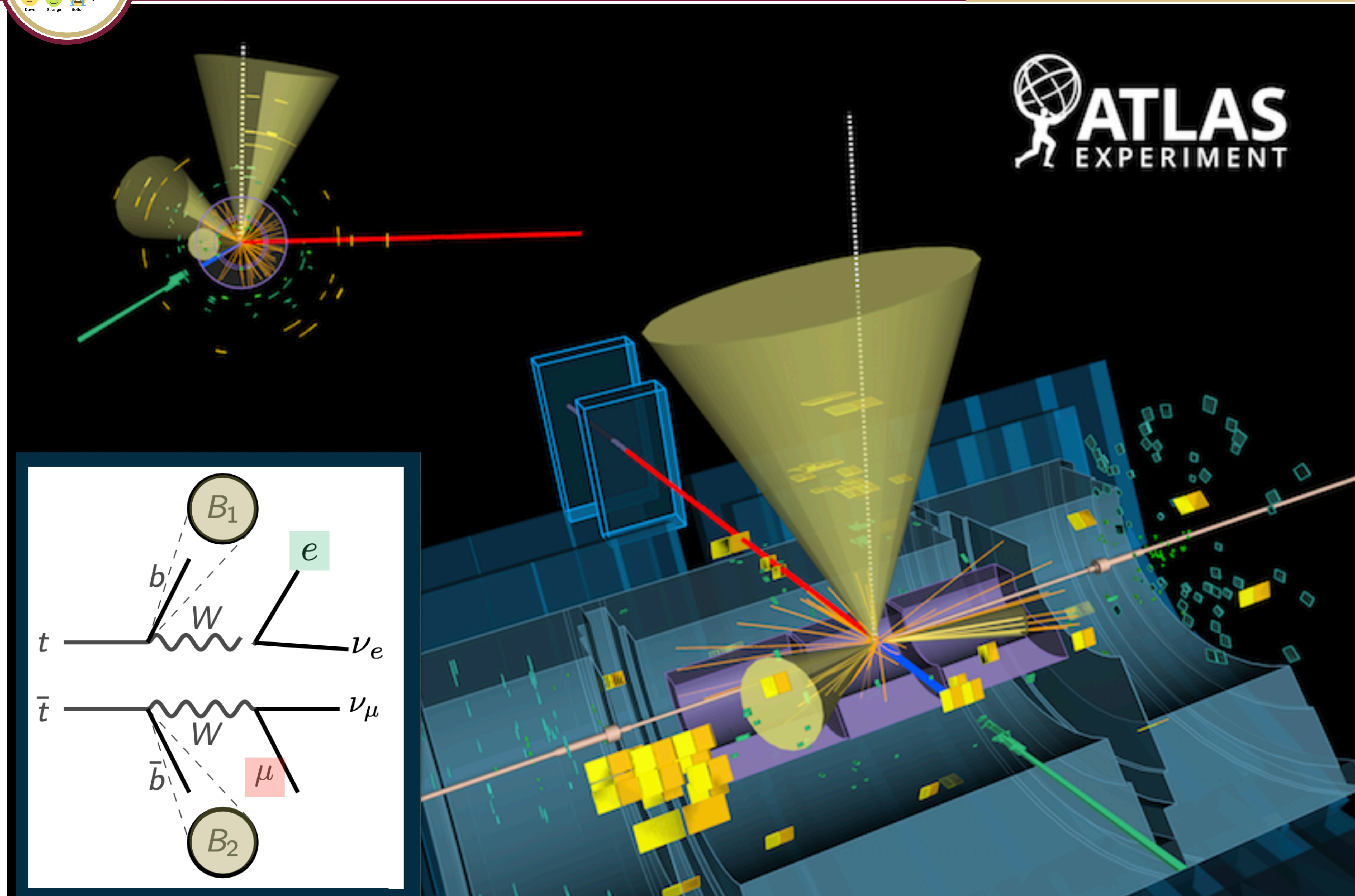
Main systematic uncertainties:

- Signal modelling (generators, QCD scales, radiation, hadronisation)
- Object efficiencies & calibrations (leptons, jets, flavour-tagging)
- Background estimates
- Luminosity (2-3%)

$t\bar{t}$ + jets at LHC



Top physics program at LHC

Top x-section

- $t\bar{t}$, $t\bar{t}$+HF
- s-channel
- t-channel
- Wt-chanel
- WbWb
- B-fragmentation
- Colour reconnection
- Top in elastic scattering
- $t\bar{t}$ in Heavy Ions
- Lund plane
- …

Top + X

- $t\bar{t}Z$, $t\bar{t}W$, $t\bar{t}\gamma$,
- tZW,
- tZ, tW, tγ
- 4tops
- $t\bar{t}W$+jet (EW)
- $t\bar{t}\gamma$ CA,
- Charged lepton flavour violation
- FCNC tH
- FCNC tZ
- FCNC t+γ
- FCNC t+gluon
- …

Top mass

- Standard template mass
- SMT mass
- Top mass J/Psi
- Top mass 2D
- Top mass combination
- MC-to-pole top mass

Top properties

- Spin-density matrix
- $t\bar{t}$ Quantum Entanglement
- Top polarisation
- Lepton flavour universality
- V_{cb}, V_{ts}
- Asymmetries
- Top width
- …

More public results here

Questions/Comments?

Reminder

Experimental background: Unfolding

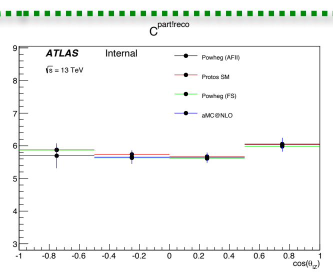
What's unfolding?

When someone says they have measured a differential cross-section, they mean that it has been unfolded

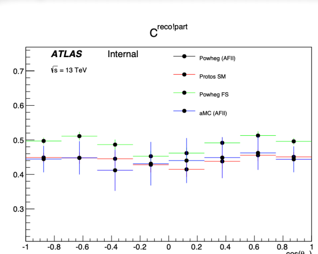
- *deconvolution of reco. spectrum to "truth" spectrum*, "removing" interrelated effects
- after unfolding data can be directly compared with theory predictions.
  - correcting data is more general and can allow for multiple theory groups to reuse the measurement

Unfolding needs to correct for interrelated effects:

- Acceptance and efficiency ⇠ Particles produced may not be measured
- Detector noise ⇠ Particles measured may not be from real particles
- Background processes ⇠ If you want to measure process X, need to remove Y from data
- Combinatorics ⇠ If N particles, chance that detector can change order
- Detector distortions ⇠ Bias and resolution effects (unresolved by calibration)



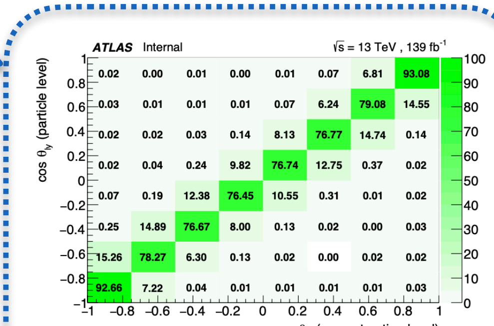
$$\frac{1}{\epsilon_k} = \frac{S_k^{\text{particle}} - S_k^{\text{particle!reco}}}{S_k^{\text{particle}}}.$$



$$\frac{S_j^{\text{reco}} - S_j^{\text{reco!particle}}}{S_j^{\text{reco}}},$$

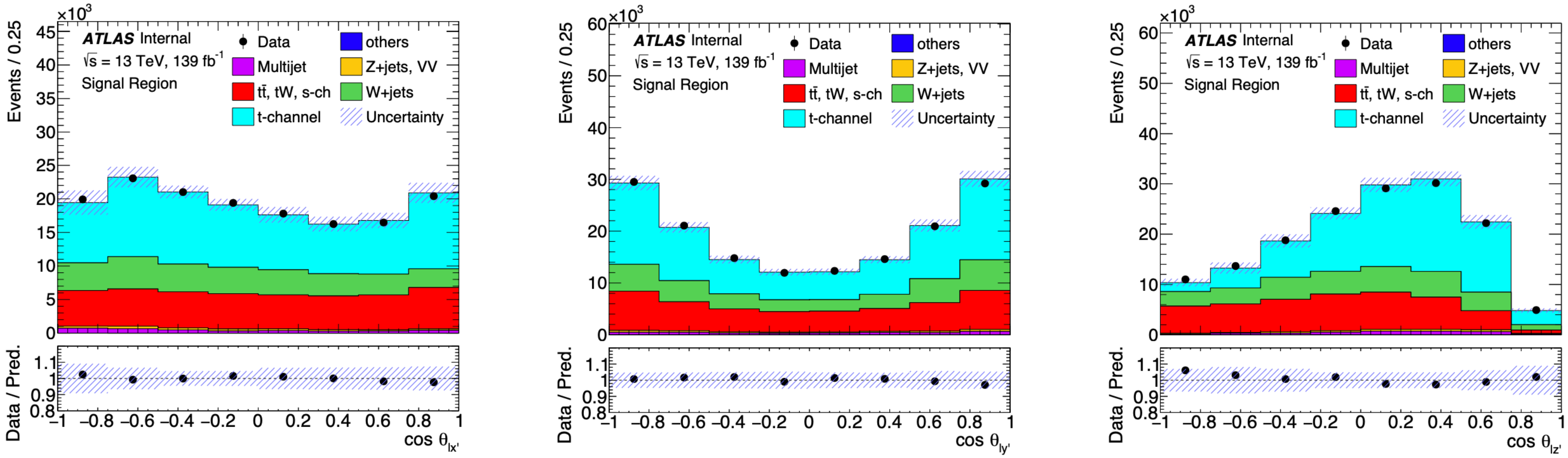
$$N_k^{\text{particle}} = C_k^{\text{particle!reco}} \sum_j M^{-1}_{jk} C_j^{\text{reco!particle}} (N_j^{\text{data}} - B_j)$$

Background subtracted data



Reco. → particle migration matrix

Unfolding example



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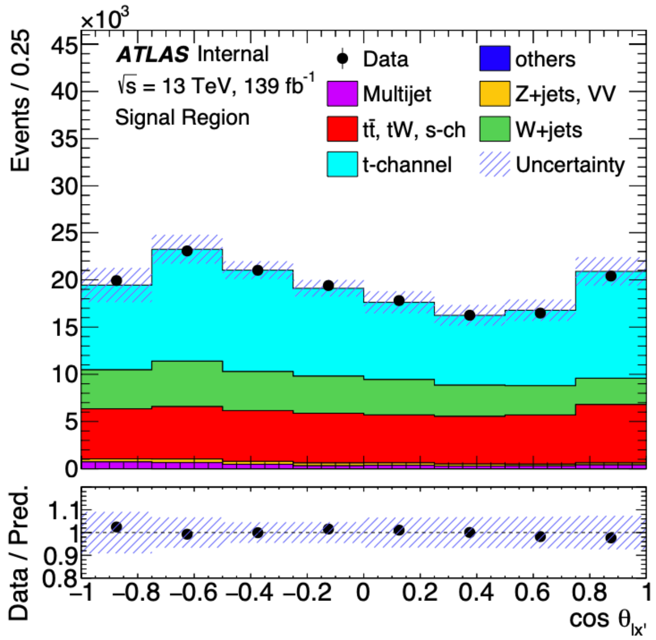

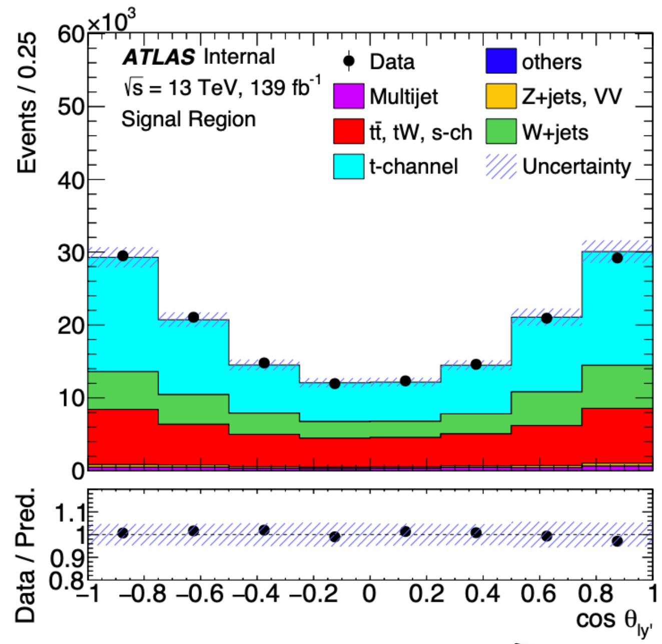

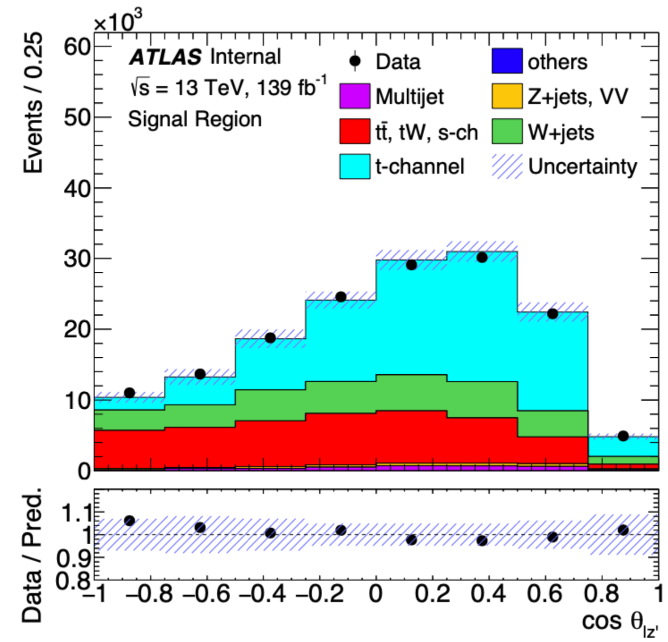

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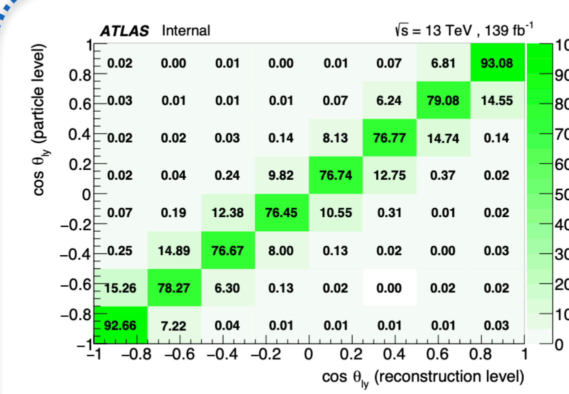

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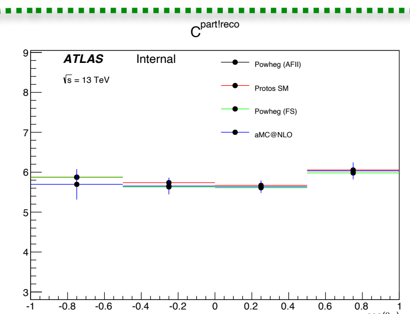

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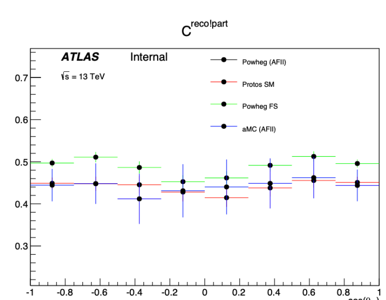

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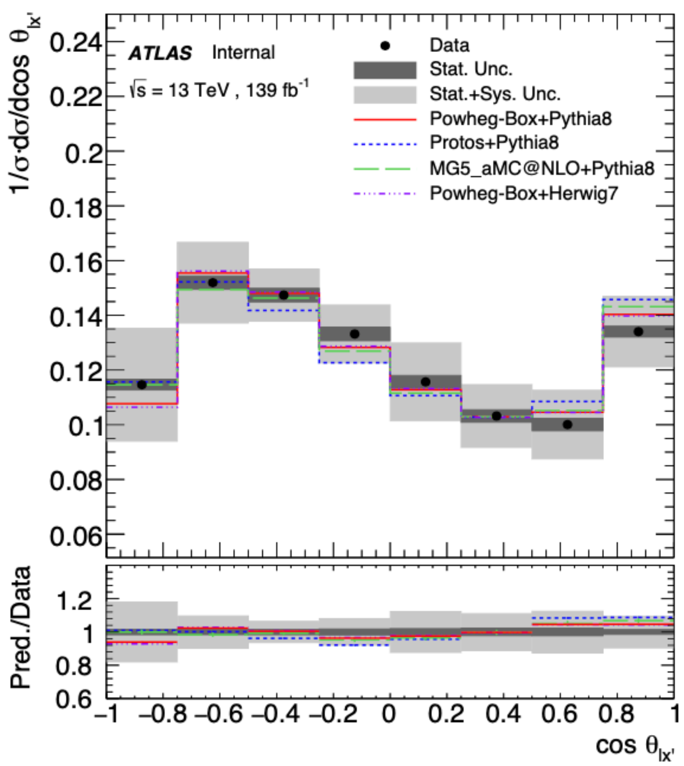
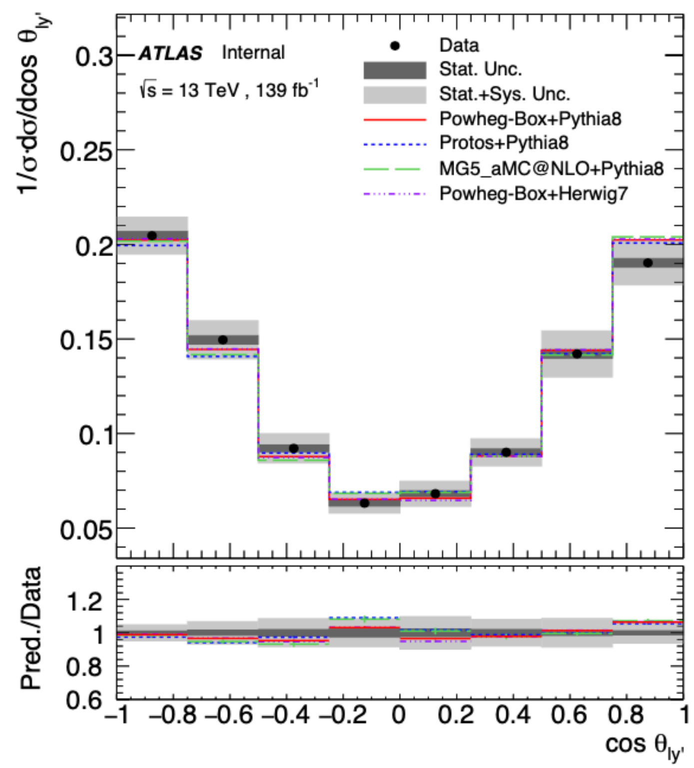
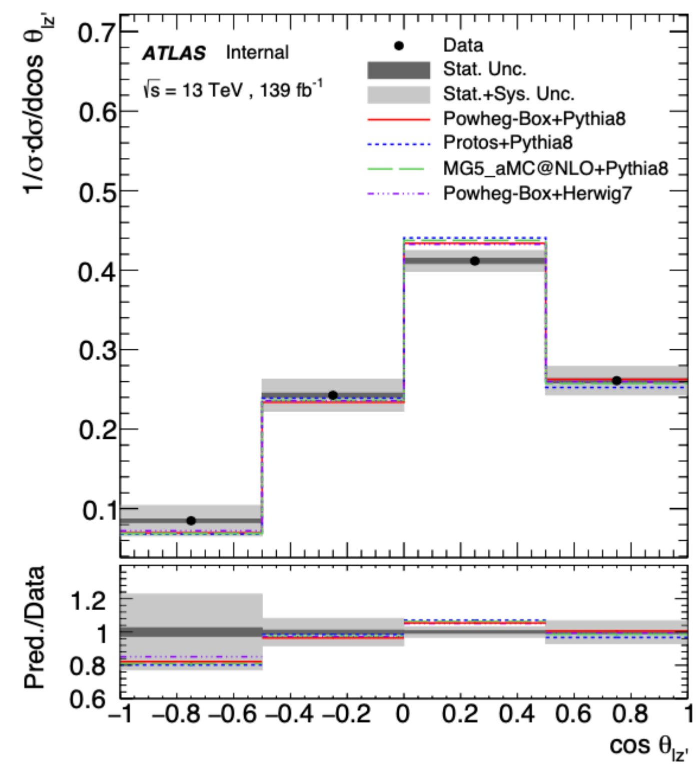
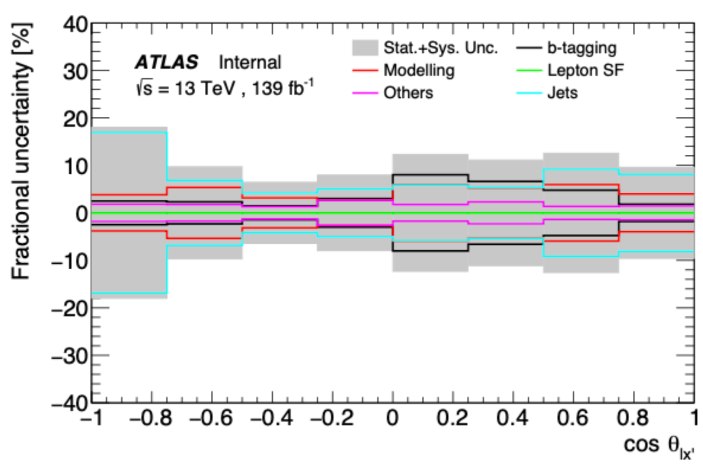
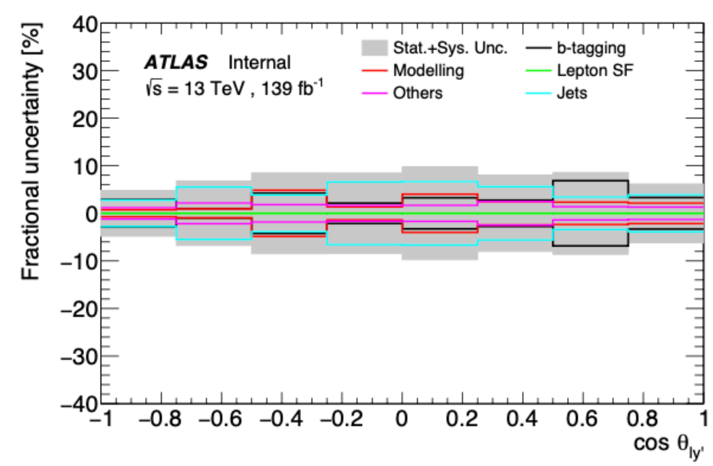
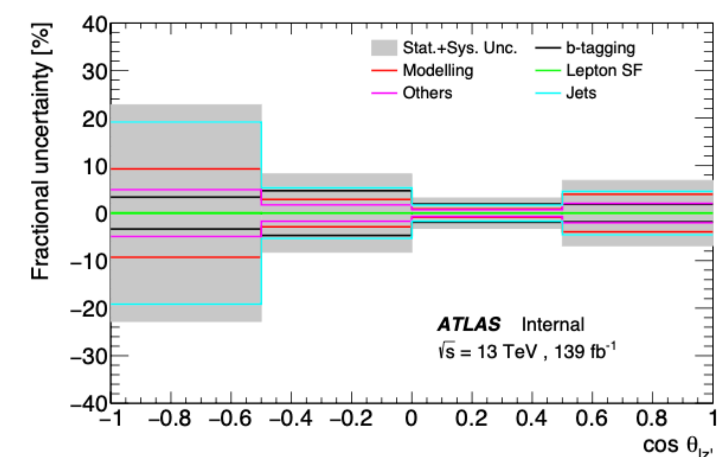












Unfolded distribution are then compared to various MC predictions (NLO, NNLO, NNLL, ….) from theorists.

Which unfolding?

$$N_k^{\text{particle}} = C_k^{\text{particle!reco}} \sum_j M_{jk}^{-1} C_j^{\text{reco!particle}} (N_j^{\text{data}} - B_j)$$

Tool: RooUnfold

IBU

D'Agostini Iterative Bayesian Unfolding
Nucl. Inst. Meth. A 362 (1995) 487

Tool: PyFBU

FBU

Fully Bayesian Unfolding
arxiv.org/1201.4612

Tool: RooUnfold

SVD

Singular Value Decomposition
Nucl. Inst. Meth. A 372 (1995) 469

Tool: TRExFitter (ATLAS)

PLU

Profile Likelihood Unfolding
CMS reference

Latest experimental results on Top x-section

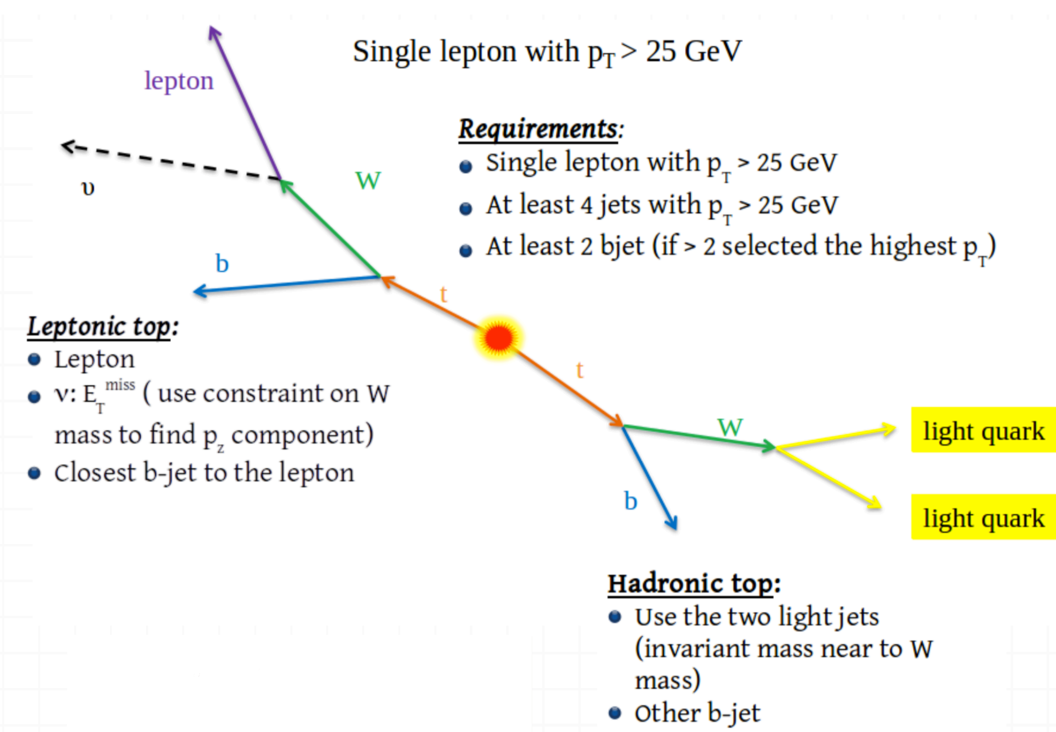
$t\bar{t}$ x-section in l+jets at $\sqrt{s}$=13 TeV

Eur. Phys. J. C 79, 1028 (2019)

Measurement of differential $t\bar{t}$ (l+jets resolved) x-sections at particle and parton level

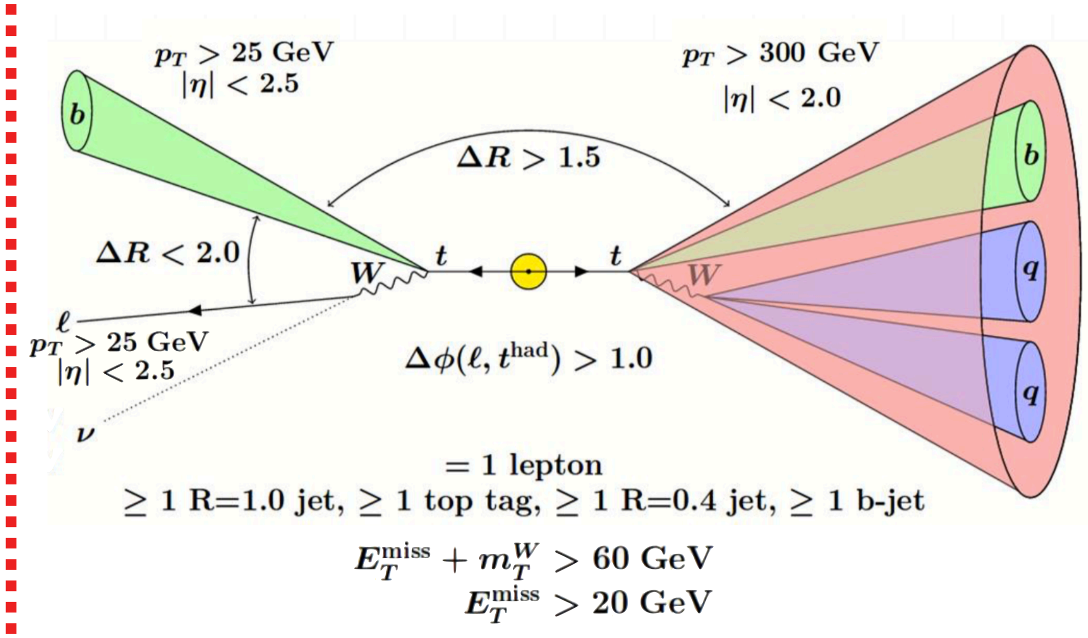
- 1D and 2D x-sections for top and $t\bar{t}$ kinematic observables, Run II data (36/fb)
  - comparison with MC simulations and NNLO predictions (MATRIX, Mitov et al., …)
  - input to the global PDF fit mentioned yesterday

Resolved regime



Algorithms for event reconstruction employed (Pseudo-top and KLFitter)

Boosted regime



Overlap with resolved events removed

Unfolded to parton and particle level with Iterative Bayesian Unfolding (IBU)

$t\bar{t}$ x-section in l+jets at $\sqrt{s}$=13 TeV

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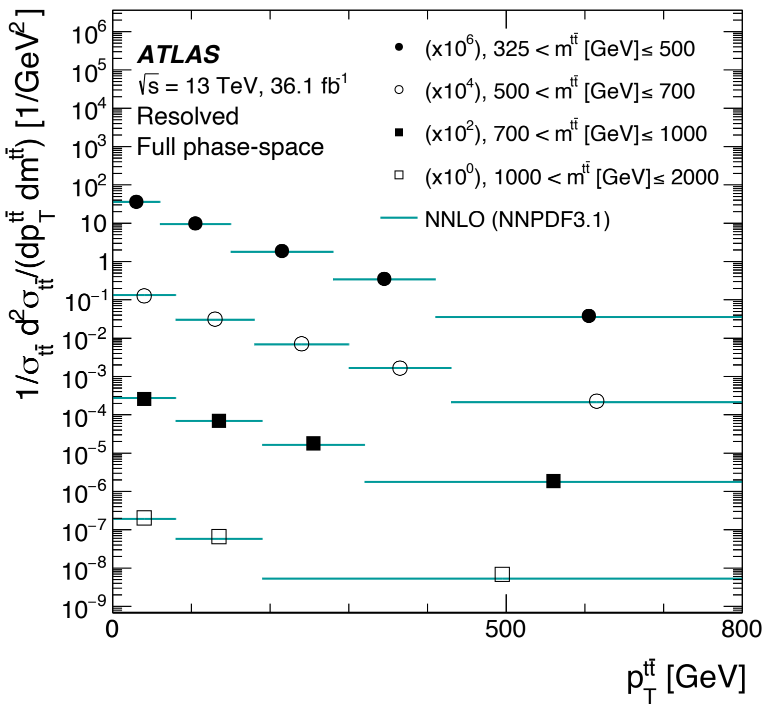

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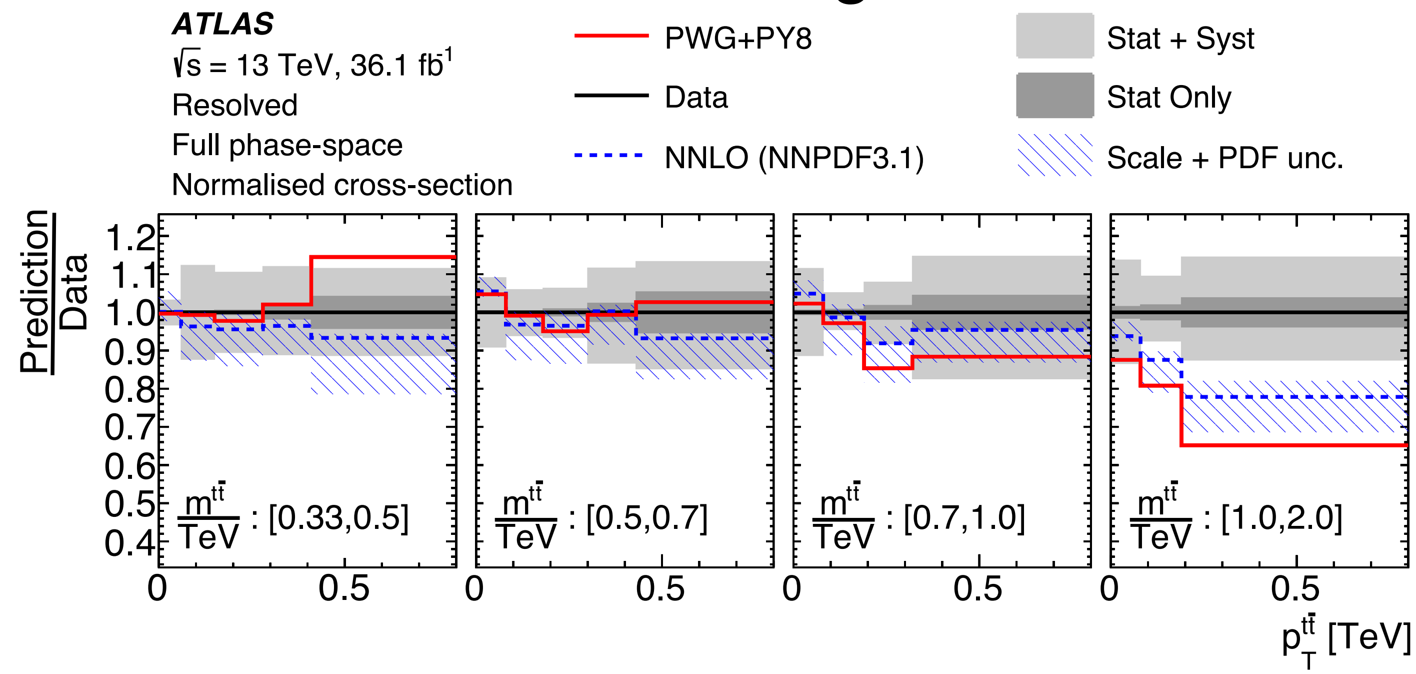

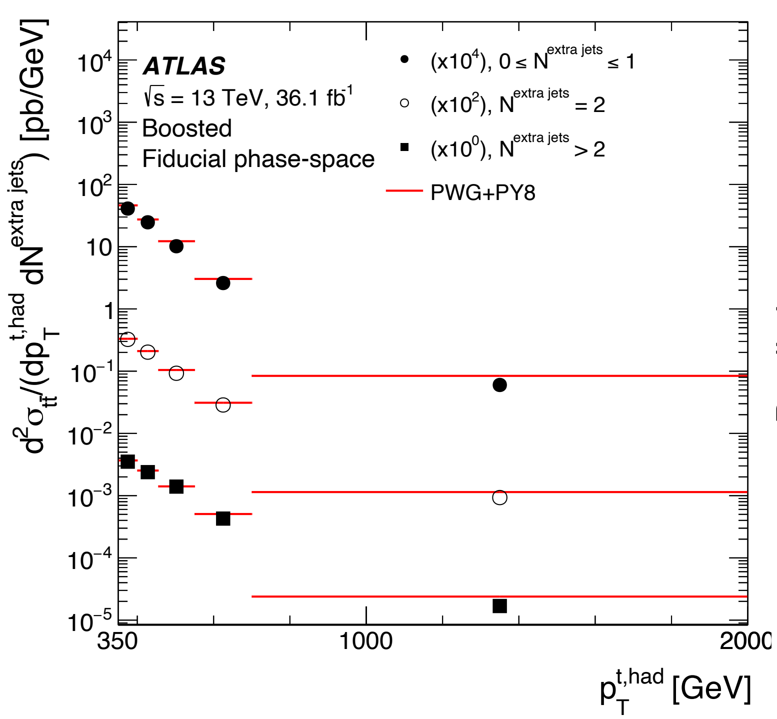

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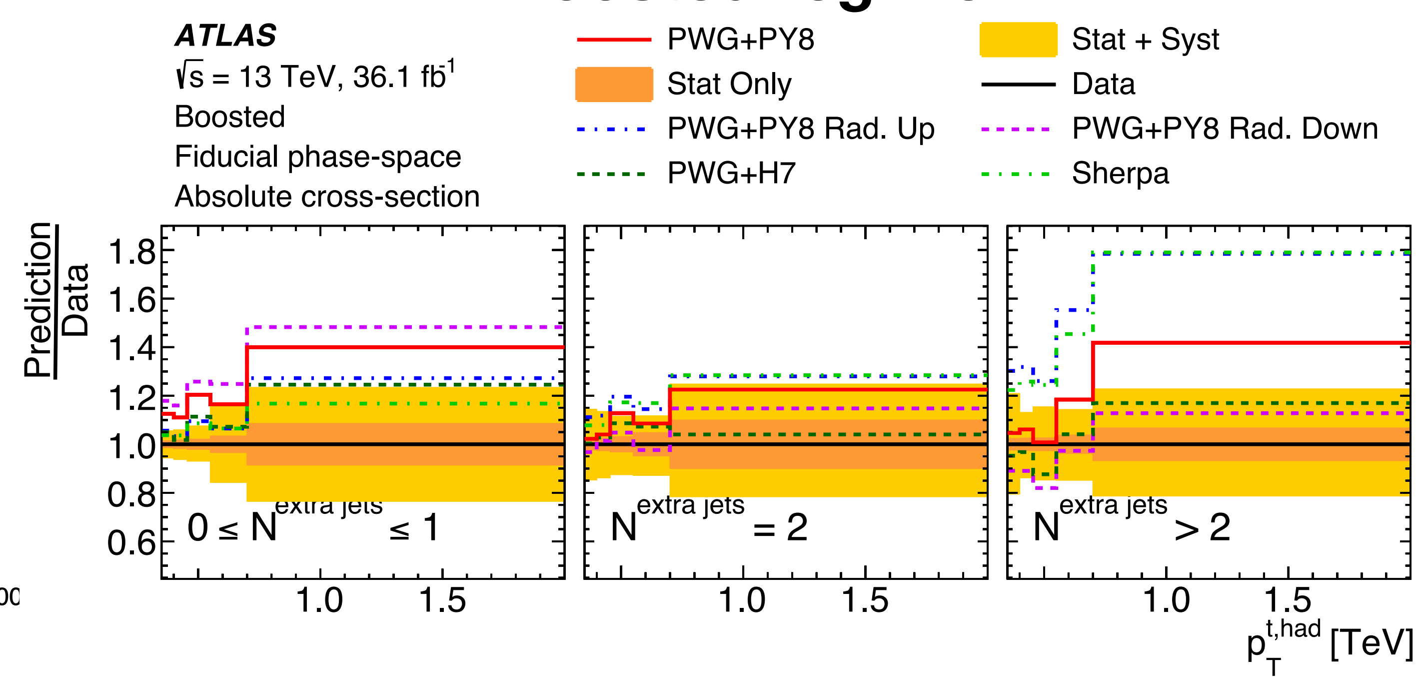

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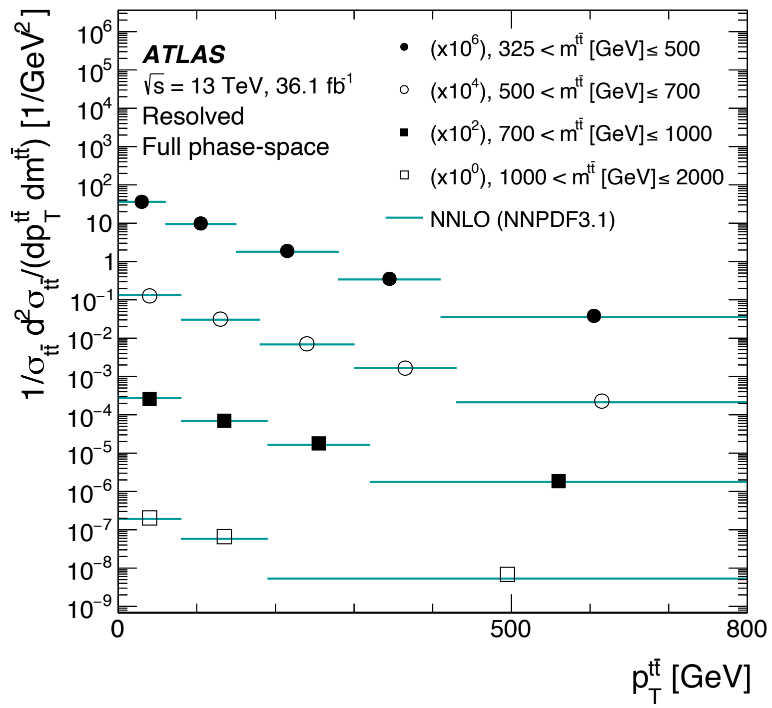
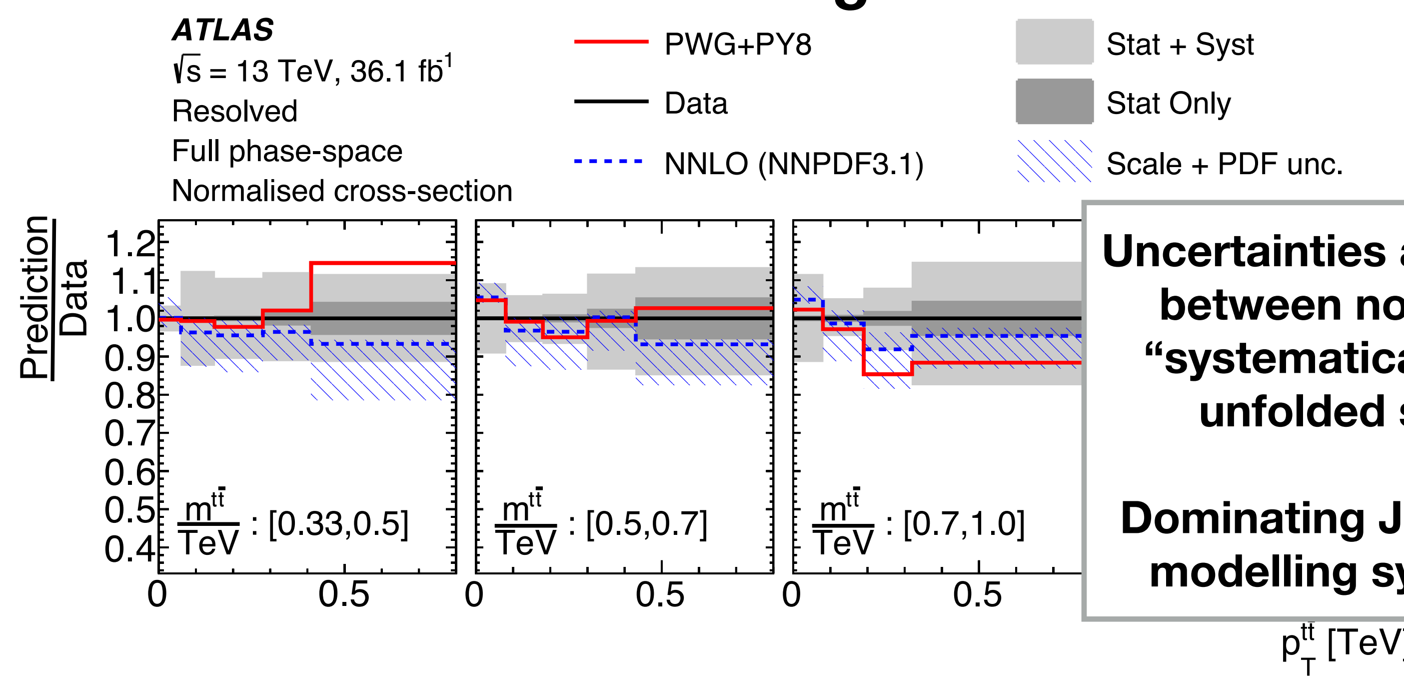
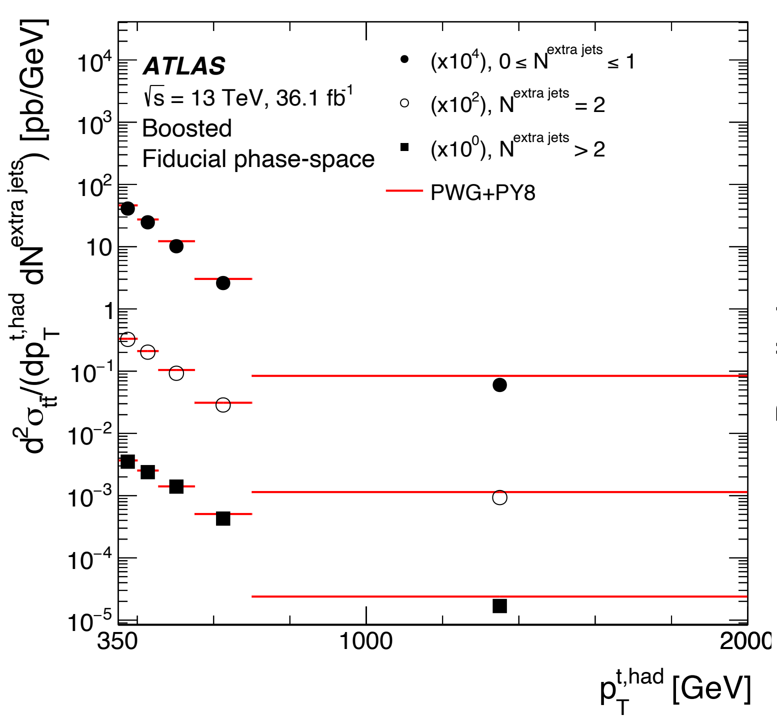


Resolved regime

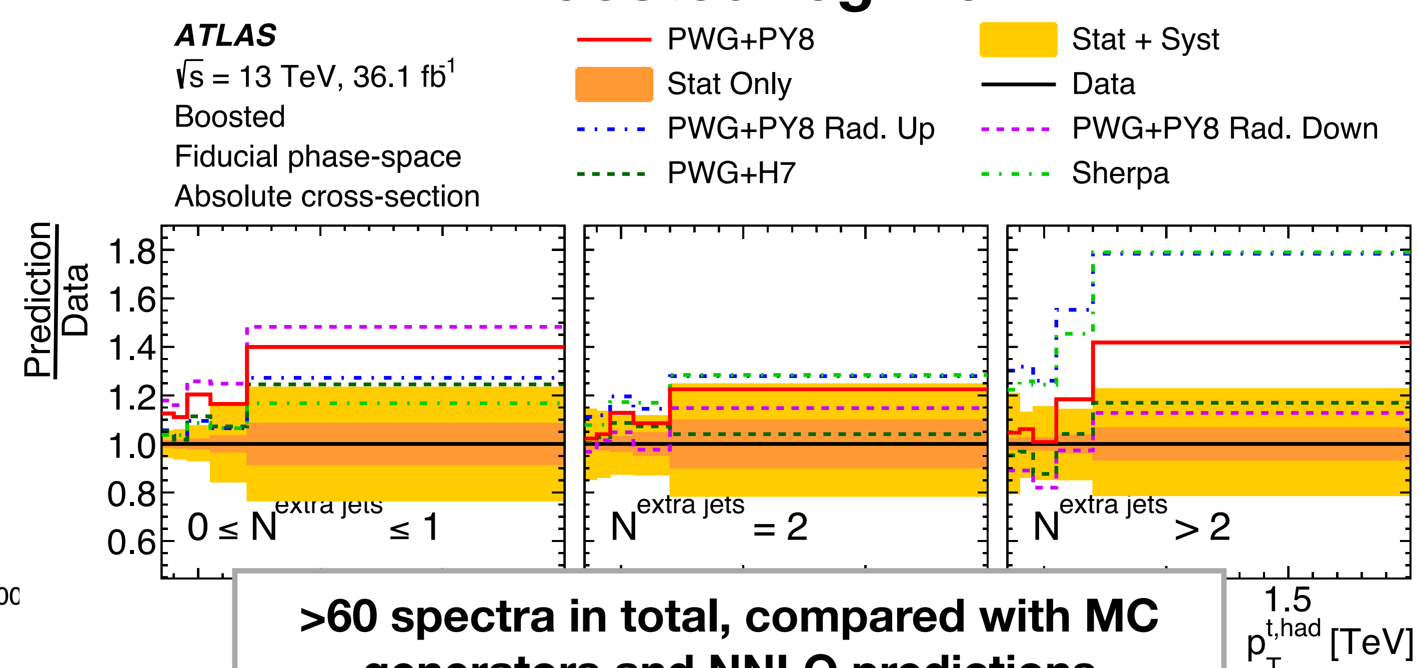


Uncertainties as difference between nominal and "systematically" varied unfolded samples

Dominating JES/JER and modelling systematics



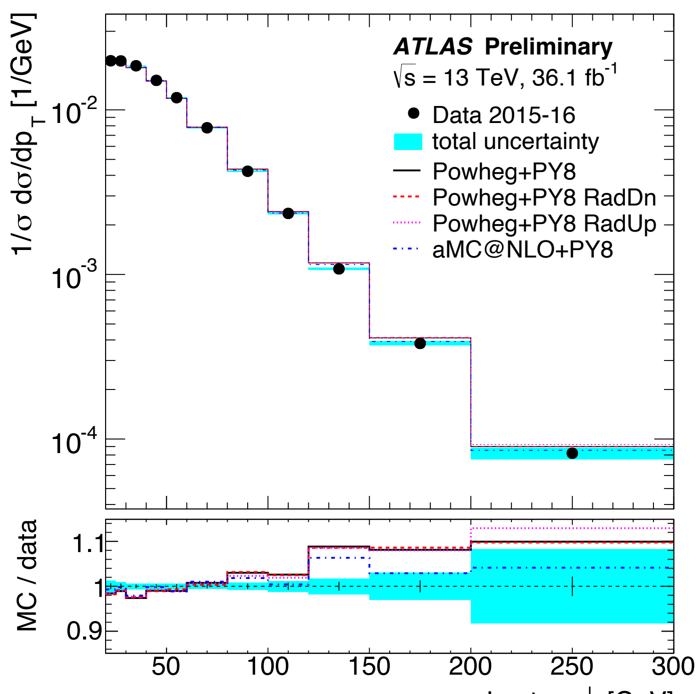
Boosted regime



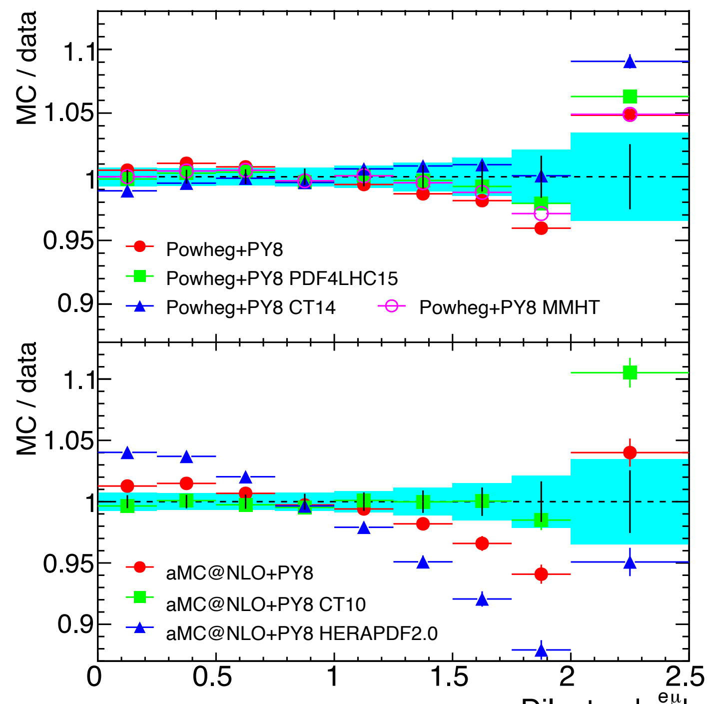
>60 spectra in total, compared with MC generators and NNLO predictions
None perfectly matches data for all spectra

$t\bar{t}$ x-section in dilepton at $\sqrt{s}$=13 TeV

[Eur. Phys. J. C 80, 528 (2020)]



overestimate of pT spectra



sensitivity to PDF thanks to rapidity

Inclusive & (2D-)differential in eμ channel, 36.1 fb^{-1} @13TeV

- **$\sigma_{t\bar{t}}$ = 826.4±19.9 pb**
  → highest precision, 2.4%
- CMS measurements
  - 4.0% in dilepton 2015+16,
  - 3.8% in l+jets 2015

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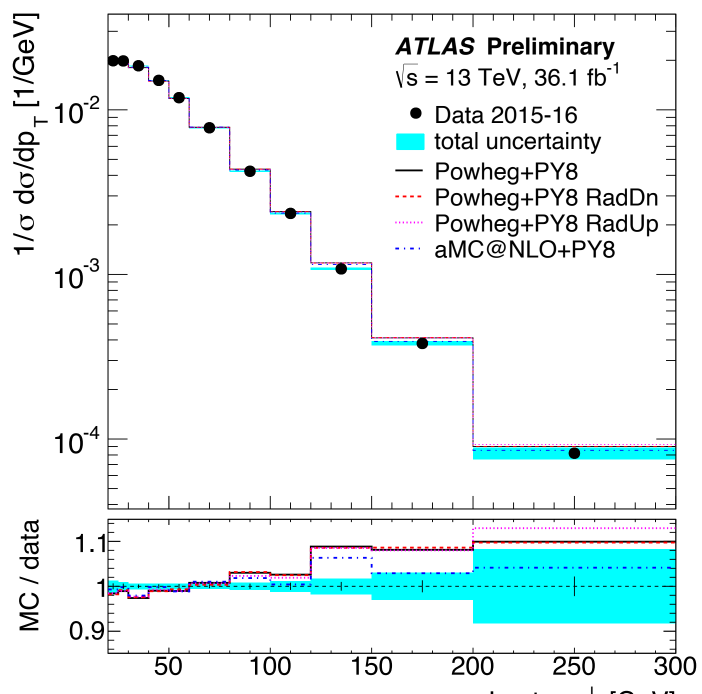

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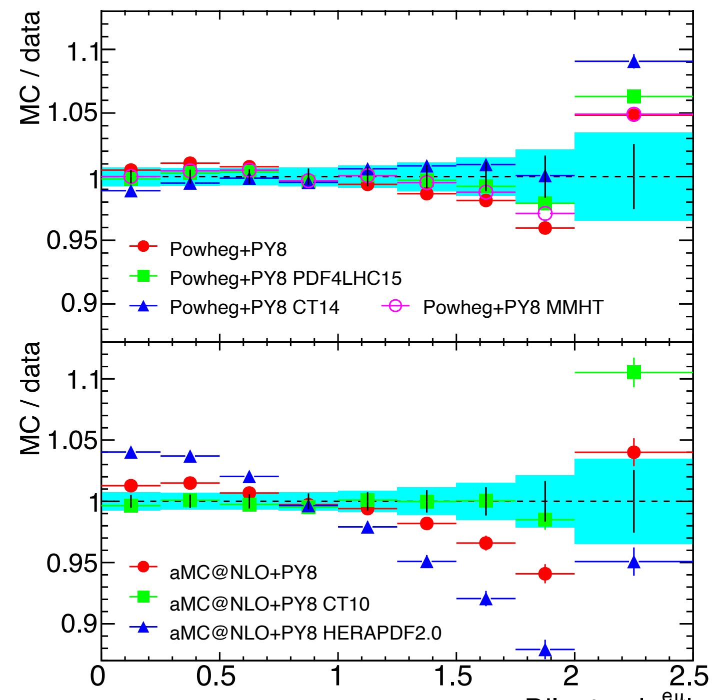

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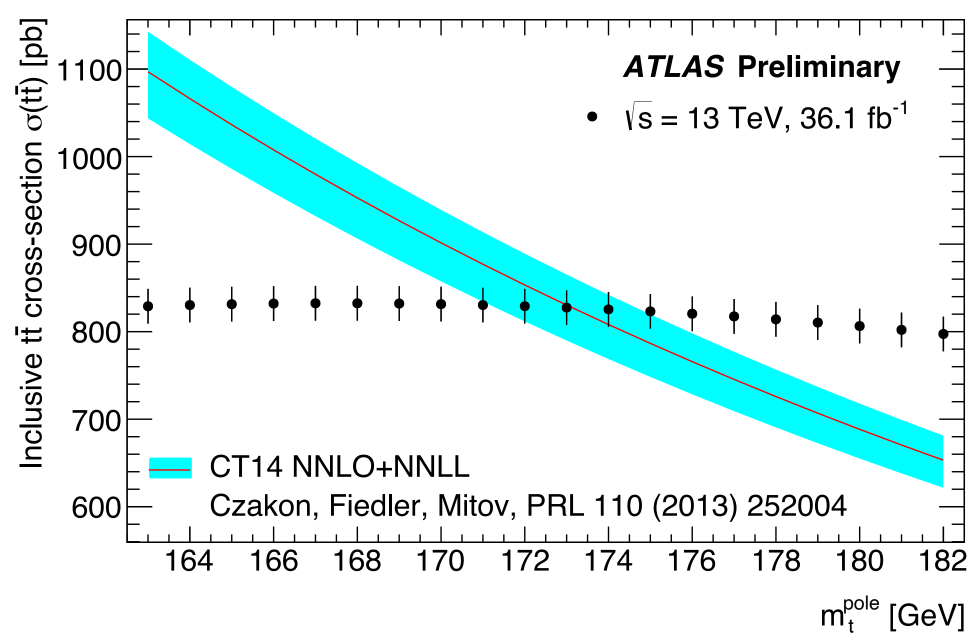


PDF set	m_t^{pole} [GeV]
CT14	$173.1^{+2.0}_{-2.1}$
CT10	$172.1^{+2.0}_{-2.0}$
MSTW	$172.3^{+2.0}_{-2.1}$
NNPDF2.3	$173.4^{+1.9}_{-1.9}$
PDF4LHC	$172.1^{+3.1}_{-2.0}$

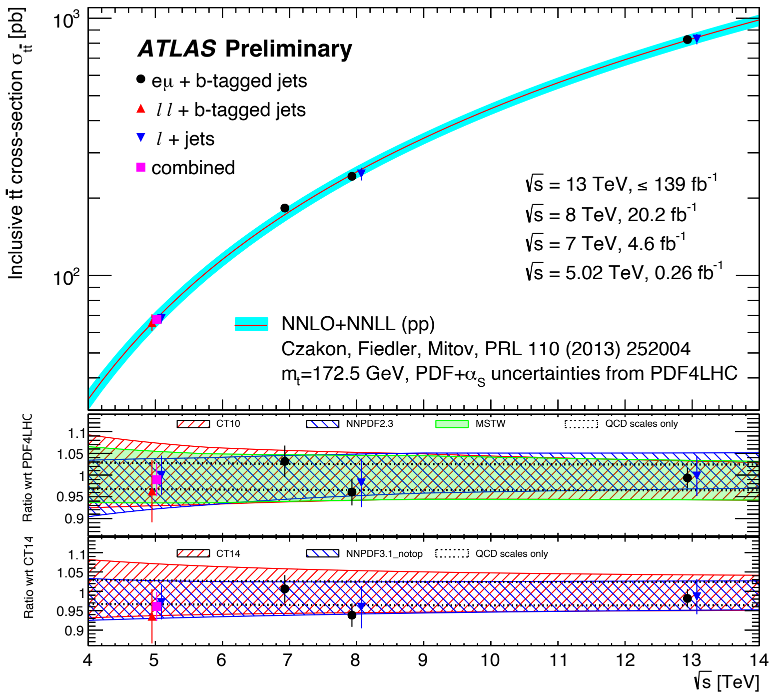
extraction of m_t^{pole} by unfolding

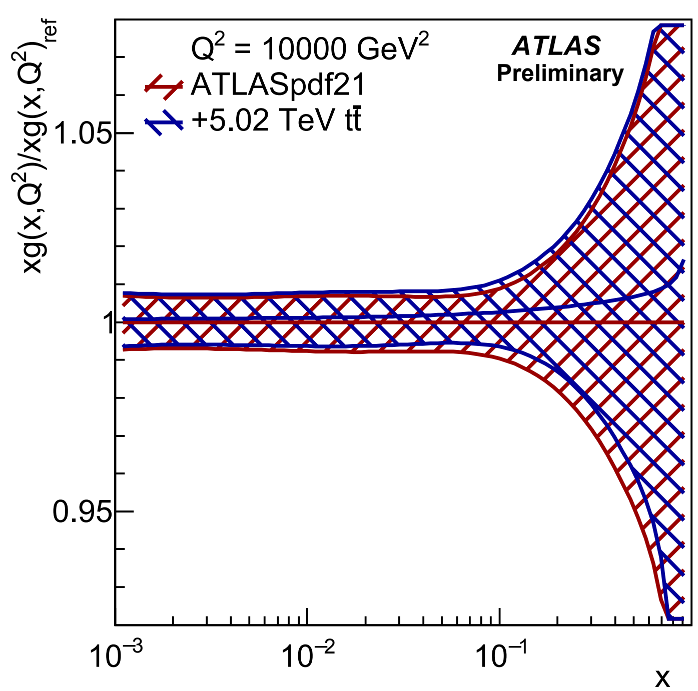
$t\bar{t}$ x-section at $\sqrt{s}$=5 TeV

ATLAS-CONF-2022-031

$t\bar{t}$ cross-section at 5 TeV in 1L and combination with 2L channel

- low PU <μ> ≈ 2 @5 TeV (w.r.t. 30 @13 TeV)
- dilepton channel already published (ATLAS-CONF-2021-003)
- CMS 5TeV combination reaches 7.9% total uncertainty
- standard $t\bar{t}$ l+jets selection:
  - exactly 1 charged lepton, ≥2 jets, ≥1 b-tag DL1r@70%
  - different E_T^{miss} && m_T^W cuts according to jet multiplicity
- lepton ID, Iso., Trigger, JES/JER, b-tag taken from high-μ, calibrated low-μ or dilepton channel
  - specific JES calibration required at 5TeV!
- k-fold BDT to separate signal and background (region-dependent input variables)
- binned profile-likelihood fit in 1L and combination with 2L "counting experiment" using Convino
- $\sigma_{t\bar{t}}$=67.5±0.9 (stat.) ±2.3 (syst.) ±1.1 (lumi.) ±0.2 (beam) pb
- Δσ/σ (ℓ+jets) = ±3.9% (dominated by lumi and el. ID systs)
- *Δσ/σ (combo) = ±1.3%(stat.) ± 3.7%(syst.) = ± 3.9%(tot.)*





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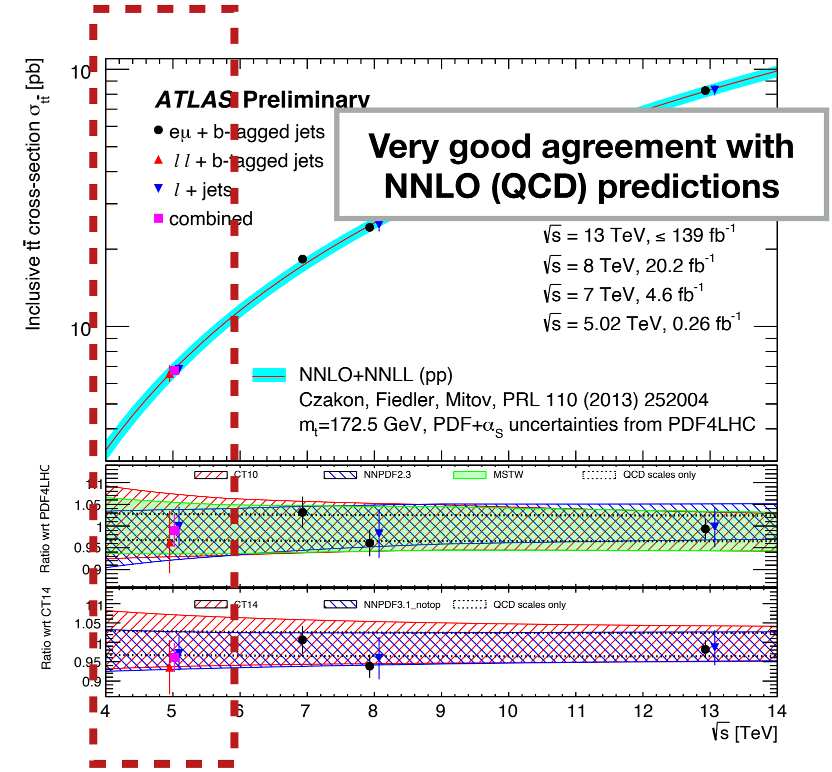
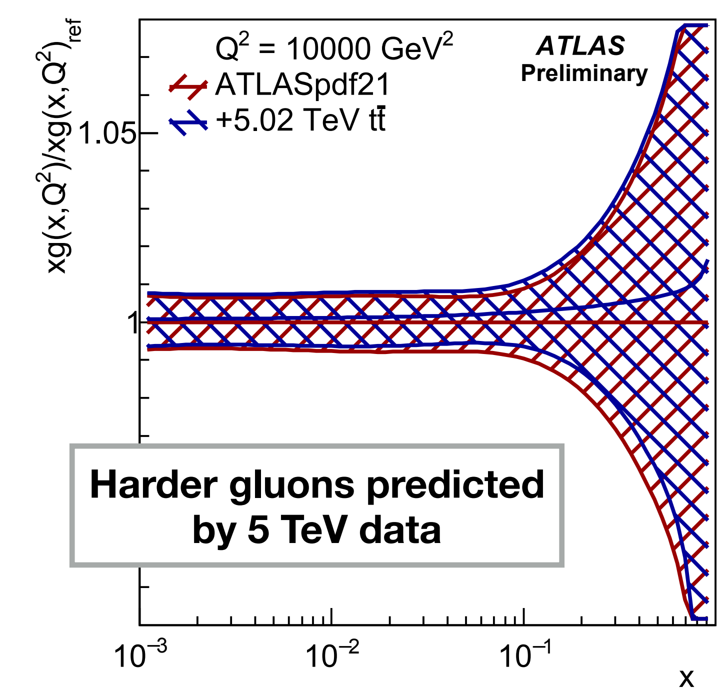




Single-top s-channel x-section

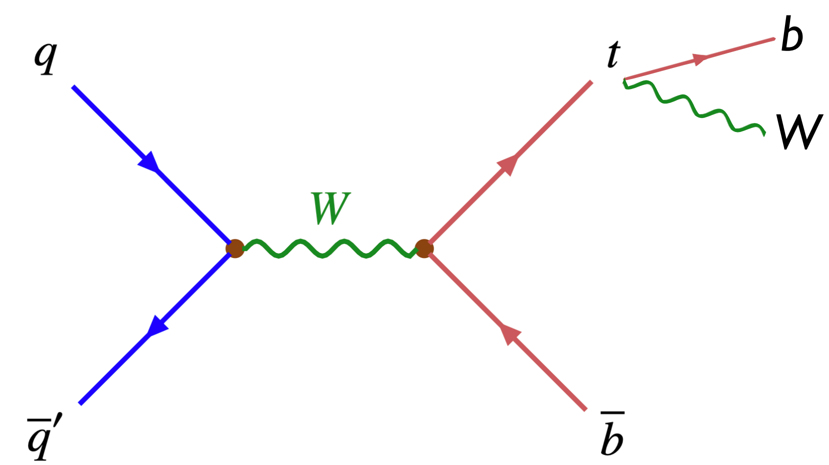
ATLAS-CONF-2022-030

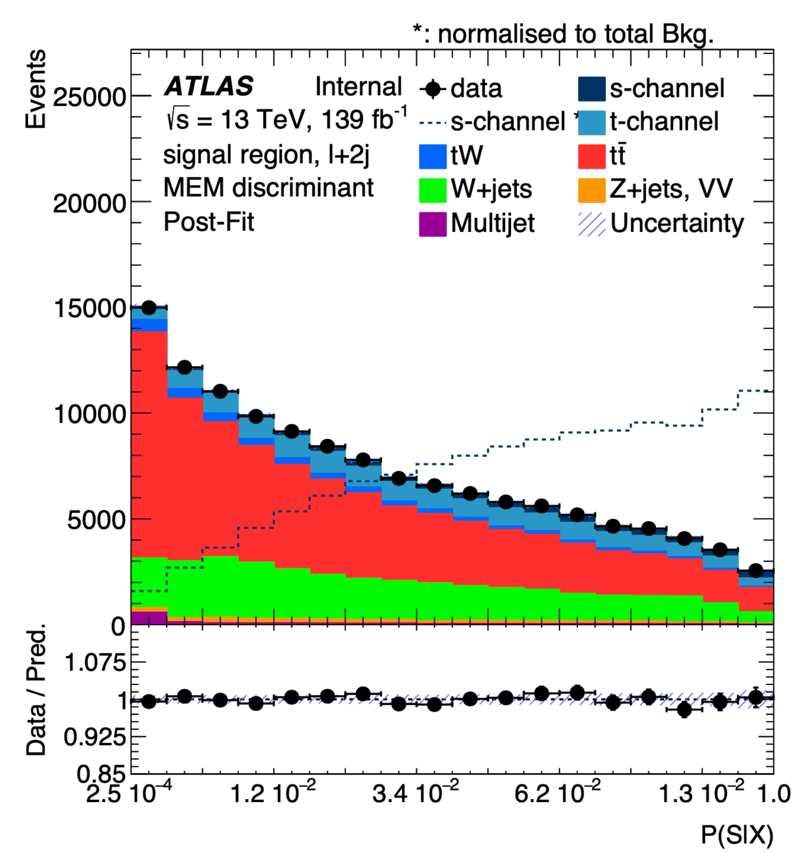
Single-top s-channel cross-section at 13 TeV

- l+jets events, 139 /fb
  - + exactly 1 charged lepton, no 2nd lepton
  - + exactly 2 b-tagged jets MV2c10@77%
  - + leading jet p_T > 40 GeV, no soft jets (p_T<30GeV)
  - + E_T^{miss} > 35 GeV, m_T^W > 30 GeV
- two control regions for $t\bar{t}$+jet (>2 jets) and W+jets (MV2c10@85%-77%)
- matrix element discriminant to separate signal from backgrounds and fit in the SR ($t\bar{t}$ and W+jets free floating)

Observed (expected) significance of 3.4σ (3.9σ)

- $\mu_{s\text{-chan}}$ = 0.87 (+0.34/-0.29)
  - + compatible with 0.86 (+0.31/-0.28) at 8 TeV
  - + sensitivity dominated by systematic uncertainty ($t\bar{t}$ SF, $t\bar{t}$ PS shape, JER, jet flavour composition, $t\bar{t}$ μ_R/hdamp)



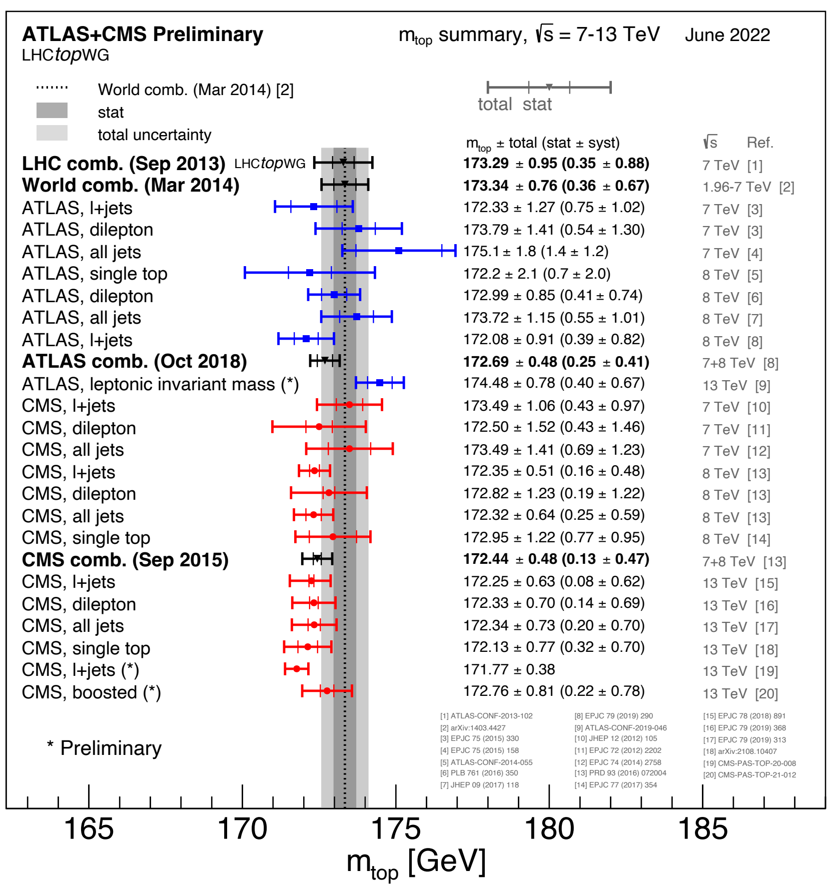


Latest experimental results on Top mass

Top mass (direct vs. indirect)

Direct measurements

- kinematic reconstruction of variables related to the top-quark momentum
- typically have a high experimental precision
- m_t extracted at detector level: difficult to define theoretically and interpretation linked to Monte Carlo (MC) implementation
- Usually ~ 0.5 GeV interpretation uncertainty taken.



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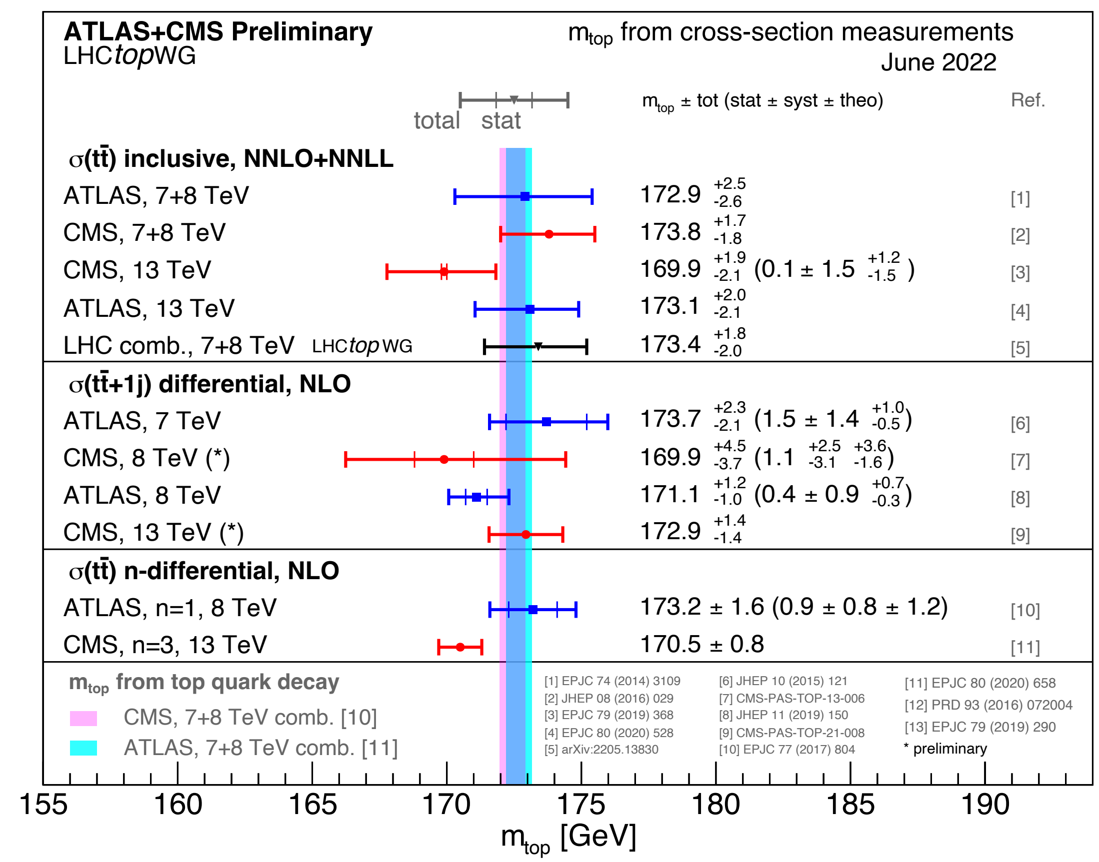
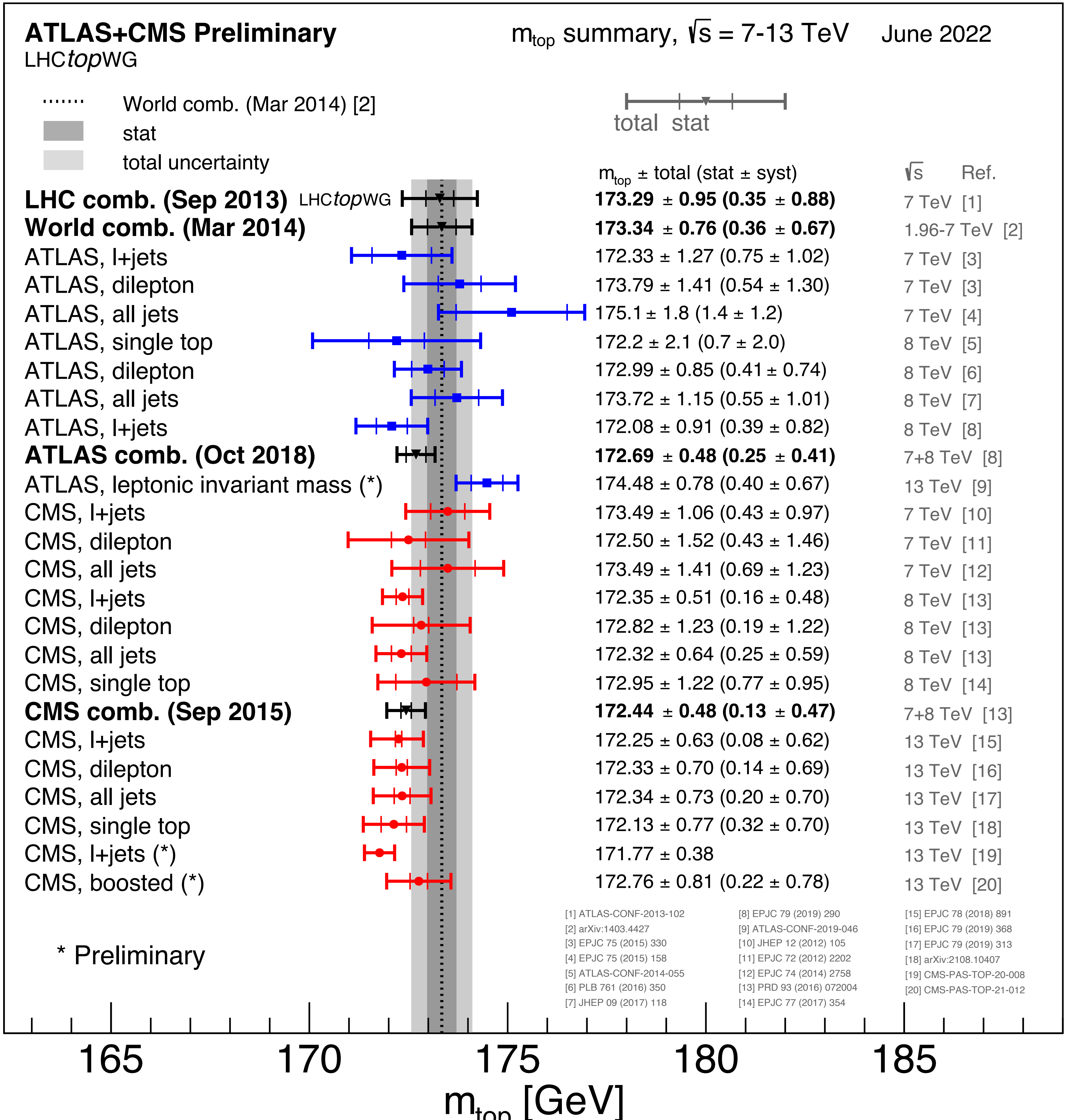
Indirect measurements

- measure observable(s) which have a strong dependence on m_t with data unfolding
- infer m_t in a theoretically well defined phase space
- compare to fixed-order predictions for a better control over the theoretical uncertainties on m_t





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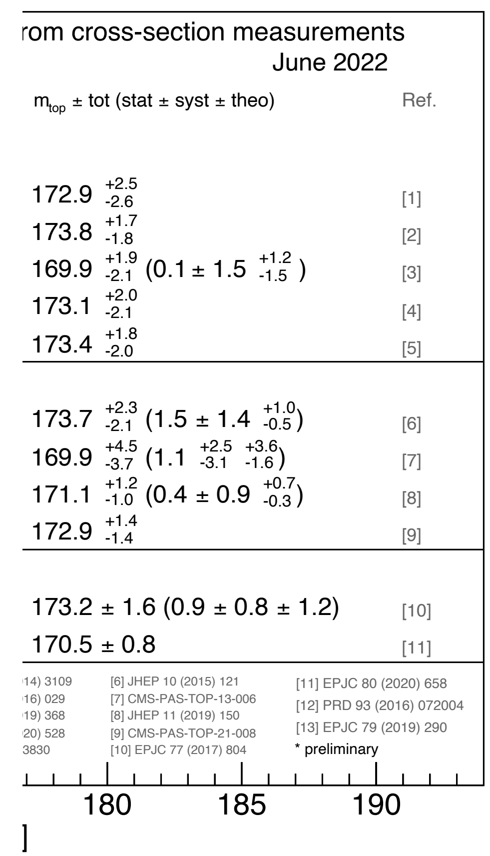

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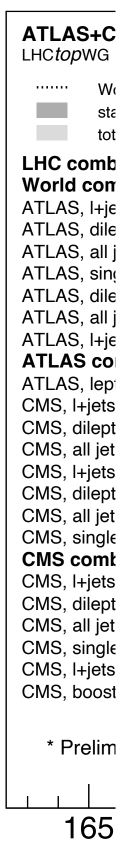

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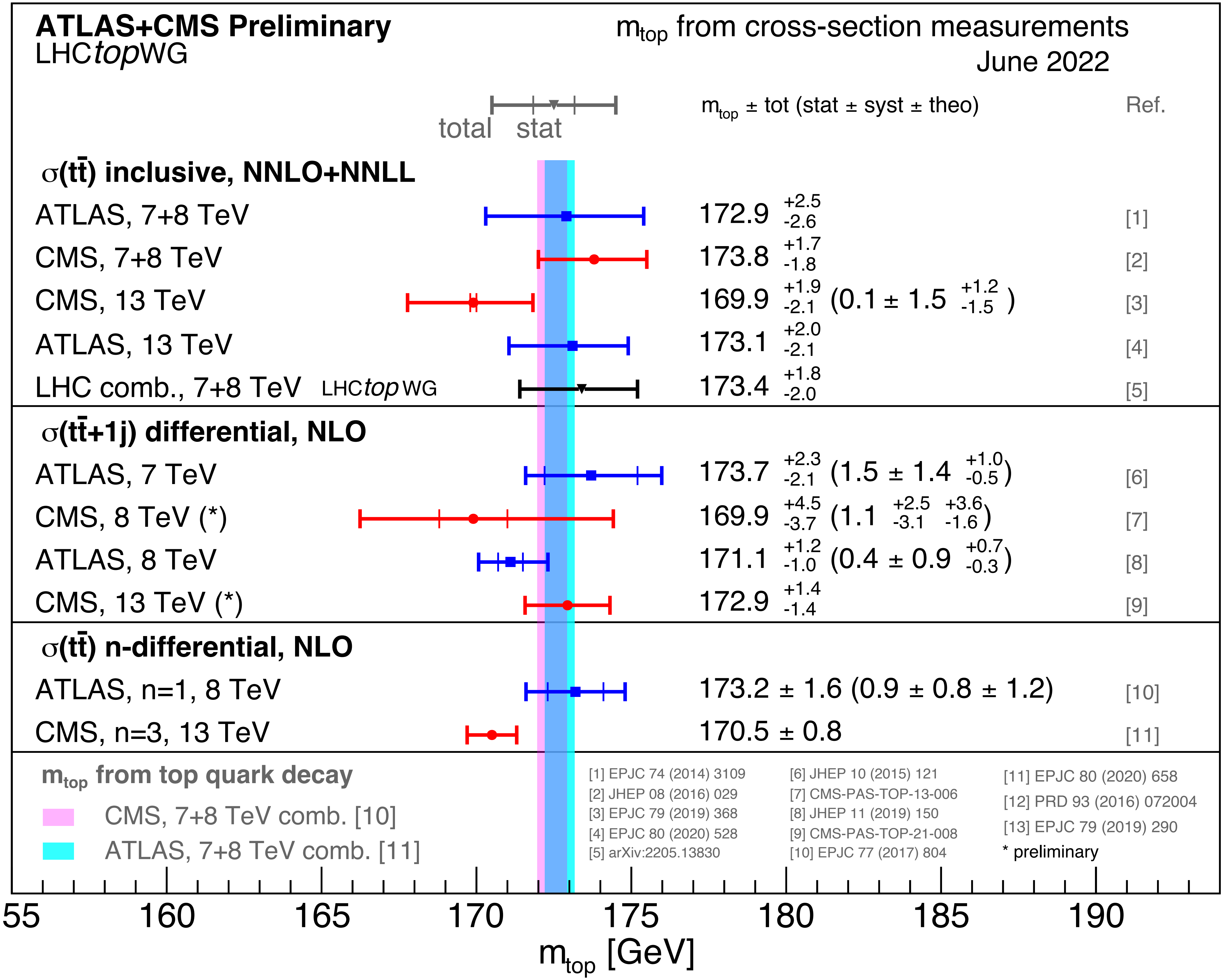
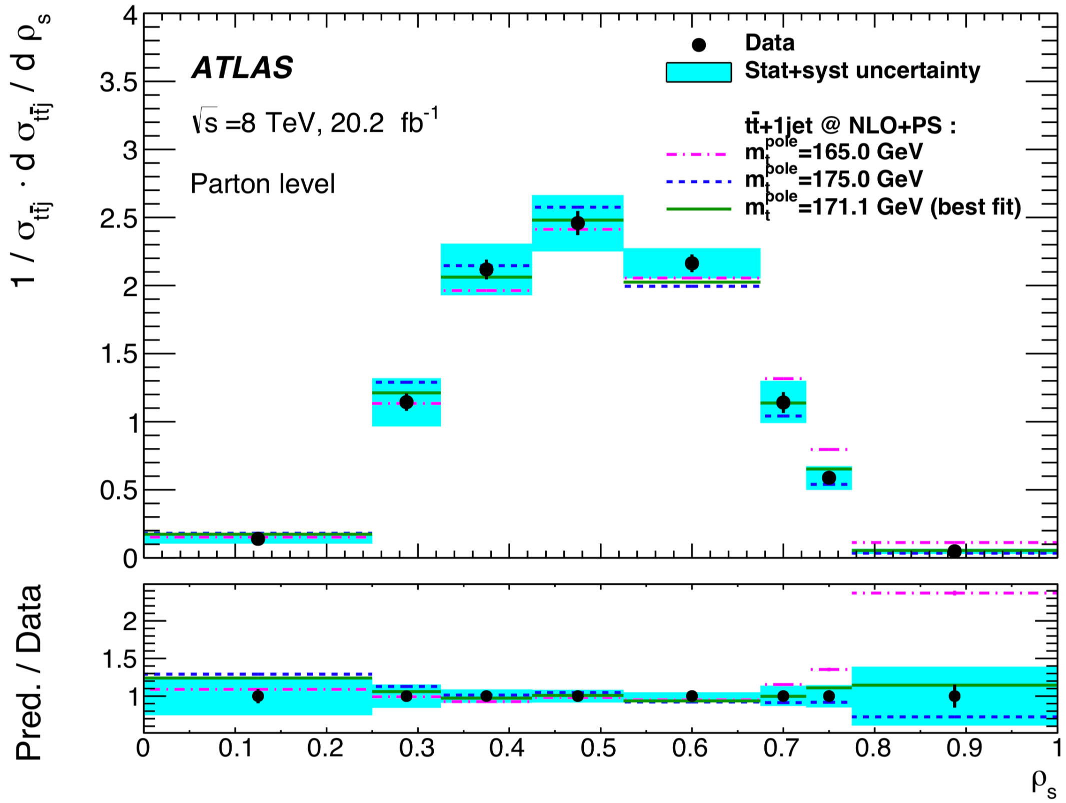


Top mass with $t\bar{t}$+1jet events

J. High Energ. Phys. 2019, 150 (2019)

$$\rho_S = \frac{2m_0}{m_{t\bar{t}+1j}} = \frac{2 \cdot 170\,\text{GeV}}{m_{t\bar{t}+1j}}$$

sensitive to m_{top}^{pole}

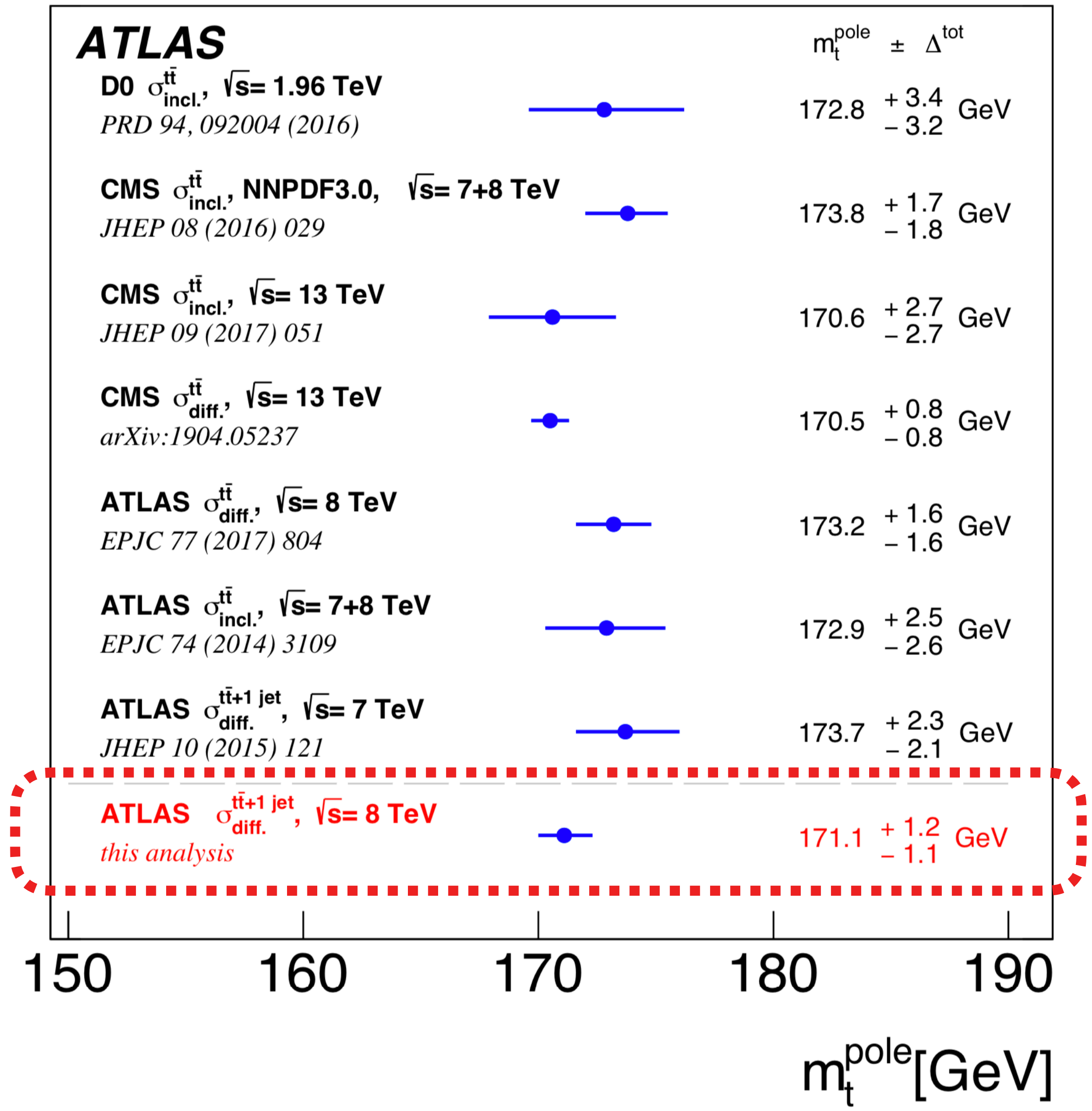


m_t^{pole} = 171.1 ± 1.2 GeV (0.7 %)

- best individual differential measurement - dominated by JES and MC modelling uncertainties

In l+jets channel @8TeV

- $\sigma_{t\bar{t}+1j}$ more sensitive than $\sigma_{t\bar{t}}$
- unfold to parton and particle level

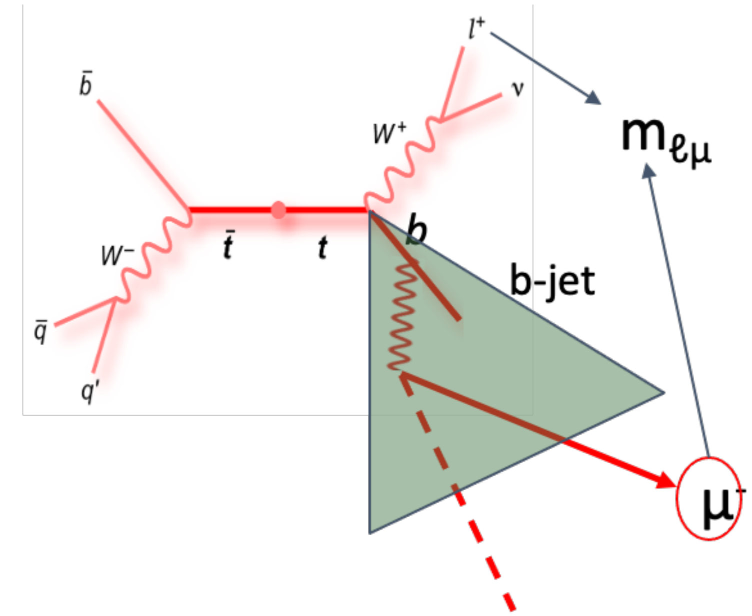


Top mass with soft-muon events

ATLAS-CONF-2019-046

$m_{\ell\mu}$ invariant mass between hard lepton from W and soft-muon from semi-leptonic b-quark decay as proxy to m_t

- useful in top mass combination since it's not sensitive to hadronic uncertainties



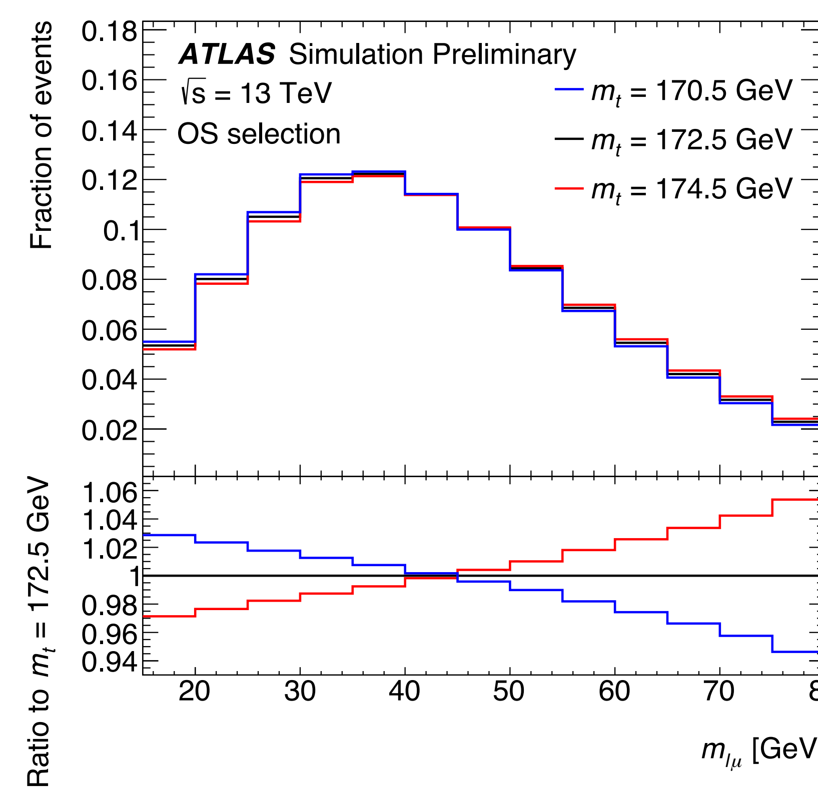
Final topology:

- 1 high-p_T isolated lepton (from $W \to \ell\nu$) + 1 low-p_T muon inside b-jet
- ≥1 b-jet + ≥4 jets + E_T^{miss} cut

Main systematic: modelling of b-quark fragmentation

- b-quark fragmentation in Pythia tuned on LEP data
- production fractions and BRs tuned to Babar/LEP and LHC measurements

Hadron	PDG (%)	Powheg+Pythia8	Scale Factor
B^0	0.404±0.006	0.429	0.941
B^+	0.404±0.006	0.429	0.942
B_s^0	0.103±0.005	0.095	1.088
b-baryon	0.088±0.012	0.047	1.874
D^+	0.226±0.008	0.290	0.780
D^0	0.564±0.015	0.553	1.020
D_s^0	0.080±0.005	0.093	0.857
c-baryon	0.109±0.009	0.038	2.898



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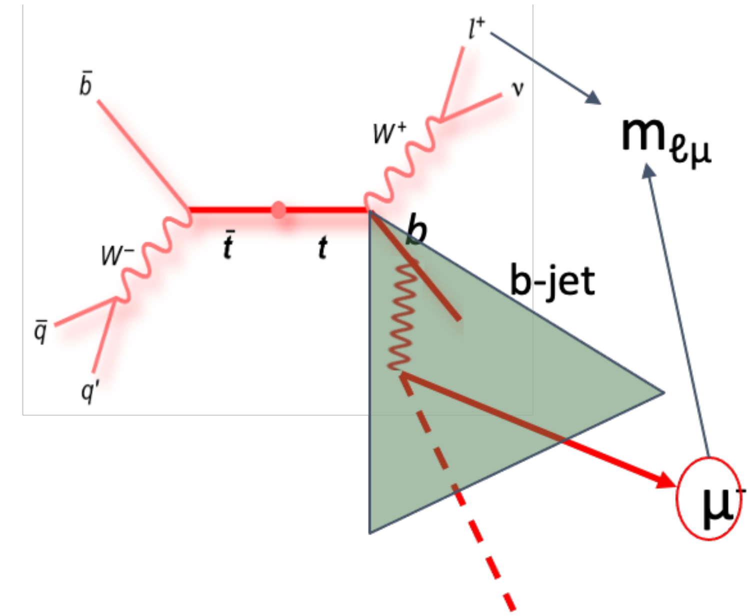

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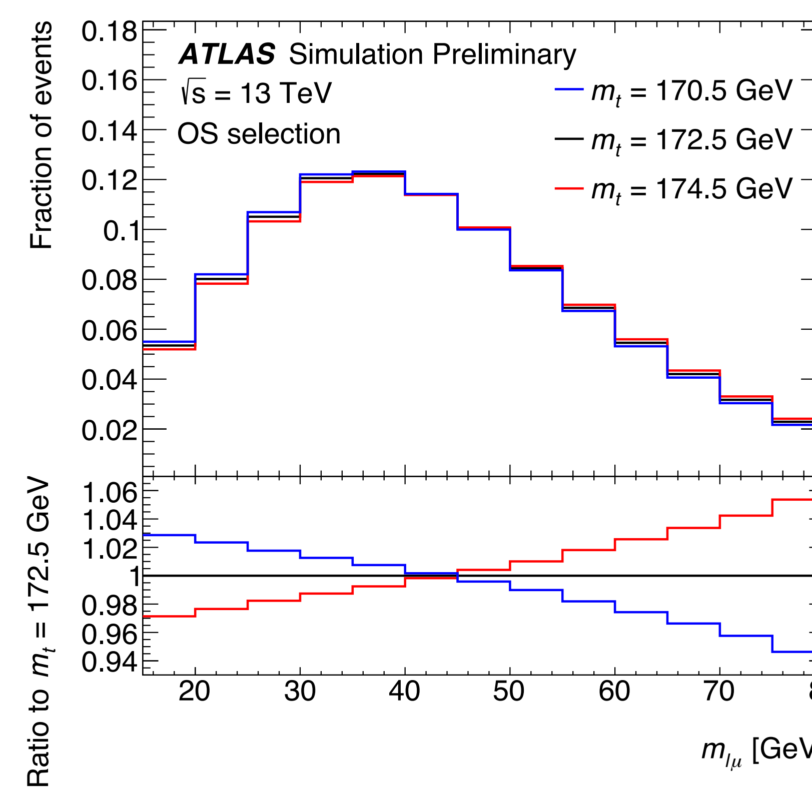


The most precise top mass analysis in ATLAS (36/fb)

- m_t = 174.48 ±0.78 GeV
  = 174.48 ± 0.40(stat) ± 0.67(syst) GeV

Questions/Comments?

Latest experimental results on Top properties

Top width using $t\bar{t}$ events

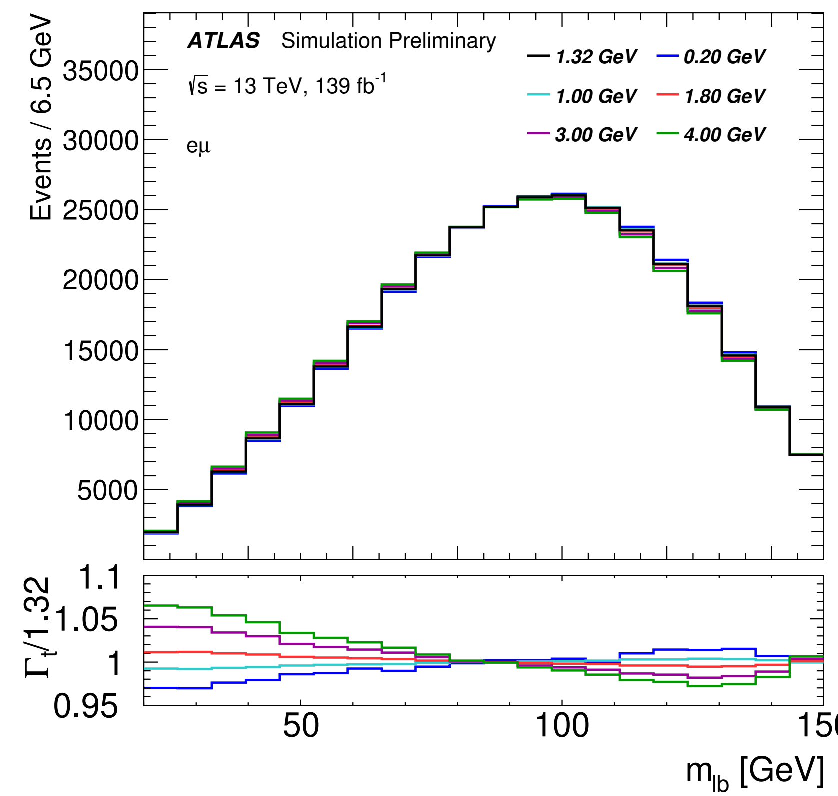
ATLAS-CONF-2019-038

Decay width (Γ) is an important property of any particle

- BSM models predict different Γ_t compared to SM
- prediction: Γ_t^{SM} = 1.32 GeV for m_t = 172.5 GeV (NNLO)
- precise 8 TeV measurement, still not enough to constrain BSM
  - Γ_t = 1.76 ± 0.33 (stat.)+0.79 −0.68 (syst.) GeV [Eur. Phys. J. C 78 (2018) 129]

Measurement performed with dilepton $t\bar{t}$ events, full Run II data (139 fb^{-1})

- m_{lb} very sensitive to Γ_t
  - templates created with different Γ_t
- profile likelihood with multiple templates



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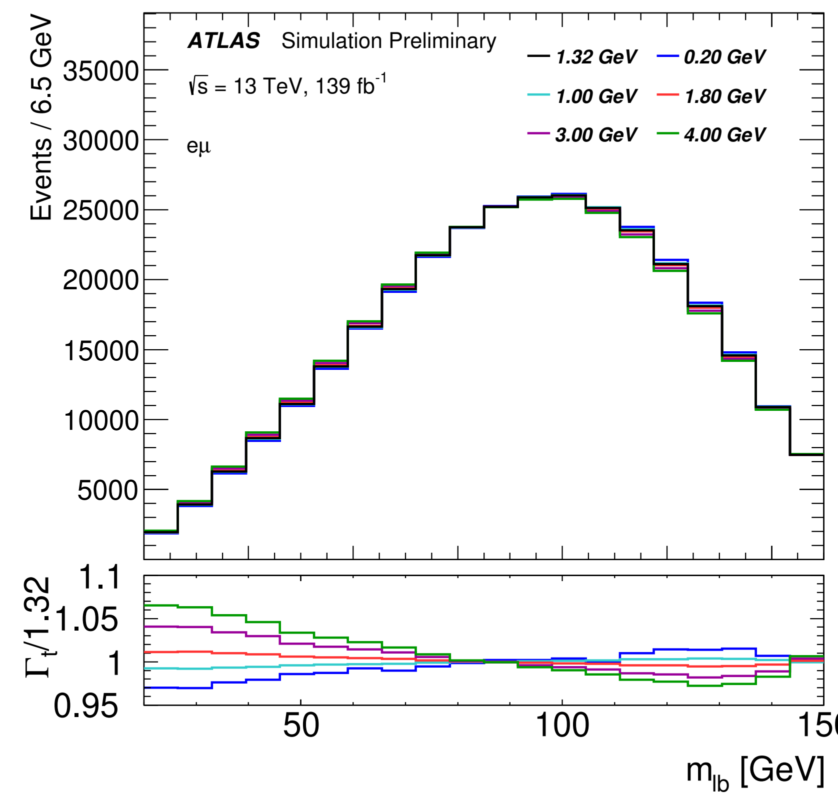

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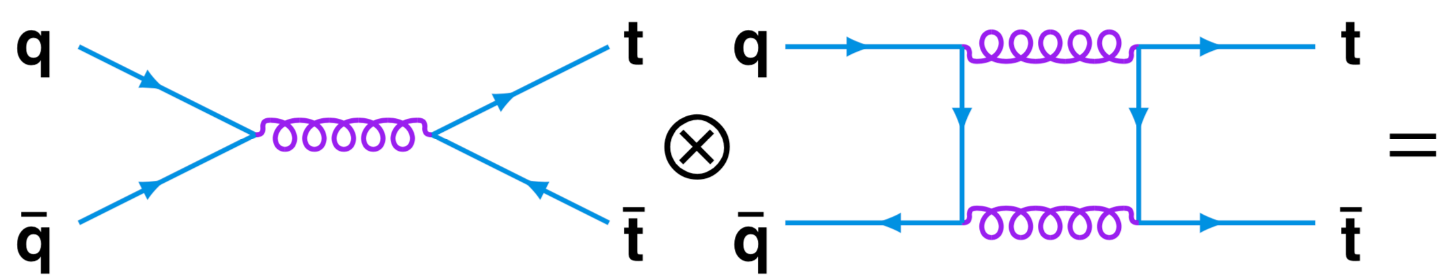
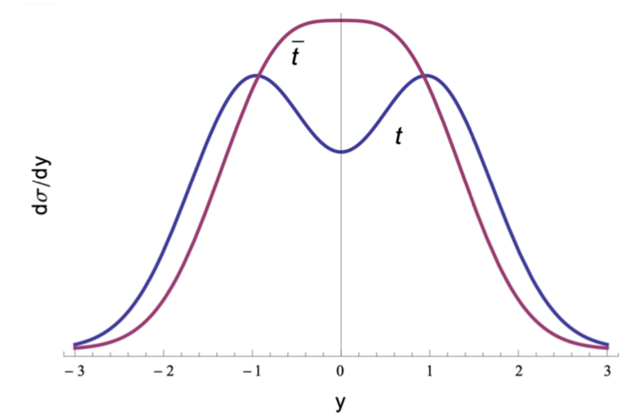
- m_{lb} very sensitive to Γ_t
  - templates created with different Γ_t
- profile likelihood with multiple templates

	m_t = 172 GeV		m_t = 172.5 GeV		m_t = 173 GeV	
	Mean [GeV]	Unc. [GeV]	Mean [GeV]	Unc. [GeV]	Mean [GeV]	Unc. [GeV]
Measured	2.01	$^{+0.53}_{-0.50}$	1.94	$^{+0.52}_{-0.49}$	1.90	$^{+0.52}_{-0.48}$
Theory	1.306	< 1%	1.322	< 1%	1.333	< 1%

Γ_t measured for different m_t
Agreement with SM predictions

Charge Asymmetry in a nutshell





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

tt̄ charge asymmetry ($A_C^{t\bar{t}}$) happens only at NLO

- gg initiated process (~90% @13 TeV) remains charge symmetric to all orders
  - → challenging to measure $A_C^{t\bar{t}}$ at LHC
- higher orders interference in qg and qq̄, and EW contributions lead to asymmetries
  - also BSM physics can lead to enhancements

tt̄+ɣ has enhanced qq̄ initiated production → perfect playground for tests of $A_C^{t\bar{t}}$

- enhancement only for events where the photon is radiated by initial state partons (a.k.a. "tt̄+ɣ production")

$t\bar{t}$ Charge Asymmetry

ATLAS-CONF-2019-026

Extracted from 139/fb @13TeV data using single lepton (e/μ) selections

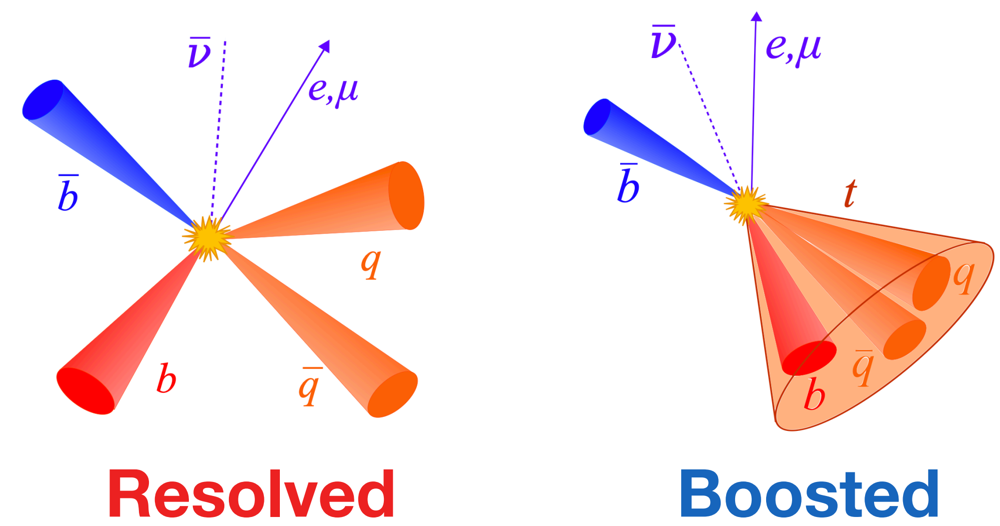
- resolved+boosted (p_T(t) ≳ 400 GeV)

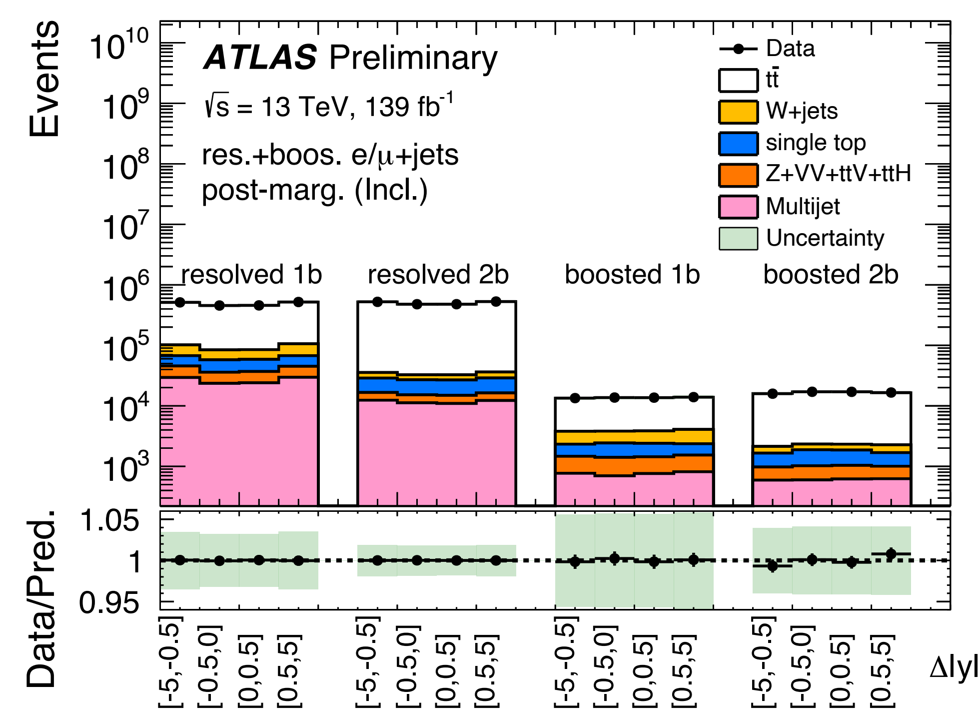
Resolved: BDT to assign the different jets to the top systems

- using a kinematic fit (KLFitter), masses of hadronic top and W, various angular variables
- best combination considered and only events with good reconstruction retained

Boosted: hadronic top reconstructed as a single large-R jet

- mass and τ_{32} used to "tag" hadronic tops
- leptonic side reconstructed from the E_T^{miss}, lepton and a R=0.4 jet





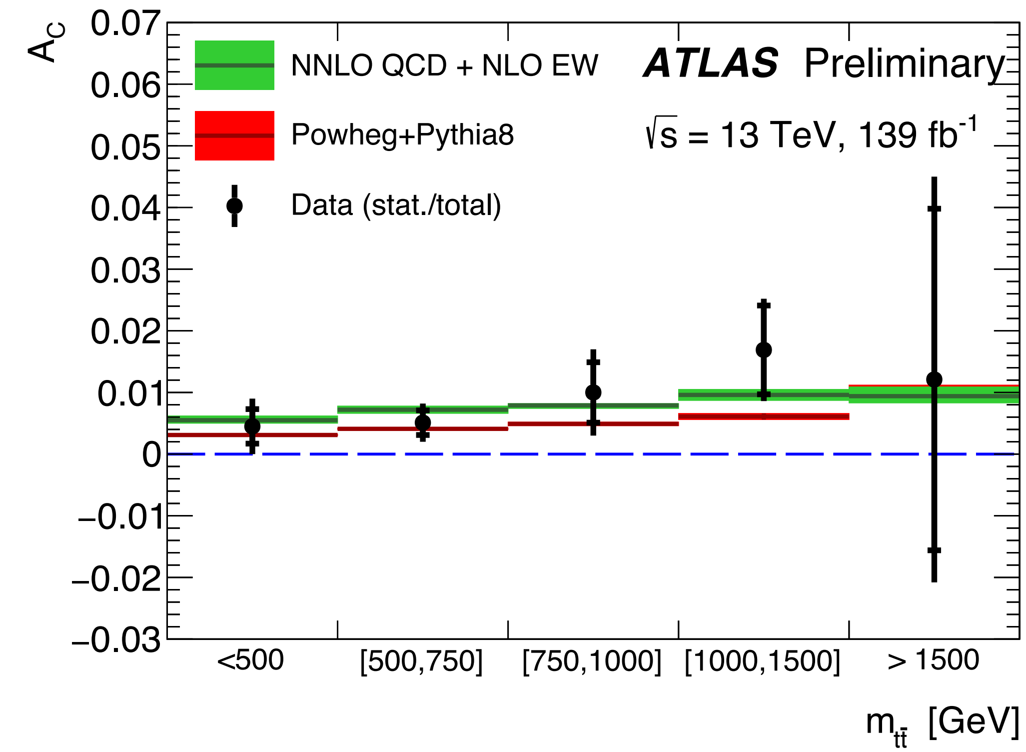
ATLAS Physics Briefing

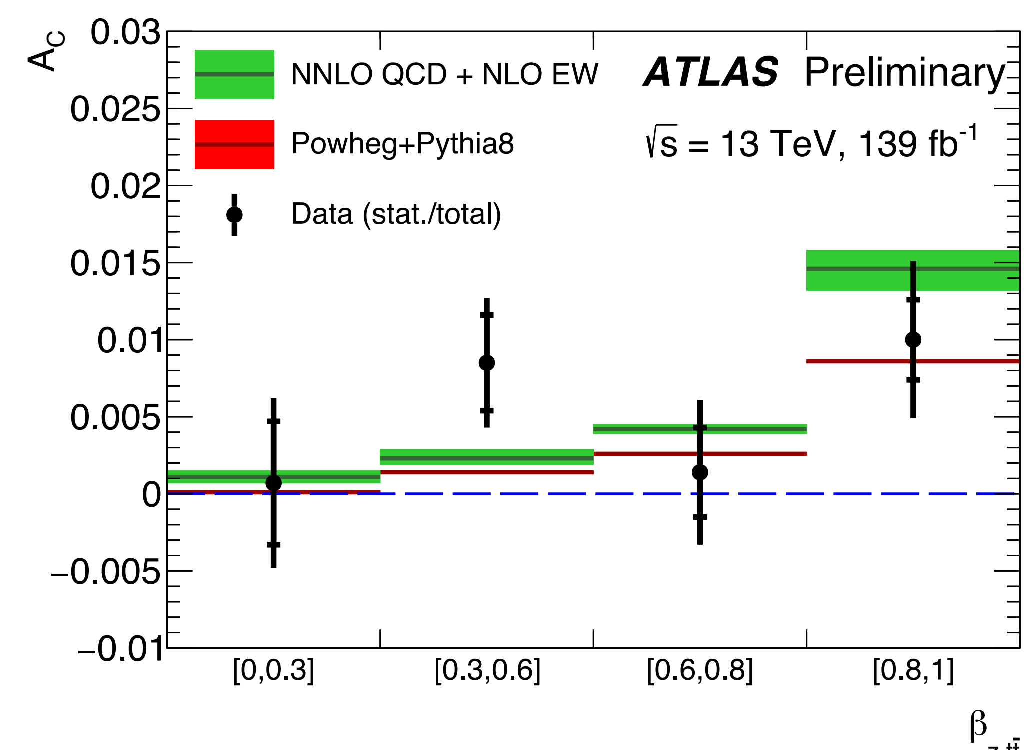
|Δ*y*| unfolded using Fully Bayesian Unfolding (FBU)

- inclusive and differential in bins of the $m_{t\bar{t}}$ and $\beta_{z,t\bar{t}}$ (absolute longitudinal boost of $t\bar{t}$ system in the *z*-direction)

Inclusive charge asymmetry A_C = (0.6±0.15)%

- in agreement with NNLO QCD + NLO EW predictions





ATLAS Physics Briefing

$t\bar{t}$ Charge Asymmetry

[ATLAS-CONF-2019-026](#)

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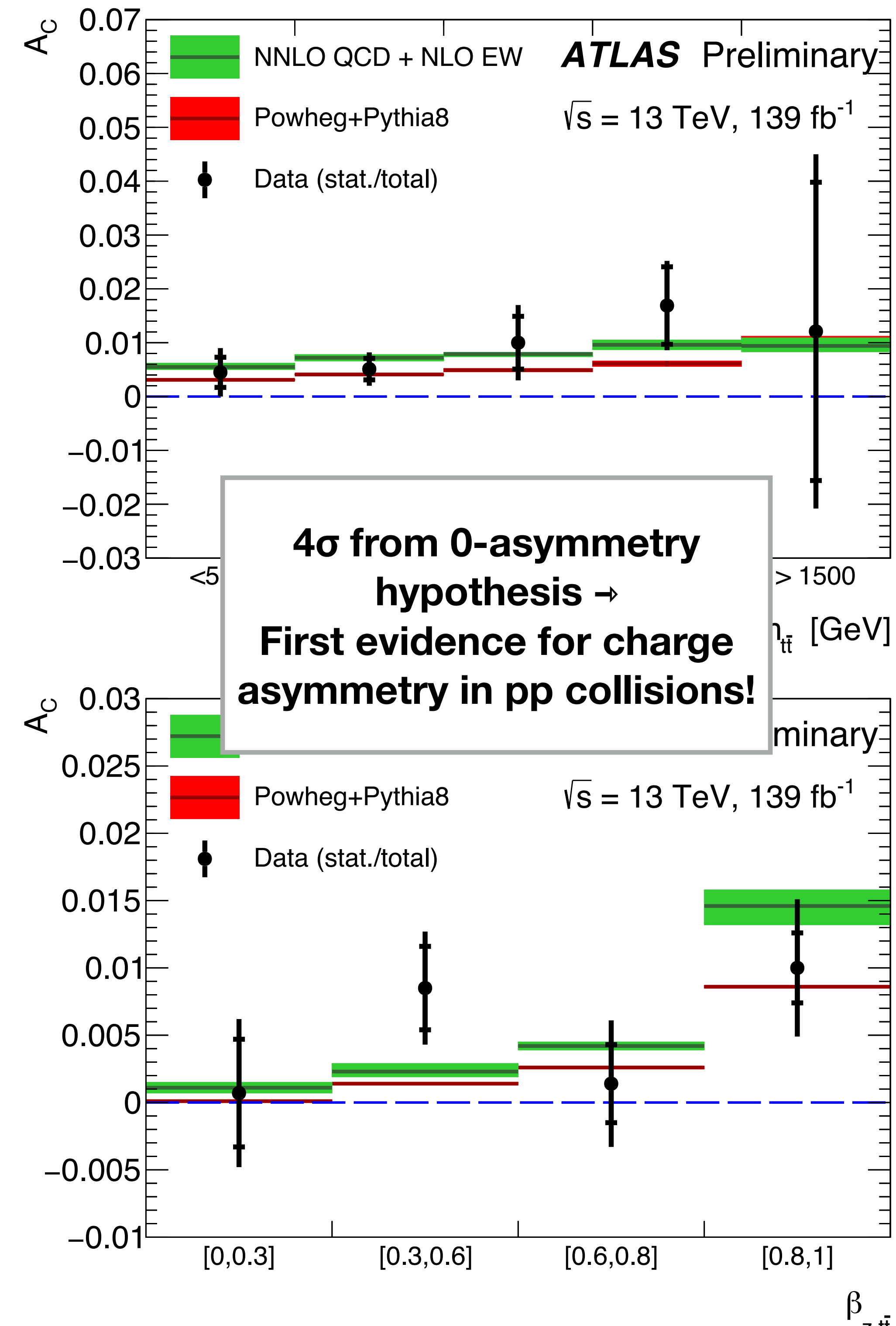

4σ from 0-asymmetry hypothesis → First evidence for charge asymmetry in pp collisions!

[ATLAS Physics Briefing](#)

$t\bar{t}$ Charge Asymmetry

ATLAS-CONF-2019-026

$|\Delta y|$ unfol ... **(FBU)**

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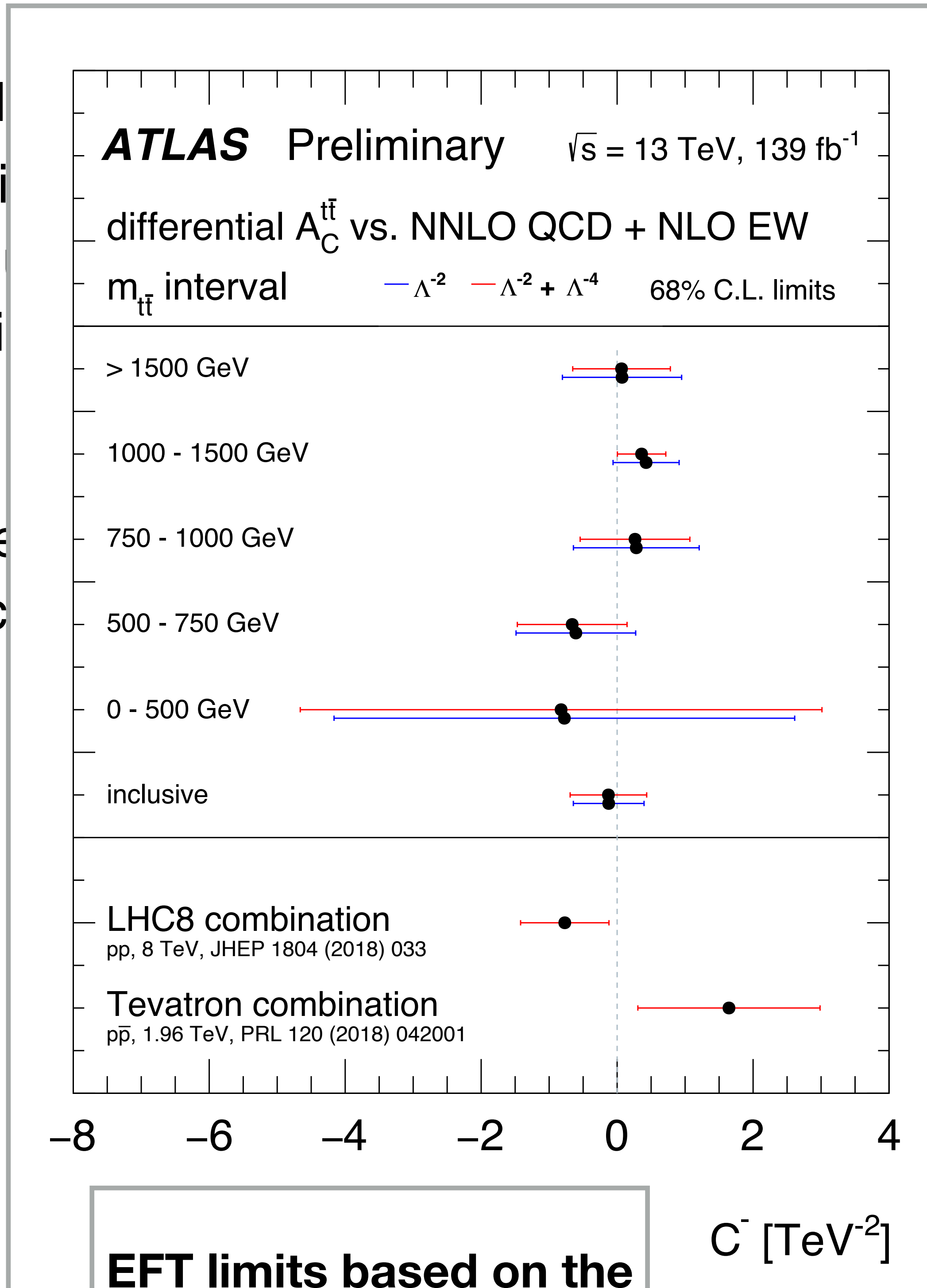
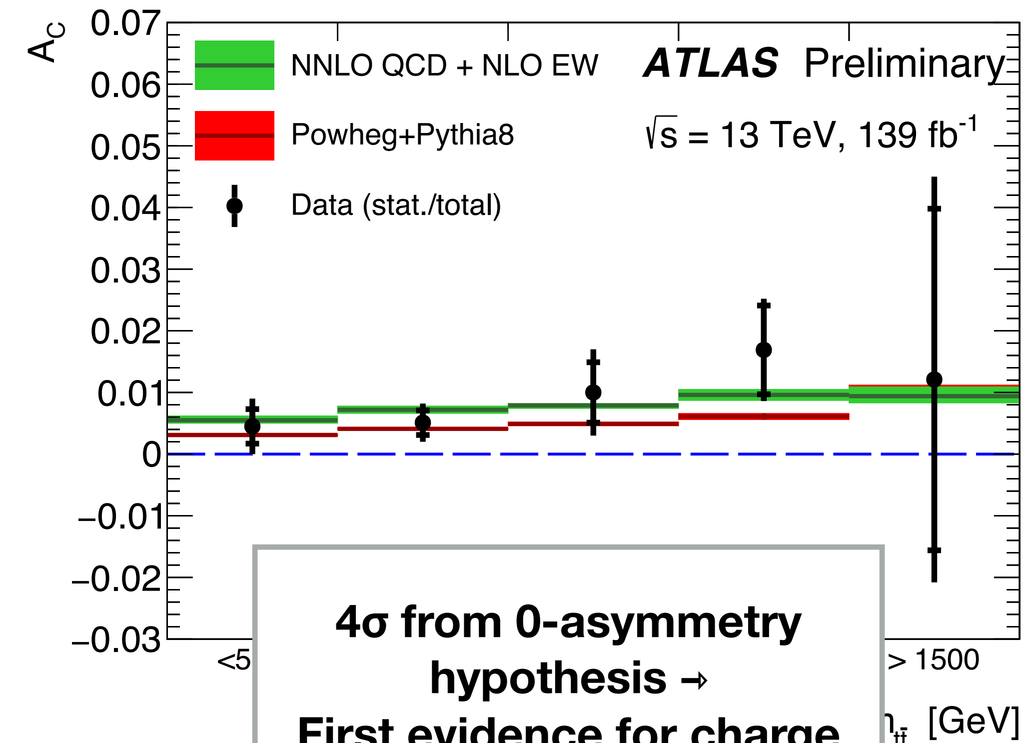


EFT limits based on the inclusive and $m_{t\bar{t}}$ results



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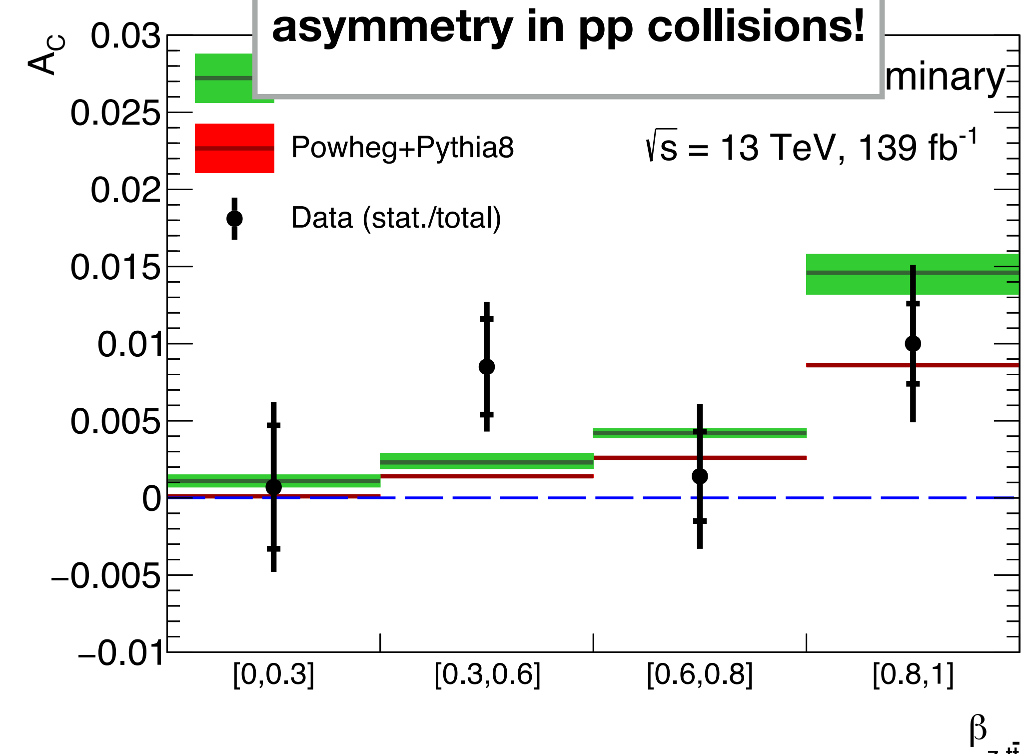
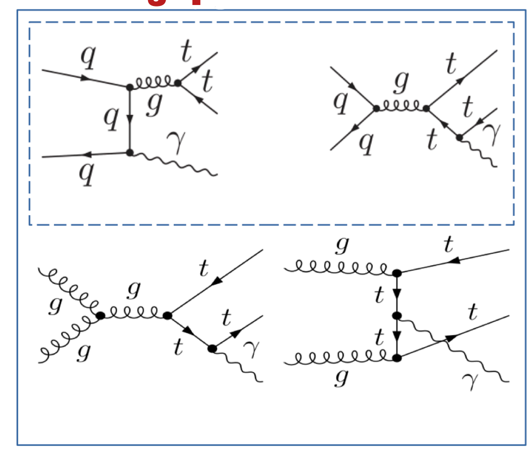


ATLAS Physics Briefing

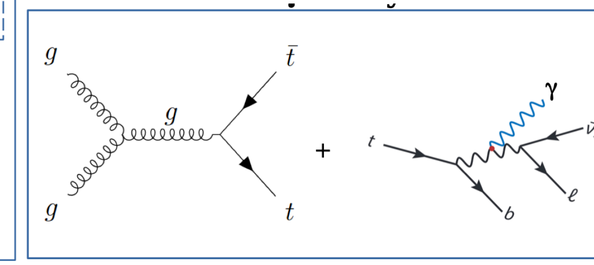
$t\bar{t}\gamma$ Charge Asymmetry

ATLAS-CONF-2022-049

$t\bar{t}+\gamma$ production

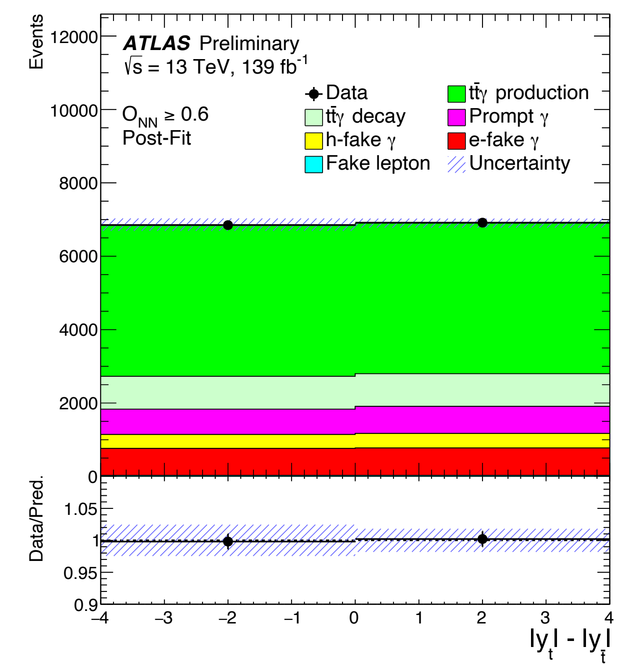


$t\bar{t}+\gamma$ decay



l+γ+jets selection with Run II data:

- e/μ trigger-matched with p_T>27 GeV
- isolated photon p_T>20 GeV and ΔR(l,γ)>0.4
- m(e,γ) outside Z-mass window (m_Z ± 5 GeV)
- ≥4 jets of which ≥1 b-tagged
- kinematic likelihood fit (KLFitter) to reconstruct $t\bar{t}$ system
- Neural Network (NN) to separate signal ($t\bar{t}$+γ production) vs. backgrounds
  - "$t\bar{t}$+γ decay" as irreducible background
  - two regions NN<0.6 and NN>0.6



Main backgrounds: prompt γ, jet- and e-faking γ

- $t\bar{t}$+γ decay (30%) and prompt-γ (15%) estimated with MC
  - validated in Zγ and Wγ dedicated regions
- data-driven e-faking γ (16%) using tag-and-probe Z→ee/eγ events
- data-driven jet-faking γ (7%) using ABCD method (γ-iso and γ-ID)

$A_C^{t\bar{t}}$ extraction by Profile Likelihood Unfolding (PLU)

- $A_C^{t\bar{t}}$ = -0.006 ± 0.030 = -0.006 ± 0.024(stat) ± 0.018(syst)
- precision is limited by the statistical uncertainty

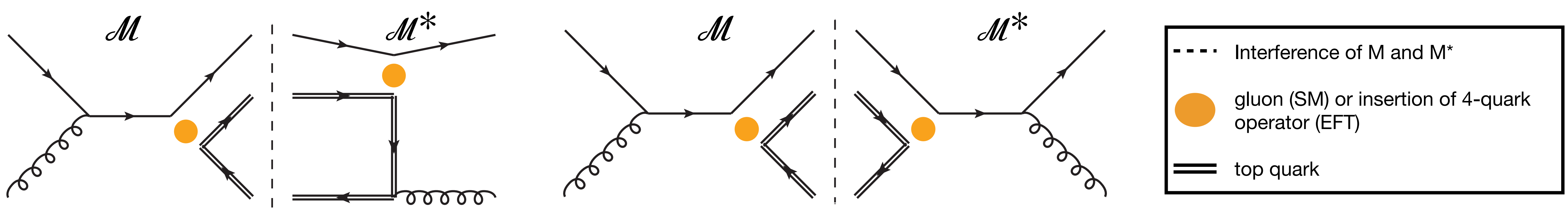
Consistent with SM prediction $A_C^{t\bar{t}}$ = -0.014±0.001 (MadGraph NLO)

Energy Asymmetry in a nutshell

Eur. Phys. J. C 82 (2022) 374

$t\bar{t}$ energy asymmetry ($A_E^{t\bar{t}}$) happens at LO mainly through qg → $t\bar{t}$g

- different probability of t and $\bar{t}$ from to be emitted in a certain phase-space
- → t and $\bar{t}$ have different energy in $t\bar{t}$ + high p_T jet
- → measure asymmetry in top quark energy in $t\bar{t}$ + 1 jet boosted events and search for BSM



Observable defined for $t\bar{t}$+j production as $A_E(\theta_j) = \dfrac{\sigma^{\mathrm{opt}}(\theta_j \,|\, \Delta E > 0) - \sigma^{\mathrm{opt}}(\theta_j \,|\, \Delta E < 0)}{\sigma^{\mathrm{opt}}(\theta_j \,|\, \Delta E > 0) + \sigma^{\mathrm{opt}}(\theta_j \,|\, \Delta E < 0)}$

- where $\Delta E = E_t - E_{\bar{t}}$ and θ_j scattering angle of additional jet in tt+j rest frame
- QCD asymmetry is closely related to the charge asymmetry in inclusive $t\bar{t}$ production
- observable probes for possible new physics in tt+j events

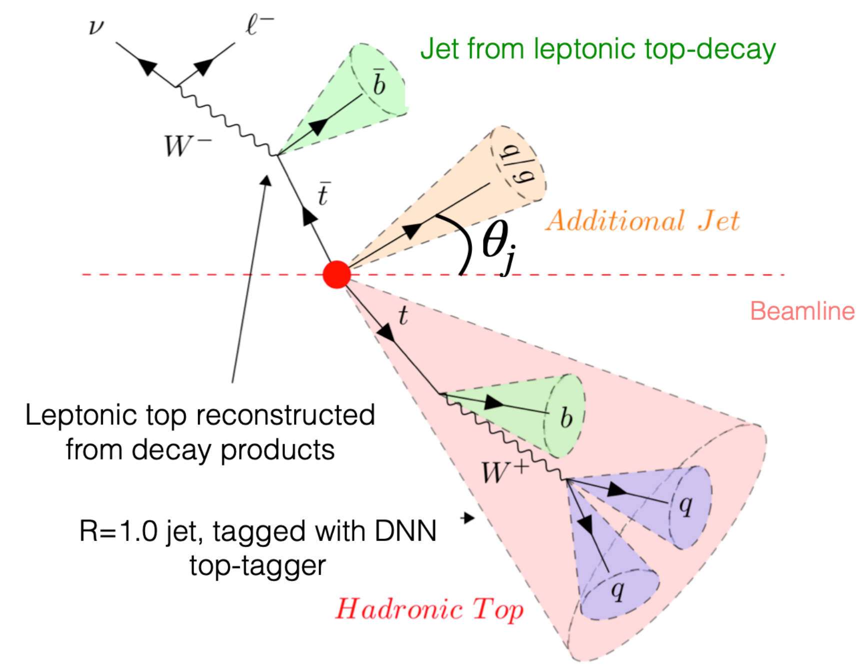
ATLAS Physics Briefing

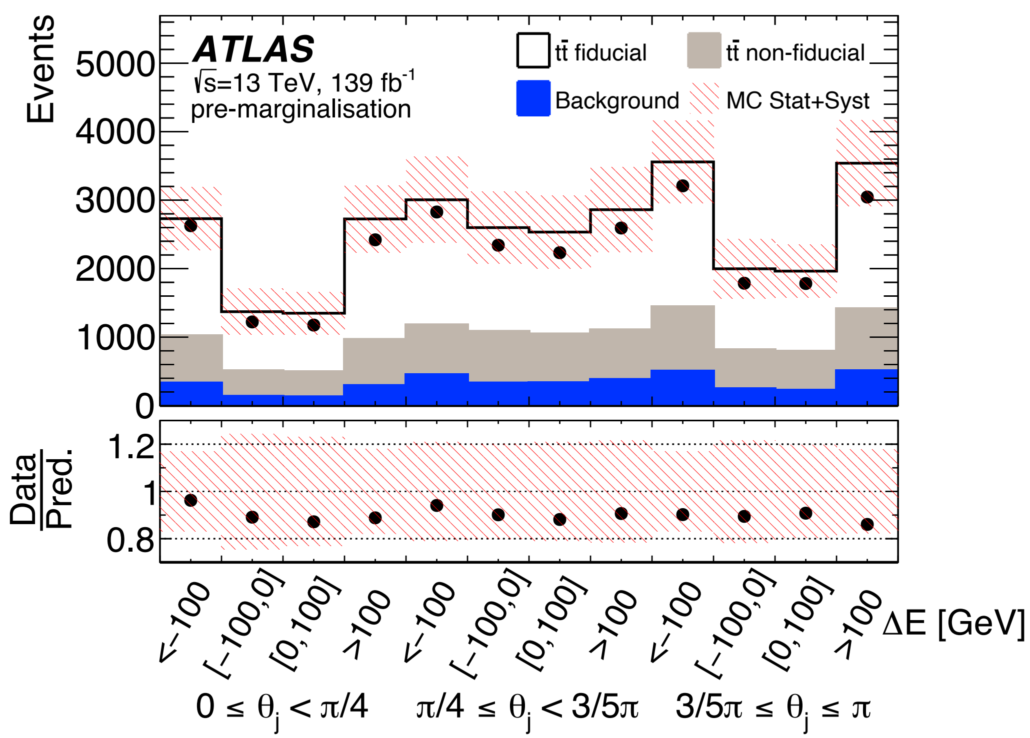
$t\bar{t}$+1jet Energy Asymmetry

Eur. Phys. J. C 82 (2022) 374

Select l+jets boosted events:

- "leptonic" top (large m_T^W and E_T^{miss})
- high p_T hadronic top (p_T > 350 GeV) as R=1 jet tagged by substructure based Neural Network (NN)
- high p_T (> 350 GeV) additional jet





ATLAS Physics Briefing

$t\bar{t}$+1jet Energy Asymmetry

[Eur. Phys. J. C 82 (2022) 374]

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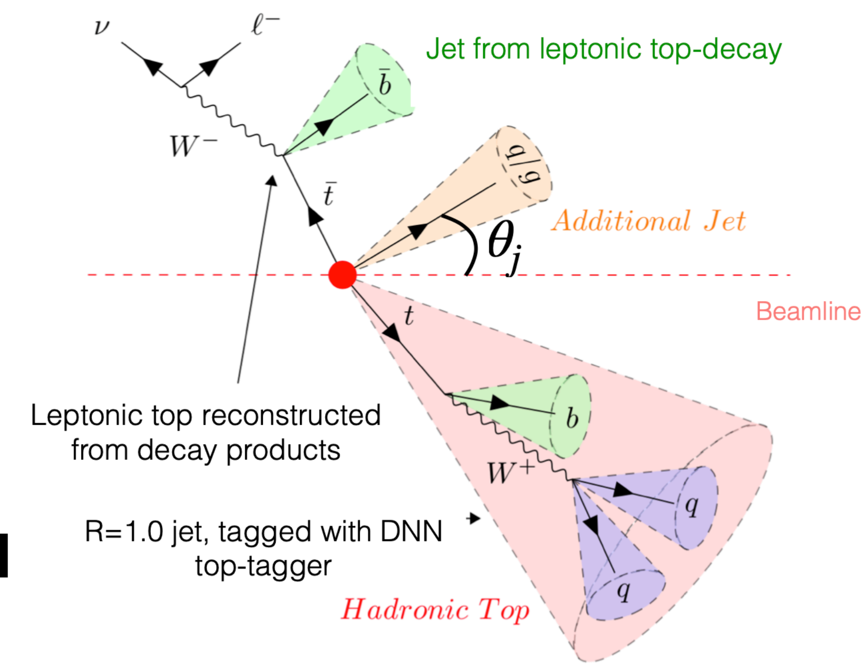
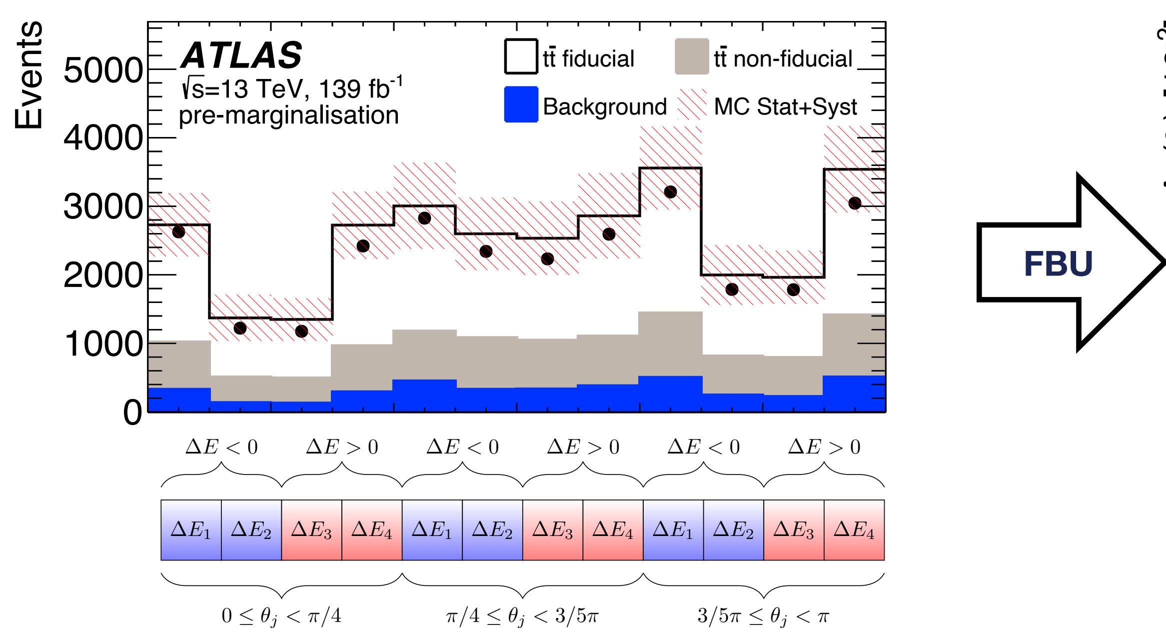
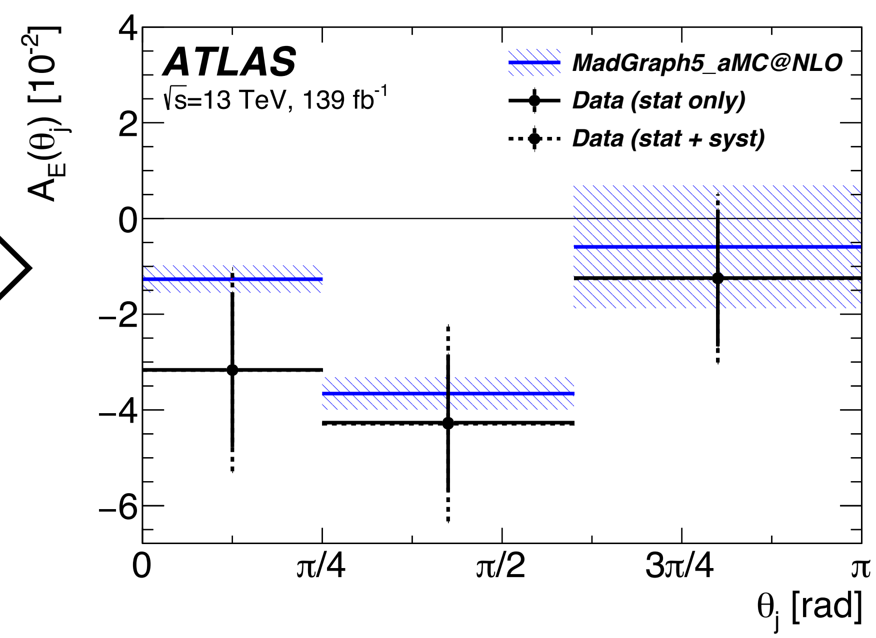


Count events with ΔE >0 or <0 in bins of θ_j and unfolded data with Fully Bayesian Unfolding technique (FBU)

- analysis currently limited by available data statistics and $t\bar{t}$ FSR modelling





Consistent with NLO QCD prediction

2.1σ deviation from 0 asymmetry in the central bin

[ATLAS Physics Briefing]

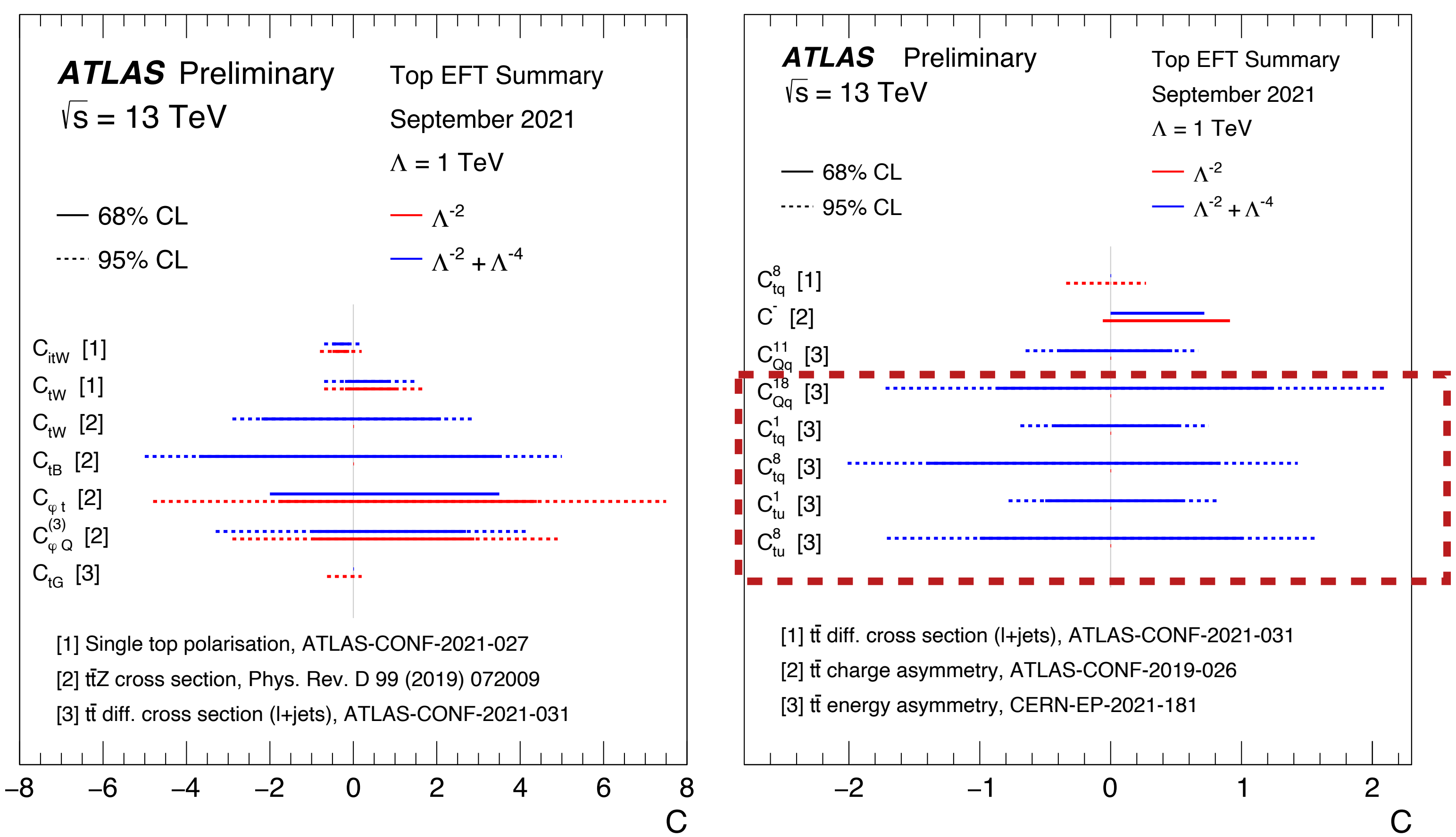
$t\bar{t}$+1jet Energy Asymmetry

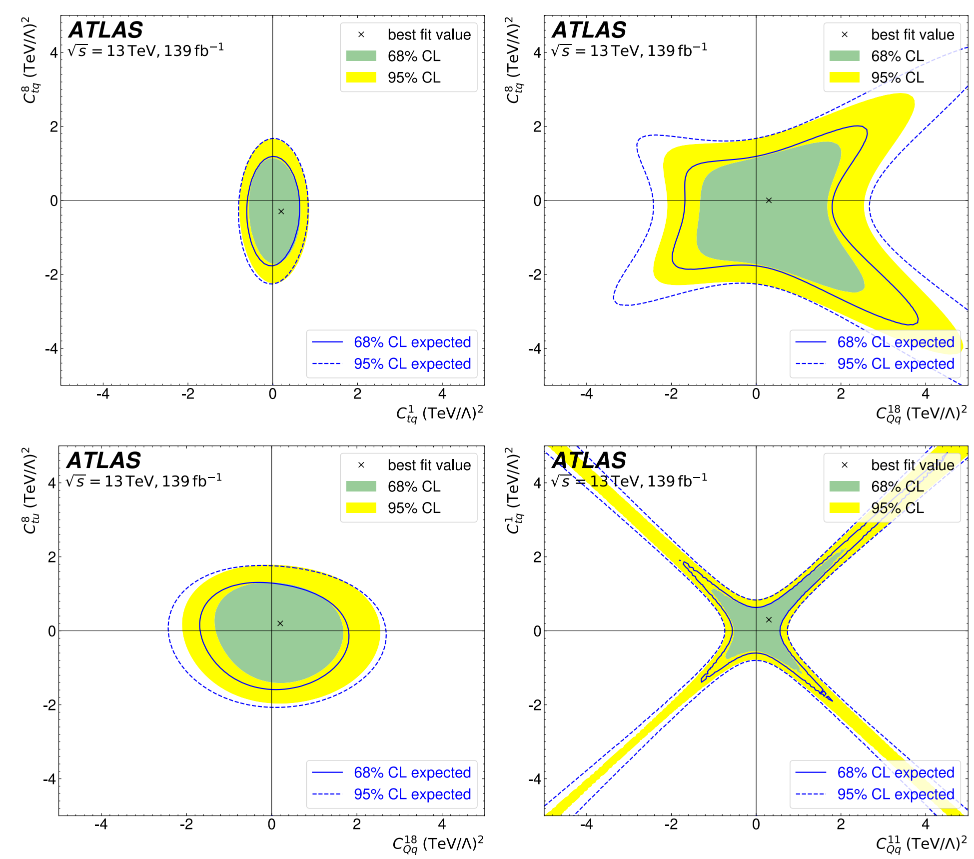
Eur. Phys. J. C 82 (2022) 374

$A_E^{t\bar{t}}$ sensitive to top chirality in 4-quark operators

- → valuable new observable in global SMEFT fits
- it probes new directions in dim-6 parameter space (w.r.t. charge asymmetry, for instance)
- 2D limits on pairs of 6 corresponding Wilson coefficients breaking degeneracy

ATL-PHYS-PUB-2021-043





ATLAS Physics Briefing

$t\bar{t}$ spin correlation

Eur. Phys. J. C 80, 754 (2020)

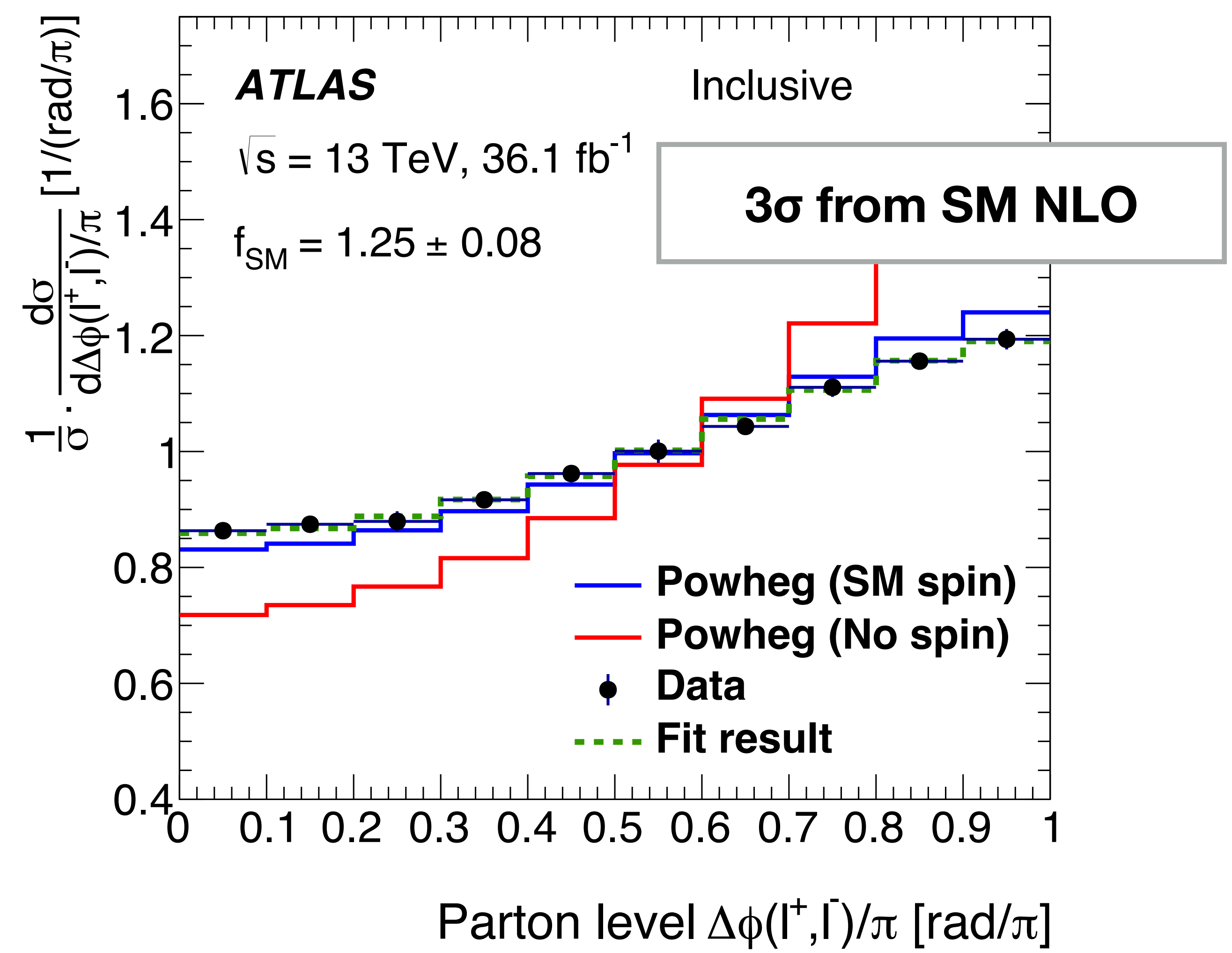
$$C = A\alpha_1\alpha_2 = \frac{N(\uparrow\uparrow) + N(\downarrow\downarrow) - N(\uparrow\downarrow) - N(\downarrow\uparrow)}{N(\uparrow\uparrow) + N(\downarrow\downarrow) + N(\uparrow\downarrow) + N(\downarrow\uparrow)}$$

Correlated spins between top pairs produced at LHC

- accessible via $|\Delta\phi_{\ell\ell}|$, in dilepton $t\bar{t}$ decays, no top reconstruction required

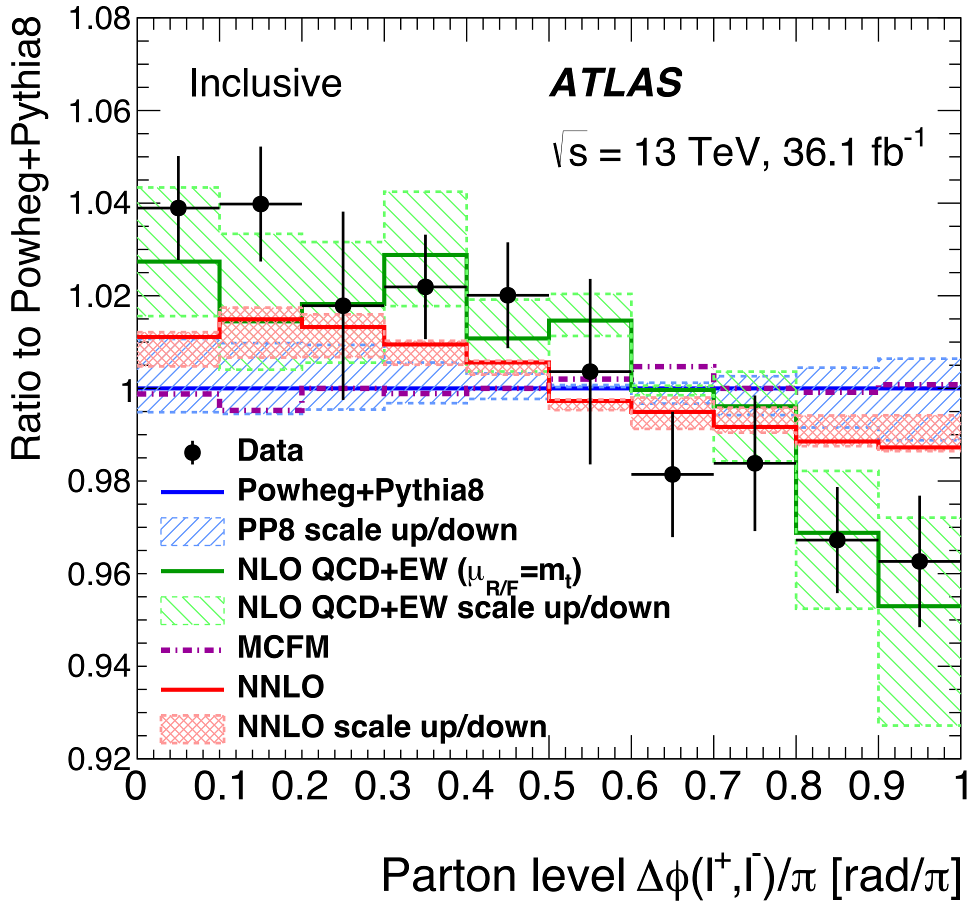
Measured @13TeV (36 fb^{-1}) in eμ+2b channel

- also differentially in $m(t\bar{t})$
- also measured the $|\Delta\eta_{\ell\ell}|$ observable, sensitive to SUSY production
- unfolded to fiducial particle level and full phase-space parton level

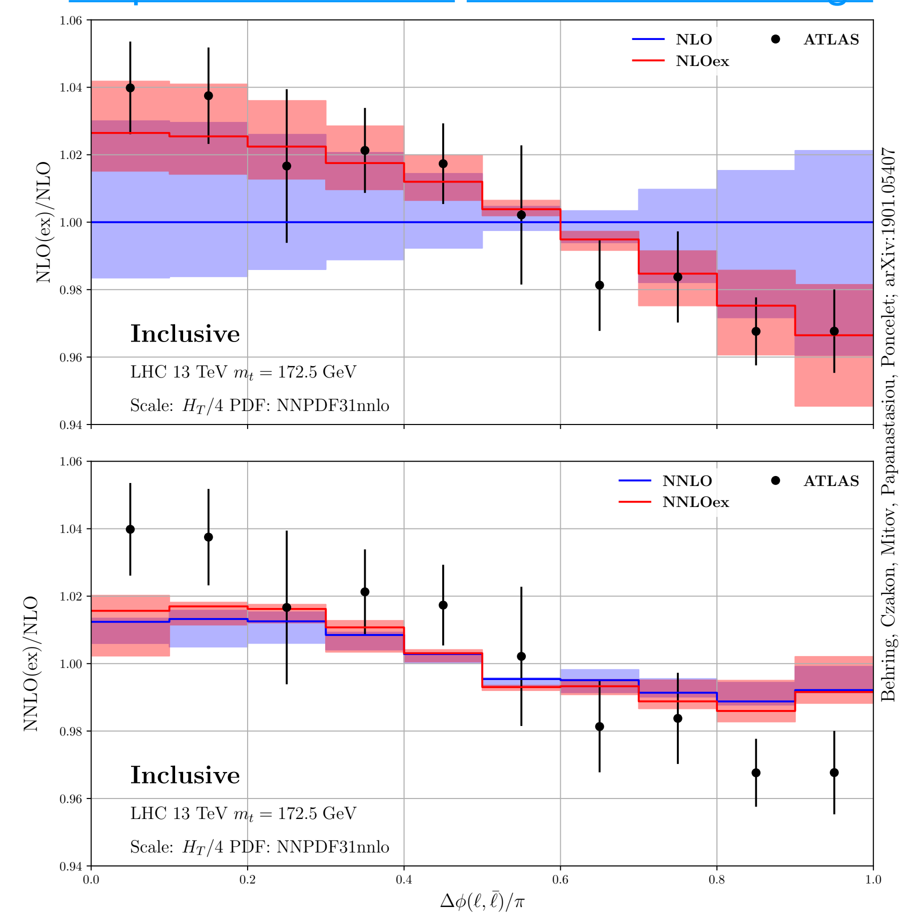


$t\bar{t}$ spin correlation

[Eur. Phys. J. C 80, 754 (2020)]



[Paper: :1901.05407] [Extension: Web Page]



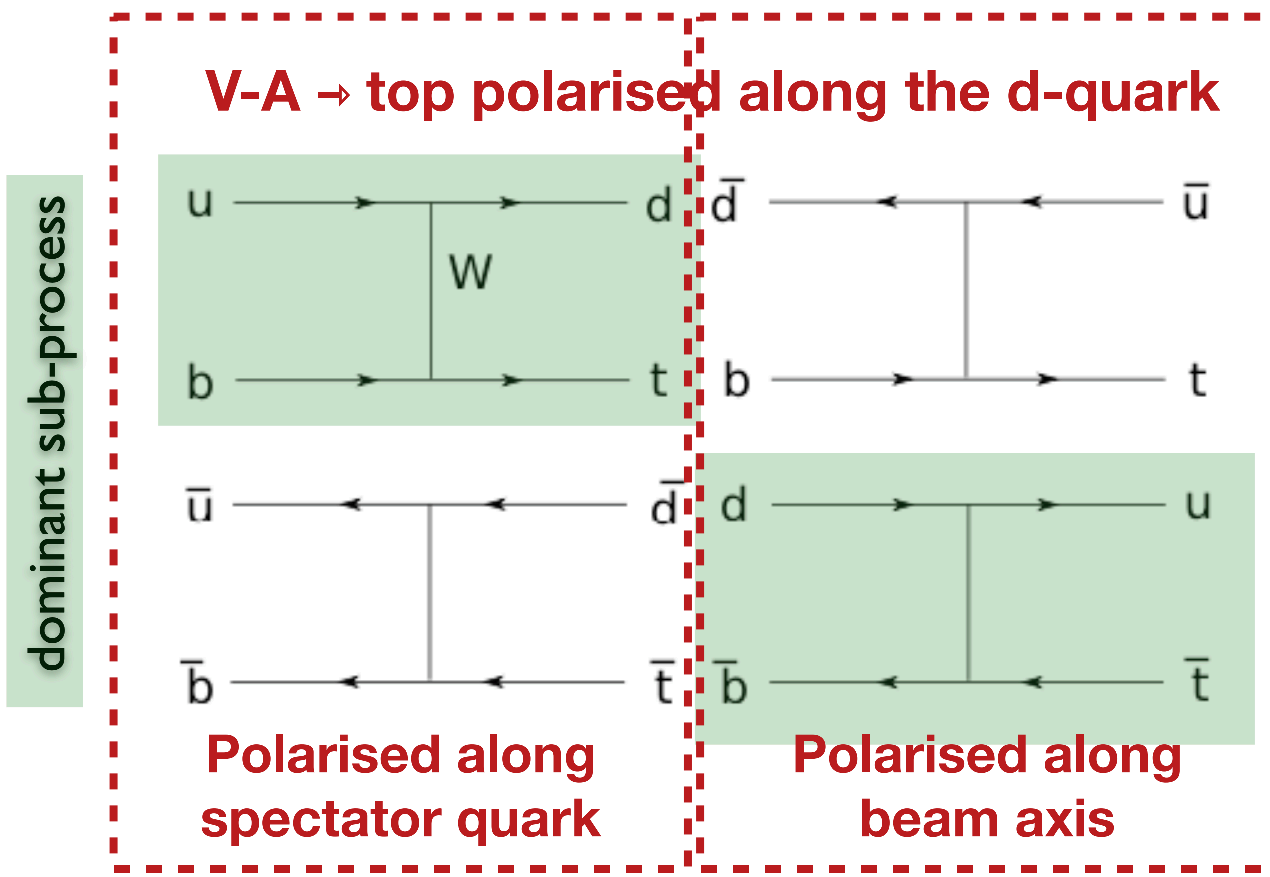
Lots of discussions in the theory community

- focus on the assumptions involved in the template hypotheses
- **NLO + Parton** shower MC consistent with fixed-order calculations from **MCFM**
- state-of the art **NNLO-QCD** predictions (Brun et. al.) closer to data (2.2σ)
- **NLO-QCD + EW** prediction agrees with data but with large scale uncertainties
  - + agreement driven by ratio expansion method
- when **ratio expanded at NNLO**, the agreement disappears

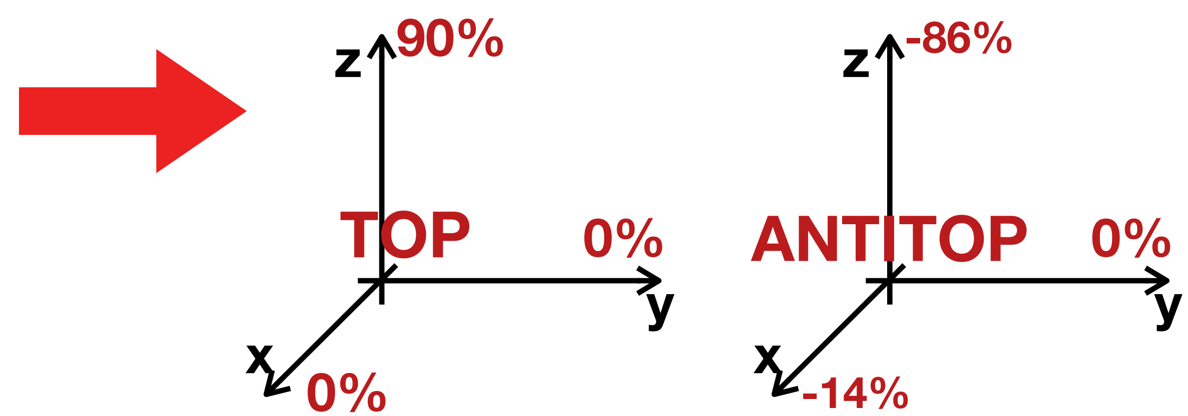
[Submitted to JHEP]

At the LHC (pp collisions)...

- *EW production:* highly polarised top quarks due to V-A nature
  - Top-quark polarisation (***P***) can only be measured in single top-quark t-channel events*
    * In $t\bar{t}$ production, top quarks are produced unpolarised because of parity conservation in QCD
- *detectable:* accessible via angular distributions (in top rest frame)
- *spin polarisation:* depends upon specific top-/antitop- sample and chosen basis
  - valence *u*-quark density ~2x valence *d*-quark density (pp collisions)
  - $P_i = \frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)}, \quad \uparrow / \downarrow$ w.r.t. i



z axis: along the top-quark boost in c.m. of colliding partons (= along dir. of spectator jet)
x axis: in the plane of production
y axis: perpendicular to the plane of production (CP violating axis)



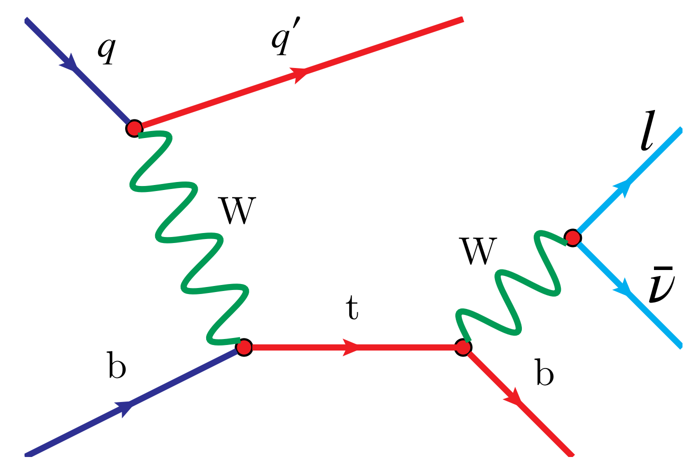
[ATLAS Physics Briefing]

Top-quark Polarisation at LHC

Submitted to JHEP

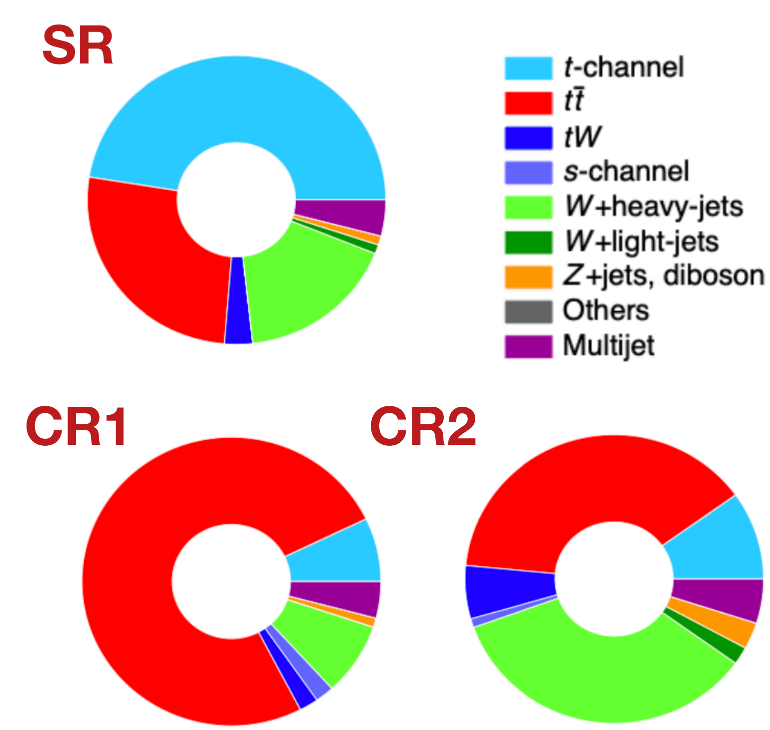
Fiducial measurement of top polarisation in t-channel with full Run II dataset (139 /fb)

- *template fit:* measurement of top quark and anti-quark polarisations (P_x,P_y,P_z) in the t-channel events, at reco. level within a fiducial region
- *unfolding:* normalised differential measurements ($\cos\theta_{x/y/z}$) unfolded at particle level within the same fiducial region
- *EFT interpretation* of the unfolded results



Cut-based analysis in 1L final state:

- exactly 1 triggering lepton (e/μ),
- exactly 2 jets, of which 1 b-quark tagged,
- m_T^W and E_T^{miss} cuts to reject QCD background
- QCD background estimated via data-driven methods
  - *jet-electron* (e-channel) and *anti-muon* (μ-channel)
- further split into 1 signal region and 2 control regions



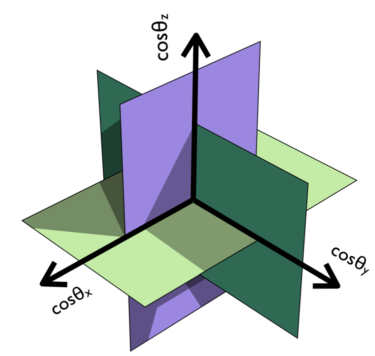
ATLAS Physics Briefing

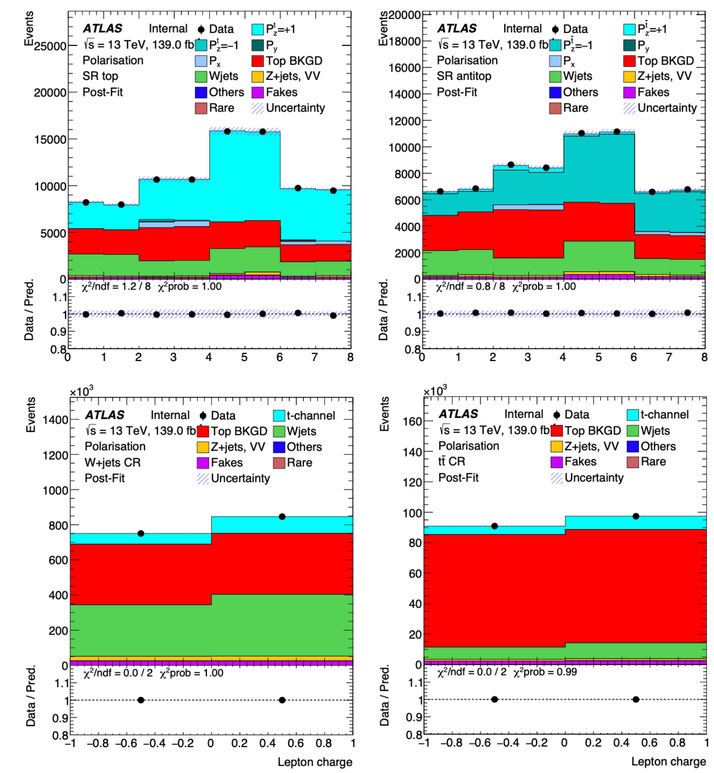
Top-quark Polarisation at LHC

[Submitted to JHEP]

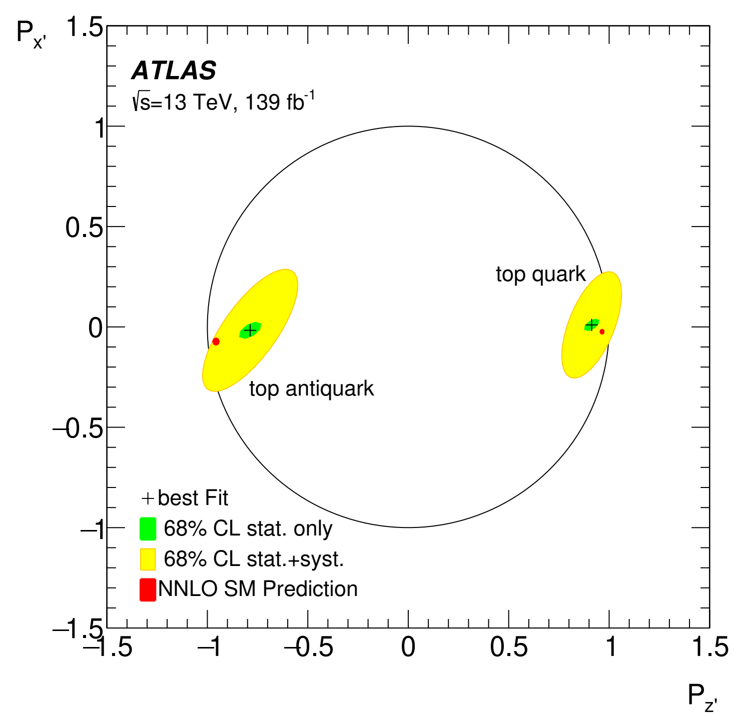
Simultaneous profile likelihood fit of top and antitop polarisations:

- $$\frac{1}{\Gamma}\frac{d\Gamma}{d\Omega d\Omega^*} = \frac{1+P_z}{2}\mathcal{F}_{z+} + \frac{1-P_z}{2}\mathcal{F}_{z-} + \frac{P_x}{2}\mathcal{F}_x + \frac{P_y}{2i}\mathcal{F}_y$$
- *4 regions:* 2 SRs (top, anti-top) + 2 CRs (W+jets, $t\bar{t}$)
- *6 polarisation parameters* $P(t)=\{P_x^t, P_y^t, P_z^t\}$ and $P(\bar{t})=\{P_x^{\bar{t}}, P_y^{\bar{t}}, P_z^{\bar{t}}\}$
- *3 normalisations* $N_{t\text{-ch}}$, $N_{t\bar{t}}$ and $N_{W+\text{jets}}$
- *Octant distribution "Q"* to fit in SR (split the phase space into 8 regions in terms of signs of **$\cos\theta_x$** / **$\cos\theta_y$** / **$\cos\theta_z$**)
- "lepton charge" distribution in CRs





Parameter	Extracted value	(stat.)
t-channel norm.	$+1.045 \pm 0.022$	(± 0.006)
$W+$jets norm.	$+1.148 \pm 0.027$	(± 0.005)
$t\bar{t}$ norm.	$+1.005 \pm 0.016$	(± 0.004)
$P^t_{x'}$	$+0.01 \pm 0.18$	(± 0.02)
$P^{\bar{t}}_{x'}$	-0.02 ± 0.20	(± 0.03)
$P^t_{y'}$	-0.029 ± 0.027	(± 0.011)
$P^{\bar{t}}_{y'}$	-0.007 ± 0.051	(± 0.017)
$P^t_{z'}$	$+0.91 \pm 0.10$	(± 0.02)
$P^{\bar{t}}_{z'}$	-0.79 ± 0.16	(± 0.03)



[ATLAS Physics Briefing]

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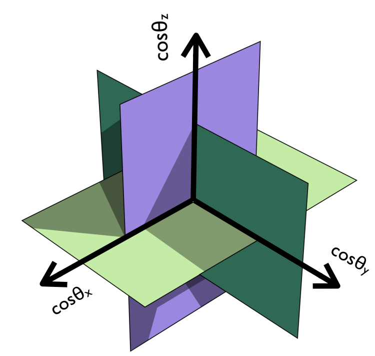

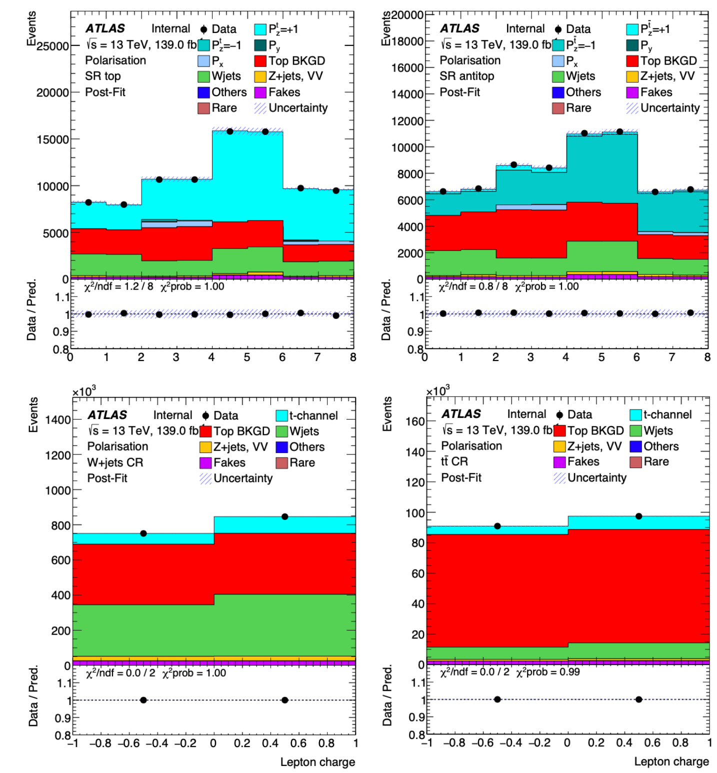

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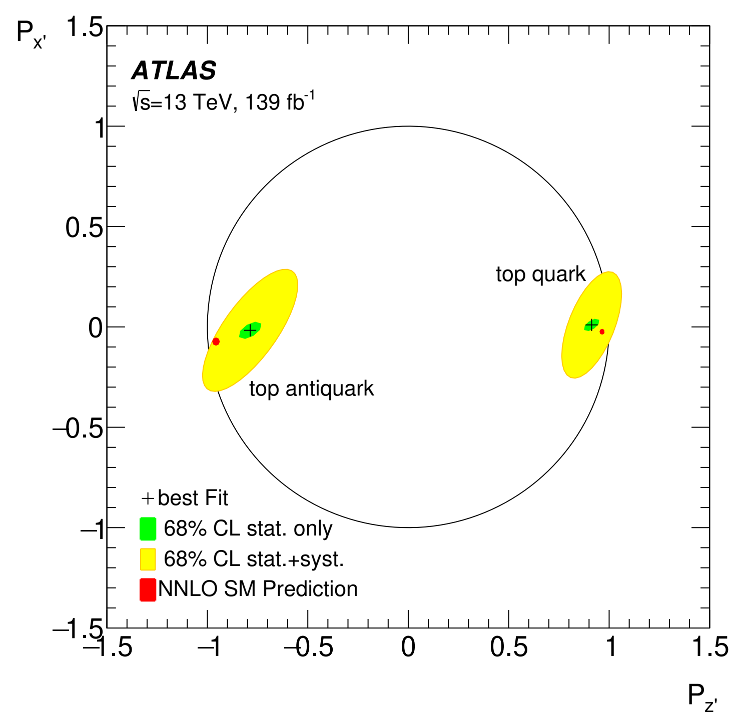


Very good agreement with NLO SM prediction
Py ≈ 0 → no CP violation
Largest uncertainty from jet-energy resolution (JER)

ATLAS Physics Briefing

Top-quark Polarisation at LHC

[Submitted to JHEP]

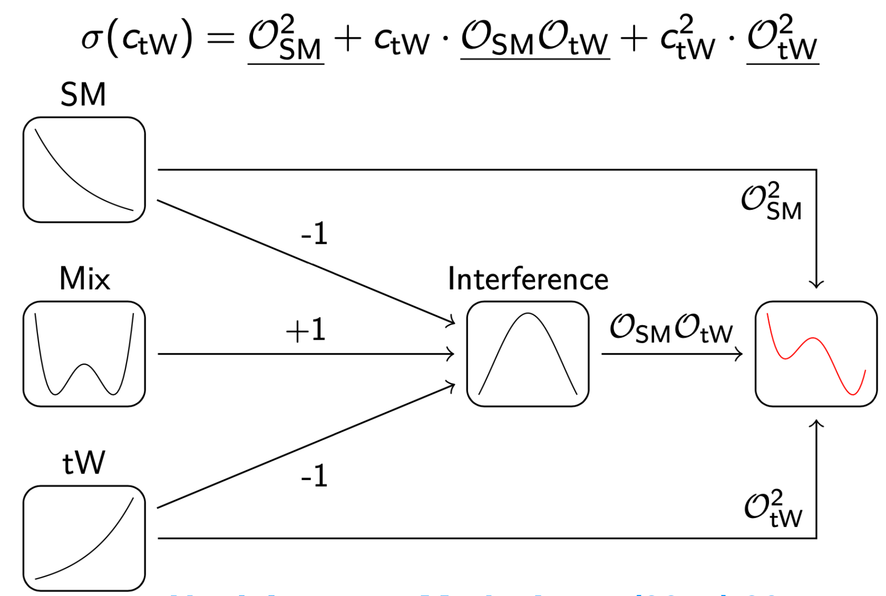
Three normalised angular observables ($\cos\theta_x$, $\cos\theta_z$, $\cos\theta_z$) unfolded to particle level

- Iterative Bayesian Unfolding (IBU) employed for deconvolution
- comparisons with different MC predictions at particle level in fiducial region
- results (including covariance matrix) to be published in HepData

EFT interpretation of normalised $\cos\theta_{x/y}$ with morphing technique

- parametric description for EFT operators using minimal number of templates
- focus on O_{tW} (variables not sensitive to $O_{\phi Q}$, O_{qQ})
  - **Re[C_{tW}] $\in$ [0.4±1.1]**
  - **Im[C_{tW}] $\in$ [-0.3±0.4]**

Sketch of a morphing example



[Nucl. Instrum. Meth. A 771 (2015) 39]

	C_{tW}		C_{itW}	
	68% CL	**95% CL**	**68% CL**	**95% CL**
All terms	[-0.2, 0.9]	[-0.7, 1.5]	[-0.5, -0.1]	[-0.7, 0.2]
Order $1/\Lambda^4$	[-0.2, 0.9]	[-0.7, 1.5]	[-0.5, -0.1]	[-0.7, 0.2]
Order $1/\Lambda^2$	[-0.2, 1.0]	[-0.7, 1.7]	[-0.5, -0.1]	[-0.8, 0.2]

[ATLAS Physics Briefing]

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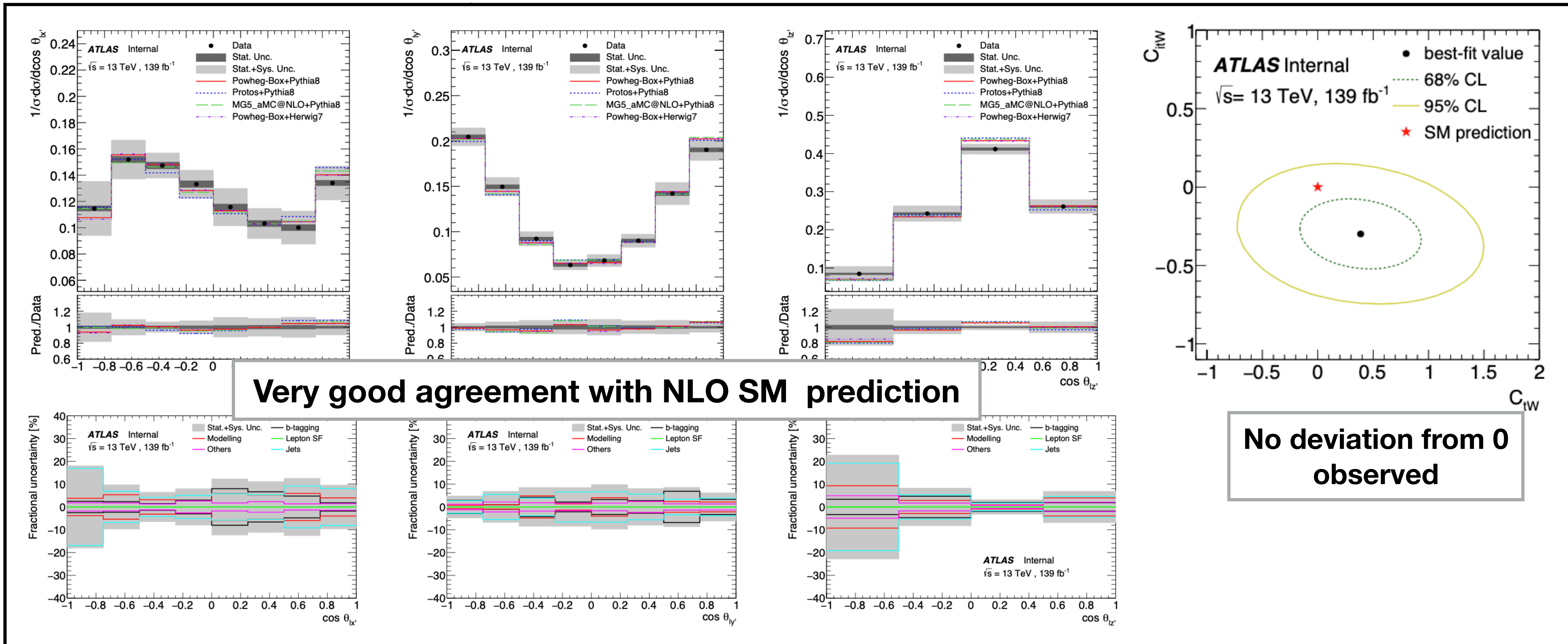


Very good agreement with NLO SM prediction

No deviation from 0 observed

Lepton flavour universality

Fundamental assumption of Standard Model (SM)

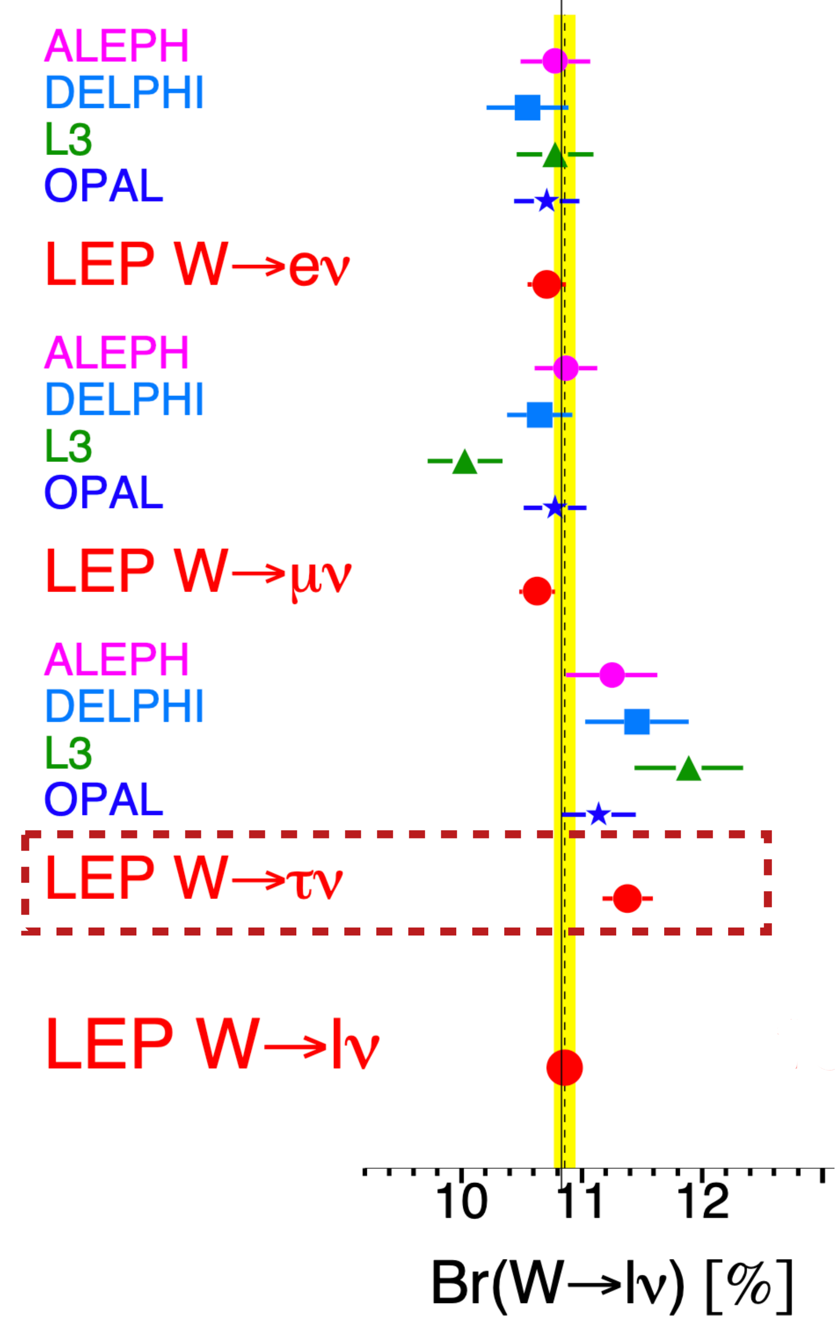
- universal coupling of the different generations of leptons to the gauge bosons
- → all charged leptons (e, μ, τ) have same coupling strength to W boson

W boson decays precisely measured at LEP

- however, observed 2.7σ deviation from SM prediction for BR(W → τν)

Measuring R(τ/μ) = BR(W → τν)/BR(W → μν) with a precision of 1-2% would either prove LEP discrepancy or rule it out

Phys.Rept. 532 (2013) 119-244

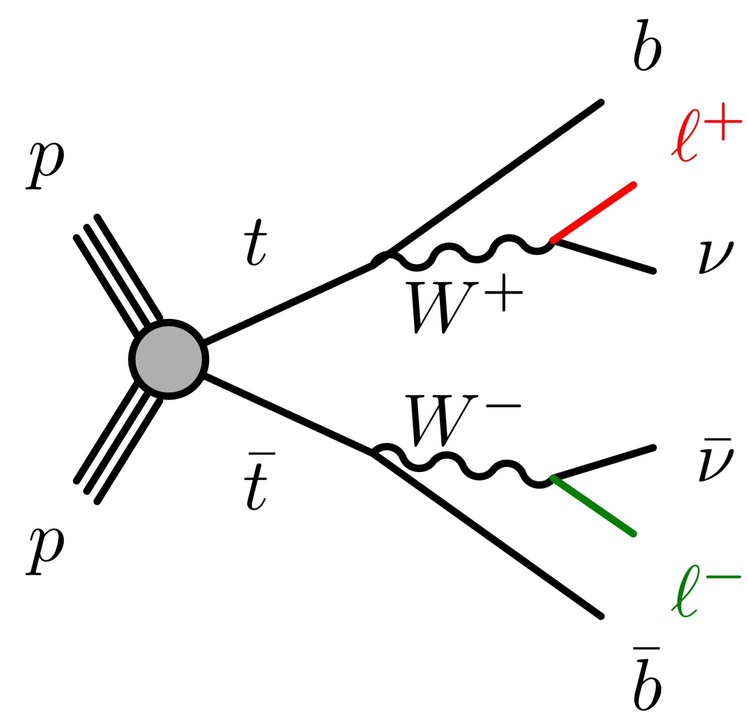


Test of LFU (μ/τ)

Nat. Phys. 17, 813–818 (2021)

In dilepton $t\bar{t}$ events, a large, unbiased sample of W-bosons can be obtained

- one decaying top used to trigger the event (tag lepton)
- the other top used to provide an (unbiased) set of W bosons for the measurement (probe lepton)
- as low in p_T(probe μ) as reconstruction allows
- only look at leptonic tau decays to profit from smaller reconstruction uncertainties



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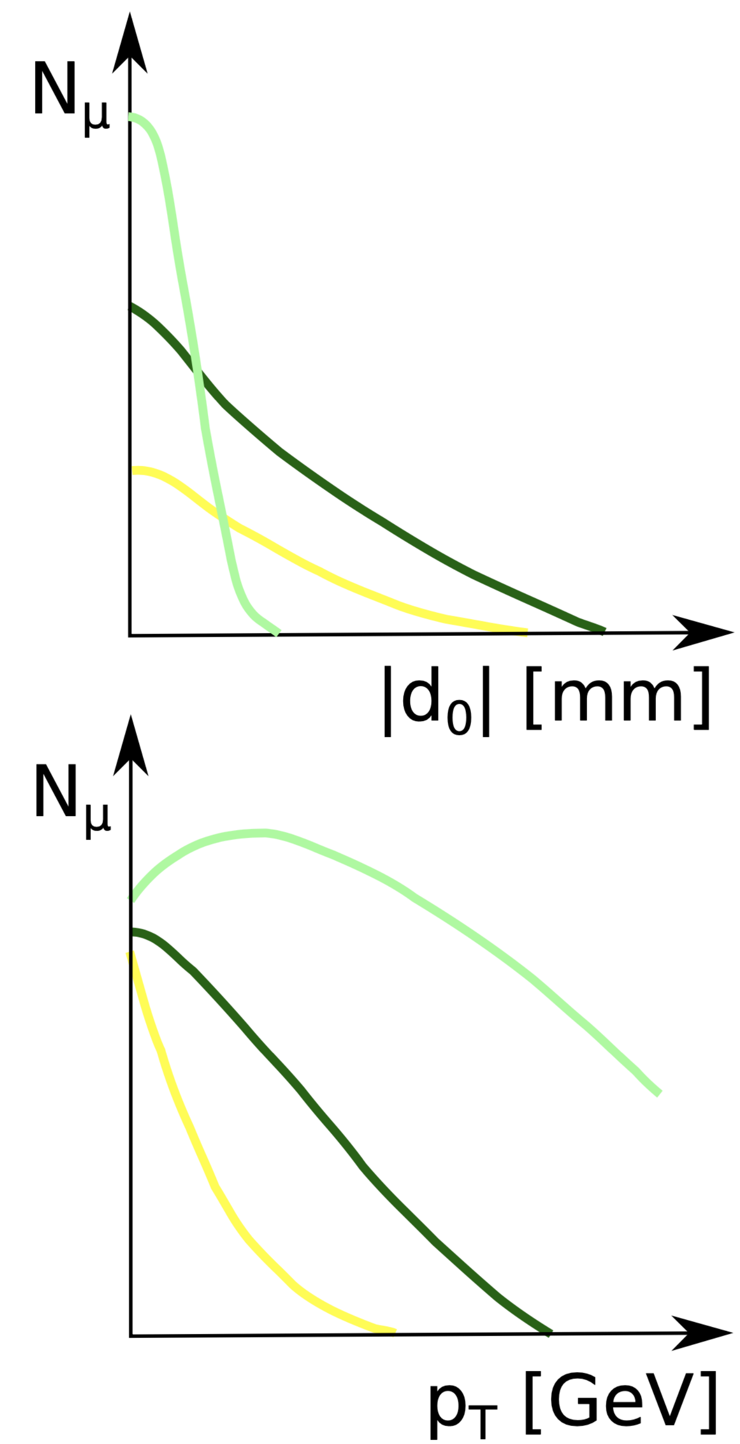
- only look at leptonic tau decays to profit from smaller reconstruction uncertainties

Main goal: distinguish prompt muons vs. taus decaying into muons and muons from hadron decays

- p_T(probe μ) and unsigned transverse impact parameter with respect to beamline ($|d_0^\mu|$) as discriminating variables



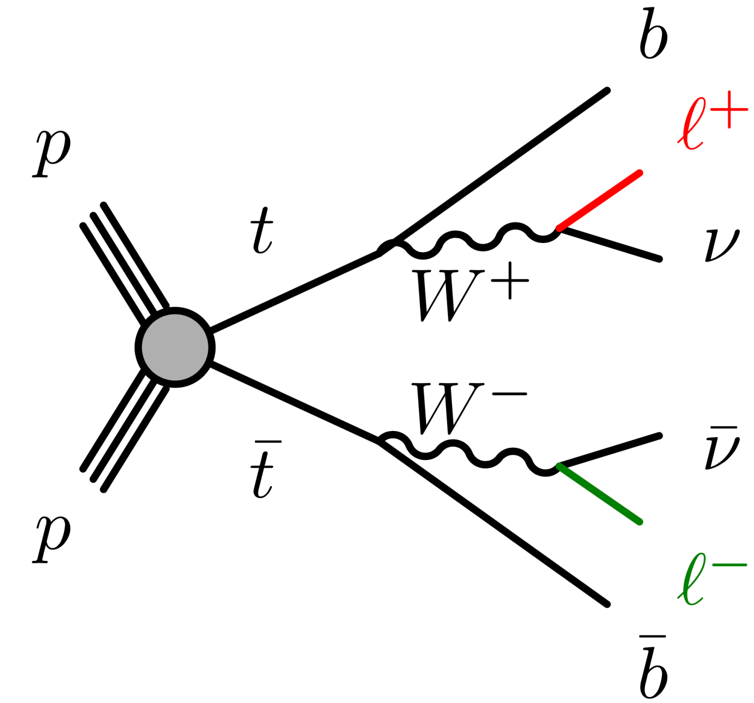
ATLAS Physics Briefing

Test of LFU (μ/τ)

[Nat. Phys. 17, 813–818 (2021)]

Applying standard $t\bar{t}$ (di-lepton, eμ/μμ) selection

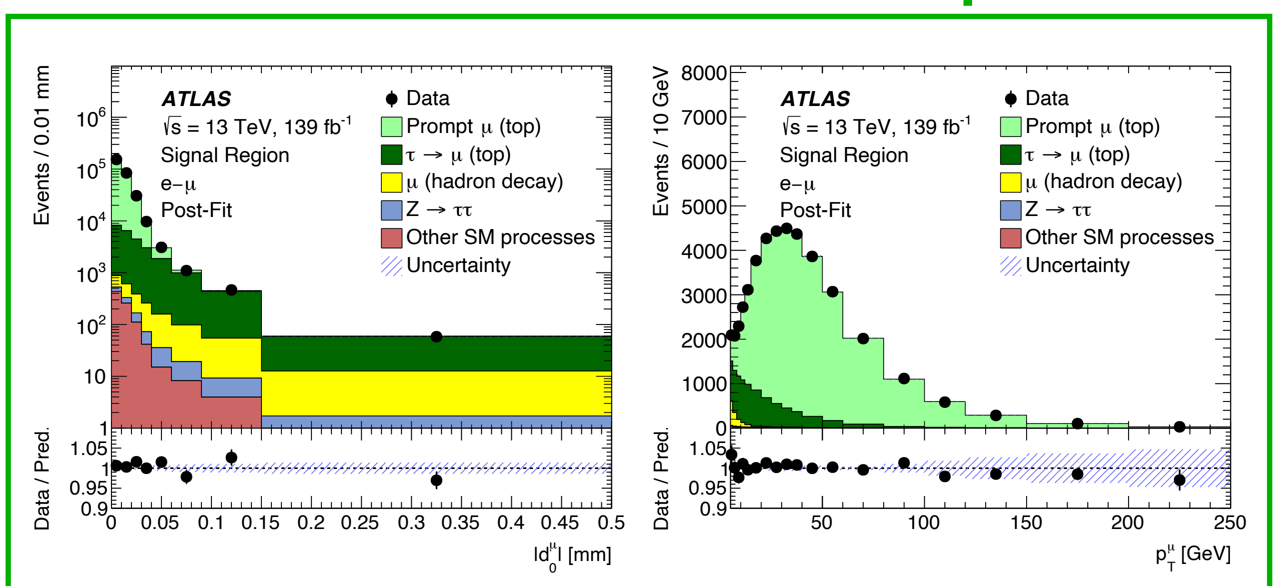
- 2 *b*-tagged jets, 2 oppositely charged leptons
- *Z* boson veto for di-muon channel
- **tag lepton** must pass trigger requirement
- **probe muon** must have $p_T > 5$GeV
  - + allows to probe a large p_T range



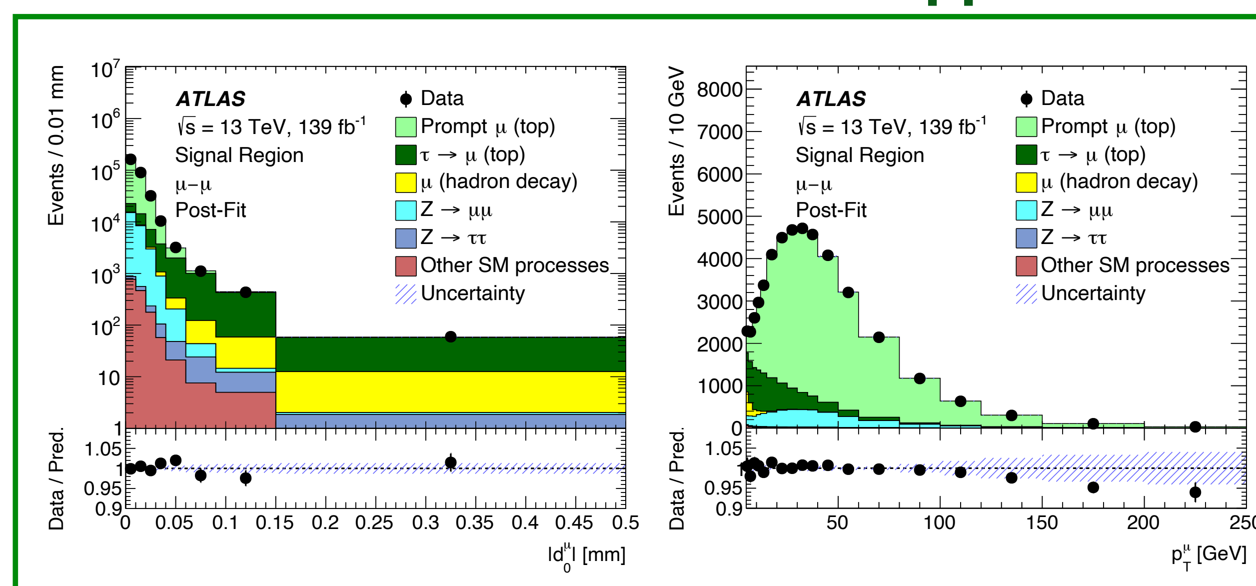
Remaining backgrounds for the measurement:

- hadrons decaying into muons
- Z+2b-tagged jets in di-muon channel

eμ channel



μμ channel



[ATLAS Physics Briefing]

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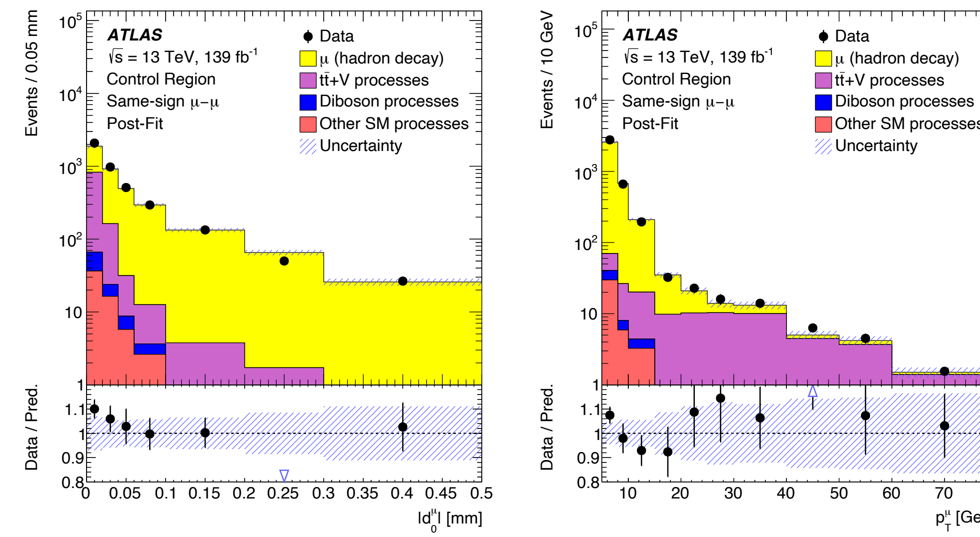
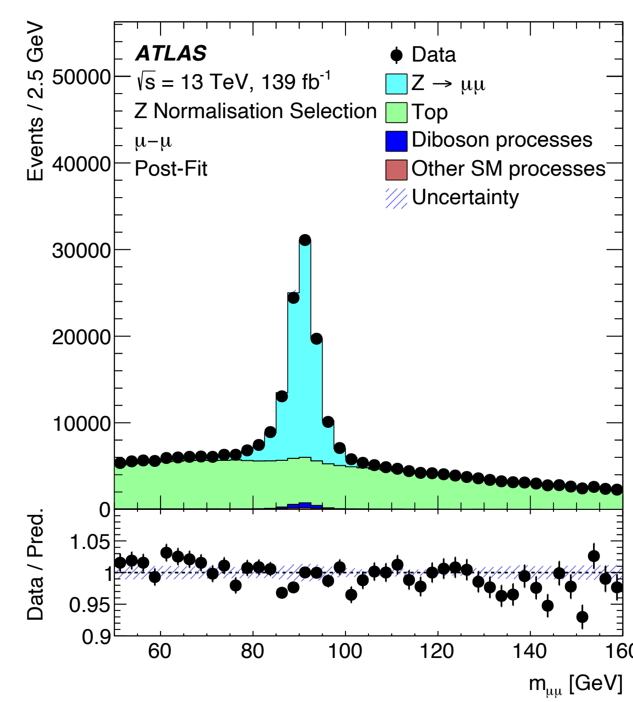


Largest background at large $|d_0^{\mu}|$ from b/c-hadrons decaying into muons

- Estimated in same sign (SS) control region:
  - shape of $|d_0^{\mu}|$ in SS region taken from MC
  - prompt contribution ($t\bar{t}$+ V) from p_T>30 GeV region subtracted
  - data/MC ratio in SS region to signal region
- Modelling differences between SS and OS from MC
- Other uncertainties arising from limited statistics of SS region, MC modelling and p_T threshold for prompt contribution



Although Z-veto in μμ channel, residual contribution from Z+2b-tagged jets left

- estimated from data by removing Z veto
- $m_{\mu\mu}$ distribution fit between 50 GeV and 140 GeV
  - convolution of Breit-Wigner and Gaussian for Z → μμ
  - 3rd order Chebychev polynomial for background
- Normalisation factor: 1.36 ± 0.01
- Use other fit functions to estimate systematic uncertainty

ATLAS Physics Briefing

Test of LFU (μ/τ)

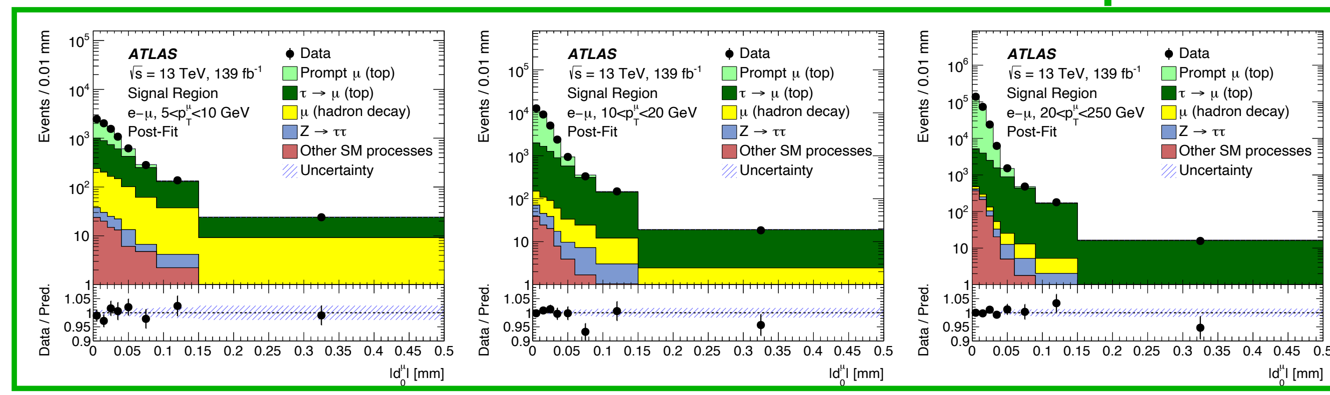
For both channels (eμ/μμ), perform 2D profile likelihood fit in muon…

- $|d_0^\mu|$: [0, 0.01, 0.02, 0.03, 0.04, 0.06, 0.09, 0.15, 0.5] mm
- p_T : [5,10,20,250] GeV
- Freely floating parameters:
  - + R(τ/μ) = BR(W → τν)/BR(W → μν)
  - + scaling factor for top processes applied to both prompt muons and leptonic tau decays

Many uncertainties correlated between prompt muons and leptonic τ decays

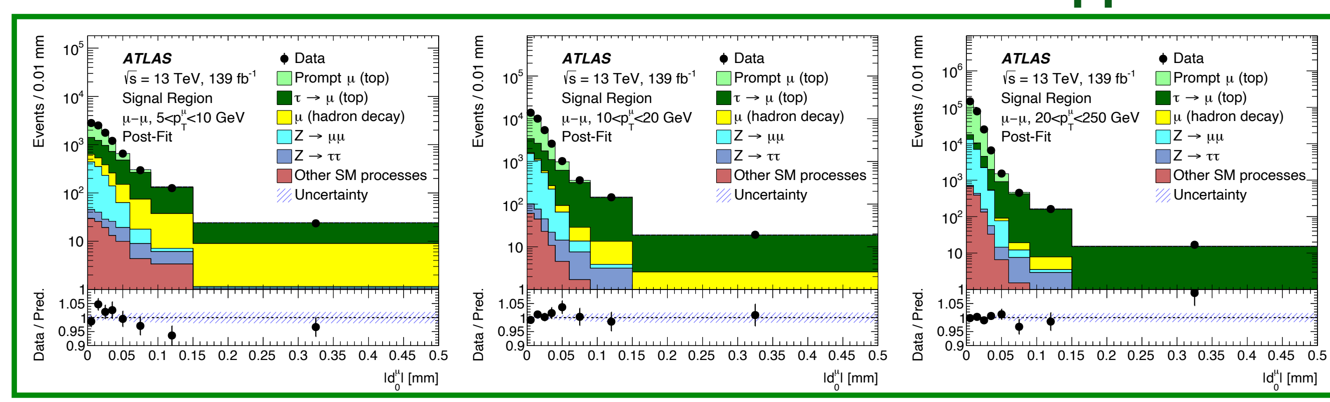
- → mostly cancel out for probe muons

eμ channel



Good Data/MC agreement observed in each signal region bin

μμ channel



Test of LFU (μ/τ)

Nat. Phys. 17, 813–818 (2021)

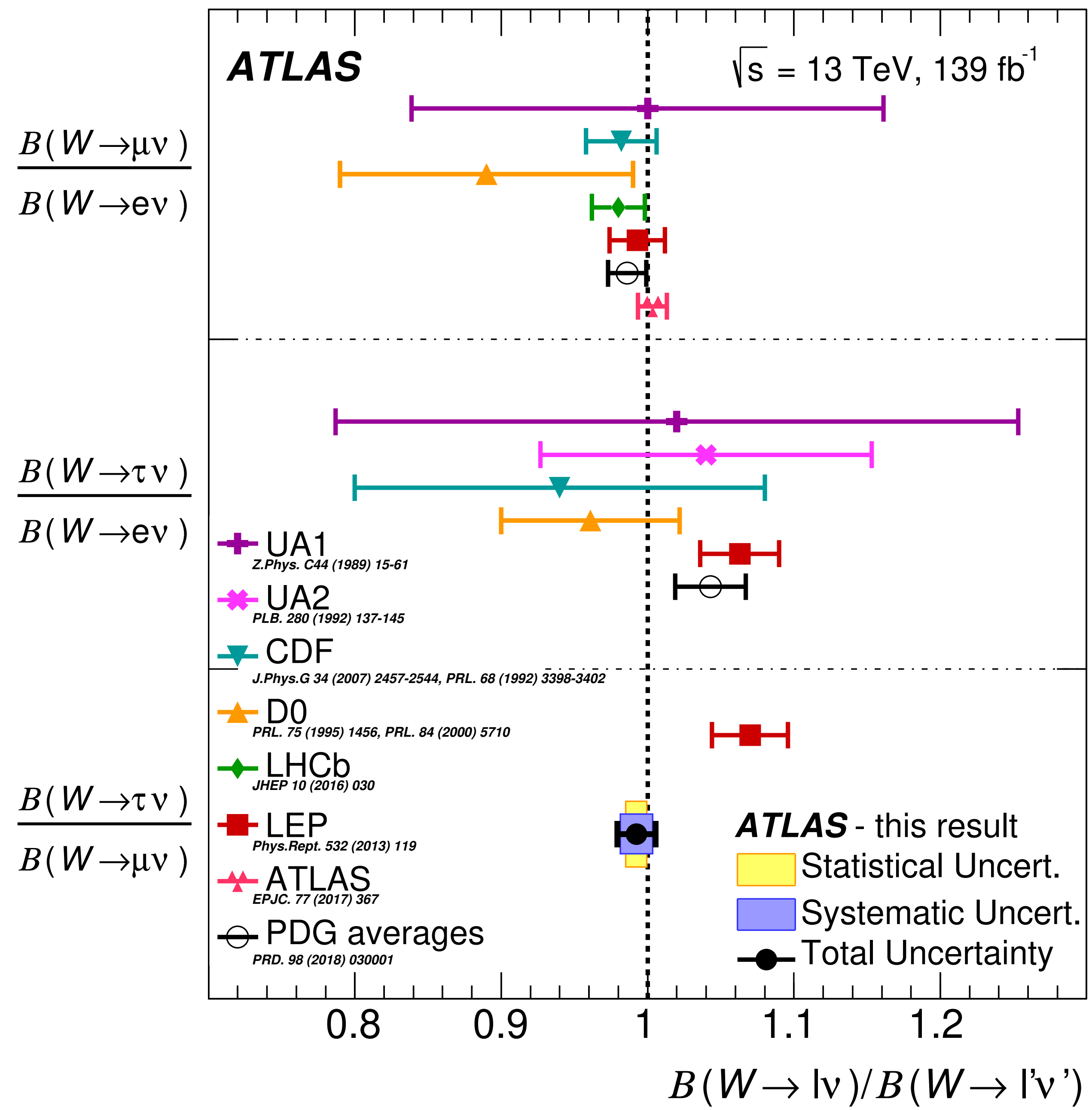
R(τ/μ)= 0.992 ± 0.013 [± 0.007(stat) ± 0.011(syst)]

Observation in very good agreement with SM expectation

- Uncertainty dominated by systematics
  - leading one is the extrapolation uncertainty on prompt $|d_0^\mu|$ templates

Most precise measurement to date

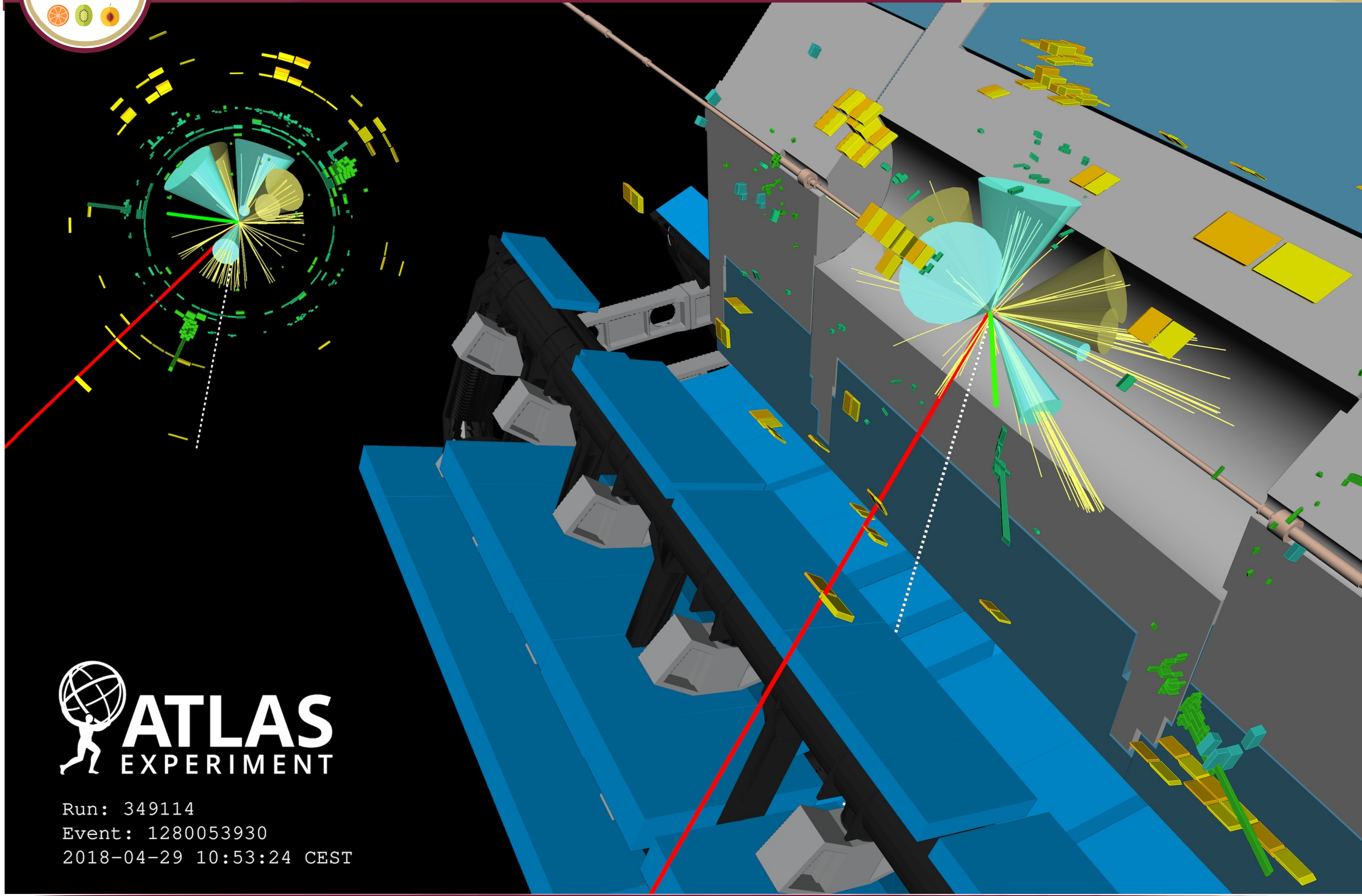
- improves over LEP combination by a factor two



ATLAS Physics Briefing

Latest experimental results on Top + X

$t\bar{t}t\bar{t}$ Event Display in ATLAS



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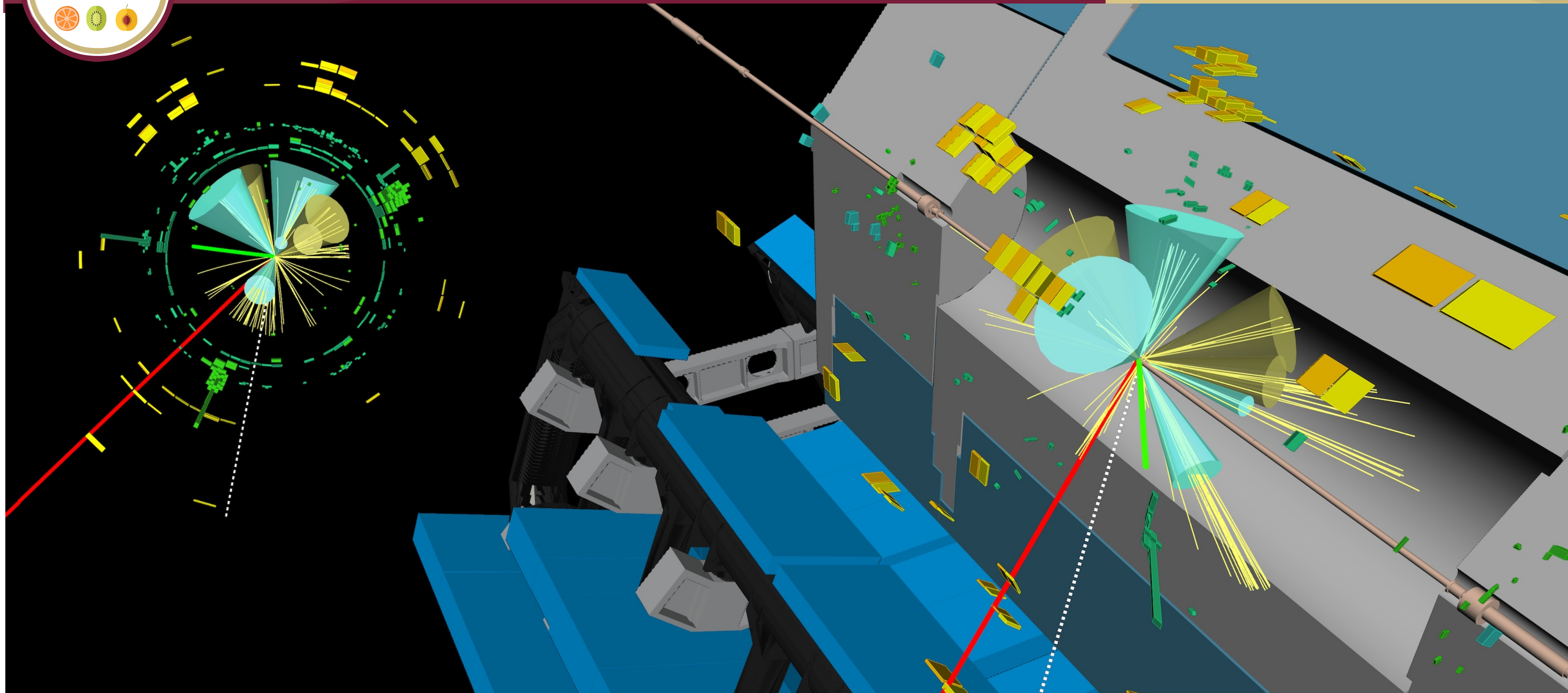


A candidate four-top-quark event with seven jets (four of them are b-tagged):

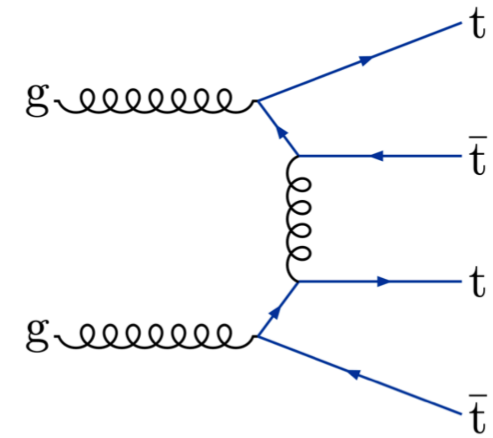
- two top quarks decay leptonically (one with a resulting muon, shown in red, and one with an electron, shown in green),
- two top quarks decay hadronically.

Green rectangles correspond to energy deposits in cells of the electromagnetic calorimeter, while yellow rectangles correspond to energy deposits in cells of the hadron calorimeter. The jets (b-tagged jets) are shown as yellow (blue) cones.

The direction of the missing transverse momentum is indicated by a dotted line.

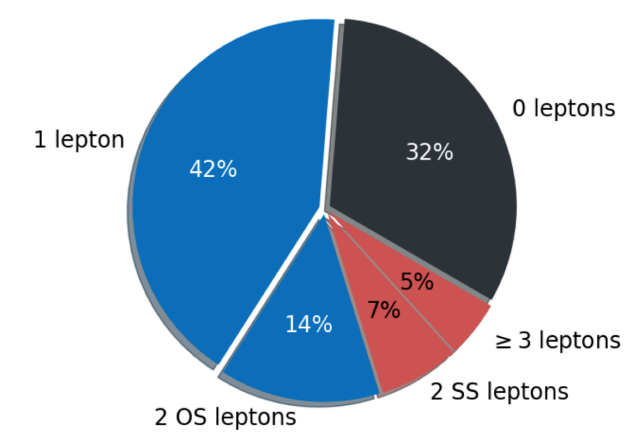
Evidence of $t\bar{t}t\bar{t}$

[EPJC 80, 1085 (2020)](#)
[JHEP 2021, 118 (2021)](#)



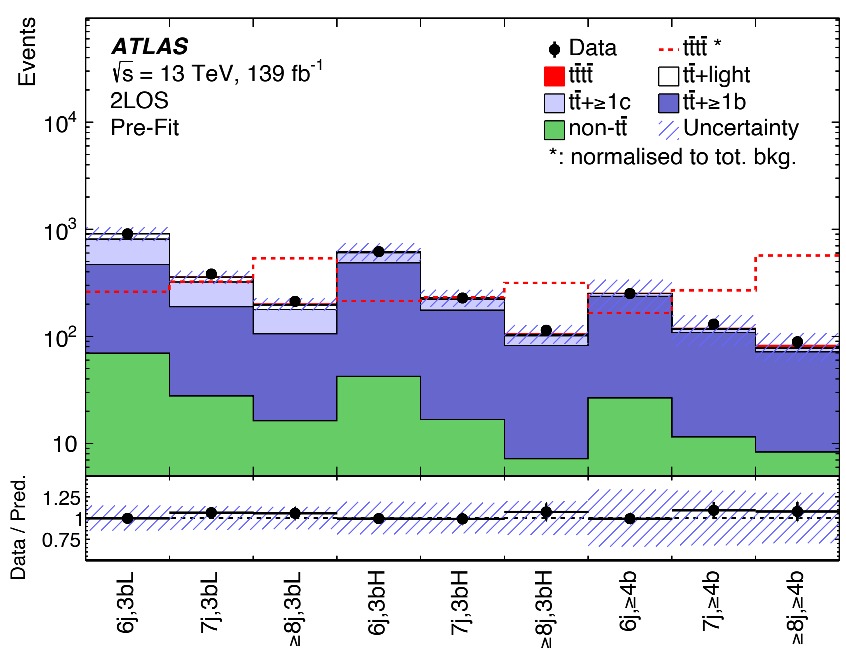
When 4 top quarks are produced, they create the heaviest particle final state ever seen at the LHC, with almost 700 GeV in total

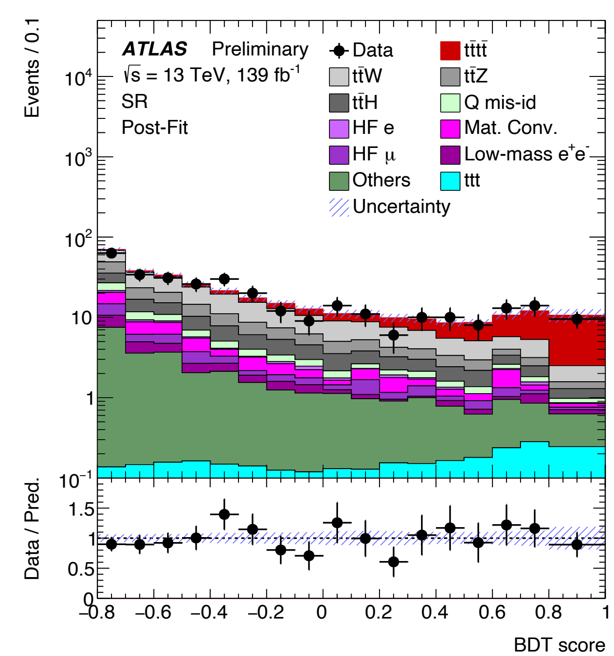
- ideal environment to search for new physics with yet unknown particles
- → additional production of 4 top quarks above what is predicted by SM



Analyses focused on 1L, 2LOS, 2LSS and 3L

- 1L and 2LOS: larger branching fraction (56%), but large irreducible background (tt+light jets, tt+heavy flavour jets)
- 2LSS and 3L: small branching fraction (12%), but lower backgrounds (ttW, ttZ, non-prompt leptons, charge misidentification)





[ATLAS Physics Briefing](#)

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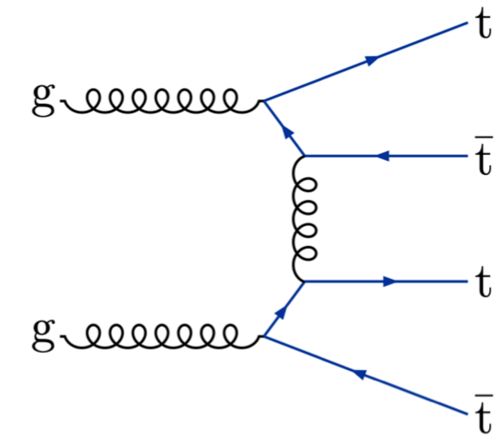

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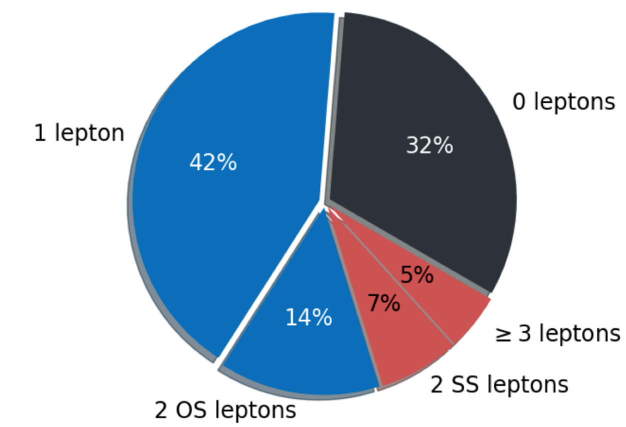

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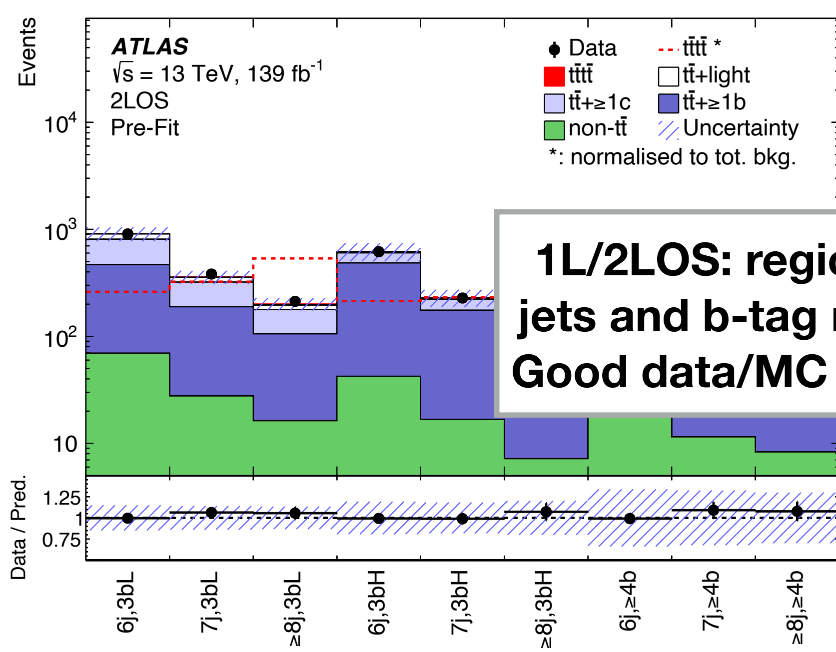
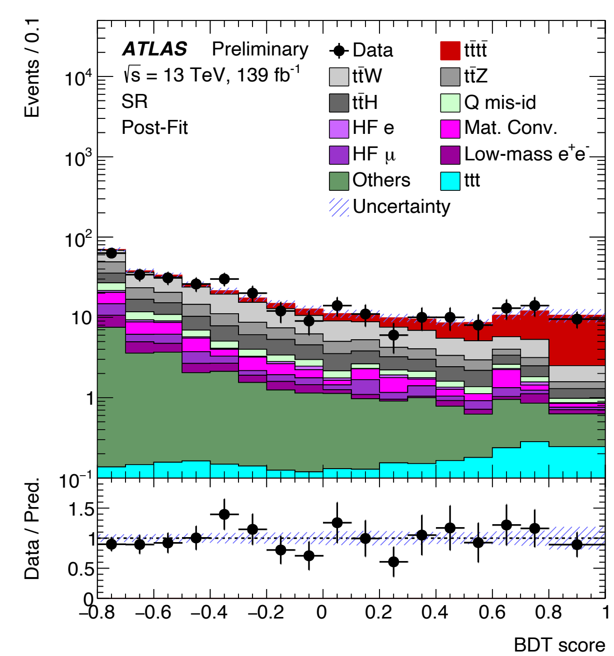


1L/2LOS: region split by jets and b-tag multiplicity
Good data/MC agreement



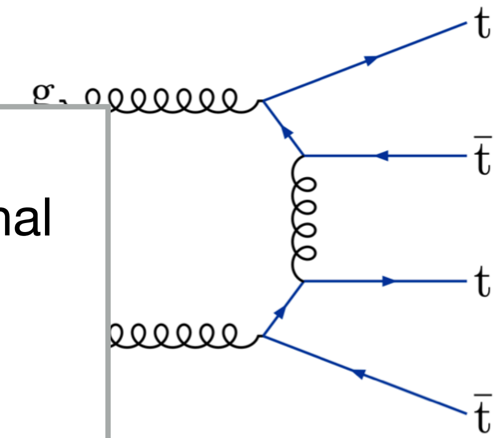
2LSS/3L: MVA approach to discriminate signal vs. background

Post-fit plot ($\sigma \approx 2\sigma_{SM}$)

[ATLAS Physics Briefing](#)

Evidence of $t\bar{t}t\bar{t}$

[EPJC 80, 1085 (2020)](#)
[JHEP 2021, 118 (2021)](#)

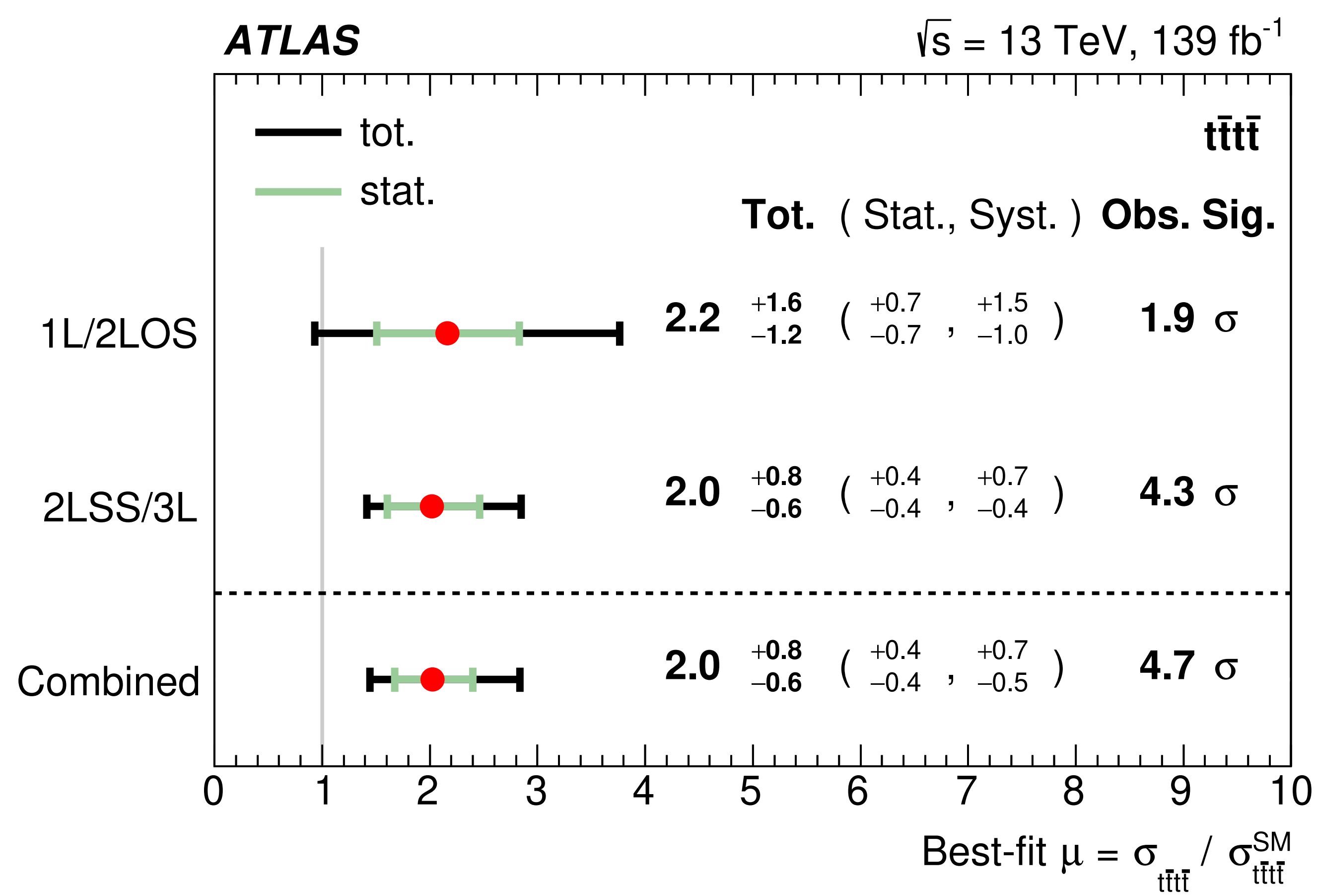


When 4 top quar
state ever seen a
- ideal environm
- → additional p

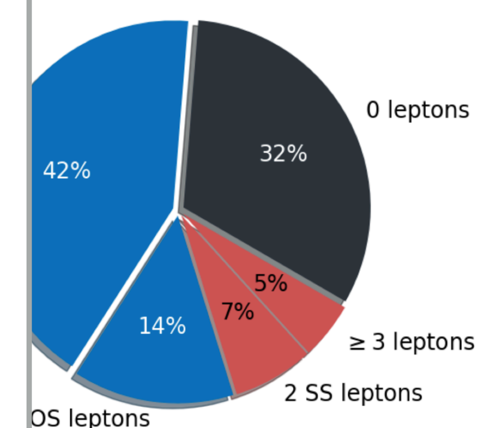
First evidence of 4 tops production at LHC

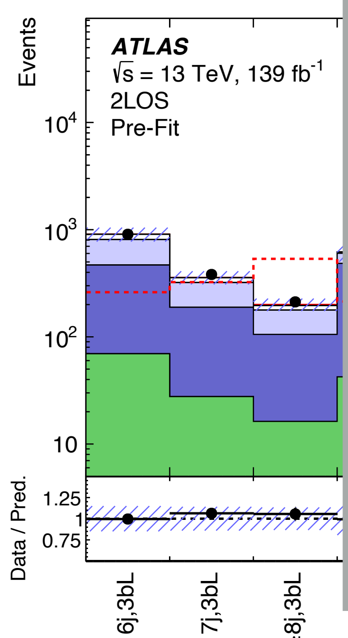
$\sigma_{tttt} \approx$ 24 +7/-6 fb, with a corresponding observed (expected) signal significance of 4.7σ (2.6σ)

1L/2LOS: main systematic uncertainty from $t\bar{t}$+HF modelling
2LSS/3L: main systematic uncertainty from fake lepton modelling



Analyses focuse
- 1L and 2LOS:
  background (t
- 2LSS and 3L:
  (ttW, ttZ, non-





MVA approach to
inate signal vs.
ckground

t plot (σ ≈2σ$_{SM}$)

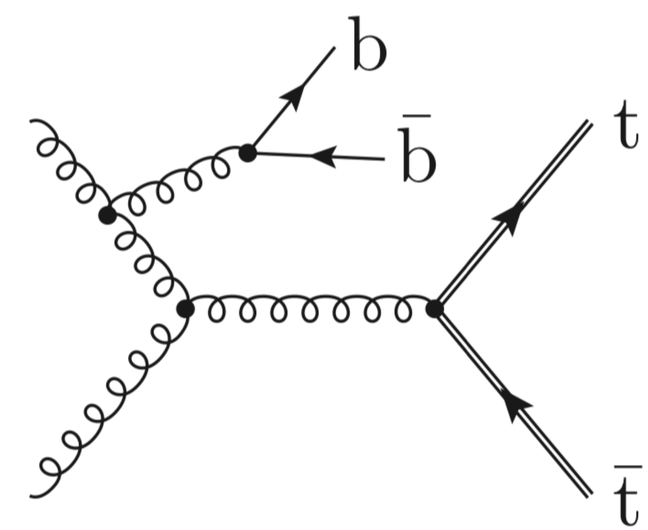
[ATLAS Physics Briefing](#)

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

JHEP 04 (2019) 046

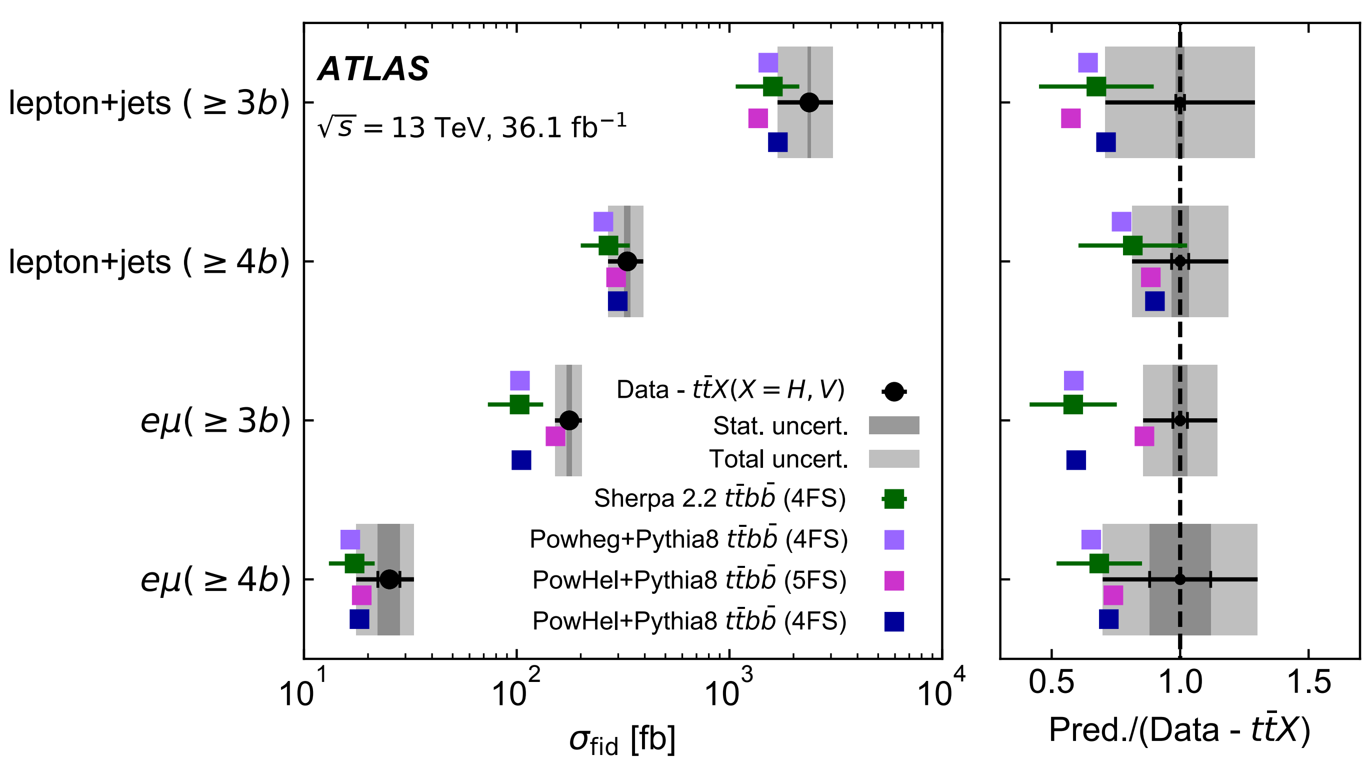
Important for new physics and rare searches

- state-of-the-art NLO predictions suffer from large uncertainty
- experimental input needed to test predictions



Fiducial and differential $t\bar{t}+b\bar{b}$ cross sections in l+jets and dilepton channels using 36 fb^{-1} (@13TeV)

- unfolded to particle level



General excess w.r.t. various NLO predictions
Still compatible within total uncertainties experimental uncertainty smaller than theory one

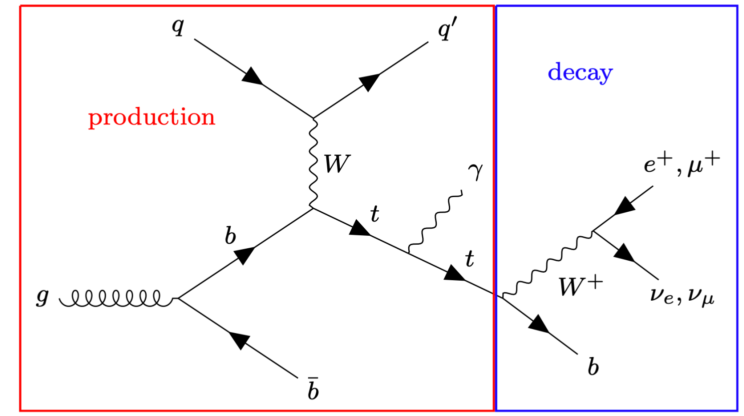
SM tqɣ search

ATLAS-CONF-2022-013

Search for single production of top quarks in association with a photon

- [CMS evidence paper] with 35.9 /fb (muon channel)
  + 4.4σ observed (3.0σ expected)
  + measured fiducial σ x BR = 115 ± 17 ± 30 fb
  + theo. fiducial σ x BR = 81± 4 fb (MG5, NLO)
- careful stitching schemes and overlap removals adopted for tqɣ, $t\bar{t}$ɣ and Vɣ

tqɣ stitching scheme:
$m_t = m_{bl\nu}$ (production) & $m_t = m_{bl\nu\gamma}$ (decay)



Single-top t-channel + ɣ selection, 139/fb:

- e→ɣ fake SF estimated from Z→eɣ / Z→ee
- j→ɣ fakes SF determined with ABCD method
  + photon narrow-strip and isolation to define ABCD
- NNs trained in SRs and ttɣ CR
  + signal=tqɣ(prod), tqɣ(dec) as background
- profile likelihood fit in 2SRs+2CRs at parton and particle level

Object/Variable	inc SR		$t\bar{t}\gamma$ CR	$W\gamma$ CR
Photons	$\geq$ 1 w/ p_T > 20 GeV		$\geq$ 1 w/ p_T > 20 GeV	$\geq$ 1 w/ p_T > 20 GeV
Leptons	= 1 w/ p_T > 27 GeV		1 w/ p_T > 27 GeV	= 1 w/ p_T > 27 GeV
Jets	$\geq$1 w/ p_T > 25 GeV		**$\geq$2 w/ p_T > 25 GeV**	$\geq$1 w/ p_T > 25 GeV
being *b*-tagged	= 1 DL1r 70% **= 1 DL1r 85%**		= 1 DL1r 70% **>1 DL1r 85%**	**= 0 DL1r 70%** **$\geq$ 1 DL1r 85%**
E_T^{miss}	> 30 GeV		> 30 GeV	> 30 GeV
$m_{e\gamma}$	not in [80, 100] GeV		not in [80, 100] GeV	not in [80, 100] GeV
	0fj SR	$\geq$ 1fj SR		
Jets with $\lvert\eta\rvert$ > 2.5	=0	$\geq$ 1		

Observed (expected) significance is 9.1σ (6.7σ)

- stat. unc.=4.9 %, total syst. unc. ≈ 10.5 % (indiv. syst. < 3.5 %)

SM tqγ search

ATLAS-CONF-2022-013

Se
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Sir

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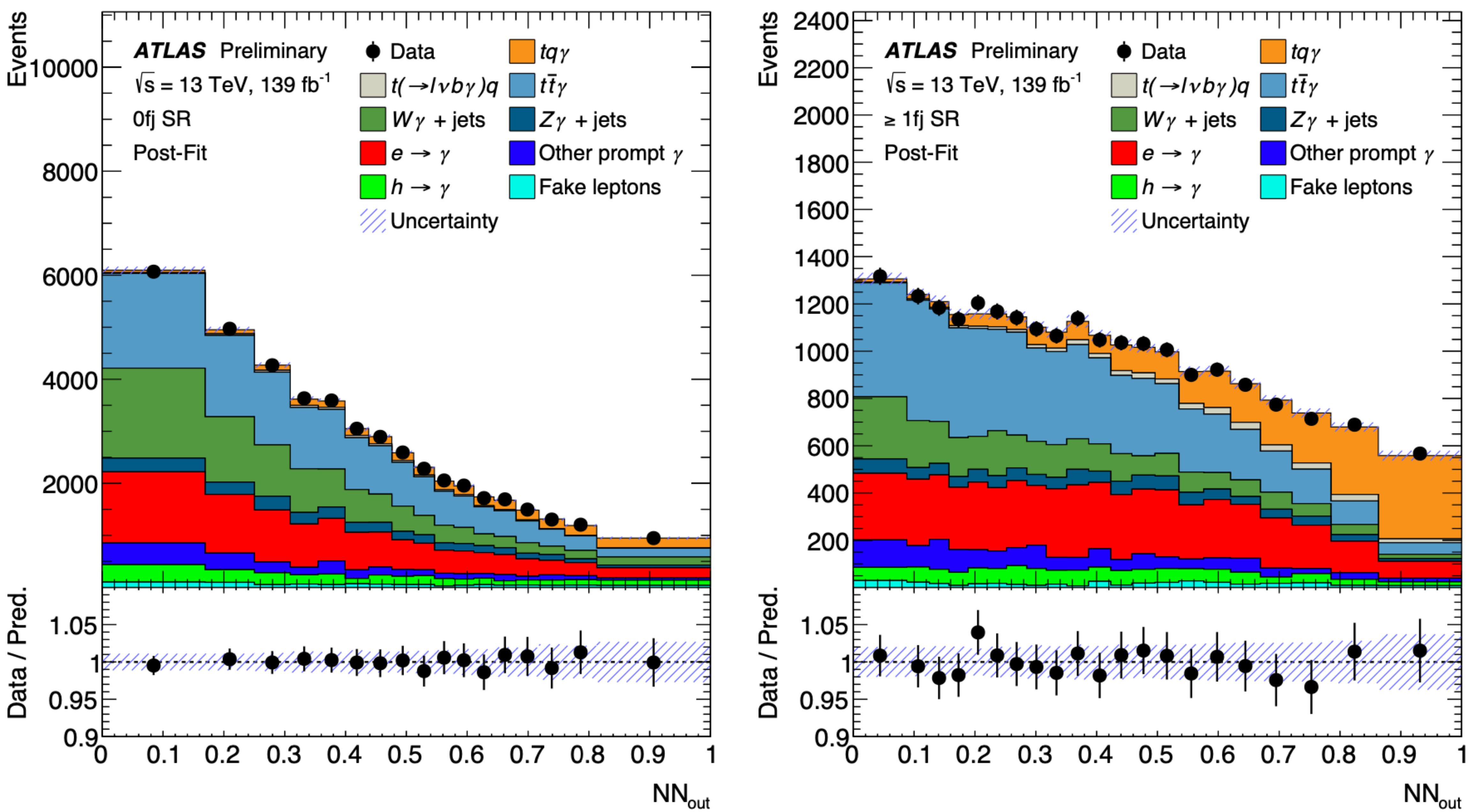
R
20 GeV
27 GeV
25 GeV
70%
85%
eV
00] GeV

First tqγ observation at LHC !

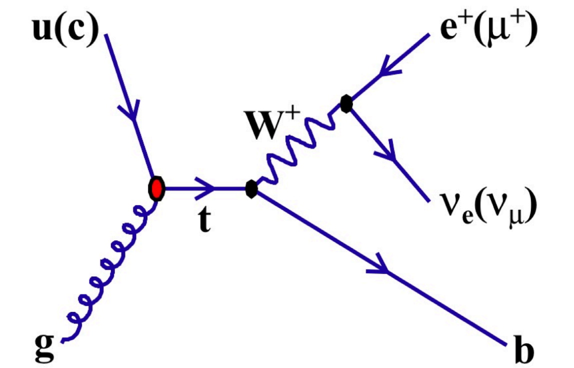


FCNC tqg search

Submitted to PLB

Single-top production via FCNC qg → t production at 13 TeV

- "direct" top-quark production (like t-channel w/o forward jet)
  → t-channel like selection
  - exactly 1 charged lepton (e/μ)
  - E_T^{miss} >30GeV, m_T^W >50GeV, $p_T^{\ell} > 50\ \mathrm{GeV} \cdot \left(1 - \frac{\pi - \delta\phi(\ell, j)}{\pi - 1}\right)$
  - 2 NN discriminants ($D_{1,2}$): utg (ctg) vs. background
  - SR and three CRs split according to b-tags (custom calibration of MV2c10@30%) and NN discriminants

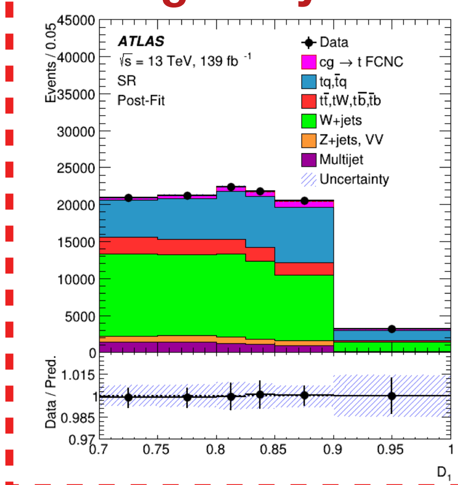


SM FCNC BR(t→qg)~$10^{-12(14)}$

Observed (expected) upper limits x2 better w.r.t. 8 TeV

- σ(ug→t) x BR(t→Wb) x BR(W→ℓv)<3.0pb (2.4pb)
- σ(cg→t) x BR(t→Wb) x BR(W→ℓv)<4.7pb (2.5pb)

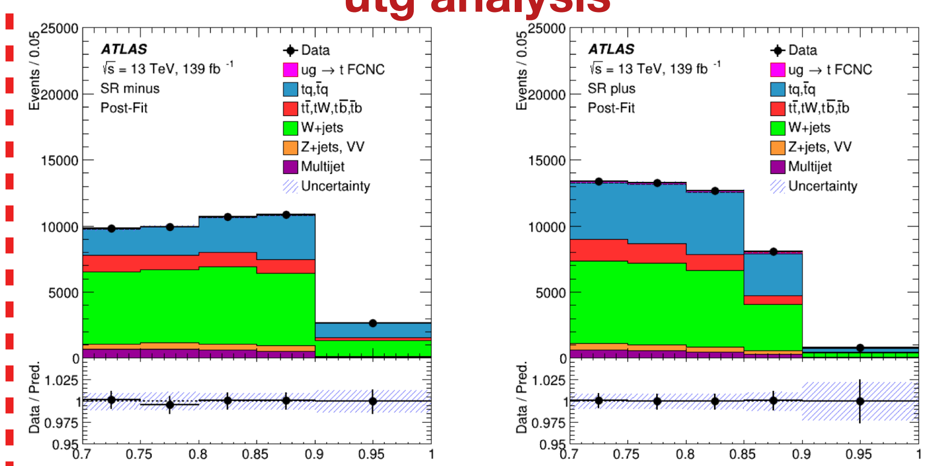
ctg analysis



EFT re-interpretation on tug and tcg couplings:

- $|C^{ut}_{uG}|/\Lambda^2 < 0.057\ \mathrm{TeV}^{-2}$ and $|C^{ct}_{uG}|/\Lambda^2 < 0.14\ \mathrm{TeV}^{-2}$

utg analysis

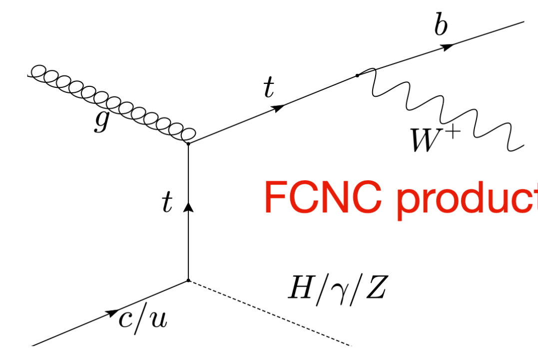


FCNC $t \to qH(H \to \tau\tau)$

ATLAS-CONF-2022-014

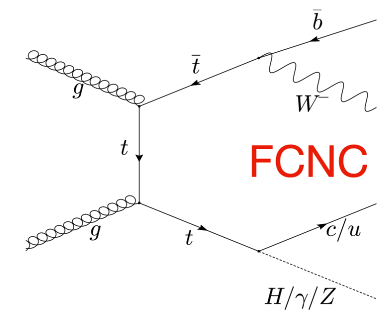
Search for FCNC in $t \to qH(H \to \tau\tau)$ interactions at 13 TeV

- hadronic/leptonic channels split by τ_{had}/lepton charge/ multiplicity
  - fake-τ background estimated by fake-SF applied to MC (leptonic) and data-driven FF (hadronic, like $H \to \tau\tau$ analysis)
  - PLIV scale factors for leptons from τ's in dedicated $Z \to \tau\tau$ region
- $t \to qH$ reconstruction/discrimination by neutrino χ^2 /BDT
- Profile Likelihood fit performed in the 7 regions



FCNC production mode

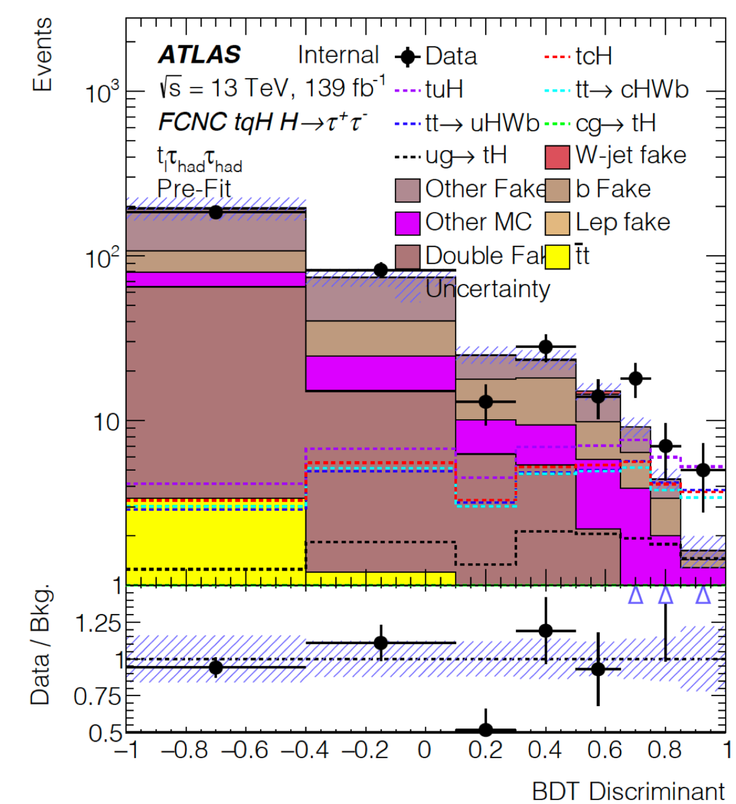
SM FCNC BR($t \to Hq$)~$10^{-15(17)}$



FCNC decay mode

20-30% improvement w.r.t. 2015+16 ATLAS combination for observed (expected) upper limits

- **$B(t \to uH) < 7.2 \times 10^{-4}$ (3.6×10^{-4})**
- **$B(t \to cH) < 9.9 \times 10^{-4}$ (5.0×10^{-4})**
- same sensitivity of latest $t \to qH(H \to bb)$ result by CMS



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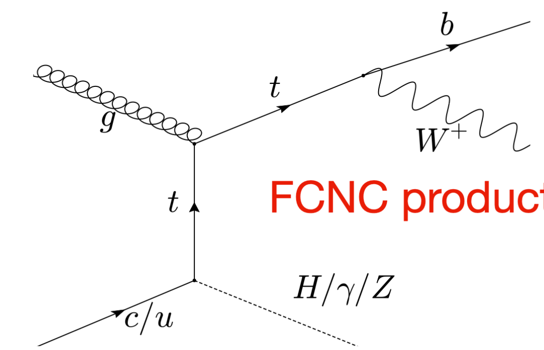

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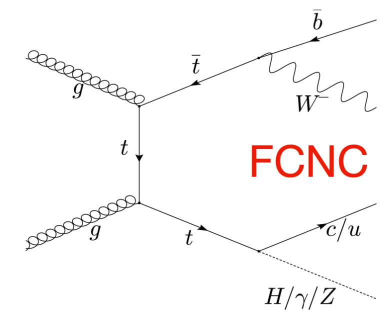

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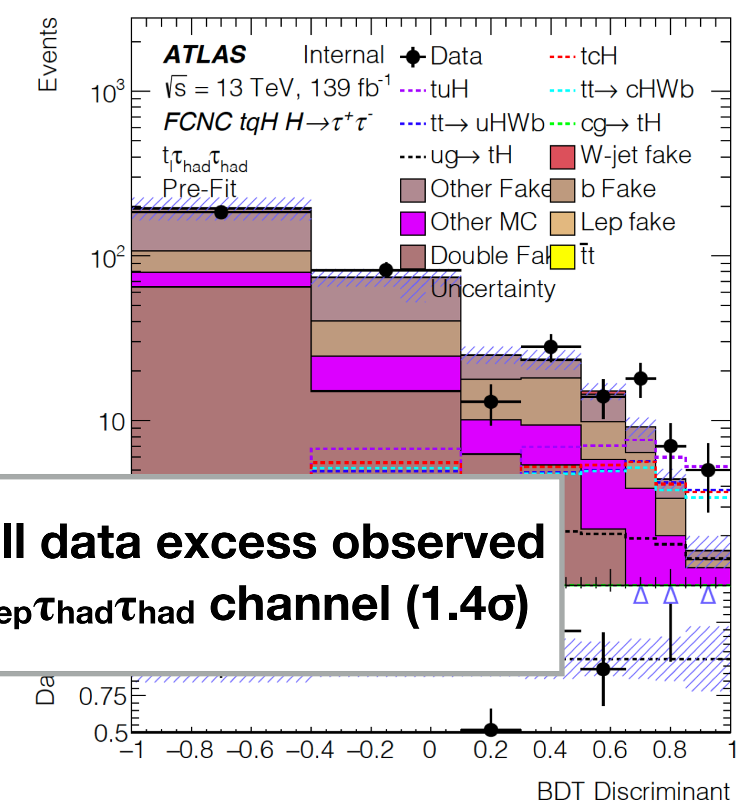


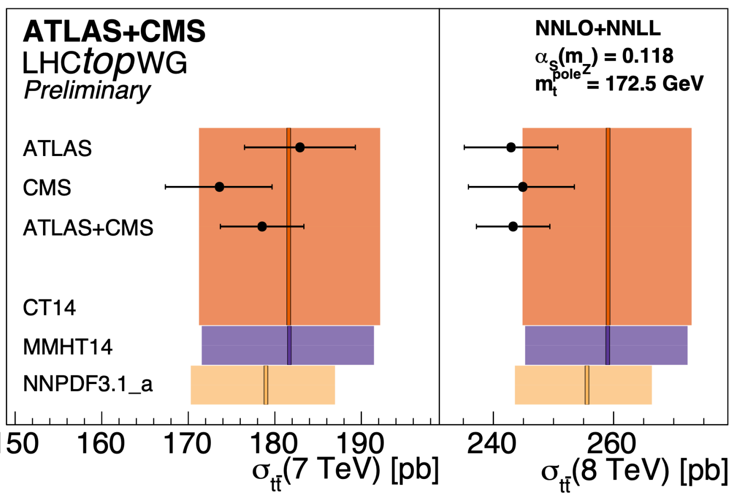
Small data excess observed in $t_{lep}\tau_{had}\tau_{had}$ channel (1.4σ)

Questions/Comments?

Other recent top results

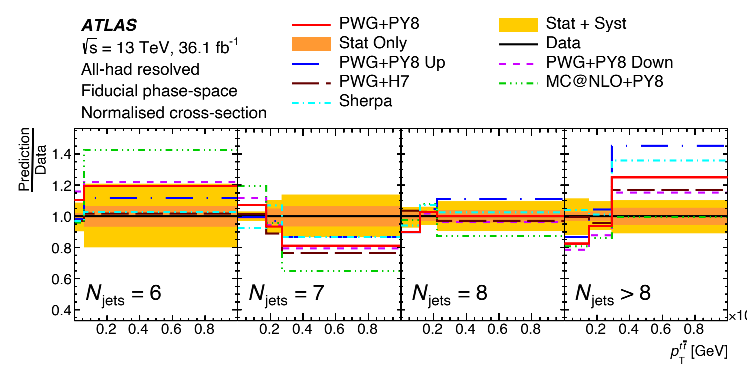
Further public results here

ATLAS+CMS Run1 $t\bar{t}$ x-sec combination
(TOPQ-2018-39)



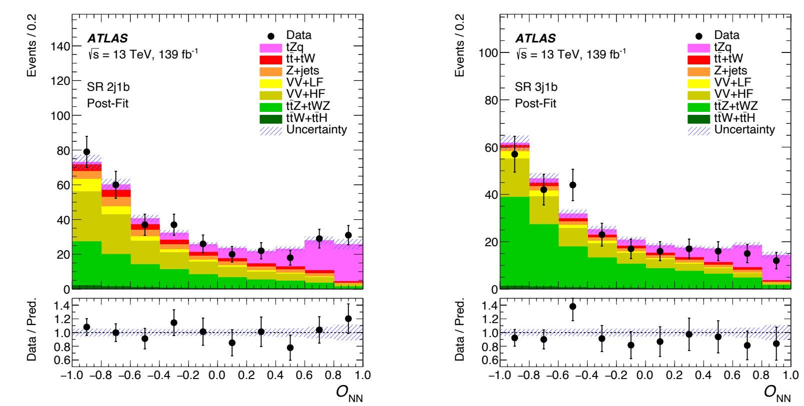
Single- and double-differential $t\bar{t}$ all-hadronic (resolved) cross section at 13 TeV
(Phys. Lett. B 810 (2020) 135797)

Different observables unfolded to parton and particle level. No MC generator considered so far perfectly matches data for any observable.

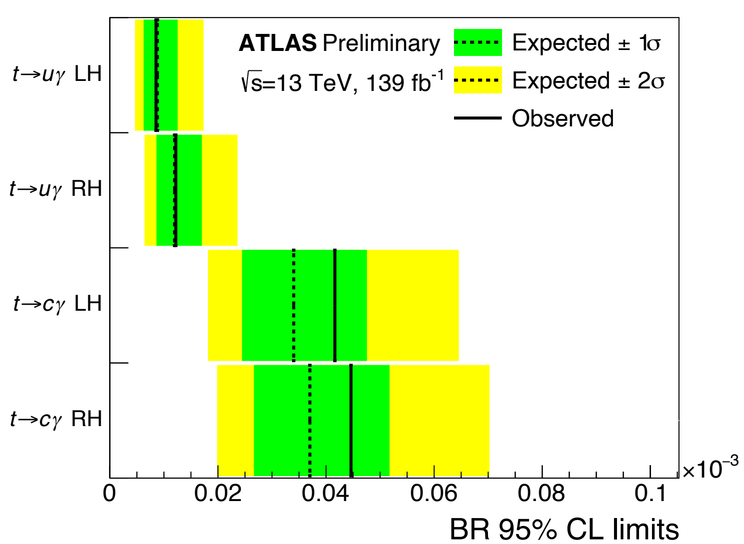


Observation of the tZ process
(JHEP 07 (2020) 124)

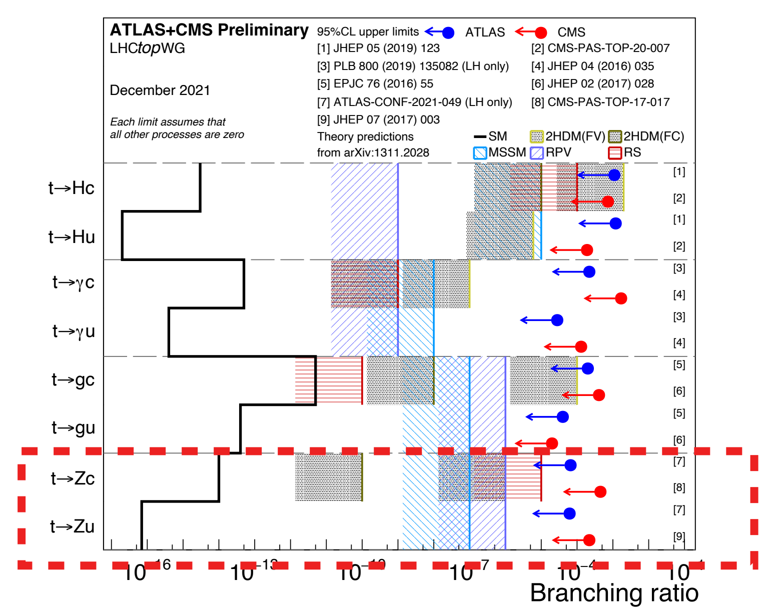
Observation of tZq in 3L channel.
Fiducial σ_{tZ} = 97 ± 13 (stat.) ± 7 (syst.) fb
(102 ± 3 fb by SM).



FCNC tqγ (prod&decay)
ATLAS-CONF-2022-003
x3-5 improvement w.r.t. previous ATLAS results

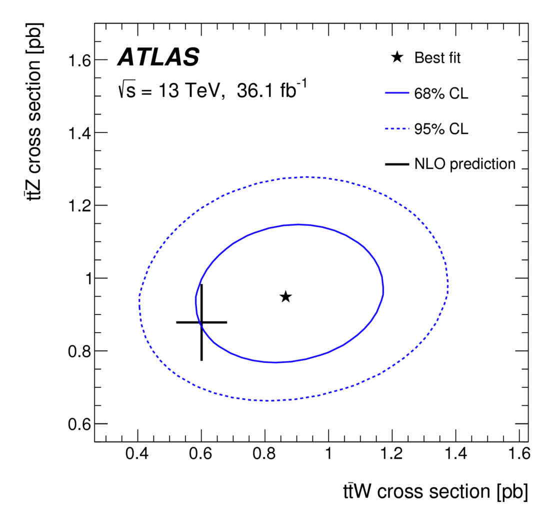


Adding ATLAS FCNC t → Zq results
LHCTopWG Open meeting



ttW/Z cross sections
(PRD 99 (2019) 072009)

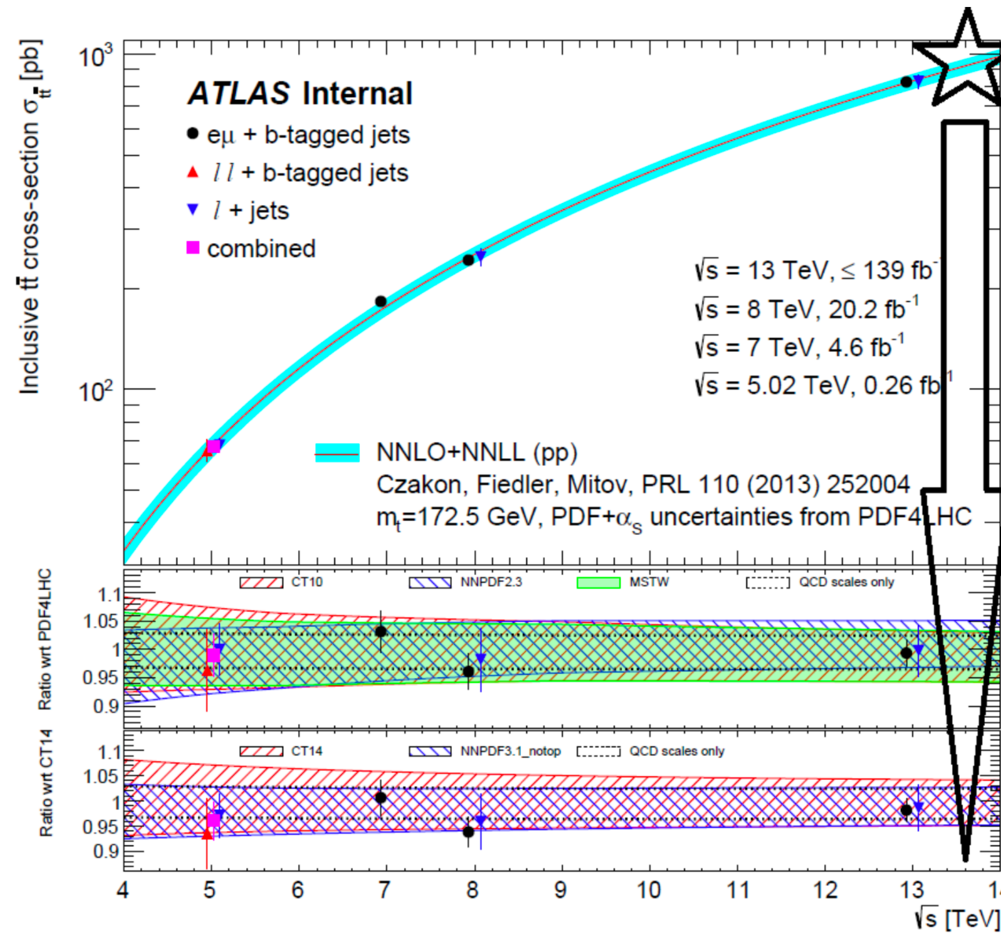
Discrete agreement with SM
Limits set to EFT O6 Wilson coefficients



Top with Run 3 data

Activity plan with **early Run 3** data (≲40/fb)

- $t\bar{t}$ inclusive x-section measurements in 2L channels
- another standard candle (√s=13.6 TeV) to famous x-section plot
- plan (best scenario):
  + *Summer Conference* - first public $t\bar{t}$ data/MC plots;
  + *Top2022* - measurement of $t\bar{t}$ / Z ratio to reduce Δlumi (≳ 5%), as a joint effort with SM groups;
  + *Moriond2023* : $t\bar{t}$ absolute x-section measurement (Δlumi < 3%);
  + *longer timescale*: differential measurements in 1 and 2L channels



Activity plan with **"late" Run 3** data (40-60/fb)

- *statistically limited analyses* (e.g., 4-tops and charge asymmetry)

Activity plan with **full Run 3** data ($L_{Run3} \approx L_{Run2}$)

- *systematically limited analyses* and *Run2+3 combinations*

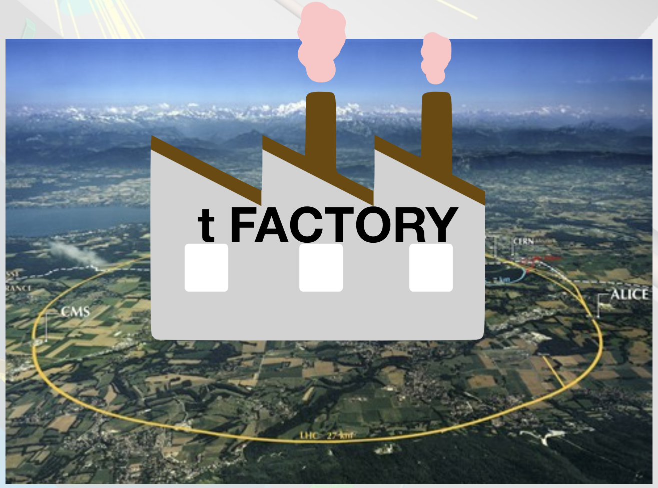
Summary and overview

The top quark has come a long way since 1995 (discovery)

- back then: missing quark, similar to other quarks
- today: know that top quark is special
- *“As far as we can see, the top quark looks like a quark, it swims like a quark, and quacks like a quark. And yet – it does not fit the pattern”* [The last quark - ATLAS Briefieng]

In precision era, top quark is key to an abundance of different research areas

- many different properties of top quarks measured by ATLAS
- so far, Standard Model describes data extremely well
- more results with the Run 2 dataset in the pipeline
- Run 3 (and beyond) promise even larger datasets



Many more exciting top physics results still to come!

ATLAS EXPERIMENT

Run: 349114
Event: 1280053930
2018-04-29 10:53:24 CEST

Summary and overview

The top quark

- back then: n
- today: know
- *"As far as w* *, and quacks like a quark.* Briefieng]

In precision era ... reas

- many differe
- so far, Stand
- more results
- Run 3 (and b

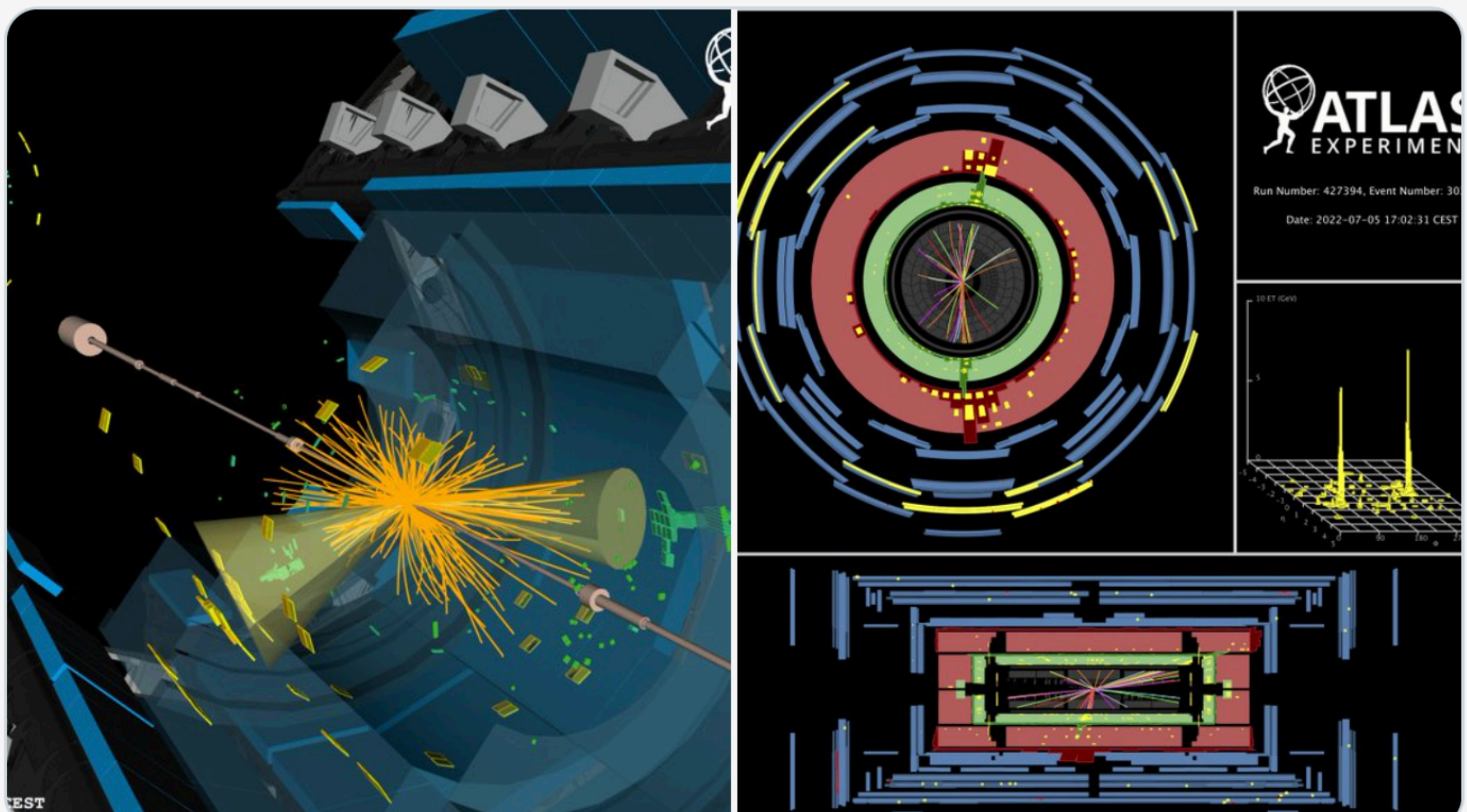
Many more exc

Run: 349114
Event: 128005393
2018-04-29 10:53

ATLAS Experiment @ATLASexperiment · Follow

Look at these stunning new collision event displays recorded in the ATLAS Experiment at @CERN!

The higher beam energy and intensity of #LHCRun3 will allow ATLAS to push the very limits of its physics research. Learn about today's exciting LHC restart: cern.ch/go/6vxq



8:30 PM · Jul 5, 2022

Summary and overview

The top quark

- back then: n
- today: know
- *"As far as w*
  like a quark.

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- so far, Stand
- more results
- Run 3 (and b

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Many more exc

ATLAS EXPERI

Run: 349114
Event: 12800539
2018-04-29 10:5

ATLAS Experiment
@ATLASexperiment · **Follow**

Look at these stunning new collision event displays recorded in the ATLAS Experiment at @CERN!

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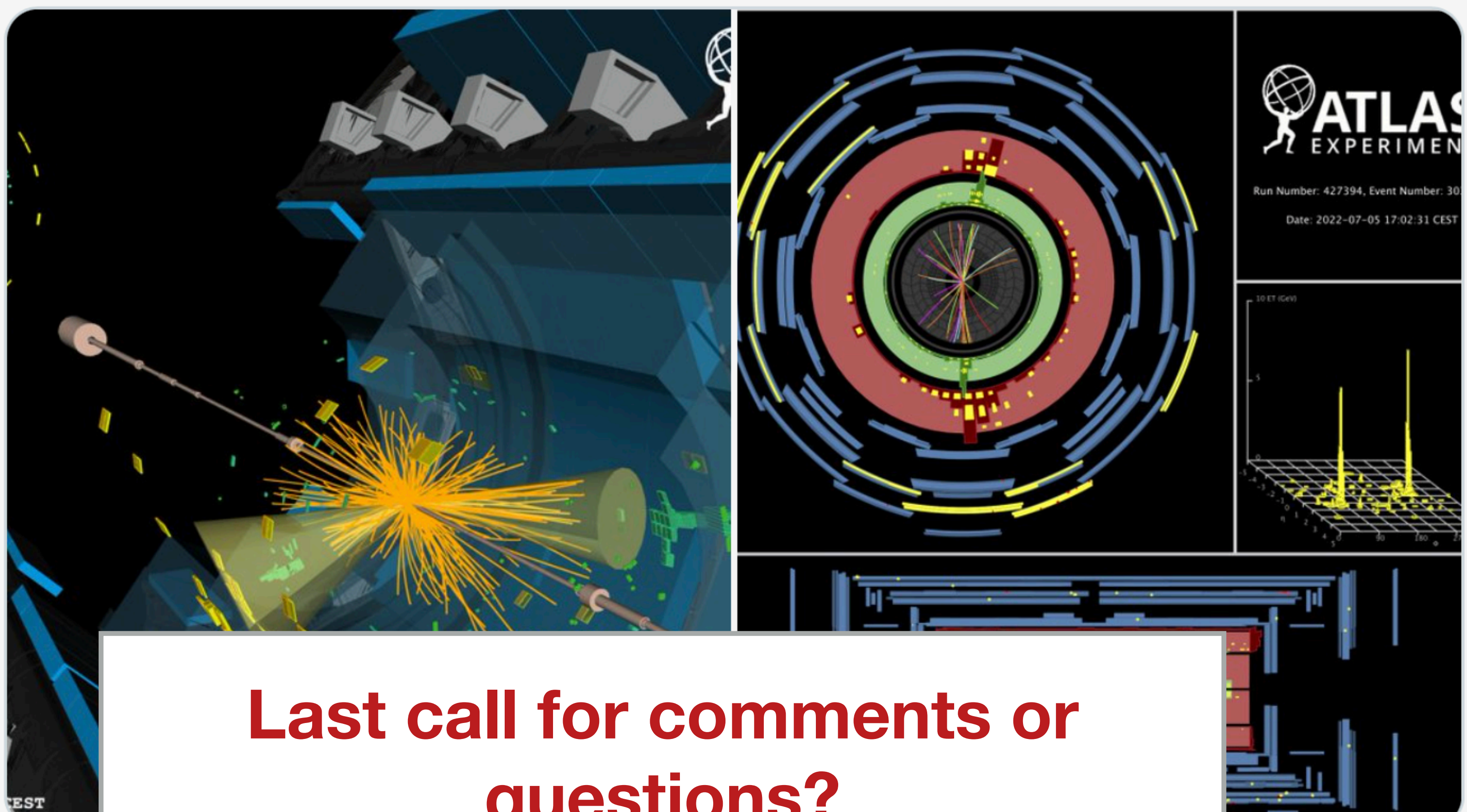

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Last call for comments or questions?

Backup

ATLAS Calorimetry

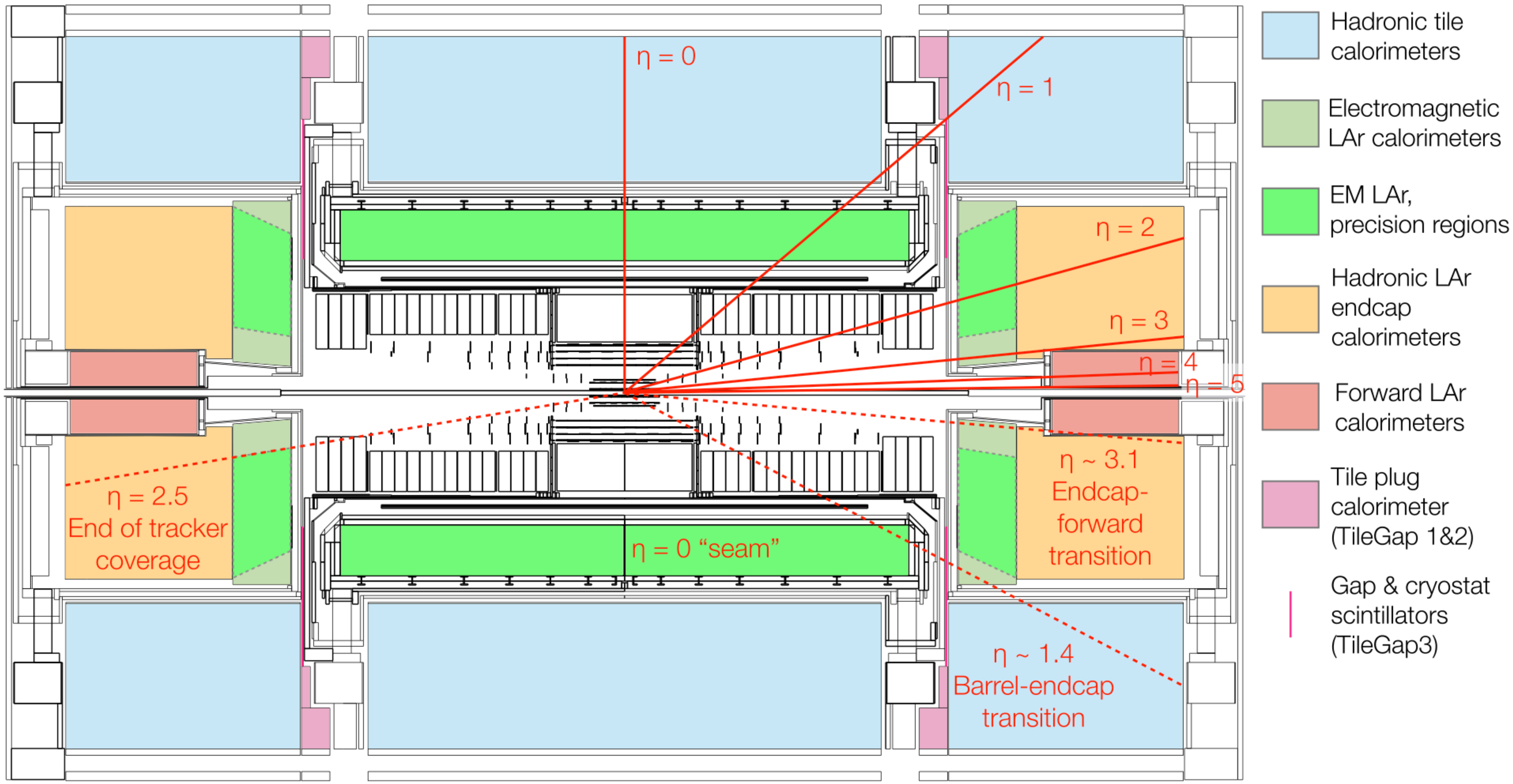
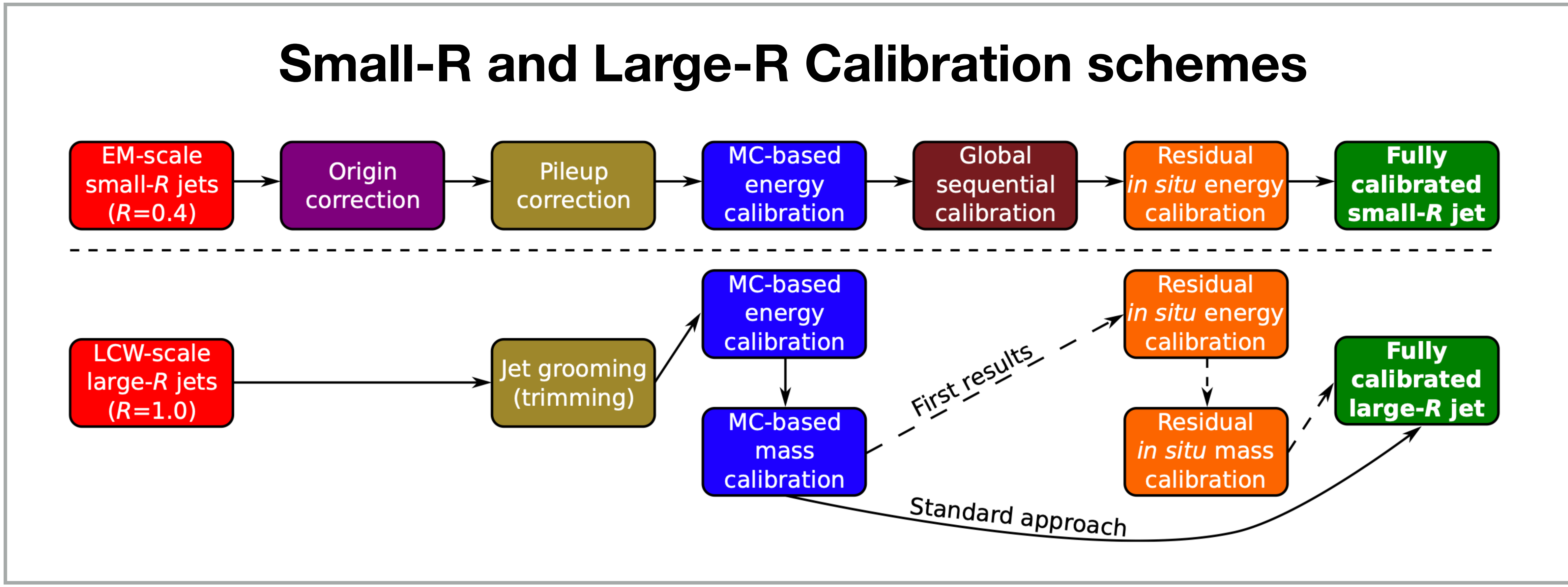


Fig. 1 Layout of the ATLAS calorimeters with pseudorapitidy (η) values marked for reference. The inner detector systems can be seen in black-and-white in the center of the diagram; tracking is provided up to $\eta = 2.5$. The electromagnetic (EM) barrel and endcap calorimeters are shown in green. The EM barrel has consistent performance throughout, but has a seam in the construction at $\eta = 0$ which can impact jet energy resolution. The EM endcap has a precision region marked in darker green and an extended region in light green, and the transition from one to the other around $\eta \sim 2.5$ involves a dramatic change in the material layers. The hadronic Tile calorimeter is shown in light blue while the hadronic endcap calorimeters based on liquid argon are illustrated in light orange. The forward calorimeters are shown in dark orange. Pink filled regions represent the tile plug calorimeter, often referred to as TileGap1 and TileGap2. The thin hot pink line marks the location of the very narrow gap and cryostat scintillators (TileGap3). The regions corresponding to the transition from barrel to endcap ($\eta \sim 1.4$) and from endcap to forward calorimeter ($\eta \sim 3.1$) are given for reference

Jet calibration



FullJER is your friend

JES and JER uncertainties are computed from a combination of many different measurements comparing data and MC

- The 'full' set of nuisance parameters is ~100 for JES and 34 for JER

The Jet/ETMiss group provides 'reductions' which combine related NP to reduce the burden on analysis

Sophisticated analyses (like those in Top Group) have a huge number of bins and signal regions

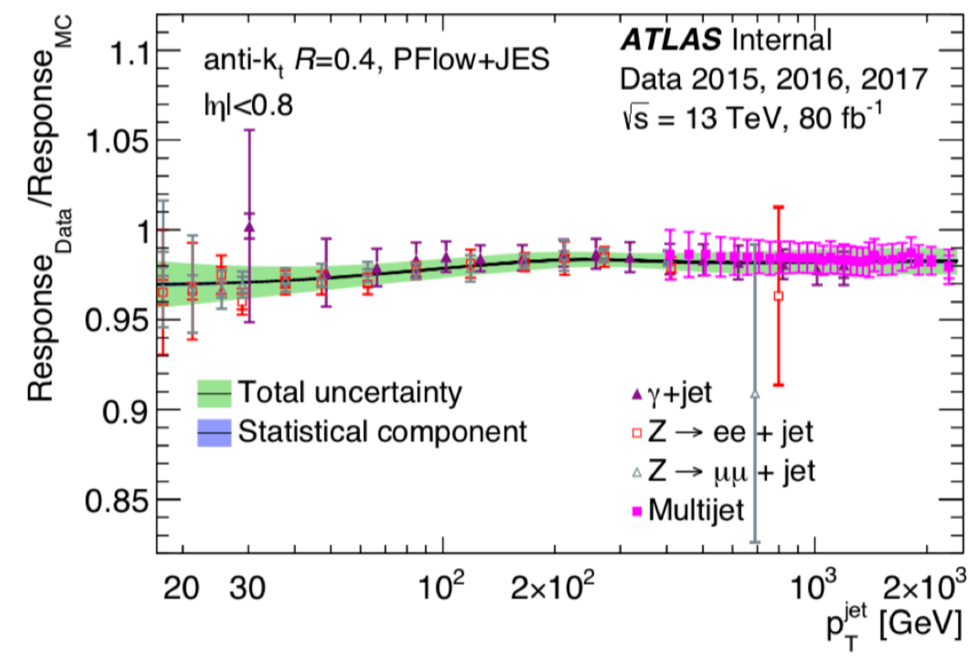
- does a wiggle in, e.g., bin1 corresponds to a wiggle in bin 107, or anti-wiggle?
- "Everything wiggles together" in the case of 1 NP: obviously overly simplistic!
- **Could result in too aggressive (or too conservative) application of uncertainties**

The more NP are combined, the more information on the correlation structure between the SRs you lose

JES/JER uncertainty

JES corrects Data to match MC, which itself is calibrated to “truth scale”

- MC reco jets calibrated to truth jets
- then, data jets calibrated to MC reco jets
- JES uncertainties correspond to how sure we are that data and MC are *actually* at the same scale

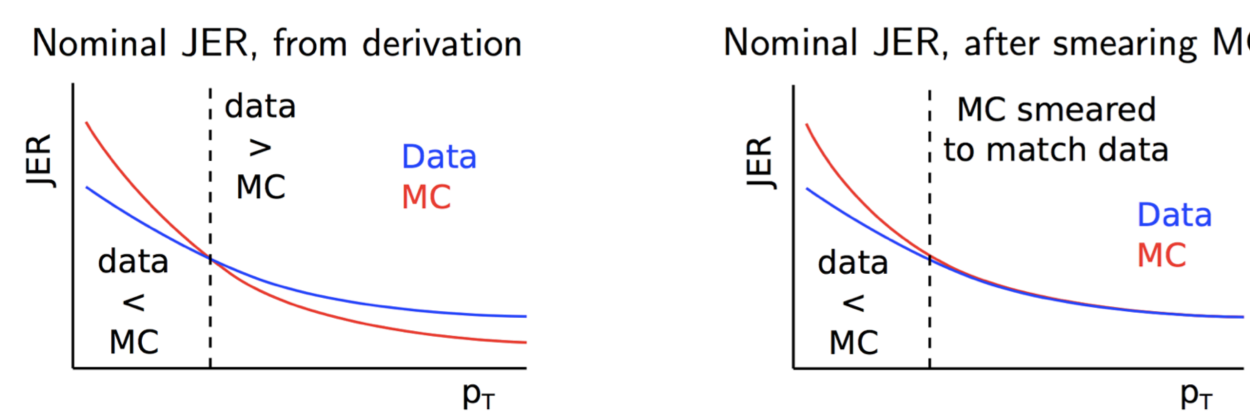


JES recommendation is “Category Reduction”

- → 30 NPs (UP and DOWN variations)

JER is a more complicated story...

- Not so easy to apply a correction like for the scale!
- You *can* smear the MC to match data, if MC resolution is better than data
- But if data resolution is better than MC, don’t want to degrade the data!



JER smearing

Uncertainties on JER propagated by smearing jets by a Gaussian width σ_{smear}:

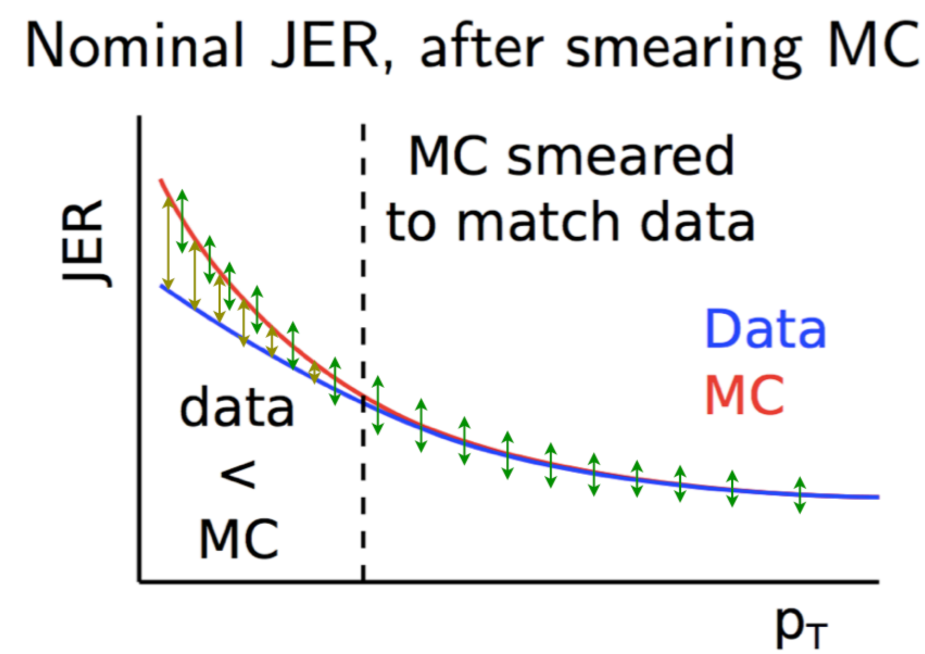
$$(\sigma_{smear})^2 = (\sigma_{nominal} - \sigma_{NP})^2 - (\sigma_{nominal})^2$$

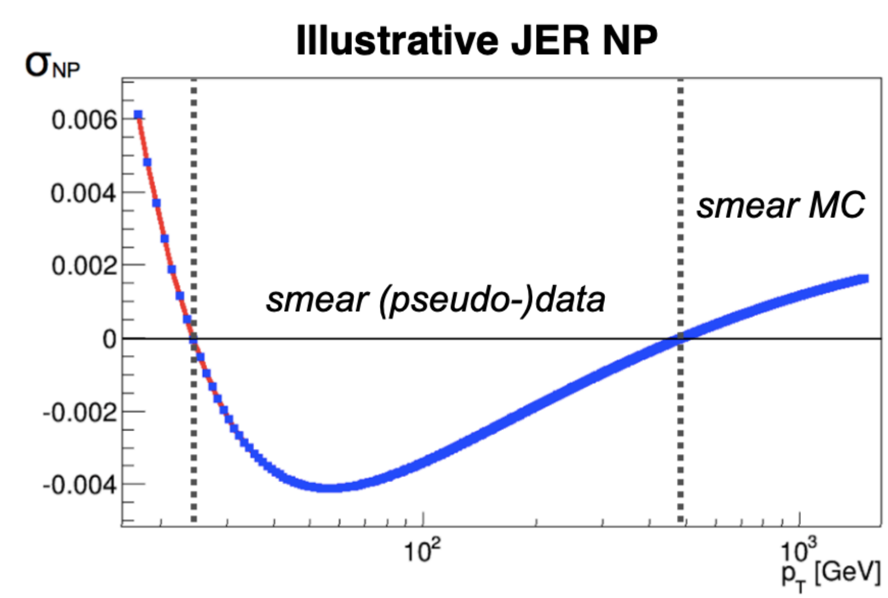
- If $\sigma_{NP} > 0$, smear MC; If $\sigma_{NP} < 0$, smear data (or pseudo-data)
- When **JER(data) < JER(MC)**, take full difference as uncertainty *in addition* to other JER uncertainties ($\sigma_{NP} = \sigma_{nominal,data} - \sigma_{nominal,MC}$)

This means that:

- **green** uncertainties are applied everywhere
- **gold** are extra uncertainties to cover cases when data resolution is better than MC

Smearing (pseudo-)data preserves anti-correlations when uncertainty components cross zero





JER In Practice...

(Pseudo-)data smearing may not always be desirable

- e.g. searches insensitive to the JER
- → provide two correlation schemes:
  + **Full correlations** (*data or MC* smearing): crossing zero = anti-correlation
    Recommended for analyses sensitive to JER.
  + **Simple correlations** (*MC-only* smearing): crossing zero = correlation
    Recommended only for analyses insensitive to JER.

Further details about the application **here**

Benefits of using FullJER:

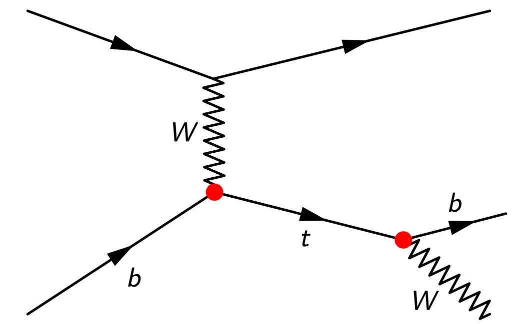
- Before using FullJER:
  + *"We unblinded and see a large pull in the JER.We need to talk to Jet/ ETMiss and understand in detail what is happening and understand our analysis sensitivity to this pull.This will slow down our analysis so much and we will miss our deadlines* 😭"
- After using FullJER:
  + *"We unblinded and we see a large pull in the JER.We implemented FullJER, so we can trust this instrumental pull.We should probably still mention this to Jet/ETMiss so they can think about why our phase space has such sensitivity to the CP NP, and they will be grateful for providing feedback on the effects of the JER on analyses.We will make our deadlines!* 😎"

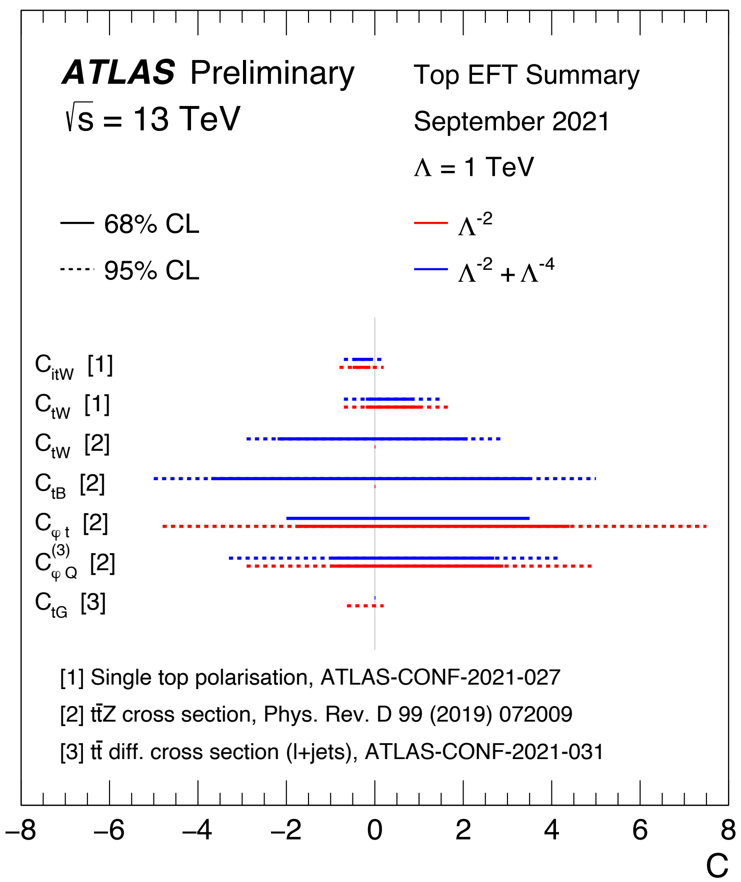
•

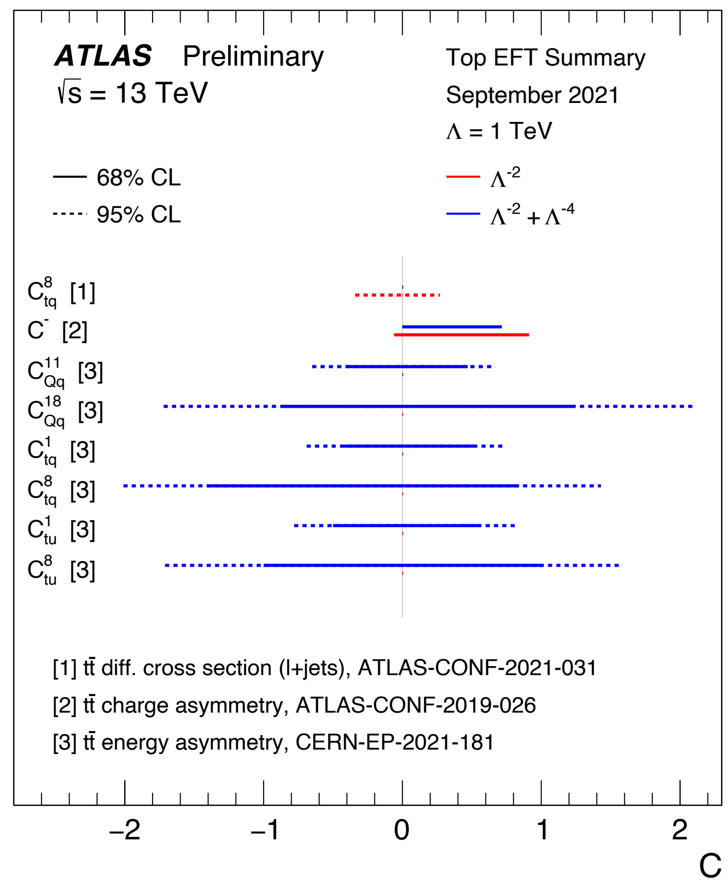
Unfolding example

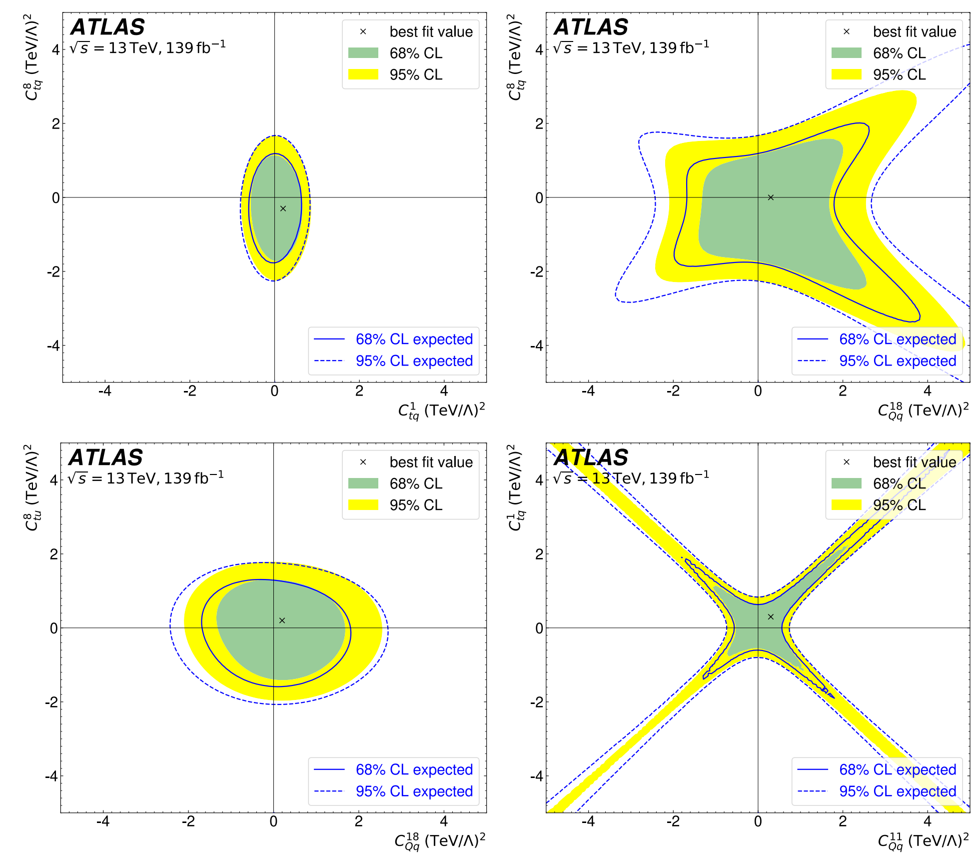
$$\sigma\left(\frac{c}{\Lambda^2}\right) = O_{SM}^2 + \frac{c}{\Lambda^2}\cdot O_{SM}O_{dim6} + \frac{c^2}{\Lambda^4}\cdot O_{dim6}^2$$

Pure SM — Interference term — Pure BSM









Reinterpreted in terms of Effective Field Theory (EFT)
→ set limits on New Physics operators!

Which unfolding?

Tool: RooUnfold

IBU

D'Agostini Iterative Bayesian Unfolding
Nucl. Inst. Meth. A 362 (1995) 487

$$N_k^{\text{particle}} = C_k^{\text{particle!reco}} \sum_j M_{jk}^{-1} G_j^{\text{reco!particle}} (N_j^{\text{data}} - B_j)$$

$$\theta_{ij} = \frac{\Pr(m_j|t_i) \cdot \Pr(t_i)}{\sum_i \Pr(m_j|t_i) \cdot \Pr(t_i)}$$

response matrix

regularization
= number of iterations

$$\Pr_{k+1}(t_i) = \sum_j \theta_{ij} \Pr_k(t_i)$$

Answer: an estimator θ_{ij} and its covariance matrix

It involves iterations and depend on a convergence criterion

- first point of an iterative procedure, named "prior".
- converges towards some of the possible solutions
- Regularization by interrupting iterations

Which unfolding?

Tool: PyFBU

FBU

Fully Bayesian Unfolding
arxiv.org/1201.4612

$$P(T|D,\mathcal{M}) \propto \mathcal{L}(D|T,\mathcal{M})\pi(T),$$

$$\mathcal{L}(D|T,\mathcal{M},B) = \prod_{i=1}^{N_r} \frac{(r_i+b_i)^{d_i}}{d_i!} \mathrm{e}^{-(r_i+b_i)},$$

$$r_i(T,\mathcal{M}) = \sum_{j=1}^{N_t} m_{ij} t_j, \qquad m_{ij} = \frac{\epsilon_{t_j} P(r_i|t_j)}{f_{\mathrm{acc},r_i}}$$

$$\mathcal{L}(D|T) = \int \mathcal{L}(D|R(T;\boldsymbol{\theta}_s), B(\boldsymbol{\theta}_s,\boldsymbol{\theta}_b)) G(\boldsymbol{\theta}_s) G(\boldsymbol{\theta}_b) \mathrm{d}\boldsymbol{\theta}_s \mathrm{d}\boldsymbol{\theta}_b$$

Answer: a posterior probability density defined in the space of possible spectra

- pdf which does not have to be Gaussian, which is important especially in bins with small Poisson event counts.

No matrix inversion and computation of eigenvalues, which makes it more stable numerically

No iterations (→ no convergence criterion)

- If more than one answers are equally likely, as can happen when the reconstructed spectrum has fewer bins than the inferred one, then FBU reveals all of them, while IBU converges towards some of the possible solutions.

Regularization by choosing a prior which favors certain characteristics, such as smoothness

Which unfolding?

Tool: RooUnfold

SVD

Singular Value Decomposition
Nucl. Inst. Meth. A 372 (1995) 469

$$R = USV^T$$

U, *V*, orthogonal, *S* diagonal & non-negative

$$d = U^T m \qquad z_i(\tau) = \frac{d_i}{s_i} \cdot \frac{s_i^2}{s_i^2 + \tau}$$

$$t = Vz$$

regularization parameter

Answer: an estimator θ_{ij} and its covariance matrix

- migrations matrix is distorted by singular value decomposition (SVD)
- works in the Gaussian regime only
- it involves a matrix inversion → sometimes numerically unstable → requires some curvature regularisation

Tool: TRExFitter (ATLAS)

PLU

Profile Likelihood Unfolding
CMS reference

$$L(\boldsymbol{\lambda}) = p(\mathbf{y}|\boldsymbol{\lambda}) = \prod_{i=1}^{n} p(y_i|\boldsymbol{\lambda}) = \prod_{i=1}^{n} \frac{\left(\sum_{j=1}^{p} K_{ij}\lambda_j\right)^{y_i}}{y_i!} e^{-\sum_{j=1}^{p} K_{ij}\lambda_j}, \quad \boldsymbol{\lambda} \in \mathbb{R}_+^p$$

Similar to FBU in terms of prior for regularisation, but it involves a Profile Likelihood fit too.

IBU vs. FBU vs. SVD vs. PLU

Reference: arxiv.org/1201.4612

FBU differs from *D'Agostini's iterative unfolding (IBU)* despite both using Bayes' theorem.

- In FBU the answer is not an estimator and its covariance matrix, but a posterior probability density defined in the space of possible spectra.
- FBU does not involve iterations, thus does not depend on a convergence criterion, nor on the first point of an iterative procedure, which in IBU is named "prior".
  + If more than one answers are equally likely, as can happen when the reconstructed spectrum has fewer bins than the inferred one, then FBU reveals all of them, while IBU converges towards some of the possible solutions.
- Regularization is not done by interrupting iterations, but by choosing a prior which favors certain characteristics, such as smoothness.
  + Thus, FBU offers intuition and full control of the regularizing condition, which makes the answer easy to interpret.

FBU differs significantly also from *SVD unfolding*.

- In FBU the migrations matrix is not distorted by singular value decomposition (SVD), therefore FBU assumes the intended migrations model.
- The answer of FBU is a probability density function which does not have to be Gaussian, which is important especially in bins with small Poisson event counts.
- FBU does not involve matrix inversion and computation of eigenvalues, which makes it more stable numerically.
- SVD imposes curvature regularization, while FBU offers the freedom to use different regularization choices. This freedom becomes necessary when the correct answer actually has large curvature, or when the answer has only two bins, thus curvature is not even defined.

PLU is similar to *FBU* in terms of prior for regularisation, but it involves a Profile Likelihood fit too.

BONUS $t\bar{t}$/tW overlap: bb4l

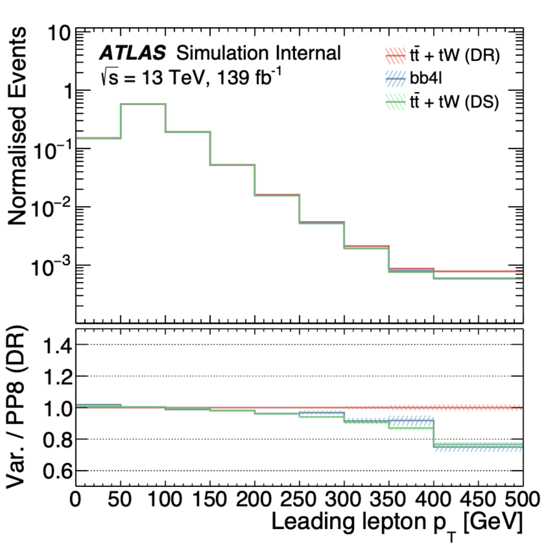
What is the bb4l generator?

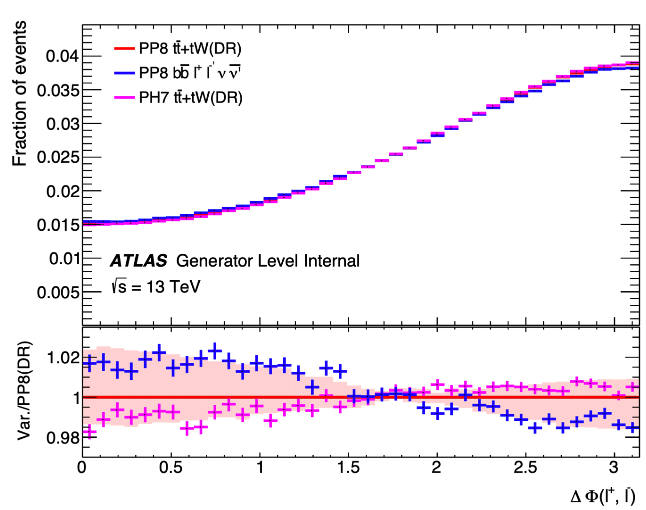
- can produce $t\bar{t}$, tW and WW with interference effects
- uses resonance-aware PS matching
- exact non-resonant / off-shell / interference / spin-correlation effects at NLO
- but: only dilepton channel, no same-flavour channels!

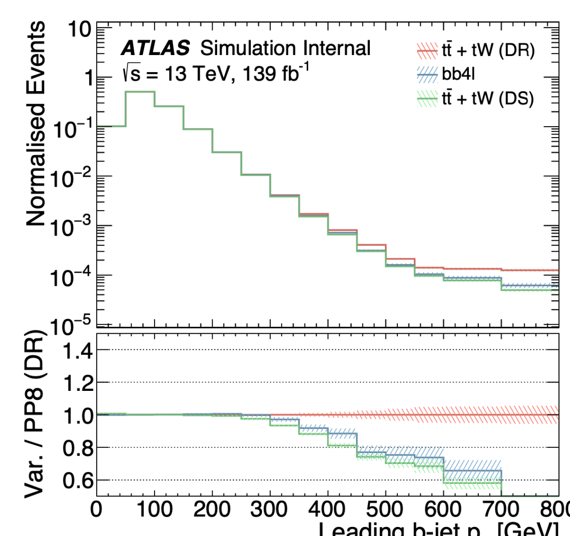
NLO predictions compared to unfolded ATLAS data and to bb4ℓ in $t\bar{t}$ phase-space.

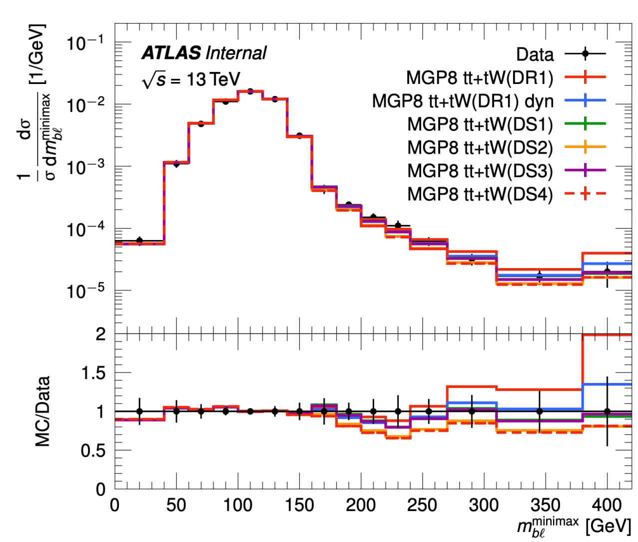
Conclusions:

- similar shape to DS than DR for some distributions (like pTℓ and mlbminavg)
- new proposal for systematic uncertainty (tW)
-



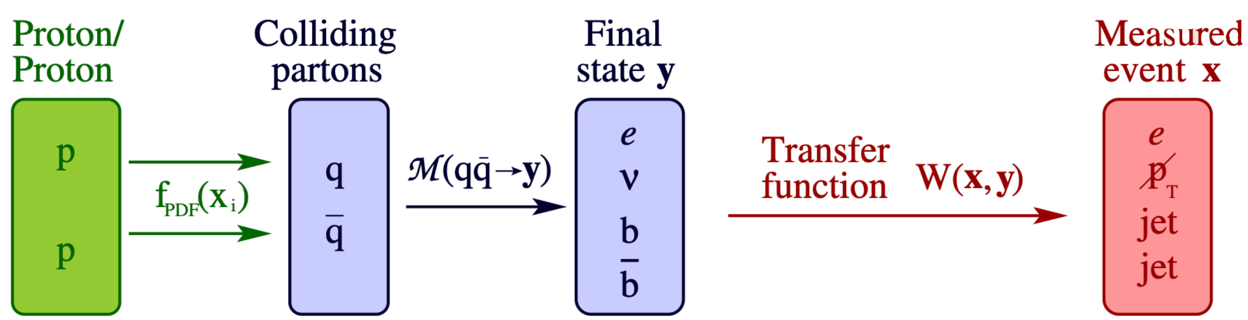






Single-top s-channel

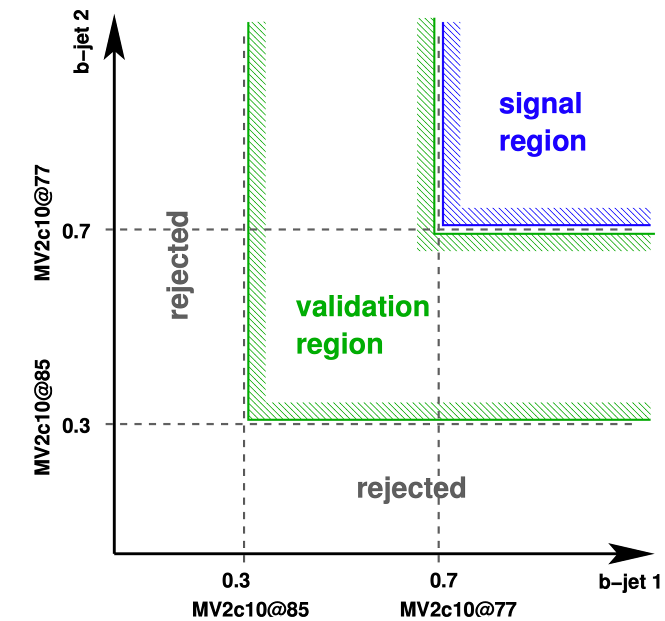
Matrix element discriminant to separate signal from backgrounds



$$\mathcal{P}(\mathbf{X}|H) = \frac{1}{\sigma\epsilon}\sum_{p\in\{\text{perms}\}}\int dx_1 dx_2 \sum_{i,j} f_i(x_1) f_j(x_2)\cdot \int d\mathbf{y}\, \underbrace{\frac{\|\mathcal{M}^H_{i,j}(\mathbf{y})\|^2}{2x_1x_2s}}_{=d\sigma_{ij}/d\mathbf{y}} \cdot W_p(\mathbf{x}|\mathbf{y})$$

- Compute for every measured event **X** the likelihood $\mathcal{P}$ that a process H leads to the event **X**
- Necessary building blocks for the calculation:
  - Hard scattering cross-section $d\sigma_{ij}/d\mathbf{y}$
  - Parton density functions (PDFs)
  - Transfer functions $W_p(\mathbf{x}|\mathbf{y})$
  - Detector acceptance and reconstruction efficiencies
  - Phase space integration $\int d\mathbf{y}$
- Build ME discriminant for each selected event
  Discriminate *s*-channel against *t*-channel, $t\bar{t}$, W+$b\bar{b}$, W+c + jet, W+jets light-flavour
- Signal probability for given event X:
  (Bayes' theorem)

$$P(S|X) = \frac{\sum_S P(S)\mathcal{P}(X|S)}{\sum_S P(S)\mathcal{P}(X|S) + \sum_B P(B)\mathcal{P}(X|B)}$$

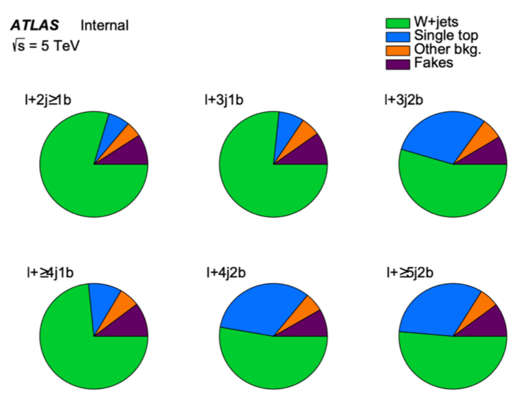


Source	$\Delta\sigma/\sigma$ [%]
$t\bar{t}$ and W+jets normalisation	+27/−20
Jet energy resolution	+19/−13
Other $t\bar{t}$ shape modelling sources	+18/−15
Jet energy scale	+18/−13
MC statistics	+12/−11
Top-quark processes ISR/FSR	+12/−10.0
Flavour tagging	+10/−8
Top-quark processes PDFs	+9/−8
Other processes normalisation	±6
W+jets ME scales	+6/−5
Other t-channel modelling sources	+4/−4
Pileup	+5/−3
Other s-channel modelling sources	+4/−2
Luminosity	+4/−3
Other tW modelling sources	±3
Missing transverse energy	±1
Multijet shape modelling	±1
Other sources	< 1
Systematics	+38/−33
Data statistics	±7
Total	+38/−33

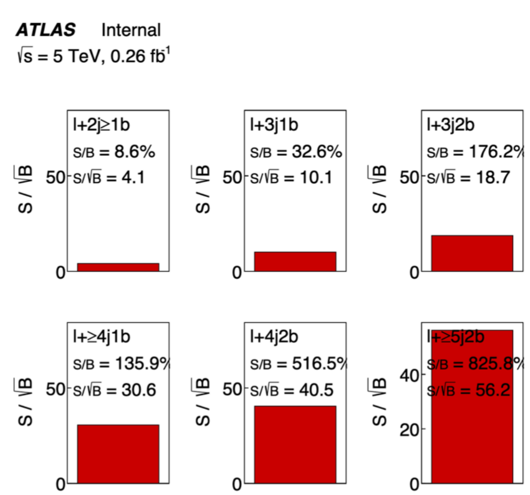
$t\bar{t}$ x-sec @5 TeV

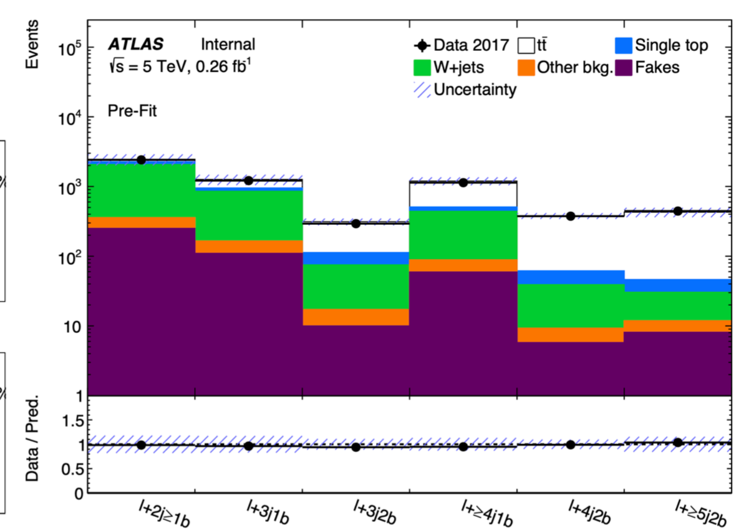
Variable	Definition	$\ell + (2,3)$j, $(1,2)$b	$\ell + (4, \geq 5)$j, $(1,2)$b
H_T^{had}	Scalar sum of all jet transverse momenta	✓	✓
FW2 (l+j)	Second Fox-Wolfram moment computed using all jets and the lepton	✓	✓
Lepton η	Lepton pseudorapidity	✓	✓
ΔR_{bl} (med.)	Median ΔR between the lepton and b-jets	✓	✓
ΔR_{jj} (med.)	Median ΔR between any two jets	✓	–
$m(jj)^{min.\Delta R}$	Mass of the combination of any two jets with the smallest ΔR	✓	–
ΔR_{uu} (med.)	Median ΔR between any two untagged jets	–	✓
$m(uu)^{min.\Delta R}$	Mass of the combination of any two untagged jets with the smallest ΔR	–	✓

- Predicted $\sigma_{t\bar{t}} = 68.2$ pb

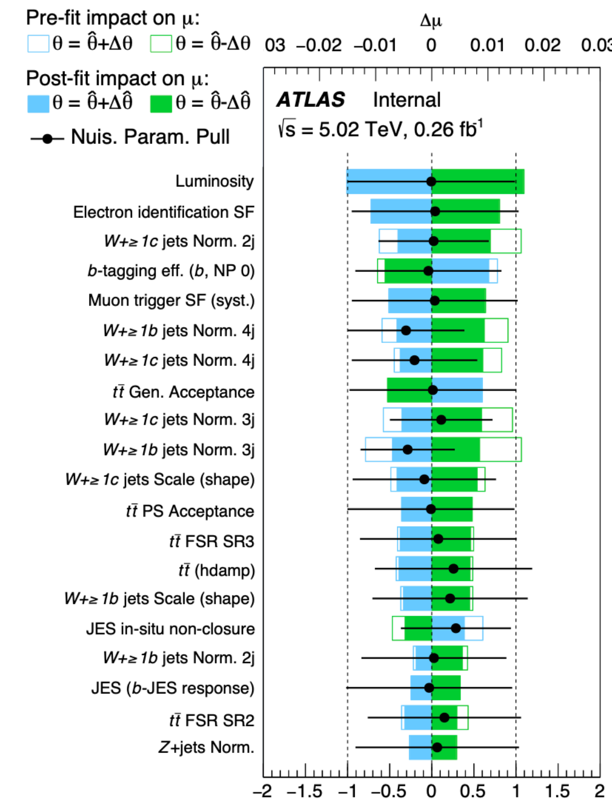


	ℓ+2j≥1b	ℓ+3j 1b	ℓ+3j 2b	ℓ+≥4j 1b	ℓ+4j 2b	ℓ+≥5j 2b
$t\bar{t}$	194 ± 27	310 ± 33	199 ± 24	690 ± 60	318 ± 32	380 ± 60
Single top	195 ± 22	98 ± 12	38 ± 5	67 ± 9	22 ± 4	15.9 ± 2.7
W+jets	1700 ± 400	690 ± 210	58 ± 23	350 ± 120	30 ± 14	19 ± 10
Other bkg.	110 ± 40	55 ± 23	7.2 ± 3.0	29 ± 12	3.5 ± 1.5	3.7 ± 1.7
Fakes	250 ± 130	110 ± 60	10 ± 5	60 ± 30	6 ± 3	8 ± 5
Total	2500 ± 400	1260 ± 210	312 ± 34	1200 ± 160	380 ± 40	430 ± 70
Data	2411	1214	293	1135	375	444

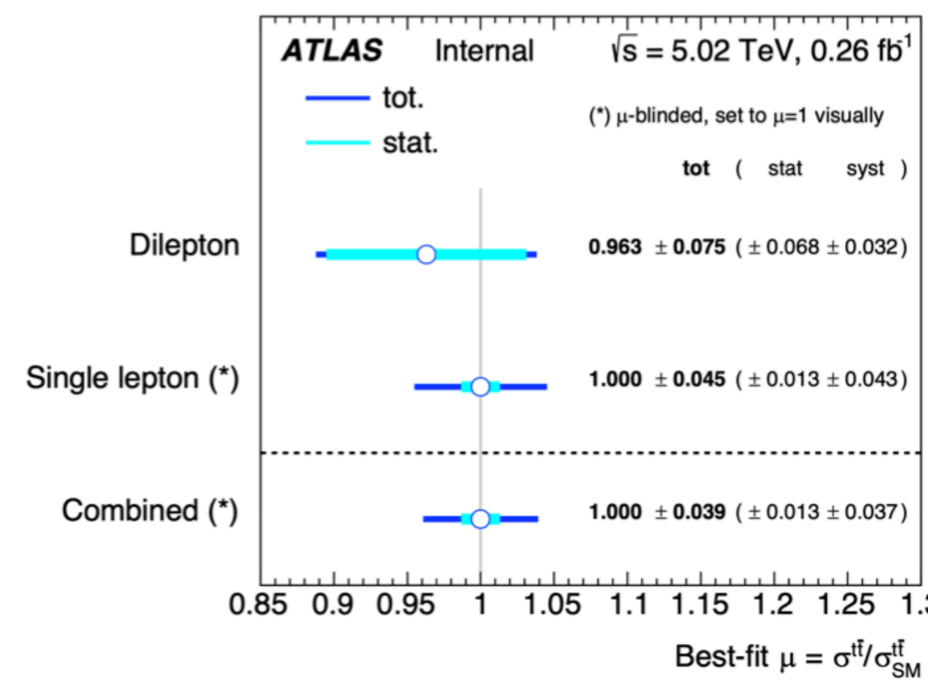




$t\bar{t}$ x-sec @5 TeV

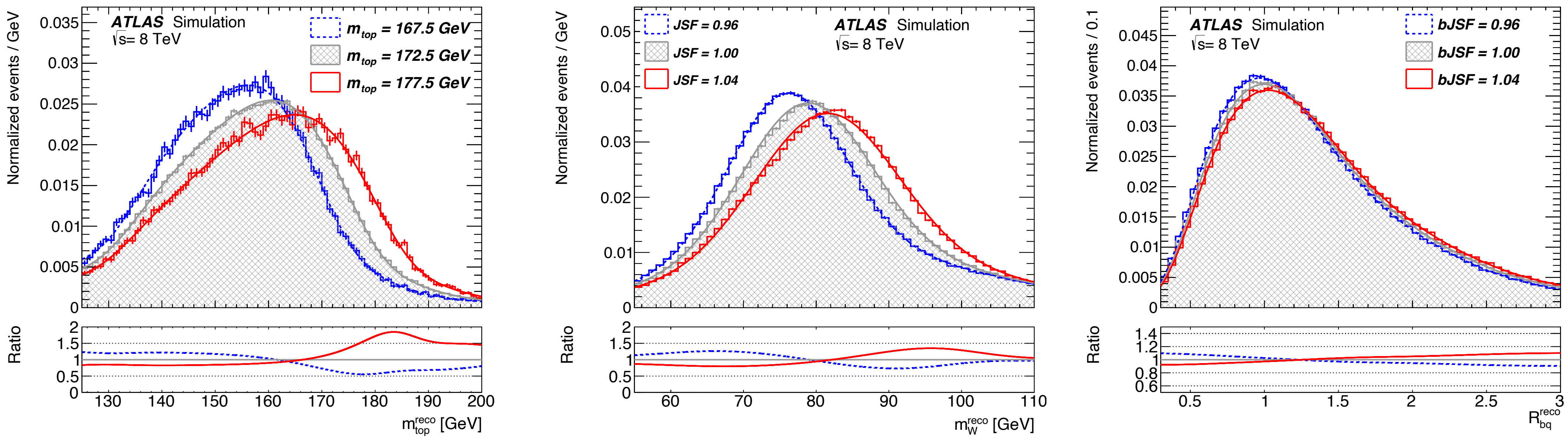


Category	l+jets [%]	Dilepton [%]	Combination [%]	Ratio [%]	Δ Quadrature [%]
$t\bar{t}$ Generator	1.0	1.2	0.8	80	0.6
$t\bar{t}$ PS	0.9	0.2	0.7	78	0.6
$t\bar{t}$ h_{damp} and scale variations*	1.0	1.1	0.8	80	0.6
$t\bar{t}$ PDF	0.2	0.2	0.2	100	0.0
Background modelling	2.2	1.5	2.1	95	0.7
Electron reconstruction	1.2	0.8	0.8	67	0.9
Jet energy scale	1.0	0.1	0.8	80	0.6
Flavour tagging	1.1	0.1	0.8	73	0.8
Muon reconstruction	0.9	0.6	0.7	78	0.6
JES in-situ non-closure	0.7	0.1	0.5	71	0.5
Jet energy resolution	0.3	0.1	0.2	67	0.2
JVT	0.2	< 0.1	0.2	100	0.0
$E_{\text{T}}^{\text{miss}}$	0.4	< 0.1	0.3	75	0.3
Luminosity	1.6	1.8	1.6	100	0.0
Simulation stat. uncertainty	0.6	0.2	0.5	83	0.3
Total systematic uncertainty	4.3	3.1	3.7	86	2.2
Total statistical uncertainty	1.3	6.9	1.3	100	0.0
Total uncertainty	4.5	7.5	3.9	87	2.2



Top mass combination

EPJC 79 (2019) 290



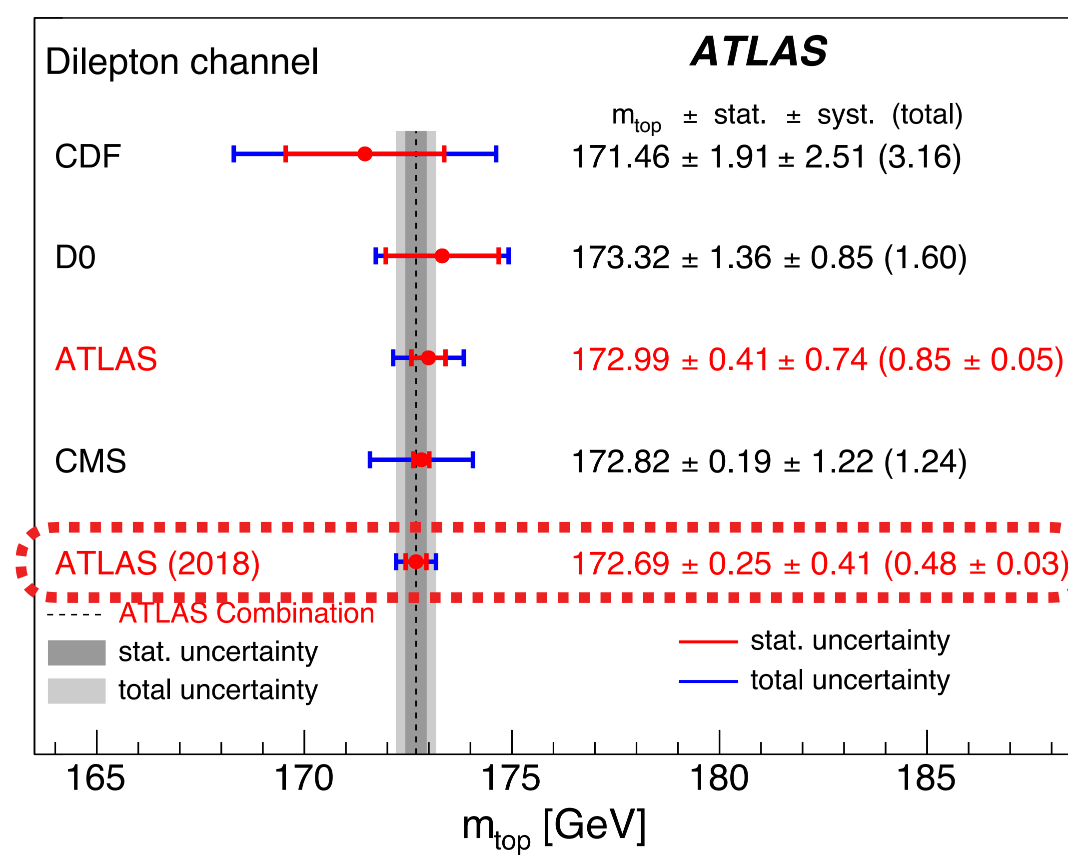
$$R_{bq}^{reco} = \frac{p_T^{b_{had}} + p_T^{b_{lep}}}{p_T^{W_{j1}} + p_T^{W_{j2}}}$$

In lepton+jets channel @8TeV

- sizeable uncertainties from JES and bJES
- ⇒ 3-D fit + BDT (19% improvement in Δm_{top})
- m_{top} = 172.08 ± 0.39 (stat) ± 0.82 (syst) GeV

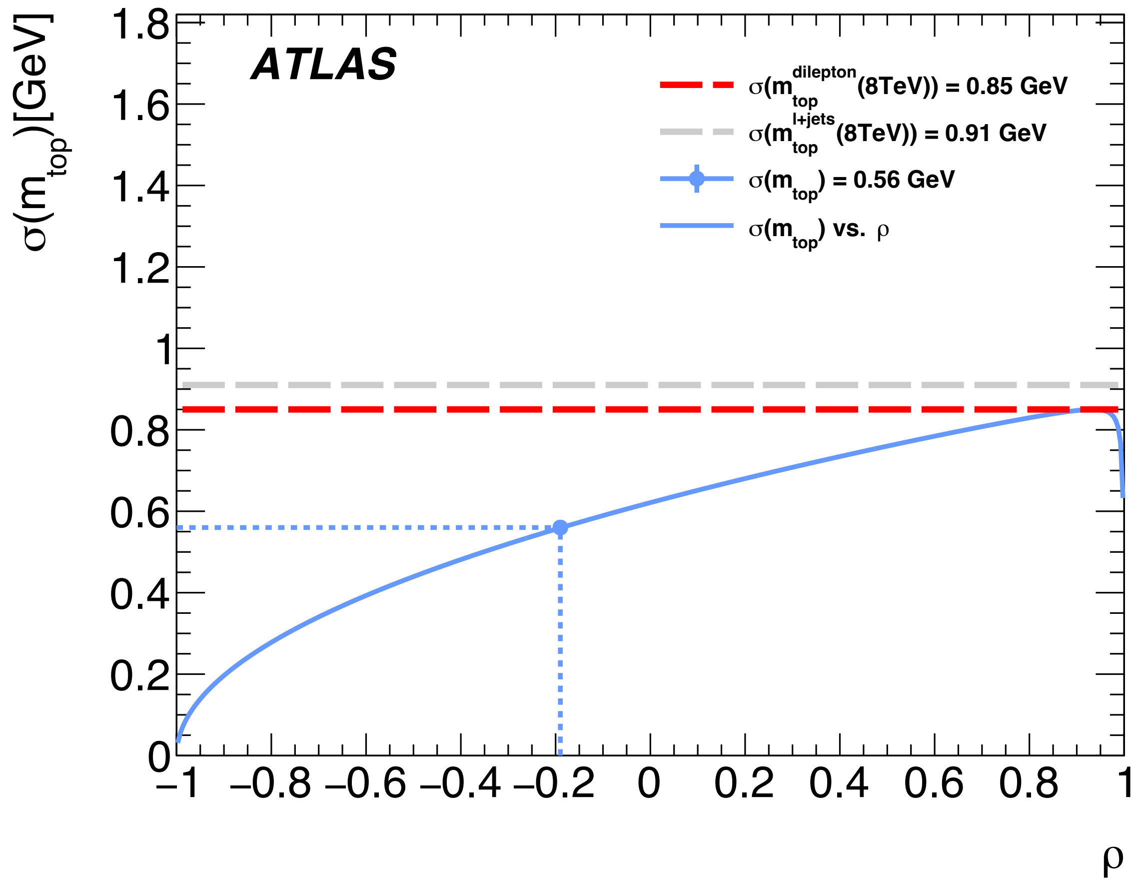
Combination of 6 measurements @7,8TeV

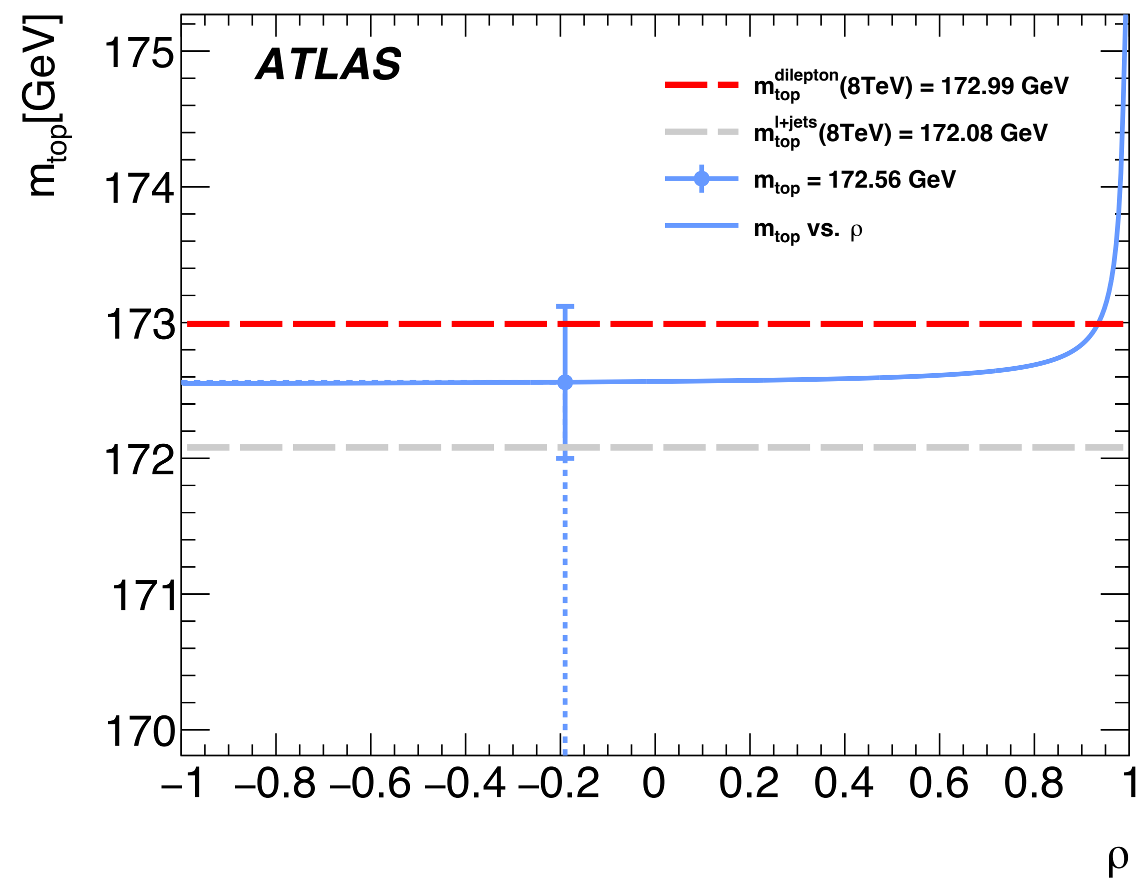
- → **relative uncertainty 0.29%!**



Mass combination

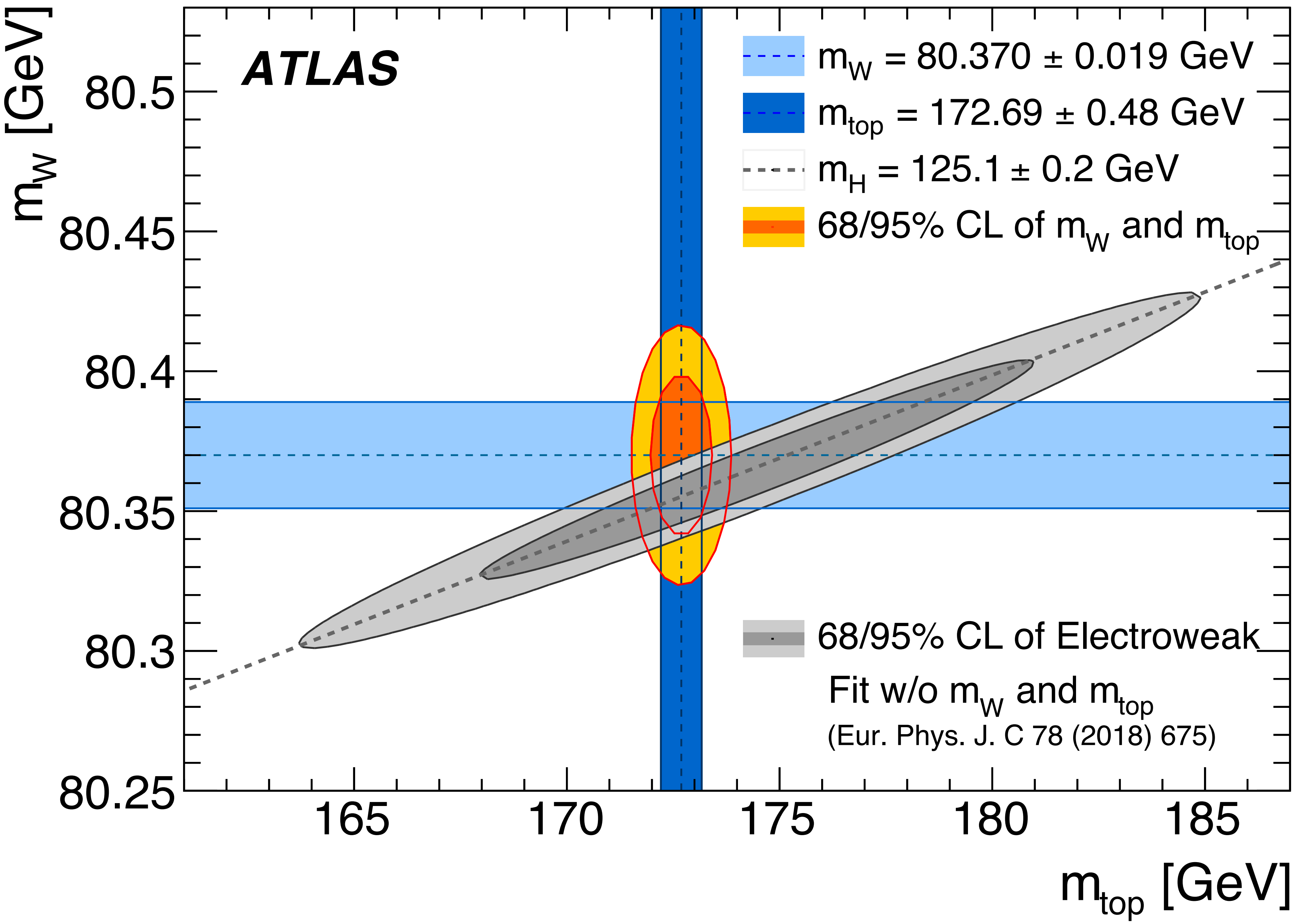
EPJC 79 (2019) 290





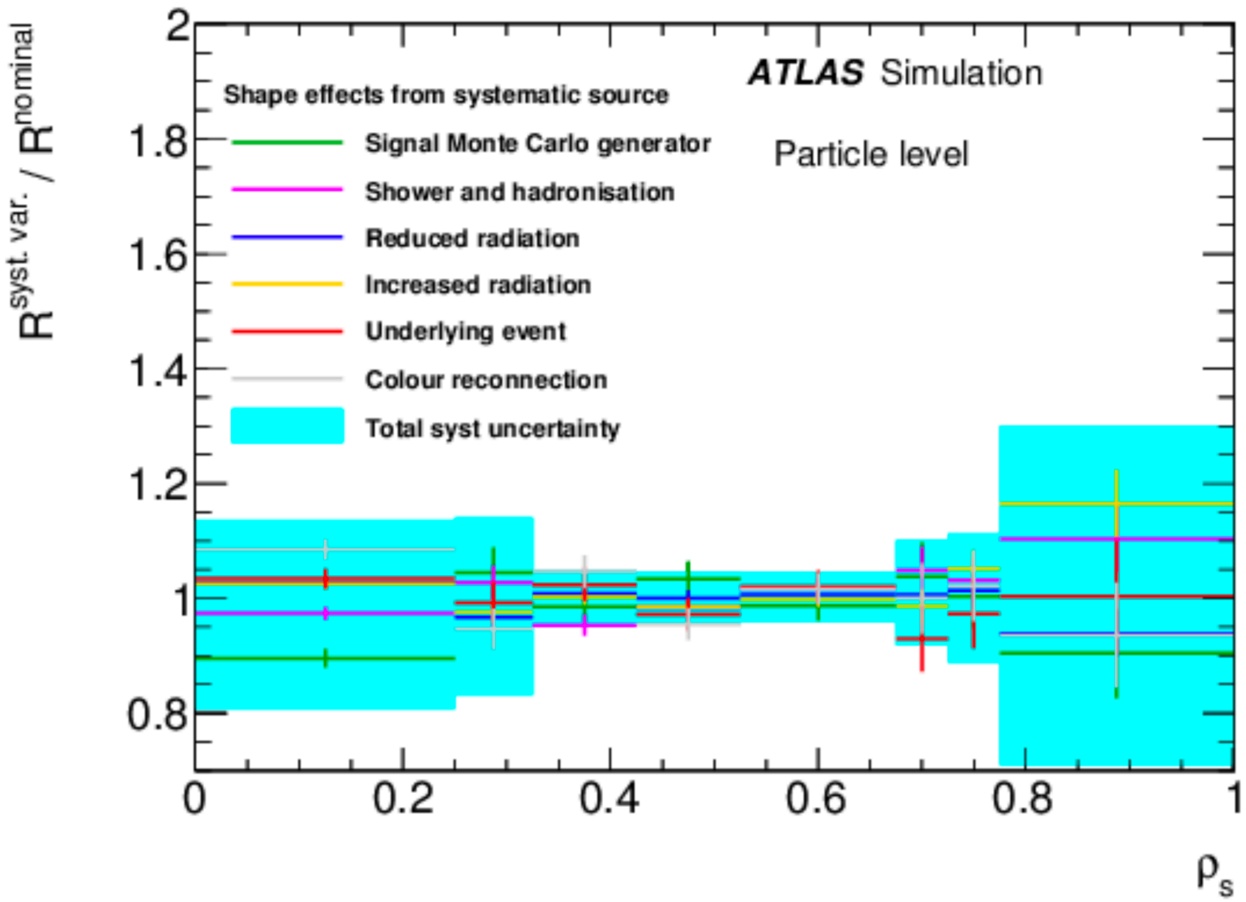
Mass: comp. w/ EW fit

EPJC 79 (2019) 290



Mass with $t\bar{t}$+1jet

Differential $t\bar{t}$+1 jet: dominated by JES and MC mod



Mass scheme	m_t^{pole} [GeV]	$m_t(m_t)$ [GeV]
Value	**171.1**	**162.9**
Statistical uncertainty	**0.4**	**0.5**
Simulation uncertainties		
Shower and hadronisation	0.4	0.3
Colour reconnection	0.4	0.4
Underlying event	0.3	0.2
Signal Monte Carlo generator	0.2	0.2
Proton PDF	0.2	0.2
Initial- and final-state radiation	0.2	0.2
Monte Carlo statistics	0.2	0.2
Background	<0.1	<0.1
Detector response uncertainties		
Jet energy scale (including b-jets)	0.4	0.4
Jet energy resolution	0.2	0.2
Missing transverse momentum	0.1	0.1
b-tagging efficiency and mistag	0.1	0.1
Jet reconstruction efficiency	<0.1	<0.1
Lepton	<0.1	<0.1
Method uncertainties		
Unfolding modelling	0.2	0.2
Fit parameterisation	0.2	0.2
Total experimental systematic	**0.9**	**1.0**
Scale variations	(+0.6, −0.2)	(+2.1, −1.2)
Theory PDF⊕α_s	0.2	0.4
Total theory uncertainty	**(+0.7, −0.3)**	**(+2.1, −1.2)**
Total uncertainty	**(+1.2, −1.1)**	**(+2.3, −1.6)**

Top mass with soft-muons

ATLAS-CONF-2019-046

Hadron	PDG (%)	POWHEG+PYTHIA8	Scale Factor
B^0	0.404±0.006	0.429	0.941
B^+	0.404±0.006	0.429	0.942
B_s^0	0.103±0.005	0.095	1.088
b-baryon	0.088±0.012	0.047	1.874
D^+	0.226±0.008	0.290	0.780
D^0	0.564±0.015	0.553	1.020
D_s^0	0.080±0.005	0.093	0.857
c-baryon	0.109±0.009	0.038	2.898

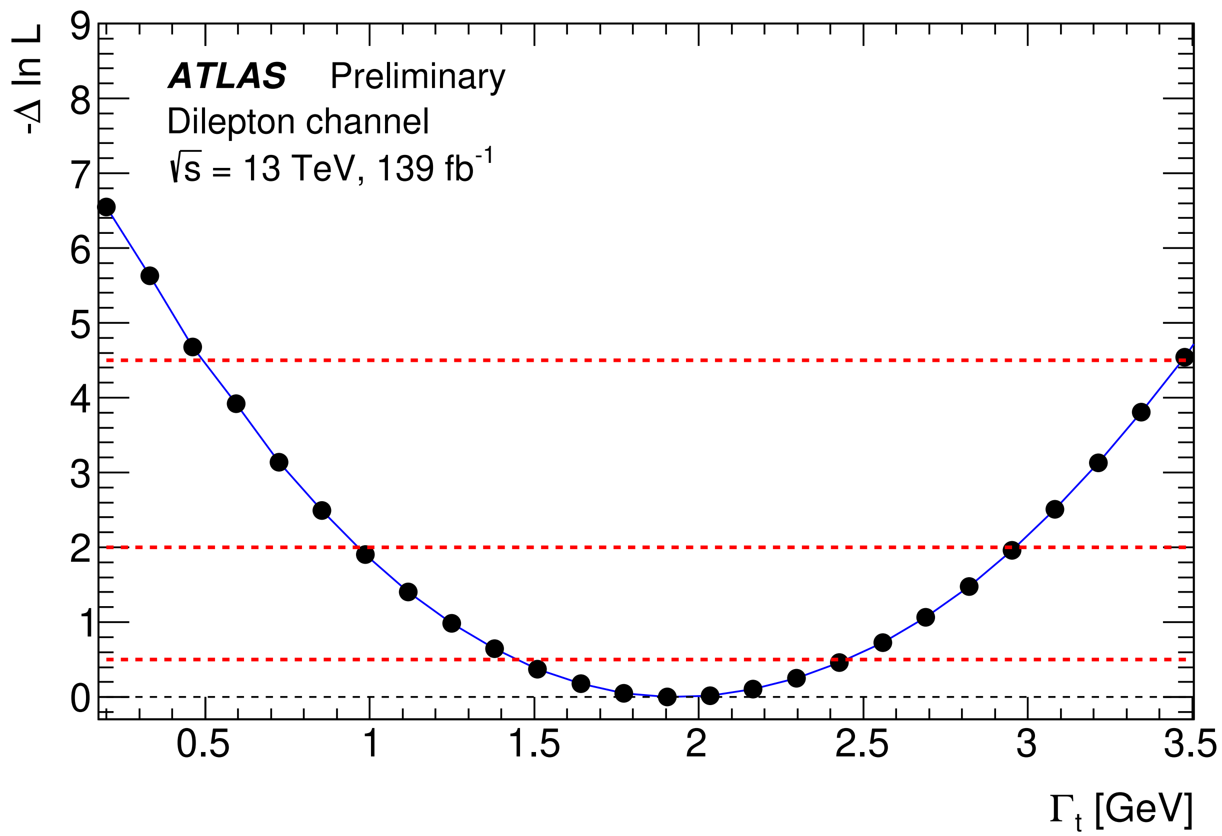
Hadron	PDG	POWHEG+PYTHIA8	Scale Factor
$b \to \mu$	$0.1095^{+0.0029}_{-0.0025}$	0.106	1.032
$b \to \tau$	0.0042 ± 0.0004	0.0064	0.661
$b \to c \to \mu$	0.0802 ± 0.0019	0.085	0.946
$b \to \bar{c} \to \mu$	$0.016^{+0.003}_{-0.003}$	0.018	0.888
$c \to \mu$	0.082 ± 0.005	0.084	0.976

Source	Unc. on m_t [GeV]	Stat. precision [GeV]
Data statistics	0.40	
Signal and background model statistics	0.16	
Monte Carlo generator	0.04	±0.07
Parton shower and hadronisation	0.07	±0.07
Initial-state QCD radiation	0.17	±0.07
Parton shower α_S^{FSR}	0.09	±0.04
b-quark fragmentation	0.19	±0.02
HF-hadron production fractions	0.11	±0.01
HF-hadron decay modelling	0.39	±0.01
Underlying event	< 0.01	±0.02
Colour reconnection	< 0.01	±0.02
Choice of PDFs	0.06	±0.01
W/Z+jets modelling	0.17	±0.01
Single top modelling	0.01	±0.01
Fake lepton modelling ($t \to W \to \ell$)	0.06	±0.02
Soft muon fake modelling	0.15	±0.03
Jet energy scale	0.12	±0.02
Soft muon jet p_T calibration	< 0.01	±0.01
Jet energy resolution	0.07	±0.05
Jet vertex tagger	< 0.01	±0.01
b-tagging	0.10	±0.01
Leptons	0.12	±0.00
Missing transverse momentum modelling	0.15	±0.01
Pile-up	0.20	±0.05
Luminosity	< 0.01	±0.01
Total systematic uncertainty	0.67	±0.04
Total uncertainty	0.78	±0.03

Top width using $t\bar{t}$ events

ATLAS-CONF-2019-038

	m_t = 172 GeV		m_t = 172.5 GeV		m_t = 173 GeV	
	Mean [GeV]	Unc. [GeV]	Mean [GeV]	Unc. [GeV]	Mean [GeV]	Unc. [GeV]
Measured	2.01	$^{+0.53}_{-0.50}$	1.94	$^{+0.52}_{-0.49}$	1.90	$^{+0.52}_{-0.48}$
Theory	1.306	< 1%	1.322	< 1%	1.333	< 1%

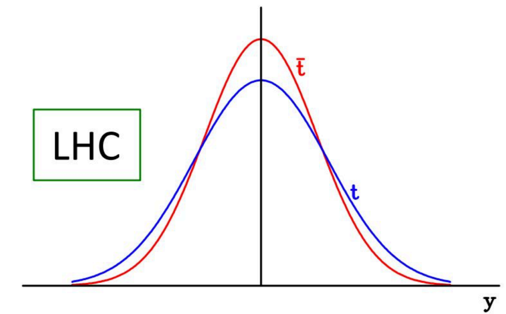


Source	Impact on Γ_t [GeV]
Jet reconstruction	±0.24
Signal and bkg. modelling	±0.19
MC statistics	±0.14
Flavour tagging	±0.13
E_T^{miss} reconstruction	±0.09
Pile-up and luminosity	±0.09
Electron reconstruction	±0.07
PDF	±0.04
$t\bar{t}$ normalisation	±0.03
Muon reconstruction	±0.02
Fake-lepton modelling	±0.01

$A_C^{t\bar{t}}$ vs. $A_E^{t\bar{t}}$

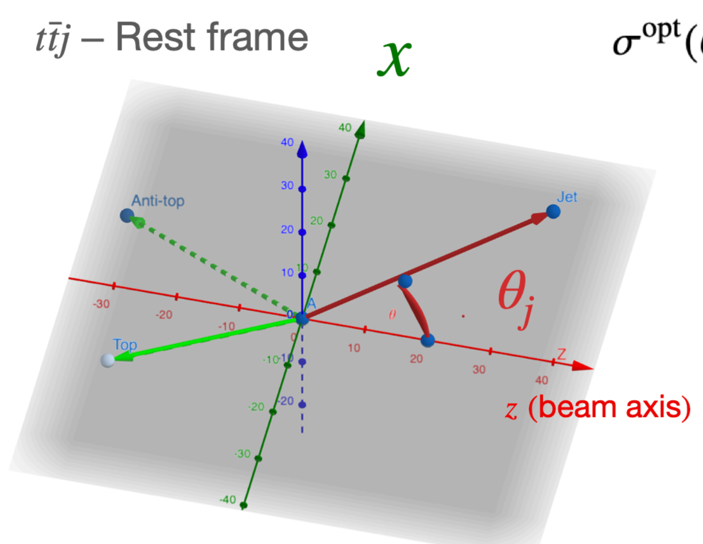
$t\bar{t}$ charge asymmetry ($A_C^{t\bar{t}}$) strongly diluted @LHC (gg-fusion (≈90%))

- $gg \to t\bar{t}$ (LO): charge symmetric to all orders
- $q\bar{q} \to t\bar{t}$ (NLO): top (anti-top) produced preferentially along q ($\bar{q}$)
- @LHC (p-p): momentum imbalance of initial-state q and $\bar{q}$
  - + → tops more longitudinally boosted than anti-tops



$t\bar{t}$+1j energy asymmetry ($A_E^{t\bar{t}}$) happens at any order thanks to the additional jet

- → gateway for $A_C^{t\bar{t}}$ in a different phase-space
- → complementary SMEFT tests

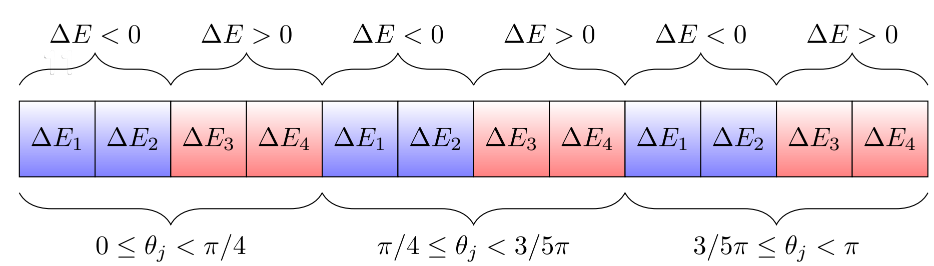


(a) (b)

$$\sigma^{\rm opt}(\theta_j) = \sigma(\theta_j | y_{t\bar{t}j} > 0) + \sigma(\pi - \theta_j | y_{t\bar{t}j} < 0)\,, \qquad \theta_j \in [0, \pi]$$

- $\Delta E = E_t - E_{\bar{t}}$

$$A_E(\theta_j) \equiv \frac{\sigma^{\rm opt}(\theta_j | \Delta E > 0) - \sigma^{\rm opt}(\theta_j | \Delta E < 0)}{\sigma^{\rm opt}(\theta_j | \Delta E > 0) + \sigma^{\rm opt}(\theta_j | \Delta E < 0)}\,,$$



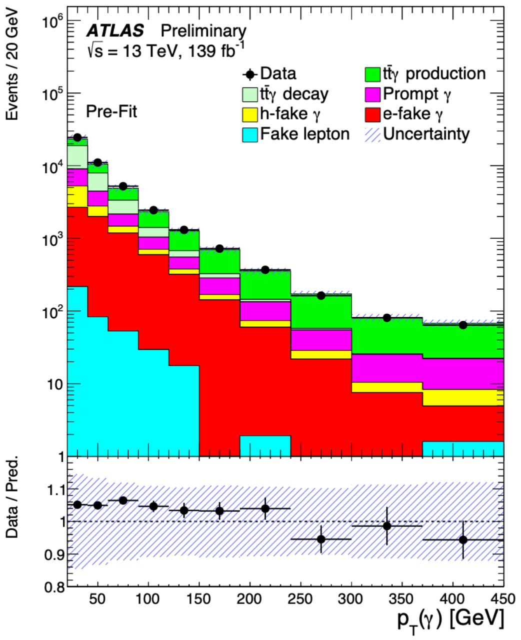
Energy Asymmetry

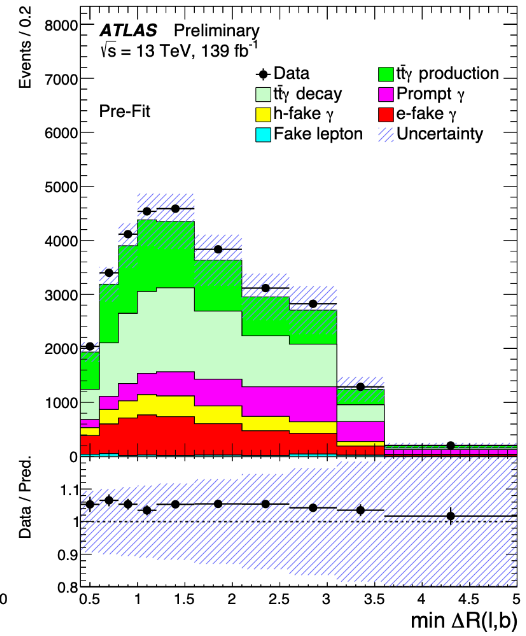
Scenario	ΔA_E $[10^{-2}]$ $0 \leq \theta_j < \frac{\pi}{4}$	$\frac{\pi}{4} < \theta_j \leq \frac{3\pi}{5}$	$\frac{3\pi}{5} \leq \theta_j \leq \pi$
Data statistical uncertainty	1.60	1.40	1.40
$t\bar{t}$ modelling	0.08	0.87	0.34
$t\bar{t}$ response MC statistics	0.51	0.42	0.42
W+jets modelling and PDF	0.29	0.49	0.42
Single-top modelling	0.28	0.60	0.29
$t\bar{t}$ and single-top PDF	0.08	0.10	0.07
Multijet	0.53	0.54	0.51
Jet energy resolution	0.98	0.40	0.36
Other detector uncertainties	0.42	0.43	0.30
Total	2.10	2.00	1.80

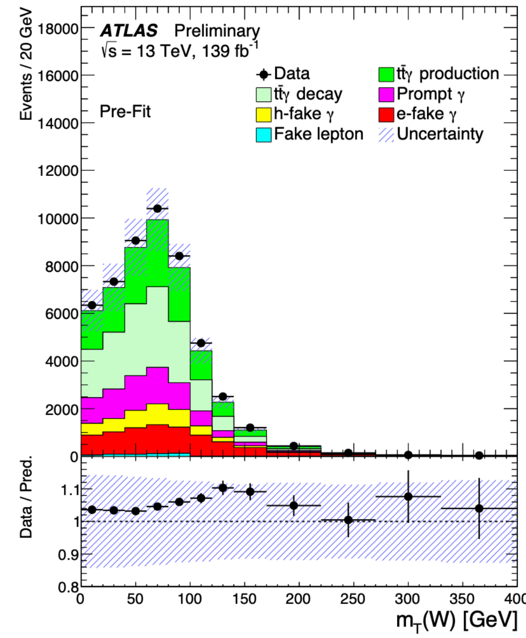
Scenario	$A_E \pm \Delta A_E$ $[10^{-2}]$ $0 \leq \theta_j \leq \frac{\pi}{4}$	$\frac{\pi}{4} \leq \theta_j \leq \frac{3\pi}{5}$	$\frac{3\pi}{5} \leq \theta_j \leq \pi$
Data	-3.2 ± 2.1	-4.3 ± 2.0	-1.3 ± 1.8
SM prediction (MadGraph5_aMC@NLO)	-1.3 ± 0.3	-3.7 ± 0.3	-0.6 ± 1.3
SM expectation	-1.3 ± 2.1	-3.7 ± 2.0	-0.6 ± 1.6

$C\,(\text{TeV}/\Lambda)^2$	A_E (Λ^{-4}) 68% CL	A_E (Λ^{-4}) 95% CL	A_E (Λ^{-2}) 68% CL	A_E (Λ^{-2}) 95% CL
C_{Qq}^{11}	$[-0.41, 0.47]$	$[-0.65, 0.67]$	$[-0.68, 4.06]$	$[-3.36, 6.16]$
C_{Qq}^{18}	$[-0.87, 1.24]$	$[-1.72, 2.10]$	$[-1.26, 4.76]$	$[-3.24, 9.64]$
C_{tq}^{1}	$[-0.43, 0.52]$	$[-0.69, 0.75]$	$[-0.60, 5.76]$	$[-3.42, 9.36]$
C_{tq}^{8}	$[-1.41, 0.84]$	$[-2.01, 1.43]$	$[-1.86, 1.70]$	$[-3.30, 3.98]$
C_{tu}^{1}	$[-0.50, 0.56]$	$[-0.78, 0.81]$	$[-0.96, 5.82]$	$[-4.72, 8.88]$
C_{tu}^{8}	$[-1.00, 1.01]$	$[-1.71, 1.56]$	$[-1.30, 2.52]$	$[-3.02, 4.66]$

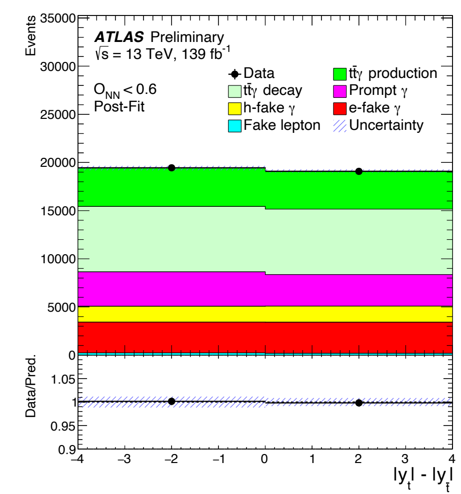
Charge Asymmetry

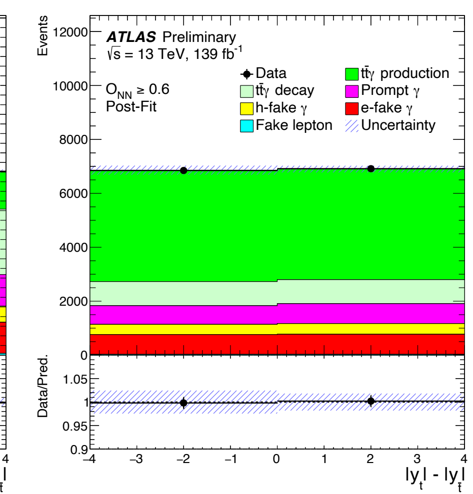


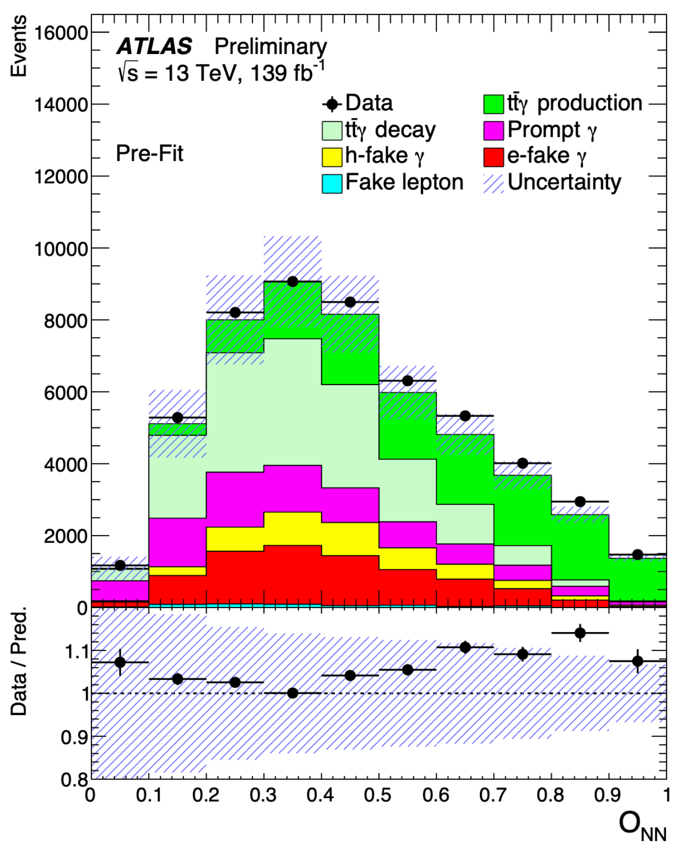




	$O_{\mathrm{NN}} < 0.6$	$O_{\mathrm{NN}} \geq 0.6$
$t\bar{t}\gamma$ prod (signal)	6660 ± 350	6910 ± 340
$t\bar{t}\gamma$ decay	14 100 ± 3100	1900 ± 560
h-fake γ	3400 ± 1400	790 ± 360
e-fake γ	6420 ± 860	1480 ± 260
prompt γ	6400 ± 2000	1300 ± 400
lepton fake	410 ± 110	57 ± 35
Total	37 400 ± 4500	12 400 ± 1100
Data	38527	13763



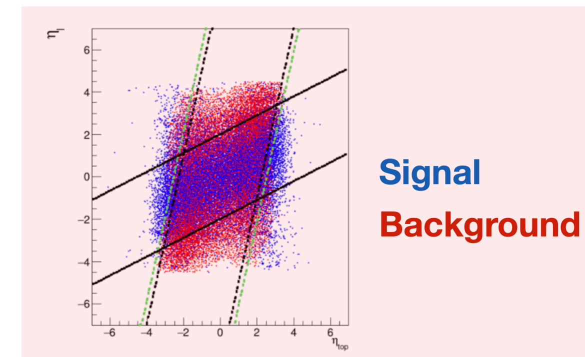


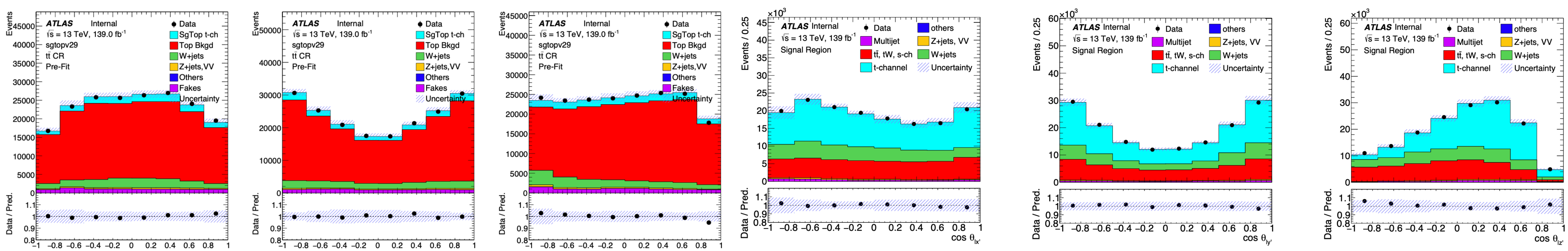


Total uncertainty	0.030
Statistical uncertainty	0.024
MC statistical uncertainties	
$t\bar{t}\gamma$ production	0.004
Background processes	0.008
Modelling uncertainties	
$t\bar{t}\gamma$ production modelling	0.003
Background modelling	0.002
Prompt background normalisation	0.003
Experimental uncertainties	
Jet and b-tagging	0.010
Fake lepton background estimate	0.005
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.009
Fake photon background estimates	0.004
Photon	0.003
Other experimental	0.004

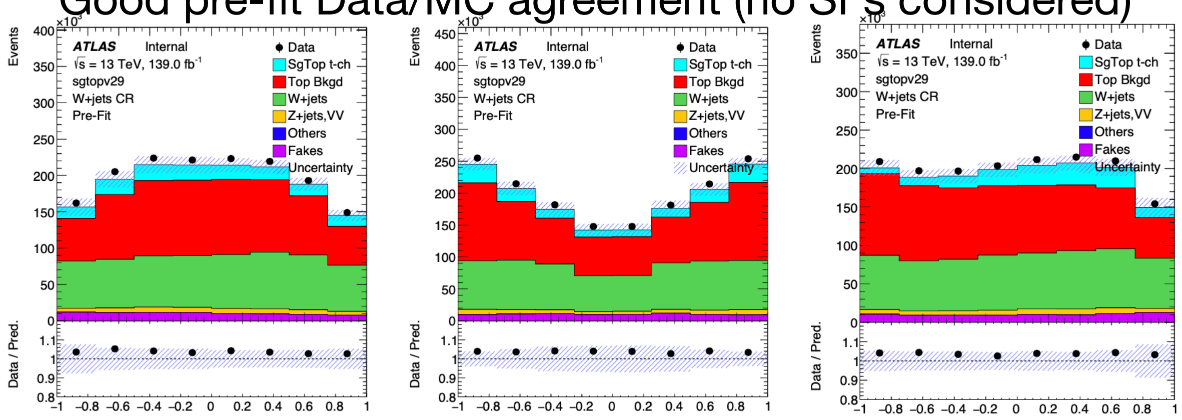
Top polarisation

Preselection region	Signal region	$t\bar{t}$ control region	W+jets control region
=1 charged tight lepton ($p_T > 30$ GeV and $\lvert\eta\rvert < 2.5$)			
Veto secondary low-p_T charged loose leptons ($p_T > 10$ GeV and $\lvert\eta\rvert < 2.5$)			
=2 jets ($p_T > 30$ GeV and $\lvert\eta\rvert < 4.5$; $p_T > 35$ GeV within $2.7 < \lvert\eta\rvert < 3.5$)			
$E_T^{miss} > 35$ GeV			
$m_T(\ell E_T^{miss}) > 60$ GeV			
$p_T(\ell) > 50\left(1 - \frac{\pi - \lvert\Delta\phi(j_1,\ell)\rvert}{\pi - 1}\right)$ GeV			
=1 b-jet ($\lvert\eta\rvert < 2.5$; 60%WP)		=2 b-jet ($\lvert\eta\rvert < 2.5$; 60%WP)	=1 b-jet ($\lvert\eta\rvert < 2.5$; 60%WP)
	$m_{\ell b} < 153$ GeV		$m_{\ell b} > 153$ GeV
	$m_{\ell E_T^{miss} b} \in [120.6, 234.6]$ GeV		$m_{\ell E_T^{miss} b} \notin [120.6, 234.6]$ GeV
	trapez. requirement		veto trapez. requirement
	$m_{j\ell E_T^{miss} b} > 320$ GeV		$m_{j\ell E_T^{miss} b} < 320$ GeV
	$H_T > 190$ GeV		$H_T < 190$ GeV





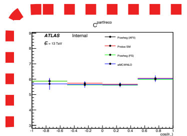
Good pre-fit Data/MC agreement (no SFs considered)



SF (top-quark bkg.): 0.996 ± 0.005 (stat.)
SF (W+jets bkg.): 1.153 ± 0.009 (stat.)
SF (t-channel): 1.073 ± 0.012 (stat.)

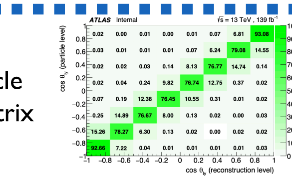
Top polarisation

Uncertainty source	$\Delta P^{t}_{x'}$	$\Delta P^{\bar{t}}_{x'}$	$\Delta P^{t}_{y'}$	$\Delta P^{\bar{t}}_{y'}$	$\Delta P^{t}_{z'}$	$\Delta P^{\bar{t}}_{z'}$
Modelling						
Modelling (t-channel)	±0.037	±0.051	±0.010	±0.015	±0.061	±0.061
Modelling ($t\bar{t}$)	±0.016	±0.021	±0.004	±0.016	±0.003	±0.016
Modelling (other)	±0.013	±0.031	±0.003	±0.006	±0.026	±0.043
Experimental						
Jet energy scale	±0.045	±0.048	±0.005	±0.007	±0.033	±0.025
Jet energy resolution	±0.166	±0.185	±0.021	±0.040	±0.070	±0.130
Jet flavour tagging	±0.004	±0.002	<0.001	±0.001	±0.007	±0.009
Other experimental uncertainties	±0.015	±0.029	±0.002	±0.007	±0.014	±0.026
Multijet estimation	±0.008	±0.021	<0.001	±0.001	±0.008	±0.013
Luminosity	±0.001	±0.001	<0.001	<0.001	<0.001	<0.001
Simulation statistics	±0.020	±0.024	±0.008	±0.015	±0.017	±0.031
Total systematic uncertainty	±0.174	±0.199	±0.025	±0.048	±0.096	±0.153
Total statistical uncertainty	±0.017	±0.025	±0.011	±0.017	±0.022	±0.034

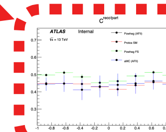


$$\frac{1}{\epsilon_k} = \frac{S_k^{\text{particle}} - S_k^{\text{particle!reco}}}{S_k^{\text{particle}}}$$

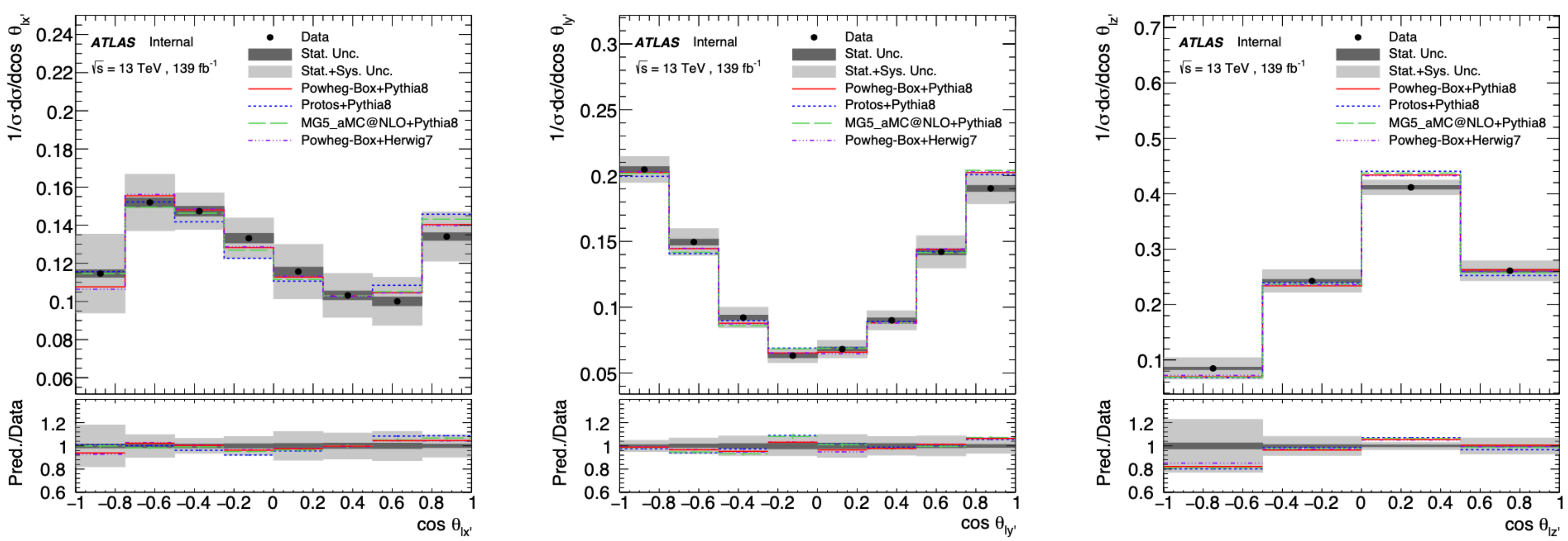
Reco. → particle migration matrix

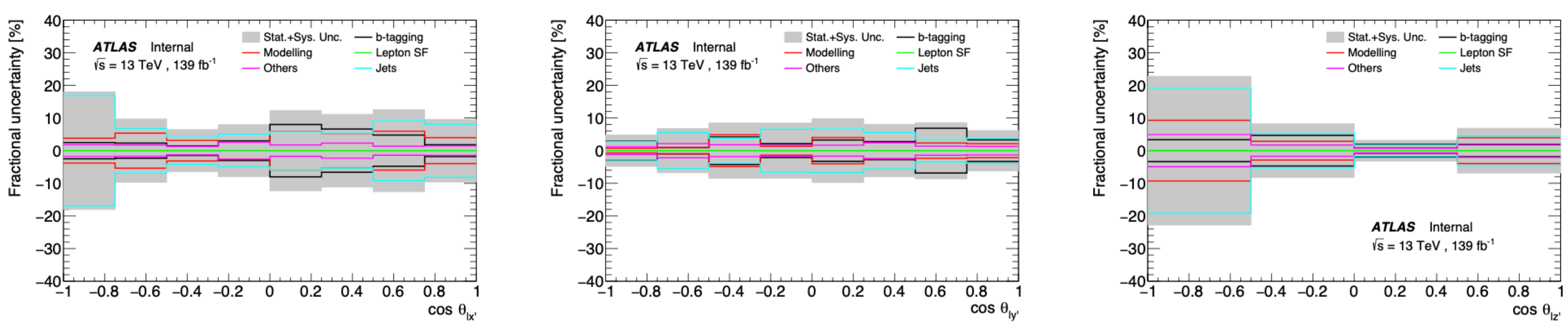


$$N_k^{\text{particle}} = C_k^{\text{particle!reco}} \sum_j M_{jk}^{-1} C_j^{\text{reco!particle}} (N_j^{\text{data}} - B_j)$$



$$\frac{S_j^{\text{reco}} - S_j^{\text{reco!particle}}}{S_j^{\text{reco}}}$$



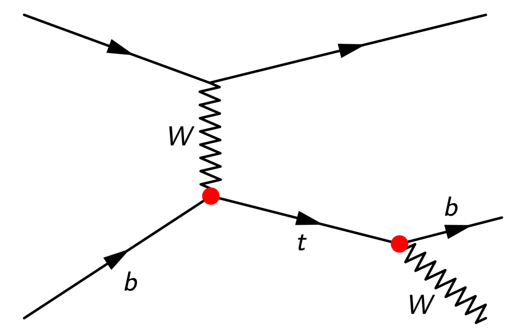


Top polarisation

BONUS

$$\sigma\left(\frac{c}{\Lambda^2}\right) = O_{\mathrm{SM}}^2 + \frac{c}{\Lambda^2} \cdot O_{\mathrm{SM}} O_{\mathrm{dim6}} + \frac{c^2}{\Lambda^4} \cdot O_{\mathrm{dim6}}^2$$

Pure SM | Interference term | Pure BSM



EFT operator can contribute to production and/or decay vertex

3 operators that interfere with SM: ***$O_{\phi Q}$, O_{tW}*** *and* ***O_{qQ}***

- four couplings: ***$C_{\phi Q}$, C_{tW} , C_{itW}*** and ***O_{qQ}***
- $C_{tW}^* \neq C_{tW}$ → CP Violation
- prediction @NLO available: arXiv:1807.03576

Interpretation of normalized $\cos\theta_{X/Y}$ focuses on C_{tW} and C_{itW}

- $O_{\phi Q}$ affects only normalisation
- $\cos\theta_{X/Y}$ not sensitive to O_{qQ}

Morphing reference: ATL-PHYS-PUB-2015-047

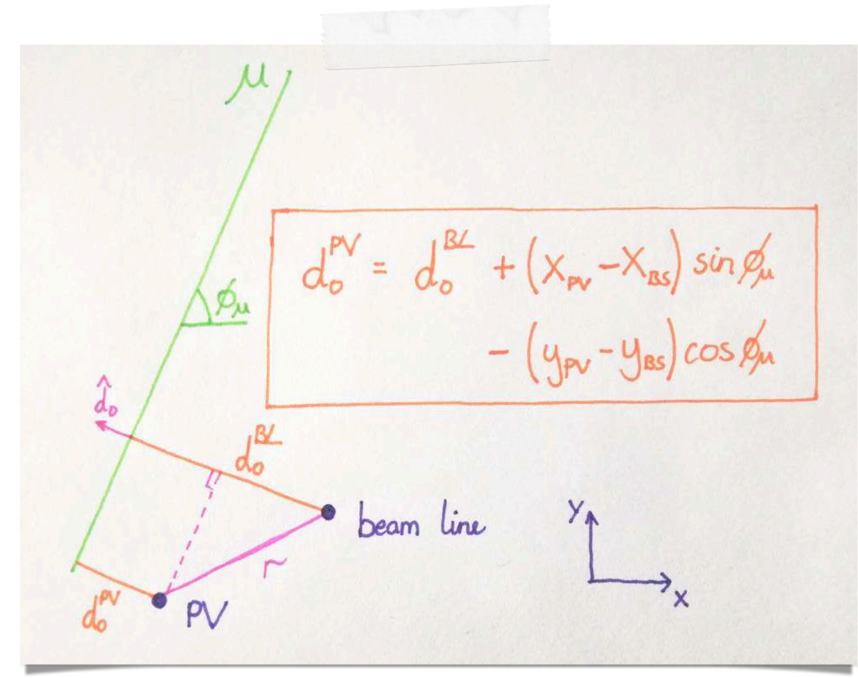
- Morphing works with any choice of templates
- Uncertainty does depend on this choice

	C_{tW}		C_{itW}	
	68% CL	95% CL	68% CL	95% CL
All terms	[-0.2, 0.9]	[-0.7, 1.5]	[-0.5, -0.1]	[-0.7, 0.2]
Order $1/\Lambda^4$	[-0.2, 0.9]	[-0.7, 1.5]	[-0.5, -0.1]	[-0.7, 0.2]
Order $1/\Lambda^2$	[-0.2, 1.0]	[-0.7, 1.7]	[-0.5, -0.1]	[-0.8, 0.2]

Test of LFU (μ/τ)

Nat. Phys. 17, 813–818 (2021)

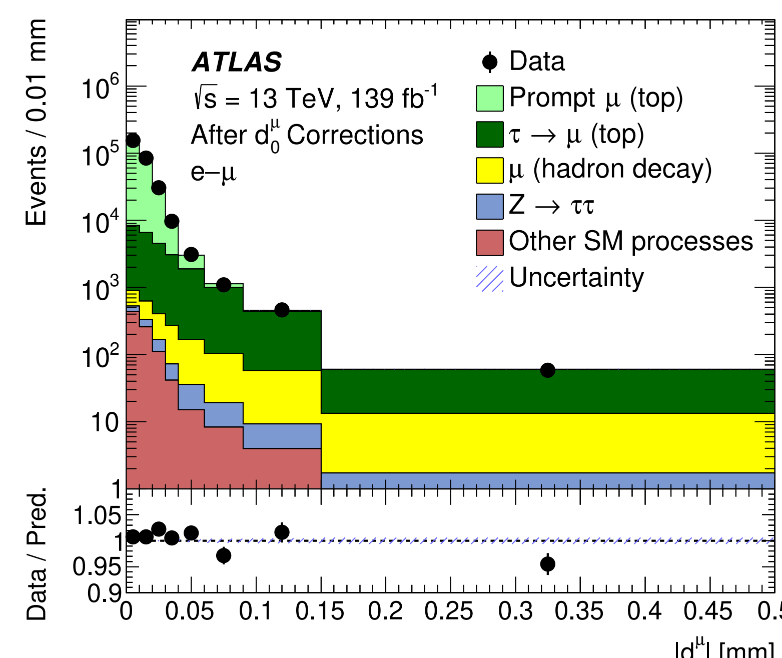
d_0^μ parameter: distance of closest approach of muon tracks in transverse plane with respect to beamline (process independent)



Determine shape of $|d_0^\mu|$ in 33 kinematic bins (p_T^μ, $|\eta^\mu|$) from data using $Z \to \mu\mu$ selection

- subtract remaining backgrounds estimated in MC
- shapes as prompt muon templates in signal region
- residual resolution correction from data

After d_0^μ correction



Systematic uncertainty due to application of $|d_0^\mu|$ shape from Z boson decays to $t\bar{t}$ signal region:

- estimated by ratio of $|d_0^\mu|$ between $t\bar{t}$ and $Z \to \mu\mu$
- done separately for core and tail of $|d_0^\mu|$ distribution

ATLAS Physics Briefing

Systematic uncertainties

BONUS

Nat. Phys. 17, 813–818 (2021)

Uncertainty of measurement dominated by systematic uncertainty

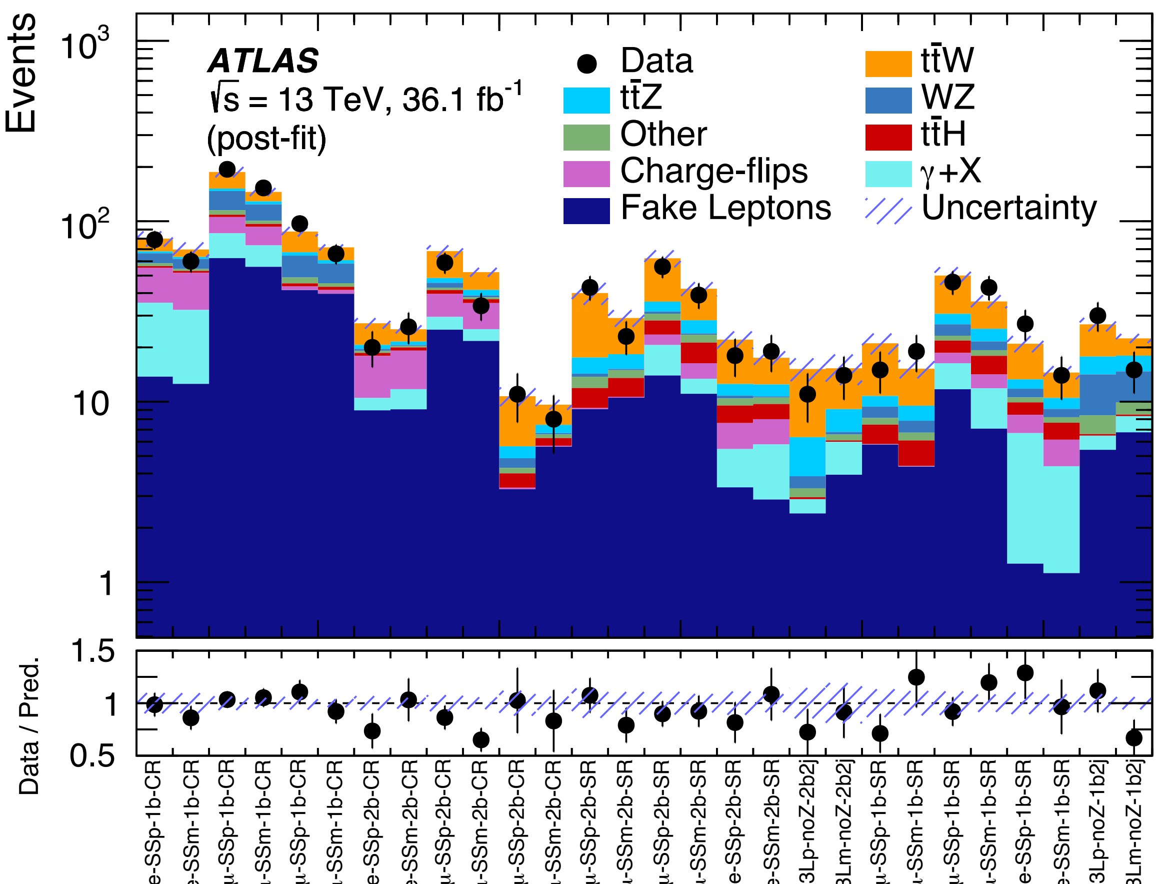
- leading one is the extrapolation uncertainty on prompt $|d_0^\mu|$ templates
- theoretical modelling uncertainties (such as parton shower or scale variations)
- hadron to muon decay background normalisation in SS region, i.e. due to MC generator used in estimate
- muon isolation requirements efficiency and low-p_T muon reconstruction efficiency

Source	**Impact on $R(\tau/\mu)$**
Prompt d_0^μ templates	0.0038
$\mu_{(prompt)}$ and $\mu_{(\tau\to\mu)}$ parton shower variations	0.0036
Muon isolation efficiency	0.0033
Muon identification and reconstruction	0.0030
$\mu_{(had.)}$ normalisation	0.0028
$t\bar{t}$ scale and matching variations	0.0027
Top p_T spectum variation	0.0026
$\mu_{(had.)}$ parton shower variations	0.0021
Monte Carlo statistics	0.0018
Pile-up	0.0017
$\mu_{(\tau\to\mu)}$ and $\mu_{(had.)}$ d_0^μ shape	0.0017
Other detector systematic uncertainties	0.0016
Z+jet normalisation	0.0009
Other sources	0.0004
$B(\tau \to \mu\nu_\tau\nu_\mu)$	0.0023
Total systematic uncertainty	0.0109
Data statistics	0.0072
Total	**0.013**

ATLAS Physics Briefing

$t\bar{t}$+W/Z

PRD 99 (2019) 072009



Uncertainty	$\sigma_{t\bar{t}Z}$	$\sigma_{t\bar{t}W}$
Luminosity	2.9%	4.5%
Simulated sample statistics	2.0%	5.3%
Data-driven background statistics	2.5%	6.3%
JES/JER	1.9%	4.1%
Flavor tagging	4.2%	3.7%
Other object-related	3.7%	2.5%
Data-driven background normalization	3.2%	3.9%
Modeling of backgrounds from simulation	5.3%	2.6%
Background cross sections	2.3%	4.9%
Fake leptons and charge misID	1.8%	5.7%
$t\bar{t}Z$ modeling	4.9%	0.7%
$t\bar{t}W$ modeling	0.3%	8.5%
Total systematic	10%	16%
Statistical	8.4%	15%
Total	13%	22%

Operator	Expression
$\mathcal{O}_{\phi Q}^{(3)}$	$(\phi^\dagger i \overleftrightarrow{D}^I_\mu \phi)(\bar{Q}\gamma^\mu \tau^I Q)$
$\mathcal{O}_{\phi Q}^{(1)}$	$(\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{Q}\gamma^\mu Q)$
$\mathcal{O}_{\phi t}$	$(\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{t}\gamma^\mu t)$
$\mathcal{O}_{tW}$	$(\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\phi}W^I_{\mu\nu}$
$\mathcal{O}_{tB}$	$(\bar{Q}\sigma^{\mu\nu} t)\tilde{\phi}B_{\mu\nu}$

Coefficients	$\mathcal{C}_{\phi Q}^{(3)}/\Lambda^2$	$\mathcal{C}_{\phi t}/\Lambda^2$	$\mathcal{C}_{tB}/\Lambda^2$	$\mathcal{C}_{tW}/\Lambda^2$
Previous indirect constraints at 68% CL	[−4.7, 0.7]	[−0.1, 3.7]	[−0.5, 10]	[−1.6, 0.8]
Previous direct constraints at 95% CL	[−1.3, 1.3]	[−9.7, 8.3]	[−6.9, 4.6]	[−0.2, 0.7]
Expected limit at 68% CL	[−2.1, 1.9]	[−3.8, 2.7]	[−2.9, 3.0]	[−1.8, 1.9]
Expected limit at 95% CL	[−4.5, 3.6]	[−23, 4.9]	[−4.2, 4.3]	[−2.6, 2.6]
Observed limit at 68% CL	[−1.0, 2.7]	[−2.0, 3.5]	[−3.7, 3.5]	[−2.2, 2.1]
Observed limit at 95% CL	[−3.3, 4.2]	[−25, 5.5]	[−5.0, 5.0]	[−2.9, 2.9]
Expected limit at 68% CL (linear)	[−1.9, 2.0]	[−3.0, 3.2]	–	–
Expected limit at 95% CL (linear)	[−3.7, 4.0]	[−5.8, 6.3]	–	–
Observed limit at 68% CL (linear)	[−1.0, 2.9]	[−1.8, 4.4]	–	–
Observed limit at 95% CL (linear)	[−2.9, 4.9]	[−4.8, 7.5]	–	–

$t\bar{t}+\gamma$

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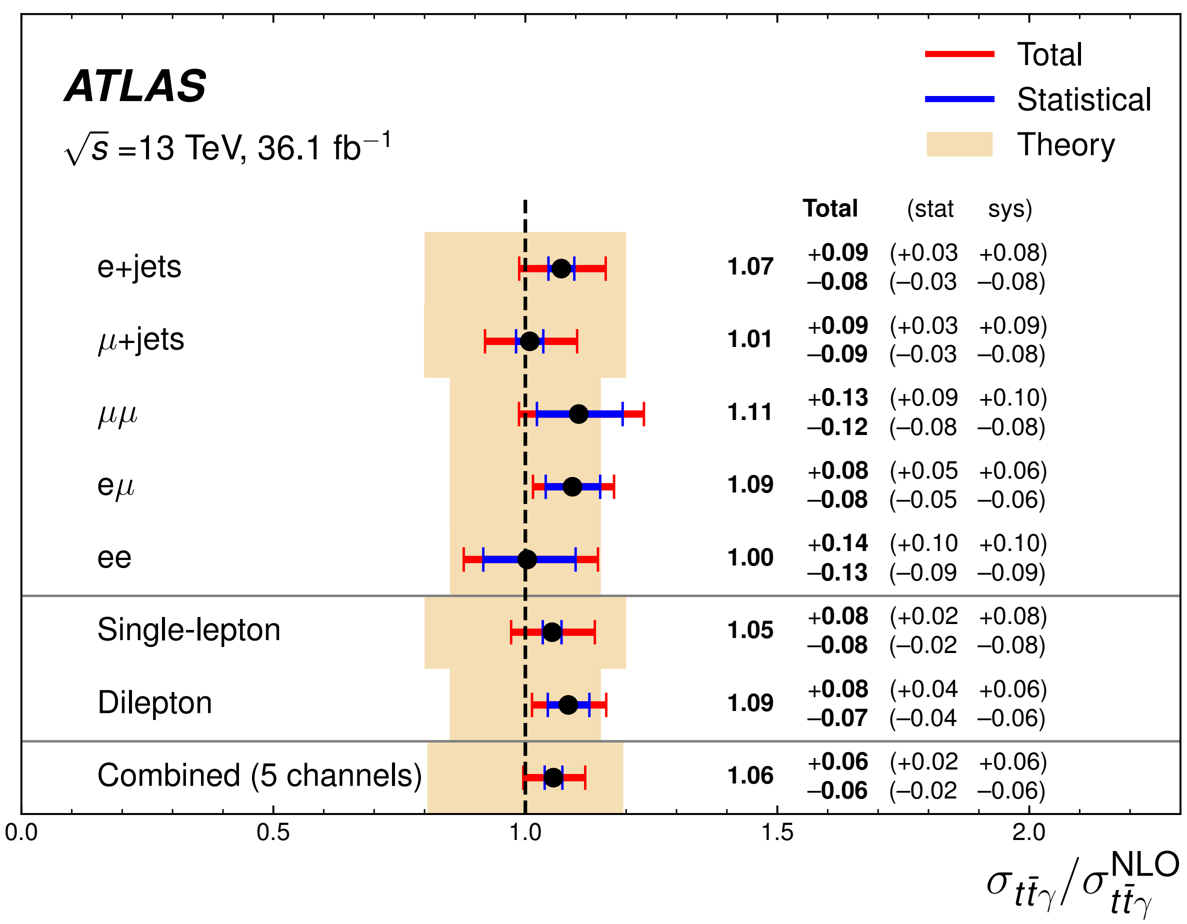
Use both the |Δϕll| and |Δηll| to set limits on SUSY stop production

Exclude Stops with a mass below ~ 220 GeV for all kinematically-allowed neutralino masses

- limit driven by | Δηll| but additional modelling uncertainties included to account for the Data/Prediction disagreement in | Δϕll |



Source	Single lepton (%)	Dilepton (%)
Signal modelling	± 1.6	± 2.9
Background modelling	± 4.8	± 2.9
Photon	± 1.1	± 1.1
Prompt-photon tagger	± 4.0	-
Leptons	± 0.3	± 1.3
Jets	± 5.4	± 2.0
b-tagging	± 0.9	± 0.4
Pile-up	± 2.0	± 2.3
Luminosity	± 2.3	± 2.3
MC sample size	± 1.9	± 1.7
Total systematic uncertainty	± 7.9	± 5.8
Data sample size	± 1.5	± 3.8
Total uncertainty	± 8.1	± 7.0

4 tops

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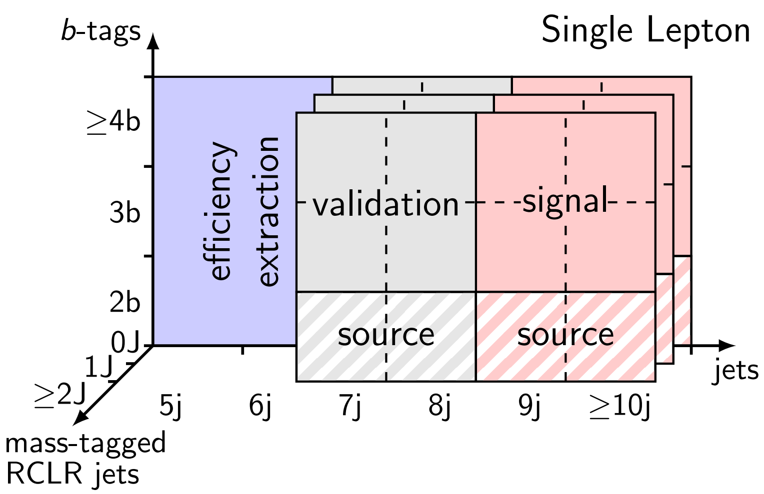
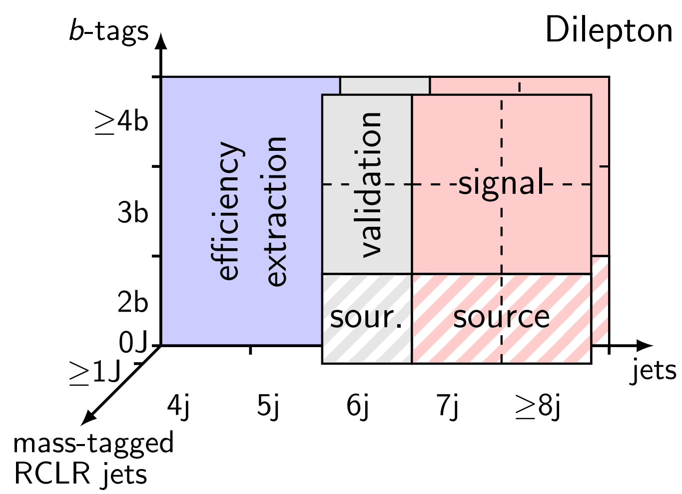
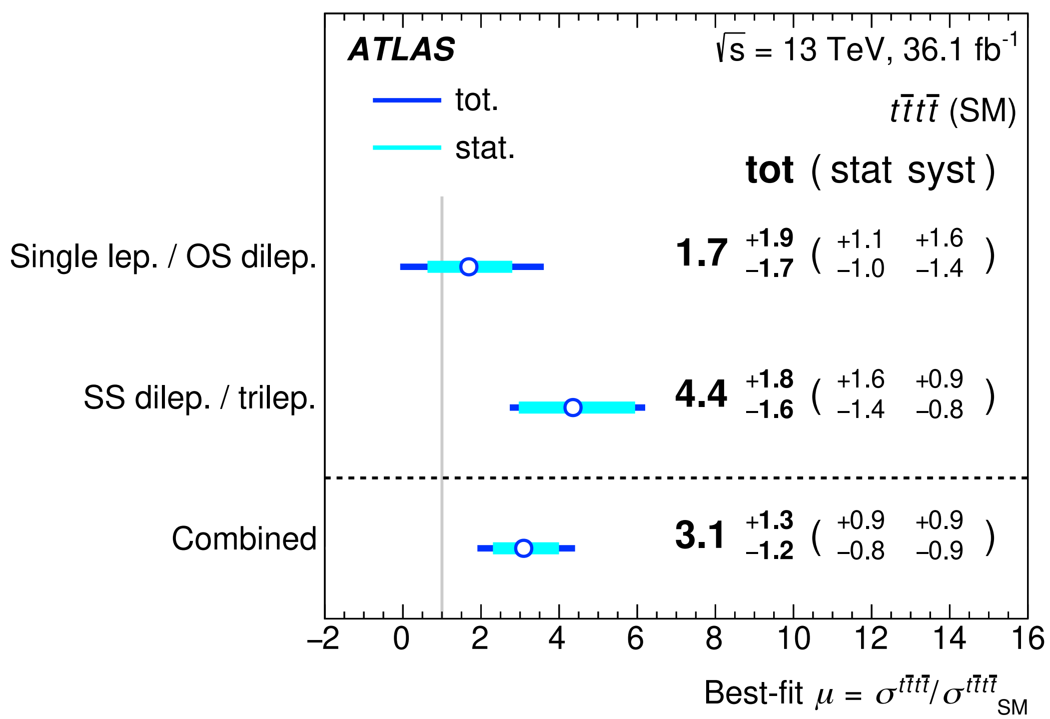
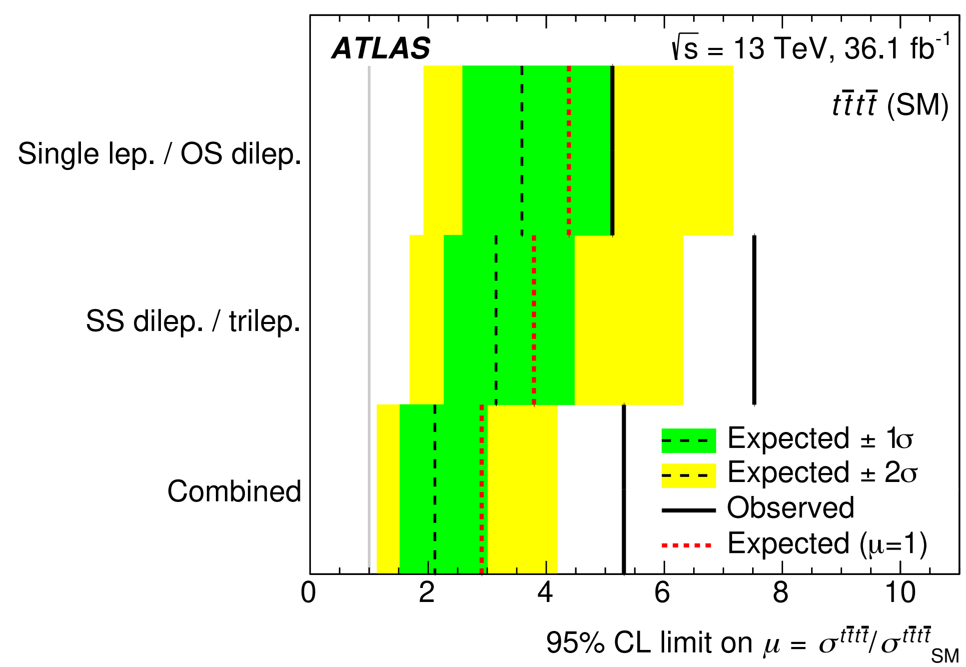




Uncertainty source	$\pm\Delta\mu$	
$t\bar{t}$+jets modeling	+1.2	−0.96
Background-model statistical uncertainty	+0.91	−0.85
Jet energy scale and resolution, jet mass	+0.38	−0.16
Other background modeling	+0.26	−0.20
b-tagging efficiency and mis-tag rates	+0.33	−0.10
JVT, pileup modeling	+0.18	−0.073
$t\bar{t} + H/V$ modeling	+0.053	−0.055
Luminosity	+0.050	−0.026
Total systematic uncertainty	+1.6	−1.4
Total statistical uncertainty	+1.1	−1.0
Total uncertainty	+1.9	−1.7





FCNC tqg search

	Analysis regions			
	SR	W+jets VR	$t\bar{t}$ VR	tq VR
$n(\|\eta(j)\| < 2.5)$	$= 1$	$= 1$	$= 2$	$= 1$
$n(b)$	$= 1$	$= 1$	$= 2$	$= 1$
ϵ_b	30%	60% (veto 30%)	30%	30%
$n(\|\eta(j)\| > 2.5)$	≥ 0	≥ 0	≥ 0	$= 1$
$D_{1(2)}$	–	$0.3 < D_{1(2)} < 0.6$	–	$0.2 < D_{1(2)} < 0.4$

Analysis	$\mathcal{B}_{95}^{\text{obs}}(t \to u + g)$	$\mathcal{B}_{95}^{\text{exp}}(t \to u + g)$	$\mathcal{B}_{95}^{\text{obs}}(t \to c + g)$	$\mathcal{B}_{95}^{\text{exp}}(t \to c + g)$
ATLAS 13 TeV	6.1×10^{-5}	4.9×10^{-5}	37×10^{-5}	20×10^{-5}
ATLAS 8 TeV [12] *	12×10^{-5}	11×10^{-5}	62×10^{-5}	56×10^{-5}
CMS 7 TeV ⊕ 8 TeV [11]	2.0×10^{-5}	2.8×10^{-5}	41×10^{-5}	28×10^{-5}

FCNC tH(ττ)

Signal regions	b-jet	light flavor jets	lepton(e /μ)	hadronic taus	charge
$t_l\tau_{\rm had}$-2j	1	2	1	1	$t_l\tau_{\rm had}$ SS
$t_l\tau_{\rm had}$-1j	1	1	1	1	$t_l\tau_{\rm had}$ SS
$t_l\tau_{\rm had}\tau_{\rm had}$	1	any	1	2	$\tau_{\rm had}\tau_{\rm had}$ OS
$t_h\tau_{\rm had}\tau_{\rm had}$-2j	1	2	0	2	$\tau_{\rm had}\tau_{\rm had}$ OS
$t_h\tau_{\rm had}\tau_{\rm had}$-3j	1	≥ 3	0	2	$\tau_{\rm had}\tau_{\rm had}$ OS
$t_h\tau_{\rm lep}\tau_{\rm had}$-2j	1	2	1	1	$\tau_{\rm lep}\tau_{\rm had}$ OS
$t_h\tau_{\rm lep}\tau_{\rm had}$-3j	1	≥ 3	1	1	$\tau_{\rm lep}\tau_{\rm had}$ OS

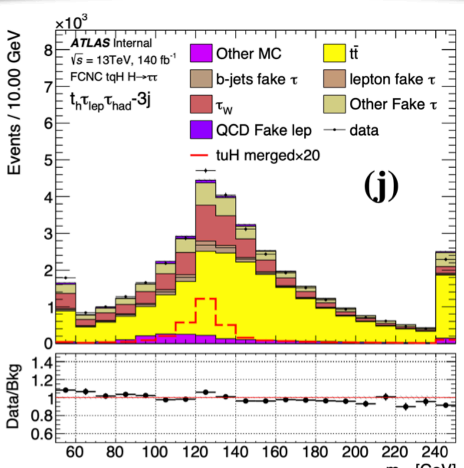
	95% CL upper limits on $\mathscr{B}(t \to cH)$ Observed (Expected)	95% CL upper limits on $\mathscr{B}(t \to uH)$ Observed (Expected)
hadronic	1.0×10^{-5} (9.8×10^{-4})	7.8×10^{-4} (7.8×10^{-4})
leptonic	1.3×10^{-5} (5.9×10^{-4})	9.2×10^{-4} (4.2×10^{-4})
Combination	9.9×10^{-4} (5.0×10^{-4})	7.2×10^{-4} (3.6×10^{-4})

- Fit is done in only in the regions where the SM top decays hadronically, to reconstruct the neutrinos from tau decays.
- Using collinear approximation fit (top decays hadronically). Two constraints are from MET and one from Higgs mass. The floating parameter is the energy ratio of the tau visible decay product.

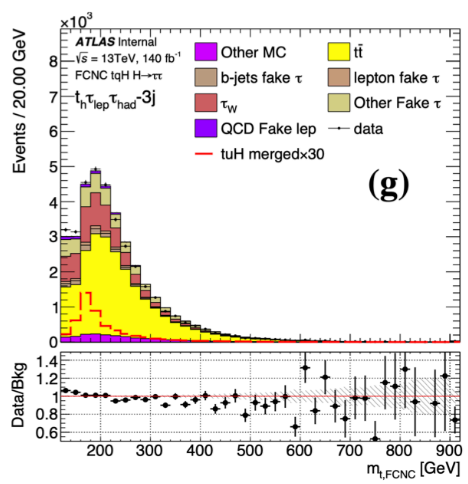
$$\chi^2 = \left(\frac{m_{\tau\tau}^{\rm fit} - 125}{\sigma_{\tau\tau}}\right)^2 + \left(\frac{E_{x,\rm miss}^{\rm fit} - E_{x,\rm miss}}{\sigma_{\rm miss,x}}\right)^2 + \left(\frac{E_{y,\rm miss}^{\rm fit} - E_{y,\rm miss}}{\sigma_{\rm miss,y}}\right)^2$$

$$\sigma_{\rm miss,x(y)} = 13.1 + 0.50\sqrt{\Sigma E_{\rm T}},$$

Performance of missing transverse momentum



Fitted Higgs mass



Fitted FCNC top mass

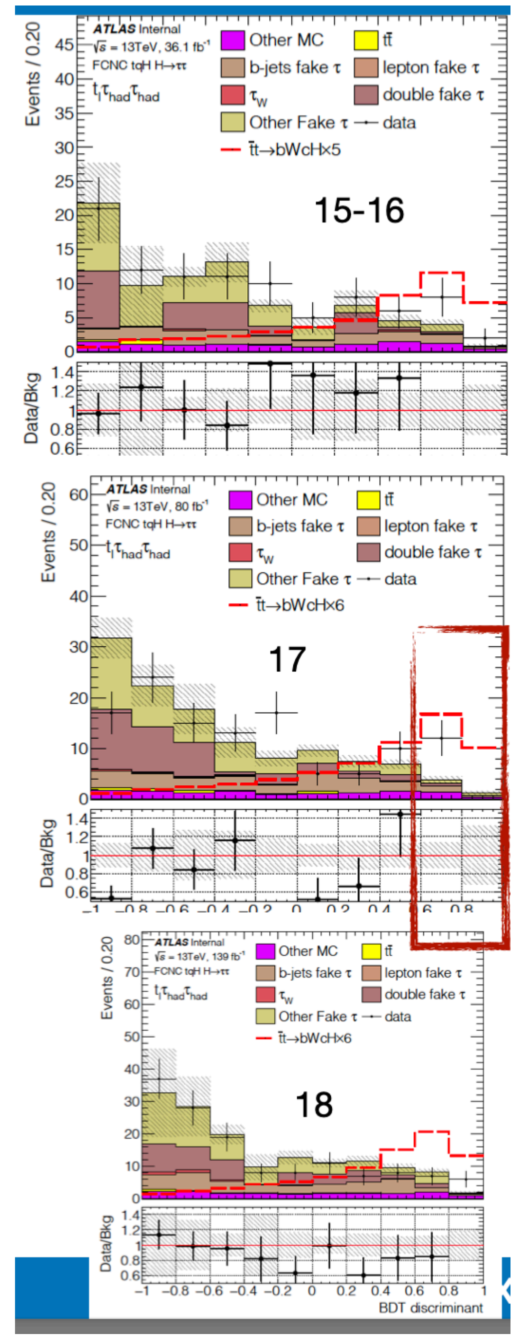
FCNC tH(ττ)

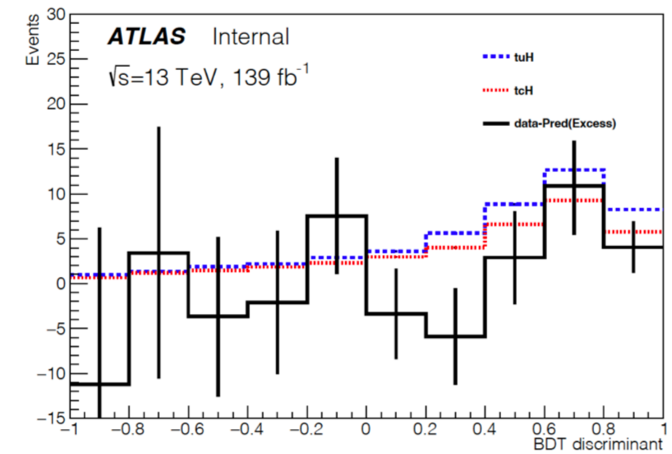
Table 49: Pre-fit yields for different years in high BDT regions(BDT score > 0.8)

	2015 – 2016(Lumi:36)	2017(Lumi:44)	2018(Lumi:58)	run2
Wjet fake	0.0052 ± 0.00238345	0.0078 ± 0.0038	0.0092 ± 0.0052	0.022 ± 0.0068
other fake	0.0027 ± 0.0027	0.47 ± 0.27	0.15 ± 0.14	0.62 ± 0.30
b fake	0.32 ± 0.19	0.22 ± 0.26	0.57 ± 0.25	1.10 ± 0.40
lep fake	0.0028 ± 0.0024	0 ± 0	0 ± 0	0.0028 ± 0.0024
doublefake	0.11 ± 0.11	0.037 ± 0.033	0.24 ± 0.12	0.39 ± 0.17
ttbar	0 ± 0	0 ± 0	0 ± 0	0 ± 0
others	0.42 ± 0.048	0.47 ± 0.053	0.88 ± 0.16	1.78 ± 0.17
total background	0.87 ± 0.22	1.20 ± 0.38	1.84 ± 0.34	3.92 ± 0.56
tuH	2.21 ± 0.081	2.65 ± 0.087	3.43 ± 0.10	8.28 ± 0.16
data	2 ± 1.41	0 ± 0	6 ± 2.45	8 ± 2.83

Table 50: Pre-fit yields for different years in high BDT regions(BDT score > 0.6)

	2015 – 2016(Lumi:36)	2017(Lumi:44)	2018(Lumi:58)	run2
Wjet fake	0.18 ± 0.19	0.030 ± 0.012	0.022 ± 0.0078	0.24 ± 0.17
other fake	1.05 ± 0.37	1.16 ± 0.38	3.68 ± 0.81	5.90 ± 0.97
b fake	1.63 ± 0.44	1.46 ± 0.46	2.02 ± 0.50	5.10 ± 0.81
lep fake	0.0040 ± 0.0025	0.0012 ± 0.00069	0.0024 ± 0.0024	0.0076 ± 0.0036
doublefake	0.32 ± 0.50	0.58 ± 0.25	1.47 ± 0.33	2.36 ± 0.65
ttbar	0 ± 0	0 ± 0	0 ± 0	0 ± 0
others	1.66 ± 0.11	1.87 ± 0.12	2.91 ± 0.19	6.44 ± 0.25
total background	4.84 ± 0.79	5.10 ± 0.66	10.10 ± 1.03	20.04 ± 1.45
tuH	5.66 ± 0.13	6.55 ± 0.14	8.75 ± 0.16	20.96 ± 0.25
data	10 ± 3.16	12 ± 3.46	13 ± 3.61	35 ± 5.92





data-Pred VS signal

FCNC tH

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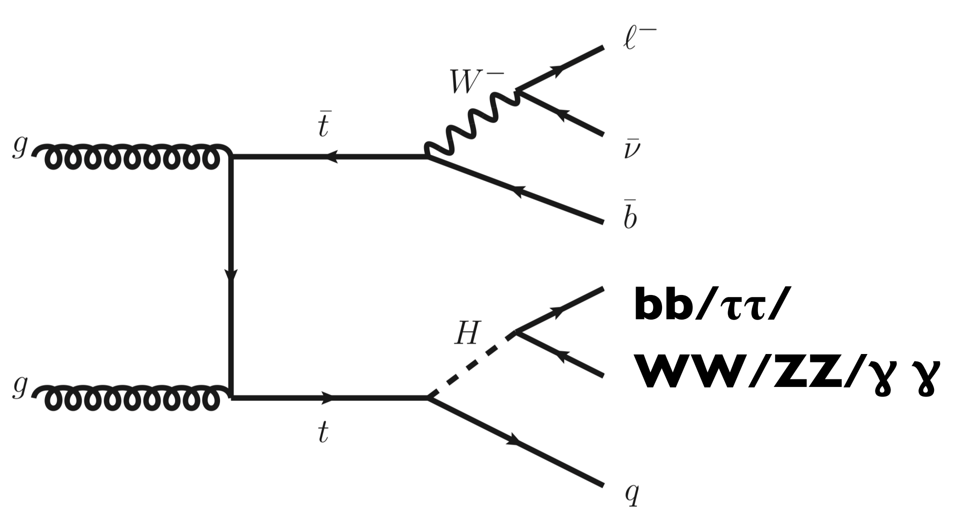


Flavour-changing neutral currents (FCNC)

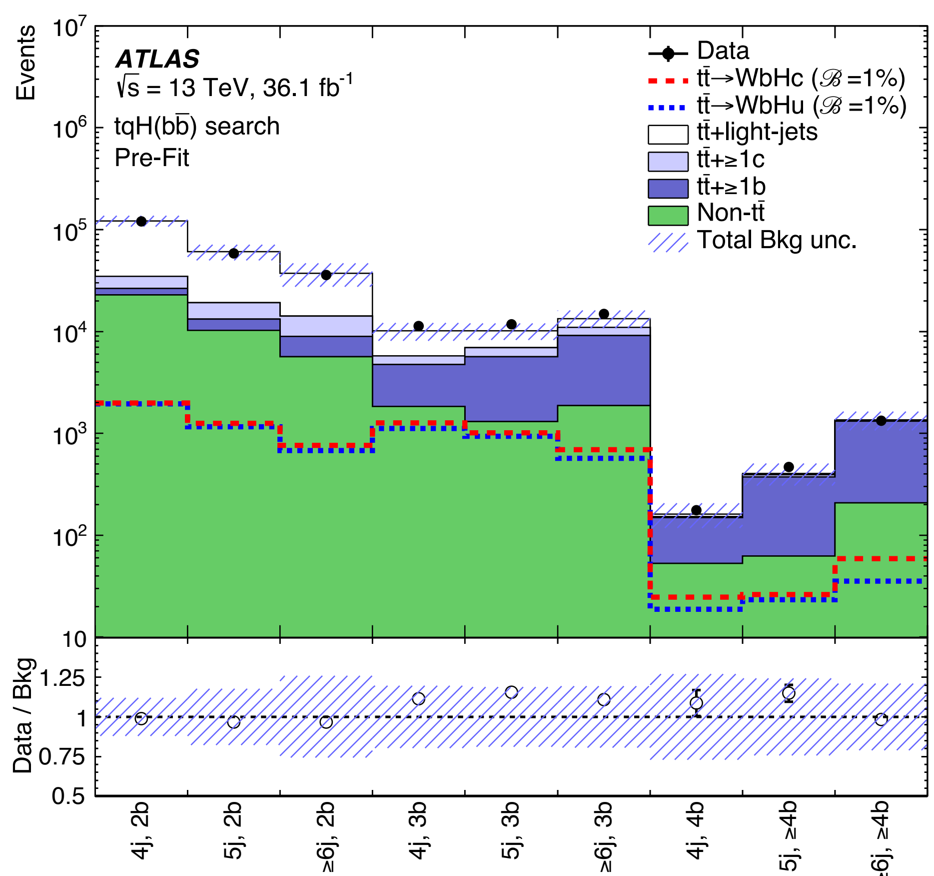
- forbidden at tree level
- BSM can enhance FCNC production

H→b$\bar{b}$: several regions (N_{jets}, $N_{b\text{-tags}}$)

- likelihood discriminant employed

H→$\tau_{had}\tau_{had}$/$\tau_{lep}\tau_{had}$: 4 regions (based on $N_{\tau had}$)

- event reco. (χ^2) + MVA technique



Combination with γγ and multilepton

- BR(t→uH)<12x10^{-4} (8.3 x10^{-4})
- BR(t→cH)< 11x10^{-4} (8.3 x10^{-4})
- $|\lambda_{tuH}|$ < 0.066 (0.055)
- $|\lambda_{tcH}|$ < 0.064 (0.055)

Early Run 3 plans

BONUS

Top x-section

Interest in $t\bar{t}$ inclusive/differential cross-section measurements in single- and di-lepton channels
Kick-off meeting: **link**
GLANCE: **ANA-TOPQ-2021-35**

PLAN A (best scenario):
- data/MC plots for *Summer Conference*;
- if Δlumi ≈ 5%, first xs conf-note by *Top2022* else, measurement of ratios (tt / Z, tt / W) to reduce Δlumi, as a joint effort with SM groups → harmonization with SM group (currently under discussion);
- separate (but harmonized) absolute cross section results for $t\bar{t}$ and Z by *Moriond23* (Δlumi < 3%), so that a ratio can still be made from HEPDATA

PLAN B (worst scenario):
- like PLAN A, but delayed by "one conference"

Top Properties & Mass

Statistically limited analyses:
not-worthy re-meeasurement with less than 20-30 /fb, even at $\sqrt{s}$=13.6 TeV

Systematically limited analyses:
mostly mass analyses, currenlty focused on releasing Run 2 measurements

Minor interest from e/μ spin correlation and top polarisation

Top + X

Nothing foreseen starting anytime soon. 13.6/13 ratio not a good argument for early Run 3 efforts

Channel	13.6 / 13 TeV
H (ggF)	7%
HH	11%
tt	11%
ttH	13%
tttt	19%
SUSY stop (1.2–1.5 TeV)	20–30%
Z' (5–6 TeV)	50–70%
QBH (9.5 TeV)	250%