Precision top physics and entanglement with the ATLAS detector

CERN Seminar, 24/10/2023

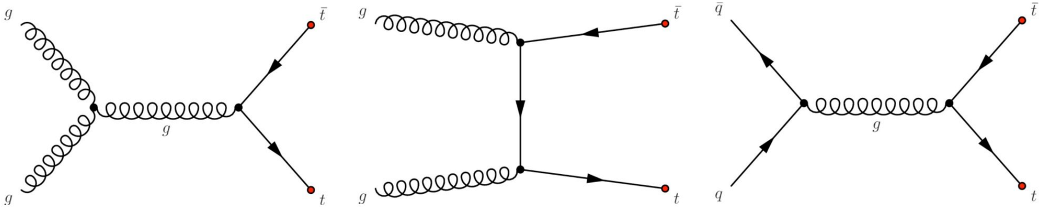
Baptiste Ravina on behalf of the ATLAS Collaboration

ATLAS EXPERIMENT

GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN IN PUBLICA COMMODA SEIT 1737

Alexander von Humboldt Stiftung / Foundation

Fundamentals of top quark physics



- Most massive fundamental particle in the SM

→ its Mass / Yukawa is a free parameter: need to measure it

- Mean lifetime ~5x10^{-25}s << $1/\Lambda_{QCD}$ ~10^{-23}s

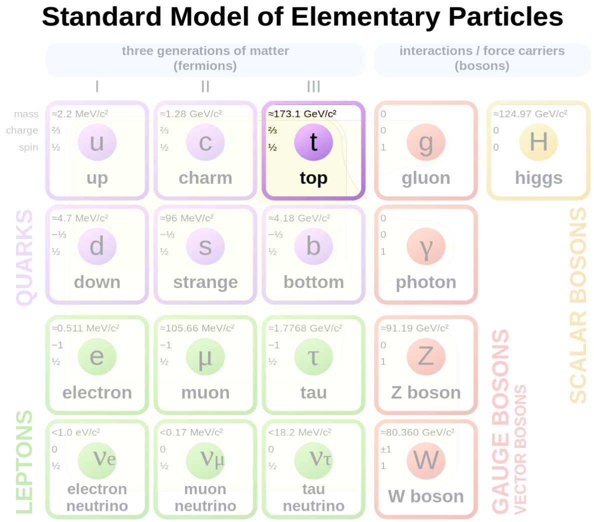
→ the only "bare quark"

- BR(t→Wb) ~ 100%

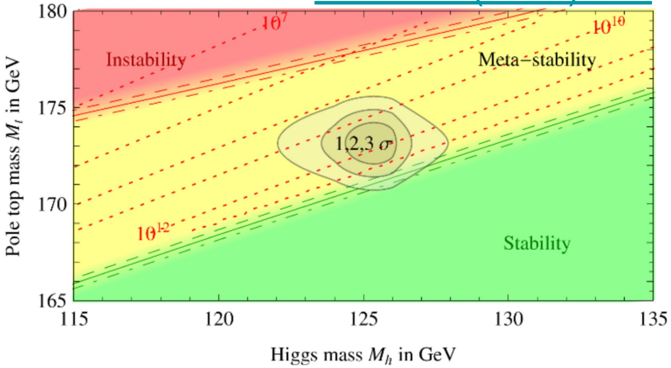
→ unique experimental signature

- Abundant production at the LHC, O(100M) pairs

→ **"standard candle"**, very useful for calibrations



JHEP 08 (2012) 098



A long way to the top...

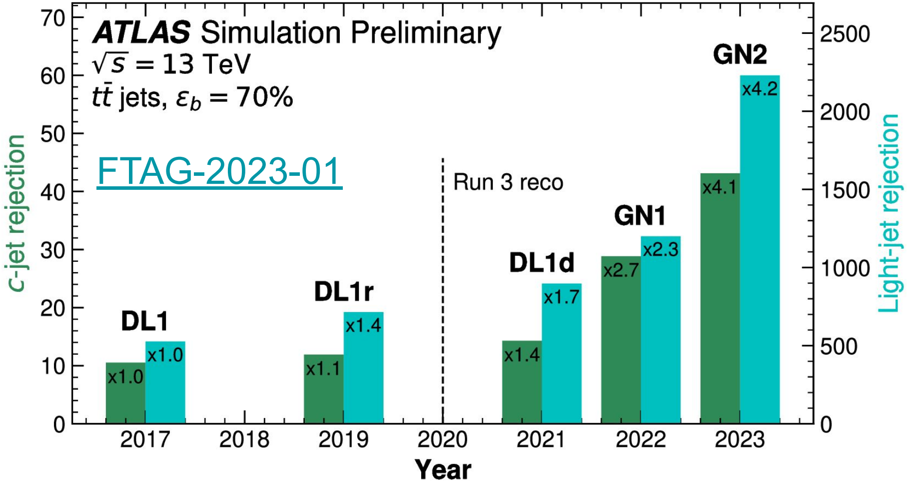
👉 CMS results
👉 ATLAS results
👉 TOP'23 conference

28 years of top quark physics!

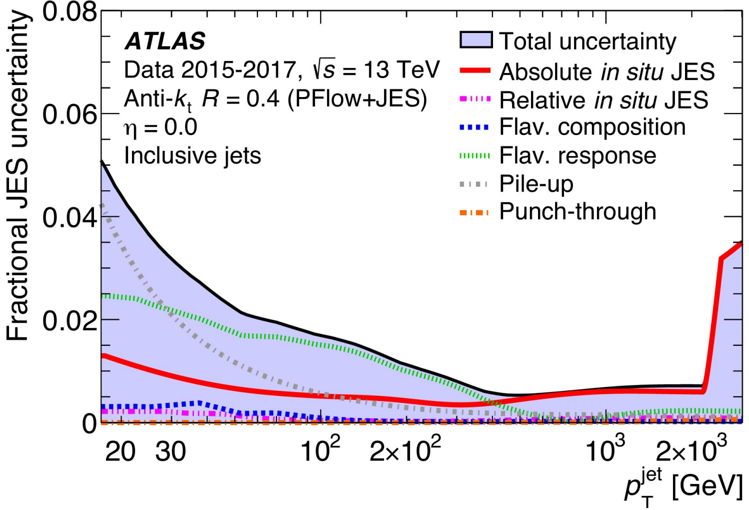
Ever more precise measurements enabled by excellent collider and detector performance

Benefit from all areas of Combined Performance:

- jets & missing energy
- flavour tagging
- lepton ID & isolation
- luminosity
- …



Eur. Phys. J. C 81 (2021) 689

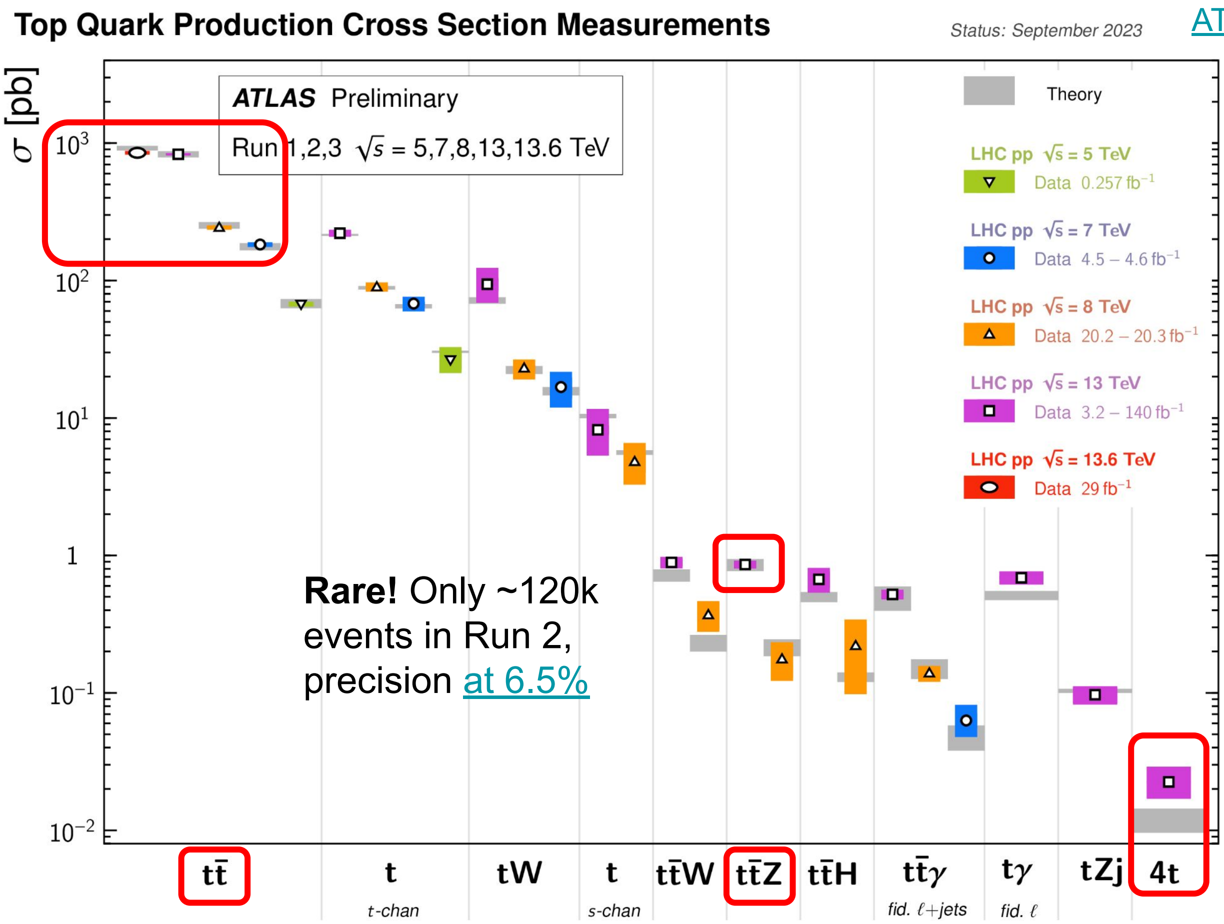


The range of top quark physics

ATL-PHYS-PUB-2023-028

Abundant production!

O(100M) events in Run 2
Precision down to 1.8%

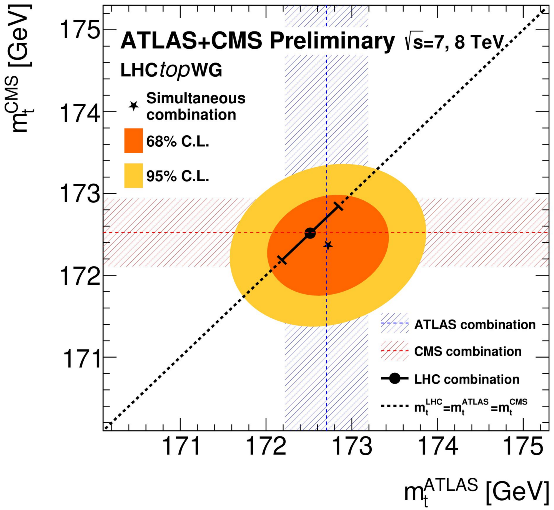


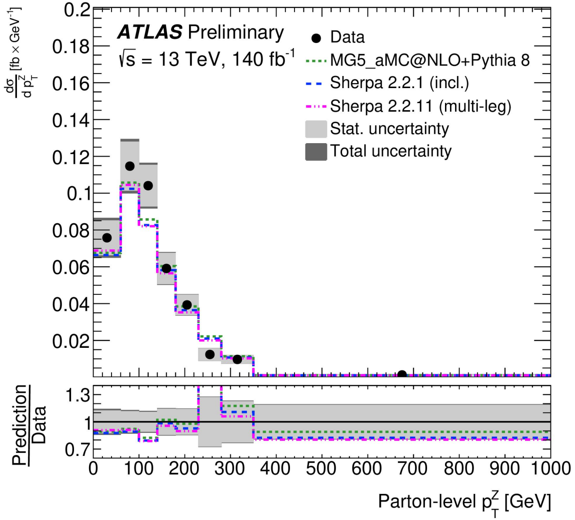
Rare! Only ~120k events in Run 2, precision at 6.5%

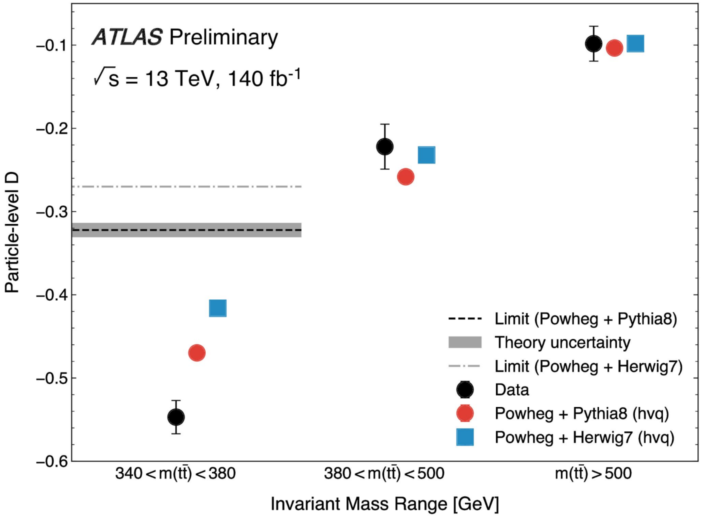
Extremely challenging!
Only ~3k events, precision ~25%

Focus of the seminar

Here I will discuss 2 ATLAS results and 1 ATLAS+CMS combination:







ATLAS-CONF-2023-066

ATLAS-CONF-2023-065

ATLAS-CONF-2023-069

High precision measurement

Rare production process

Top quark pair properties

The top quark mass at the end of Run 1

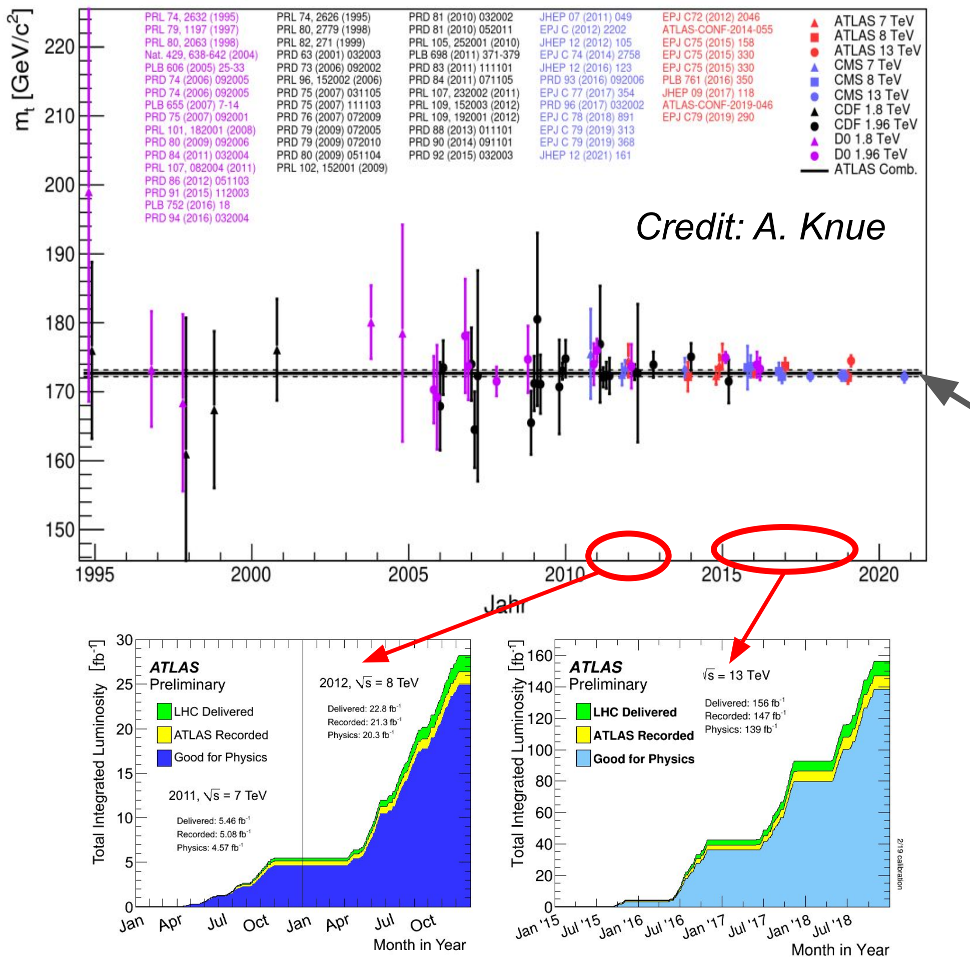
Measuring the mass of the top quark

- Traditionally **two approaches** are possible:
  1. **“indirect”** measurements: use the known dependence of a differential cross section on m_{top} → O(1-2 GeV) precision
  2. **“direct”** measurements: reconstruct the top kinematics and compare various m_{top}-varied templates from the MC → O(≤1 GeV) precision

- Direct measurements can be **very precise, *but***
  - the top is colour-charged: there is no unambiguous way to define all its decay products
  - we are really measuring the “MC mass parameter”: *what is that?* → interplay of ME+PS
  - no self-energy corrections in MC → absorbed in mass parameter, therefore close to m_{top}(pole)
  - see recent discussion on m_{top}(MSR) in ATL-PUB-2021-034 and A. Hoang arXiv:2004.12915

- Main takeaway: direct mass measurements are precise and can be understood theoretically!

A (partial) history of top mass measurements



Credit: A. Knue

Top mass measurements have a come a long way since the top discovery in 1995!

- more and more precise
- convergence of central values
- grey band: ATLAS Run 1 combination

What if we combined measurements from ATLAS and CMS?

The landscape of direct mass measurements in Run 1

ALL-JETS @7 TeV

Eur. Phys. J. C 74, 2758 (2014)

Eur. Phys. J. C 75, 158 (2015)

LEPTON+JETS @7 TeV

JHEP 12 (2012) 105

DILEPTON @7 TeV

Eur. Phys. J. C 72, 2202 (2012)

LEPTON+JETS / DILEPTON @7 TeV

Eur. Phys. J. C 75, 330 (2015)

ALL-JETS @8 TeV

JHEP 09 (2017) 118

LEPTON+JETS @8 TeV

Eur. Phys. J. C 79, 290 (2019)

DILEPTON @8 TeV

Phys. Rev. D 96 (2017), 032002

Phys. Let. B 761 (2016) 350

ALL-JETS / LEPTON+JETS / DILEPTON @8 TeV

Phys. Rev. D 93 (2016), 072004

OTHER MEASUREMENTS @8 TeV

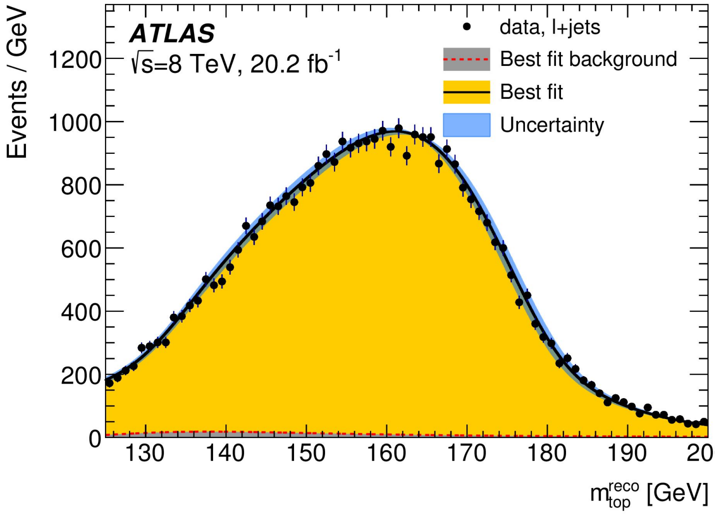
[J/ψ] JHEP 12 (2016) 123

[single top] Eur. Phys. J. C 77, 354 (2017)

[secondary vertex] Phys. Rev. D 93 (2017), 092006

Direct mass measurements

- Three main decay channels:
  - **all-jets:** jet combinatorics, QCD background, but all decay products are visible
  - **lepton+jets:** cleaner reconstruction, but still large impact of jet uncertainties (**JES**)
  - **dilepton:** very pure final state, limited impact of JES, but full reconstruction much harder (2 neutrinos)
- Auxiliary measurements help!
  - can use the hadronic W candidates to measure a jet scale factor
  - or properties of the b-jets to measure a b-jet scale factor
  - **larger datasets → more control on uncertainties**



Eur. Phys. J. C 79, 290 (2019)

Statistical tool for the combination: BLUE

- Best Linear Unbiased Estimator $m_{\mathrm{top}} = \sum_i w^i m^i_{\mathrm{top}}$ $\sum_i w^i = 1$
    - **unbiased**: as long as the input measurements are also unbiased
    - **best**: pick the weights such that the final total uncertainty on m_{top} is minimised
- Taking **correlations** into account
    - orthogonal measurements → no statistical correlations!
        - except for the CMS Secondary Vertex analysis, but very different observables → safe to assume uncorrelated (assumption tested)
    - correlations enter via systematic uncertainties
        - this was NOT taken into account in e.g. PDG combination
- Estimating correlations:
    - split systematic uncertainties into **categories**
    - ***calculate*** or ***estimate*** the correlations
    - sum all the covariance matrices, assuming sources are independent (uncorrelated)

Determining the strength of correlations

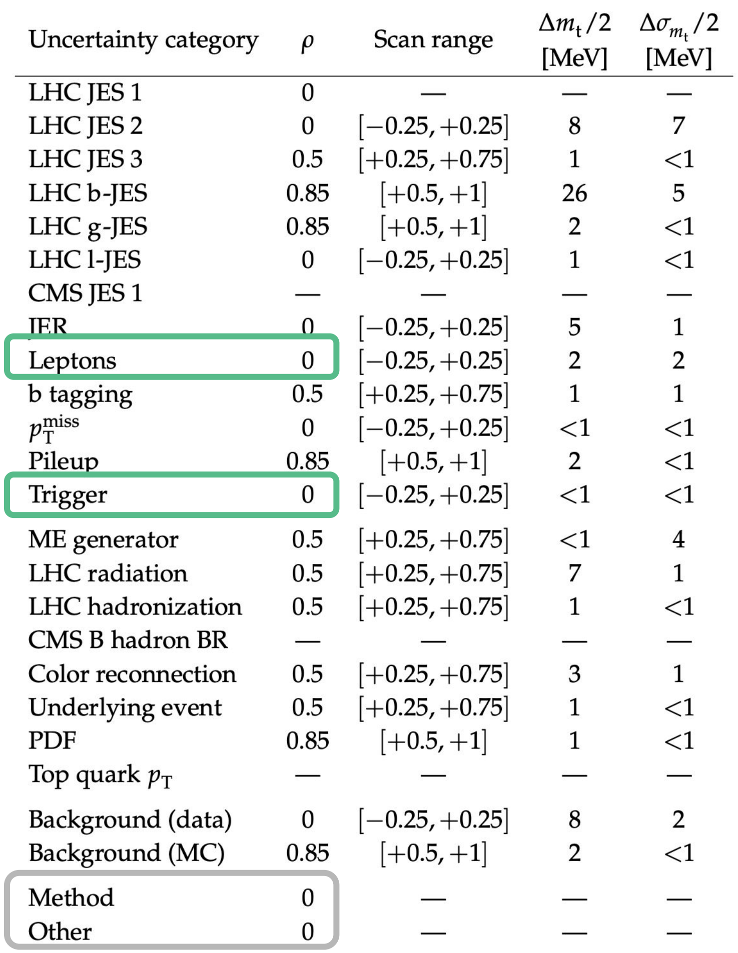
- Assuming the same systematic prescriptions are used between measurements of the same experiment, the correlation for a given uncertainty can be taken into account
  - the sign matters! e.g. JES could increase m_{top} in lepton+jets, but decrease it in all-jets
  - was already done in previous ATLAS combinations

- Then for each pair of measurements (i,j) and each uncertainty k, can compute:

$$\rho_{ij} = \frac{\sum_{k=1}^{N_{\text{comp}}} \rho_{ijk}\sigma_{ik}\sigma_{jk}}{\sigma_i\sigma_j}$$

- But how to determine correlations between ATLAS and CMS? *guesstimate…*
  - **uncorrelated**: **ρ = 0** [-0.25,0.25]
  - **partially correlated**: **ρ = 0.5** [0.25,0.75]
  - **strongly correlated**: **ρ = 0.85** [0.75,1.0]
  - *scan around nominal correlation to test the stability of the guess*

Systematic uncertainties and their correlations



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Leptons	0	$[-0.25, +0.25]$	2	2
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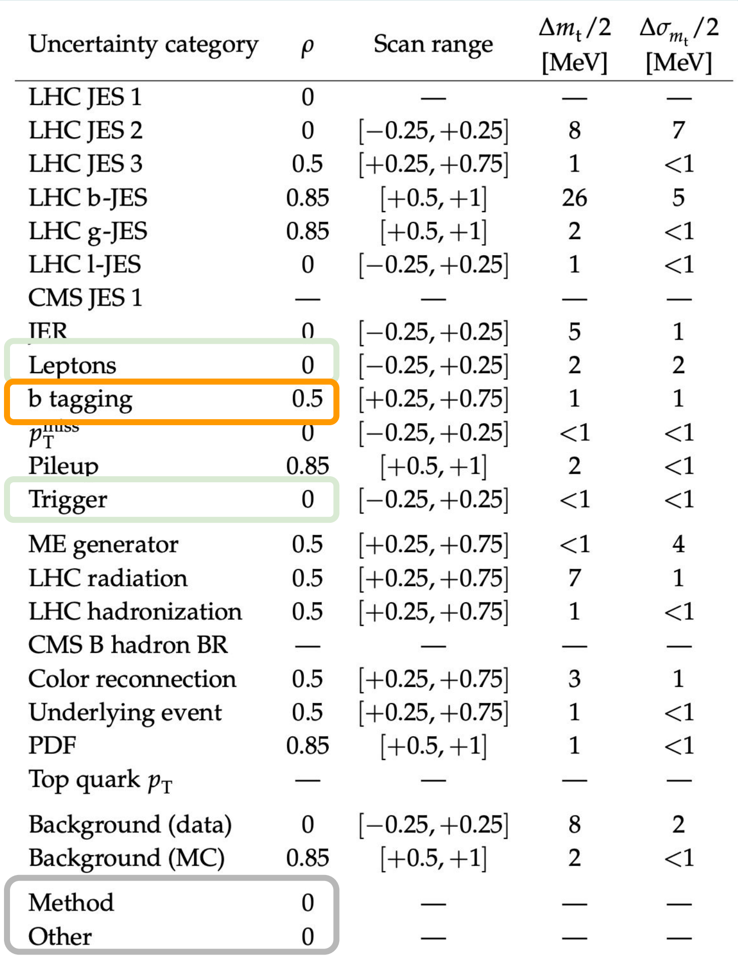
Method	0	—	—	—
Other	0	—	—	—

Leptons/Trigger: from data

“Method”: limited statistics of alternative m_{top} samples → **uncorrelated**

“Other”: uncertainties that only show up in one/few analyses → **uncorrelated**

Systematic uncertainties and their correlations



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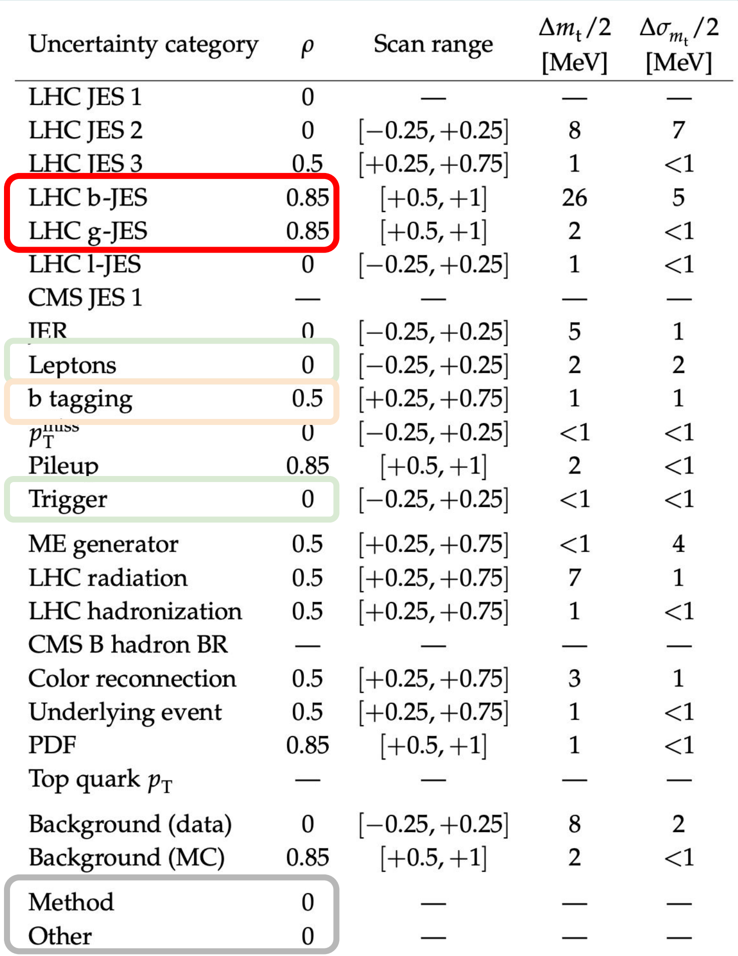

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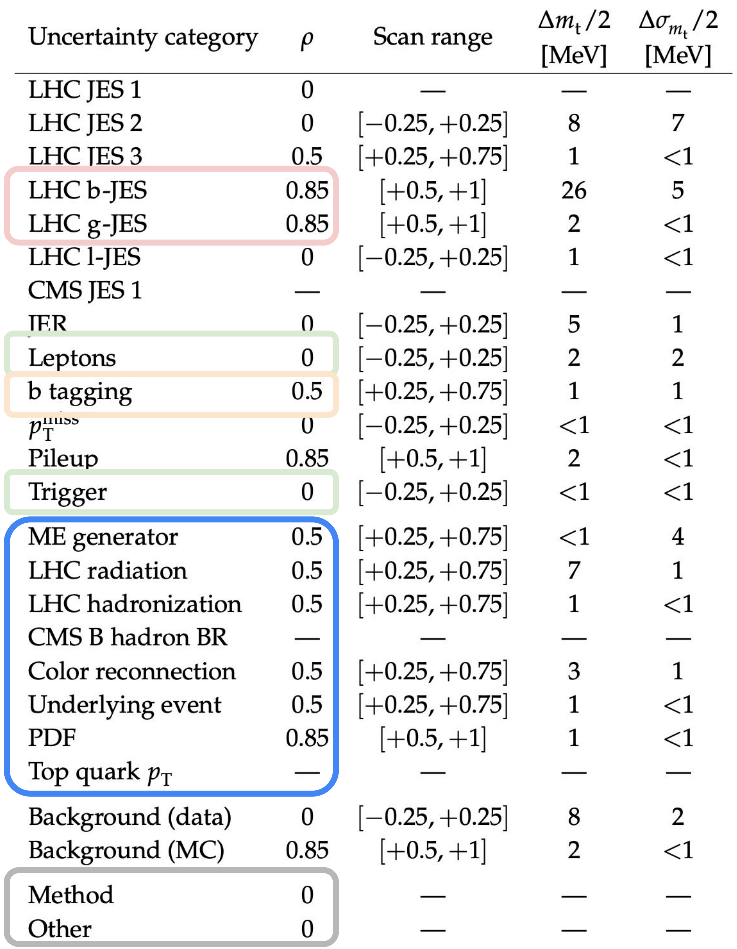

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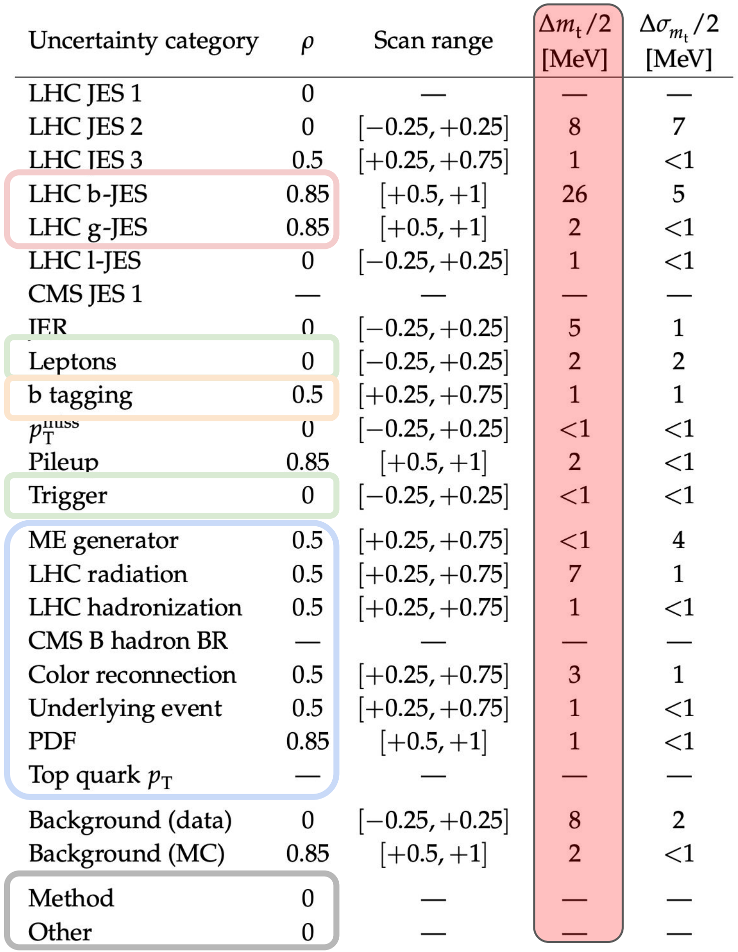

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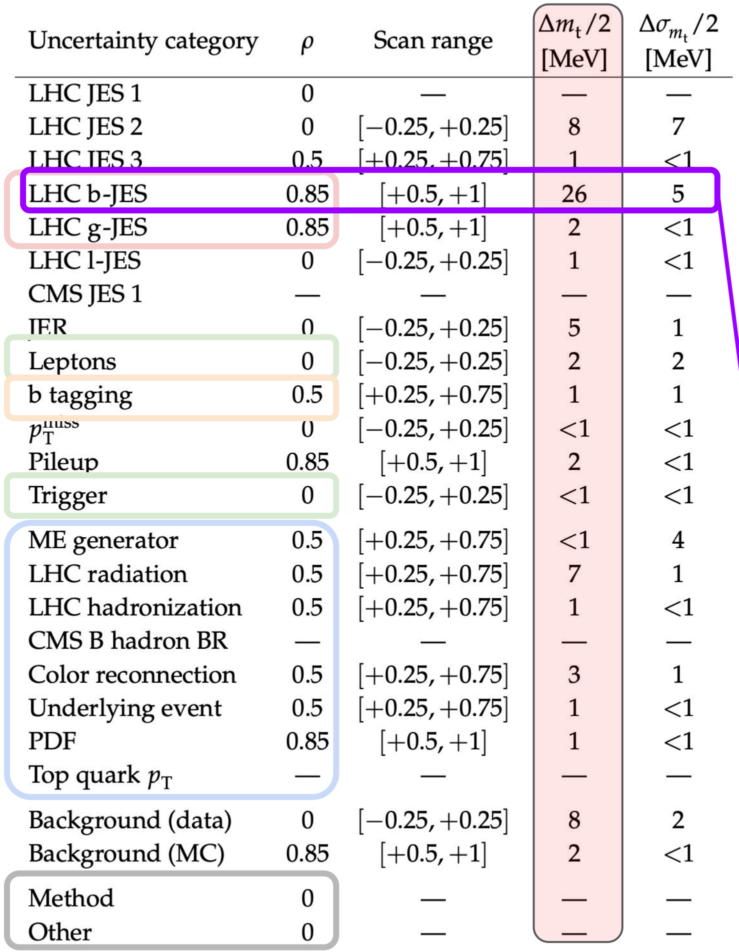

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Largest impact from b-JES

ATLAS and CMS top mass combinations

ATLAS

172.71 ± 0.25 (stat) ± 0.41 (syst) GeV

Similar to Eur. Phys. J. C 79, 290 (2019) but:

- **correlation for b-tagging** between all-jets and lepton+jets/dilepton changed from +1 to 0: different algorithm and calibration!
- **correlation for pileup** between all channels at same √s changed from 0 to +1: common modelling!
- **correlation for pileup** between different √s is 0

CMS

172.52 ± 0.14 (stat) ± 0.39 (syst) GeV

Similar to Phys. Rev. D 93 (2016), 072004 but:

- **improved dilepton** measurement (M_{T2}), **new** single-top, J/ψ and SV **measurements**
- **signed uncertainties and correlations**
- also quote statistical precision on the systematic uncertainties

LHC top mass combination

172.52 ± 0.14 (stat) ± 0.30 (syst) GeV

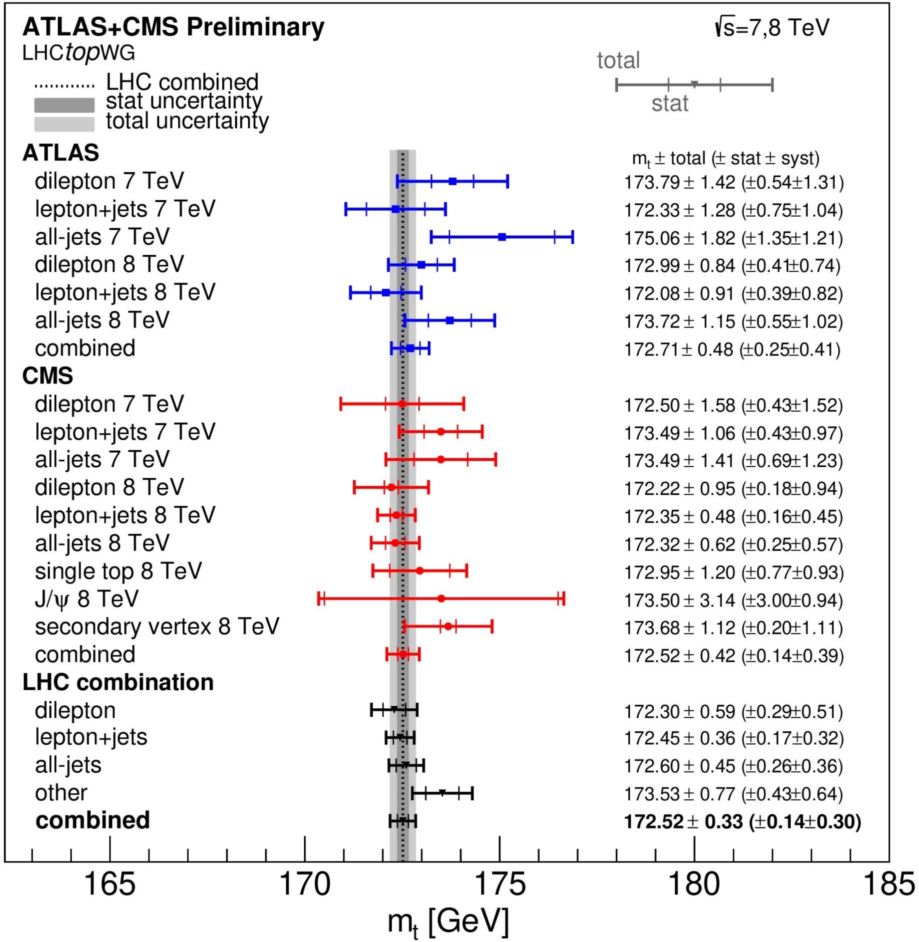
Total uncertainty of 0.33 GeV (**< 2 permil!**)

31% improvement on most precise input

Excellent compatibility: χ^2=7.5, p(χ^2)=0.91

Most precise m_{top} measurement to date

Consistency checked with per-channel combinations

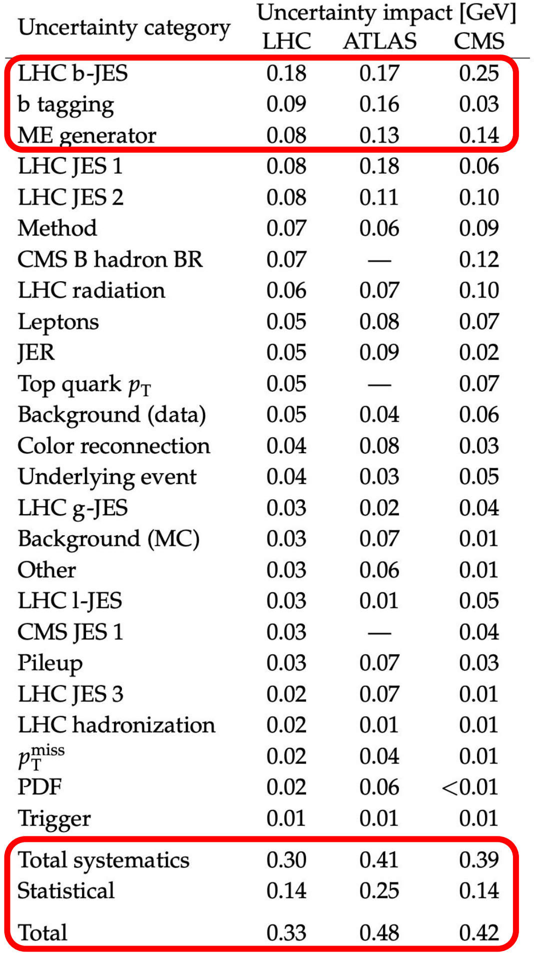


LHC top mass combination

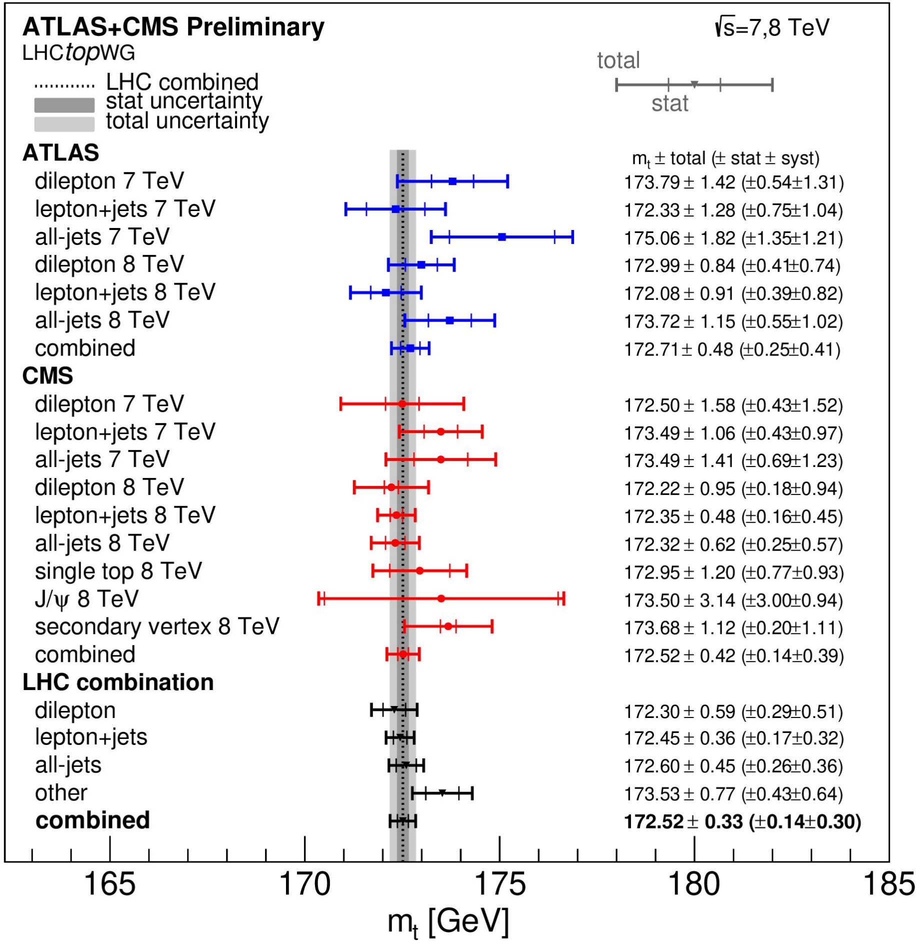
b-JES is dominant systematic uncertainty, followed by stats, b-tagging, ME generator and JES.

BLUE weights: **rank measurements** by importance

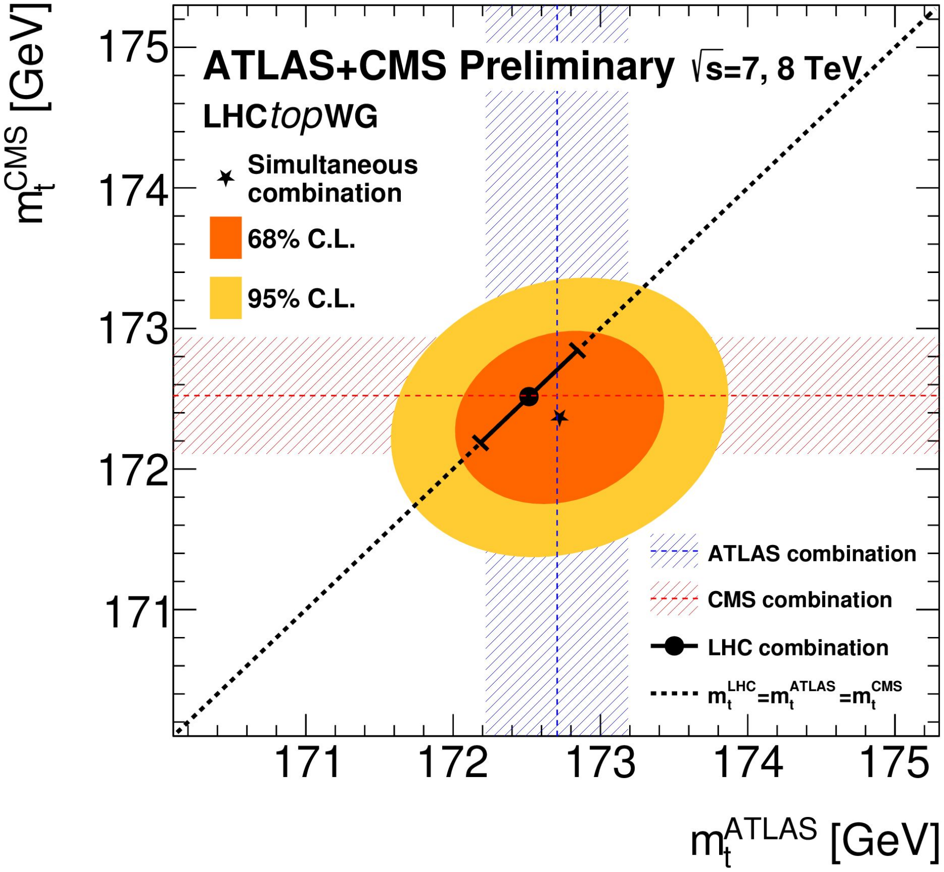
- CMS 8 TeV lepton+jets, dilepton and all-jets
- ATLAS 8 TeV lepton+jets and dilepton



Uncertainty category	Uncertainty impact [GeV] LHC	 ATLAS	 CMS
LHC b-JES	0.18	0.17	0.25
b tagging	0.09	0.16	0.03
ME generator	0.08	0.13	0.14
LHC JES 1	0.08	0.18	0.06
LHC JES 2	0.08	0.11	0.10
Method	0.07	0.06	0.09
CMS B hadron BR	0.07	—	0.12
LHC radiation	0.06	0.07	0.10
Leptons	0.05	0.08	0.07
JER	0.05	0.09	0.02
Top quark p_T	0.05	—	0.07
Background (data)	0.05	0.04	0.06
Color reconnection	0.04	0.08	0.03
Underlying event	0.04	0.03	0.05
LHC g-JES	0.03	0.02	0.04
Background (MC)	0.03	0.07	0.01
Other	0.03	0.06	0.01
LHC l-JES	0.03	0.01	0.05
CMS JES 1	0.03	—	0.04
Pileup	0.03	0.07	0.03
LHC JES 3	0.02	0.07	0.01
LHC hadronization	0.02	0.01	0.01
p_T^{miss}	0.02	0.04	0.01
PDF	0.02	0.06	<0.01
Trigger	0.01	0.01	0.01
Total systematics	0.30	0.41	0.39
Statistical	0.14	0.25	0.14
Total	0.33	0.48	0.42



LHC top mass combination



Final cross-check: compare the m_{top} results obtained from

- ATLAS-only combination
- CMS-only combination
- simultaneous combination but with 2 mass parameters*
- simultaneous combination with 1 mass parameter = LHC combination

All in excellent agreement with each other!

*fully exploiting the correlations

$$m_t^{ATLAS} = \sum_i w_i m_i^{ATLAS} + \sum_j \lambda_j m_j^{CMS} \qquad \sum_i w_i = 1; \sum_j \lambda_j = 0$$

The top quark mass

- Mass measurements are also being made at 13 TeV: novel analysis techniques, more sophisticated MC generators, and much larger dataset!

- Many developments have been made in **modelling**
  - improving the description of off-shell effects
  - reduced uncertainties in additional QCD radiation
  - new models of colour reconnection
  - availability of NNLO+PS
  - modelling of the radiation patterns in the top quark decay

See e.g.
arXiv:2302.01967
EPJC 83 (2023) 560
JHEP 06 (2023) 019
ATLAS-CONF-2022-058

$$m_{top} = 172.52 \pm 0.33 \text{ GeV } (< 2‰)$$

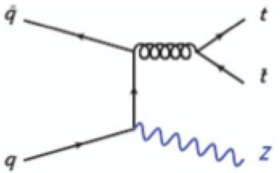
Excellent example of collaboration between two experiments!

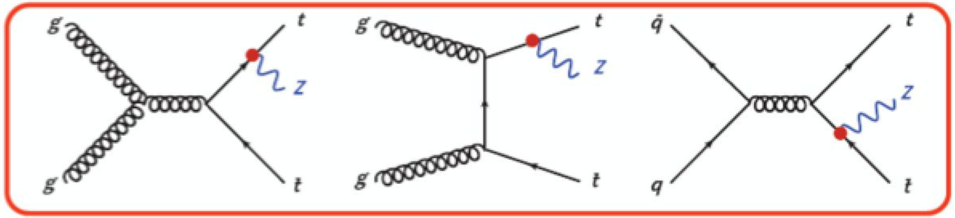
ttZ production at the end of Run 2

Anatomy of the ttZ process

Top pair production in association with a Z boson: rare process!
→ Direct access to the top EW couplings (T_3 and Q)

(~800x smaller cross section than ttbar)





Key background to many important analyses: ttH measurement, ttbar+DM searches

Each decay channel has its own challenges, but **benefit from inclusive approach!**

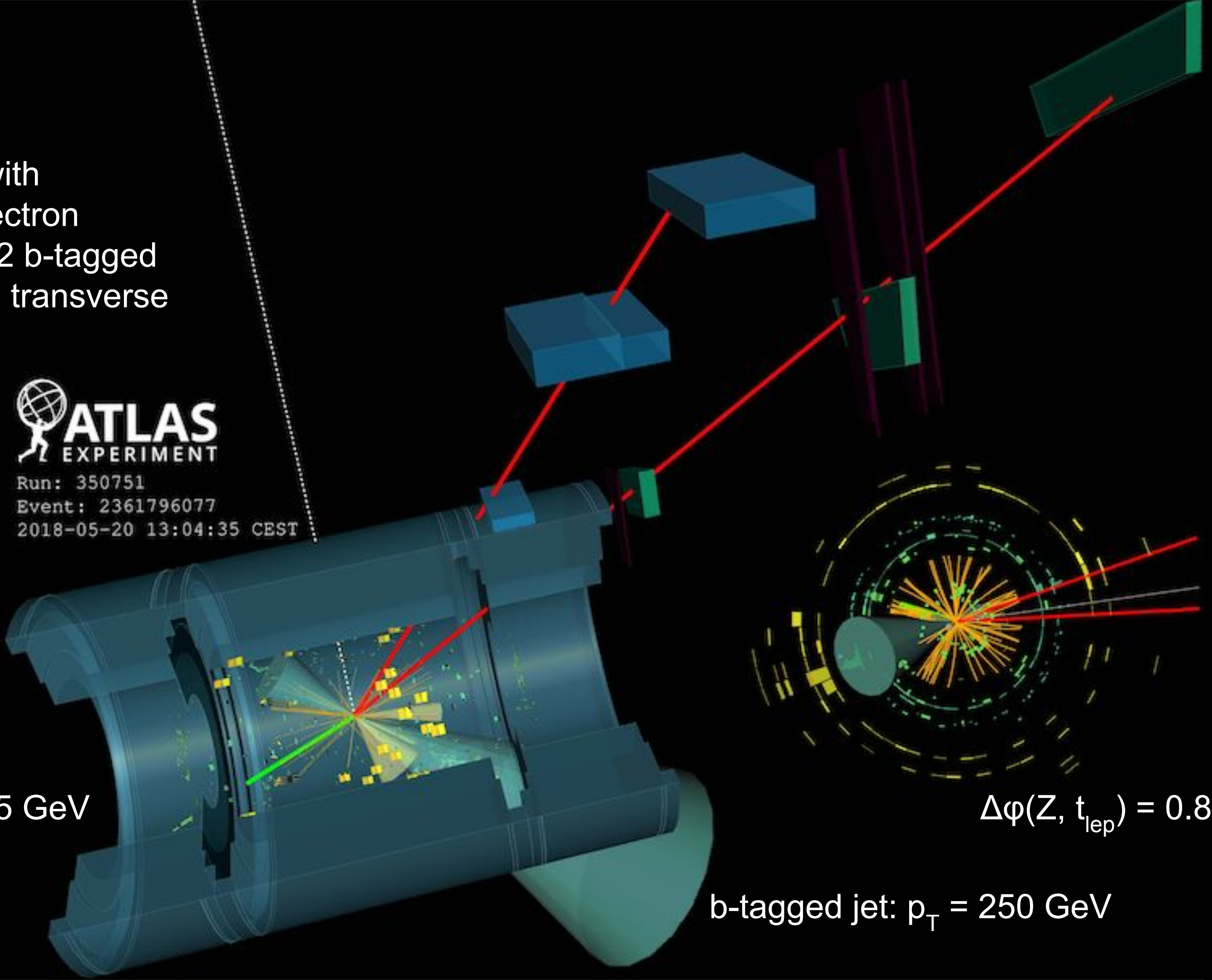
Want to measure the **inclusive production cross section**, but also **differentially** in a number of observables

- test state-of-the-art MC modelling
- recast in terms of BSM exclusions (SMEFT)
- spin correlations

Already measured by ATLAS with the full Run 2 dataset: *Eur. Phys. J. C 81 (2021) 737*

Candidate ttZ event with

- 2 muons + 1 electron
- 4 jets, of which 2 b-tagged
- 30 GeV missing transverse energy



Z→μμ
90.6 GeV

electron: p_T = 45 GeV

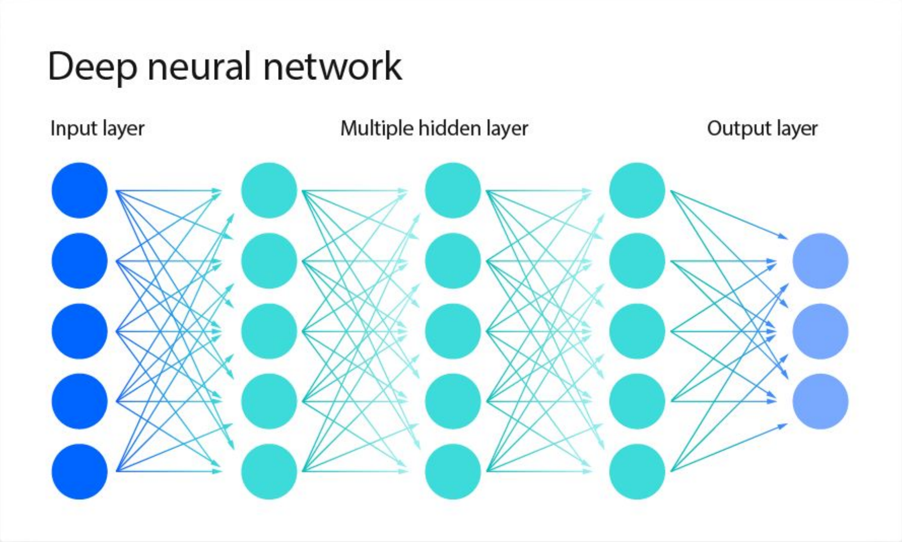
$\Delta\varphi(Z, t_{lep})$ = 0.814 rad/π

b-tagged jet: p_T = 250 GeV

Analysis strategy: 3 channels with DNNs

- Previously had only considered simple topological bins
  - split by number of leptons, number of jets, number of b-jets
  - leads to a partial but **suboptimal** separation of the signal from the backgrounds
- Now rely fully on **Deep Neural Networks** (DNNs)
  - **exploit the full kinematic information of the event**
  - multi-class DNNs: can isolate specific backgrounds to measure in data (**major improvement**)

- Channels based on the decays of the ttbar system
  - all-jets → 2 leptons (2L)
  - lepton+jets → 3 leptons (3L)
  - dilepton → 4 leptons (4L)
  - require at least 1 b-tagged jet
  - try to remain as inclusive as possible → **better MVA perf.**

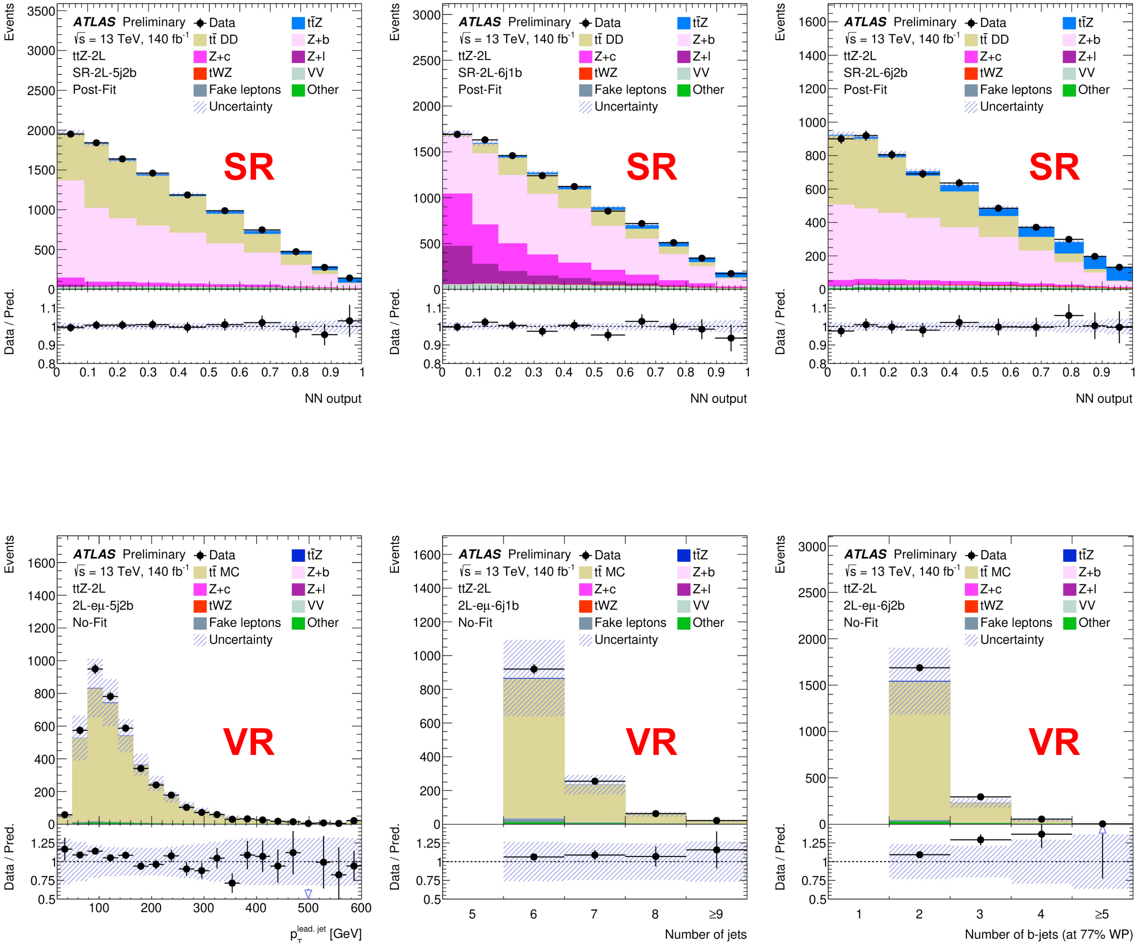


The 2L channel in the detector-level fit

Main **backgrounds** come from **dilepton ttbar and Z+HF**.

→ we can measure Z+c and Z+b normalisations directly in the fit

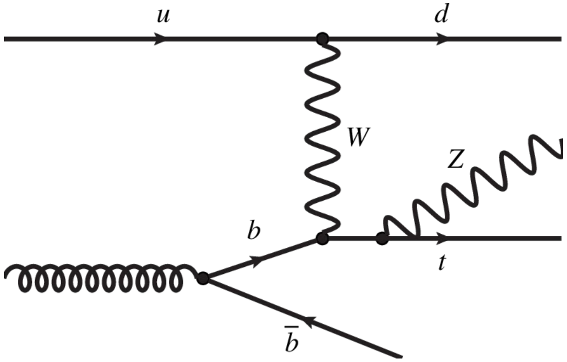
→ ttbar+jets poorly modelled: rely on data-driven approach

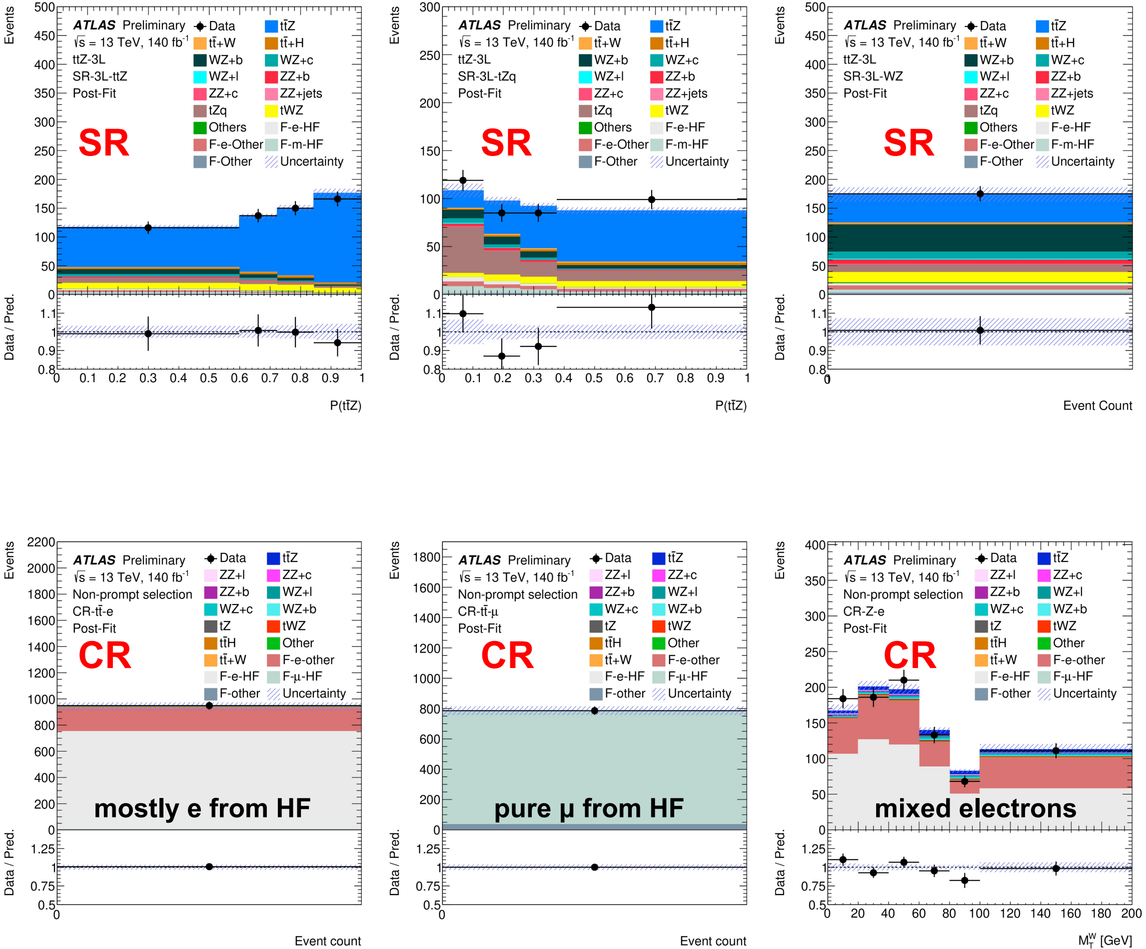


The 3L channel in the detector-level fit

Multi-class DNN allows us to separate the **leading tZq and WZ+HF backgrounds**.

→ not enough stats to measure tZq properly: fixed to SM



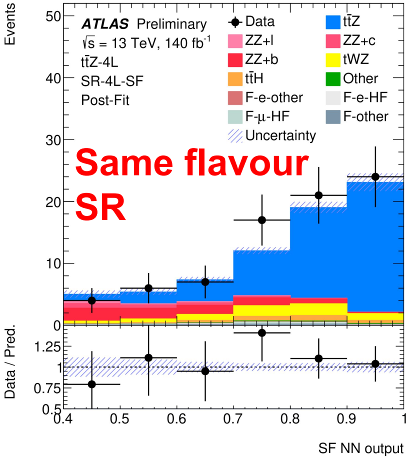


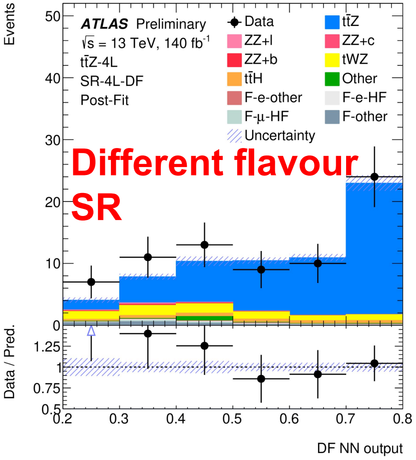
The 4L channel in the detector-level fit

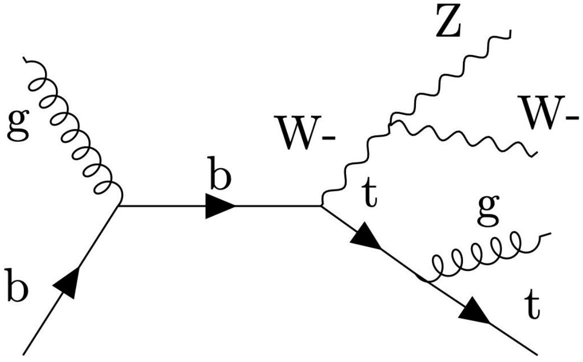
Very pure selection, only two relevant **backgrounds: tWZ and ZZ+HF**.

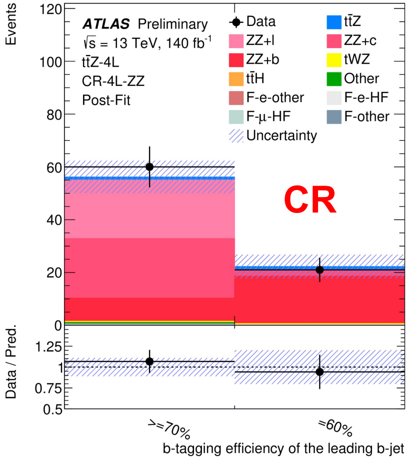
→ we can measure ZZ+b directly in the fit, ZZ+c/light are suppressed

→ not enough statistics to measure tWZ (irreducible, semi-resonant ttZ) properly: fixed to SM





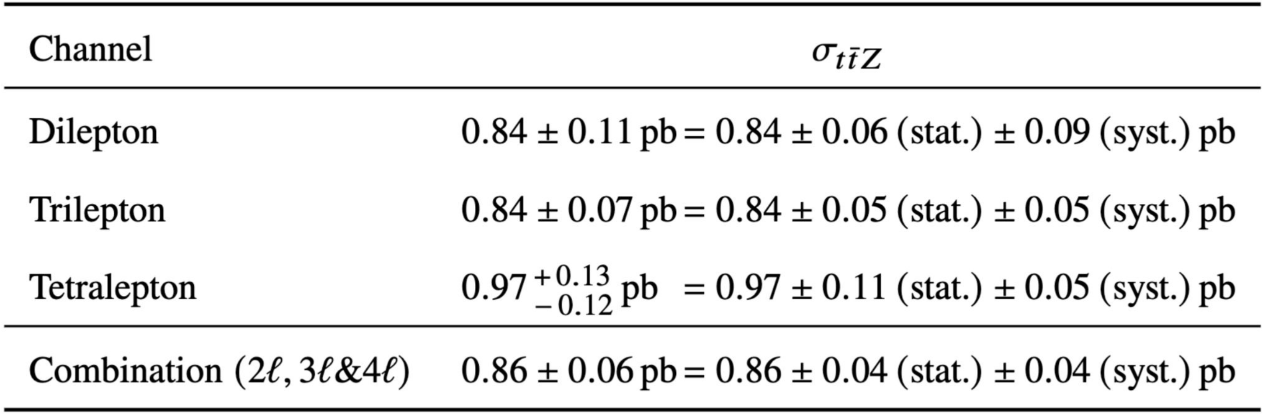




Results of the inclusive detector-level fit

Simultaneously fit all regions:

- fit is well behaved and stable
- background normalisations consistent with SM
- 2L and 3L yield almost exactly the SM prediction, 4L has slight excess
- leading systematics related to background normalisation and JES/Flavour tagging

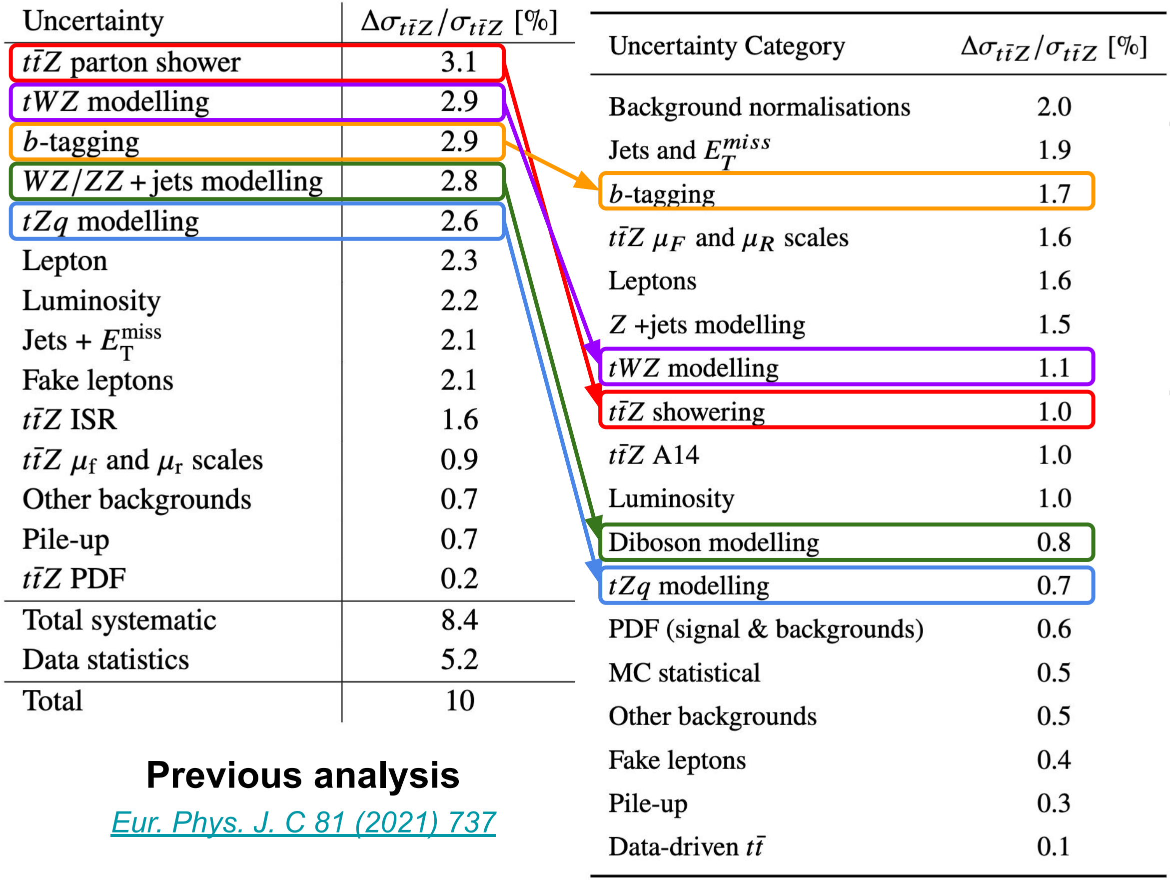


Channel	$\sigma_{t\bar{t}Z}$
Dilepton	$0.84 \pm 0.11\,\text{pb} = 0.84 \pm 0.06\,(\text{stat.}) \pm 0.09\,(\text{syst.})\,\text{pb}$
Trilepton	$0.84 \pm 0.07\,\text{pb} = 0.84 \pm 0.05\,(\text{stat.}) \pm 0.05\,(\text{syst.})\,\text{pb}$
Tetralepton	$0.97\,^{+0.13}_{-0.12}\,\text{pb} = 0.97 \pm 0.11\,(\text{stat.}) \pm 0.05\,(\text{syst.})\,\text{pb}$
Combination ($2\ell, 3\ell\&4\ell$)	$0.86 \pm 0.06\,\text{pb} = 0.86 \pm 0.04\,(\text{stat.}) \pm 0.04\,(\text{syst.})\,\text{pb}$

Theory prediction (NLO+NNLL)
Eur. Phys. J. C 79 (2019) 249

$$\sigma_{t\bar{t}Z} = 0.863^{+0.07}_{-0.09}\,(\text{scale}) \pm 0.03\,(\text{PDF} + \alpha_S)\,\text{pb}.$$

Comparison to previous analysis



Uncertainty	$\Delta\sigma_{t\bar{t}Z}/\sigma_{t\bar{t}Z}$ [%]
$t\bar{t}Z$ parton shower	3.1
tWZ modelling	2.9
b-tagging	2.9
$WZ/ZZ+$jets modelling	2.8
tZq modelling	2.6
Lepton	2.3
Luminosity	2.2
Jets + $E_{\mathrm{T}}^{\mathrm{miss}}$	2.1
Fake leptons	2.1
$t\bar{t}Z$ ISR	1.6
$t\bar{t}Z$ μ_{f} and μ_{r} scales	0.9
Other backgrounds	0.7
Pile-up	0.7
$t\bar{t}Z$ PDF	0.2
Total systematic	8.4
Data statistics	5.2
Total	10

Previous analysis

Eur. Phys. J. C 81 (2021) 737

Uncertainty Category	$\Delta\sigma_{t\bar{t}Z}/\sigma_{t\bar{t}Z}$ [%]
Background normalisations	2.0
Jets and E_T^{miss}	1.9
b-tagging	1.7
$t\bar{t}Z$ μ_F and μ_R scales	1.6
Leptons	1.6
Z +jets modelling	1.5
tWZ modelling	1.1
$t\bar{t}Z$ showering	1.0
$t\bar{t}Z$ A14	1.0
Luminosity	1.0
Diboson modelling	0.8
tZq modelling	0.7
PDF (signal & backgrounds)	0.6
MC statistical	0.5
Other backgrounds	0.5
Fake leptons	0.4
Pile-up	0.3
Data-driven $t\bar{t}$	0.1

This analysis

Cross sections (in pb)

Theory prediction
[~10%] 0.86 ± 0.08 (scale) ± 0.03 (PDF)

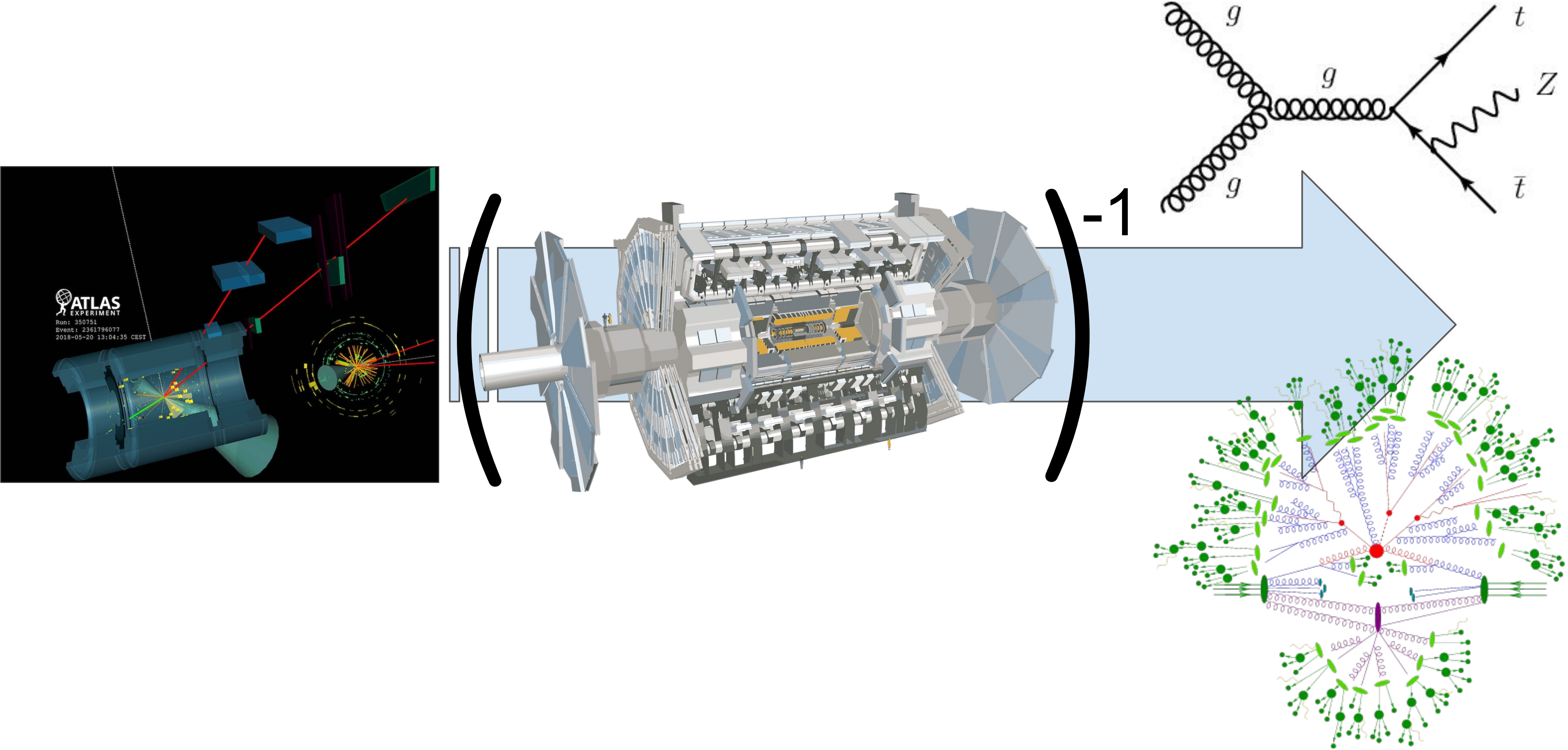
Previous measurement
[~10%] 0.99 ± 0.05 (stat) ± 0.08 (syst)

This measurement
[~6.5%] 0.86 ± 0.04 (stat) ± 0.04 (syst)

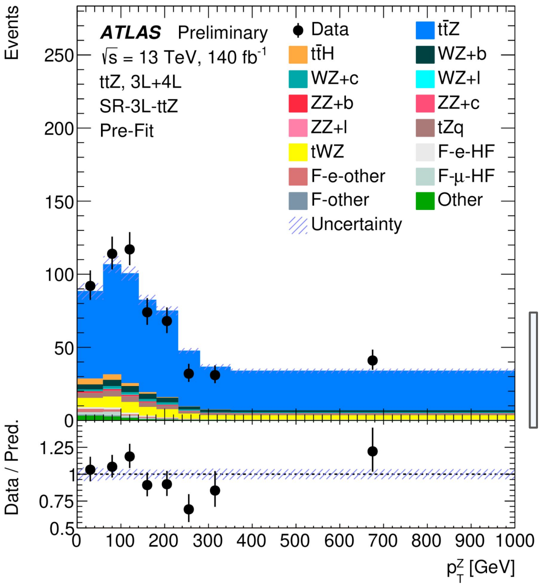
35% improvement overall, but systematics cut down in half!
→ better background separation
→ data-driven techniques
→ improved MC modelling

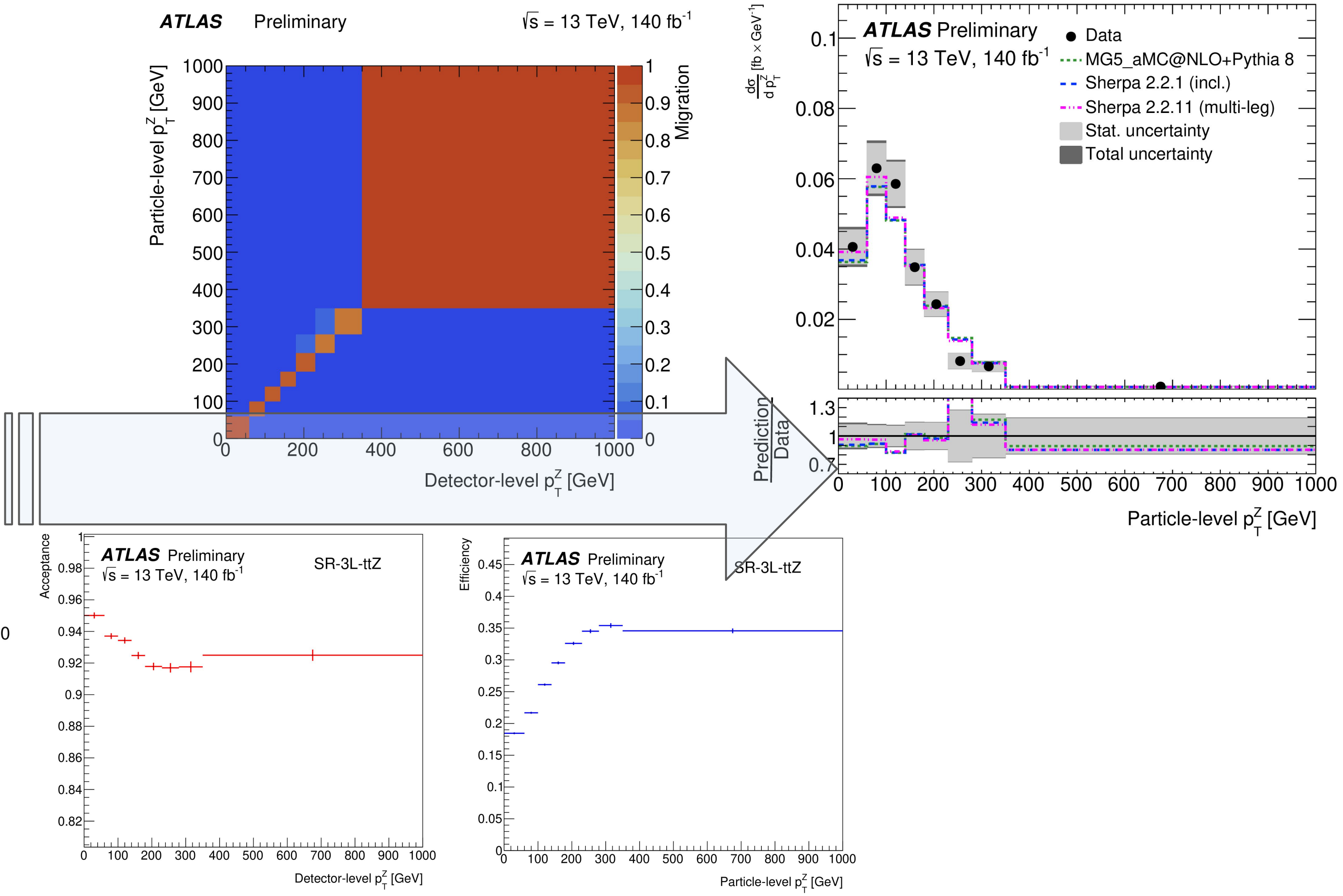
Re-analysis can be important (e.g. 4tops)

Correcting for detector effects: unfolding



Correcting for detector effects: unfolding





Differential measurements

Recent development in ATLAS: **profile-likelihood unfolding**.

Multiple benefits: pulls and constraints of the uncertainties, normalisation of backgrounds, inclusion of control regions and multiple signal regions, ability to save the full likelihood for HEPdata!

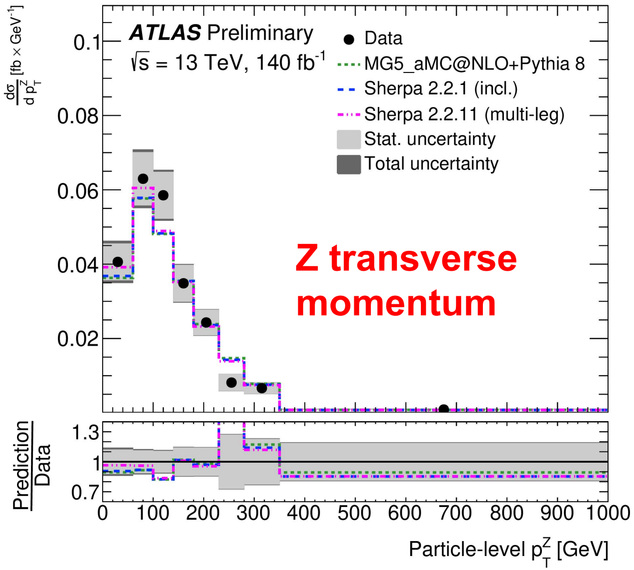
Tikhonov regularisation whenever hadronic top or full ttbar reconstruction is needed.

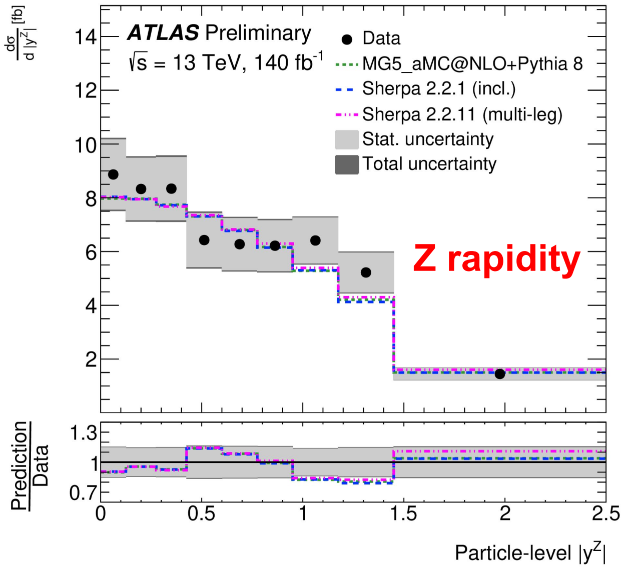
Observables:

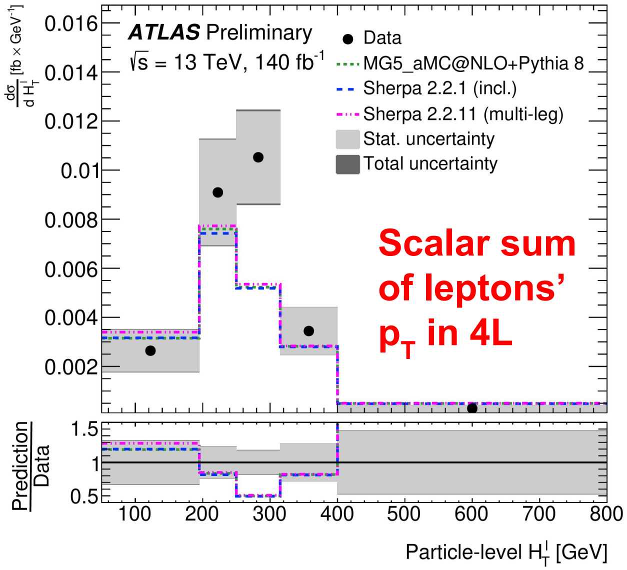
- mainly **kinematics of the Z boson and ttbar system**
- angular distributions, jet multiplicities

	Variable
$3\ell + 4\ell$	p_{T}^{Z}
	$\lvert y^{Z}\rvert$
	$\cos\theta_{Z}^{*}$
	p_{T}^{t}
	$p_{\mathrm{T}}^{t\bar{t}}$
	$\lvert\Delta\phi(t\bar{t}, Z)\rvert$
	$m^{t\bar{t}Z}$
	$m^{t\bar{t}}$
	$\lvert y^{t\bar{t}Z}\rvert$
3ℓ	H_{T}^{ℓ}
	$\lvert\Delta\phi(Z, t_{\mathrm{lep}})\rvert$
	$\lvert\Delta y(Z, t_{\mathrm{lep}})\rvert$
	$p_{\mathrm{T}}^{\ell,\mathrm{non}-Z}$
	N_{jets}
4ℓ	H_{T}^{ℓ}
	$\lvert\Delta\phi(\ell_{t}^{+}, \ell_{\bar{t}}^{-})\rvert$
	N_{jets}

Results of the differential measurements







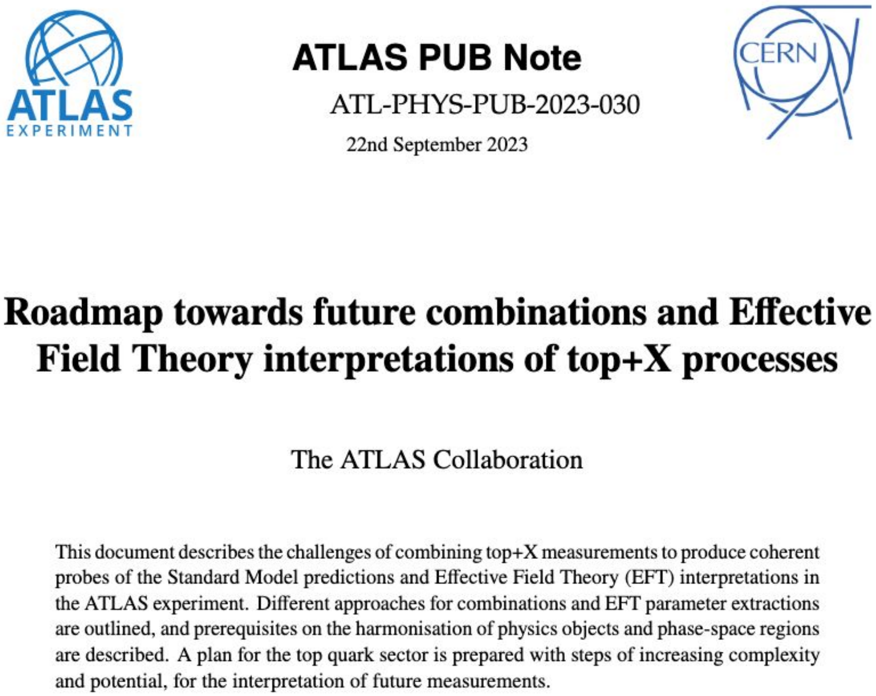
- 17 observables unfolded to particle- and parton-level, normalised and absolute
- Chosen for relevance to both SM and BSM modelling
- **Still largely stat-dominated** → no single MC generator performs clearly better than the others
- Can be combined using the provided likelihoods and correlations

A legacy measurement of a rare production process

- **Inclusive and differential measurements of the ttZ cross section in multi-lepton final states (2L, 3L & 4L) using 140 fb^{-1} of Run 2 data**
  - now also including interpretations (spin correlations & EFT → see backup slides)
- Analysis builds and improves upon the previous one: MC modelling, MVA-based strategy, fake lepton estimation, systematics model.
  - 35% improvement on the inclusive cross section, **50% reduction of systematics**!
- Results are consistent with the SM:
  - cross section is 0.86 ± 0.06 pb → 6.5% uncertainty
  - best theory prediction 0.86 ± 0.09 pb → 10% uncertainty
- Differential measurements are performed for 17 kinematic observables
- First search for ttbar spin correlation effects: still statistically dominated!
- Comprehensive picture of top-EW EFT
- Inclusive & differential likelihoods are available: ready for combinations!

Where to next? An ATLAS roadmap for top+X

- Recognises **top-multilepton final states** as a valuable addition to global EFT fits
- Most processes already measured (to varying degrees of precision), some discrepancies
- How do we move forward?
  - **multi-process fits**: no longer a distinction between "signal" and "background"
  - **optimise** the search for new physics with **EFT and MVA**
  - technical challenge: **multi-process unfolding**



ATLAS PUB Note

ATL-PHYS-PUB-2023-030

22nd September 2023

Roadmap towards future combinations and Effective Field Theory interpretations of top+X processes

The ATLAS Collaboration

This document describes the challenges of combining top+X measurements to produce coherent probes of the Standard Model predictions and Effective Field Theory (EFT) interpretations in the ATLAS experiment. Different approaches for combinations and EFT parameter extractions are outlined, and prerequisites on the harmonisation of physics objects and phase-space regions are described. A plan for the top quark sector is prepared with steps of increasing complexity and potential, for the interpretation of future measurements.

ATL-PHYS-PUB-2023-030

Top quark pair properties: entanglement

Prelude: top quark spin correlations

The top quark has a mean lifetime ~5x10^{-25}s << 1/Λ_{QCD} ~10^{-23}s

→ **spin information is correlated and transferred** to decay products

BR(t→Wb)~100% + weak interaction is maximally parity-violating

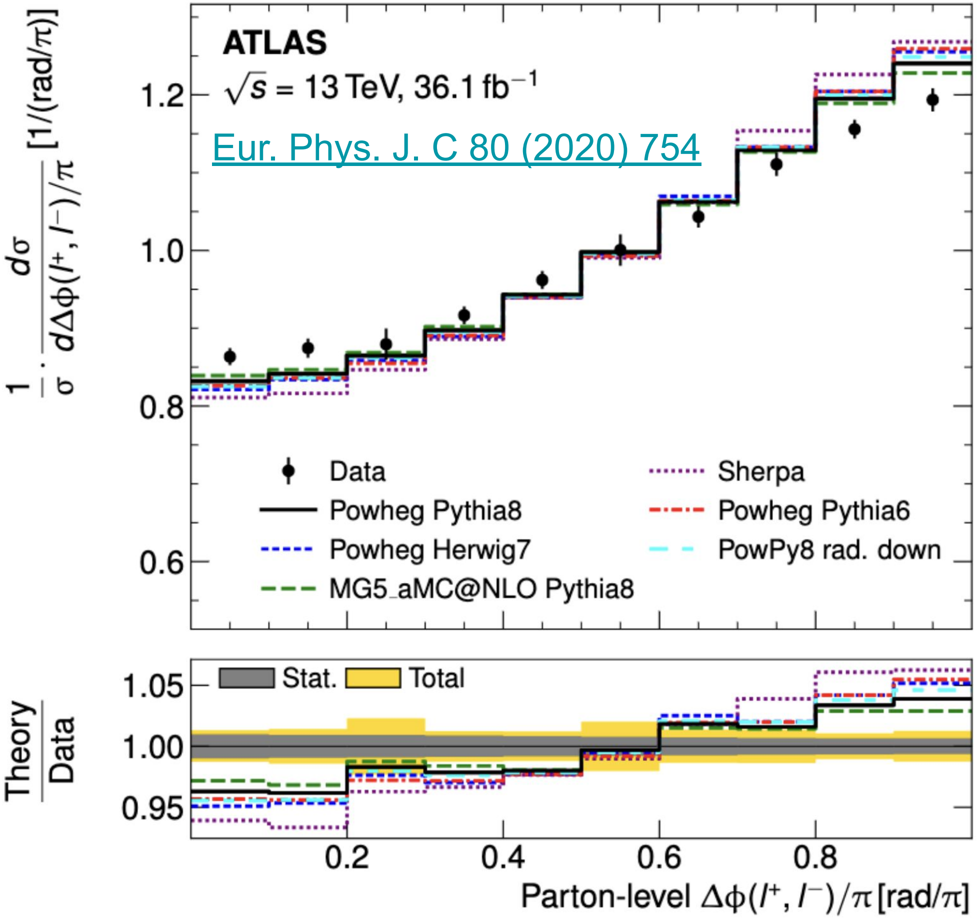
→ **correlations are observable!**

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega_1\Omega_2} = \frac{1}{4\pi^2}\left(1 + \alpha_1\,\mathbf{B}_1\cdot\hat{\ell}_1 + \alpha_2\,\mathbf{B}_2\cdot\hat{\ell}_2 + \alpha_1\alpha_2\,\hat{\ell}_1\cdot\mathbb{C}\cdot\hat{\ell}_2\right)$$

top polarisations + spin correlations

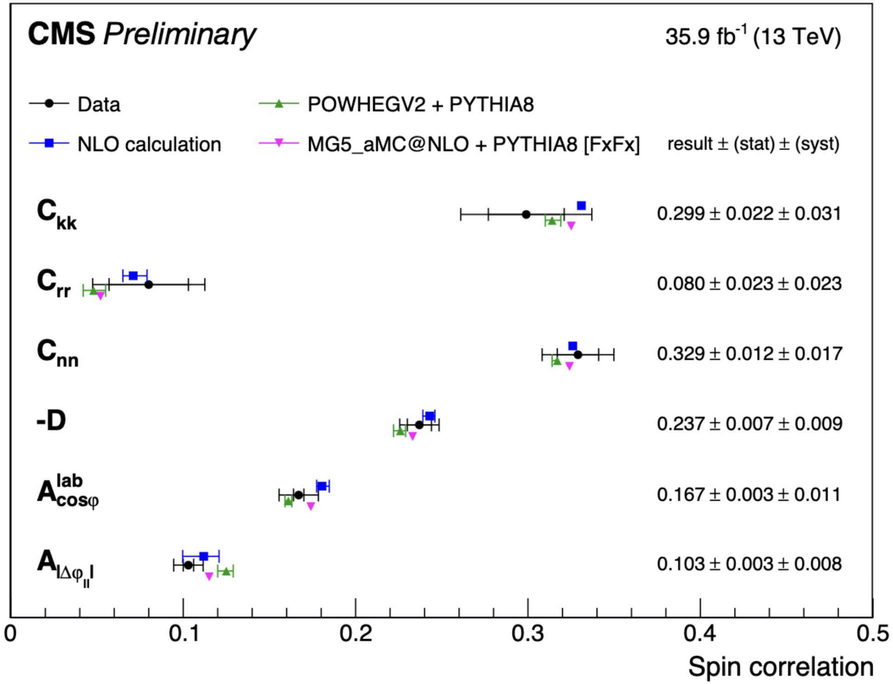
= full spin density matrix

State-of-the-art in 2020…



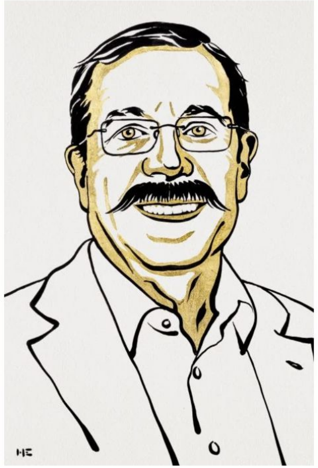
Eur. Phys. J. C 80 (2020) 754

Spin correlations in ttbar are well-established



Phys. Rev. D 100 (2019) 072002

As you may have heard...



Ill. Niklas Elmehed © Nobel Prize Outreach

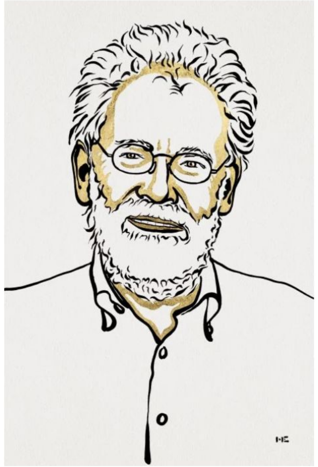
Alain Aspect

Prize share: 1/3

Ill. Niklas Elmehed © Nobel Prize Outreach

John F. Clauser

Prize share: 1/3

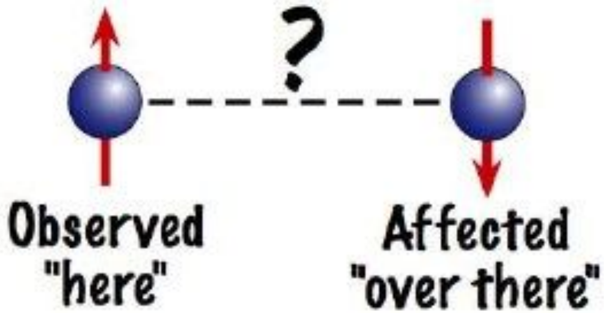


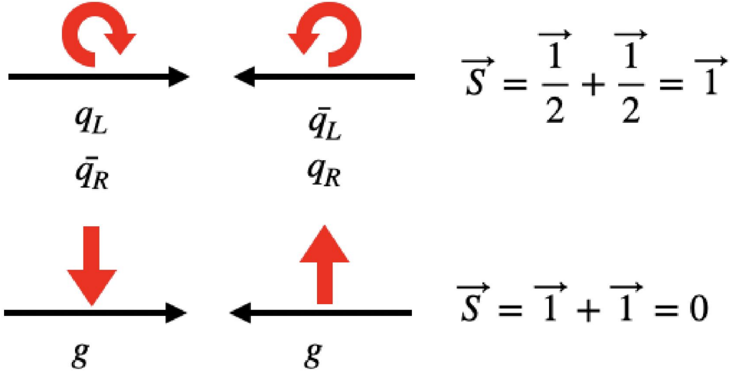
Ill. Niklas Elmehed © Nobel Prize Outreach

Anton Zeilinger

Prize share: 1/3

The Nobel Prize in Physics 2022 was awarded jointly to Alain Aspect, John F. Clauser and Anton Zeilinger "for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science"



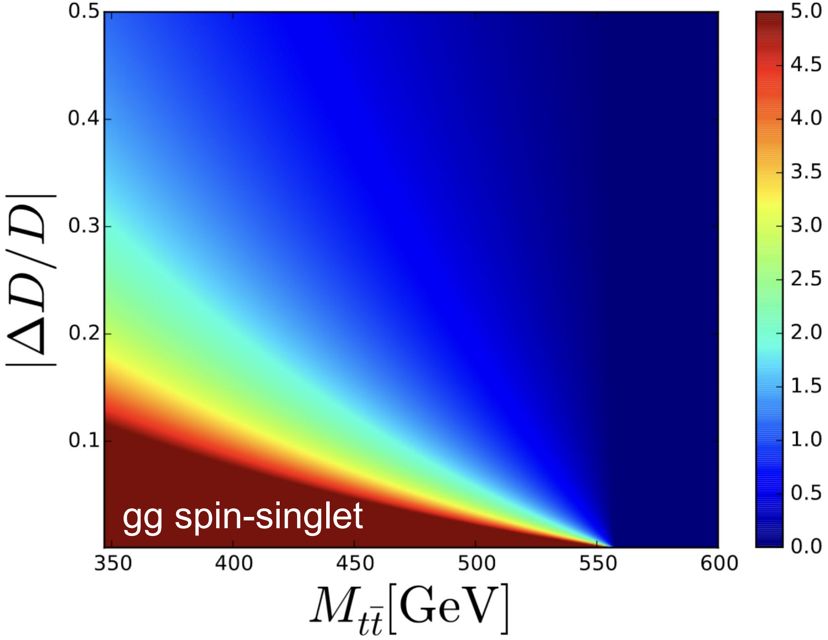


gg→ttbar: spin-singlet state at threshold

Quantum tops beyond (classical) spin correlations

Eur. Phys. J. Plus (2021) 136 (March 2020) → first analysis of top quark pair production *from the quantum information point of view*: “**bipartite qubit system**”

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega_1\Omega_2} = \frac{1}{4\pi^2}\left(1 + \alpha_1\, \cancelto{0}{\mathbf{B}_1} \cdot \hat{\ell}_1 + \alpha_2\, \cancelto{0}{\mathbf{B}_2} \cdot \hat{\ell}_2 + \alpha_1\alpha_2\, \hat{\ell}_1\, \mathbb{C}\, \hat{\ell}_2\right)$$



$$\mathrm{Tr}\left[\mathbb{C}\right] < -1$$ *Peres-Horodecki criterion*

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\varphi} = \frac{1}{2}\left(1 - D\cos\varphi\right)$$ *a simple observable*

$$D = \frac{\mathrm{Tr}\left[\mathbb{C}\right]}{3} \Rightarrow D < -\frac{1}{3}$$ *a quantum entanglement marker!*

Quantum entanglement in dilepton ttbar

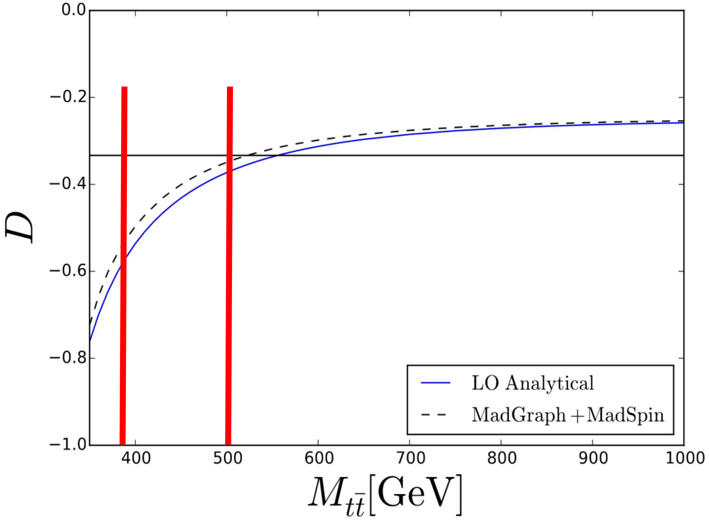
Dilepton eμ final state is very clean (90% purity) and at the end of Run 2 we have about a million events after preselection.

$$D = \frac{\mathrm{Tr}\left[\mathbb{C}\right]}{3} \Rightarrow D < -\frac{1}{3}$$

Then partition events into three selections:

- **340<M_{tt}<380: entanglement signal region**
- 380<M_{tt}<500: validation region
  (dilution from mis-reconstruction)
- **500<M_{tt}: no-entanglement** validation region

The mass cuts are crucial!

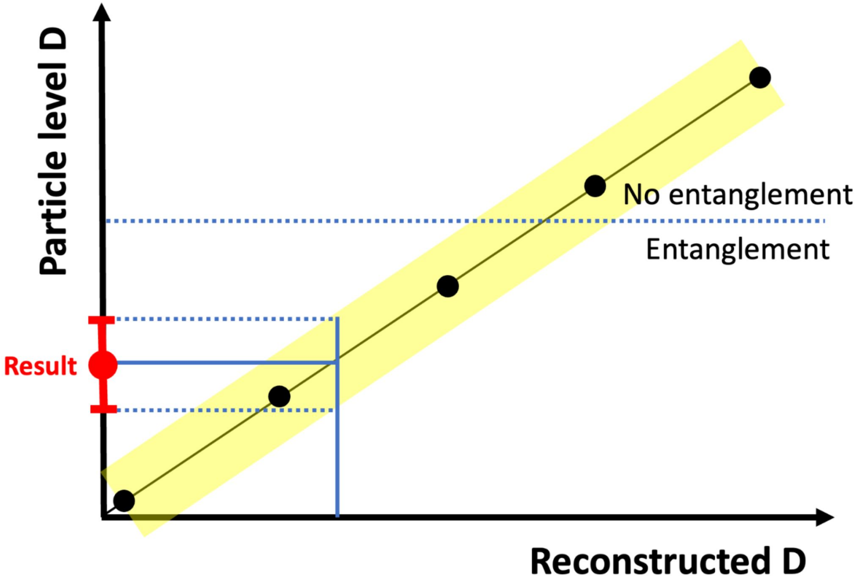


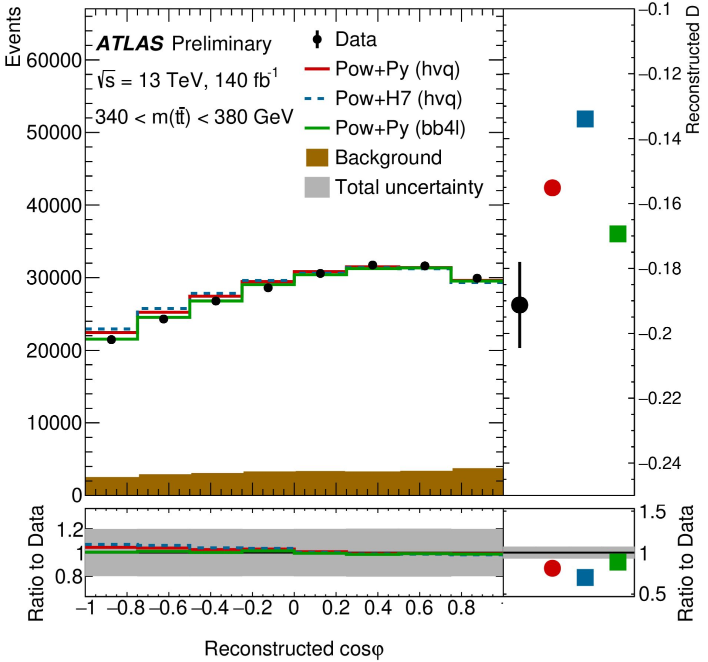
Analysis procedure

“Calibration curve” method: use the nominal MC to map the detector-level D value (average of distribution) to the fiducial particle-level D.

Systematics are propagated with their own curves, quadratic envelope.

→ Build the curve by sampling different D values.



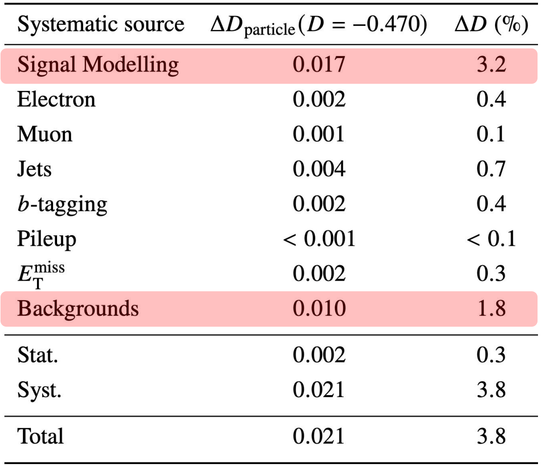


A closer look at uncertainties

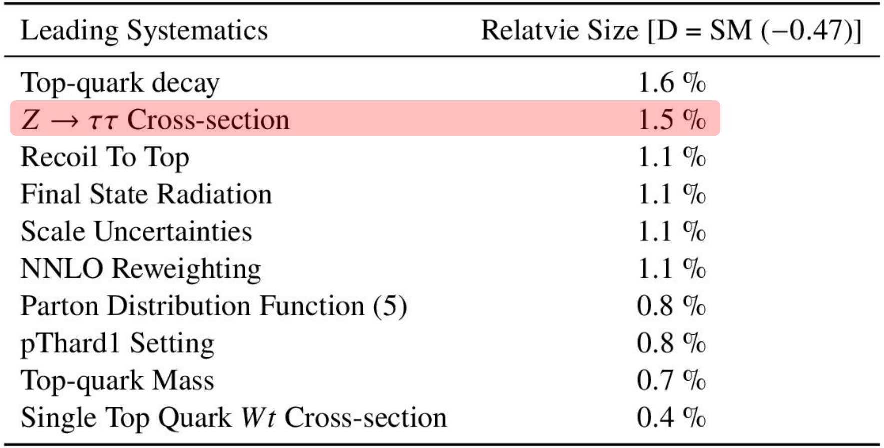
“Backgrounds”: mostly $Z \rightarrow \tau\tau$, which leads to a flat cos(φ) distribution (spin information from taus is lost)

Calibrating to fiducial particle-level reduces the parton shower uncertainty (Pythia vs Herwig) : full details in the CONF.

Signal modelling: by far the largest contribution

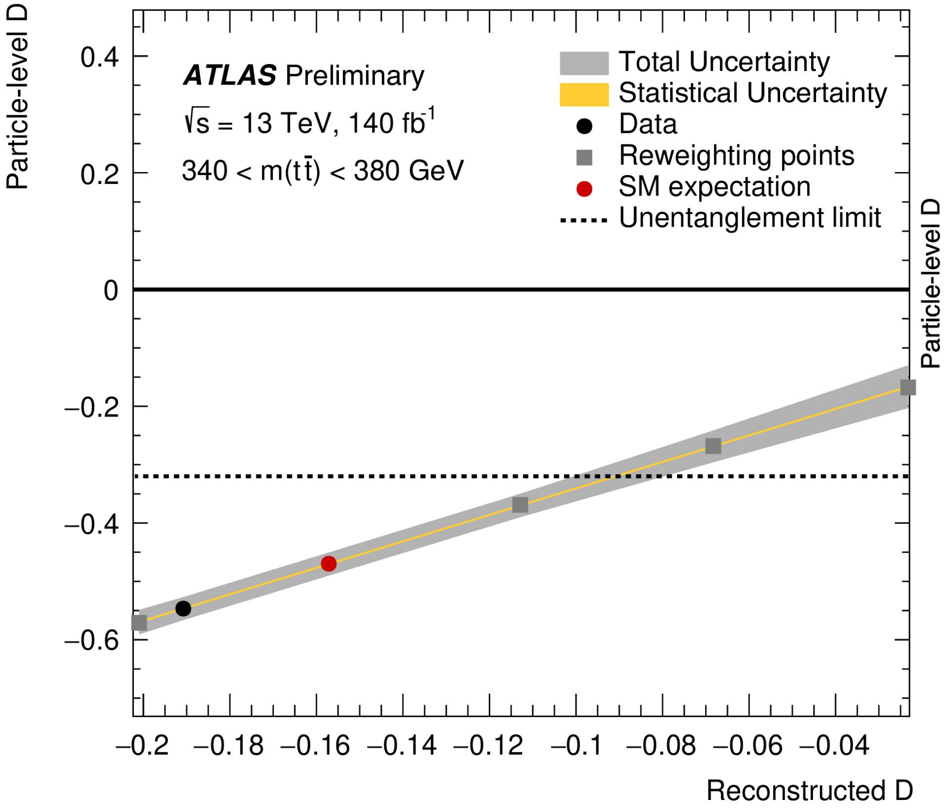


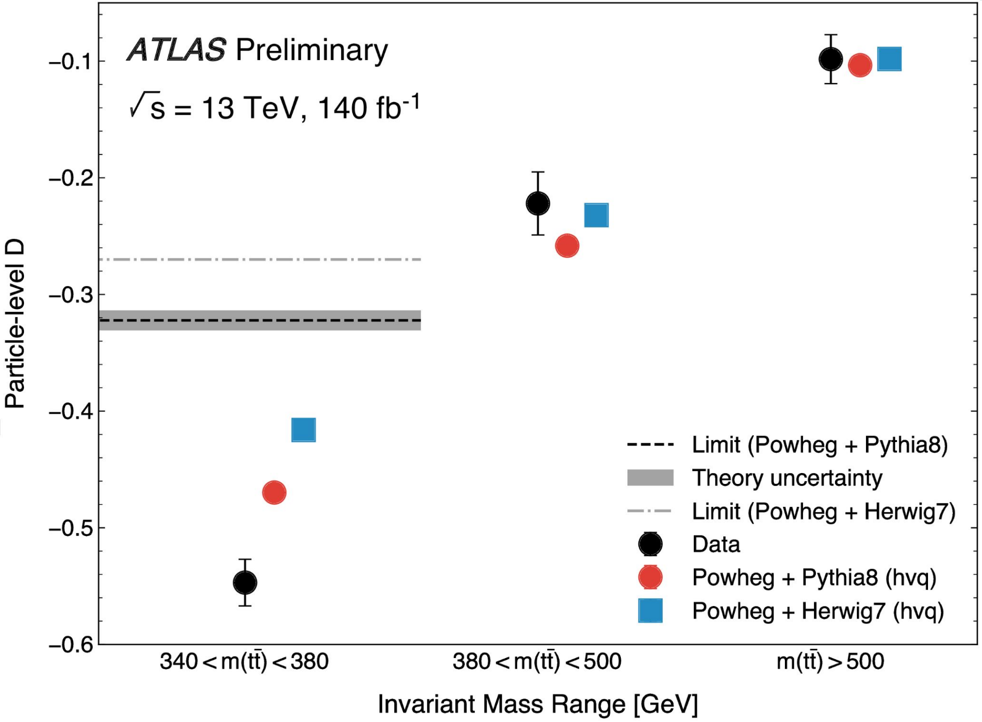
Systematic source	$\Delta D_{\text{particle}}$ ($D = -0.470$)	ΔD (%)
Signal Modelling	0.017	3.2
Electron	0.002	0.4
Muon	0.001	0.1
Jets	0.004	0.7
b-tagging	0.002	0.4
Pileup	< 0.001	< 0.1
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.002	0.3
Backgrounds	0.010	1.8
Stat.	0.002	0.3
Syst.	0.021	3.8
Total	0.021	3.8



Leading Systematics	Relatvie Size [D = SM (−0.47)]
Top-quark decay	1.6 %
$Z \rightarrow \tau\tau$ Cross-section	1.5 %
Recoil To Top	1.1 %
Final State Radiation	1.1 %
Scale Uncertainties	1.1 %
NNLO Reweighting	1.1 %
Parton Distribution Function (5)	0.8 %
pThard1 Setting	0.8 %
Top-quark Mass	0.7 %
Single Top Quark Wt Cross-section	0.4 %

Observation of quantum entanglement in dilepton ttbar



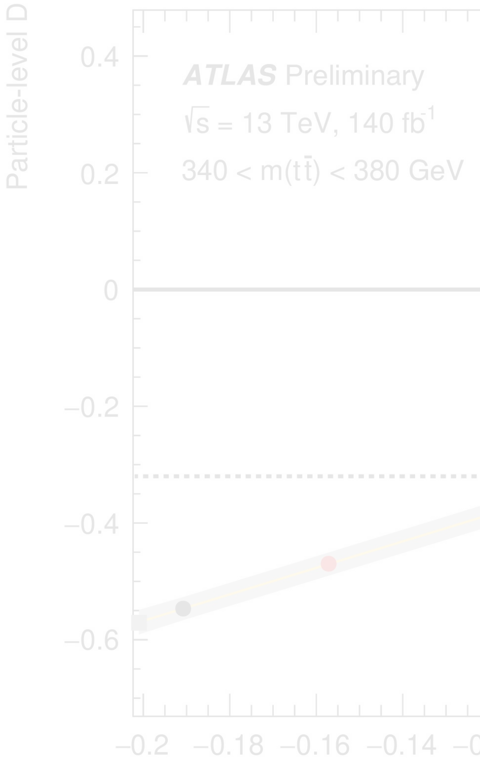


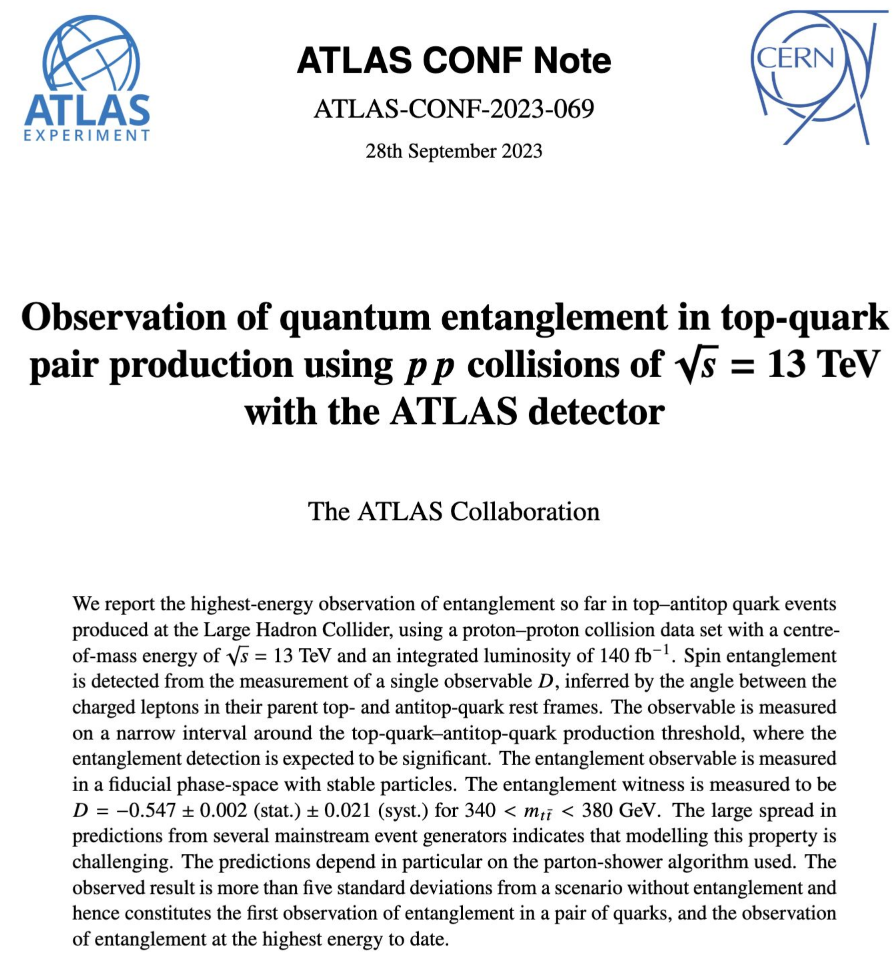
non-relativistic QCD effects close to threshold, not included in MC generators → would only affect predictions, not calibration

expected: D = -0.470 ± 0.002 (stat.) ± 0.017 (syst.)

D = -0.547 ± 0.002 (stat.) ± 0.020 (syst.)

Observation of quantum entanglement in dilepton ttbar





ATLAS CONF Note

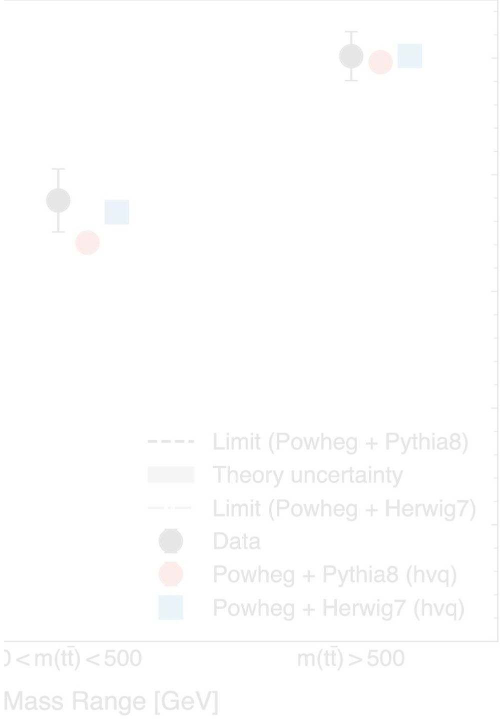
ATLAS-CONF-2023-069

28th September 2023

Observation of quantum entanglement in top-quark pair production using pp collisions of $\sqrt{s}$ = 13 TeV with the ATLAS detector

The ATLAS Collaboration

We report the highest-energy observation of entanglement so far in top–antitop quark events produced at the Large Hadron Collider, using a proton–proton collision data set with a centre-of-mass energy of $\sqrt{s}$ = 13 TeV and an integrated luminosity of 140 fb^{-1}. Spin entanglement is detected from the measurement of a single observable D, inferred by the angle between the charged leptons in their parent top- and antitop-quark rest frames. The observable is measured on a narrow interval around the top-quark–antitop-quark production threshold, where the entanglement detection is expected to be significant. The entanglement observable is measured in a fiducial phase-space with stable particles. The entanglement witness is measured to be $D = -0.547 \pm 0.002$ (stat.) ± 0.021 (syst.) for $340 < m_{t\bar{t}} < 380$ GeV. The large spread in predictions from several mainstream event generators indicates that modelling this property is challenging. The predictions depend in particular on the parton-shower algorithm used. The observed result is more than five standard deviations from a scenario without entanglement and hence constitutes the first observation of entanglement in a pair of quarks, and the observation of entanglement at the highest energy to date.



) effects close to threshold, not
erators

$D = -0.547 \pm 0.00$

[stat.] ± 0.017 [syst.])

SIGNIFICANT interest from the THEORY community

[Submitted on 10 Mar 2022 (v1), last revised 20 Sep 2022 (this version, v2)]

Quantum information with top quarks in QCD

Yoav Afik, Juan Ramón Muñoz de Nova

Top quarks represent unique high-energy systems since their spin correlations can be
high-energy colliders. We present here the general framework of the quantum state of
energy collider. We argue that, in general, the total quantum state that can be probed i
rise to a mixed state. We compute the quantum state of a $t\bar{t}$ pair produced from the mo
different regions of phase space. We show that any realistic hadronic production of a $t\bar{}$
experimentally relevant cases of proton-proton and proton-antiproton collisions, perfo
energy of the collisions. We provide experimental observables for entanglement and Cl
single observable, which in the case of entanglement represents the violation of a Cauc
pair proposed in the literature to more general quantum states, and for any production
form of violation of Bell's theorem, necessarily containing a number of loopholes.

Comments: 36 pages, 10 figures, 1 table. Accepted version of the manuscript
Subjects: Quantum Physics (quant-ph); High Energy Physics - Phenomenology (hep-ph); High
Cite as: arXiv:2203.05582 [quant-ph]
(or arXiv:2203.05582v2 [quant-ph] for this version)
https://doi.org/10.48550/arXiv.2203.05582
Journal reference: Quantum 6, 820 (2022)
Related DOI: https://doi.org/10.22331/q-2022-09-29-820

[Submitted on 8 Sep 2022]

Quantum discord and steering in top quarks at the LHC

Yoav Afik, Juan Ramón Muñoz de Nova

Top quarks have been recently shown to be a promising system to study quantum information problems at the hi
discuss topics such as entanglement, Bell nonlocality or quantum tomography. Here, we provide the full picture o
discord and steering. We find that both phenomena are present at the LHC. In particular, quantum discord in a se
statistical significance. Interestingly, due to the singular nature of the measurement process, quantum discord ca
ellipsoid can be experimentally reconstructed, both highly-demanding measurements in conventional setups. In c
discord and steering can provide witnesses of new physics beyond the Standard Model.

Comments: 6 pages, 3 figures
Subjects: Quantum Physics (quant-ph); High Energy Physics - Experiment (hep-ex); High Energy Physics - Phenomenology (hep-p
Cite as: arXiv:2209.03969 [quant-ph]
(or arXiv:2209.03969v1 [quant-ph] for this version)
https://doi.org/10.48550/arXiv.2209.03969

[Submitted on 4 Mar 2020 (v1), last revised 6 Sep 2021 (this version, v3)]

Entanglement and quantum tomography with top quarks at the LHC

Yoav Afik, Juan Ramón Muñoz de Nova

Entanglement is a central subject in quantum mechanics. Due to its genuine relativistic behavior and fundamental nature, high-energy colliders are attractive systems for the
experimental study of fundamental aspects of quantum mechanics. We propose the detection of entanglement between the spins of top-antitop-quark pairs at the LHC,
representing the first proposal of entanglement detection in a pair of quarks, and also the entanglement observation at the highest energy scale so far. We show that entanglement
can be observed by direct measurement of the angular separation between the leptons arising from the decay of the top-antitop pair. The detection can be achieved with high
statistical significance, using the current data recorded during Run 2 at the LHC. In addition, we develop a simple protocol for the quantum tomography of the top-antitop pair. This
experimental te
experimental te

Comments: 15
Subjects: Qu
Cite as: ar
(o
ht
Journal reference: Eu
Related DOI: ht

[Submitted on 28 Sep 2022 (v1), last revised 11 Oct 2022 (this version, v2)]

Quantum state tomography, entanglement detection and Bell violation prospects in weak decays of massive particles

Rachel Ashby-Pickering, Alan J. Barr, Agnieszka Wierzchucka

A rather general method for determining the spin density matrix of a multi-particle system from angular decay data is presented. The method is based on a Bloch parameterisation
of the d-dimensional generalised Gell-Mann representation of ρ and exploits the associated Wigner- and Weyl-transforms on the sphere. Each parameter of a (possibly multipartite)
spin density matrix can can b
non-projective decays are des
Monte Carlo simulations of $p\bar{}$
$H \to ZZ^*$. Measurements are

Comments: v2: additional references
Subjects: Quantum Physics (quan

[Submitted on 10 Mar 2022 (v1), last revised 30 Aug 2022 (this version, v2)]

Quantum SMEFT tomography: top quark pair production at the LHC

Rafael Aoude, Eric Madge, Fabio Maltoni, Luca Mantani

Quantum information observables, such as entanglement measures, provide a powerful way to characterize the properties of quantum states. We propose to use them
structure of fundamental interactions and to search for new physics at high energy. Inspired by recent proposals to measure entanglement of top quark pairs produced
we examine how higher-dimensional operators in the framework of the SMEFT modify the Standard Model expectations. We explore two regions of interest in the phas
the Standard Model produces maximally entangled states: at threshold and in the high-energy limit. We unveil a non-trivial pattern of effects, which depend on the init
partons, $q\bar{q}$ or gg, on whether only linear or up to quadratic SMEFT contributions are included, and on the phase space region. In general, we find that higher-dimensi
lower the entanglement predicted in the Standard Model.

[Submitted on 2 Jun 2021 (v1), last revised 26 Jul 2022 (this version, v4)]

Testing Bell inequalities in Higgs boson decays

Alan Barr

Higgs boson decays produce
of the $W^\pm$ pair may be recon
determined. Numerical simul
near-maximally violated. Exp
controlled then statistically s

Comments: Sign corrections t
Subjects: High Energy Phy
Cite as: arXiv:2106.01377
(or arXiv:2106.01
https://doi.org/1
Journal reference: Physics Letters B
Related DOI: https://doi.org/1

[Submitted on 28 Sep 2022]

Laboratory-frame tests of quantum entanglement in $H \to WW$

J. A. Aguilar-Saavedra

Quantum entanglement between
frame observables that only invol
be used to observe the quantum
dimensional) angular distribution

Comments: LaTeX 6 pages
Subjects: High Energy Physics -
Report number: IFT-UAM/CSIC-22-119
Cite as: arXiv:2209.14033 [hep-
(or arXiv:2209.14033v1
https://doi.org/10.4855

[Submitted on 27 Sep 2022]

Testing entanglement and Bell inequalities in $H \to ZZ$

J. A. Aguilar-Saavedra, A. Bernal, J. A. Casas, J. M. Moreno

We discuss quantum entanglement and violation of Bell inequalities in the $H \to ZZ$ decay, in particular when the two Z−bosons decay into light leptons. Although such pr
implies an important suppression of the statistics, this is traded by clean signals from a "quasi maximally-entangled" system, which makes it very promising to check thes
phenomena at high energy. In this paper we devise a novel framework to extract from $H \to ZZ$ data all significant information related to this goal, in particular spin correl
observables. In this context we derive sufficient and necessary conditions for entanglement in terms of only two parameters. Likewise, we obtain a sufficient and improved
for the violation of Bell-type inequalities. The numerical analysis shows that with a luminosity of $L = 300\text{fb}^{-1}$ entanglement can be probed at $> 3\sigma$ level. For $L = 3\text{ab}^{-1}$ (
entanglement can be probed beyond the 5σ level, while the sensitivity to a violation of the Bell inequalities is at the 4.5σ level

heory (hep-th); Quantum Physics (quant-ph)

[Submitted on 1 May 2022 (v1), last revised 1 Aug 2022 (this version, v2)]

Improved tests of entanglement and Bell inequalities with LHC tops

J. A. Aguilar-Saavedra, J. A. Casas

We discuss quantum entanglement in top pair production at the LHC. Near the $t\bar{t}$ threshold, entanglement observa
subprocesses, which is achieved by a simple cut on the velocity of the $t\bar{t}$ system in the laboratory frame. Furtherm
combinations of $t\bar{t}$ spin correlation coefficients involved in the measurement of entanglement and Bell inequalities
7 for Bell inequalities near threshold

[Submitted on 19 Oct 2021 (v1), last revised 25 Mar 2022 (this version, v2)]

Quantum tops at the LHC: from entanglement to Bell inequalities

Claudio Severi, Cristian Degli Esposti Boschi, Fabio Maltoni, Maximiliano Sioli

We present the prospects of detecting quantum entanglement and the violation of Bell inequalities in $t\bar{t}$ events at the LHC. We introduce a unique set of observables suitable fo
measurements, and then perform the corresponding analyses using simulated events in the dilepton final state, reconstructing up to the unfolded level. We find that entanglem
only very high-p_T events are sensitive to a vio
different unfolding methods and independent
he high luminosity LHC run.

[Submitted on 24 Aug 2022]

Constraining new physics in entangled two-qubit systems: top-quark, tau-lepton and photon pairs

Marco Fabbrichesi, Roberto Floreanini, Emidio Gabrielli

The measurement of quantum entanglement can provide a new and most sensitive probe to physics beyond the Standard Model. We use the concurrence of the top-quark pairs spi
states produced at colliders to constrain the magnetic dipole term in the coupling between top quark and gluons, that of τ-lepton pairs spin states to bound contact interactions an
that of τ-lepton pairs or two photons spin states from the decay of the Higgs boson to try distinguishing between CP-even and odd couplings. These four examples show the powe
of the new approach as well as its limitations. We show that differences in the entanglement in the top-quark and τ-lepton pairs production cross sections can provide constraints
better than those previously estimated from total cross sections or classical correlations. Instead, the final states in the decays of the Higgs boson remain maximally entangled even
in the presence of CP-odd couplings and cannot be used to set bounds on new physics. We discuss the violation of Bell inequalities featured in all four processes and find that the
decays of the Higgs boson into τ-lepton pairs or two photons constitute the best instances to observe such violations.

Comments: 31 pages, 16 Figures
Subjects: High Energy Physics - Phenomenology (hep-ph); High Energy Physics - Experiment (hep-ex)
Cite as: arXiv:2208.11723 [hep-ph]
(or arXiv:2208.11723v1 [hep-ph] for this version)
https://doi.org/10.48550/arXiv.2208.11723

[Submitted on 23 Feb 2021 (v1), last revised 27 Oct 2021 (this version, v2)]

Testing Bell inequalities at the LHC with top-quark pairs

M. Fabbrichesi, R. Floreanini, G. Panizzo

Entanglement between the spins of top-quark pairs produced at a collider can be used to test a (generalized) Bell inequality at energies never explored so far. We show how the
measurement of a single observable can provide a test of the violation of the Bell inequality at the 98% CL with the data already collected at the Large Hadron Collider and at the
99.99% CL with the higher luminosity of the next run.

Comments: 4 pages, 1 figure
Subjects: High Energy Physics - Phenomenology (hep-ph); High Energy Physics - Experiment (hep-ex); Quantum Physics (quant-ph)
Cite as: arXiv:2102.11883 [hep-ph]
(or arXiv:2102.11883v2 [hep-ph] for this version)
https://doi.org/10.48550/arXiv.2102.11883
Journal reference: Phys.Rev.Lett. 127 (2021) 16, 161801
Related DOI: https://doi.org/10.1103/PhysRevLett.127.161801

Wrapping it up

Multiple final states to study quantum information:

- ttbar, HWW*, HZZ* – qubits and qutrits with elementary particles
- multi-lepton final states are prime experimental candidates

The ultimate goal is to **measure the full spin density matrices** (in several bases and differentially in the invariant mass of the system)

- can also target observation of entanglement by using dedicated observables (few caveats of SM-like assumptions)
- Bell's inequality violation very challenging
- use the **large spin-randomised samples provided by the LHC** to measure quantum theoretic quantities according to their strong definitions

First observation of quantum entanglement in quarks and at relativistic energies!

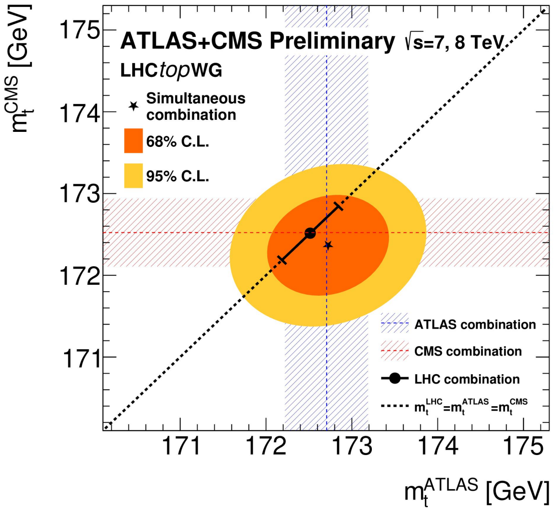
A new subfield emerges: **quantum information at the LHC**

In summary…

to find out more

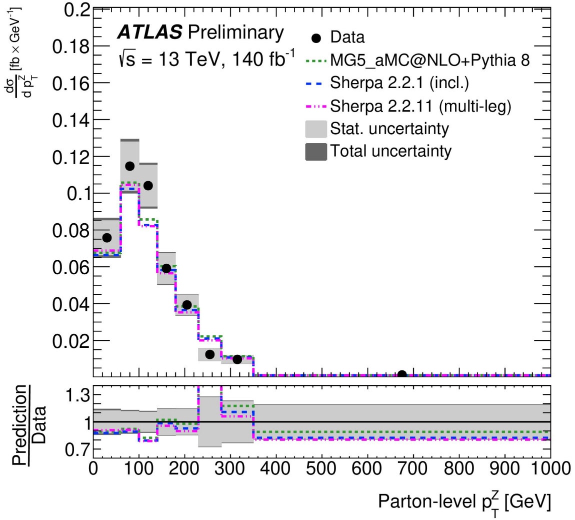
- 👉 CMS results
- 👉 ATLAS results
- 👉 TOP'23 conference

Top quark physics: an **exciting and very active** research program at the LHC!



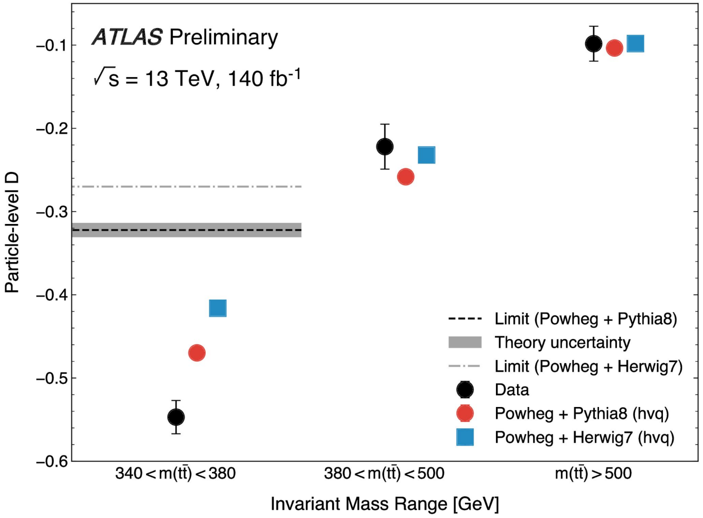
ATLAS-CONF-2023-066

Most precise top mass measurement: importance of correlations!



ATLAS-CONF-2023-065

Legacy ttZ results: new analysis techniques significantly improve the precision!

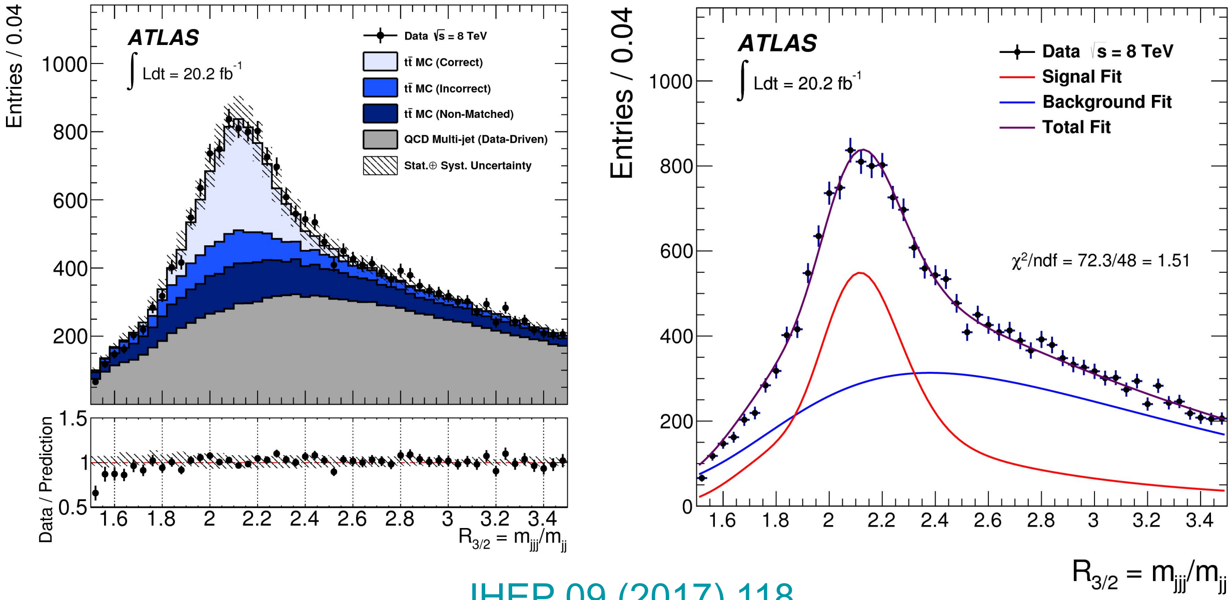


ATLAS-CONF-2023-069

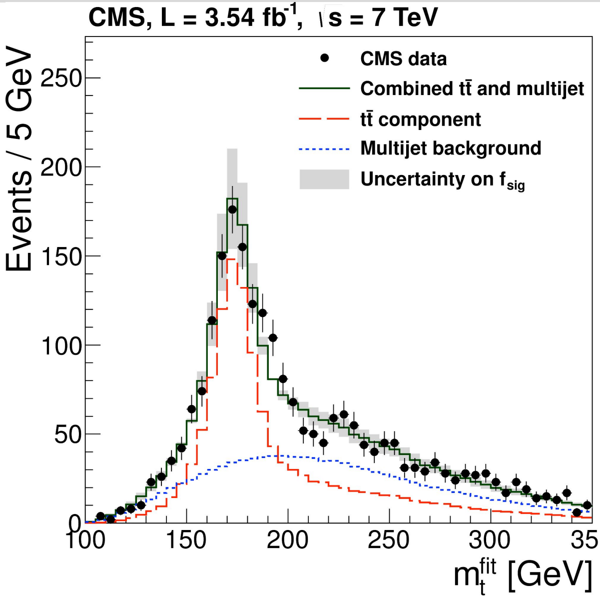
First observation of quantum entanglement in quarks and at high energies!

Backup

[mass] A brief look at: all-jets measurements



JHEP 09 (2017) 118

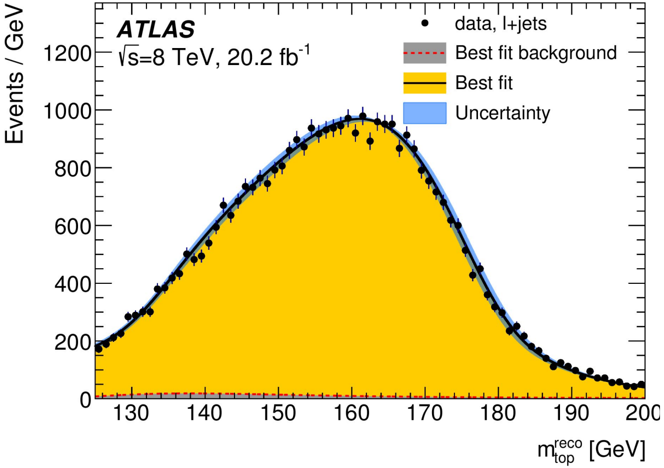


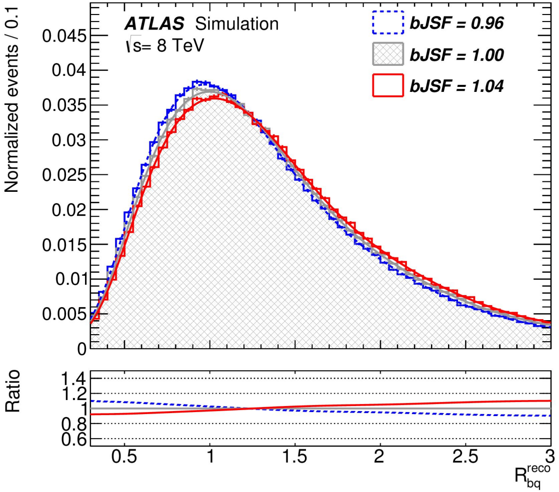
Eur. Phys. J. C 74, 2758 (2014)

- Use a □^{2} fit to find the best W→jj and t→jjb assignments
- Consider the ratio $R_{3/2}=m_{jjj}/m_{jj}$
- Benefit from **partial cancellation of uncertainties** (JES)
- Fit the top mass twice per event

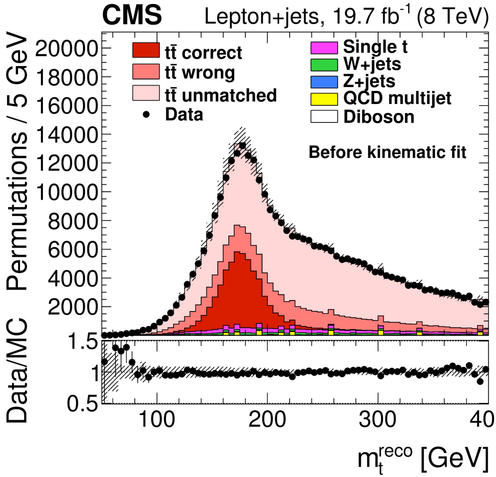
- Perform a kinematic fit to improve the resolution of m_{top}
- Use mass of the W candidates to **measure the JES in-situ**

[mass] A brief look at: lepton+jets measurements

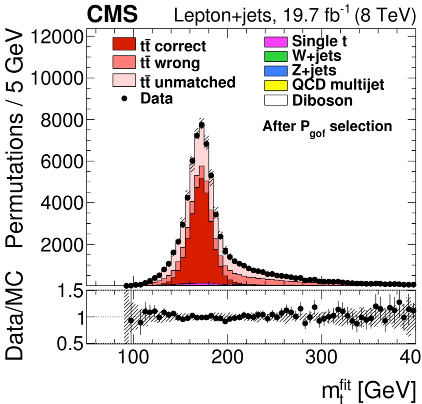




Eur. Phys. J. C 79, 290 (2019)



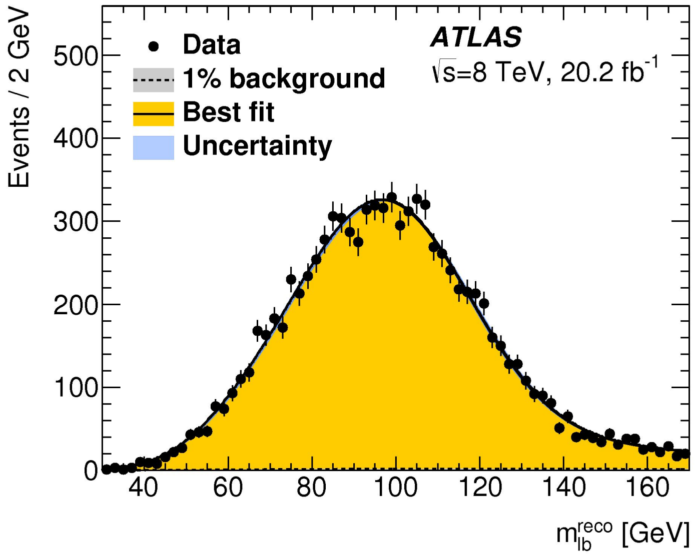
Phys. Rev. D 93 (2016), 072004



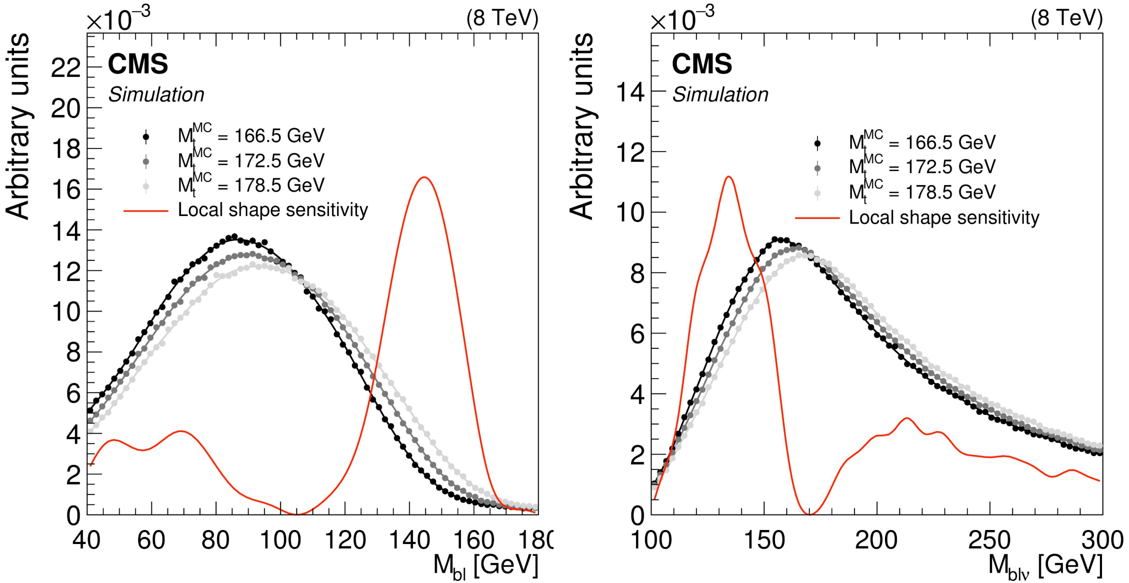
- **Reconstruct the full ttbar system** with KLFitter: likelihood fit with transfer functions to correct the kinematics
- Further **extract the JES** from the hadronic W mass, and the **b-JES** from the ratio of $\sum$(b-jet p_T) to $\sum$(light-jet p_T)

- CMS: same idea of kinematic fit + **extract JES** from m_W

[mass] A brief look at: dilepton measurements



Phys. Let. B 761 (2016) 350

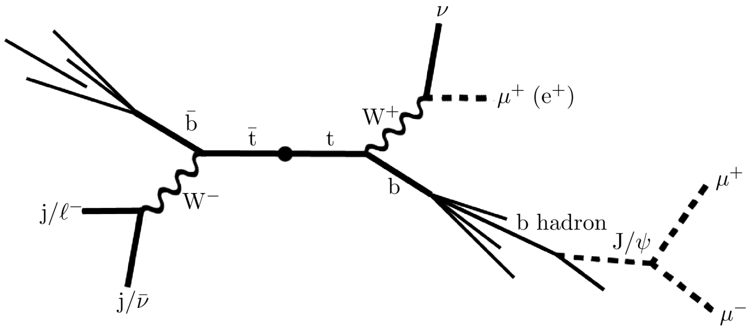


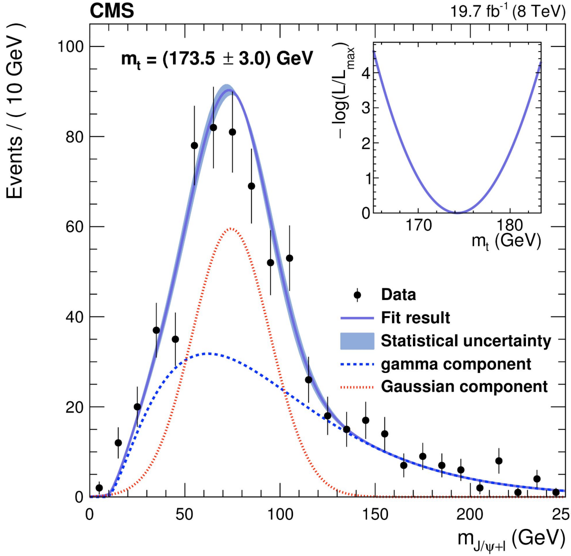
Phys. Rev. D 96 (2017), 032002

- Very pure dilepton selection, but two neutrinos → **underconstrained system**, very challenging reconstruction
- Rely on the visible particles: min(<m_{lb}>)

- Further observables considered: m_{bl}, m_{T2}, $m_{bl\nu}$
- Different sensitivity to m_{top} → complementarity
- Model the distributions with Gaussian Process regression, and plug into 2D/3D likelihood fit

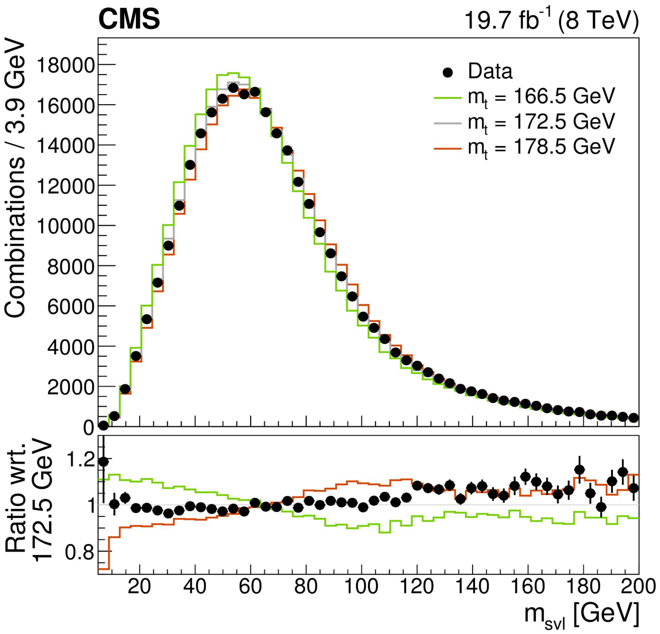
[mass] A brief look at: other types of measurements





JHEP 12 (2016) 123

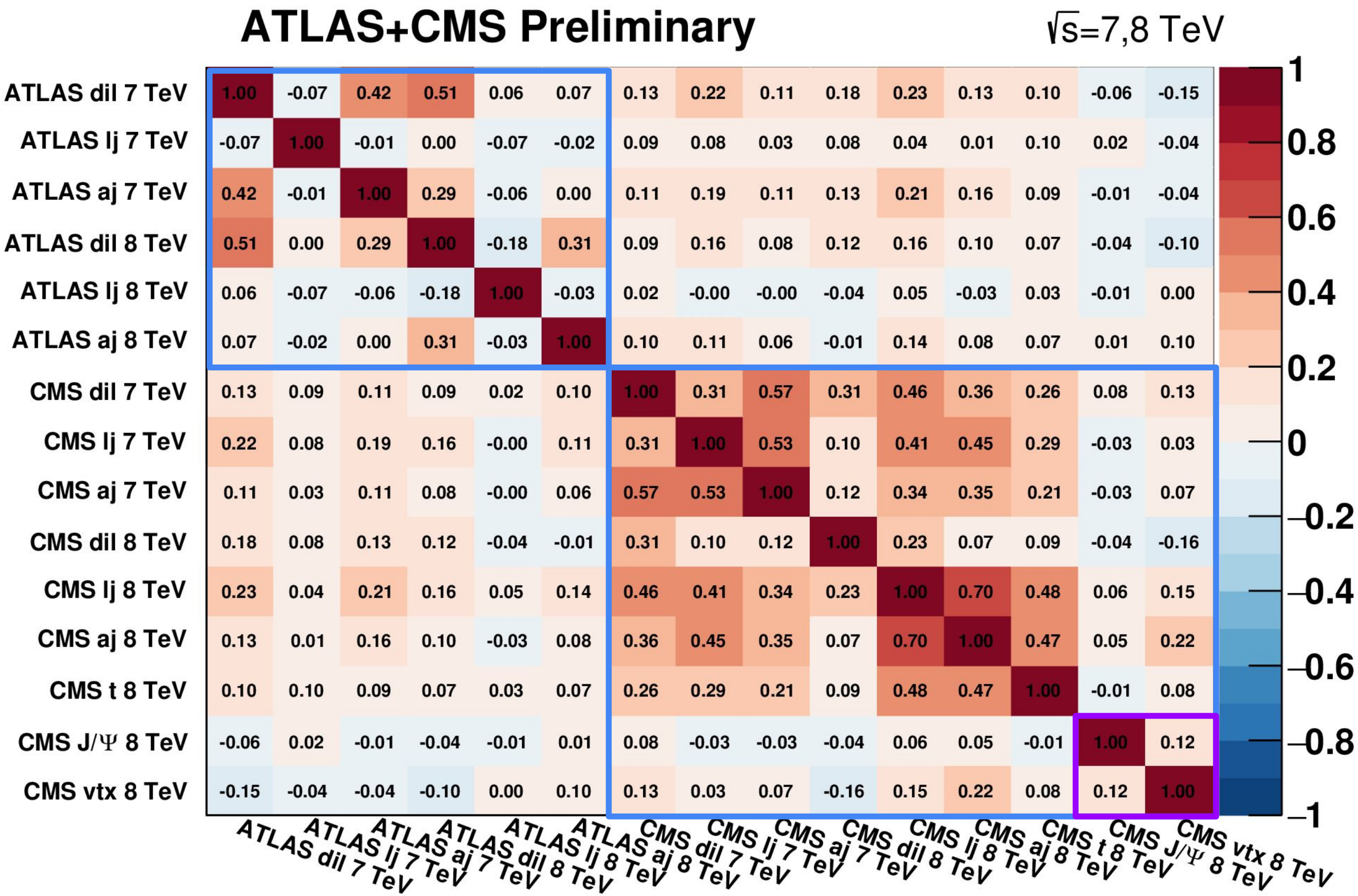
- Use a **clean J/ψ→μμ** system as a proxy for the b-jet
- Avoids the large jet and tagging uncertainties



Phys. Rev. D 93 (2017), 092006

- Alternatively, use the **charged particles** (pions) from the secondary vertex
- Minimally sensitive to JES, but b-fragmentation new challenge

[mass] Final overall correlations



	ATLAS dil 7 TeV	ATLAS lj 7 TeV	ATLAS aj 7 TeV	ATLAS dil 8 TeV	ATLAS lj 8 TeV	ATLAS aj 8 TeV	CMS dil 7 TeV	CMS lj 7 TeV	CMS aj 7 TeV	CMS dil 8 TeV	CMS lj 8 TeV	CMS aj 8 TeV	CMS t 8 TeV	CMS J/Ψ 8 TeV	CMS vtx 8 TeV
ATLAS dil 7 TeV	1.00	-0.07	0.42	0.51	0.06	0.07	0.13	0.22	0.11	0.18	0.23	0.13	0.10	-0.06	-0.15
ATLAS lj 7 TeV	-0.07	1.00	-0.01	0.00	-0.07	-0.02	0.09	0.08	0.03	0.08	0.04	0.01	0.10	0.02	-0.04
ATLAS aj 7 TeV	0.42	-0.01	1.00	0.29	-0.06	0.00	0.11	0.19	0.11	0.13	0.21	0.16	0.09	-0.01	-0.04
ATLAS dil 8 TeV	0.51	0.00	0.29	1.00	-0.18	0.31	0.09	0.16	0.08	0.12	0.16	0.10	0.07	-0.04	-0.10
ATLAS lj 8 TeV	0.06	-0.07	-0.06	-0.18	1.00	-0.03	0.02	-0.00	-0.00	-0.04	0.05	-0.03	0.03	-0.01	0.00
ATLAS aj 8 TeV	0.07	-0.02	0.00	0.31	-0.03	1.00	0.10	0.11	0.06	-0.01	0.14	0.08	0.07	0.01	0.10
CMS dil 7 TeV	0.13	0.09	0.11	0.09	0.02	0.10	1.00	0.31	0.57	0.31	0.46	0.36	0.26	0.08	0.13
CMS lj 7 TeV	0.22	0.08	0.19	0.16	-0.00	0.11	0.31	1.00	0.53	0.10	0.41	0.45	0.29	-0.03	0.03
CMS aj 7 TeV	0.11	0.03	0.11	0.08	-0.00	0.06	0.57	0.53	1.00	0.12	0.34	0.35	0.21	-0.03	0.07
CMS dil 8 TeV	0.18	0.08	0.13	0.12	-0.04	-0.01	0.31	0.10	0.12	1.00	0.23	0.07	0.09	-0.04	-0.16
CMS lj 8 TeV	0.23	0.04	0.21	0.16	0.05	0.14	0.46	0.41	0.34	0.23	1.00	0.70	0.48	0.06	0.15
CMS aj 8 TeV	0.13	0.01	0.16	0.10	-0.03	0.08	0.36	0.45	0.35	0.07	0.70	1.00	0.47	0.05	0.22
CMS t 8 TeV	0.10	0.10	0.09	0.07	0.03	0.07	0.26	0.29	0.21	0.09	0.48	0.47	1.00	-0.01	0.08
CMS J/Ψ 8 TeV	-0.06	0.02	-0.01	-0.04	-0.01	0.01	0.08	-0.03	-0.03	-0.04	0.06	0.05	-0.01	1.00	0.12
CMS vtx 8 TeV	-0.15	-0.04	-0.04	-0.10	0.00	0.10	0.13	0.03	0.07	-0.16	0.15	0.22	0.08	0.12	1.00

[mass] Stability of the LHC combination

172.52 ± 0.14 (stat) ± 0.30 (syst) GeV

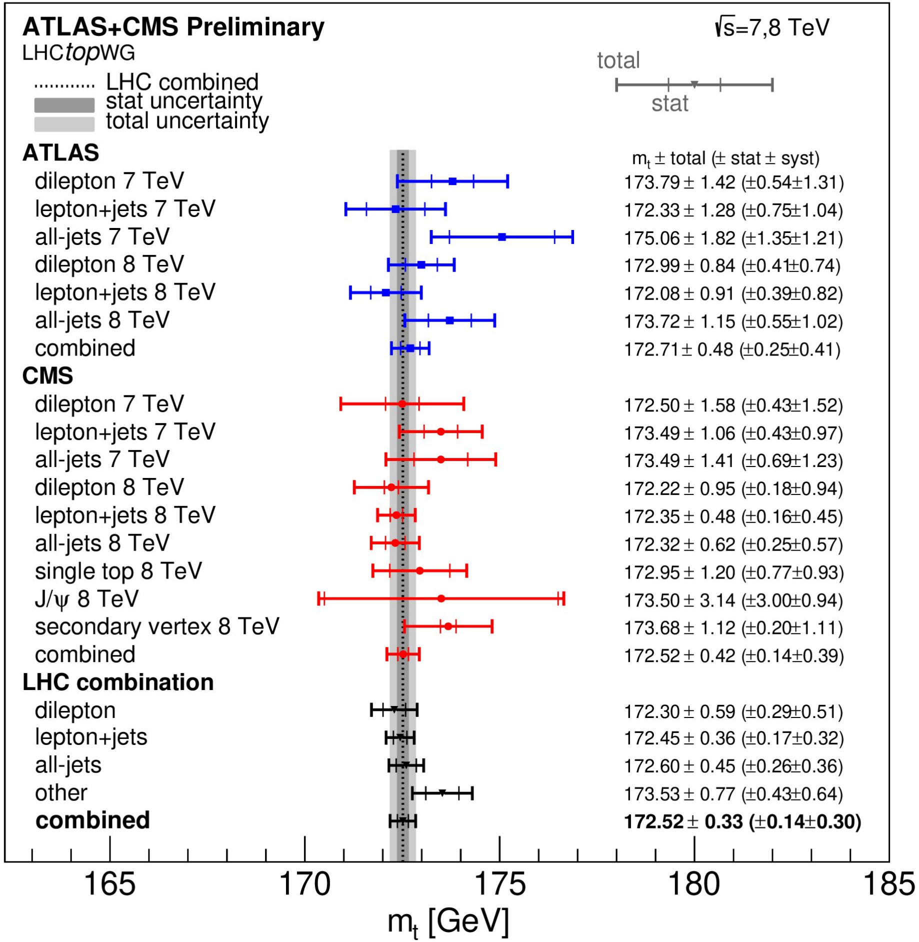
But how well do we know our systematic uncertainties?

Use pseudo-experiments to determine the statistical precision of the systematic templates

→ RMS of m_{top} is 63 MeV

→ RMS of its uncertainty is 19 MeV

→ stability of the combination



[ttZ] Systematic uncertainties

- **Detailed description of signal modelling**, based on state-of-the-art MC
  - parton shower and underlying event
  - initial state radiation
  - scale uncertainties as a proxy for unknown NNLO QCD
  - PDF uncertainties (PDF4LHC prescriptions)
  - alternative multi-leg generators used for comparisons
- **Background uncertainties** also revisited
  - measure all dominant backgrounds directly in data
  - only **tZq** can not be constrained precisely enough
    → rely on 14% ATLAS result, motivates future joint measurements?
  - singly-resonant **tWZ**: recent evidence from CMS, but still “unobserved”;
    large theory uncertainty → challenge for modelling!
- **Experimental uncertainties**: 200-300 NPs at the end of Run 2
  - more sophisticated JER, JES, electron and muon efficiencies breakdown
  - as seen in the Top Mass example, this is the way towards **more correct combinations**!

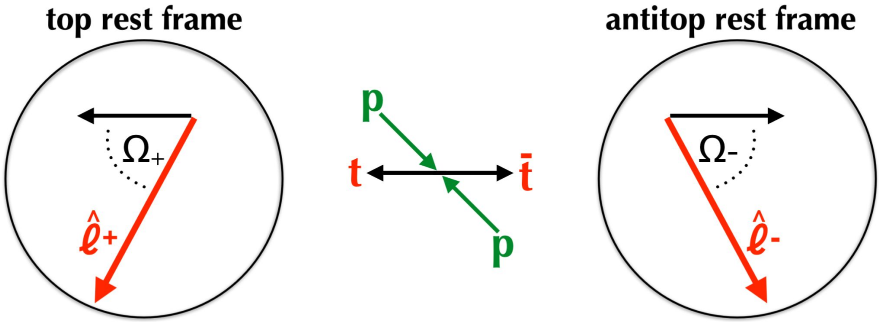
[ttZ] Spin correlations interpretation

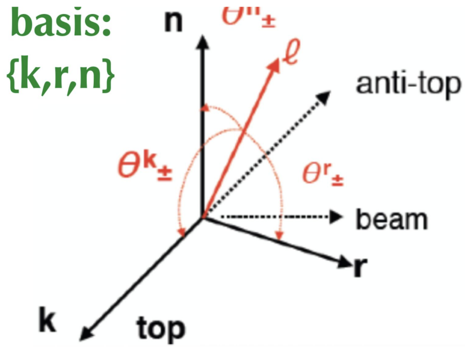
Presence of the Z boson modifies the SM expectations for spin correlations between the two tops: attempt to measure this effect **at detector-level**.

Consider 9 angular distributions probing the ttbar spin density matrix, and perform a template fit between SM hypothesis and “spin-off” hypothesis.

For each angular observable, extract f_{SM}, then combine in χ^2 fit (with stat. and syst. correlations)

Null hypothesis disfavoured at 1.8σ level





$$f_{SM}^{obs.} = 1.20 \pm 0.63\ (\text{stat.}) \pm 0.25\ (\text{syst.}) = 1.20 \pm 0.68\ (\text{tot.})$$

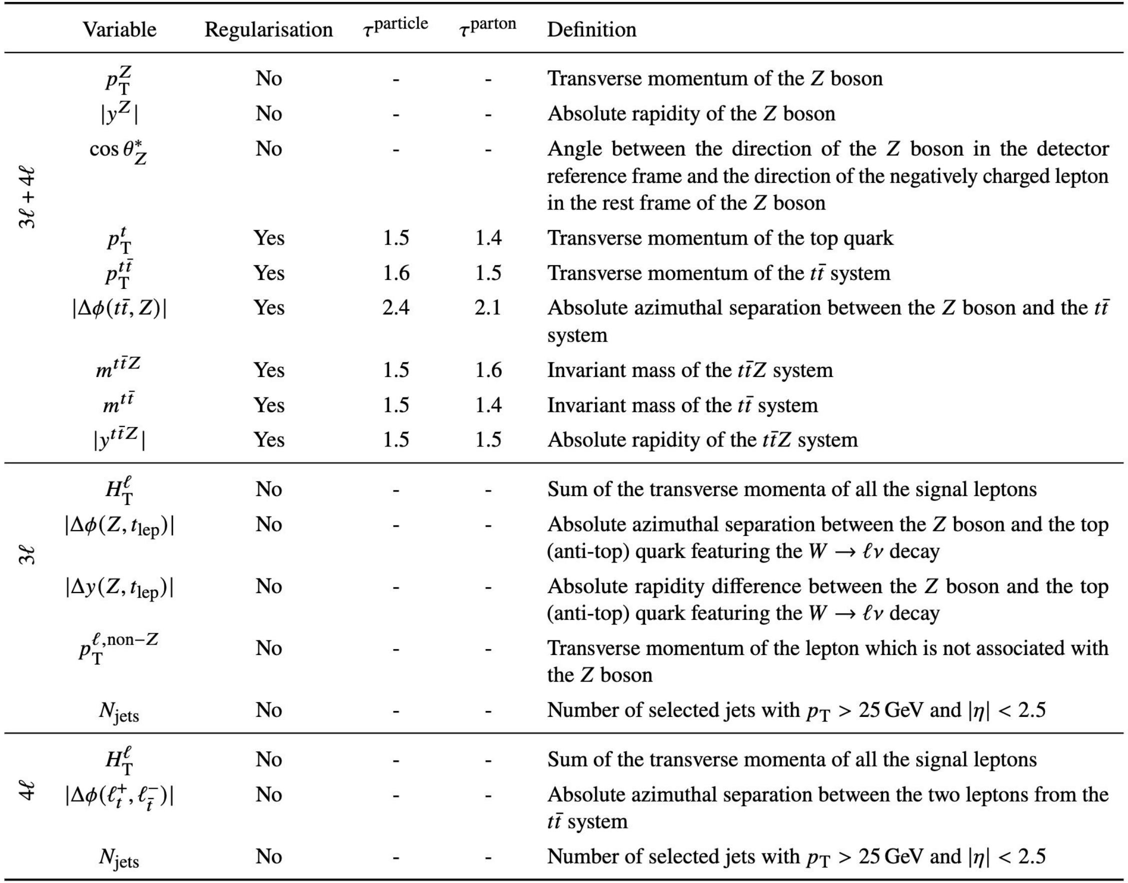
Looking forward: additional sensitivity to modification of top-Z coupling.

[ttZ] Differential measurements

Recent development in ATLAS: **profile-likelihood unfolding**.

Multiple benefits: pulls and constraints of the uncertainties, normalisation of backgrounds, inclusion of control regions and multiple signal regions, ability to save the full likelihood for HEPdata!

Tikhonov regularisation whenever hadronic top or full ttbar reconstruction is needed.



	Variable	Regularisation	τ^{particle}	τ^{parton}	Definition
$3\ell + 4\ell$	p_{T}^{Z}	No	-	-	Transverse momentum of the Z boson
	$\lvert y^{Z}\rvert$	No	-	-	Absolute rapidity of the Z boson
	$\cos\theta_{Z}^{*}$	No	-	-	Angle between the direction of the Z boson in the detector reference frame and the direction of the negatively charged lepton in the rest frame of the Z boson
	p_{T}^{t}	Yes	1.5	1.4	Transverse momentum of the top quark
	$p_{\mathrm{T}}^{t\bar{t}}$	Yes	1.6	1.5	Transverse momentum of the $t\bar{t}$ system
	$\lvert\Delta\phi(t\bar{t}, Z)\rvert$	Yes	2.4	2.1	Absolute azimuthal separation between the Z boson and the $t\bar{t}$ system
	$m^{t\bar{t}Z}$	Yes	1.5	1.6	Invariant mass of the $t\bar{t}Z$ system
	$m^{t\bar{t}}$	Yes	1.5	1.4	Invariant mass of the $t\bar{t}$ system
	$\lvert y^{t\bar{t}Z}\rvert$	Yes	1.5	1.5	Absolute rapidity of the $t\bar{t}Z$ system
3ℓ	H_{T}^{ℓ}	No	-	-	Sum of the transverse momenta of all the signal leptons
	$\lvert\Delta\phi(Z, t_{\text{lep}})\rvert$	No	-	-	Absolute azimuthal separation between the Z boson and the top (anti-top) quark featuring the $W \to \ell\nu$ decay
	$\lvert\Delta y(Z, t_{\text{lep}})\rvert$	No	-	-	Absolute rapidity difference between the Z boson and the top (anti-top) quark featuring the $W \to \ell\nu$ decay
	$p_{\mathrm{T}}^{\ell,\text{non}-Z}$	No	-	-	Transverse momentum of the lepton which is not associated with the Z boson
	N_{jets}	No	-	-	Number of selected jets with $p_{\mathrm{T}} > 25$ GeV and $\lvert\eta\rvert < 2.5$
4ℓ	H_{T}^{ℓ}	No	-	-	Sum of the transverse momenta of all the signal leptons
	$\lvert\Delta\phi(\ell_{t}^{+}, \ell_{\bar{t}}^{-})\rvert$	No	-	-	Absolute azimuthal separation between the two leptons from the $t\bar{t}$ system
	N_{jets}	No	-	-	Number of selected jets with $p_{\mathrm{T}} > 25$ GeV and $\lvert\eta\rvert < 2.5$

[ttZ] SMEFT interpretation

ttZ production is sensitive to **dim-6 EFT operators** both in the top-Z coupling and in the qq/gg→ttbar vertex.

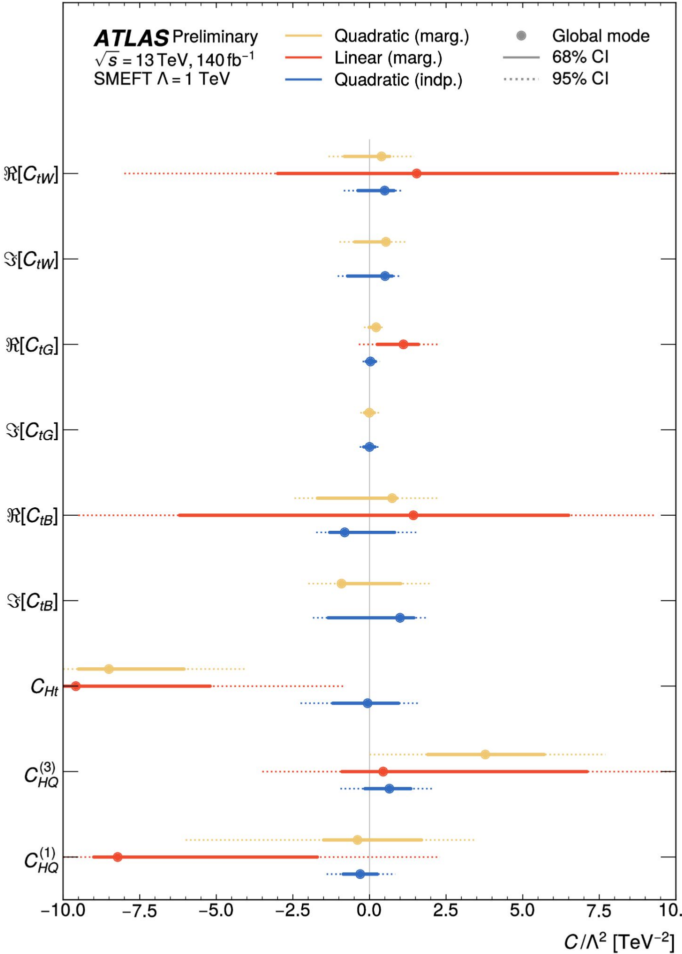
Use the differential distributions at particle-level as input to the EFT fit (with proper correlations taken into account), relying on LO QCD parameterisation from `SMEFTsim 3.0`.

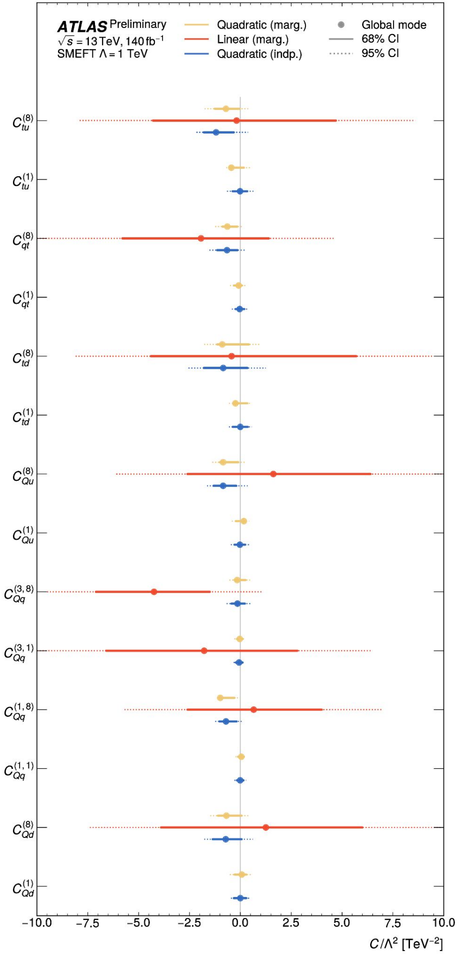
$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{d>4} \mathcal{L}^{(d)}, \quad \mathcal{L}^{(d)} = \sum_{i=1}^{n_d} \frac{C_i^{(d)}}{\Lambda^{d-4}} Q_i^{(d)} \qquad \mathcal{O} = \mathcal{O}_{\text{SM}} + \sum_i C_i A_i + \sum_{i,j} C_i C_j B_{ij}.$$

Perform **3 different fits** to assess the relevance of SM/EFT interference and pure EFT terms, and the sensitivity to each operator individually.

Also perform PCA to **identify directions of sensitivity** probed by the measurement.

[ttZ] Results of the SMEFT interpretation



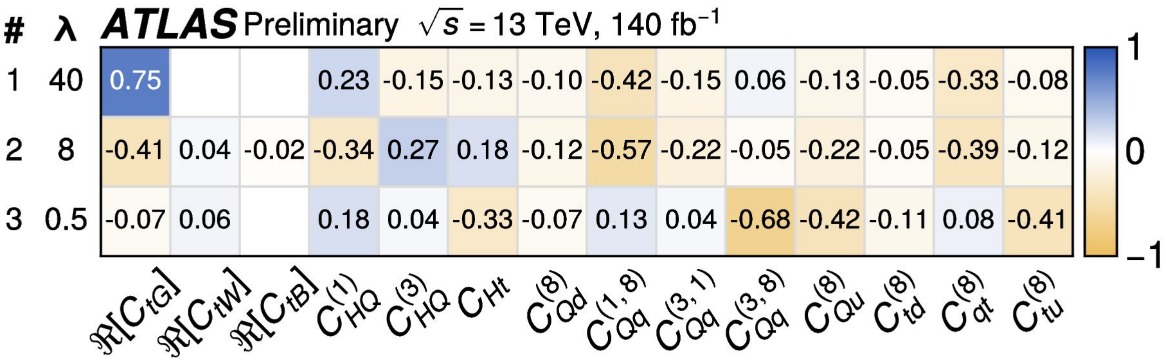


Separate fits to top-boson and four-quark operators in the Warsaw basis: no significant deviation from the SM, but patterns indicating the need to take into account linear combinations → **PCA / Fisher information matrix**

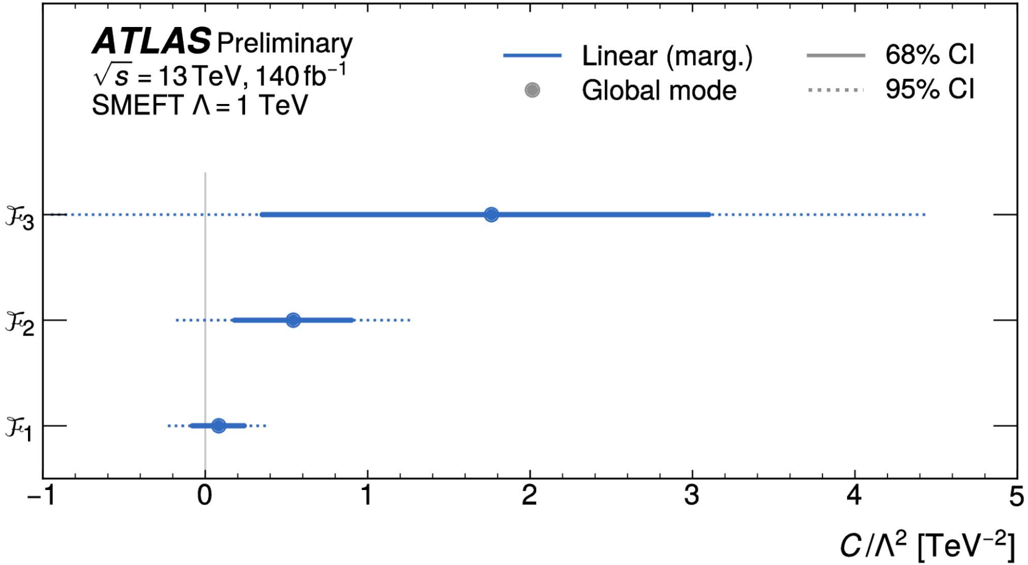
Top-boson operators: affect the strength of the V-A coupling of the Z boson to the top, allow new Lorentz structure (dipole), CP-violation (imaginary parts).

Four-quark operators: only relevant for the subdominant qq→ttbar channel, but different sensitivity than simple ttbar due to possible ISR Z.
Particularly important to take into account EFT-EFT interference!

[ttZ] SMEFT interpretation in the rotated basis



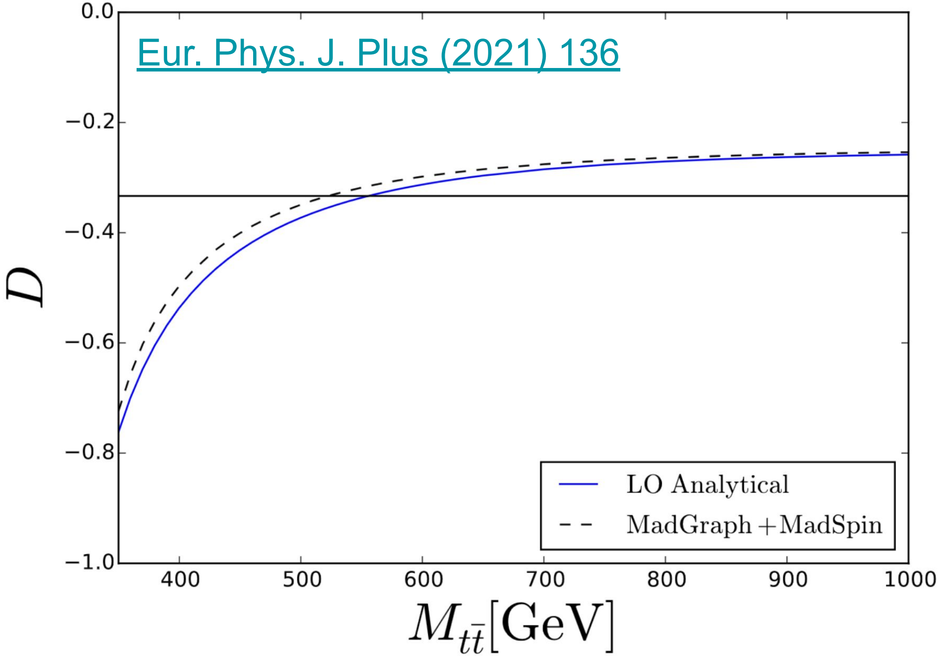
#	λ	$\Re[C_{tG}]$	$\Re[C_{tW}]$	$\Re[C_{tB}]$	$C_{HQ}^{(1)}$	$C_{HQ}^{(3)}$	C_{Ht}	$C_{Qd}^{(8)}$	$C_{Qq}^{(1,8)}$	$C_{Qq}^{(3,1)}$	$C_{Qq}^{(3,8)}$	$C_{Qu}^{(8)}$	$C_{td}^{(8)}$	$C_{qt}^{(8)}$	$C_{tu}^{(8)}$
1	40	0.75			0.23	-0.15	-0.13	-0.10	-0.42	-0.15	0.06	-0.13	-0.05	-0.33	-0.08
2	8	-0.41	0.04	-0.02	-0.34	0.27	0.18	-0.12	-0.57	-0.22	-0.05	-0.22	-0.05	-0.39	-0.12
3	0.5	-0.07	0.06		0.18	0.04	-0.33	-0.07	0.13	0.04	-0.68	-0.42	-0.11	0.08	-0.41



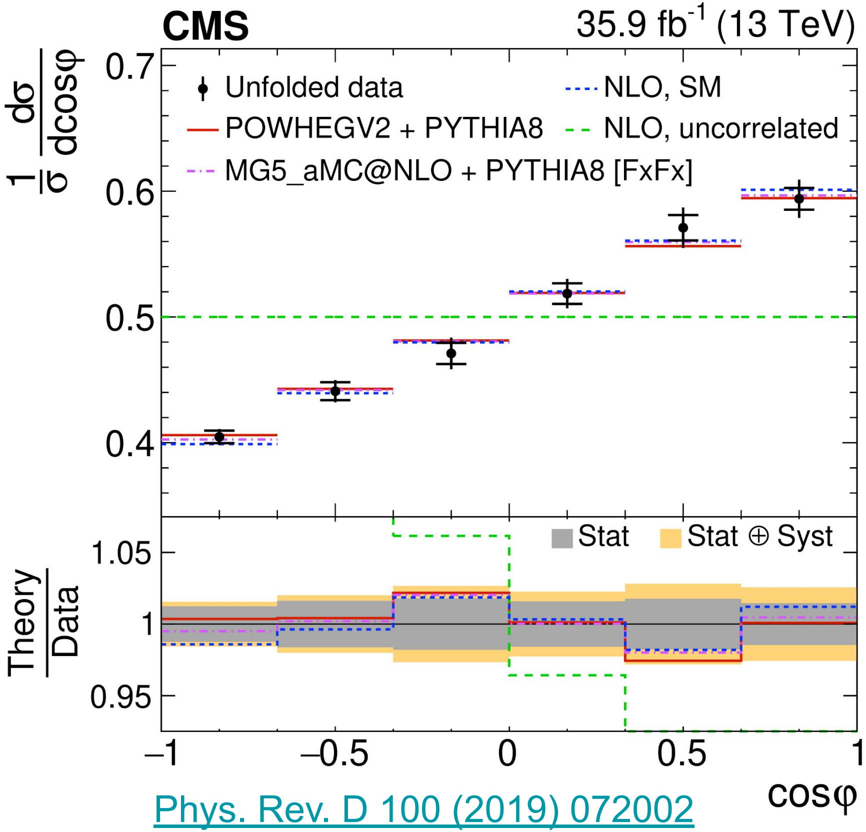
Since we are very close to the SM, use a **linear EFT approximation** and **rotate** the Warsaw basis into 3 new directions of sensitivity:

- **ctG dominates** because of large impact on gg→ttbar, but four-quark operators still important;
- **top-boson operators** more discrete, but recover some of the expected linear combinations;
- pattern of positive central values accommodates the slight excess in 4L, but still consistent with SM.

[entanglement] The 2019 CMS measurement



Eur. Phys. J. Plus (2021) 136

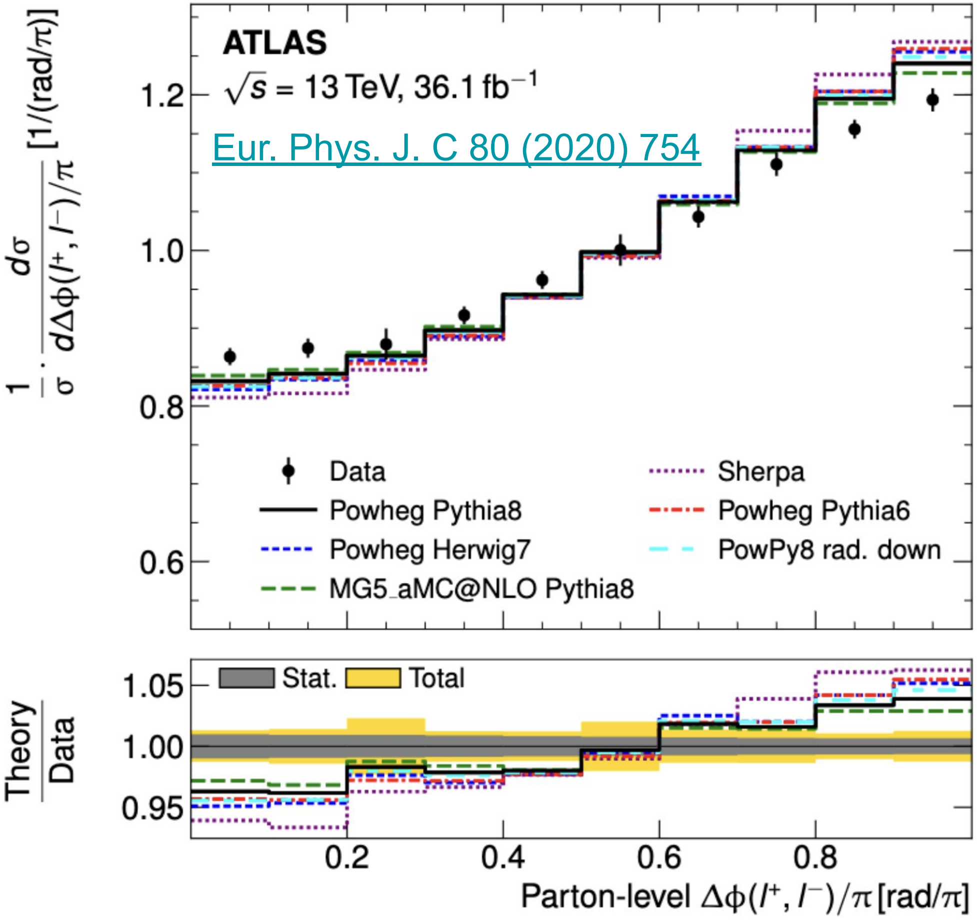


Phys. Rev. D 100 (2019) 072002

CMS measured $D = -0.237 \pm 0.011 > -\frac{1}{3}$

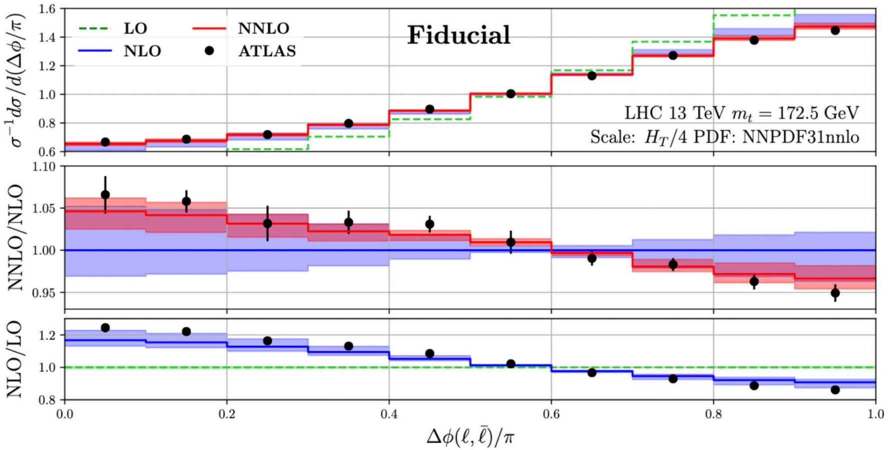
inclusively → need to go differential in M(ttbar)

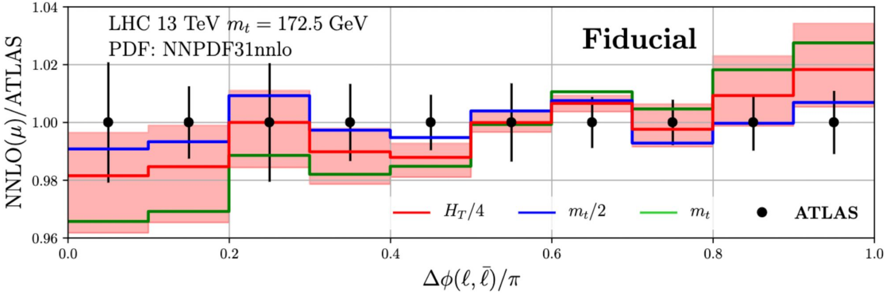
[entanglement] Spin correlations at NNLO



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

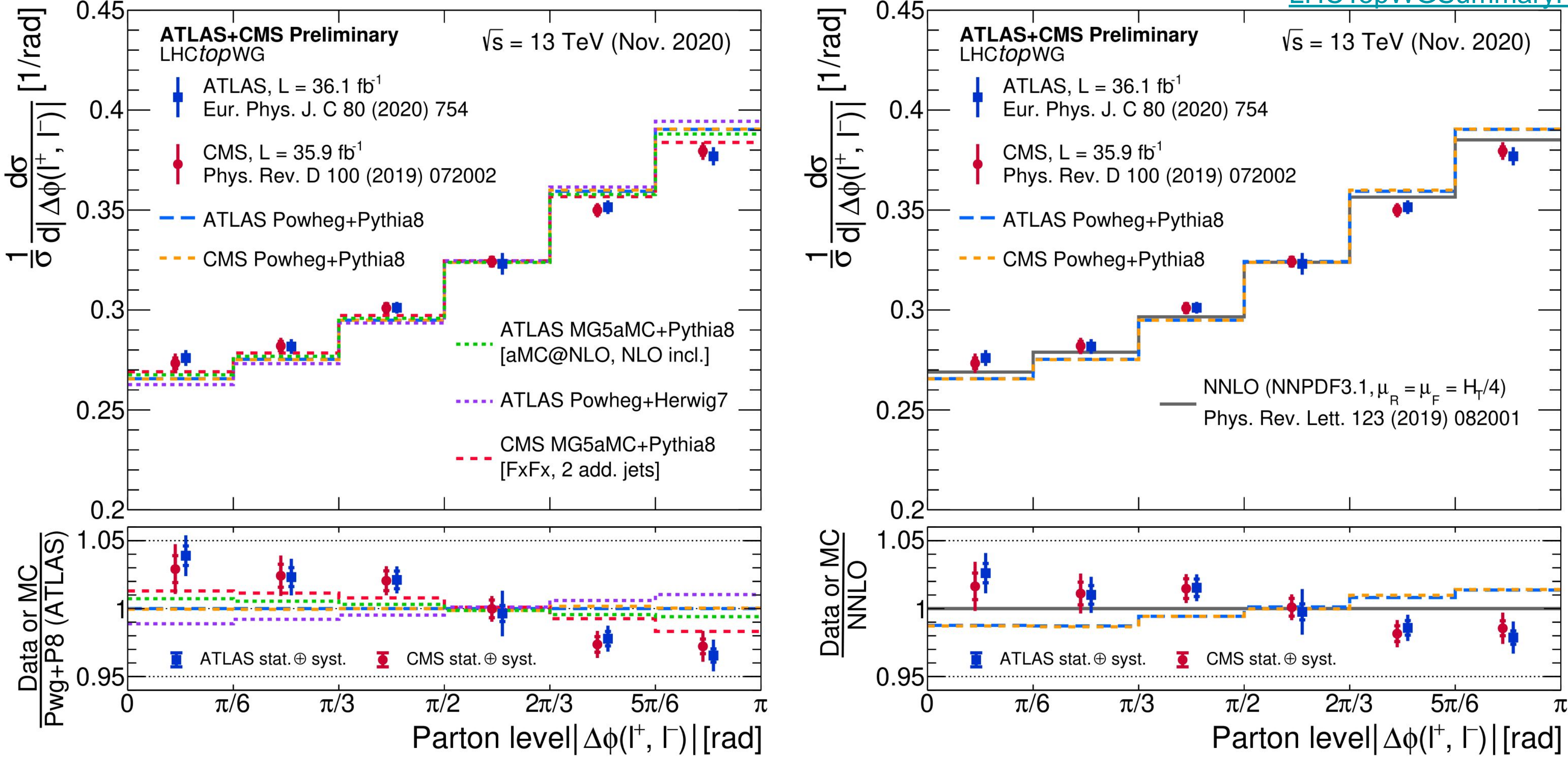
arXiv:1901.05407





[entanglement] Spin correlations: ATLAS and CMS

LHCTopWGSummaryPlots



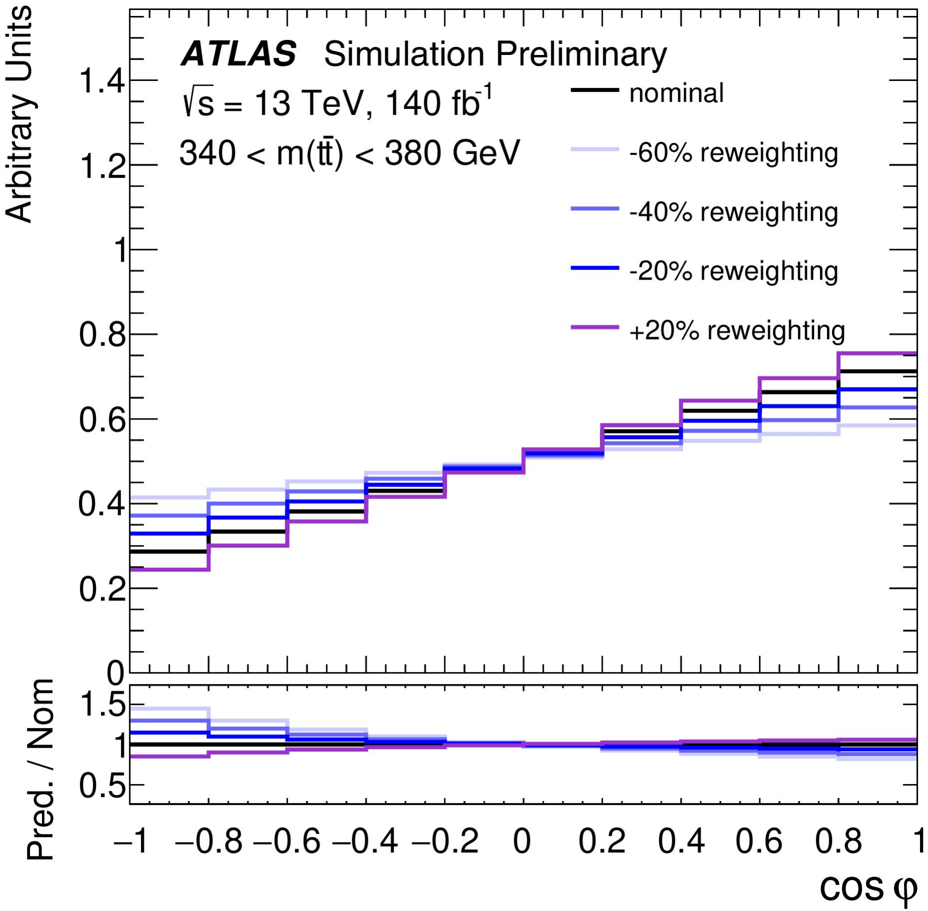
[entanglement] The reweighting method

- We have no handle on the "amount of entanglement" in the generators, but we know exact functional forms at parton-level → can reweight D
- Fit a 3rd order polynomial to extract the dependence on M(ttbar)

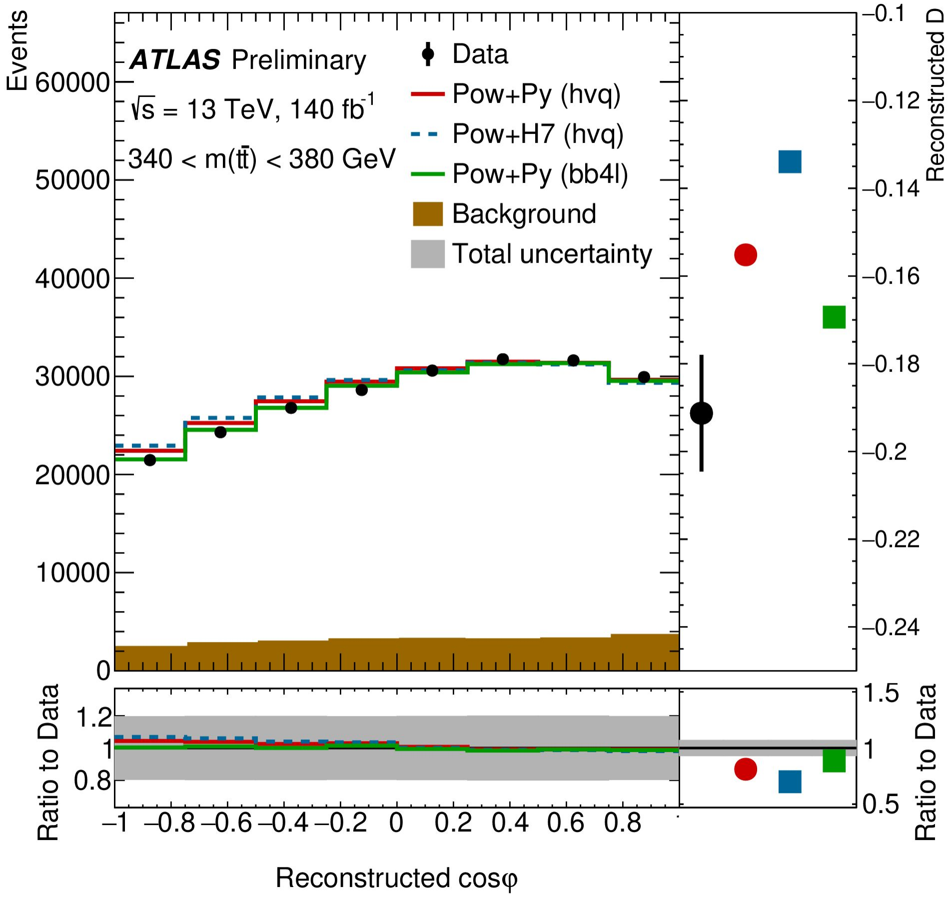
$$D_\Omega(m_{t\bar{t}}) = x_0 + x_1 \cdot m_{t\bar{t}}^{-1} + x_2 \cdot m_{t\bar{t}}^{-2} + x_3 \cdot m_{t\bar{t}}^{-3}$$

- Then reweight each event as

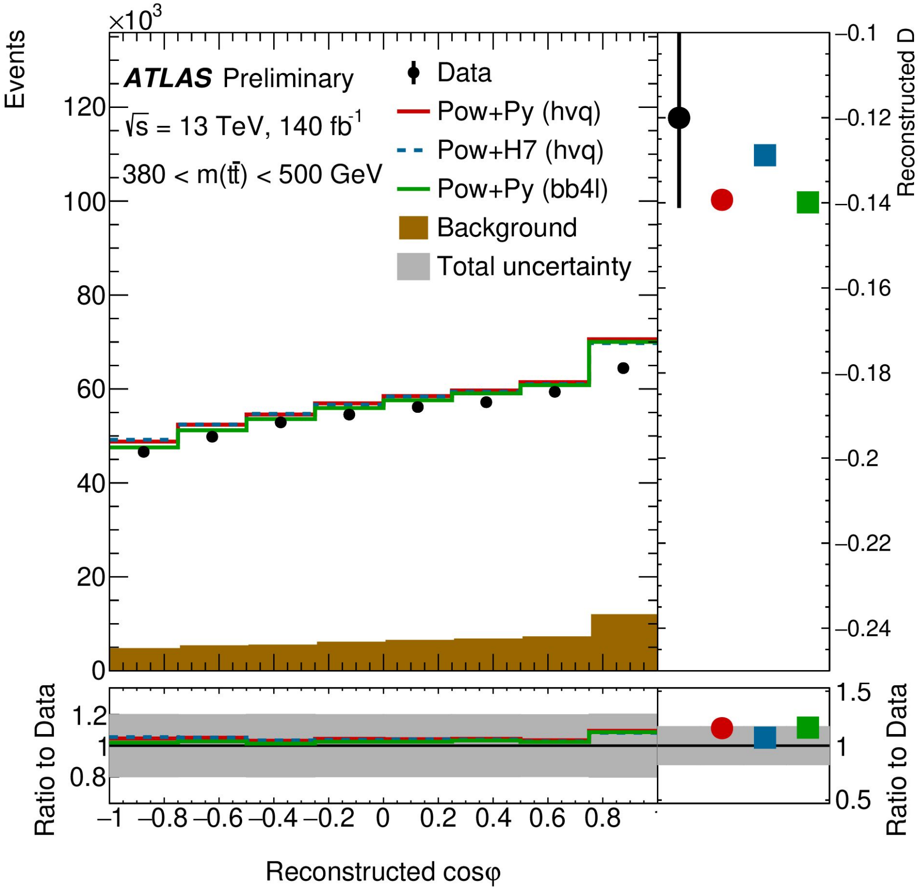
$$w = \frac{1 - D_\Omega(m_{t\bar{t}}) \cdot \mathcal{X} \cdot \cos\varphi}{1 - D_\Omega(m_{t\bar{t}}) \cdot \cos\varphi}$$

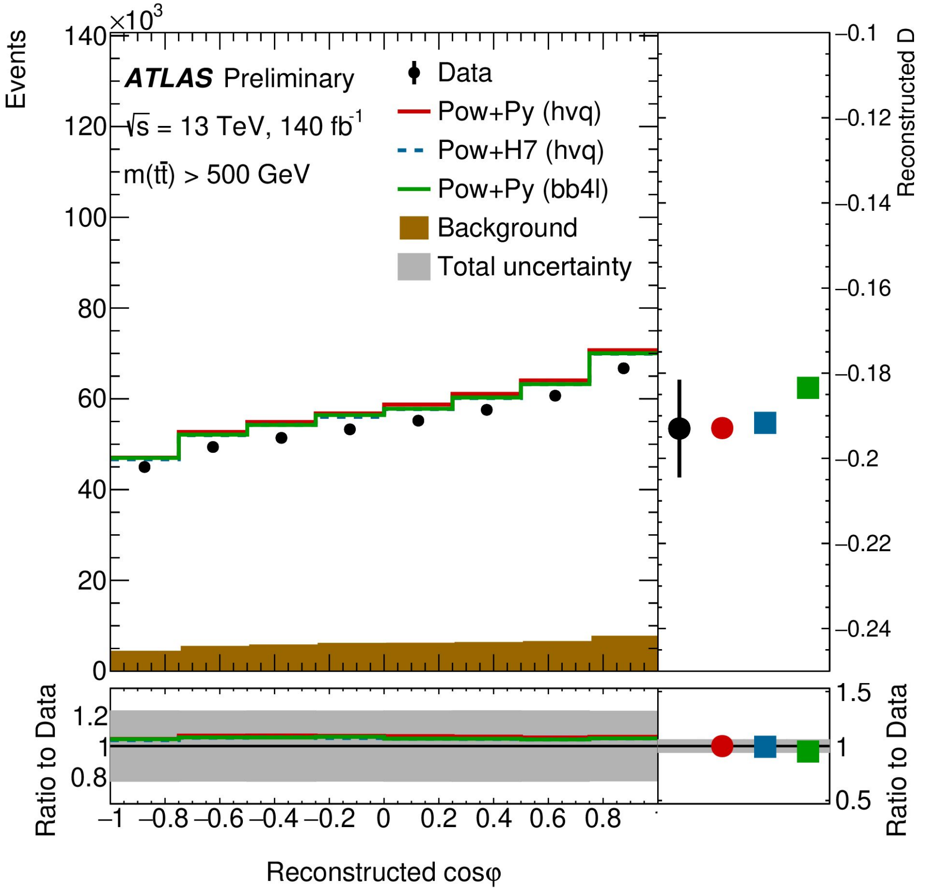


[entanglement] Data / MC in the signal region

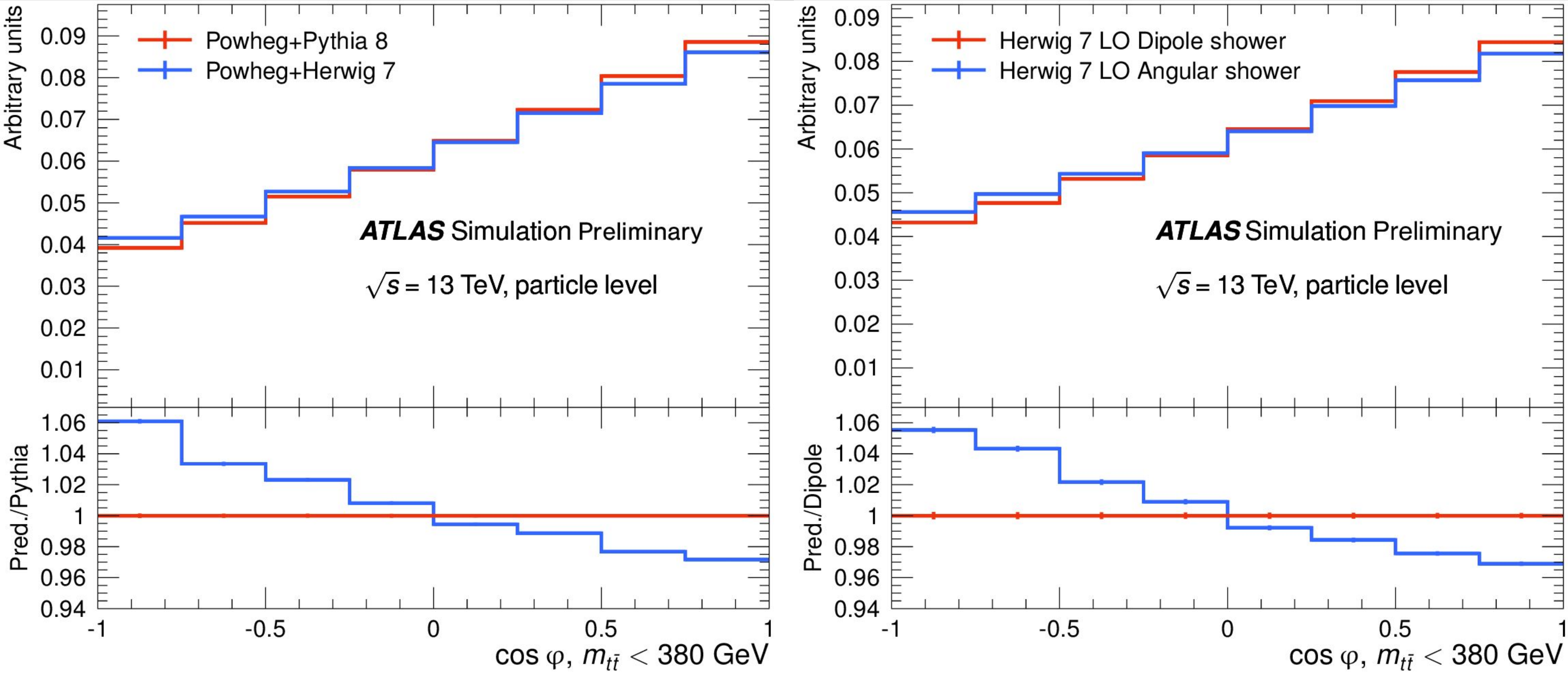


[entanglement] Data / MC outside the signal region





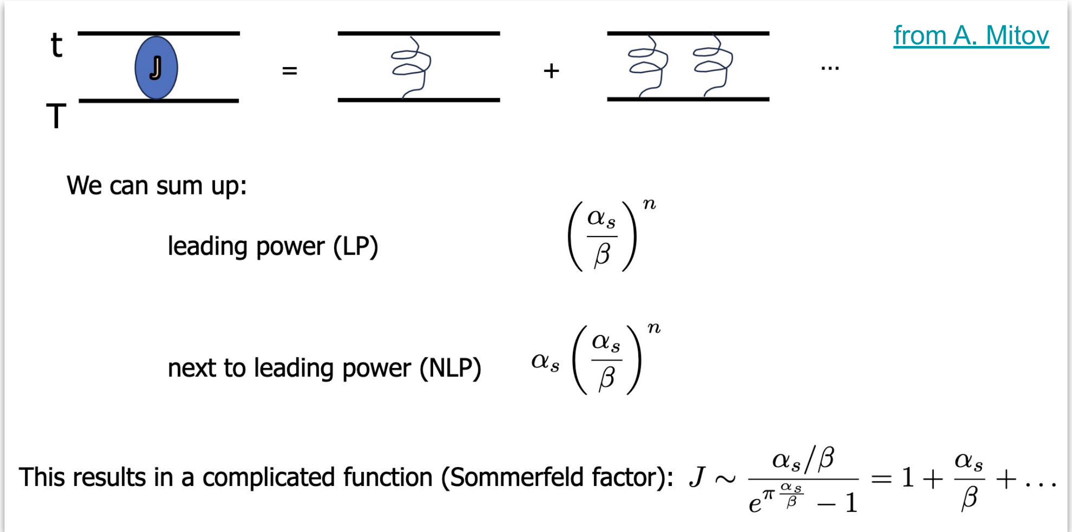
[entanglement] Investigations of parton shower effects



Differences appear in the parton→particle level transition,
and seem to largely match the Dipole vs Angular ordering schemes

[entanglement] At threshold: need input from the theorists

- Our MC generators don’t include the necessary non-perturbative effects – how do we get around that?
  - Fuks et al. implemented a BSM Lagrangian in MadGraph → **toponium**
  - A number of calculations available, most recently Ju et al.
    - pure parton-level calculation (stable tops), resums leading-power and next-to-leading-power calculations and matches to NNLO differential ttbar



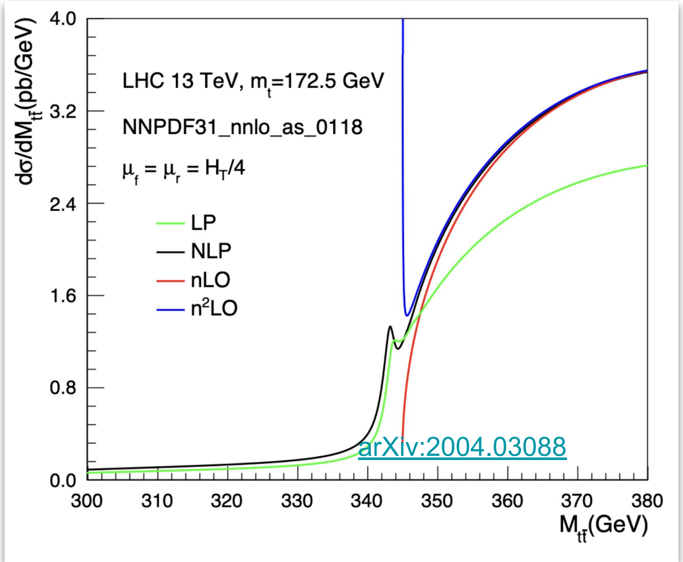
from A. Mitov

We can sum up:

leading power (LP) $\left(\frac{\alpha_s}{\beta}\right)^n$

next to leading power (NLP) $\alpha_s \left(\frac{\alpha_s}{\beta}\right)^n$

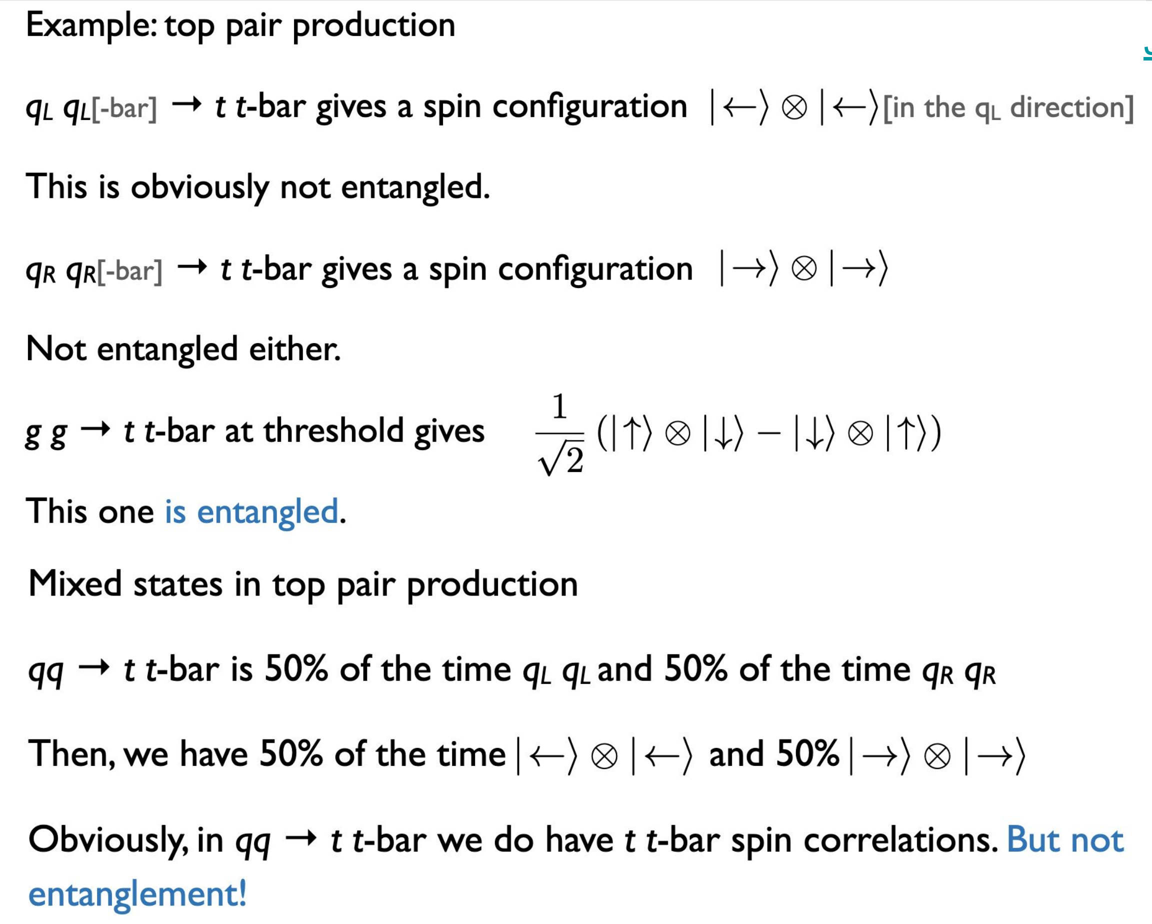
This results in a complicated function (Sommerfeld factor): $J \sim \frac{\alpha_s/\beta}{e^{\pi\frac{\alpha_s}{\beta}}-1} = 1 + \frac{\alpha_s}{\beta} + \ldots$



arXiv:2004.03088

[entanglement] Separable and entangled states

J.A. Aguilar Saavedra



Example: top pair production

q_L q_L[-bar] → *t t*-bar gives a spin configuration $|\leftarrow\rangle \otimes |\leftarrow\rangle$[in the q_L direction]

This is obviously not entangled.

q_R q_R[-bar] → *t t*-bar gives a spin configuration $|\rightarrow\rangle \otimes |\rightarrow\rangle$

Not entangled either.

g g → *t t*-bar at threshold gives $\frac{1}{\sqrt{2}}\left(|\uparrow\rangle \otimes |\downarrow\rangle - |\downarrow\rangle \otimes |\uparrow\rangle\right)$

This one is entangled.

Mixed states in top pair production

qq → *t t*-bar is 50% of the time q_L q_L and 50% of the time q_R q_R

Then, we have 50% of the time $|\leftarrow\rangle \otimes |\leftarrow\rangle$ and 50% $|\rightarrow\rangle \otimes |\rightarrow\rangle$

Obviously, in *qq* → *t t*-bar we do have *t t*-bar spin correlations. But not entanglement!

[entanglement] General bipartite qubit system

$$\rho = \frac{1}{4}\left(\mathbb{1}\otimes\mathbb{1} + \sum_i \left(B_i^+ \sigma_i \otimes \mathbb{1} + B_i^- \mathbb{1}\otimes\sigma_i\right) + \sum_{ij} C_{ij}\sigma_i\otimes\sigma_j\right)$$

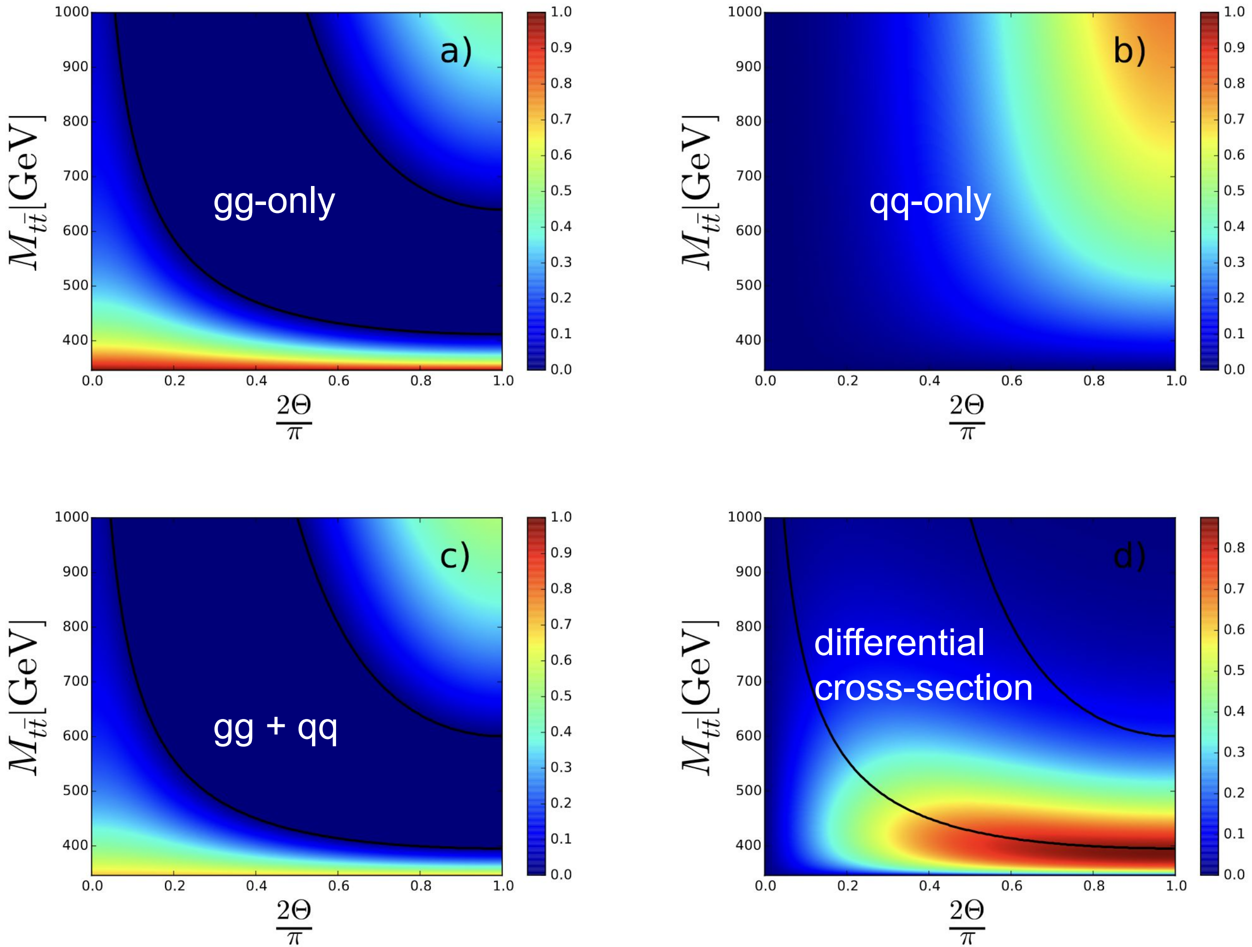
$$\rho = \frac{1}{4}\begin{bmatrix} 1+B_3^+ + B_3^- + C_{33} & B_1^- + C_{31} - i(B_2^- + C_{32}) & B_1^+ + C_{13} - i(B_2^+ + C_{23}) & C_{11} - C_{22} - i(C_{12} + C_{21}) \\ B_1^- + C_{31} + i(B_2^- + C_{32}) & 1 + B_3^+ - B_3^- - C_{33} & C_{11} + C_{22} + i(C_{12} - C_{21}) & B_1^+ - C_{13} - i(B_2^+ - C_{23}) \\ B_1^+ + C_{13} + i(B_2^+ + C_{23}) & C_{11} + C_{22} - i(C_{12} - C_{21}) & 1 - B_3^+ + B_3^- - C_{33} & B_1^- - C_{31} - i(B_2^- - C_{32}) \\ C_{11} - C_{22} + i(C_{12} + C_{21}) & B_1^+ - C_{13} + i(B_2^+ - C_{23}) & B_1^- - C_{31} + i(B_2^- - C_{32}) & 1 - B_3^+ - B_3^- + C_{33} \end{bmatrix}$$

$$\rho^{T_2} = \frac{1}{4}\begin{bmatrix} 1+B_3^+ + B_3^- + C_{33} & B_1^- + C_{31} + i(B_2^- + C_{32}) & B_1^+ + C_{13} - i(B_2^+ + C_{23}) & C_{11} + C_{22} + i(C_{12} - C_{21}) \\ B_1^- + C_{31} - i(B_2^- + C_{32}) & 1 + B_3^+ - B_3^- - C_{33} & C_{11} - C_{22} - i(C_{12} + C_{21}) & B_1^+ - C_{13} - i(B_2^+ - C_{23}) \\ B_1^+ + C_{13} + i(B_2^+ + C_{23}) & C_{11} - C_{22} + i(C_{12} + C_{21}) & 1 - B_3^+ + B_3^- - C_{33} & B_1^- - C_{31} + i(B_2^- - C_{32}) \\ C_{11} + C_{22} - i(C_{12} - C_{21}) & B_1^+ - C_{13} + i(B_2^+ - C_{23}) & B_1^- - C_{31} - i(B_2^- - C_{32}) & 1 - B_3^+ - B_3^- + C_{33} \end{bmatrix}$$

Peres-Horodecki: if ρ^{T2} has at least one negative eigenvalue, the state is entangled

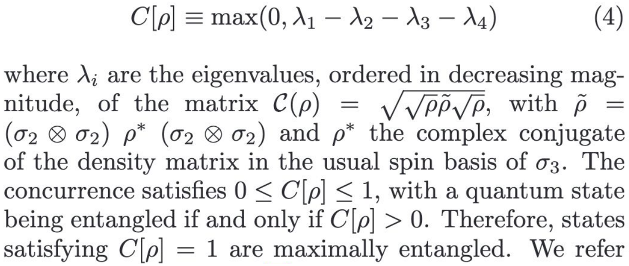
$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_1\Omega_2} = \frac{1}{4\pi^2}\left(1 + \alpha_1\,\mathbf{B}_1\cdot\hat{\ell}_1 + \alpha_2\,\mathbf{B}_2\cdot\hat{\ell}_2 + \alpha_1\alpha_2\,\hat{\ell}_1\cdot\mathbb{C}\cdot\hat{\ell}_2\right)$$

[entanglement] Production phase-space



Eur. Phys. J. Plus (2021) 136

z-axis: concurrence C[ρ]



$$C[\rho] \equiv \max(0, \lambda_1 - \lambda_2 - \lambda_3 - \lambda_4) \tag{4}$$

where λ_i are the eigenvalues, ordered in decreasing magnitude, of the matrix $\mathcal{C}(\rho) = \sqrt{\sqrt{\rho}\tilde{\rho}\sqrt{\rho}}$, with $\tilde{\rho} = (\sigma_2 \otimes \sigma_2)\ \rho^*\ (\sigma_2 \otimes \sigma_2)$ and ρ^* the complex conjugate of the density matrix in the usual spin basis of σ_3. The concurrence satisfies $0 \le C[\rho] \le 1$, with a quantum state being entangled if and only if $C[\rho] > 0$. Therefore, states satisfying $C[\rho] = 1$ are maximally entangled. We refer

C[ρ] > 0 ⇔ entanglement

[entanglement] Dilepton ttbar selection