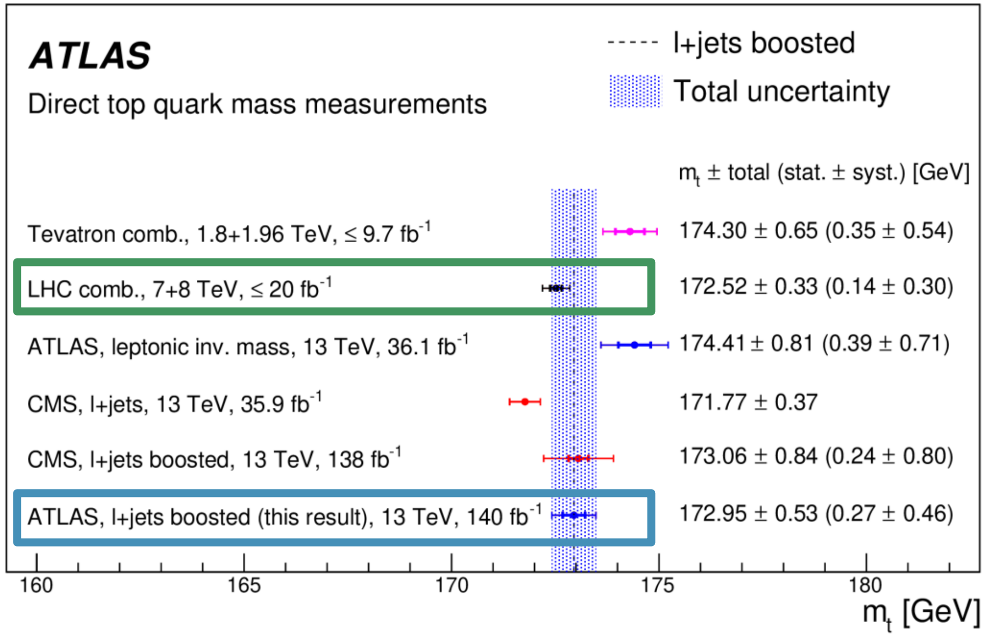
TOP PROPERTIES AND MASS

F. FABBRI, ON BEHALF OF THE ATLAS AND CMS COLLABORATIONS

TOP QUARK MASS AND PROPERTIES AT LHC

- LHC is called a top-quark factory, this has several implications
  - The measurement of the top mass can reach un-precedented precision
    - ATLAS+CMS top mass combination
  - Extreme region of the phase space have enough statistics to lead to precise measurements and allow to study unexplored characteristics of the top-quark
    - ATLAS top-quark mass measurements using boosted top quarks
    - ATLAS top-quark Lund Jet plane measurement
  - It is possible to measure for the first time the spin density matrix of the top-quark pair differentially
    - CMS top-quark pair spin density matrix and entanglement differential
      - **First measurement of Magic**
  - The top quark pair final state can be used to probe the fundamentals of the SM
    - ATLAS Lepton Flavour Universality test in $\frac{W\rightarrow e\nu}{W\rightarrow \tau\nu}$

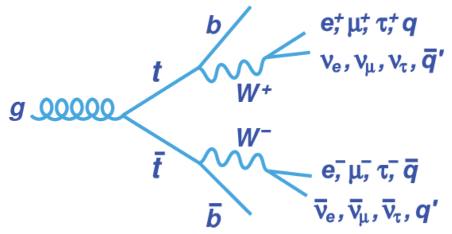
TOP QUARK MASS



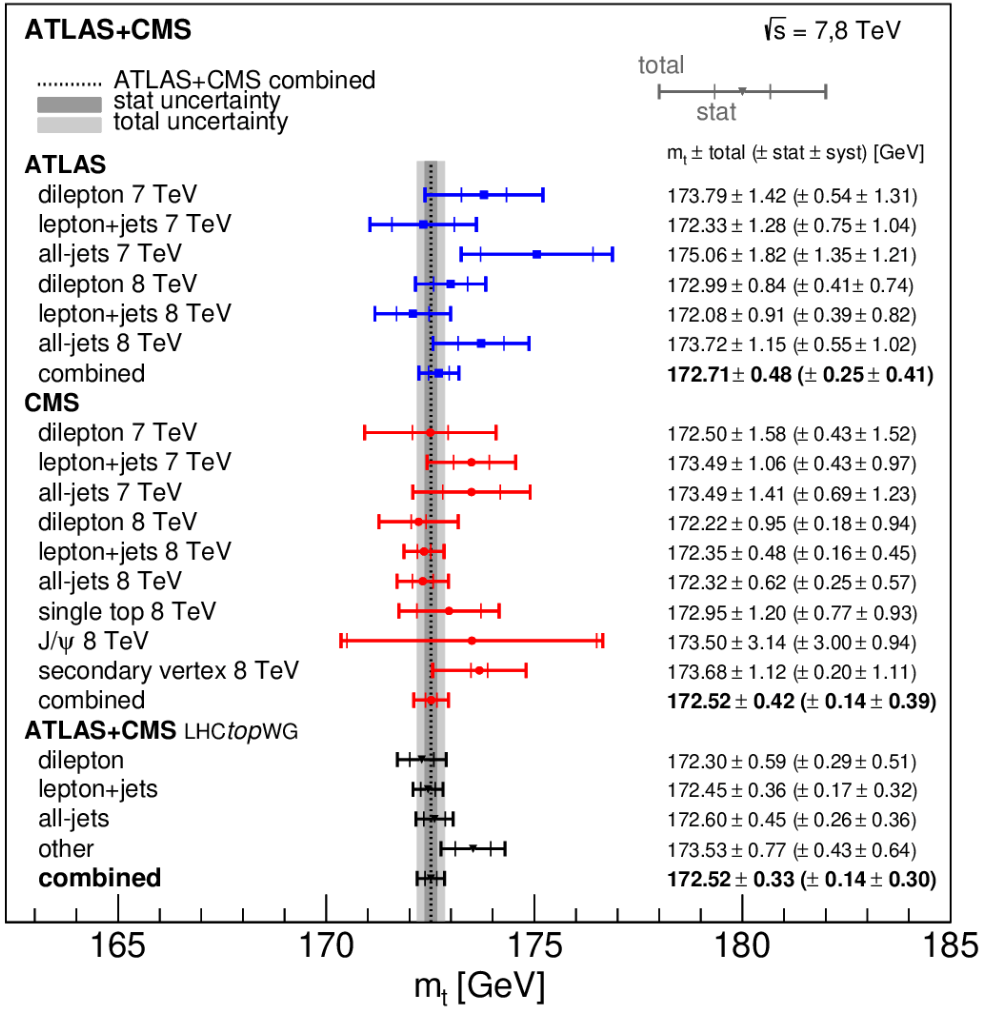
arXiv:2502.18216

- The top quark mass is a free parameter of the SM
  - It is extremely related to the Higgs mass and the electroweak sector
  - Direct measurement are a strict constraint of the SM consistency
- There are two main approaches at measuring the top quark mass
  - Indirect measurement: exploit the correlation with the top-quark pair production cross-section
  - **Direct measurement:** exploiting an observable reconstructed at detector level sensitive to the mass
- Recent results:
  - **ATLAS top mass measurement using boosted top quarks**
    - Most precise ATLAS individual measurement
    - Covered later in E. Watton talk
  - **ATLAS and CMS combination using Run1 data**

LHC TOP MASS COMBINATION WITH RUNI DATA

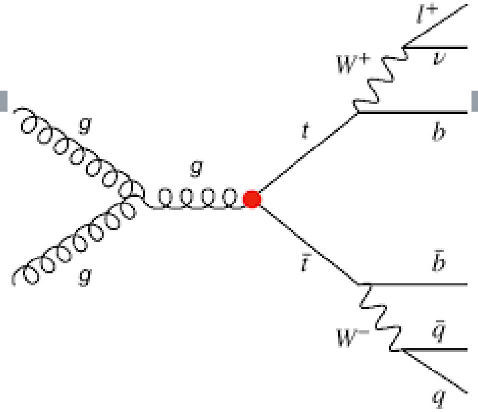


- 15 ATLAS and CMS top-quark mass measurements done at $\sqrt{s}$ = 7/8 TeV combined
  - All direct measurements
- All correlations considered in the combination
  - Uncertainties grouped in 25 categories
  - Correlation between measurements in the same experiment based on the covariance matrices
  - Correlation cross-experiment evaluated on the categories based on the similarities of approaches and input.
- 31% improvement in precision compared to the most precise input measurement
- Currently most precise top-quark mass measurement
  - Dominant uncertainty due to the jet energy scale of b-jets



Phys. Rev. Lett. 132 (2024) 261902

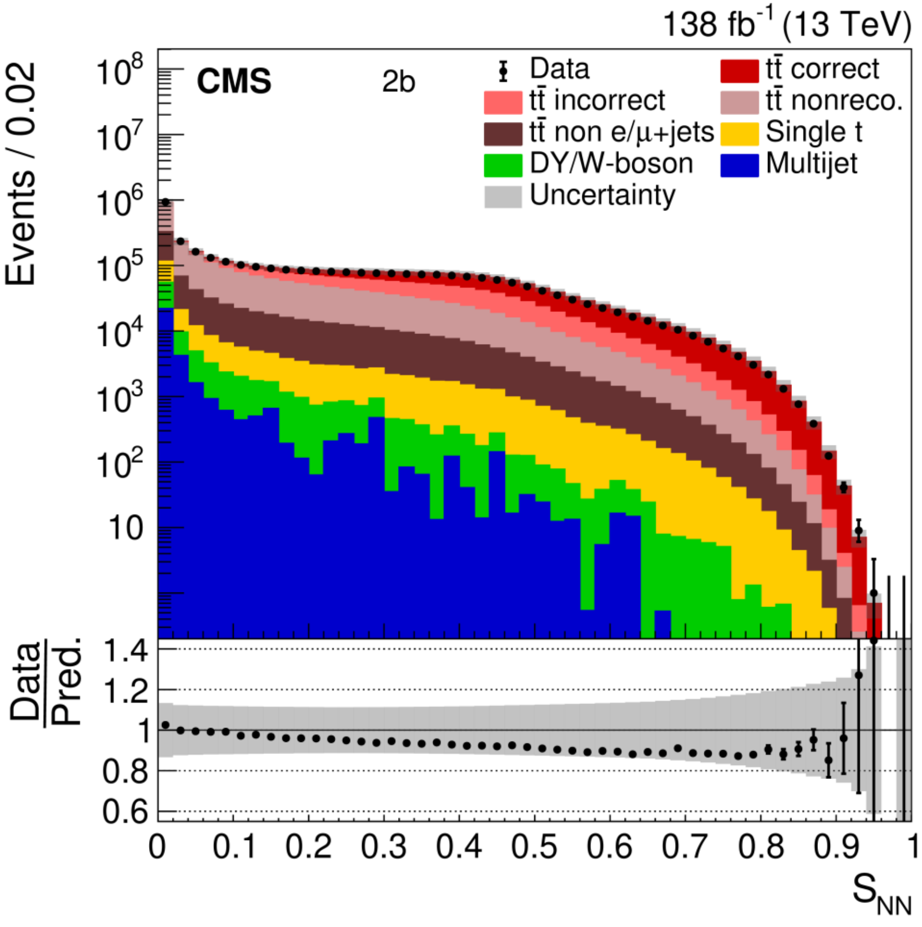
SPIN DENSITY MATRIX – ANALYSIS STRATEGY



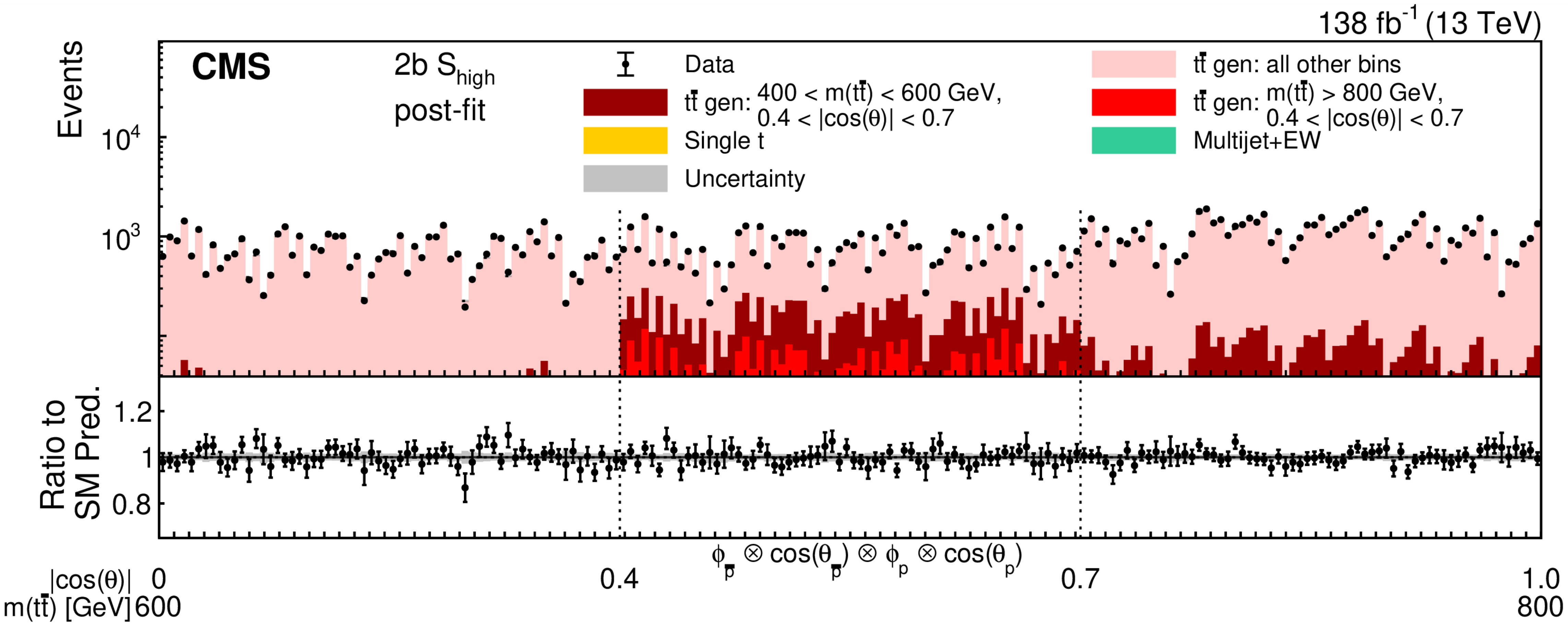
- The top-quark decays faster than the spin decorrelation time
- The direction of the final state particle in the parent top rest frame can be used to measure the spin density matrix (ρ)
  - Related by the spin analysing power (k)
- The semi-leptonic final state is employed for the measurement
  - MVA approach to reconstruct the system
  - Also targeting the identification of the **down-type quark**
- The measurement of the ρ coefficients $(\boldsymbol{P}, \boldsymbol{C})$ is performed exploiting the relation with the cross section

$$\Sigma_{\text{tot}}(\phi_{\text{p}(\bar{\text{p}})}, \theta_{\text{p}(\bar{\text{p}})}) = \frac{\text{d}^4\sigma}{\text{d}\phi_{\text{p}}\text{d}\cos(\theta_{\text{p}})\text{d}\phi_{\bar{\text{p}}}\text{d}\cos(\theta_{\bar{\text{p}}})}$$
$$= \sigma_{\text{norm}}\left(1 + \kappa\mathbf{P}\cdot\boldsymbol{\Omega} + \bar{\kappa}\bar{\mathbf{P}}\cdot\bar{\boldsymbol{\Omega}} - \kappa\bar{\kappa}\boldsymbol{\Omega}\cdot(C\bar{\boldsymbol{\Omega}})\right)$$

  - Template built reweighting the nominal generator
  - Weights obtained varying the spin density matrix coefficients
  - Results obtained fitting the template to data on a multidimensional distribution, depending on the spin analysers angular distributions

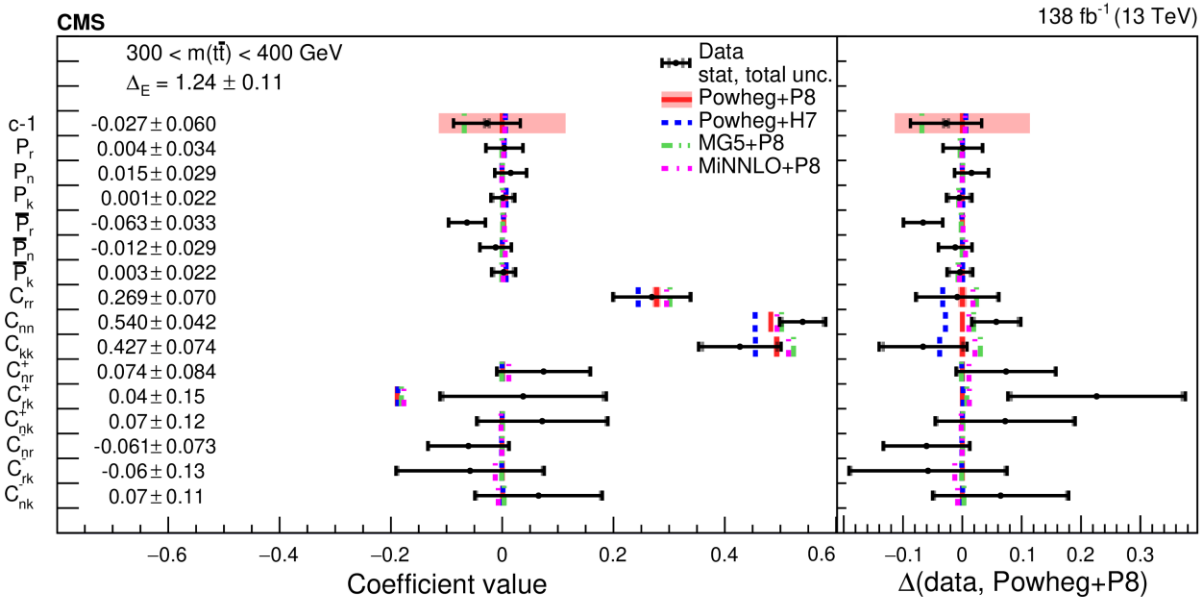


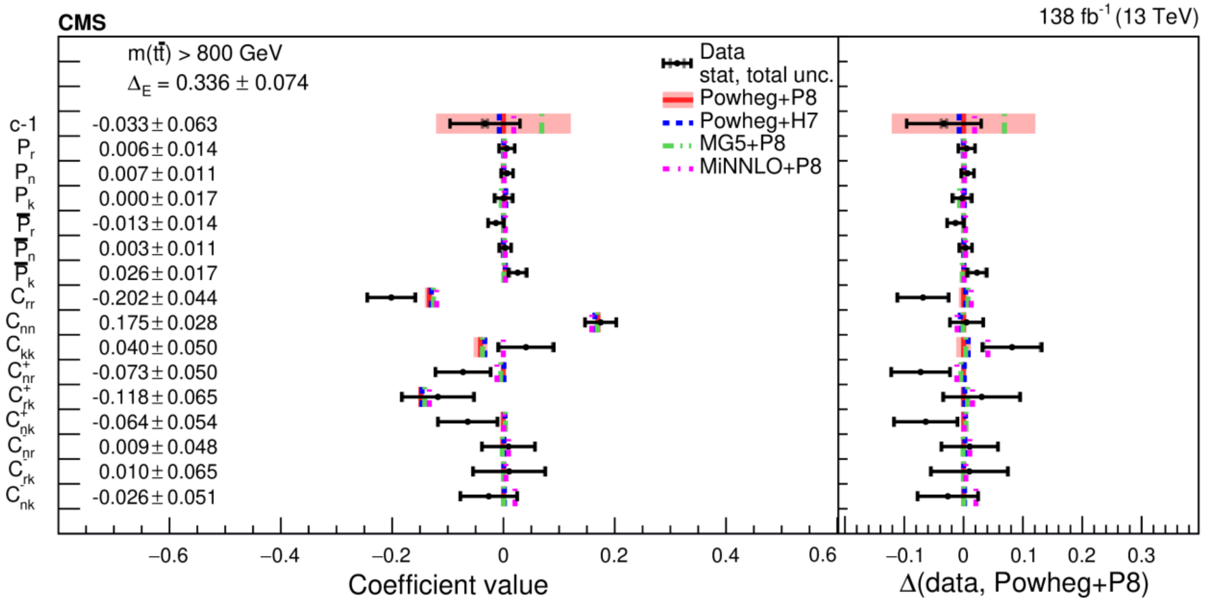
Phys. Rev. D 110 (2024) 112016


138 fb^{-1} (13 TeV)
CMS
2b S_{high}
post-fit
Data
$t\bar{t}$ gen: 400 < m($t\bar{t}$) < 600 GeV, 0.4 < |cos(θ)| < 0.7
Single t
Uncertainty
$t\bar{t}$ gen: all other bins
$t\bar{t}$ gen: m($t\bar{t}$) > 800 GeV, 0.4 < |cos(θ)| < 0.7
Multijet+EW
Events
Ratio to SM Pred.
$\phi_{\bar{p}} \otimes \cos(\theta_{\bar{p}}) \otimes \phi_p \otimes \cos(\theta_p)$
|cos(θ)| 0 0.4 0.7 1.0
m($t\bar{t}$) [GeV] 600 800

SPIN DENSITY MATRIX - RESULTS

- The coefficients of the spin density matrix are extracted differentially in bins of $m_{t\bar{t}}$, the angle for top-quark production in the top-quark pair frame and p_T
- Dominant uncertainty dependent on the phase space region
- Good agreement with the SM





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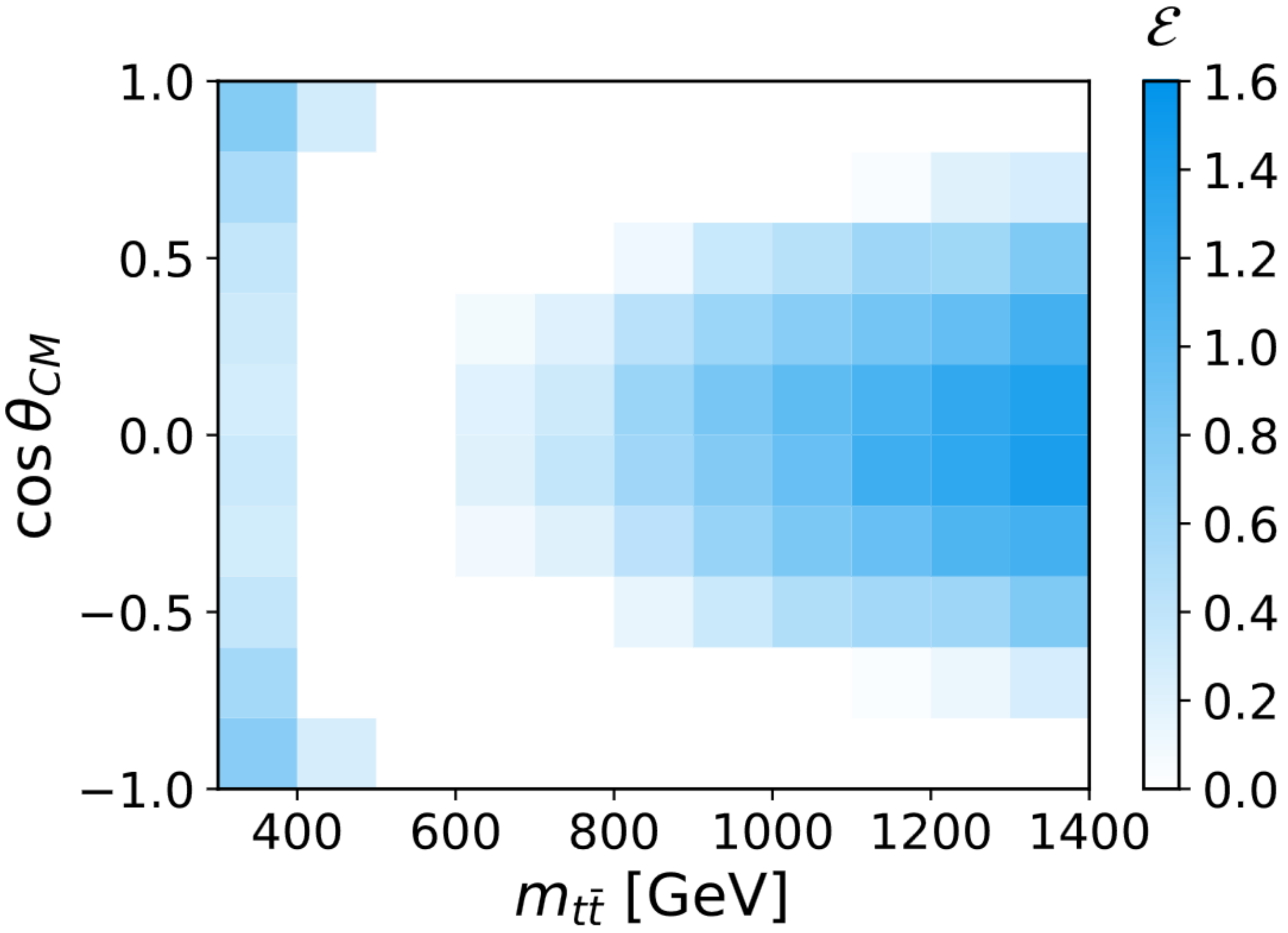
QUANTUM OBSERVABLES

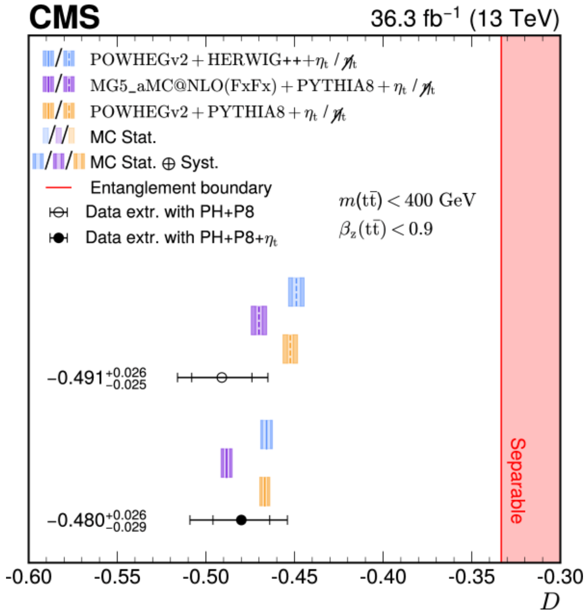
- The spins of the top-quarks produced at LHC can also be interpreted as a pair of qubits
- Concepts taken from quantum information and computing can be applied to these systems, e.g. entanglement
- The spin density matrix is the ingredient to then measure all quantum state properties
  - In addition, there are specific entanglement witnesses

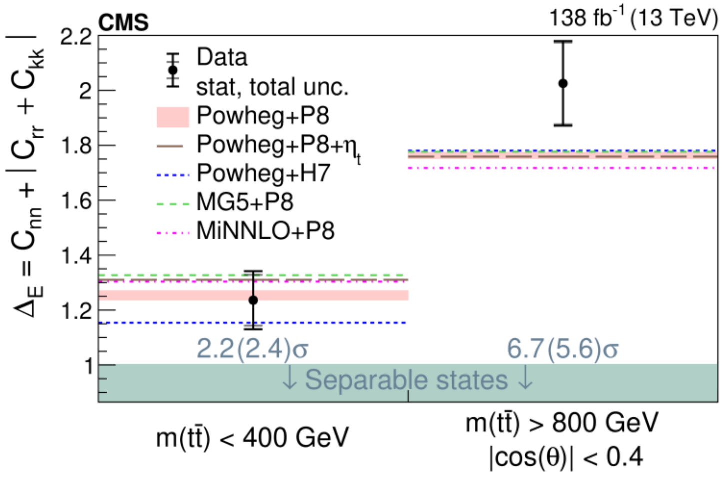
Phys. Rev. D 109, 115023



ENTANGLEMENT MEASUREMENT

- Both ATLAS and CMS also performed measurements of entanglement
- A stronger entanglement is observed in data compared to nominal predictions at threshold
  - CMS observed that including the "toponium" in the simulation improves the agreement
  - *Toponium*: pseudo-bound state predicted by the SM in the top-quark pair threshold
    - See B. Fuks talk





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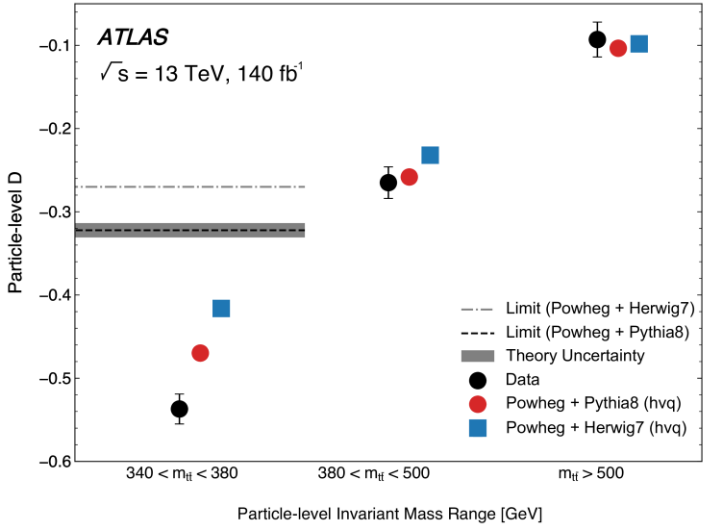
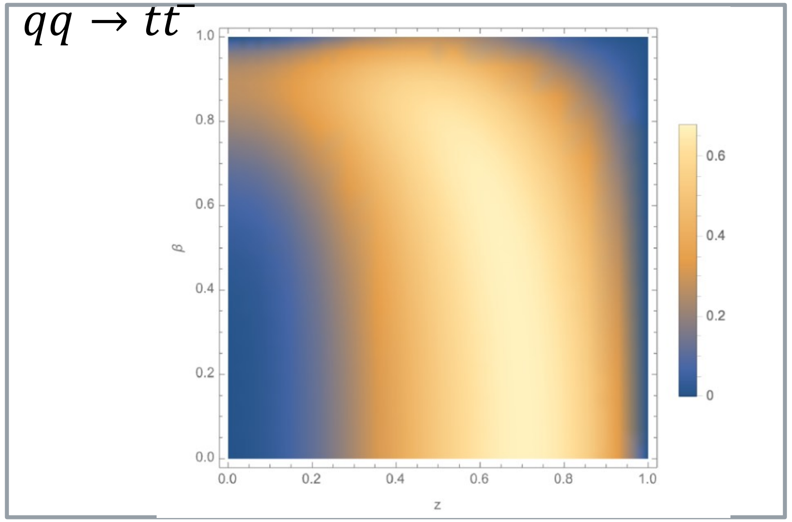
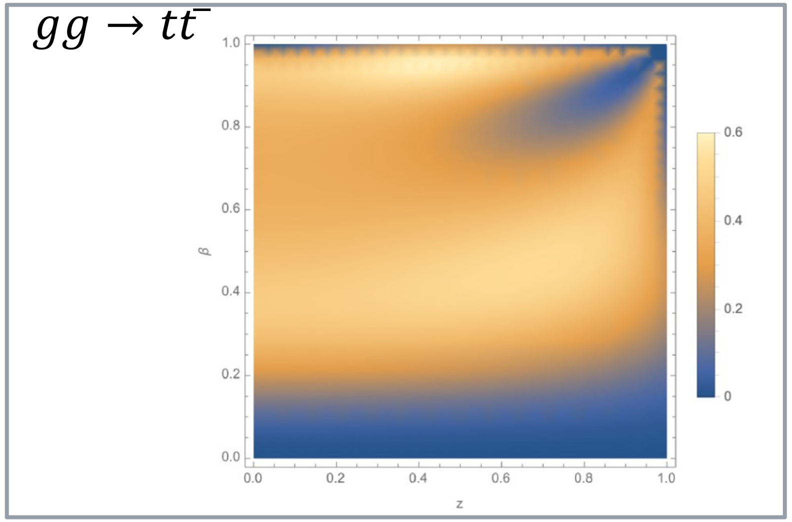
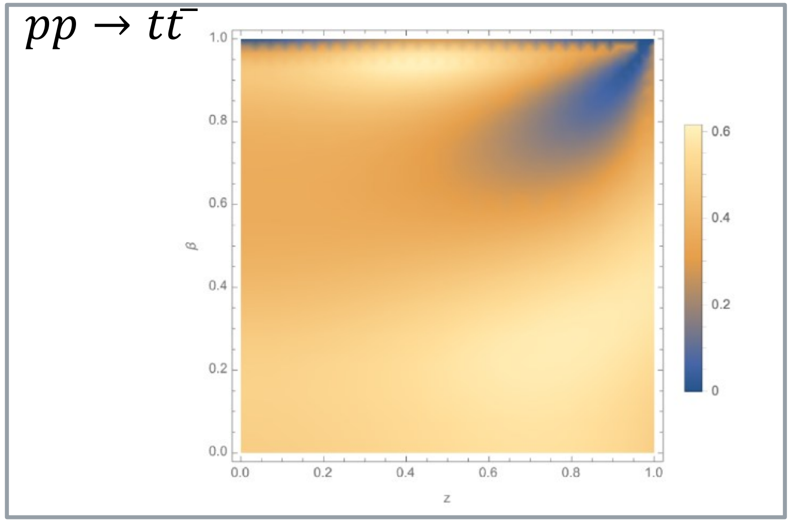


Nature 633 (2024) 542







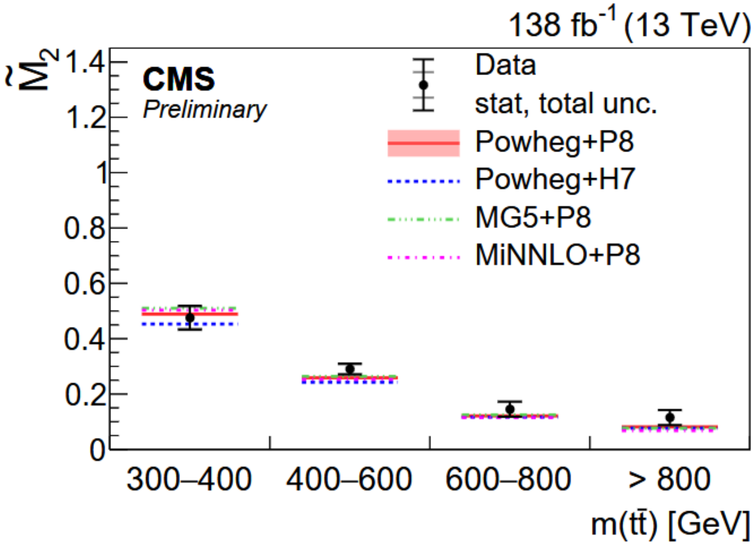
SPIN DENSITY MATRIX - MAGIC

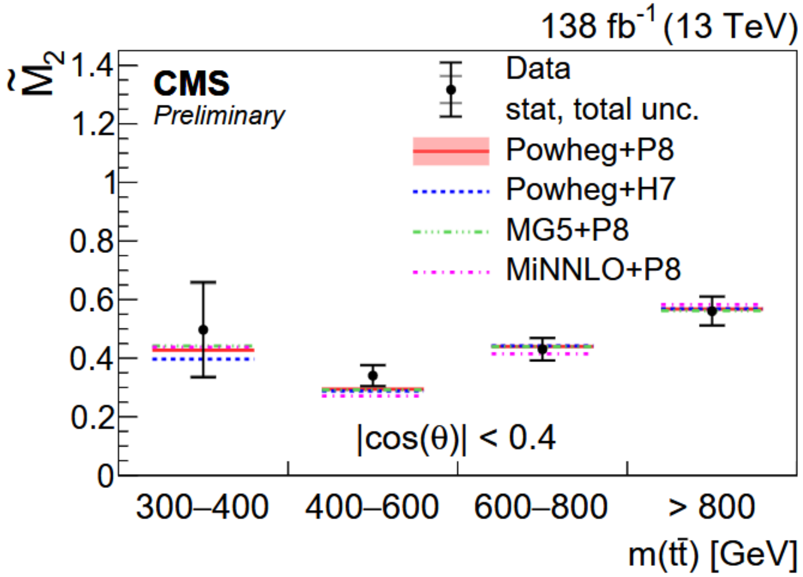
- Magic is a property of quantum states designed to quantify the potential computational advantage over classical states, related to stabilizer state
- Quantum circuits including only stabilizer state can be efficiently simulated on classical computer
  - Stabilizer state have 0 magic
- Magic can also be measured between top-quarks
  - Deeper understanding on how to realise this state
- Non-linear definition → can not be easily derived by averaging the different top pair initial states

PhysRevD.110.116016

FIRST MEASUREMENT OF MAGIC BETWEEN TOP-QUARKS

$$\tilde{M}_2 = -\log_2 \left(\frac{1 + \sum_{i \in n,k,r} [(P_i^4 + \bar{P}_i^4)] + \sum_{i,j \in n,k,r} C_{ij}^4}{1 + \sum_{i \in n,k,r} [(P_i^2 + \bar{P}_i^2)] + \sum_{i,j \in n,k,r} C_{ij}^2} \right)$$

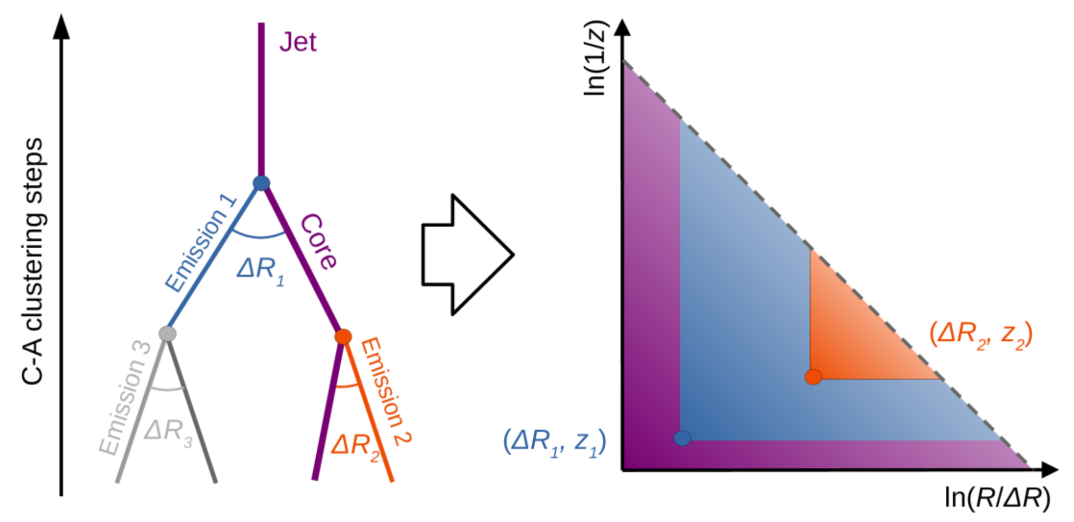




- First measurement of magic, performed by the CMS collaboration
  - Starting from the measurement of the spin density matrix elements and their correlation
- The resulting $\widetilde{M}_2$ is maximal near the top-quark pair threshold
  - Flat when requiring a cut on |cos(θ)|
- In agreement with the SM
- Measurement dominated by statistical uncertainty

CMS PAS TOP-25-001

LUND JET PLANE - DEFINITION

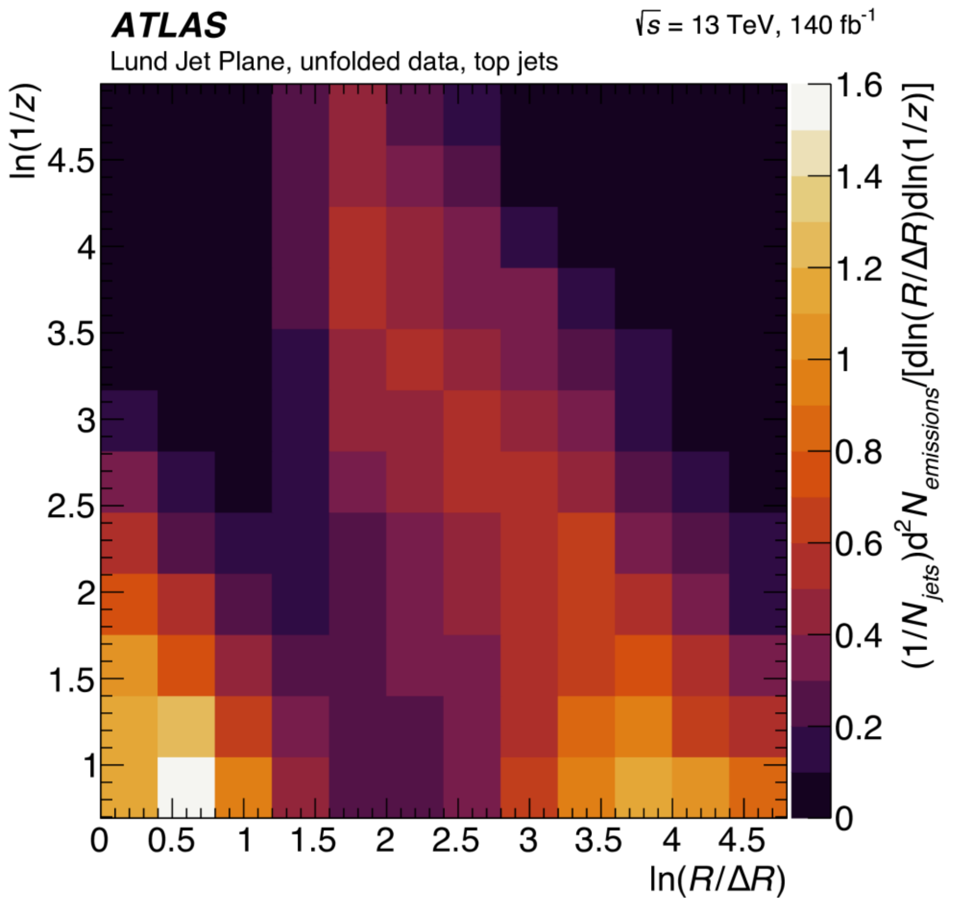


arXiv:2407.10879

- The primary lund jet plane (LJP) is a representation of the jet formation
  - The jet clustering obtained with the C/A algorithm is travelled back
  - At each step an emitter and an emission are defined
  - Emissions are included in a 2D representation of the available phase space in angle and momentum
  - The emitter is followed for the next emission
- This observable has many applications:
  - Jet tagging
  - Study of parton shower properties
  - MC tuning
  - Improve calibration

LUND JET PLANE MEASUREMENT

- ATLAS and CMS previously measured light-jets originated LJP
- First measurement of the heavy boosted objects LJP
- The semi-leptonic top-quark pair final state is targeted from the event selection
  - The hadronically decaying top quark is reconstructed
    - As a single large-R jet → boosted top-quark selection
    - A large-R jet for a W and an additional b-tagged → boosted W selection
    - Large-R jets are trimmed
- The LJP is reconstructed using only the tracks associated to the jet
  - Or the charged particles at particle level
- The result is unfolded to particle level in a fiducial phase space
  - Compared to multiple NLO+PS generators



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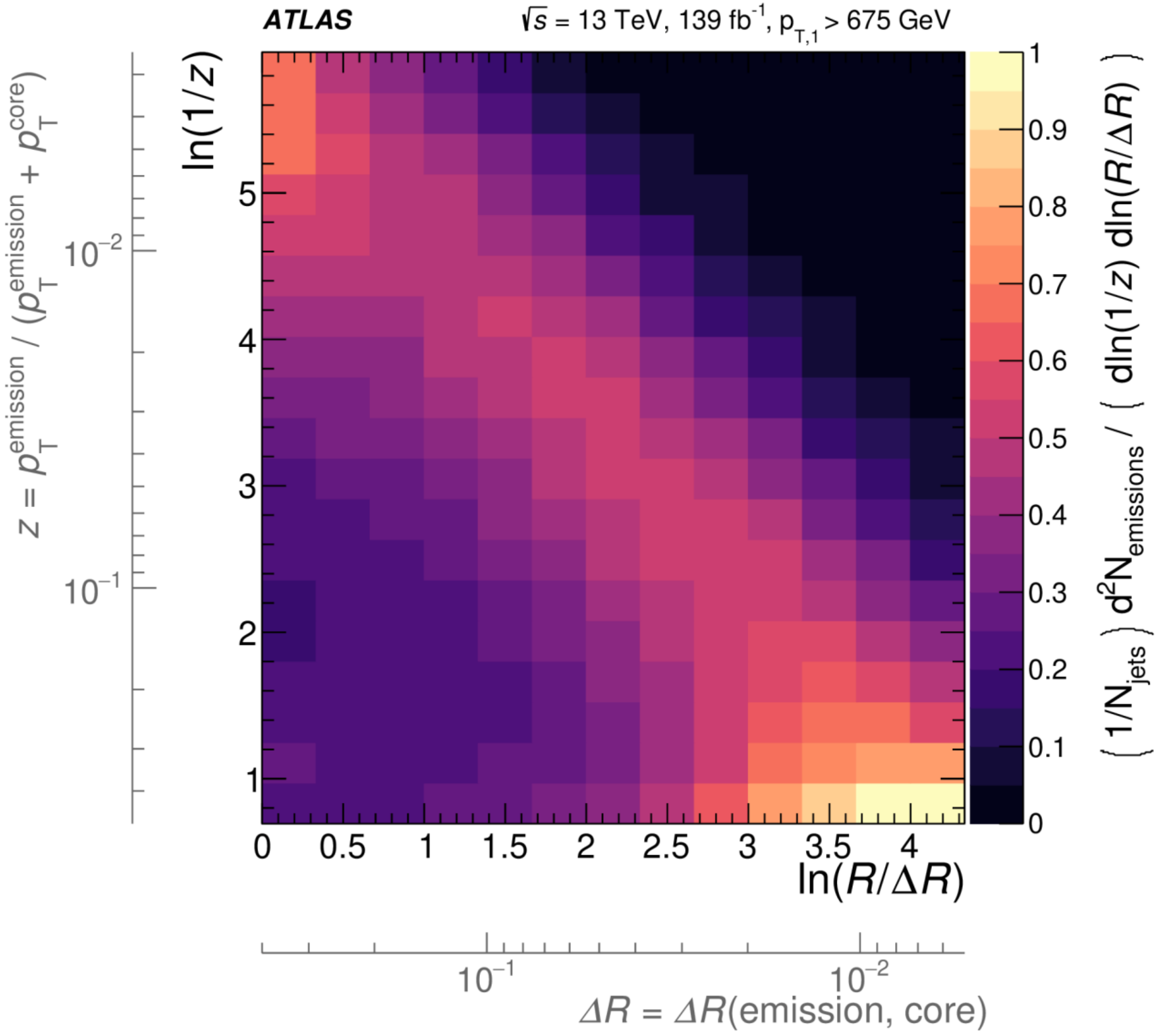

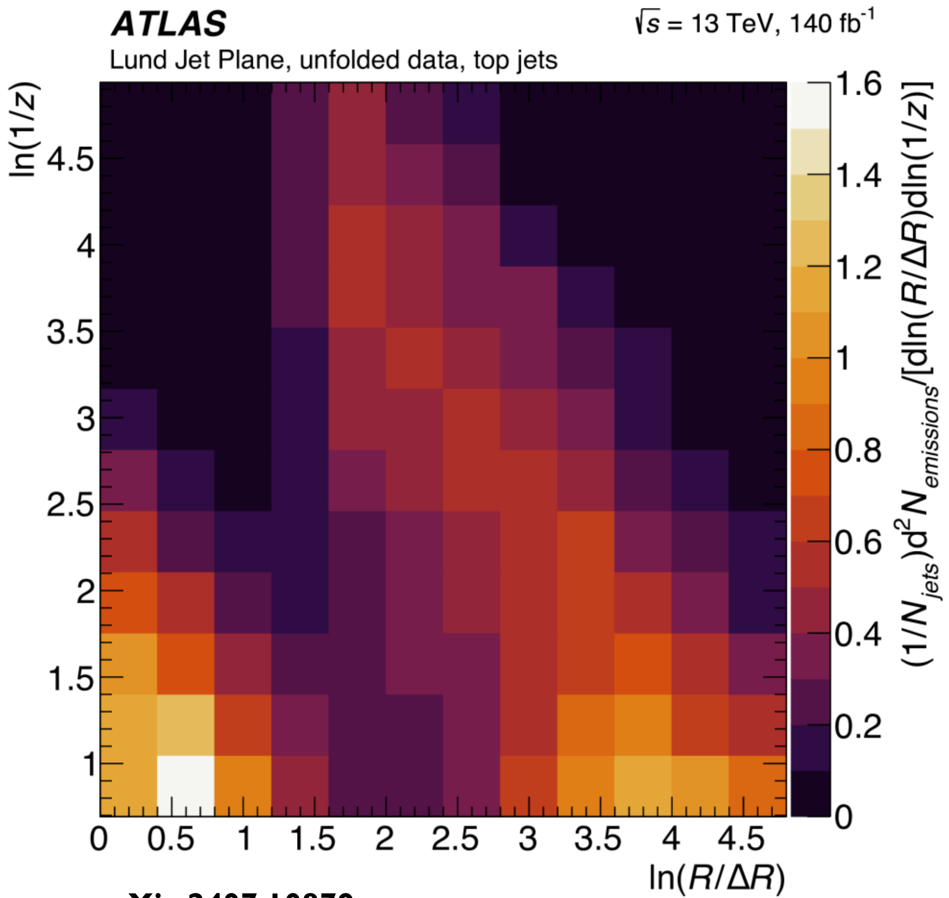

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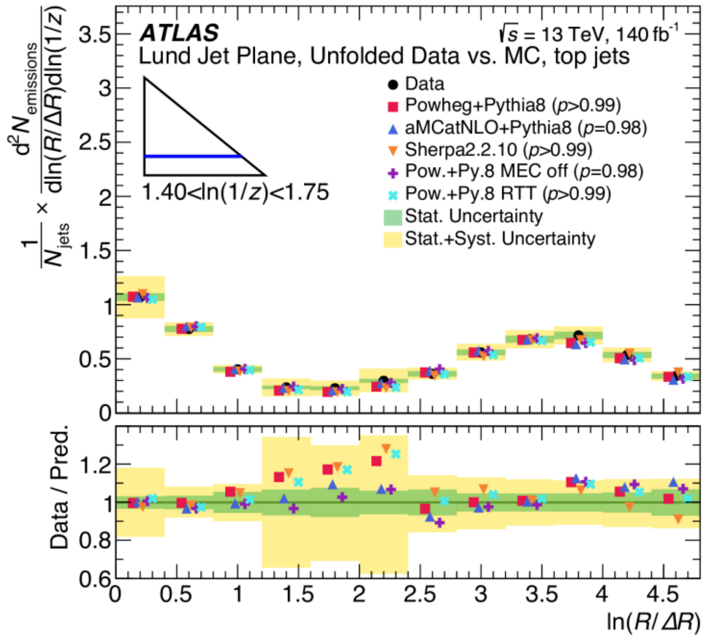
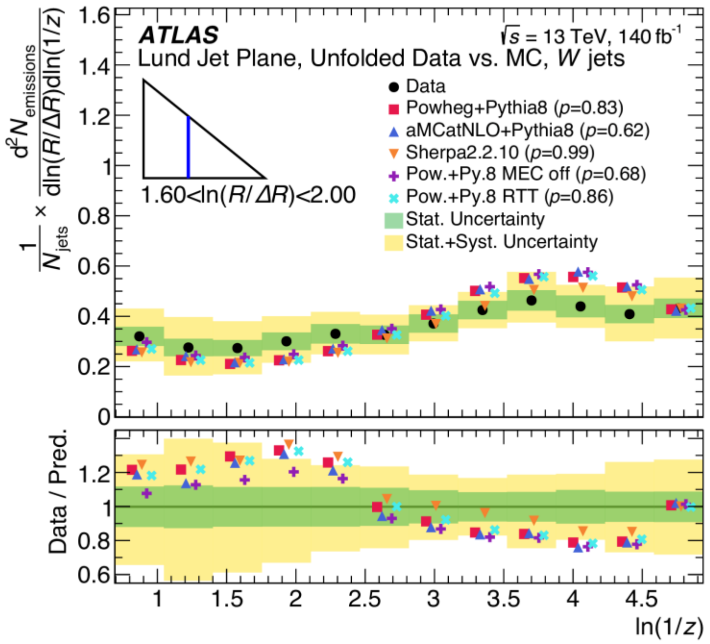
LUND JET PLANE MEASUREMENT

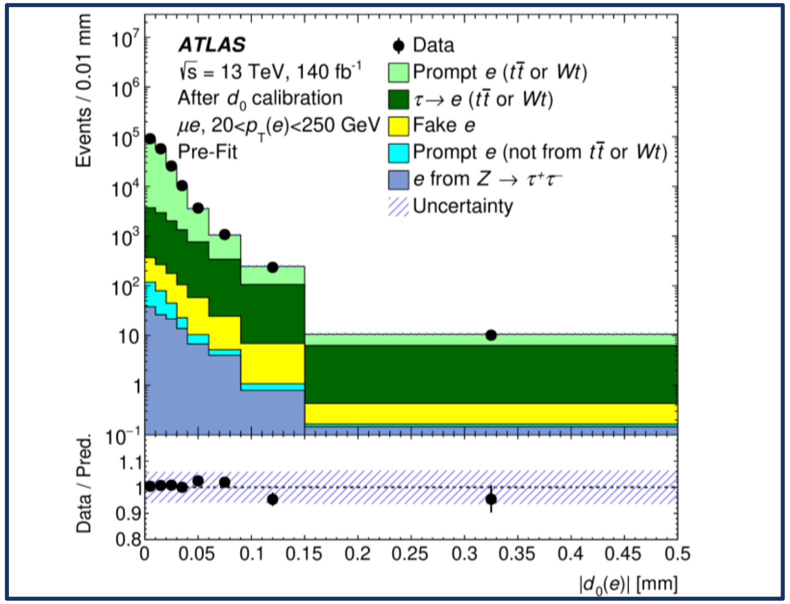


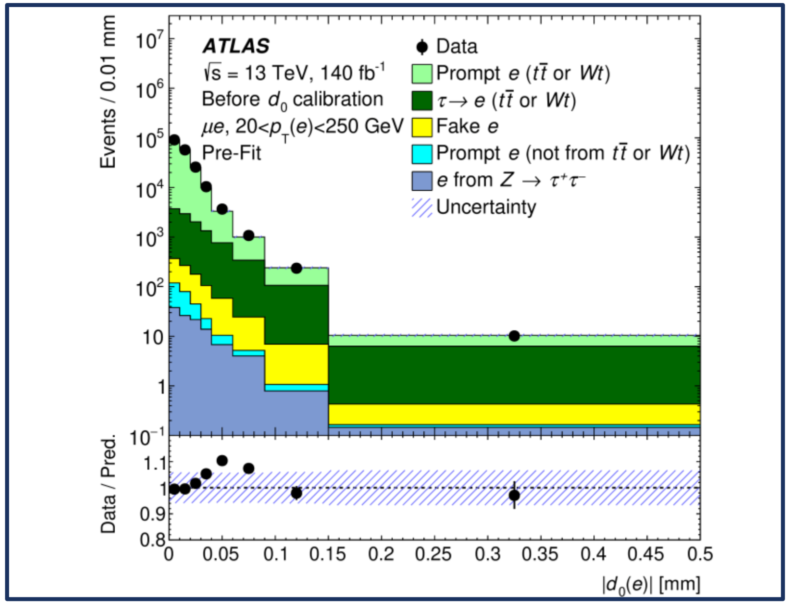


- On average the top-jets count one extra emission compared to the W-jets
- All generators struggle to describe the whole LJP, with few exceptions in the top jet case
- Beyond the full 2D LJP spectrum the results are also presented as slices of the plane
  - Here it is visible that the agreement with the various generators is highly dependent on the region of the plane
- Dominant uncertainty is modelling

arXiv:2407.10879

$BR(W \rightarrow e\nu)/BR(W \rightarrow \tau\nu)$ - STRATEGY

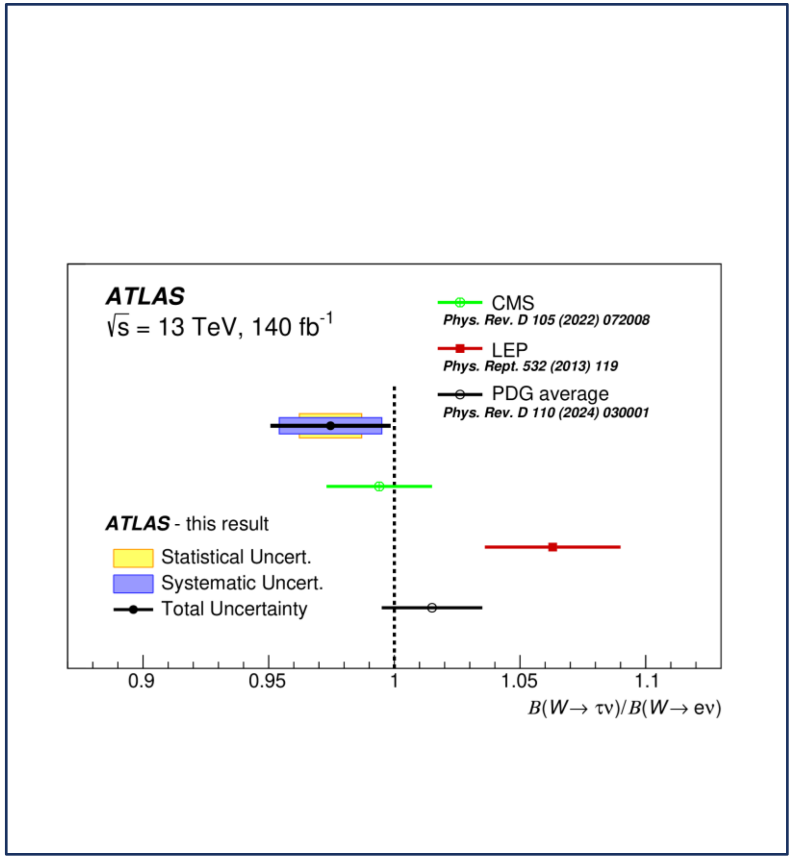


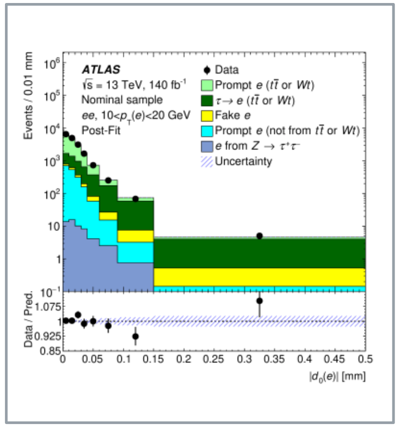


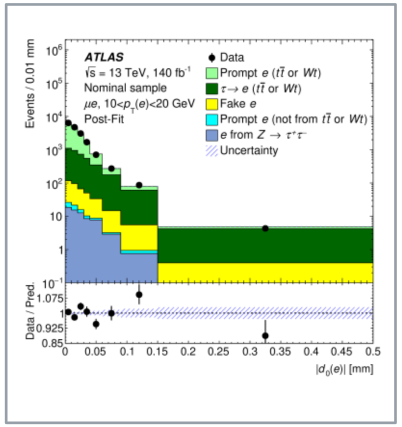
arXiv:2412.11989

- The top-quark pair in the dilepton final state is used to measure the ratio $R_{\frac{e}{\tau}} = \frac{BR(W\rightarrow e\nu)}{BR(W\rightarrow \tau\nu)}$
  - Only final states with $\tau \rightarrow e\nu_e\nu_\tau$ are targeted
- Test of the LFU
  - Fundamental property of the SM
  - Some deviation observed at LEP
- The events are selected with a tag-and-probe method,
  - the origin of the probe electron is then measured: prompt or from τ decay
- Two main observables are employed to identify the origin of the probe electron:
  - Impact parameter d_0
    - Dedicated corrections and calibrations using $Z \rightarrow e^+e^-$ data significantly improve the agreement between data and MC
  - Lepton p_T

$BR(W \to e\nu)/BR(W \to \tau\nu)$ - STRATEGY







- Result extracted using a binned profile likelihood fit on a multidimensional distribution
- Major backgrounds entirely or partially data-driven
- Dominant uncertainty:
  - Signal modelling
  - d_0 calibration
- The result is consistent with the SM expectation value and CMS
- The precision is comparable to that of the LEP combination and the CMS Collaboration → will improve world average

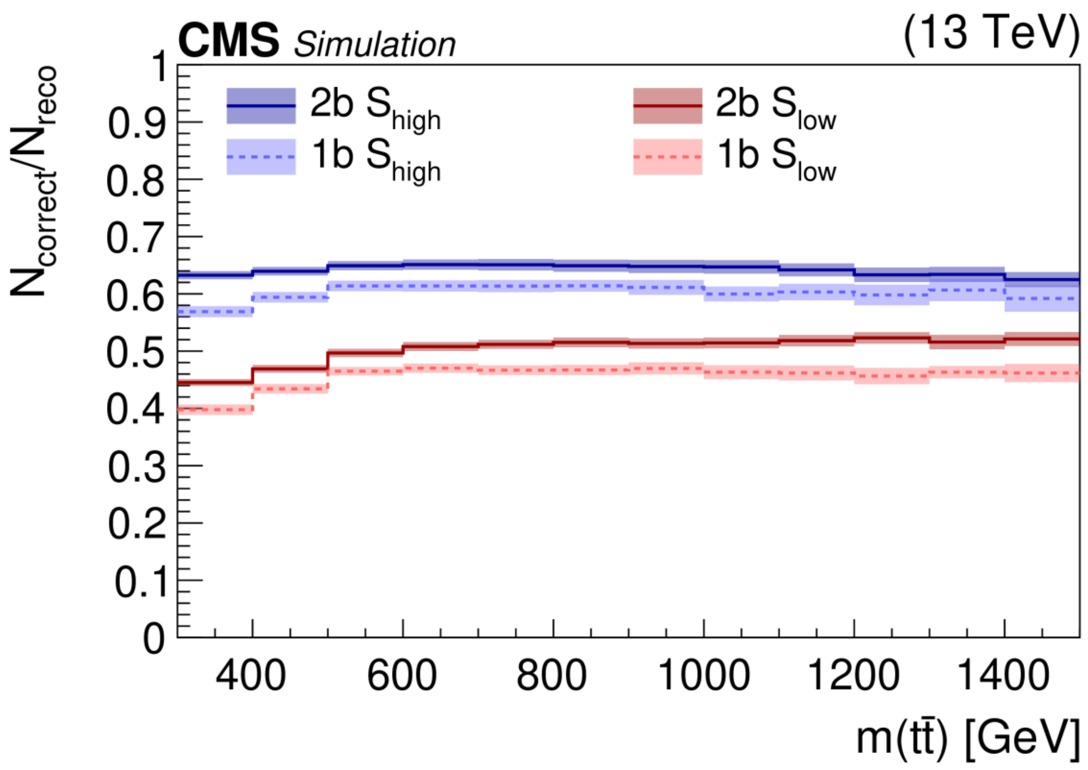
arXiv:2412.11989

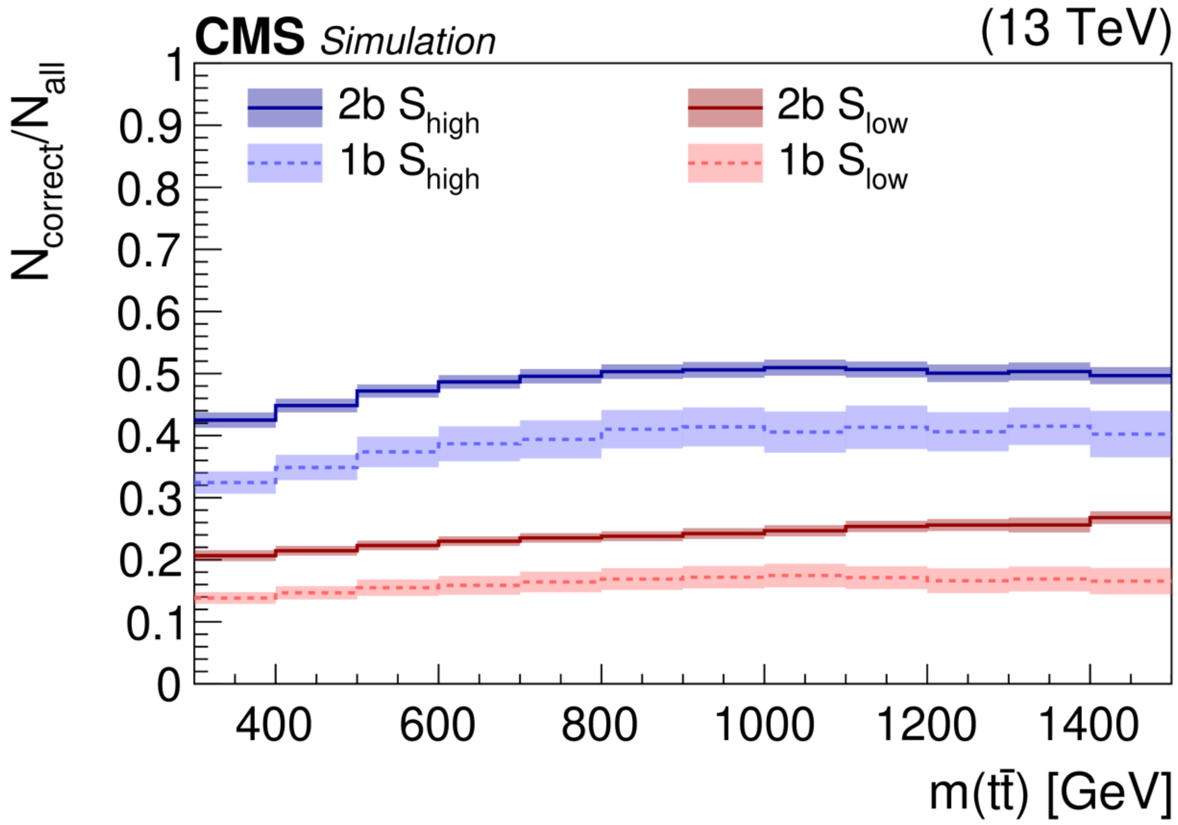
CONCLUSIONS

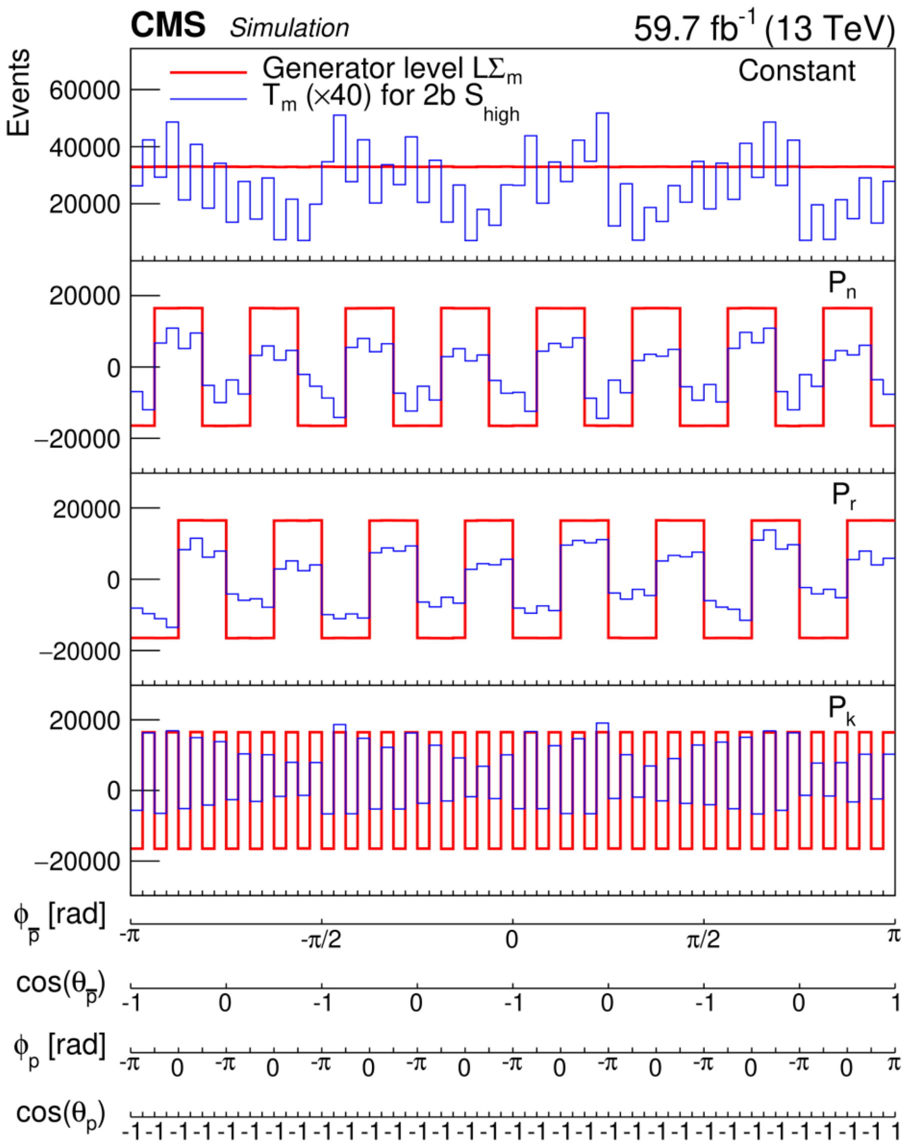
- Presented many recent results of the ATLAS and CMS collaborations on the top-quark properties:
  - Masses:
    - The new techniques being applied, combinations and very large available statistics allow to reach unprecedent precision in the measurement
  - Spin density matrix:
    - Measured differentially for the first time
    - Window to investigate the foundation of quantum mechanics at LHC
      - ***First measurement of magic!***
  - The LJP on boosted W and top-quark has been measured for the first time, showing distinctive feature compared to light jets and the potential to improve the MC modelling
  - Top-quark pair production allows to probe a fundamental property of the SM, the lepton flavour universality, at the same precision reached at LEP
  - All results based on Run2 data, new data are ready to be measured, stay tuned

THANK YOU!

PERFORMANCE OF THE SNN

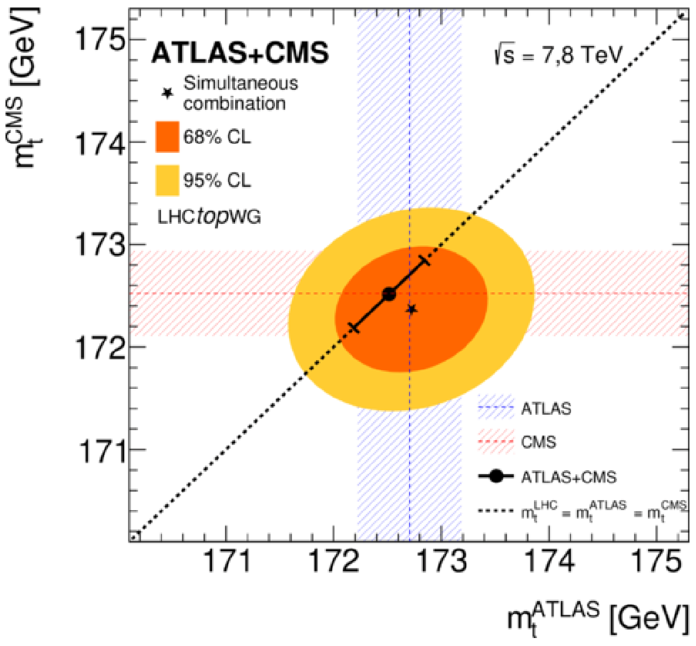






TEMPLATE BUILDING

Phys. Rev. D 110 (2024) 112016

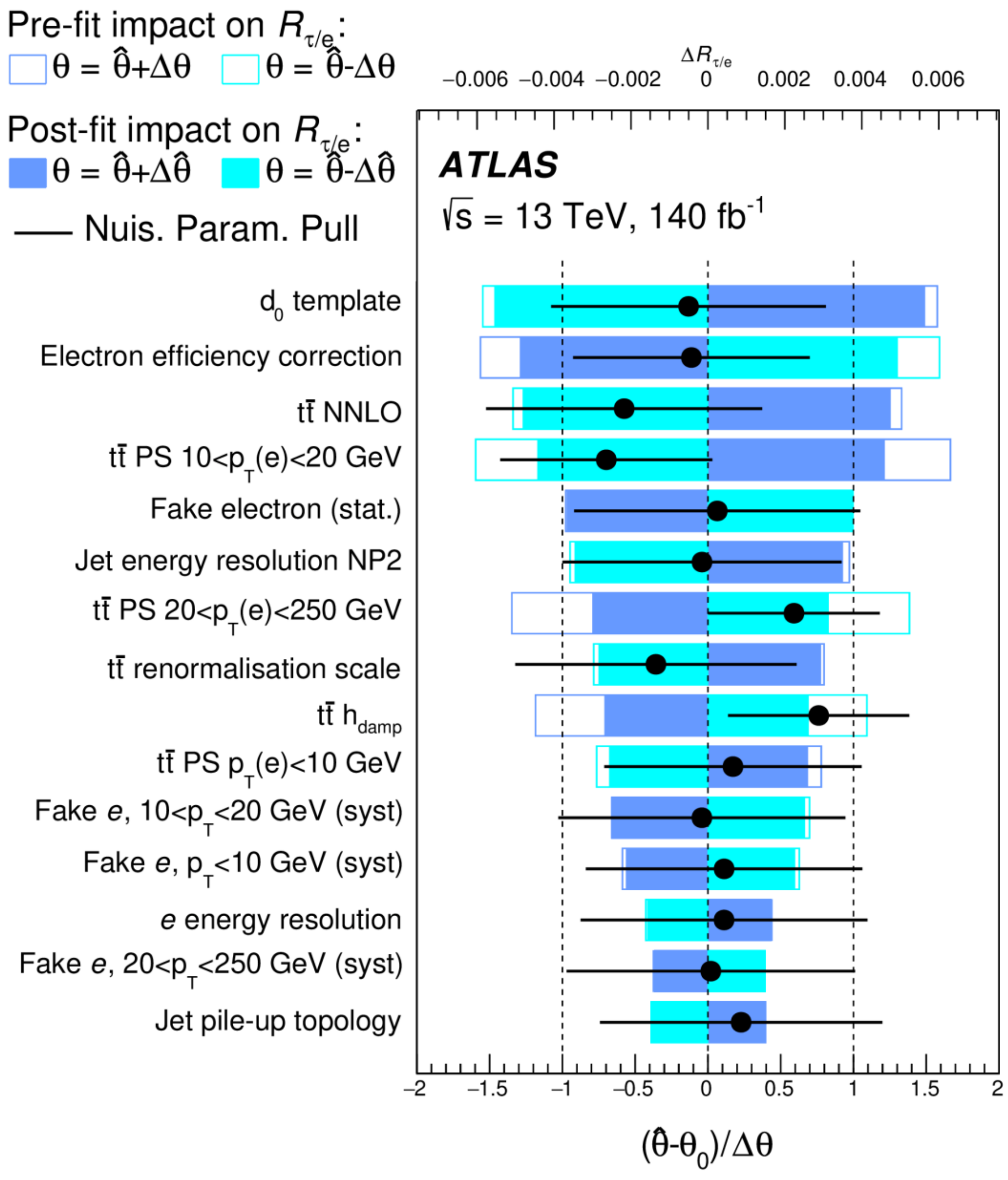


Uncertainty category	Uncertainty impact [GeV]		
	LHC	ATLAS	CMS
b-JES	0.18	0.17	0.25
b tagging	0.09	0.16	0.03
ME generator	0.08	0.13	0.14
JES 1	0.08	0.18	0.06
JES 2	0.08	0.11	0.10
Method	0.07	0.06	0.09
CMS b hadron $\mathcal{B}$	0.07	—	0.12
QCD radiation	0.06	0.07	0.10
Leptons	0.05	0.08	0.07
JER	0.05	0.09	0.02
CMS 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
g-JES	0.03	0.02	0.04
Background (MC)	0.03	0.07	0.01
Other	0.03	0.06	0.01
l-JES	0.03	0.01	0.05
CMS JES 1	0.03	—	0.04
Pileup	0.03	0.07	0.03
JES 3	0.02	0.07	0.01
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 systematic	0.30	0.41	0.39
Statistical	0.14	0.25	0.14
Total	0.33	0.48	0.42

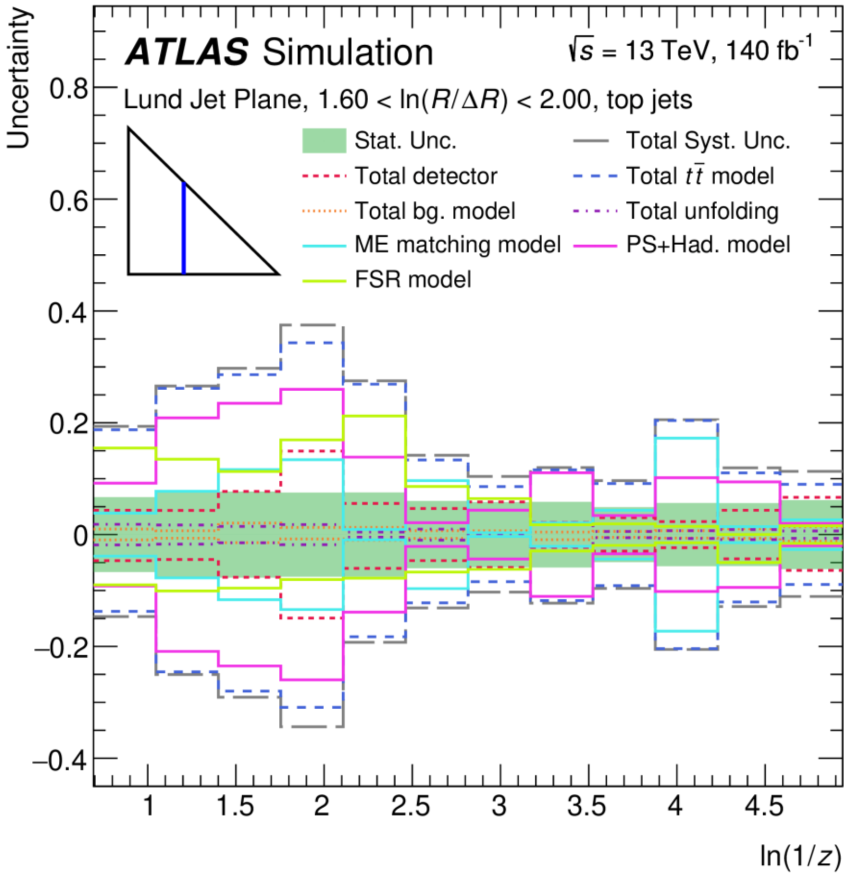
TOP QUARK MASS COMBINATION

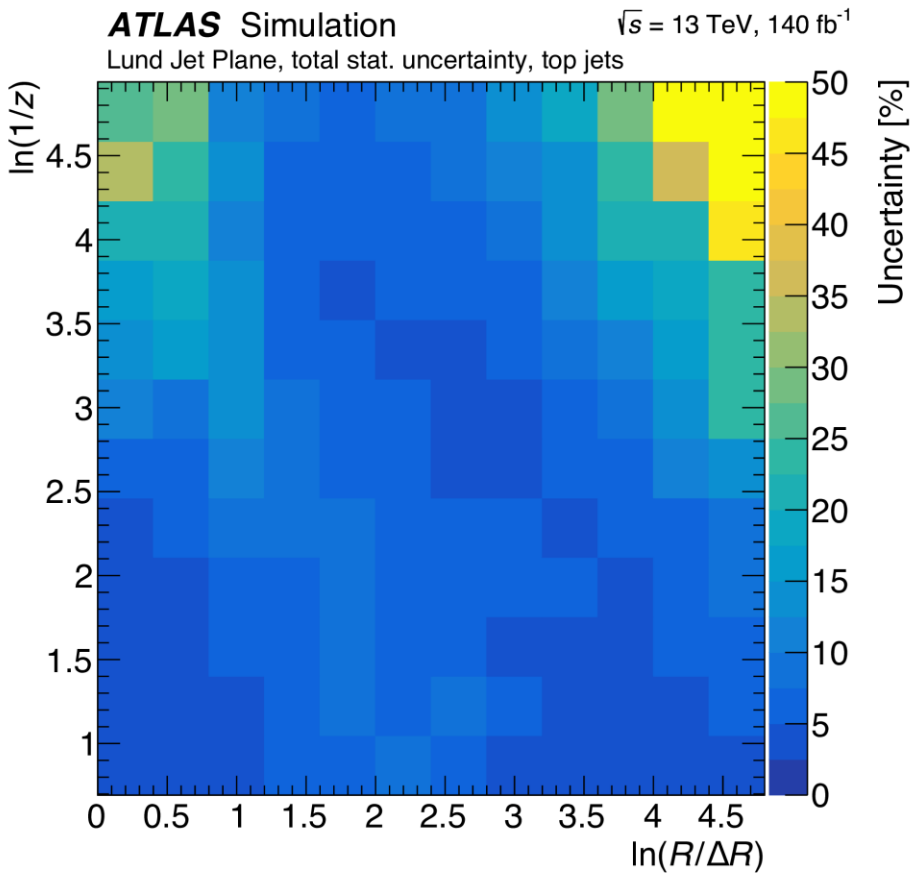
LFU

- **[Phys. Rev. Lett. 132 (2024) 261902]**



LUND JET PLANE





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