ATLAS results at the $t\bar{t}$ threshold

LHC Top France

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April 29th 2025

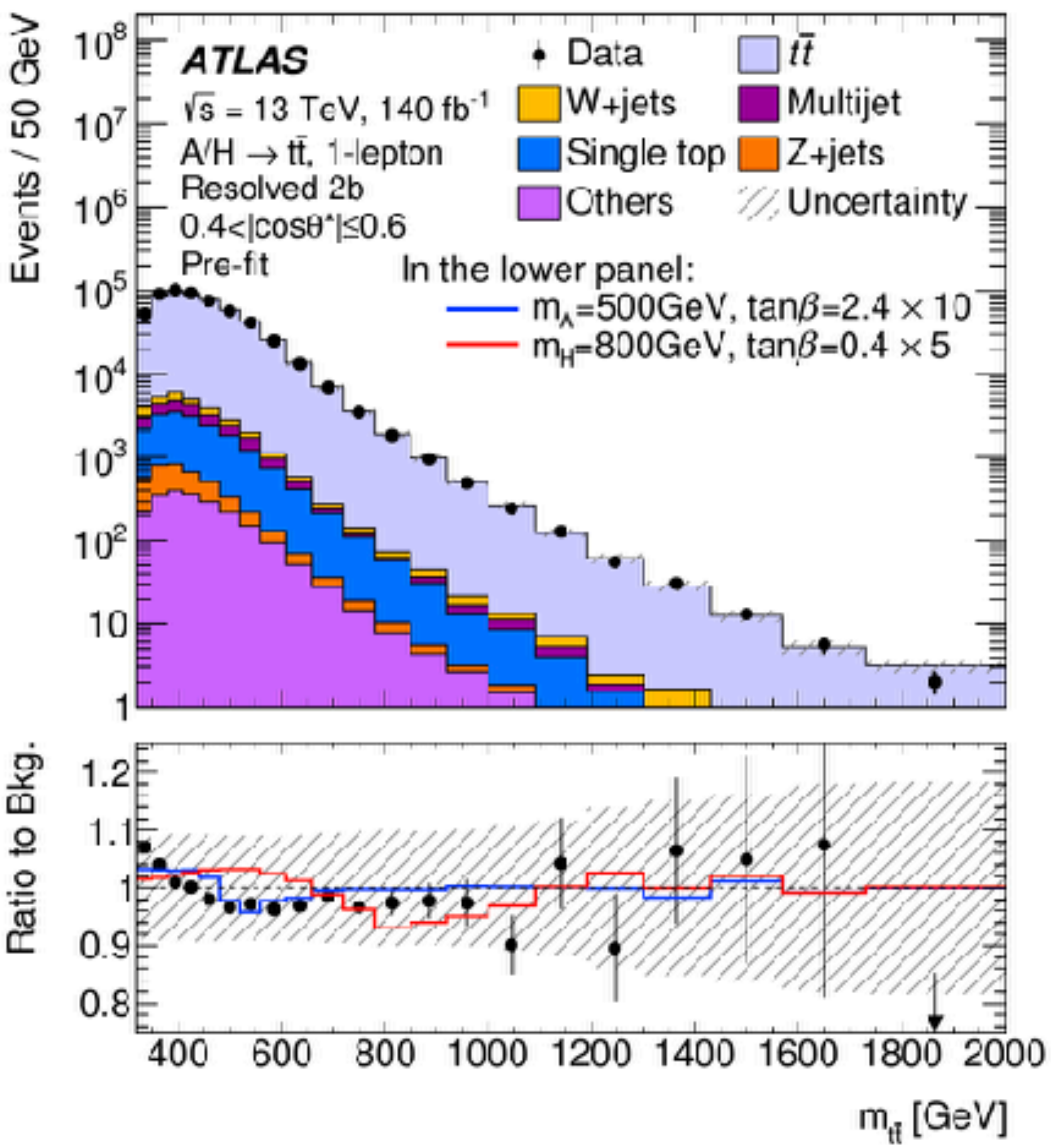
$t\bar{t}$ Production at Threshold

- The threshold region is defined:

$$m_{t\bar{t}}^{\text{threshold}} = 2\ m_{\text{top}} \approx 345\ \text{GeV}$$

- Region poses several modelling challenges
  - EW corrections
  - Non-relativistic QCD
  - Spin correlations & entanglement
  - NWA - assumes both tops are on shell

JHEP08 (2024) 013



$t\bar{t}$ Production at Threshold

- **Active Research Frontier :**
  - The threshold region, where top–antitop pairs are produced nearly at rest, is a major focus for ATLAS and CMS
- **Quantum Entanglement Studies:**
  - Key for exploring top-quark entanglement and testing quantum mechanics at high energies
- **Focus of Today's Presentation:**
  - Public results on the observation of quantum entanglement in top-quark pairs with the ATLAS detector

Nature 633 (2024) 542

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

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March 20, 2024

Observation of quantum entanglement with top quarks at the ATLAS detector

The ATLAS Collaboration

Entanglement is a striking feature of quantum mechanics [1–3], with applications in fields such as metrology, cryptography, quantum information, and quantum computation [4–8]. It has been observed in a wide variety of systems and length scales, ranging from the microscopic [9–13] to the macroscopic [14–16]. However, entanglement remains largely unexplored at the highest accessible energy scales. We report the highest-energy observation of entanglement, in top–antitop quark events produced at the Large Hadron Collider, using a proton–proton collision data set with a center-of-mass energy of $\sqrt{s} = 13$ TeV and an integrated luminosity of 140 fb^{-1} recorded with the ATLAS experiment. Spin entanglement is detected from the measurement of a single observable D, inferred from the angle between the charged leptons in their parent top- and antitop-quark rest frames. The observable is measured in a narrow interval around the top–antitop quark production threshold, where the entanglement detection is expected to be significant. It is reported in a fiducial phase space defined with stable particles to minimize the uncertainties that stem from limitations of the Monte Carlo event generators and the parton shower model in modeling top-quark pair production. The entanglement marker is measured to be $D = -0.537 \pm 0.002$ (stat.) ± 0.019 (syst.) for $340 < m_{t\bar{t}} < 380$ GeV. The observed result is more than five standard deviations from a scenario without entanglement and hence constitutes both the first observation of entanglement in a pair of quarks and the highest-energy observation of entanglement to date.

Entanglement Theory

- Spin correlations between top and anti-top provide novel approach to measure entanglement

- Tops have an extremely short lifetime

$$\boxed{5 \times 10^{-25}\ \mathbf{s}} \ll \boxed{\sim 10^{-24}\ \mathbf{s}} \ll \boxed{\sim 10^{-21}\ \mathbf{s}}$$

Top lifetime **Hadronization** **Spin**

- The $t\bar{t}$ system forms a bipartite spin $1/2$ system

- The spin of the $t\bar{t}$ decay products are correlated to the spin of the tops

Spin Density Matrix

$$\rho = \frac{1}{4}\left[I_4 + \underbrace{\sum_i \left(B_i^+ \sigma^i \otimes I_2 + B_i^- I_2 \otimes \sigma^i \right)}_{\text{Top polarization}} + \underbrace{\sum_{i,j} C_{ij} \sigma^i \otimes \sigma^j}_{\text{Spin correlations}} \right]$$

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Entanglement Theory

$$\rho = \frac{1}{4}\left[I_4 + \sum_i \left(B_i^+ \sigma^i \otimes I_2 + B_i^- I_2 \otimes \sigma^i\right) + \sum_{i,j} C_{ij} \sigma^i \otimes \sigma^j\right]$$

- At LHC $t\bar{t}$ has negligible polarisation
- Observable
  - From the Peres-Horodecki criterion

$$\text{tr}[C] < -1$$

  - Define the spin correlation coefficient

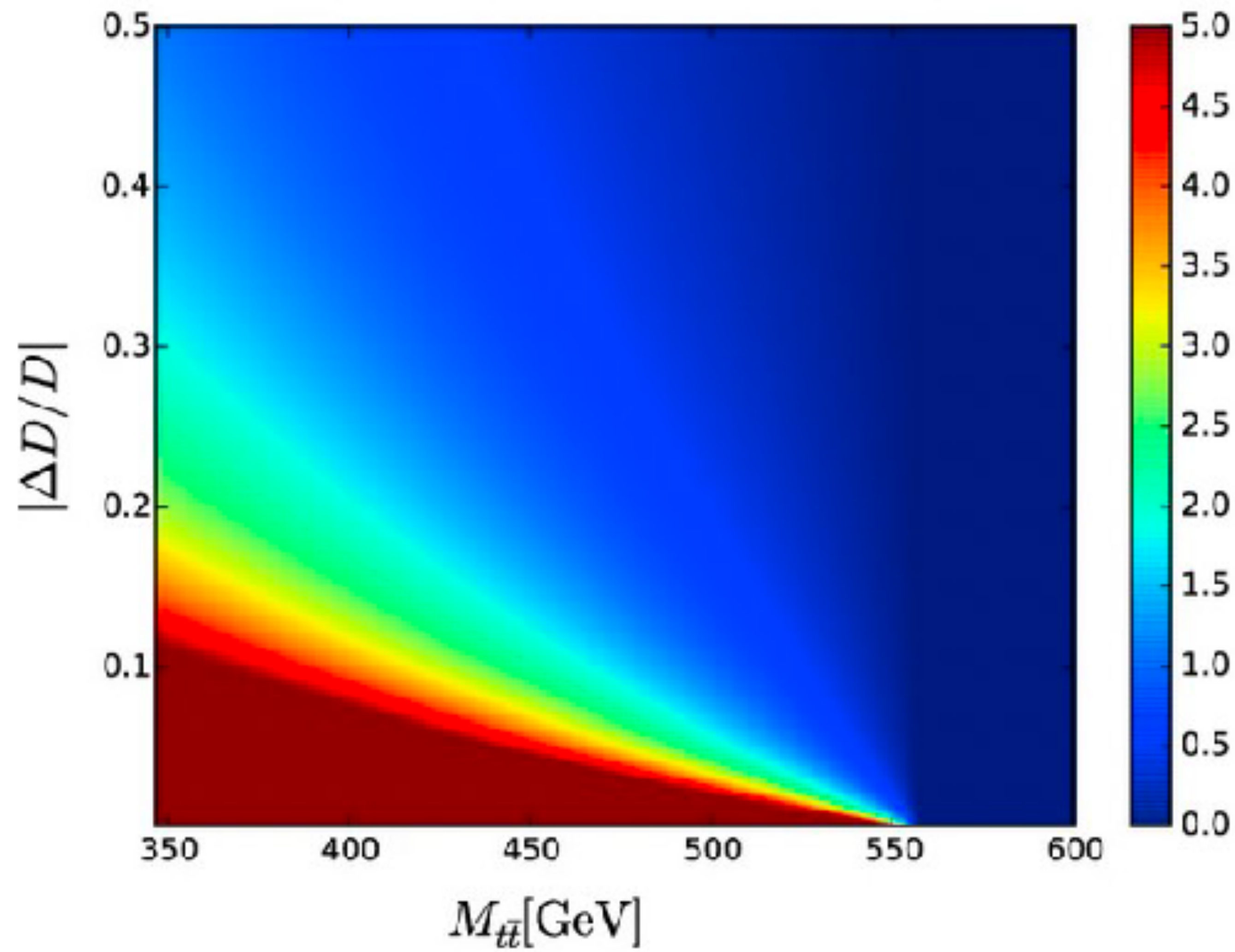
$$D = \text{tr}[C] \rightarrow D < -1/3$$

  - D can be determined from

$$\hat{\ell}_1 \cdot \hat{\ell}_2 = \cos(\phi_{\ell\ell})$$

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\varphi} = \frac{1}{2}(1 - D\cos\varphi)$$

The statistical deviation from the null hypothesis for different assumptions of relative uncertainty on D



Eur. Phys. J. Plus (2021) 136:907

Entanglement Theory

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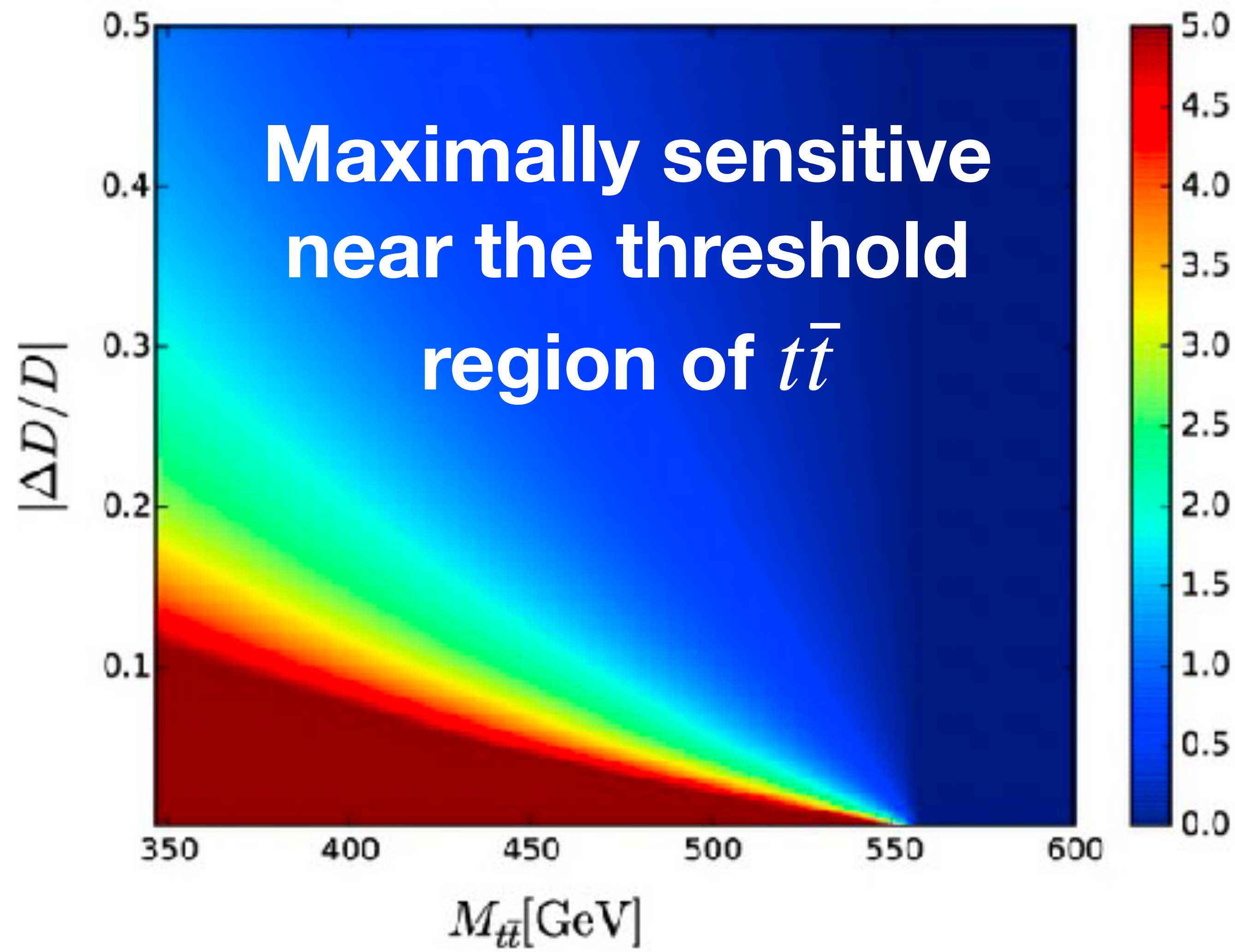

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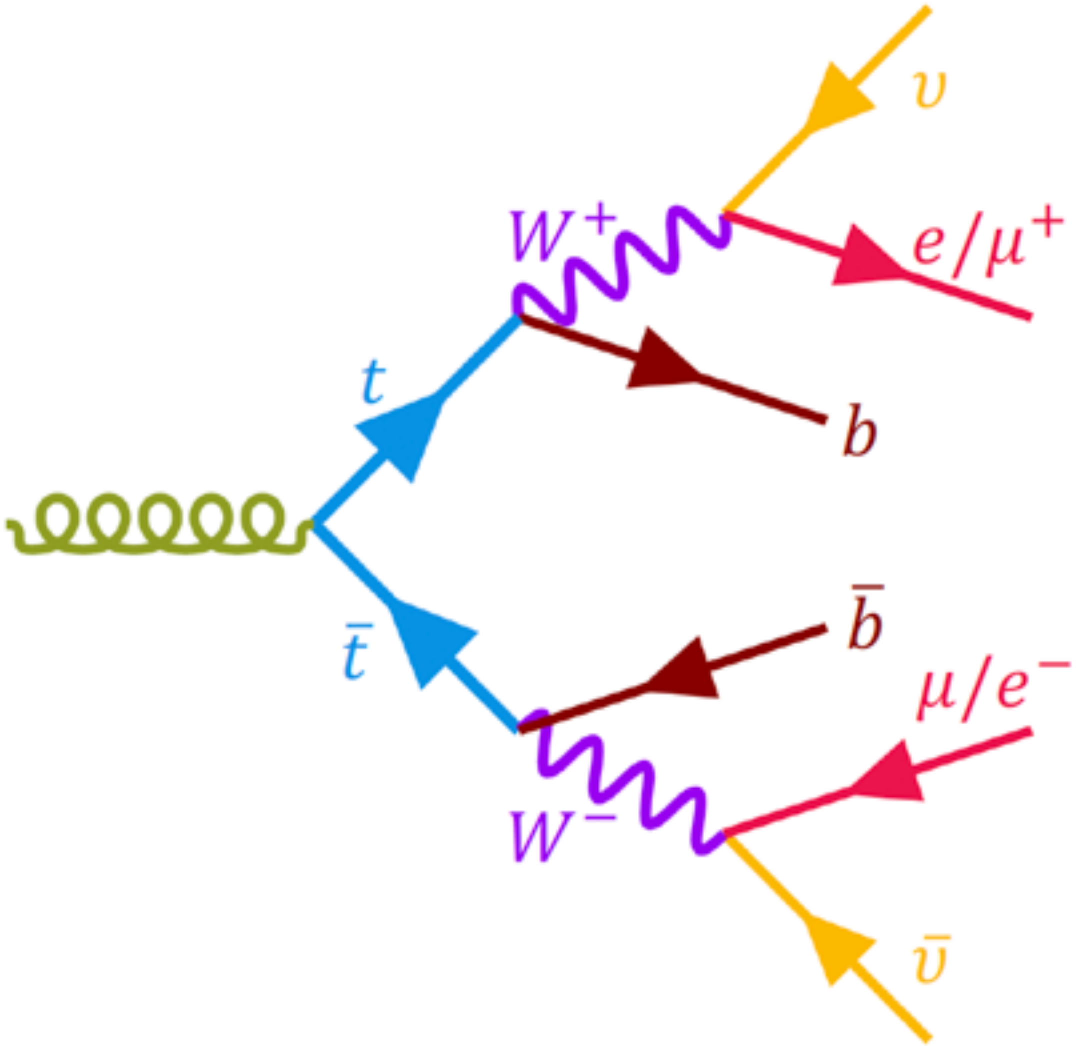
Analysis Strategy

- **Event Selection**
  - Select eμ dilepton tt events
  - Extremely pure channel (~90% tt)



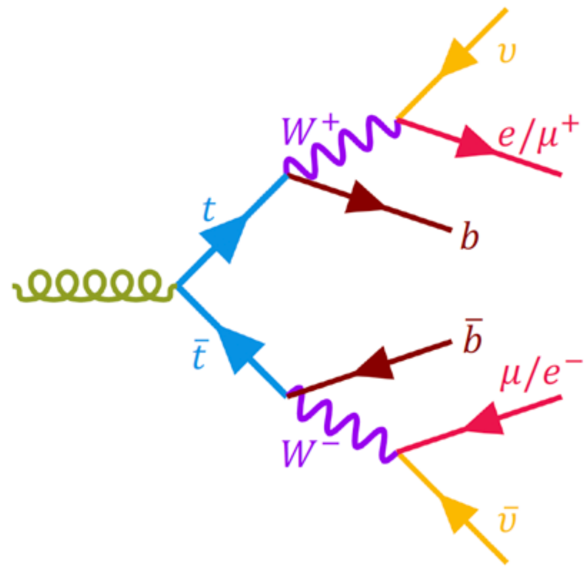
Analysis Strategy

- **Event Selection**
  - Select eμ dilepton tt events
  - Extremely pure channel (~90% tt)
- **Top Reconstruction**
- **Estimate Calibration curve**
  - Data and simulation corrected to fiducial particle level using **calibration curve**
- **Extract spin correlation coefficient**
  - Extract D at fiducial particle level

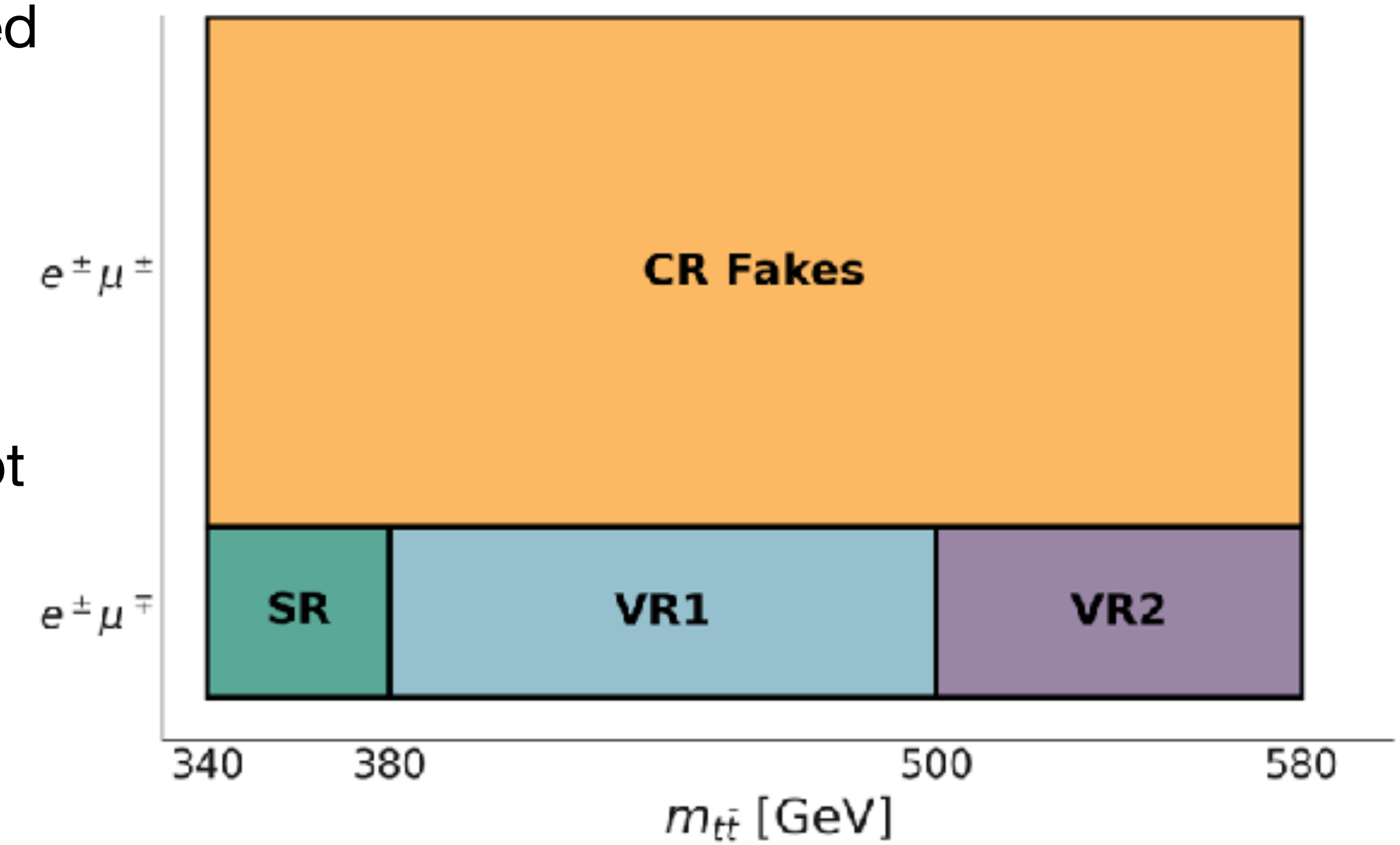
$$\mathbf{D} = -3 \cdot < \cos\phi >$$

Event Selection

- Full run 2 data-set ($140\ \mathrm{fb}^{-1}$)
- Dominant backgrounds
  - Wt, diboson, $Z \to \tau\tau$, fakes
- Split into four regions
  - **SR** : Tops are maximally entangled
  - **VR1** : Entanglement diluted
  - **VR2** : No entanglement
  - **CR** : Used to estimate non-prompt lepton contribution



Selection	Requirement
Leptons	$N_e = 1$, $N_\mu = 1$
Lepton p_t	$\ell \geq 15$ GeV (ℓ = e or μ)
Jets	$N_{jets} \geq 2$, $p_t \geq 25$ GeV
B-jets	$N_b \geq 2$, DL1r = 85%



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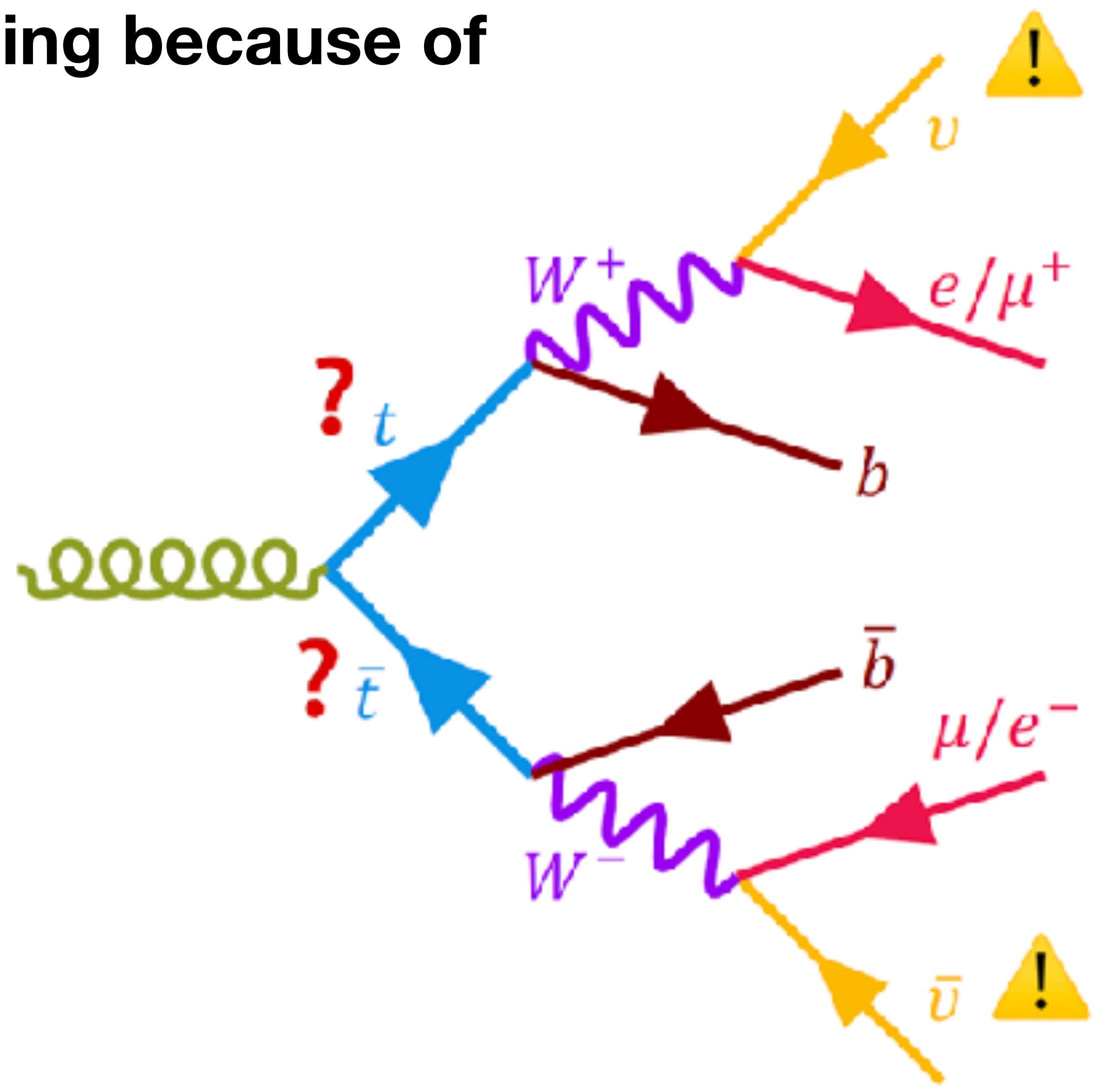
Top Reconstruction

- Need to reconstruct the top and anti-top

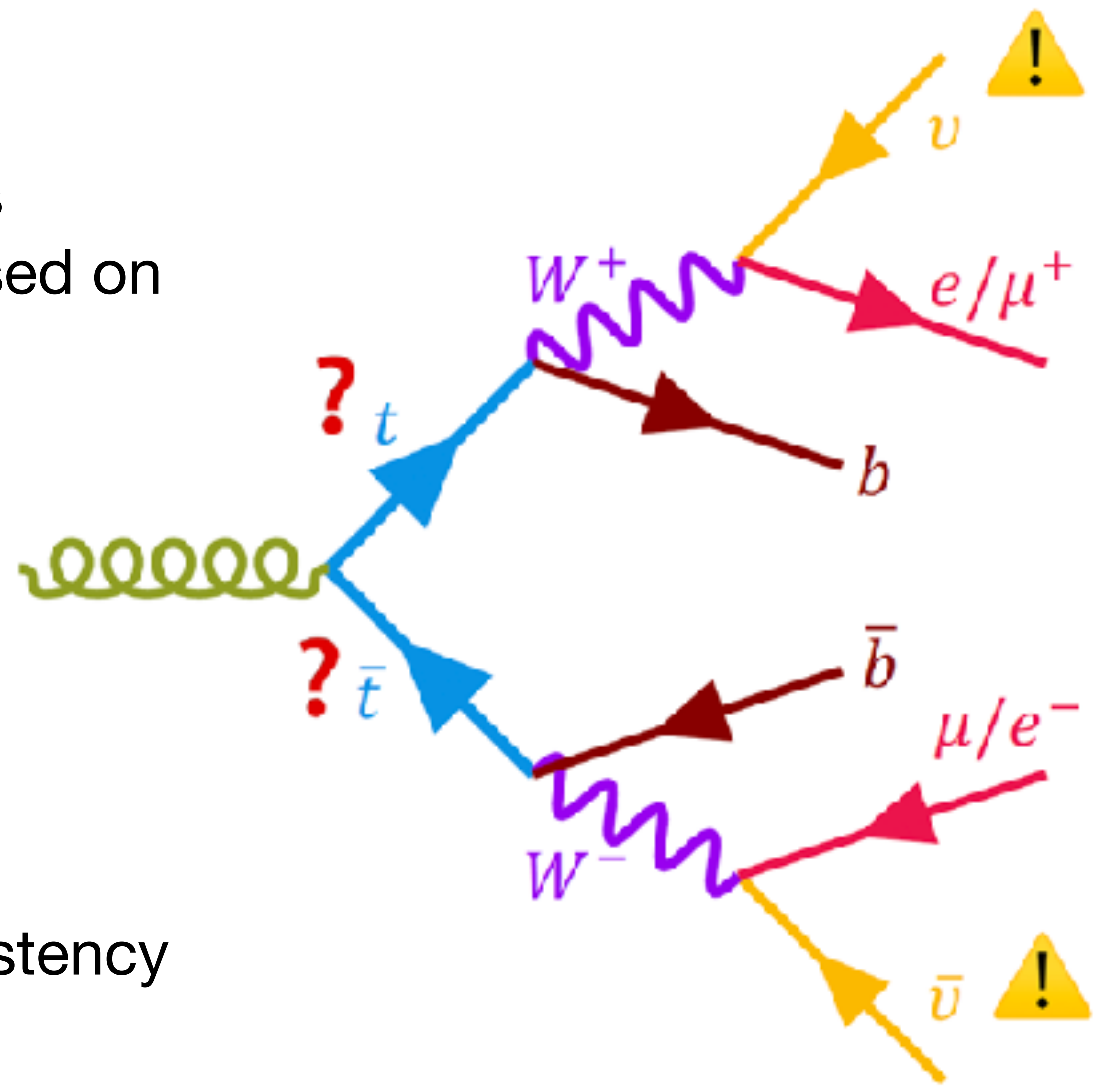
- **Top Reconstruction**

  - $t = b + e/\mu^{+} + \nu$ **.... is challenging because of MET**



Top Reconstruction

- Primary technique:
  - Ellipse Method : A geometric approach that provides **analytical solutions for the neutrino momenta** based on kinematic constraints in dileptonic top decays
- Alternative techniques:
  - Neutrino Weighting method:
    - Scans over possible neutrino pseudo-rapidities
    - Assigns weights to solutions based on their consistency with the observed missing transverse momentum
  - Simple kinematic matching
    - Simplified method pairing each lepton with the closest **b-tagged jet**
    - No explicit neutrino reconstruction; used as a proxy for reconstructing the top and antitop quarks

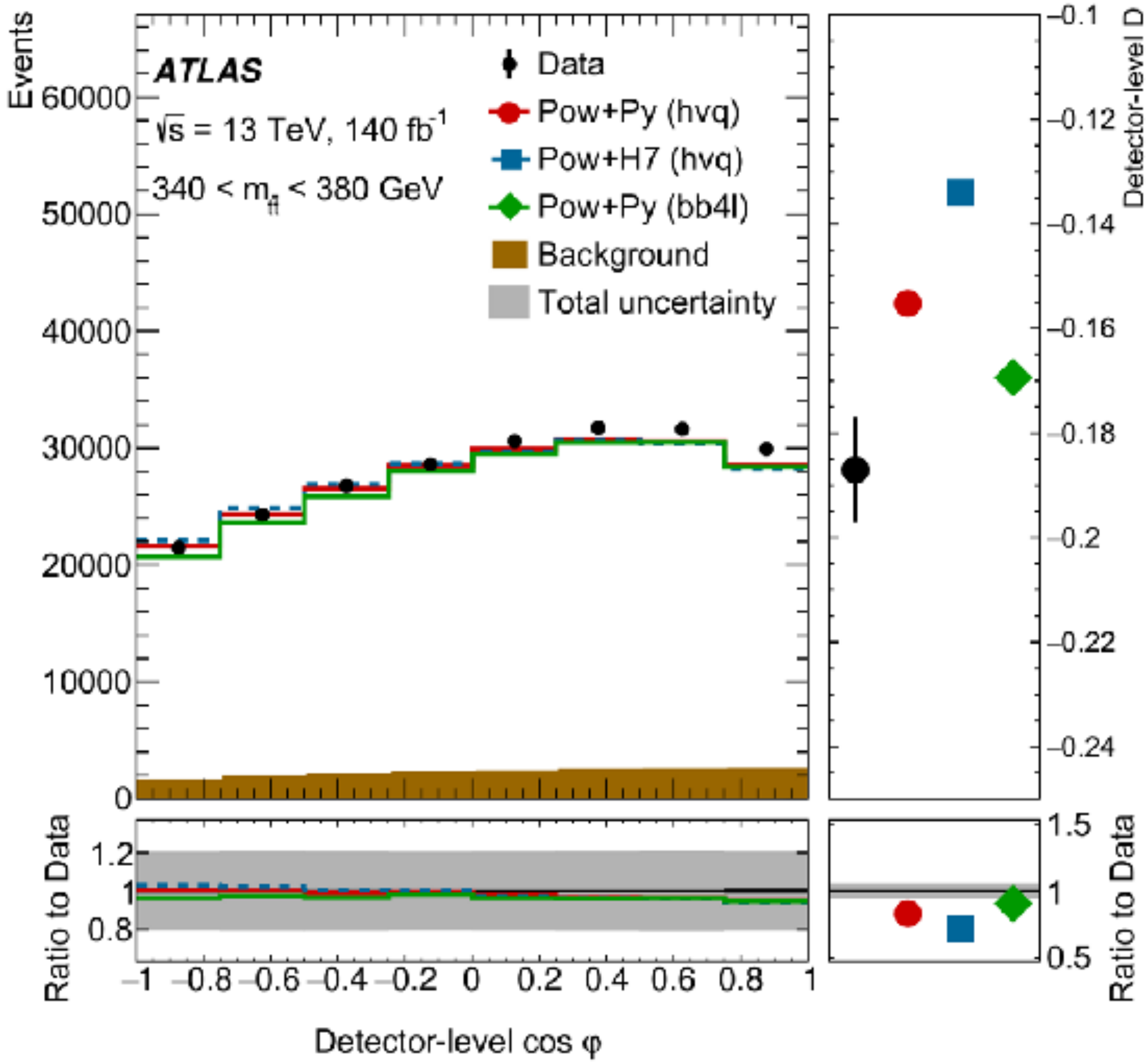


Top Reconstruction

- Allows for the reconstruction of $m_{t\bar{t}}$ and $cos(\phi_{ll})$
- Estimate spin correlation coefficient

$$D = -3. < cos\phi >$$

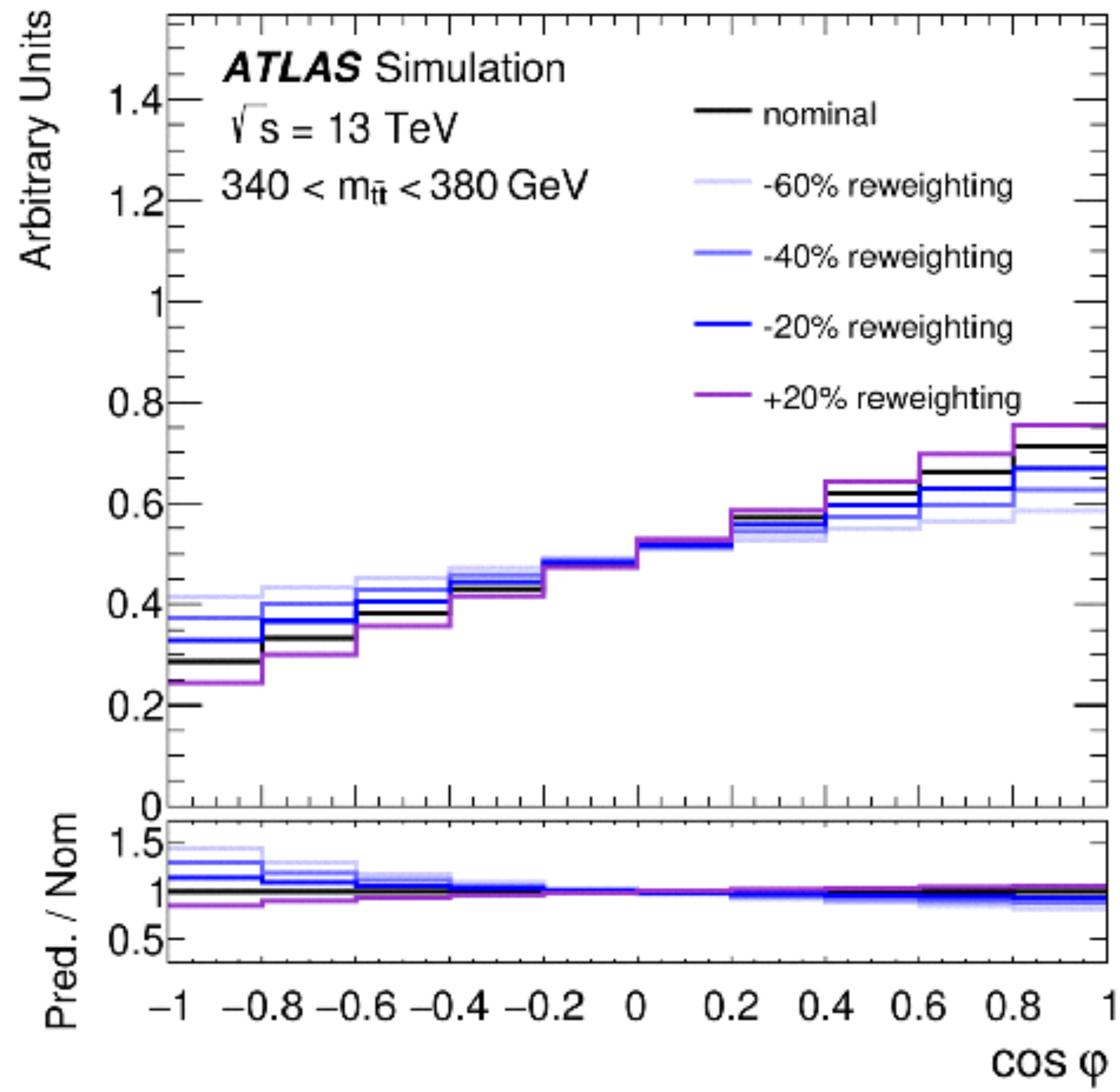
Reconstructed $cos\phi$ at detector level in the SR



Mapping to particle level

- **Using MC : create a map between detector and fiducial particle level for different values of D**
- Simulation is re-weighted at particle level for different values of D
  - Implemented as a function of $m_{t\bar{t}}$ & $cos\phi$
- Systematics propagated with their own curves
  - Added in quadrature
- Corrects for detector effects
- D extracted at a fiducial particle level

Re-weighting of $cos\phi$ for different values of D is shown at particle level



Calibration curve

- **Using MC : create a map between detector and fiducial particle level for different values of D**
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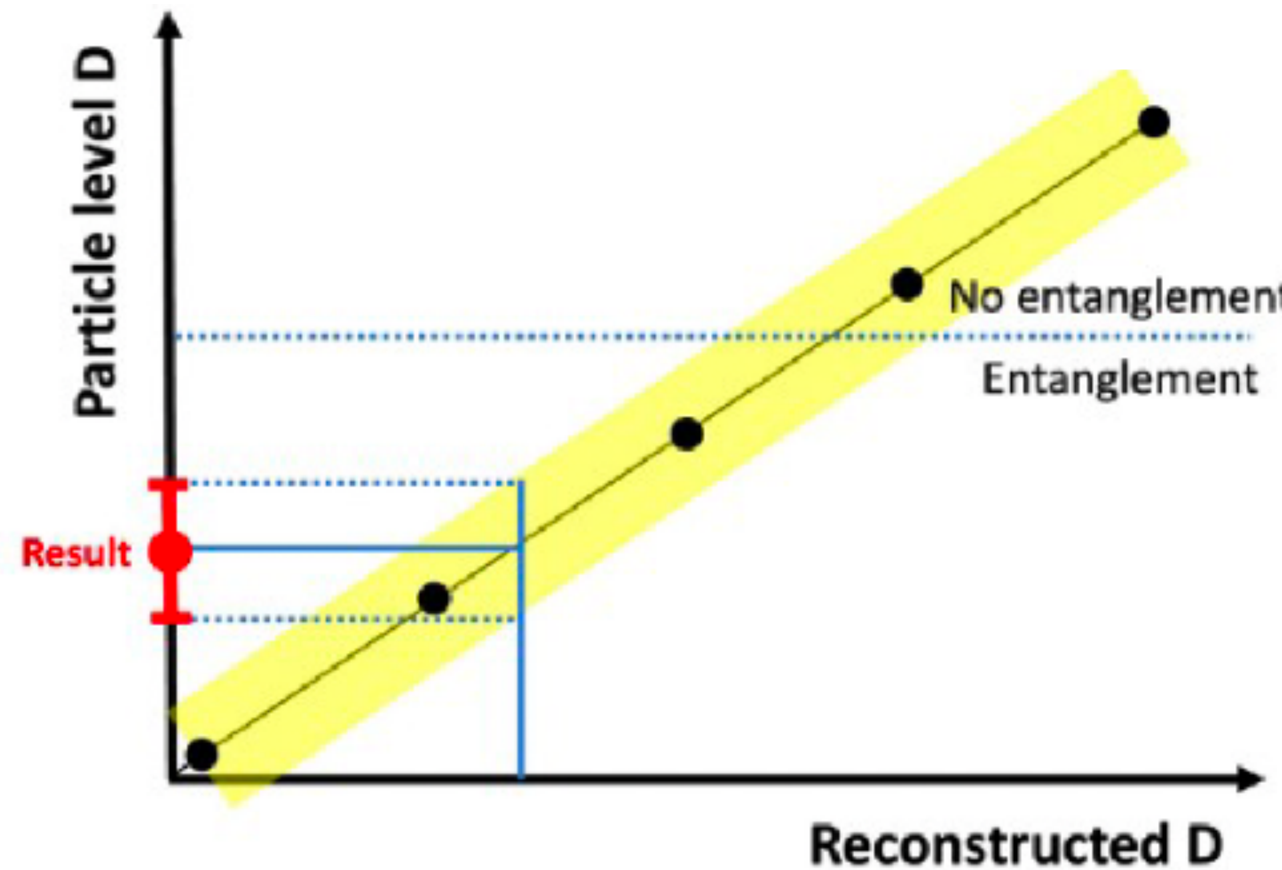
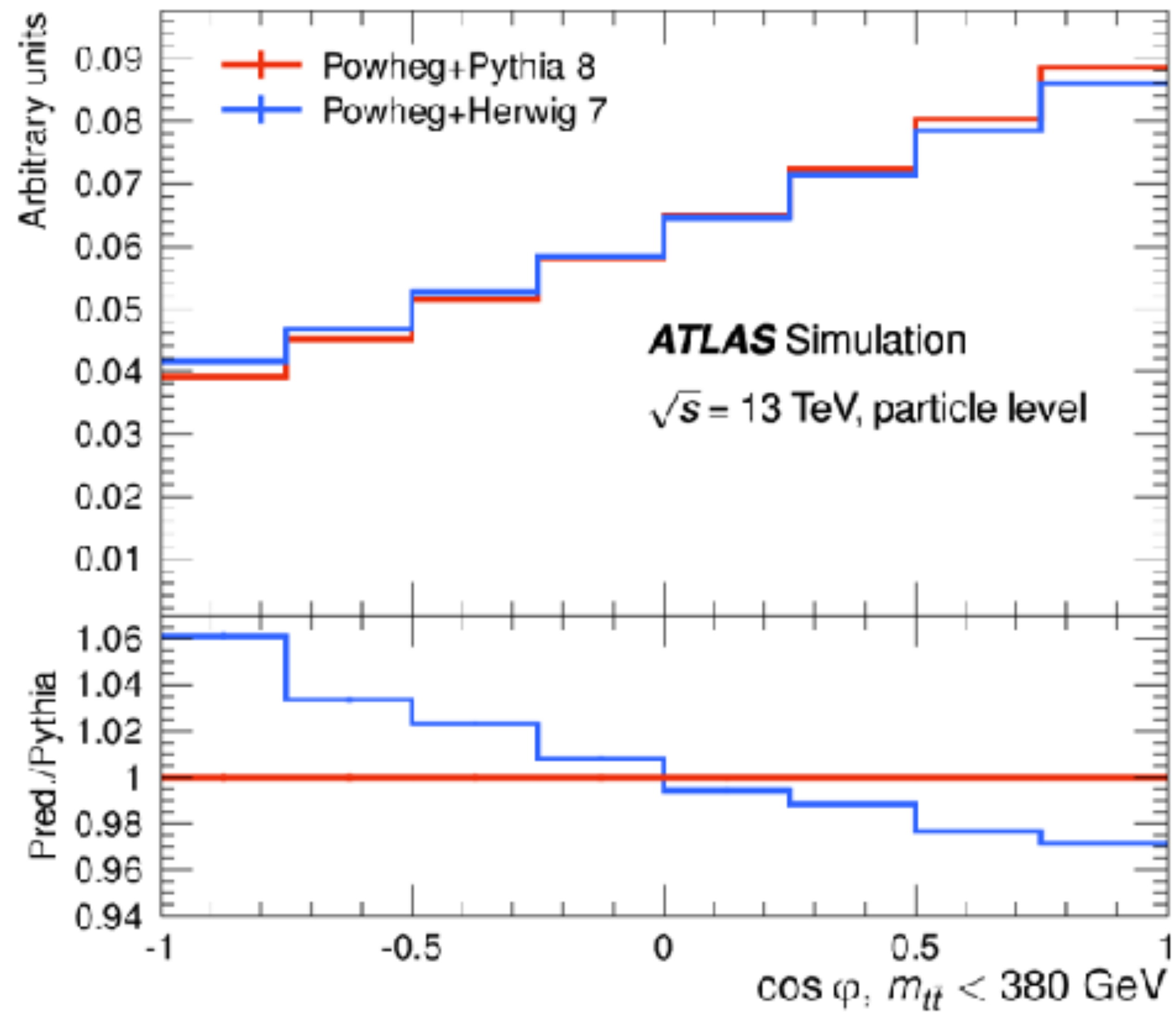
An illustration of the calibration curve mapping between detector and particle level



Generator Discrepancy

- Good agreement between PhPy8 and PhHw7 at parton level
- Discrepancy arises at stable particle level
  - Difference also present at detector level
- Isolated to shower ordering
- Treatment of spin effects in Monte Carlo generators requires attention

Differences in $cos\phi$ distribution between PhPy8 and PhHw7 at particle level



	Pythia 8	Herwig 7
Tune	A14	H7-UE-MMHT
Hadronisation model	Lund string	Cluster
Shower ordering	p_T	angular

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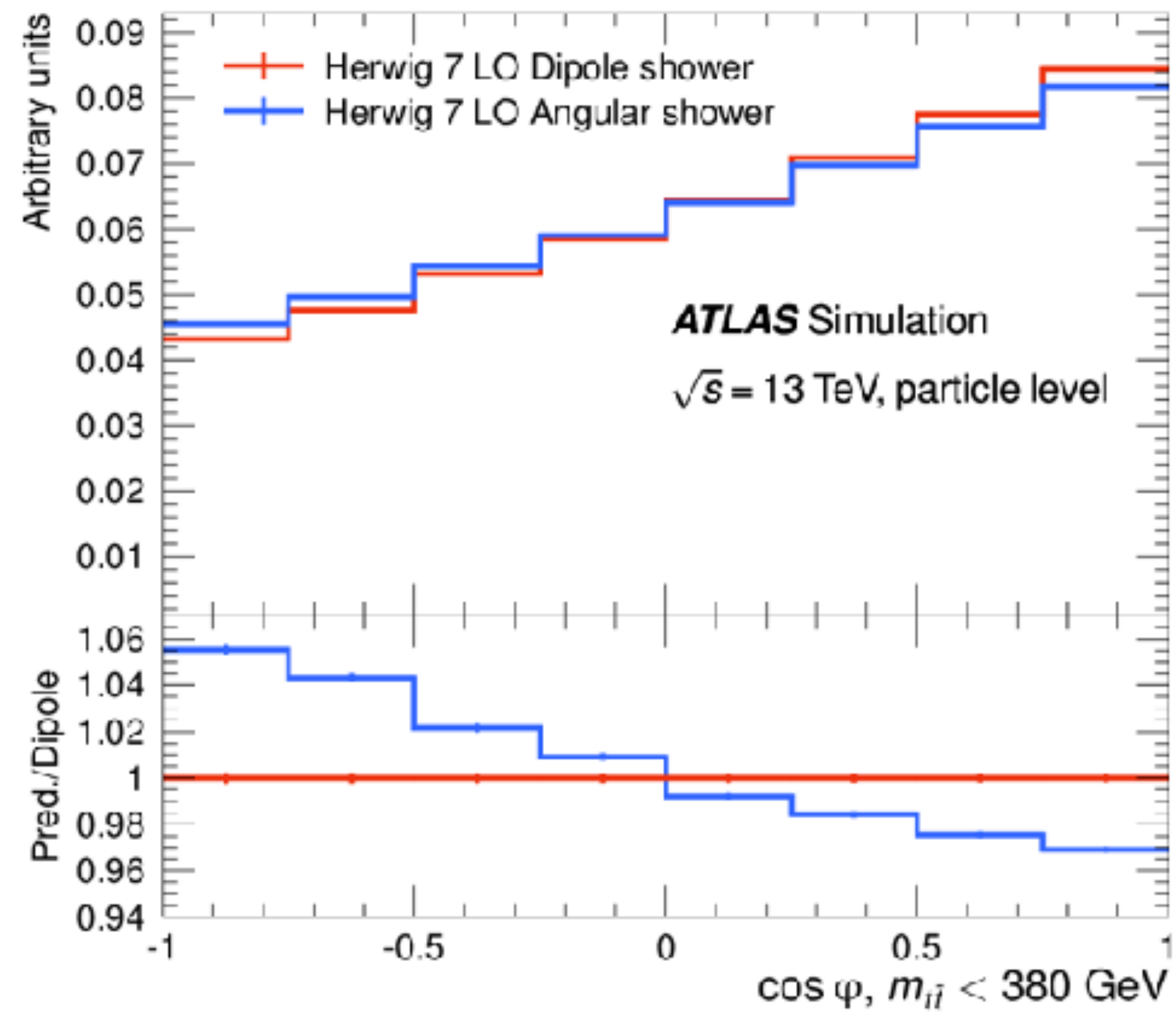
Differences in $cos\phi$ distribution between Dipole shower and Angular shower at particle level



	Pythia 8	Herwig 7
Tune	A14	H7-UE-MMHT
Hadronisation model	Lund string	Cluster
Shower ordering	p_T	angular

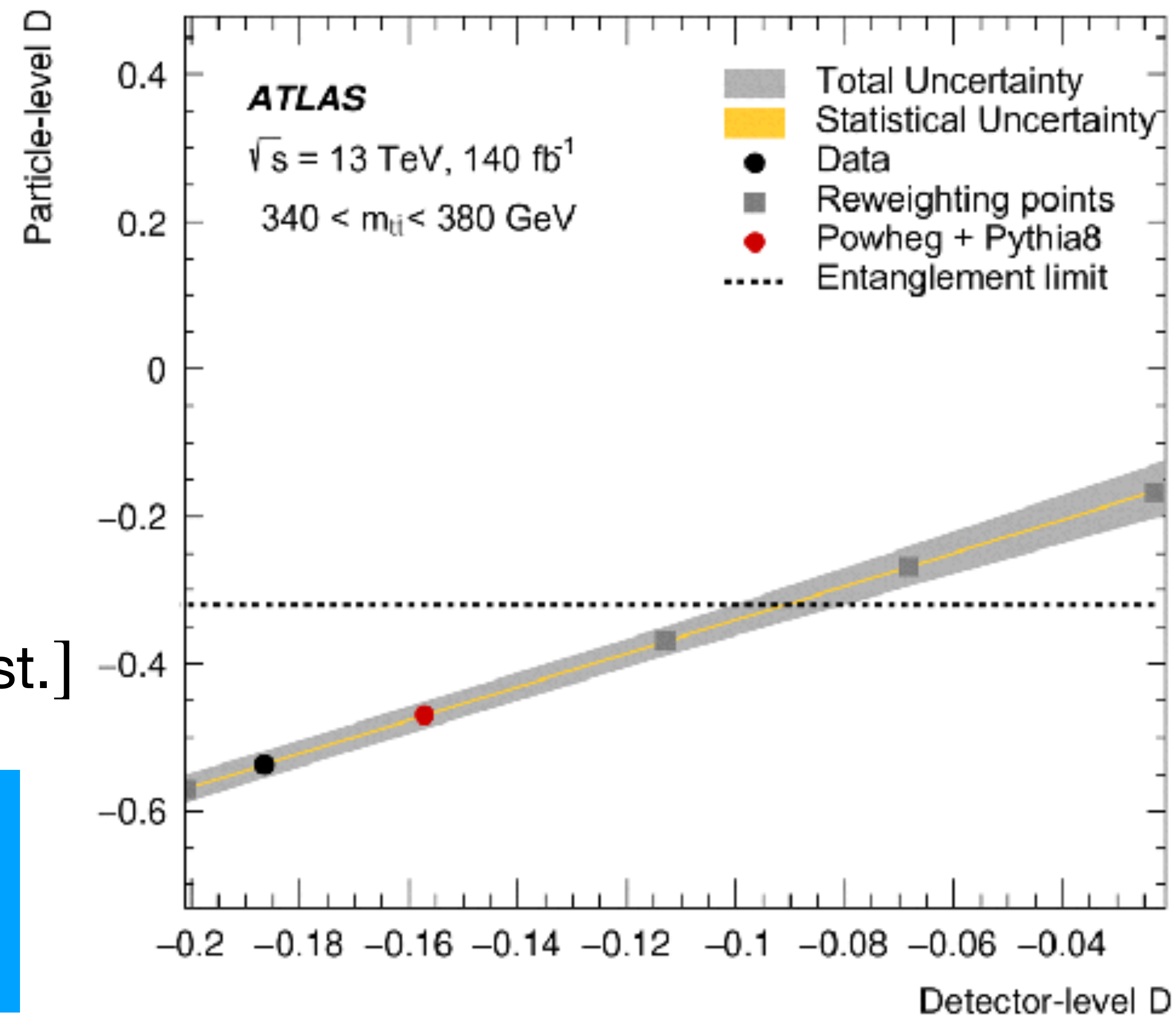
Results

- Calibration curve created using outline procedure
- Uncertainty dominated by $t\bar{t}$ modelling
  - Top quark decay
  - PDF uncertainty
- Observed results in the SR are

$$D = -0.547 \pm 0.002[\text{stat.}] \pm 0.021[\text{syst.}]$$

First observation of entanglement in quarks

Constructed calibration curve for the SR showing the measured D in data and simulation



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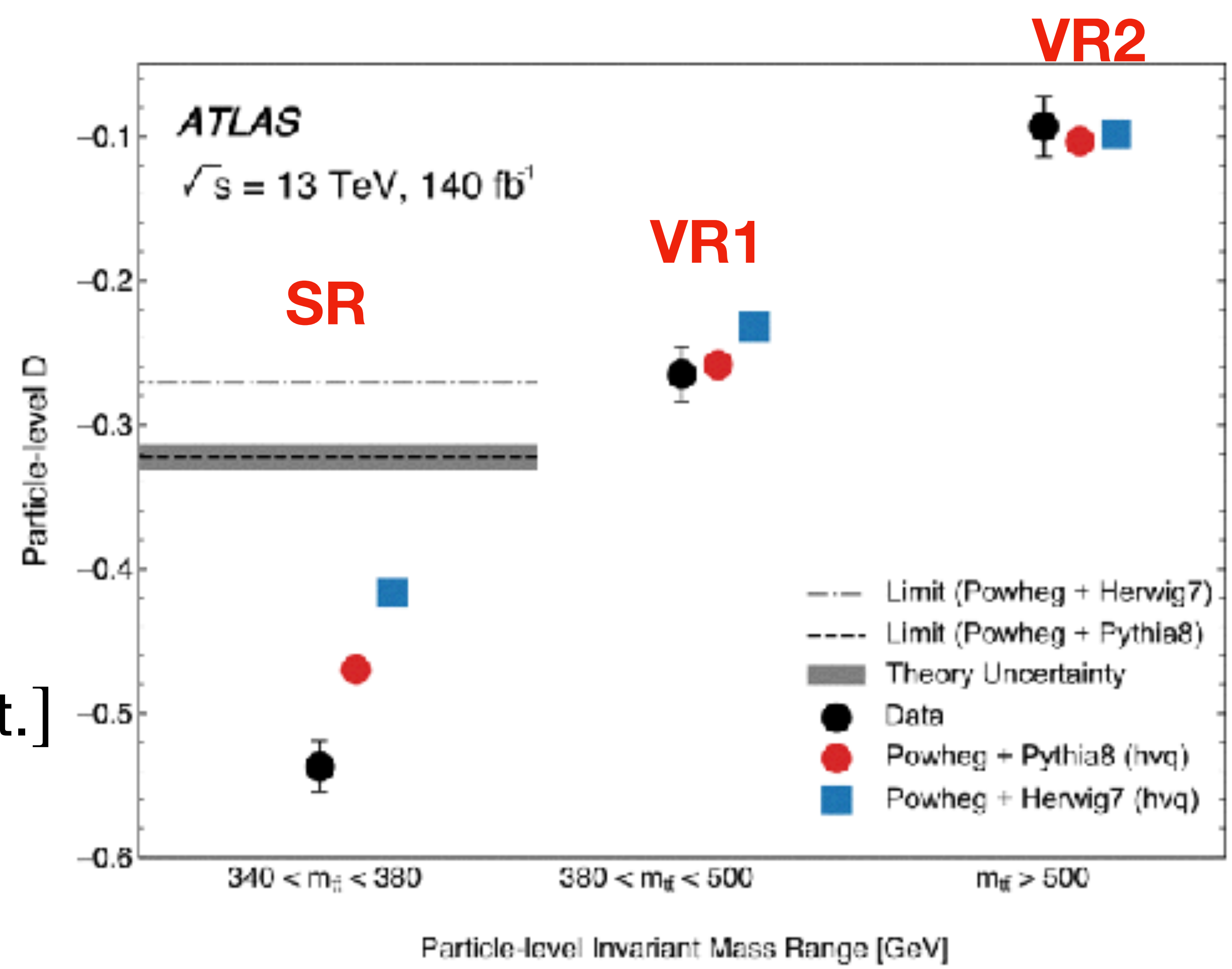
First observation of entanglement in quarks

Measured values of D for data and simulation for the SR and VRs.



Uncertainties

Source of uncertainty	$\Delta D_{\text{observed}}(D = -0.537)$	ΔD [%]	$\Delta D_{\text{expected}}(D = -0.470)$	ΔD [%]
Signal modeling	0.017	3.2	0.015	3.2
Electrons	0.002	0.4	0.002	0.4
Muons	0.001	0.2	0.001	0.1
Jets	0.004	0.7	0.004	0.8
b-tagging	0.002	0.4	0.002	0.4
Pile-up	< 0.001	< 0.1	< 0.001	< 0.1
$E_{\text{T}}^{\text{miss}}$	0.002	0.4	0.002	0.4
Backgrounds	0.005	0.9	0.005	1.1
Total statistical uncertainty	0.002	0.3	0.002	0.4
Total systematic uncertainty	0.019	3.5	0.017	3.6
Total uncertainty	0.019	3.5	0.017	3.6

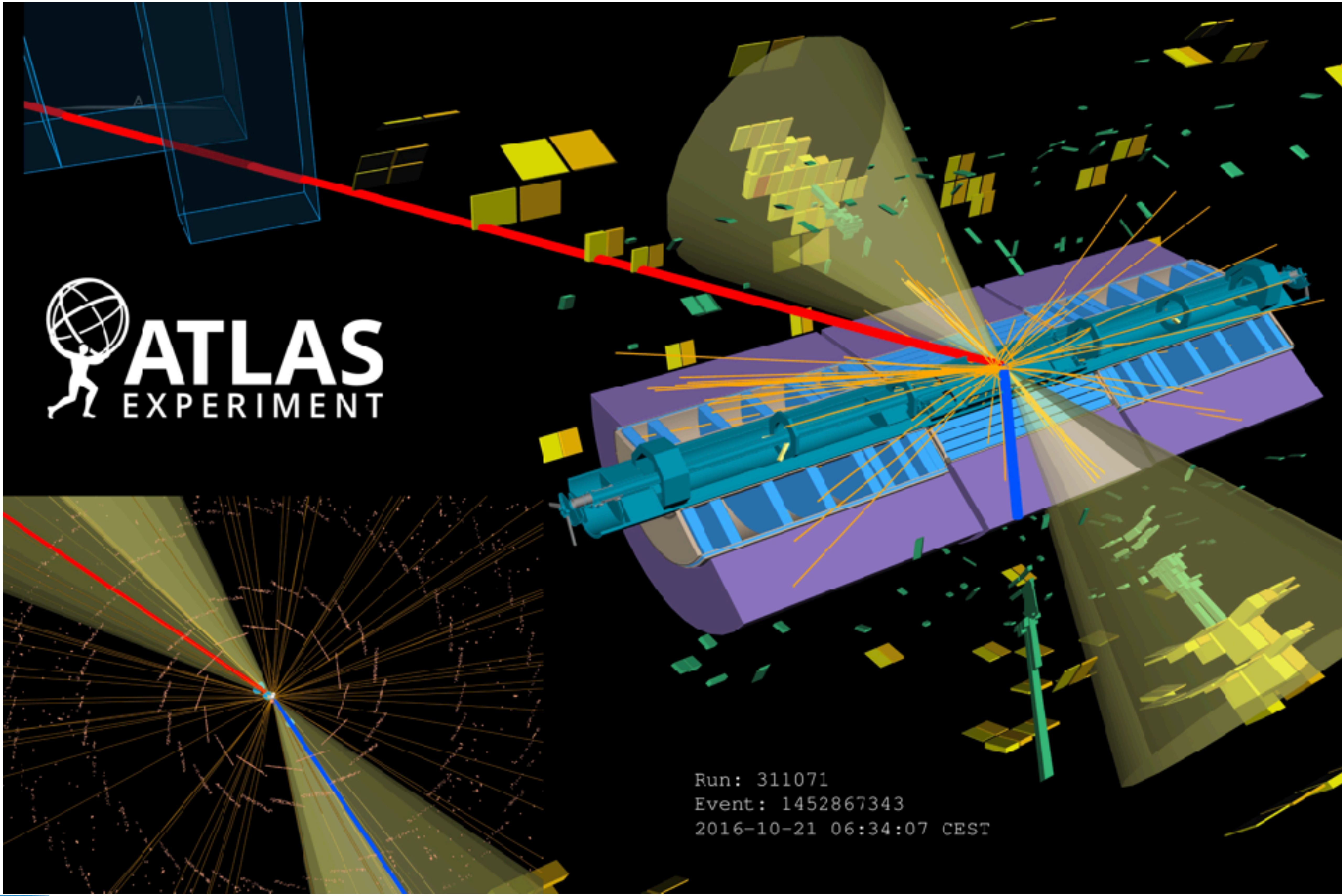
Systematic uncertainty source	Relative size (for SM D value)
Top-quark decay	1.6%
Parton distribution function	1.2%
Recoil scheme	1.1%
Final-state radiation	1.1%
Scale uncertainties	1.1%
NNLO QCD + NLO EW reweighting	1.1%
pThard setting	0.8%
Top-quark mass	0.7%
Initial-state radiation	0.2%
Parton shower and hadronization	0.2%
h_{damp} setting	0.1%

Conclusions

- Threshold region is a very active area of research
- Quantum entanglement measured for the first time in quarks
  - Measured in the region $340\ \text{GeV} < M_{t\bar{t}} < 380\ \text{GeV}$
- Results shown at fiducial particle level

$$D = -0.547 \pm 0.002[\text{stat.}]\ \pm 0.021[\text{syst.}]$$

- Discrepancy between generators at particle level
- Isolated to angular ordering used by Herwig7


ATLAS
EXPERIMENT
Run: 311071
Event: 1452867343
2016-10-21 06:34:07 CEST

Merci!

Most Recent Search

Published for SISSA by Springer
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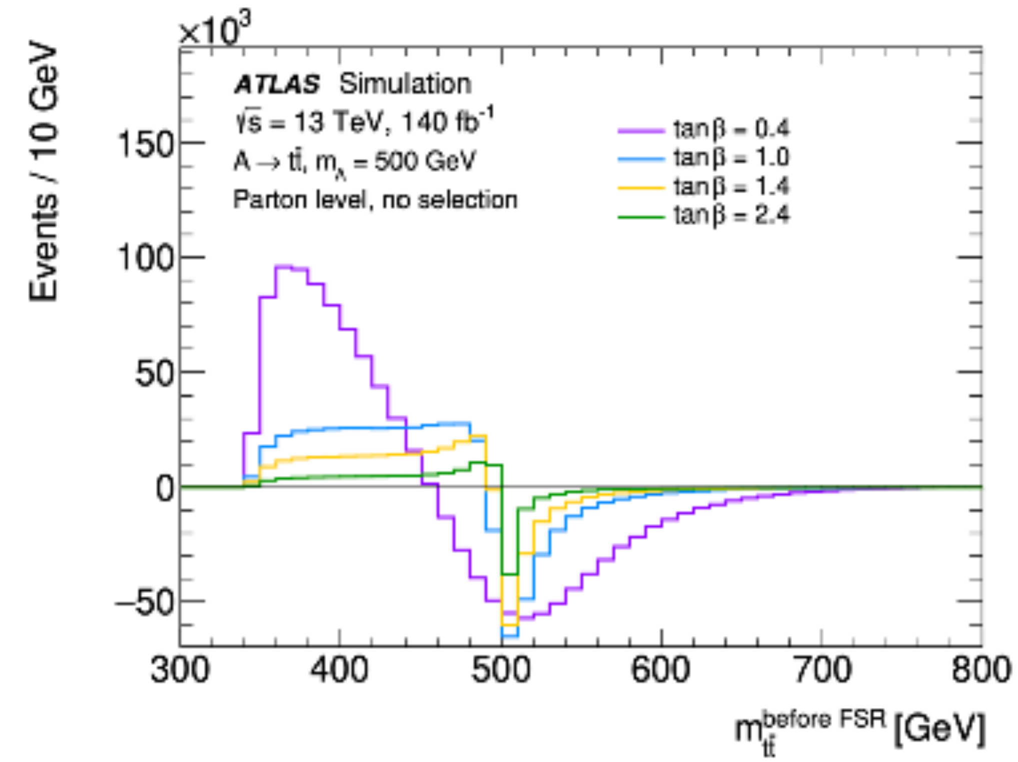
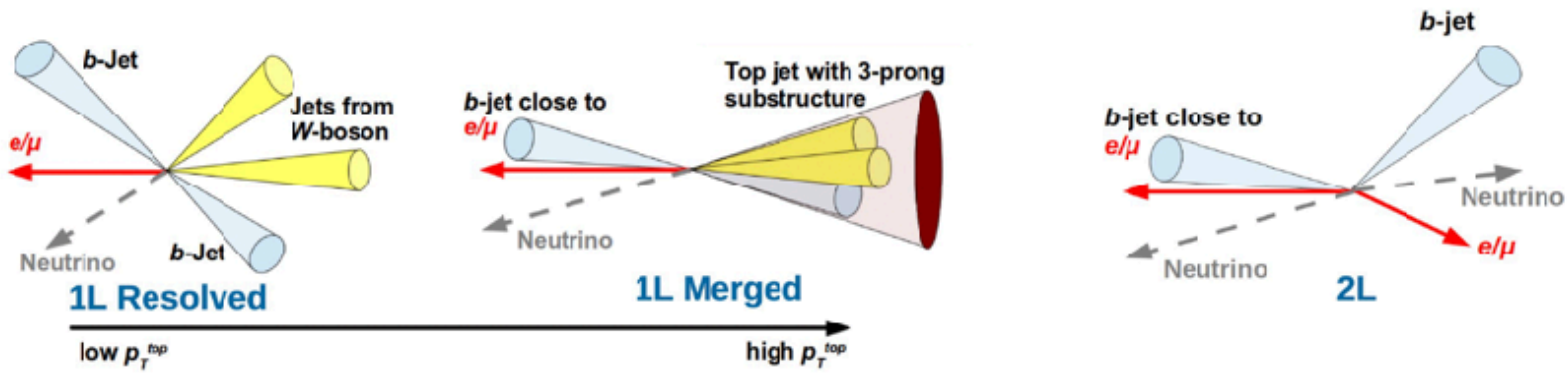
Accepted: July 2, 2024
Published: August 2, 2024

Search for heavy neutral Higgs bosons decaying into a top quark pair in 140 fb^{-1} of proton-proton collision data at $\sqrt{s} = 13$ TeV with the ATLAS detector



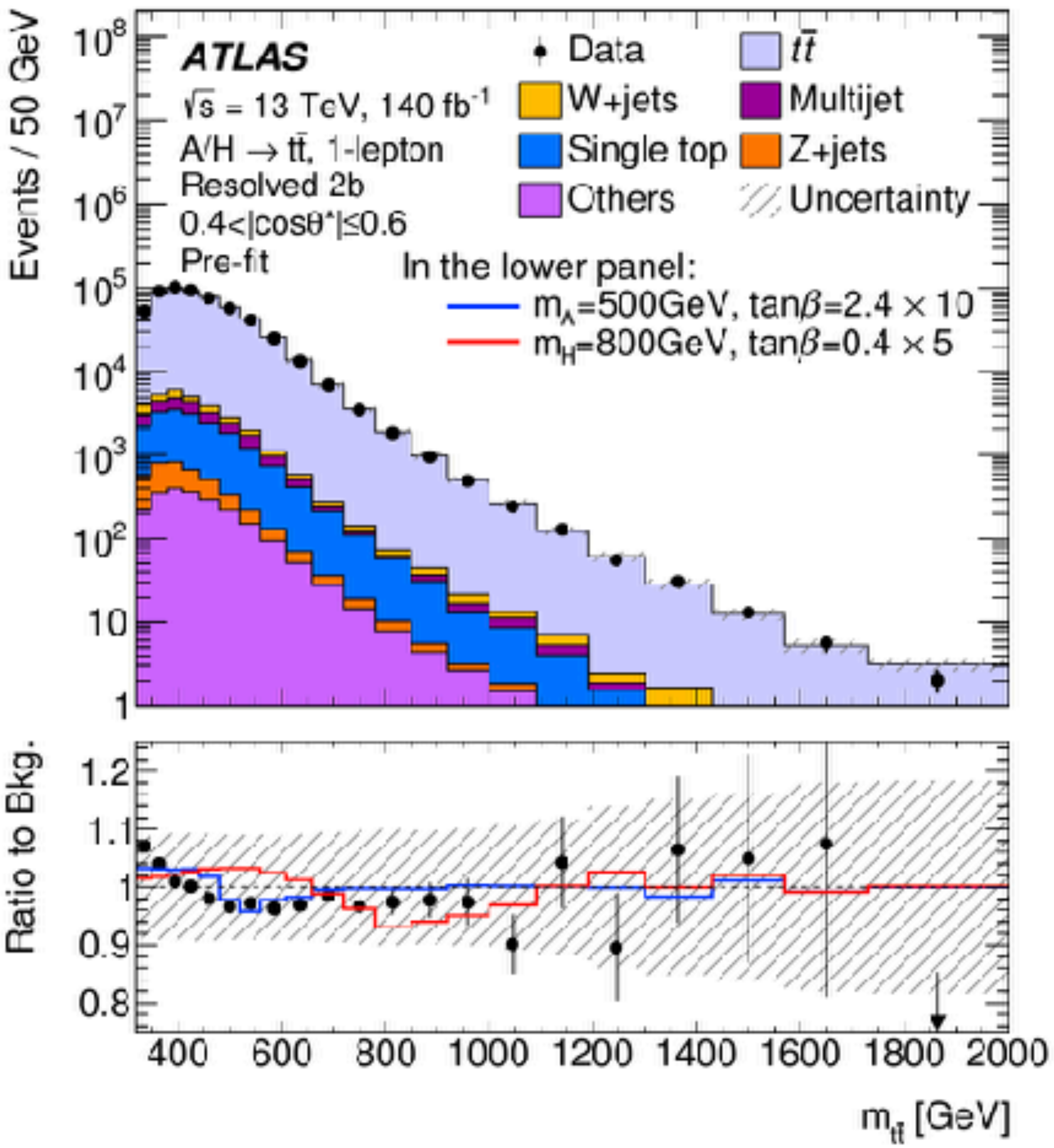
Signal was type-II 2HDM scalar
and pseudo-scalar

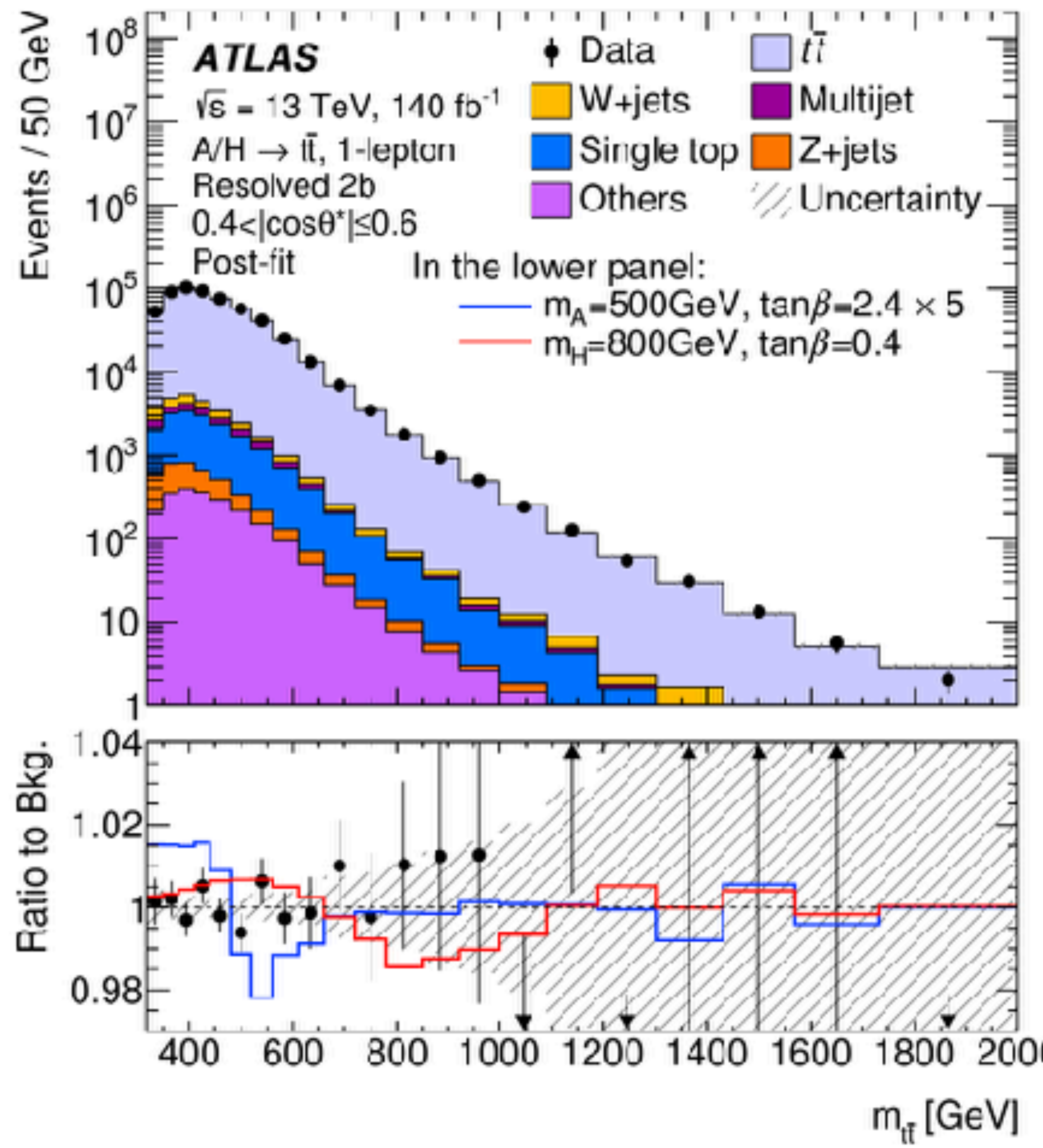
Analysis Specifics



1-Lepton		2-Lepton	
$m_{t\bar{t}}$	$\cos\theta^*$	m_{llbb}	$\Delta\phi$

1L Distributions





Limits on BSM Model