Entangled Tops at the ATLAS Experiment

Ethan Simpson

on behalf of the ATLAS entanglement measurement

Foundational Tests of Quantum Mechanics @ LHC

Tuesday 21st March, 2023

University of Glasgow

THE ROYAL SOCIETY

ATLAS EXPERIMENT

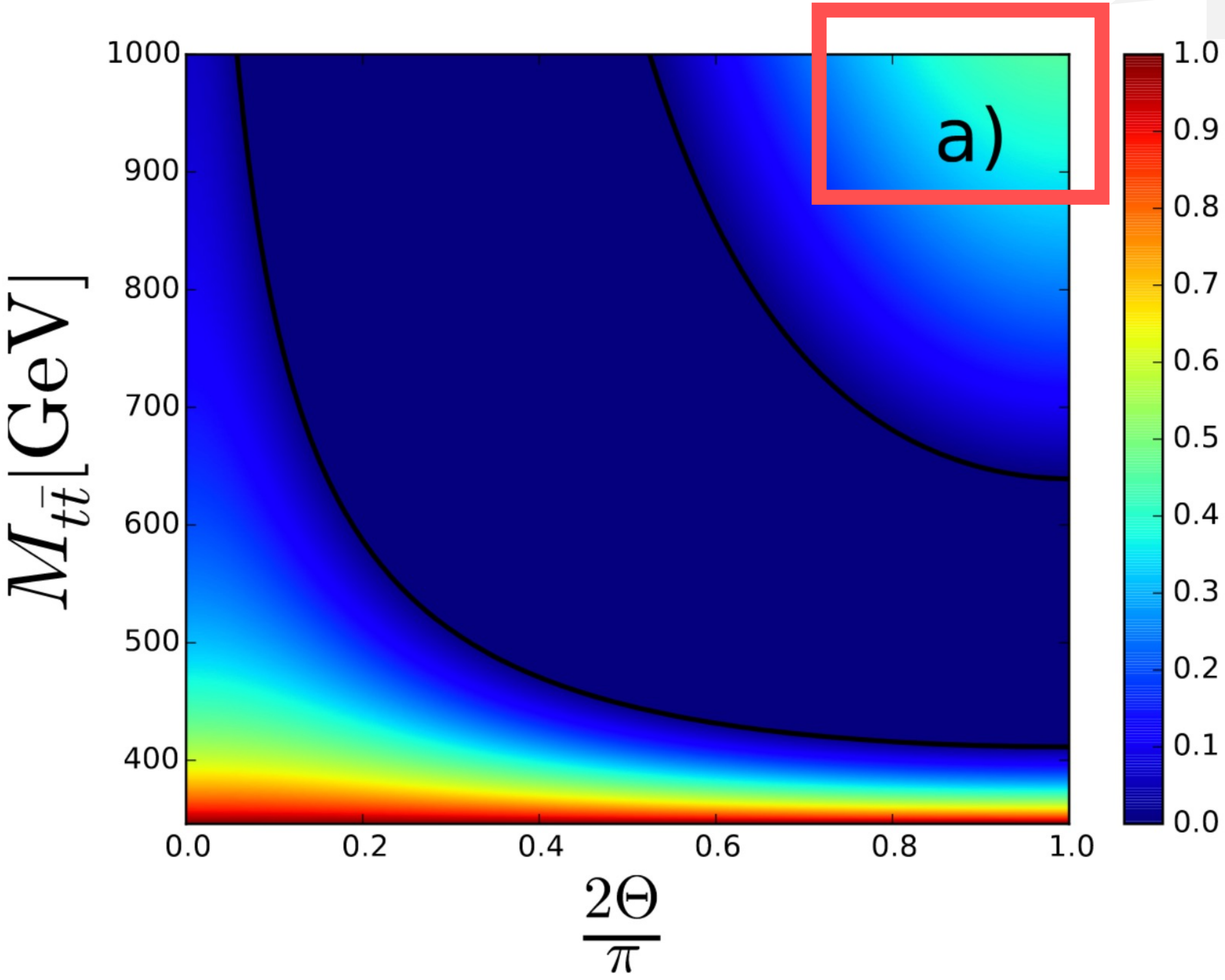
1. Experimental considerations
2. ATLAS dileptonic analysis
3. ATLAS lepton+jets analysis

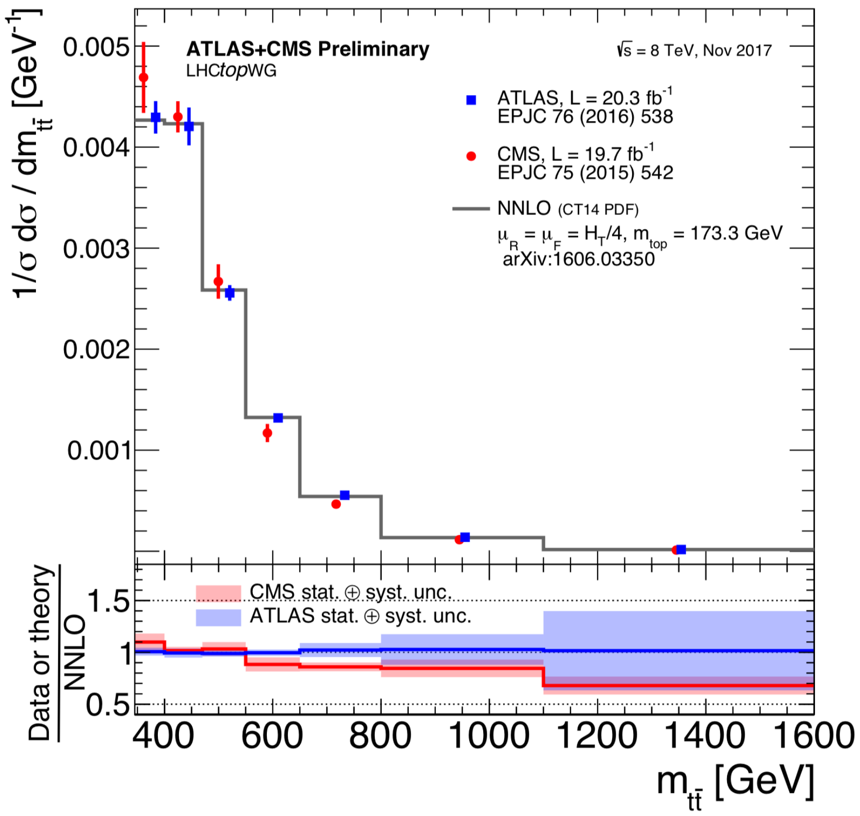
“Theoretically clean, but experimentally quite nasty”

Alan Barr, yesterday

Tangled Up in Tops

- Low statistics
- qq process further dilutes stats
- Use some qq tag?





Tangled Up in Tops

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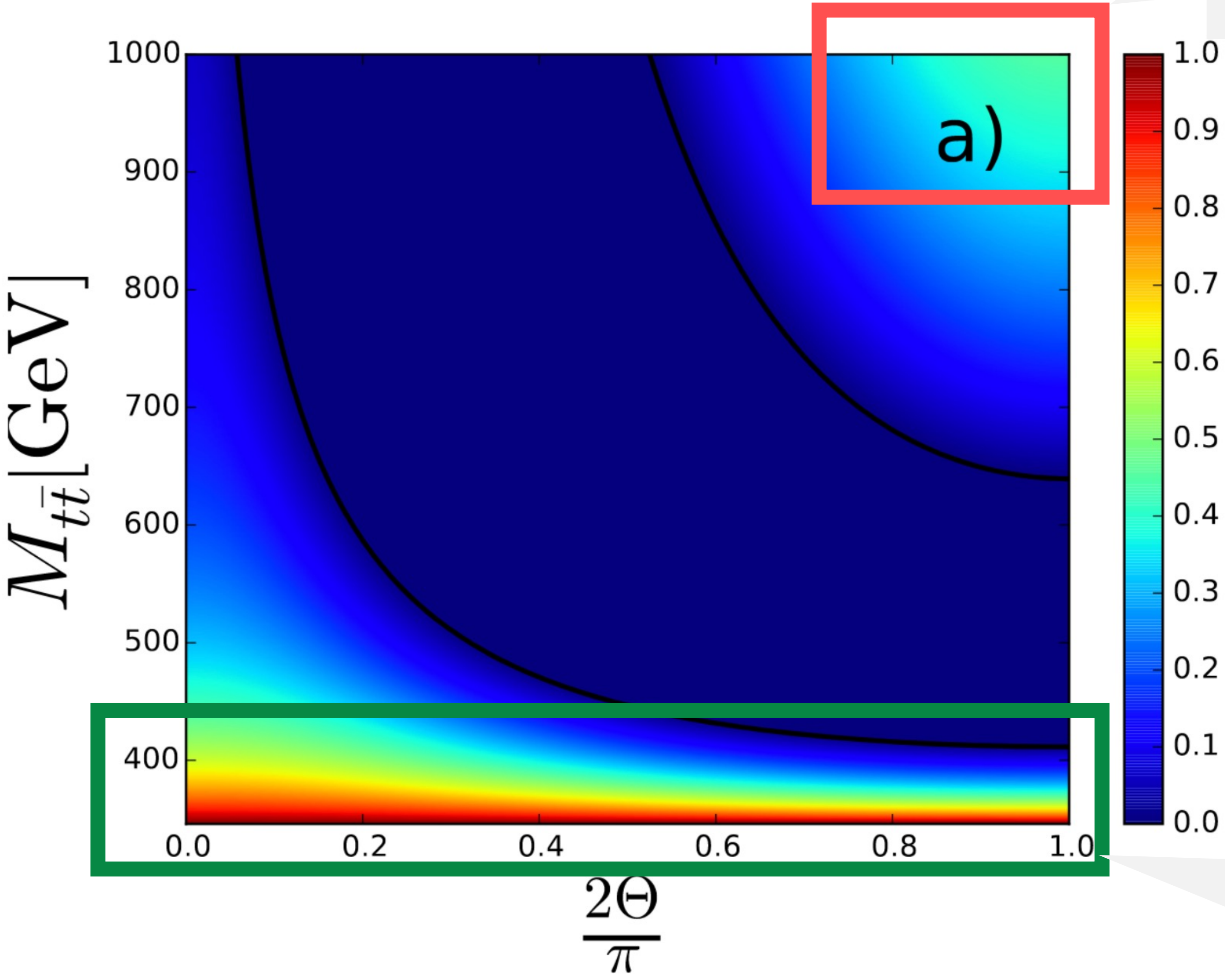
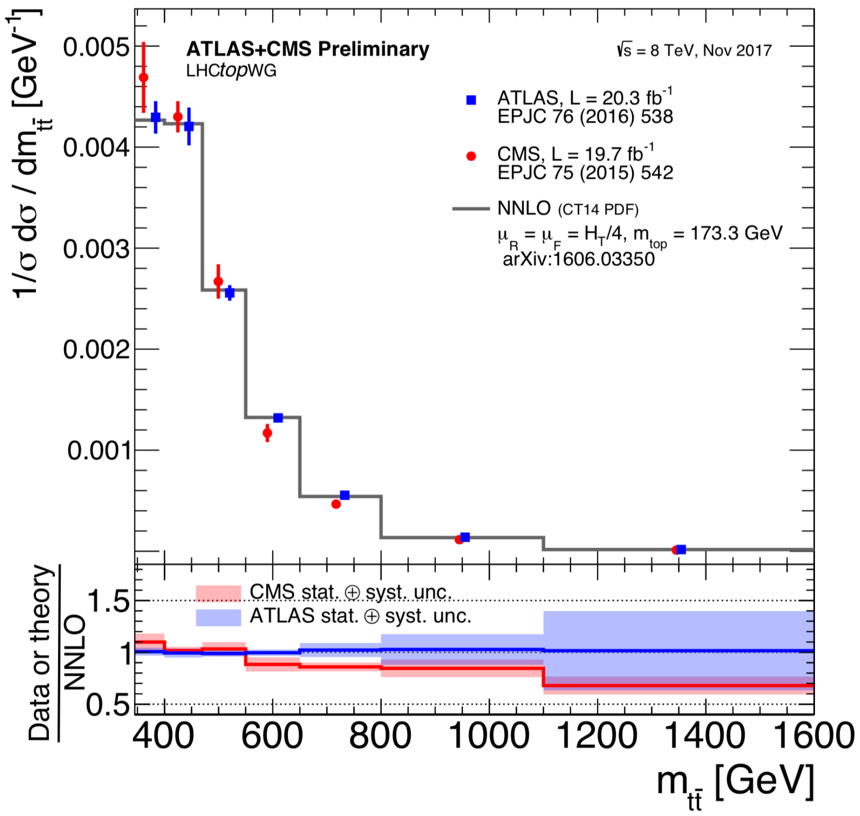
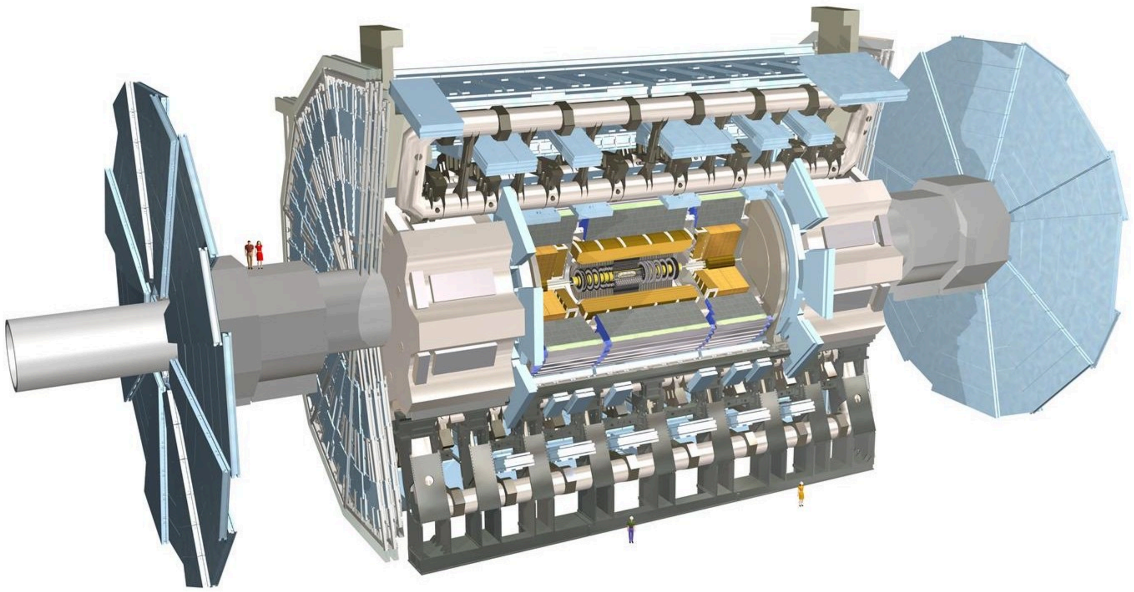


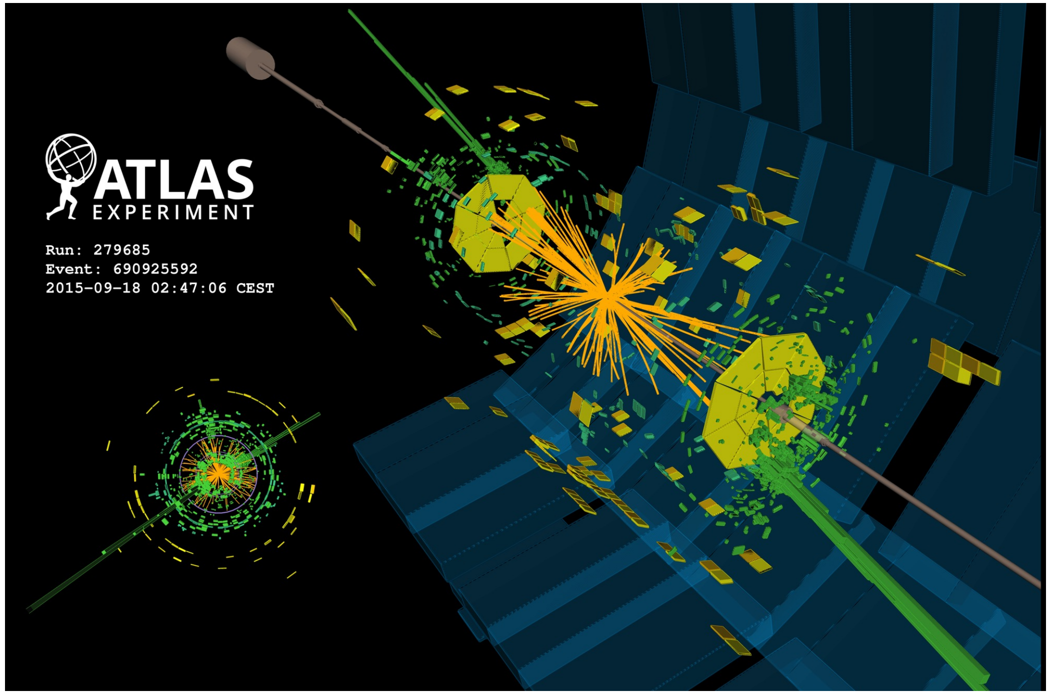


- Plentiful statistics
- gg-initiated

ATLAS

Measurement of a QI phenomenon relies on precise understanding of our detector.





Pedigree

ATLAS history of such observables

PRL **108,** 212001 (2012) PHYSICAL REVIEW LETTERS week ending 25 MAY 2012

Observation of Spin Correlation in $t\bar{t}$ Events from pp Collis[...] Using the ATLAS Detector

G. Aad *et al.**
(ATLAS Collaboration)
(Received 19 March 2012; published 24 May 2012)

A measurement of spin correlation in $t\bar{t}$ production is reported using data co[...] detector at the LHC, corresponding to an integrated luminosity of 2.1 fb^{-1}. Cand[...] in the dilepton topology with large missing transverse energy and at least tw[...] azimuthal angle between the two charged leptons in the laboratory frame is used [...] between the top and antitop quark spins. In the helicity basis the measure[...] corresponds to $A_{\mathrm{helicity}} = 0.40^{+0.09}_{-0.08}$, in agreement with the next-to-leading-order [...] tion. The hypothesis of zero spin correlation is excluded at 5.1 standard deviati[...]

DOI: 10.1103/PhysRevLett.108.212001 PACS numbers: 14.[...]

PRL **114,** 142001 (2015) PHYSICAL REVIEW LETTERS week ending 10 APRIL 2015

Measurement of Spin Correlation in Top-Antitop Quark Events and Search for Top Squark Pair Production in pp Collisions at $\sqrt{s} = 8$ TeV Using the ATLAS Detector

G. Aad *et al.**
(ATLAS Collaboration)
(Received 16 December 2014; published 8 April 2015)

A measurement of spin correlation in $t\bar{t}$ production is presented using data collected with the [...] detector at the Large Hadron Collider in proton-proton collisions at a center-of-mass energy o[...] corresponding to an integrated luminosity of 20.3 fb^{-1}. The correlation between the top and antit[...] spins is extracted from dilepton $t\bar{t}$ events by using the difference in the azimuthal angle between [...] charged leptons in the laboratory frame. In the helicity basis the measured degree of co[...] corresponds to $A_{\mathrm{helicity}} = 0.38 \pm 0.04$, in agreement with the standard model prediction. A s[...] performed for pair production of top squarks with masses close to the top quark mass deca[...] predominantly right-handed top quarks and a light neutralino, the lightest supersymmetric parti[...] squarks with masses between the top quark mass and 191 GeV are excluded at the 95% confiden[...]

[...]Qk, 13.85.Qk, [...]

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

Submitted to: JHEP

CERN-EP-2022-166
26th August 2022

Evidence for the charge asymmetry in $pp \to t\bar{t}$ production at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS Collaboration

Eur. Phys. J. C (2020) 80:754
https://doi.org/10.1140/epjc/s10052-020-8181-6

THE EUROPEAN PHYSICAL JOURNAL C

Check for updates

Regular Article - Experimental Physics

Measurements of top-quark pair spin correlations in the $e\mu$ channel at $\sqrt{s} = 13$ TeV using pp collisions in the ATLAS detector

ATLAS Collaboration*

CERN, 1211 Geneva 23, Switzerland

Received: 19 March 2019 / Accepted: 23 June 2020 / Published online: 19 August 2020
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Entanglement Observable

Upper bound on trace of spin density matrix

$$D = \frac{\mathrm{tr}[C]}{3} < -\frac{1}{3}$$

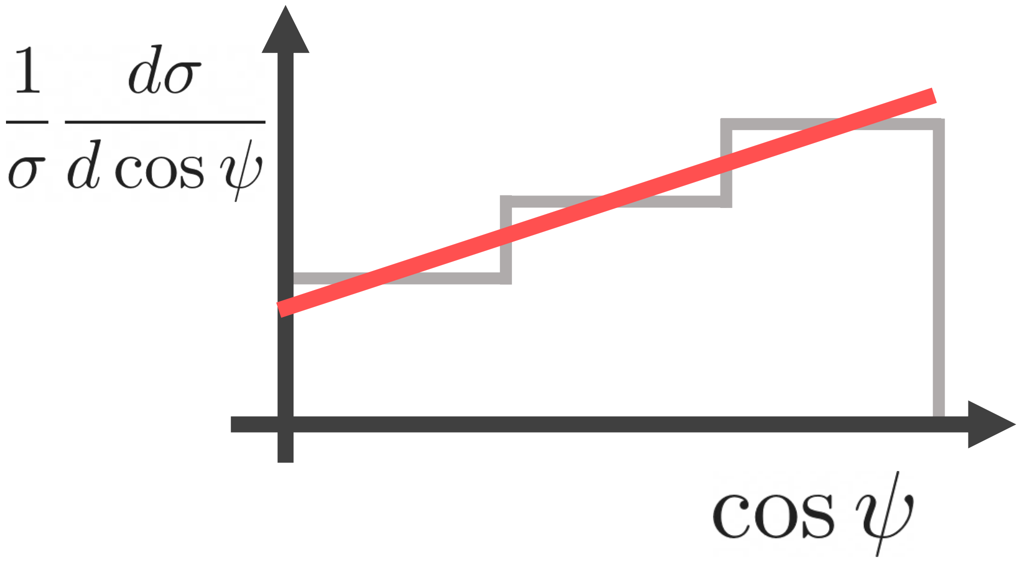
Entanglement Observable

Upper bound on trace of spin density matrix

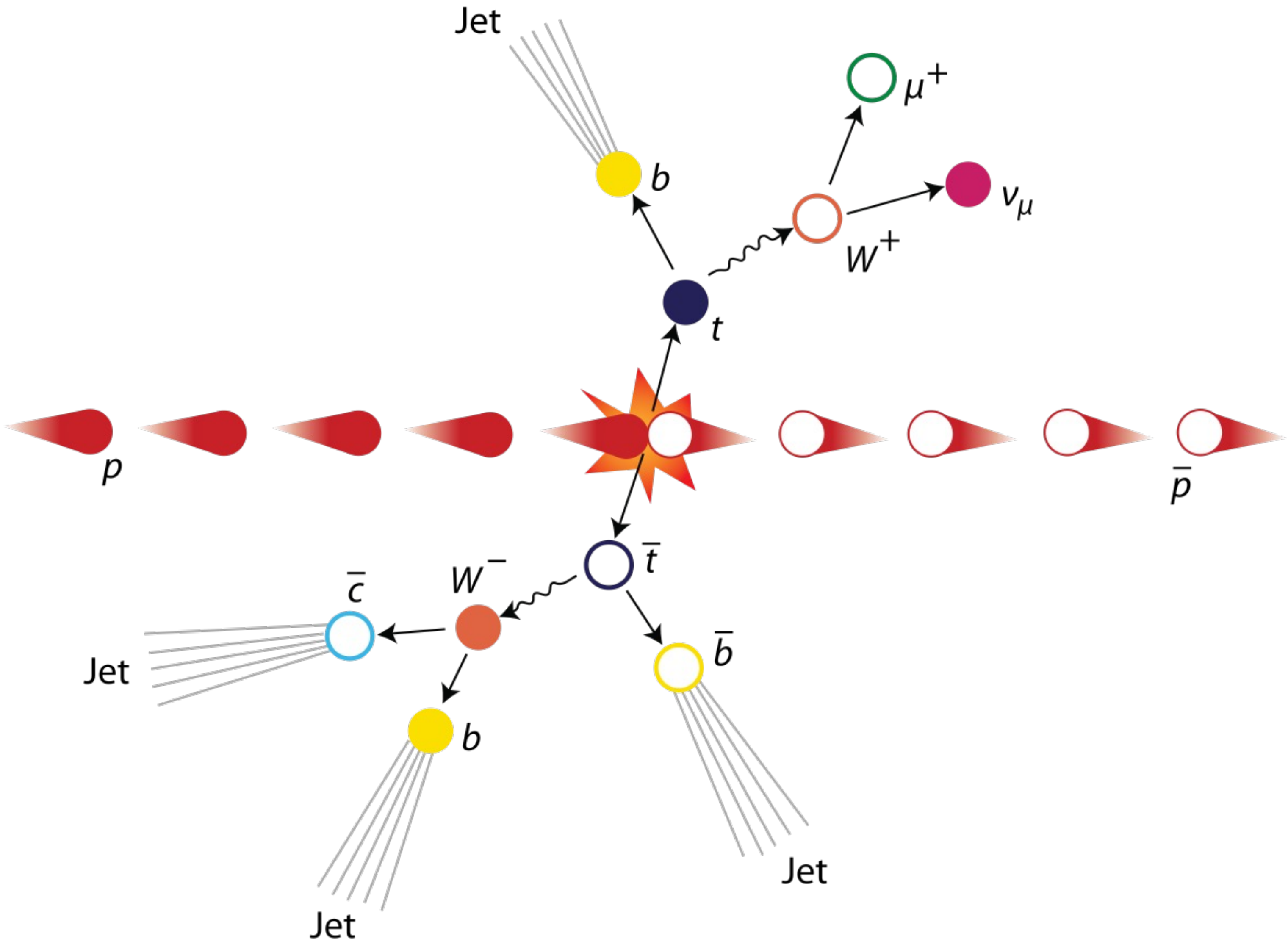
$$D = \frac{\mathrm{tr}[C]}{3} < -\frac{1}{3}$$

No requirement to measure the spin density matrix!

$$\left.\frac{1}{\sigma}\frac{d\sigma}{d\cos\psi}\right|_{m_{t\bar{t}}<M} = \frac{1}{2}(1 - D\cos\psi)$$



$t\bar{t}$ decay



Spin Analysing Power

Which decay products to use?

$$\frac{1}{\Gamma_i}\frac{d\Gamma_i}{d\cos\theta_i} = \frac{1+\alpha_i\cos\theta_i}{2}$$

Extent to which decay product's spin is correlated to parent top's

	b-quark	W^+	l^+	$\bar{d}$-quark or $\bar{s}$-quark	u-quark or c-quark
α_i (LO)	-0.41	0.41	1	1	-0.31
α_i (NLO)	-0.39	0.39	0.998	0.97	-0.32

Ingredients

Top reconstruction

- Build tops' kinematics from decay kinematics
- Required for boosts and mttbar

Selection

- Simple (optimised?) threshold cut on mttbar
- Cut on other kinematic parameters to isolate gg?

Mitigate detector effects

- Estimate observables at truth-level

Selections

Dileptonic

- 2 opposite-sign leptons
- >= 2 jets
- 1 jet must be b-tagged
- Exclude Z-mass window
- $M_{tt} < 380$ GeV

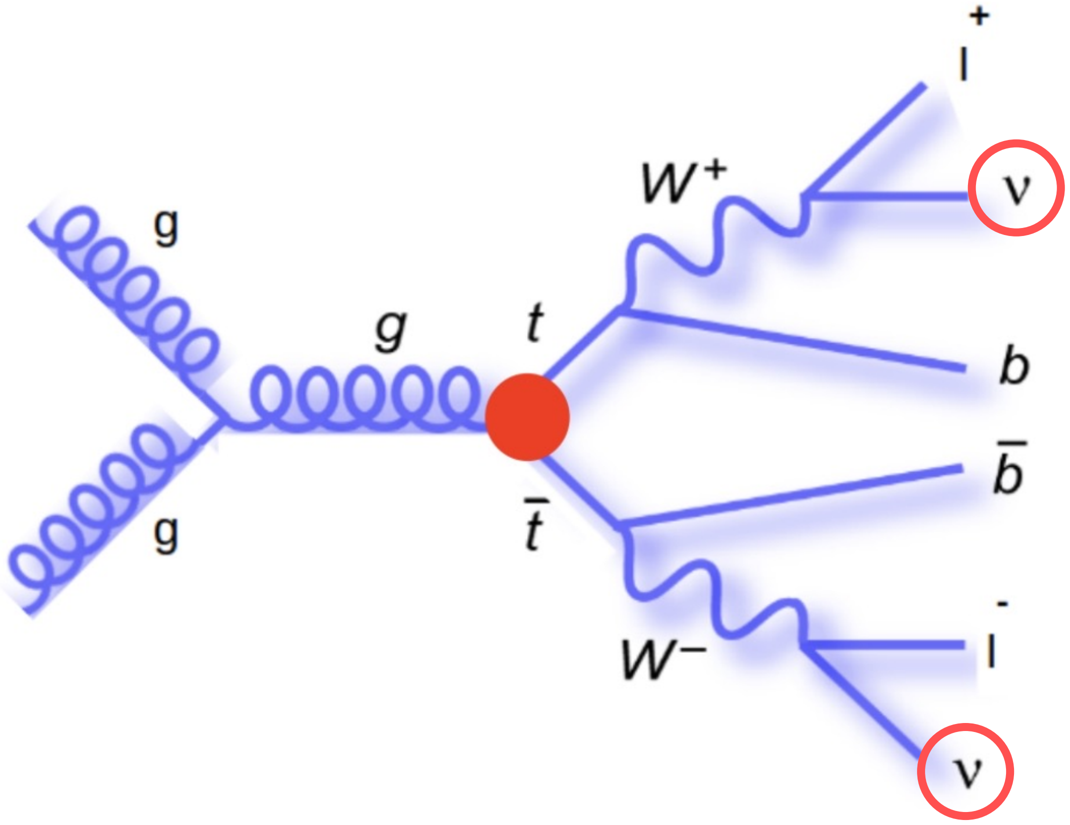
Lepton + Jets

- 1 lepton
- >= 4 jets
- 2 jets must be b-tagged
- MET > 20 GeV
- $M_{tt} < 390$ GeV

Objects are all subject to minimum pT cuts.

Dileptonic Analysis

Reconstruction



$$
\begin{aligned}
\not{E}_x &= p_{\nu_x} + p_{\bar{\nu}_x} \\
\not{E}_y &= p_{\nu_y} + p_{\bar{\nu}_y} \\
E_\nu^2 &= p_{\nu_x}^2 + p_{\nu_y}^2 + p_{\nu_z}^2 + m_\nu^2 \\
E_{\bar{\nu}}^2 &= p_{\bar{\nu}_x}^2 + p_{\bar{\nu}_y}^2 + p_{\bar{\nu}_z}^2 + m_{\bar{\nu}}^2 \\
m_{W^+}^2 &= (E_{\ell^+} + E_\nu)^2 - (p_{\ell^+_x} + p_{\nu_x})^2 \\
&\quad - (p_{\ell^+_y} + p_{\nu_y})^2 - (p_{\ell^+_z} + p_{\nu_z})^2 \\
m_{W^-}^2 &= (E_{\ell^-} + E_{\bar{\nu}})^2 - (p_{\ell^-_x} + p_{\bar{\nu}_x})^2 \\
&\quad - (p_{\ell^-_y} + p_{\bar{\nu}_y})^2 - (p_{\ell^-_z} + p_{\bar{\nu}_z})^2 \\
m_t^2 &= (E_b + E_{\ell^+} + E_\nu)^2 - (p_{b_x} + p_{\ell^+_x} + p_{\nu_x})^2 \\
&\quad - (p_{b_y} + p_{\ell^+_y} + p_{\nu_y})^2 - (p_{b_z} + p_{\ell^+_z} + p_{\nu_z})^2 \\
m_{\bar{t}}^2 &= (E_{\bar{b}} + E_{\ell^-} + E_{\bar{\nu}})^2 - (p_{\bar{b}_x} + p_{\ell^-_x} + p_{\bar{\nu}_x})^2 \\
&\quad - (p_{\bar{b}_y} + p_{\ell^-_y} + p_{\bar{\nu}_y})^2 - (p_{\bar{b}_z} + p_{\ell^-_z} + p_{\bar{\nu}_z})^2 \, .
\end{aligned} \tag{1}
$$

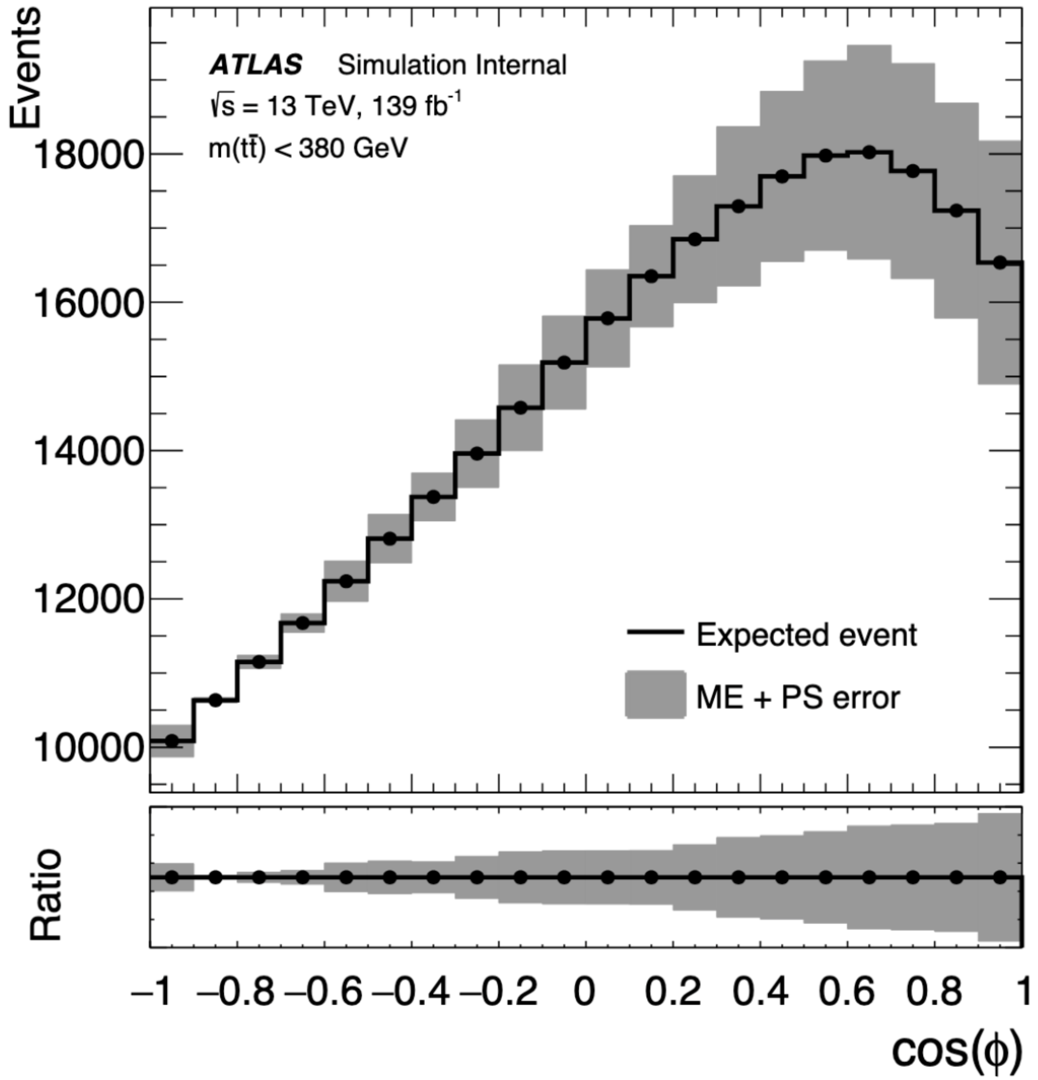
Dileptonic Reconstruction

Investigated several techniques:

- NeutrinoWeighter
- Sonnenschein method
- Ellipse method

Implement hierarchically so the system is always solved.

Reco-level cos-phi



- Efficiency decreases when the leptons approach collinearity
- Requires some correction of the detector effects.

Correcting Detector Effects

Vital to extract underlying physics…

Unfolding is a deconvolution of the signal
from detector effects

Many unfolding techniques exist.

All compare MC simulation of truth-level and detector-level

Unfolding

Unfold *cos_phi*, then extract D.

Techniques tested:

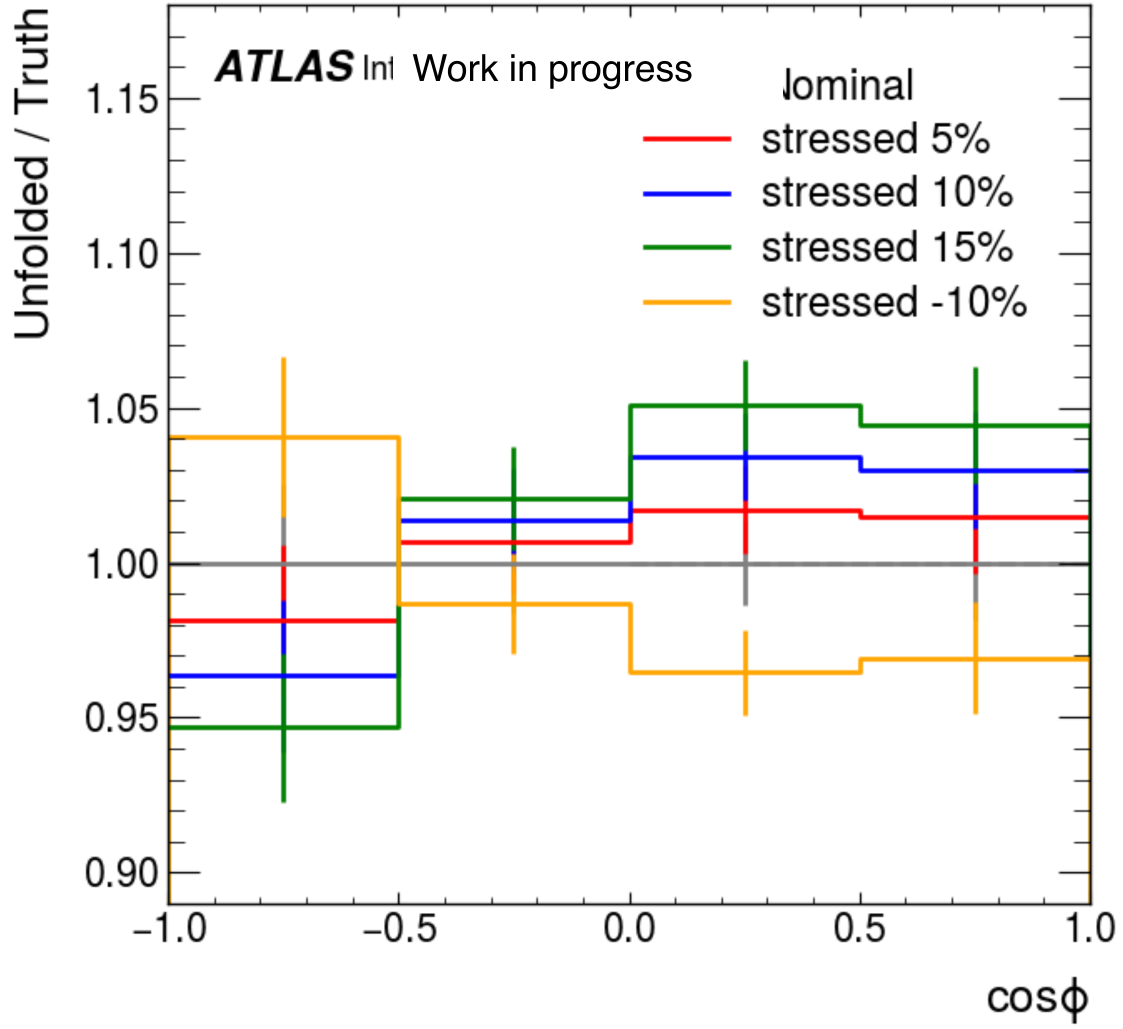
- Iterative Bayesian unfolding
- Profile likelihood unfolding
- SVD unfolding

Must test the unfolding for SM bias

Stressful Tests

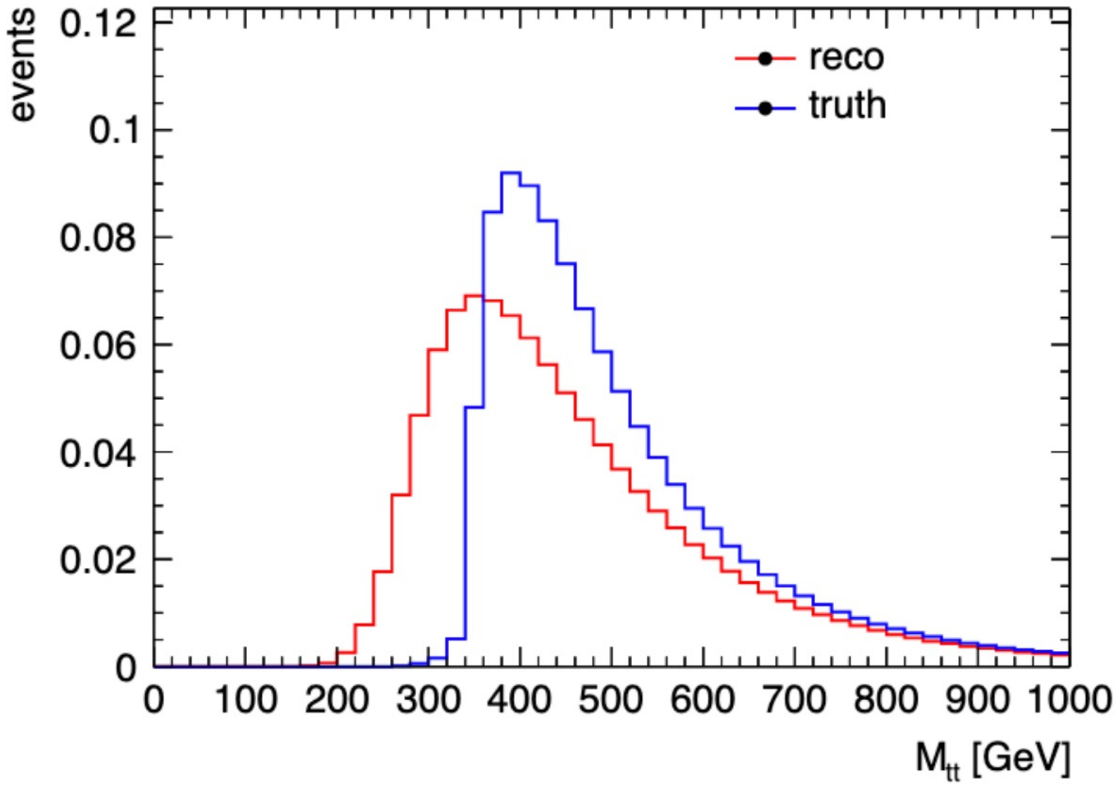
1. Inject a bias
2. Unfold the reco back to truth
3. Check we've recovered the bias.

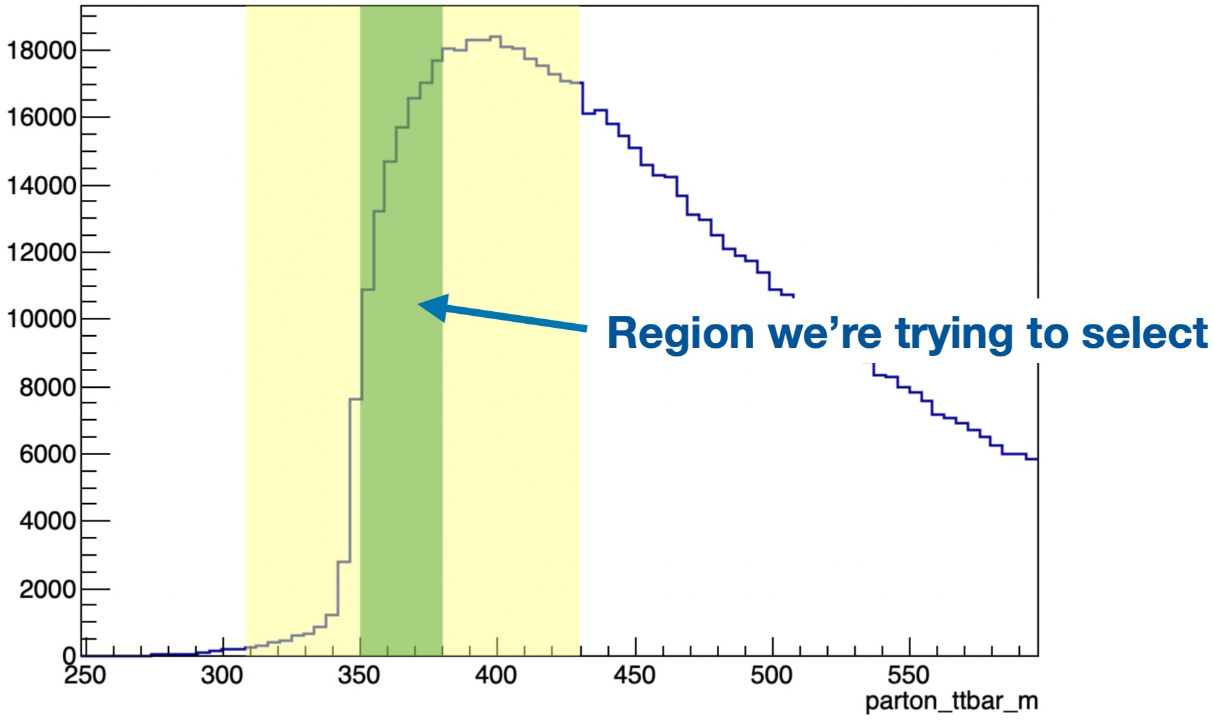
Distortion is a linear change in the slope of the distribution



Issues

The resolution of mttbar is the problem…





Require better top reconstruction when considering such narrow phase-space.

Change of Strategy

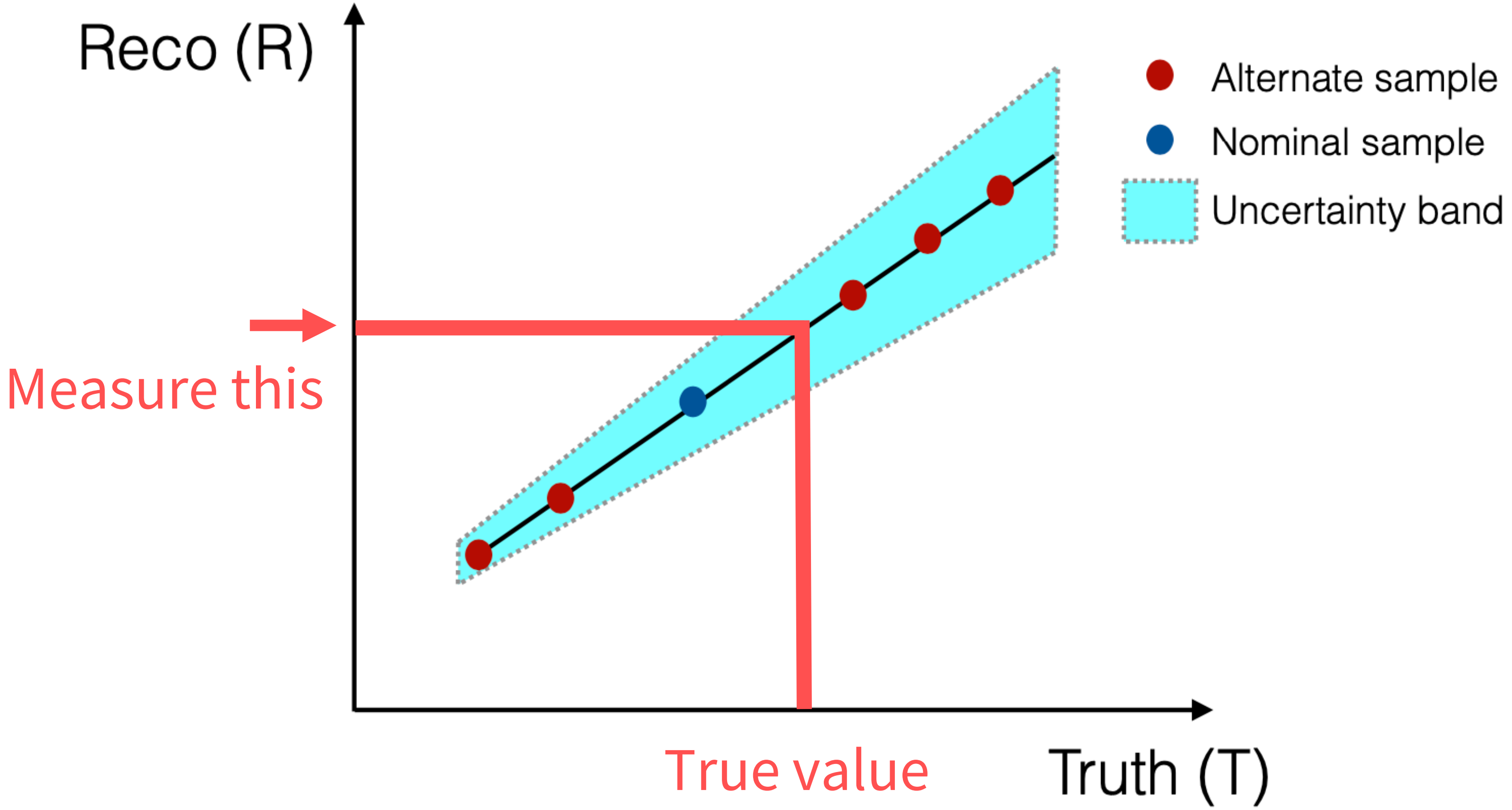
OLD

1. Unfold cos_phi
2. Extract D from truth

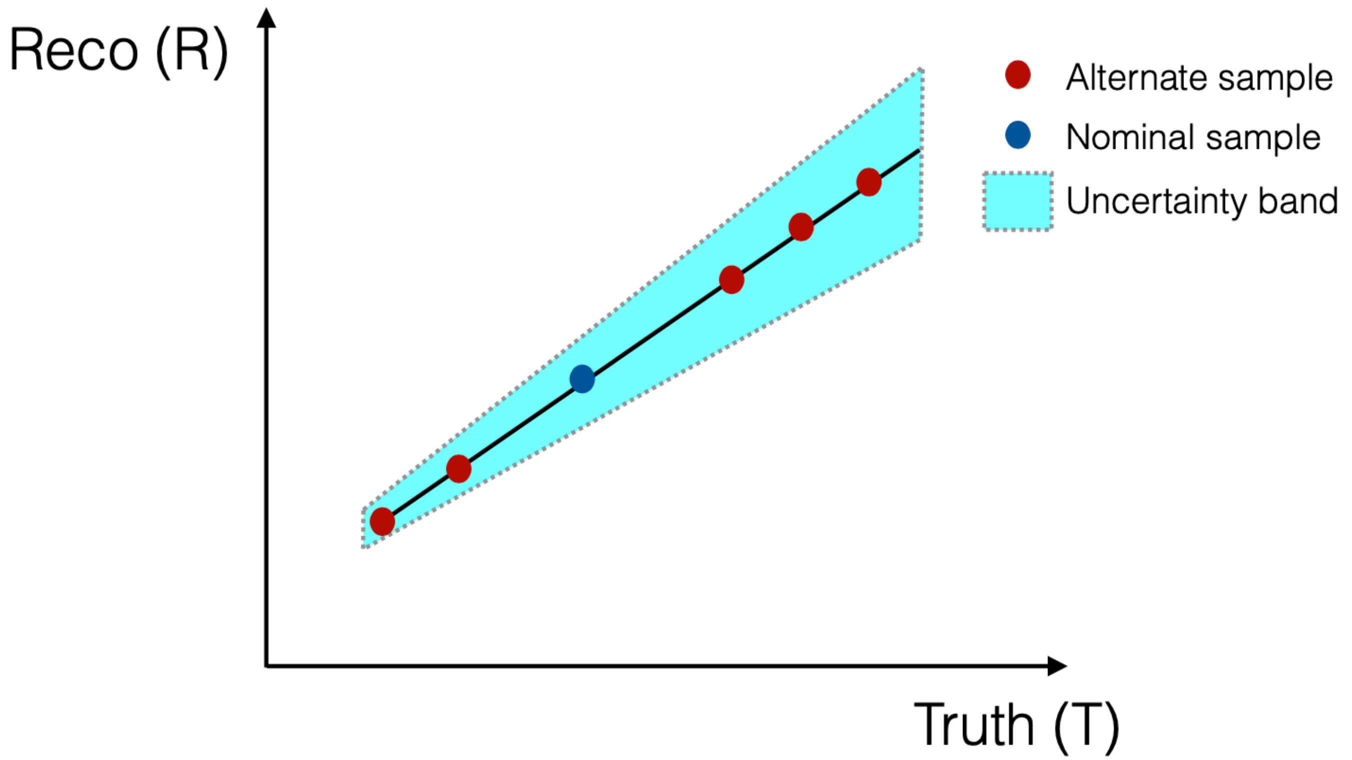
NEW

1. Extract D from reco
2. “Unfold” D

Calibration Curve



Calibration Curve



- Alternative generators move Truth value
- Experimental systematics have same Truth value

- How to generate alternate samples?

How do we change entanglement?

What would nature look like with a different value of entanglement?

We require this to generate our calibration curve…

This is not a free parameter in the SM.

In MC event generators, not an input parameter which we can alter…

Alter slope of *cos_phi* artificially.

Reweighting

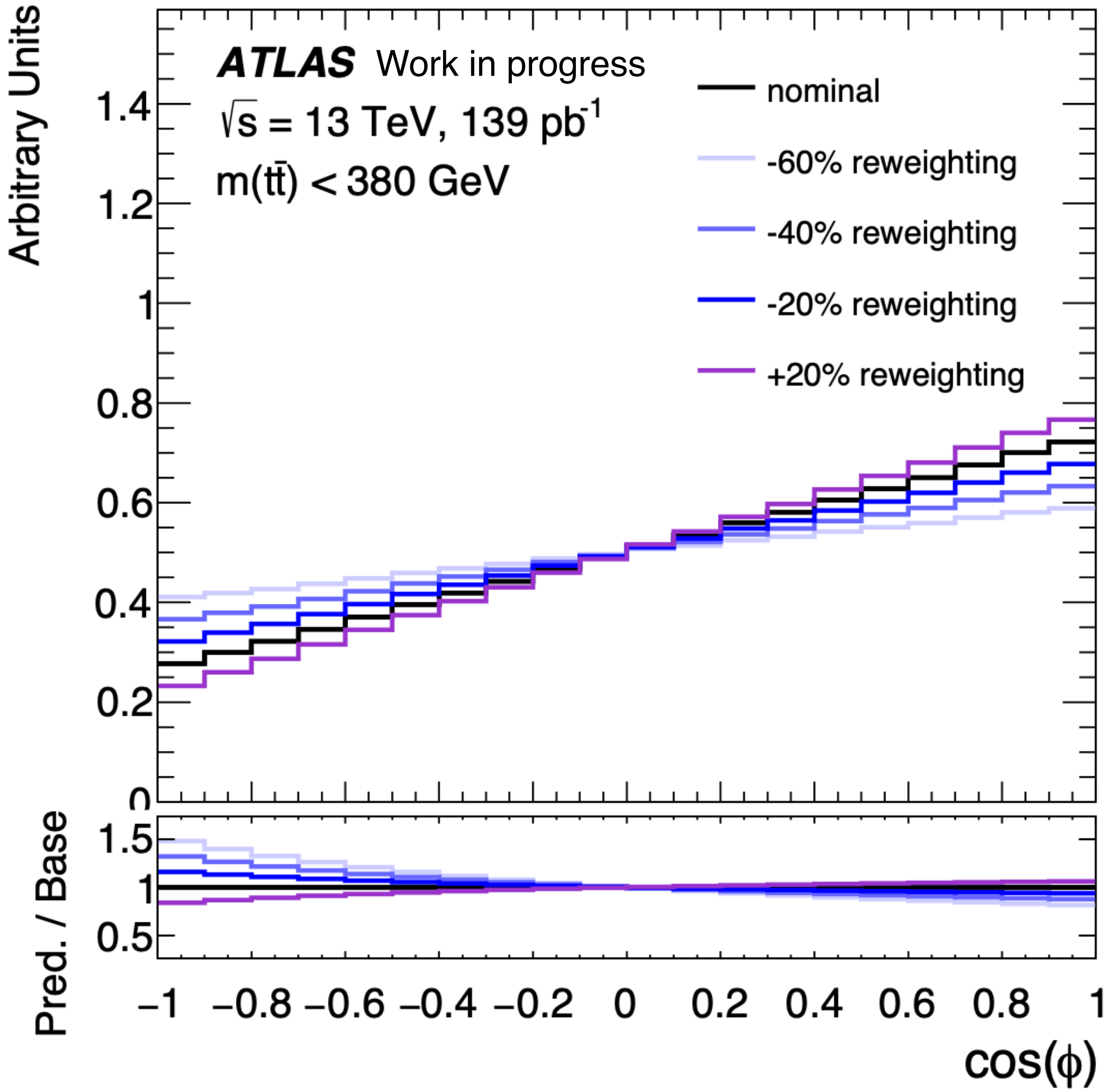
Apply a per-event reweighting $w\left(M_{t\bar{t}}, \cos\phi\right)$

Preserves linearity of cos_phi but alters slope.

Other possible reweightings:

- Did not preserve linearity
- Preserved inclusive value of D

Reweighting



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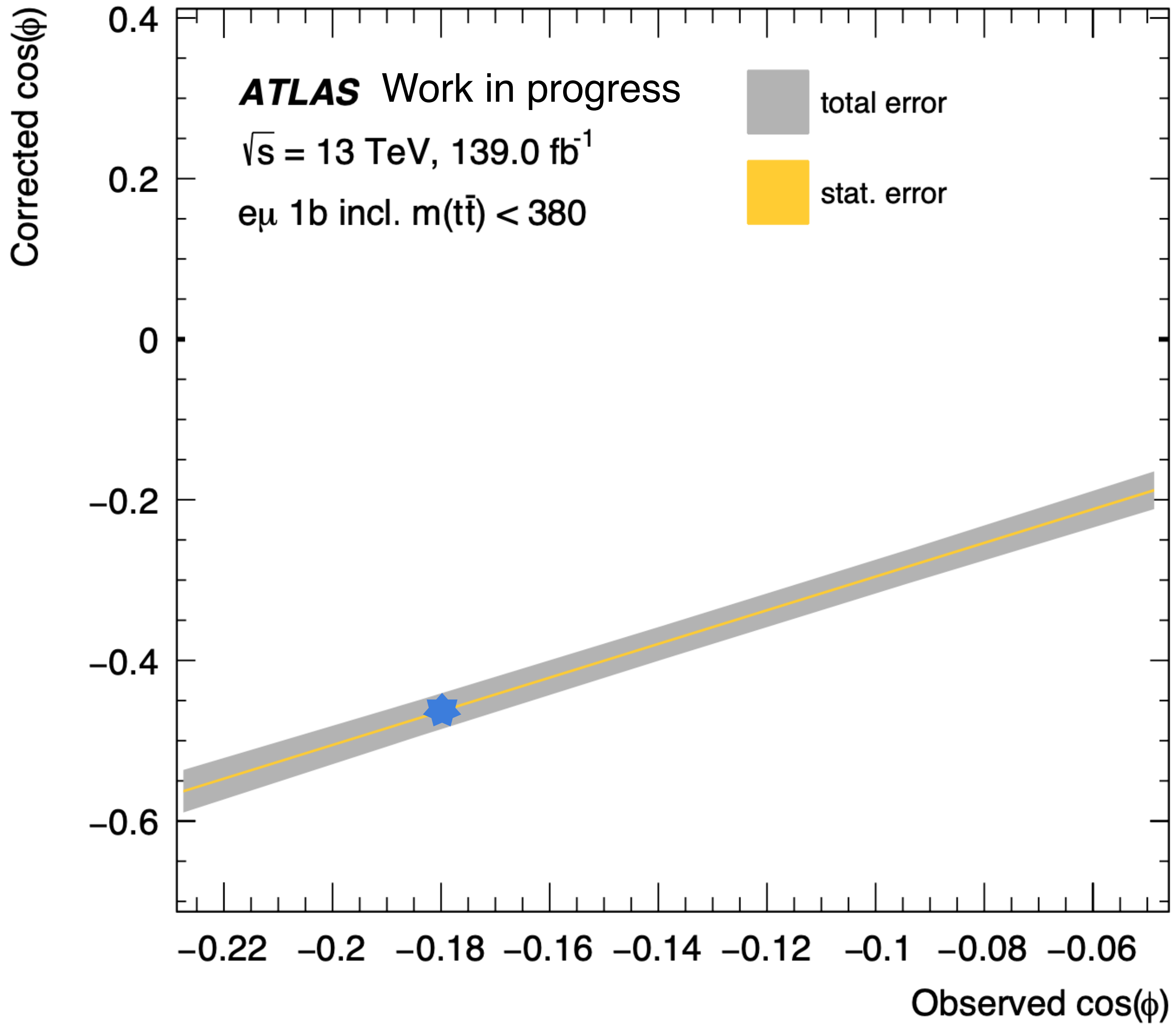
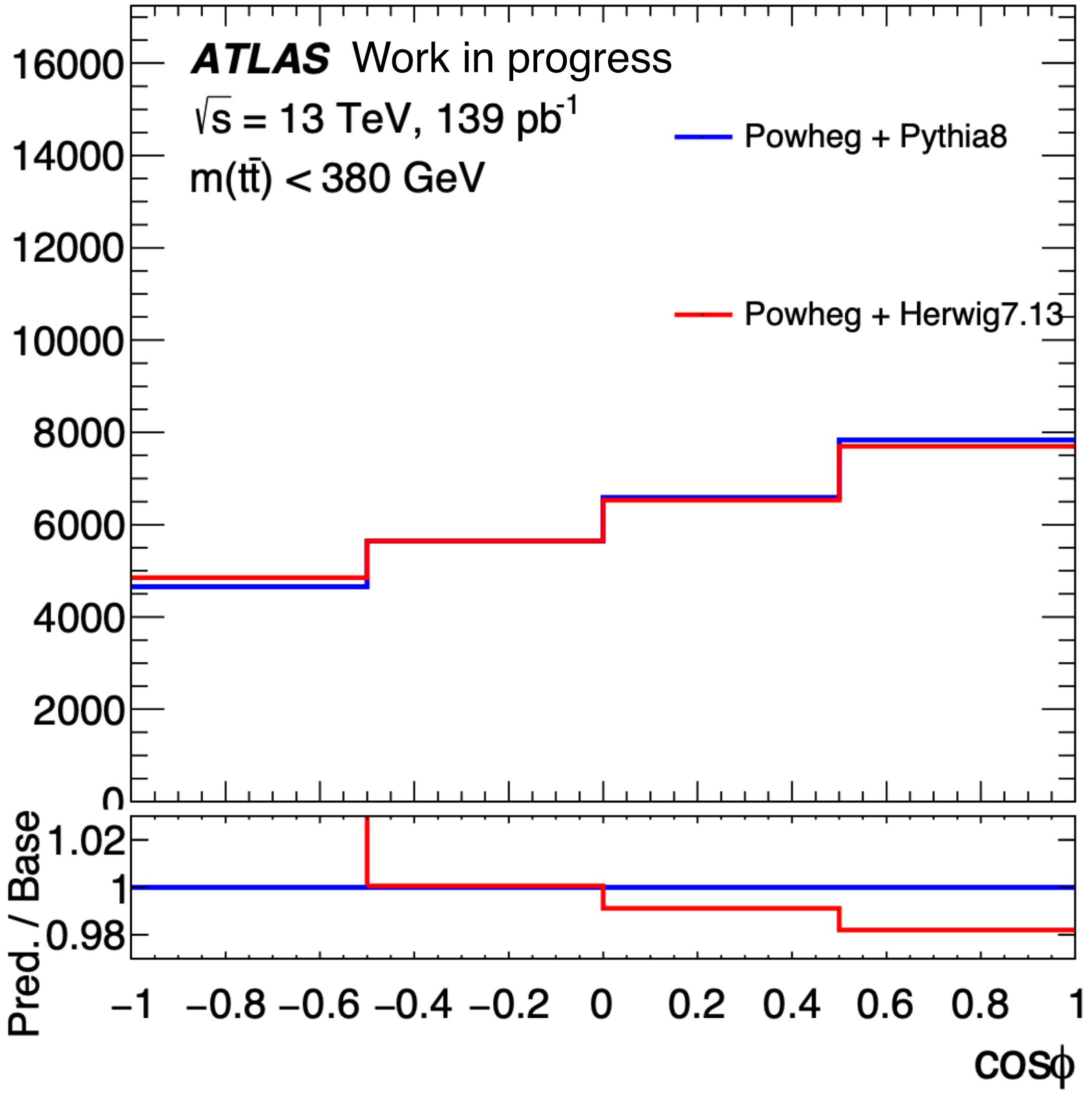


Omits most impactful systematic….

Surprising Problems



- The leading uncertainty relates to the parton shower
- Parton shower systematic considers:
    - QCD showering
    - Hadronisation
- Soft QED effects in the shower lead to difference in this 2-point uncertainty.

Status

- Analysis is in a mature state.
- Understanding some systematics represents the final hurdle.
- Hope to provide evidence of entanglement in HEP system in coming months…

Lepton + Jets Analysis

Why?

Advantages

- Increased statistics
- Easier top reconstruction (1 neutrino)

Challenges

- Tagging the correct jet
- High-multiplicity jet final state

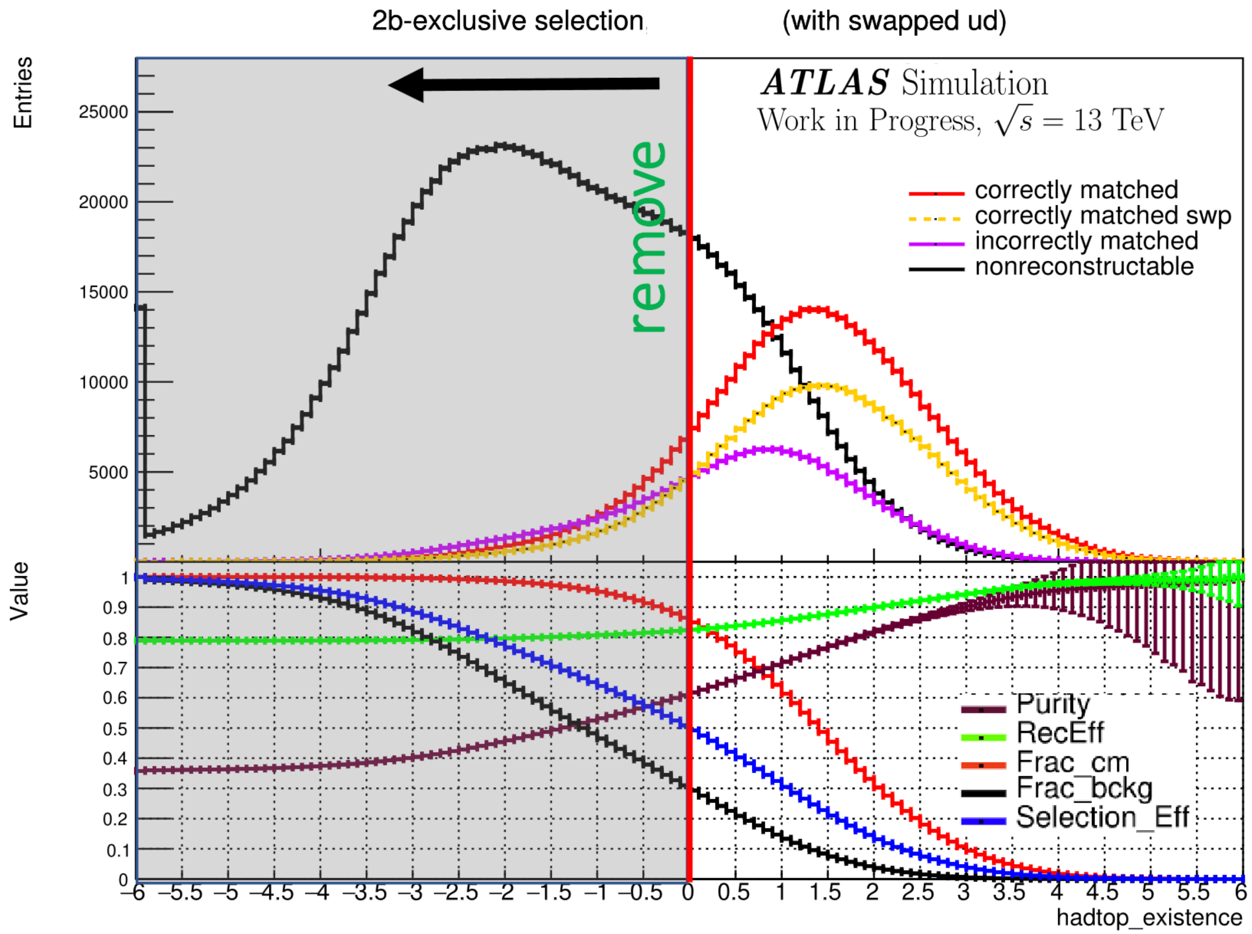
Dileptonic entanglement

Lepton + jets

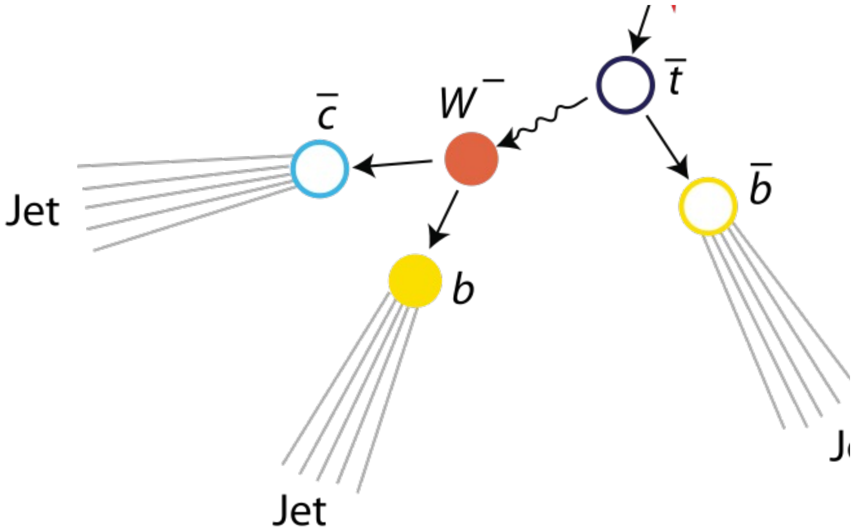
Top Reconstruction

- **Use the SPANNET method:**
  ML for multi-jet final state

- **Defines observable:**
  - Cut selects better reconstructed events
  - Improves signal/background.

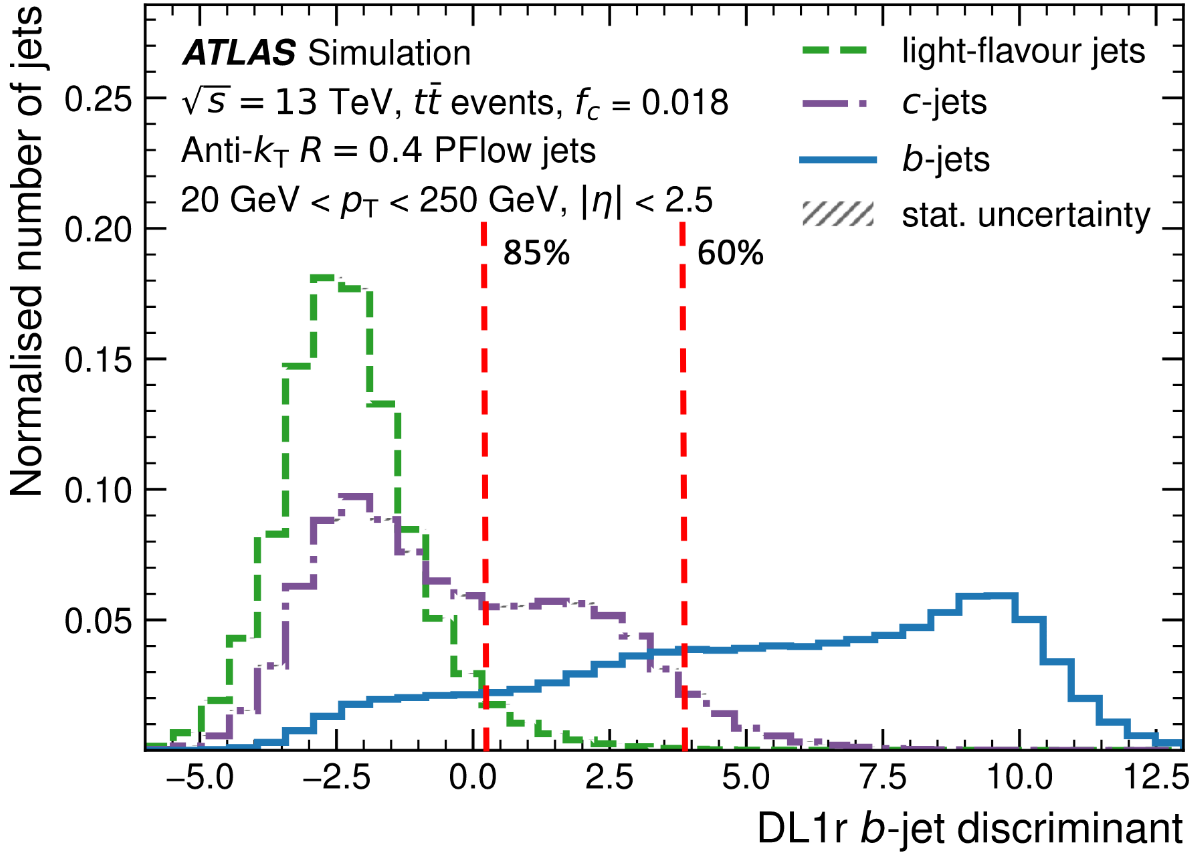


Charm Tagging



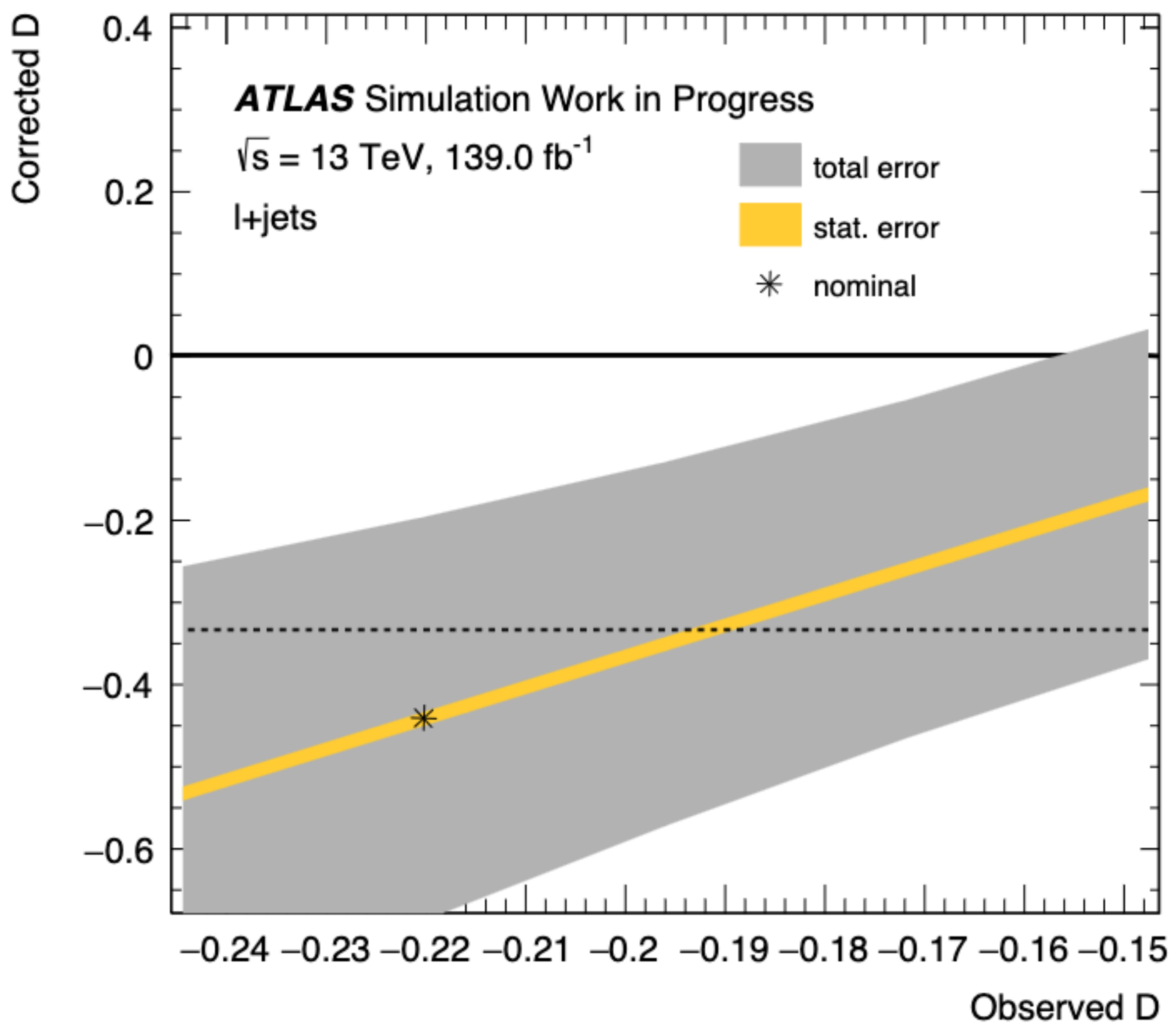
- Tag the charm-jet: its partner is the down-type spin-analyser

- Tagging uses b-tag discriminant:
  - Pass 85% WP
  - Not pass 60% WP



https://arxiv.org/abs/2211.16345

Calibration Curve



- Systematics-dominated
- Requires greater understanding of the modelling systematics

Modelling Systematics

description	relative %	absolute
Powheg+Pythia 8.230 vs Powheg+Herwig 7.1.3	42	0.19
variation of Powheg damping factor (hard emission)	22	0.10
variation of the FSR α_S	18	0.08
comparison of recoil-to-colour settings in Pythia with recoil-to-top	18	0.08
variation of the pThard parameter of Powheg (separation between the ME and the PS)	14	0.06
variation of renormalisation scale μ_R	7	0.04
variation of factorisation scale μ_F	7	0.03

Conclusions

Conclusions

- Simple observable from single differential cross-section.
- Narrow phase-space is problematic.
- Real requirement for superior top reconstruction.
- Modelling effects seem to be large.

Auxiliary Material

Dileptonic Reconstruction