Measurement of $t\bar{t}$ spin entanglement in the 1-lepton channel in ATLAS

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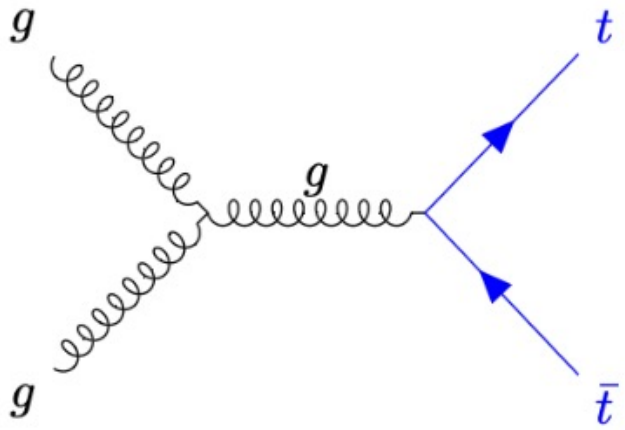


DPG 2024

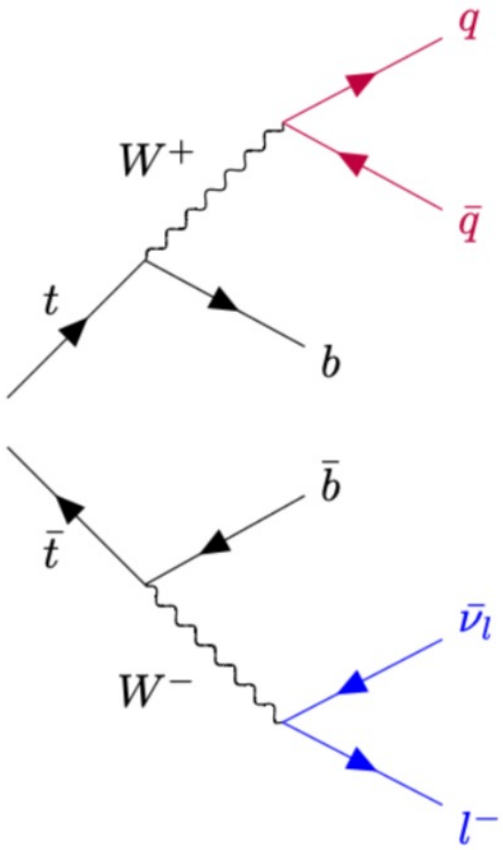
HELMHOLTZ

ATLAS EXPERIMENT

DESY.

Motivation

- $t\bar{t}$ final states sensitive to characteristic quantum effects like quantum entanglement.
- Top quarks have a short lifetime -> spin information transferred to decay products.



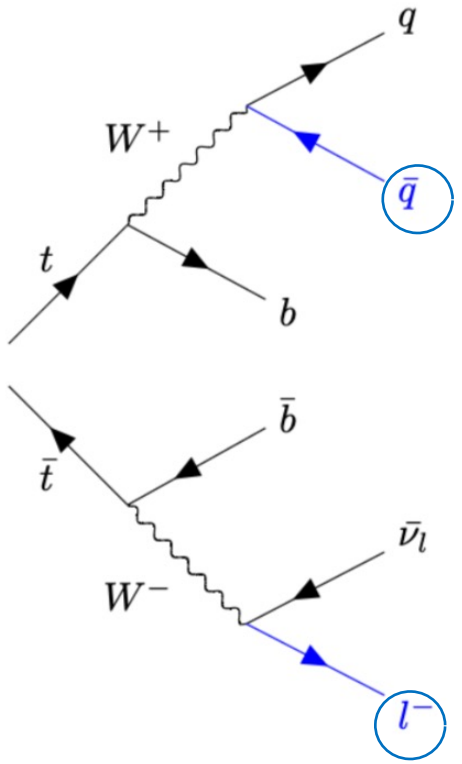
1L channel

- Complementary systematics to 2L channel.
- Sensitive variable: $\cos\varphi$ -> between lepton and one of the jets in top rest frame.
- Measurement most sensitive close to threshold ($m_{t\bar{t}}$ < 380 GeV).
- This talk-> measurement of $t\bar{t}$ spin entanglement using two orthogonal regions.

3b inclusive region

1L channel

- Sensitive variable: $\cos\varphi(l,d)$, d = down-type quark.
- No d- or s-jet taggers available.
- Indirect identification of down-type jets using c-jets.
- Limits search to events with W ---> cs/cd decays.
- ~23% of total 1L $t\bar{t}$ events.
- See also talk from Theresa Reisch.



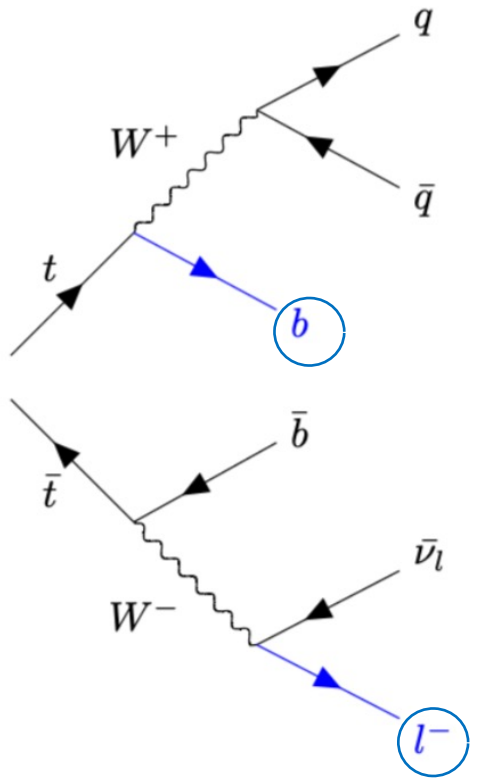
	b	l	$\bar{d}$
α_i (LO)	-0.41	1	1

Spin analysing powers [1]

2b exclusive region

1L channel

- Events with no real c-quark or an untagged c-jet.
- Alternative spin analyser: b = b quark from hadronically decaying top quark.
- Sensitive variable: $\cos\varphi(l, b)$.
- ~77% of total 1L $t\bar{t}$ events.



	b	l	$\bar{d}$
α_i (LO)	-0.41	1	1

Spin analysing powers [1]

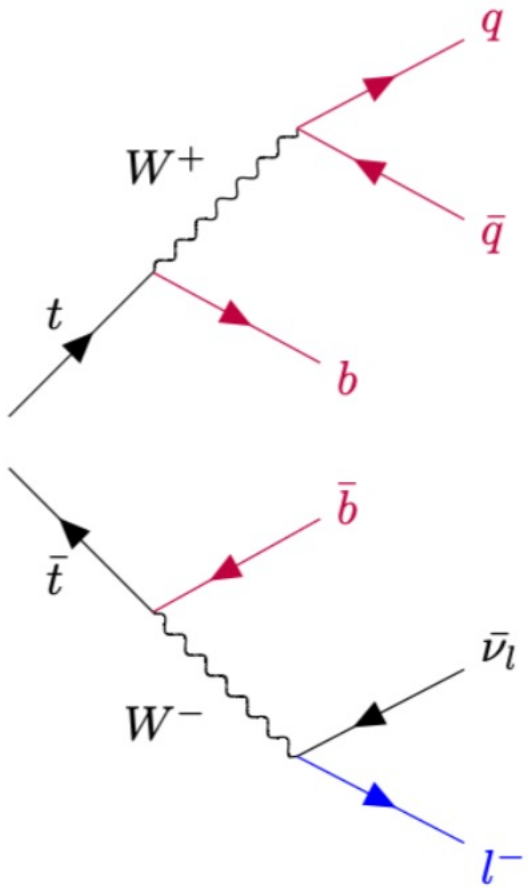
Analysis

1L channel

- Event Selection
  - 1 e/μ with p_T > 28 GeV.
  - E_T^{miss} > 20 GeV.
  - ≥ 4 jets with p_T > 25 GeV.
  - b-tagging

    3b inclusive
    - 2 b-tagged jets at 60% WP.
    - ≥ 1 b-tagged jet(s) at loose 85% WP (charm enriched).

    2b exclusive
    - 2 b-tagged jets at 60% WP.



- Full event reconstruction using SpaNet (**S**ymmetry **P**reserving **A**ttention **Net**works).

Definition of the observable

1L channel

Normalised differential cross-section:

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\varphi} = \frac{1}{2}(1 + \alpha_1\alpha_2 D\cos\varphi)$$

3b inclusive

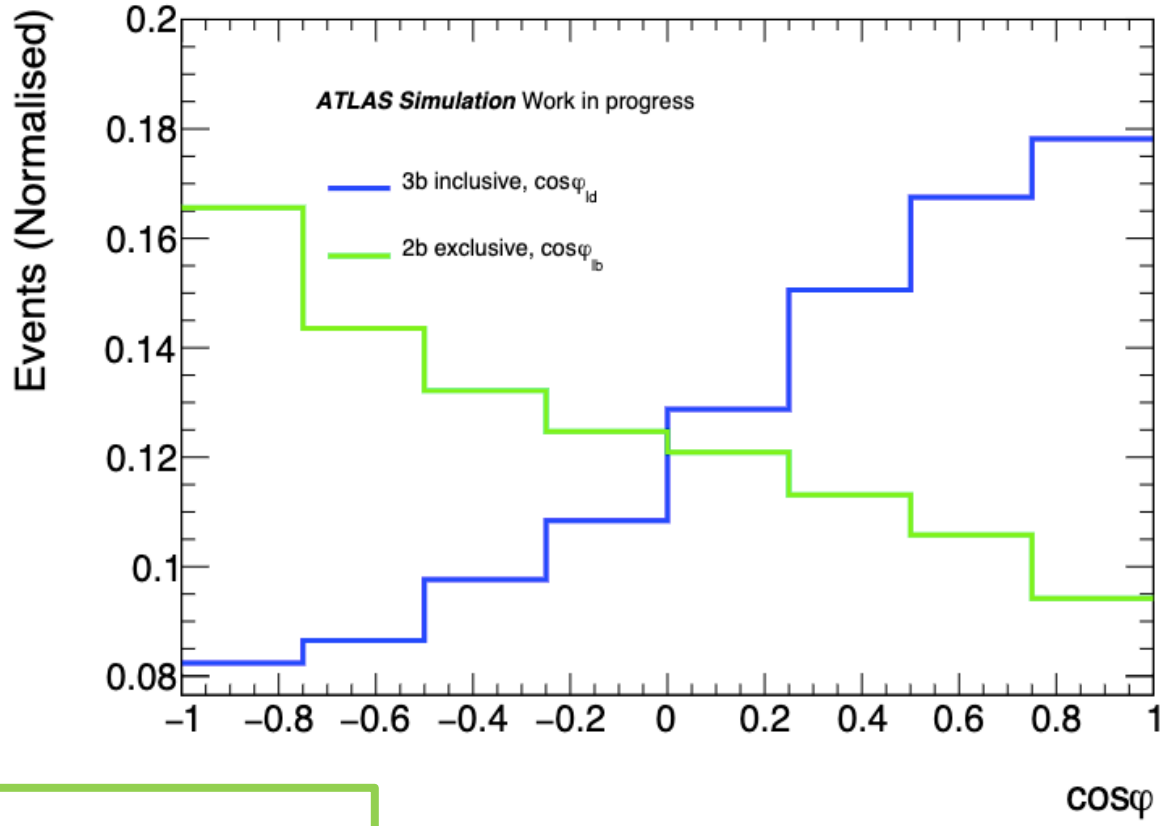
2b exclusive

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

D = -3 $\langle\cos\varphi(l,d)\rangle$

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\varphi} = \frac{1}{2}(1 + 0.41\,D\cos\varphi(l,b))$$

D = (3/0.41) $\langle\cos\varphi(l,b)\rangle$

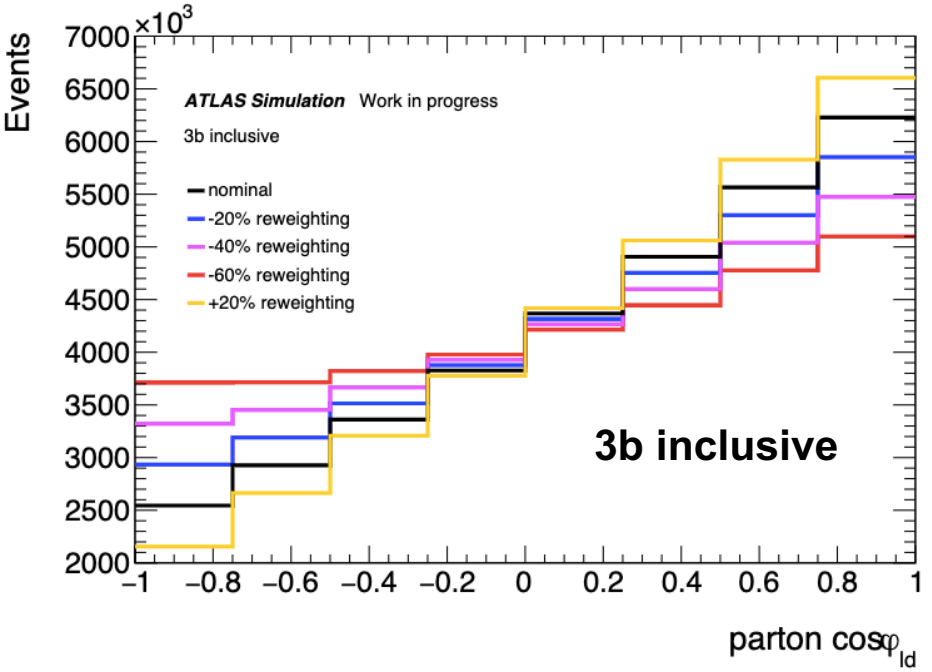


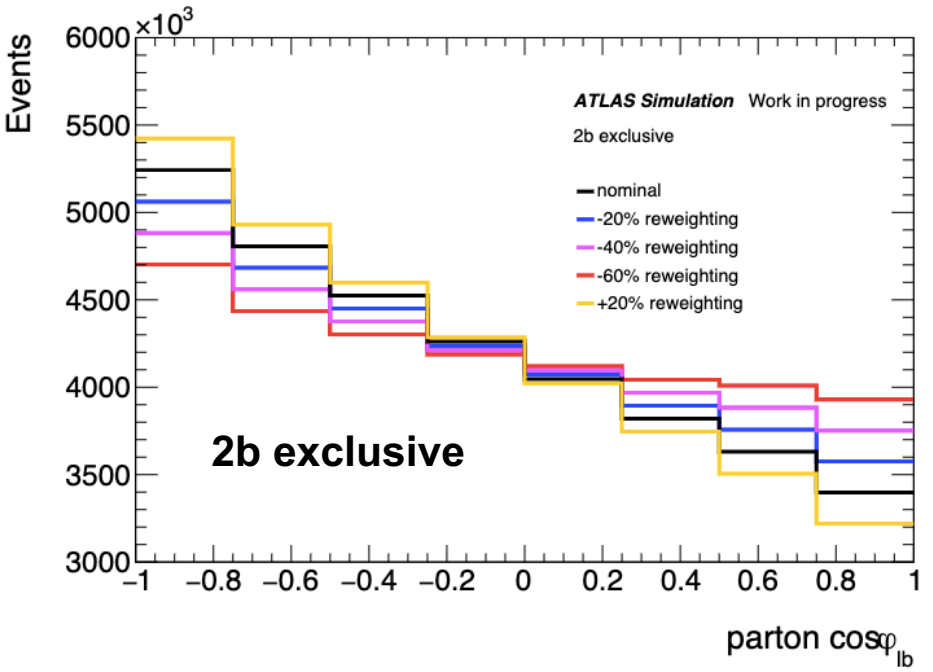
Entanglement criterion: D < -1/3

Calibration curve

1L channel

- Relating reconstructed and particle level values of D via calibration curve.
- Events reweighted based on parton level $\cos\varphi$ distribution to obtain different D values.
- Additional selection at particle level: Objects obtained after ΔR matching with the corresponding parton level objects.





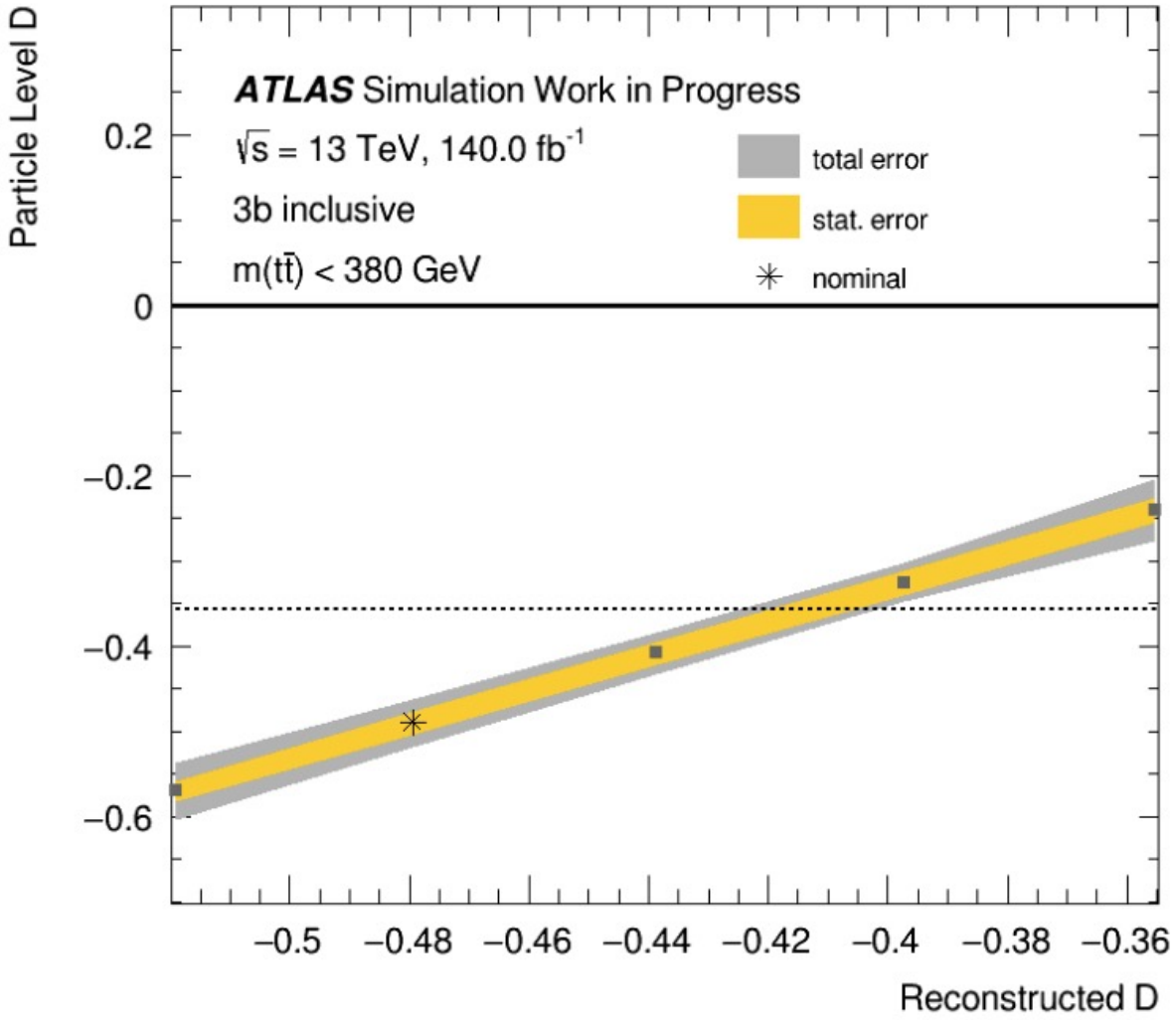
Reco/Particle calibration curve

3b inclusive region

$$D_{\text{nom}}^{\text{particle}} = -0.490 \pm 0.013\,(\text{stat.})\ ^{+0.025}_{-0.029}(\text{syst.})$$

Leading systematic uncertainties for nominal point:

Systematic	relative %
JET Pileup RhoTopology	3%
JET EtaIntercalibration Modelling	2%
JET EffectiveNP Modelling1	1.9%
JET Pileup OffsetNPV	1.3%
bTagSF DL1r Continuous eigenvars Light 0	1%



Entanglement limit D = -1/3 propagated from parton to particle level shown by dotted line

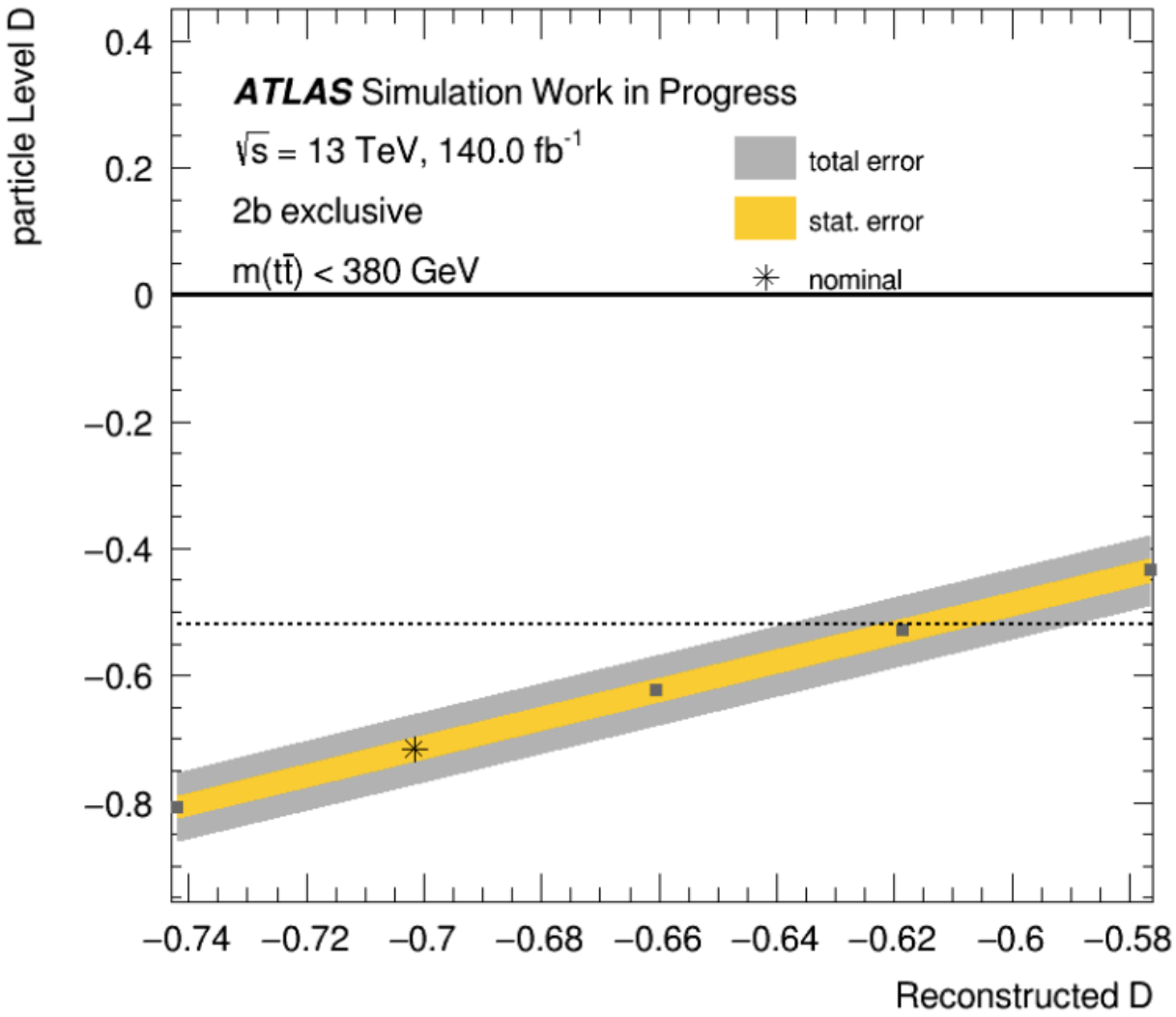
Reco/Particle calibration curve

2b exclusive region

$$D_{\text{nom}}^{\text{particle}} = -0.716 \pm 0.019\,(\text{stat.})\ ^{+0.052}_{-0.073}(\text{syst.})$$

Leading systematic uncertainties for nominal point:

Systematic	relative %
JET Pileup RhoTopology	4.8%
JET EffectiveNP Modelling1	3.5%
JET EtaIntercalibration Modelling	2.3%
JET Pileup OffsetNPV	1.6%
JET JER EffectiveNP 4	1.4%

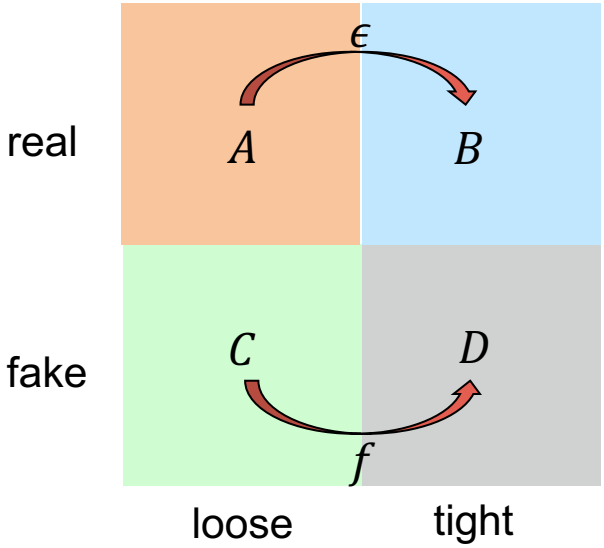


Entanglement limit D = -1/3 propagated from parton to particle level shown by dotted line

Multi-jet background estimation

1L channel

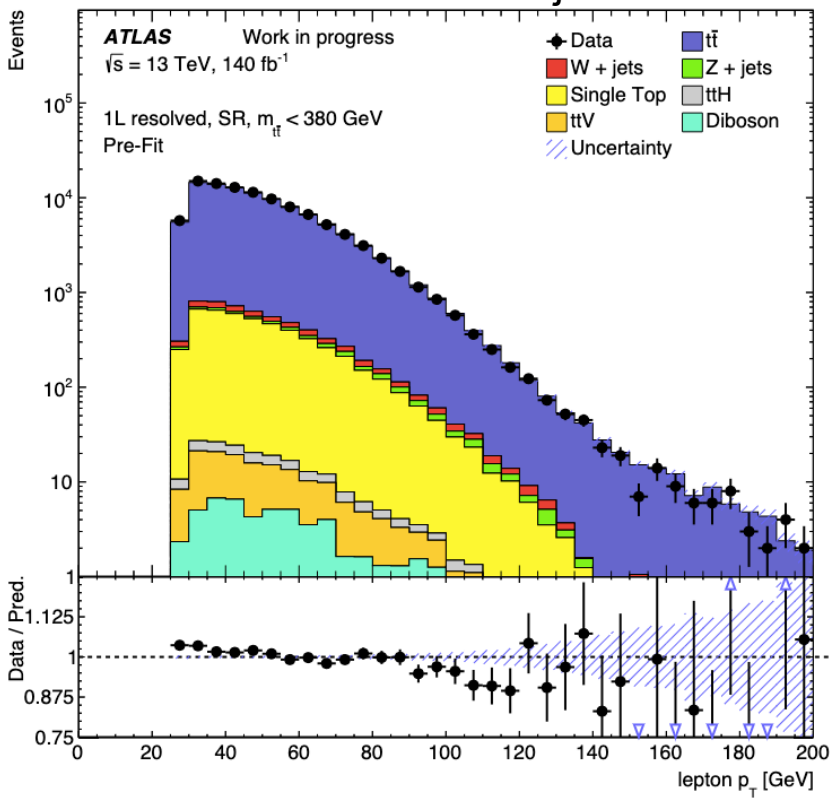
- QCD multi-jet background difficult to be modelled in simulation.
- The likelihood of multi-jet contamination higher in the turn-on region, $m_{t\bar{t}}$ < 380 GeV.
- Multi-jet estimated using a data-driven Matrix Method (MM) from an ongoing search for A/H→ $t\bar{t}$.



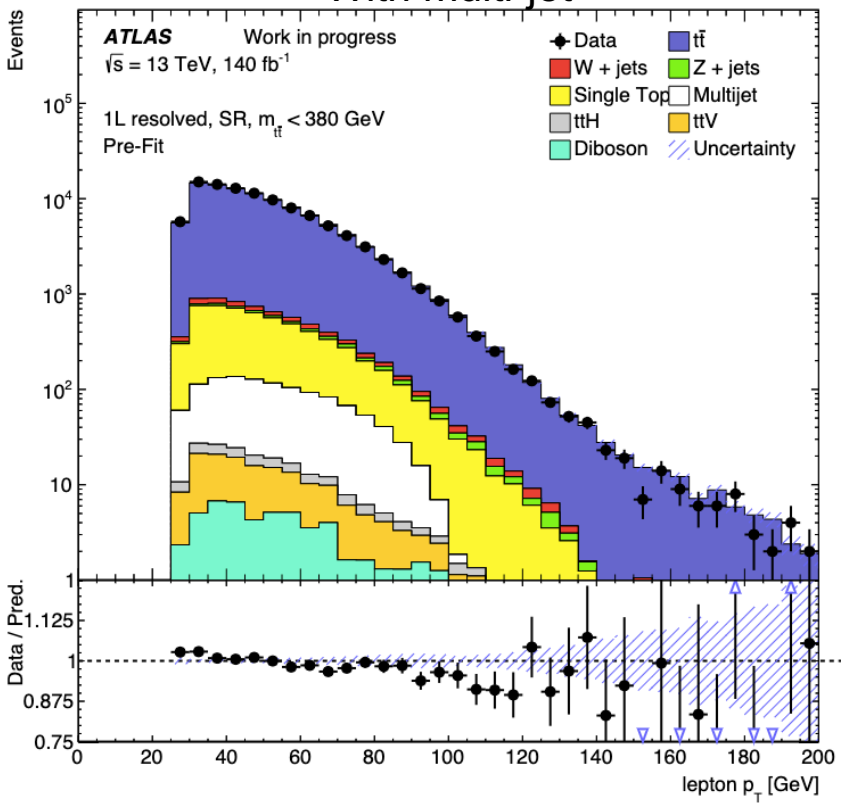
Multi-jet background estimation

Control plot, $m_{t\bar{t}}$ < 380 GeV signal region

Without multi-jet



With multi-jet



Background	%*
Single Top	67%
Multi-jet	14%
W +jets	10.6%
Z + jets	5.2%
$t\bar{t}$ + V	1.6%
Diboson	0.8%
$t\bar{t}$ + H	0.6%

* wrt total background

Outlook

$t\bar{t}$ quantum entanglement

- $t\bar{t}$ quantum entanglement observed for the first time in the 2L channel. First search in the 1L channel.
- Measurement performed using calibration curves. Modelling systematics to be included.
- QCD multi-jet is an important background in the turn-on region.
- Experience gained from 1L channel measurement can pave the way for more quantum measurements.

Backup

SpaNet cuts

- Hadtop/leptop detection: probability that particle is reconstructable.
- Hadtop/leptop assignment: probability that selected jets are truth matched ones.

- SpaNet cuts :

  3b inclusive
  - hadtop: assignment*detection > 0.31
  - leptop: assignment*detection > 0.1

  2b exclusive
  - hadtop: assignment*detection > 0.22
  - leptop: assignment*detection > 0.1

Multi-jet background estimation

1L channel

Real rate

$$\epsilon = \frac{N_{MC}^{tight}(SR)}{N_{MC}^{loose}(SR)}$$

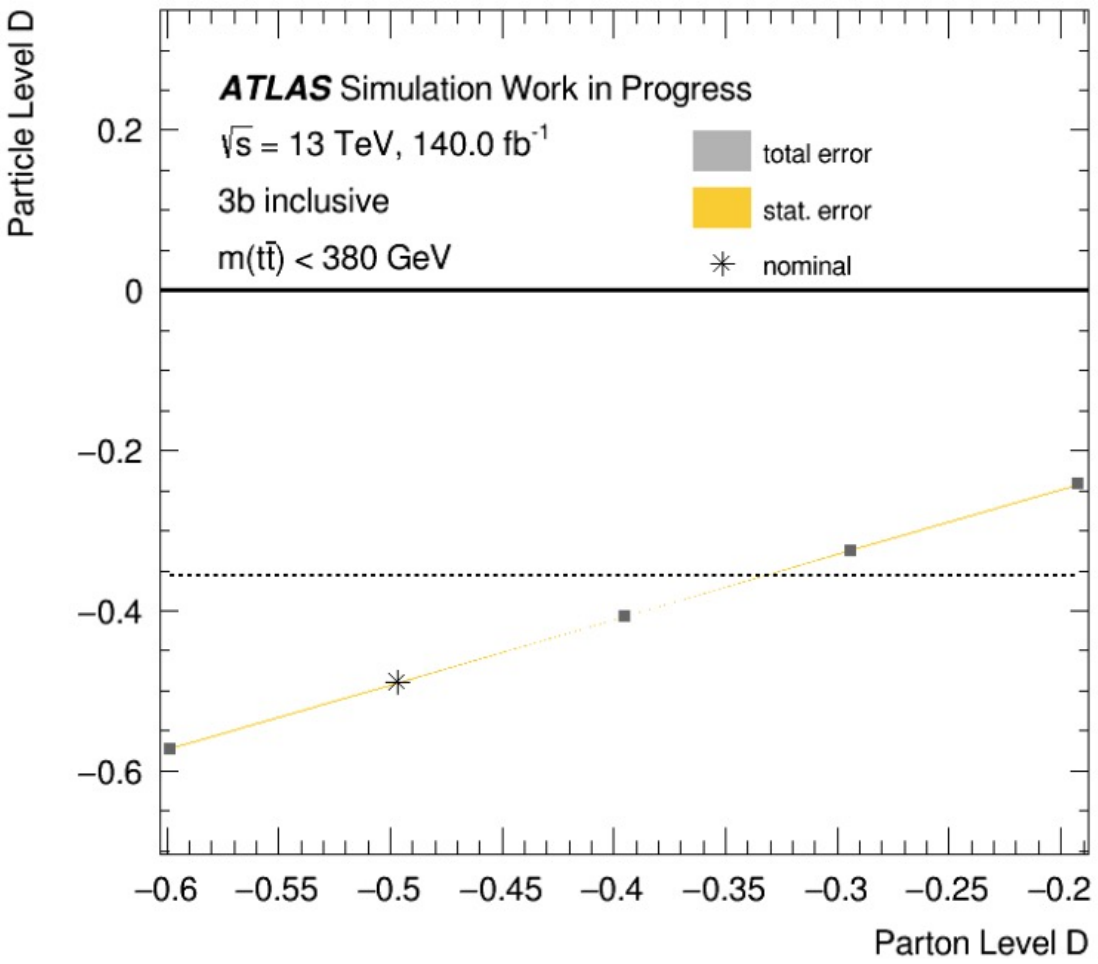
Fake rate

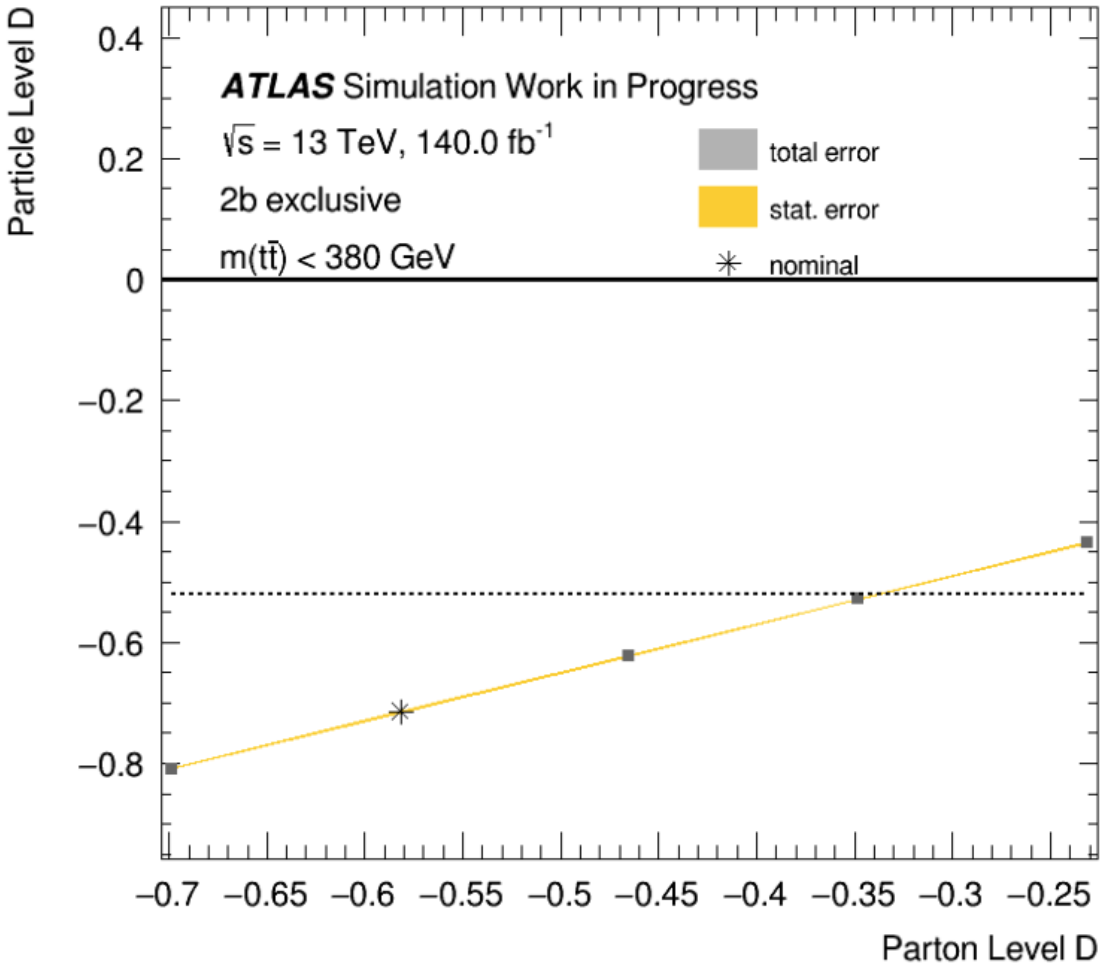
$$f = \frac{N_{Data}^{tight}\left(CR_{QCD}^{4j,1b}\right) - N_{MC}^{tight}(CR_{QCD}^{4j,1b})}{N_{Data}^{loose}\left(CR_{QCD}^{4j,1b}\right) - N_{MC}^{loose}(CR_{QCD}^{4j,1b})}$$

Multi-jet weight, $w_{QCD}(N_T, N_A) = \frac{\epsilon f - f}{\epsilon - f} N_T + \frac{\epsilon f}{\epsilon - f} N_A$

N_T: Number of events with a tight lepton.
N_A: Number of events with a loose lepton that failed the tight cuts.

Parton/Particle calibration curves





Particle level D for parton level D=-1/3 shown by dotted line.
No systematics included.

Event reconstruction studies

SpaNet vs χ^2