Measurement of $t\bar{t}$ spin correlation using Run 2 and Run 3 data with the ATLAS detector

Nikolaos Kamaras

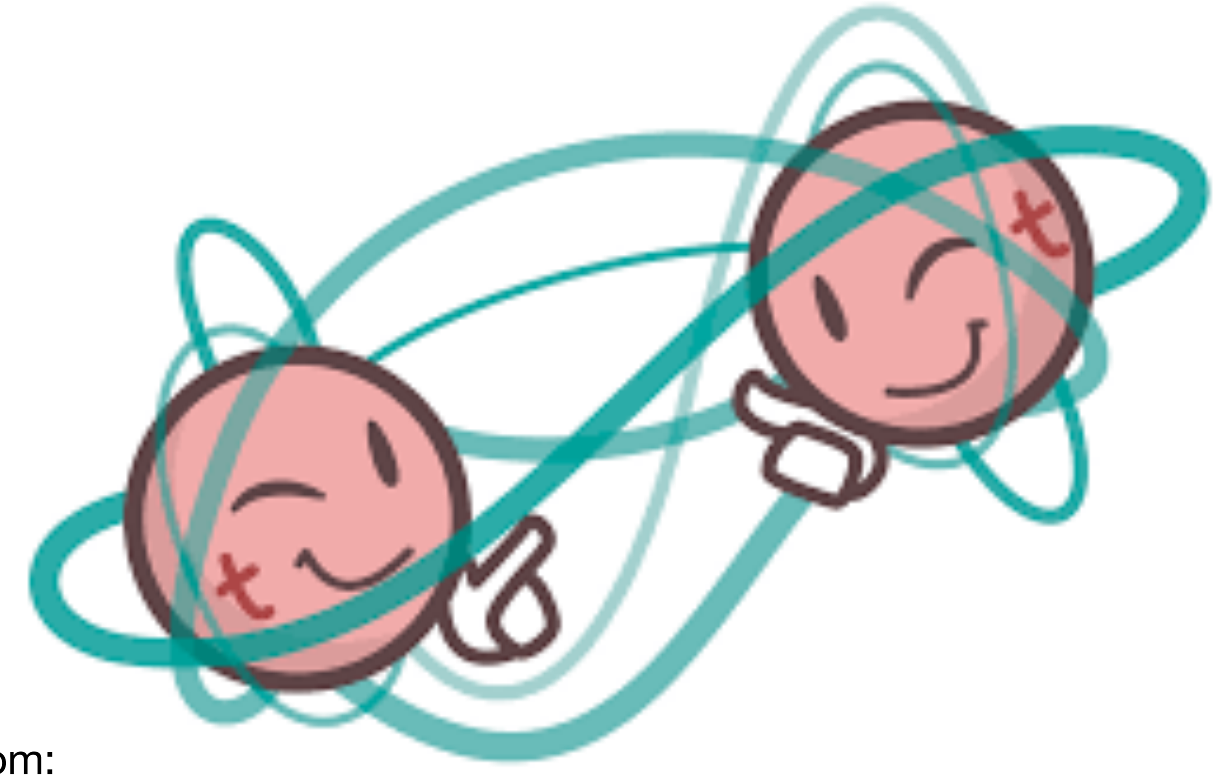
Motivation

- Top quarks are ideal to measure spin

Lifetime < QCD timescale << spin-flip timescale

10^{-25} s < 10^{-24} s << 10^{-21} s → top quark decays before it can hadronize

- Spin information is preserved in the decay
- Spin Correlations can be measured from angular distribution of its decay products



Sketch from:

Georgescu, I. Entanglement between a pair of top quarks. Nat Rev Phys 6, 85 (2024)

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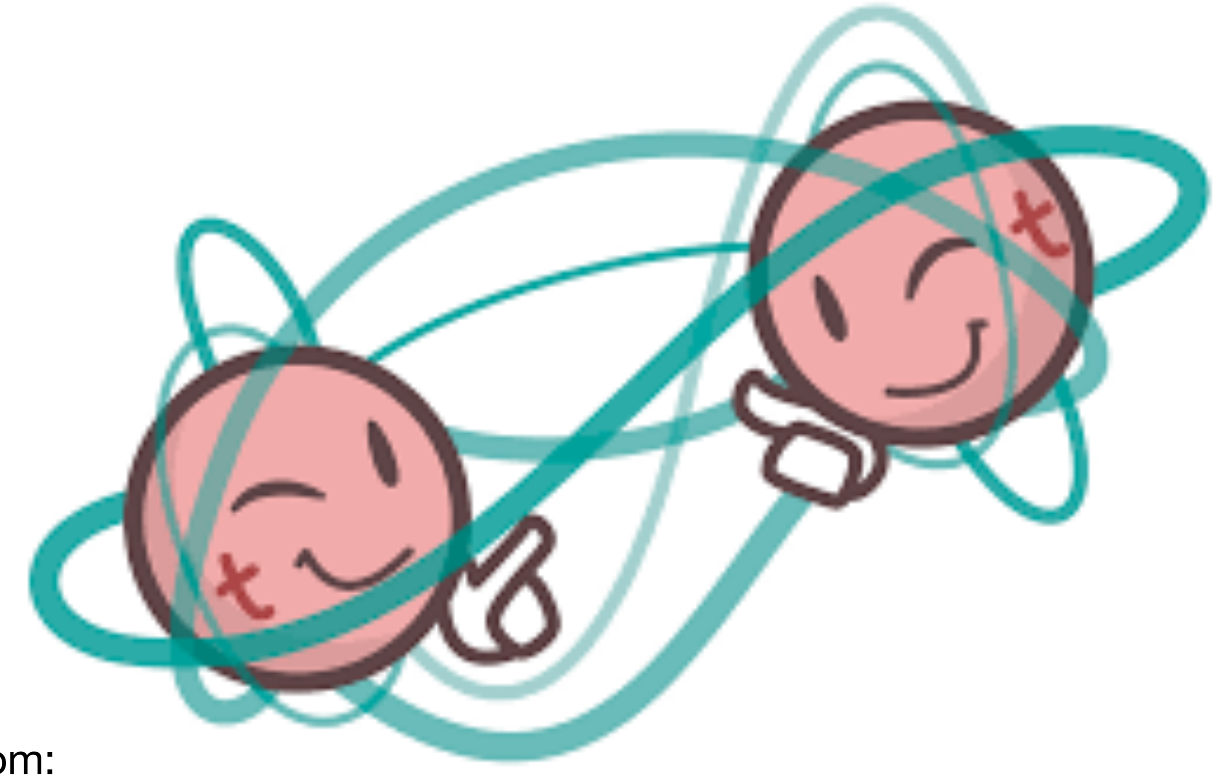

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$t\bar{t}$

Quantum Effects at highest possible energy (eg Quantum Entanglement)

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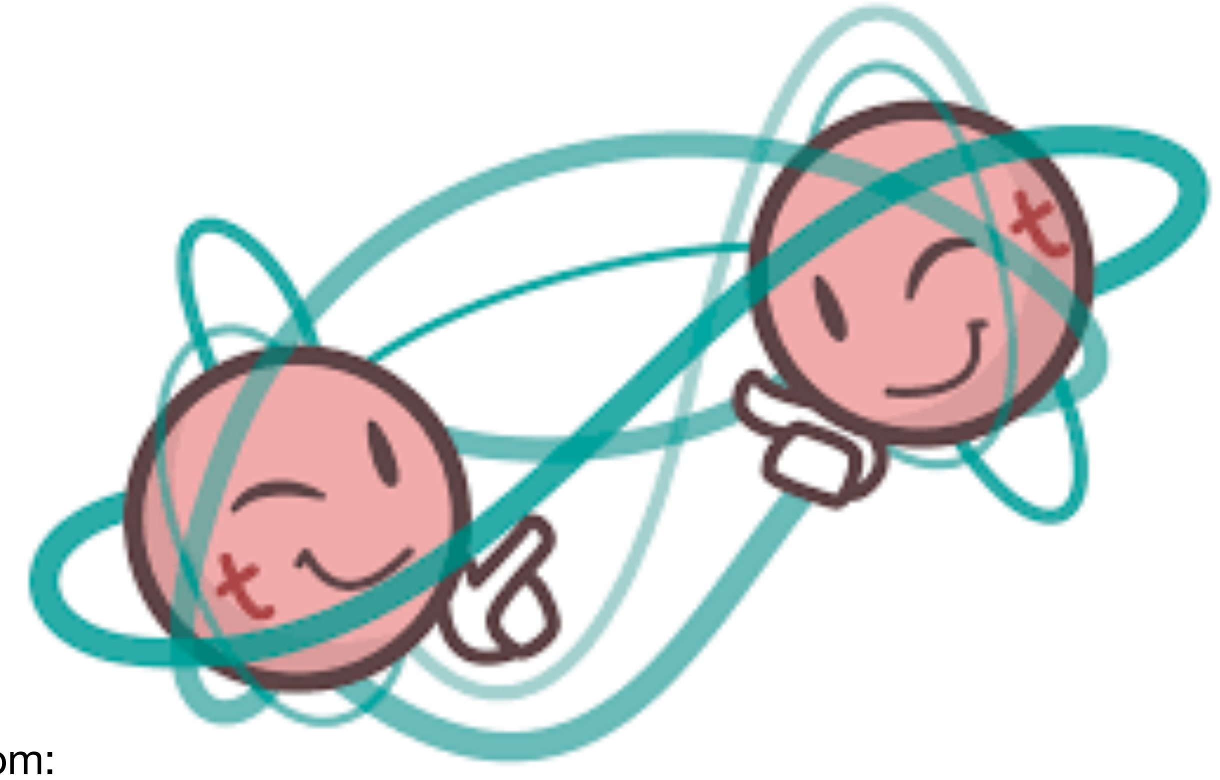

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$t\bar{t}$ used to study → Spin Correlations

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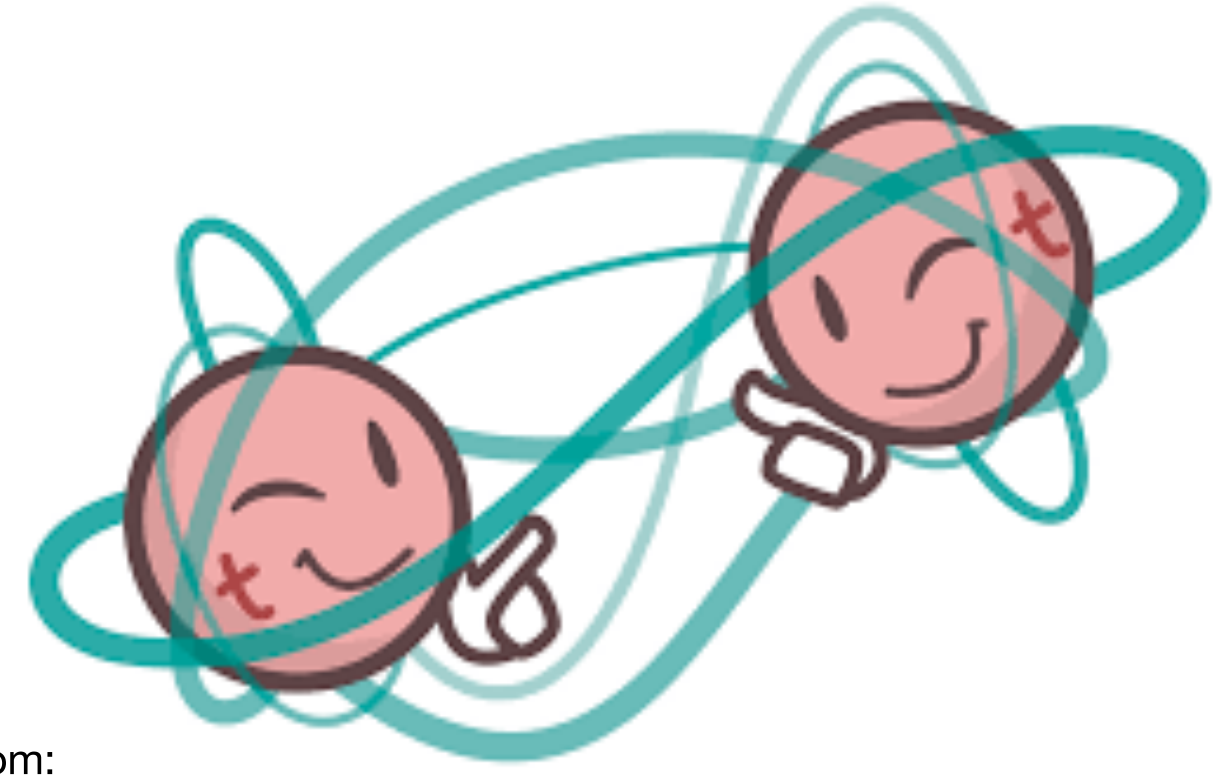

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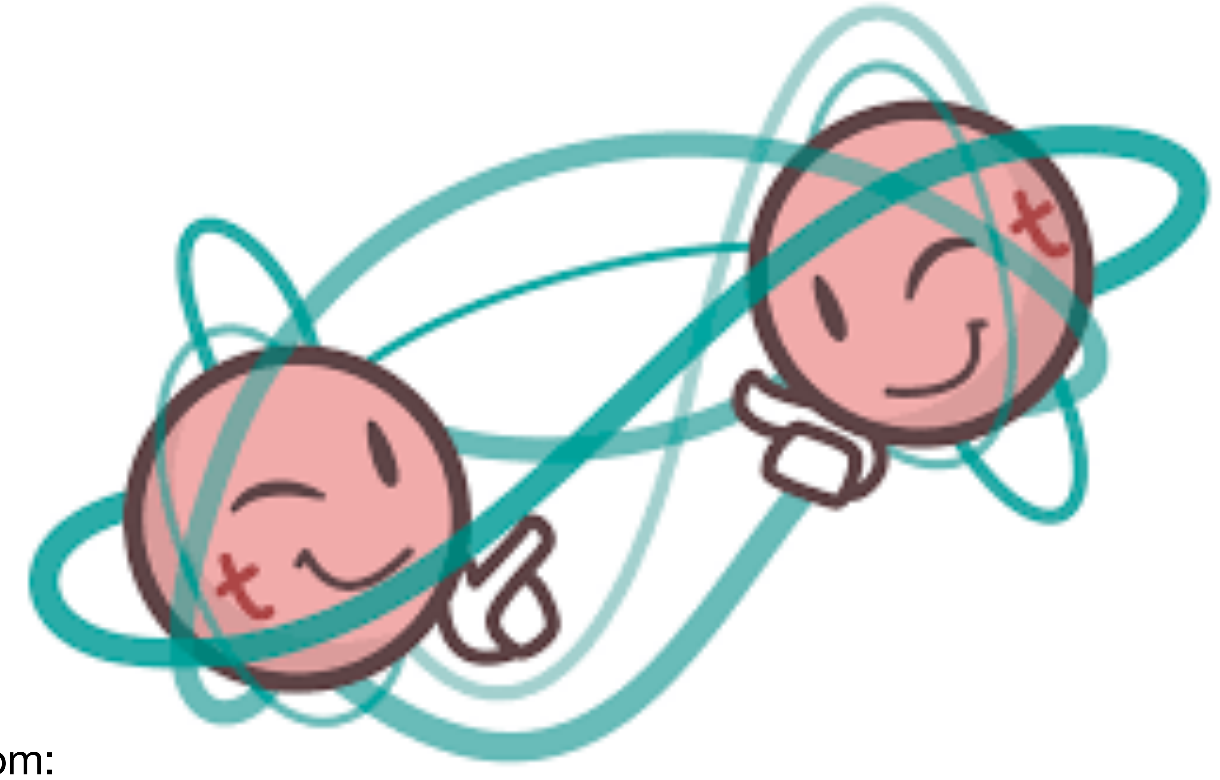

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$t\bar{t}$ used to study → Spin Correlations measurements allow the determination of → Quantum Effects at highest possible energy (eg Quantum Entanglement)

Focusing here:

Spin Correlation in Top Quarks

Measure the differential cross section as functions of 1D angular distributions at parton level to extract the coefficients of the Spin Density Matrix

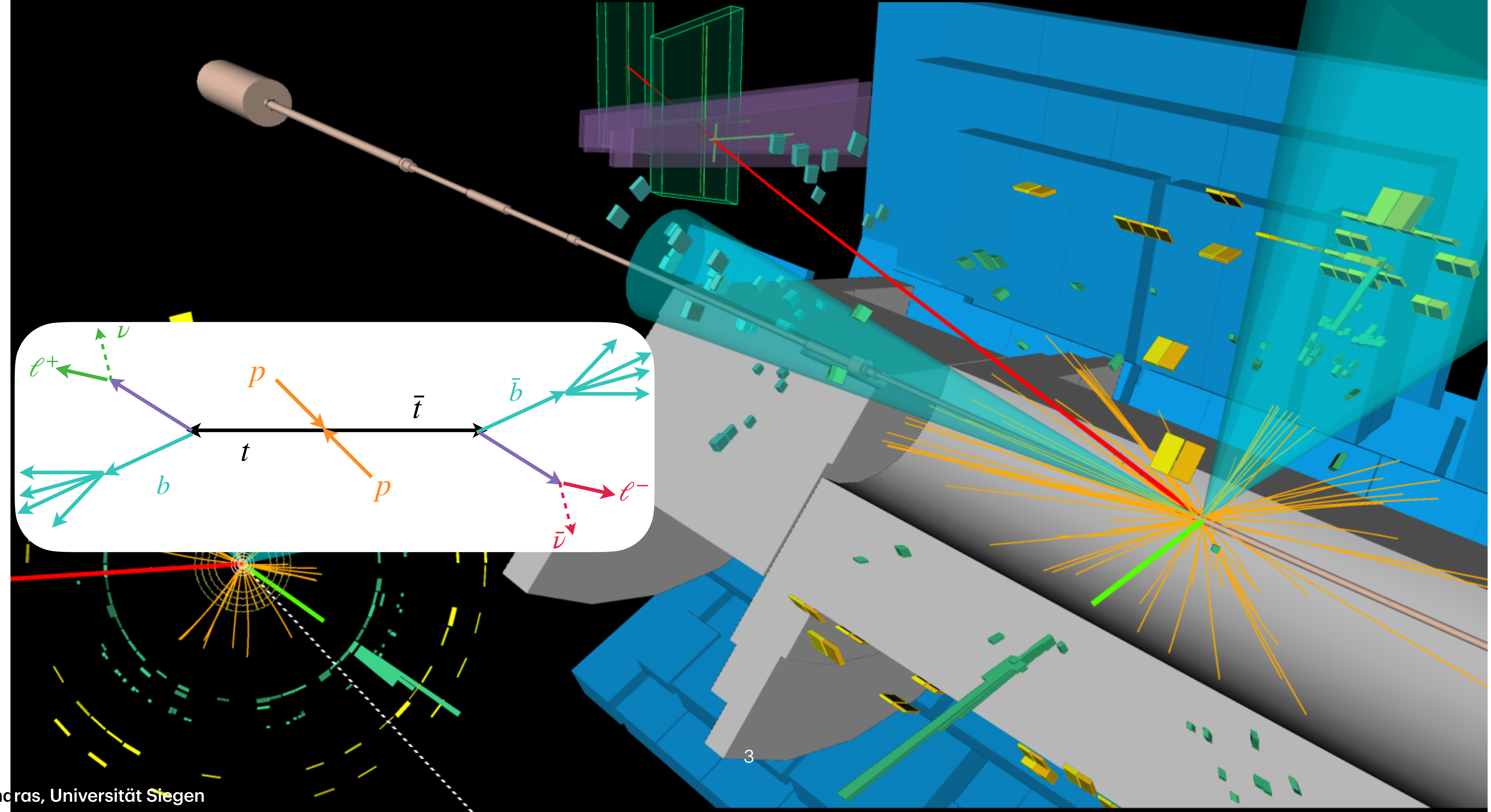
ATLAS EXPERIMENT

Using the ATLAS Run 3 data (159 fb^{-1}) here but the goal is to use both Run 2 and Run 3

Focusing on the dilepton decay channel (ee, $\mu\mu$, $e\mu$)

- Small branching ratio
- Very good signal to background ratio

Run: 428580
Event: 612079972
2022-07-18
05:46:19 CEST



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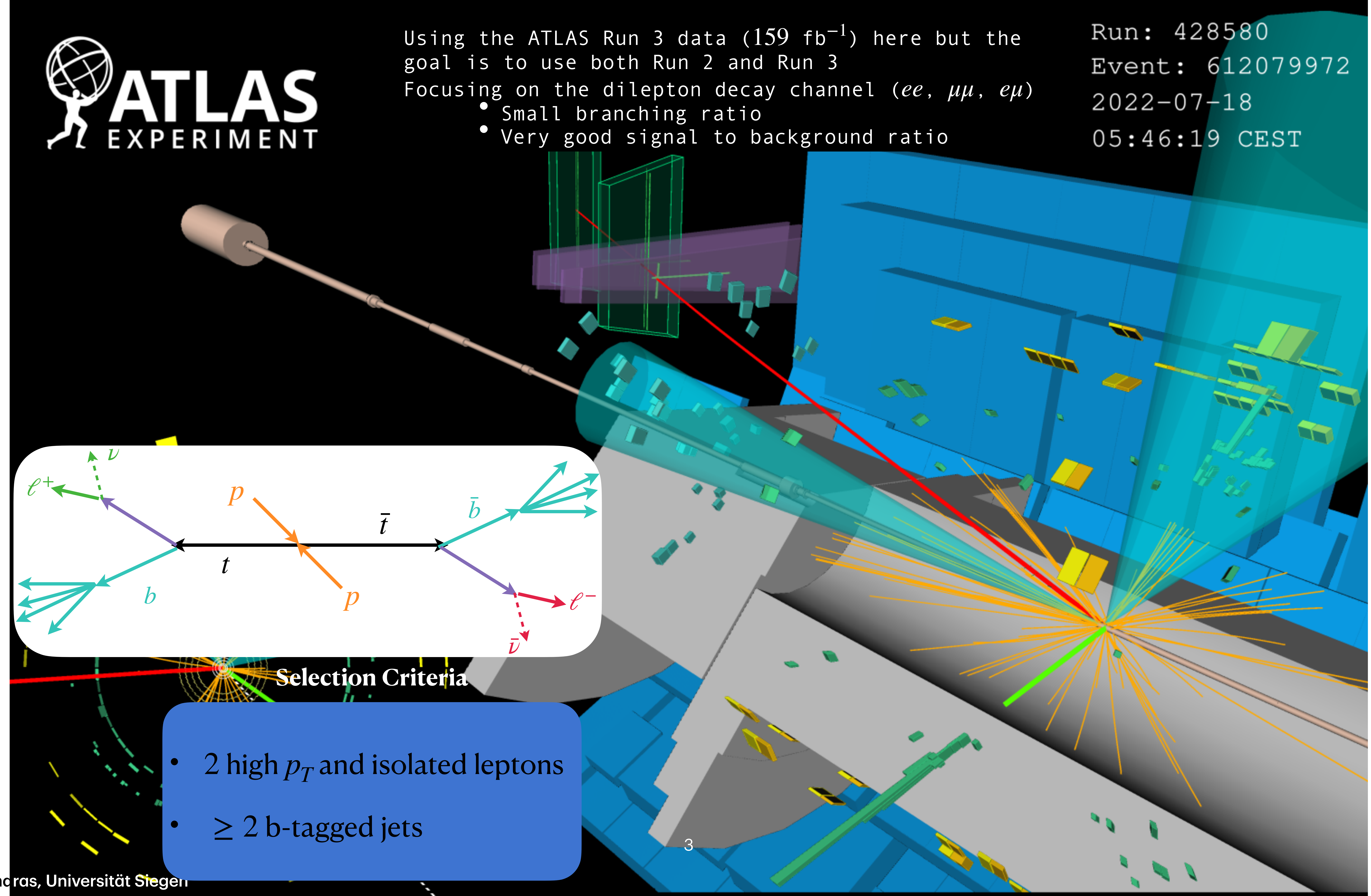

Selection Criteria

- 2 high p_T and isolated leptons
- ≥ 2 b-tagged jets

Spin Correlation

- In the SM the $t\bar{t}$ production is unpolarised, but has a rich structure of spin correlation
- Spin of the top and antitop quark are correlated

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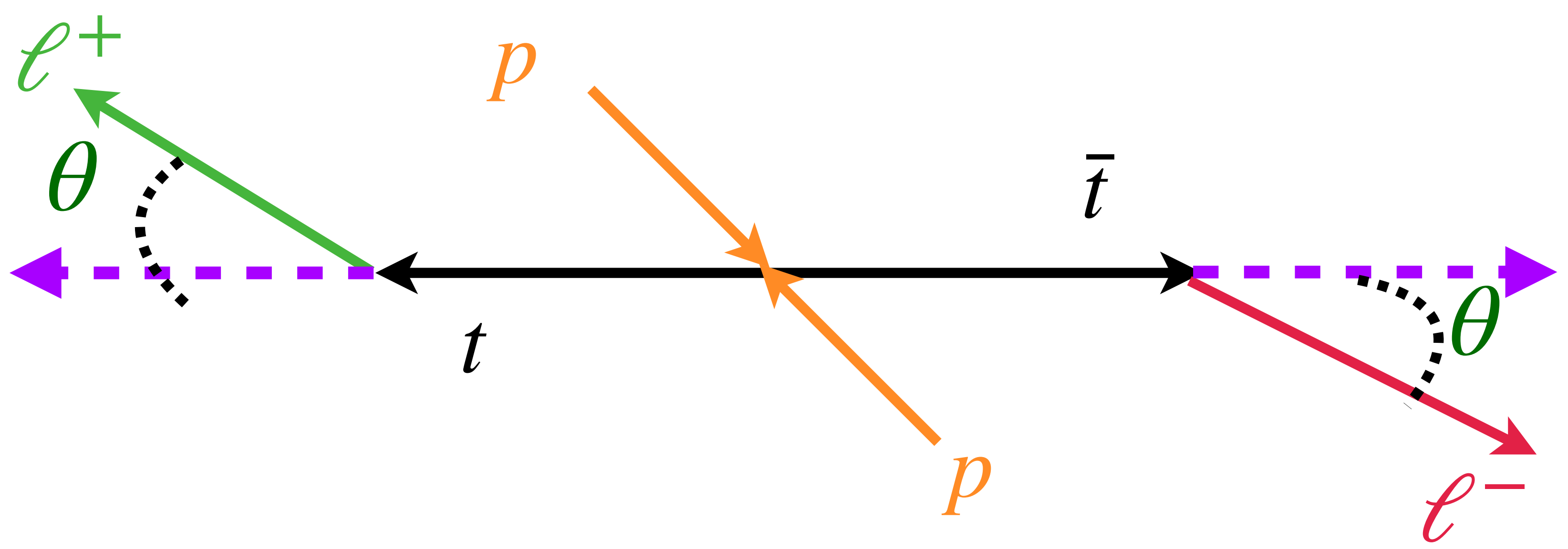

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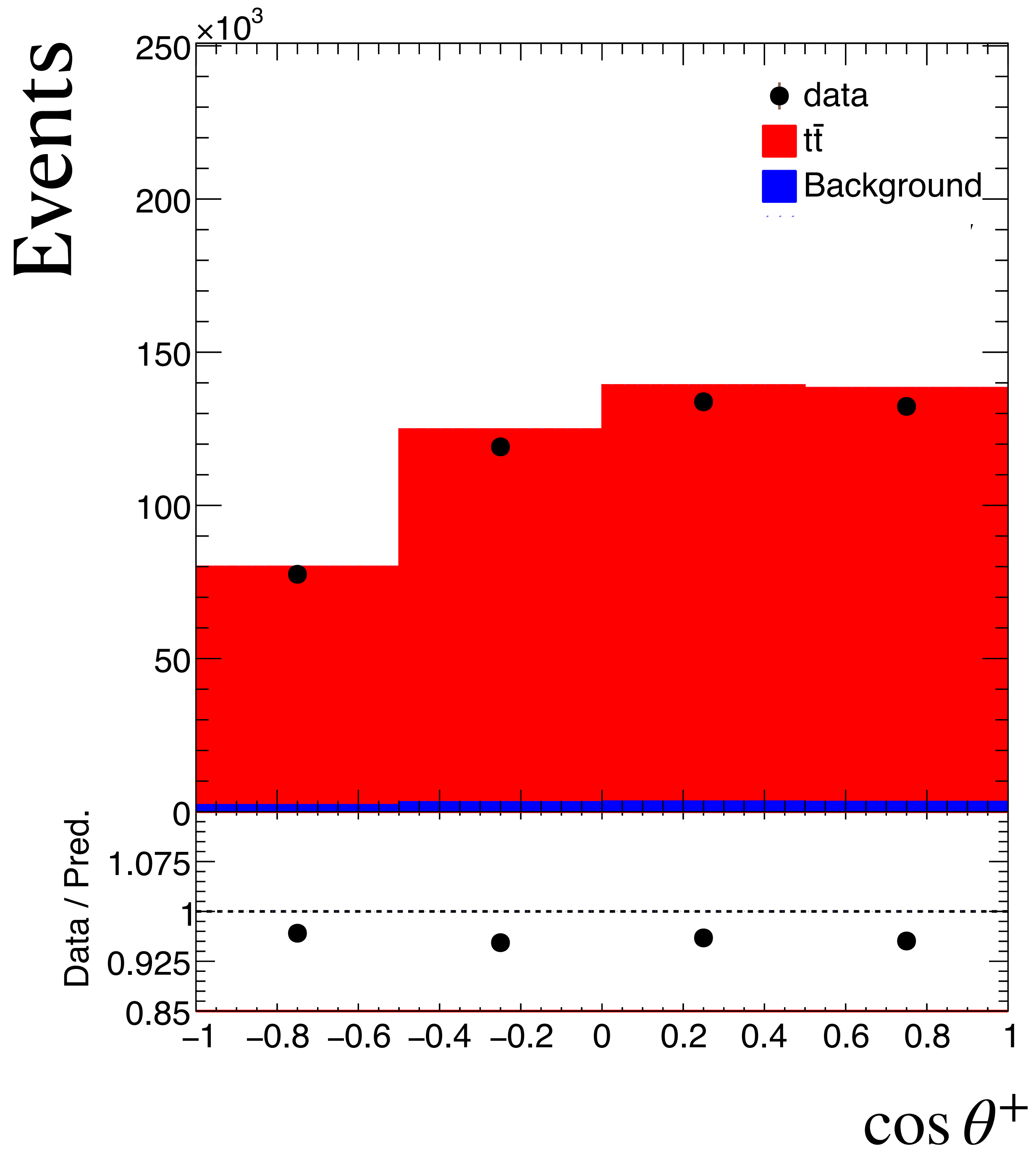
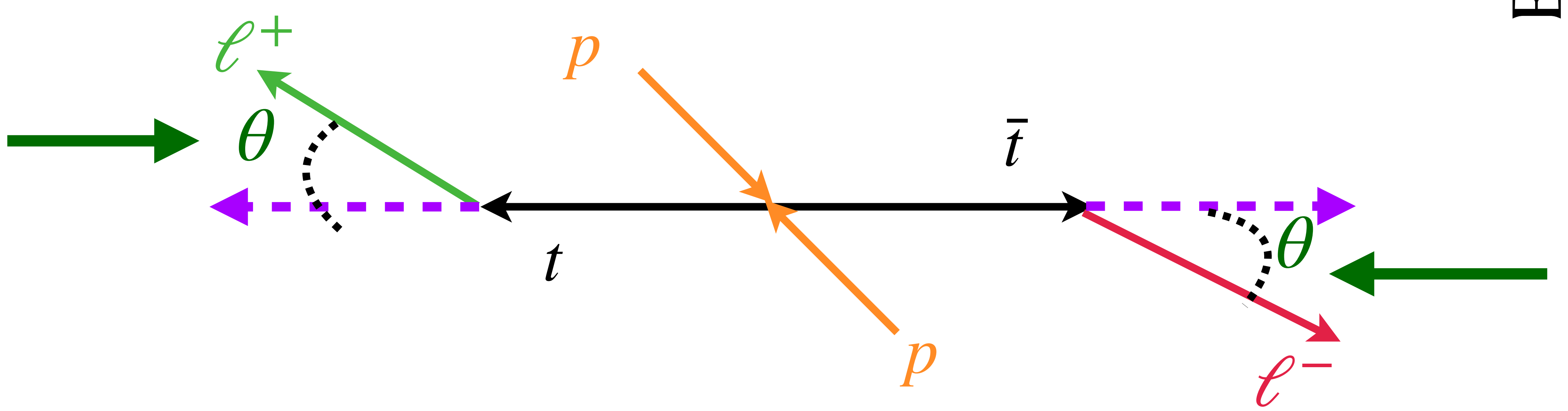
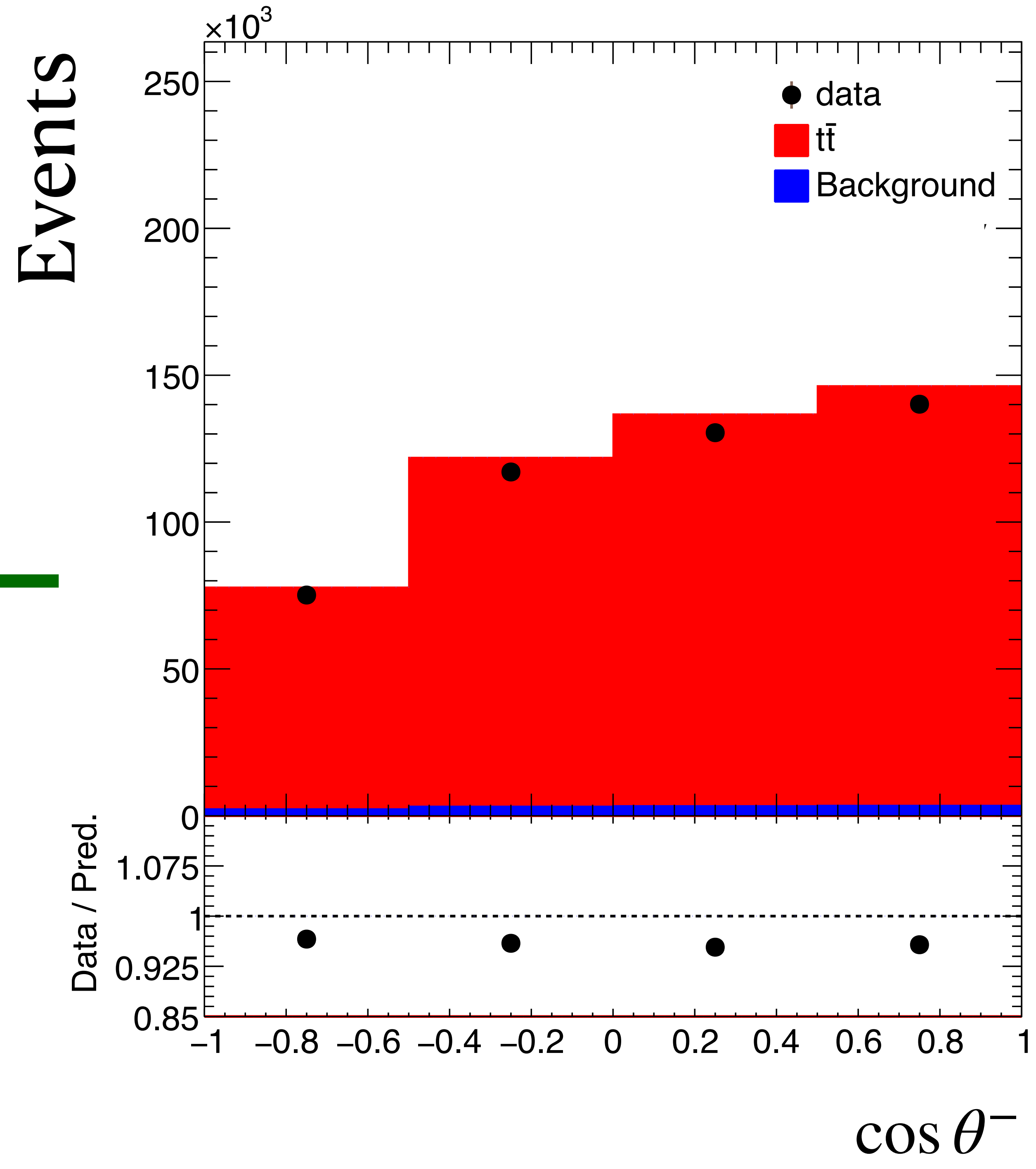
Angle #1 - t quark





Angle #2 - $\bar{t}$ quark



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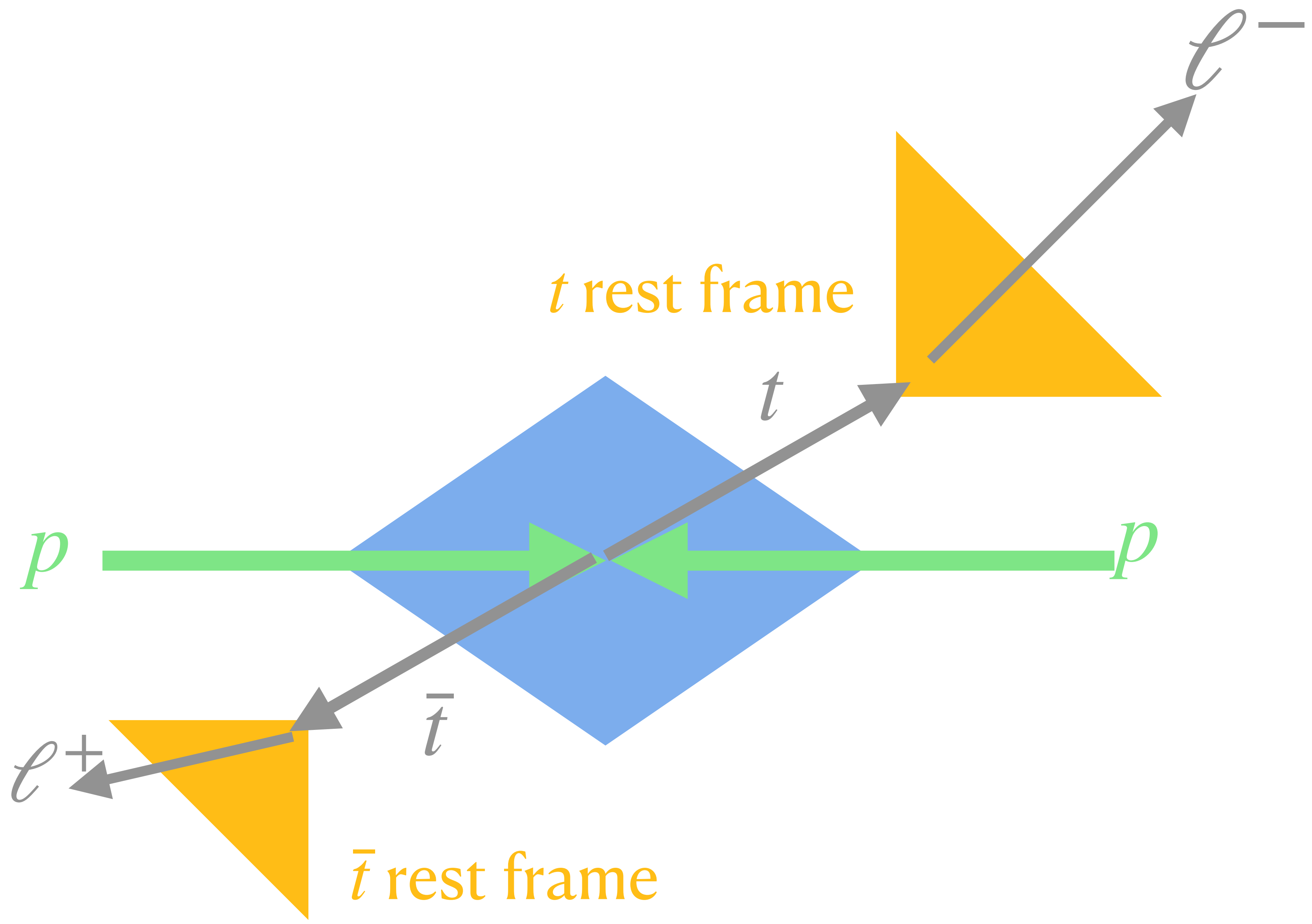
Spin Correlation

Spin Density Matrix

$$\rho_{ij} = \frac{1}{4}\left[I_4 + B_i^+ \cos\theta_i^+ + B_j^- \cos\theta_j^- - C_{ij}\cos\theta_i^+ \cos\theta_j^-\right] \text{where } i, j = k, r, n$$

Top polarisations

Spin correlations



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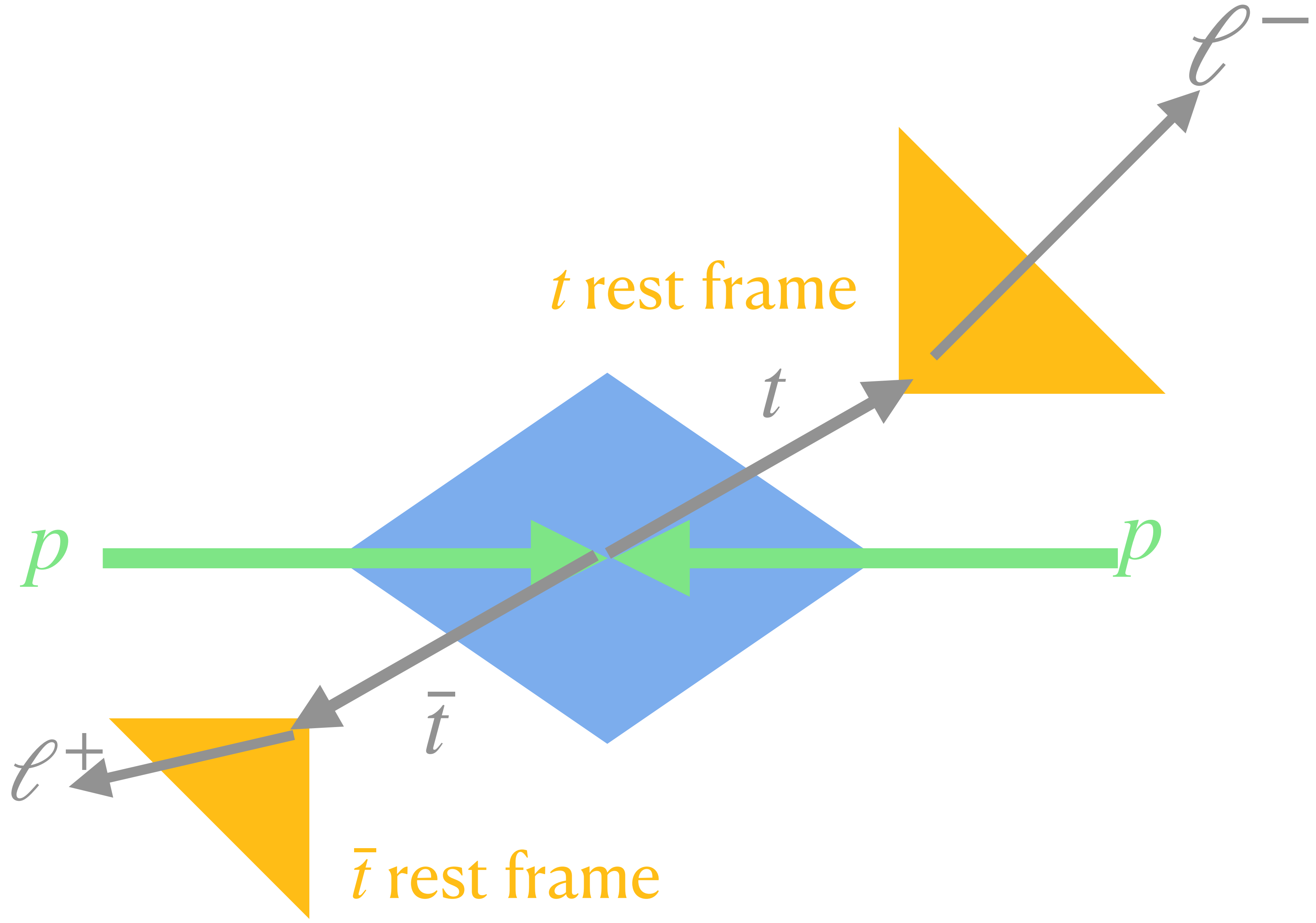

$$\begin{matrix} C_{kk} C_{kr} C_{kn} \\ C_{rk} C_{rr} C_{rn} \\ C_{nk} C_{nr} C_{nn} \end{matrix}$$

Spin Correlation Matrix

B^-/B^+: top/antitop quark spin polarisation vectors (three vector)

C: spin correlation matrix (3x3)

ℓ^-/ℓ^+: lepton direction in its parent quark rest frame

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Top polarisations

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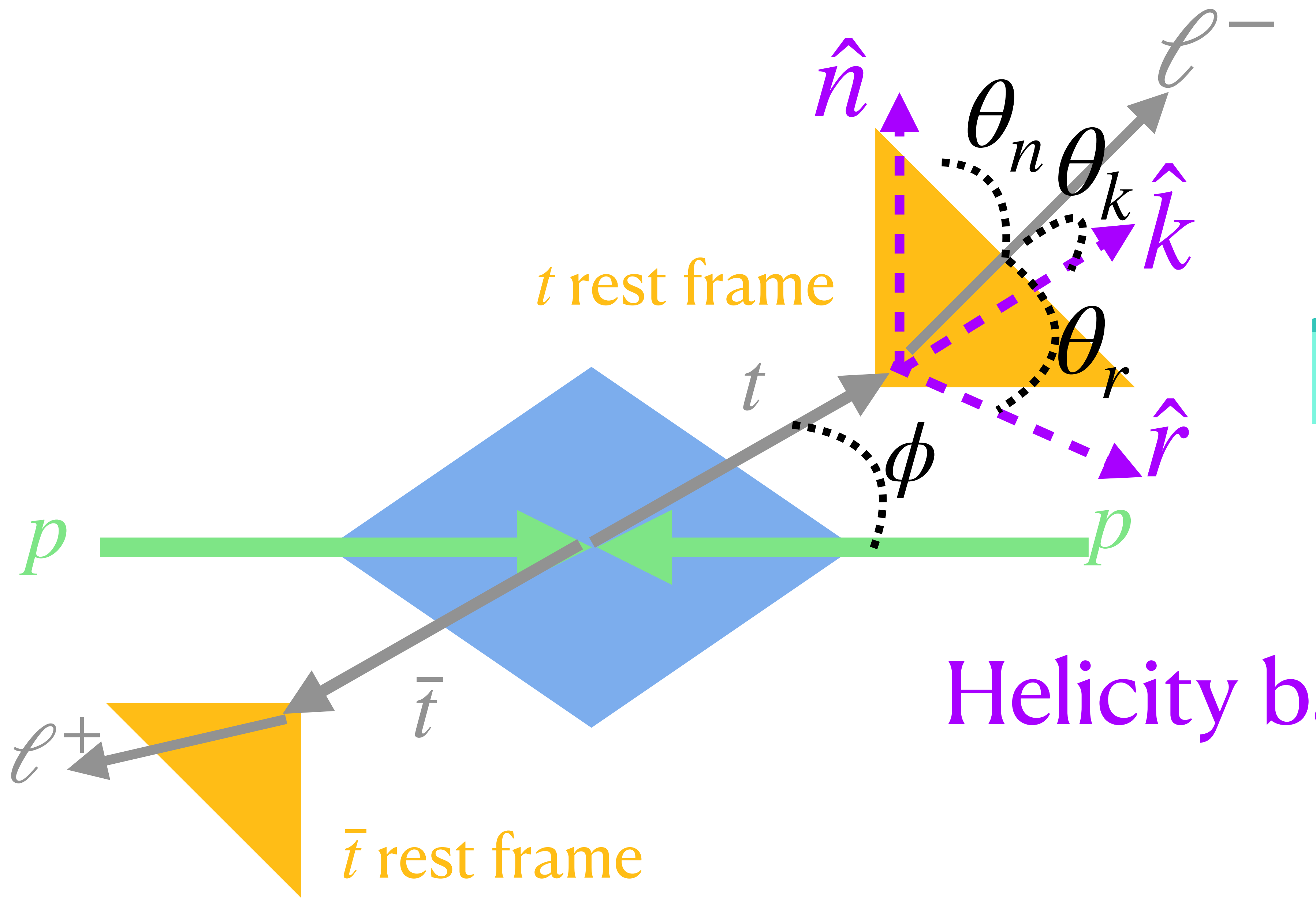


$$\begin{matrix} C_{kk} & C_{kr} & C_{kn} \\ C_{rk} & C_{rr} & C_{rn} \\ C_{nk} & C_{nr} & C_{nn} \end{matrix}$$

Spin Correlation Matrix

B^-/B^+: top/antitop quark spin polarisation vectors (three vector)

C: spin correlation matrix (3x3)

ℓ^-/ℓ^+: lepton direction in its parent quark rest frame

Helicity basis: $\hat{k} = top\ direction, \quad \hat{r} = \frac{\hat{p} - \hat{k}\cos\phi}{\sin\phi}, \quad \hat{n} = \frac{\hat{p} \times \hat{k}}{\sin\phi}$

Spin Density Matrix

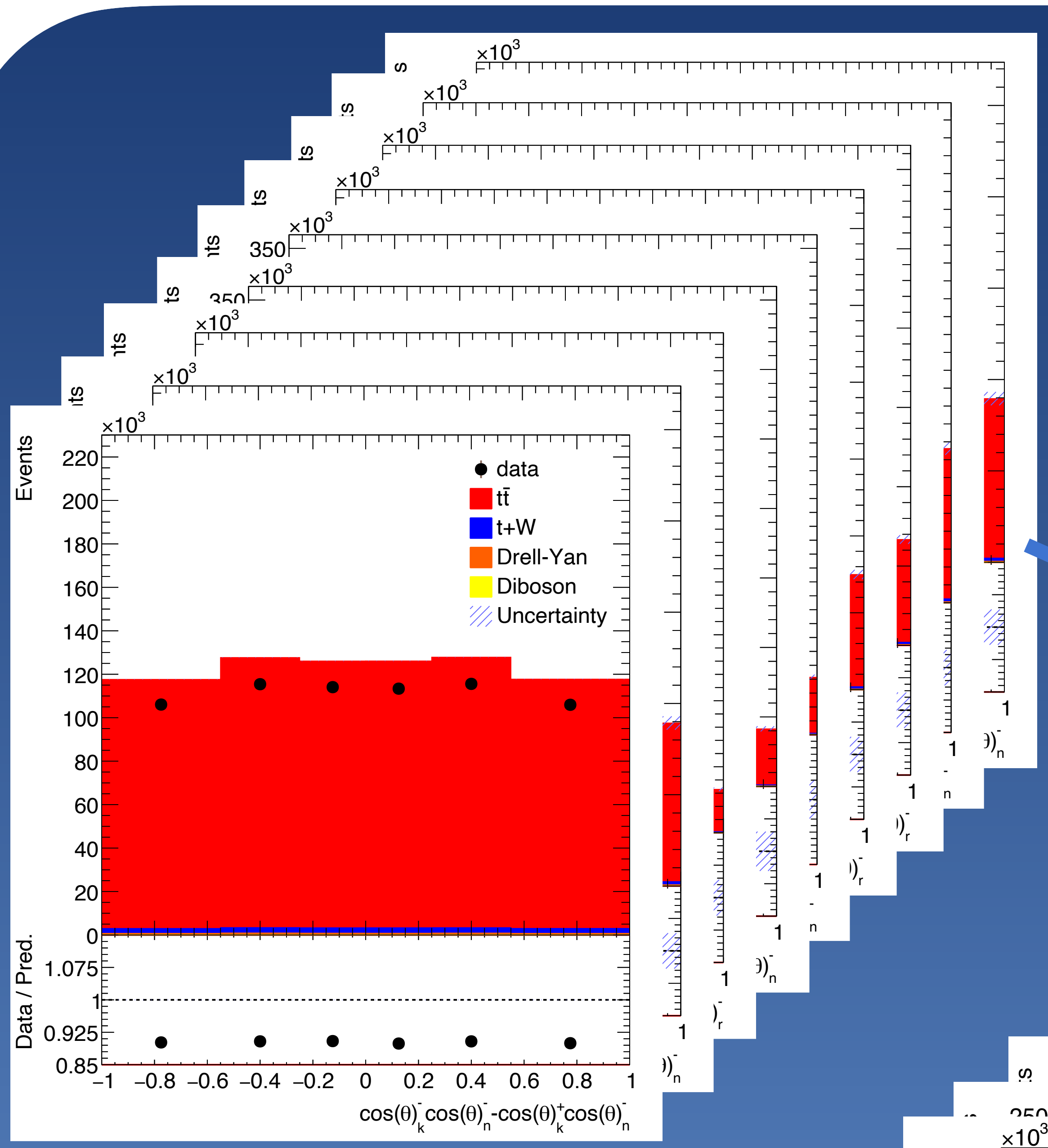
Parametrisation

$$C_{kk} C_{kr} C_{kn}$$
$$C_{rk} C_{rr} C_{rn}$$
$$C_{nk} C_{nr} C_{nn}$$

Spin Correlation Matrix

$$\rho = \frac{1}{4}\left[I_4 + B_i^+ \cos\theta_i^+ + B_j^- \cos\theta_j^- - C_{ij} \cos\theta_i^+ \cos\theta_j^- \right]$$

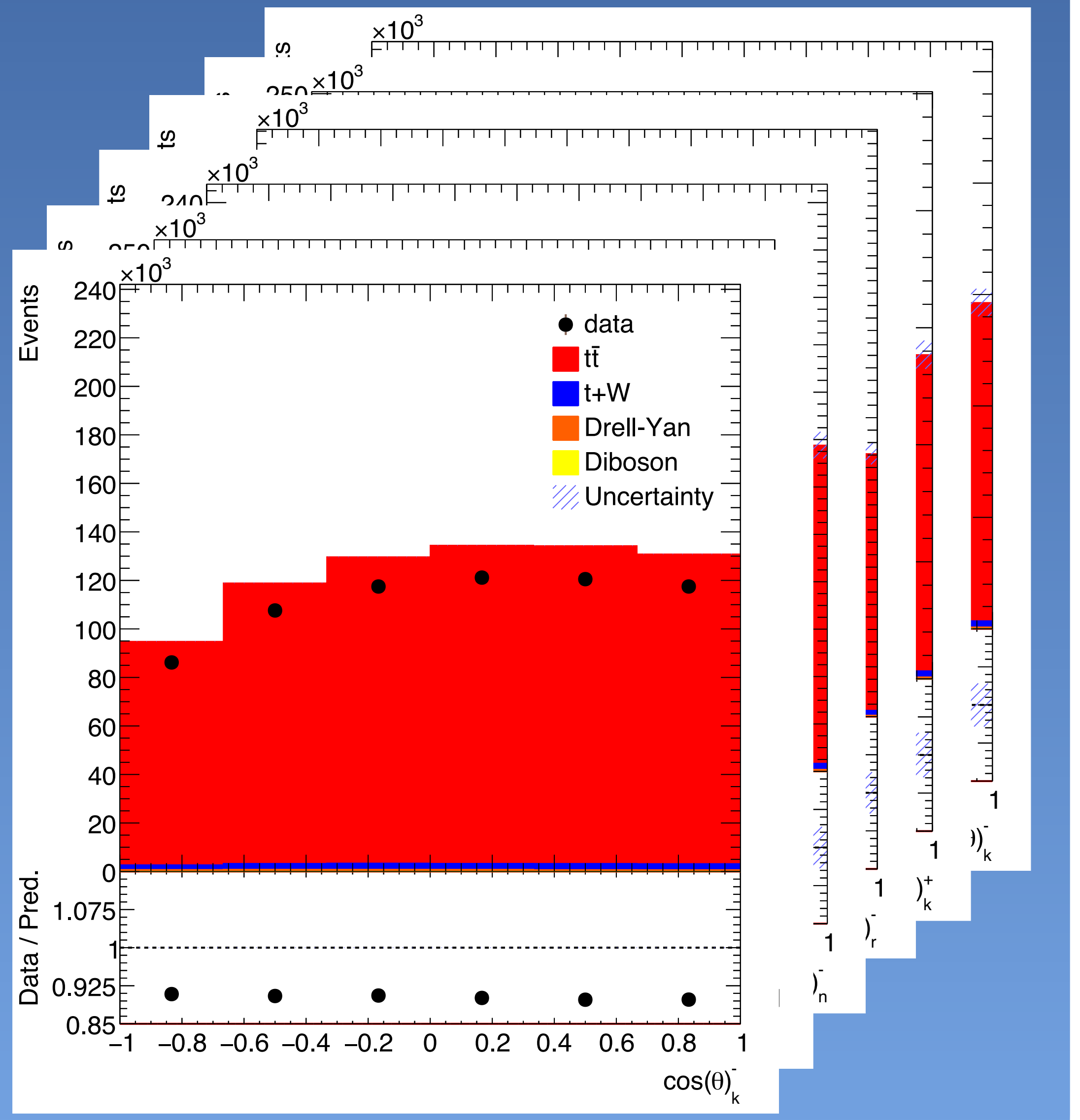
We can fully parameterise the SDM with 15 parameters



9 combinations

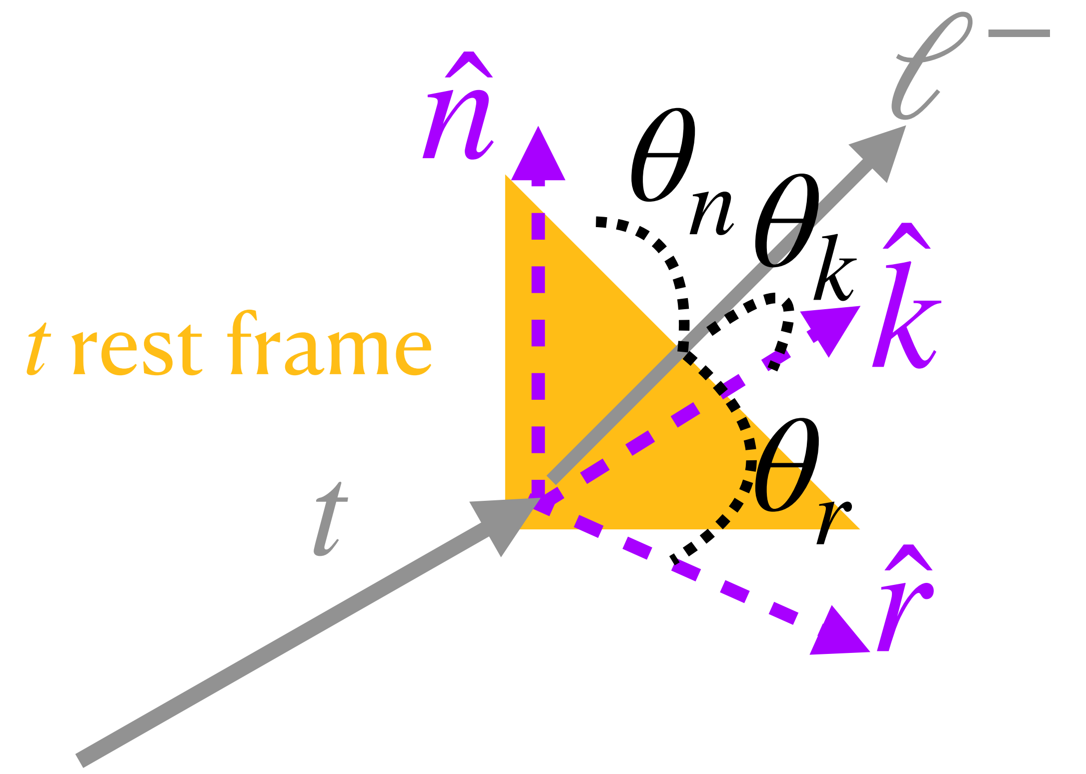
Diagonal entries: probabilities of finding $t\bar{t}$ pair in specific spin states

Off-diagonal: interference between different spin states



6 angles

Individually probed by measuring angular distributions of the leptons from t and $\bar{t}$ decays at parton level.



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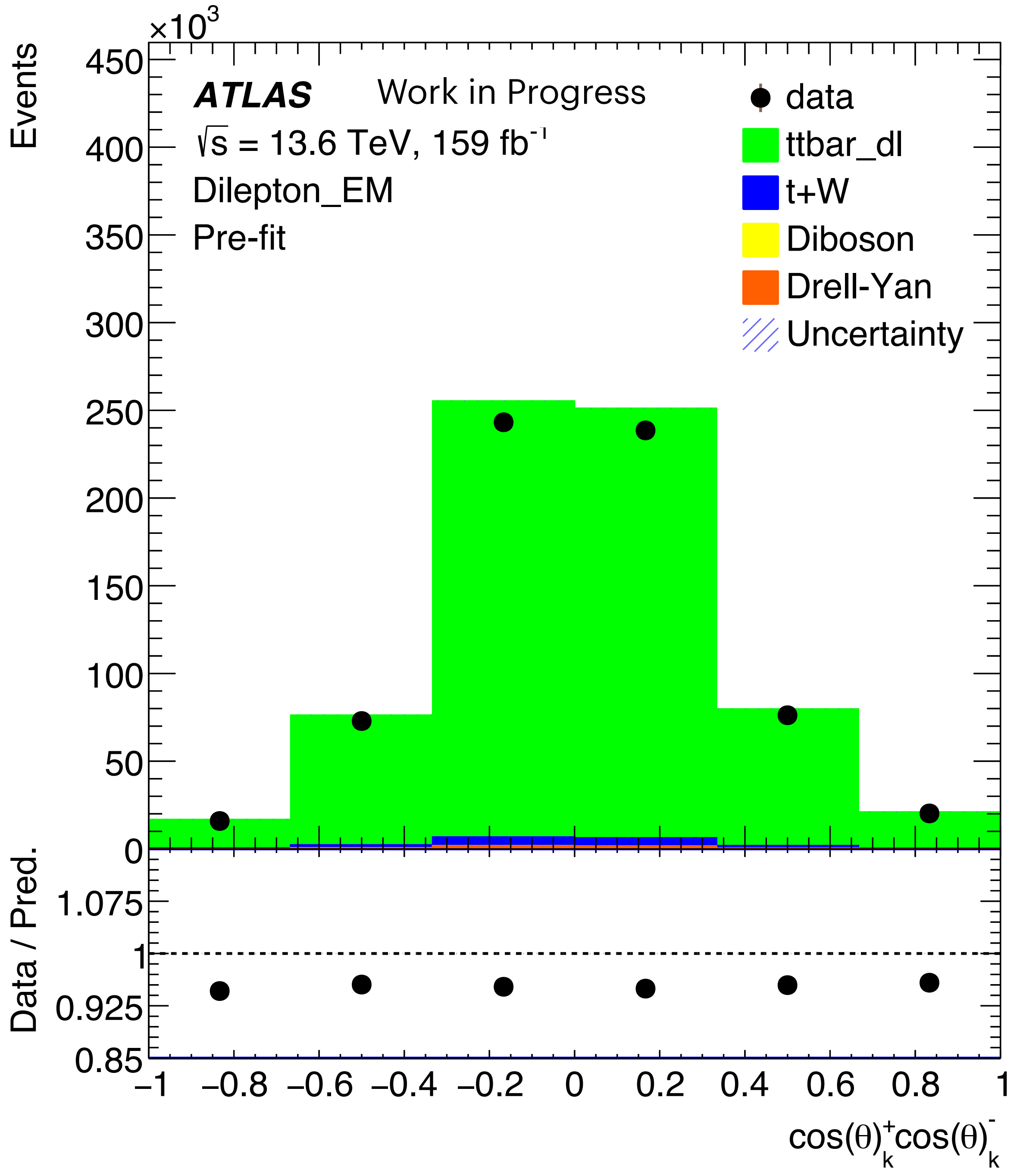
$C_{kk} C_{kr} C_{kn}$
$C_{rk} C_{rr} C_{rn}$
$C_{nk} C_{nr} C_{nn}$

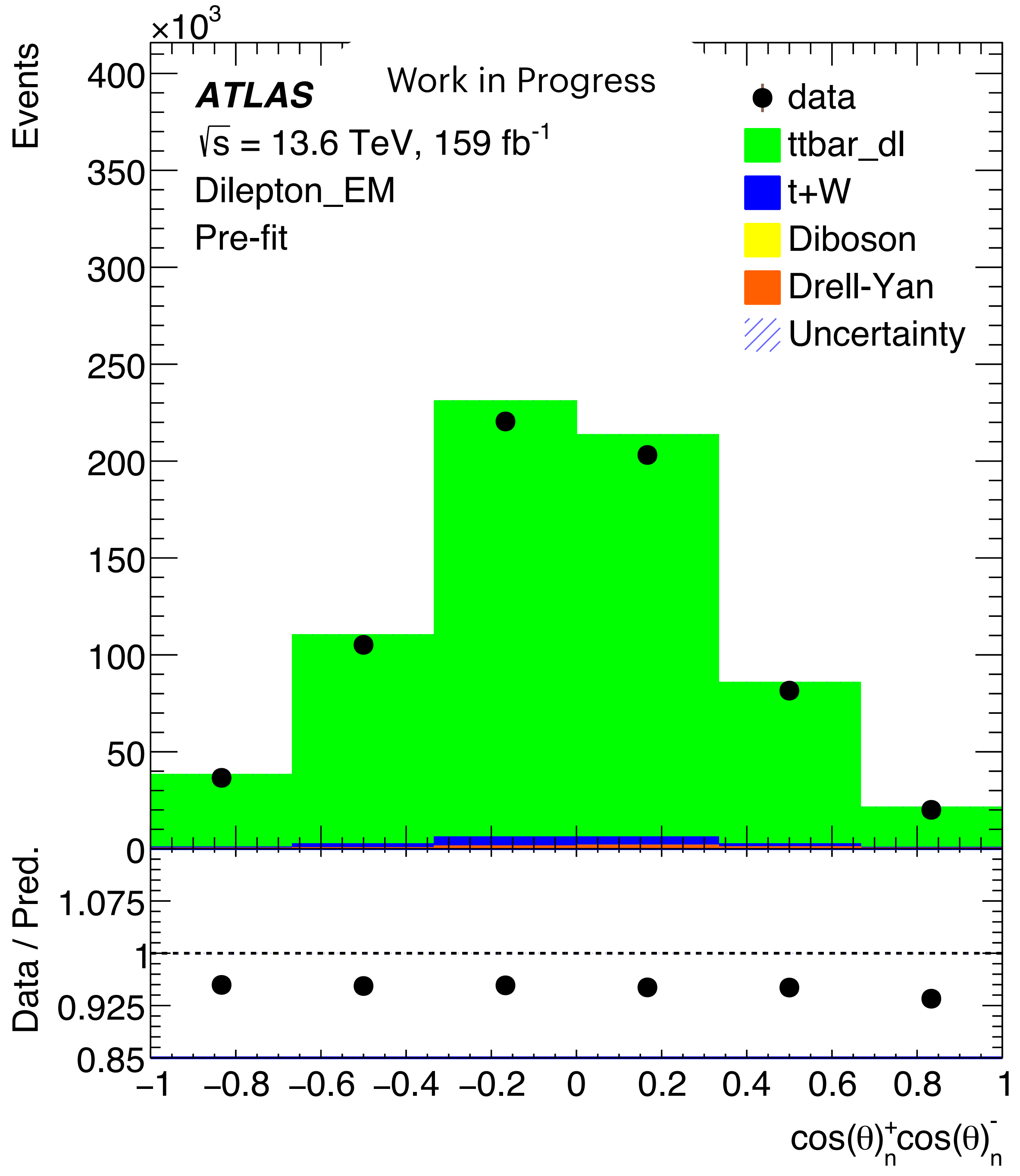
Spin Density Matrix variables

Dilepton
$ee \,|\, \mu\mu \,|\, e\mu$ channels
Run 3 data

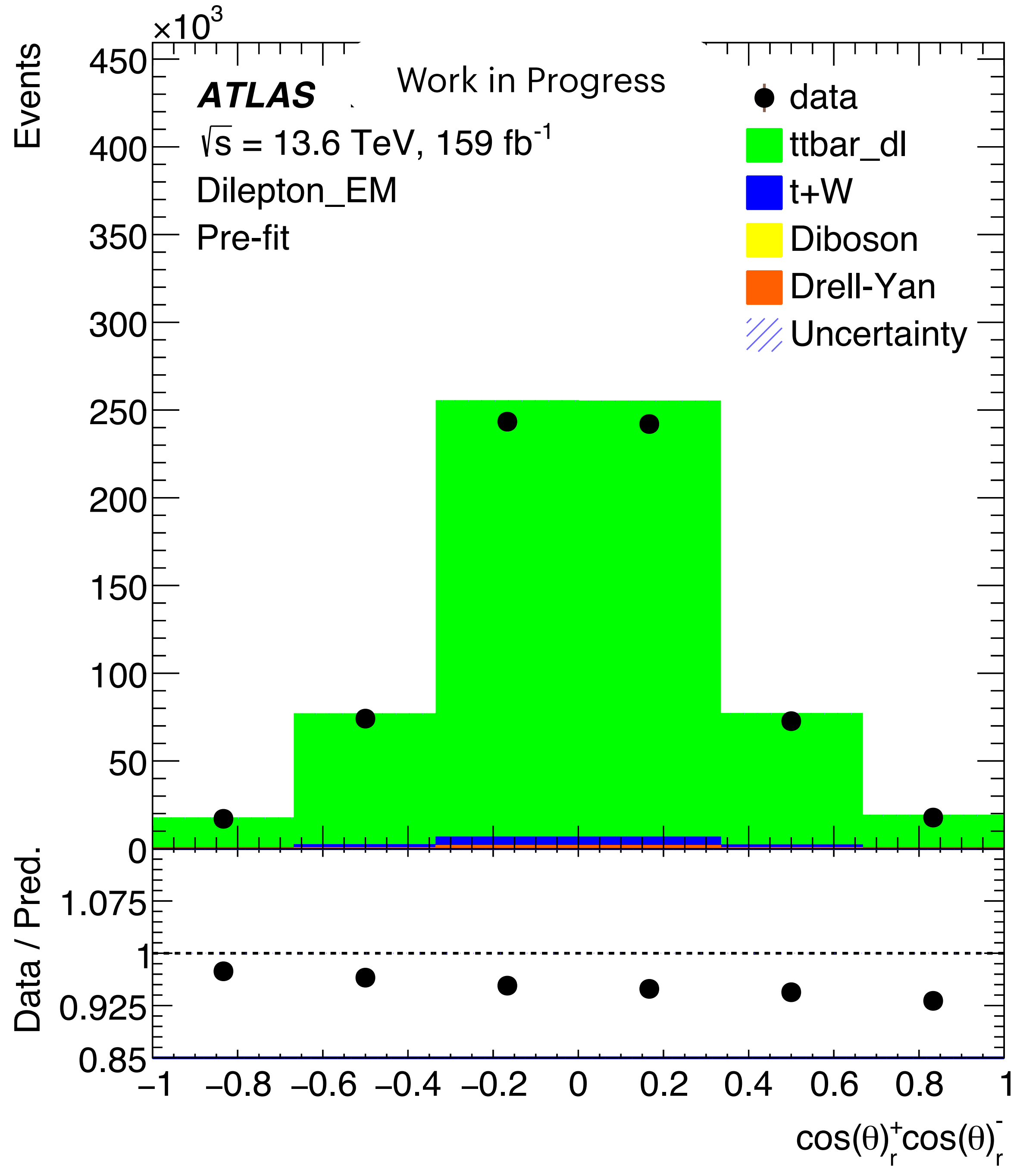
Variables for diagonal matrix elements



$\cos\theta_k^+ \cos\theta_k^-$



$\cos\theta_n^+ \cos\theta_n^-$



$\cos\theta_r^+ \cos\theta_r^-$

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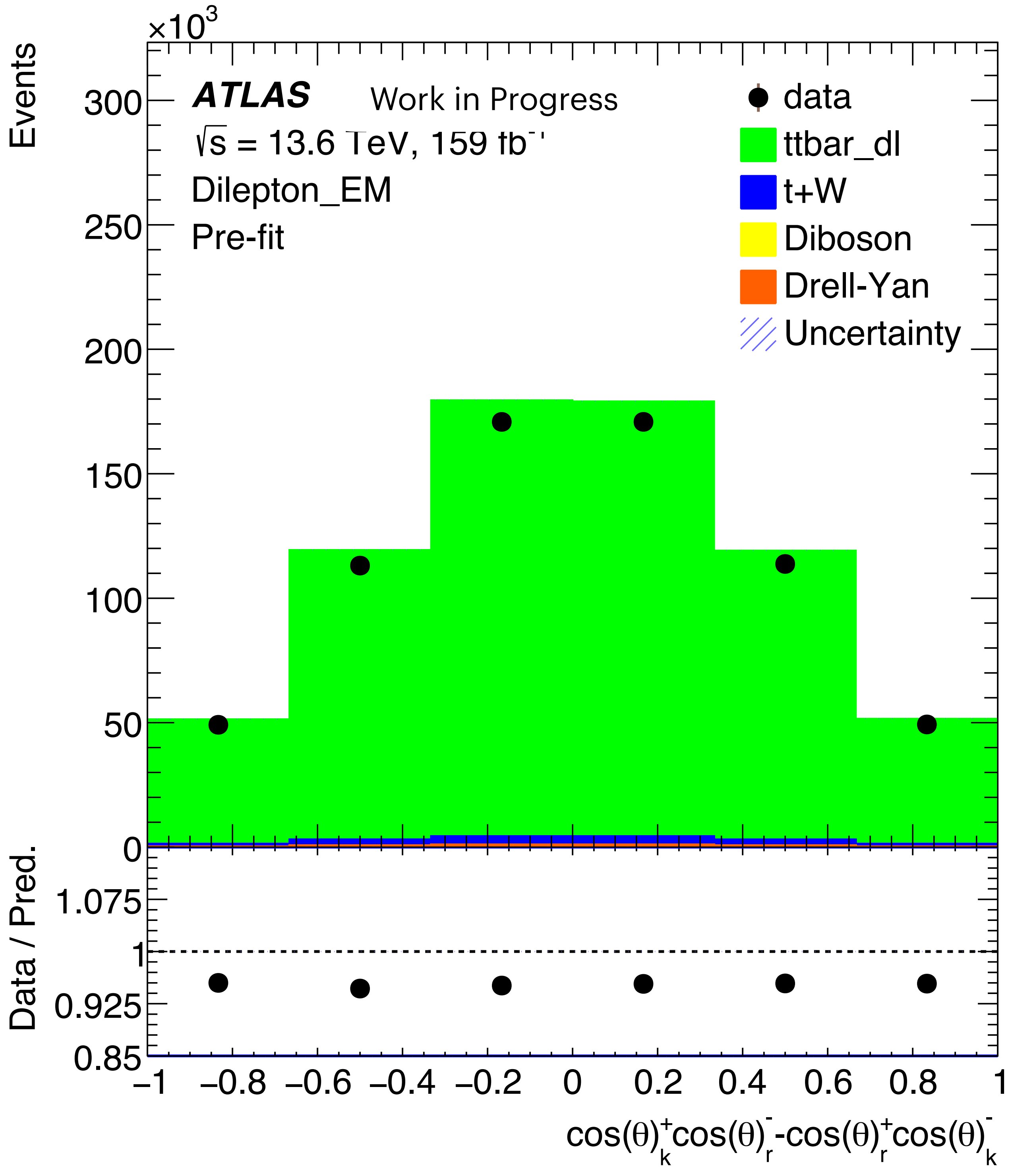
$$C_{kk}C_{kr}C_{kn}$$
$$C_{rk}C_{rr}C_{rn}$$
$$C_{nk}C_{nr}C_{nn}$$

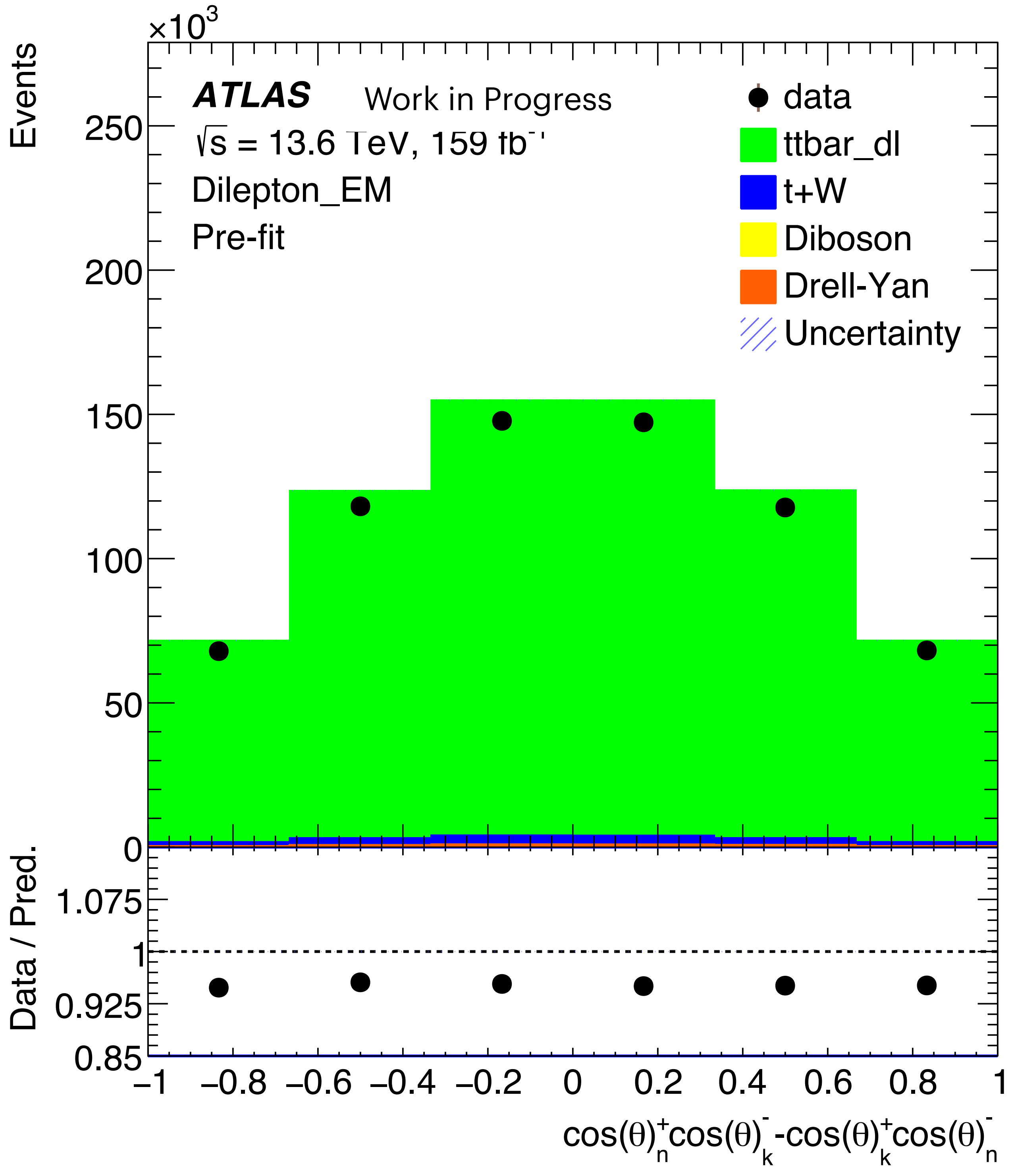
Spin Density Matrix variables

Dilepton
$ee \,|\, \mu\mu \,|\, e\mu$ channels
Run 3 data

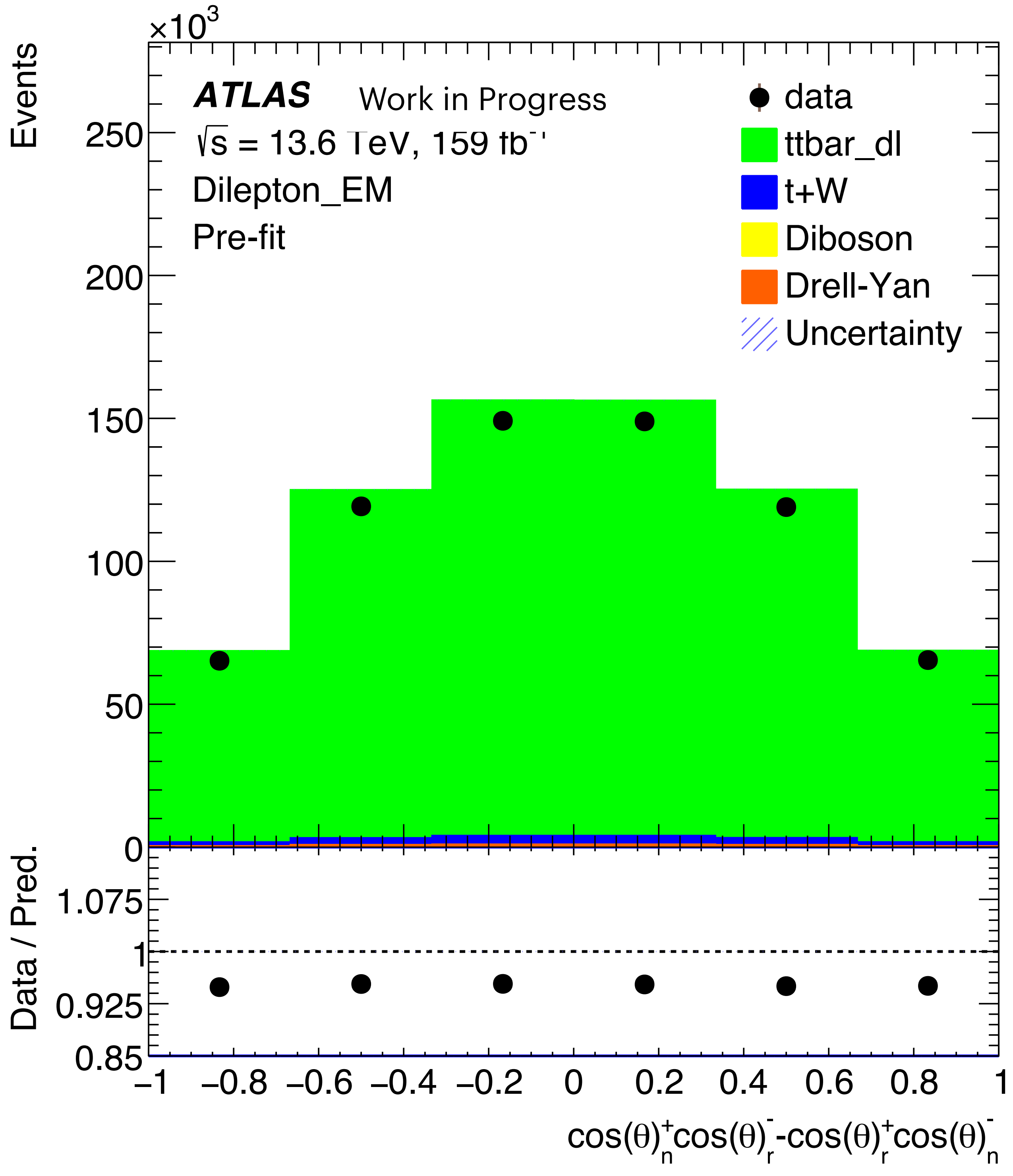
Example variables for off-diagonal matrix elements



$\cos\theta_k^+ \cos\theta_r^- - \cos\theta_r^+ \cos\theta_k^-$



$\cos\theta_n^+ \cos\theta_k^- - \cos\theta_k^+ \cos\theta_n^-$



$\cos\theta_n^+ \cos\theta_r^- - \cos\theta_r^+ \cos\theta_n^-$

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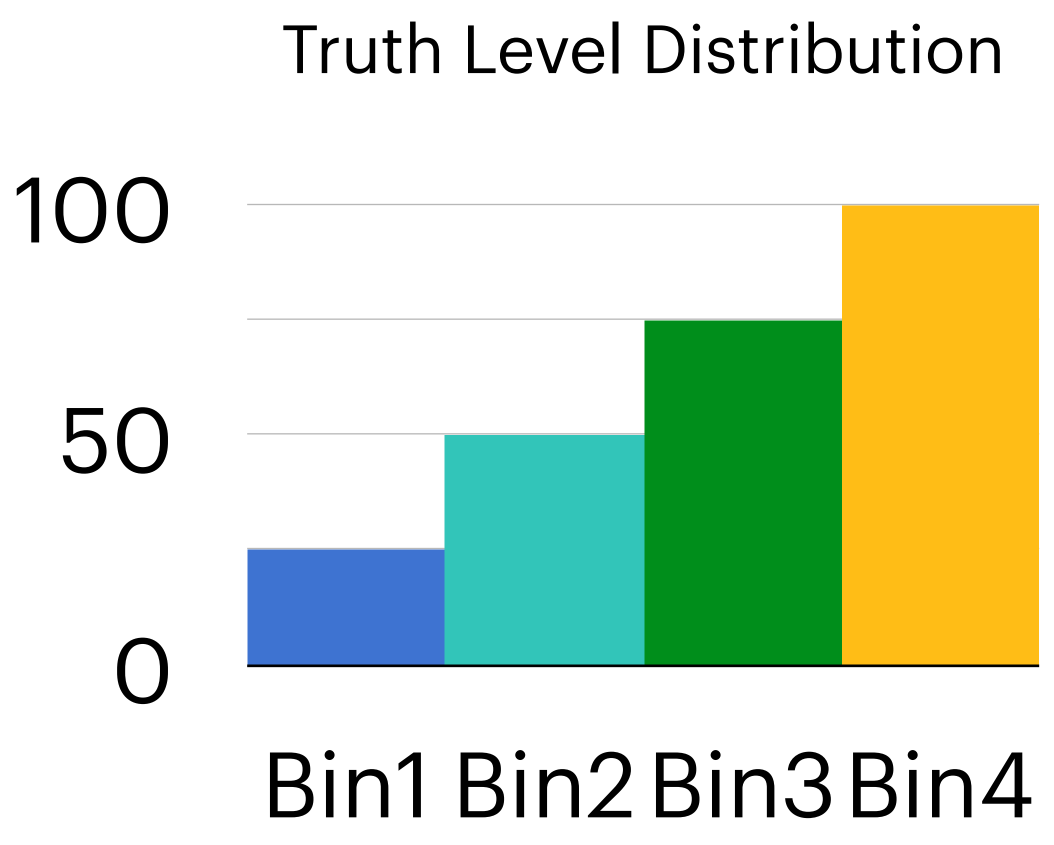
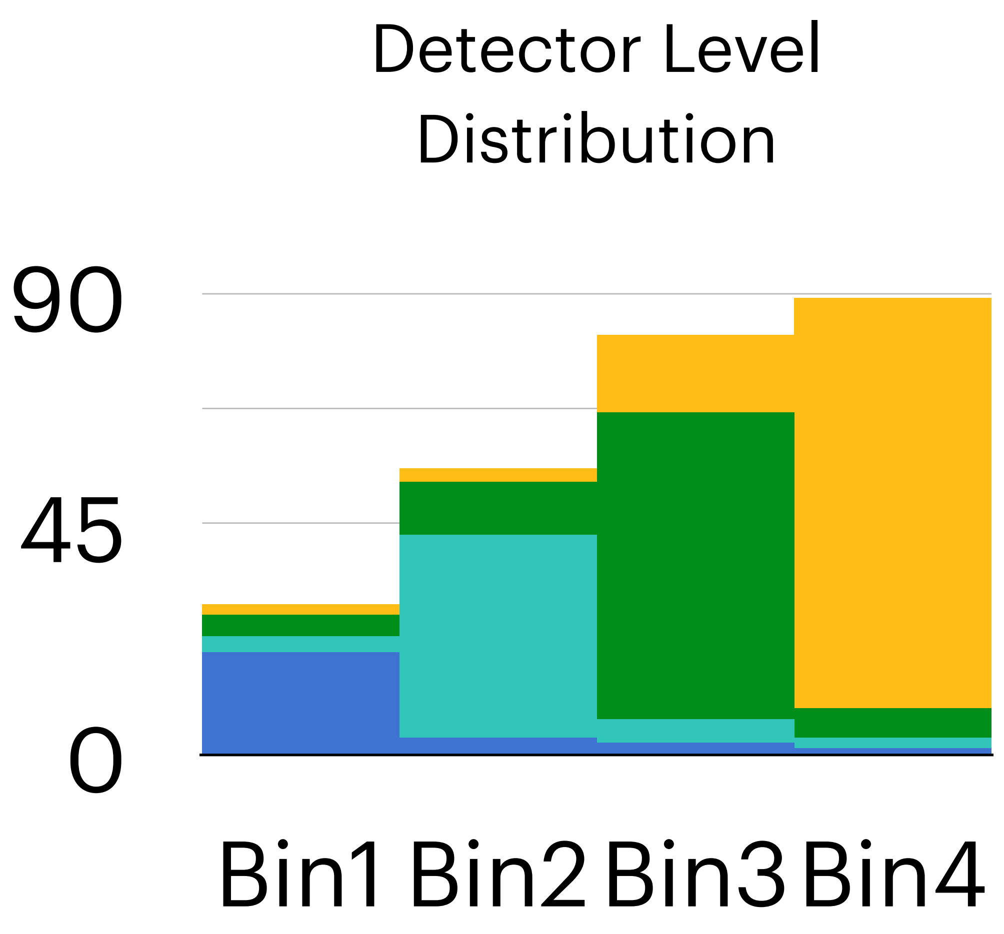
Profile Likelihood Unfolding



The true physics distribution



What the detector "sees"

Correct for detector effects via a profile likelihood unfolding.
Implementing PLU to measure cross section

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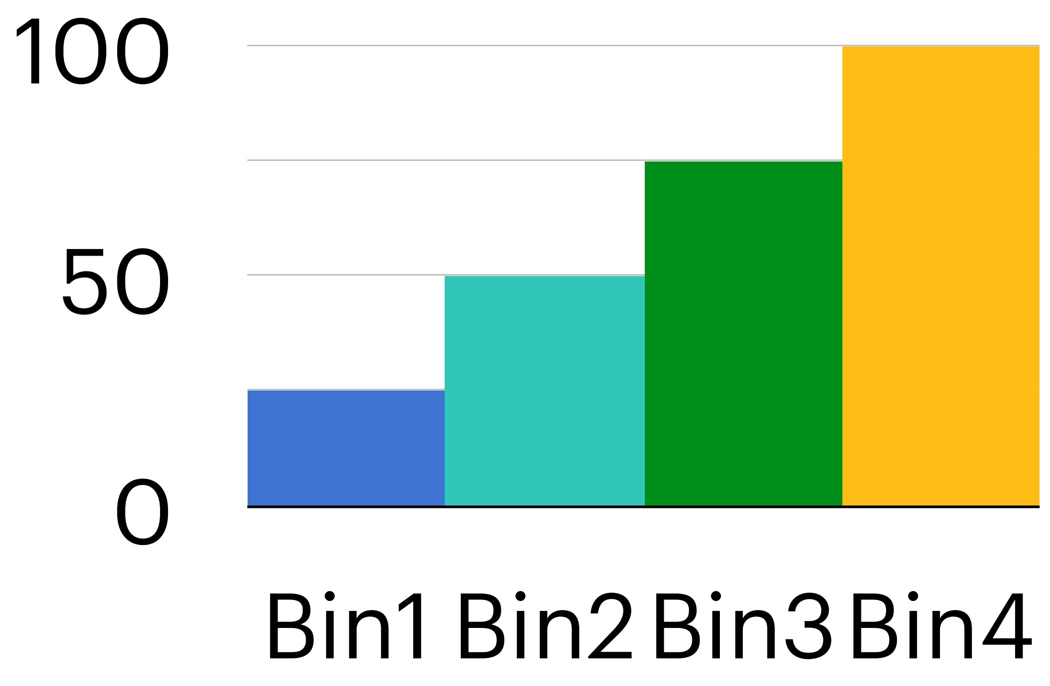
Parton level using Asimov Data

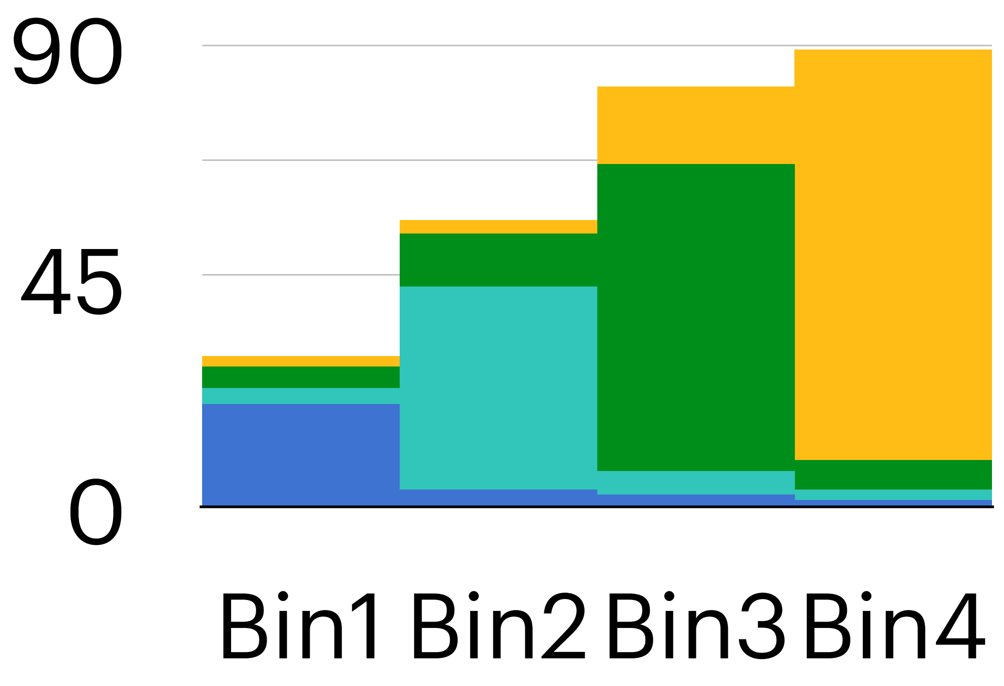
Profile Likelihood Unfolding

Truth Level Distribution



The true physics distribution

Detector Level Distribution



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Correct for detector effects via a profile likelihood unfolding.
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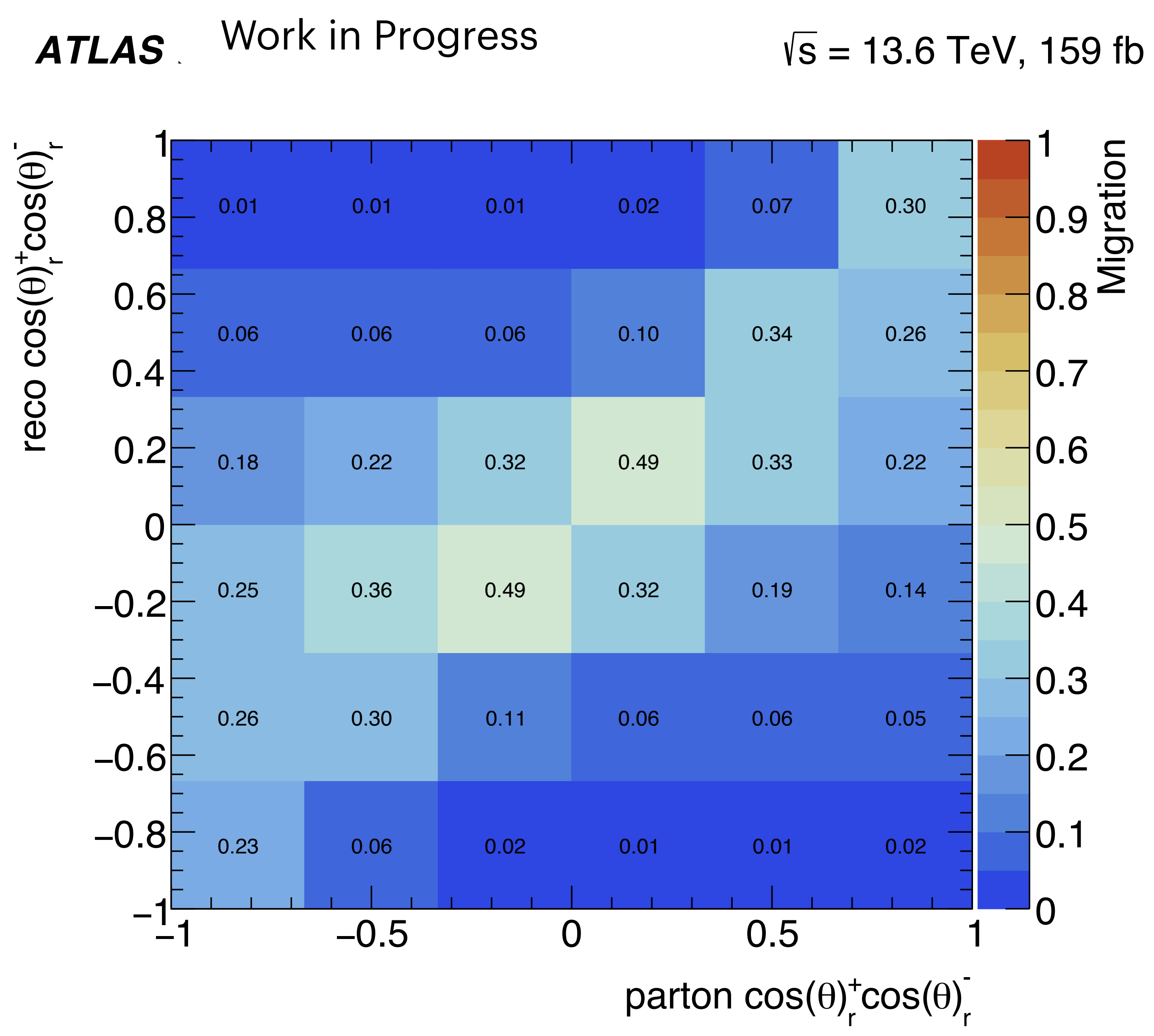
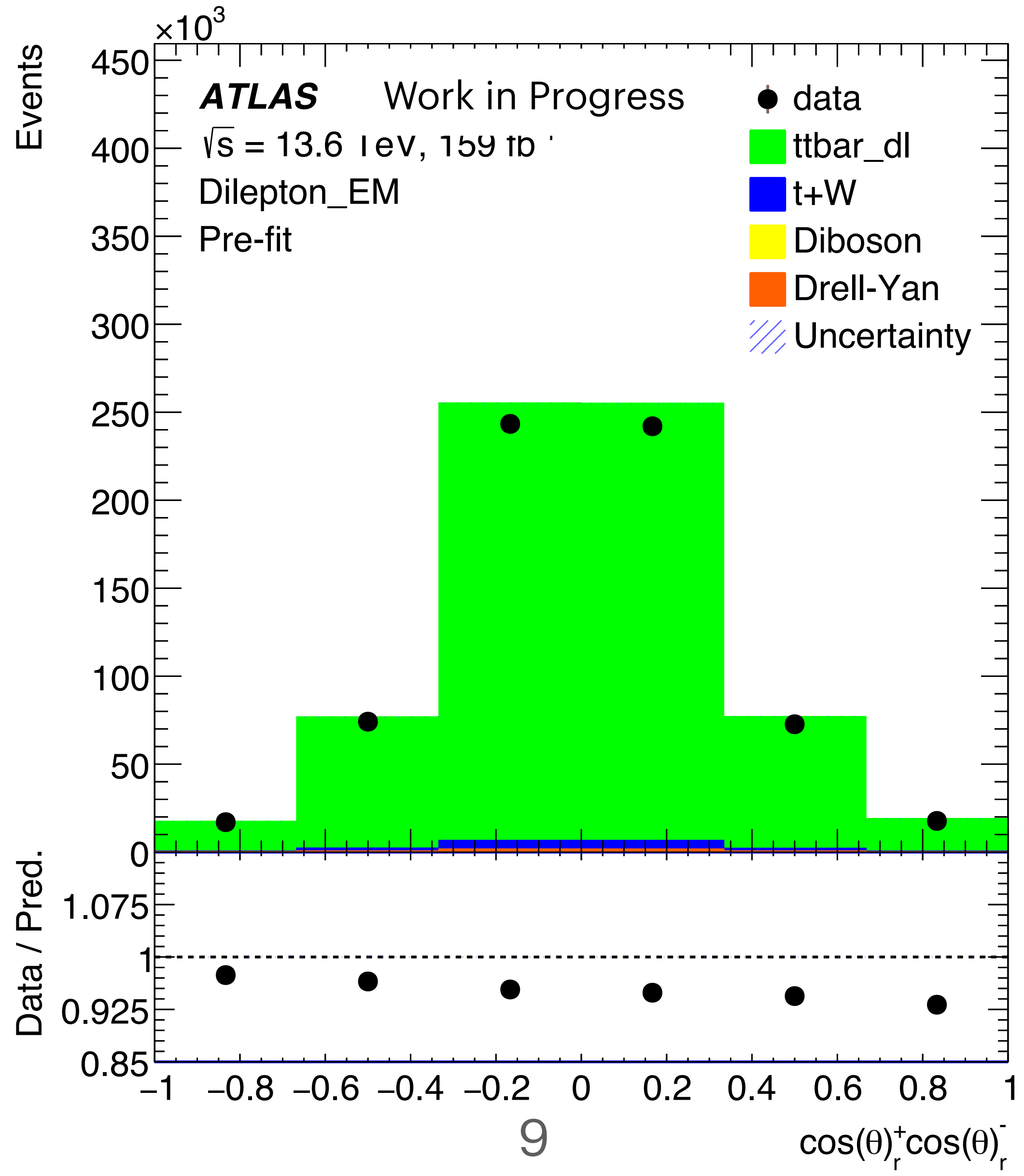
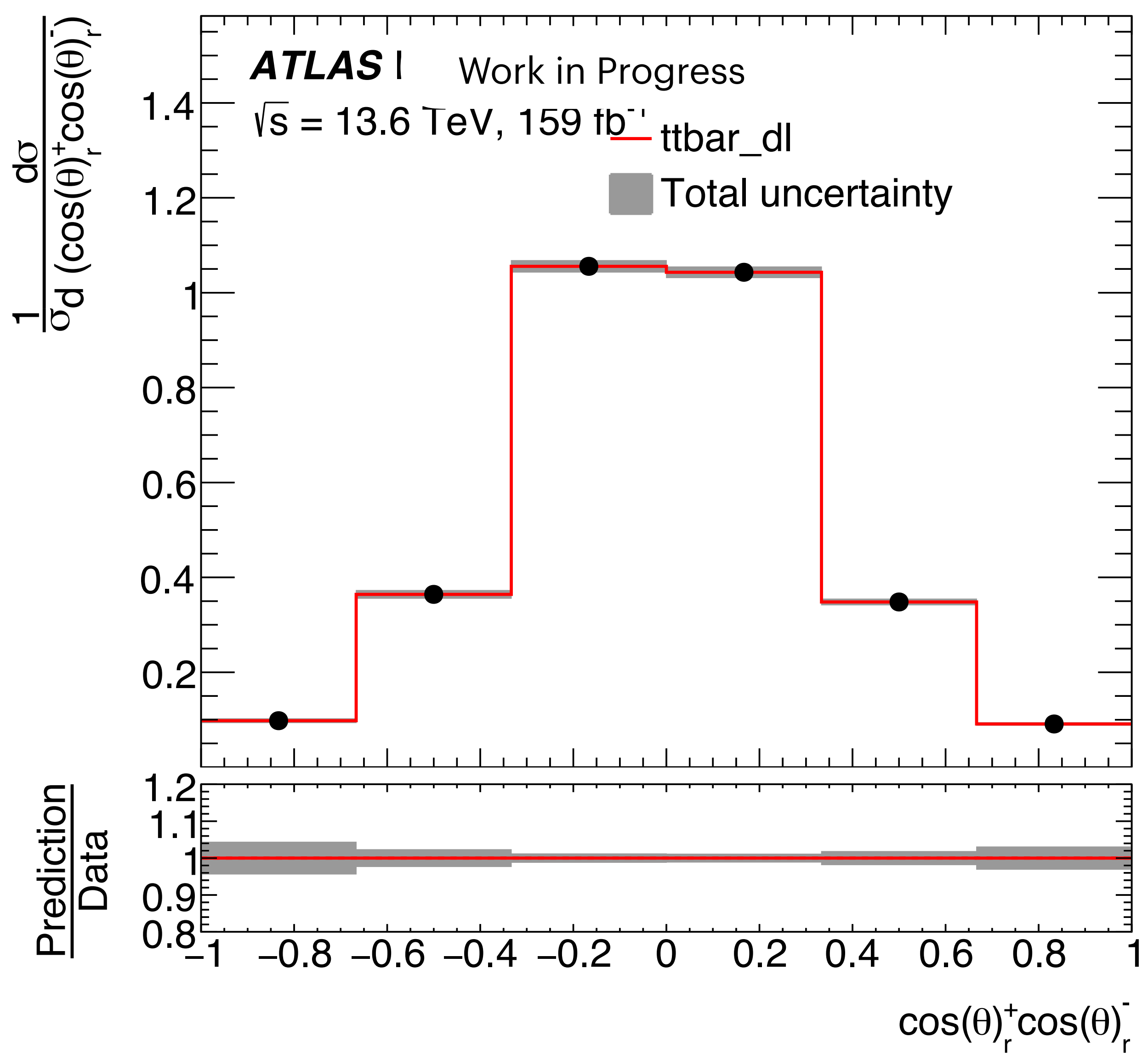
Migration Matrix



Reconstruction Plot



Normalised Cross Section



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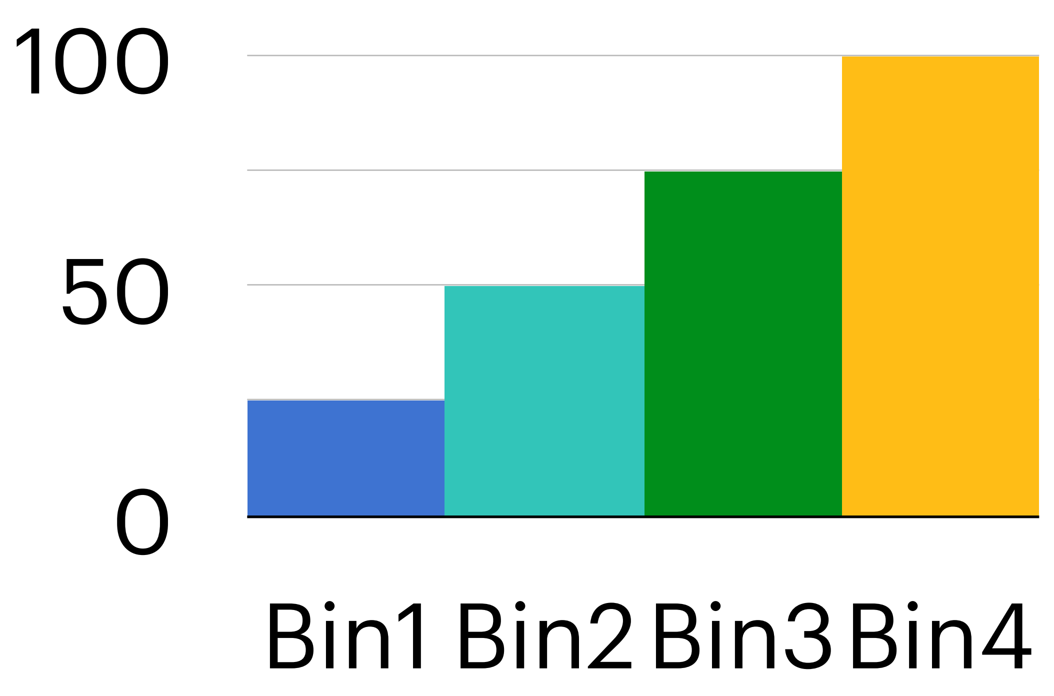
Parton level using Asimov Data

Profile Likelihood Unfolding

Truth Level Distribution



The true physics distribution

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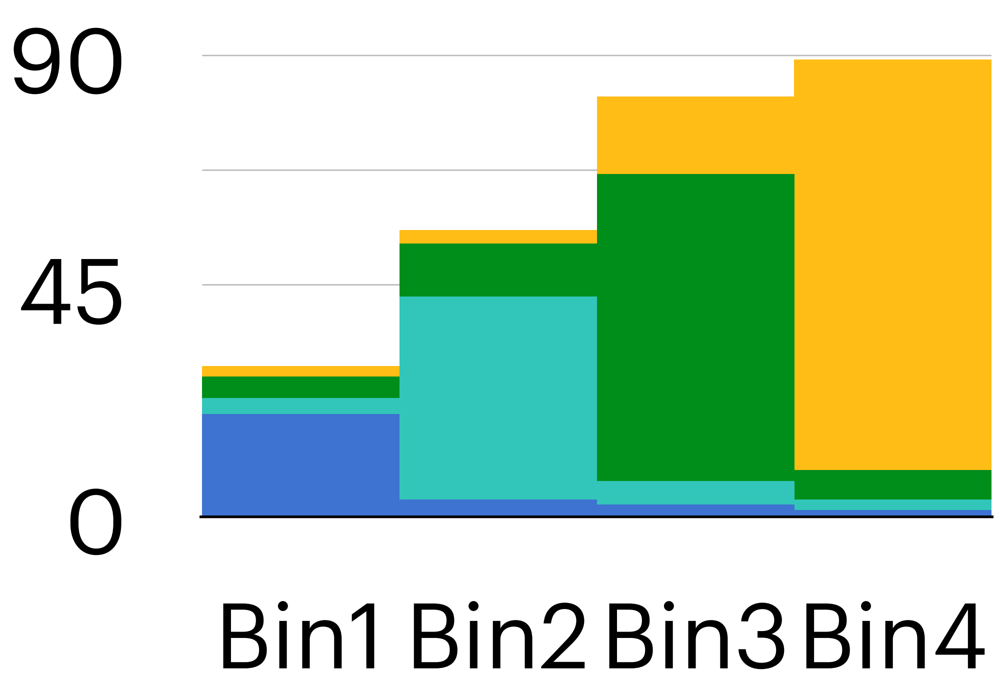
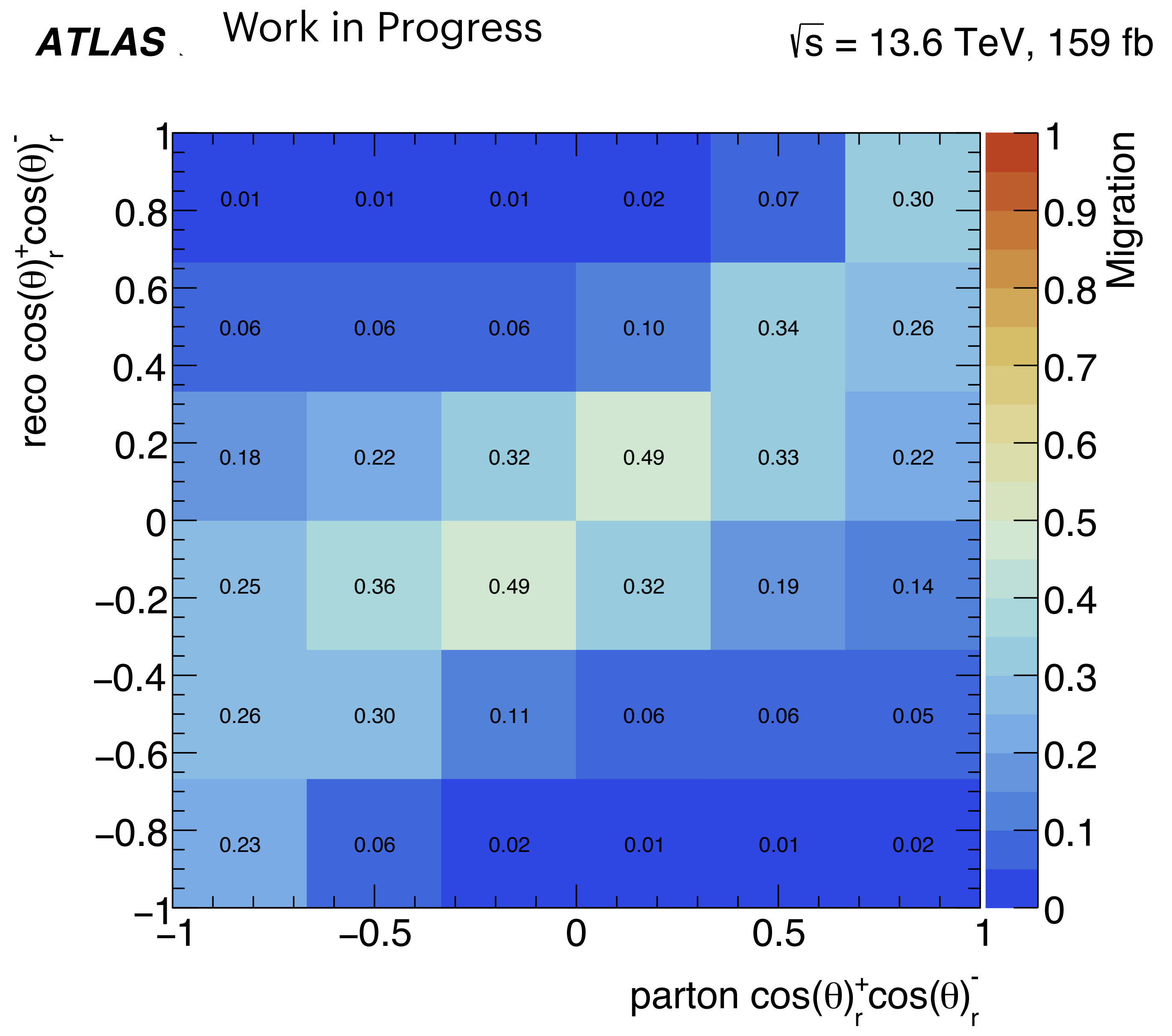


What the detector “sees”

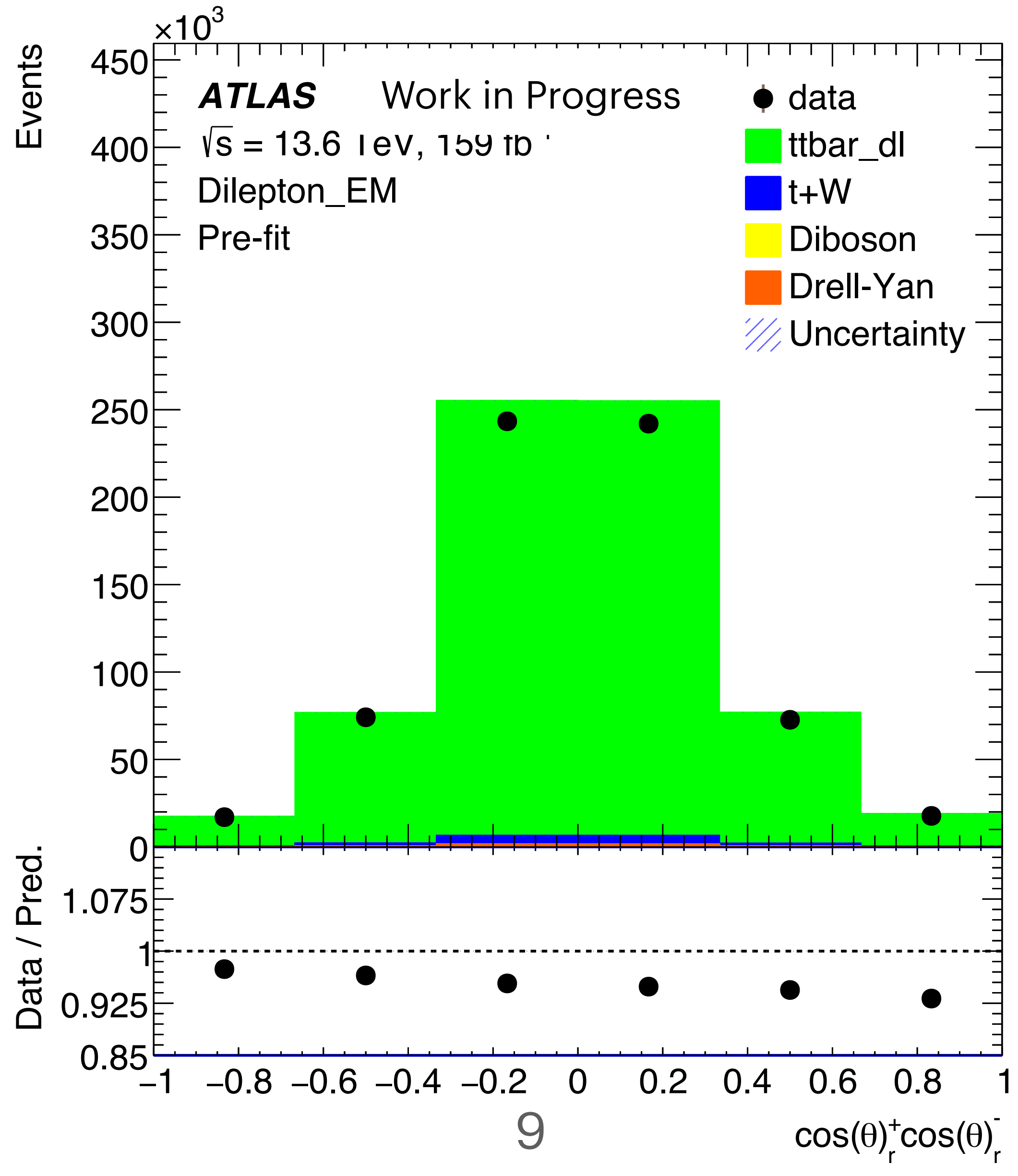
Correct for detector effects via a profile likelihood unfolding.
Implementing PLU to measure cross section
The values of the SDM coefficients are obtained from the mean of the distribution:

$$Cij = -9\frac{\sum Yield \times BinCenter}{\sum Yield}$$

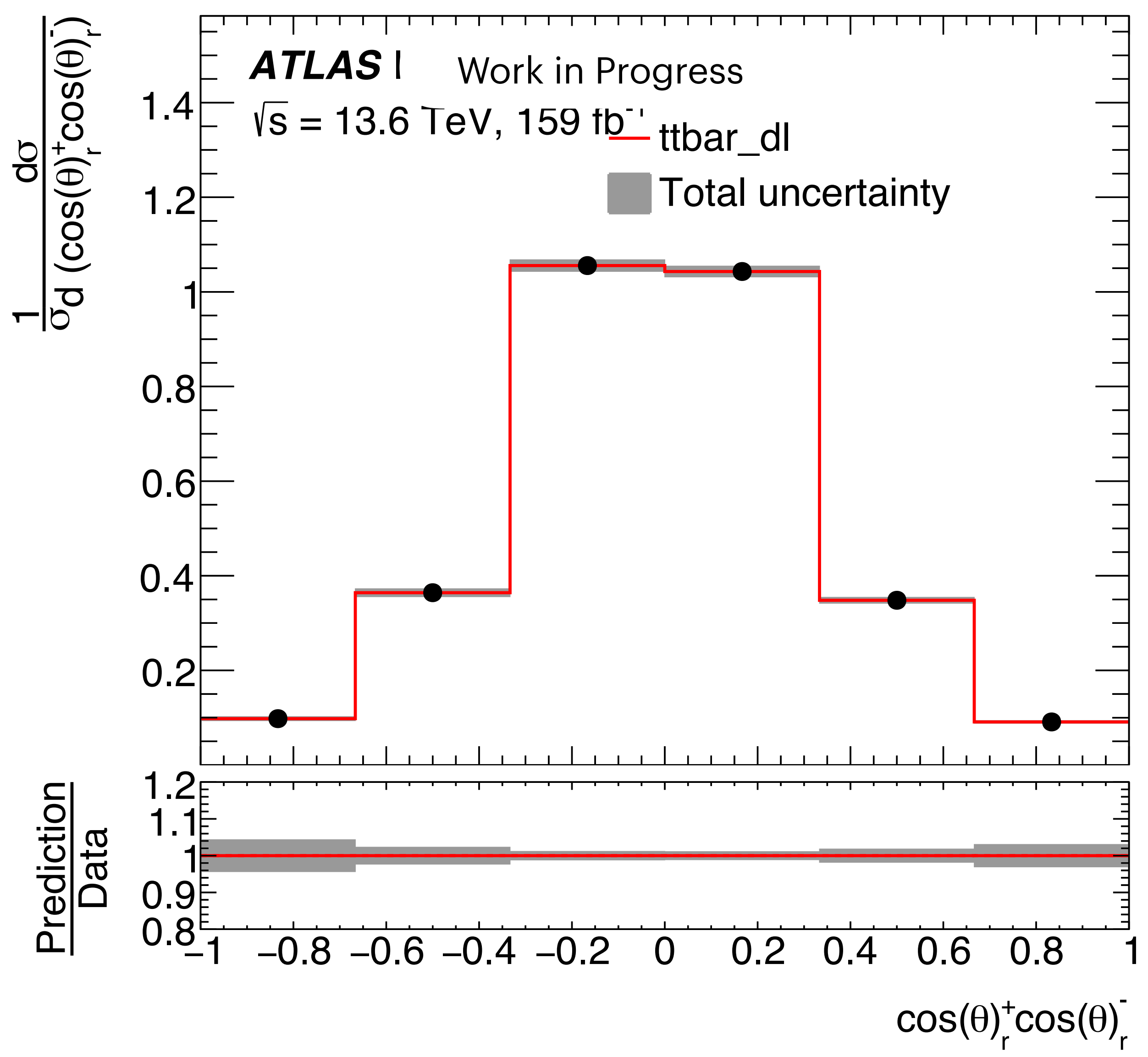
Migration Matrix



Reconstruction Plot



Normalised Cross Section



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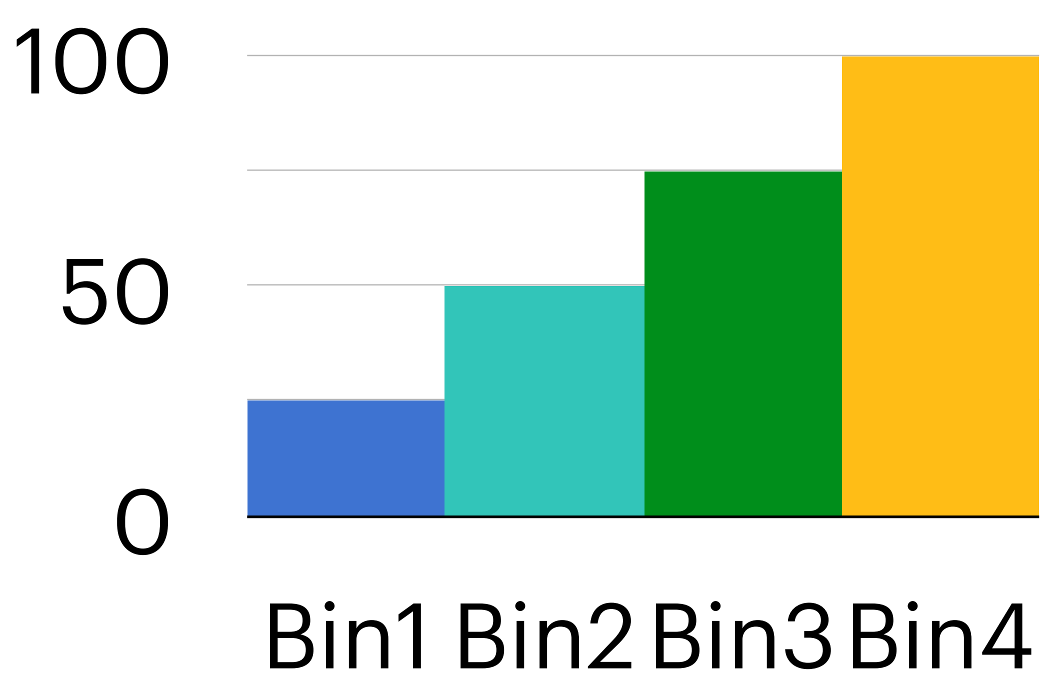
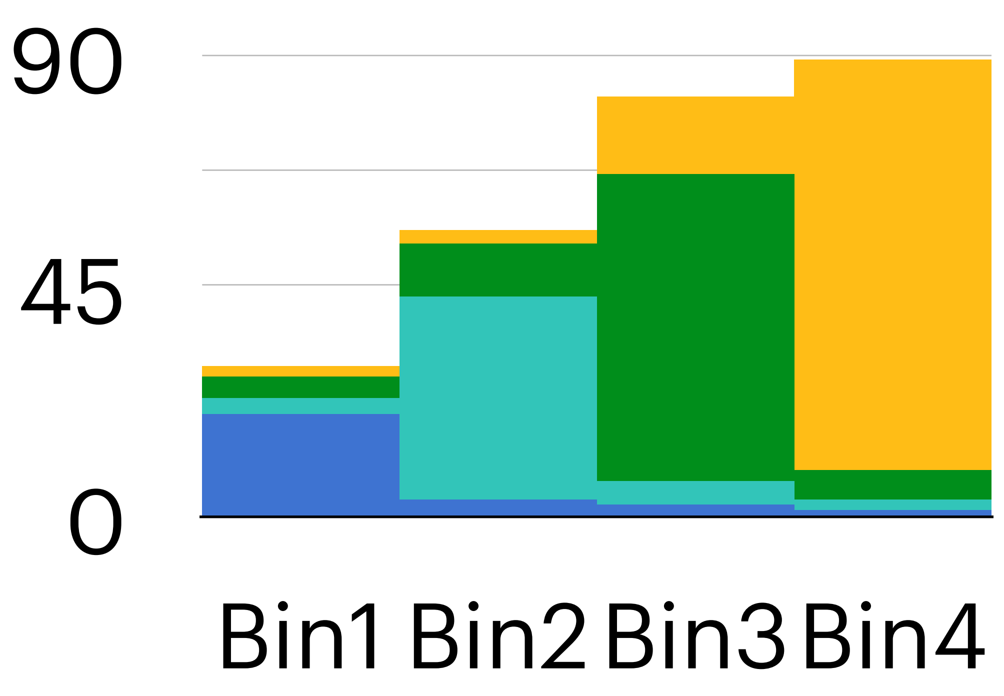
Extraction of the coefficient via Reparametrization

Truth Level Distribution



The true physics distribution

Detector Level Distribution

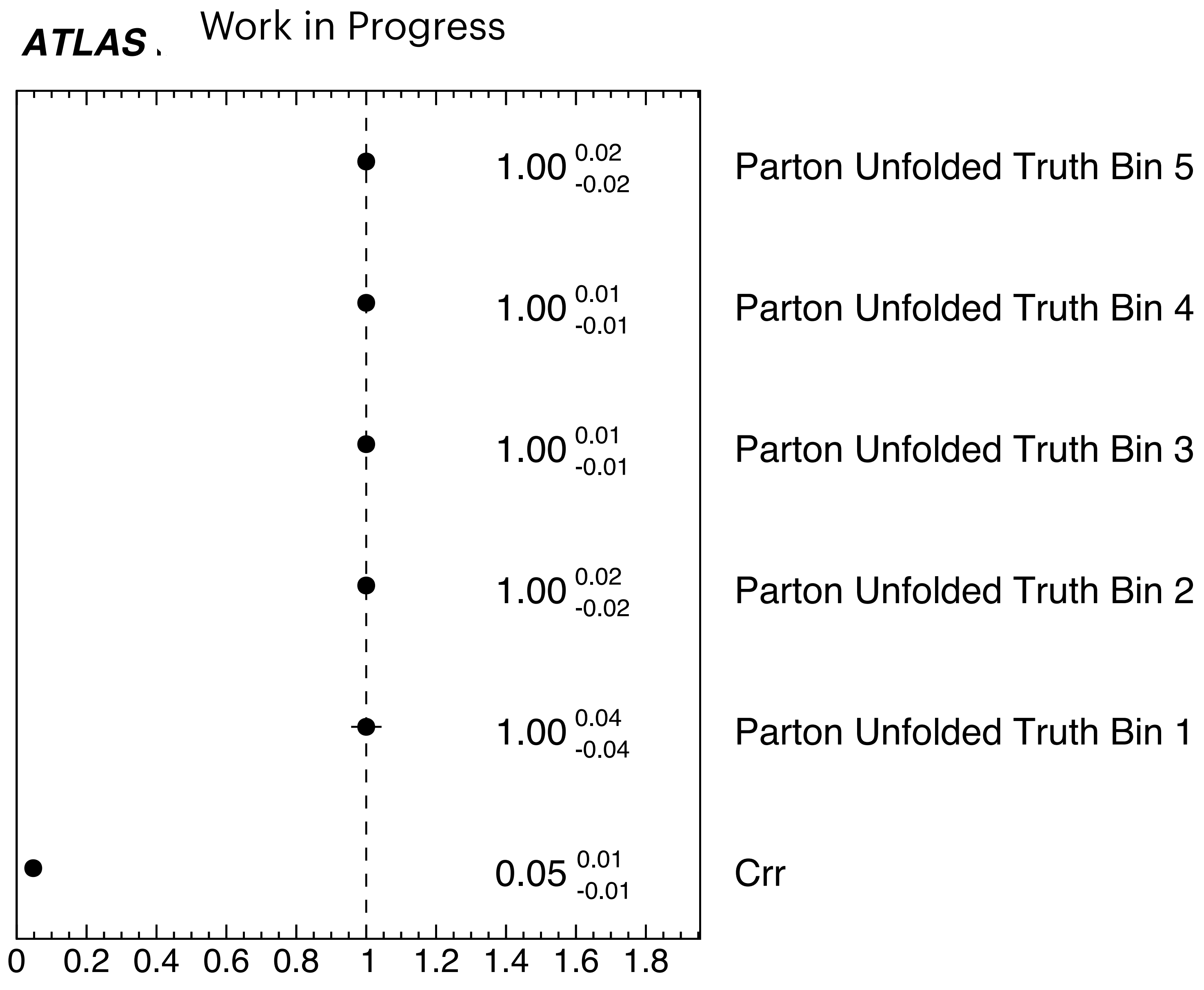


What the detector "sees"

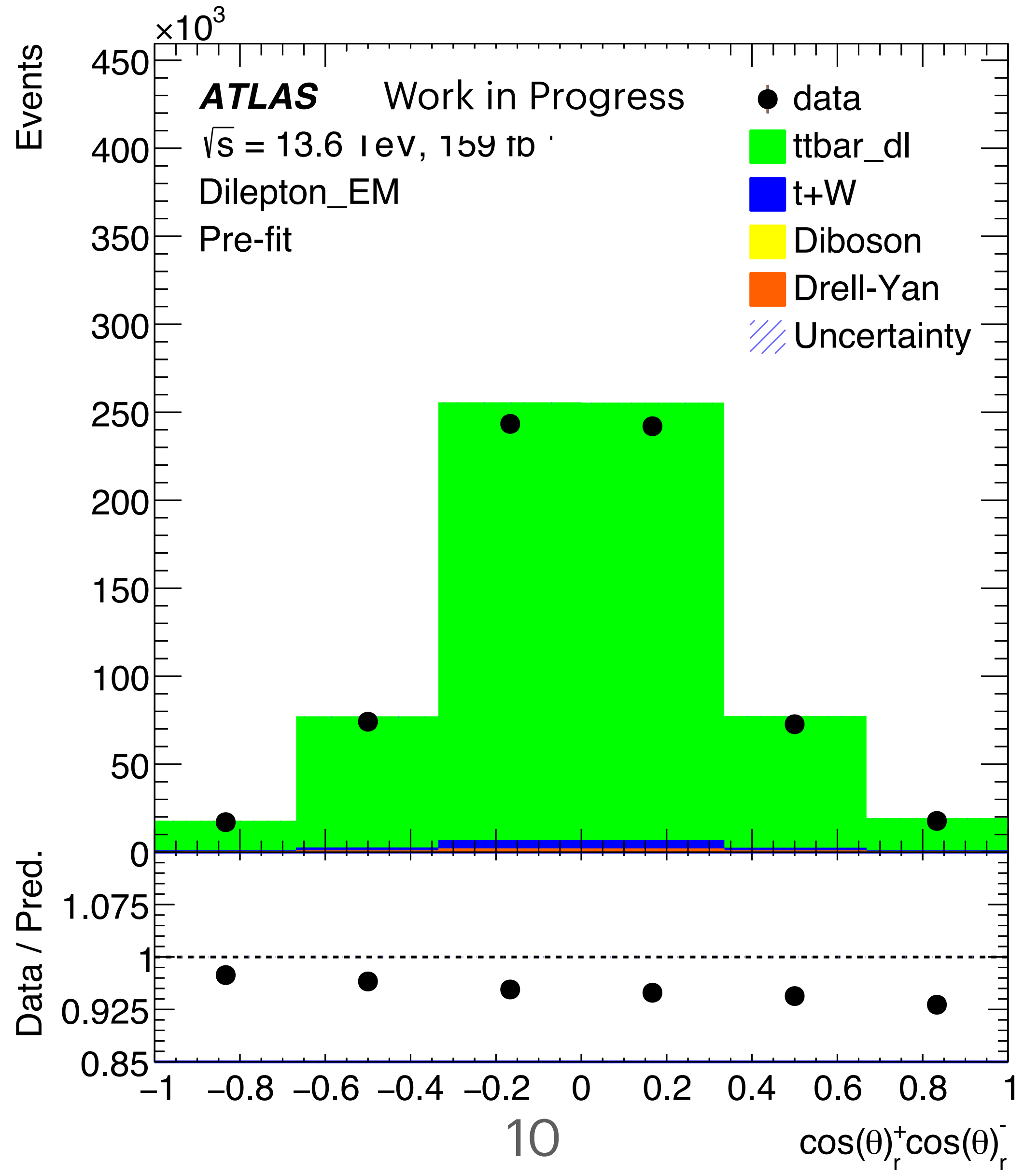
Alternative: Extract the coefficients directly when measuring the cross section by using one of the bins as a Parameter of Interest in terms of the value of the coefficient and the other bins

$$N_4 = f(Cij, N_1, N_2, N_3)$$

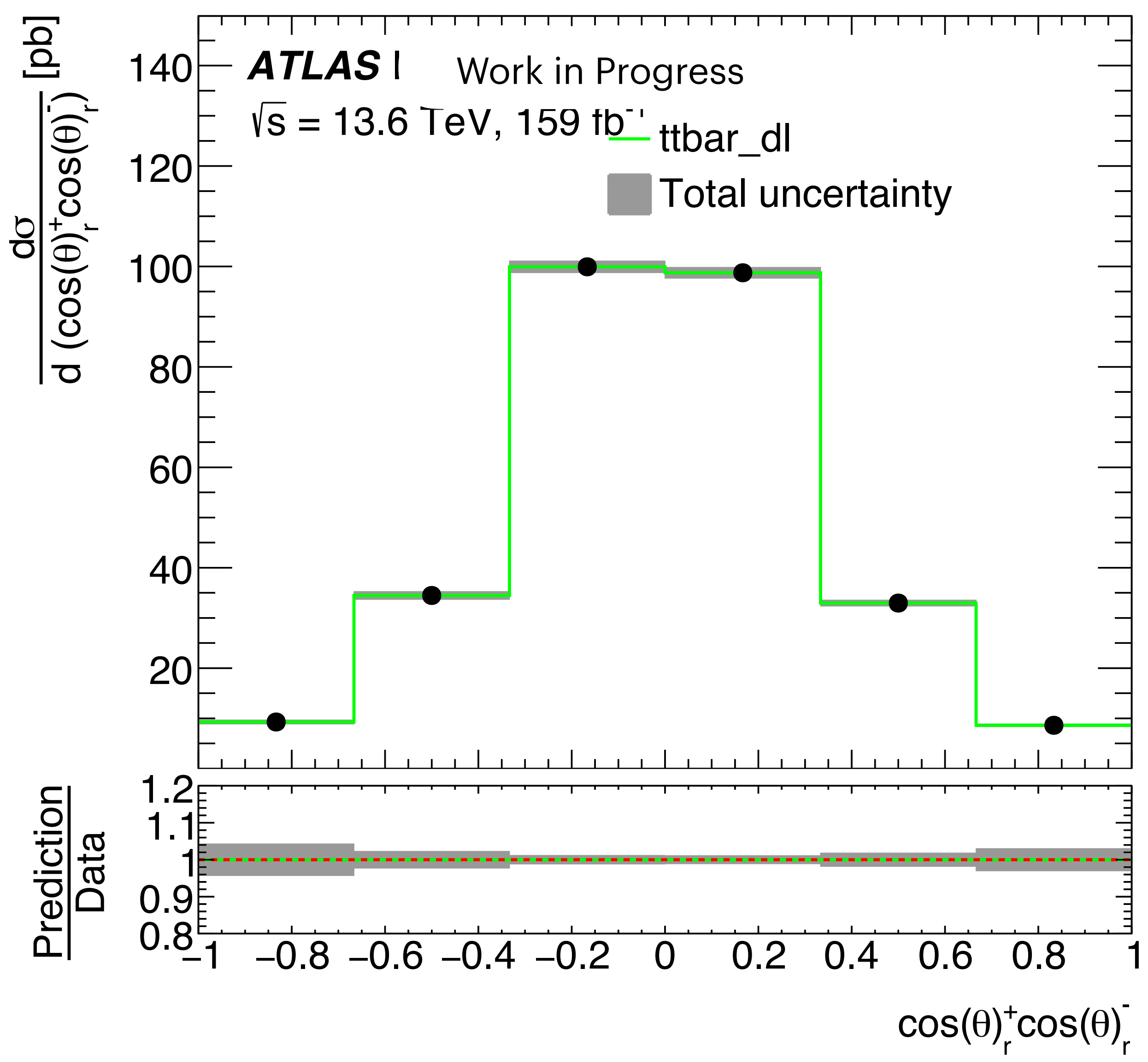
Normalisation Factors



Reconstruction Plot



Absolute Cross Section



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NO SYS

SDM Coefficient closure test

	Measured in Asimov	MC
Ckk	0.3149 +/- 0.0083	0.314886
Cnn	0.3164 +/- 0.0051	0.316386
Crr	0.0475 +/- 0.0094	0.047460
Ckr+Crk	-0.201 +/- 0.014	-0.200904
Ckr-Crk	0.001 +/- 0.015	0.000656
Ckn+Cnk	0.000 +/- 0.014	0.000316
Ckn-Cnk	0.000 +/- 0.011	-0.000025
Cnr+Crn	0.000 +/- 0.014	-0.000191
Cnr-Crn	0.000 +/- 0.015	-0.000039

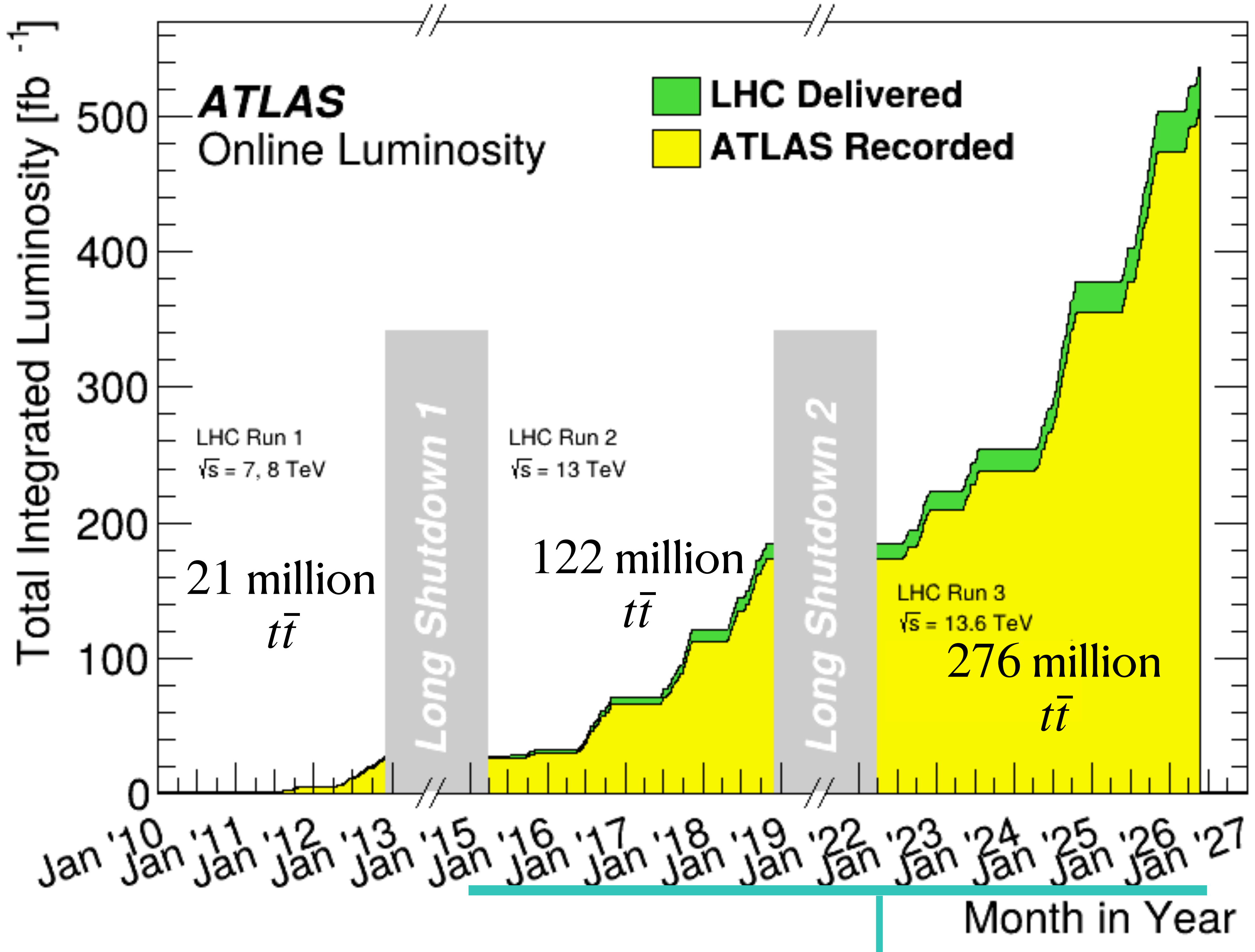
Summary

Presented:

- ☑ All SDM coefficients calculated with no systematic uncertainties
- ☑ Closure obtained: Asimov results agree with Monte Carlo expectation

Next:

- ☐ Binning is not optimised yet
- ☐ Still need to add the systematic uncertainties to have a full picture
- ☐ Extend the analysis to Run 2 data



ATLAS measurement using more data than ever before

Vielen Dank

Back up

$t\bar{t}$: Event Selection and Reconstruction

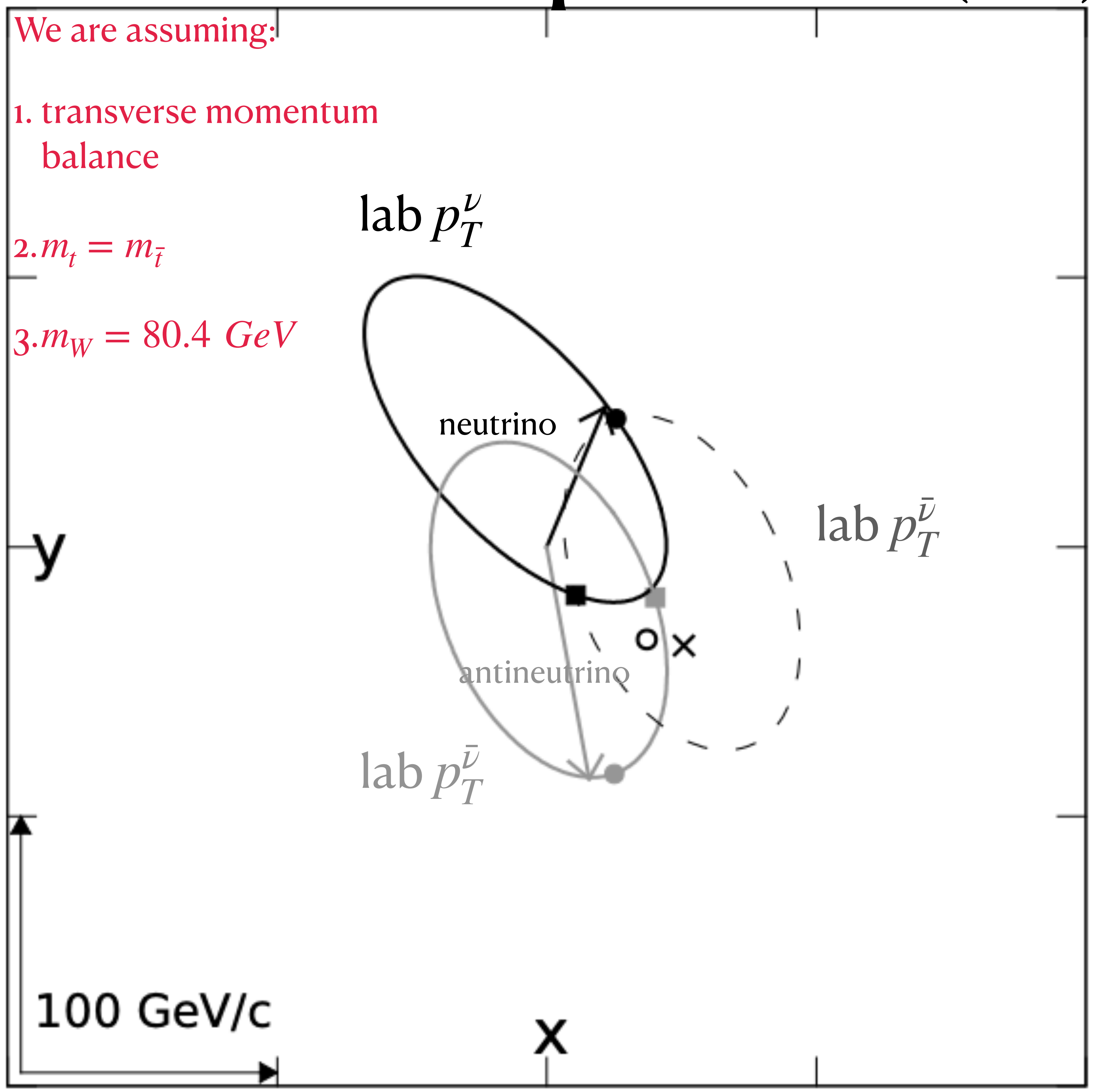
- Using the ATLAS Run 3 data (159 fb^{-1}) here but the goal is to use both Run 2 and Run 3
- Focusing on the dilepton decay channel (ee, $\mu\mu$, $e\mu$)
  - Small branching ratio
  - Very good signal to background ratio

Selection Criteria

- 2 high p_T and isolated leptons
- ≥ 2 b-tagged jets
- Veto in invariant mass (Z-boson mass) in ee, $\mu\mu$ channels

- The presence of two neutrinos in the final state causes $t\bar{t}$ kinematic reconstruction to be underconstrained
- $t\bar{t}$ reconstruction = solving the neutrino equations
- Analytically calculate two ellipses for neutrino momenta and find intersections

Ellipse Method (EM)



arXiv:1305.1878 [hep-ph]

Systematic Uncertainties to take into account

Object Uncertainties:

- Trigger and Lepton
- Jet energy scale/resolution
- Flavour tagging
- Pileup
- Luminosity
- Missing Transverse Energy (MET)

$t\bar{t}$ Uncertainties

- Renormalization scale μ_R, Factorization scale μ_F, Parton Density Functions
- hdamp variations (regulates first high-p_T emission)
- Recoil scheme (probes uncertainties in how the shower conserves energy–momentum)
- Shower veto region (pThard)
- Top mass variation
- Initial State Radiation (ISR) and Final State Radiation (FSR) effects
- Dipole vs angular order parton showers (Pythia8 vs Herwig7)
- Lineshape ($m_{t\bar{t}}$)

Background modelling Uncertainties

- $tW - t\bar{t}$ interference modelling
  - shape uncertainty estimated by comparing samples generated with the **Diagram Removal (DR)** scheme (nominal) and the alternative **Diagram Subtraction (DS)** scheme to account for overlap with $t\bar{t}$ production
- Other background samples
  - Drell-Yan, Diboson