Precision measurement in the Top quark sector using Effective Field Theory and entanglement and violation of Bell inequalities at LHC

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Top LHC France

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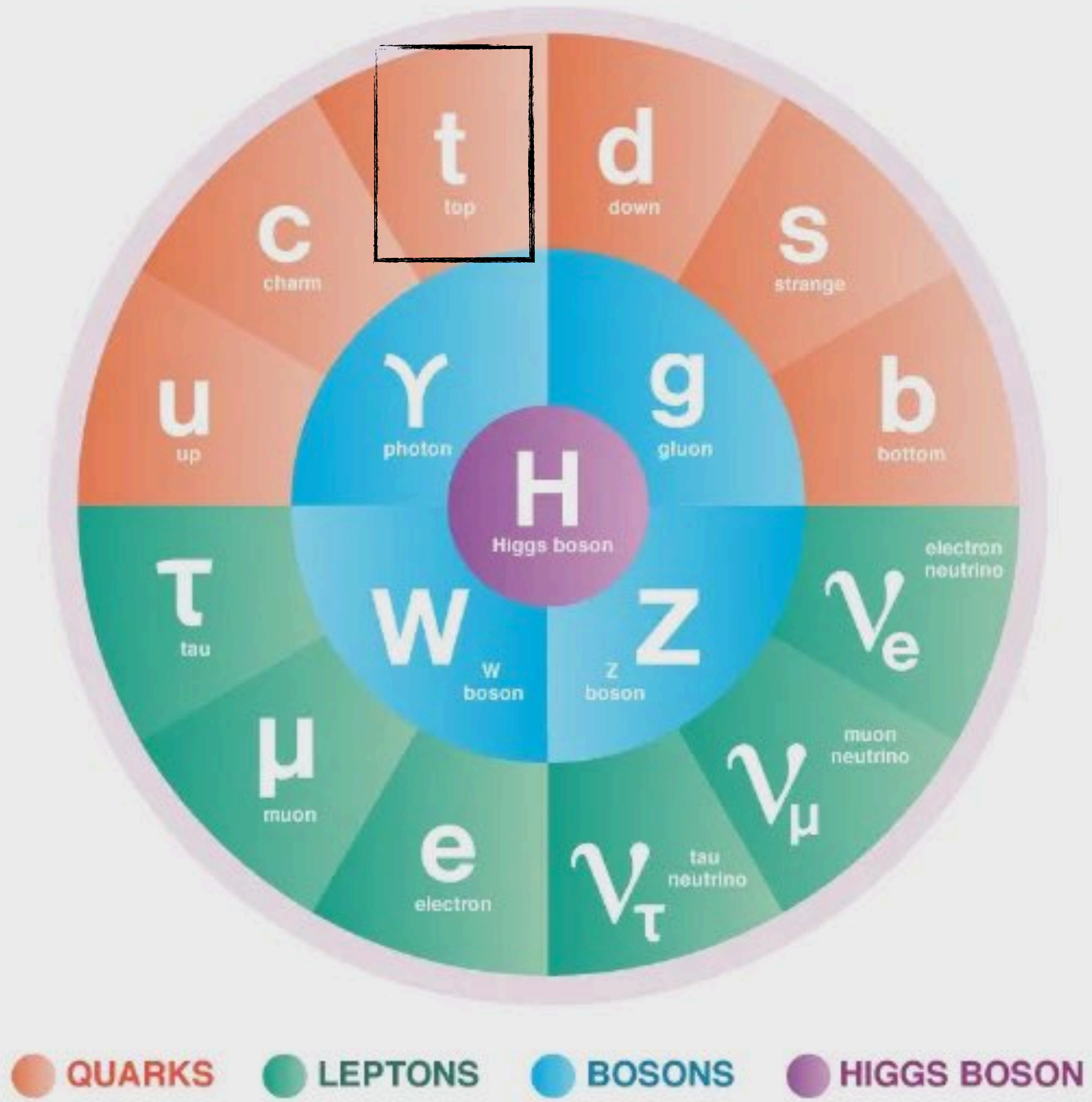
The Standard Model of Particle Physics

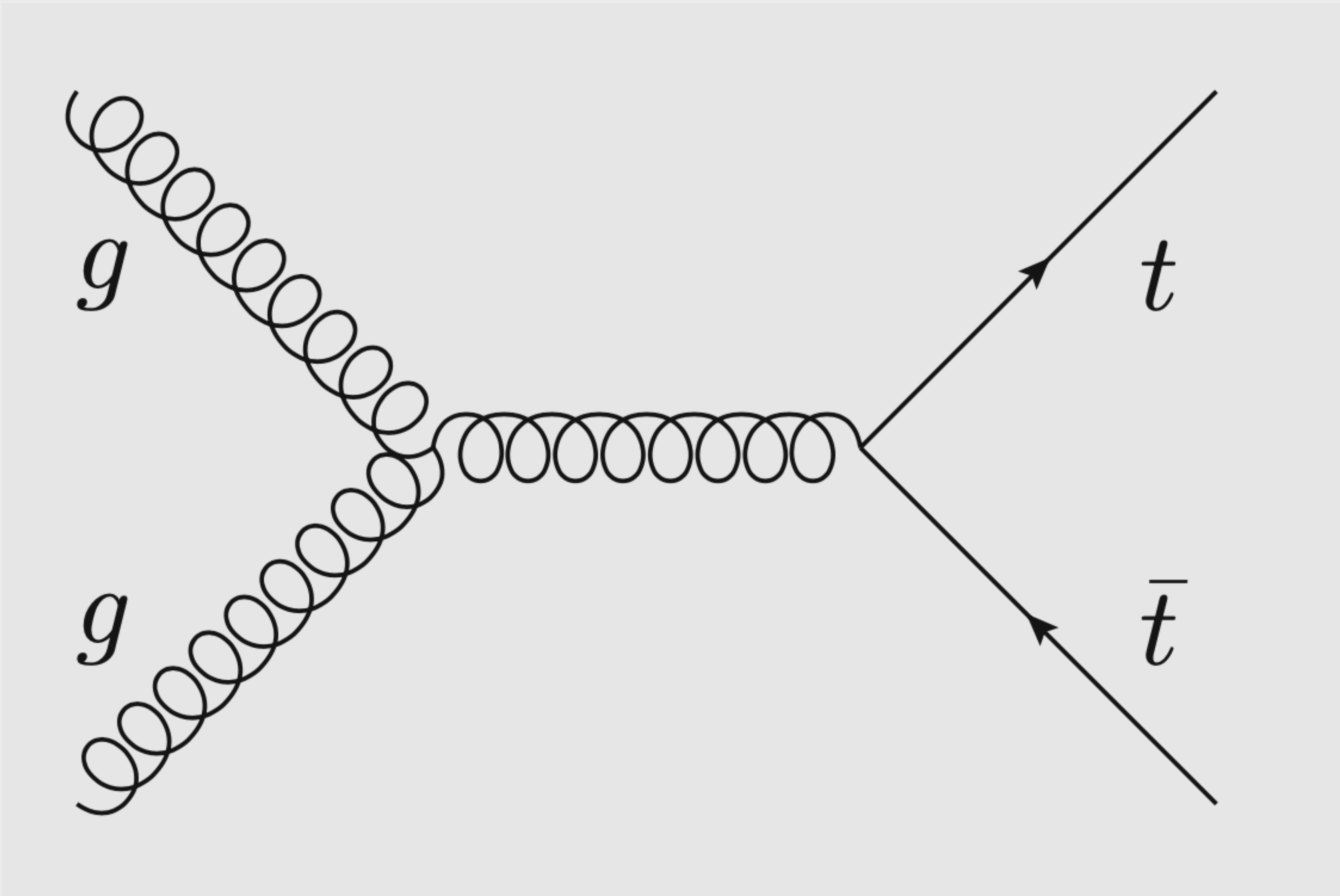


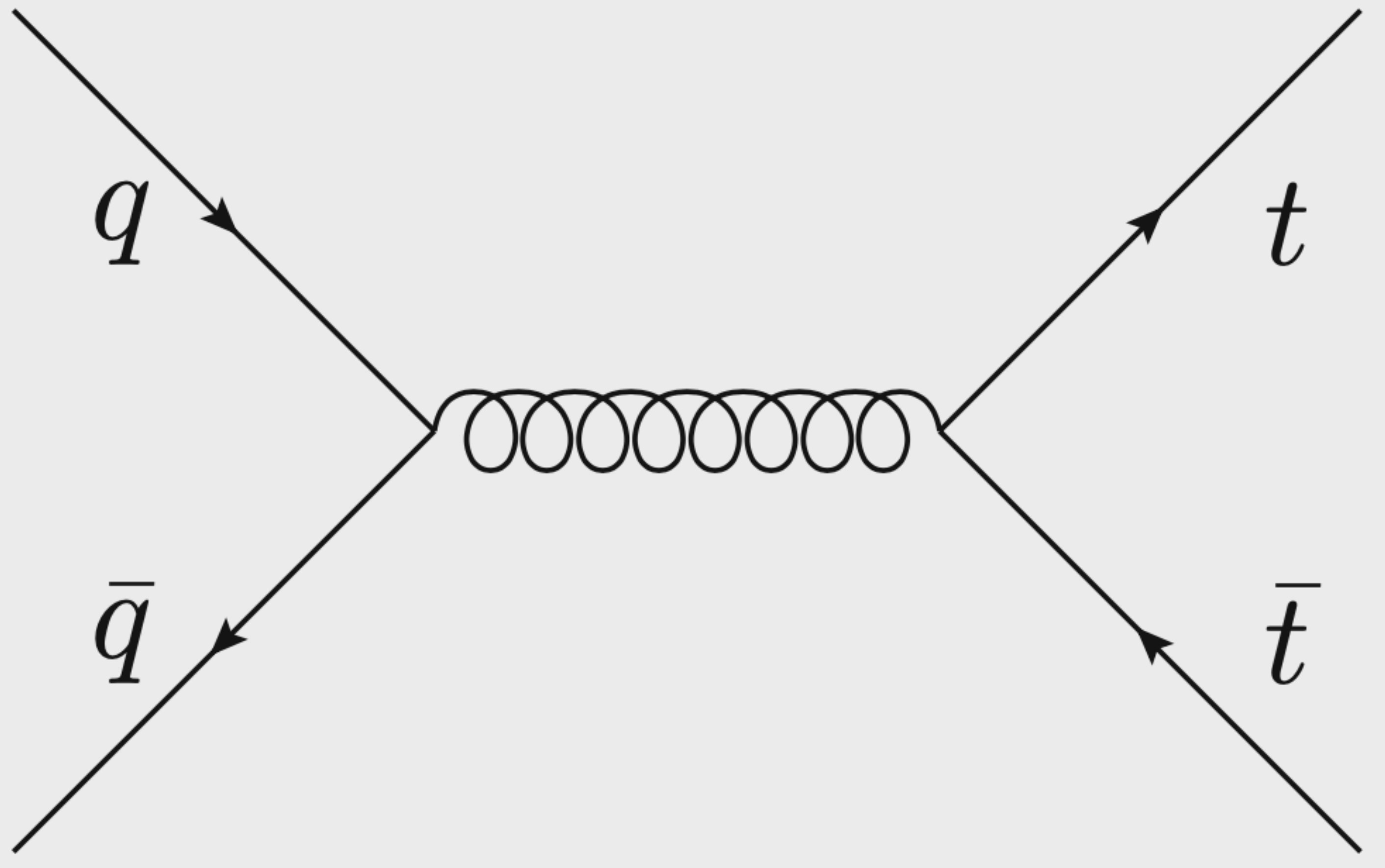
lifetime	<	QCD timescale	≪	spin-flip timescale
10^{-25} s	<	10^{-24} s	≪	10^{-21} s

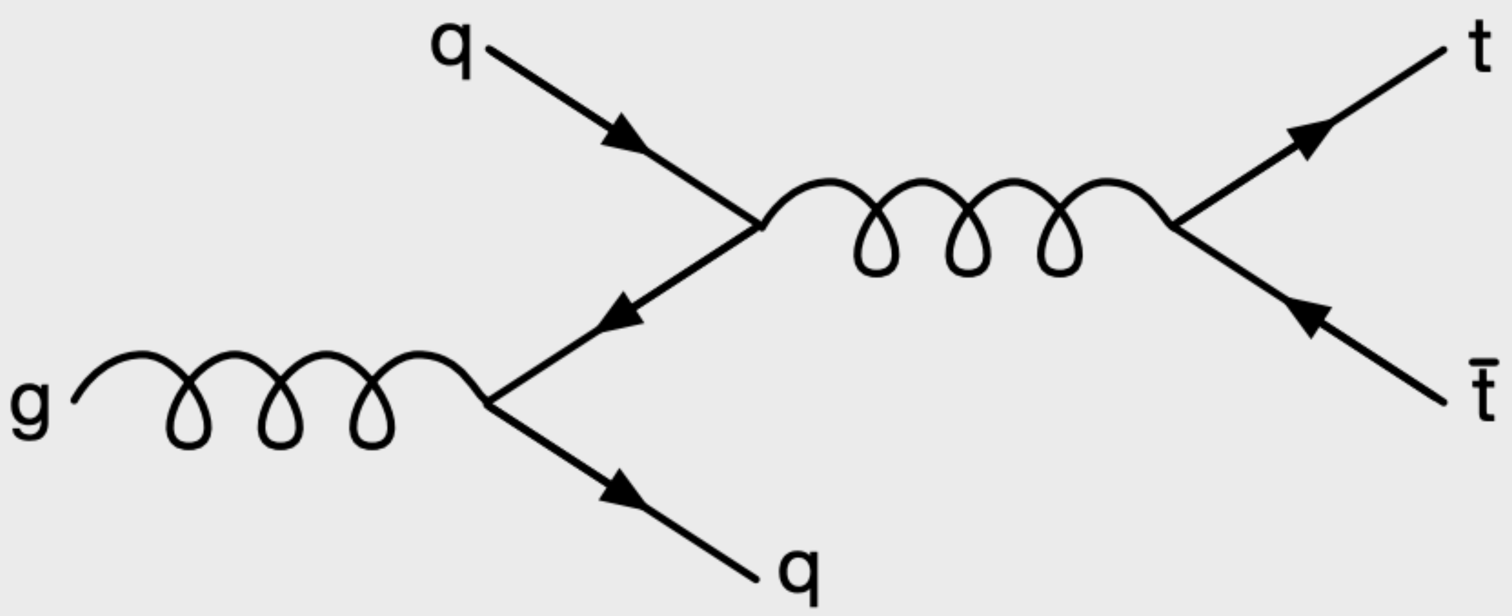
- Top Decays before it can form bound states:
  - Unique opportunity to study the spin information of top quark.

Top Quark pair production at LHC

◉ Top quark-antiquark pairs ($t\bar{t}$) produced via strong interaction





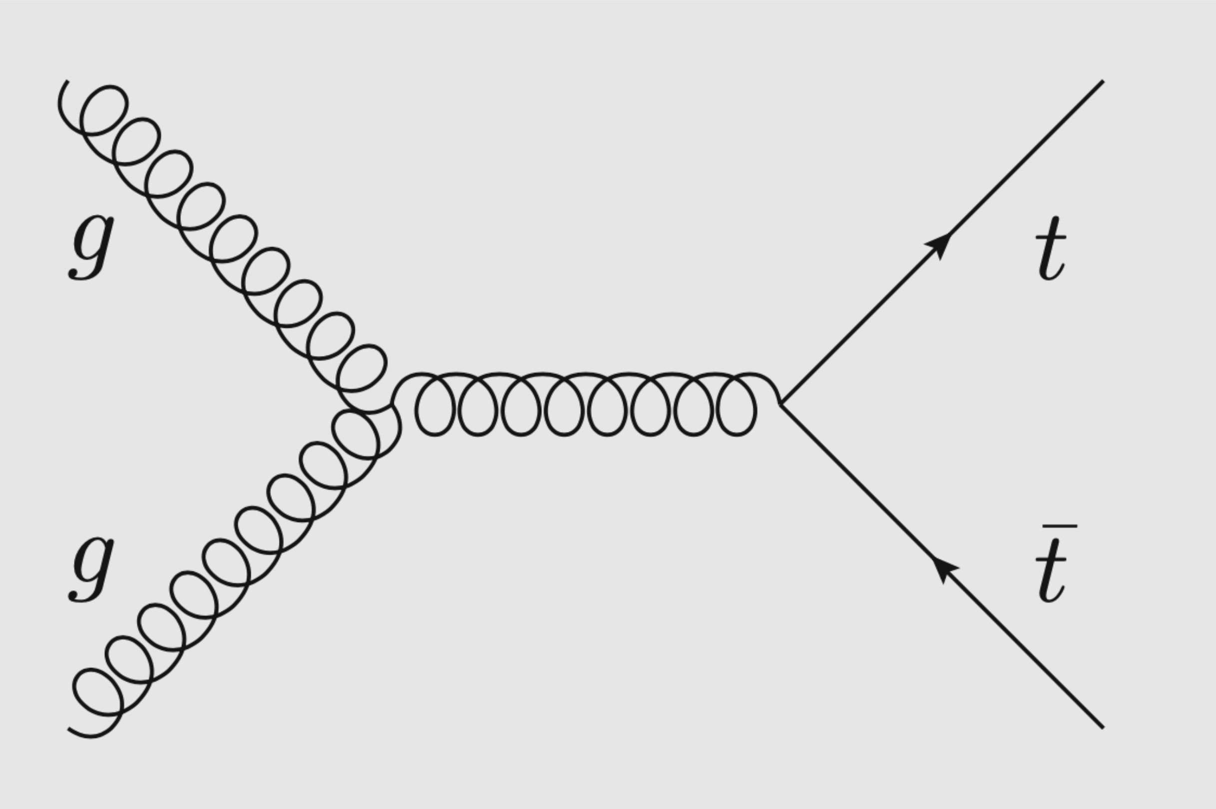


◉ gluon fusion ≈ 90%

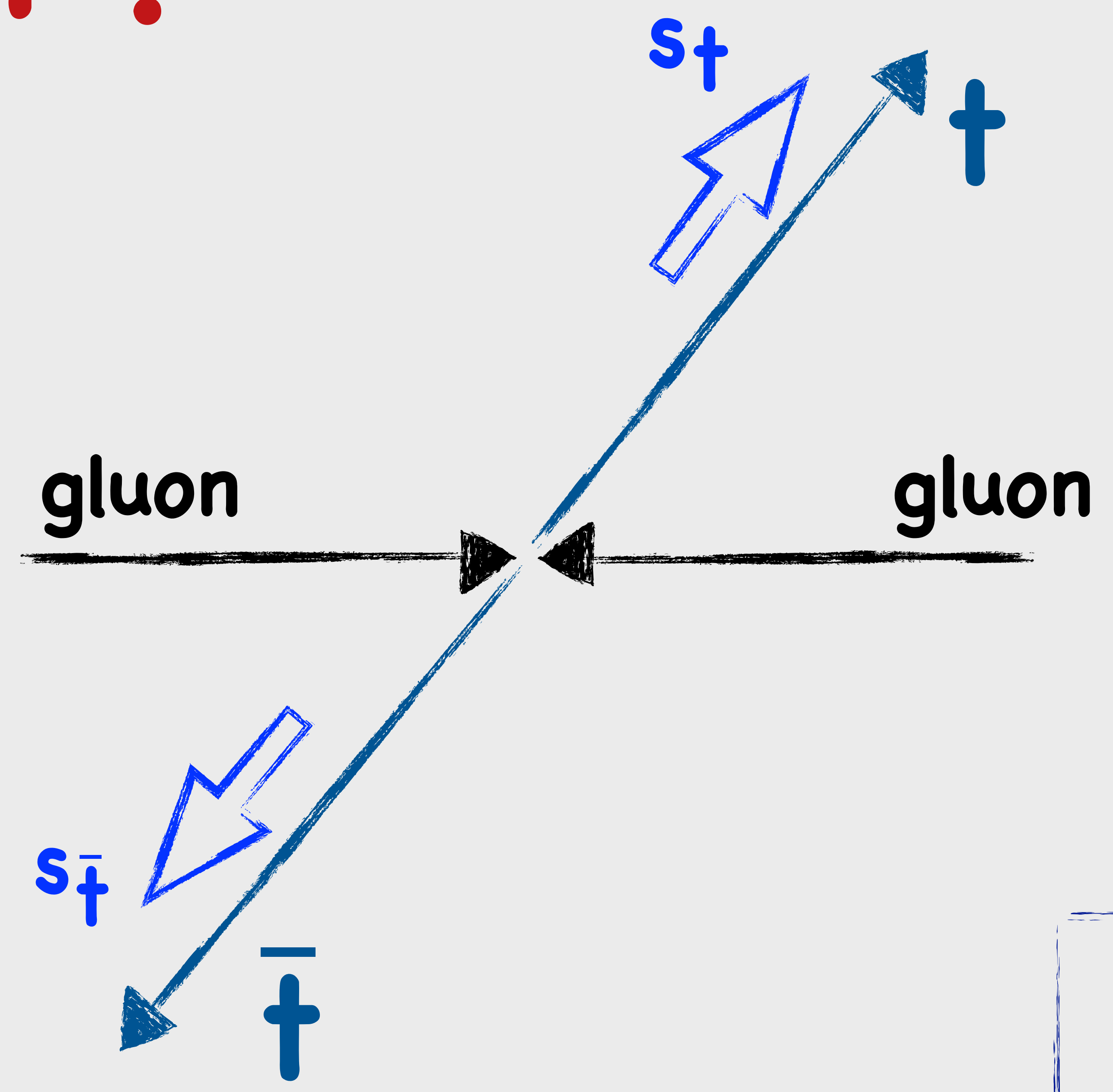
◉ $q\bar{q}$ annihilation ≈ 8%

◉ qg ≈ 2%

What is spin correlation ?

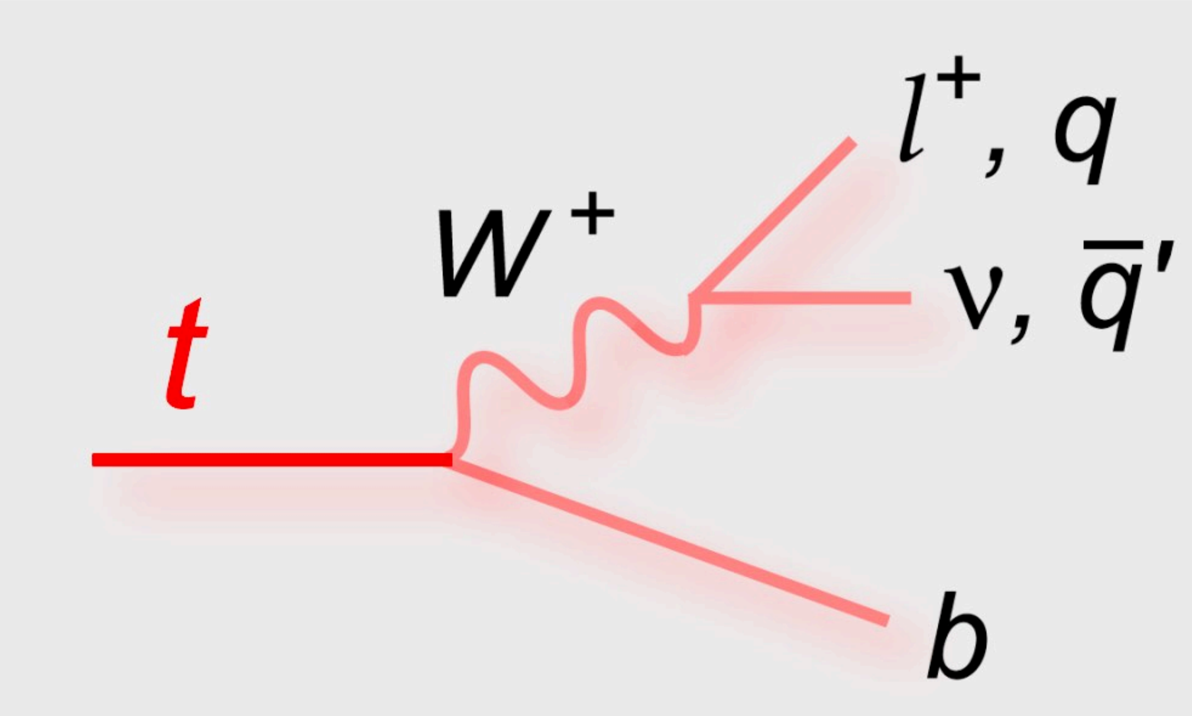


Centre Mass Frame



Can we measure spin correlations between top and anti-top ?

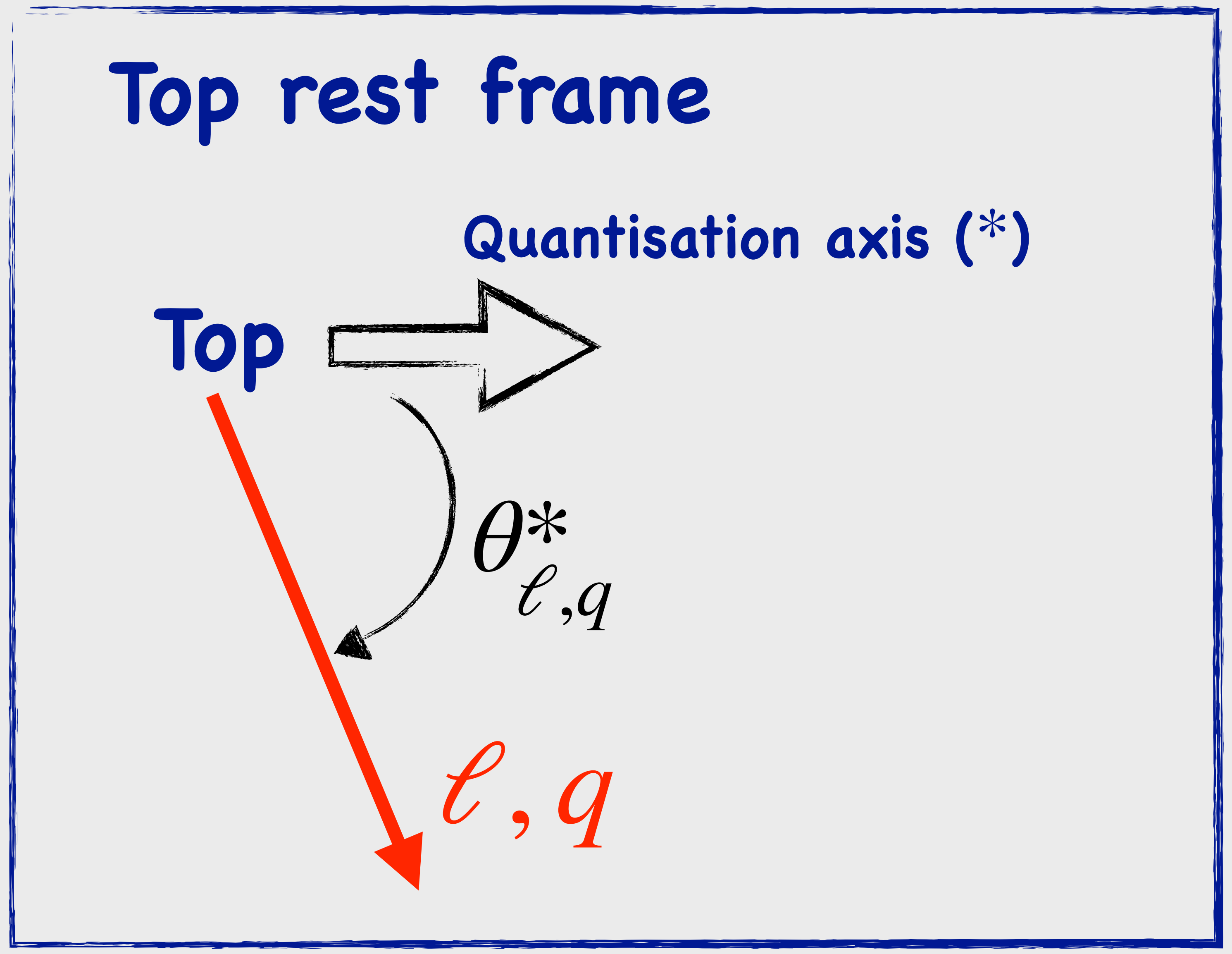
lifetime	$<$	QCD timescale	$\ll$	spin-flip timescale
$10^{-25}\,\mathrm{s}$	$<$	$10^{-24}\,\mathrm{s}$	$\ll$	$10^{-21}\,\mathrm{s}$



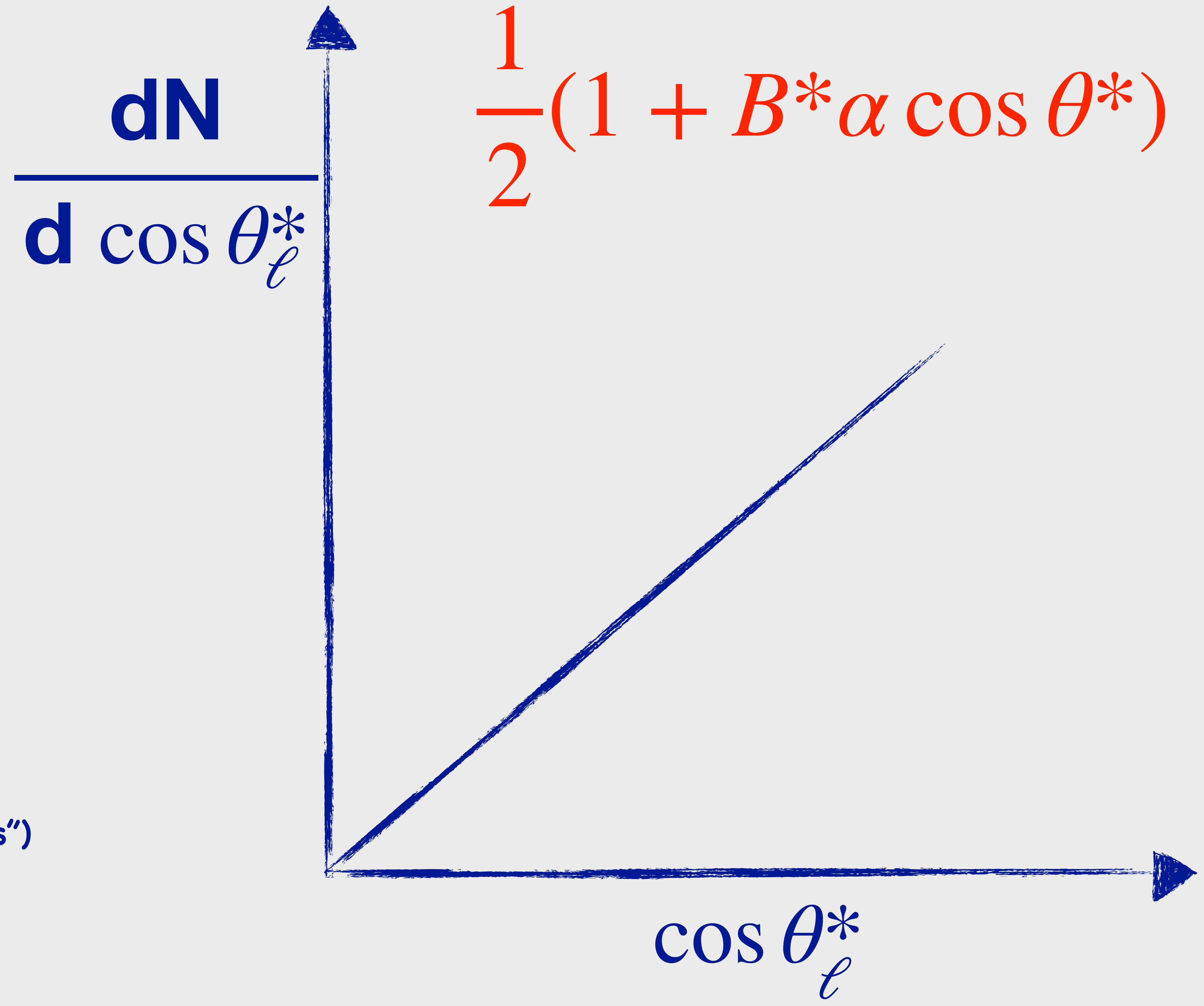
Spin information transferred to daughter particles

Spin analysis power α

◉ α **measures how well a given daughter probes the spin of its parent**



$\theta^*_{\ell,q}$ measured in top rest frame relative to boost direction ("helicity basis")

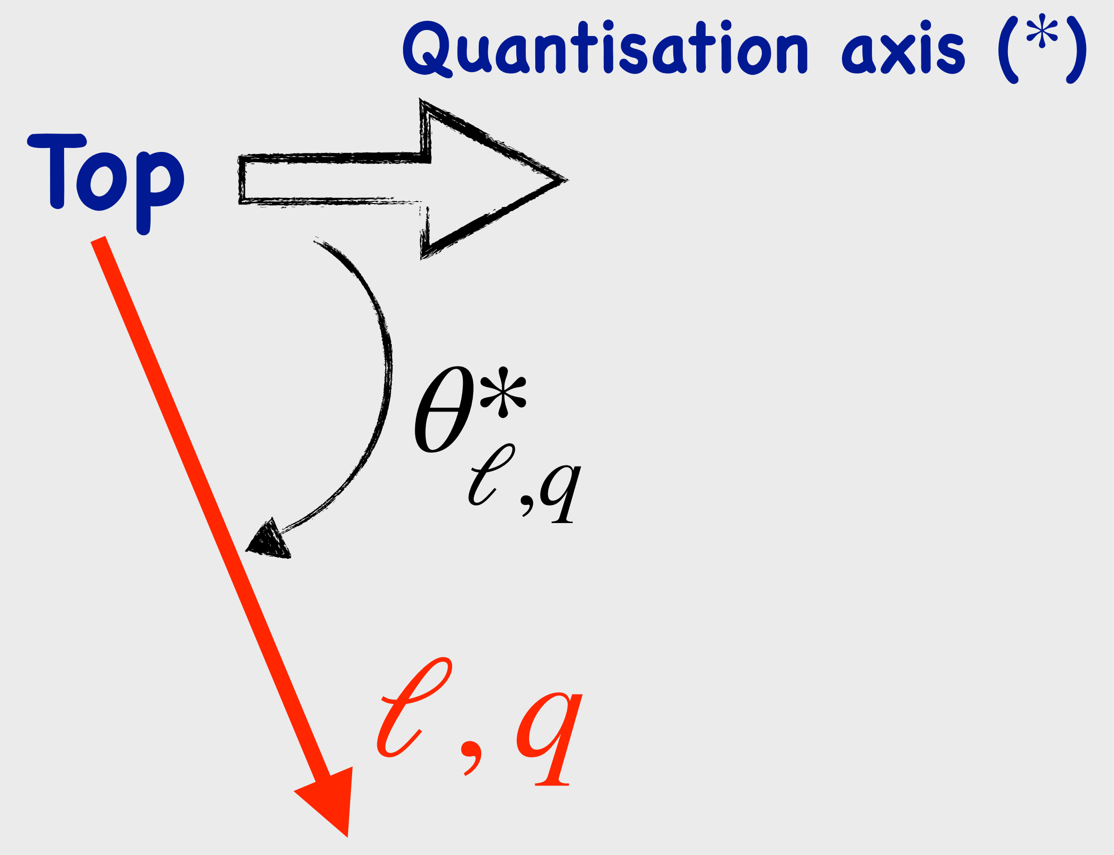


Particle	α
e^+, μ^+, τ^+	1.00
$\bar{d},\ \bar{s}$	0.94
$u,\ c$	-0.30
b	-0.39

Spin analysis power α

◉ α measures how well a given daughter probes the spin of its parent

Top rest frame



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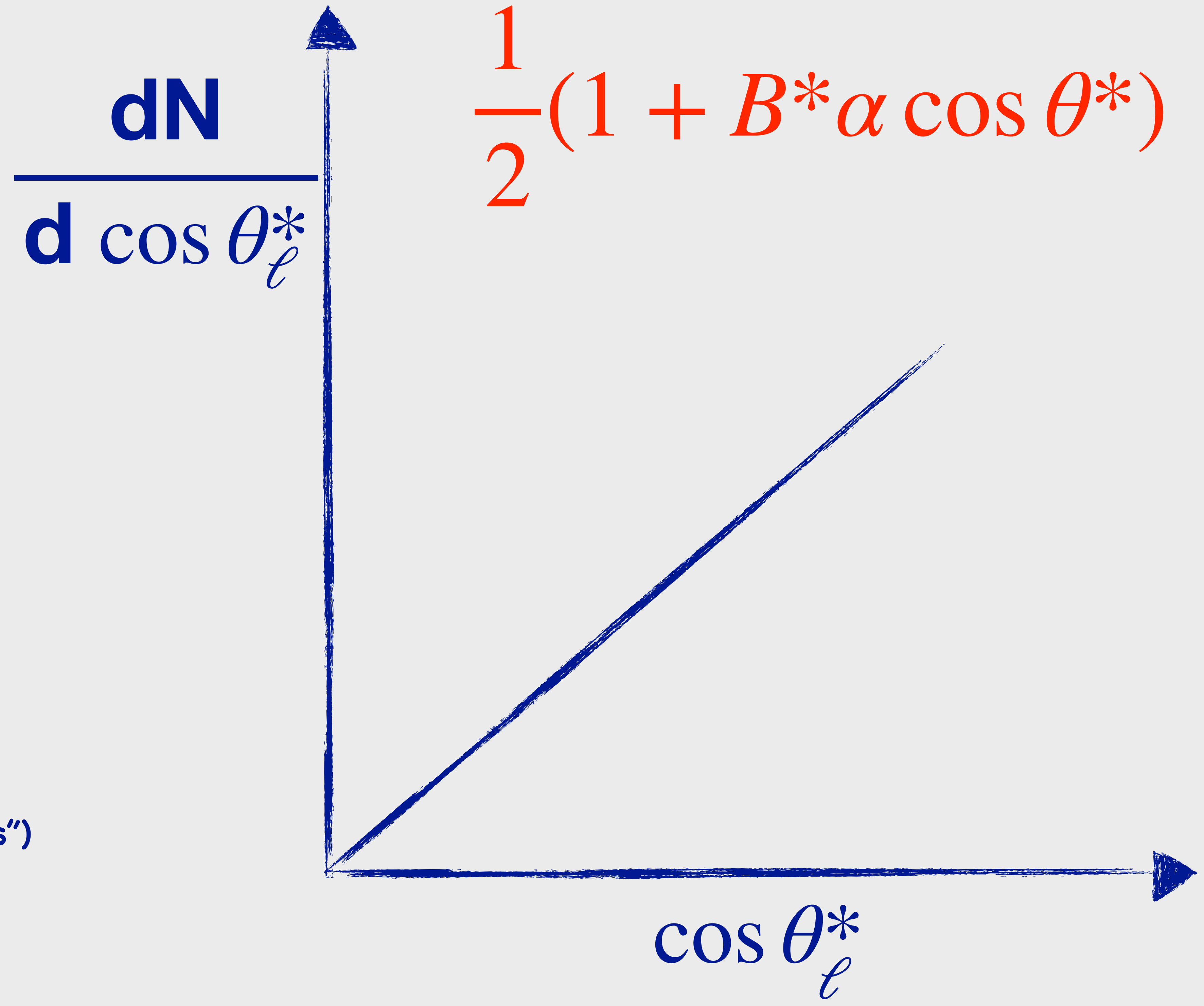
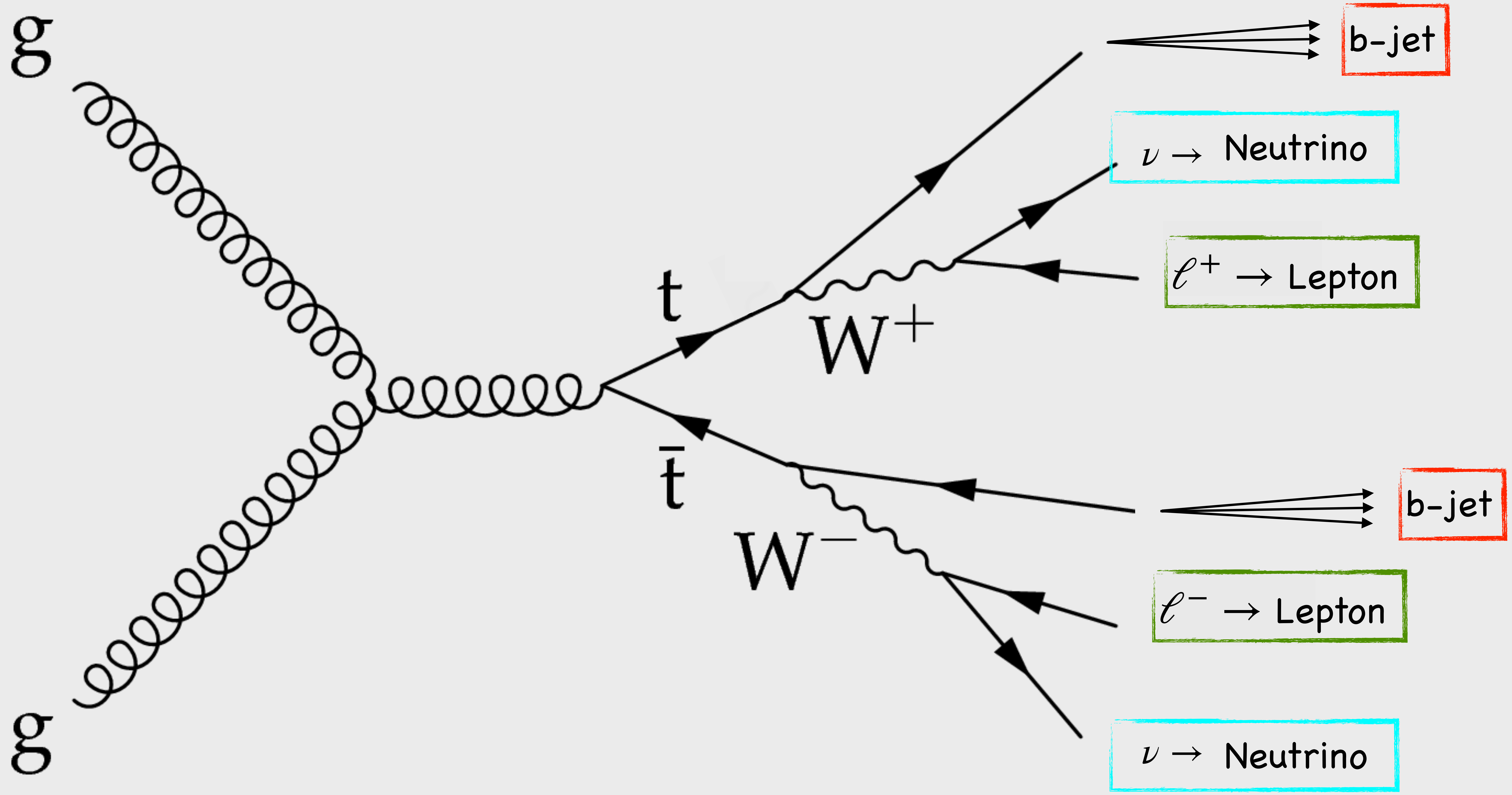


◉ For lepton α=1

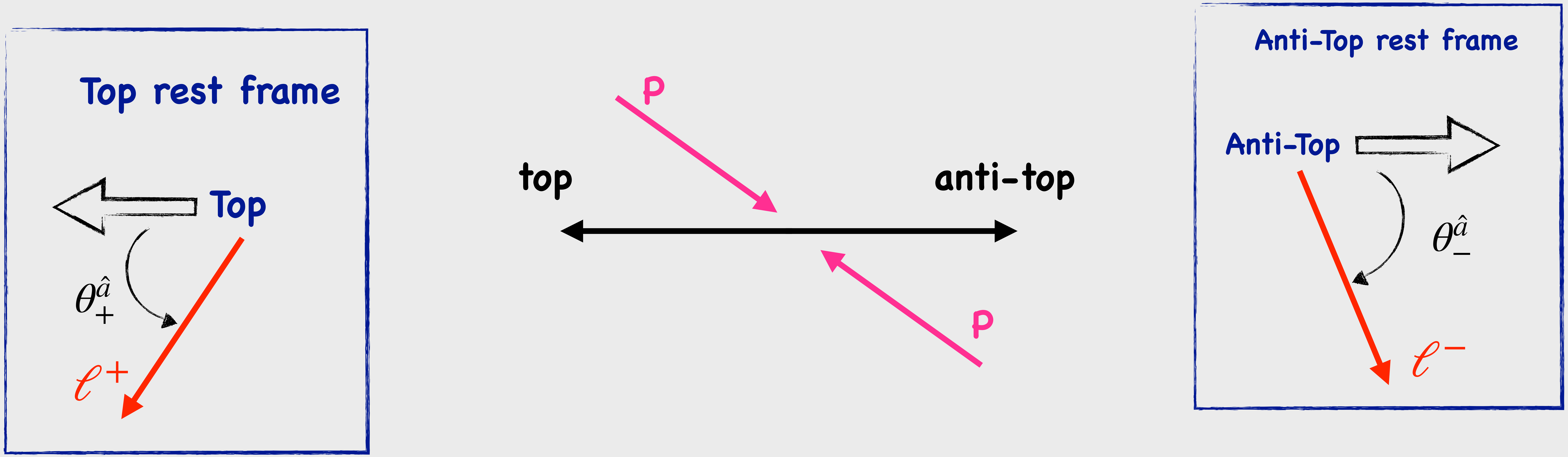
- ✤ Leptons (ℓ) are preferentially produced in the top spin direction
- ✤ Measurements of $\cos\theta^*$ lepton can provide information about top spin

$t\bar{t}$ di-lepton channel

◉ The best spin analyser is Lepton, which is why di-lepton channel should be chosen



$t\bar{t}$ Spin Correlations in the di-lepton channel



$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_{+}^{\hat{a}}\,d\cos\theta_{-}^{\hat{b}}} = \frac{1}{4}\left(1 + B_{+}^{\hat{a}}\cos\theta_{+}^{\hat{a}} + B_{-}^{\hat{b}}\cos\theta_{-}^{\hat{b}} - C(\hat{a},\hat{b})\cos\theta_{+}^{\hat{a}}\cos\theta_{-}^{\hat{b}}\right)$$

$t\bar{t}$ Spin Correlations in the di-lepton channel

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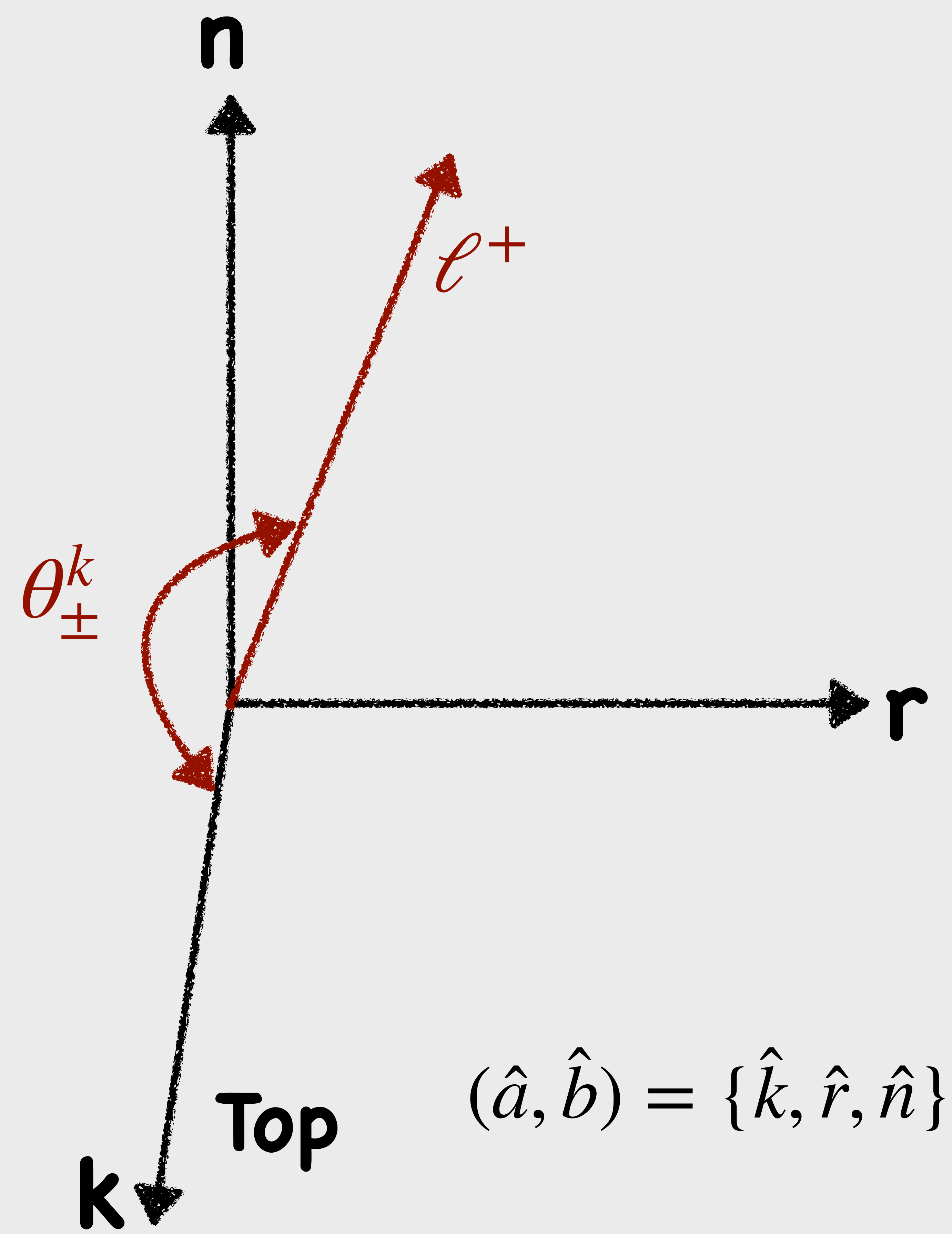
Top (+)	Anti-Top (-)
cos $(\theta_+^{\hat{k}})$	cos $(\theta_-^{\hat{k}})$
cos $(\theta_+^{\hat{r}})$	cos $(\theta_-^{\hat{r}})$
cos $(\theta_+^{\hat{n}})$	cos $(\theta_-^{\hat{n}})$



$(\hat{a},\hat{b}) = \{\hat{k},\hat{r},\hat{n}\}$

$t\bar{t}$ Spin Correlations in the di-lepton channel

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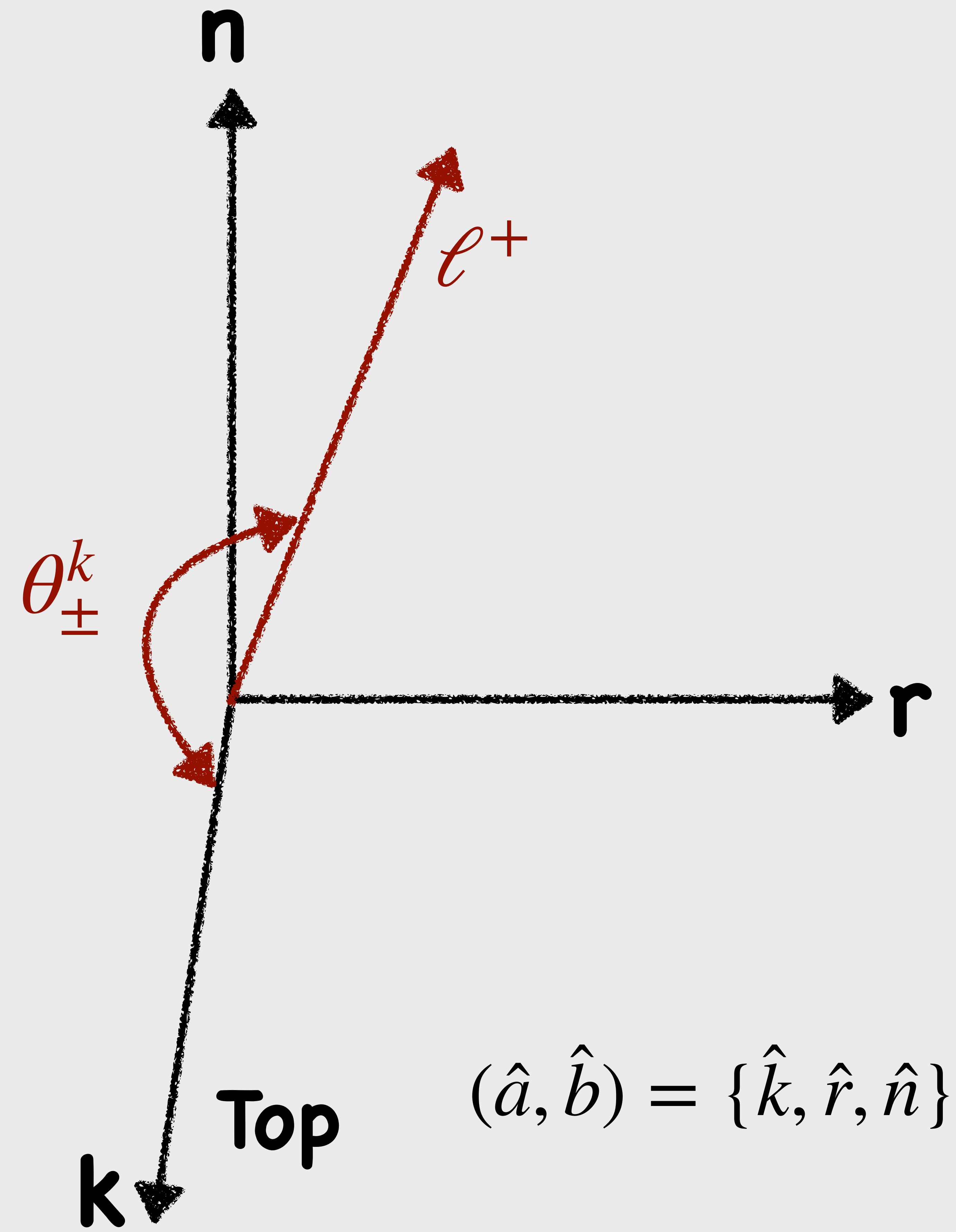
$B_\pm^{\hat{a},\hat{b}}$ = 6 polarisations observables



$(\hat{a},\hat{b}) = \{\hat{k},\hat{r},\hat{n}\}$

$t\bar{t}$ Spin Correlations in the di-lepton channel

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_+^{\hat{a}}\, d\cos\theta_-^{\hat{b}}} = \frac{1}{4}\left(1 + B_+^{\hat{a}}\cos\theta_+^{\hat{a}} + B_-^{\hat{b}}\cos\theta_-^{\hat{b}} - C(\hat{a},\hat{b})\cos\theta_+^{\hat{a}}\cos\theta_-^{\hat{b}}\right)$$

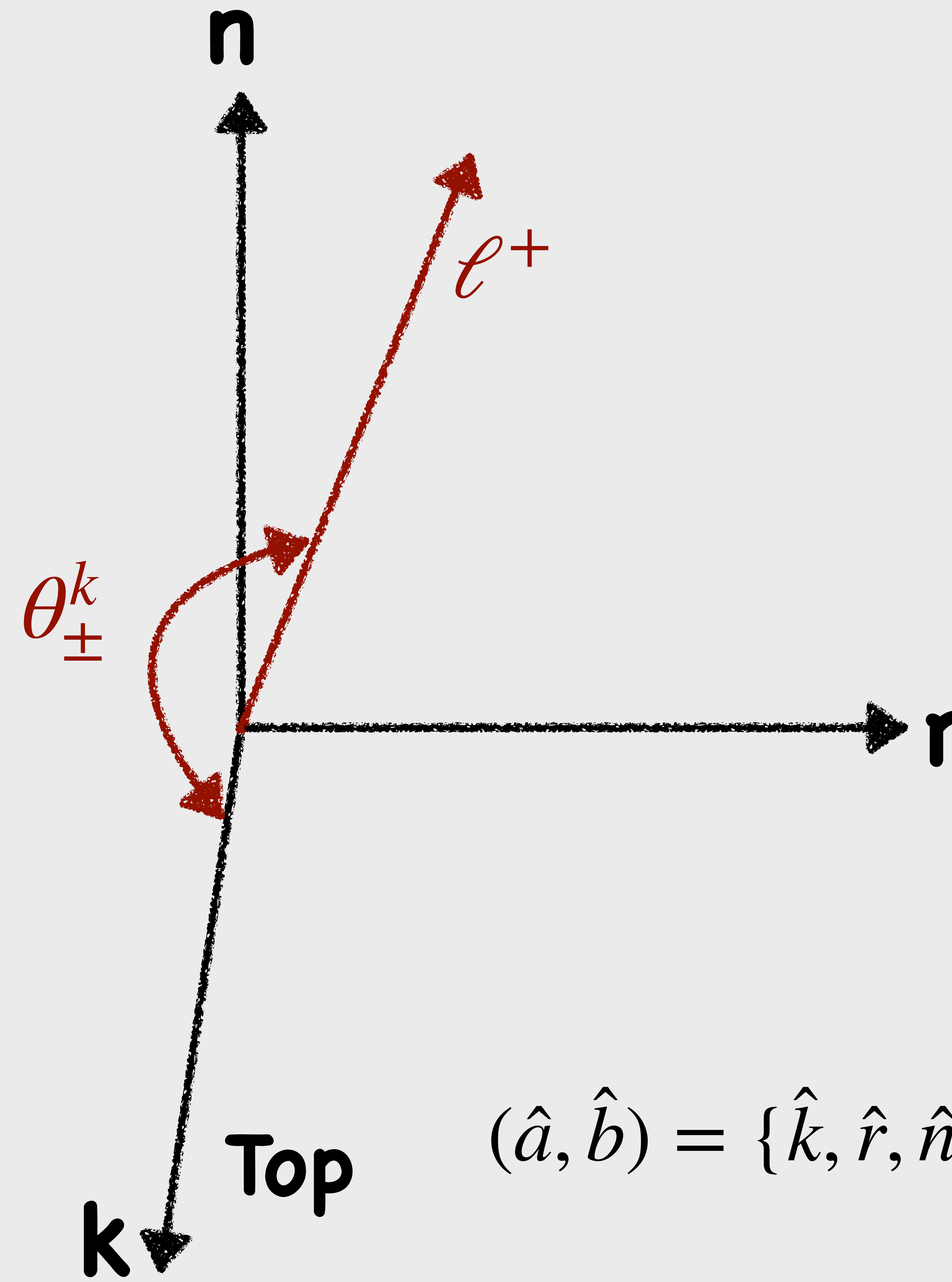
Top (+) **Anti-Top (-)**

cos $(\theta_+^{\hat{k}})$ cos $(\theta_-^{\hat{k}})$ → $C(\hat{k},\hat{k})$ $C(\hat{r},\hat{k})$ $C(\hat{n},\hat{k})$

cos $(\theta_+^{\hat{r}})$ cos $(\theta_-^{\hat{r}})$ → $C(\hat{k},\hat{r})$ $C(\hat{r},\hat{r})$ $C(\hat{n},\hat{r})$

cos $(\theta_+^{\hat{n}})$ cos $(\theta_-^{\hat{n}})$ → $C(\hat{k},\hat{n})$ $C(\hat{r},\hat{n})$ $C(\hat{n},\hat{n})$

3x3 matrix $C(\hat{a},\hat{b})$ of spin correlation coefficients.



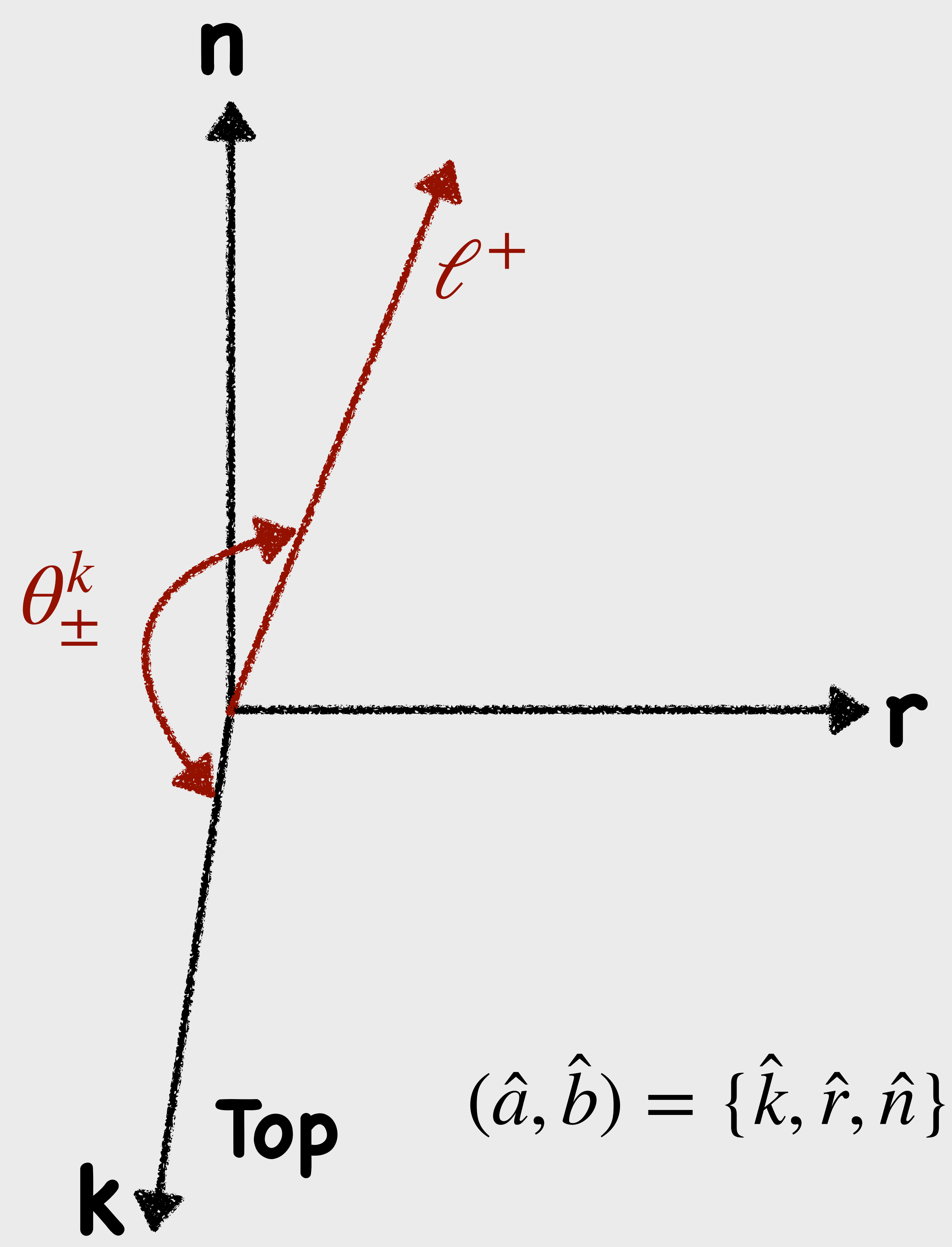
$(\hat{a},\hat{b}) = \{\hat{k},\hat{r},\hat{n}\}$

$t\bar{t}$ Spin Correlations in the di-lepton channel

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_+^{\hat{a}}\, d\cos\theta_-^{\hat{b}}} = \frac{1}{4}\left(1 + B_+^{\hat{a}}\cos\theta_+^{\hat{a}} + B_-^{\hat{b}}\cos\theta_-^{\hat{b}} - C(\hat{a},\hat{b})\cos\theta_+^{\hat{a}}\cos\theta_-^{\hat{b}}\right)$$

$B_+^{\hat{k}}$	$B_-^{\hat{k}}$	$C(\hat{k},\hat{k})$	$C(\hat{r},\hat{k})$	$C(\hat{n},\hat{k})$
$B_+^{\hat{r}}$	$B_-^{\hat{r}}$	$C(\hat{k},\hat{r})$	$C(\hat{r},\hat{r})$	$C(\hat{n},\hat{r})$
$B_+^{\hat{n}}$	$B_-^{\hat{n}}$	$C(\hat{k},\hat{n})$	$C(\hat{r},\hat{n})$	$C(\hat{n},\hat{n})$

15 polarisation and spin correlation observables



$(\hat{a},\hat{b}) = \{\hat{k},\hat{r},\hat{n}\}$

How to probe Spin Correlation observables ?

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_+^{\hat{a}}\, d\cos\theta_-^{\hat{b}}} = \frac{1}{4}\left(1 + B_+^{\hat{a}}\cos\theta_+^{\hat{a}} + B_-^{\hat{b}}\cos\theta_-^{\hat{b}} - C(\hat{a},\hat{b})\cos\theta_+^{\hat{a}}\cos\theta_-^{\hat{b}}\right)$$

$$\frac{1}{\sigma}\frac{d\sigma}{dx} = \frac{1}{2}\left(1 + [\textbf{Coef.}]\; x\right)\; f(x)$$

$x = \cos\theta_+^{\hat{a}}$, $\cos\theta_-^{\hat{b}}$ or $\cos\theta_+^{\hat{a}}\cos\theta_-^{\hat{b}}$

$B_+^{\hat{a}} = 3 < \cos\theta_+^{\hat{a}} >$, $B_-^{\hat{b}} = 3 < \cos\theta_-^{\hat{b}} >$

$C(\hat{a},\hat{b}) = -9 < \cos\theta_+^{\hat{a}}\cos\theta_-^{\hat{b}} >$

Mean Method

$B_\pm^{\hat{a},\hat{b}}$ $\quad C(\hat{a},\hat{b})$

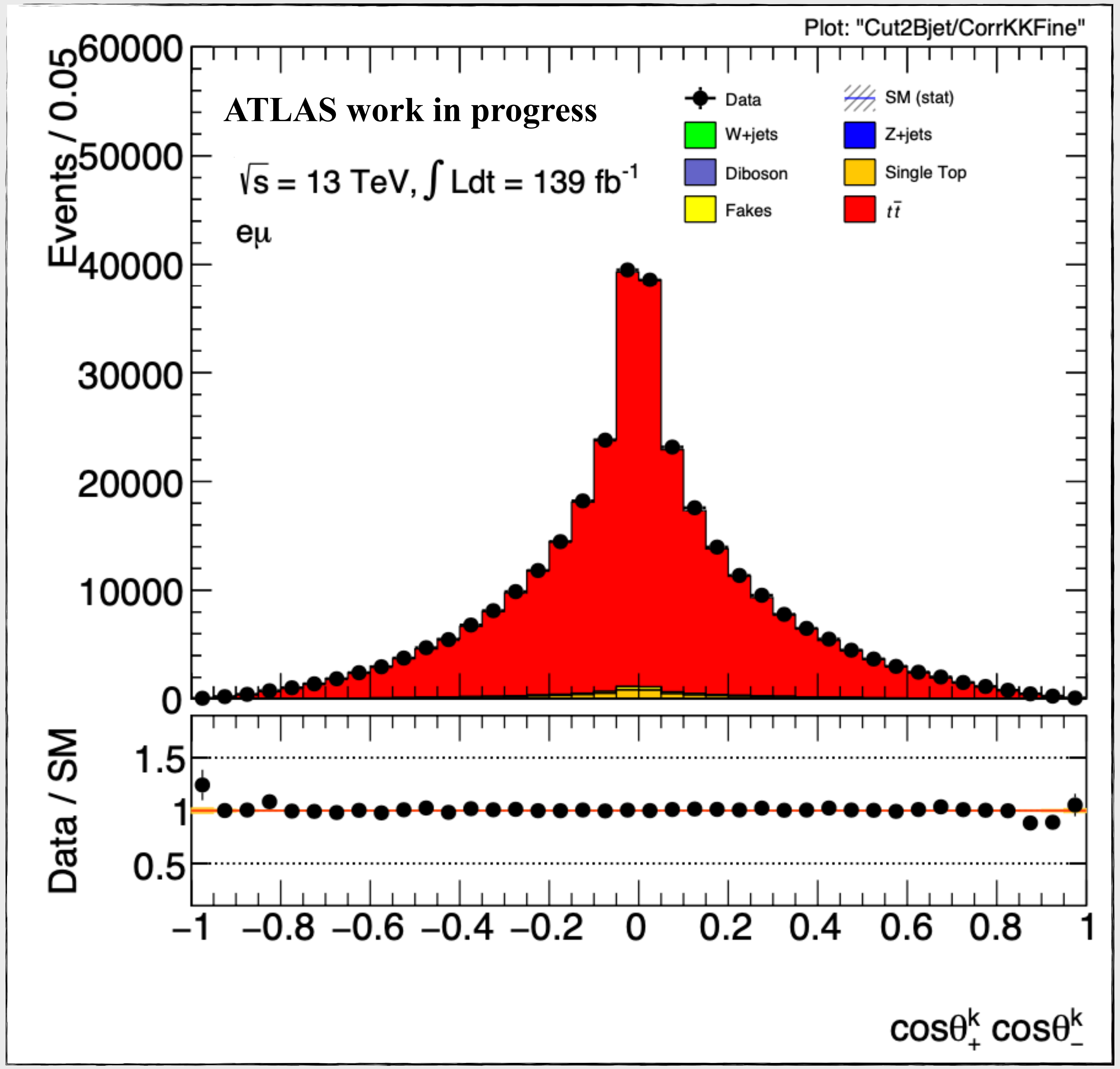
Slope Method

Spin Correlation Measurements

Spin correlation, Data/MC

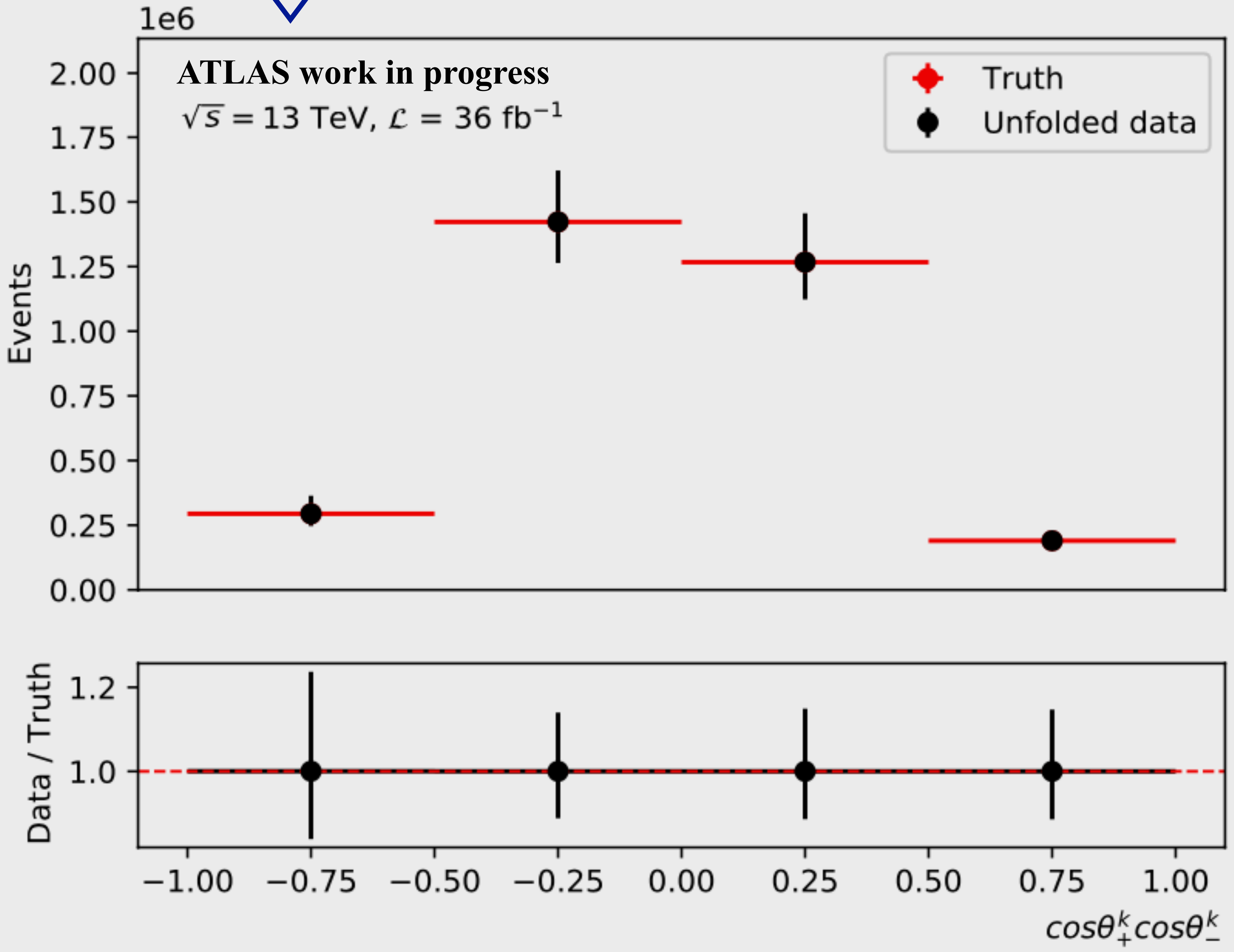
- Full Run2 data
- MC Samples
  - Signal: $t\bar{t}$ (PowHeg + Pythia8)
  - Backgrounds:
    - Z and W+jets
    - Single top (Wt channel)
    - Di-boson
    - Fakes from $t\bar{t}$ and single-top
- Event Selection
  - Exactly two leptons (e or μ), $p_T^{lep} \geq 25\,Gev$
  - Opposite charge leptons
  - $N_{b-jets} \geq 2$

S/B is extremely high and Data/MC is very good



Spin correlation, Unfolding

Using Mc16a only as a starting point but the analysis is aimed at using the full Run2 dataset.



- Using TRExFitter to perform a profile likelihood unfolding
- Included systematics:
  - $t\bar{t}$ modelling systematics
  - Weight systematics

➡ Larger impact from $t\bar{t}$ modelling systematics

- Unfolded C(k,k) = $0.332^{+0.054}_{-0.067}$ (mean method, in agreement with the SM prediction)

Uncertainty source	$\Delta\, C(k,k)$
$t\bar{t}$ modelling	+0.043 / -0.058
Weight systematics	+0.002 / -0.003
Background MC stat. (gammas)	+0.007 / -0.006
Total systematic uncert.	+0.044 / -0.059
Statistical uncert.	±0.032
Total	+0.054 / -0.067

EFT Interpretation

Bottom-up approach, SM-EFT

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}}^{(4)} + \sum_i \frac{c_i^{(5)} \mathcal{O}_i^{(5)}}{\Lambda} + \sum_i \frac{c_i^{(6)} \mathcal{O}_i^{(6)}}{\Lambda^2} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right) = \mathscr{L}_{\text{NP}}$$

Dim 5

Dim 6

Lagrangian with new particles at Λ

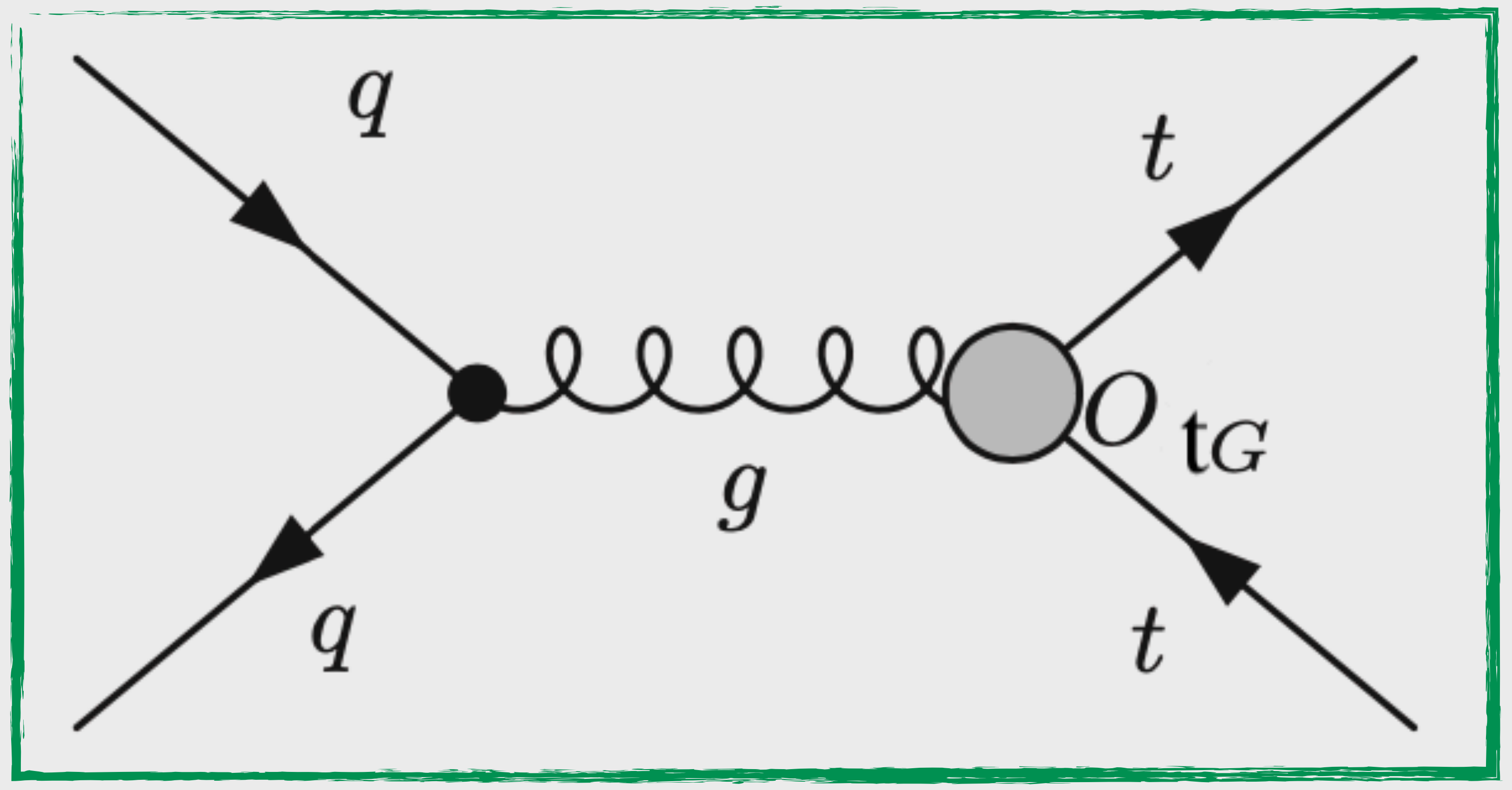
- 1 operator with D=5: $\mathcal{O}^{(5)} = \bar{L}_L \tilde{\Phi} \tilde{\Phi}^T L_L^c$
  → Weinberg operator

- 59 independent $\mathcal{O}^{(6)}$ preserving B and L
- 5 independent $\mathcal{O}^{(6)}$ violating B and L
- 3 generations: 2499 operators!

SM-EFT, D=6 Basis, Top pair Sector

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}^{(4)}_{\text{SM}} + \sum_i \frac{c_i^{(5)}\mathcal{O}_i^{(5)}}{\Lambda} + \sum_i \frac{c_i^{(6)}\mathcal{O}_i^{(6)}}{\Lambda^2} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

- In Top quark sector, pair production, two examples:
  - Top and an anti-top and one gluon operator

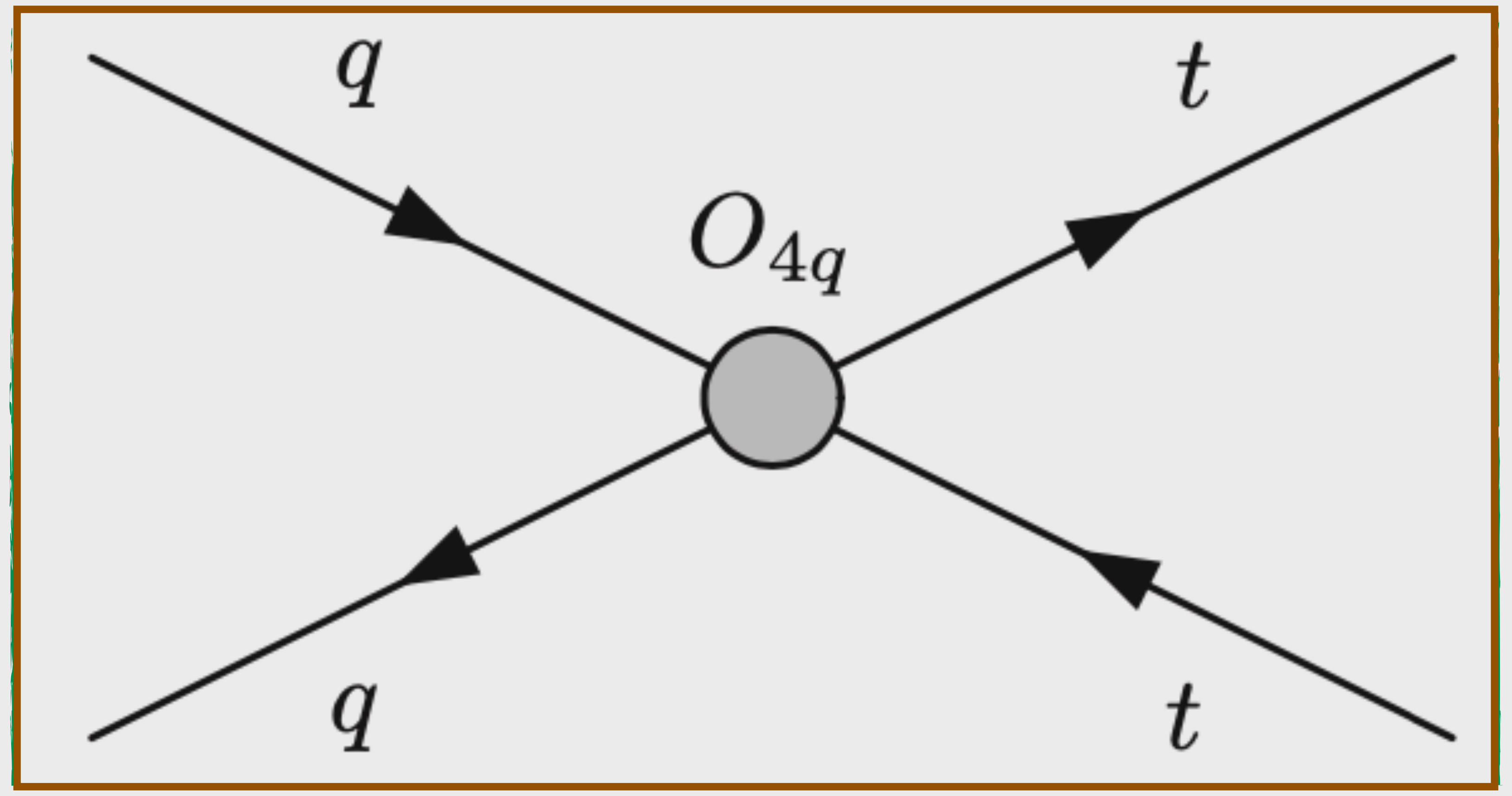


$$\mathcal{O}_{tG} = \left(\bar{Q}\sigma^{\mu\nu}T^A t\right)\widetilde{\phi}\, G^A_{\mu\nu}$$

SM-EFT, D=6 Basis, Top pair Sector

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}}^{(4)} + \sum_i \frac{c_i^{(5)}\mathcal{O}_i^{(5)}}{\Lambda} + \sum_i \frac{c_i^{(6)}\mathcal{O}_i^{(6)}}{\Lambda^2} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

- In Top quark sector, pair production, two examples:
  - Top and an anti-top and one gluon operator
  - 4-quark fermion operator



$$\mathcal{O}_{tq}^{8} = \left(\bar{t}\gamma_\mu T^A t\right)\left(\bar{q}_i\gamma^\mu T^A q_i\right)$$

Introduction

Motivation

- Preform Global Fit using spin correlation observables at LO or NLO to constrain Wilson Coefficient ?

◉ Generate simulation samples:

- Define EFT model : SMEFT@NLO model (LO / NLO)
  - SM
  - SMEFT@NLO model ==> LO and NLO

- What Wilson coefficients should be considered ?
  - Ctg
  - 4-quark operators: ctq8

- Decay tops (using MadSpin)
  - Possible at LO and <u>impossible</u> at NLO

ATLAS Top Workshop, slide 5

- What effect does this have on the EFT contribution to spin correlation at NLO?

Global Fit at LO or NLO ?

Motivation

- What effect does this have on the EFT contribution to spin correlation at NLO?

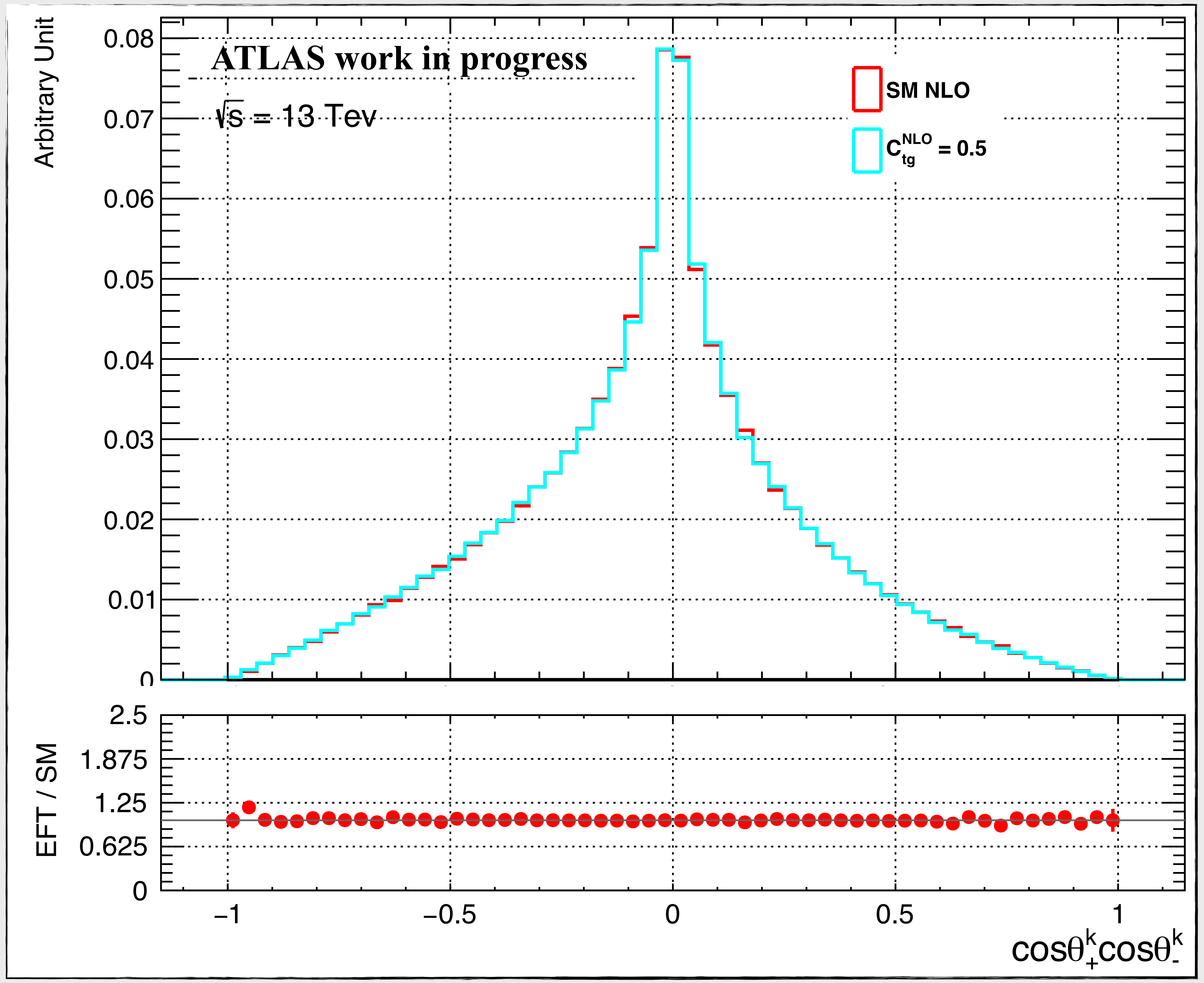
Results

◉ Mean Method: $C(\hat{k},\hat{k}) = -9 < \cos\theta_{+}^{\hat{k}} \cos\theta_{-}^{\hat{k}} >$

SM NLO : C(k, k) = 0.366313 +/- 0.0042 (stat)

Ctg NLO : C(k, k) = 0.375982 +/- 0.0042 (stat)

◉ C_{tg}=0.5 affect the SM value by 10%



Global Fit at LO or NLO ?

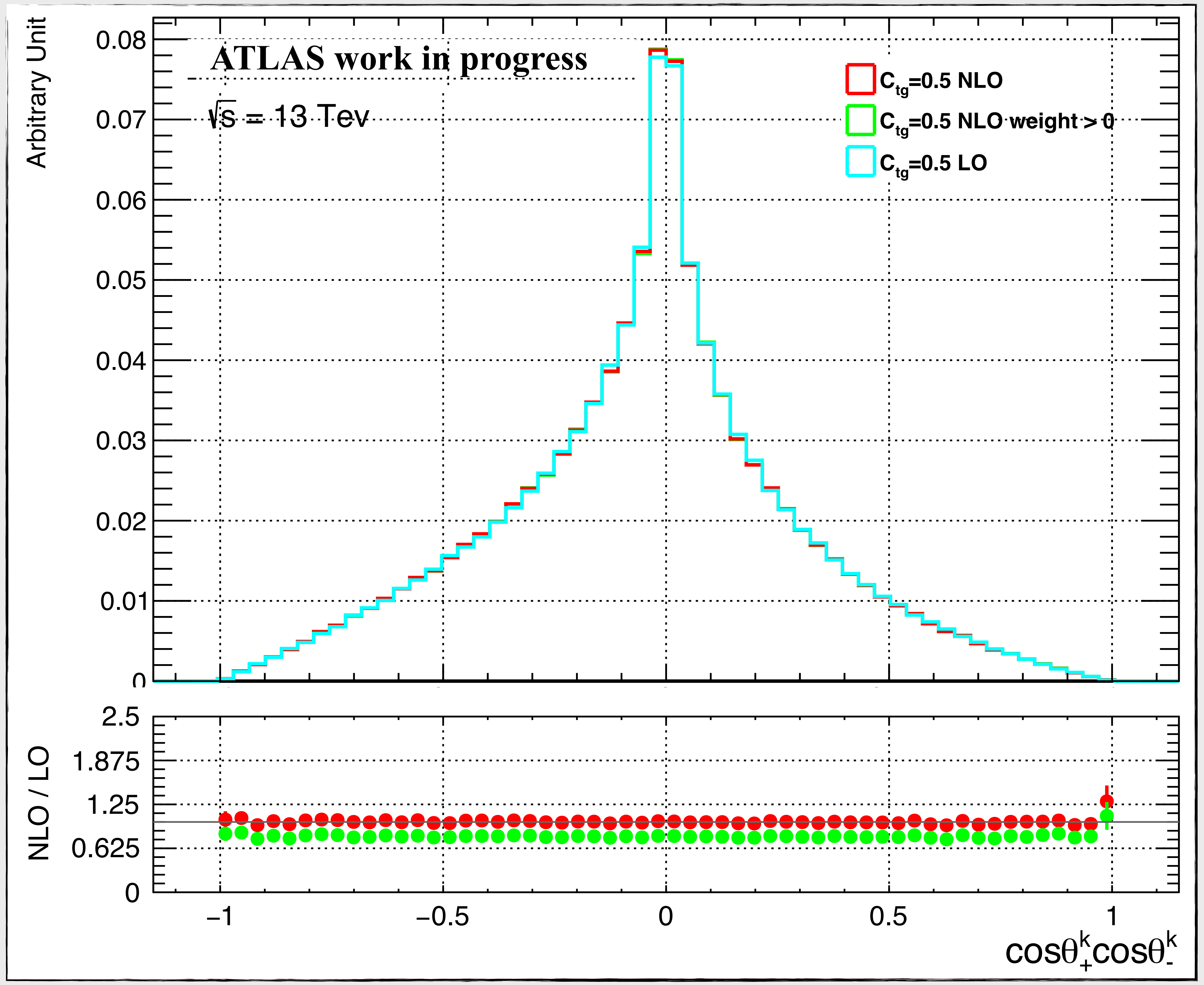
Motivation

- What effect does this have on the EFT contribution to spin correlation at NLO?

Results

◉ The impact of c_{tg} at NLO/LO is low

◉ Preform Global Fit at NLO using spin correlation observables.



SMEFT dependence on Spin Correlation observables

Motivation

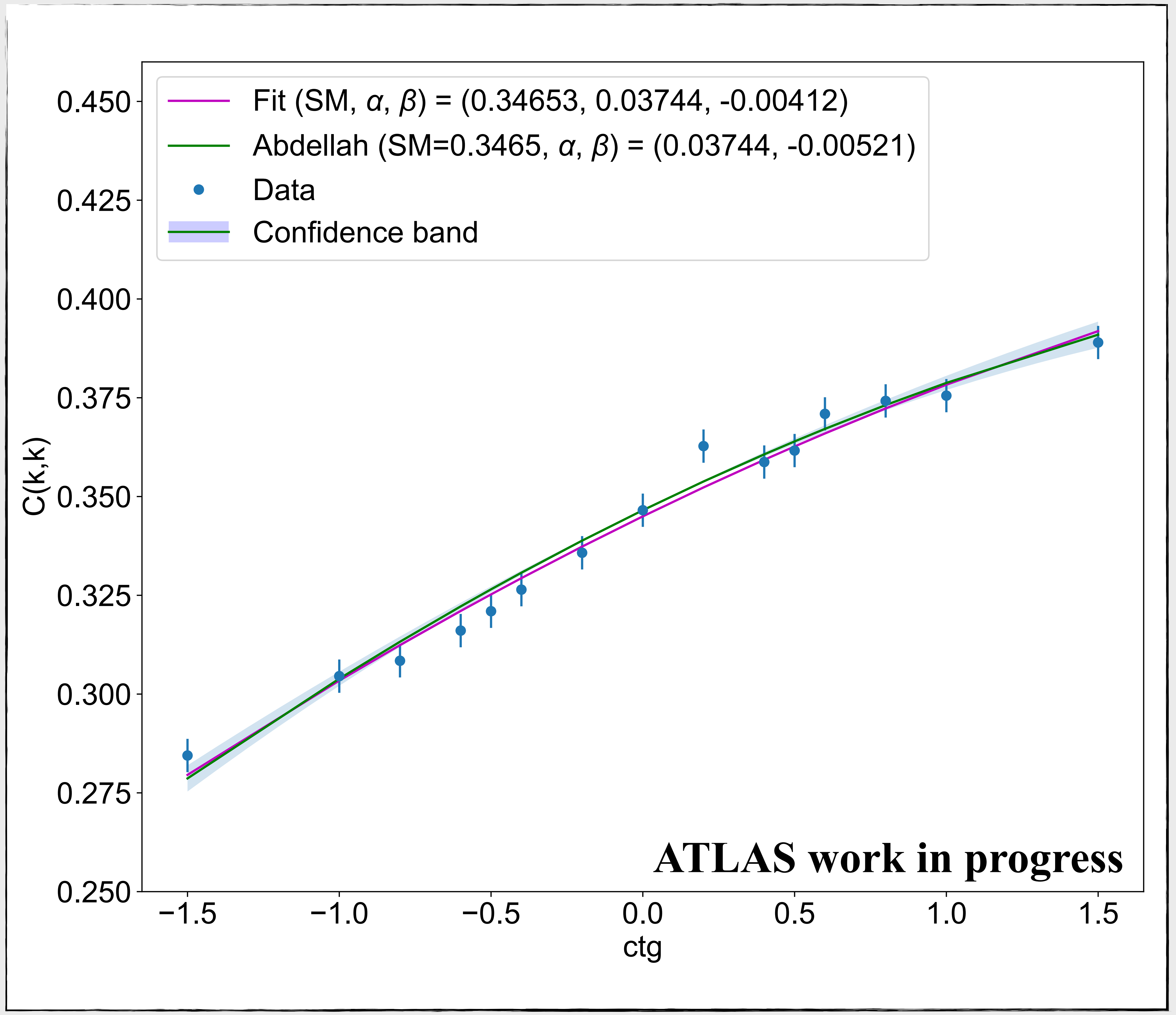
- SMEFT dependence parameterised as polynomials in Wilson coefficients:

$$C(k,k) = C(k,k)_{SM} + \frac{C_{tg}}{\Lambda^2}\alpha + \frac{C_{tg}^2}{\Lambda^4}\beta$$

Results

- Compute $\alpha_{c_{tg}}$ and $\beta_{c_{tg}}$.
- We can use the measured $C(k,k)$, the estimated $C(k,k)_{SM}$ with their statistical and systematic uncertainties, and the $\alpha_{c_{tg}}$ and $\beta_{c_{tg}}$, to derive global constraints on the c_{tg} operator coefficient.

- C_{tg} strongly affect the $C(k,k)$ observable



BONUS: SMEFT@NLO Vs Dim6Top

Motivation

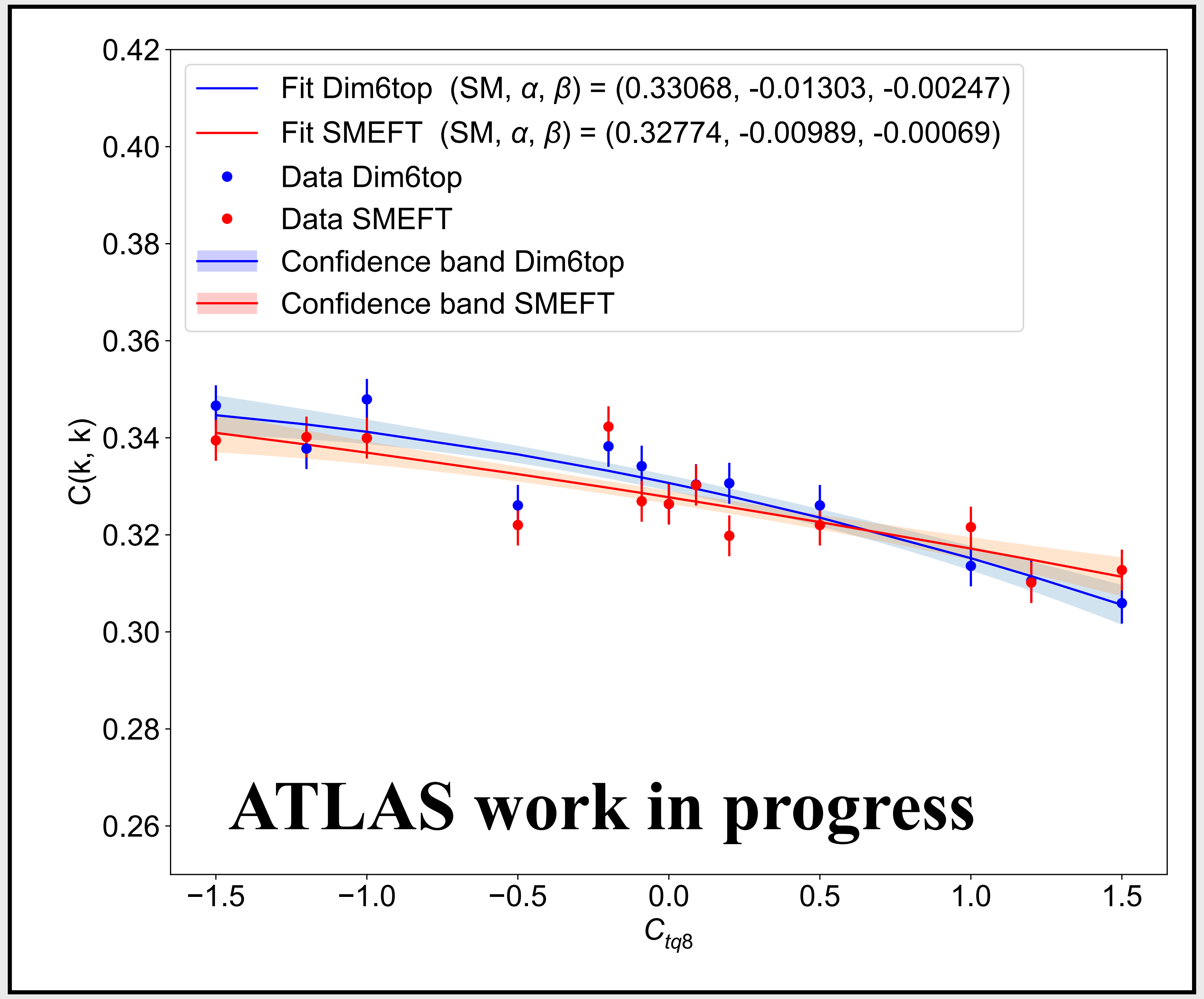
- Standalone: Individually generate EFT sample for given Wilson coefficient value (with same seeds …)
- Re-weighting: User Re-weighting to generate EFT samples

Results

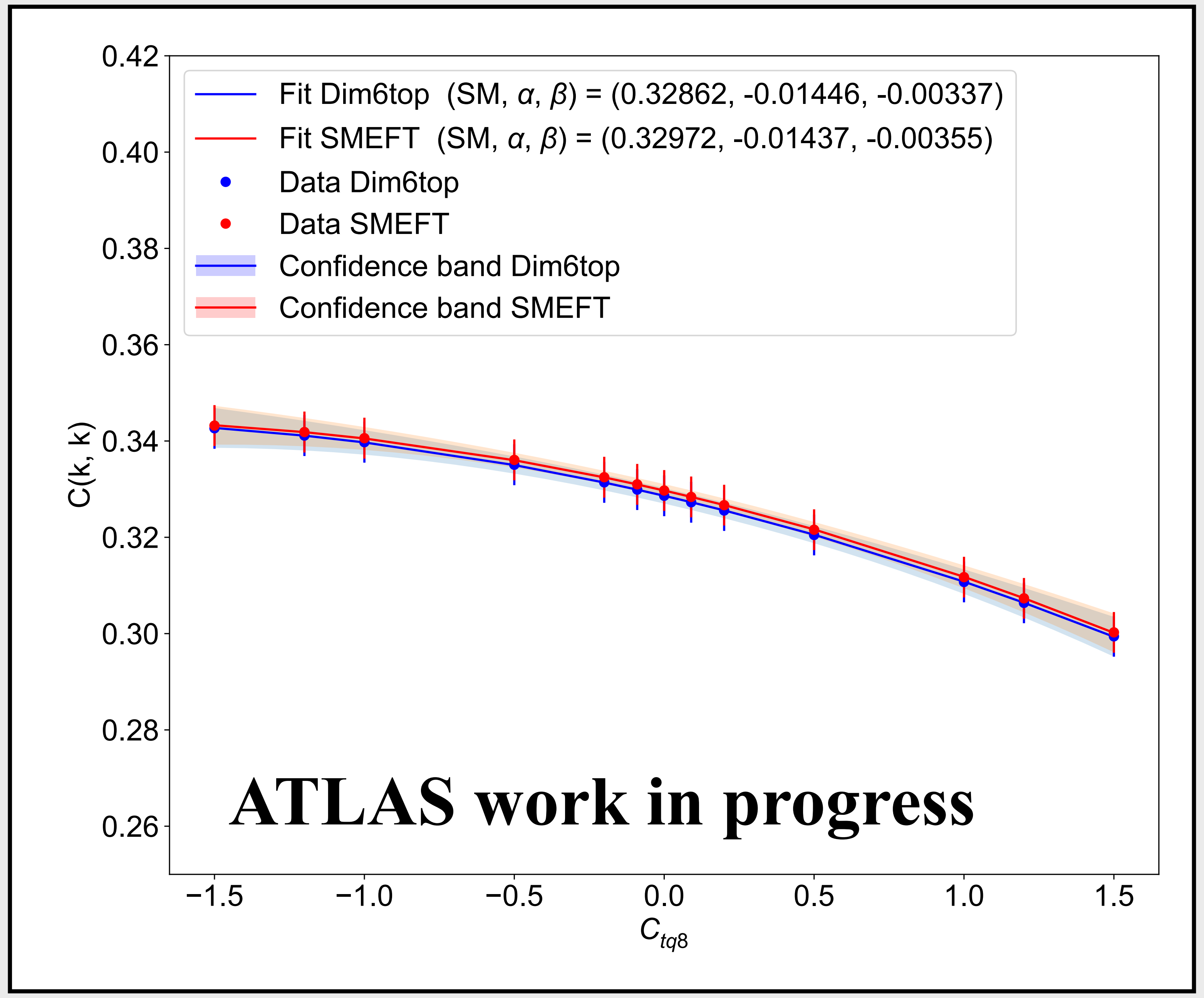
- Perfect agreement between two model using Re-weighting
  ➡ Cost: weighted events have larger statistical uncertainty that an unweighted sample (Standalone) with the same number of events.

- SMEFT@NLO model and Dim6top model show appx. same value of α_{ctq8} and β_{ctq8} [within the statistical uncertainties.]

Standalone



Re-weighting



Summary

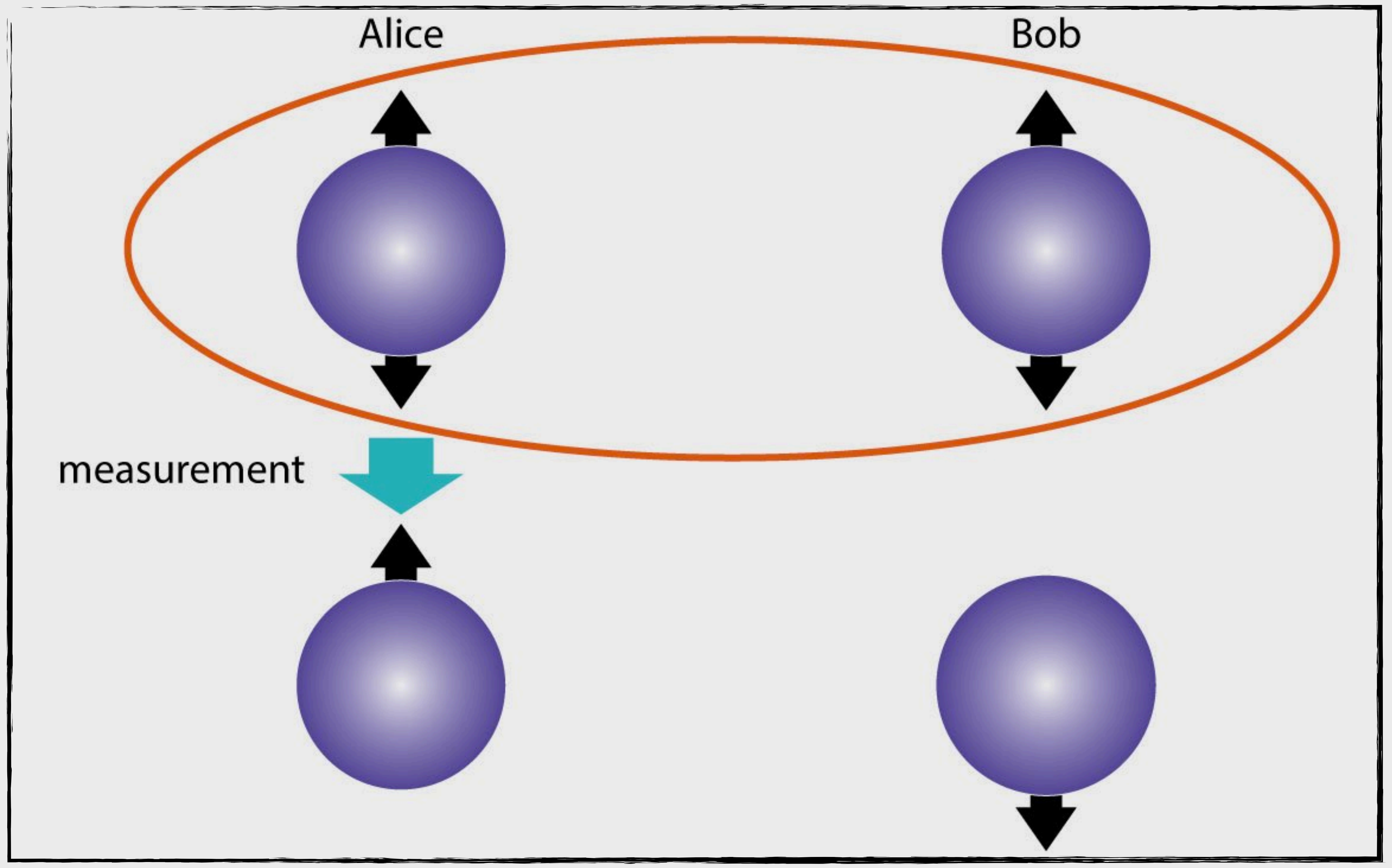
- Direct measurements of spin correlations in close agreement with SM predictions
- Precision top quark spin measurements are a powerful probe of new physics and complementary to other approaches.
- Study the impact of EFT at LO and NLO on spin correlation observables
  - Preform Global Fit at NLO
  - SMEFT@NLO and Dim6Top comparaison

- Quantum Entanglement at LHC
- Violation of Bell inequalities (BIs) at LHC

Quantum Entanglement in $t\bar{t}$

Motivation

What is Quantum Entanglement?



◉ Observed in photons, atoms, superconductors …. Humm LHC ?

Quantum Entanglement in $t\bar{t}$

Motivation

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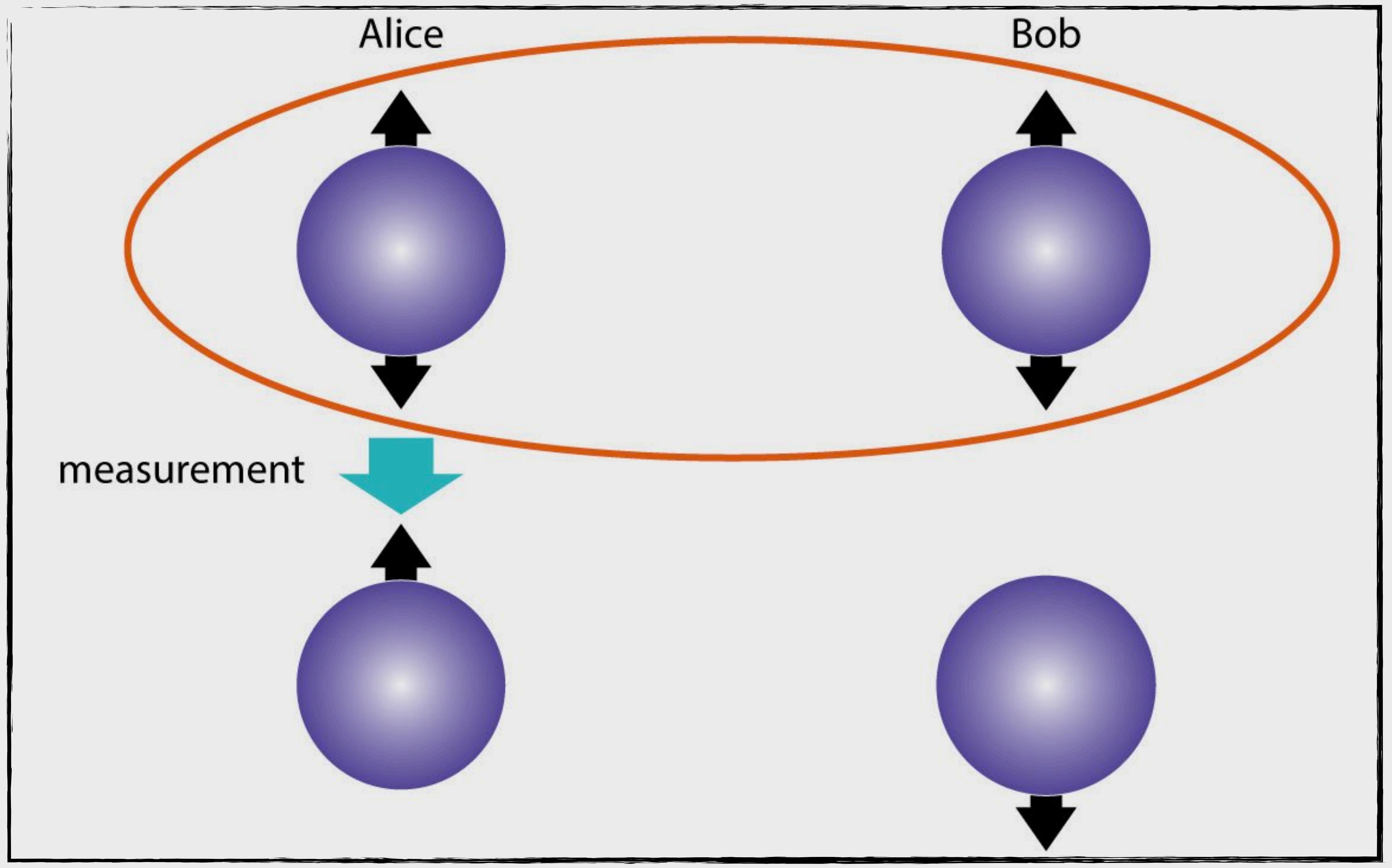

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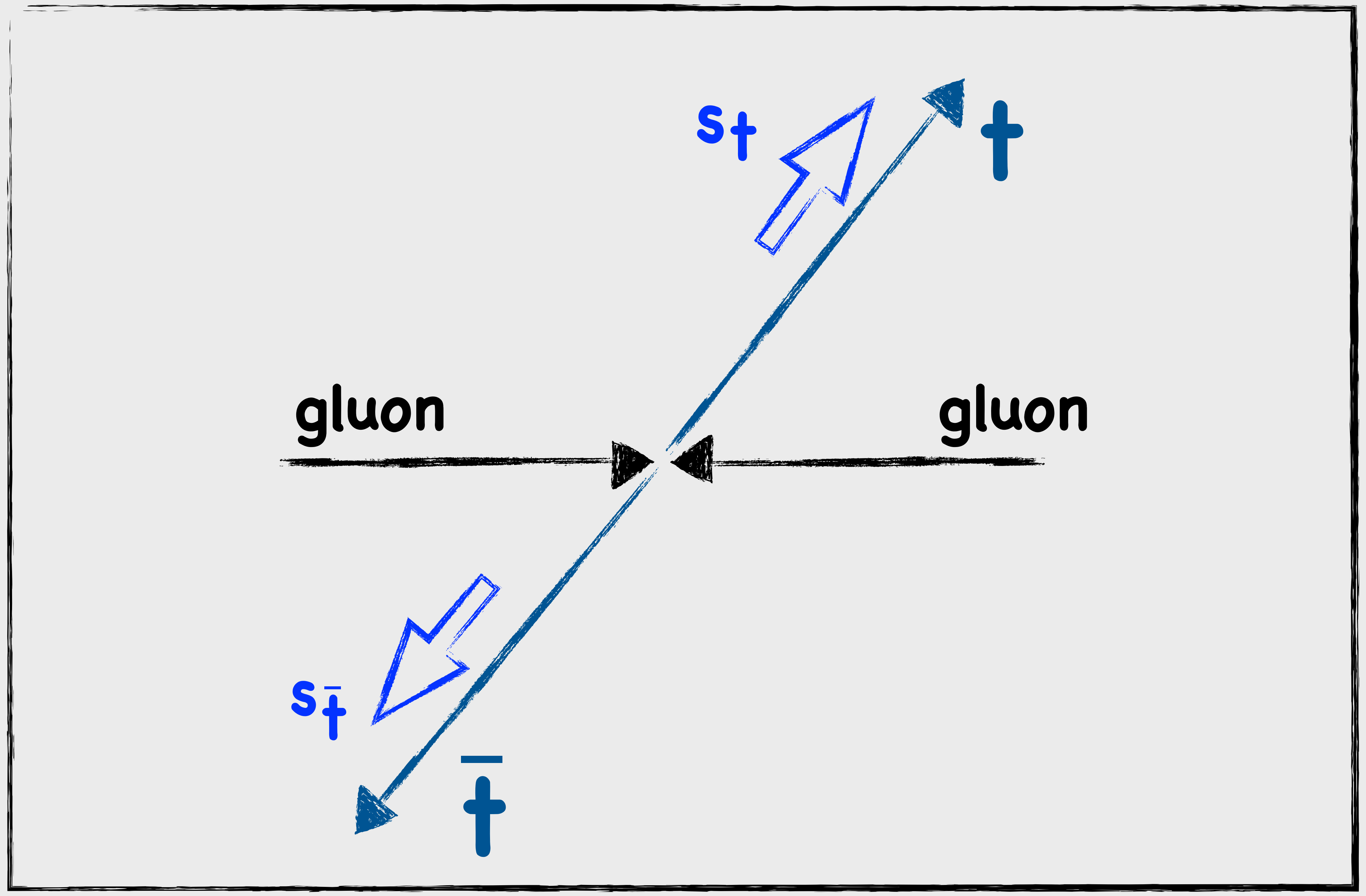
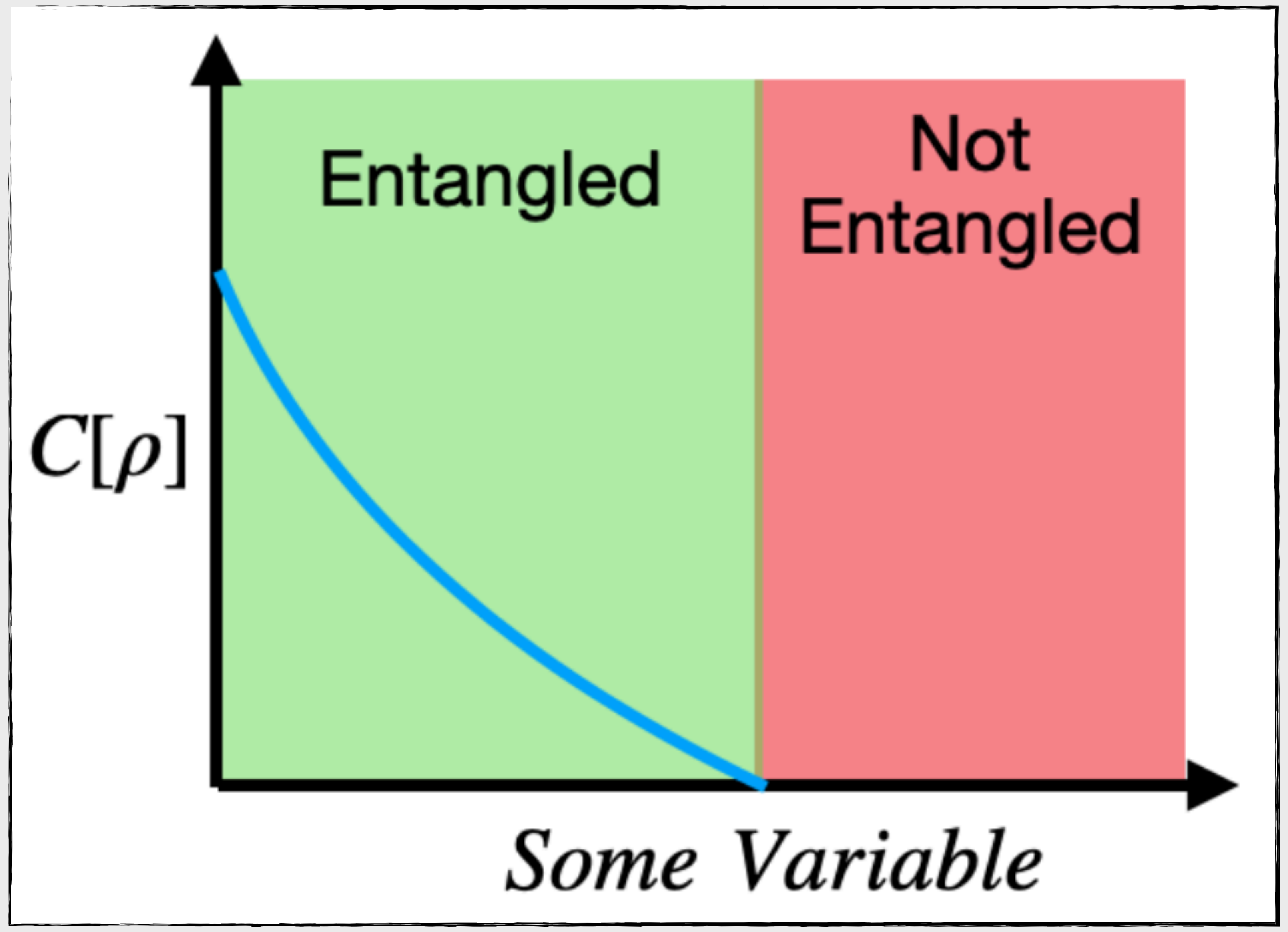
How is it reflected in a $t\bar{t}$ production?



◉ Spin state of t and $\bar{t}$ quarks produced at the LHC can be entangled, and this can be probed experimentally

Where to look for Quantum Entanglement in $t\bar{t}$?

Theory paper



Entanglement Criterion - Concurrence

- The $t\bar{t}$ production is described by the production spin density matrix:

$$\rho = \frac{1}{4}\left(1 \otimes 1 + B_i \sigma_i \otimes 1 + \bar{B}_j 1 \otimes \sigma_j + C_{ij} \sigma_i \otimes \sigma_j\right)$$

- By invoking the Peres-Horodecki criterion:

$$\Delta \equiv -C_{nn} + \left|C_{kk} + C_{rr}\right| - 1 > 0$$

is a sufficient condition for the presence of entanglement

- Concurrence $C[\rho] = \dfrac{\max(\Delta,0)}{2}$

Where to look for Quantum Entanglement in $t\bar{t}$?

Theory paper

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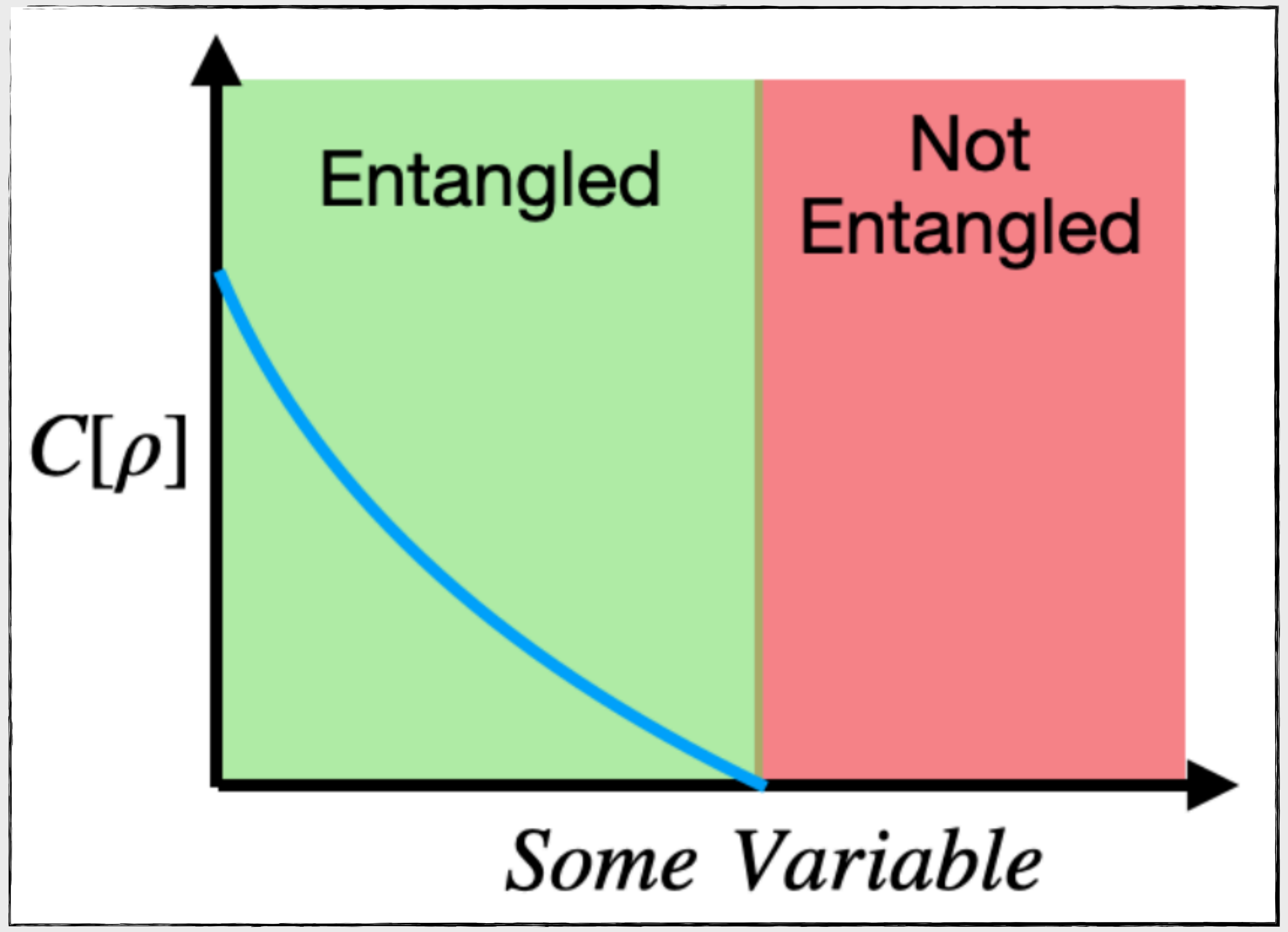
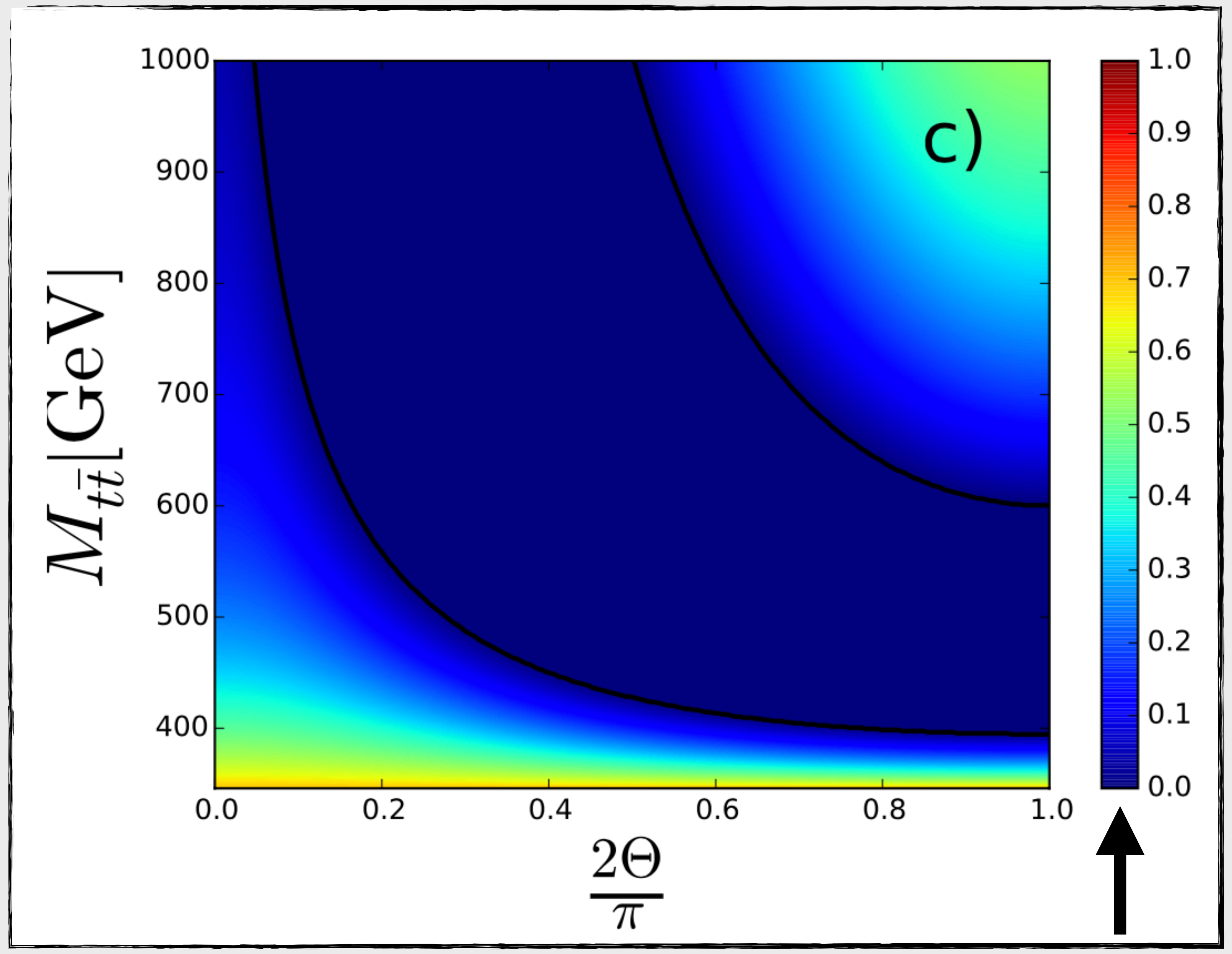




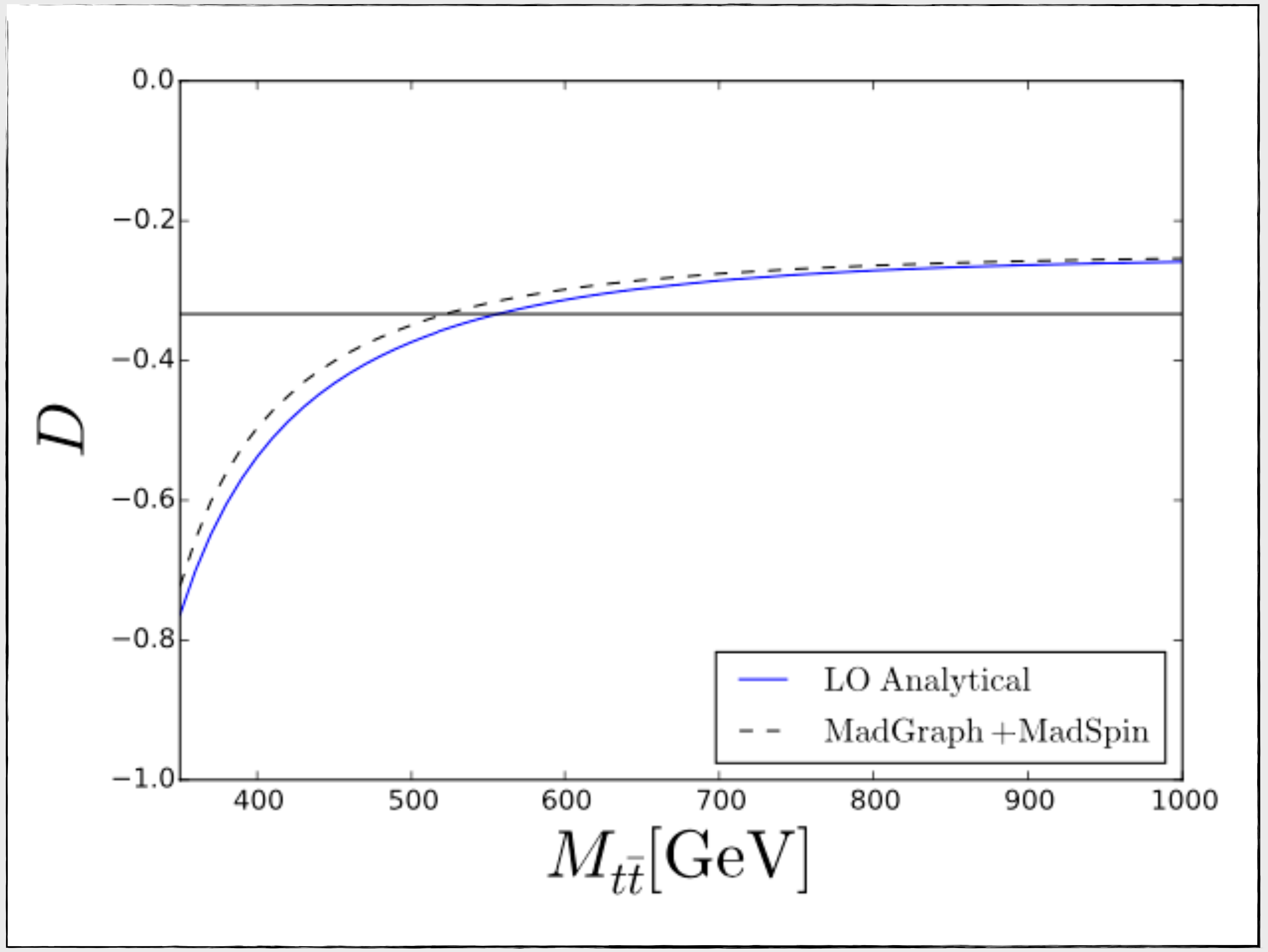
Concurrence $C[\rho]$

Where to look for Quantum Entanglement in $t\bar{t}$?

Theory paper

Equivalent Measurable Observable

- The condition $\Delta > 0$ translates into $D < -1/3$,
  - $D = -\left(C_{kk} + C_{rr} + C_{nn}\right)/3$
- Experimentally : $\frac{1}{\sigma}\frac{d\sigma}{d\cos\varphi_{\ell\ell}} = \frac{1}{2}\left(1 - D\cos\varphi_{\ell\ell}\right)$
- Needs to be measured differentially as a function of $M_{t\bar{t}}$

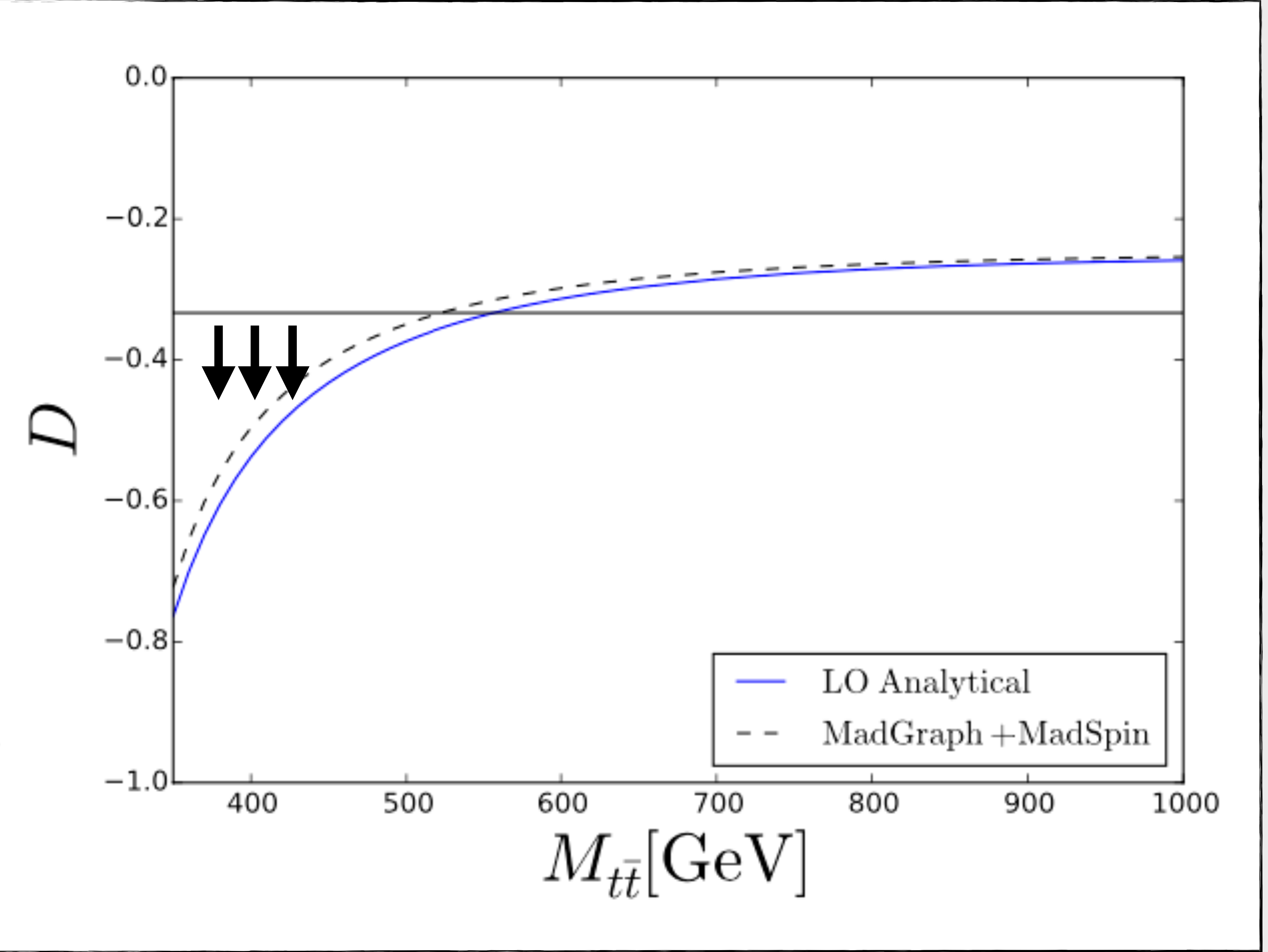


Where to look for Quantum Entanglement in $t\bar{t}$?

Theory paper

Equivalent Measurable Observable

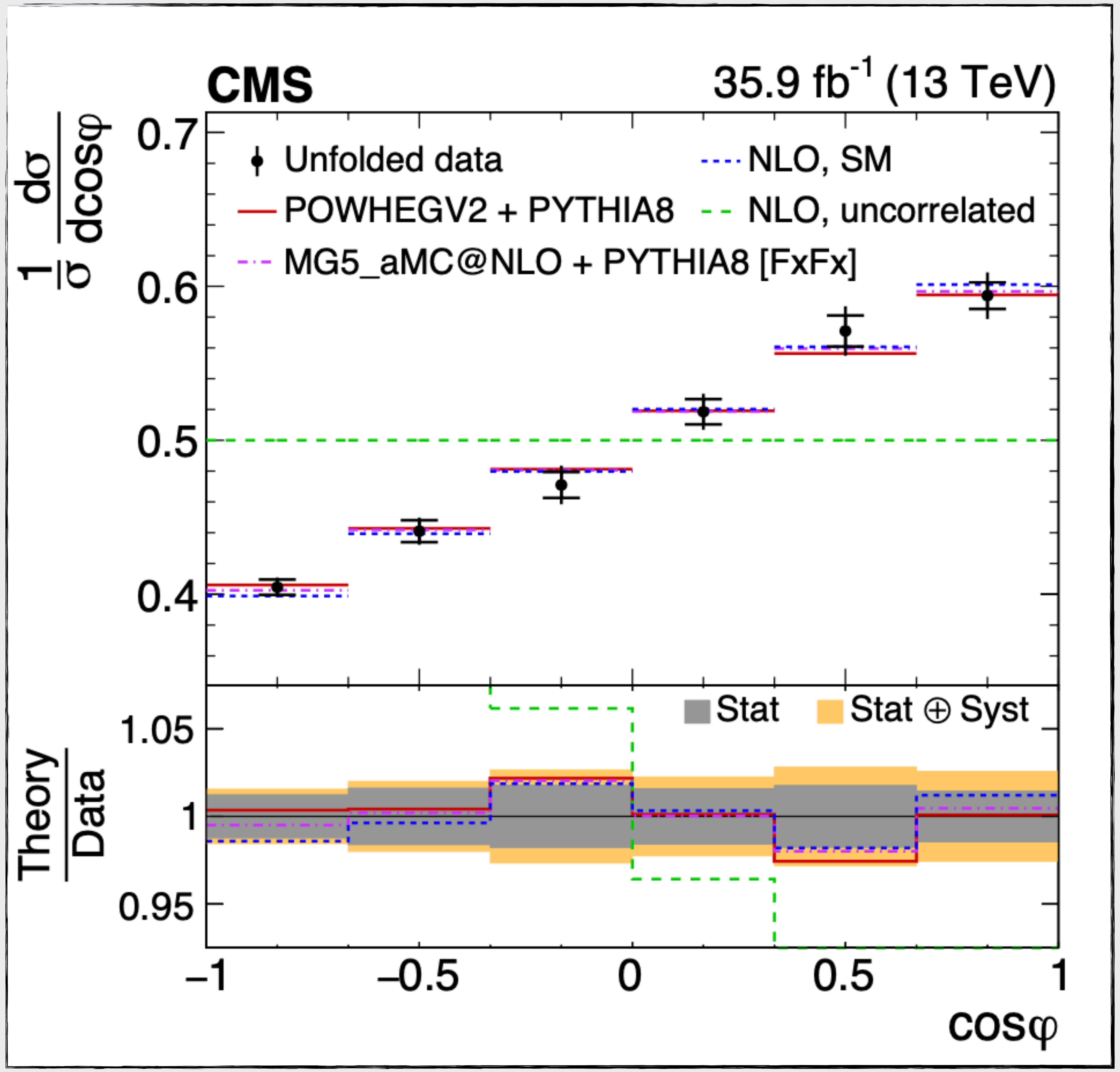
- The condition $\Delta > 0$ translates into $D < -1/3$,
  - $D = -\left(C_{kk} + C_{rr} + C_{nn}\right)/3$
- Experimentally : $\frac{1}{\sigma}\frac{d\sigma}{d\cos\varphi_{\ell\ell}} = \frac{1}{2}\left(1 - D\cos\varphi_{\ell\ell}\right)$
- Needs to be measured differentially as a function of $M_{t\bar{t}}$
  - $M_{t\bar{t}}$ <= 400 Gev:
    - ➡ if D < -1/3, the stat is entangled!



Recent Related Measurement

- Recently, D was measured with no selection on $M_{t\bar{t}}$ by the CMS collaboration.

  - D = −0.237 ± 0.011 > −1/3
  - No search for entanglement



CMS paper

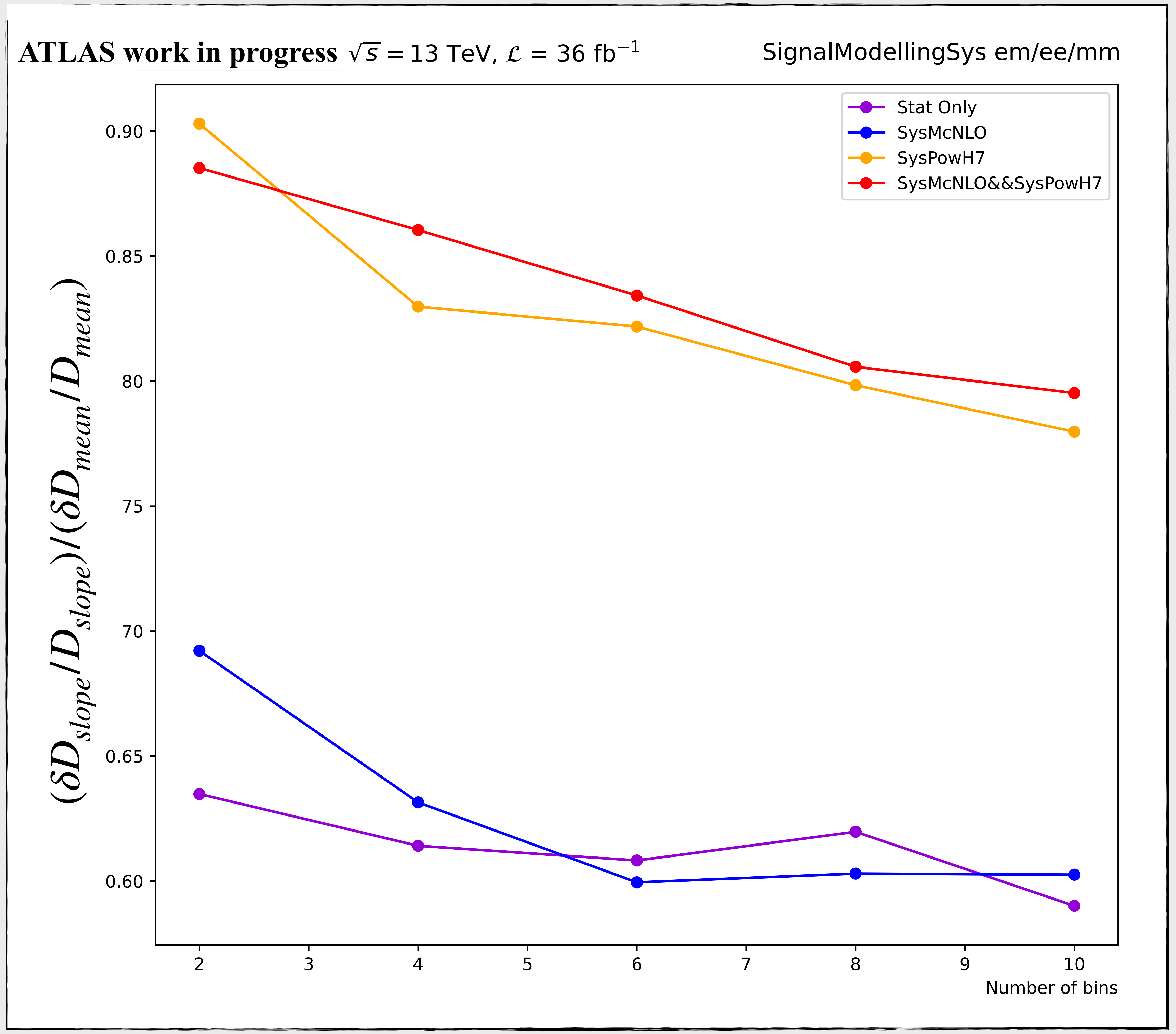
What is the best method for measuring D observable ?

Method

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\varphi_{\ell\ell}} = \frac{1}{2}\left(1 - D\cos\varphi_{\ell\ell}\right)$$

- **Slope method: Measuring the slope of the differential normalised cross-section**
- **Mean method: After integration, one can just measure the mean of the distribution:** $D = -3\left\langle\cos\varphi_{\ell\ell}\right\rangle$
- **Compare both methods:**
  - **Measure the unfolded D using different bin of the distribution** $\cos\varphi_{\ell\ell}$**: 2/4/6/8/10 Bins**
- **With Slope method**
  - ➡ **Stat Only: Gain 40%**
  - ➡ **Stat+syst: Gain 17%**

Results



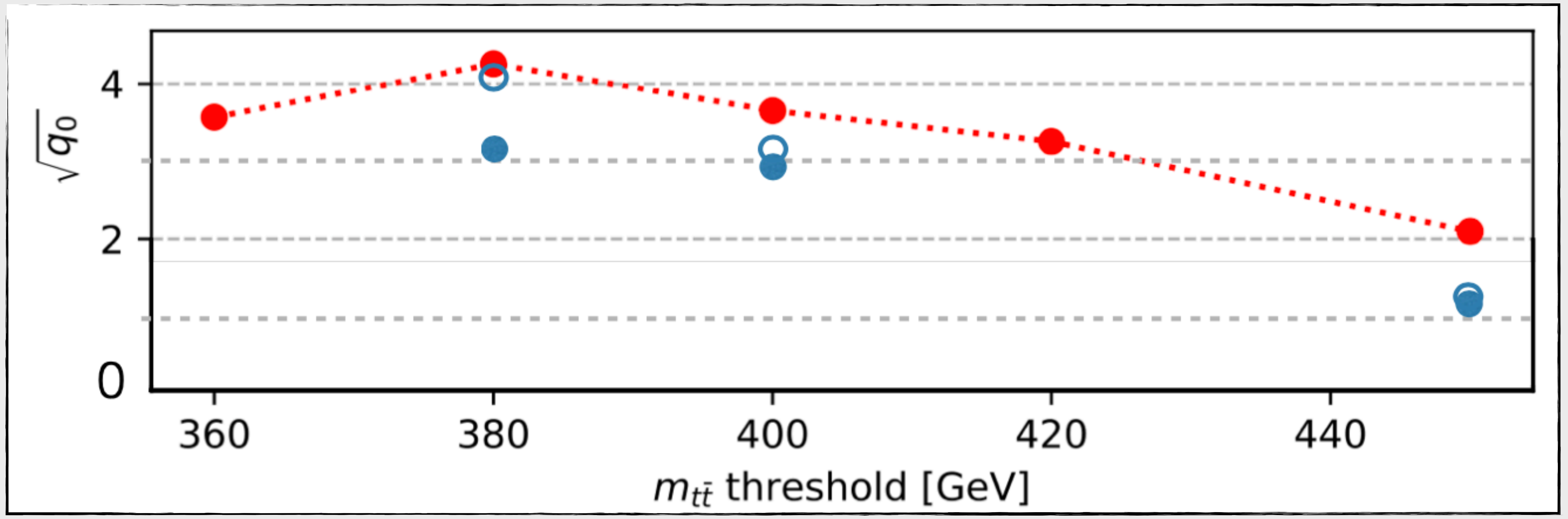
– Use Slope method for the measurement of D observable

Entanglement at LHC ?

- Calculate the likelihood ratio by comparing the observed and the non-entangled values:

$$q_0 = -2\ln\frac{\mathscr{L}(D=-1/3)}{\mathscr{L}(\hat{D})}$$

ATLAS work in progress



- **PLU**
- **IBU*** (ME Pythia)
- **IBU*** (ME herwig)

*all modelling systematics in PLU, only ME & PS in IBU

- Unfold to parton-level:
  - ➡ Profile Likelihood Unfolding (PLU)
  - ➡ Iterative Bayesian Unfolding (IBU)

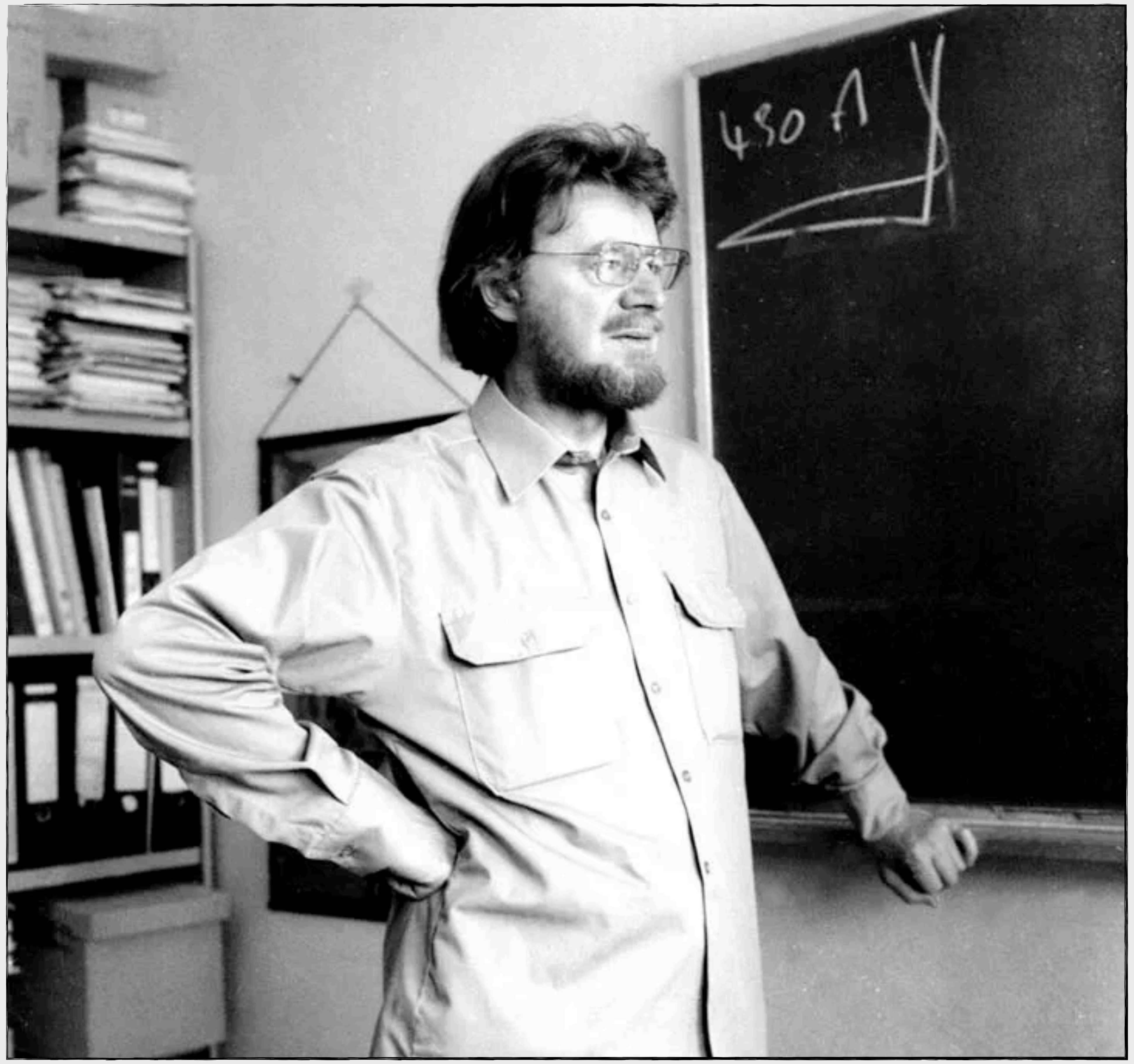
- Tests of both methods are ongoing, but a decision has not been made yet on which method to use.
- Possible first-time measurement of quantum entanglement.

Bell inequalities (BIs) Historically?

- **EPR Paradox:** There are some hidden variables that are missing in order to have a full theory.

- If local hidden variables holds, they should satisfy some inequality.

  - $\mathscr{C}_{A,B} \leq$ constant , where $\mathscr{C}$ measures correlation between the supposedly non-interacting subsystems A and B.

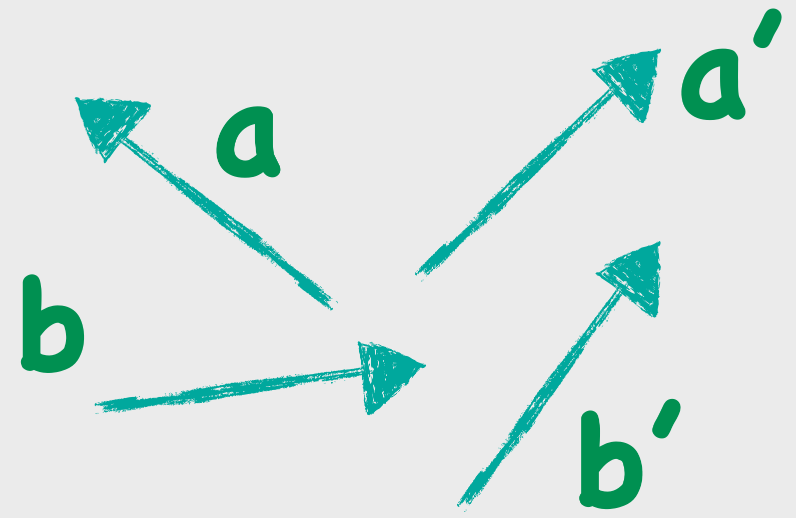


$$\text{Violation of BIs} \implies \text{Entanglement}$$

~~$$\text{Violation of BIs} \impliedby \text{Entanglement}$$~~

Evidence of Bell inequality violation

2110.10112
2102.11883



- **The Bell/CHSH inequality**

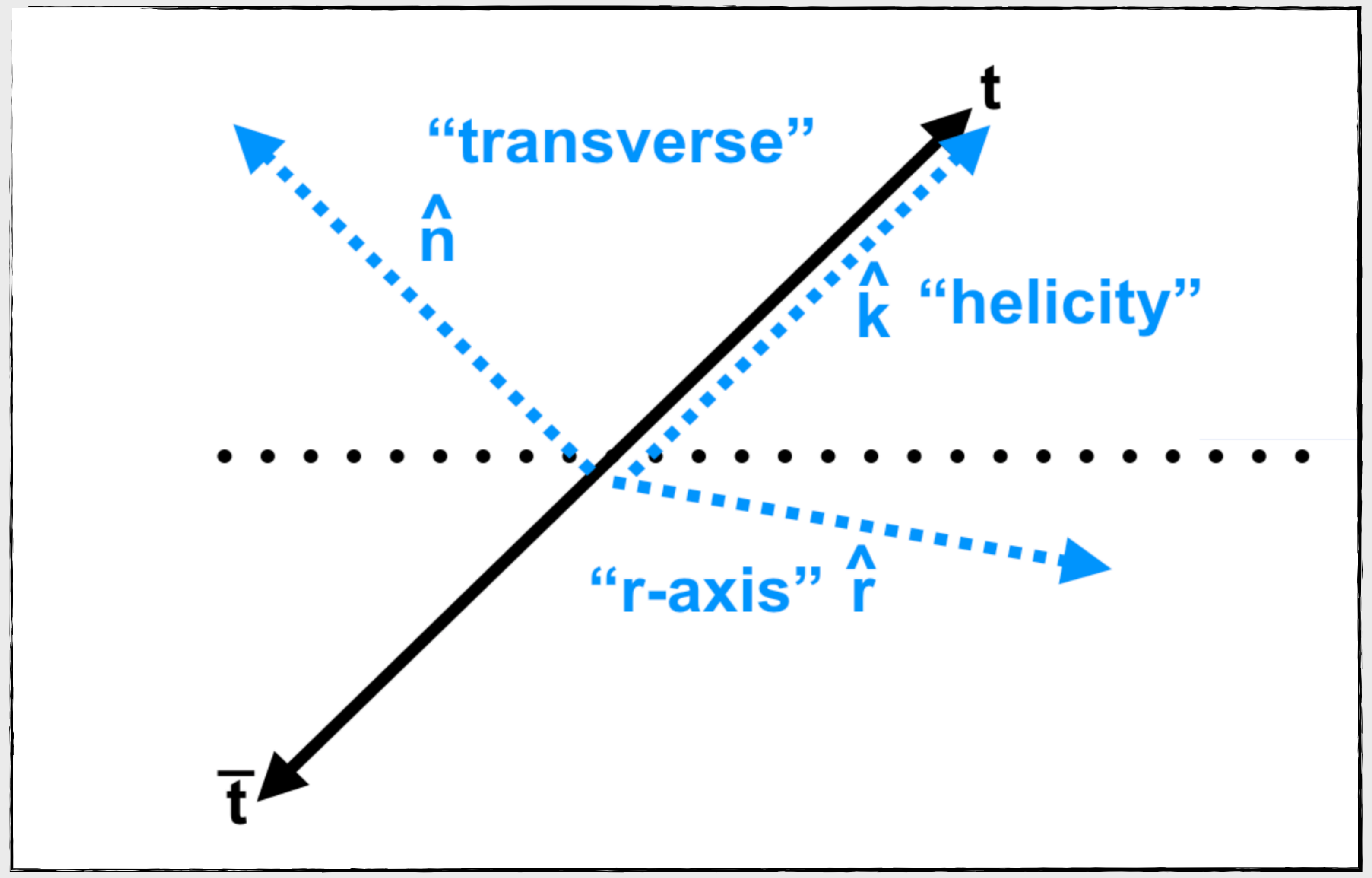
$$\left|\langle ab\rangle - \langle ab'\rangle + \langle a'b\rangle + \langle a'b'\rangle\right| \leq 2$$

- **The Bell/CHSH inequality evaluated for a system described by the $t\bar{t}$ spin density matrix:**

➡ **Method 1:** $\max_{aa'bb'}\left|\langle ab\rangle - \langle ab'\rangle + \langle a'b\rangle + \langle a'b'\rangle\right| = 2\sqrt{\lambda + \lambda'}$

➡ **Method 2:** $|-C_{rr} + C_{nn}| < \sqrt{2}$ (At high $m_{t\bar{t}}$ and θ_{CM})

where λ and λ' are the two largest eigenvalues of C^TC



$$C = \begin{pmatrix} C(\hat{k},\hat{k}) & C(\hat{r},\hat{k}) & C(\hat{n},\hat{k}) \\ C(\hat{k},\hat{r}) & C(\hat{r},\hat{r}) & C(\hat{n},\hat{r}) \\ C(\hat{k},\hat{n}) & C(\hat{r},\hat{n}) & C(\hat{n},\hat{n}) \end{pmatrix}$$

Evidence of Bell inequality violation

- **The Bell/CHSH inequality**

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  - **Method 2:** $|-C_{rr} + C_{nn}| < \sqrt{2}$ **(At high $m_{t\bar{t}}$ and θ_{CM})**

where λ and λ′ are the two largest eigenvalues of C^TC

$$C = \begin{pmatrix} C(\hat{k},\hat{k}) & C(\hat{r},\hat{k}) & C(\hat{n},\hat{k}) \\ C(\hat{k},\hat{r}) & C(\hat{r},\hat{r}) & C(\hat{n},\hat{r}) \\ C(\hat{k},\hat{n}) & C(\hat{r},\hat{n}) & C(\hat{n},\hat{n}) \end{pmatrix}$$

Evidence of Bell inequality violation

- **The Bell/CHSH inequality**

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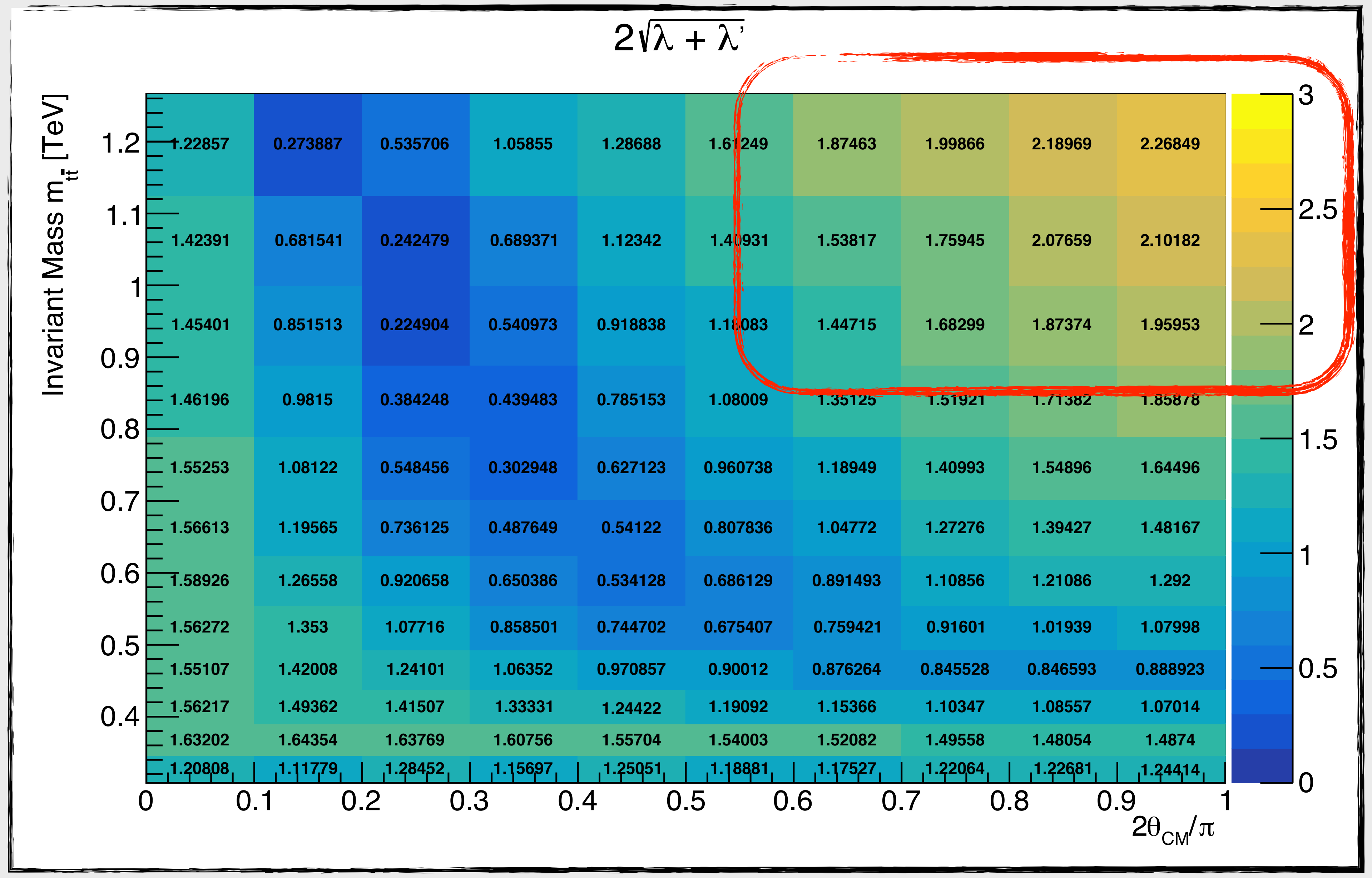
  - ➡ **Method 2:** $|-C_{rr} + C_{nn}| < \sqrt{2}$ (At high $m_{t\bar{t}}$ and θ_{CM})

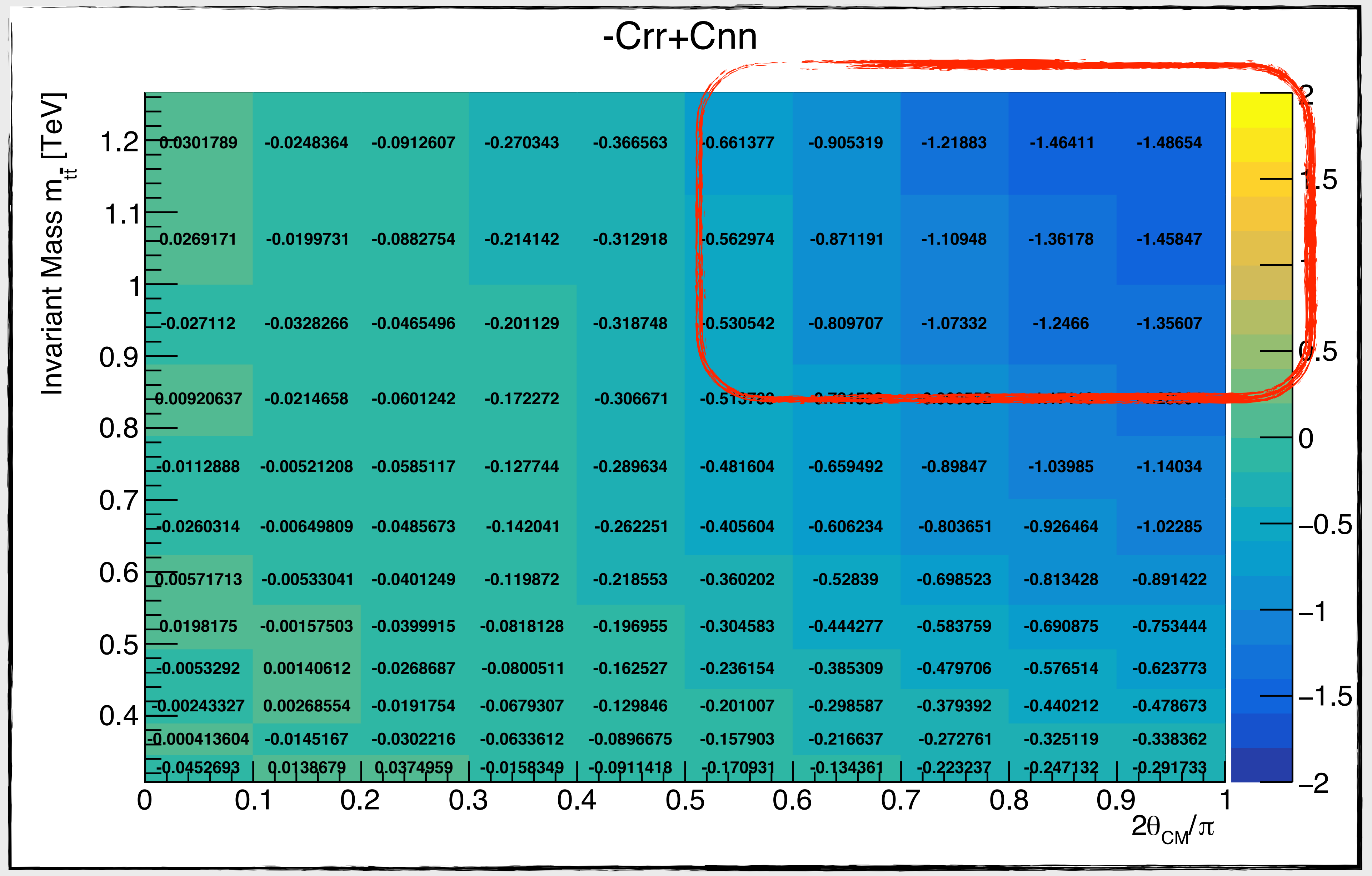
where λ and λ' are the two largest eigenvalues of $C^T C$

$$C = \begin{pmatrix} C(\hat{k},\hat{k}) & C(\hat{r},\hat{k}) & C(\hat{n},\hat{k}) \\ C(\hat{k},\hat{r}) & C(\hat{r},\hat{r}) & C(\hat{n},\hat{r}) \\ C(\hat{k},\hat{n}) & C(\hat{r},\hat{n}) & C(\hat{n},\hat{n}) \end{pmatrix}$$

ATLAS work in progress >= 2 is a violation



ATLAS work in progress <$-\sqrt{2}$ or > $\sqrt{2}$ is a violation



Summary

- Spin correlation ant EFT interpretation
  - ➡ Direct measurements of spin correlations with Full Run2 Data
  - ➡ Precision top quark spin measurements are a powerful probe of new physics and complementary to other approaches.
- Entanglement and BIs
  - ➡ ATLAS preliminary results show the sensitivity of Entanglement between top quarks at the LHC for the first time.
  - ➡ Bell inequalities violations can be tested with LHC data, which is an important test that has not been conducted before.

Thank You

Back-up

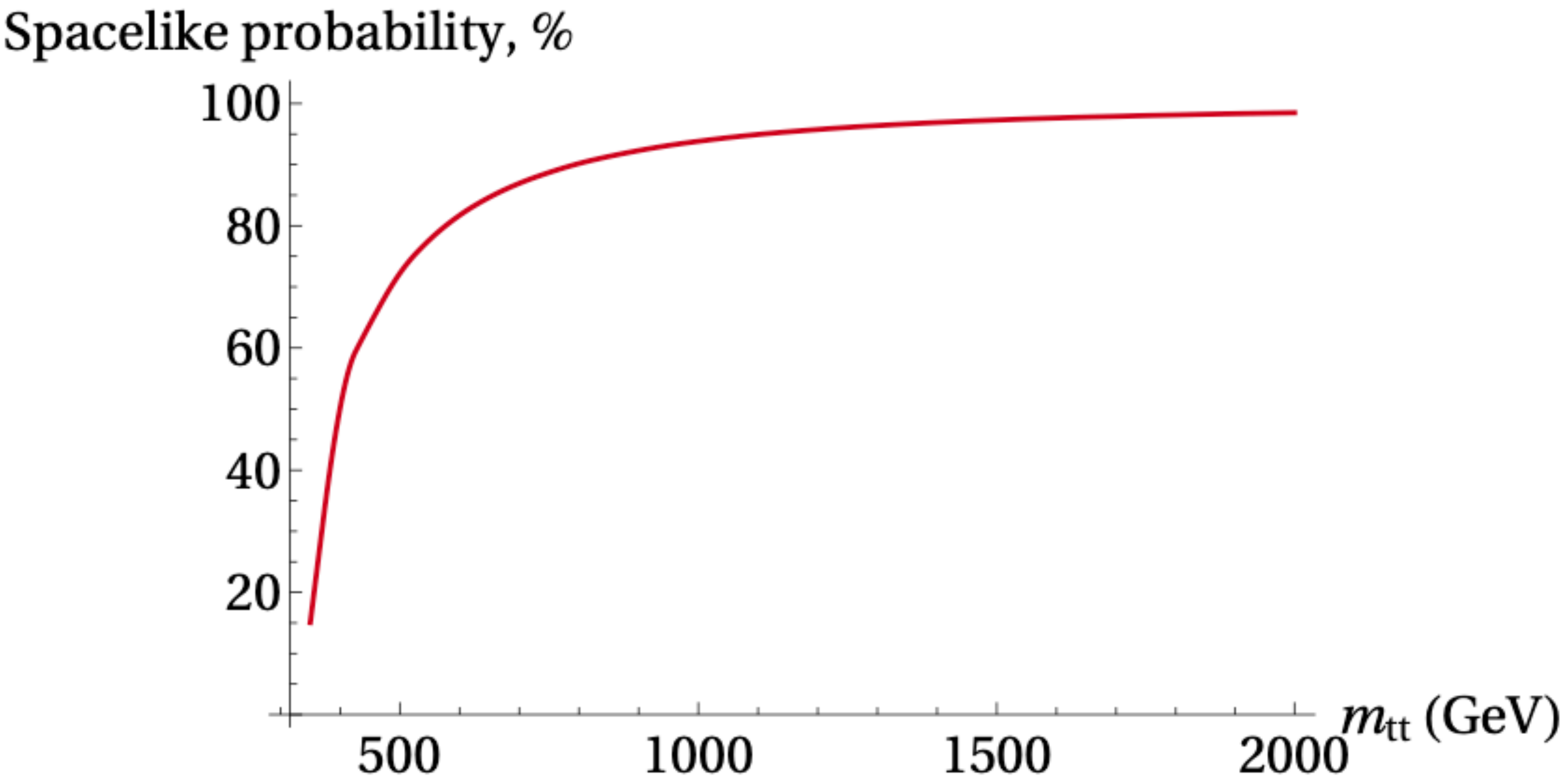


Figure 3.4: Fraction of t and $\bar{t}$ decays that are spacelike separated, for $t\bar{t}$ pairs with a given $m_{t\bar{t}}$.

Comparison of methods

- Disclaimer: there are other unfolding method on the market

IBU:

- ✓ well established method
- ? nominal result indep. on syst.
- ? cannot constrain systematics
- ✗ non-trivial to combine channels
- ✓ can have $N_{truth} \neq N_{reco}$
- ✗ not easy to add control regions, simultaneous background fit...

FBU:

- ✓ successfully used in top analyses
- ✓ syst. included in the formalism
- ? regularization can be added as prior
- ✗ can become computationally intense
- ✓ can handle channel combination, $N_{truth} \neq N_{reco}$, secondary parameter extraction
- ? can constrain systematics (*)

PFU:

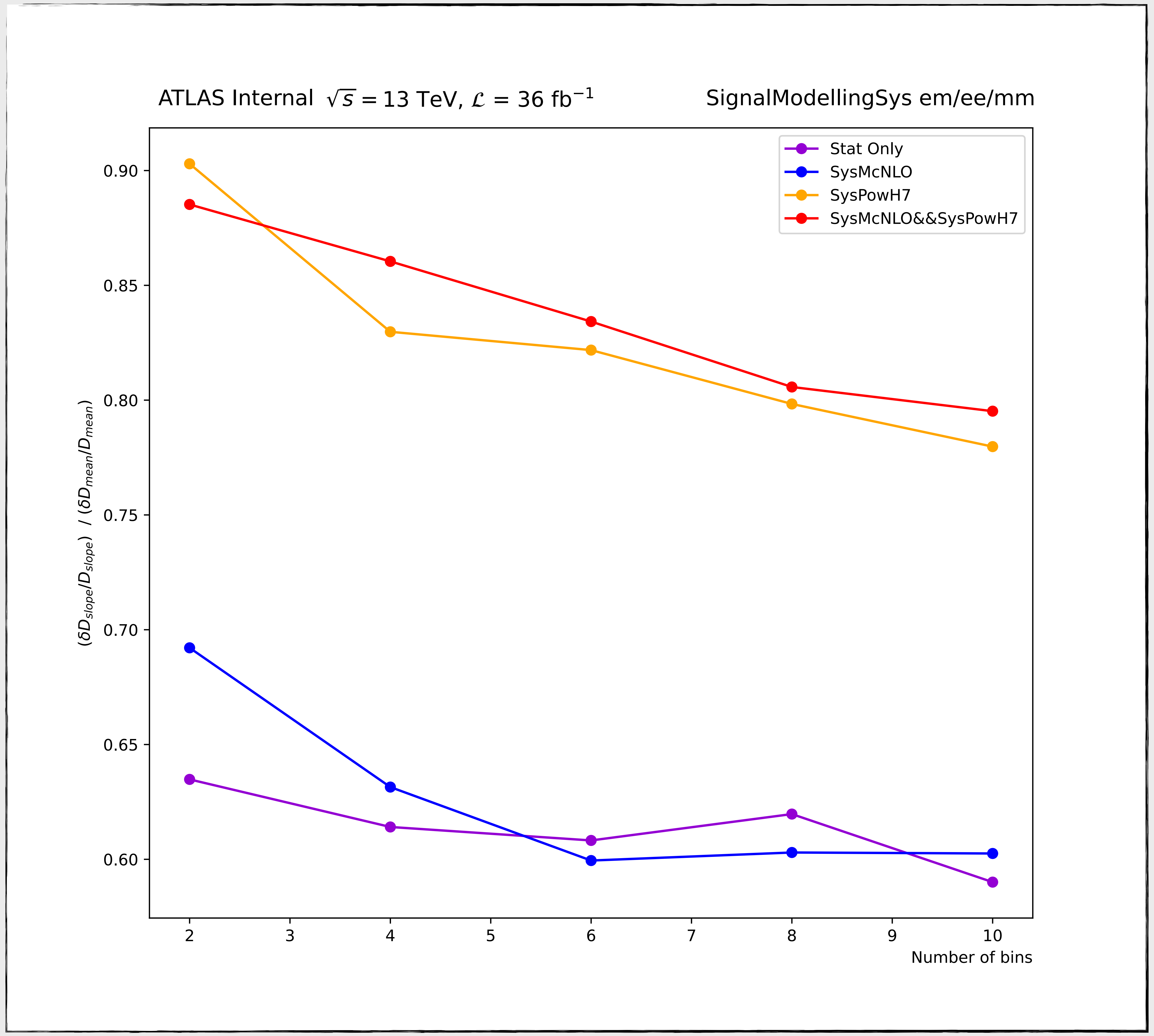
- ? relatively new → need testing!
- ✓ syst. included in the formalism
- ✓ regularization can be added as constraint term(s)
- ✓ easily handles channel combination, $N_{truth} \neq N_{reco}$, secondary parameter extraction
- ? can constrain systematics (*)
- ✓ can easily add control regions
- ✓ coherent formalism with e.g. total cross-sections

ATLAS

32

source

Measurement of D observables: Mean V.s Slope Uncertainty



☑ Uncertainty Gained

NumOfBins	Stat Only	Sys McNLO	Sys PowH7	Sys McNLO,PowH7
2	36 %	31 %	10 %	12 %
4	39 %	37 %	18 %	14 %
6	40 %	41 %	18 %	17 %
8	39 %	40 %	21 %	20 %
10	42 %	40 %	22 %	20 %

What is the best method for measuring D observable ?

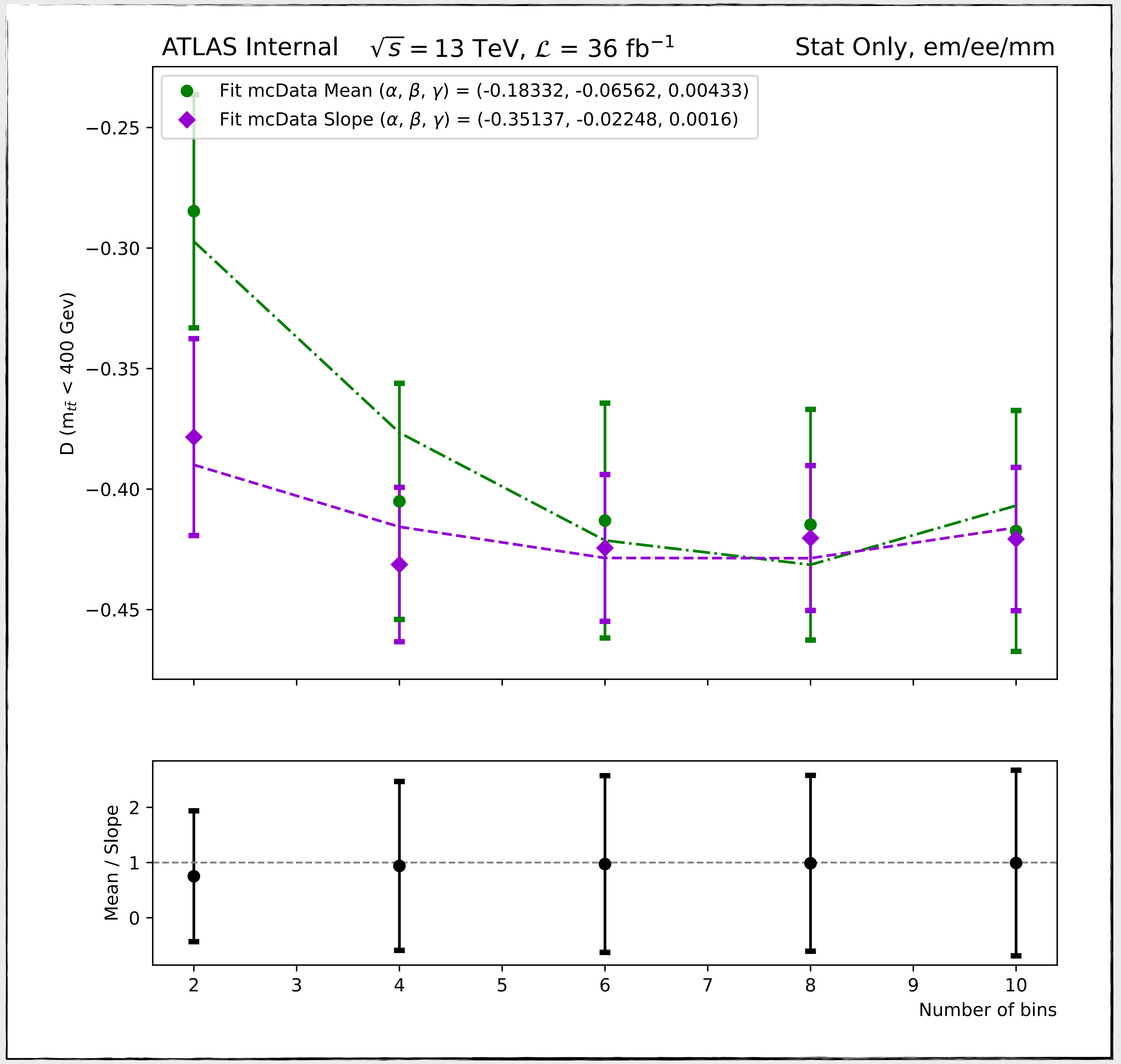
Method

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\varphi_{\ell\ell}} = \frac{1}{2}\left(1 - D\cos\varphi_{\ell\ell}\right)$$

- Slope: Measuring the slope of the differential normalised cross-section
- Mean: After integration, one can just measure the mean of the distribution: $D = -3\left\langle\cos\varphi_{\ell\ell}\right\rangle$
- Compare both methods:
  - Measure the unfolded D using different bin of the distribution $\cos\varphi_{\ell\ell}$: 2/4/6/8/10 Bins
    - ➡ Stat Only
    - ➡ Add Signal modelling systematics

Results

work in progress



- The Mean method is biased by the number of bins
- The Slope method displays a small static error

Define theory model | Process | Detector | Reconstruction | Analysis

Theory paper

Goal

Parton Level

- Where to look for Quantum Entanglement ? → **Entanglement Criterion - Concurrence**

Concurrence $C[\rho] = \frac{\max(\Delta, 0)}{2}$

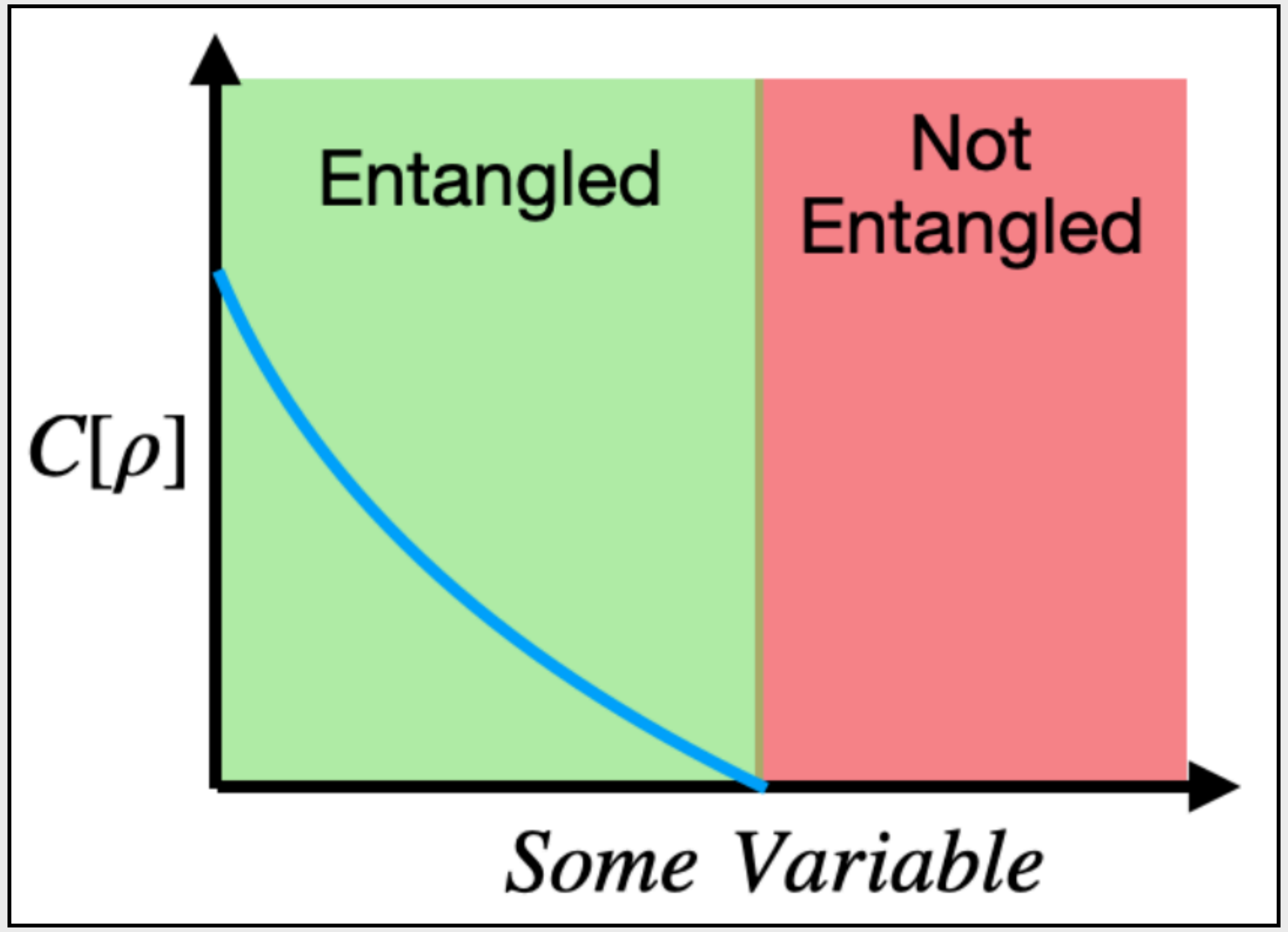
- The $t\bar{t}$ production is described by the production spin density matrix:

$$\rho = \frac{1}{4}\left(1 \otimes 1 + B_i \sigma_i \otimes 1 + \bar{B}_j 1 \otimes \sigma_j + C_{ij} \sigma_i \otimes \sigma_j\right)$$

- By invoking the Peres-Horodecki criterion:

$$\Delta \equiv -C_{nn} + \left|C_{kk} + C_{rr}\right| - 1 > 0$$

is a sufficient condition for the presence of entanglement



Theoretical prediction (LO)

Define theory model | Process | Detector | Reconstruction | Analysis

Theory paper

Goal

Parton Level

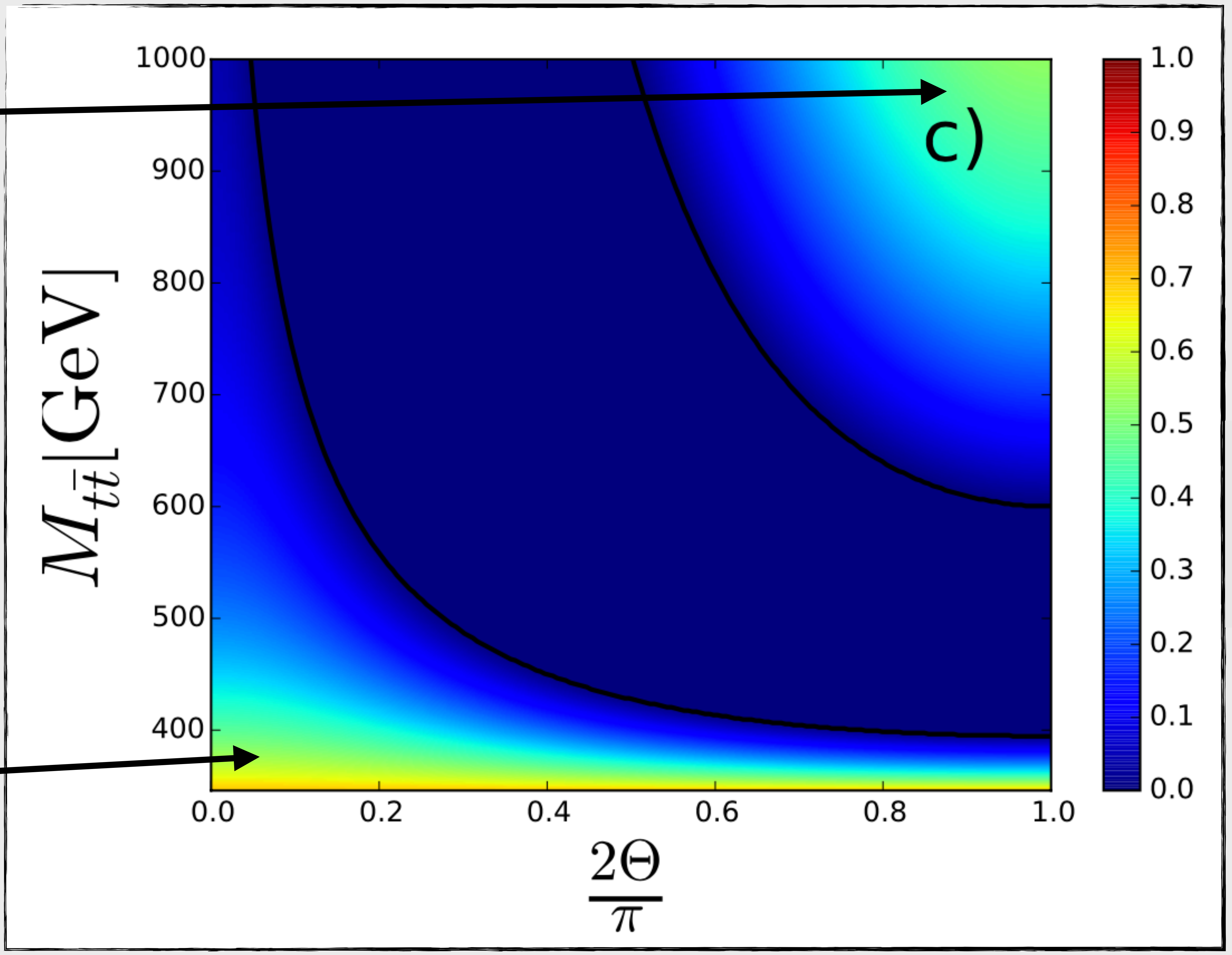
- Where to look for Quantum Entanglement ? → **Entanglement Criterion - Concurrence**

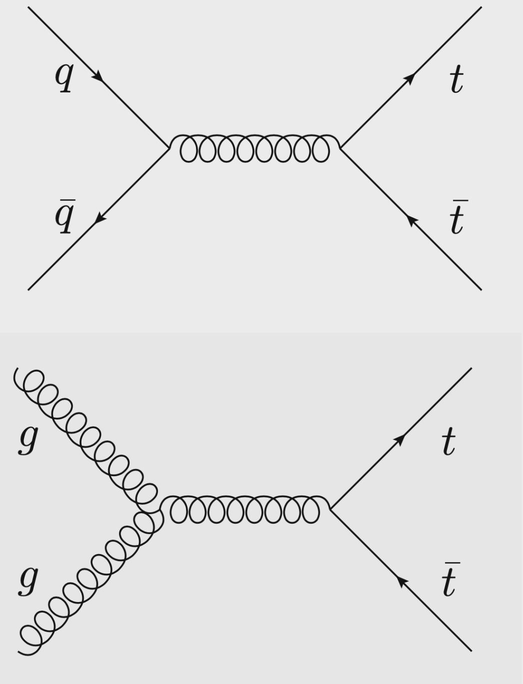
◉ At high energies and production angles, $t\bar{t}$ pair are produced in a spin-triplet pure state, not separable → Max. Entangled

$$|\Psi_\infty\rangle = \frac{|\uparrow_{\hat{n}}\downarrow_{\hat{n}}\rangle + |\downarrow_{\hat{n}}\uparrow_{\hat{n}}\rangle}{\sqrt{2}}$$

◉ At threshold, $t\bar{t}$ pair are produced in a spin-singlet state, not separable → Max. Entangled

$$|\Psi_0\rangle = \frac{|\uparrow_{\hat{n}}\downarrow_{\hat{n}}\rangle - |\downarrow_{\hat{n}}\uparrow_{\hat{n}}\rangle}{\sqrt{2}}$$





Theoretical prediction (LO)

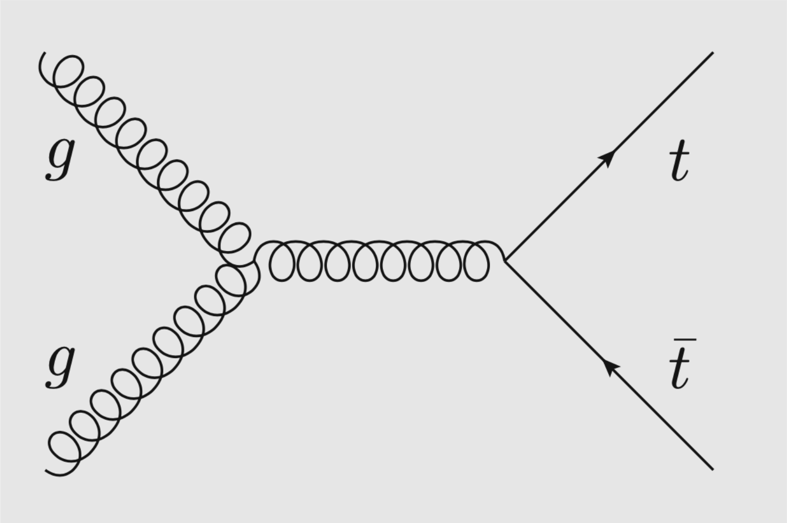
Define theory model | Process | Detector | Reconstruction | Analysis

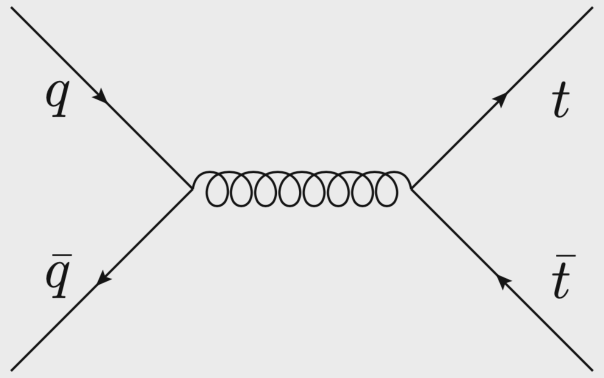
Theory paper

Goal

Parton Level

- Where to look for Quantum Entanglement ? → **Entanglement Criterion - Concurrence**





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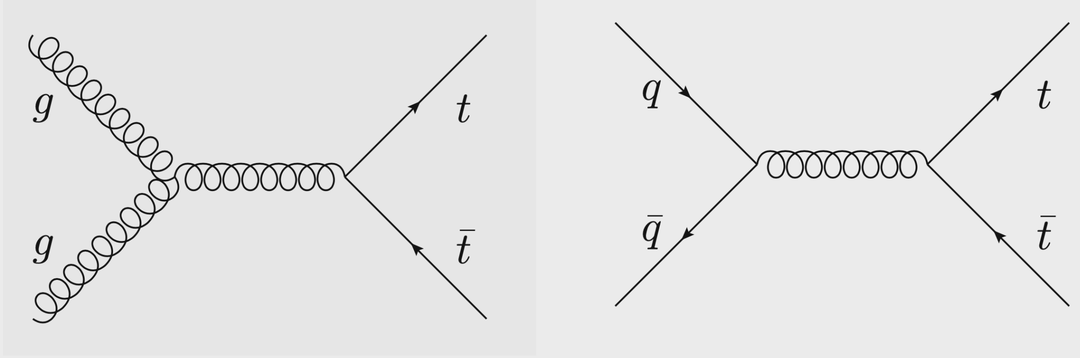

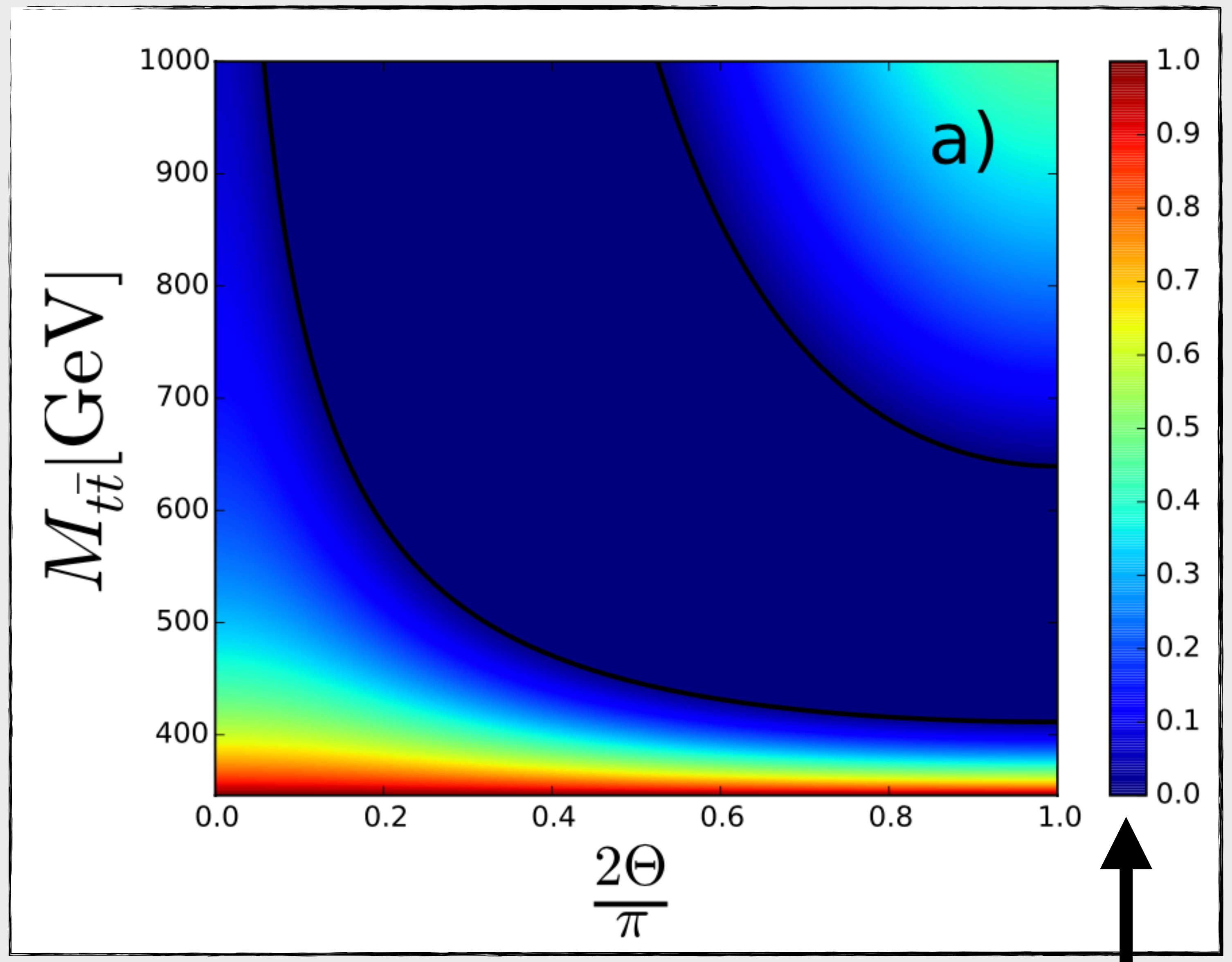

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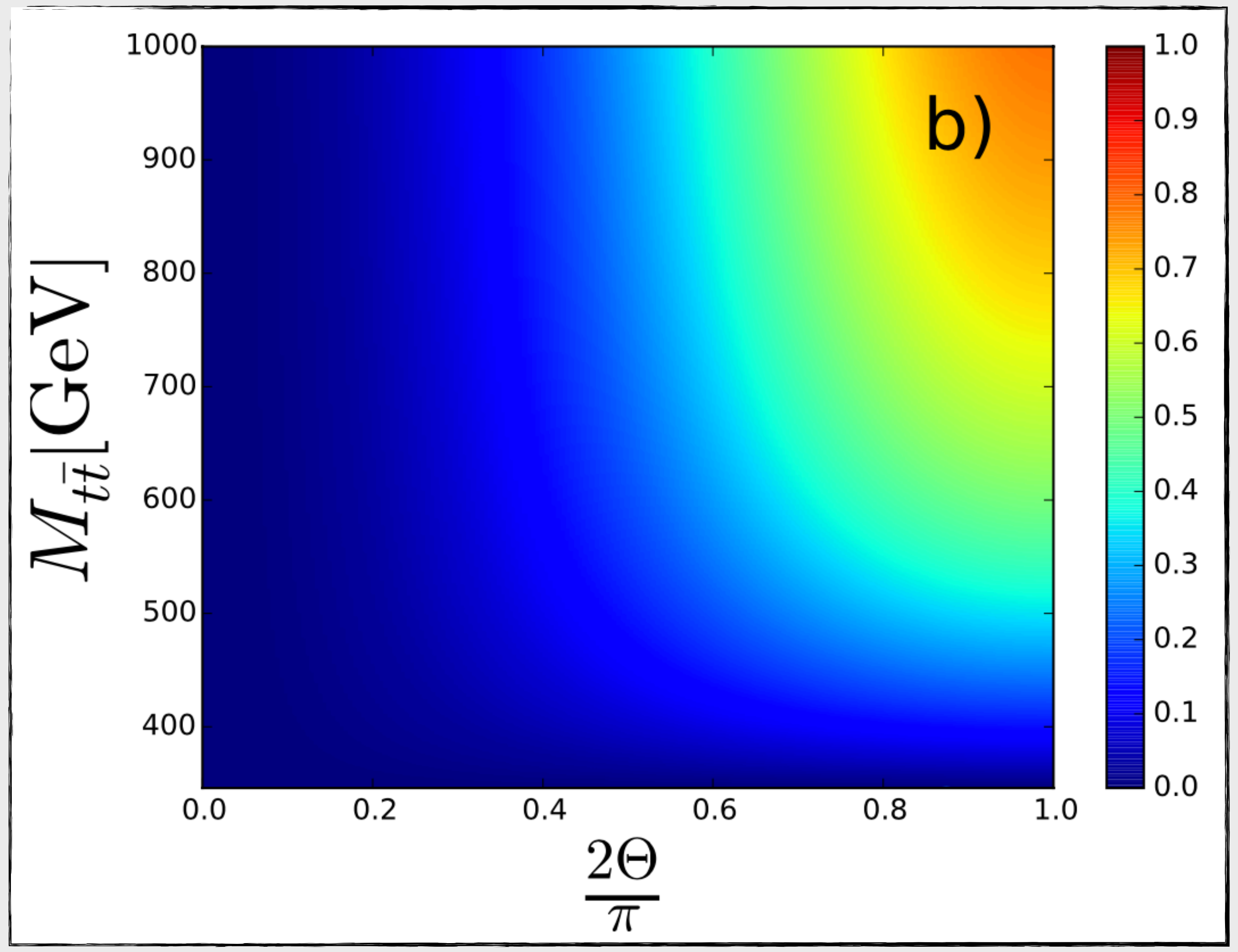

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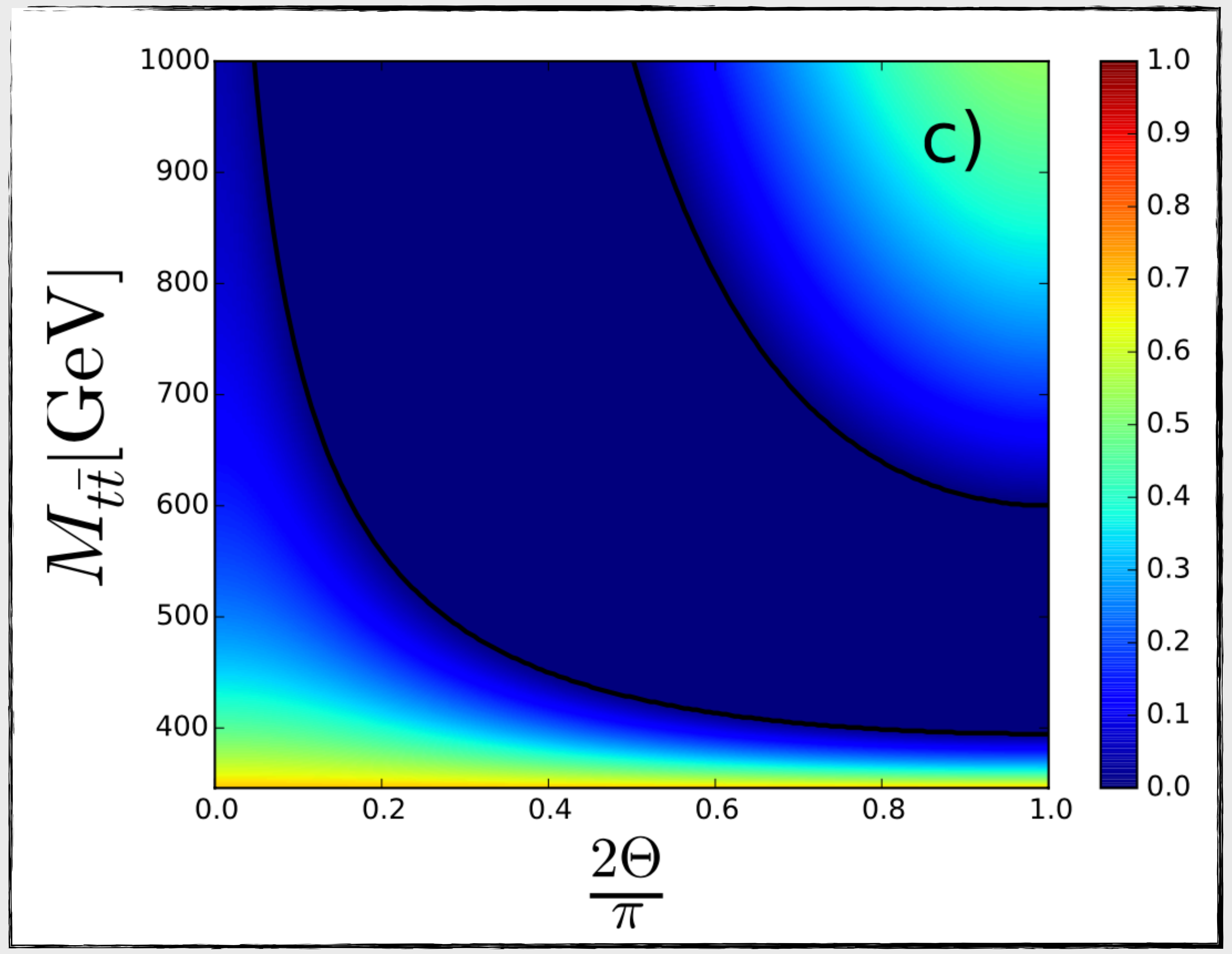


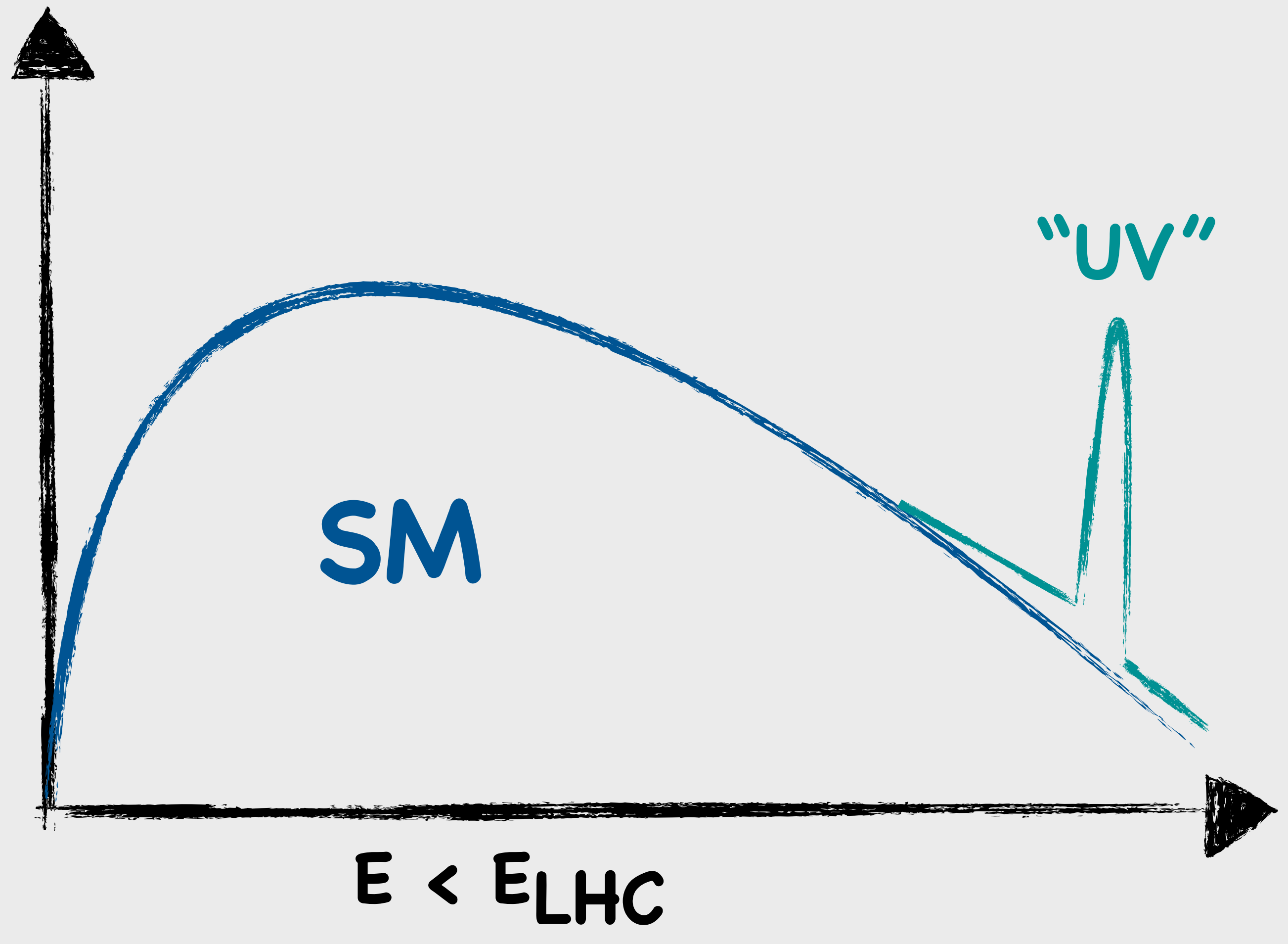
Concurrence $C[\rho]$

Theoretical prediction (LO)

How to look for new physics, physics beyond SM ?

Direct searches

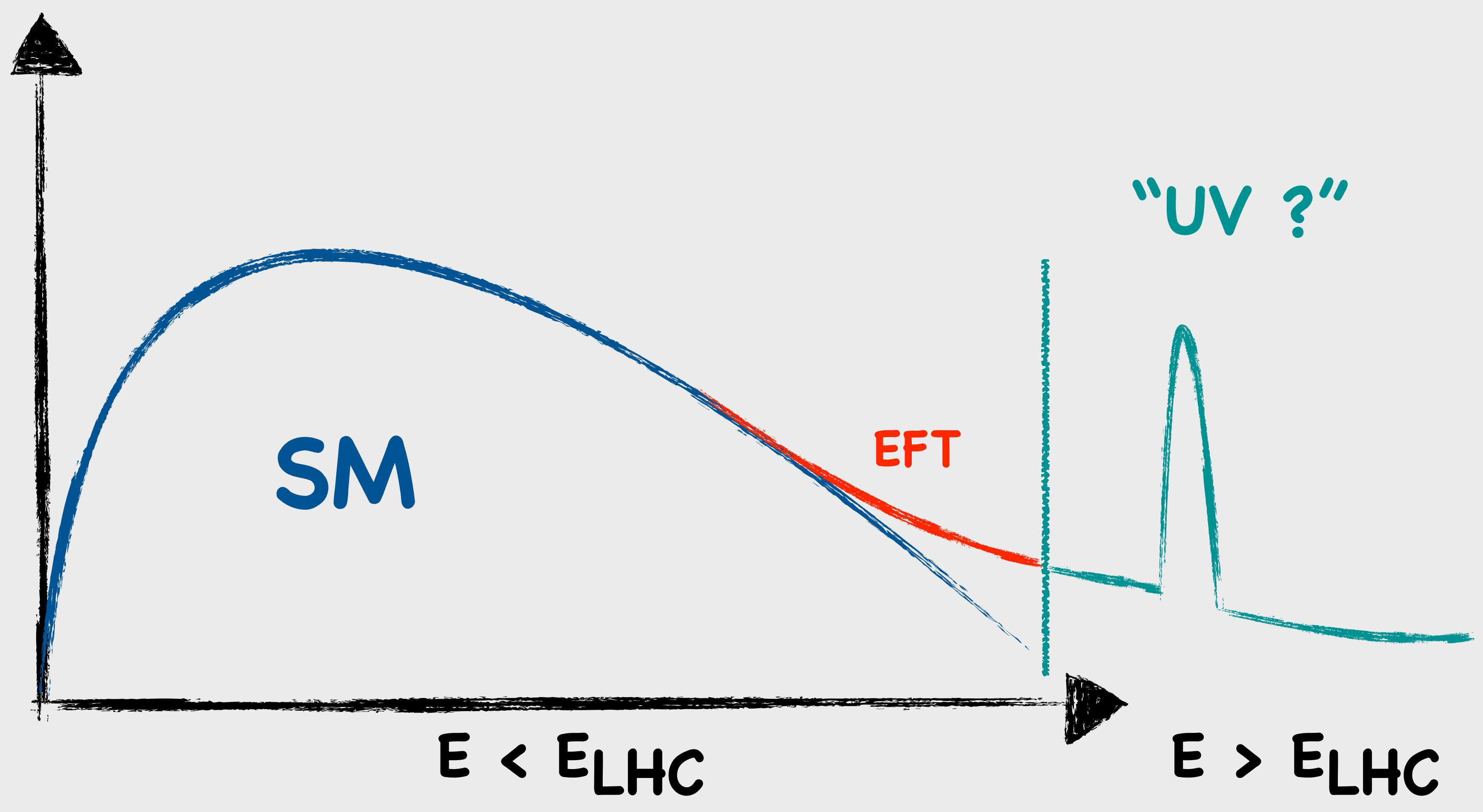
Model-Dependent, e.g. SUSY



Bump hunts

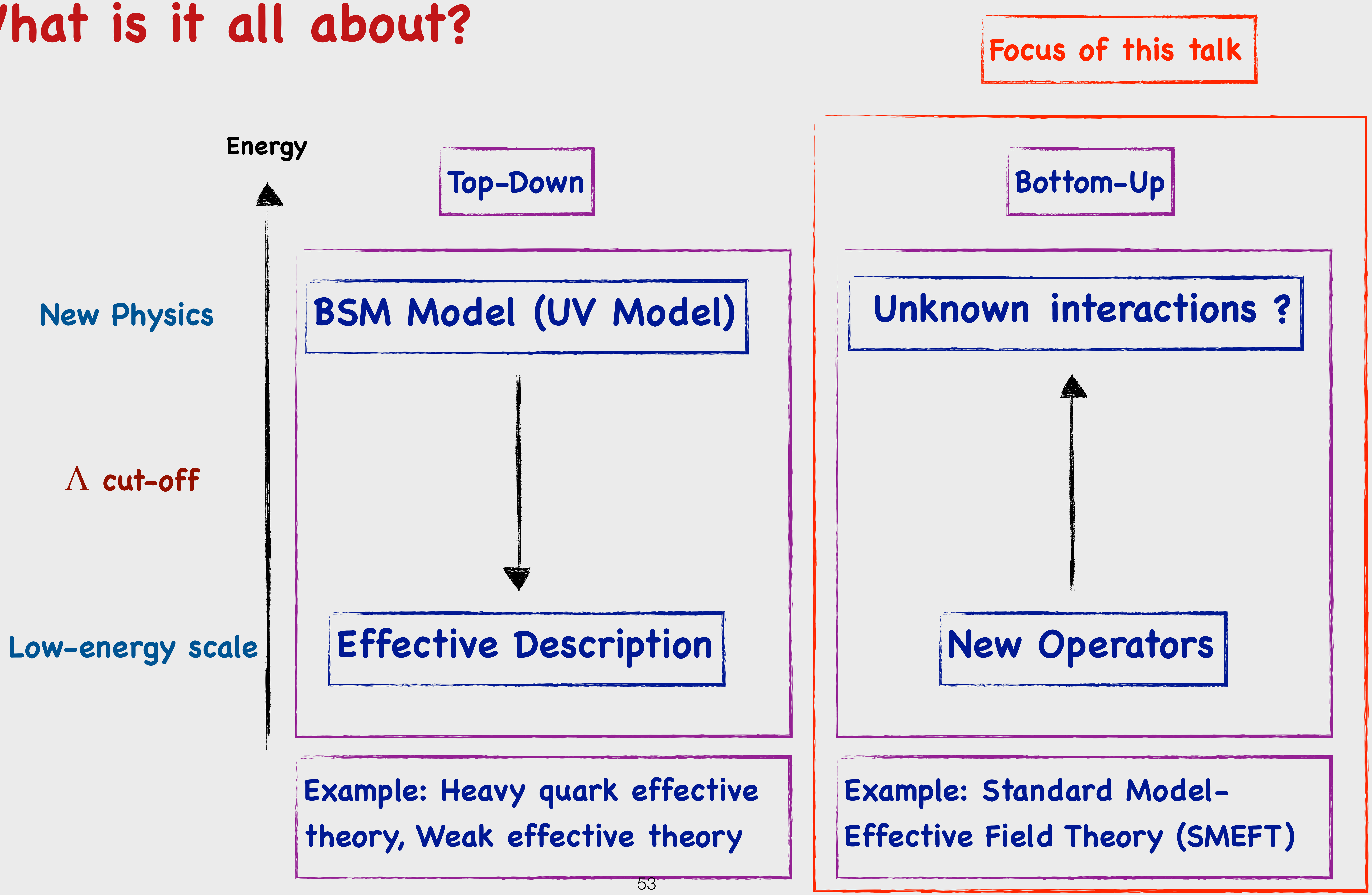
Indirect searches

Model-Independent, e.g. Effective Field Theory (EFT)



Scouting tails

EFT: What is it all about?



SM-EFT: Dim6 operators

	ψ	Φ	X	D
Dim	3/2	1	2	1

'Warsaw' basis

Grzadkowski–Iskrzynski–Misiak–Rosiek

$(\bar L L)(\bar L L)$		$(\bar R R)(\bar R R)$		$(\bar L L)(\bar R R)$	
$\mathcal{O}_{ll}$	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$	$\mathcal{O}_{ee}$	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$	$\mathcal{O}_{le}$	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
$\mathcal{O}_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$	$\mathcal{O}_{uu}$	$(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$	$\mathcal{O}_{lu}$	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
$\mathcal{O}_{qq}^{(3)}$	$(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$	$\mathcal{O}_{dd}$	$(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$	$\mathcal{O}_{ld}$	$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$
$\mathcal{O}_{lq}^{(1)}$	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$	$\mathcal{O}_{eu}$	$(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$	$\mathcal{O}_{qe}$	$(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$
$\mathcal{O}_{lq}^{(3)}$	$(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$	$\mathcal{O}_{ed}$	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$	$\mathcal{O}_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
		$\mathcal{O}_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$\mathcal{O}_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
		$\mathcal{O}_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$	$\mathcal{O}_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
				$\mathcal{O}_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$

$(\bar L R)(\bar R L)$ and $(\bar L R)(\bar L R)$		B-violating	
$\mathcal{O}_{ledq}$	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	$\mathcal{O}_{duq}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$\mathcal{O}_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	$\mathcal{O}_{qqu}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$\mathcal{O}_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	$\mathcal{O}_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$\mathcal{O}_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	$\mathcal{O}_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$\mathcal{O}_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$	$\mathcal{O}_{duu}$	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

$q = q_L$, $l = l_L$, $u = u_R$, $d = d_R$, $e = e_R$, p, r, s, t = generation indices

Grzadkowski–Iskrzynski–Misiak–Rosiek

X^3		Φ^6 and $\Phi^4 D^2$		$\psi^2\Phi^3$	
$\mathcal{O}_G$	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$\mathcal{O}_\Phi$	$(\Phi^\dagger\Phi)^3$	$\mathcal{O}_{e\Phi}$	$(\Phi^\dagger\Phi)(\bar l_p e_r \Phi)$
$\mathcal{O}_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$\mathcal{O}_{\Phi\Box}$	$(\Phi^\dagger\Phi)\Box(\Phi^\dagger\Phi)$	$\mathcal{O}_{u\Phi}$	$(\Phi^\dagger\Phi)(\bar q_p u_r \widetilde\Phi)$
$\mathcal{O}_W$	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$\mathcal{O}_{\Phi D}$	$(\Phi^\dagger D^\mu\Phi)^\star(\Phi^\dagger D_\mu\Phi)$	$\mathcal{O}_{d\Phi}$	$(\Phi^\dagger\Phi)(\bar q_p d_r \Phi)$
$\mathcal{O}_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\Phi^2$		$\psi^2 X\Phi$		$\psi^2\Phi^2 D$	
$\mathcal{O}_{\Phi G}$	$\Phi^\dagger\Phi\, G^A_{\mu\nu} G^{A\mu\nu}$	$\mathcal{O}_{eW}$	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I\Phi\, W^I_{\mu\nu}$	$\mathcal{O}_{\Phi l}^{(1)}$	$(\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar l_p\gamma^\mu l_r)$
$\mathcal{O}_{\Phi\widetilde G}$	$\Phi^\dagger\Phi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	$\mathcal{O}_{eB}$	$(\bar l_p \sigma^{\mu\nu} e_r)\Phi\, B_{\mu\nu}$	$\mathcal{O}_{\Phi l}^{(3)}$	$(\Phi^\dagger i\overleftrightarrow{D}^I_\mu\Phi)(\bar l_p\tau^I\gamma^\mu l_r)$
$\mathcal{O}_{\Phi W}$	$\Phi^\dagger\Phi\, W^I_{\mu\nu} W^{I\mu\nu}$	$\mathcal{O}_{uG}$	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\Phi\, G^A_{\mu\nu}$	$\mathcal{O}_{\Phi e}$	$(\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar e_p\gamma^\mu e_r)$
$\mathcal{O}_{\Phi\widetilde W}$	$\Phi^\dagger\Phi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	$\mathcal{O}_{uW}$	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I\widetilde\Phi\, W^I_{\mu\nu}$	$\mathcal{O}_{\Phi q}^{(1)}$	$(\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar q_p\gamma^\mu q_r)$
$\mathcal{O}_{\Phi B}$	$\Phi^\dagger\Phi\, B_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{uB}$	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\Phi\, B_{\mu\nu}$	$\mathcal{O}_{\Phi q}^{(3)}$	$(\Phi^\dagger i\overleftrightarrow{D}^I_\mu\Phi)(\bar q_p\tau^I\gamma^\mu q_r)$
$\mathcal{O}_{\Phi\widetilde B}$	$\Phi^\dagger\Phi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{dG}$	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\Phi\, G^A_{\mu\nu}$	$\mathcal{O}_{\Phi u}$	$(\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar u_p\gamma^\mu u_r)$
$\mathcal{O}_{\Phi WB}$	$\Phi^\dagger\tau^I\Phi\, W^I_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{dW}$	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I\Phi\, W^I_{\mu\nu}$	$\mathcal{O}_{\Phi d}$	$(\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar d_p\gamma^\mu d_r)$
$\mathcal{O}_{\Phi\widetilde WB}$	$\Phi^\dagger\tau^I\Phi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{dB}$	$(\bar q_p \sigma^{\mu\nu} d_r)\Phi\, B_{\mu\nu}$	$\mathcal{O}_{\Phi ud}$	$i(\widetilde\Phi^\dagger D_\mu\Phi)(\bar u_p\gamma^\mu d_r)$

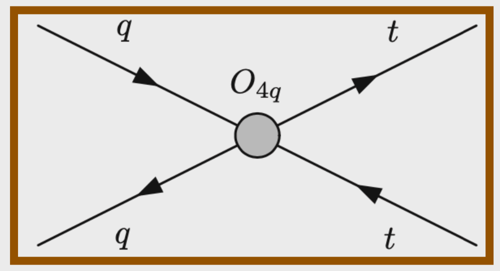
$q = q_L$, $l = l_L$, $u = u_R$, $d = d_R$, $e = e_R$, $\overleftrightarrow{D}^I_\mu \equiv \tau^I\overrightarrow{D}_\mu - \overleftarrow{D}_\mu\tau^I$, p, r = generation indices

Field strength tensors, $X_{\mu\nu} \in \left\{G^A_{\mu\nu}, W^I_{\mu\nu}, B_{\mu\nu}\right\}$

Define theory model → Process → Detector → Reconstruction → Analysis

Parton Level

Mean Method



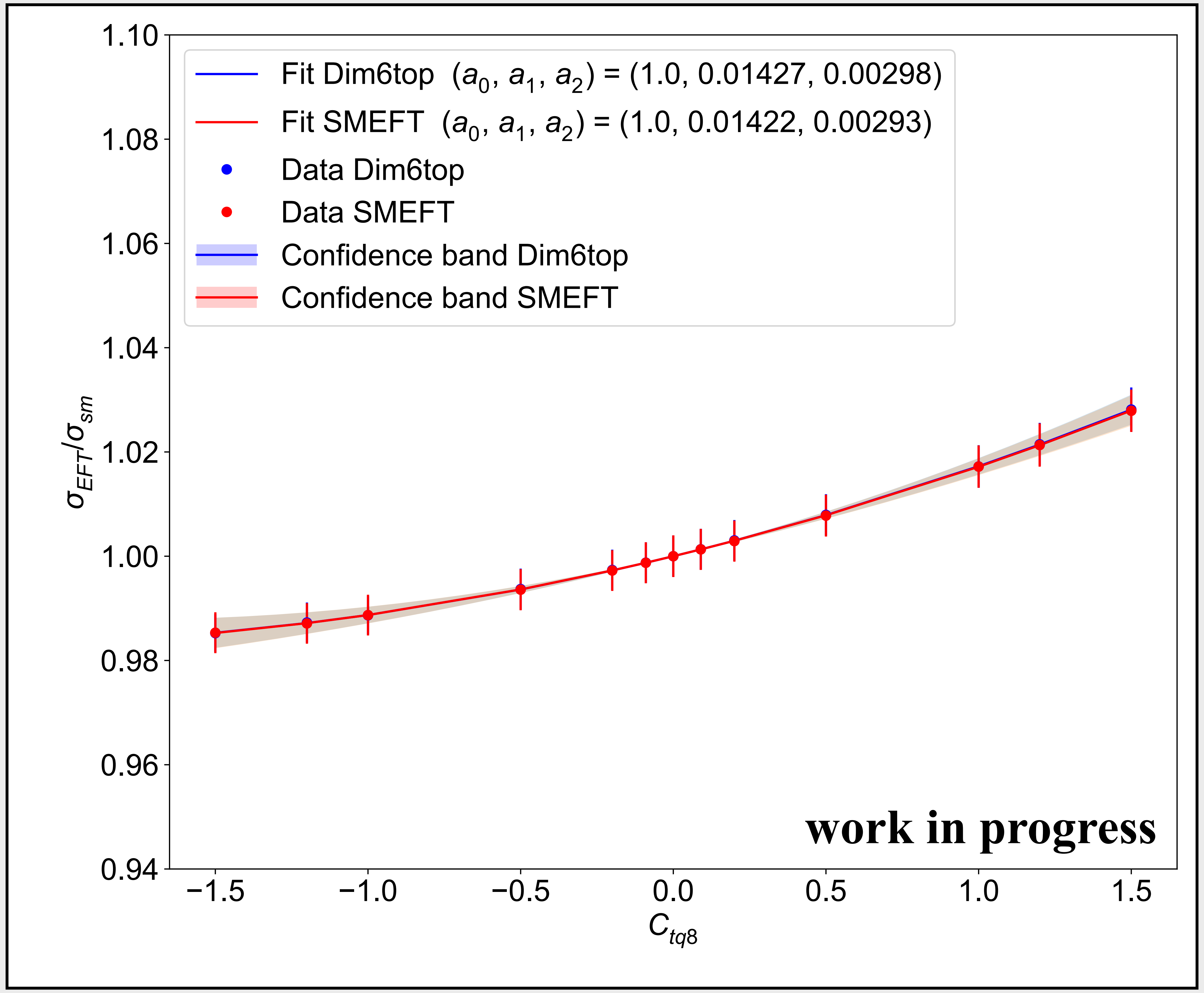
$$\sigma^k = \sigma^k_{SM} + \frac{C_{tq8}}{\Lambda^2}\alpha + \frac{C^2_{tq8}}{\Lambda^4}\beta$$

Goal

In what way does the EFT affect the spin correlation at LO and NLO?

Method

- Cross validate the SMEFT@NLO implementation agains Dim6Top model



Comments

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- SMEFT@NLO model and Dim6top model show appx. same value of α_{ctq8} and β_{ctq8} [within the statistical uncertainties.]

Analysis strategy

Define theory model

- ☑ Standard Model (SM)
- ☑ EFT model to predict new physics (SMEFT@NLO, Dim6Top)

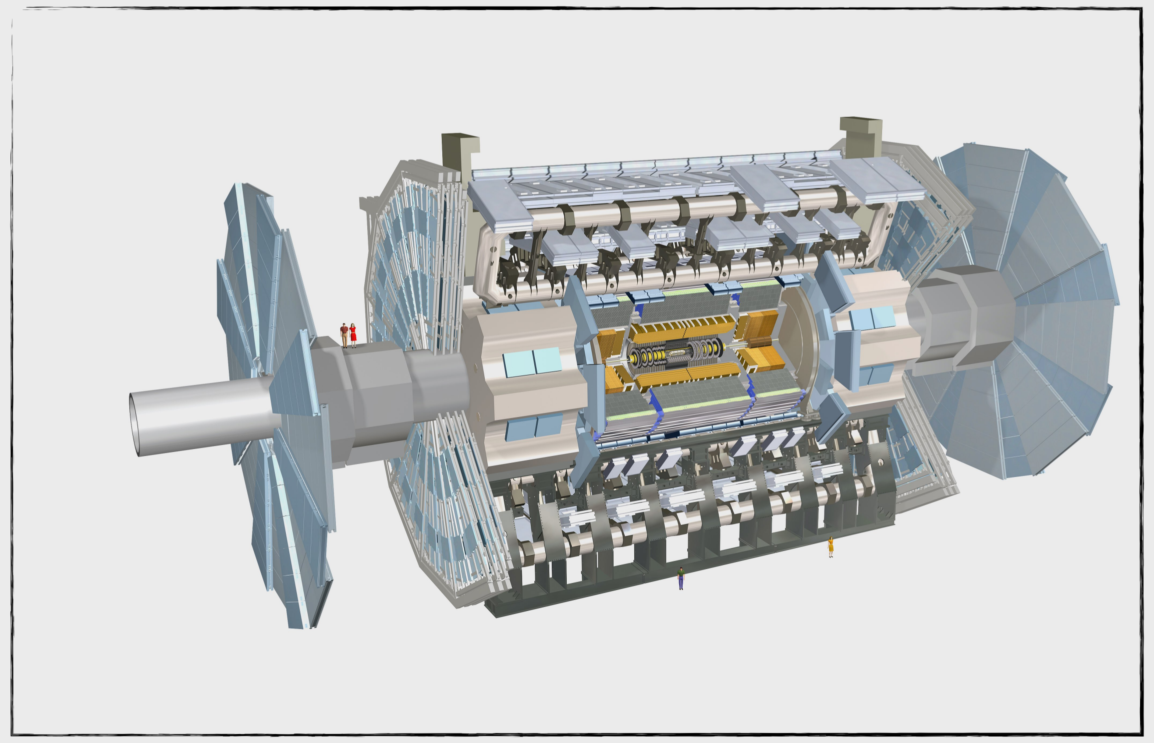
Analysis strategy

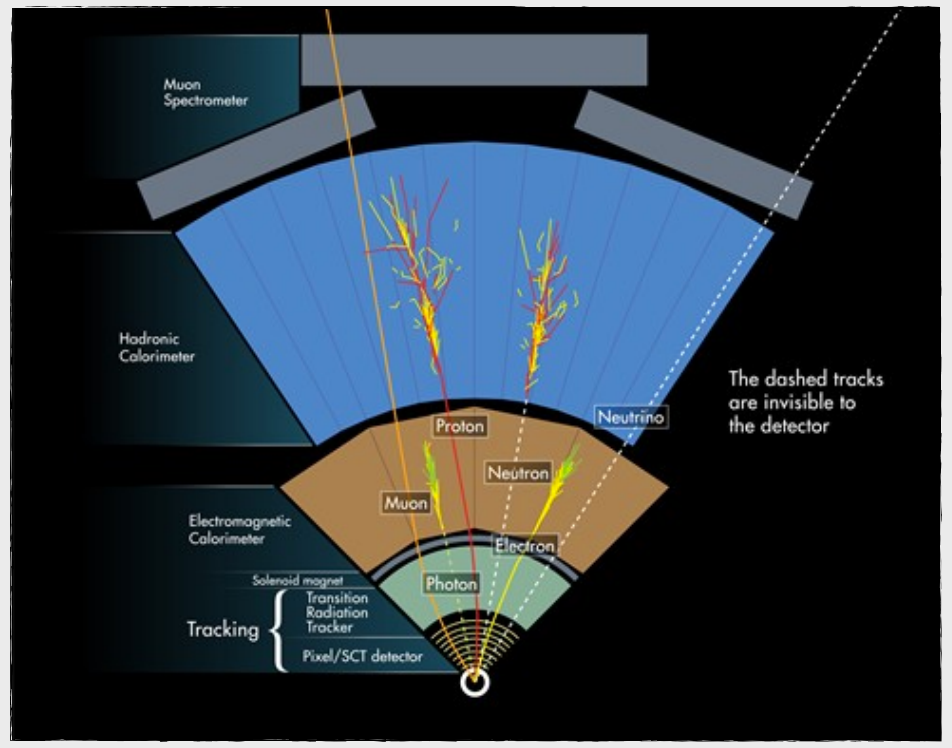
Define theory model → Process

- ☑ Generate proton-proton collision
- ☑ Define the degree of precision of the simulation: LO / NLO ...

Analysis strategy

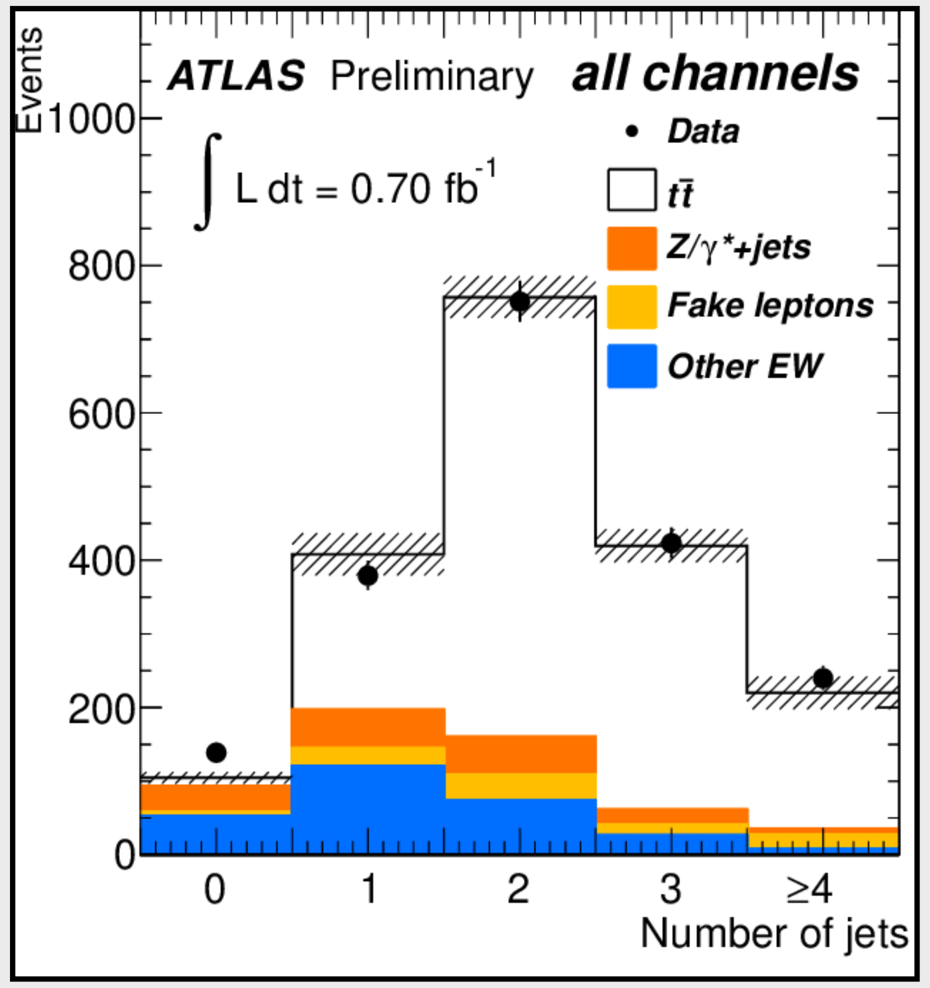
Define theory model → Process → Detector → Reconstruction



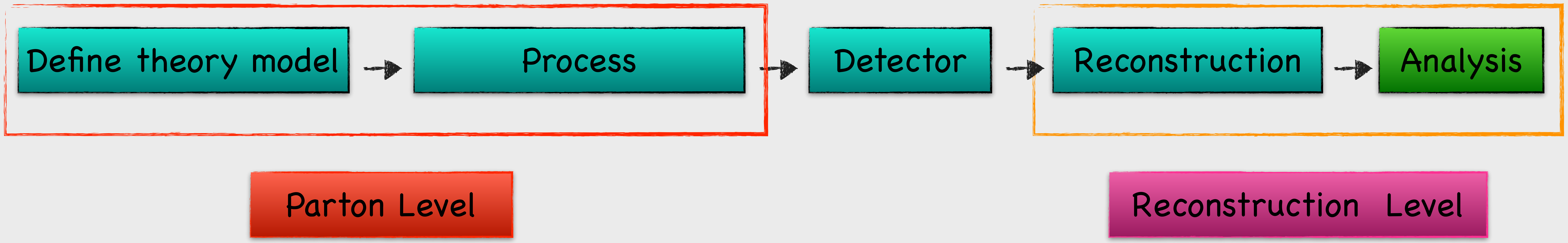


Analysis strategy

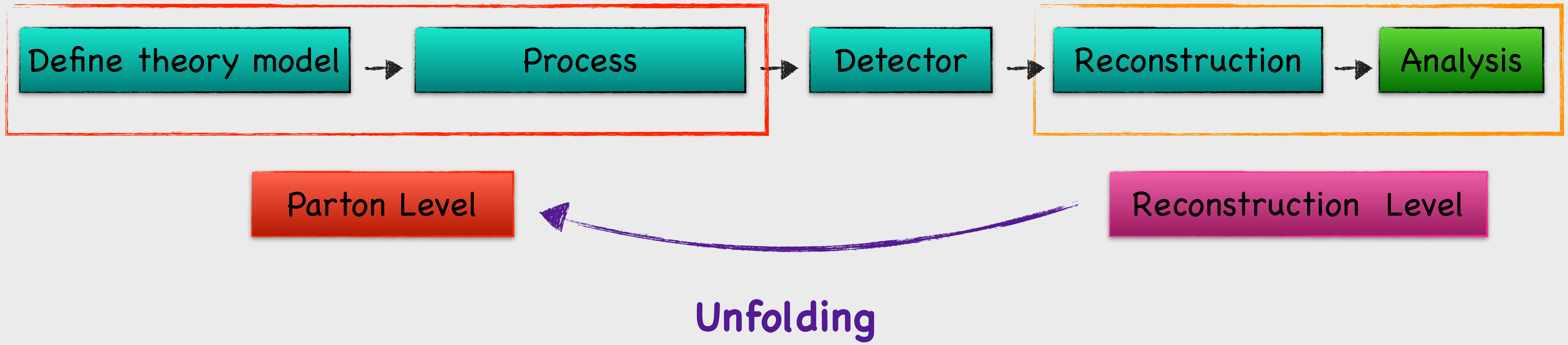
Define theory model → Process → Detector → Reconstruction → **Analysis**



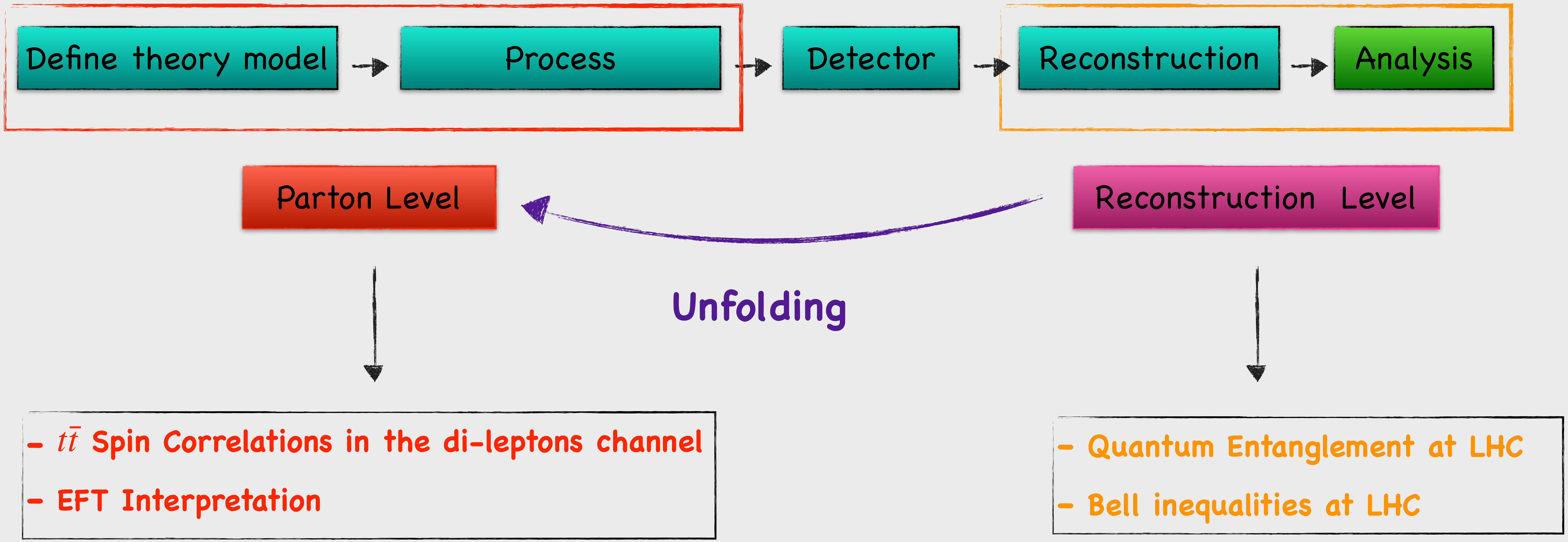
Analysis strategy



Analysis strategy



Analysis strategy



Define theory model → Process → Detector → Reconstruction → Analysis

Parton Level

Motivation

- Preform Global Fit using Spin correlation observes at LO or NLO to constrain Wilson Coefficient ?

Method

- Generate simulation samples:
  - Define EFT model : SMEFT@NLO model (LO / NLO)
    - SM
    - SMEFT@NLO model ==> LO and NLO

Define theory model → Process → Detector → Reconstruction → Analysis

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- What Wilson coefficients should be considered ?
  - Ctg
  - 4-quark operators: ctq8

Define theory model → Process → Detector → Reconstruction → Analysis

Parton Level

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- Decay tops (using MadSpin)
  - Possible at LO and impossible at NLO

Define theory model → Process → Detector → Reconstruction → Analysis

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- What Wilson coefficients should be considered ?
  - Ctg
  - 4-quark operators: ctq8

- Decay tops (using MadSpin)
  - Possible at LO and impossible at NLO

- What effect does this have on the EFT contribution to spin correlation at LO and NLO?

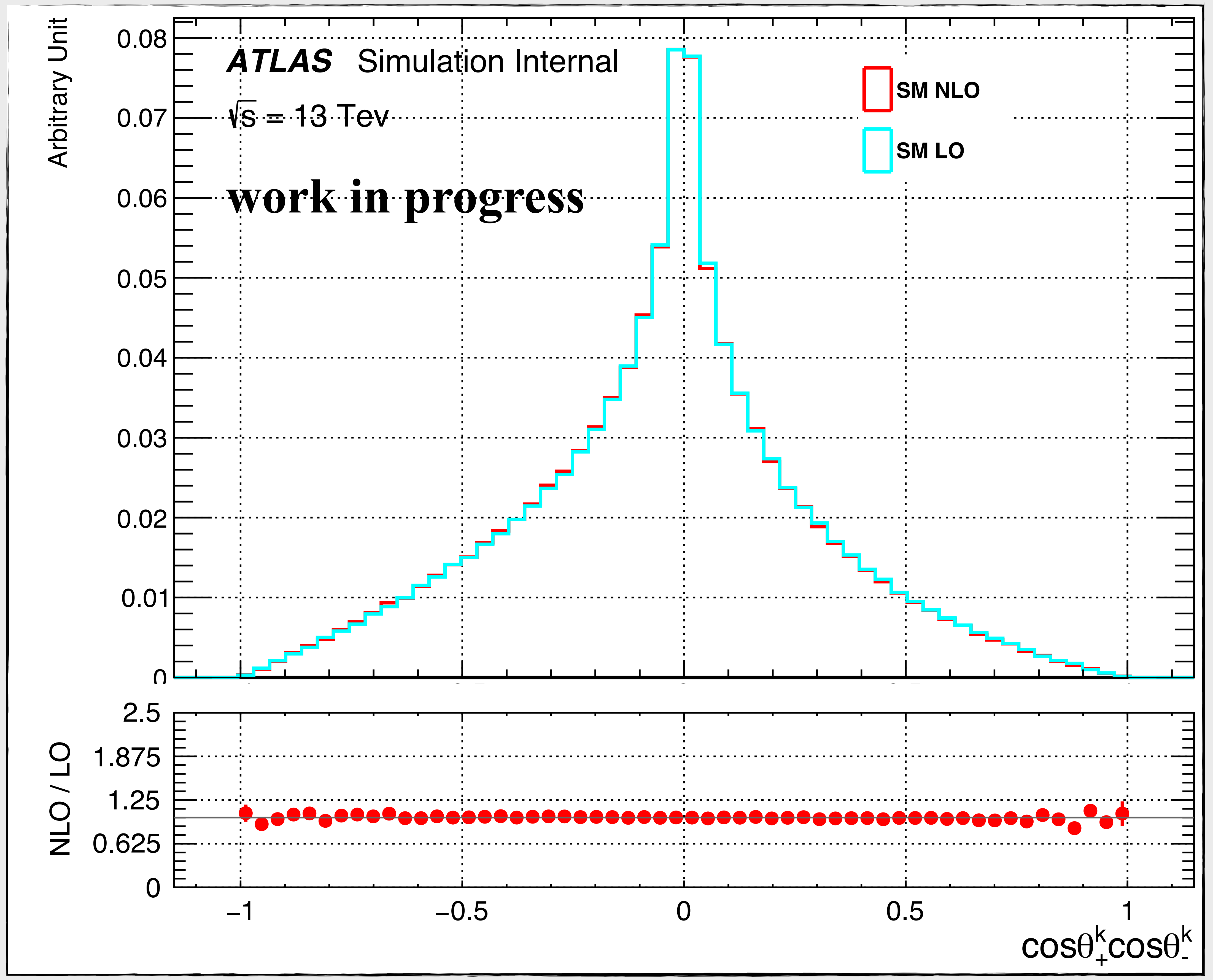
Define theory model → Process → Detector → Reconstruction → Analysis

Parton Level

Goal

- **How does spin correlation change in SM at LO and NLO?**
- In what way does the EFT affect the spin correlation at LO and NLO?

Results



Mean Method: $C(\hat{k},\hat{k}) = -9 < \cos\theta_+^{\hat{k}} \cos\theta_-^{\hat{k}} >$

SM LO : C(k, k) = 0.341 +/- 0.004 (stat)

SM NLO : C(k, k) = 0.366 +/- 0.004 (stat)

- **Consistent with SM expectations (NLO from 1508.05271)**
- **Using SM at NLO: Gain 2%**

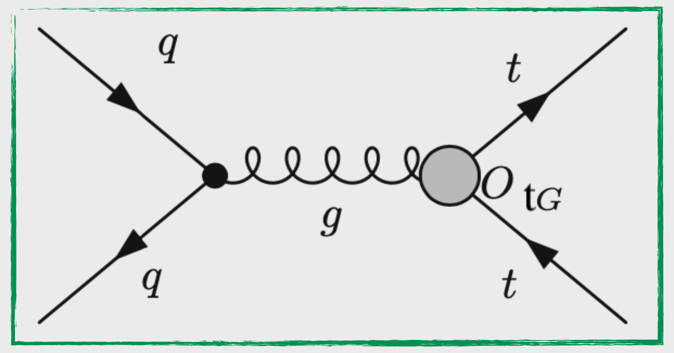
Define theory model → Process → Detector → Reconstruction → Analysis

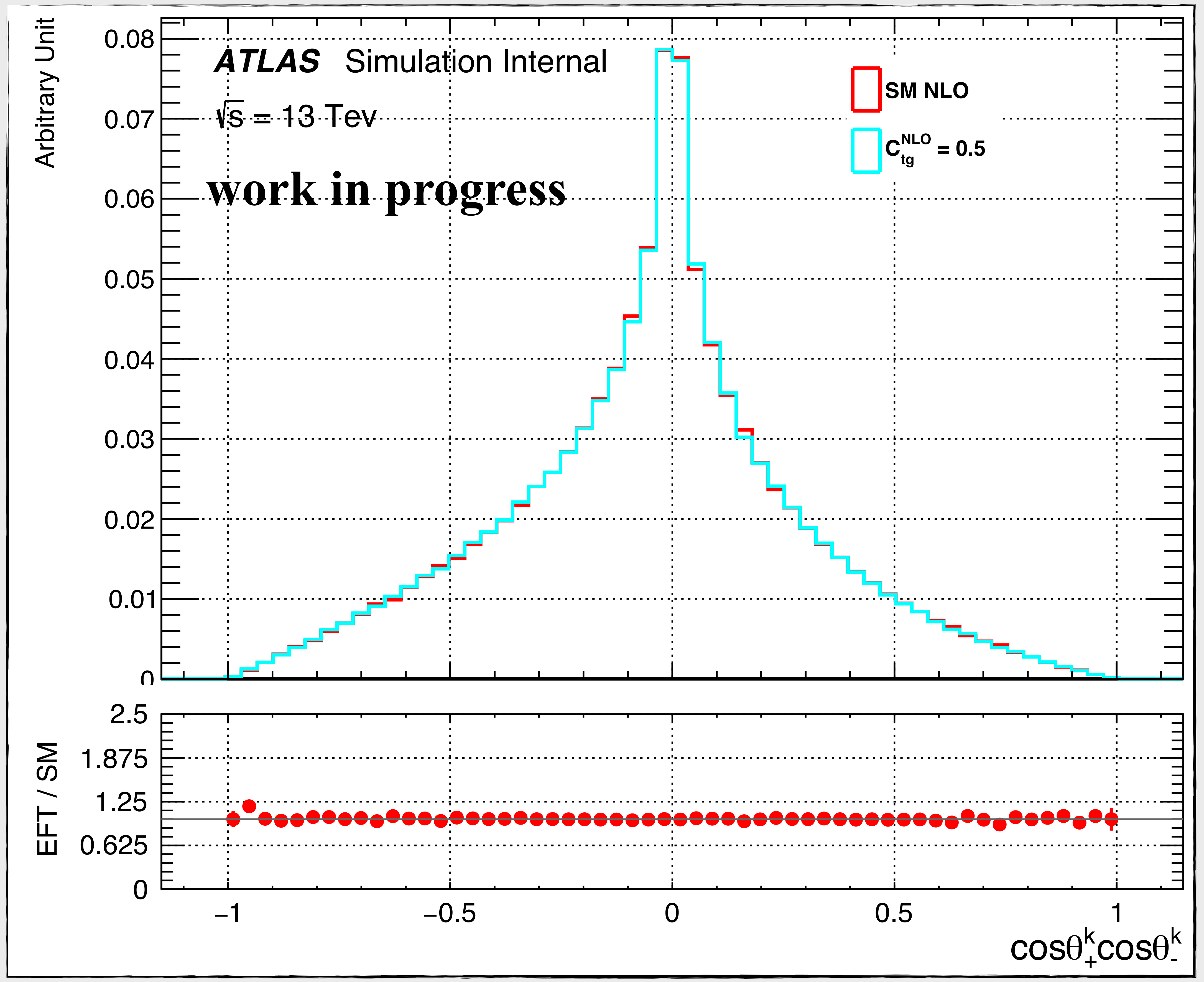
Parton Level

Goal

- How does spin correlation change in SM at LO and NLO?
- **In what way does the EFT affect the spin correlation at LO and NLO?**

Results





Mean Method: $C(\hat{k}, \hat{k}) = -9 < \cos\theta_{+}^{\hat{k}} \cos\theta_{-}^{\hat{k}} >$

SM NLO : C(k, k) = 0.366313 +/- 0.0042 (stat)

Ctg NLO : C(k, k) = 0.375982 +/- 0.0042 (stat)

- c_{tg}=0.5 affect the SM value by 10%.

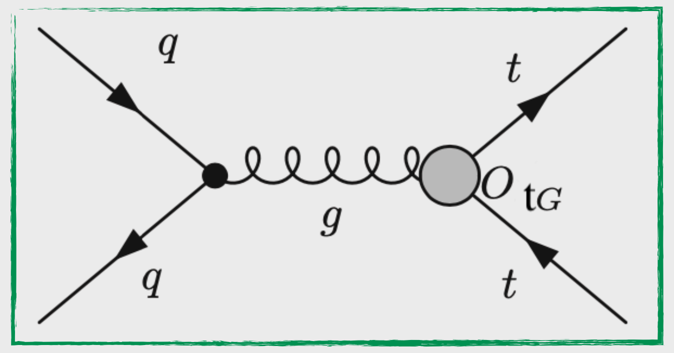
Define theory model → Process → Detector → Reconstruction → Analysis

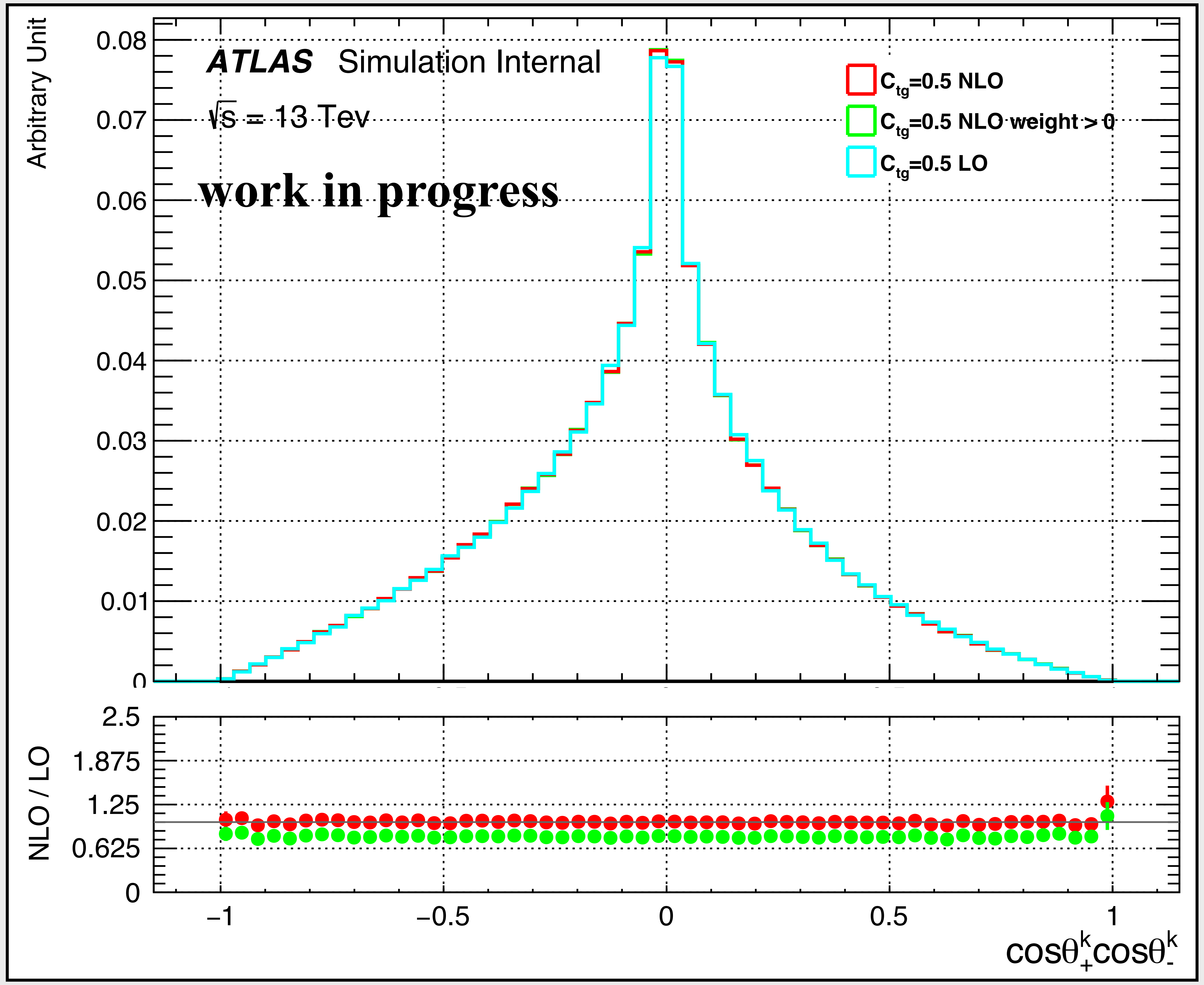
Parton Level

Goal

- How does spin correlation change in SM at LO and NLO?
- In what way does the EFT affect the spin correlation at LO and NLO?

Results





◉ The impact of Ctg at NLO/LO is low

◉ Preform Global Fit at NLO using spin correlation observables.

Define theory model → Process → Detector → Reconstruction → Analysis

Mean Method

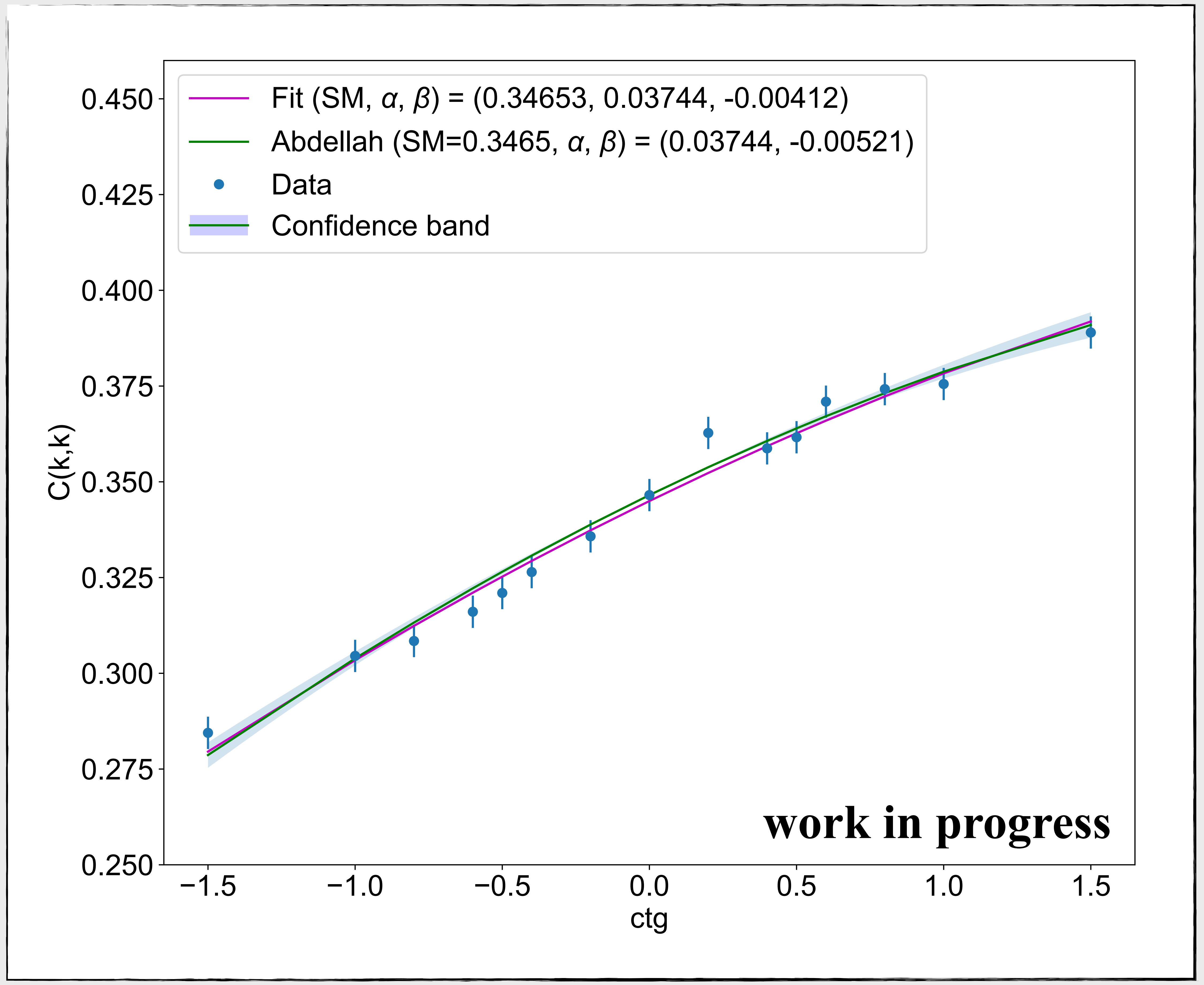
Parton Level

Goal

$$C(k,k) = C(k,k)_{SM} + \frac{C_{tg}}{\Lambda^2}\alpha + \frac{C_{tg}^2}{\Lambda^4}\beta$$

In what way does the EFT affect the spin correlation at LO and NLO?

- **Compute α and β ?**



Comments

◉ **We can use the measured $c(k,k)$, the estimated $c(k,k)_{SM}$ with their statistical and systematic uncertainties, and the α and β, to derive global constraints on the c_{tq8} operator coefficients.**

Summary

- Precision top quark spin measurements are a powerful probe of new physics and complementary to other approaches.

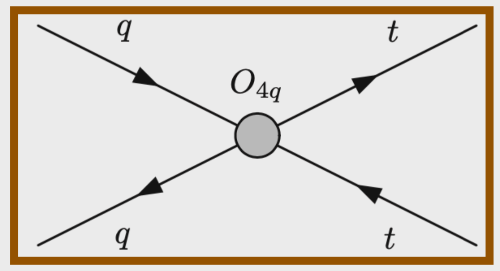
- Study the impact of EFT at LO and NLO on spin correlation observables

  - Preform Global Fit at NLO

Define theory model → Process → Detector → Reconstruction → Analysis

Parton Level

Mean Method



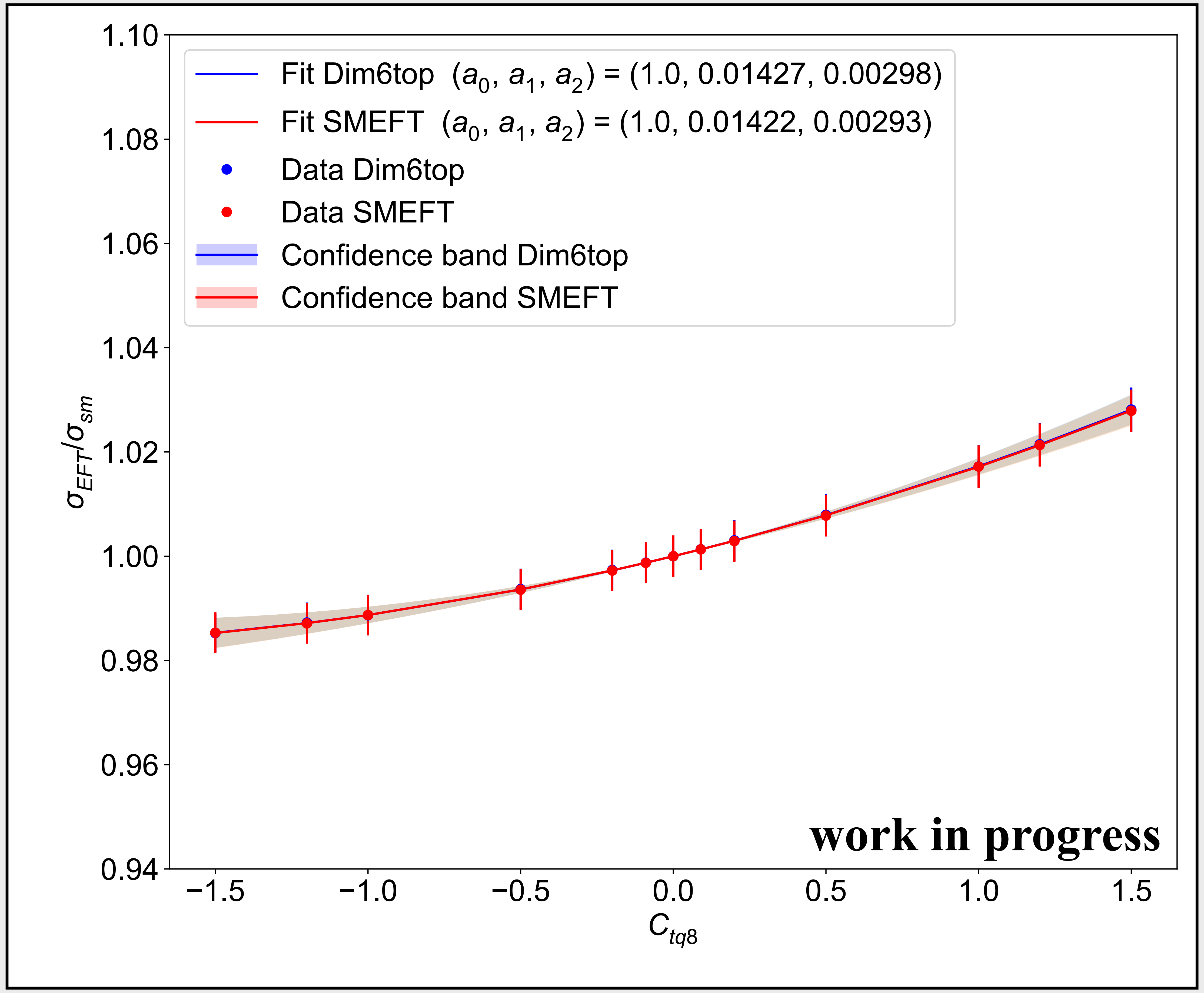
$$\sigma^k = \sigma^k_{SM} + \frac{C_{tq8}}{\Lambda^2}\alpha + \frac{C^2_{tq8}}{\Lambda^4}\beta$$

Goal

In what way does the EFT affect the spin correlation at LO and NLO?

Method

- Cross validate the SMEFT@NLO implementation agains Dim6Top model



Comments

- α_{ctq8} **and** β_{ctq8} **are model dependent**

- SMEFT@NLO model and Dim6top model show appx. same value of α_{ctq8} **and** β_{ctq8} **[within the statistical uncertainties.]**

Which Wilson coefficients affects $t\bar{t}$ production the most ?

- 18 operator expect to affect $t\bar{t}$ process :
  - 4-quark (2-heavy, 2-light) operator
  - Heavy quark boson
- We Can not prob gluon self-coupling cG in dim6top or SMEFT@NLO

parameter	$t\bar{t}$	single t
$C_{Qq}^{1,8}$	Λ^{-2}	–
$C_{Qq}^{3,8}$	Λ^{-2}	Λ^{-4} $[\Lambda^{-2}]$
C_{tu}^{8}, C_{td}^{8}	Λ^{-2}	–
$C_{Qq}^{1,1}$	Λ^{-4} $[\Lambda^{-2}]$	–
$C_{Qq}^{3,1}$	Λ^{-4} $[\Lambda^{-2}]$	Λ^{-2}
C_{tu}^{1}, C_{td}^{1}	Λ^{-4} $[\Lambda^{-2}]$	–
C_{Qu}^{8}, C_{Qd}^{8}	Λ^{-2}	–
C_{tq}^{8}	Λ^{-2}	–
C_{Qu}^{1}, C_{Qd}^{1}	Λ^{-4} $[\Lambda^{-2}]$	–
C_{tq}^{1}	Λ^{-4} $[\Lambda^{-2}]$	–
$C_{\phi Q}^{-}$	–	–
$C_{\phi Q}^{3}$	–	Λ^{-2}
$C_{\phi t}$	–	–
$C_{\phi tb}$	–	Λ^{-4}
C_{tZ}	–	–
C_{tW}	–	Λ^{-2}
C_{bW}	–	Λ^{-4}
C_{tG}	Λ^{-2}	$[\Lambda^{-2}]$

1910.03606

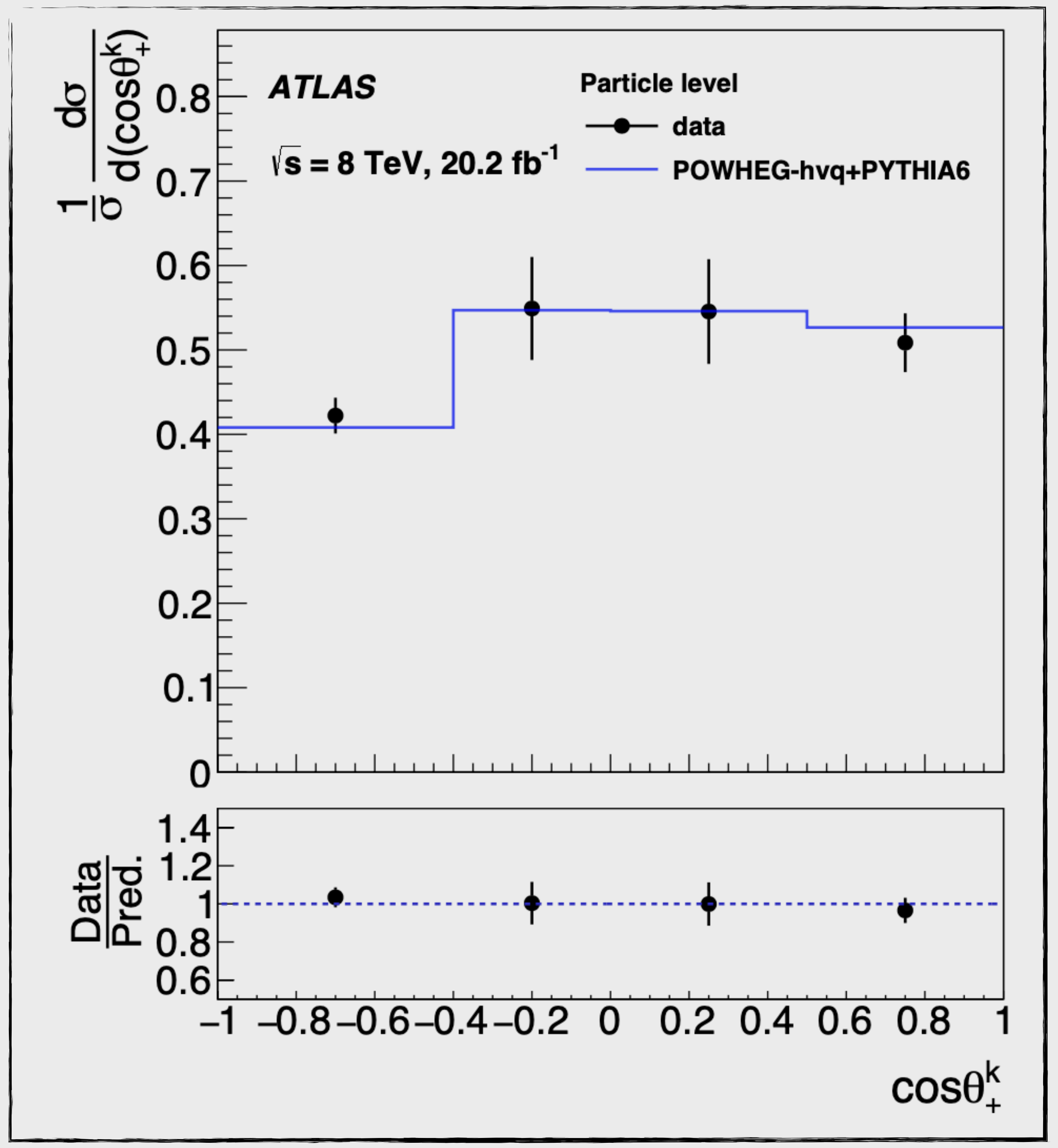
Top quark polarisation

$B_+^{\hat{k}}$ $B_-^{\hat{k}}$

$B_+^{\hat{r}}$ $B_-^{\hat{r}}$

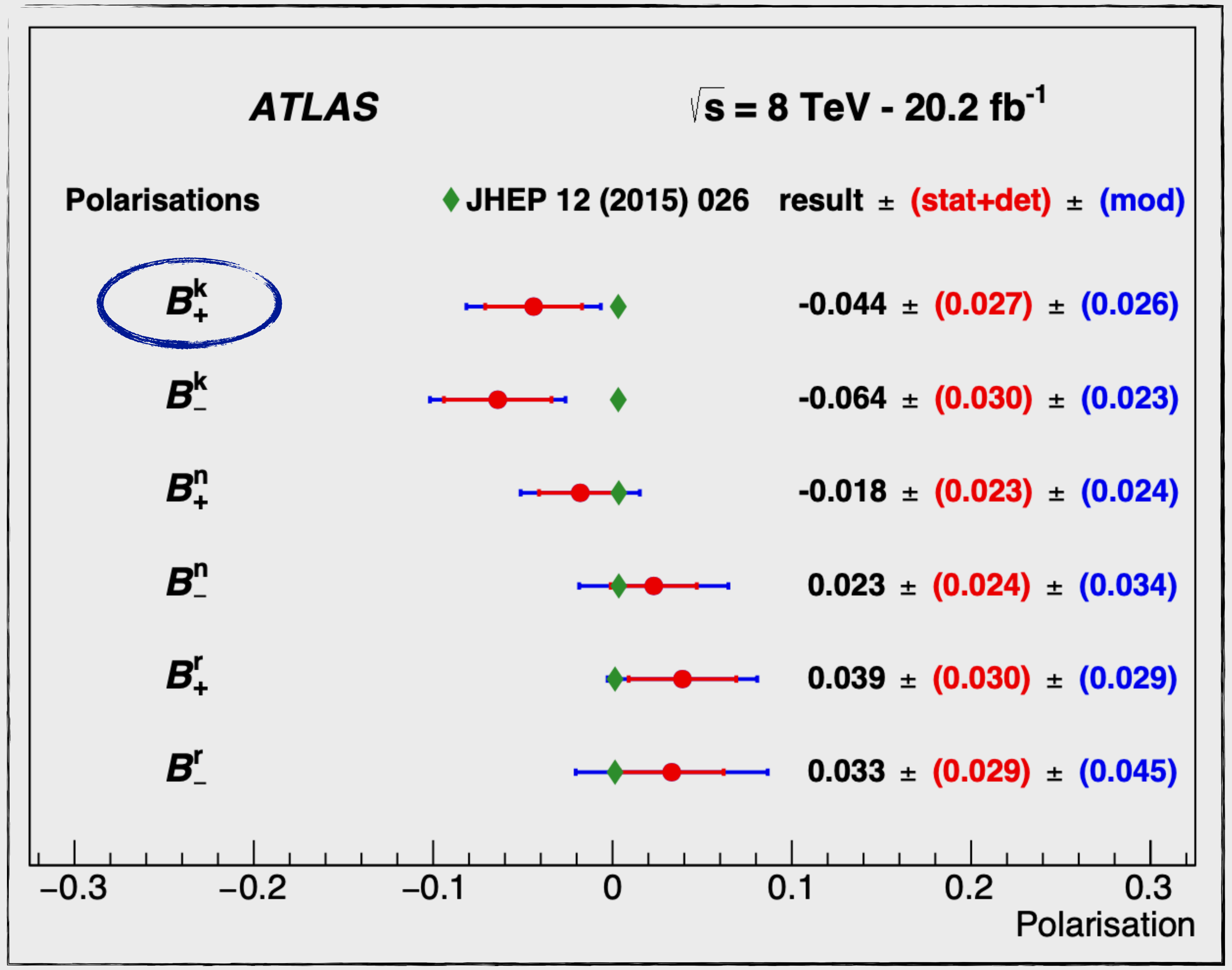
$B_+^{\hat{n}}$ $B_-^{\hat{n}}$

In agreement with the predictions



ATLAS

$$\frac{1}{2}(1 + B_+^{\hat{k}} \cos\theta_+^{\hat{k}})$$



ATLAS

- Measurements not yet sensitive to small level of polarisation in the SM
- This distribution should be sloped if top quarks are produced with high polarisation:
  - ➡ Dominant uncertainty affects top rest frame reconstruction

Spin correlation

$C(\hat{k},\hat{k})$ $C(\hat{r},\hat{k})$ $C(\hat{n},\hat{k})$

$C(\hat{k},\hat{r})$ $C(\hat{r},\hat{r})$ $C(\hat{n},\hat{r})$

$C(\hat{k},\hat{n})$ $C(\hat{r},\hat{n})$ $C(\hat{n},\hat{n})$

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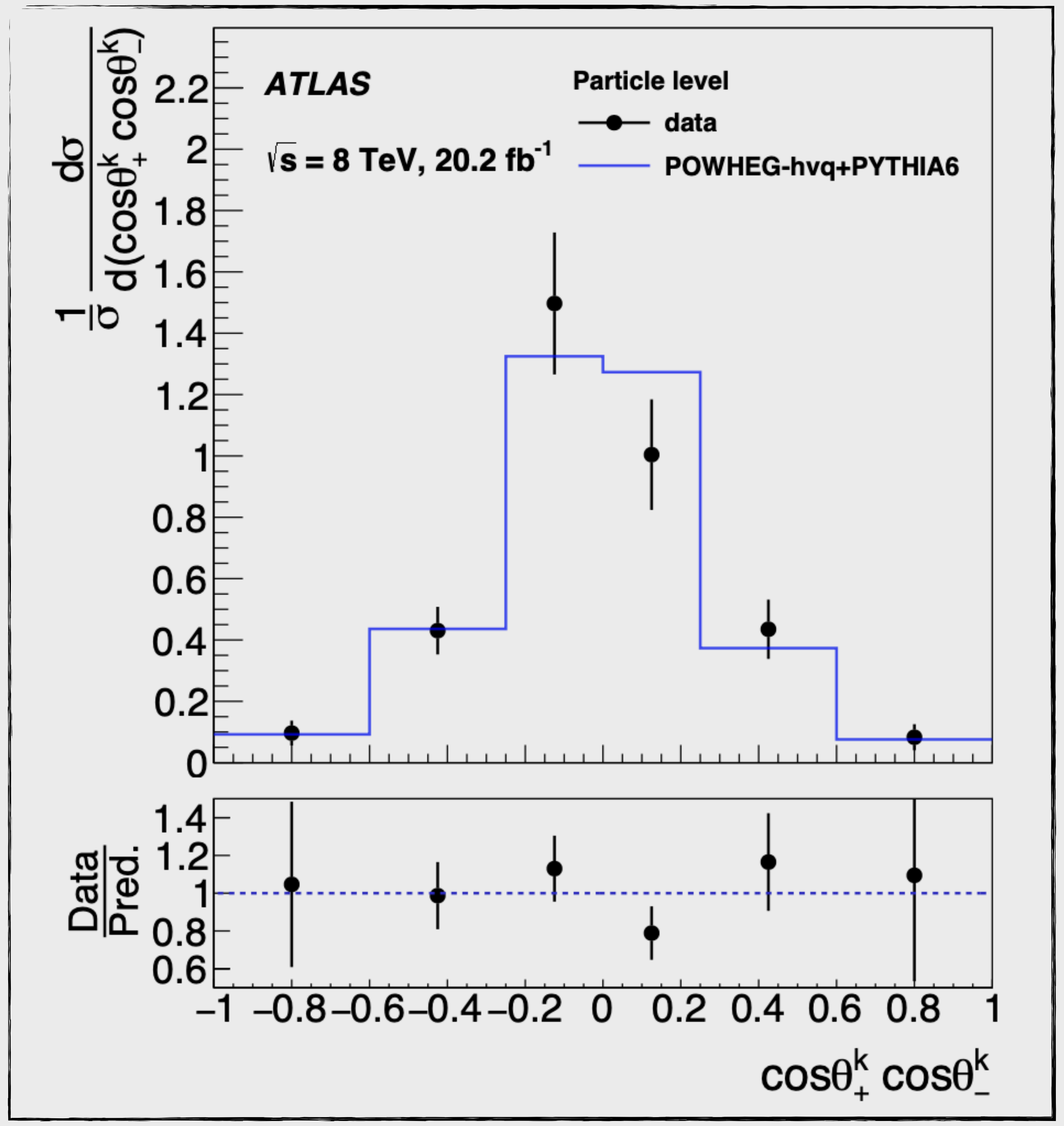
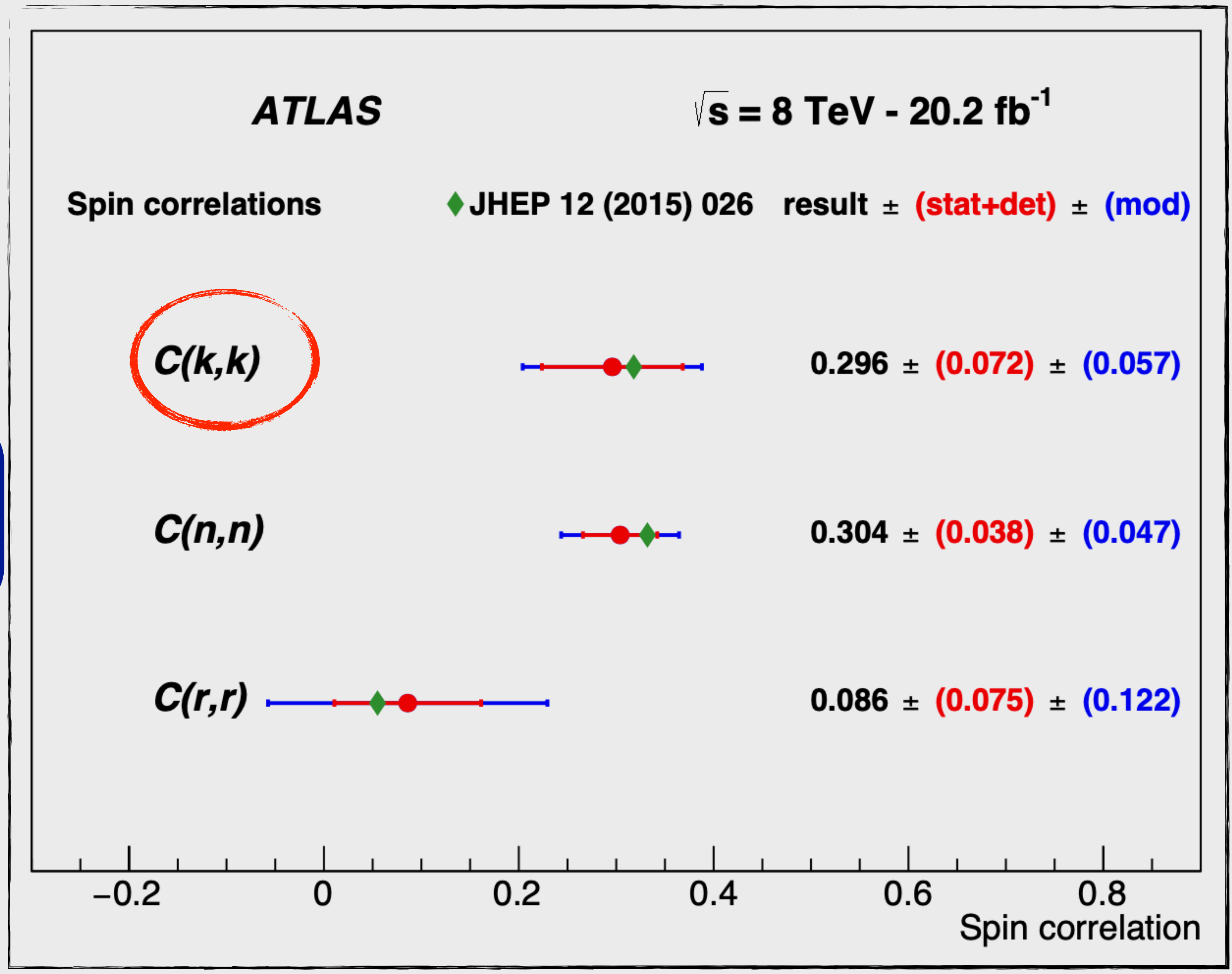


ATLAS

$$\frac{1}{2}\left(1 - C(\hat{k},\hat{k})\cos\theta_+^{\hat{k}}\cos\theta_-^{\hat{k}}\right)\log\left(\frac{1}{\left|\cos\theta_+^{\hat{k}}\cos\theta_-^{\hat{k}}\right|}\right)$$



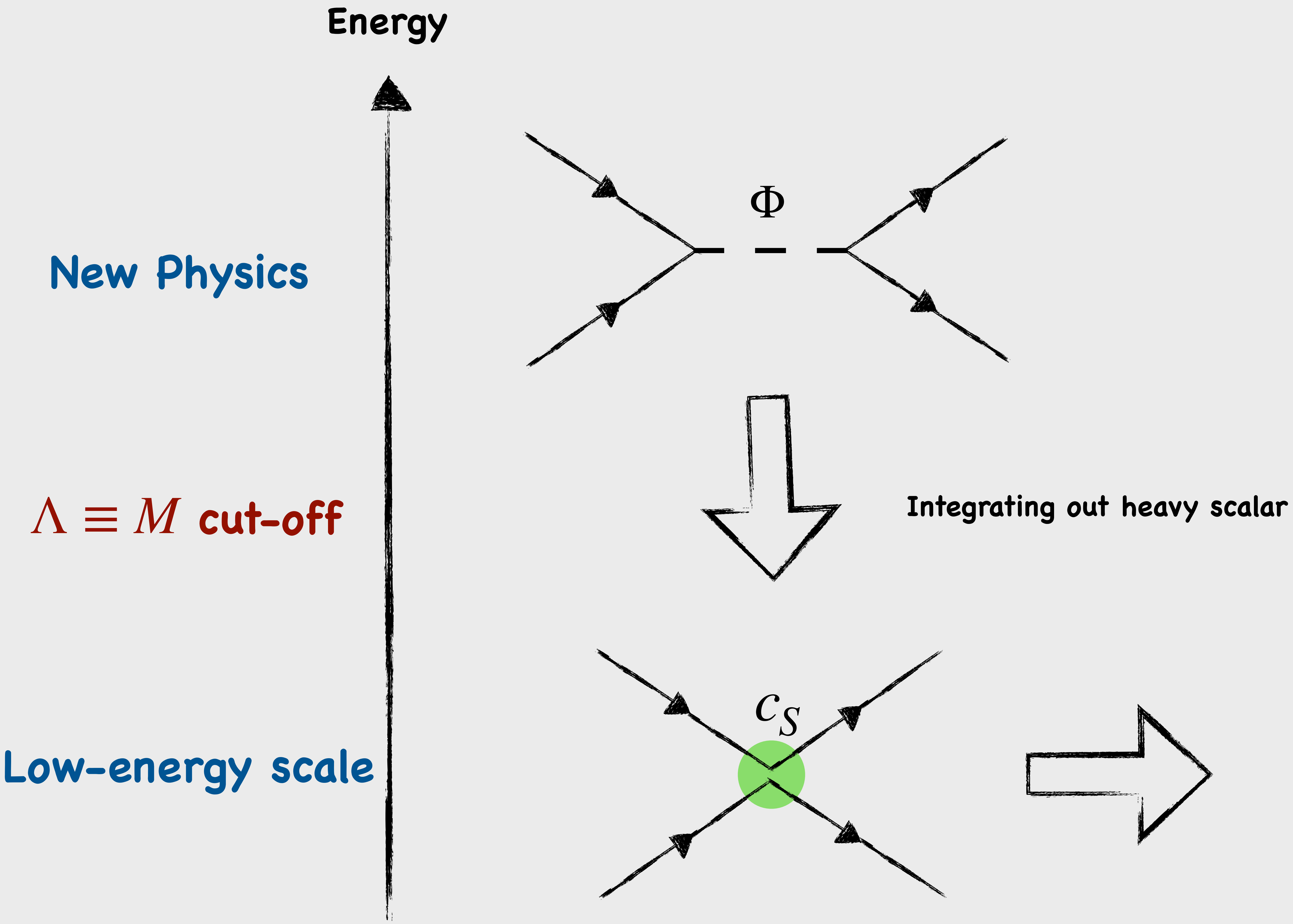
ATLAS

- This distribution should be symmetric if there was no spin correlations
- Spin correlations along each axis consistent with SM expectations

SM-EFT: What is it all about?

Fermions: ψ

Heavy scalar: Φ

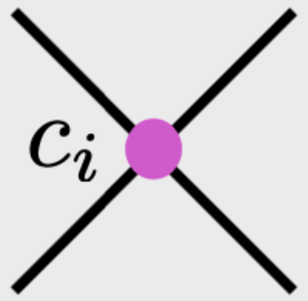


$$\mathscr{L}_{\text{Full}} = \mathscr{L}(\psi) + \mathscr{L}(\psi, \Phi)$$

$$\mathscr{L}_{\text{EFT}} = \mathscr{L}(\psi) + \frac{c_S}{M^2}\frac{1}{2}(\bar{\psi}\psi)(\bar{\psi}\psi)$$

SM-EFT: What is it all about?

Couplings = Wilson coefficients



$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}}^{(4)} + \sum_i \frac{c_i^d \mathscr{O}_i^d}{\Lambda^{d-4}}$$

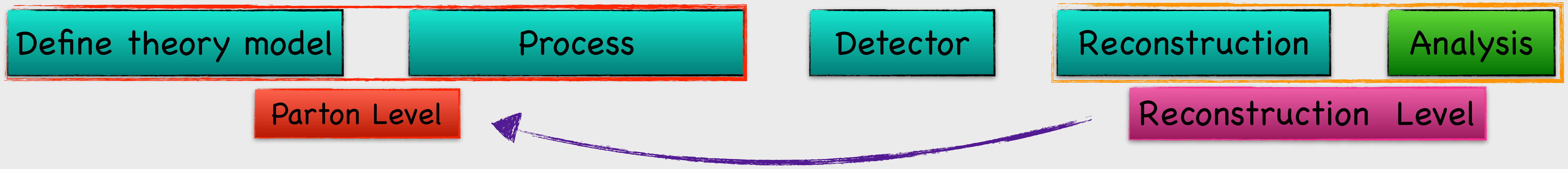
SM particles

Higher (mass) dimension operators suppressed by NP scale

SM-EFT validly

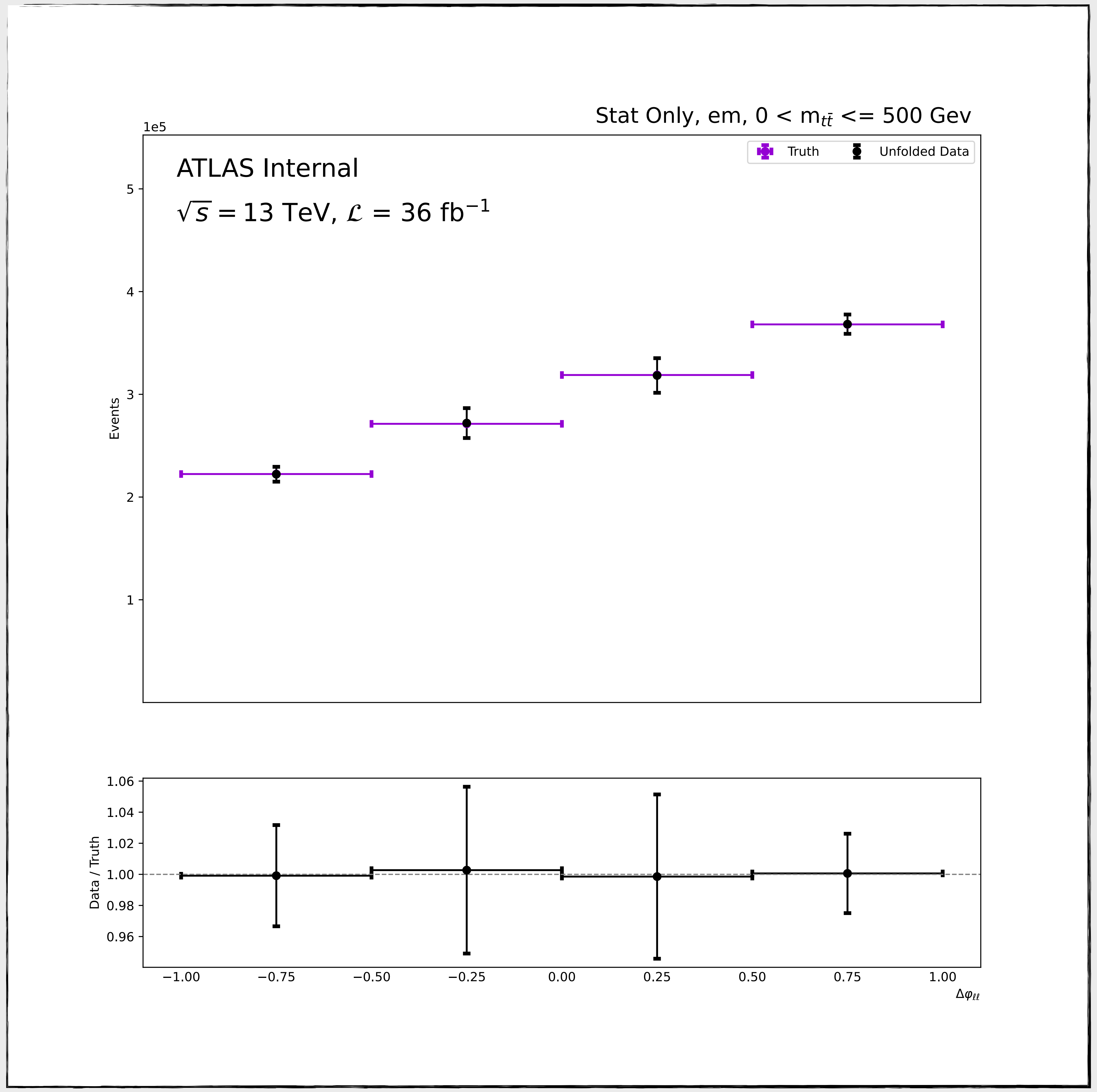
◉ $\mathscr{L}_{eft} = \sum_{i,d\geq 5} \frac{c_i \mathscr{O}_i^d}{\Lambda^{d-4}}$, should respect:

✤ $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$



Unfolding

- Unfolding: remove detector effects, to get the truth-level distribution.
- Systematic uncertainties, for now only considering the main uncertainties, signal modelling systematics:
  - aMCNLO-Herwig Vs. aMCNLO-Pythia8

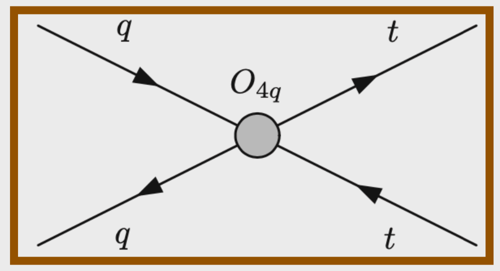


closure test

Define theory model → Process → Detector → Reconstruction → Analysis

Parton Level

Mean Method



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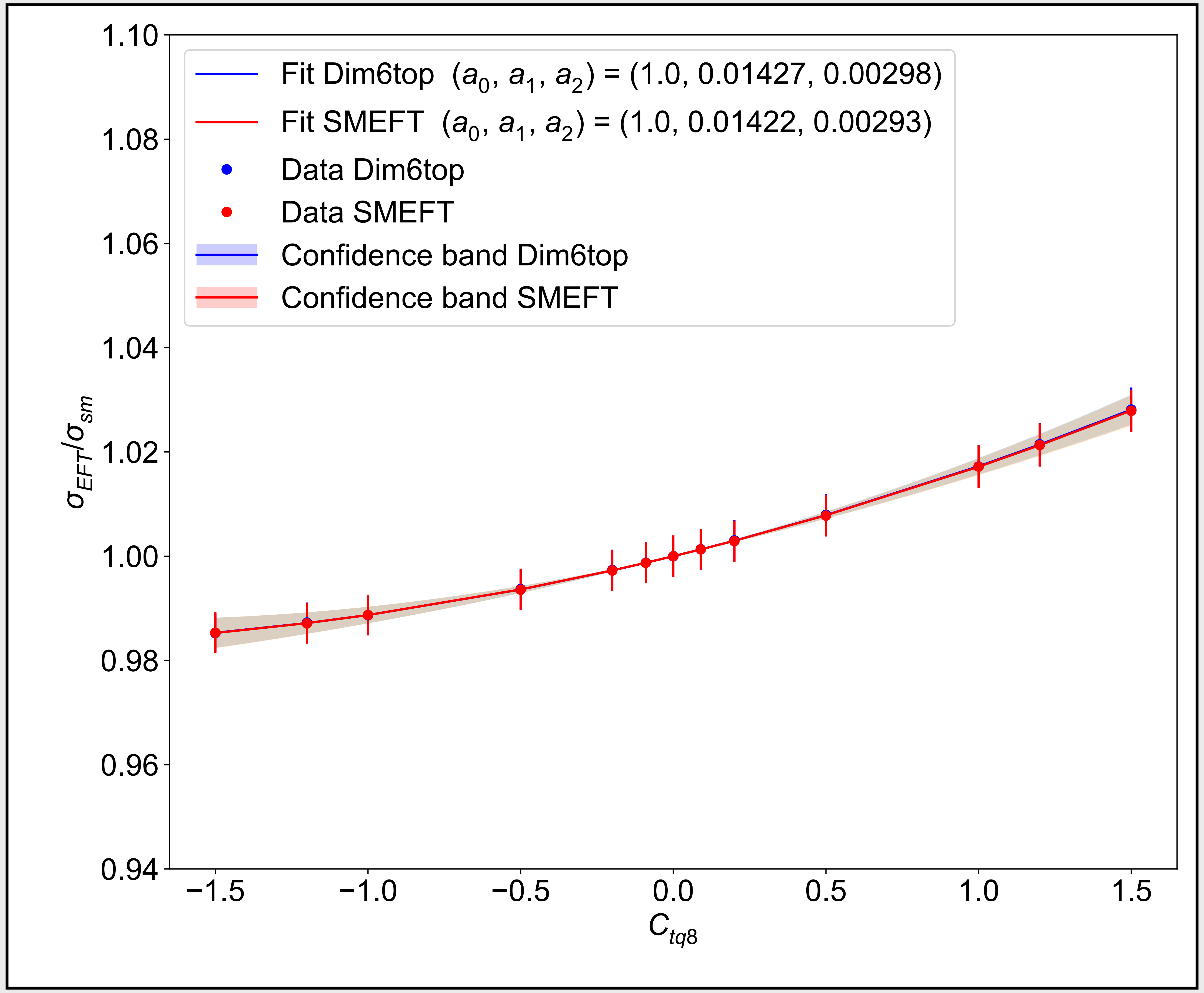

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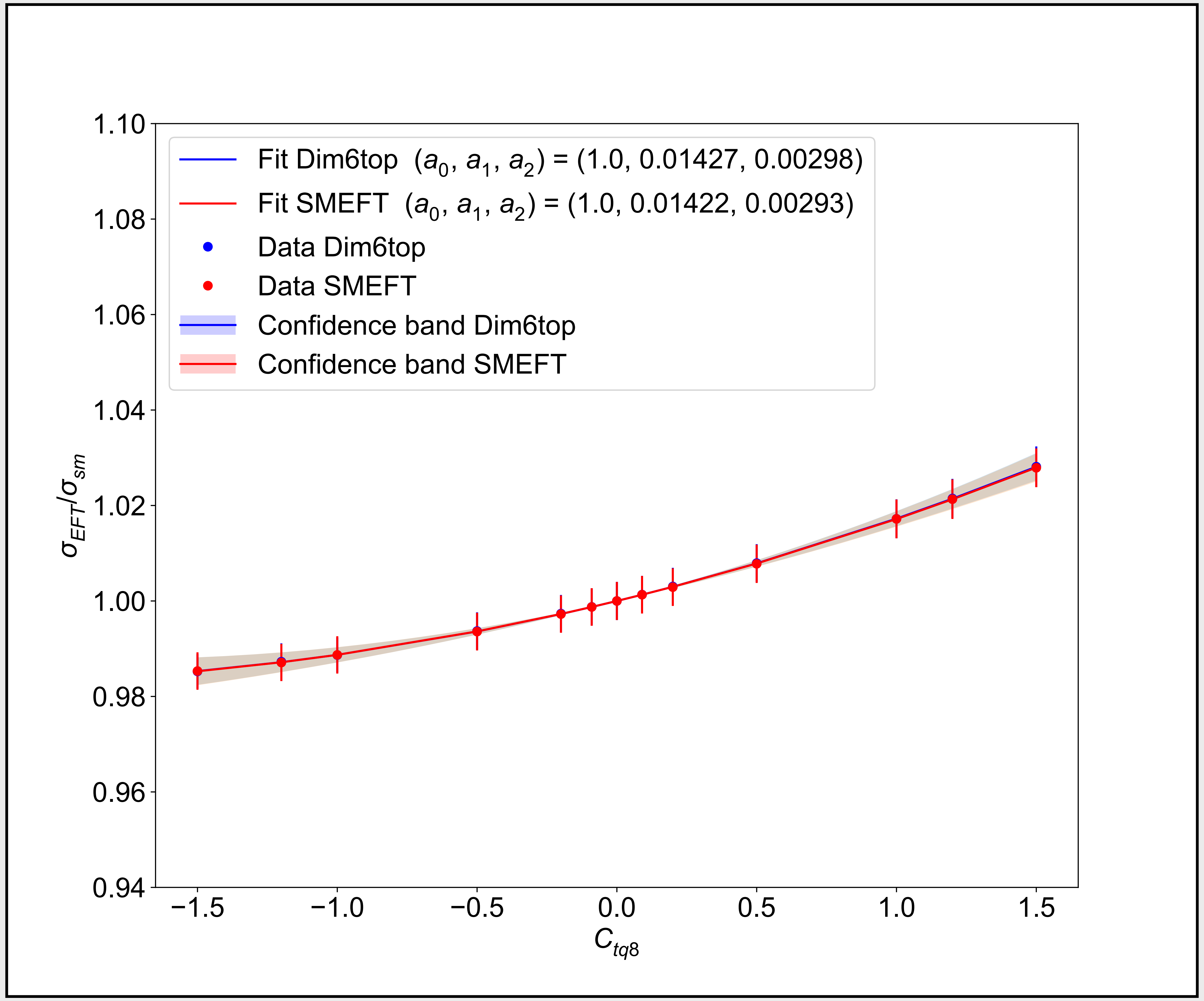
Cress Section, ctq8



Evidence of Entanglement

- Base selection:
  - Two OS leptons ($e\mu, \mu\mu, ee$).
  - At least ~~two~~ one b-tagged jet

- Other approach to look for Entanglement in $t\bar{t}$ events:
  - $-C_{kk} - C_{rr} - C_{nn} > 1$ at threshold (equivalent to measuring D)
  - $C_{kk} + C_{rr} - C_{nn} > 1$ at high regime (high $m_{t\bar{t}}$ and θ_{CM})

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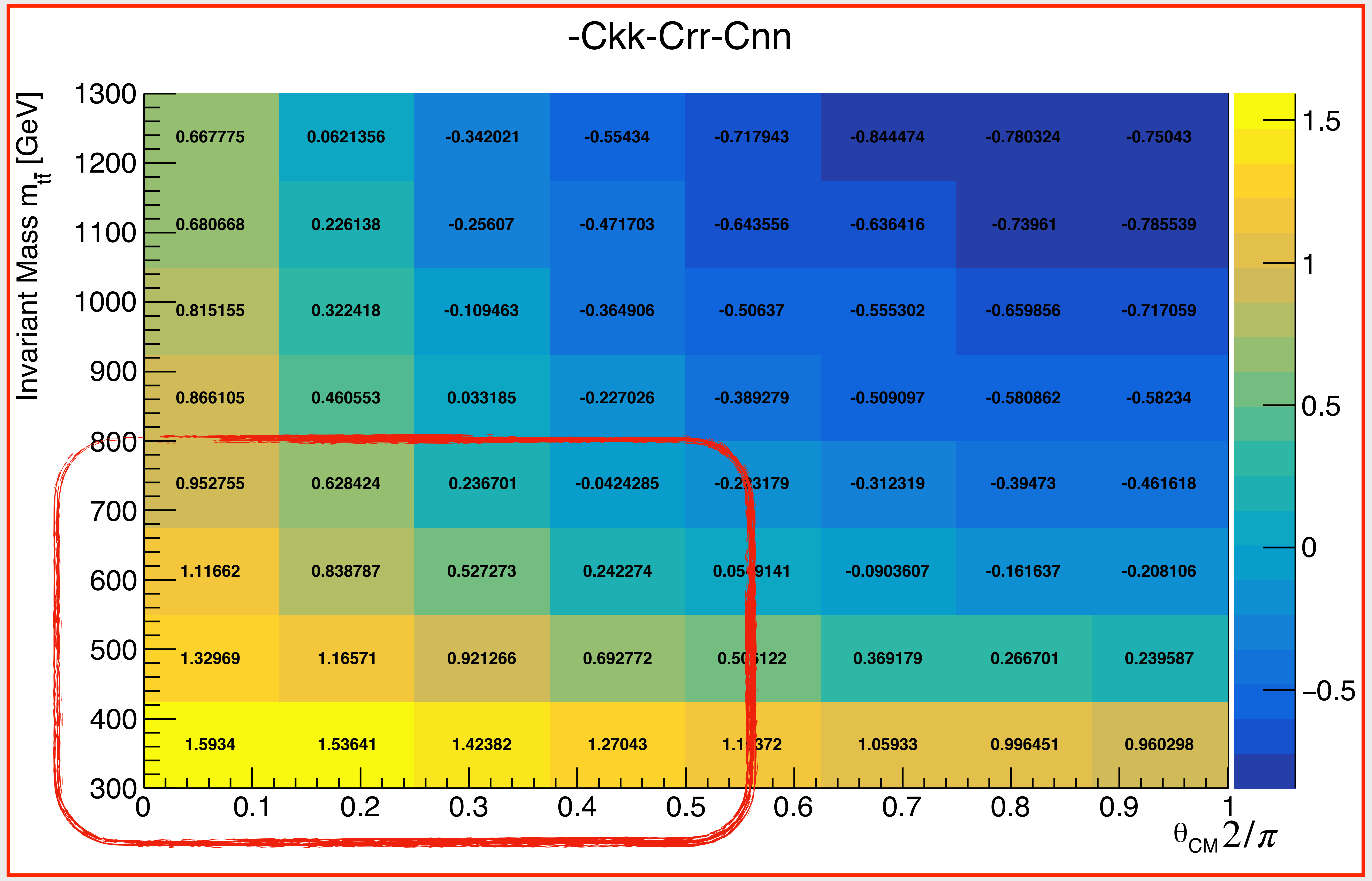
- Work in progress, fresh results



- > 1 sufficient conditions for entanglement.

- 2110.10112
- 2102.11883

- At parton lavel

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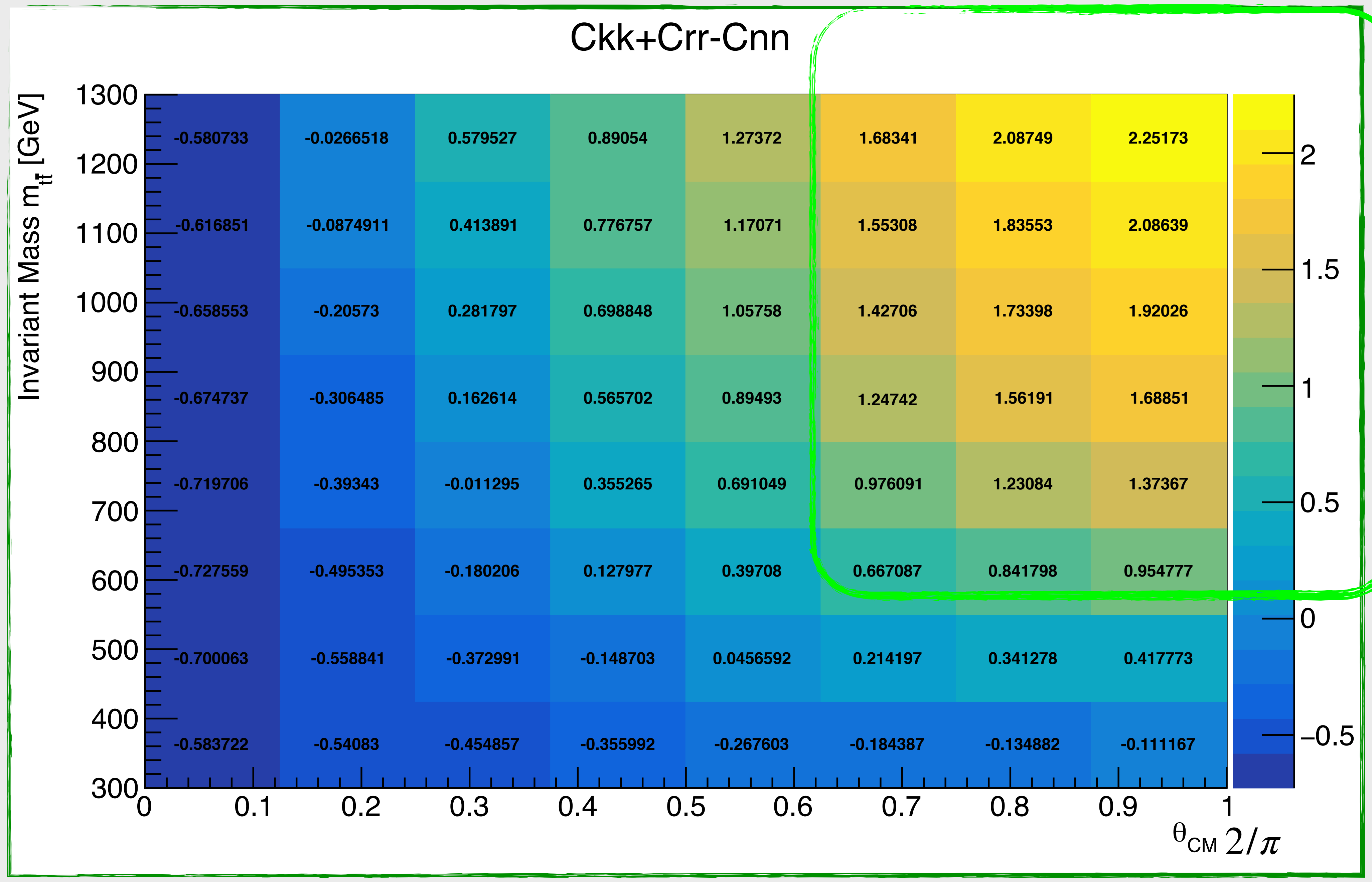


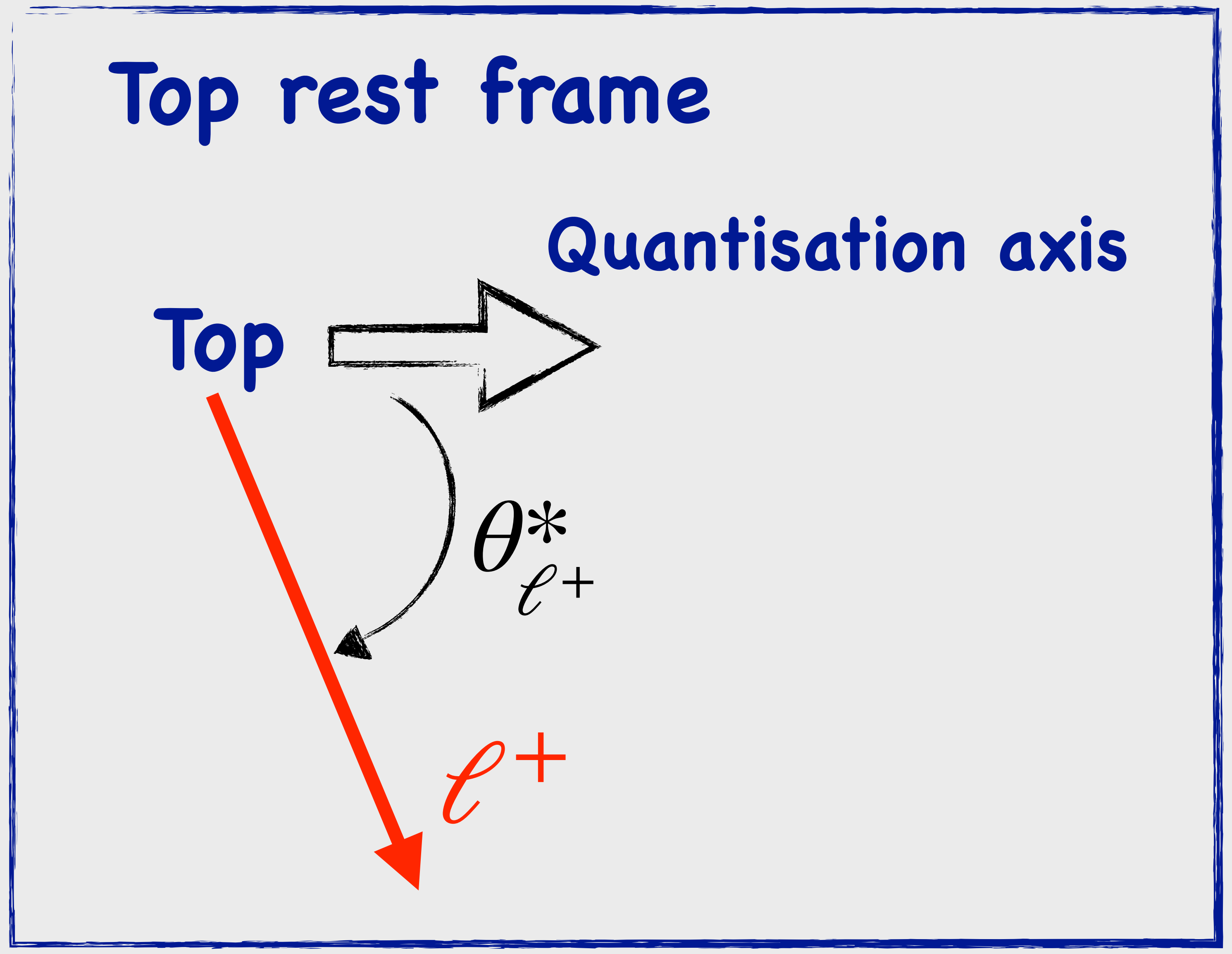
- > 1 sufficient conditions for entanglement.

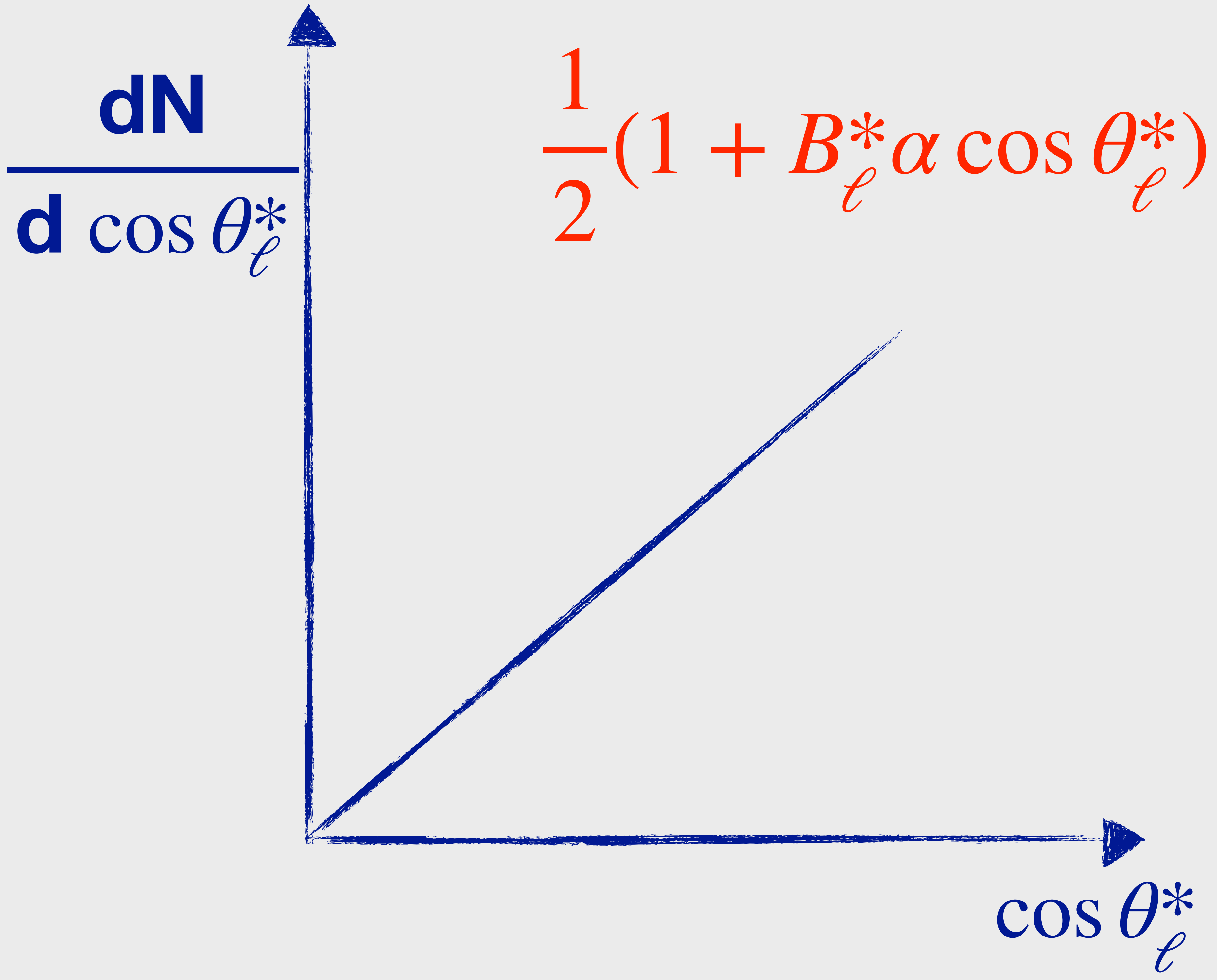
Selections	$C_{kk} + C_{rr} - C_{nn}$
Weak	
Intermediate	
Strong	

- At parton lavel

- 2110.10112
- 2102.11883

Polarised Top quark decay

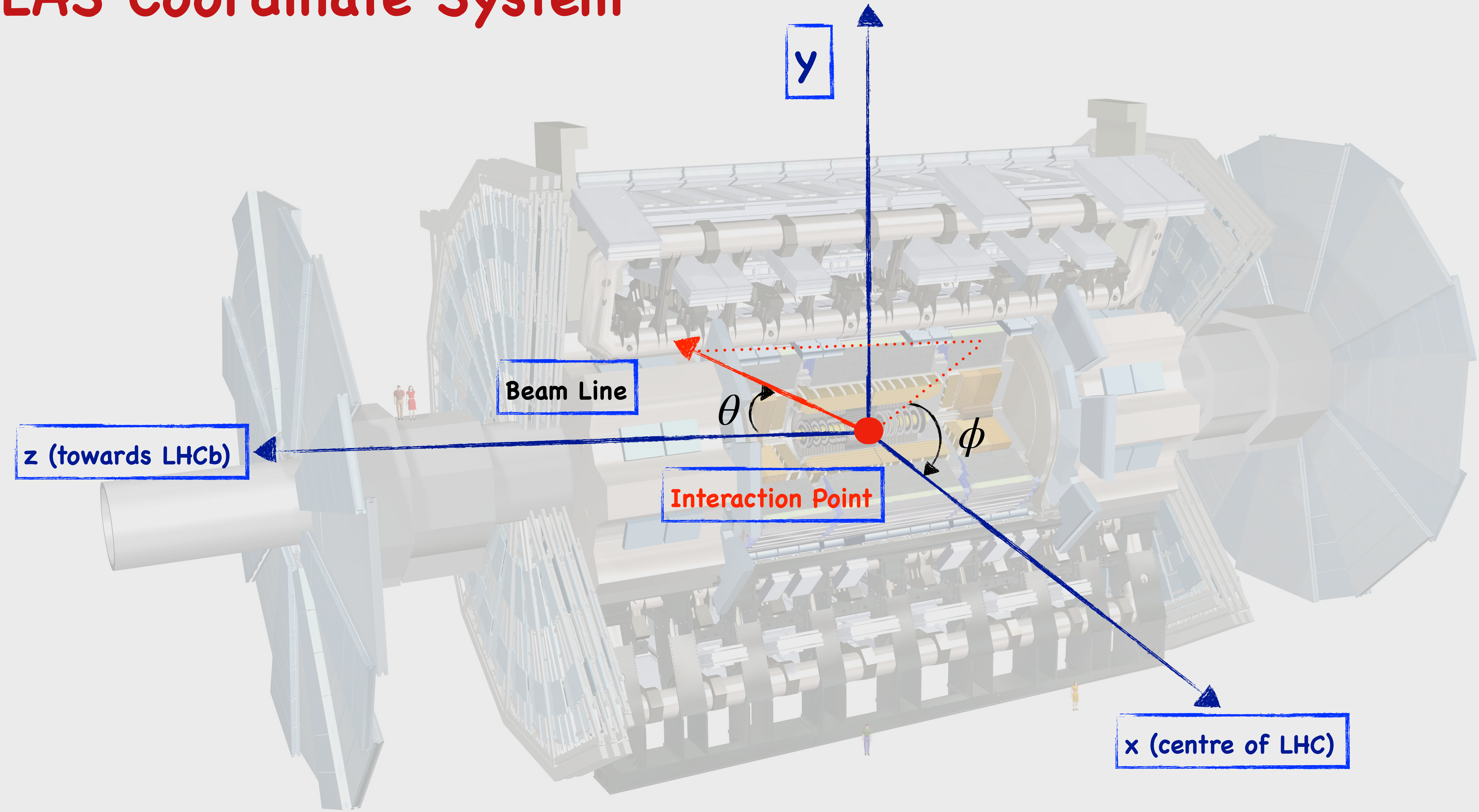




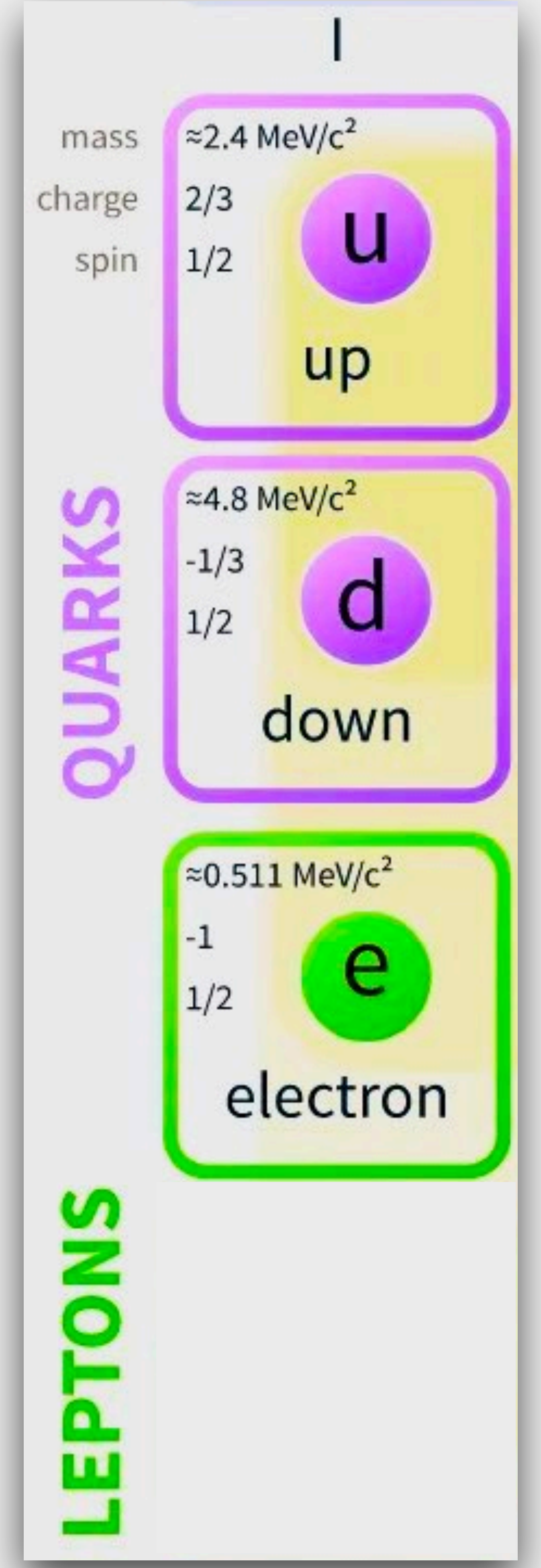
- $-1 \leq B^*_\ell \leq 1$ is polarisation, measured along chosen axis (*)
- For a fully polarised ensemble of top quarks, $B^*_\ell = 1$.

ATLAS Coordinate System

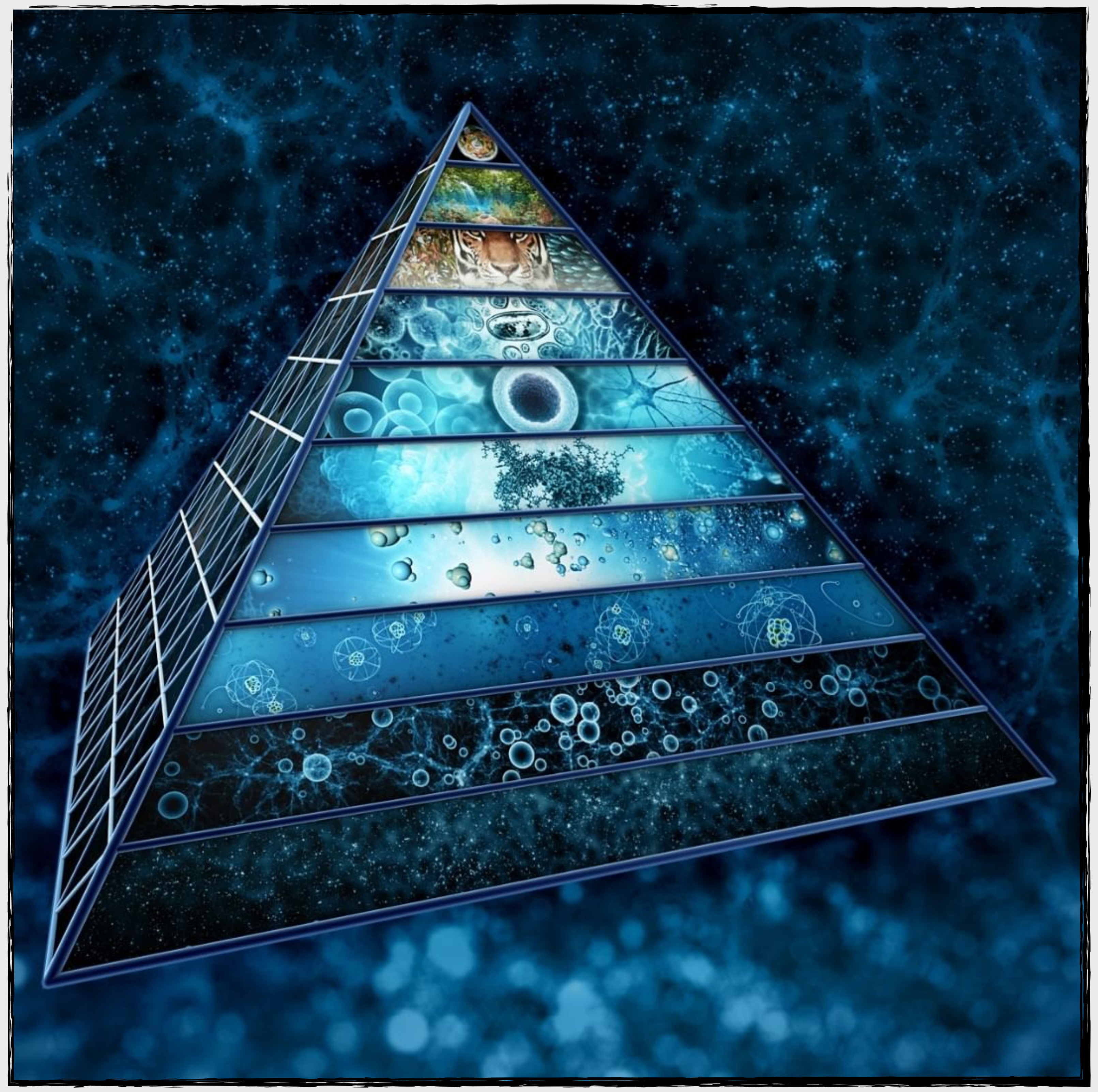
source



The Standard Model of Particle Physics

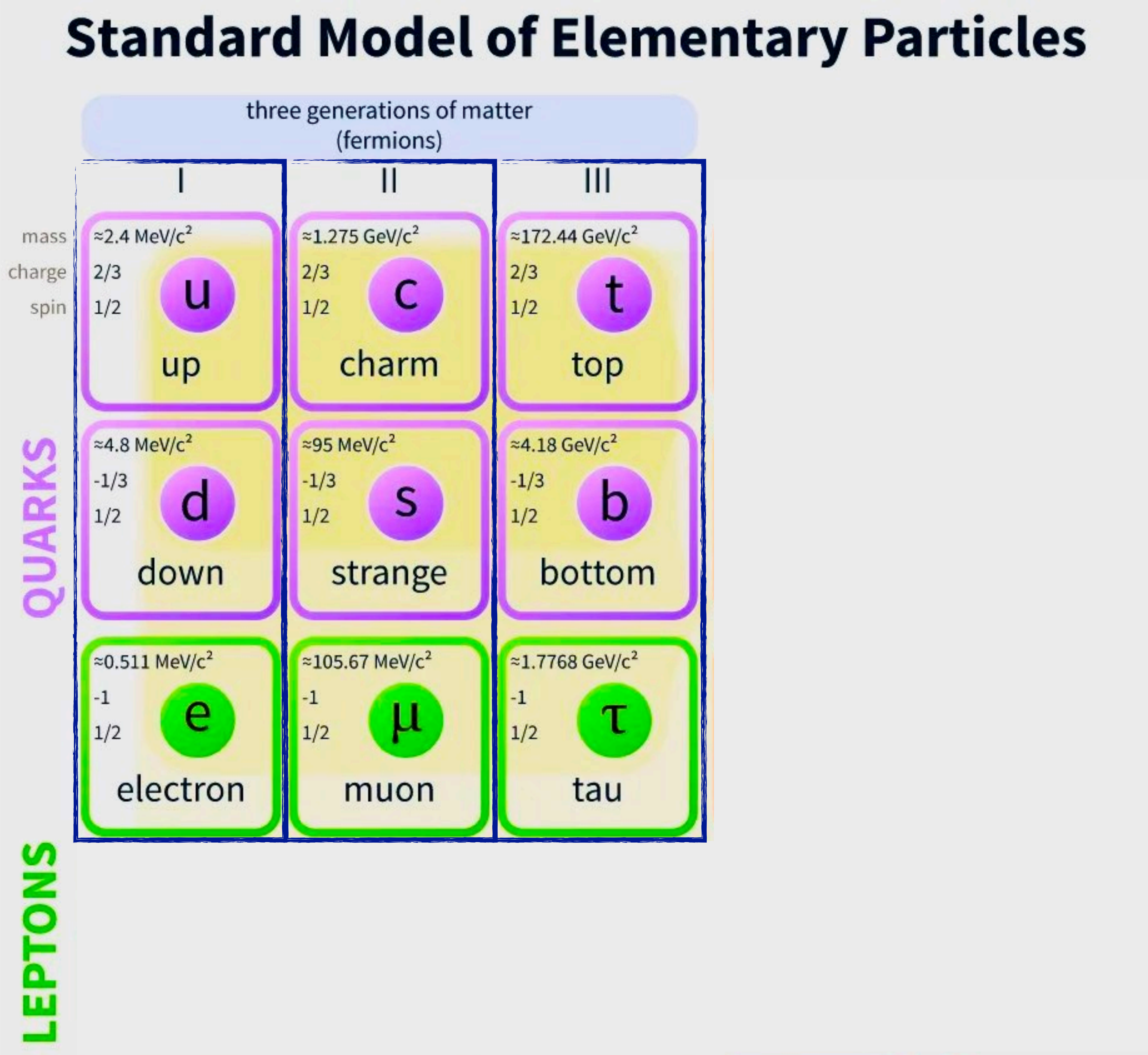


- All ordinary matter is made from up quarks, down quarks, and electrons.



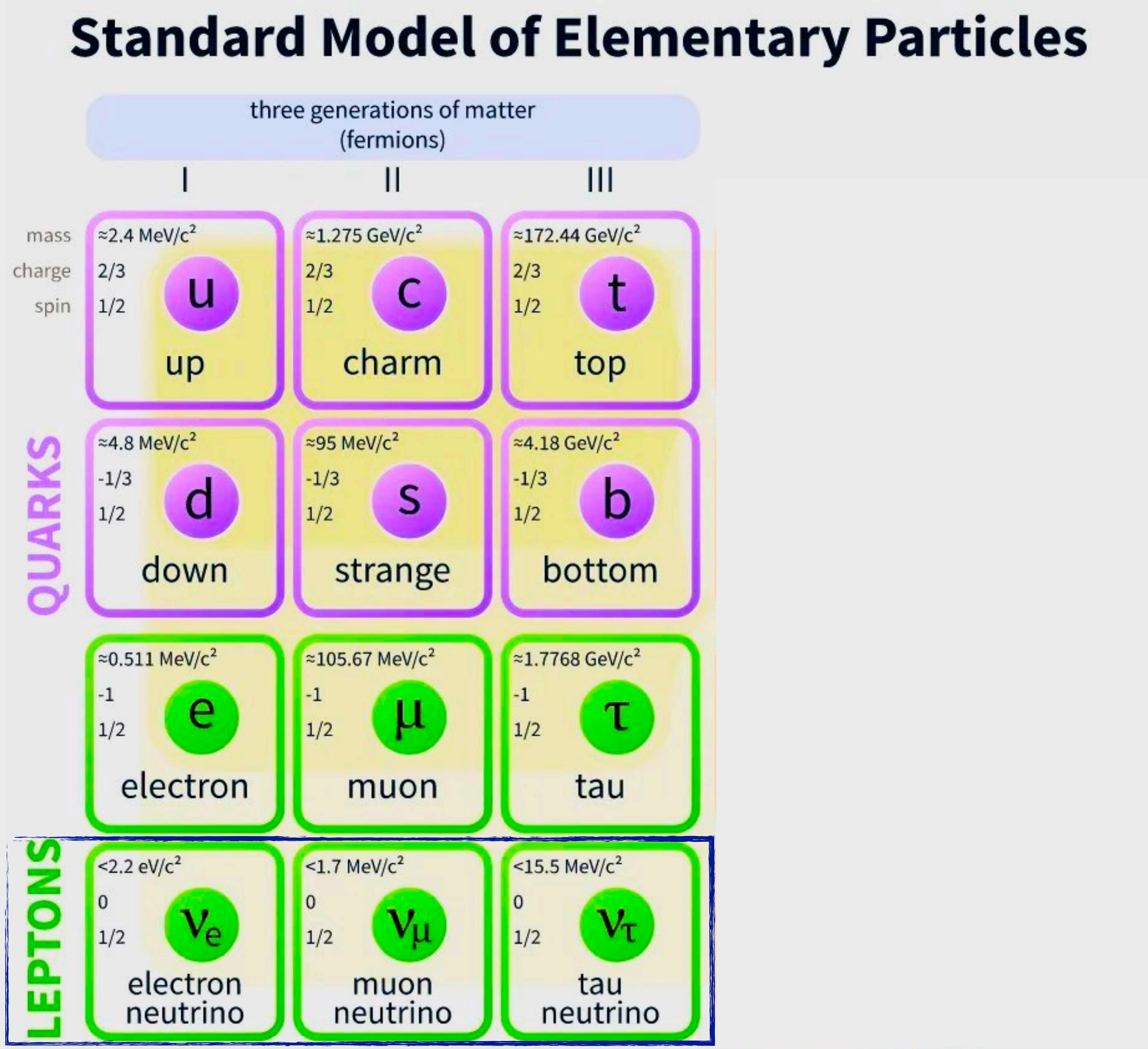
The Pyramid of Complexity

The Standard Model of Particle Physics



- There are three copies, or generations, of quarks and leptons
  Same properties, only heavier

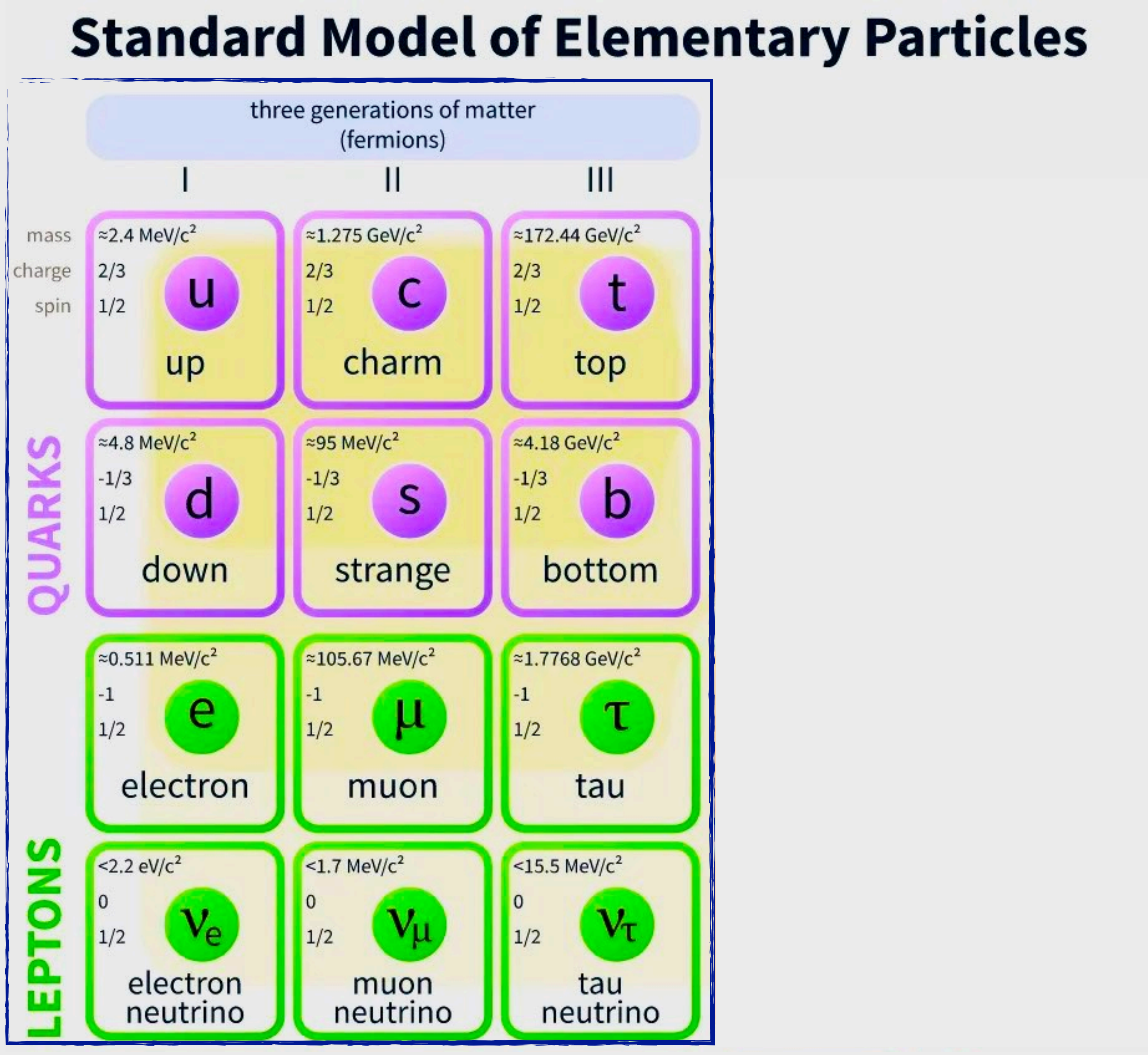
The Standard Model of Particle Physics



- There are three copies, or generations, of quarks and leptons Same properties, only heavier

- Leptons also include neutrinos, one for each generation

The Standard Model of Particle Physics



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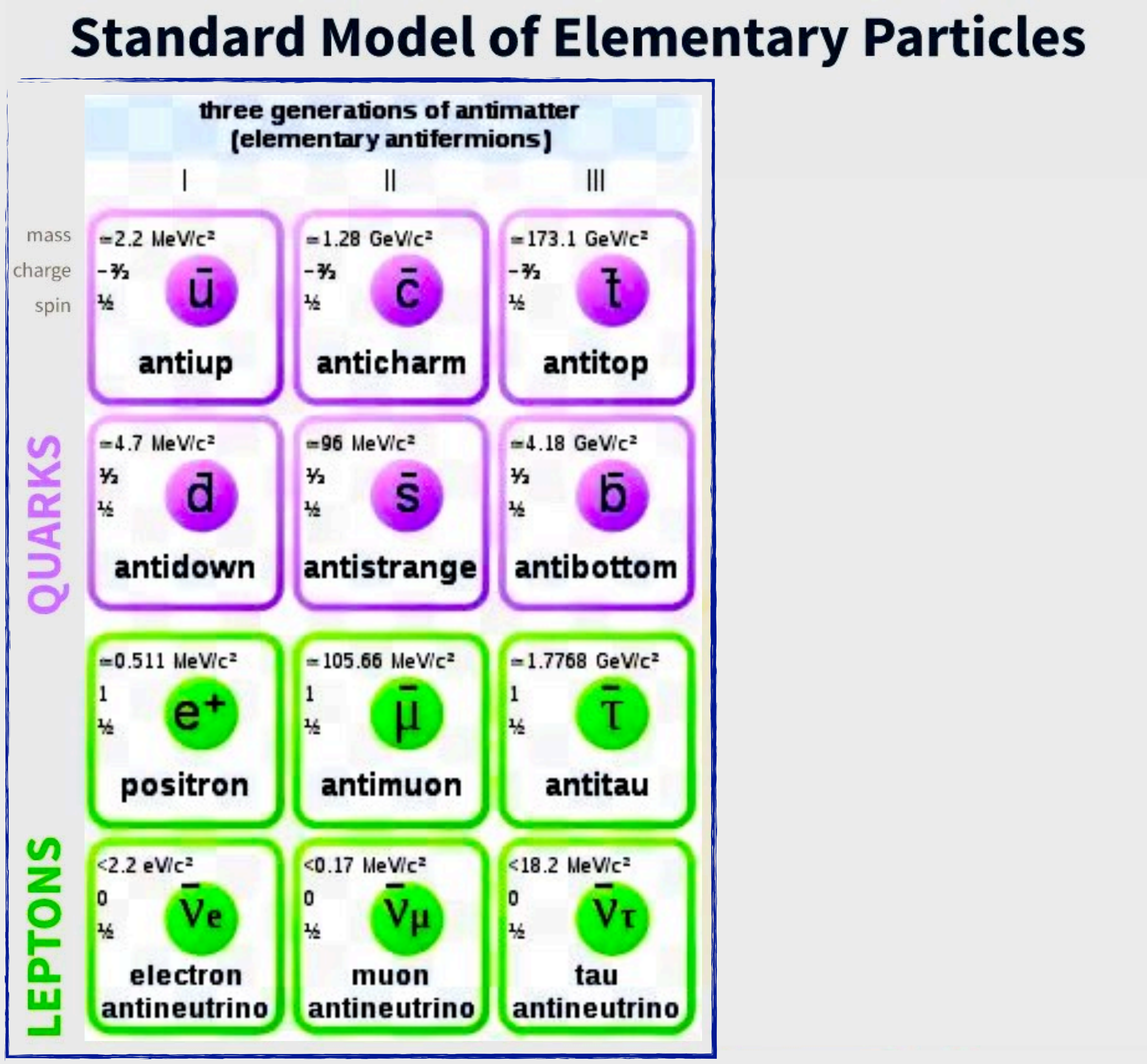
The Standard Model of Particle Physics



- There are three copies, or generations, of quarks and leptons Same properties, only heavier
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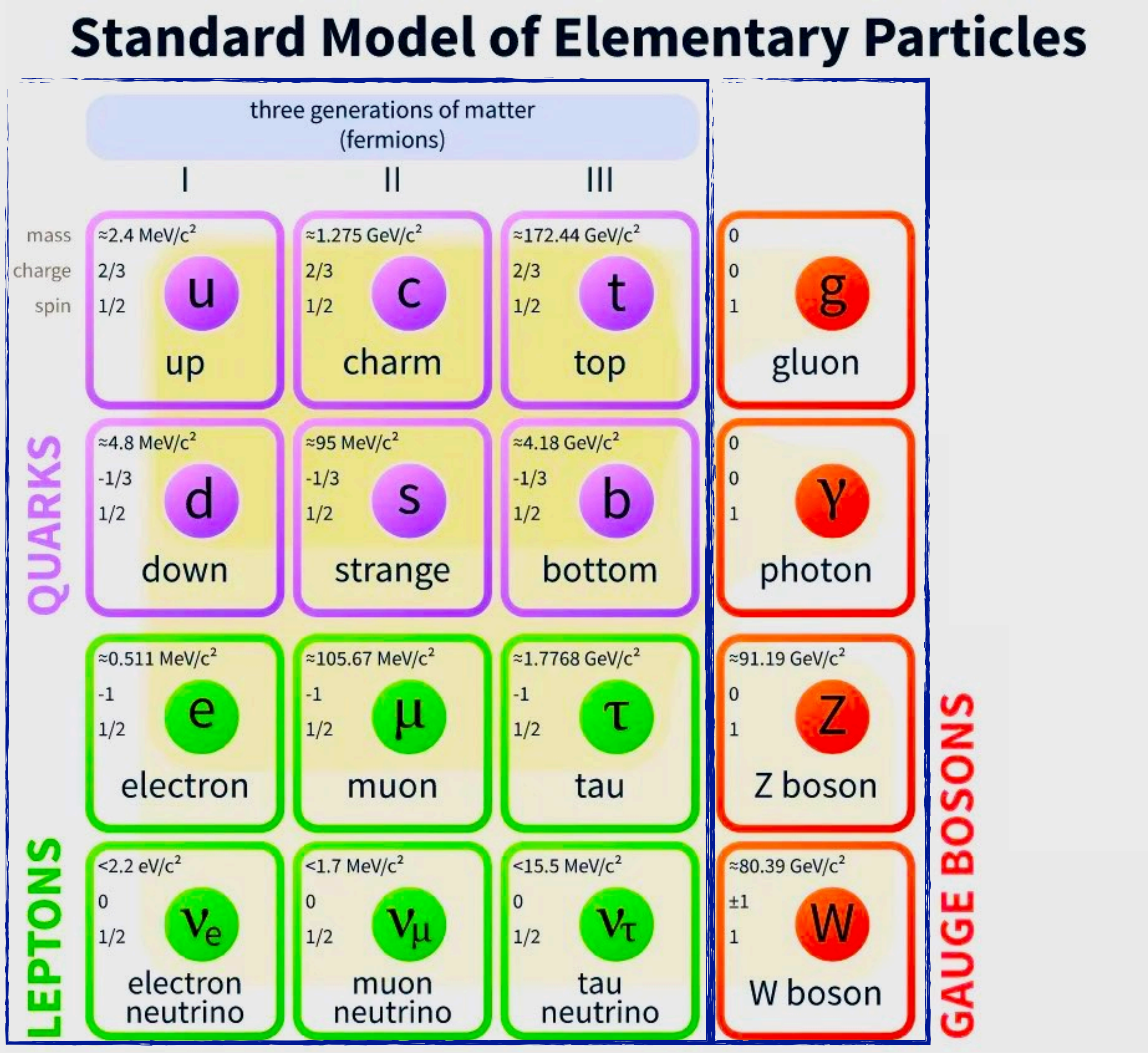
- All of these are matter particles, or fermions
- Antimatter is exactly the same as matter except one attribute is flipped: the charge

The Standard Model of Particle Physics



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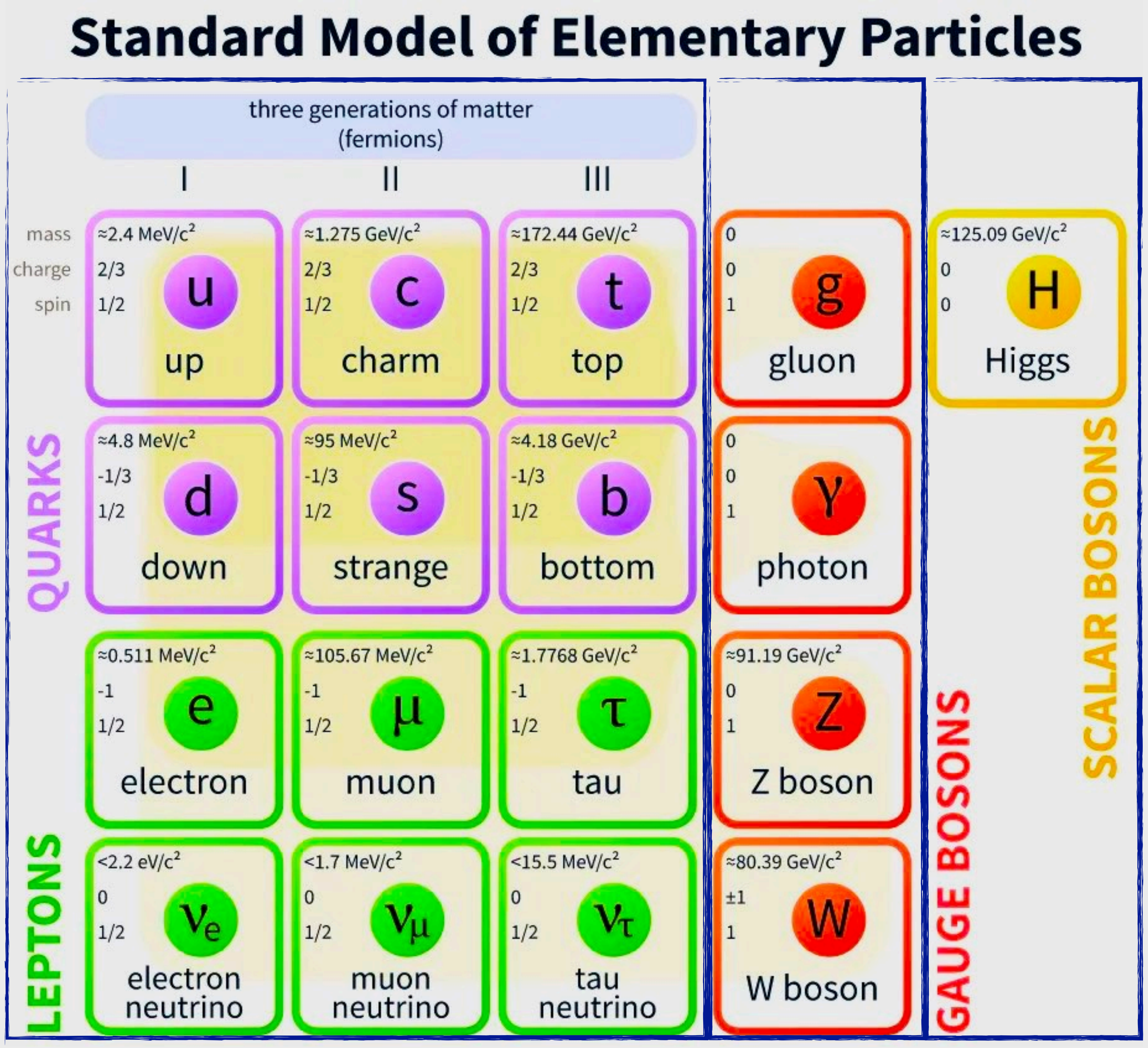
- The other group of particles in the Standard Model are bosons

  ➡ These are the force carriers

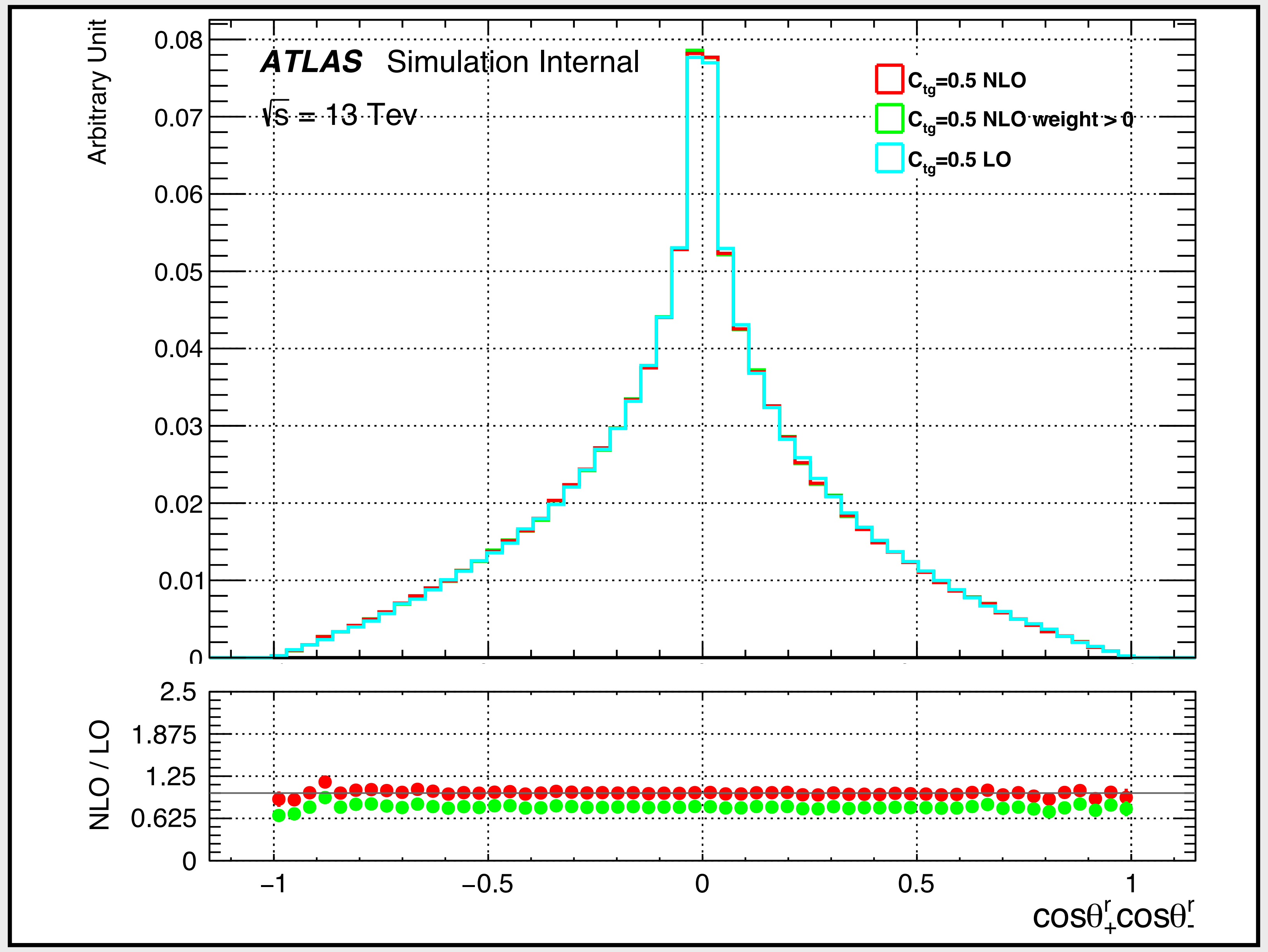
The Standard Model of Particle Physics

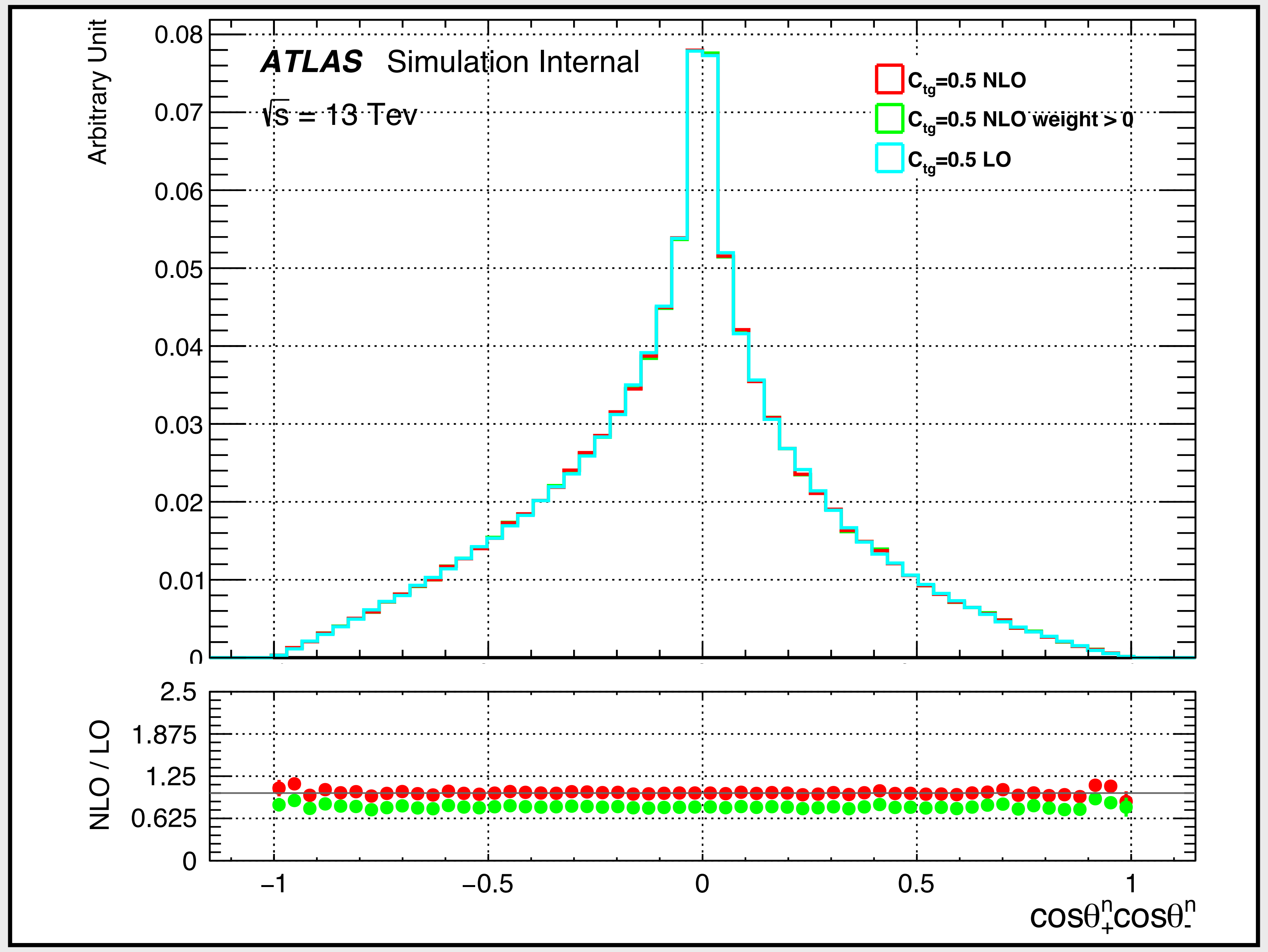


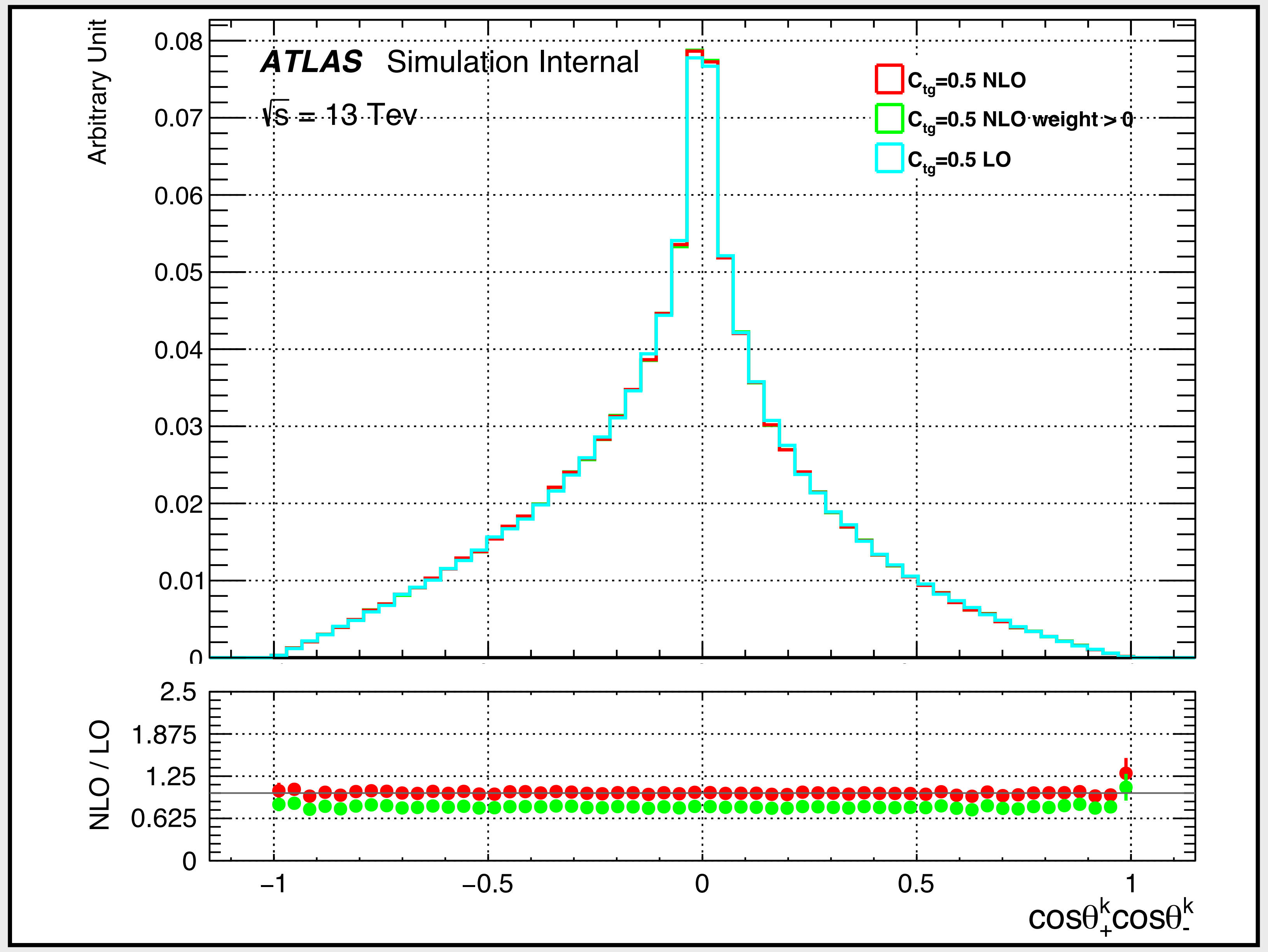
- There are three copies, or generations, of quarks and leptons Same properties, only heavier
- Leptons also include neutrinos, one for each generation
- All of these are matter particles, or fermions
- The other group of particles in the Standard Model are bosons
- **Higgs mechanism explains how particles get their mass**

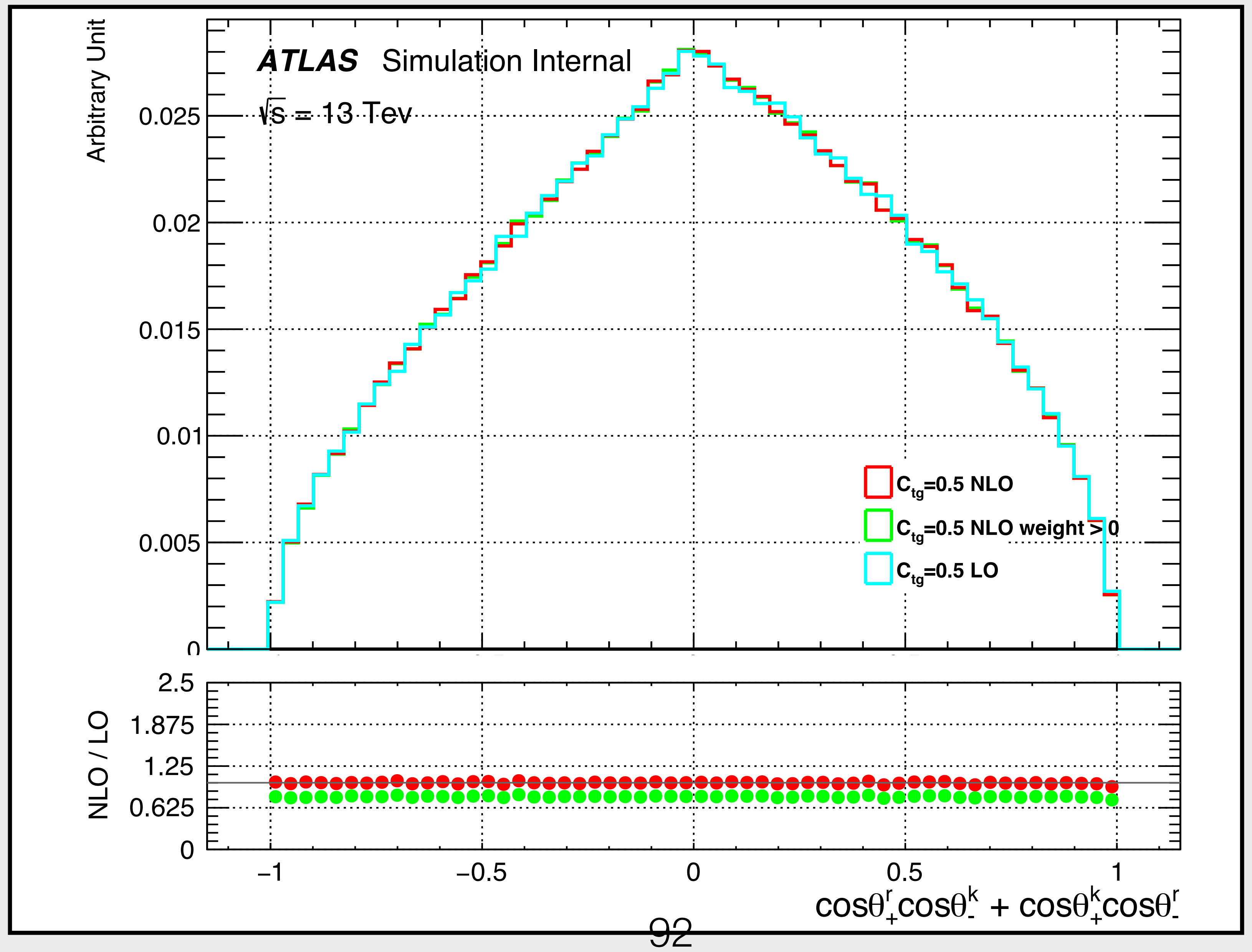
SM-EFT vs Dim6Top, Ctg

work in progress

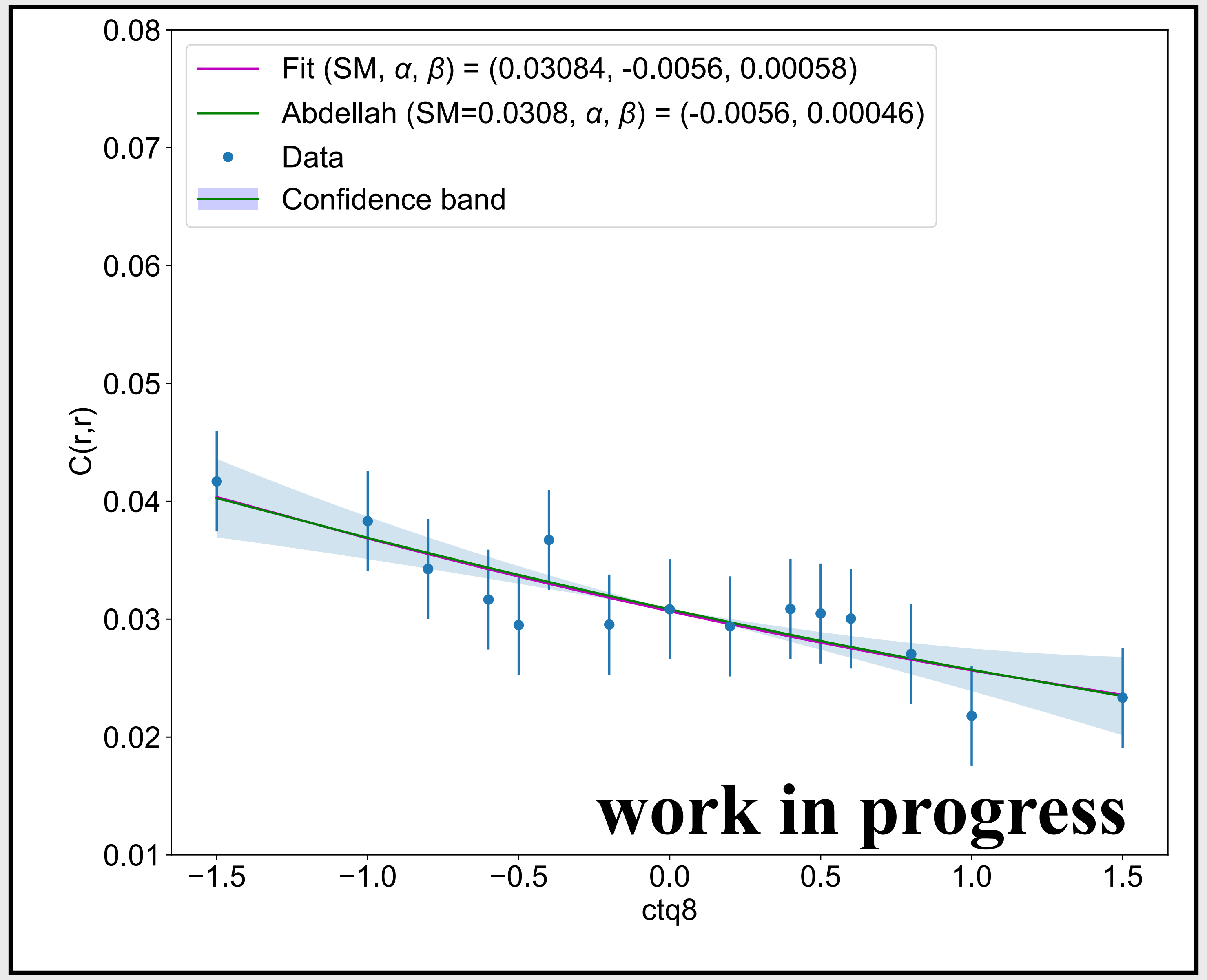


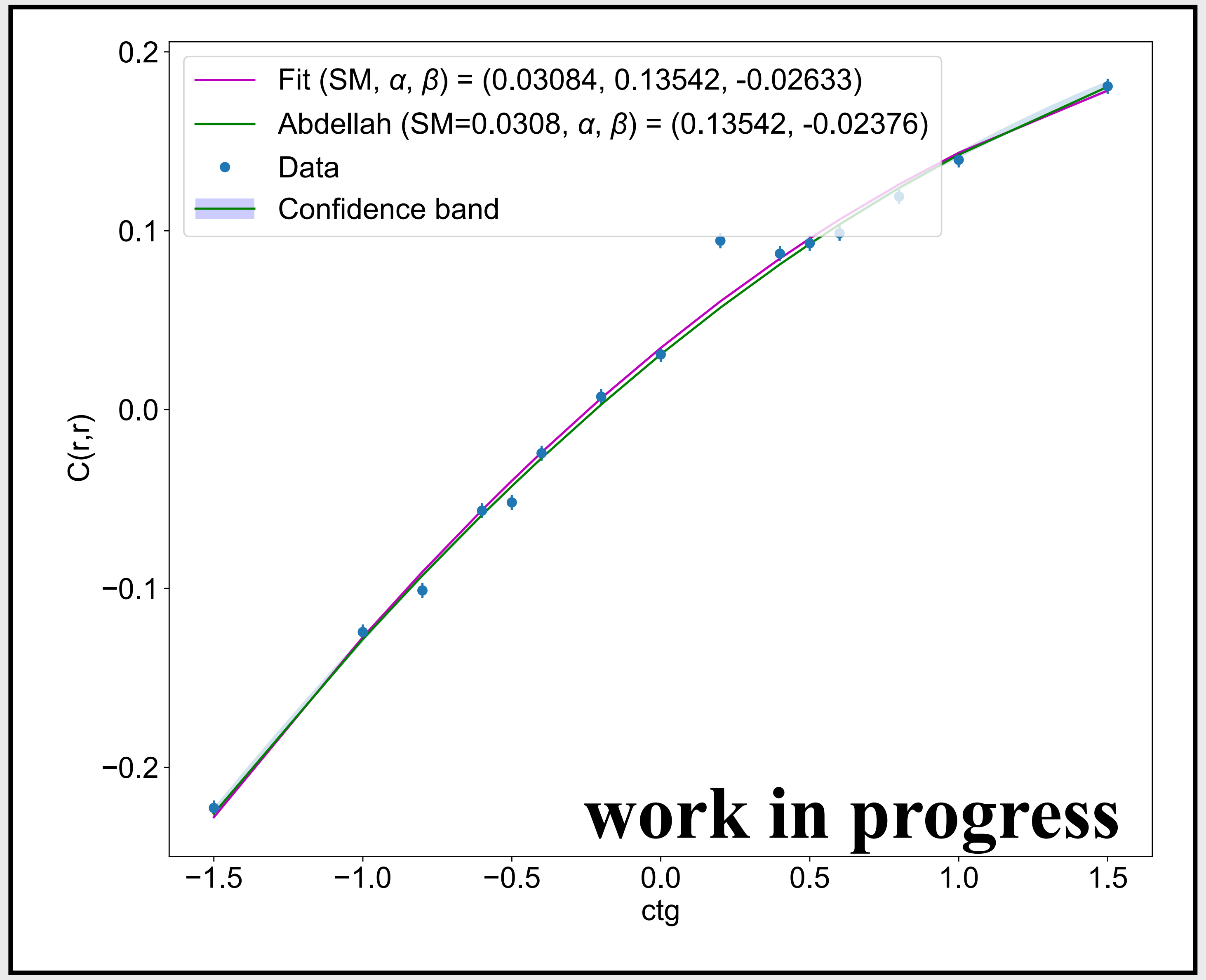


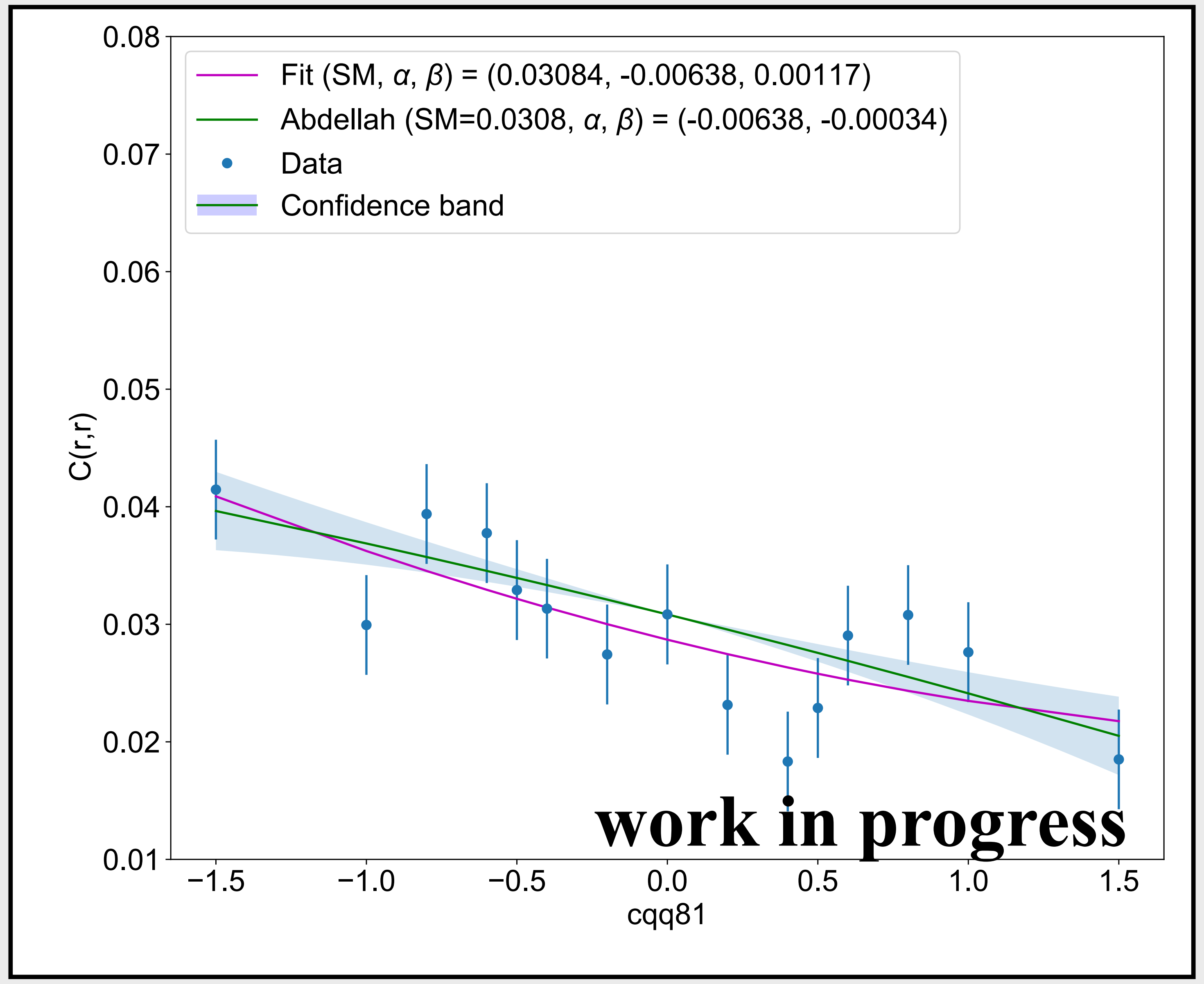


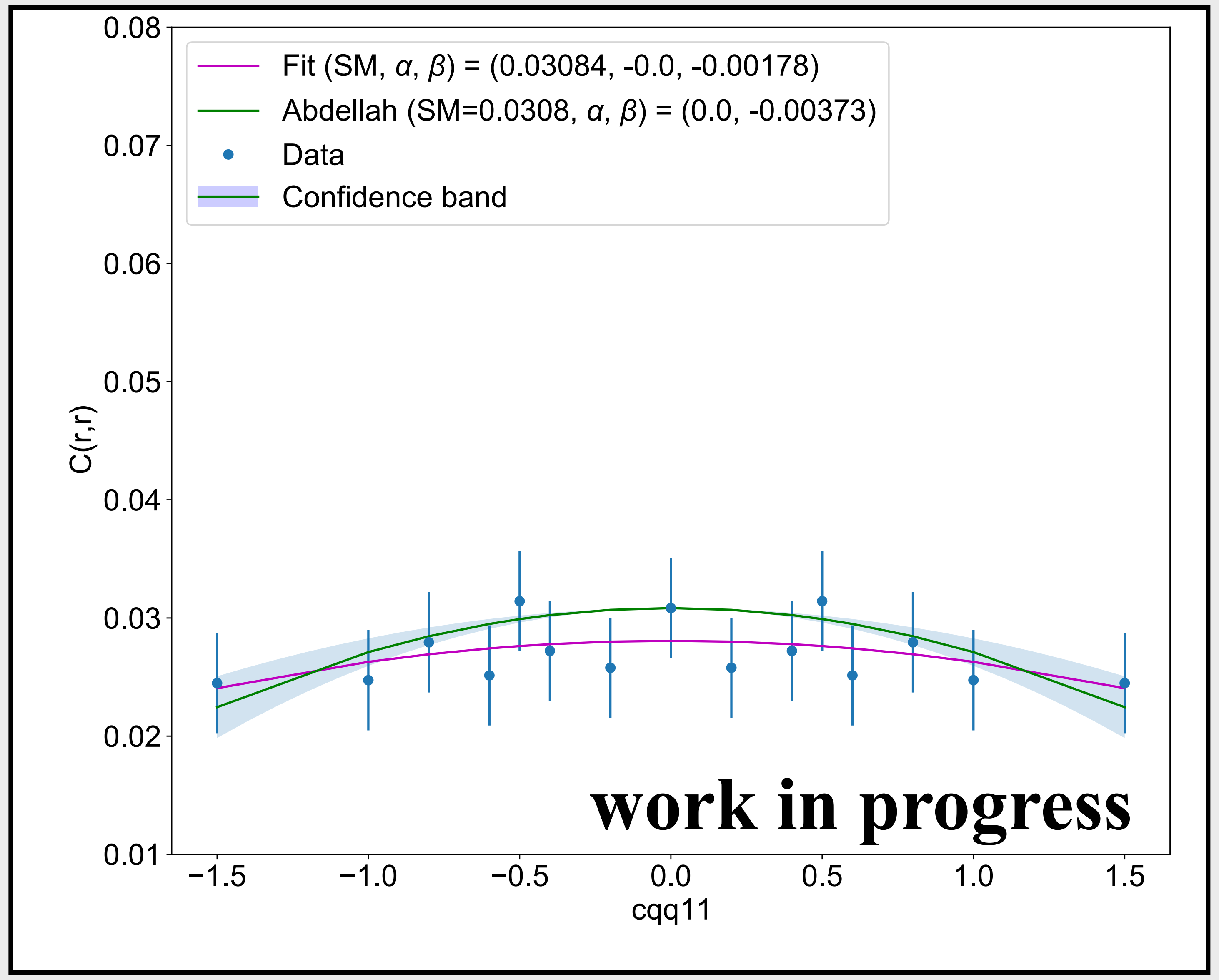


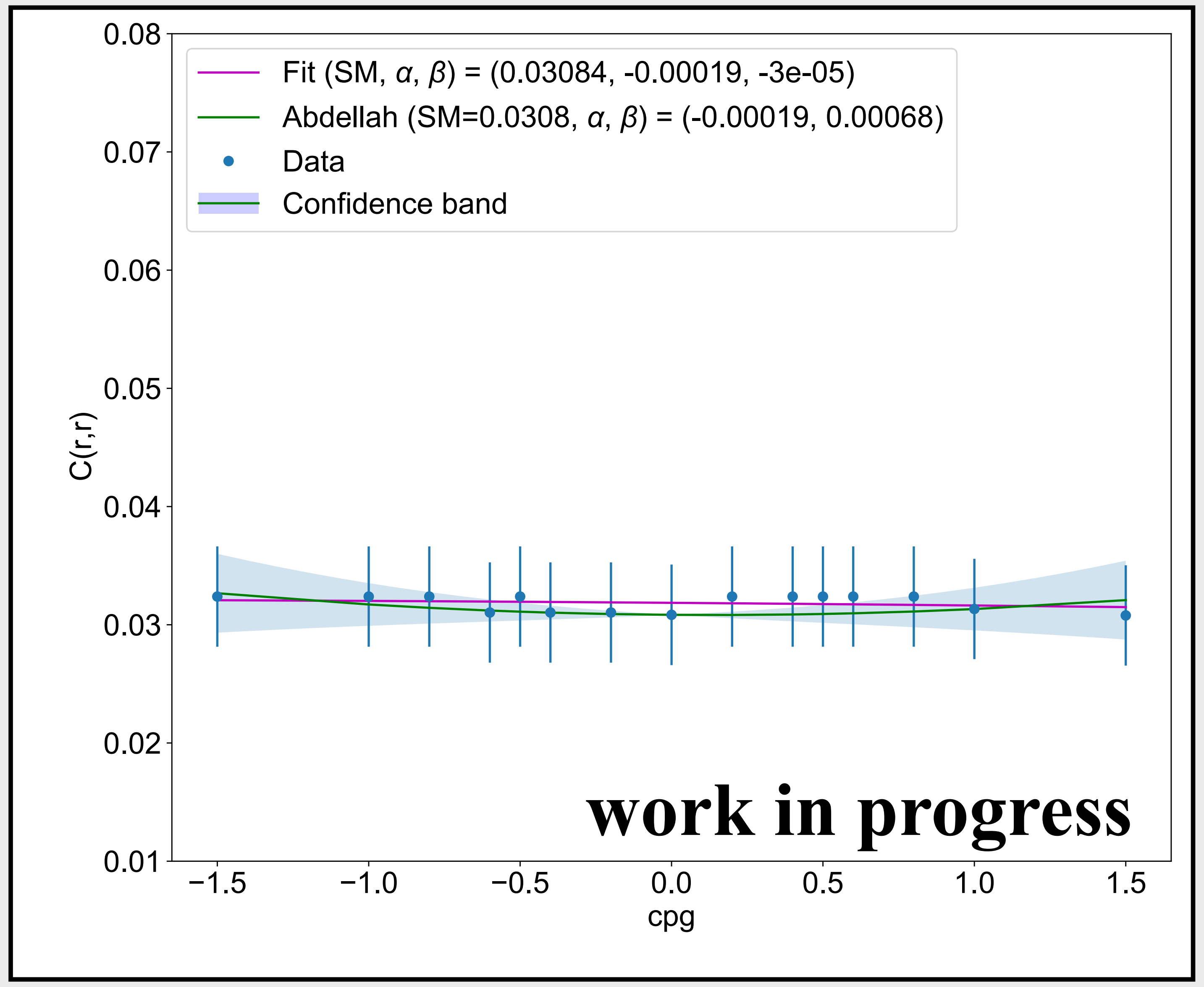
α_i/Λ^2 and β_i/Λ^4 at LO : C(r,r)





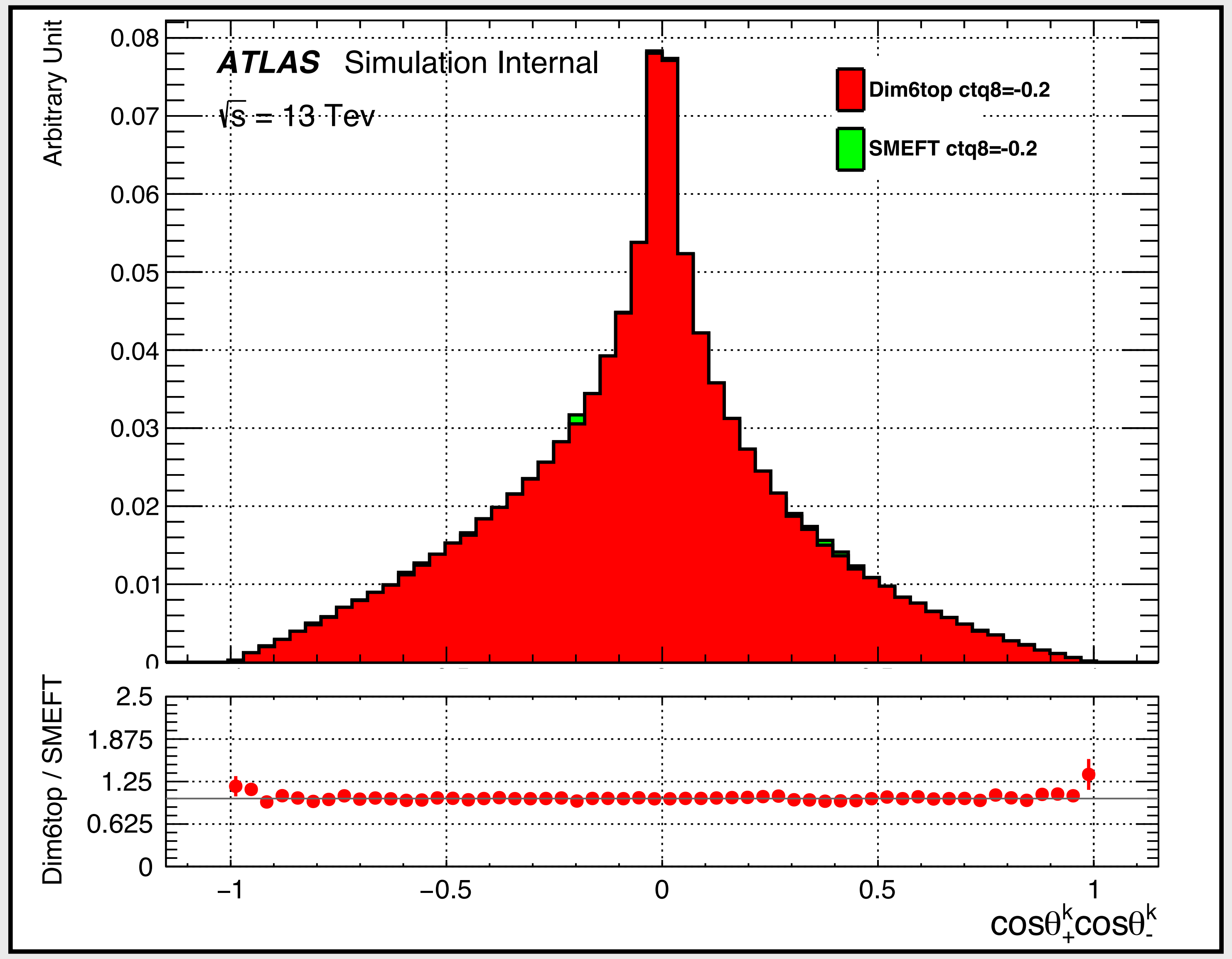


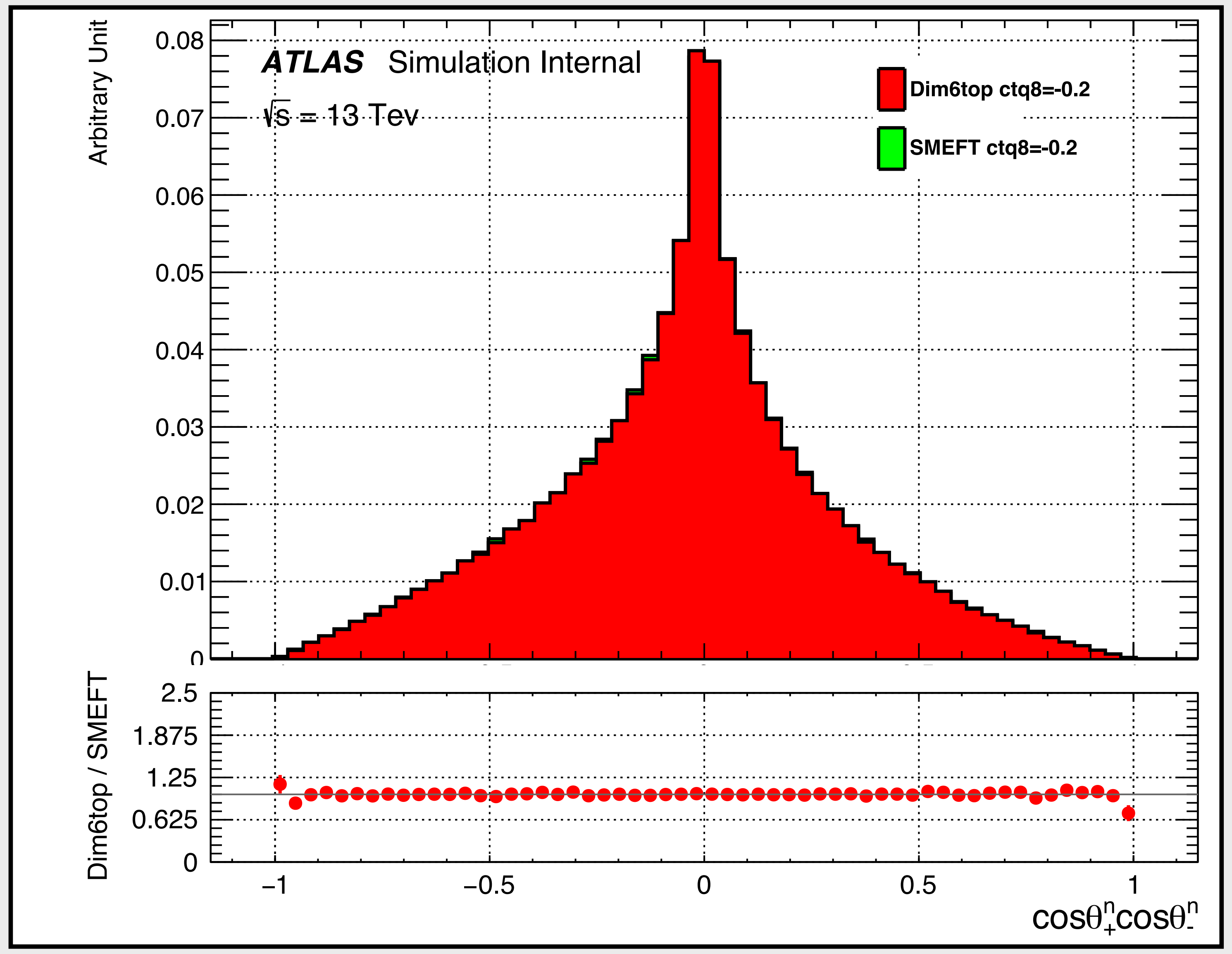


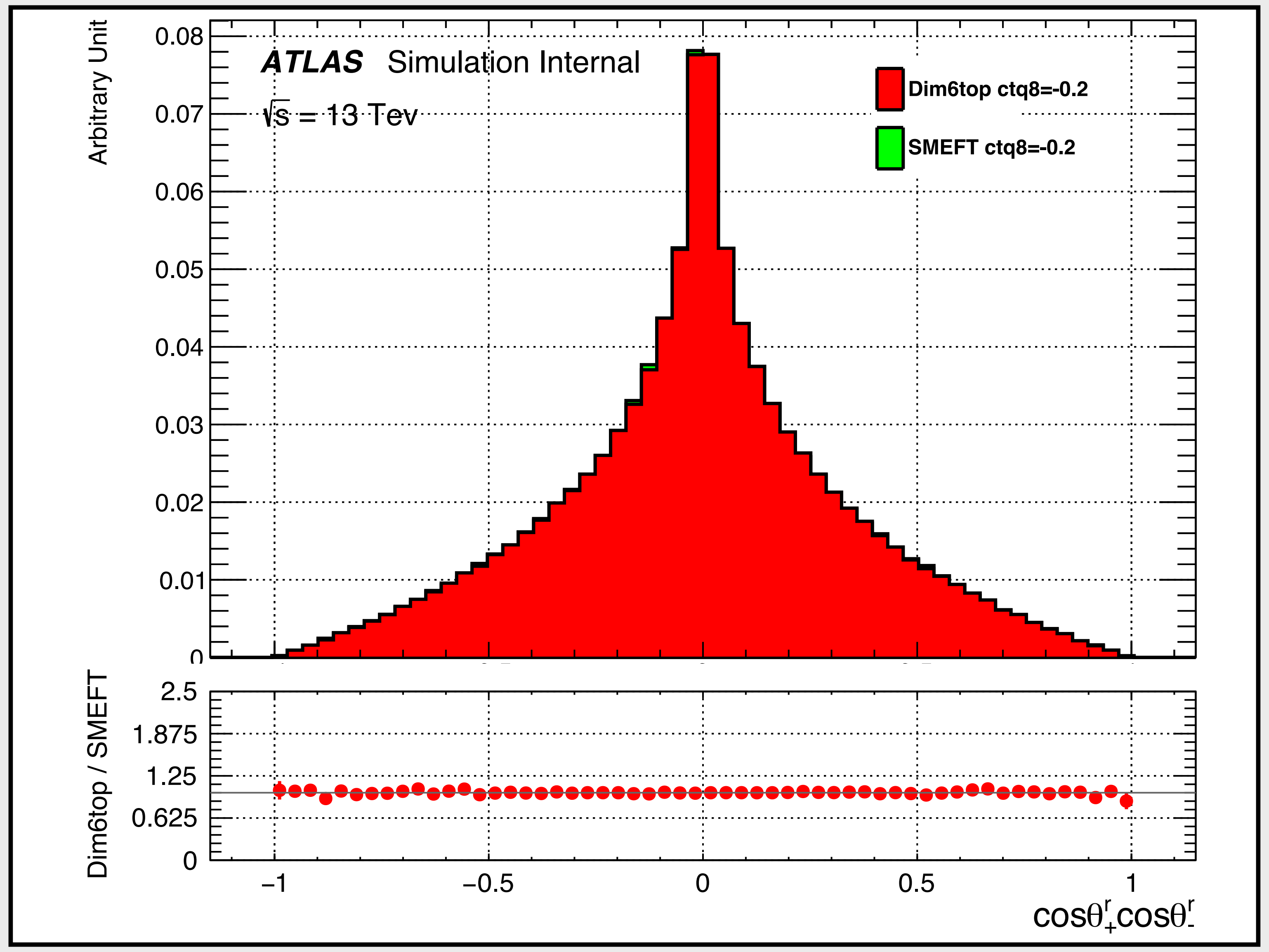


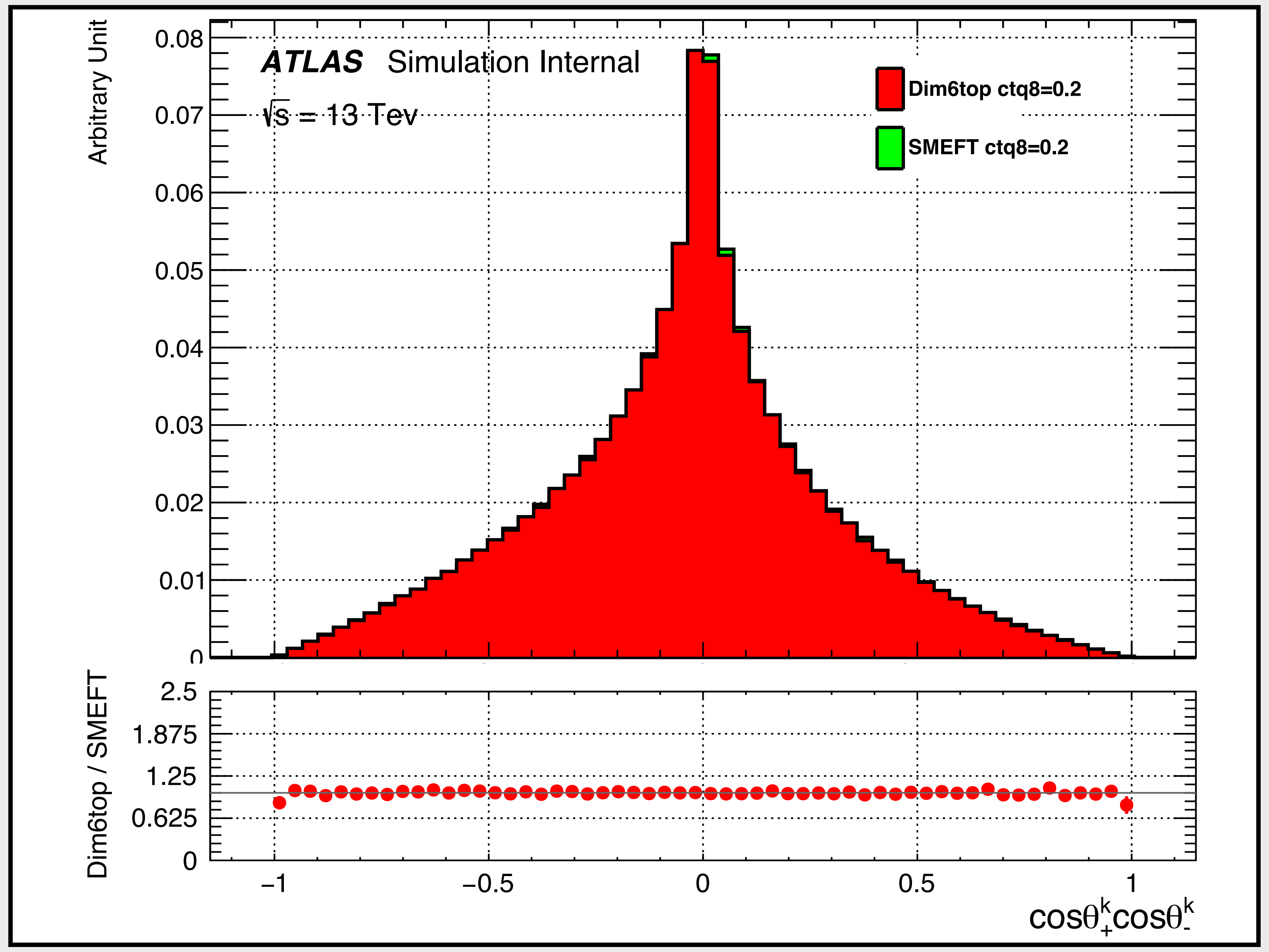
SM-EFT vs Dim6Top, Ctq8 +/- 0.2

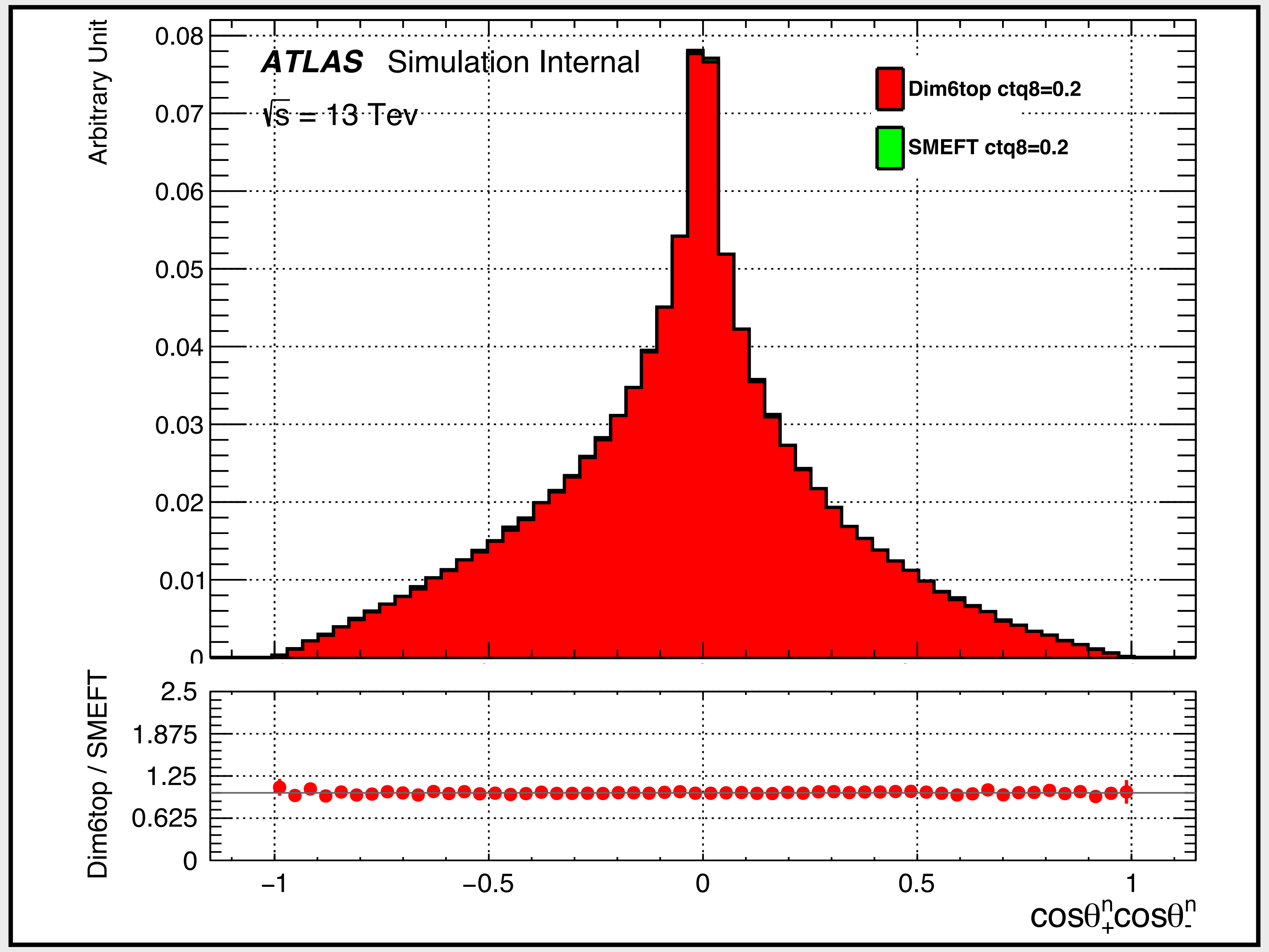
work in progress

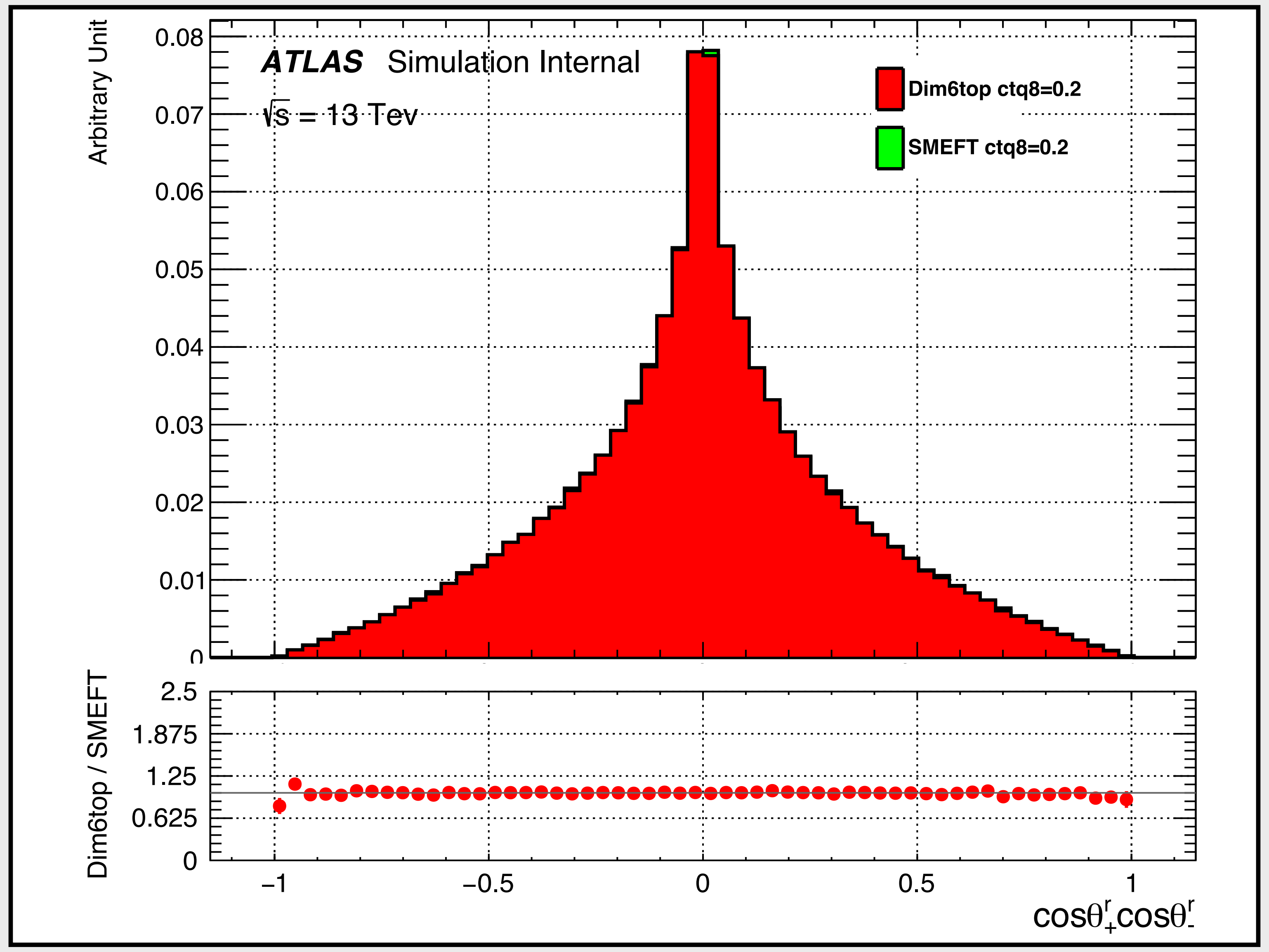






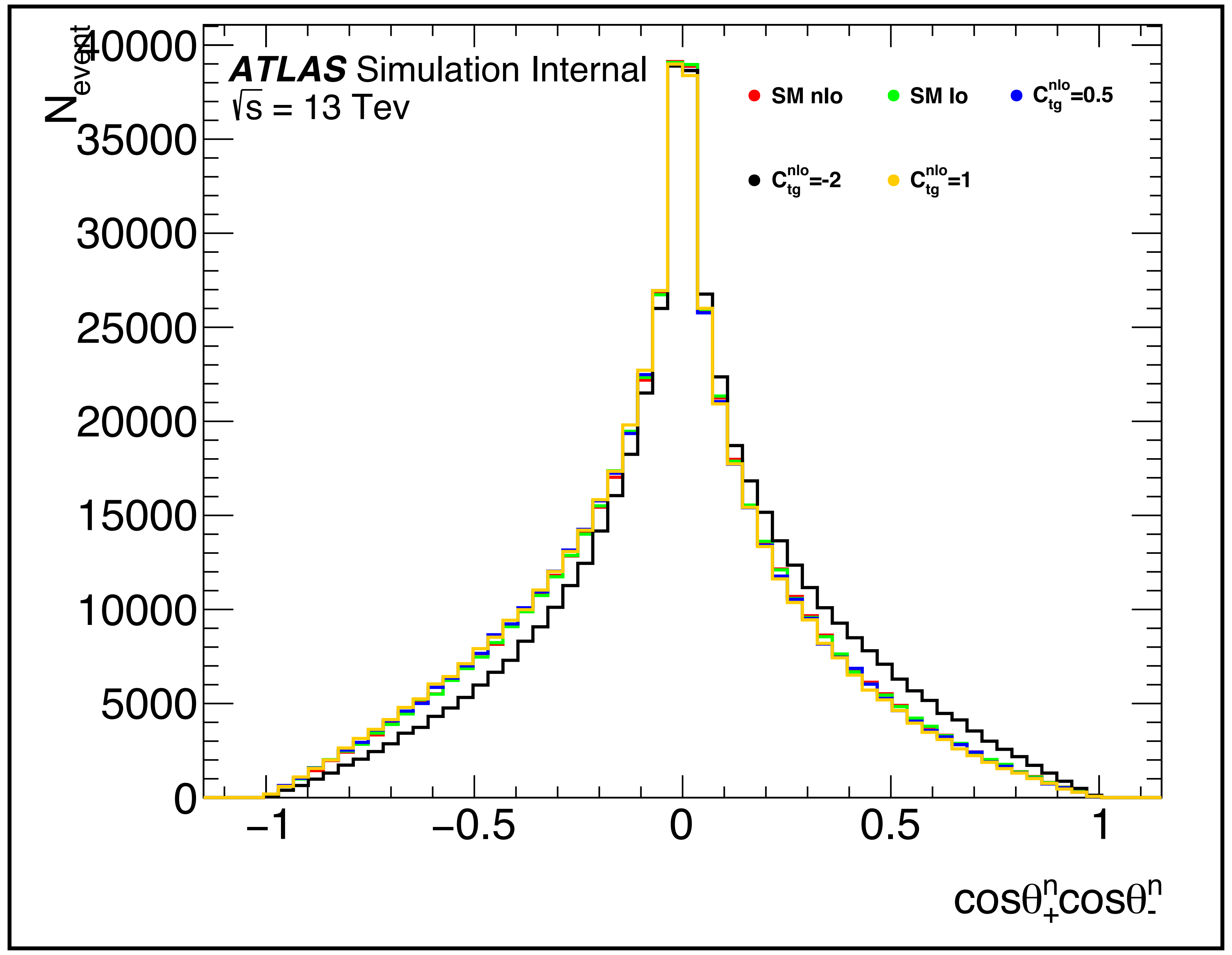


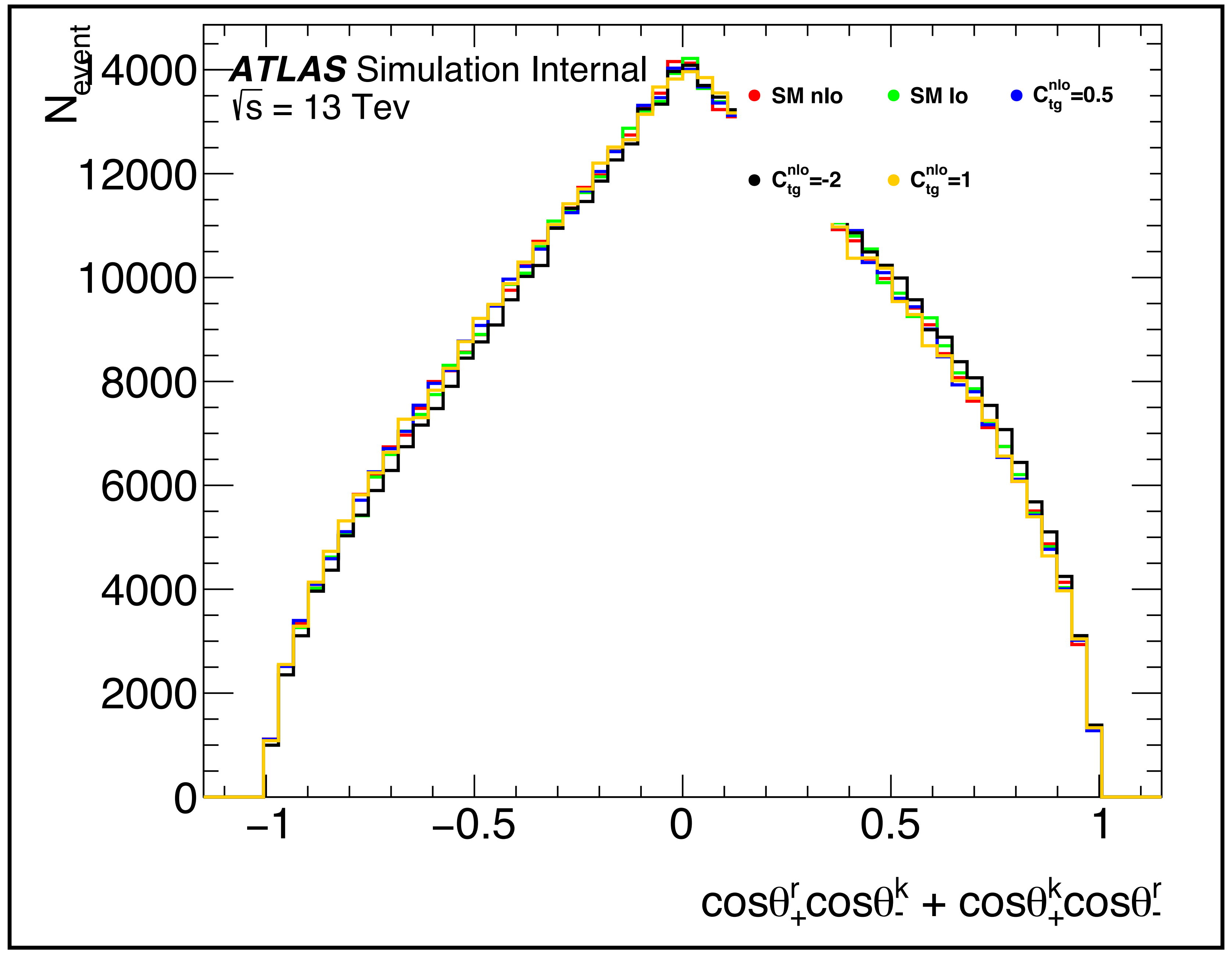


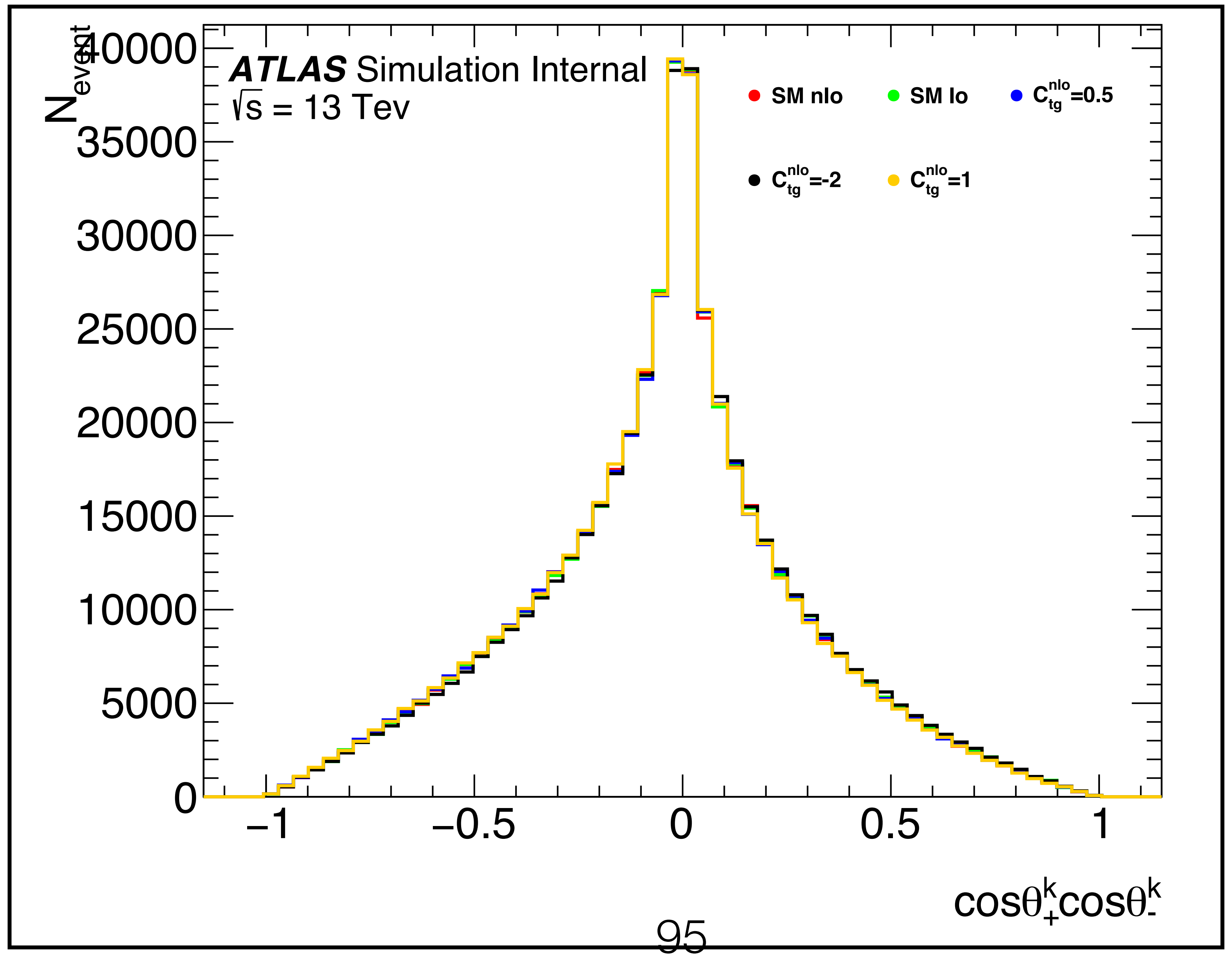


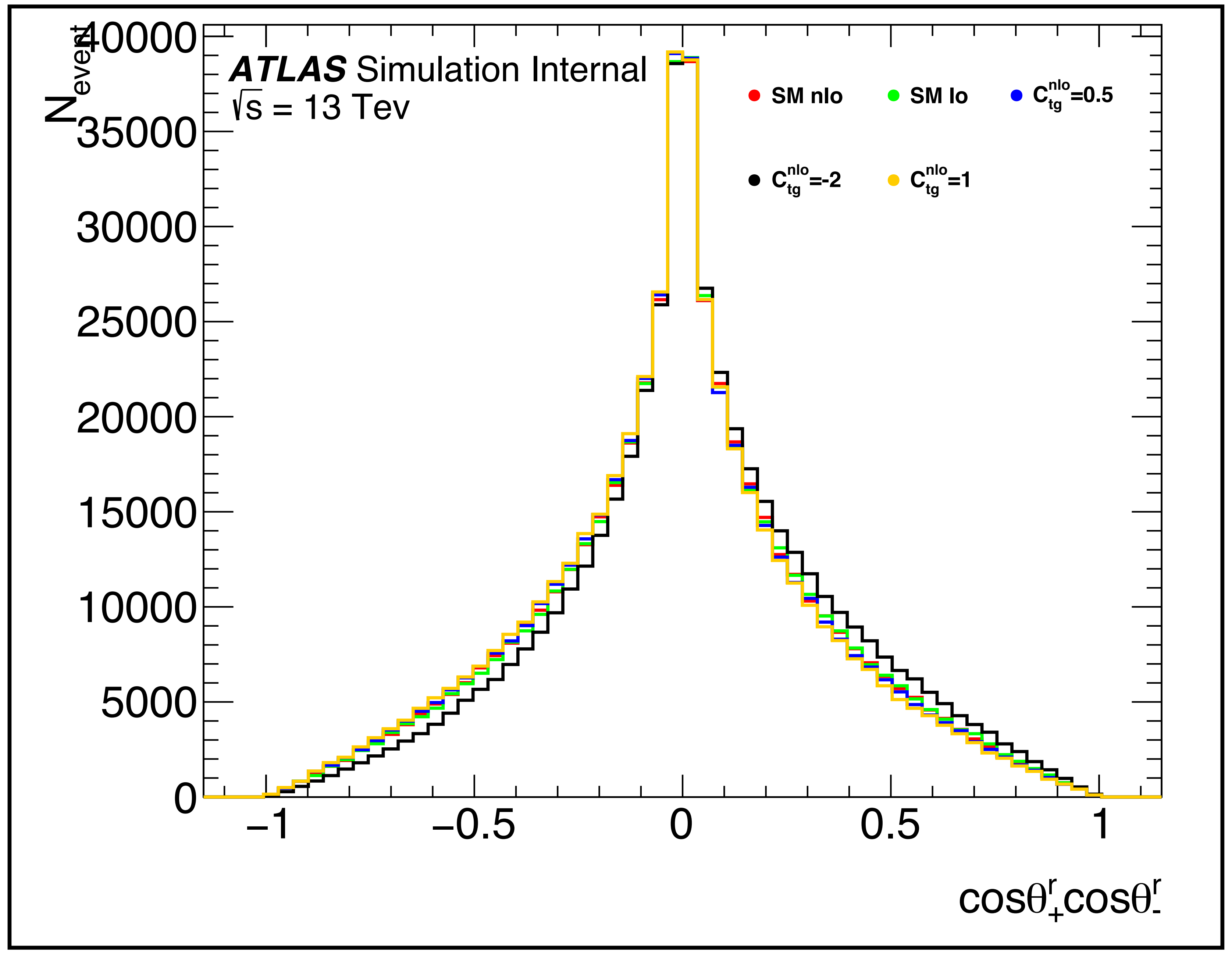
SM NLO/LO, Ctg

- **Spin correlation :**
  - Are directly affected by Ctg expect Ckk where the impact is small (we will discus it in details in part 2 also).
  - For other spin corrections observables, the effect is very low or not observed.



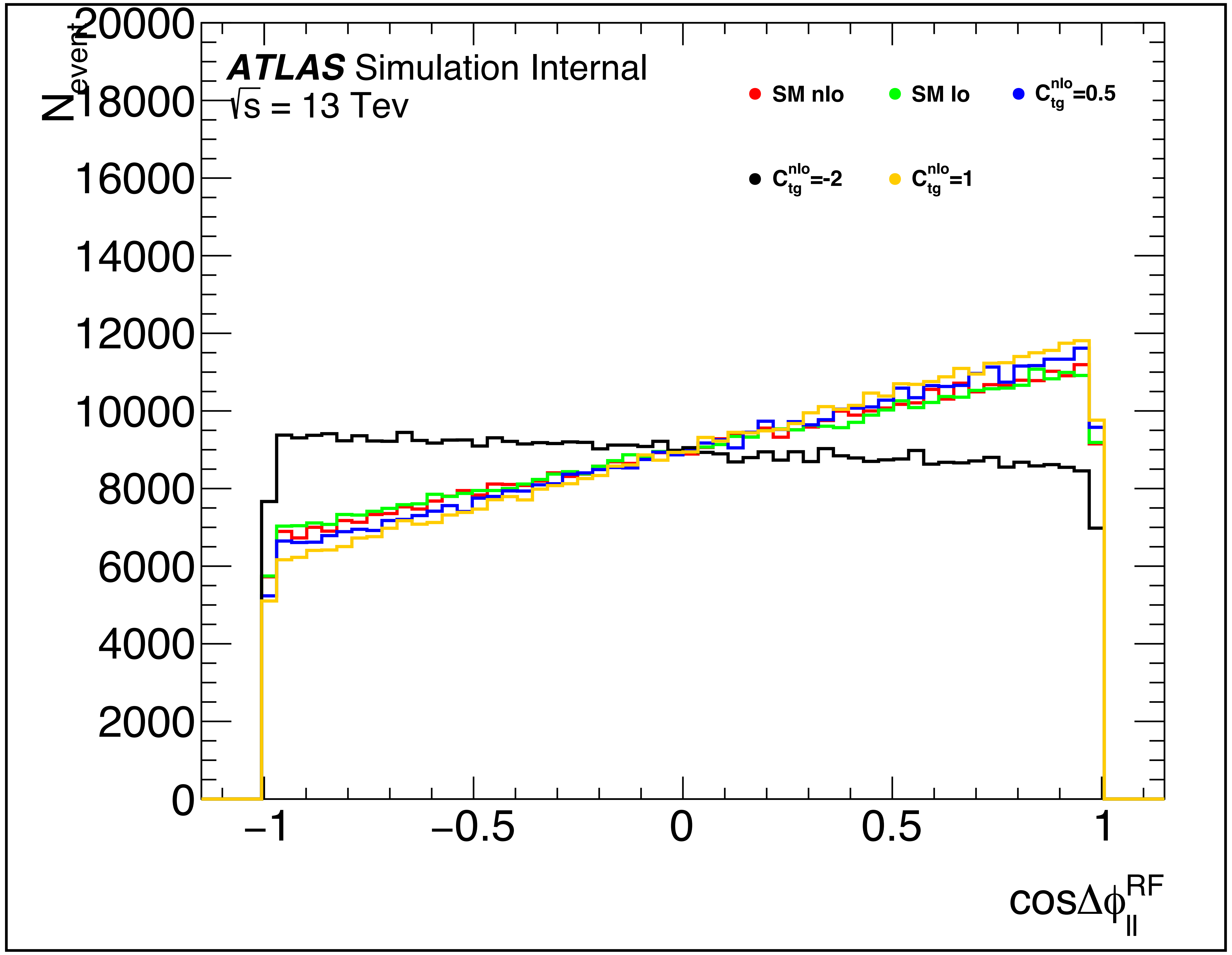






SM NLO/LO Ctg

- $cos\Delta\phi_{ll}^{RF}$:
    - For Ctg=-2, the distribution is ~ flat !!!



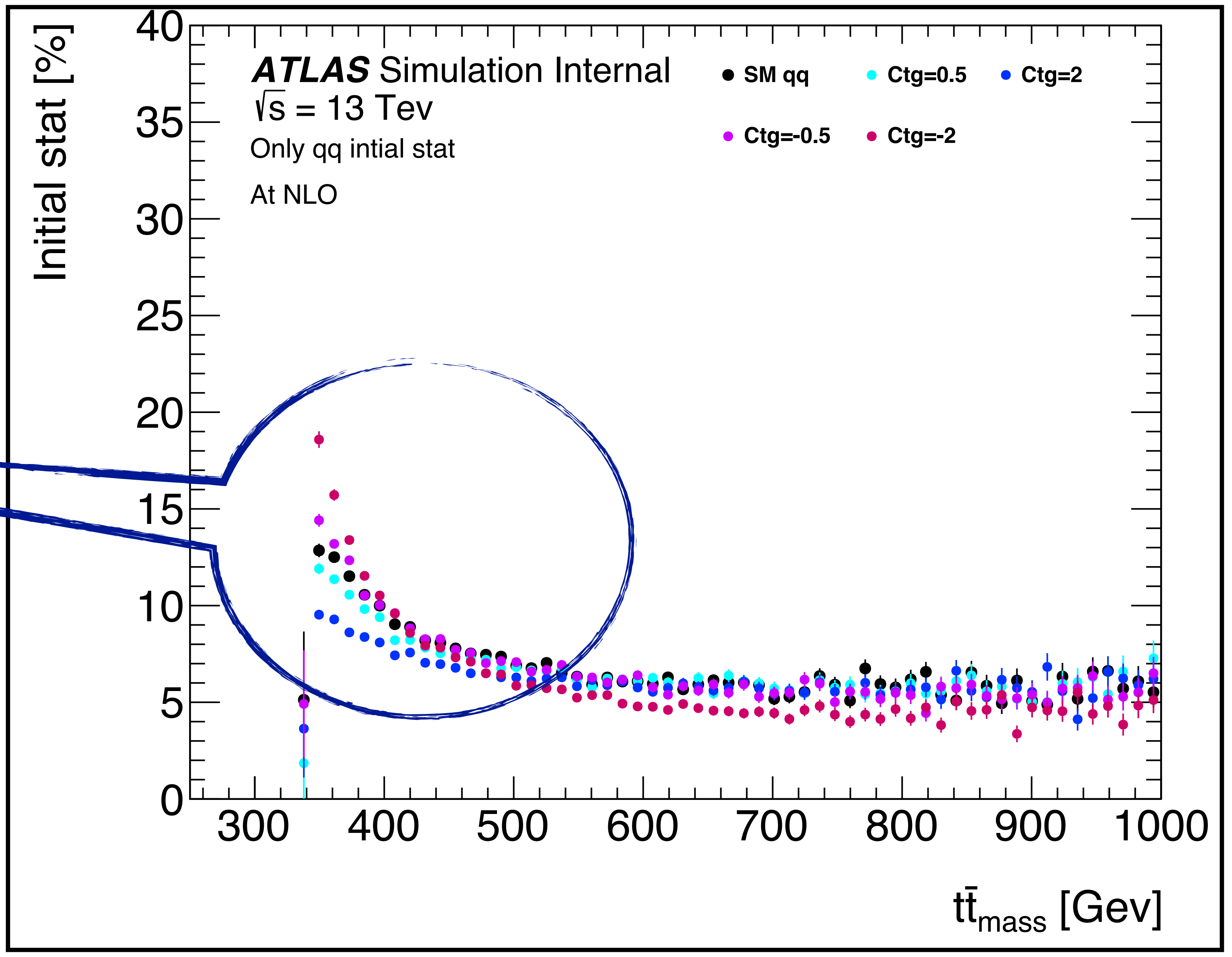
Initial stat qq VS Ctg $M_{t\bar{t}}$

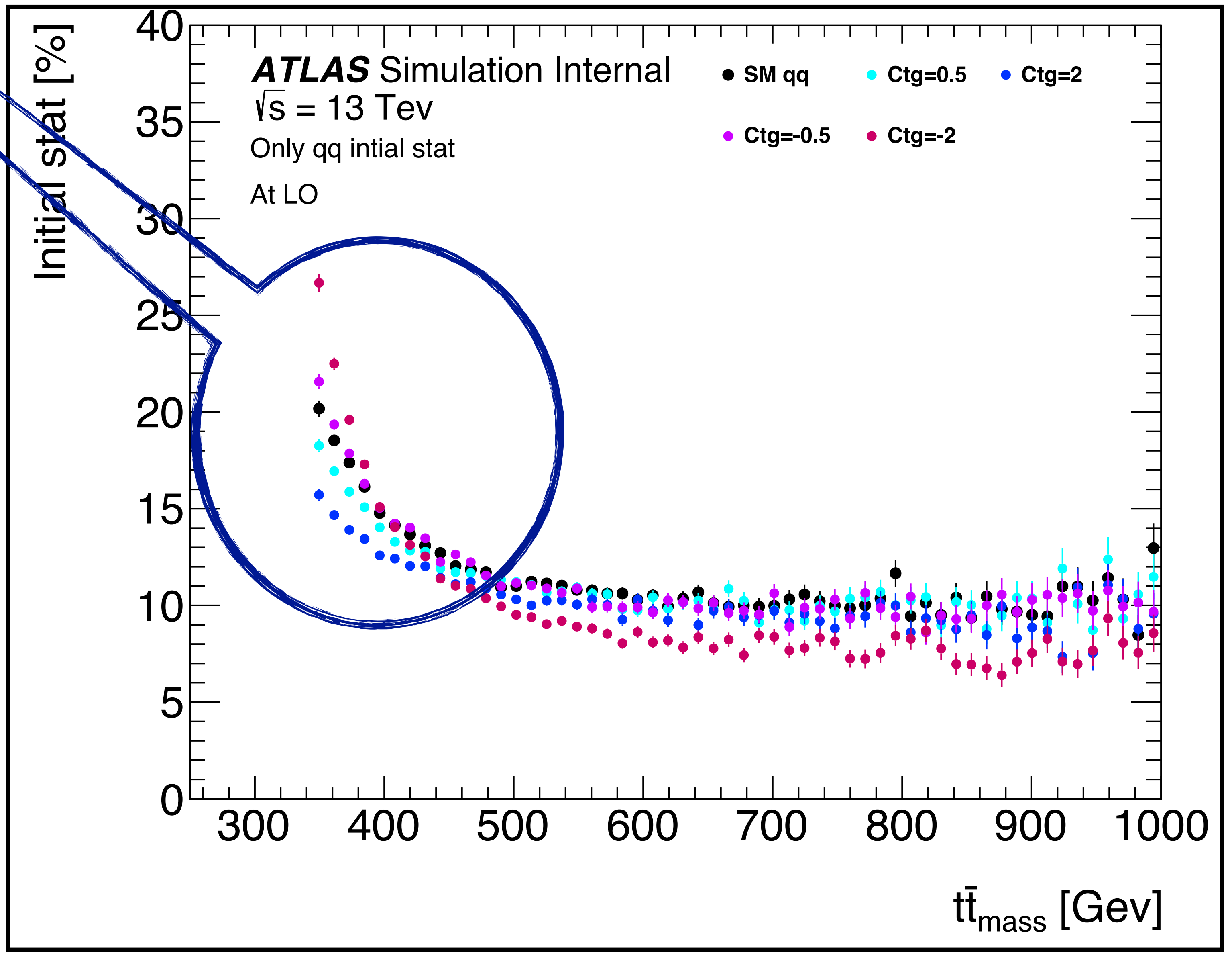
- Near Threshold

  - ☑ Fraction of gg is effected by Ctg = +/- 2 (also +/- 1, 1,5)

- Above Threshold:

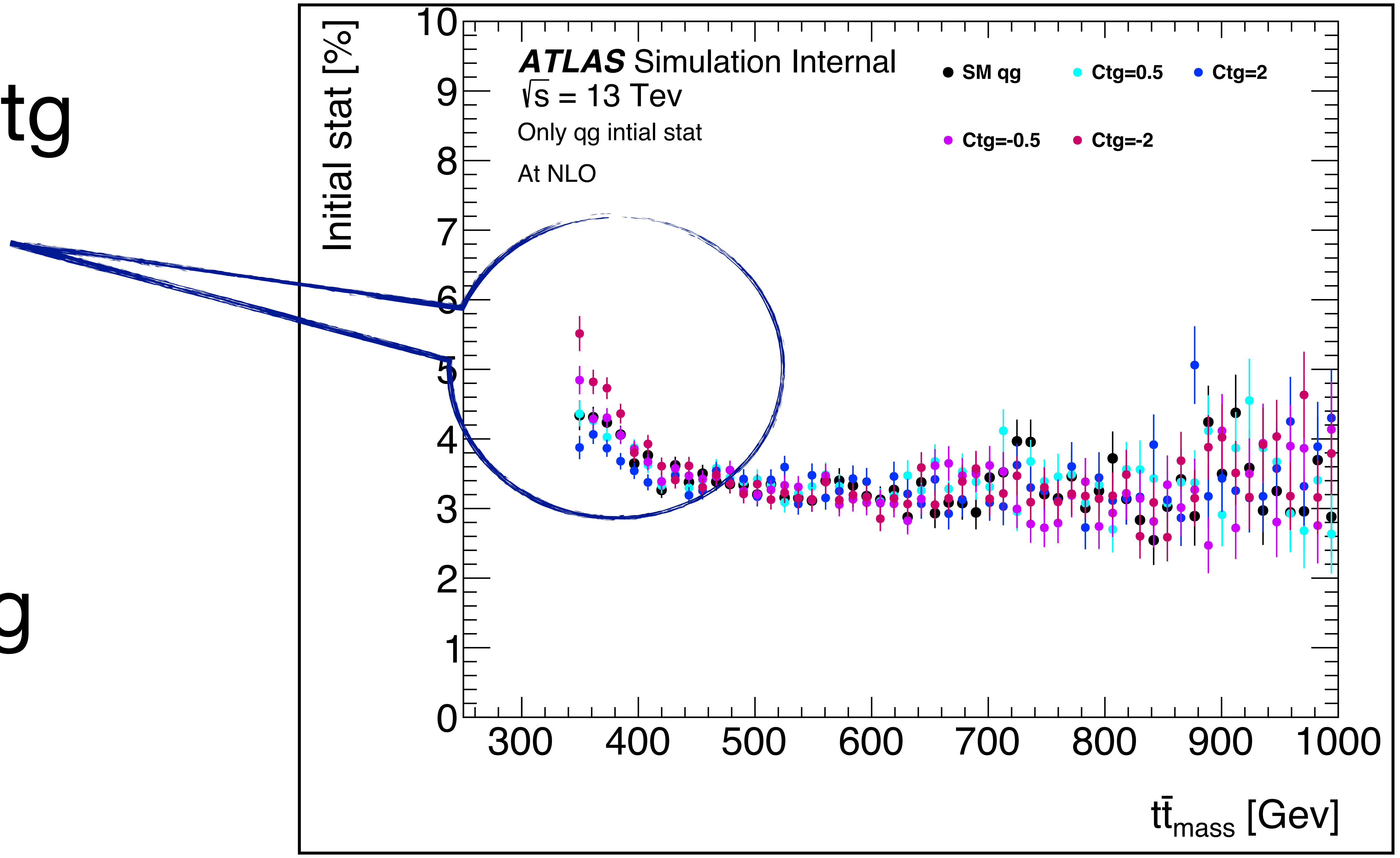
  - ☑ Fraction of gg is stable w.r.t Ctg values !



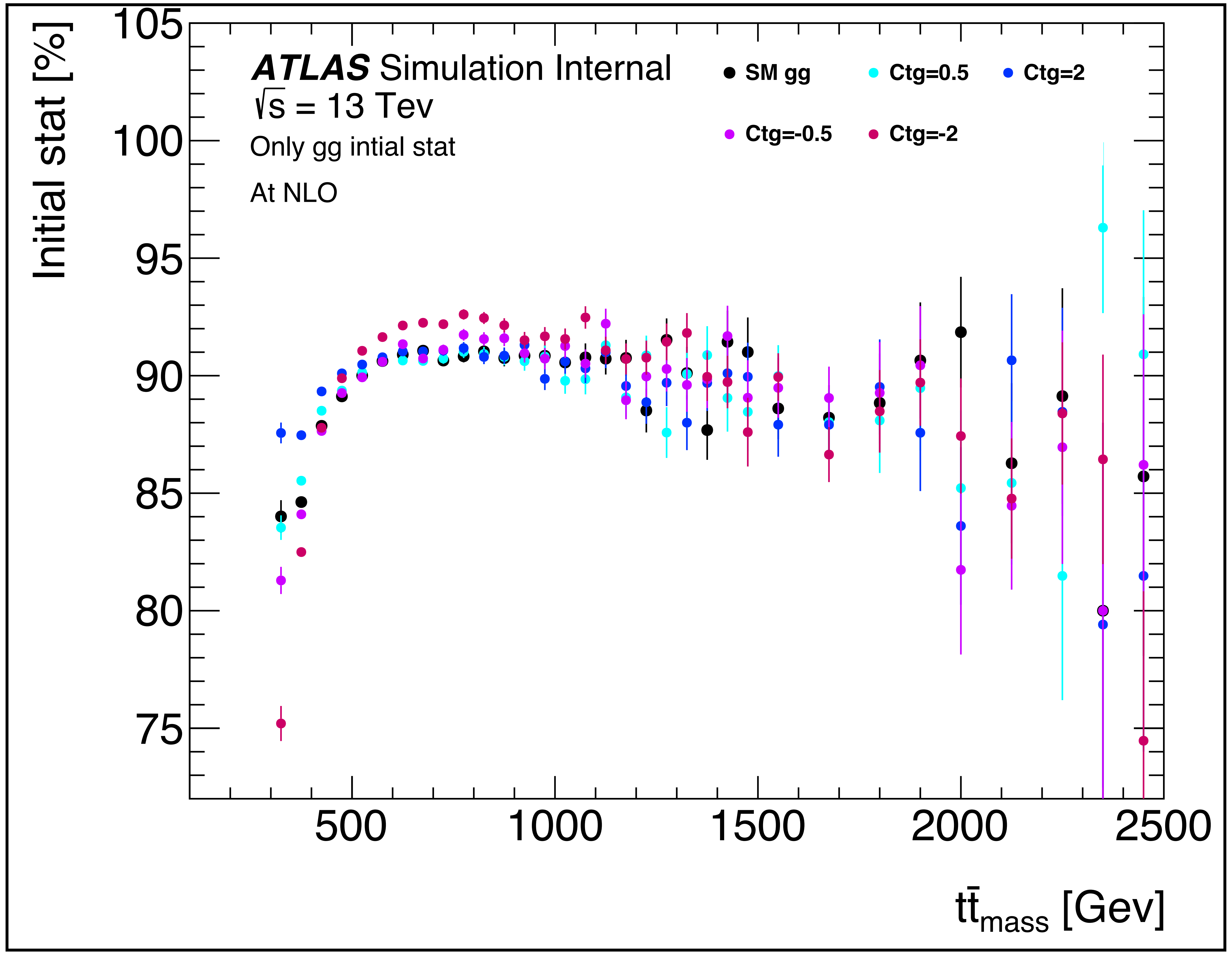


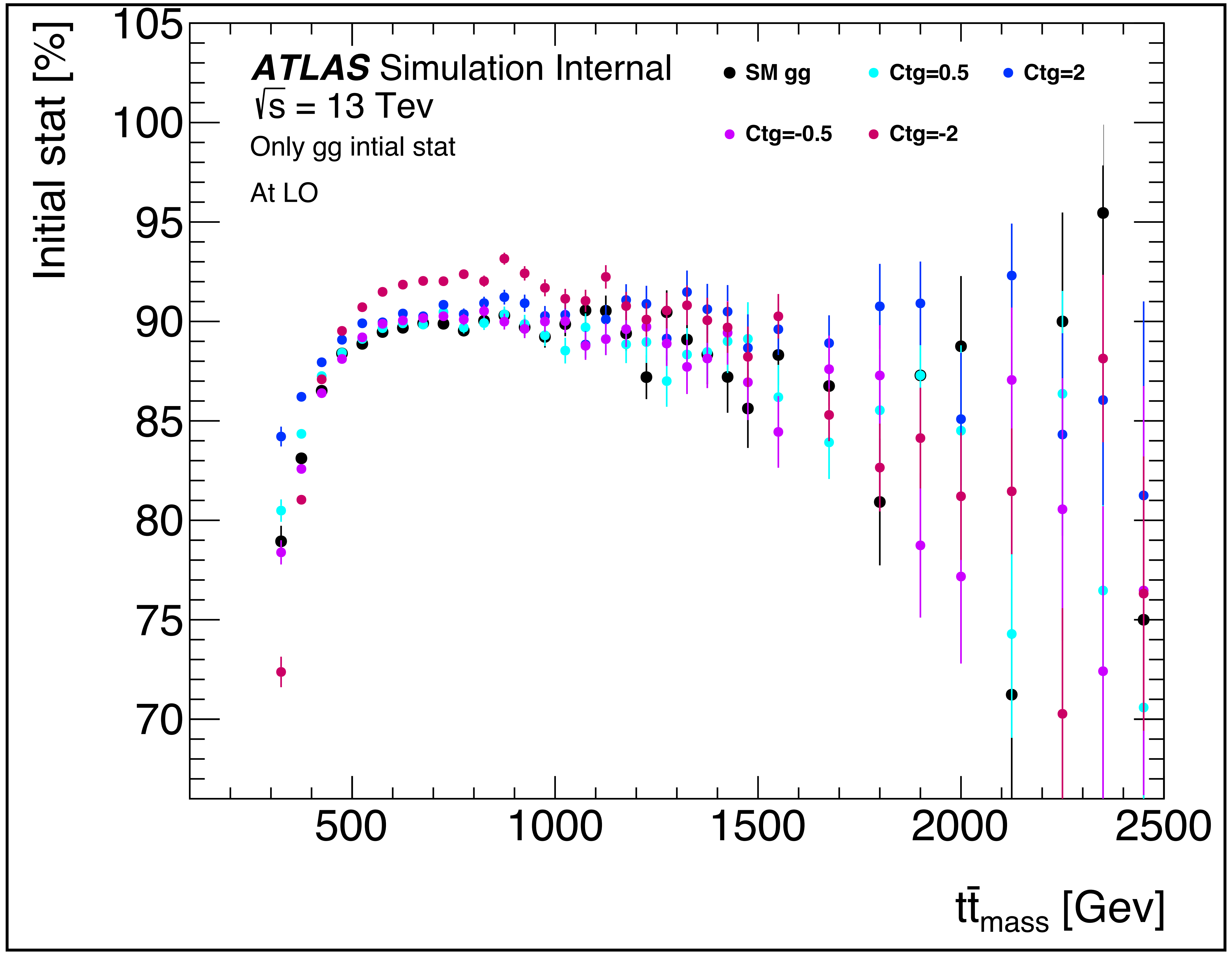
Initial stat qg VS Ctg $M_{t\bar{t}}$

- Near Threshold
  - Fraction of gg is effected by Ctg = +/- 2 (also +/- 1, 1,5)
- Above Threshold:
  - Fraction of gg is stable w.r.t Ctg values !
- Same comments for qq and qg (for NLO) ==> See BackUp.

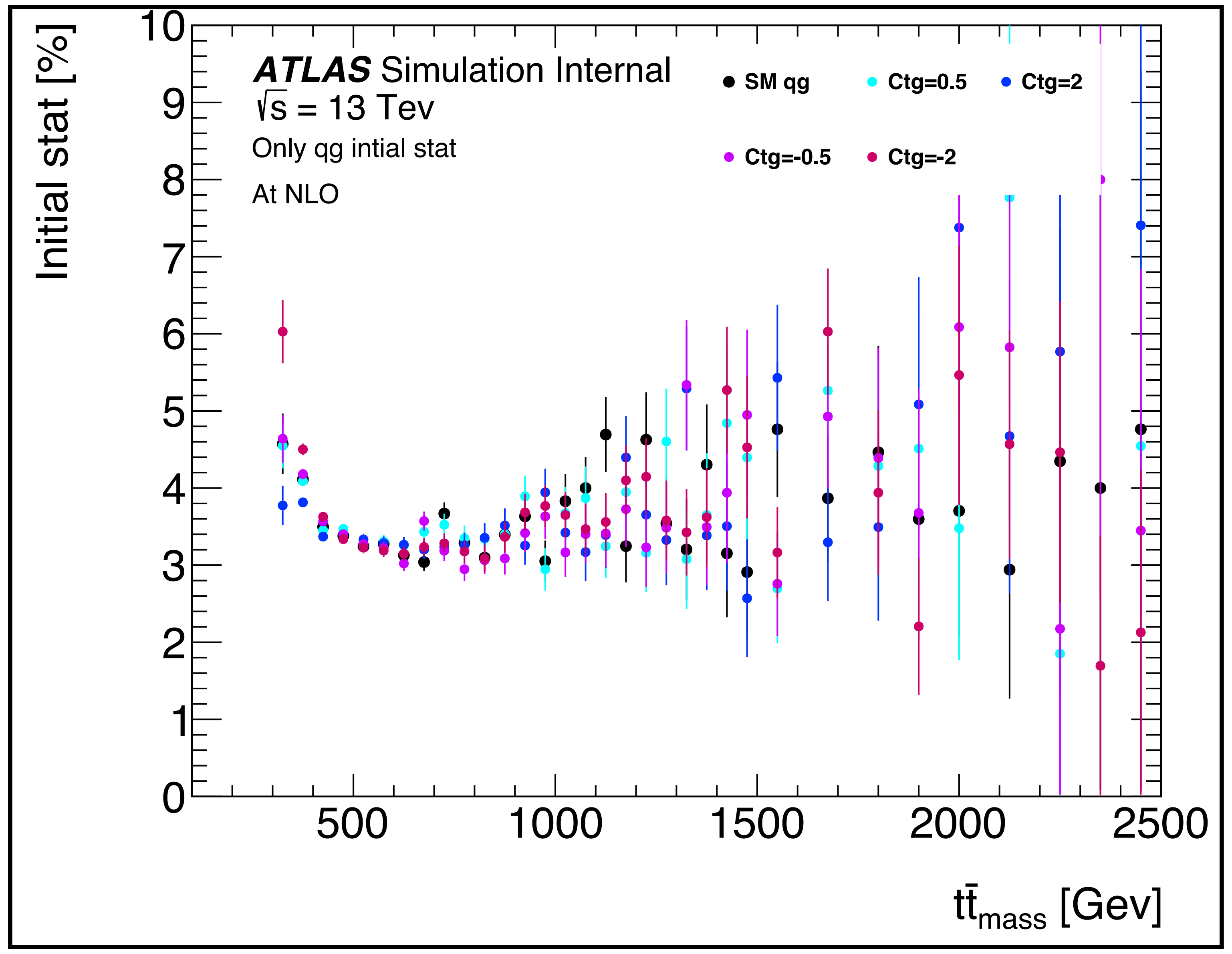


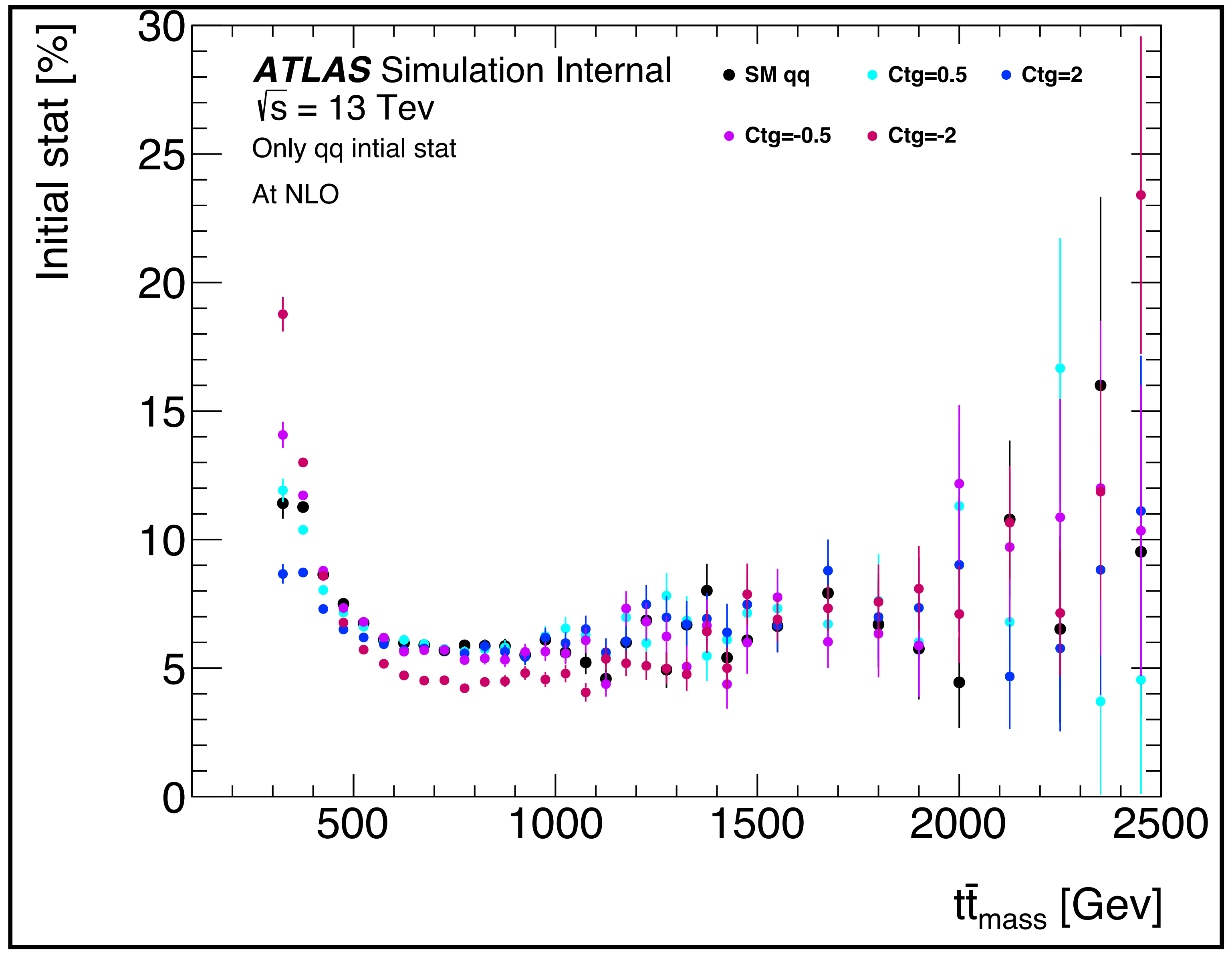
gg initial stat VS $t\bar{t}$ mass

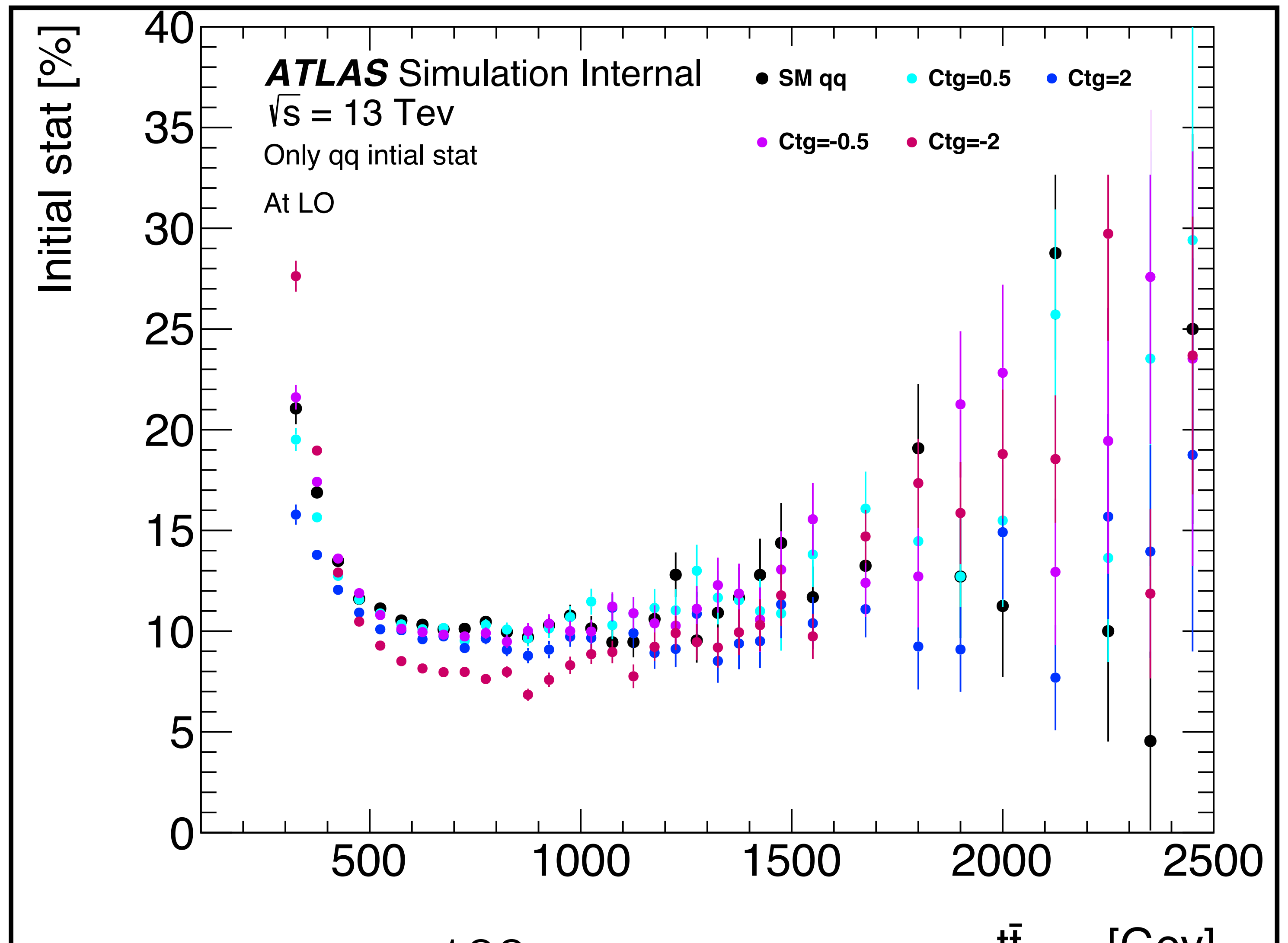




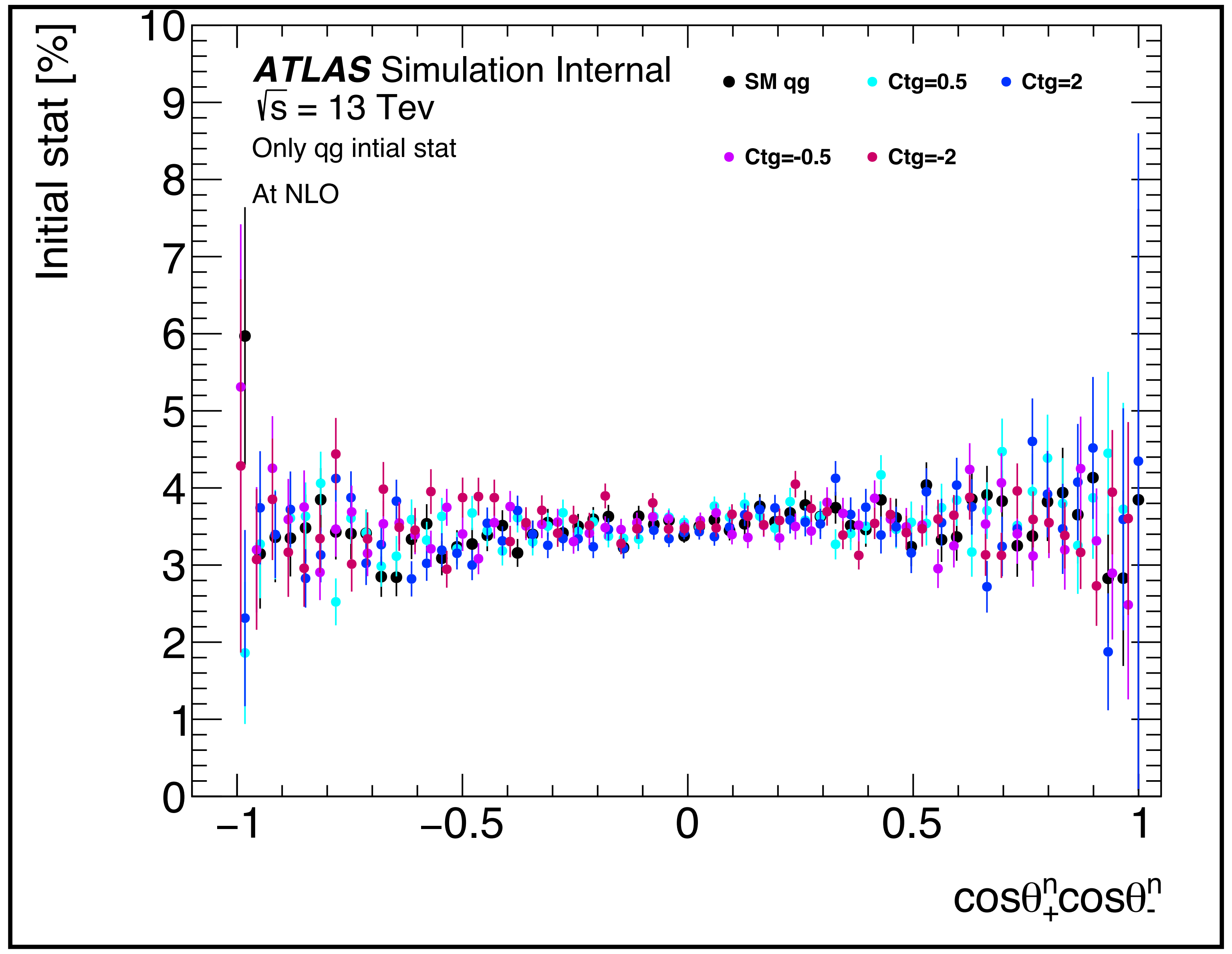
qq/qg initial stat VS $t\bar{t}$ mass

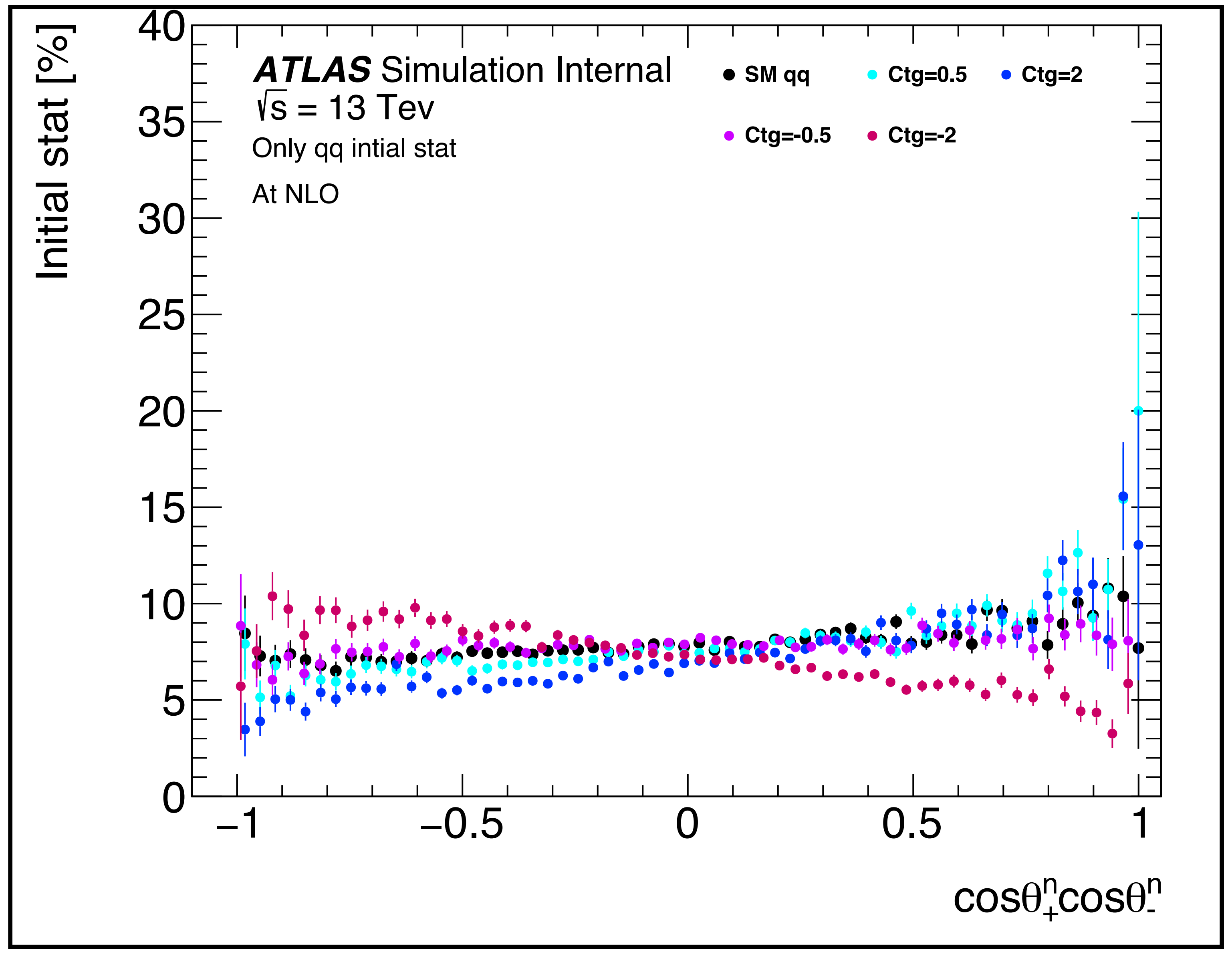


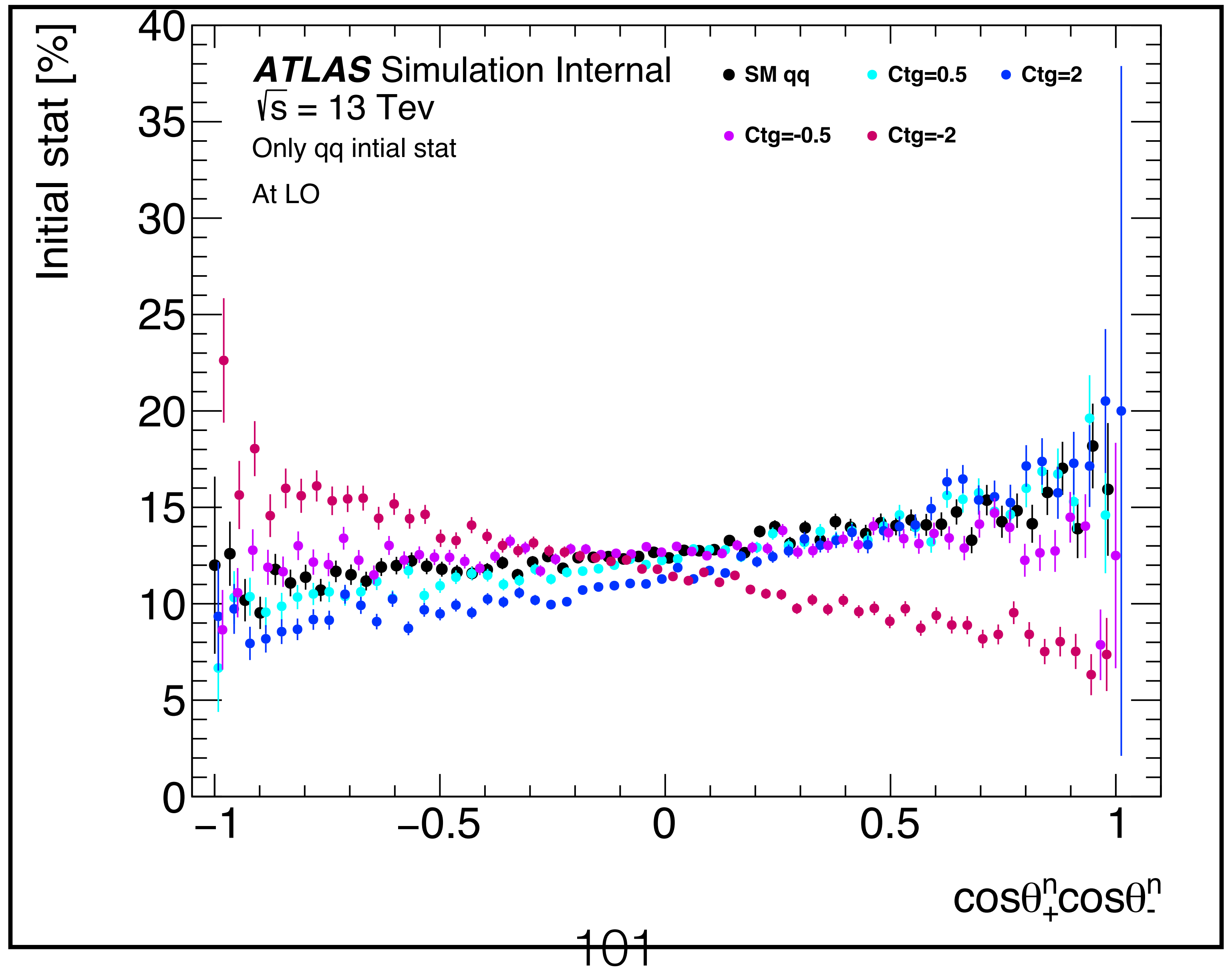




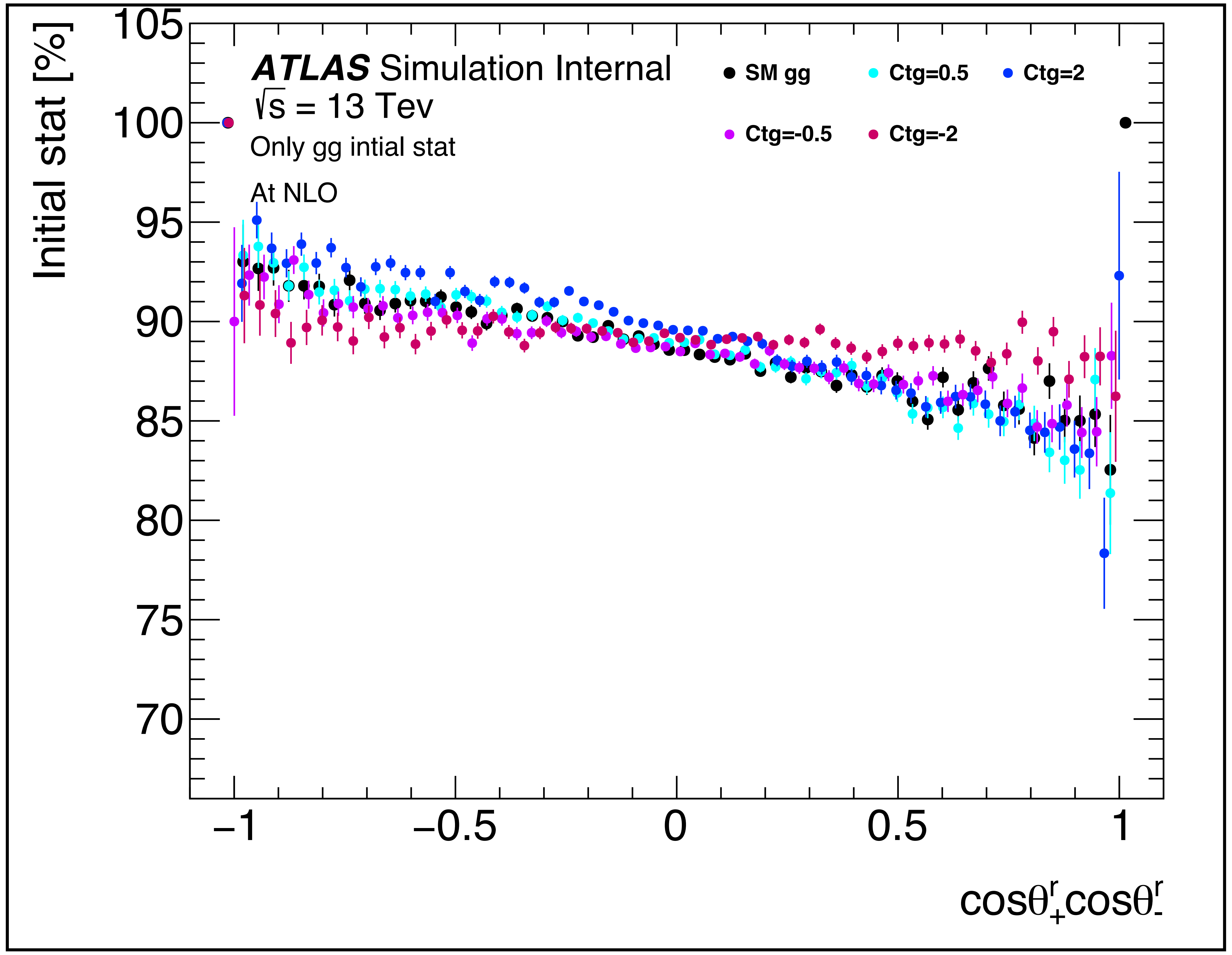
qq/qg Initial stat VS C(n,n)

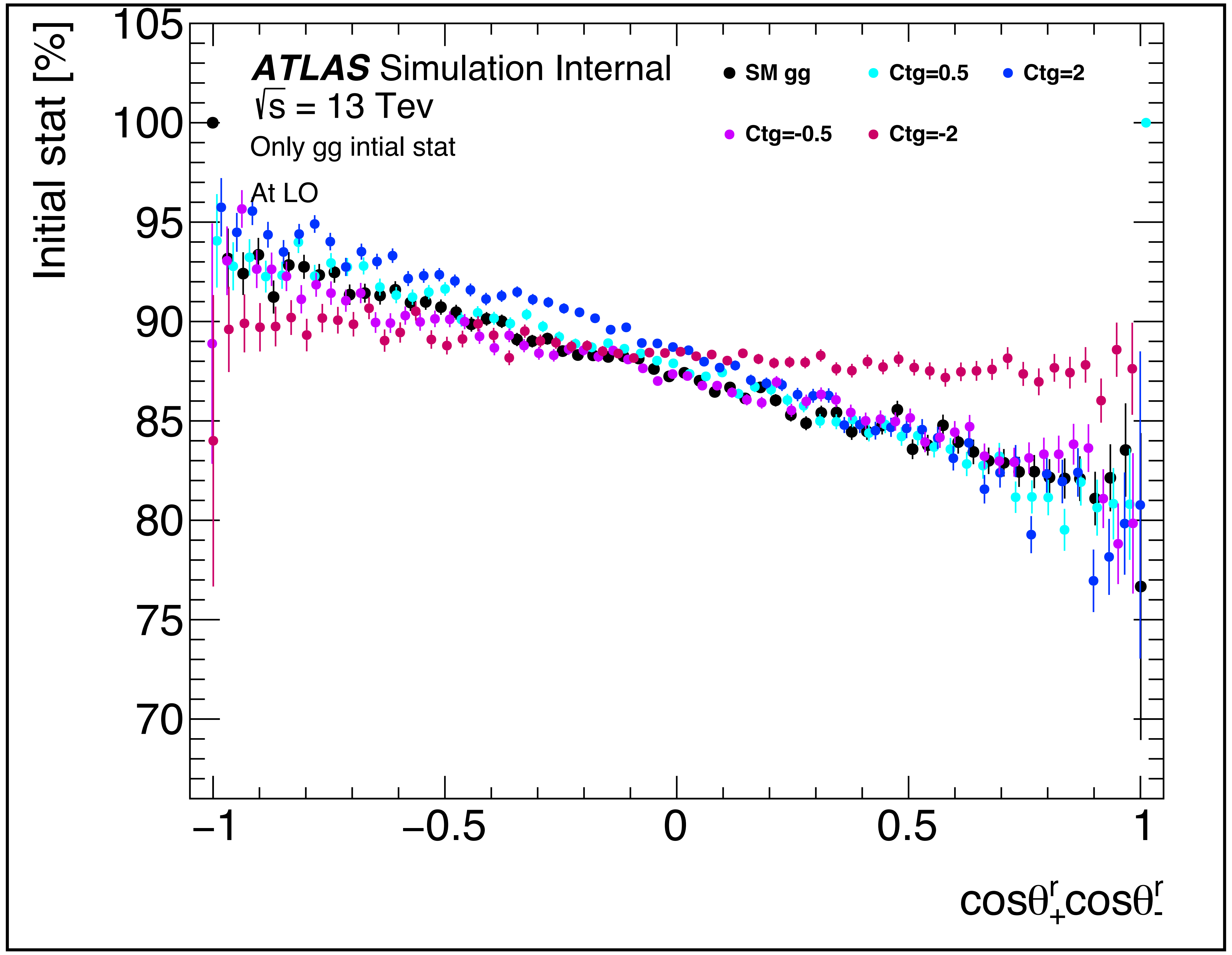




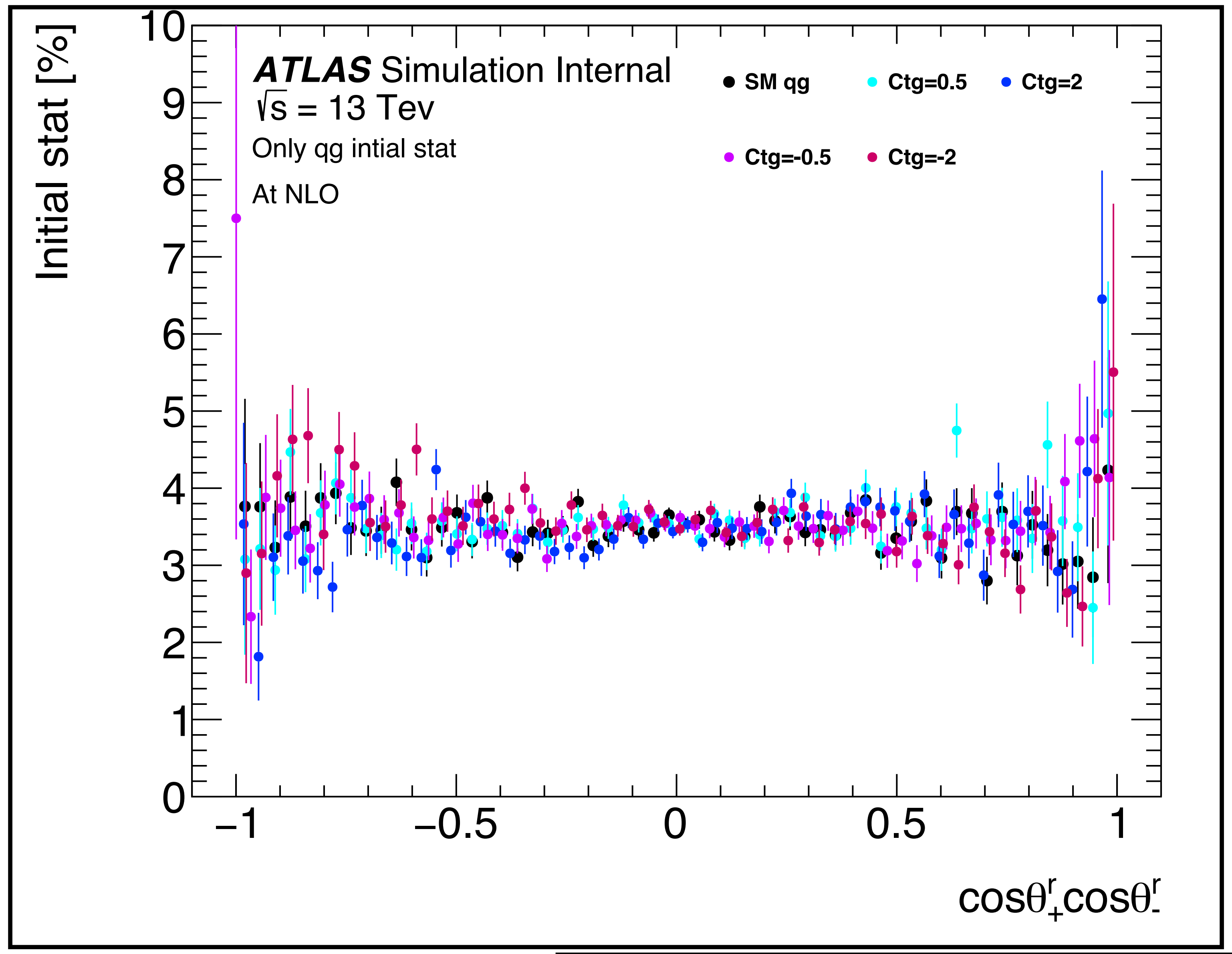


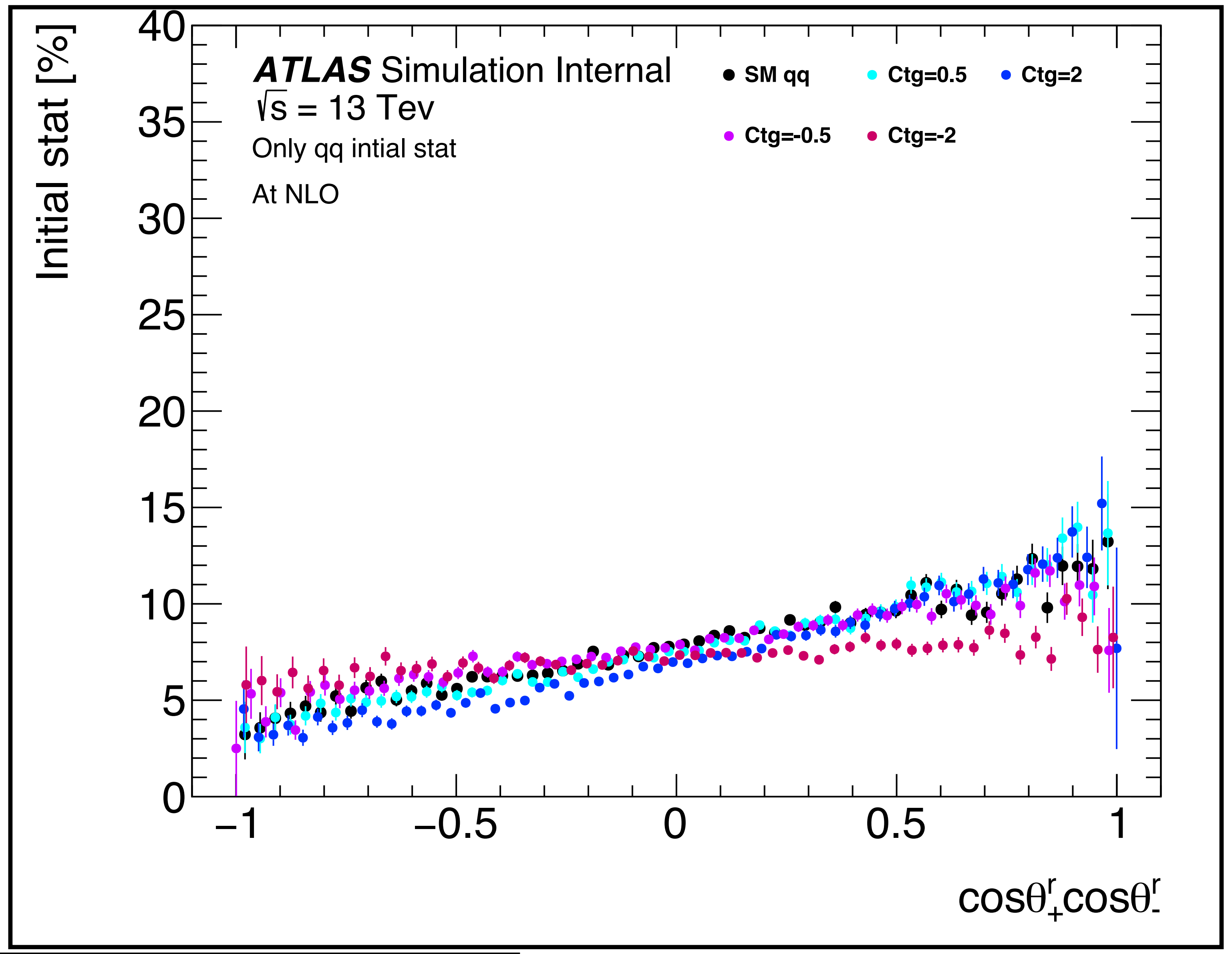
gg Initial stat VS C(r,r)

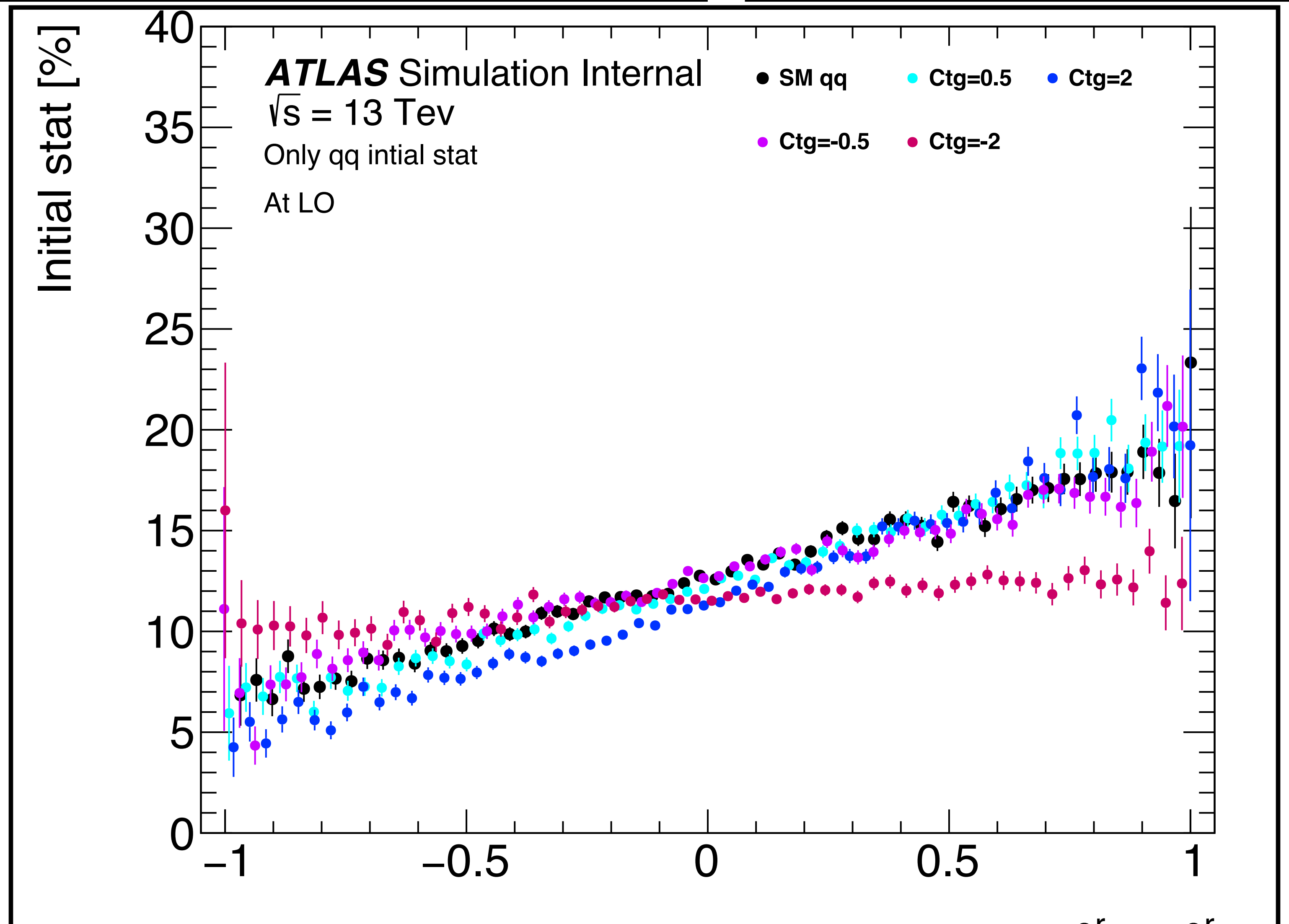




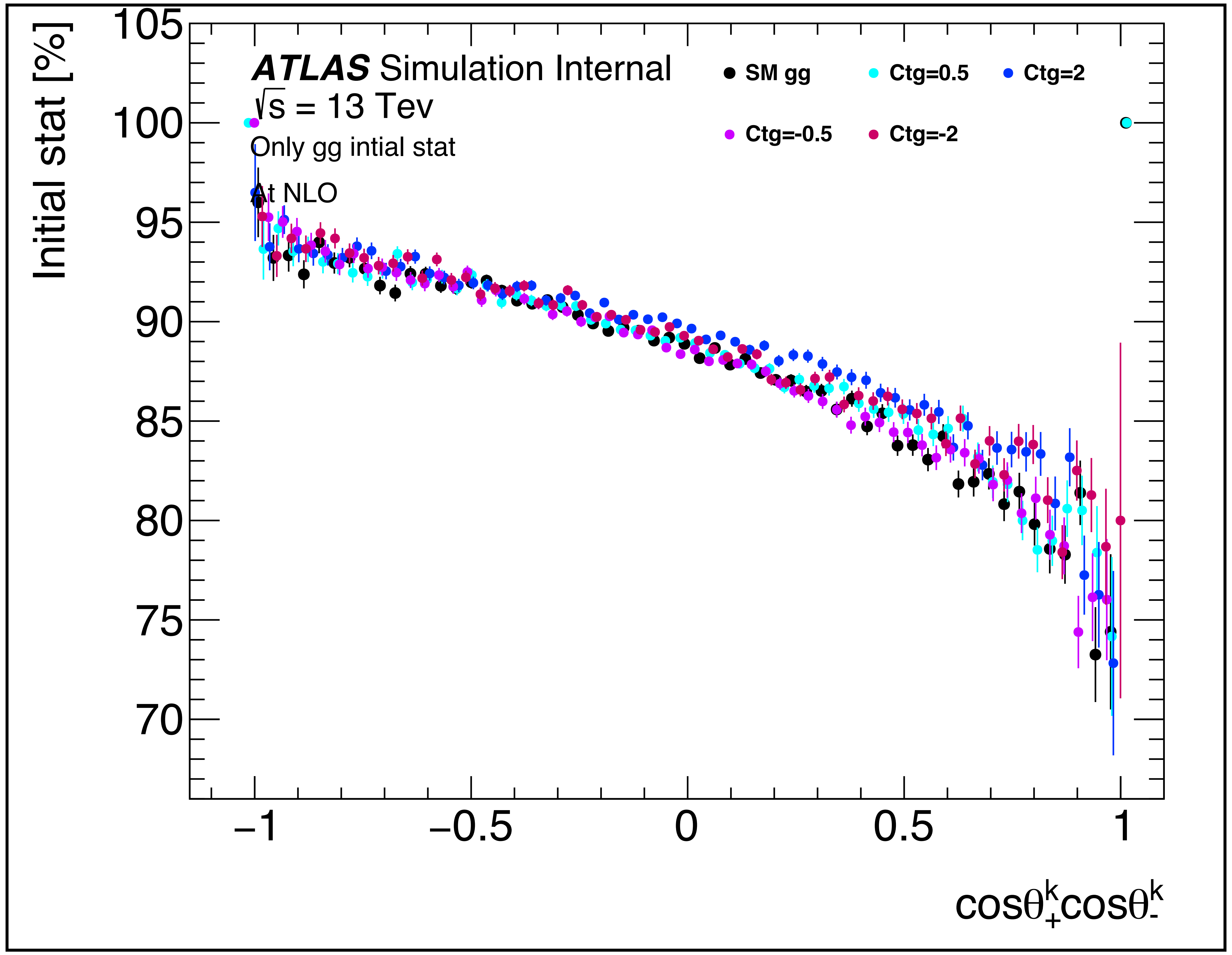
qq/qg Initial stat VS C(r,r)

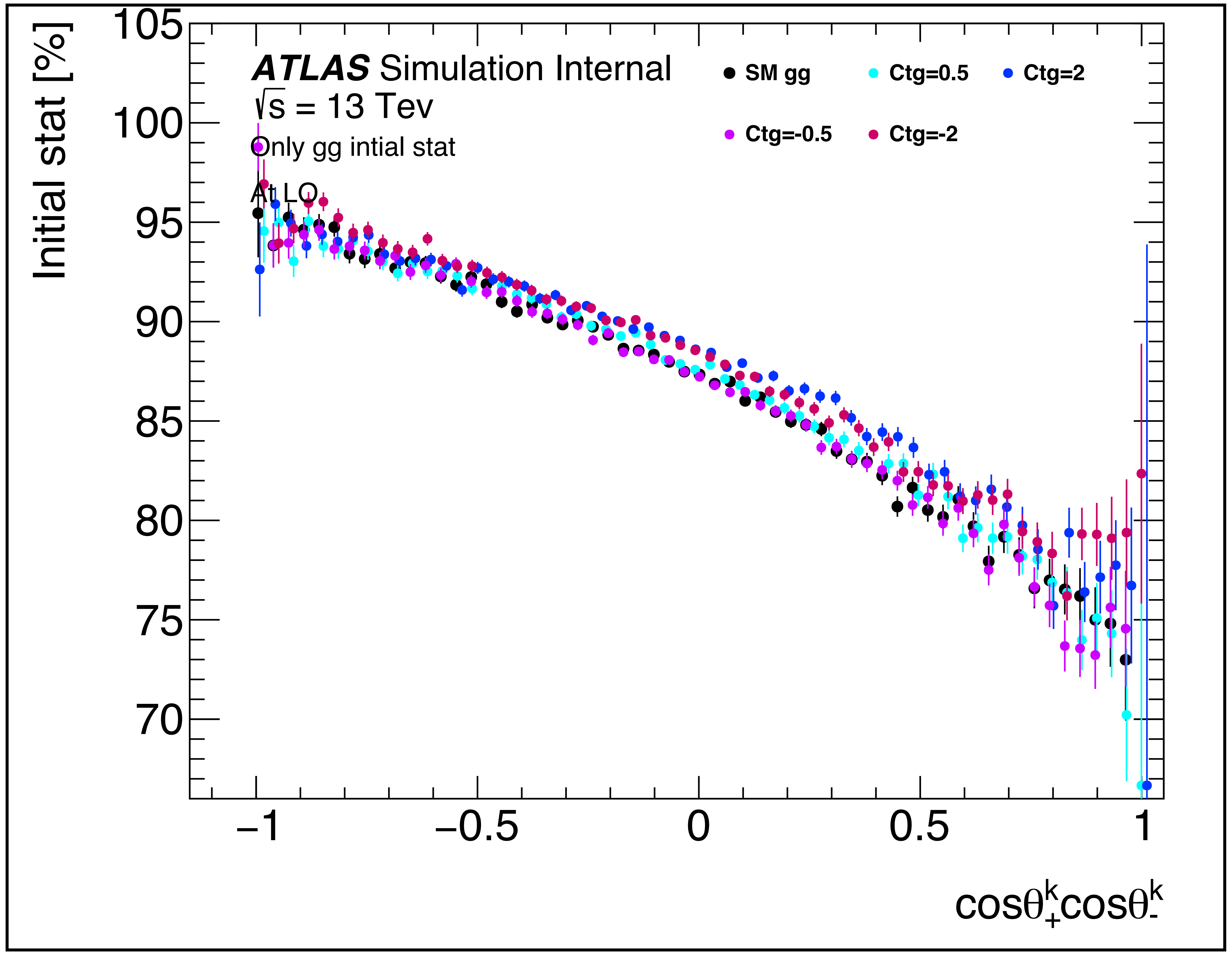




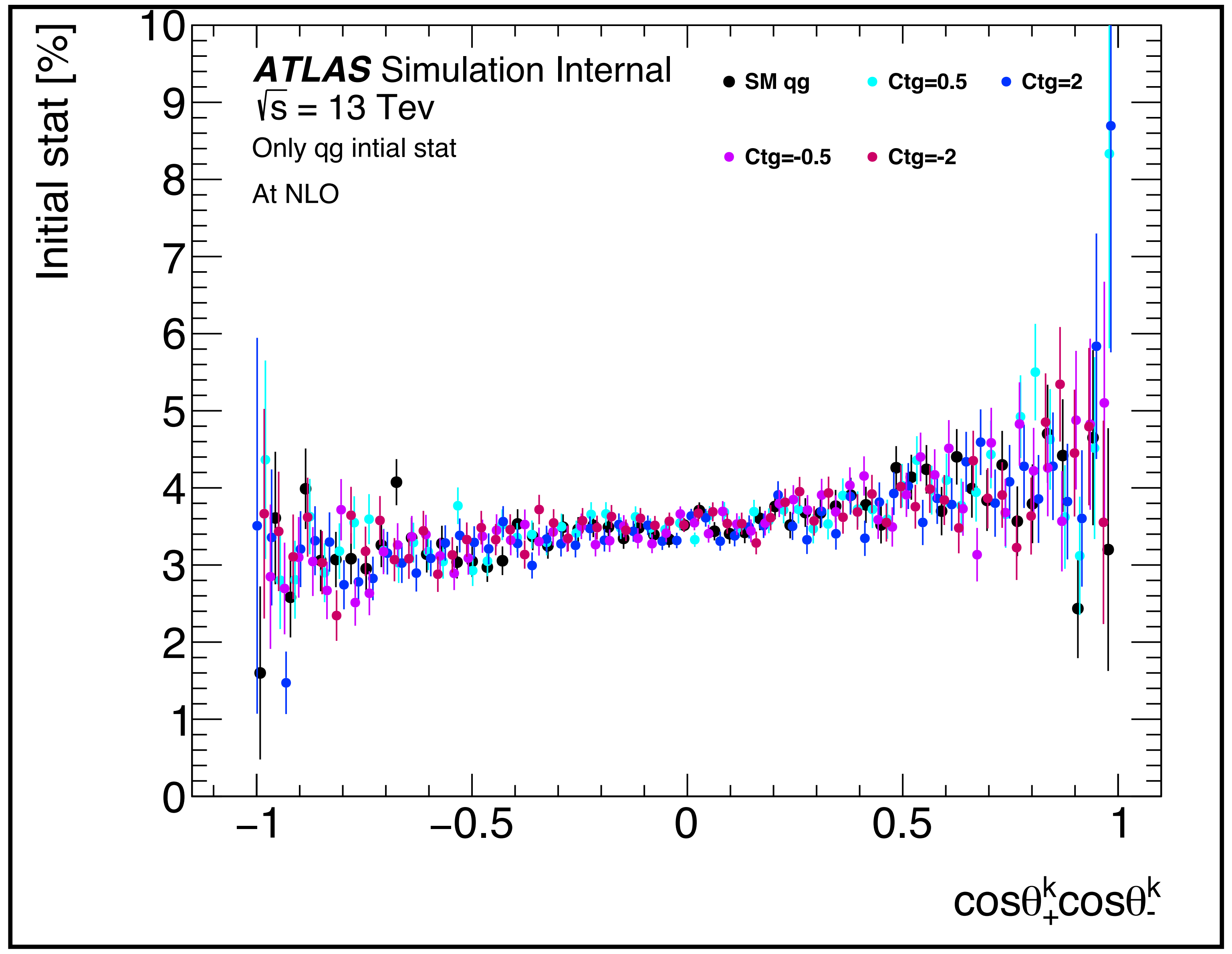


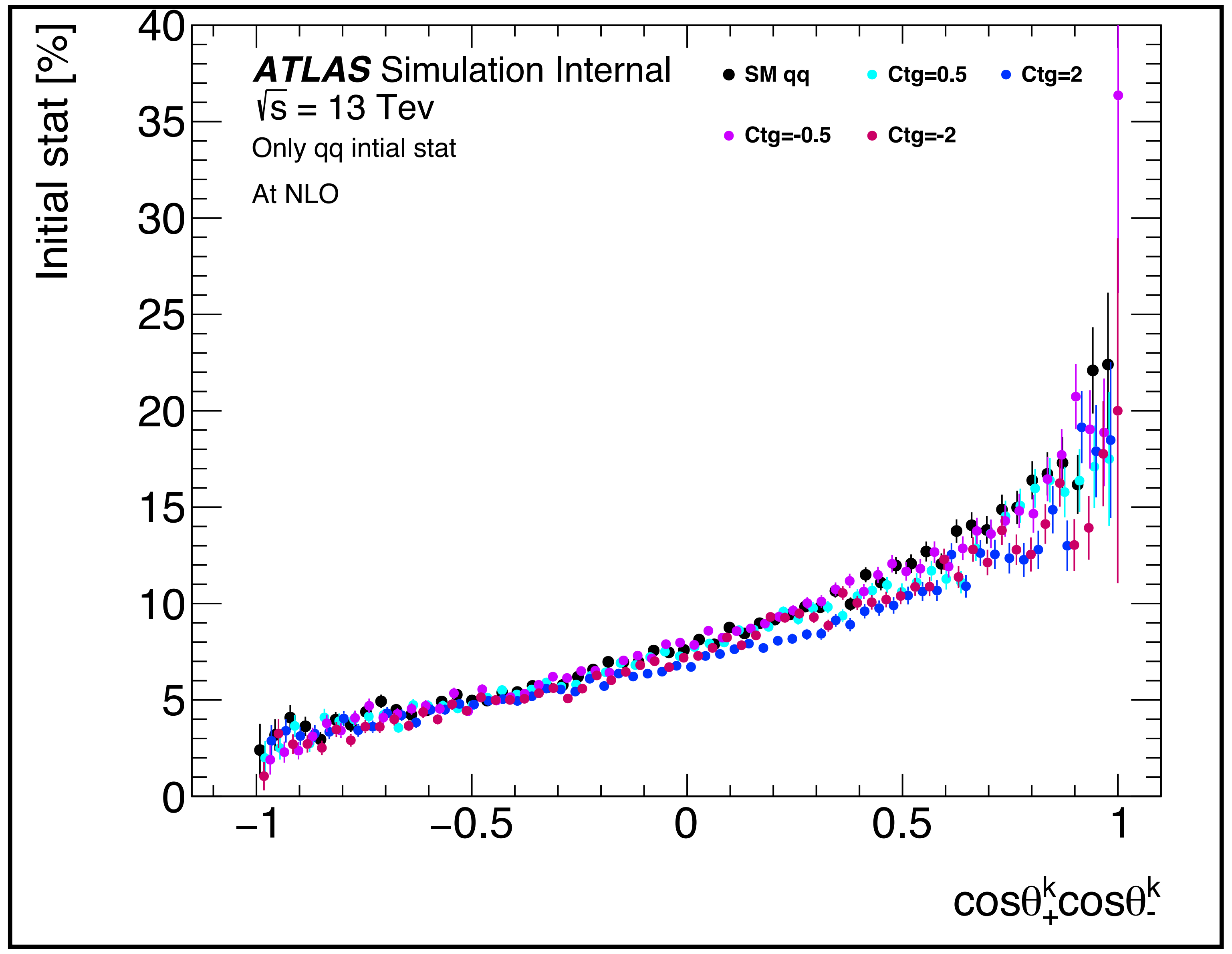
gg Initial stat VS C(k,k)

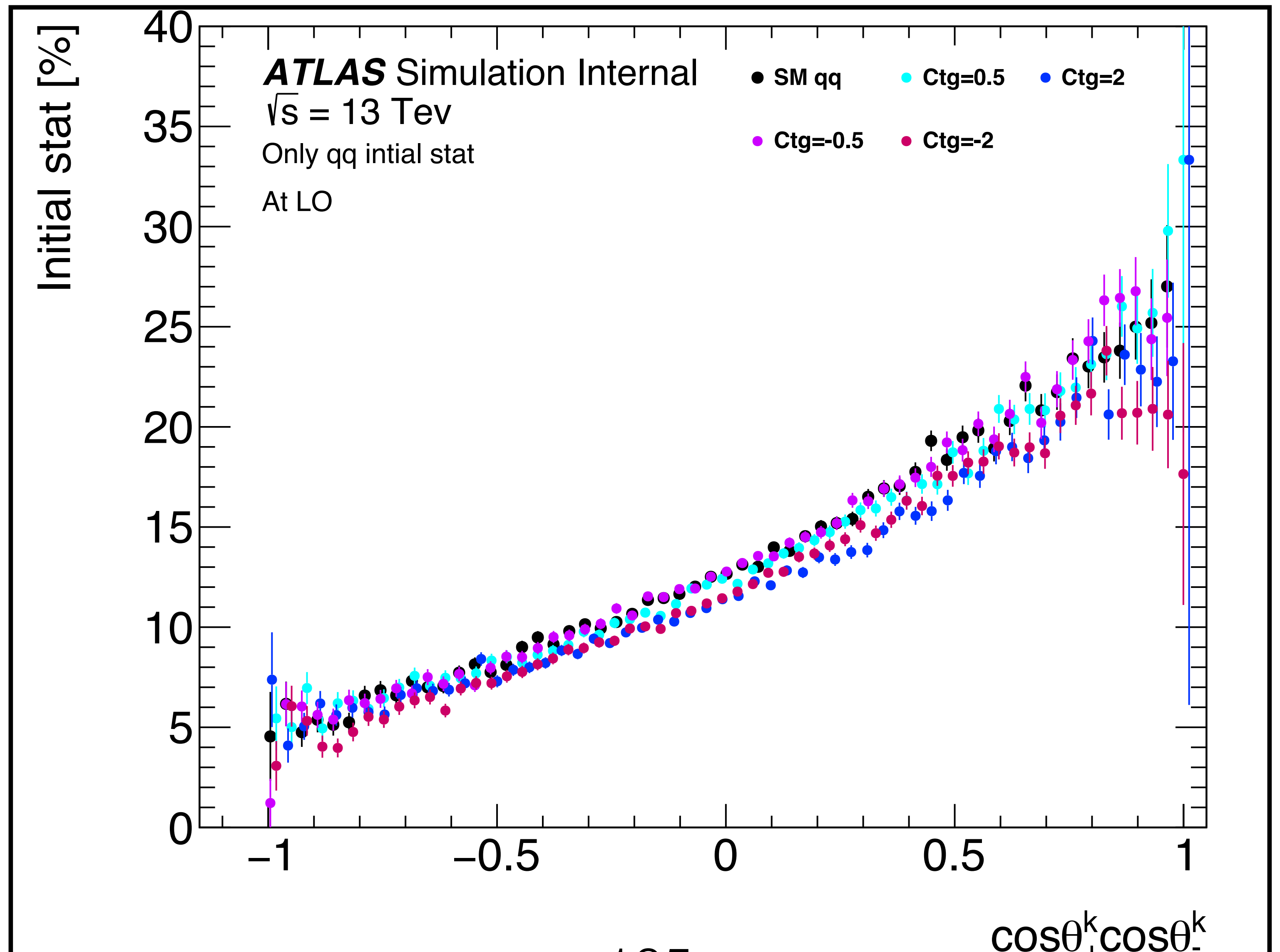




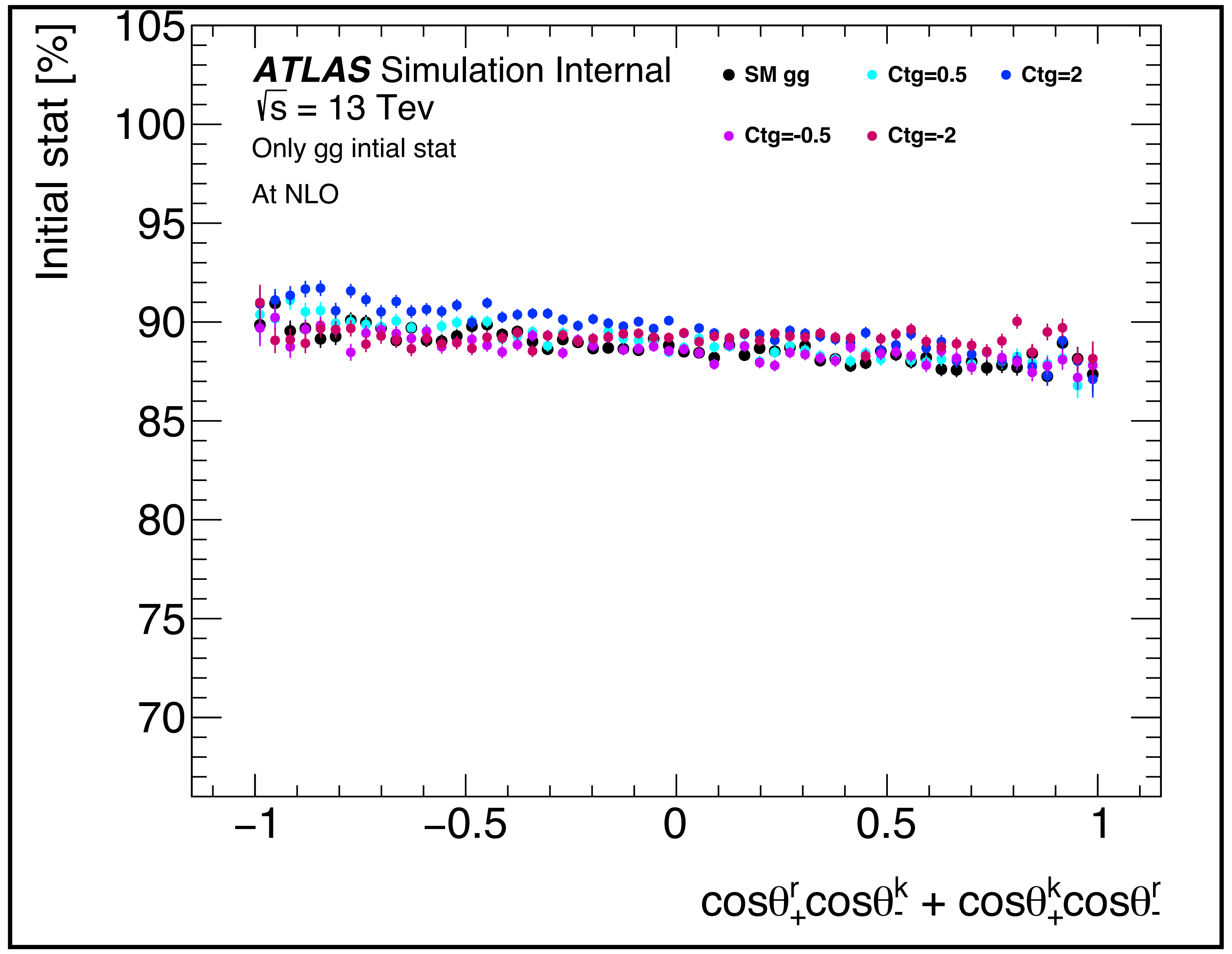
qq/qg Initial stat VS C(k,k)

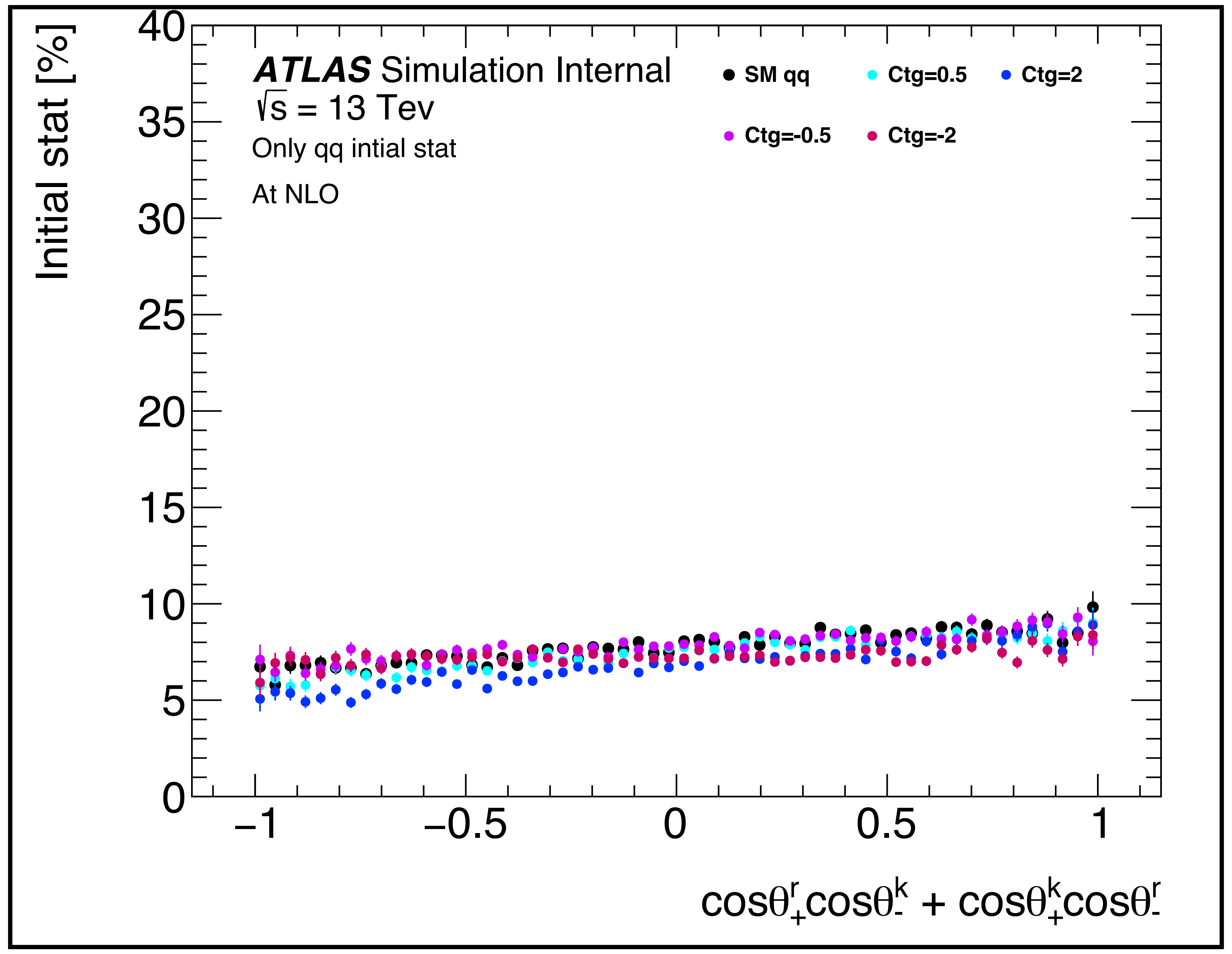


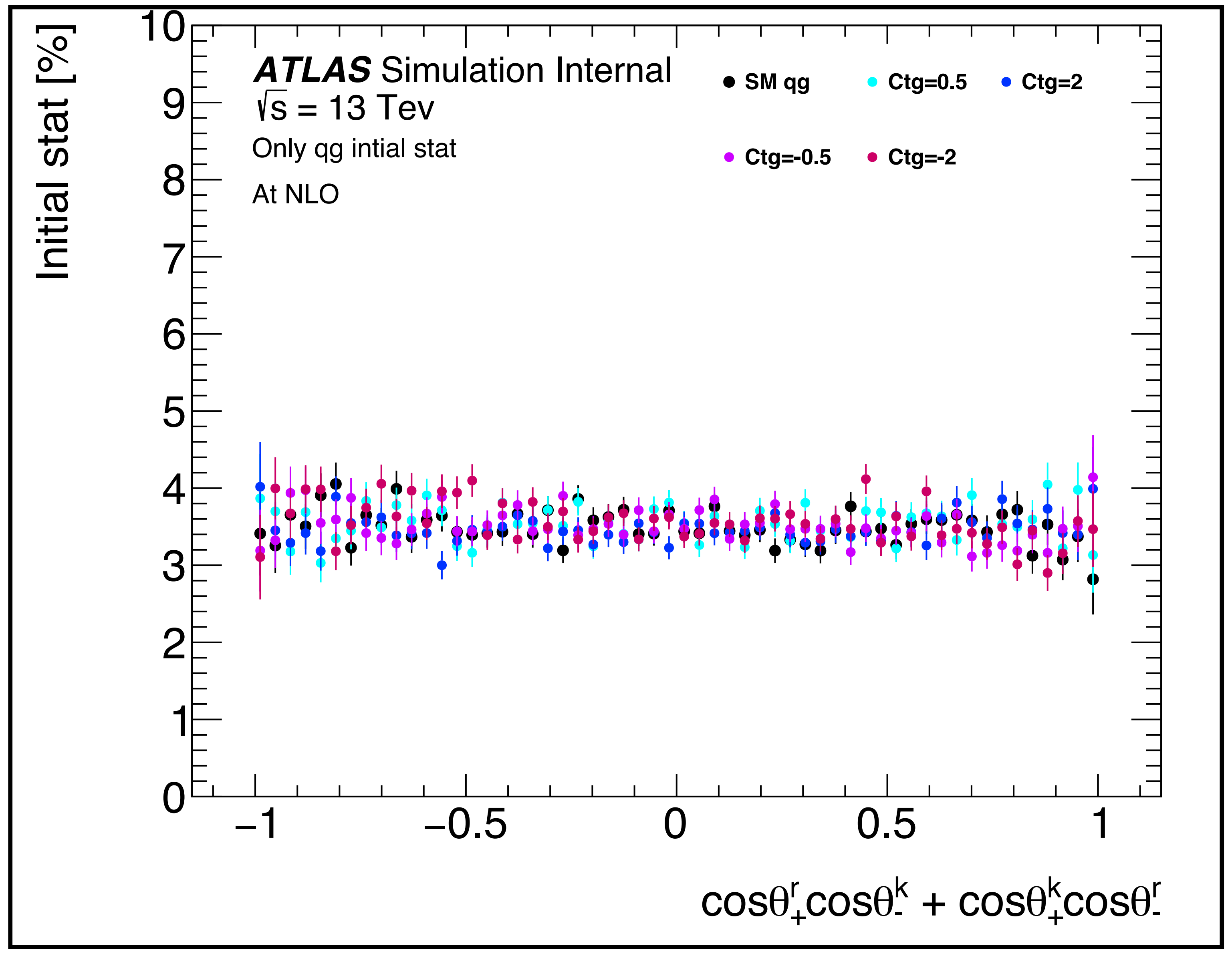


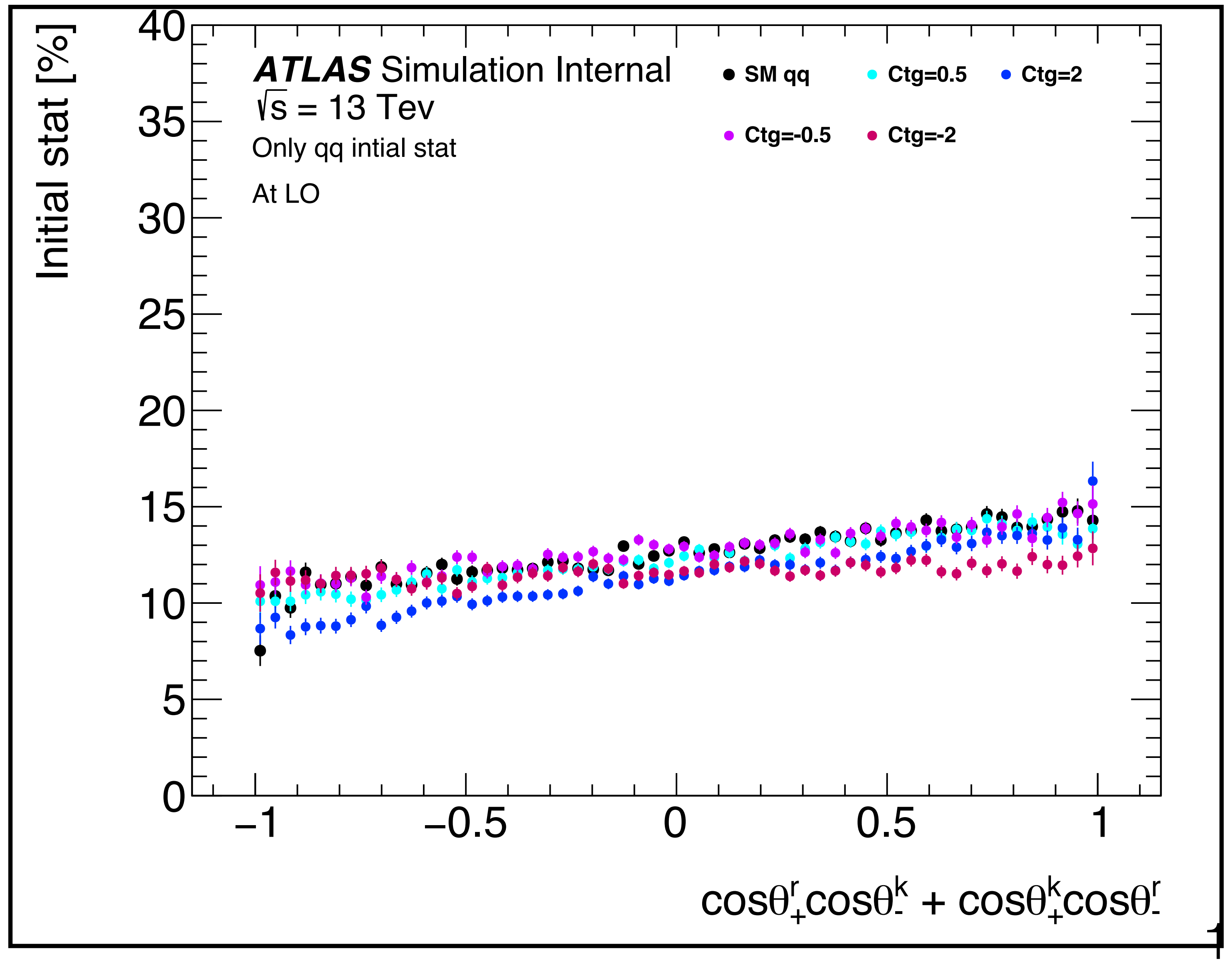


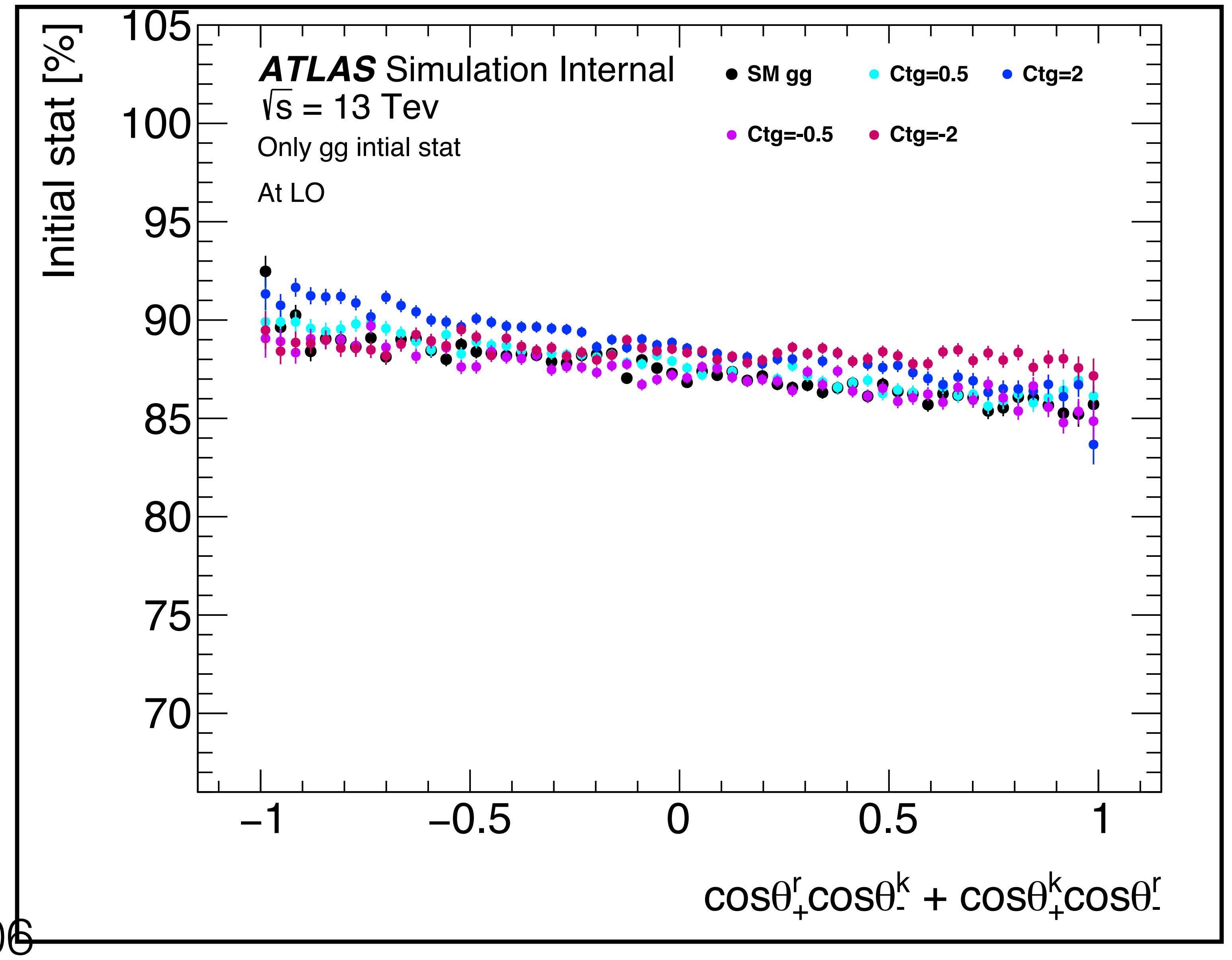
Initial stat VS C(r,k) + C(k,r)



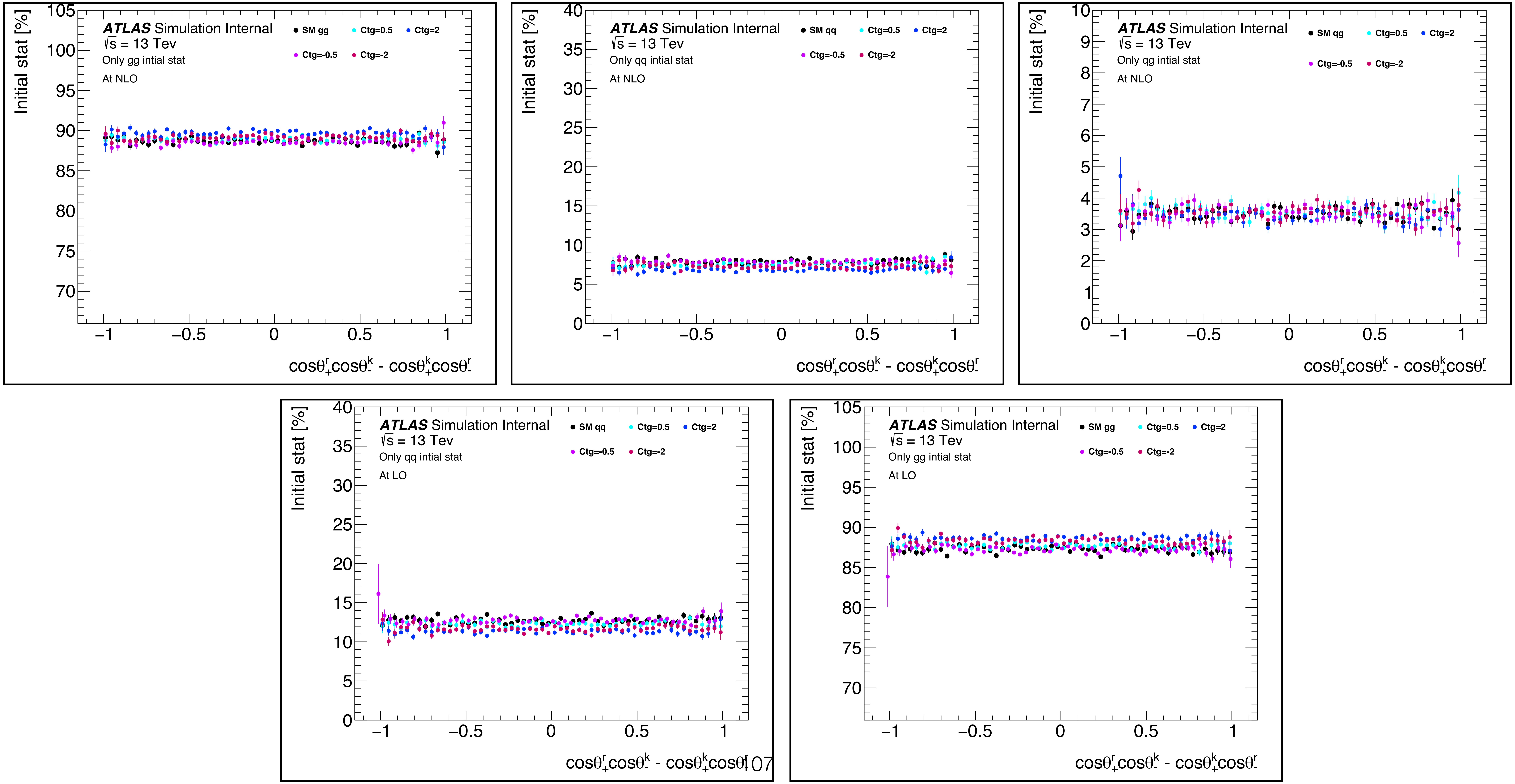








Initial stat VS C(r,k) - C(k,r)



Initial stat VS Ctg

- ☑ Ctg = 0 corresponds to the SM value.