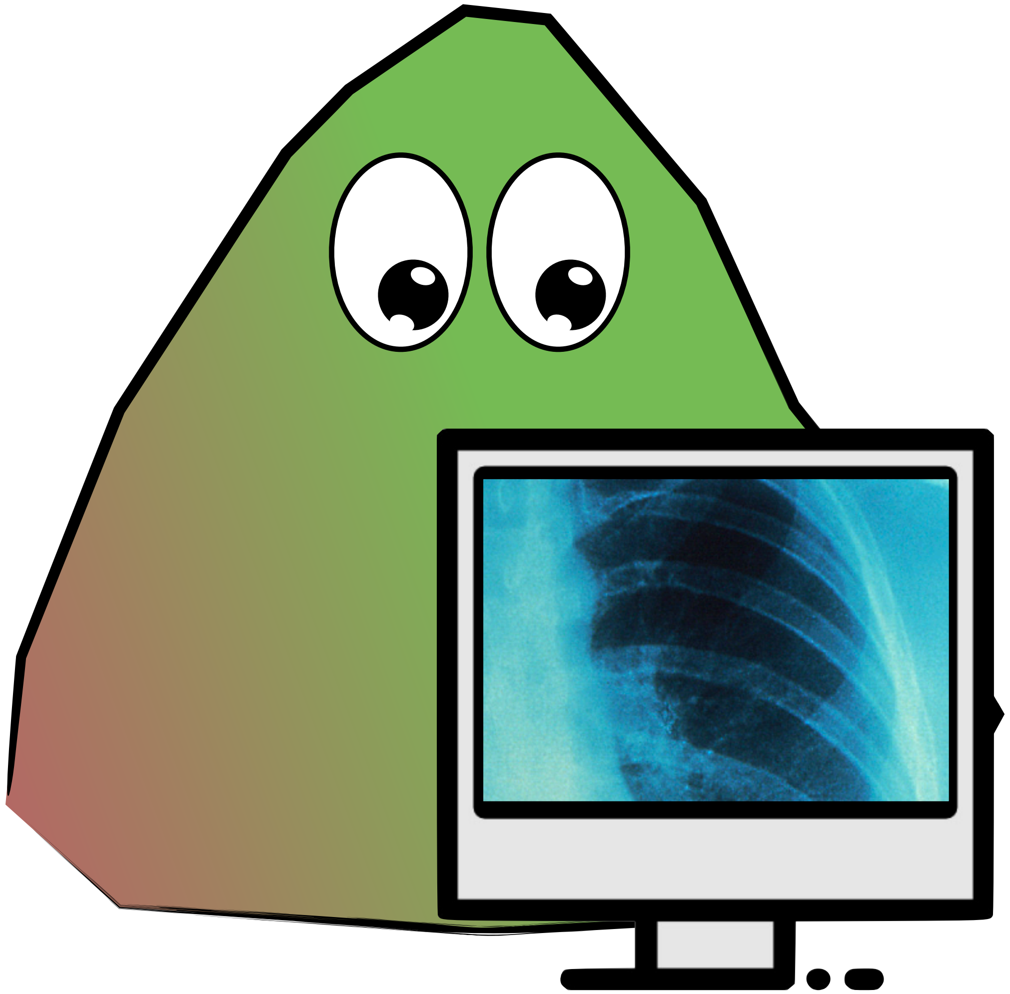
PROPERTIES

of the

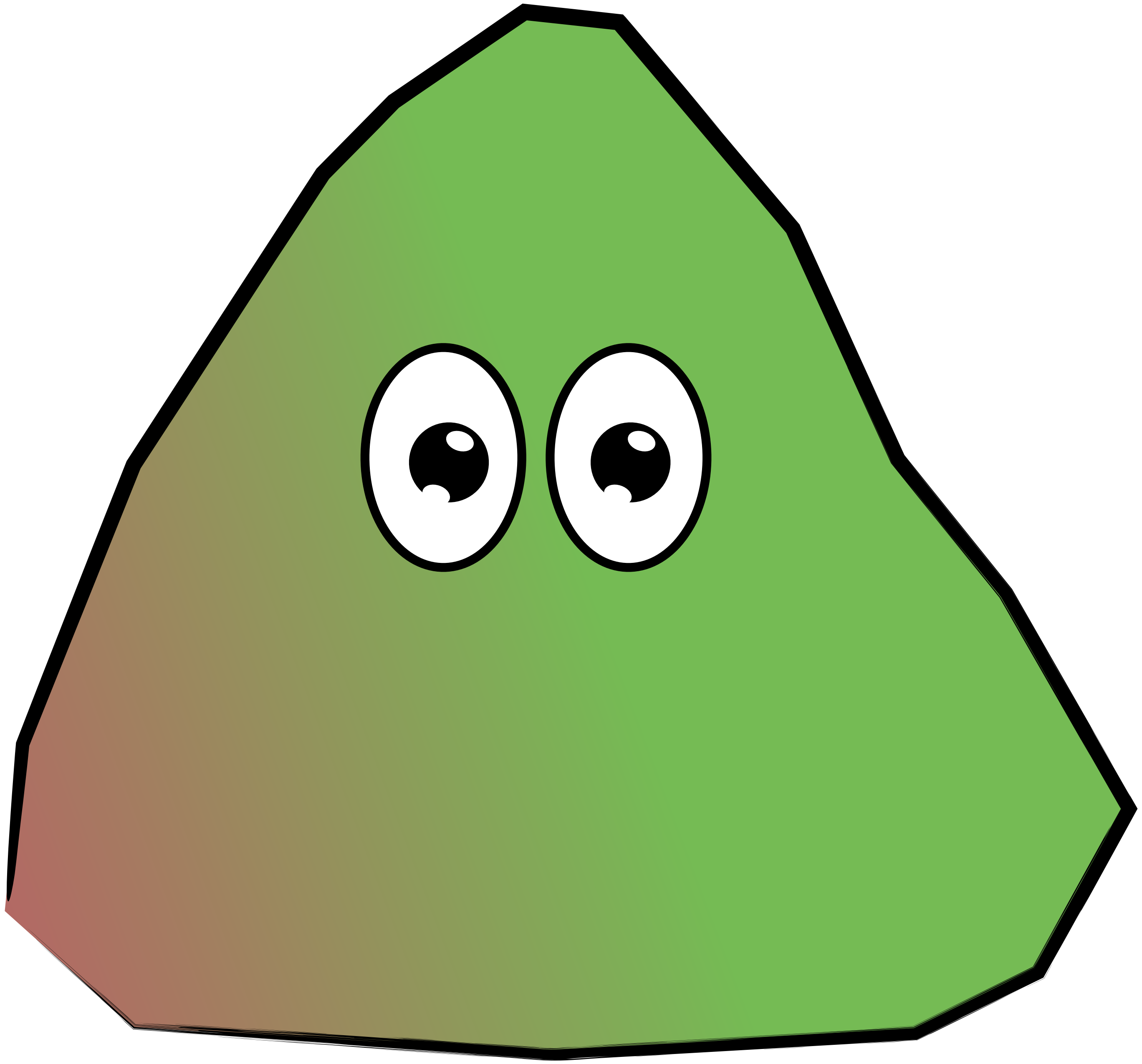
TOP QUARK

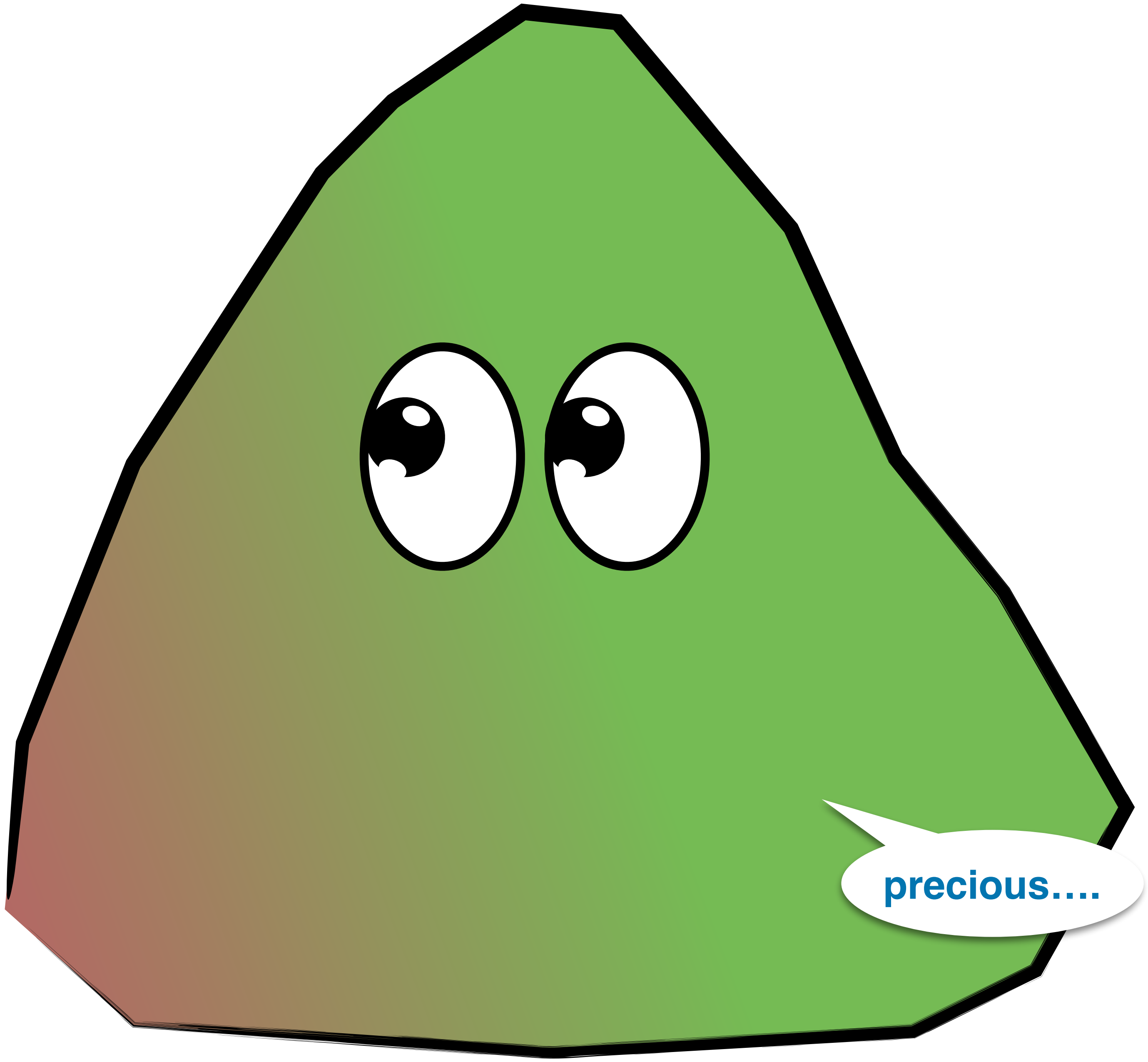


Jay Howarth

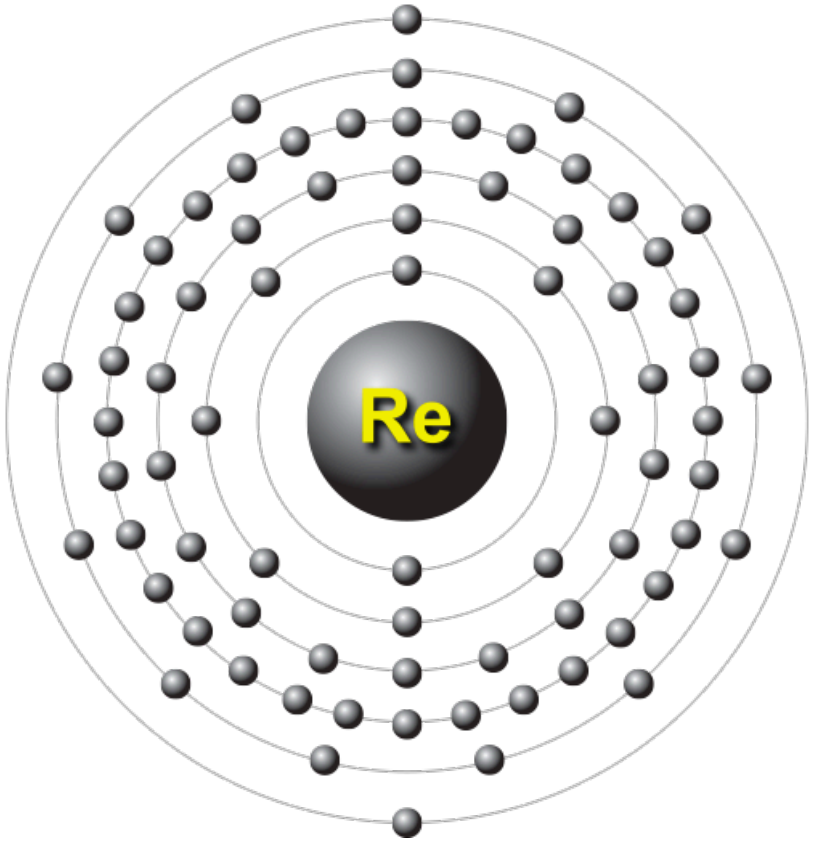
Jay Howarth

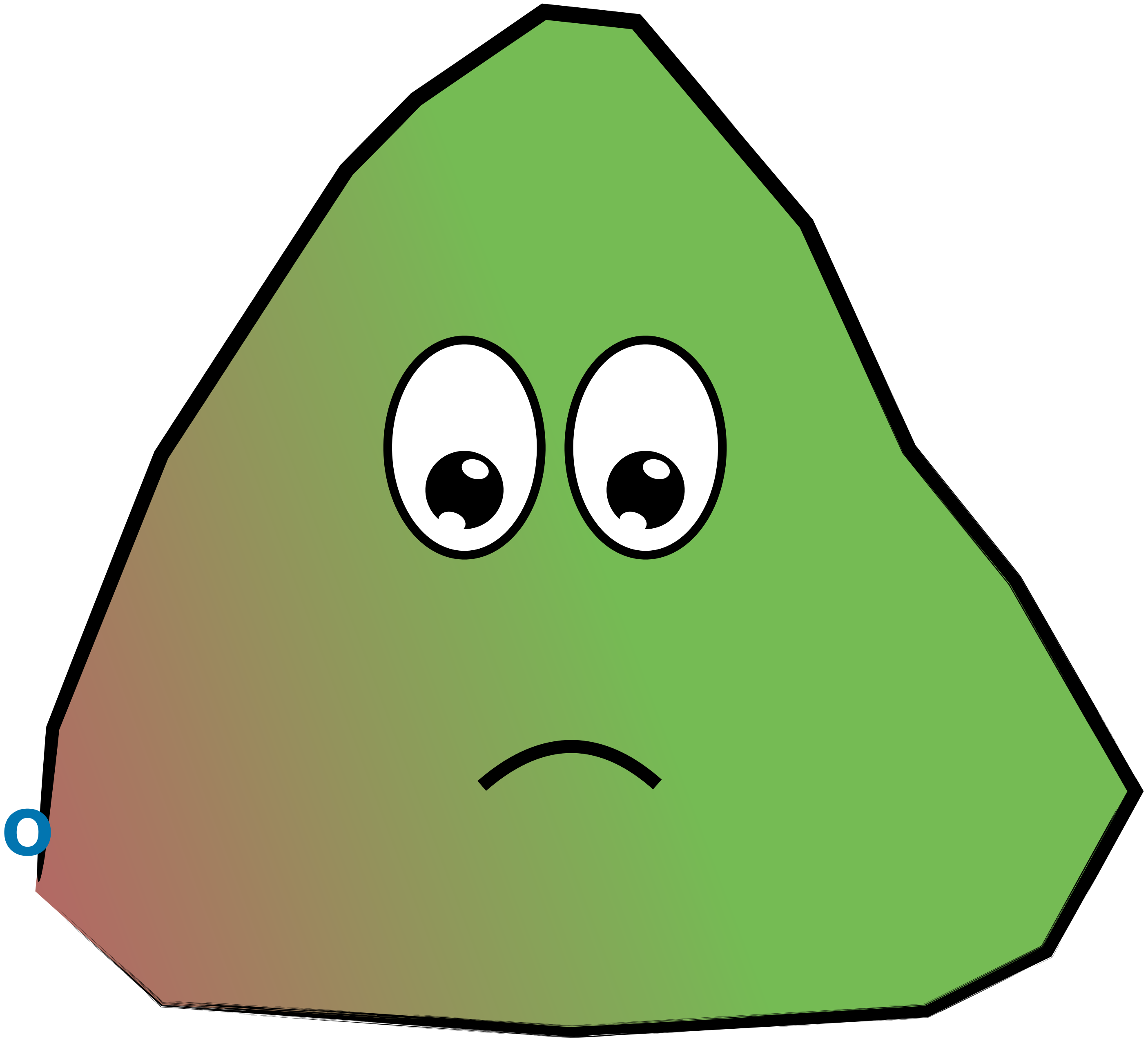
- The top quark is extremely heavy!





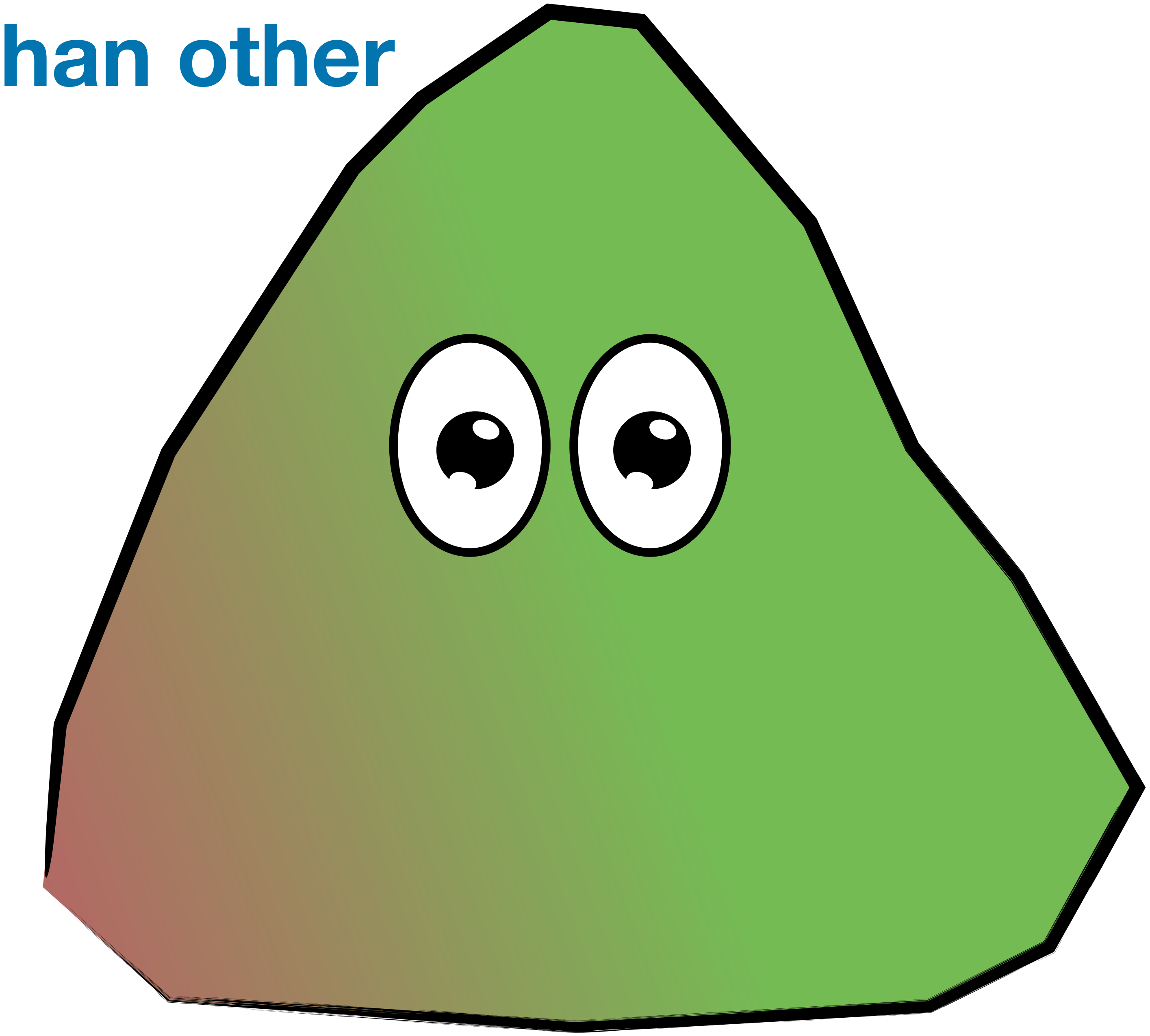
- The top quark is extremely heavy!
- Single quark almost as heavy as an entire gold nucleus.





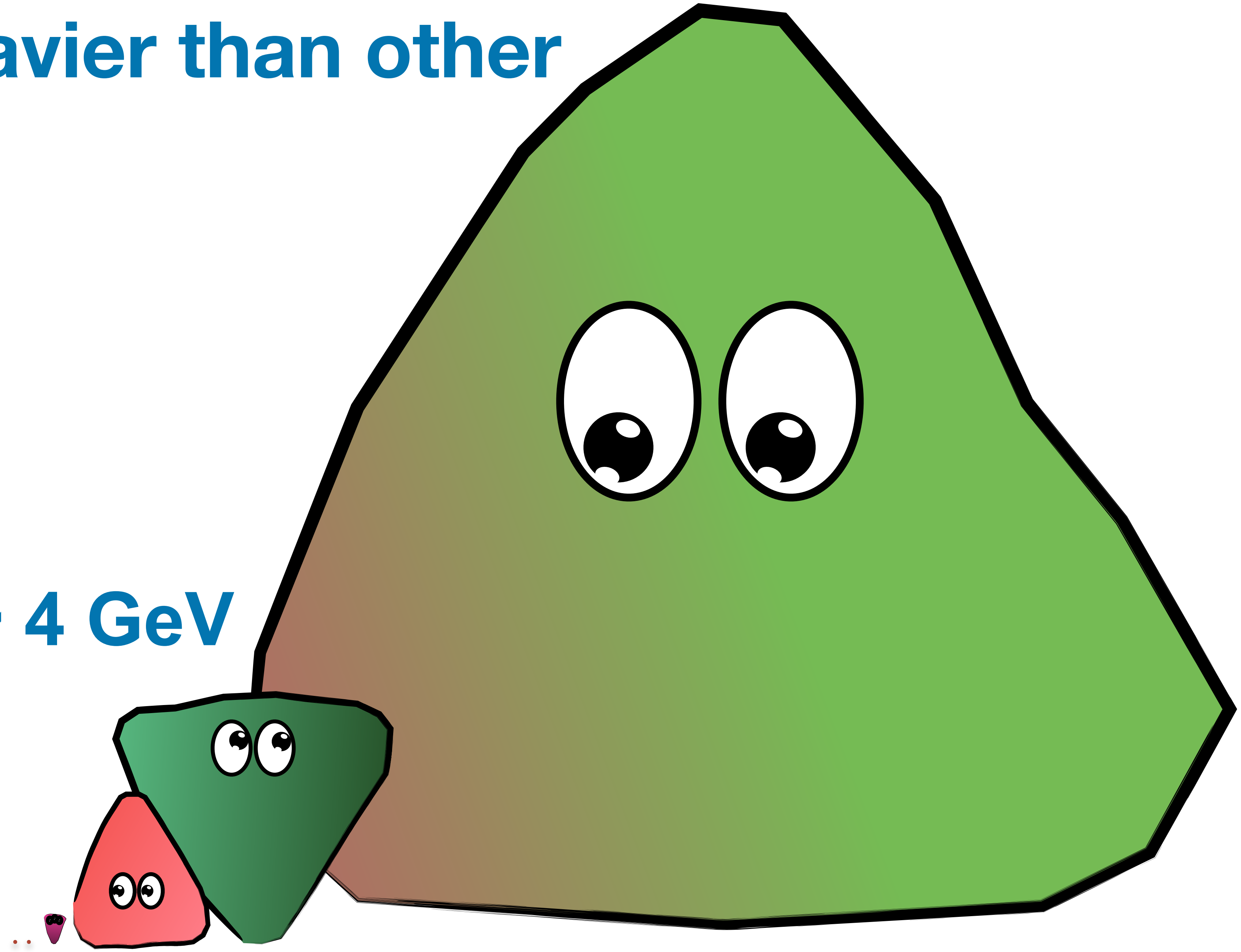
- It’s actually closer to Rhenium:
m(t) ~ 172.5 GeV
m(Re) ~ 173 GeV

- Dramatically heavier than other quarks



m_t ~ 170 GeV

- **Dramatically heavier than other quarks**

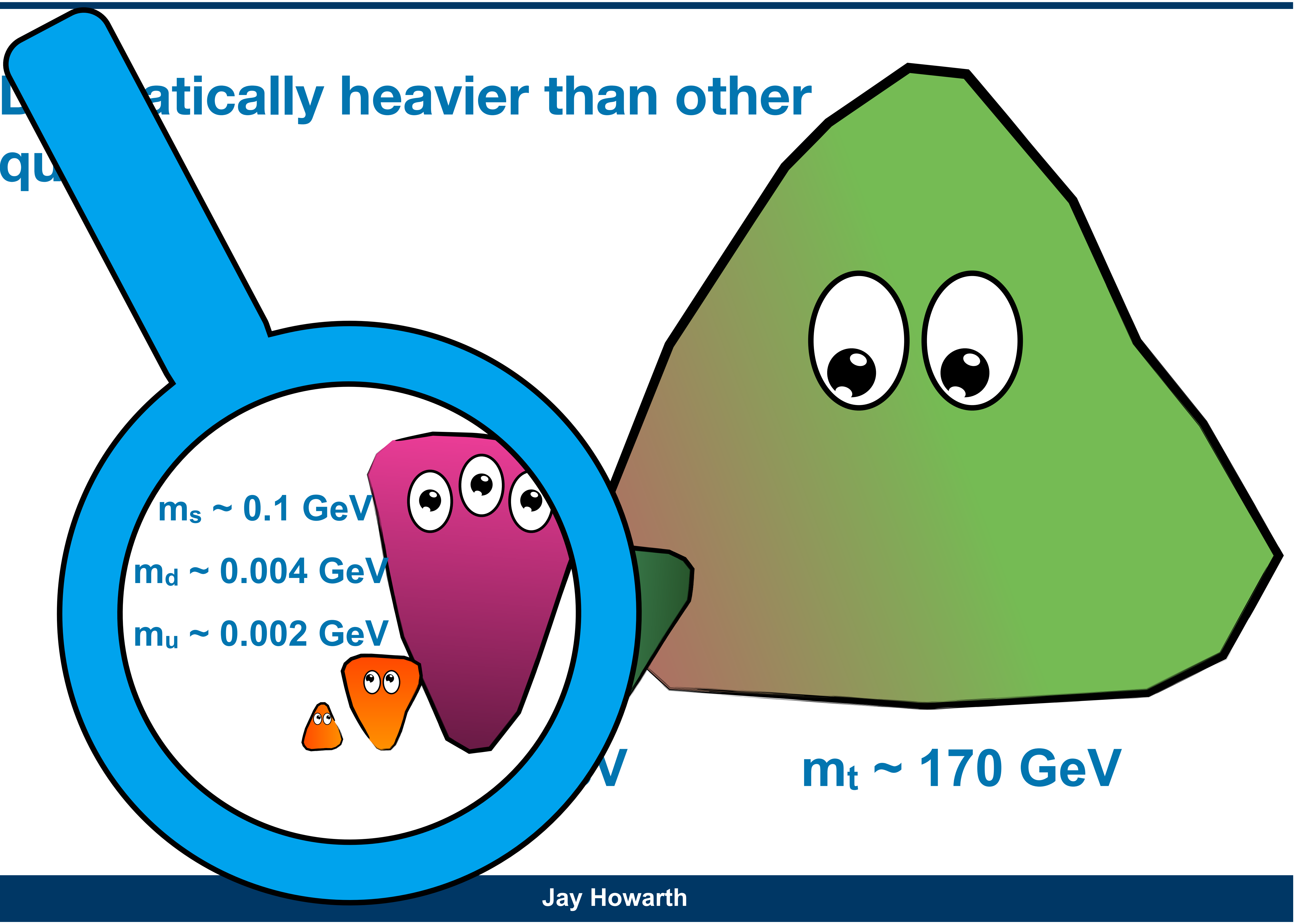


$m_b \sim 4$ GeV

$m_c \sim 1$ GeV

$m_t \sim 170$ GeV

- D atically heavier than other qu



m_s ~ 0.1 GeV

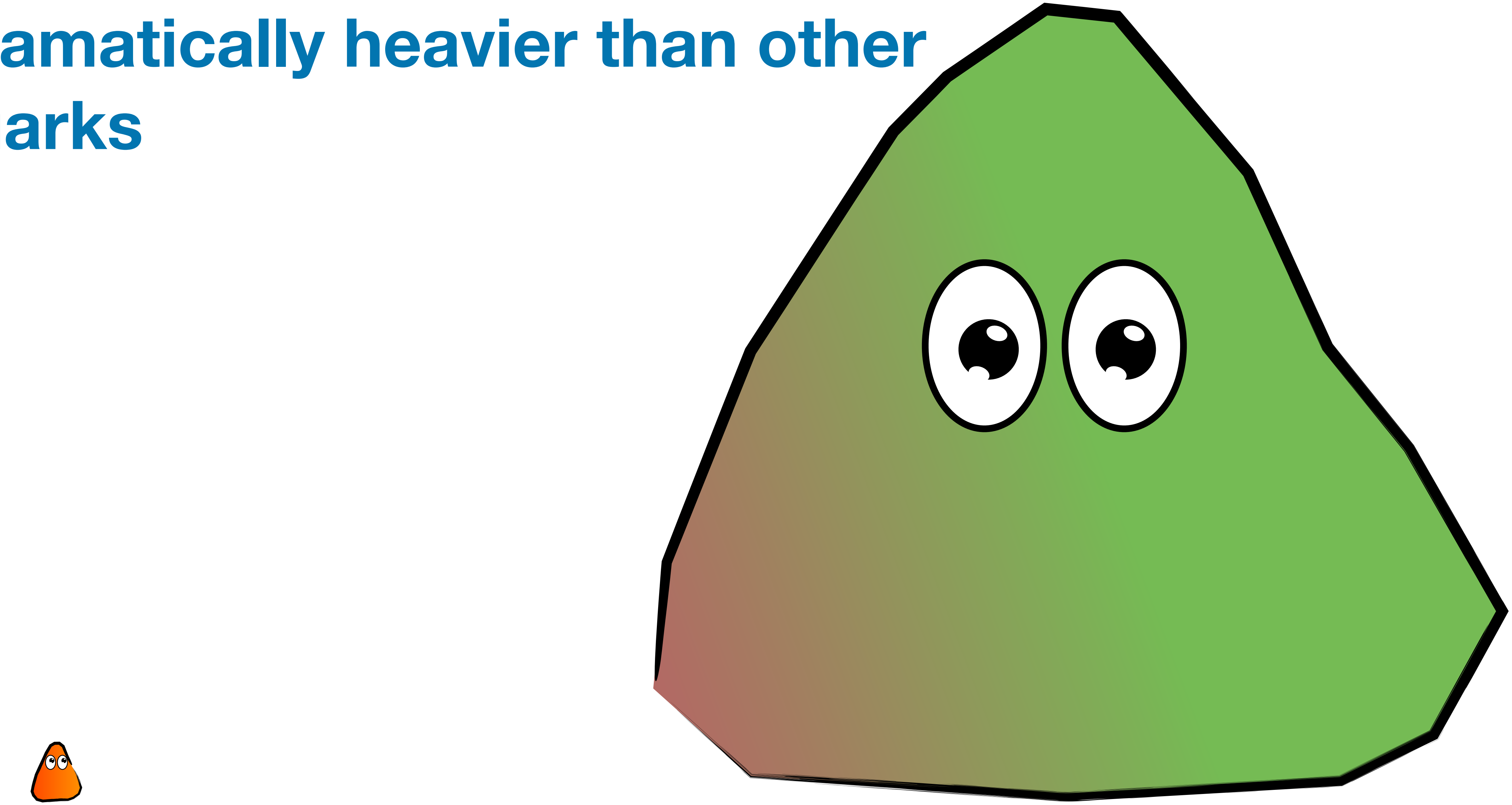
m_d ~ 0.004 GeV

m_u ~ 0.002 GeV

V

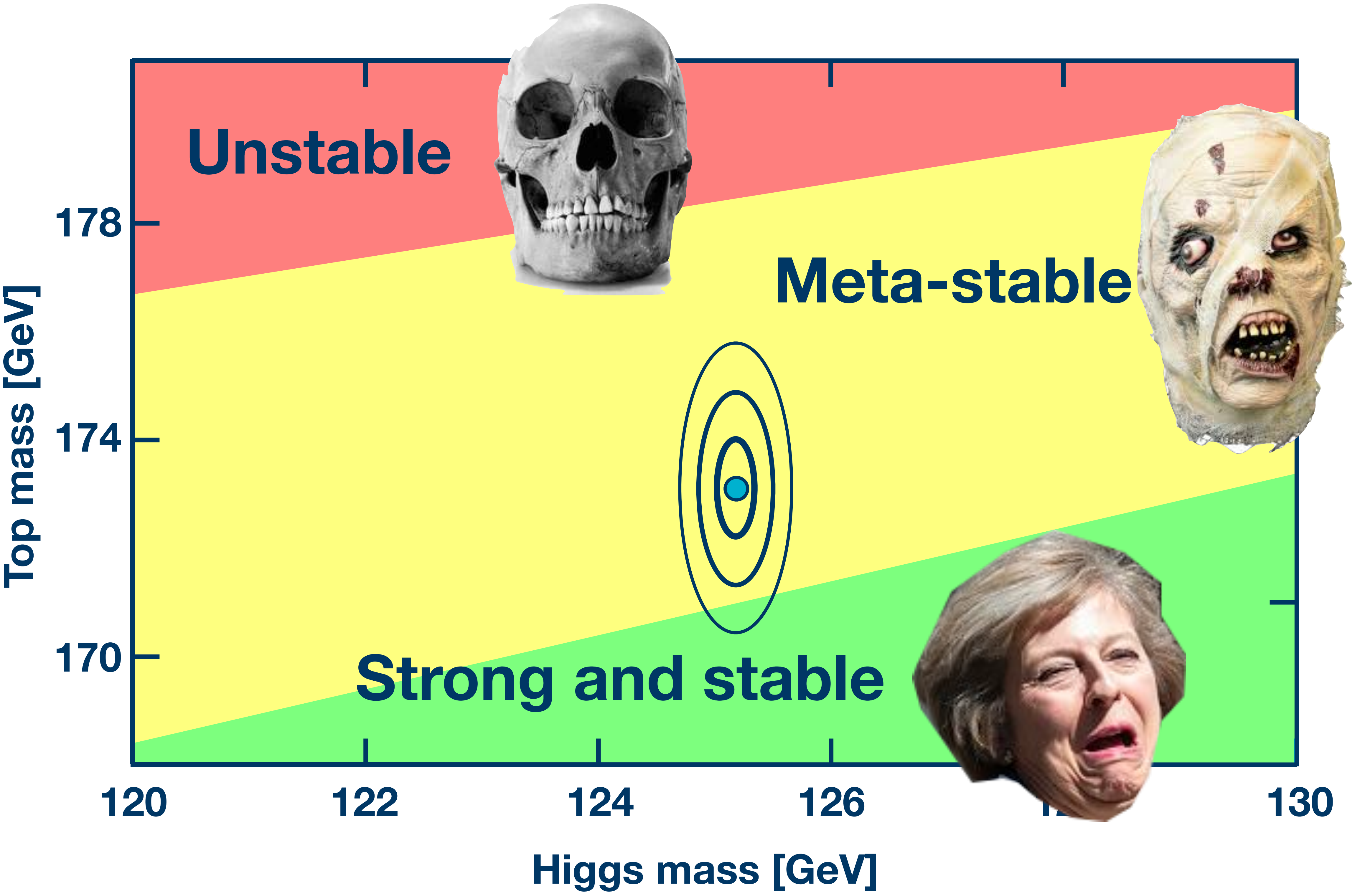
m_t ~ 170 GeV

- Dramatically heavier than other quarks

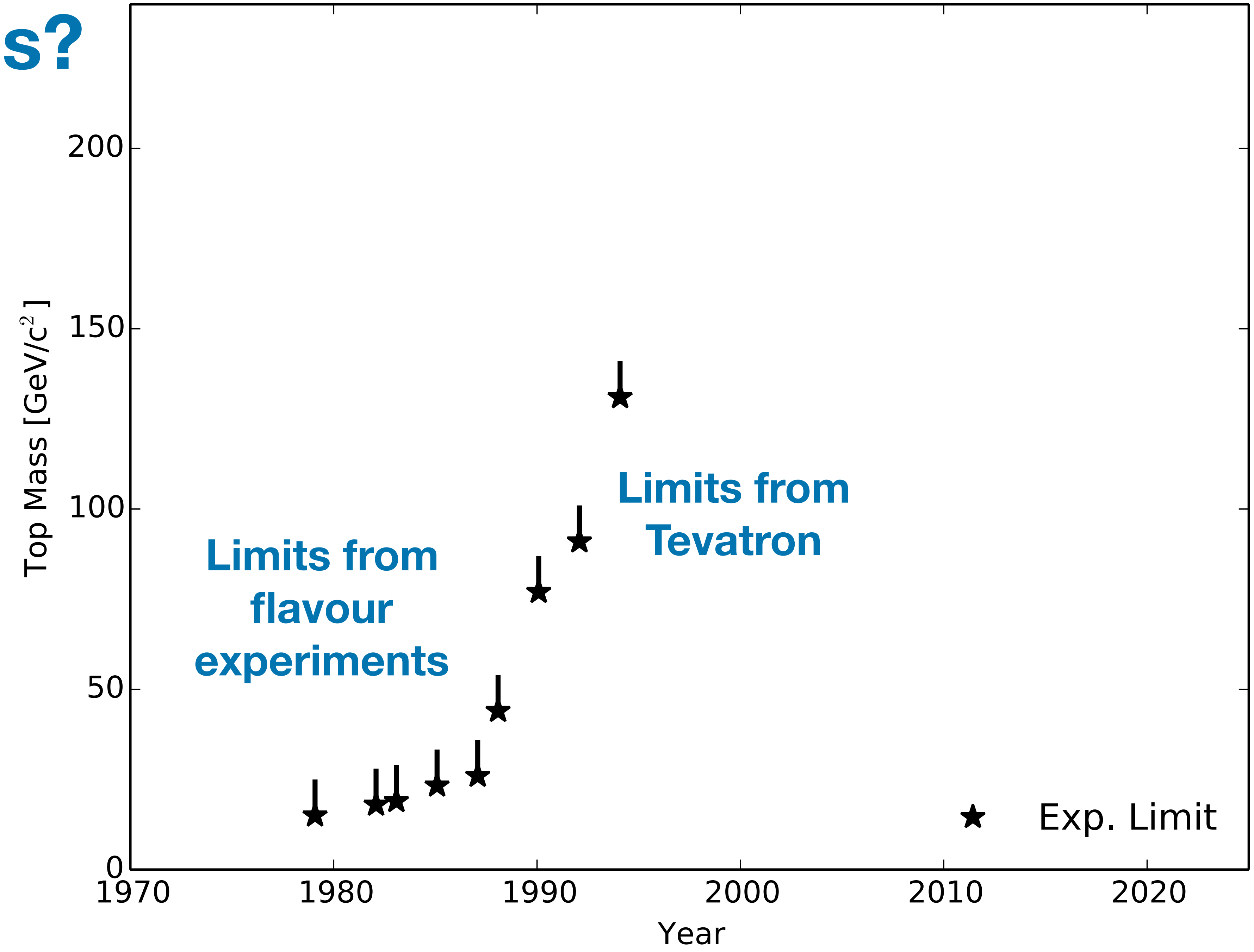


Jay Howarth

- What do we know about the Top?
  - **Mass:** 172.5 GeV (dozens of measurements)
  - **Charge:** 2/3e (0.64 ± 0.08) [arXiv]
  - **Spin:** 1/2 (indirect)
  - **Yukawa:** 1 (1.07, ratio to SM) [arXiv]
- Not to mention lots of QCD-related production effects (production cross-section, charge asymmetry, spin correlation).
- Why do we care about any of these?

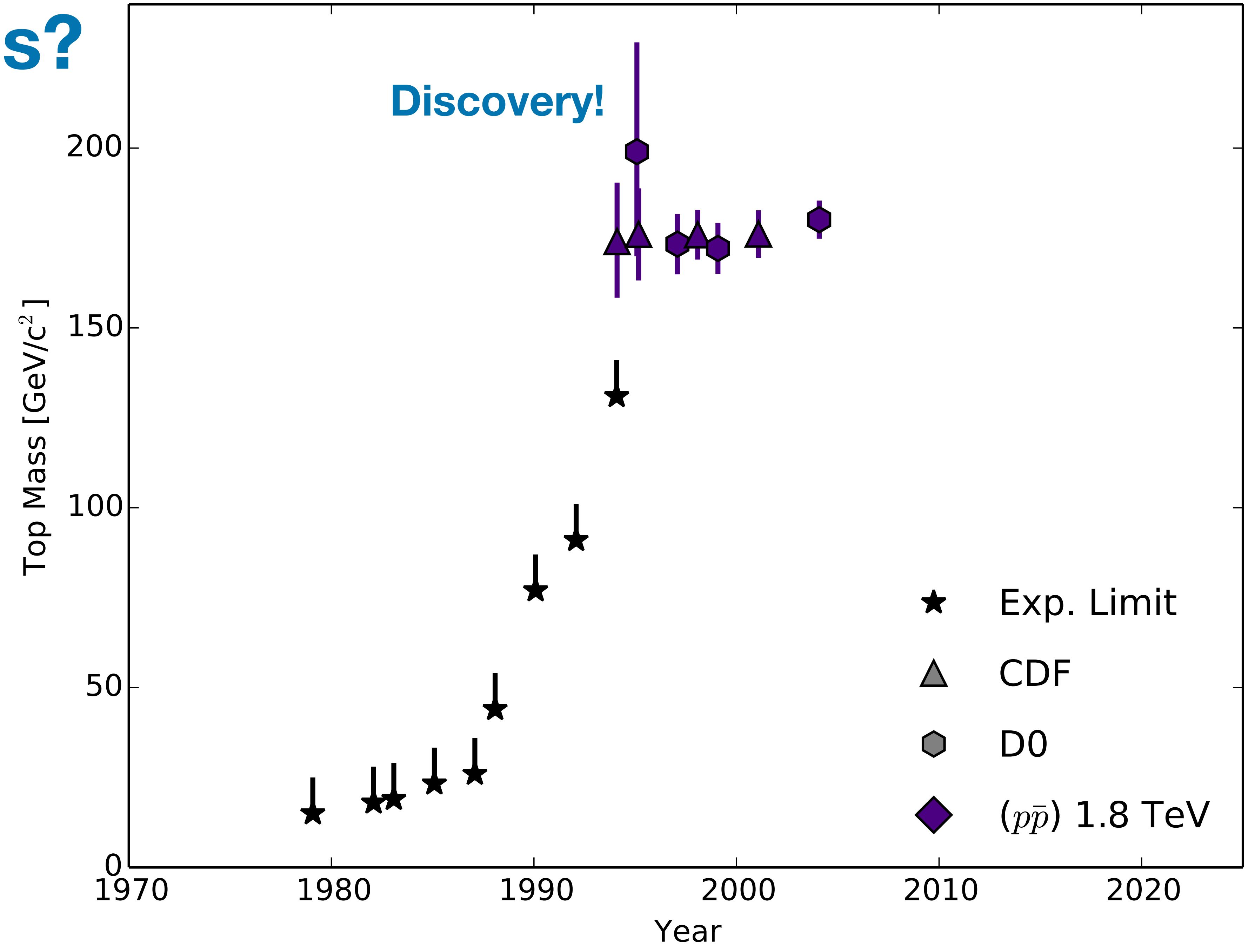

Unstable
Meta-stable
Strong and stable
178
174
170
Top mass [GeV]
120
122
124
126
130
Higgs mass [GeV]

- **How well do we understand this high mass?**

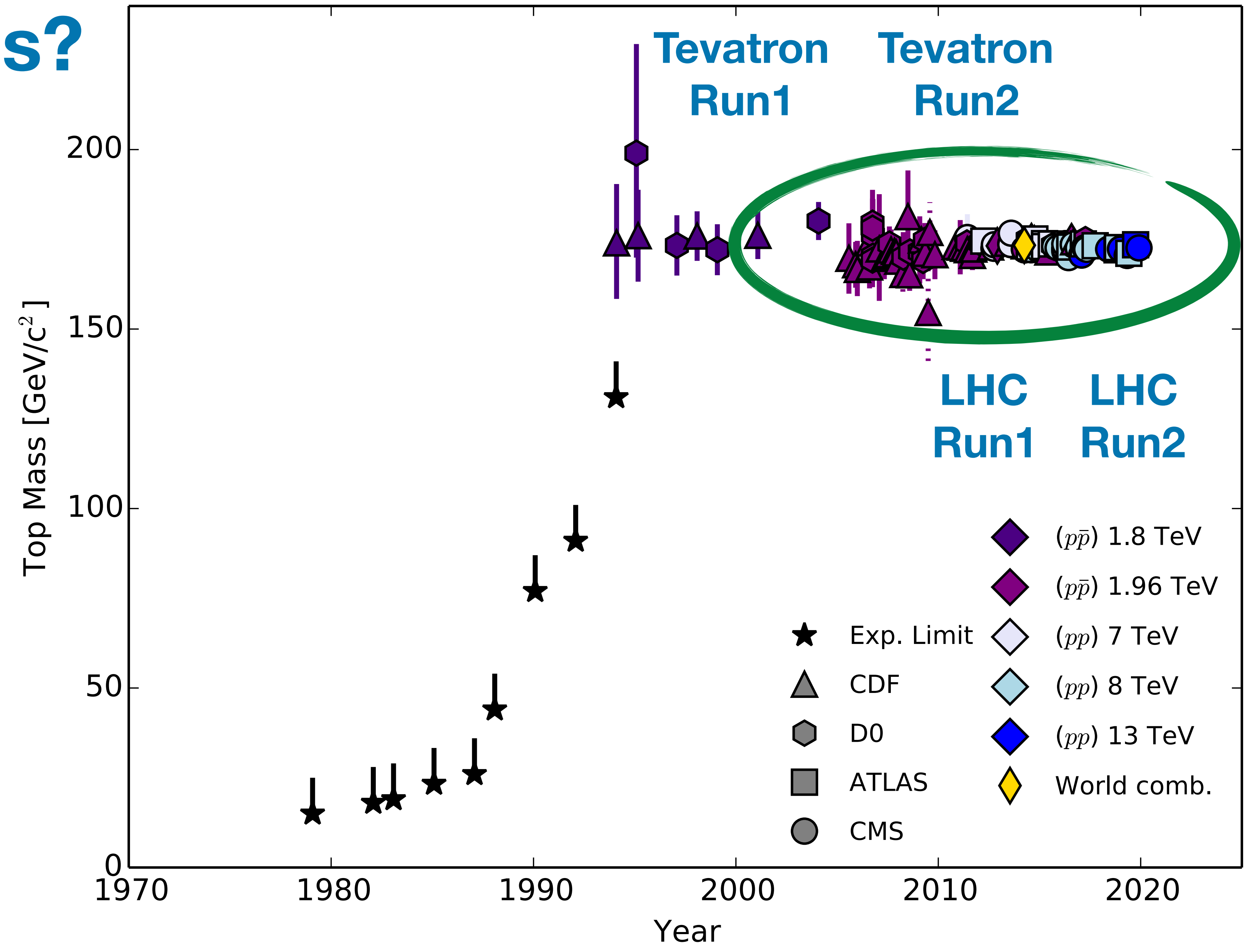


* not including Limits from Theory (e.g. global EW fits)

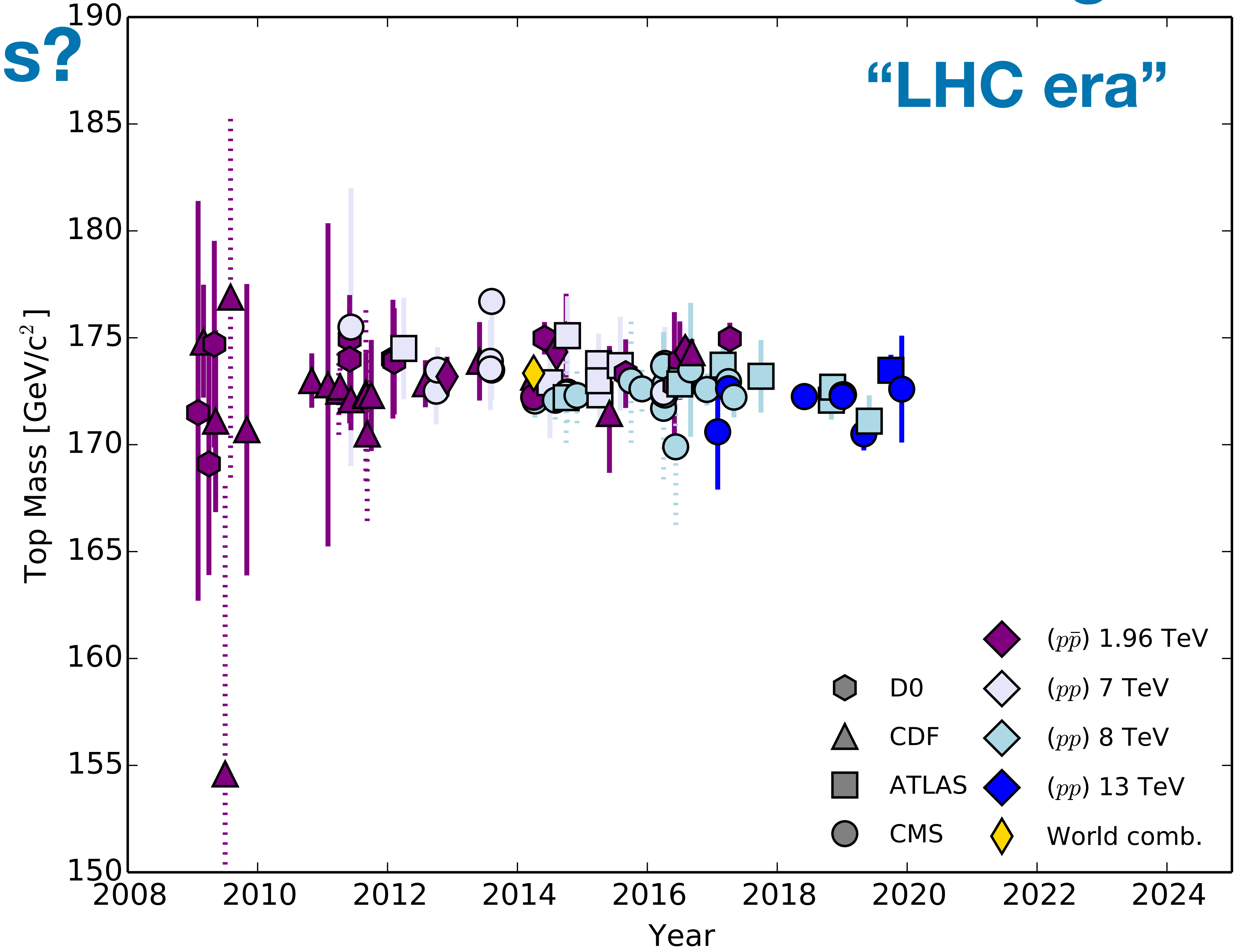
- **How well do we understand this high mass?**



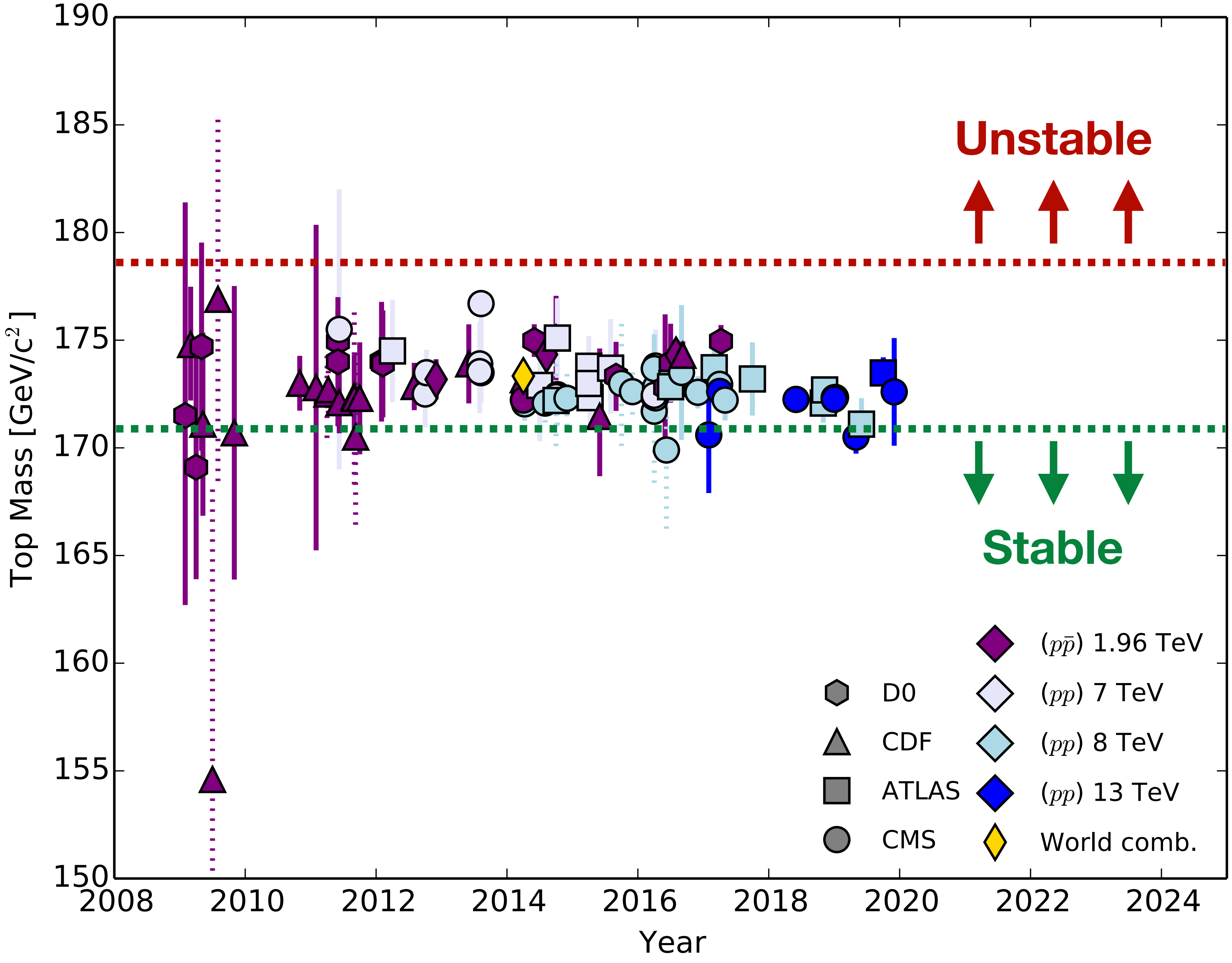
- **How well do we understand this high mass?**



- **How well do we understand this high mass?**



- Certainly at 1 GeV level, below is arguable…

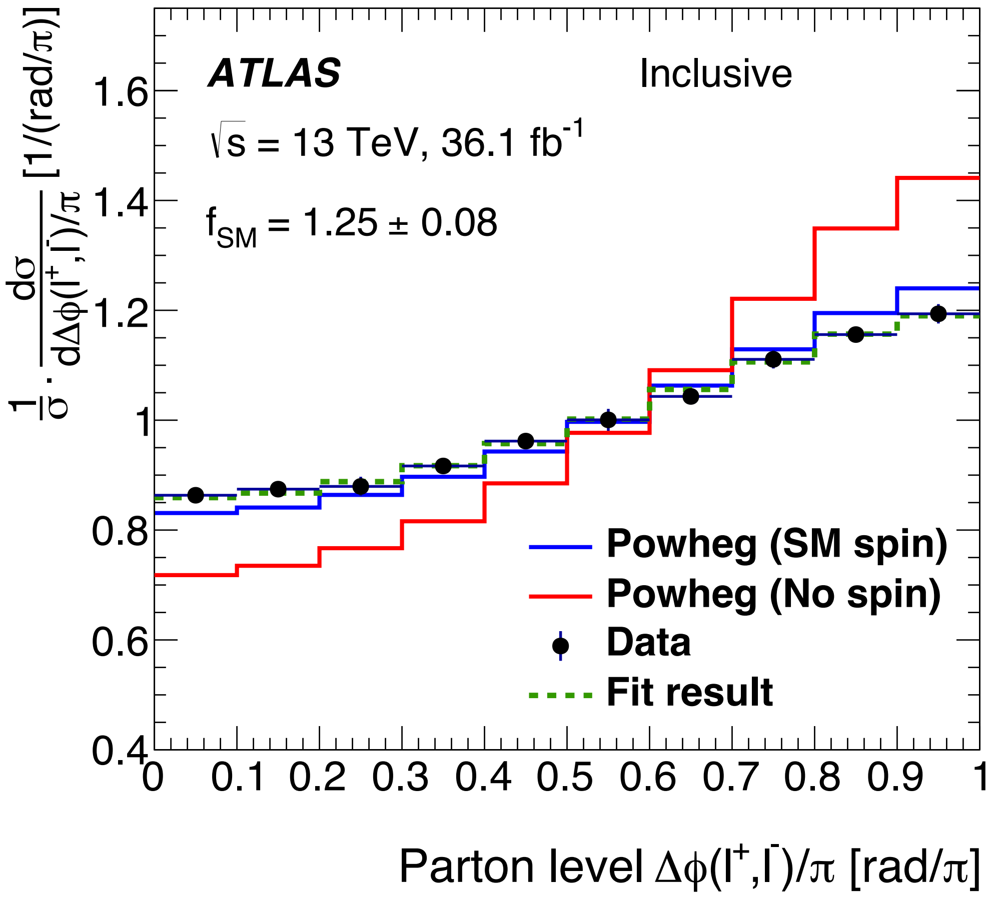

Unstable
Stable
Top Mass [GeV/c^2]
Year
190
185
180
175
170
165
160
155
150
2008
2010
2012
2014
2016
2018
2020
2022
2024
⬢ D0
▲ CDF
■ ATLAS
● CMS
◆ ($p\bar{p}$) 1.96 TeV
◆ (pp) 7 TeV
◆ (pp) 8 TeV
◆ (pp) 13 TeV
◆ World comb.

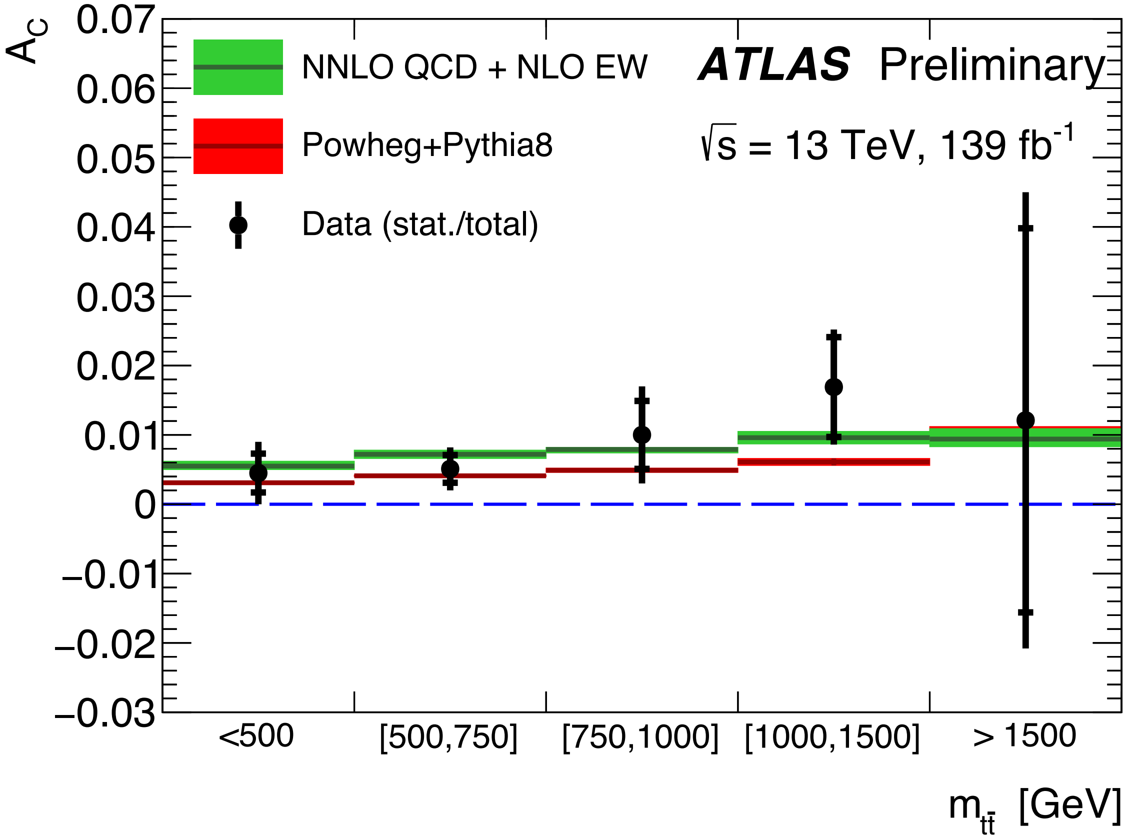
- **Effects of this high mass?**

Production		Lifetime		Hadronisation		Spin decorr.
$\frac{1}{m(t)}$	$<<$	$\frac{1}{\Gamma(t)}$	$<<$	$\frac{1}{\Lambda_{QCD}}$	$<<$	$\frac{m(t)}{\Lambda_{QCD}}$
$\sim 10^{-27}$ s		$\sim 10^{-25}$ s		$\sim 10^{-24}$ s		$\sim 10^{-22}$ s

- **Short lifetime means quantum numbers** (e.g. spin) **transferred directly to decay particles.**

- **Many unique features not present in other quark phenomenology:**





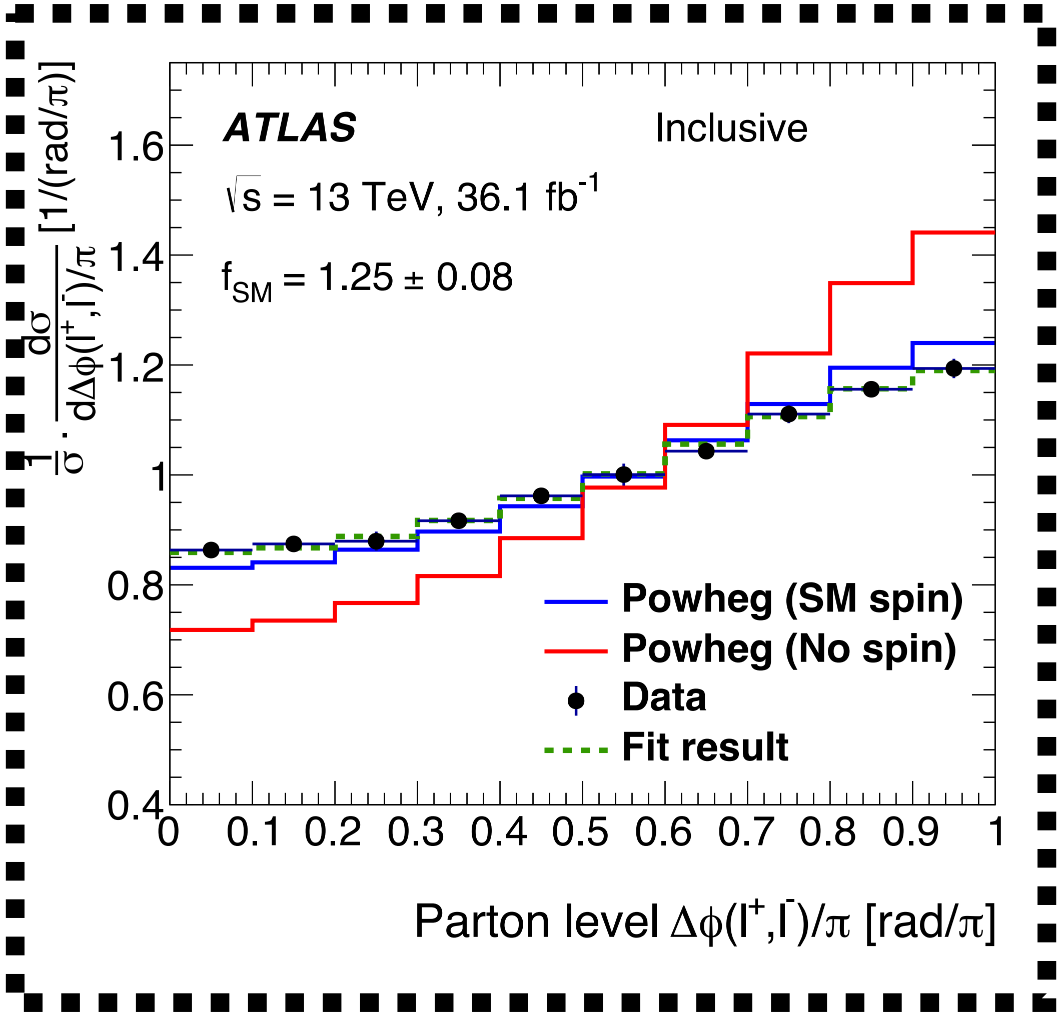
Spin Correlation

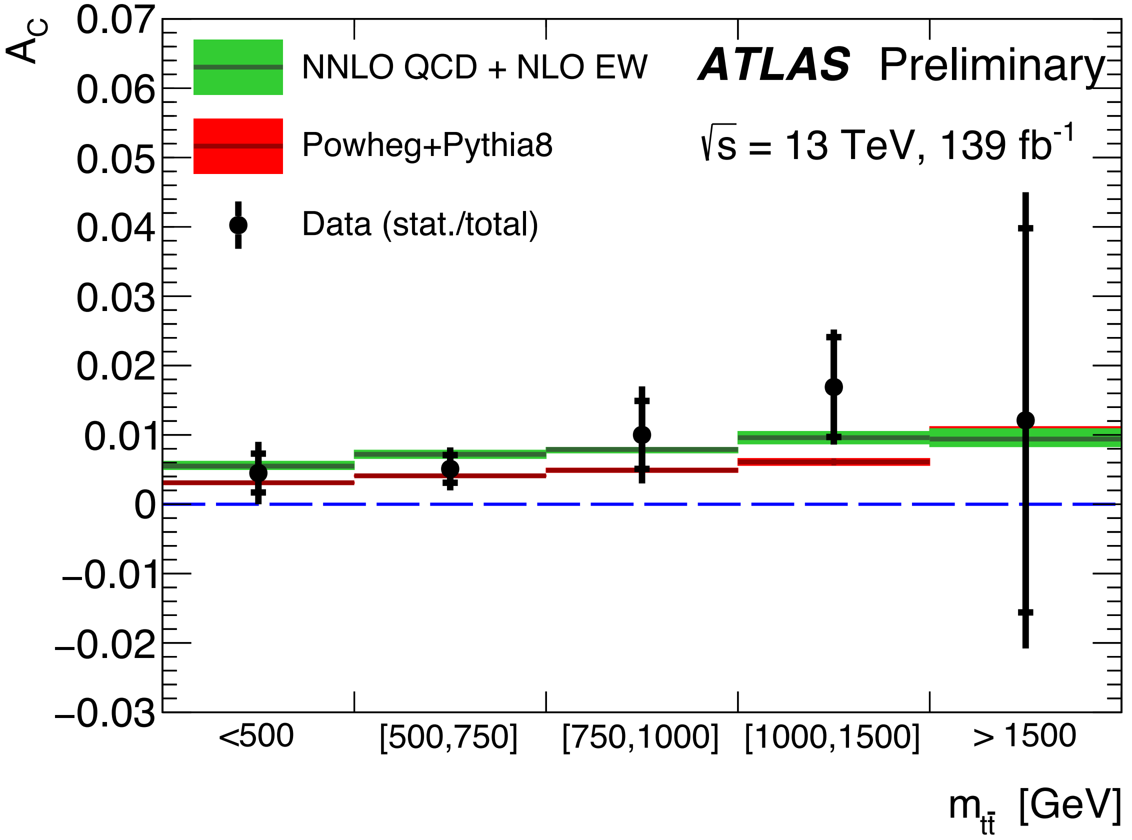
(TOPQ-2016-10)

Charge Asymmetry

(ATLAS-CONF-2019-026)

- **Many unique features not present in other quark phenomenology:**





Spin Correlation

(TOPQ-2016-10)

Charge Asymmetry

(ATLAS-CONF-2019-026)

- **What is spin correlation?**

$$C = \frac{N(\uparrow\uparrow) + N(\downarrow\downarrow) - N(\uparrow\downarrow) - N(\downarrow\uparrow)}{N(\uparrow\uparrow) + N(\downarrow\downarrow) + N(\uparrow\downarrow) + N(\downarrow\uparrow)}$$

Polarisation Spin Correlation

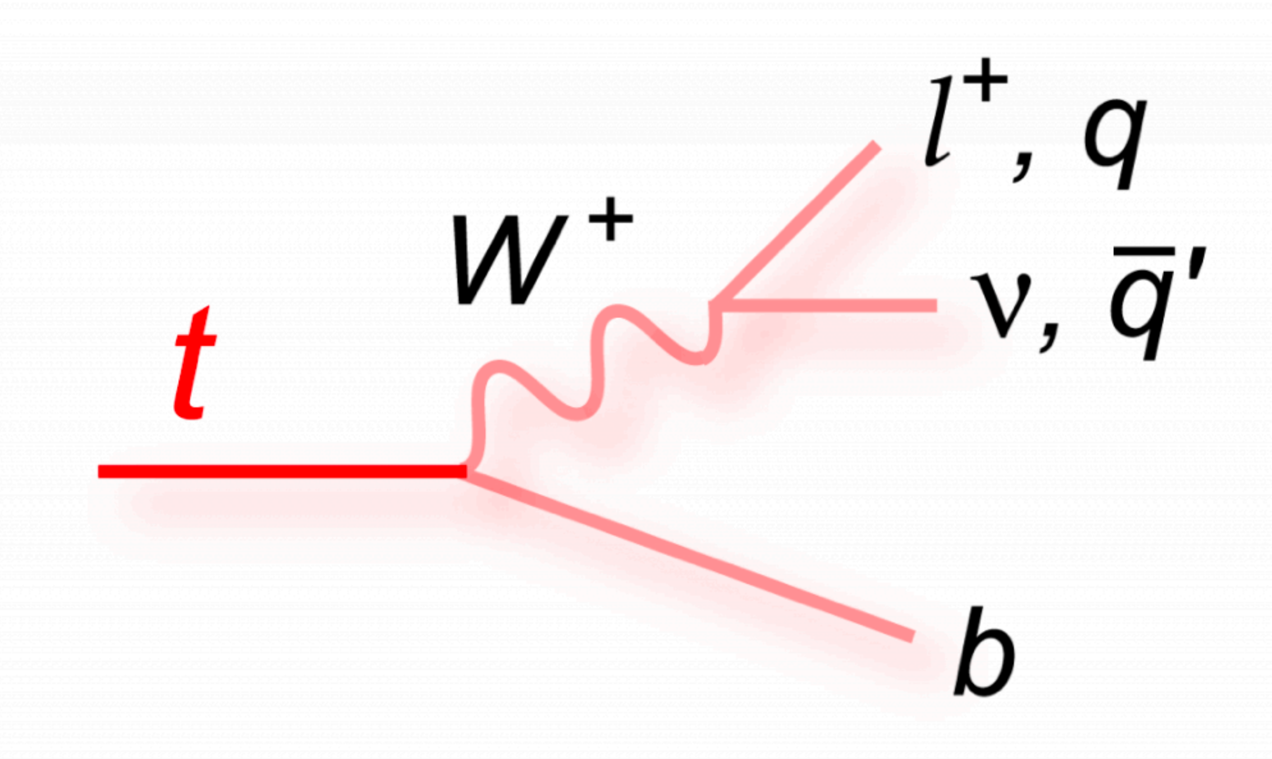
$$\frac{1}{\sigma}\frac{\mathrm{d}^2\sigma}{\mathrm{d}\cos\theta_+^a\,\mathrm{d}\cos\theta_-^b} = \frac{1}{4}(1 + B_+^a\cos\theta_+^a + B_-^b\cos\theta_-^b - C(a,b)\cos\theta_+^a\cos\theta_-^b)$$

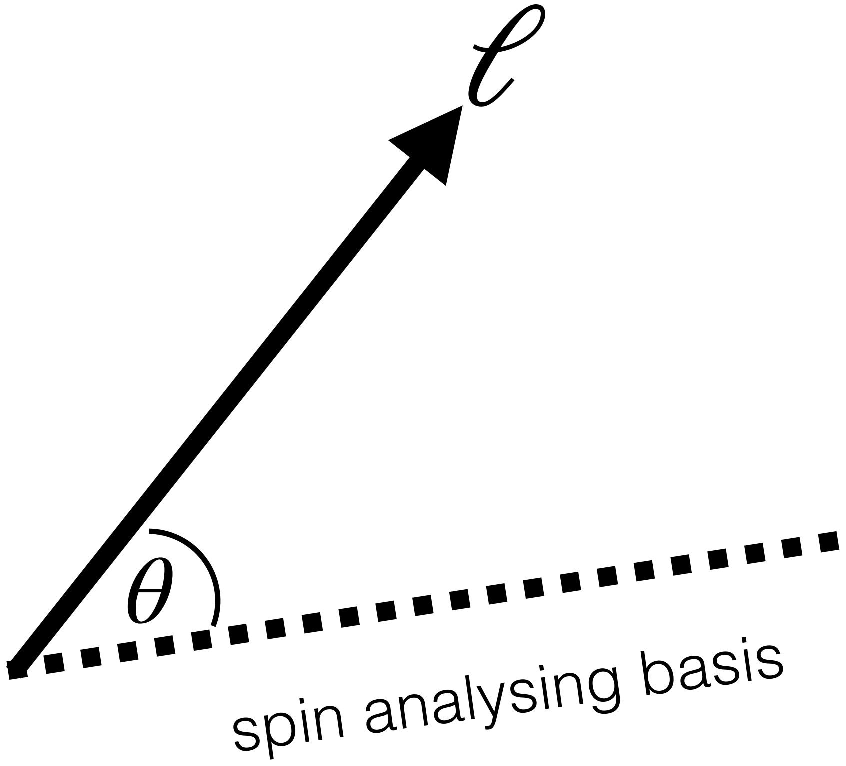
- **Measuring these angles means we can measure B and C**

$$B_+ = 3 \cdot < cos(\theta_+) >$$

$$C = -9 \cdot < cos(\theta_+) cos(\theta_-) >$$

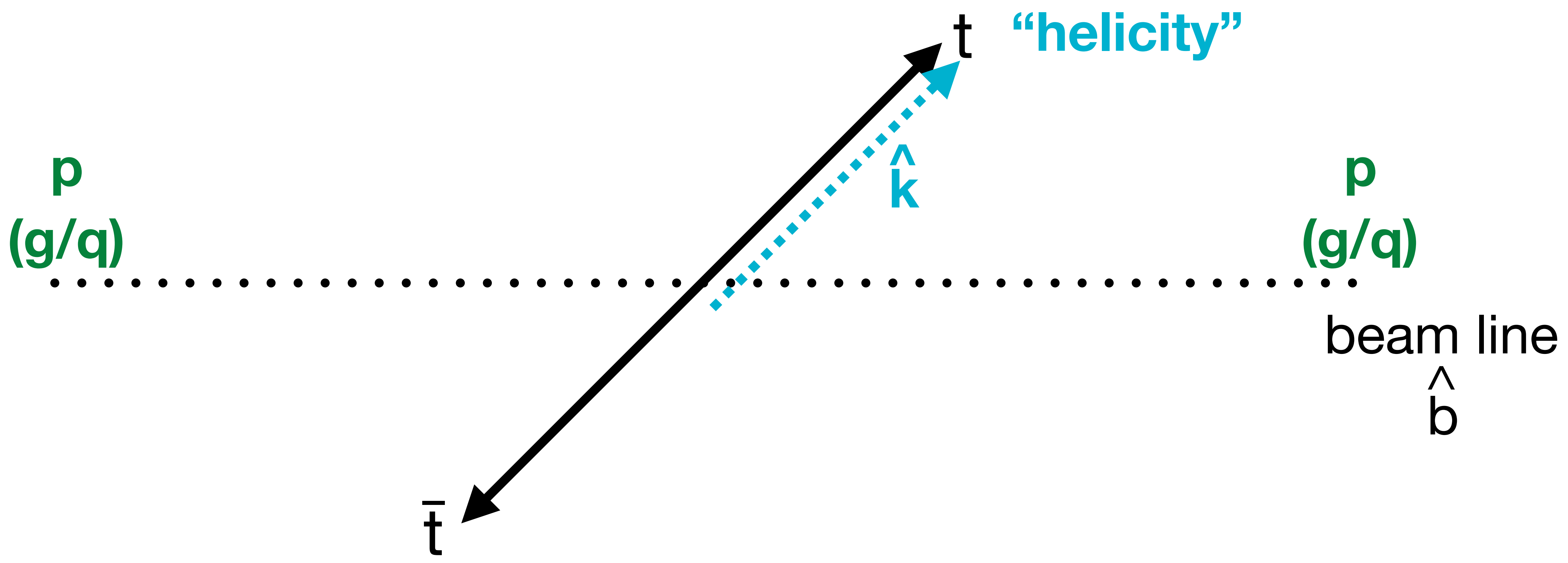
- **How do we measure these angles**





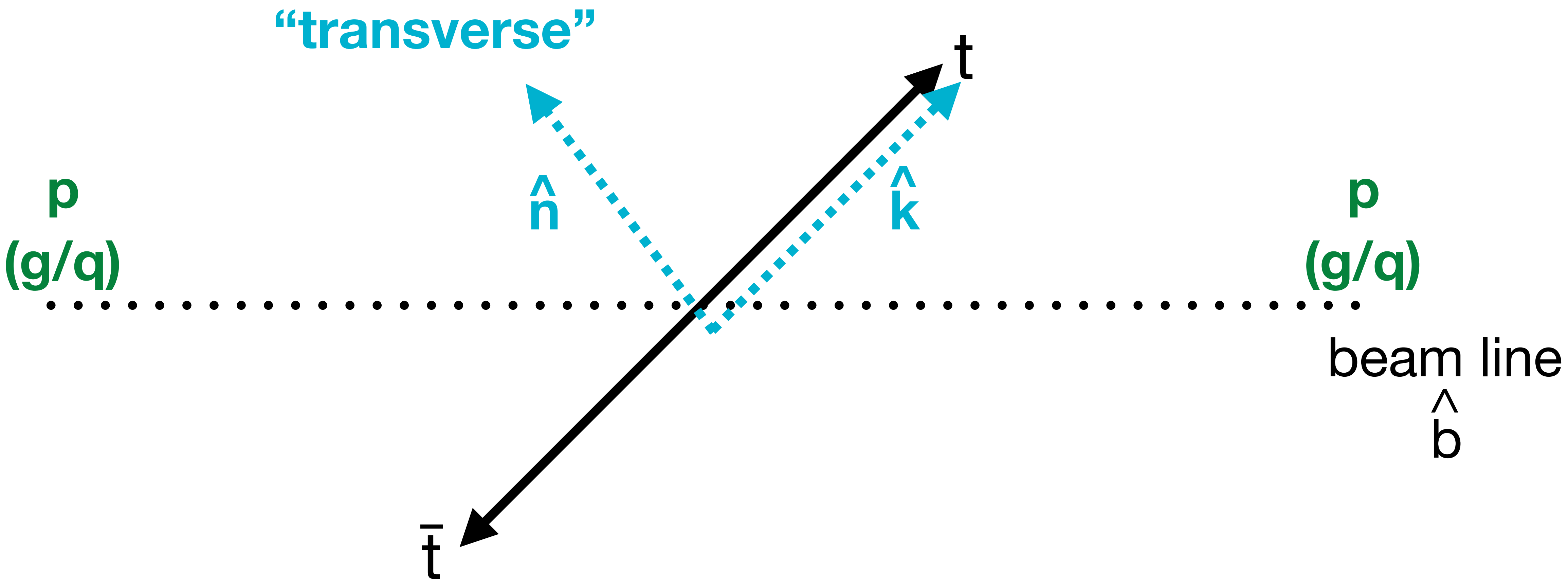
- **Angle formed between lepton and some spin-analysis basis.**

- Less simple for hadron colliders…



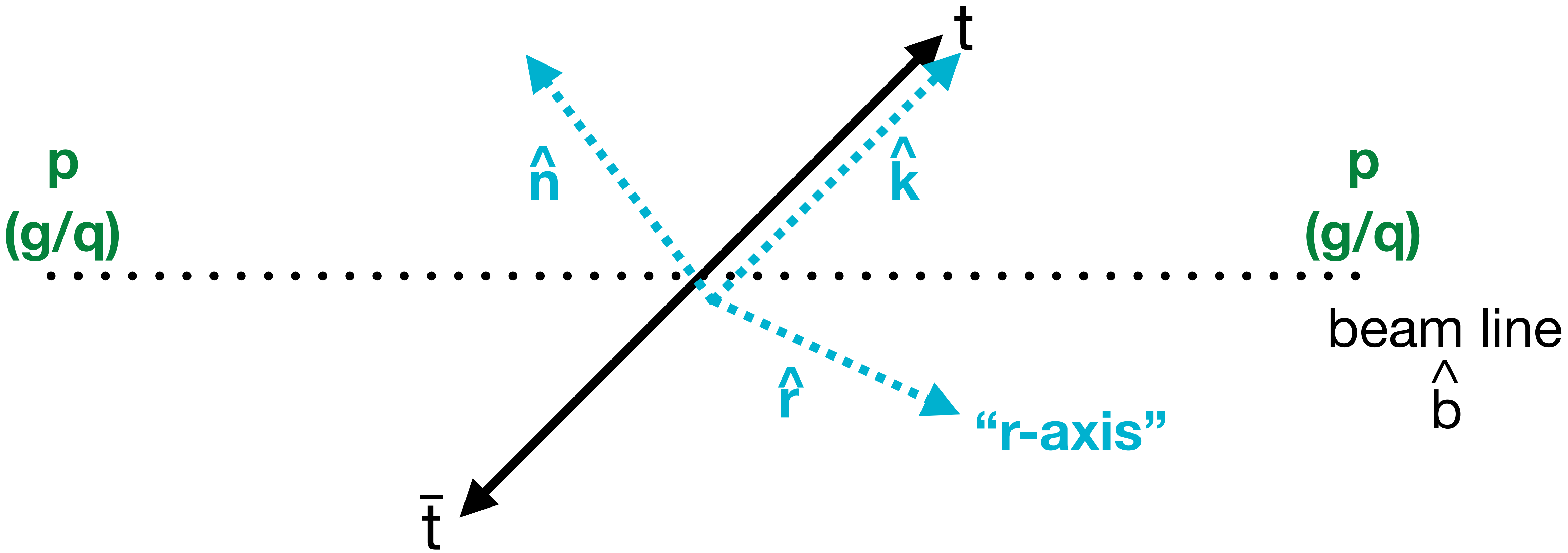
- Helicity: direction of t in $t\bar{t}$ rest frame.
- C ~ 0.31

- Less simple for hadron colliders…



- Transverse: orthogonal to plane formed by t and b
- C ~ 0.32

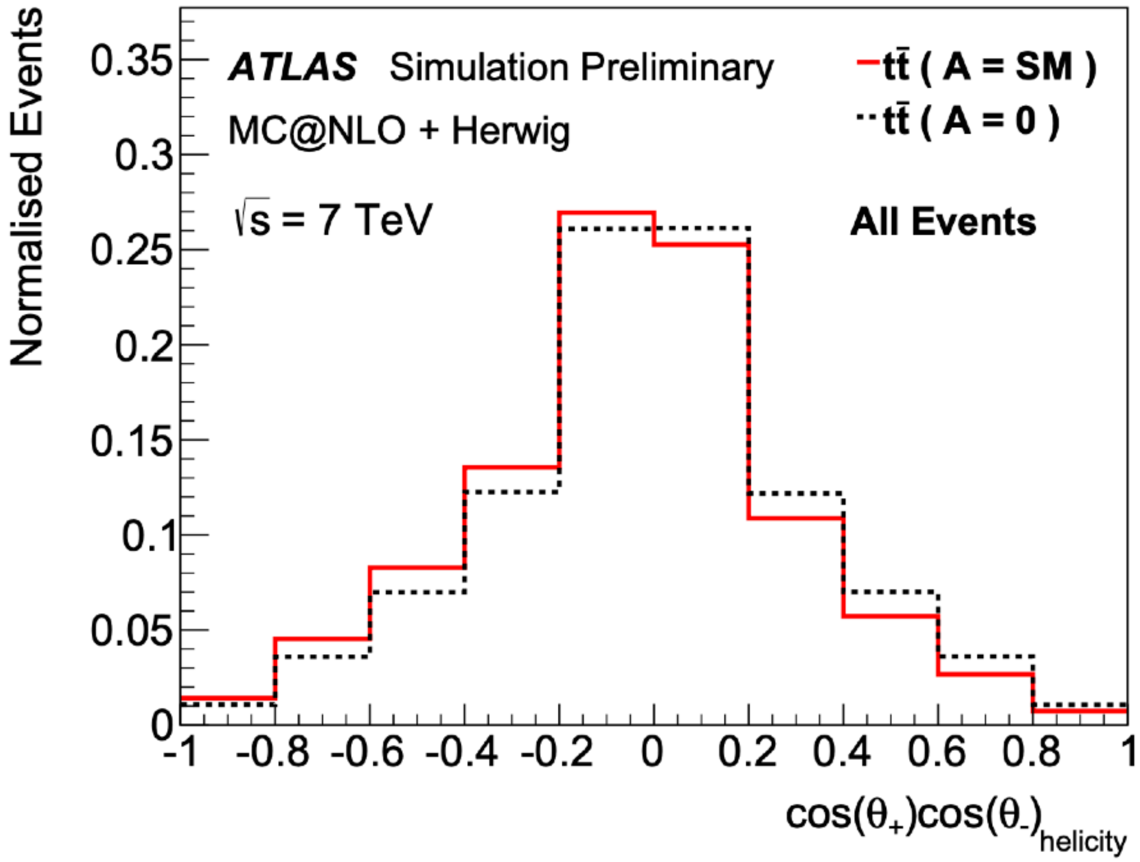
- **Less simple for hadron colliders…**



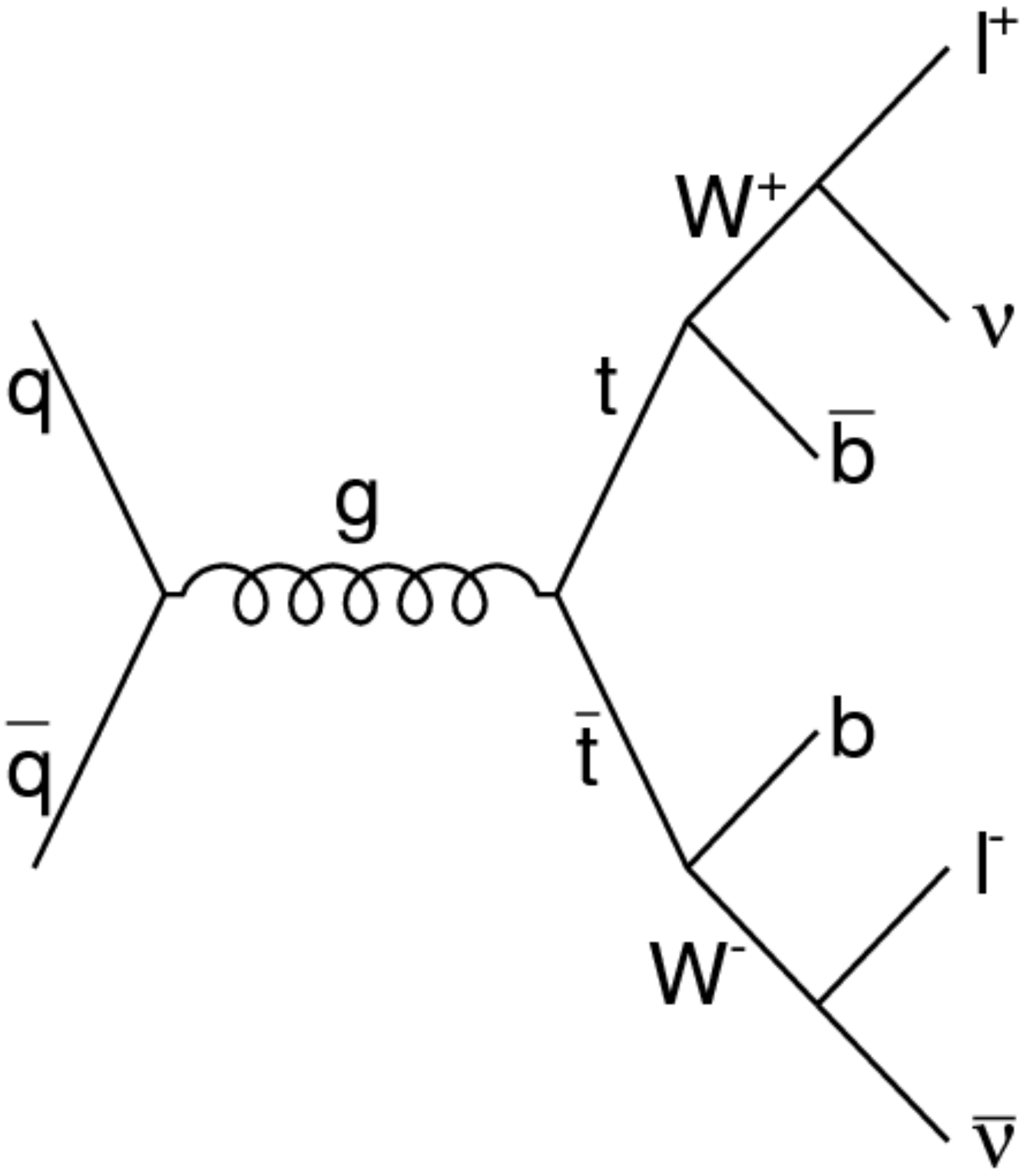
- **r-axis: remaining orthogonal direction**
- **C ~ 0.01**

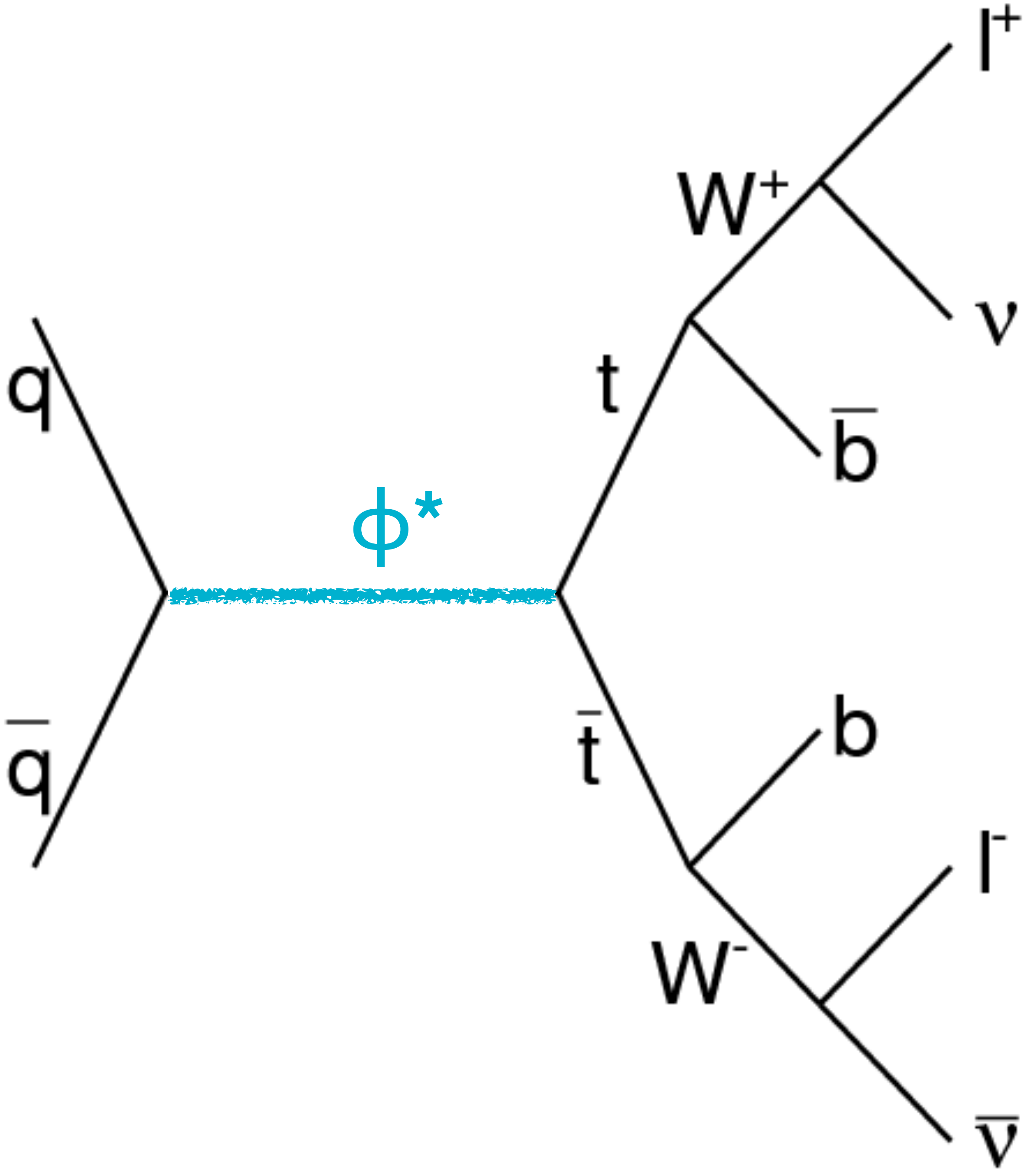
- This coordinate system allows us to fully probe the spin density matrix:

$$|M|^2 \propto X + \mathbf{B}^+ \cdot \mathbf{s_1} + \mathbf{B}^- \cdot \mathbf{s_2} + C_{ij} s_{1i} s_{2i},$$

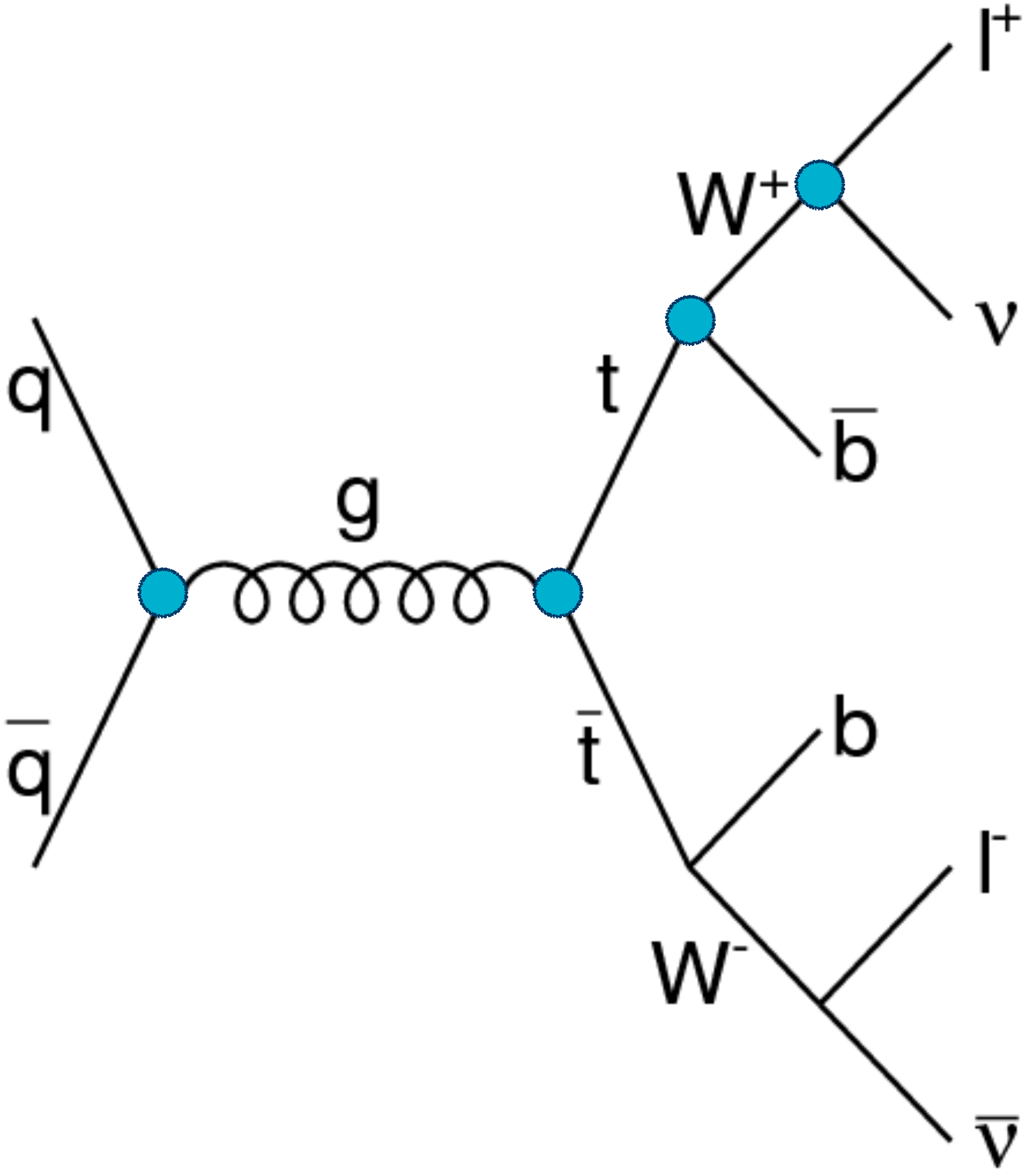


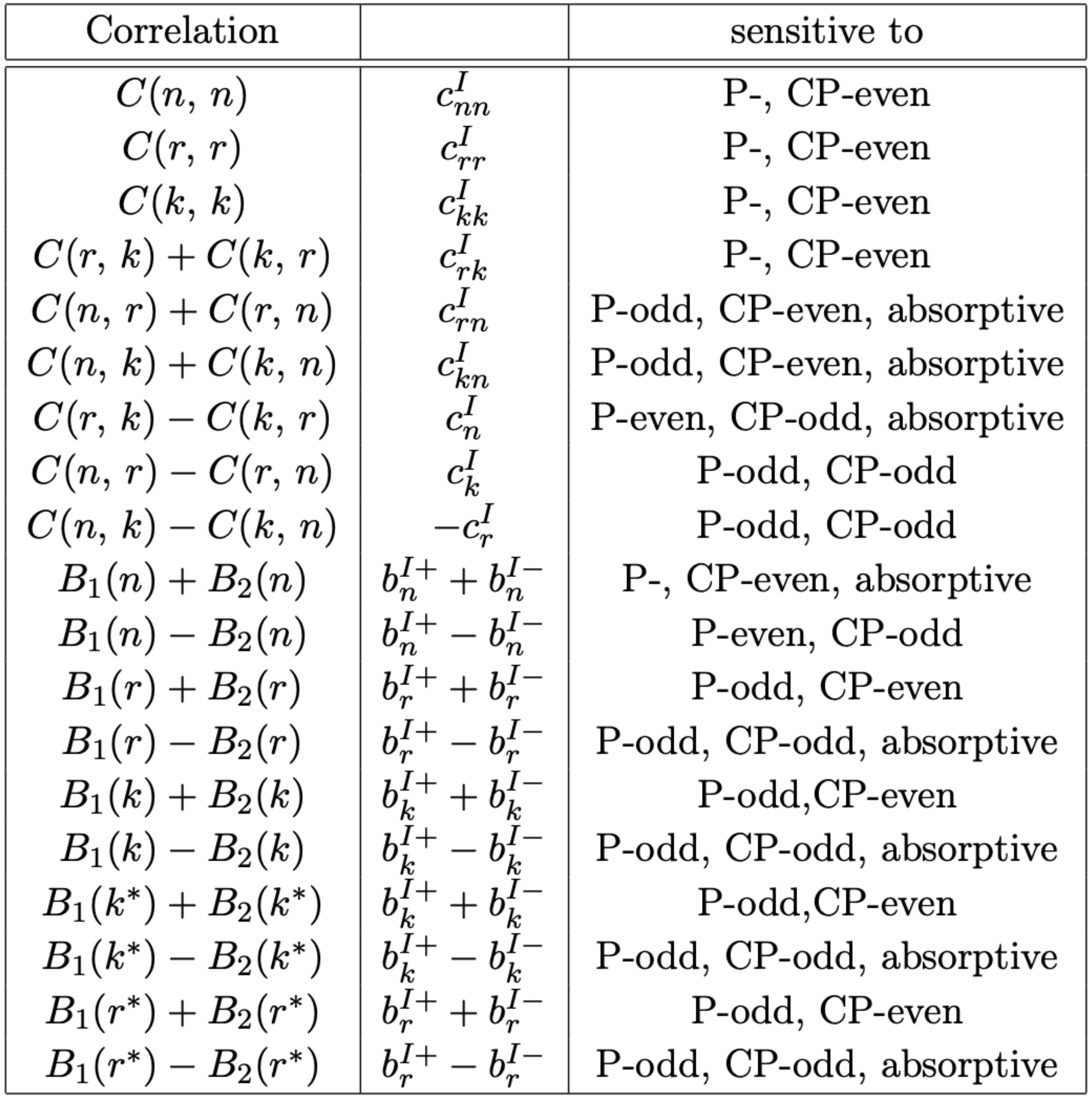
$$\begin{pmatrix} C_{kk} & X & X \\ X & C_{nn} & X \\ X & X & C_{rr} \end{pmatrix}$$


q
$\bar{q}$
g
t
$\bar{t}$
W^+
W^-
$\bar{b}$
b
l^+
ν
l^-
$\bar{\nu}$



l^+
W^+
ν
q
t
$\bar{b}$
ϕ^*
$\bar{q}$
$\bar{t}$
b
l^-
W^-
$\bar{\nu}$


q
$\bar{q}$
g
t
$\bar{t}$
W^+
l^+
ν
$\bar{b}$
b
W^-
l^-
$\bar{\nu}$

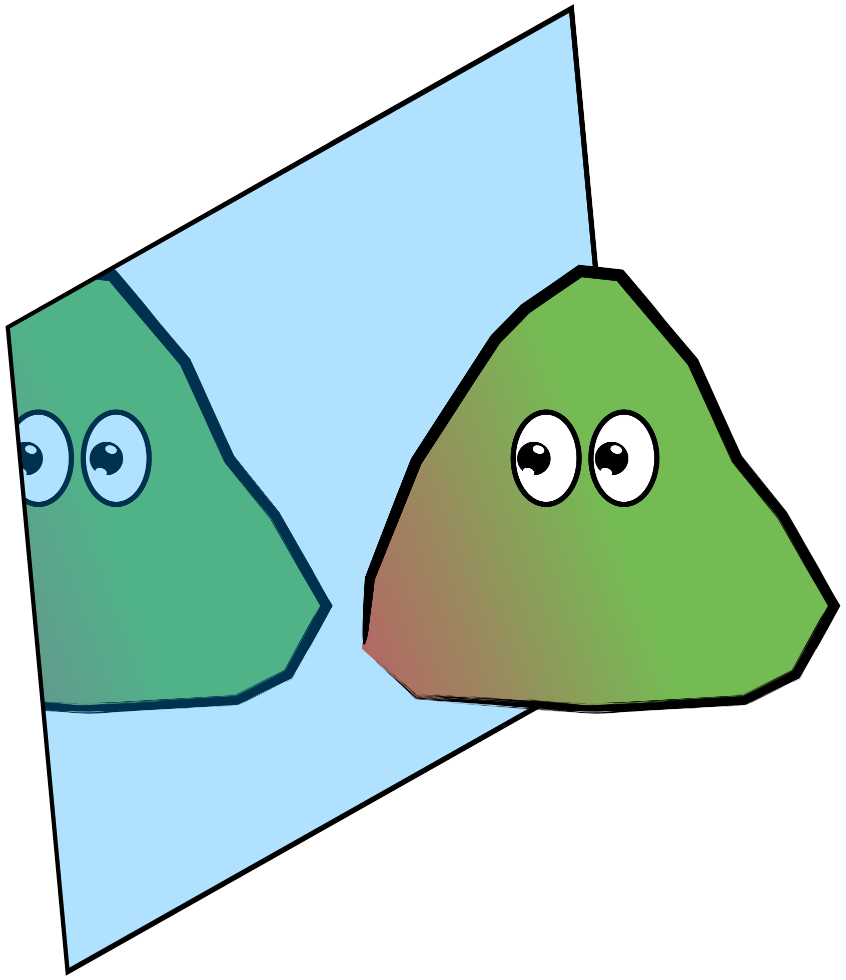


Correlation		sensitive to
$C(n, n)$	c^I_{nn}	P-, CP-even
$C(r, r)$	c^I_{rr}	P-, CP-even
$C(k, k)$	c^I_{kk}	P-, CP-even
$C(r, k) + C(k, r)$	c^I_{rk}	P-, CP-even
$C(n, r) + C(r, n)$	c^I_{rn}	P-odd, CP-even, absorptive
$C(n, k) + C(k, n)$	c^I_{kn}	P-odd, CP-even, absorptive
$C(r, k) - C(k, r)$	c^I_{n}	P-even, CP-odd, absorptive
$C(n, r) - C(r, n)$	c^I_{k}	P-odd, CP-odd
$C(n, k) - C(k, n)$	$-c^I_{r}$	P-odd, CP-odd
$B_1(n) + B_2(n)$	$b^{I+}_n + b^{I-}_n$	P-, CP-even, absorptive
$B_1(n) - B_2(n)$	$b^{I+}_n - b^{I-}_n$	P-even, CP-odd
$B_1(r) + B_2(r)$	$b^{I+}_r + b^{I-}_r$	P-odd, CP-even
$B_1(r) - B_2(r)$	$b^{I+}_r - b^{I-}_r$	P-odd, CP-odd, absorptive
$B_1(k) + B_2(k)$	$b^{I+}_k + b^{I-}_k$	P-odd,CP-even
$B_1(k) - B_2(k)$	$b^{I+}_k - b^{I-}_k$	P-odd, CP-odd, absorptive
$B_1(k^*) + B_2(k^*)$	$b^{I+}_k + b^{I-}_k$	P-odd,CP-even
$B_1(k^*) - B_2(k^*)$	$b^{I+}_k - b^{I-}_k$	P-odd, CP-odd, absorptive
$B_1(r^*) + B_2(r^*)$	$b^{I+}_r + b^{I-}_r$	P-odd, CP-even
$B_1(r^*) - B_2(r^*)$	$b^{I+}_r - b^{I-}_r$	P-odd, CP-odd, absorptive

- Spin correlation, polarisaton, and cross correlation have sensitivity to different symmetries

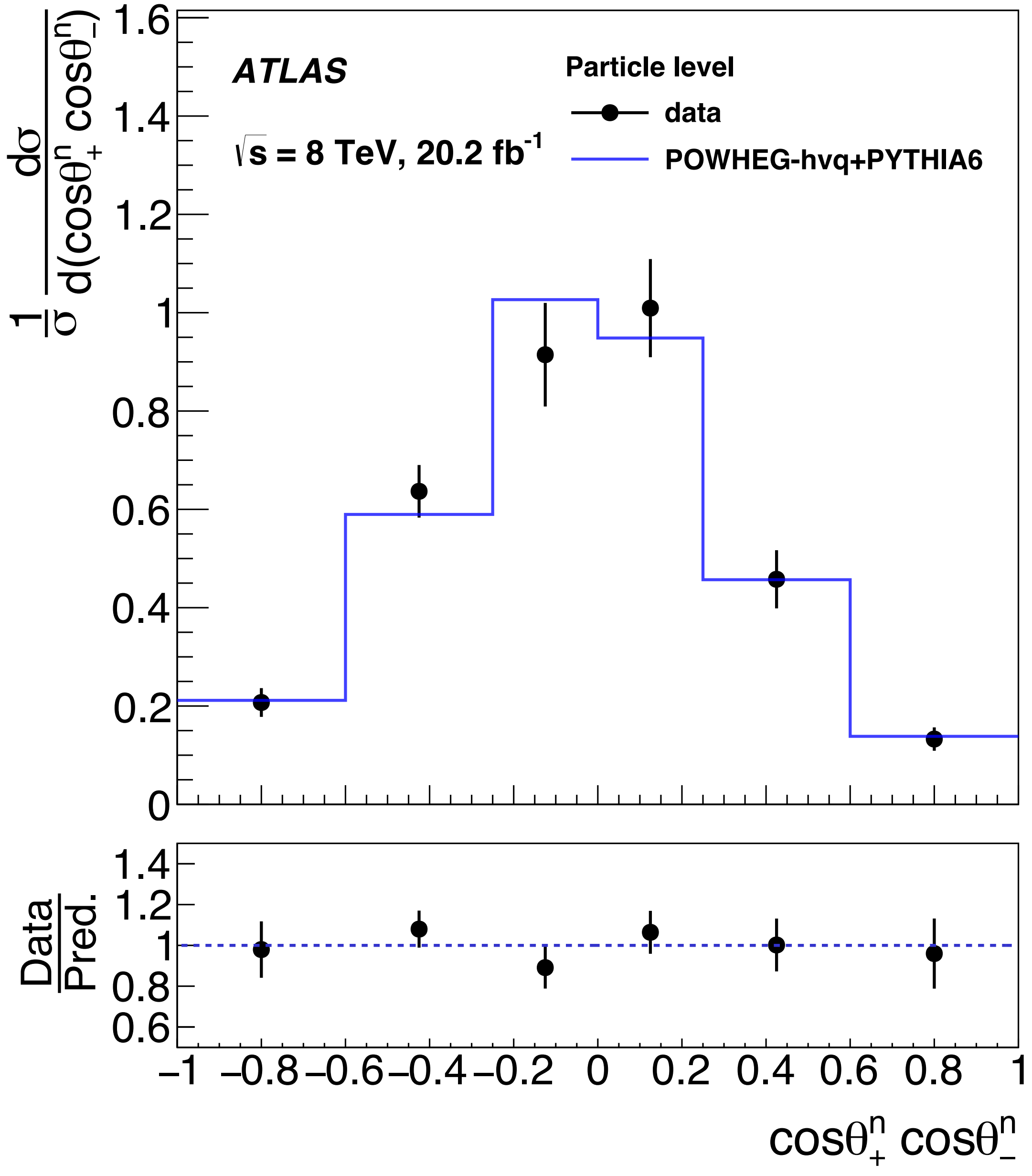
Correlation		sensitive to
$C(n, n)$	c^I_{nn}	P-, CP-even
$C(r, r)$	c^I_{rr}	P-, CP-even
$C(k, k)$	c^I_{kk}	P-, CP-even
$C(r, k) + C(k, r)$	c^I_{rk}	P-, CP-even
$C(n, r) + C(r, n)$	c^I_{rn}	P-odd, CP-even, absorptive
$C(n, k) + C(k, n)$	c^I_{kn}	P-odd, CP-even, absorptive
$C(r, k) - C(k, r)$	c^I_n	P-even, CP-odd, absorptive
$C(n, r) - C(r, n)$	c^I_k	P-odd, CP-odd
$C(n, k) - C(k, n)$	$-c^I_r$	P-odd, CP-odd
$B_1(n) + B_2(n)$	$b^{I+}_n + b^{I-}_n$	P-, CP-even, absorptive
$B_1(n) - B_2(n)$	$b^{I+}_n - b^{I-}_n$	P-even, CP-odd
$B_1(r) + B_2(r)$	$b^{I+}_r + b^{I-}_r$	P-odd, CP-even
$B_1(r) - B_2(r)$	$b^{I+}_r - b^{I-}_r$	P-odd, CP-odd, absorptive
$B_1(k) + B_2(k)$	$b^{I+}_k + b^{I-}_k$	P-odd,CP-even
$B_1(k) - B_2(k)$	$b^{I+}_k - b^{I-}_k$	P-odd, CP-odd, absorptive
$B_1(k^*) + B_2(k^*)$	$b^{I+}_k + b^{I-}_k$	P-odd,CP-even
$B_1(k^*) - B_2(k^*)$	$b^{I+}_k - b^{I-}_k$	P-odd, CP-odd, absorptive
$B_1(r^*) + B_2(r^*)$	$b^{I+}_r + b^{I-}_r$	P-odd, CP-even
$B_1(r^*) - B_2(r^*)$	$b^{I+}_r - b^{I-}_r$	P-odd, CP-odd, absorptive

- non-SM observations in



these would be signs of CP violation.

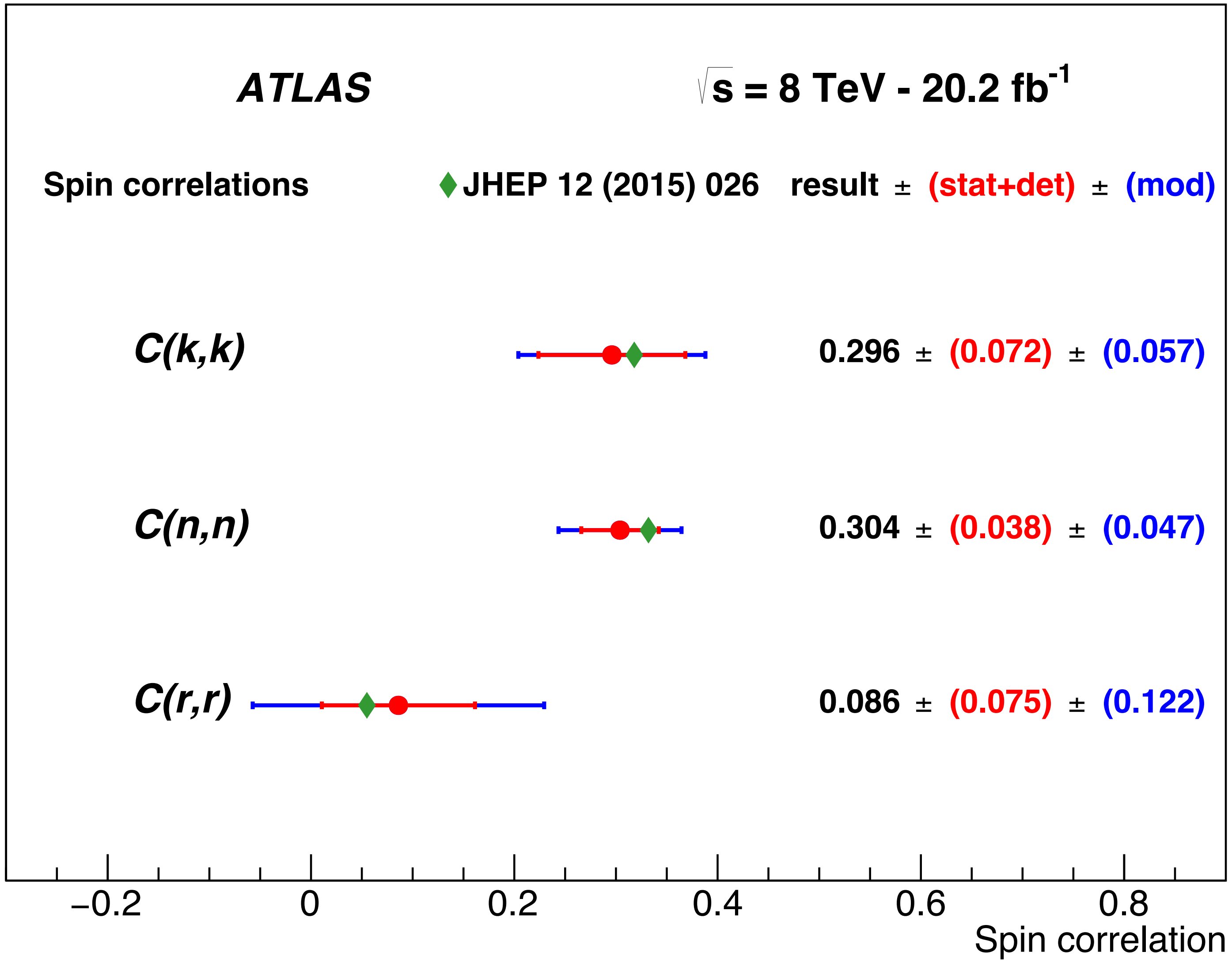
- At 8 TeV, ATLAS performed a measurement of the full spin density matrix using dilepton events.



- Observables corrected to parton level and compared to theory.

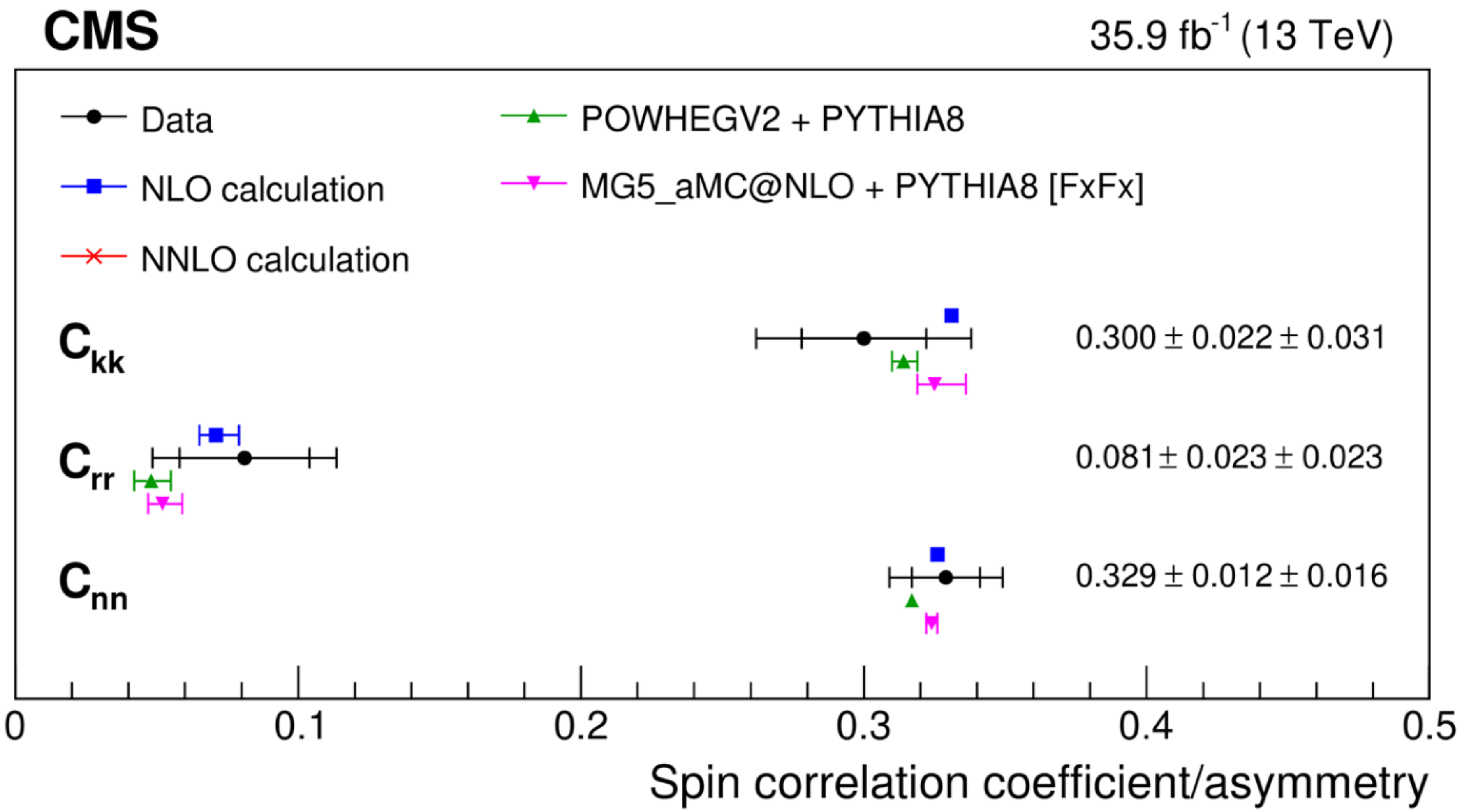
- Leading uncertainties come from the reconstruction of the tops, and MC models.

- ATLAS results from Run1

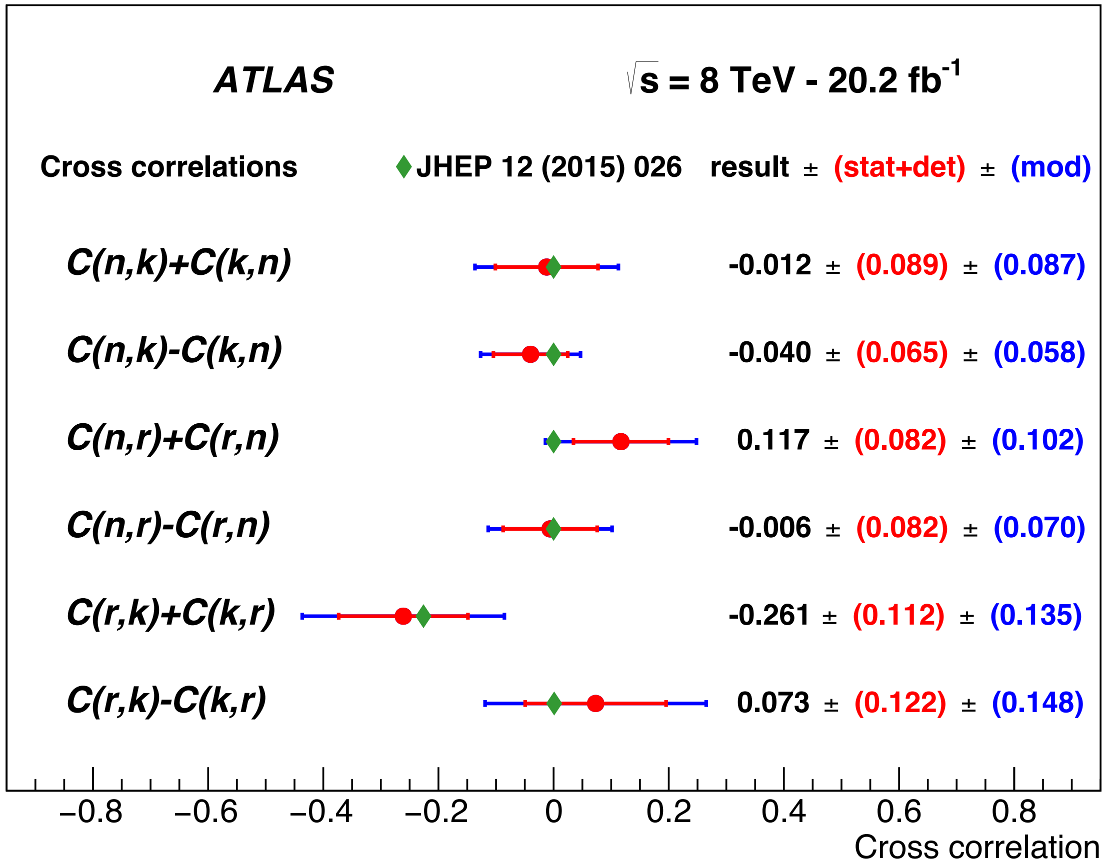


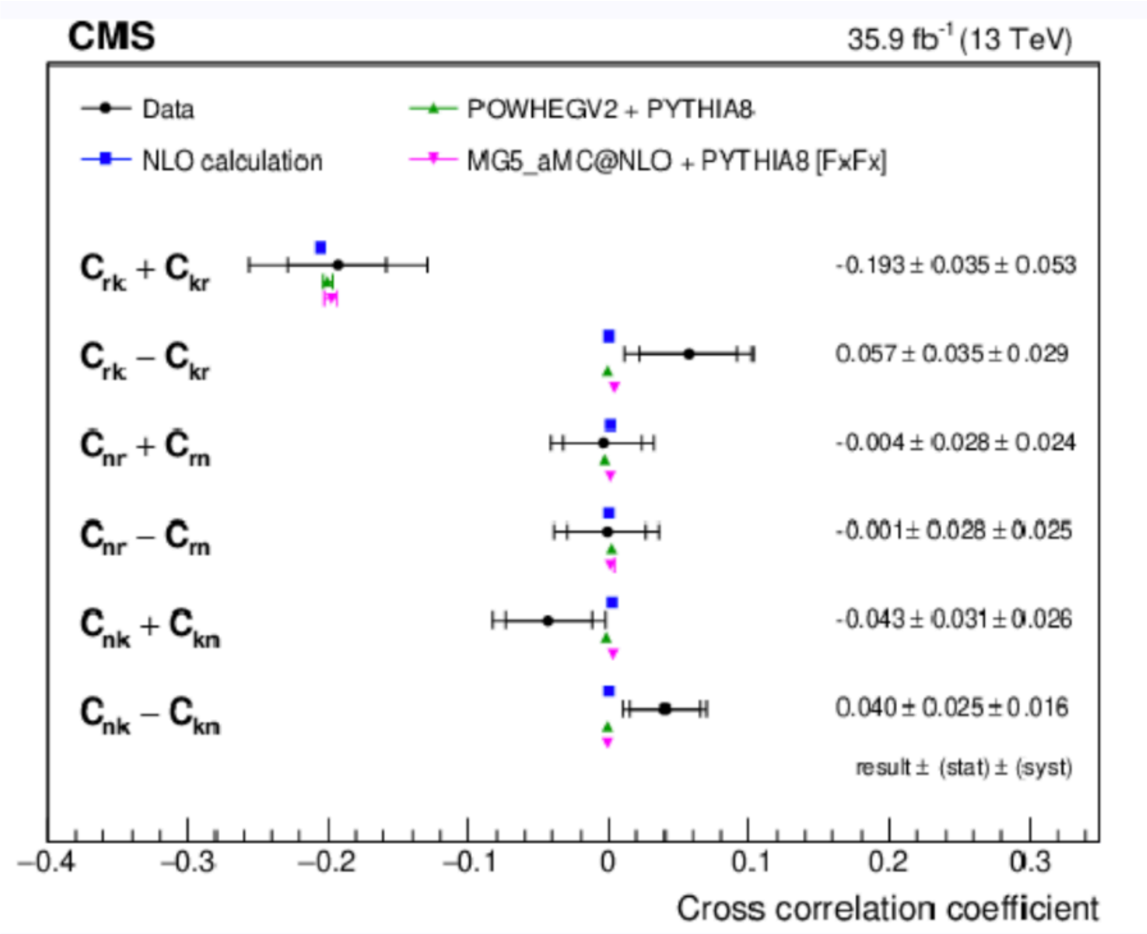
- Uncertainties O(30%), dominated by MC modelling

- CMS results from Run2



- Uncertainties O(10%), dominated by MC modelling

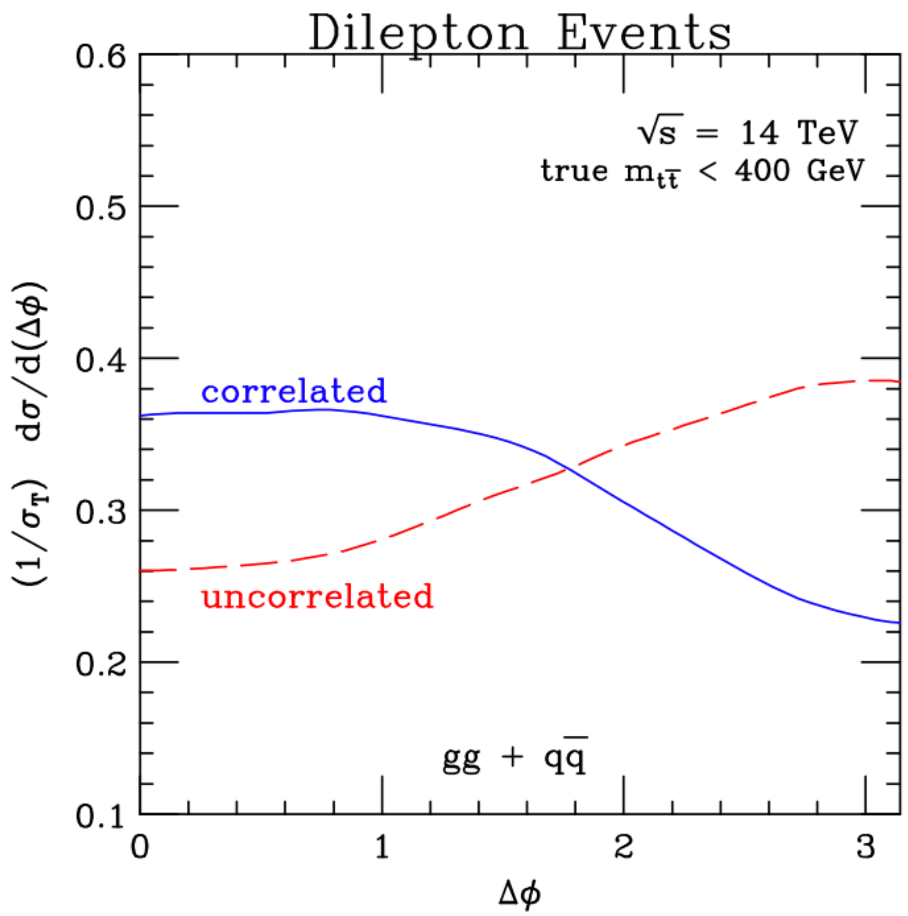


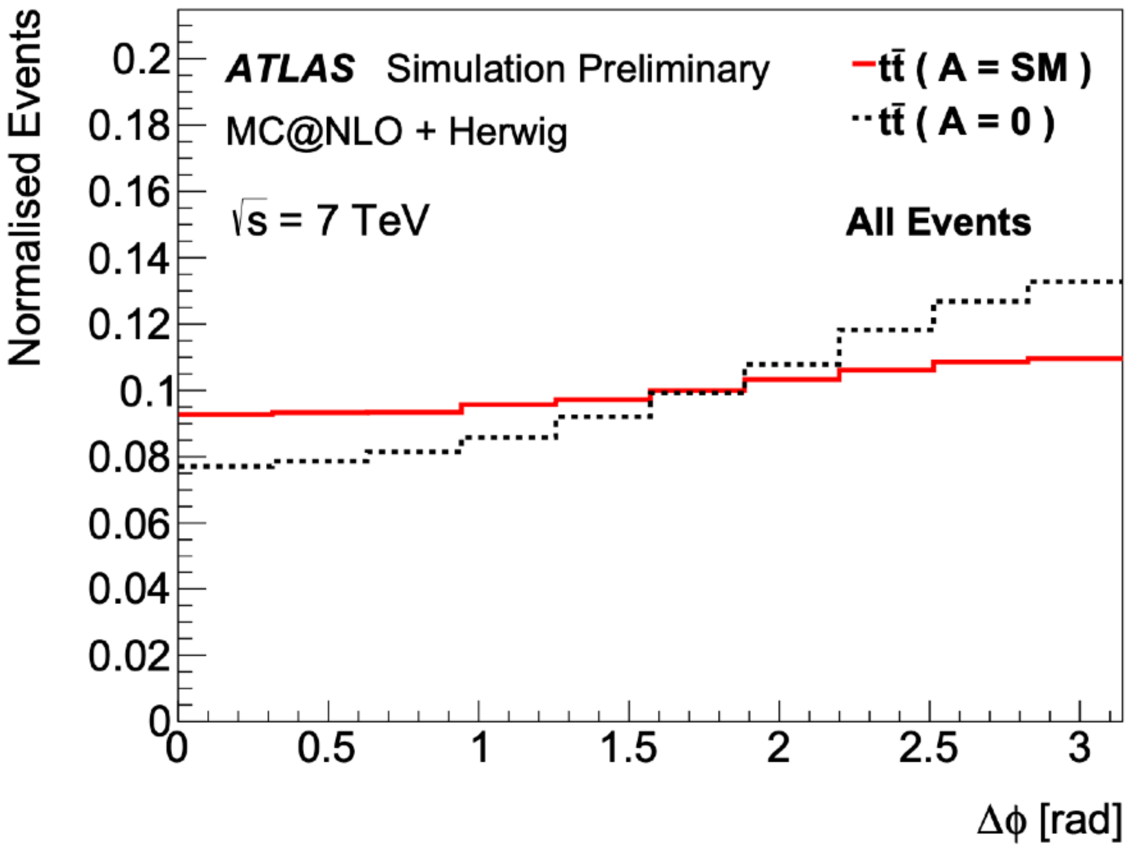


- No obvious signs, but uncertainties are still large.
- Maybe there’s a better way?

- Maybe there’s an easier way?

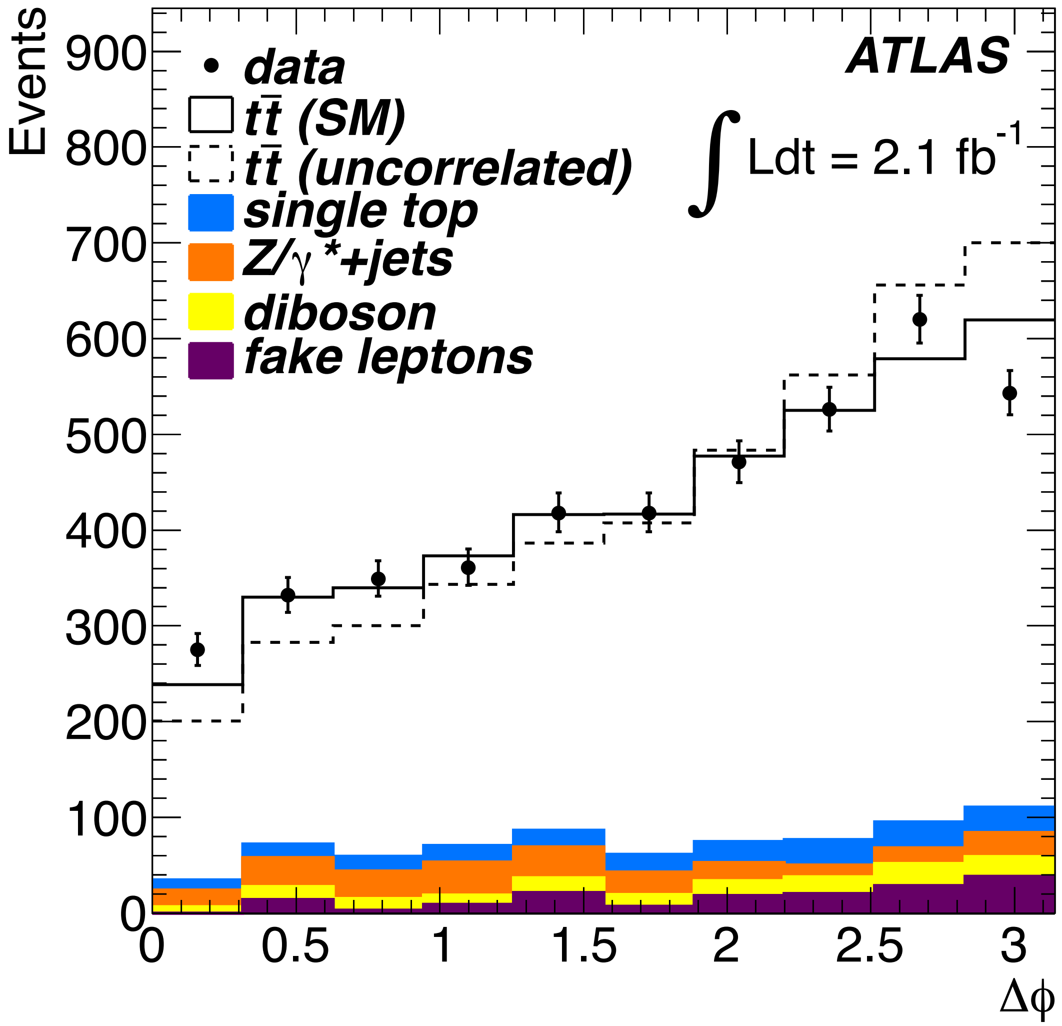
Mahlon, Parke, 2010





- Lab frame observables don’t have as nice of an interpretation, but they do have great sensitivity!

- First observation!



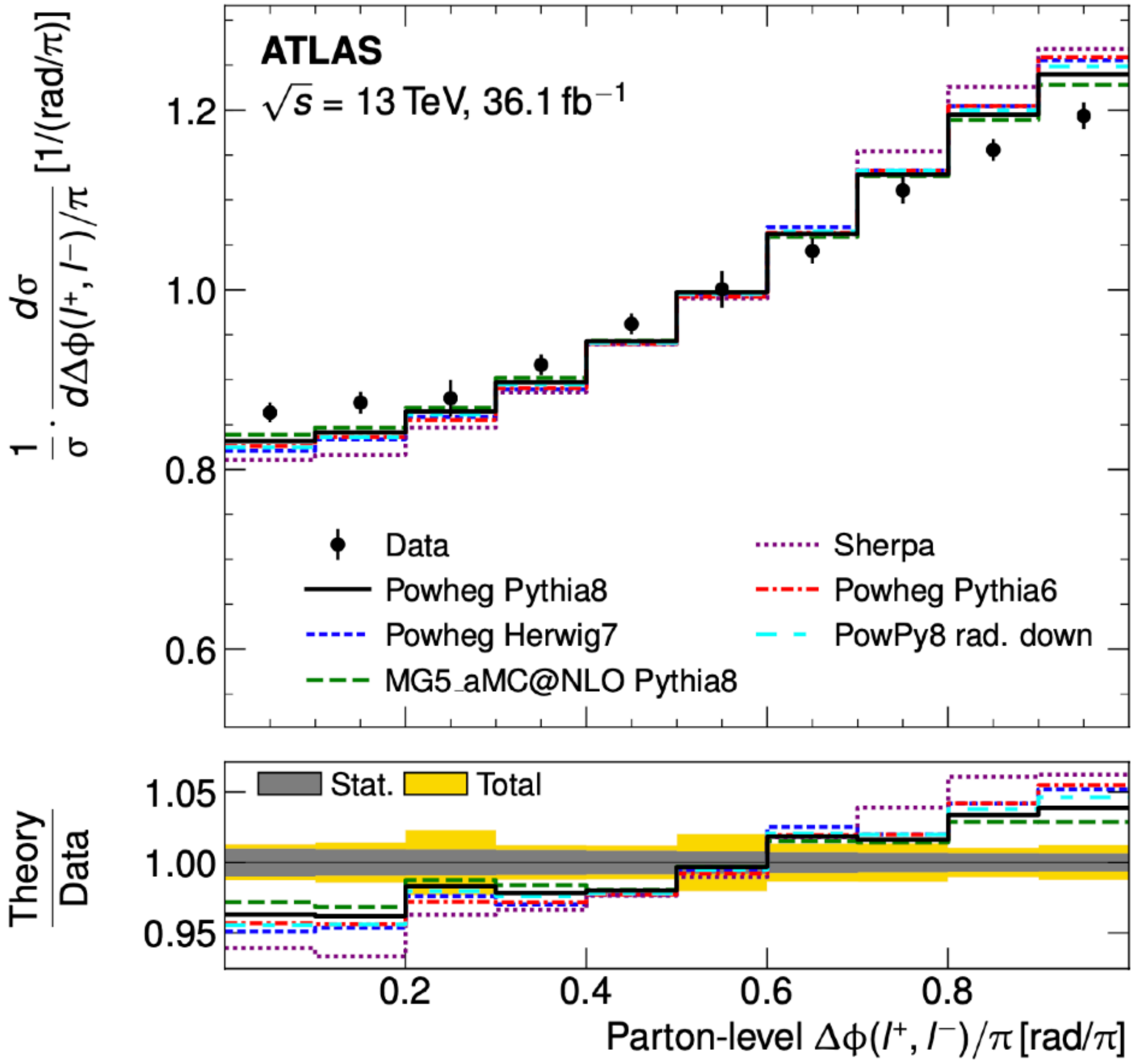
- Excluded the no-spin hypothesis with a significance of 5.1σ.

- The infamous Run2 result

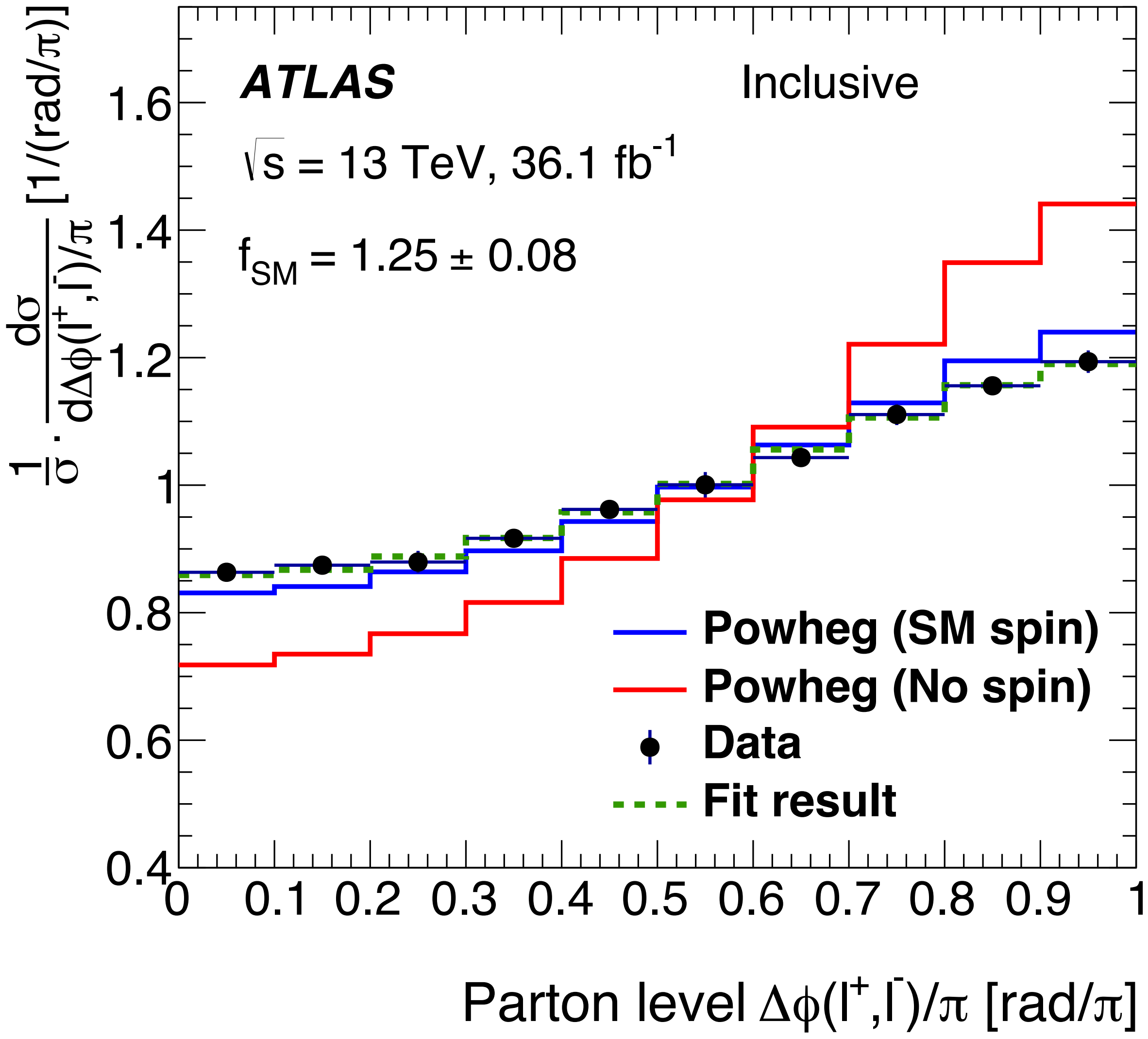
- Uses 36.1 fb-1 of ATLAS eμ + 1 or more b-tag data.

- Corrected for detector effects using iterative Bayesian unfolding.

- Uncertainties between 1 and 2% per bin.



- Use a template likelihood fit to extract the “fraction of SM-like spin correlation”:
  - $f_{SM} = 1$ (SM)
  - $f_{SM} = 0$ (No corr.)
- Templates are SM spin correlation and uncorrelated tops.



Region	$f_{\mathrm{SM}} \pm$ (stat.,syst.,theory)	Significance (excl. theory)
Inclusive	$1.249 \pm 0.024 \pm 0.061 \,^{+0.067}_{-0.090}$	2.2 (3.8)
$m_{t\bar{t}} < 450$ GeV	$1.12 \pm 0.04 \,^{+0.12}_{-0.13} \,^{+0.06}_{-0.07}$	0.78 (0.87)
$450 \leq m_{t\bar{t}} < 550$ GeV	$1.18 \pm 0.08 \,^{+0.13}_{-0.14} \,^{+0.13}_{-0.15}$	0.84 (1.1)
$550 \leq m_{t\bar{t}} < 800$ GeV	$1.65 \pm 0.19 \,^{+0.31}_{-0.41} \,^{+0.26}_{-0.33}$	1.2 (1.4)
$m_{t\bar{t}} \geq 800$ GeV	$2.2 \pm 0.9 \,^{+2.5}_{-1.7} \,^{+1.2}_{-1.5}$	0.49 (0.61)

- Large tension observed with the SM, at a (conservative) significance of 3.2σ.

- Conservative because of the MC-based uncertainties on the templates.

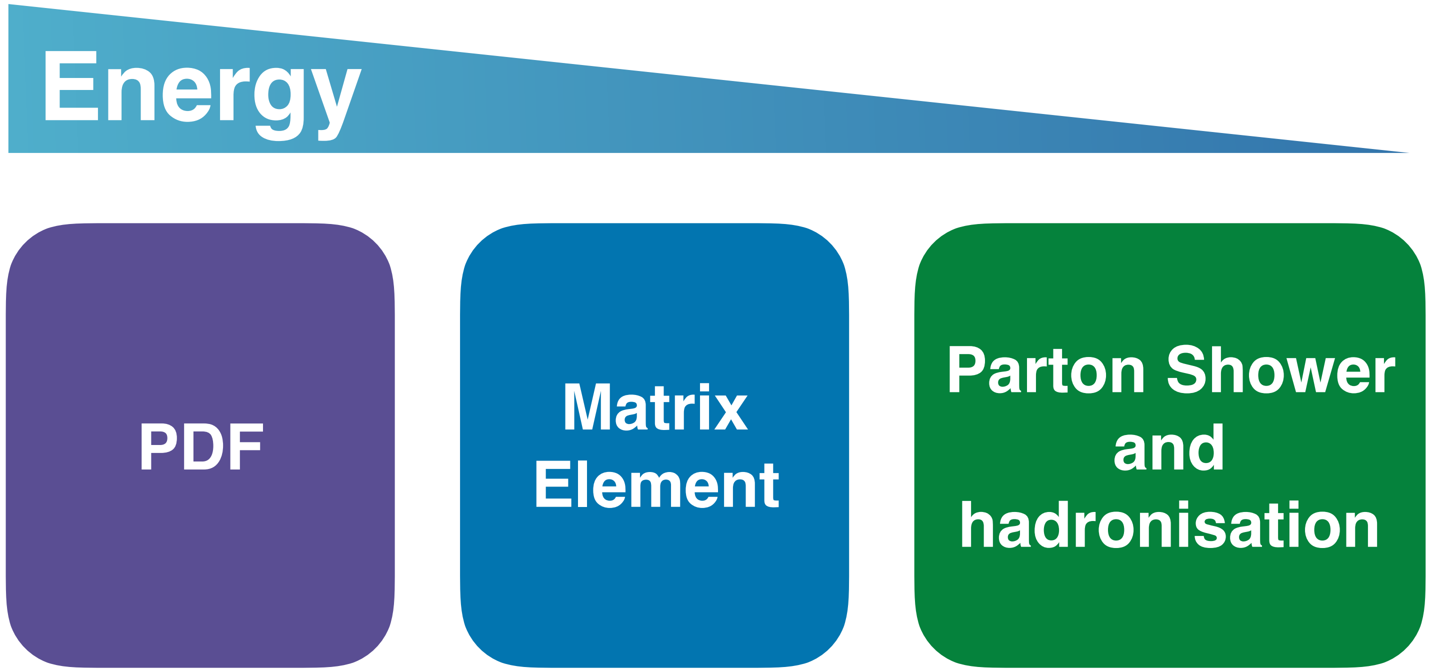
		$m_{t\bar{t}}$ range [GeV]			
Systematic	Inclusive	$m_{t\bar{t}} < 450$	$450 \leq m_{t\bar{t}} < 550$	$550 \leq m_{t\bar{t}} < 800$	$m_{t\bar{t}} \geq 800$
Matrix element	± 0.006	± 0.11	± 0.064	± 0.01	± 0.3
Parton shower and hadronisation	± 0.010	± 0.02	± 0.005	± 0.01	± 1.4
Radiation and scale settings	± 0.055	± 0.05	± 0.061	± 0.23	< 0.1
PDF	± 0.002	< 0.01	± 0.003	± 0.01	< 0.1
Background modelling	± 0.009	± 0.01	$^{+0.014}_{-0.015}$	± 0.01	± 0.1
Lepton ID and reconstruction	± 0.008	± 0.01	$^{+0.030}_{-0.036}$	$^{+0.03}_{-0.10}$	$^{+0.5}_{-0.2}$
b-tagging	$^{+0.004}_{-0.003}$	± 0.01	± 0.025	$^{+0.04}_{-0.02}$	$^{+0.1}_{-0.2}$
Jet ID and reconstruction	$^{+0.014}_{-0.017}$	$^{+0.02}_{-0.05}$	$^{+0.076}_{-0.093}$	$^{+0.17}_{-0.26}$	$^{+1.7}_{-0.6}$
$E_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction	< 0.001	$^{+0.01}_{-0.02}$	$^{+0.042}_{-0.034}$	$^{+0.12}_{-0.14}$	$^{+0.9}_{-0.7}$
Pile-up effects	$^{+0.013}_{-0.010}$	< 0.01	$^{+0.015}_{-0.019}$	$^{+0.07}_{-0.04}$	$^{+0.2}_{-0.4}$
Luminosity	± 0.001	< 0.01	$^{+0.002}_{-0.000}$	< 0.01	< 0.1
MC statistical uncertainty	± 0.005	< 0.01	± 0.007	± 0.03	± 0.05
Total systematics	± 0.061	$^{+0.12}_{-0.13}$	$^{+0.13}_{-0.14}$	$^{+0.31}_{-0.41}$	$^{+2.5}_{-1.7}$

- An aside on Monte Carlo:

Monte Carlo Sample

An aside on Monte Carlo:

- ➡ PDF choice
- ➡ Matching scheme
- ➡ Shower algorithm



Energy

PDF

Matrix Element

Parton Shower and hadronisation

- **NNPDF**
- **CT14**
- **MSTW**
- **AMB**

- **Powheg**
- **aMC@NLO**

- **Pythia8**
- **Herwig7**
- **DIRE**
- **Sherpa**

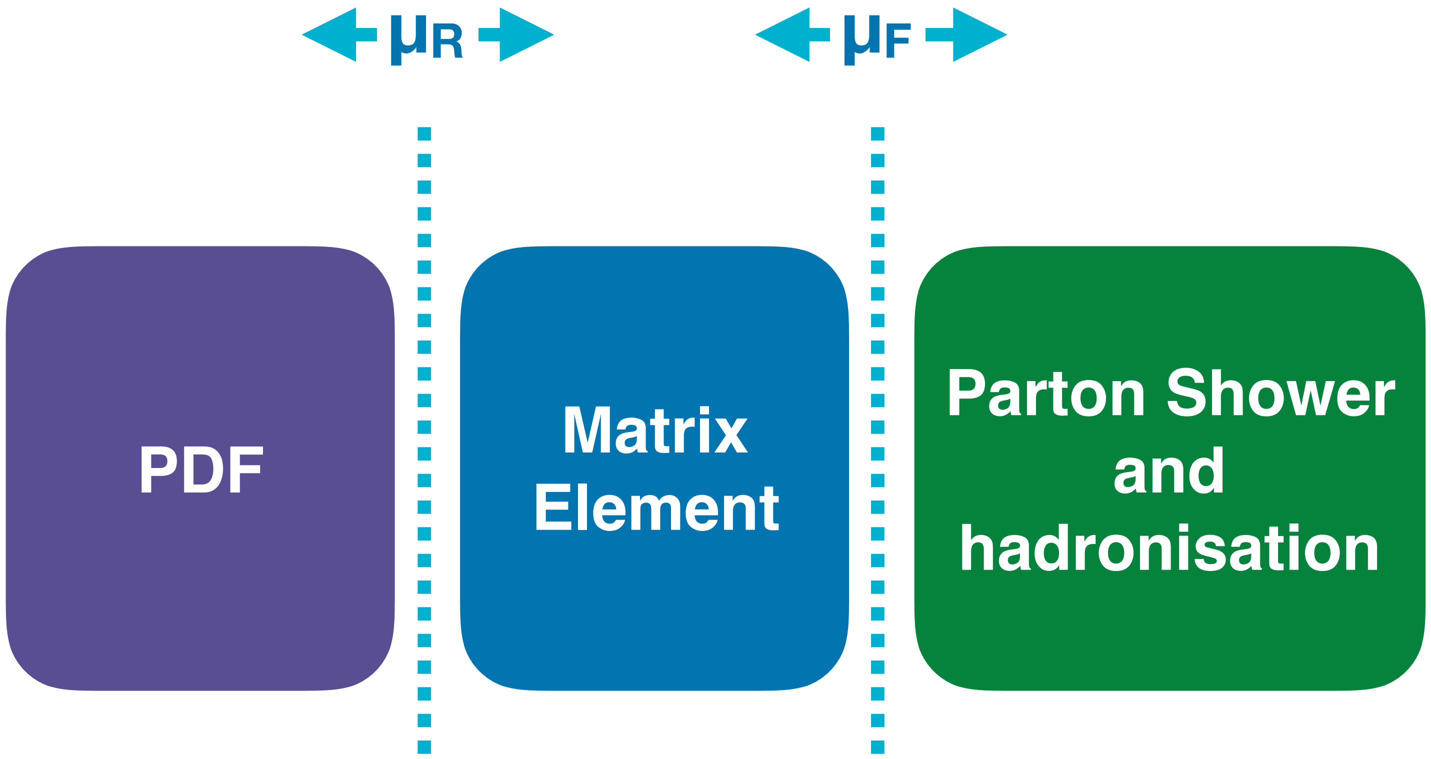
➡ PDF choice
➡ Matching scheme
➡ Shower algorithm
➡ Choice of α_s x 3

PDF

Matrix Element

Parton Shower and hadronisation

• α_s ≠ • α_s ≠ • α_s



μ_R μ_F

PDF

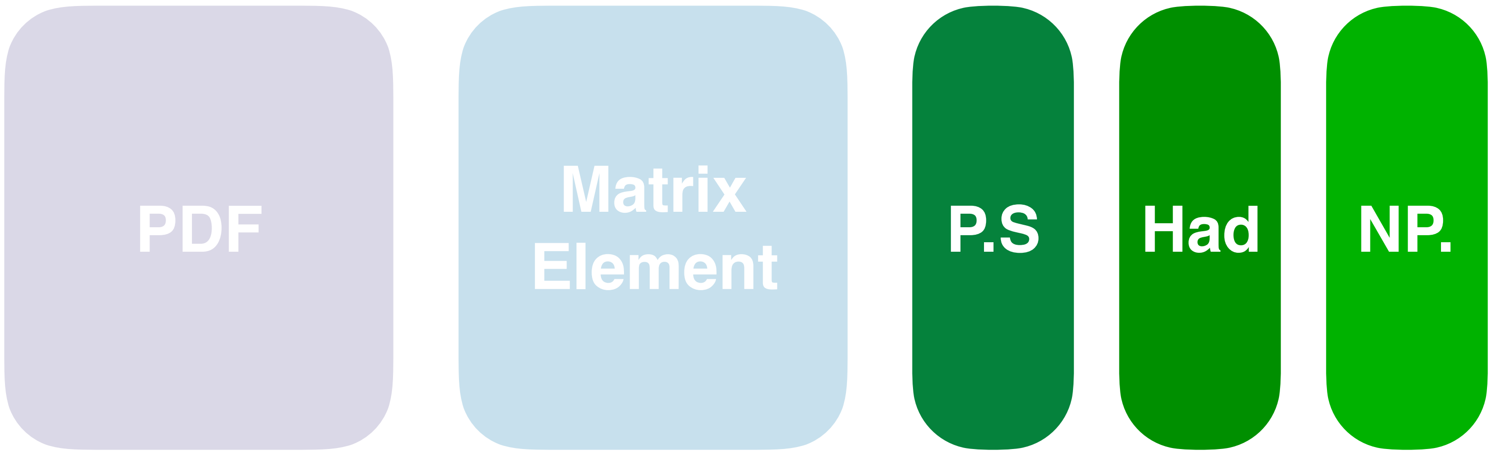
Matrix Element

Parton Shower and hadronisation

- ➡ PDF choice
- ➡ Matching scheme
- ➡ Shower algorithm
- ➡ Choice of α_S x 3
- ➡ μ_R/μ_F values
- ➡ μ_R/μ_F func. Form
- ➡ Shower scale
- ➡ Shower sc. form
- ➡ hdamp* (Powheg)

- **Q**
- **hdamp**
- **Starting scale**

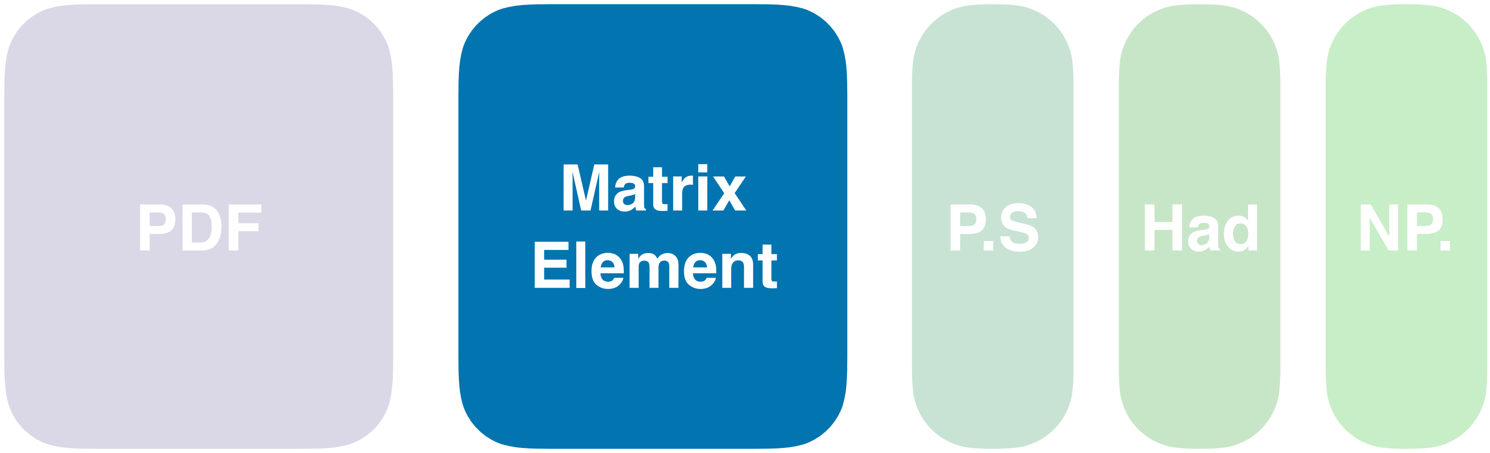
- **Colour reconnection model?**
- **MPI tune?**



- **Lund string model or cluster model?**
- **pT ordered shower vs angular ordered?**

➡ PDF choice
➡ Matching scheme
➡ Shower algorithm
➡ Choice of α_S x 3
➡ μR/μF values
➡ μR/μF func. Form
➡ Shower scale
➡ Shower sc. form
➡ hdamp* (Powheg)
➡ pT vs angular
➡ String vs. cluster
➡ UE tune
➡ CR model

- **NLO only in production, LO in decay**


PDF

Matrix Element

P.S

Had

NP.

- **Production and decay factorised with narrow-width-approximation**

- ➡ PDF choice
- ➡ Matching scheme
- ➡ Shower algorithm
- ➡ Choice of α_S x 3
- ➡ μR/μF values
- ➡ μR/μF func. Form
- ➡ Shower scale
- ➡ Shower sc. form
- ➡ hdamp* (Powheg)
- ➡ pT vs angular
- ➡ String vs. cluster
- ➡ UE tune
- ➡ CR model
- ➡ Precision in decay
- ➡ N.W.A.

- An aside on Monte Carlo:
  - NLO only in production, LO in

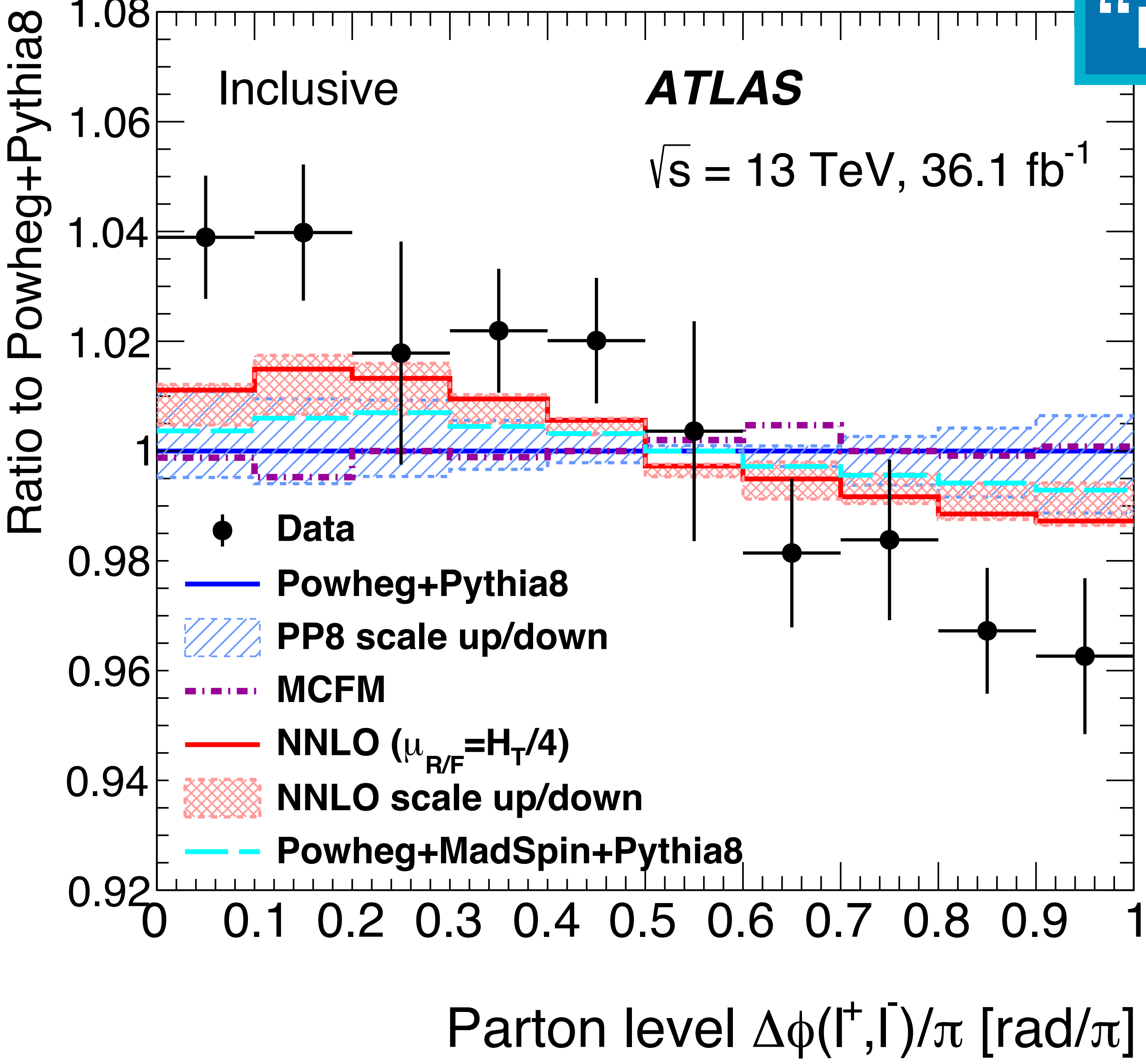
- **Take away message here is that MC are extremely complex and not magic black boxes…**

- **Understanding these limitations is crucial for precision measurements**

with narrow-width-approximation

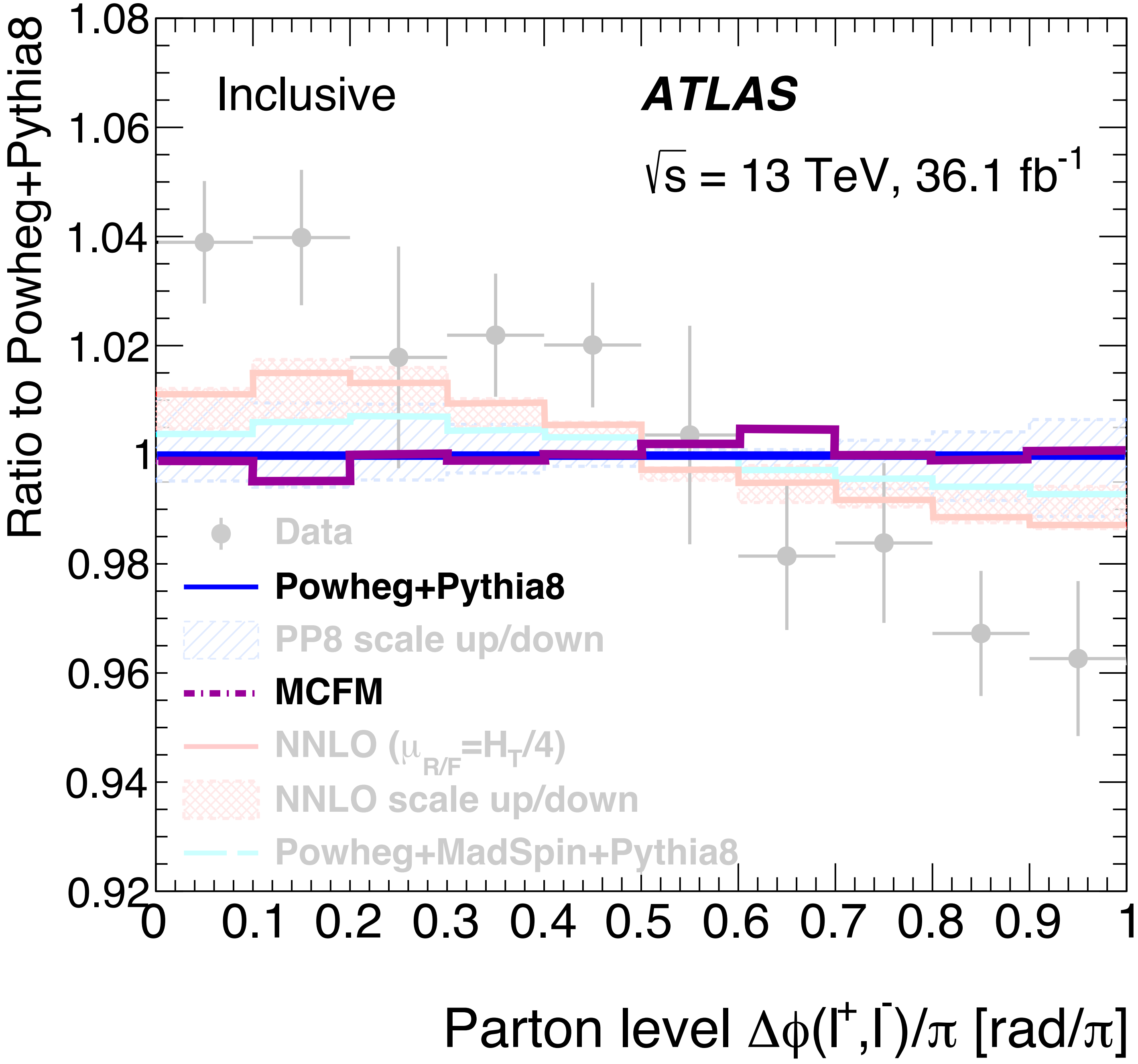
- ➡ PDF choice
- ➡ Matching scheme
- ➡ Shower algorithm
- x 3
- Form
- e
- orm
- heg)
- ster
- ➡ Precision in decay
- ➡ N.W.A.

- **Understanding the Run2 result**

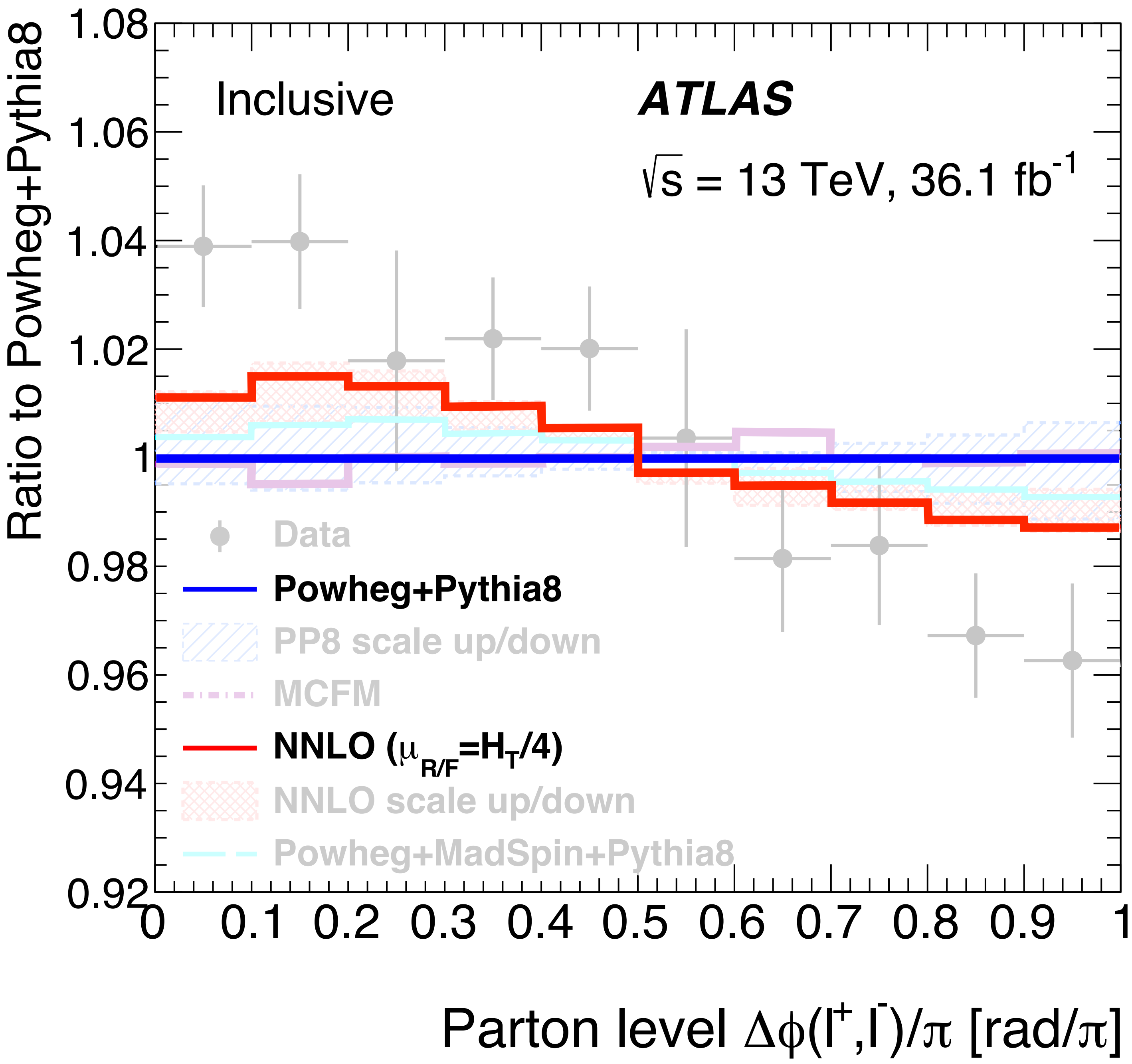


“new”

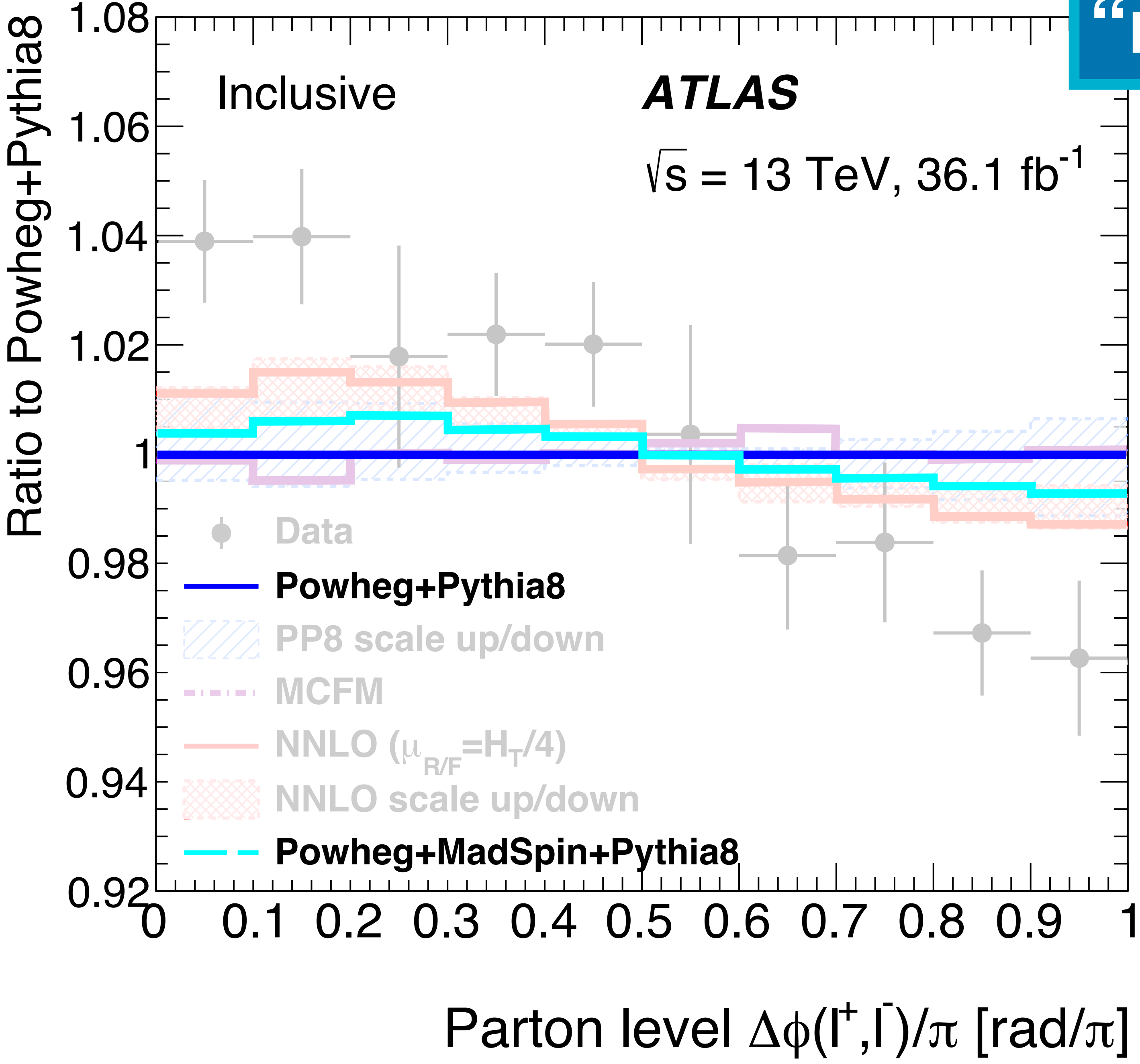
- # Is our NLO MC correct?



- **Higher orders (in production help), but not completely**

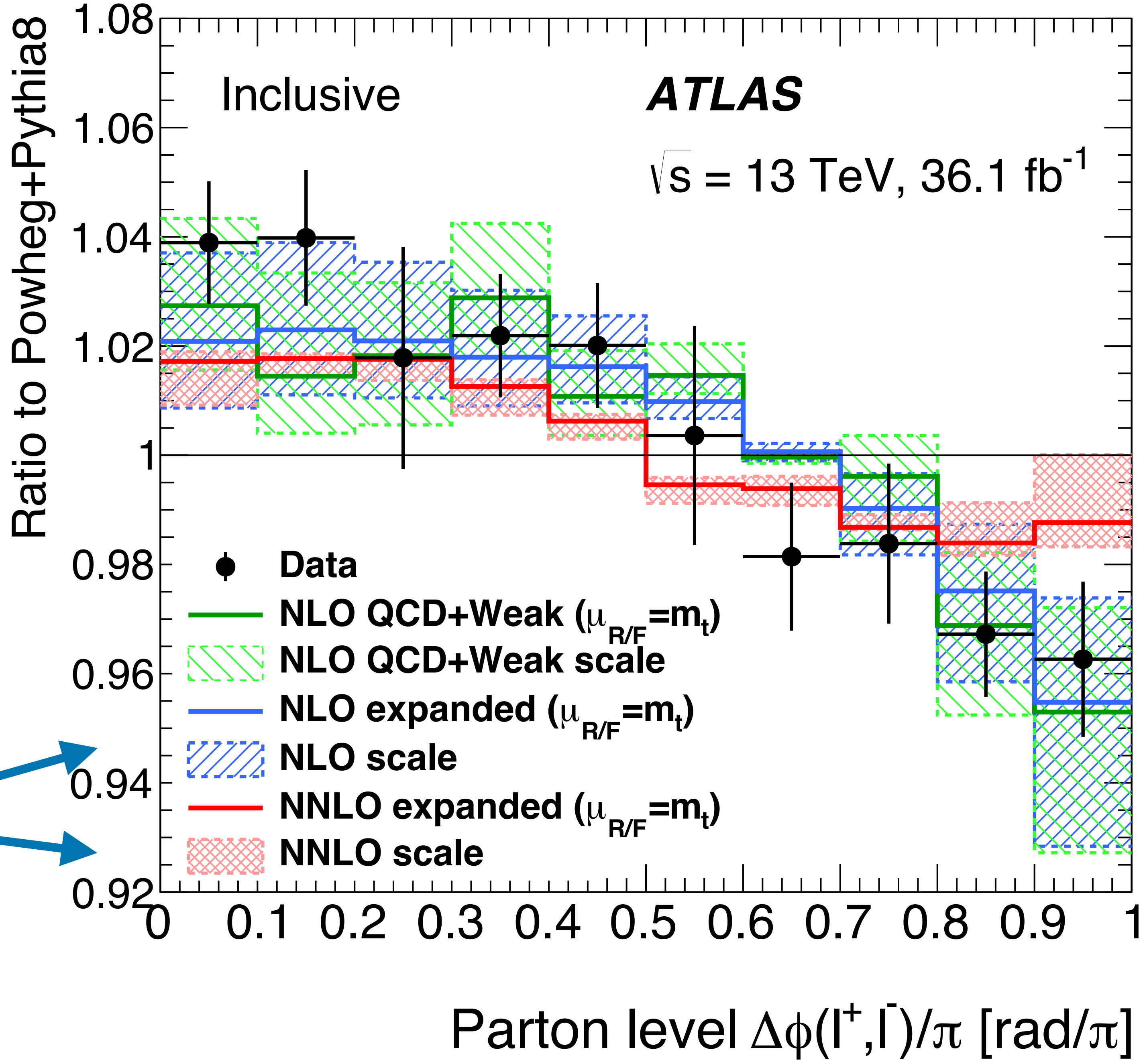


- **Also, how tops are decayed plays a role**



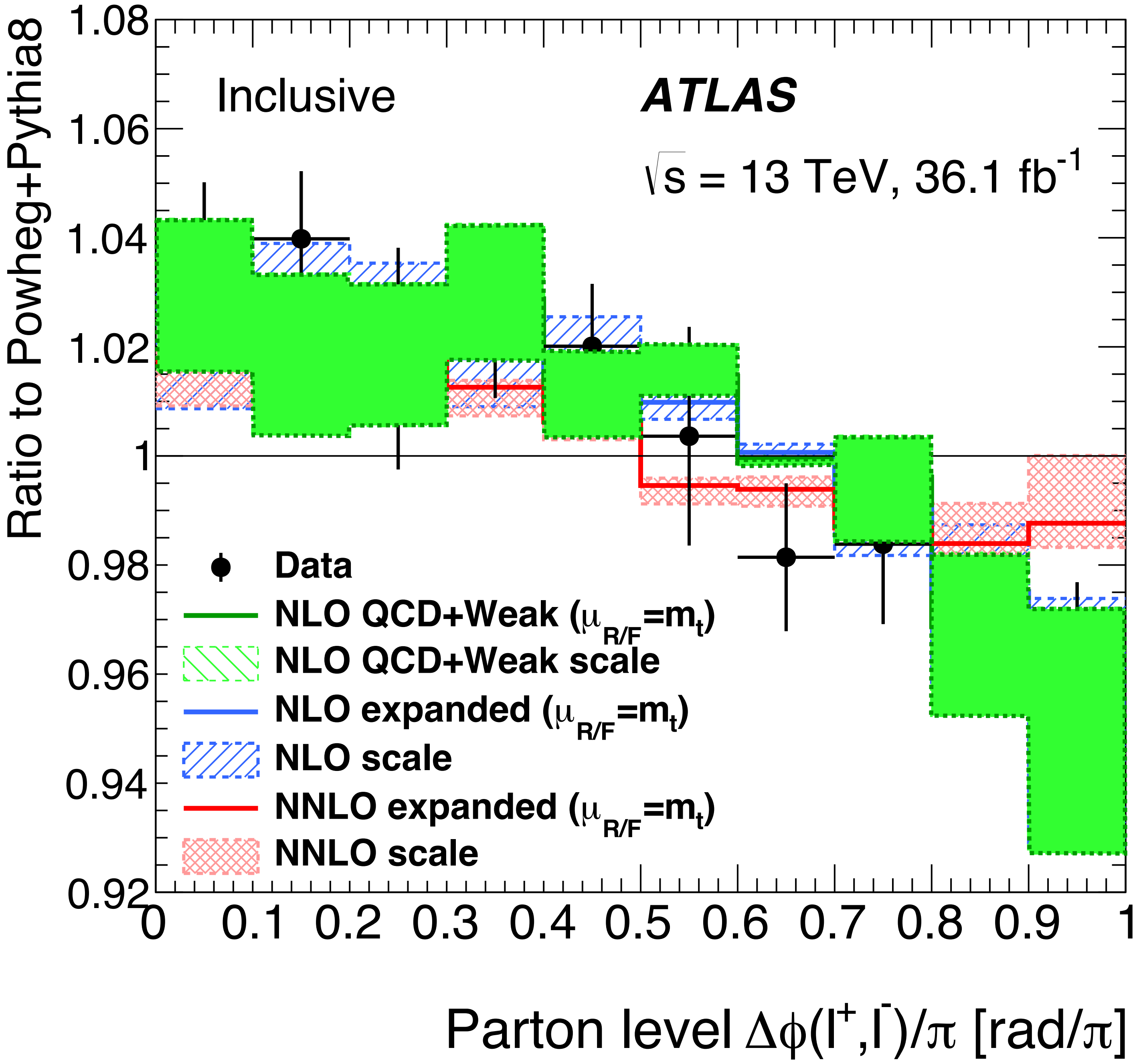
“new”

- **A new kind of calculation looks better, however…**

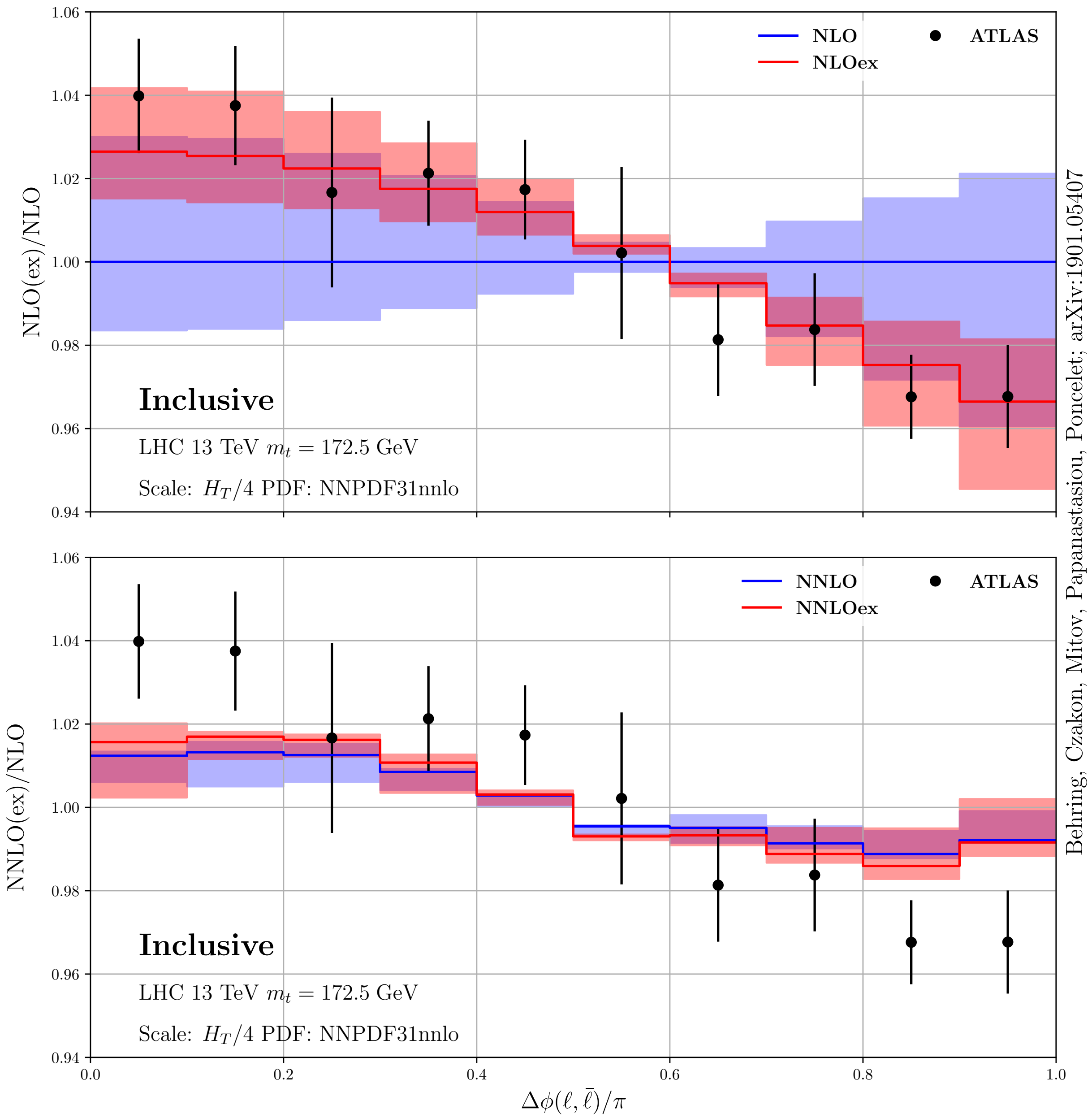


“new”

- **A new kind of calculation looks better, however…**



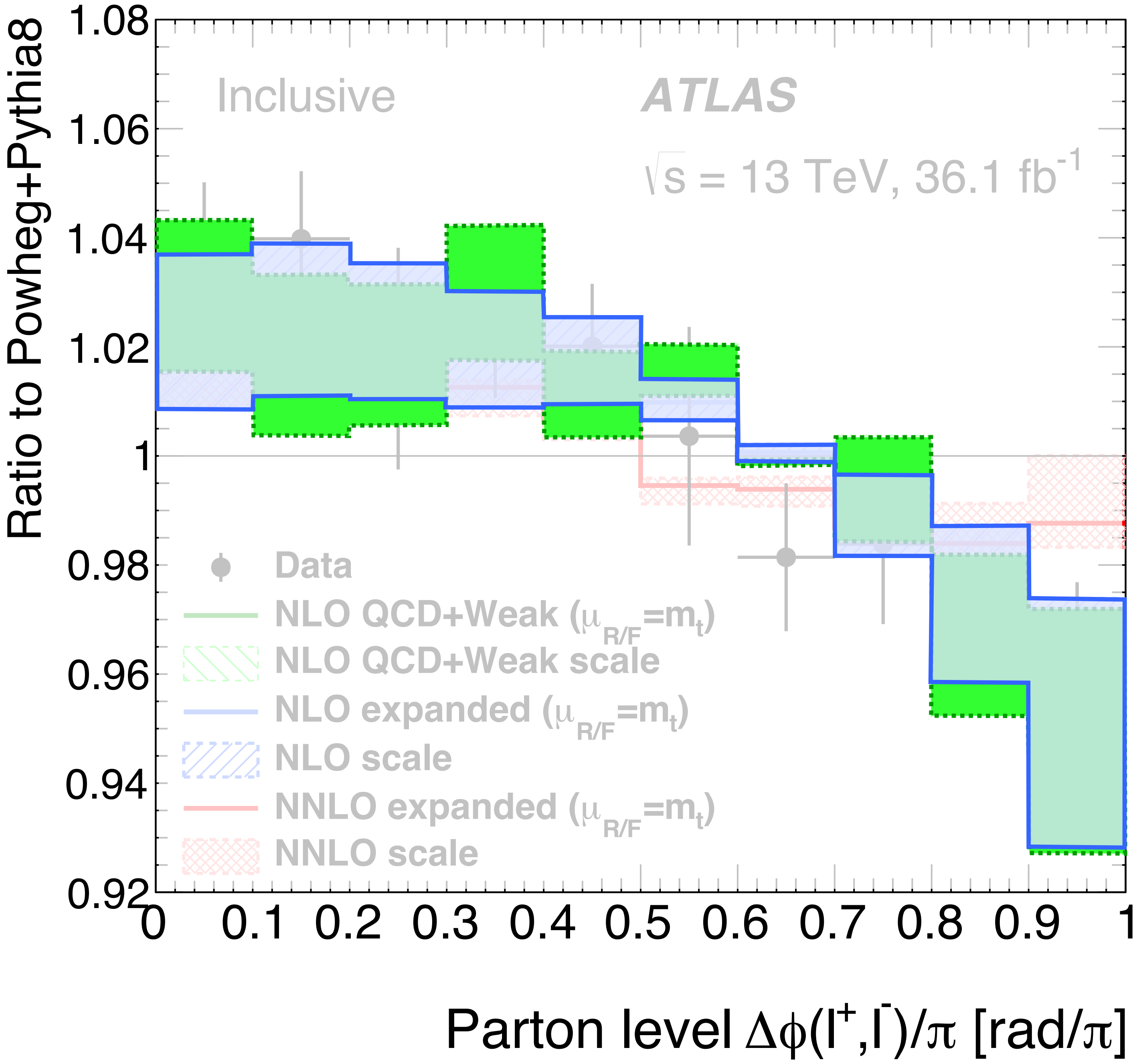
- **Improvement disappears at NNLO**



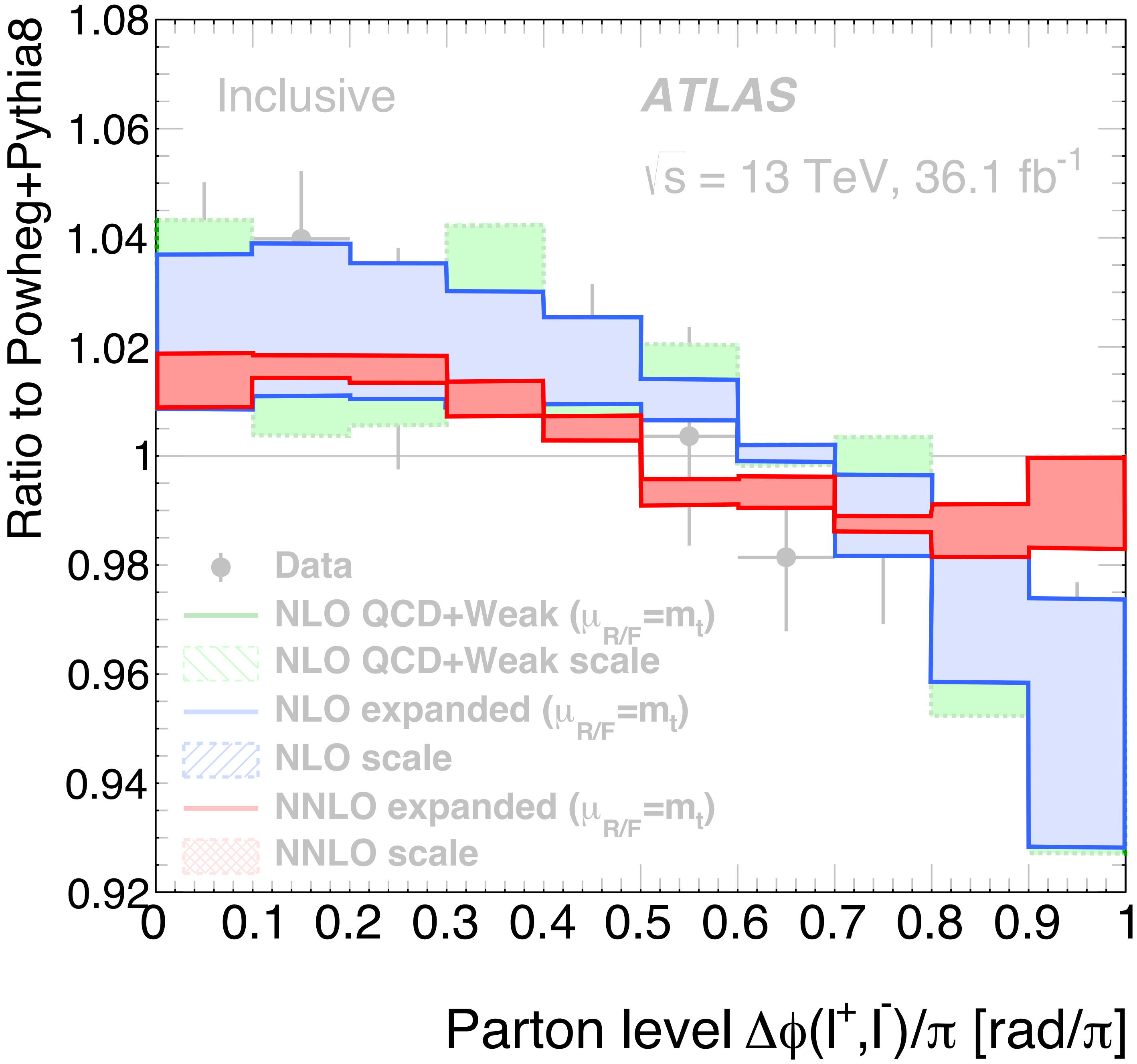
Behring, Czakon, Mitov, Papanastasiou, Poncelet; arXiv:1901.05407

More details on this ratio expansion (**link**)

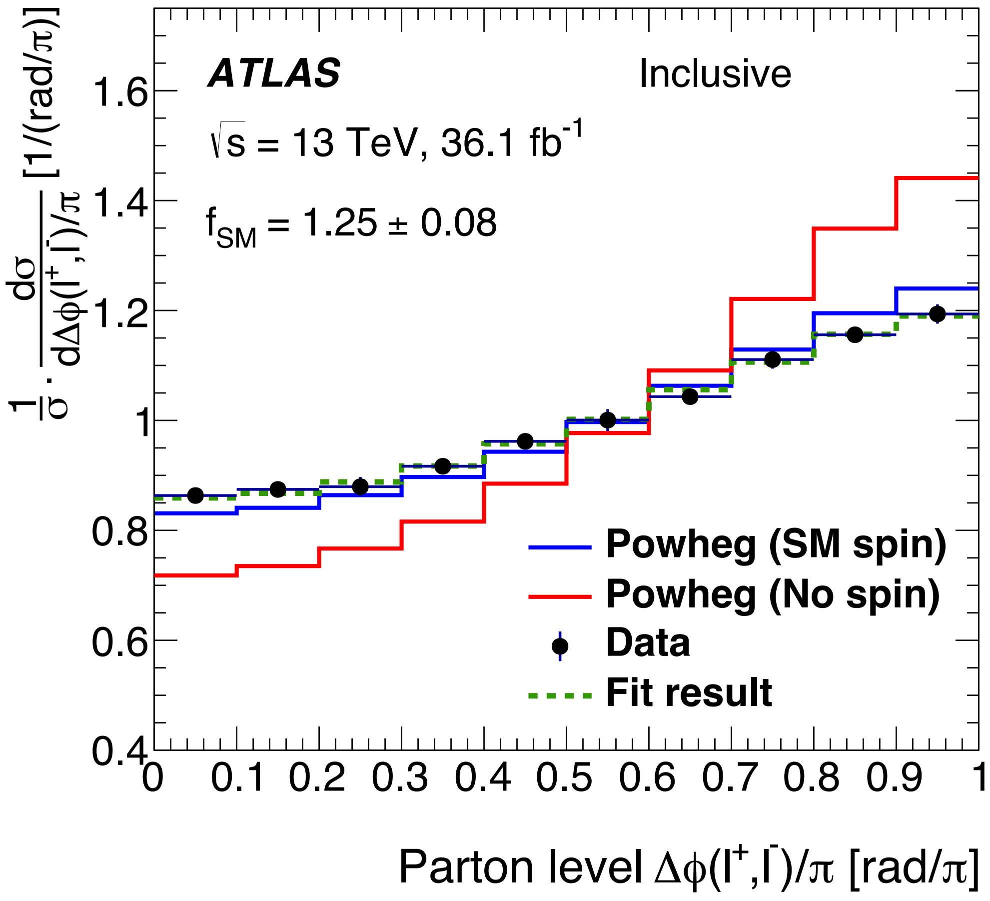
- **New calculation not well-behaved**

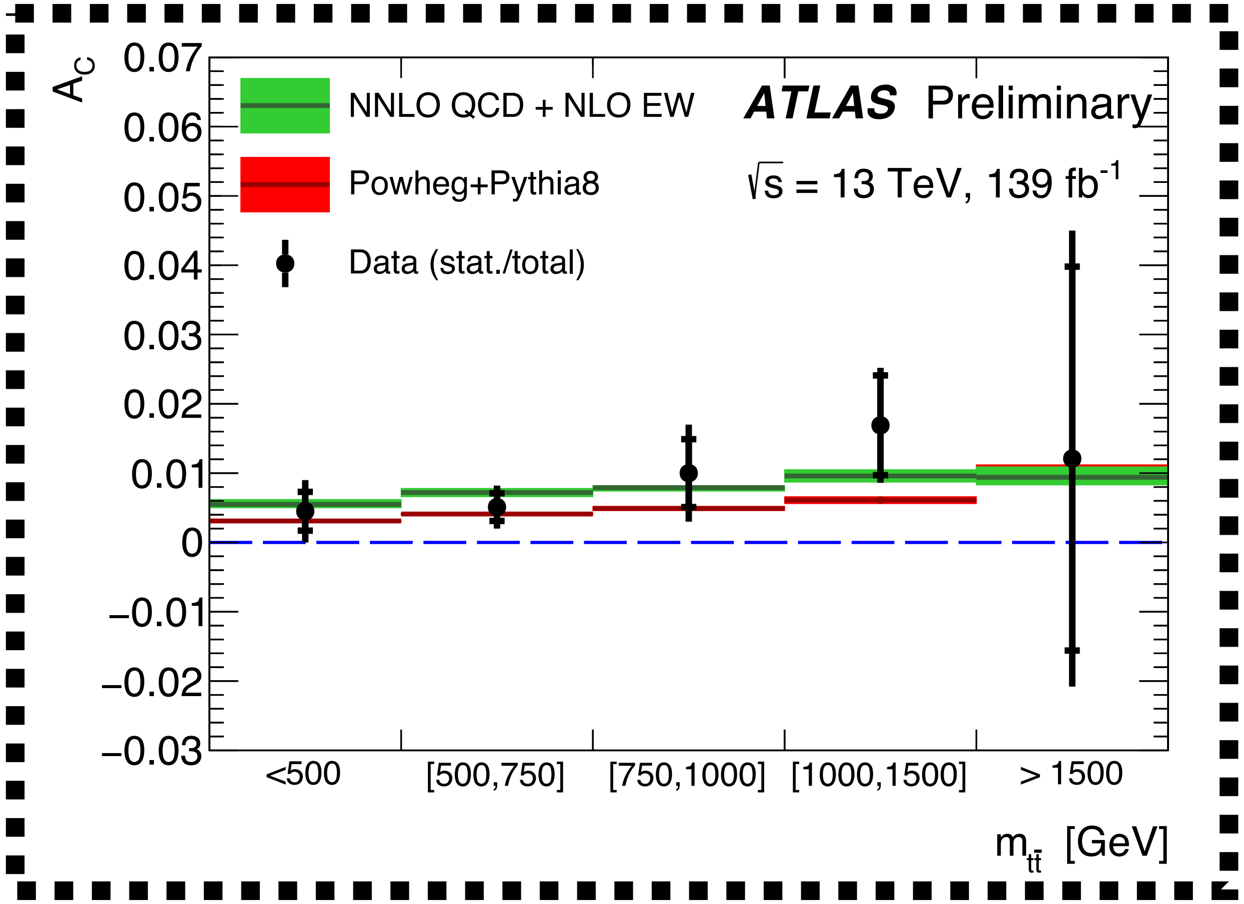


- **New calculation not well-behaved**



- **Recent analysis has an interesting way of tackling these modelling issues:**





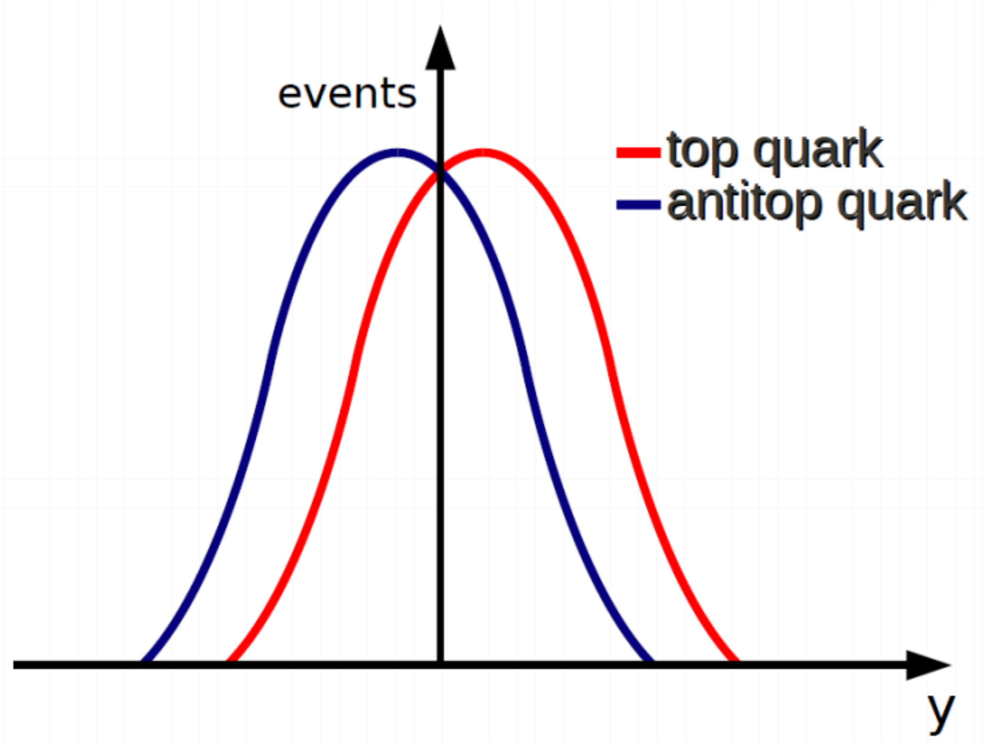
Spin Correlation

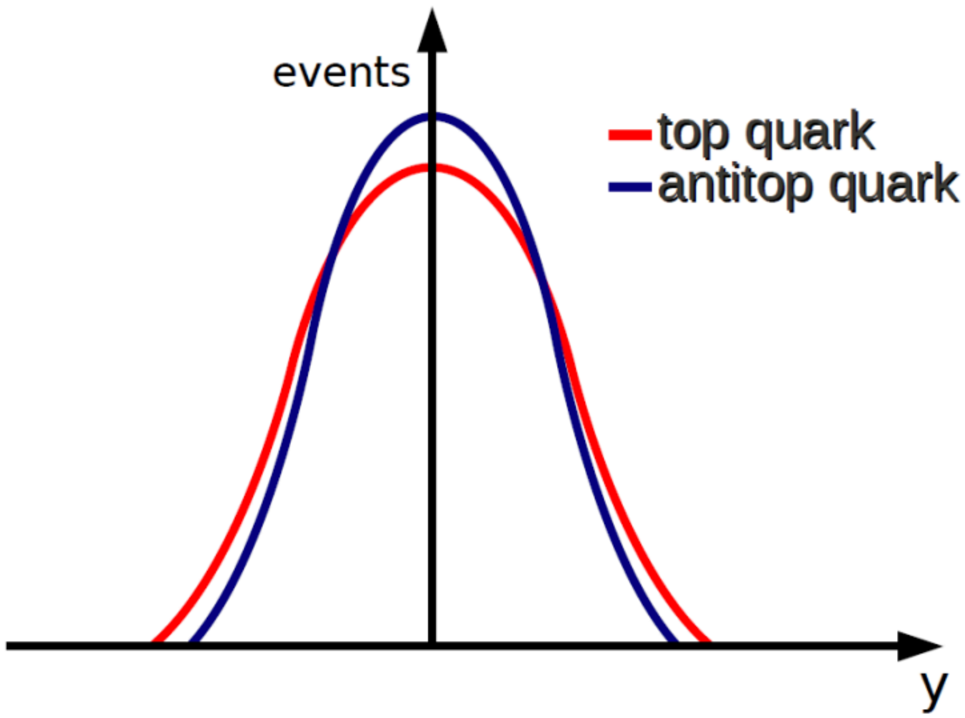
(TOPQ-2016-10)

Charge Asymmetry

(ATLAS-CONF-2019-026)

• Charge asymmetry

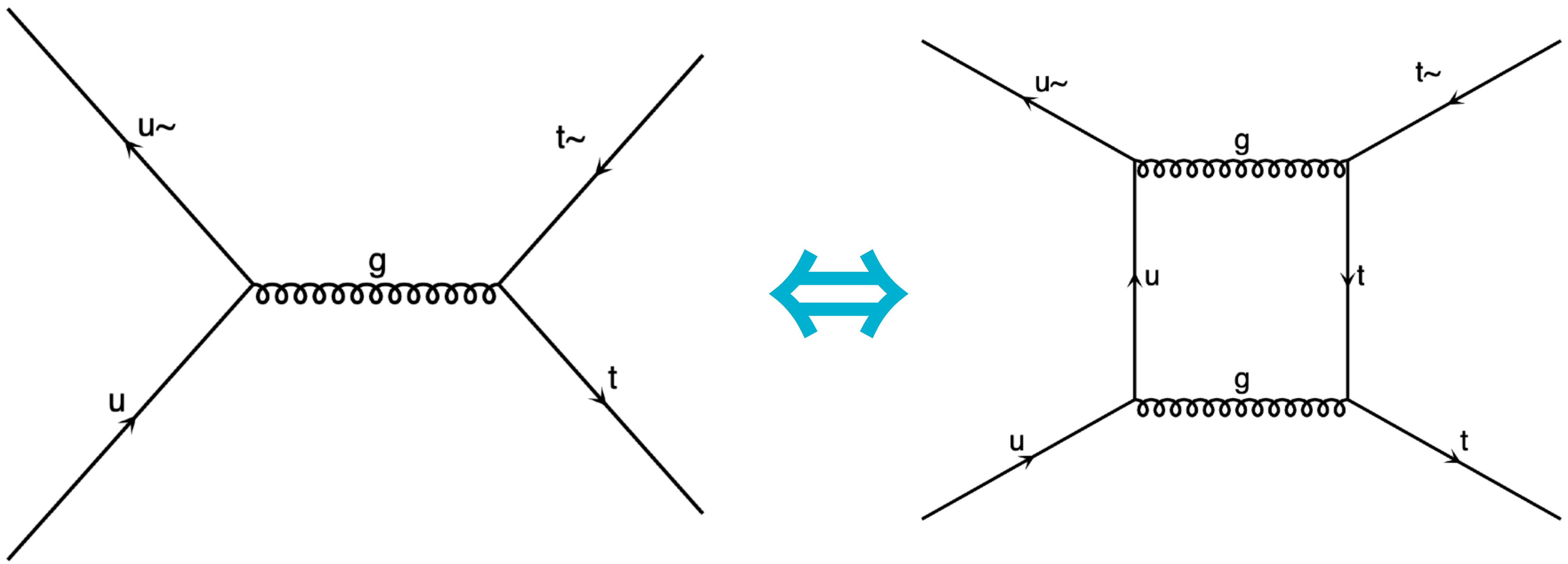




$$A_{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)} = 0.087(10)$$

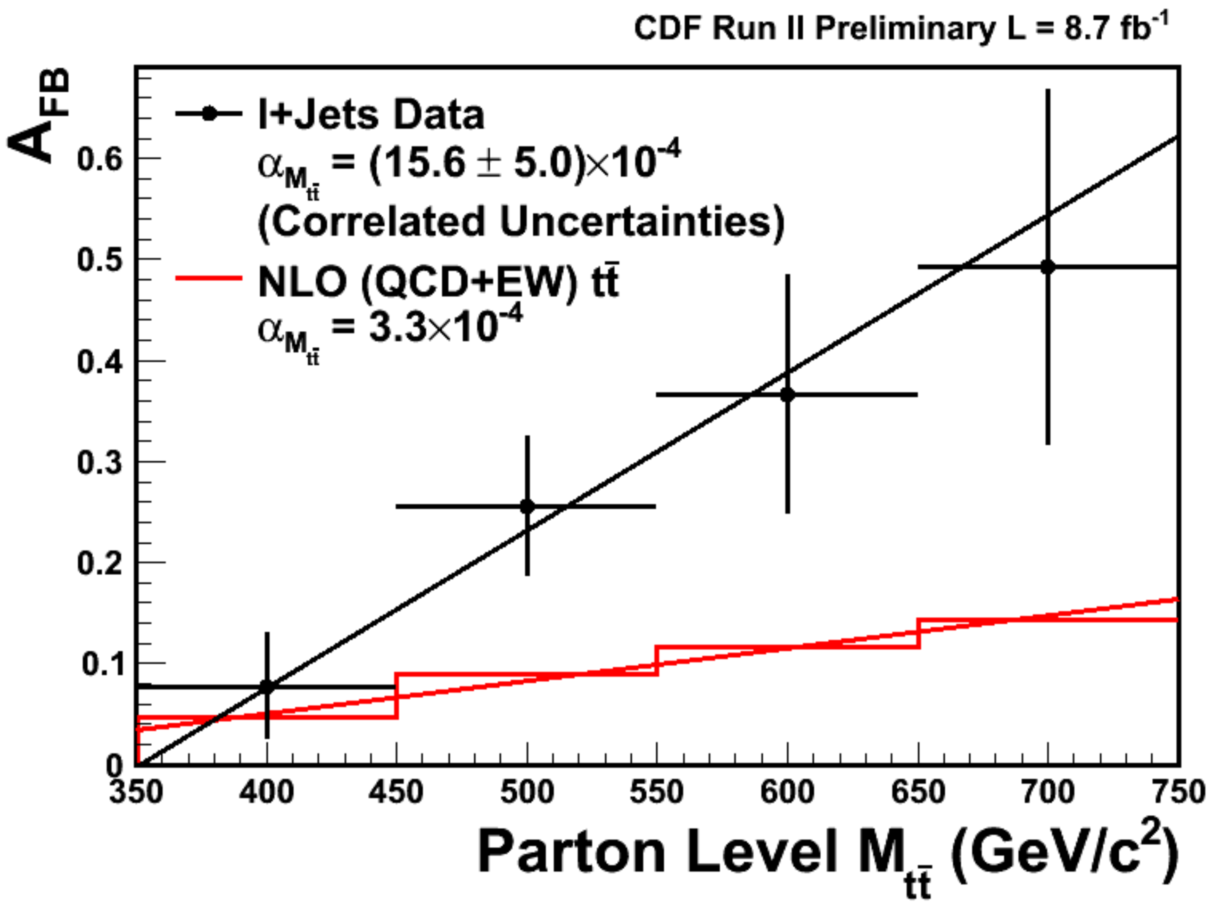
$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)} = \begin{cases} 0.0115(6)@7\text{TeV} \\ 0.0102(5)@8\text{TeV} \\ 0.0059(3)@14\text{TeV} \end{cases}$$

- Higher order effects in $t\bar{t}$ production mean:
  - ➡ Top prefers direction of incoming q
  - ➡ Anti-top prefers direction of qbar

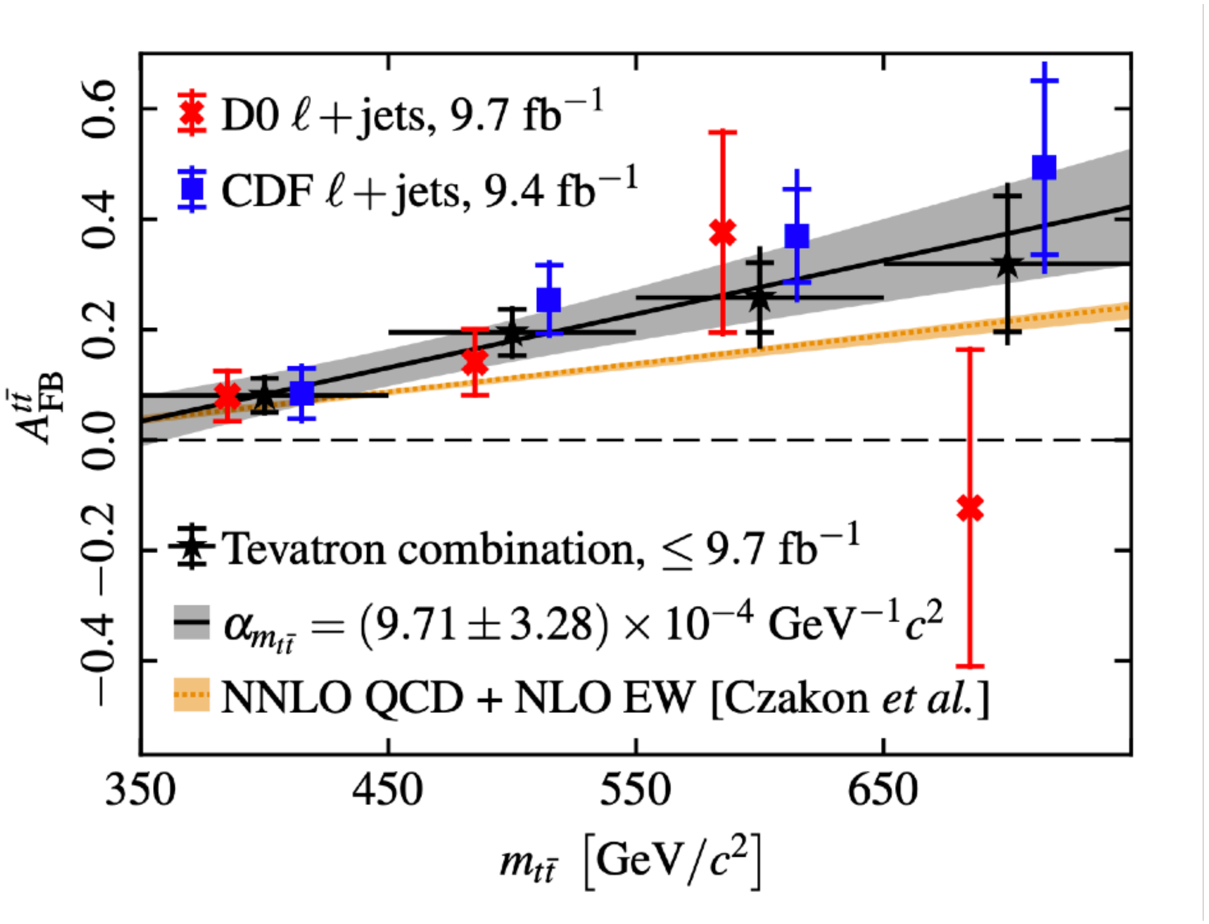


- **Majority of the effect comes from interference between born and box diagrams in qqbar annihilation.**

The infamous Tevatron result

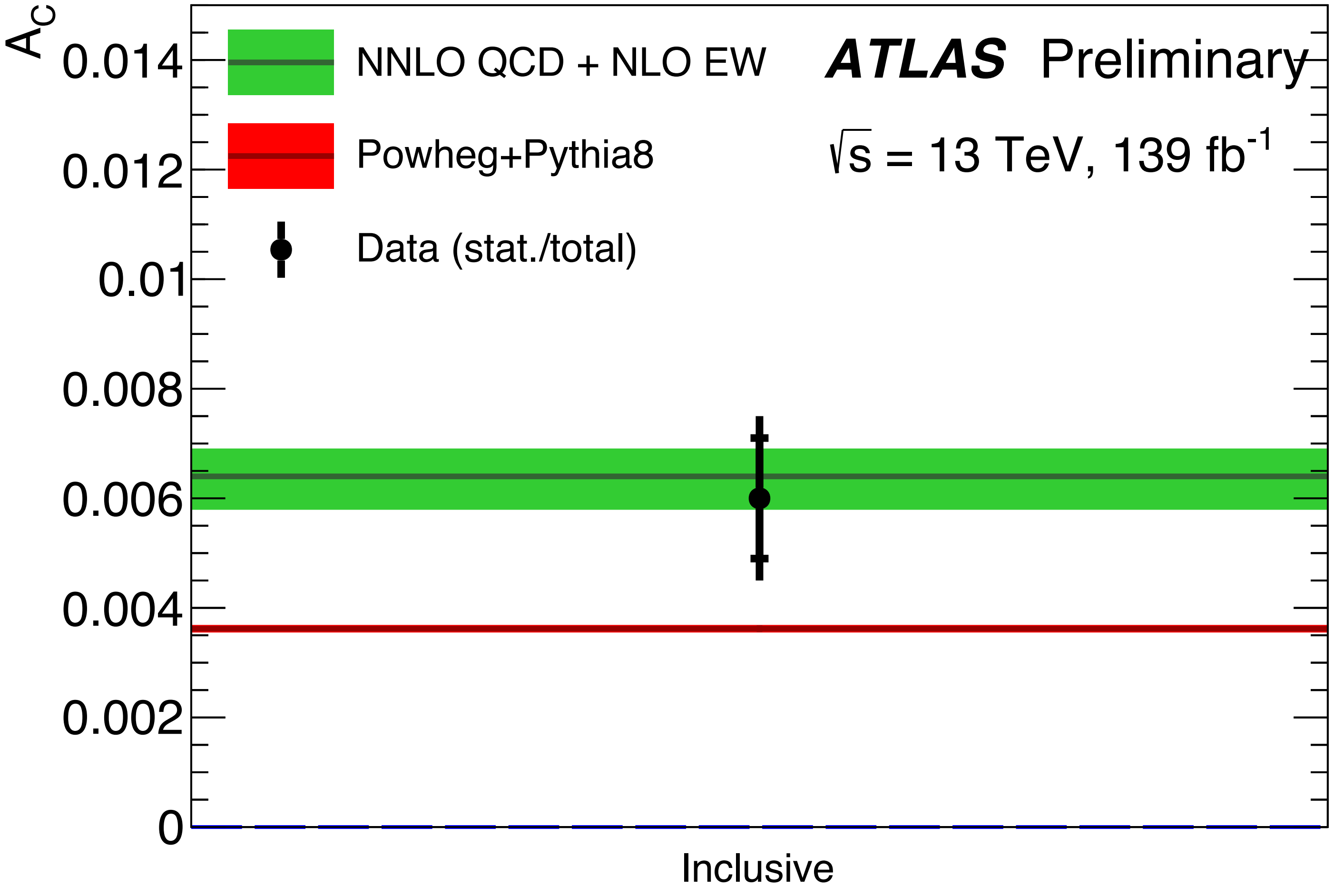


*The CDF Collaboration, Conf. Note 10807 (2012).

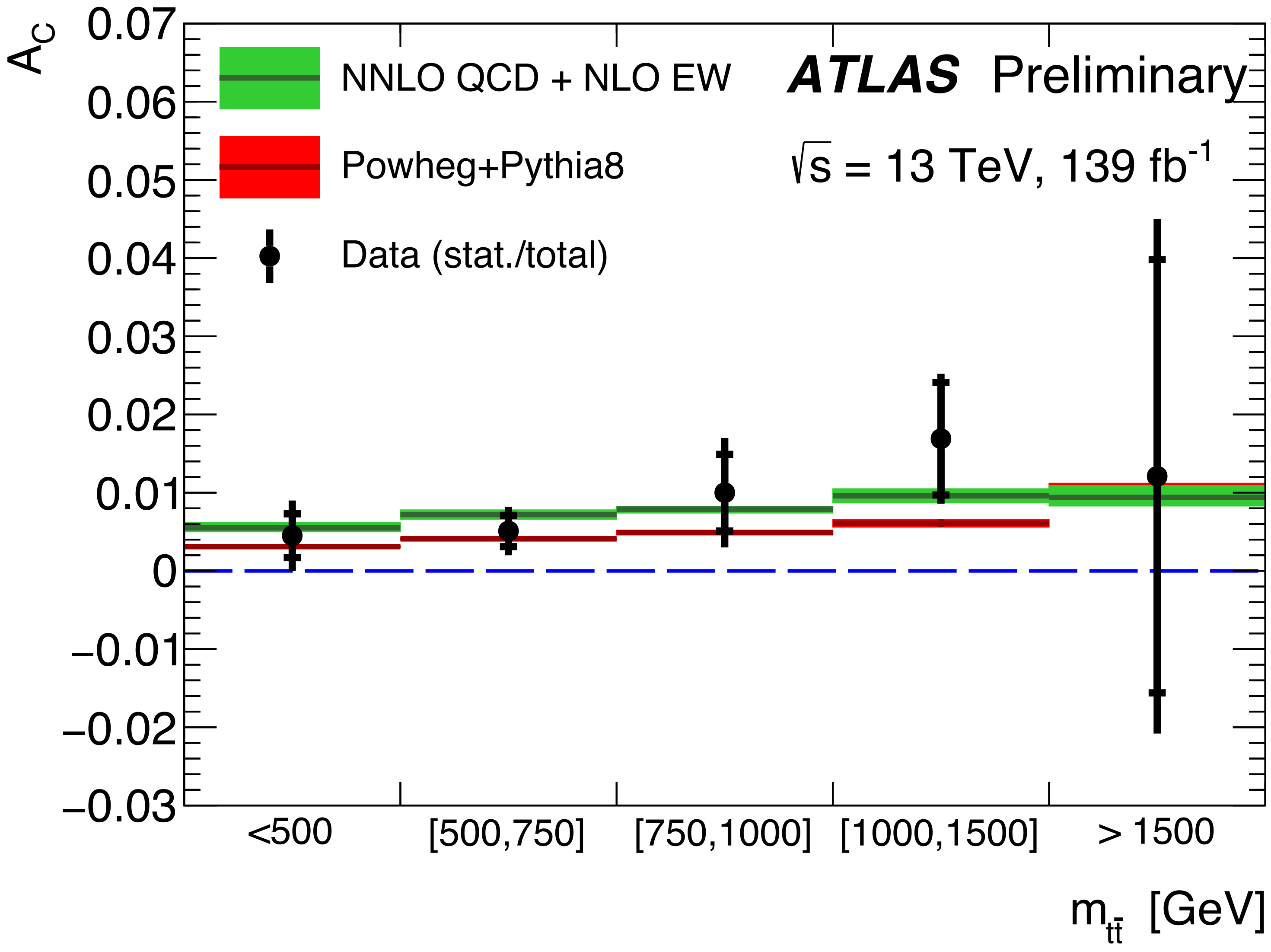


- **Fun feature of top physics: NNLO usually very important!**

- The latest attempt by ATLAS

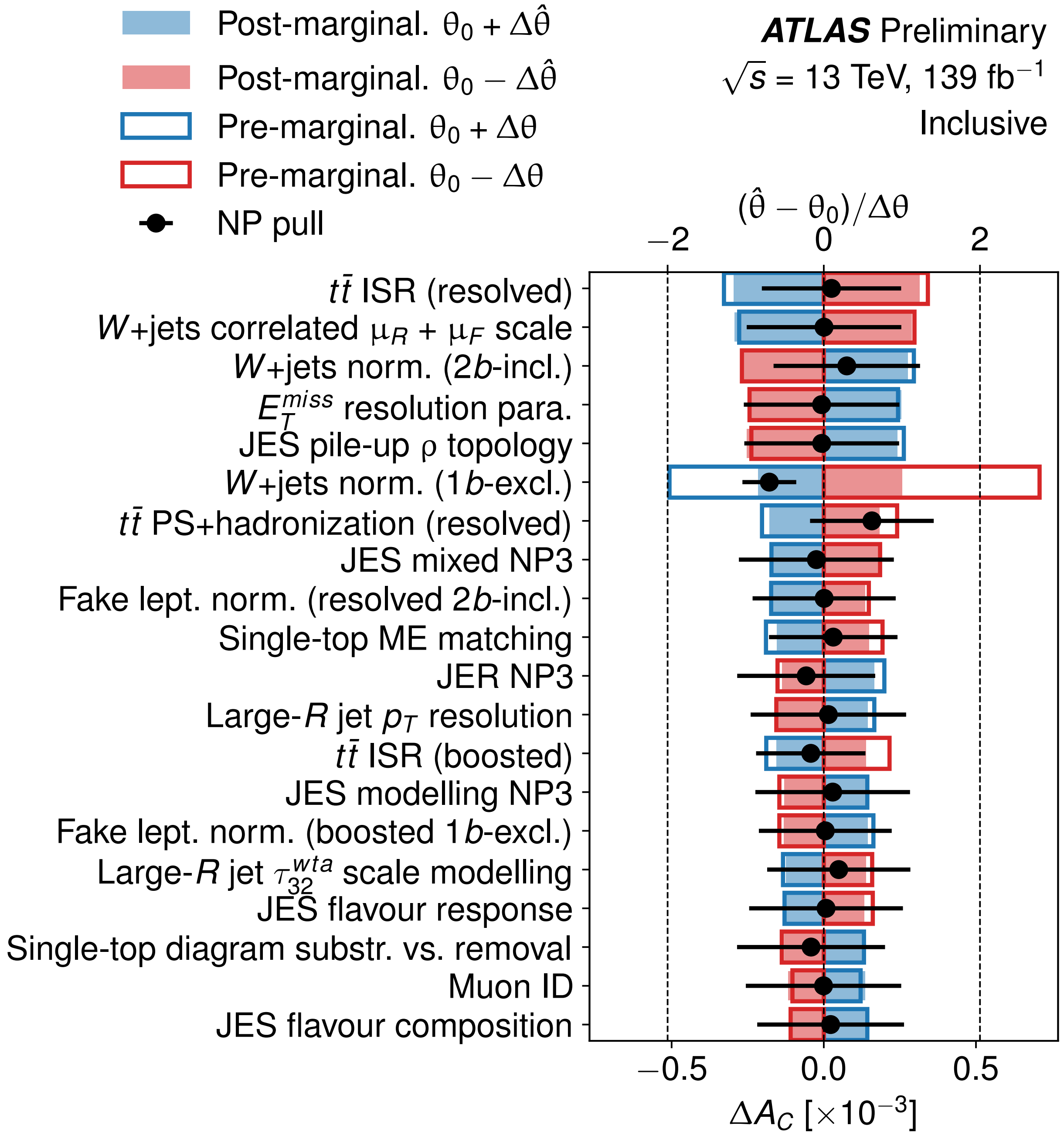


- Strongly disfavours no charge asymmetry:
  ➡ Huge achievement for a pp collider!

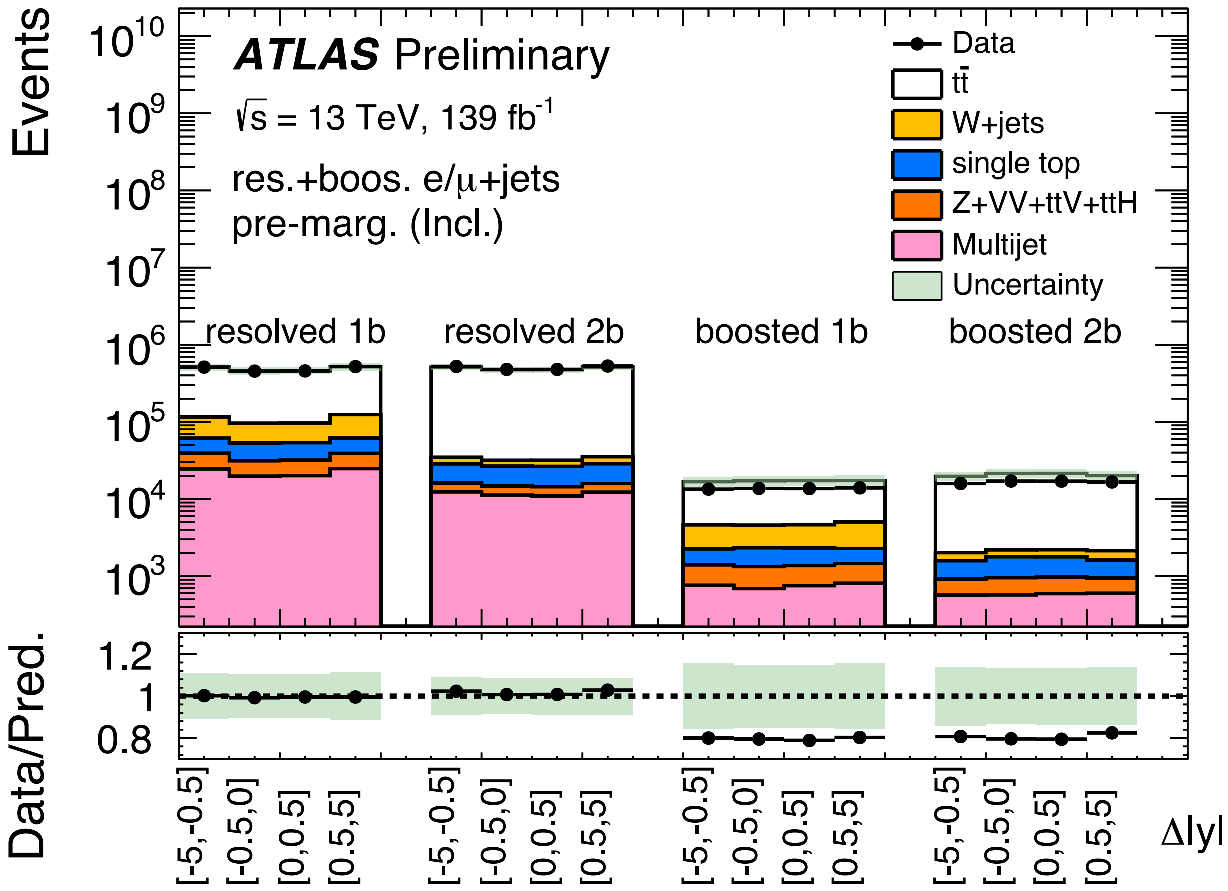


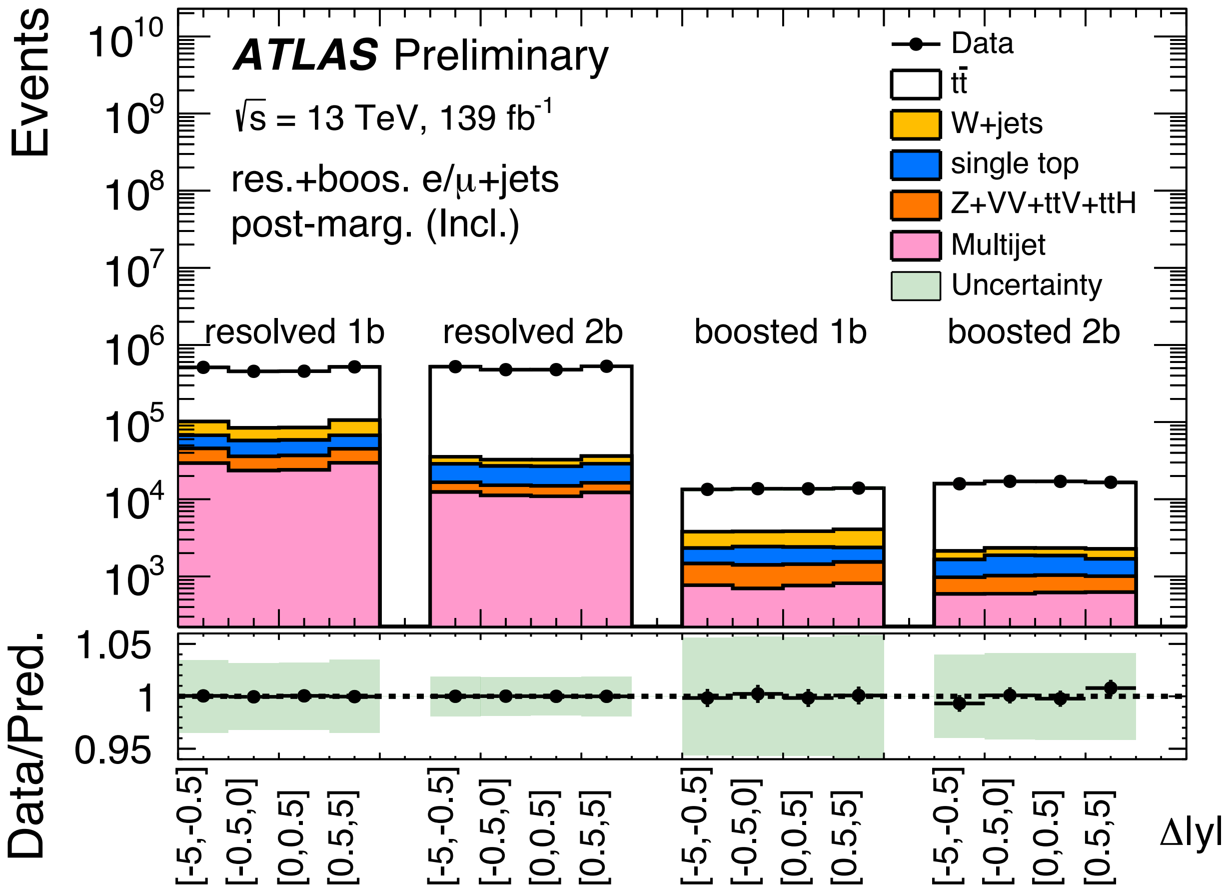
- **Even more striking differentially.**
- **Can see that the asymmetry gets larger at higher m($t\bar{t}$)**

- **How did this analysis achieve such precision?**
- **This analysis makes use of a likelihood-based unfolding.**
- **Modelling uncertainties can be treated as nuisance parameters and constrained.**



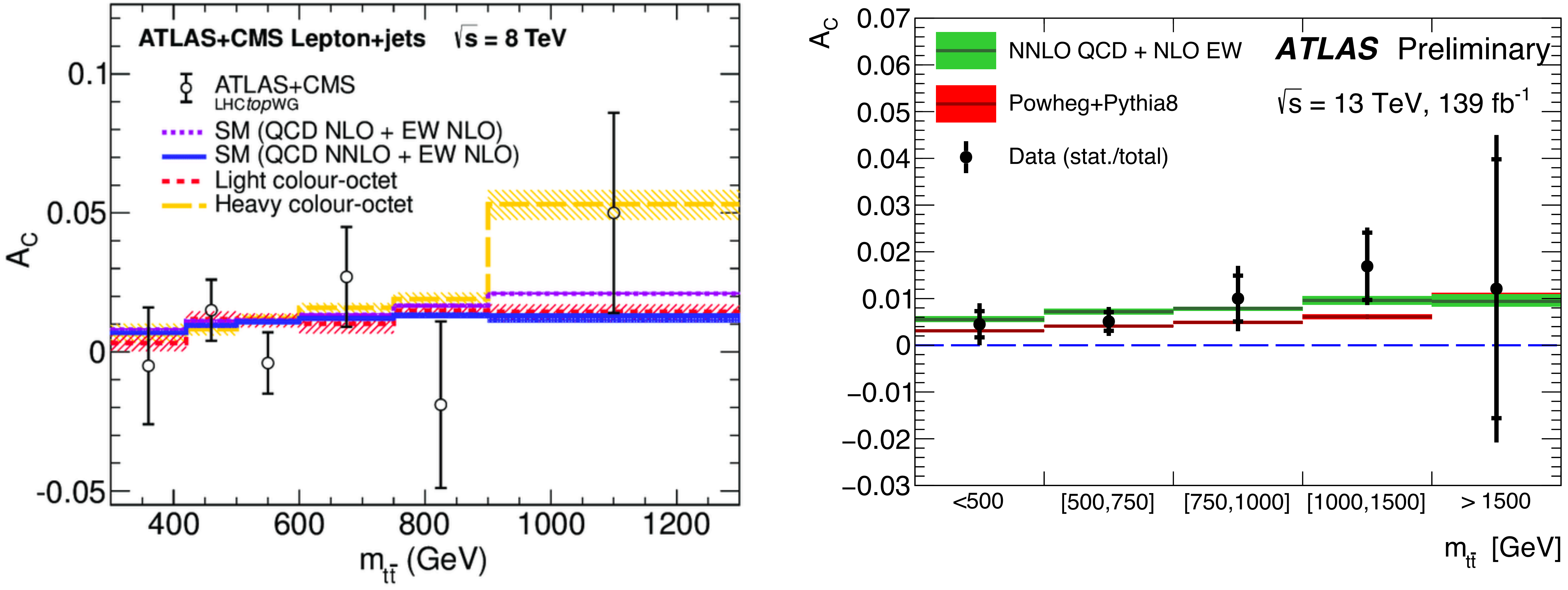
- **Profiling allows the data to constrain the uncertainties**





- **Often results in significantly reduced systematic uncertainties (note the scales on the ratio plots).**

- **Massive improvement, compared to Run1**



- **Isn't (just) from increased statistics (signal actually gets smaller), it's from improved analysis techniques.**

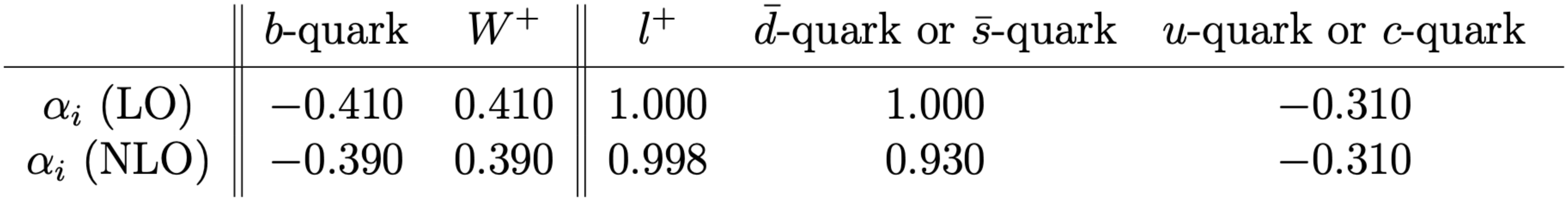
- **So, is the spin correlation result new physics?**

- **Not possible to say, we simply don't understand the SM well enough** (not in theory nor MC)

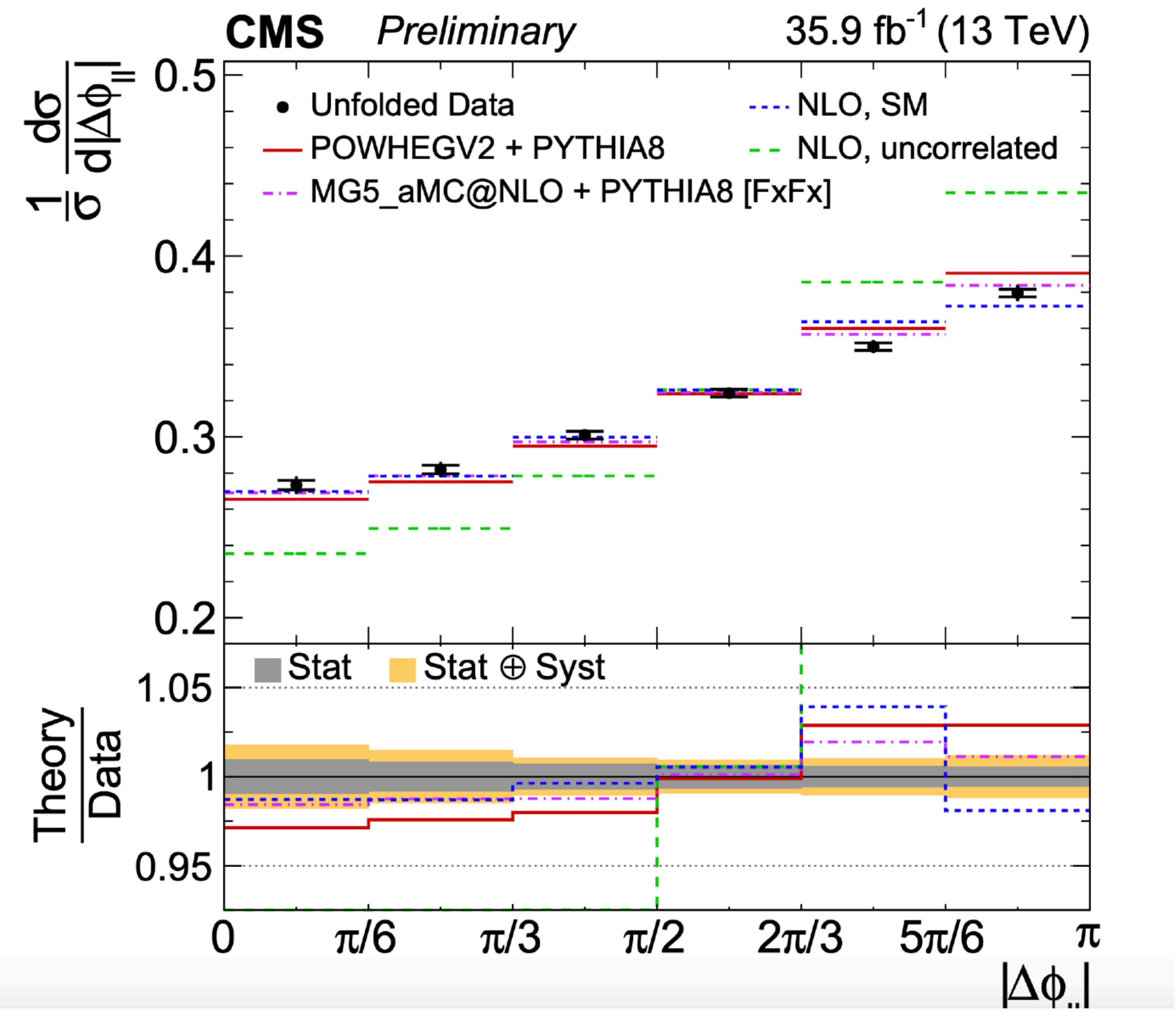
- **We are sensitive enough to see charge asymmetry** (with advanced techniques)**.**

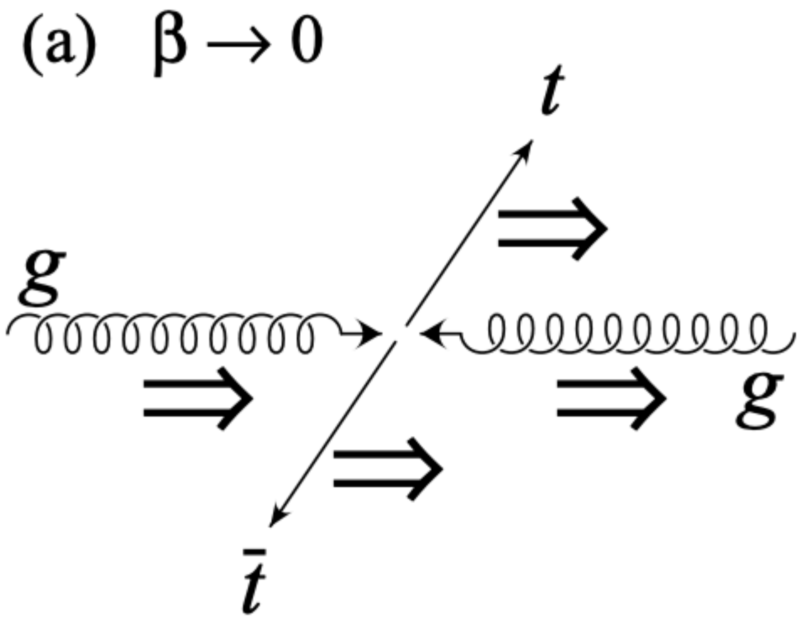
- **If new physics is subtle** (and not some obvious bump) **understand results and spectra like these is crucial, otherwise <u>we could write-off new physics as modelling!</u>**

Backup

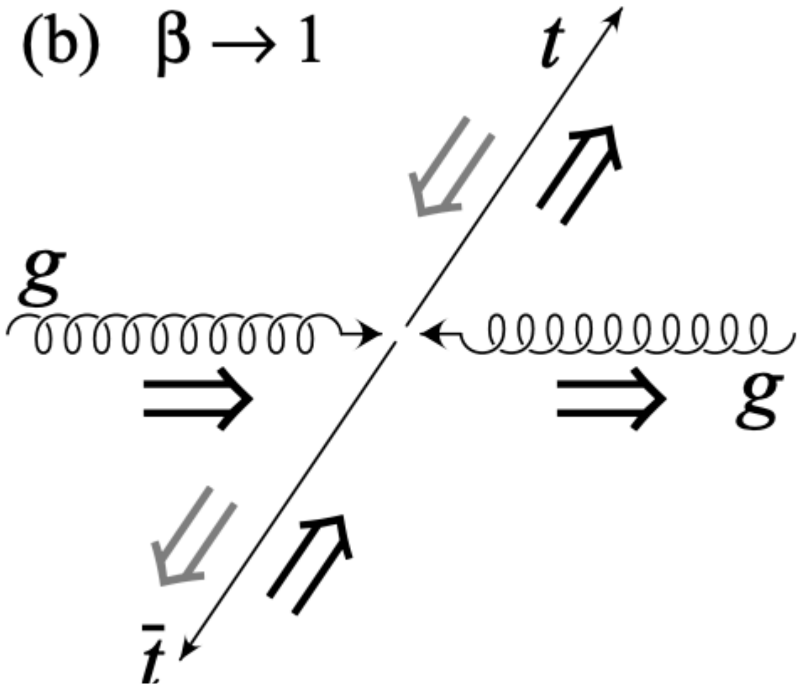


	b-quark	W^+	l^+	$\bar{d}$-quark or $\bar{s}$-quark	u-quark or c-quark
α_i (LO)	-0.410	0.410	1.000	1.000	-0.310
α_i (NLO)	-0.390	0.390	0.998	0.930	-0.310

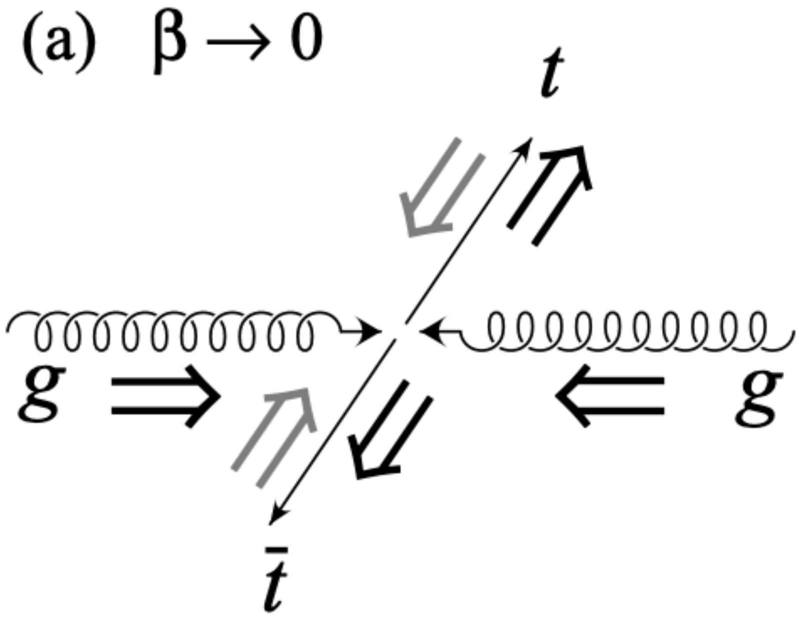

CMS Preliminary
35.9 fb-1 (13 TeV)
1/σ dσ/d|Δφ_ll|
0.5
0.4
0.3
0.2
● Unfolded Data
POWHEGV2 + PYTHIA8
MG5_aMC@NLO + PYTHIA8 [FxFx]
NLO, SM
NLO, uncorrelated
Theory/Data
1.05
1
0.95
Stat
Stat ⊕ Syst
0
π/6
π/3
π/2
2π/3
5π/6
π
|Δφ_ll|



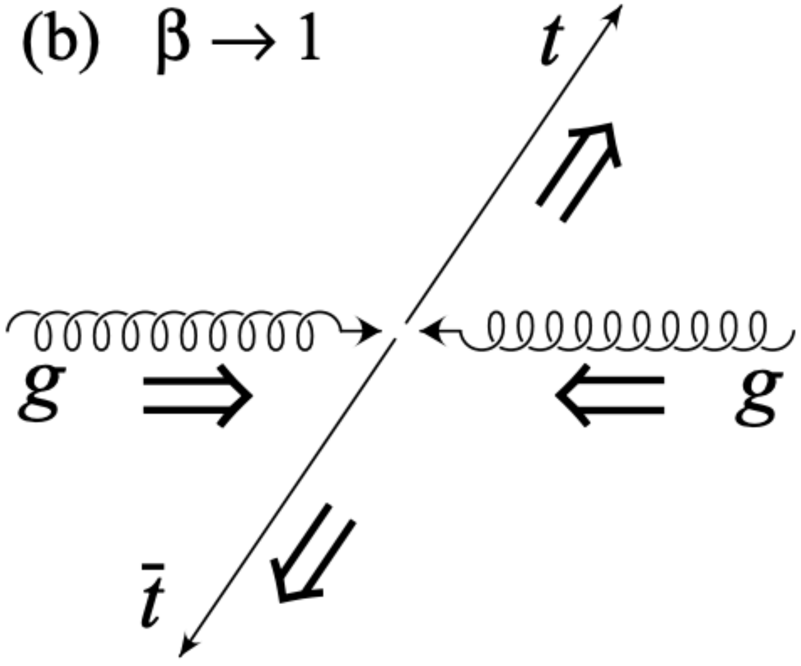
(a) $\beta \to 0$



(b) $\beta \to 1$



(a) $\beta \to 0$



(b) $\beta \to 1$