Observation of Entanglement

in

Top Quark Pairs at ATLAS

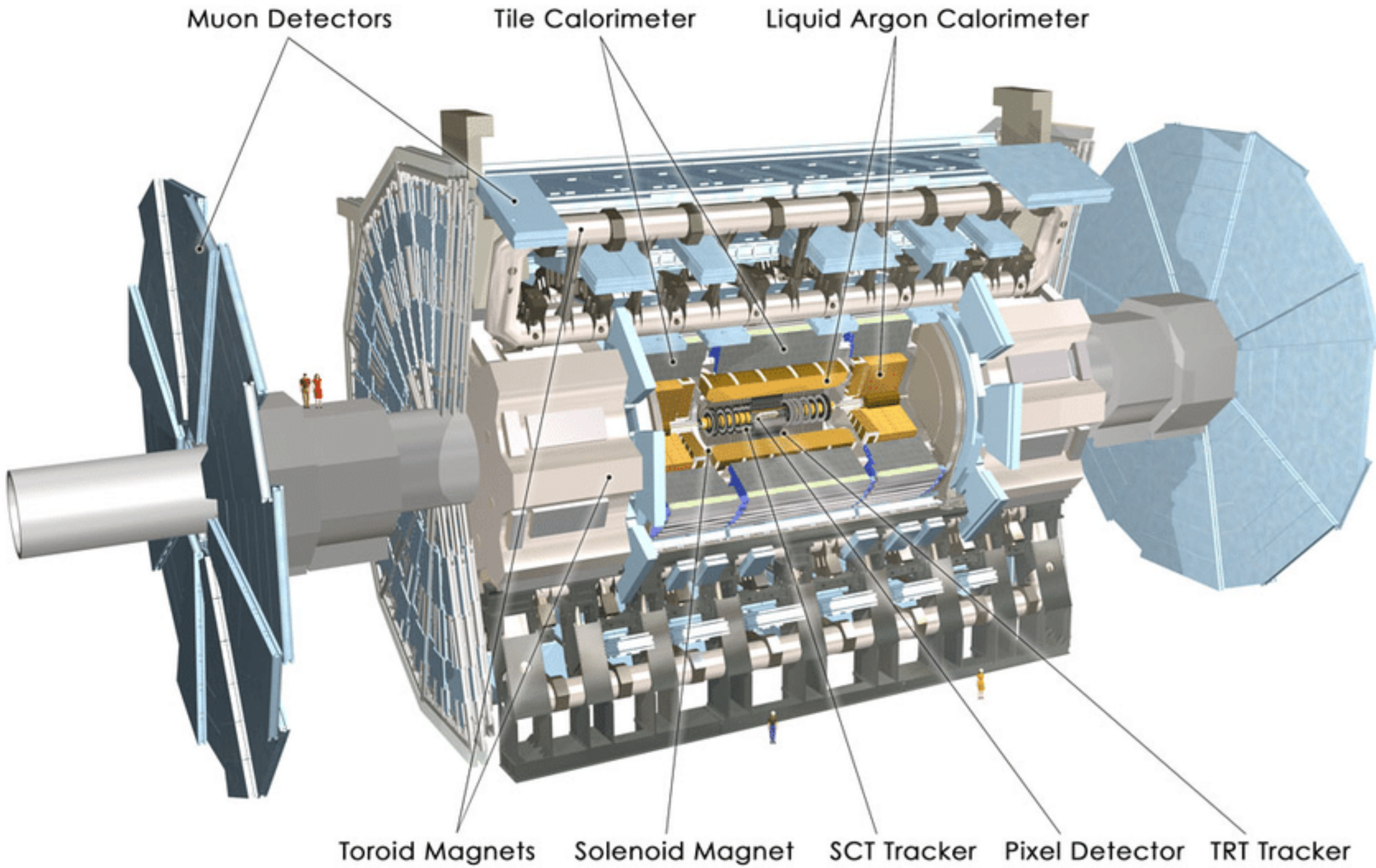
Oxford, 01/10/2024

Jay Howarth

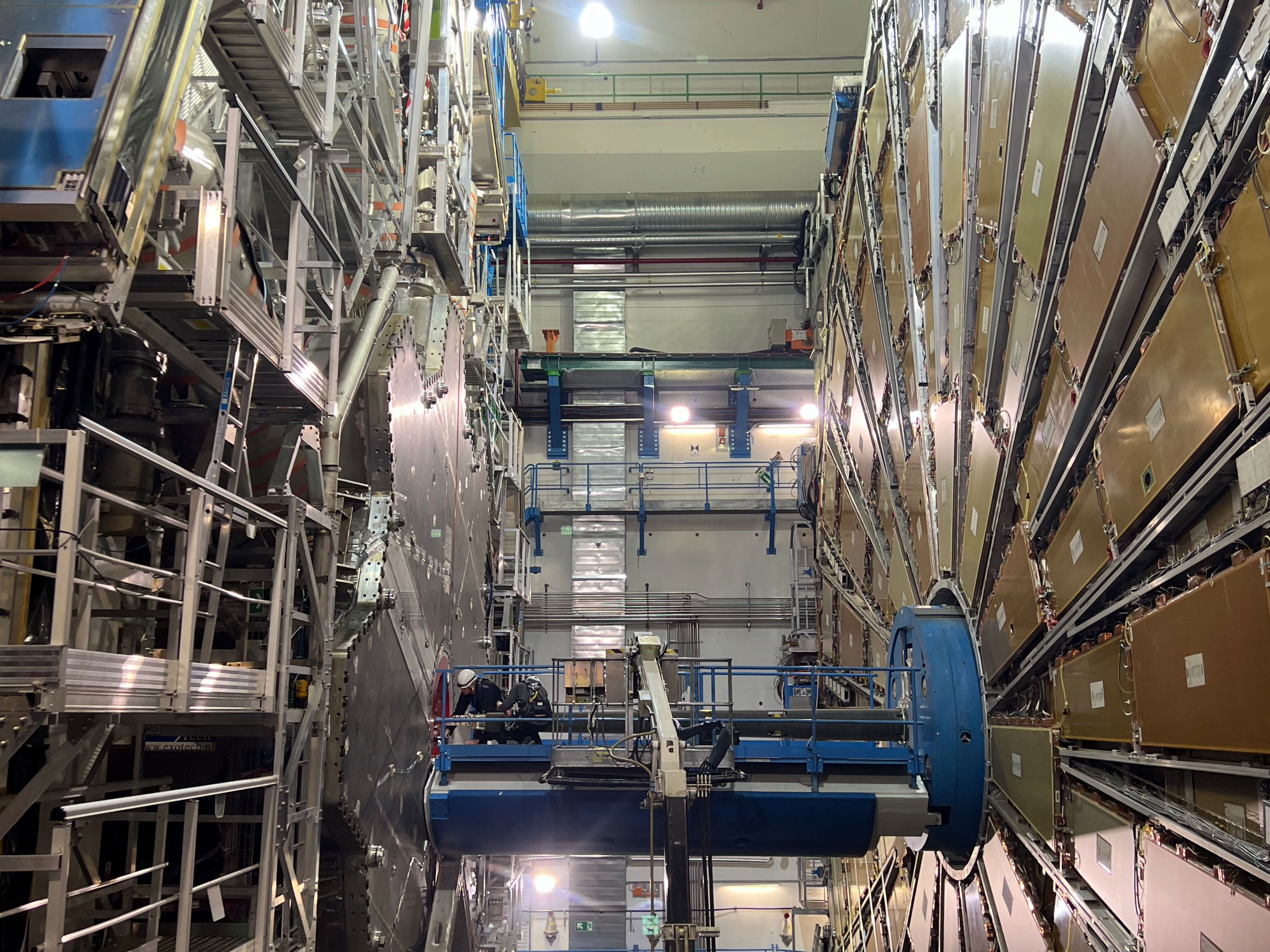
Introduction

- Top Physics and properties measurements at hadron colliders
- Quantum information in high energy particle physics
- The recent ATLAS result
- Implications and expected future results

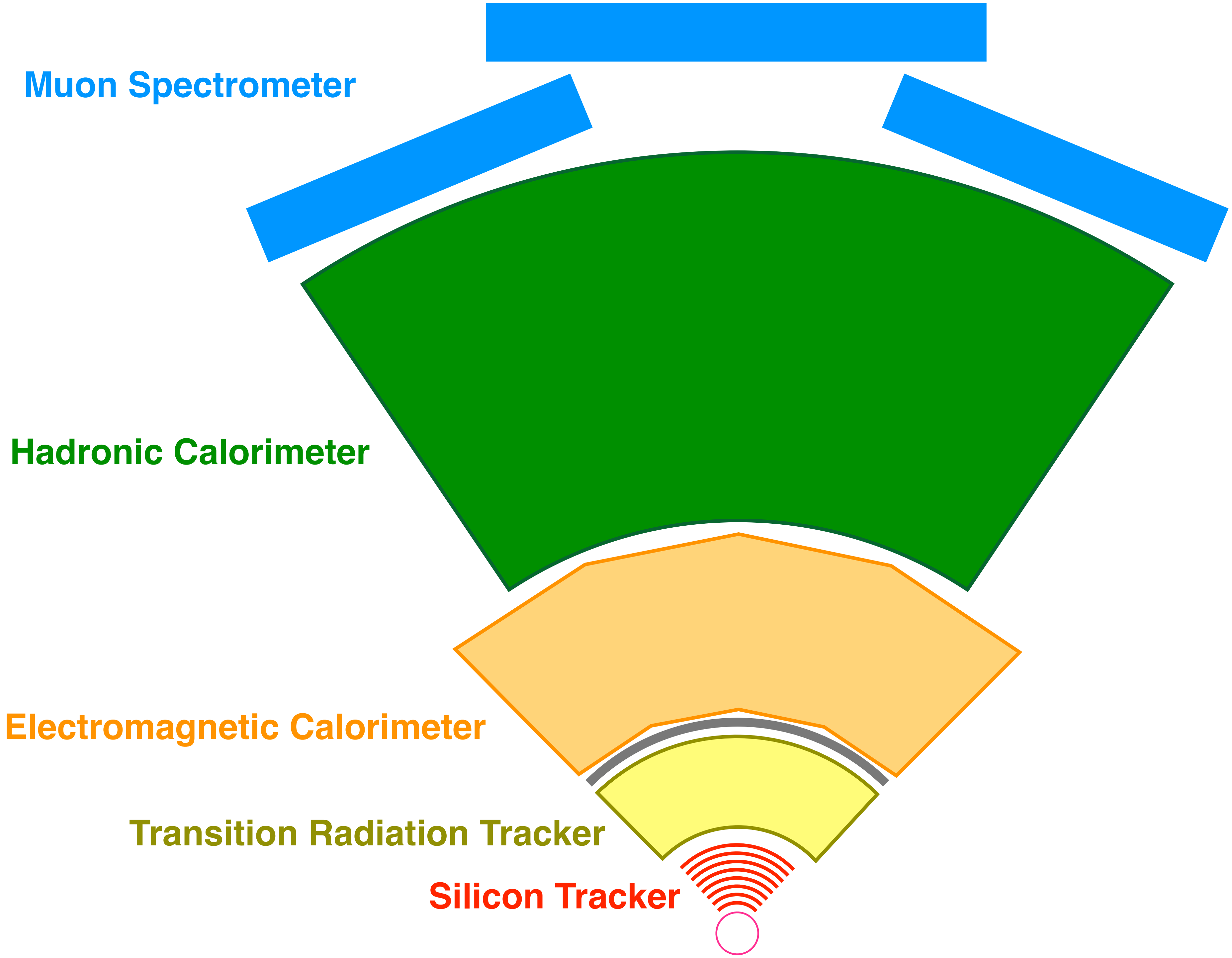
ATLAS



- **A Toroidal LHC ApparatuS:**
  "the best experiment with the worst acronym."



(ATLAS) Measurement Problem



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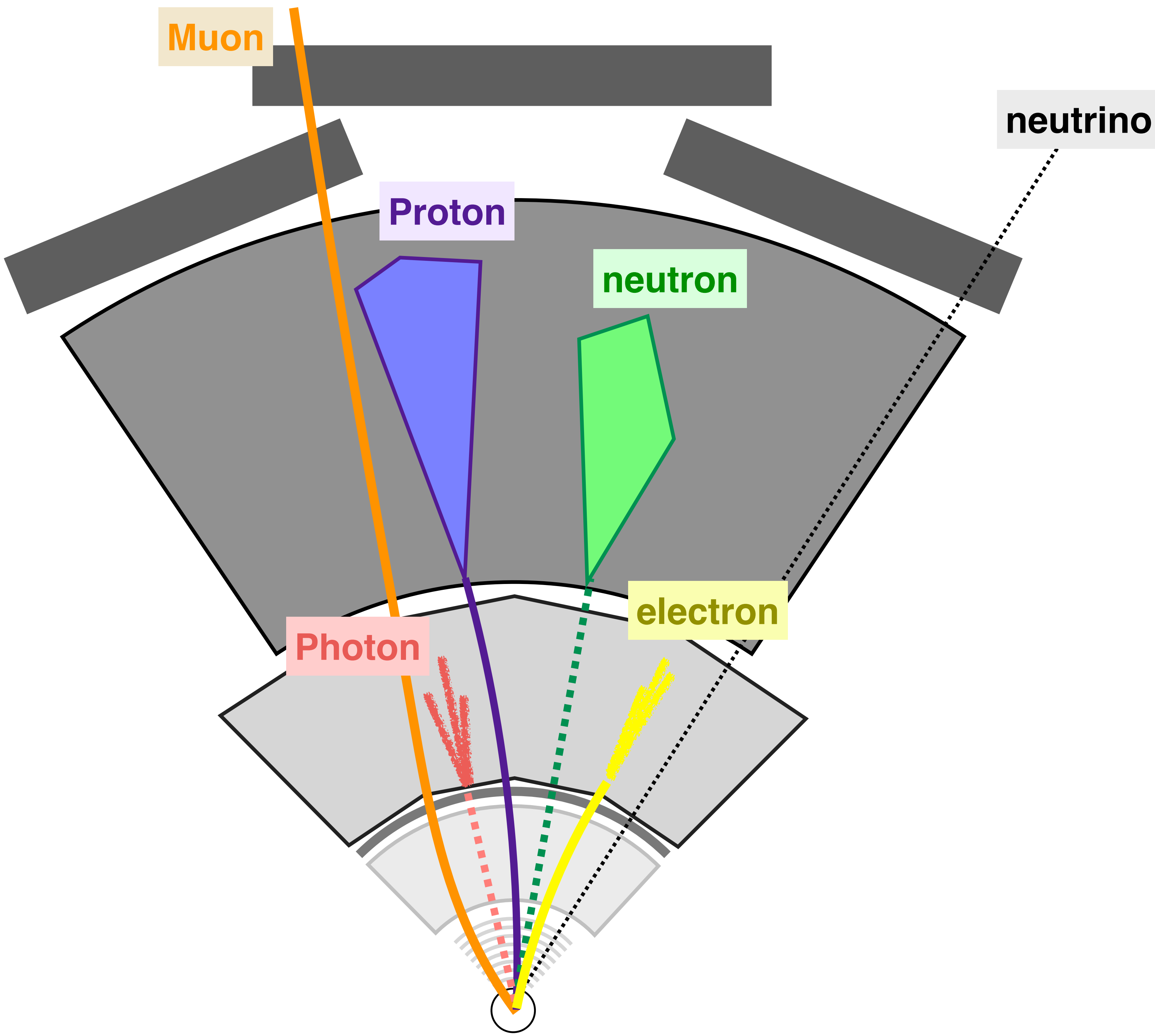

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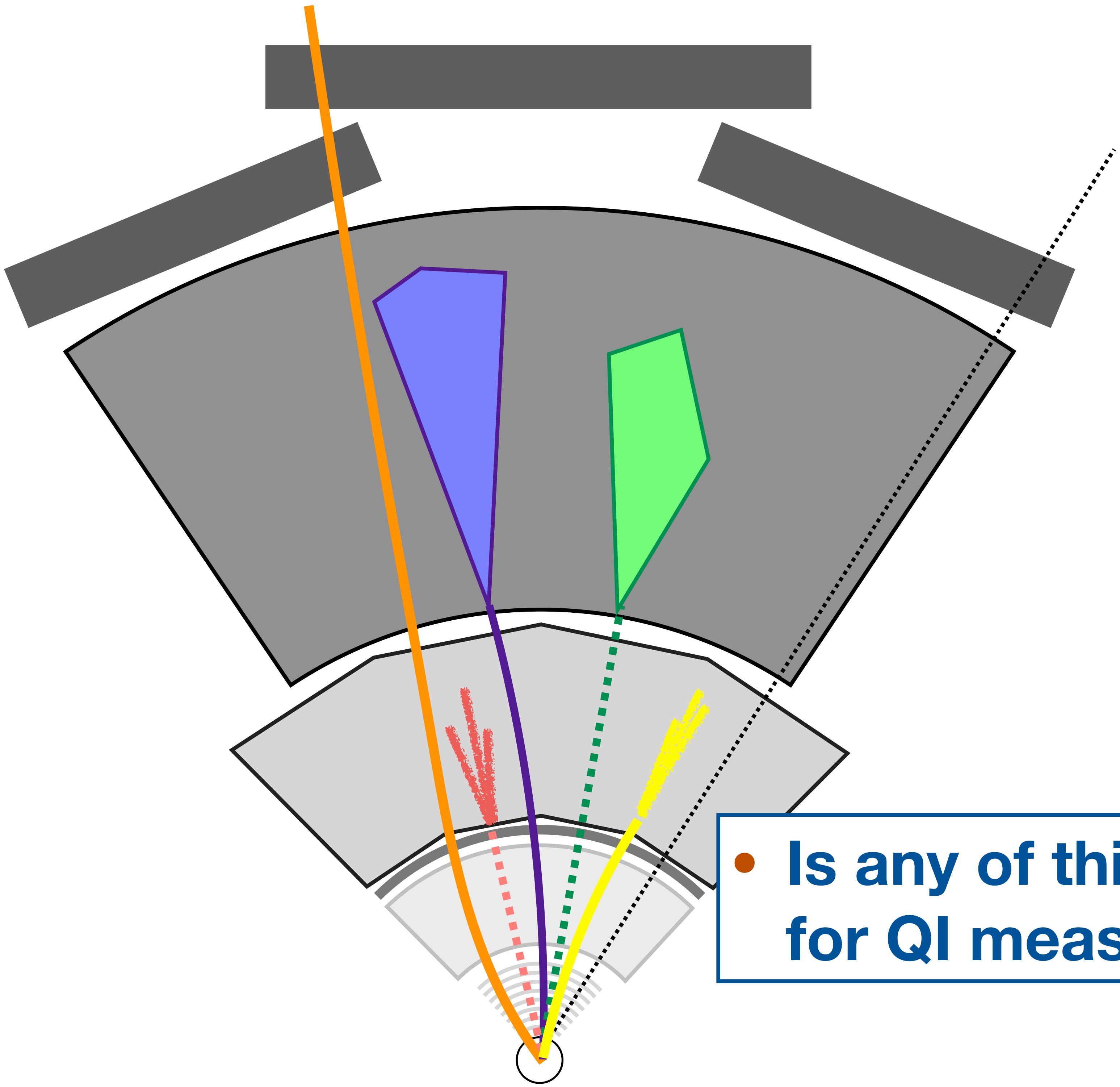
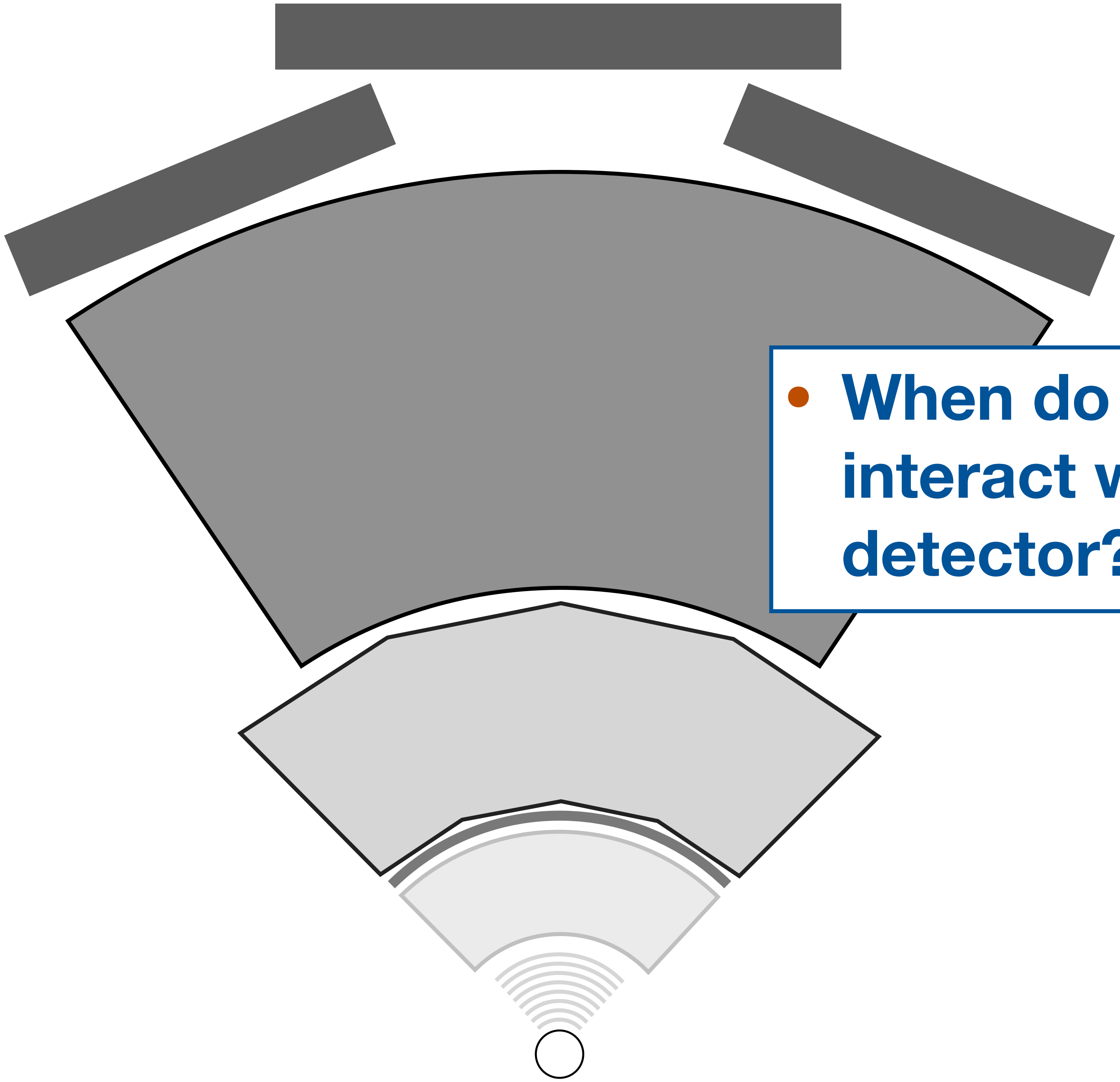


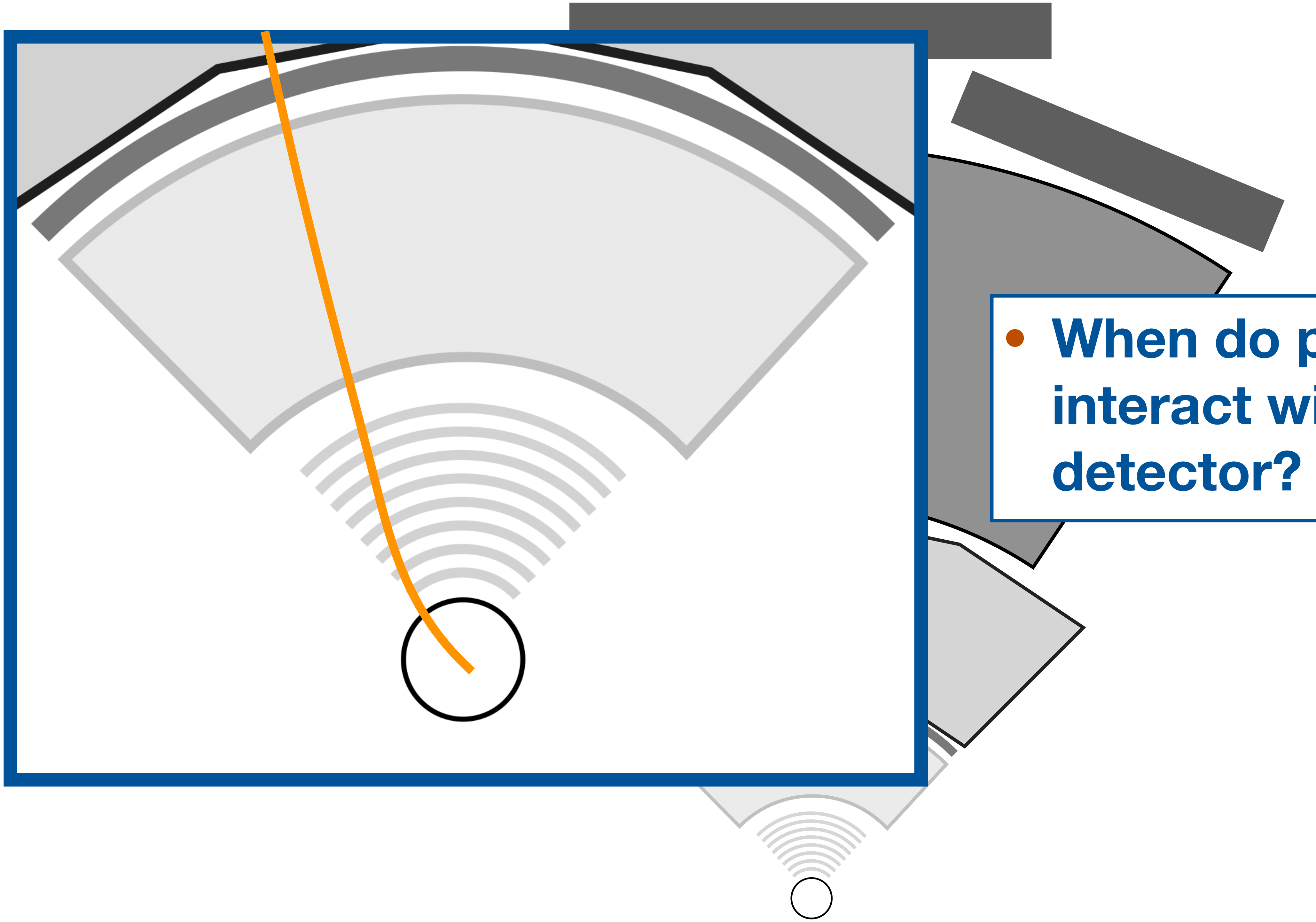
- Is any of this relevant for QI measurements?

(ATLAS) Measurement Problem



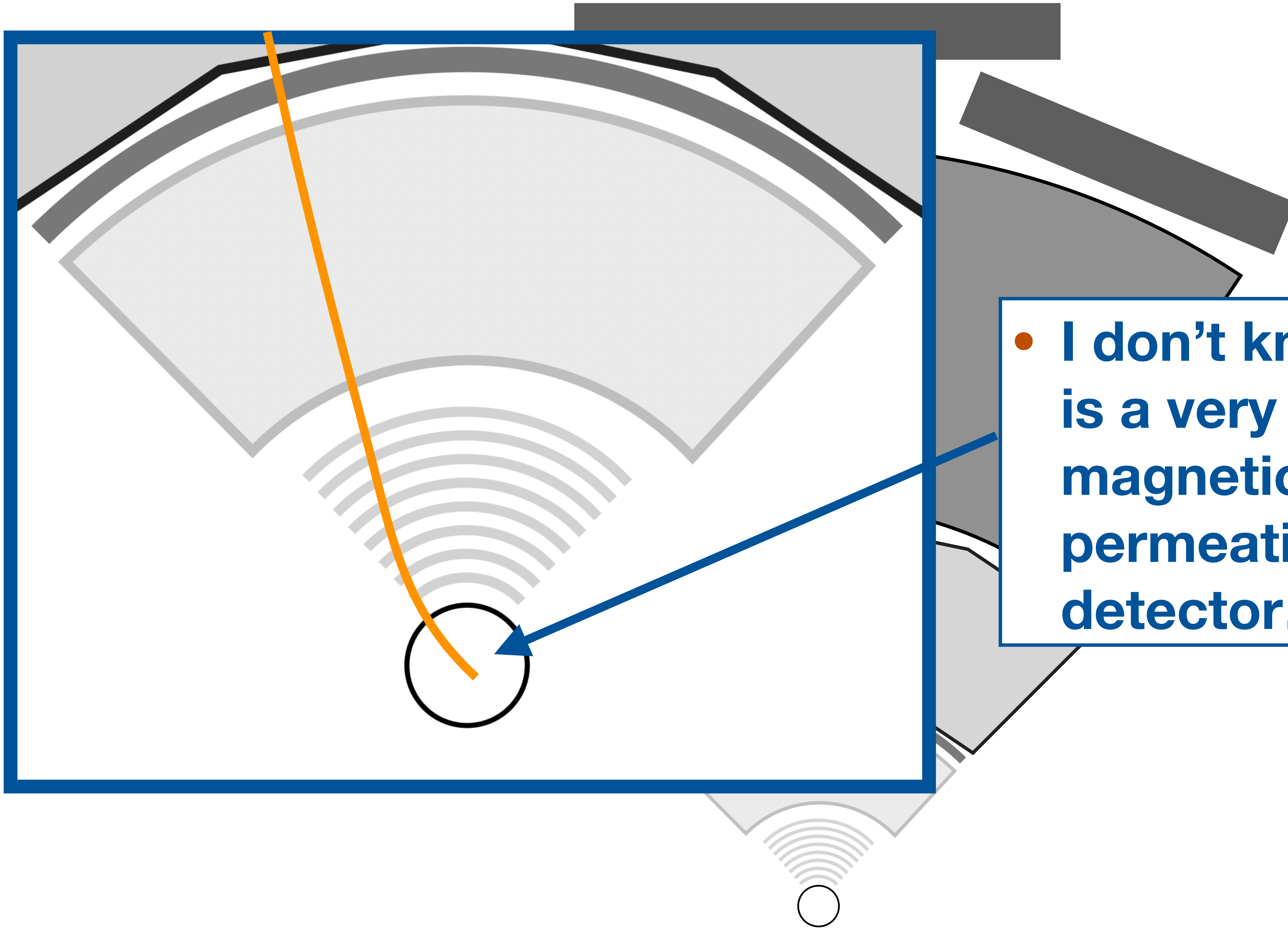
- When do particles interact with the detector?

(ATLAS) Measurement Problem



- **When do particles interact with the detector?**

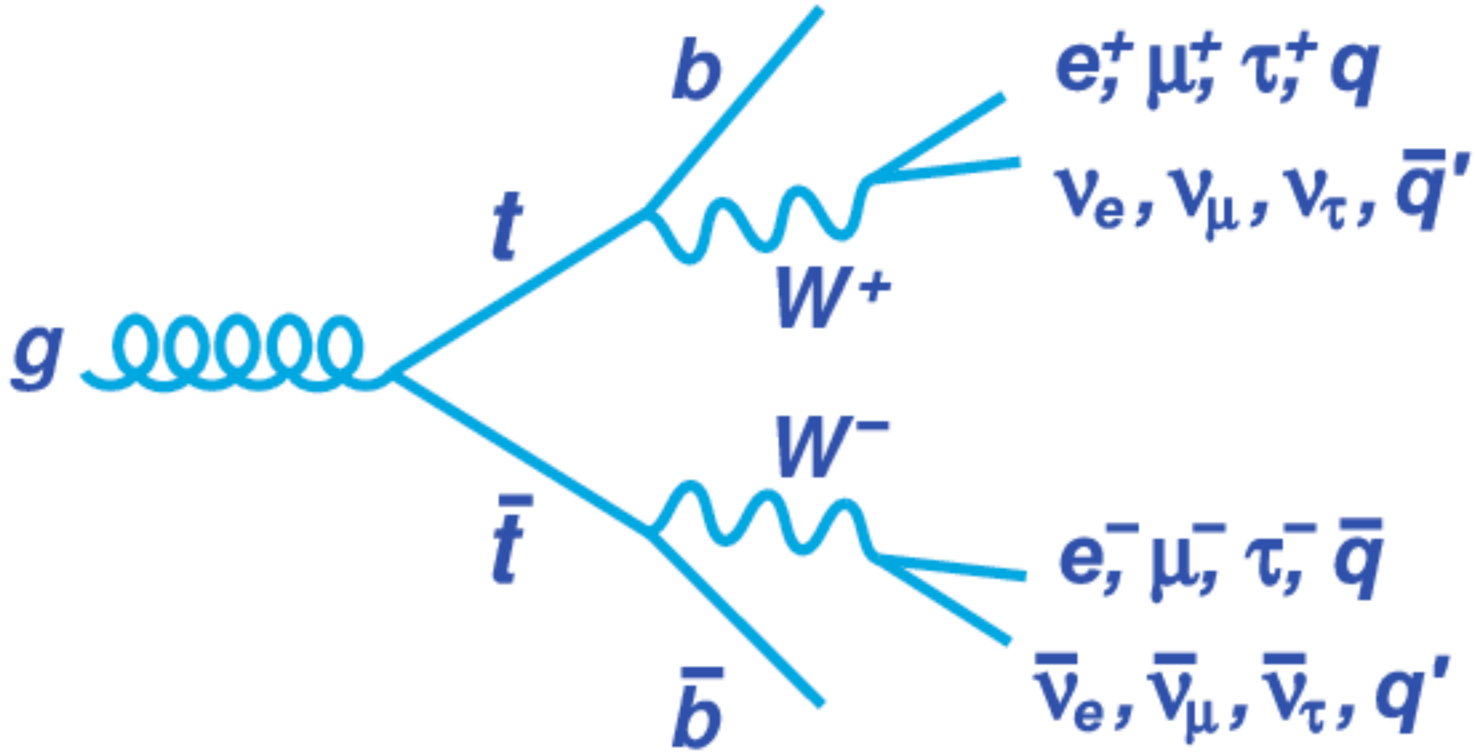
(ATLAS) Measurement Problem



- I don't know, but there is a very strong magnetic field permeating the whole detector…

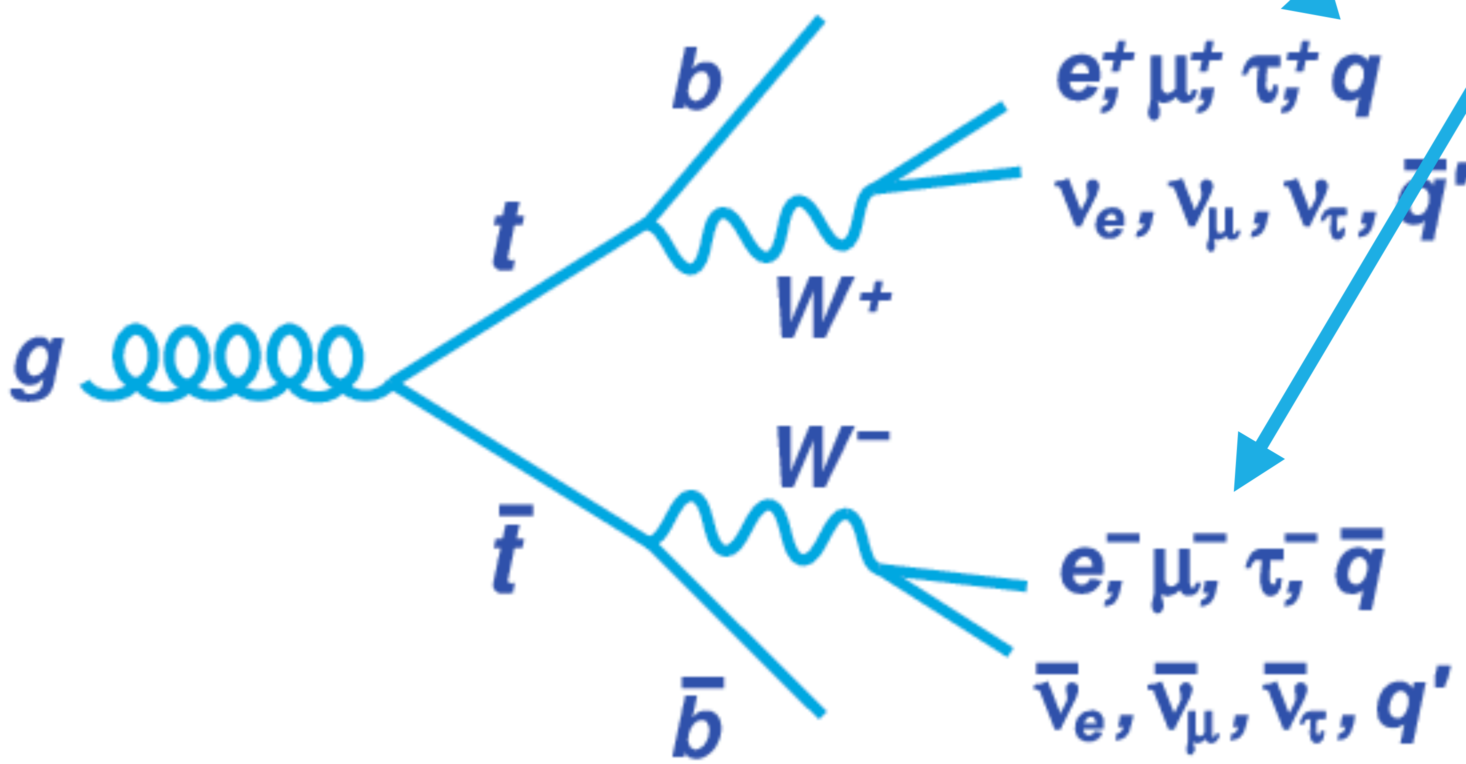
Top Decays

- **This measurement uses dileptonic $t\bar{t}$ events, which are difficult to reconstruct.**



Top Decays

- **Why is it hard to reconstruct top quarks?**



Charged leptons are the perfect spin analyser!

Top Decays

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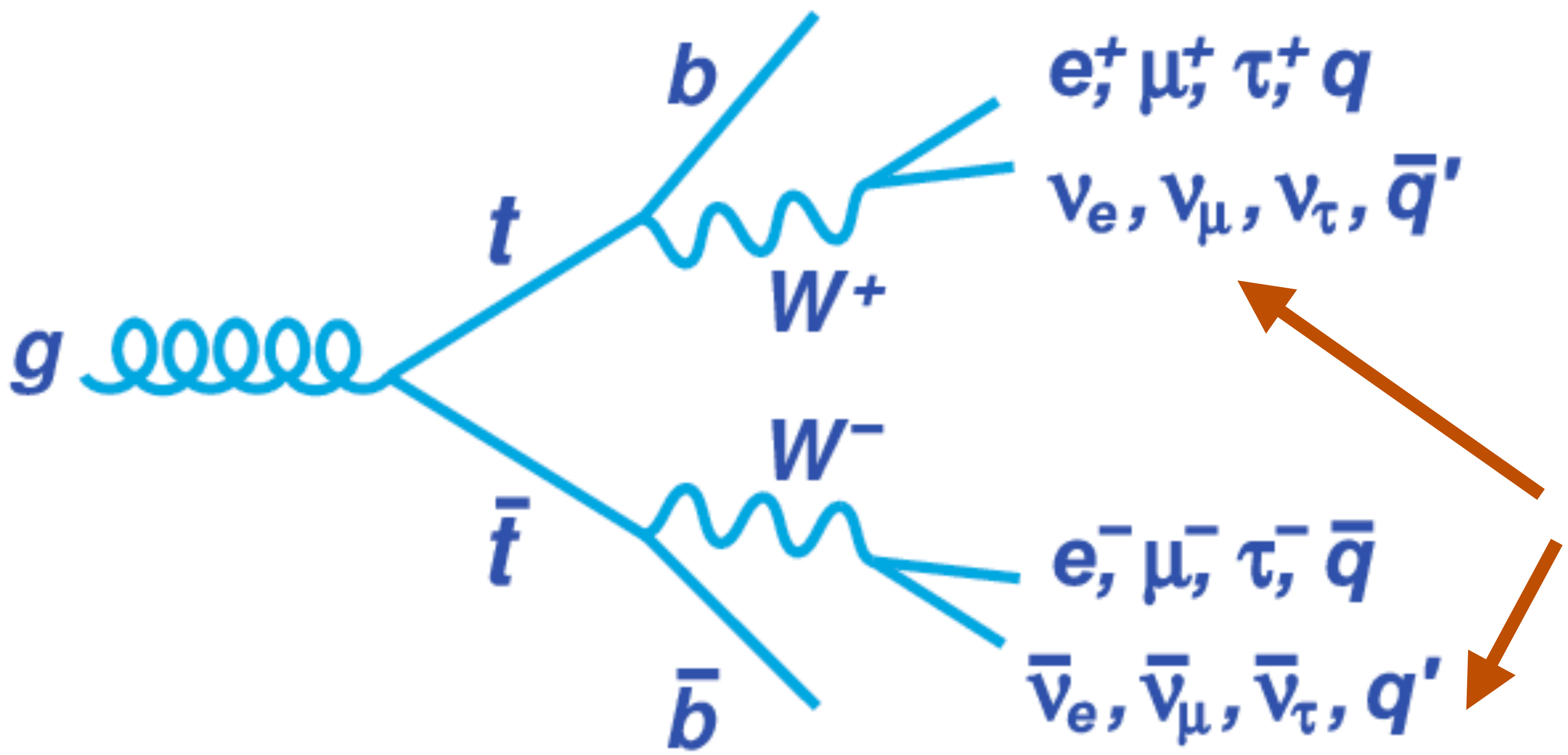
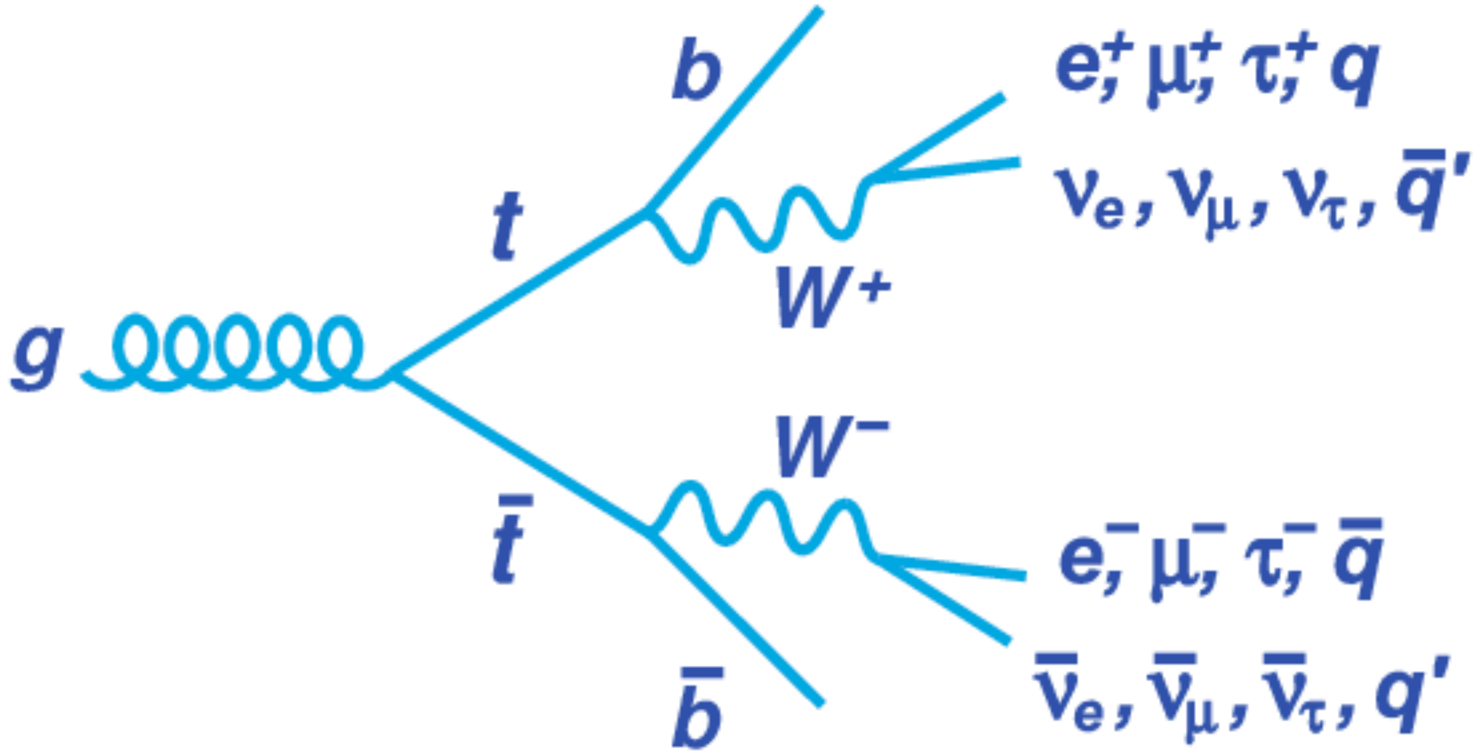


Neutrinos not detected (directly) **by ATLAS**

Top Decays

- **Why is it hard to reconstruct top quarks?**

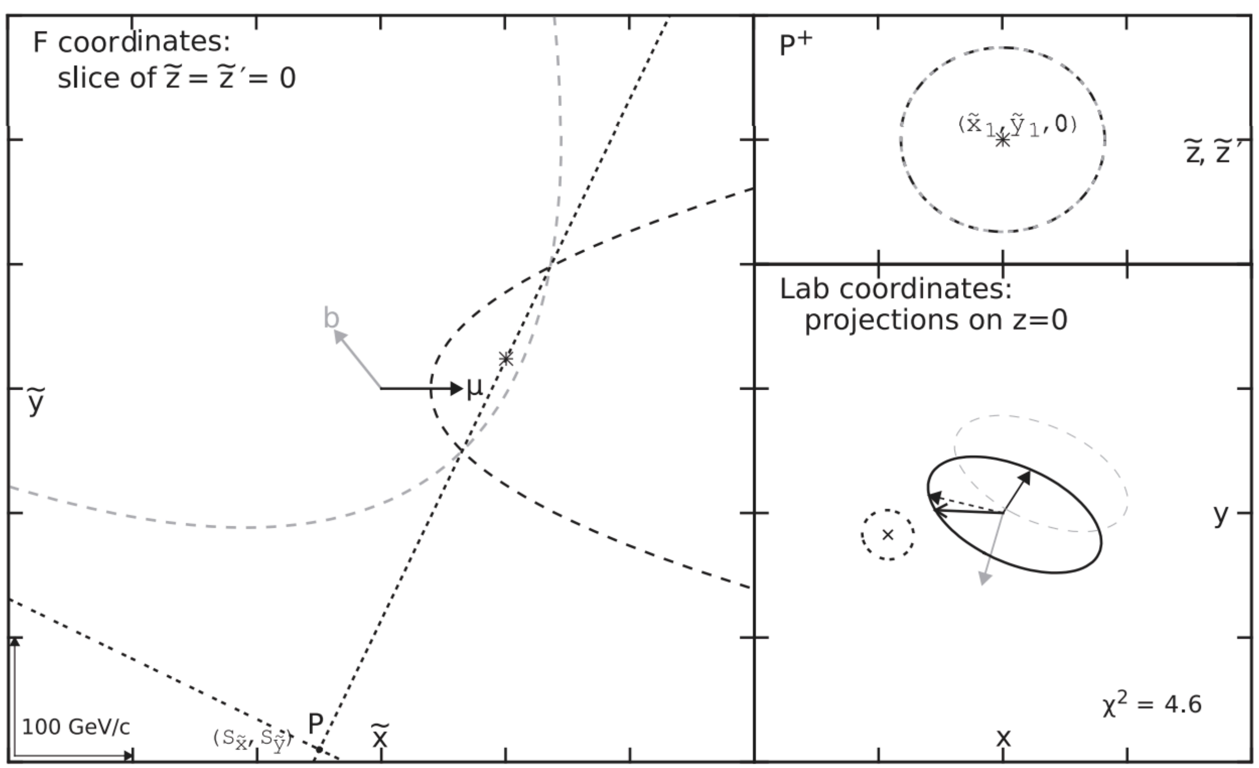


- **ATLAS selects events with two charged leptons in the final state** (+ 1 or more b-tagged jets)**.**

Reconstructing Tops

- **In order to measure D, we need to fully reconstruct both tops** (we need measure cos(Φ) in parent top rest frames)**.**
  ➡ **This means somehow dealing with two neutrinos**

- **There are a number of methods to achieve this, but this measurements relies heavily on the “**Ellipse method**”.**



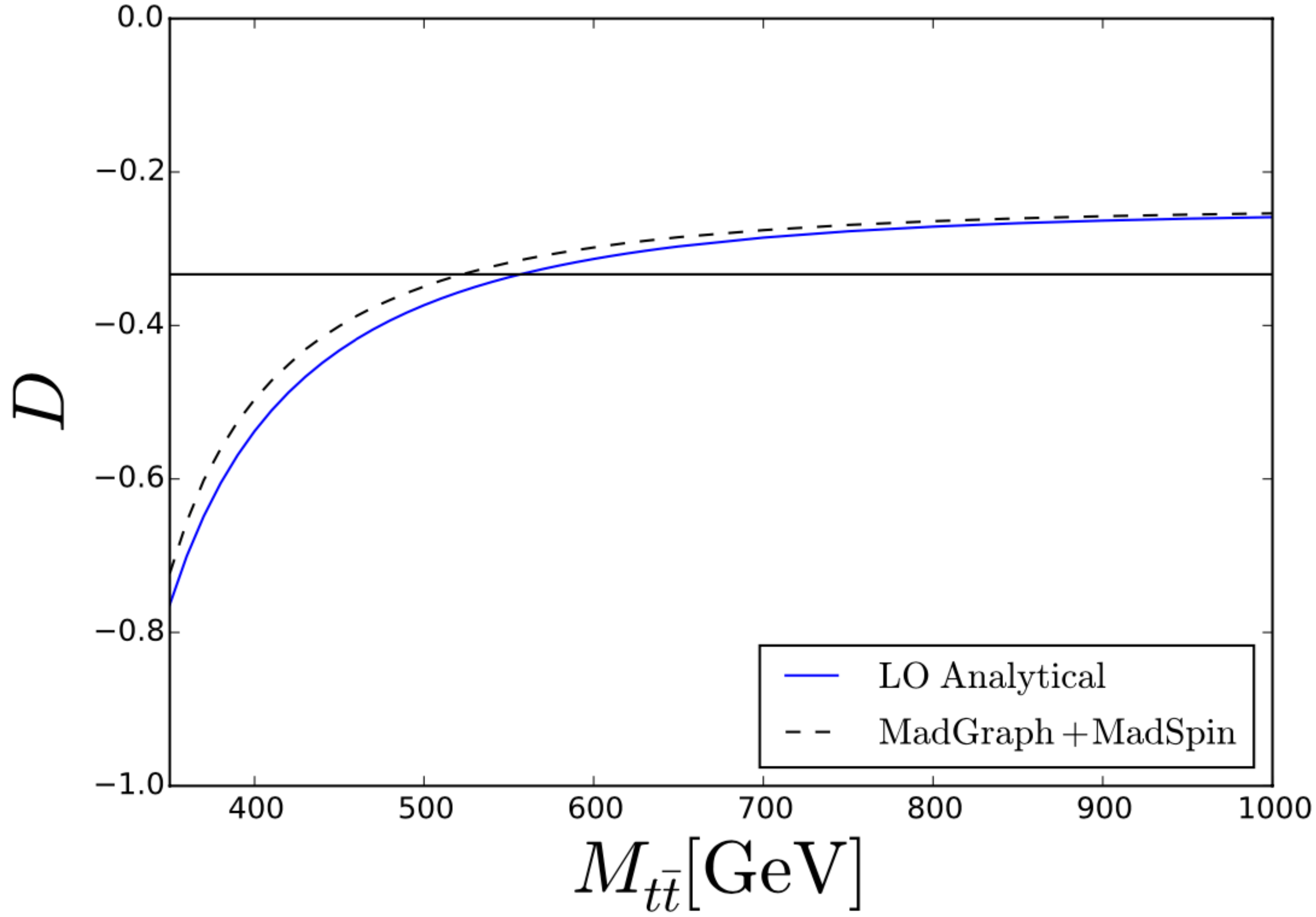
Nucl.Instrum.Meth.A 736 (2014) 169-178

- **Employs a geometry approach to analytically solve the system using linear algebra.**

- **Some other numerical methods used in small number of events.**

Signal/Validation Regions

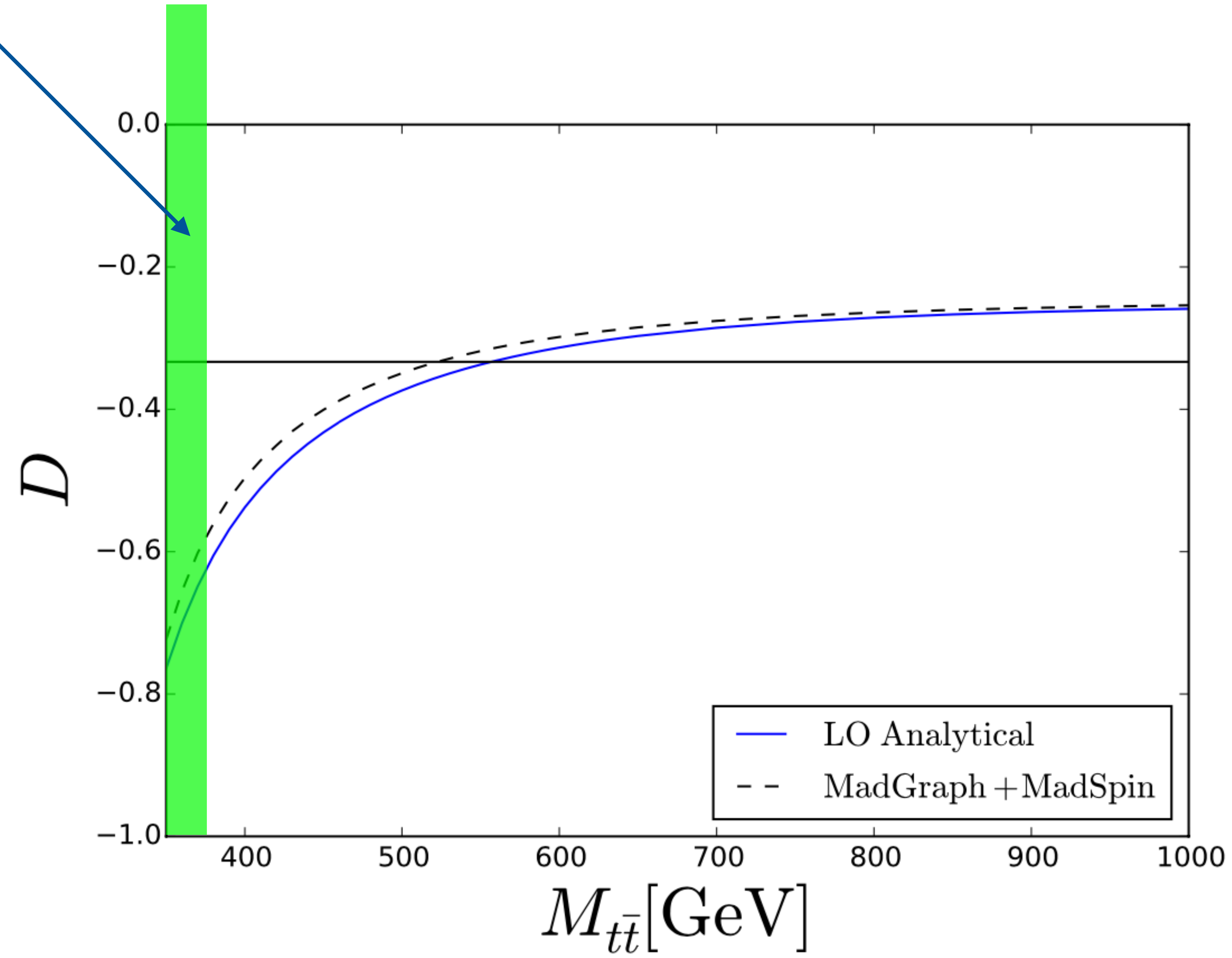
- **We split our measurement based on $m_{t\bar{t}}$:**



Signal/Validation Regions

- **We split our measurement based on $m_{t\bar{t}}$:**

SR: 340 - 380 GeV



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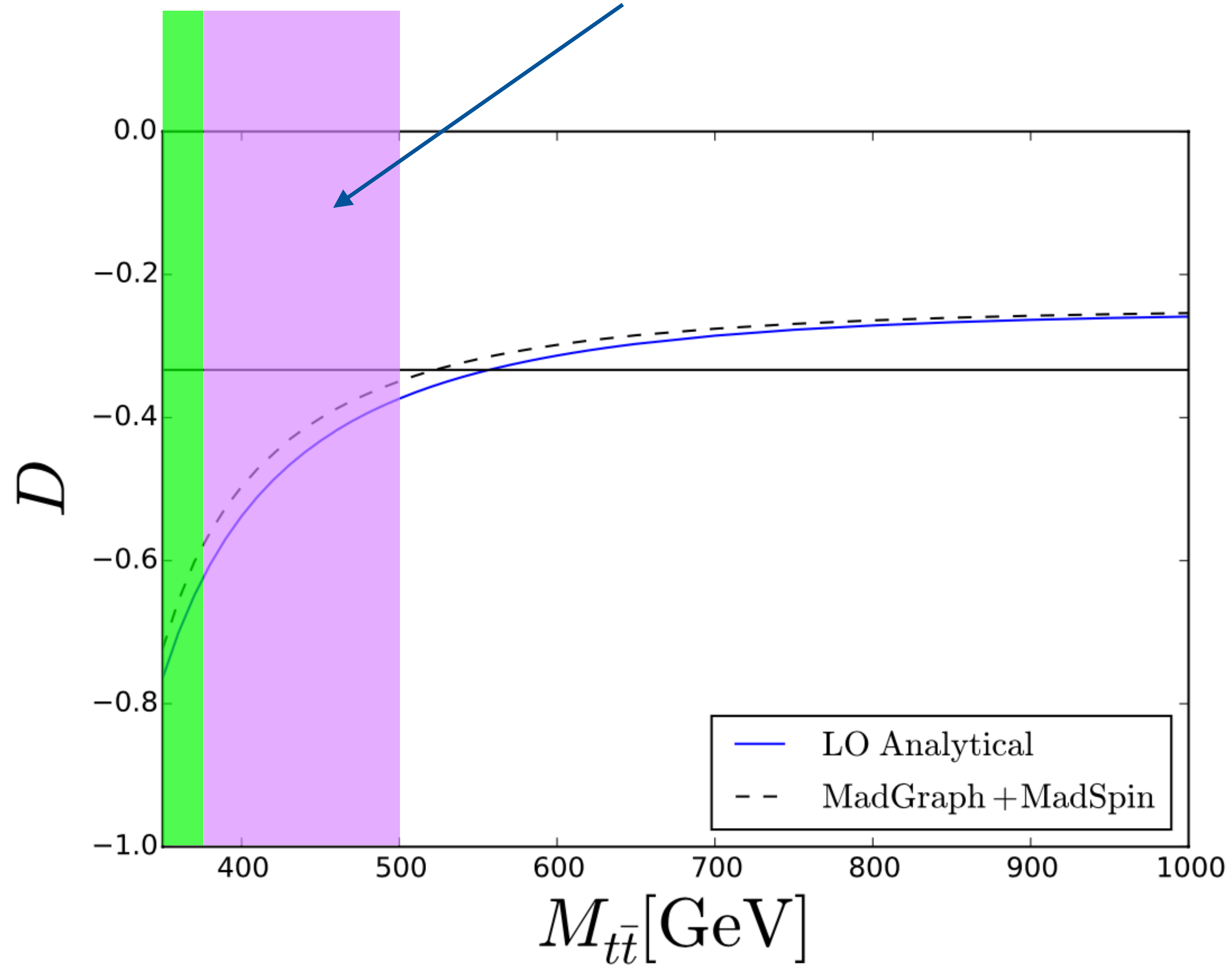
VR1: 380 - 500 GeV



Signal/Validation Regions

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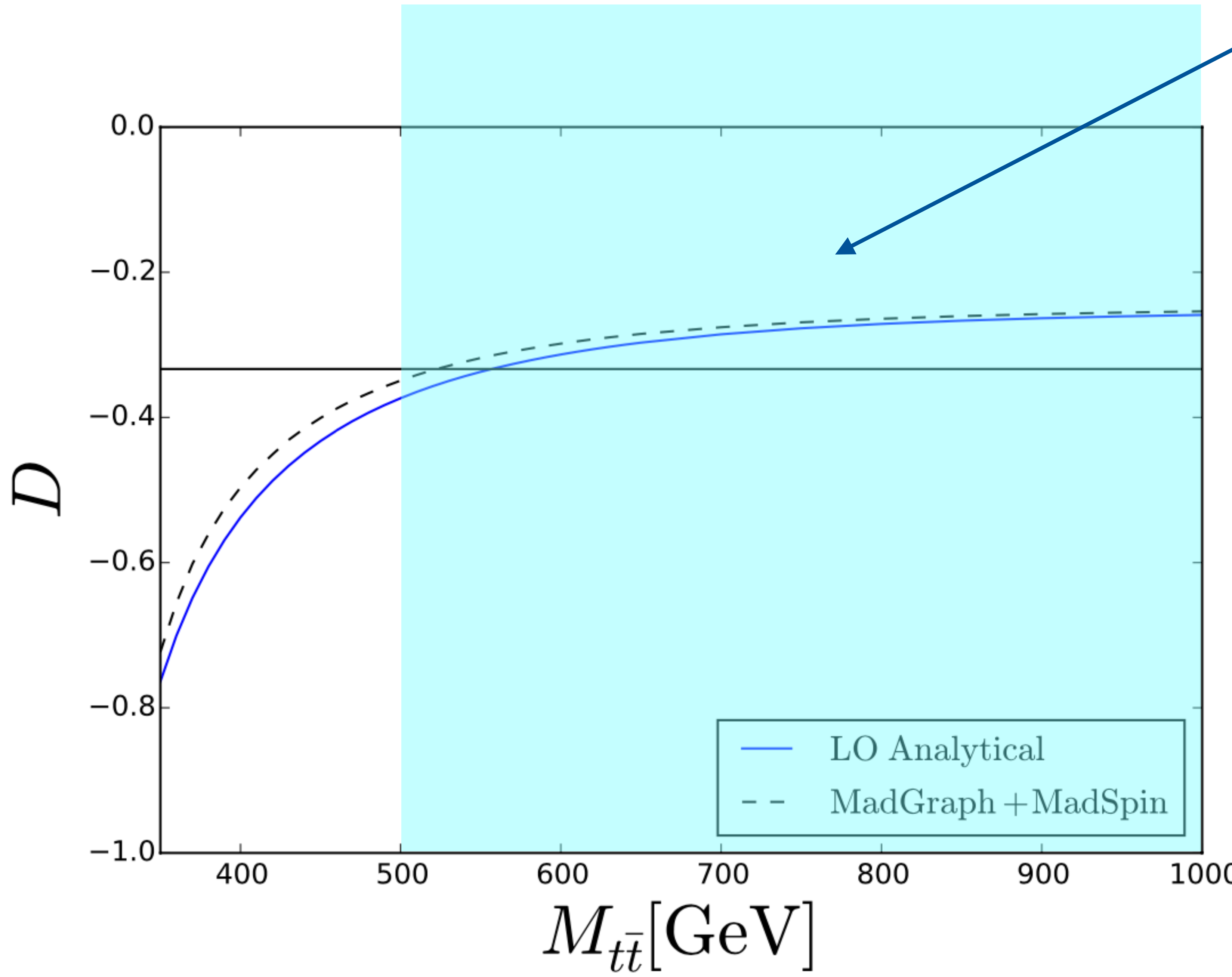
VR2: > 500 GeV



Signal/Validation Regions

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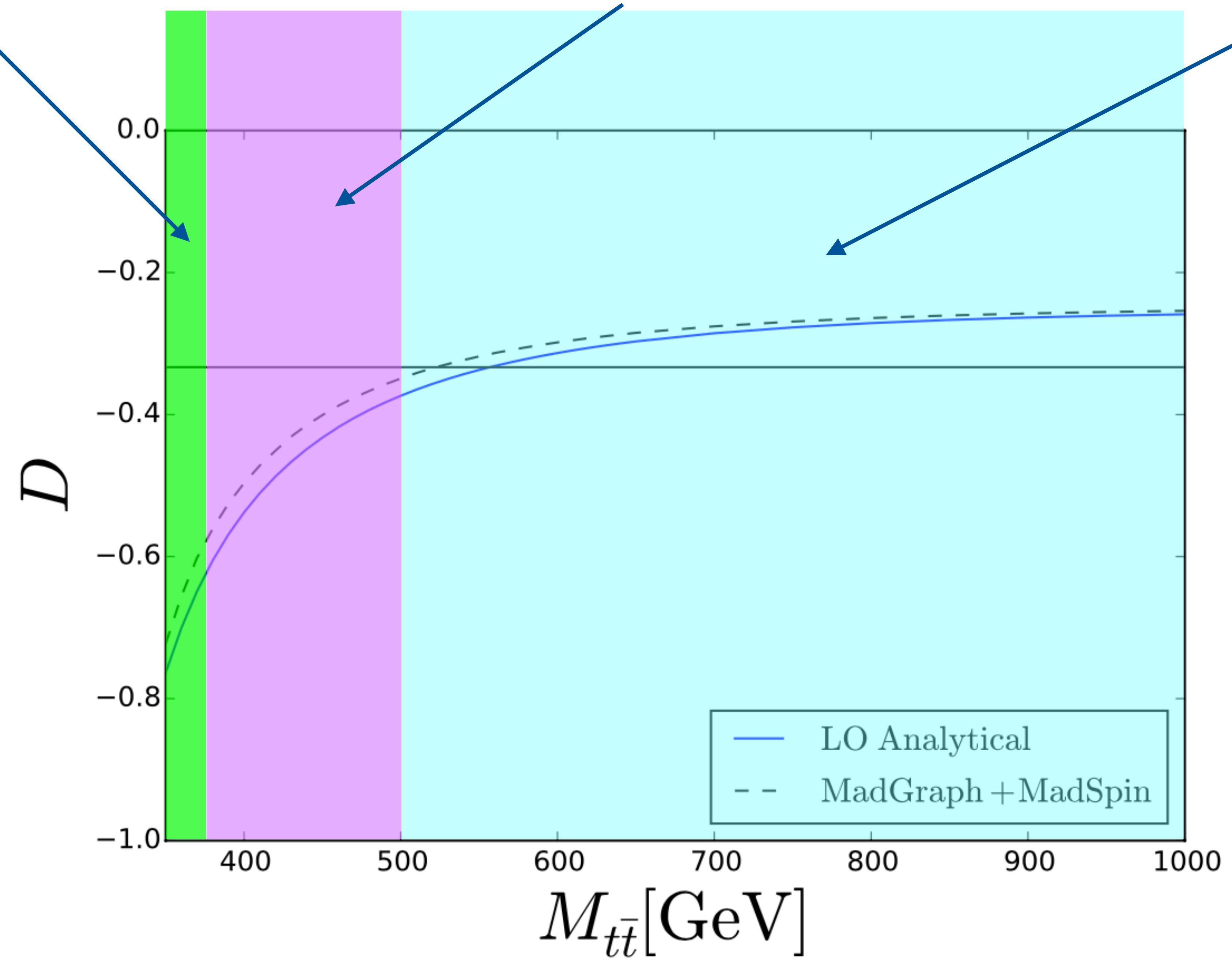
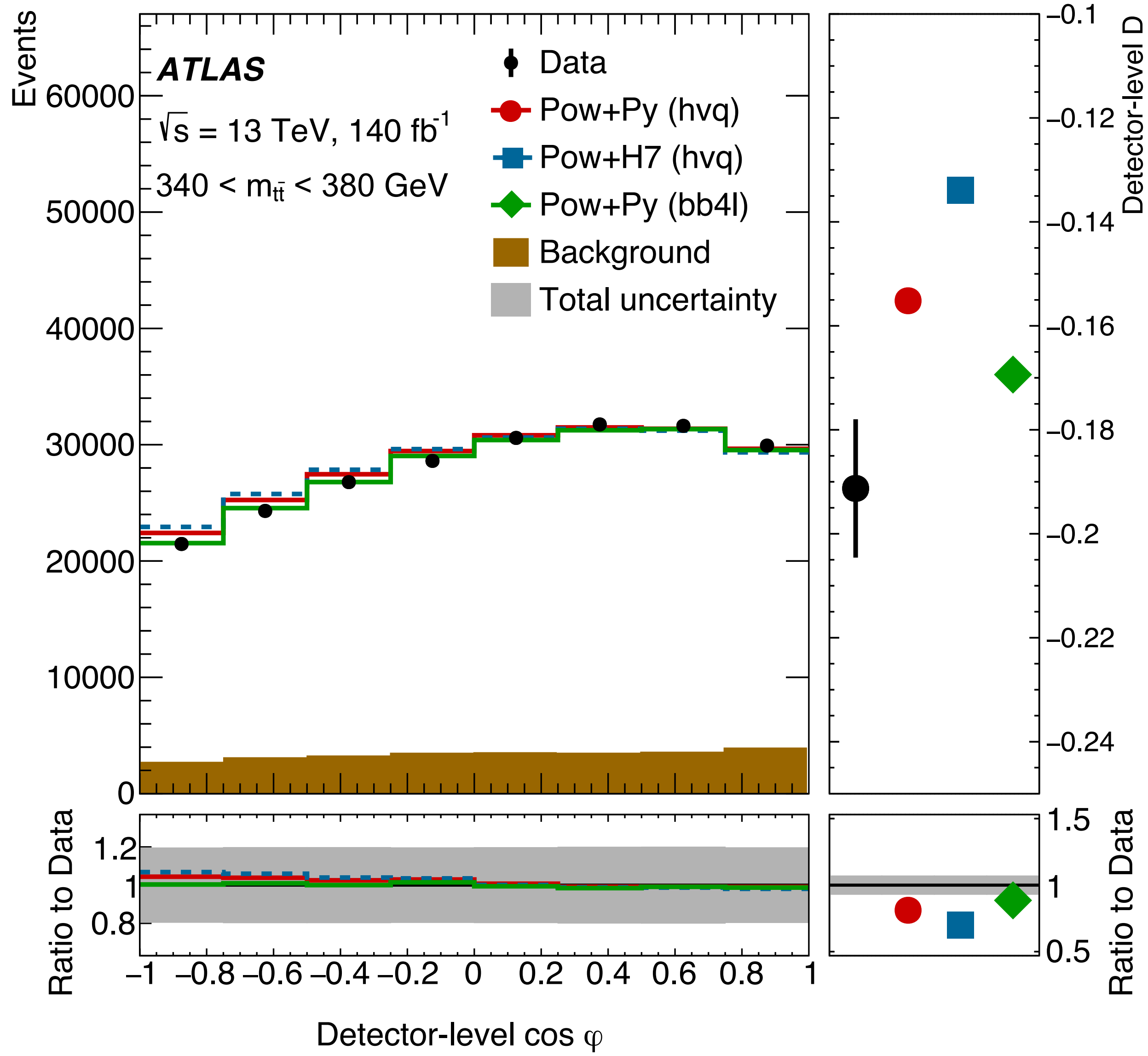
SR: 340 - 380 GeV **VR1**: 380 - 500 GeV **VR2**: > 500 GeV



Selection



- **Events are selected with exactly 1 electron and 1 muon.**
- **Require 1 or more b-tagged jets (85% W.P):**
  ➡ loose working point to ensure high stats in signal region.

Leptonic Spin analysers

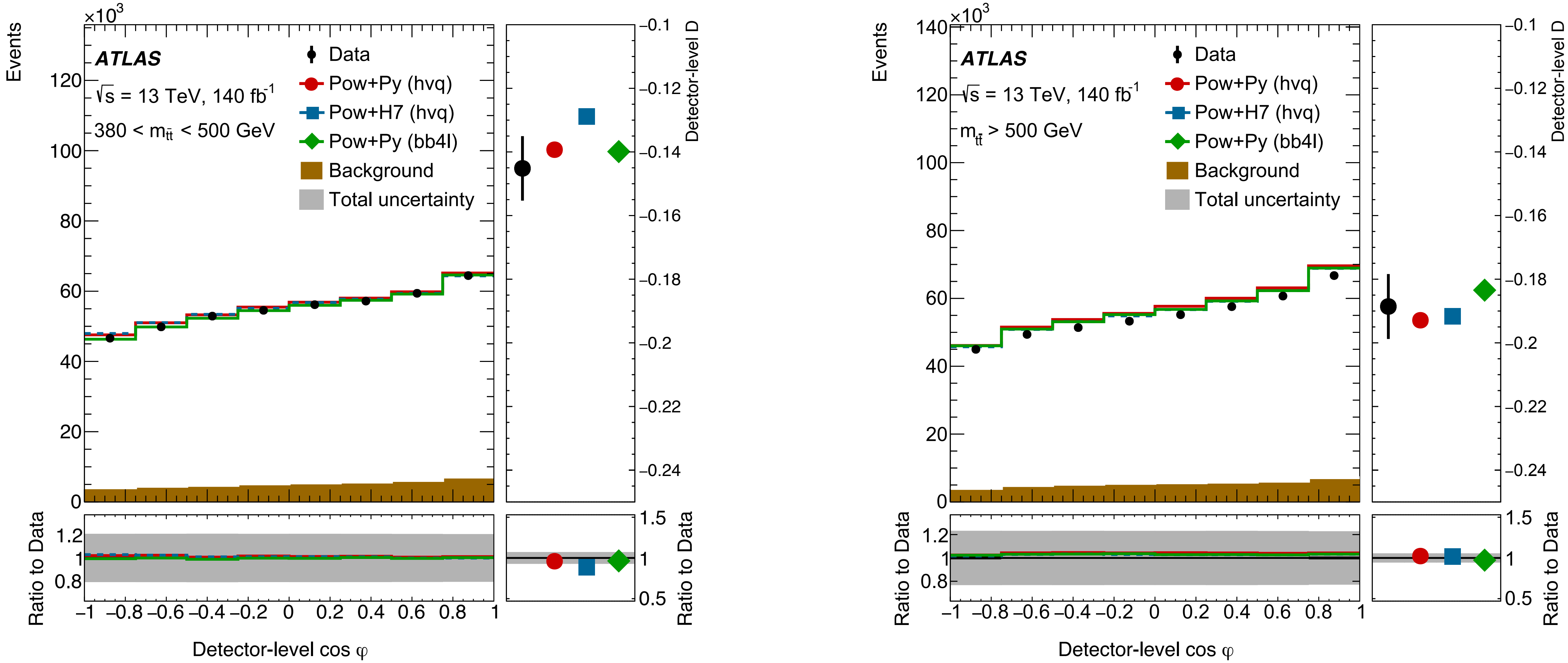
- **Top decay products have "spin analysing power":**

	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

- $\alpha_i = 1$ **means a particle carries the full spin information.**
  $\alpha_i = 0$ **means a particle carries none of the spin info.**
- **Almost all published spin measurements in top physics use the leptonic decay mode:**
  ➡ easiest to identify experimentally.
- **In ~~Run3~~ now! we will start to see results using down-type jets.**
- **Interesting question about implications of these not being exactly 1.**

Selection

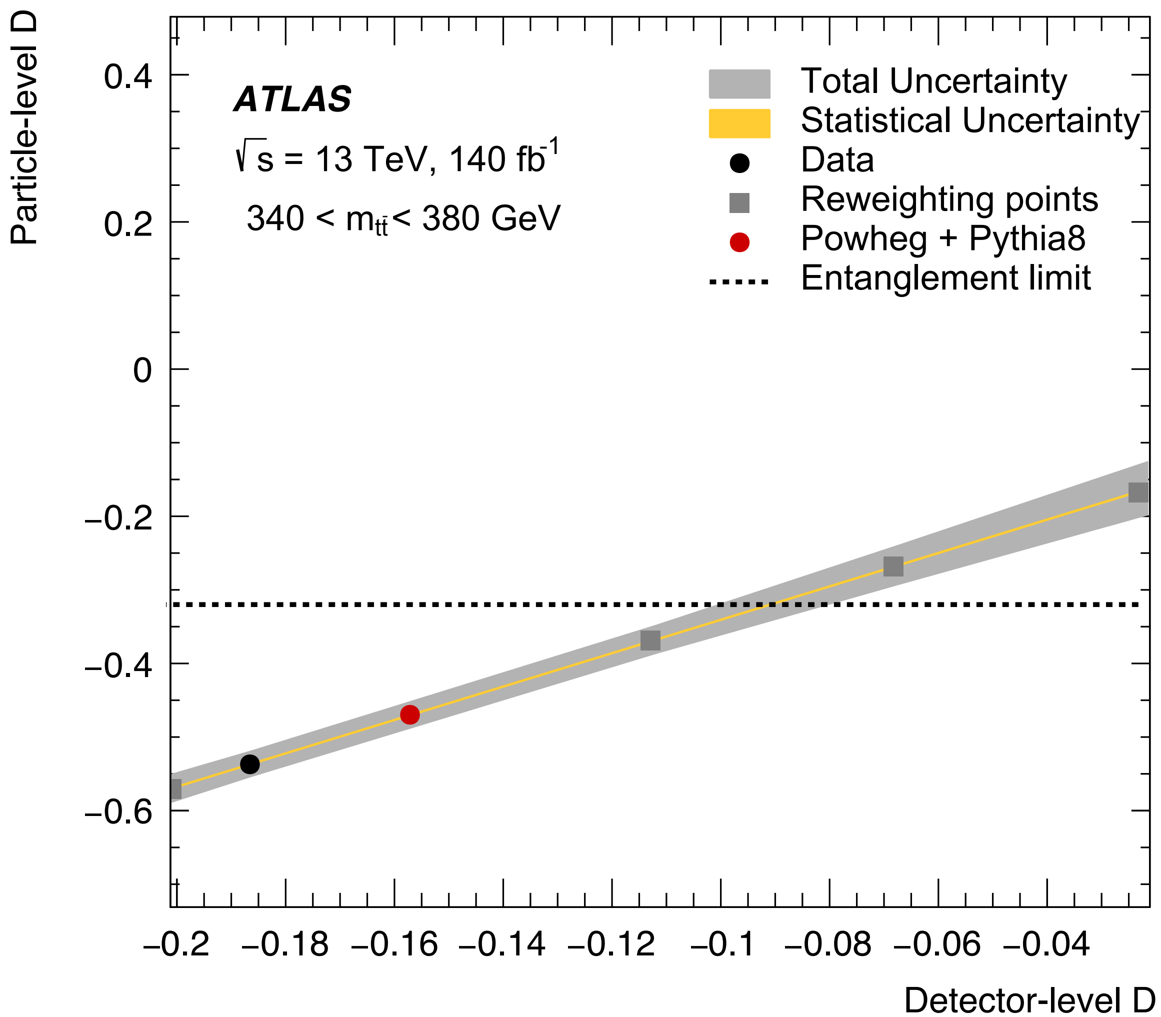
- **This selection is a very robust one** (similar selection used in dozens of analyses)**.**



- **Very good overall agreement between the number of signal+background events and the observed number of events in data.**

Calibration Curve

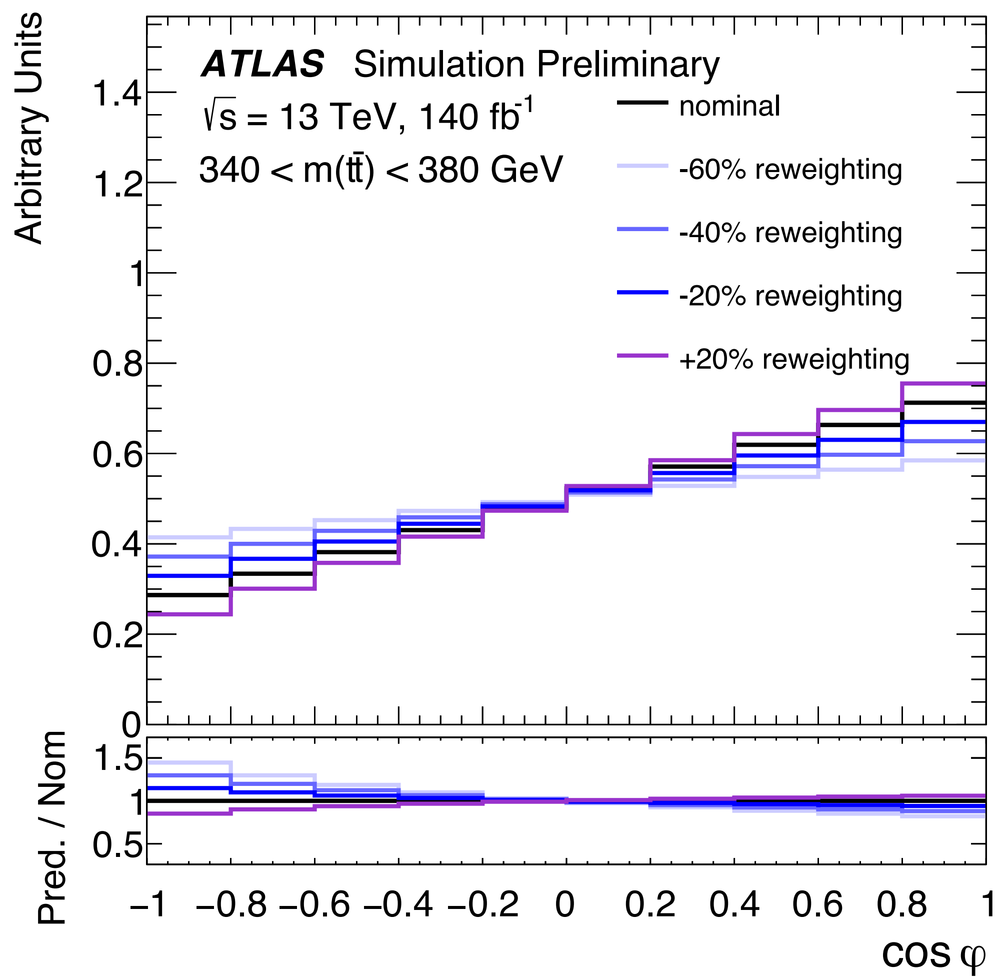
- **We somehow need to correct our observed D for detector effects to some 'truth' level** (particle in this case)**:**
  ➡ **We achieve this with a calibration curve.**



- **To construct this curve we need to change the amount of entanglement in our MC.**
- **We create 5 hypothesis points corresponding to the SM and 4 different reweighing points:**
  (+20%, -20%, -40%, -60%)

Reweighting

- **How these alternative hypothesis points are constructed is one of the key points of the measurement.**
- **We cannot dial entanglement up or down in the MC, so we reweight the cos(Φ) distribution as a function of m(tt̄).**



- **If this is not done correctly, the relation:**

$$D = \frac{tr[C]}{3} = -3 \cdot < \cos(\phi) >$$

does not hold.

- **The method we have used ensures that this relationship remains correct.**

Systematic Uncertainties

- **The relative size of the systematics is not fixed and changes at each hypothesis point:**

Source of uncertainty	$\Delta D_{\text{observed}}(D = -0.537)$	ΔD [%]	$\Delta D_{\text{expected}}(D = -0.470)$	ΔD [%]
Signal modeling	0.017	3.2	0.015	3.2
Electrons	0.002	0.4	0.002	0.4
Muons	0.001	0.2	0.001	0.1
Jets	0.004	0.7	0.004	0.8
b-tagging	0.002	0.4	0.002	0.4
Pile-up	< 0.001	< 0.1	< 0.001	< 0.1
$E_{\text{T}}^{\text{miss}}$	0.002	0.4	0.002	0.4
Backgrounds	0.005	0.9	0.005	1.1
Total statistical uncertainty	0.002	0.3	0.002	0.4
Total systematic uncertainty	0.019	3.5	0.017	3.6
Total uncertainty	0.019	3.5	0.017	3.6

- **As with most top measurements, we are limited by signal modelling** (also note that the relative uncertainty depends on D)**.**

Systematic Uncertainties

- **We have a large suite of MC modelling related systematic uncertainties:**

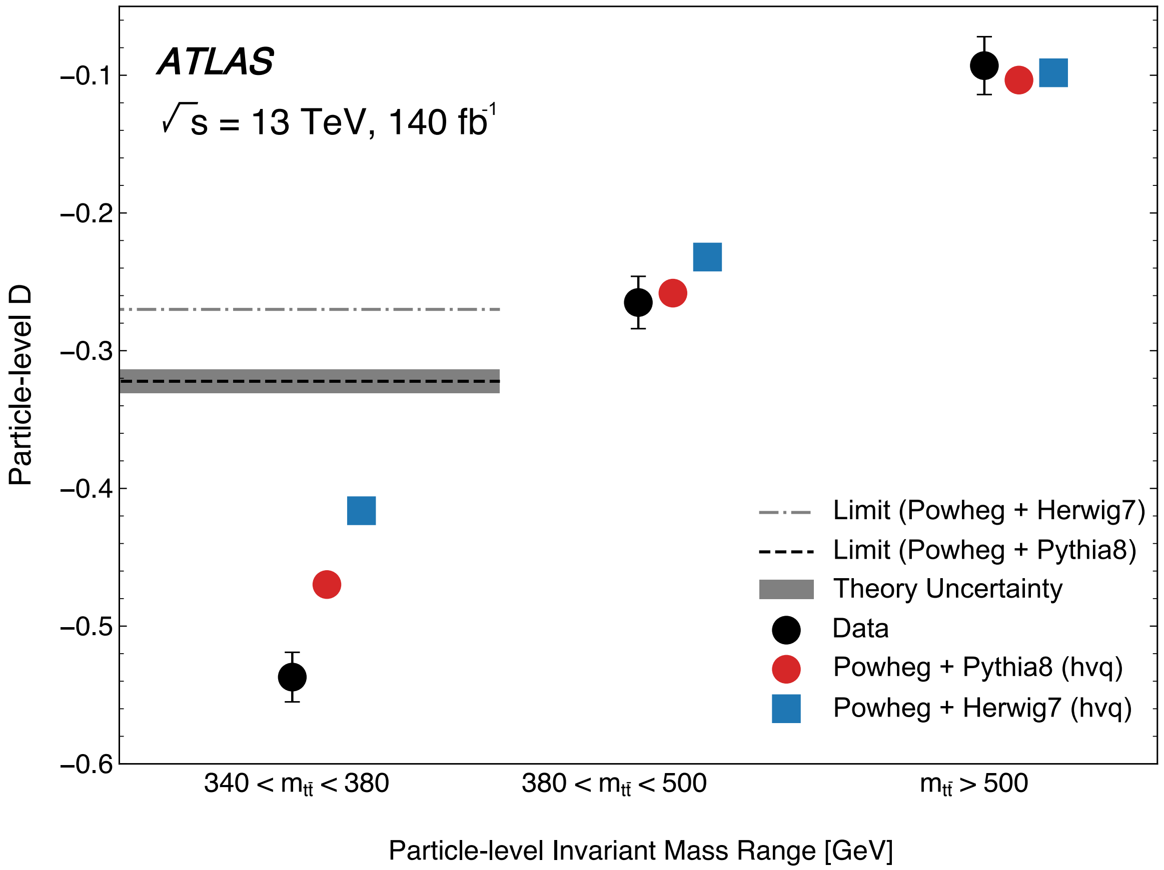
Systematic uncertainty source	Relative size (for SM D value)
Top-quark decay	1.6%
Parton distribution function	1.2%
Recoil scheme	1.1%
Final-state radiation	1.1%
Scale uncertainties	1.1%
NNLO reweighting	1.1%
pThard setting	0.8%
Top-quark mass	0.7%
Initial-state radiation	0.2%
Parton shower and hadronization	0.2%
h_{damp} setting	0.1%

- **Colour reconnection, string vs cluster fragmentation, spin correlation in parton shower, EW shower were all tested but found to be negligible effects.**

Results

- **The observed (expected) results are:**

$$\textbf{SR} \quad D = -0.537 \pm 0.002\ [\text{stat.}] \pm 0.018\ [\text{syst.}]\ (-0.470 \pm 0.002\ [\text{stat.}] \pm 0.016\ [\text{syst.}])\,,$$
$$\textbf{VR1} \quad D = -0.265 \pm 0.001\ [\text{stat.}] \pm 0.019\ [\text{syst.}]\ (-0.258 \pm 0.001\ [\text{stat.}] \pm 0.019\ [\text{syst.}])\,,$$
$$\textbf{VR2} \quad D = -0.093 \pm 0.001\ [\text{stat.}] \pm 0.021\ [\text{syst.}]\ (-0.103 \pm 0.001\ [\text{stat.}] \pm 0.021\ [\text{syst.}])\,,$$

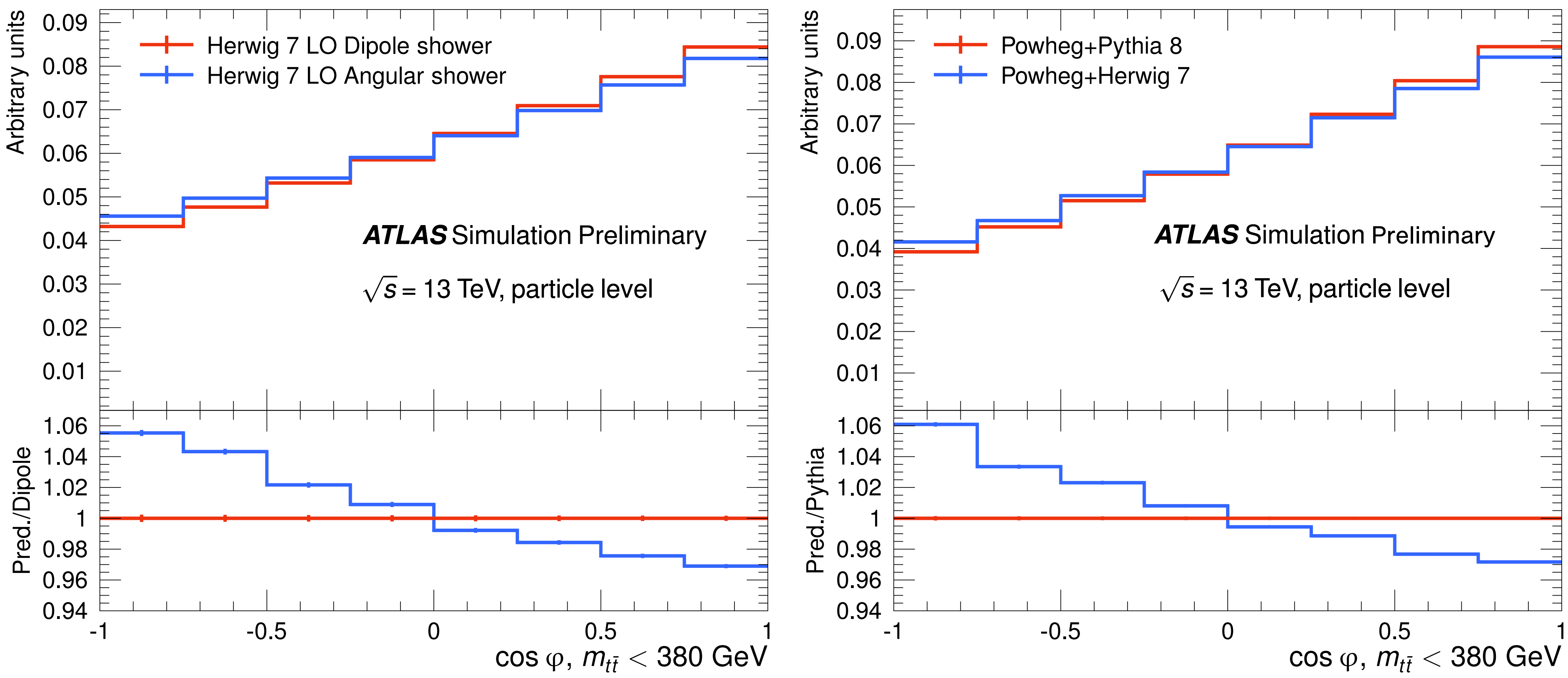


Nature 633 (2024) 542

- **The observed results excludes the entanglement limit at** (much) **more than 5 sigma significance.**

Parton Shower

- Difference seems to come from the ordering of the shower.

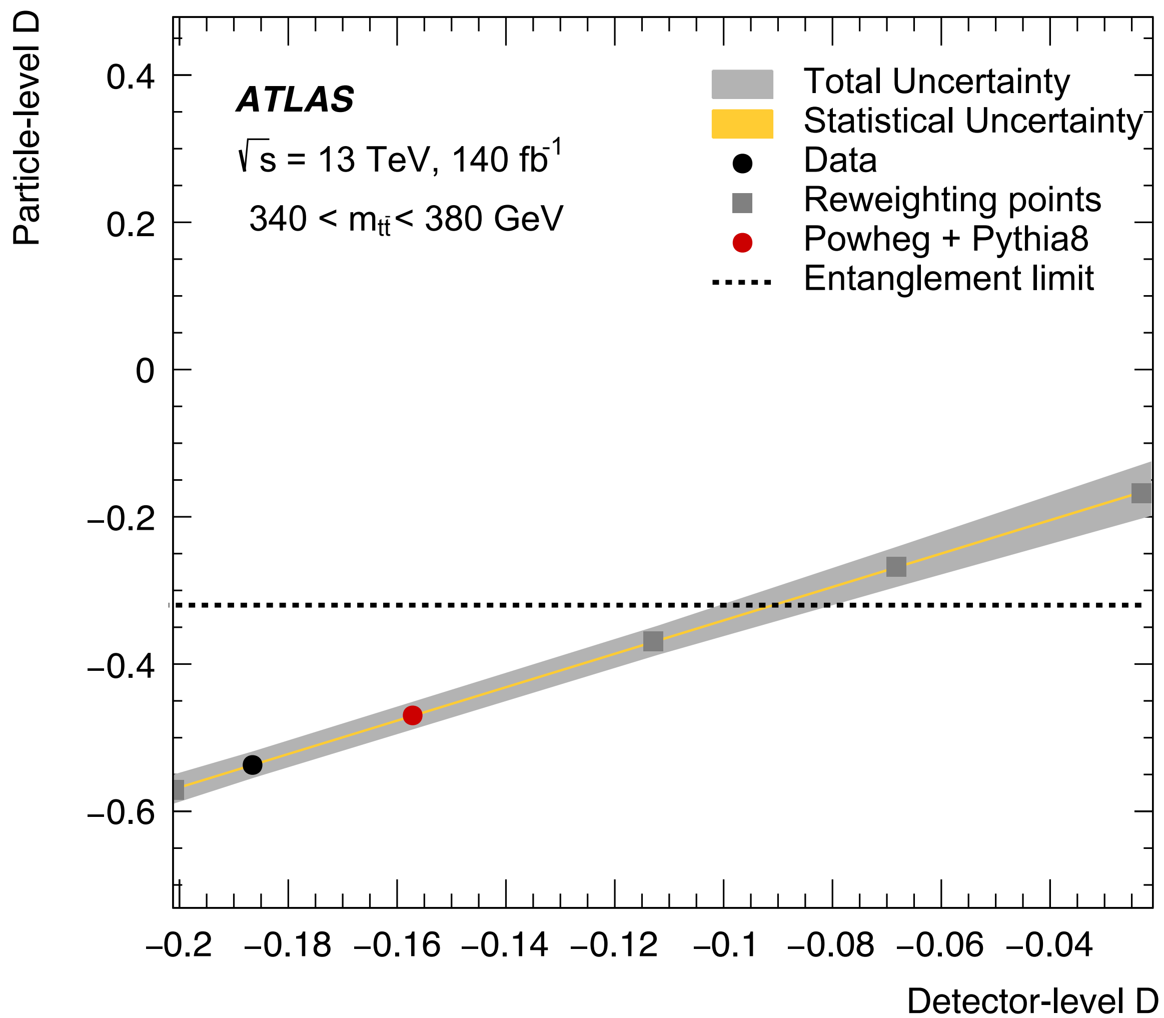


- Angular ordered showers have a large effect compared to dipole showers.

- Doesn’t effect detector corrections significantly.

Calibration Curve

- **This difference between parton showers IS included in the calibration curve!**



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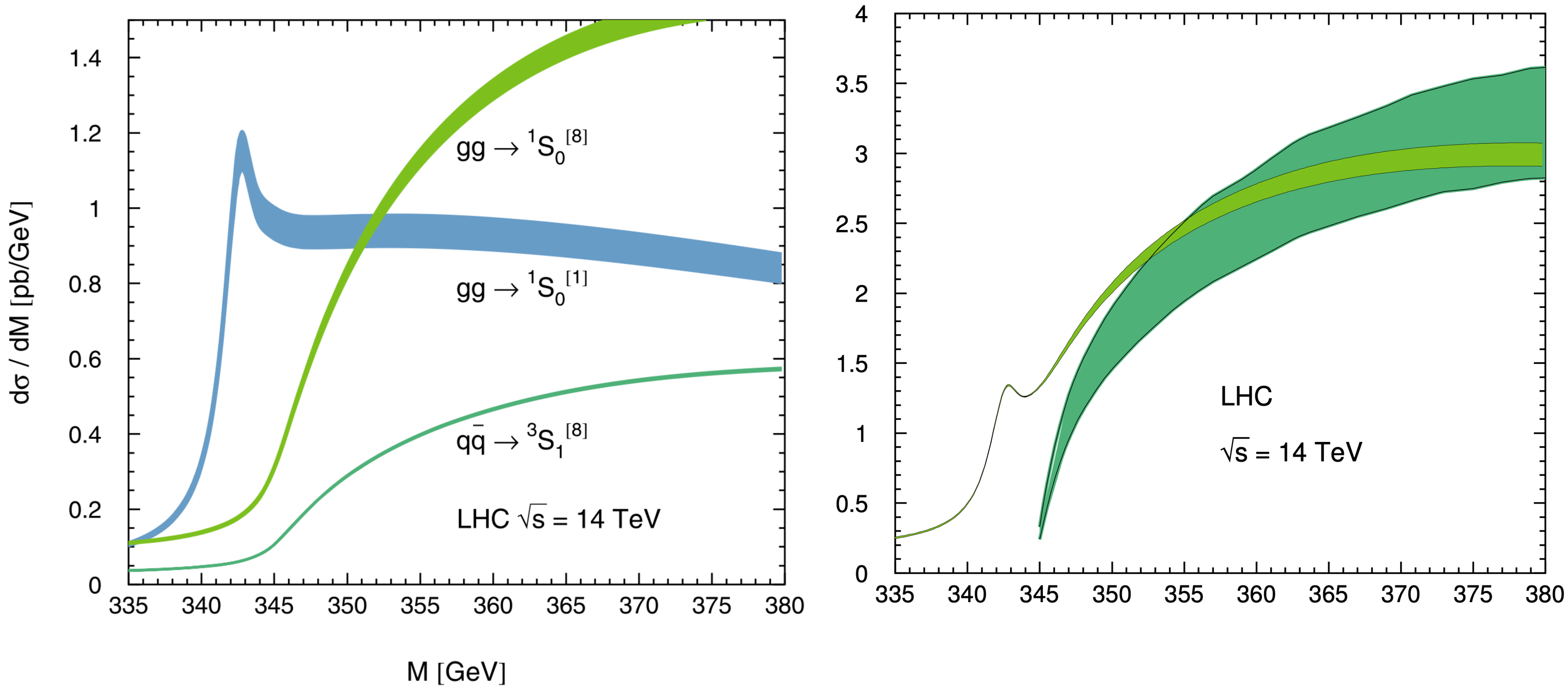
- **Big differences in prediction don't necessarily mean large detector correction effects.**

What about 'Topponium'?

- **Bound state effects are most prevalent in the region that we care about.**

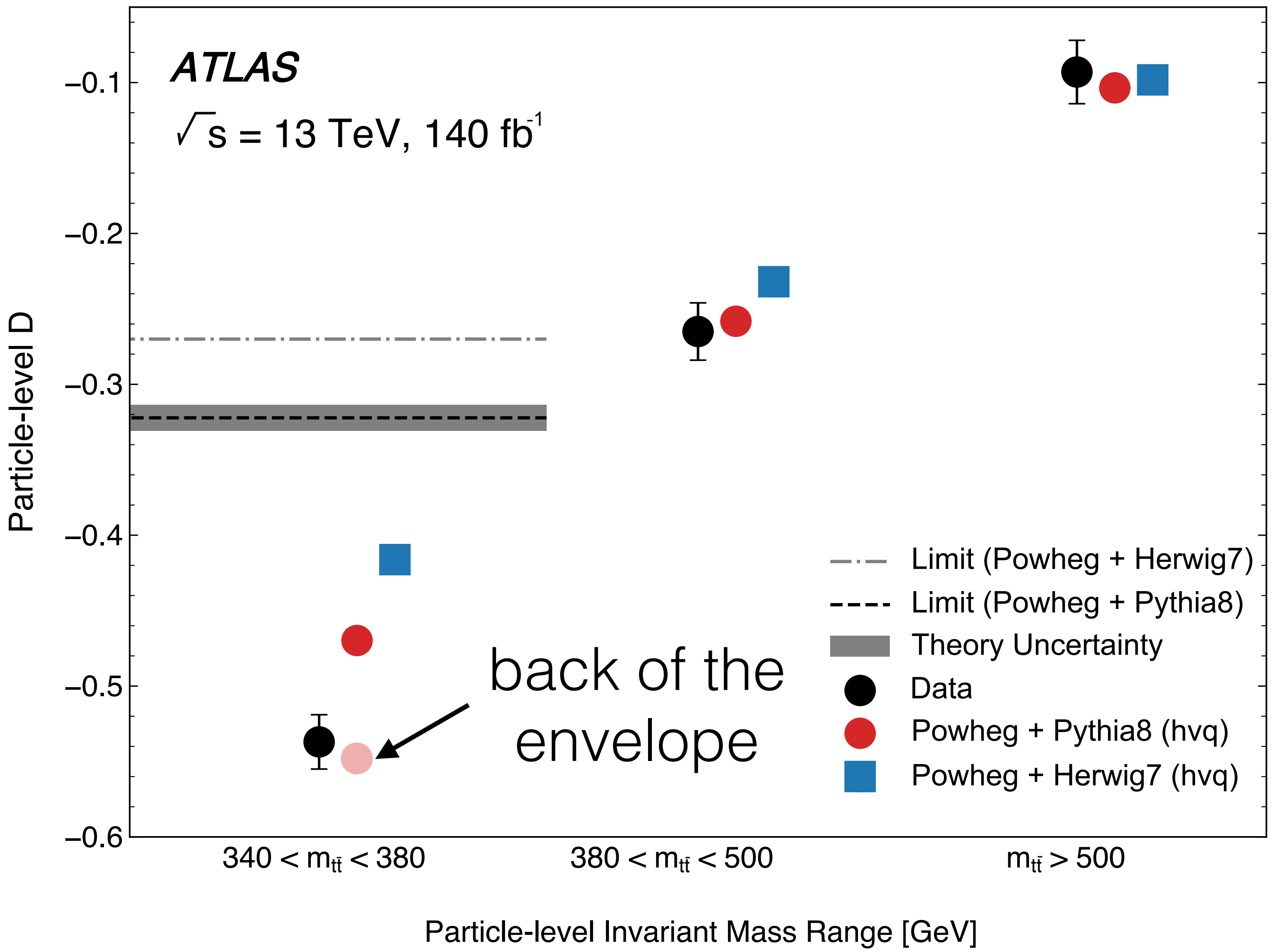
<u>Kiyo, Kühn, Moch, Steinhauser, Uwer, 2009</u>



- **These are not directly included in our MC simulations** (but we have attempted to introduce them as a cross-check and other uncertainties cover similar effects)**.**

Topponium

- **Effect on data correction is ~0.5%** (adding it into the total uncertainty doesn't change the error within the precision we quote).



- **If added to predictions, would move them closer to data** (but not clear by how much as we cannot isolate the spin singlet).

Conclusions

- **ATLAS has observed quantum entanglement for the first time in a pair of fundamental quarks, at the highest lab-made energies.**

- **ATLAS has not made any claims about Bell operators or locality.**

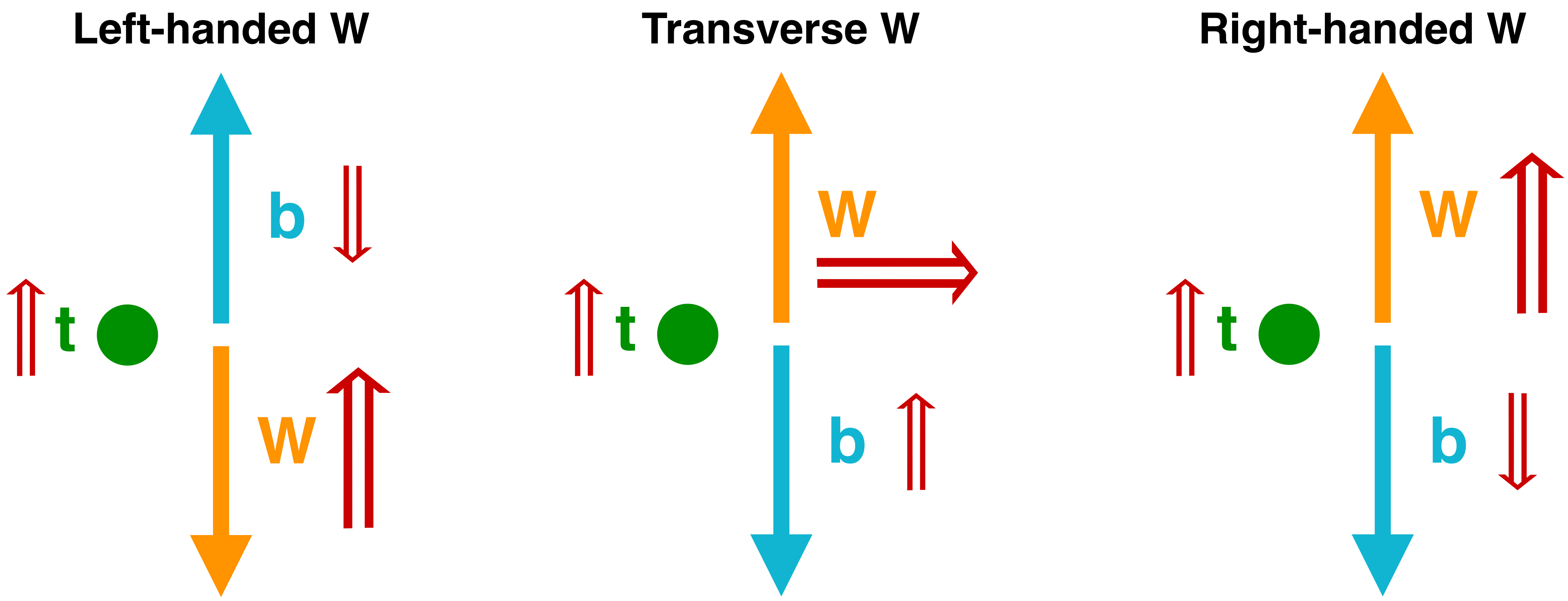
- **This is the first step in a program to use the LHC as a tool for exploring quantum information.**

- **Important questions about how entanglement** (and spin correlation) **is modelled in this threshold region:**
  ➡ **Would be a very profitable area for further study in the theory community!**

Backup

Top Quark Decays

- **W bosons act as their own polarimeters**



Top Quark Decays

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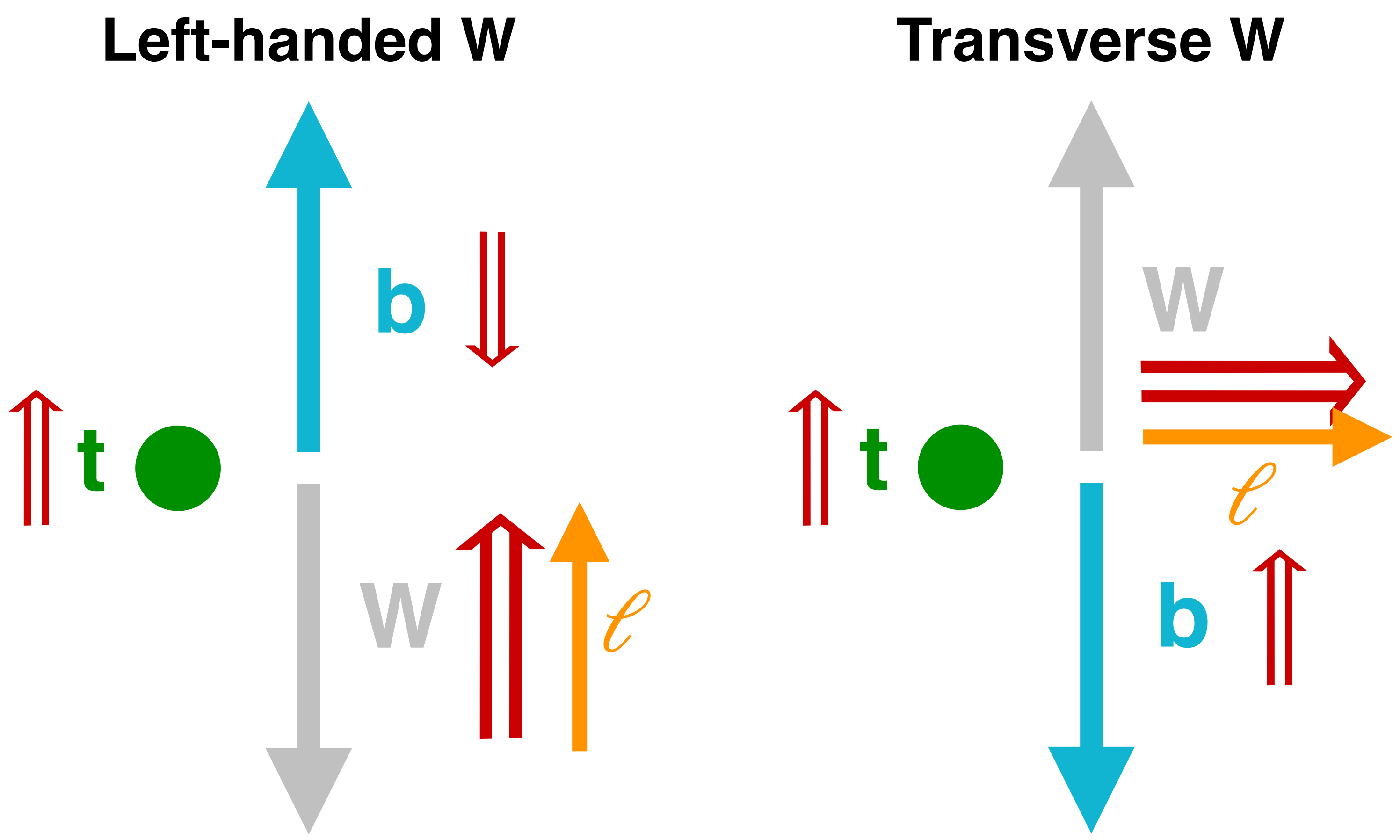
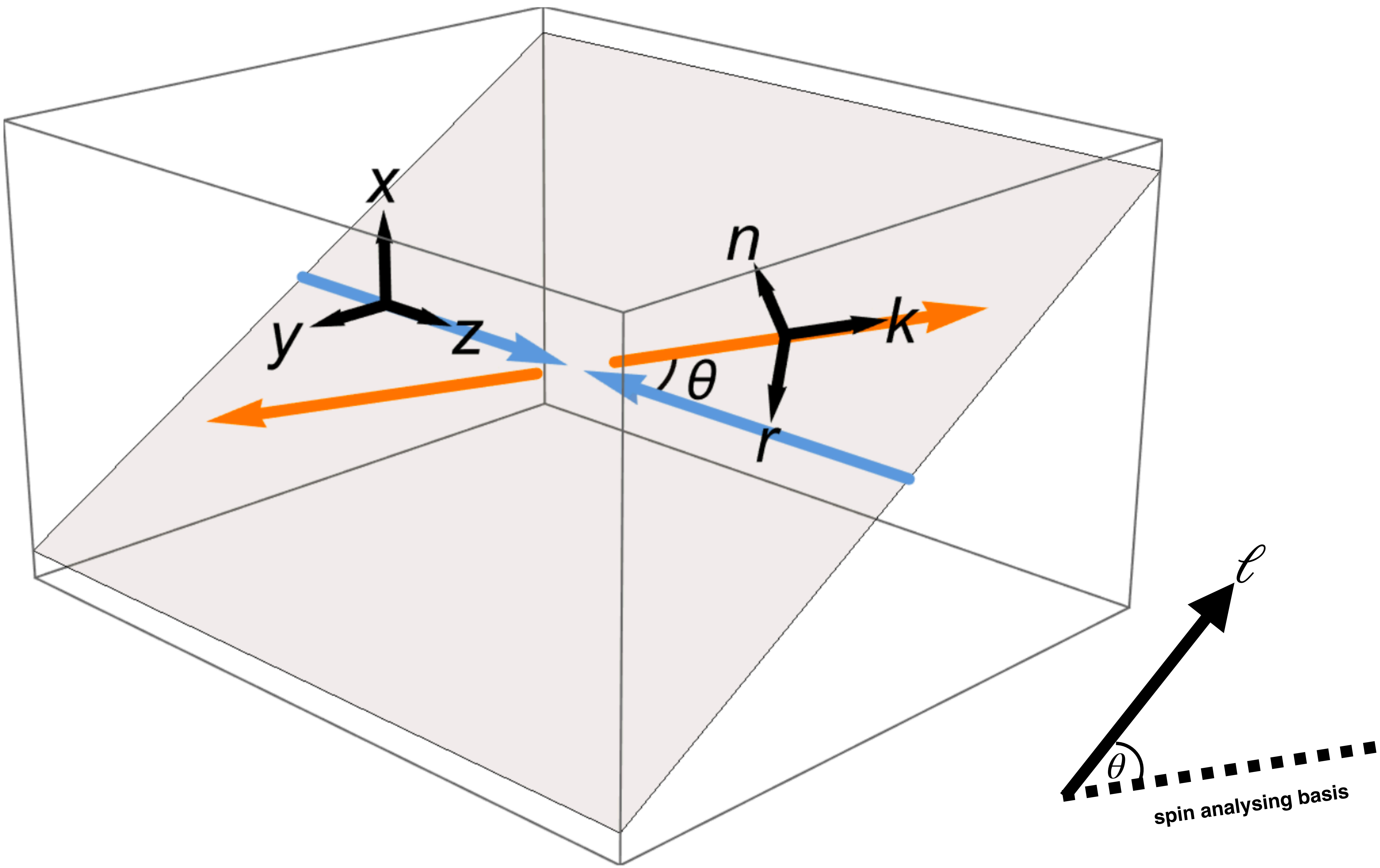


- Their down-type decay particle momenta always points in the direction of their spin!

Spin Correlation in $t\bar{t}$

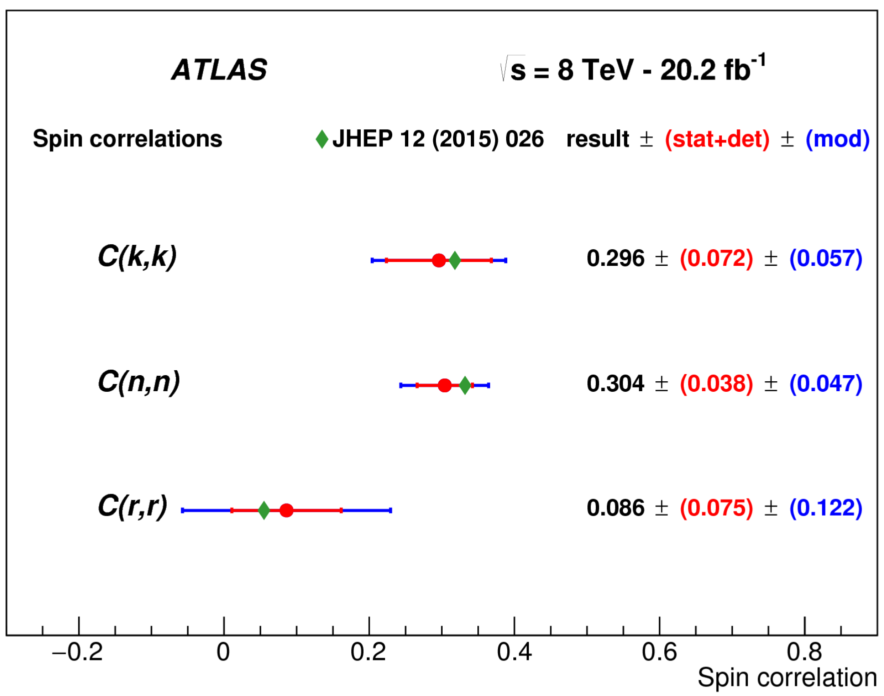
- **It matters how you measure these angles!**



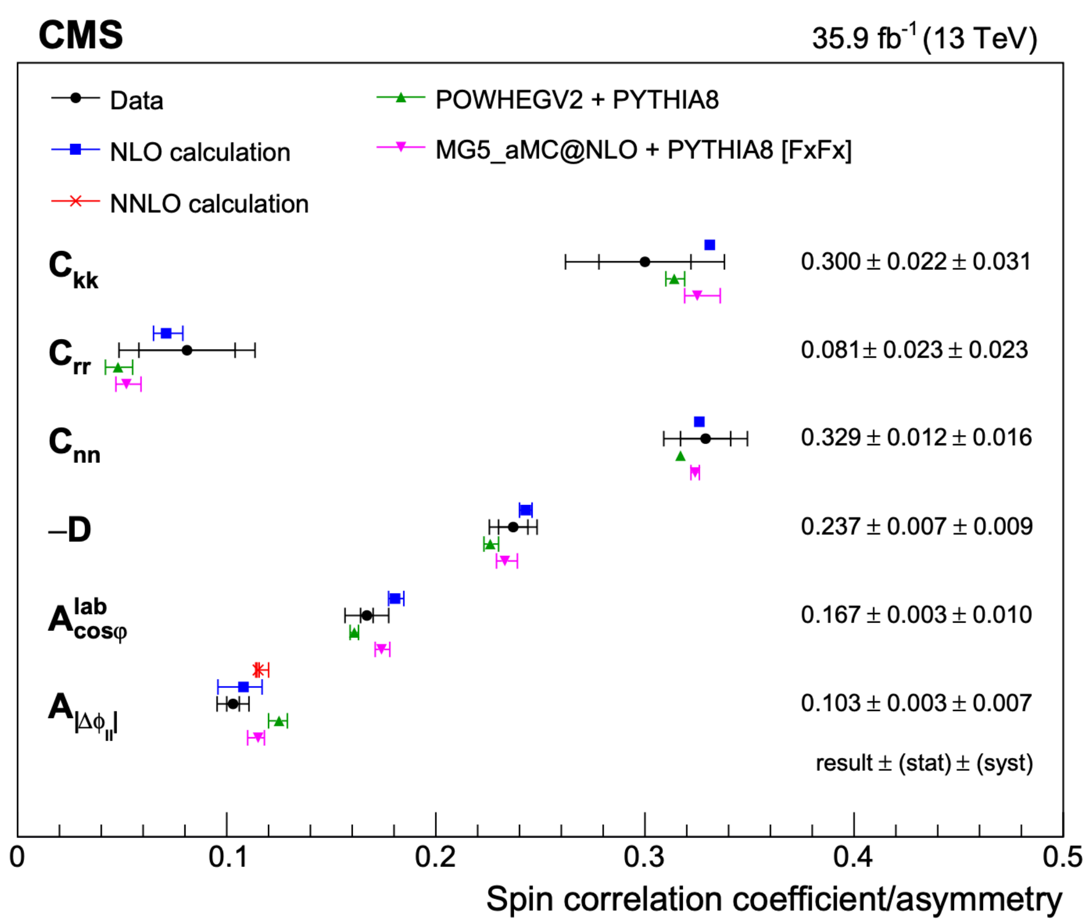
Spin Correlation in $t\bar{t}$

- **You can build spin sensitive observables and measure them in data:**

JHEP 03 (2017) 113



Phys. Rev. D 100, 072002 (2019)

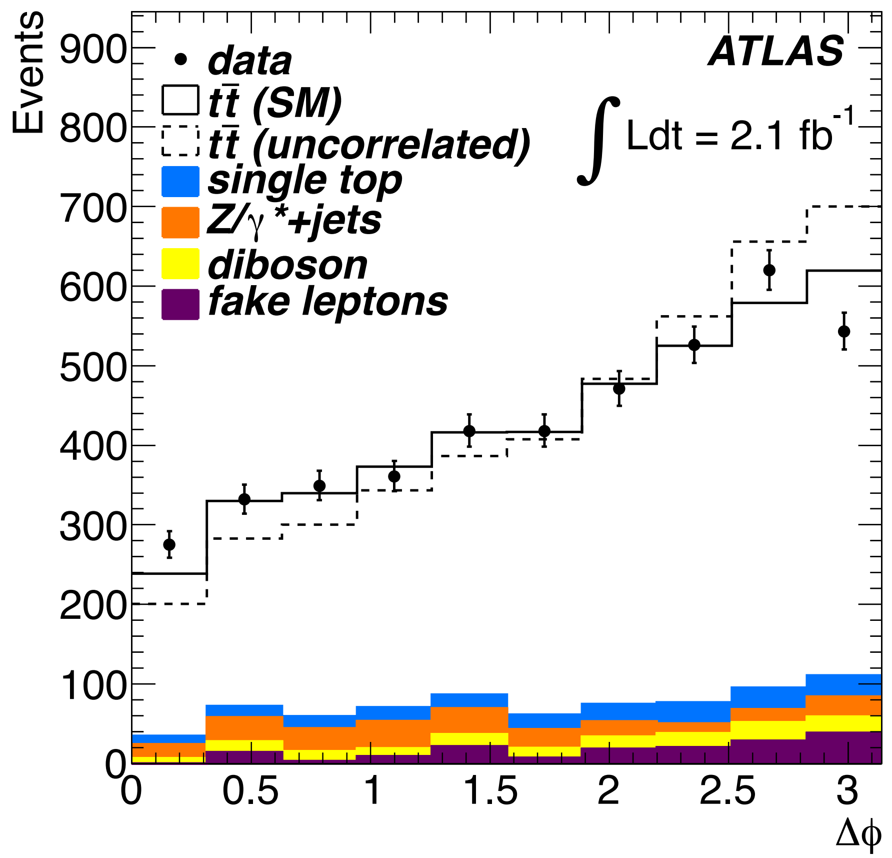


- **Many more observables with interesting symmetry structures and BSM potential** (ask me if you're interested)**.**

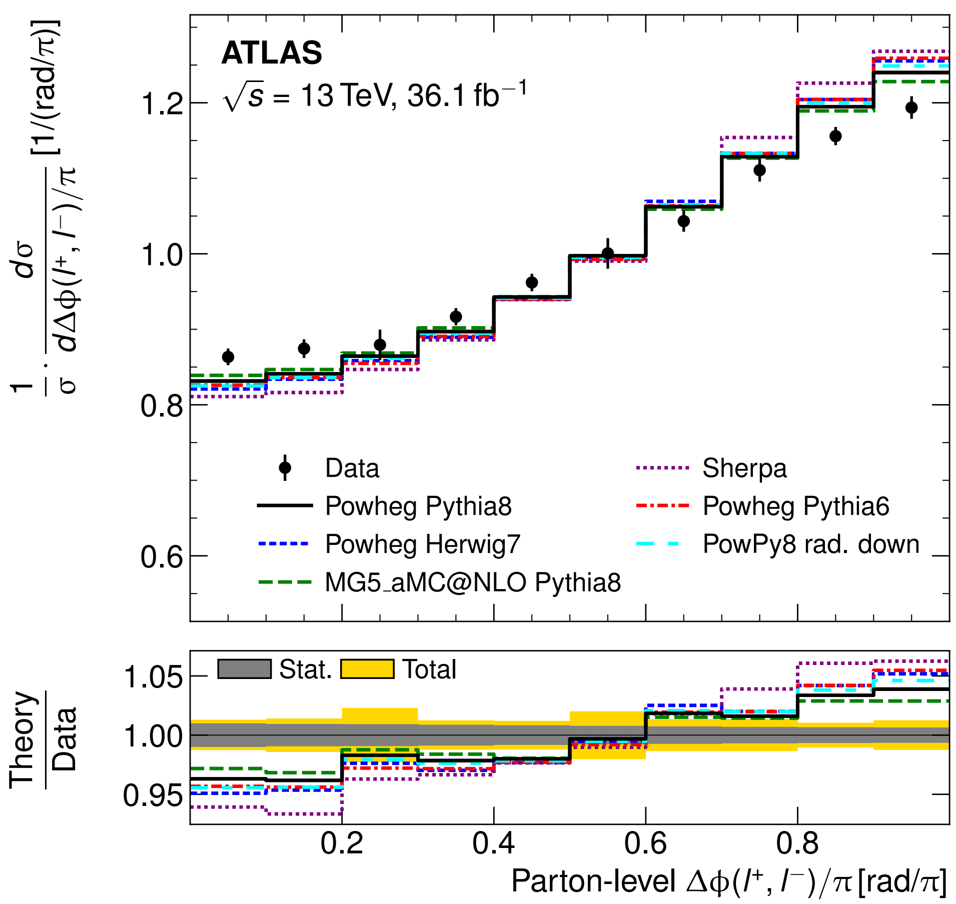
Spin Correlation in $t\bar{t}$

- An easy lab-frame observable that you can build is the $\Delta\phi$ between two leptons in dilepton events:

Phys. Rev. Lett. 108 (2012) 212001



Eur. Phys. J. C 80 (2020) 754



- Was used to discover spin correlation in tops, to exclude light stops, and currently has a 3σ tension with the SM.

Introduction

- It's important to note that:

Entanglement $\not\Rightarrow$ Bell Inequality Violation

- Something can be quantum entangled but not strongly enough measure but not to violate a Bell inequality.

Entanglement in $t\bar{t}$

- **The goal of the ATLAS measurement is to measure:**

$$D = \frac{tr[C(k, n, r)]}{3} = -3 \cdot < \cos(\phi) >$$

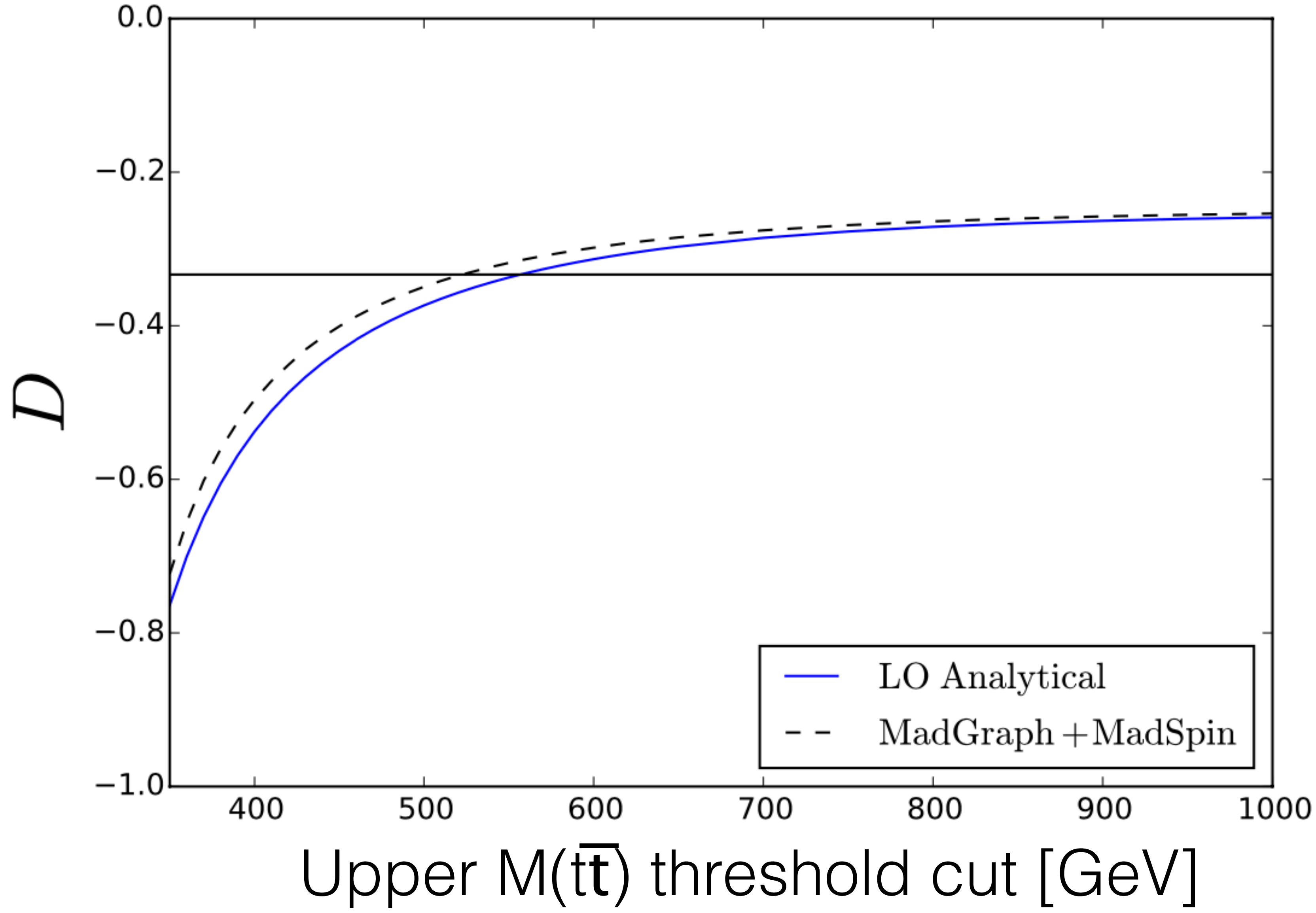
- **Where cos(ϕ) is the dot product of the top spin analysers in their parent top rest frames.**

- **An observation of D < -1/3 is a sufficient condition to claim entanglement in $t\bar{t}$ pairs** (equivalently, that their density matrices are not factorable)**.**

- **ATLAS has measured this D in $t\bar{t}$ events using 140 fb^{-1} of 13 TeV data.**

Getting the small D

- **The primary experimental challenges in this result are to reconstruct the tops with sufficient sensitivity to isolate the threshold region where tops are entangled.**



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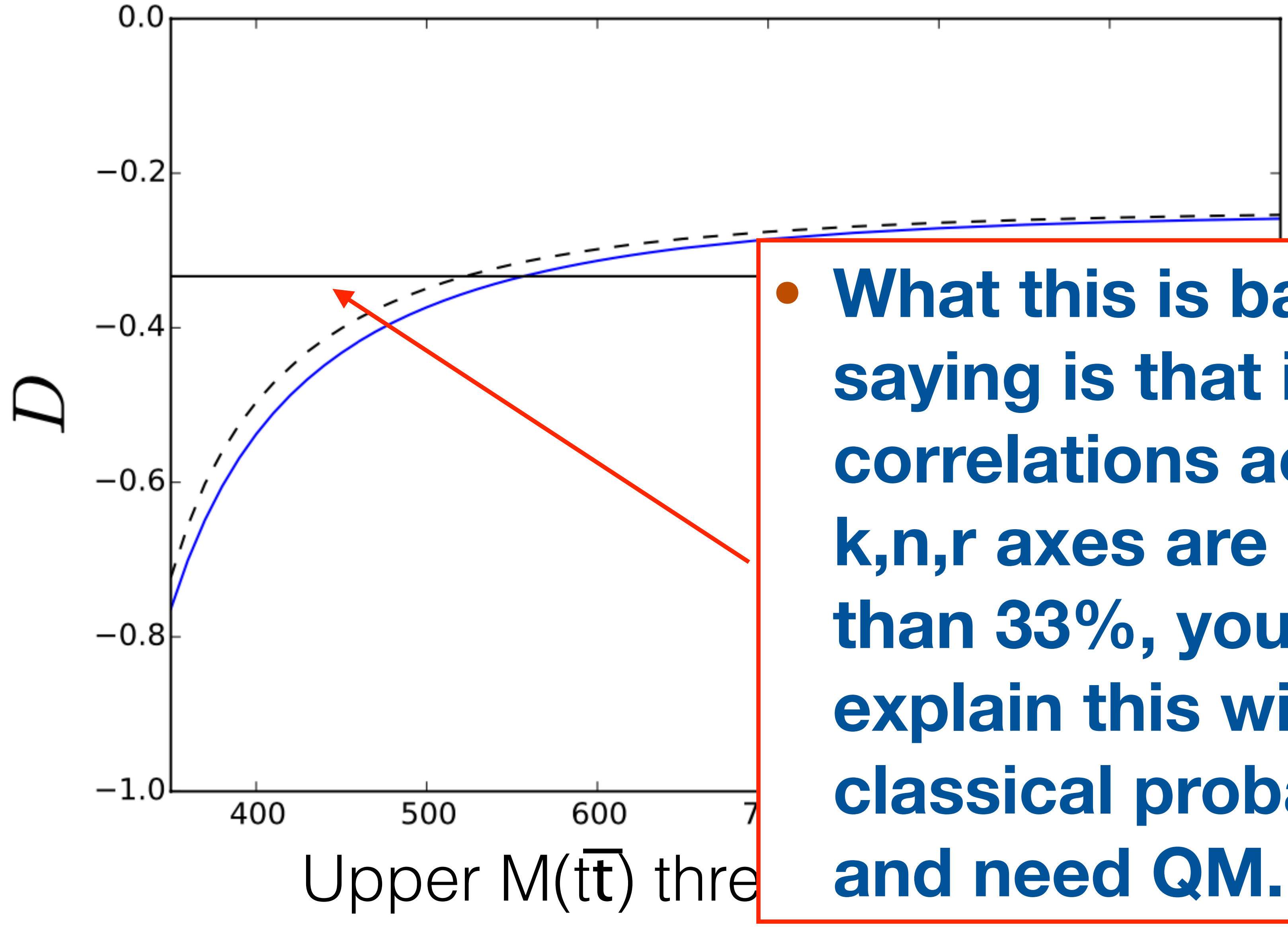
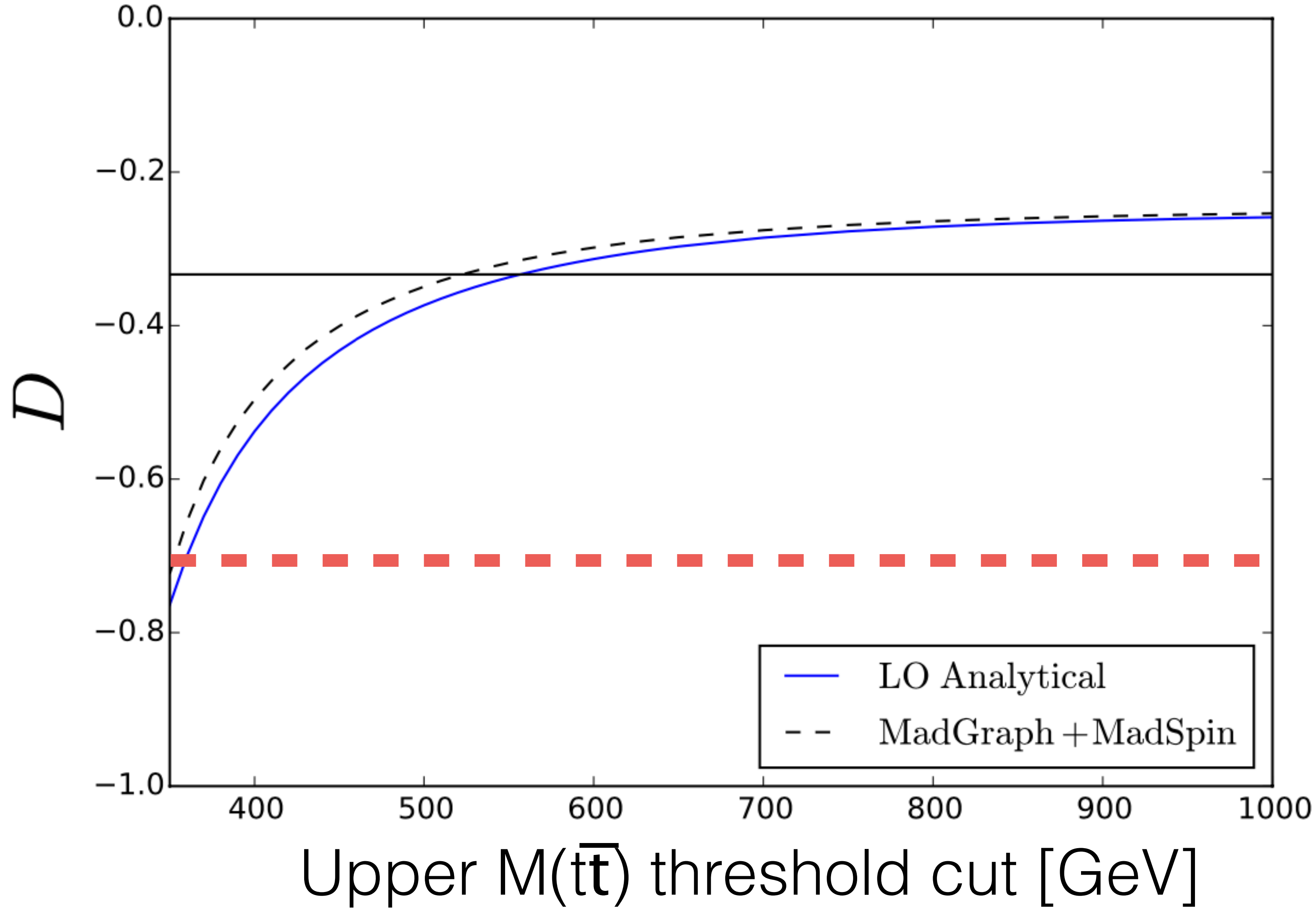


- **What this is basically saying is that if the spin correlations across the k,n,r axes are stronger than 33%, you can't explain this with purely classical probabilities and need QM.**

Getting the small D

- **You can actually use D to do a Bell test if you wanted to** (though it isn't an optimal way)**.**



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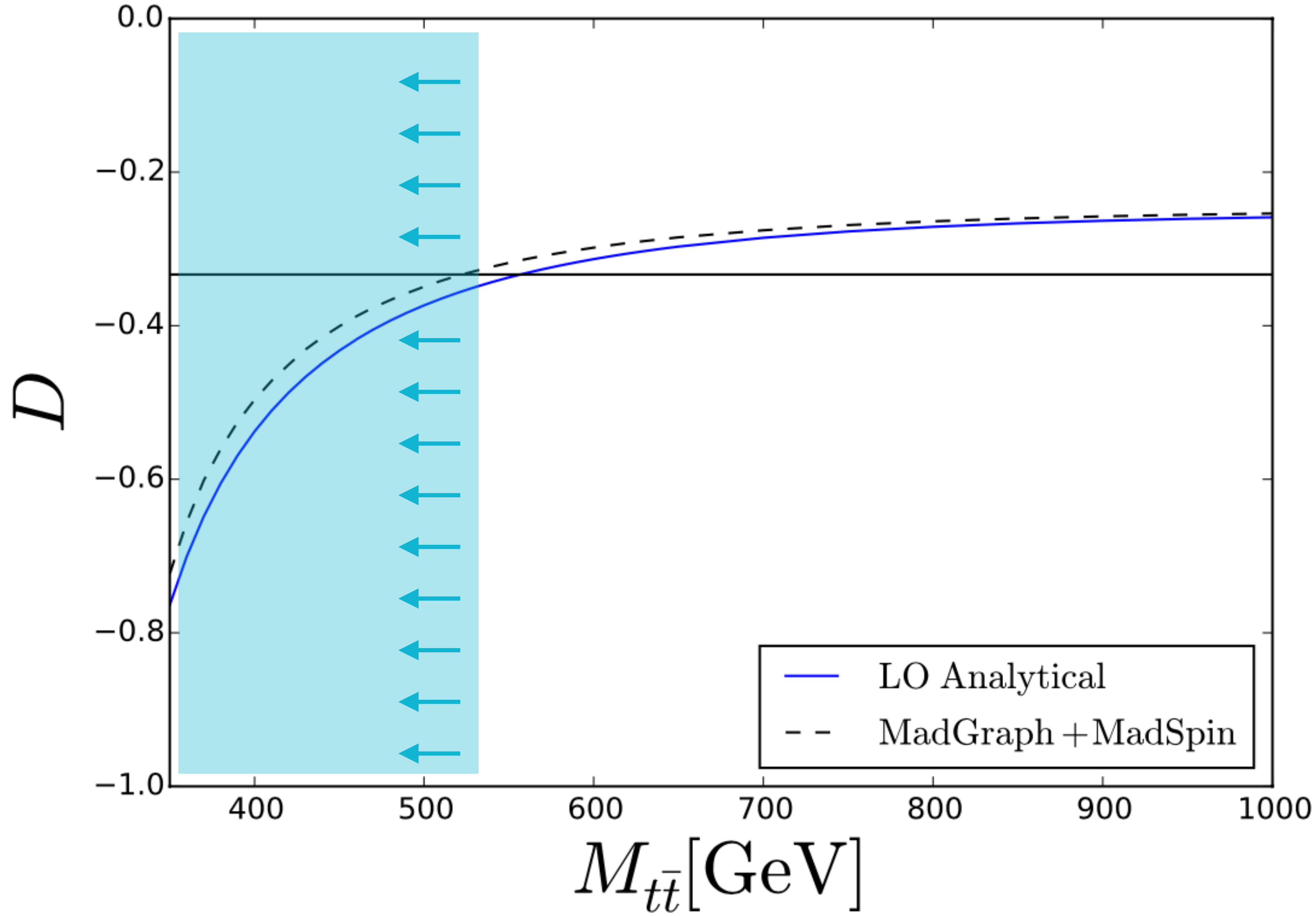
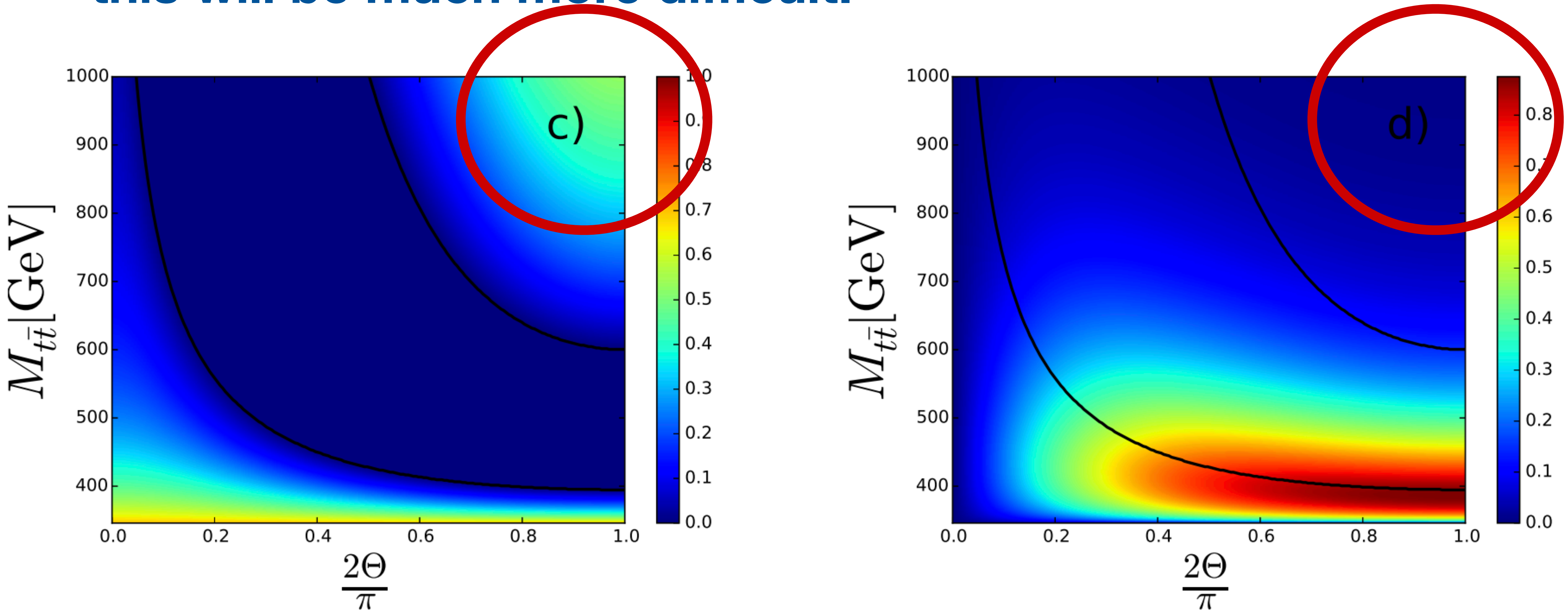


What next?

- **The next target will be to test Bell inequalities** (CHSH)**, but this will be much more difficult.**



- **We have a lot of experience in looking at high-scale boosted top events, but not for spin correlation measurements.**

What would non QM look like?

- **What is allowed without violating relativity** (i.e. non-signalling)

  ➡ **CHSH <= 2**: Purely classical correlations.

  ➡ **CHSH <= $2\sqrt{2}$**: Maximum allowed by QM correlations.

  ➡ **CHSH <= 4**: Maximum allowed by non-signalling.

- **Particle physics measurements aim to minimise the dependence of detector corrections to the POI** (e.g. CHSH)**.**

- **Easy to be sensitive to exotic values for QI observables in principle** (not trivial to test in practice)**.**

Other Processes?

- **Why stop at top quarks? The SM offers many more ways to explore QI, with more exotic spin states:**

- **Higgs decays:**
  - ➡ **HWW** (semileptonic and dileptonic)
  - ➡ **HZZ** (4 lepton)

- **Diboson events:**
  - ➡ **Vector boson processes** (ZZ, WW, WZ etc)

- **Other top decay modes:**
  - ➡ **Boosted semi-leptonic**
  - ➡ **Single top** [brand new idea]

- **Not just stamp collecting, each of these offers unique spin structures.**

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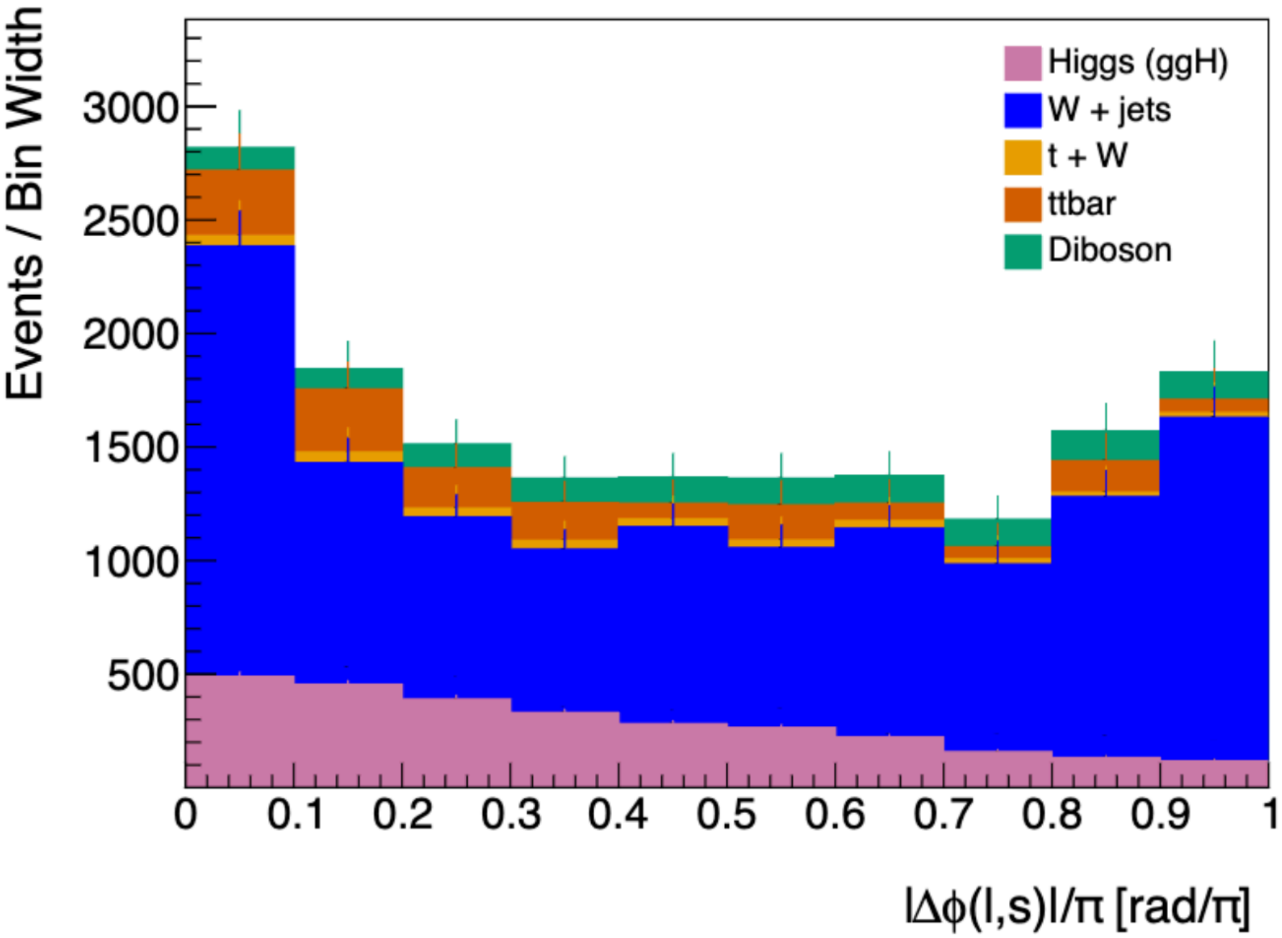

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Unique Opportunities

- **Are there things we can do that no one else can?**
- **"*Autodistillation*" is the idea that as particle systems decay, their entanglement gets stronger.**

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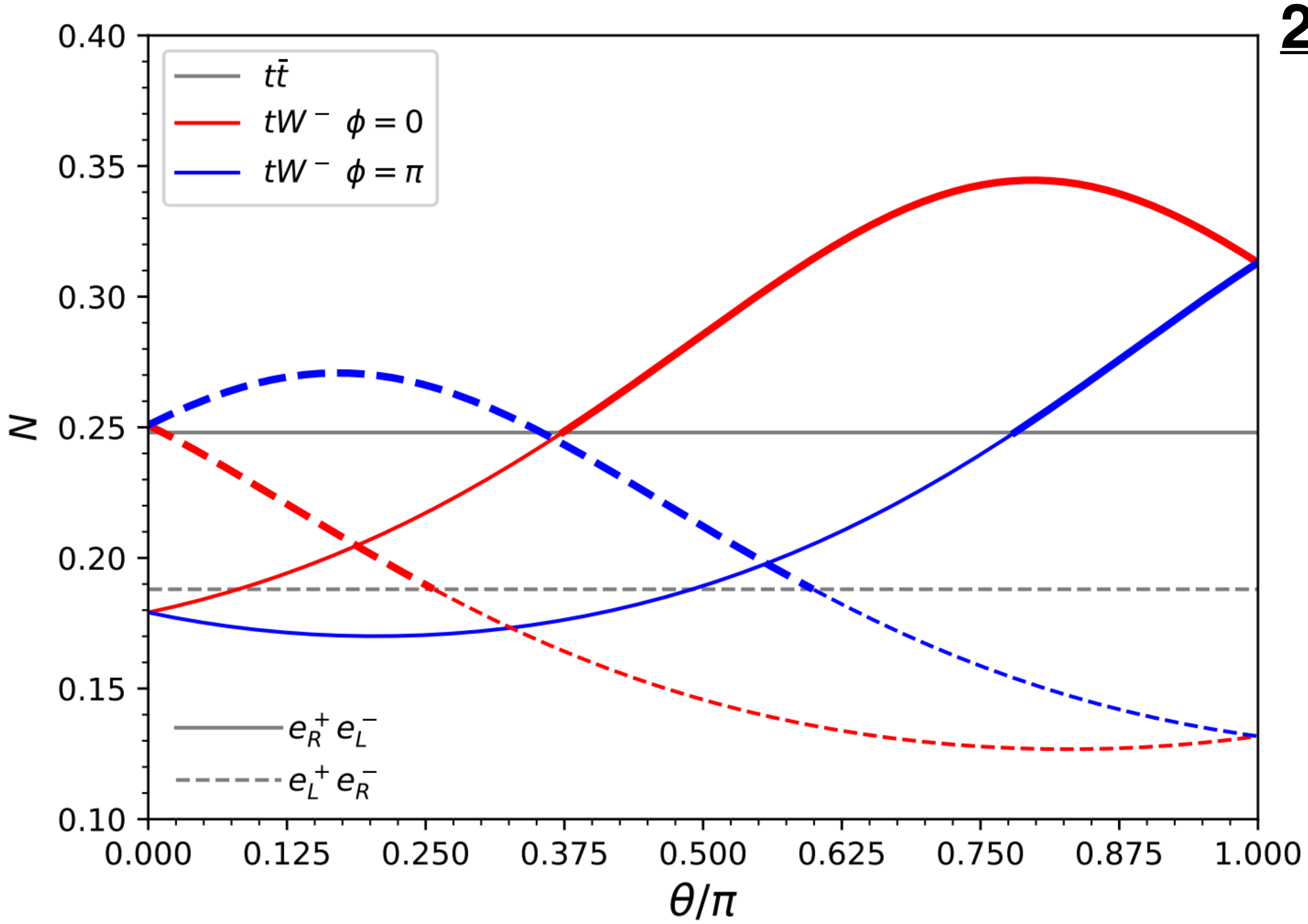


Top Quark Decays

- **This leads to the concept of "spin analysing power":**

	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

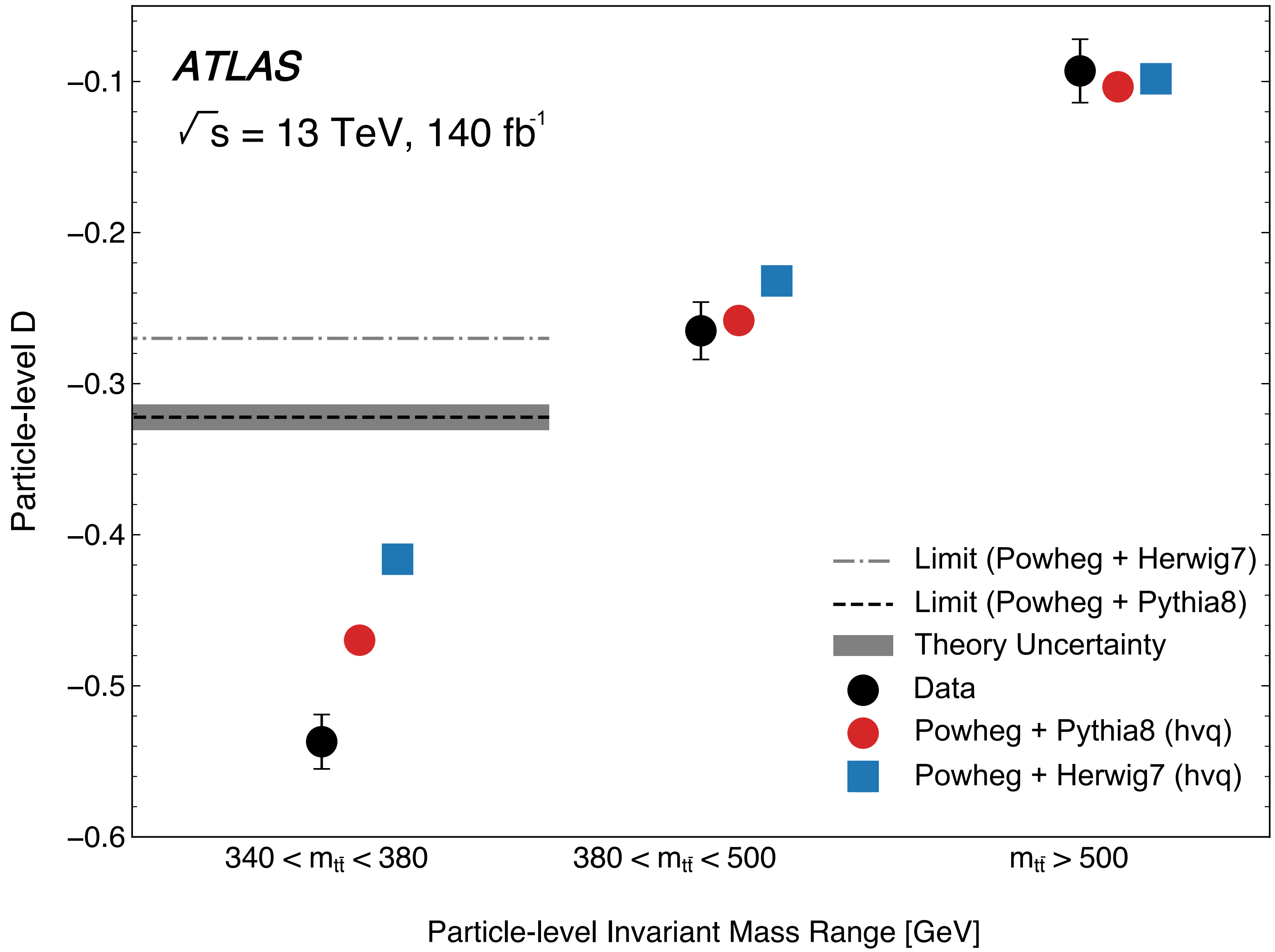
- $\alpha_i = 1$ **means a particle carries the full spin information.**
  $\alpha_i = 0$ **means a particle carries none of the spin info.**

- **Almost all published spin measurements in top physics use the leptonic decay mode:**
  ➡ easiest to identify experimentally.

- **In Run3 we will start to see results using down-type jets.**

Common Questions

- **How reliable are the elements of this result?**



Common Questions

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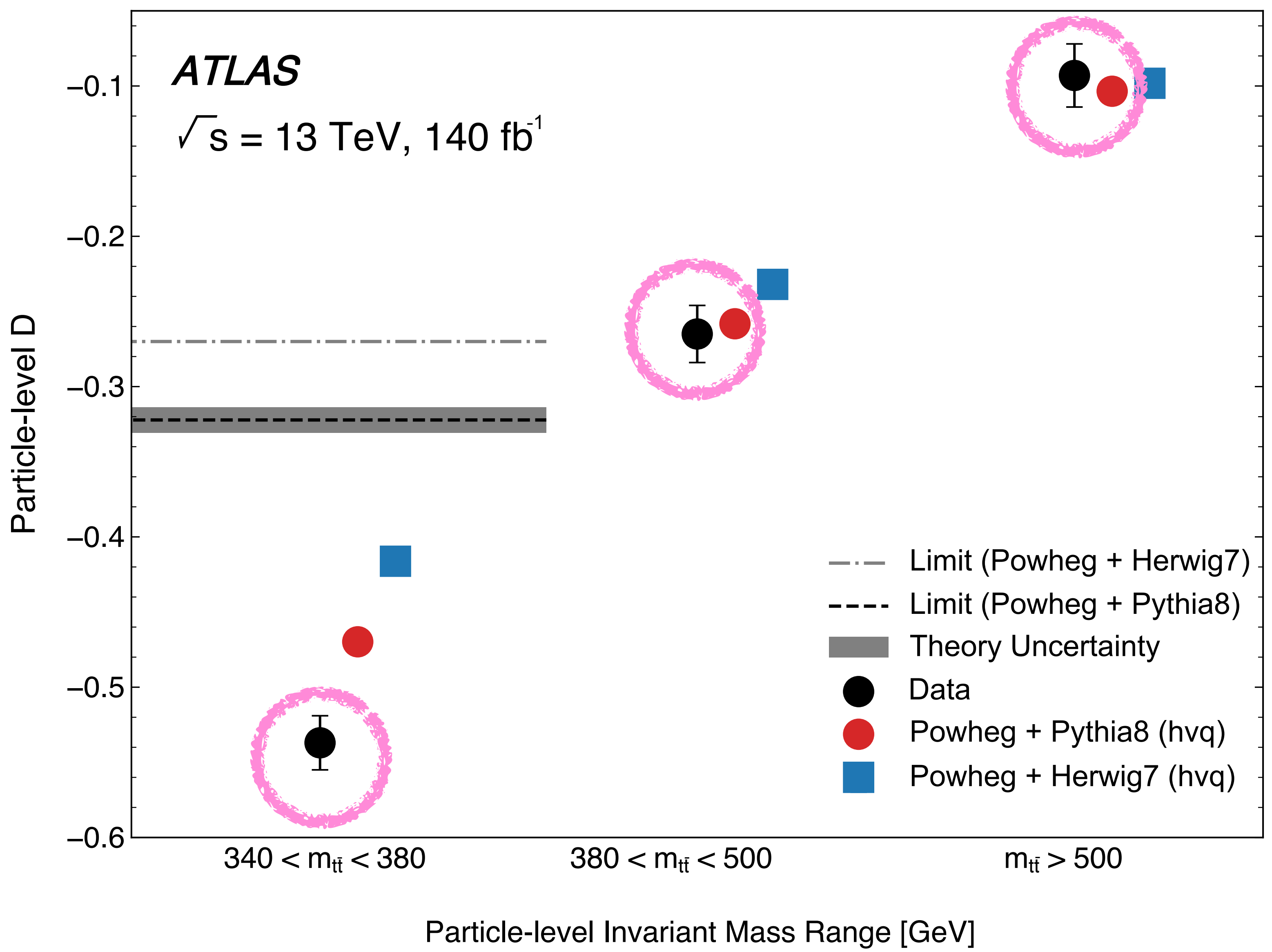
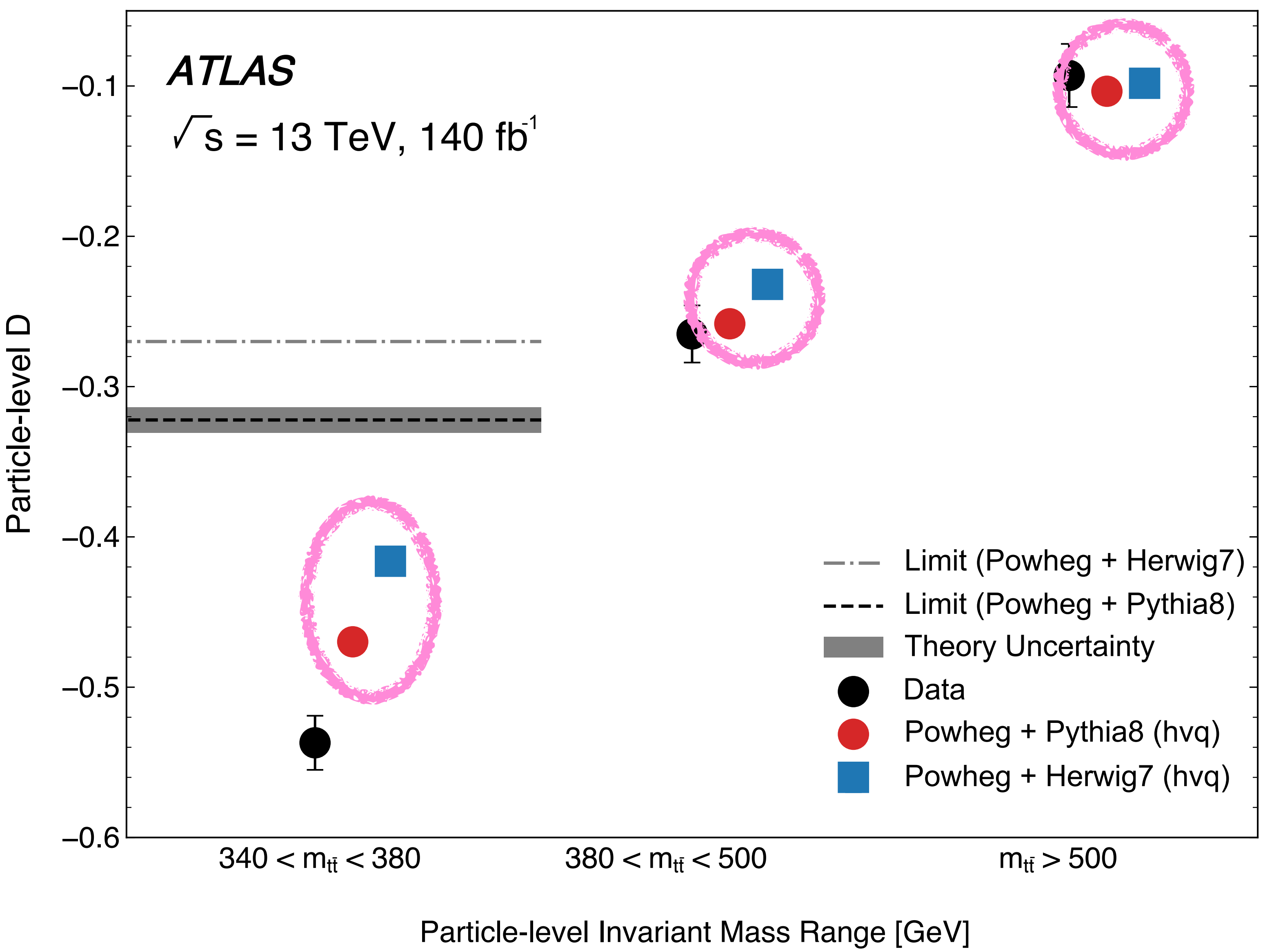


- **Corrections to the data: very reliable**
- **A comprehensive and conservative** (even by ATLAS's standards) **list of systematic uncertainties has been considered on all aspects of the analysis.**

Common Questions

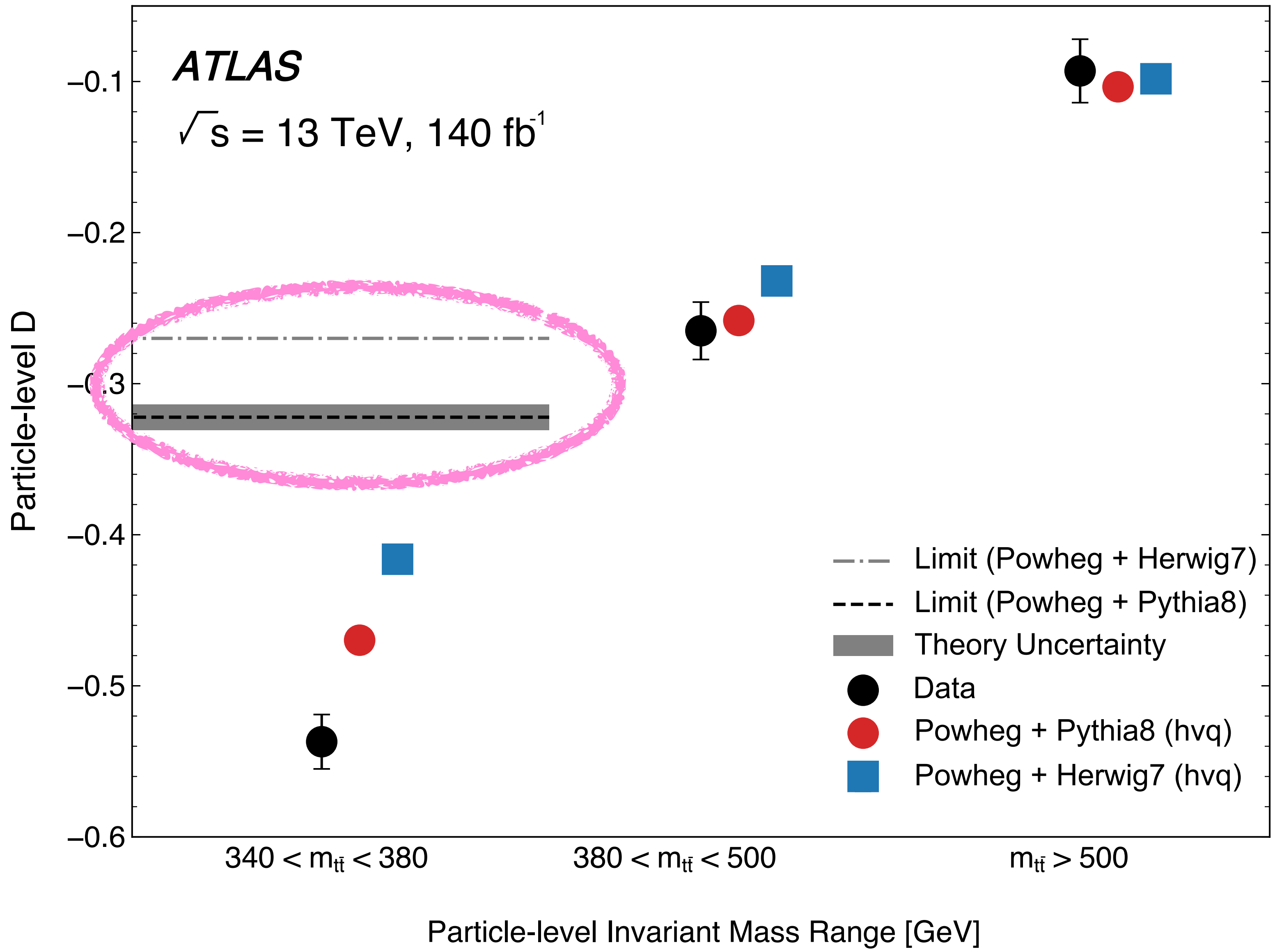
- **How reliable are the elements of this result?**



- **Predictions of the SM: Reliable but limited.**
- **These predictions come from general purpose MC generators:**
  - ➡ We understand them very well, but they are not designed to model threshold perfectly.

Common Questions

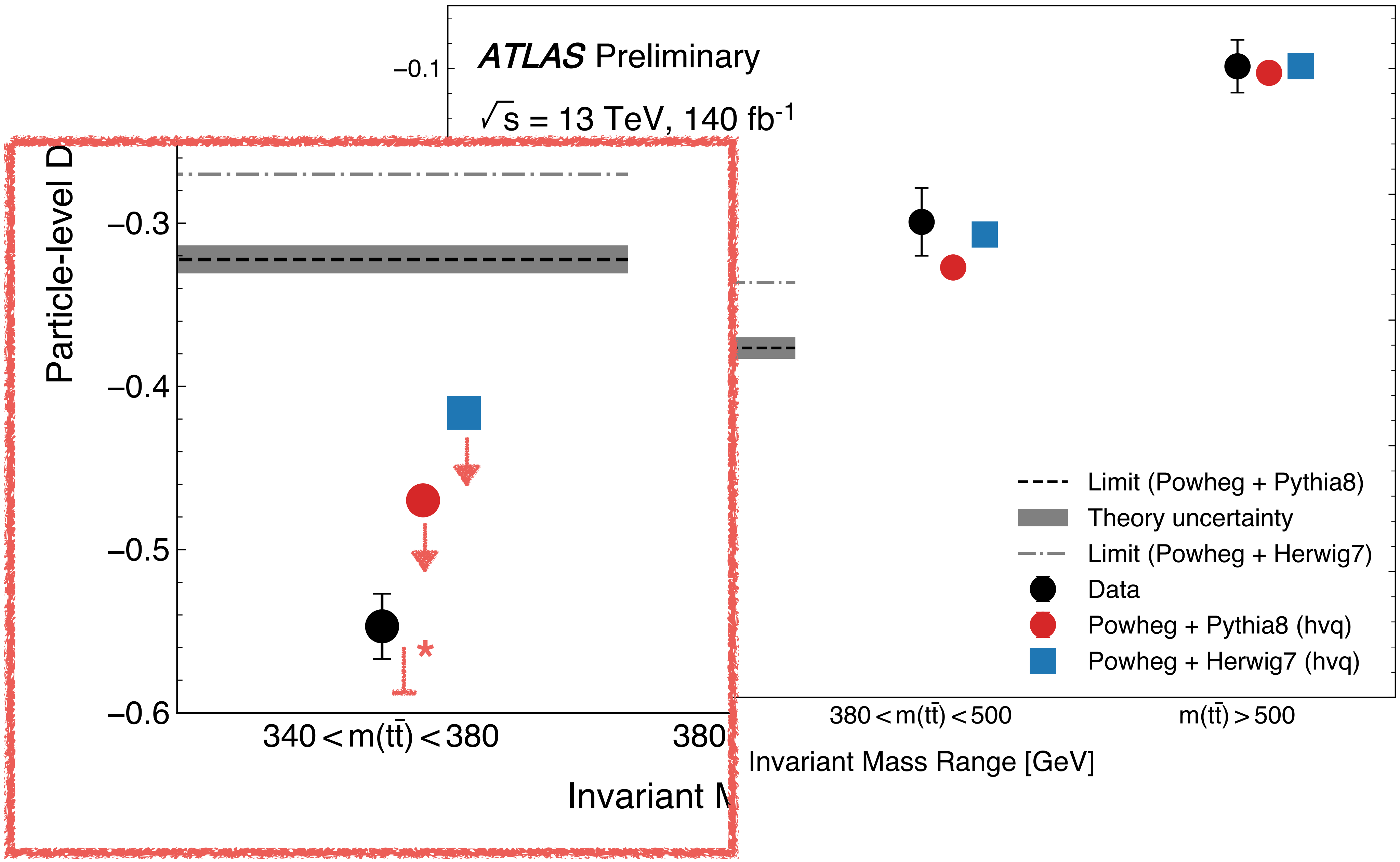
- **How reliable are the elements of this result?**



- **Entanglement limits: Reliable but limited.**
- **Same limitations as predictions.**
- **Two models give different limits, but source is understood and we've taken the most conservative of the two.**

Common Questions

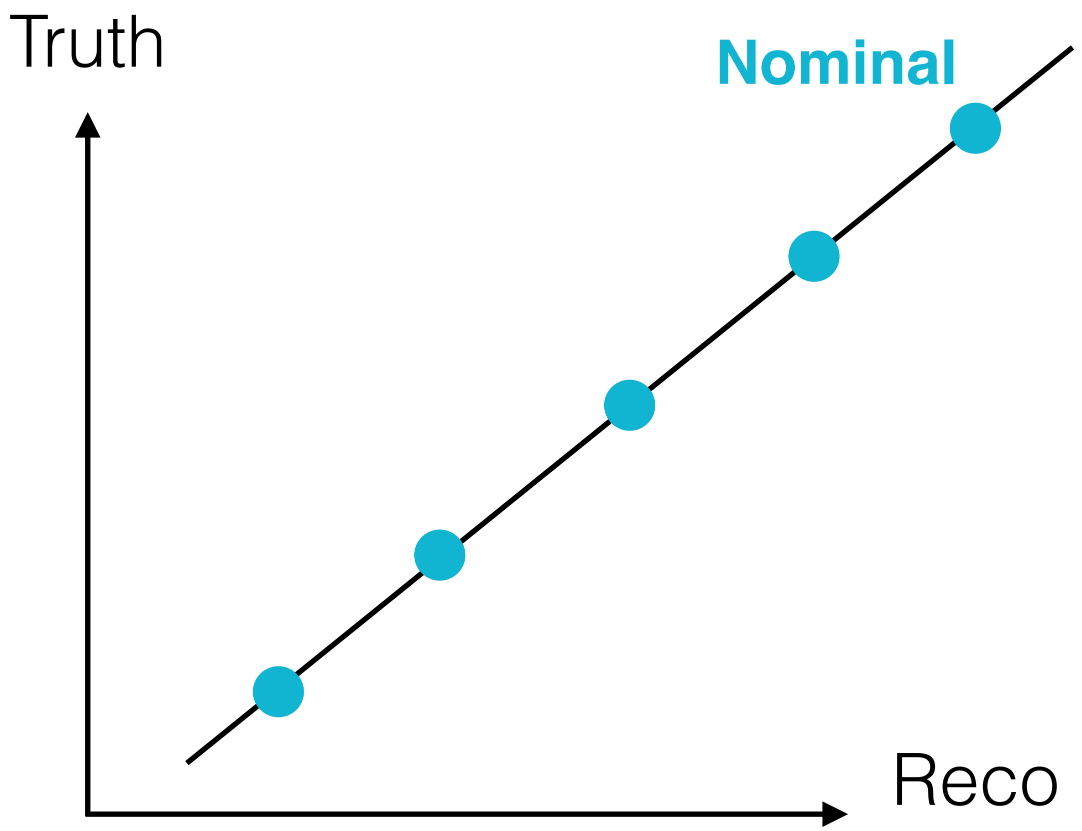
- **Bound state effects should be increasing entanglement:**
  ➡ Including them only makes result <u>more</u> significant, not less.



*exaggerated, the effect on the error bars would be too small to see.

Systematic Uncertainties

- **The relative size of the systematics is not fixed and changes at each hypothesis point:**



Systematic Uncertainties

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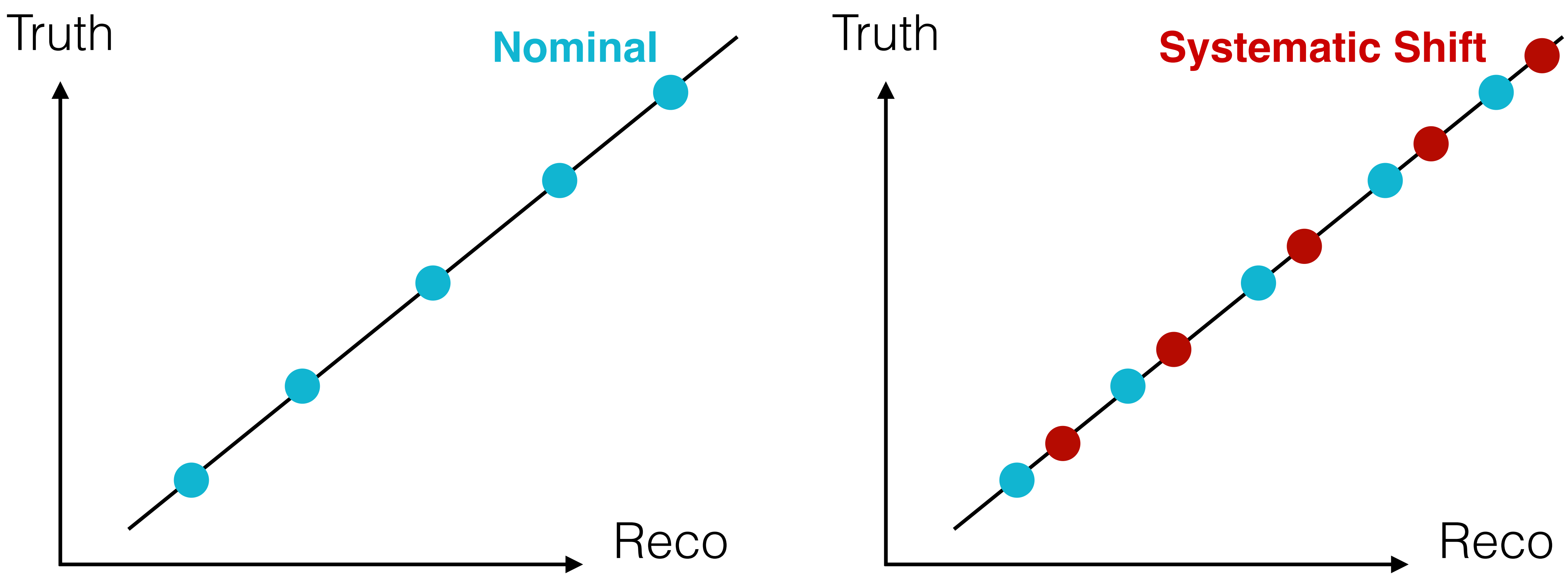
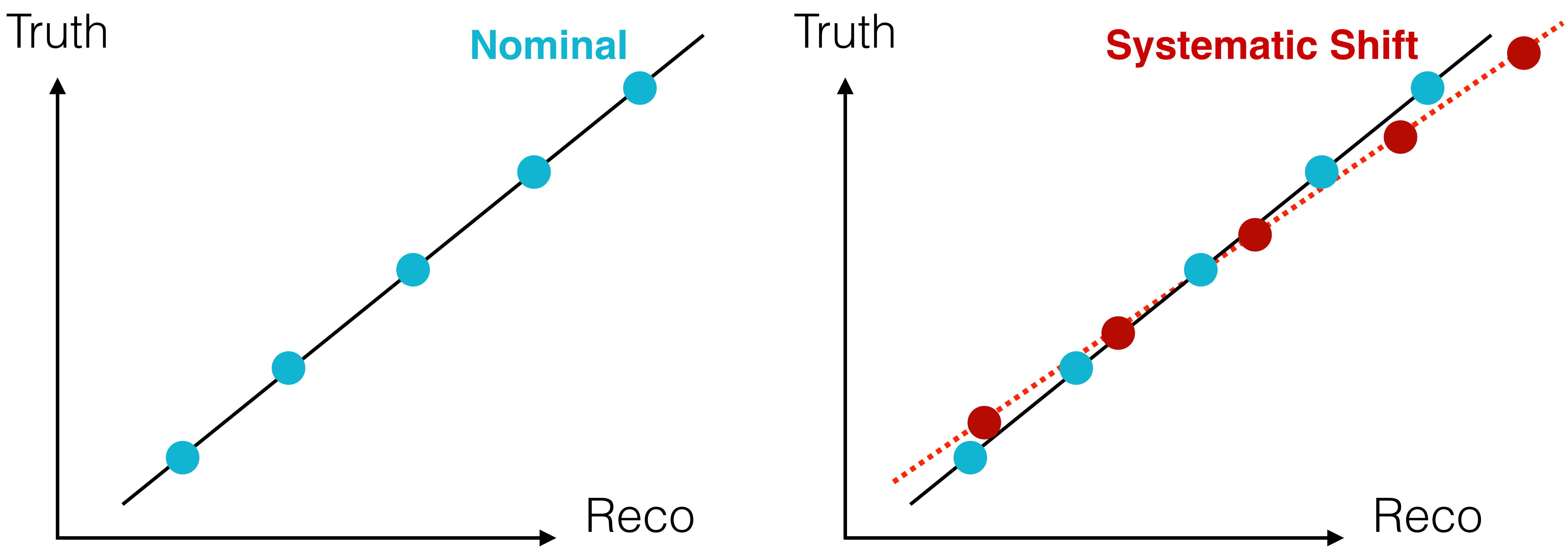


- **Ideally, truth and reco shift in a correlated way, and there is no resultant uncertainty.**

Systematic Uncertainties

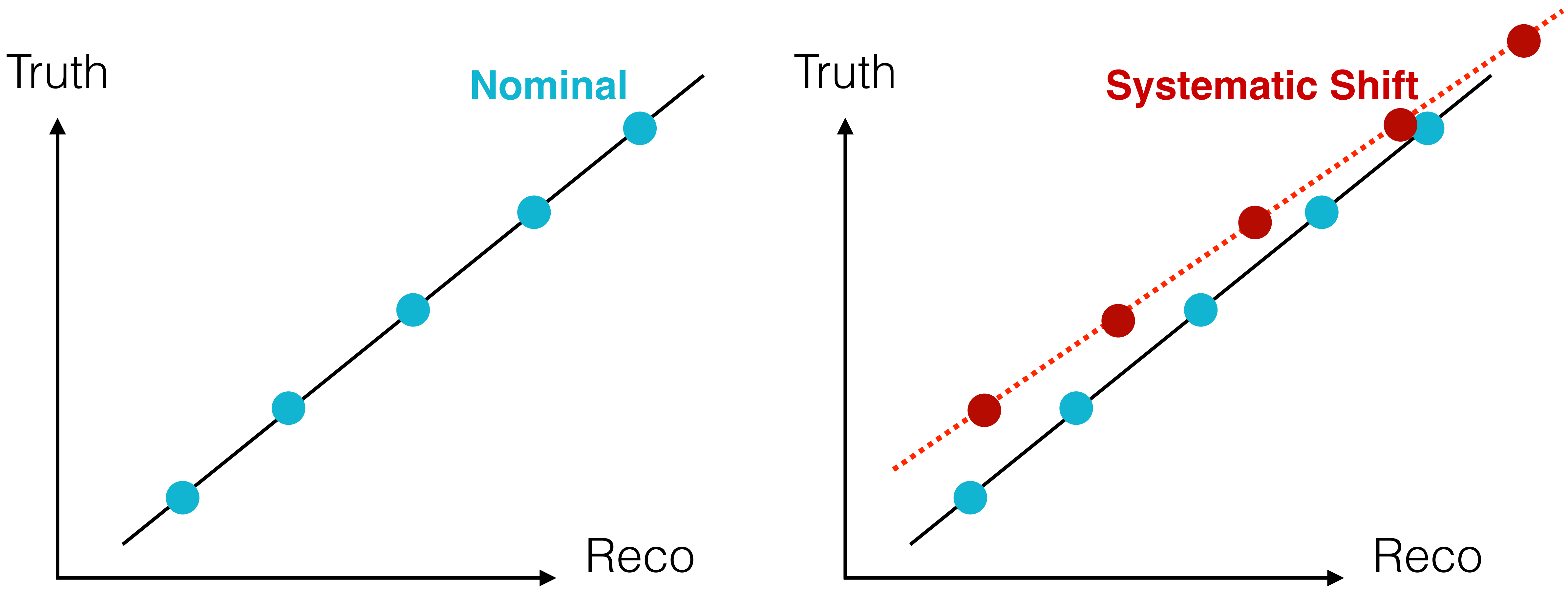
- **The relative size of the systematics is not fixed and changes at each hypothesis point:**



- **In practice, most uncertainties shift reco but not truth and therefore change the slope** (all detector uncertainties do this)**.**

Systematic Uncertainties

- **The relative size of the systematics is not fixed and changes at each hypothesis point:**



- **In the worst case, systematics shift slope and offset and have a large effect** (our dominant uncertainties behave this way)**.**