What is next in top and diboson?

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Quantum observables for collider physics
Firenze, November 10th 2023

Projects PID2019-110058GB-C21 &
PID2022-142545NB-C21funded by
MINISTERIO DE CIENCIA E INNOVACIÓN
UNIÓN EUROPEA
FONDO EUROPEO DE DESARROLLO REGIONAL
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AGENCIA ESTATAL DE INVESTIGACIÓN

Basic question:

why?

Why?

☑ Quantum mechanics is a fundamental pillar of modern physics!
We have to test QM at all times!

However, it is not clear that we should see any effect at LHC even if QM has to be corrected (e.g. with non-linear terms)

low energies:
precision ~ 10^{-10} (?)

top, Higgs:
precision ≳ 10^{-2}

effects must be mass-dependent to be observable

… and it remains to be shown that effects should precisely be seen in entanglement measurements!

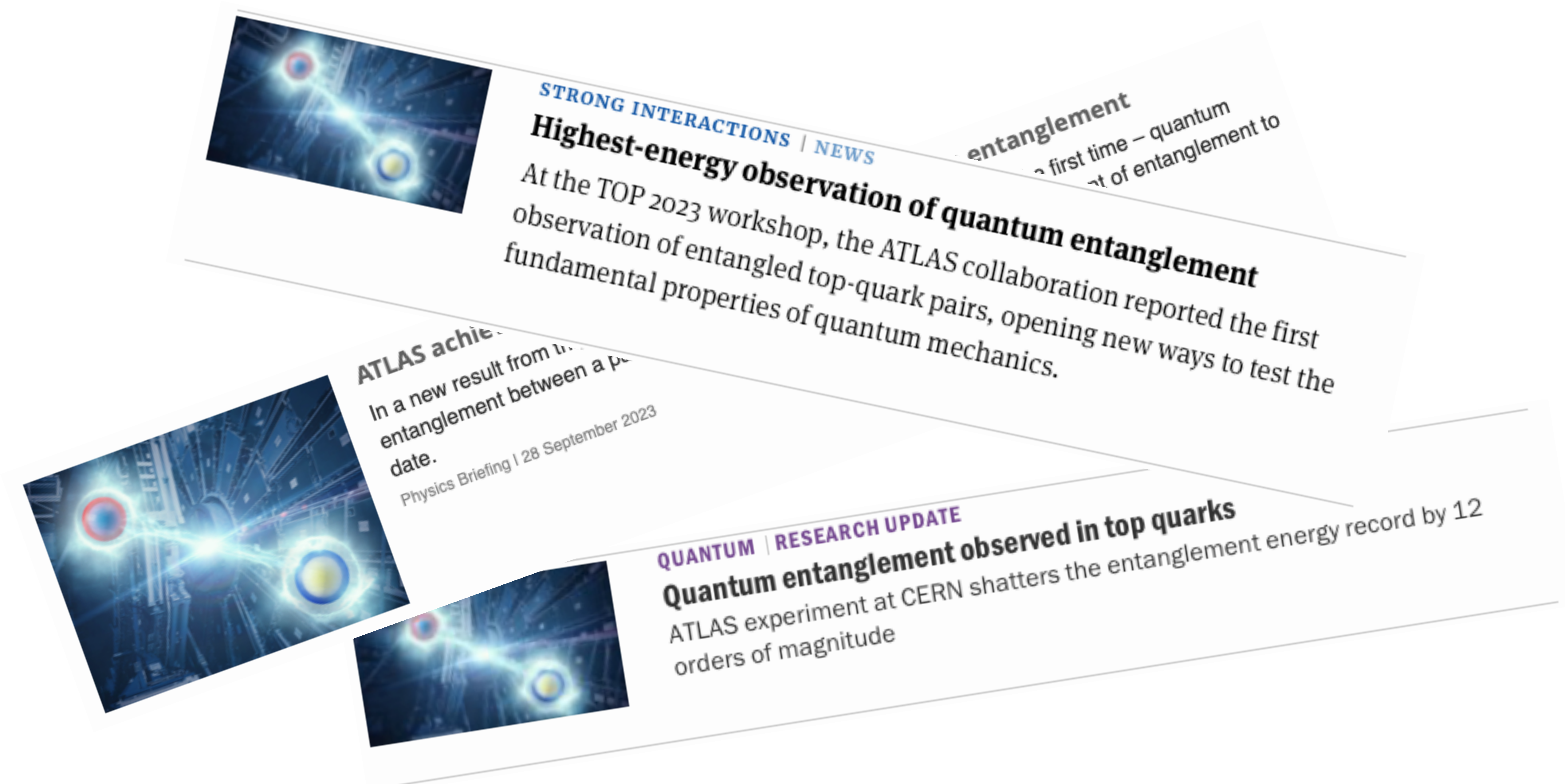
The possibility of QM violation is interesting but does not give a compelling argument for a sustained theoretical / experimental effort

Why?

According to quick poll with a small sample, people are not very enthusiastic with the possibility of QM disproval at LHC…

Why?

☑ It is a new topic that gets headlines and publicity



… but after the initial novelty, future measurements will likely attract less attention …

Why?

☑ Looking for new physics

Yes, but only if we use dedicated observables.

Example: ATLAS and CMS measured spin-correlation coefficients C_{kk}, C_{rr}, C_{nn} in t t-bar production.

If we consider entanglement observables

$$C_{kk} + C_{rr} + C_{nn} \equiv 3D$$
$$C_{kk} + C_{rr} - C_{nn} \equiv 3D_3$$

and measure them indirectly from C_{kk}, C_{rr}, C_{nn}, it is unlikely to have any sensitivity gain.

The way to improve sensitivity is to consider observables that directly measure D and D_3 from distributions.

[an observable for D is known since long]

Why?

☑ Novel entanglement tests that were not possible before.

What is genuinely new in particle physics with respect to experiments with electrons and photons? Particle decay.*

- Post-decay entanglement: JAAS 2307.06991

A and B entangled
$A \to A_1 A_2$

$\Rightarrow$

A_1, A_2 and B entangled
A_1 and B entangled

- Entanglement and post-selection: JAAS 2308.07412

A and B entangled
$A \to A_1 A_2$
Measurement on B

time

$\Rightarrow$

$\asymp$ spin selection on A,
which already has decayed

* J. Bernabéu, talk at 7th Red LHC workshop, Madrid, May 10-12 2023

Why?

☑ Novel entanglement tests that were not possible before.

Also, tests with qutrits have only been performed with non-elementary objects. At LHC we have W and Z pairs in many processes:

- Higgs decays $H \to WW$ — Barr 2106.01377; JAAS 2208.14033; Fabbri, Howarth, Maurin 2307.13783
- Higgs decays $H \to ZZ$ — JAAS, Bernal, Casas, Moreno 2209.13441
- Electroweak production — Ashby-Pickering, Barr, Wierzchucka 2209.13990; Fabbrichesi, Floreanini, Gabrielli, Marzola 2302.00683
- VBF — Morales 2306.17247

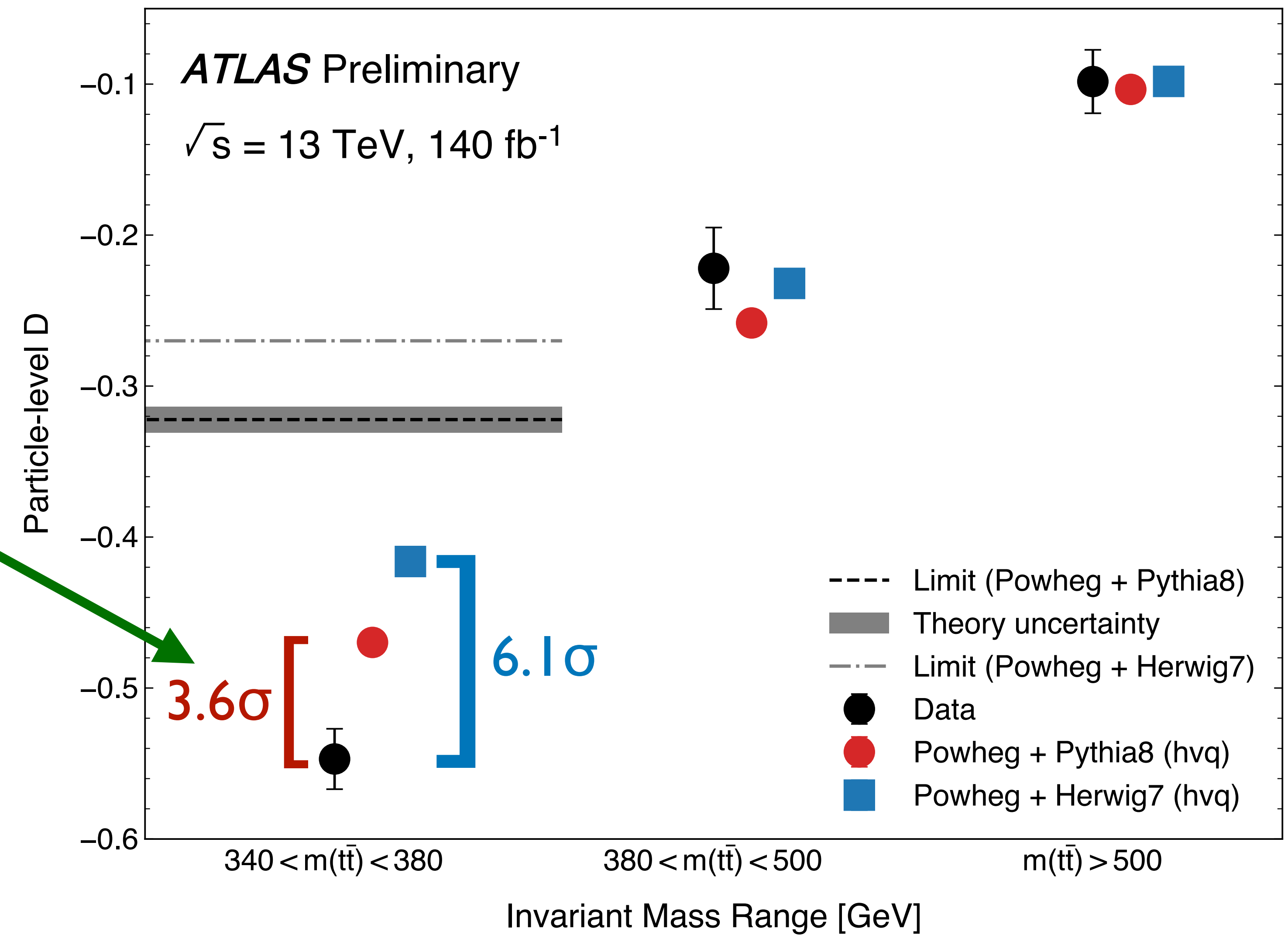
Why?

☑ Last, but not least, entanglement measurements are quite demanding, and provide a stress test on our current understanding of

- theoretical modeling
- experimental systematic uncertainties

Example: ATLAS entanglement measurement

Even if ATLAS does not make such claim, everybody can see that predictions and measurement are quite off and digitise the plot

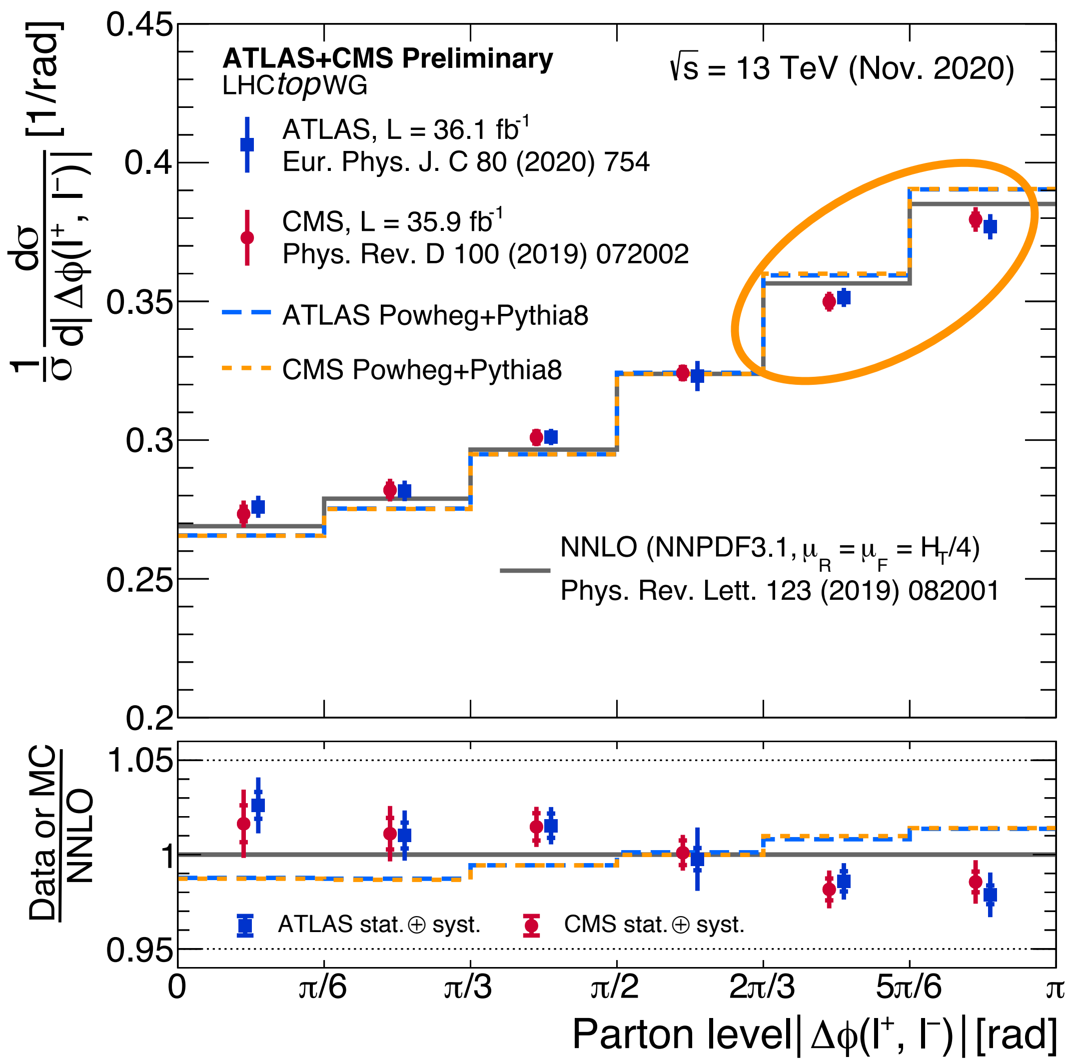


Why?

In this respect, it is good to remember the ΔΦ anomaly in top pair production

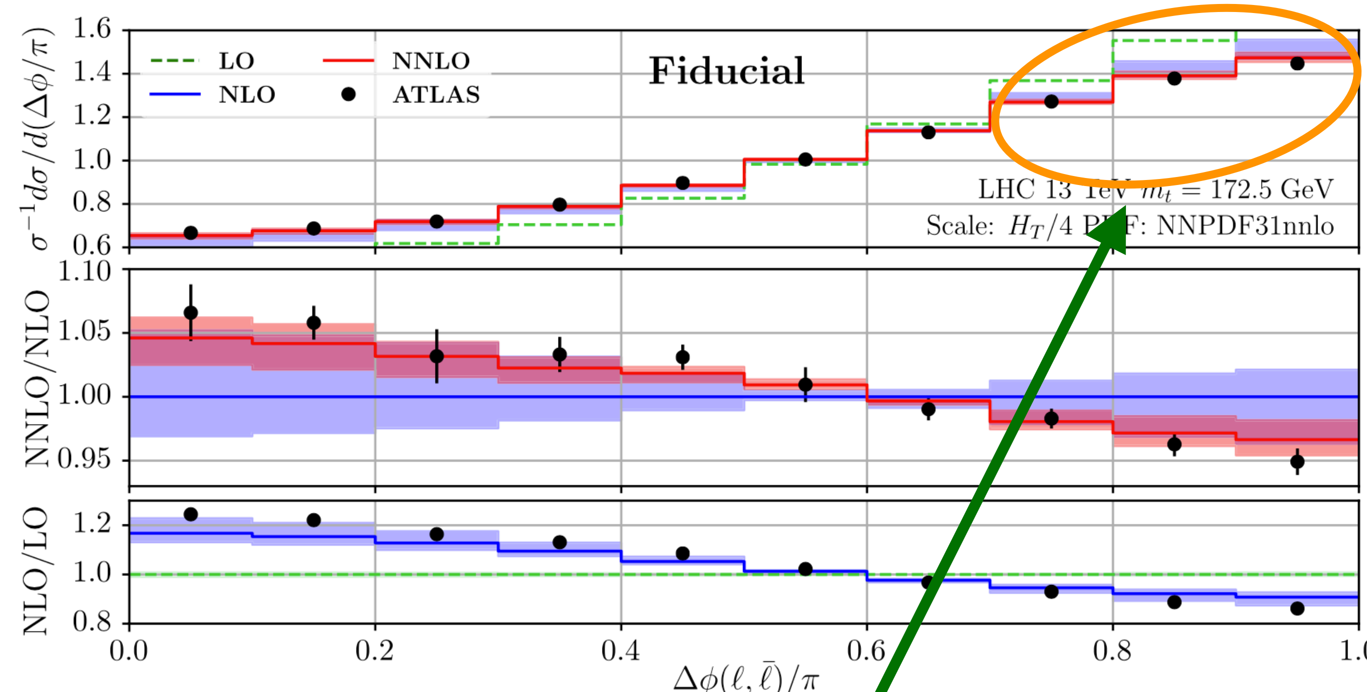
lab-frame azimuthal angle between leptons

Parton level full phase space



Parton level fiducial

Behring et al. 1901.05407



better agreement

New physics explanations break Δη and σ, see here and here

Probing new physics

Probing new physics

Entanglement observables involve spin correlations, which are sensitive to new physics.

→ we can parameterise deviations from SM in terms of dim-6 operators, which provide a definite framework for comparisons

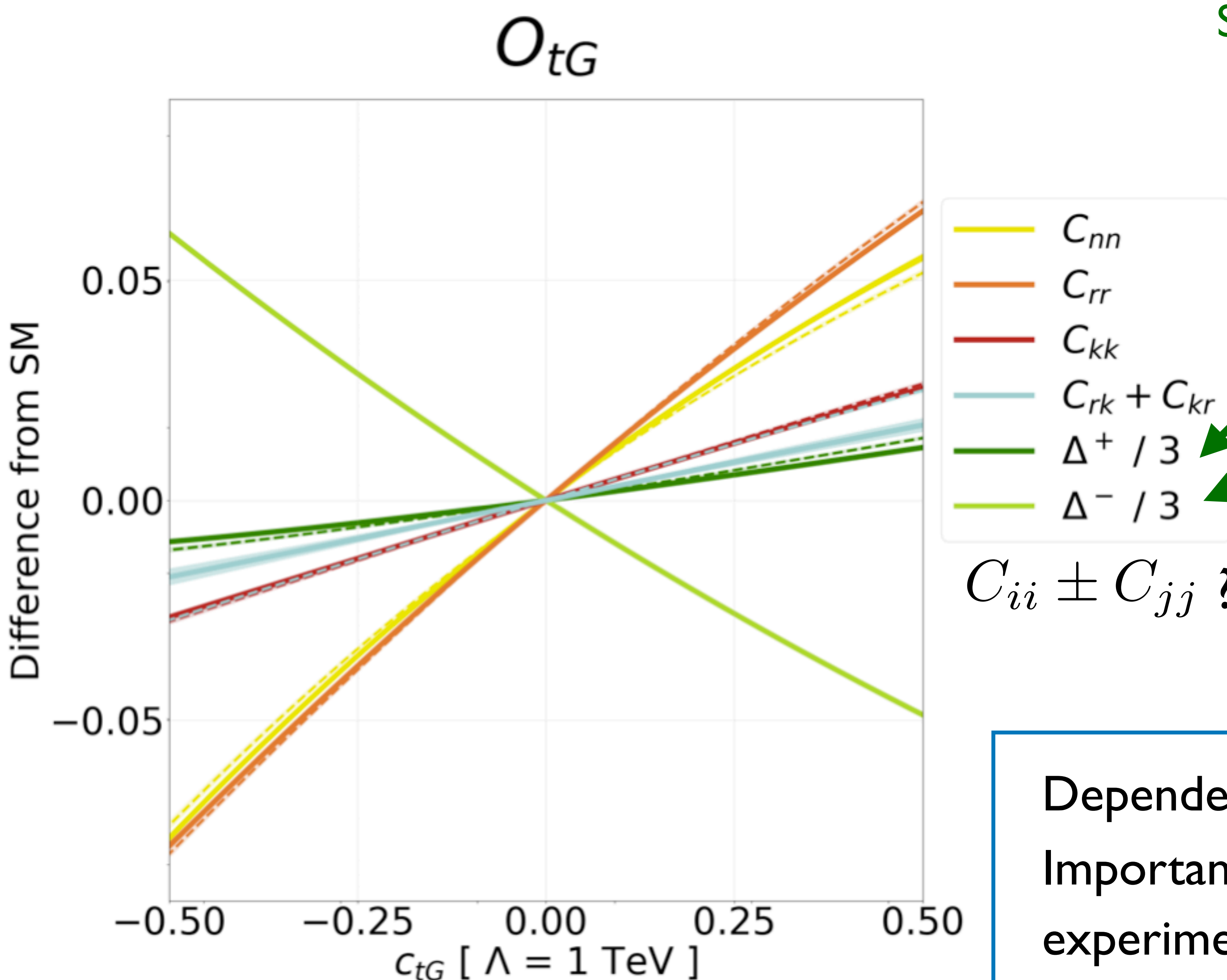
Spin correlations are measured with angular distributions, with a relation that may be modified by new physics

→ we can also introduce dim-6 operators for the decay of top, W, Z, but typically there are better ways to constrain them

> EFT is <u>not</u> a model. When evaluating sensitivity, one should beware flat directions, which may be natural in actual models

t t-bar example: top chromomagnetic dipole operator

Severi, Vryonidou, 2210.09330



this is a new observable

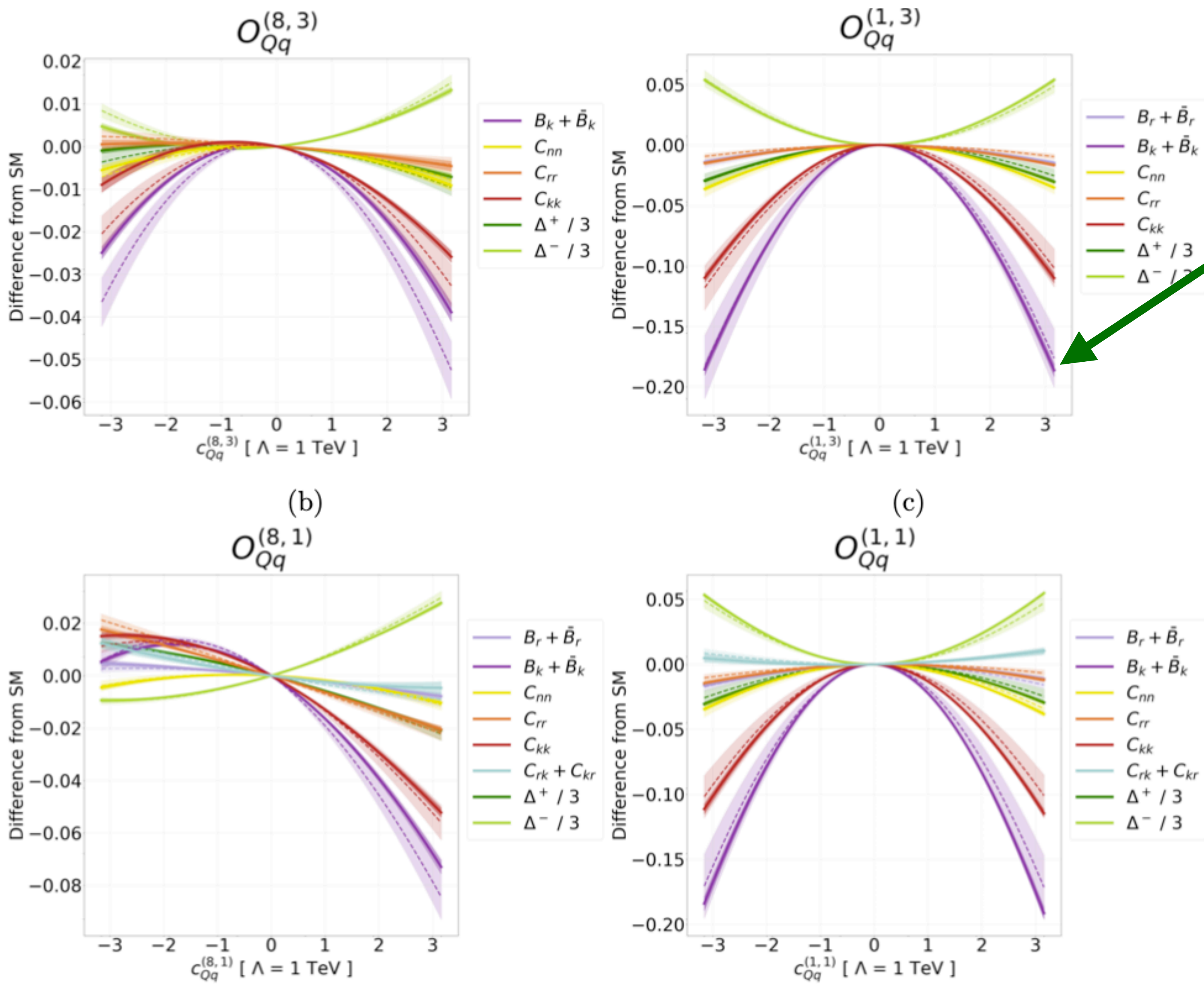
this is essentially the old good D

$C_{ii} \pm C_{jj}$???

Dependence on c is the first step. Important missing piece: expected experimental error bars for these quantities

Probing new physics

t t-bar example: some four-fermion operators



polarisation in helicity direction

Polarisation seems to outperform the rest of observables [note that experimental uncertainties are likely smaller] but this statement is basis-dependent (!)

Probing new physics

H → *ZZ* example: test anomalous *HZZ* interaction Fabbrichesi et al. 2304.02403

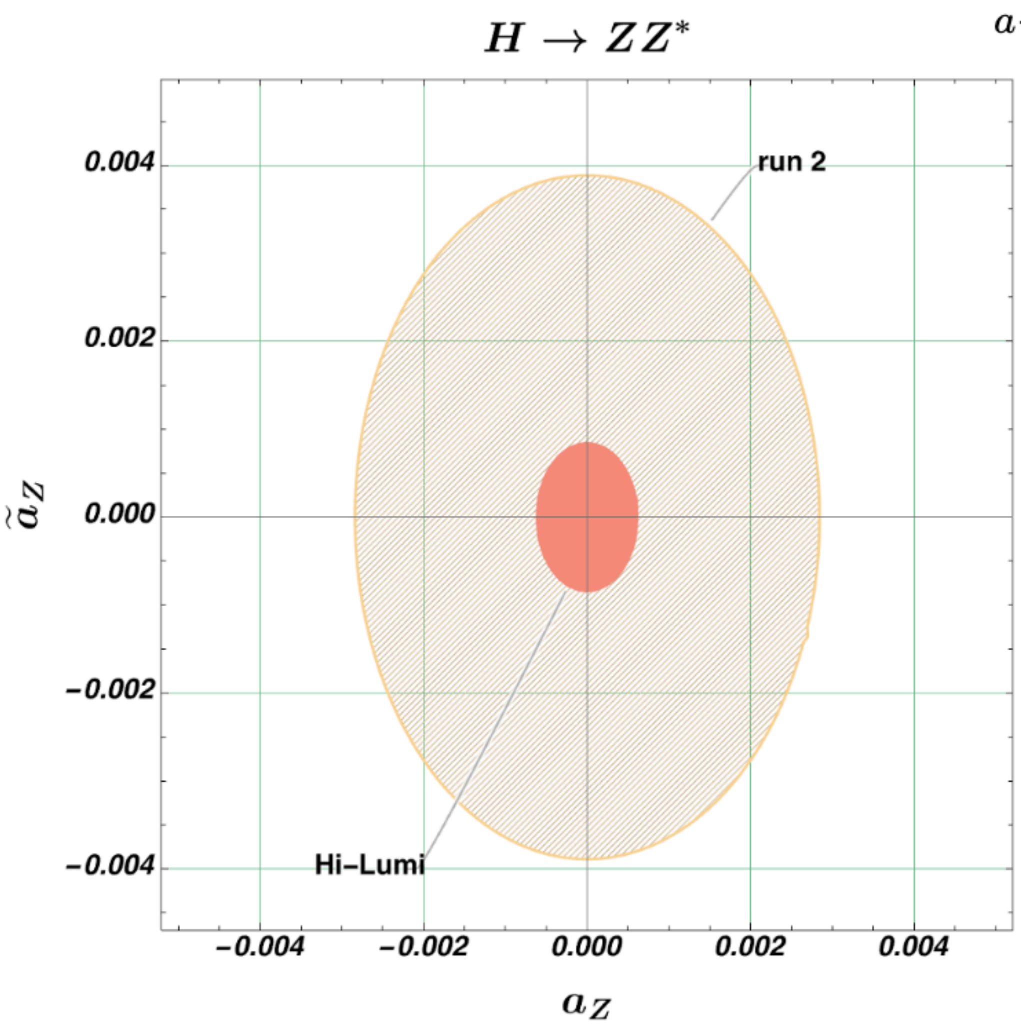
entanglement witness

$$\mathscr{C}_2 = 2\max\Big[0,\ -\frac{2}{9} - 12\sum_a f_a^2 + 6\sum_a g_a^2 + 4\sum_{ab} h_{ab}^2\,,$$
$$-\frac{2}{9} - 12\sum_a g_a^2 + 6\sum_a f_a^2 + 4\sum_{ab} h_{ab}^2\Big]$$

nothing to do with entanglement

$$\mathscr{C}_{\rm odd} = \frac{1}{2}\sum_{\substack{a,b\\ a<b}} \left|h_{ab} - h_{ba}\right|$$

parameters of *ZZ* density matrix



- Why not using *ZZ* density matrix elements instead ofx $\mathscr{C}_2$?
- Why use $\mathscr{C}_{\rm odd}$ and not dedicated triple-product observables?
- Same applies to EW diboson production Aoude et al. 2307.09675

Useful by-products of entanglement studies are new measurement-friendly parameterisations of the V_1V_2 density matrix [$V = W,Z$]

$$\rho = \frac{1}{9}\left(1_{9\times 9} + A^1_{LM} T^L_M \otimes 1_{3\times 3} + A^2_{LM} 1_{3\times 3} \otimes T^L_M + C_{L_1 M_1 L_2 M_2} T^{L_1}_{M_1} \otimes T^{L_2}_{M_2}\right)$$

8 polarisations for V_1

8 polarisations for V_2

64 spin correlations

where T^L_M [L = 1,2] are irreducible tensors

$$T^1_1 = \sqrt{\frac{3}{2}}\begin{pmatrix} 0 & -1 & 0 \\ 0 & 0 & -1 \\ 0 & 0 & 0 \end{pmatrix} \quad T^1_0 = \sqrt{\frac{3}{2}}\begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -1 \end{pmatrix}$$

$$T^2_2 = \sqrt{3}\begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad T^1_2 = \sqrt{\frac{3}{2}}\begin{pmatrix} 0 & -1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{pmatrix}$$

$$T^2_0 = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 0 & 0 \\ 0 & -2 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$T^1_{-1} = -(T^1_1)^\dagger$$
$$T^2_{-2} = -(T^2_2)^\dagger$$
$$T^2_{-1} = -(T^2_1)^\dagger$$

Alternative: Gell-Mann matrices

… whose corresponding 4-d angular distribution for the $V_1 V_2$ decay products is [using the charged leptons in leptonic decays]

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_1 d\Omega_2} = \frac{1}{(4\pi)^2}\Big[1 + B^1_{L_1} A^1_{L_1 M_1} Y^{M_1}_{L_1}(\Omega_1) + B^2_{L_2} A^2_{L_2 M_2} Y^{M_2}_{L_2}(\Omega_2) + B^1_{L_1} B^2_{L_2} C_{L_1 M_1 L_2 M_2} Y^{M_1}_{L_1}(\Omega_1) Y^{M_2}_{L_2}(\Omega_2)\Big]$$

$$\Omega_1 = (\theta_1, \varphi_1) \qquad \Omega_2 = (\theta_2, \varphi_2)$$

$$\eta_\ell = \begin{cases} \dfrac{g_L^2 - g_R^2}{g_L^2 + g_R^2} & Z \\ 1 & W^- \\ -1 & W^+ \end{cases}$$

$$B_1 = -\sqrt{2\pi}\eta_\ell\,, \quad B_2 = \sqrt{\frac{2\pi}{5}}$$

Because spherical harmonics are orthogonal functions, to pick selected terms in the distribution one just has to take averages

$$\int \frac{1}{\sigma}\frac{d\sigma}{d\Omega_1 d\Omega_2} Y^{M_1}_{L_1}(\Omega_1)^* Y^{M_2}_{L_2}(\Omega_2)^* = \frac{1}{(4\pi)^2} B_{L_1} B_{L_2} C_{L_1 M_1 L_2 M_2}$$

constants you can calculate

data follow this distribution

calculate the average of this quantity on your data

the quantity you want

What is next?

- New observables more sensitive than old ones? That is yet to be determined
- When dedicated observables are not found, perhaps forget about entanglement and go for density matrix elements
- UV matching may help identify interesting observables and scenarios

Novel tests: decay and entanglement

Novel tests: decay and entanglement

Consider a system of two particles *A*, *B*, with spin state described by

$$\rho = \sum_{ijkl} p_{ij}^{kl} |\phi_i\, \chi_k\rangle\langle\phi_j\, \chi_l| \qquad |\phi_i\rangle \in \mathcal{H}_A\,, \quad |\chi_k\rangle \in \mathcal{H}_B$$

$\mathcal{H}$ are the spin spaces

Let *A* decay *A* → A_1 A_2 … with amplitudes

$$M_{ij} = \langle p; \xi_i | T | \phi_j\rangle \qquad |\xi_i\rangle \in \mathcal{H}_{A_1} \otimes \mathcal{H}_{A_2} \otimes \dots$$

Then, the spin state of A_1 A_2 … and *B* is described by

$$\rho' = \frac{1}{\sum_{ik} (M \rho^{kk} M^\dagger)_{ii}} \sum_{ijkl} (M \rho^{kl} M^\dagger)_{ij} |\xi_i\, \chi_k\rangle\langle\xi_j\, \chi_l|$$

Entanglement between *A* and *B* is inherited by the decay products of *A*.
Post-decay entanglement is a novel test that cannot be performed with electrons / photons

Novel tests: decay and entanglement 2/7

Post-decay entanglement can be measured in top quark decays

When *t* *t*-bar are entangled and *t*-bar decays into $W^- b$,
t is entangled with the W^- *b*-bar pair

Problem:

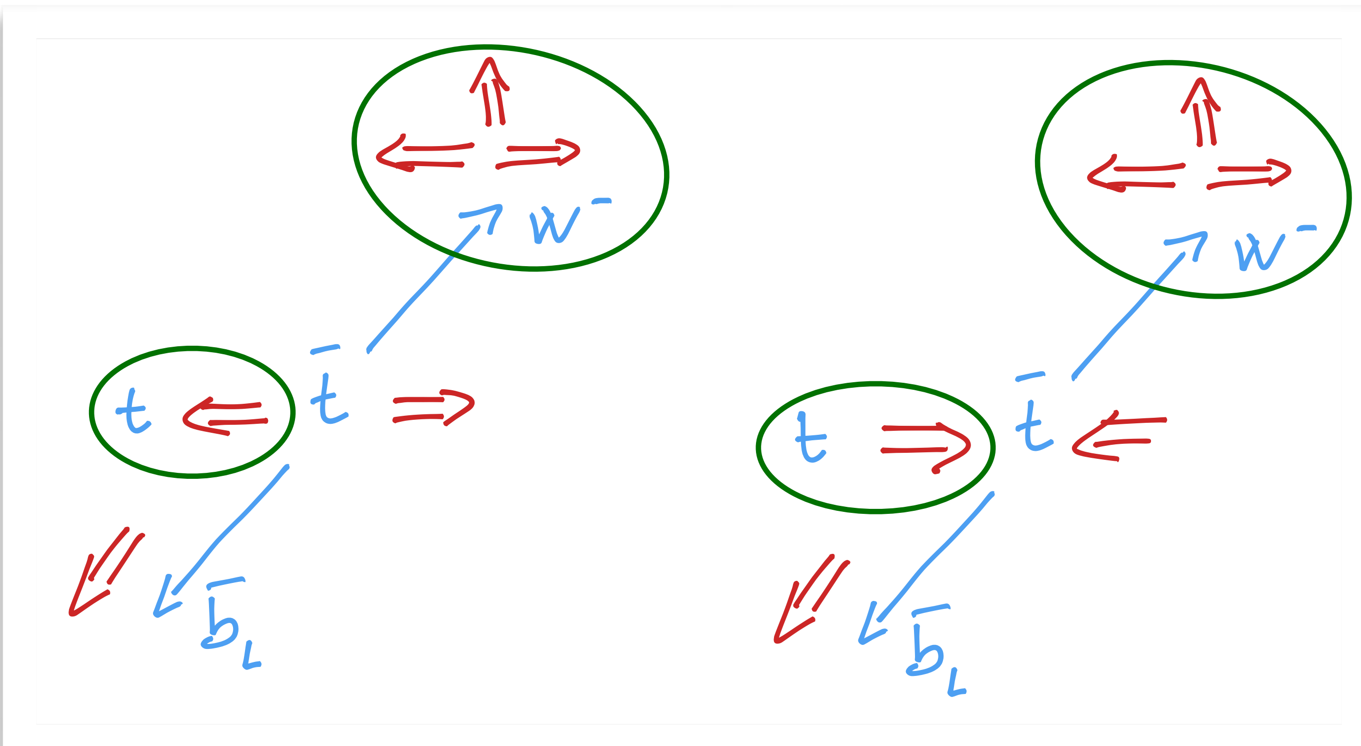
When we have several entangled particles and trace over [unobserved] degrees of freedom, entanglement may be lost.

The *b*-bar spin is not measured, and summing over it destroys entanglement.

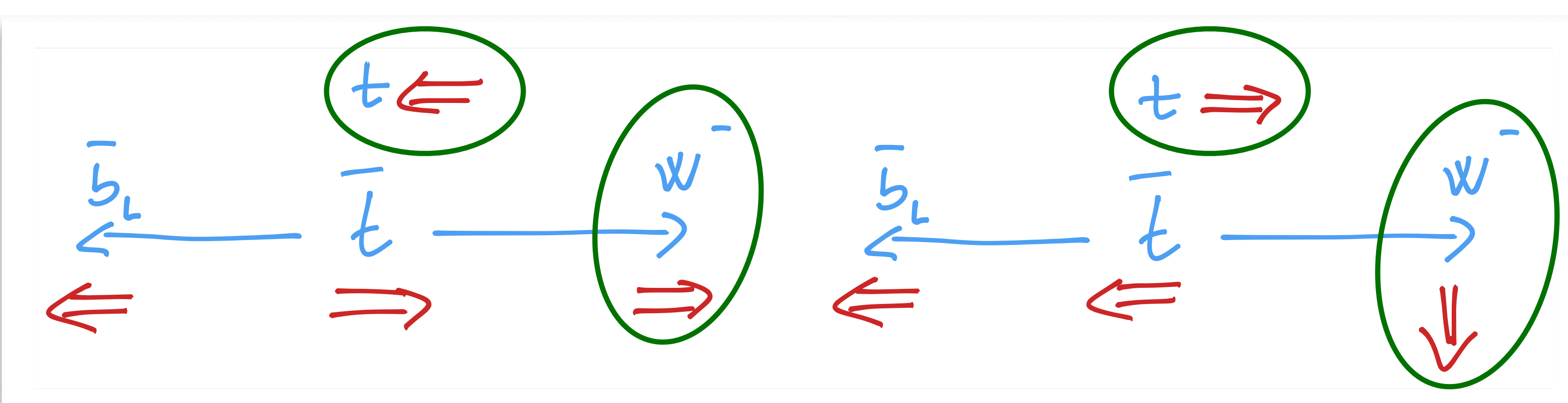
Solution:

Consider a kinematical region where the *b*-bar spin aligns with the *t*-bar one (!)

Assume t t-bar are in a spin-triplet state $\frac{1}{\sqrt{2}}(|\uparrow\rangle \otimes |\downarrow\rangle + |\downarrow\rangle \otimes |\uparrow\rangle)$



t W^- not entangled in general



but in some kinematical configurations they are!

Novel tests: decay and entanglement

Threshold, beamline basis z = (0,0,1)

θ_W 👉 angle between W^- momentum in t-bar rest frame and z axis

$$m_{t\bar{t}} \leq 390 \text{ GeV}\,, \beta \leq 0.9\,, \cos\theta_W \geq 0.3$$

Looser cut
more statistics

$$\rho_{tW} \simeq 0.49 |\Psi\rangle\langle\Psi| + \ldots$$

$$|\Psi\rangle \simeq \frac{1}{\sqrt{2}} \left[|\tfrac{1}{2}0\rangle - |-\tfrac{1}{2}1\rangle \right]$$

Entanglement measure?

$$m_{t\bar{t}} \leq 390 \text{ GeV}\,, \beta \leq 0.9\,, \cos\theta_W \geq 0.9$$

Tighter cut
less statistics

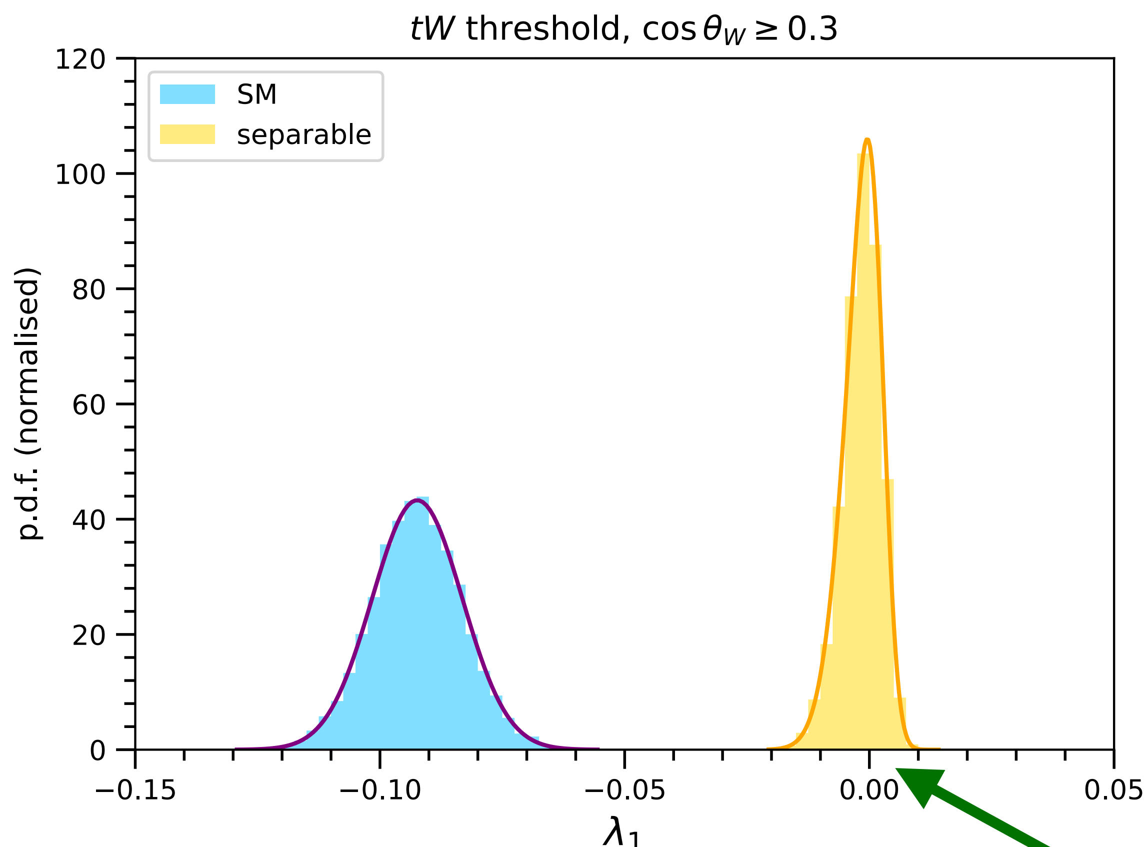
$$\rho_{tW} \simeq 0.62 |\Psi\rangle\langle\Psi| + \ldots$$

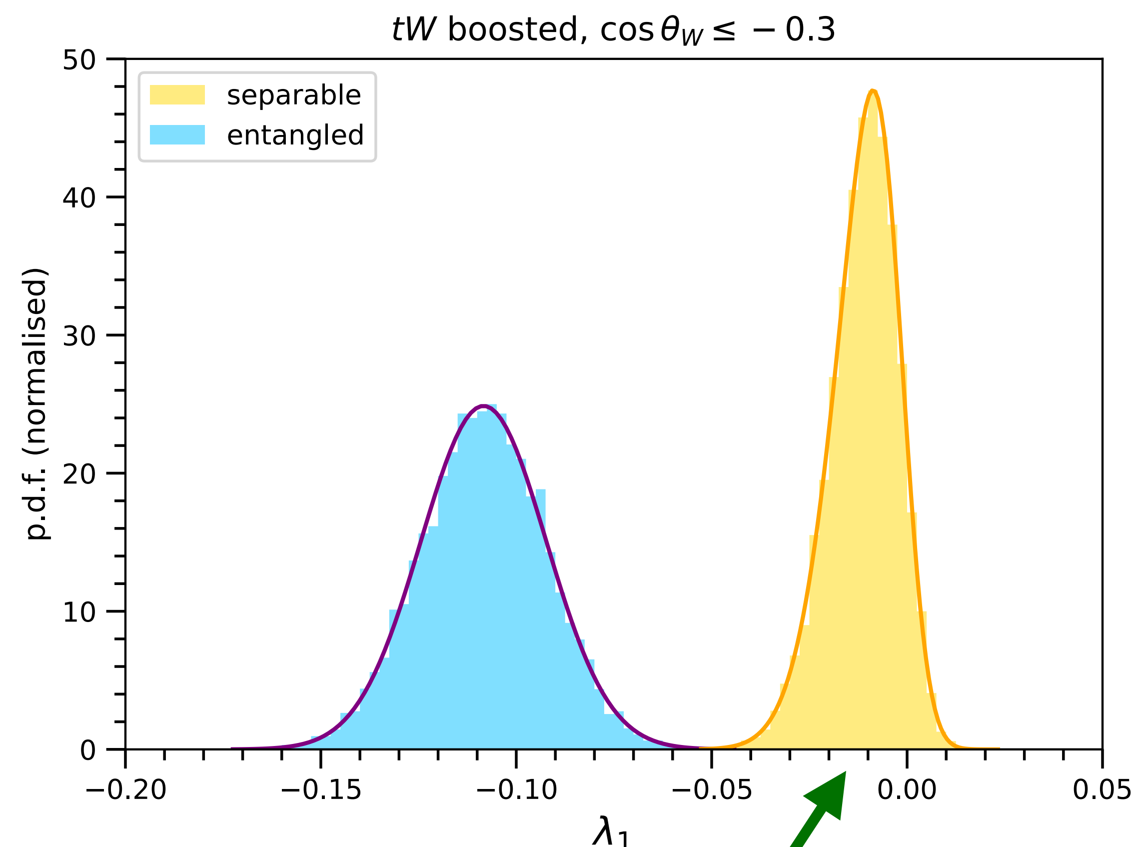
$$|\Psi\rangle \simeq 0.82 |\tfrac{1}{2}0\rangle - 0.57 |-\tfrac{1}{2}1\rangle$$

Novel tests: decay and entanglement

Entanglement indicator:
lowest eigenvalue λ_1 of the ρ^{T_2} matrix for *tW*

$\lambda_1 < 0 \Leftrightarrow$ Entanglement





Run 2	Significance [stat + 10% sys + bias]
Threshold	7.0 σ
Boosted	5.0 σ

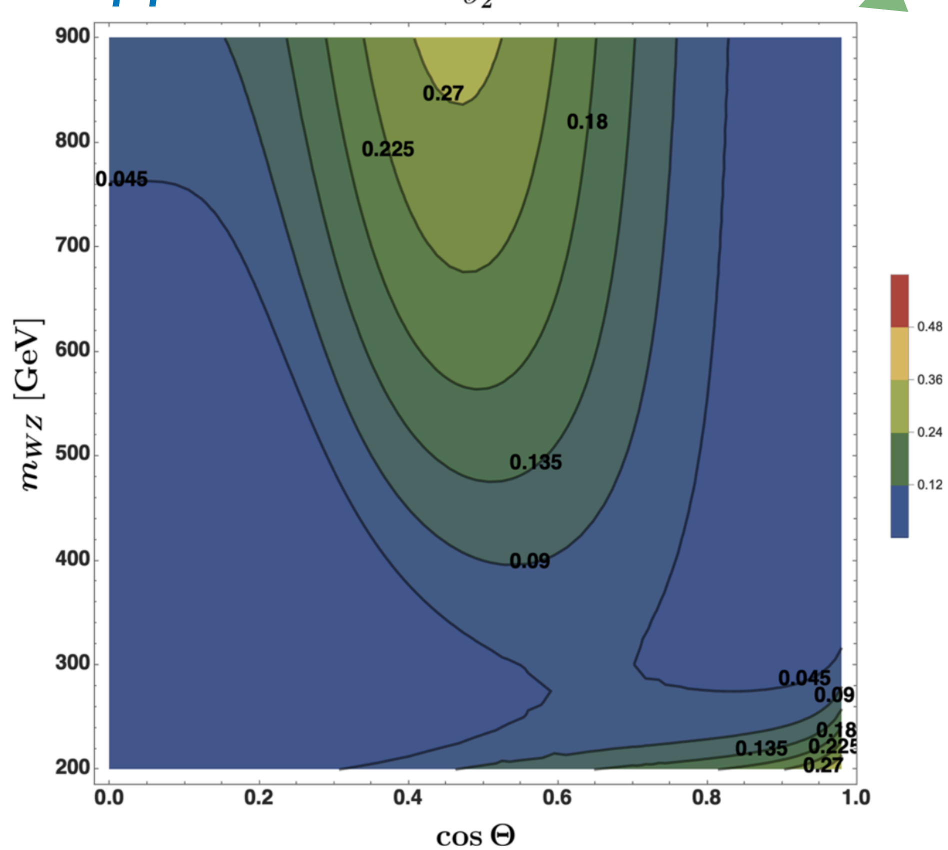
Bias: even if $\lambda_1 > 0$, in a small sample we may find it negative

Novel tests: decay and entanglement

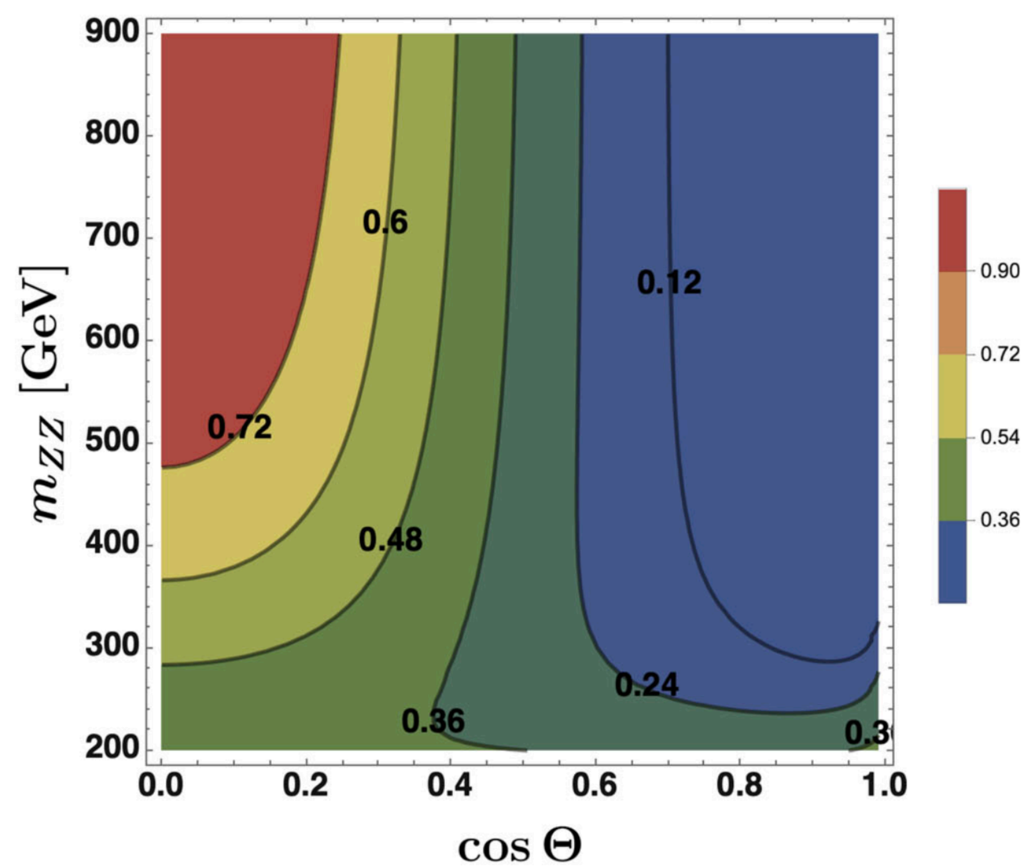
Other than top? Not many options [need decay products with measurable spin]

- $WW \to \tau\nu\,\ell\nu$: too many neutrinos.
- $ZZ \to \tau\tau\,\ell\ell$: in principle doable at linear colliders; ZZ entangled and $Z \to \tau\tau \sim H \to \tau\tau$ which may be reconstructed   Altakach et al. 2211.10513
- $WZ \to \tau\nu\,\ell\ell$: perhaps feasible at LHC, but WZ entanglement is small

$pp \to W^+Z\ \mathscr{C}_2$



$e^+e^- \to ZZ\ \mathscr{C}_2$



Plots from   Fabbrichesi et al. 2302.00683

What is next?

- Post-decay entanglement: unique test of QM not possible in experiments with e^- and γ
- Shows that decay is <u>not</u> in general a spin \`measurement´ in the QM sense
- Boson-fermion spin entanglement tests are quite rare, too!

Novel tests: qutrits

Novel tests: qutrits

The *ZZ* final state is clean and easy to reconstruct

Talks by A. Barr, J. Moreno, A. Bernal, L. Marzola

… but the *WW* final state is clearly superior in terms of both statistics and spin analysing power

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_1 d\Omega_2} = \frac{1}{(4\pi)^2}\left[1 + B^1_{L_1} A^1_{L_1 M_1} Y^{M_1}_{L_1}(\Omega_1) + B^2_{L_2} A^2_{L_2 M_2} Y^{M_2}_{L_2}(\Omega_2) + B^1_{L_1} B^2_{L_2} C_{L_1 M_1 L_2 M_2} Y^{M_1}_{L_1}(\Omega_1) Y^{M_2}_{L_2}(\Omega_2)\right]$$

$$B_1 = -\sqrt{2\pi}\eta_\ell \longrightarrow \eta_\ell = \pm 1 \ (W) \ ; \ 0.13 \ (Z)$$

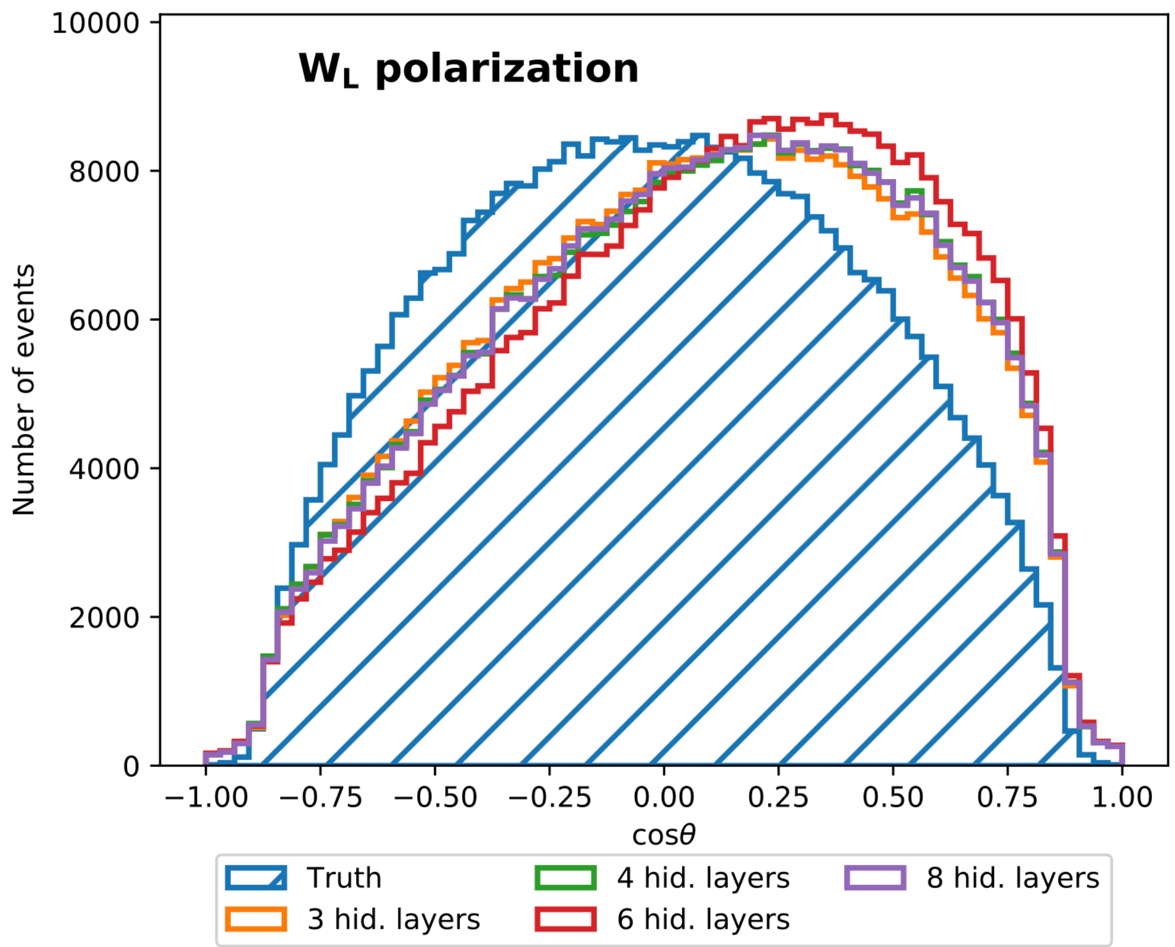
- Coefficients A_{1M}, $C_{1M2M'}$ have a suppression 1/10 for *Z* ⟶ $\Delta_{\rm stat}$ 3x penalty
- Coefficients $C_{1M1M'}$ have a suppression 1/100 for *ZZ* ⟶ $\Delta_{\rm stat}$ 10x penalty

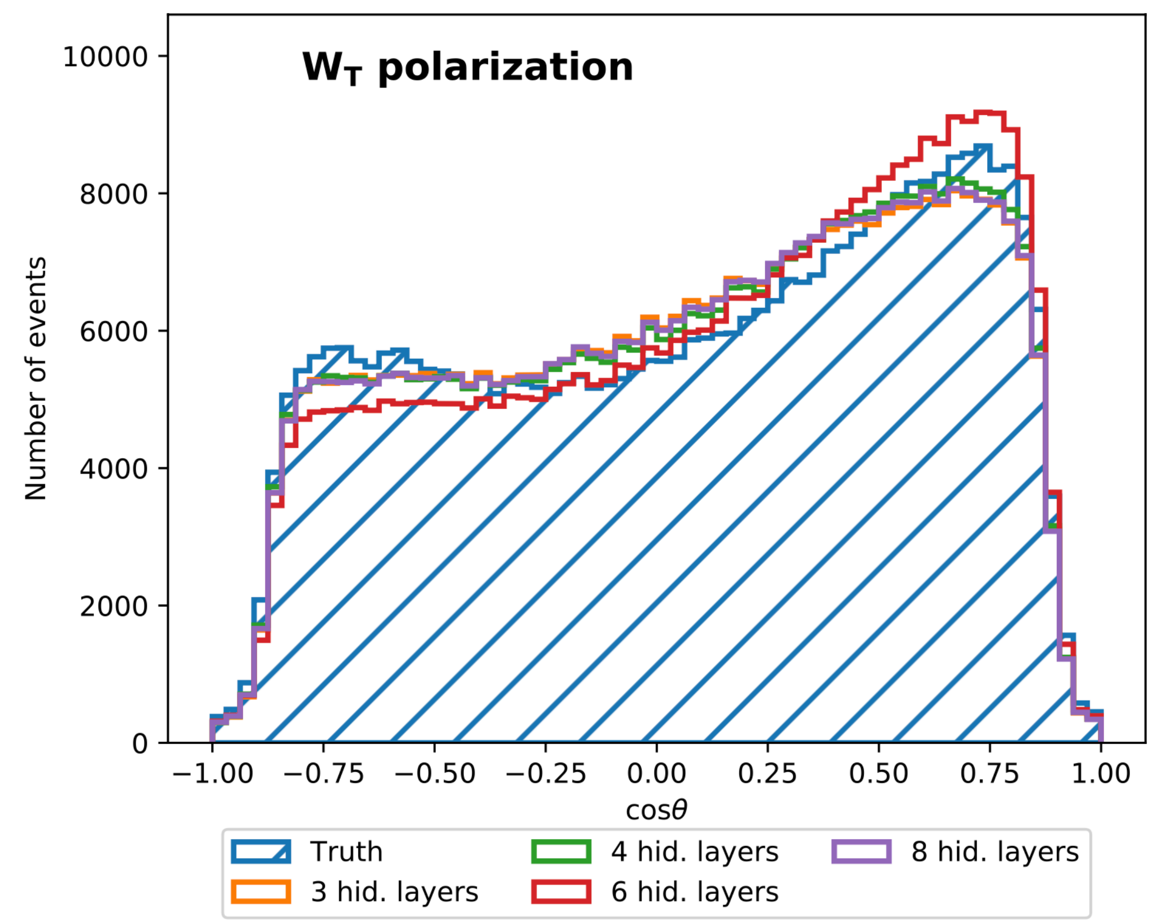
Additional efforts towards realistic methods for *WW* are necessary!

Novel tests: qutrits

The decay $WW \to 2\ell\, 2\nu$ cannot be uniquely reconstructed because of the two neutrinos: the system is underconstrained.

Promising attempts in VBF $WW \to 2\ell\, 2\nu$ using NNs Grossi et al, 2008.5316



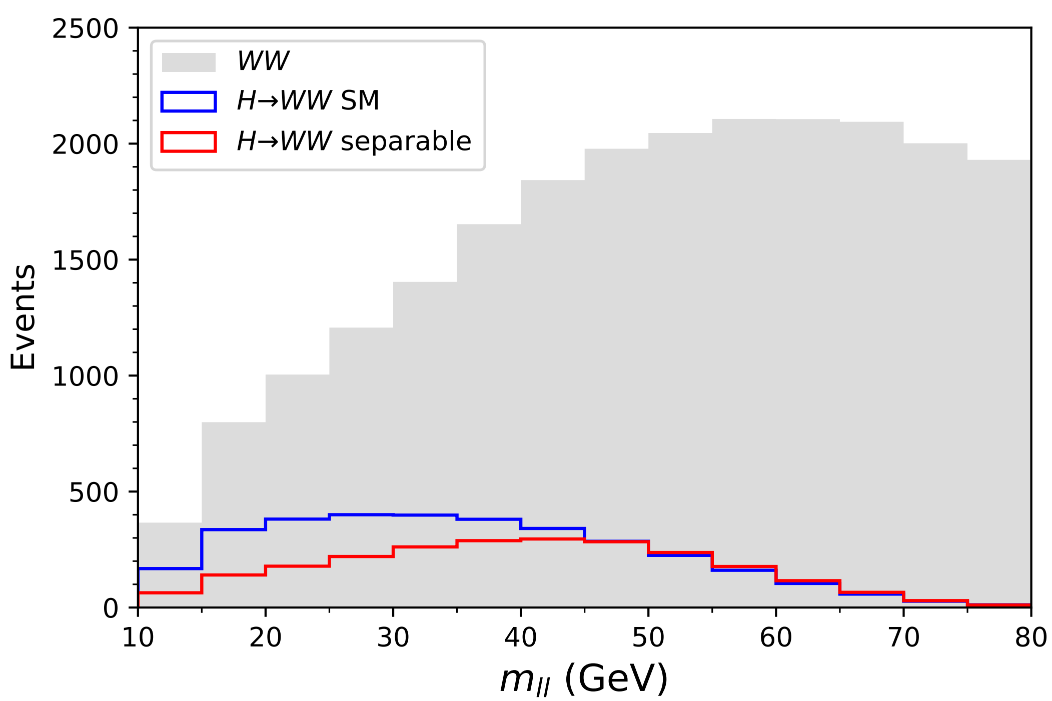


No studies for (θ,ϕ) reconstruction nor for general polarisations.
Entanglement measurements are quite demanding!

For $H \to WW \to 2\ell\, 2\nu$, entanglement conditions can be recast into a binary test using lab-frame dilepton kinematical distributions. JAAS, 2209.14033

SM vs separability hypothesis $\equiv$

$$C_{212-1} = 0$$
$$C_{222-2} = 0$$



$$\hat{h}_0 \hat{h}_-^* = h_{16} + i\,(h_{17} - h_{26}) + h_{27}$$
$$\hat{h}_+ \hat{h}_-^* = h_{44} + i\,(h_{45} - h_{54}) + h_{55}$$

	Run 2 Significance
stat only	7.1σ
stat + modeling syst	6.1σ

Such an easy trick is not possible to test Bell inequalities but…
is there a meaningful mapping of CGLMP violation into $\Delta\eta_{ll}$, $\Delta\phi_{ll}$, m_{ll} regions?

Novel tests: qutrits

Full reconstruction of $H \to WW \to \ell\nu qq$ possible by using c-tagging to distinguish jets

Fabbri, Howarth, Maurin, 2307.13783

Penalties of full reconstruction:

to reduce bkg

- 1/2 BR because $W \to ud$ is not usable
- 1/2 BR because $W \to cs$ is assumed on shell, $W \to \ell\nu$ off shell
- 0.4 efficiency for charm tagging

With BR 12x larger than $WW \to 2\ell\, 2\nu$, still 20% more statistics

Reconstruction procedure might be adapted to electroweak WW, replacing H mass constraint by $W \to \ell\nu$ mass constraint.

What is next?

- First-ever measurement of elementary qutrit entanglement!
- Test done at energy frontier
- Improved reconstruction of $H \to WW \to \ell\nu qq$
- Improved reconstruction of $H \to WW \to 2\ell\, 2\nu$

Further tests with top pairs

Further tests with top pairs

After measurement in the threshold region, there are several items in the experimental to-do list:

- Entanglement in boosted region — Afik, Nova 2003.02280; Severi et al. 2110.10112; JAAS, Casas 2205.00542
- Semi-leptonic channel — Dong, Gonçalves, Kong, Navarro 2305.07075; Han, Low, Wu 2310.17696
- Bell inequalities — Fabbrichesi, Floreanini, Panizzo 2102.11883; Severi et al. 2110.10112; Afik, Nova 2203.05582; JAAS, Casas 2205.00542
- Other quantum measurements — Afik, Nova 2209.03969

$$\text{Priority} = \frac{1}{\sqrt{5}}\left[2\left|\begin{array}{l}\text{expected}\\ \text{significance}\end{array}\right\rangle + \left|\begin{array}{l}\text{personal}\\ \text{preference}\end{array}\right\rangle\right]$$

Further tests with top pairs

Entanglement in boosted region

Entanglement witness: $E \equiv C_{kk} + C_{rr} - C_{nn} - 1 > 0$

It is equivalent to Peres-Horodecki criterion for $C_{kr} = 0$

For boosted region $m_{tt} \geq 800$ GeV, $\cos\theta \leq 0.6$

σ	C_{kk}	C_{rr}	C_{nn}	C_{kr}	C_{xx}	C_{yy}	C_{zz}
93 fb	0.661	0.680	-0.574	0.121	~0	~0	0.786

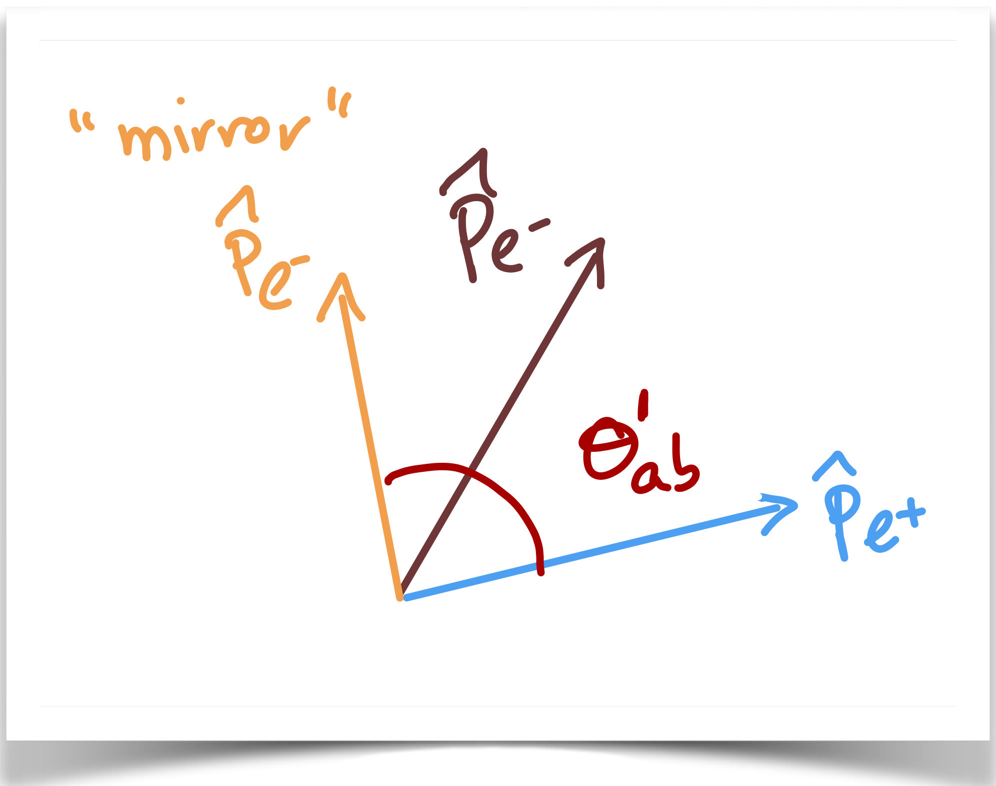
E is close to optimal.

Direct application of Peres-Horodecki criterion [which has bias] is not likely to improve sensitivity.

Further tests with top pairs

Direct measurement using D_3 observable has smaller statistical uncertainty

JAAS, Casas 2205.00542



angle between ℓ^+ and mirror image of ℓ^- momentum, reflected in the K-R plane

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta'_{ab}} = \frac{1}{2}\left(1 + \alpha_a\alpha_b D_3 \cos\theta'_{ab}\right)$$

Entanglement test for boosted region: $3D_3 - 1 > 0$

Reconstruction uncertainty in semileptonic channel also smaller

Han, Low, Wu 2310.17696

Further tests with top pairs

Measurements in semi-leptonic channel final state

Dong et al. 2305.07075
Han, Low, Wu 2310.17696

Using optimal hadronic polarimeter, statistical uncertainty decreases by a factor 1.6. What about systematic uncertainties?

Early ATLAS analysis with 4.6 fb^{-1} at 7 TeV may give us a hint. 1407.4314

dilepton: $C_{kk} = 0.23 \pm 0.06$ (stat) $\pm$ 0.07 (syst)

semileptonic: $C_{kk} = 0.35 \pm 0.03$ (stat) $\pm$ 0.08 (syst)

no other spin correlation analysis in l+jets channel since then

- Comparison cannot simply be extrapolated to other C´s / distributions …
- … but suggests that systematics [which likely will dominate] will be comparable …
- … and in any case, threshold measurement in the semileptonic channel is a must, given the discrepancies found [likely due to mismodeling].

Further tests with top pairs

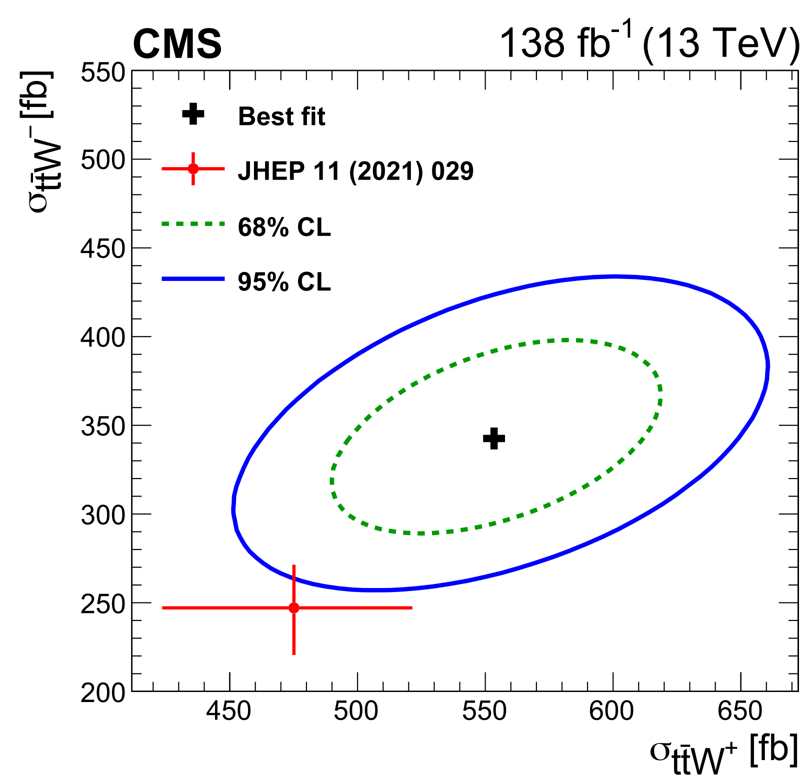
Beyond top pairs: *t t*-bar *W*

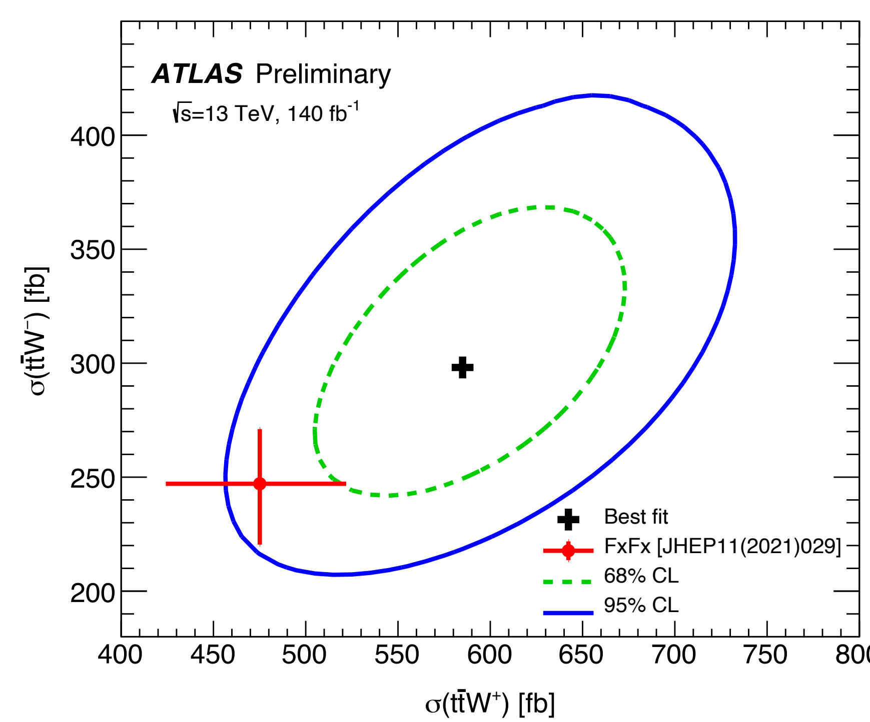
Enormous spin correlations. For example, at the LO [inclusively]

$$\begin{aligned}\rho_{ttW^+} = \frac{1}{12}\big[1 &- 0.83\,\mathbb{1}\otimes\mathbb{1}\otimes T^2_0 + 0.88\,t^1_0\otimes t^1_0\otimes\mathbb{1}\\ &+ 0.2\,(t^1_0\otimes\mathbb{1}\otimes T^1_0 - t^1_1\otimes\mathbb{1}\otimes T^1_{-1} - t^1_{-1}\otimes\mathbb{1}\otimes T^1_1)\\ &+ 0.2\,(\mathbb{1}\otimes t^1_0\otimes T^1_0 - \mathbb{1}\otimes t^1_1\otimes T^1_{-1} - \mathbb{1}\otimes t^1_{-1}\otimes T^1_1)\\ &- 0.2\,(t^1_1\otimes t^1_0\otimes T^2_{-1} + t^1_{-1}\otimes t^1_0\otimes T^2_1 + t^1_0\otimes t^1_1\otimes T^2_{-1} + t^1_0\otimes t^1_{-1}\otimes T^2_1)\\ &-0.88\,t^1_0\otimes t^1_0\otimes T^2_0\big]\end{aligned}$$

three-particle measurements possible!

especially interesting because of cross section excesses





What is next?

- Measurements in boosted region
- Semi-leptonic check of threshold measurement
- Studies in *t t*-bar+X also possible

End

Naming a cancellation as `flat direction´ is misleading because that suggests some fine-tuning.

Well-known examples of operators & models that produce such cancelations.

JAAS, 0811.3842

...

$$\mathcal{L}_{Ztt} = -\frac{g}{2c_W}\bar{t}\gamma^\mu(c_L^t P_L + c_R^t P_R)tZ_\mu \qquad \delta c_L^t = \left[C_{\phi q}^{(3,3+3)} - C_{\phi q}^{(1,3+3)}\right]\frac{v^2}{\Lambda^2}$$

$$\mathcal{L}_{Zbb} = -\frac{g}{2c_W}\bar{b}\gamma^\mu(c_L^b P_L + c_R^b P_R)bZ_\mu \qquad \delta c_L^b = \left[C_{\phi q}^{(3,3+3)} + C_{\phi q}^{(1,3+3)}\right]\frac{v^2}{\Lambda^2}$$

In the one-operator-at-a-time framework, both $C_{\phi q}^{(3,3+3)}$ and $C_{\phi q}^{(1,3+3)}$ are tightly constrained by $Z \to bb$ at LEP.

But a VLQ singlet T precisely generates $C_{\phi q}^{(1,3+3)} = -C_{\phi q}^{(3,3+3)}$ and no tree-level contribution to the *Zbb* vertex (!!!)

Novel tests: qutrits

This is a decay 0 → 1 + 1. Angular momentum conservation implies that many *A* and *C* coefficients are zero. The non-zero ones are

$$
\begin{aligned}
& A^1_{10} = -A^2_{10}\,, \quad A^1_{20} = A^2_{20} \\
& C_{1010}\,, \quad C_{2020}\,, \quad C_{1020}\,, \quad C_{2010} \\
& C_{111-1} = C^*_{1-111}\,, \quad C_{222-2} = C^*_{2-222}\,, \quad C_{212-1} = C^*_{2-121}\,, \\
& C_{112-1} = C^*_{1-121}\,, \quad C_{211-1} = C^*_{2-111}
\end{aligned}
$$

and the 9×9 ρ matrix is sparse [relations among coefficients used below]

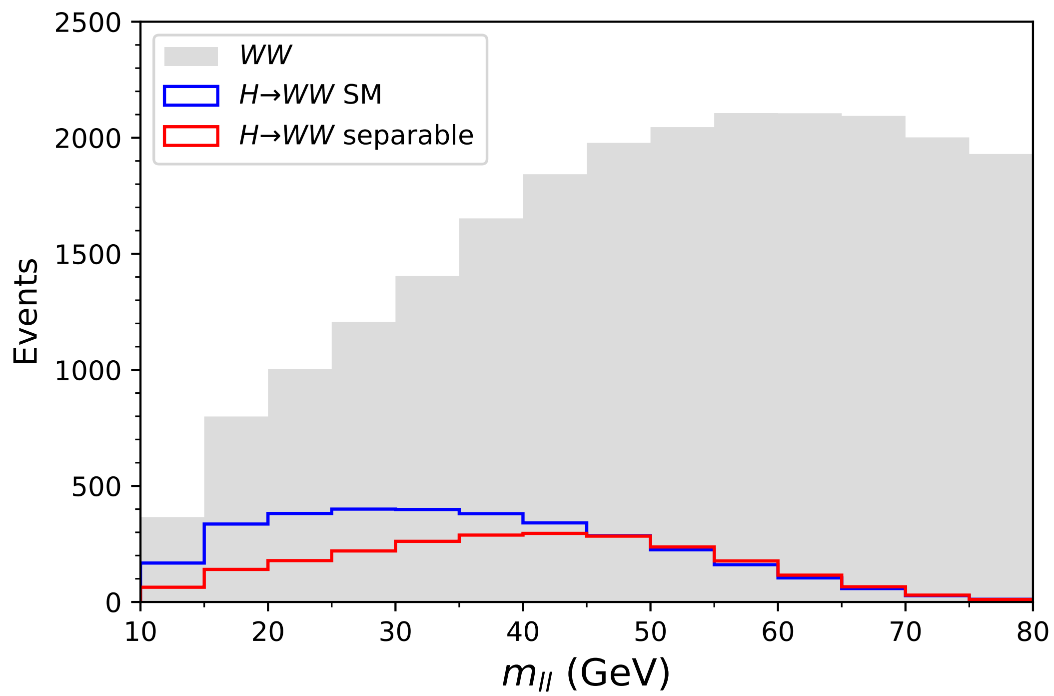
$$
\rho = \frac{1}{3} \begin{pmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 2 - C_{2020} & 0 & C_{212-1} & 0 & C_{222-2} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & C^*_{212-1} & 0 & -1 + 2C_{2020} & 0 & C_{212-1} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & C^*_{222-2} & 0 & C^*_{212-1} & 0 & 2 - C_{2020} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{pmatrix}
$$

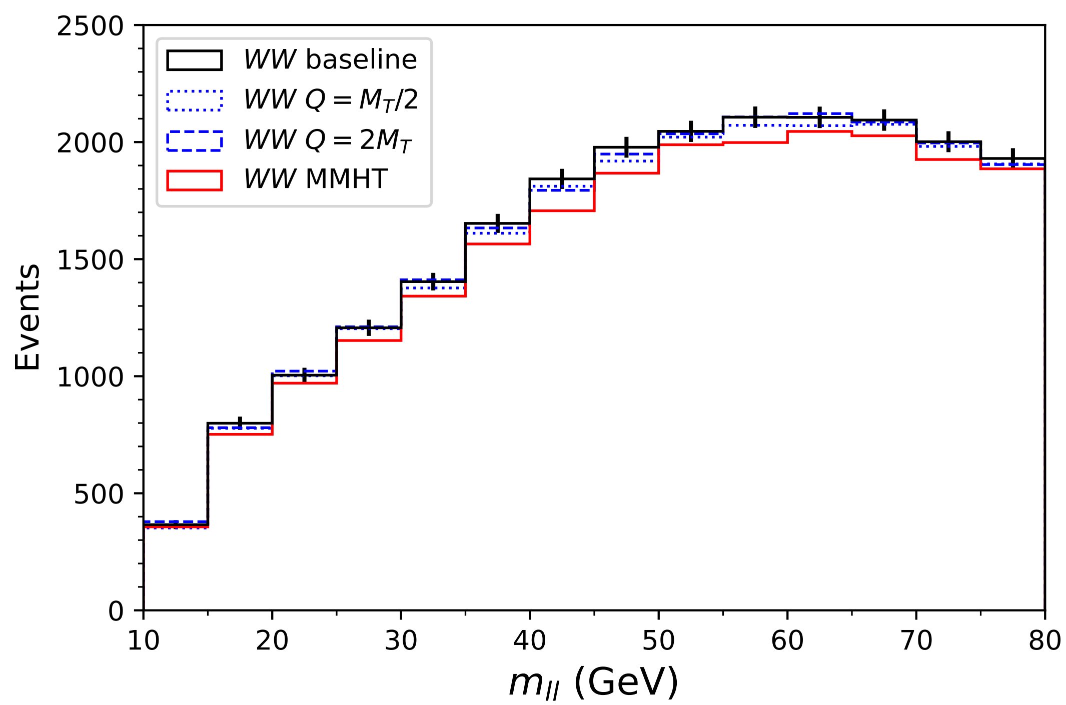
Separability $\xrightarrow{\text{Peres-Horodecki}}$ $C_{212-1} = 0\,, \quad C_{222-2} = 0$

Separability $\xleftarrow{H \to VV \text{ special case}}$ $C_{212-1} = 0\,, \quad C_{222-2} = 0$

Novel tests: qutrits

Results after Delphes simulation, eμ channel, L = 138 fb^{-1}





The differences between the SM and separable hypotheses arise in the region with smaller bkg

The bkg systematics are small provided we normalise it with a sideband

	Significance
stat only	7.1σ
stat + modeling syst	6.1σ

likely, observation possible already for Run 2 now this is the end