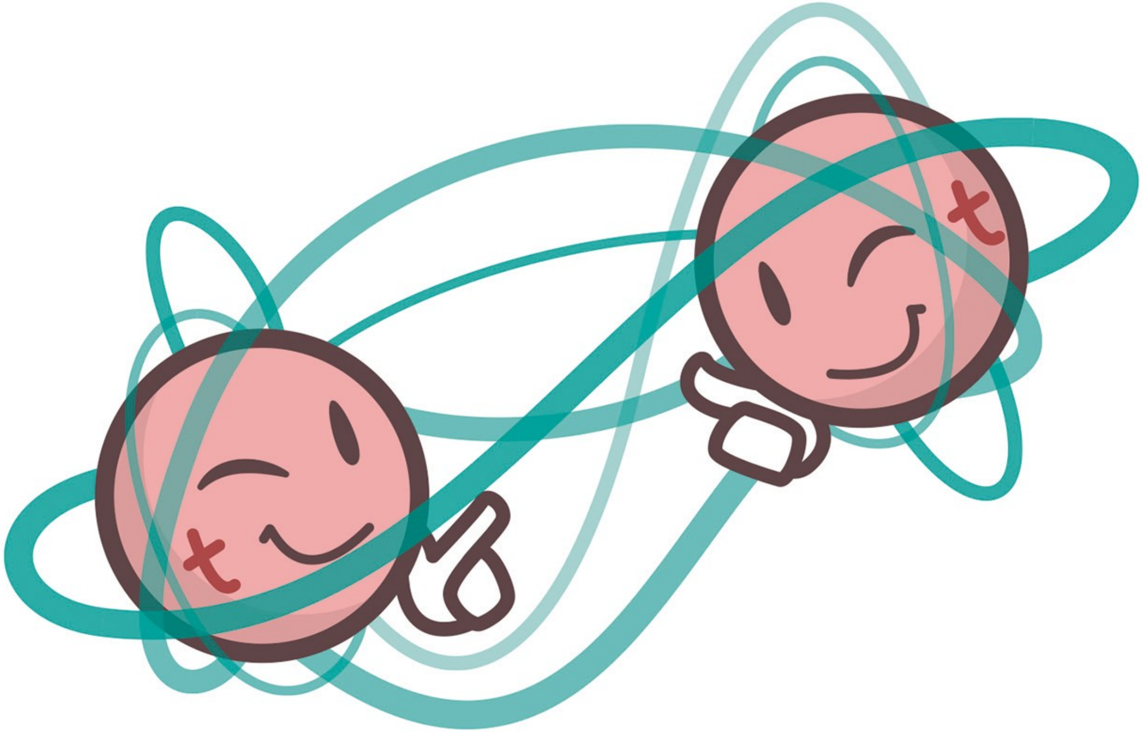
Quantum Entanglement at the LHC

Top LHC France,
10th of April 2024,
LPNHE, Paris

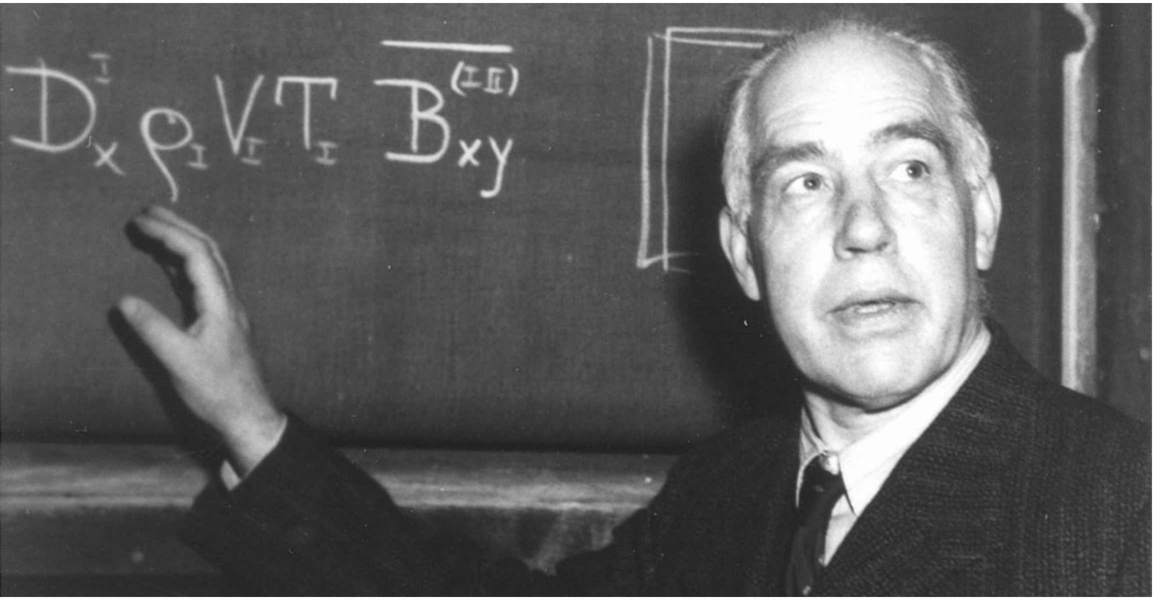


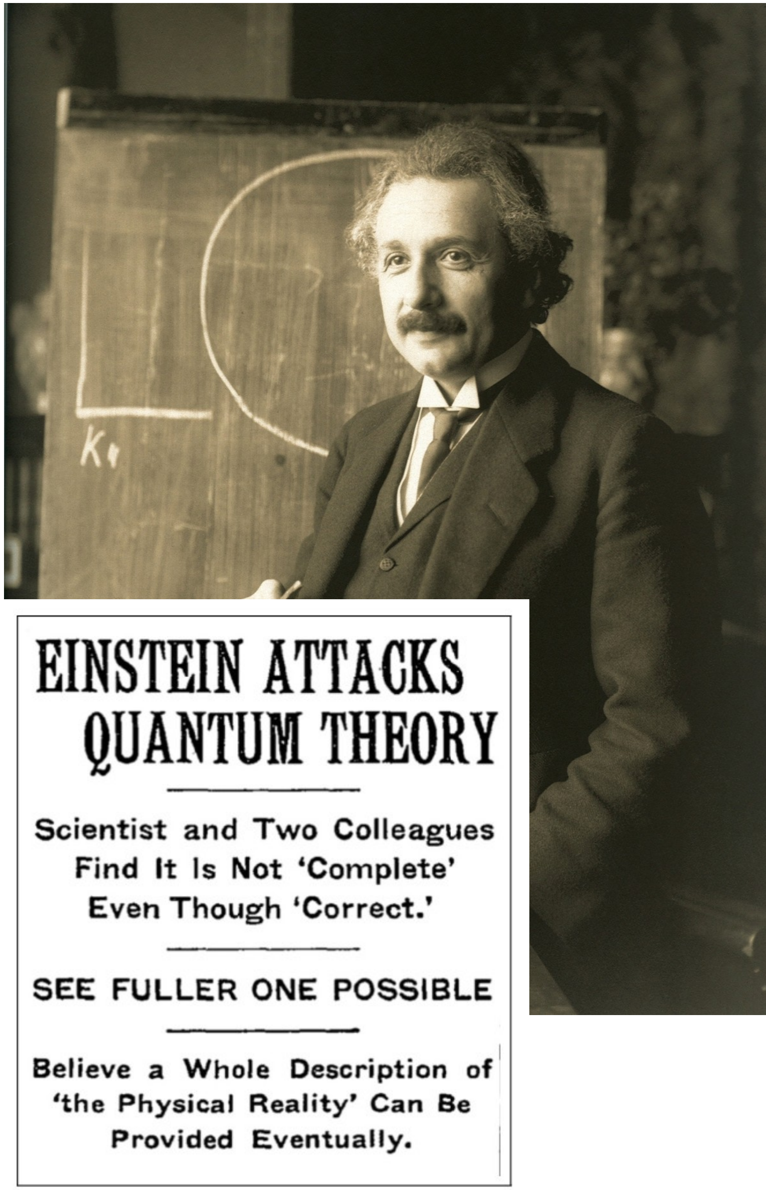
Marcel Vos,

IFIC, CSIC/UV,

Valencia, Spain

Foundations of quantum mechanics





EINSTEIN ATTACKS QUANTUM THEORY

Scientist and Two Colleagues
Find It Is Not 'Complete'
Even Though 'Correct.'

SEE FULLER ONE POSSIBLE

Believe a Whole Description of
'the Physical Reality' Can Be
Provided Eventually.

Philosophical debate among founders of quantum mechanics (and hence modern physics)

Einstein (and common sense):
Particles have properties

Bohr (and quantum mechanics):
Quantum probabilities are all there is to know

1935: Einstein-Podolsky-Rosen thought experiment

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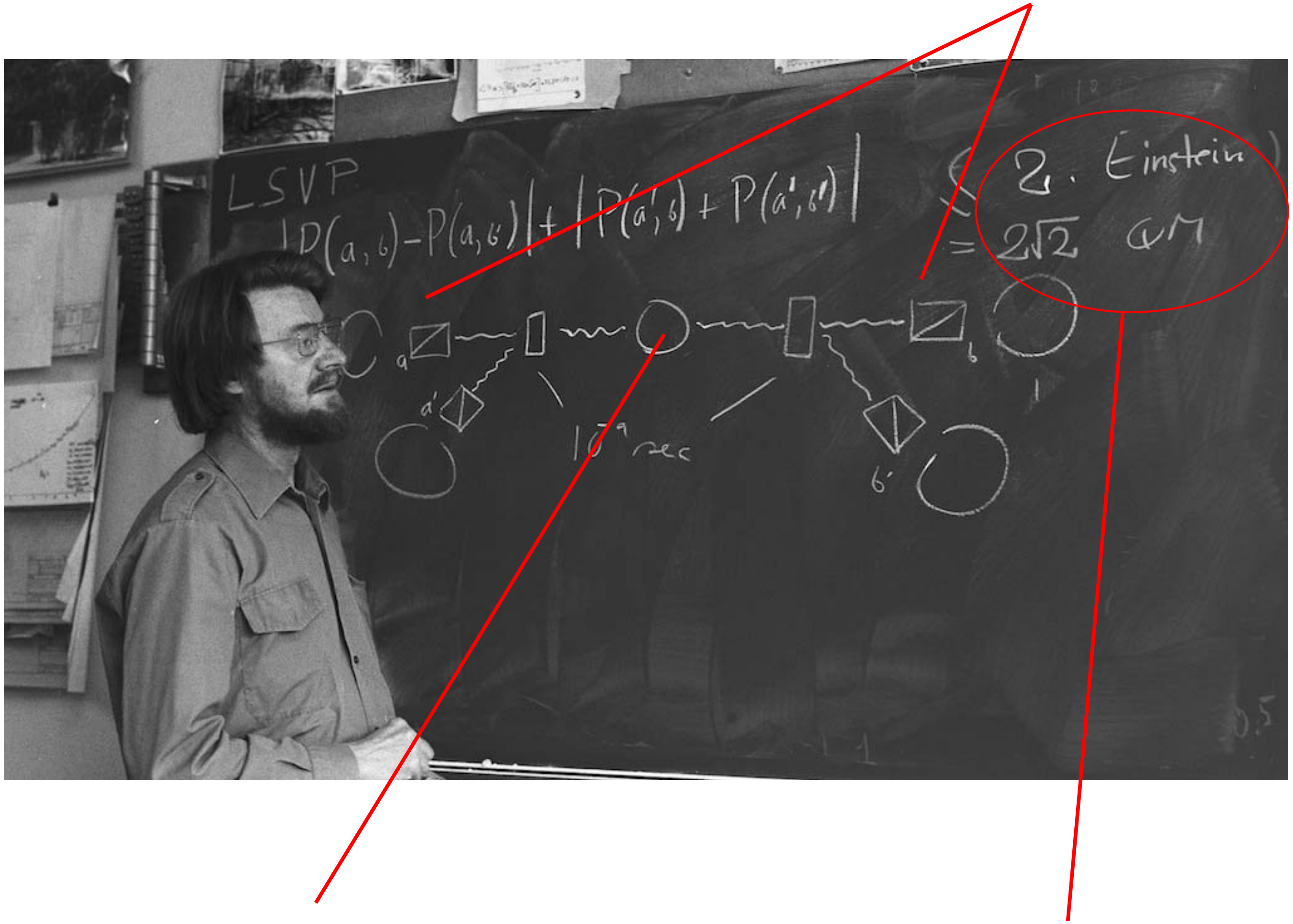
The Bell inequality



Two well-separated & independent detectors

Source of quantum-correlated "entangled" photons

Outcome of the Bell tests decides between "Einstein" (local realistic theory with hidden variables) and "Bohr" (probablistic interpretation of QM)

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Experimental quantum information

1970s-now: Aspect, Clauser, Zeilinger and many others designed and performed experiments that can test Bell inequalities

The result: Bohr was right, Einstein and common sense were wrong

A triumph of emprical science: settle a philosophical debate with an experiment

2022 Nobel prize “for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science"

© Nobel Prize Outreach. Photo: Stefan Bladh

Alain Aspect

Prize share: 1/3

© Nobel Prize Outreach. Photo: Stefan Bladh

John F. Clauser

Prize share: 1/3

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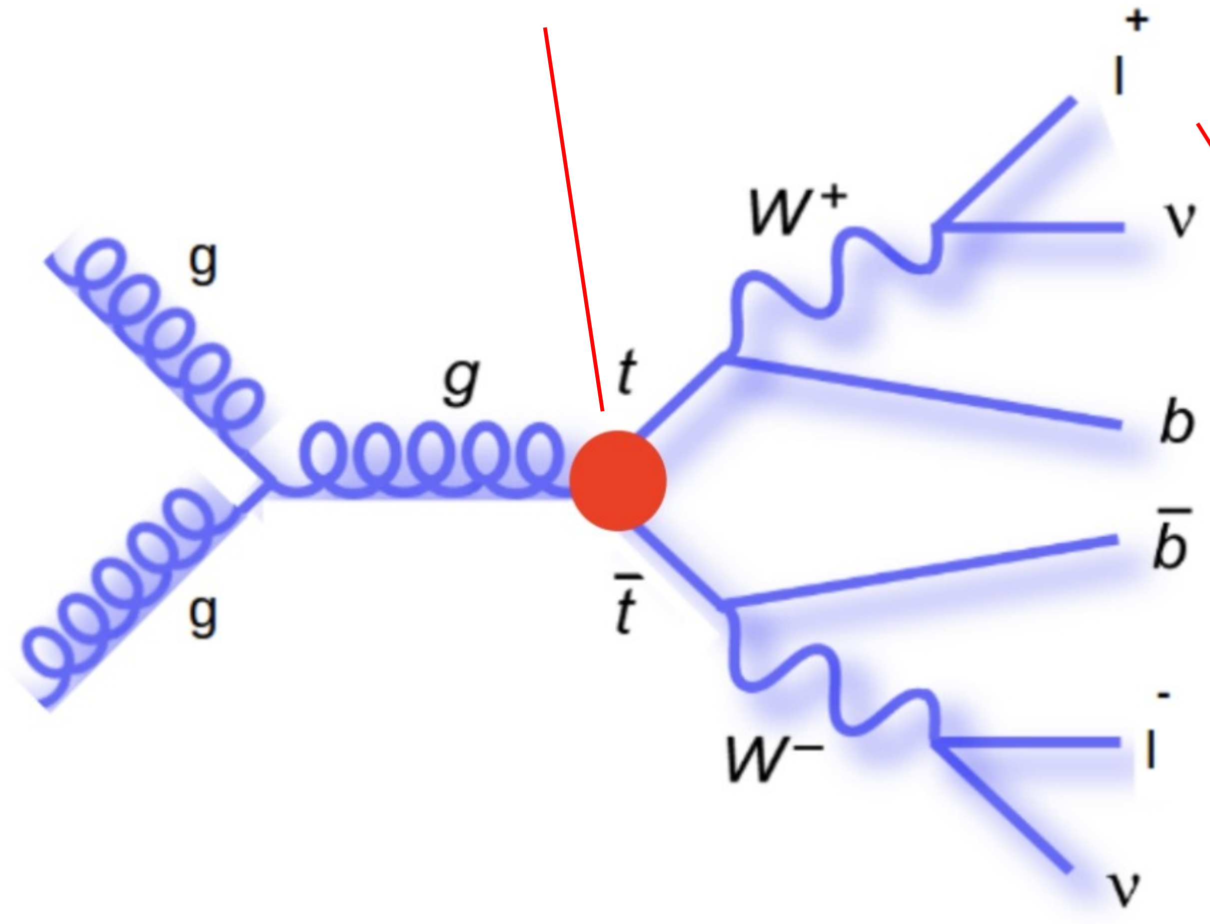
Anton Zeilinger

Prize share: 1/3

Afik & de Nova, EPJPlus, 2021

High energy collisions

Source of entangled particles: pp → $t\bar{t}$



Two polarimeters:
top quark decay
t → Wb, W→ $l^\pm \nu$

Entanglement (see Luca’s talk for much more)

Entanglement: one calls a mixed state of two systems entangled if it cannot be written as a convex combination of product states...

Horodecki, Horodecki, Horodecki & Horodecki, RMP81 (2009), arXiv

$$\rho = \sum_j p_j \rho_j^{(A)} \otimes \rho_j^{(B)}$$

In $t\bar{t}$ production, an entangled system yields:

Afik & de Nova, EPJPlus, 2021

D < -1/3, at threshold, where D = angle between decay leptons in t and $\bar{t}$ rest frames

C[ρ] > 0 in boosted regime, where C[ρ] = max eigenvalue and ρ = spin-density matrix

Fabbrichesi et al., Severi & Maltoni,
J.A. Aguilar-Saavedra & A. Casas

Talks by J.R. Muñoz de Nova and Alan Barr at GGI workshop for qubit and qutrit case, respectively

Review paper from Barr, Fabbrichesi, Floreanini, Gabrielli, Marzola,

Entanglement in top quark pair production

ATLAS entanglement **observation** at TOP23

Submitted to Nature as arXiv:2311.07288

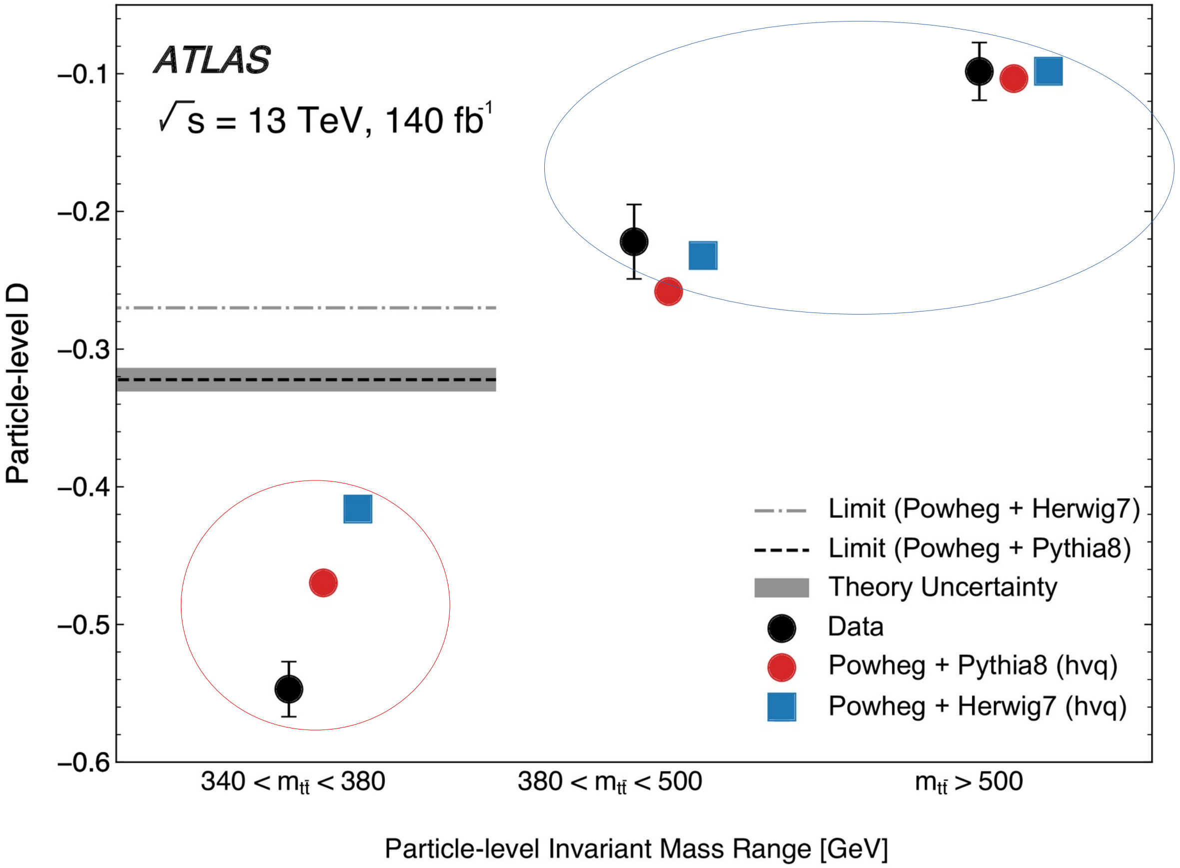
Particle-level measurement obtained by correcting data with a calibration curve

Three regions; only threshold sensitive to entanglement

D = -0.547 ± 0.021

Some tension with MC
(but note limitations of MC)

D != 0: spin correlation (since 2013)



D < -1/3: Entanglement (new!)

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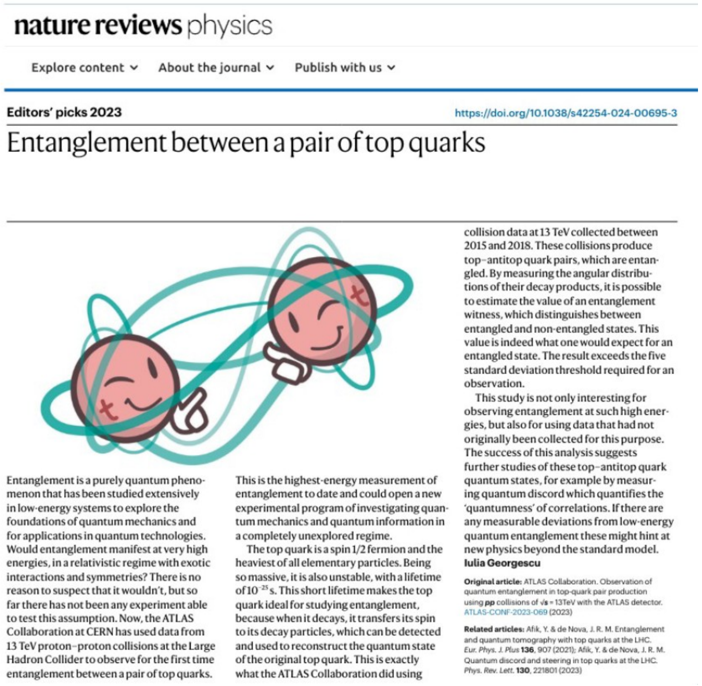
Quantum entanglement accessible at colliders!



Editors' picks 2023

https://doi.org/10.1038/s42254-024-00695-3

Entanglement between a pair of top quarks

Entanglement is a purely quantum phenomenon that has been studied extensively in low-energy systems to explore the foundations of quantum mechanics and for applications in quantum technologies. Would entanglement manifest at very high energies, in a relativistic regime with exotic interactions and symmetries? There is no reason to suspect that it wouldn't, but so far there has not been any experiment able to test this assumption. Now, the ATLAS Collaboration at CERN has used data from 13 TeV proton–proton collisions at the Large Hadron Collider to observe for the first time entanglement between a pair of top quarks.

This is the highest-energy measurement of entanglement to date and could open a new experimental program of investigating quantum mechanics and quantum information in a completely unexplored regime.

The top quark is a spin 1/2 fermion and the heaviest of all elementary particles. Being so massive, it is also unstable, with a lifetime of 10^{-25} s. This short lifetime makes the top quark ideal for studying entanglement, because when it decays, it transfers its spin to its decay particles, which can be detected and used to reconstruct the quantum state of the original top quark. This is exactly what the ATLAS Collaboration did using collision data at 13 TeV collected between 2015 and 2018. These collisions produce top–antitop quark pairs, which are entangled. By measuring the angular distributions of their decay products, it is possible to estimate the value of an entanglement witness, which distinguishes between entangled and non-entangled states. This value is indeed what one would expect for an entangled state. The result exceeds the five standard deviation threshold required for an observation.

This study is not only interesting for observing entanglement at such high energies, but also for using data that had not originally been collected for this purpose. The success of this analysis suggests further studies of these top–antitop quark quantum states, for example by measuring quantum discord which quantifies the 'quantumness' of correlations. If there are any measurable deviations from low-energy quantum entanglement these might hint at new physics beyond the standard model.

Iulia Georgescu

Original article: ATLAS Collaboration. Observation of quantum entanglement in top-quark pair production using ***pp*** collisions of $\sqrt{s}$ = 13TeV with the ATLAS detector. ATLAS-CONF-2023-069 (2023)

Related articles: Afik, Y. & de Nova, J. R. M. Entanglement and quantum tomography with top quarks at the LHC. *Eur. Phys. J. Plus* **136**, 907 (2021); Afik, Y. & de Nova, J. R. M. Quantum discord and steering in top quarks at the LHC. *Phys. Rev. Lett.* **130**, 221801 (2023)

Physics

Large Hadron Collider turned into world's biggest quantum experiment

Physicists have used the famous particle smasher to investigate the strange phenomena of quantum entanglement at far higher energies than ever before

By Alex Wilkins

3 October 2023

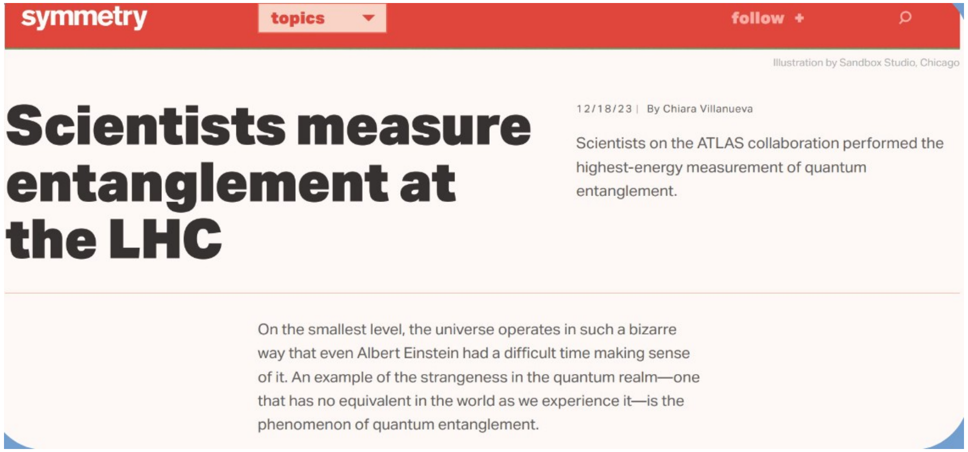


Illustration by Sandbox Studio, Chicago

Scientists measure entanglement at the LHC

12/18/23 | By Chiara Villanueva

Scientists on the ATLAS collaboration performed the highest-energy measurement of quantum entanglement.

On the smallest level, the universe operates in such a bizarre way that even Albert Einstein had a difficult time making sense of it. An example of the strangeness in the quantum realm—one that has no equivalent in the world as we experience it—is the phenomenon of quantum entanglement.

Question: isn't this just spin correlations with some buzz words?

The validation regions (and many previous measurements) show that D != 0
→ top and anti-top spins are correlated

Only a measurement in a narrow region at threshold demonstrates that D < -1/3
→ top and anti-top form a non-separable (= entangled) system

The Bell inequality is yet a more stringent condition
→ probably possible at the (HL-) LHC

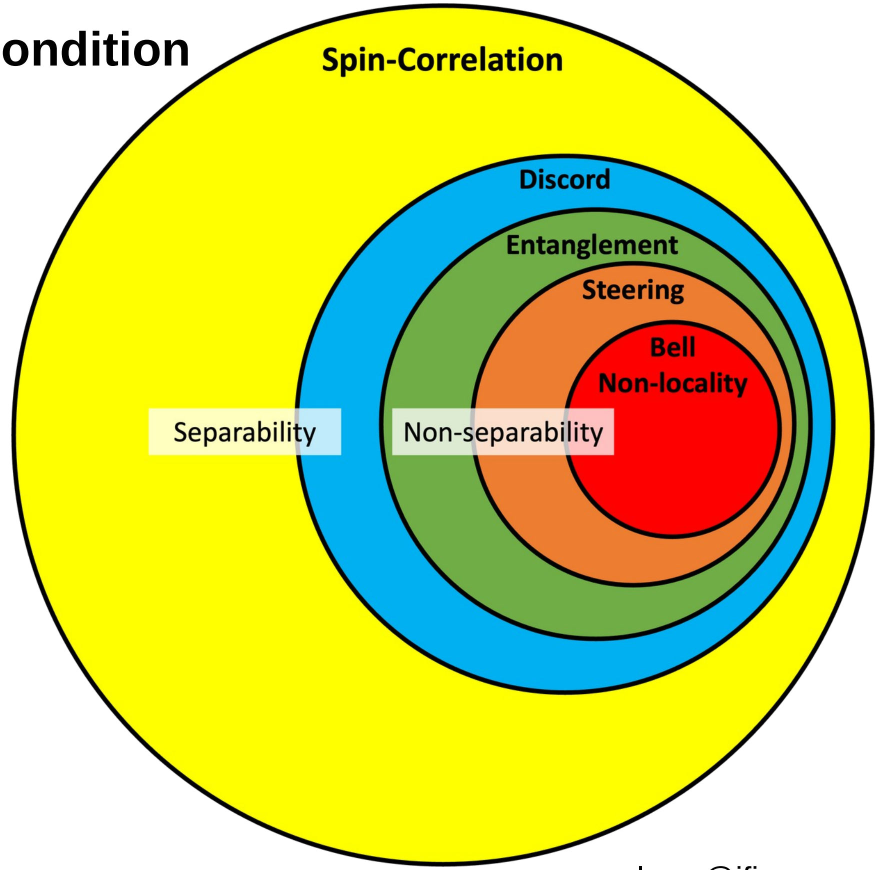


Illustration from Yoav Afik

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Question: wasn't this done at B-factories?

Older attempts

A. Go & Chung Li, quant-ph/0310192v1 (but see: Bertlmann et al., 2005, Ichikawa et al., 2008).
Bell inequality, Go et al. (Belle), PRL99 (2007) → 5σ rejection of Pompili-Selleri local realism
T-violation: Bernabeu et al., JHEP 08, Babar, PRL109 (2012)

More recent results

Bell inequality violation in B^0 → J/psiK,*
Fabbrichesi et al., arXiv:2305.04982, based on $B^0 \rightarrow J/\psi\, K^*$, $J/\psi \rightarrow \mu\mu$, $K^* \rightarrow K^+\pi^-$
polarization amplitudes published by LHCb (arXiv:1307.2782)

Upcoming

Bell inequality violation in tau pairs at Belle 2
Ehatäht, Fabbrichesi, Marzola, Veelken, arXiv:2311.17555

Takubo et al., Feasibility of Bell inequality violation at the ATLAS experiment with flavor entanglement of $B^0\overline{B}^0$ pairs from pp collisions
https://journals.aps.org/prd/pdf/10.1103/PhysRevD.104.056004

What about Higgs factories?

Mohammad Altakach

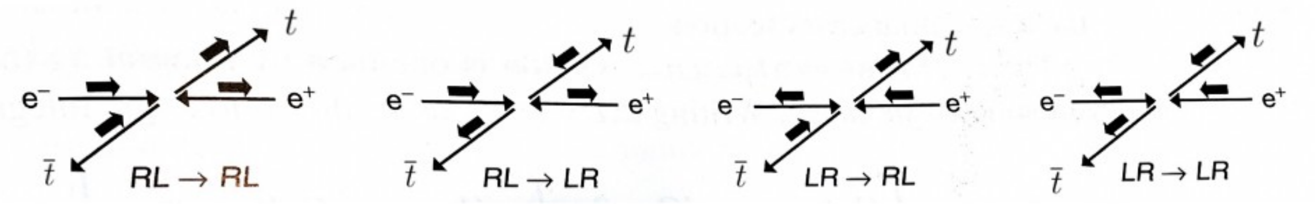
(with Lamba, Maltoni, Mawatari, Sakurai, Phys.Rev.D 107 (2023) 9, 093002)

-- H → ττ offers access to entanglement at ILC and FCCee
-- Statistics is a problem: Bell inequalities marginal at FCCee, and worse at ILC (luminosity spectrum?)
-- Fast simulation study, but ILD full-sim yields more promising CP results

Alan Barr, Clelia Altamonte

(Quantum State-Channel Duality for the calculation of SM scattering amplitudes)

-- $e^+e^- \rightarrow t\bar{t}$ maps a two-qubits initial state onto a two-qubit final state



-- beam polarization can be controlled at will (at linear colliders P(e-)=80%, P(e+)=30%)
-- final-state top quark polarization can be measured
-- Map out (at least parts of) Choi matrix

Predictions for basic entanglement witnesses:
Subba, Rahaman, https://arxiv.org/pdf/2404.03292.pdf

CMS entanglement

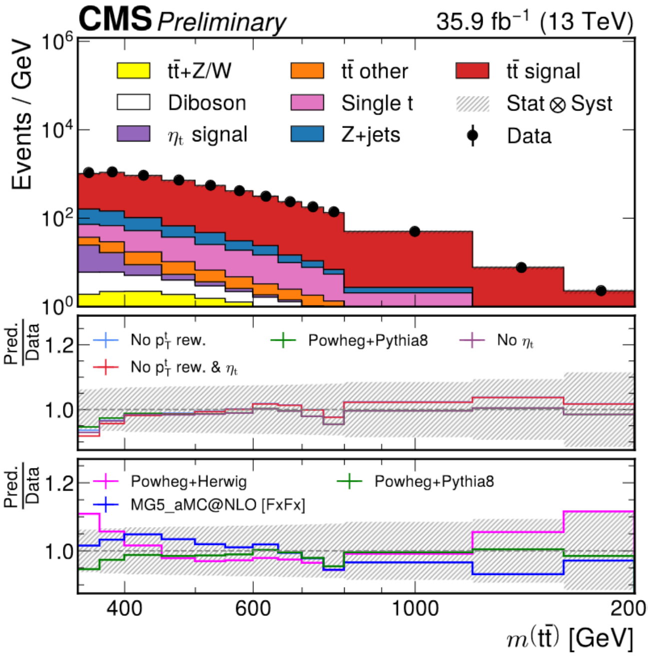
New: CMS entanglement **observation** at Moriond24

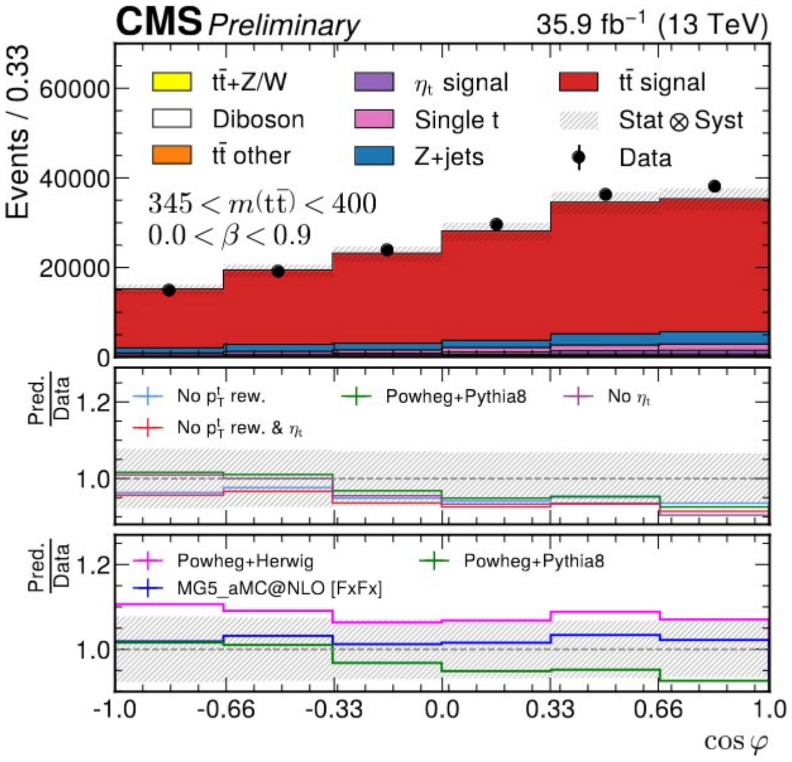
CMS-PAS-TOP-2023-001

Partial dataset, slightly broader mass window + cut on boost

Toponium contribution accounted for approximately in MC sample

Parton-level measurement with Profile Likelihood fit to cos ϕ





Top quark pair production

New: CMS entanglement **observation** at Moriond24

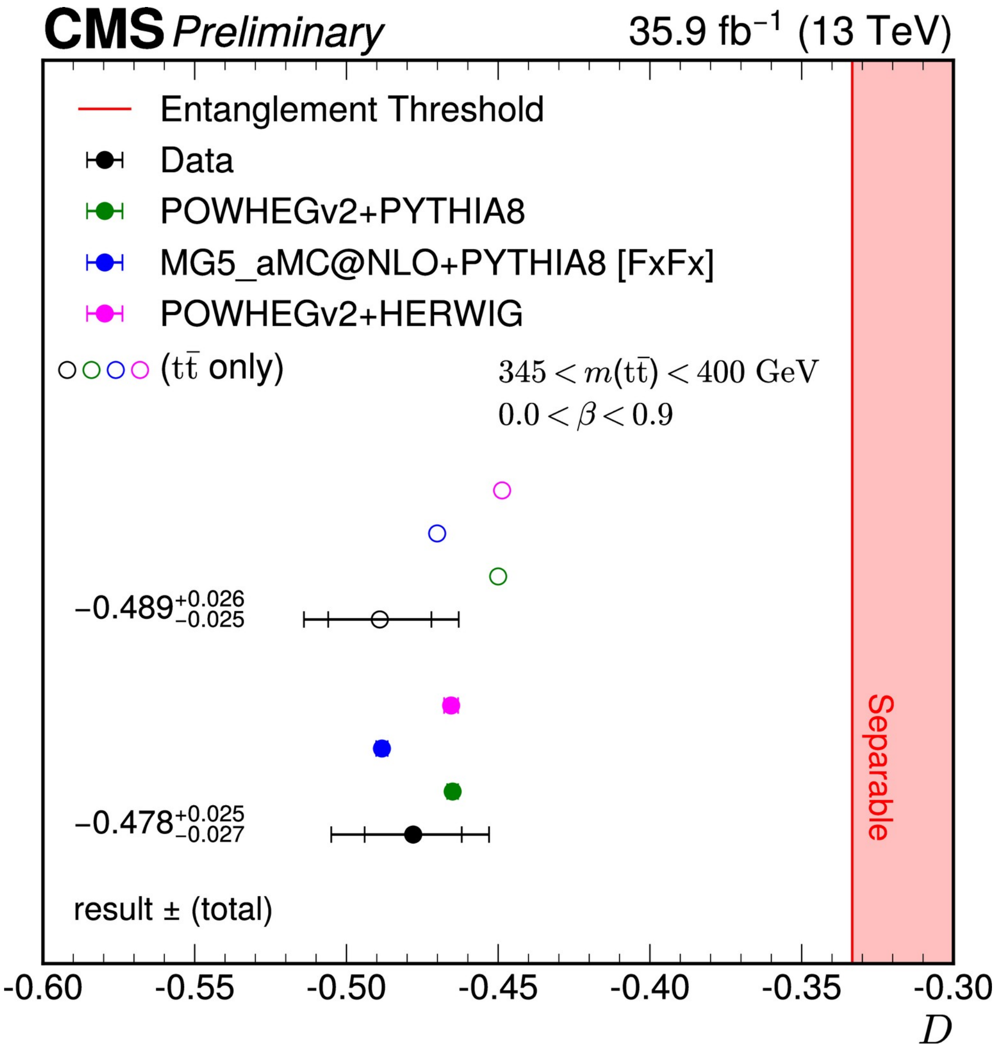
CMS-PAS-TOP-2023-001

$D = -0.478 \pm 0.026$

In good agreement with MC

Toponium and especially MG5-FxFx have large impact on prediction

Note Powheg+Pythia8 prediction ($t\bar{t}$ only) is slightly below ATLAS PP8



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ATLAS vs CMS

What did ATLAS and CMS do differently?

	ATLAS	CMS
Data set	Full run 2	2015+2016
Result reported	particle-level	parton-level
Corrections	Calibration curve	PL fit
Reweighting	Ent. marker D	Spin correlation
Total error	0.021 (4%)	0.026 (5%)
Dominant systematic	Top quark decay	JES + toponium + ISR

Or, maybe the question should be: what didn’t they do differently?

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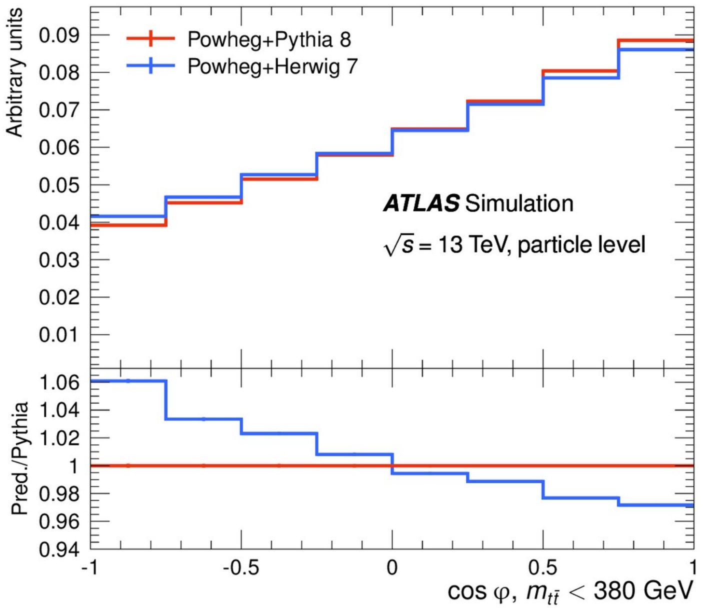
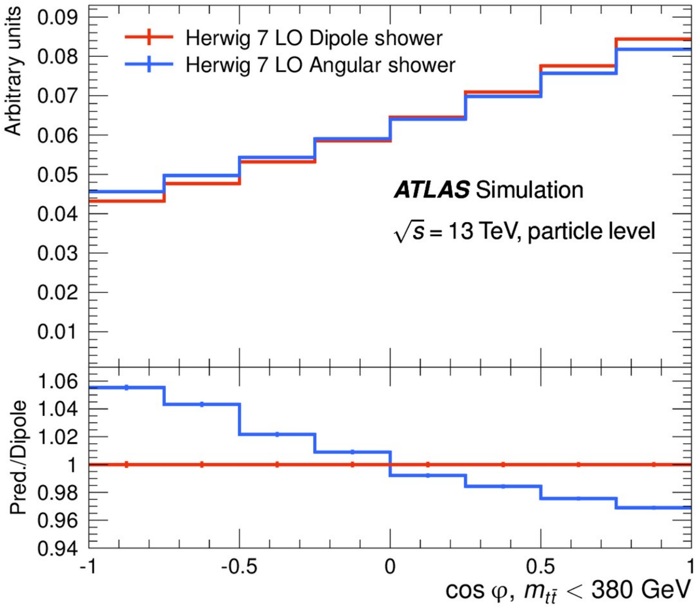
ATLAS vs CMS

ATLAS note points to the importance of PS ordering:
angular (Herwig7) vs. dipole (Pythia8)





CMS discards Pythia vs. Herwig as PS uncertainty, but includes Powheg+H7 prediction

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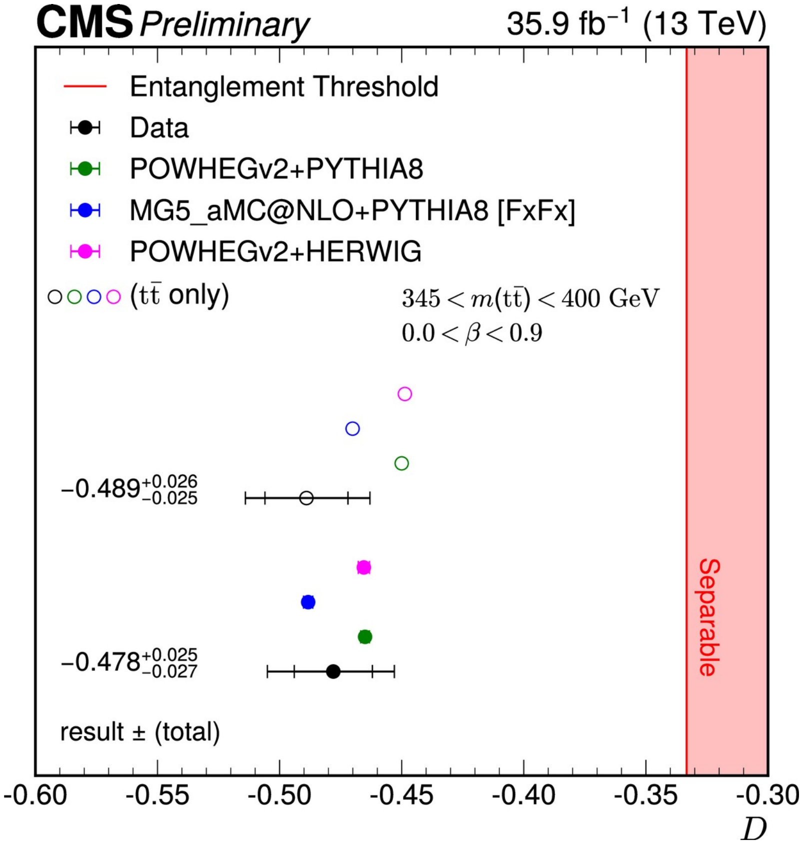
ATLAS vs CMS



CMS insists on importance of toponium modelling (Δ = 0.11 in measurement)

“Thus, for our specific technique of extracting the entanglement, an overestimation of the observed D value would be obtained, if one would ignore contributions from toponium.”

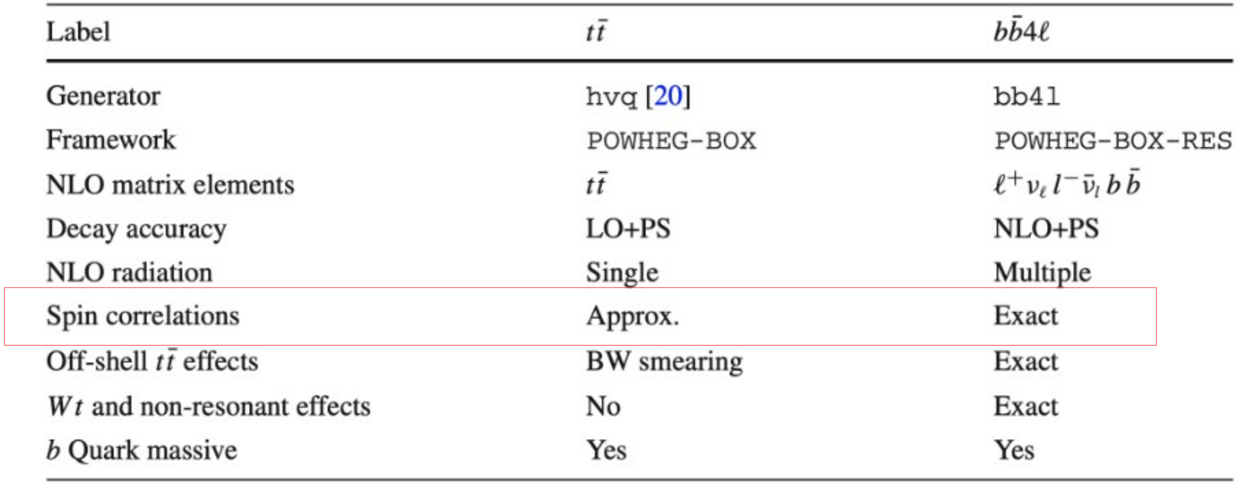
ATLAS includes top decay unc. (δ = 0.017); toponium has minor impact in stress tests

SM predictions & Monte Carlo modelling

Robust observables? An angle between two leptons: how hard can it be?
NNLOxNNLO and EW corrections are small, virtual corrections somewhat larger:
https://arxiv.org/pdf/2008.11133.pdf and *https://arxiv.org/pdf/2105.11478.pdf*

Top decay in Powheg-hvq and MadSpin performed with algorithm from Frixione et al., JHEP 0704, 081 (2007) [hep-ph/0702198]

Exact Matrix Element is available in Powheg-bb4l



Label	$t\bar{t}$	$b\bar{b}4\ell$
Generator	`hvq` [20]	`bb4l`
Framework	`POWHEG-BOX`	`POWHEG-BOX-RES`
NLO matrix elements	$t\bar{t}$	$\ell^+\nu_\ell l^-\bar{\nu}_l b\bar{b}$
Decay accuracy	LO+PS	NLO+PS
NLO radiation	Single	Multiple
Spin correlations	Approx.	Exact
Off-shell $t\bar{t}$ effects	BW smearing	Exact
Wt and non-resonant effects	No	Exact
b Quark massive	Yes	Yes

Jezo et al arXiv:1607.04538

From: Eleni Vryonidou, MC and predictions for spin correlations

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Constructing the SM prediction

Guessing the uncertainties on the Powheg-hvq + Pythia8 prediction

Difference with Powheg-hvq + Herwig7: **(δ_{PS} ~ ± 13%)**

Difference with Powheg-bb4l + Pythia8: **(δ_{ME} ~ 10%)**

Difference with MG5-FxFx + Pythia8: **(δ_{dec} ~ 7%)**

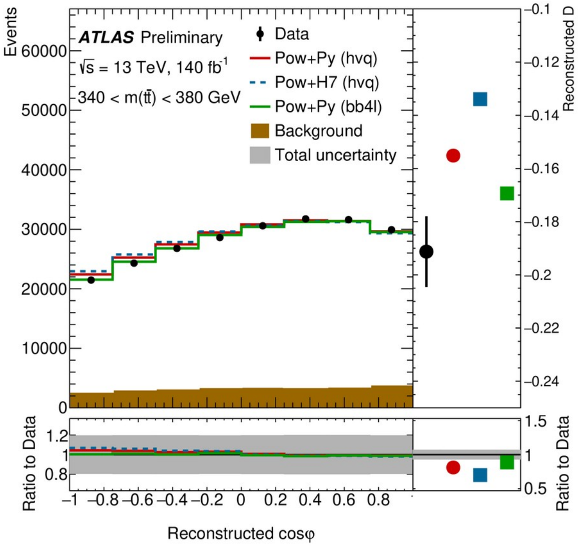
Pseudo-bound-state effects: **(δ_{BS} ~ ± 5%)**

My private best guess:

ΔD = ± 20% (based on rough $\delta_{PS}\oplus\delta_{ME}\oplus\delta_{dec}\oplus\delta_{BS}$)

Taking into account SM uncertainty: $D_{ATLAS} - D_{SM} < 1\sigma$

We need a better SM prediction!



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The big picture:
where do we go next?

What do we learn about the foundations of QM that’s new?
Which techniques and ideas from QI can further the HEP programme?

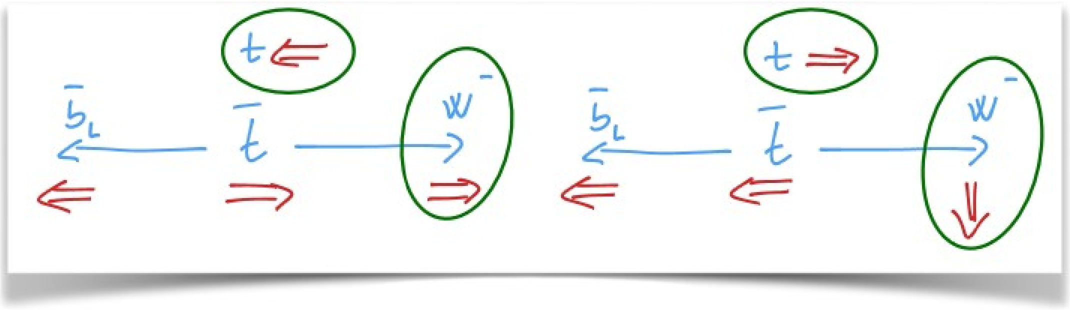
New measurements in $t\bar{t}$

What CAN we do in top quark pair production that's NEW?

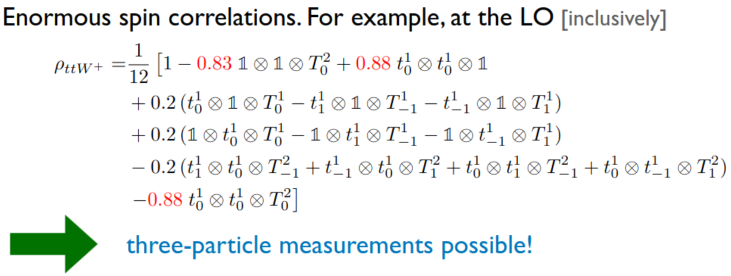
-- entanglement and Bell inequality in boosted top quark pair production

-- full quantum tomography, discord and steering

-- measuring post-decay t-W entanglement (fermion-boson; decay vs. measurement)



-- QI studies in ttW:



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

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

➡ three-particle measurements possible!

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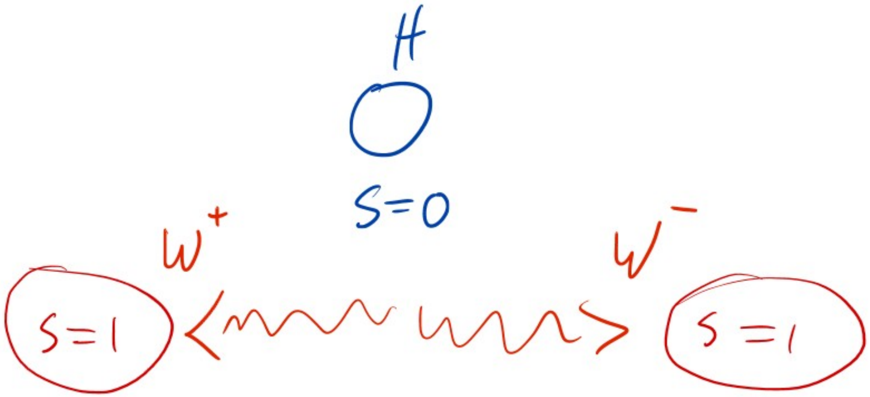
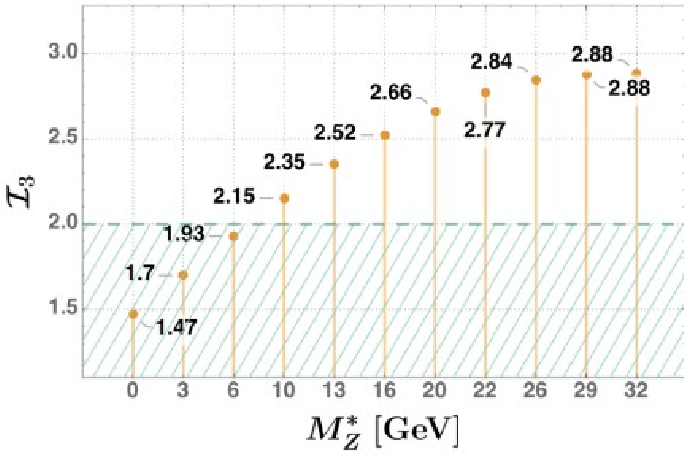
Higgs decays, qutrits, virtual particles

Higgs decays may be the ideal source of entangled particles
Higgs is a scalar with no memory (i.e. all pairs of decay will be prepared identically)
Maximally entangled W pairs, easy-to-reconstruct Z-boson pairs

W and Z are qutrits, while most tests are done on qubits
Formalism for CGLMP Bell inequality exists

Tests of Bell inequalities with virtual particles
A nuisance or a unique possibilty at colliders…





Optimised Bell Operator
> 2?

Fabbrichesi et al. 2302.00683

A virtual W or Z is described by the same degrees of freedom and remains a qutrit

Testing QM, QFT, SM

With quantum measurements we are testing fundamental predictions of QM/QFT - and hence the SM - in new ways.

This is the core business of the LHC.

→ should the focus remain on rejecting local realism?
  (i.e. loopholes are probably tractable to some extent, but not our forte)

→ can we arrive at a sharp formulation of questions and alternative hypotheses?
  (i.e. scenarios that break QM at the LHC)

→ focus on unique possibilities at colliders, that are not possible in low-energy expts.?
  (i.e. develop measurements in “exotic” configurations: post-decay, qubit-vs-qutrit, etc.)

Testing the SM

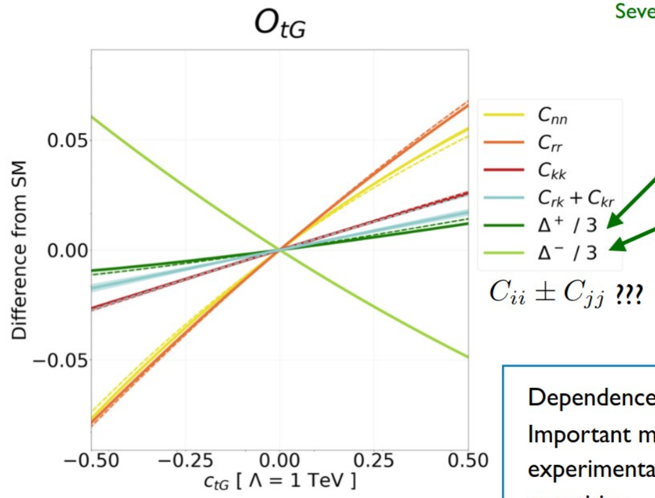
If QM turns out to be correct we can use the Quantum Information measurement as “just another observable”

→ test the usual extensions of the SM & SMEFT, with a new set of observables

→ C. Severi et al.: entanglement is as powerful as all other $t\bar{t}$ observables combined

t t-bar example: top chromomagnetic dipole operator

Severi, Vryonidou, 2210.09330



this is a new observable

this is essentially the old good *D*

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

JAAS

Don’t forget the theory uncertainty on the SM prediction; this may well be the bottle neck today.

MV

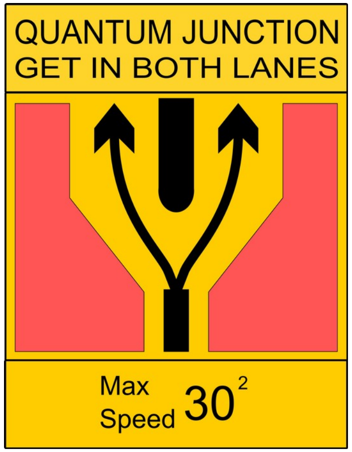
Conclusion

Observation of quantum entanglement by ATLAS and CMS (new!) have brought the foundations of quantum mechanics to colliders

Enables tests of QM at the highest energy and in new systems:
spin entanglement in tt & (H→)WW/ZZ, flavour-entanglement in B^0-$\overline{B}^0$.

New observables: new challenges and new opportunities
Incentive for a fresh look at Monte Carlo generators and SM predictions
New and enhanced sensitivity to beyond-the-SM physics

More QI/HEP workshops coming up: Oxford, 1-3 October '24



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Quantum information recovery course (Oxford , GGI workshop)

Lectures from J.I. Latorre, Michael Spannowsky, Pawel Horodecki, Stefano Carraza, Sofia Vallecorsa on several different aspects of "quantum meets HEP"

- talks by Michal Eckstein,
Juan de Nova, Ian Low, Alan Barr,
Recommended as didactic material.

- a lot of material is available:

Youtube playlist:
https://www.youtube.com/watch?v=gBhUpOd4TAQ&list=PL1CFLtxeIrQpAH1RGphax-xv7wSf-JM7o
Videos linked on the GGI webpage:
https://www.ggi.infn.it/showevent.pl?id=461
INDICO:
https://agenda.infn.it/event/34555/

QUANTUM OBSERVABLES FOR COLLIDER PHYSICS
06-10 NOV 2023, GGI FLORENCE

The workshop aims at gathering theorists as well as experimentalists interested in employing quantum information observables, such as entanglement and Bell inequalities, as means to probe fundamental interactions at the scales accessible at current and future high-energy colliders. The programme includes presentations and in-depth discussions of new proposals and their experimental feasibility, as well as a series of introductory lectures on quantum information and overview talks by renowned experts on quantum technology applications for high-energy physics

GUEST SPEAKERS:
Jose Ignacio Latorre (Abu Dhabi/Singapore/Barcelona)
Michael Spannowsky (Durham)
Sofia Vallecorsa (CERN)
Stefano Carrazza (Milano)

ORGANIZERS:
Marco Fabbrichesi (Trieste)
Andreas Jung (Purdue)
Fabio Maltoni (Bologna/Louvain)
Marcel Vos (Valencia)

CONVENERS:
Yoav Afik (CERN)
Rafael Aoude (Louvain/Edinburgh)
Federica Fabbri (Glasgow/Bologna)

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Bell inequality

Bell inequality: stronger condition that implies that the results cannot be explained with a local realistic theory

In $t\bar{t}$ production, with polarization and spin density matrix:

$$\rho = \frac{1}{4}\Big[\mathbb{1}\otimes\mathbb{1} + \sum_i A_i(\sigma_i\otimes\mathbb{1}) + \sum_j B_j(\mathbb{1}\otimes\sigma_j) + \sum_{ij} C_{ij}(\sigma_i\otimes\sigma_j)\Big] \,,$$

The Bell inequality can be written as:

Fabbrichesi et al., PRL 127 (2021)

$$m_1 + m_2 > 1 \,.$$

Where m1 and m2 are the two largest eigenvalues of spin correlation matrix Cij

Quantum Information and High Energy Physics

Several recent results kick off new inter-disciplinary work:
“quantum information meets high energy physics”

$B^0 \rightarrow J/\psi K^*$ @LHCb, Fabbrichesi et al., arXiv:2305.04982
Top quark pairs, ATLAS, arXiv:2311.07288
CMS, CMS-PAS-TOP-23-001

Collider experiments can indeed study quantum information in a unique high-energy environment with self-analyzing weak decays

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Loopholes

Marco Fabbrichesi and Dorival Gonçalves discussed loopholes at colliders

-- detection loophole: “if Alice and Bob measure only a small fraction of the emitted photons (or top quarks, or ...), correlations of the measurements may be unrepresentative. Problem avoided with detection effificiency > 60-80%”

Fabbrichesi: probably OK, as detection efficiency for energetic leptons is high
experimentalists: we’re not so sure, fraction of reconstructed tt events is small

-- locality loophole: “the choice of setting at a measurement site should not be able to influence the result of the other. Requiere space-like separation between the two measurements.”

Fabbrichesi: OK for boosted tops and $B \rightarrow \phi\phi$, but not for tops at threshold

-- free-will or setting independence loophole: “the choice of setting at each measurement site must be freely chosen”

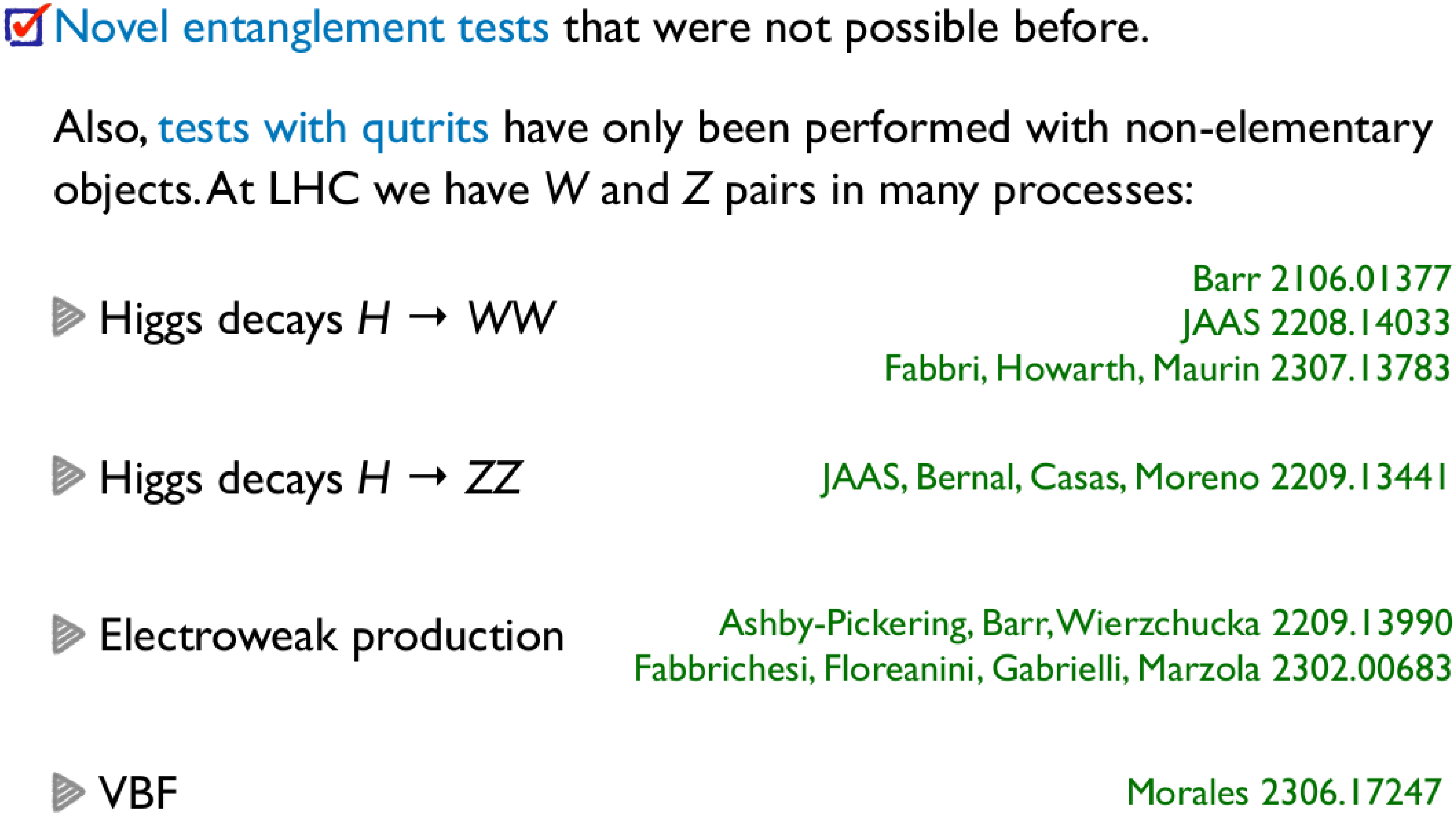
Most QI-experts: not OK, probably not possible to fix

Conclusion: we’re doing surprisingly well, maybe, but clearly collider experiments are not designed for Bell-type experiments…

Note from Juan de Nova: relevant for Bell tests, not for entanglement studies

Pheno studies - non-tt

Slide from JA Aguilar



☑ 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:

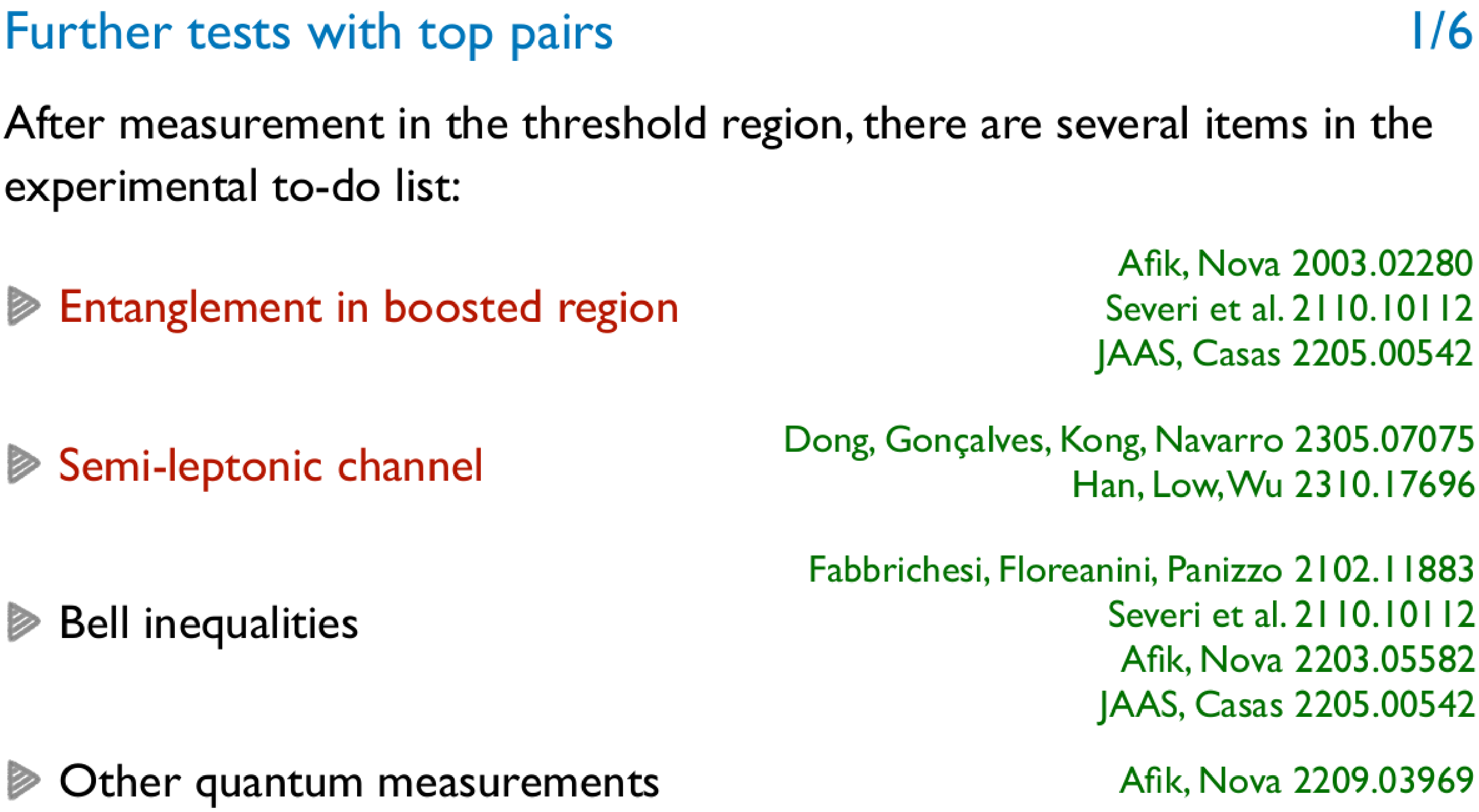
- Higgs decays $H \to WW$ — Barr 2106.01377
JAAS 2208.14033
Fabbri, Howarth, Maurin 2307.13783
- Higgs decays $H \to ZZ$ — JAAS, Bernal, Casas, Moreno 2209.13441
- Electroweak production — Ashby-Pickering, Barr, Wierzchucka 2209.13990
Fabbrichesi, Floreanini, Gabrielli, Marzola 2302.00683
- VBF — Morales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

Also: Alexander Bernal & Luca Marzola, H→ZZ with anomalous couplings,
Erik Madge, new physics in di-boson production, arXiv:2307.09675

Warning: pheno studies! Differing degrees of realism.
2-3 sigma stat.-only in an idealized environment and for full HL-LHC is actually a NO!!!

Pheno studies - tt

Slide from JA Aguilar



Further tests with top pairs

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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