Quantum observables for colliders

Workshop summary

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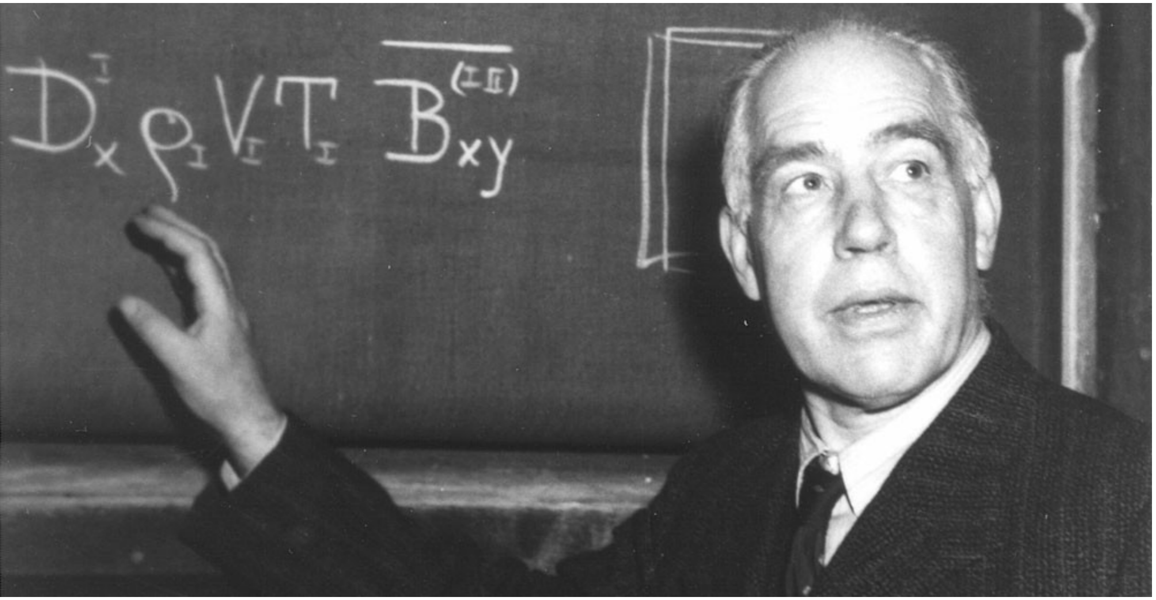
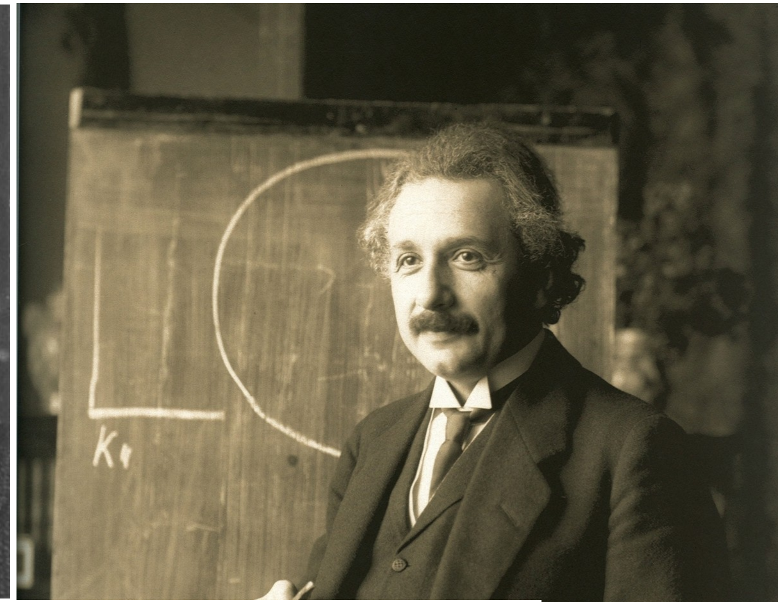
GGI workshop quantum observables for HEP

49 participants, mixed theory-experiment, mixed QI-HEP, lots of lectures, some talks...

good attendance from ATLAS & CMS (>10), interest from Belle 2

Foundations of quantum mechanics





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

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.

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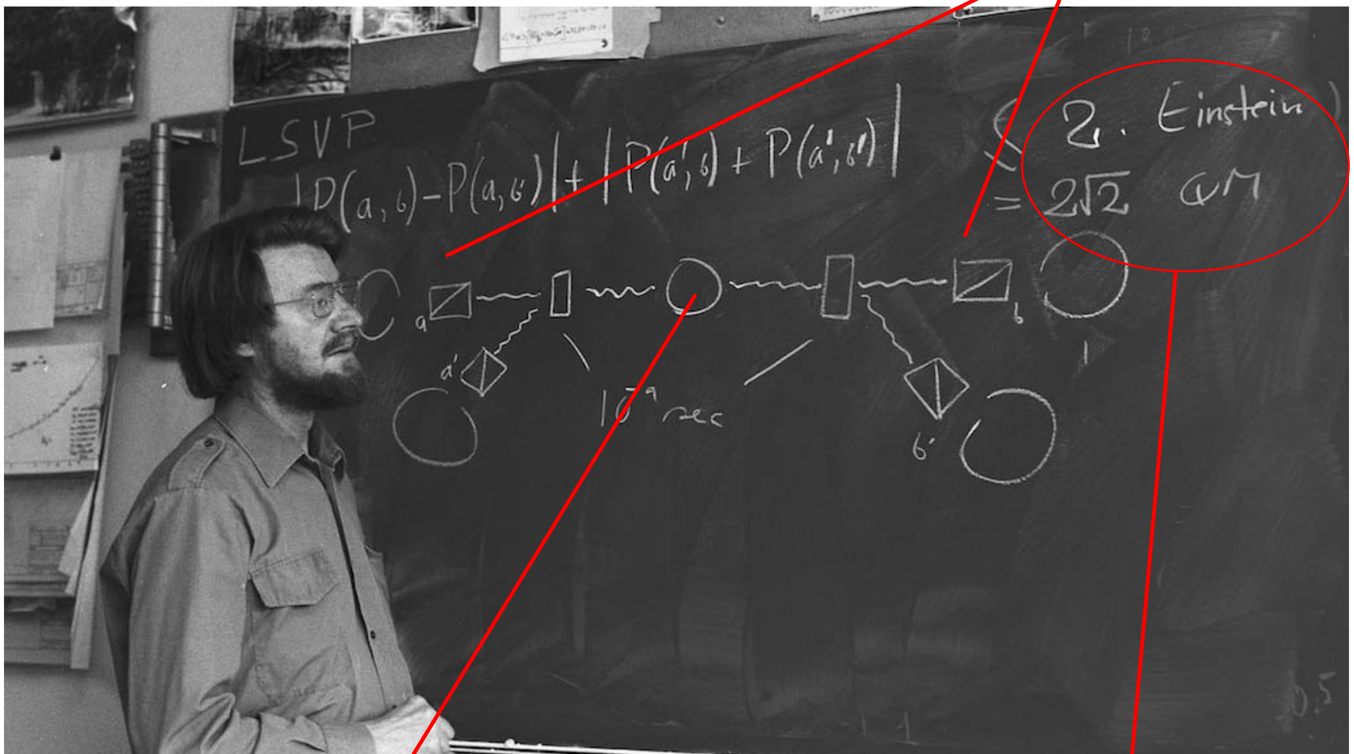
Bell-style experiments

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)

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

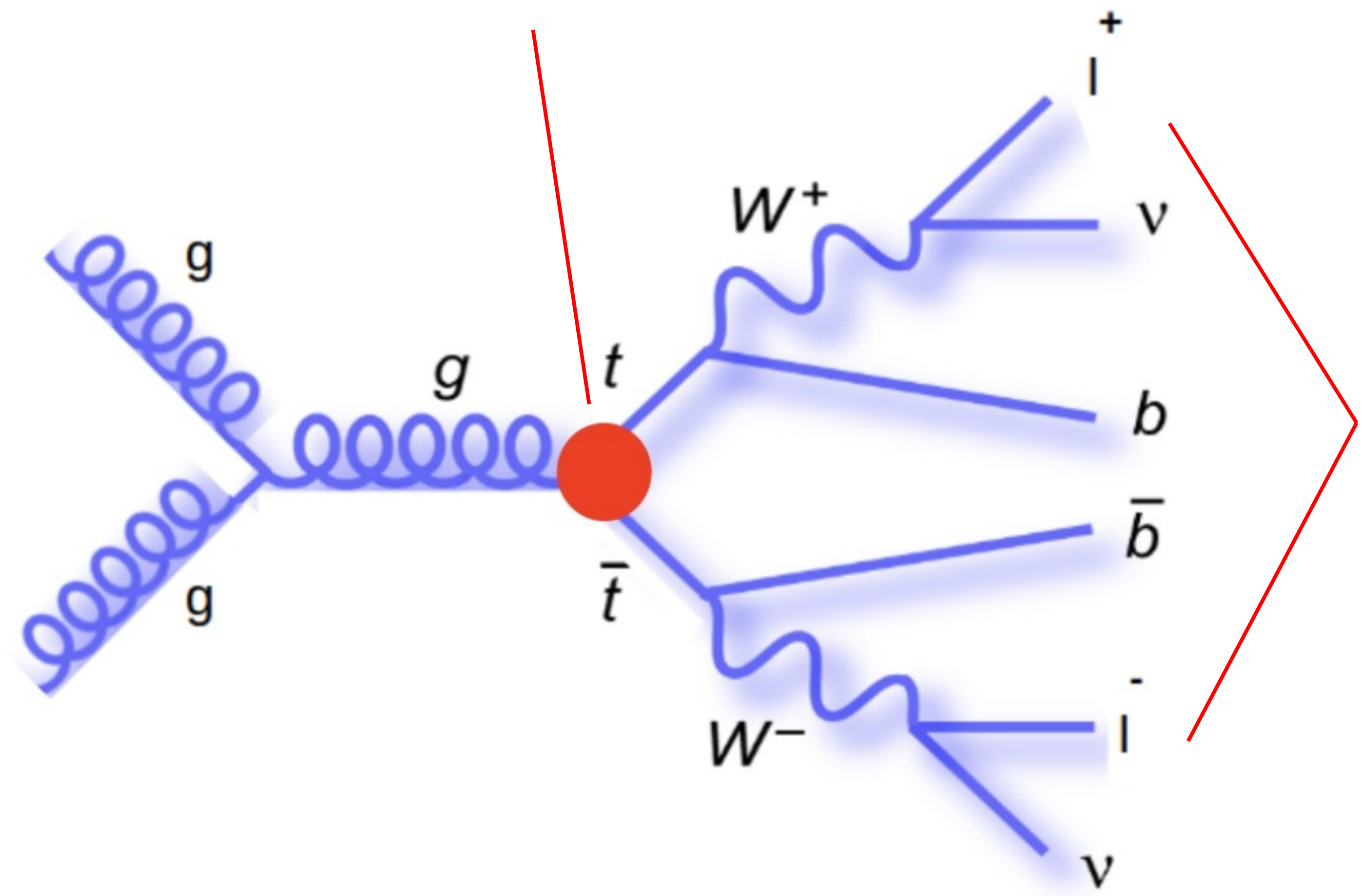
A triumph of emprical science: settle a philosophical debate with an experiment

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

High energy collisions

Afik & de Nova, EPJPlus
ATLAS, arXiv:2311.07288

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



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

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

Quantum Information and High Energy Physics

2023: Several new results kick off new inter-disciplinary work:
“quantum information meets high energy physics”

Bell inequality, Go et al. (Belle), PRL99 (2007)
T-violation: Bernabeu et al., JHEP 08, Babar, PRL109 (2012)
Top quarks, arXiv:2311.07288, and soon CMS?
$B^0 \rightarrow J/\psi K^*$ @LHCb, Fabbrichesi et al., arXiv:2305.04982

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

Lots of interest (Oxford workshop, GGI workshop)

Alpinism analogy

In 1980, Reinhold Messner climbed Everest, solo, in alpine style, new route, without oxygen

This kicks off a new discipline in alpinism

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Alpinism analogy

In 1980, Reinhold Messner climbed Everest, solo, in alpine style, new route, without oxygen

And, of course, some people had to respond to the challenge!

Jerzy Kukuczka, same, but in winter

Andrzej Bargiel, same, but on skis

Harila, Nims, different, but fast

Pierre Carter, In parapente

Alpinism analogy

In 1980, Reinhold Messner climbed everest, solo, in alpine style, new route, without oxygen

An anonymous dentist from Oklahoma...

Jerzy Kukuczka, same, but in winter

Andrzej Bargiel, same, but on skis

Harila, Nims, Jornet, different, but fast

Pierre Carter, In parapente

Where do we go next?

What should we measure?
Which processes are promising?
What do we learn about the foundations of QM that's new?
Which techniques and ideas from QI can further the HEP programme?

Lectures – everything quantum you need to know

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

- from proper blackboard lectures on foundations of QM to overview of activities in quantum computing of the CERN quantum initiative)

- also talks by Michal Eckstein, Juan de Nova, Ian Low, Alan Barr, etc. are highly recommended as didactic material.

- (nearly) everything 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/

With a big thank you to Alessio Attardi

Lectures – minimal or maximal entanglement

Discussion by both Ian Low and Jose Latorre whether nature picks maximum or minimum entanglement.

Entanglement suppression... https://arxiv.org/pdf/1812.03138.pdf
"We conjecture that the suppression of entanglement is an important element of strong-interaction physics that is correlated with enhanced emergent symmetries"

Maximal entanglement..., https://arxiv.org/pdf/1703.02989.pdf
"QED couplings are found to be the solution to a MaxEnt principle [requiring maximum entanglement] once some global symmetries (C, P and T) are imposed"

Numerology: Weinberg angle in SM is close to "optimal" choice of $\theta_W = \pi/6$ (coincidence? or a deep hint from mother Nature?)

Paraphrasing Alan Barr:

"In practice, entanglement is neither maximized nor minimized (exactly)".

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Lectures – physics beyond QM

Discussion by Michal Eckstein and Pawel Horodecki on physics beyond QM

Michal Eckstein: New Physics beyond QM, but assuming relativity. There might be a "Bell-like inequality" between QFT and QM.

Horodecki: freedom to perform any measurement is incompatible with universal laws of physics
https://link.springer.com/article/10.1007/s10699-020-09711-y

The Experiment Paradox in Physics

Michał Eckstein[1,2,3] · Paweł Horodecki[4,5]

Accepted: 3 October 2020 / Published online: 30 October 2020

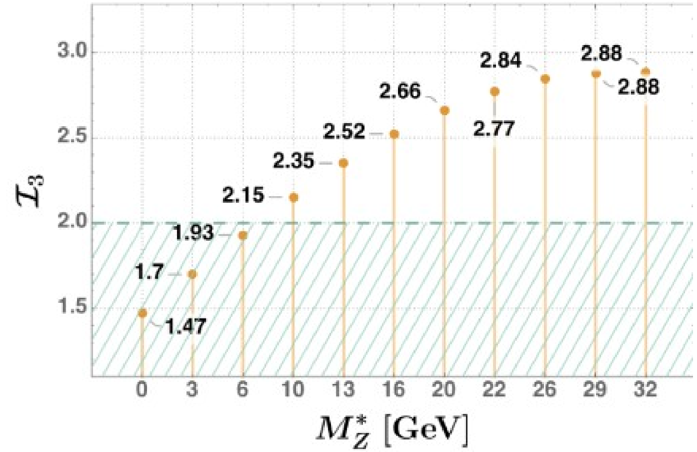
Horodecki points at "smart Bell inequalities" where QM touches "no signalling*" bound.

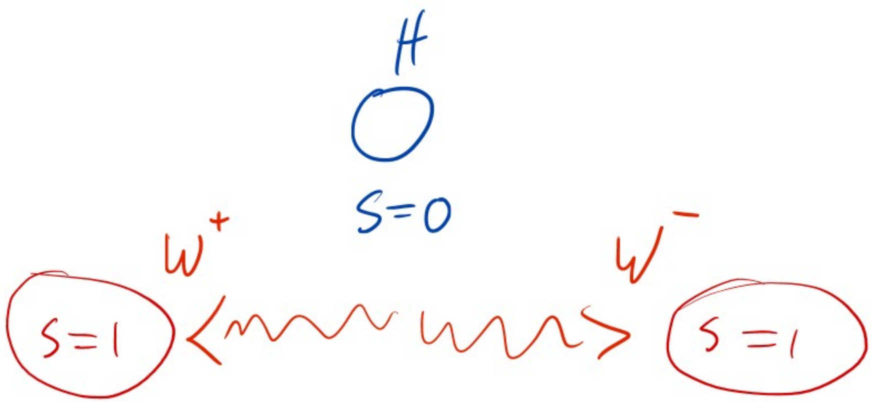
(*) no-signaling principle: space-like separated parties cannot use the nonlocal correlations [of QM] to communicate superluminally.

Expert panel discussion

Tests of Bell inequalities in systems with virtual particles …
(raised by Alan Barr and picked up again in the theory panel discussion).

This is a nuisance …
… or a unique possibilty at colliders…
… in any case, it's inevitable in $H \rightarrow ZZ, WW$.





Optimised Bell Operator
> 2?

Fabbrichesi et al. 2302.00683

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

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!!!

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

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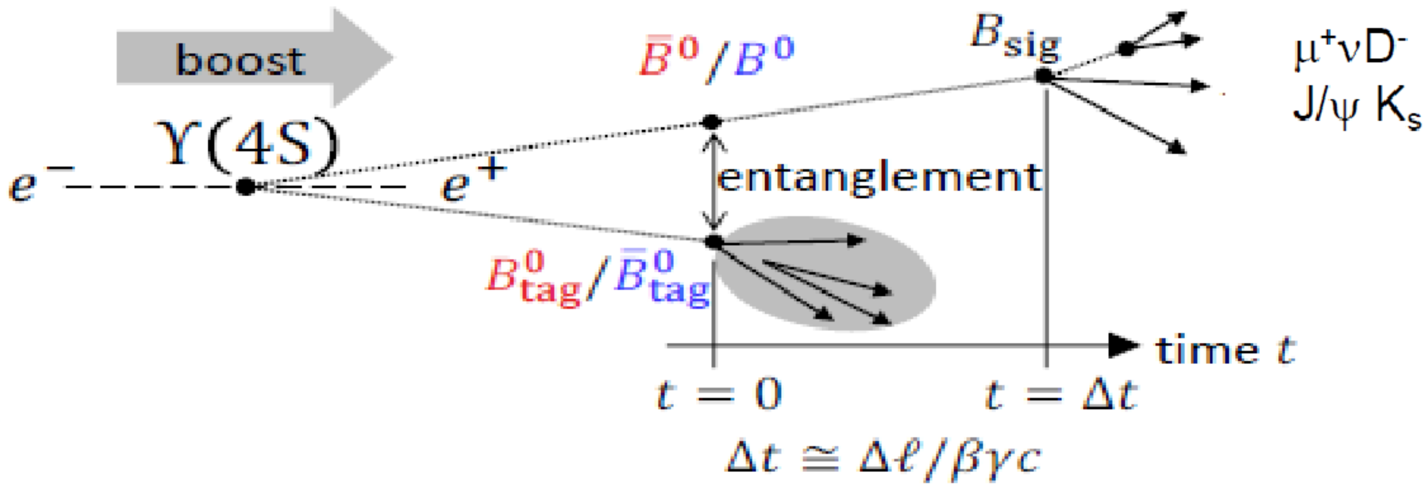
Meanwhile, at the B-factories…

Meanwhile at the B-factories!!

Hans-Gunther Moser, Belle 2 decoherence studies,
Studies of CP violation assume entangled B-mesons from Y(4S).
Decoherence (i.e. due to Y → $B^0\bar{B}^0\gamma$, or…) → systematic uncertainties.



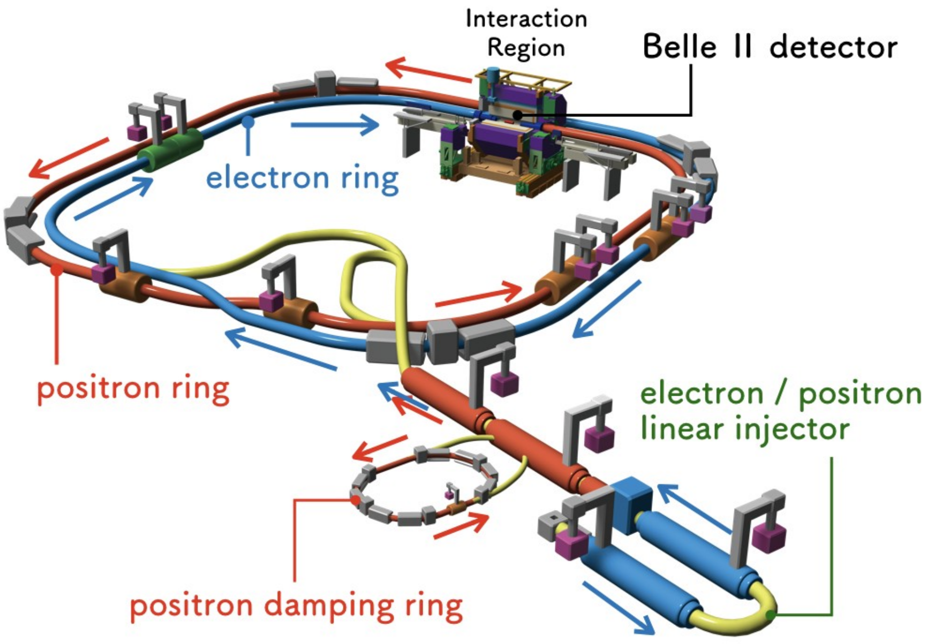
:

-- First Bell test yielded S=2.8 (cf. 2sqrt(2))
A. Go & Chung Li, quant-ph/0310192v1.
However, short B life time leads to S=2.3 even without quantum entanglement.
-- decoherence < 10%, explicit local realistic Pompili & Selleri model discarded
A.Go & Belle, PRL99 (2007) 131802 →

Future: Belle 2 needs to constrain decoherence better and can do Bell tests with Bs,
constrain lifetime of first (tag) B0 better to avoid spurious correlations

More from the B-factories (even if not from Belle 2 and LHCb)

Christian Veelken projects potential of Belle 2 tau data,
400 M tau pairs without much background
Tau polarization from hadronic channels
Horodecki observable m12 = sum of 1st two eigenvalues



Expected statistical significance of Bell inequality violation ~ 80 standard deviations

Full study needed, but missing experimental systematics expected to be small and a lot of margin!!

More from the B-factories (even if not from Belle 2 and LHCb)

Emidio Gabrielli, Bell inequality violation in $B^0 \to J/psiK^*$,
Fabbrichesi et al., arXiv:2305.04982, based on $B^0 \to J/psi\ K^*$, $J/psi \to \mu\mu$, $K^* \to K^+\pi^-$

Polarization amplitudes published by LHCb (arXiv:1307.2782)
J/psi K* are spin 1 → qutrits → CGLMP inequality: 4 > I3 > 2 implies QM

Observation of Bell inequality violation with collider data, in multiple decays

2305.04982 [hep-ph]

0< von Neumann entropy < ln[3] ~ 1.1

$$\mathcal{I}_3 = \mathrm{Tr}\left[\rho\, \mathcal{B}\right]$$

	$\mathscr{E}$	$\mathcal{I}_3$	
• $B^0 \to J/\psi\, K^*(892)^0$ [5]	0.756 ± 0.009	2.548 ± 0.015	
• $B^0 \to \phi\, K^*(892)^0$ [20]	$0.707 \pm 0.133^*$	$2.417 \pm 0.368^*$	→ 1.1σ
• $B^0 \to \rho\, K^*(892)^0$ [21]	$0.450 \pm 0.067^*$	$2.208 \pm 0.129^*$	→ 1.6σ
• $B_s \to \phi\, \phi$ [22]	$0.734 \pm 0.050^*$	$2.525 \pm 0.084^*$	→ 6.2σ
• $B_s \to J/\psi\, \phi$ [23]	0.731 ± 0.032	2.462 ± 0.080	→ 5.8σ

What about the Higgs factory?

What about Higgs factories?

Mohammad Altakach

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

-- $H \rightarrow \tau\tau$ offers access to entanglement at ILC and FCCee

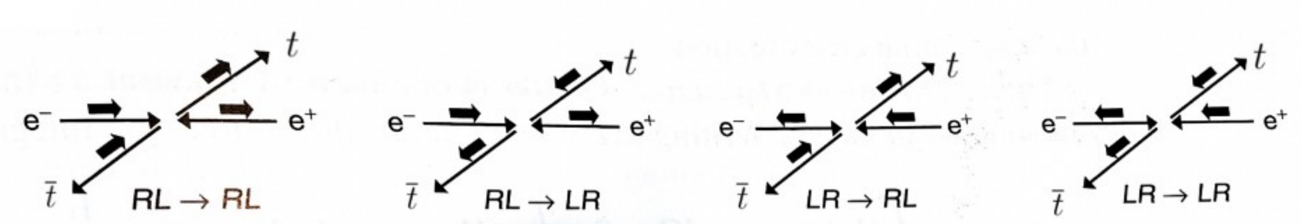
-- Statistics is a problem: Bell inequalities marginal at FCCee, and worse at ILC (luminosity spectrum?)

-- Fast simulation study, but ILD full-sim yields more promising CP results

Alan Barr, private communication

(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% and LR, RL periods are foreseen, as well as short LL, RR)

-- final-state top quark polarization can be measured

-- Map out (at least parts of) Choi matrix

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Top quark pair production...

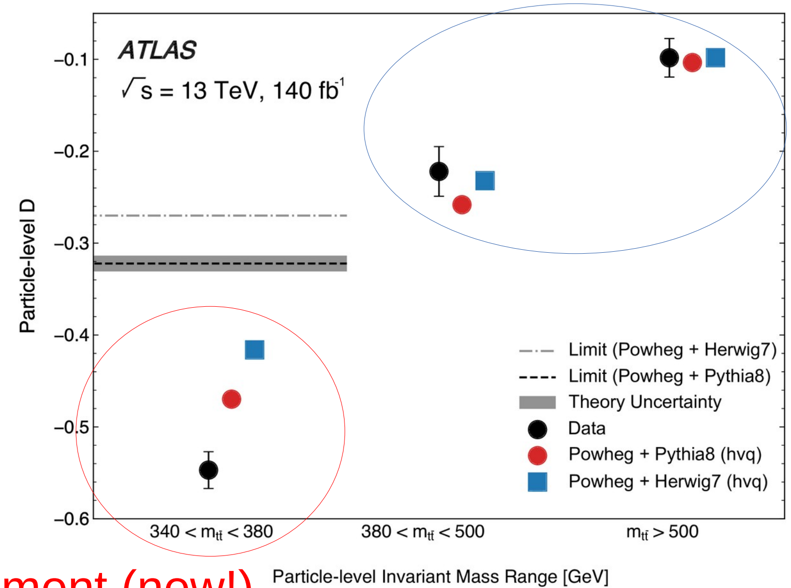
Top quark pair production

Good old spin correlations (since 2013)

ATLAS entanglement result
(Jay Howarth@GGI, Ethan Lewis today)

ATLAS-CONF-2023-069
→ now arXiv:2311.07288

CMS result was not ready in time for GGI
(hopefully soon!)



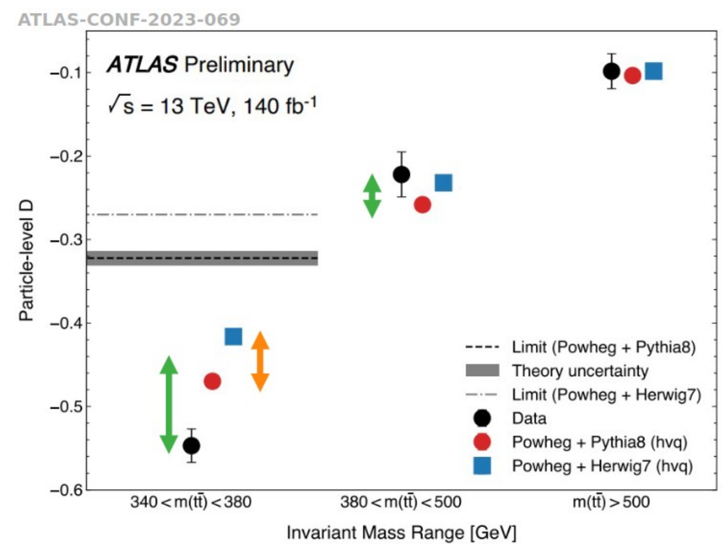
Entanglement (new!)

Claudio Severi: explanations for “ATLAS excess”…. (note: protest from ATLAS)

-- Pseudo-bound-state with D=-1
-» must have pretty large strength

-- EFT has difficulty to reproduce the pattern,
-» A new scalar could work

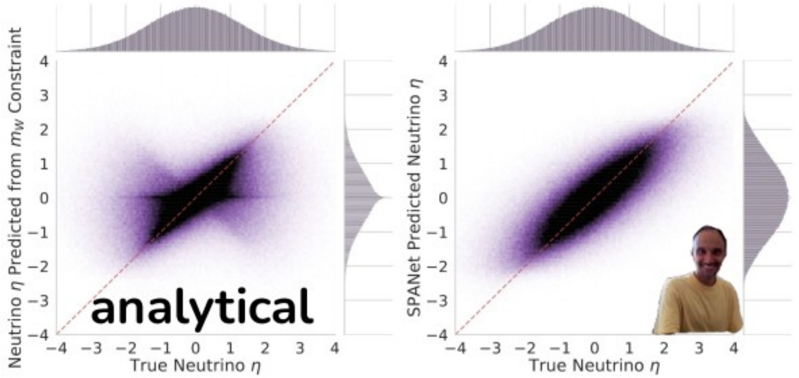
More on SM predictions and uncertainties later



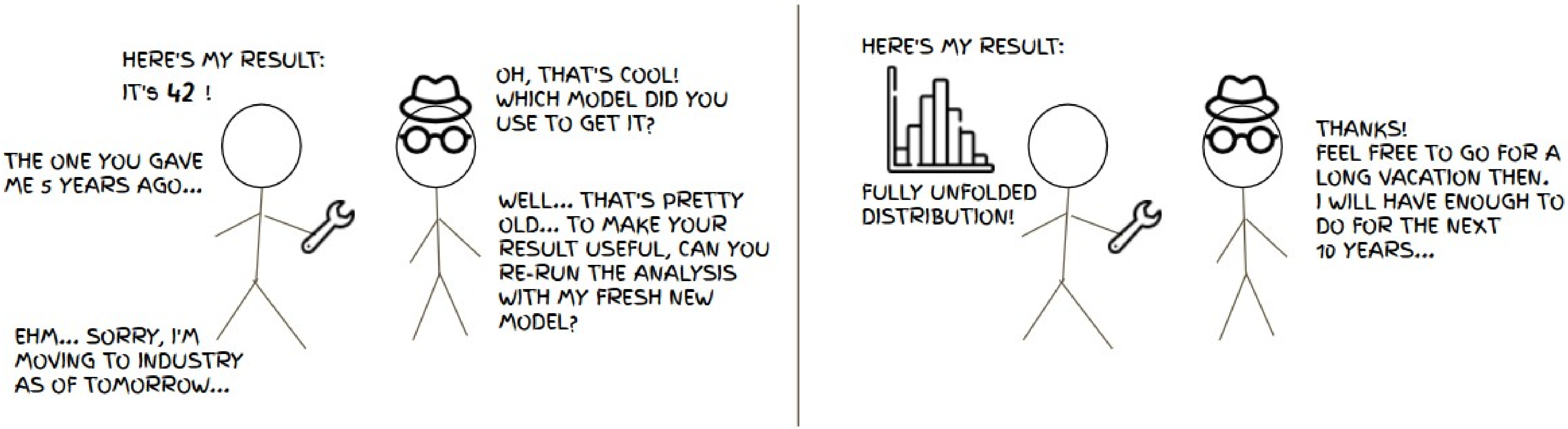
Top-ics close to our heart

Baptiste Ravine: top reconstruction is key

Use ML for better tt reconstruction, or better selection of well-reconstructed events
No need to develop ML; it's there already!



Michele Pinamonti: unfolding is key difference between Severi et al. ("Bell inequalities maybe at HL-LHC") and Fabbrichesi et al. ("Bell inequalities already now"). Third opinion from Arthur Wu in the next talk.



Monte Carlo modelling

Eleni Vryonidou: MC and predictions for spin correlations

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

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

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

Lots of discussion on parton-level pseudo-top definition inside bb4l.

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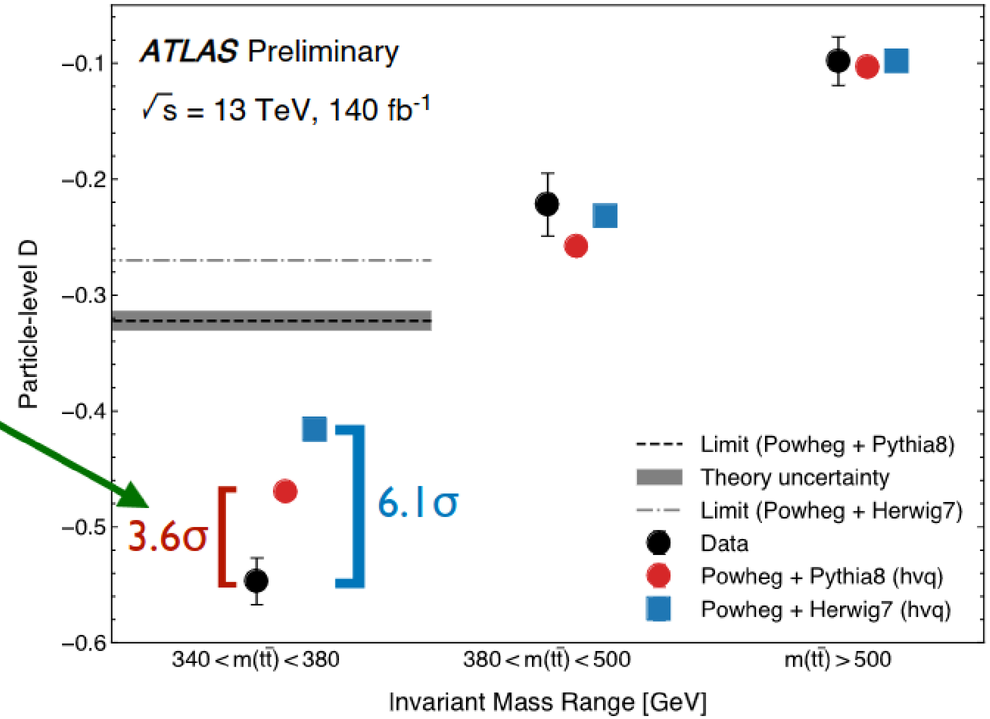
Theory summary by J.A. Aguilar

- 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



Constructing the SM prediction

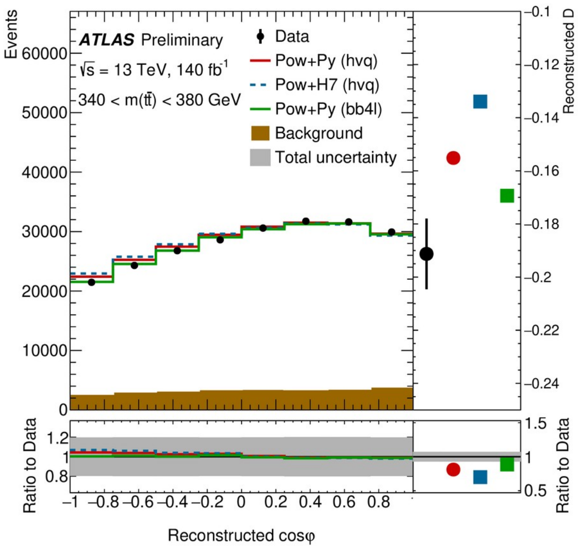
ATLAS provides Powheg-hvq+Pythia8 : $D_{particle}$ = -0.47 (with no uncertainty!!)

So, we can safely ignore SM uncertainties, now? NO!

ATLAS also gives Powheg-hvq + Herwig7 : $D_{particle}$ ~ -0.41 **(δ_{PS} ~ ± 13%)**

And: Powheg-bb4l + Pythia8 differs by a similar amount: **(δ_{ME} ~ 10%)**

But, neither of these models includes
pseudo-bound-state effects:
Assume 20% admixture with D = -1 **(δ_{BS} ~ ± 19%)**



My private best guess:
$D_{particle}$ = -0.47 (but probably quite a bit lower)
± 25% (based on rough $\delta_{PS} \oplus \delta_{ME} \oplus \delta_{BS}$)

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

We need a better prediction before we can play the BSM game!

Theory summary

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

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

A small and maybe not so representative sample of theorists expects …

Tests of Quantum Mechanics – the basis of everything we do – should of course be done, but I guess we're warned NOT to expect any immediate surprises

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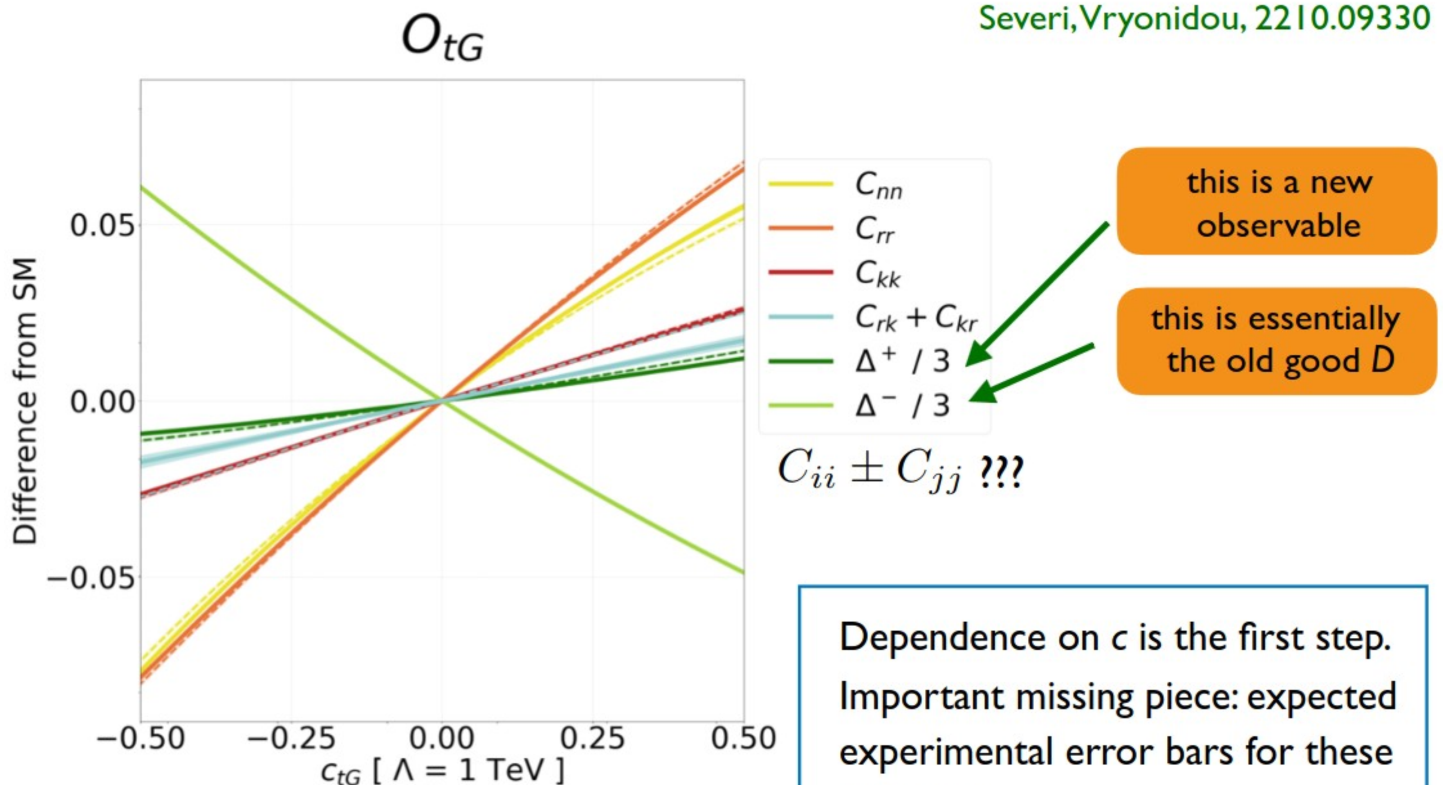
Theory summary

BSM sensitivity of “quantum observables” is well-established (Maltoni, Severi, Vryonidiou & others)

t t-bar example: top chromomagnetic dipole operator

Severi, Vryonidou, 2210.09330



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

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.

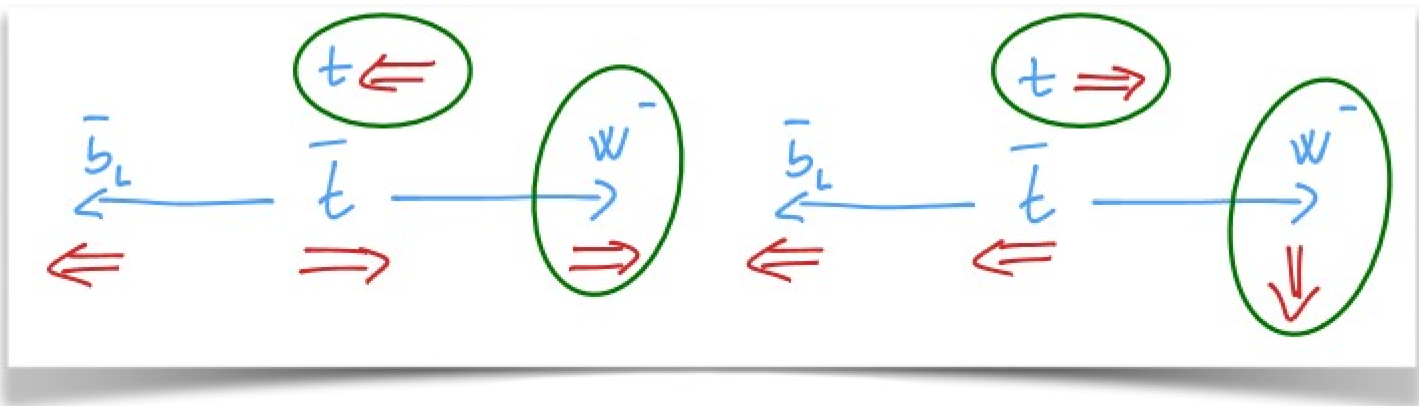
MV

What CAN we do that's NEW?

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

-- entanglement and Bell inequality in boosted top quark pair production
(pheno to figure out optimal observable, channel, reconstruction…
Gonçalves et al., arXiv:2305.07075 & Fabbri et al., 2307.13783 for l+jets)

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



-- QI studies in ttW:

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

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

three-particle measurements possible!

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Thanks

A big thanks, also on behalf of Fabio Maltoni, Andy Jung & Marco Fabbrichesi, to:

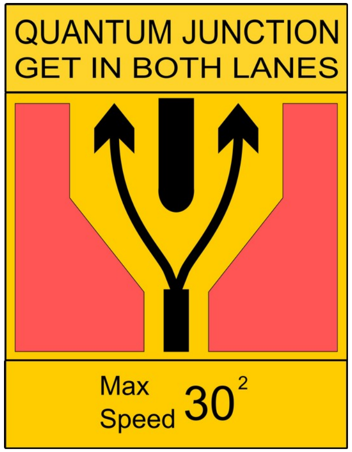
-- Stefania de Curtis and GGI staff
for hosting the workshop in beautiful Florence

-- Yoav Afik, Rafael Aoude, Federica Fabbri,
for organizing and running most of the sessions

-- all participants
for lively discussions, excellent talks, many new insights

BBC news 19 February 2015

Conclusion



There's a new game in town!

High-energy colliders as "quantum information laboratories":
experiments like ATLAS, CMS, LHCb and Belle 2 can study quantum information in a unique high-energy environment with self-analyzing weak decays

Join the fun! But try not to be the dentist!