Quantum decoherence at colliders
- experimental feasibility studies

Maria Moreno Llácer, José Manuel Camacho, Marcel Vos, Katinka Wandall-Christensen

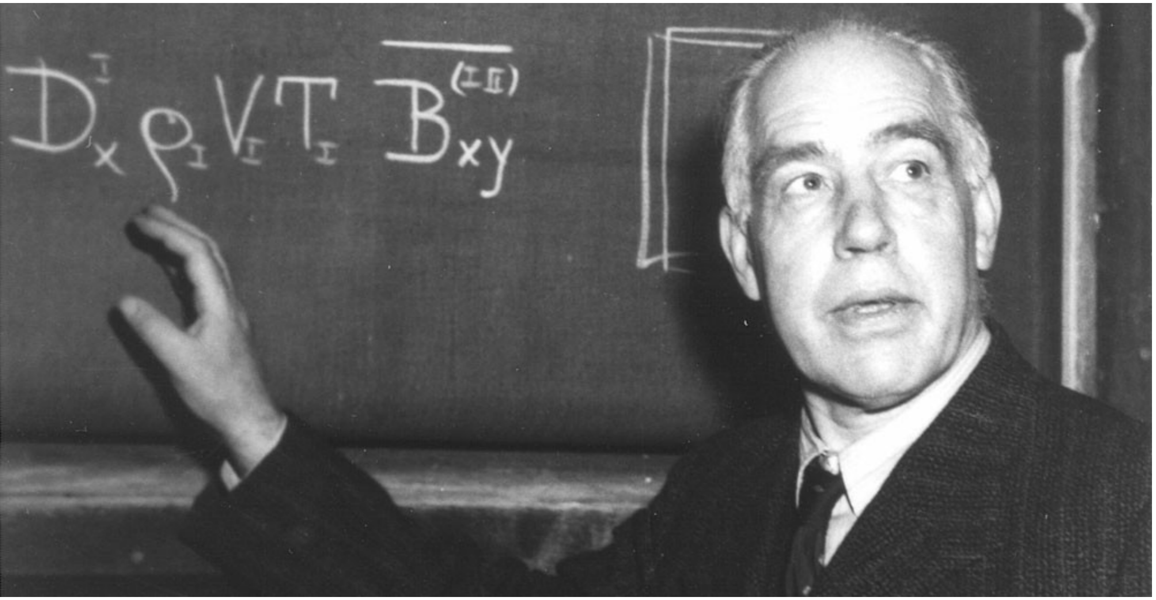
IFIC, CSIC/UV, Valencia, Spain

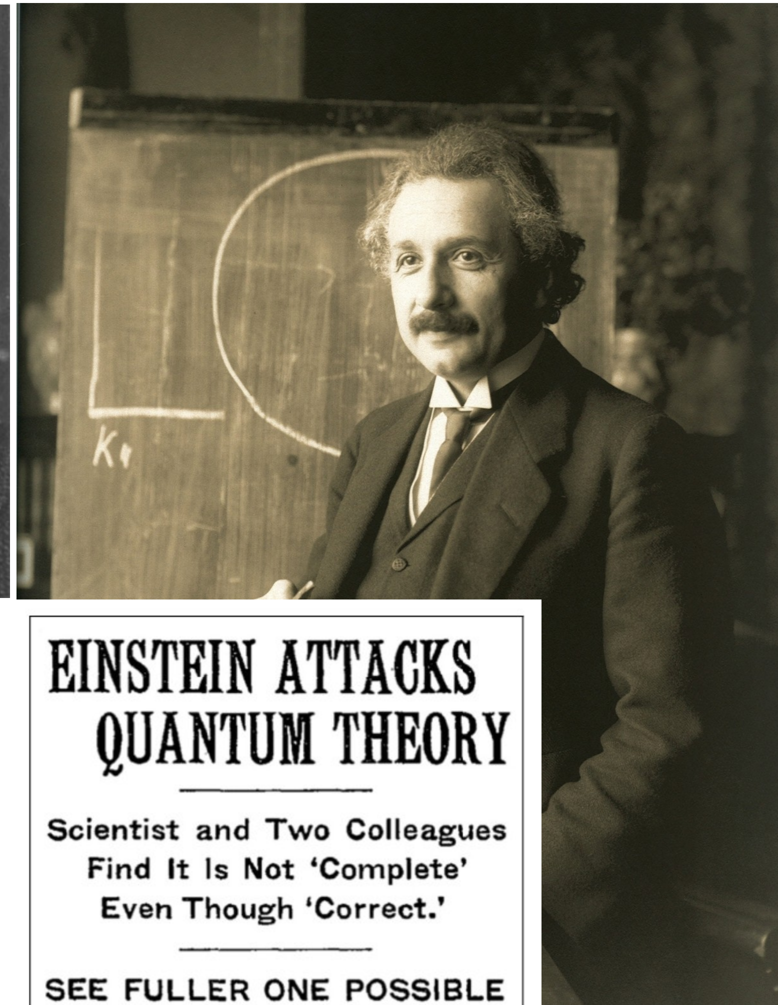
Work in progress with Rafael Aoude (U. Edinburgh), Fabio Maltoni (U. Bologna+Louvain), Leonardo Satrioni (U. Louvain)

CSIC
Consejo Superior de Investigaciones Científicas
Universitat de València
IFIC Institut de Física Corpuscular
Excelencia Severo Ochoa
Generalitat Valenciana
AITANA

marcel.vos@ific.uv.es

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.'

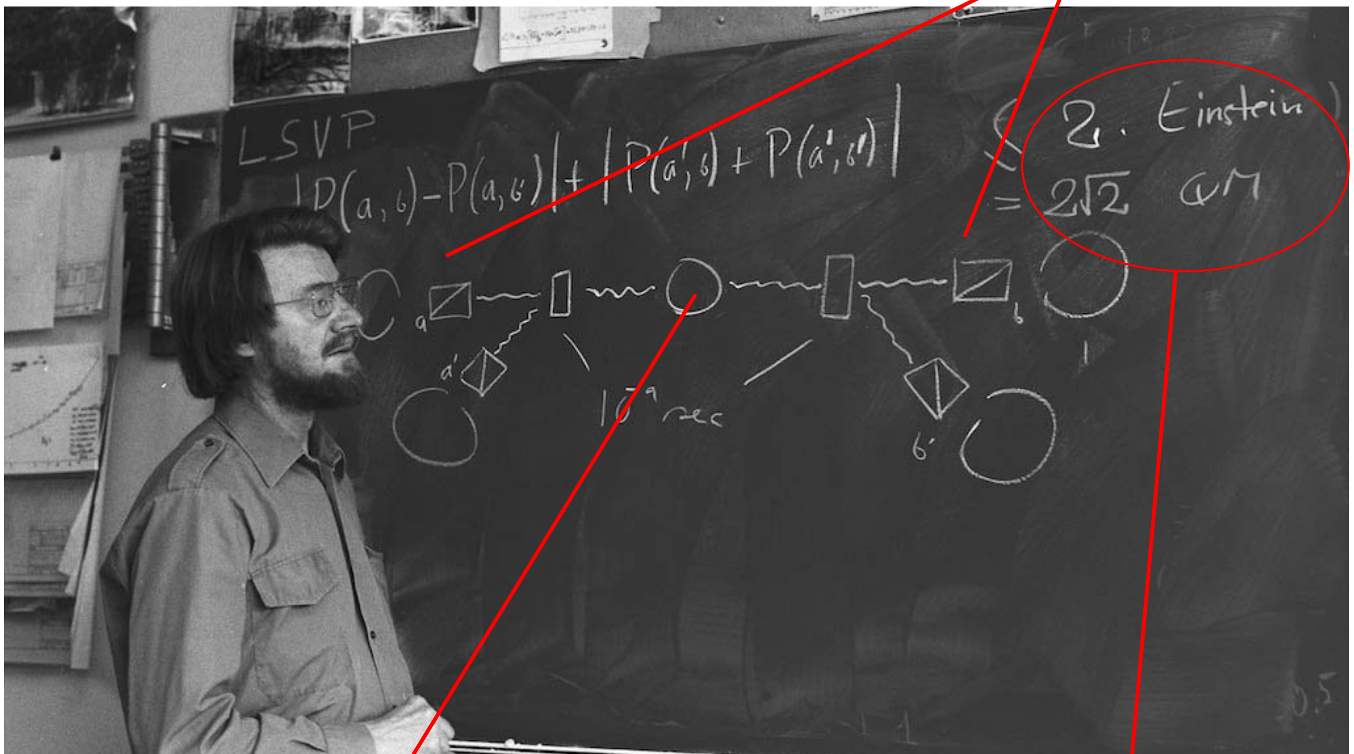
SEE FULLER ONE POSSIBLE

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

marcel.vos@ific.uv.es

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"

© Nobel Prize Outreach. Photo: Stefan Bladh
Alain Aspect
Prize share: 1/3

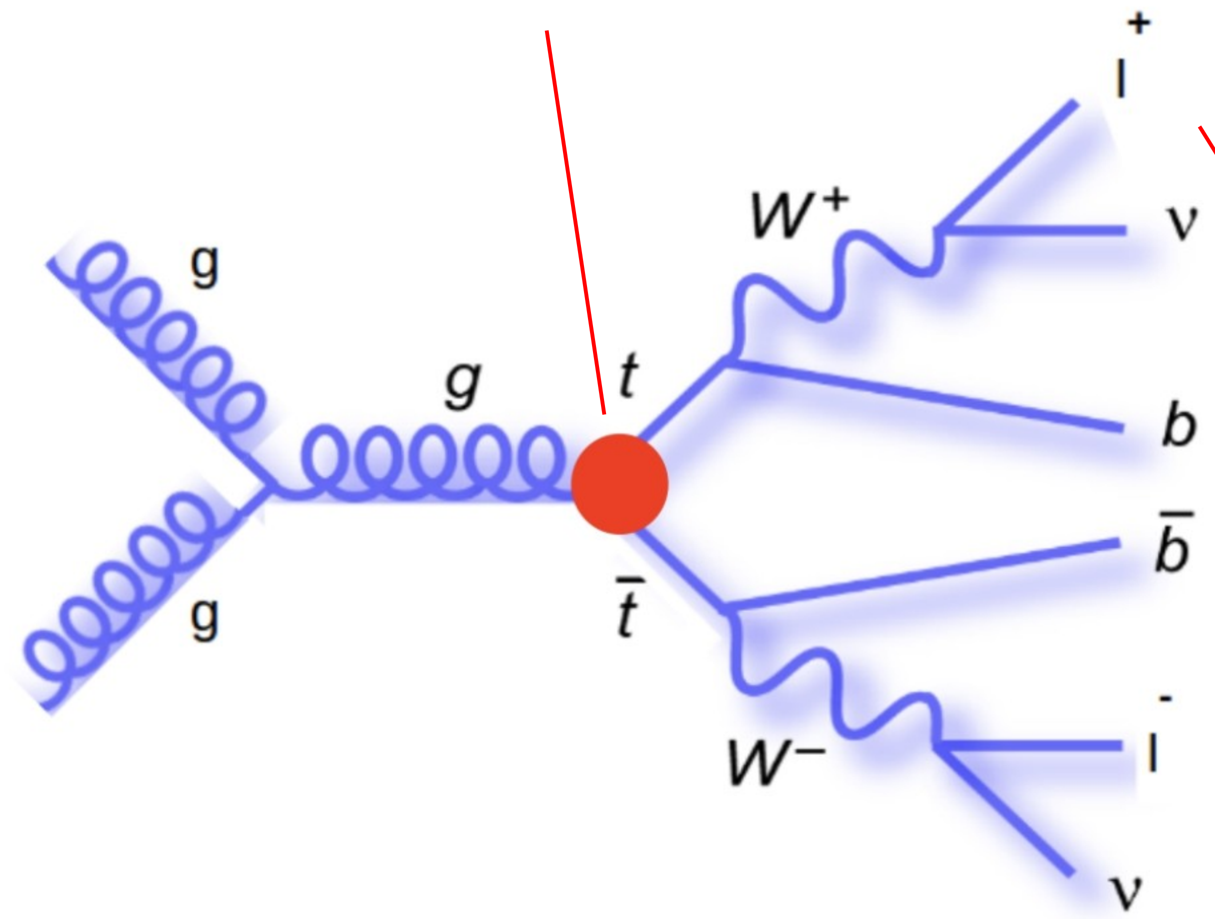
© Nobel Prize Outreach. Photo: Stefan Bladh
John F. Clauser
Prize share: 1/3

© Nobel Prize Outreach. Photo: Stefan Bladh
Anton Zeilinger
Prize share: 1/3

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

The measurement problem

The Schrödinger equation describes the continuous and unitary evolution of quantum systems. A measurement provokes a discontinuous and non-unitary collapse of the wave function

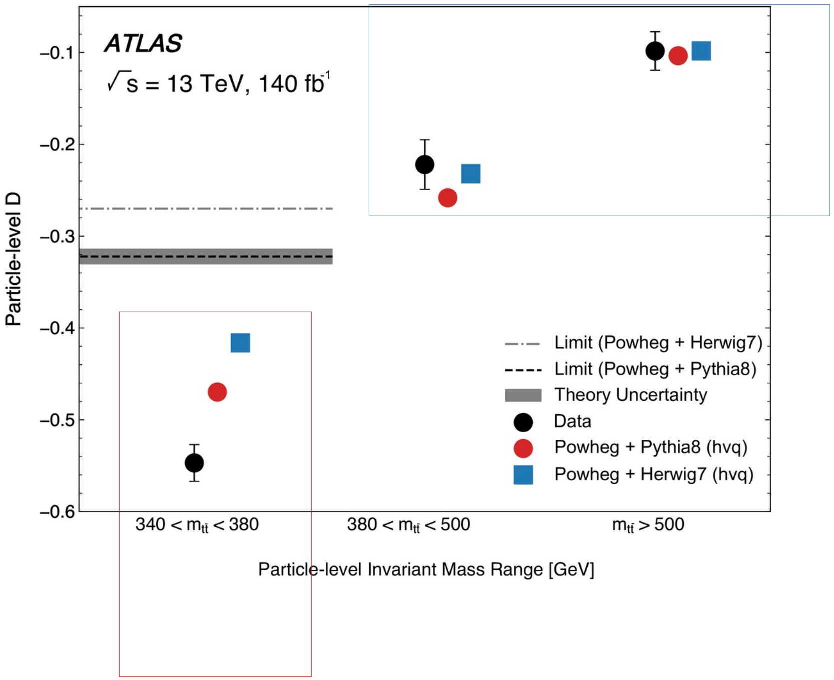
Microscopic quantum systems can exist in superpositions of states, macroscopic (classical) measurement systems are never found in a superposition (but: Schödinger cat states)

The decoherence paradigm poses that quantum coherence is shared between the quantum system and measurement apparatus through the measurement interaction and then diluted in the many degrees of freedom of apparatus + environment

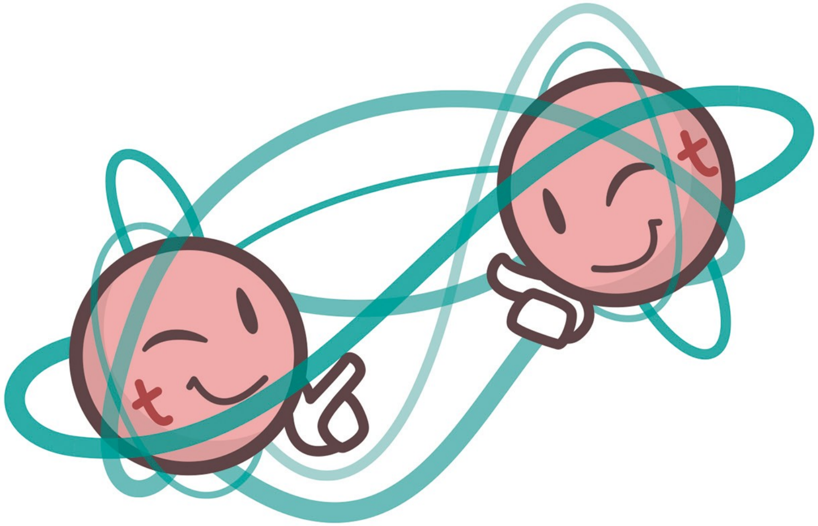
Von Neumann, Zurek, Yeh, reviews by Schlosshauer

Observation of entanglement

ATLAS, TOP23, September ‘23



D != 0 top spins are correlated
(nice, but known since 2013)



D < -1/3 top spin correlations are "quantum"
(new! Opens the door to QI@LHC)

Quantum entanglement observed in top quark pair production

marcel.vos@ific.uv.es

Observation of entanglement – part 2

New: CMS entanglement **observation** at Moriond24

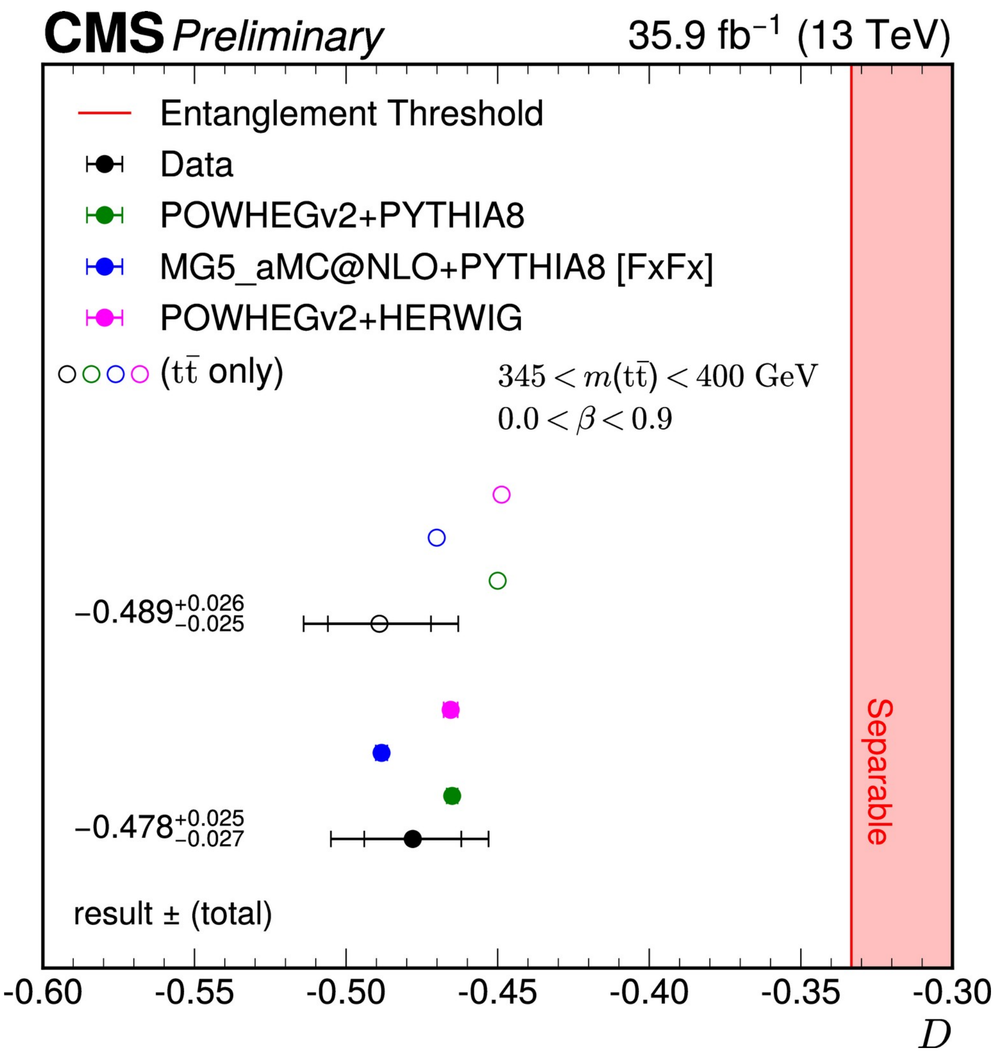
CMS-PAS-TOP-2023-001

D = -0.478 ± 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



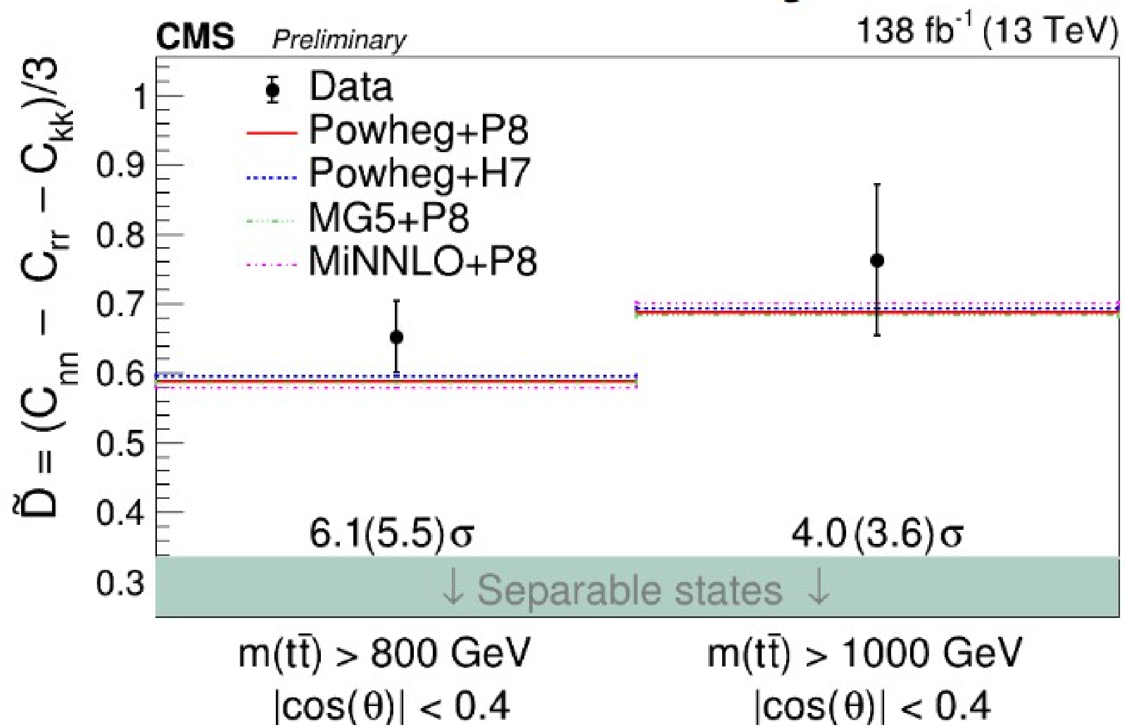
Observation of entanglement – part 3

New at LHCp24 in Boston:

CMS **observes entanglement** in boosted top quark pair production

Nice confirmation, but also:
- less affected by threshold uncertainties
- boosted top quark pairs are more space-like separated

High M_{tt} $\tilde{D} > \frac{1}{3}$



A critical appraisal

Herbi Dreiner had tried all this at LEP in the 1990s

Colliders are Testing neither Locality via Bell's Inequality nor Entanglement versus Non-Entanglement #1
Steven A. Abel (Durham U., IPPP and Durham U. (main)), Herbi K. Dreiner (U. Bonn (main)), Rhitaja Sengupta (U. Bonn (main)), Lorenzo Ubaldi (Stefan Inst., Ljubljana) (Jul 21, 2025)
e-Print: 2507.15949 [hep-ph]
pdf cite claim reference search 5 citations

A critical appraisal of tests of locality and of entanglement versus non-entanglement at colliders #2
Philip Bechtle (Bonn U.), Cedric Breuning (Bonn U.), Herbi K. Dreiner (Bonn U. and U. Bonn, Phys. Inst., BCTP), Claude Duhr (Bonn U. and U. Bonn, Phys. Inst., BCTP) (Jul 21, 2025)
e-Print: 2507.15947 [hep-ph]
pdf cite claim reference search 4 citations

Testing locality at colliders via Bell's inequality? #3
S.A. Abel (Oxford U.), M. Dittmar (UC, Riverside), Herbert K. Dreiner (Oxford U.) (May 19, 1992)
Published in: *Phys.Lett.B* 280 (1992) 304-312
DOI cite claim reference search 59 citations

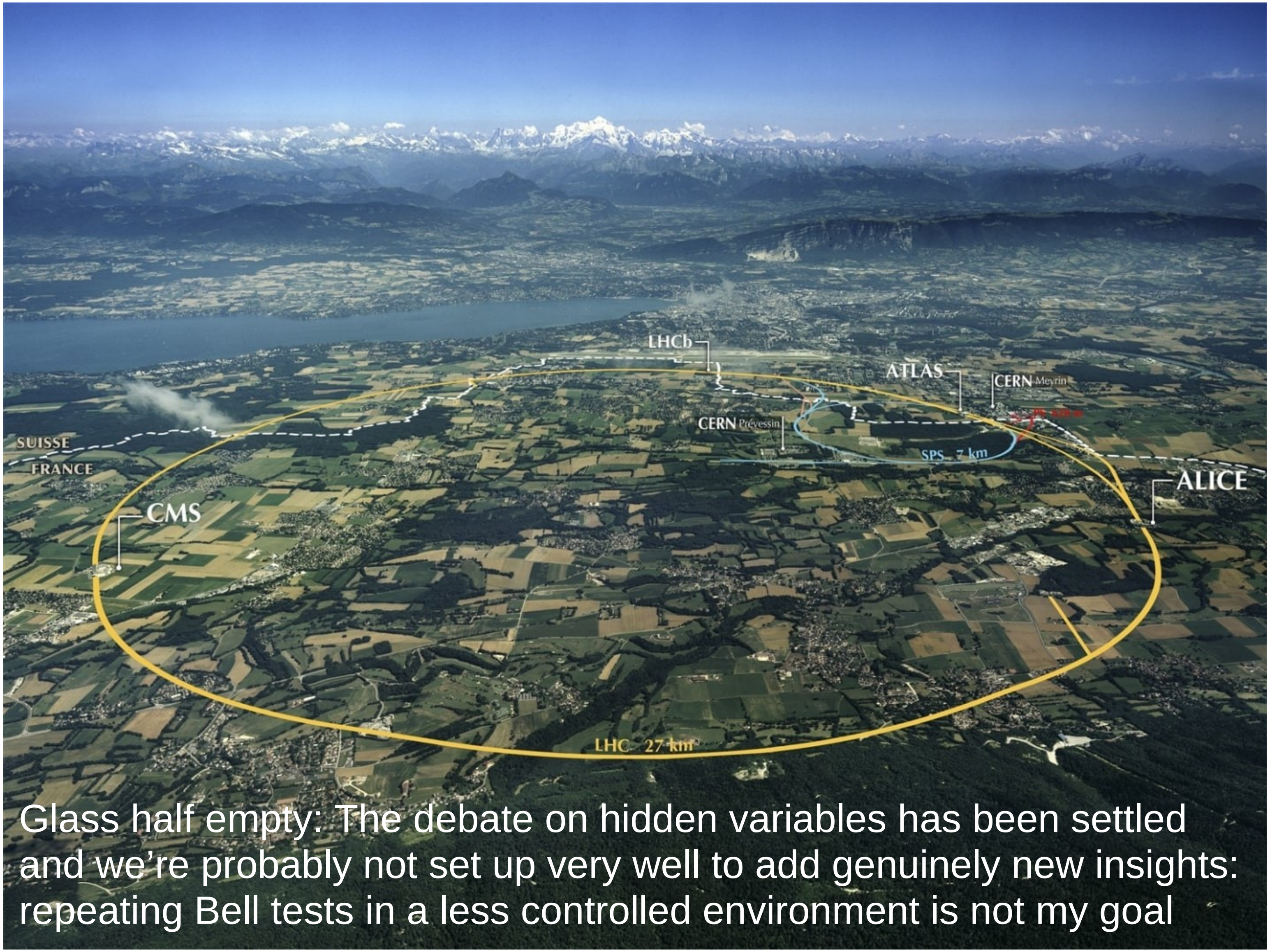
Not finding what you are looking for?
Please click here to give us some quick information about your query and help us improve!

The initial verdict: tests with commuting observables (momentum, not spin) can never rule out all hidden variable theories → locality cannot be tested conclusively

The more recent criticism: to probe the quantum (i.e. degree of entanglement) we rely on decays described by SM → nothing can be tested at colliders

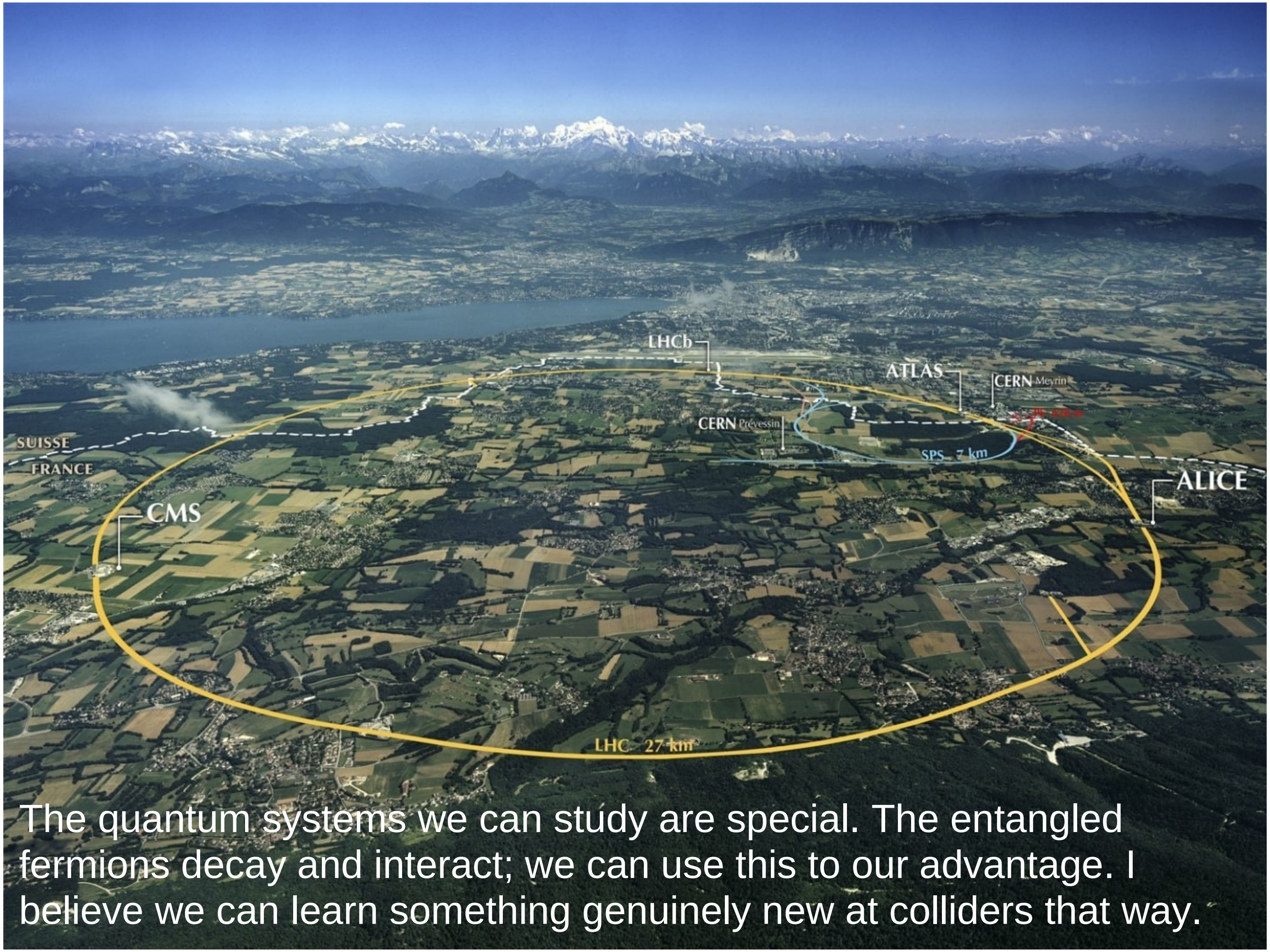
Lesson: spell out assumptions more clearly, and test them in-situ (e.g. spin correlation in non-entangled region offers a control sample to test spin analyzing power)

Can we do Quantum Information at the LHC?



Glass half empty: The debate on hidden variables has been settled and we're probably not set up very well to add genuinely new insights: repeating Bell tests in a less controlled environment is not my goal

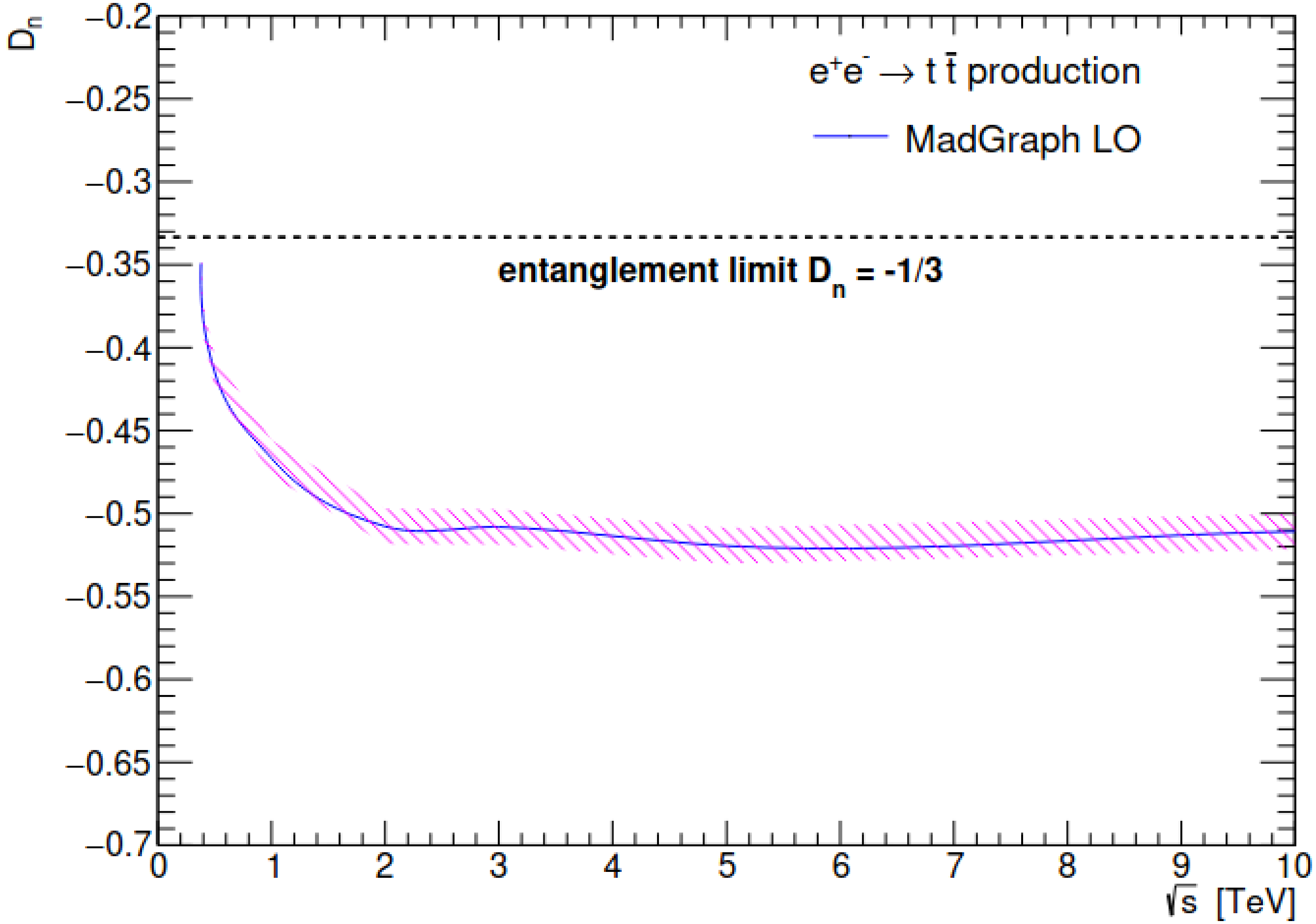
Can we do Quantum Decoherence at colliders?



The quantum systems we can study are special. The entangled fermions decay and interact; we can use this to our advantage. I believe we can learn something genuinely new at colliders that way.

Case I: e+e- → tt production at sqrt(s) = 1 TeV

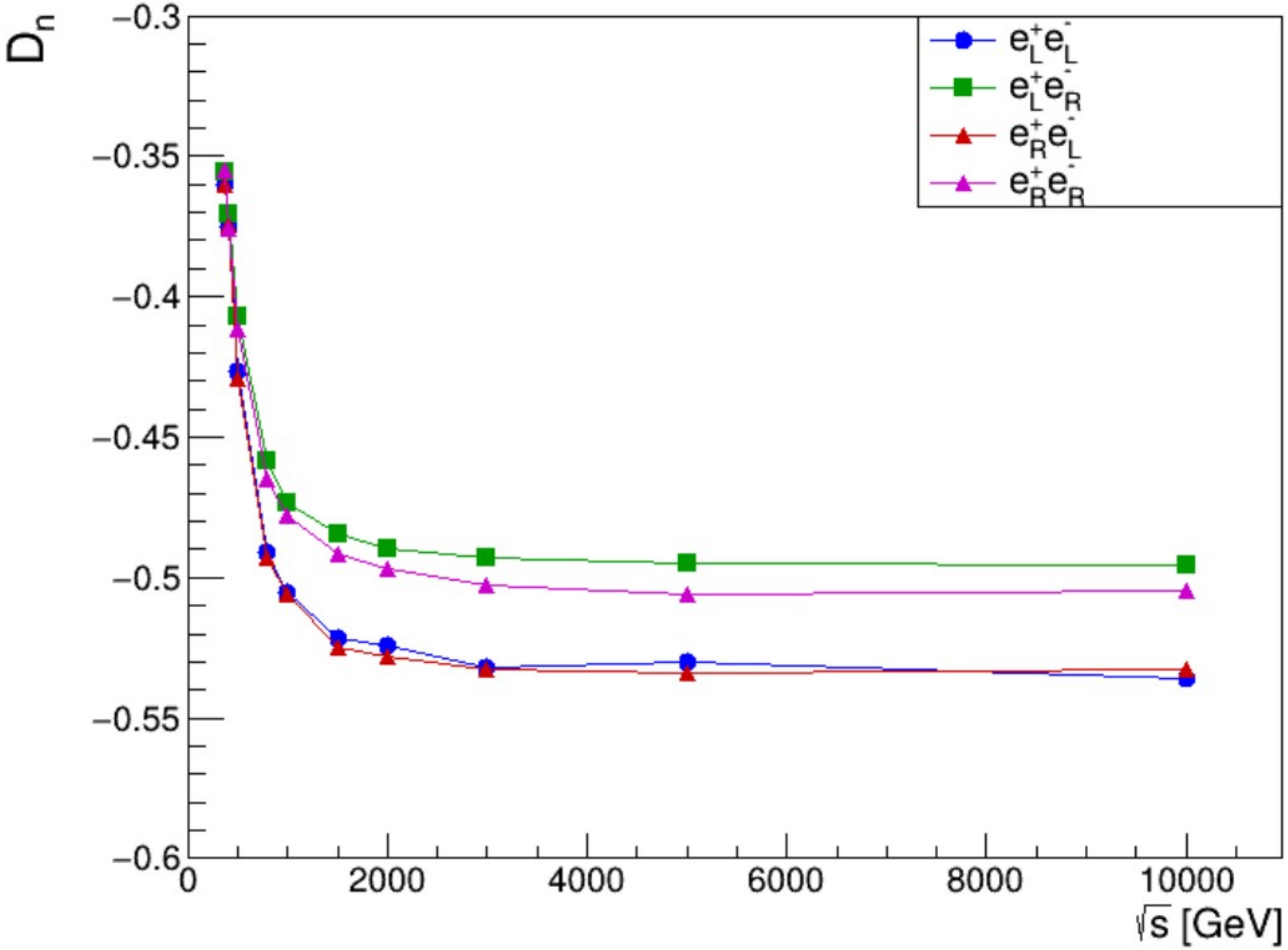
Figure: Katinka Wandall, MV, MM, arXiv:2503.19983



An easy system to study: given a little boost, the top quark pairs are entangled in the full phase space. Also, ISR phtotons and FSR gluons are readily distinguished.

Case I: e+e- → tt production at sqrt(s) = 1 TeV

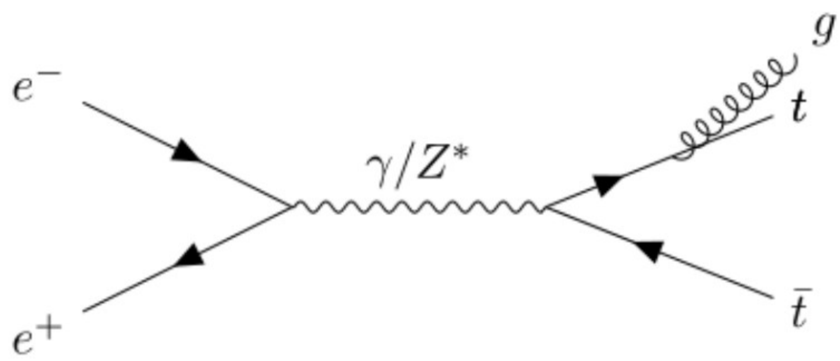
Figure: J.M. Camacho, MV, MM, U. Valencia '25



Beam polarization gives us some control over the degree of entanglement
8/ab at 1 TeV is sufficient for 5σ entanglement with di-lepton channel only

Case II: e+e- → ttg production at sqrt(s) = 1 TeV

Figure: J.M. Camacho, MV, MM, U. Valencia ‘25



Radiation has small effect in inclusive analysis (Aoude et al., arXiv:2504.07030)

In events with a hard gluon emission, the tt concurrence changes strongly

Machine	$\sqrt{s}$ [GeV]	$\int \mathcal{L}dt$ [ab^{-1}]	final state	# $t\bar{t}$ events	concurrence $e^+e^- \to$ $t\bar{t}$	$t\bar{t}g$	decoherence significance
linear e^+e^-	1000	8	di-lepton (ee, $e\mu$, $\mu\mu$)	$10^6 \times 4\%$	0.25	0.06	3.9σ
(LCF [10])	1000	8	all channels	10^6	idem	idem	19σ

Difference can be made 5σ significant, if all final states are used (hadronic polarimetry)

Case III: e+e- → $\tau\tau\gamma$ production at sqrt(s) = 10 GeV or mZ

This works for tau-pairs that emit a photon too!

Efficient polarimetry with hadronic decays (Ehataht et al. 2023)

Apparently, ISR is not a problem for this type of analysis
(note: suppressed by central region cut at Belle 2, naturally suppressed at Z-pole)

Mild cuts on photon energy are sufficient, especially at Belle II

Huge samples

Strong decoherence

Machine	$\sqrt{s}$ [GeV]	$\int \mathcal{L}dt$ [ab^{-1}]	# $\tau^+\tau^-$ events	concurrence $e^+e^- \to$ $\tau^+\tau^-$	$\tau^+\tau^-\gamma$	decoherence significance
Belle II 2025 [22]	10.579	0.5	5×10^8	0.73	0.30 ($p_T > 2$ GeV)	34σ
Belle II target [23]	10.579	50	5×10^{10}	idem	idem	339σ
Z-pole (GigaZ [10])	91.2	0.1	10^8	0.48	0.21 ($p_T > 20$ GeV)	14σ
Z-pole (TeraZ [20, 21])	91.2	300	2×10^{11}	idem.	idem.	756σ

Pretty entangled

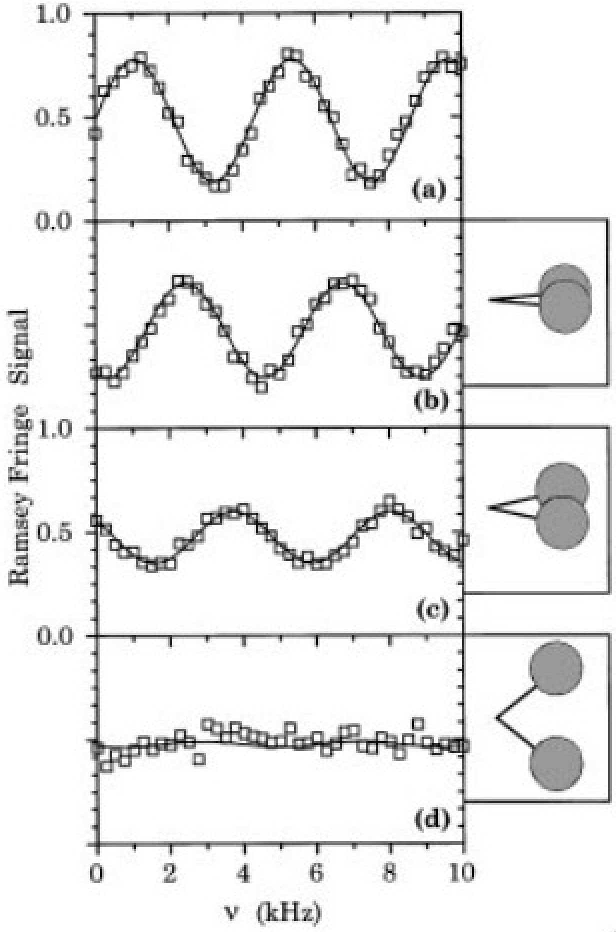
Table: J.M. Camacho, MV, MM, ‘25

Discussion: what do we learn?

Decoherence has been observed in low-energy experiments
M. Brune et al., PRL77 (1996)

Colliders have looked for de-coherence, finding null results
CPLear, KLOE,

Quantum computers struggle against decoherence every day



We offer a decohering quantum system that we can understand completely (no undetected degrees of freedom, no magical collapse of the wave function, no impact of the conscious observer…)

Discussion: tri-partite entanglement

The "isolated" quantum system is an idealization and a source of great confusion around the "measurement problem"

We can contrast the "idealization" (measuring the entanglement of the fermion pair after the emission, ignoring the emitted boson) with the "correct treatment of the complete quantum system" (measuring the tri-partite entanglement between fermions and boson)

This measurement is complicated, but not impossible. Possible avenues:

- tau-lepton pairs with photons at Belle II or the Z-pole
  photon polarimetry with conversions, as proposed by Yuval Grossman

- boosted ttZ at the HL-LHC
  the Z-boson emission de-coheres the tt system
  polarimetry of top, anti-top and Z boson

My proposal: calculate tri-partite entanglement (for ttg?), point out this possibility and explore experimental possibilities in detail later

Do interactions de-cohere quantum systems?

Clear opportunities to detect de-coherence at colliders have been identified

Belle II: the low-hanging fruit, current data set is enough

(HL-)LHC: statistics is there; feasibility study is more involved

LCF: high-energy lepton collider can entangle and de-cohere top quark pairs

Z-pole: GigaZ is enough, TeraZ is (obviously) better

A model of an interaction decohering a quantum system that we can predict and measure precisely → demystify the measurement problem

Work in progress with Rafael Aoude & Fabio Maltoni, Leonardo Satrioni (theory) and José Manuel Camacho, Maria Moreno and Katinka Wandall (experiment)