Quantum information & high energy physics

Martin White with Rafael Aoude, Hannah Banks, Giorgio Busoni, John Gargalionis, Nathan Moynihan, Sokratis Trifinopolous, Ewan Wallace, Chris White

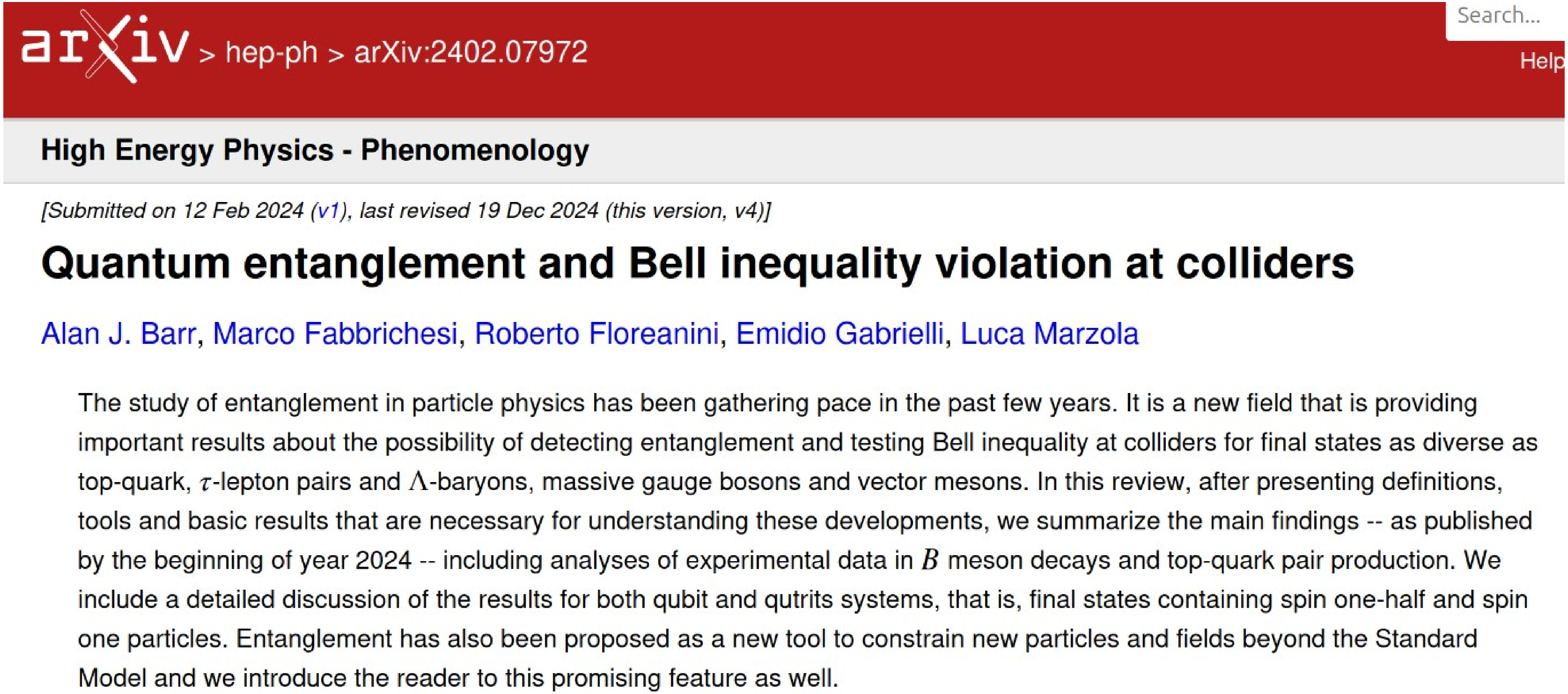
The basic idea

- There is a ton of recent interest in applying **quantum information** concepts to particle physics

- ***Actually this isn’t new*** – I’m still catching up with decades of literature

- Today I will review some topics that have garnered recent interest however

Topic 1: Measurement of QI concepts at colliders



High Energy Physics - Phenomenology

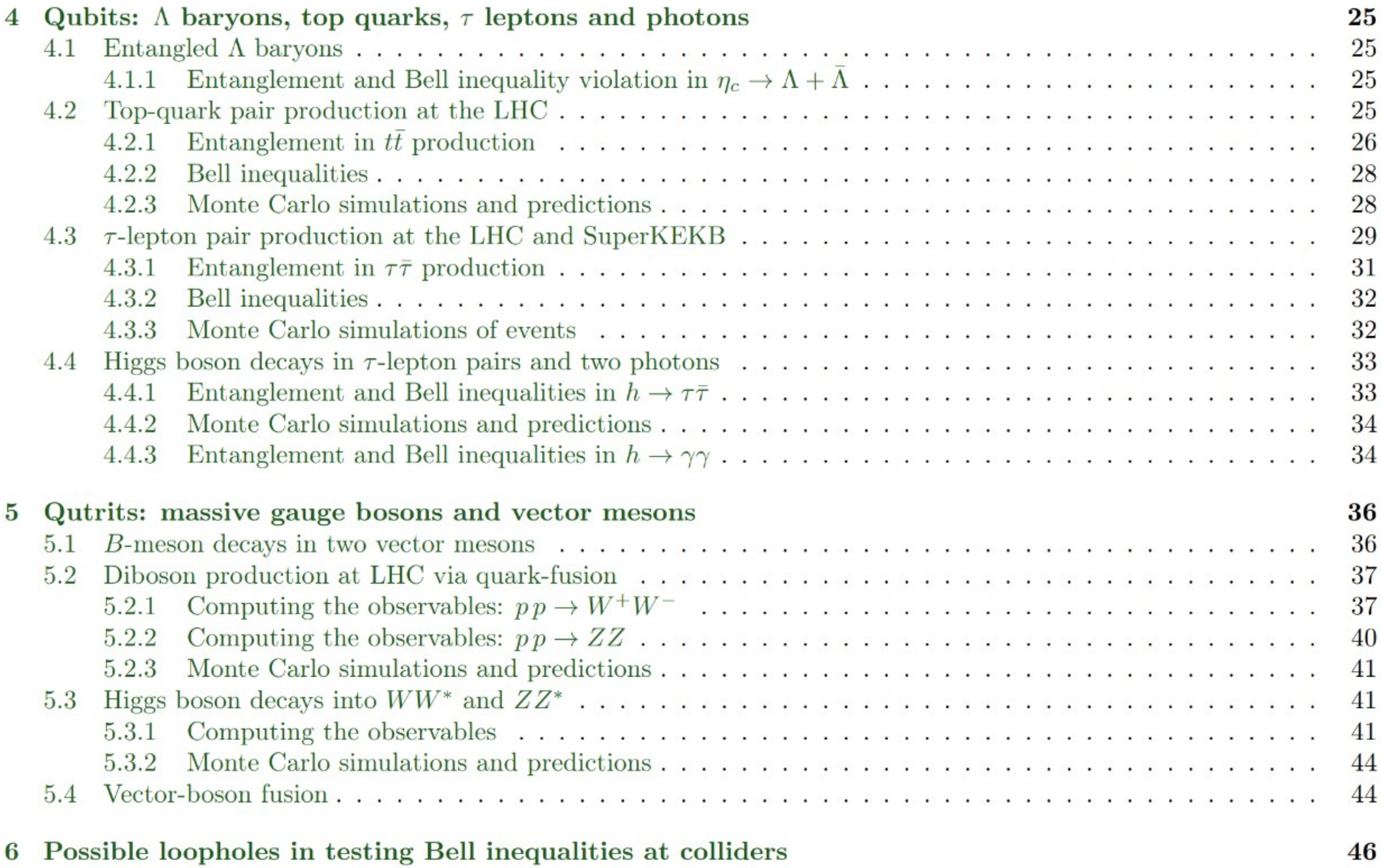
[Submitted on 12 Feb 2024 (v1), last revised 19 Dec 2024 (this version, v4)]

Quantum entanglement and Bell inequality violation at colliders

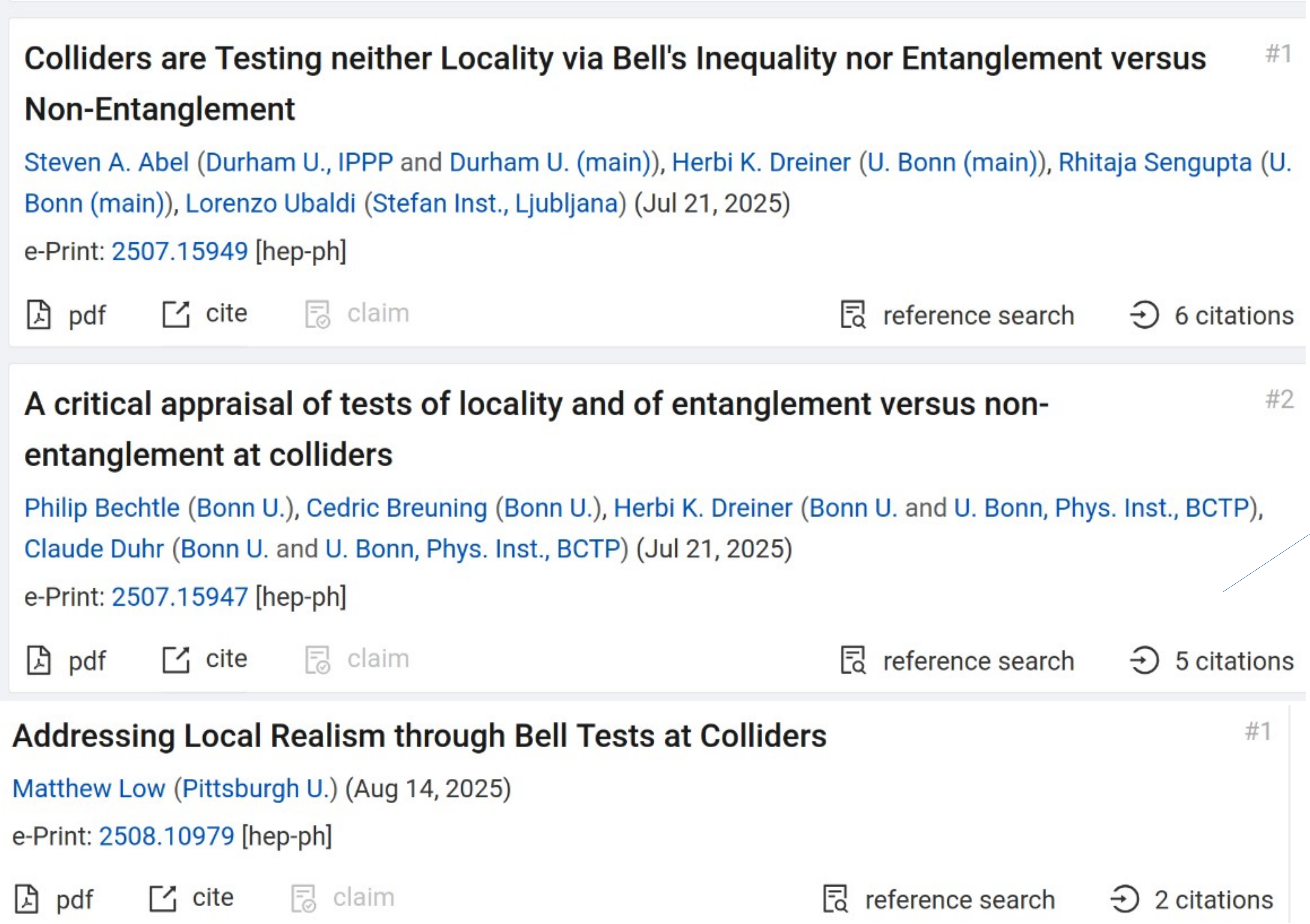
Alan J. Barr, Marco Fabbrichesi, Roberto Floreanini, Emidio Gabrielli, Luca Marzola

The study of entanglement in particle physics has been gathering pace in the past few years. It is a new field that is providing important results about the possibility of detecting entanglement and testing Bell inequality at colliders for final states as diverse as top-quark, τ-lepton pairs and Λ-baryons, massive gauge bosons and vector mesons. In this review, after presenting definitions, tools and basic results that are necessary for understanding these developments, we summarize the main findings -- as published by the beginning of year 2024 -- including analyses of experimental data in B meson decays and top-quark pair production. We include a detailed discussion of the results for both qubit and qutrits systems, that is, final states containing spin one-half and spin one particles. Entanglement has also been proposed as a new tool to constrain new particles and fields beyond the Standard Model and we introduce the reader to this promising feature as well.

In the review



A note of caution



Colliders are Testing neither Locality via Bell's Inequality nor Entanglement versus Non-Entanglement

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]

A critical appraisal of tests of locality and of entanglement versus non-entanglement at colliders

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)

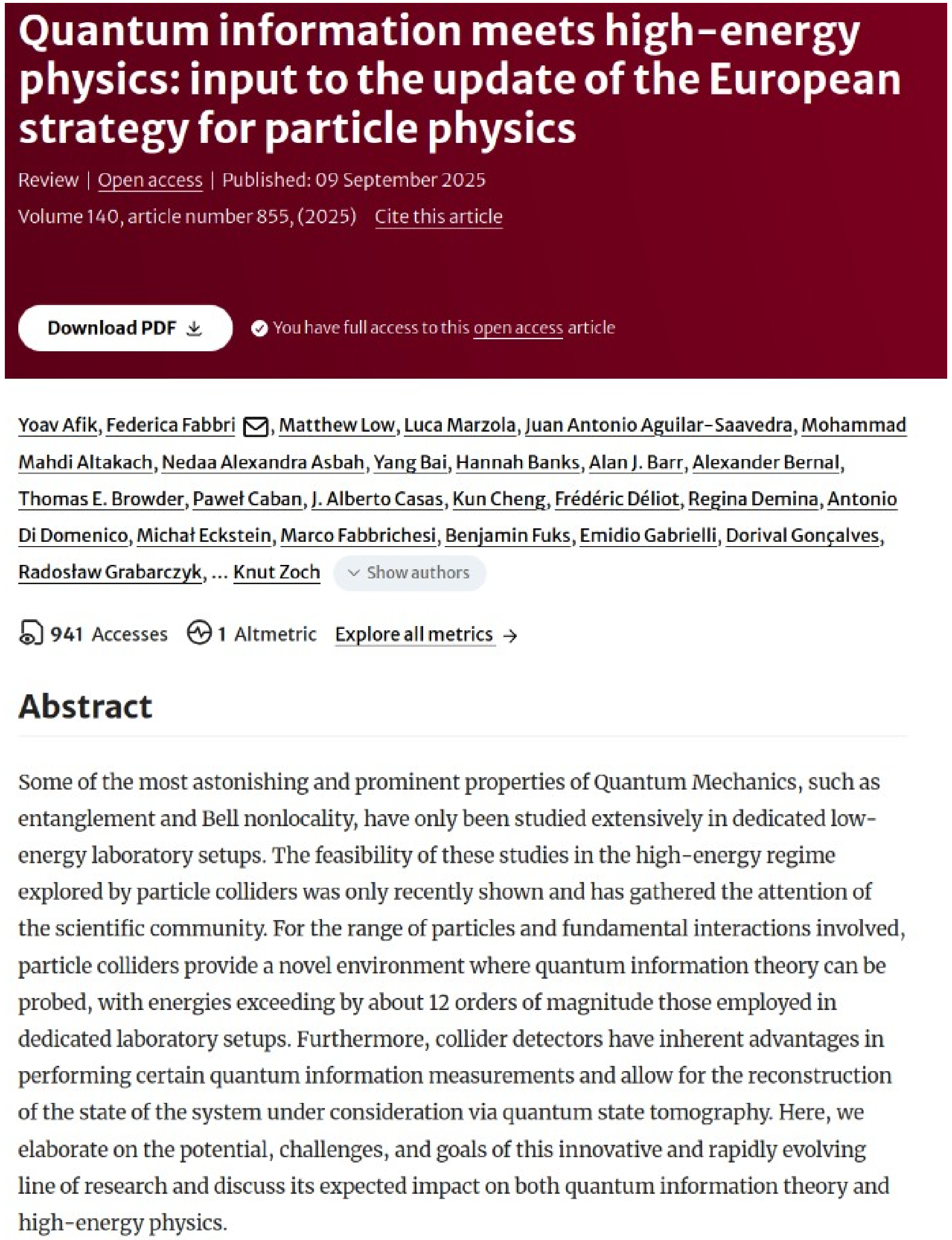
e-Print: 2507.15947 [hep-ph]

Addressing Local Realism through Bell Tests at Colliders

Matthew Low (Pittsburgh U.) (Aug 14, 2025)

e-Print: 2508.10979 [hep-ph]

“We stress that the no-go theorem does not apply to measurements of observables inspired from entanglement and Quantum Information Theory to test the Standard Model of particle physics.”



Quantum information meets high-energy physics: input to the update of the European strategy for particle physics

Review | Open access | Published: 09 September 2025

Volume 140, article number 855, (2025) Cite this article

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Yoav Afik, Federica Fabbri, Matthew Low, Luca Marzola, Juan Antonio Aguilar-Saavedra, Mohammad Mahdi Altakach, Nedaa Alexandra Asbah, Yang Bai, Hannah Banks, Alan J. Barr, Alexander Bernal, Thomas E. Browder, Paweł Caban, J. Alberto Casas, Kun Cheng, Frédéric Déliot, Regina Demina, Antonio Di Domenico, Michał Eckstein, Marco Fabbrichesi, Benjamin Fuks, Emidio Gabrielli, Dorival Gonçalves, Radosław Grabarczyk, … Knut Zoch

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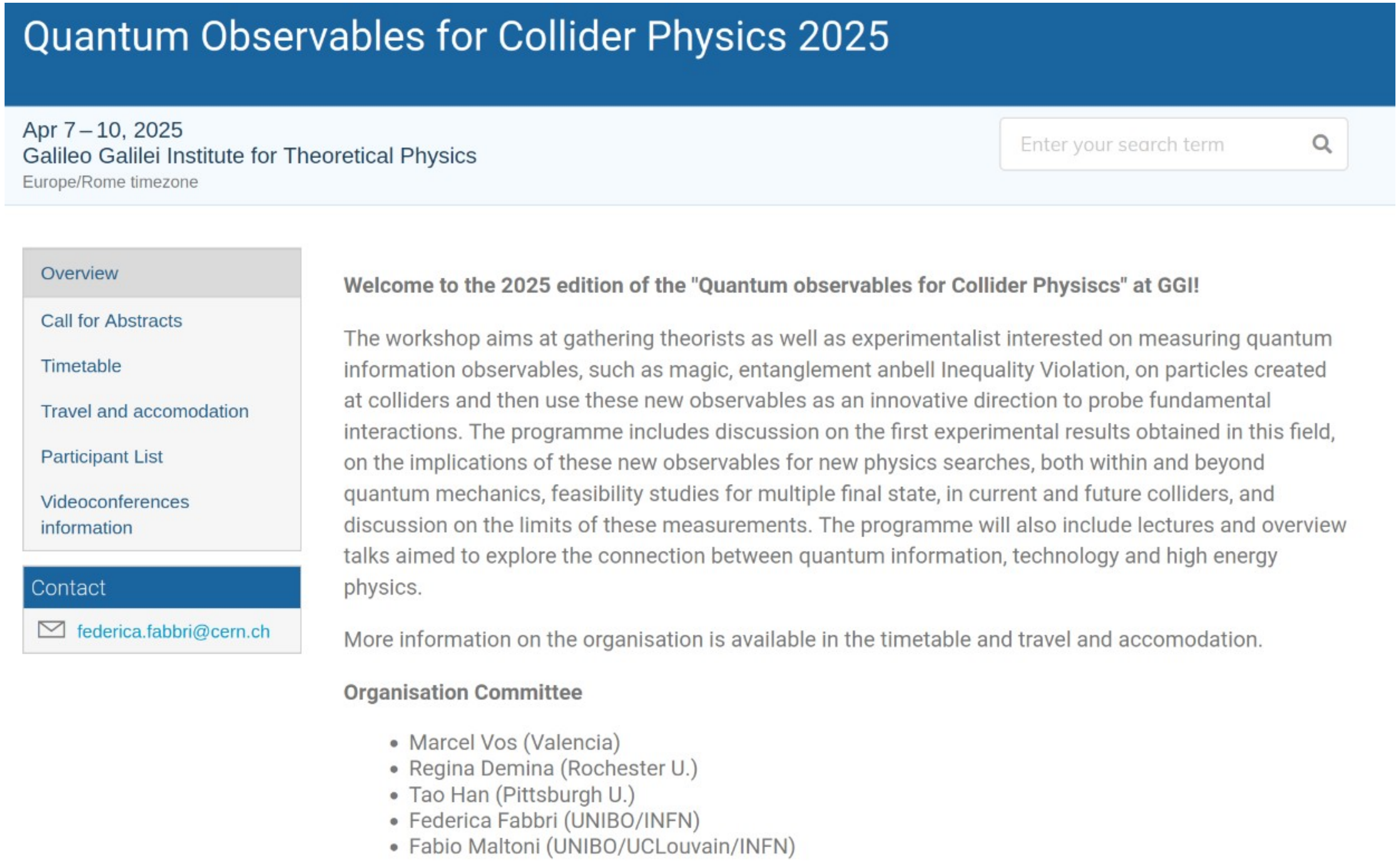
Abstract

Some of the most astonishing and prominent properties of Quantum Mechanics, such as entanglement and Bell nonlocality, have only been studied extensively in dedicated low-energy laboratory setups. The feasibility of these studies in the high-energy regime explored by particle colliders was only recently shown and has gathered the attention of the scientific community. For the range of particles and fundamental interactions involved, particle colliders provide a novel environment where quantum information theory can be probed, with energies exceeding by about 12 orders of magnitude those employed in dedicated laboratory setups. Furthermore, collider detectors have inherent advantages in performing certain quantum information measurements and allow for the reconstruction of the state of the system under consideration via quantum state tomography. Here, we elaborate on the potential, challenges, and goals of this innovative and rapidly evolving line of research and discuss its expected impact on both quantum information theory and high-energy physics.



Quantum Observables for Collider Physics 2025

Apr 7 – 10, 2025
Galileo Galilei Institute for Theoretical Physics
Europe/Rome timezone

federica.fabbri@cern.ch

Welcome to the 2025 edition of the "Quantum observables for Collider Physiscs" at GGI!

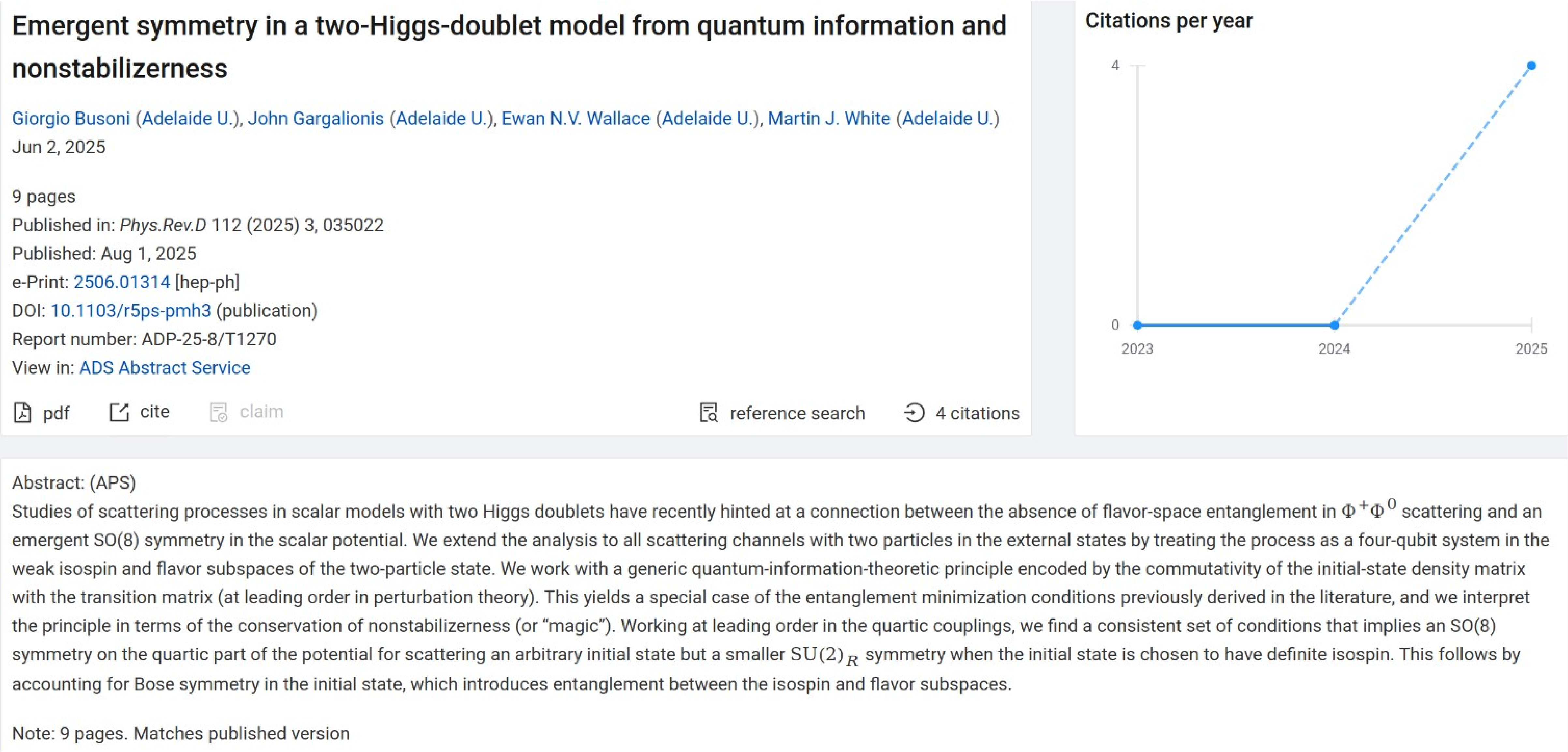
The workshop aims at gathering theorists as well as experimentalist interested on measuring quantum information observables, such as magic, entanglement anbell Inequality Violation, on particles created at colliders and then use these new observables as an innovative direction to probe fundamental interactions. The programme includes discussion on the first experimental results obtained in this field, on the implications of these new observables for new physics searches, both within and beyond quantum mechanics, feasibility studies for multiple final state, in current and future colliders, and discussion on the limits of these measurements. The programme will also include lectures and overview talks aimed to explore the connection between quantum information, technology and high energy physics.

More information on the organisation is available in the timetable and travel and accomodation.

Organisation Committee

- Marcel Vos (Valencia)
- Regina Demina (Rochester U.)
- Tao Han (Pittsburgh U.)
- Federica Fabbri (UNIBO/INFN)
- Fabio Maltoni (UNIBO/UCLouvain/INFN)

Topic 2: Emergent symmetry/structure of SM



Emergent symmetry in a two-Higgs-doublet model from quantum information and nonstabilizerness

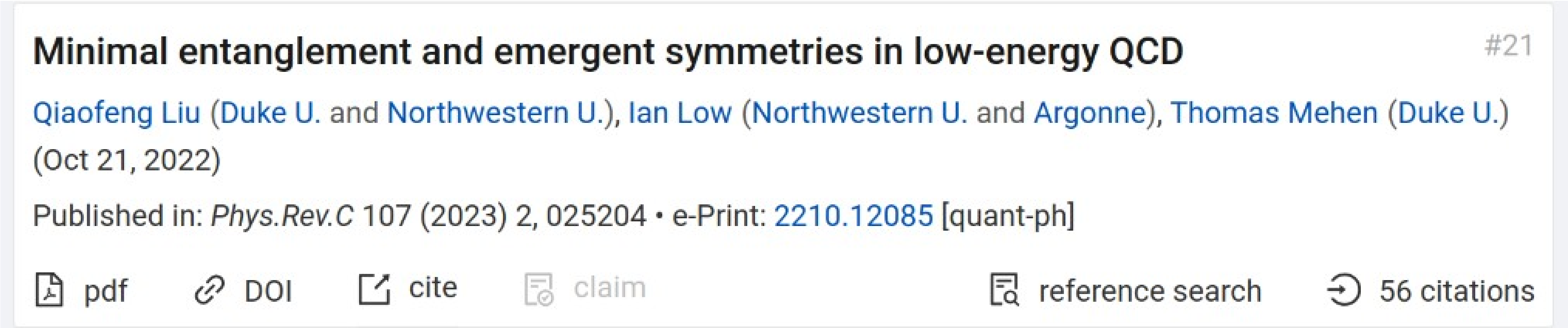
Giorgio Busoni (Adelaide U.), John Gargalionis (Adelaide U.), Ewan N.V. Wallace (Adelaide U.), Martin J. White (Adelaide U.)
Jun 2, 2025

9 pages
Published in: *Phys.Rev.D* 112 (2025) 3, 035022
Published: Aug 1, 2025
e-Print: 2506.01314 [hep-ph]
DOI: 10.1103/r5ps-pmh3 (publication)
Report number: ADP-25-8/T1270
View in: ADS Abstract Service

Abstract: (APS)
Studies of scattering processes in scalar models with two Higgs doublets have recently hinted at a connection between the absence of flavor-space entanglement in $\Phi^+\Phi^0$ scattering and an emergent SO(8) symmetry in the scalar potential. We extend the analysis to all scattering channels with two particles in the external states by treating the process as a four-qubit system in the weak isospin and flavor subspaces of the two-particle state. We work with a generic quantum-information-theoretic principle encoded by the commutativity of the initial-state density matrix with the transition matrix (at leading order in perturbation theory). This yields a special case of the entanglement minimization conditions previously derived in the literature, and we interpret the principle in terms of the conservation of nonstabilizerness (or "magic"). Working at leading order in the quartic couplings, we find a consistent set of conditions that implies an SO(8) symmetry on the quartic part of the potential for scattering an arbitrary initial state but a smaller $\mathrm{SU}(2)_R$ symmetry when the initial state is chosen to have definite isospin. This follows by accounting for Bose symmetry in the initial state, which introduces entanglement between the isospin and flavor subspaces.

Note: 9 pages. Matches published version

Topic 2: Emergent symmetry/structure of SM



Minimal entanglement and emergent symmetries in low-energy QCD

#21

Qiaofeng Liu (Duke U. and Northwestern U.), Ian Low (Northwestern U. and Argonne), Thomas Mehen (Duke U.) (Oct 21, 2022)

Published in: *Phys.Rev.C* 107 (2023) 2, 025204 • e-Print: 2210.12085 [quant-ph]

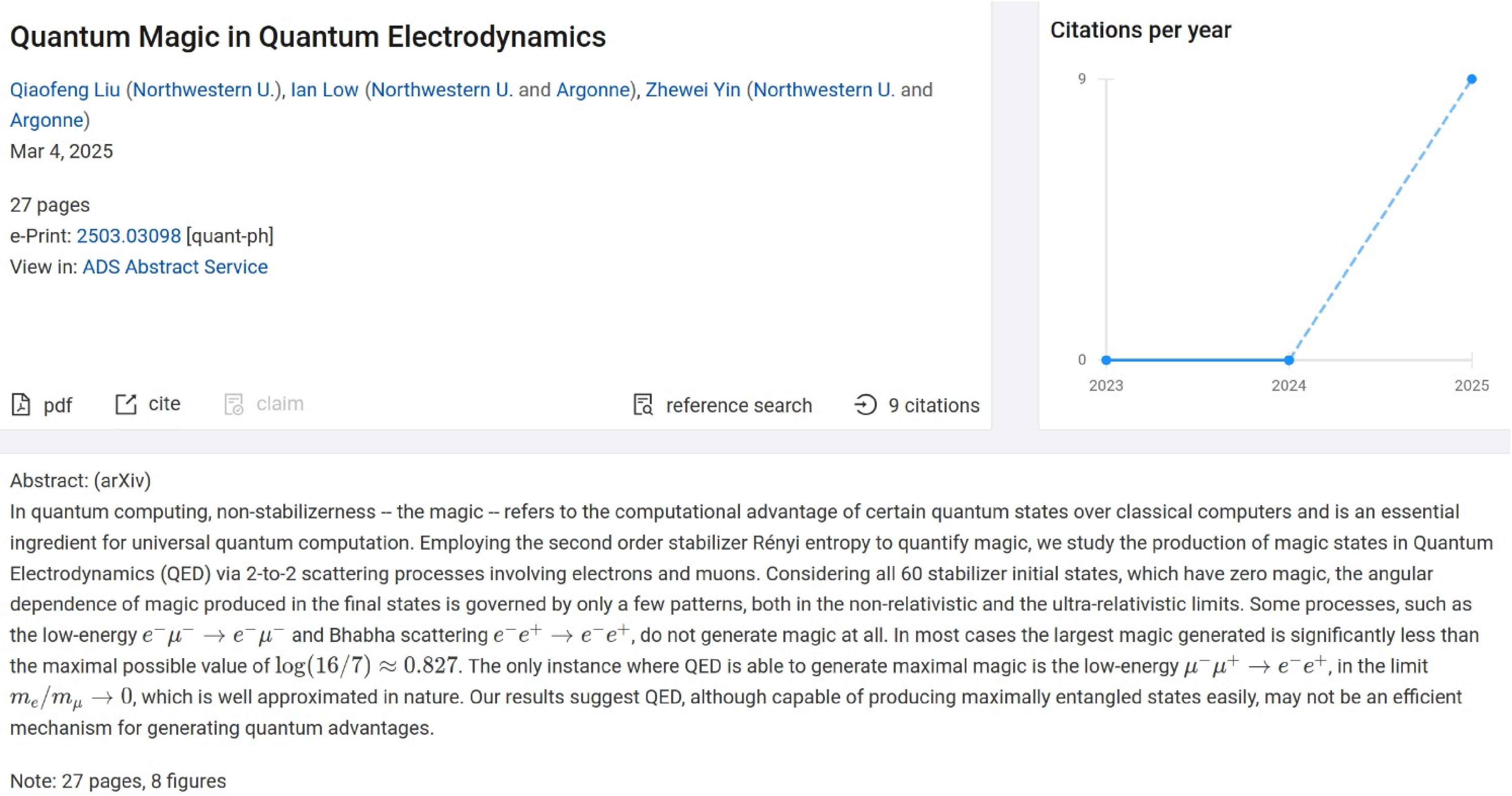
Flavor patterns of fundamental particles from quantum entanglement?

#7

Jesse Thaler (MIT, Cambridge, CTP), Sokratis Trifinopoulos (MIT, Cambridge, CTP) (Oct 30, 2024)

Published in: *Phys.Rev.D* 111 (2025) 5, 056021 • e-Print: 2410.23343 [hep-ph]

Topic 3: QI properties of scattering processes



Quantum Magic in Quantum Electrodynamics

Qiaofeng Liu (Northwestern U.), Ian Low (Northwestern U. and Argonne), Zhewei Yin (Northwestern U. and Argonne)
Mar 4, 2025

27 pages
e-Print: 2503.03098 [quant-ph]
View in: ADS Abstract Service

Abstract: (arXiv)
In quantum computing, non-stabilizerness -- the magic -- refers to the computational advantage of certain quantum states over classical computers and is an essential ingredient for universal quantum computation. Employing the second order stabilizer Rényi entropy to quantify magic, we study the production of magic states in Quantum Electrodynamics (QED) via 2-to-2 scattering processes involving electrons and muons. Considering all 60 stabilizer initial states, which have zero magic, the angular dependence of magic produced in the final states is governed by only a few patterns, both in the non-relativistic and the ultra-relativistic limits. Some processes, such as the low-energy $e^-\mu^- \to e^-\mu^-$ and Bhabha scattering $e^-e^+ \to e^-e^+$, do not generate magic at all. In most cases the largest magic generated is significantly less than the maximal possible value of $\log(16/7) \approx 0.827$. The only instance where QED is able to generate maximal magic is the low-energy $\mu^-\mu^+ \to e^-e^+$, in the limit $m_e/m_\mu \to 0$, which is well approximated in nature. Our results suggest QED, although capable of producing maximally entangled states easily, may not be an efficient mechanism for generating quantum advantages.

Note: 27 pages, 8 figures

Quantum computing 101

- In quantum computers, classical bits (with values {0,1}) are replaced by *qubits*:

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

Orthogonal
basis
states

where the complex coefficients satisfy $|\alpha|^2 + |\beta|^2 = 1$.

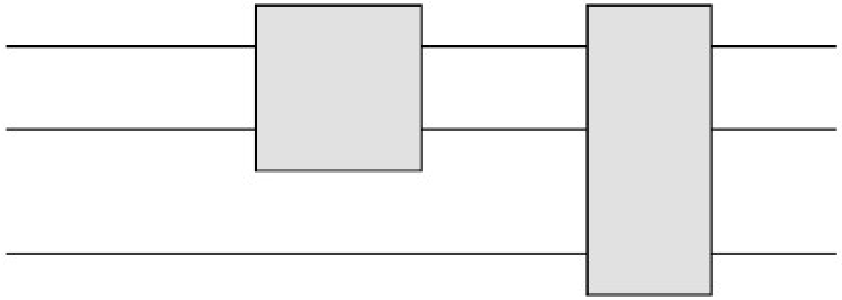
- Example: a spin-1/2 particle is a single “qubit”, where the above states are spin states.

- For multi-qubit systems, a choice of basis states is

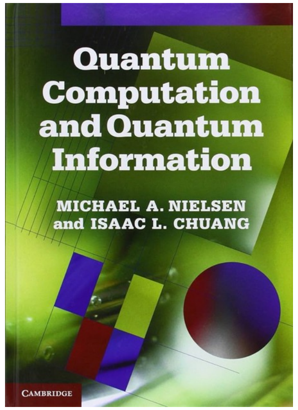
$$|\psi_1\psi_2\ldots\psi_n\rangle \equiv |\psi_1\rangle \otimes |\psi_2\rangle \otimes \ldots \otimes |\psi_n\rangle$$

Quantum computing 101

- Quantum computers take qubits, and subject them to unitary transformations.
- We can draw circuit diagrams, with fancy symbols to represent the transformations ("quantum gates"):



- These are the equivalent of logic gates in classical computers…
- …and change the quantum state at each intermediate step.



- The gates have names like *Hadamard*, *phase*, *CNOT*, *Pauli* etc.

Are quantum computers always better?

- Quantum computers are expected to vastly outperform classical computers.
- Naïvely, this is due to quantum *superposition* and *entanglement*.
- However, this not quite true.
- To see why, we need the concept of a *stabiliser state.*
- These are states that give a simple spectrum for *Pauli string* operators*:*

$$\mathcal{P}_n = P_1 \otimes P_2 \otimes \ldots \otimes P_N, \quad P_a \in \{\sigma_1^{(a)}, \sigma_2^{(a)}, \sigma_3^{(a)}, I^{(a)}\}$$

Pauli matrix
acting on qubit *a*

Identity matrix
acting on qubit *a*

- Can make such states by acting on $|0\rangle \otimes |0\rangle \otimes \ldots \otimes |0\rangle$ with Hadamard, phase, CNOT and Pauli gates.

The Gottesman-Knill theorem

- Given a state $|\psi\rangle$, we can consider the *Pauli spectrum*

$$\mathrm{spec}(|\psi\rangle) = \{\langle\psi|P|\psi\rangle, \quad P \in \mathcal{P}_n\}$$

(i.e. expectation values of each Pauli string).

- Stabiliser states have 2^n values +1 or -1, and the rest zero.
- These states are important because of the *Gottesman-Knill theorem*:

For every quantum computer containing stabiliser states only, there is a classical computer that is just as efficient! 😅

- Stabiliser states include certain maximally entangled states.
- Something other than entanglement is needed for efficient quantum computers!

Magic

The “something else” has been called *magic* in the literature…

…and basically means “non-stabiliserness” of a quantum state.

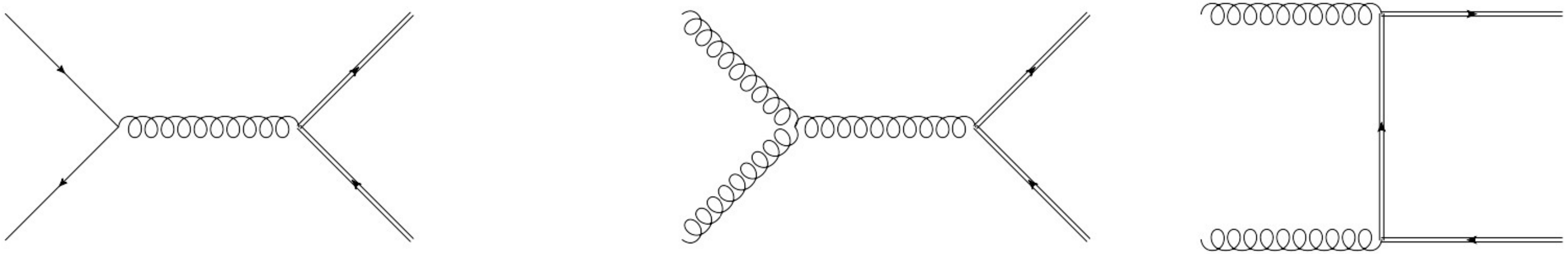
Different definitions exist. We use *Stabilizer Rényi Entropies*: (Leone, Oliviero, Hamma)

$$M_q = \frac{1}{1-q}\log_2\left(\zeta_q\right), \quad \zeta_q \equiv \sum_{P\in\mathcal{P}_n} \frac{\langle\psi|P|\psi\rangle^{2q}}{2^n}$$

Each (integer) *q* corresponds to a higher moment of the Pauli spectrum.

The magic is additive, **vanishes** for stabiliser states, and is crucial for making fault-tolerant quantum computers.

Are top quarks magic?



- Consider top quark production at the LHC - the final state is a two-qubit system

- However, the final state is a *mixed state* (superposition of many different *pure states*), where the SM tells us what this is in principle.

- Mixed states can be described in terms of their *density matrix*:

$$\rho = \sum_i p_i |\psi_i\rangle\langle\psi_i|$$

Are top quarks magic?

- On general grounds, the top quark spin density matrix has decomposition:

$$\rho^I \sim \tilde{A}^I I_4 + \sum_i \left(\tilde{B}_i^{I+} \sigma_i \otimes I_2 + \tilde{B}_i^{I-} I_2 \otimes \sigma_i + \sum_{i,j} \tilde{C}_{ij}^I \sigma_i \otimes \sigma_j \right)$$

Contribution from partonic channel I

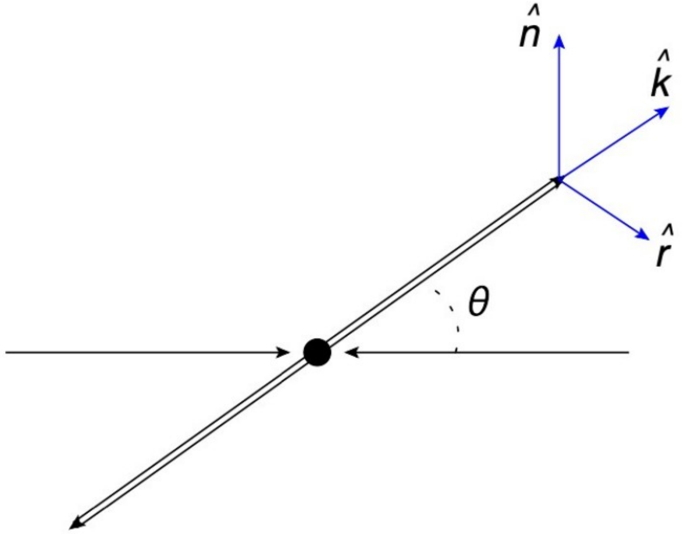
Identity matrix

Identity matrix

Pauli matrix

- The *Fano coefficients* $\{\tilde{A}^I, \tilde{B}_i^{I\pm}, \tilde{C}_{ij}^I\}$ depend on the top quark kinematics…
- …as well as the basis relating spin directions (1,2,3) to physical space.
- A common choice is the *helicity basis*.

The helicity basis



- Helicity basis: choose an axis parallel to the top quark direction and two transverse directions (Baumgart, Tweedie).

- Each Fano coefficient is then a function of

$$z = \cos\theta, \quad \beta = \sqrt{1 - \frac{4m_t^2}{\hat{s}}}.$$

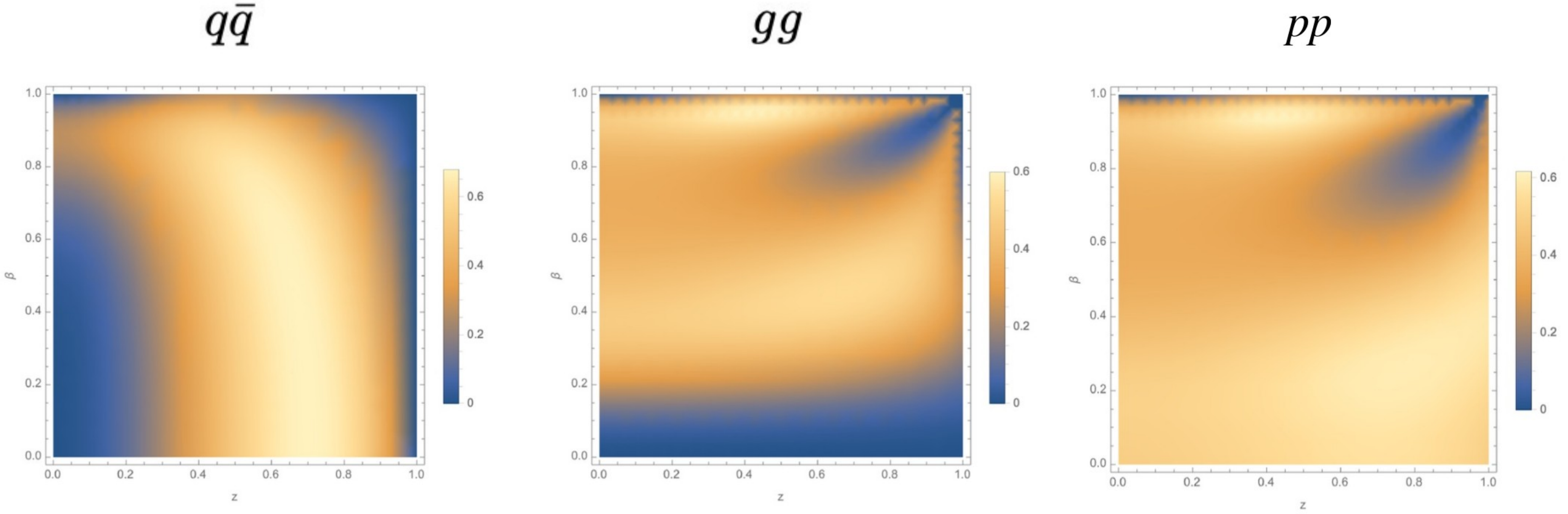
- At LO in the SM, one has:

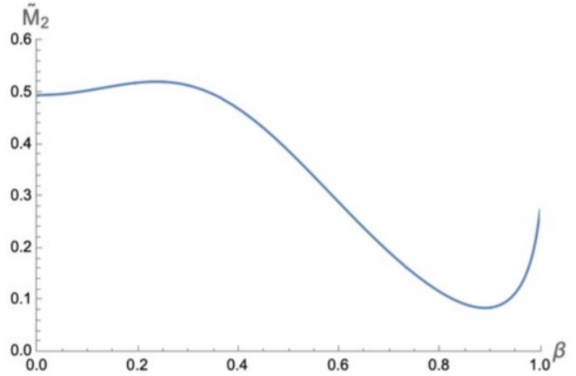
$$\tilde{B}_i^{I+} = \tilde{B}_i^{I-} = \tilde{C}_{nr}^I = \tilde{C}_{nk}^I = 0, \quad \tilde{C}_{ij}^I = \tilde{C}_{ji}^I$$

- The SSRE can be corrected for mixed states (Leone, Oliviero, Hamma), and yields

$$\tilde{M}_2(\rho^I) = -\log_2\left(\frac{(\tilde{A}^I)^4 + (\tilde{C}_{nn}^I)^4 + (\tilde{C}_{kk}^I)^4 + (\tilde{C}_{rr}^I)^4 + 2(\tilde{C}_{rk}^I)^4}{(\tilde{A}^I)^2[(\tilde{A}^I)^2 + (\tilde{C}_{nn}^I)^2 + (\tilde{C}_{kk}^I)^2 + (\tilde{C}_{rr}^I)^2 + 2(\tilde{C}_{rk}^I)^2]}\right)$$

Results

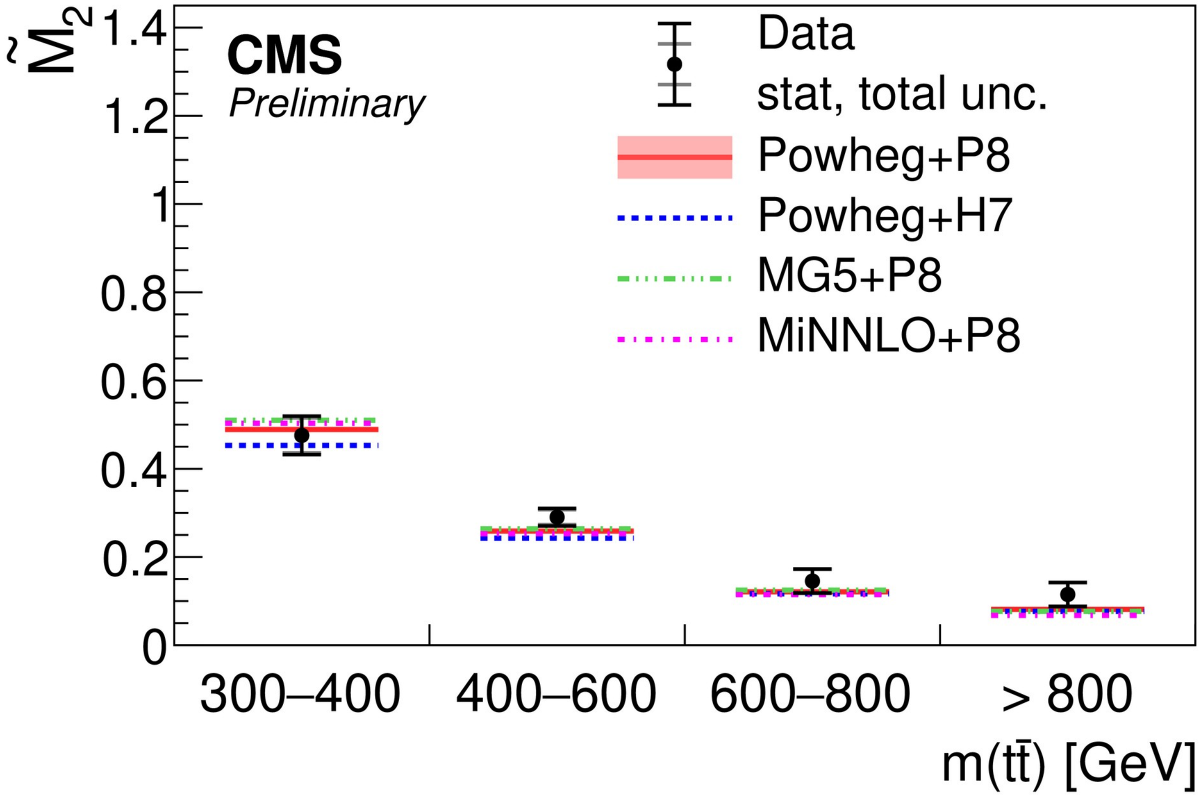




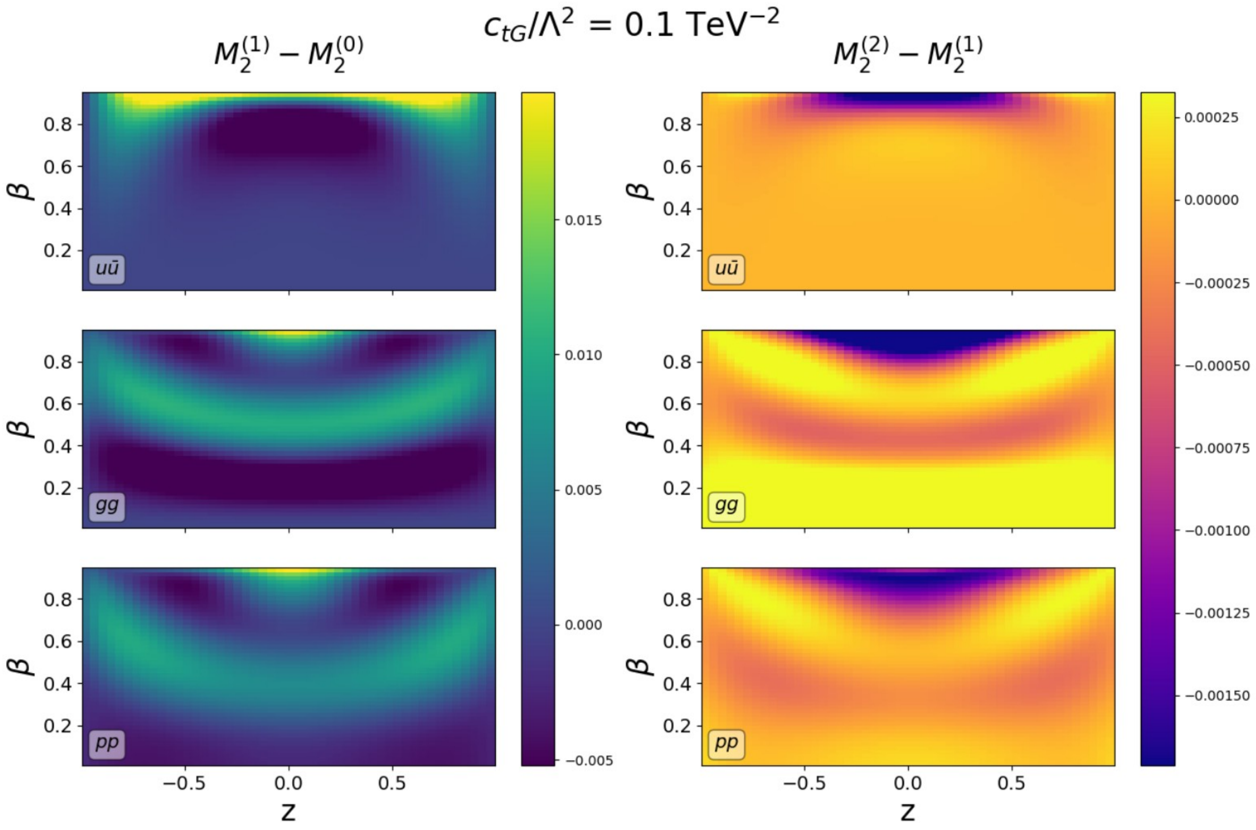
- Regions of zero magic in individual partonic channels correspond to known entanglement behaviour
- Averaging (PDF plus angular) leads to more mixed states → increases magic!

Actual measurement

CMS-PAS-TOP-25-001



What about new physics in the top sector?



$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_{n=1}^{\infty} \frac{1}{\Lambda^n} \sum_i c_i^{(n)} \mathcal{O}_i^{(n)}.$$

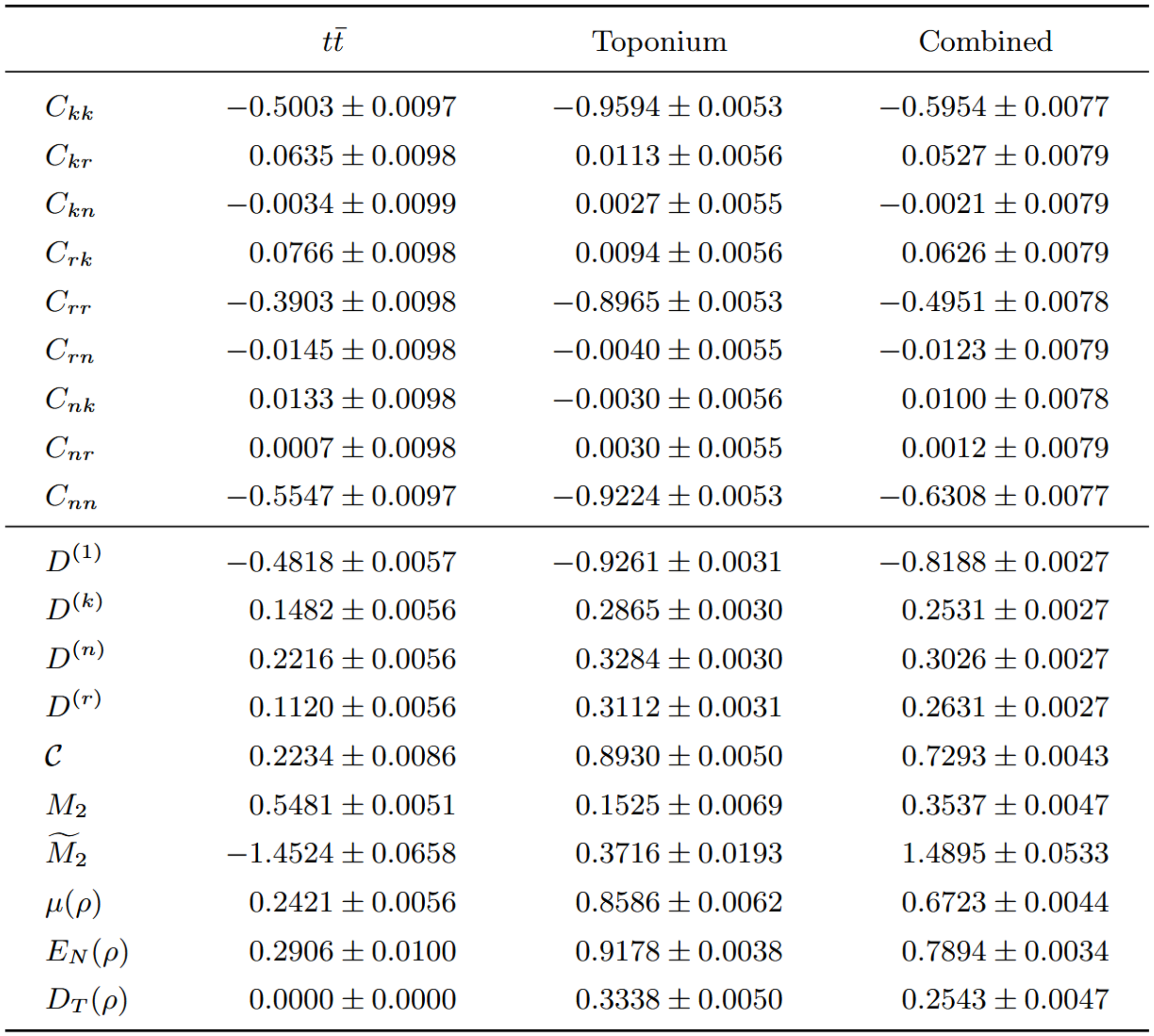
$$\mathcal{O}_G = g_s f^{ABC} G_\nu^{A,\mu} \, G_\rho^{B,\nu} \, G_\mu^{C,\rho}, \quad \mathcal{O}_{\phi G} = \left(\phi^\dagger \phi - \frac{v^2}{2}\right) G_A^{\mu\nu} \, G_{\mu\nu}^A,$$

$$\mathcal{O}_{tG} = g_s \left(\bar{Q} \sigma^{\mu\nu} T^A t\right) \tilde{\phi} \, G_{\mu\nu}^A + \text{h.c.}$$

$$\begin{aligned}
\mathcal{O}_{Qq}^{(8,1)} &= (\bar{Q}_L \gamma_\mu T^A Q_L)\,(\bar{q}_L \gamma^\mu T^A Q_L)\,, \quad \mathcal{O}_{Qq}^{(8,3)} = (\bar{Q}_L \gamma_\mu T^A \tau^a Q_L)\,(\bar{q}_L \gamma^\mu T^A \tau^a q_L)\,,\\
\mathcal{O}_{tu}^{(8)} &= (\bar{t}_R \gamma_\mu T^A t_R)\,(\bar{u}_R \gamma^\mu T^A u_R)\,, \quad \mathcal{O}_{td}^{(8)} = (\bar{t}_R \gamma_\mu T^A t_R)\,(\bar{d}_R \gamma^\mu T^A d_R)\,,\\
\mathcal{O}_{Qu}^{(8)} &= (\bar{Q}_L \gamma_\mu T^A Q_L)\,(\bar{u}_R \gamma^\mu T^A u_R)\,, \quad \mathcal{O}_{Qd}^{(8)} = (\bar{Q}_L \gamma_\mu T^A Q_L)\,(\bar{d}_R \gamma^\mu T^A d_R)\,,\\
\mathcal{O}_{tq}^{(8)} &= (\bar{t}_R \gamma_\mu T^A t_R)\,(\bar{q}_L \gamma^\mu T^A q_L)\,,
\end{aligned}$$

m_{tt} GeV	$\lvert z\rvert < 0.4$	$\lvert z\rvert > 0.4$
$2m_t < m_{tt} < 400$	$\mathcal{D}^T$, $\mathcal{C}$, M_2, $\mathcal{D}^F$	$\mathcal{D}^T$, $\mathcal{C}$, M_2, $\mathcal{D}^F$
$400 < m_{tt} < 600$	$\mathcal{D}^T$, $\mathcal{C}$, $\mathcal{D}^F$, M_2	$\mathcal{C}$, $\mathcal{D}^T$, M_2, $\mathcal{D}^F$
$600 < m_{tt} < 800$	$\mathcal{C}$, $\mathcal{D}^T$, M_2, $\mathcal{D}^F$	$\mathcal{D}^T$, $\mathcal{C}$, $\mathcal{D}^F$, M_2
$m_{tt} > 800$	$\mathcal{C}$, M_2, $\mathcal{D}^F$, $\mathcal{D}^T$	$\mathcal{C}$, M_2, $\mathcal{D}^F$, $\mathcal{D}^T$
Inclusive	$\mathcal{C}$, M_2, $\mathcal{D}^F$, $\mathcal{D}^T$	

What about “old” new physics?



	$t\bar{t}$	Toponium	Combined
C_{kk}	-0.5003 ± 0.0097	-0.9594 ± 0.0053	-0.5954 ± 0.0077
C_{kr}	0.0635 ± 0.0098	0.0113 ± 0.0056	0.0527 ± 0.0079
C_{kn}	-0.0034 ± 0.0099	0.0027 ± 0.0055	-0.0021 ± 0.0079
C_{rk}	0.0766 ± 0.0098	0.0094 ± 0.0056	0.0626 ± 0.0079
C_{rr}	-0.3903 ± 0.0098	-0.8965 ± 0.0053	-0.4951 ± 0.0078
C_{rn}	-0.0145 ± 0.0098	-0.0040 ± 0.0055	-0.0123 ± 0.0079
C_{nk}	0.0133 ± 0.0098	-0.0030 ± 0.0056	0.0100 ± 0.0078
C_{nr}	0.0007 ± 0.0098	0.0030 ± 0.0055	0.0012 ± 0.0079
C_{nn}	-0.5547 ± 0.0097	-0.9224 ± 0.0053	-0.6308 ± 0.0077
$D^{(1)}$	-0.4818 ± 0.0057	-0.9261 ± 0.0031	-0.8188 ± 0.0027
$D^{(k)}$	0.1482 ± 0.0056	0.2865 ± 0.0030	0.2531 ± 0.0027
$D^{(n)}$	0.2216 ± 0.0056	0.3284 ± 0.0030	0.3026 ± 0.0027
$D^{(r)}$	0.1120 ± 0.0056	0.3112 ± 0.0031	0.2631 ± 0.0027
$\mathcal{C}$	0.2234 ± 0.0086	0.8930 ± 0.0050	0.7293 ± 0.0043
M_2	0.5481 ± 0.0051	0.1525 ± 0.0069	0.3537 ± 0.0047
$\widetilde{M}_2$	-1.4524 ± 0.0658	0.3716 ± 0.0193	1.4895 ± 0.0533
$\mu(\rho)$	0.2421 ± 0.0056	0.8586 ± 0.0062	0.6723 ± 0.0044
$E_N(\rho)$	0.2906 ± 0.0100	0.9178 ± 0.0038	0.7894 ± 0.0034
$D_T(\rho)$	0.0000 ± 0.0000	0.3338 ± 0.0050	0.2543 ± 0.0047

Extracting a Toponium Signal at the LHC with Spin and Quantum Information Tools

Laura Antozzi (U. Bologna, DIFA and INFN, Bologna), Esteban Chalbaud (LIP and Coimbra U.), Frédéric Déliot (IRFU, Saclay, DPP), Federica Fabbri (U. Bologna, DIFA and INFN, Bologna and Bologna U.), Miguel C.N. Fiolhais (LIP and Coimbra U. and Kingsborough Coll. and City Coll., N.Y. and CUNY, Graduate School - U. Ctr.) Show All(9)

Feb 26, 2026

18 pages

e-Print: 2602.23426 [hep-ph]

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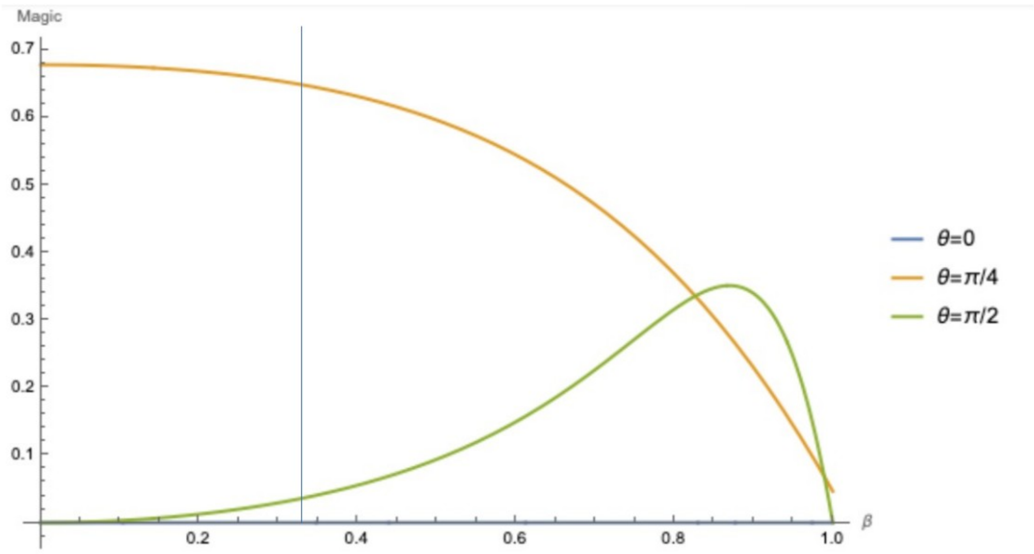
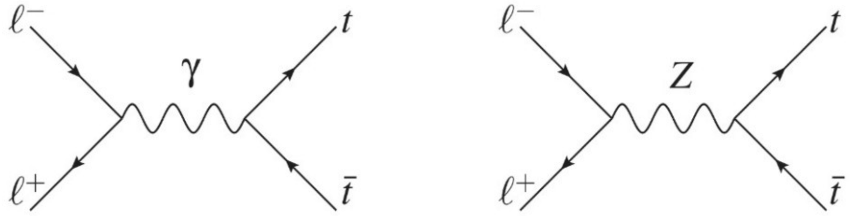
Future lepton colliders

- Entanglement in top quark production at future lepton colliders was previously studied in (Maltoni, Severi, Tentori, Vryonidou)



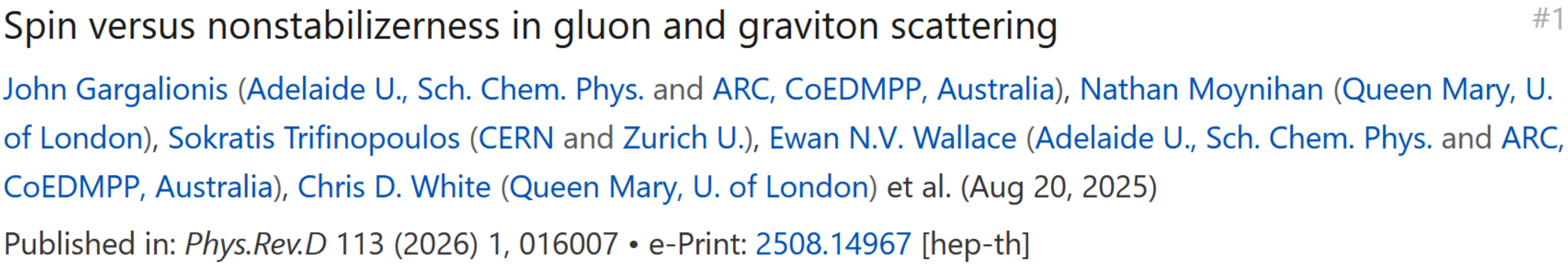
Aoude, Banks, White^2

PRELIMINARY



- Top quark pairs are now produced via EW processes → different quantum states are probed, complementary to LHC measurements
- Possible to observe non-zero magic over a wide range of centre of mass energies (dependent on θ)

Studying more general scattering processes...



Spin versus nonstabilizerness in gluon and graviton scattering

#1

John Gargalionis (Adelaide U., Sch. Chem. Phys. and ARC, CoEDMPP, Australia), Nathan Moynihan (Queen Mary, U. of London), Sokratis Trifinopoulos (CERN and Zurich U.), Ewan N.V. Wallace (Adelaide U., Sch. Chem. Phys. and ARC, CoEDMPP, Australia), Chris D. White (Queen Mary, U. of London) et al. (Aug 20, 2025)

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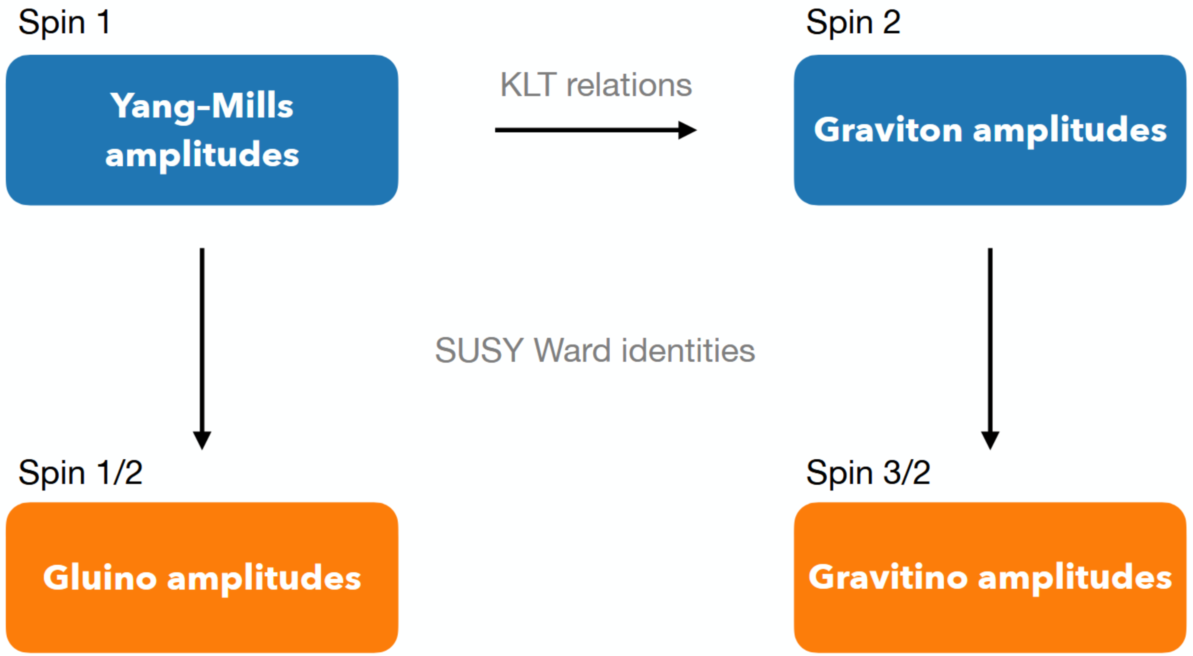


Spin 1

Yang-Mills amplitudes

KLT relations

Spin 2

Graviton amplitudes

SUSY Ward identities

Spin 1/2

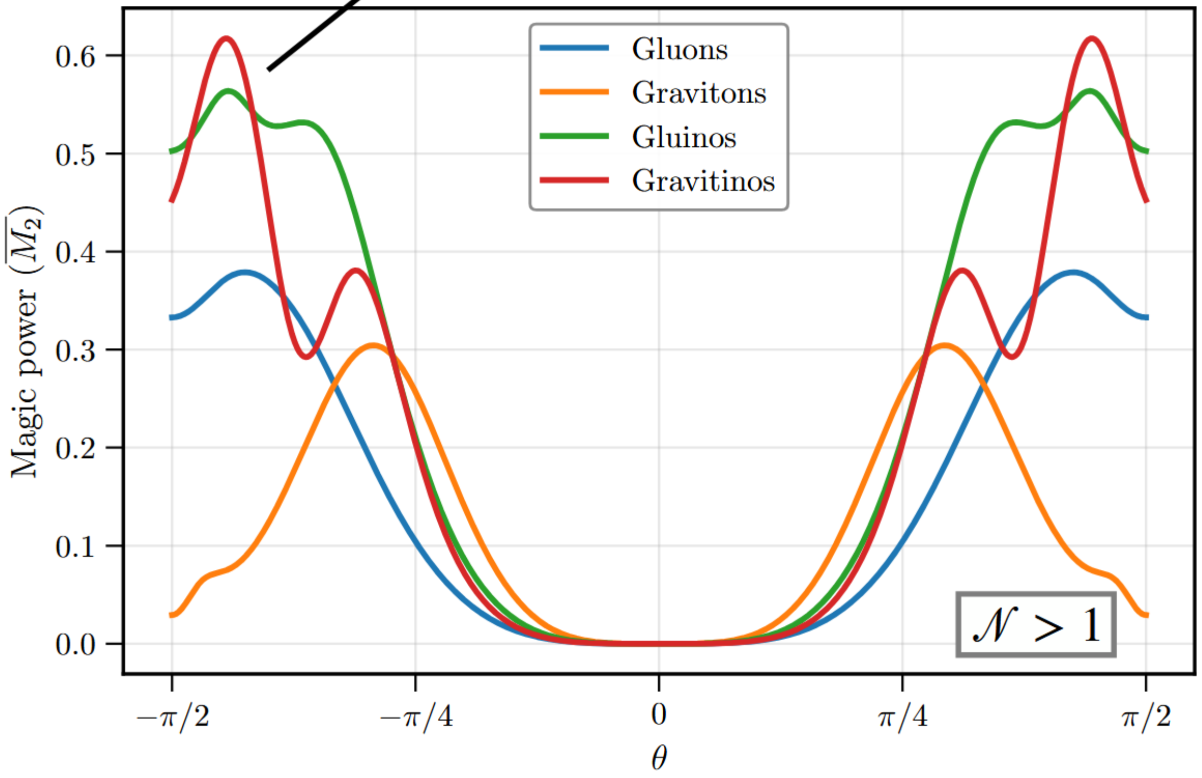
Gluino amplitudes

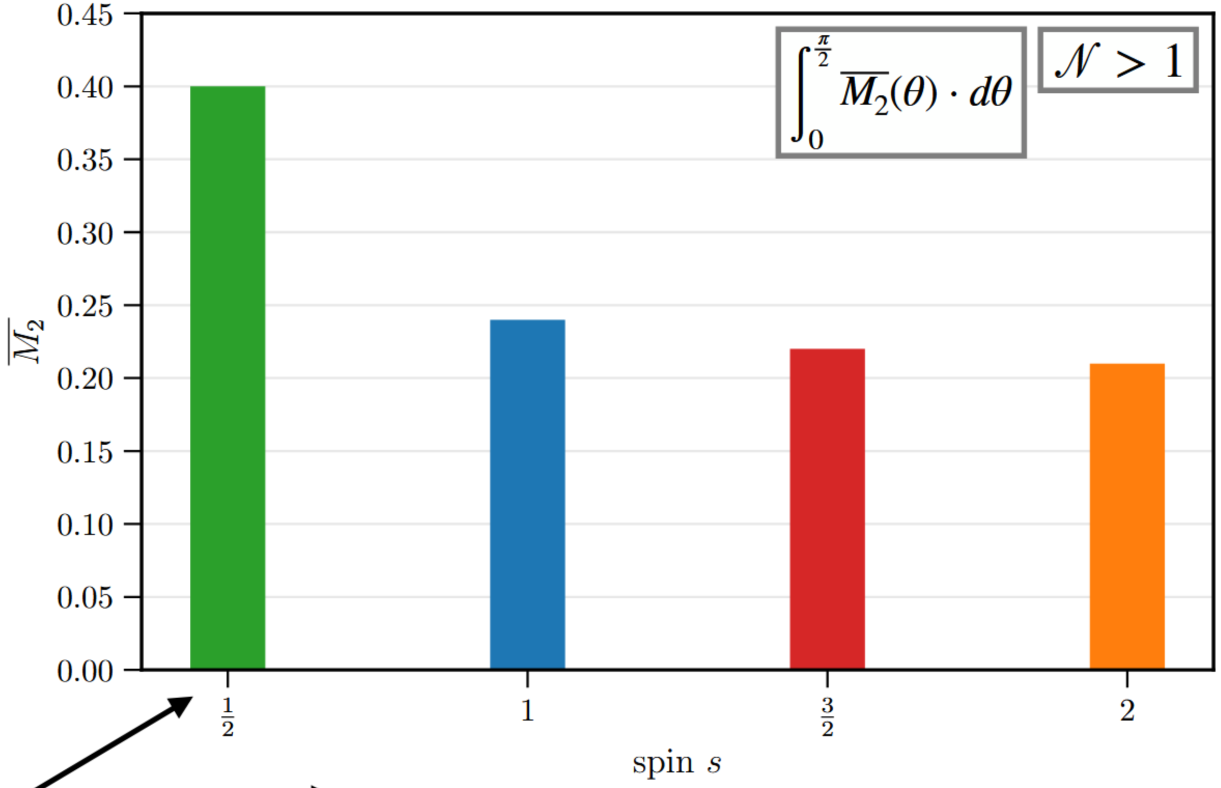
Spin 3/2

Gravitino amplitudes

Studying more general scattering processes...

Fermions generate more magic on average **in central region**





Gluinos generate more magic on average **integrated over scattering angle**

Magic power decreases with **increasing spin**

Conclusions

- The interface of high energy physics and quantum information theory is a really fun area to work in right now

- Exploring concepts like magic in high energy processes is generating new insights into how they work

- There is much interest in the collider community in measuring these concepts, or seeing if they give us a handle on BSM physics