A Quantum Observable for a Quantum Phenomenon? Measuring tau Dipoles with Resurrection

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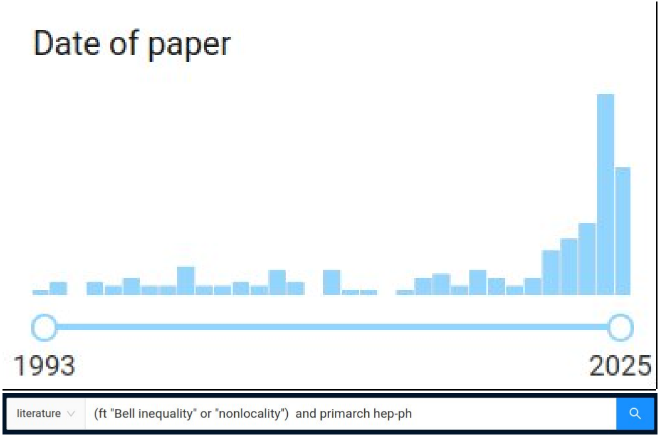
Based on **arXiv:2408.04553** (accepted just yesterday to PRD!)

JG|U

PRISMA+

Entanglement at Colliders

- Large interest in Bell tests using spin correlations at collider after prediction + detection of entanglement in $t\bar{t}$ at LHC



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- In 1992, it was realised that the proposed strategy does **not** give a Bell test! Abel, Dittmar, Dreiner Phys.Lett.B 280 (1992), 304-312
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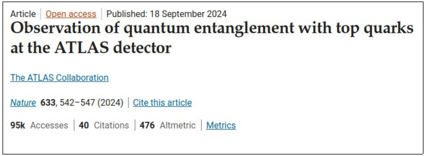

Article | Open access | Published: 18 September 2024

Observation of quantum entanglement with top quarks at the ATLAS detector

The ATLAS Collaboration

Nature **633**, 542–547 (2024) | Cite this article

95k Accesses | **40** Citations | **476** Altmetric | Metrics

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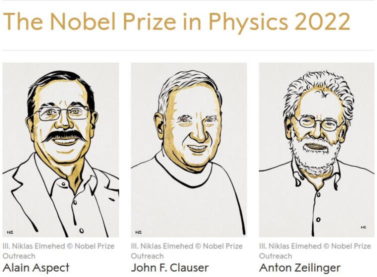

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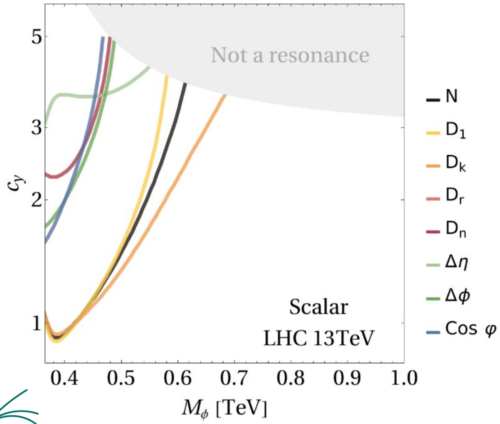
Aside from Bell test, how can we make use of detection of entanglement at colliders?
But as a New Physics probe, of course!

Quantum Supremacy?

In $t\bar{t}$ production, it was suggested that quantum information observables can be competitive/superior to "traditional" observables.

Maltoni, Severi, Tentori, Vryonidou JHEP 03 (2024), 099



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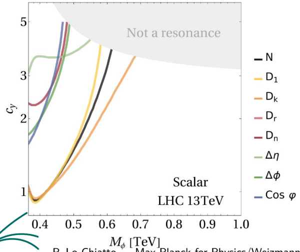
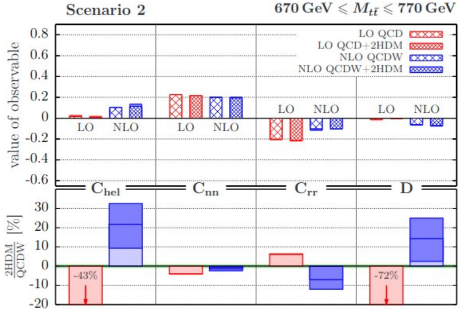
However, entanglement is measured using an angular distribution that has a long history.

Do we need quantum information at all? Or is it just a coincidence?





Bernreuther, Galler, Si, Uwer
PRD 95 (2017) 9, 095012

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Study spin correlation and entanglement $e^+e^- \to \tau^-\tau^+ \to \pi^+\pi^-\bar{\nu}\nu$ mediated by SM, as well as SMEFT dipoles operators

Resulting quantum state is not as simple as QCD-produced $t\bar{t}$, so quantum information observables do not coincide with known combinations angular observables

Tau Dipole

We consider the addition of

$$\mathcal{L}_{\text{dipole}} = \frac{v}{\Lambda^2}(\tau_L^{\dagger}\sigma^{\mu\nu}\tau_R)(c_Z Z_{\mu\nu} + c_\gamma F_{\mu\nu}) + h.c.$$

- It generates $(g-2)_\tau$

$$\Delta a_\tau = \frac{2\sqrt{2}}{e}\frac{m_\tau v}{\Lambda^2}\Re(c_\gamma) + \dots,$$

$$\Delta d_\tau = -\sqrt{2}\frac{v}{\Lambda^2}\Im(c_\gamma) + \dots$$

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It imposes different helicity structure than SM

Consider massless limit of $e^+(h_1)e^-(h_2) \to \tau^+(h_3)\tau^-(h_4)$:

Operator	Helicity$(h_1 h_2 h_3 h_4)$
SM	$(+-+-),(+--+),(-++-),(-+-+)$
Dipole	$(+-++),(+---),(-+++),(-+--)$

Lack of interference between SM and SMEFT dipole at $s \gtrsim 30\,\text{GeV}$

Mass effects only restore interference at $O(vm_\tau/\Lambda^2)$

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Effect of dipole on Scattering amplitudes

$\mathcal{M} = \mathcal{M}_{SM} + \mathcal{M}_{\rm dipole}$ but $\mathcal{M}_{SM}\, \mathcal{M}^*_{\rm dipole} \approx 0$ due to chiral nature of SM

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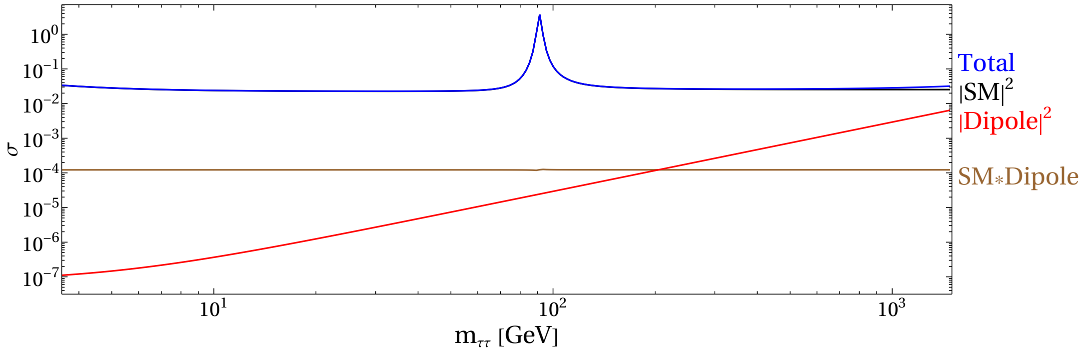

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Spin correlations are instead dominated by interference (resurrection)

Perfect arena to showcase quantum phenomena in collider physics

4-fermion Scattering in Density Matrix Language

$|\tau^+\tau^-\rangle$ has 4 possible spin configuration Convenient description: 4×4 density matrix

$$\rho = |\tau^+\tau^-\rangle\langle\tau^+\tau^-| = \sum_n p_n |\phi_n\rangle\langle\phi_n|,$$

$$p_n \in \mathbb{R}, \sum_n p_n = 1 \Rightarrow Tr(\rho) = 1$$

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Fano Decomposition

$$\rho = \frac{1}{4}\mathbb{1}_2\otimes\mathbb{1}_2 + B_i^+\,\tau^i\otimes\mathbb{1}_2 + B_i^-\,\mathbb{1}_2\otimes\tau^i + C_{ij}\tau^i\otimes\tau^j$$

Helicity (B_i^+) Pauli Matrix (τ^i) **Correlations** (C_{ij})

Density Matrix

The density matrix formalism easily accomodates for admixtures:

$$R_{\alpha\beta\gamma\delta} \equiv \sum_{\alpha'\beta'\gamma'\delta'} \mathcal{M}^*_{\alpha\beta\alpha'\beta'} \mathcal{M}_{\gamma\delta\gamma'\delta'} ,$$

$$\mathcal{M}_{h_3 h_4, h_1 h_2} \equiv \langle \tau^+(p_3, h_3)\tau^-(p_4, h_4)| S |e^+(p_1, h_1)\bar{e}(p_2, h_2)\rangle ,$$

Since we single out final state, R is not normalised. Define $\rho = \dfrac{R}{4A}$

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Fano Decomposition

$$R = A\, \mathbb{1}_2 \otimes \mathbb{1}_2 + \tilde{B}_i^+\, \tau^i \otimes \mathbb{1}_2 + \tilde{B}_i^-\, \mathbb{1}_2 \otimes \tau^i + \tilde{C}_{ij} \tau^i \otimes \tau^j$$

Cross-Section (A) **Helicity** ($\tilde{B}_i^+$) Pauli Matrix (τ^i) **Correlations** ($\tilde{C}_{ij}$)

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Resurrection

Off-diagonal terms involve different helicity structure

No Helicity suppression of interference!

Indeed, for some (ij) ρ_{ij} is dominated by interference

Interference Resurrection

Take $\rho_i = \frac{\mathbb{1}_4}{4}$, act with $S = \begin{pmatrix} 0 & 0 & 0 & 0 \\ a & b & b & a \\ a & b & b & a \\ 0 & 0 & 0 & 0 \end{pmatrix}$

Cross section receives no contribution from interference

$\sigma \propto A = Tr(S\rho_i S^\dagger) = |a|^2 + |b|^2$

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Consider instead the spin correlation matrix:

$$C = Tr(\vec{\tau}^- \otimes \vec{\tau}^- S\rho_i S^\dagger) = \begin{pmatrix} |b|^2 + |a|^2 & 0 & 0 \\ 0 & |b|^2 - |a|^2 & 2\Im(ab^*) \\ 0 & 2\Im(ba^*) & |a|^2 - |b|^2 \end{pmatrix}$$

Spin correlations “resurrect” interference

Resurrection and Unitarity

Interference suppression implies

$$A \overset{\sqrt{s}\gg m_\tau}{\to} A^{(0)} + \frac{v m_\tau}{\Lambda^2} A^{(2)} + \frac{v^2 s}{\Lambda^4} A^{(4)}$$

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if we naively truncate at order Λ^2:

$$\frac{R_{ij}^{(0)} + \frac{v\sqrt{s}}{\Lambda^2} R_{ij}^{(2)}}{A^{(0)} + \frac{v m_{\tau^-}}{\Lambda^2} A^{(2)}} \overset{\sqrt{s}\gg m_{\tau^-}}{\longrightarrow} \frac{R_{ij}^{(0)} + \frac{v\sqrt{s}}{\Lambda^2} R_{ij}^{(2)}}{A^{(0)}} \quad i \neq j \, .$$

which grows like $\sqrt{s}$ and violates unitarity at $\sqrt{s} < \Lambda$

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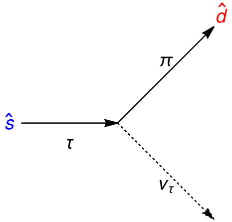
which grows like $\sqrt{s}$ and violates unitarity at $\sqrt{s} < \Lambda$

To undertstand the effect of interference and avoid spurious unitarity violation we define

$$\rho^{\text{No Int}} = \frac{R^{(0)} + (\frac{v m_{\tau\tau^-}}{\Lambda^2})^2 R^{(4)}}{A^{(0)} + (\frac{v m_{\tau\tau^-}}{\Lambda^2})^2 A^{(4)}}\,.$$

Measuring Spin at Colliders



Decaying particle act as own polarimeters, imprinting helicity s into decay product's flight direction d: $P(d|s) = 1 + \alpha s \cdot d$

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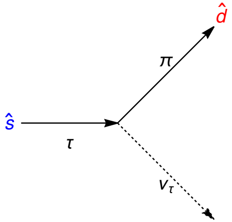

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In spin space we express this in term of decay matrix $\mathcal{D}$

$d\sigma(e^+e^- \to \tau^+\tau^- \to \pi^+\bar{\nu}\pi^-\nu) \propto$
$R_{\alpha\alpha'\beta\beta'} \mathcal{D}^{\tau^-}_{\alpha\alpha'} \mathcal{D}^{\tau^+}_{\beta\beta'} d\mathbf{q}^3_{\tau^-} d\mathbf{q}^3_{\tau^+} d\Omega$

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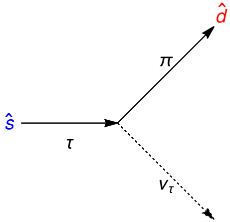

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The Fano coefficients

$$\frac{d\sigma}{d\Omega} \propto A$$

$$\frac{1}{\sigma}\frac{d\sigma}{dc^{\pm}_{\theta i}} = \frac{1}{2}\left(1 \pm \alpha_{\pm} B^{\pm}_{i} c^{\pm}_{\theta i}\right),$$

$$\frac{1}{\sigma}\frac{d\sigma}{d(c^{+}_{\theta i} c^{-}_{\theta j})} = -\frac{1}{2}\left(1 + \alpha_{+}\alpha_{-} C_{ij} c^{+}_{\theta i} c^{-}_{\theta j} \ln(|c^{+}_{\theta i} c^{-}_{\theta j}|)\right)$$

In spin space we express this in term of decay matrix $\mathcal{D}$

$$d\sigma(e^{+}e^{-} \to \tau^{+}\tau^{-} \to \pi^{+}\bar{\nu}\pi^{-}\nu) \propto R_{\alpha\alpha'\beta\beta'} \mathcal{D}^{\tau^{-}}_{\alpha\alpha'} \mathcal{D}^{\tau^{+}}_{\beta\beta'} d\mathbf{q}^{3}_{\tau^{-}}\, d\mathbf{q}^{3}_{\tau^{+}}\, d\Omega$$

From Fano Coefficients to Entanglement

Amount of entanglement can be quantified **in any basis**

Horodecki $\mathfrak{m}_{12}$

- Defined using C only
- 0 if state separable
- ≥ 1 is Bell inequality viol
- 2 if state maximally entangled

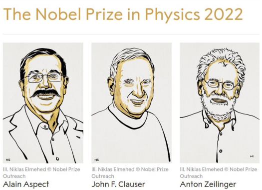
Clauser,Horne,Shimony,Holt PRL 23 (1969);

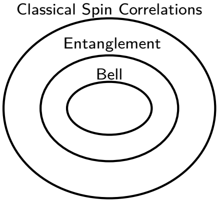
Horodecki, Horodecki, Horodecki, Phys.Lett. A 200 (1995)

Concurrence $\mathcal{C}[\rho]$

- Defined using whole ρ
- 0 if state separable
- 1 if state maximally entangled

W. K. Wootters, PRL 80, 2245 (1998)





Quantum Information vs Simple Spin Correlations

Wishlist to claim "quantum supremacy"

- Resurrection successful: interference dominates observable's deviation from SM
- Sensitivity to phase of Wilson coefficient

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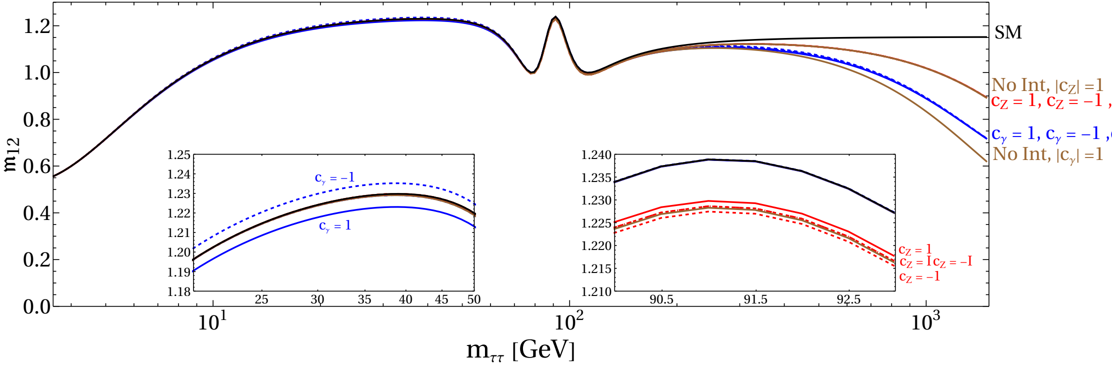
We will now compare $\mathfrak{m}_{12}$, $\mathcal{C}[\rho]$, and a judiciously-chosen element of the C matrix.

We fix $\Lambda = 1.5\,\mathrm{TeV}$ for definiteness.

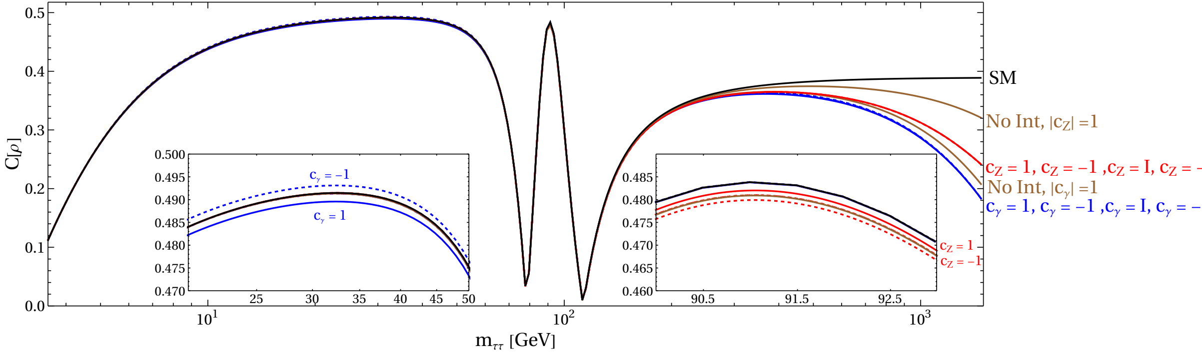
Comparison of $\mathfrak{m}_{12}$, $\mathcal{C}[\rho]$ and $\mathcal{C}_{23}$



Resurrection: No Int and With Int lines are separated

$\mathfrak{m}_{12}$ does not distinguish sign of $c_{\gamma/Z}$, resurrection *reduces* deviation from SM

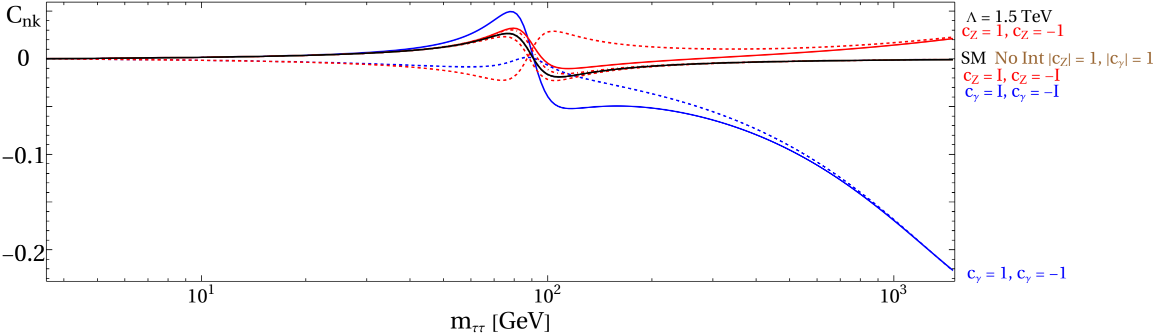
Comparison of $\mathfrak{m}_{12}$, $\mathcal{C}[\rho]$ and C_{23}



Resurrection: No Int and With Int lines are separated

$\mathcal{C}[\rho]$ does not distinguish sign of $c_{\gamma/Z}$, resurrection *increases* deviation from SM

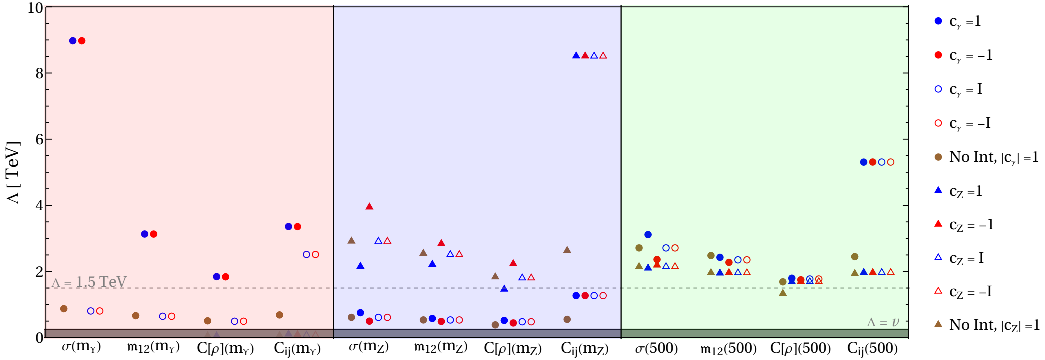
Comparison of $\mathfrak{m}_{12}$, $\mathcal{C}[\rho]$ and $\mathcal{C}_{23}$



Resurrection: No Int and With Int lines are separated

C_{nk} distinguishes signs, deviation dominated by interference

Results: Sensitivity to NP Scale



- Sensitivity to new Physics scale at: $\sqrt{s} = 10.58, 91.2, 500\,\mathrm{GeV}$
- Resurrection gives large sensitivity boost for C_{ij} only

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- What can quantum information teach us about particle physics?
  - Exclusion of local hidden variable unlikely at colliders
  - All information on NP already in fully-differentiable cross section
  - Min/Max Entanglement $\Rightarrow$ global symmetries?

    Beane *et al.* Phys. Rev. Lett. 122 (2019), Cervera-Lierta *et al.* SciPost Phys. 3 (2017) 5, 036

    Enticing, but at the moment also too symplistic argument for UV theories Kowalska, Sessolo JHEP 07 (2024) 156
  - Can we recast "optimal observables" framework in terms of entanglement?
- Learning more about resurrection in angular observables (*e.g.* interplay with soft radiation)

SPARES

Bounds

	$\Delta a_\tau\,(\times 10^{-4})$	$\lvert\Delta d_\tau\rvert\,(\times 10^{-18}\,e\,\mathrm{cm})$	$\Delta a_\tau^Z\,(\times 10^{-4})$	$\lvert\Delta d_\tau^Z\rvert\,(\times 10^{-18}\,e\,\mathrm{cm})$
$\sqrt{s} = m_\Upsilon$	0.50	3.6	350	396
$\sqrt{s} = m_Z$	25	14	0.55	0.31
$\sqrt{s} = 500\,\mathrm{GeV}$	1.4	0.81	10	5.8

A Mysterious QCD Symmetry

$$N = \{n^{\uparrow}, n^{\downarrow}, p^{\uparrow}, p^{\downarrow}\}$$

$$\mathcal{L}_{LO}^{n_f=2} \supset -\frac{1}{2} C_S (N^{\dagger} N)^2 - \frac{1}{2} C_T (N^{\dagger} \sigma N) \cdot (N^{\dagger} \sigma N)$$

- $C_0 = C_S - 3C_T$
  $C_1 = C_S + C_T$
- $C_0 \approx C_T \approx C_* \to SU(4)$ symm.
- No quark model explanation: Violates Coleman-Mandula

Symmetry $\leftrightarrow$ entanglement?

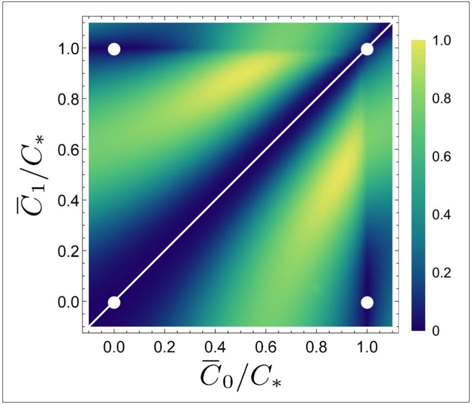
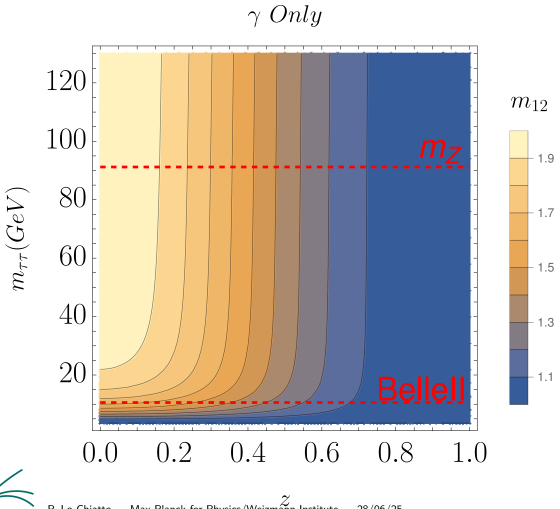
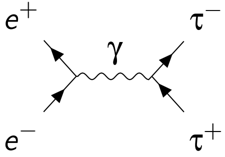


Figure: Entanglement vs (C_0, C_1).
Beane *et al.* Phys. Rev. Lett. 122 (2019)

Standard Model

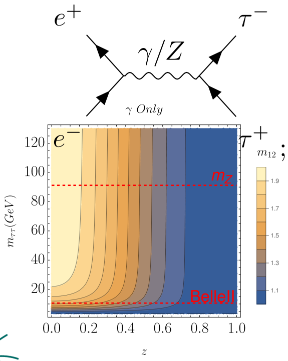
$z = \cos\theta$

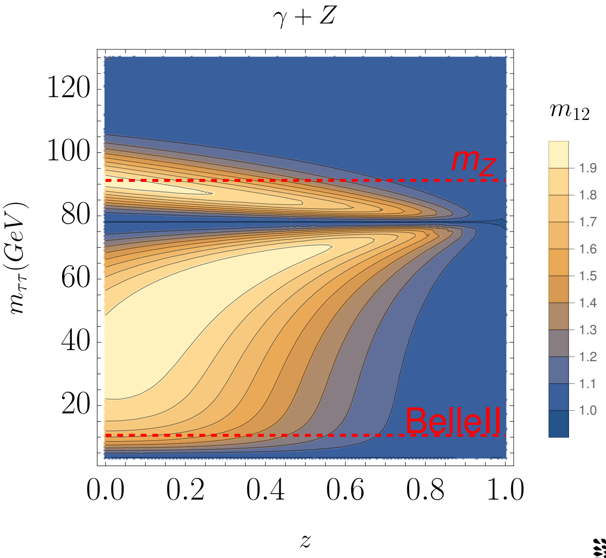




- Threshold: $m_{12} = 1$
- $m_{\tau\tau} \to \infty, z = 0$:
  $m_{12} \to 2$
  (helicity selection)

Standard Model





Interference kills entanglement. Almost max at m_Z.

Abs min. at $m_{\tau\tau} \simeq 78$ GeV. Why?

Tomography in the Helicity Basis

Fano coefficients of $|\psi_f\rangle$ can be measured from angular correlations.
In which basis?

Tomography in the Helicity Basis

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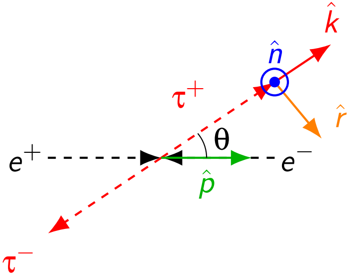
Helicity basis

- Boost decay products to τ rest frame
- $\hat{k}$ is τ^+ flight direction
- $\hat{p} \cdot \hat{k} = \cos\theta$
- $\hat{n} = \hat{p} - \cos\theta\hat{k}$
- $\hat{r} = \hat{k} \times \hat{p}$



Entanglement

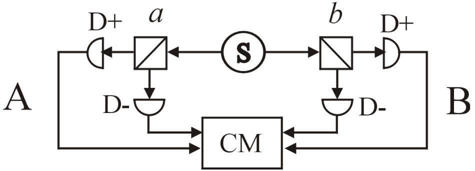
Entanglement: **The** defining phenomenon of quantum mechanics.

CHSH Formulation

- Alice and Bob get one half of a bipartite qubit each
- Make **independent** and **freely tunable** measurements at angles a, a', b, b'.
- Measure coincidences:

$$C_{a,b} = \frac{N_{++} - N_{+-} - N_{-+} + N_{--}}{N_{++} + N_{+-} + N_{-+} + N_{--}}$$

Clauser,Horne,Shimony,Holt PRL 23 (1969); Horodecki, Horodecki, Horodecki, Phys.Lett. A 200 (1995)



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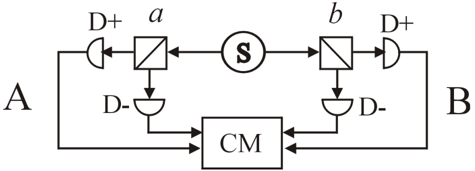

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Classically:

$$S = |C_{a,b} - C_{a,b'} + C_{a',b} + C_{a',b'}| \leq 2$$

In QM, one can find $|\psi\rangle$, (a, a', b, b') s.t. $S = 2\sqrt{2}$ **(EPR or Bell States)**

Simulations

We simulate $e^+e^- \to \tau^+\tau^- \to \pi^+\bar{\nu}\pi^-\nu$ events to estimate statistical uncertainties

- $\sqrt{s} = 10.58\,(\text{Belle II}), 91.2\,(\text{Giga-Z}), 500\,(\text{FCC-ee})\,\text{GeV}$
- ISR taken into account using lepton-PDF formalism in MadGraph
- Detector effects using Delphes' standard cards
- Combinatoric ambiguity (ν not observed) resolved using impact parameters

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Comparison: C matrix ($\sqrt{s} = 91.2\,\text{GeV}$, 1M events), SM only

Analytic

$$\begin{pmatrix} 0.4825 & 0.008 & 0 \\ 0.008 & -0.4825 & 0.0011 \\ 0 & 0.0011 & 1 \end{pmatrix}$$

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Truth-level

$$\begin{pmatrix} 0.479 \pm 0.003 & 0.012 \pm 0.003 & -0.001 \pm 0.003 \\ 0.008 \pm 0.003 & -0.479 \pm 0.003 & 0.004 \pm 0.003 \\ 0.001 \pm 0.003 & 0.0017 \pm 0.002 & 0.997 \pm 0.003 \end{pmatrix}$$

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ISR + Detector

$$\begin{pmatrix} 0.504 \pm 0.003 & 0.008 \pm 0.003 & -0.005 \pm 0.003 \\ 0.011 \pm 0.003 & -0.477 \pm 0.003 & 0.0004 \pm 0.003 \\ 0.007 \pm 0.003 & -0.007 \pm 0.003 & 1.03 \pm 0.003 \end{pmatrix}$$