

Entangled Taus at Colliders

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arXiv:23xx:xxxx

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Quantum Information at Colliders

Entanglement: **The** defining phenomenon of quantum mechanics.
Until now, only few direct studies at colliders.

Spin correlation functions → quantum correlations.

$$\langle S_i S_j \rangle$$



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What is it good for?

- Bell inequalities @ High E
- SM **and beyond** via new observables
- It from qubit? Entanglement \leftrightarrow Enhanced symm.

Quantum Information at Colliders

Collider processes

- $pp \rightarrow t\bar{t}$, Afik, de Nova, Eur. Phys. J. Plus 136, 907 (2021); Auode et al. PRD 106 5 (2022)
- $pp \rightarrow Z^{(*)} \rightarrow \tau\tau$ Fabbrichesi et al. Eur. Phys. J. C (2023) 83:162
- $pp \rightarrow H \rightarrow ZZ^*$ Fabbrichesi et al. arXiv: 2302.00683
- $e^+e^- \rightarrow H \rightarrow \tau\tau$ Altakach et al. arXiv:2211.10513

Speculations

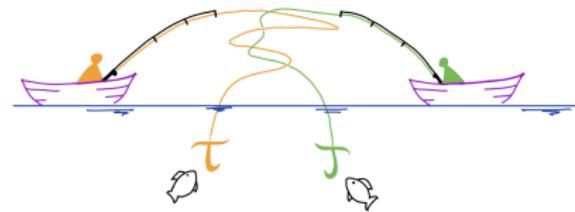
- Min. Ent. \rightarrow Extra symm in low E QCD
Beane et al. Phys. Rev. Lett. 122 (2019)
- Max. Ent. $\rightarrow \sin\theta_W$
Cervera-Lierta et al. SciPost Phys. 3, 036 (2017)

Bell@Belle

Study purely leptonic $2 \rightarrow 2$

$$e^+ e^- \rightarrow \tau^+ \tau^-$$

- Clean interpretation
 - Can be tested now! (BelleII)
 - Gives access to tau dipole
- $$\mathcal{L}_{SMEFT} \supset \frac{v}{\Lambda^2} (\bar{\tau}_L \sigma^{\mu\nu} \tau_R) (c_Z Z_{\mu\nu} + c_\gamma F_{\mu\nu}) + h.c.$$
- Relevant for future Z factories
(FCCee, ILC, μ colliders)



Spin Density Matrix

Basic object: spin density matrix

$$R_{abcd} = \frac{1}{N_i N_j} \sum_{initial} \mathcal{M}_{abij} \mathcal{M}_{ijcd}^* \quad a, b, c, d = \uparrow, \downarrow$$

Normalize $\rho = \frac{R}{4 Tr(R)}$ ← $\propto \frac{d\sigma}{ds}$

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Fano Decomposition

$$\rho = 1_2 \otimes 1_2 + B_i^+ \sigma^i \otimes 1_2 + B_i^- 1_2 \otimes \sigma^i + C_{ij} \sigma^i \otimes \sigma^j$$



Entanglement and Bell Inequalities

Entanglement \leftrightarrow
non-separability

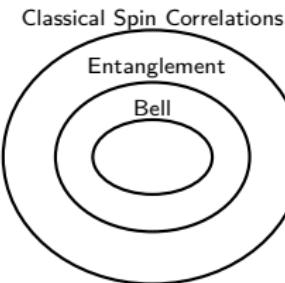
- Hard to prove
- Non-quantitative

Easier: Bell Inequality

Separability

$$\rho = \rho_{\tau^+} \otimes \rho_{\tau^-}$$

$$\text{E.g. } \rho = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$



Maximal violation

Bell State (**EPR**):

$$\frac{1}{\sqrt{2}}(|0\rangle|0\rangle + |1\rangle|1\rangle)$$

$$\rho = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix}$$

Quantifying Violation

$\tau\tau$ is a bipartite 2-qubit.
We have measure of
Bell Inequality Violation.

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

Horodecki³, Phys.Lett. A 200 (1995)

The Nobel Prize in Physics 2022



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Alain Aspect



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$$m_{12} = m_1 + m_2$$

$m_{1/2}$: two biggest eigenvalues of $M = C^T C$

- $m_{12} > 1 \rightarrow$ violation of Bell Inequality
- $m_{12} = 2 \rightarrow$ max. violation

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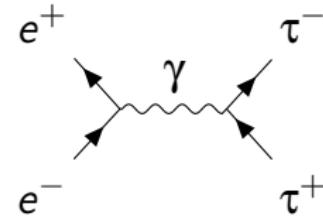
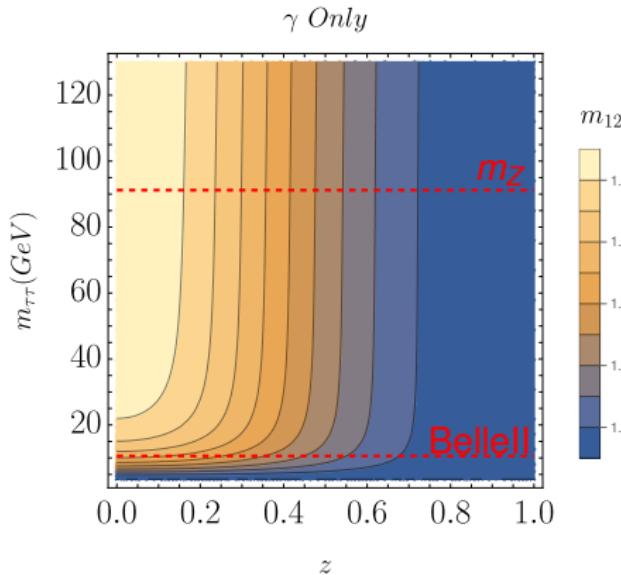
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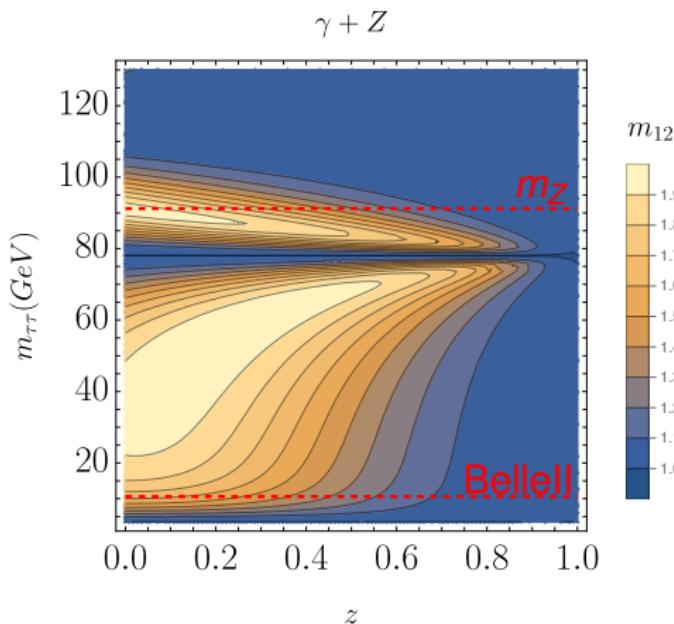
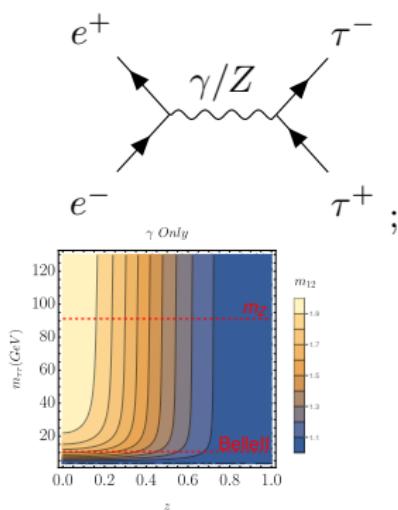
Standard Model

$$z = \cos \theta$$



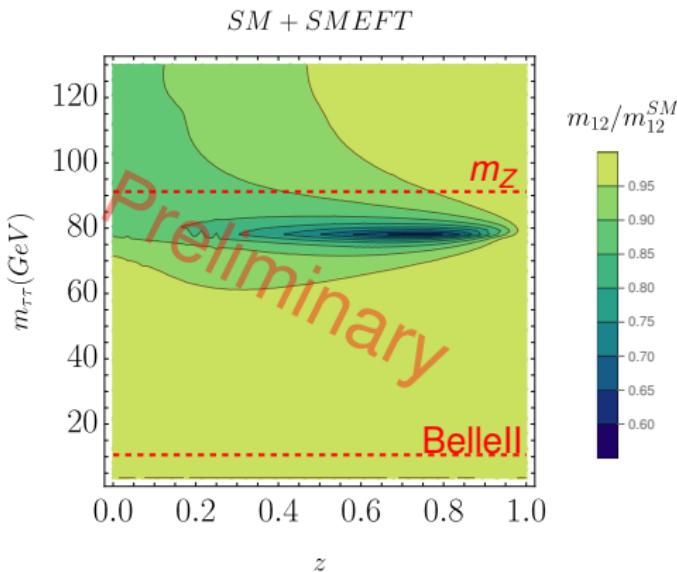
- Threshold:
 $m_{12} = 1$
- $m_{\tau\tau} \rightarrow \infty, z = 0 :$
 $m_{12} \rightarrow 2$
(helicity selection)

Standard Model

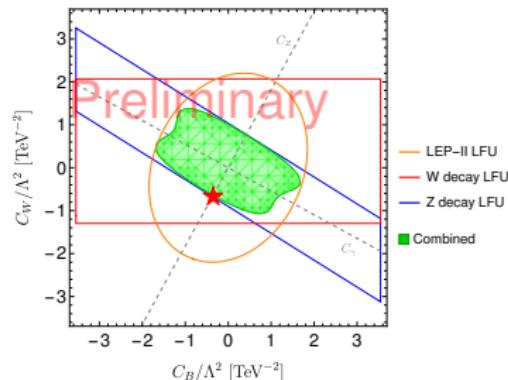


Interference kills entanglement. Almost max at m_Z .
 Abs min. at $m_{\tau\tau} \sim 78$ GeV. Why?

Adding SMEFT τ dipole



$$\frac{v}{\Lambda^2} (\bar{\tau}_L \sigma^{\mu\nu} \tau_R) (c_Z Z_{\mu\nu} + c_Y F_{\mu\nu}) + h.c.$$



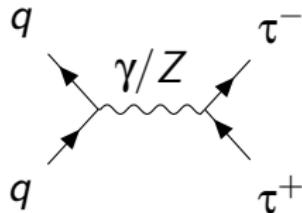
Edge of current bounds:
Gonzalez-Sprinberg (2000) + LHC Data

$$\left(\frac{c_Y}{\Lambda^2}, \frac{c_Z}{\Lambda^2} \right) = (-1.6, -0.8) \text{TeV}^{-2}$$

- Large deviation at m_Z
- More features at ~ 78 GeV

Better bounds at LHC

weigh



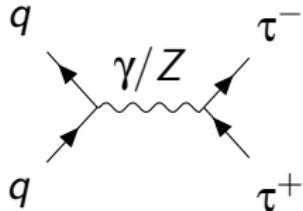
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Luminosity Function

$$\rho_{abcd}^{pp} = \frac{\sum_q I_q R_{abcd}^{qq}}{\sum_q I_q \tilde{A}^{qq}}$$

Better bounds at LHC

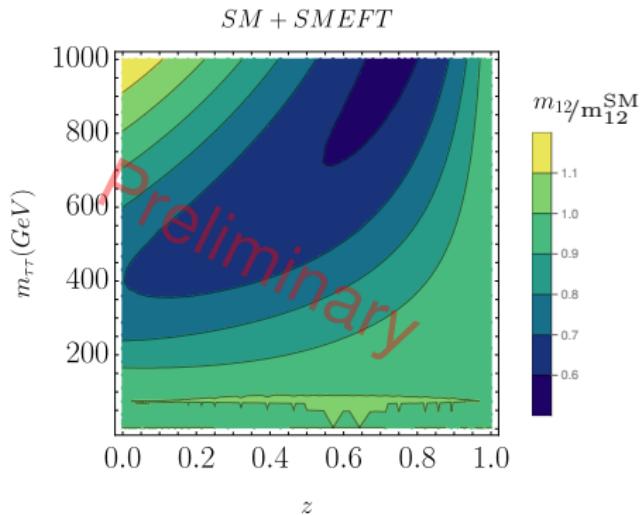
weigh



with PDF

Luminosity Function

$$\rho_{abcd}^{pp} = \frac{\sum_q I_q R_{abcd}^{qq}}{\sum_q I_q \tilde{A}^{qq}}$$



- No deviations at low E.
- Large dev. at high E.

Conclusions

Quantum information is a good arena for particle physics

- Sizable deviations from the SM predictions for specific kinematical configurations
- Complementary to other SMEFT probes
- Can be tested now!
- Maxima and minima of entanglement may reveal hidden symmetries of theory.

Conclusions

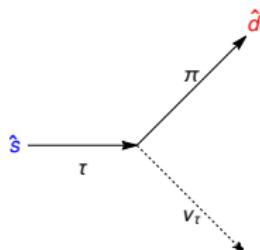
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Outlook

- Is BI violation optimal observable for spin correlation?
- NLO: Soft radiation, IR divergence?

Measuring Spin Correlations



The taus act as their own polarimeters when decaying, imprinting polarization s into decay product's flight direction d :

$$P(d|s) = 1 + \alpha s \cdot d$$

Best understood in $\tau \rightarrow \pi v_\tau$ ($BR \sim 10\%$)

$$\therefore d\Gamma/dz = 1/2 (1 + P_\tau z).$$

Can reconstruct C matrix directly using:

$$d\sigma/d < u_i u_j > \propto (1 + \alpha^2 C_{ij} u_{ab}) \dots$$

Bounds

Observables used
(@95 CL)
(assumes real WC)

Gonzalez-Sprinberg et al. Nucl.Phys.B 98
(2001)+ LHC Data for W (preliminary)

- $\frac{\sigma(ee \rightarrow \tau\tau)}{\sigma(ee \rightarrow \mu\mu)}$
- $\frac{\sigma(W \rightarrow \tau\nu)}{\sigma(W \rightarrow \mu\nu)}$
- $\frac{\sigma(Z \rightarrow \tau\tau)}{\sigma(Z \rightarrow \mu\mu)}$

