Features of Quantum Information at Colliders

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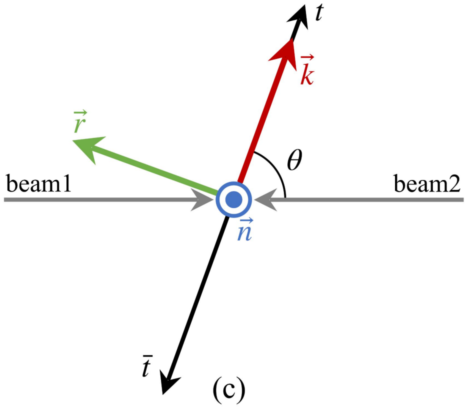
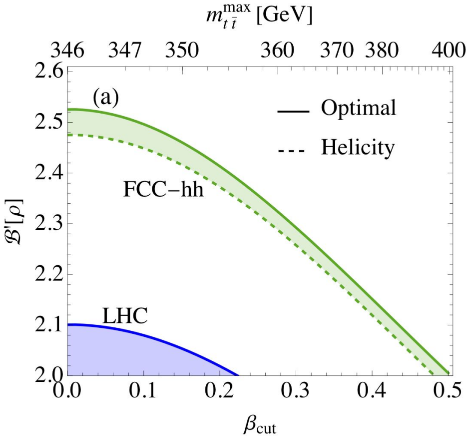
Physics Potential of Future Colliders, TRIUMF, Canada

Main References: 2310.17696, 2311.09166, 2407.01672

with Kun Cheng, Tao Han, Arthur Wu

Outline

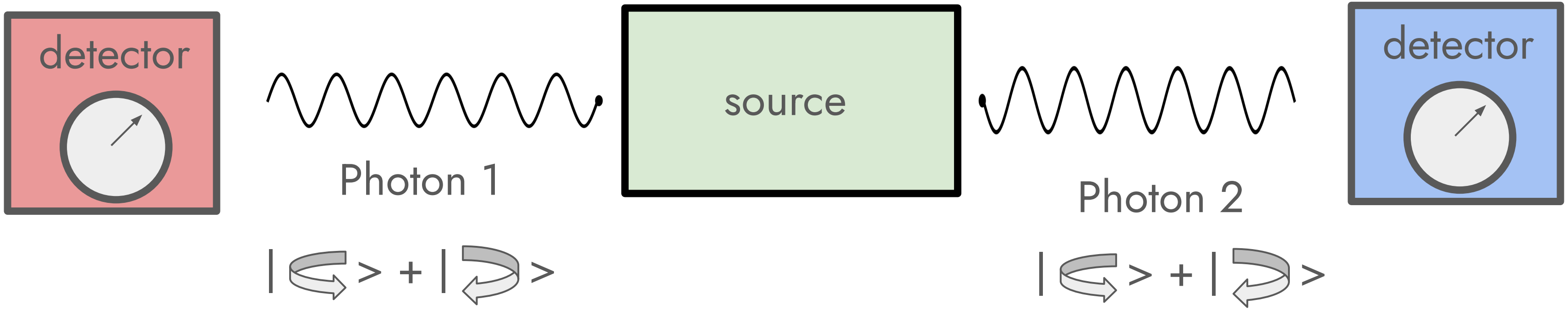




Low vs. High Energy → Bell Tests → Future Colliders

Quantum Information at High Energies

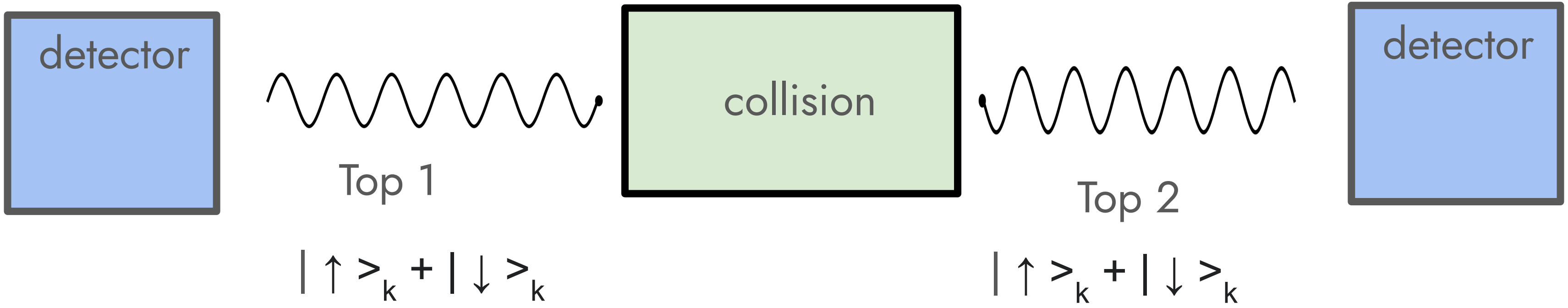
- Recall the traditional quantum experiments with two photons



- A source creates *similarly-prepared* quantum states
- The quantum states includes *quantum correlations* between polarizations
- Detectors choose an *axis*, then detect *left* or *right* polarized

Quantum Information at High Energies

- The set-up at colliders is a bit different


detector

Top 1

$|\uparrow>_k + |\downarrow>_k$

collision

Top 2

$|\uparrow>_k + |\downarrow>_k$

detector

- Collisions create “similarly-prepared” quantum states
- The quantum states involves *quantum correlations* between *spins*
- Use decay products of top to *infer* spin

Quantum Information at High Energies

- Consider the density matrix for two qubits

$$\rho = \frac{1}{4}\left(\mathbb{I}_4 + \sum_i B_i^+ \sigma_i \otimes \mathbb{I}_2 + \sum_j B_j^- \mathbb{I}_2 \otimes \sigma_j + \sum_{ij} C_{ij} \sigma_i \otimes \sigma_j\right)$$

- Polarization of first top (3 DOF): B_i^+
- Polarization of second top (3 DOF): B_j^-
- Spin correlations (9 DOF): C_{ij}
    - Calculated before interest in entanglement

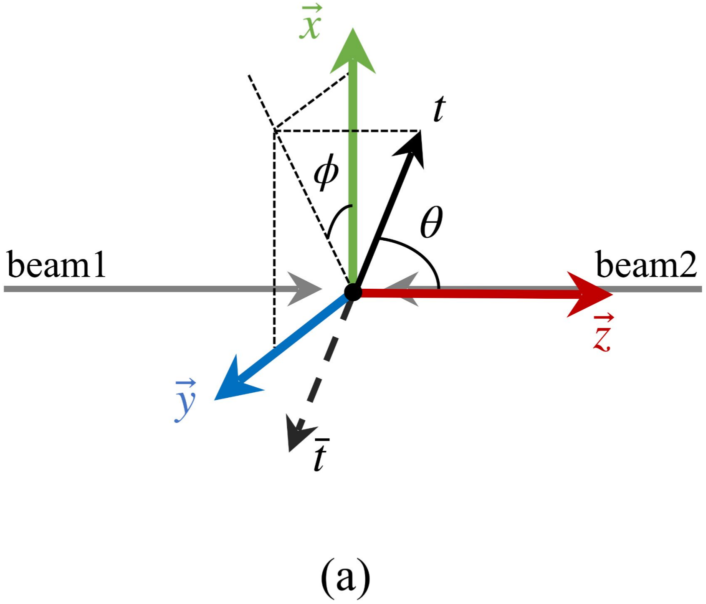
$$C_{33} = \begin{cases} -0.456 & (-0.389) \quad \text{Helicity at Tevatron} \\ +0.910 & (+0.806) \quad \text{Beamline at Tevatron} \\ +0.918 & (+0.913) \quad \text{Off} - \text{Diagonal at Tevatron} \\ \\ +0.305 & (+0.311) \quad \text{Helicity at LHC(14 TeV)}, \end{cases}$$

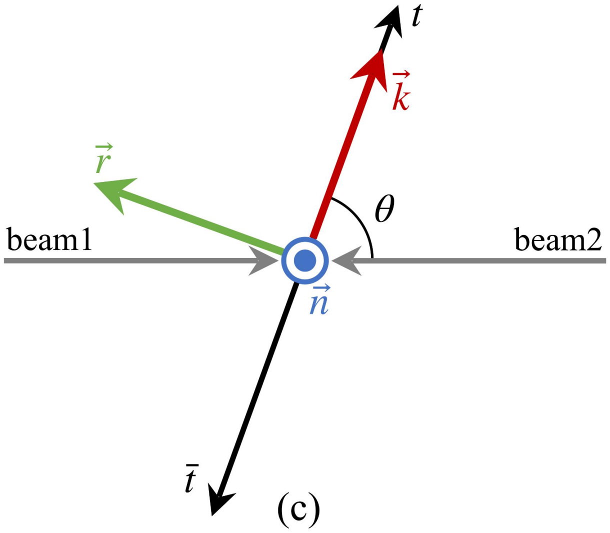
Parke 1202.2345

Quantum Information at High Energies

- Beamline Basis (x,y,z)

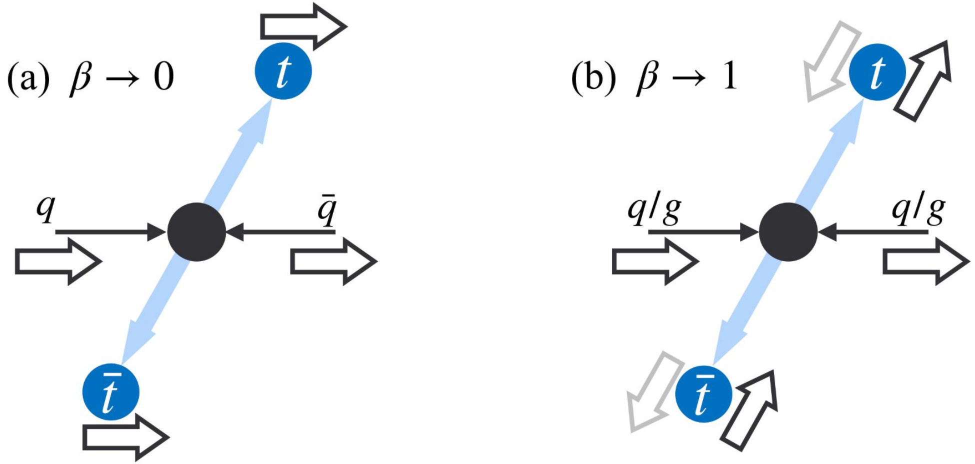
Helicity basis (k,r,n)





Quantum Information at High Energies

- Example: $q\bar{q} \to t\bar{t}$



- Spin correlations intuitively *depend* on basis choice
- Quantum states *cannot depend* on basis choice

Quantum Information at High Energies

Cheng, Han, ML 2311.09166

Cheng, Han, ML 2407.01672

- Consider reconstructing the density matrix from collider events
    - If $\sigma_i \otimes \sigma_j$ is the same for each event

$$C_{ij} = \mathrm{tr}(\rho(\sigma_i \otimes \sigma_j))$$

    - If $\sigma_i \otimes \sigma_j$ is the different for each event

$$\langle C_{ij} \rangle_a = \mathrm{tr}(\rho(\sigma_i \otimes \sigma_j)_a)$$

- Rather than quantum states, at colliders we reconstruct "**fictitious states**"
    - Entangled fictitious state => entanglement (but numerical value not meaningful)
    - Bell non-local fictitious state => Bell non-locality (but numerical value not meaningful)

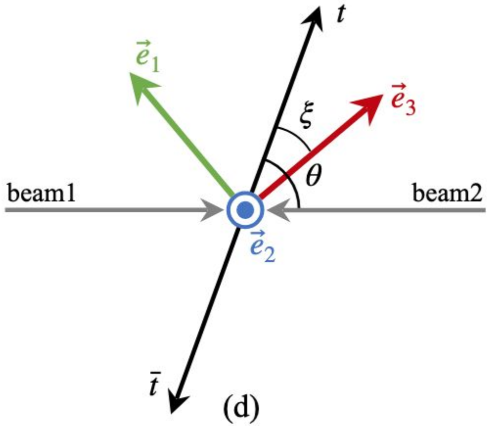
Quantum Information at High Energies

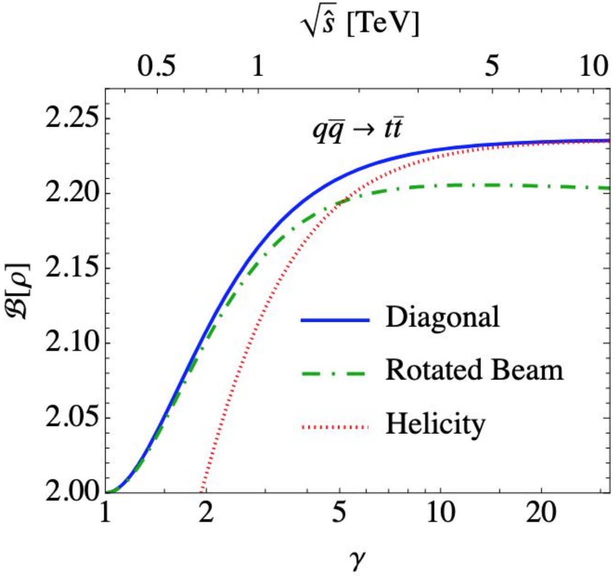
Cheng, Han, ML [2311.09166](2311.09166)

Cheng, Han, ML [2407.01672](2407.01672)

- Fictitious states *depend* on the spin quantization axis
- There is an *optimal* direction to maximize:
  - Entanglement
  - Bell inequality violation

- Rotate by ξ from helicity basis

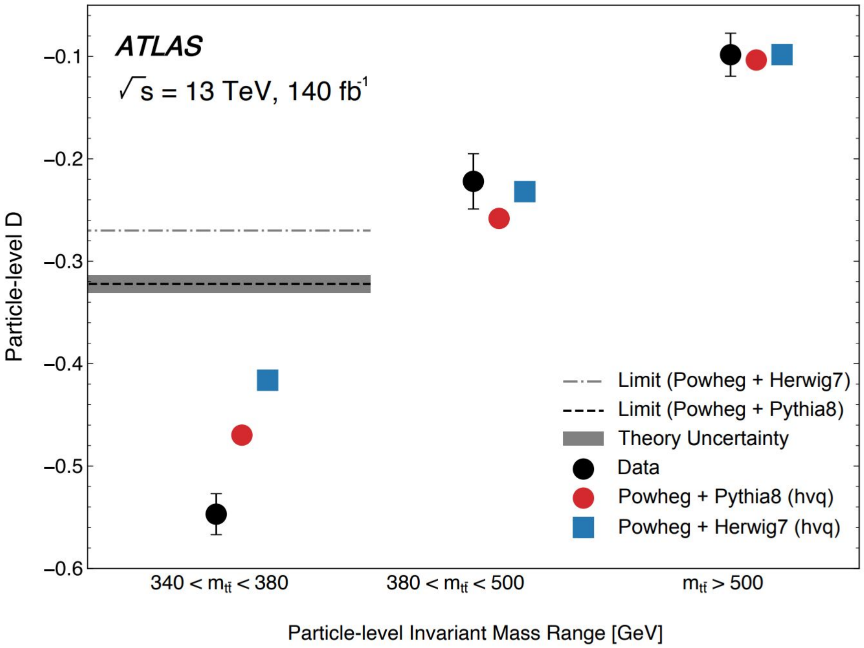




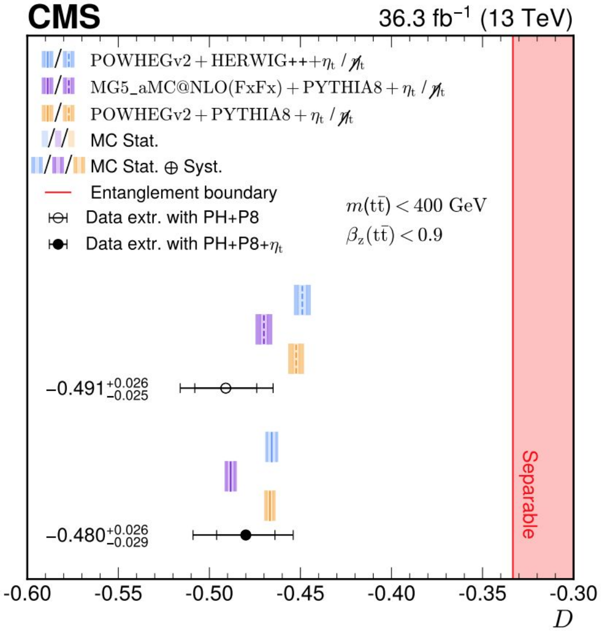
Quantum Information at High Energies

- Entanglement already detected in leptonic top pair events

ATLAS 2311.07288

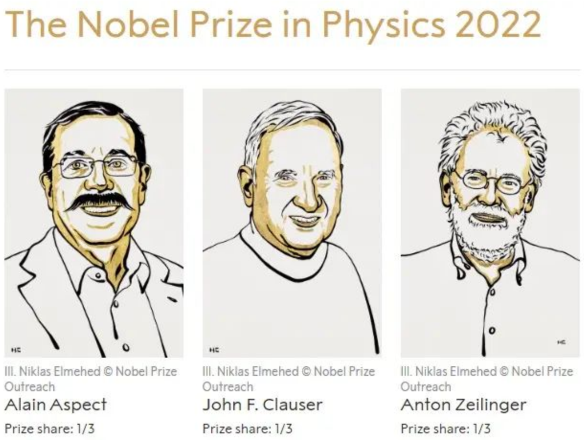


CMS 2406.03976



Bell Tests

- Inequality that is satisfied by all local hidden variable theories
  - Bell (1964)
  - Clauser, Horne, Shimony, Holt (1969)
- “for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science.”
- For two qubits, the CHSH inequality is the Bell inequality



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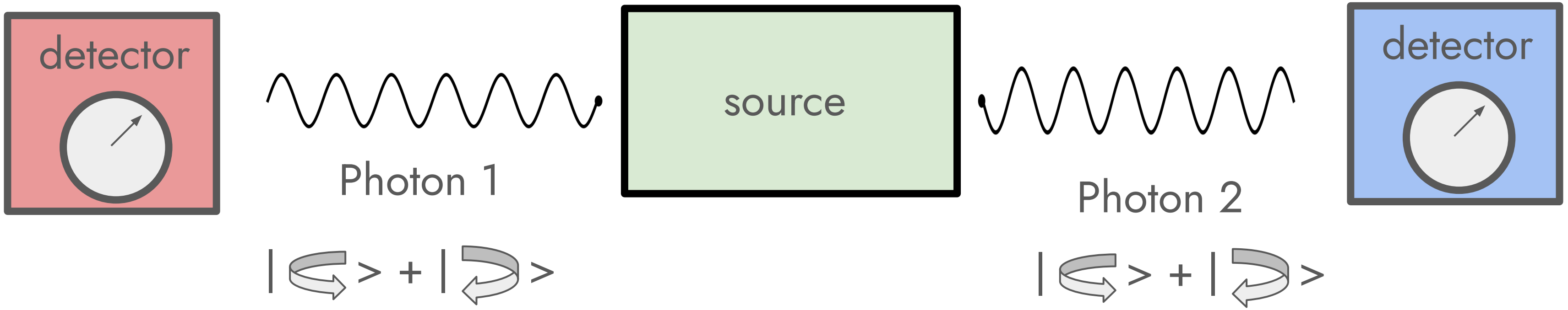
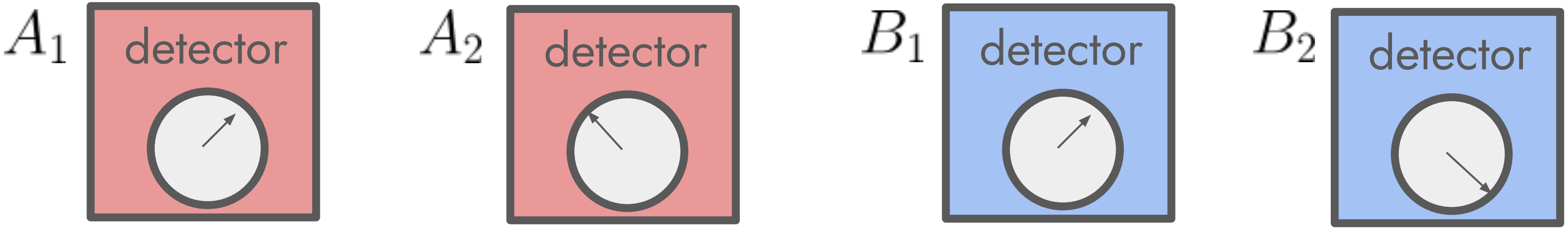
$$|\langle A_1 B_1\rangle - \langle A_1 B_2\rangle + \langle A_2 B_1\rangle + \langle A_2 B_2\rangle| \leq 2$$

Bell Tests

- CHSH inequality

$$|\langle A_1B_1\rangle - \langle A_1B_2\rangle + \langle A_2B_1\rangle + \langle A_2B_2\rangle| \leq 2$$





Bell Tests: example

$$|\langle A_1B_1\rangle - \langle A_1B_2\rangle + \langle A_2B_1\rangle + \langle A_2B_2\rangle| \leq 2$$

- Example: $|\psi\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$
  - Detector settings: $A_1 = \sigma_x$ $\quad B_1 = \frac{-1}{\sqrt{2}}(\sigma_x + \sigma_z)$; $A_2 = \sigma_z$ $\quad B_2 = \frac{1}{\sqrt{2}}(\sigma_x - \sigma_z)$
  - Result: $\text{LHS} = 2\sqrt{2}$
- A different choice of detector settings may not violate the inequality

$$\begin{aligned} A_1 &= \sigma_x & B_1 &= \tfrac{1}{\sqrt{2}}(\sigma_x + \sigma_z) \\ A_2 &= \sigma_z & B_2 &= \tfrac{1}{\sqrt{2}}(\sigma_x - \sigma_z) \end{aligned}$$

$$\text{LHS} = 0$$

Bell Tests

- Bell's inequality (CHSH inequality)

$$|\langle A_1 B_1\rangle - \langle A_1 B_2\rangle + \langle A_2 B_1\rangle + \langle A_2 B_2\rangle| \leq 2$$

    - All local theories, even with hidden variables, obey inequality
    - A quantum state may or may not violate CHSH
    - QM allows violation because spins *anti-commute*

- At colliders, we don't measure spins *directly*
    - Only measure *momenta* of decayed particles
    - *Infer* spin value, assuming spin properties
    - Cannot "*test*" quantum mechanics at colliders

Abel, Dittmar, Dreiner 1992

Bell Tests

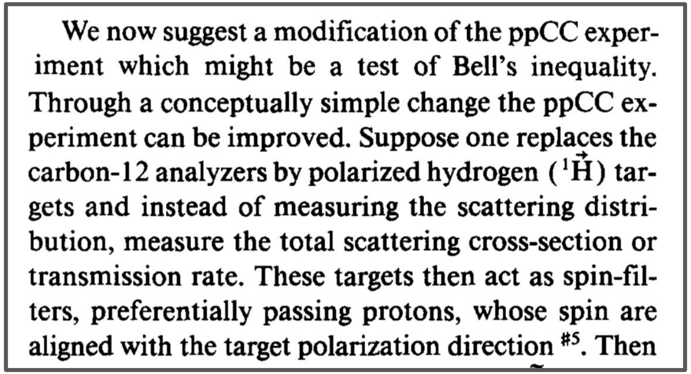
- Bell's inequality (CHSH inequality)

$$|\langle A_1B_1\rangle - \langle A_1B_2\rangle + \langle A_2B_1\rangle + \langle A_2B_2\rangle| \le 2$$

- At colliders, we don't compare hidden variable vs. QM
- Instead, we compare Bell-local QM with Bell-non-local QM
- At a future collider, we can imagine detectors with different capabilities
  - Partially polarized calorimeters?
  - Stern-Gerlach extensions?

Han, ML, Wu [2310.17696](2310.17696)

Abel, Dittmar, Dreiner 1992

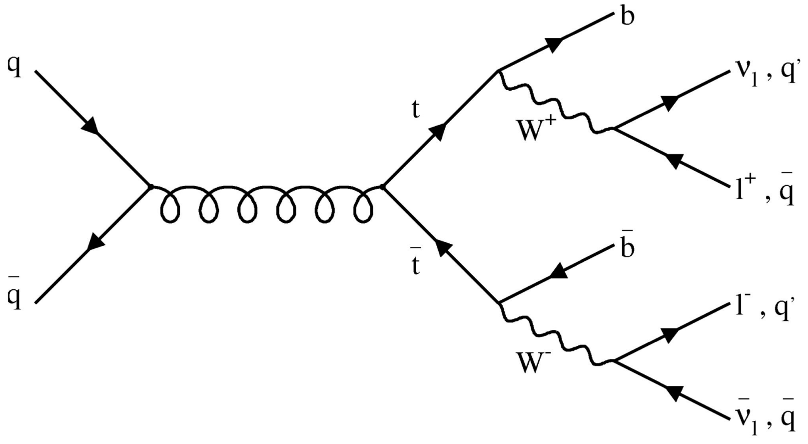


We now suggest a modification of the ppCC experiment which might be a test of Bell's inequality. Through a conceptually simple change the ppCC experiment can be improved. Suppose one replaces the carbon-12 analyzers by polarized hydrogen ($^1\vec{\mathrm{H}}$) targets and instead of measuring the scattering distribution, measure the total scattering cross-section or transmission rate. These targets then act as spin-filters, preferentially passing protons, whose spin are aligned with the target polarization direction [#5]. Then

Future Colliders

- Top pair production
    - The top is a qubit and the anti-top

(See talk by Dorival Gonçalves)



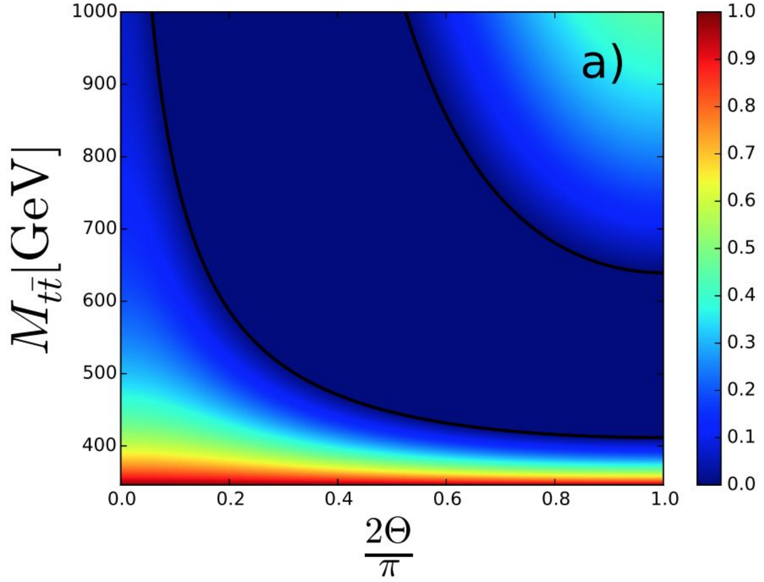
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_v} = \frac{1}{2}\left(1+|\vec{B}|\kappa_v\cos\theta_v\right)$$

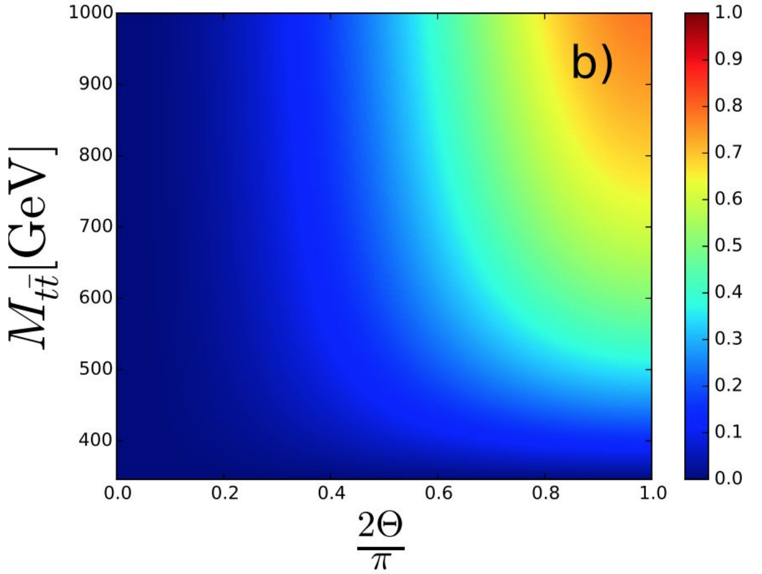
Spin analyzing power

- For the leptonic decay (bbℓvℓv), the lepton spin analyzing power is 1.0
- For the semi-leptonic decay (bbℓvqq), the hadronic spin analyzing power is 0.6

Future Colliders

- Top pair production
  - The top is a qubit and the anti-top
  - Density matrix is a mixed state of qq-initiated and gg-initiated



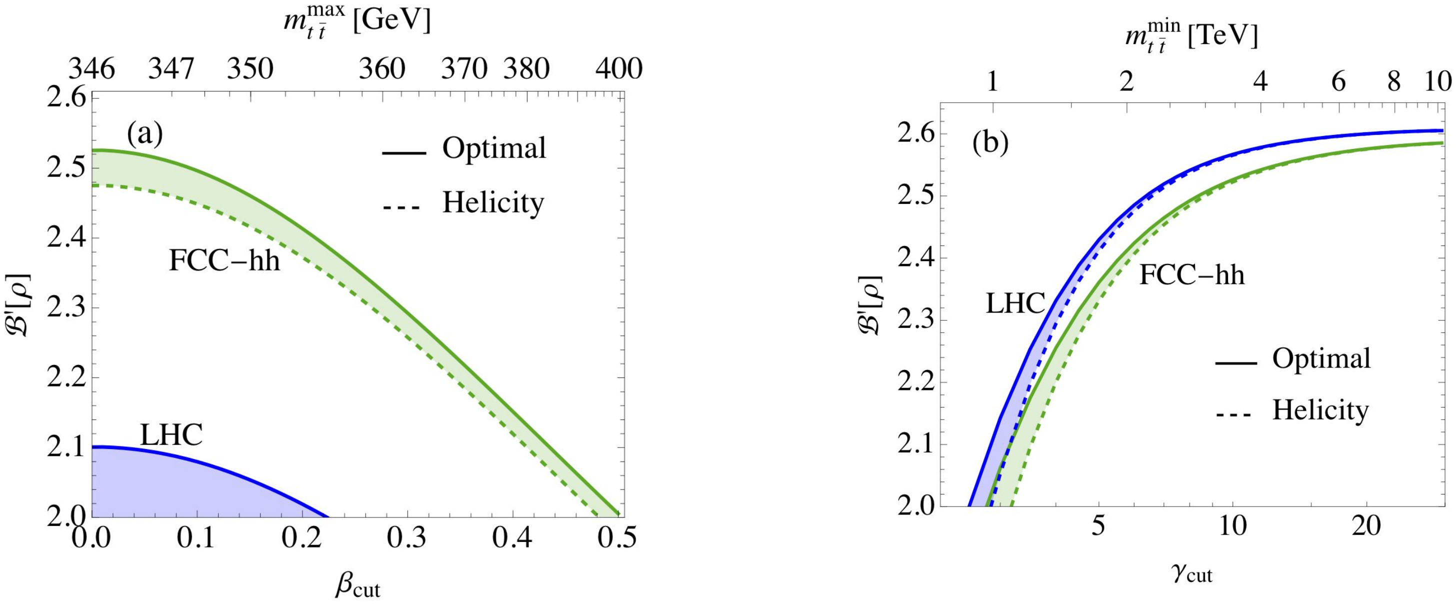


Afik, de Nova 2003.02280

Future Colliders

- Top pair production
  - FCC-hh (100 TeV) has a different gg/qq fraction
  - Increases signal at threshold
  - Decreases signal at high-p_T

(B > 2 violates Bell inequality)



Future Colliders

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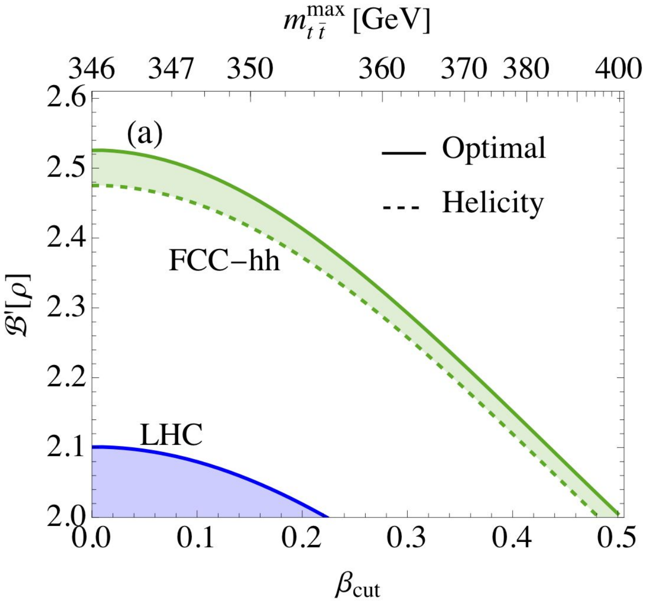
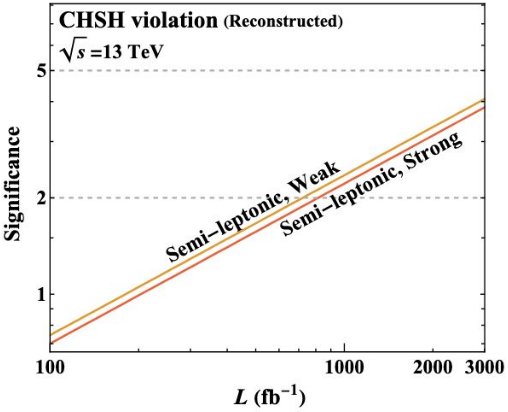


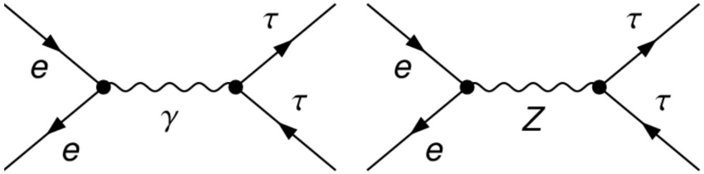
Prediction at HL-LHC



Future Colliders

Fabbrichesi, Marzola 2405.09201

- Tau pair production
    - FCC-ee would be sensitive to tau pair production



    - Electroweak production leads to non-zero polarization

$$C = \begin{pmatrix} 0.4878 & 0 & 0 \\ 0 & -0.4878 & 0.0011 \\ 0 & 0.0011 & 1 \end{pmatrix} \qquad B^{+} = B^{-} = \begin{pmatrix} 0 \\ 0.0001 \\ 0.2194 \end{pmatrix}$$

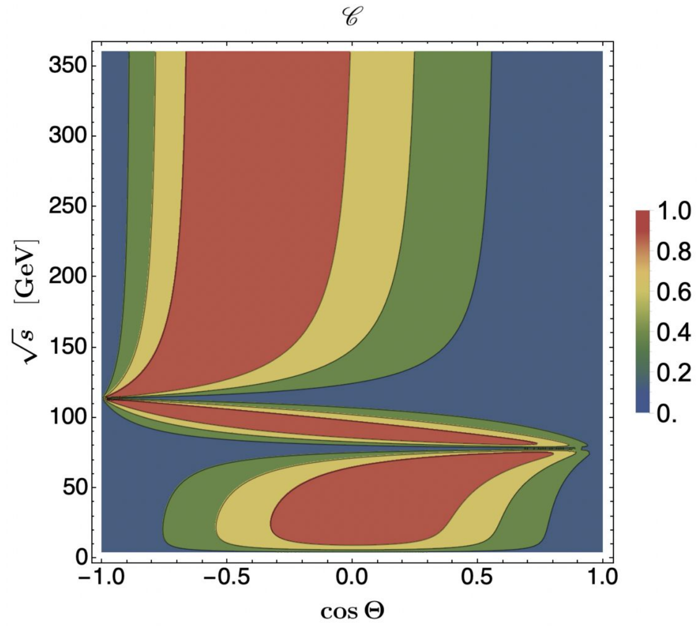
    - Ideal decay is τ -> π ν

Decay Product(τ^-)	**Branch(%)**	**Spin Analyzing Power**
$\nu_\tau \pi^-$	10.82 ± 0.05	1.000 ± 0.005
$\nu_\tau \pi^- \pi^+ \pi^-$	9.31 ± 0.05	$-0.148 \pm 0.006(\pi^+)$ $-0.038 \pm 0.005(\pi^-)$
$\nu_\tau \mu^- \bar{\nu}_\mu$	17.39 ± 0.04	-0.341 ± 0.005
$\nu_\tau e^- \bar{\nu}_e$	17.82 ± 0.04	-0.336 ± 0.005

Future Colliders

Fabbrichesi, Marzola [2405.09201](https://arxiv.org/abs/2405.09201)

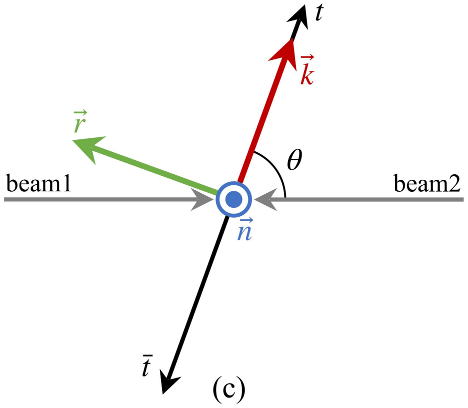
- Tau pair production
  - The entanglement as a function of scattering angle and collision energy

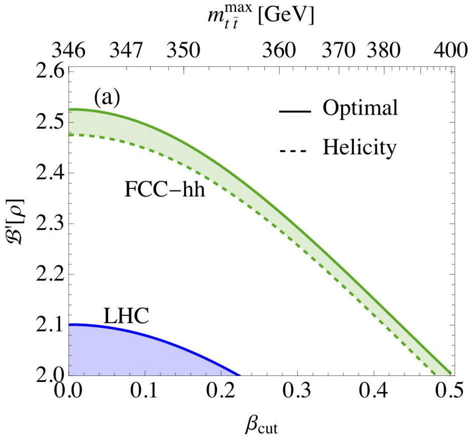


- Entangled (>0)
- Separable (=0)

  - Statistical significance >> 5σ for entanglement and for Bell inequality violation

Summary





Low vs. High Energy → Bell Tests → Future Colliders