Parity and Environmental Effects on Quantum Entanglement and Bell Tests

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Workshop on Quantum Entanglement at the Energy Frontier
PKU, Apr 26, 2025

Based on

2409.15418, with Xiao-Gang He, Chia-Wei Liu, Jian-Ping Ma

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Introduction

nature > nature physics > editorials > article

Editorial | Published: 08 September 2022

Survey the foundations

Nature Physics **18**, 961 (2022) | Cite this article

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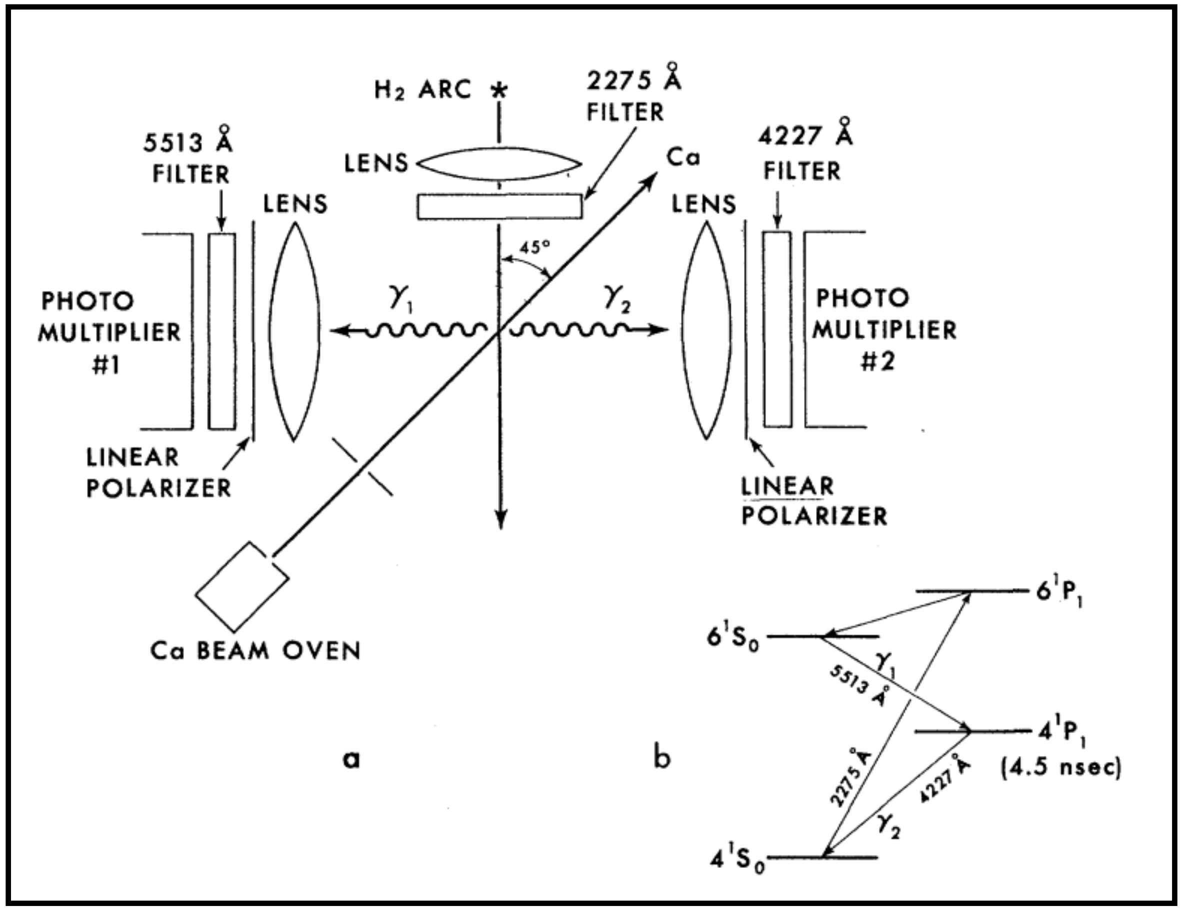
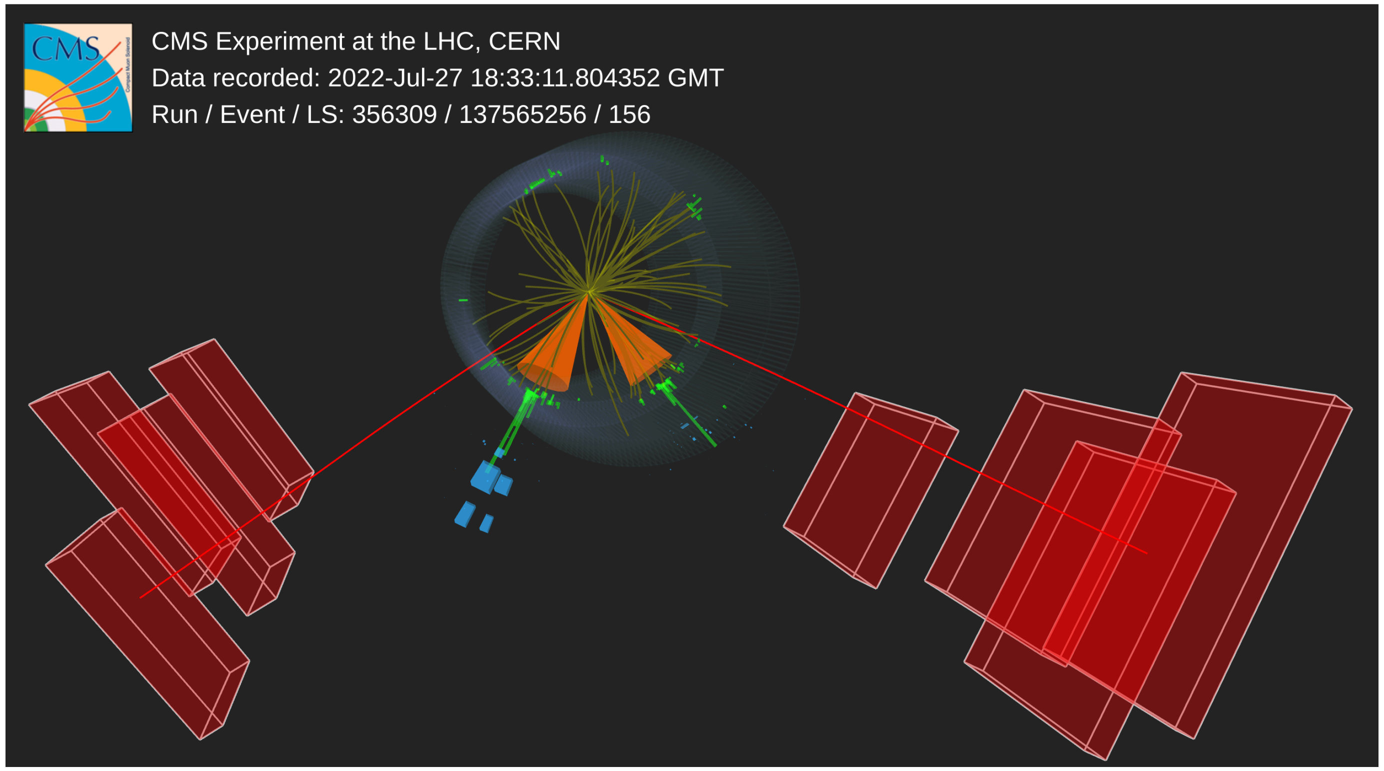
Qubits: low- *vs* high-energy production examples

Cascade photons



Kocher & Commins, PRL, 1967

$t\bar{t}$ at the LHC



CMS-PHO-EVENTS-2022-033

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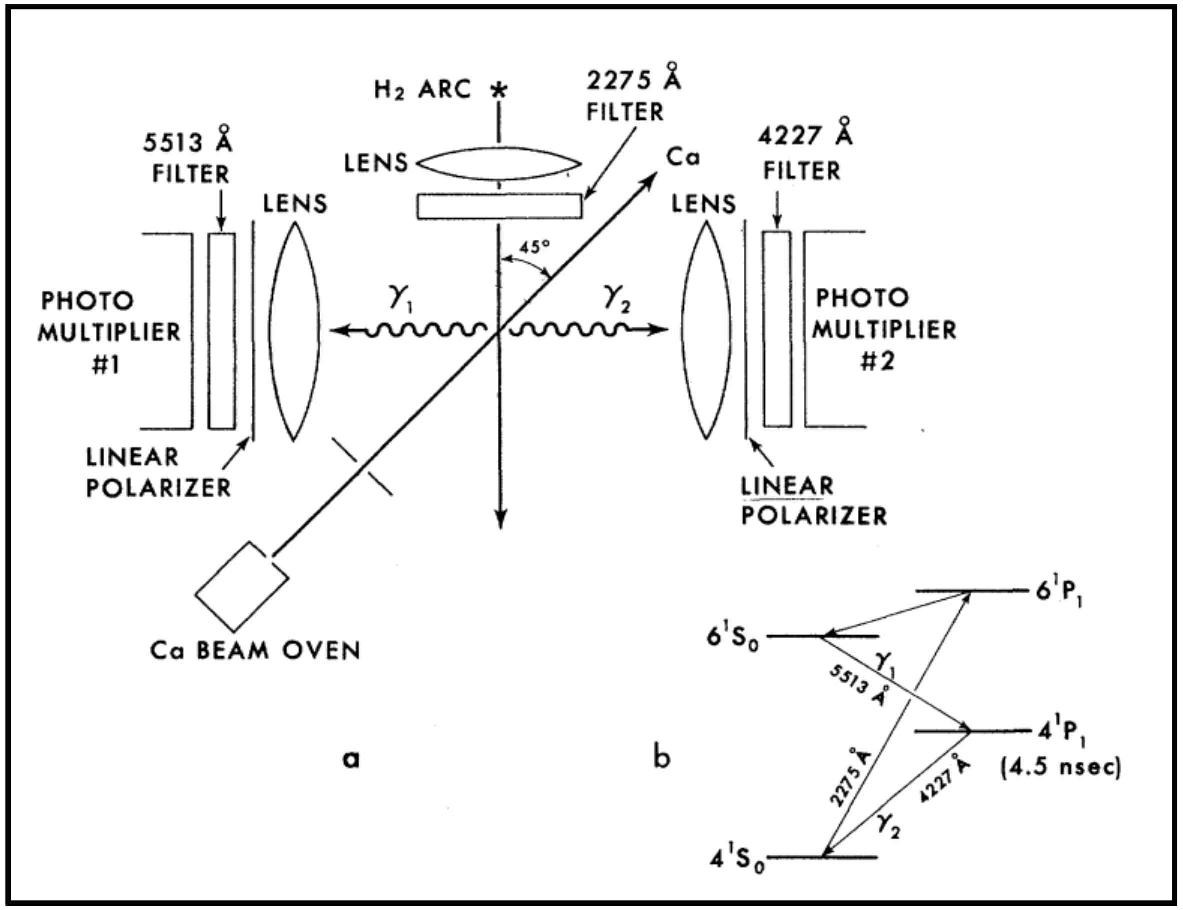

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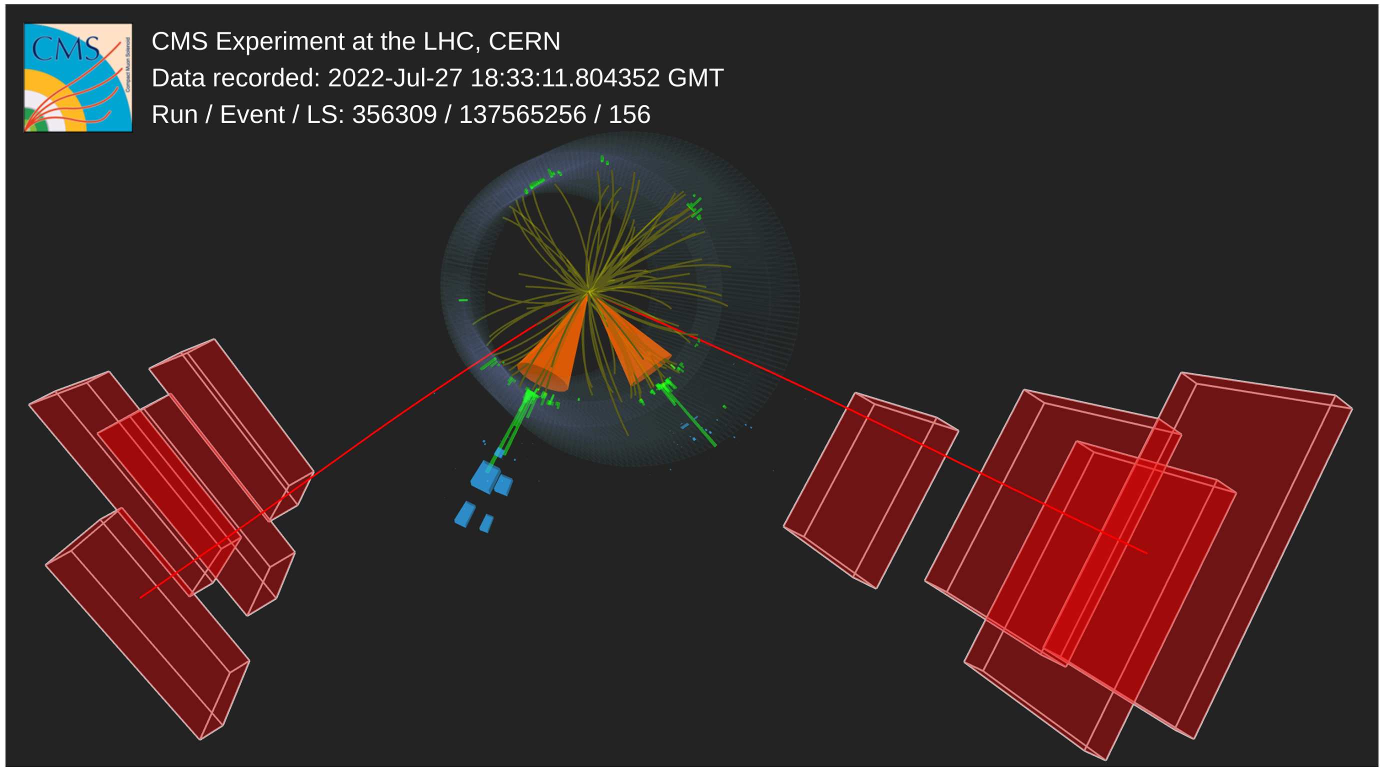


CMS-PHO-EVENTS-2022-033

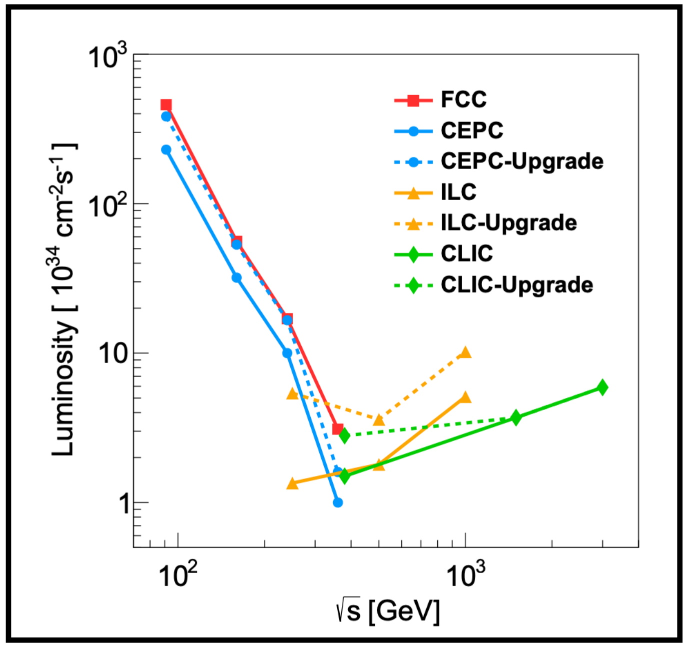
The challenges lie in performing a loophole free test, and now there are well-established methods for that. *Luminosity will probably be the key ingredient as we'll see later.*

Introduction

The high-luminosity of BESIII/STCF/SuperKEKB/CEPC/FCC-ee makes it ideal for this kind of studies

STCF CDR, 2303.15790

CME (GeV)	Lumi (ab^{-1})	Samples	σ(nb)	No. of Events	Remarks
3.097	1	J/ψ	3400	3.4×10^{12}	
3.670	1	$\tau^+\tau^-$	2.4	2.4×10^{9}	
3.686	1	$\psi(3686)$	640	6.4×10^{11}	
		$\tau^+\tau^-$	2.5	2.5×10^{9}	
		$\psi(3686)\to\tau^+\tau^-$		2.0×10^{9}	
3.770	1	$D^0\bar{D}^0$	3.6	3.6×10^{9}	
		$D^+\bar{D}^-$	2.8	2.8×10^{9}	
		$D^0\bar{D}^0$		7.9×10^{8}	Single tag
		$D^+\bar{D}^-$		5.5×10^{8}	Single tag
		$\tau^+\tau^-$	2.9	2.9×10^{9}	
4.009	1	$D^{*0}\bar{D}^0+c.c$	4.0	1.4×10^{9}	$CP_{D^0\bar{D}^0}=+$
		$D^{*0}\bar{D}^0+c.c$	4.0	2.6×10^{9}	$CP_{D^0\bar{D}^0}=-$
		$D_s^+D_s^-$	0.20	2.0×10^{8}	
		$\tau^+\tau^-$	3.5	3.5×10^{9}	
4.180	1	$D_s^{+*}D_s^-$+c.c.	0.90	9.0×10^{8}	
		$D_s^{+*}D_s^-$+c.c.		1.3×10^{8}	Single tag
		$\tau^+\tau^-$	3.6	3.6×10^{9}	
4.230	1	$J/\psi\pi^+\pi^-$	0.085	8.5×10^{7}	
		$\tau^+\tau^-$	3.6	3.6×10^{9}	
		$\gamma X(3872)$			
4.360	1	$\psi(3686)\pi^+\pi^-$	0.058	5.8×10^{7}	
		$\tau^+\tau^-$	3.5	3.5×10^{9}	
4.420	1	$\psi(3686)\pi^+\pi^-$	0.040	4.0×10^{7}	
		$\tau^+\tau^-$	3.5	3.5×10^{9}	
4.630	1	$\psi(3686)\pi^+\pi^-$	0.033	3.3×10^{7}	
		$\Lambda_c\bar{\Lambda}_c$	0.56	5.6×10^{8}	
		$\Lambda_c\bar{\Lambda}_c$		6.4×10^{7}	Single tag
		$\tau^+\tau^-$	3.4	3.4×10^{9}	
4.0–7.0	3	300-point scan with 10 MeV steps, 1 fb^{-1}/point			
> 5	2–7	Several ab^{-1} of high-energy data, details dependent on scan results			



CEPC Snowmass 2021, 2205.08553

So we are good!

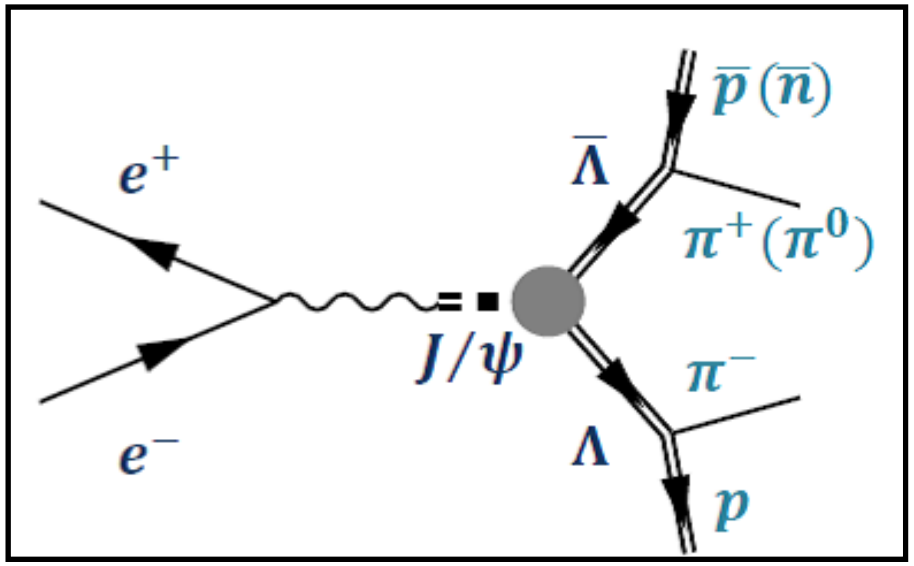
Formalism and Exp Extraction

Formalism and Exp Extraction

The entangled spin-half bipartite system can be properly described by the spin-density matrix expanded in the $\mathrm{SU}(2) \otimes \mathrm{SU}(2)$ Hilbert space:

$$\rho = \frac{1}{4}\left(\boldsymbol{I}_4 + \sum_i B_i^+ s^i \otimes \boldsymbol{I}_2 + \sum_j B_j^- \boldsymbol{I}_2 \otimes s^j + \sum_{i,j} C_{ij} s^i \otimes s^j\right)$$

Polarization of the subsystem



$$\frac{d\Gamma_\Lambda}{d\Omega_p}\left(\vec{s}_1, \hat{l}_p\right) \propto 1 + \alpha \vec{s}_1 \cdot \hat{l}_p$$

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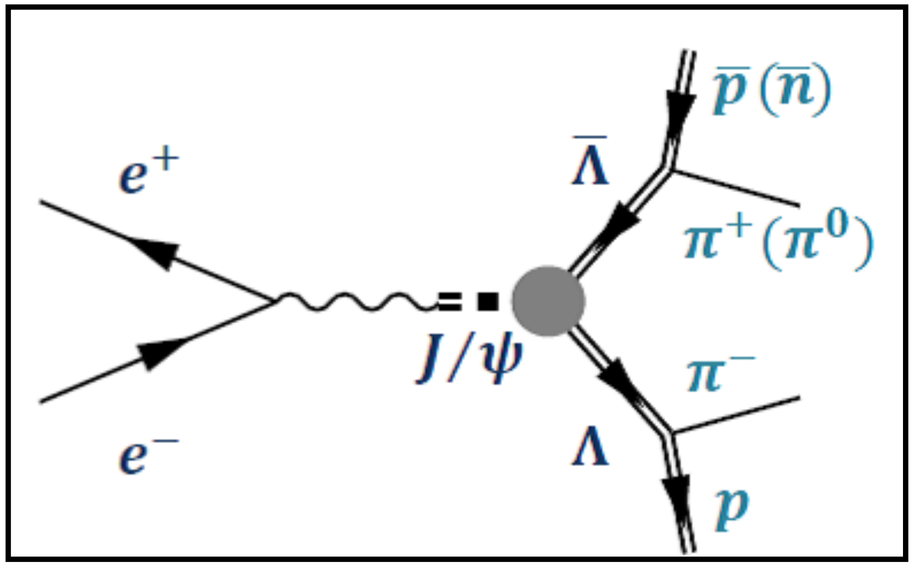

Spin correlation

$$\frac{d\sigma}{d\Omega_k d\Omega_p d\Omega_{\bar{p}}} \propto \mathrm{Tr}\left[\rho\left(1 + \alpha s_1 \cdot \hat{\boldsymbol{l}}_p\right)\left(1 - \bar{\alpha} s_2 \cdot \hat{\boldsymbol{l}}_{\hat{p}}\right)\right]$$

Equally applies to LHC, Belle II, CEPC, FCC-ee ($e^+e^-/pp \to \tau^+\tau^-/t\bar{t}$ for instance)!

QT = Entanglement = Bell Nonlocality?

The underlying assumption is that the fermion pair is entangled, which is not guaranteed to be present!

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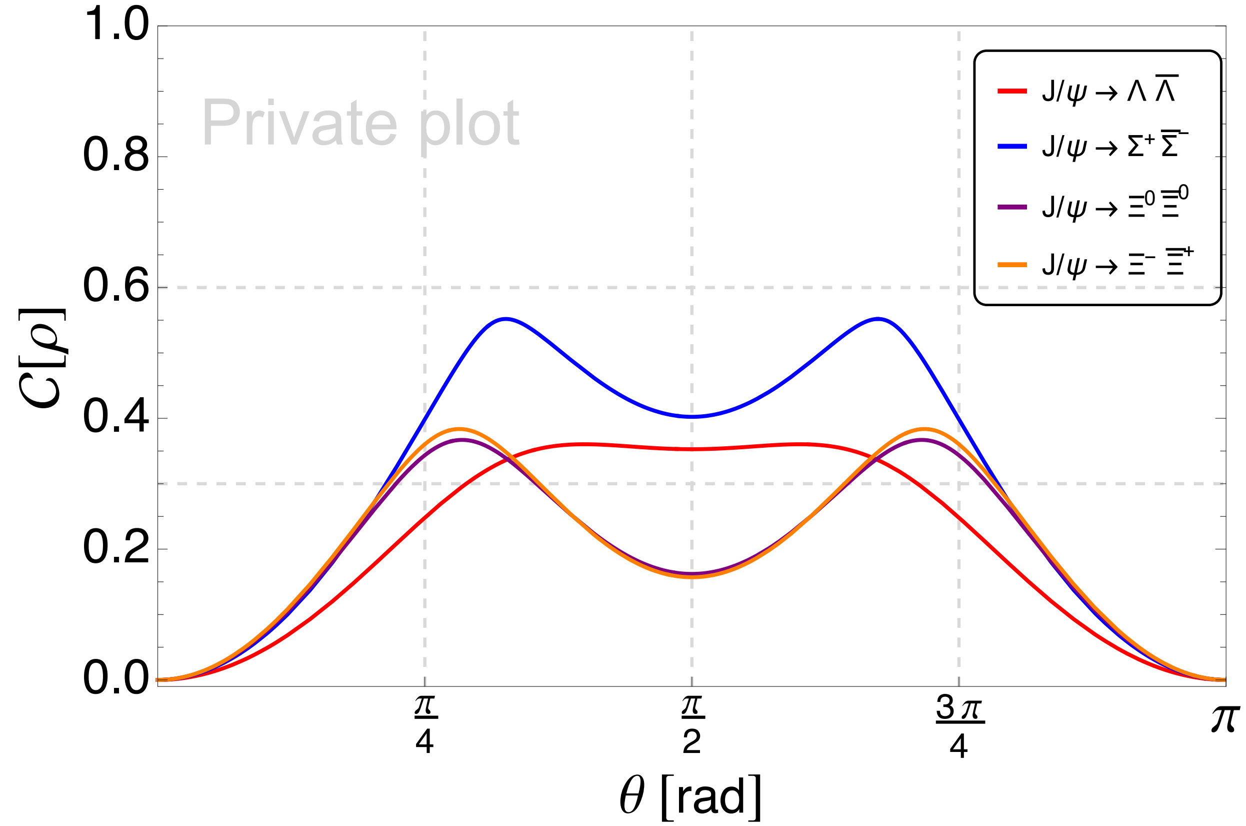
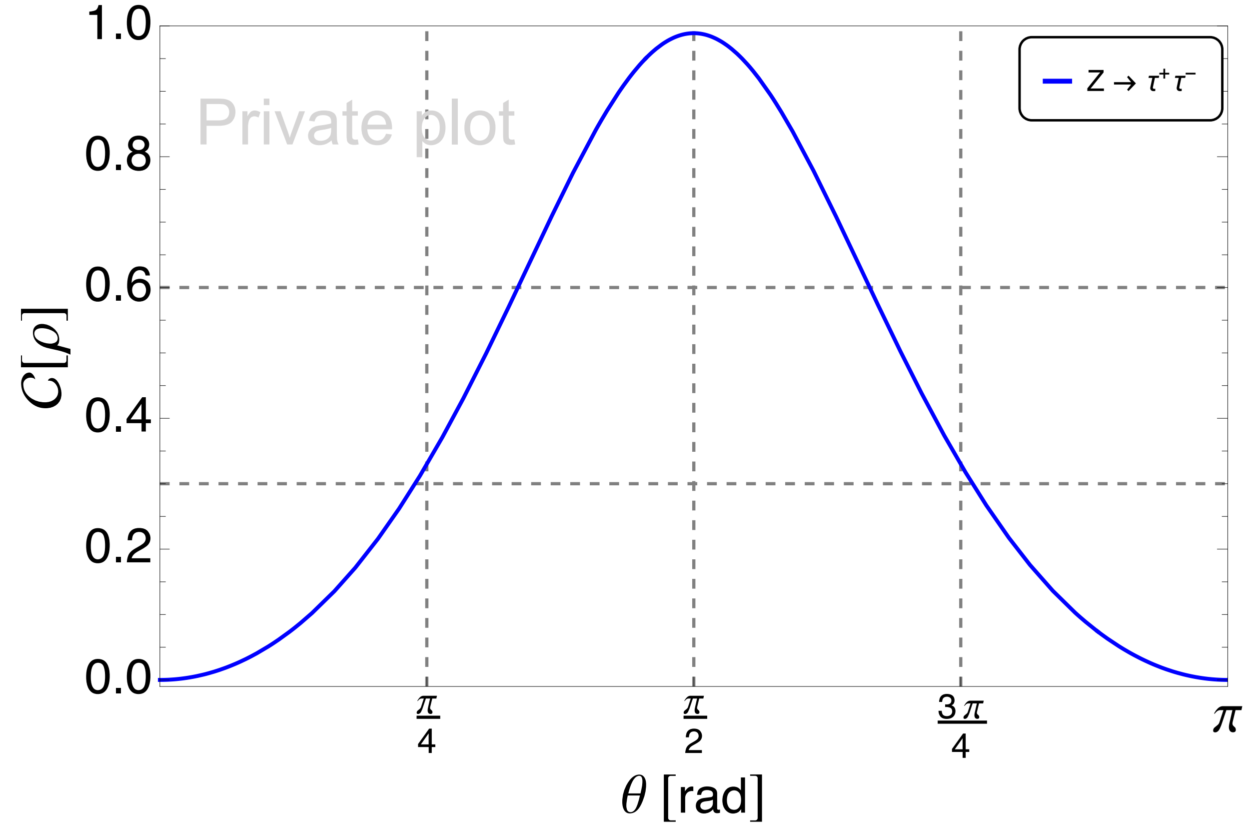
Concurrence quantifies the entanglement of the fermion pair

$$C(\rho) = \max[0, 2\,\lambda_{\max} - \mathrm{Tr}\,R] \qquad R = \sqrt{\sqrt{\rho}(\sigma_y \otimes \sigma_y)\rho^*(\sigma_y \otimes \sigma_y)\sqrt{\rho}}$$





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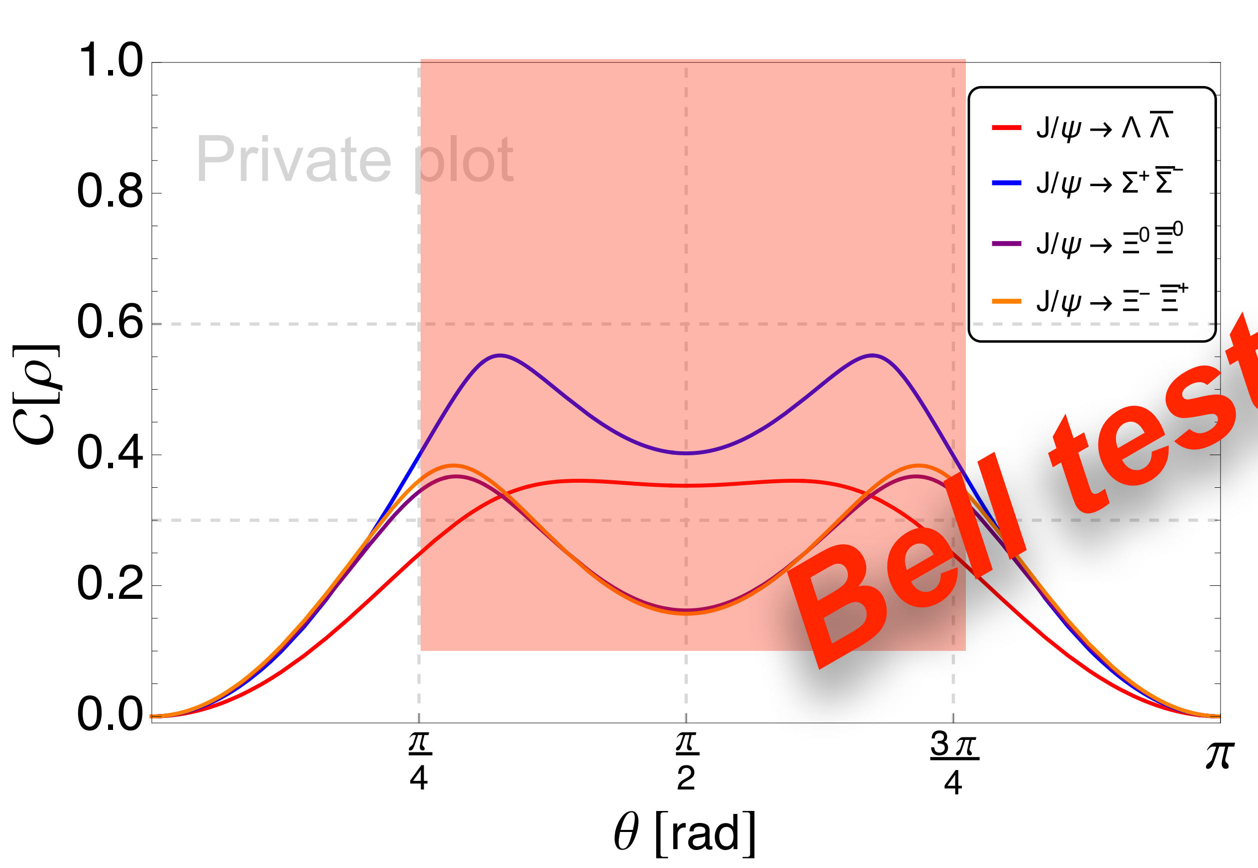

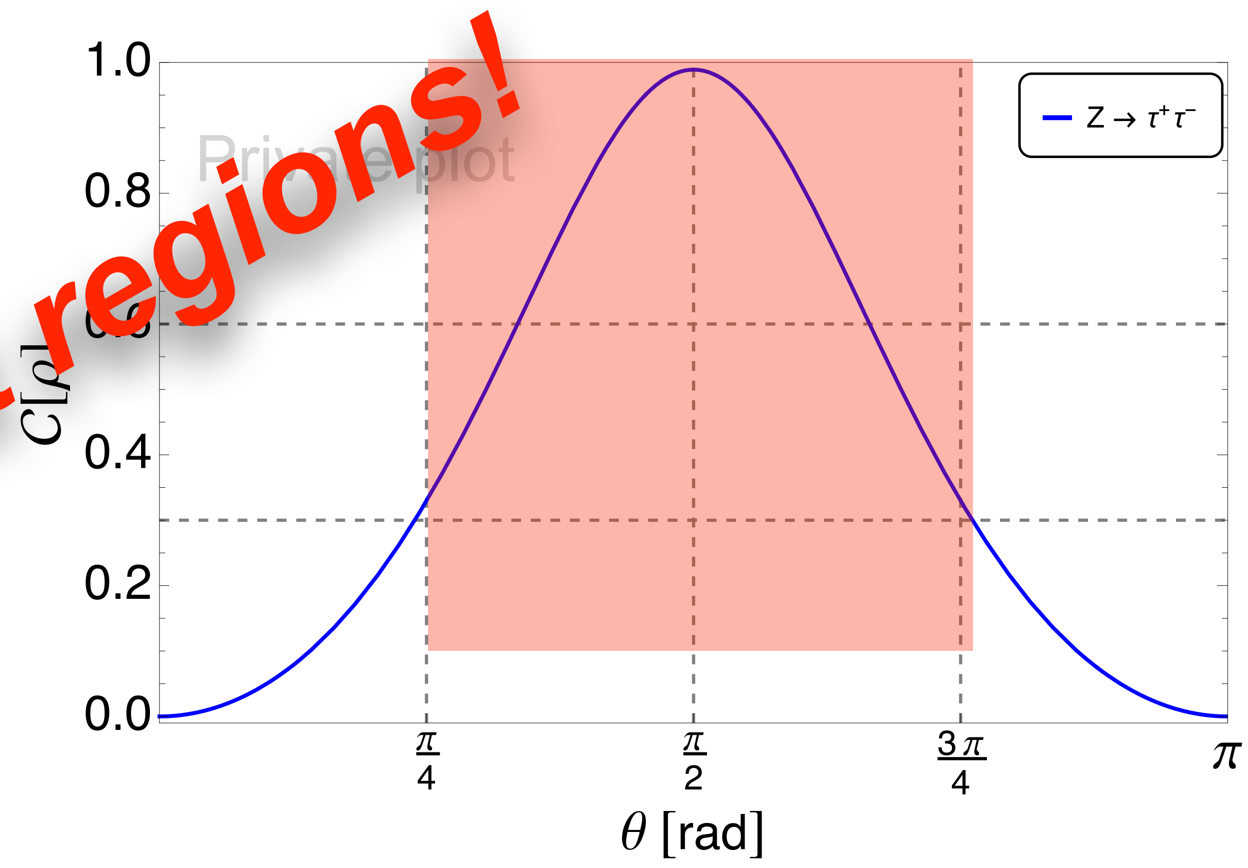

QT = Entanglement = Bell Nonlocality?

The original Bell inequality requires simultaneously adjusting two directions with a spacelike separation randomly, thus practically very challenging.

The CHSH inequality instead avoids this simultaneity:

$$\mathscr{B}(\rho) = 2\sqrt{\mu_1 + \mu_2} \leq 2\sqrt{2}$$

$\mu_{1,2}$ the largest two eigenvalues of $C^T C$

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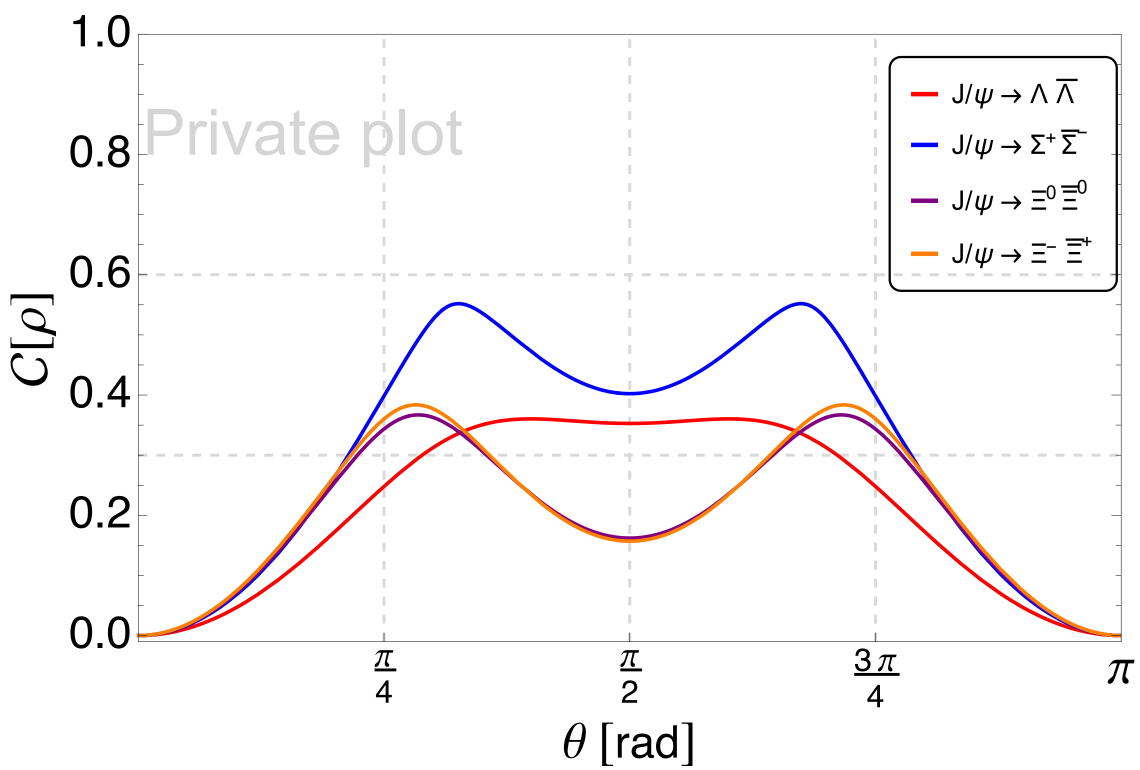

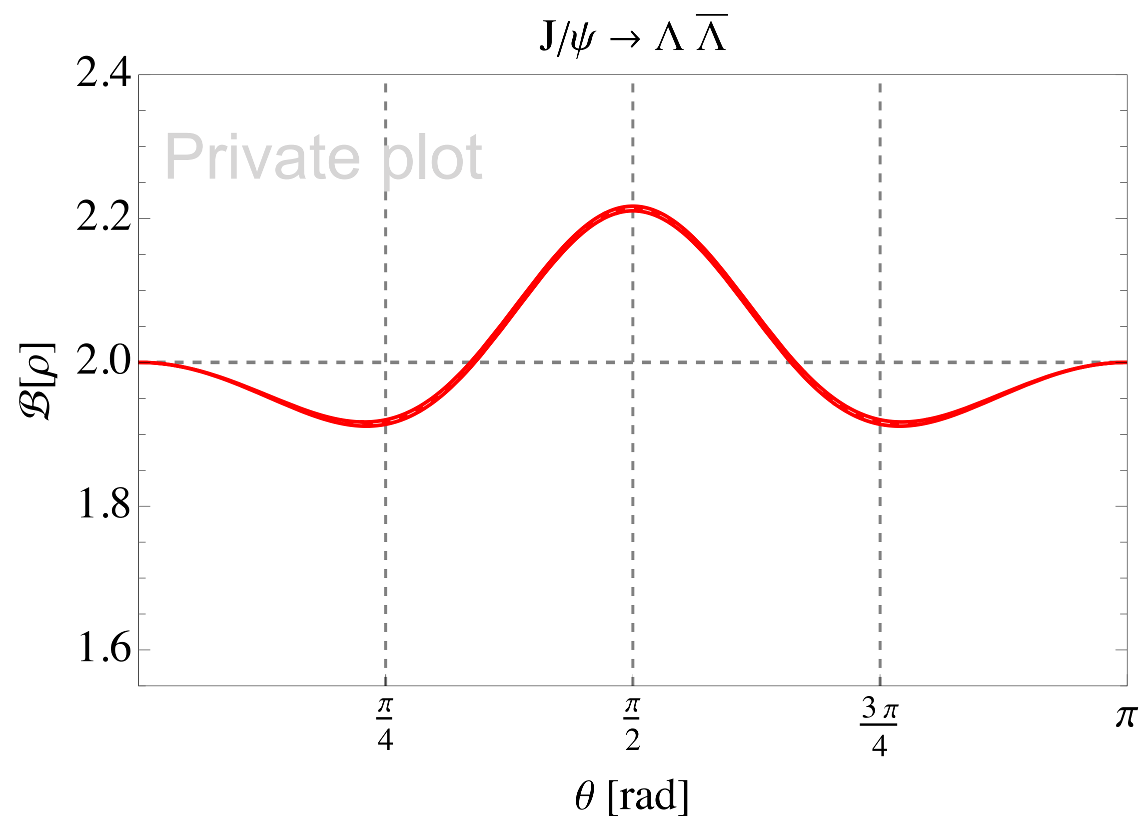

See also Wu et al, 2406.16298

Quantum entanglement $\supset$ Bell inequality violation

Parity on Bell Tests

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Current studies on Bell tests focused on parity-conserving interactions: QED conserves it, $\Lambda_{\rm QCD}^2 G_F$ suppression for octet baryons from J/ψ decay. *But not generically true!*

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Q1: Isolating P V, impact on Bell tests?

Q2: What are our targets?

Parity on Bell Tests

The simplest case is the spin-1/2 bipartite system resulting from spin-0 and spin-1 particle decays

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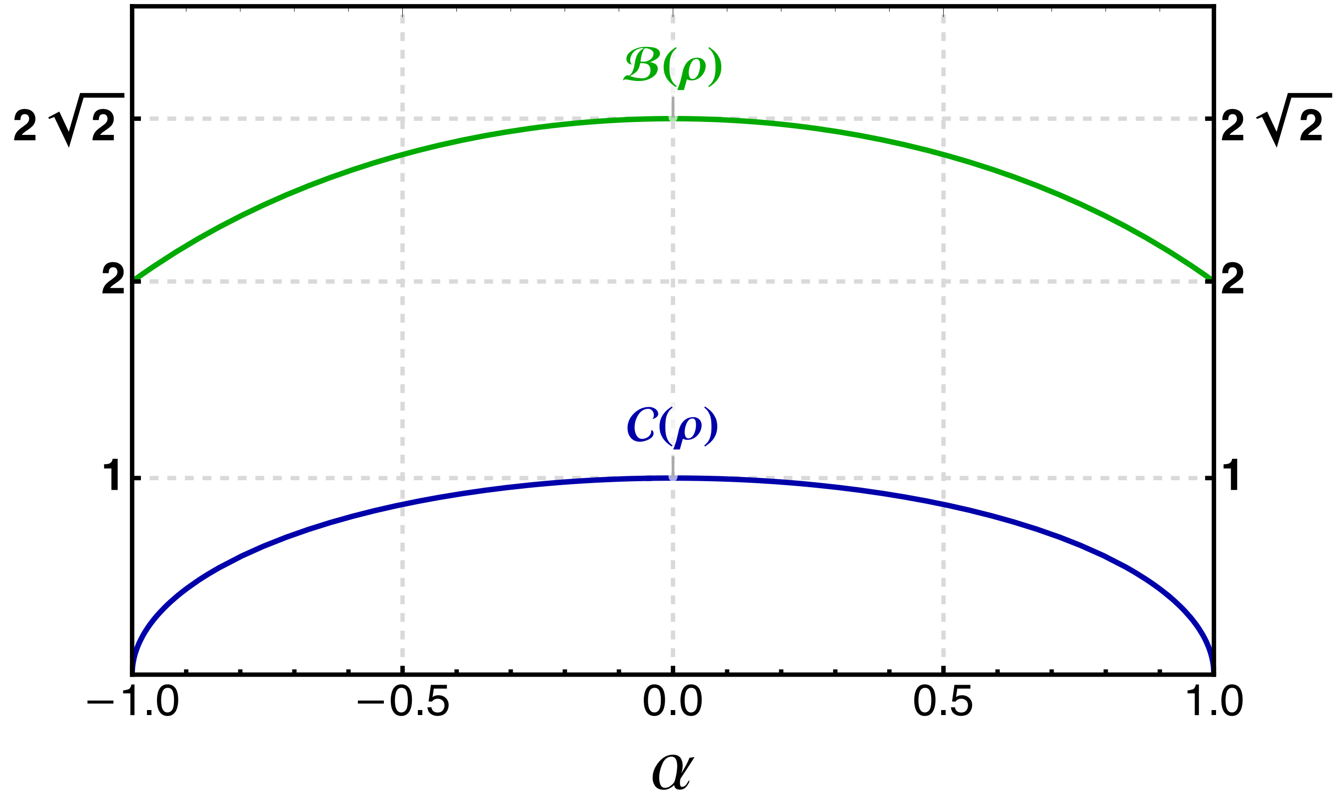
The silly simple *spin-0 case* ($h \to f_1 \bar{f}_2$ *or* crossed channels): $\mathscr{L} = h \bar{f}_1 \left(g_S - g_P \gamma_5 \right) f_2$

$$|\Psi\rangle = \frac{S+P}{\sqrt{2(|S|^2+|P|^2)}} |\uparrow\downarrow\rangle + \frac{S-P}{\sqrt{2(|S|^2+|P|^2)}} |\downarrow\uparrow\rangle$$



$$\alpha = \frac{2\mathrm{Re}(S^* P)}{|S|^2 + |P|^2}$$

$$S = \sqrt{m_i^2 - (m_1 + m_2)^2} g_S$$

$$P = \sqrt{m_i^2 - (m_1 - m_2)^2} g_P$$

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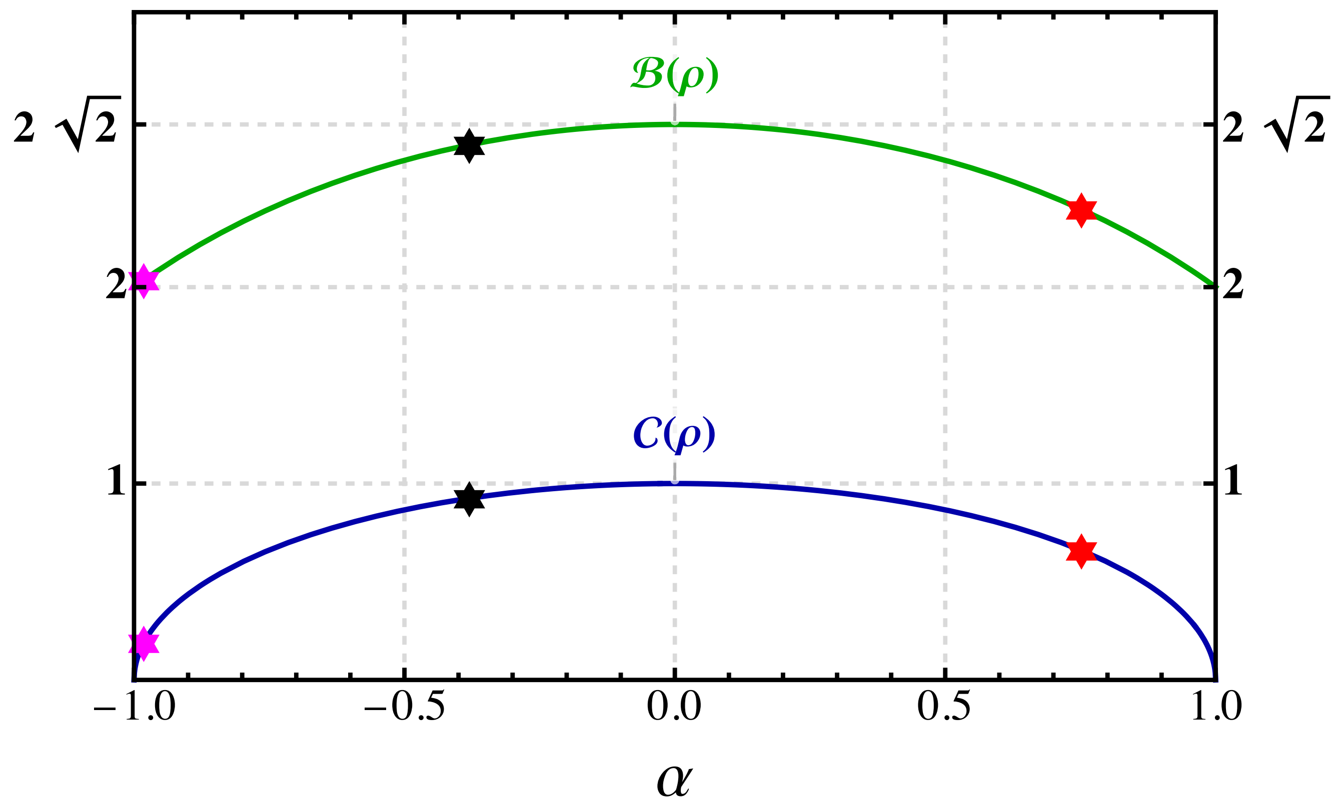

$\alpha_\Lambda = 0.7519 \pm 0.0043$

BESIII, 2204.11058

$\alpha_{\Xi^0} = -0.3750 \pm 0.0038$

BESIII, 2305.09218

$\alpha_{\Xi^-} = -0.376 \pm 0.008$

BESIII, 2105.11155

$\alpha_{\Sigma^+} = -0.982 \pm 0.14$

PDG 2022

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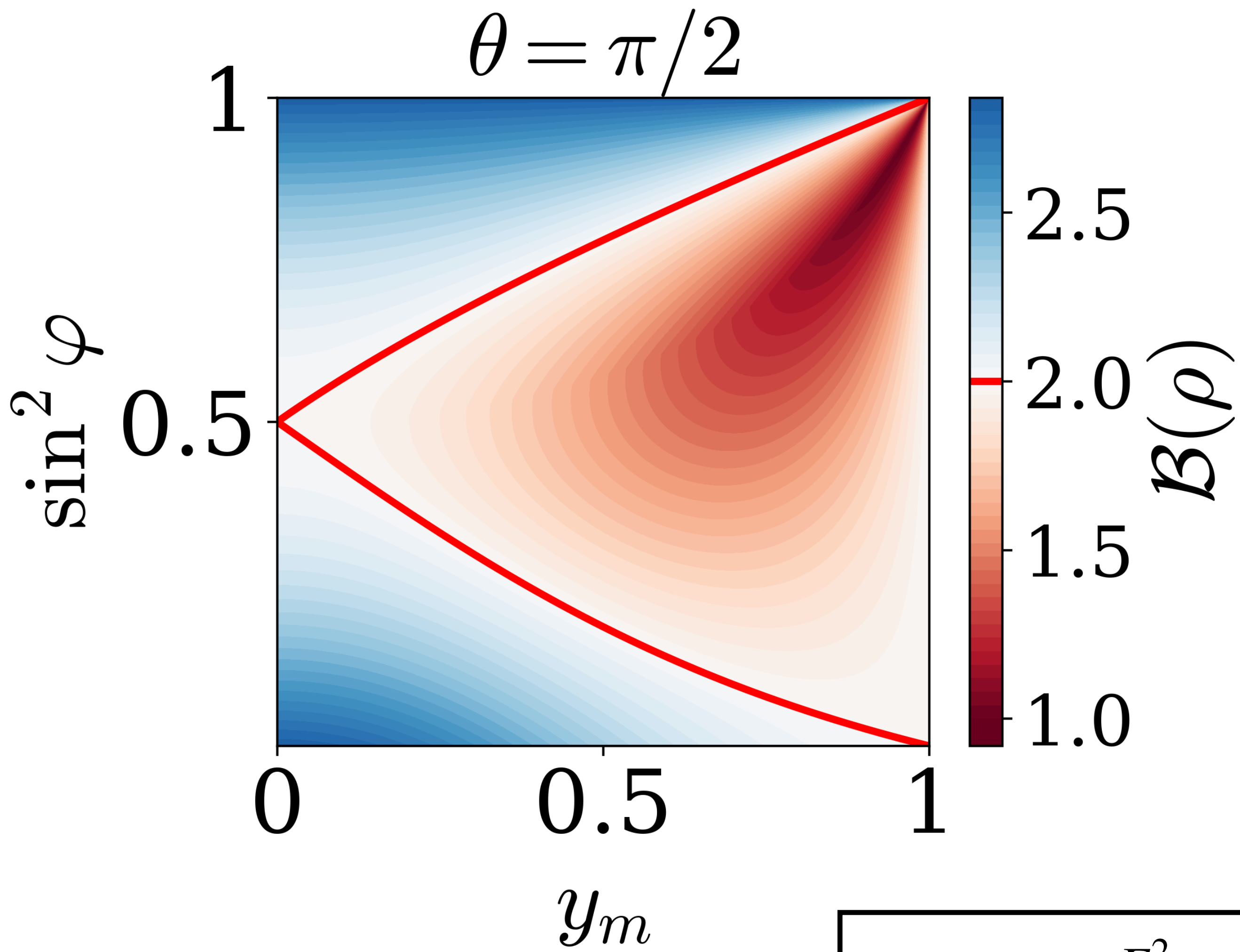

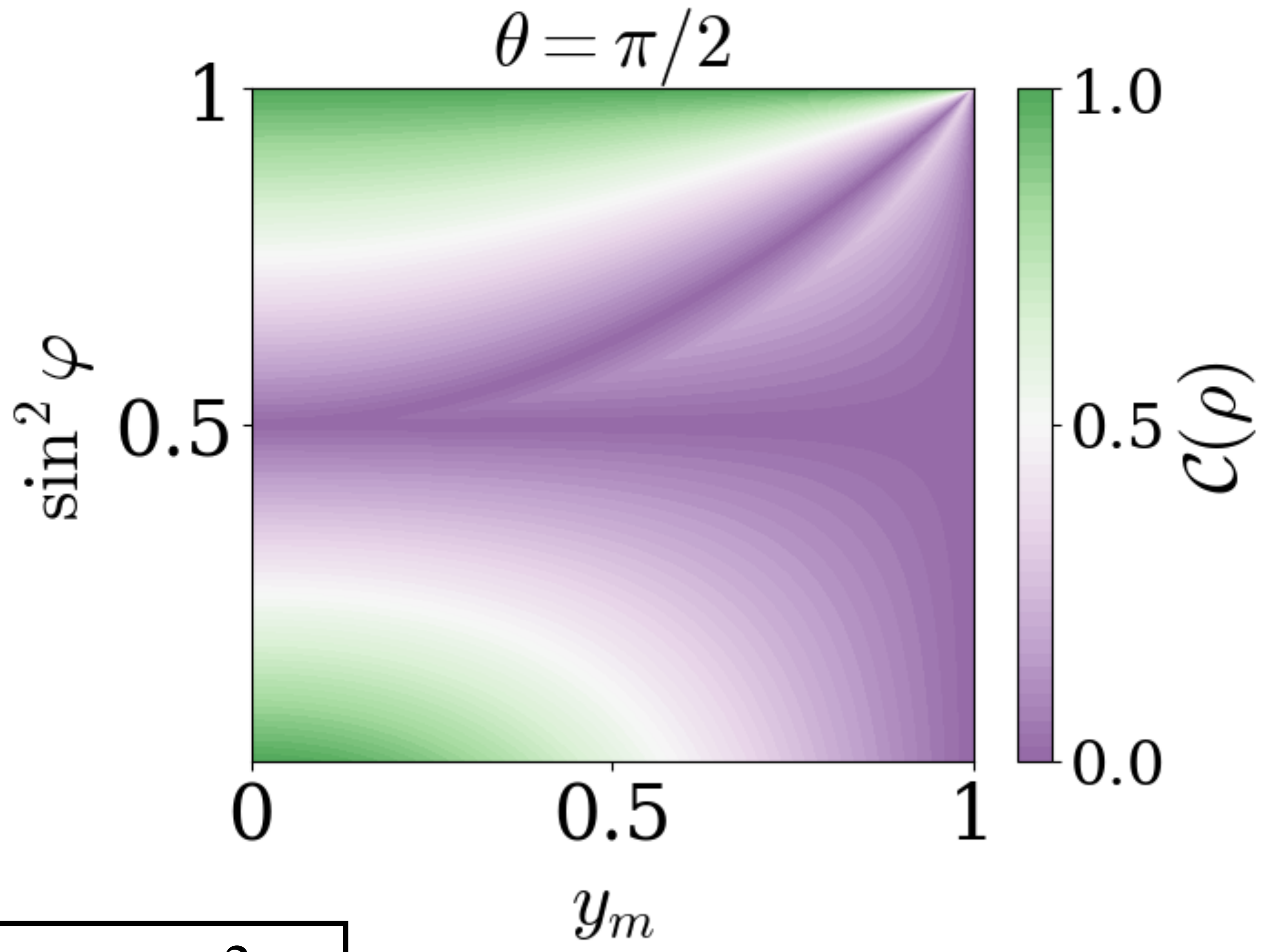

$$\sin^2\varphi = \frac{F_A^2}{F_A^2 + F_V^2} \qquad y_m = \frac{2m_f}{m_V}$$

YD, He, Liu, Ma, 2409.15418

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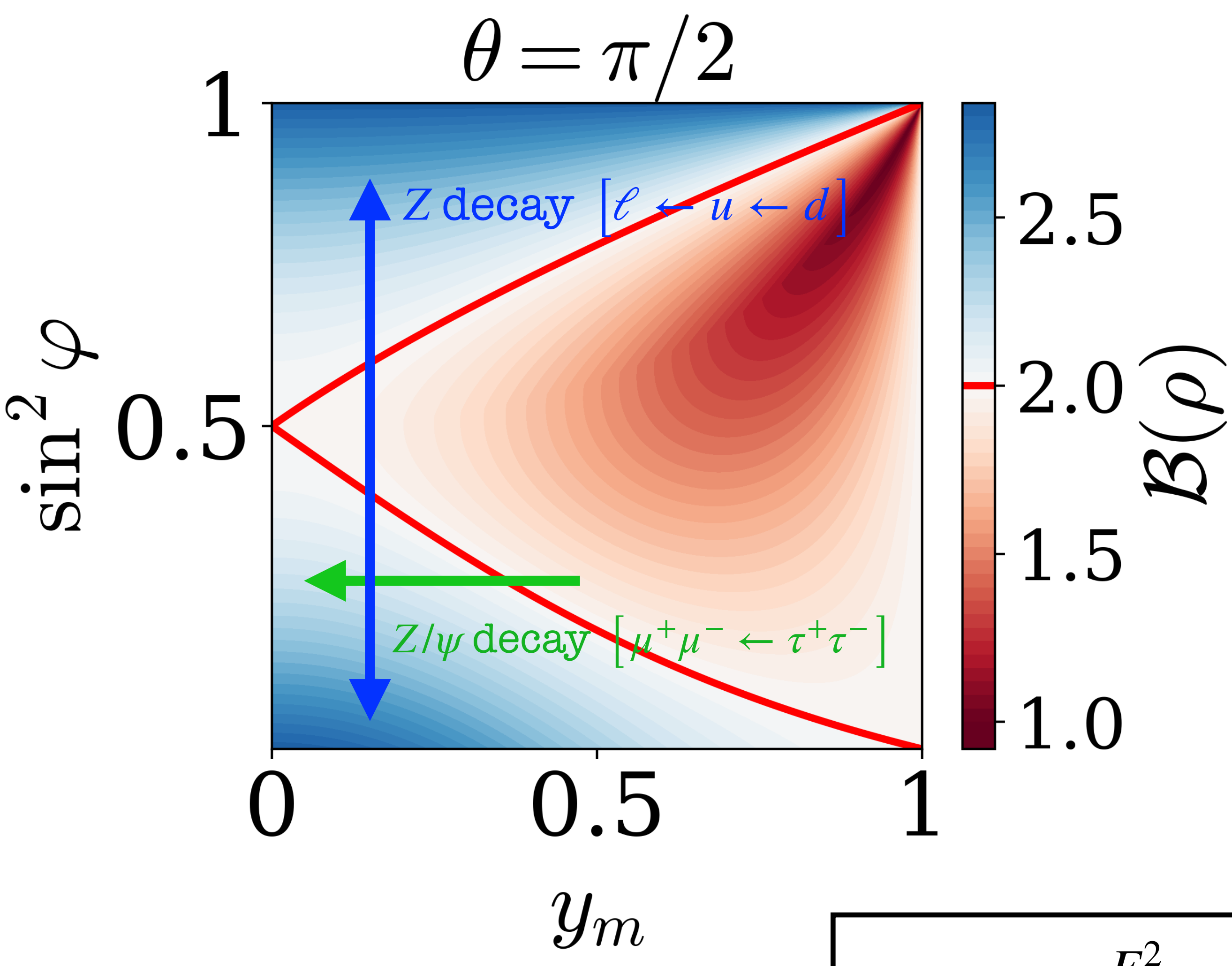

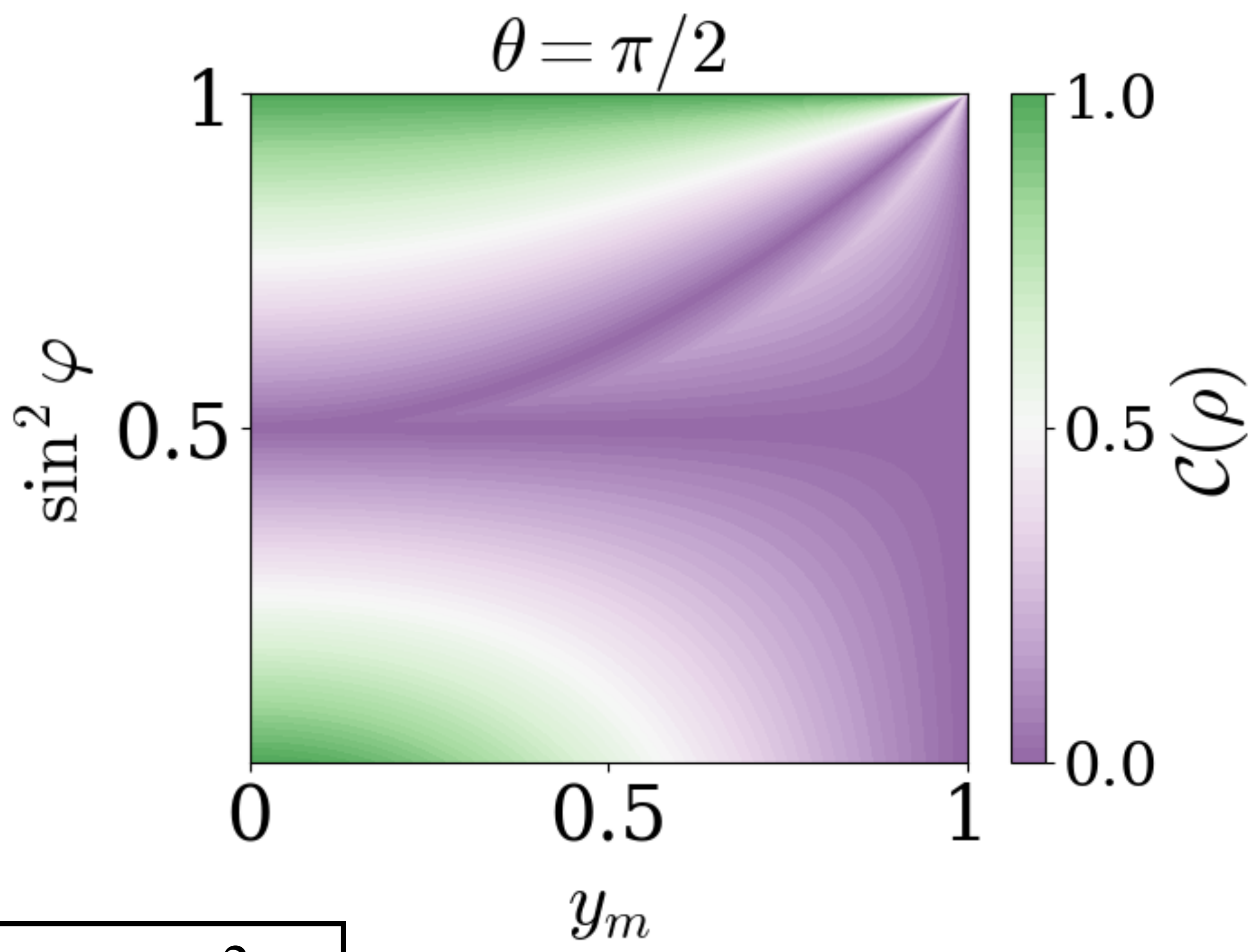

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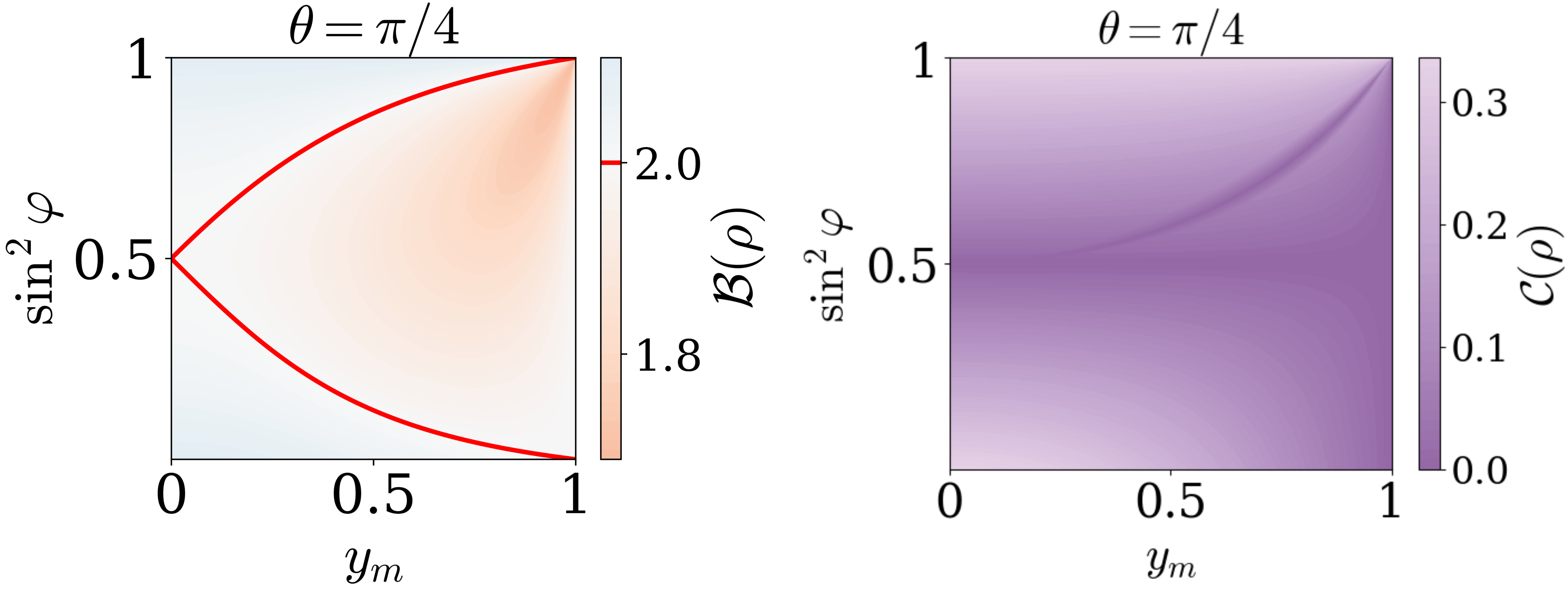

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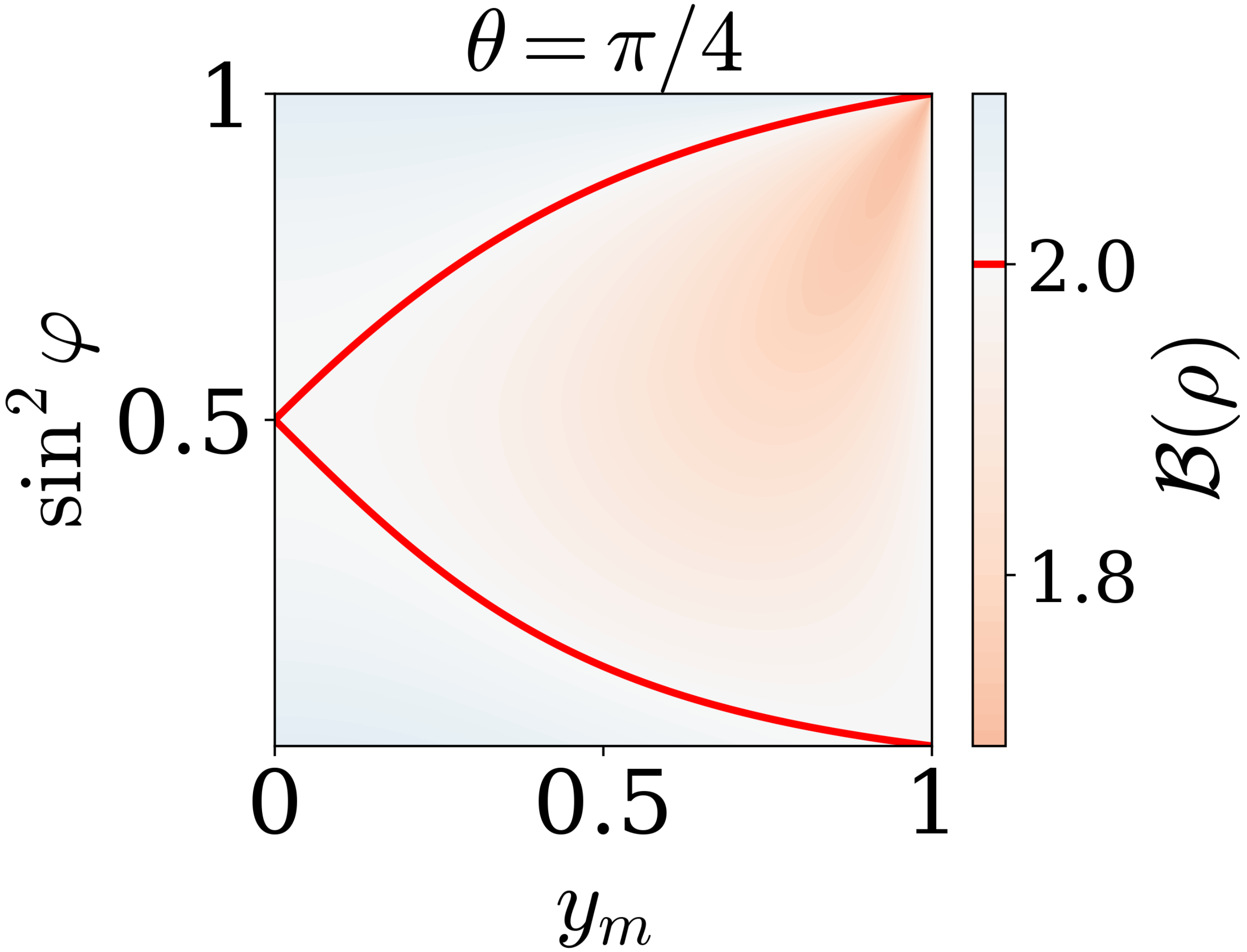

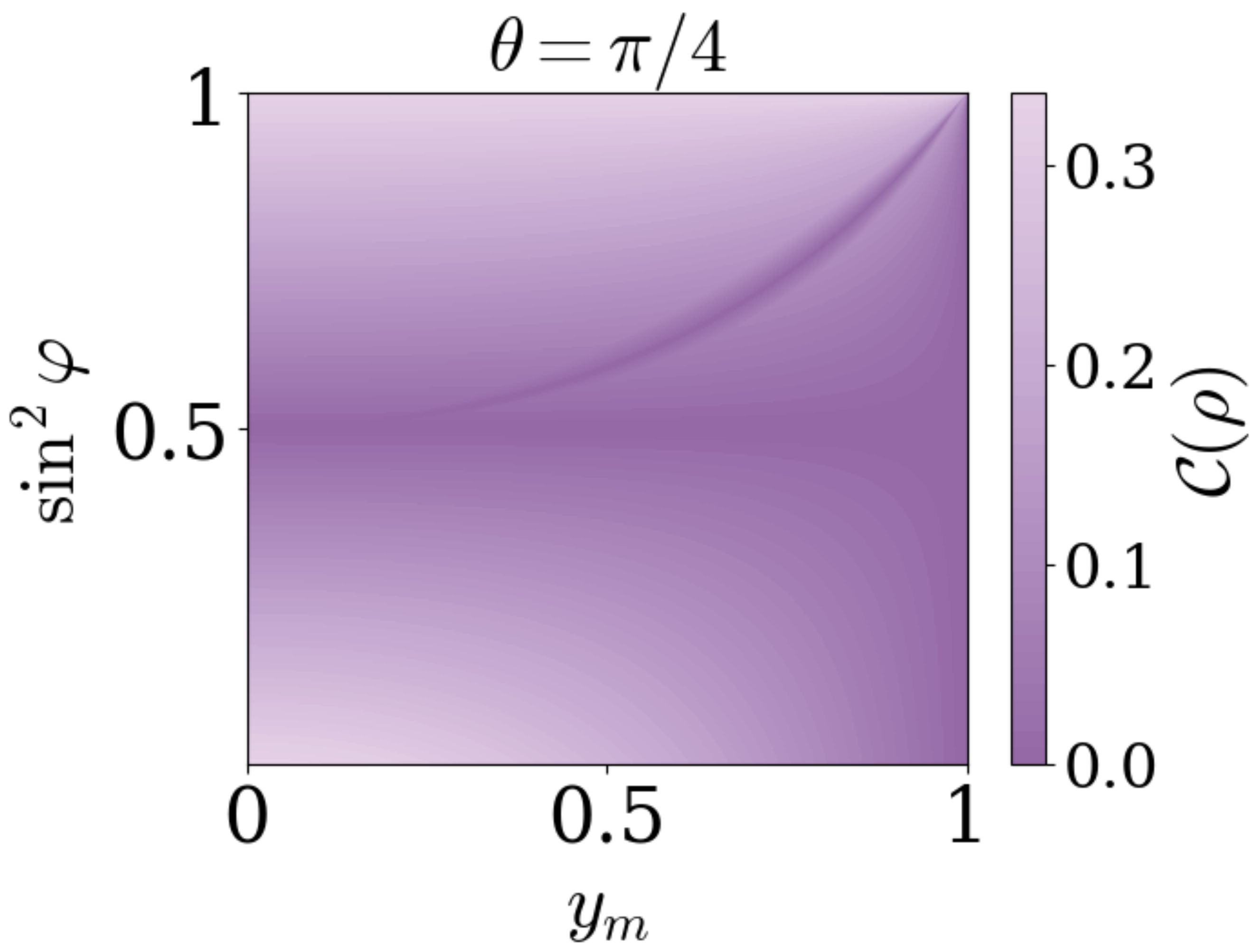

Stat. improvement!

YD, He, Liu, Ma, 2409.15418

Environmental effects

What is missing? Interactions with the surroundings (as has always been).

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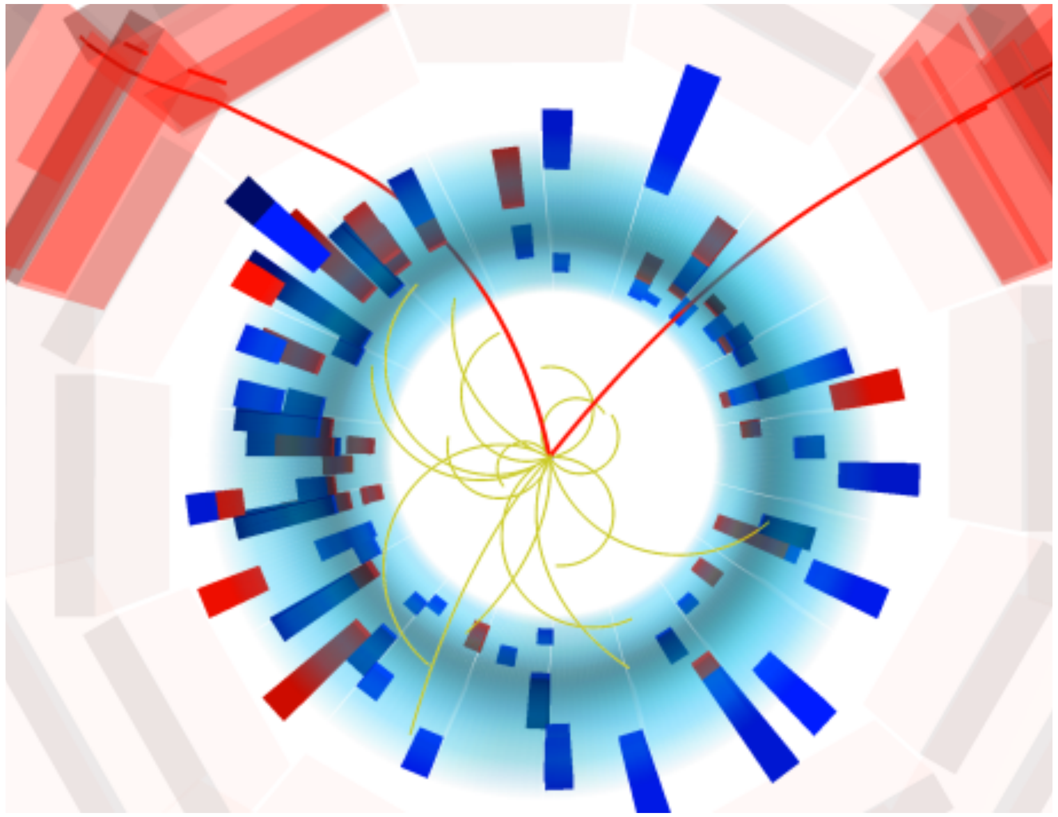
Figure credit: CMS collaboration



This environmental effect is largely overlooked in literature. As I will show soon, this ignorance may lead to misunderstandings in interpreting the physical results.

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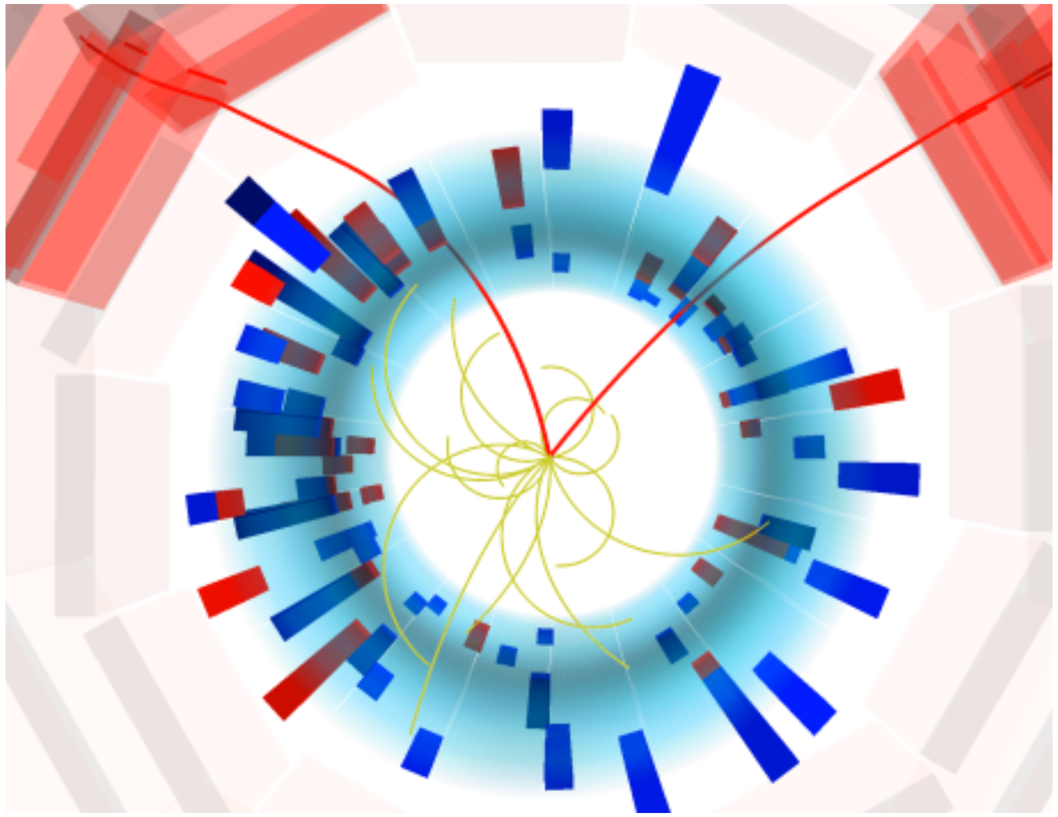

This environmental effect is largely overlooked in literature. As I will show soon, this ignorance may lead to misunderstandings in interpreting the physical results.

To isolate the effects from the magnetic field and to make our point, we focus on particles decay before hitting the detector. Good examples are τ, Λ_c^+ and Ξ^- for LEP/CEPC/FCC-ee and BESIII/STCF, respectively.

Environmental effects

For the momenta, the magnetic field simply induces a rotation along the $\hat{z}$ direction due to the Lorentz force:

$$R_p = e^{-i\boldsymbol{J}\cdot\left(\frac{q\boldsymbol{H}}{m\gamma}\right)t}$$

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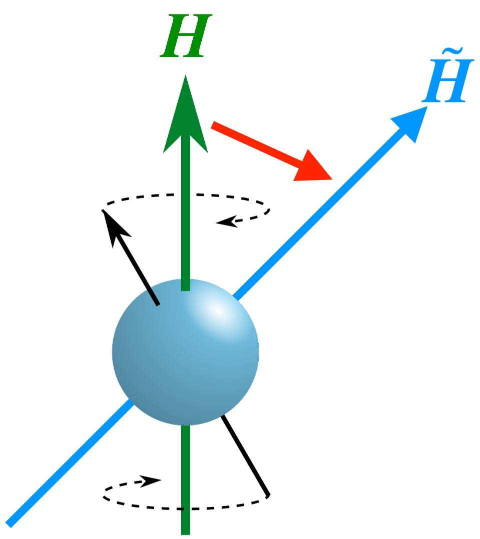
For the spins, induction instead of spin precession as described by the Bargmann-Michel-Telegdi equation: Bargmann, Michel, Telegdi, PRL 1959

$$\frac{d\boldsymbol{S}(t)}{dt} = \frac{ge}{2m}\boldsymbol{S}(t)\times\left[\gamma\boldsymbol{H} + (1-\gamma)\frac{\boldsymbol{H}\cdot\boldsymbol{v}}{v^2}\boldsymbol{v}\right] \equiv \boldsymbol{S}(t)\times\tilde{\boldsymbol{H}}$$



First-order Magnus expansion is sufficient $\left|\tilde{\boldsymbol{H}}\right| \approx \frac{ge\tau_f\left|\boldsymbol{H}\right|\gamma}{m} \sim \mathcal{O}(10^{-2}\sim 10^{-4})$

$$R_s = e^{-i\boldsymbol{J}\cdot\Omega_1(t)} \qquad \boldsymbol{\Omega}_1(t) = \int_0^t dt'\frac{ge}{2m}\left[\gamma\boldsymbol{H} + (1-\gamma)\frac{\boldsymbol{H}\cdot\boldsymbol{v}(t')}{v^2}\boldsymbol{v}(t')\right]$$

Environmental effects

Due to the magnetic effect

YD, He, Liu, Ma, 2409.15418

$$\rho(0,0) = \frac{1}{4}\left(\boldsymbol{I}_4 + \sum_i B_i^+ s^i \otimes \boldsymbol{I}_2 + \sum_j B_j^- \boldsymbol{I}_2 \otimes s^j + \sum_{i,j} C_{ij} s^i \otimes s^j\right)$$

$$\downarrow$$

$$\rho(t_1,t_2) = \frac{1}{4}\left(\boldsymbol{I}_4 + \sum_i B_i^+ s^i \otimes \boldsymbol{I}_2 + \sum_j B_j^- \boldsymbol{I}_2 \otimes s^j + \sum_{i,j} C_{ij} s^i \otimes s^j\right)$$

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↓

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Statistical average is taken over the decay time through a Gaussian PDF:

$$p(t_1, t_2) = \frac{1}{2\pi\sigma_{\rm TOF}^2} e^{-\frac{(t_1-\tau)^2 + (t_2-\tau)^2}{2\sigma_{\rm TOF}^2}}$$

$$\sigma_{\rm TOF}^{\rm BESIII} = 33\ {\rm ps}$$

$$\sigma_{\rm TOF}^{\rm LEP} = 150\ {\rm ps}$$

* a Poisson PDF instead barely affects our conclusion

Decay time correlation is ignored as we lack this info (*also crucial for a loophole free test!*), thus high luminosity would possibly be urgently needed for a loophole free test at colliders.

Environmental effects

Q: How large is this environmental effect?

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$$\rho = \frac{1}{4}\Big(\boldsymbol{I}_4 + \sum_i B_i^+ s^i \otimes \boldsymbol{I}_2 + \sum_j B_j^- \boldsymbol{I}_2 \otimes s^j + \sum_{i,j} C_{ij} s^i \otimes s^j\Big)$$

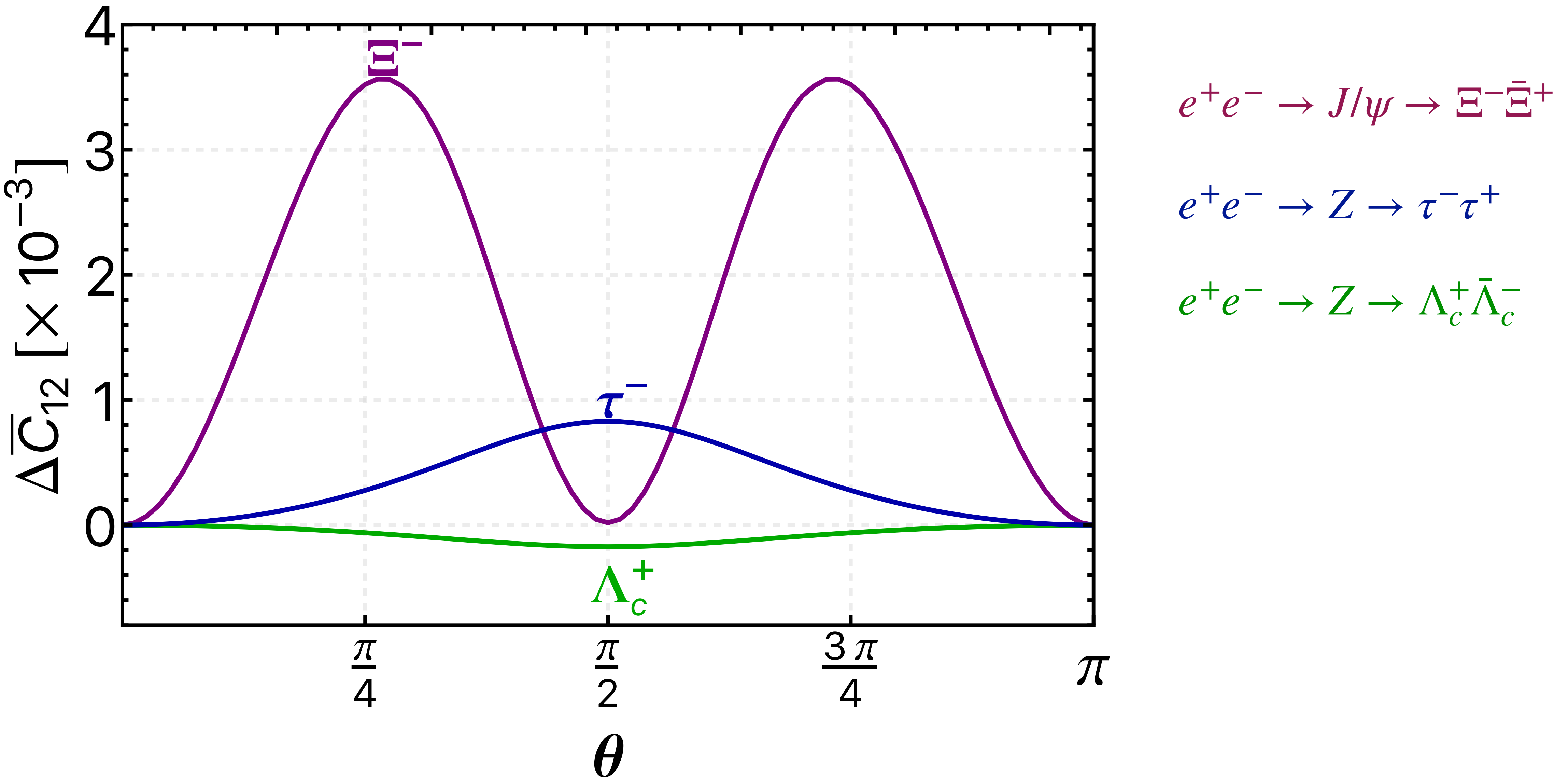
Rotational invariance puts constraints on the generic form of R (backup slide), and P and CP invariance will lead to, for instance, $C_{12} = C_{21}$ under P or CP invariance

$$\Delta \bar{C}_{12} \equiv \bar{C}_{12} - \bar{C}_{21}$$

$\Delta \bar{C}_{12} \neq 0$ would correspond to a spurious P and/or CP violation due to interaction with the environmental magnetic field.

Environmental effects

Spurious P and/or CP violation can be of $\mathcal{O}(10^{-3})$ for $|\boldsymbol{H}| = 1$ tesla.



Non-negligible and may become observable at a future high-lumi electron collider!

New Physics/Paradigm

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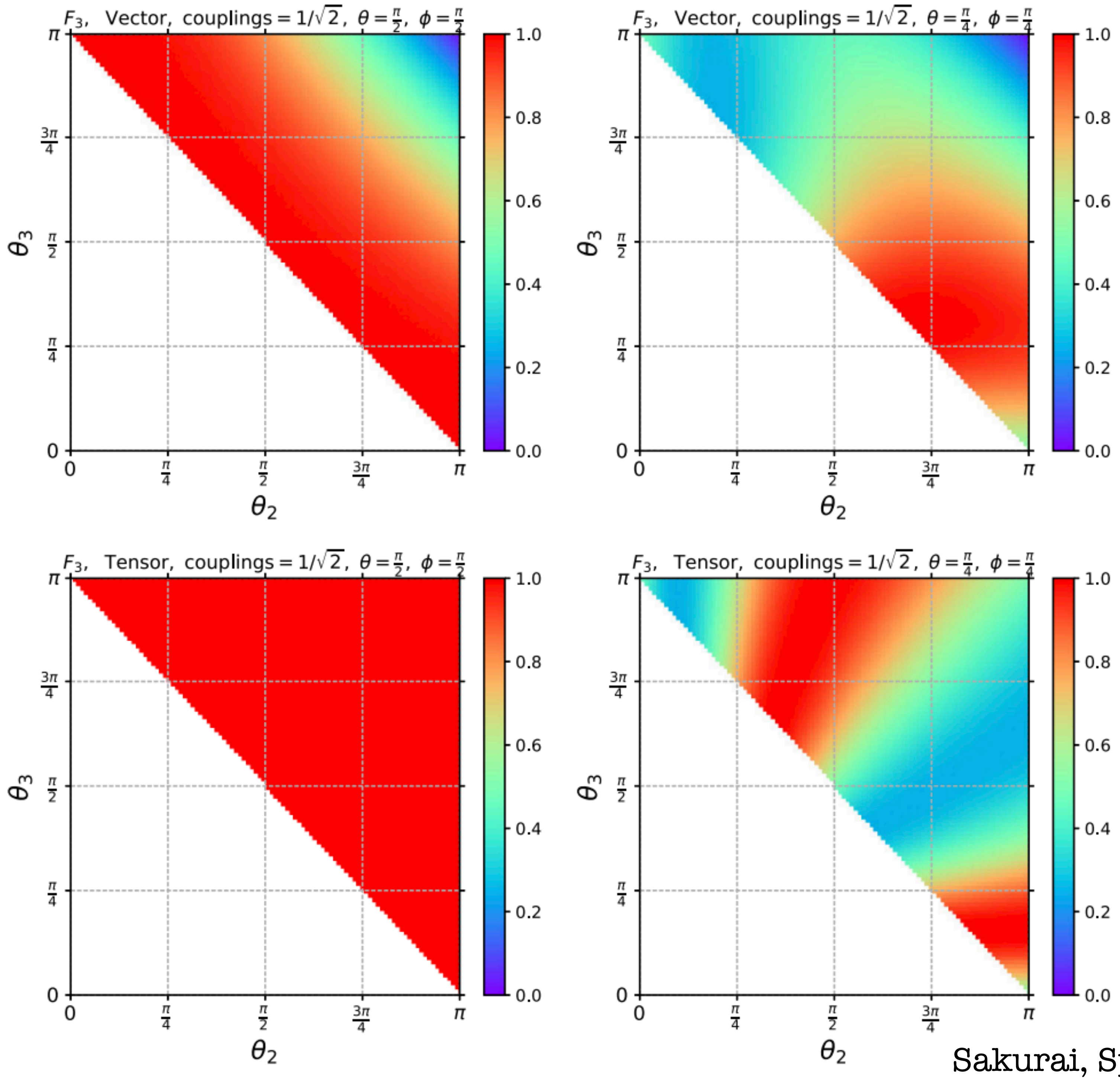
The spin correlation can be easily modified by the presence of new physics, *e.g.*, U(1) gauge boson or 4-fermion operators: New physics in the heatmap



Sakurai, Spannowsky, PRL 2024

New Physics/Paradigm

Up to now, the discussion, though free of referring to any specific local hidden variable theory, however does rely on the knowledge of a quantum one.

Q: Do we have to?

New Physics/Paradigm

Challenging the validity of general QFT can be achieved from the simple spin-0 h decay:

$$\rho = \frac{1}{4}\left(\boldsymbol{I}_4 + \sum_i B_i^+ s^i \otimes \boldsymbol{I}_2 + \sum_j B_j^- \boldsymbol{I}_2 \otimes s^j + \sum_{i,j} C_{ij} s^i \otimes s^j\right)$$

Assuming no special direction for nature, *i.e.*, SO(3) invariance alone (in the rest frame of h)

$$\overrightarrow{B}^+ = b_{1k}\hat{k}\,, \quad \overrightarrow{B}^- = b_{2k}\hat{k} \qquad\qquad C_{ij} = c_0\,\delta_{ij} + c_2\,\epsilon_{ijl}\,\hat{k}_l + c_5\left(\hat{k}_i\hat{k}_j - \frac{\delta_{ij}}{3}\right)$$

New Physics/Paradigm

Challenging the validity of general QFT can be achieved from the simple spin-0 h decay:

$$\rho = \frac{1}{4}\left(\boldsymbol{I}_4 + \sum_i B_i^+ s^i \otimes \boldsymbol{I}_2 + \sum_j B_j^- \boldsymbol{I}_2 \otimes s^j + \sum_{i,j} C_{ij} s^i \otimes s^j\right)$$

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Angular momentum conservation immediately leads to (3 independent parameters):

$$b_{1k} = -\,b_{2k} \qquad\qquad c_0 = -1 - \frac{2}{3}c_5$$

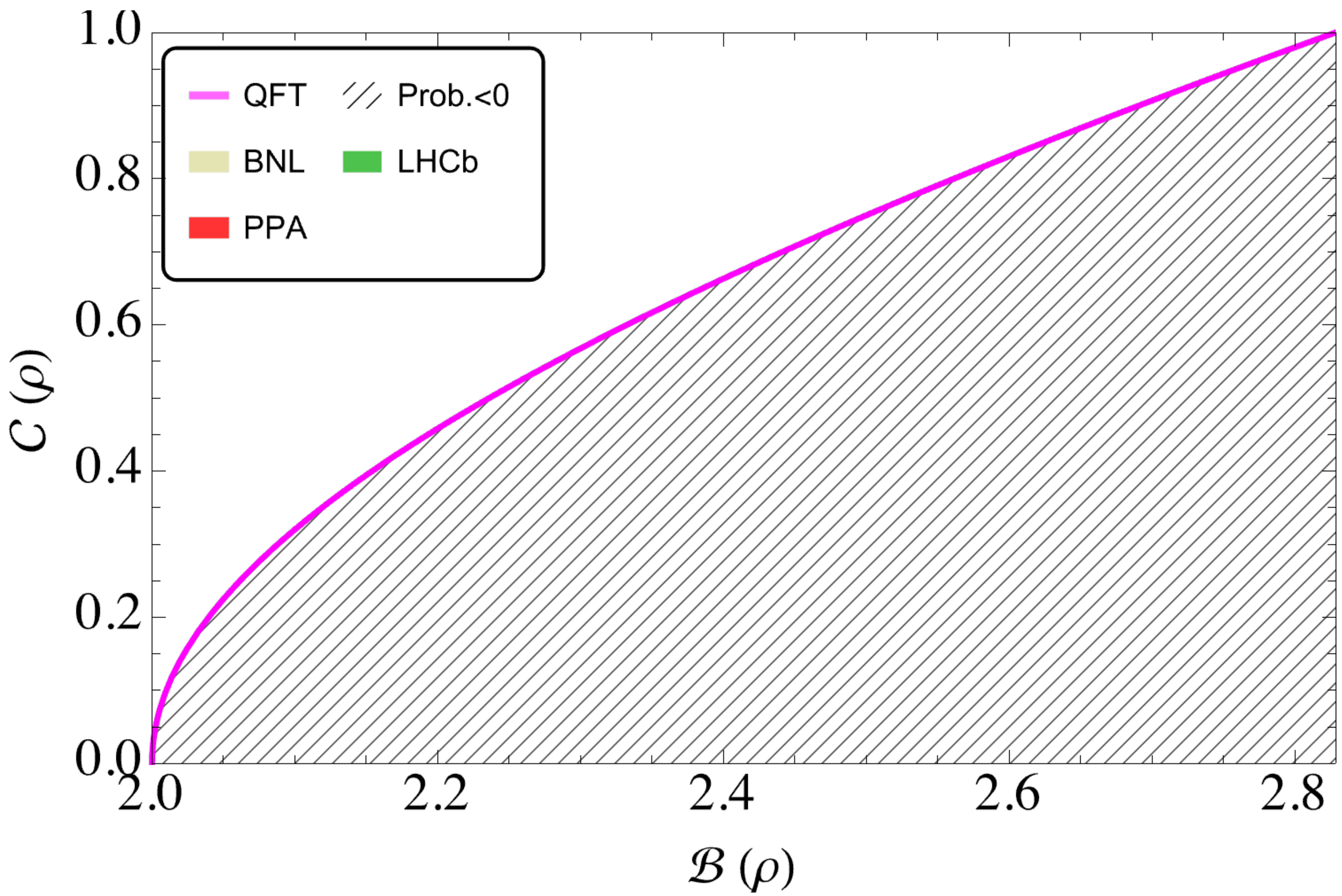
$$\mathscr{B}(\rho) = 2\sqrt{2 - b_{1k}^2 - \epsilon} \qquad\qquad \mathrm{C}(\rho) = \frac{1}{2}\left[(\mathscr{B}(\rho)^2 - 4)(\mathscr{B}(\rho)^2 - 4 + 4\epsilon)\right]^{\frac{1}{4}}$$

α^2 β^2 γ^2

$\epsilon = 1 - b_{1k}^2 - c_2^2 - (1 + c_5)^2$. In *any* QFT, $\epsilon = 0$ is guaranteed and *unprovenly* utilized for fitting.

New Physics/Paradigm

Free test of QFT along with the Bell tests



If $\epsilon \neq 0$ were observed, new paradigm beyond the QFT will be needed!

New Physics/Paradigm

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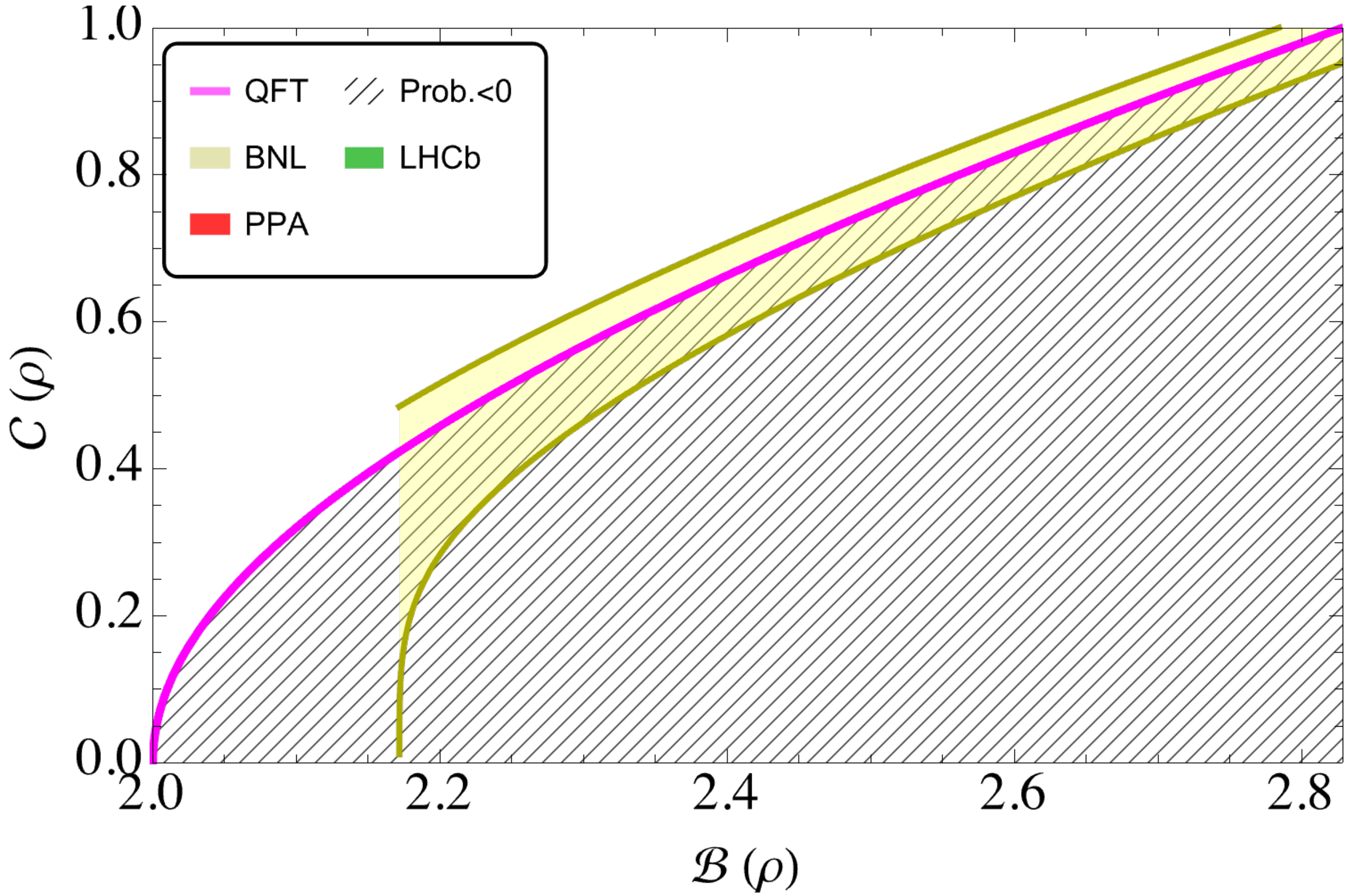

$\epsilon_{\text{BNL}} = -0.025 \pm 0.154$

Cronin & Overseth , PR 1963

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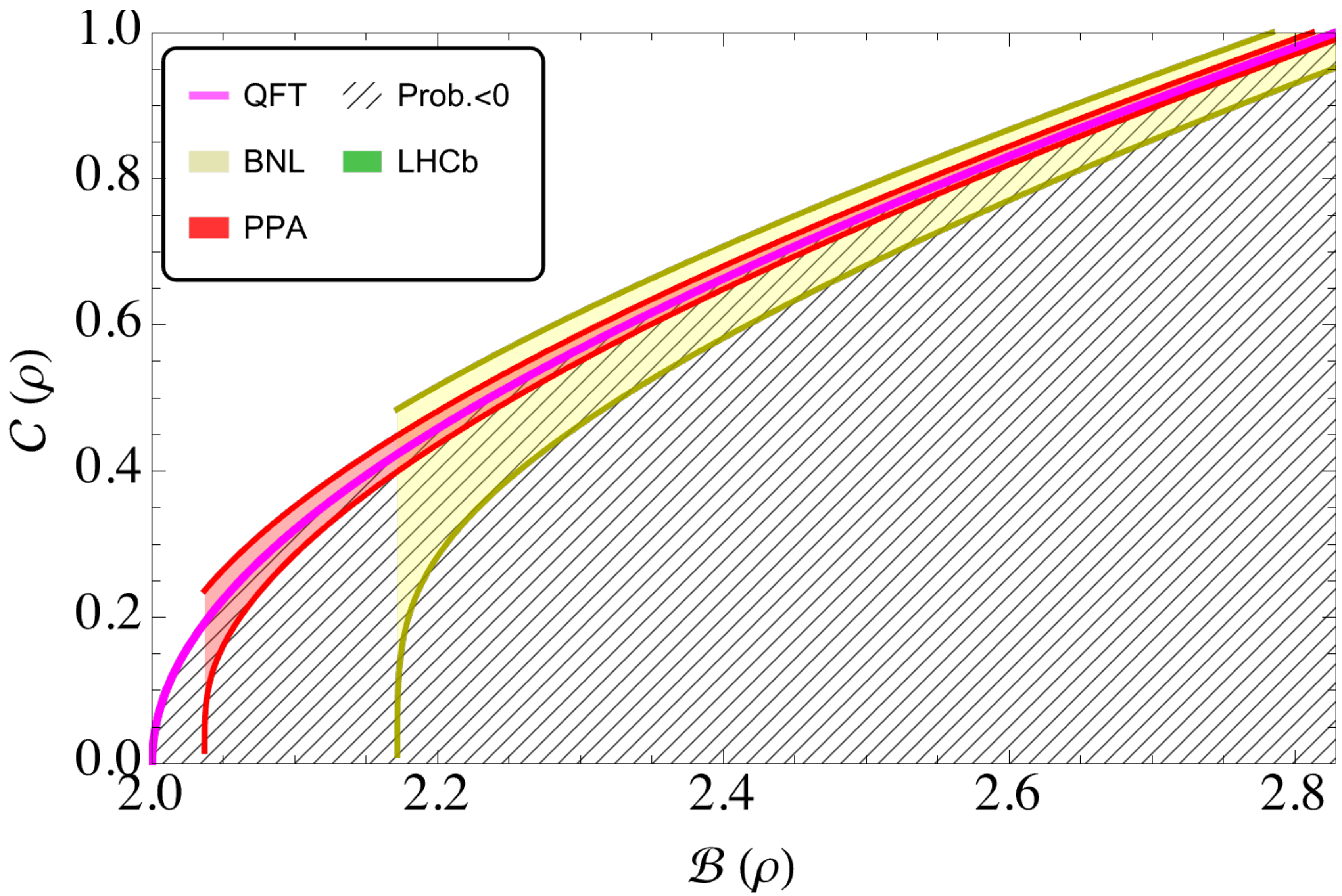

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$\epsilon_{\rm PPA} = 0.005 \pm 0.042$

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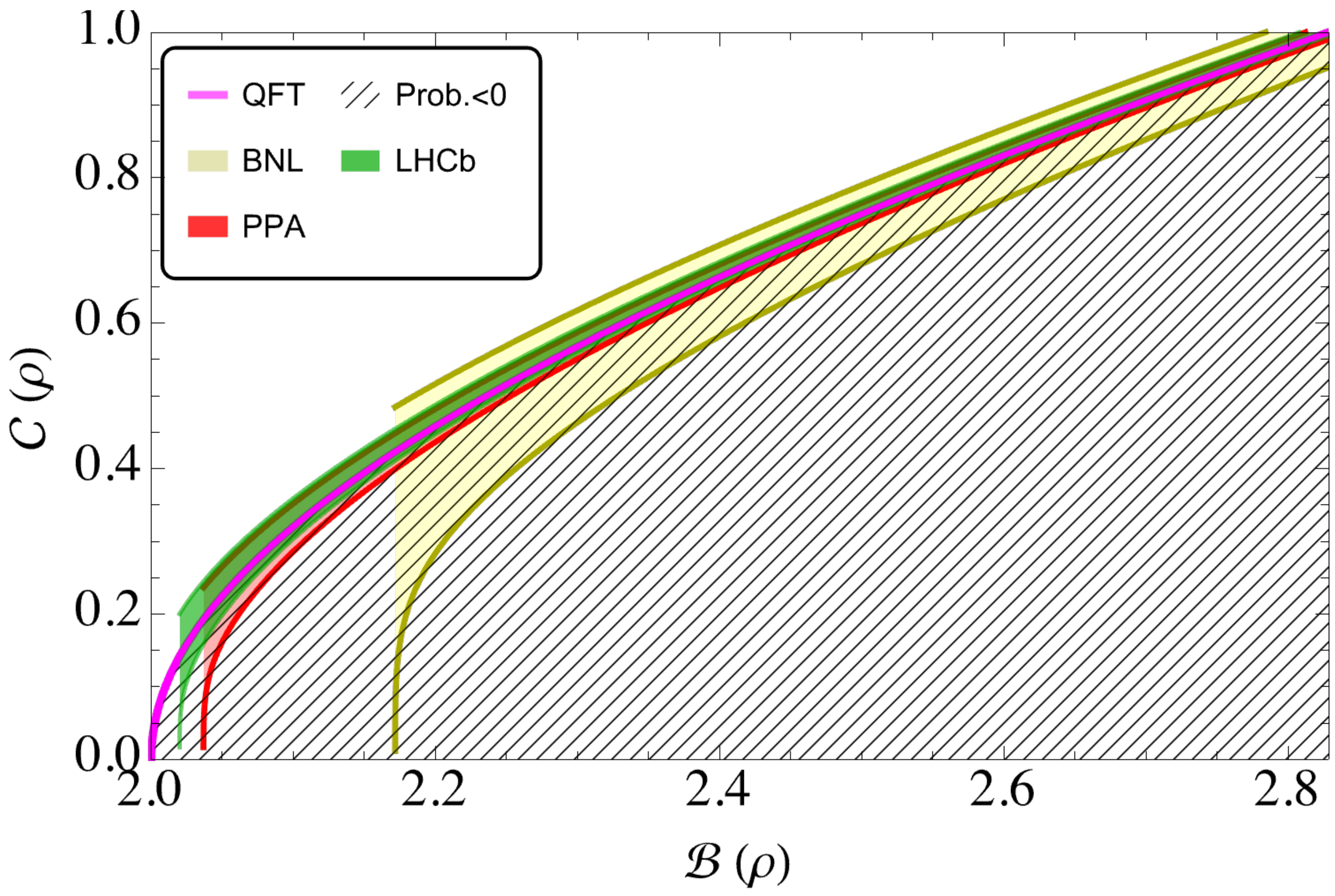

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Private communication w/ Yanxi Zhang (2409.02759)

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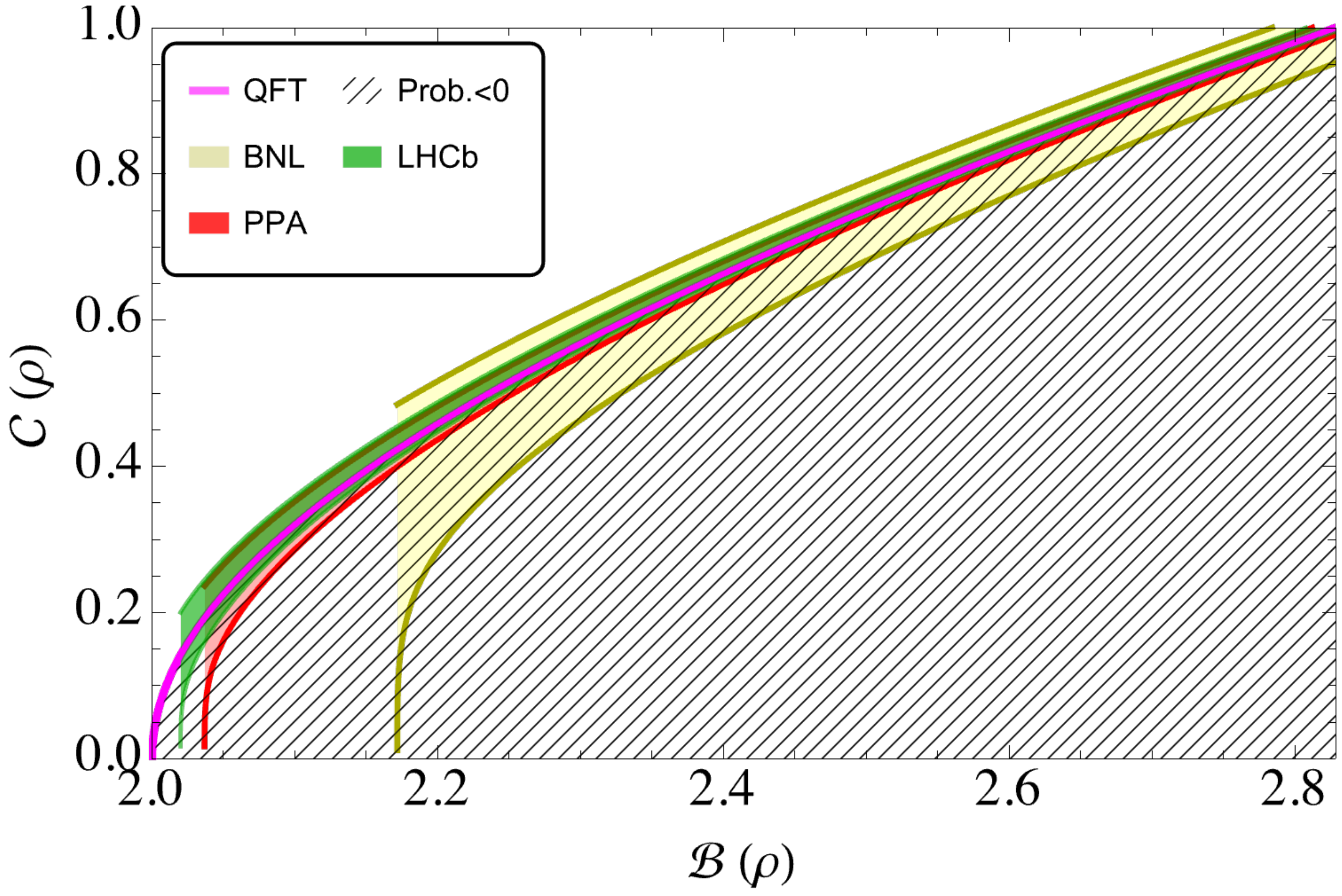

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* Not mentioning BESIII here as $\epsilon = 0$ is taken as the starting point.

If $\epsilon \neq 0$ were observed, new paradigm beyond the QFT will be needed!

Time for data reanalysis is NOW!

Summary

- The entangled fermion pair can be utilized for testing quantum entanglement and Bell nonlocality. We found parity violation could significantly modify the spin correlations of the bipartite system from both spin-0 and spin-1 particle decays.

- The largely overlooked environmental effect was examined and a spurious P and/or CP violation of $\mathcal{O}(10^{-4} \sim 10^{-3})$ can be induced. This has to be subtracted for a genuine determination of P and CP violation at a future high-lumi lepton collider.

- We also propose a free test of the QFT framework using the simplest spin-0 decay and encourage our experimental colleagues to do such tests NOW

Backup