Entanglement and high energy physics

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EXCELENCIA
SEVERO
OCHOA

Quantum Entanglement

- Entanglement is perhaps the aspect of quantum mechanics that shows the greatest departure from classical conceptions

- 1935: a strange phenomenon of quantum mechanics, questioning the completeness of the theory

Einstein, Podolsky, and Rosen 1935

Schrödinger 1935

- 1964: Bell realised that entanglement leads to experimentally testable deviations of quantum mechanics from classical physics

Bell 1964

- With the emergence of quantum information theory, entanglement was recognized as a resource, enabling tasks like quantum cryptography, quantum teleportation or measurement based quantum computation: a *threat* became an *opportunity*

- Worth mentioning: the problem of classifying and quantifying the entanglement of general multipartite systems is still an open problem

O. Gühne, G.Tóth 2009

The ABC

Let us consider an state of two subsystems, Alice and Bob

$$\mathcal{H} = \mathcal{H}_A \otimes \mathcal{H}_B$$

- Pure states are entangled iff

$$\psi \neq \psi_A \otimes \psi_B$$

ie

$$\rho \neq \rho_A \otimes \rho_B \,, \qquad \rho \equiv |\psi\rangle\langle\psi|$$

- In general (pure or mixed) states are entangled iff

$$\rho_{\text{ent}} \neq \rho_{\text{sep}} = \sum_n p_n \, \rho_n^A \otimes \rho_n^B$$

with $p_n > 0$

The physical consequence of entanglement that departs from classical intuition is the violation of Bell inequalities, an impossible result in any local-realistic (“classical") theory of nature.

CHSH

Clauser, Horne, Shimony and Holt, 1969

Alice (Bob) chooses to measure certain (bi-valued) observables, $A, A' \; (B, B')$.

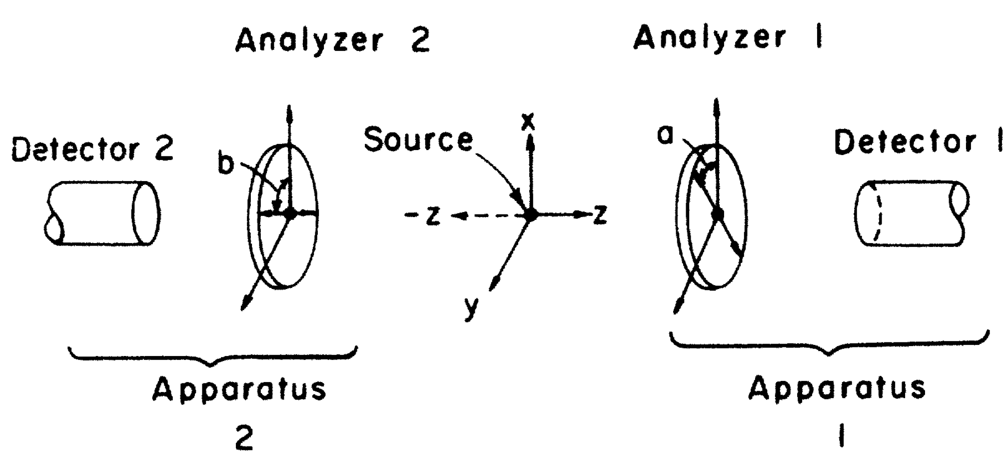

FIG. 1. Scheme considered for a discussion of objective local theories. A source emitting particle pairs is viewed by two apparatuses. Each apparatus consists of an analyzer and an associated detector. The analyzers have parameters, a and b respectively, which are externally adjustable. In the above example, a and b represent the angles between the analyzer axes and a fixed reference axis.

From Clauser, Horne, PRD 10 (1974) 526

Bell inequalities

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Alice (Bob) chooses to measure certain (bi-valued) observables, A, A' (B, B') .

Then, classically,

$$\left|\langle AB\rangle - \langle AB'\rangle + \langle A'B\rangle + \langle A'B'\rangle\right| \leq 2$$

It is optimal for two qubits (e.g, a state of two photons or two fermions)

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Experimental loop-hole free Bell inequality violations have been shown in 2-photon experiments

- Closing the locality loophole: pair of photons separated by a large distance
- Closing the detection loophole: fair sampling

And also in atoms, solid state systems, …

Exploring Bell inequalities in HEP

It is interesting to test both, entanglement and Bell inequalities, at different energy scales, in particular at the highest possible energies

See **F. Botella talk** on Entanglement in B factories

- **Bell inequalities in a HEP experiment were first explored in meson-anti meson states, e.g.**

Bertlmann, Grimus,and Hiesmayr 2001

$$\Upsilon(4S) \to B^0 \bar{B}^0$$

$$|\psi\rangle = \frac{1}{\sqrt{2}}\Big[|B^0\rangle_1 \otimes |\bar{B}^0\rangle_2 - |\bar{B}^0\rangle_1 \otimes |B^0\rangle_2\Big]$$

Go (BELLE) 2004

Bramon, Escribano and Garbarino 2004

....

Fabbrichesi, Floreanini, Gabrielli and Marzola 2023

$$B^0 \to J/\psi\, K^*(892)^0$$

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Exp

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Fabbrichesi, Floreanini, Gabrielli and Marzola 2023

- In last two years, test of entanglement and Bell-type inequalities have been proposed at the LHC - and future colliders - in several final states ($t\bar{t},\ ZZ, WW, \tau^+\tau^-$ ....)

> 30 papers

Several devoted workshops (Oxford, Cracow, GGI) '2023

Entanglement and Bell-type inequalities @ the LHC: some references

Entanglement and Quantum tomography with tops at the LHC	Y. Afik and J.R.M. de Nova, 2021
Testing Bell Inequalities at the LHC with Top-Quark Pairs	M. Fabbrichesi, R. Floreanini , G. Panizzo, 2021
Quantum tops at the LHC: from entanglement to Bell inequalities	C. Severi, C.D.E. Boschi, F. Malton, M Sioli 2022
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Improved tests of entanglement an Bell inequalities with LHC tops	J.A. Aguilar-S…
Quantum discord and stearing and discord in top quarks at the LH	Y…
Testing Bell inequalities in Higgs boson d…	
Bell-type inequalities for systems of relativisti…	…ki, 2022
Laboratory test frames of quantum…	…, 2022
Testing entan…	…ilar-Saavedra, A. Bernal, J. A. Casas, J. M. Moreno
Quantum state tomography, e…	R. Ashby-Pickering, A. J. Barr, A. Wierzchucka , 2022
Constraining new… …lepton & $\gamma\gamma$	M. Fabbrichesi, R. Floreanini, E. Gabrielli, 2023
Q… …EFT at higher orders,	C. Severi , E. Vryonidou, 2023
…quark pair production at the LHC	R. Aoude, E. Madge, F. Maltoni, L. Mantani, 2022
…quantum entanglement in top pair production	J.A. Aguilar-Saavedra, 2023
Quantum inf… …d CP measurement in $H \to \tau^+\tau^-$ at future lepton colliders	MM Altakach, P. Lamba et al 2023
Entanglement and Bell inequalities violation in H→ZZ with anomalous coupling	A. Bernal, P.Caban, J. Rembieliński, 2023
Decay of entangled fermion pairs with post-selection	J.A. Aguilar-Saavedra, 2023
Probing new physics through entanglement in diboson production	R. Aoude, E. Madge, F. Maltoni, L. Mantani 2023
Isolating semi-leptonic H→WW* decays for Bell inequality tests	F.Fabbri, J. Howarth, T. Maurin 2023

INCOMPLETE LIST

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Quantum discord and stearing and discord in top quarks at the LH	Y. Afik and J.R.M. de Nova, 2022
Testing Bell inequalities in Higgs boson decays	A.J. Barr, 2022
Bell-type inequalities for systems of relativistic vector bosons	A.J. Barr, P. Caban, J. Rembieliński, 2022
Laboratory test frames of quantum entanglement in H $\rightarrow$ WW	J.A. Aguilar-Saavedra, 2022
Testing entanglement and Bell-inequalities in H $\rightarrow$ ZZ	J. A. Aguilar-Saavedra, A. Bernal, J. A. Casas, J. M. Moreno
Quantum state tomography, entanglement detection and Bell violation prospects ..	R. Ashby-Pickering, A. J. Barr, A. Wierzchucka , 2022
Constraining new physics in entangled two-qubit systems: top-quark, τ-lepton & $\gamma\gamma$	M. Fabbrichesi, R. Floreanini, E. Gabrielli, 2023
Quantum entanglement and top spin correlations in SMEFT at higher orders,	C. Severi , E. Vryonidou, 2023
Quantum SMEFT tomography: Top quark pair production at the LHC	R. Aoude, E. Madge, F. Maltoni, L. Mantani, 2022
Post-decay quantum entanglement in top pair production	J.A. Aguilar-Saavedra, 2023
Quantum information and CP measurement in H $\rightarrow$ $\tau^+\tau^-$ at future lepton colliders	MM Altakach, et al 2023 (see **P. Lamba talk <<<<**)
Entanglement and Bell inequalities violation in H$\rightarrow$ZZ with anomalous coupling	A. Bernal, P.Caban, J. Rembieliński, 2023
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Based on:

PHYSICAL REVIEW D **107,** 016012 (2023)

Testing entanglement and Bell inequalities in $H \to ZZ$

J. A. Aguilar-Saavedra,* A. Bernal,† J. A. Casas,‡ and J. M. Moreno§
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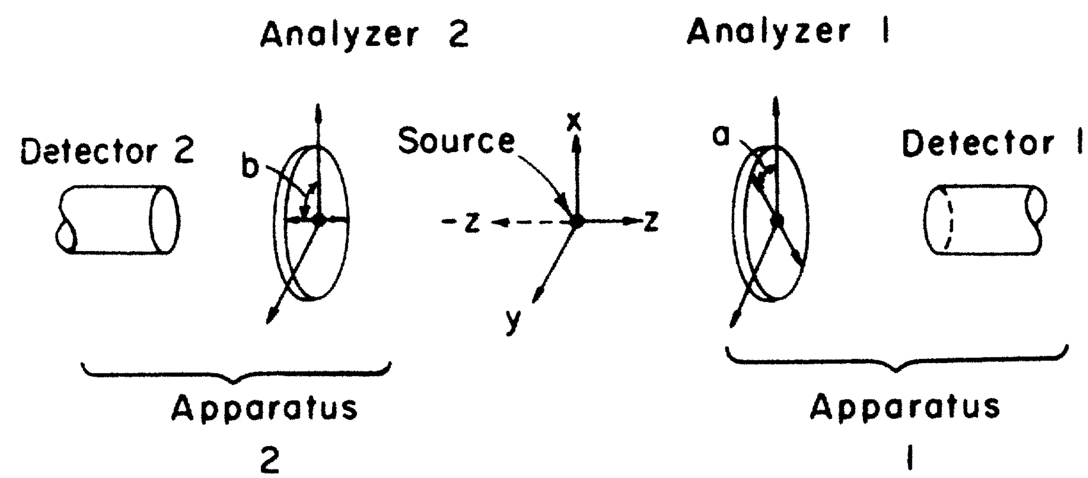
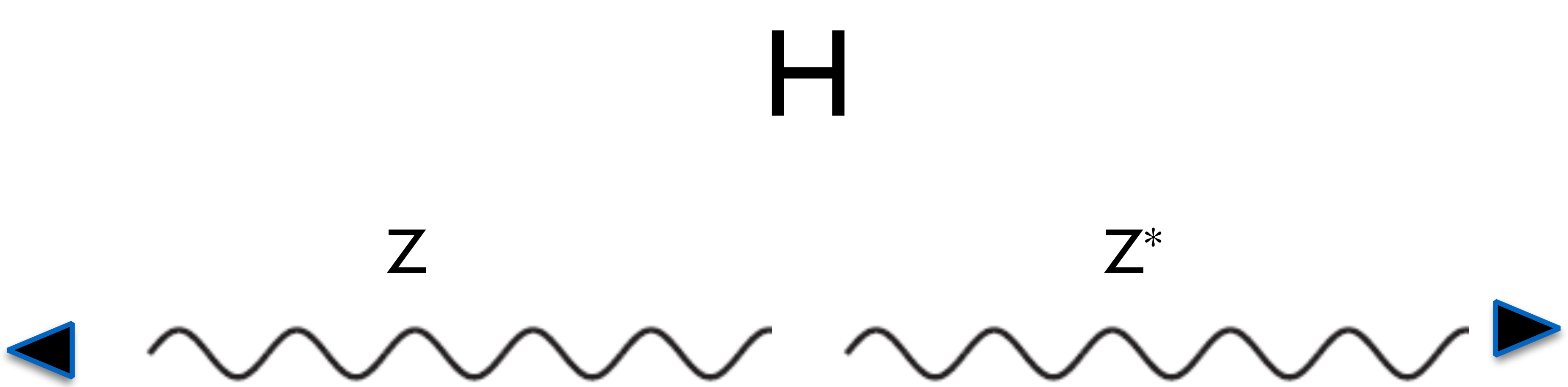
(Received 4 October 2022; accepted 3 January 2023; published 20 January 2023)

We discuss quantum entanglement and violation of Bell inequalities in the $H \to ZZ$ decay, in particular when the two Z-bosons decay into light leptons. Although such process implies an important suppression of the statistics, this is traded by clean signals from a "quasi maximally entangled" system, which makes it very promising to check these crucial phenomena at high energy. In this paper we devise a novel framework to extract from $H \to ZZ$ data all significant information related to this goal, in particular spin correlation observables. In this context we derive sufficient and necessary conditions for entanglement in terms of only two parameters. Likewise, we obtain a sufficient and improved condition for the violation of Bell-type inequalities. The numerical analysis shows that with a luminosity of $L = 300\ \text{fb}^{-1}$ entanglement can be probed at $> 3\sigma$ level. For $L = 3\ \text{ab}^{-1}$ (HL-LHC) entanglement can be probed beyond the 5σ level, while the sensitivity to a violation of the Bell inequalities is at the 4.5σ level.

DOI: 10.1103/PhysRevD.107.016012

Exploring Bell inequalities in vector boson Higgs decays





ZZ $\approx$ maximally entangled state

Barr, 2022

Exploring Bell inequalities in H ⟶ ZZ

- Let $(m_{Z_1},\ m_{Z_2})$ the invariant masses for a *particular event:*

  In the CM reference, z-axis along Z_1 momentum $\vec{k}$

  $|\vec{k}|$ fixed by $(m_{Z_1}, m_{Z_2},\ m_H)$

- J_z - and parity - conservation imply $$|\psi_{ZZ}\rangle = \frac{1}{\sqrt{2+\beta^2}}\left(|{+-}\rangle - \beta\,|00\rangle + |{-+}\rangle\right)$$

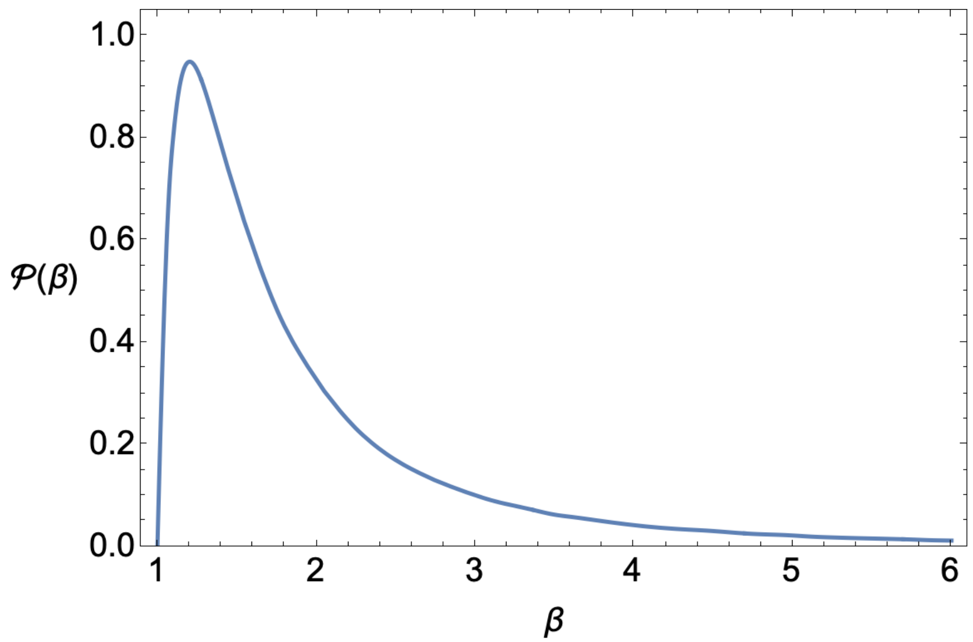
- From the Lorentz structure of SM HZZ vertex:

$$|\psi_{ZZ}\rangle = \eta_{\mu\nu}\ e^{\mu}_{\sigma}(m_1,\vec{k})\ e^{\nu}_{\lambda}(m_2,-\vec{k})\ |\vec{k},\sigma\rangle_A|{-\vec{k}},\lambda\rangle_B \qquad e^{\mu}_{\sigma}(m,\vec{k}) = \begin{pmatrix} 0 & \frac{|\vec{k}|}{m} & 0 \\ -\frac{1}{\sqrt{2}} & 0 & \frac{1}{\sqrt{2}} \\ \frac{i}{\sqrt{2}} & 0 & \frac{i}{\sqrt{2}} \\ 0 & -\frac{\sqrt{|\vec{k}|^2+m^2}}{m} & 0 \end{pmatrix}$$

One obtains

$$\beta = 1 + \frac{m_H^2 - (m_1+m_2)^2}{2m_1m_2} \qquad \beta \geq 1$$

Exploring Bell inequalities in H ⟶ ZZ

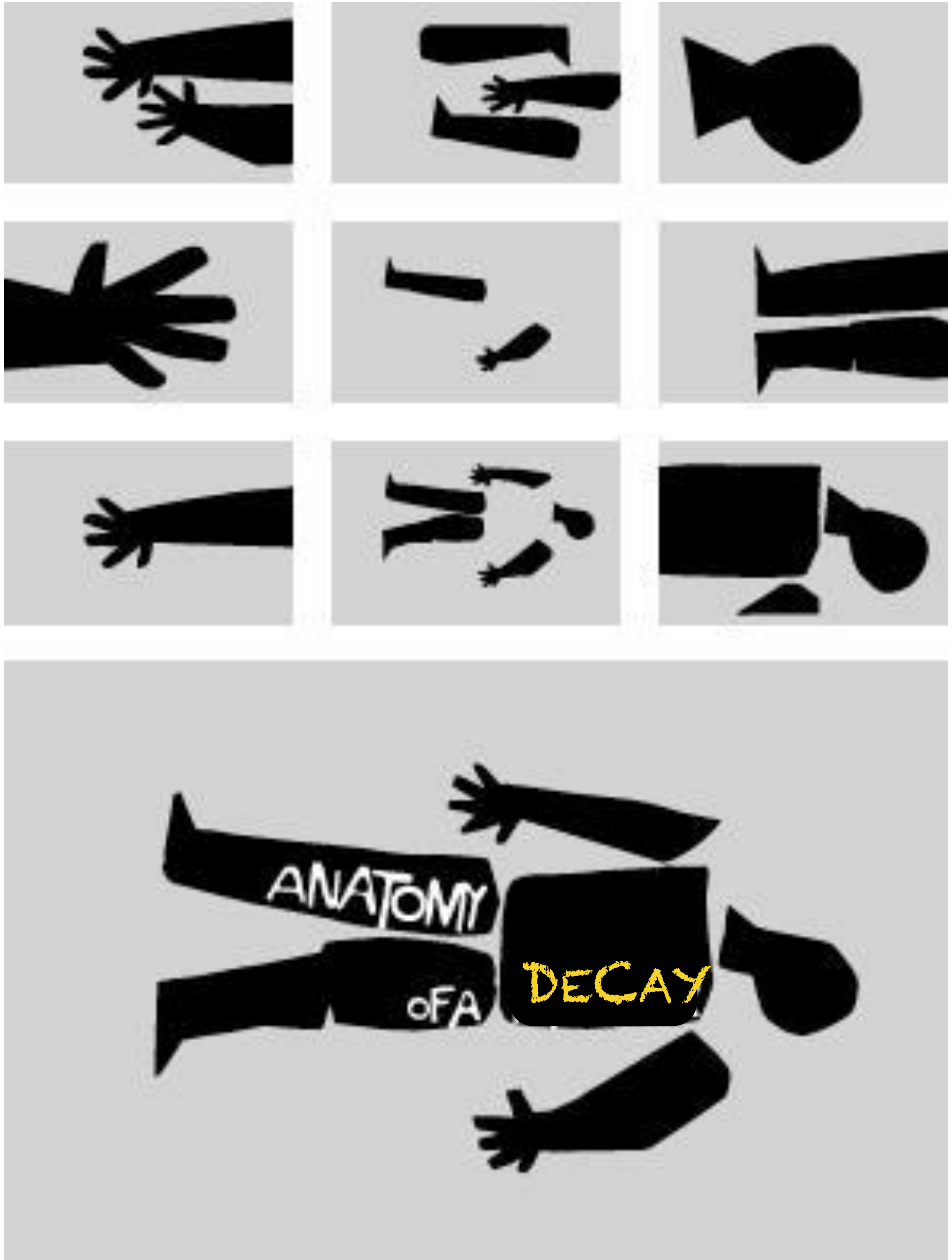


The quantum ZZ state is a mixed state, shaped by the kinematics

$$\rho = \int d\beta \; \mathcal{P}(\beta)\rho_\beta$$

The ***numerical*** probability $\mathcal{P}(\beta)$ obtained with the Monte Carlo agrees (~3 %) with the ***analytical*** one obtained by phase space analysis of three body decay $H \to Z\ell^+\ell^-$

$$\rho = \frac{1}{2+w^2}\begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & -y & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -y & 0 & w^2 & 0 & -y & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & -y & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$



QUANTUM TOMOGRAPHY

Reconstructing a quantum state

i) Choose an optimal basis (symmetries, etc) for ρ

ii) Express the experimental measurements as functions of the expansion coefficients

Exploring Bell inequalities in H ⟶ ZZ

- A convenient way to parametrize the 9 × 9 spin density-operator of the two vector bosons is to use the basis of irreducible tensor operators $\{T^{L_1}_{M_1} \otimes T^{L_2}_{M_2}\}$

$$T^{L_1}_{M_1}, T^{L_2}_{M_2} \in \{\mathbb{1}_3; T^1_1, T^1_0, T^1_{-1}; T^2_2, T^2_1, T^2_0, T^2_{-1}, T^2_{-2}\} \qquad \mathrm{Tr}\left\{T^L_M \ (T^L_M)^\dagger\right\} = 3,$$

T^L_M vs Gell-Mann matrices

$$T^1_1 = \sqrt{\frac{3}{2}} \begin{pmatrix} 0 & -1 & 0 \\ 0 & 0 & -1 \\ 0 & 0 & 0 \end{pmatrix}, \quad T^1_0 = \sqrt{\frac{3}{2}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -1 \end{pmatrix}, \quad T^1_{-1} = \sqrt{\frac{3}{2}} \begin{pmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix}.$$

$$\begin{aligned} T^2_{\pm 2} &= \frac{2}{\sqrt{3}} (T^1_{\pm 1})^2, \\ T^2_{\pm 1} &= \sqrt{\frac{2}{3}} \left[T^1_{\pm 1} T^1_0 + T^1_0 T^1_{\pm 1}\right], \\ T^2_0 &= \frac{\sqrt{2}}{3} \left[T^1_1 T^1_{-1} + T^1_{-1} T^1_1 + 2 (T^1_0)^2\right] \end{aligned}$$

$$\rho = \frac{1}{9}\left[\mathbb{1}_3 \otimes \mathbb{1}_3 + A^1_{LM}\, T^L_M \otimes \mathbb{1}_3 + A^2_{LM}\, \mathbb{1}_3 \otimes T^L_M + C_{L_1 M_1 L_2 M_2}\, T^{L_1}_{M_1} \otimes T^{L_2}_{M_2}\right]$$

8 +8+64

80 components

$$\rho = \frac{1}{9}\left[\mathbb{1}_3 \otimes \mathbb{1}_3 + A^1_{LM}\; T^L_M \otimes \mathbb{1}_3 + A^2_{LM}\; \mathbb{1}_3 \otimes T^L_M + C_{L_1M_1L_2M_2}\; T^{L_1}_{M_1} \otimes T^{L_2}_{M_2}\right]$$

The differential $ZZ \to \ell_1^+\ell_1^-\ell_2^+\ell_2^-$ cross section is given by

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_1 d\Omega_2} = \left(\frac{3}{4\pi}\right)^2 \mathrm{T}r\left\{\rho\left(\Gamma_1 \otimes \Gamma_2\right)^T\right\}$$

with Γ, the decay density matrix of a Z boson into $\ell^+\ell^-$, given by

$$\Gamma = \frac{1}{4}\begin{pmatrix} 1+\cos^2\theta - 2\eta_\ell\cos\theta & \frac{1}{\sqrt{2}}(\sin 2\theta - 2\eta_\ell \sin\theta)e^{i\varphi} & (1-\cos^2\theta)e^{i2\varphi} \\ \frac{1}{\sqrt{2}}(\sin 2\theta - 2\eta_\ell\sin\theta)e^{-i\varphi} & 2\sin^2\theta & -\frac{1}{\sqrt{2}}(\sin 2\theta + 2\eta_\ell\sin\theta)e^{i\varphi} \\ (1-\cos^2\theta)e^{-i2\varphi} & -\frac{1}{\sqrt{2}}(\sin 2\theta + 2\eta_\ell\sin\theta)e^{-i\varphi} & 1+\cos^2\theta - 2\eta_\ell\cos\theta \end{pmatrix}$$

η_ℓ

Using

$$\mathrm{Tr}\left\{\mathbb{1}_3\;\Gamma^T\right\} = 2\sqrt{\pi}\;Y_0^0(\theta,\varphi),\quad \mathrm{Tr}\left\{T^1_M\;\Gamma^T\right\} = -\sqrt{2\pi}\eta_\ell\;Y_1^M(\theta,\varphi),\quad \mathrm{Tr}\left\{T^2_M\;\Gamma^T\right\} = \sqrt{\frac{2\pi}{5}}\;Y_2^M(\theta,\varphi)$$

We can *very easily* extract

$$A^j_{LM} \equiv \int \frac{1}{\sigma}\frac{d\sigma}{d\Omega_1 d\Omega_2} Y^M_L(\Omega_j)d\Omega_j \qquad C_{L_1M_1L_2M_2} \equiv \int \frac{1}{\sigma}\frac{d\sigma}{d\Omega_1 d\Omega_2} Y^{M_1}_{L_1}(\Omega_1) Y^{M_2}_{L_2}(\Omega_2) d\Omega_1 d\Omega_2$$

$$\rho = \frac{1}{9}\left[\mathbb{1}_3 \otimes \mathbb{1}_3 + A^1_{LM}\, T^L_M \otimes \mathbb{1}_3 + A^2_{LM}\, \mathbb{1}_3 \otimes T^L_M + C_{L_1M_1L_2M_2}\, T^{L_1}_{M_1} \otimes T^{L_2}_{M_2}\right]$$

The differential $ZZ \to \ell_1^+\ell_1^-\ell_2^+\ell_2^-$ cross section is given by

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This Quantum Tomography Method can be generalized to other processes !!

A. Bernal 2023

$$A^j_{LM} \equiv \int \frac{1}{\sigma}\frac{d\sigma}{d\Omega_1 d\Omega_2} Y^M_L(\Omega_j)\, d\Omega_j \qquad C_{L_1M_1L_2M_2} \equiv \int \frac{1}{\sigma}\frac{d\sigma}{d\Omega_1 d\Omega_2} Y^{M_1}_{L_1}(\Omega_1) Y^{M_2}_{L_2}(\Omega_2)\, d\Omega_1 d\Omega_2$$

$$
\rho = \begin{pmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & \frac{1}{6}\left(\sqrt{2}A^1_{2,0}+2\right) & 0 & \frac{1}{3}C_{2,1,2,-1} & 0 & \frac{1}{3}C_{2,2,2,-2} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & \frac{1}{3}C_{2,1,2,-1} & 0 & \frac{1}{3}\left(1-\sqrt{2}A^1_{2,0}\right) & 0 & \frac{1}{3}C_{2,1,2,-1} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & \frac{1}{3}C_{2,2,2,-2} & 0 & \frac{1}{3}C_{2,1,2,-1} & 0 & \frac{1}{6}\left(\sqrt{2}A^1_{2,0}+2\right) & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{pmatrix} .
$$

- ENTANGLEMENT ?

  - Checking separability is not , in general, an easy task

  - BUT in this case, symmetries come to rescue:

  entanglement IFF one of the spin correlations is non vanishing, ie

A. Peres 1996
P Horodecki 1997

$$C_{2,1,2,-1} \neq 0 \qquad \text{or} \qquad C_{2,2,2,-2} \neq 0$$

- BELL INEQUALITIES ?

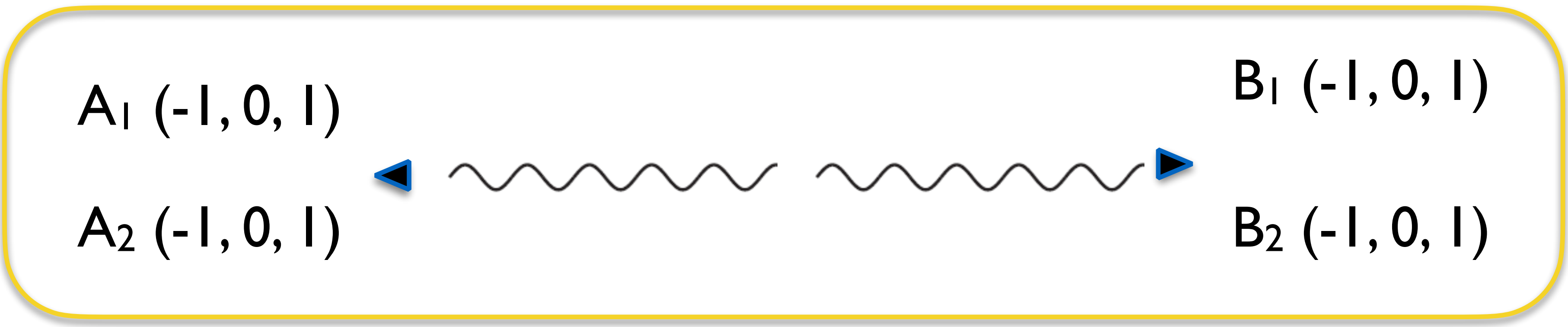
  Technical issue: We are dealing with "qutrits" (- , 0, +)

  The optimal inequalities are not CHSH but CGLMP

Qutrits: CGLMP Bell-type inequality

Collins, Gisin, Linden, Massar, Popescu, 2002

- $$I_3 = P(A_1 = B_1) + P(B_1 = A_2 + 1) + P(A_2 = B_2) + P(B_2 = A_1) - [P(A_1 = B_1 - 1) + P(B_1 = A_2) + P(A_2 = B_2 - 1) + P(B_2 = A_1 - 1)] \leq 2$$



$(A_{1,2}, B_{1,2})$ chosen to optimize I_3

In terms of the (Bell) operator associated to I_3

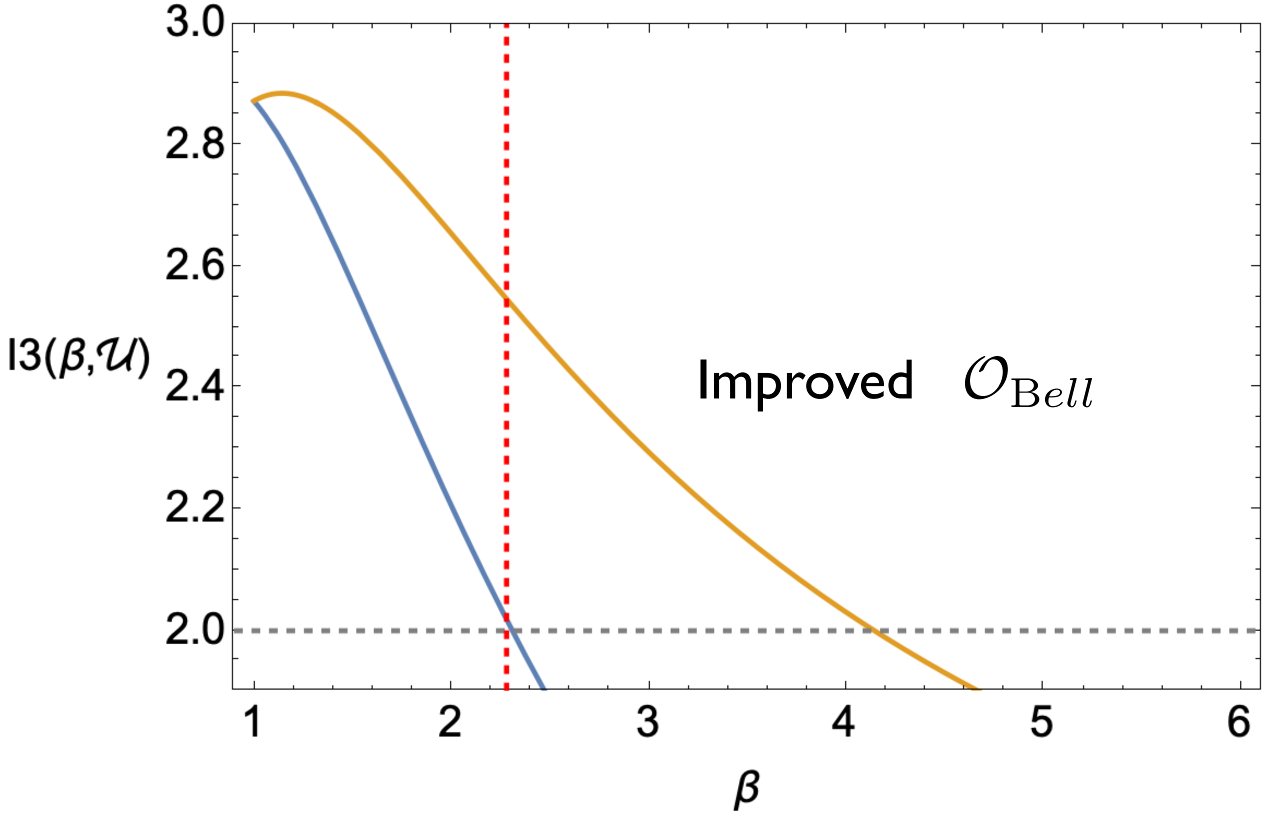
$$I_3 = \mathrm{Tr}\{\rho\, \mathcal{O}_{Bell}\} > 2$$

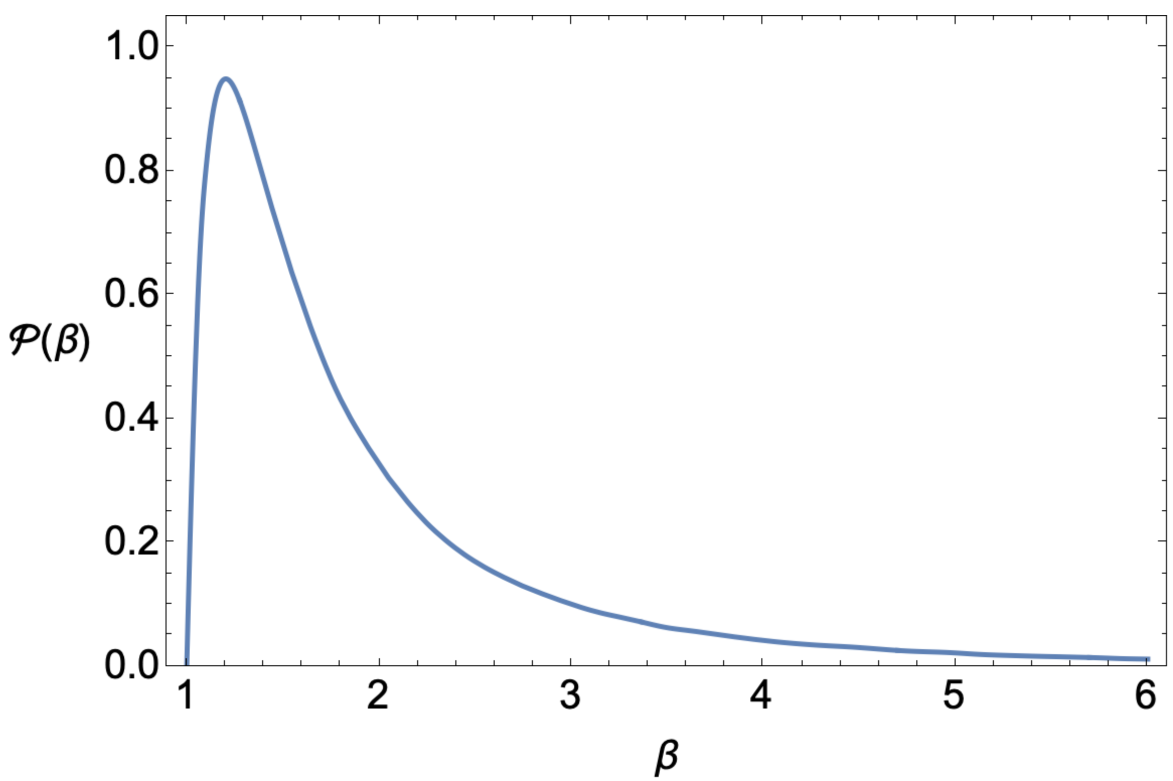
- Optimal operator for the pure singlet (β=0)

$$\mathcal{O}_{\rm Bell} \equiv \frac{4}{3\sqrt{3}} \left(T^1_1 \otimes T^1_1 + T^1_{-1} \otimes T^1_{-1}\right) + \frac{2}{3} \left(T^2_2 \otimes T^2_2 + T^2_{-2} \otimes T^2_{-2}\right)$$

for $\rho_{singlet}$, $I_3 \approx 2.8$

- We have built an improved version of $\mathcal{O}_{\mathrm{Bell}}$ for $\beta \neq 0$





Sizeable improvement in the k-momentum peak region

- In terms of spin polarization and spin correlations:

$$I_3 = \frac{1}{36}\left(18 + 16\sqrt{3} - \sqrt{2}\left(9 - 8\sqrt{3}\right) A^1_{2,0} - 8\left(3 + 2\sqrt{3}\right) C_{2,1,2,-1} + 6\, C_{2,2,2,-2}\right)$$

Numerical results

We have generated

$$pp \to H \to ZZ^* \to 4\ell$$

BR 1.24×10^{-4}

using MadGraph and implementing our analysis in $e^+e^-\mu^+\mu^-$ final state

Some technical details:

- Axis orientation: $\hat{z}$ along $\vec{k}_Z$, $\hat{x}$ in the production plane
- Cross section NNNL order is 48.61 pb at a centre-of-mass energy of 13 TeV (6.02 fb in the specific final state)
- Lepton detection efficiency: 0.7 (ie, overall 0.25)
- Luminosity: 300 fb^{-1} (3. ab^{-1}) for LHC Runs 2+3 (HL-LHC) respectively
- Stat. uncertainty in the observables is determined by performing 10^3 pseudo-experiments.
- Results are presented with / without cuts in m_{Z_2}

Numerical results

LHC Runs 2+3

300 fb^{-1}

	min m_{Z_2}			
	0	10 GeV	20 GeV	30 GeV
N	450	418	312	129
$C_{2,1,2,-1}$	-0.98 ± 0.31	-0.97 ± 0.33	-1.05 ± 0.38	-1.06 ± 0.61
$C_{2,2,2,-2}$	0.60 ± 0.37	0.64 ± 0.38	0.74 ± 0.43	0.82 ± 0.63
I_3	2.66 ± 0.46	2.67 ± 0.49	2.82 ± 0.57	2.88 ± 0.89

Entanglement ~ 2 σ

~~Bell~~ < 2 σ

Numerical results

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I_3	2.66 ± 0.46	2.67 ± 0.49	2.82 ± 0.57	2.88 ± 0.89

Entanglement ~ 2 σ

~~Bell~~ < 2 σ

HL - LHC

3 ab^{-1}

	min m_{Z_2}			
	0	10 GeV	20 GeV	30 GeV
N	4500	4180	3120	1290
$C_{2,1,2,-1}$	-0.95 ± 0.10	-1.00 ± 0.10	-1.04 ± 0.12	-1.04 ± 0.19
$C_{2,2,2,-2}$	0.60 ± 0.12	0.64 ± 0.12	0.74 ± 0.14	0.83 ± 0.20
I_3	2.63 ± 0.15	2.71 ± 0.16	2.81 ± 0.18	2.84 ± 0.28

Entanglement ~ 5 σ

~~Bell~~ ~ 4.5 σ

If New Physics in HZZ: consequences?

- At lowest other the Standard Model HZZ vertex is modified as:

$$V^{\mu\nu}_{HZZ} = \frac{igm_Z}{\cos\theta_W}\left[a\, g_{\mu\nu} + b\,\frac{p_\mu p_\nu}{m_Z^2} + c\,\epsilon_{\mu\nu\alpha\beta}\,\frac{p^\alpha k^\beta}{m_Z^2}\right]$$

CP conserving tree-level SM coupling: a=1, (b, c)=0

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- The previous results can be generalized

$$|\psi_{ZZ}\rangle \equiv |\psi_{ZZ}\rangle\,(k_Z\,, b, c)$$

$$\rho \equiv \rho\,(b, c)$$

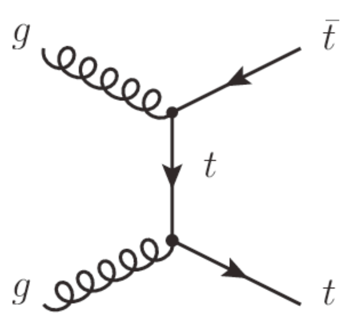
Aoude, Madge, Maltoni, Mantani 2023

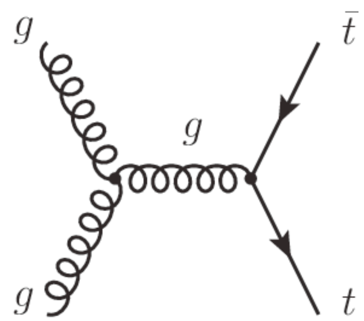
Fabbrichesi, Floreanini, Gabrielli, Marzola, 2023

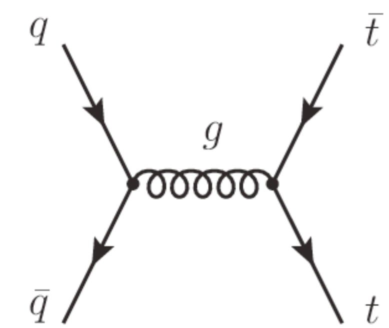
The optimal Bell operator will depend on (b,c)

Bernal, Caban, Rembieliński 2023

$t\bar{t}$ tomography at @ LHC







The generated $t\bar{t}$ system is in a (mixed) entangled state of spin, i.e. a 2-qubit system

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

3+3+9 components

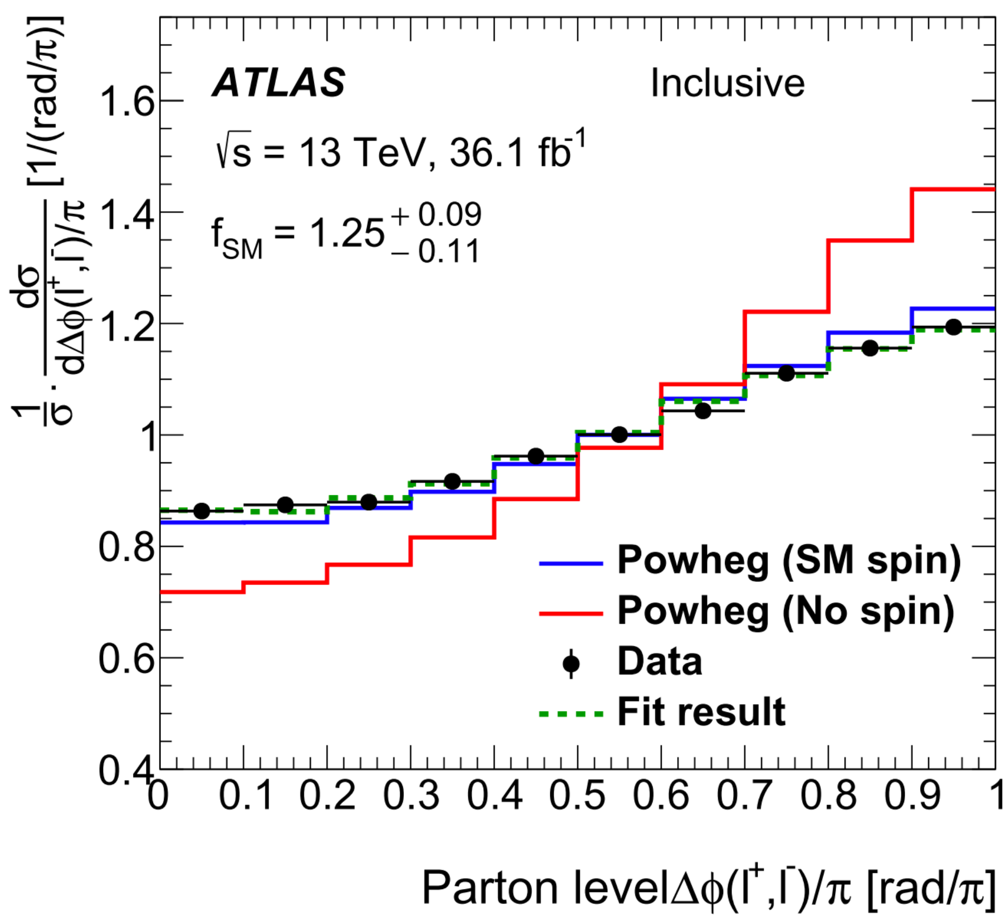
Afik , de Nova, 2021

…..

(See previous list)

$t\bar{t}$ spin correlations: origin & effects

One effect: dilepton azimutal correlation in $t\bar{t} \to W^+ b\, W^- \bar{b} \to l^+ \nu b\, l^- \bar{\nu} \bar{b}$



ATLAS, Eur. Phys.J.C 80 (2020) 8, 754

Origin of the correlation?

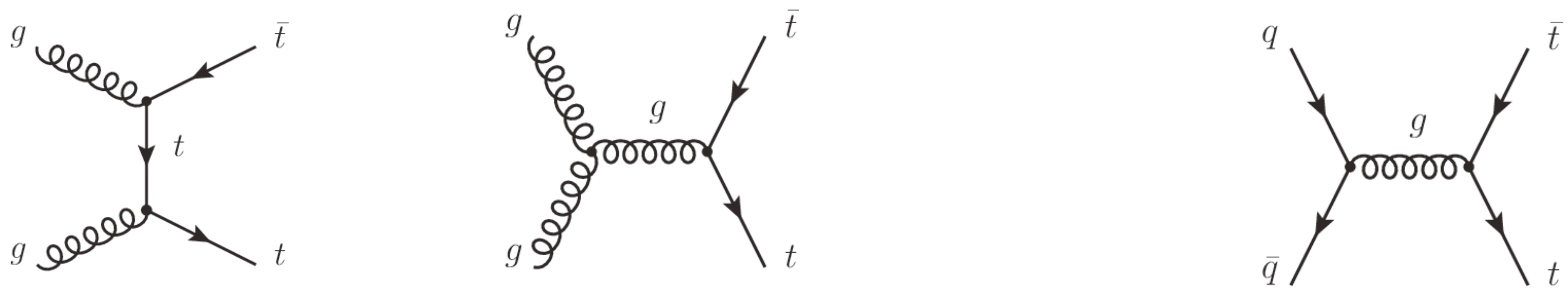
G. Mahlon, S.J. Parke, Phys.Rev.D81:074024,2010

- At the LHC top quark pairs are mainly produced via gluon fusion: gg → tt
- They are unpolarized at leading order (LO)
- A small longitudinal polarization arises from electroweak corrections
- The spins of the top quarks and antiquarks are strongly correlated
- The configuration of spins depends on m_{tt}, the invariant mass of the tt pair with same (oposite) helicity pairs dominating at low (high) m_{tt}

Extracting the spin correlations:

Aguilar Saavedra, Fiolhais, Martin-Ramiro, Moreno, Onofre 2021

$t\bar{t}$ tomography at @ LHC



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Afik , de Nova, 2021
…..
(See previous list)

- ENTANGLEMENT By imposing kinematical cuts (e.g. $m_{t\bar{t}}$) it is possible to *reshape* ρ enhancing the entanglement (larger near threshold) of the top pair system. Also, dedicated observables have been proposed

- BELL $|C_{ii} \pm C_{jj}| > \sqrt{2}$ ~~CHSH~~

Aguilar-Saavedra, Casas 2023

- PROSPECTS Feasible to detect entanglement in Run 2 and CHSH violation at HL LHC

Conclusions

- LHC data offer us the opportunity to test both, entanglement and Bell inequalities, at high energies
- The quantum state of ZZ pairs produced in Higgs decays is a great system to test them:
  - Run 2+3: ρ_{ZZ} entangled ~ 2σ
  - HL-LHC: ρ_{ZZ} entangled > 5σ and ~~Bell Inequalities~~ 3σ.

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- Relevant (and perhaps crucial) aspects

  - Improving Quantum Tomography (careful choice of ρ basis, etc)
  - Optimizing Bell operators

THANKS