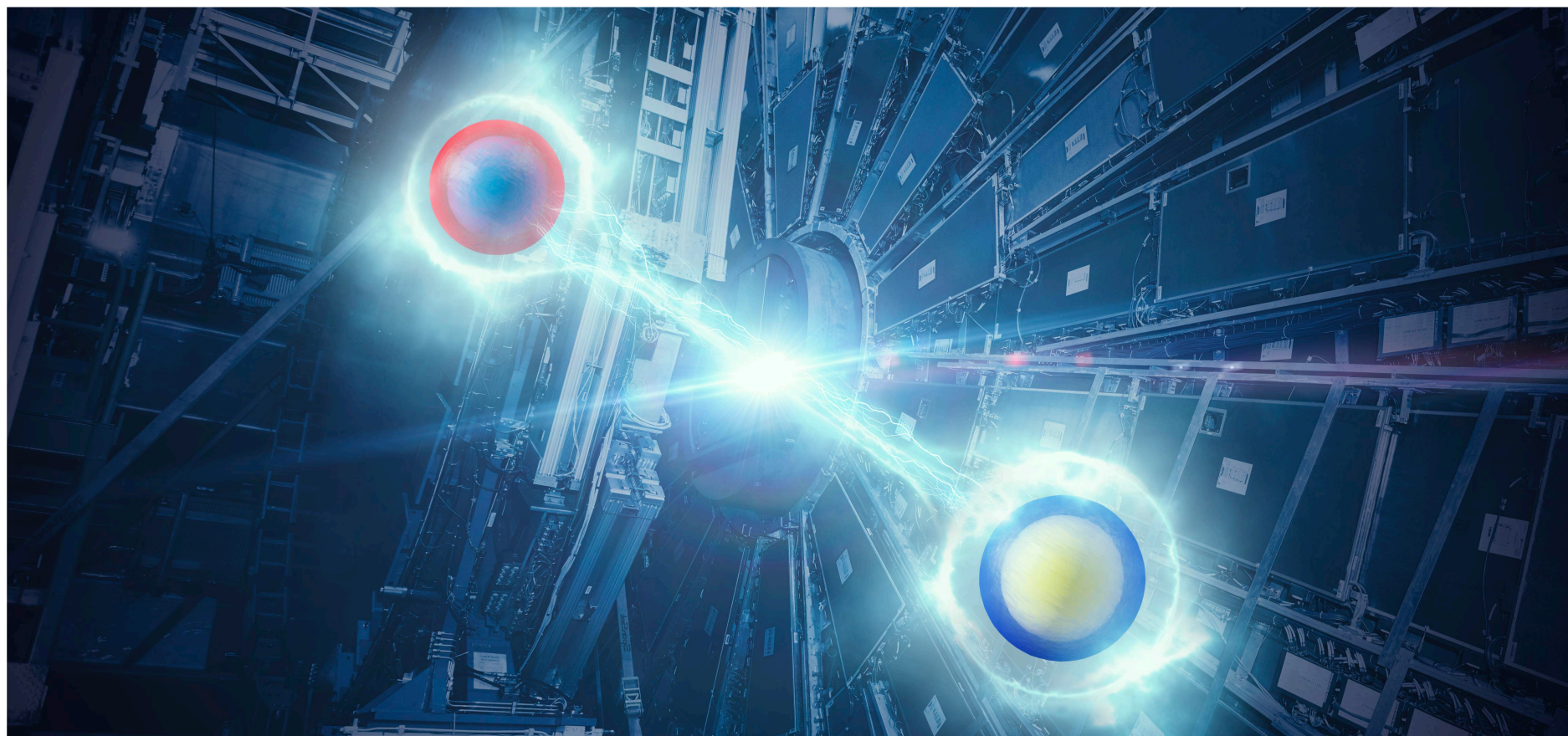


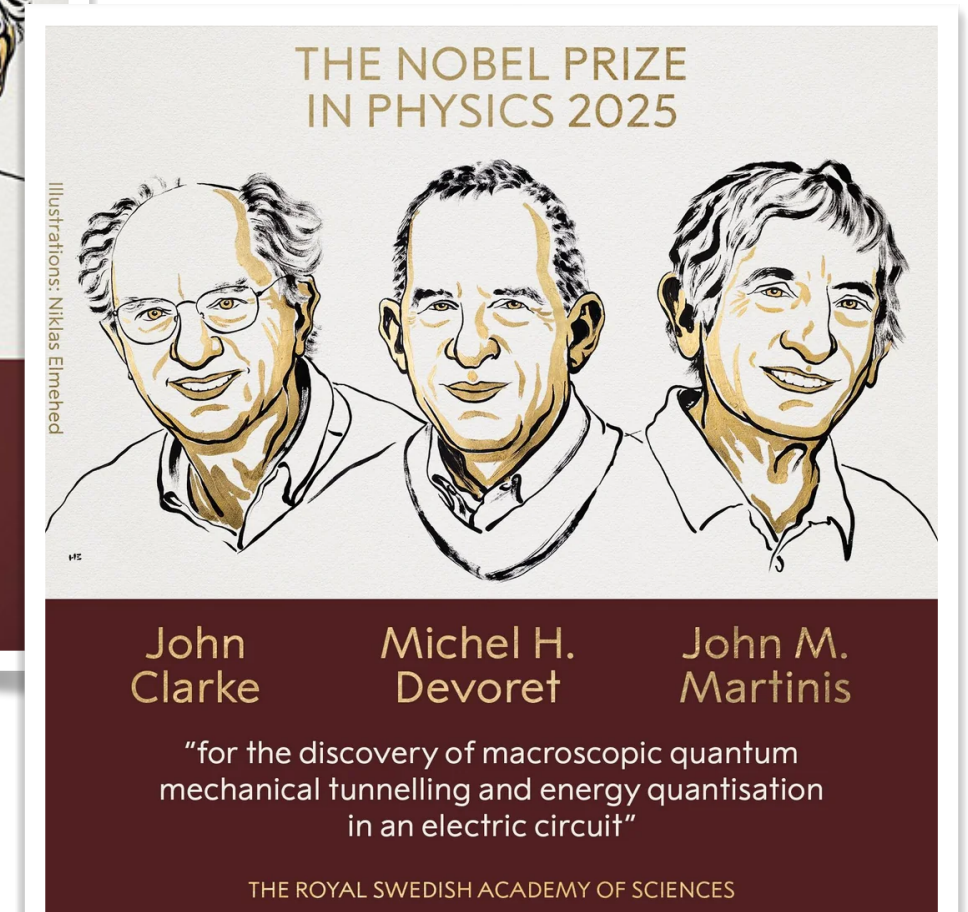
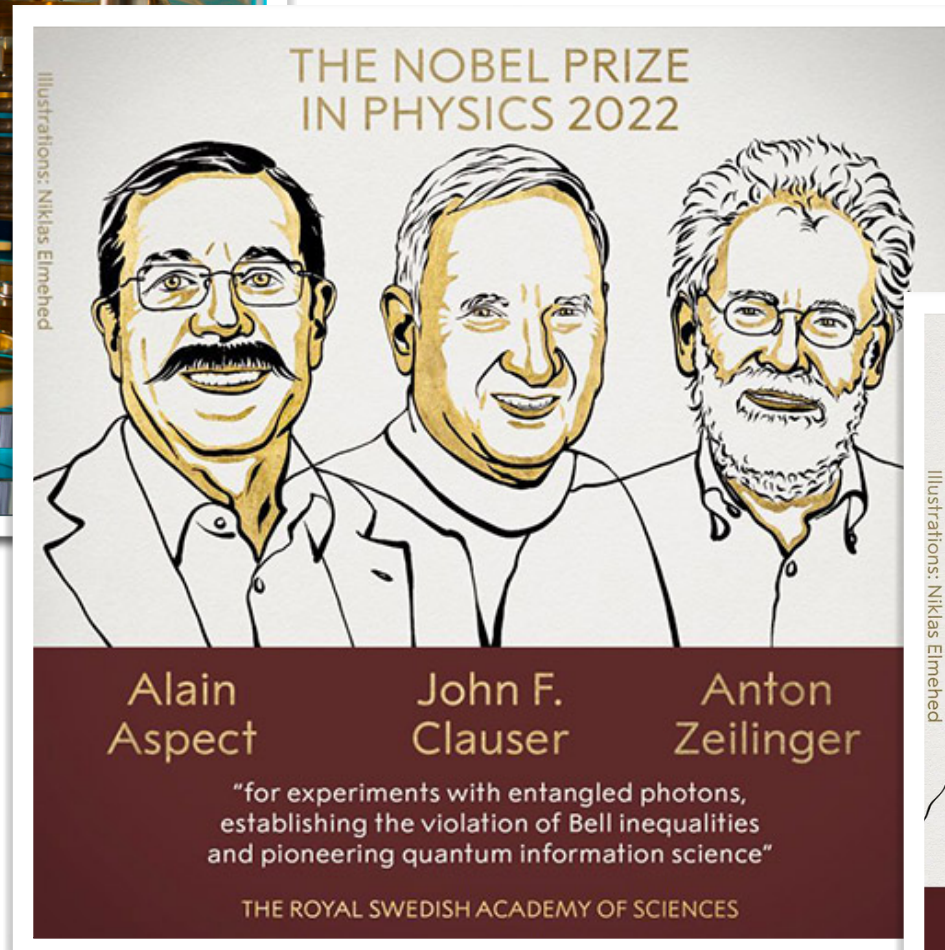
Quantum Information Meets Collider Physics

PARTIQAL 2026 - 07.16.2026

Dorival Gonçalves 

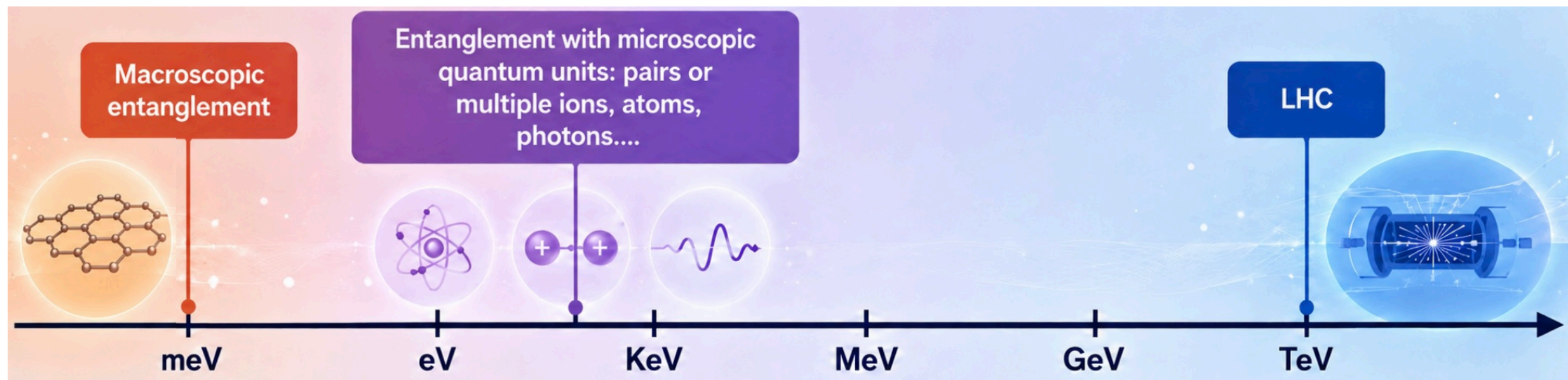


Introduction



QIS provides a set of tools designed to probe the inner behavior of QM. While these phenomena have been widely tested at low energies, their study at higher energy scales is still largely unexplored

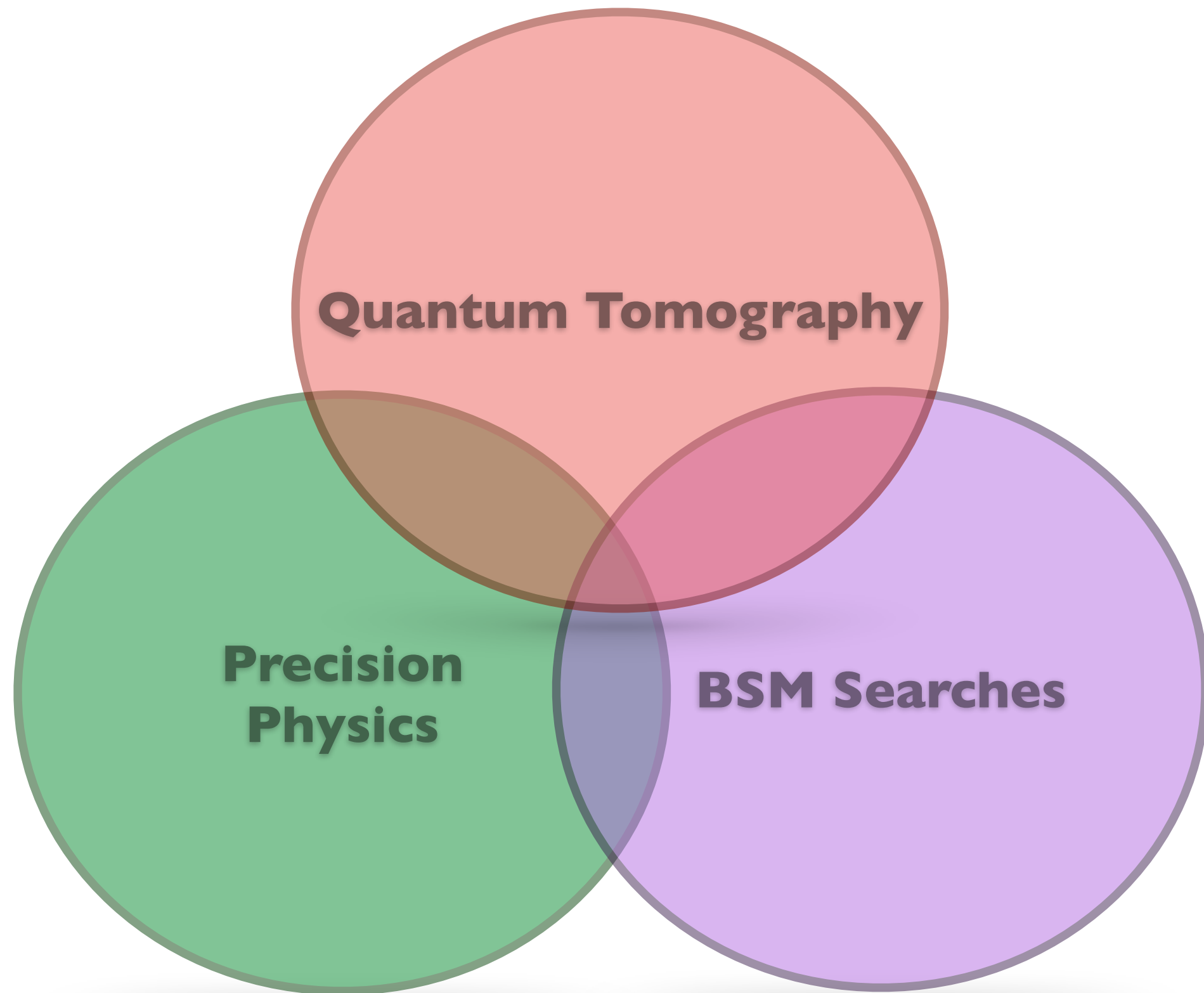
Introduction



LHC can provide a unique environment to study quantum correlations such as entanglement at the highest energy available to date

Introduction

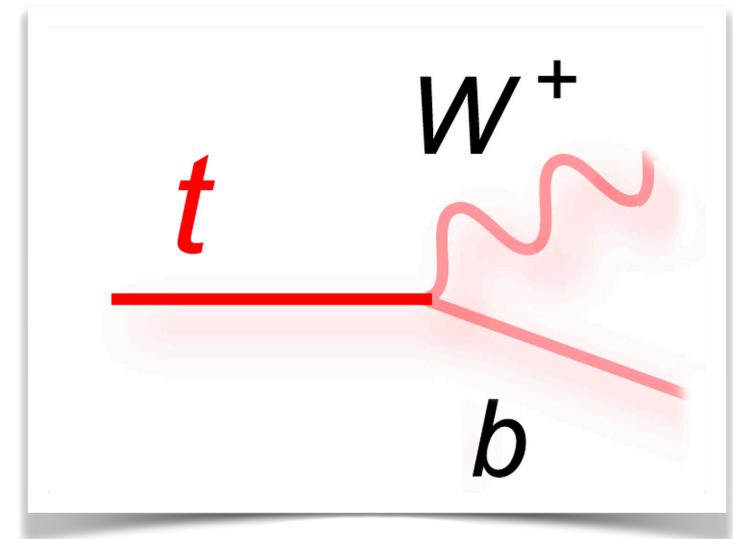
- The quantum nature of particle physics is obviously foundational, as it is formulated within QFT
- Numerous tools/ideas in QIS. What insights can they bring to HEP? And conversely
- Numerous new systems at the LHC:
 - New particles
 - Highly energetic
 - Bipartite ($t\bar{t}$, $\tau\tau$, VV , tW ,...) and multipartite ($t\bar{t}Z$, $t\bar{t}W$,...)
 - Presence of weak and strong interactions
- Can we use QIS tools to inform BSM searches?
- Can we use these tools as a guide for model building?
- Recent growing interest in HEP community



Top quark as a one qubit system

- As a spin-1/2 particle, the most general spin density matrix for the top quark is

$$\rho = \frac{\mathbb{I} + B_i \sigma_i}{2}$$



- Characterized by three parameters: $B_i = \langle \sigma_i \rangle = \text{tr}(\sigma_i \rho)$

➡ However, the top quark decays. In general, spin information could be lost by hadronization or spin decorrelation effects

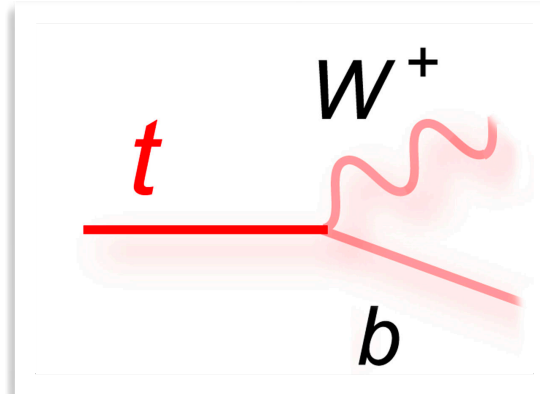
Top Quark is Unique

- Decays before it hadronizes or its spin flips

$$\tau_{top} \approx 5 \times 10^{-25} s$$

$$\tau_{had} \sim 1/\Lambda_{QCD} \sim 10^{-24} s$$

$$\tau_{flip} \sim m_t/\Lambda_{QCD}^2 \sim 10^{-21} s$$



Bottom quark is several orders of magnitude behind $\tau_b \approx 10^{-12} s$

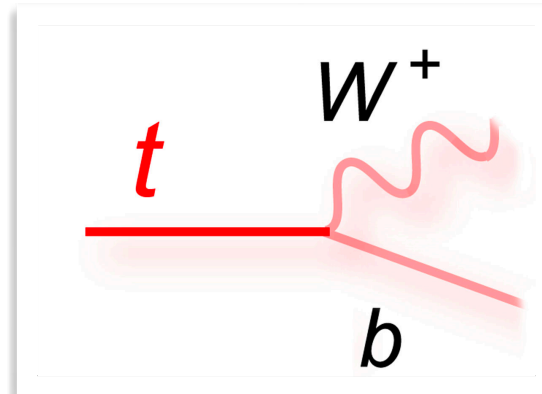
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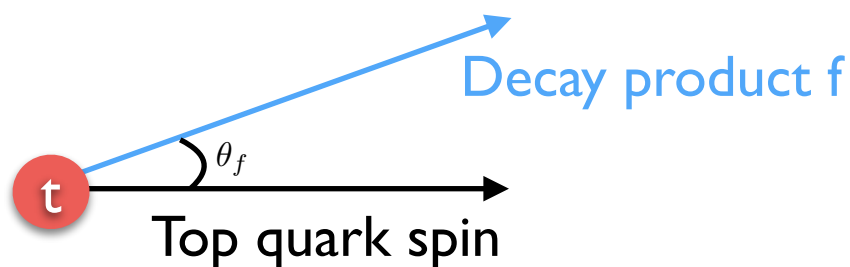
Bottom quark is several orders of magnitude behind $\tau_b \approx 10^{-12} s$

- Top polarization directly observable via angular distributions of its decay products

$$\frac{1}{\Gamma} \frac{d\Gamma}{d \cos \theta_f} = \frac{1}{2} (1 + \beta_f p \cos \theta_f)$$

	$l^+, \bar{d}$	b	$\bar{\nu}, u$
β_f	1	-0.4	-0.3

Spin analyzing power: maximum for charged leptons



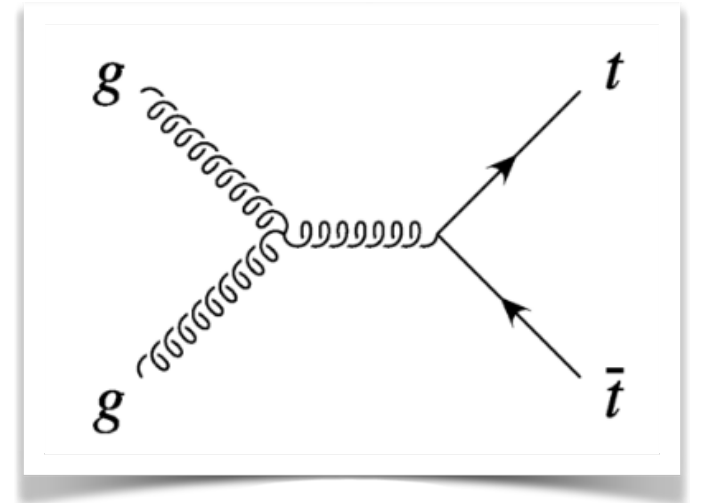
$$\beta_{\ell^+}^{\text{NLO}} = 0.998, \beta_{\bar{d}}^{\text{NLO}} = 0.966, \beta_b^{\text{NLO}} = -0.393$$

Brandenburg, Si, Uwer (2002)

Top quark pair production as a two qubit system

- The most general two-qubit system can be represented by

$$\rho = \frac{\mathbb{I} \otimes \mathbb{I} + (B_i \sigma_i \otimes \mathbb{I} + \bar{B}_i \mathbb{I} \otimes \sigma_i) + C_{ij} \sigma_i \otimes \sigma_j}{4}$$



- Characterized by 15 parameters: B_i , $\bar{B}_i$, and C_{ij}

$$\begin{aligned} B_i &= \langle \sigma_i \otimes \mathbb{I} \rangle \\ \bar{B}_i &= \langle \mathbb{I} \otimes \sigma_i \rangle \end{aligned} \quad \begin{array}{l} \searrow \\ \nearrow \end{array} \quad \text{Polarizations}$$

$$C_{ij} = \langle \sigma_i \otimes \sigma_j \rangle \longrightarrow \text{Spin correlations}$$

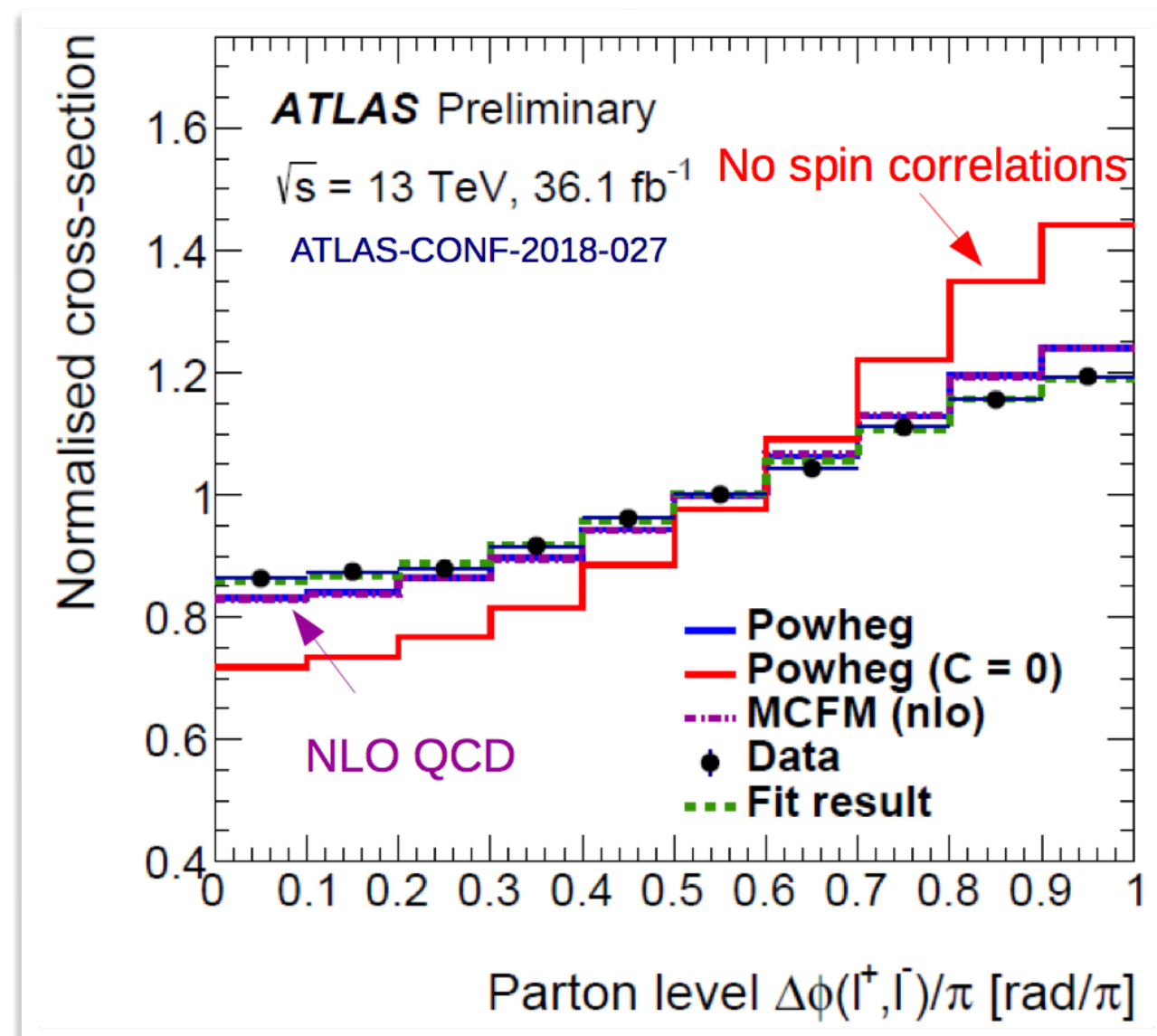
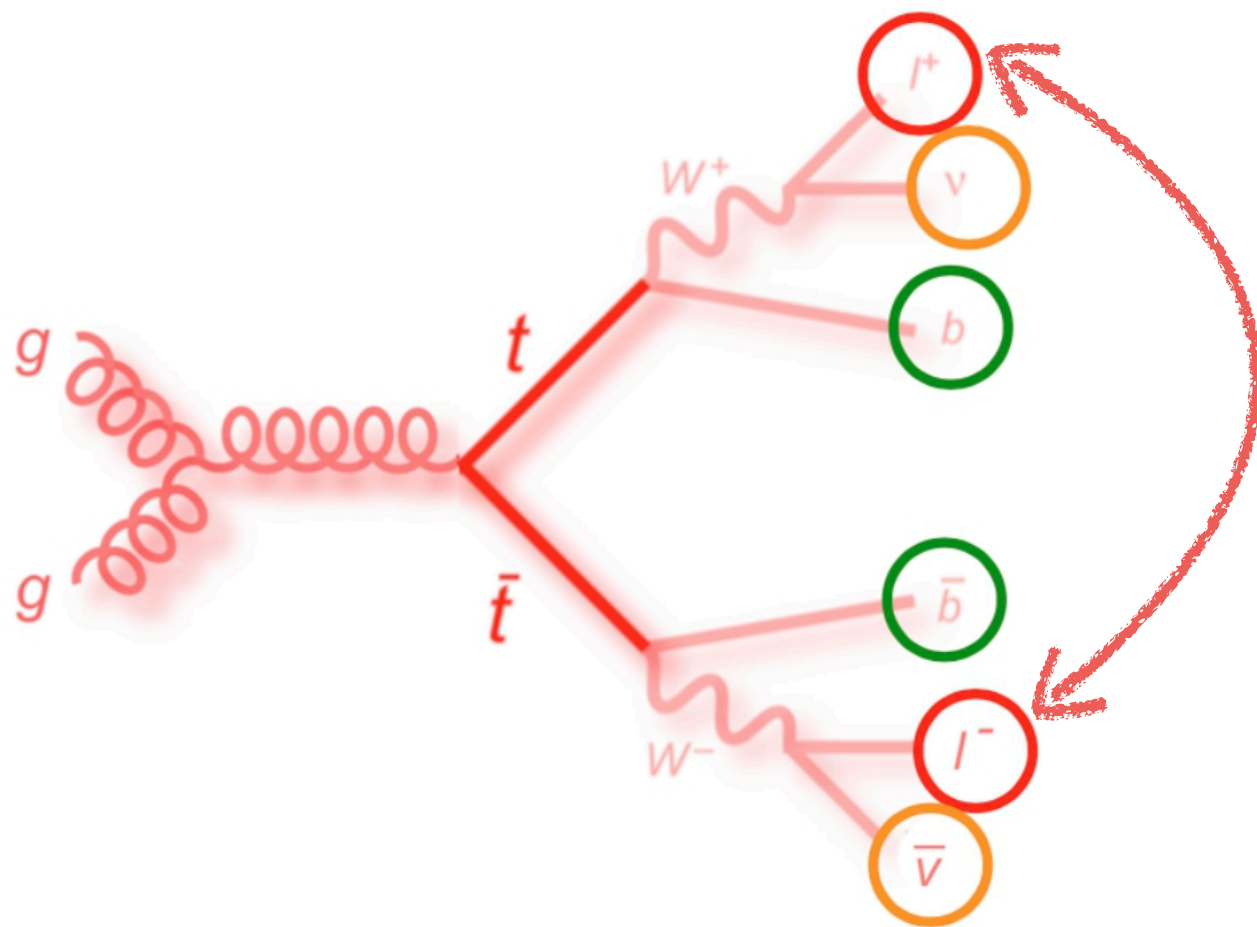
- P and CP invariance under $t\bar{t}$ production $\rightarrow B_i = \bar{B}_i = 0$ and $C_{ij} = C_{ji}$

- Things further simplify in the helicity basis: only non-vanishing parameters are the diagonal terms C_{ii} and one off-diagonal term C_{12}

Bernreuther, Heisler, Si '15
Czakon, Mitov, Poncelet '20
Frederix, Tsinikos, Vitos '21

Top quark pair production as a two qubit system

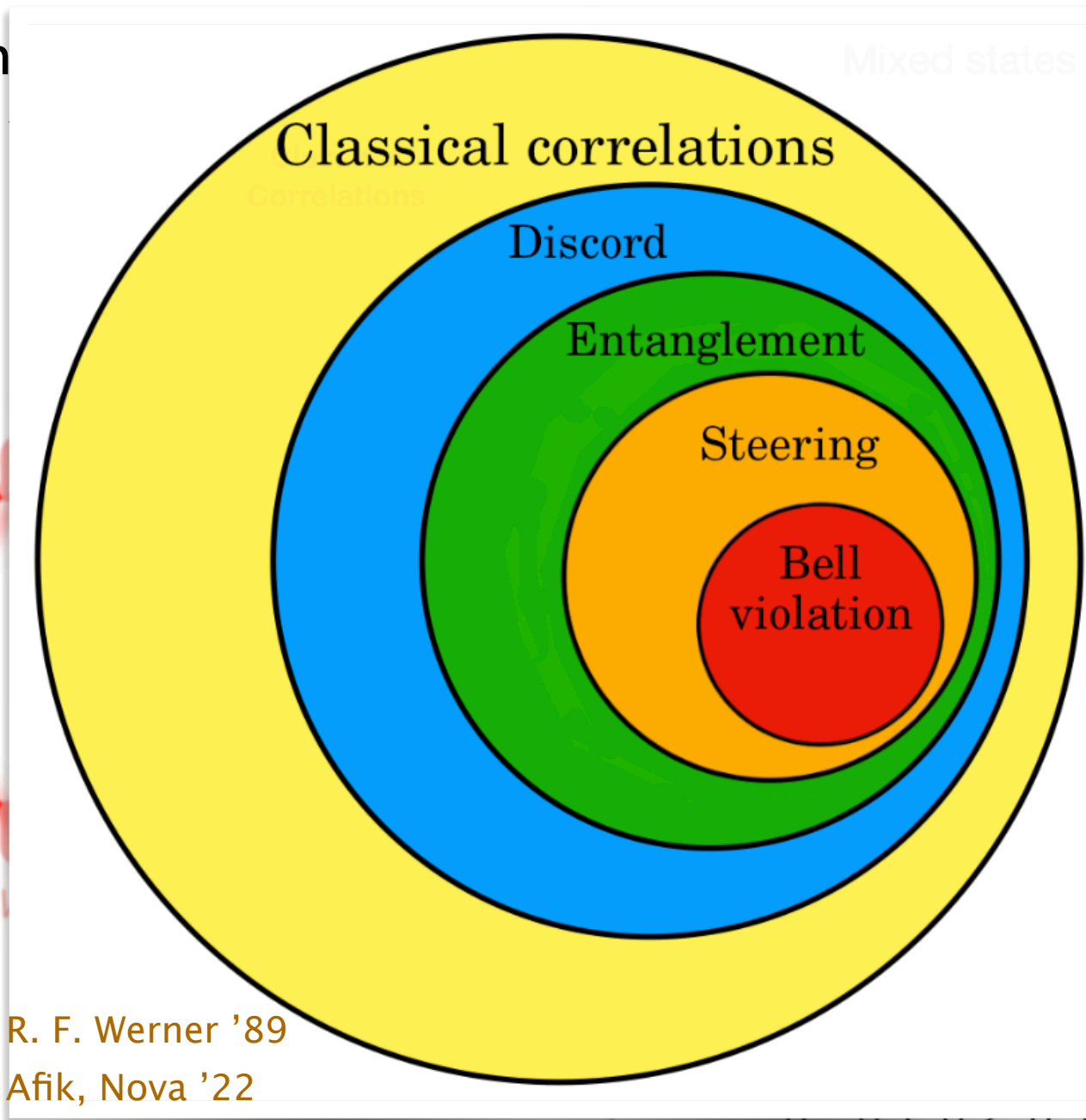
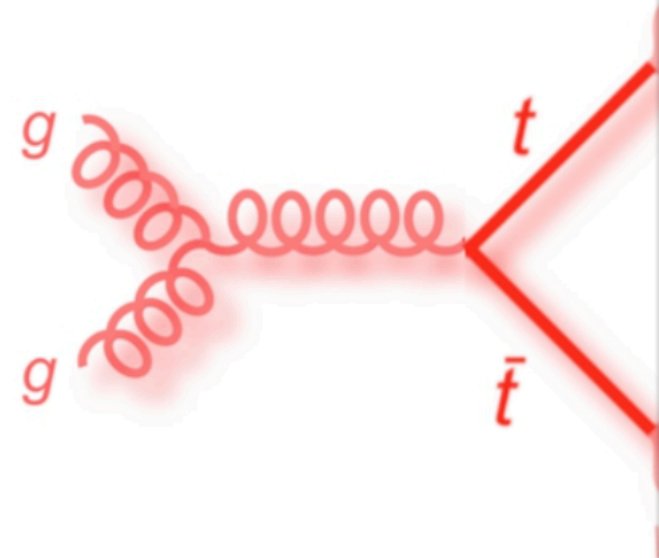
- We are probing the spin correlations of top and anti-top since the Tevatron era and continue to study them at the LHC in different forms: relevant precision observable



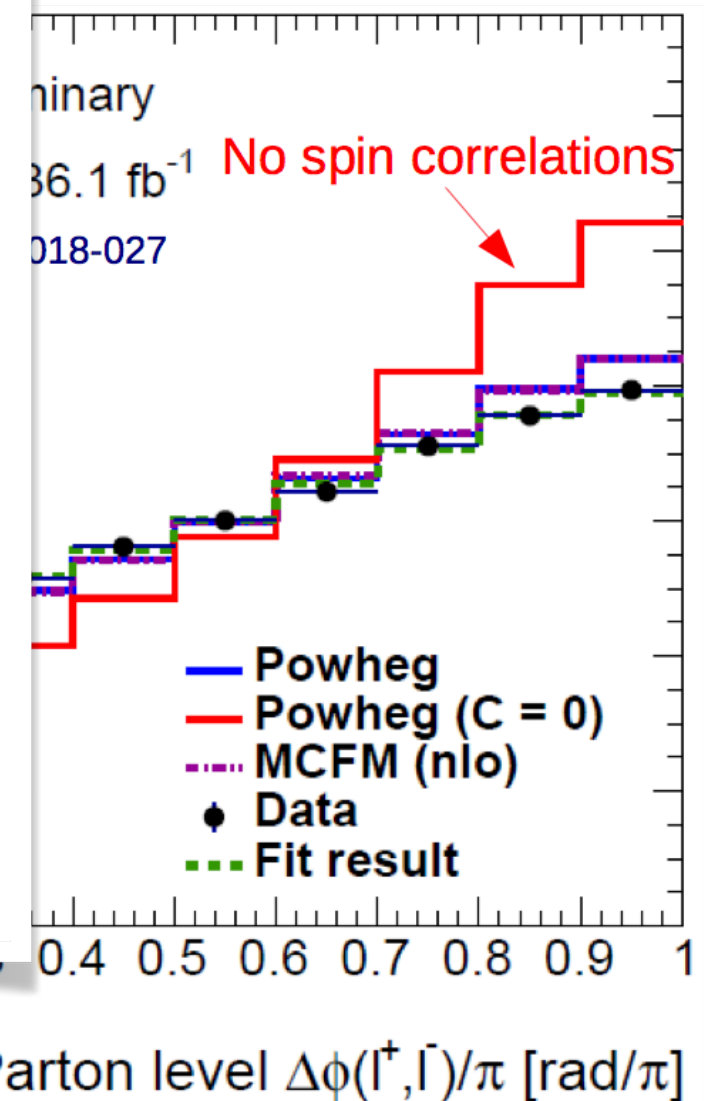
Parke, Mahlon '95

Top quark pair production as a two qubit system

● We are probing the
continue to study



the Tevatron era and
precision observable



Parke, Mahlon '95

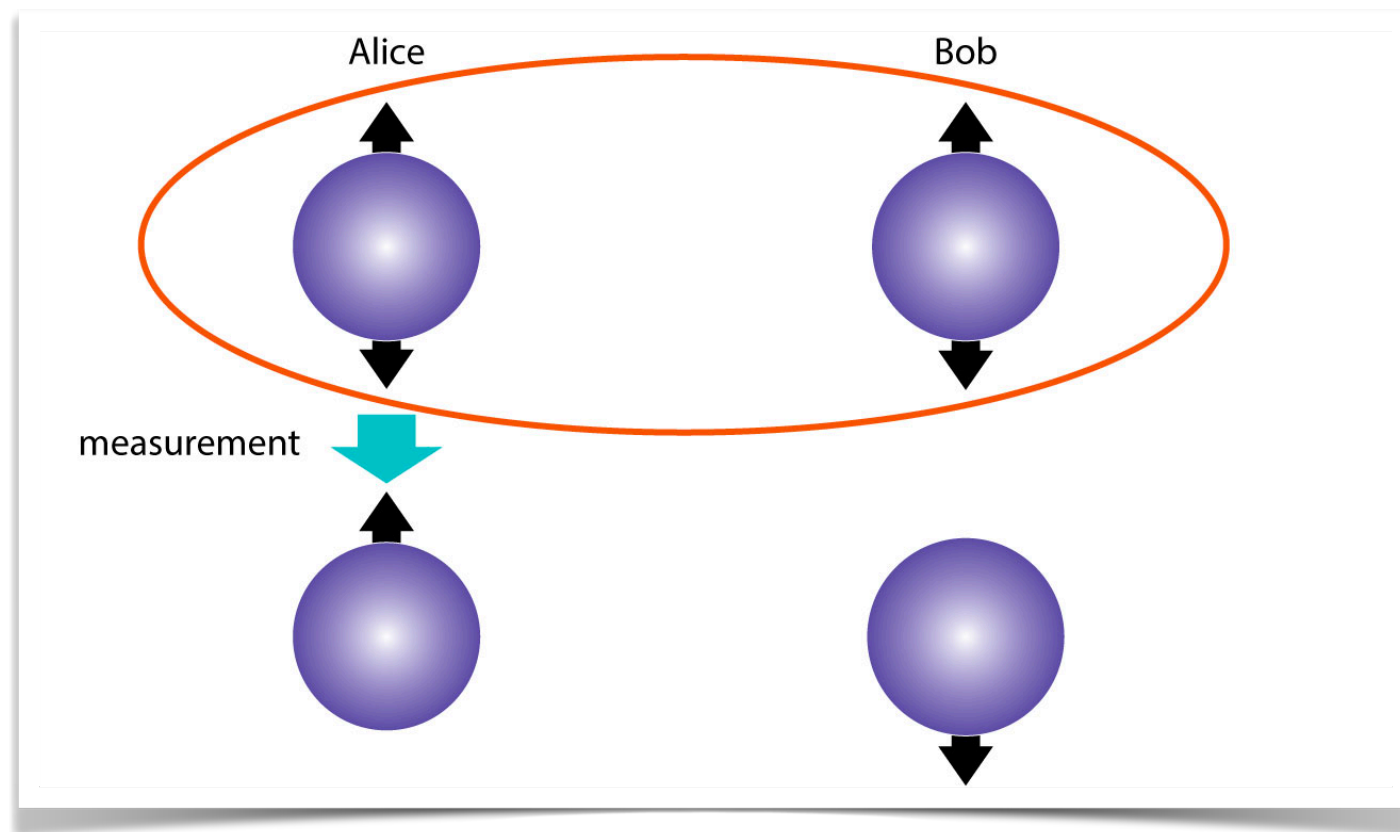
$$\rho = \frac{\mathbb{I} \otimes \mathbb{I} + (B_i \sigma_i \otimes \mathbb{I} + \bar{B}_i \mathbb{I} \otimes \sigma_i) + C_{ij} \sigma_i \otimes \sigma_j}{4}$$

Quantum Entanglement

- A quantum state of two subsystems A and B is separable when its density matrix ρ can be expressed as a convex sum

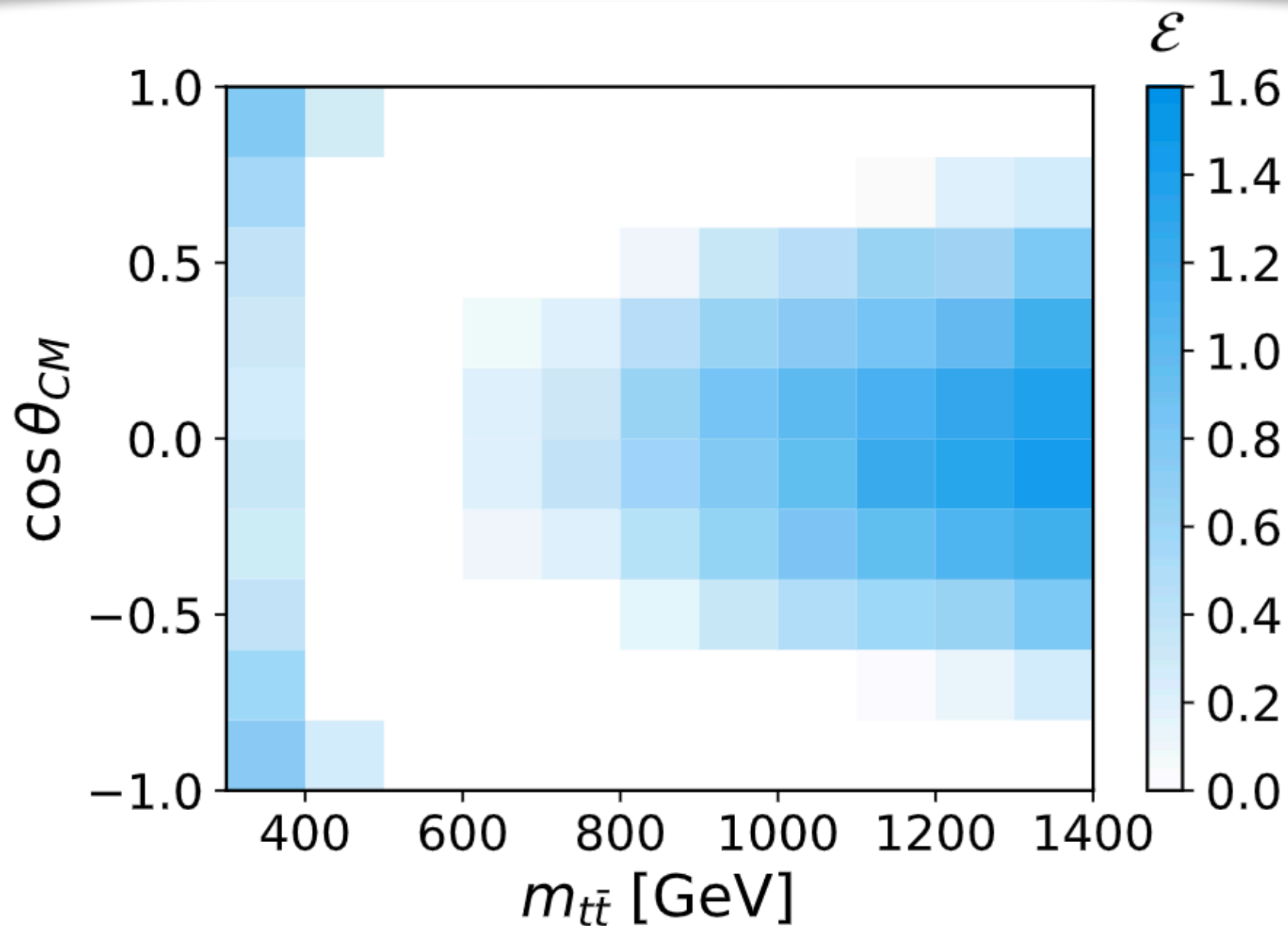
$$\rho = \sum_i p_i \rho_A^i \otimes \rho_B^i$$

→ If the state is not separable, it is named *entangled*



Measurement in one subsystem immediately affect the other, even if they are causally disconnected

Entanglement with Top Quark Pairs



→ Top pair displays entanglement in two disconnected regimes: **threshold** and **boosted** regions

dilepton:

Afik, Nova '20

Fabbrichesi, Floreanini, Panizzo '21

Severi, Boschi, Maltoni, Sioli '21

Saavedra, Casas '22; Severi, Vryonidou '22

lepton+jets:

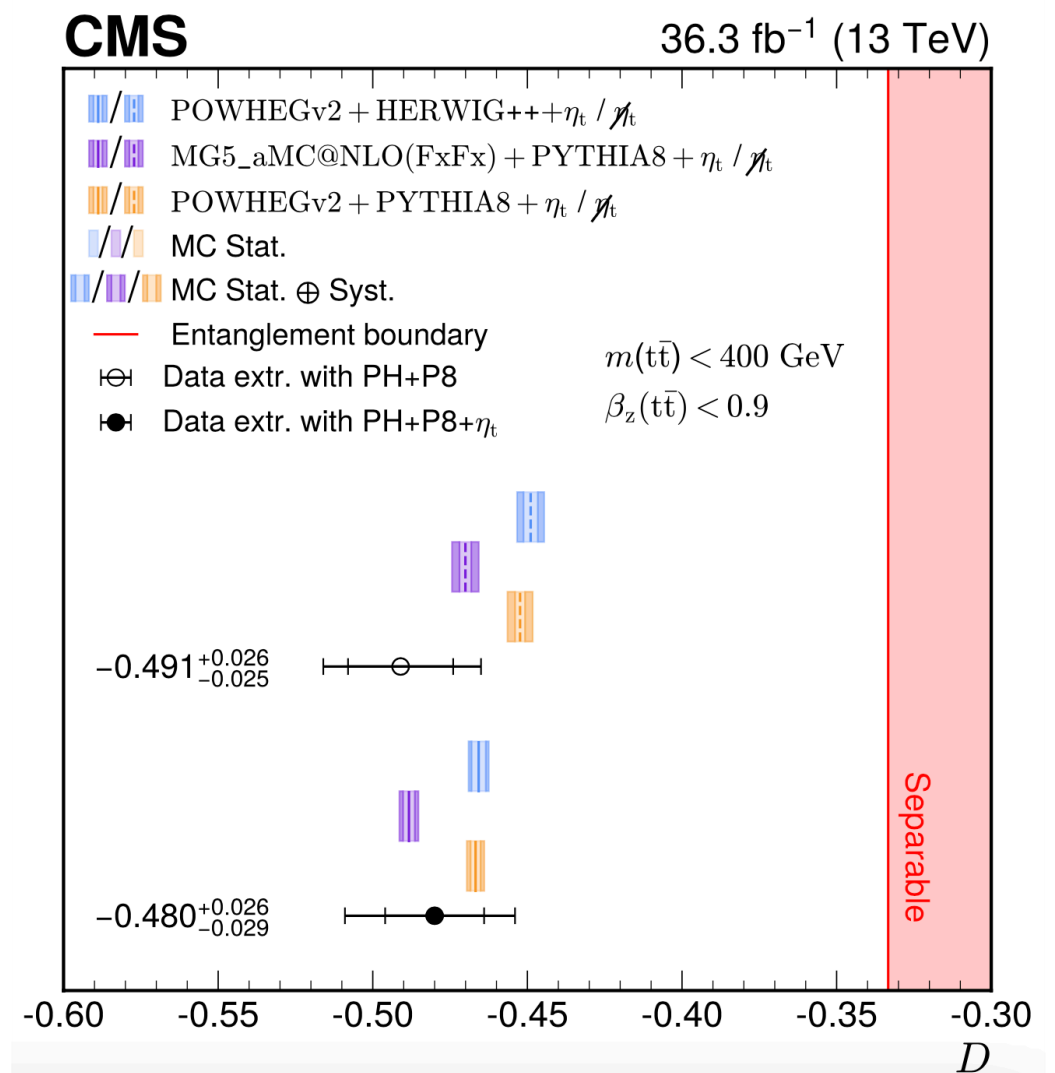
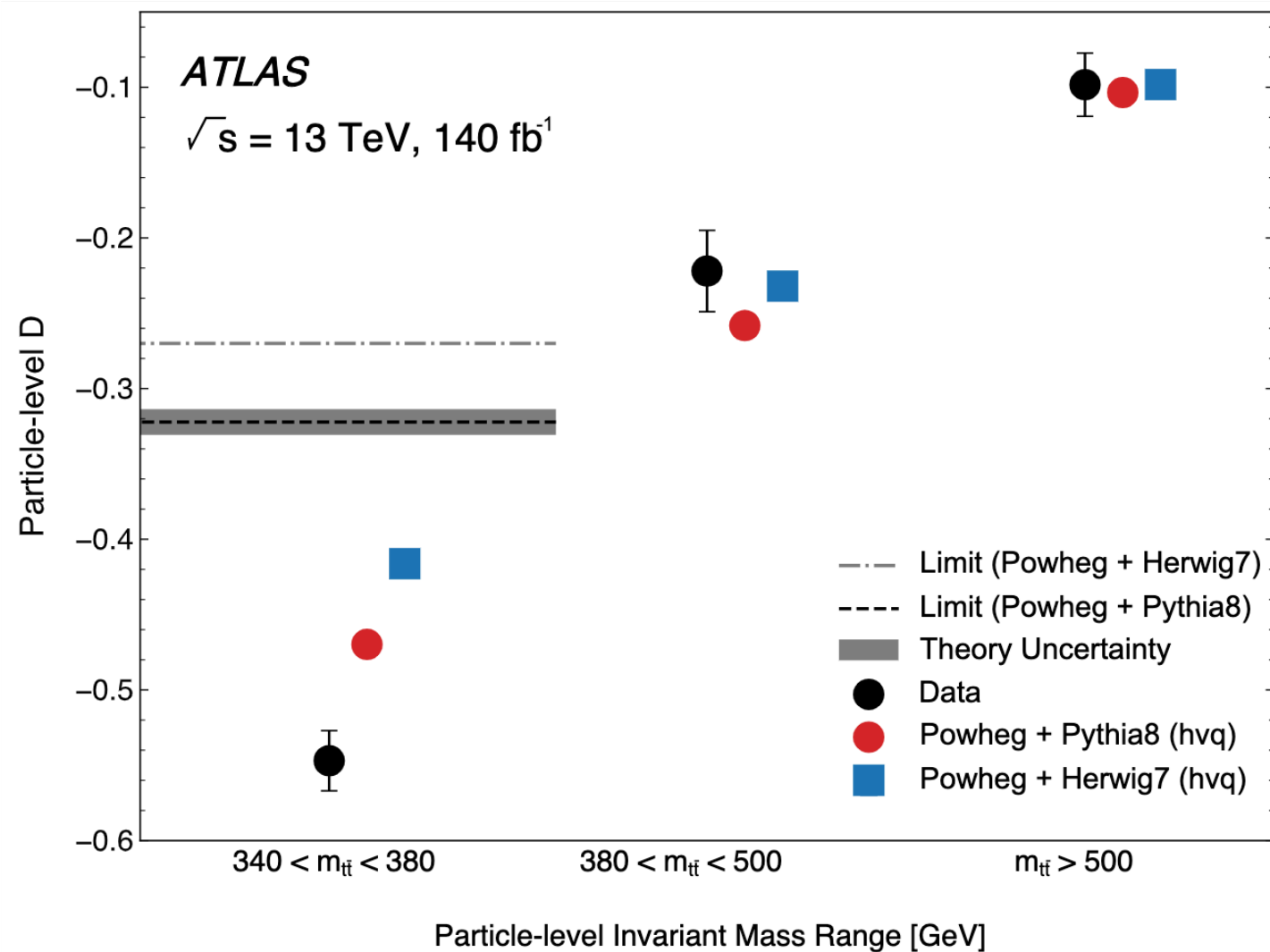
Dong, DG, Kong, Navarro '23

Han, Low, Wu '23

Experimental Observation



First observation of entanglement in a pair of quarks and the highest-energy observation of entanglement so far



Dilepton channel at $t\bar{t}$ threshold: [ATLAS Nature vol 633, 542–547 \(2024\)](#)

[CMS 2406.03976](#)

Lepton+jets channel at boosted regime: [CMS 2409.11067](#)

Entanglement above 5σ level, in agreement with theory expectations: [Dong, DG, Kong, Navarro '23](#)

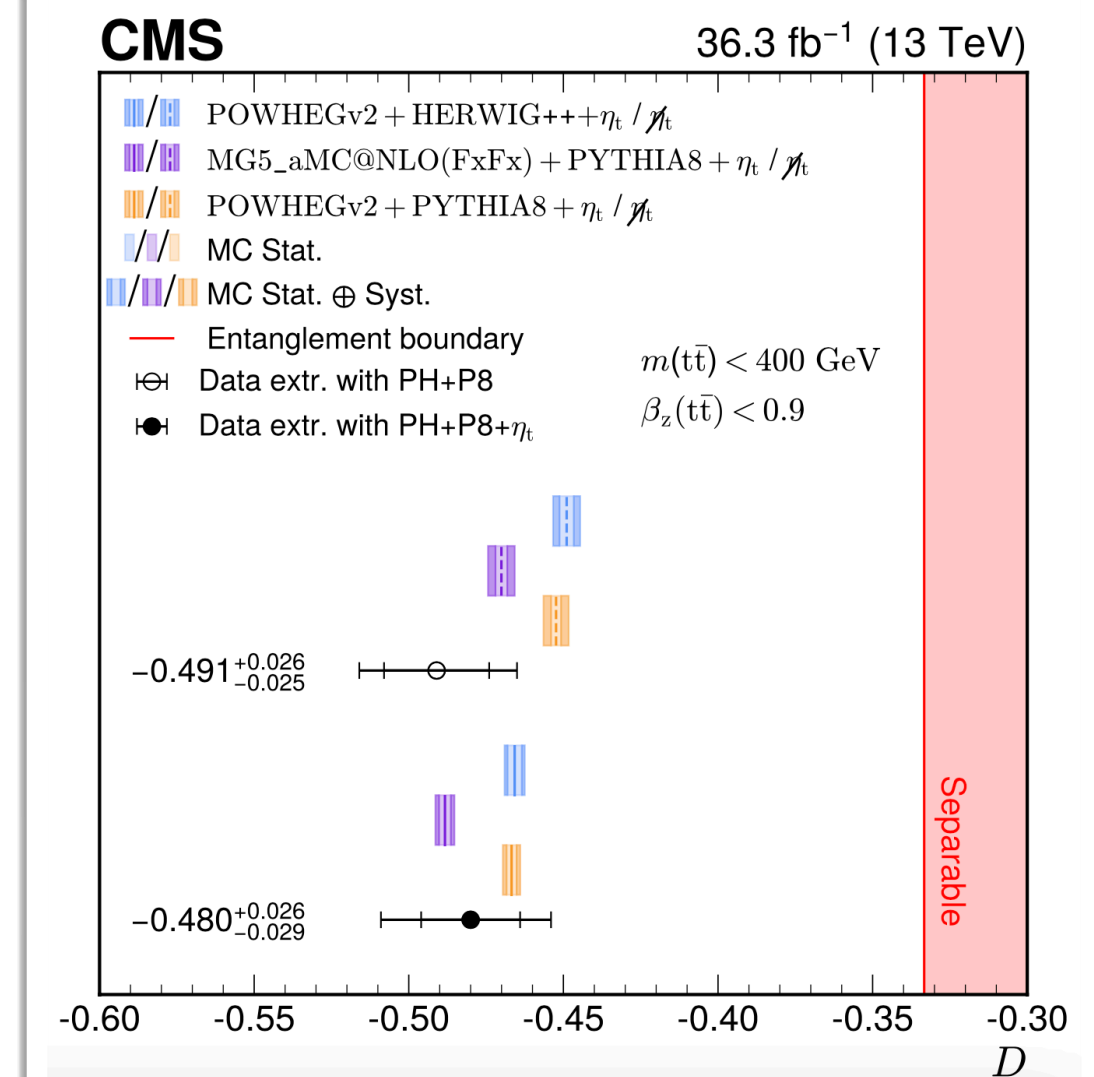
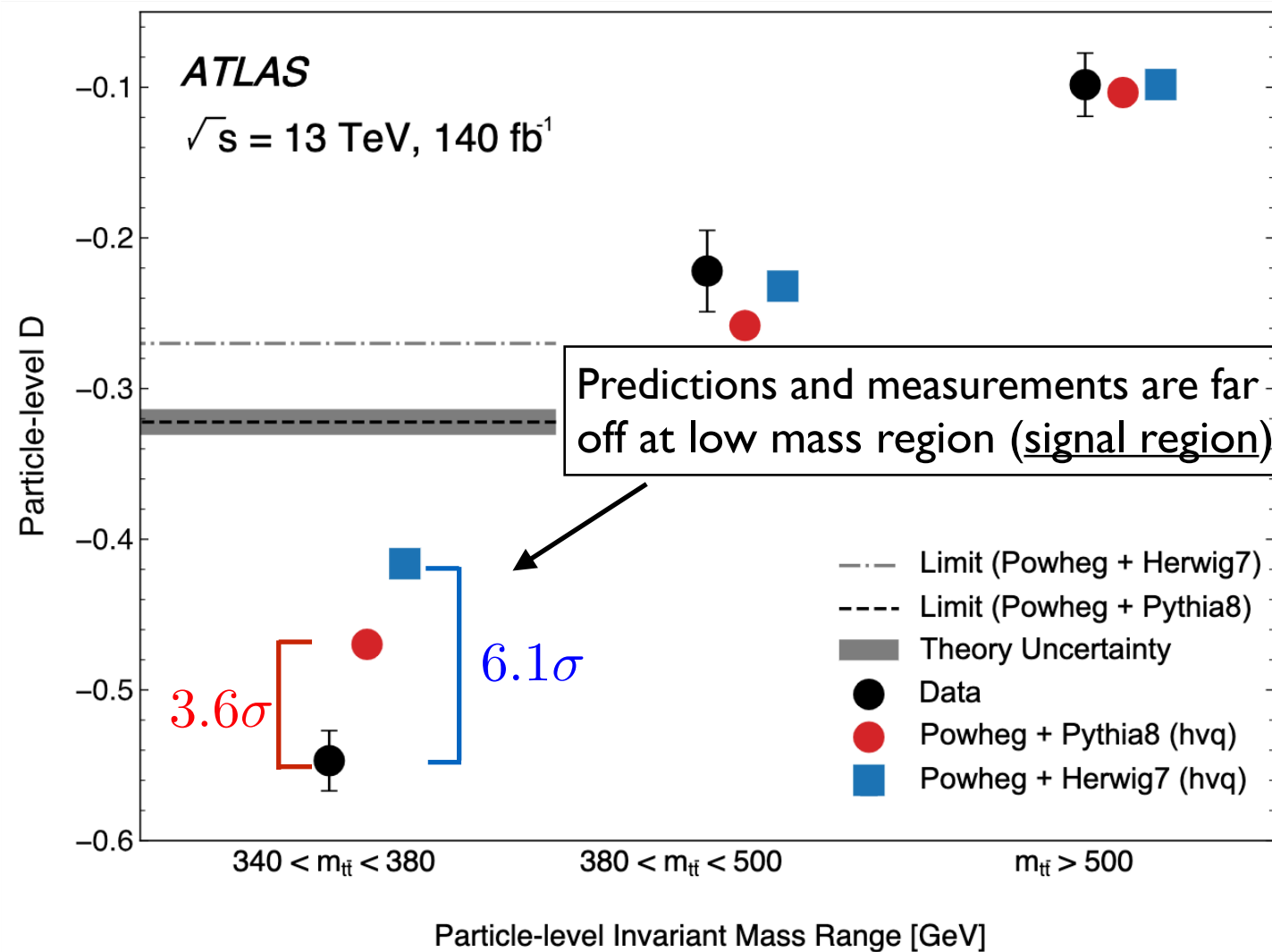
Hadronic top quark polarimetry with ML: [Dong, DG, Kong, Larkoski, Navarro '24](#)

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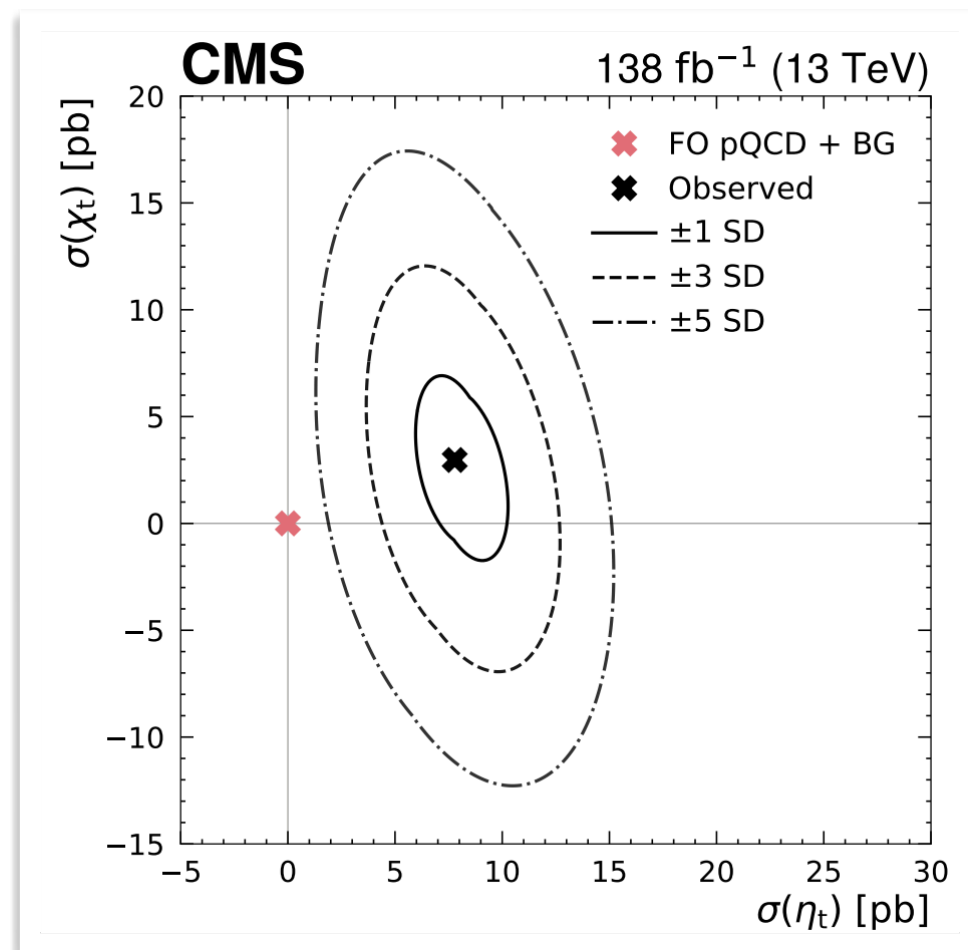
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[Dong, DG, Kong, Larkoski, Navarro '24](#)

Quantum Advantage in New Physics Searches?

Observation of a pseudoscalar excess at the top quark pair production threshold

The CMS Collaboration*



arXiv:2503.22382

Observation of new (SM) physics:

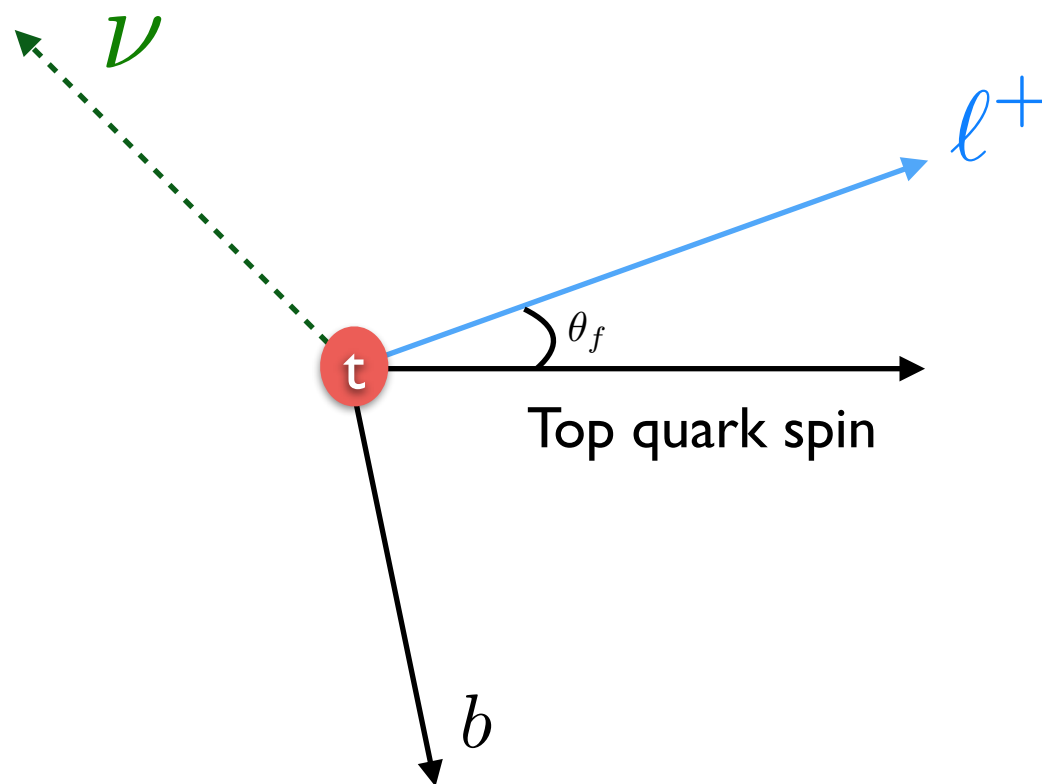
Theory effort to better understand the threshold region

Improve MC adding non-relativistic approximation

Fuks,Hagiwara,Ma,Zheng '24

Nason, Re, Rottoli '25...

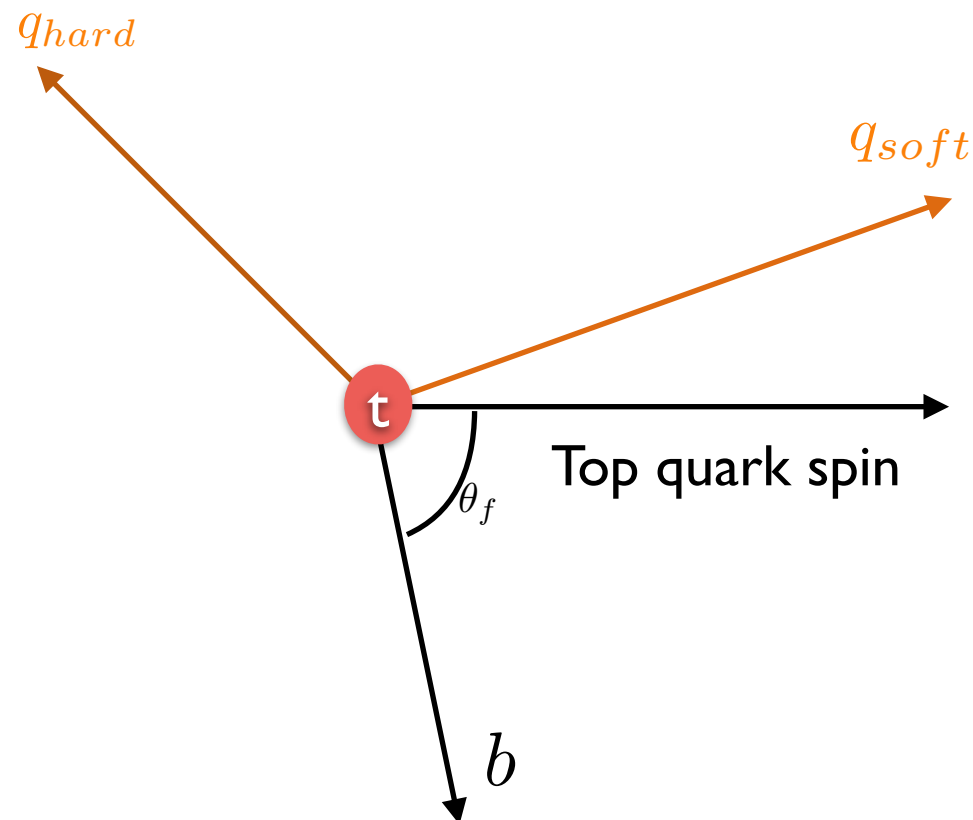
Hadronic top quark polarimetry



$$\frac{1}{\Gamma_f} \frac{d\Gamma_f}{d\cos\theta_f} = \frac{1}{2} (1 + \mathbf{1.0} \cos\theta_f)$$

Hadronic top quark polarimetry

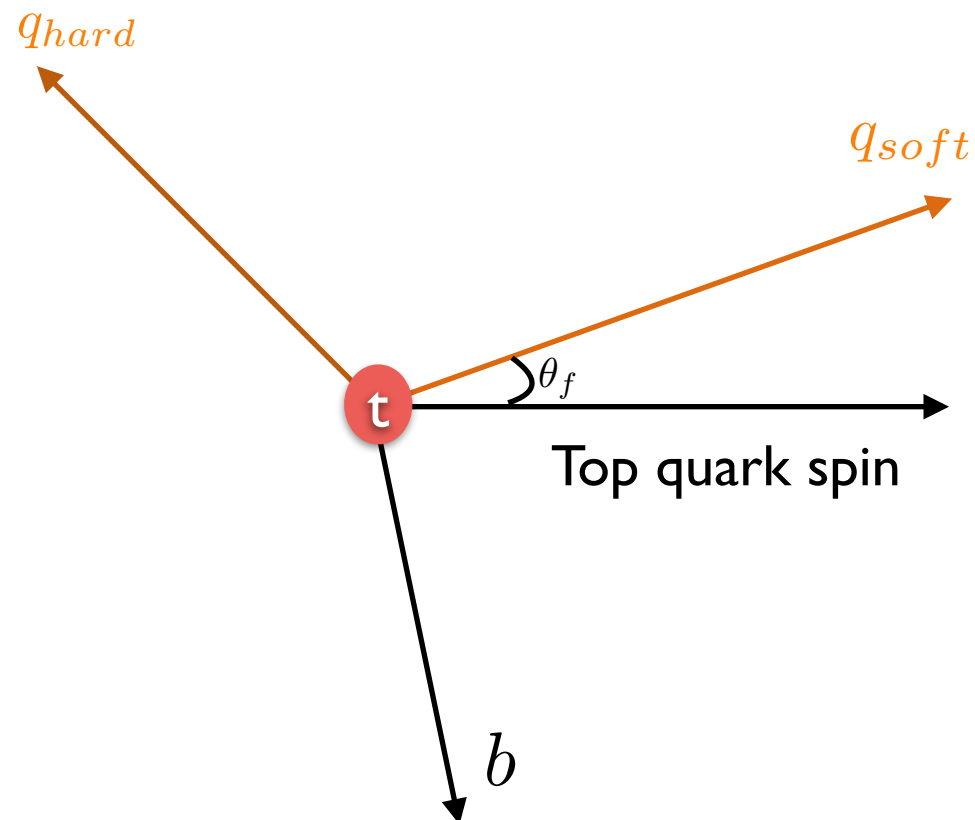
- In the high-energy regime, boosted techniques can be employed to tag the hadronic top and efficiently identify a spin analyzer



$$\frac{1}{\Gamma_f} \frac{d\Gamma_f}{d\cos\theta_f} = \frac{1}{2} (1 - 0.4 \cos\theta_f)$$

Hadronic top quark polarimetry

- In the high-energy regime, boosted techniques can be employed to tag the hadronic top and efficiently identify a spin analyzer

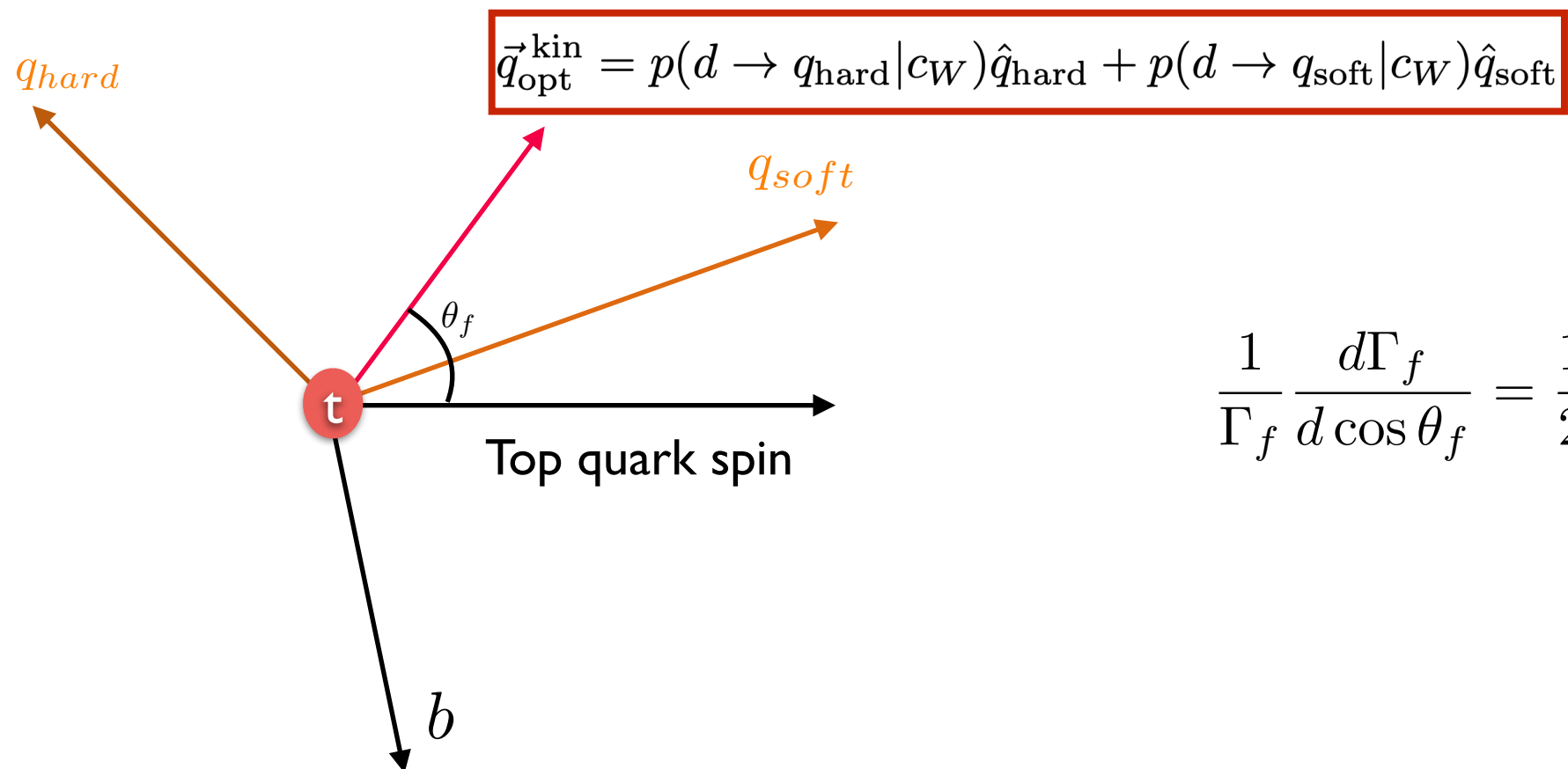


$$\frac{1}{\Gamma_f} \frac{d\Gamma_f}{d\cos\theta_f} = \frac{1}{2} (1 + \mathbf{0.5} \cos\theta_f)$$

Jezabek '94

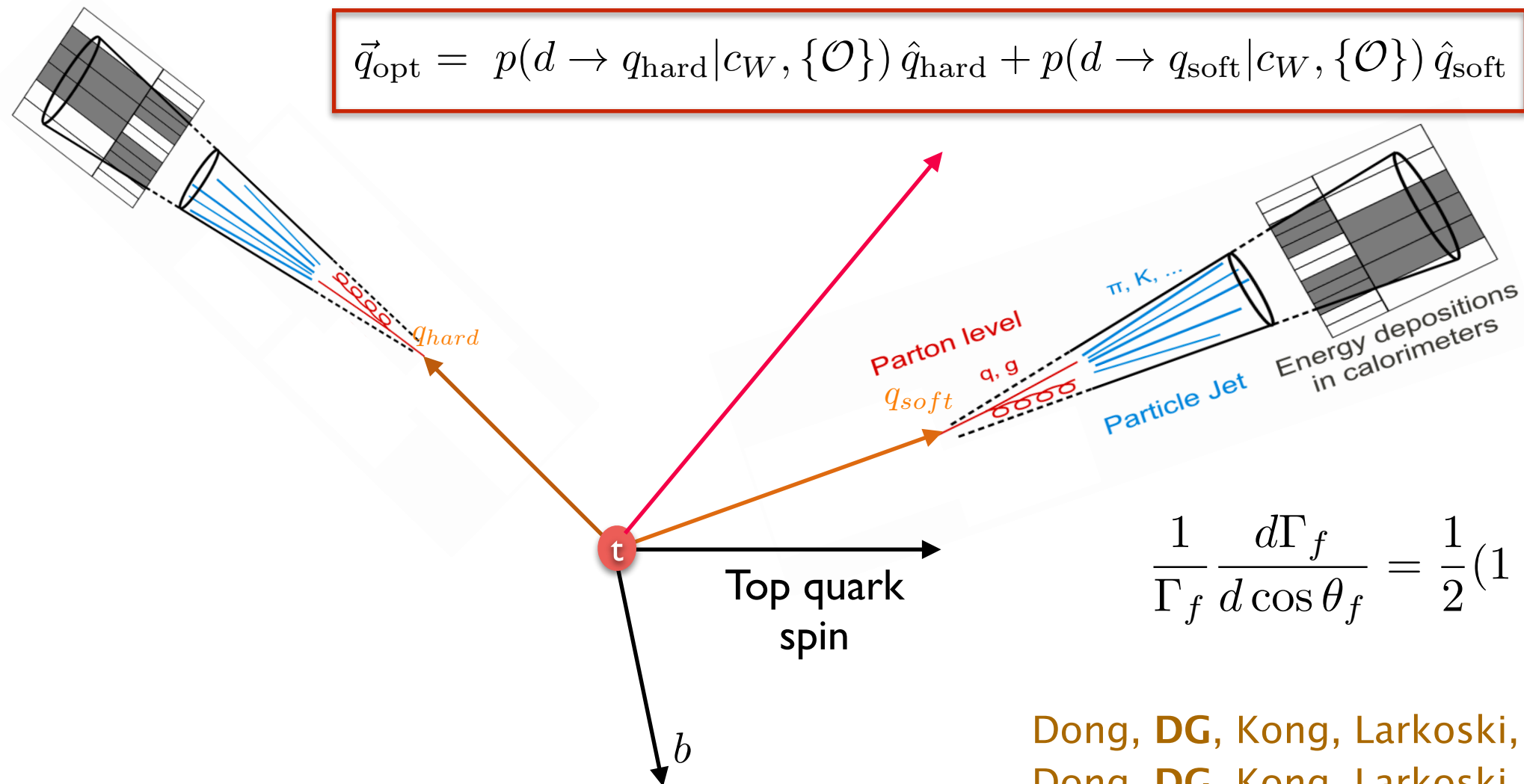
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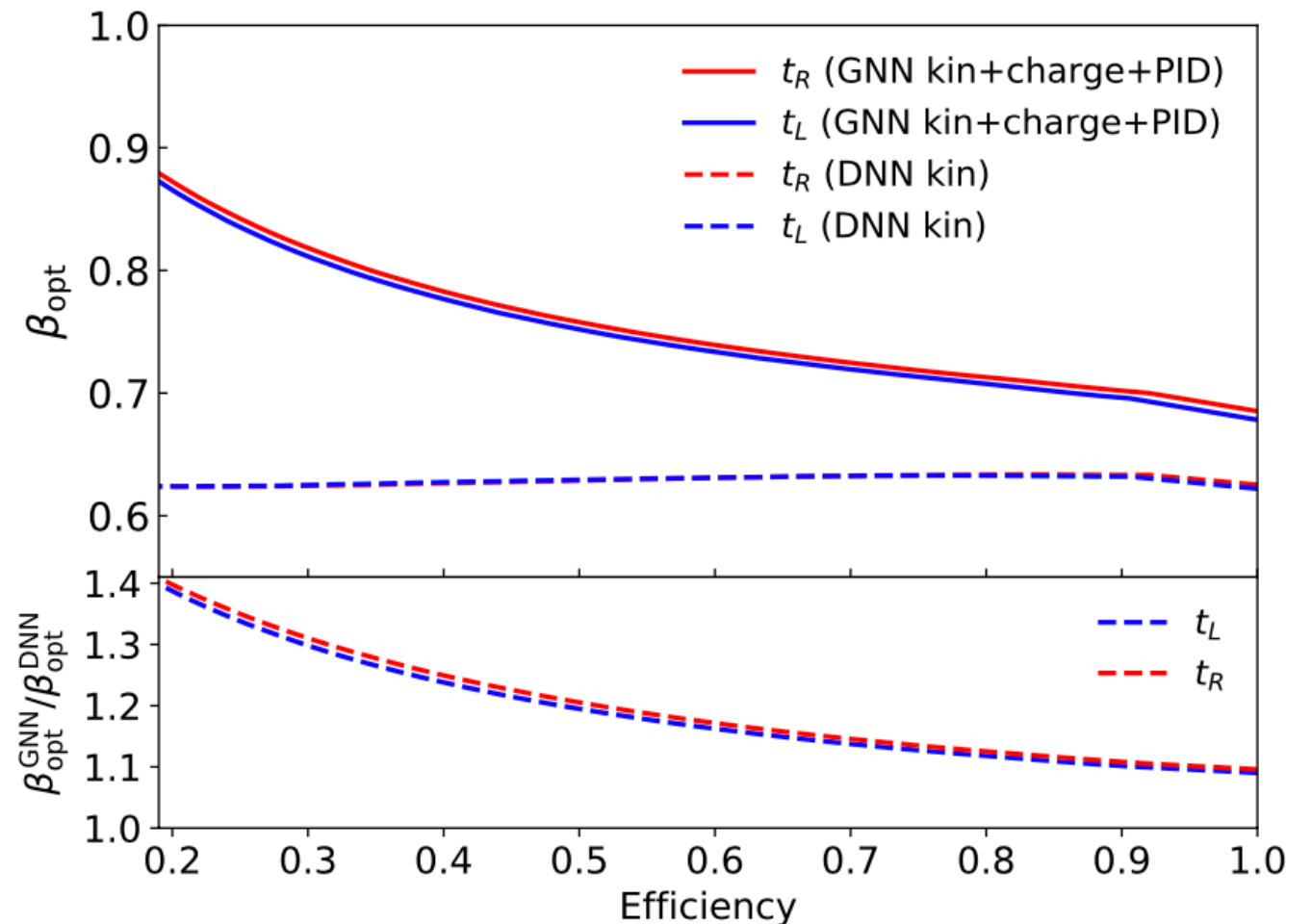
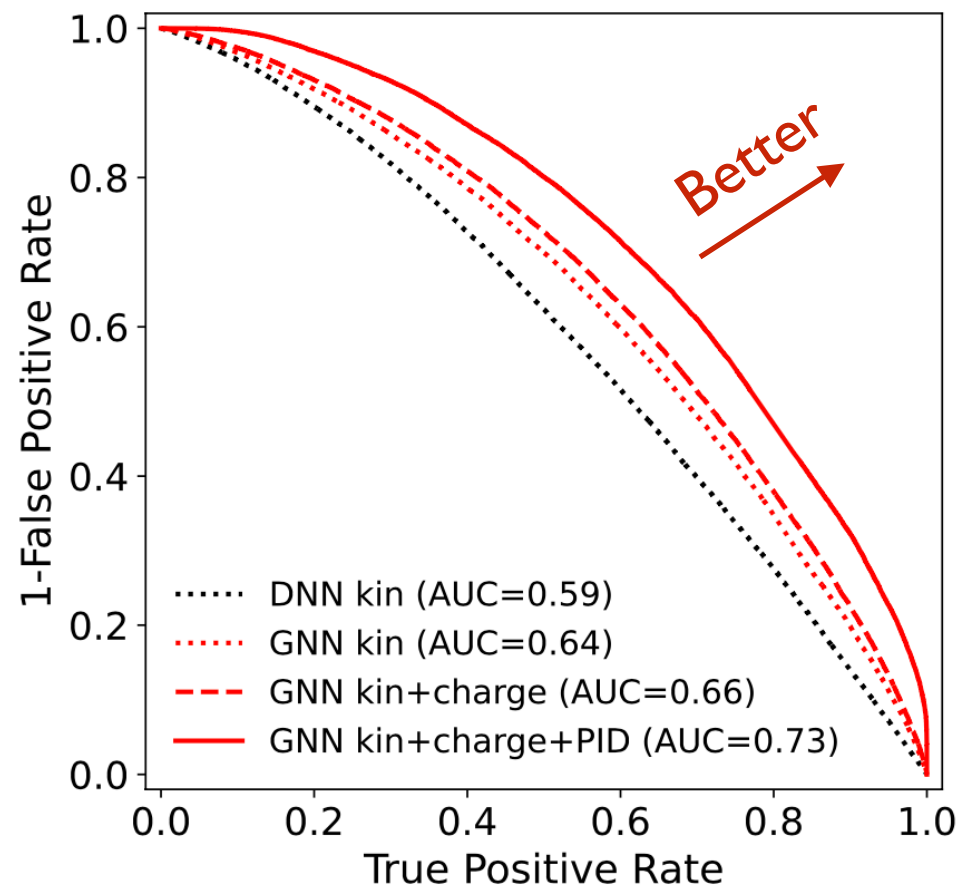
$$\frac{1}{\Gamma_f} \frac{d\Gamma_f}{d \cos \theta_f} = \frac{1}{2} (1 + \mathbf{0.64} \cos \theta_f)$$

Hadronic Top Quark Polarimetry with ParticleNet



Dong, **DG**, Kong, Larkoski, Navarro '24
 Dong, **DG**, Kong, Larkoski, Navarro '24

Hadronic Top Quark Polarimetry with ParticleNet



This can significantly boost spin correlations, BSM searches, QIS observables such as entanglement...

Dong, **DG**, Kong, Larkoski, Navarro '24

Dong, **DG**, Kong, Larkoski, Navarro '24

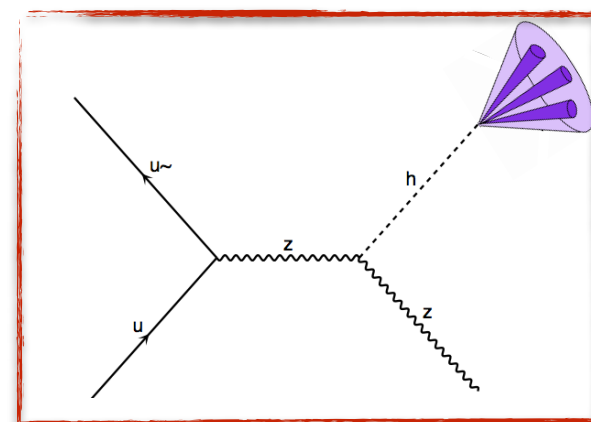
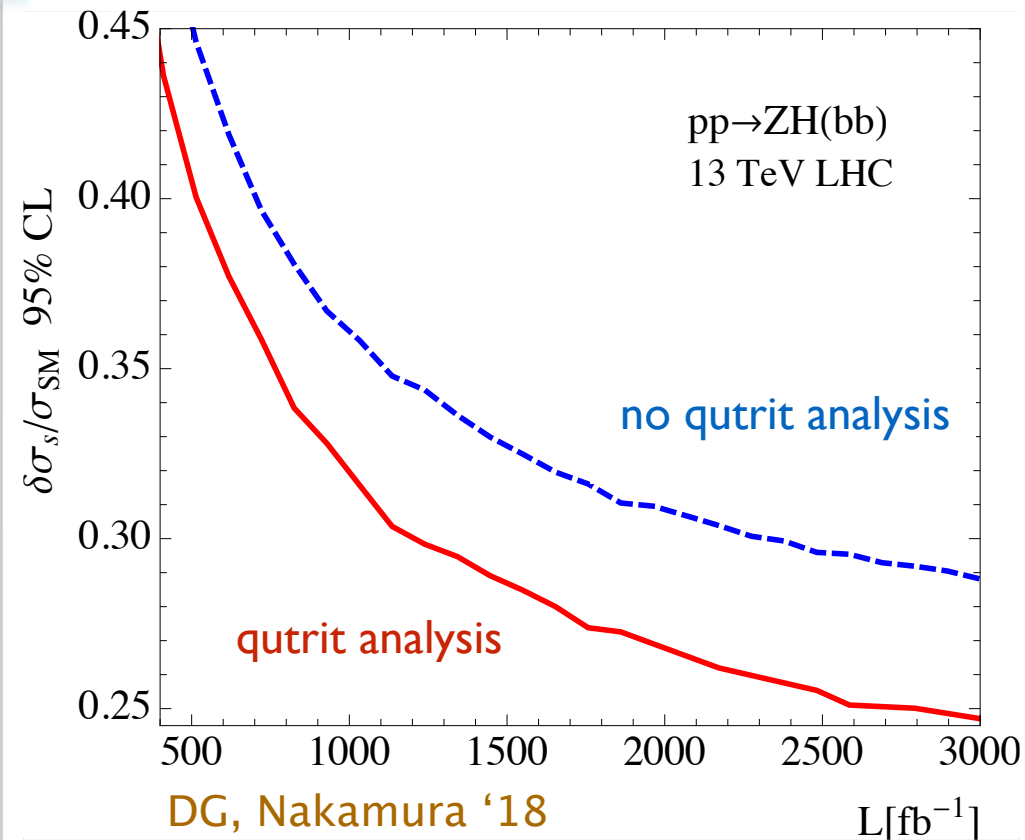
Quantum Advantage in New Physics Searches?

Ex: W/Z bosons as qutrits

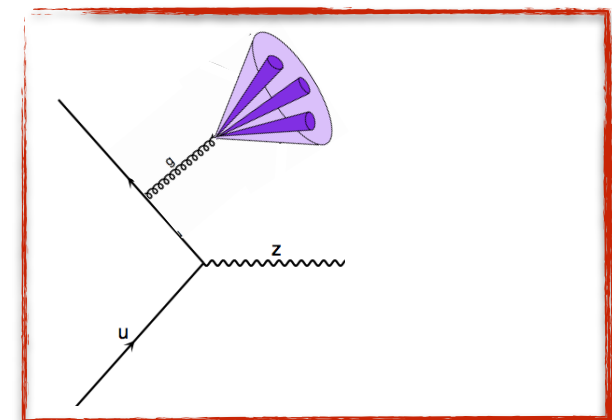
Spin density matrix displays a rich amount of information (8 multipoles coef.) and is **not systematically limited**

$$\frac{1}{\sigma} \frac{d\sigma}{d\cos\theta d\phi} = \frac{3}{16\pi} \left[1 + \cos^2\theta + A_0 \frac{1}{2} (1 - 3\cos^2\theta) + A_1 \sin 2\theta \cos\phi + A_2 \frac{1}{2} \sin^2\theta \cos 2\phi \right. \\ \left. + A_3 \sin\theta \cos\phi + A_4 \cos\theta + A_5 \sin^2\theta \sin 2\phi + A_6 \sin 2\theta \sin\phi + A_7 \sin\theta \sin\phi \right]$$

Precision measurements for Zh(bb):



Vs



→ Lepton angular distribution works as an analyzer, probing **underlying production dynamics** encoded in the A_i coefficients: Zh(bb) vs Zbb

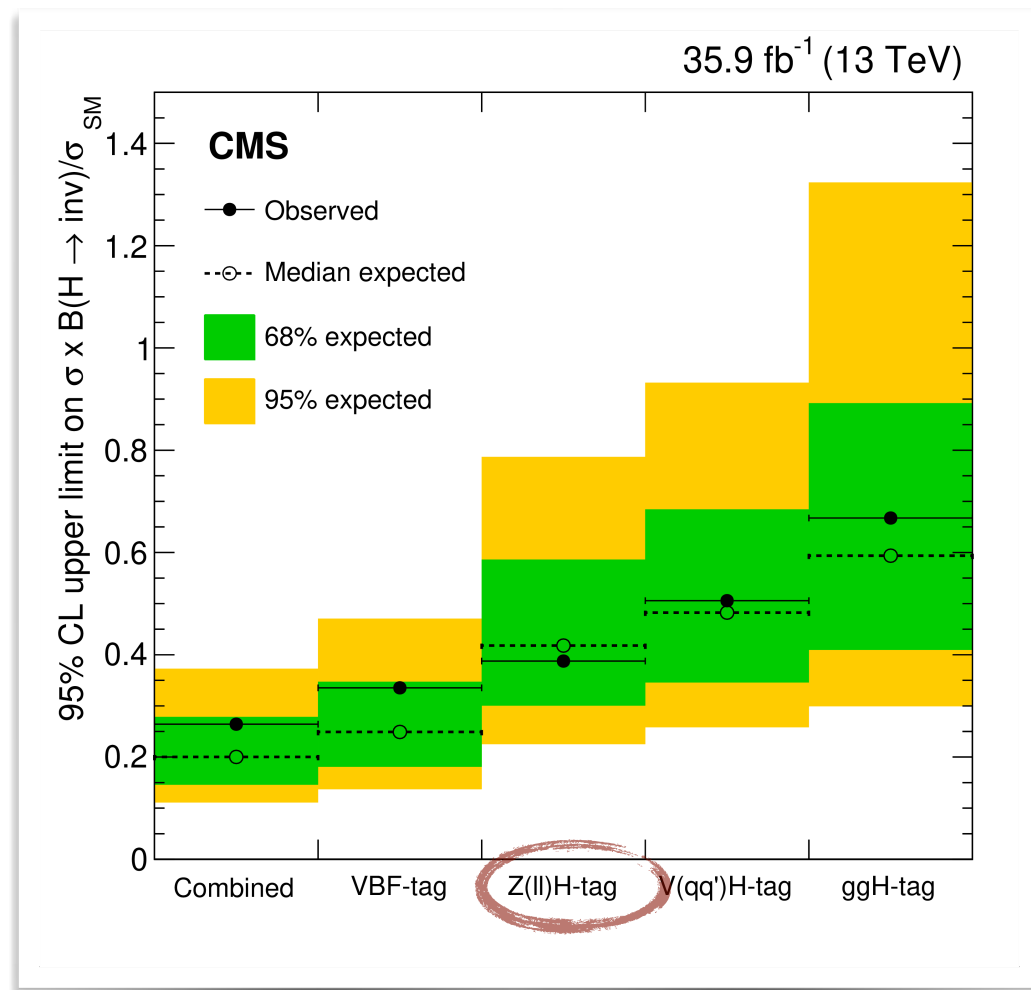
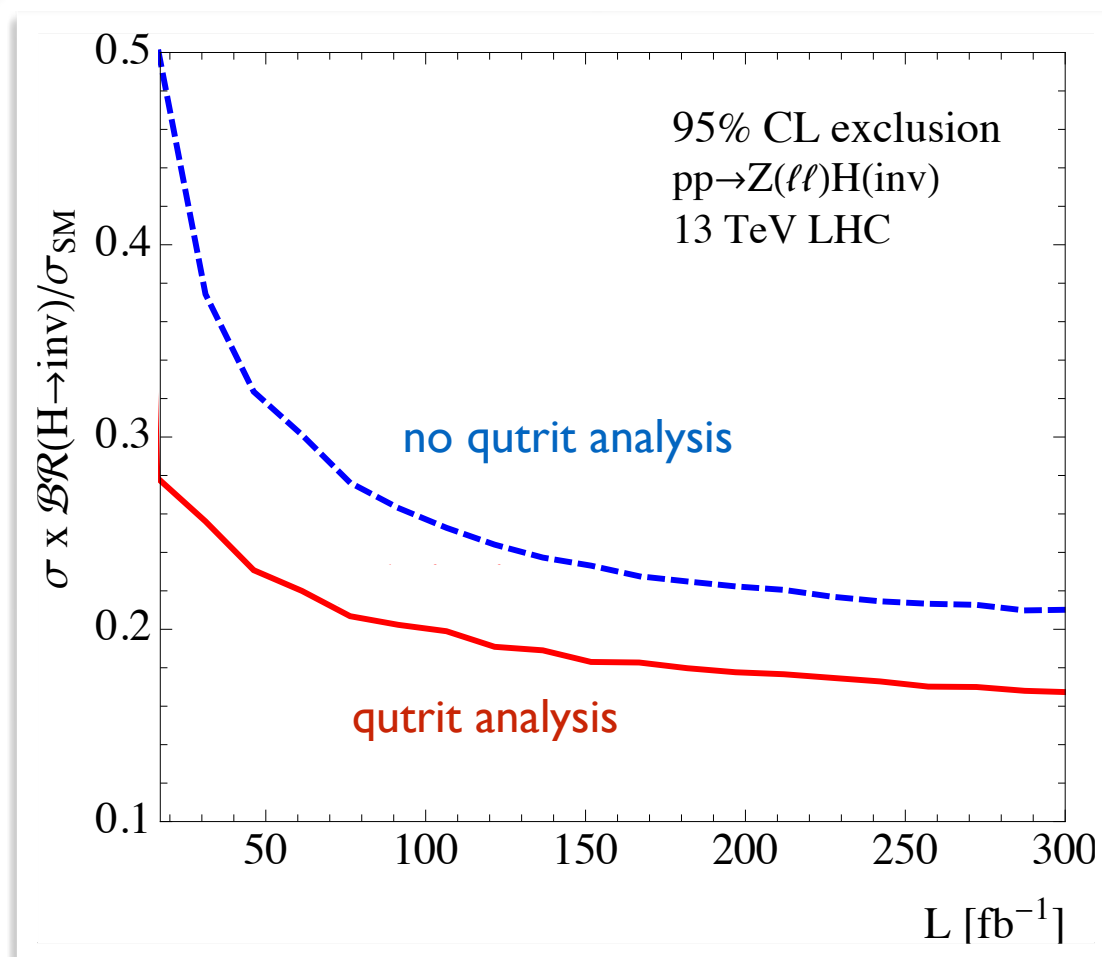
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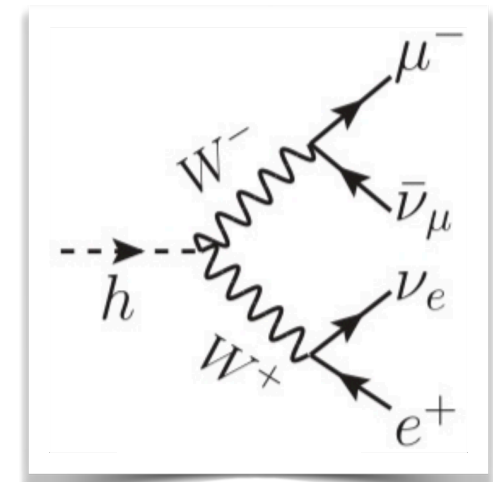
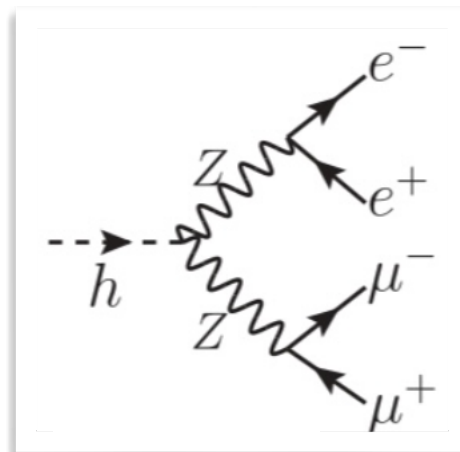
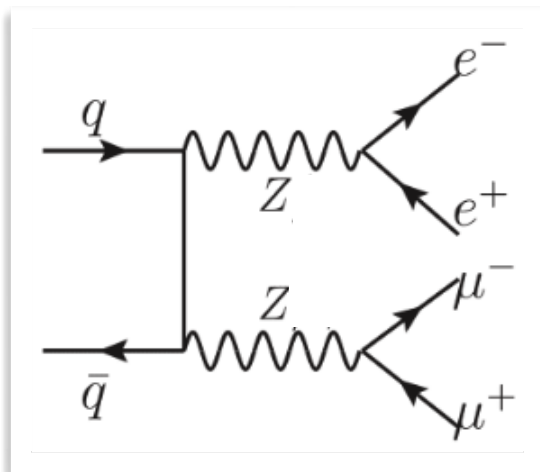
$$\frac{1}{\sigma} \frac{d\sigma}{d\cos\theta d\phi} = \frac{3}{16\pi} \left[1 + \cos^2\theta + A_0 \frac{1}{2} (1 - 3\cos^2\theta) + A_1 \sin 2\theta \cos\phi + A_2 \frac{1}{2} \sin^2\theta \cos 2\phi \right. \\ \left. + A_3 \sin\theta \cos\phi + A_4 \cos\theta + A_5 \sin^2\theta \sin 2\phi + A_6 \sin 2\theta \sin\phi + A_7 \sin\theta \sin\phi \right]$$

New physics searches: Invisible Higgs decays



Diboson as a two-qutrit system

- Polarization and spin correlations in diboson systems serve as powerful tools for precision measurements and searches for new physics



- The most general two-qutrit system can be represented by

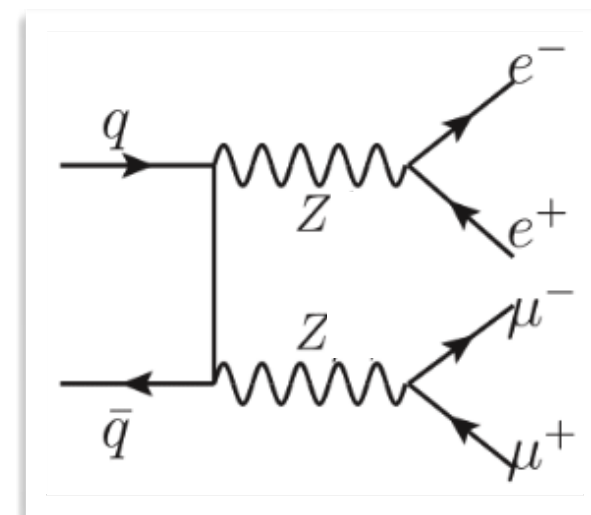
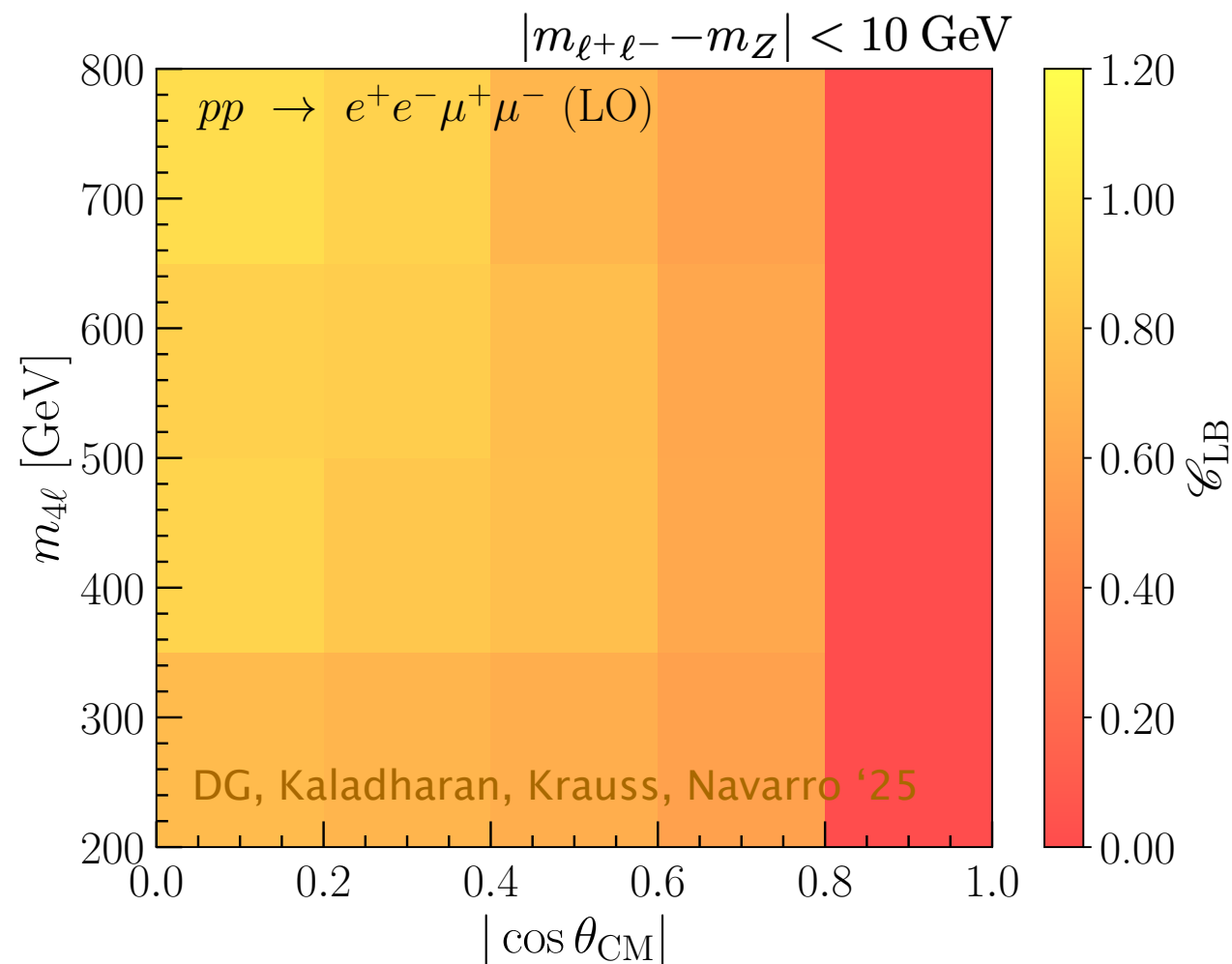
$$\rho = \frac{1}{9} \left(\mathbb{I}_3 \otimes \mathbb{I}_3 + A_{LM}^1 T_M^L \otimes \mathbb{I}_3 + A_{LM}^2 \mathbb{I}_3 \otimes T_M^L + C_{L_1 M_1 L_2 M_2} T_{M_1}^{L_1} \otimes T_{M_2}^{L_2} \right)$$

ρ is fully characterized by 80 independent real parameters

Diboson as a two-qutrit system



Entanglement estimates @LO:

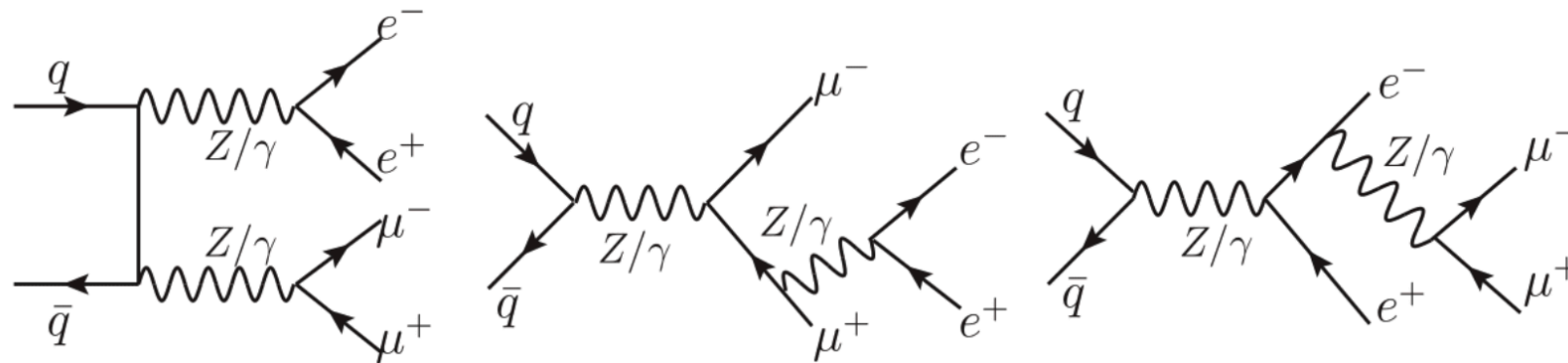


See also: Barr 2106.01377 Saavedra 2403.13942
 Saavedra et al 2209.13441 Sullivan 2410.10980
 Maltoni et al 2307.09675 Pelliccioli et al 2409.16731
 Fabbrichesi et al 2302.00683 Gratta et al 2504.03841
 Fabbri et al 2307.13783 ...
 Bernal et al 2307.13496

Quantum Entanglement is Quantum

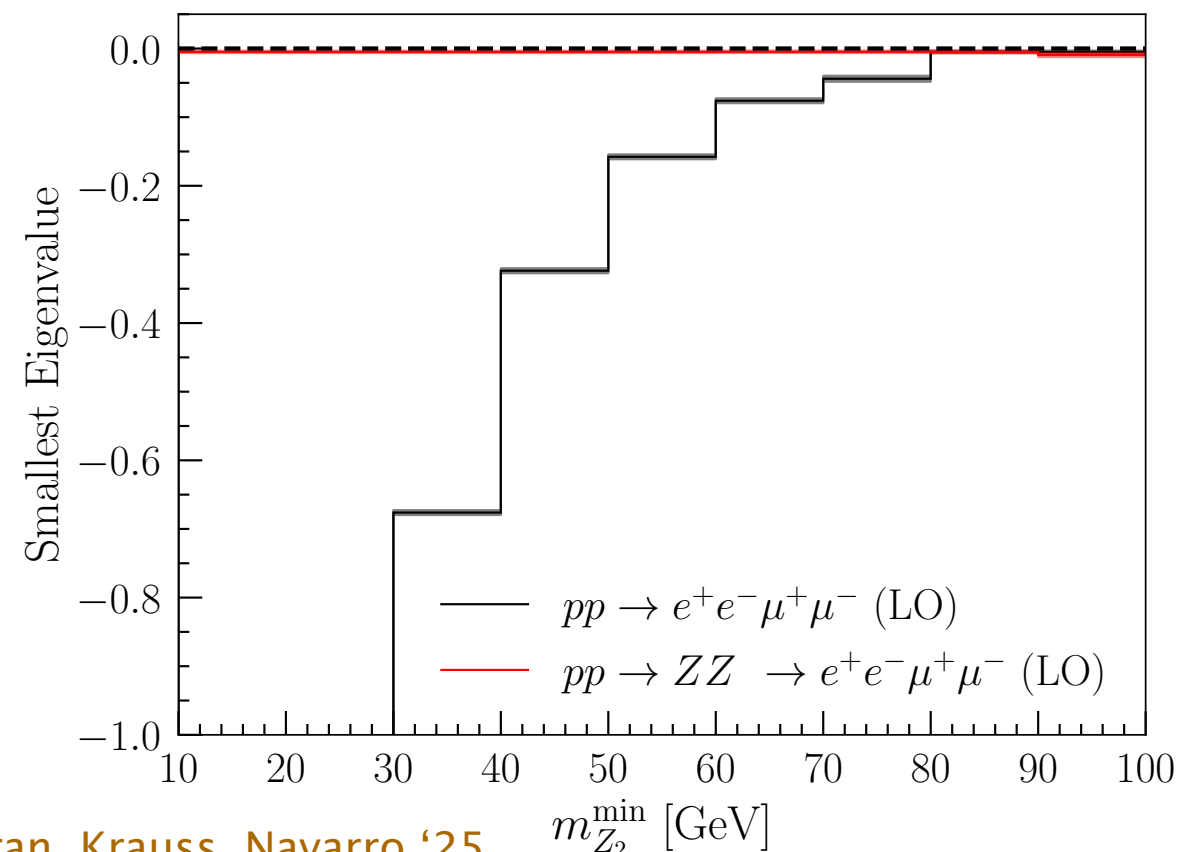
Given the interest from the community for these measurements, it is timely to study the corresponding higher-order effects

Leading order:



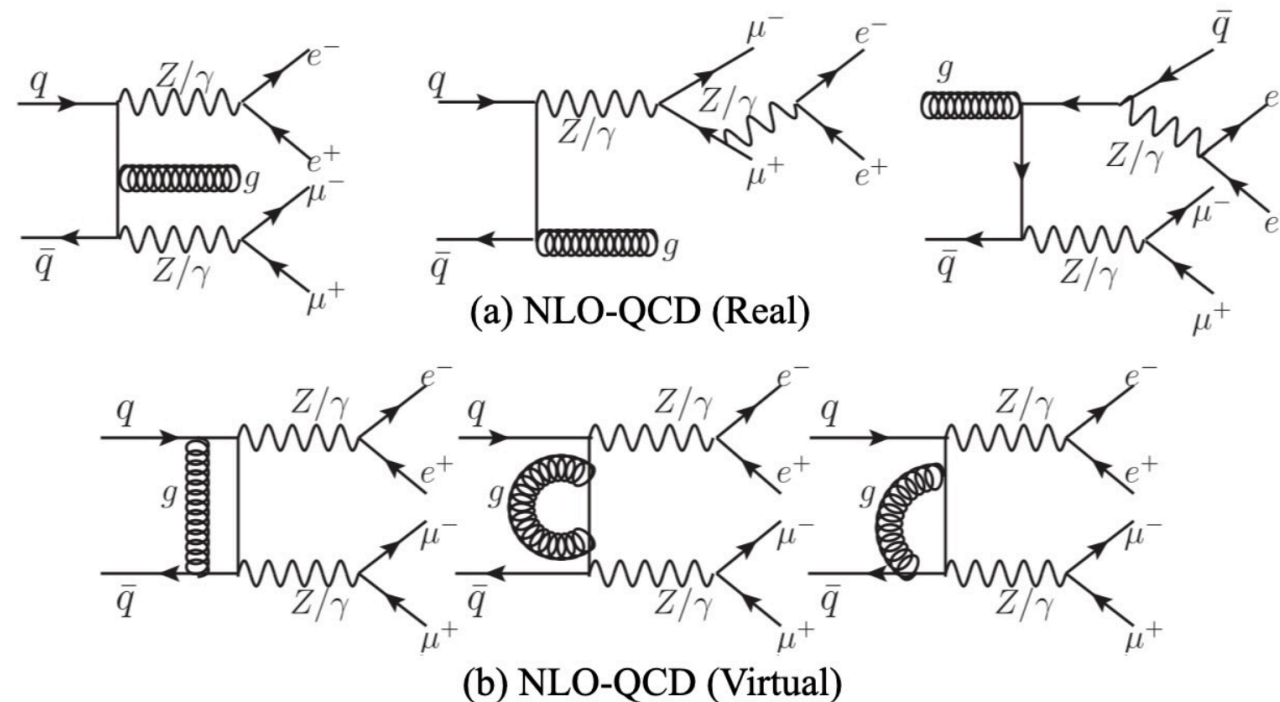
Density matrix must satisfy the following properties:

- Unit trace: $\text{Tr}(\rho) = 1$
- Hermitian: $\rho^\dagger = \rho$
- Positive semi-definite: $\langle \Psi_i | \rho | \Psi_i \rangle \geq 0$



Quantum Entanglement is Quantum

NLO QCD:



Angular coefficients work as analyzers of the underlying production dynamics

$$|m_{\ell^+\ell^-} - m_Z| < 10 \text{ GeV}$$

➡ Sizable NLO QCD corrections

➡ Crucial effects for precision measurements and new physics studies (EFT analyses,...)

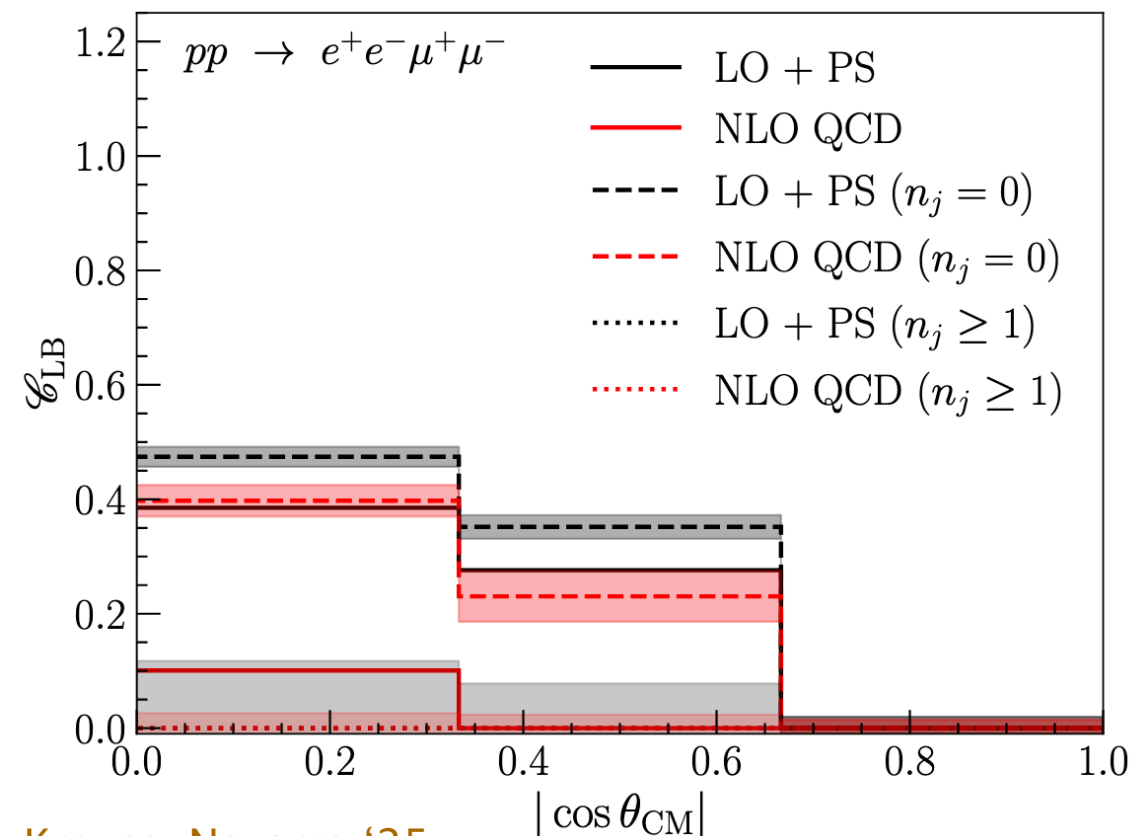
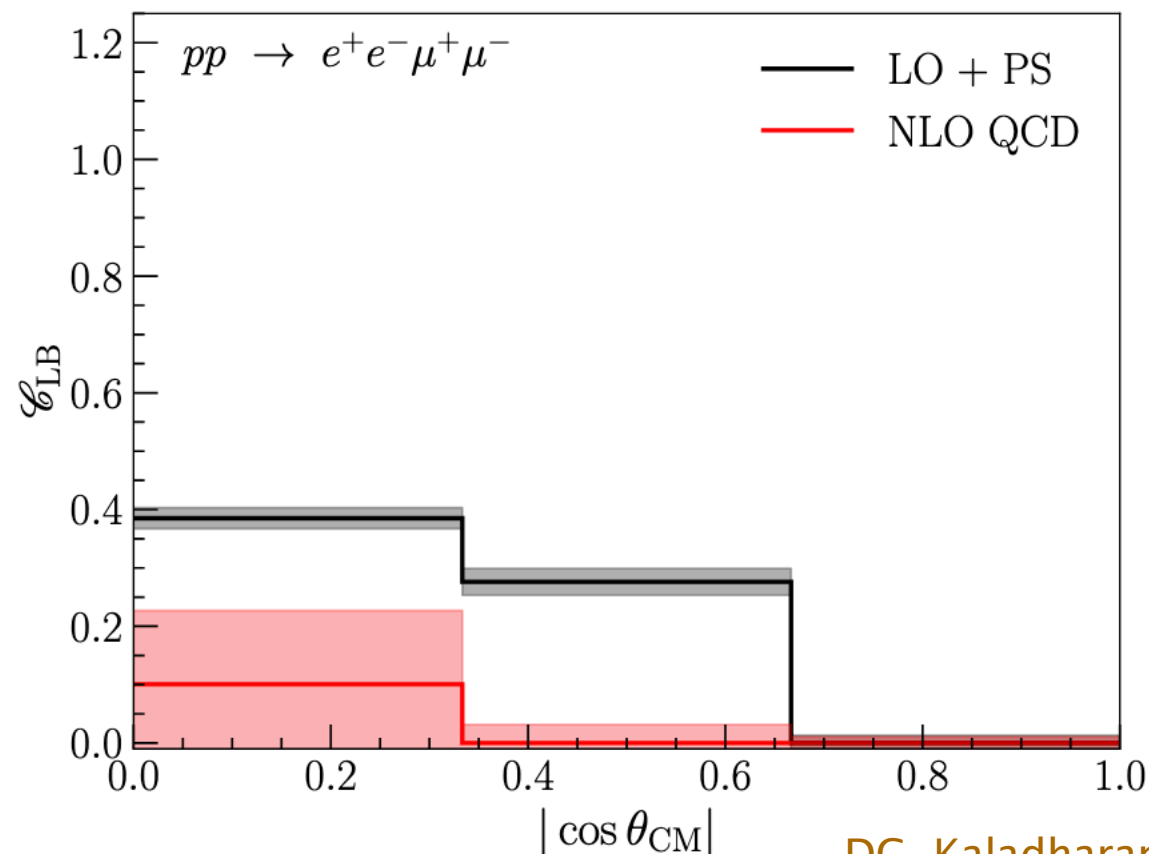
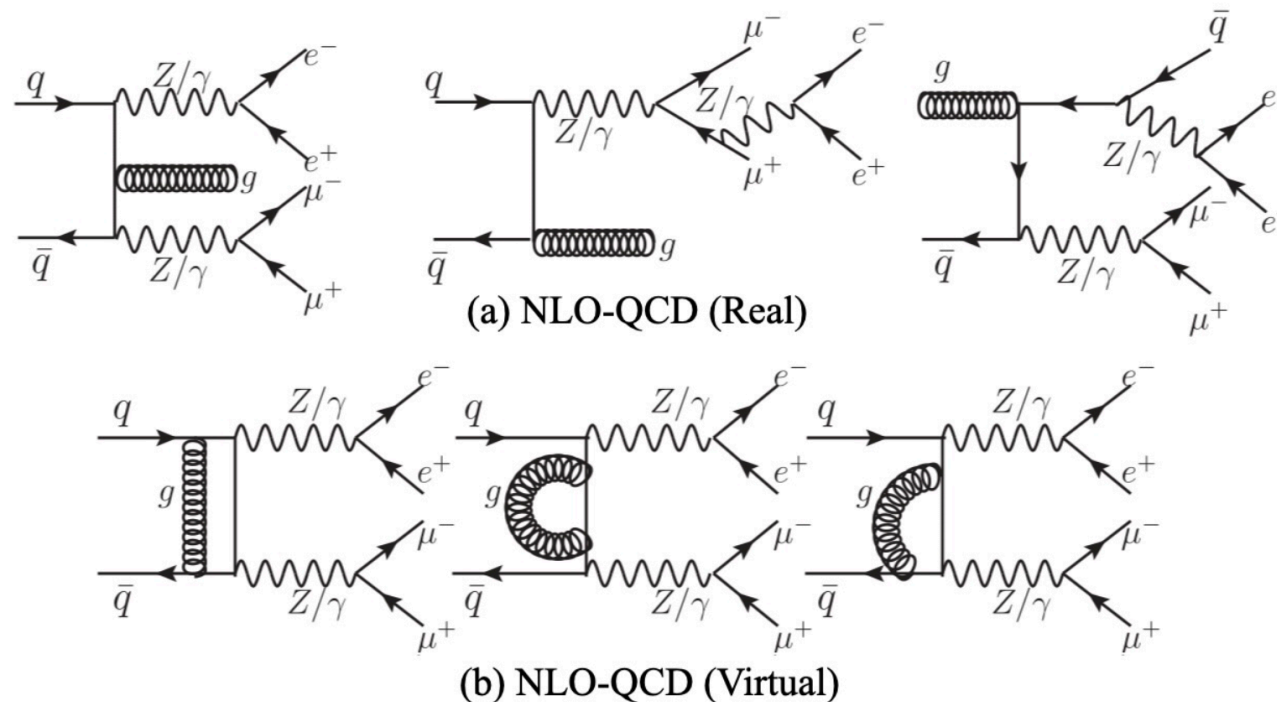
Coefficient	LO+PS	NLO QCD	NLO/LO
$A_{1,0}^1$	-0.008(2)	-0.035(3)	4.37
$A_{2,0}^1$	0.3224(9)	0.301(1)	0.93
$A_{2,1}^1$	0.0758(6)	0.1023(7)	1.35
$C_{1,0,1,0}$	0.94(1)	0.75(1)	0.80
$C_{2,0,2,0}$	0.221(2)	0.198(3)	0.89
$C_{2,1,2,0}$	0.005(2)	0.024(2)	4.80

DG, Kaladharan, Krauss, Navarro '25

Grossi, Pelliccioli, Vicini '24

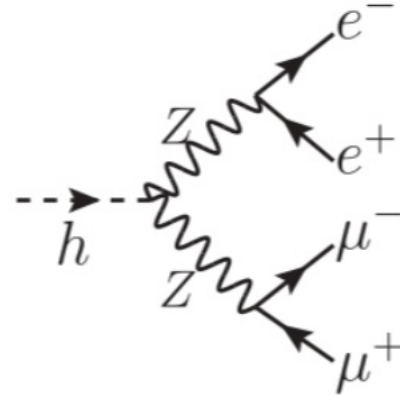
Quantum Entanglement is Quantum

 NLO QCD:



DG, Kaladharan, Krauss, Navarro '25

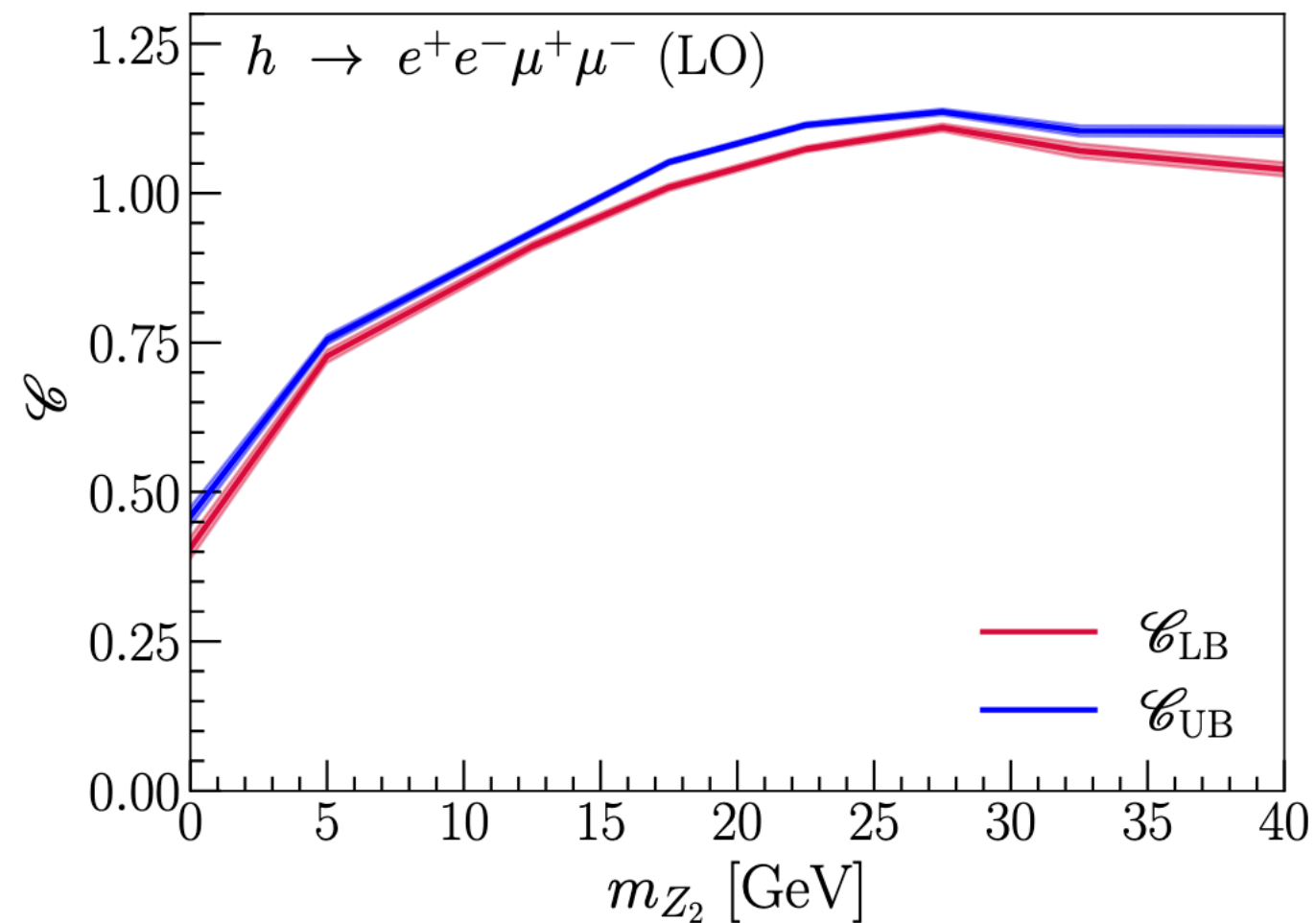
$h \rightarrow e^+ e^- \mu^+ \mu^-$ at LO



$$\rho_{\text{LO}} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{3}C_{2,2,2,-2} & 0 & \frac{1}{3}C_{2,1,2,-1} & 0 & \frac{1}{3}C_{2,2,2,-2} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{3}C_{2,1,2,-1} & 0 & \frac{1}{3}(3 - 2C_{2,2,2,-2}) & 0 & \frac{1}{3}C_{2,1,2,-1} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{3}C_{2,2,2,-2} & 0 & \frac{1}{3}C_{2,1,2,-1} & 0 & \frac{1}{3}C_{2,2,2,-2} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

matrix depend on just two independent parameters

Saavedra, Bernal, Casas, Moreno 22'



DG, Kaladharan, Krauss, Navarro '25

Experimental Observation



Two-qutrit entanglement:

Measurements of Z-boson pair entanglement in decays of Higgs bosons at the ATLAS experiment

The ATLAS Collaboration

Entanglement is a key property of quantum systems. In this Letter the first measurements of quantum entanglement between spins in pairs of Z bosons are reported, using proton–proton collision data from the Large Hadron Collider (LHC) at center-of-mass energies of 13 TeV and 13.6 TeV, recorded with the ATLAS detector. Measurements of angular observables sensitive to ZZ^* spin-density-matrix elements in the $H \rightarrow ZZ^* \rightarrow \ell^+ \ell^- \ell^+ \ell^-$ process yield coefficients $C_{2,1,2,-1} = -0.71 \pm 0.45$ and $C_{2,2,2,-2} = 0.08 \pm 0.44$, consistent with their Standard Model predictions. A complementary hypothesis test using the full angular distribution, and relying on several Standard Model assumptions in the decays, provides substantially higher sensitivity to quantum correlations and disfavors the separable-state hypothesis at a significance of 4.7 standard deviations (expected 4.9σ) relative to the entangled Standard Model hypothesis. These results provide strong evidence of quantum entanglement between massive bosons (spin qutrits) at the electroweak scale.

Barr '21, ATLAS arXiv:2603.26463, CMS-PAS-HIG-25-011



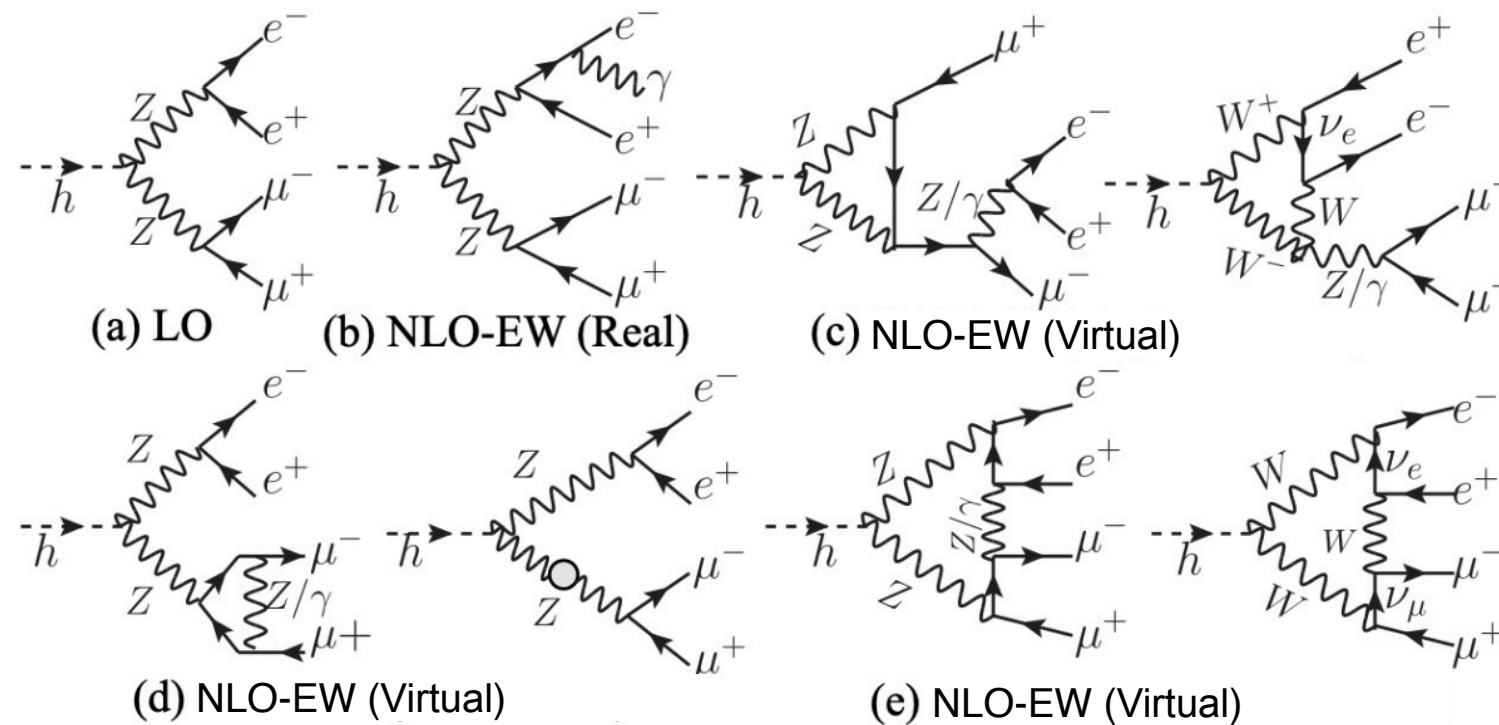
What about higher order effects?

DG, Kaladharan, Krauss, Navarro, JHEP12(2025)122

DG, Kaladharan, Navarro, JHEP11(2025)158

DG, Kaladharan, Navarro, arXiv.2604.16218

$h \rightarrow e^+ e^- \mu^+ \mu^-$: NLO EW Corrections



While NLO EW corrections to partial width are only $\sim 1.4\%$, they induce sizable effects in the angular coefficients

Coefficient	LO	NLO	NLO/LO
$A_{2,0}^1$	$-0.4910(8)$	$-0.486(1)$	0.989
$A_{2,0}^2$	$-0.4915(8)$	$-0.471(1)$	0.958
$C_{1,0,1,0}$	$-0.65(1)$	$0.42(3)$	-0.646
$C_{1,1,1,-1}$	$1.008(9)$	$-0.37(3)$	-0.279
$C_{2,1,2,-1}$	$-0.993(2)$	$-0.985(3)$	0.992
$C_{2,0,2,0}$	$1.335(2)$	$1.328(4)$	0.995
$C_{2,2,2,-2}$	$0.646(2)$	$0.635(3)$	0.983

$$|m_{Z_1} - m_Z| < 5 \text{ GeV}$$

$$m_{Z_2} > 10 \text{ GeV}$$

NLO EW is crucial for a robust BSM analysis

DG, Kaladharan, Krauss, Navarro '25

see also Gratta, Fabbri, Lamba, Maltoni, Pagani 25'; Saavedra, Giardino 26'

$h \rightarrow e^+ e^- \mu^+ \mu^-$: NLO EW Corrections

Angular observables are very sensitive to NLO EW corrections

$$\rho_{ZZ}^{\text{LO}} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.193(1) & 0 & -0.313(1) & 0 & 0.192(1) & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -0.313(1) & 0 & 0.611(1) & 0 & -0.311(1) & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.192(1) & 0 & -0.311(1) & 0 & 0.193(1) & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

$$\rho_{ZZ}^{\text{NLO}} = \begin{pmatrix} 0.102(4) & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.103(4) & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.100(4) & 0 & -0.207(4) & 0 & 0.188(1) & 0 \\ 0 & 0.103(4) & 0 & 0.003(1) & 0 & 0 & 0 & 0 \\ 0 & 0 & -0.207(4) & 0 & 0.591(1) & 0 & -0.199(4) & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.004(1) & 0 & 0.109(4) \\ 0 & 0 & 0.188(1) & 0 & -0.199(4) & 0 & 0.100(4) & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.109(4) & 0 & 0.098(4) \end{pmatrix}$$

DG, Kaladharan, Krauss, Navarro '25; See also Gratta, Fabbri, Lamba, Maltoni, Pagani 25'; Saavedra, Giardino 26'

Large corrections to the LO coefficients

Different texture to the density matrix at NLO with new coefficients

Density matrix is not positive semidefinite. Negative eigenvalues proportional to $-|\rho_{24}|$ and $-|\rho_{68}|$.

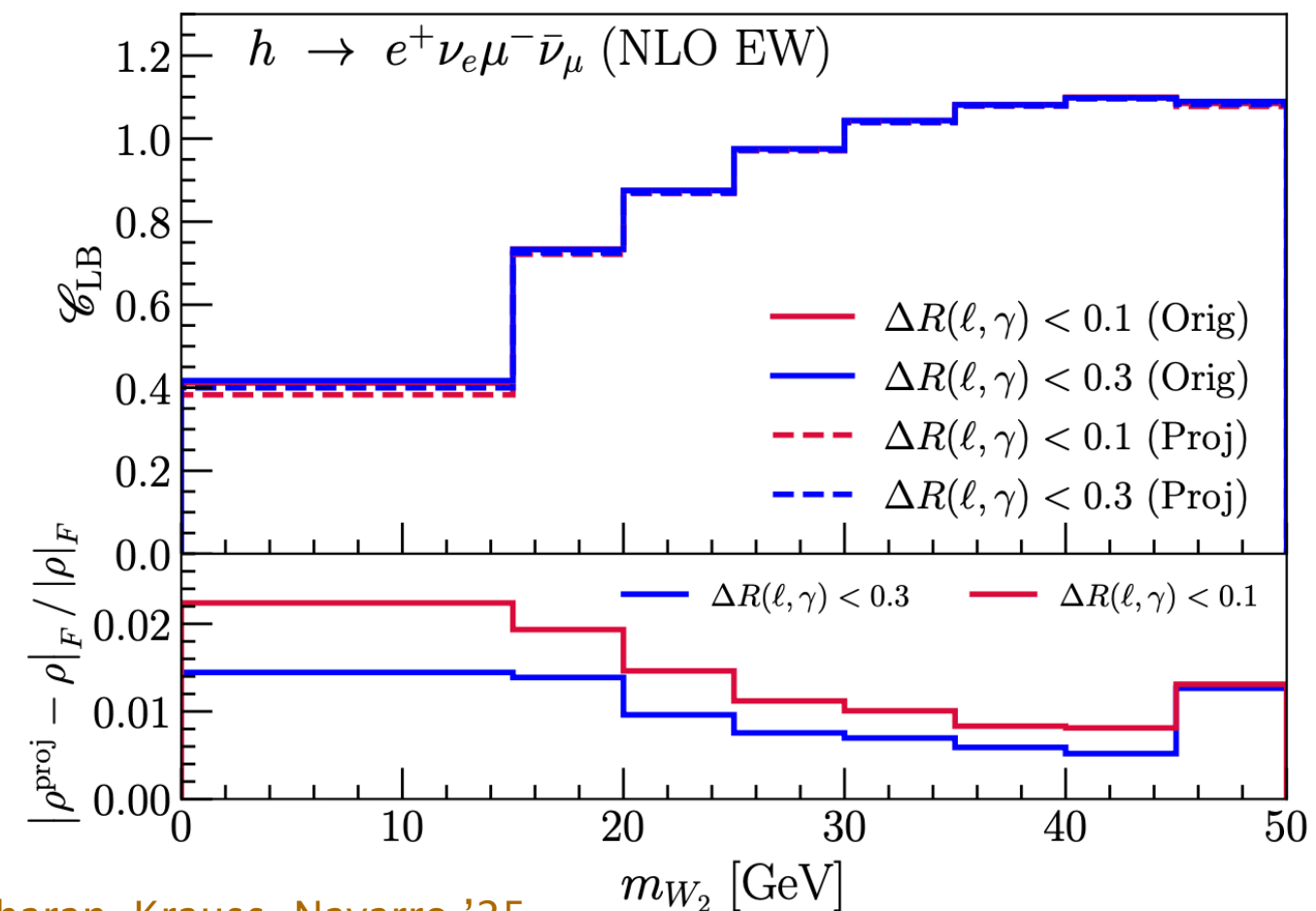
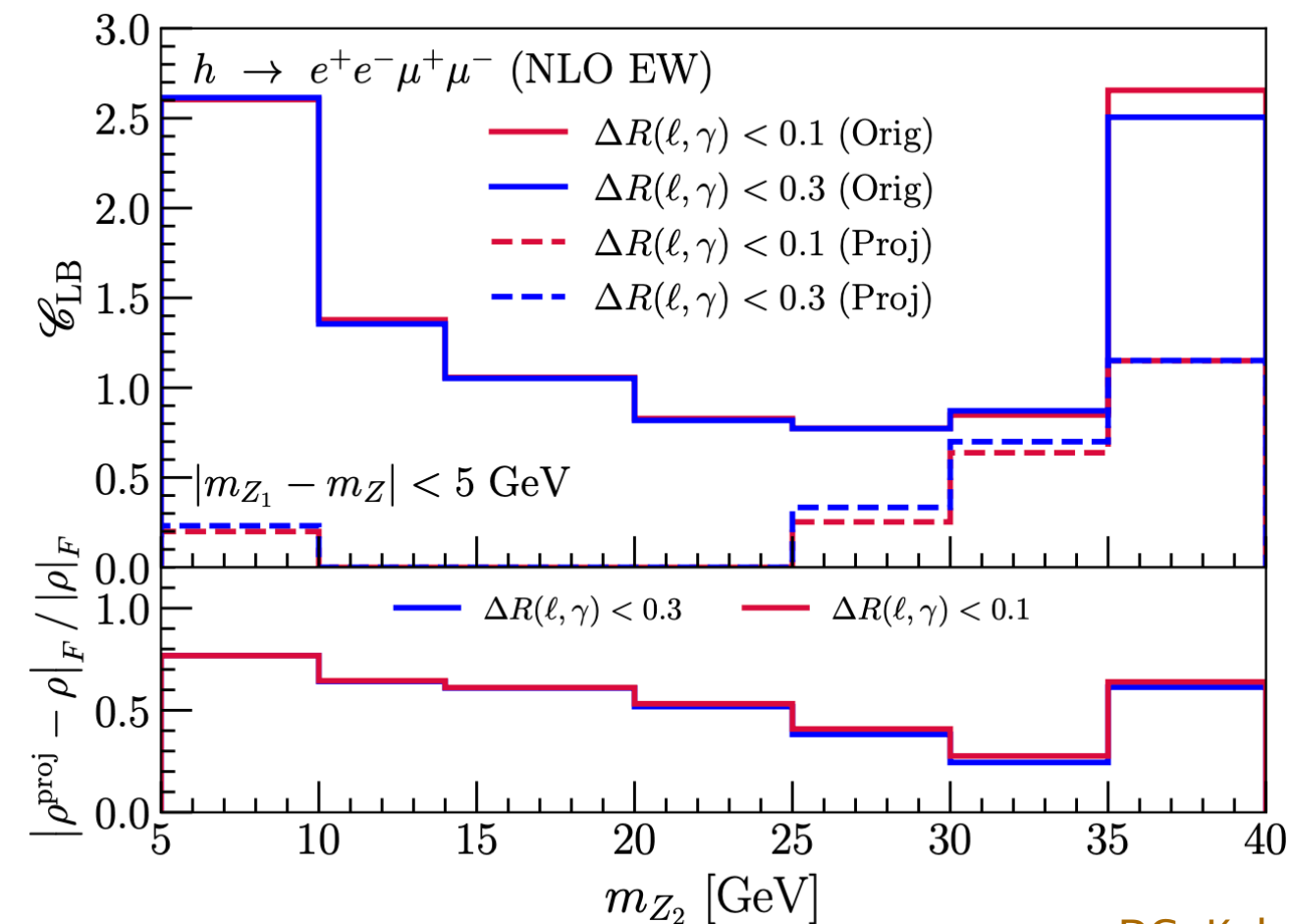
$$|\rho_{24}| \approx |\rho_{68}| \approx 0.103(4)$$

$h \rightarrow ZZ^*$ vs $h \rightarrow WW^*$



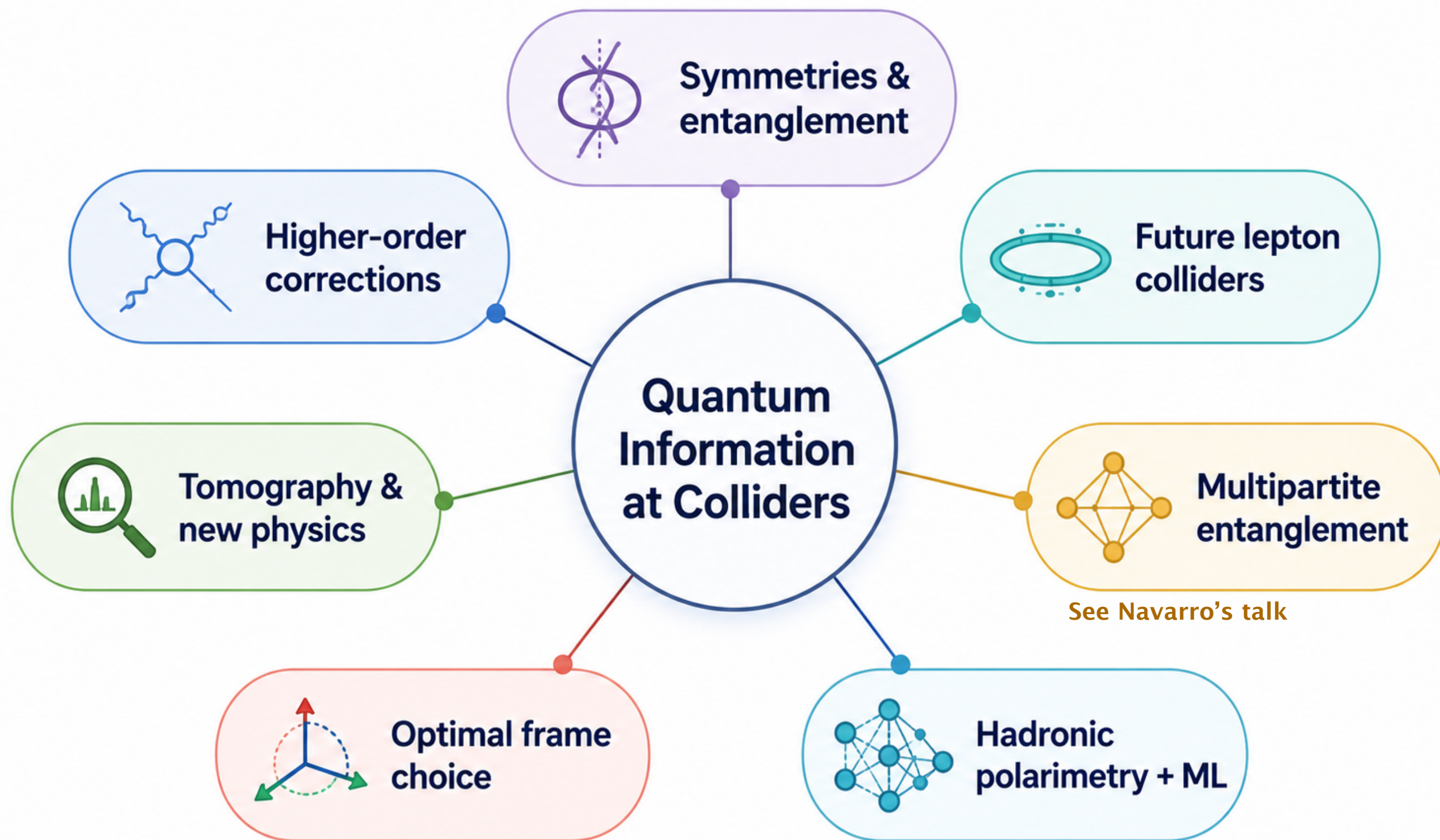
Projecting the original matrix to a well defined state (unit trace, hermitian, and positive eigenvalues)
minimizing the Frobenius norm:

$$|\rho^{\text{proj}} - \rho|_F \equiv \sqrt{\sum_{i,j} |\rho_{ij}^{\text{proj}} - \rho_{ij}|^2}$$



DG, Kaladharan, Krauss, Navarro '25
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Ultimately, NLO EW corrections are crucial for precision measurements and new physics studies

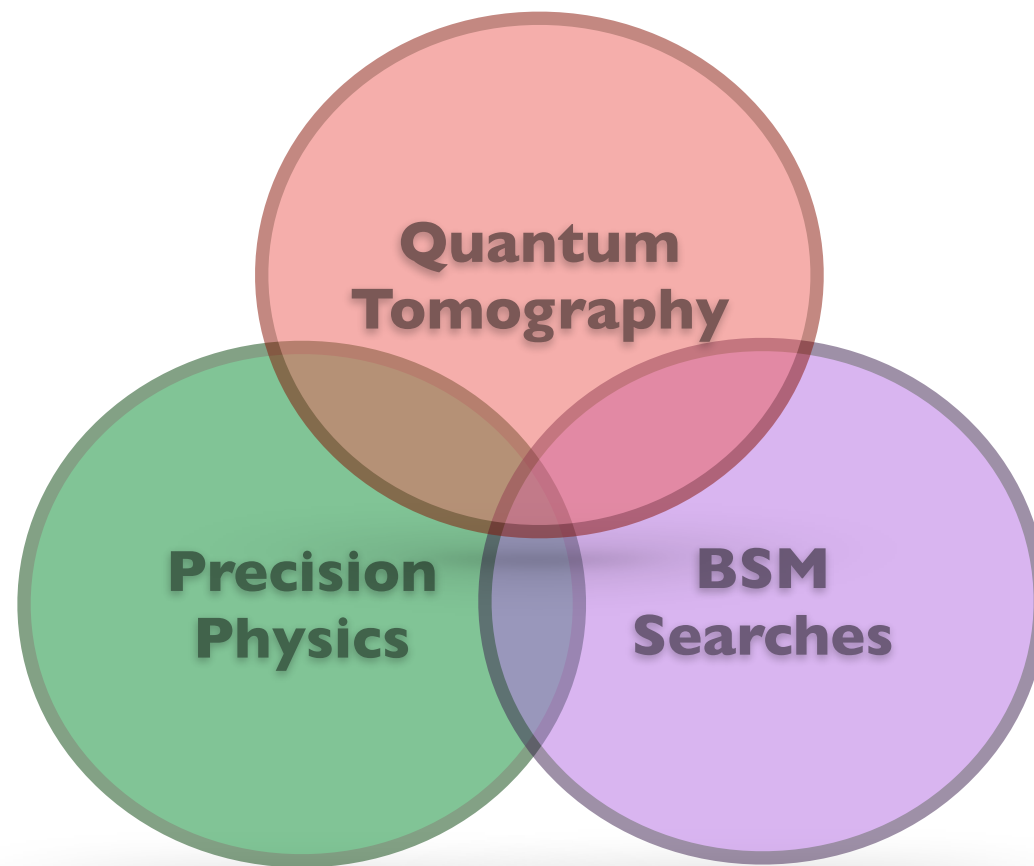


Summary



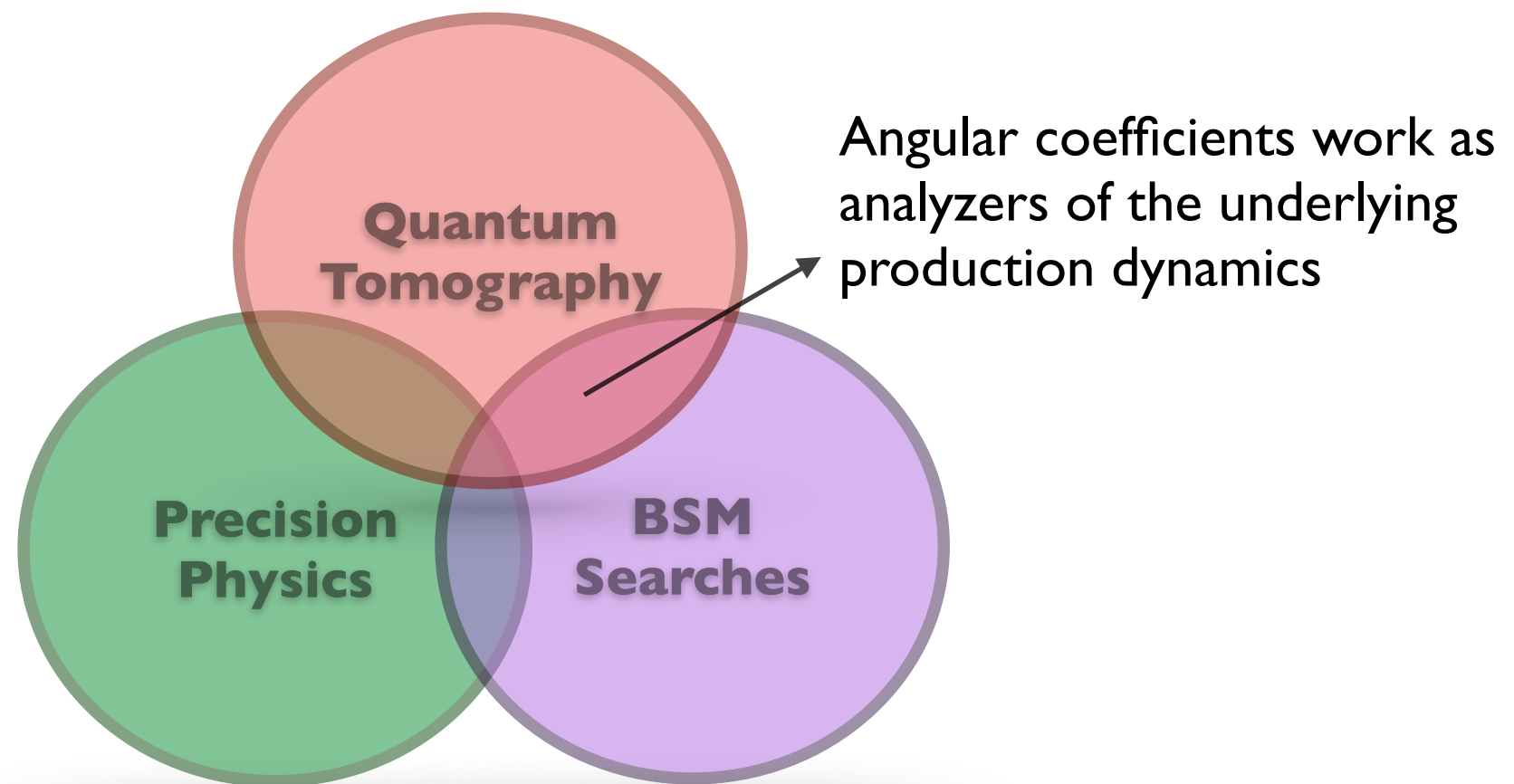
LHC provides a unique opportunity to study quantum correlations, such as entanglement, at high energy scales:

- New systems: Bipartite ($t\bar{t}, \tau\tau, VV, tW, \dots$) and multipartite ($t\bar{t}Z, t\bar{t}W, \dots$)
- Highly energetic
- Presence of weak and strong interactions



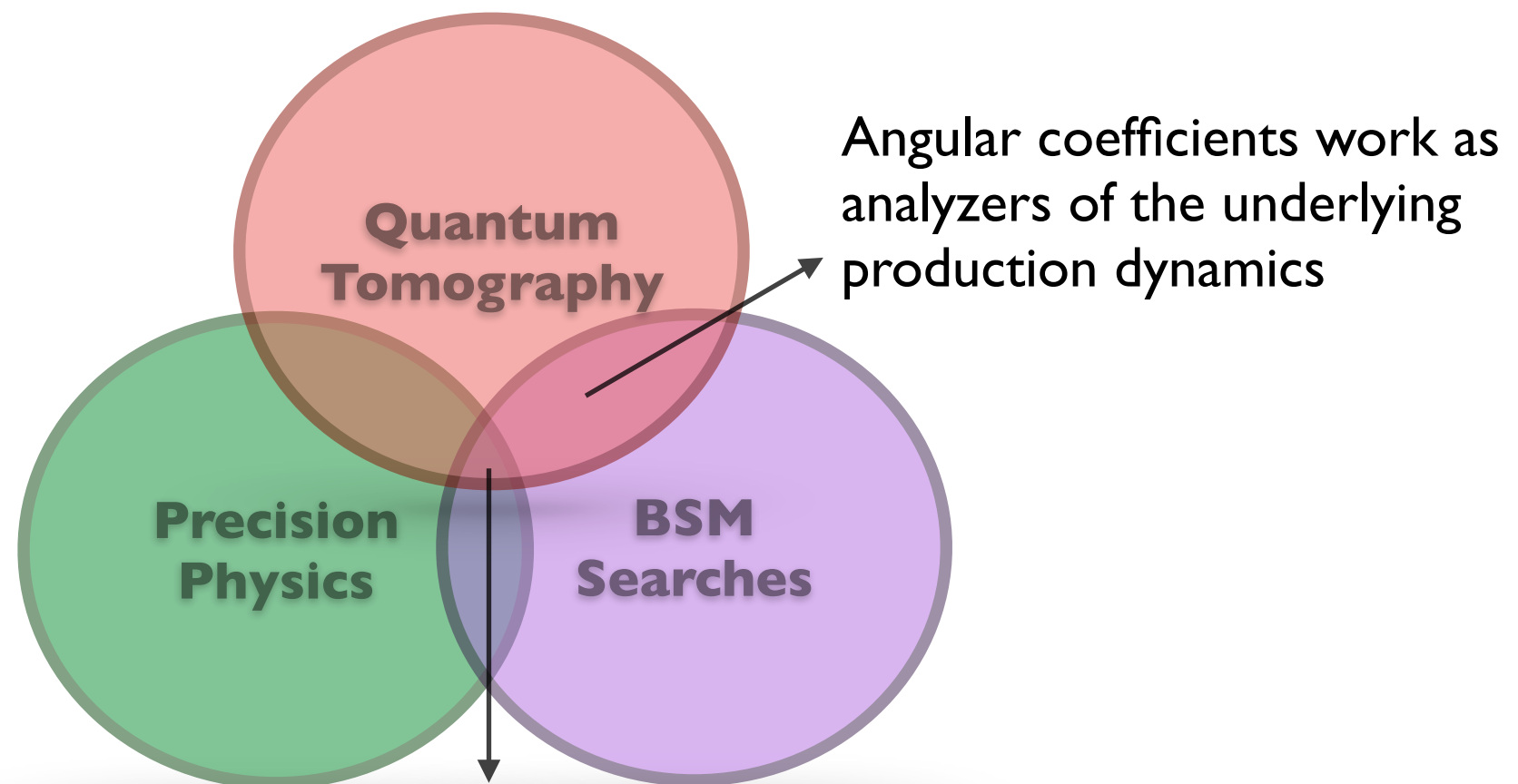
Summary

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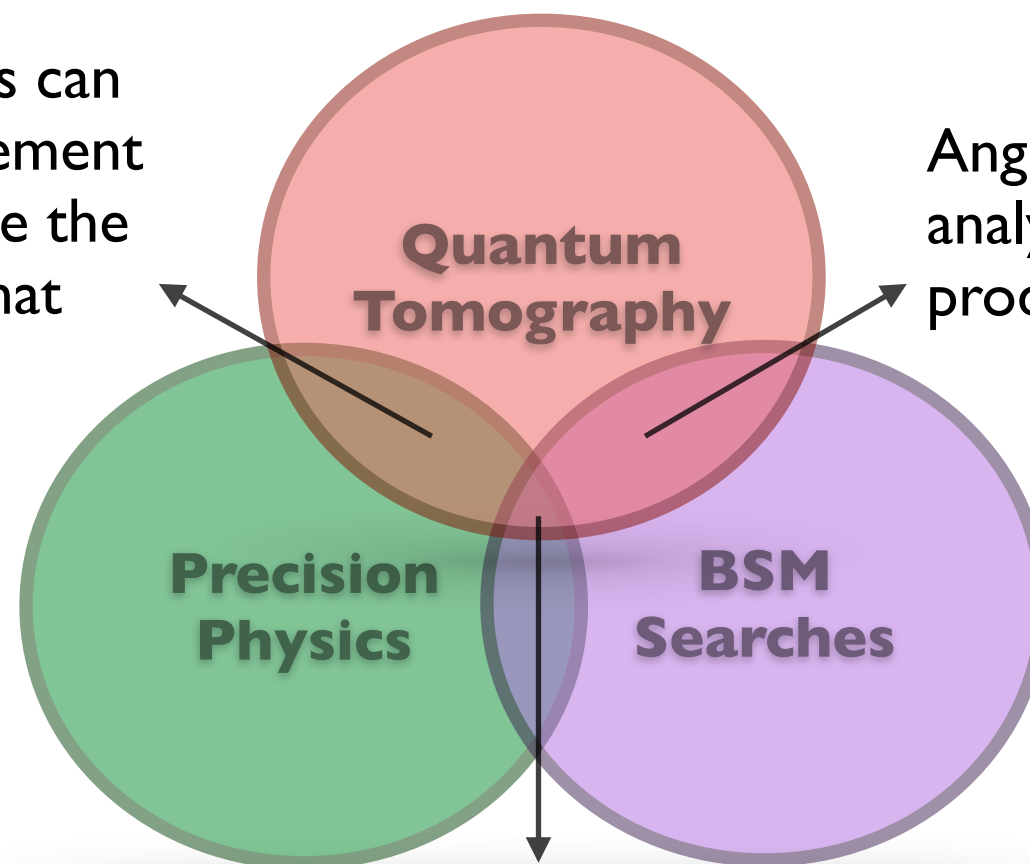


Higher-order (QCD and EW) corrections to angular coefficients are crucial for precision measurements and new physics studies

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Sizable radiative corrections can significantly modify entanglement indicators and may challenge the interpretation of systems that appear well-defined at LO



Angular coefficients work as analyzers of the underlying production dynamics

Higher-order (QCD and EW) corrections to angular coefficients are crucial for precision measurements and new physics studies

Work in collaboration with



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