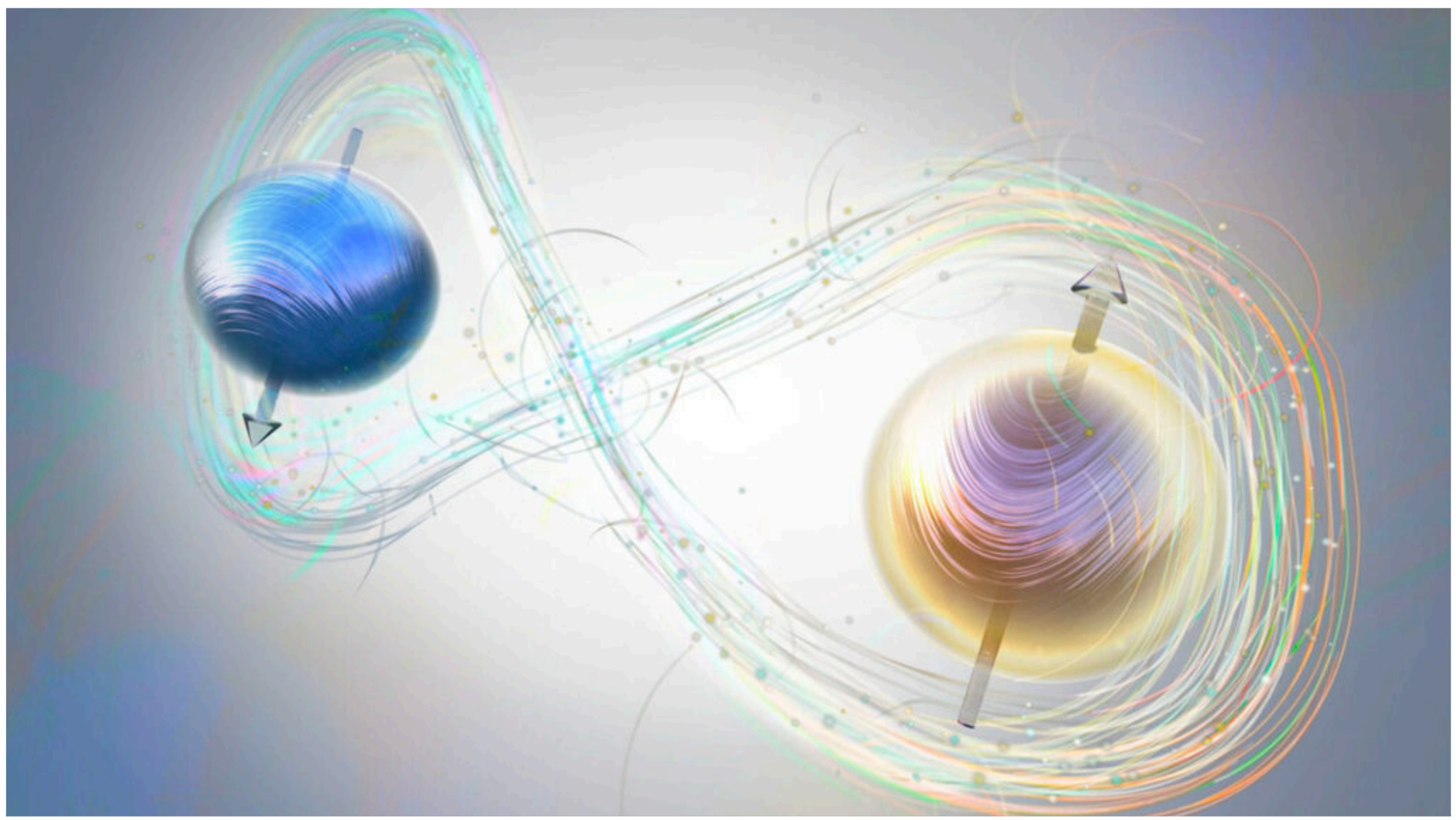
Hadronic Top Quark Polarimetry

Top 2024, Saint-Malo, Sep 25, 2024

Dorival Gonçalves



Dong, DG, Kong, Navarro '23
Dong, DG, Kong, Larkoski, Navarro '24
Dong, DG, Kong, Larkoski, Navarro '24

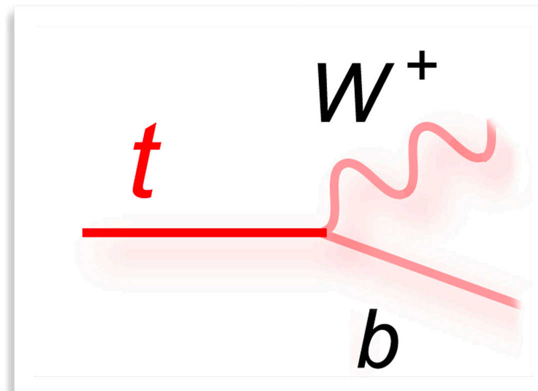
Top Quark is Unique

- Decays before it hadronizes or its spin flips

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

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

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

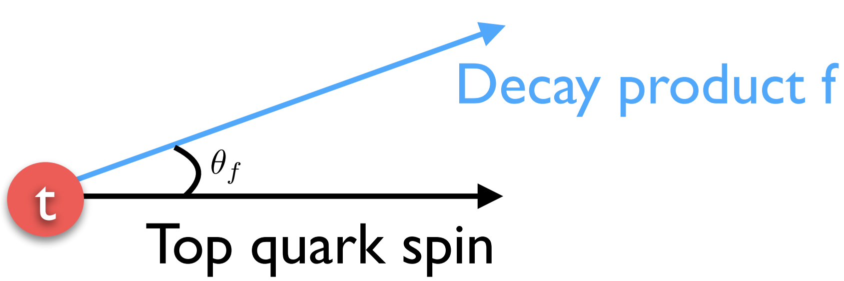


- Top polarization directly observable via angular distributions of its decay products

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

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

Spin analyzing power: maximum for charged leptons



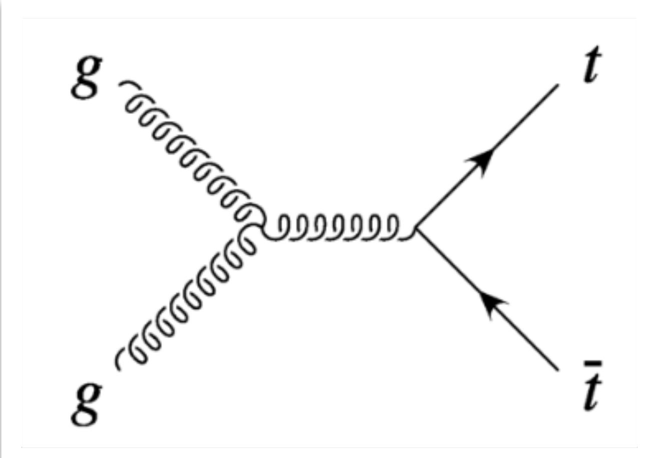
$$\beta_{\ell+}^{\rm NLO} = 0.998,\ \beta_{\bar{d}}^{\rm NLO} = 0.966,\ \beta_{b}^{\rm NLO} = -0.393$$

Brandenburg, Si, Uwer (2002)

Top quark pair production as a two qubit system

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

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



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

$B_i = \langle\sigma_i \otimes \mathbb{I}\rangle$, $\bar{B}_i = \langle\mathbb{I} \otimes \sigma_i\rangle$ → Polarizations

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

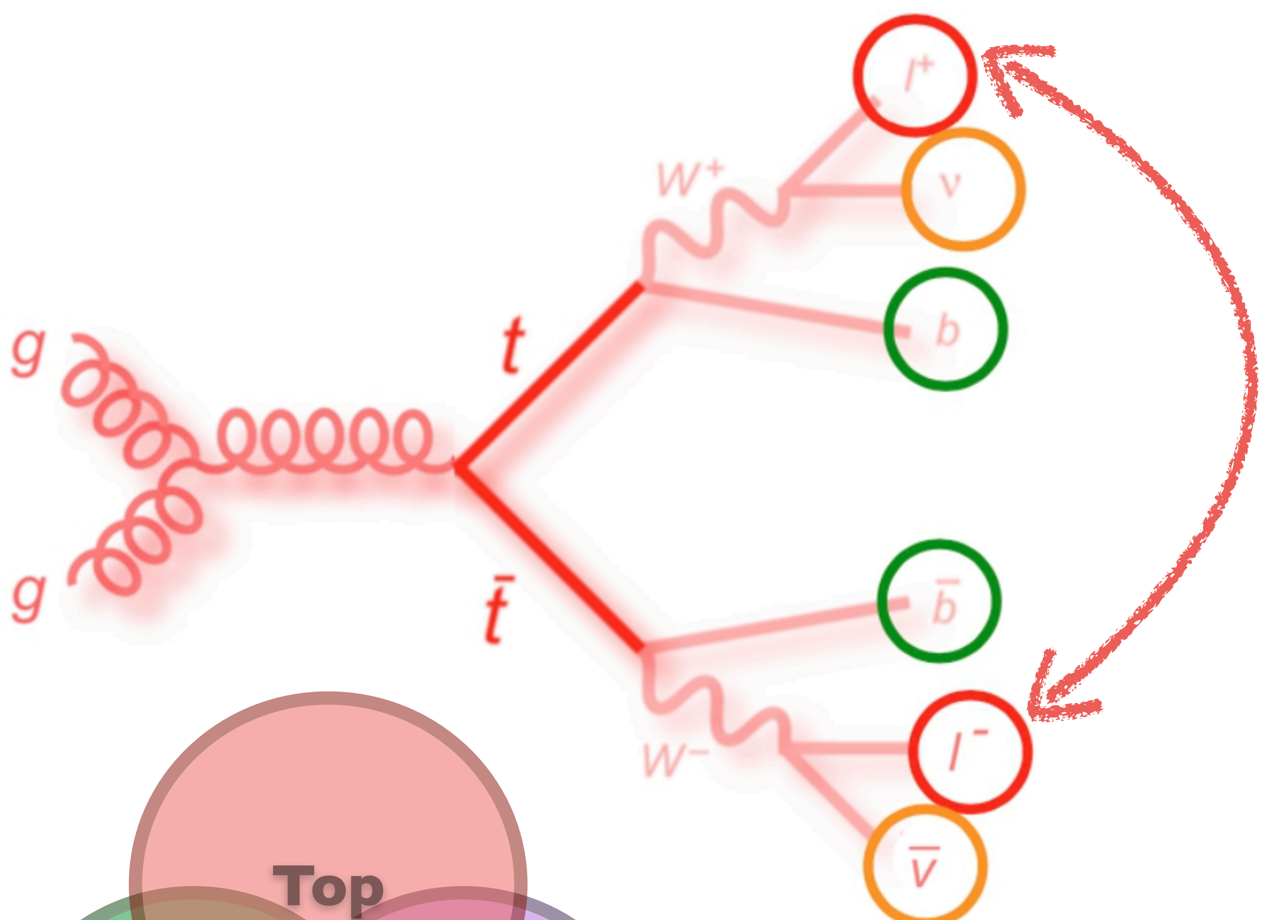
- P and CP invariance under $t\bar{t}$ production $\rightarrow B_i = \bar{B}_i = 0$ and $C_{ij} = C_{ji}$

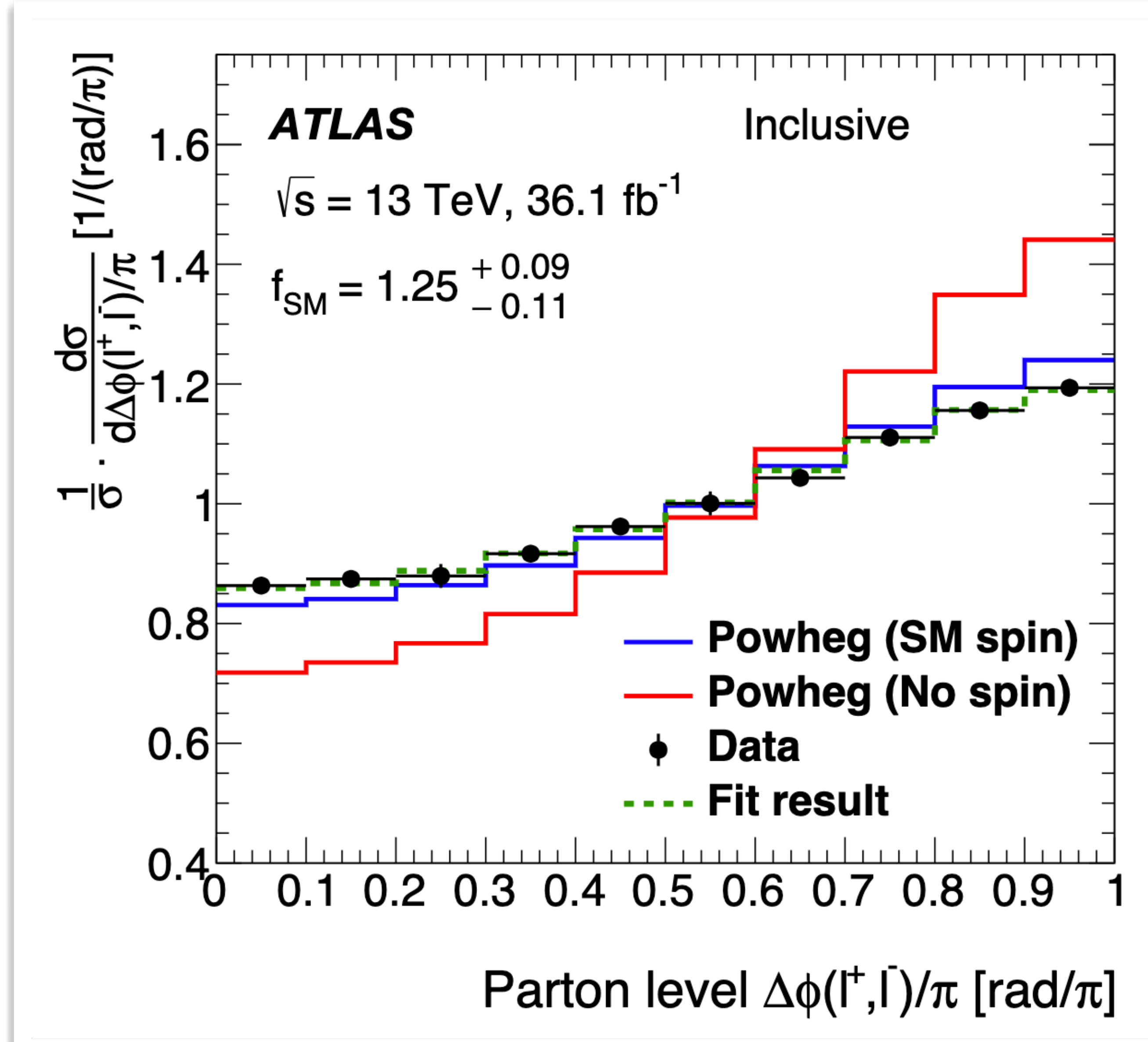
- Things further simplify in the helicity basis: only non-vanishing parameters are the diagonal terms C_{ii} and one off-diagonal term $C_{12} \simeq C_{21}$

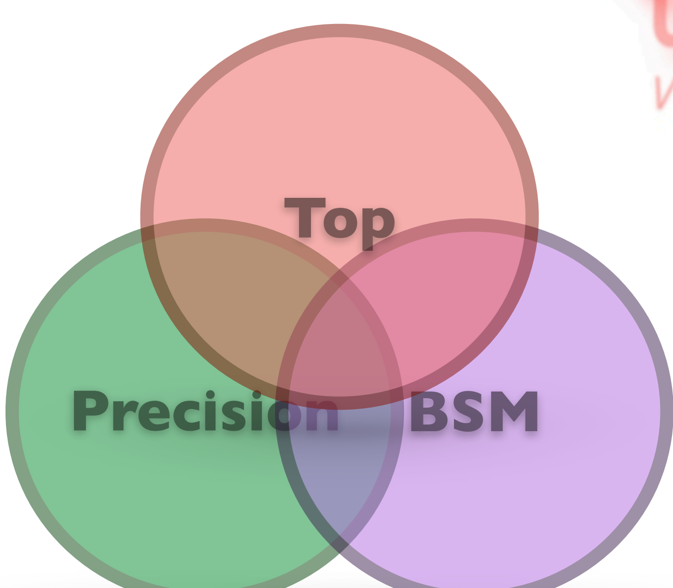
Bernreuther, Heisler, Si '15
Czakon, Mitov, Poncelet '20
Frederix, Tsinikos, Vitos '21

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

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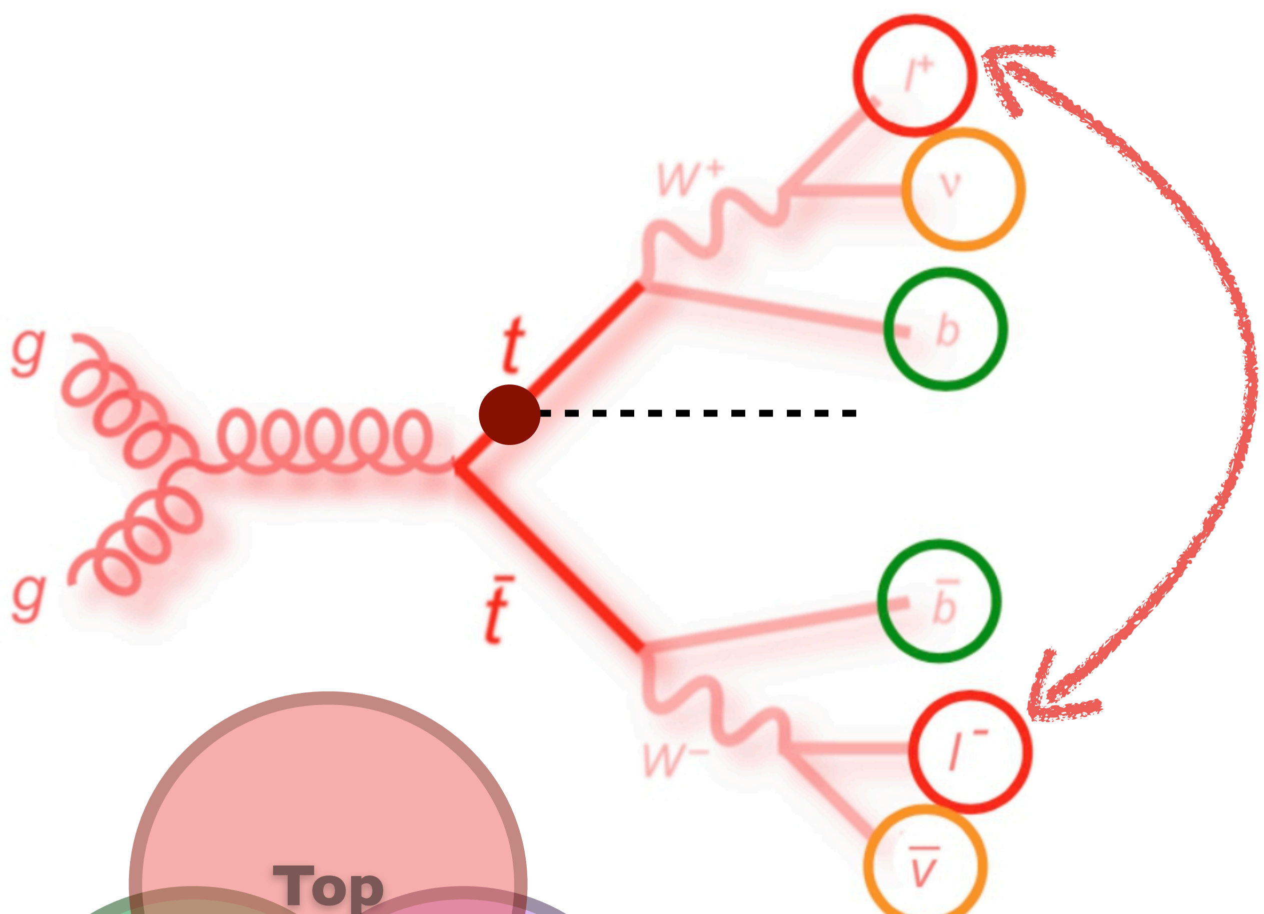
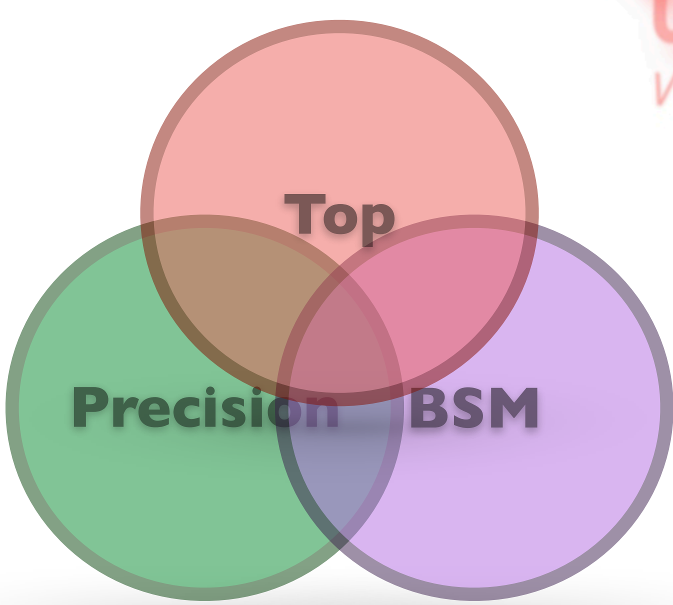
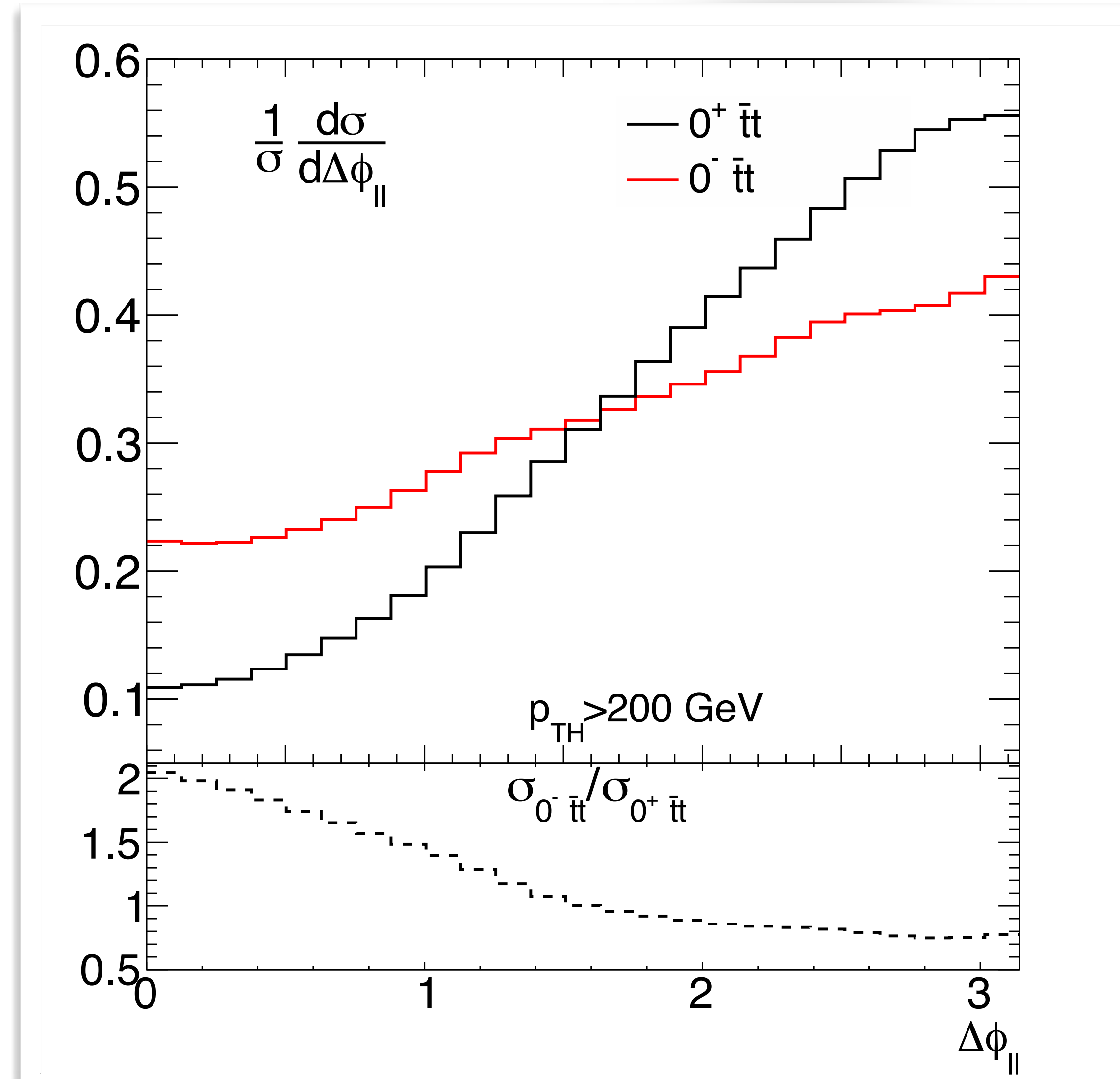




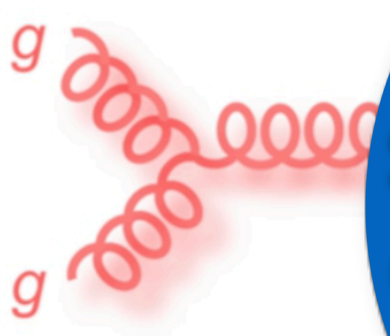
$$\mathcal{L} \supseteq -\frac{m_t}{v} K \bar{t} \left(\cos\alpha + i\gamma_5 \sin\alpha\right) t\, H$$

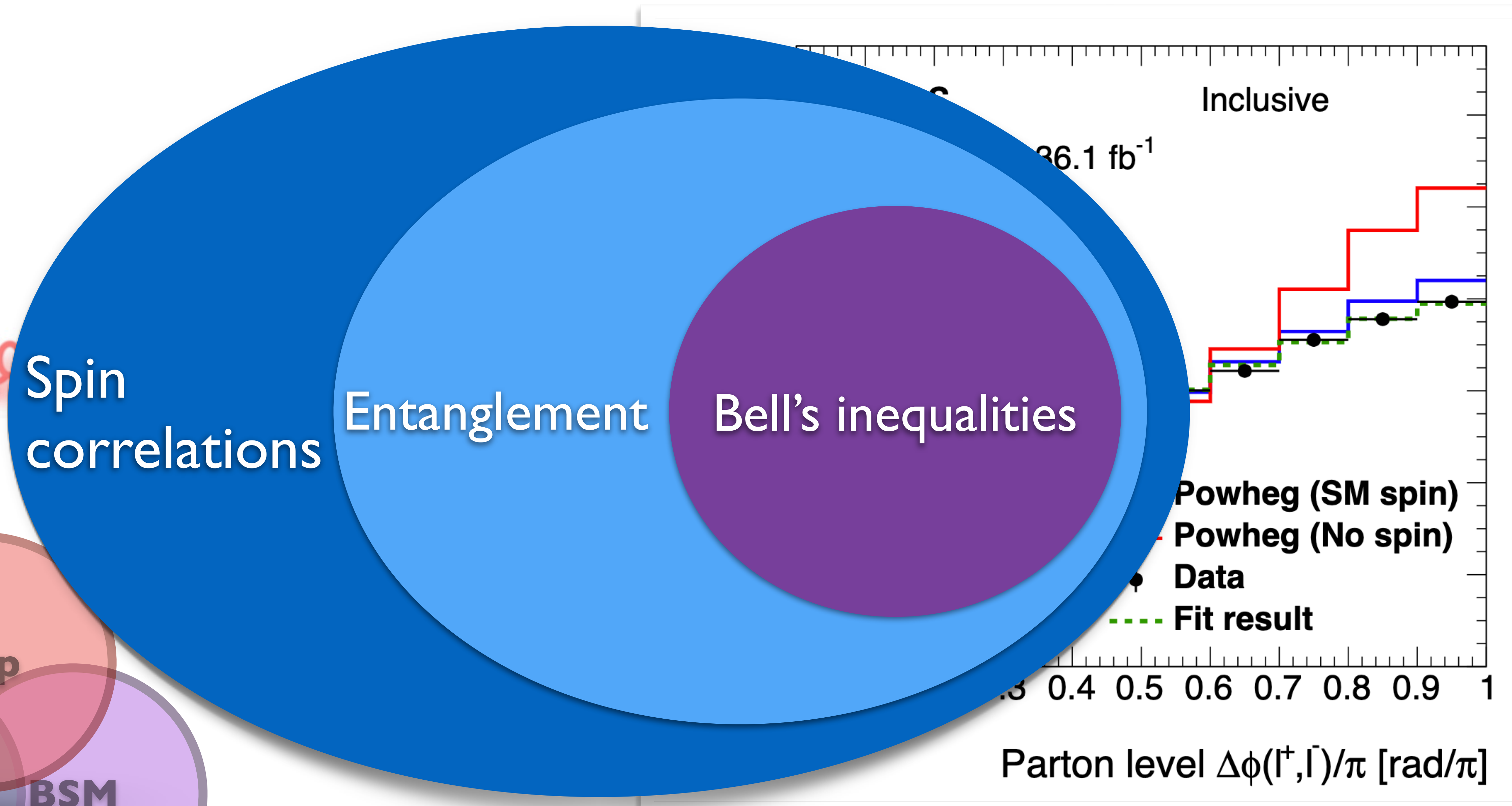


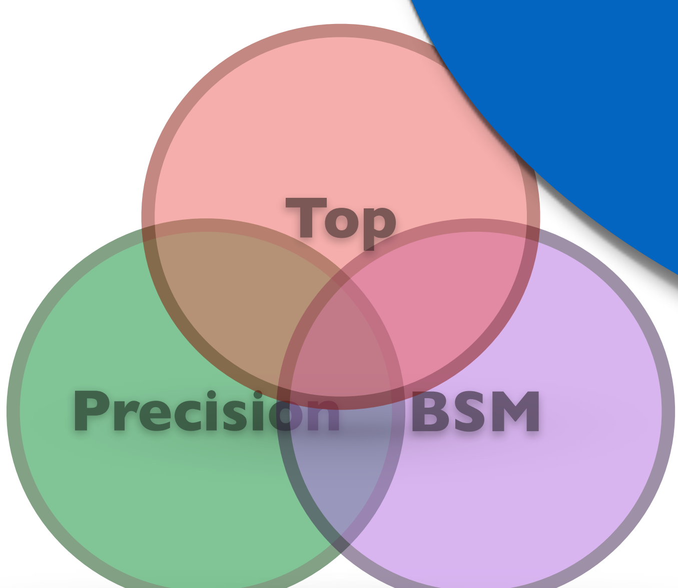
Buckley, DG (PRL '15)

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





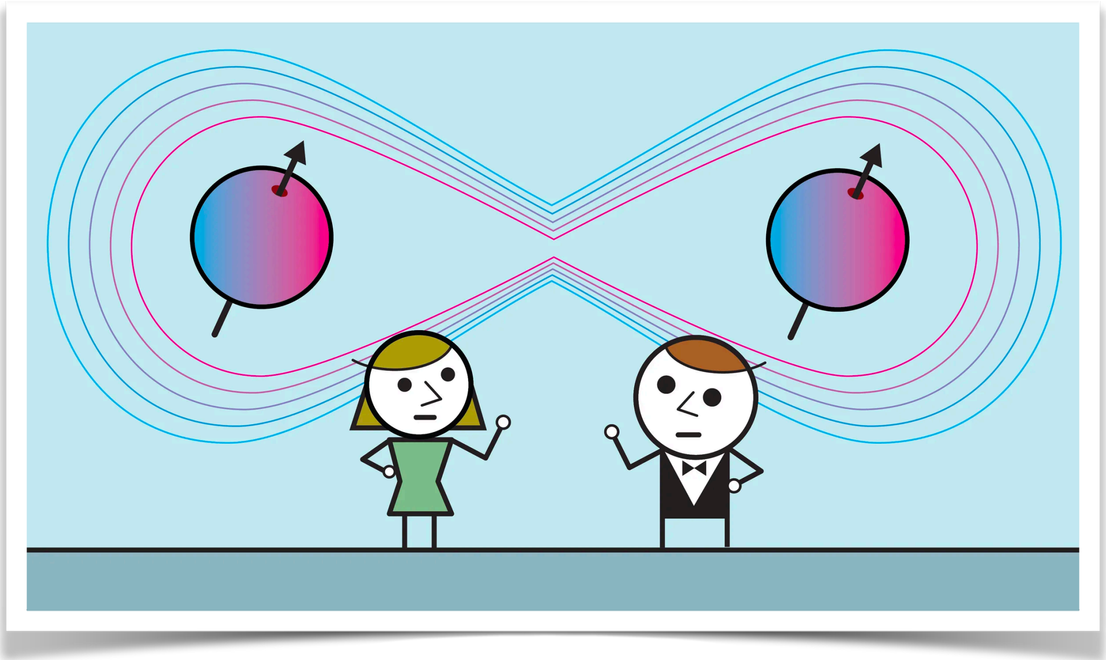


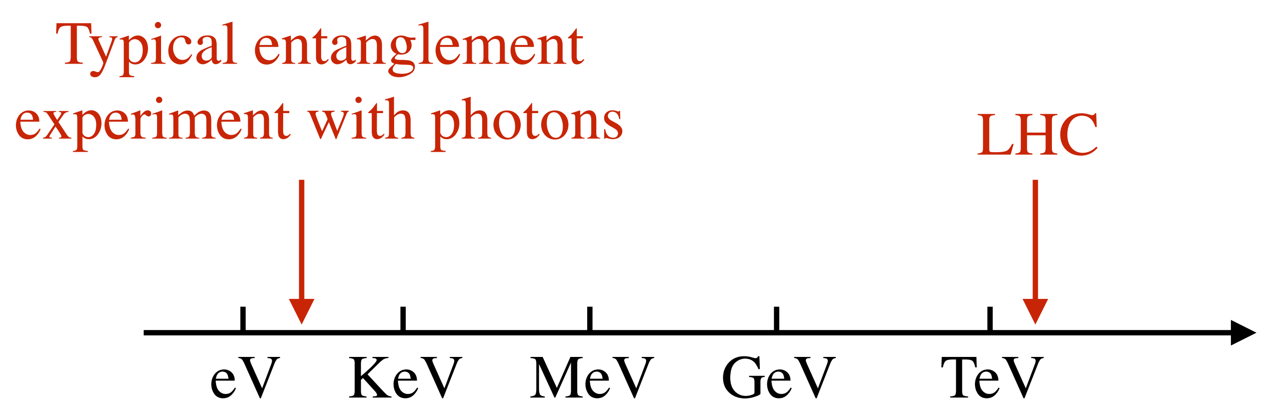
$$\rho = \frac{\mathbb{I}\otimes\mathbb{I} + \left(B_i \sigma_i \otimes \mathbb{I} + \bar{B}_i \mathbb{I}\otimes\sigma_i\right) + C_{ij}\sigma_i\otimes\sigma_j}{4}$$

Parke, Mahlon '95

Entanglement and Bell Inequalities with Top Quarks

- LHC can provide a unique environment to study entanglement and violation of Bell's inequalities at the highest energy available to date





- Top quark pair production is an optimal candidate for these studies

Afik, Nova '20; Fabbrichesi, Floreanini, Panizzo '21; Severi, Boschi, Maltoni, Sioli '21
Saavedra, Casas '22; Severi, Vryonidou 22
Dong, DG, Kong, Navarro '23
Han, Low, Wu '23
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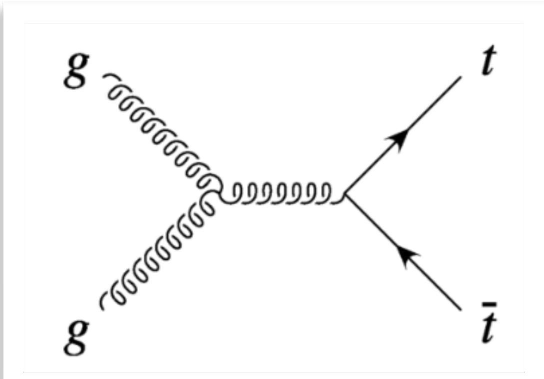
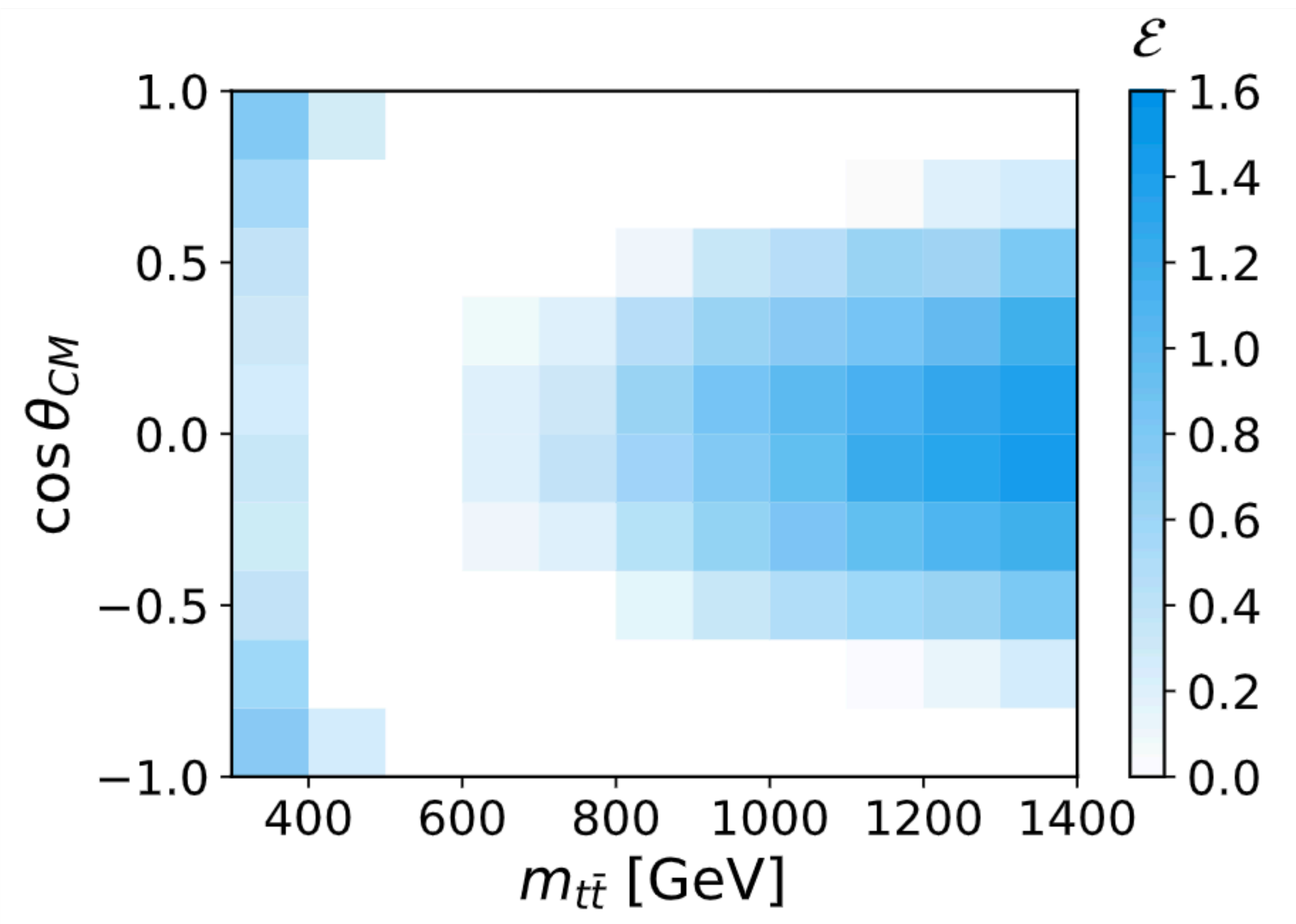
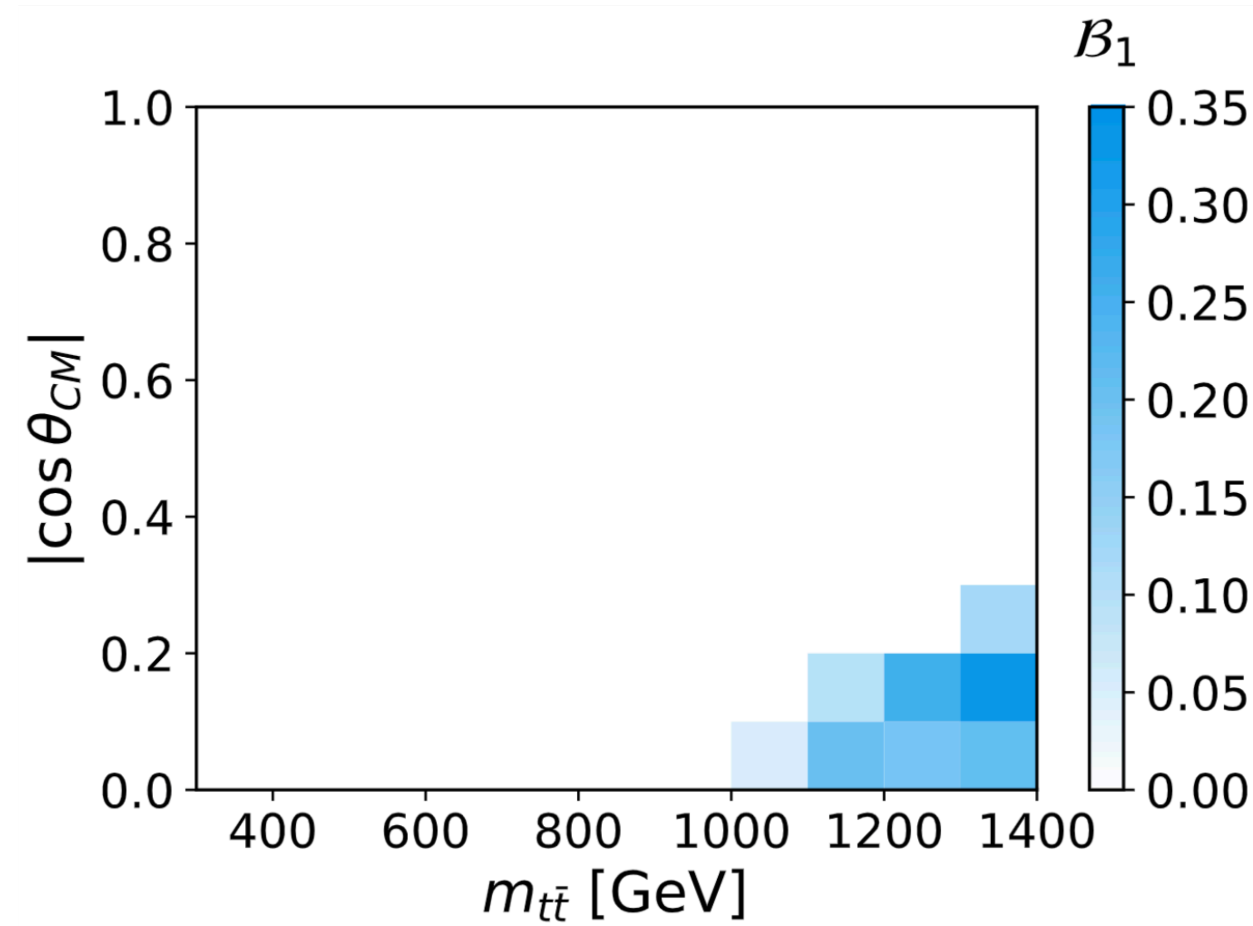


See talks by Eleni Vryonidou, Chris White, Juan Antonio A. Saavedra, Giulia Negro, Roman Lysak

Quantum Correlations

- Entanglement
- Bell/CHSH inequalities





Dong, DG, Kong, Navarro ’23

Afik, Nova ’20
Severi, Boschi, Maltoni, Sioli ‘21
Saavedra, Casas ‘22

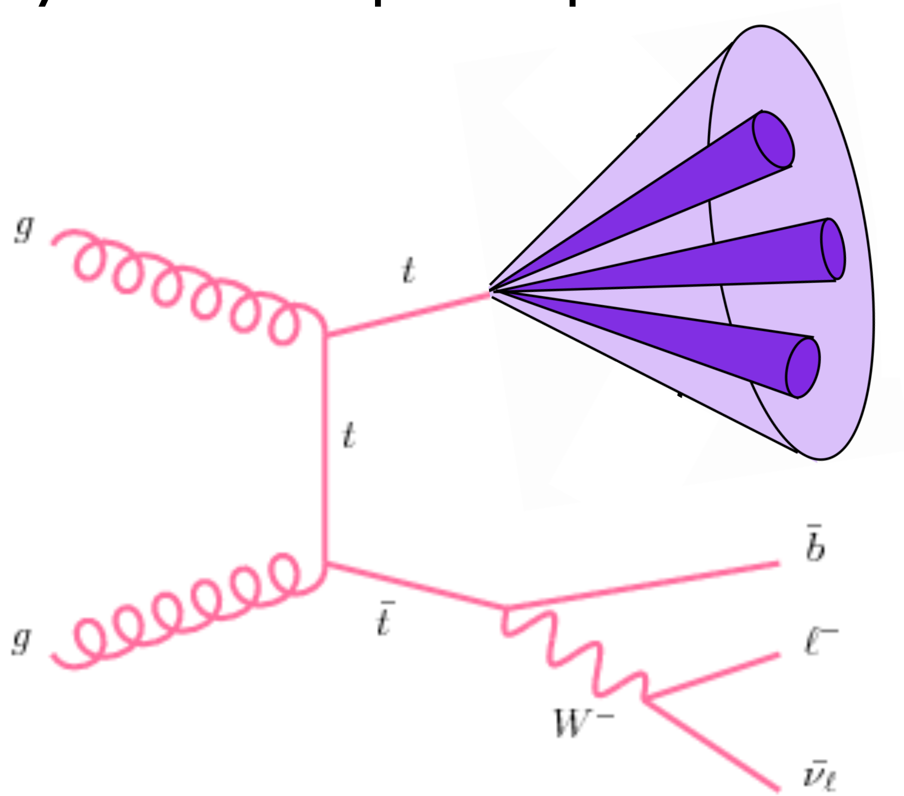
→ Entanglement and Bell/CHSH violation studies well match **boosted** top pair searches

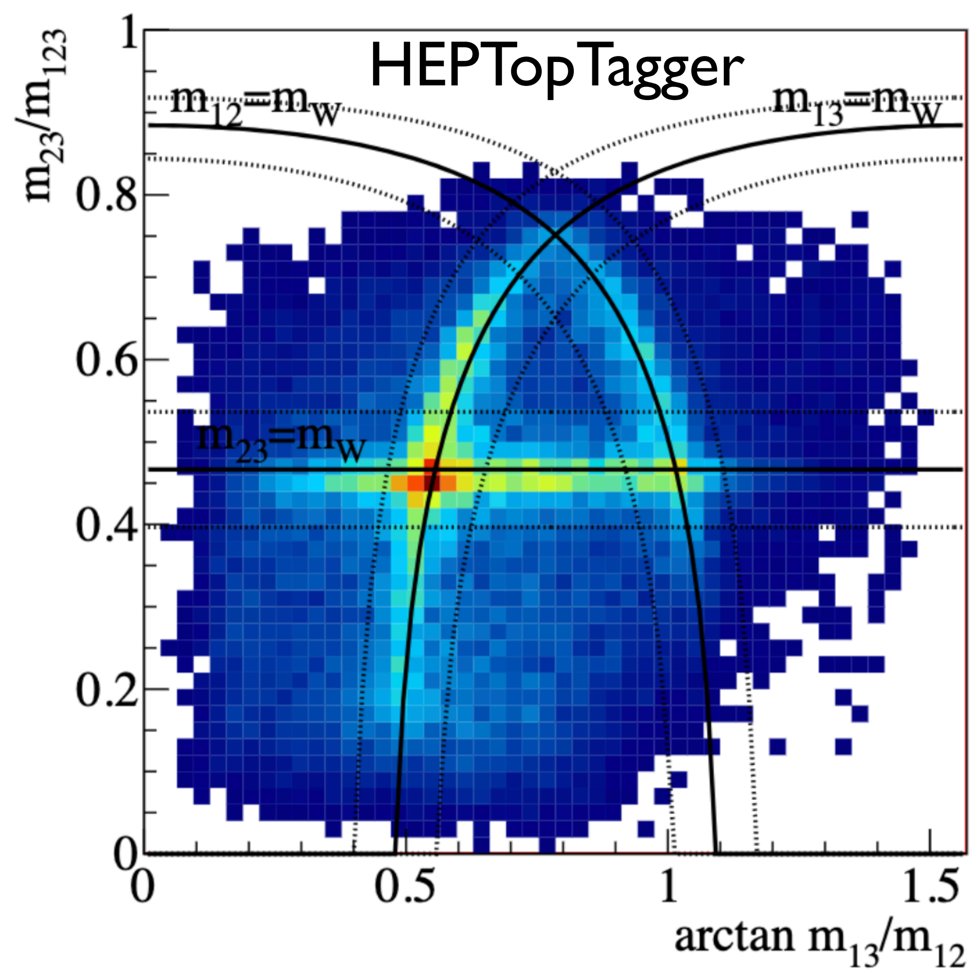
Semi-leptonic top pair

- Pros:
  - 6 times higher event rate than dileptonic case
  - It can more effectively probe the boosted regime
  - Easier reconstruction
- Cons:
  - down-type quark is best polarimeter, but tagging it in a collider environment is challenging

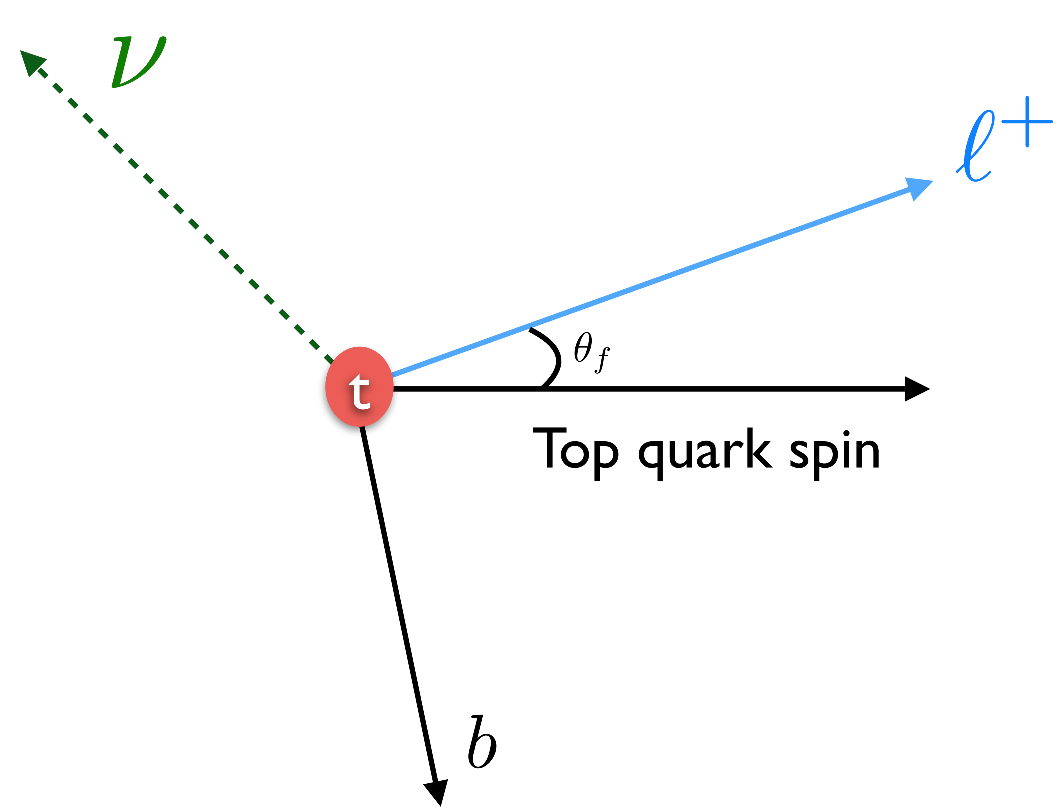
→ Solution:

- Boosted top tagging to aid subjet and light quark matching
- Proxy for down-quark: optimal hadronic polarimeter



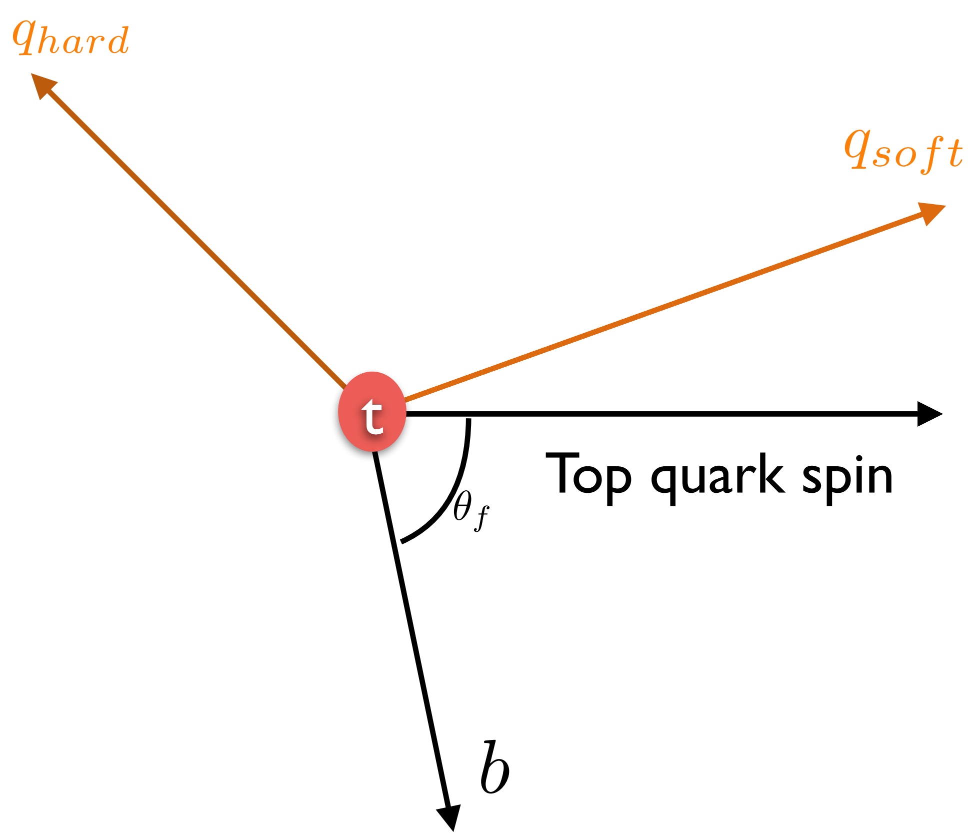


Hadronic top quark polarimetry



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

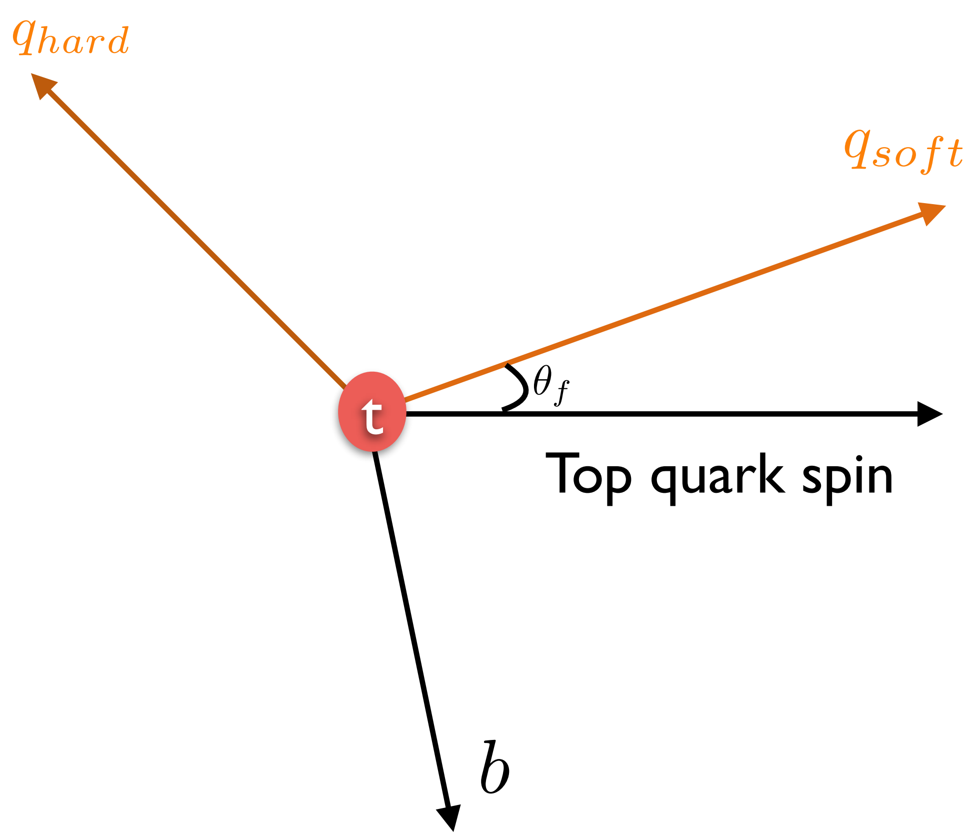
Hadronic top quark polarimetry



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

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

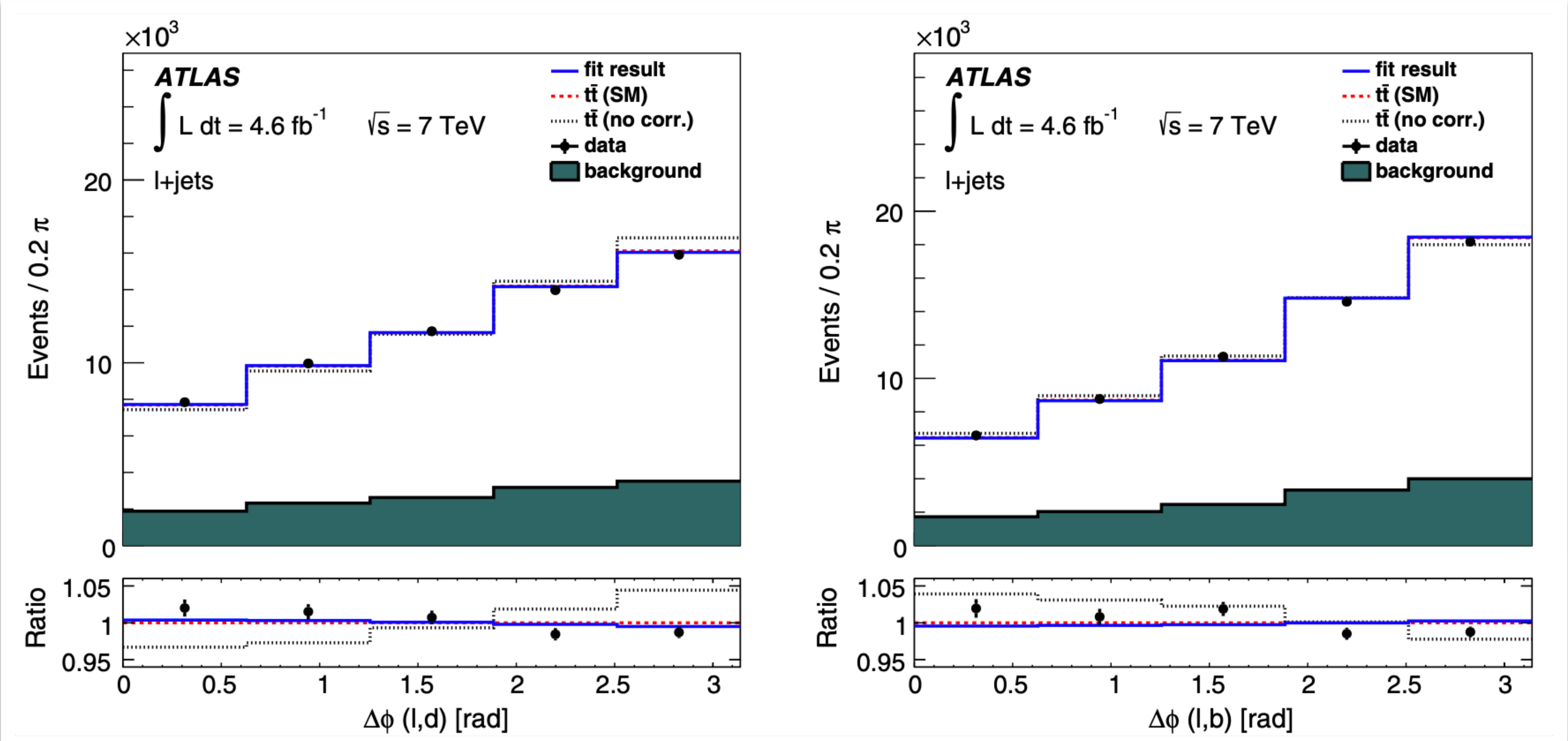


$$\frac{1}{\Gamma_f}\frac{d\Gamma_f}{d\cos\theta_f} = \frac{1}{2}(1 + \mathbf{0.5}\,\cos\theta_f)$$

Jezabek '94

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



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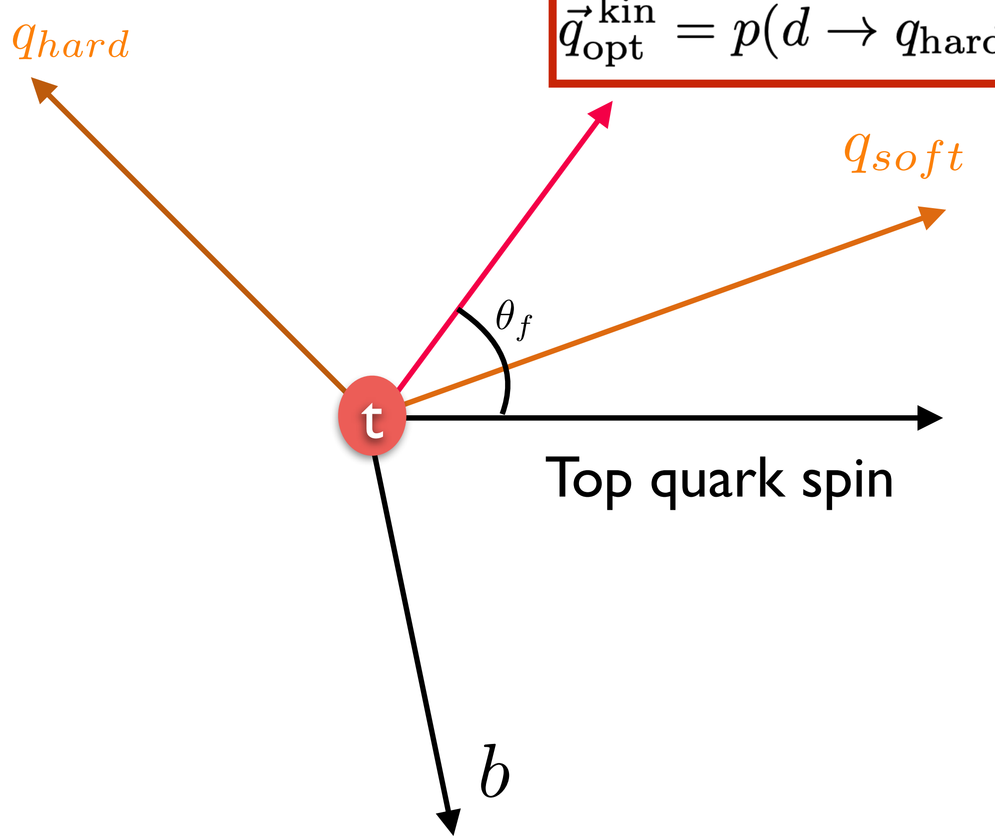
Hadronic top quark polarimetry

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

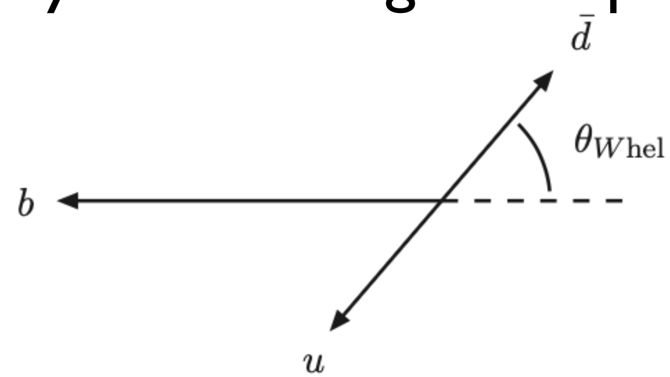
$$\vec{q}_{\rm opt}^{\,\rm kin} = p(d \to q_{\rm hard}|c_W)\hat{q}_{\rm hard} + p(d \to q_{\rm soft}|c_W)\hat{q}_{\rm soft}$$



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

Hadronic top quark polarimetry

- We begin by considering the top quark decay in the W boson rest frame



$W^{\pm}$ is given by

$$\rho(c_{W_{\text{hel}}}) = \frac{3}{8} f_R (1 \pm c_{W_{\text{hel}}})^2 + \frac{3}{4} f_0 (1 - c^2_{W_{\text{hel}}}) + \frac{3}{8} f_L (1 \mp c_{W_{\text{hel}}})^2.$$

- If we do not distinguish the d-subjet and u-subjet, we need to identify $c_{W\text{hel}} \leftrightarrow -c_{W\text{hel}}$
However,

$$p(d \to q_{\text{hard}}) = \frac{\rho(|c_{W_{\text{hel}}}|)}{\rho(|c_{W_{\text{hel}}}|) + \rho(-|c_{W_{\text{hel}}}|)}$$

→ quark emitted in forward direction in W rest frame will be harder and more separated from b-quark in top rest frame

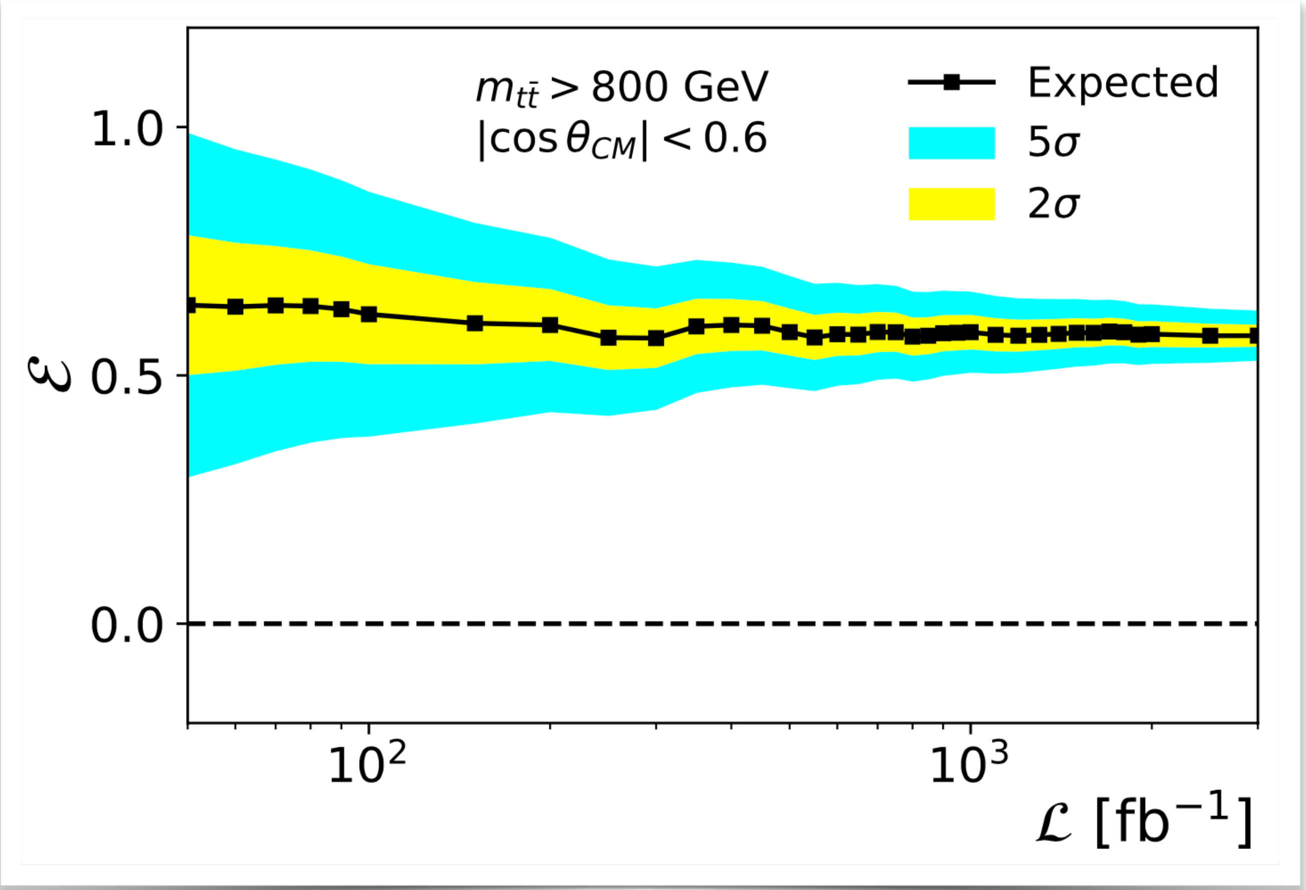
$$p(d \to q_{\text{soft}}) = \frac{\rho(-|c_{W_{\text{hel}}}|)}{\rho(|c_{W_{\text{hel}}}|) + \rho(-|c_{W_{\text{hel}}}|)}$$

→ quark emitted in backward direction in W rest frame will be softer and more aligned with b-quark in top rest frame

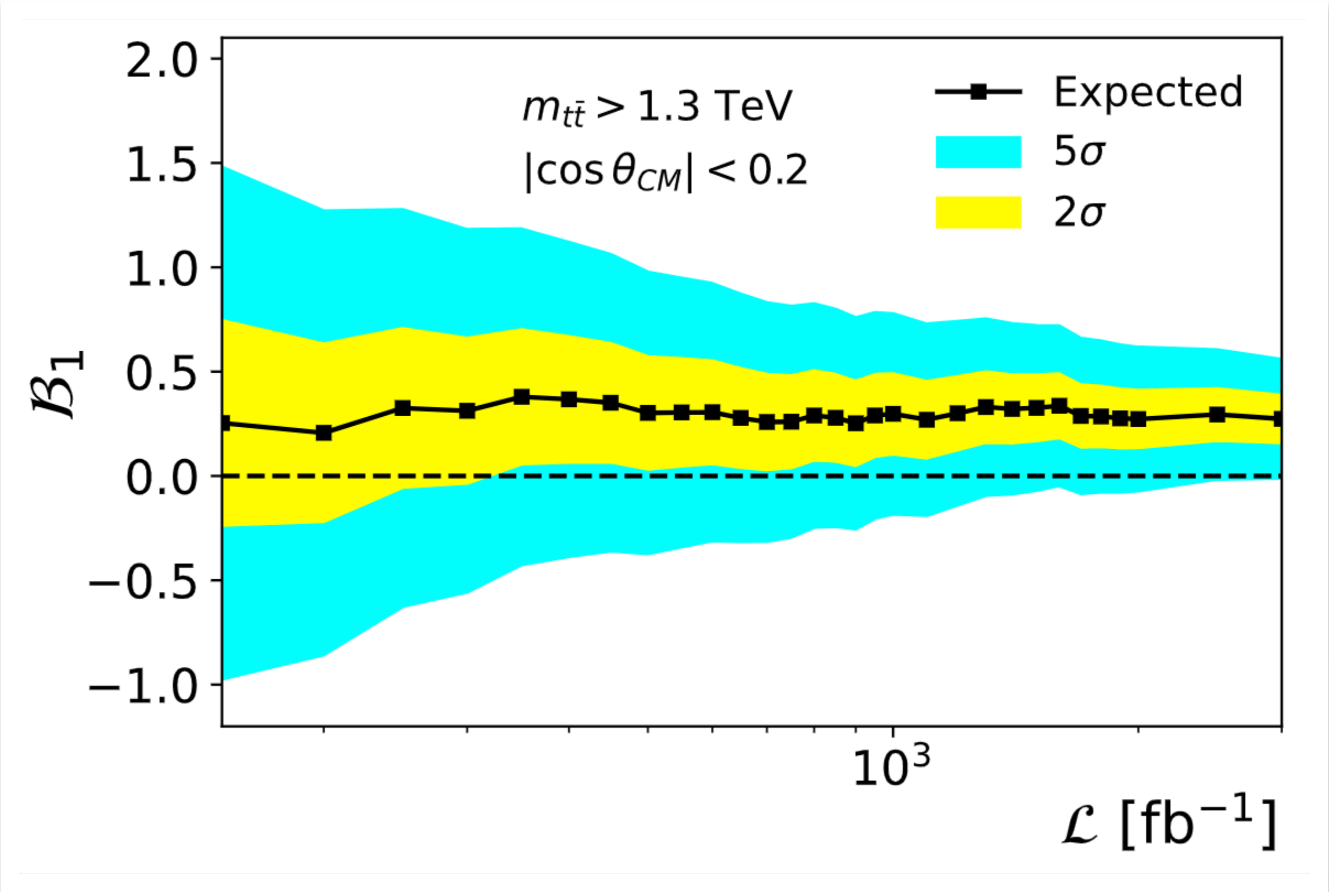
$$\vec{q}^{\,\text{kin}}_{\text{opt}} = p(d \to q_{\text{hard}} | c_W)\hat{q}_{\text{hard}} + p(d \to q_{\text{soft}} | c_W)\hat{q}_{\text{soft}}$$

LHC Projections

- Entanglement



- Bell/CHSH inequalities:



Dong, DG, Kong, Navarro ‘23

See talks by Eleni Vryonidou, Chris White, Juan Antonio A. Saavedra, Giulia Negro, Roman Lysak

LHC Projections

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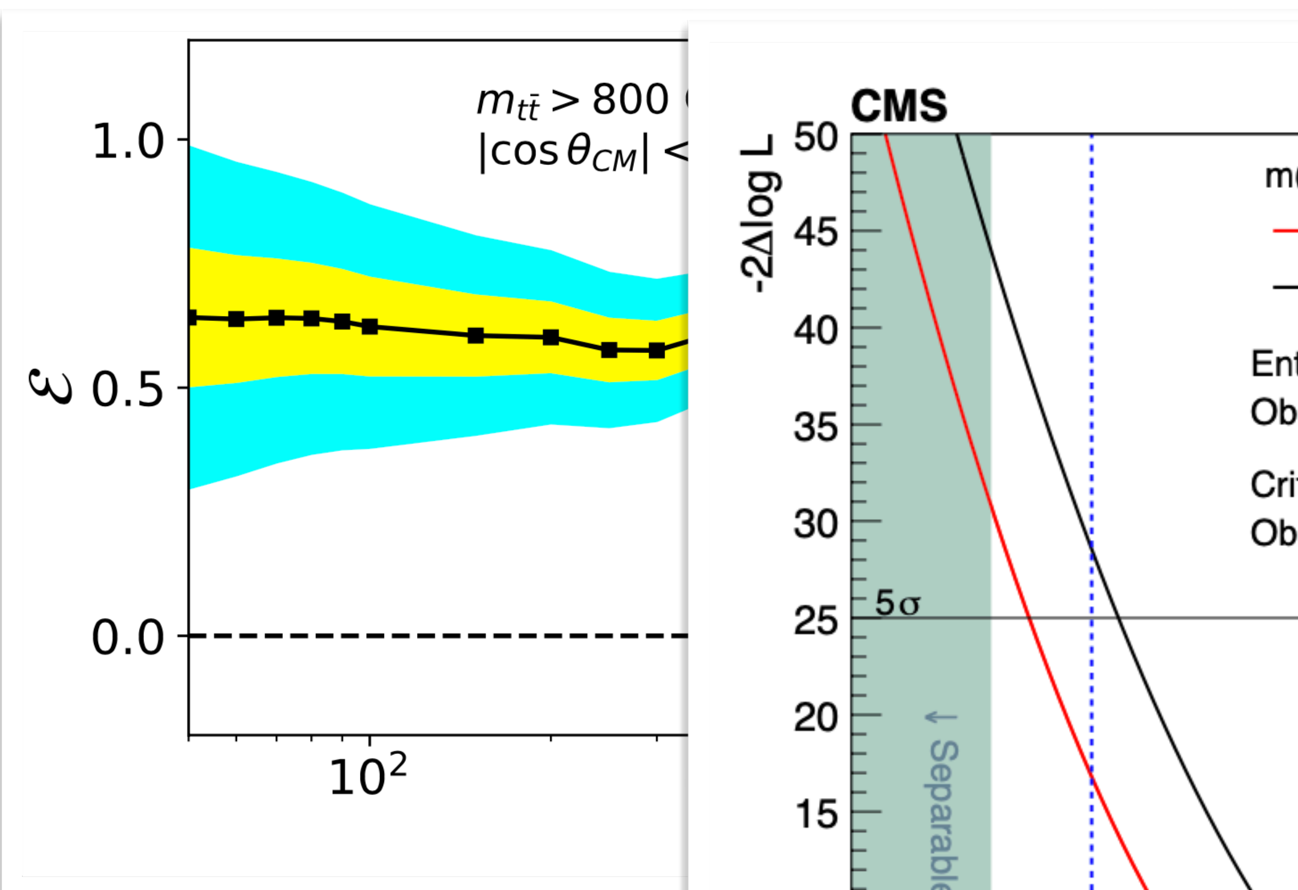

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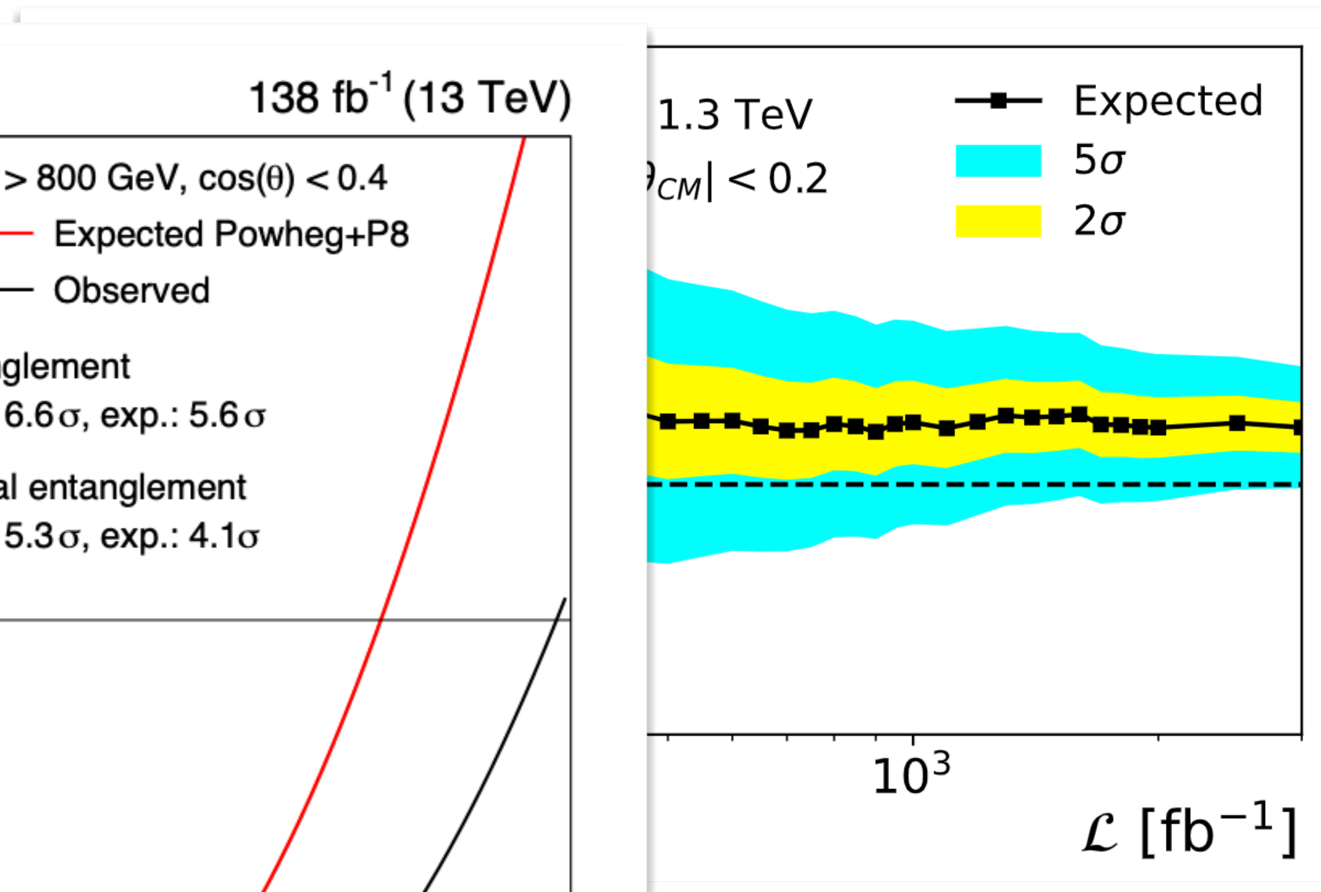
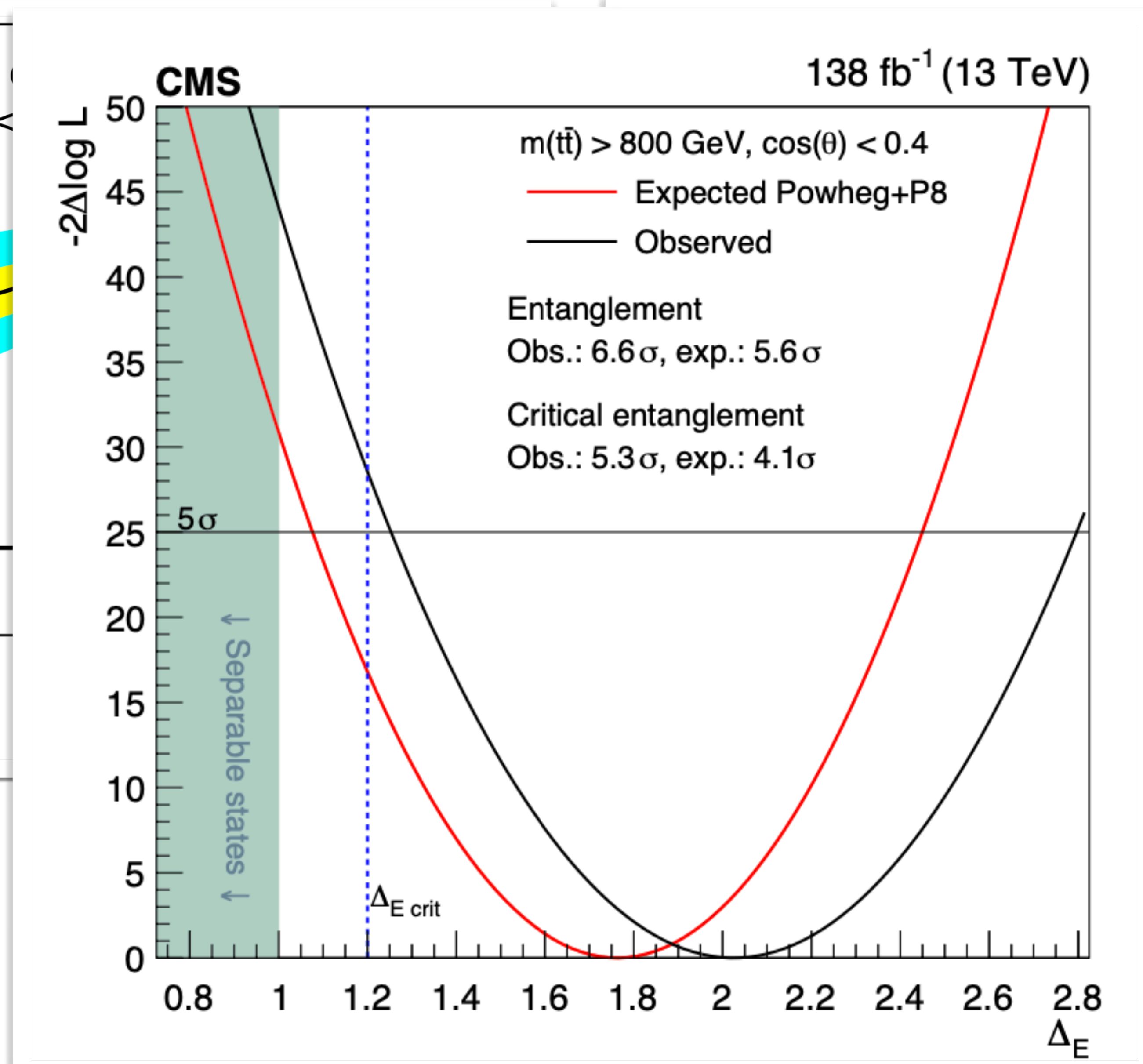


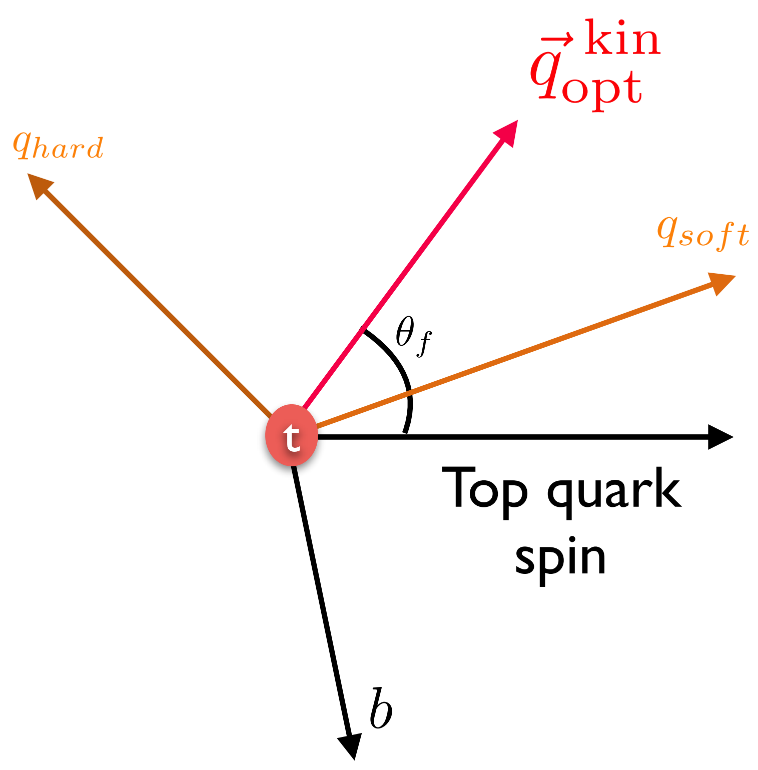


...ong, Navarro '23

CMS 2409.11067

... Eleni Vryonidou, Chris White, Juan Antonio A. Saavedra, Giulia Negro, Roman Lysak

Hadronic Top Quark Polarimetry with ParticleNet



$$\vec{q}_{\rm opt}^{\,\rm kin} = \; p(d \to q_{\rm hard}|c_W)\,\hat{q}_{\rm hard} + p(d \to q_{\rm soft}|c_W)\,\hat{q}_{\rm soft}$$

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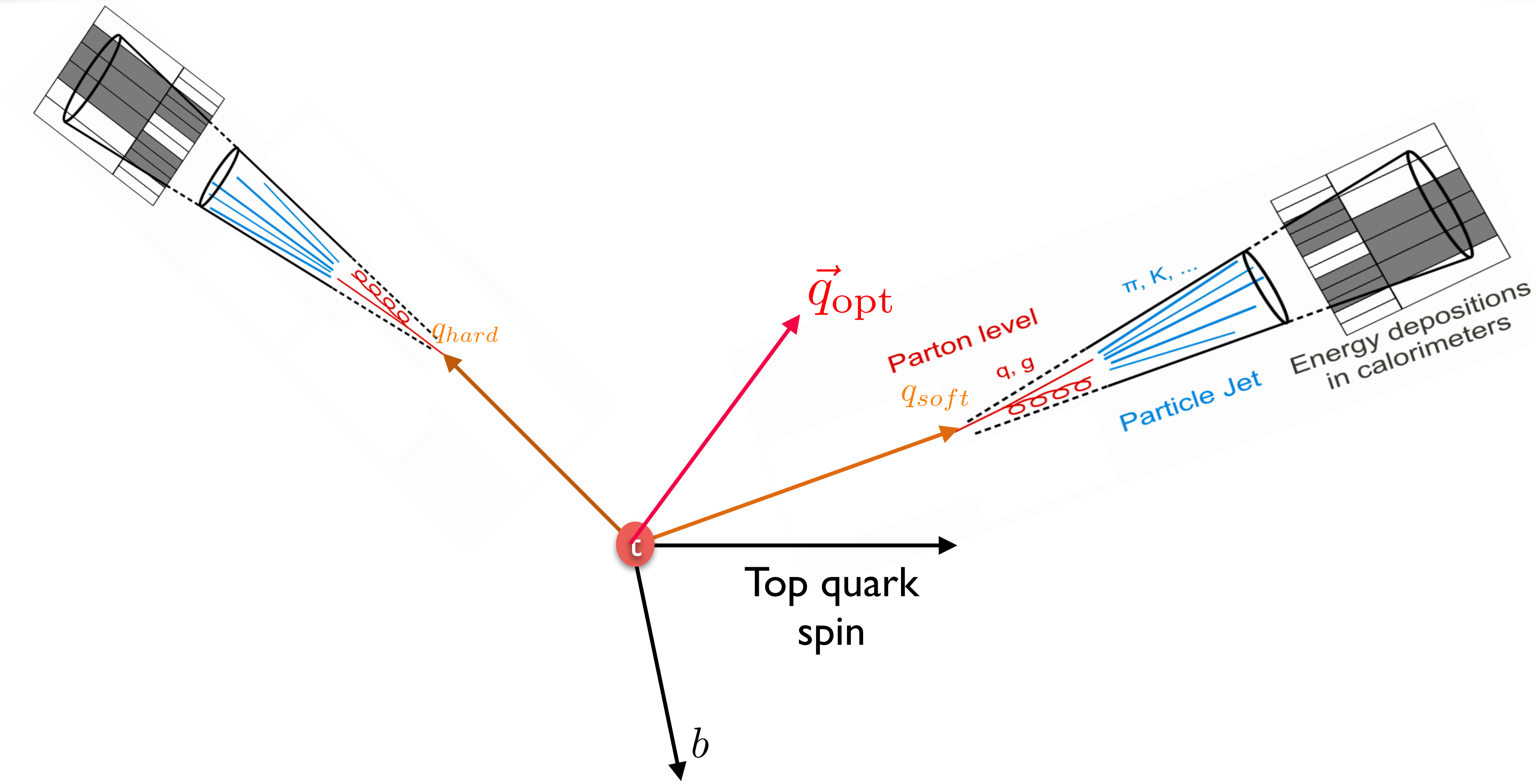
Hadronic Top Quark Polarimetry with ParticleNet



$$\vec{q}_{\rm opt} = \; p(d \to q_{\rm hard}|c_W, \{\mathcal{O}\})\, \hat{q}_{\rm hard} + p(d \to q_{\rm soft}|c_W, \{\mathcal{O}\})\, \hat{q}_{\rm soft}$$

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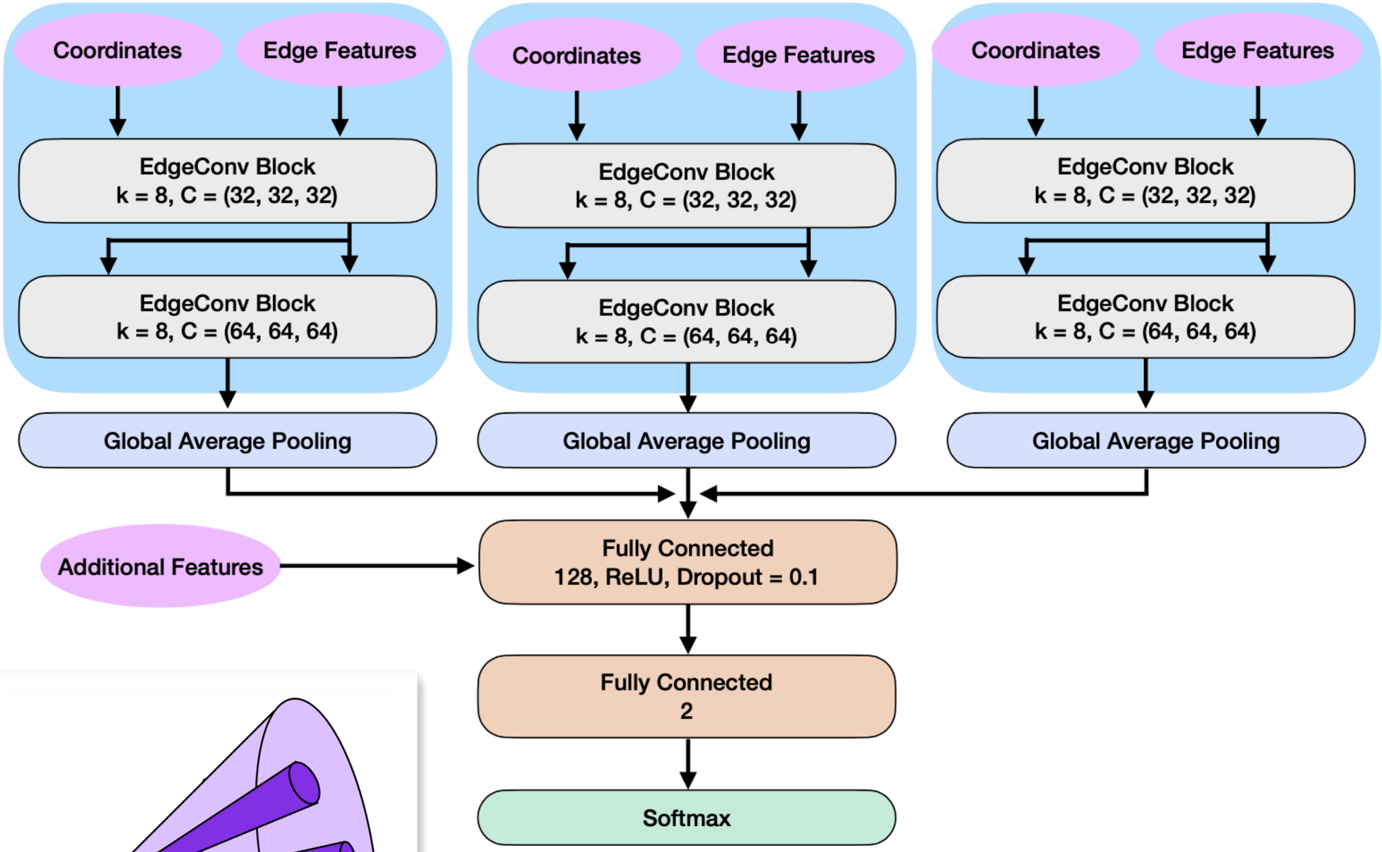
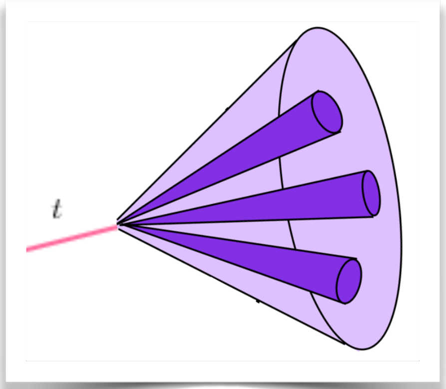
Dong, DG, Kong, Larkoski, Navarro ’24

Hadronic Top Quark Polarimetry with ParticleNet

- Instead of viewing a jet as an ordered set of constituents, it is treated as an unordered set of its constituent particles or a "particle cloud". This approach efficiently captures low-level jet details while respecting permutation symmetry Qu, Gouskos 2019

Variable	Definition
$\Delta\eta_t$	difference in pseudorapidity between the particle and the top jet axis
$\Delta\phi_t$	difference in azimuthal angle between the particle and the top jet axis
$\Delta\eta_j$	difference in pseudorapidity between the particle and the subjet axis
$\Delta\phi_j$	difference in azimuthal angle between the particle and the subjet axis
$\log p_T$	logarithm of the particle's p_T
$\log E$	logarithm of the particle's Energy
q	electric charge of the particle
isElectron	if the particle is an electron
isMuon	if the particle is a muon
isPhoton	if the particle is a photon
isChargedHadron	if the particle is a charged hadron
isNeutralHadron	if the particle is a neutral hadron





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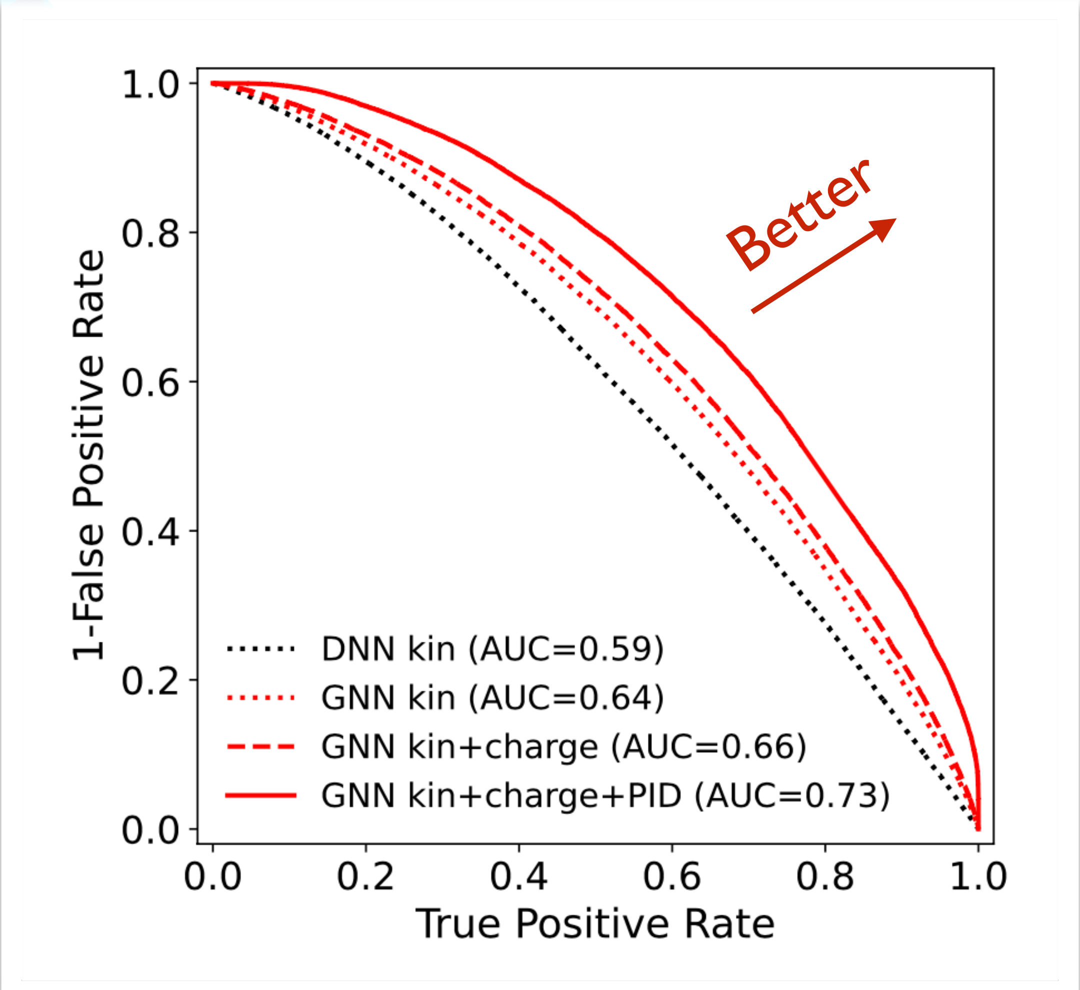
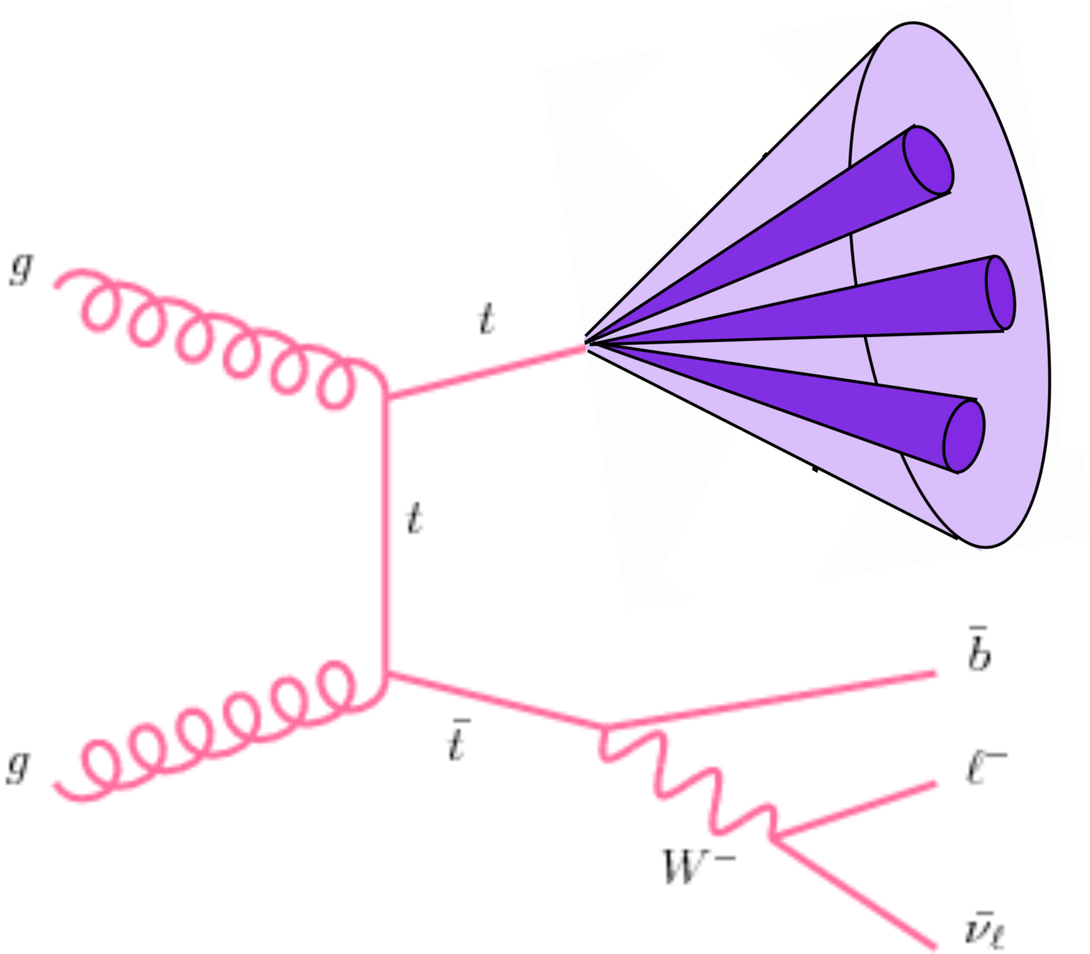
Hadronic Top Quark Polarimetry with ParticleNet

- Down-type subjet flavor identification within fatjet





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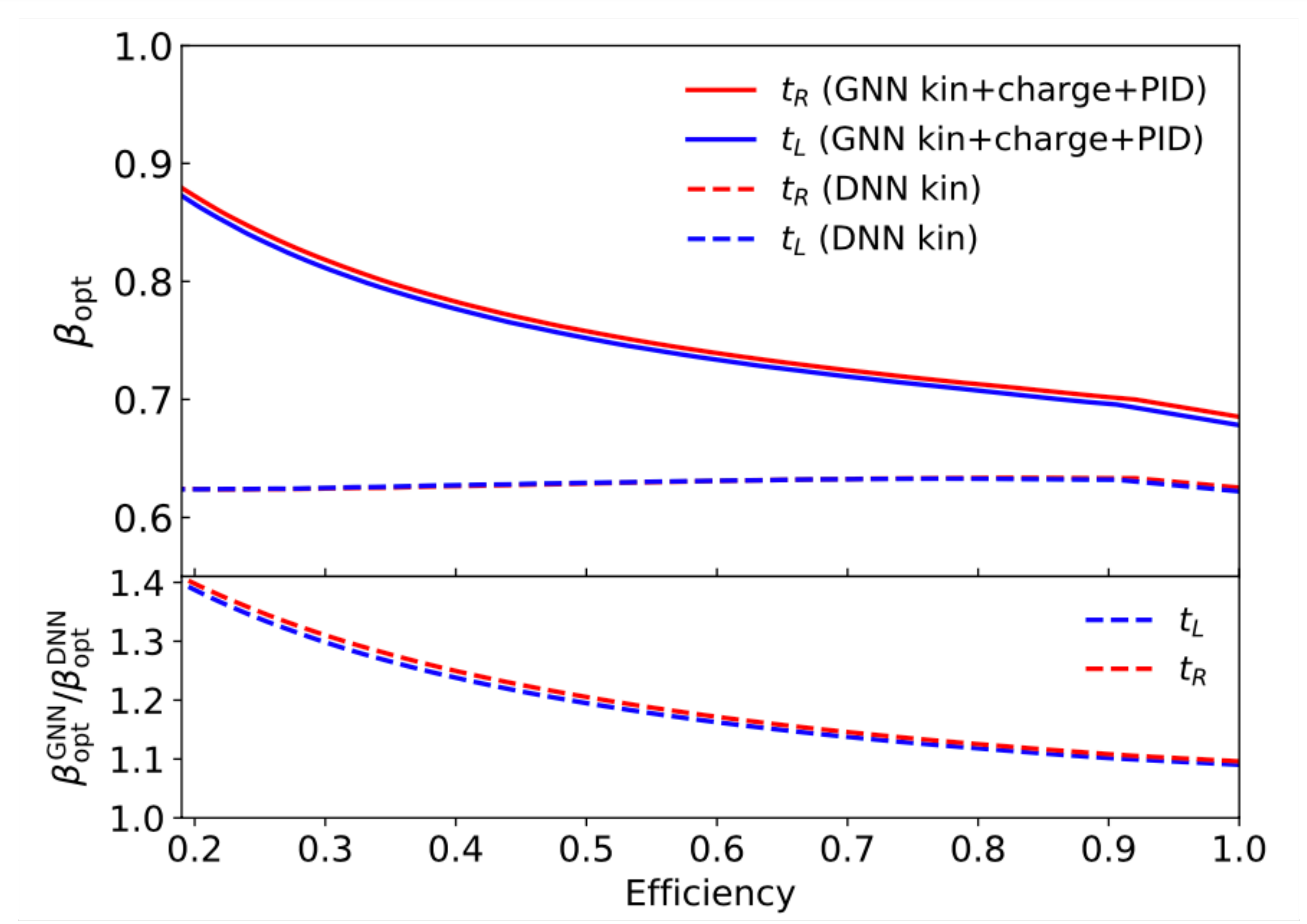
Hadronic Top Quark Polarimetry with ParticleNet



	$\beta_{opt}^{t_L}$	$\beta_{opt}^{t_R}$
$\text{DNN}_{\text{Eff}=100\%}$	0.622	0.625
$\text{GNN}_{\text{Eff}=100\%}$	0.678	0.685
$\text{GNN}_{\text{Eff}=50\%}$	0.751	0.758
$\text{GNN}_{\text{Eff}=20\%}$	0.863	0.869

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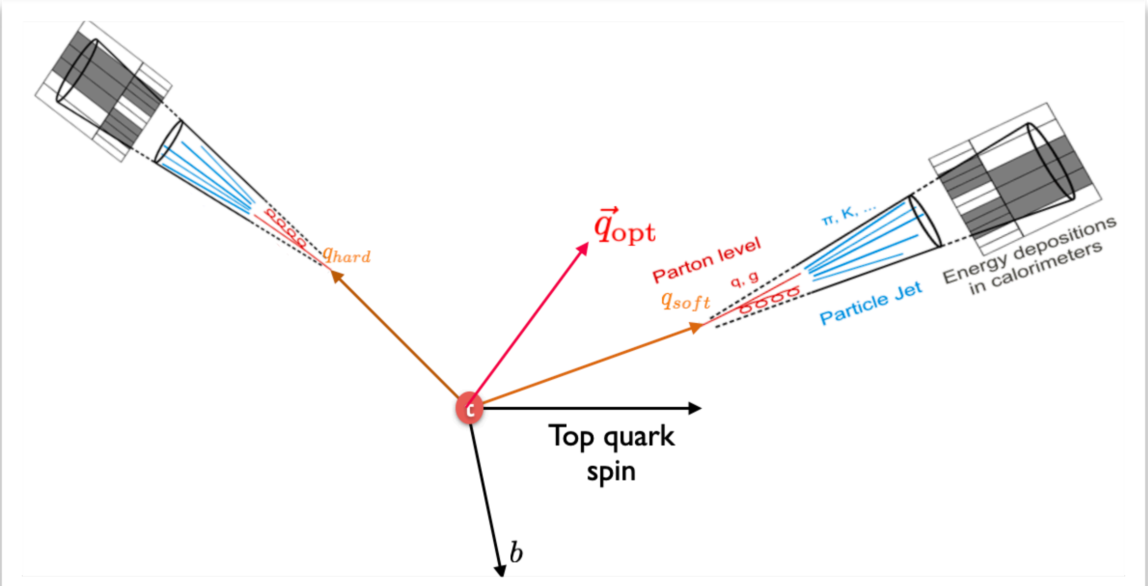
Summary

- Optimal hadronic polarimeter: crucial ingredient to access higher event rate from hadronic final states
- Down-type Jet flavor tagging significantly improve spin analyzing power in hadronic decays, going beyond exclusive kinematic information
- Imposing an efficiency of 50% (20%) can increase the spin analyzing power of the new artificial direction to β_{opt}=0.75 (0.86)
- These improvements can potentially boost spin correlations studies for precision physics, BSM searches, entanglement, Bell inequalities,…



Quantum Entanglement

- Entanglement stress test our current understanding
  - Theoretical modeling
  - Experimental uncertainties

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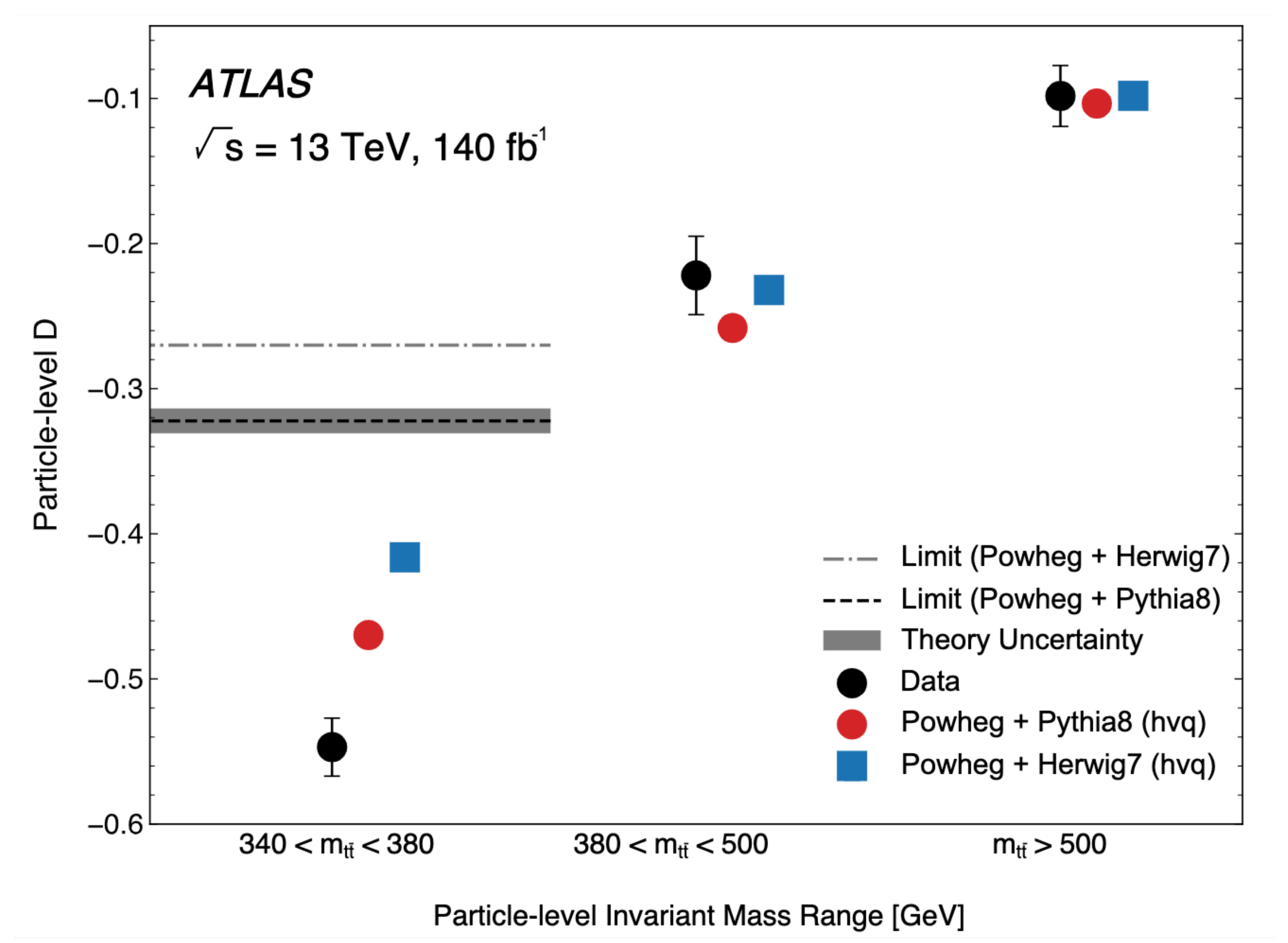
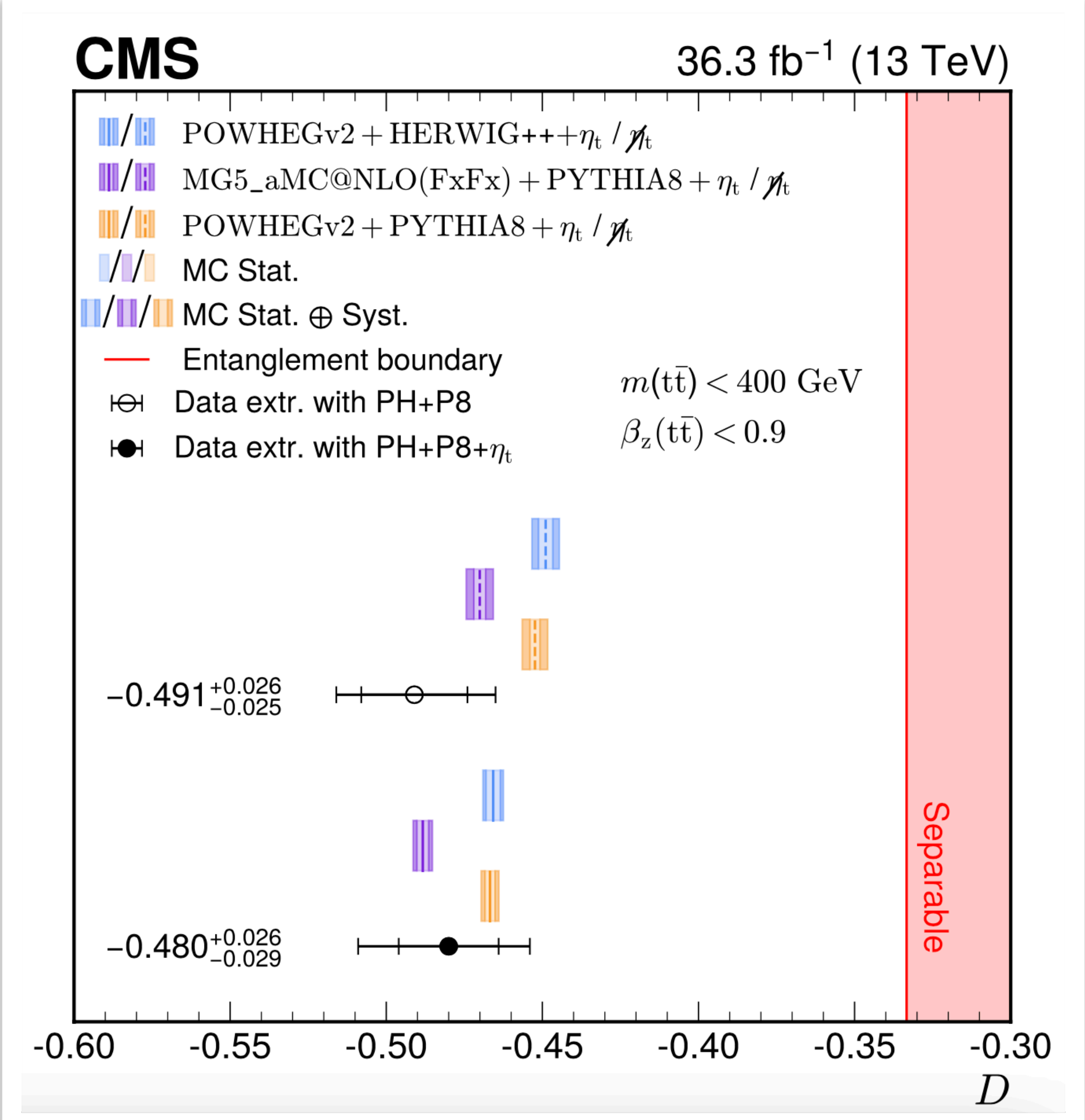
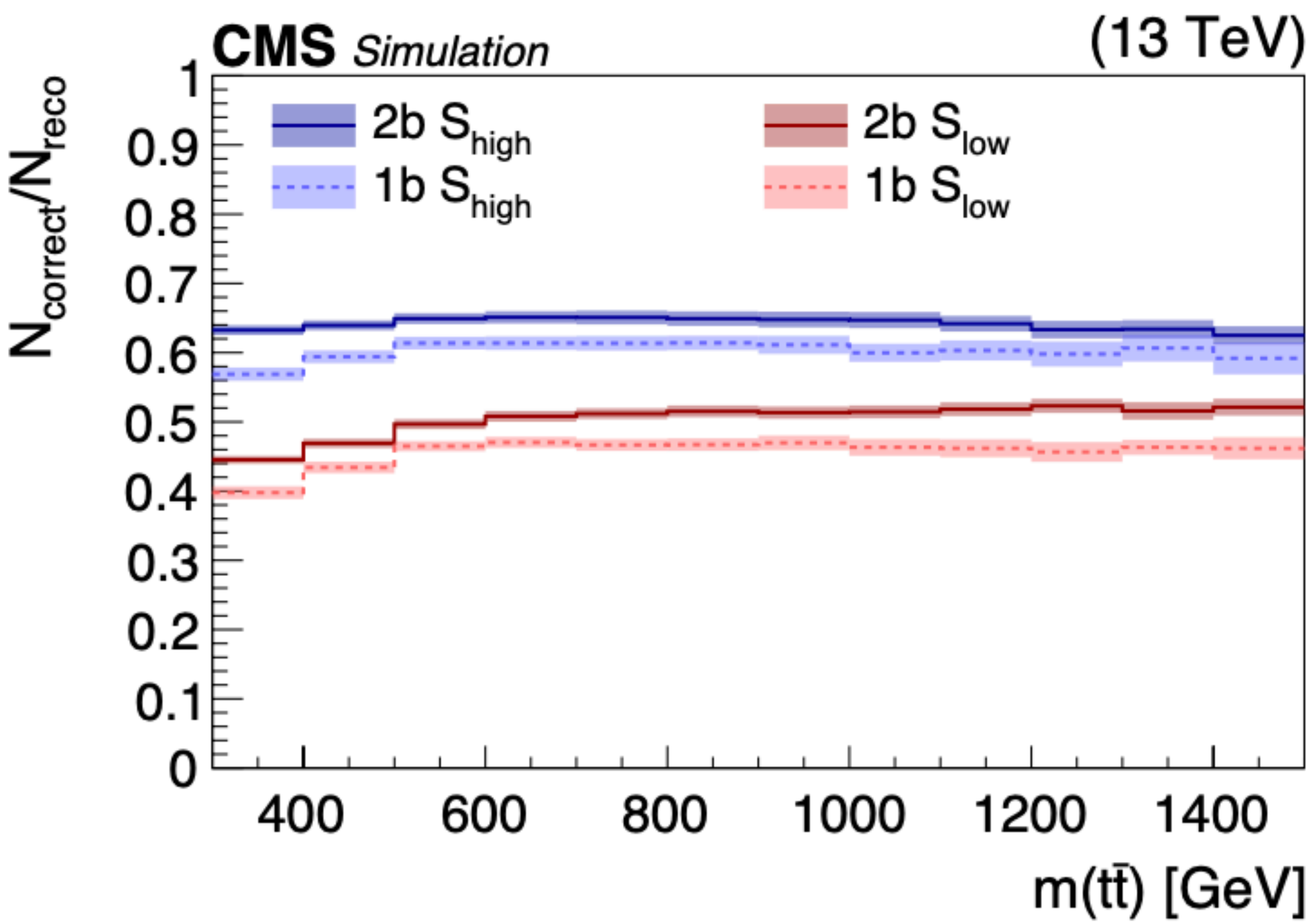
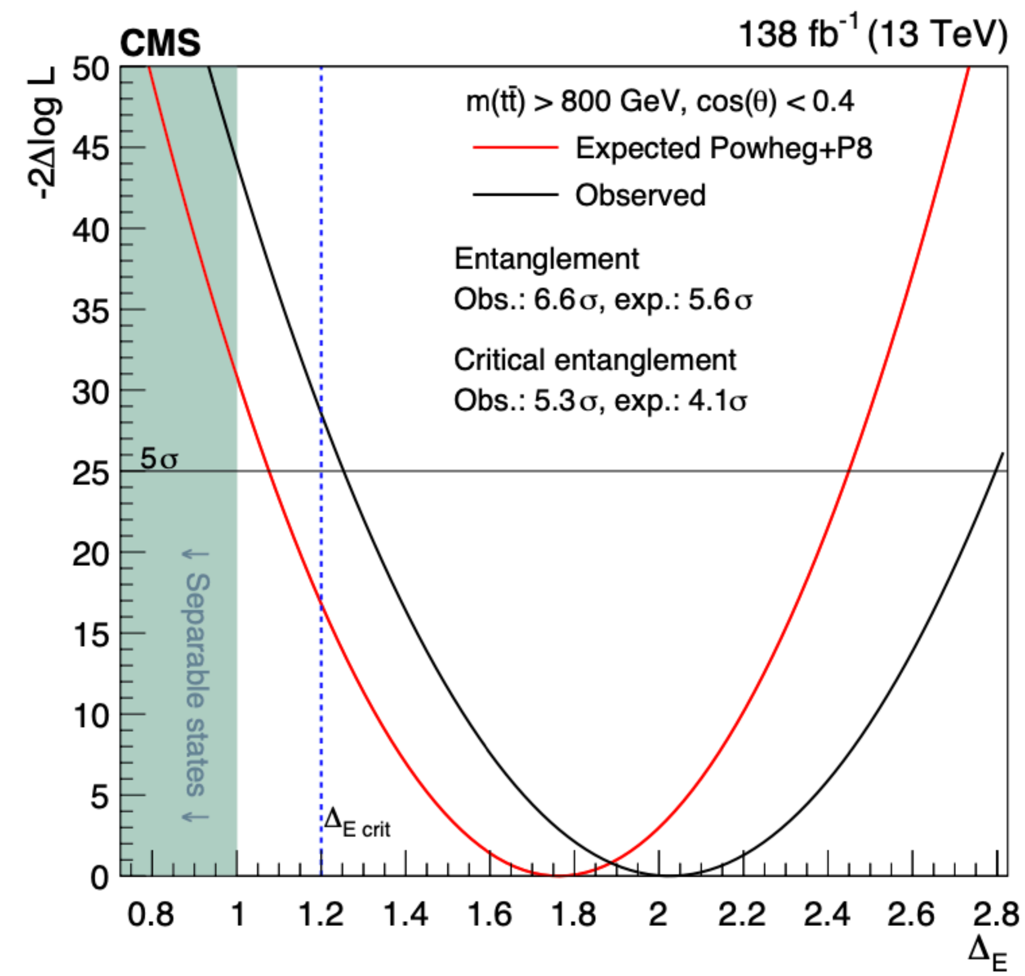




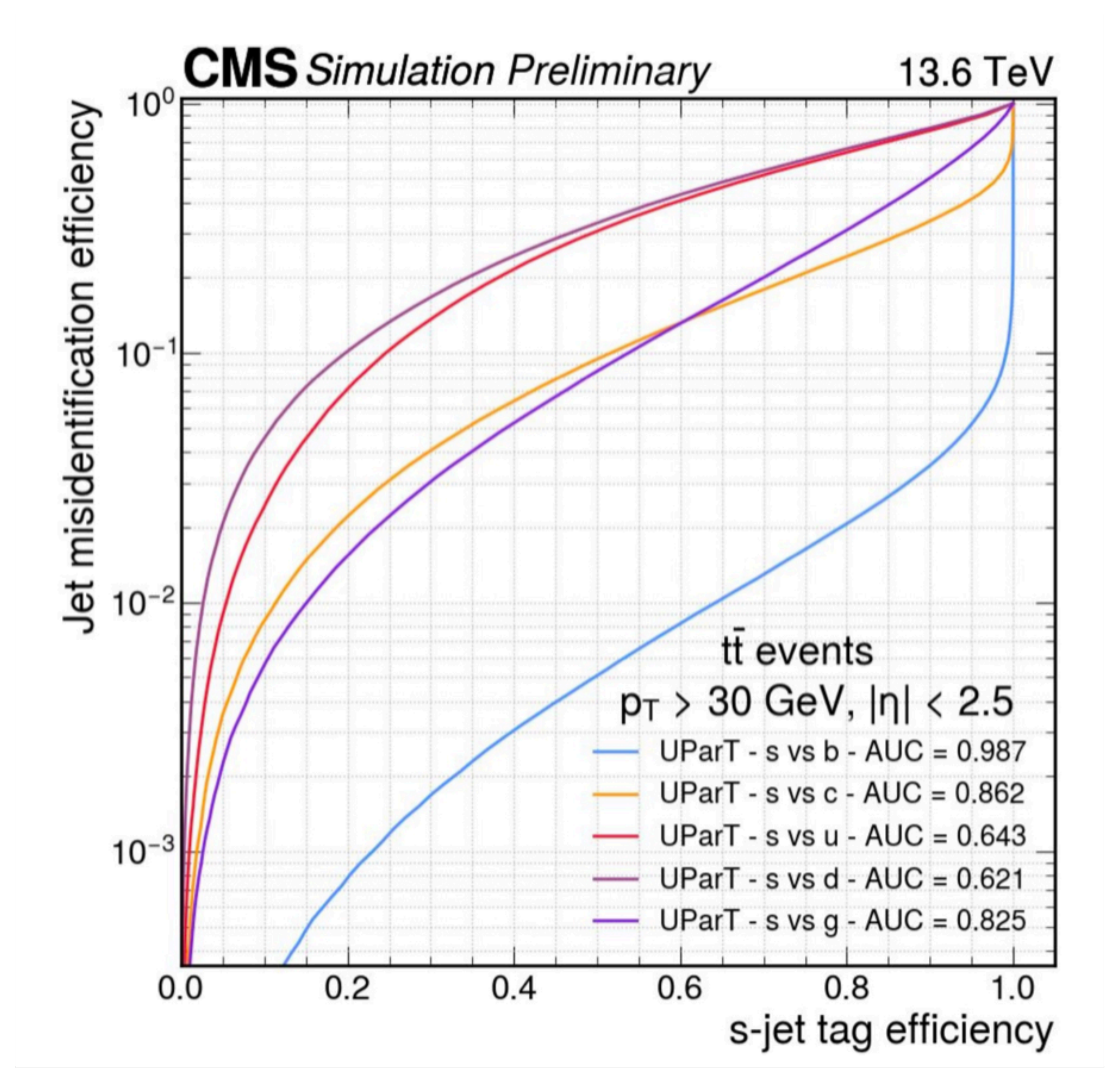
Quantum Entanglement

- Semi-leptonic final state





s-tagging performance



See talk by Jieun Choi

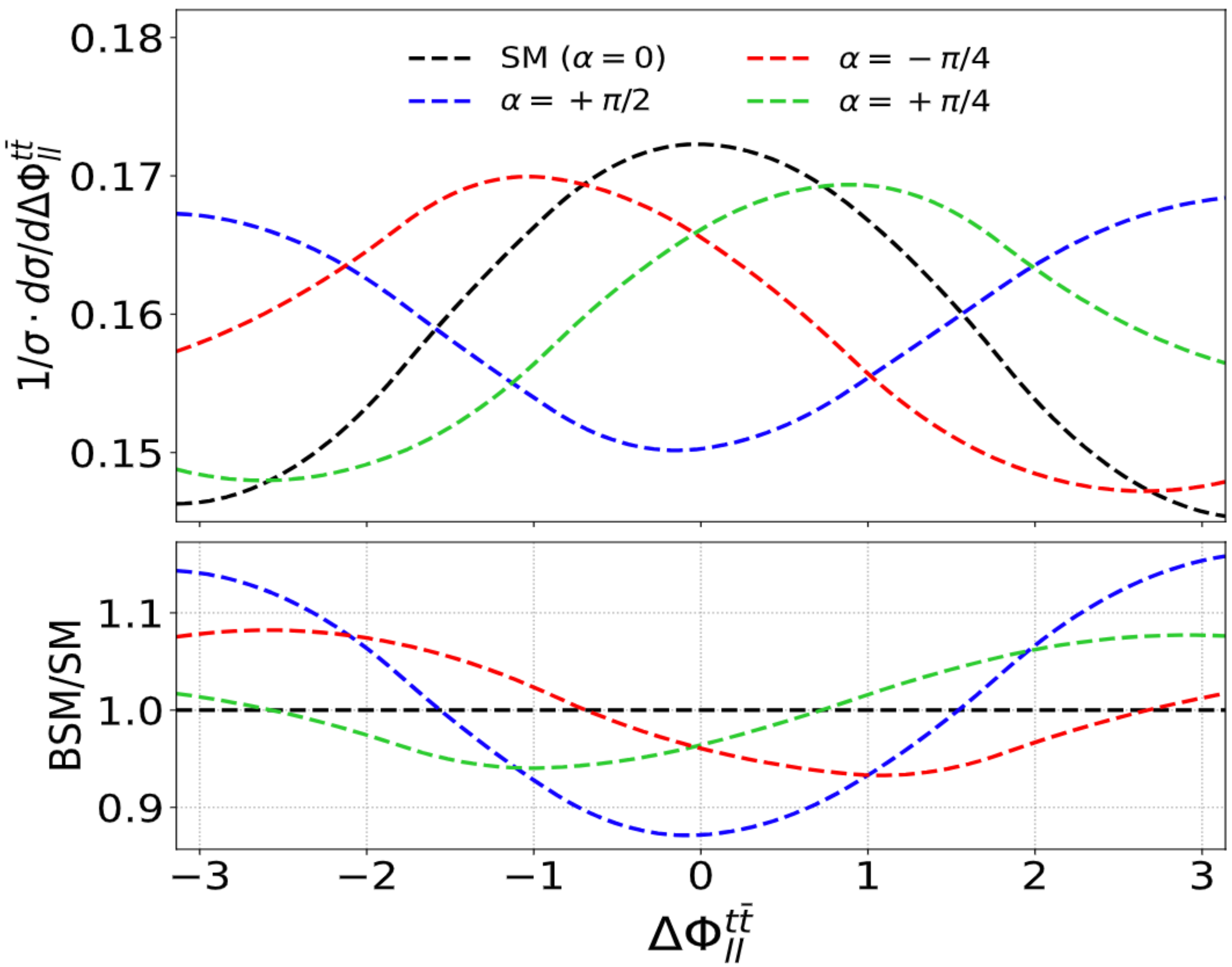
CP sensitive observables

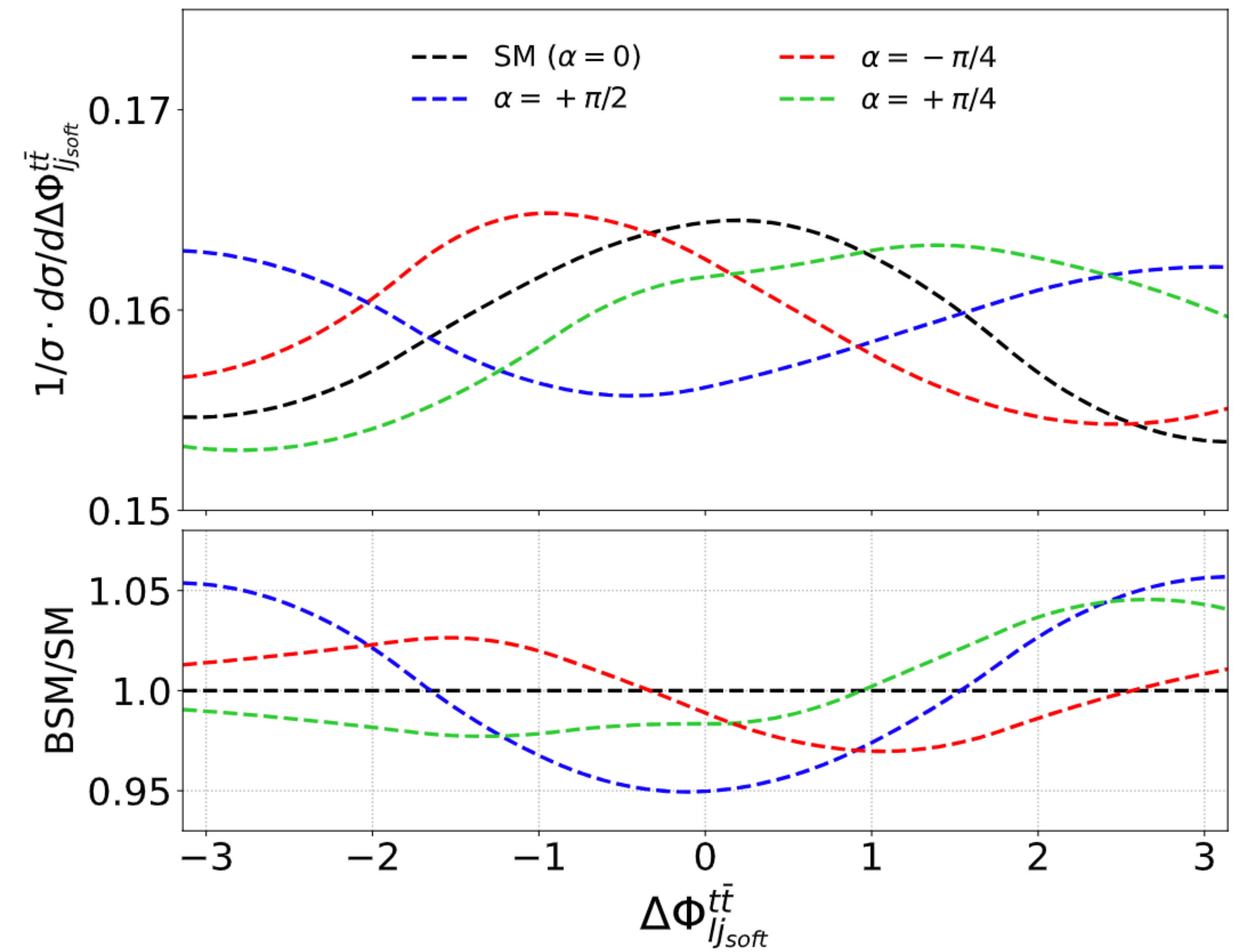
- CPV observables best defined at the top pair rest frame:

$$d\sigma(gg \to t(n_t)\bar{t}(n_{\bar{t}})H) = \sin^2\alpha f_1(p_i.p_j) + \cos^2\alpha f_2(p_i.p_j) + \sin\alpha\cos\alpha \sum_l g(p_i.p_j)\epsilon_l$$

$$\epsilon_{\mu\nu\rho\sigma} p_a^\mu p_b^\nu p_c^\rho p_d^\sigma = \begin{aligned} & E_a\, \vec{p_b}\cdot(\vec{p_c}\times\vec{p_d}) + E_c\, \vec{p_d}\cdot(\vec{p_a}\times\vec{p_b}) \\ & -E_b\, \vec{p_c}\cdot(\vec{p_d}\times\vec{p_a}) - E_d\, \vec{p_a}\cdot(\vec{p_b}\times\vec{p_c}) \end{aligned}$$

$$\epsilon(p_t, p_{\bar{t}}, p_{\ell^+}, p_{\ell^-})|_{t\bar{t}\ CM} \propto p_t \cdot (p_{\ell^+} \times p_{\ell^-})$$





DG, Kong, Kim '18 & '21, Barman, DG, Kling '21