



Spin Physics in Nuclear and Collider Experiments

- Spin as a probe of QCD matter and hadron structure -

Takafumi Niida
(新井田 貴文)

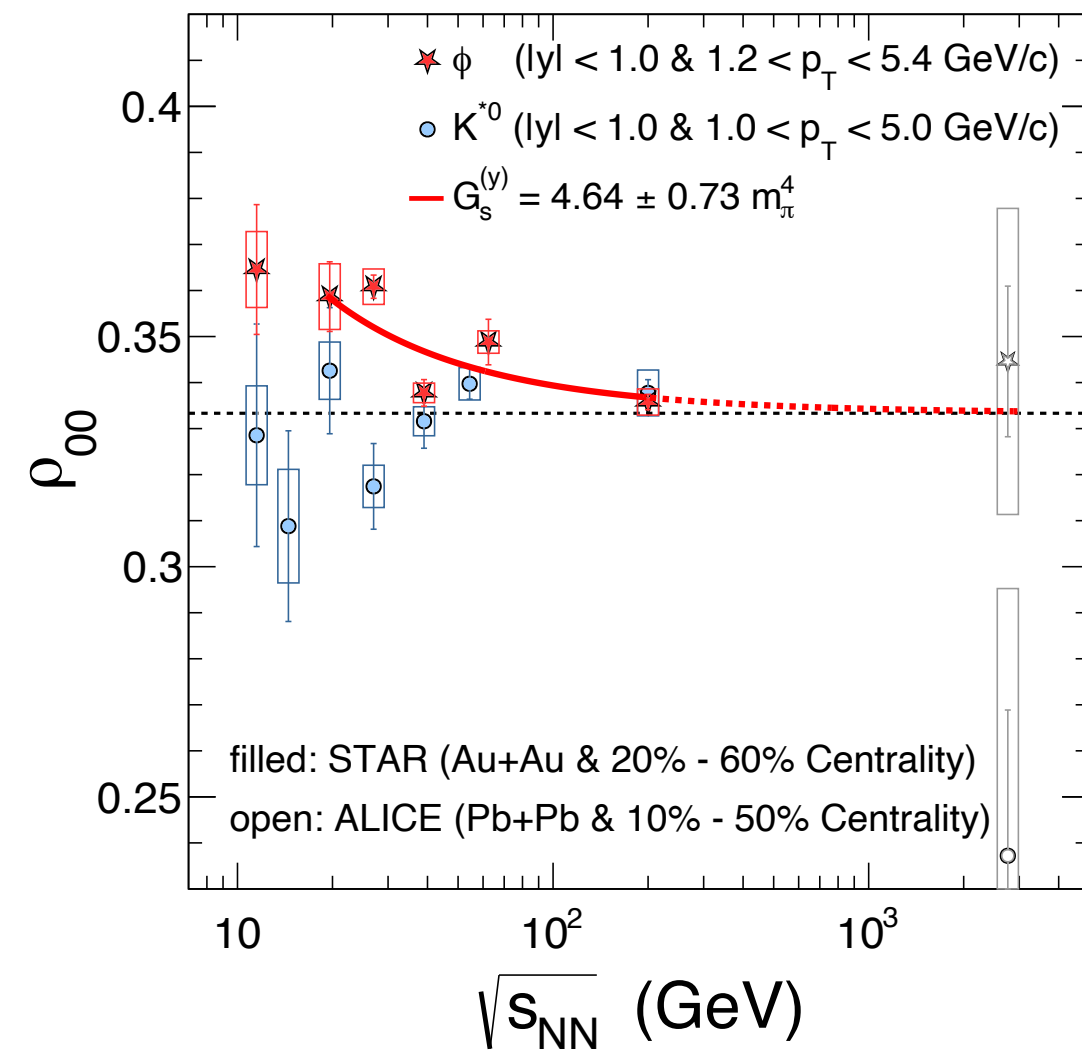
 **筑波大学**
University of Tsukuba

Contents of this lecture

- ▶ Day-1: The birth of spin physics: Stern-Gerlach to Wu
- ▶ Day-2: Spin structure of nucleon and Transverse spin phenomena
- ▶ Day-3: Spin polarization in relativistic heavy-ion collisions (1)
- ▶ Day-4: Spin polarization in relativistic heavy-ion collisions (2)
- ▶ Day-5: Spin correlations and Future directions

Recap of Day-4

STAR, Nature 614, 244 (2023)
ALICE, JHEP10(2025)094

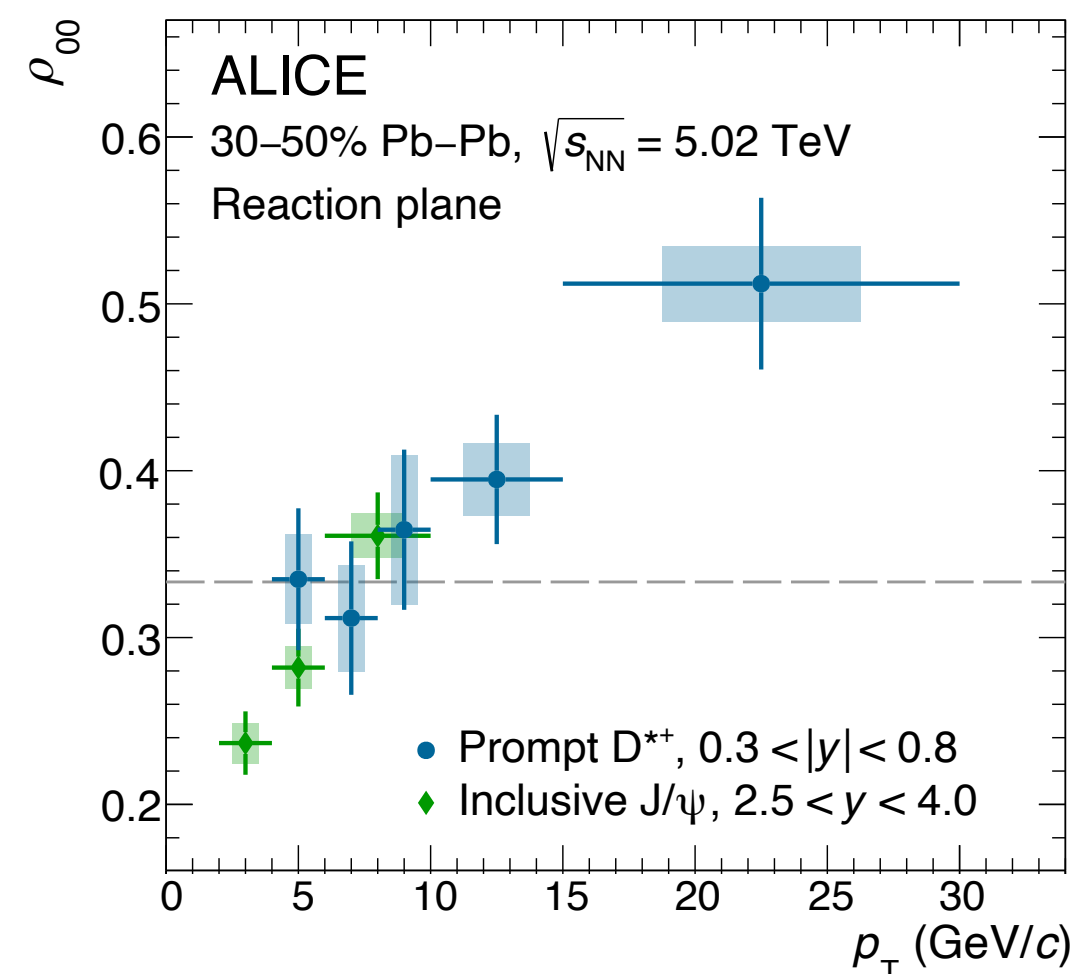


Hyperon polarization mainly probes **single-quark** polarization

$$P_\Lambda \sim \langle P_s \rangle$$

Vector-meson spin alignment is sensitive to **$q\bar{q}$ spin correlation**

$$\rho_{00} \simeq \frac{1}{3} - \frac{4}{9} [C_{s\bar{s}} + (\langle P_s P_{\bar{s}} \rangle - \langle P_s \rangle \langle P_{\bar{s}} \rangle)]$$

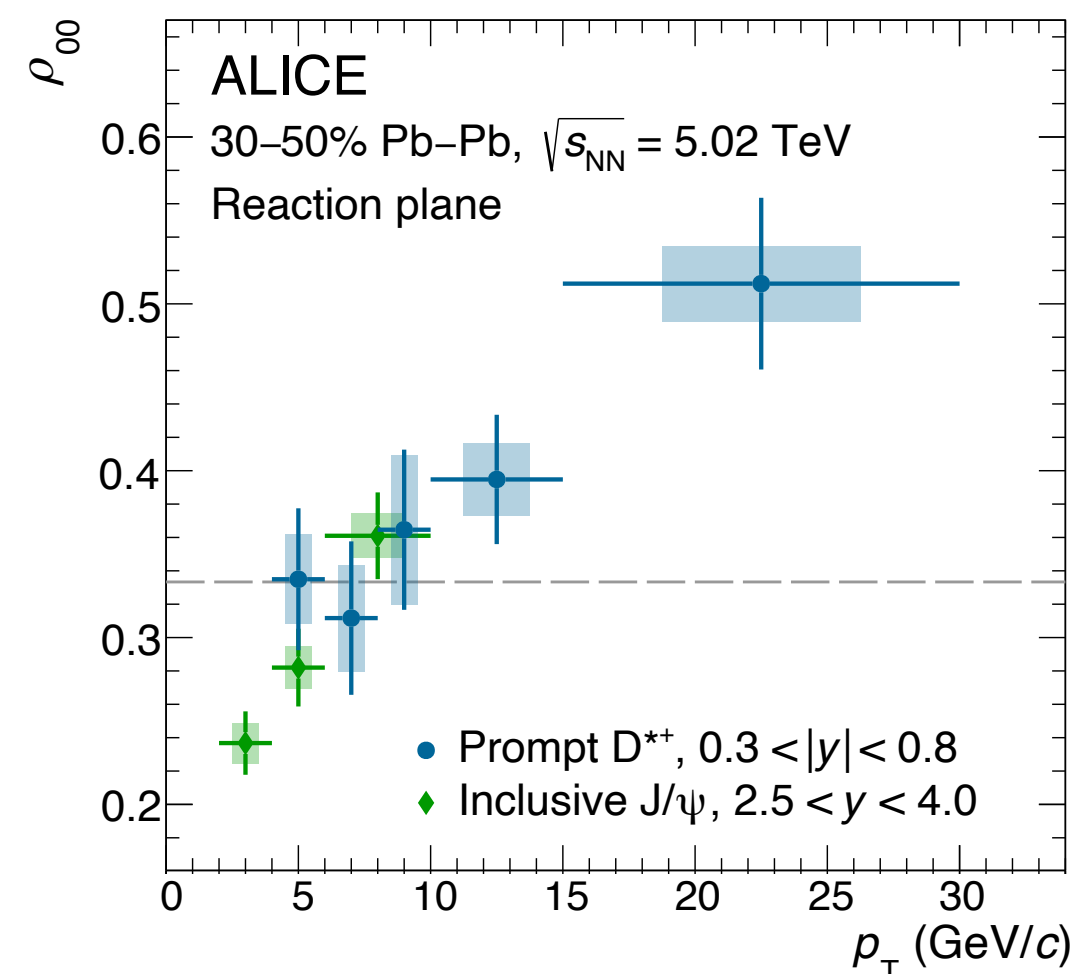
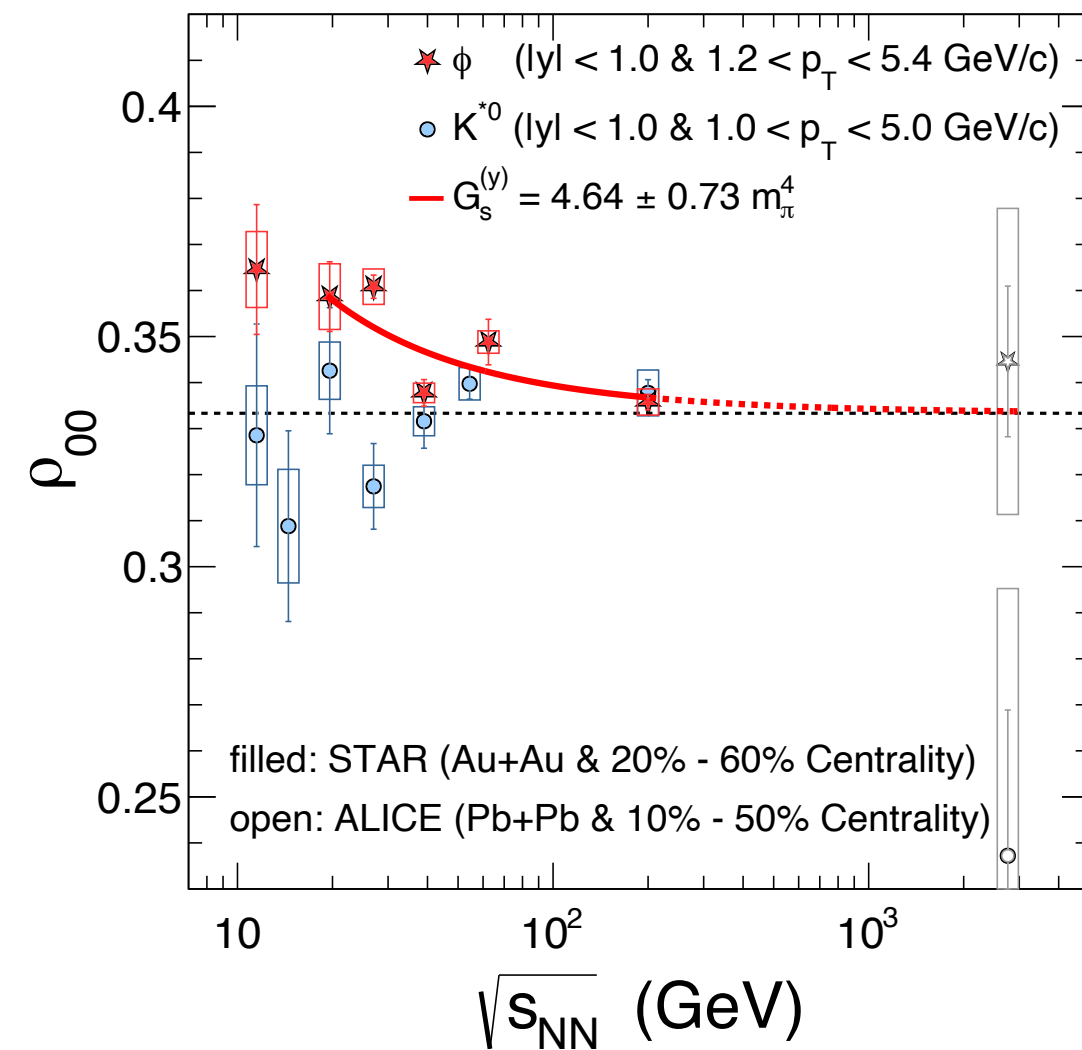


J.-P. Lv, Z.-H. Yu, Z.-T. Liang, Q. Wang, and X.-N. Wang,
PRD109, 114003 (2024)

Important to understand contribution from spin-spin correlation

Recap of Day-4

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Genuine correlation: direct correlation between s and sbar

Induced correlation: Correlation from fluctuations of local polarization

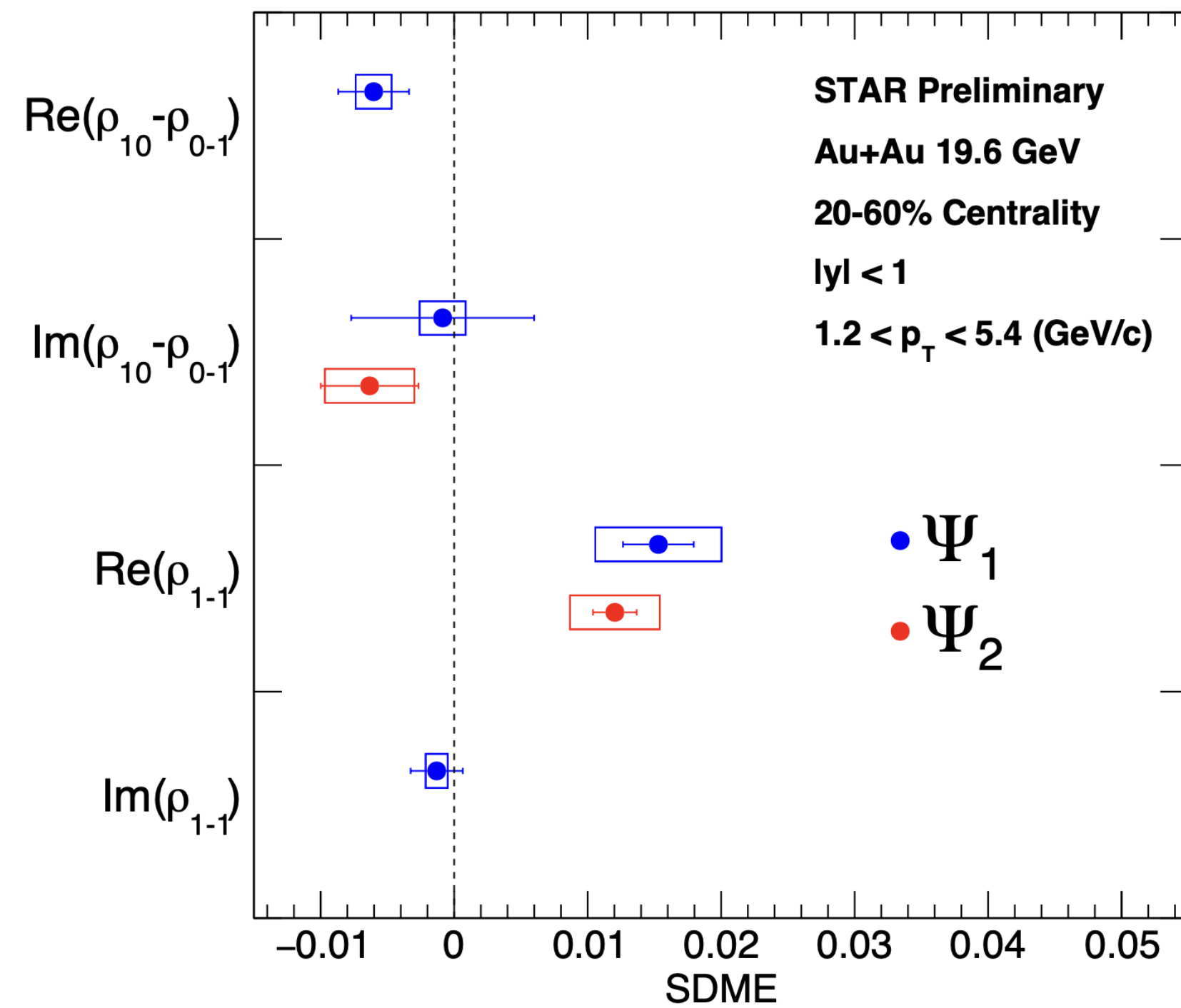
J.-P. Lv, Z.-H. Yu, Z.-T. Liang, Q. Wang, and X.-N. Wang,
PRD109, 114003 (2024)

Important to understand contribution from spin-spin correlation

Recap of Day-4

G. Wilks and Z. Ye (STAR), SQM2026

Off-diagonal elements of ϕ -meson spin alignment



$$\text{Re}(\rho_{1-1}) = \frac{1}{C_V} \left[\underline{c_{xx}^{(q_1 \bar{q}_2)} - c_{yy}^{(q_1 \bar{q}_2)}} + P_{q_1 x} P_{\bar{q}_2 x} - P_{q_1 y} P_{\bar{q}_2 y} \right]$$

Contributions from spin-spin correlation

J.-P. Lv, Z.-H. Yu, Z.-T. Liang, Q. Wang, and X.-N. Wang, PRD109, 114003 (2024)

Indication of non-zero s-sbar spin correlation

From polarization to spin-spin correlation

Spin density matrix for spin-1/2 single particle

$$\begin{aligned}\rho &= \frac{1}{2}(\mathbf{I} + \mathbf{P} \cdot \boldsymbol{\sigma}) \\ &= \frac{1}{2} \begin{pmatrix} 1 + P_z & P_x - iP_y \\ P_x + iP_y & 1 - P_z \end{pmatrix}\end{aligned}$$

$\mathbf{P}$: polarization vector
 $\boldsymbol{\sigma}$: Pauli matrices

Spin density matrix for spin-1/2 particle pair

$$\rho_{YY} = \frac{1}{4} \left(\underbrace{I \otimes I}_{\text{unpolarized}} + \underbrace{\mathbf{P}_1 \cdot \boldsymbol{\sigma}}_{\text{polarization of particle 1}} \otimes I + I \otimes \underbrace{\mathbf{P}_2 \cdot \boldsymbol{\sigma}}_{\text{polarization of particle 2}} + \sum_{ij} \underbrace{C_{ij} \sigma_i \otimes \sigma_j}_{\text{spin-spin correlation}} \right)$$

$\mathbf{P}_1, \mathbf{P}_2$: polarization vectors of particle 1&2
 $\boldsymbol{\sigma}$: Pauli matrices
 C_{ij} : spin correlation matrix

Polarization describes the spin state of a single particle.

Spin correlation contains additional information about the two-particle systems

How do we measure spin correlations?

- Utilize weak decay as spin analyzer

$$\frac{dN}{d\Omega} = \frac{1}{4\pi} (1 + \alpha \mathbf{P} \cdot \hat{\mathbf{p}})$$

- Considering the double decay, $\Lambda \bar{\Lambda} \rightarrow p\pi^- \bar{p}\pi^+$,
the combined angular distribution of daughter baryons in their respective parent rest frames
can be written as follows

$$\frac{dN}{d\Omega_1 d\Omega_2} \propto \left[1 + \alpha_1 \mathbf{P}_1 \cdot \hat{\mathbf{p}}_1 + \alpha_2 \mathbf{P}_2 \cdot \hat{\mathbf{p}}_2 + \alpha_1 \alpha_2 \sum_{ij} C_{ij} \hat{p}_{1i} \hat{p}_{2j} \right] \quad C_{ij} = \frac{9}{\alpha_1 \alpha_2} \langle \hat{p}_{1i} \hat{p}_{2j} \rangle$$

no net spin polarization: $\mathbf{P}_1=0, \mathbf{P}_2=0$
isotropic spin correlation: $C_{ij}=P_{\Lambda\Lambda}\delta_{ij}$

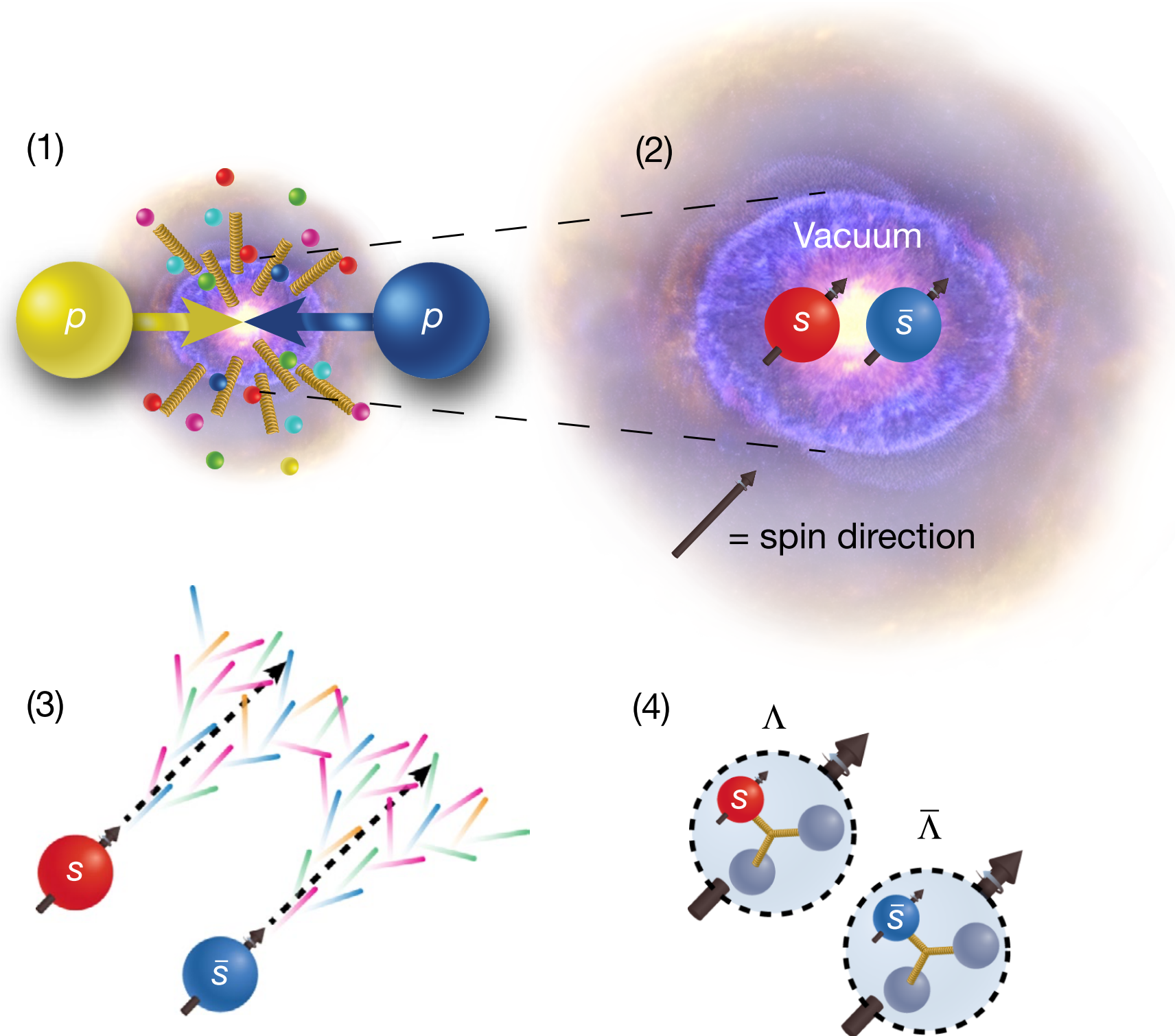
Hamann, NPA558, 287-309 (1993)

$$\frac{dN}{d\Omega_1 d\Omega_2} \propto [1 + \alpha_1 \alpha_2 P_{\Lambda\Lambda} \hat{\mathbf{p}}_1 \cdot \hat{\mathbf{p}}_2]$$

Spin-spin correlation in pp collisions

► $\Lambda\bar{\Lambda}$ spin-spin correlation in pp collisions at $\sqrt{s} = 200$ GeV from STAR

STAR, Nature 650, 65-71 (2026)



- The QCD vacuum has quantum numbers $J^{PC}=0^{++}$
- Quark–antiquark pairs from the vacuum are expected to be in the spin-triplet state ($S=1$), with correlated spins.
- Ellis, Kharzeev, and Kotzinian, Z.Phys.C69, 467 (1996)

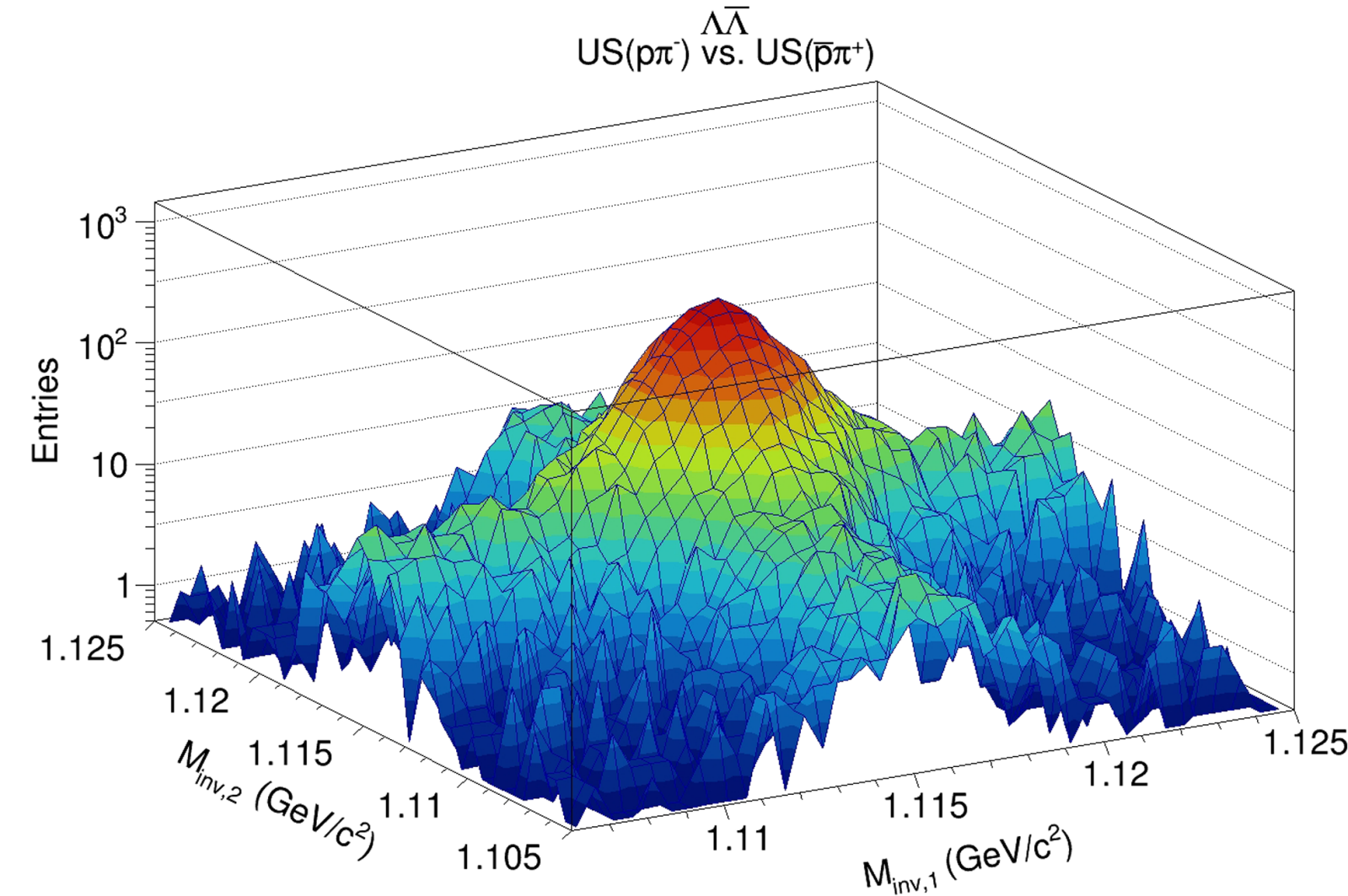
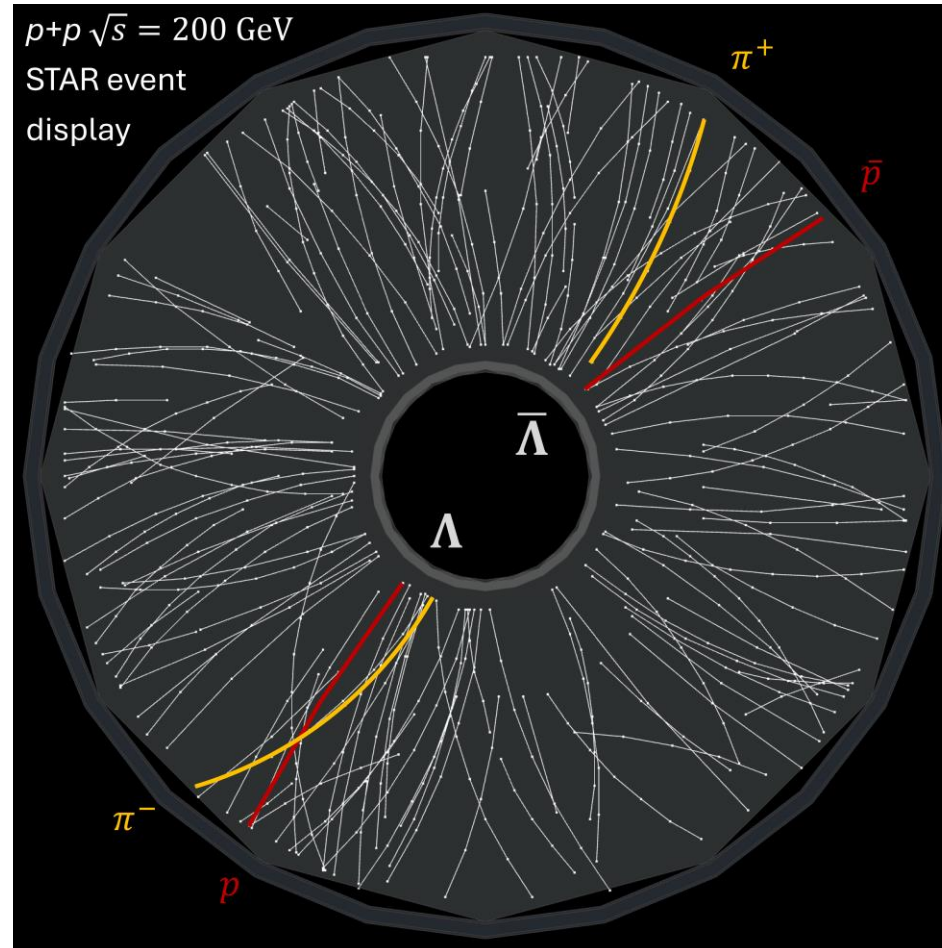
$$S = s_q + s_{\bar{q}}, \quad S = 1$$

$$S = 1, \quad L = 1, \quad J = 0$$

Experimentally probe how the spin correlations of $s\bar{s}$ pairs evolve through hadronization

Spin-spin correlation in 200 GeV pp collisions

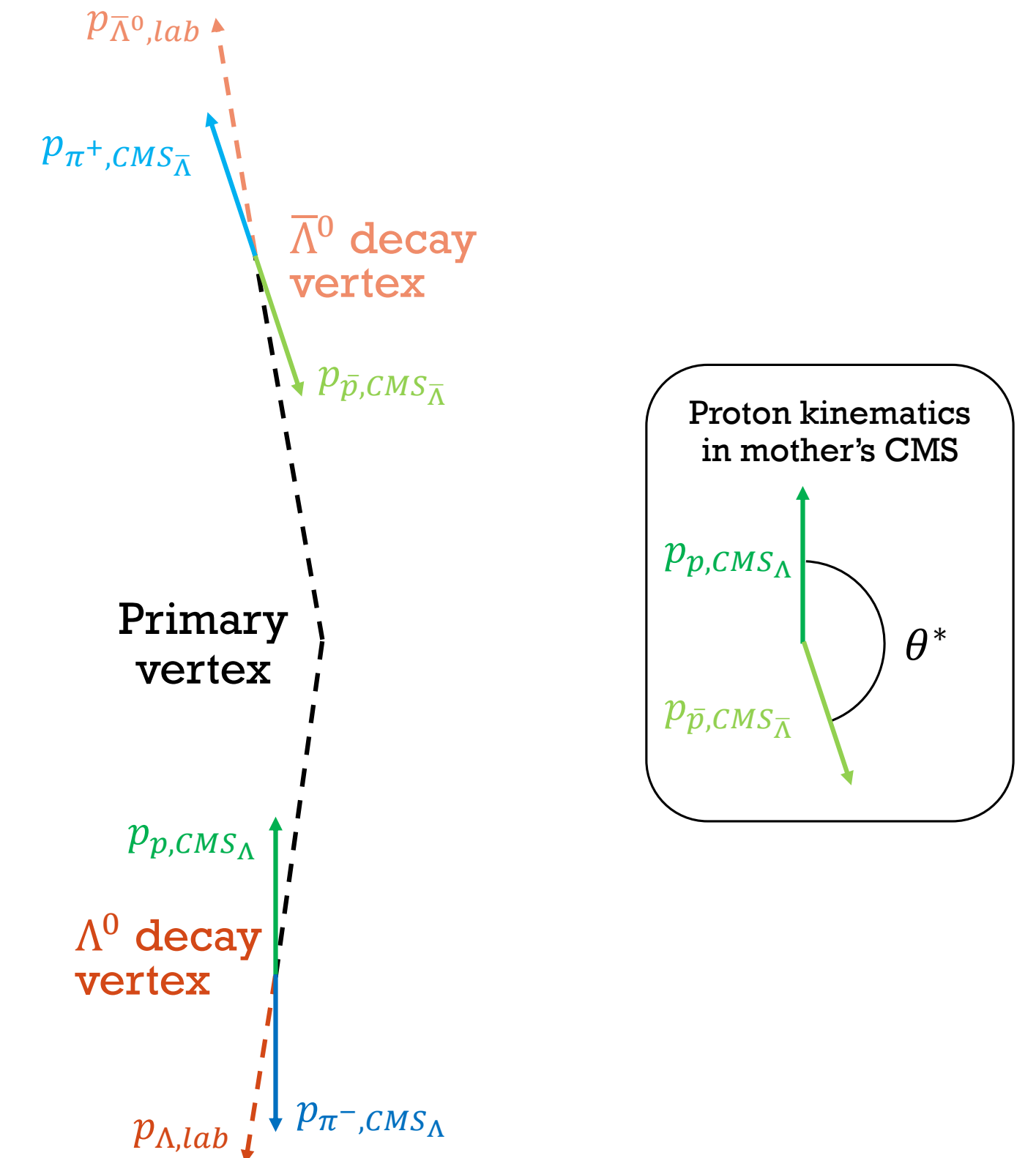
STAR, Nature 650, 65-71 (2026)



$$\frac{1}{N} \frac{dN}{d \cos \theta^*} = \frac{1}{2} [1 + \alpha_1 \alpha_2 P_{\Lambda_1 \Lambda_2} \cos \theta^*],$$

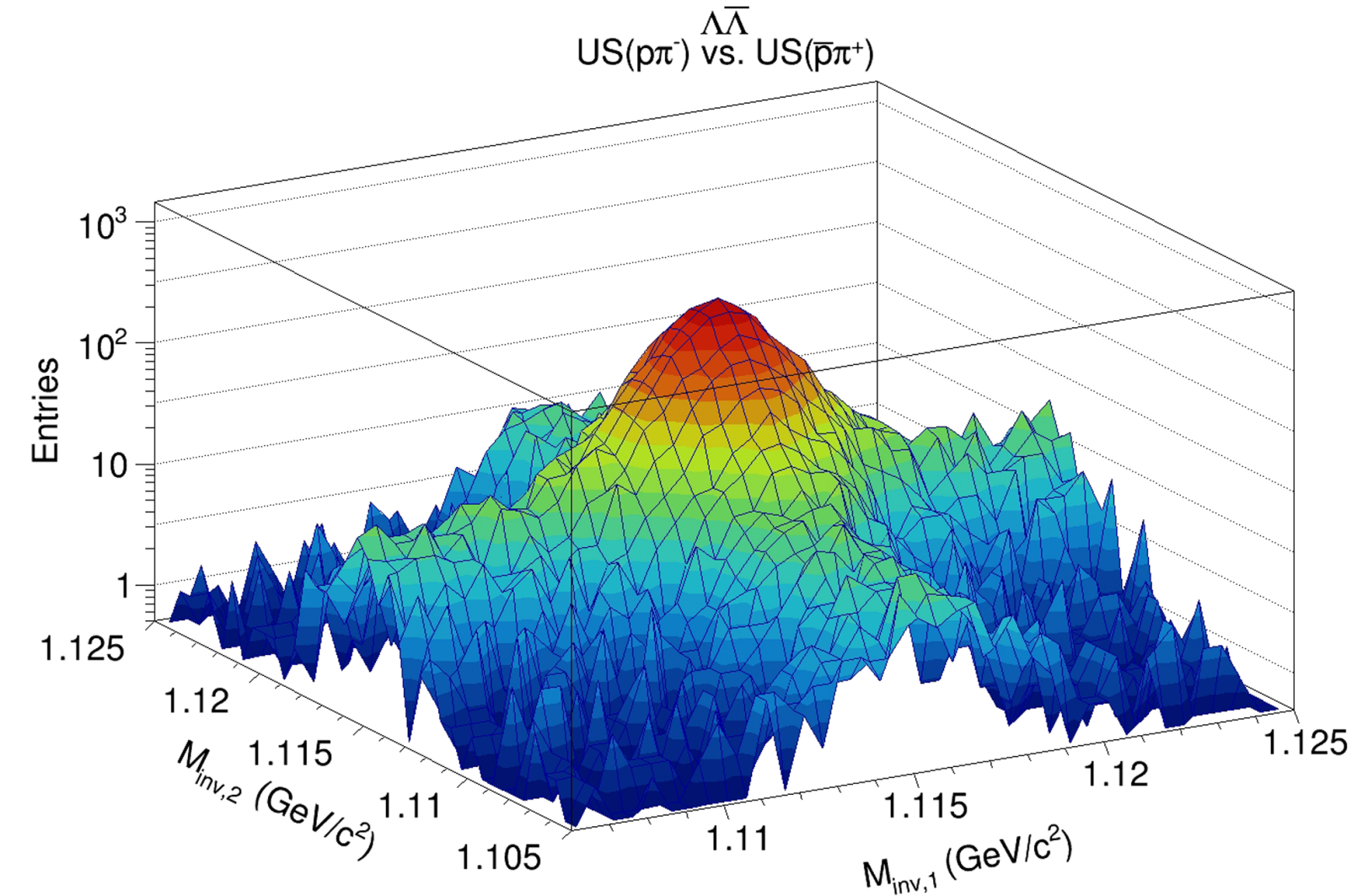
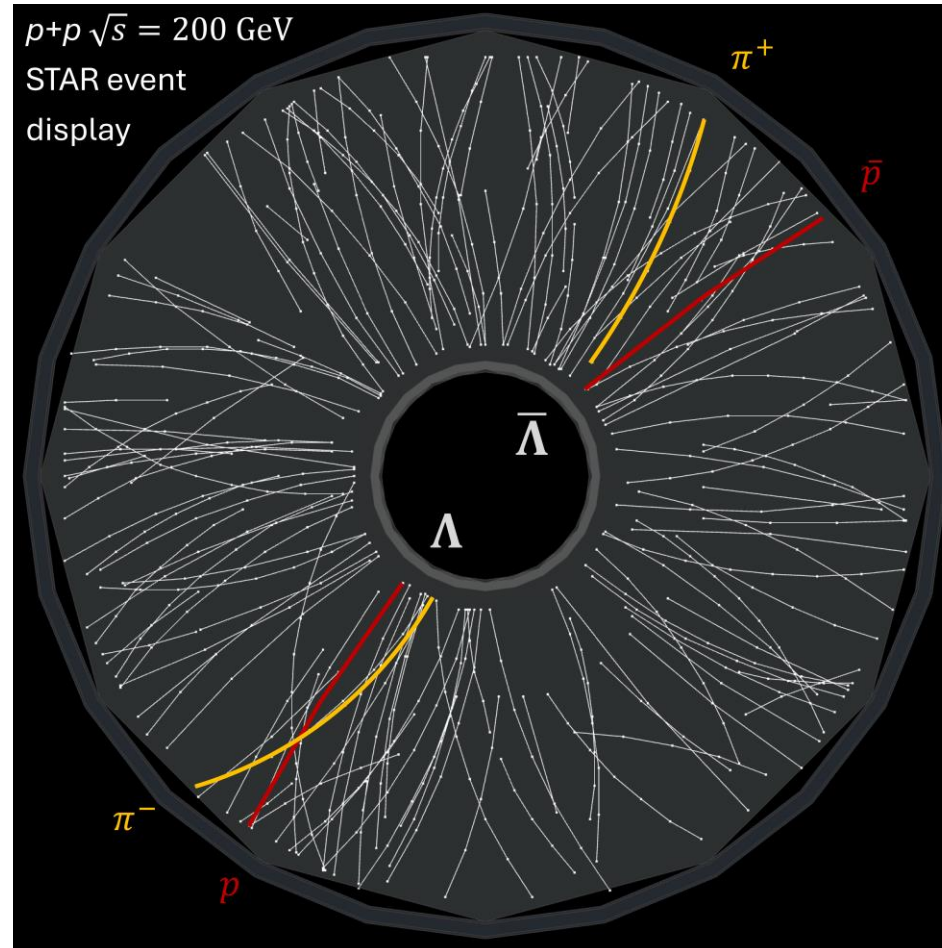
θ^* : angle between two boosted (anti)protons in their parent rest frame

- Λ and $\bar{\Lambda}$ are paired and signal region is selected
- Acceptance correction using event mixing

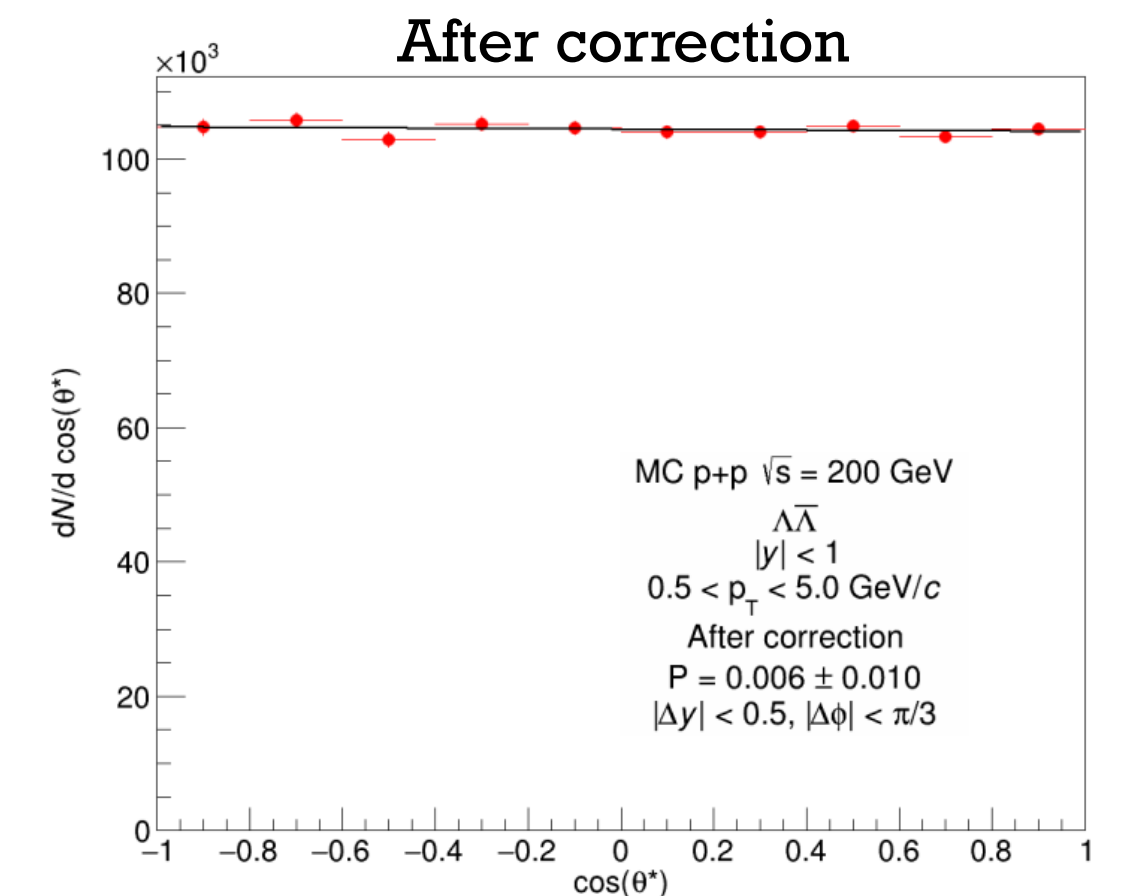
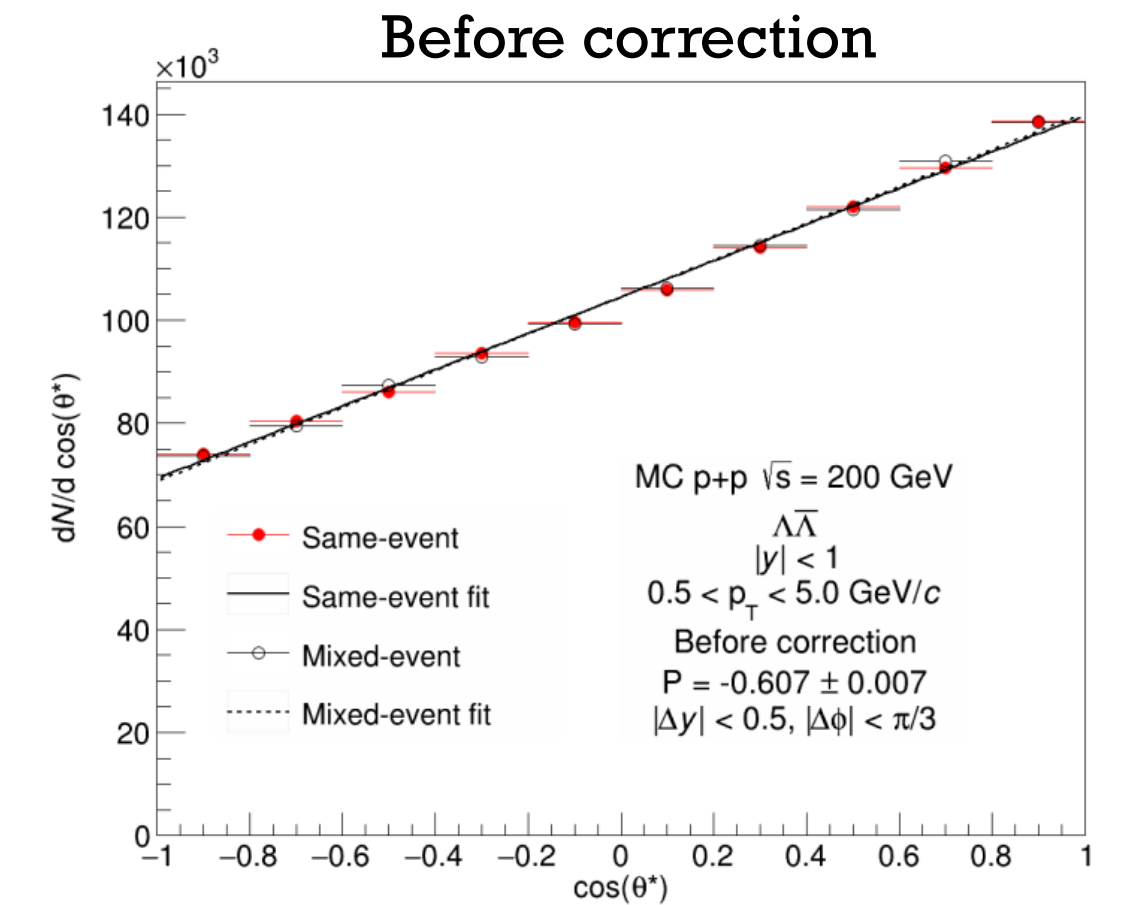


Spin-spin correlation in 200 GeV pp collisions

STAR, Nature 650, 65-71 (2026)



PYTHIA+GEANT simulation



$$\frac{1}{N} \frac{dN}{d \cos \theta^*} = \frac{1}{2} [1 + \alpha_1 \alpha_2 P_{\Lambda_1 \Lambda_2} \cos \theta^*],$$

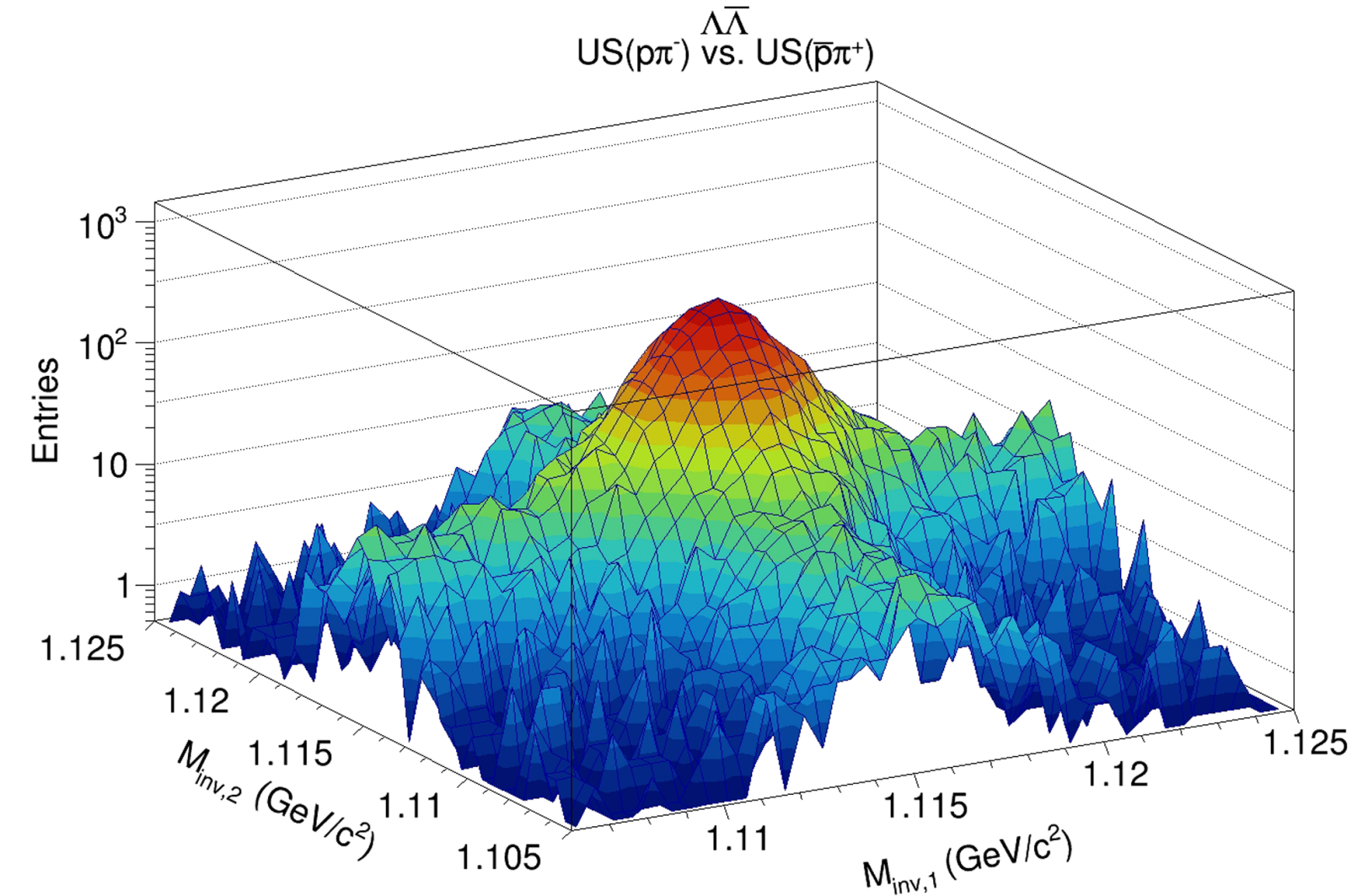
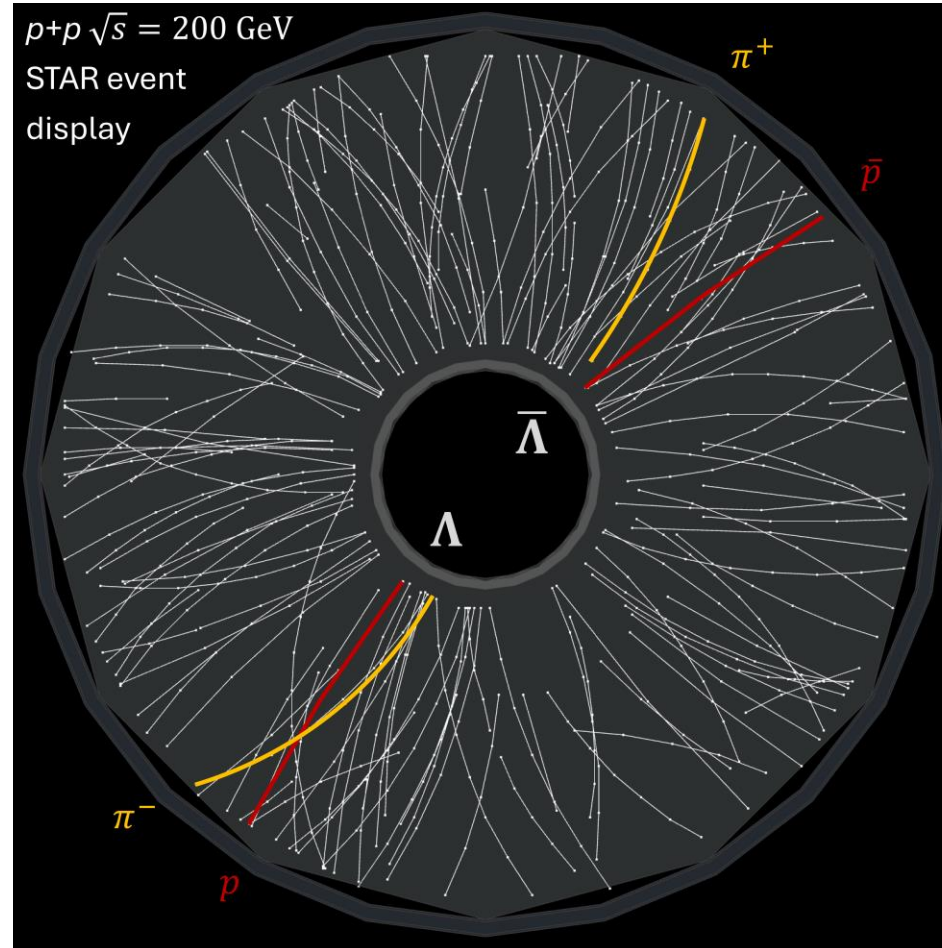
θ^* : angle between two boosted (anti)protons in their parent rest frame

- Λ and $\bar{\Lambda}$ are paired and signal region is selected
- Acceptance correction using event mixing

$$\begin{aligned} |p_{T,SE} - p_{T,single}| &< 0.1 \text{ GeV}/c \\ |y_{SE} - y_{single}| &< 0.1 \\ |\phi_{SE} - \phi_{single}| &< 0.1 \end{aligned}$$

Spin-spin correlation in 200 GeV pp collisions

STAR, Nature 650, 65-71 (2026)

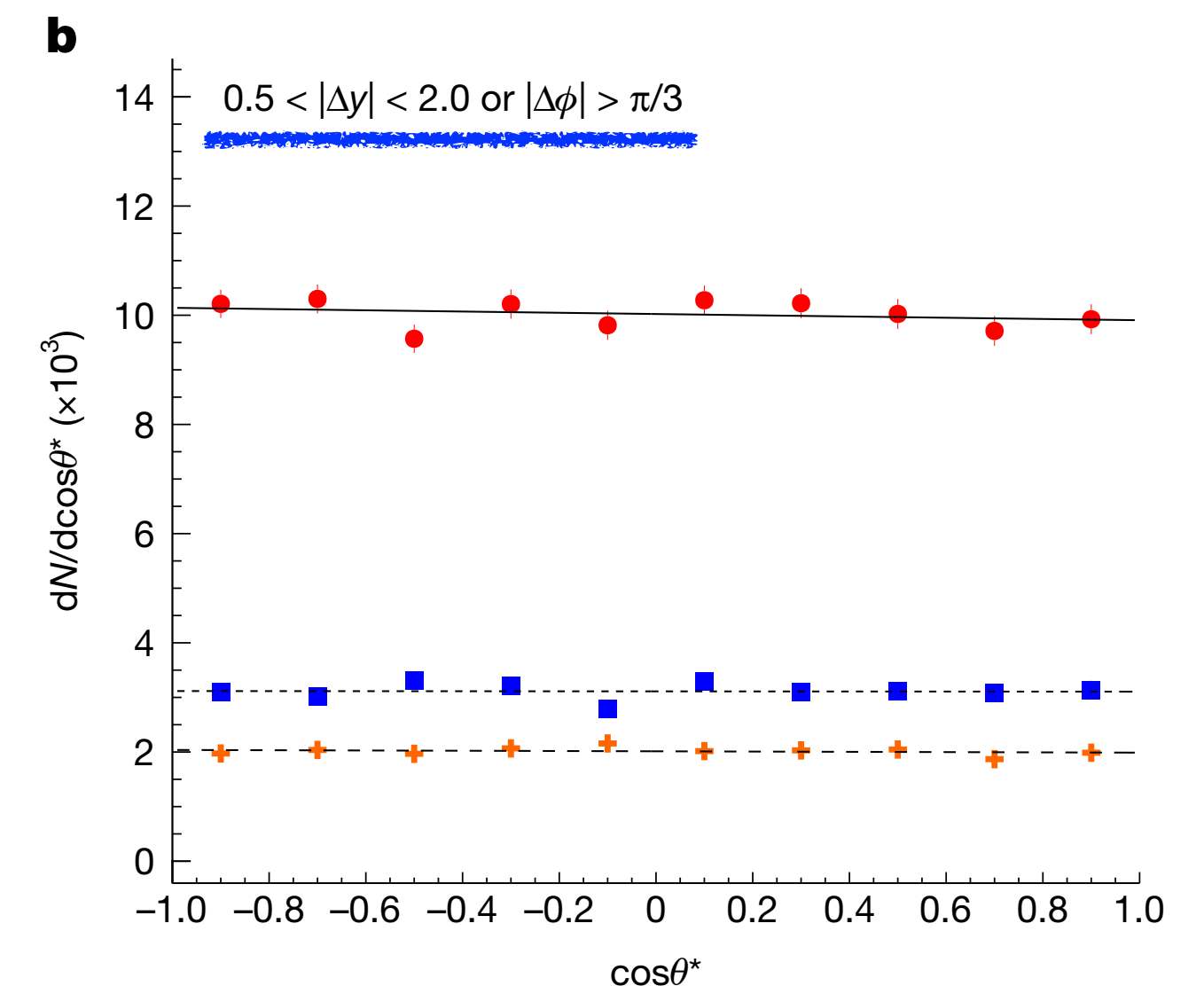
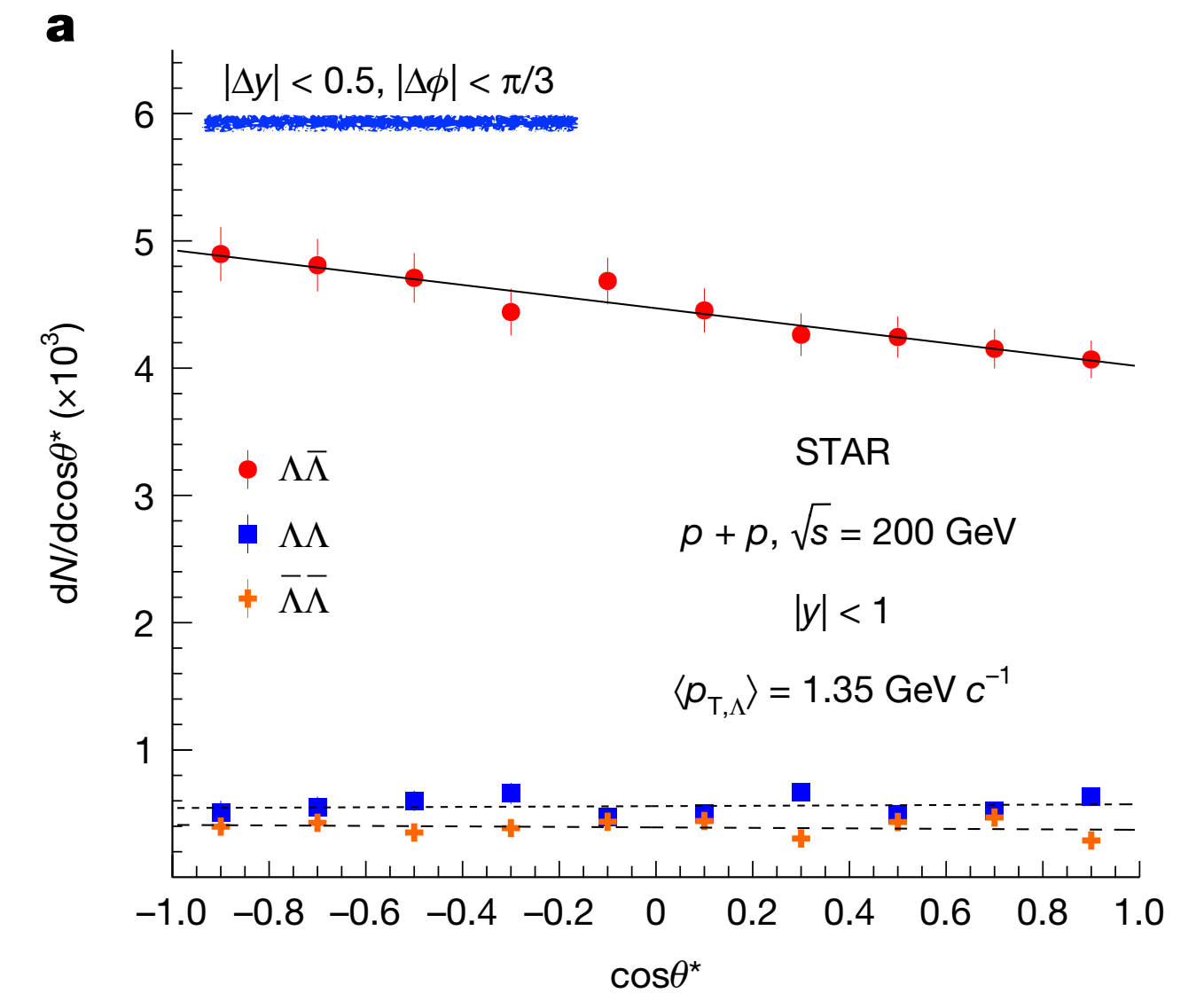


$$\frac{1}{N} \frac{dN}{d \cos \theta^*} = \frac{1}{2} [1 + \alpha_1 \alpha_2 P_{\Lambda_1 \Lambda_2} \cos \theta^*],$$

θ^* : angle between two boosted (anti)protons in their parent rest frame

- Λ and $\bar{\Lambda}$ are paired and signal region is selected
- Acceptance correction using event mixing
- For small $|\Delta y|$ and $|\Delta \phi|$, a clear slope in $\cos \theta^*$ distributions is seen

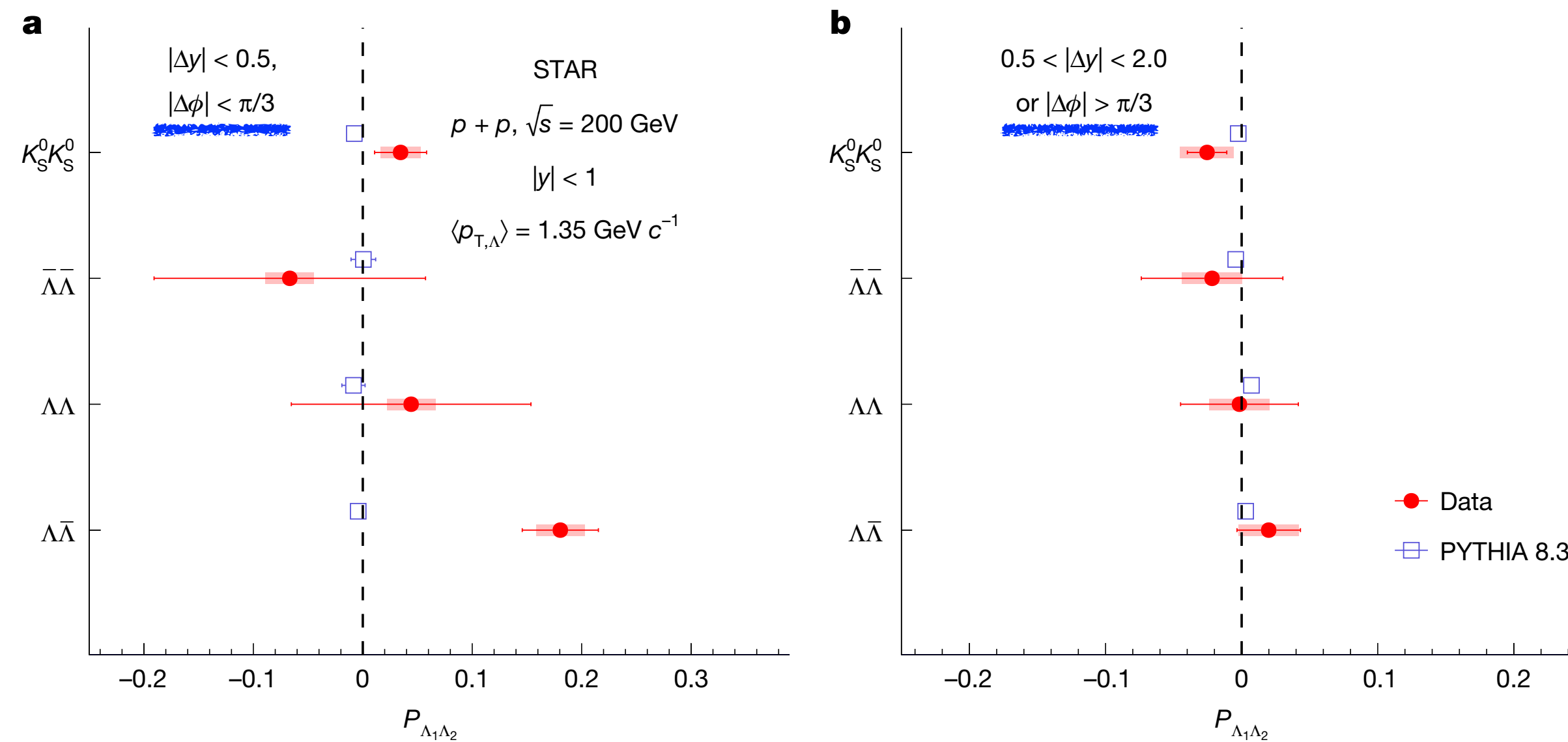
$$\text{slope} \propto \alpha_1 \alpha_2 P_{\Lambda_1 \Lambda_2}$$



Spin-spin correlation in 200 GeV pp collisions

STAR, Nature 650, 65-71 (2026)

► $\Lambda\bar{\Lambda}$ spin-spin correlation in 200 GeV pp collisions from STAR

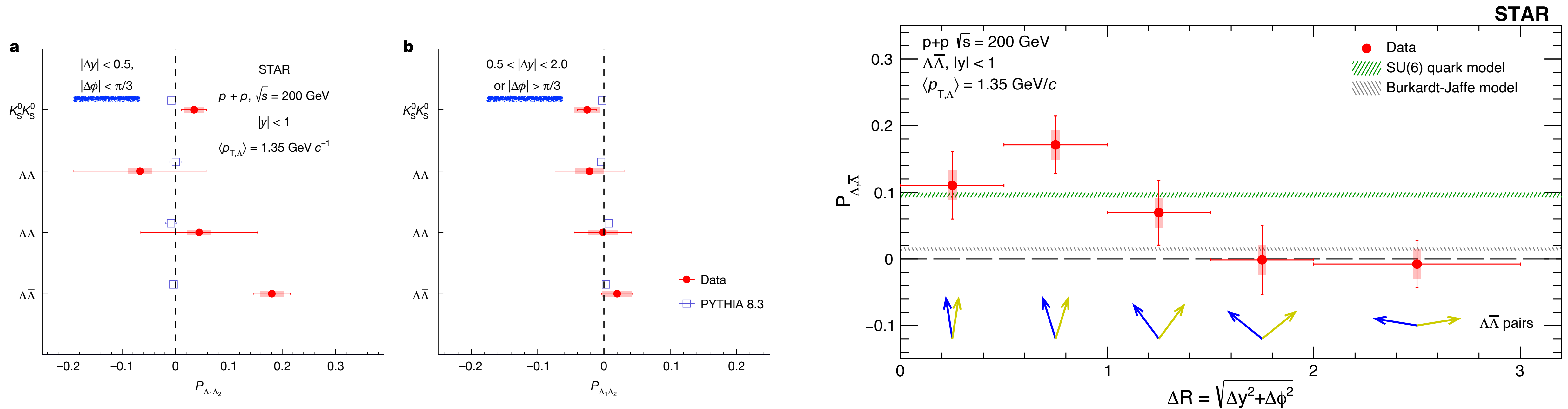


- A positive correlation appears for short-range $\Lambda\bar{\Lambda}$ pairs, while correlations consistent with zero for identical pairs

Spin-spin correlation in 200 GeV pp collisions

STAR, Nature 650, 65-71 (2026)

► $\Lambda\bar{\Lambda}$ spin-spin correlation in 200 GeV pp collisions from STAR



- A positive correlation appears for short-range $\Lambda\bar{\Lambda}$ pairs, while correlations consistent with zero for identical pairs
- The correlation seems to vanish at larger pair separation

What do we expect for the correlation ?

- Quark-antiquark pairs from QCD vacuum ($J^{PC}=0^{++}$) are expected to be spin triplet-state (3P_0)

$S = 1, \quad L = 1, \quad J = 0$

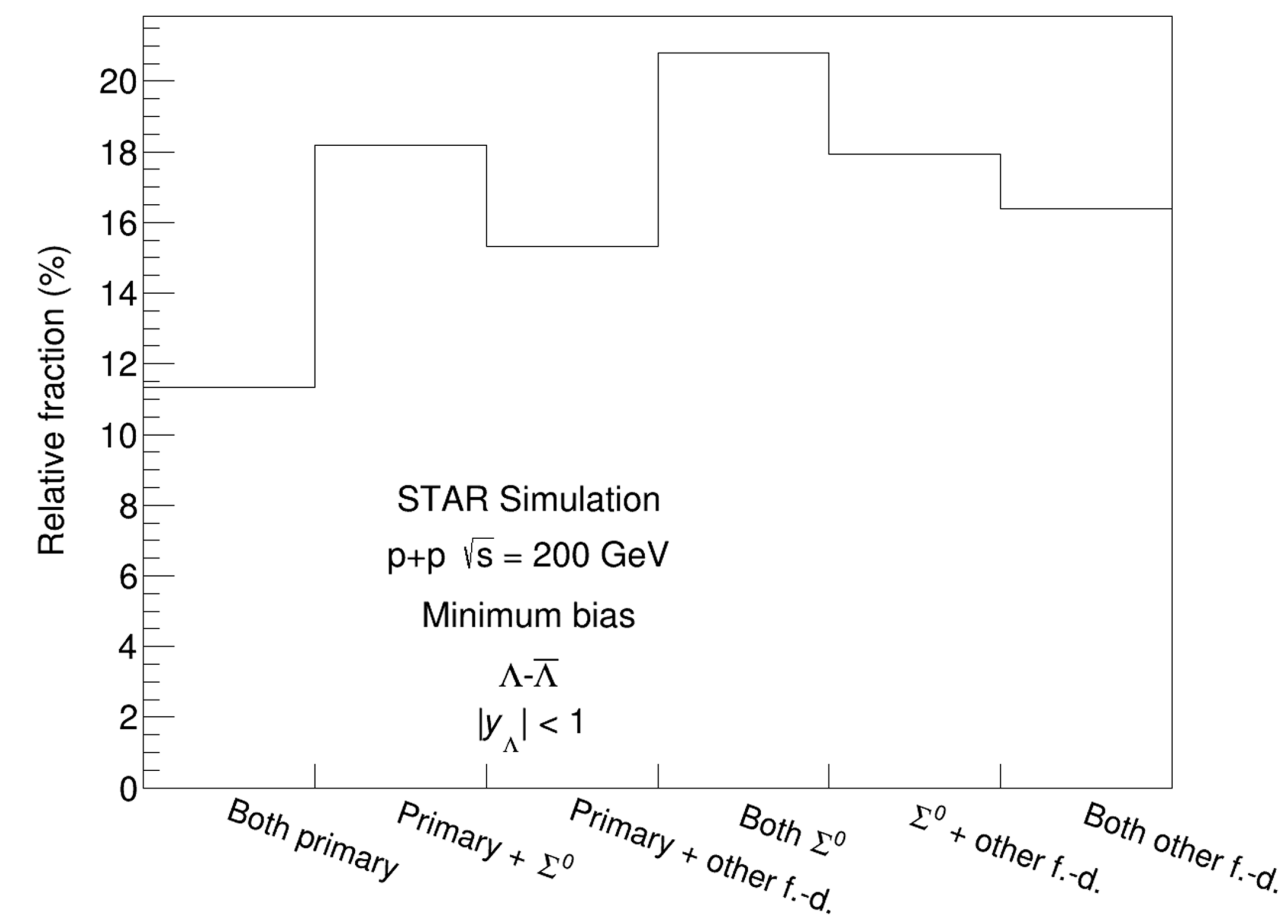
$|1, +1\rangle = |\uparrow\uparrow\rangle$
 $|1, 0\rangle = \frac{1}{\sqrt{2}} (|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)$
 $|1, -1\rangle = |\downarrow\downarrow\rangle$

Considering the z-axis, $C_{zz} = (+1-1+1)/3 = 1/3$.

For an equally populated mixture of three triplet substates,
 $P_{\Lambda\Lambda} = 1/3$

- Feed-down (PYTHIA8) + Spin transfer from s-quark ($\rightarrow \Sigma/\Xi \rightarrow \Lambda$ based on SU(6) or BJ model

Feed-down fraction with detector effect
estimated by PYTHIA+GEANT



s-quark contribution to Λ spin
& spin-transfer in feed-down

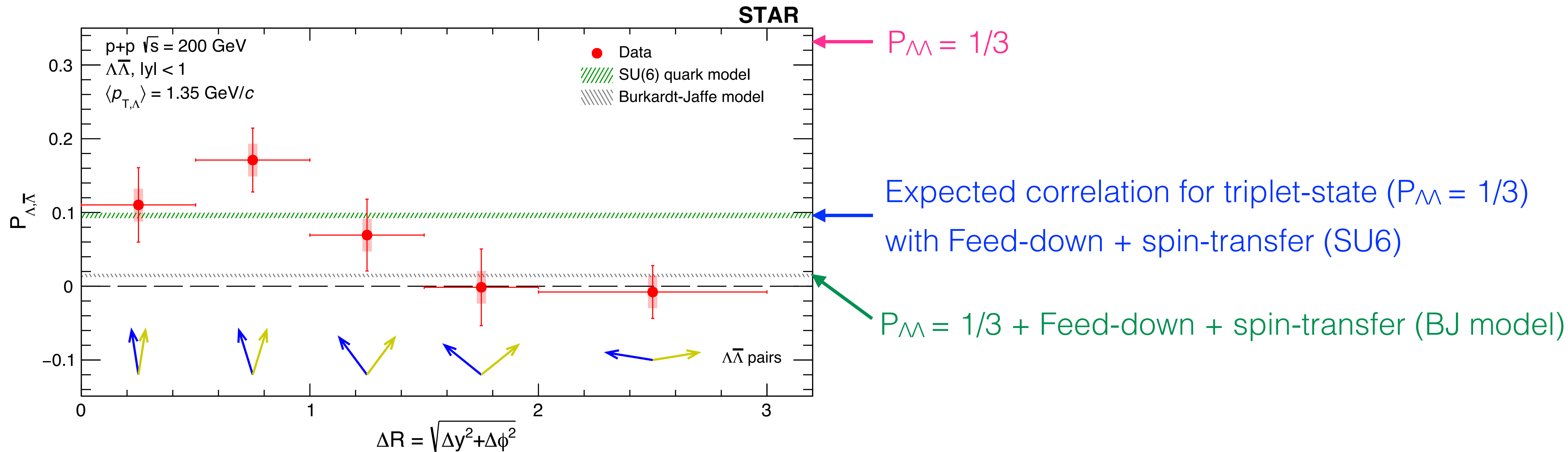
Λ 's parent SU(6) Burkardt-Jaffe		
s quark	1	0.63
Σ^0	1/9	0.15
Ξ^0	0.6	-0.37
Ξ^-	0.6	-0.37
Σ^*	5/9	N/A

The BJ model estimates the quark spin content of the Λ using polarized proton DIS data, hyperon β -decay constants, and flavor SU(3) symmetry

Burkardt and Jaffe, PRL70, 2537 (1993)

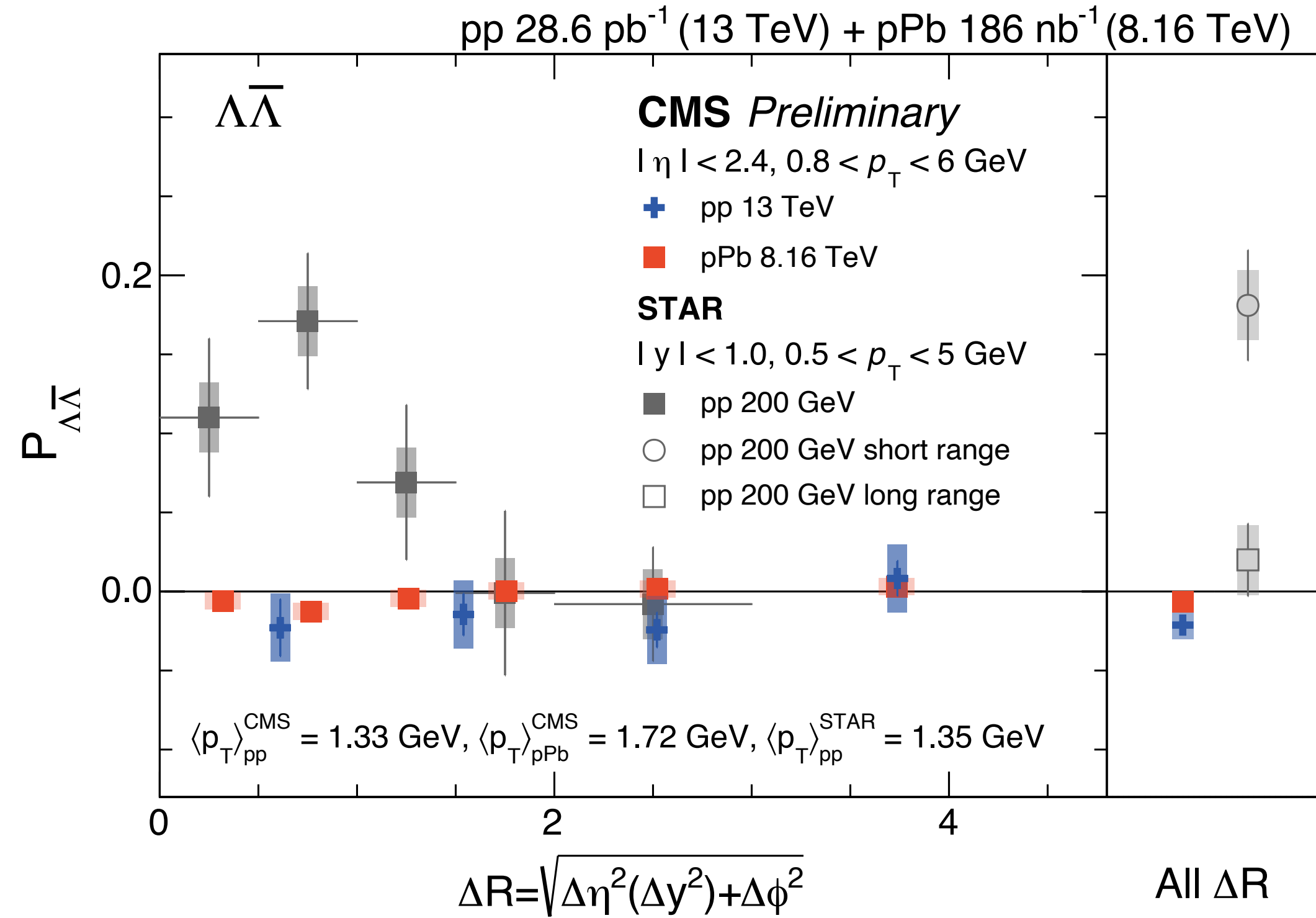
Ellis et al., EPJC2, 283-294 (2007)

Spin-spin correlation in 200 GeV pp collisions



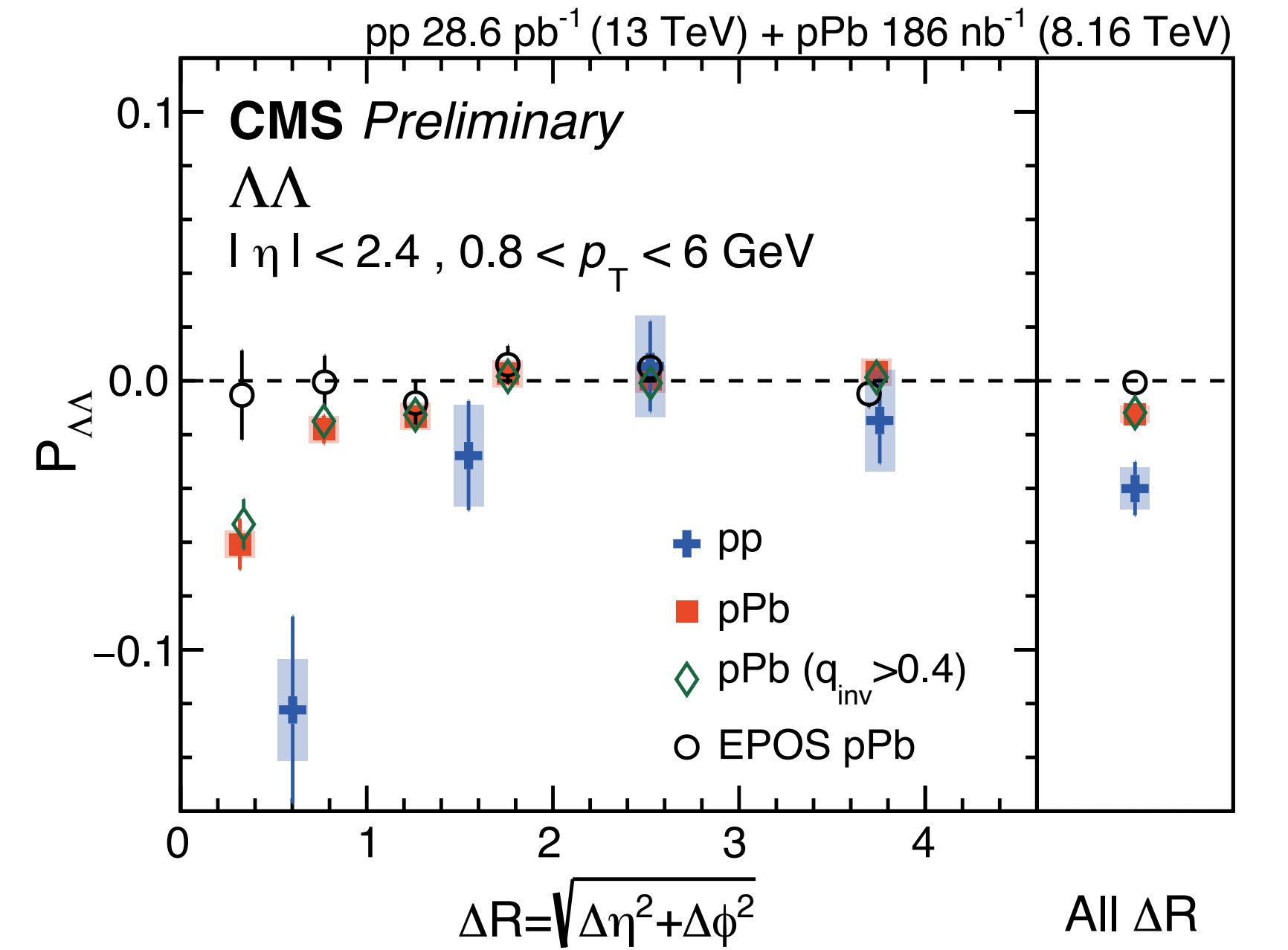
Spin-spin correlations at the LHC

J. Wang (CMS) @DIS2026



$P_{\Lambda\bar{\Lambda}}$ in 13 TeV pp collisions is consistent with zero, unlike the case for 200 GeV.

Indication of slight negative values in 8.16 TeV pPb collisions



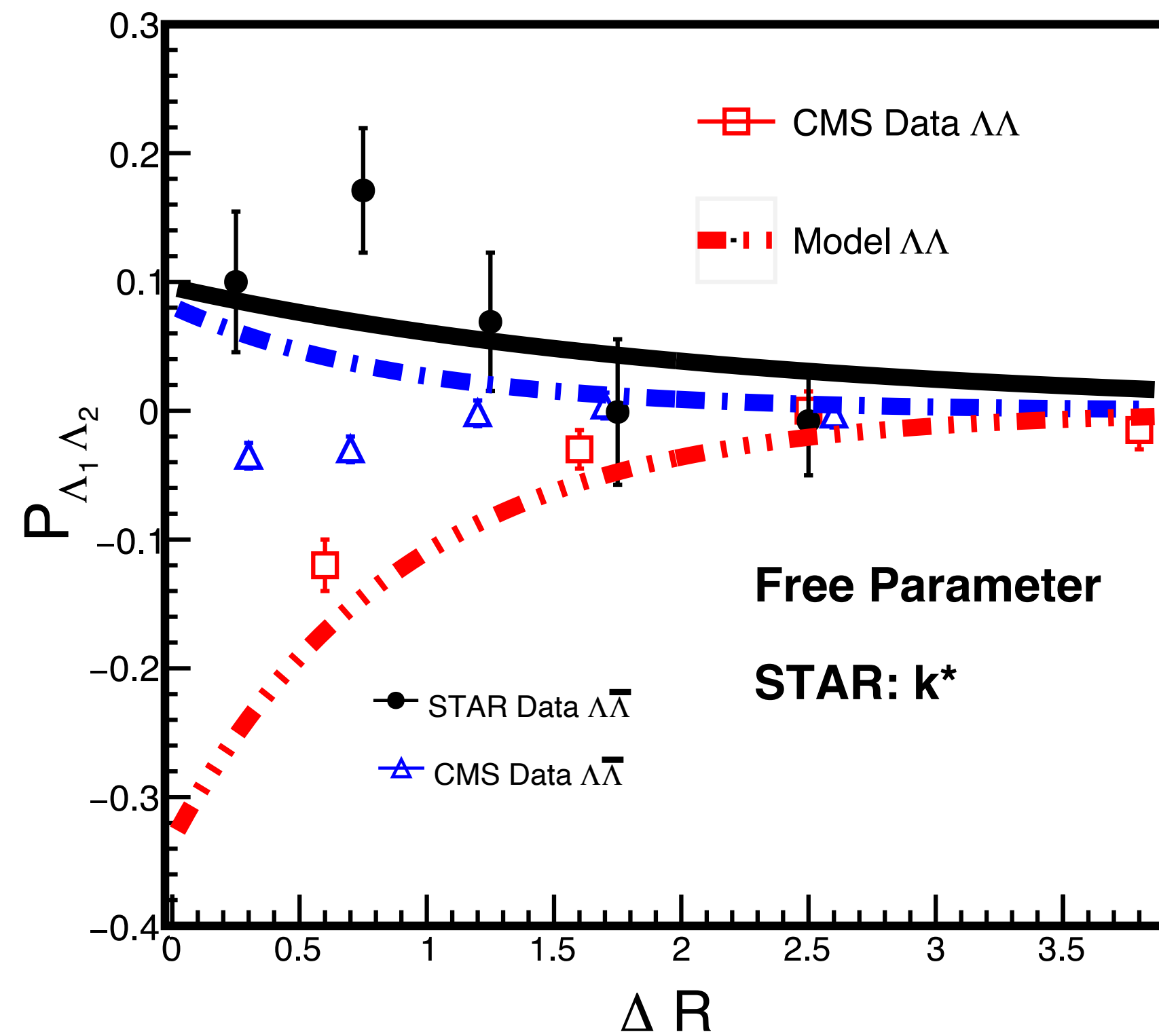
Identical Λ pairs show negative correlations especially at small ΔR .

Stronger correlation in pp collisions than in pPb

Simple decoherence model

Liu and Tu, arXiv:2606.17240

Maximum correlation $P_{\Lambda\Lambda}=1/3$ + Spin transfer from s-quark $\rightarrow \Lambda$ (SU(6))
+ Feed-down dilution (PYTHIA8) + decoherence



$$P(\Delta R) = \alpha(\Delta R) P = P e^{-k^* \Delta R},$$

$$k^* \propto \frac{dN}{d\eta},$$

More particles in the environment leads to stronger decoherence

$$k_{\text{LHC}}^* = k_{\text{RHIC}}^* \frac{dN/d\eta|_{\eta=0, \text{LHC}}}{dN/d\eta|_{\eta=0, \text{RHIC}}},$$

For left plot case:

Fit the STAR data and calculate $P(\Delta R)$ for the LHC based on $dN/d\eta$

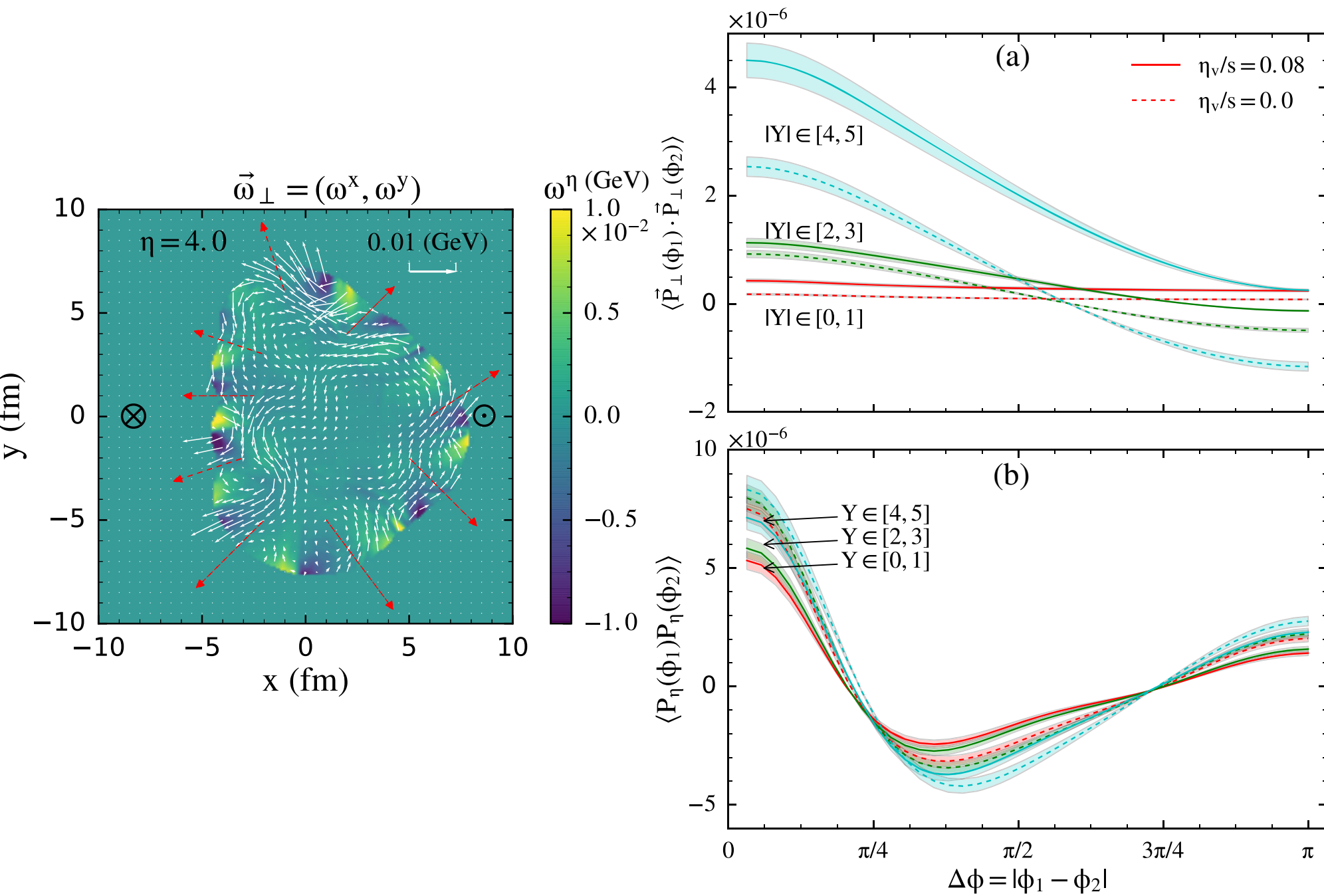
Spin-spin correlation in heavy-ion collisions

Spin-spin correlation in heavy-ion collisions

No data so far

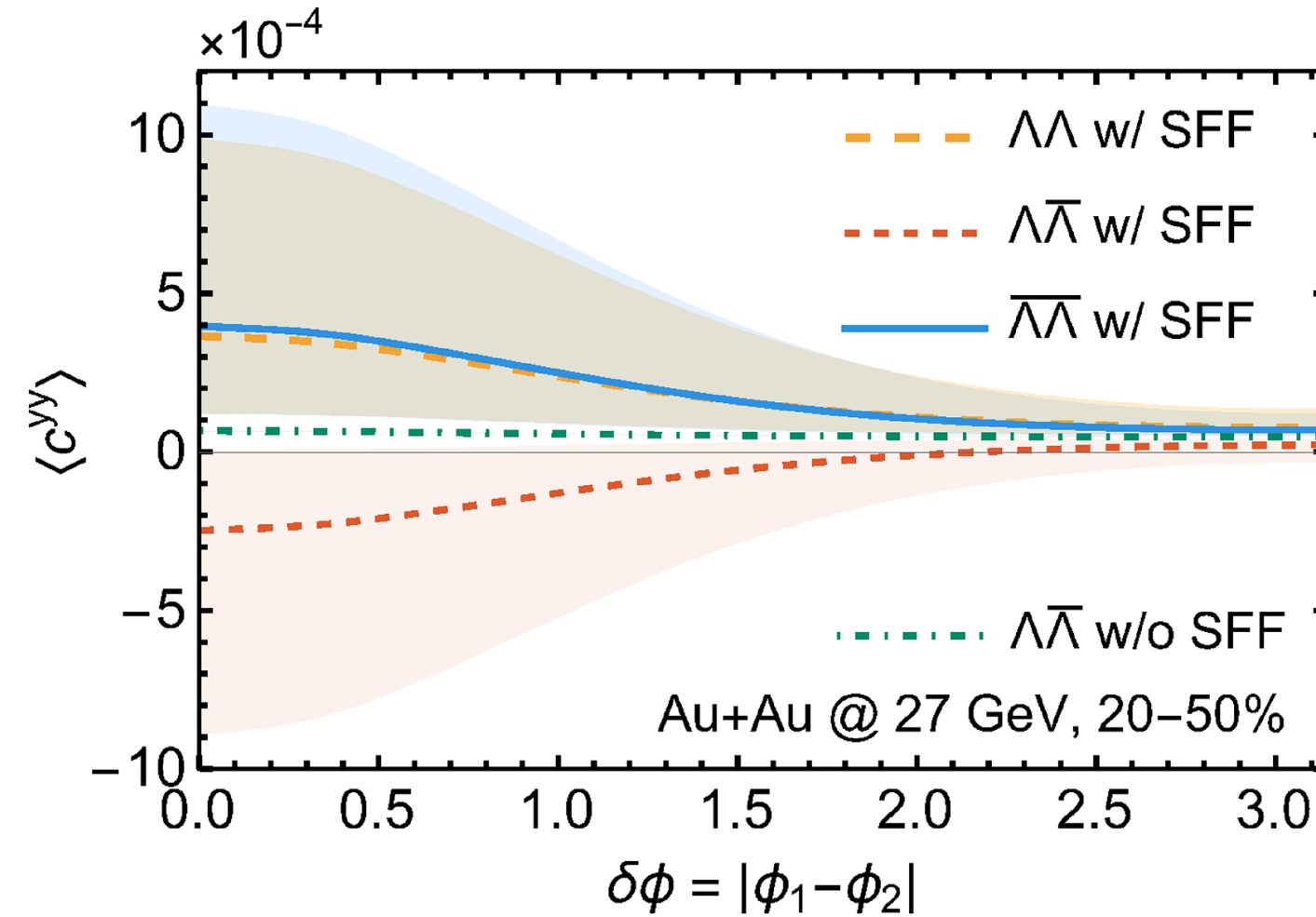
Spin-spin correlation in heavy-ion collisions

L.G. Pang, H. Petersen, Q. Wang, and X.N. Wang,
PRL117,192301 (2016)



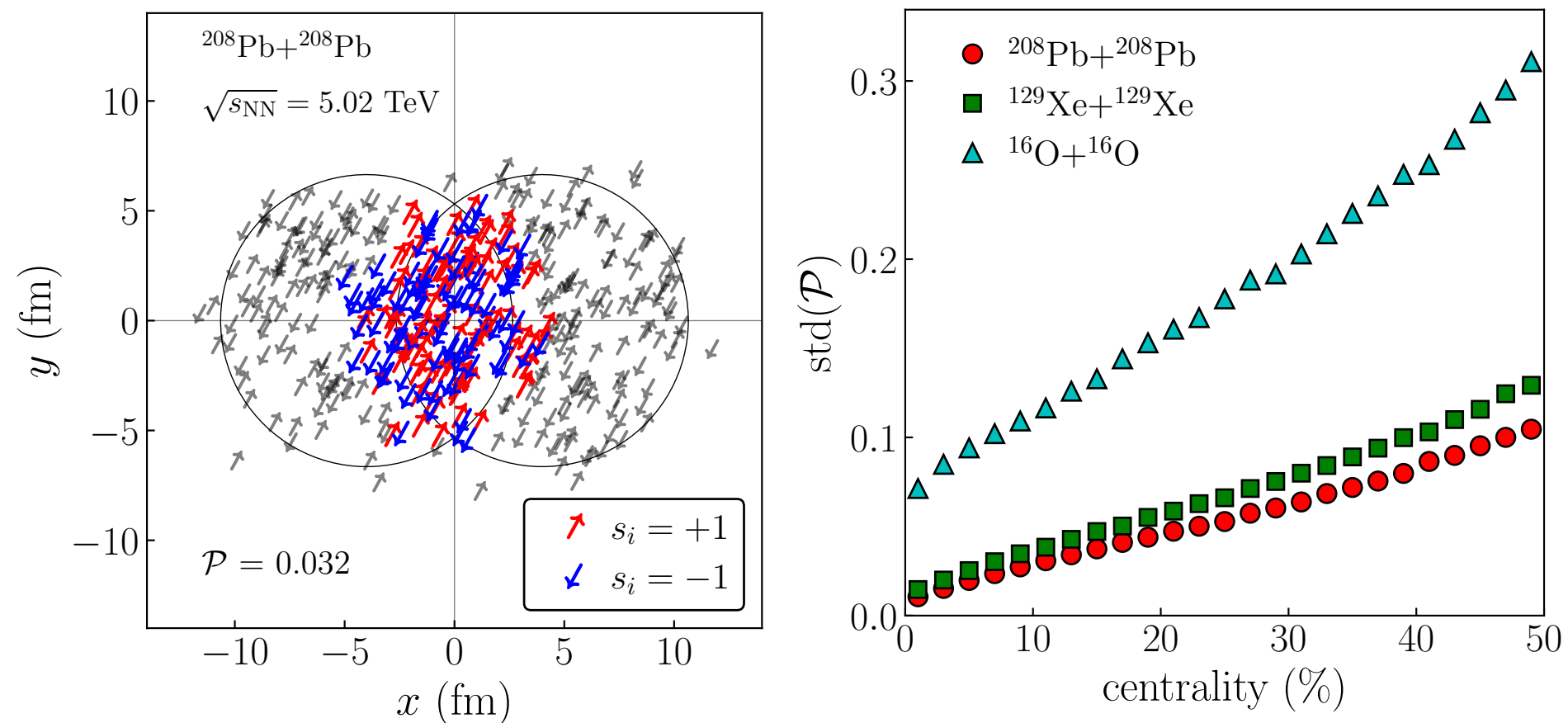
Spin correlations reflecting
the vortical structure of QGP

X.L. Sheng, X.Y. Wu, D.H. Rischke and X.N. Wang,
PRL136, 082301 (2026)



A fluctuating strong-force field (SFF)
polarizes quarks and antiquarks
in opposite directions, leading to
negative $\Lambda\bar{\Lambda}$ spin correlations but
positive $\Lambda\Lambda$ and $\bar{\Lambda}\bar{\Lambda}$ correlations.

Giaccalone and Speranza, arXiv:2502.13102, 2509.26424



Initial-state spin fluctuations
- larger in smaller systems
- long range correlation

Quantum entanglement of $t\bar{t}$ in 13 TeV pp collisions

ATLAS, Nature 633, 542 (2024)
CMS, PRD110, 112016 (2024)

- ▶ Top quark pairs are produced from gluon-gluon fusion

$$gg \rightarrow t\bar{t}$$

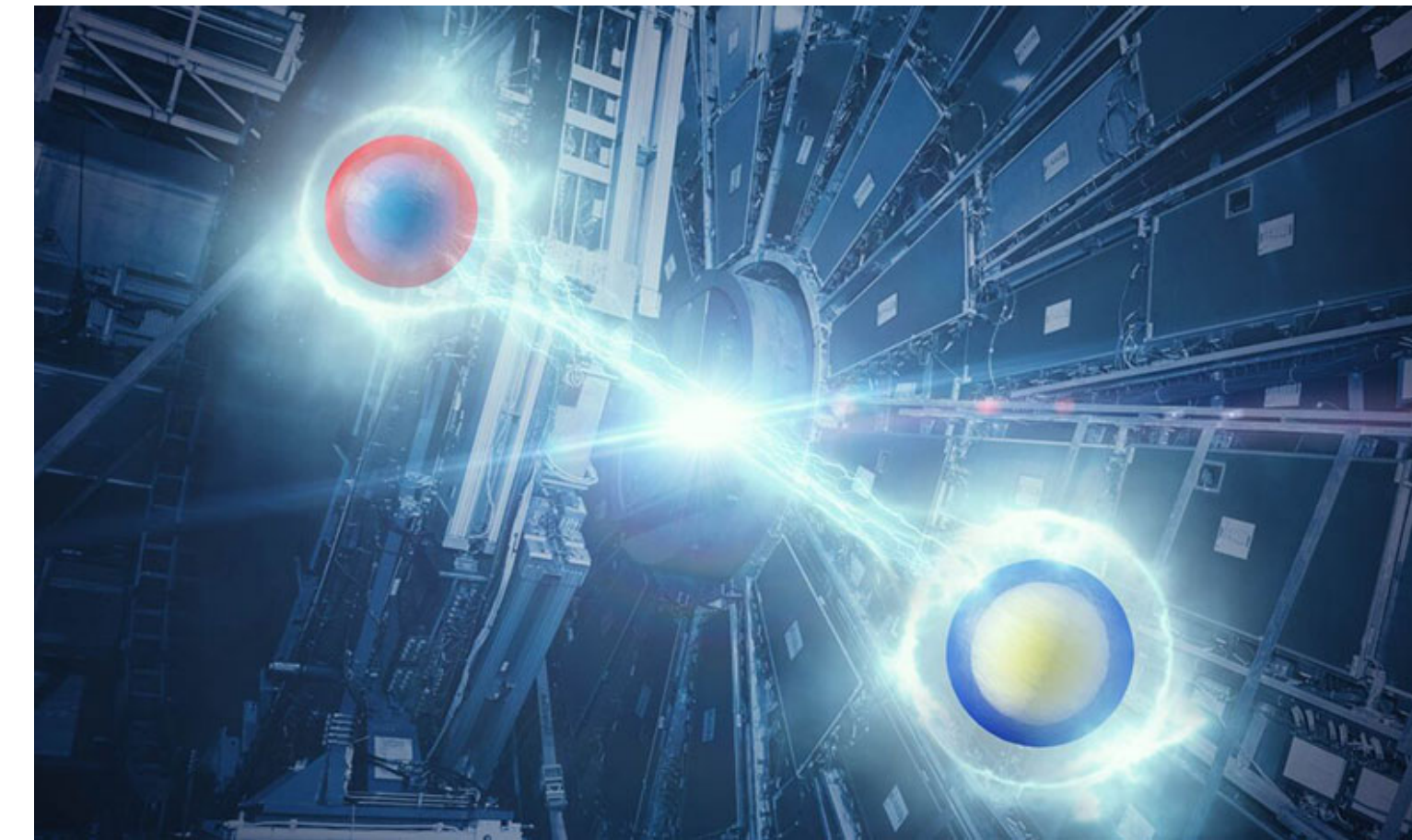
- ▶ At the near-threshold energy, most top-quark pairs are in the spin-singlet state
 - Because of the low relative momentum, they are in S-wave state

$$\frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$$

- ▶ Therefore, their spin states are expected to be maximally entangled
- ▶ The top-quark spin can be analyzed using the charged lepton's momentum direction
 - Nearly perfect spin analyzing power due to the V–A weak interaction

$$t \rightarrow bW^+ \rightarrow b\ell^+\nu$$

$$\bar{t} \rightarrow \bar{b}W^- \rightarrow \bar{b}\ell^-\bar{\nu}$$



Quantum entanglement of $t\bar{t}$ in 13 TeV pp collisions

Angular distribution of the two charged leptons

$$\frac{1}{\sigma} \frac{d\sigma}{d\Omega_+ d\Omega_-} = \frac{1 + \mathbf{B}^+ \cdot \hat{\mathbf{q}}_+ - \mathbf{B}^- \cdot \hat{\mathbf{q}}_- - \hat{\mathbf{q}}_+ \cdot \mathbf{C} \cdot \hat{\mathbf{q}}_-}{(4\pi)^2},$$

Spin singlet-state (maximally entangled state)
perfectly anti-correlated along any axis

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle) \quad C_{xx}=C_{yy}=C_{zz}=-1, D=-1$$

Entanglement marker D

$$D = \frac{1}{3} \text{Tr} C = \frac{1}{3} (C_{xx} + C_{yy} + C_{zz})$$

$$D = -3 \langle \hat{\mathbf{q}}_{\ell+} \cdot \hat{\mathbf{q}}_{\ell-} \rangle$$

D < -1/3 if entangled

Statistical mixture

anti-parallel in z, but uncorrelated along x, y

$$|\psi\rangle = \frac{1}{2}(|\uparrow\downarrow\rangle\langle\downarrow\uparrow| + \frac{1}{2}|\downarrow\uparrow\rangle\langle\uparrow\downarrow|) \quad C_{xx}=C_{yy}=0, C_{zz}=-1, D=-1/3$$

Spin correlation does not necessarily imply quantum entanglement

Observation of quantum entanglement $t\bar{t}$ at the LHC

Entanglement marker D

$$D = \frac{1}{3} \text{Tr} C = \frac{1}{3} (C_{xx} + C_{yy} + C_{zz})$$

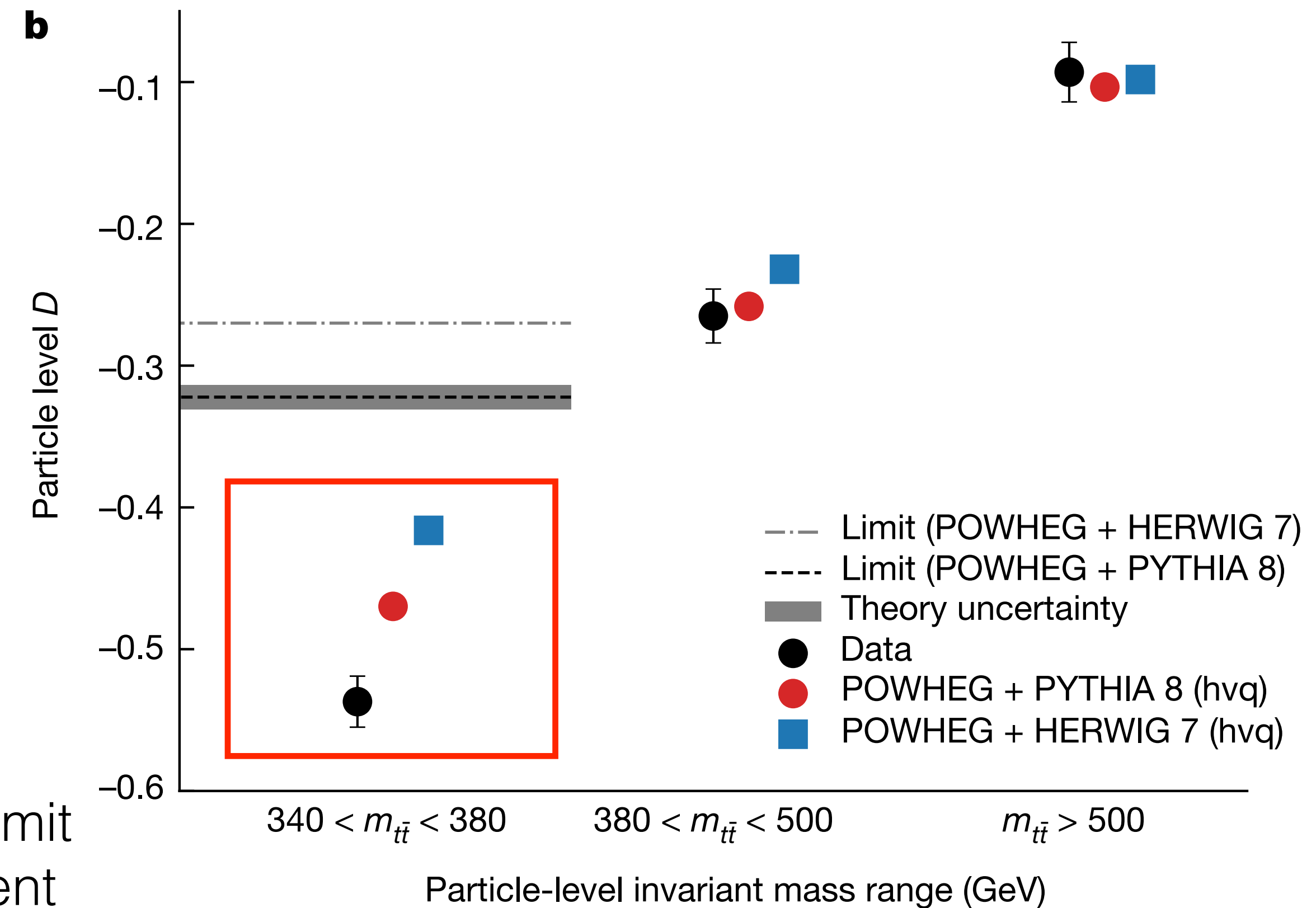
$$D = -3 \langle \hat{\mathbf{q}}_{\ell+} \cdot \hat{\mathbf{q}}_{\ell-} \rangle \quad \boxed{D < -1/3 \text{ if entangled}}$$

$$D = -0.537 \pm 0.002(\text{stat}) \pm 0.019(\text{syst}) < -1/3$$

for $340 < m_{t\bar{t}} < 380 \text{ GeV}$

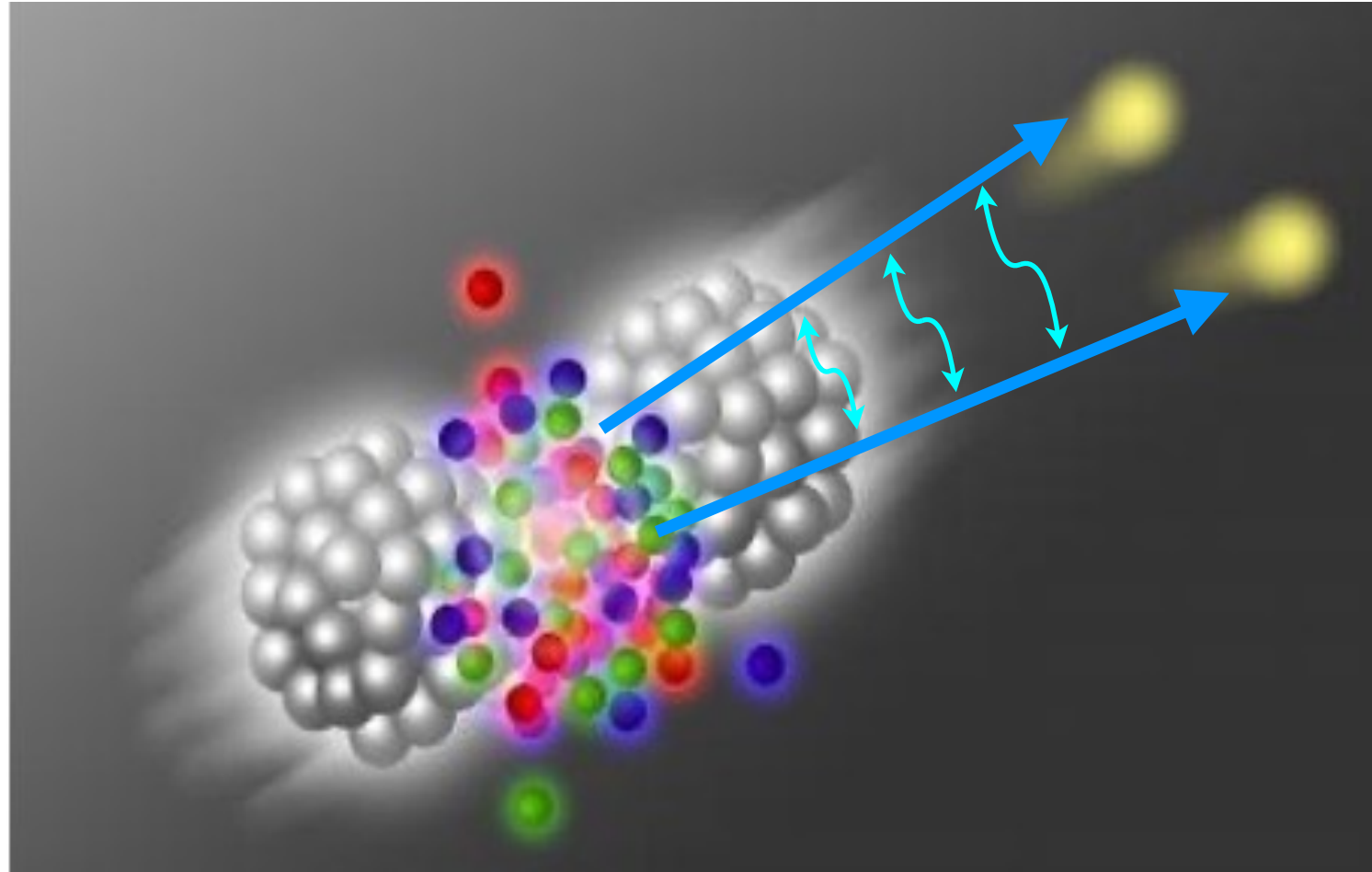
The measured spin correlation exceeds the separable-state limit by more than 5σ , providing evidence of quantum entanglement

ATLAS, Nature 633, 542 (2024)
CMS, PRD110, 112016 (2024)



The model predictions include spin entanglement arising from QCD top-quark pair production

Femtoscopy



Femtoscopy: two-particle momentum correlations

$$C(q) = \int S(r) |\Psi(r, q)|^2 d^3r$$

$$C(q) = 1 \pm |\tilde{S}(q)|^2$$

assume Gaussian source- $\rightarrow$

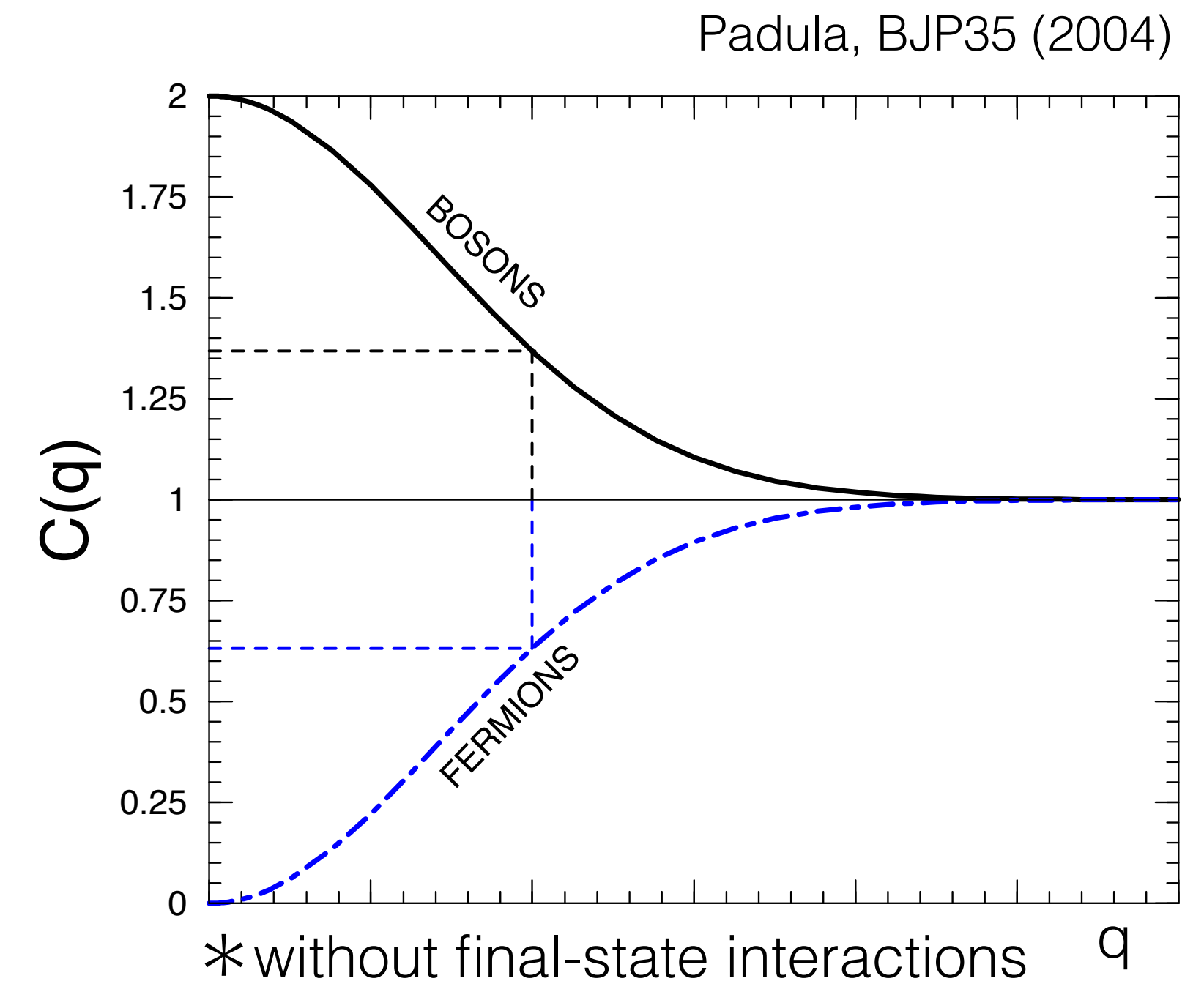
$$= 1 \pm e^{-q^2 R^2}$$

$$\rightarrow 1 \pm \lambda e^{-q^2 R^2}$$

$S(r)$: source function
 $\Psi(r)$: two-particle wave function
 r : relative distance
 q : relative momentum
 R : Gaussian source size

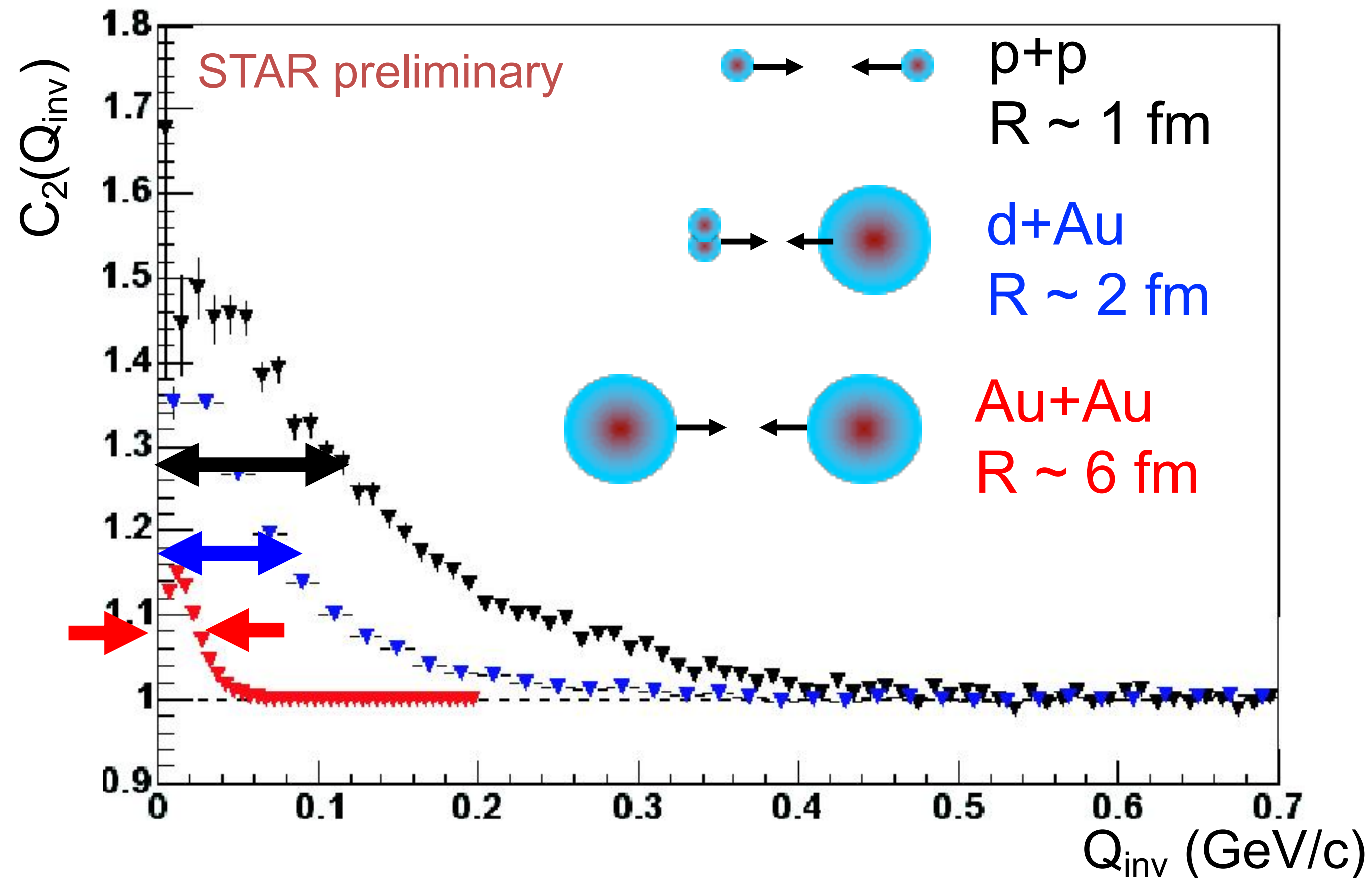
$$C(q) = 1 \pm \lambda e^{-q^2 R^2}$$

$\downarrow$
 $+$ for bosons, $-$ for fermions
 due to (anti)symmetrization of wave-function



Bose-Einstein or Fermi-Dirac statistical effects

"HBT" correlations

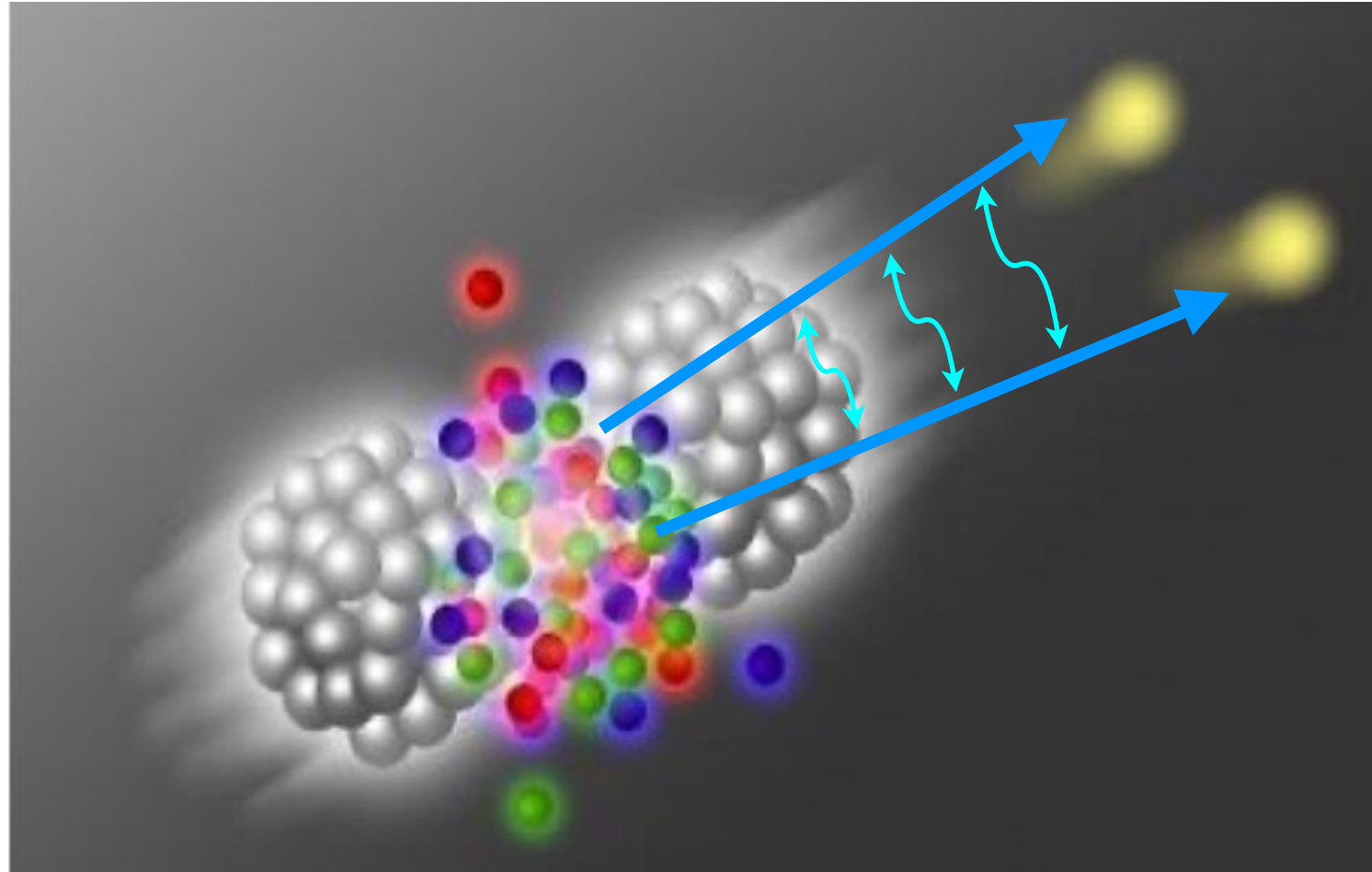


$$C(q) = 1 \pm \lambda e^{-q^2 R^2}$$

Pion HBT correlations in three systems

The width of $C(q)$ is proportional to the inverse of source size R

Spin correlations as a femtoscopic probe



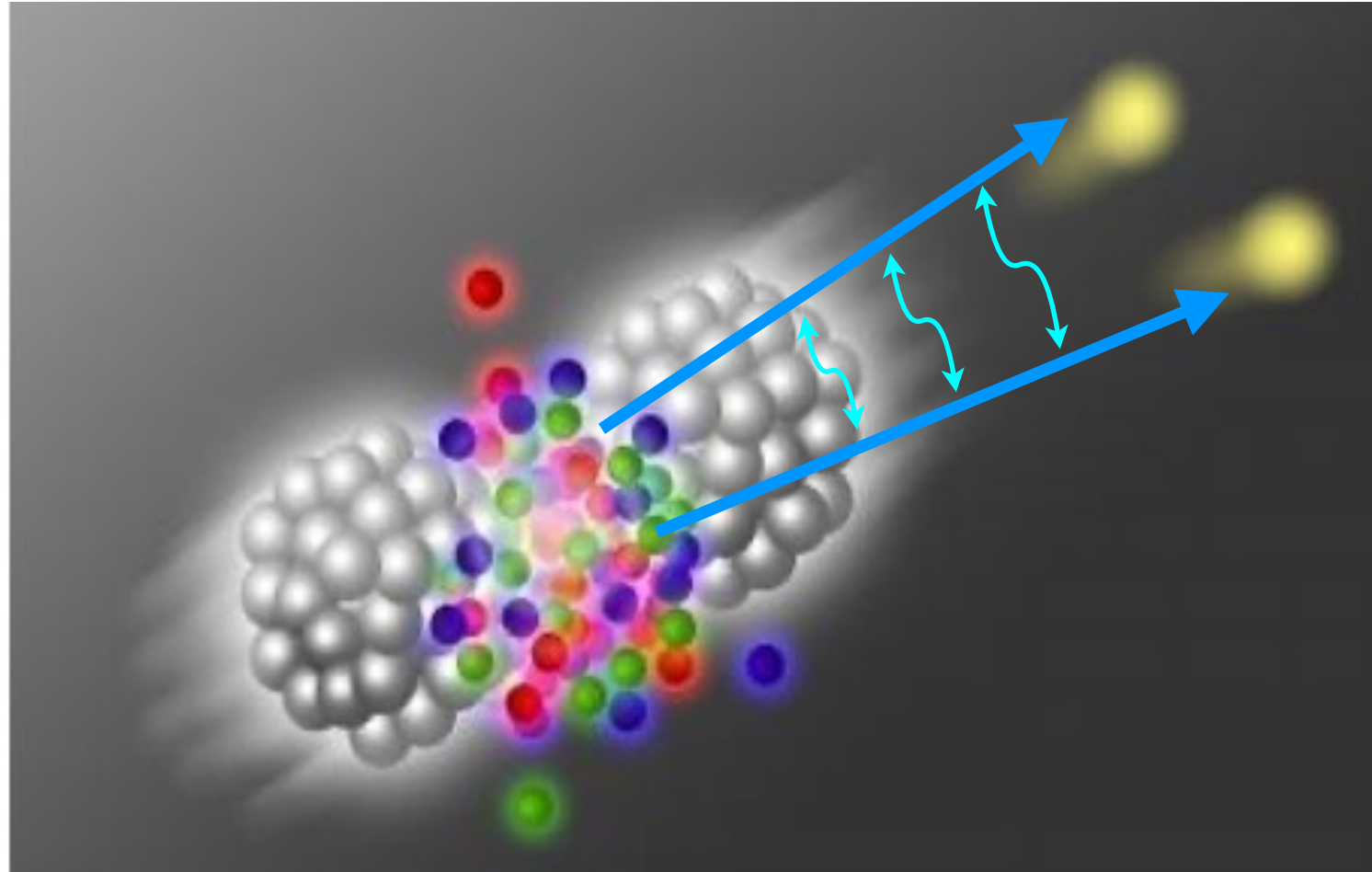
$$C(q) = \int S(r) |\Psi(r, q)| d^3r$$

$S(r)$: source function
 $\Psi(r)$: two-particle wave function
 r : relative distance
 q : relative momentum
 R : Gaussian source size

Final-state interactions, e.g.
Coulomb, strong interaction, are also included

Therefore, recently the femtoscopy has been actively used to study hadron-hadron interactions

Spin correlations as a femtoscopic probe



$$C(q) = \int S(r) |\Psi(r, q)| d^3r$$

$S(r)$: source function
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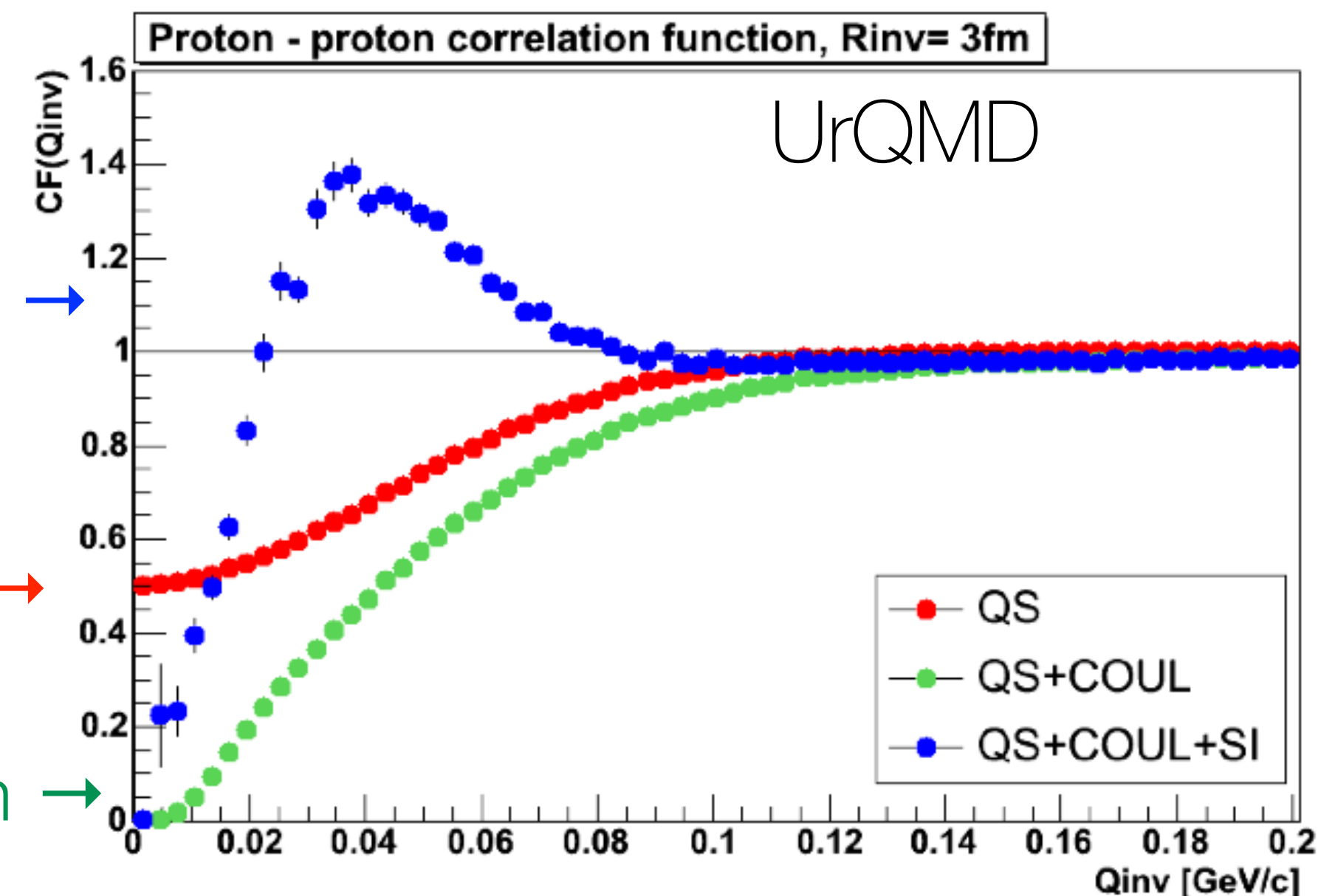
Therefore, recently the femtoscopy has been actively used to study hadron-hadron interactions

H. Zbroszczyk, Zymanyi School (2021)

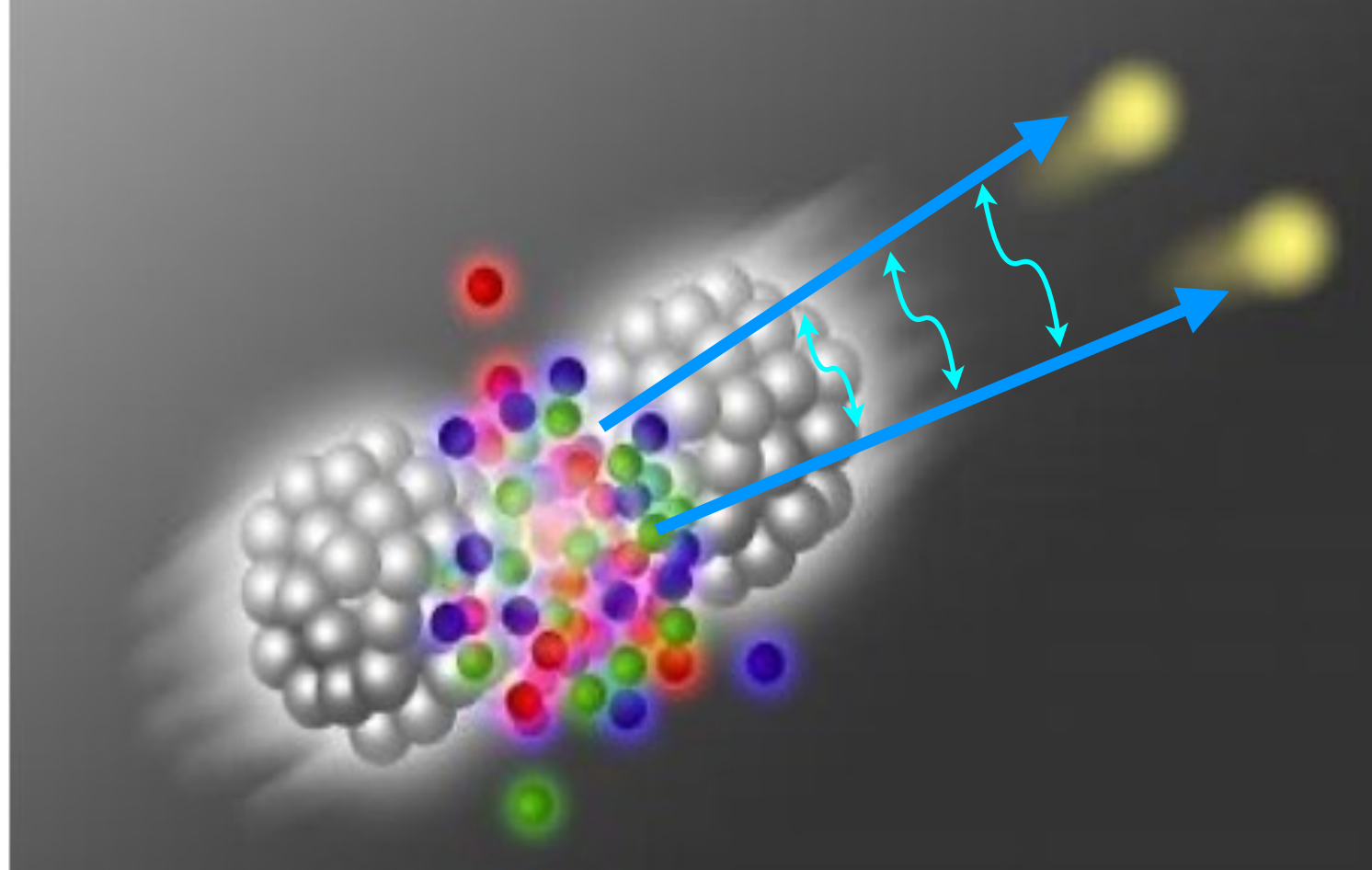
Attractive interaction at intermediate distance →

Fermi-Dirac statistical effect →

(repulsive) Coulomb interaction →



Spin correlations as a femtoscopic probe



$$C(q) = \int S(r) |\Psi(r, q)| d^3r$$

$S(r)$: source function
 $\Psi(r)$: two-particle wave function
 r : relative distance
 q : relative momentum
 R : Gaussian source size

Final-state interactions, e.g.
Coulomb, strong interaction, are also included

Therefore, recently the femtoscopy has been actively used to study hadron-hadron interactions

$$C(q) = 1 + \lambda \sum_S p_s \eta_s e^{-q^2 R^2}$$

p_s : population fraction of spin state S

$$\eta_s = (-1)^S \text{ (fermion)}$$

$$\eta_s = 1 \text{ (spin-0 boson)}$$

Alexander and Lipkin, PLB352(1995)162

Lyuboshitz and Lyuboshitz, Phys.Atom.Nucl.73, 805 (2010)

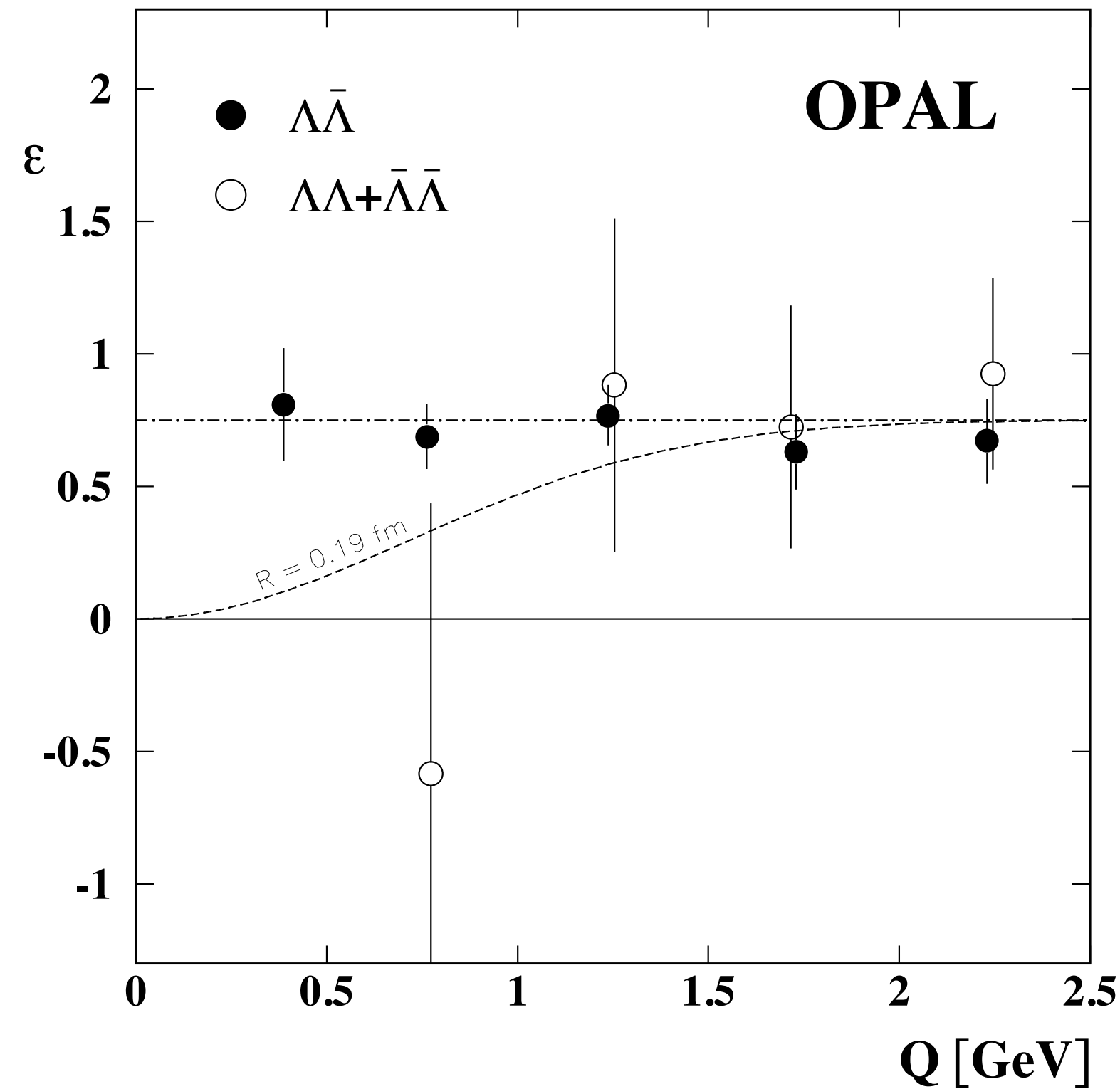
Conventional femtoscopic measurements are spin-averaged.

Spin-resolved femtoscopic correlation functions have yet to be measured.

For certain particle pairs (e.g. hyperons), spin-decomposition of hadron interaction is possible

Spin decomposition of $\Lambda\Lambda$ pairs

OPAL Collaboration, PLB384(1996)377



fit function:

$$\epsilon(Q) = 0.75 \cdot (1 - e^{-Q^2 R_{\Lambda\Lambda}^2})$$

LEP e^+e^- collisions at $\sqrt{s} = 91$ GeV

$$e^+e^- \rightarrow Z^0 \rightarrow q\bar{q} \rightarrow \Lambda\Lambda, \Lambda\bar{\Lambda}, \bar{\Lambda}\bar{\Lambda} + X$$

$$\frac{dN}{d\cos\theta_{12}} = (1 - \epsilon) \left. \frac{dN}{d\cos\theta_{12}} \right|_{S=0} + \epsilon \left. \frac{dN}{d\cos\theta_{12}} \right|_{S=1}$$

θ_{12} : angle btw daughter proton and antiproton in their parent rest frame

ϵ : fraction of $S=1$ state

$$\begin{aligned} \Lambda\bar{\Lambda} : \quad \left. \frac{dN}{d\cos\theta_{12}} \right|_{S=0} &= 1 + \alpha^2 \cos\theta_{12}, & \left. \frac{dN}{d\cos\theta_{12}} \right|_{S=1} &= 1 - \frac{\alpha^2}{3} \cos\theta_{12} \\ \Lambda\Lambda(\bar{\Lambda}\bar{\Lambda}) : \quad \left. \frac{dN}{d\cos\theta_{12}} \right|_{S=0} &= 1 - \alpha^2 \cos\theta_{12}, & \left. \frac{dN}{d\cos\theta_{12}} \right|_{S=1} &= 1 + \frac{\alpha^2}{3} \cos\theta_{12} \end{aligned}$$

- $\Lambda\Lambda$: An indication of a suppressed spin-triplet fraction at low relative momentum, consistent with Pauli exclusion
- $\Lambda\bar{\Lambda}$: $\epsilon \sim 0.75$, consistent with statistical spin mixture

Spin-resolved femtoscopy can provide constraints on spin-dependent interactions

Summary of day-5

► Spin-spin correlations

- ❑ Weak-decays of hyperons allow us to measure the correlation between particle pairs
- ❑ STAR observed a positive $\Lambda\Lambda^-$ spin correlation at small pair separation in 200 GeV pp collisions, while preliminary CMS results show different behavior at LHC energies
- ❑ Spin correlations offer new probes of the QCD vacuum, hadronization and the vortical structure of the QGP.

► Quantum entanglement and femtoscopy

- ❑ Entanglement has been observed in top-quark pairs at the LHC
 - Spin correlation does not necessarily imply quantum entanglement
- ❑ Spin-resolved femtoscopy could provide new constraints on spin-dependent hadron–hadron interactions

Summary of 5-day lectures

- ▶ Day-1: The birth of spin physics
From Stern–Gerlach to parity violation: spin as a fundamental quantum property and weak decay as a spin analyzer
- ▶ Day-2: Nucleon spin structure and transverse spin
Global and local hyperon polarization as probes of QGP vorticity and spin dynamics
- ▶ Day-3: Spin polarization in heavy-ion collisions (1)
DIS, the proton spin puzzle, gluon and sea-quark polarization, and transverse spin phenomena
- ▶ Day-4: Spin polarization in heavy-ion collisions (2)
Vector-meson spin alignment and its sensitivity to quark–antiquark spin correlations
- ▶ Day-5: Spin correlations and future directions
Hyperon spin correlations, quantum entanglement and spin-resolved femtoscopy

Spin provides a unique probe of hadron structure and QCD matter,
from individual quarks to the collective dynamics of the QGP