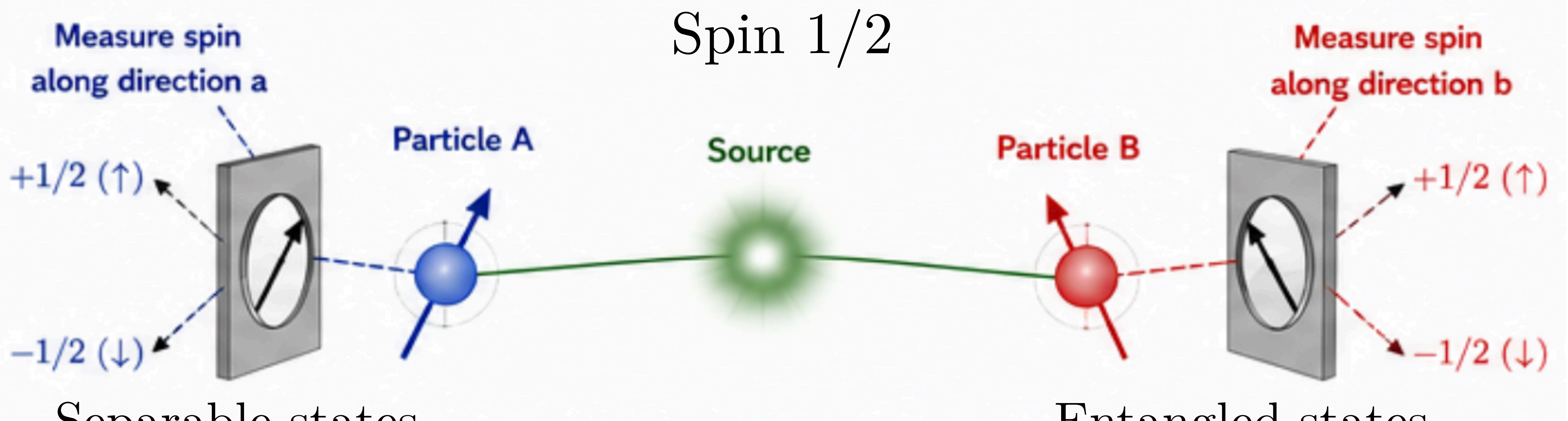
Spin-spin correlations in $\Lambda\bar{\Lambda}$ production at SPD

D. Gubachev, A. Guskov, JINR on behalf of the SPD collaboration
avg@jinr.int

Correlation vs entanglement

Spin 1/2



Separable states

$$\rho_{AB} = \sum_k p_k \, \rho_A^{(k)} \otimes \rho_B^{(k)}$$

Entangled states

$$\rho_{AB} \neq \sum_k p_k \, \rho_A^{(k)} \otimes \rho_B^{(k)}$$

	Correlation	**Entanglement**
Definition	statistical dependence	quantum correlation that cannot be written as a mixture of a product states
Can be classical?	yes	no
Bell inequalities	always satisfied	can be violated

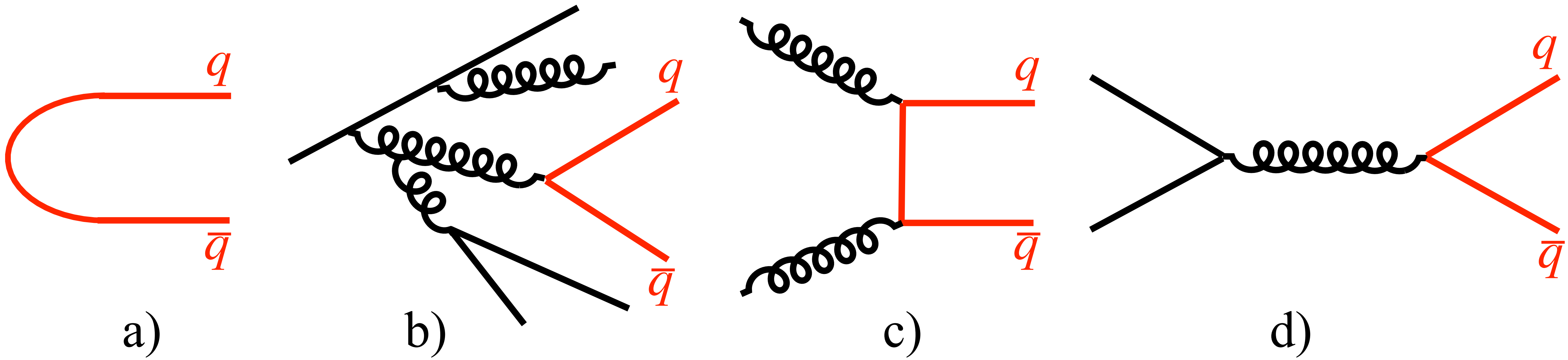
Separable states can still exhibit classical correlations!

Signature of entanglement

$$\rho = \frac{1}{4}\left[1 \otimes 1 + \mathbf{P}_1 \cdot \boldsymbol{\sigma} \otimes 1 + 1 \otimes \mathbf{P}_2 \cdot \boldsymbol{\sigma} + \sum_{i,j} C_{ij}\, \sigma_i \otimes \sigma_j\right]$$

Criterion/measure	What it tells us	Scope
PPT (Peres-Horodecki)	$\boldsymbol{\rho}^{TB}$ has a negative eigenvalue $\rightarrow$ entangled	Necessary & sufficient
Negativity $\mathcal{N}$	$\mathcal{N} = \sum_{\lambda_i<0} \lvert\lambda_i\rvert$	Exact entanglement measure for two qubits
$\mathbf{Tr}(C_{ij})<-1$	Detects entanglement from spin correlations	Special case: unpolarized, isotropic two-qubit states
CHSH/Bell inequality	Violation demonstrates nonlocal quantum correlations	Sufficient, not necessary for entanglement
Concurrence $\mathcal{C}$	...	...
Entanglement entropy S	...	...
...	...	...

$q\bar{q}$ pair production in pp collisions



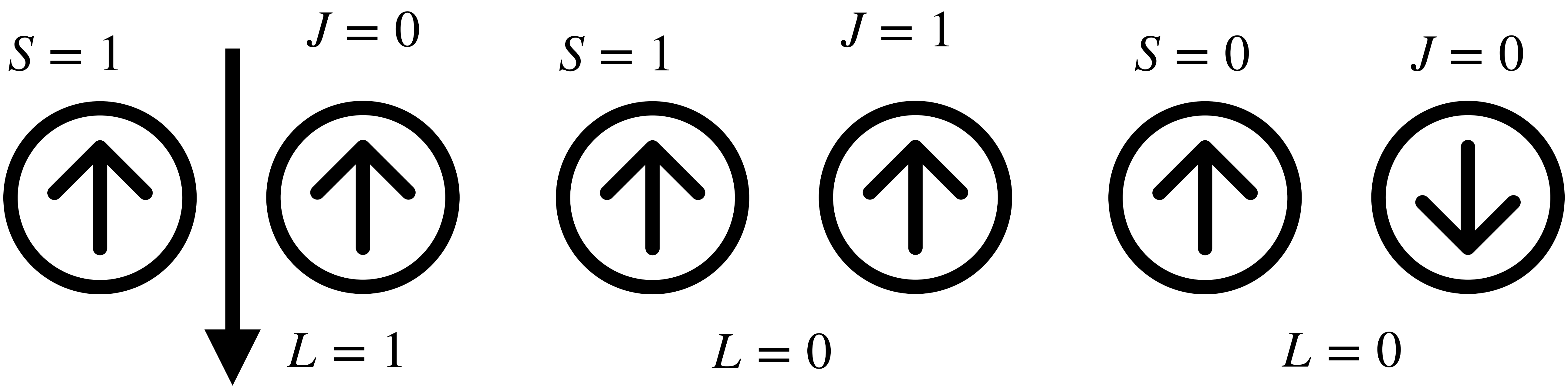
a) materialization from the QCD vacuum condensate

b) gluon splitting in the parton shower evolution

c , d) production in hard interaction

Spin singlets and triplets

In general case $q\bar{q}$ pair is produced in a quantum superposition of different **S**, **L** and **J**. However, limiting cases do exist:



QCD vacuum

mainly ${}^3P_0$ $J^{PC} = 0^{++}$

Gluon splitting

$m_q \to 0$

$gg \to Q\bar{Q}$

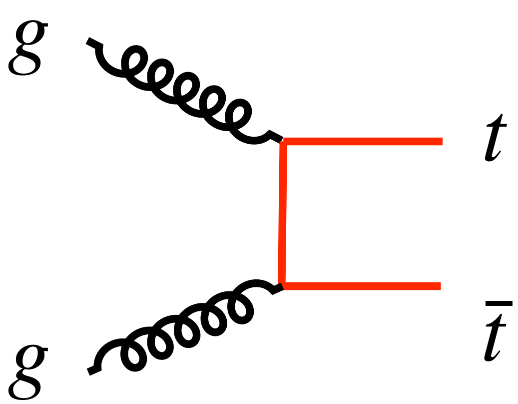
near threshold

C — spin correlation matrix $P = Tr(C)/3$ - spin correlation parameter

$$C = \begin{pmatrix} 1/3 & 0 & 0 \\ 0 & 1/3 & 0 \\ 0 & 0 & 1/3 \end{pmatrix} \quad C = \begin{pmatrix} 1/3 & 0 & 0 \\ 0 & 1/3 & 0 \\ 0 & 0 & 1/3 \end{pmatrix} \quad C = \begin{pmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix}$$

$\mathbf{P = 1/3}$ for triplets **$\mathbf{P = -1}$ for singlets**

Quantum entanglement: t-quarks

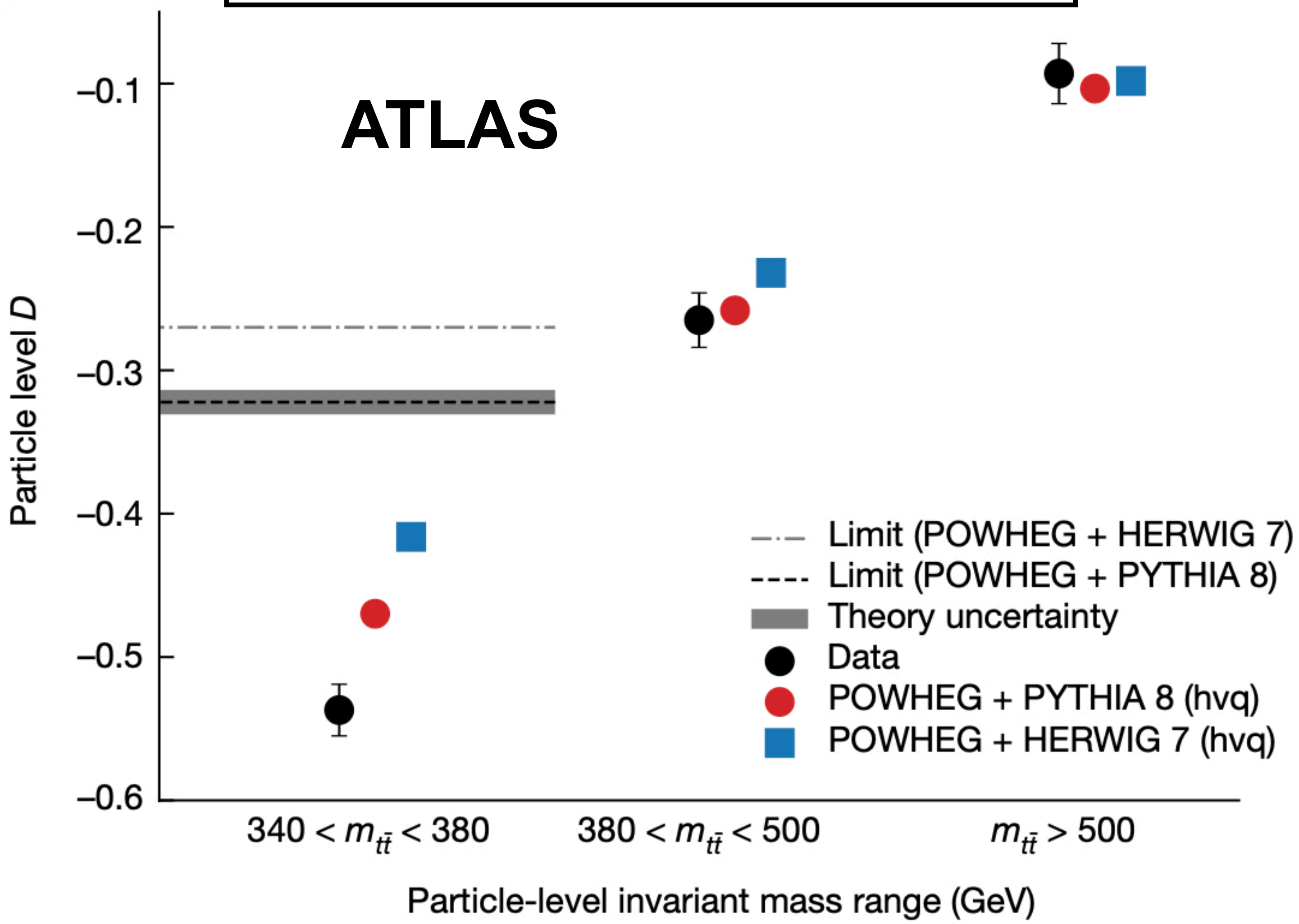


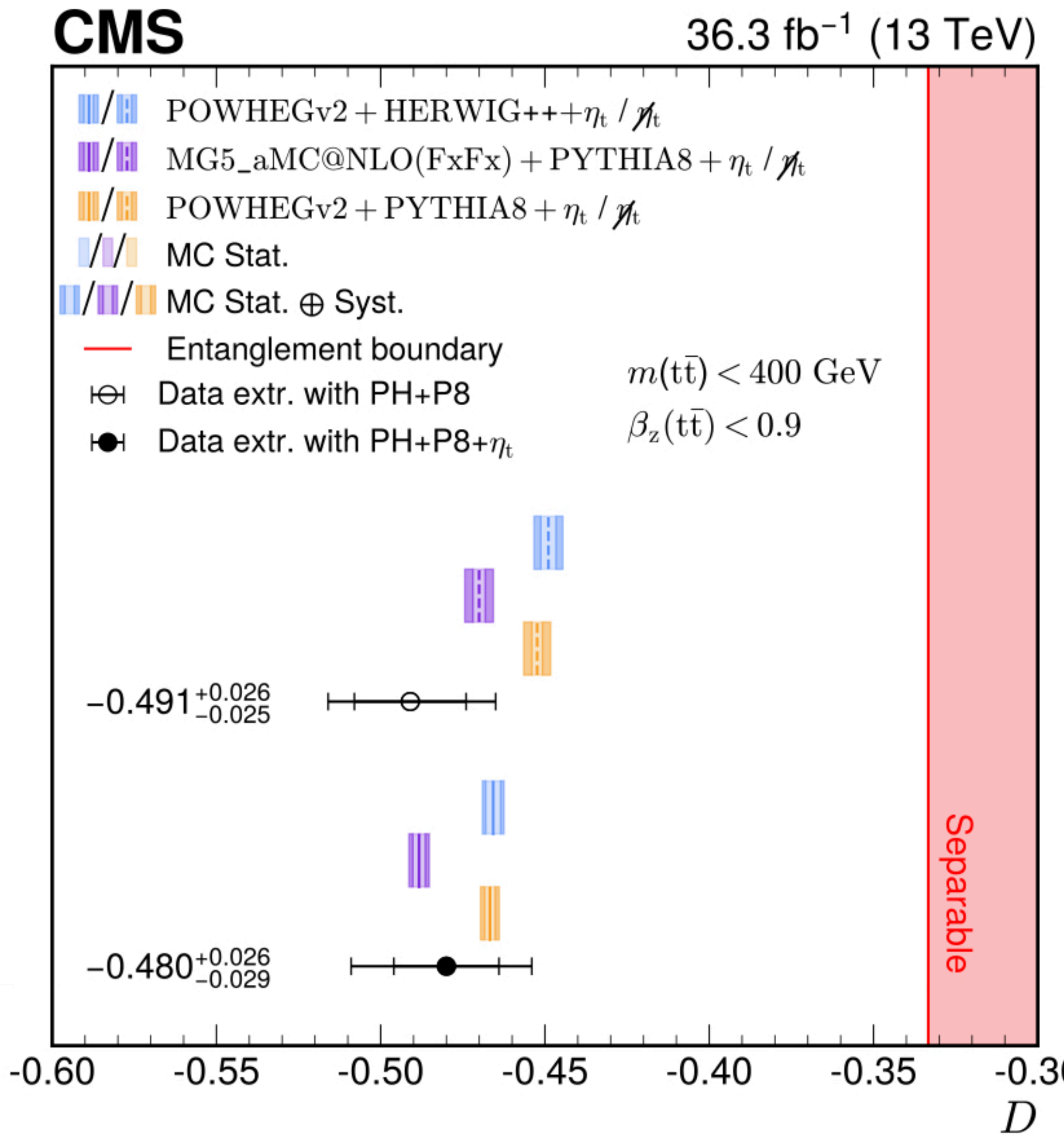
G.Aad et al. [ATLAS], Nature 633 (2024)
A.Hayrapetyan et al. [CMS] Rept. Prog. Phys. 87 (2024)

$$D = -3\langle\cos\phi\rangle$$

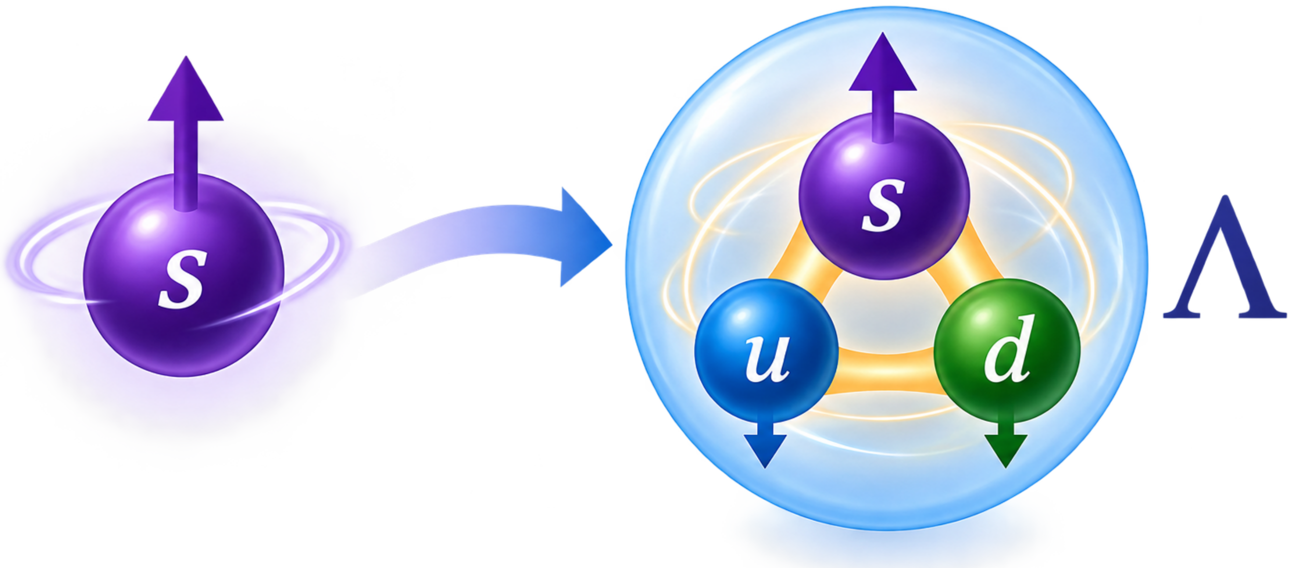
ϕ - angle between e and μ

$$D = -0.537 \pm 0.002_{stat} \pm 0.029_{syst}$$





From s-quark to Λ

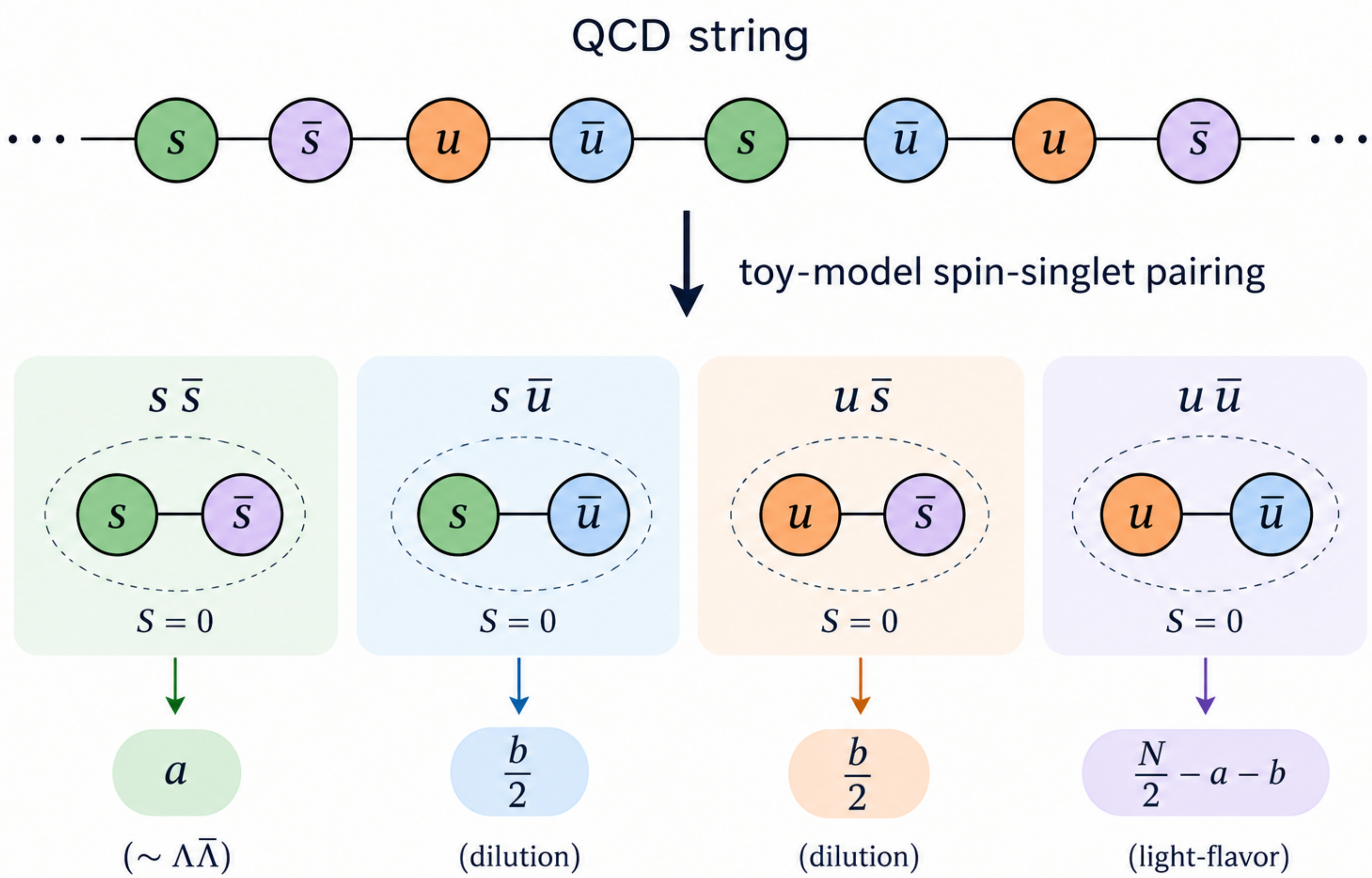


SU(6) model — based on SU(6) symmetry
BJ model — phenomenological model constrained by polarized DIS data

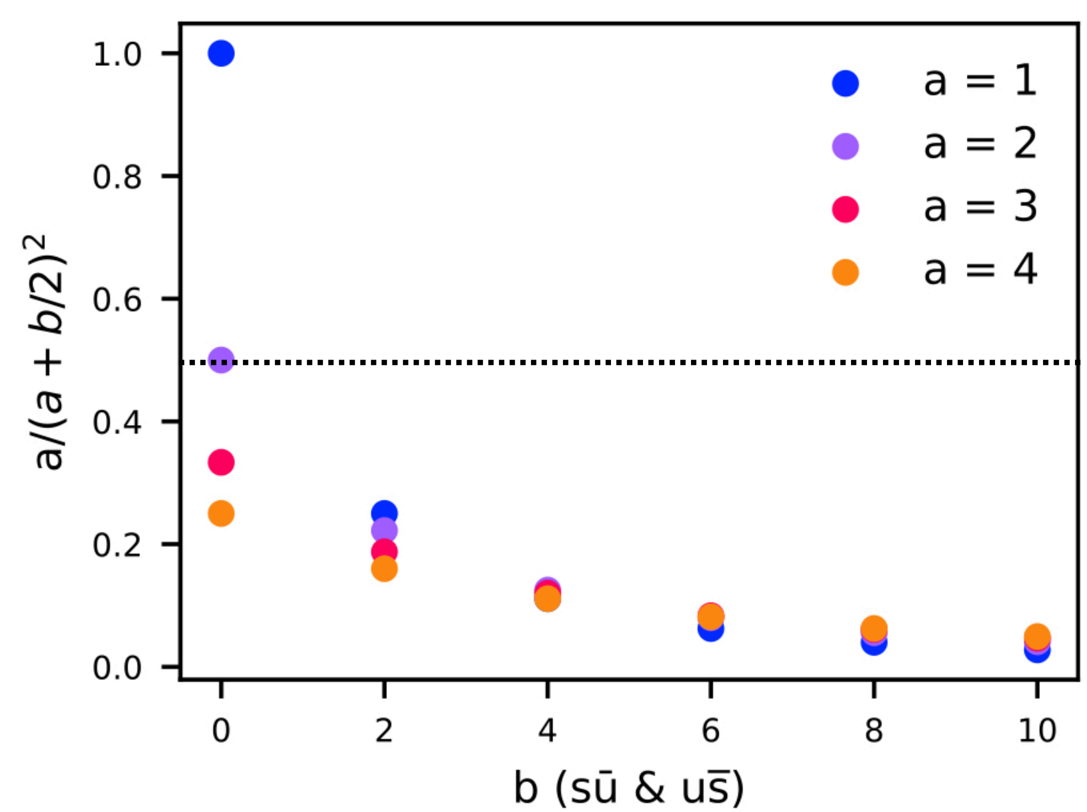
Λ's parent	$c\tau$, cm	Main decay channel, %	$P_{\Lambda(\bar{\Lambda})}$, SU(6) model	$P_{\Lambda(\bar{\Lambda})}$, Burkardt–Jaffe model
s-quark	-	-	1	0.63
Σ^0	2.2×10^{-9}	$\Lambda\gamma$, 100	1/9	0.15
Ξ^0	8.7	$\Lambda\pi^0$, 99.5	0.6	-0.37
Ξ^-	4.9	$\Lambda\pi^-$, 99.9	0.6	-0.37
$\Sigma^*(1385)$	7×10^{-13},	$\Lambda\pi$, 87	5/9	-

The negative sign for Ξ in the BJ model significantly modifies the correlation prediction

Entanglement and hadronization



W.Gong, et al., Phys. Rev. D 106 (2022)

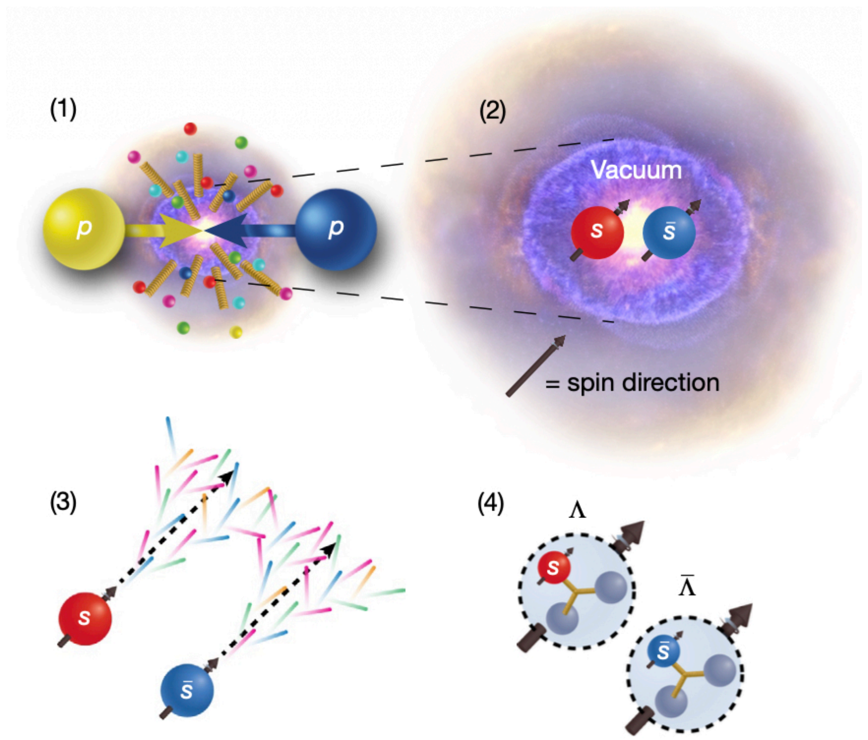


$$\frac{P(|\hat{n}_1\rangle, |\hat{n}_2\rangle)}{P(|\hat{n}_1\rangle)P(|\hat{n}_2\rangle)} = 1 - \boxed{\frac{a}{(a+b/2)^2}}\cos(\theta_2-\theta_1)$$

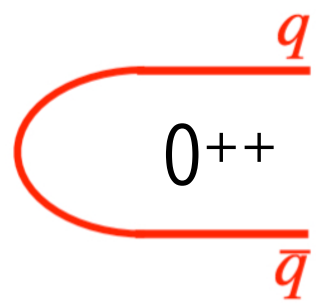
correlation strength; >0.5
— entanglement criterion

lower $\sqrt{s}$ → lower multiplicity → larger correlation!

$\Lambda\bar{\Lambda}$ spin correlation: STAR

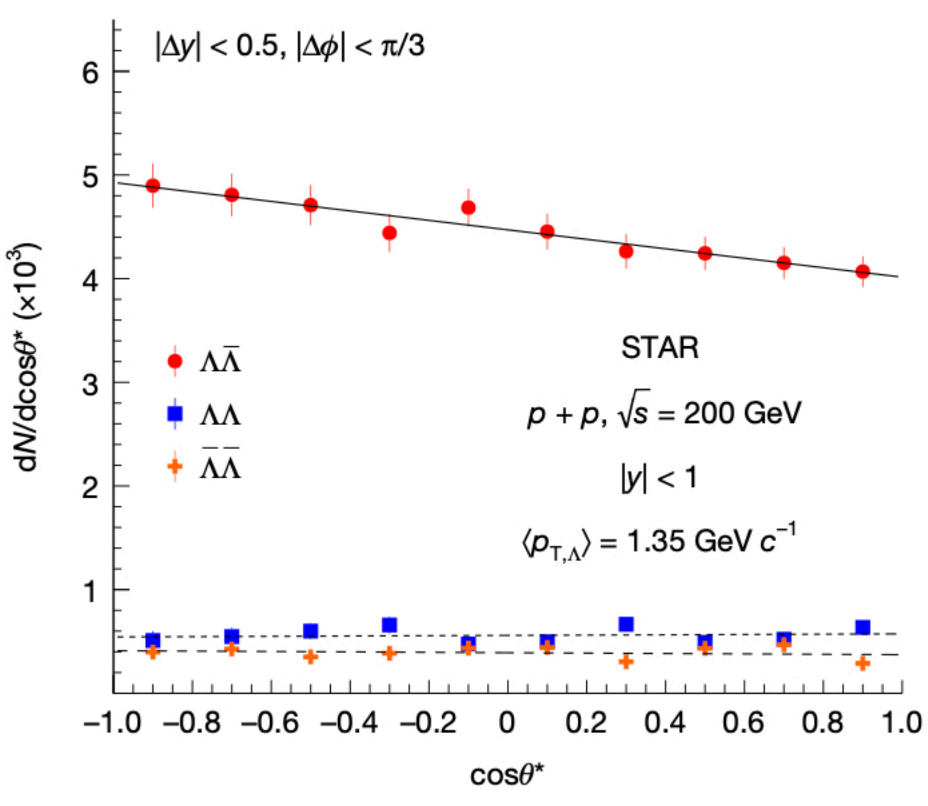


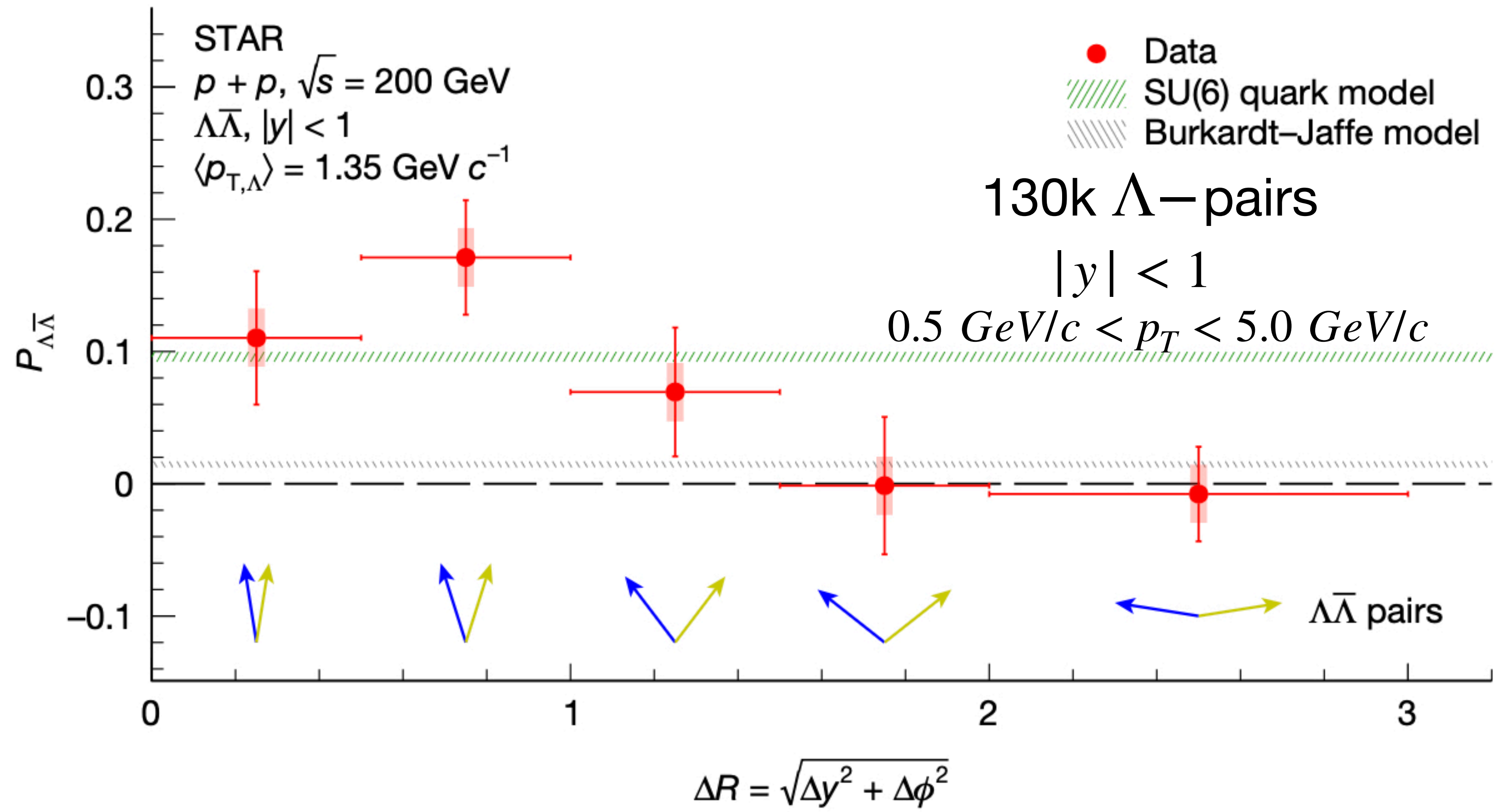
B.E.Aboona et al. [STAR], Nature 650 (2026)



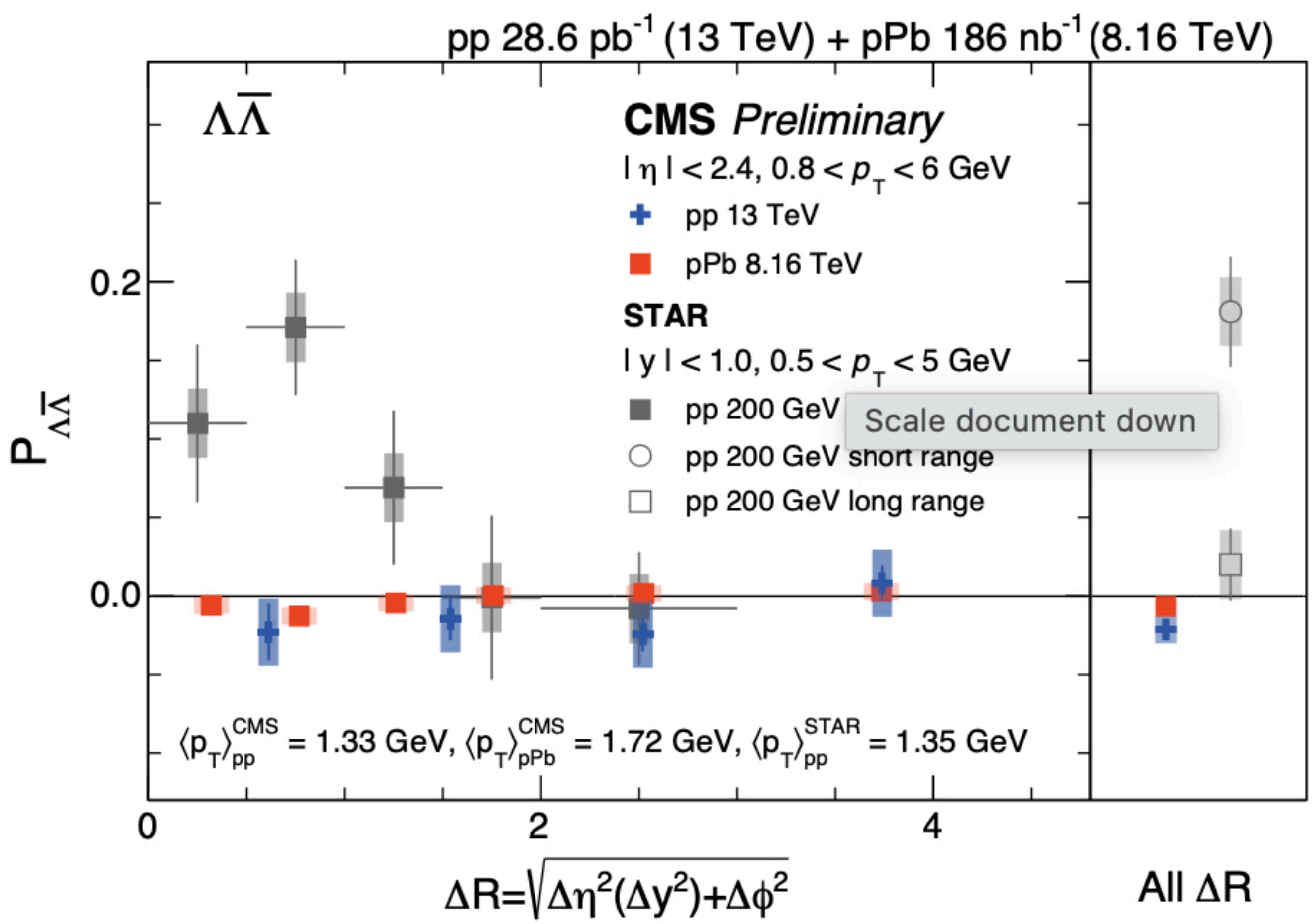
$$\frac{1}{N}\frac{dN}{d\cos\theta^\star} = \frac{1}{2}(1+\alpha_-\alpha_+P_{\Lambda\bar{\Lambda}}\cos\theta^\star)$$

$$\boxed{P_{\Lambda\bar{\Lambda}} = 0.181 \pm 0.035_{stat} \pm 0.022_{syst}}$$



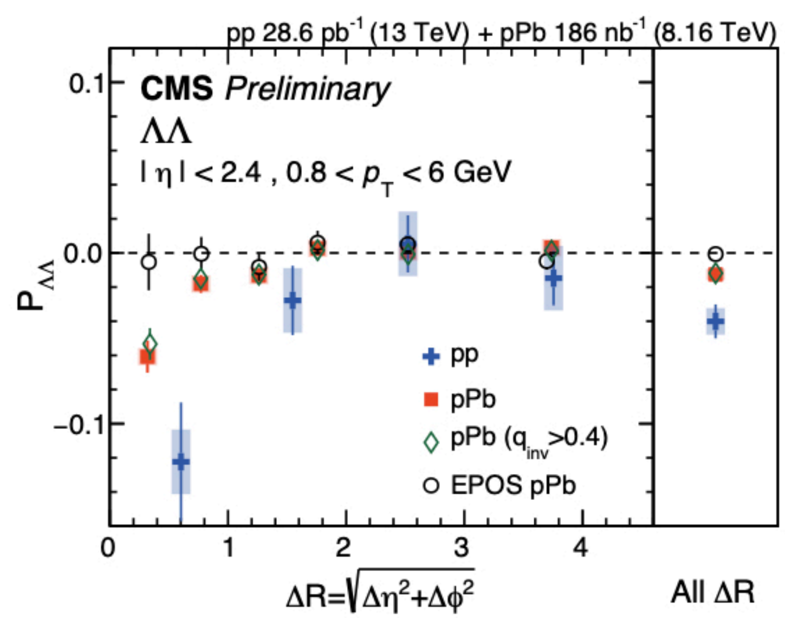


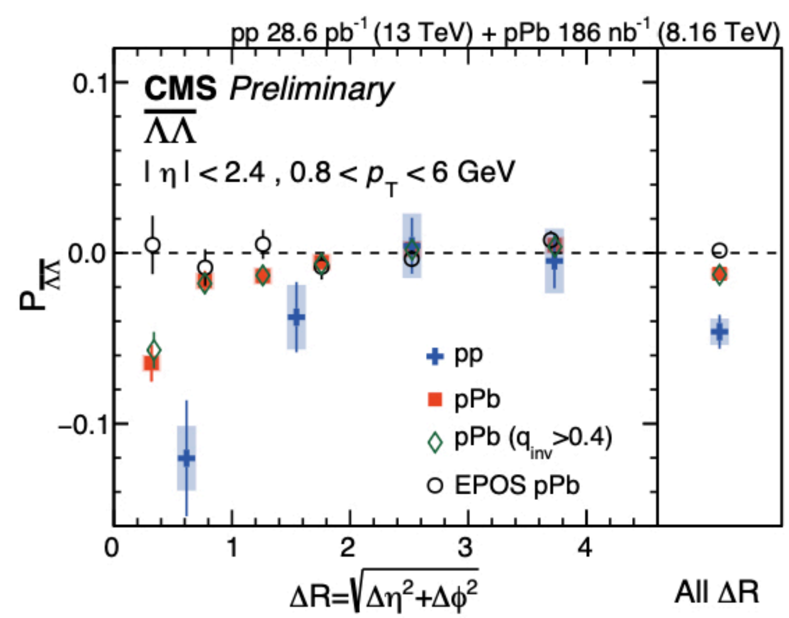
$\Lambda\bar{\Lambda}$ spin correlation: CMS



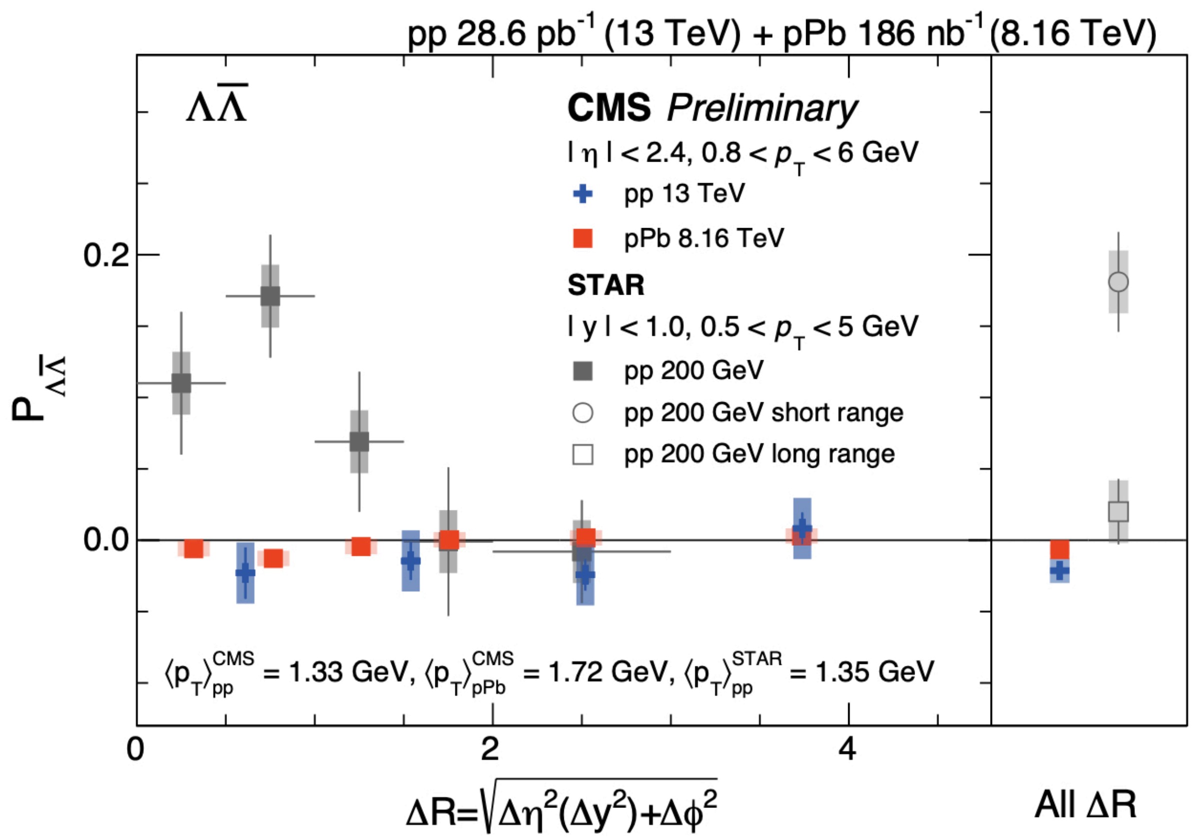
CMS-PAS-HIN-26-002 (2026)

BUT...





Space decoherence



J.Barata, et al., arXiv:2606.30737 (2026)

$$P_{\Lambda\bar{\Lambda}}(\Delta R) = P^0_{\Lambda\bar{\Lambda}} \times e^{(-2[\gamma-\xi(\Delta R)]t)}$$

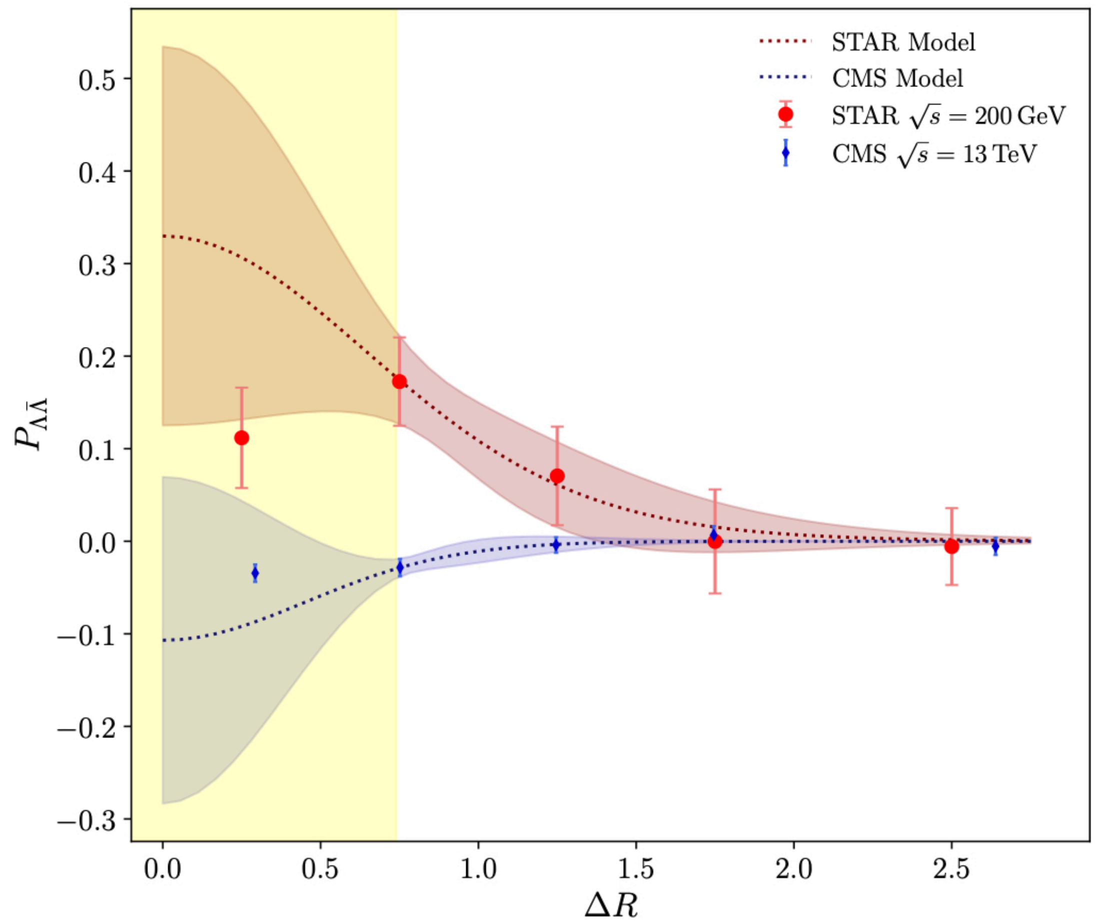
$$\xi(\Delta R) = \gamma \frac{\sin \Delta R}{\Delta R}$$

γ - local decoherence rate

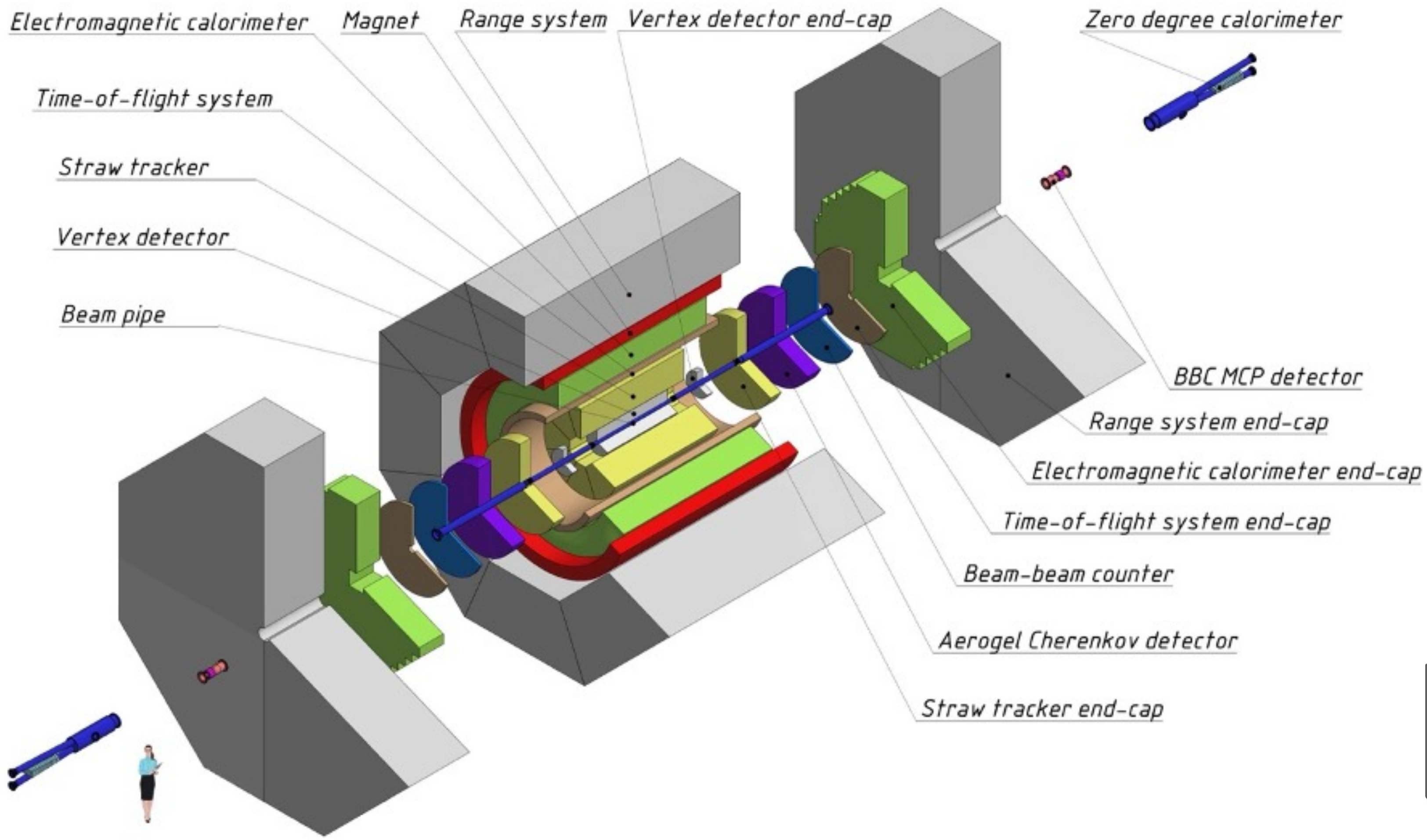
t - effective interaction time

E, TeV	γt	$P_{\Lambda\Lambda}(0)$
0.2	*3.5±2.7*	*0.33±0.21*
13	*7.2±8.6*	*-0.11±0.18*

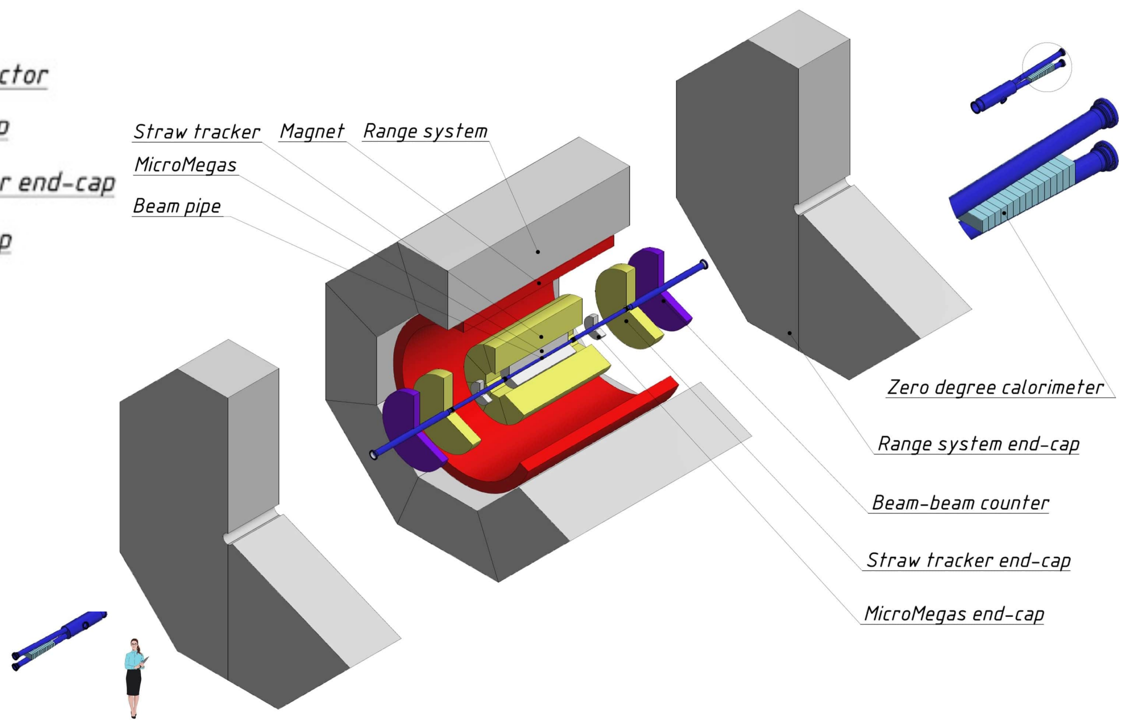
- decoherence
- ~~dephasing~~
- ~~amplitude damping~~

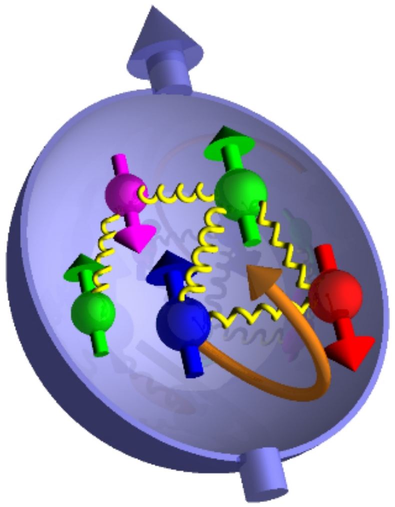


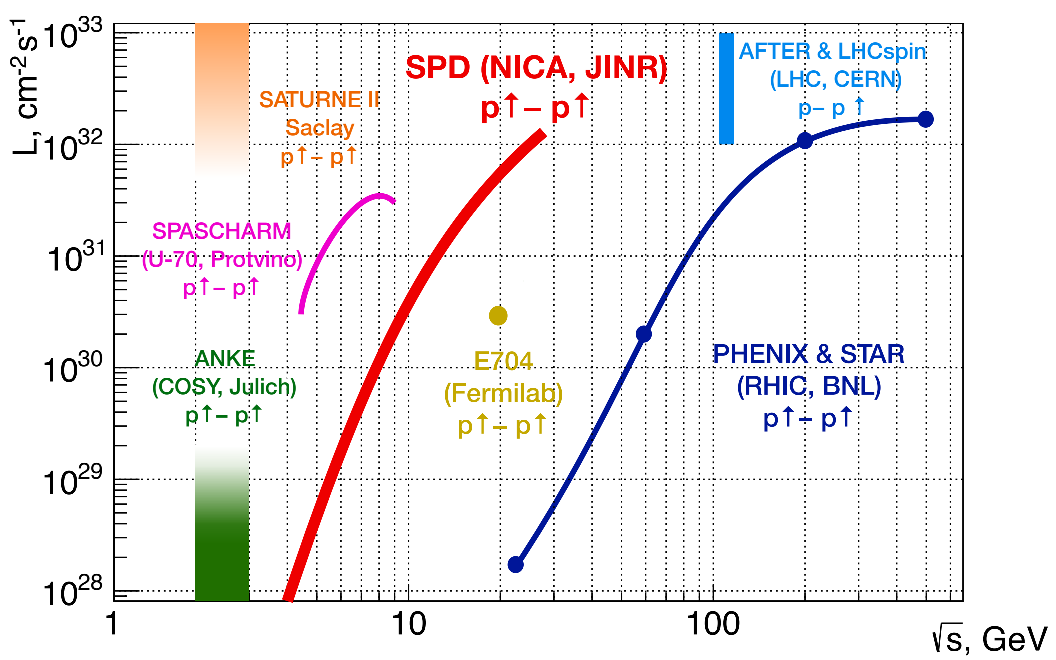
SPD at NICA



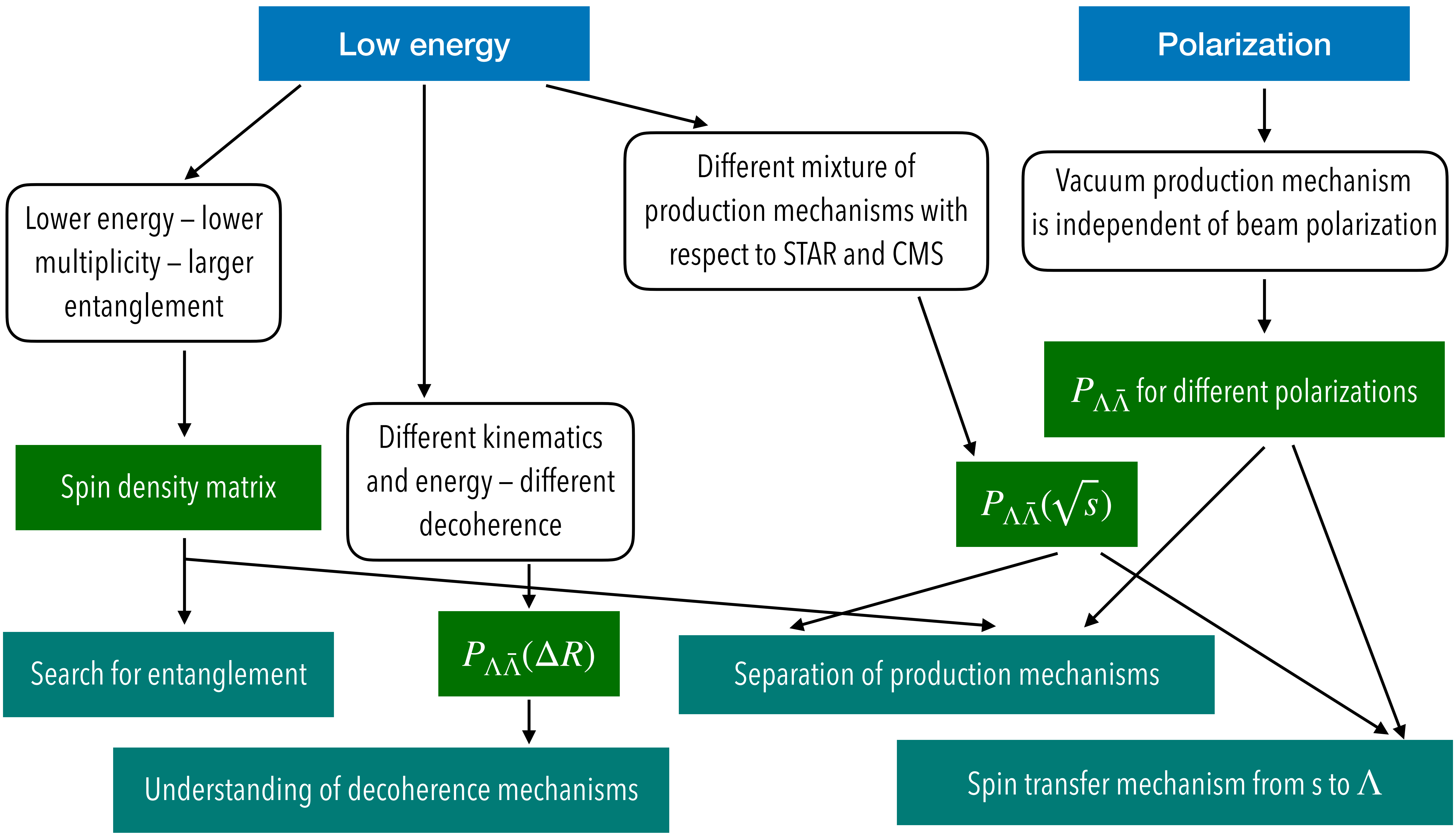
First stage:







How SPD can contribute?



Feed-down and direct production

Only less than 15% of $\Lambda\bar{\Lambda}$ pairs are produced directly ($P_{\Lambda\bar{\Lambda}} = 1/3$). Feed-down contribution smears correlation significantly:

$$\boxed{P_{\Lambda\bar{\Lambda}} = \frac{1}{3}\sum_{i,j} R_{ij}\, P^{i}_{\Lambda} P^{j}_{\bar{\Lambda}},}$$

$P^{i/j}_{\Lambda/\bar{\Lambda}}$

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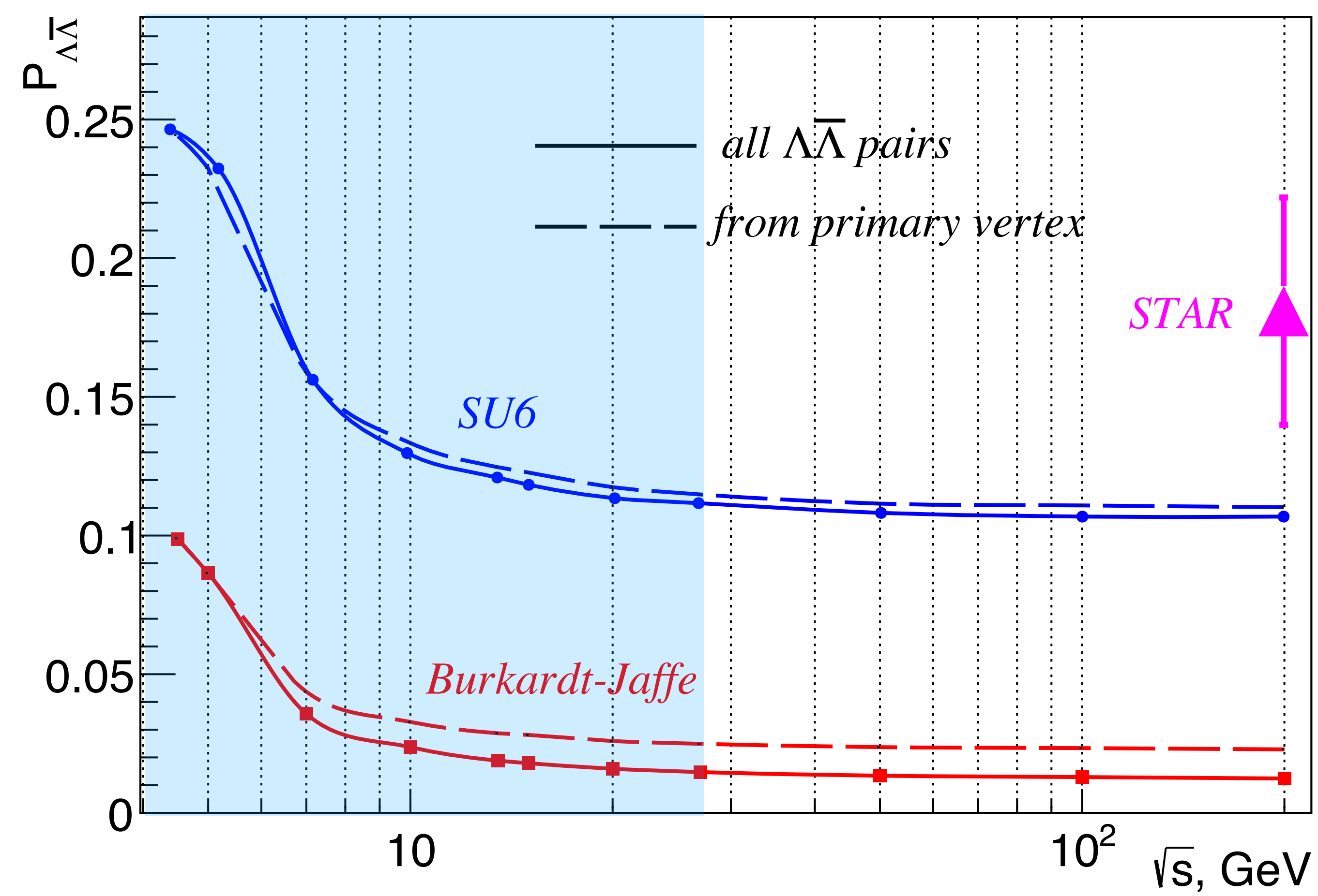
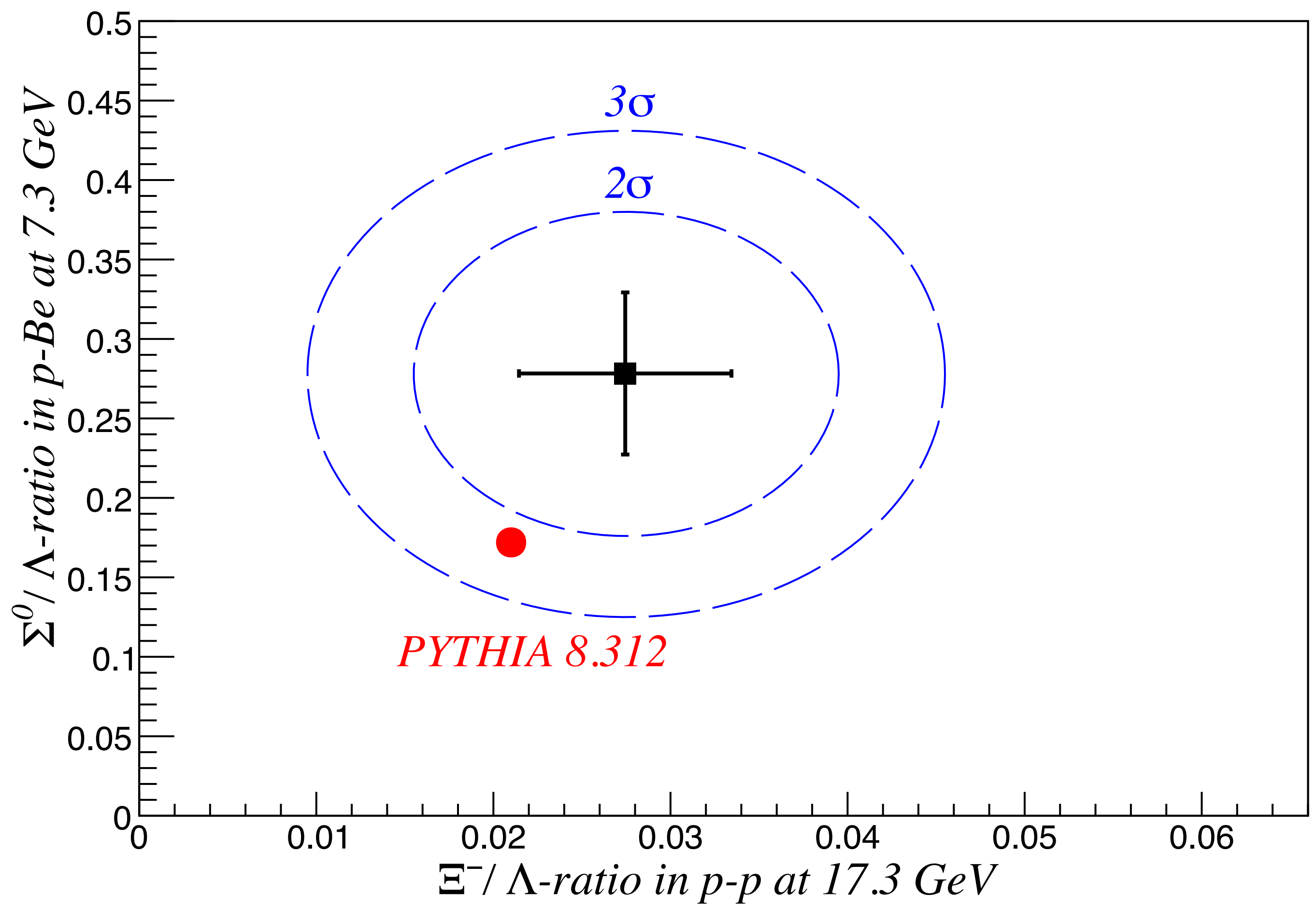
$R_{i,j}$

$\bar{\Lambda}$ \ Λ	*direct*	Σ^0	$\Xi^{0,-}$	Σ^*
direct	**0.140**	**0.078**	**0.029**	**0.069**
$\bar{\Sigma}^0$	**0.089**	**0.165**	**0.050**	**0.039**
$\bar{\Xi}^{0,+}$	**0.042**	**0.052**	**0.029**	**0.026**
$\bar{\Sigma}^*$	**0.051**	**0.028**	**0.018**	**0.094**



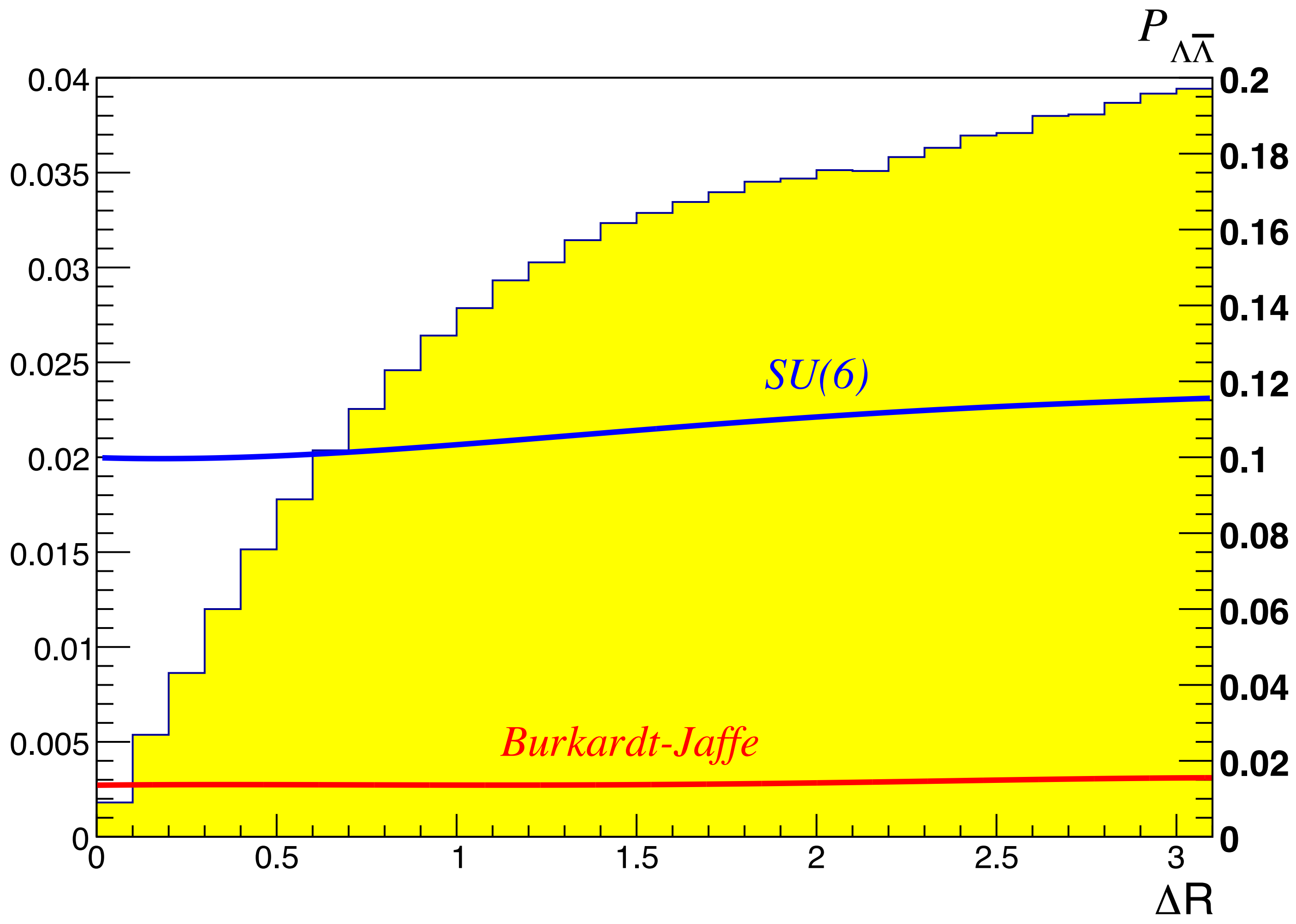
$\Lambda/\Sigma/\Xi$: Pythia8 consistency check

Ratio	$\sqrt{s}$, GeV	Measurement	PYTHIA 8.312
Ξ^-/Λ	17.3 (p-p)	0.028 ± 0.0060	0.021
Σ^0/Λ	7.3 (p-Be)	0.278 ± 0.051	0.171



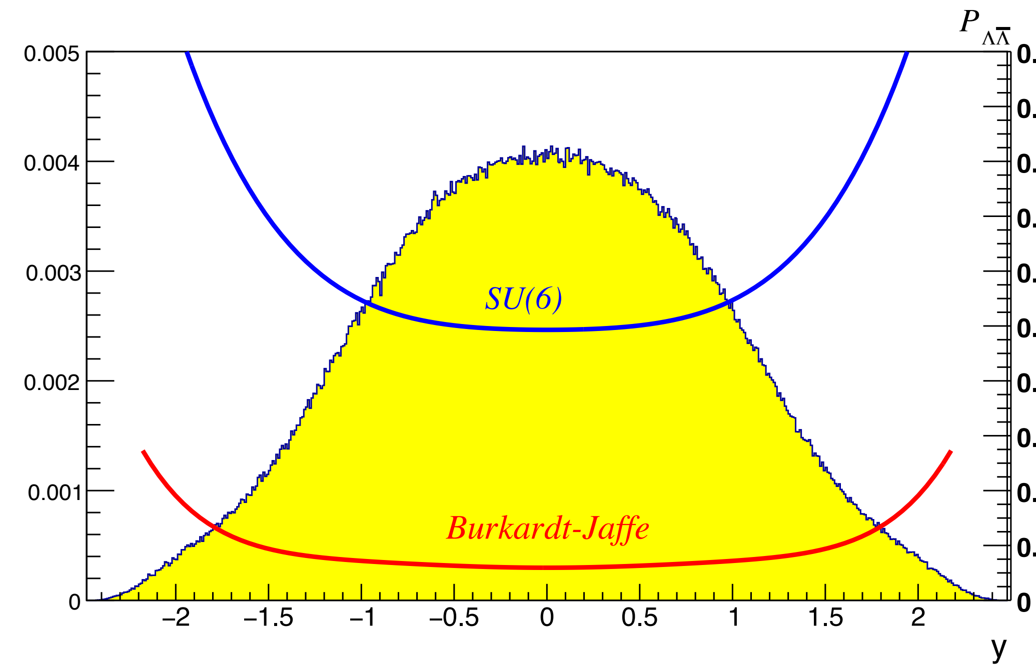
SPD: kinematics

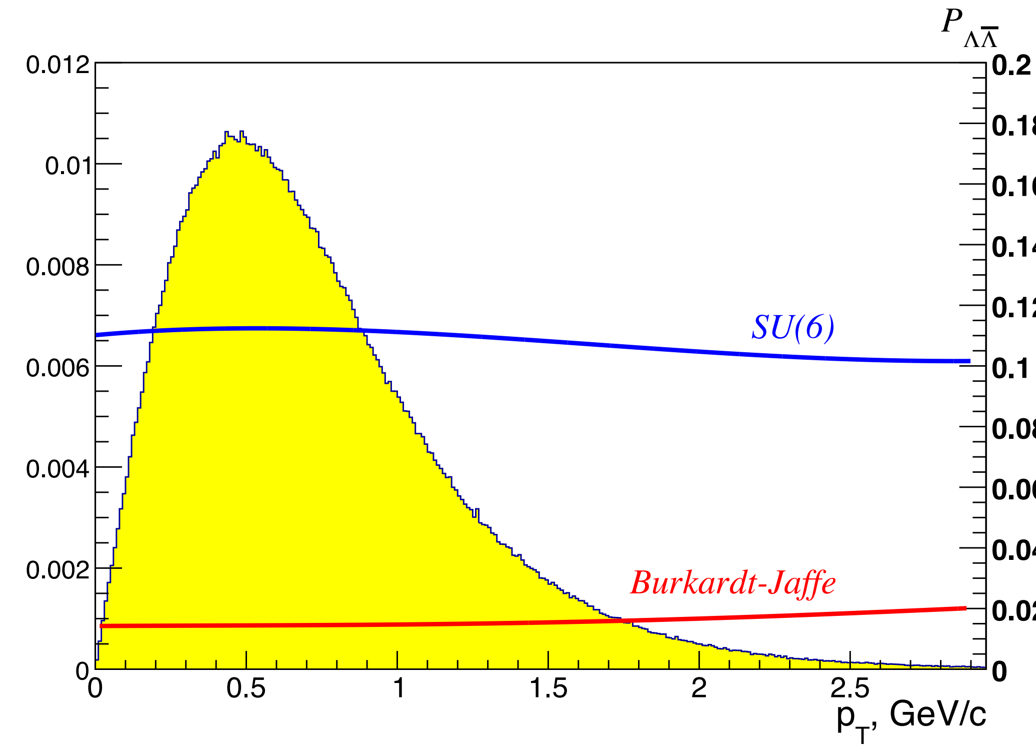
pp, $\sqrt{s} = 27$ GeV



$$\Delta R = \sqrt{\Delta\phi^2 + \Delta y^2}$$

For $\Lambda\bar{\Lambda}$ pairs





SPD: correlation vs entanglement

In unpolarized case and assuming diagonal C-matrix and rotational symmetry $C_{xx} = C_{yy} = C_T$: $P_{\Lambda\bar{\Lambda}} = \frac{1}{3}(C_{xx} + C_{yy} + C_{zz}) = \frac{1}{3}(2C_T + C_L)$

Peres-Horodecki entanglement criterion: $\lambda_i < 0$

$$\rho = \begin{pmatrix} \frac{1+C_L}{4} & 0 & 0 & 0 \\ 0 & \frac{1-C_L}{4} & \frac{3P_{\Lambda\bar{\Lambda}} - C_L}{4} & 0 \\ 0 & \frac{3P_{\Lambda\bar{\Lambda}} - C_L}{4} & \frac{1-C_L}{4} & 0 \\ 0 & 0 & 0 & \frac{1+C_L}{4} \end{pmatrix}$$

$$\lambda_1 = \frac{1 + 3P_{\Lambda\bar{\Lambda}}}{4},$$
$$\lambda_2 = \frac{1 + 2C_L - 3P_{\Lambda\bar{\Lambda}}}{4},$$
$$\lambda_3 = \lambda_4 = \frac{1 - C_L}{4}.$$

for $P_{\Lambda\bar{\Lambda}} > -\frac{1}{3}$

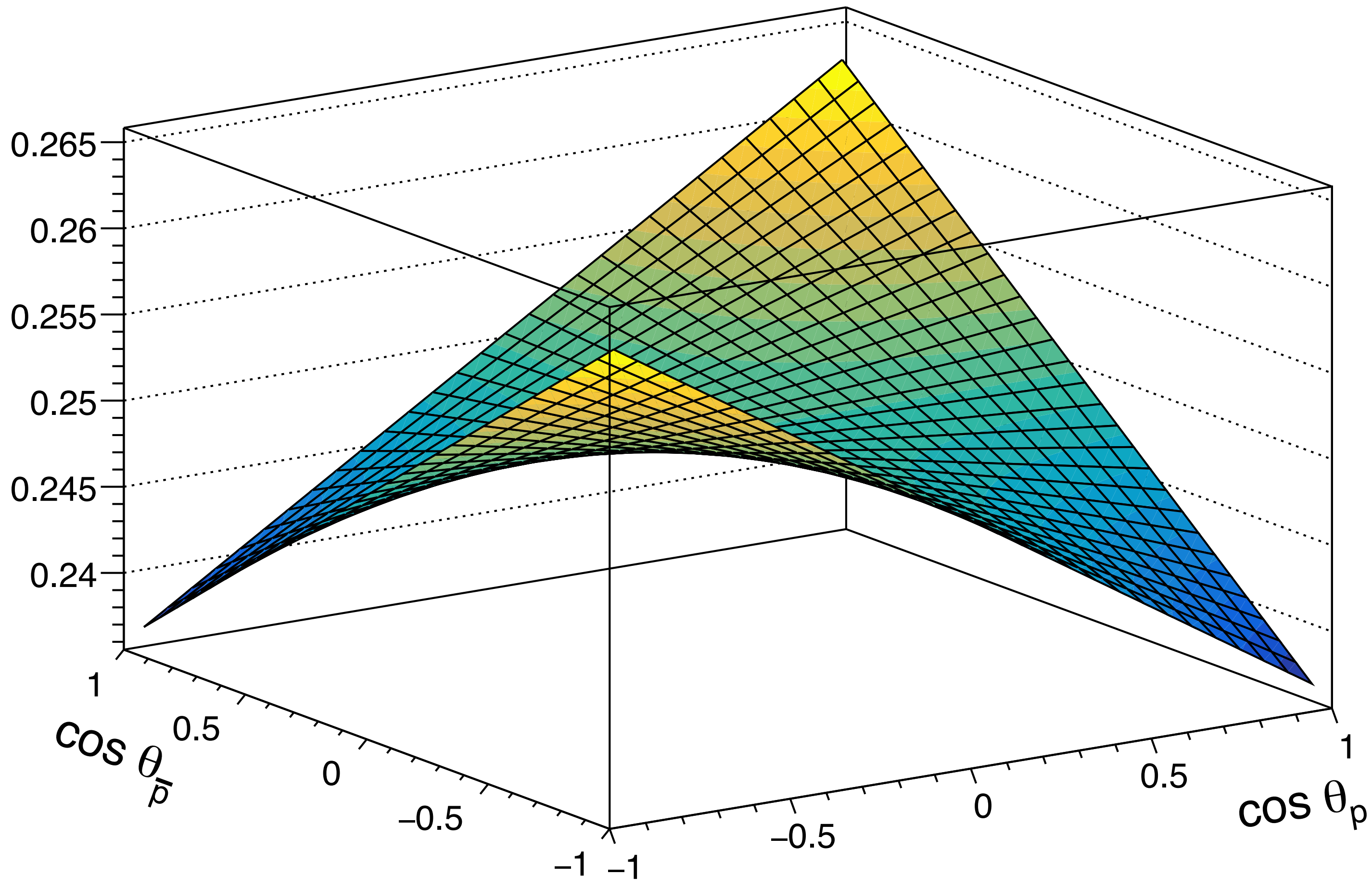
Assuming rotational symmetry For $P_{\Lambda\bar{\Lambda}} = 0.1$ hyperons are entangled if $C_L < -0.35$

$$\mathcal{N} = \max\left[0, \frac{3P_{\Lambda\bar{\Lambda}} - 1 - 2C_L}{4}\right]$$

For spherical symmetry for $P_{\Lambda\bar{\Lambda}} > -\frac{1}{3}$ $(P_{\Lambda\bar{\Lambda}} = C_{xx} = C_{yy} = C_{zz})$ entanglement is impossible

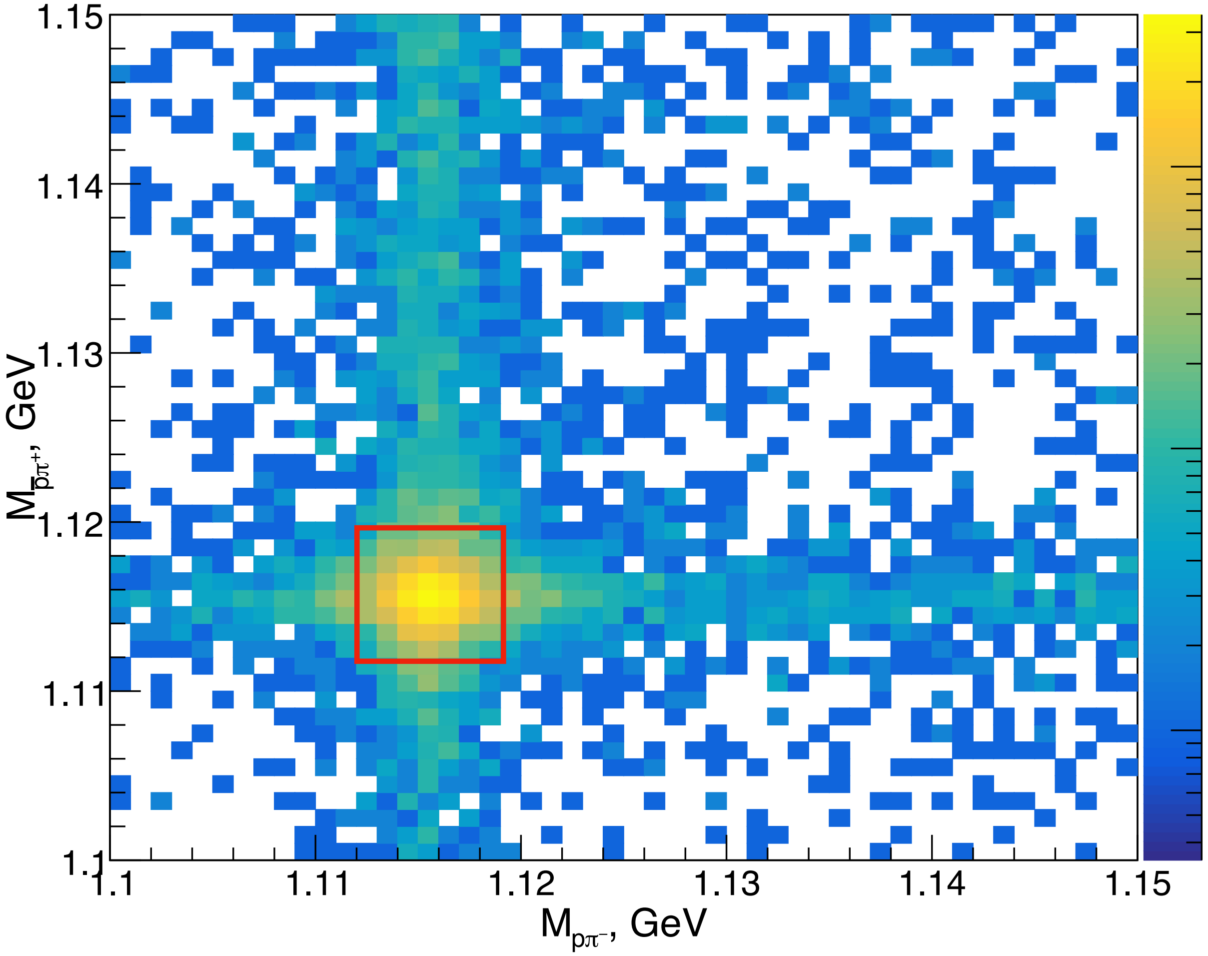
C_L measurement

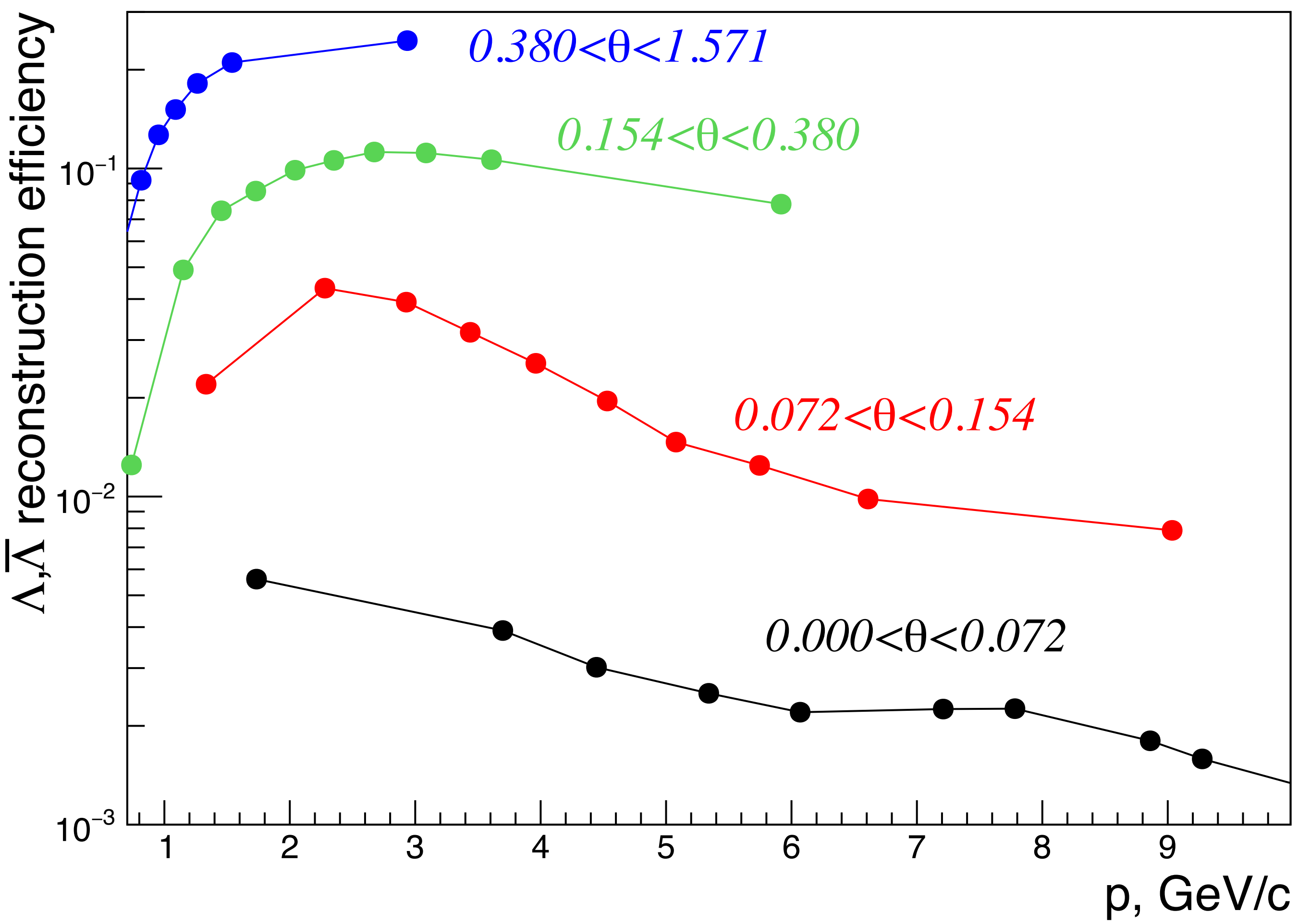
$$\frac{d^2N}{d(\cos\theta_p)\,d(\cos\theta_{\bar{p}})} = \frac{1}{4}\left[1 + \alpha_\Lambda \alpha_{\bar{\Lambda}} C_L\ \cos\theta_p \cos\theta_{\bar{p}}\right]$$



$$C_L = \frac{9}{\alpha_\Lambda \alpha_{\bar{\Lambda}}} \langle \cos\theta_p \cos\theta_{\bar{p}} \rangle$$

SPD: kinematics





Mass resolution ~1.6 MeV

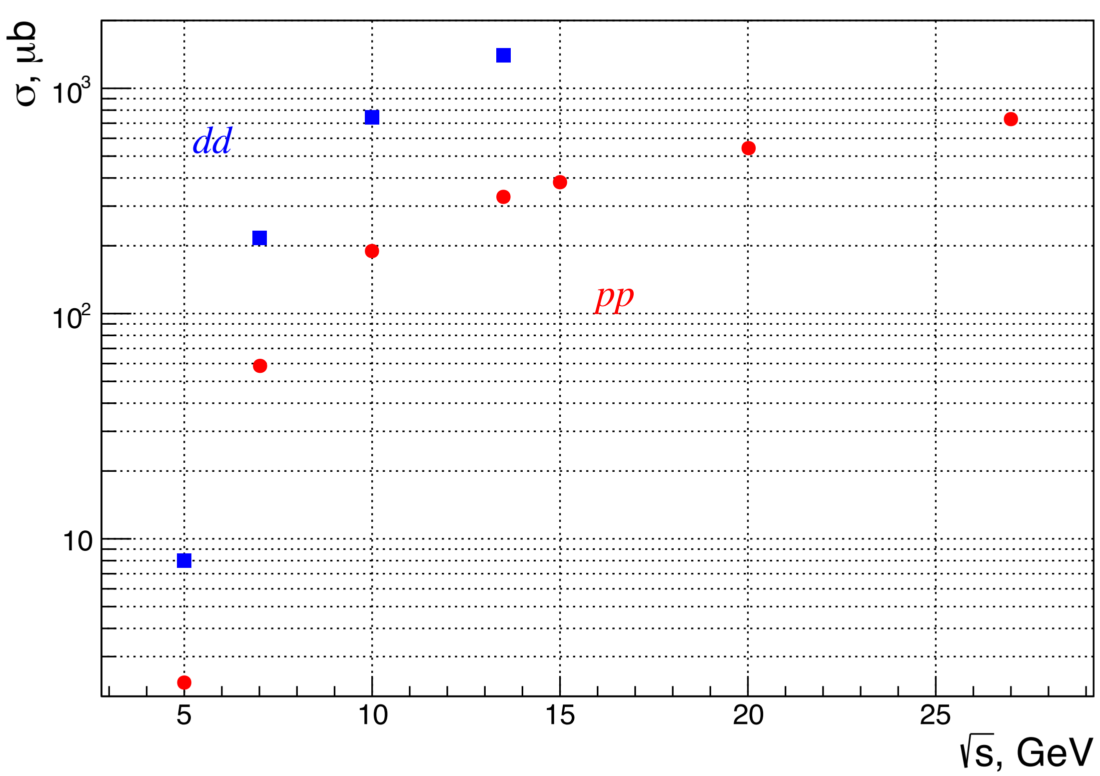
Signal fraction in the signal region ~0.8

$\Lambda\bar{\Lambda}$ reconstruction efficiency

Energy, GeV	full range	pT>0.5 |y|<1
27	1.5 %	5 %
10	0.4 %	1.8 %

SPD: expectations

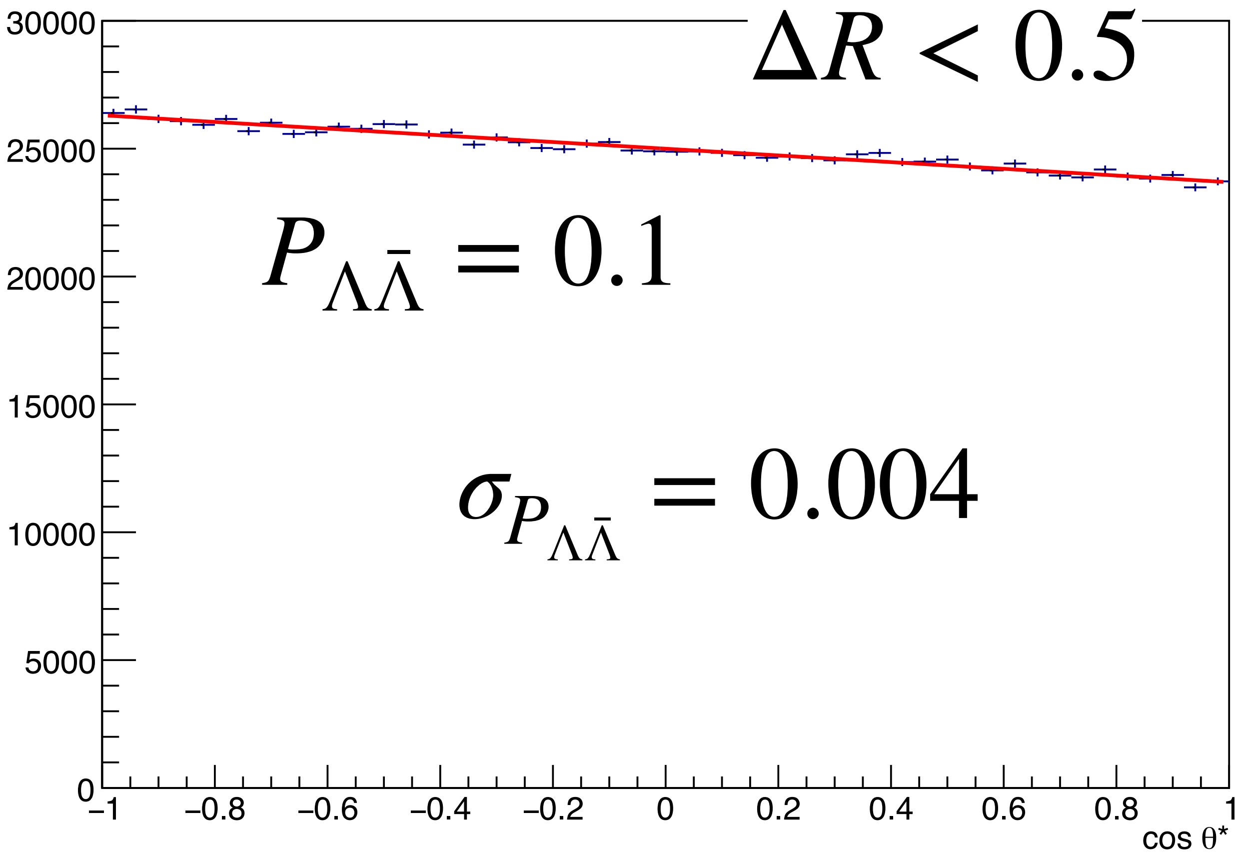
Pythia + Angantyr (Glauber + color reconnection for *dd*)

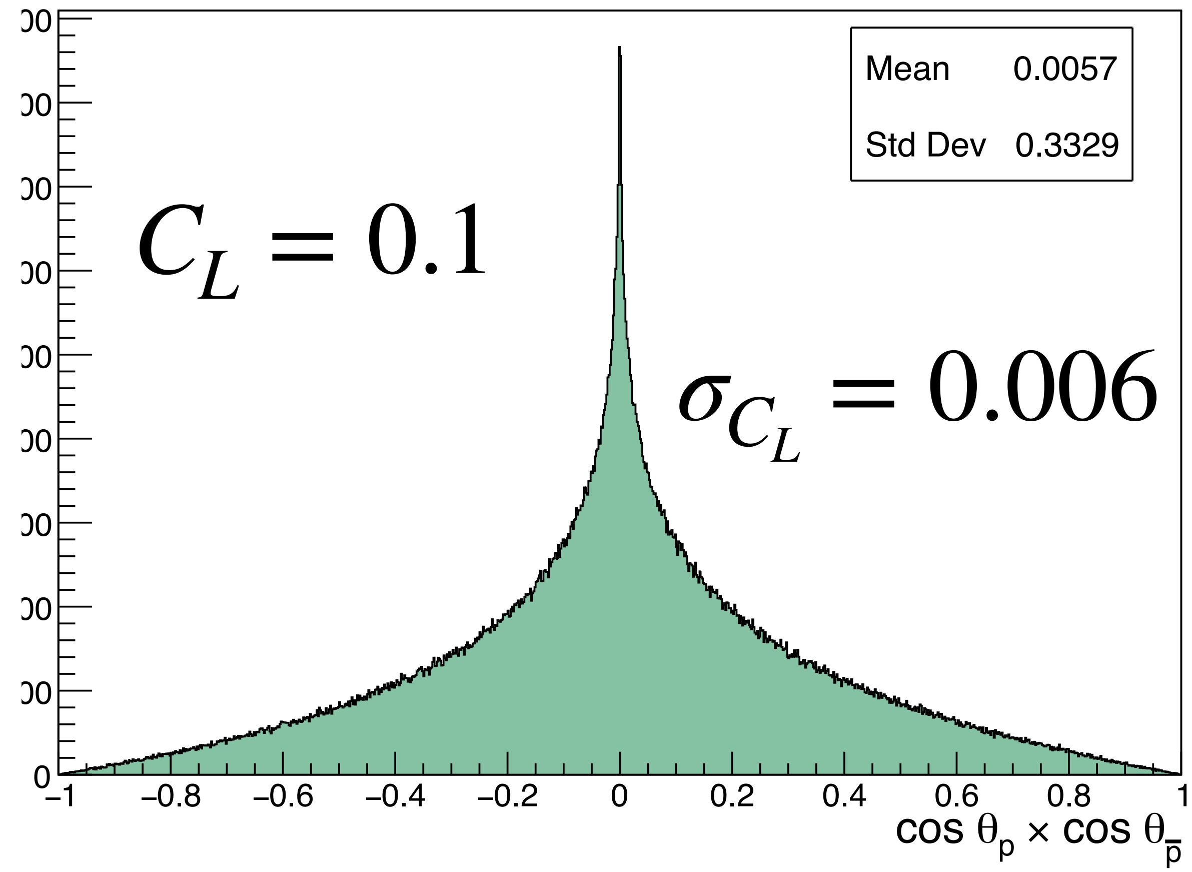


	27 GeV pp	10 GeV dd	27 GeV pp	10 GeV dd
Range	full		$p_T>0.5$, $\|y\|<1$	
σ, μb	730	1400	51	78
L, cm^{-1} s^{-1}	10^{32}	5×10^{30}	10^{32}	5×10^{30}
Efficiency, %	1.5	0.4	5.0	1.8
Offline filter efficiency, %	100			
Time	1 month			
Duty factor	0.7			
EVENTS, 10^6	**820**	**30**	**190**	$\boxed{\textbf{7.5}}$

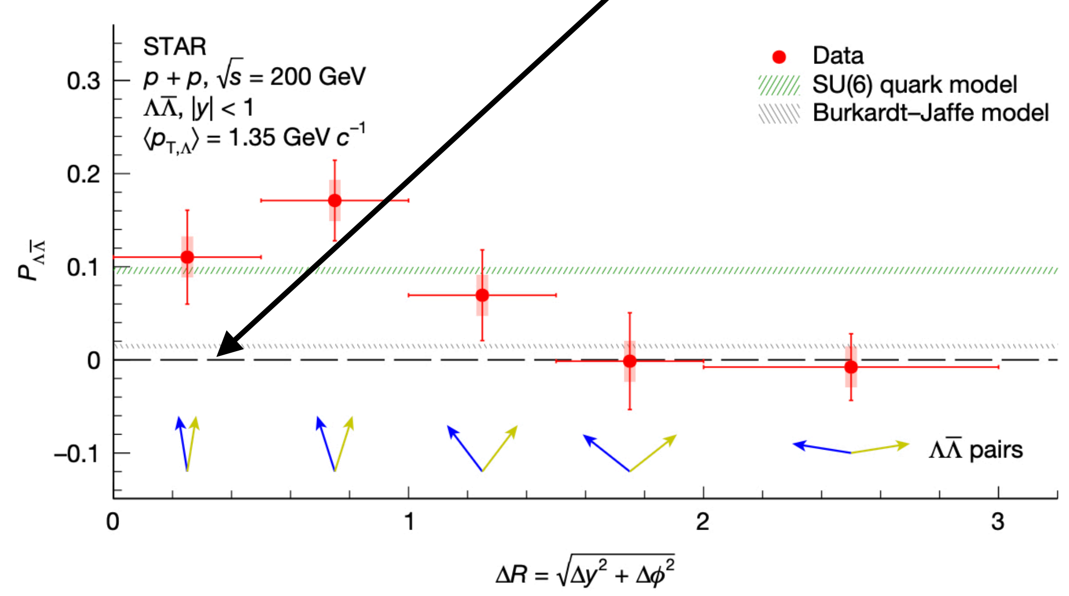
STAR: 0.13 M

SPD: accuracy





~1.2M events at $\Delta R < 0.5$ after 1 month of data taking with *dd* collisions at 10 GeV



Other low-energy experiments

NICA MPD: *Bi-Bi* at 11 GeV ($\sigma = 130$ mb) and 10^{27} cm^{-1} s^{-1} at similar experimental conditions one can expect about 1 M events per month — **nuclear effects**

SPASCHARM: π^--p with 26.5 GeV beam and p-p with 50 GeV beam ($\sqrt{s} = 7$ GeV and 9.7 GeV) ($\sigma = 90$ μb and 170 μb). In the pion case the $q\bar{q} \to s\bar{s}$ **production mechanism becomes important.**

but low efficiency with present DAQ

HIAF: Tiny cross section for p-p for 10 GeV beam ($\sigma = 4$ nb) but it could be much larger in p-A due to **near-threshold effects.**

Summary

- The SPD experiment has a good chance to measure $\Lambda\bar{\Lambda}$ spin-spin correlations in a new energy domain $\sqrt{s} \leq 27$ GeV , below the STAR and CMS ranges.
- Studies of $P_{\Lambda\bar{\Lambda}}$ correlation in wide energy range (together with STAR and CMS results) and involving polarized beams could separate different production mechanisms and probe the transfer of spin from the s-quark to the final-state Λ-hyperon.
- Measurement of $P_{\Lambda\bar{\Lambda}}(\Delta R)$ and multiplicity dependence will probe the mechanisms of spin decoherence during hadronization due to angular separation and the hadronic environment.
- Low multiplicities at NICA provide a favorable regime for searching for and measurement of quantum entanglement in the $\Lambda\bar{\Lambda}$ system; measuring $P_{\Lambda\bar{\Lambda}}$ together with C_L enables an entanglement test under transverse rotational invariance for the unpolarized case, while the general polarized case requires reconstruction of the full spin density matrix.
- SPD provides a high reconstruction efficiency for $\Lambda\bar{\Lambda}$ pairs and is capable of accumulating a sizeable sample of such pairs for analysis over a short period of time already at the first stage of the experiment.

Thank you!