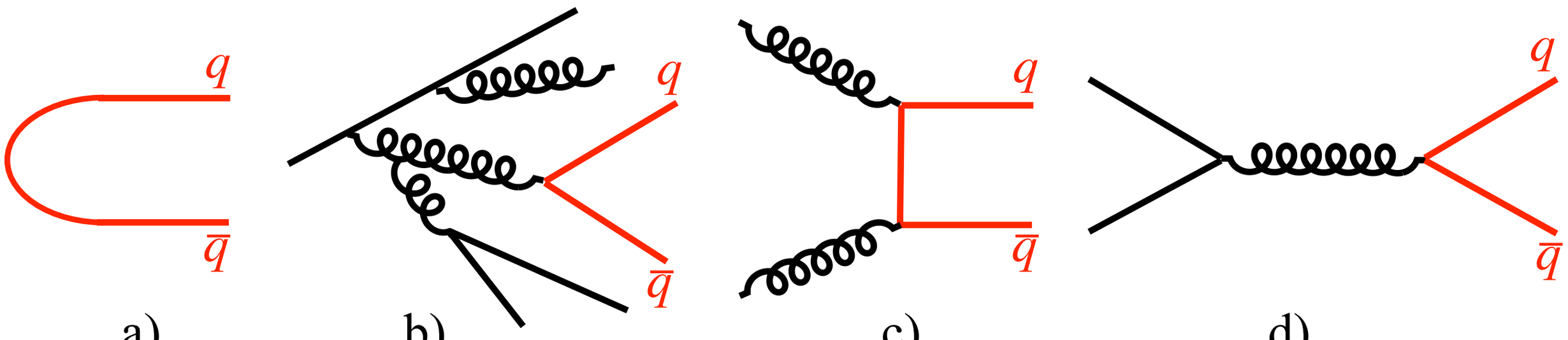
Spin-spin correlations in $\Lambda\bar{\Lambda}$ production at SPD

Guskov Alexey

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



a) materialization from the QCD vacuum condensate

b) gluon splitting in the parton shower evolution

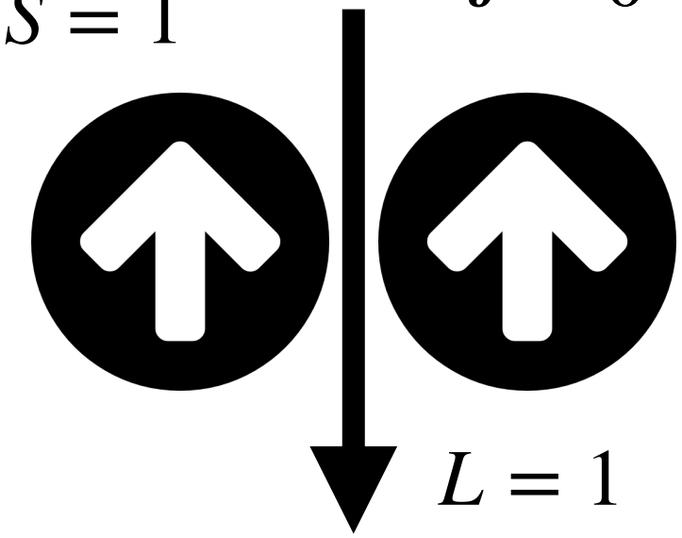
c , d) production in hard interaction

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:

$S = 1$ $J = 0$ $L = 1$



QCD vacuum

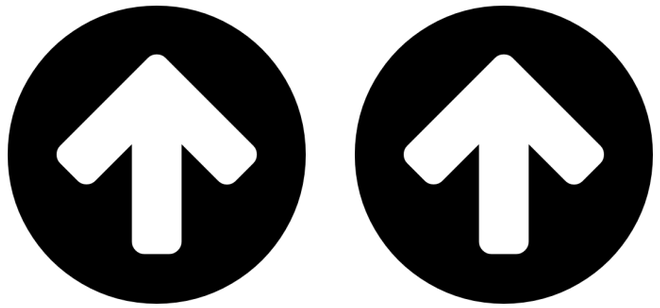
mainly $J^{PC} = 0^{++}$

C – spin correlation matrix

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

P = 1/3 for triplets

$S = 1$ $J = 1$ $L = 0$



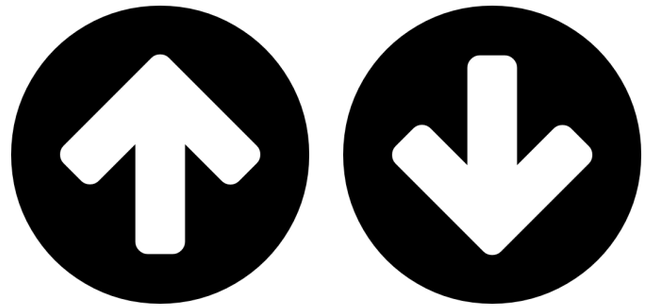
Gluon splitting

$m_q \to 0$

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

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

$S = 0$ $J = 0$ $L = 0$



$gg \to Q\bar{Q}$

near threshold

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

P = −1 for singlets

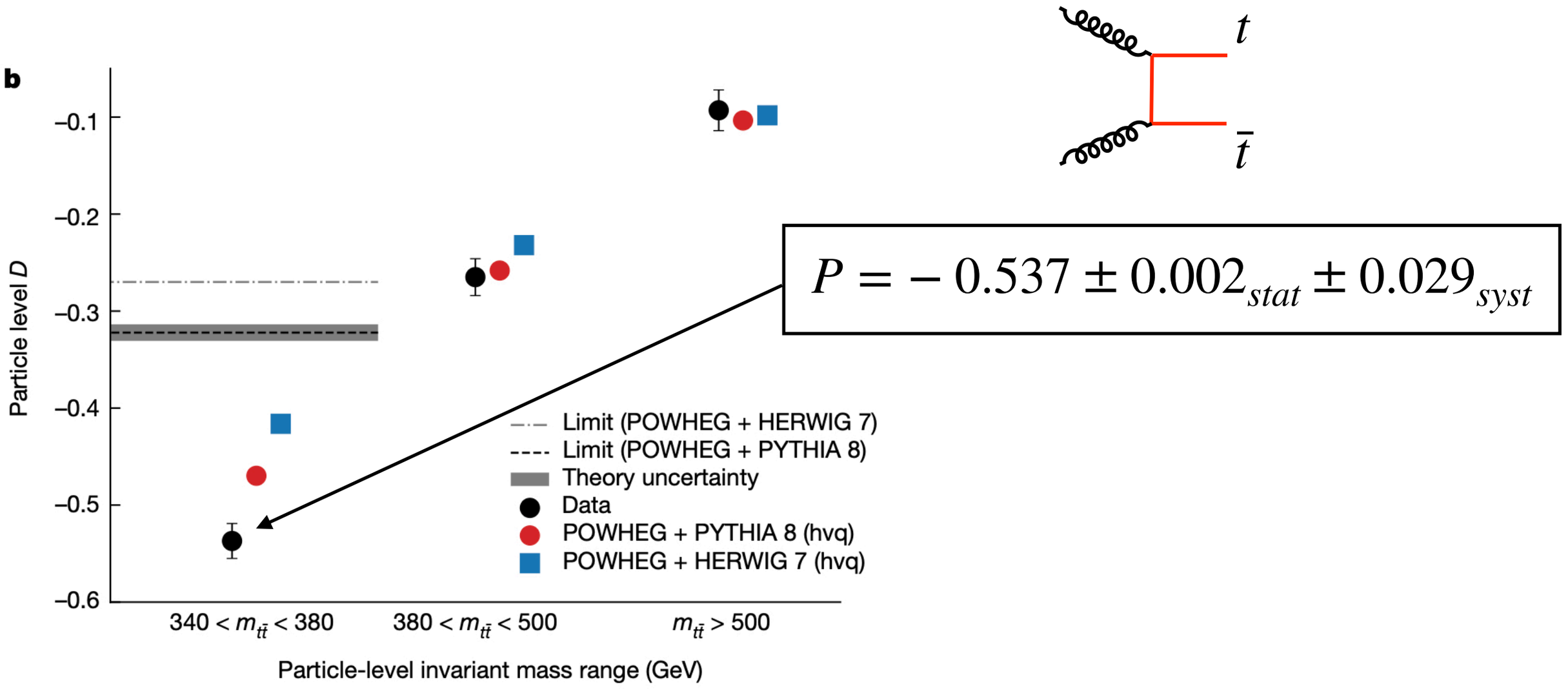
Article

Observation of quantum entanglement with top quarks at the ATLAS detector

https://doi.org/10.1038/s41586-024-07824-z

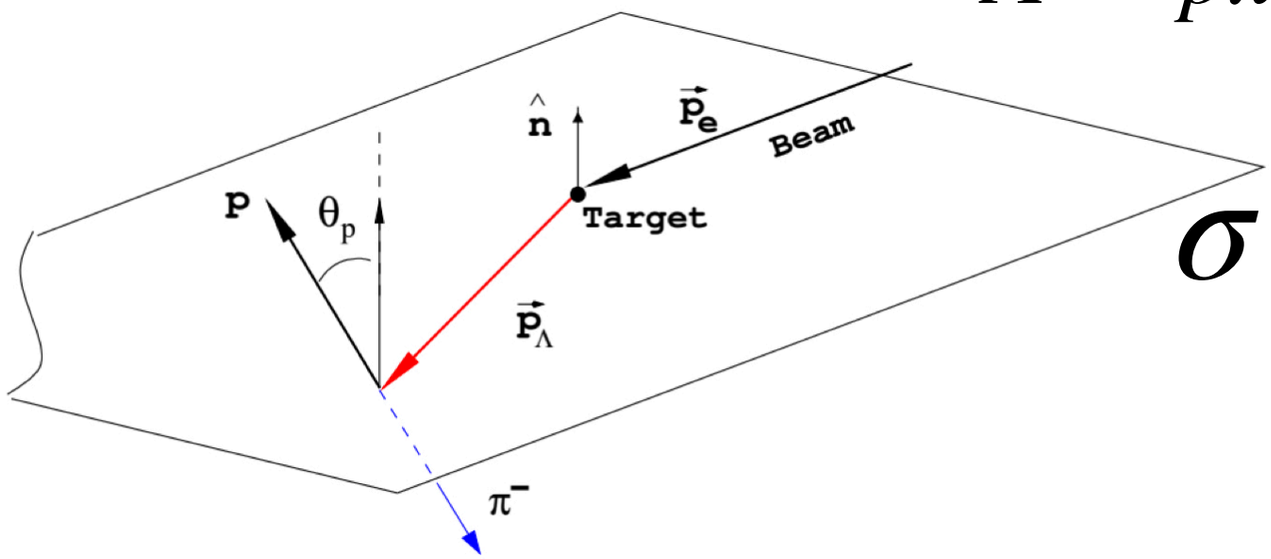
Received: 14 November 2023

The ATLAS Collaboration*✉



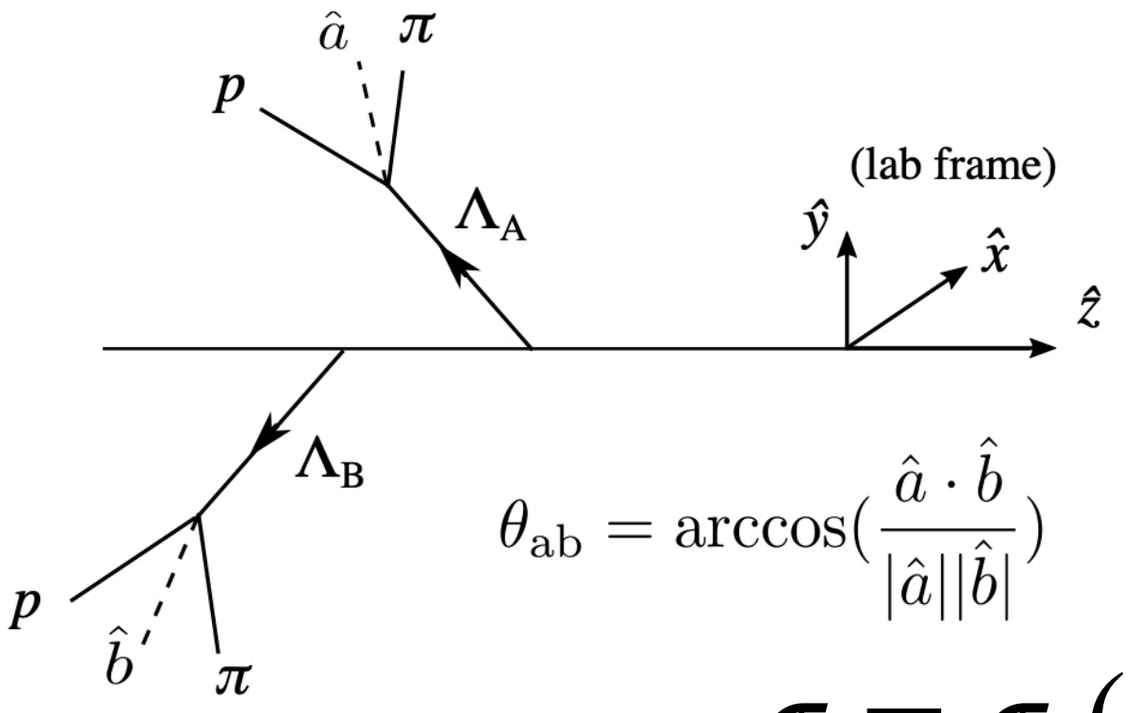
$\Lambda\bar{\Lambda}$ *pairs as a probe*

$\Lambda \to p\pi$ is a self-analyzing decay



$$\sigma \sim 1 + \alpha_0 P_\Lambda \cos\theta_p$$

$$\alpha \approx 0.75$$



$$\theta_{\rm ab} = \arccos\left(\frac{\hat{a}\cdot\hat{b}}{|\hat{a}||\hat{b}|}\right)$$

$$\sigma = \sigma_0(1 + \alpha_\Lambda \alpha_{\bar{\Lambda}} P_{\Lambda\bar{\Lambda}} \cos\theta_{ab})$$

From s-quark to Λ

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	-

Correlation and entanglement

Correlation ≠ Entanglement

$\psi = |\uparrow\rangle_1 \otimes |\downarrow\rangle_2$ — *correlation*

predetermination (local realism)

$\psi = \frac{1}{\sqrt{2}}\left(|\uparrow\rangle_1 \otimes |\downarrow\rangle_2 + |\downarrow\rangle_1 \otimes |\uparrow\rangle_2\right)$ — entanglement

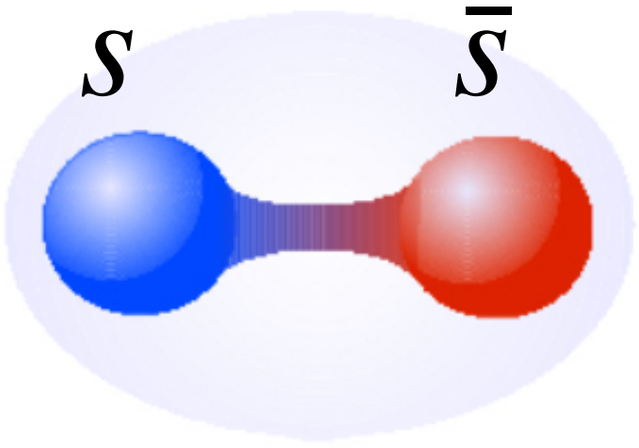
particle properties are not predetermined, but arise upon measurement, with the state of one particle instantly fixing the state of the other, independently of their separation (nonlocality)

Full reconstruction of spin density matrix (4x4) is needed to determine the entanglement. But numerous **sufficient criteria** do exist:

Entanglement is demonstrated if $P < -1/3$, (Peres–Horodecki criterion)

Triplet: correlation ***Singlet: 100% entanglement***

Entanglement and hadronization



Measurement of Bell-type inequalities and quantum entanglement from Λ-hyperon spin correlations at high energy colliders

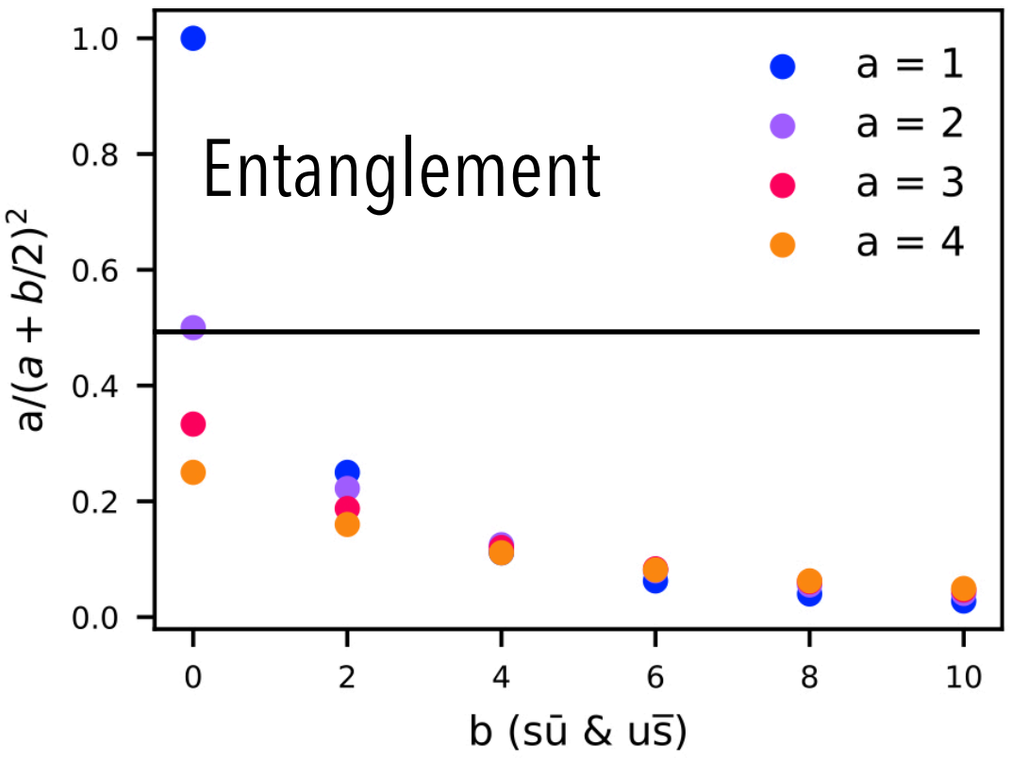
Wenjie Gong,[1,*] Ganesh Parida,[2,†] Zhoudunming Tu,[3,4,‡] and Raju Venugopalan[3,§]

[1] *Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*
[2] *Department of Physics, University of Wisconsin-Madison, Madison, Wisconsin 53706, USA*
[3] *Department of Physics, Brookhaven National Laboratory, Upton, New York 11973, USA*
[4] *Center for Frontiers in Nuclear Science, Stony Brook, New York 11794, USA*

(Dated: August 10, 2022)

Two flavor spin chain model

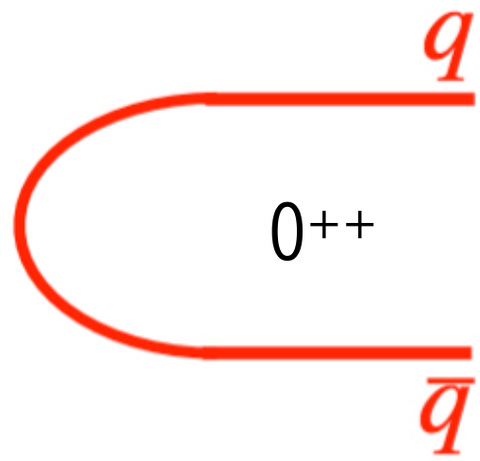
String hadronization into **a** $s\bar{s}$ and **b** $s\bar{u}$, $u\bar{s}$ singlets



$$1 - \frac{a}{(a+b/2)^2}\cos(\theta_2 - \theta_1)$$

Article

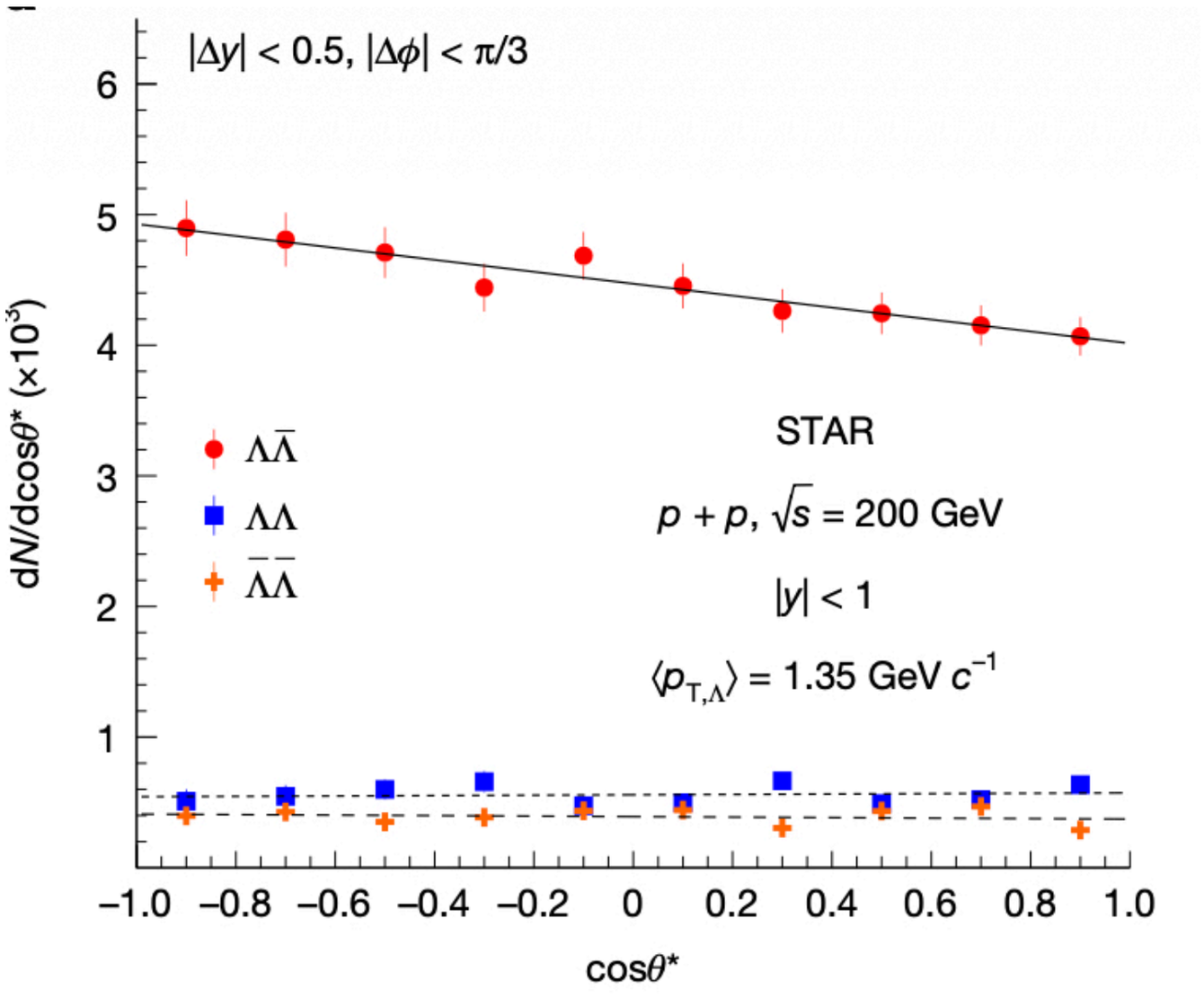
Measuring spin correlation between quarks during QCD confinement



https://doi.org/10.1038/s41586-025-09920-0

Received: 5 June 2025

STAR Collaboration*



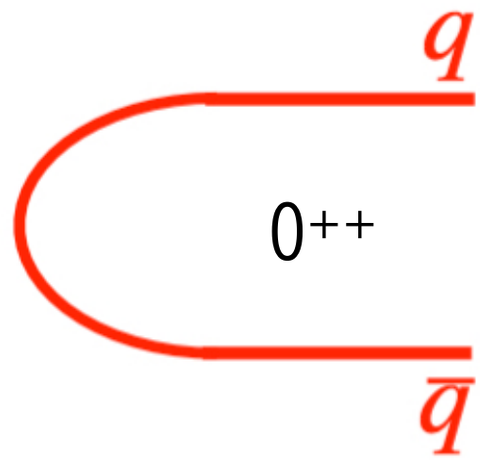
130k $\Lambda-$pairs

$0.5\ GeV/c < p_T < 5.0\ GeV/c$

$|y| < 1$

Article

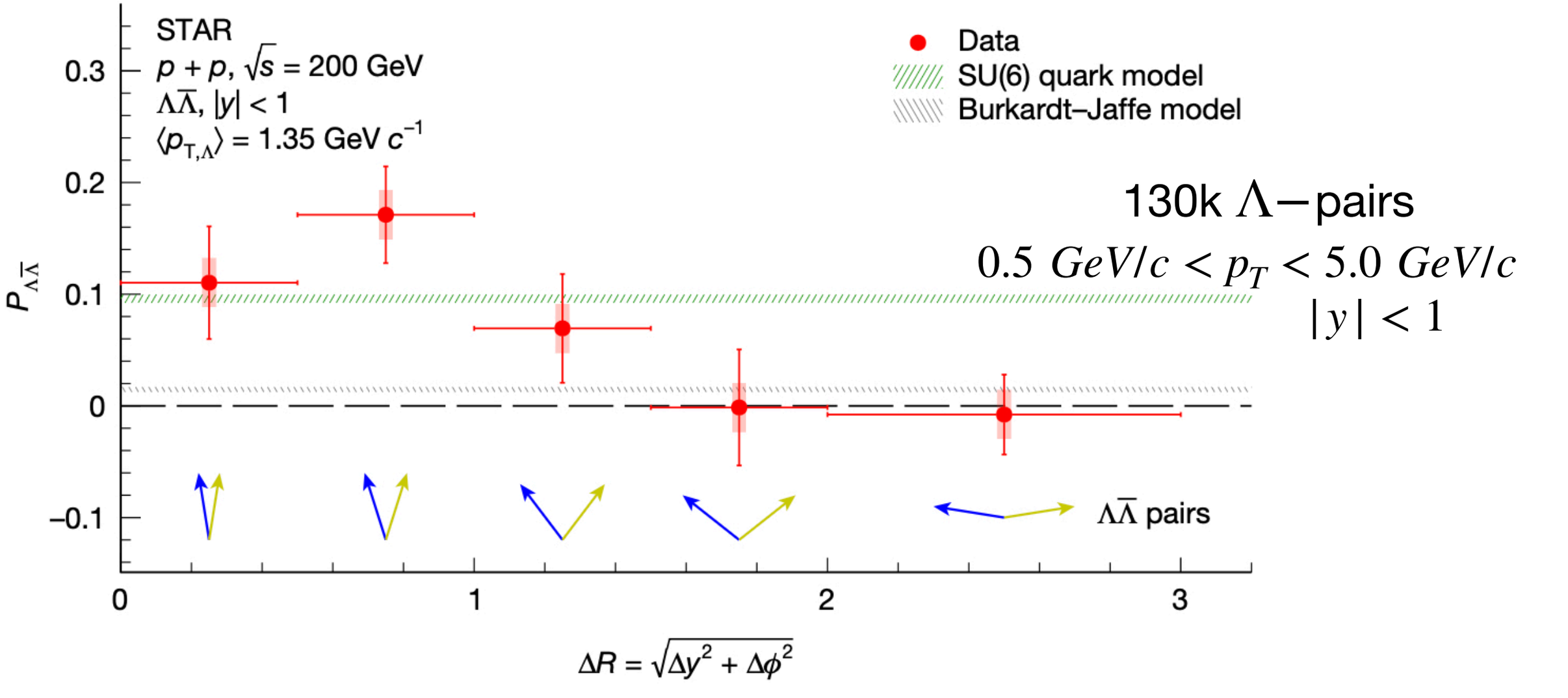
Measuring spin correlation between quarks during QCD confinement



https://doi.org/10.1038/s41586-025-09920-0

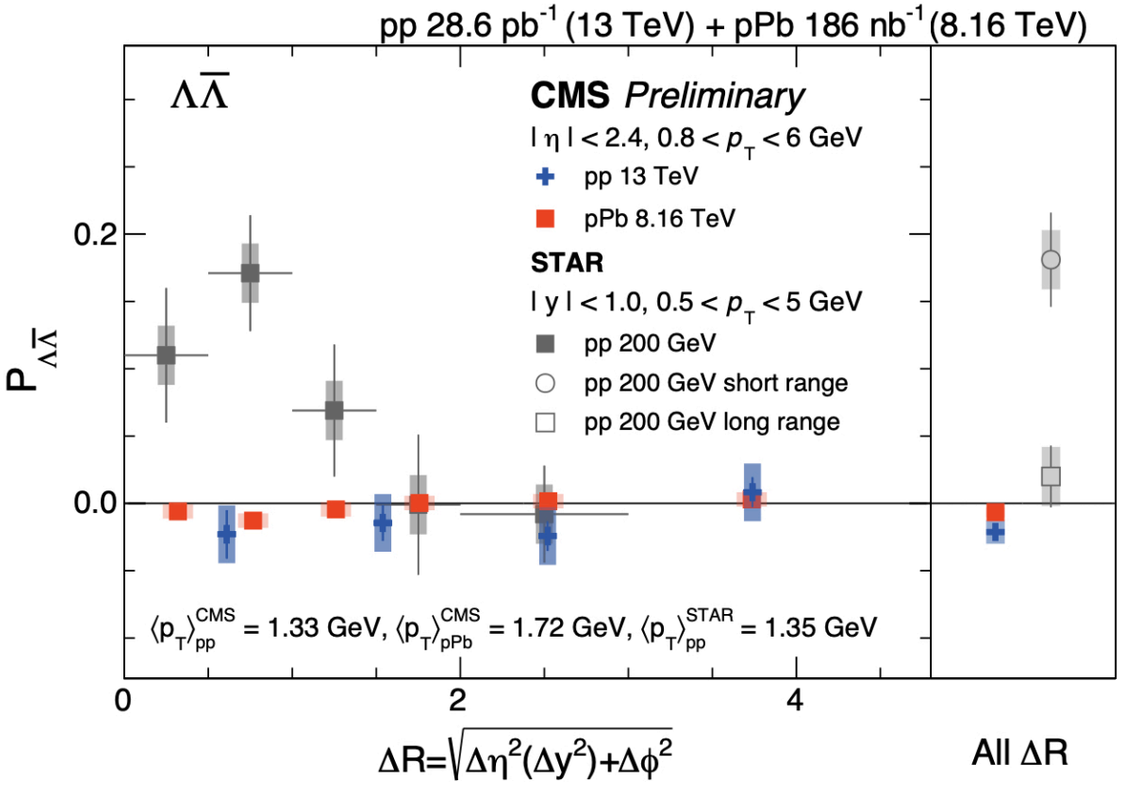
Received: 5 June 2025

STAR Collaboration*



Further development

CMS: pp at 13 TeV



E, GeV	γt	$P_{\Lambda\Lambda}(0)$
200	3.5±2.7	0.33±0.21
13000	7.2±8.6	-0.11±0.18

$\Lambda\bar{\Lambda}$ spin correlations in high-energy collisions from quantum channels: an open quantum system view of hadronization

João Barata,[1,*] Iván Cuntín,[1,2,†] Enrique Rico,[1,3,4,5,‡] and Bin Wu[2,§]

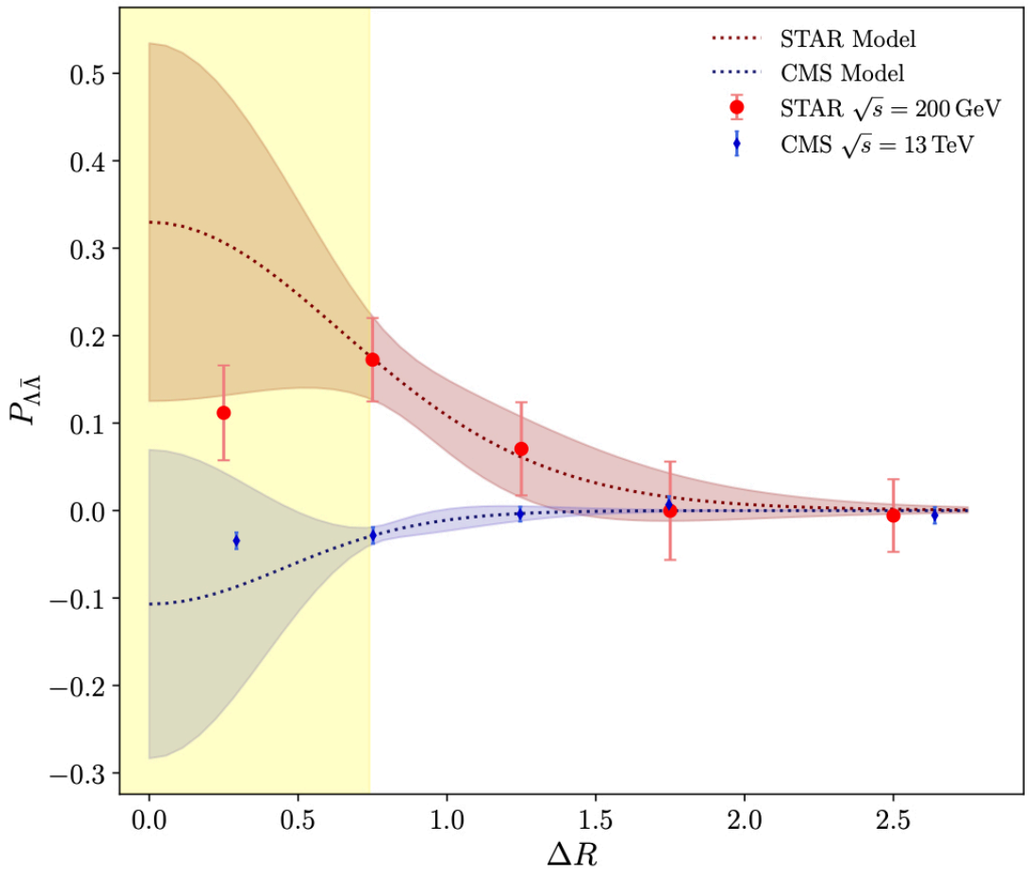
[1] *CERN, Theoretical Physics Department, CH-1211, Geneva 23, Switzerland*
[2] *Instituto Galego de Física de Altas Enerxías, Universidade de Santiago de Compostela, Santiago de Compostela 15782, Spain*
[3] *EHU Quantum Center and Department of Physical Chemistry, University of the Basque Country UPV/EHU, P.O. Box 644, 48080 Bilbao, Spain*
[4] *DIPC - Donostia International Physics Center, Paseo Manuel de Lardizabal 4, 20018 San Sebastián, Spain*
[5] *IKERBASQUE, Basque Foundation for Science, Plaza Euskadi 5, 48009 Bilbao, Spain*

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

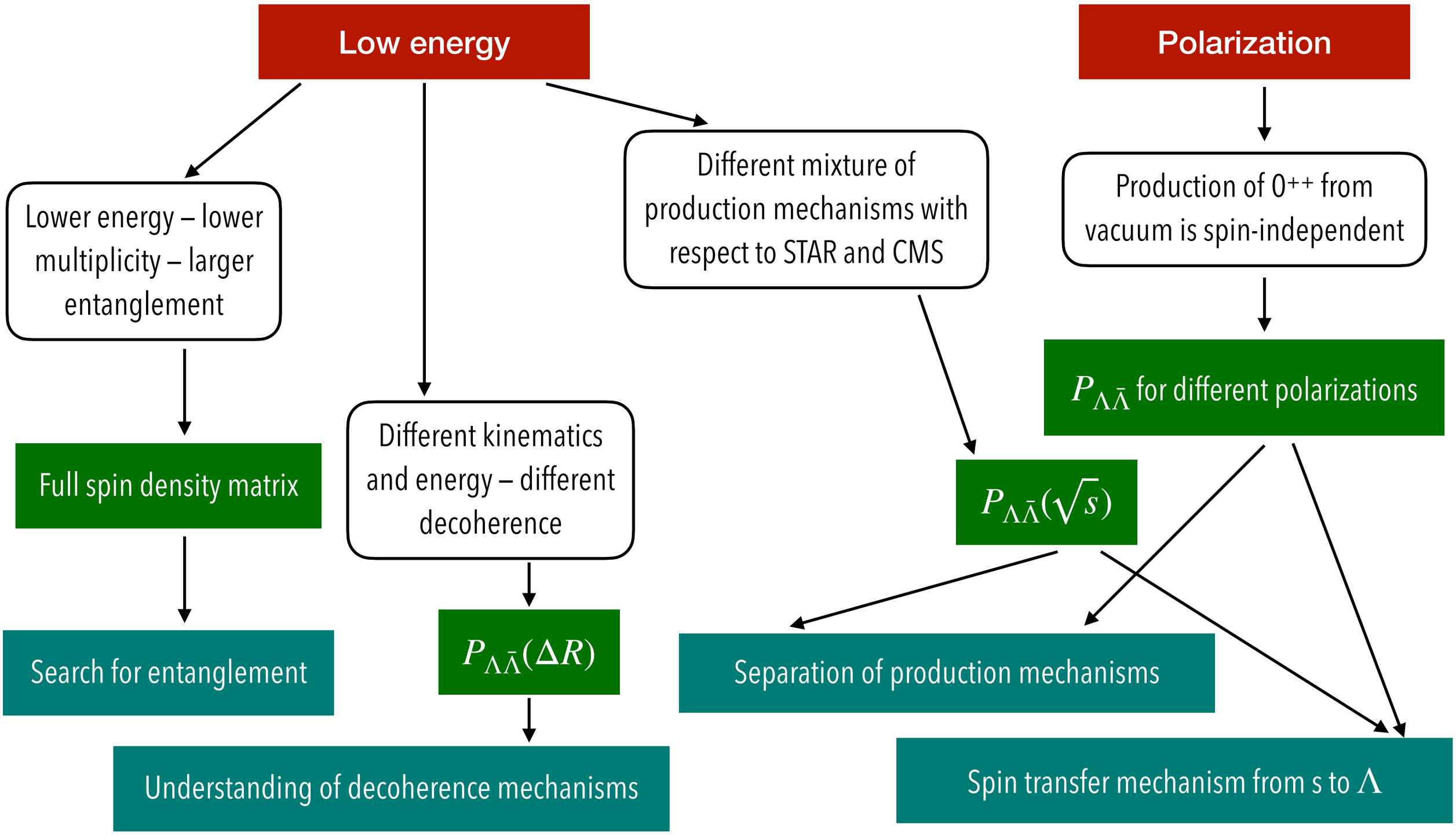
$$\xi(\Delta R) = \gamma \frac{\sin \Delta R}{\Delta R}$$

γ - local decoherence rate

t - effective interaction time



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:

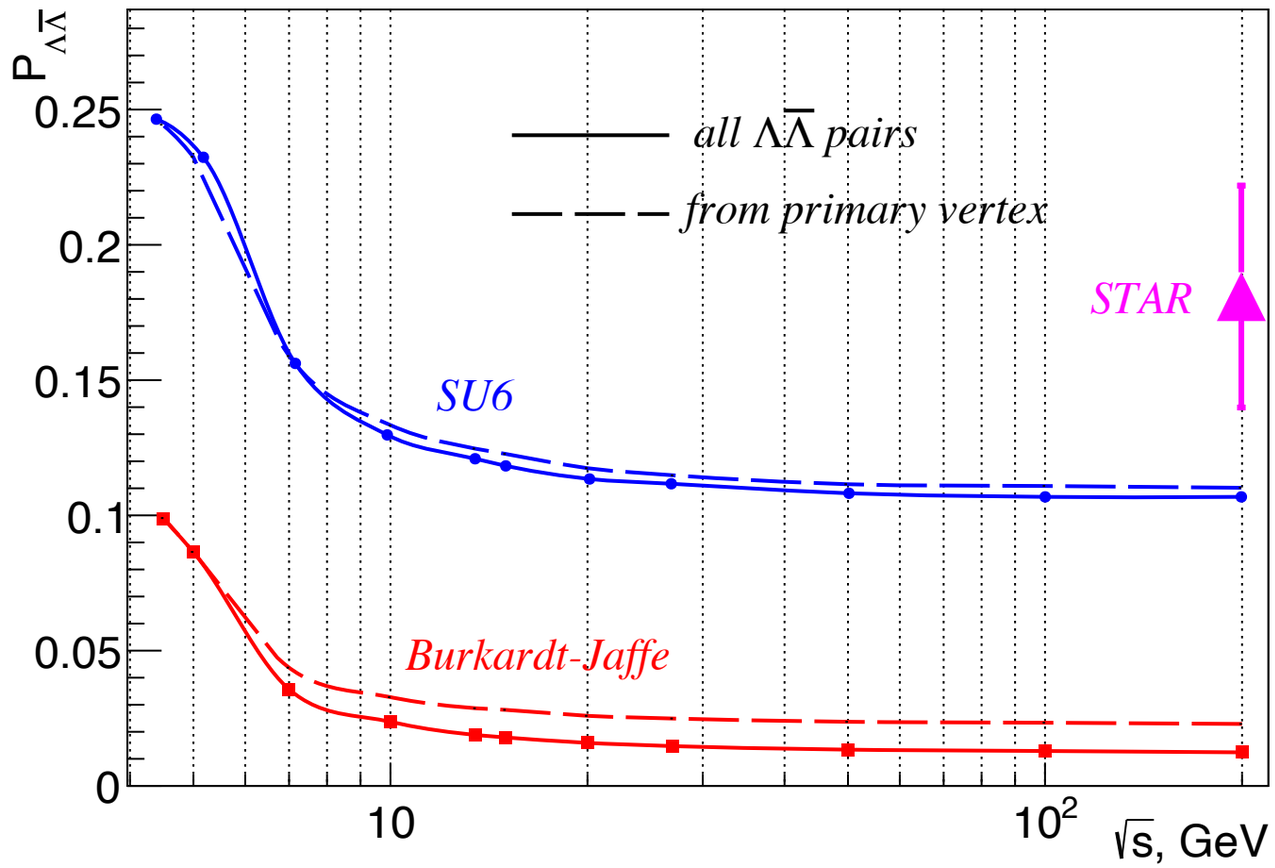
$$P_{\Lambda\bar{\Lambda}} = \frac{1}{3}\sum_{i,j} R_{ij}\, P^i_{\Lambda} P^j_{\bar{\Lambda}},$$

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

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	-

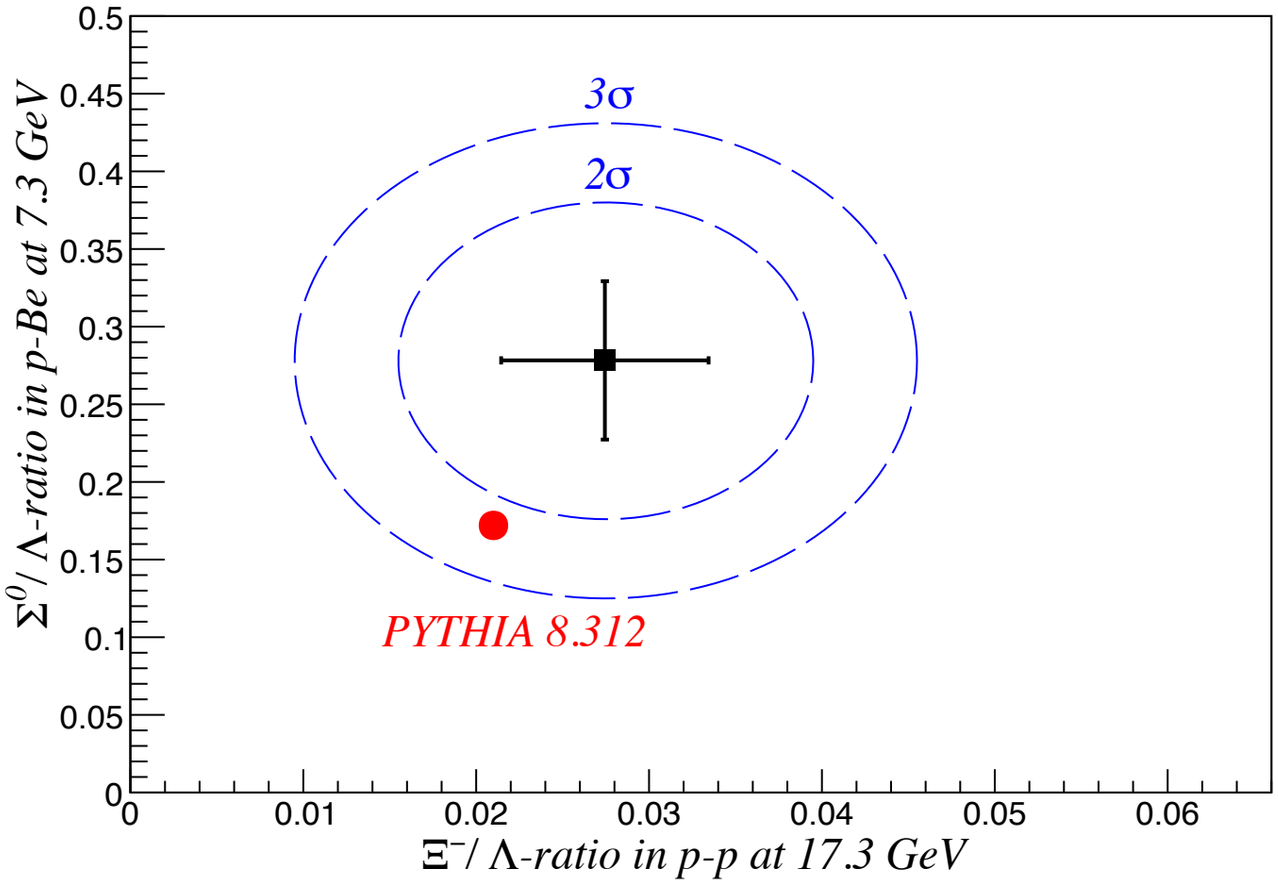
$R_{i,j}$

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

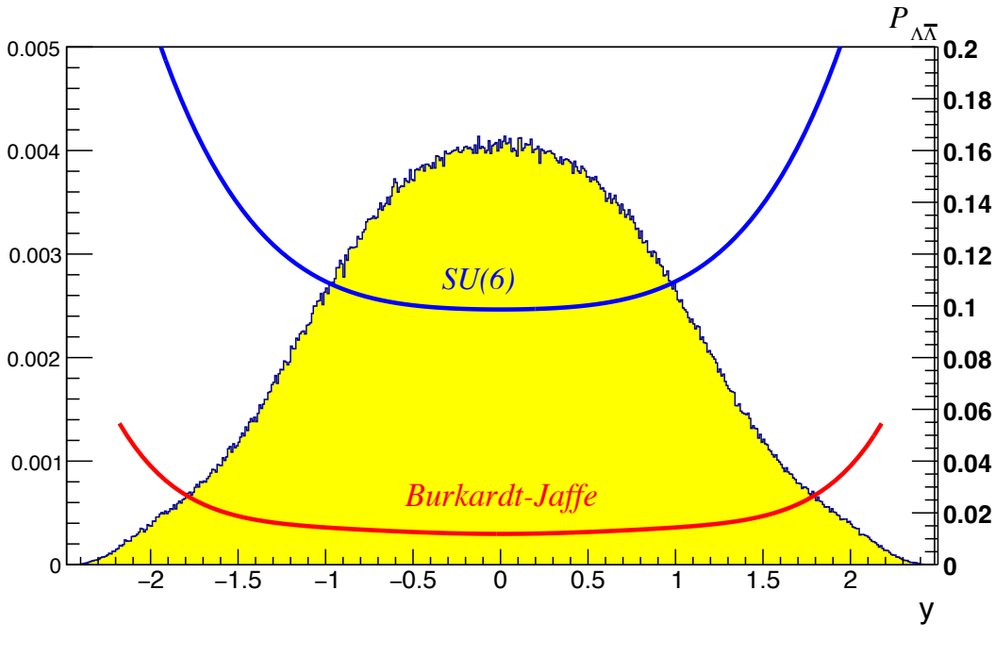


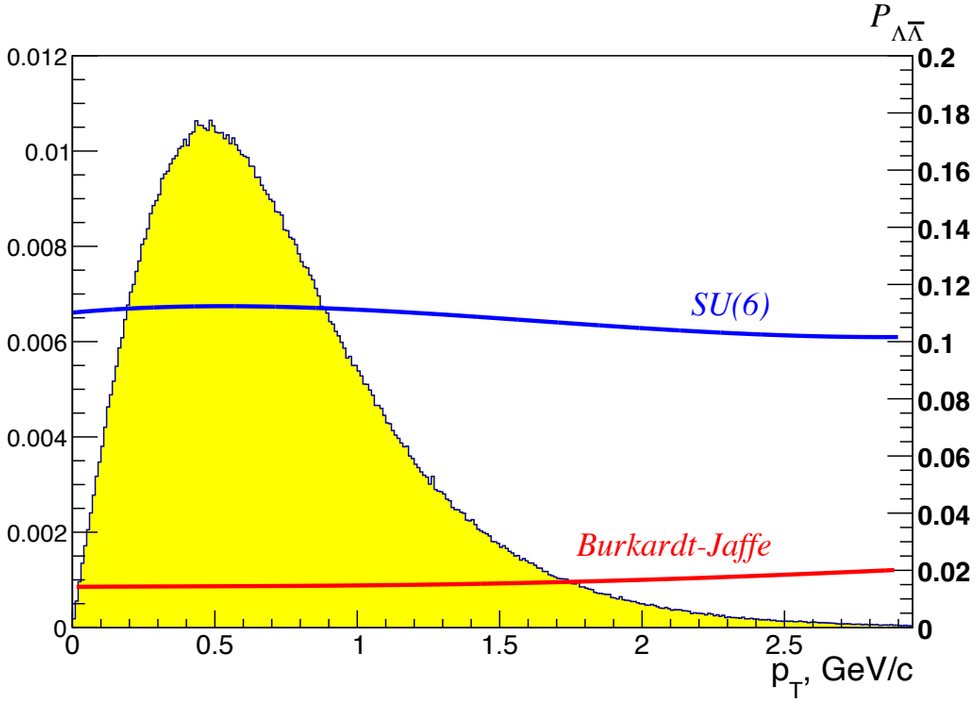
Hyperon production: Pythia tests

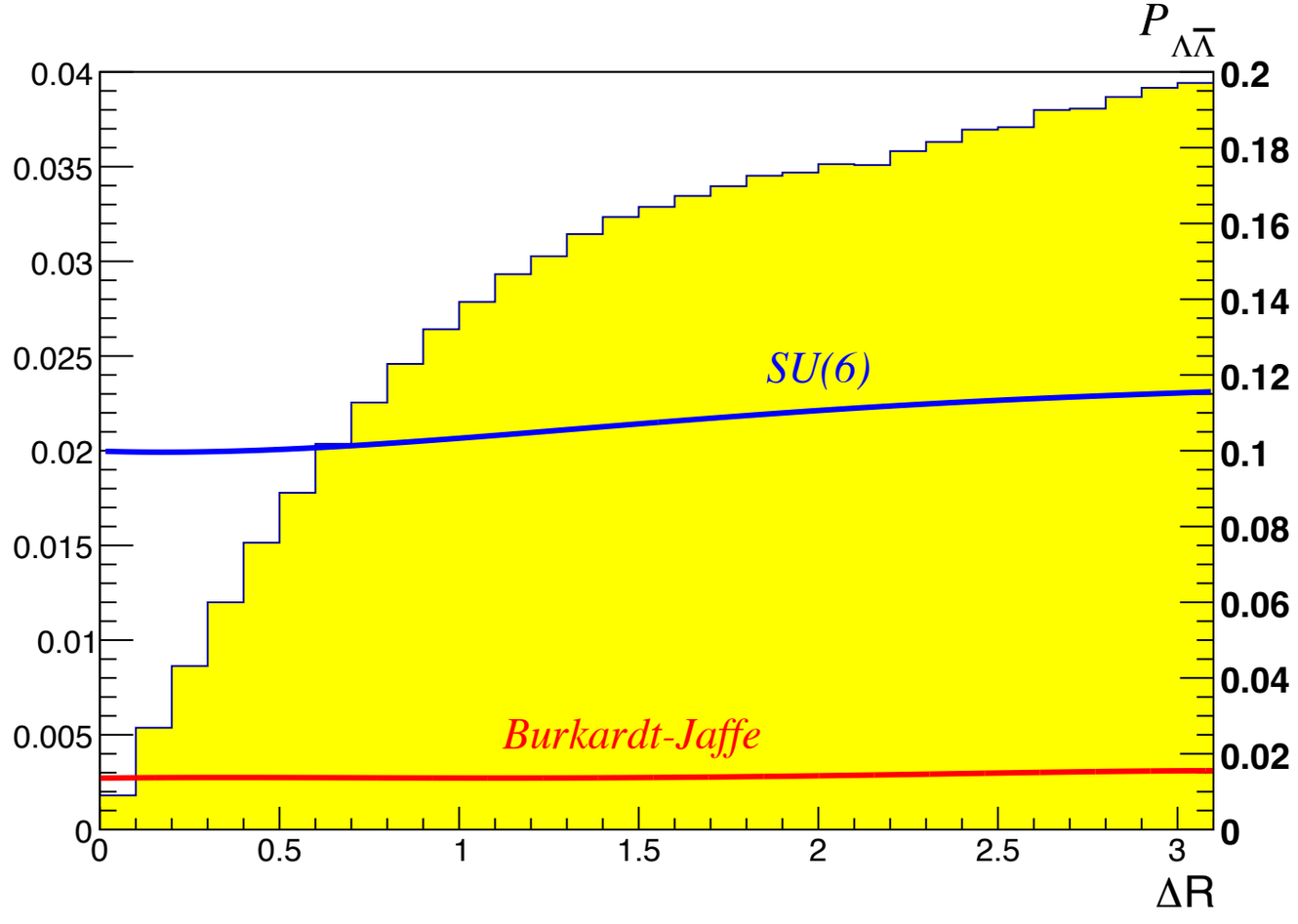
Ratio	$\sqrt{s}$, GeV	Measurement	PYTHIA 8.312
Ξ^-/Λ	17.3 (p-p)	0.028±0.0060 [17, 18]	0.021
Σ^0/Λ	7.3 (p-Be)	0.278±0.051 [19]	0.171



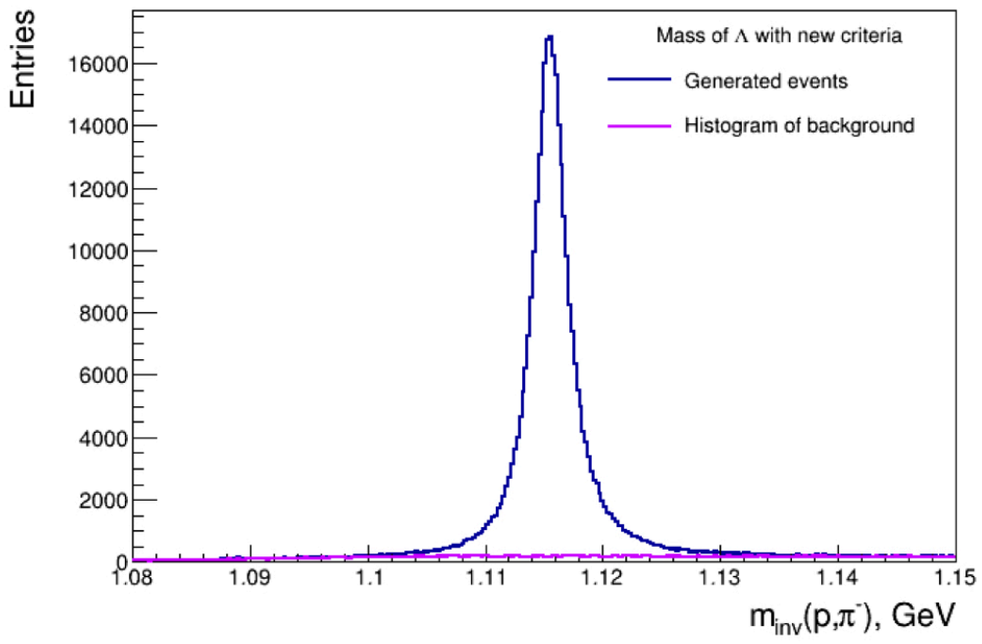
Kinematics

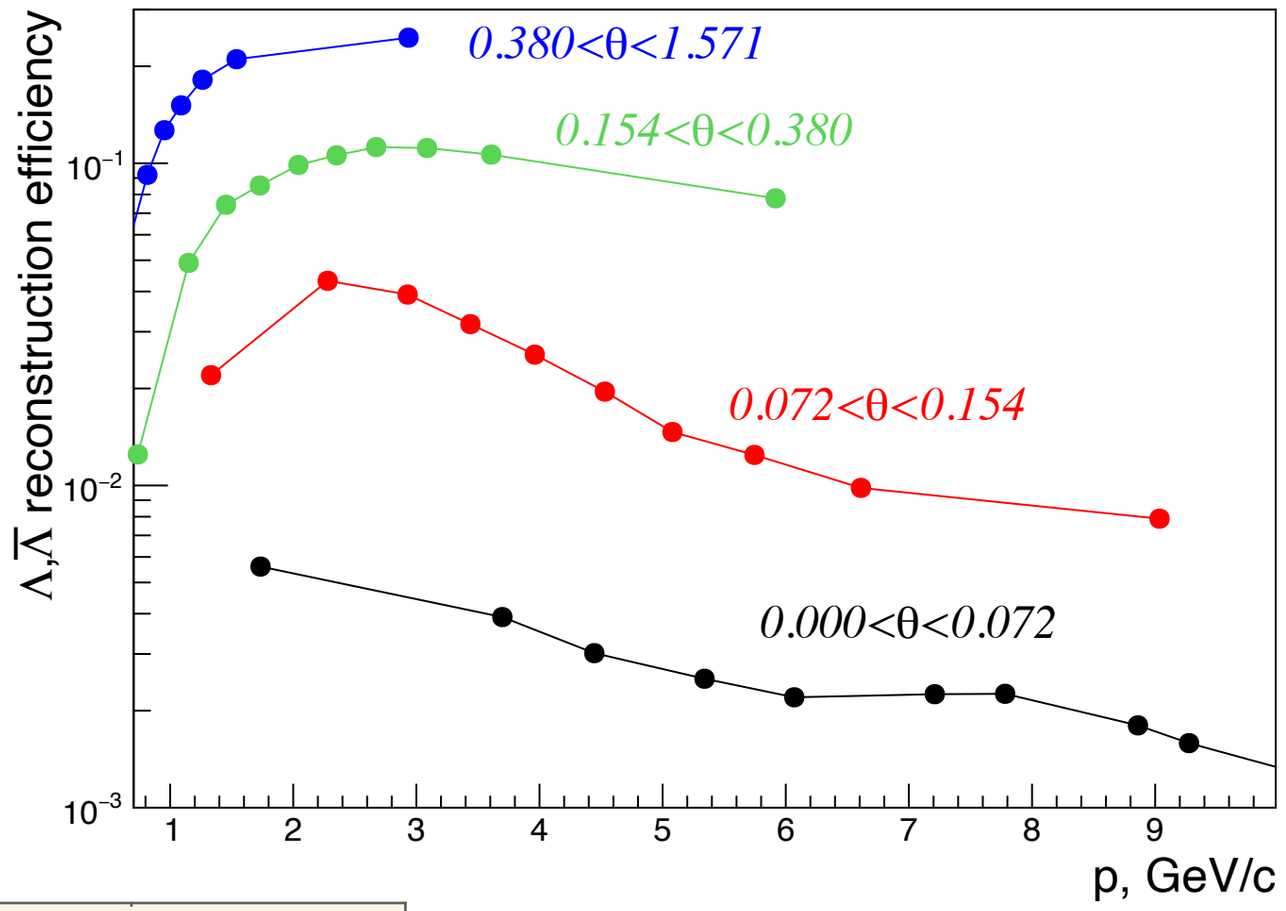

$P_{\Lambda\bar{\Lambda}}$
SU(6)
Burkardt-Jaffe
y


$P_{\Lambda\bar{\Lambda}}$
SU(6)
Burkardt-Jaffe
p_T, GeV/c


$P_{\Lambda\bar{\Lambda}}$
SU(6)
Burkardt-Jaffe
ΔR

Full simulation

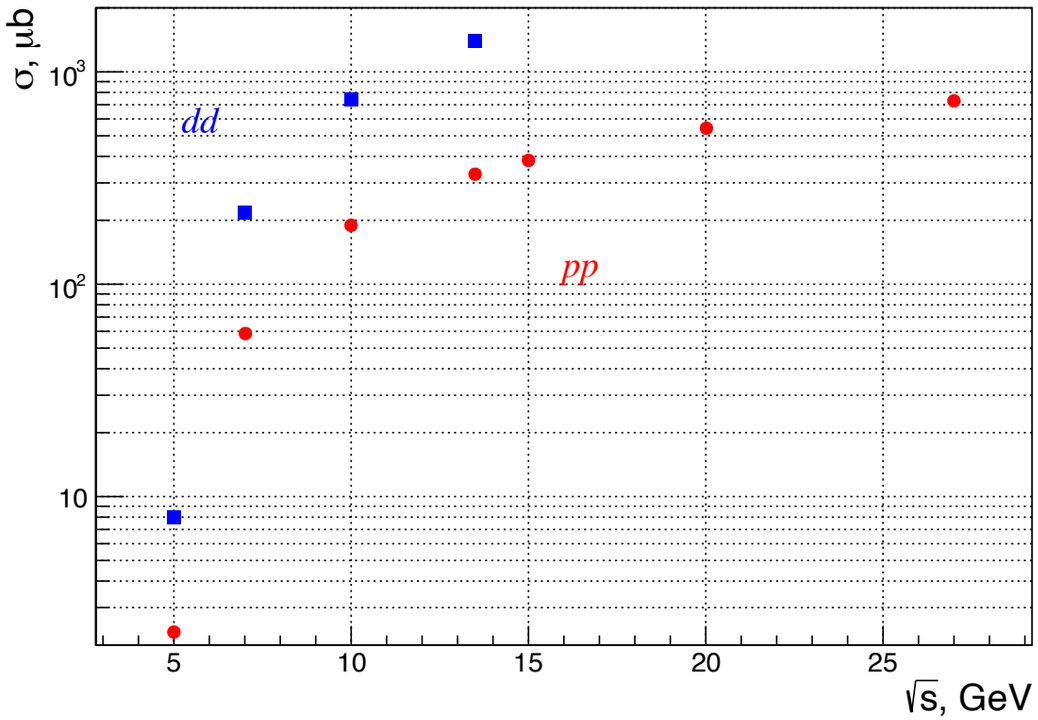




Energy, GeV	full range	pT>0.5 |y|<1
27	1.5 %	5 %
10	0.4 %	1.8 %

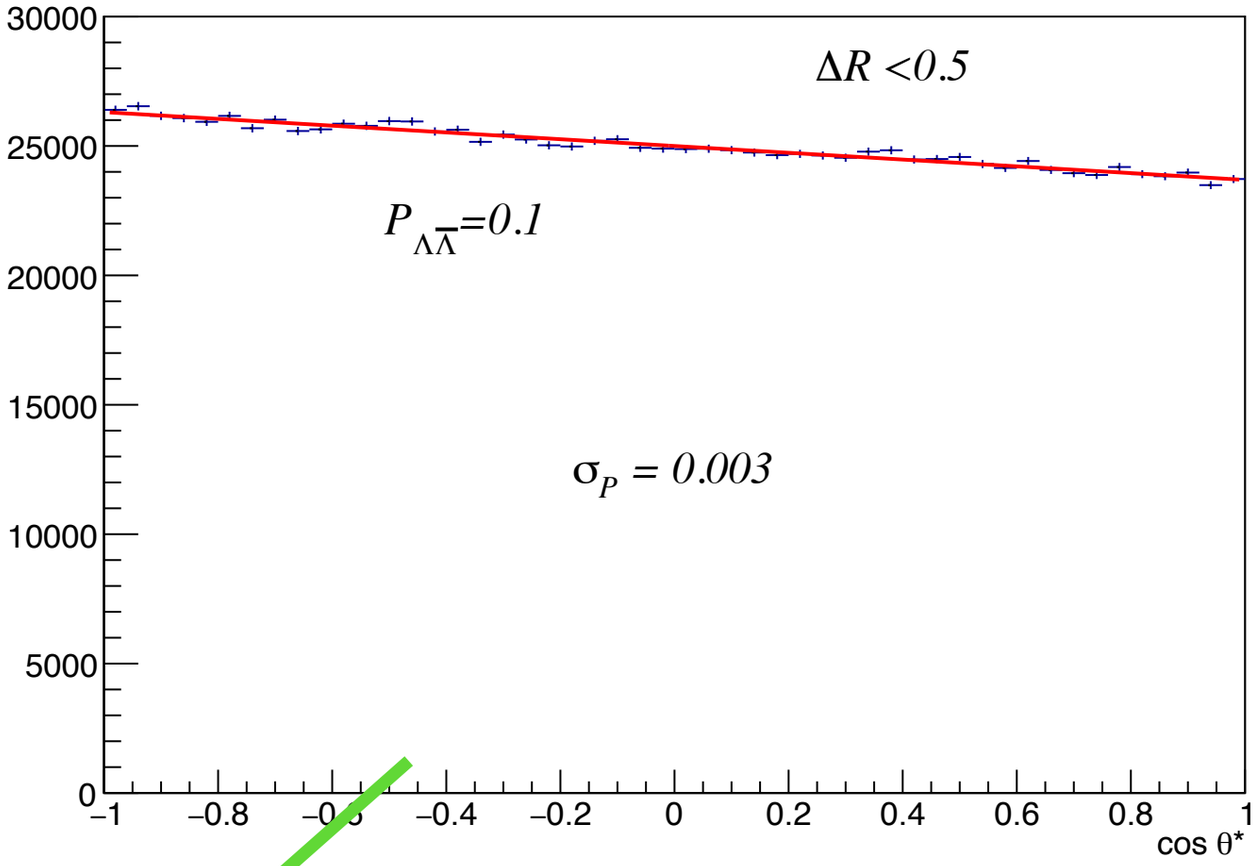
Cross section and rates

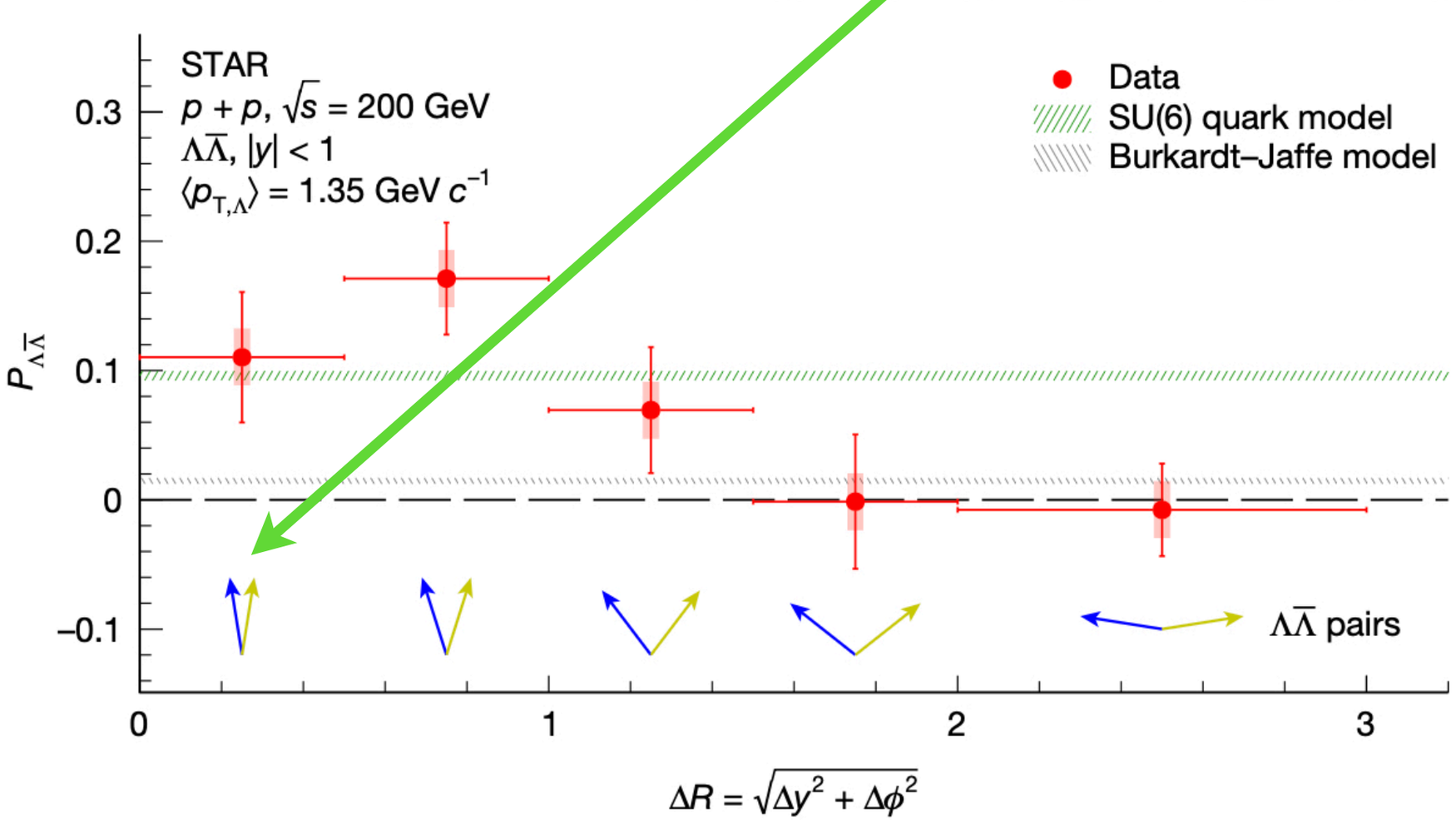
Pythia + Angantyr (Glauber + color reconnection for dd)



STAR: 0.13 M

	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}
e,%	1.5	0.4	5.0	1.8
OF eff, %	100			
Time	1 month			
Duty factor	0.7			
EVENTS, 10^6	**820**	**30**	**190**	**7.5**


ΔR <0.5
$P_{\Lambda\bar{\Lambda}}$=0.1
σ_P = 0.003
30000
25000
20000
15000
10000
5000
0
−1
−0.8
−0.6
−0.4
−0.2
0
0.2
0.4
0.6
0.8
1
cos θ*


STAR
$p + p$, $\sqrt{s}$ = 200 GeV
$\Lambda\bar{\Lambda}$, $|y| < 1$
$\langle p_{T,\Lambda} \rangle$ = 1.35 GeV c^{-1}
Data
SU(6) quark model
Burkardt–Jaffe model
$\Lambda\bar{\Lambda}$ pairs
$P_{\Lambda\bar{\Lambda}}$
0.3
0.2
0.1
0
−0.1
0
1
2
3
$\Delta R = \sqrt{\Delta y^2 + \Delta\phi^2}$

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 quantum entanglement in the $\Lambda\bar{\Lambda}$ system via reconstruction of the full spin density matrix, enabling tests of Bell-type inequalities.

- 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.