The Emergence and Disappearance of Λ Spin Correlations: From QCD Vacuum to Hadronization

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In collaboration with

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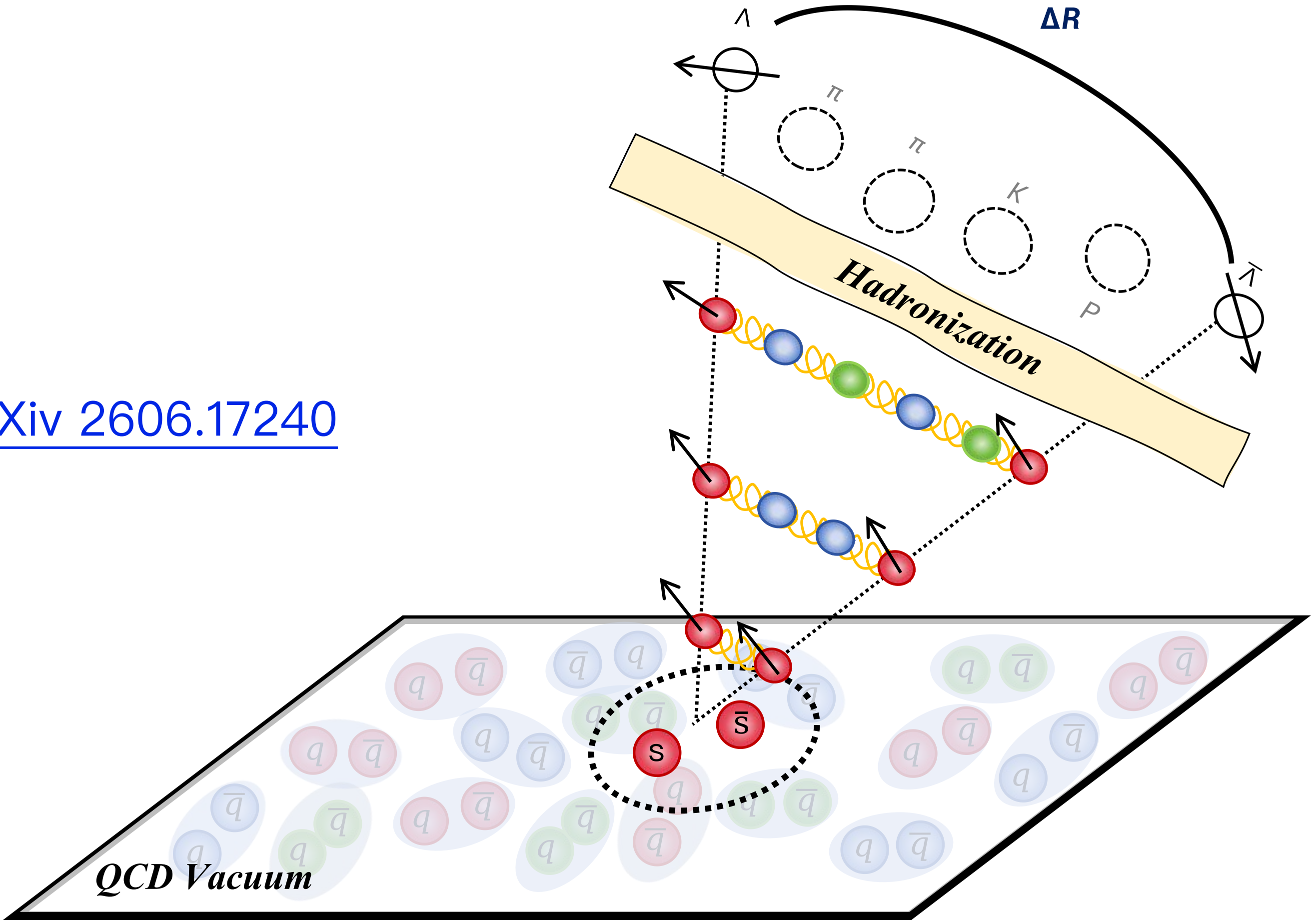
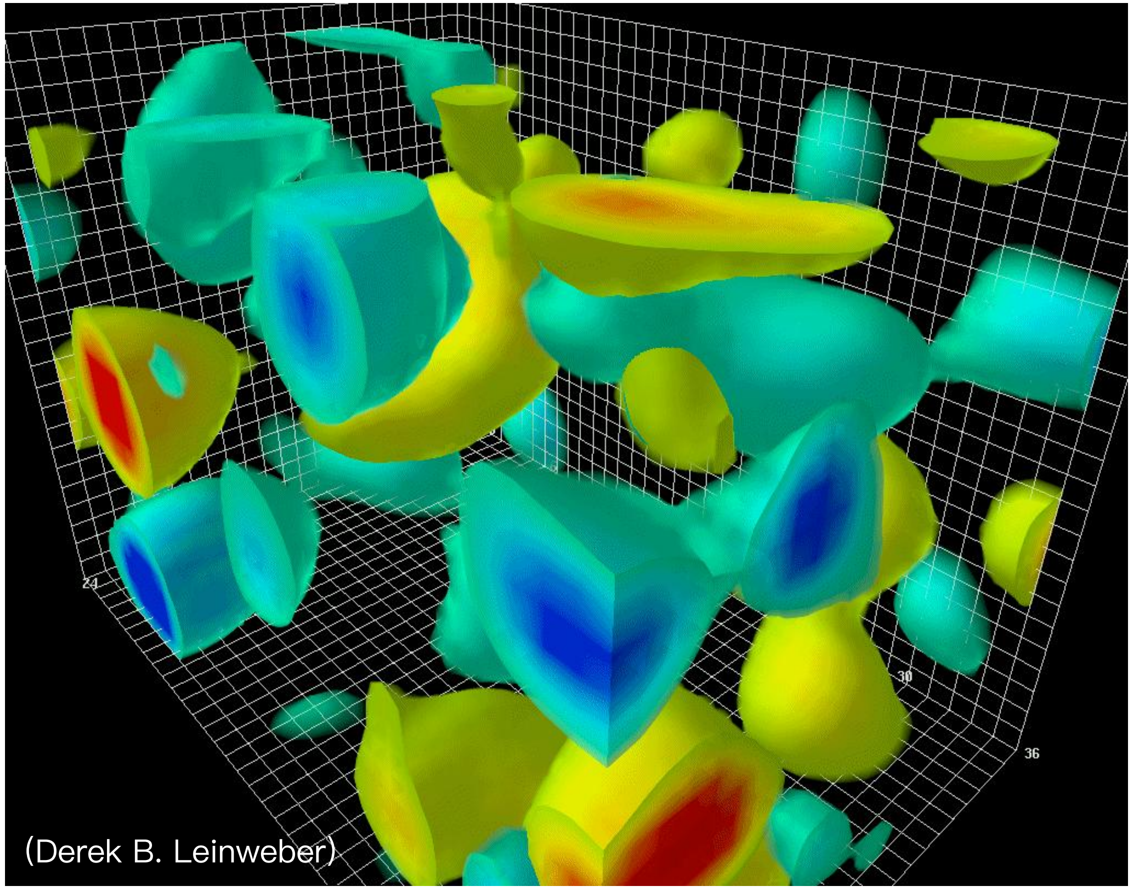
Based on Nature 650,65—71 (2026), arXiv 2606.17240

Stony Brook University



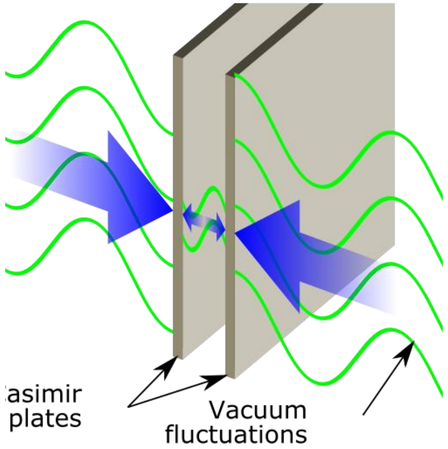
QCD Vacuum has complex structure

- The QCD vacuum is filled with fluctuation of virtual pairs
- The spontanesous breaking of chiral symmetry gives rises to the non-vanishing condensate
- Topological charge fluctuation

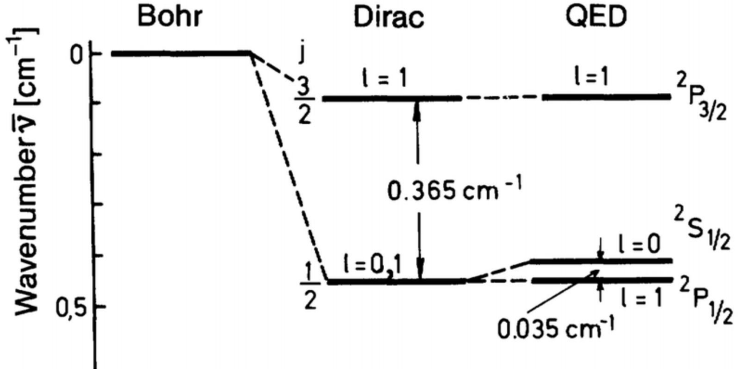


Is there an experimental way to probe vacuum fluctuation ?

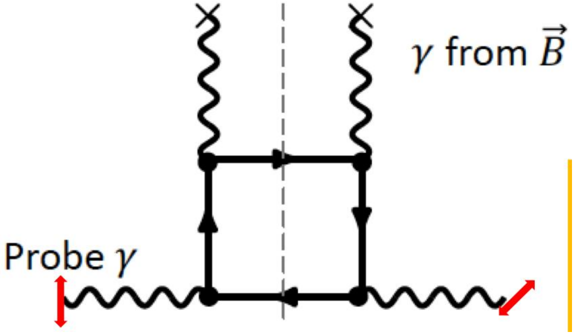
Experimental evidences of vacuum fluctuation



Casmir effect



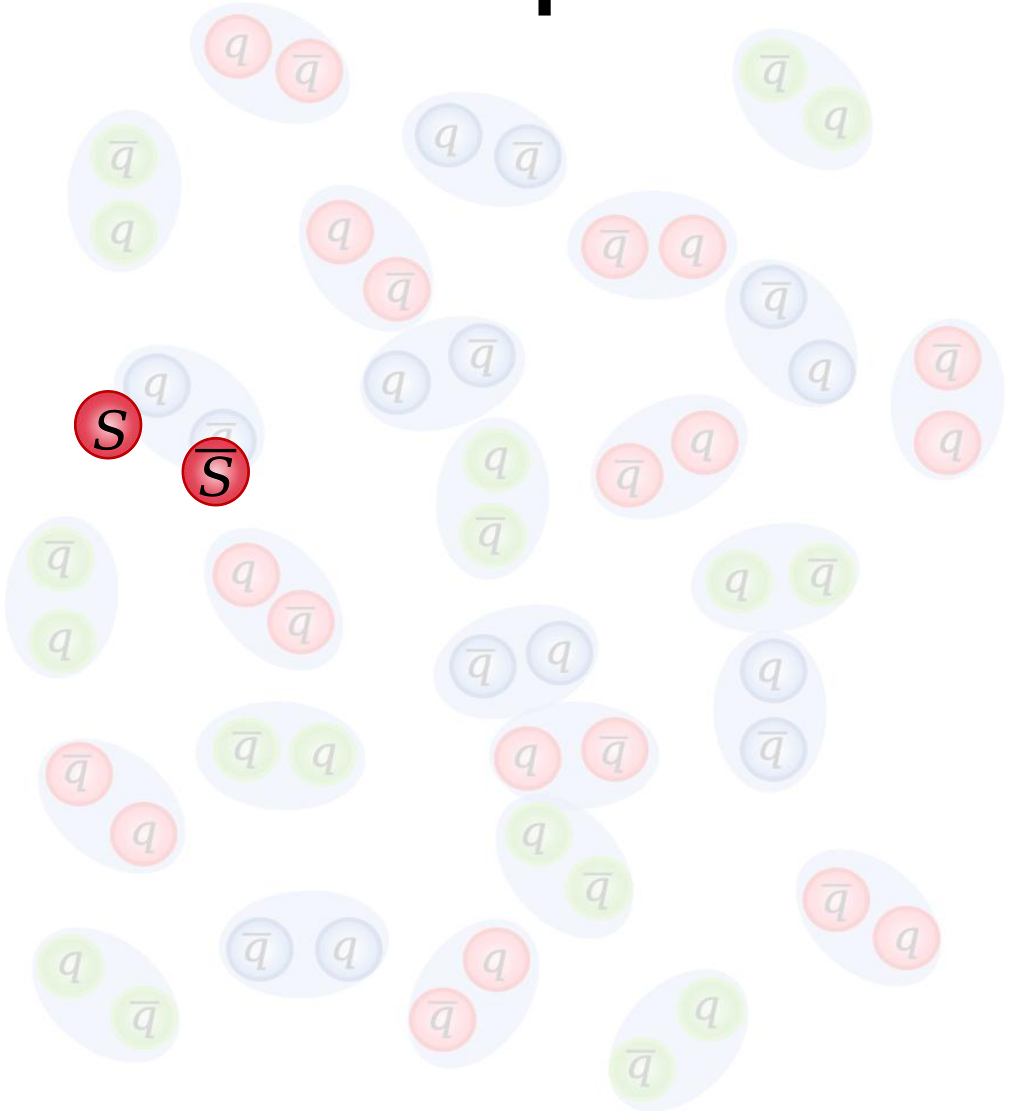
Lamb shift



Vacuum Birefringence

A New perspective: Λ hyperon pair spin correlation

Vacuum pair carries vacuum quantum number $J^{PC} = 0^{++}$



Let S and L be total spin and orbital angular momentum of the pair

Spin-entangled pairs from vacuum

$$J = L + S, L + S - 1, ..., |L - S|$$

$$P = (-1)^{L+1}$$

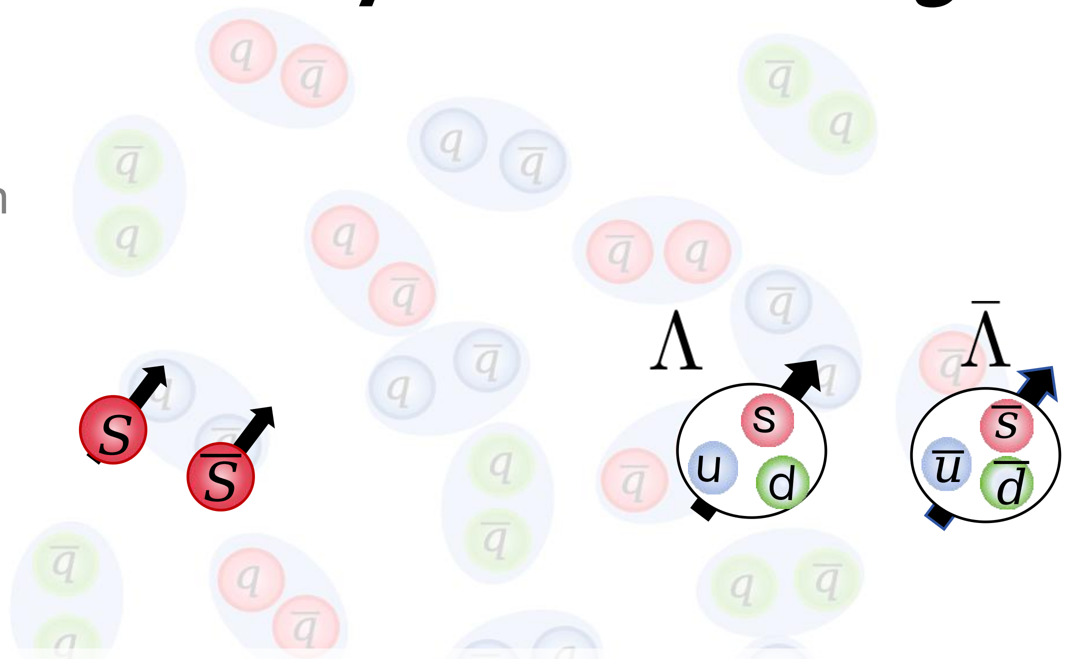
$$C = (-1)^{L+S}$$

$$\Rightarrow \quad L = S = 1$$

Let S and L be total spin and orbital angular momentum of the pair

Λ spin is totally carried by the its *strange* quark.

In SU(6) quark model, Λ spin 100% from its strange quark, making Λ experimental probe of quark spin.



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$$P = (-1)^{L+1}$$

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$$\Rightarrow \quad L = S = 1$$

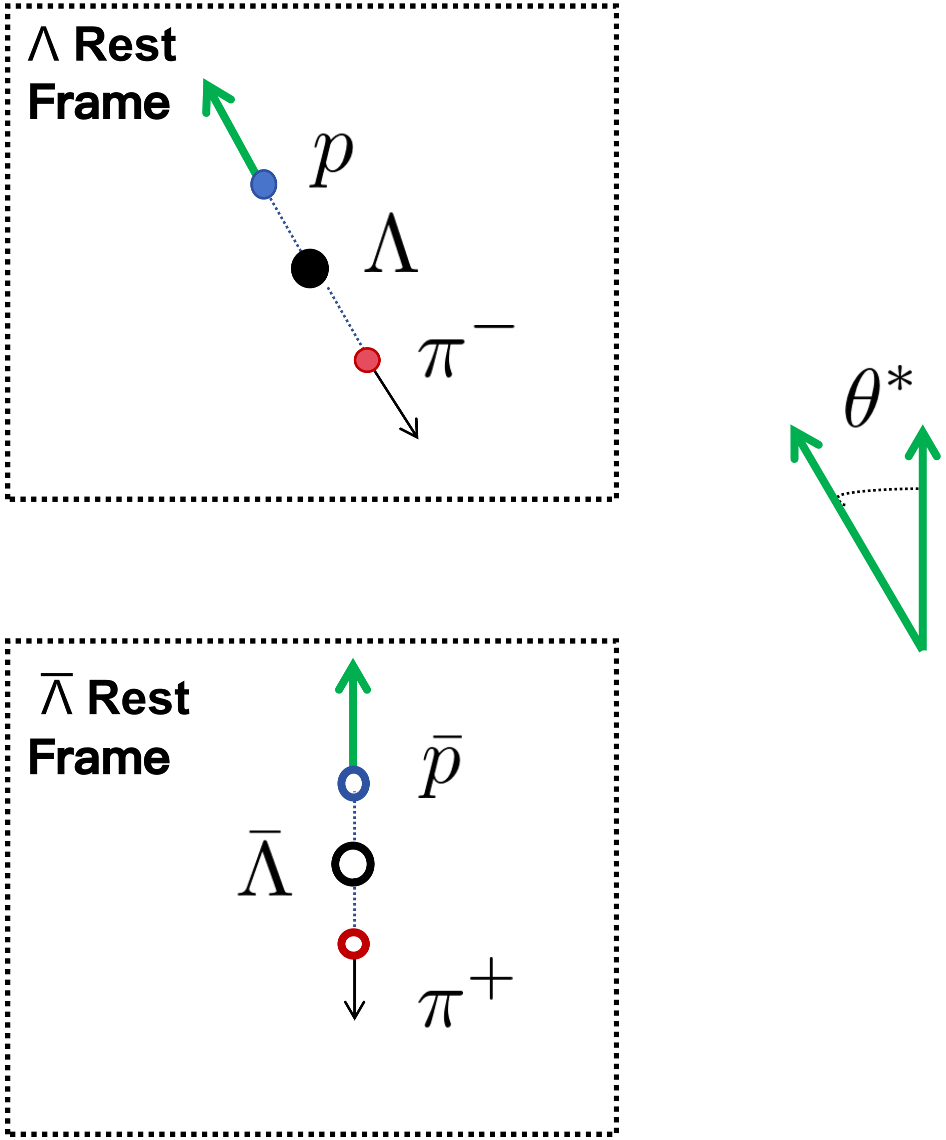
Let S and L be total spin and orbital angular momentum of the pair

Extract Λ pair spin correlation

- **The spin correlation between Λ pairs is extracted through decay kinematics, i.e.,**

$$\frac{1}{N}\frac{\mathrm{d}N}{\mathrm{d}\cos\theta^{\star}} = \frac{1}{2}[1 + \alpha_1\alpha_2 \boxed{P_{\Lambda_1\Lambda_2}} \cos\theta^{\star}]$$

spin correlation observable



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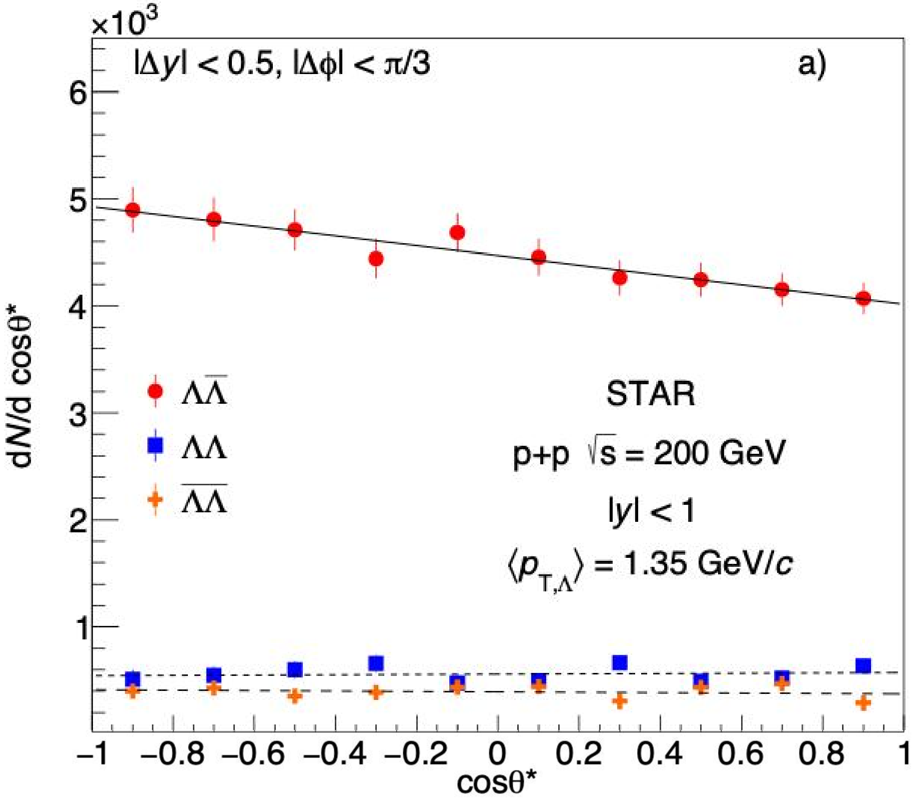
$$\frac{1}{N}\frac{\mathrm{d}N}{\mathrm{d}\cos\theta^\star} = \frac{1}{2}[1+\alpha_1\alpha_2 P_{\Lambda_1\Lambda_2}\cos\theta^\star]$$

- **A linear fit is performed to extract the spin correlation** $P_{\Lambda_1\Lambda_2}$

- **Mix-event method is used to correct the acceptance effect.**



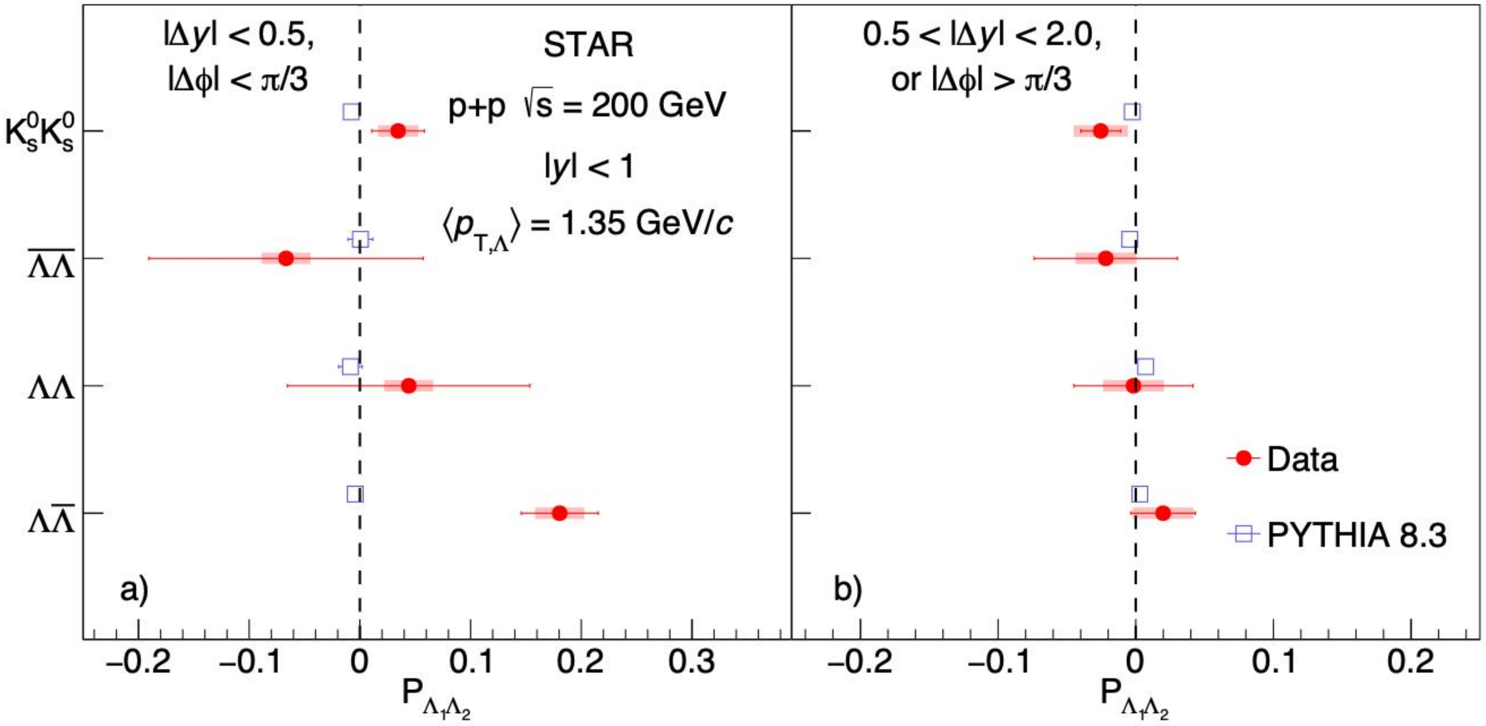
Nature volume 650, pages 65—71 (2026)

The key STAR results

- ***Significant*** **spin correlation is observed for $\Lambda\bar{\Lambda}$ with small relative angle distance (short range), while consistent with zero at long range.**

- **$\Lambda\Lambda$ and $\bar{\Lambda}\bar{\Lambda}$ do not show significant spin correlation.**

Short–range pair　　*Long–range pair*



Nature volume 650, pages 65—71 (2026)

The key STAR results

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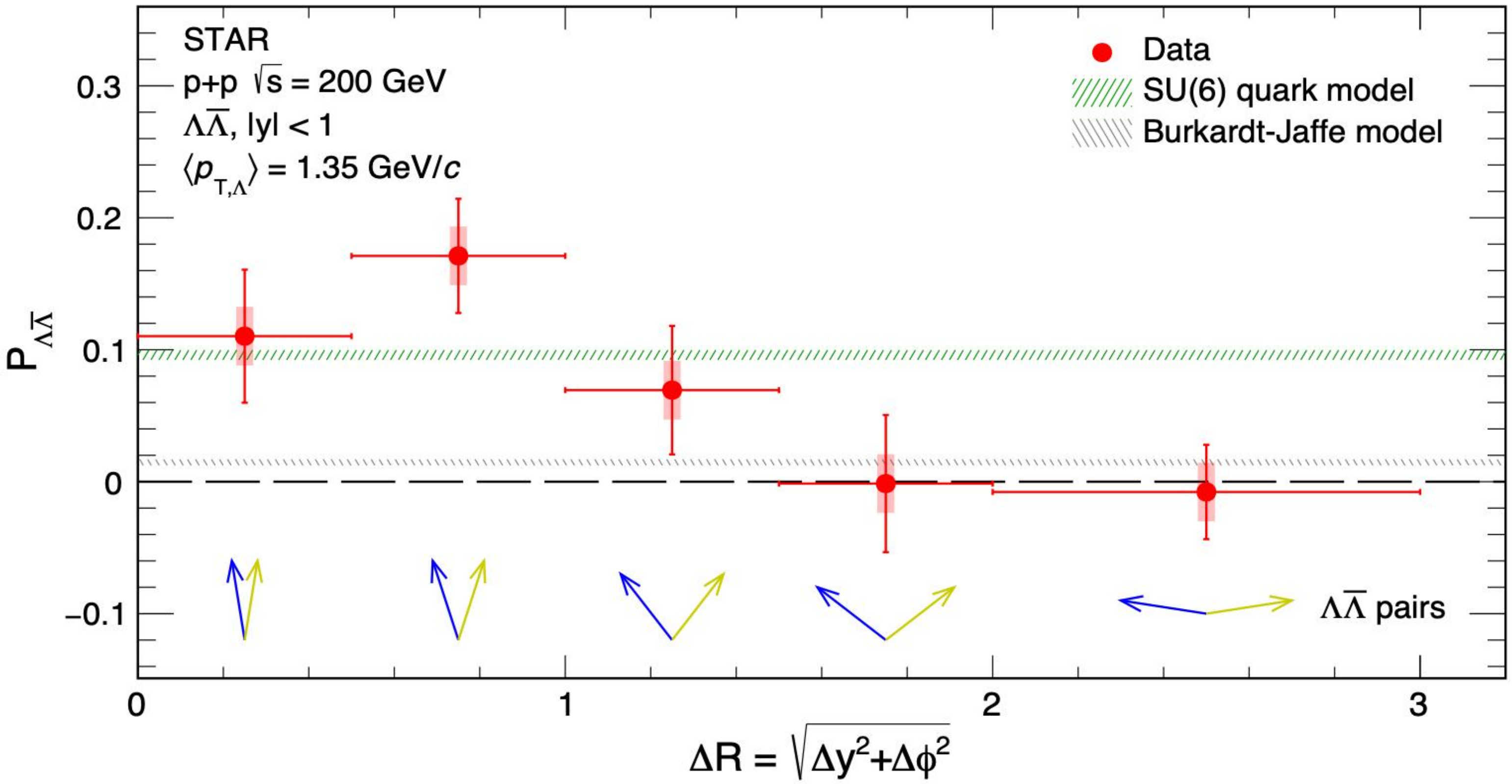
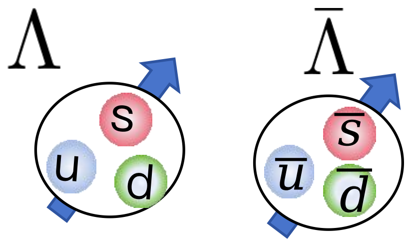


- ~ 10 % signal is observed at very low ΔR.
- Clear dependence on ΔR.

Quantitatively connect the STAR result with vacuum excitation



$$S = 1$$

$$P^{obs}_{\Lambda\bar{\Lambda}} = P_{\Lambda\bar{\Lambda}} \times A_{feed-down} \approx 10\%$$

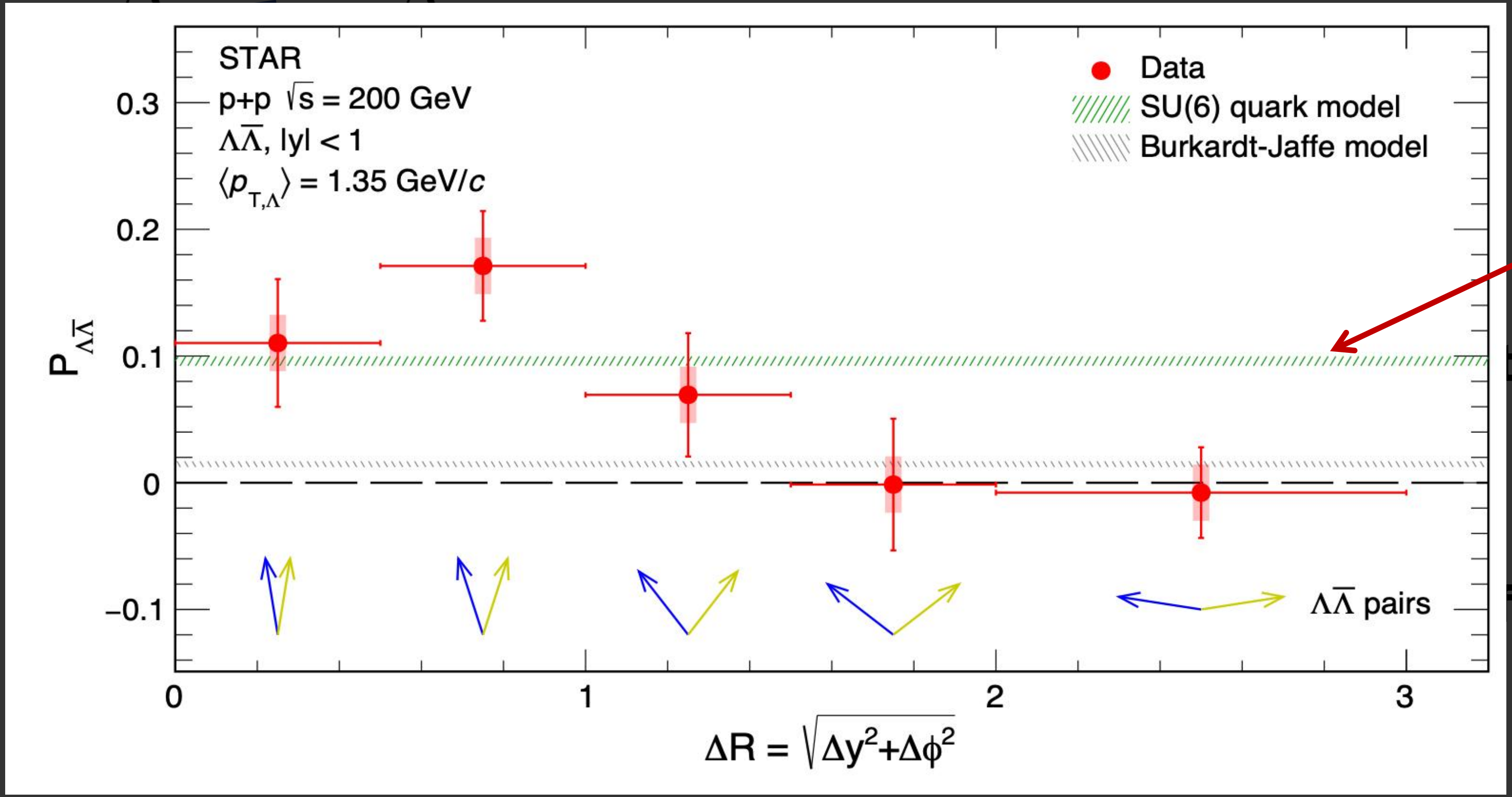
1/3

Spin–Triplet Pairs

1/3

Feed–down diulation estimated
by PYTHIA8 + SU(6) quark model

Quantitatively connect the STAR result with vacuum excitation

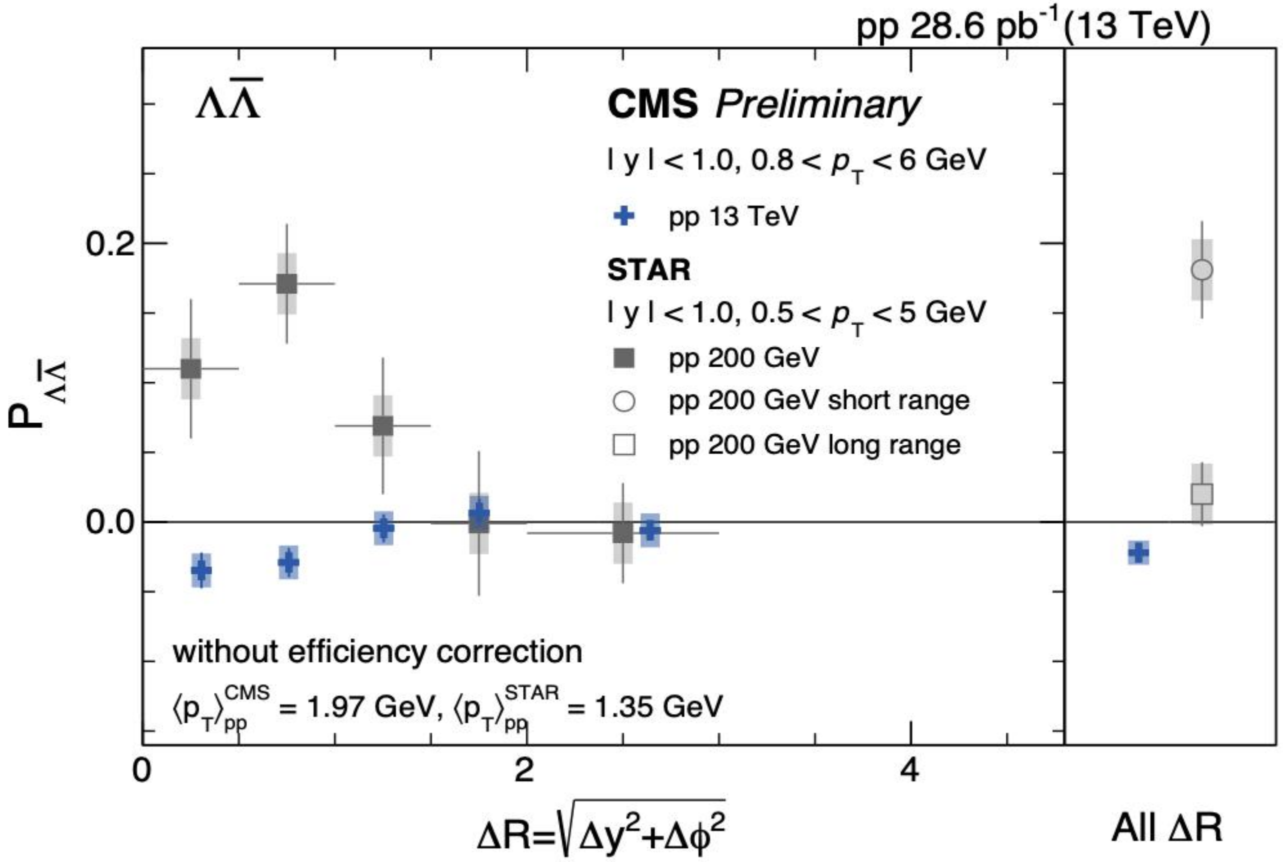


Expectation from *vacuum excitation + SU(6) quark model* (No dymanics, thus no ΔR dependence)

- …t, from which the spin
- …ffect. Based on SU(6) quark
- **Account for feed-down effect, the expectation of observed spin correlation is** $P_{\Lambda\bar{\Lambda}}^{obs} \approx 10\%$

New insight from higher energy

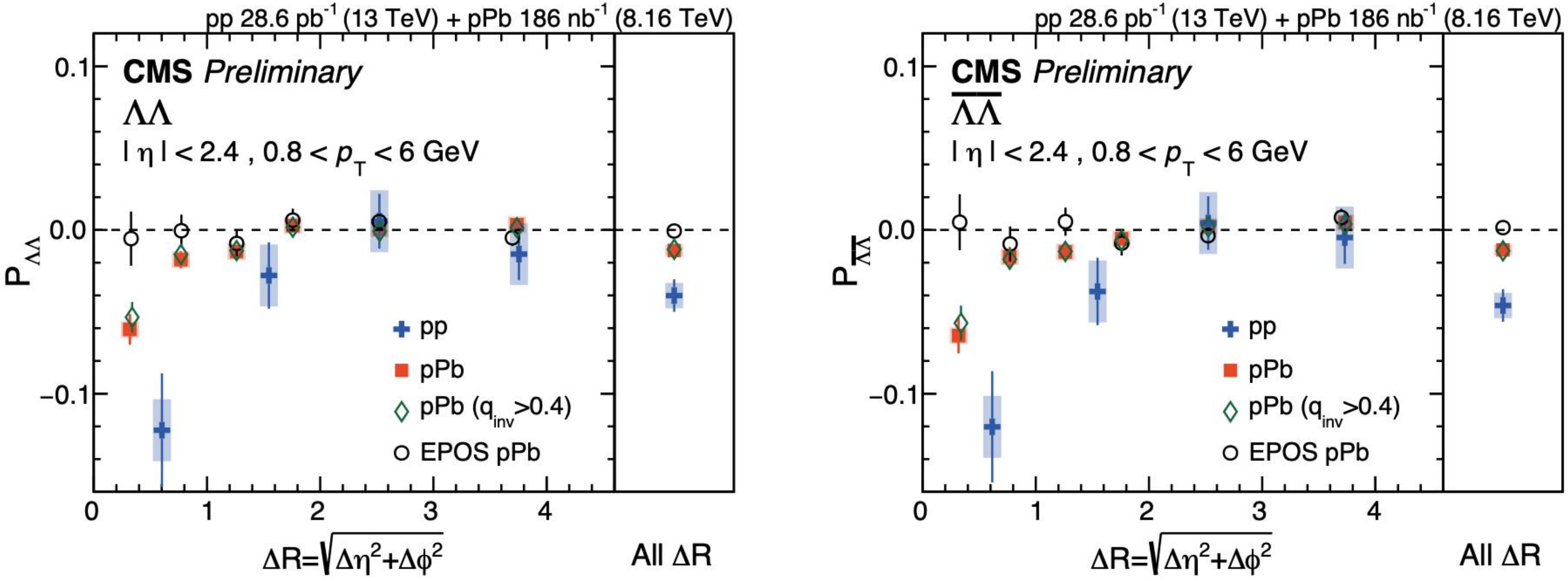
CMS–PAS–HIN–26–002



- $\Lambda\bar{\Lambda}$ **spin correlation is negative.**
- **A clear ΔR depenence can be observed.**

$\Lambda\Lambda$ ($\overline{\Lambda\Lambda}$) Spin is Correlated

CMS–PAS–HIN–26–002

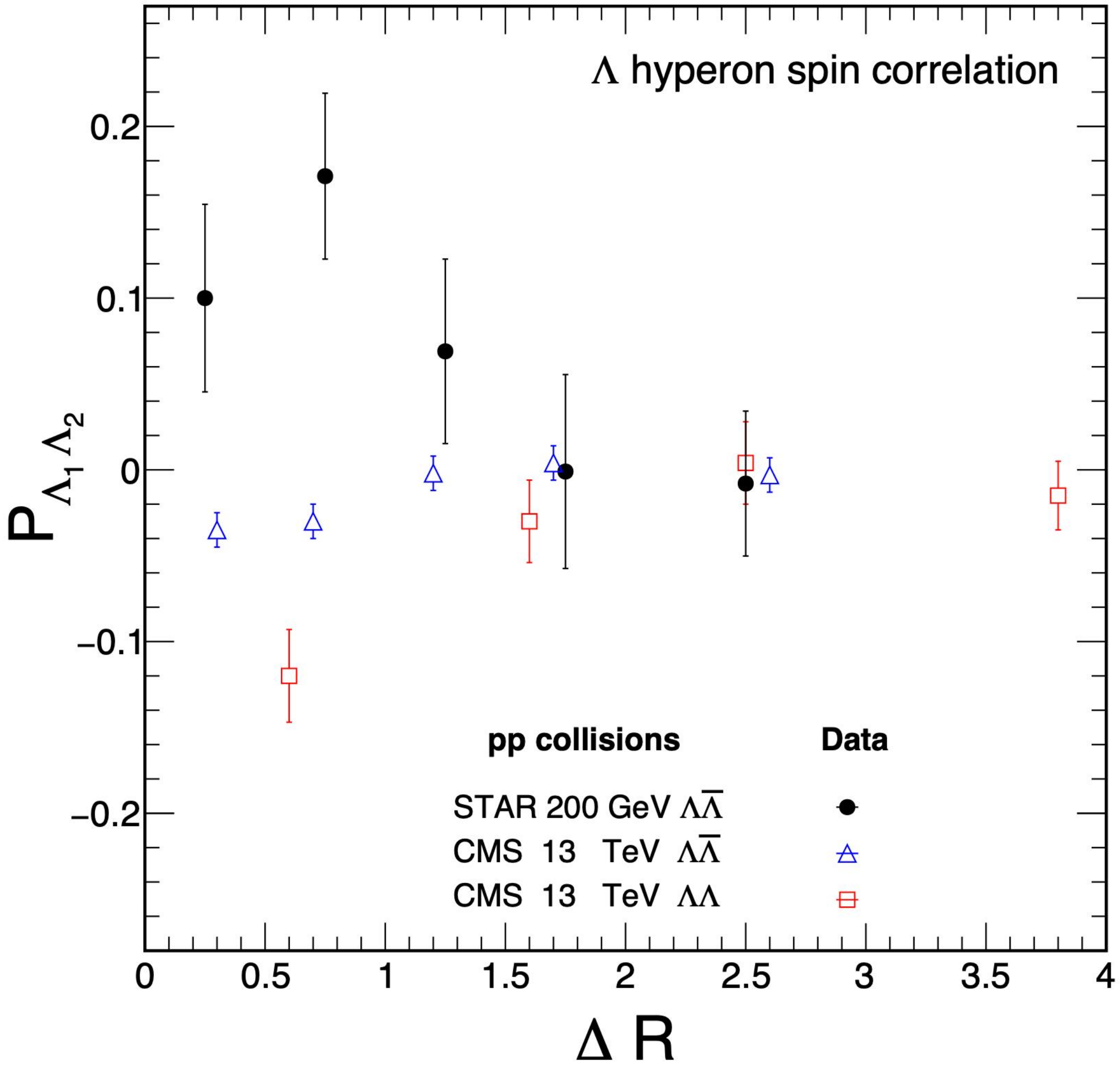


- **The $\Lambda\Lambda$ ($\overline{\Lambda\Lambda}$) spin correlation is observed to be signifiantly negative.**
- **Clear ΔR dependence.**

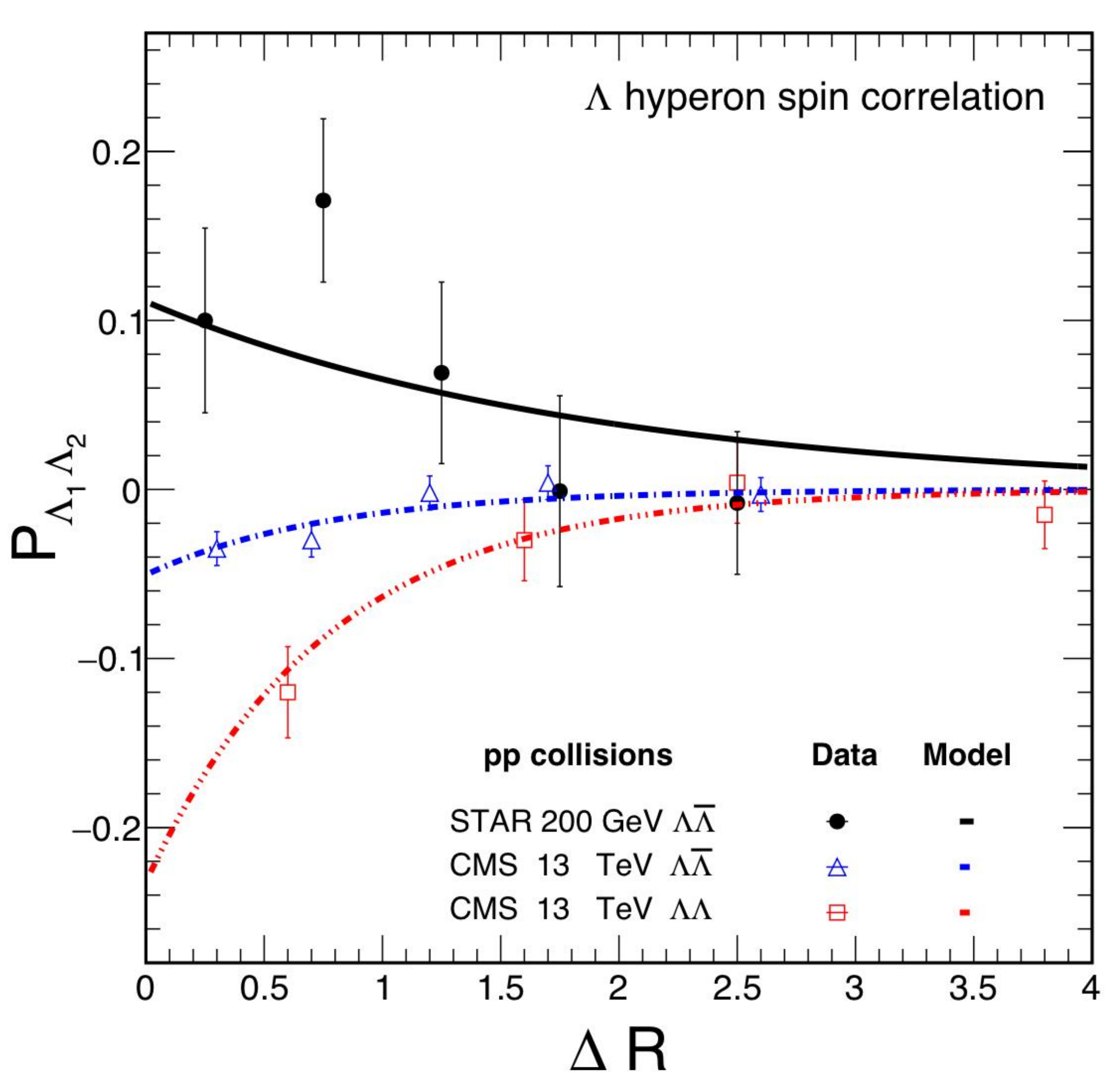
Different energy seems to show distinct spin correlations, while ΔR dependence is similar

Is the picture of vacuum consistent with data ?

Where ΔR dependence comes from ?

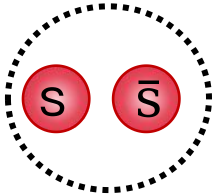


A New Model : Extend the picture of *vacuum excitaion* + *Quantum Decoherence* induced by hadronization



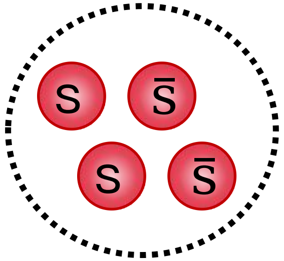
Vacuum excitation carries vacuum quantum number

- **One–Pair Channel:**



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

- **Two–Pair Channel:**



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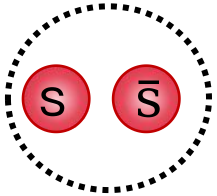

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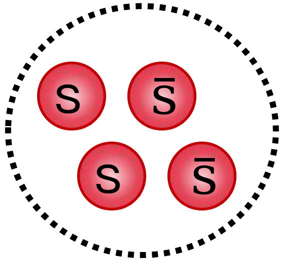

$$J^{PC} = 0^{++}$$

Two pairs of $q\bar{q}$ (diquark + antiquark) excitation from vacuum has long been proposed to explain baryon formation. There are even some experimental evidences.

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Vacuum excitation carries vacuum quantum number

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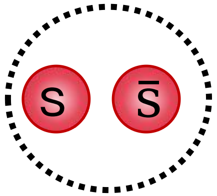

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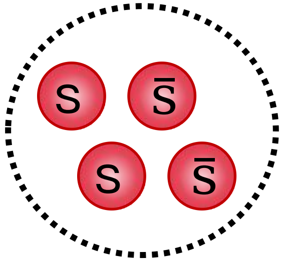
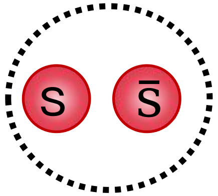


$$J^{PC} = 0^{++}$$

What would be the spin correlation of $s\,s\,\bar{s}\,\bar{s}$ excited from vacuum ?

One–pair channel $s\bar{s}$

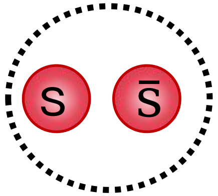
- The vacuum quantum number $\mathbf{J^{PC} = 0^{++}}$ leads to L = S =1.



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

One–pair channel $s\bar{s}$

- **The vacuum quantum number $\mathbf{J^{PC} = 0^{++}}$ leads to L = S =1.**



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

- **If one continues with the addition rule of angular momentum**

$$|J=0\rangle = \frac{1}{\sqrt{3}}|L_z=1\rangle|S_z=-1\rangle - \frac{1}{\sqrt{3}}|L_z=0\rangle|S_z=0\rangle + \frac{1}{\sqrt{3}}|L_z=-1\rangle|S_z=1\rangle$$

One–pair channel $s\bar{s}$

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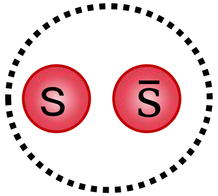

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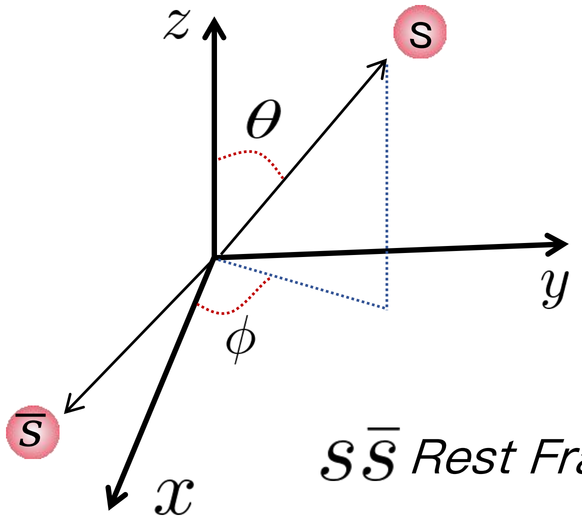
In momentum representation,

$$|L_z=1\rangle = -\sqrt{\frac{3}{8\pi}}\sin\theta e^{i\phi} \qquad |S_z=1\rangle = |\uparrow\uparrow\rangle$$

$$|L_z=0\rangle = \sqrt{\frac{3}{4\pi}}\cos\theta \qquad |S_z=0\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)$$

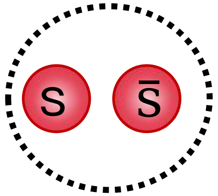
$$|L_z=-1\rangle = \sqrt{\frac{3}{8\pi}}\sin\theta e^{-i\phi} \qquad |S_z=-1\rangle = |\downarrow\downarrow\rangle$$



$s\bar{s}$ *Rest Frame*

One–pair channel $s\bar{s}$

- The vacuum quantum number $J^{PC} = 0^{++}$ leads to L = S =1.



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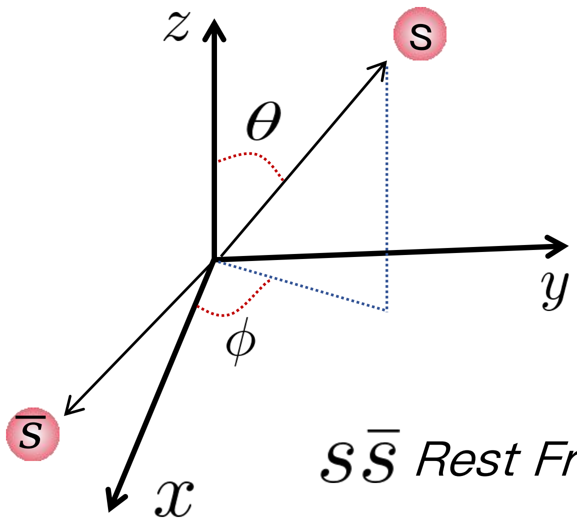

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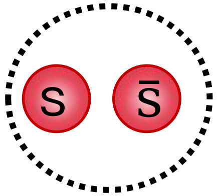

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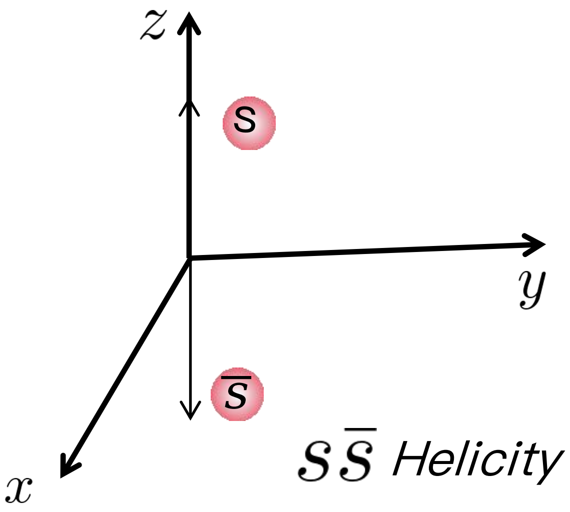
- If one rotate the frame into helicity frame, i.e., $\boldsymbol{\theta} = 0$,

$$|s\bar{s}\rangle \propto \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)$$

which is a Bell state* with *maximal quantum entanglement.*



$s\bar{s}$ *Helicity Frame*

Recently, ATLAS measured another Bell state in $t\bar{t}$ system. Nature volume 633, pages 542–547 (2024)

One–pair channel $s\overline{s}$

- **The spin state of one–pair $s\overline{s}$ in the helicity frame:**

$$|s\bar{s}\rangle^{(1)} \propto \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)$$

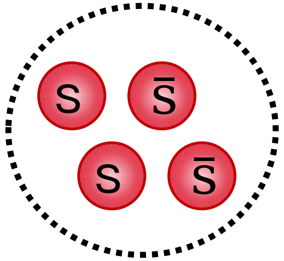
- **One can construct the density matrix:**

$$\rho_{s\bar{s}}^{(1)} = |s\bar{s}\rangle^{(1)} \langle s\bar{s}|^{(1)} = \frac{1}{2}\begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 \\ 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

- **The spin correlaiton between s and $\overline{s}$ quark:**

$$P_{s\bar{s}}^{(1)} = \frac{1}{3}$$

Two–pair channel $ss\overline{ss}$



- To consider the identical particle symmetry, the $ss\overline{ss}$ can be decomposed into ss and $\overline{ss}$.

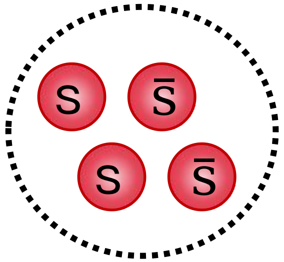
$$J^{PC} = 0^{++}$$

- Total wave function must be anti–symmetric (*AS*) under the exchange of identical particles.

$$|ss\bar{s}\bar{s}\rangle = |\text{flavor}\rangle \otimes |\text{spatial}\rangle \otimes |\text{spin}\rangle \otimes |\text{color}\rangle$$

(*AS*)

Two–pair channel $ss\overline{ss}$



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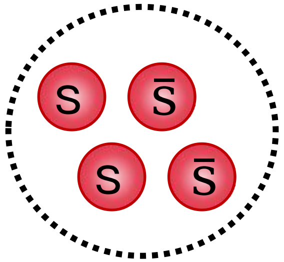
$$|ss\bar{s}\bar{s}\rangle = |\text{flavor}\rangle \otimes |\text{spatial}\rangle \otimes |\text{spin}\rangle \otimes |\text{color}\rangle$$

(*AS*)

  - flavor: *symmetric*

  - spatial: only consider zero orbital angular momentum (lowest kinematic energy), *symmetric*

Two–pair channel $ss\overline{ss}$



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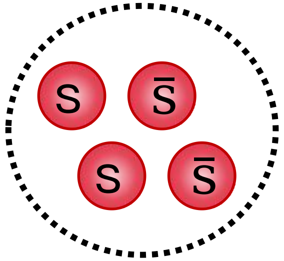
$$\underset{(AS)}{|ss\bar{s}\bar{s}\rangle} = \underset{(S)}{|\text{flavor}\rangle} \otimes \underset{(S)}{|\text{spatial}\rangle} \otimes \underset{(AS)}{\boxed{|\text{spin}\rangle \otimes |\text{color}\rangle}}$$

  - spin: spin state of diquark can be S = 0 (*anti–symmetric*) or S = 1 (*symmetric*)

  - color: color state of diquark can be antitriplet state $\overline{\mathbf{3}}_c$ (*anti–symmetric*) or sextet $\mathbf{6}_c$ (*symmetric*)

Two–pair channel $ss\overline{ss}$



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  - color: color state of diquark can be antitriplet state $\overline{\mathbf{3}}_c$ (*anti–symmetric*) or sextet $\mathbf{6}_c$ (*symmetric*)

- Configuration (a): spin in singlet (S=0) and color in sextet ($\mathbf{6}_c$).

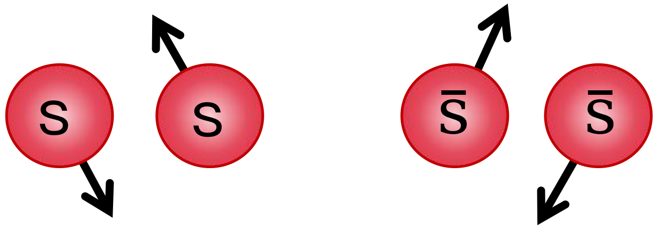
- Configuration (b): spin in triplet (S=1) and color in antitriplet ($\overline{\mathbf{3}}_c$).

Configuration (a): spin in singlet (S=0) and color in sextet (6_c)

- The ss and $\overline{ss}$ are in spin singlet, and total spin of the $ss\overline{ss}$ is 0:

$$|ss\bar{s}\bar{s};6_c\otimes\bar{6}_c\rangle^{(2)}=\frac{1}{2}\left(|\uparrow\downarrow\rangle-|\downarrow\uparrow\rangle\right)\left(|\uparrow\downarrow\rangle-|\downarrow\uparrow\rangle\right)$$

ss $\overline{ss}$



Spin correlation:

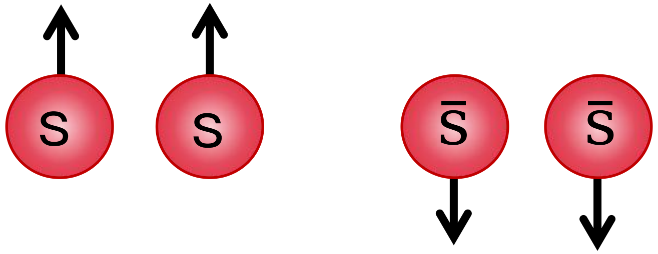
$$P^{(2)}_{ss(\bar{s}\bar{s}),(a)}=-1$$

$$P^{(2)}_{s\bar{s},(a)}=0$$

Configuration (b): spin in triplet (S=1) and color in antitriplet ($\overline{3}_c$).

- The ss and $\overline{ss}$ are in spin triplet, and total spin of $ss\overline{ss}$ is 0:

$$\left|ss\bar{s}\bar{s};\bar{3}_c\otimes 3_c\right\rangle^{(2)}=\frac{1}{\sqrt{3}}\left|S=1\right\rangle_{ss}\left|S=-1\right\rangle_{\bar{s}\bar{s}}$$
$$-\frac{1}{\sqrt{3}}\left|S=0\right\rangle_{ss}\left|S=0\right\rangle_{\bar{s}\bar{s}}+\frac{1}{\sqrt{3}}\left|S=-1\right\rangle_{ss}\left|S=1\right\rangle_{\bar{s}\bar{s}}$$



Spin correlation:

$$P^{(2)}_{ss(\bar{s}\bar{s}),(b)}=\frac{1}{3}\qquad\qquad P^{(2)}_{s\bar{s},(b)}=-\frac{2}{3}.$$

True spin correlation is a mixture of all channels/configurations

- **One-pair spin correlation is quite certain:** $P_{s\bar{s}}^{(1)} = \frac{1}{3}$
- **Two-pair spin correlation allows more possibilities**

	Color(a)	Color(b)
ΛΛ ($\overline{\Lambda\Lambda}$)	$P^{(2)}_{ss(\bar{s}\bar{s}),(a)} = -1$	$P^{(2)}_{ss(\bar{s}\bar{s}),(b)} = \frac{1}{3}$
Λ$\overline{\Lambda}$	$P^{(2)}_{s\bar{s},(a)} = 0$	$P^{(2)}_{s\bar{s},(b)} = -\frac{2}{3}$

True spin correlation is a mixture of all channels/configurations

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- **Introduce two parameters:**

$\boldsymbol{F}$: $N_{s\bar{s}}/(N_{s\bar{s}} + N_{ss\bar{s}\bar{s}})$

$\boldsymbol{f}$: $N_{color(a)}/(N_{color(a)} + N_{color(b)})$

$$P_{s_1 s_2} = F \cdot P^{(1)}_{s_1 s_2} + (1-F) \cdot \left(f \cdot P^{(2)}_{s_1 s_2,(a)} + (1-f) \cdot P^{(2)}_{s_1 s_2,(b)}\right)$$

True spin correlation is a mixture of all channels/configurations

- One-pair spin correlation is quite certain: $P^{(1)}_{s\bar{s}} = \frac{1}{3}$
- Two-pair spin correlation allows more possibilities

Strong spin correlation is naturally expected for vacuum-excited quark pairs with $J^{PC} = 0^{++}$.

	Color(a)	Color(b)
$\Lambda\Lambda$ ($\overline{\Lambda\Lambda}$)	$P^{(2)}_{ss(\bar{s}\bar{s}),(a)} = -1$	$P^{(2)}_{ss(\bar{s}\bar{s}),(b)} = \frac{1}{3}$
$\Lambda\bar{\Lambda}$	$P^{(2)}_{s\bar{s},(a)} = 0$	$P^{(2)}_{s\bar{s},(b)} = -\frac{2}{3}$

What happen when quarks *hadronize* into hadrons ?

Connection with $\Delta \mathbf{R}$ dependence ?

- Introduce two parameters:

$\boldsymbol{F}$: $N_{s\bar{s}}/(N_{s\bar{s}} + N_{ss\bar{s}\bar{s}})$

$\boldsymbol{f}$: $N_{color(a)}/(N_{color(a)} + N_{color(b)})$

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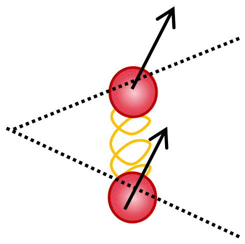
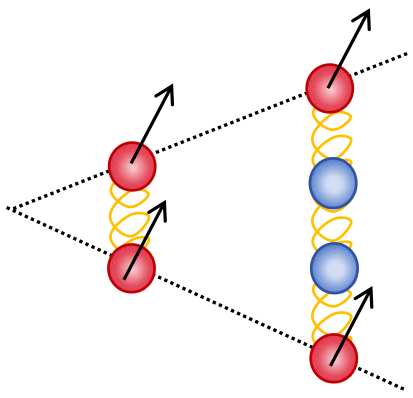
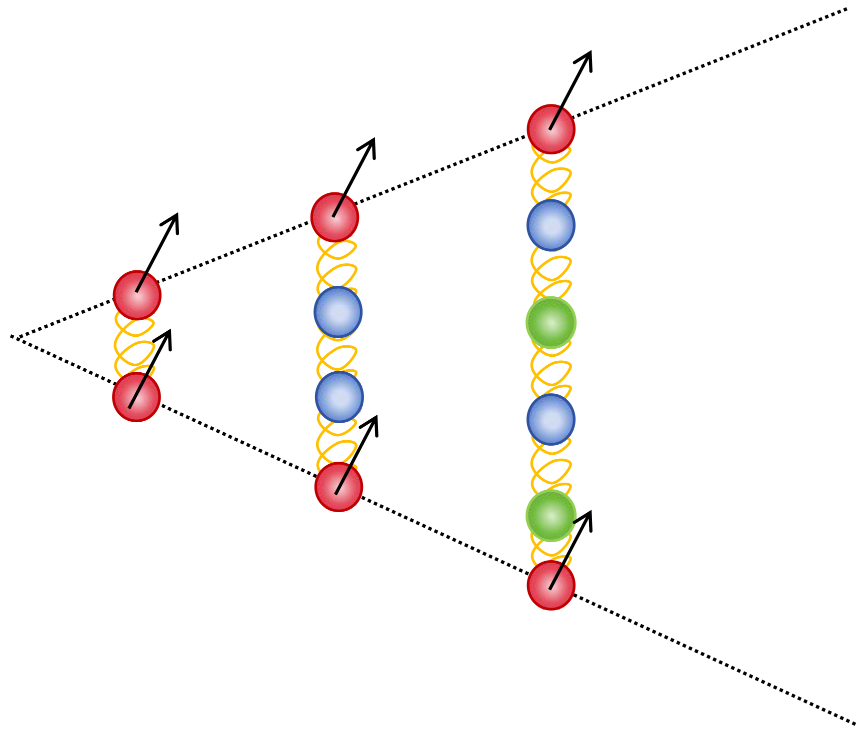
Hadornization via String Breaking



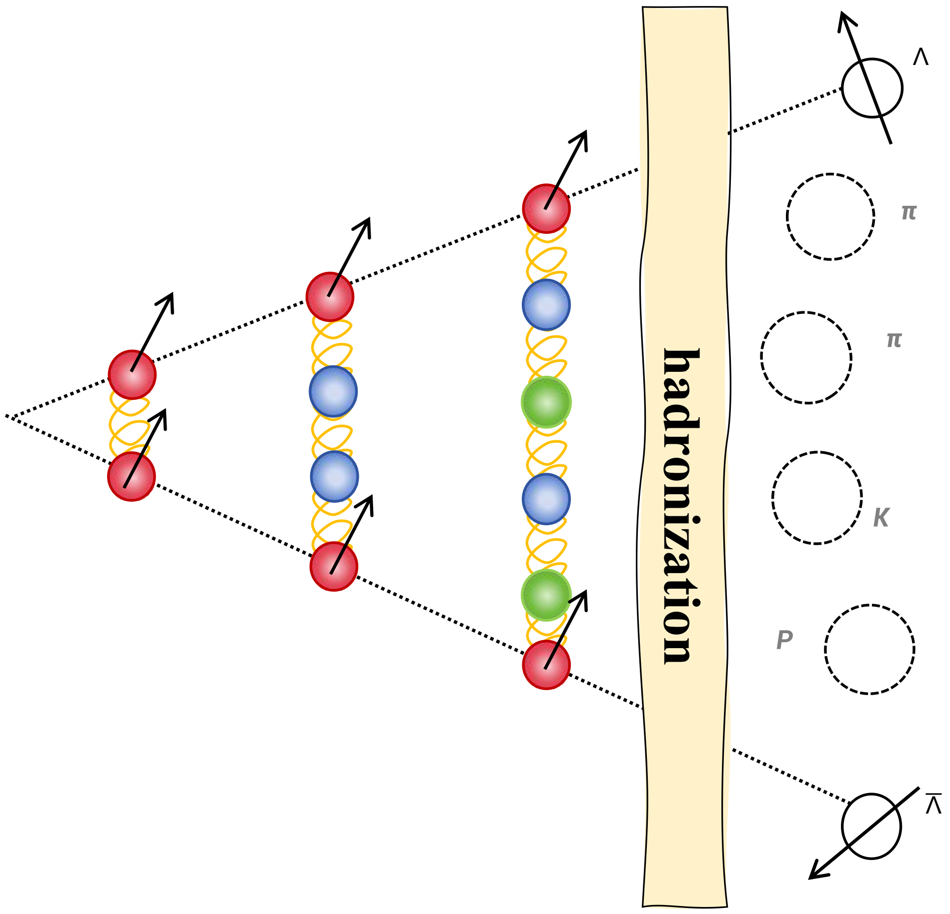
Hadornization via String Breaking



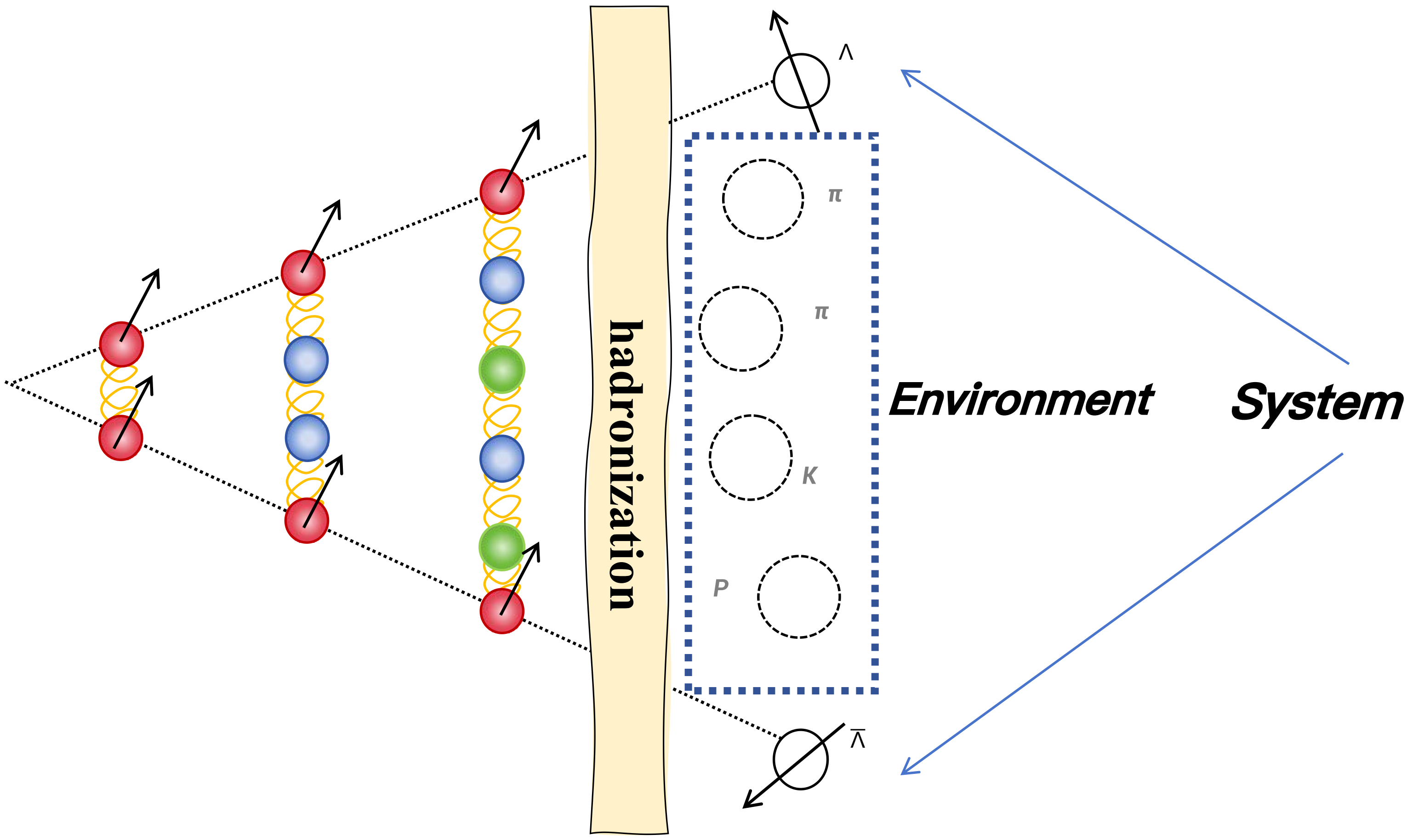
Hadornization via String Breaking



A string evolves into multiple hadrons



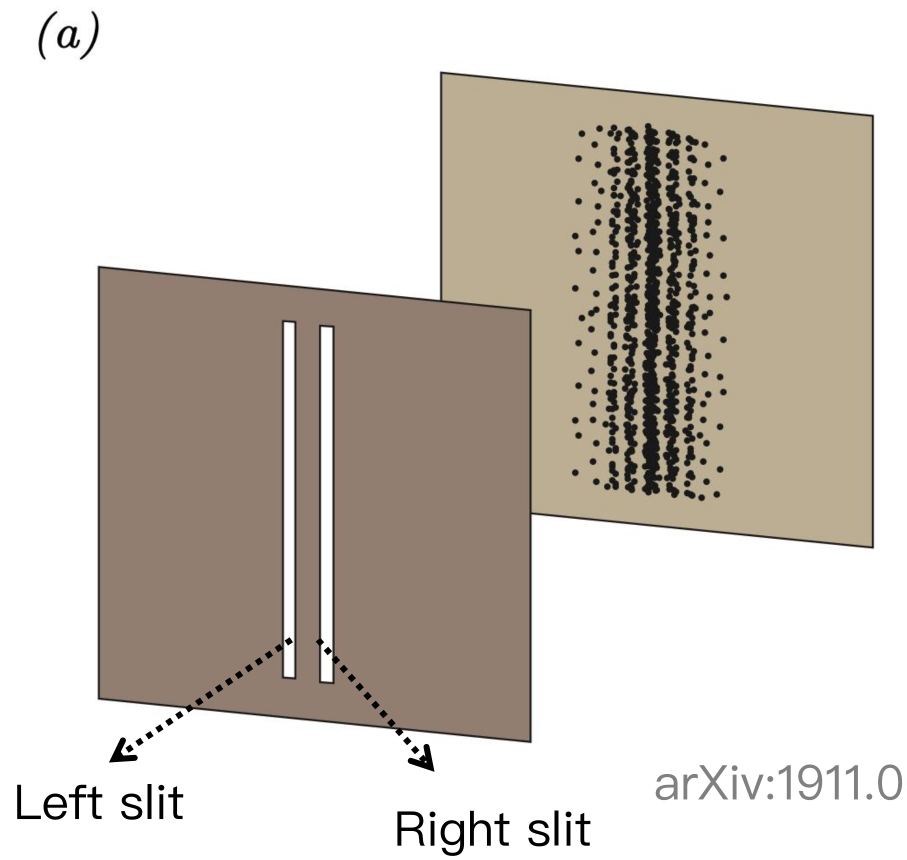
Identify environment and system degrees of freedom



What's the outcome of Interplay between environment and system ?

A Thought Experiment: double-slit experiment of electron

Send a beam of electrons through a double slit, and record the positions where eletrons arrive at the screen



arXiv:1911.06282

A Thought Experiment: double-slit experiment of electron

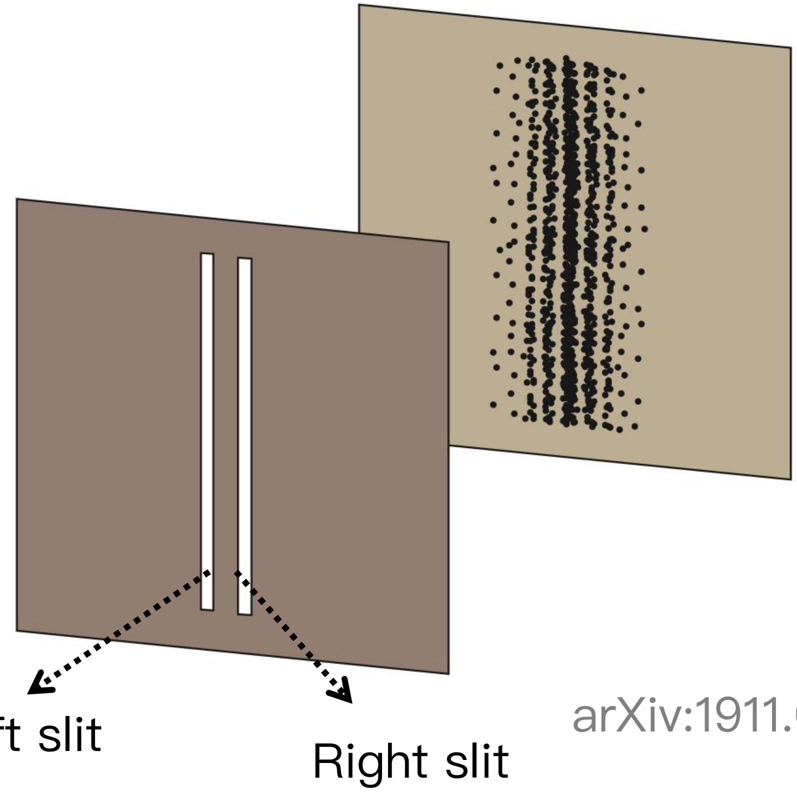
Send a beam of electrons through a double slit, and record the positions where eletrons arrive at the screen

- **One woule expect a interference pattern**
- **Since electron behaves like a wave, and one must use wave function to describe it.**

$$|e\rangle = |L\rangle + |R\rangle$$

$$\rho = |e\rangle\langle e| = |L\rangle\langle L| + |R\rangle\langle R| + \boxed{|L\rangle\langle R| + |R\rangle\langle L|}$$

(a)



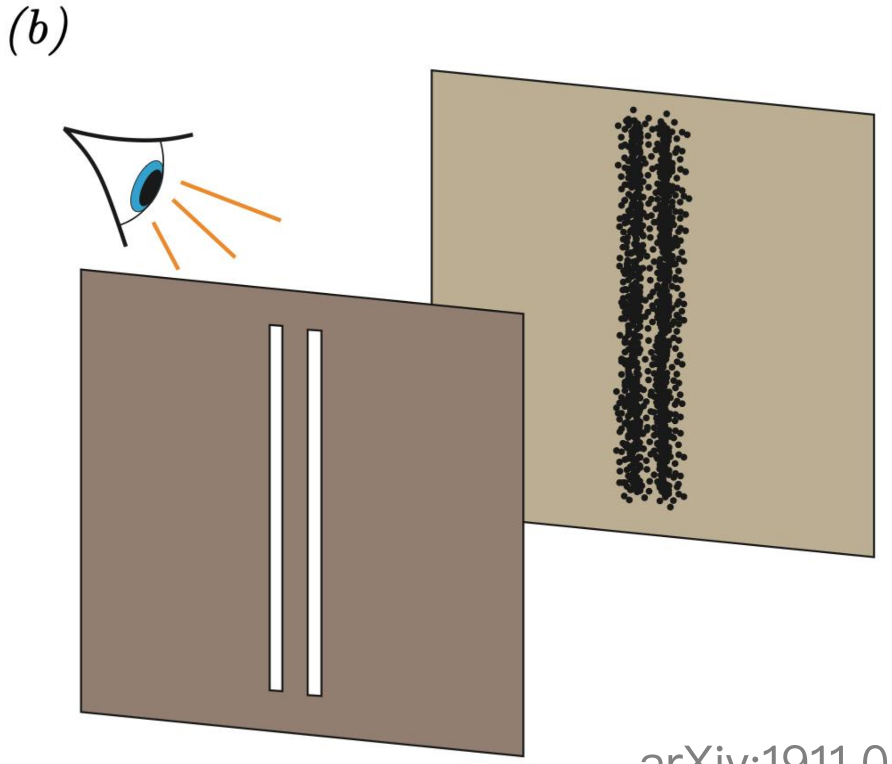
arXiv:1911.06282

Off-diagonal is responsible for quantum interference

A Thought Experiment: double-slit experiment of electron

But when an observer trys to detect which slit the electron went through...

- **The interference pattern immediately disapper, the electron behaves like just classical particle**



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A Thought Experiment: double-slit experiment of electron

But when an observer trys to detect which slit the electron went through...

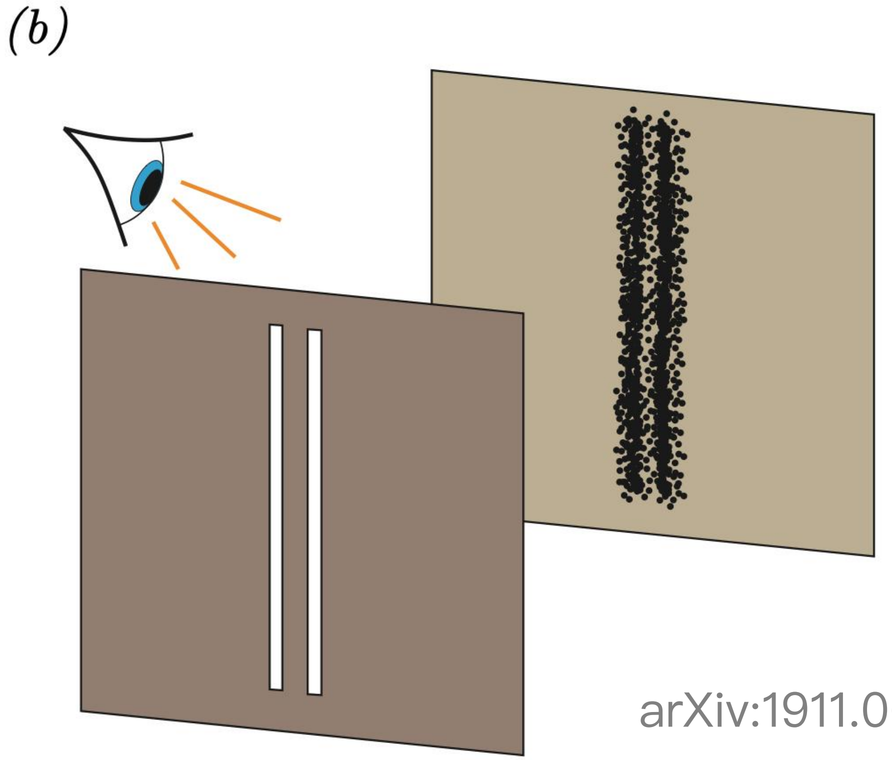
- **The wave function for electron-observer system**

$$|e \otimes O\rangle = |L\rangle|O_1\rangle + |R\rangle|O_2\rangle$$

- **Trace out the observer,**

$$\rho = \mathrm{Tr}_O |e \otimes O\rangle\langle e \otimes O|$$

$$= |L\rangle\langle L| + |R\rangle\langle R| + |L\rangle\langle R| \boxed{\langle O_2|O_1\rangle} + |R\rangle\langle L| \boxed{\langle O_1|O_2\rangle}$$



arXiv:1911.06282

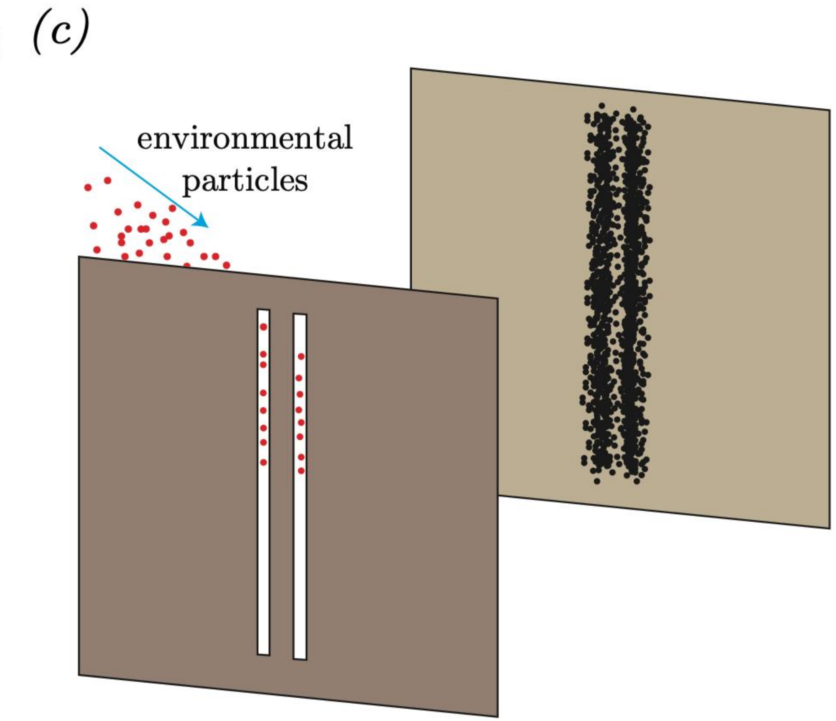
Off-diagonal is reduced

Decoherence is a General result in quantum system with environment/system

- **Observer can be any environmental degrees of freedom, as long as they can obtain *“which–way”* information.**

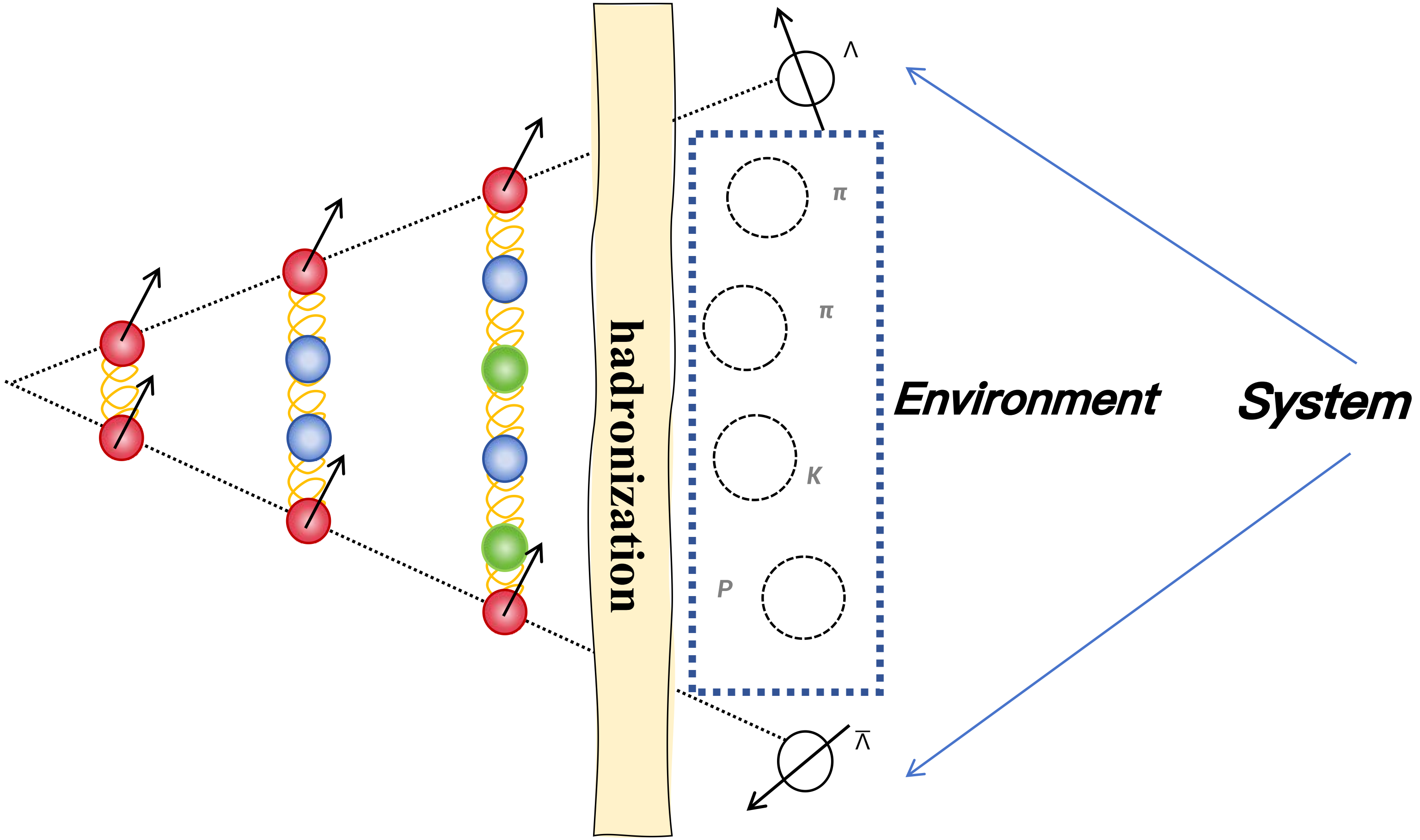
- **Decoherence should be applied to any quantum system, e.g., a highly entangled color string.**

Phys. Rev. D 113, 036013
Phys.Lett.B 868 (2025) 139806
arXiv 2601.17199



arXiv:1911.06282

Larger ΔR, more environmental degrees of freedom, then stronger decoherence



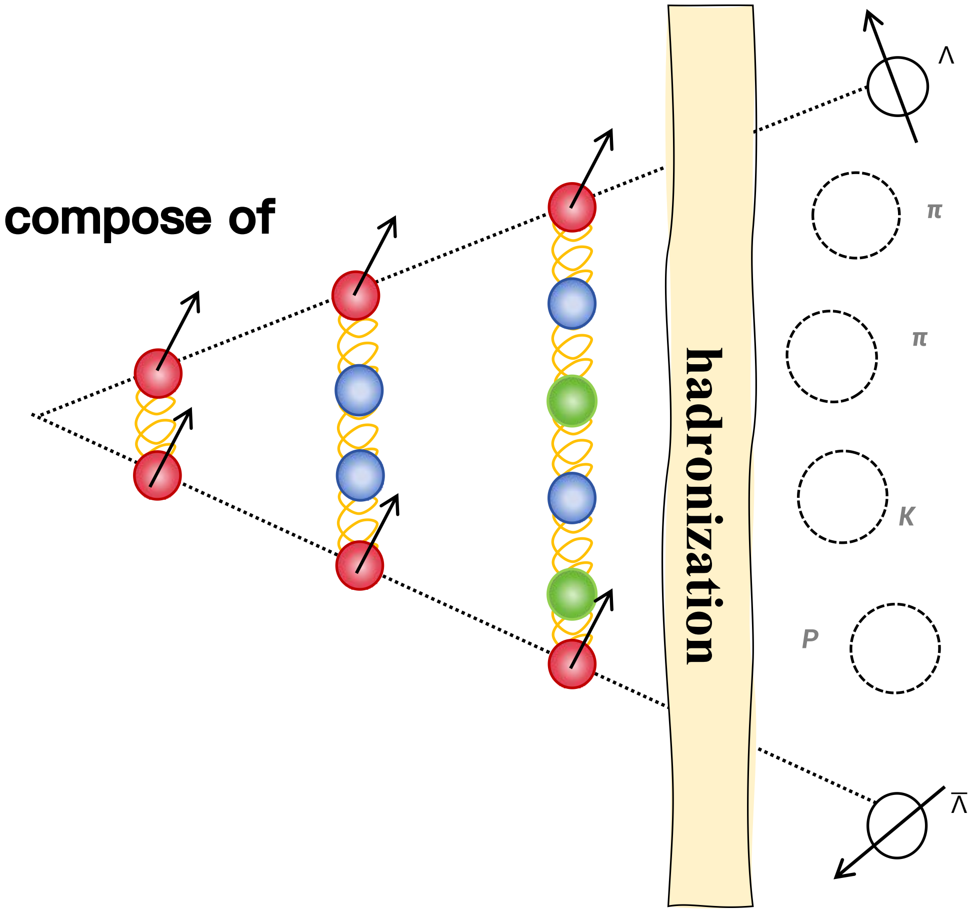
Quantum Decoherence in String Breaking

- **The system ($s\bar{s}$) is initially in the entangled state.**

$$|\mathrm{sys}\rangle = |\psi_1\rangle + |\psi_2\rangle$$

- **As the string breaking going on, intermediate quarks compose of environment.**

$$|\mathrm{sys} \otimes \mathrm{env}\rangle = |\psi_1\rangle\,|E_1\rangle + |\psi_2\rangle\,|E_2\rangle$$



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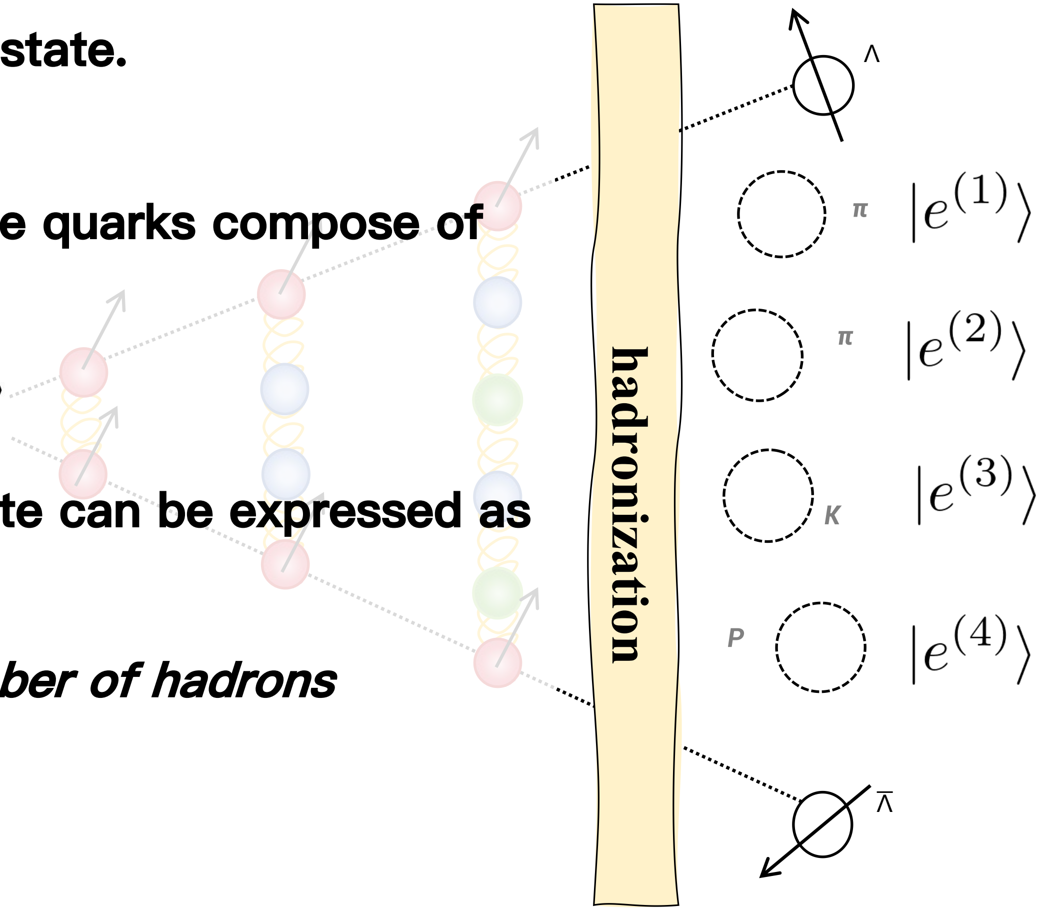
- **After hadron formation, the environment state can be expressed as individual hadron states**

$$|E_{1(2)}\rangle = \left(\prod_{i=1}^{n} \otimes\right) |e_{1(2)}^{(i)}\rangle$$

n is the number of hadrons



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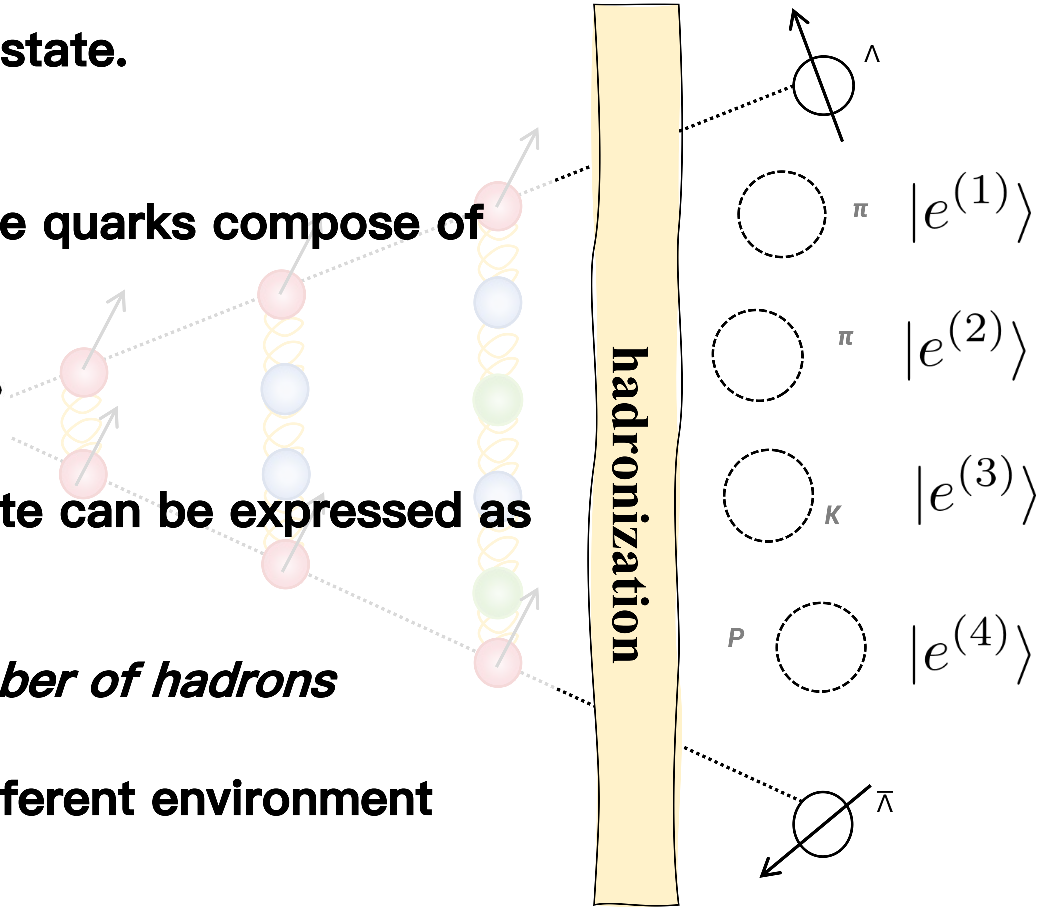
- **The decoherence factor is the overlap of different environment states,**

$$\alpha_n = \langle E_1 | E_2 \rangle = \prod_{i=1}^{n} \langle e^{(i)}_1 | e^{(i)}_2 \rangle$$



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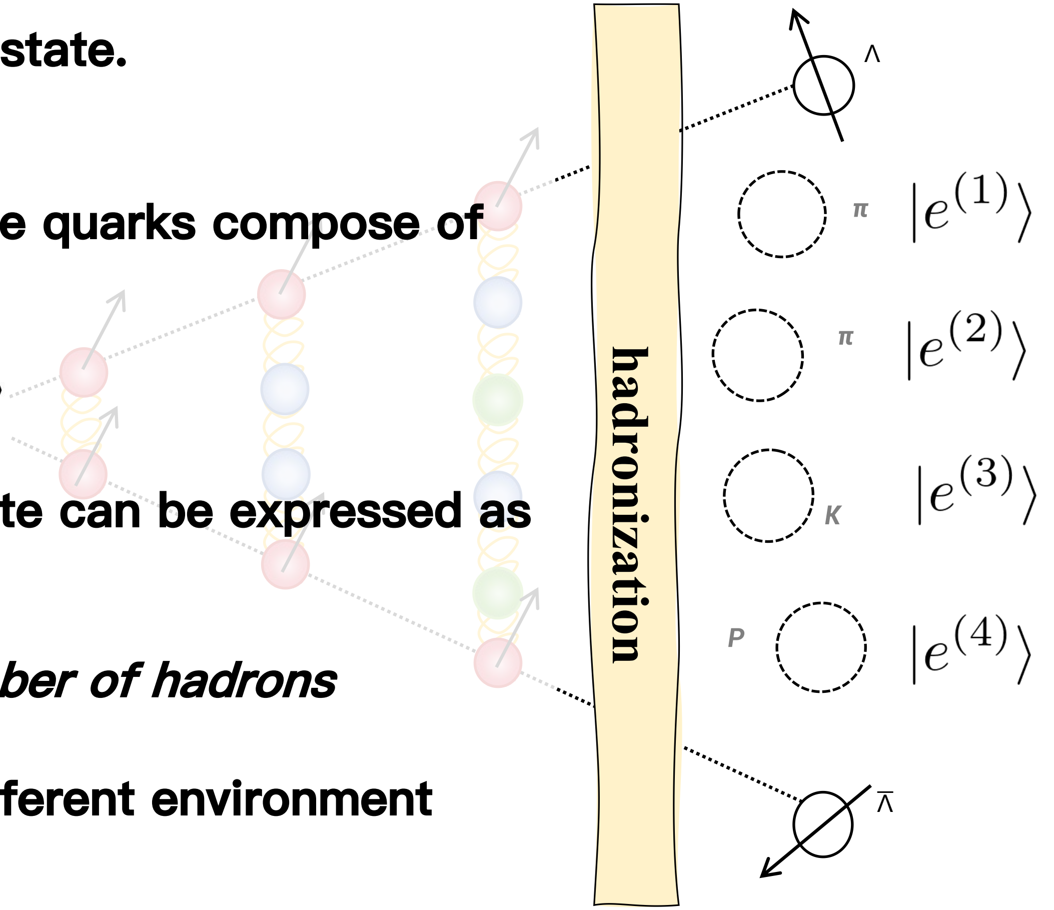
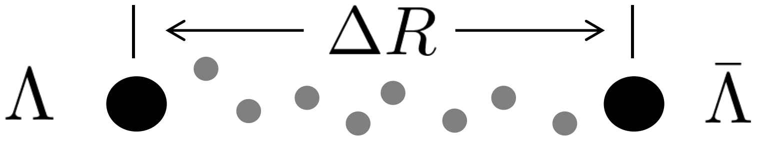


Quantum Decoherence in String Breaking

- **Decoherence factor**

$$\alpha_n = \prod_{i=1}^{n} \langle e_1^{(i)} | e_2^{(i)} \rangle = \beta^n$$

n is the number of hadrons



n Environemental hadrons

Quantum Decoherence in String Breaking

- **Decoherence factor**

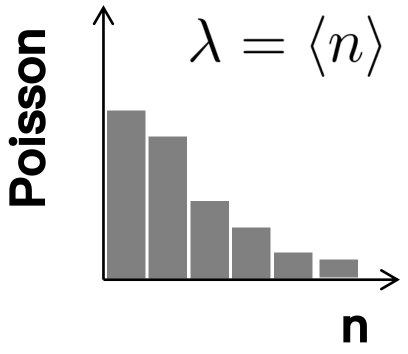
$$\alpha_n = \prod_{i=1}^{n} \langle e_1^{(i)} | e_2^{(i)} \rangle = \beta^n$$

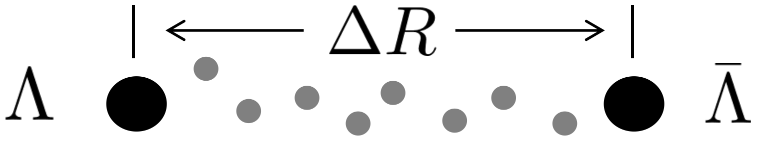
n is the number of hadrons

- **Assume the number of hadrons within in $\Delta \boldsymbol{R}$ window follows Poisson distribution:**

$$p(n) = \frac{\lambda^n}{n!} e^{-\lambda}$$

$\boldsymbol{\lambda}$ is the average number of hadrons within $\Delta \boldsymbol{R}$





n Environemental hadrons

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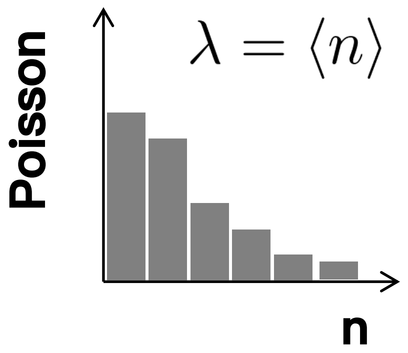
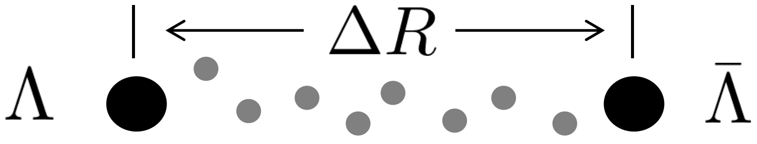


- **Assume the number of hadrons within in $\Delta \boldsymbol{R}$ window follows Poisson distribution:**

$$p(n) = \frac{\lambda^n}{n!} e^{-\lambda} \qquad \lambda = k\Delta R$$

$\boldsymbol{\lambda}$ is the average number of hadrons within $\Delta \boldsymbol{R}$

***k* is the density (per unit of $\Delta \boldsymbol{R}$) of environmental hadrons**



n Environonemental hadrons

Quantum Decoherence in String Breaking

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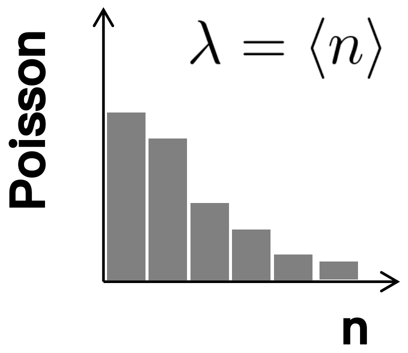
n is the number of hadrons



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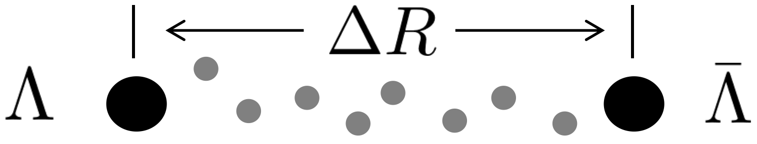


- **Average decoherence factor:**

$$\alpha(\Delta R) = \sum_n \alpha_n \, p(n) = \exp\left(-k^* \cdot \Delta R\right) \qquad k^* = (1-\beta)k$$

n Environemental hadrons

k* is proportional to the number of hadrons per unit of $\Delta \boldsymbol{R}$: $k^* \propto \dfrac{\langle n \rangle}{\Delta R}$

Put everything together, vacuum excitation and witness effect

- **The ΔR dependence:**

$$P(\Delta R) = P_{s_1 s_2} \cdot e^{-k^* \Delta R}$$

where $P_{s_1 s_2}$ **is the spin correlation at the production of $s\bar{s}$, i.e. ,**

$$P_{s_1 s_2} = F \cdot P^{(1)}_{s_1 s_2} + (1-F) \cdot \left(f \cdot P^{(2)}_{s_1 s_2,(a)} + (1-f) \cdot P^{(2)}_{s_1 s_2,(b)} \right)$$

- **Three free parameters to describe all:**

Parameter	Definition
One-/two-pair fraction, F	$N_{s\bar{s}}/(N_{s\bar{s}} + N_{ss\bar{s}\bar{s}})$
Color-configuration fraction, f	$N_{\lvert ss\bar{s}\bar{s};6_c\otimes\bar{6}_c\rangle}/(N_{\lvert ss\bar{s}\bar{s};6_c\otimes\bar{6}_c\rangle} + N_{\lvert ss\bar{s}\bar{s};\bar{3}_c\otimes 3_c\rangle})$
Decoherence factor, k^*	Strength of the decoherence effect

Describe STAR and CMS data

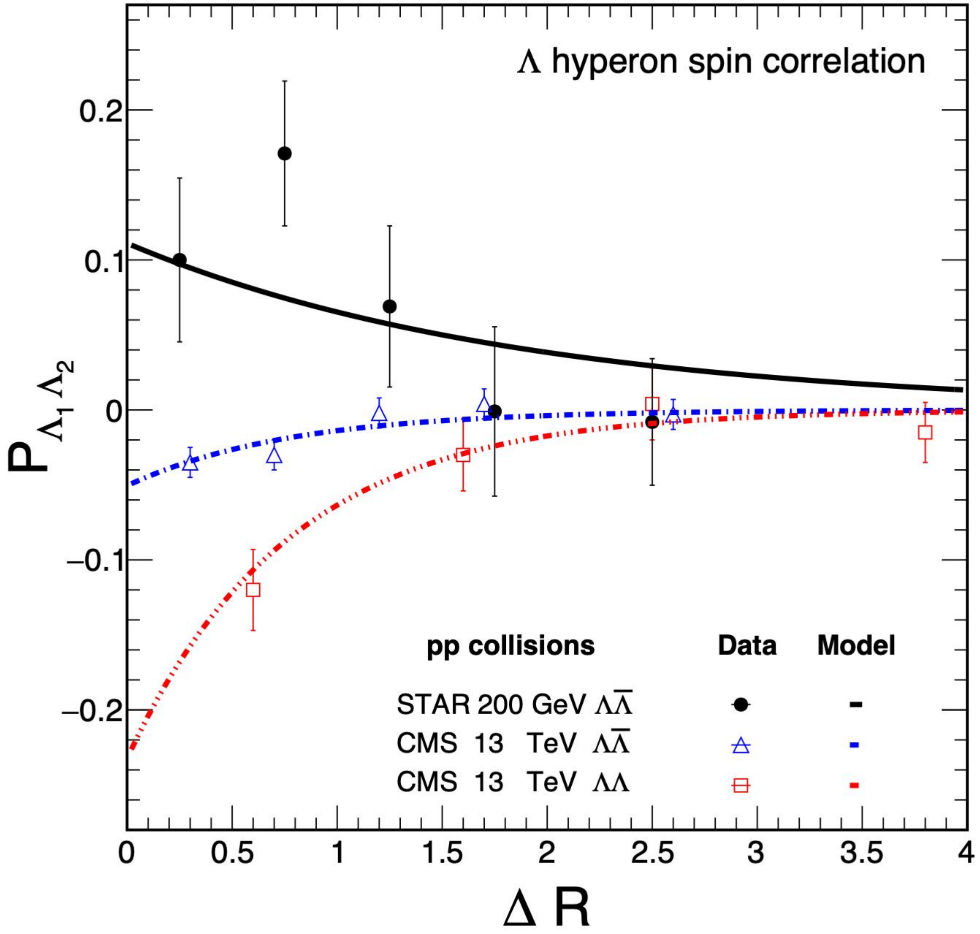
Parameter	Definition
One-/two-pair fraction, F	$N_{s\bar{s}}/(N_{s\bar{s}} + N_{ss\bar{s}\bar{s}})$
Color-configuration fraction, f	$N_{\lvert ss\bar{s}\bar{s};6_c\otimes\bar{6}_c\rangle}/(N_{\lvert ss\bar{s}\bar{s};6_c\otimes\bar{6}_c\rangle} + N_{\lvert ss\bar{s}\bar{s};\bar{3}_c\otimes 3_c\rangle}$
Decoherence factor, k^*	Strength of the decoherence effect

- **Fit the STAR data with all three free parameters.**

- **Predict the paramter k^* at LHC energy using that at RHIC energy, leaving two free parameters for describing $\Lambda\Lambda$ ($\overline{\Lambda\Lambda}$) at CMS.**

$$k^* \propto \frac{\langle n \rangle}{\Delta R}$$

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



Describe STAR and CMS data

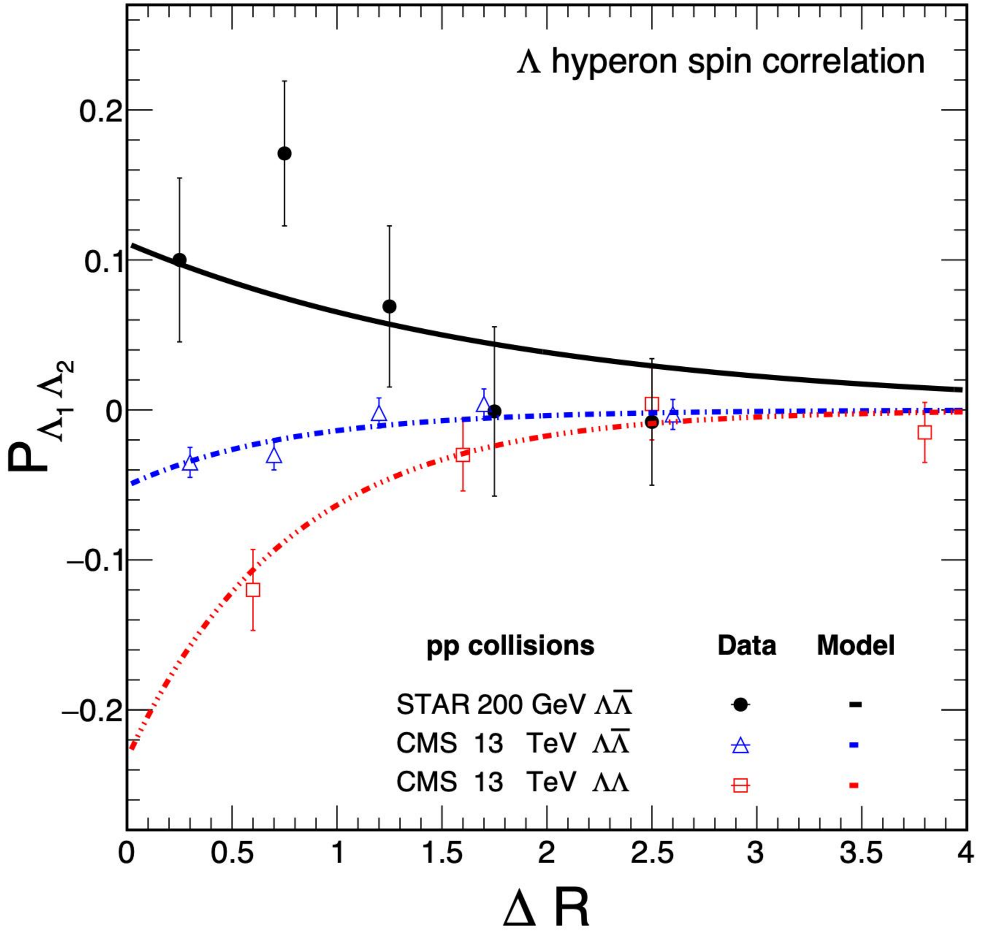
Parameter	Definition	STAR	CMS
One-/two-pair fraction, F	$N_{s\bar{s}}/(N_{s\bar{s}} + N_{ss\bar{s}\bar{s}})$	1.0 ± 0.72	0.0 ± 0.12
Color-configuration fraction, f	$N_{\lvert ss\bar{s}\bar{s};6_c\otimes\bar{6}_c\rangle}/(N_{\lvert ss\bar{s}\bar{s};6_c\otimes\bar{6}_c\rangle} + N_{\lvert ss\bar{s}\bar{s};\bar{3}_c\otimes 3_c\rangle})$	0.93 ± 0.51	0.78 ± 0.05
Decoherence factor, k^*	Strength of the decoherence effect	0.53 ± 0.29	1.29 ± 0.737 (fixed para.)

- **One-pair/Two-pair fraction F:** one-pair excitation dominant at RHIC energy, while two-pair excitation at LHC energies.

- **Color configurations fraction f:** two color configuration is mixed.

- **Decoherence factor $\mathbf{k}^*$:** the scaling relation is consistant with data.

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



Summary

- **We propose a model:**
  - **Extend the vacuum excitation, considering one-pair and two-pair channels.**
  - **Observed ΔR dependence can be explained by the quantum decoherence in hadronization.**
- **The model can describe all available data quite well.**
- **Future measurements at different energies/systems could provide more test on the model.**