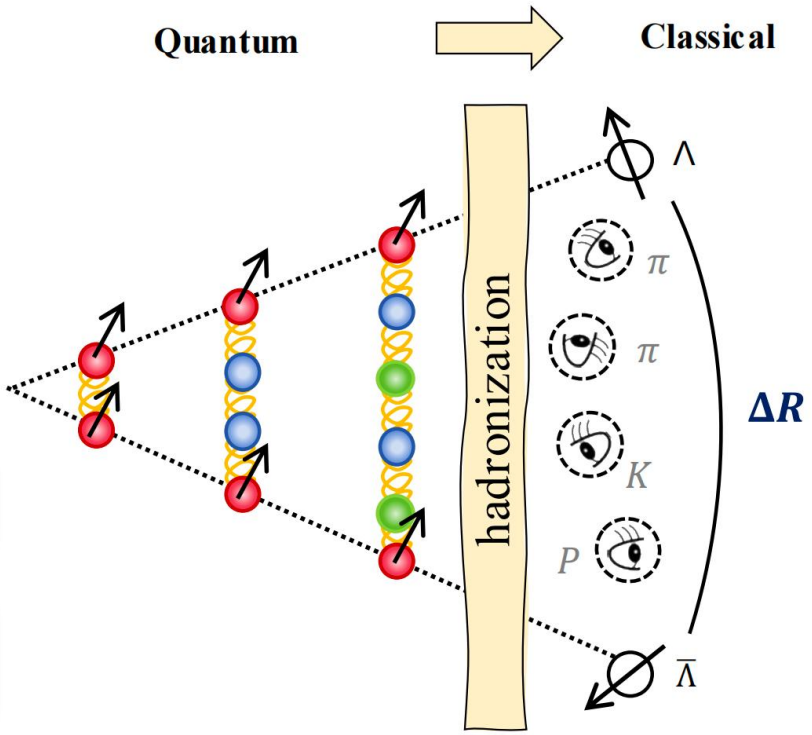
Understanding Quantum Decoherence during Hadronization with Hyperon Spin Correlation

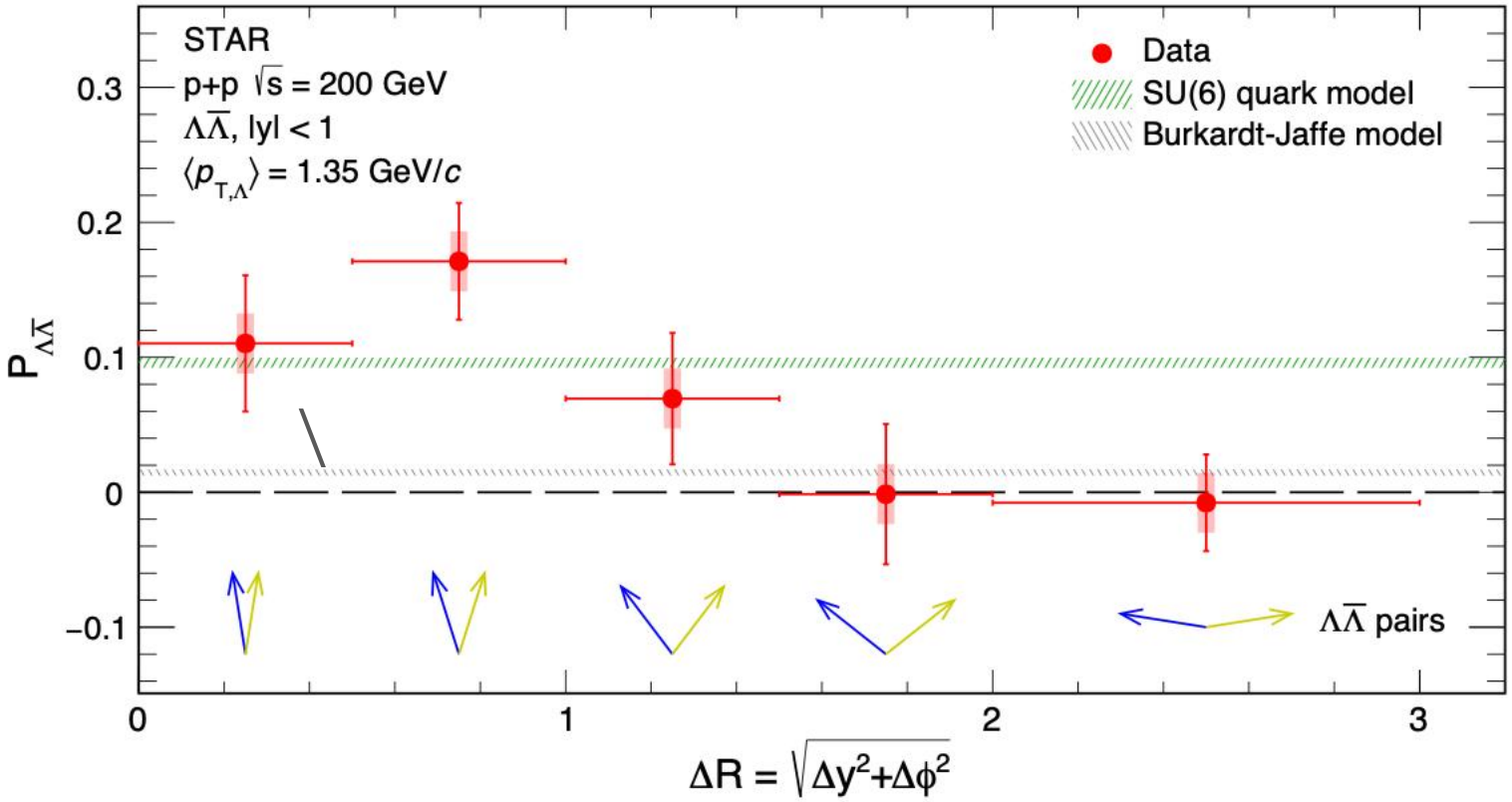
Feng Liu ,SBU
In Collaboration With
Zhoudunming(Kong) Tu, SBU/BNL



Vacuum Excitation: Virtual $q\bar{q}$ becomes Real

- If a pair of $q\bar{q}$ carries vacuum quantum number $J^{PC} = 0^{++}$, they will be in the spin triplet.
- One can even show that the pair is in a Bell state with *maximal quantum entanglement.*

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



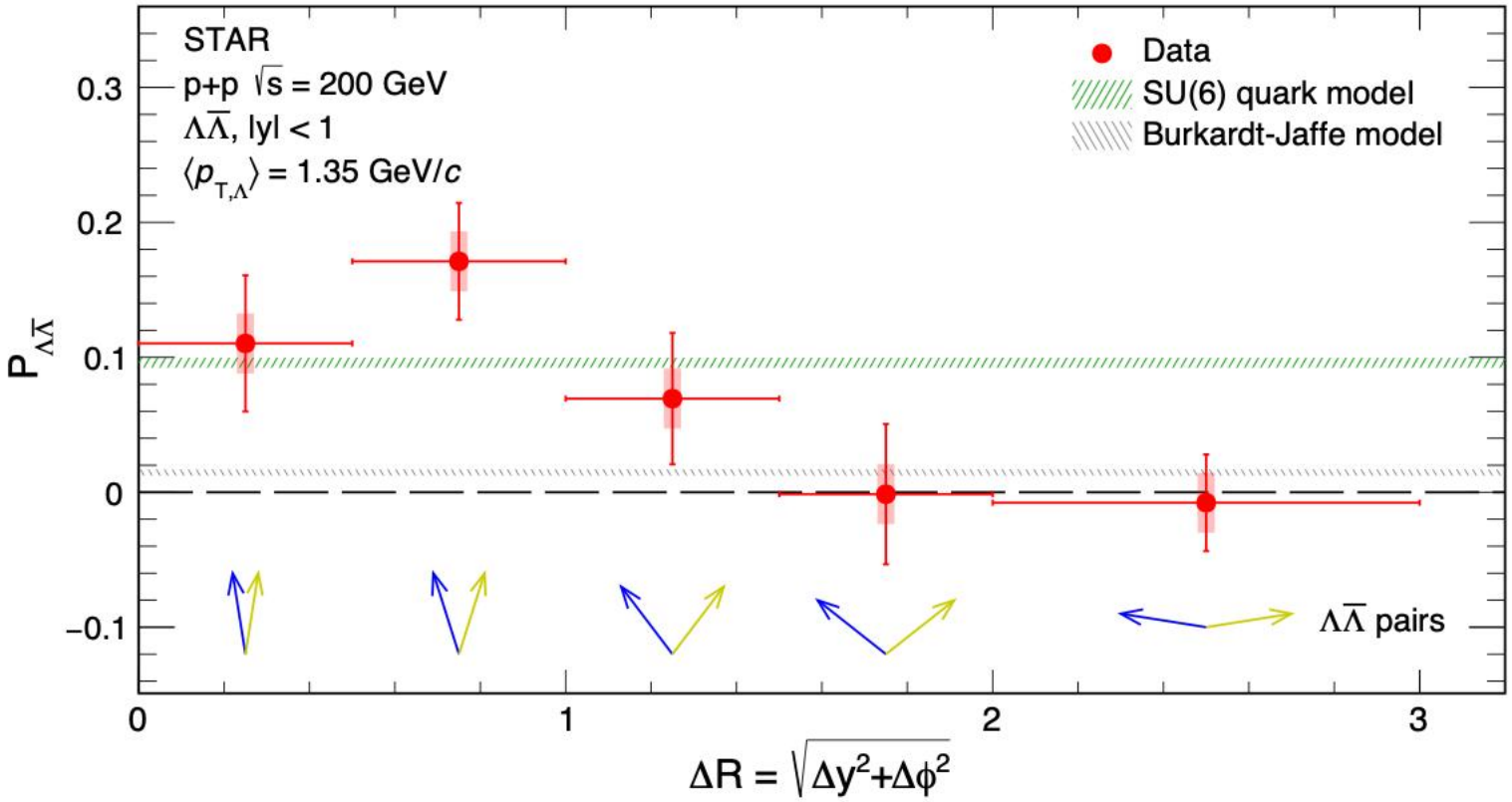
Nature volume 650, pages 65–71 (2026)

Consistent with *vacuum excitation*, but where does ΔR dependence come from ?

- If a pair of $q\bar{q}$ carries vacuum quantum number $J^{PC} = 0^{++}$, they will be in the spin triplet.
- One can even show that the pair is in a Bell state with *maximal quantum entanglement.*

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

- Vacuum excitation does not tell where the ΔR dependence come from ???



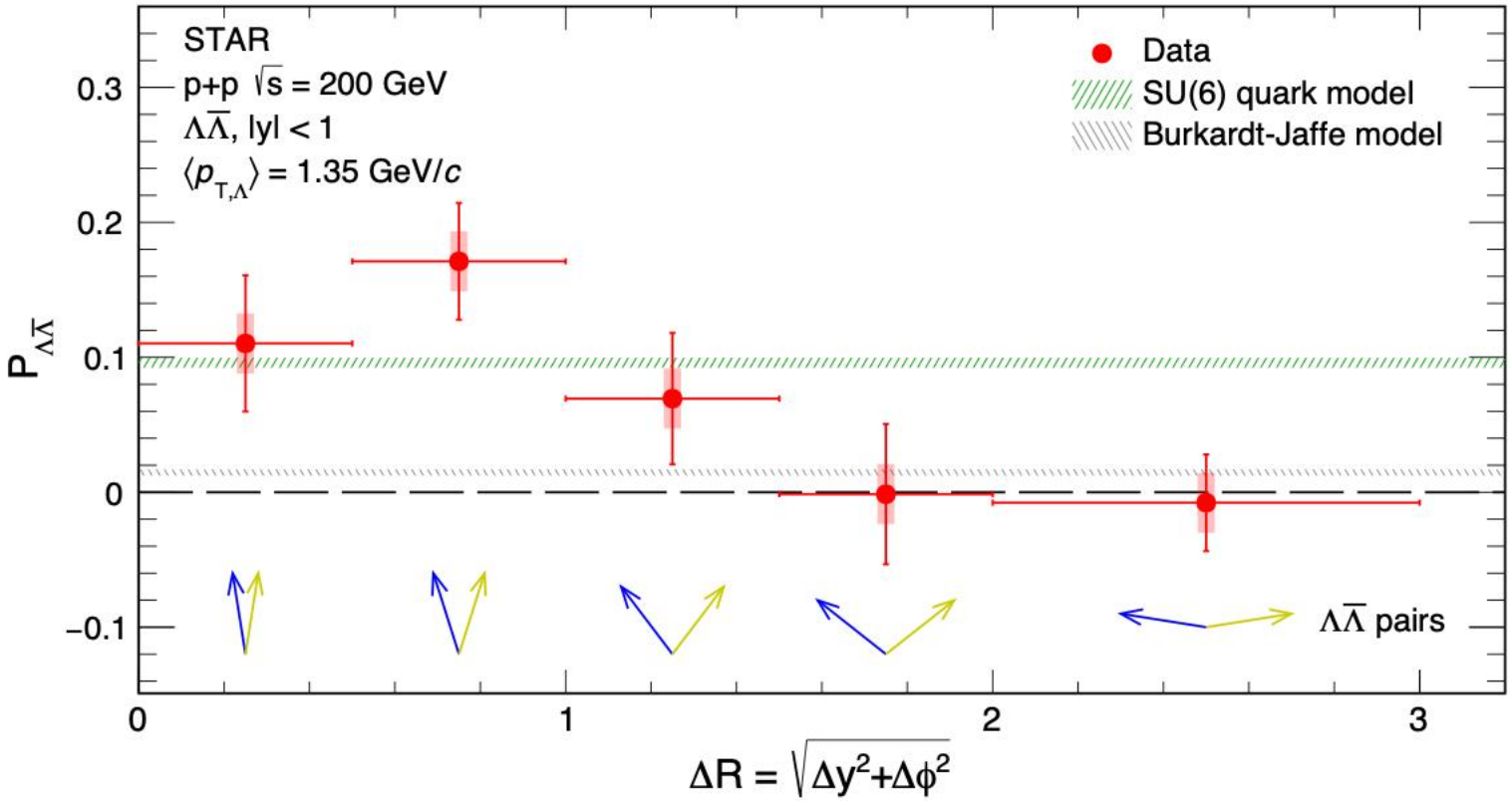
Nature volume 650, pages 65–71 (2026)

Consistent with *vacuum excitation*, but where does ΔR dependence come from ?

- If a pair of $q\bar{q}$ carries vacuum quantum number $J^{PC} = 0^{++}$, they will be in the spin triplet.
- One can even show that the pair is in a Bell state with *maximal quantum entanglement.*

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

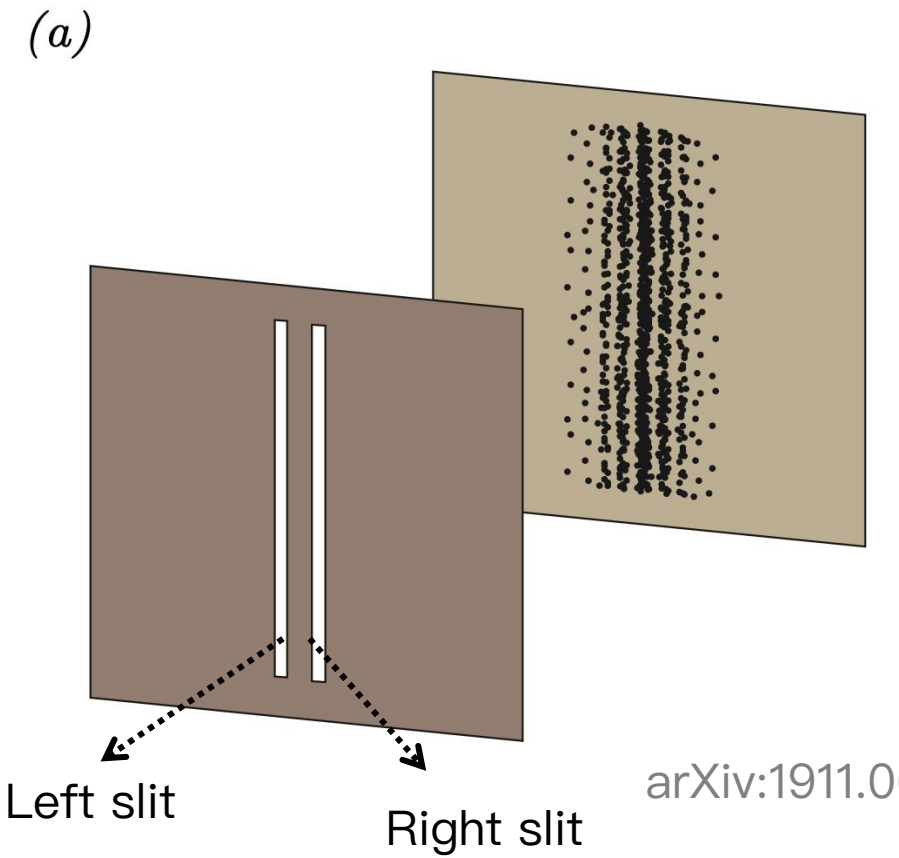
- Vacuum excitation does not tell where the ΔR dependence come from ???



In this talk, a picture based on quantum decoherence will be introduced.

Let's do 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

Let's do a Thought Experiment: double-slit experiment of electron

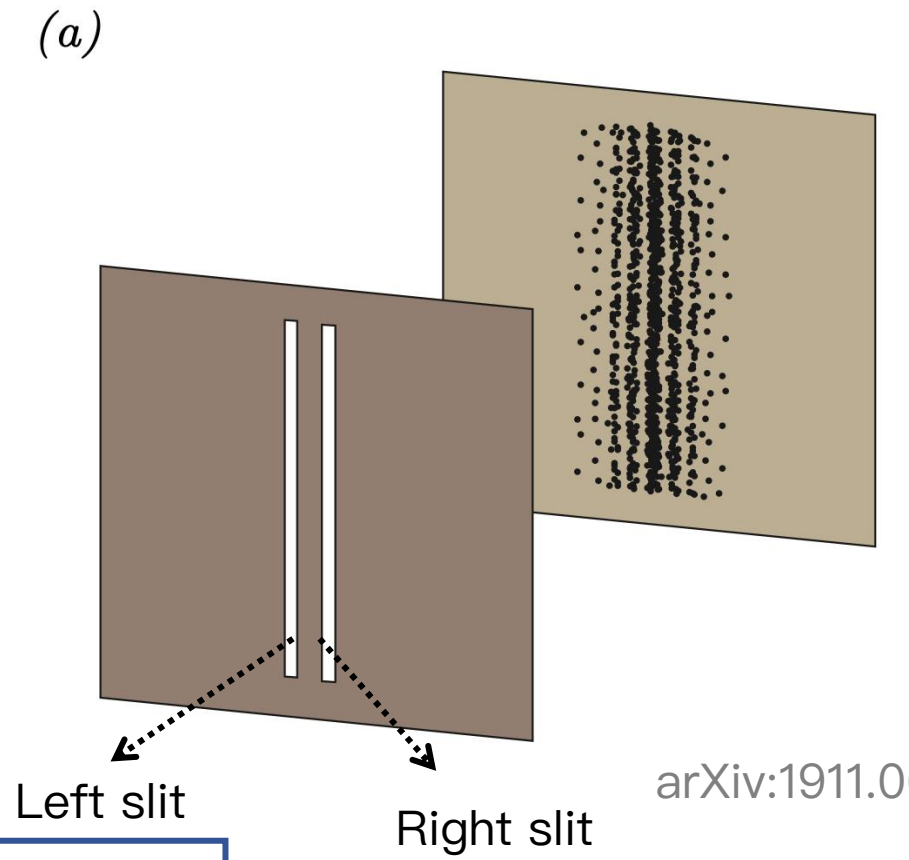
Send a beam of electrons through a double slit, and record the positions where eletrons arrive at the screen

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

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

$$\rho = |e\rangle\langle e|$$

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



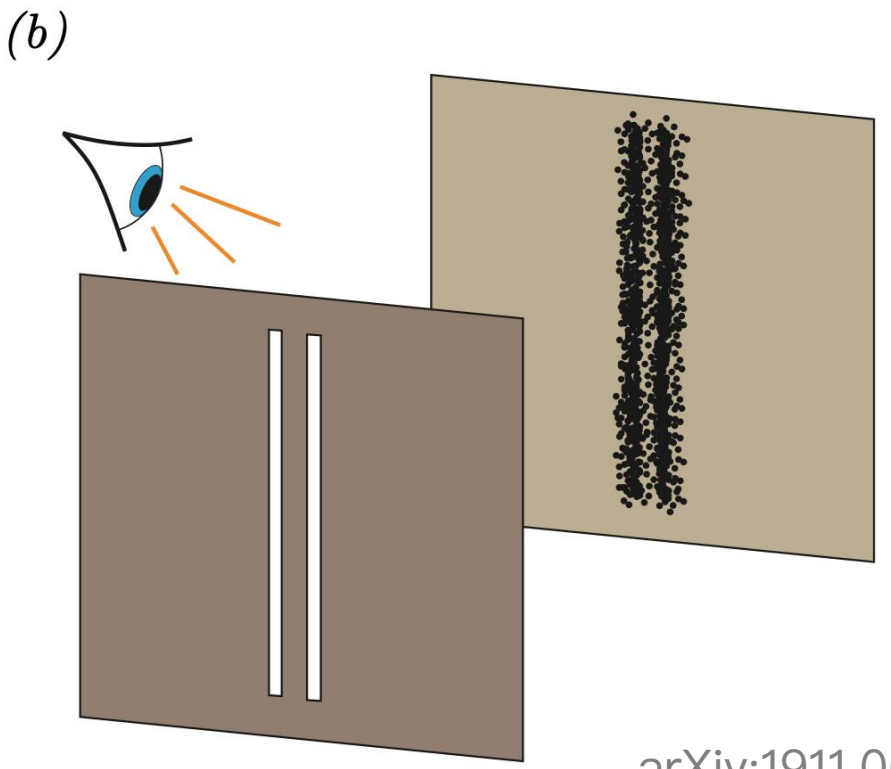
arXiv:1911.06282

Off-diagonal is responsible for quantum interference

Let's do a Thought Experiment: double-slit experiment of electron

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

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



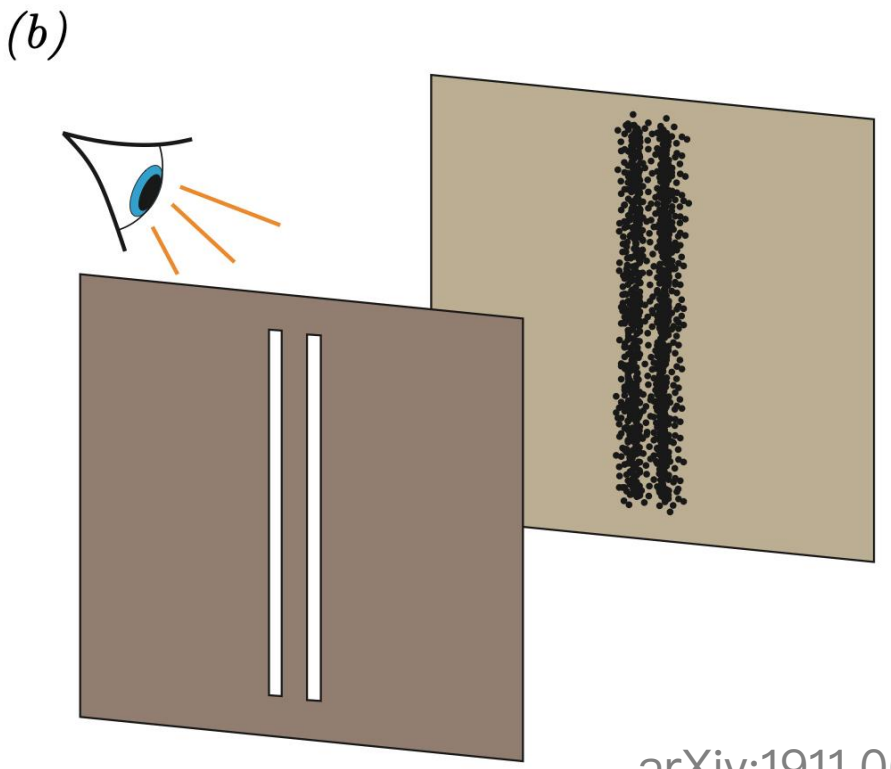
arXiv:1911.06282

Let's do a Thought Experiment: double-slit experiment of electron

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

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

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



arXiv:1911.06282

Let's do a Thought Experiment: double-slit experiment of electron

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

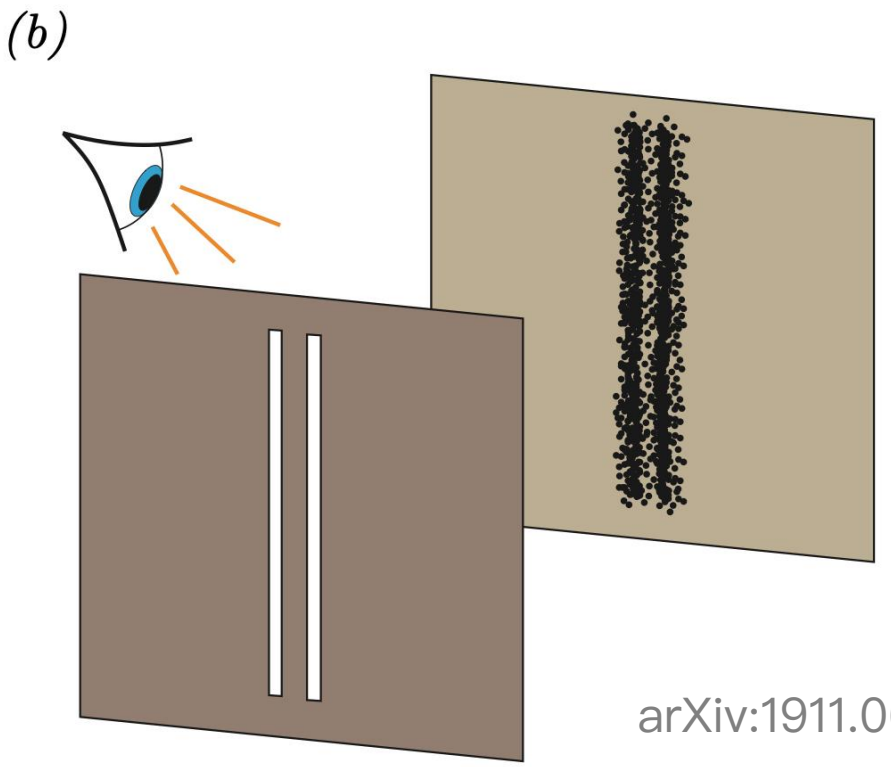
- **The wave function for electron–observer system**

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

- **Trace out the observer,**

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

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

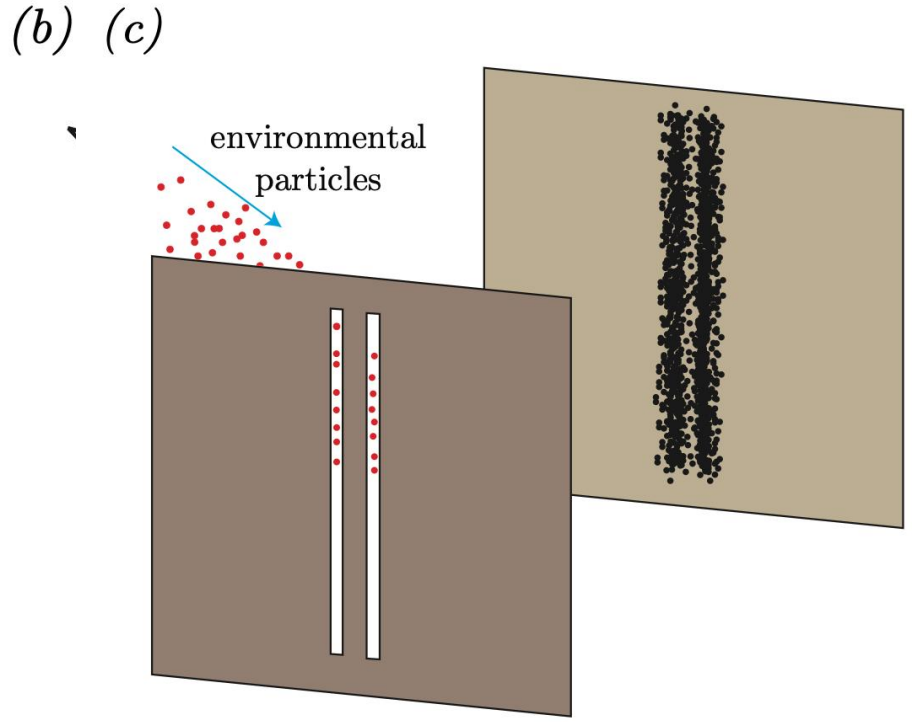


arXiv:1911.06282

Off-diagonal is reduced

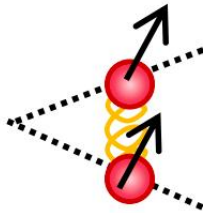
Decoherence is induced by environmental degrees of freedom

- Observer can be any environmental degrees of freedom.
- In hadronization, partons produced by string break dynamics can act as environmental degrees of freedom.



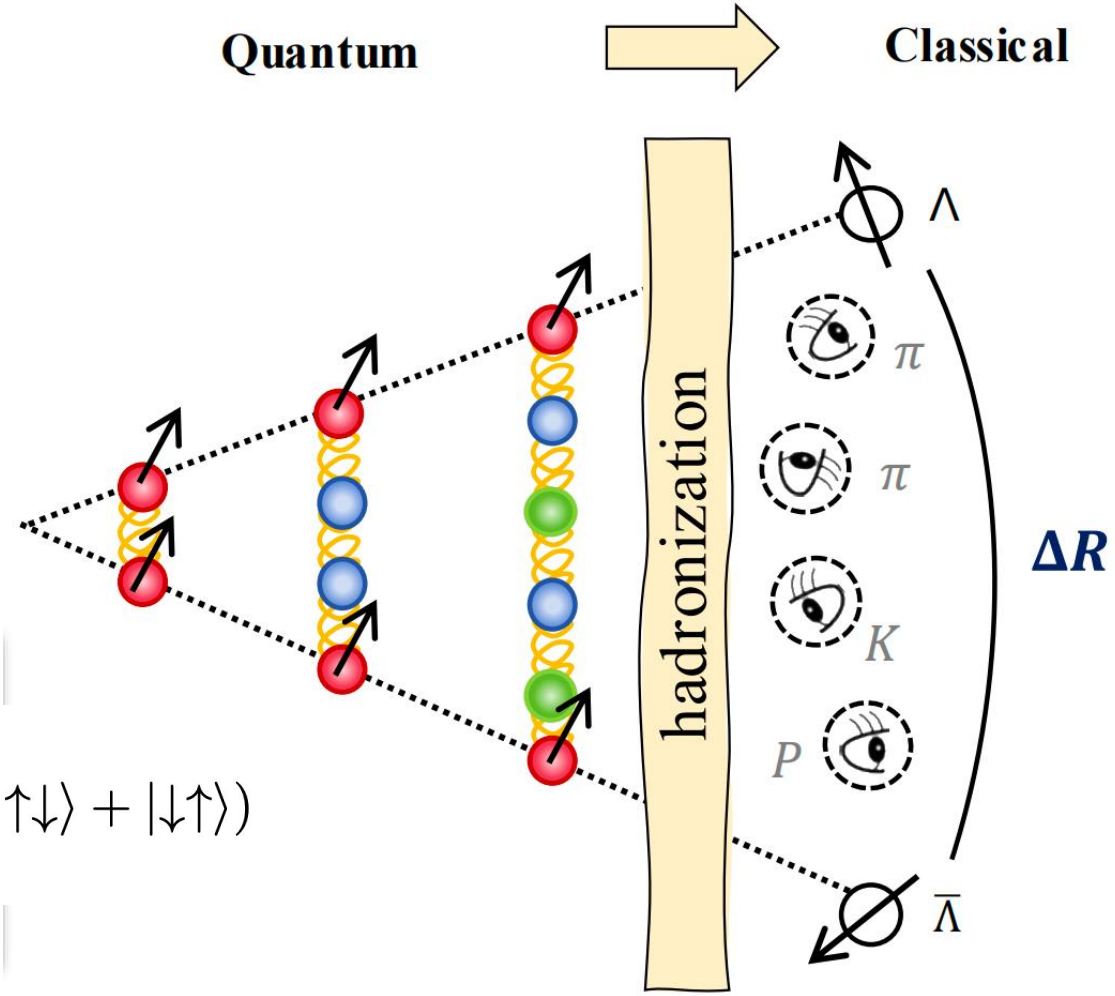
arXiv:1911.06282

Vacuum Excitation, and what next ?

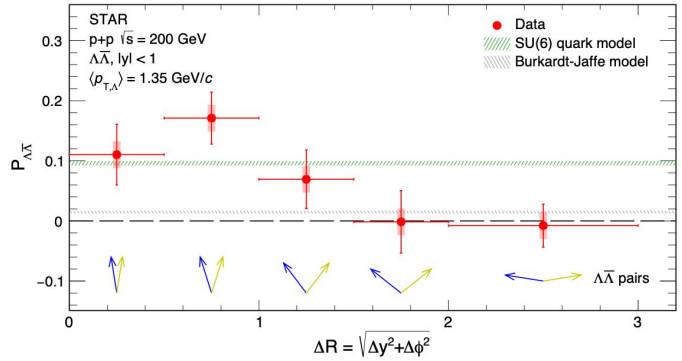


$$|s\bar{s}\rangle^{(1)} = \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle\right)$$

String breaking dynamics induce quantum decoherence



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



Intermediate hadrons serve as observers.

How well it can describe data?

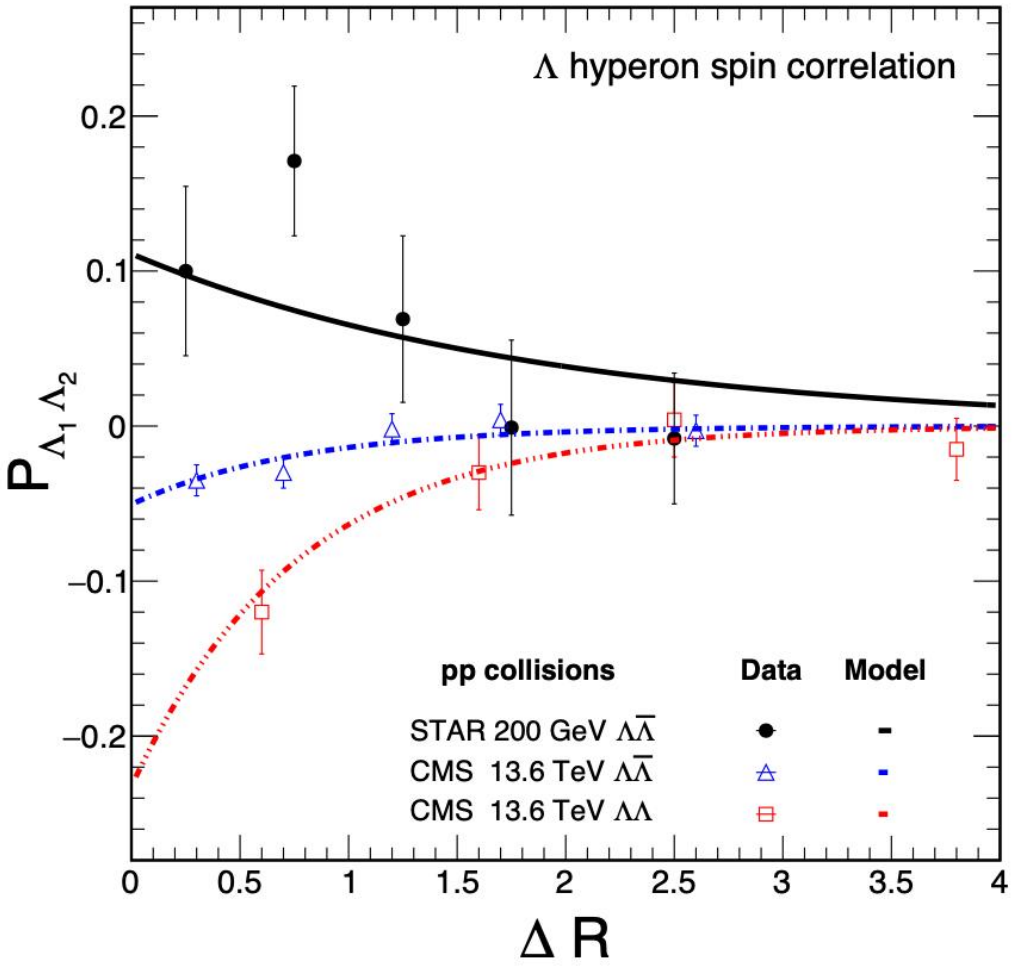
One can show, with some assumption, that [*]

$$P_{\Lambda_1\Lambda_2} = P \cdot e^{-k^* \Delta R}$$

- **Fit STAR data to extract the k* at 200 GeV**
- **Using published data of dN/deta, one can predict the k* at 13 TeV**

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

- **Leaving only paramter P free at 13 TeV.**



Describe data at 200GeV and 13 TeV remarkly well !

[*] *The paper draft is in preparation, and will come out soon.*

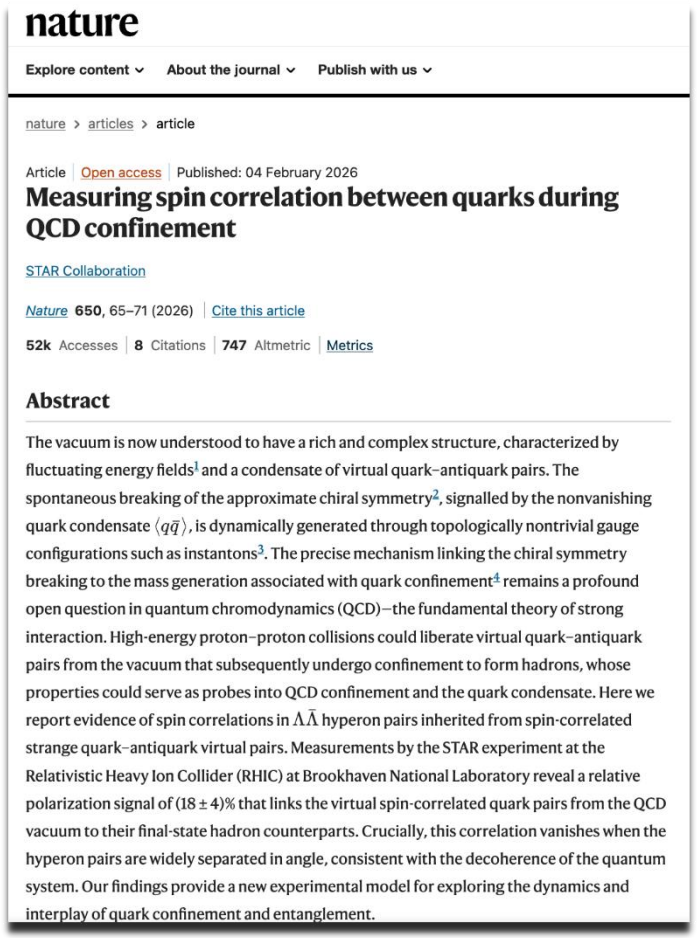
Nature volume 650, pages 65–71 (2026)

CMS-PAS-HIN-26-002

Summary

- **Hadronization can induce quantum decoherence, leading to quantum–to–classical transition.**
- **In the context of lambda hyperon spin correlation, the intermadiate hadrons serve as environmental degrees of freedom.**
- **This picture can explain the STAR and CMS data quite well.**

Vacuum Excitation: Virtual $q\bar{q}$ becomes Real



nature

Explore content | About the journal | Publish with us

nature › articles › article

Article | Open access | Published: 04 February 2026

Measuring spin correlation between quarks during QCD confinement

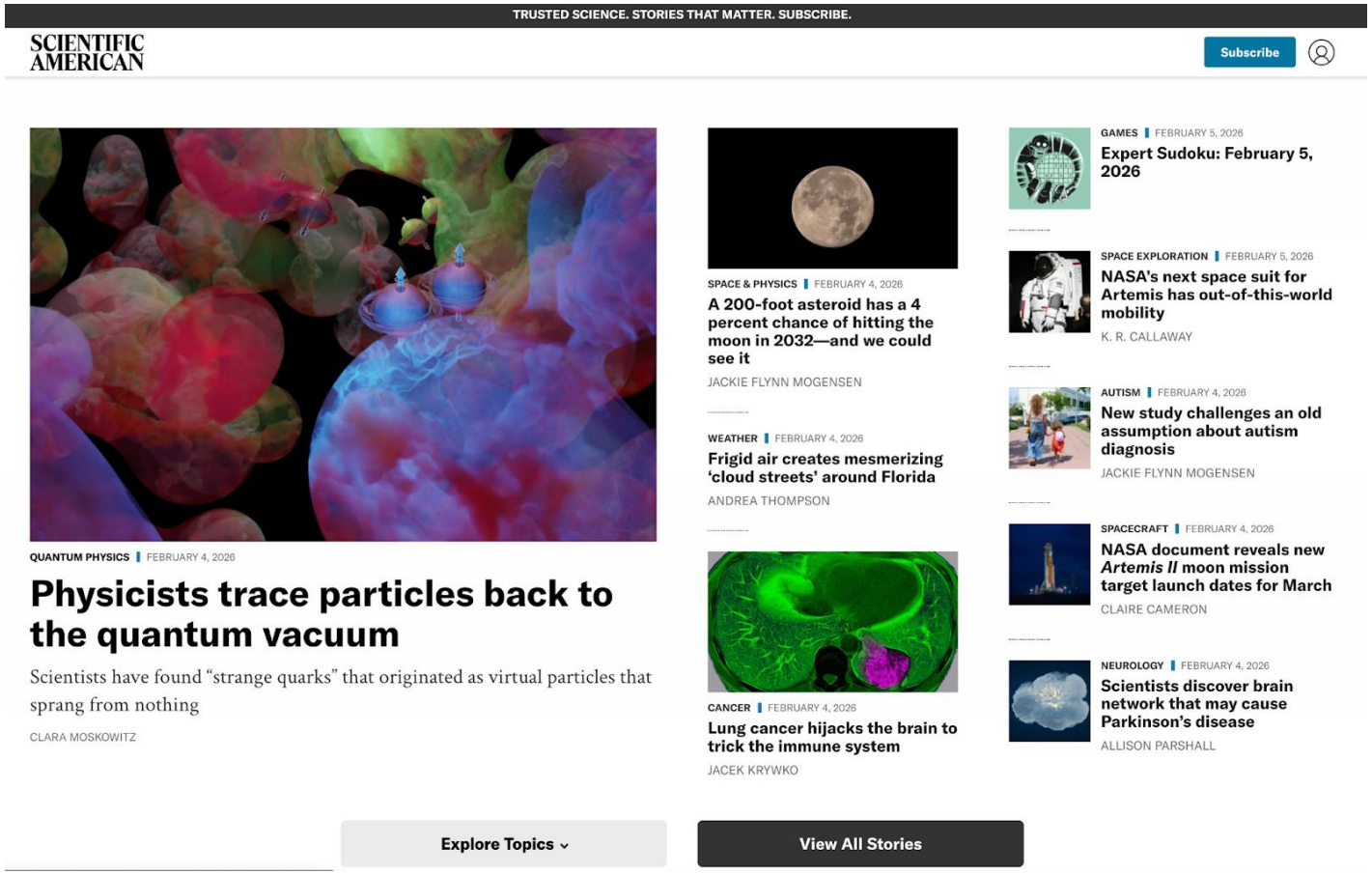
STAR Collaboration

Nature **650**, 65–71 (2026) | Cite this article

52k Accesses | **8** Citations | **747** Altmetric | Metrics

Abstract

The vacuum is now understood to have a rich and complex structure, characterized by fluctuating energy fields[1] and a condensate of virtual quark–antiquark pairs. The spontaneous breaking of the approximate chiral symmetry[2], signalled by the nonvanishing quark condensate $\langle q\bar{q}\rangle$, is dynamically generated through topologically nontrivial gauge configurations such as instantons[3]. The precise mechanism linking the chiral symmetry breaking to the mass generation associated with quark confinement[4] remains a profound open question in quantum chromodynamics (QCD)—the fundamental theory of strong interaction. High-energy proton–proton collisions could liberate virtual quark–antiquark pairs from the vacuum that subsequently undergo confinement to form hadrons, whose properties could serve as probes into QCD confinement and the quark condensate. Here we report evidence of spin correlations in $\Lambda\bar{\Lambda}$ hyperon pairs inherited from spin-correlated strange quark–antiquark virtual pairs. Measurements by the STAR experiment at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory reveal a relative polarization signal of $(18 \pm 4)\%$ that links the virtual spin-correlated quark pairs from the QCD vacuum to their final-state hadron counterparts. Crucially, this correlation vanishes when the hyperon pairs are widely separated in angle, consistent with the decoherence of the quantum system. Our findings provide a new experimental model for exploring the dynamics and interplay of quark confinement and entanglement.



TRUSTED SCIENCE. STORIES THAT MATTER. SUBSCRIBE.

SCIENTIFIC AMERICAN

Subscribe

QUANTUM PHYSICS | FEBRUARY 4, 2026

Physicists trace particles back to the quantum vacuum

Scientists have found "strange quarks" that originated as virtual particles that sprang from nothing

CLARA MOSKOWITZ

SPACE & PHYSICS | FEBRUARY 4, 2026

A 200-foot asteroid has a 4 percent chance of hitting the moon in 2032—and we could see it

JACKIE FLYNN MOGENSEN

WEATHER | FEBRUARY 4, 2026

Frigid air creates mesmerizing 'cloud streets' around Florida

ANDREA THOMPSON

CANCER | FEBRUARY 4, 2026

Lung cancer hijacks the brain to trick the immune system

JACEK KRYWKO

GAMES | FEBRUARY 5, 2026

Expert Sudoku: February 5, 2026

SPACE EXPLORATION | FEBRUARY 5, 2026

NASA's next space suit for Artemis has out-of-this-world mobility

K. R. CALLAWAY

AUTISM | FEBRUARY 4, 2026

New study challenges an old assumption about autism diagnosis

JACKIE FLYNN MOGENSEN

SPACECRAFT | FEBRUARY 4, 2026

NASA document reveals new *Artemis II* moon mission target launch dates for March

CLAIRE CAMERON

NEUROLOGY | FEBRUARY 4, 2026

Scientists discover brain network that may cause Parkinson's disease

ALLISON PARSHALL

Explore Topics

View All Stories

[Nature volume 650, pages 65–71 (2026)]

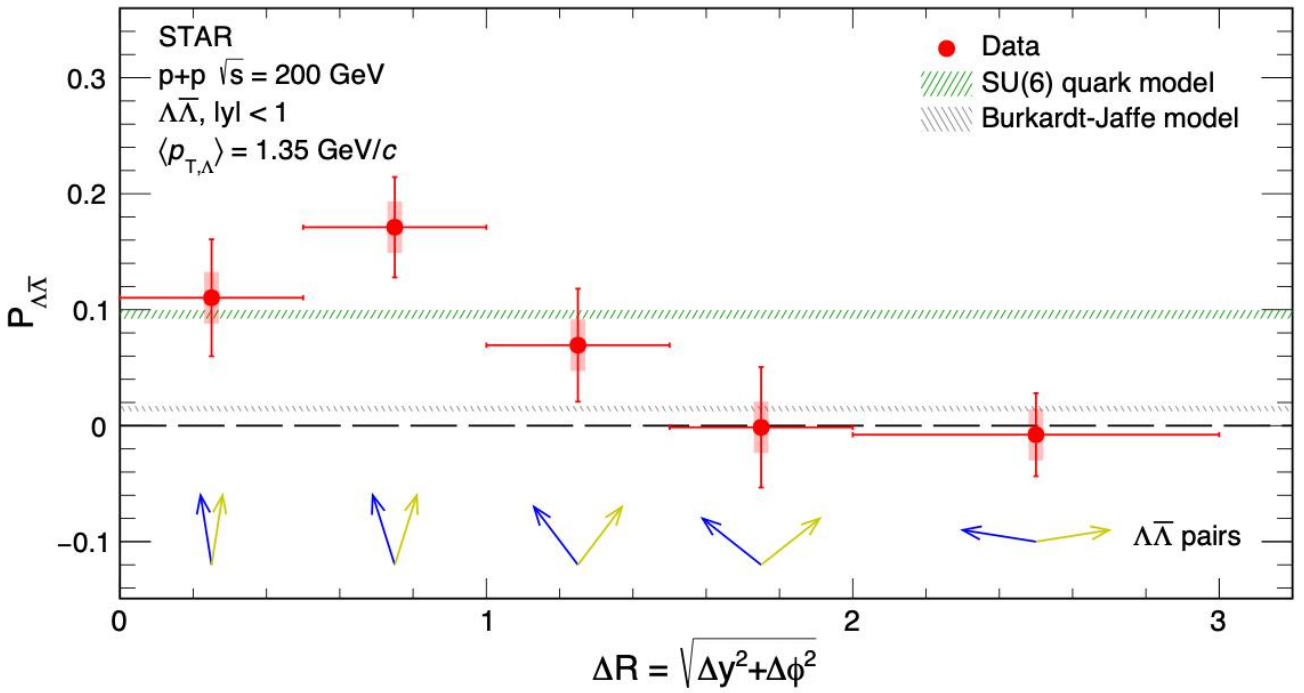
More environmental hadrons, Stronger Decoherence

One can show, with some assumption, that [*]

$$P_{\Lambda_1\Lambda_2} = P \cdot e^{-k^* \Delta R}$$

- **To include more environmental hadrons, one can increase Delta R.**
- **k* is proportional to the desnity (per unit of delta R) of environmental hadrons.**

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



Nature volume 650, pages 65–71 (2026)

[*] *The paper draft is in preparation, and will come out soon.*