Recent highlights of the BESIII experiment

60th International Winter Meeting of Nuclear Physics,
Bormio, Italy, January 22-26, 2024

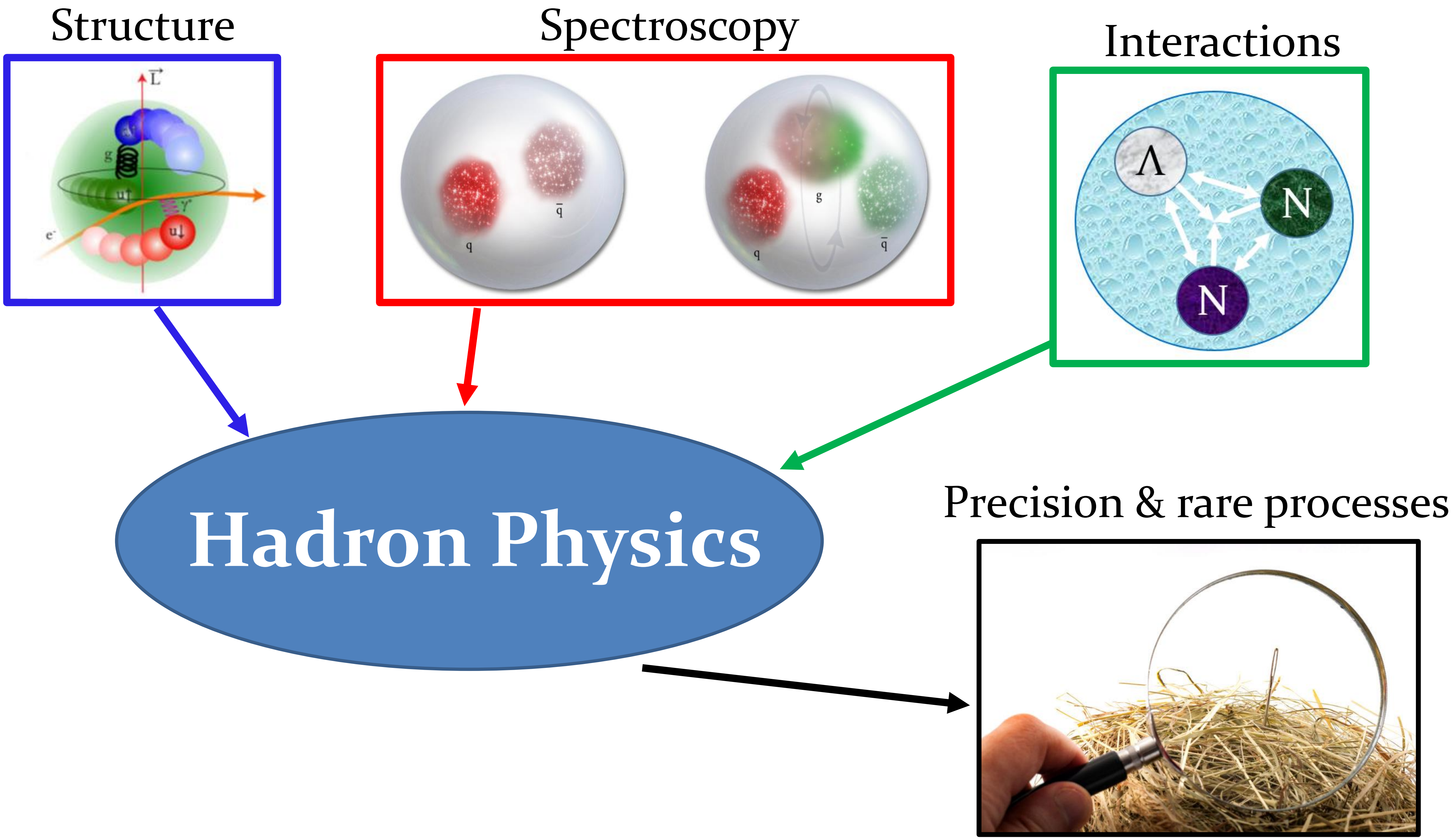
Prof. Dr. Karin Schönning, Uppsala University

Outline

- BESIII at BEPC-II

- Recent highlights:
  - Hadron structure
  - Hadron spectroscopy
  - Hadron interactions
  - Precision and rare processes

How does the strong interaction form visible matter form the fundamental quarks and gluons?



Structure
Spectroscopy
Interactions
Hadron Physics
Precision & rare processes
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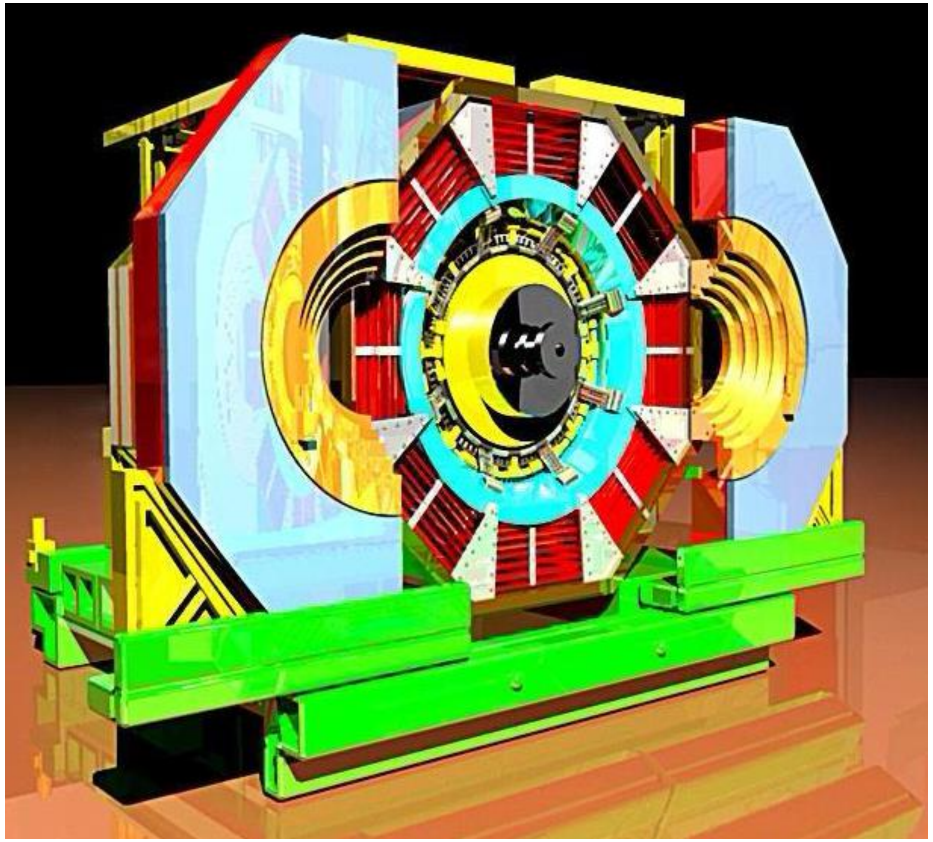
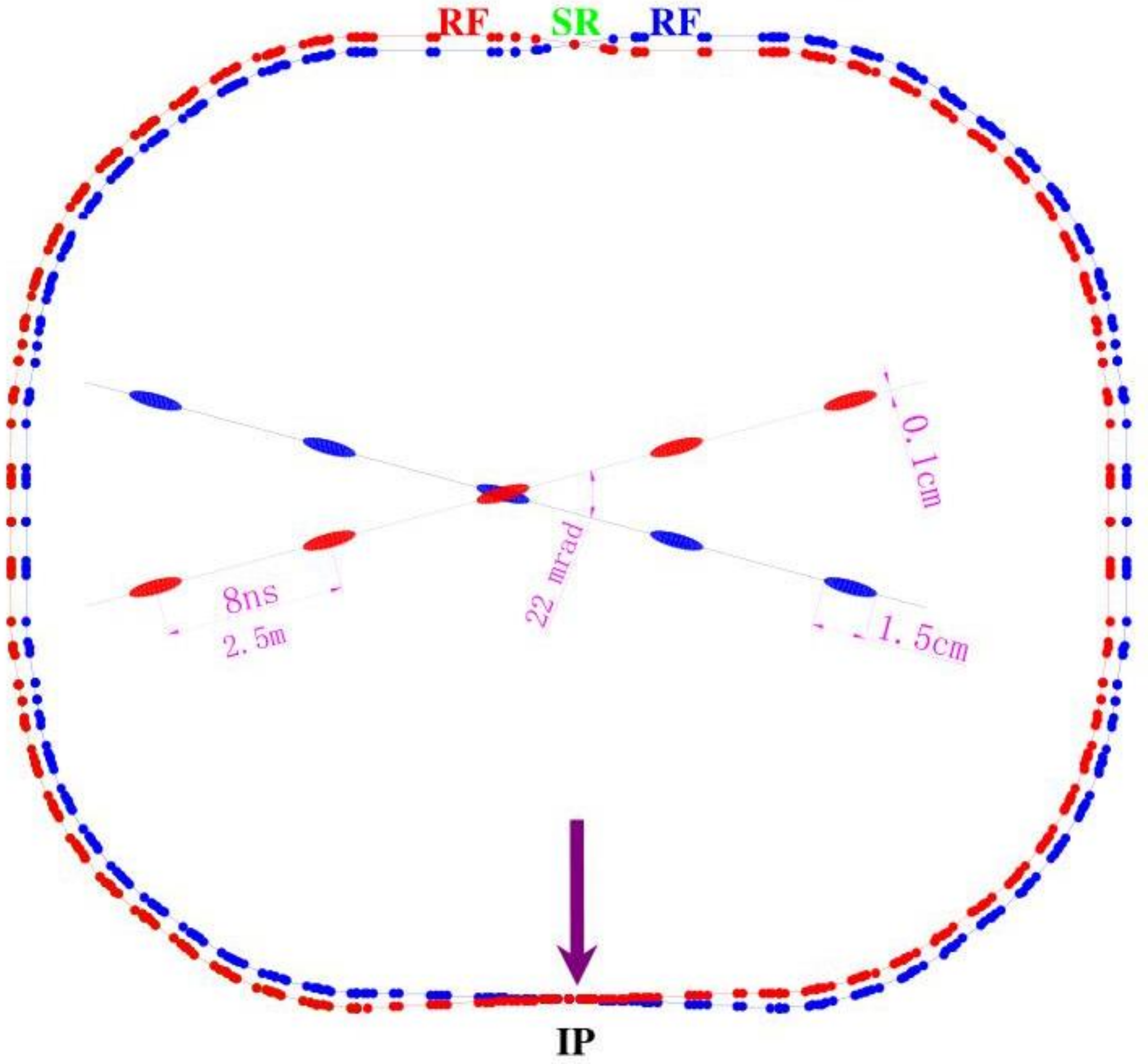
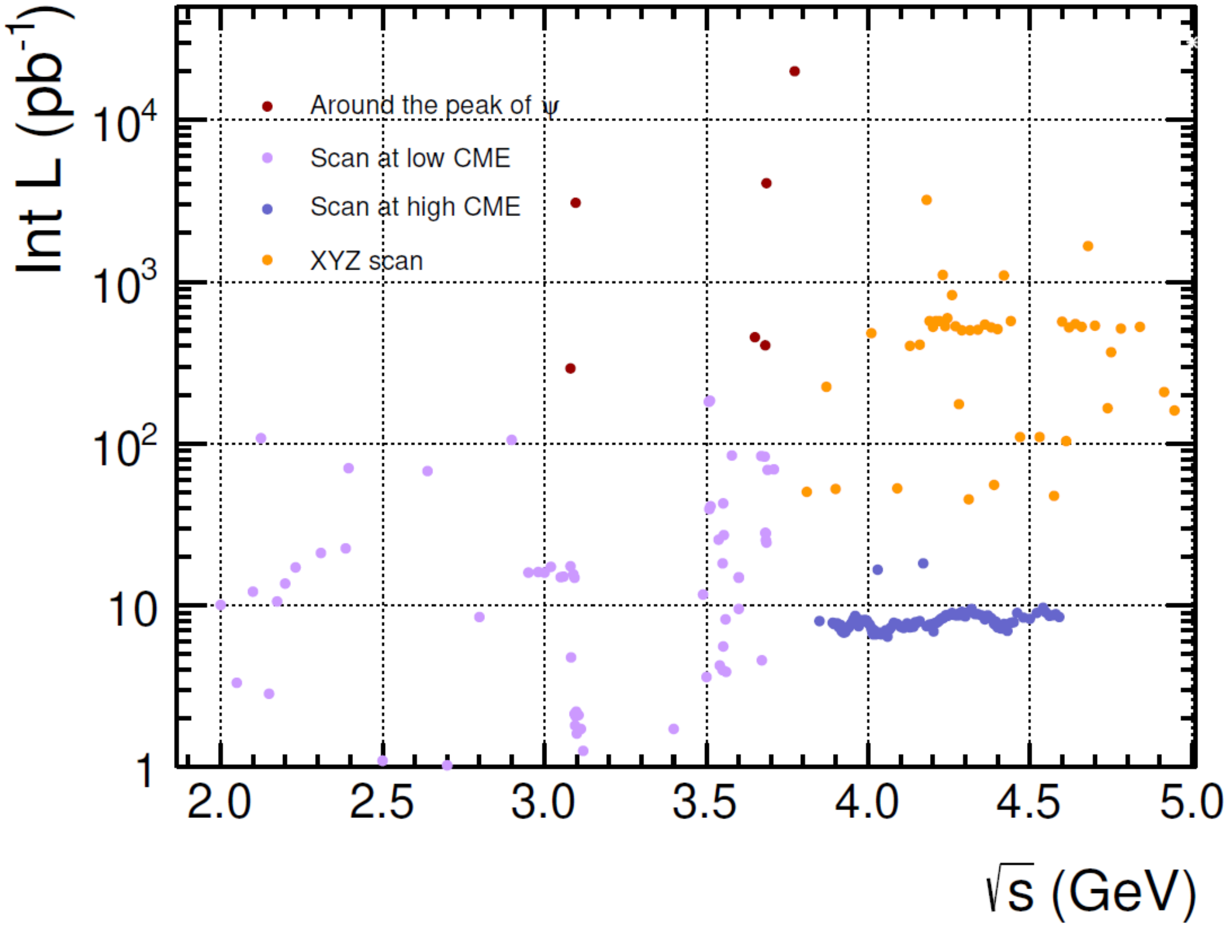
BESIII at BEPC-II



The Beijing Electron-Positron Collider (BEPC-II)

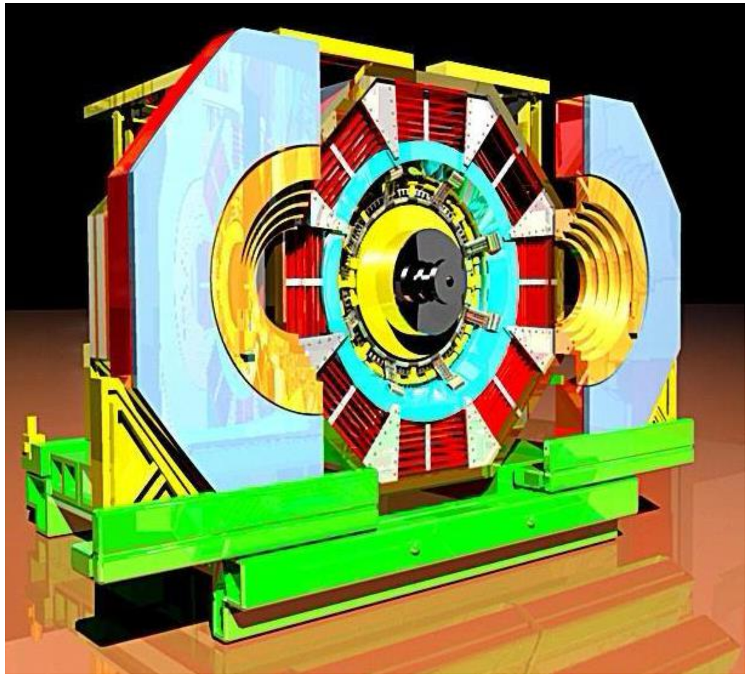


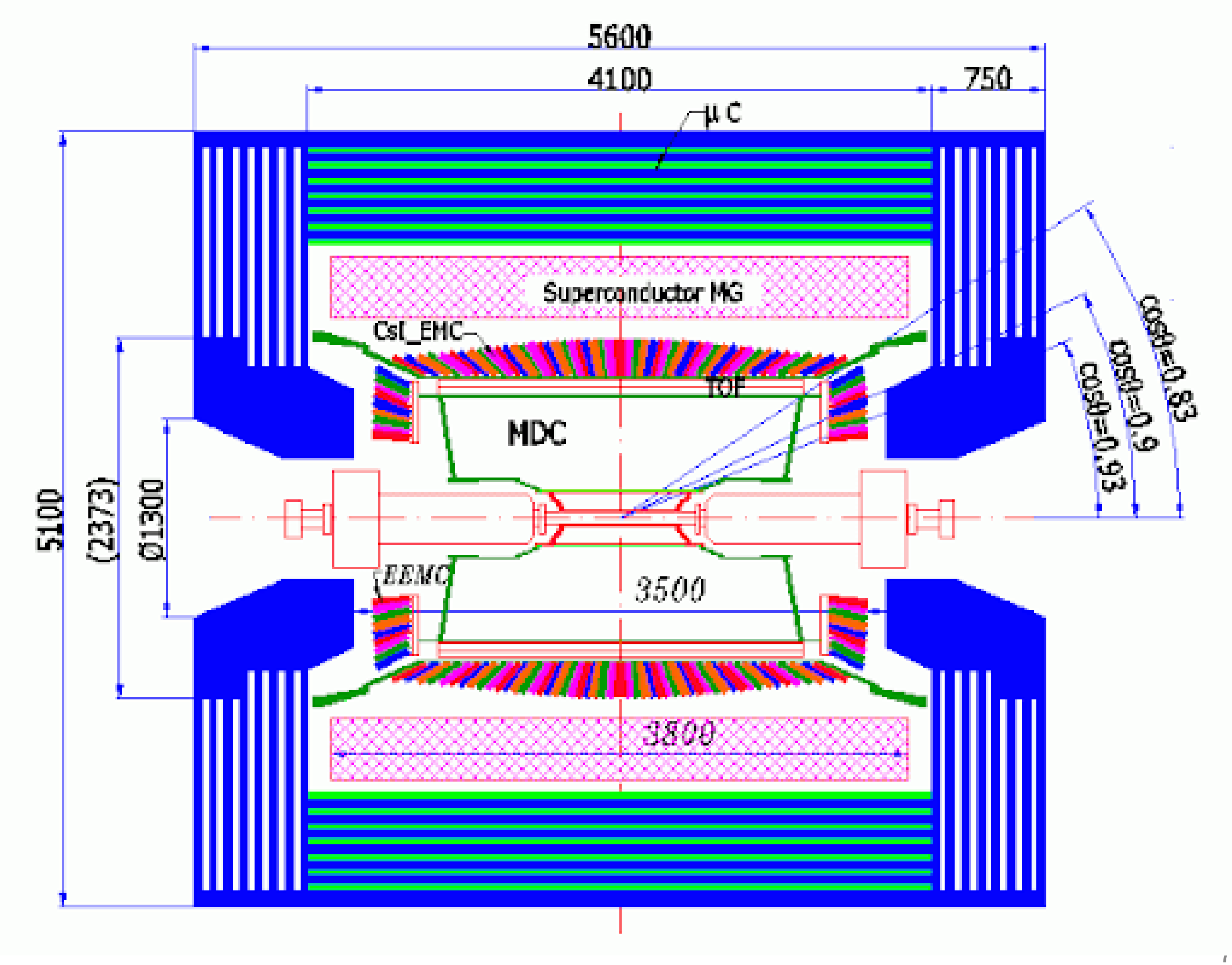
- CMS energies within 2.0 - 4.95 GeV.
- Optimised in the τ-charm region
- Luminosity ~ 10^{33} $cm^{-2}s^{-1}$

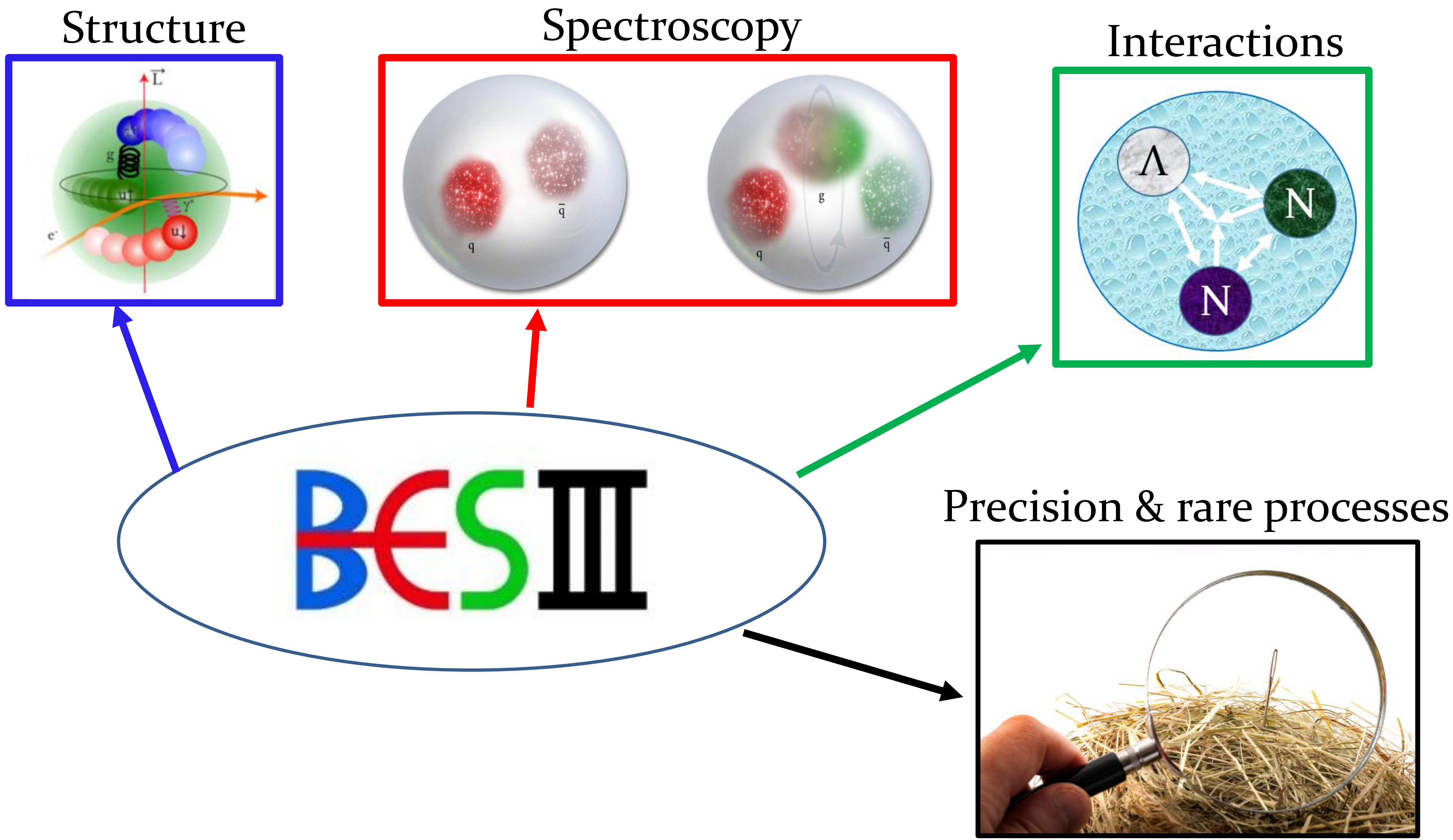


The Beijing Spectrometer (BESIII)

- Near 4π coverage
- Tracking, PID, Calorimetry



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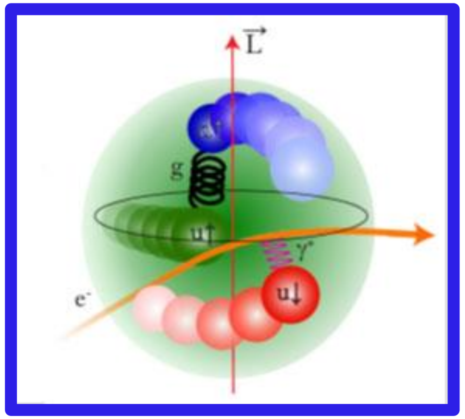
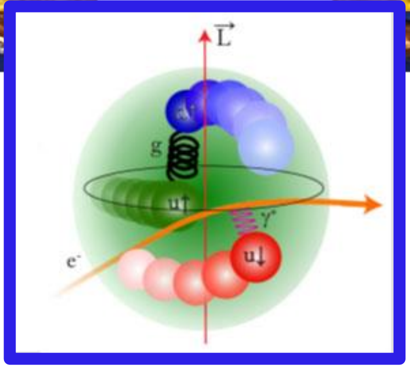
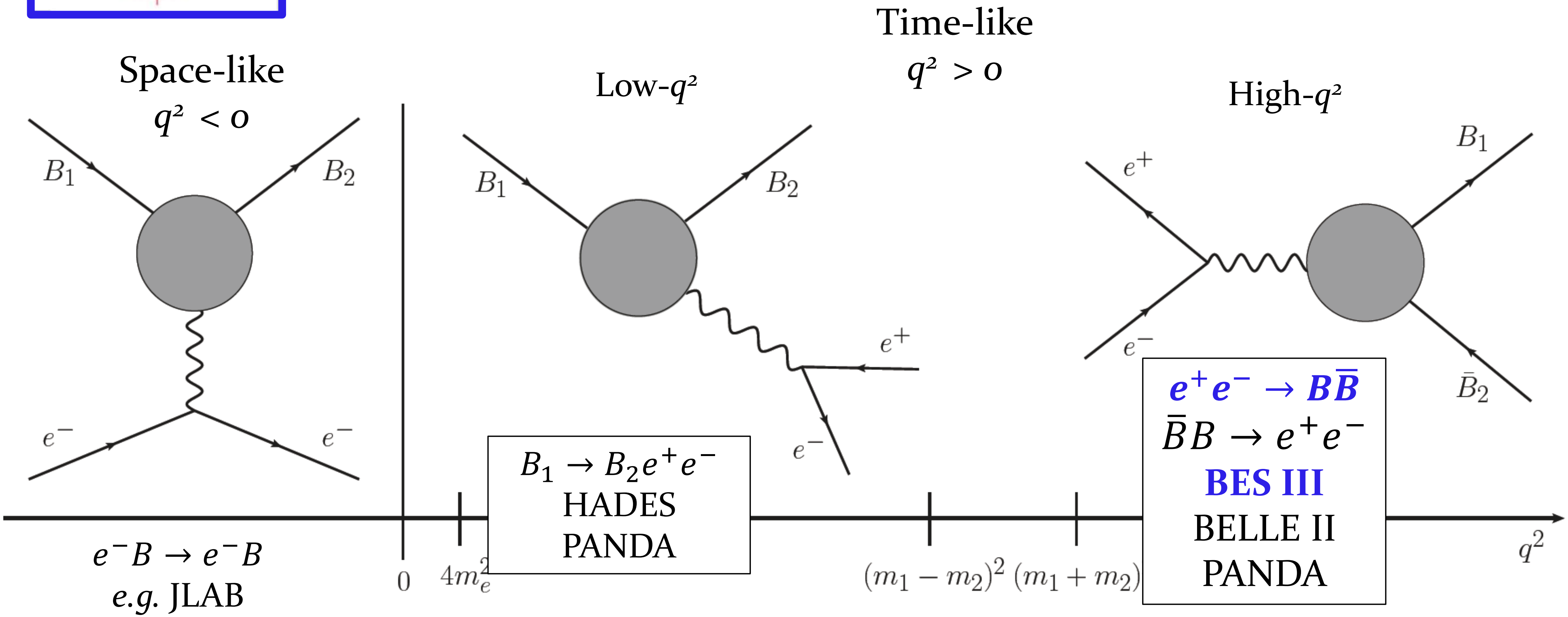


HADRON STRUCTURE WITH BESIII

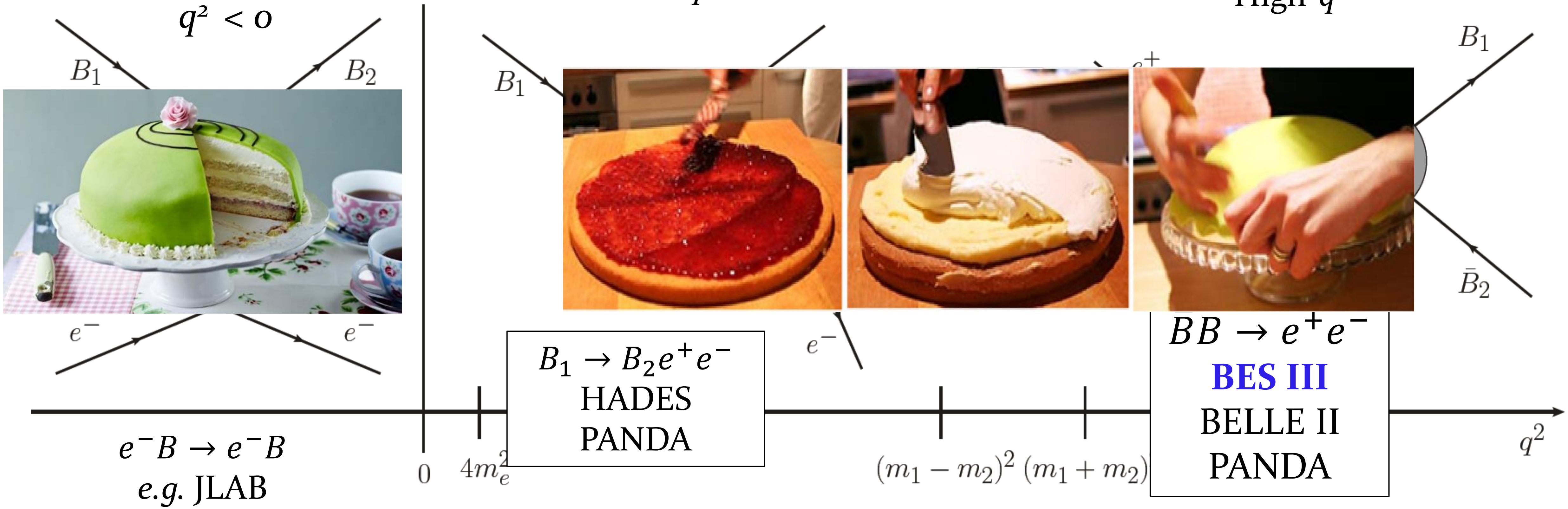


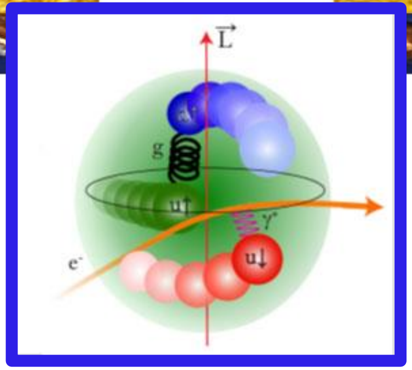
Electromagnetic Form Factors (EMFFs)



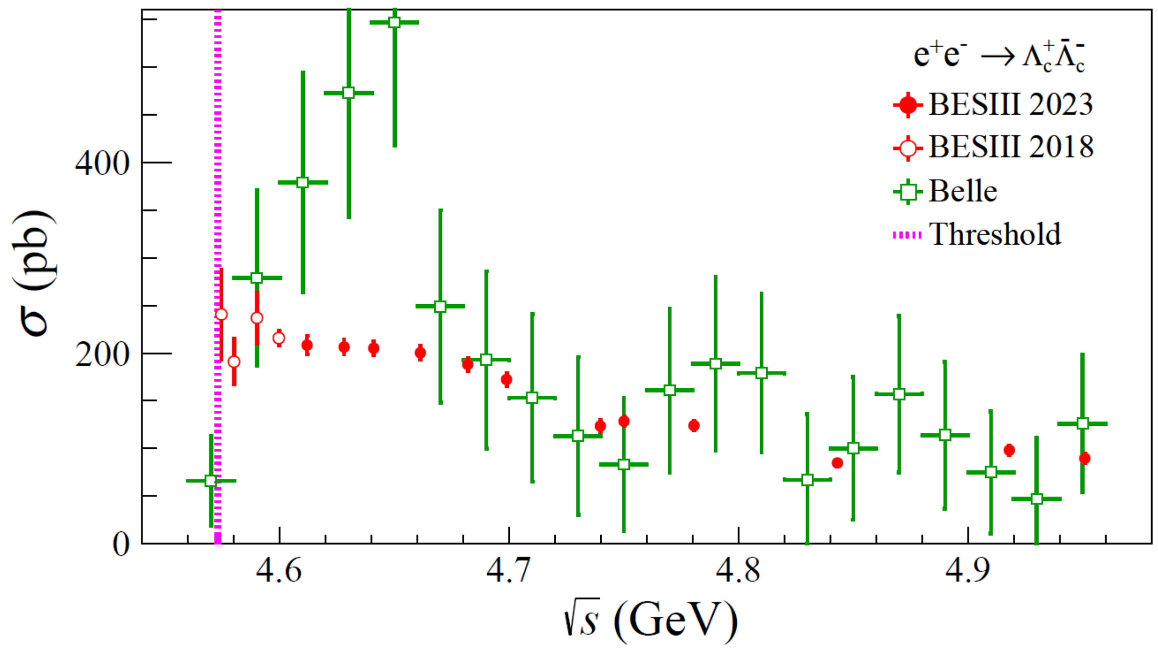
Picture cred. E. Perotti, PhD thesis (UU 2020)

Electromagnetic Form Factors (EMFFs)





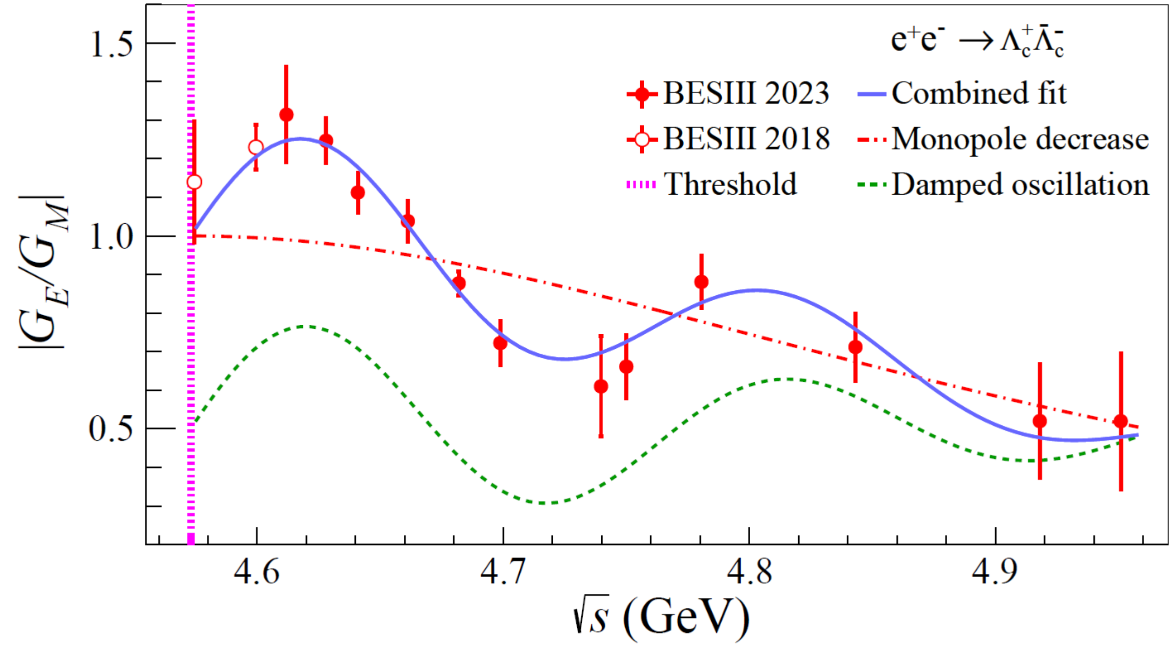
Charm Λ_c^+ baryons



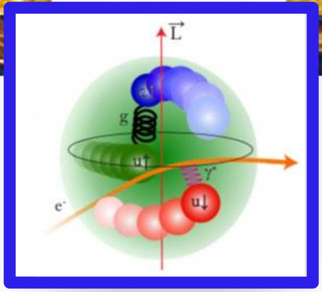
BESIII energy scans from 2018* and 2023**

- Sharp rise in cross section near threshold
- Disagreement with Belle data*** near 4.6 GeV
- No discernible G_{eff} oscillations
- Energy dependence of R = $|G_E/G_M|$* :

  → Damped oscillations with frequency ~3.5 times larger than for the proton



BESIII:
*Phys. Rev. Lett. 120, 132001 (2018)
**Phys. Rev. Lett. 131, 191901
Belle:
***Phys. Rev. Lett. 101, 172001 (2008)



Complete decomposition of EMFFs

Production parameters of spin ½ baryons:

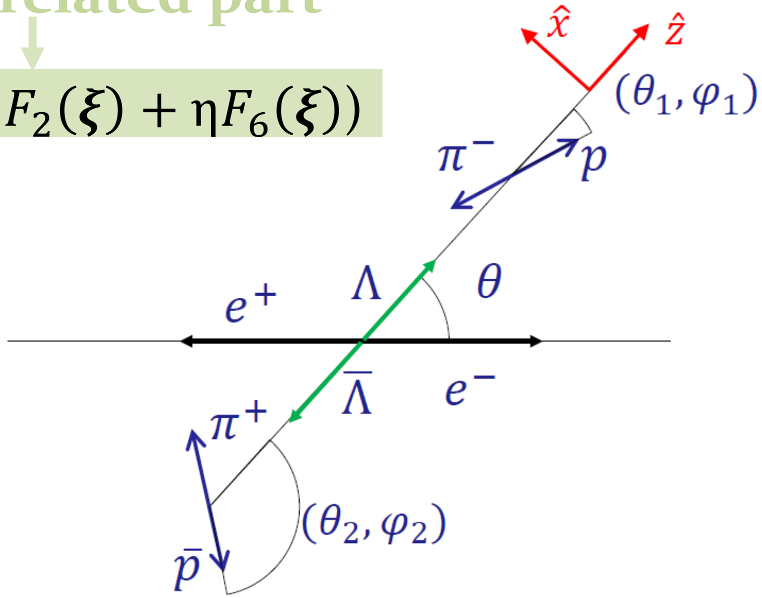
- Angular distribution parameter $\eta = \frac{\tau - R^2}{\tau + R^2}$ where $\tau = q^2/4M^2_B$
- Phase $\Delta\Phi$

Decay parameters for 2-body decays: α_1 and α_2. If CP symmetry, $\alpha_1 = -\alpha_2 = \alpha$

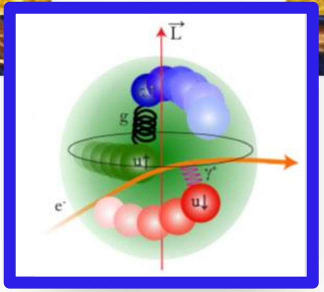
Unpolarized part — Polarized part — Spin correlated part

$$W(\xi) = F_0(\xi) + \eta F_5(\xi) + \alpha^2 \left(F_1(\xi) + \sqrt{1-\eta^2}\cos(\Delta\Phi) F_2(\xi) + \eta F_6(\xi)\right)$$
$$+ \alpha\sqrt{1-\eta^2}\sin(\Delta\Phi)(F_3(\xi) + F_4(\xi))$$

$$\mathcal{F}_0(\xi) = 1$$
$$\mathcal{F}_1(\xi) = \sin^2\theta \sin\theta_1 \sin\theta_2 \cos\phi_1 \cos\phi_2 + \cos^2\theta \cos\theta_1 \cos\theta_2$$
$$\mathcal{F}_2(\xi) = \sin\theta \cos\theta (\sin\theta_1 \cos\theta_2 \cos\phi_1 + \cos\theta_1 \sin\theta_2 \cos\phi_2)$$
$$\mathcal{F}_3(\xi) = \sin\theta \cos\theta \sin\theta_1 \sin\phi_1$$
$$\mathcal{F}_4(\xi) = \sin\theta \cos\theta \sin\theta_2 \sin\phi_2$$
$$\mathcal{F}_5(\xi) = \cos^2\theta$$
$$\mathcal{F}_6(\xi) = \cos\theta_1 \cos\theta_2 - \sin^2\theta \sin\theta_1 \sin\theta_2 \sin\phi_1 \sin\phi_2$$

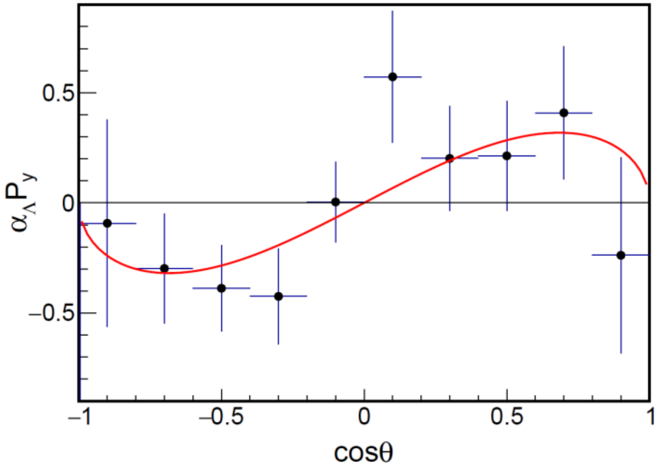


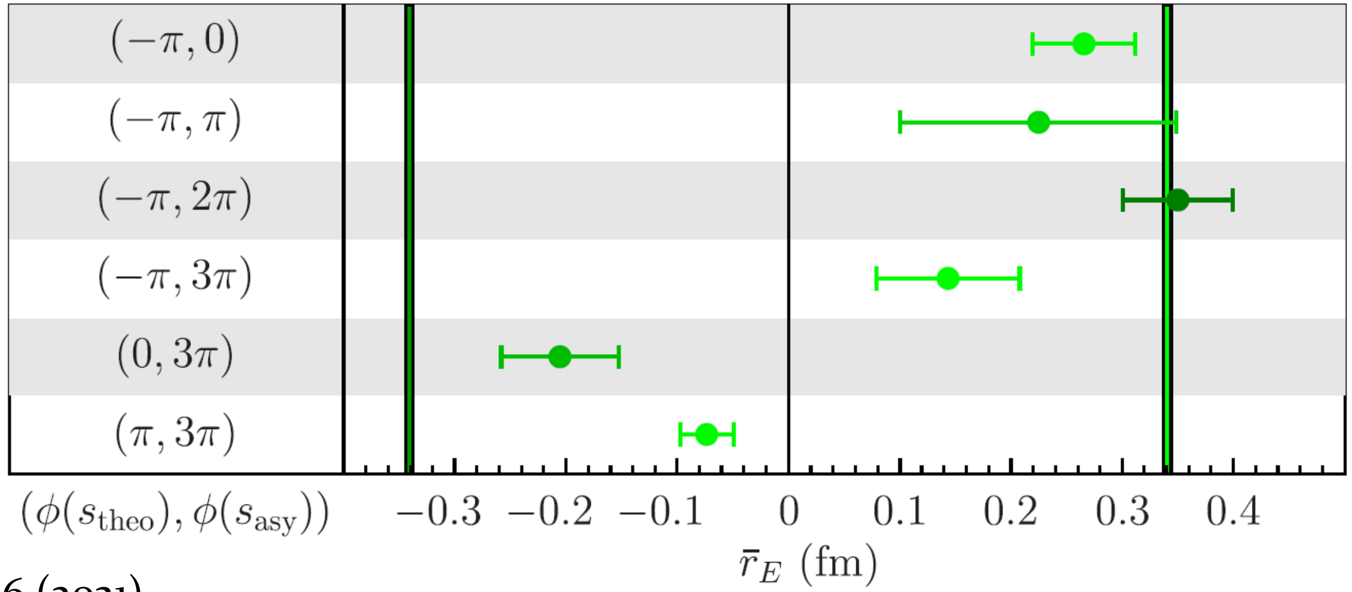
*Fäldt & Kupsc, PLB 772 (2017) 16.



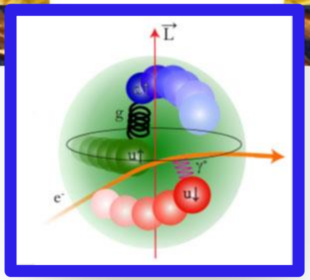
Complete decomposition of EMFFs

- First conclusive measurement of ΔΦ in 2019*.
- Dispersive calculations by Mangoni, Pacetti and Tommasi-Gustafsson**
  - Calculation of Λ charge radius
  - ΔΦ only at one energy → many solutions possible

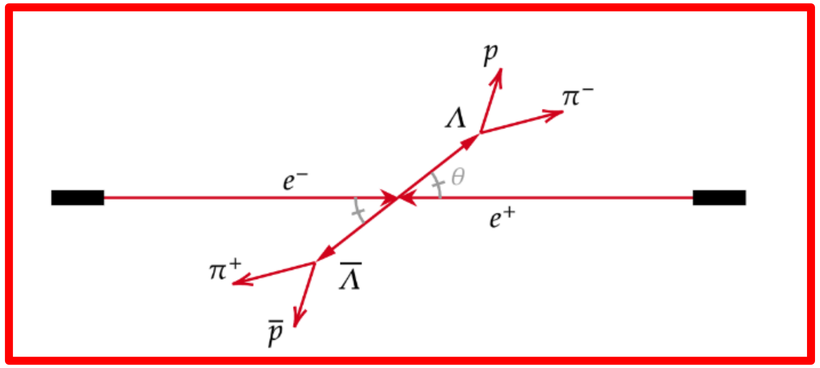




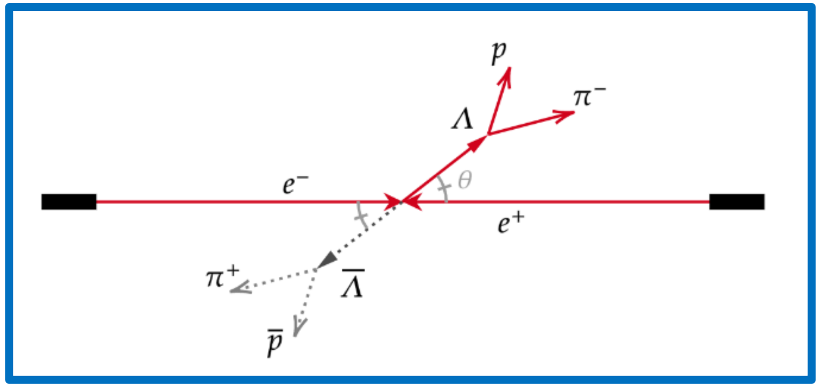
*Mangoni *et al.*, Phys. Rev. D 104, 116016 (2021)
**BESIII: Phys. Rev. Lett. 123, 122003 (2019)

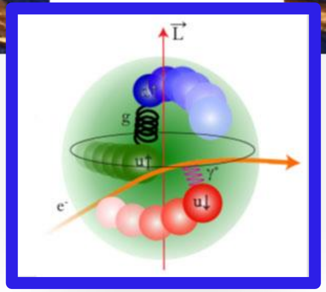


New: Complete hyperon EMFFs



- Utilizes scan data collected in 2015.
- Combines **double-tag** and **single-tag** data.

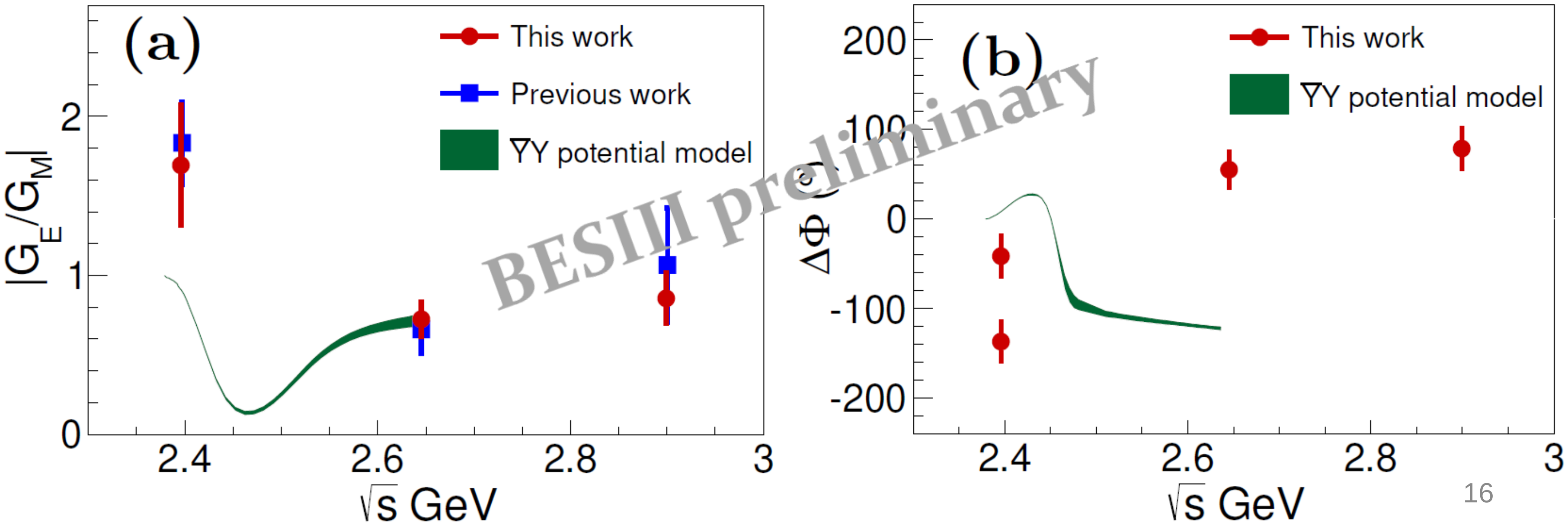




New: Complete Σ^+ EMFFs

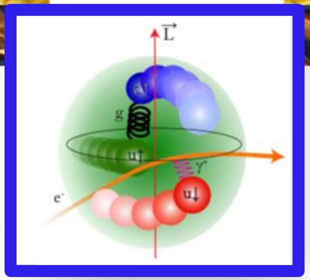
- Energy dependence of R and ΔΦ in 3 points*
  - Double-tag $e^+e^- \to \Sigma^+\bar{\Sigma}^- \to p\pi^0\bar{p}\pi^0$ at 2.64 GeV and 2.9 GeV
  - Single-tag $e^+e^- \to \Sigma^+\bar{\Sigma}^- \to p\pi^0 X + c.c.$ at 2.396 GeV

    → ΔΦ / 180° – ΔΦ ambiguity
- Disagreement with $Y\bar{Y}$ potential model **.



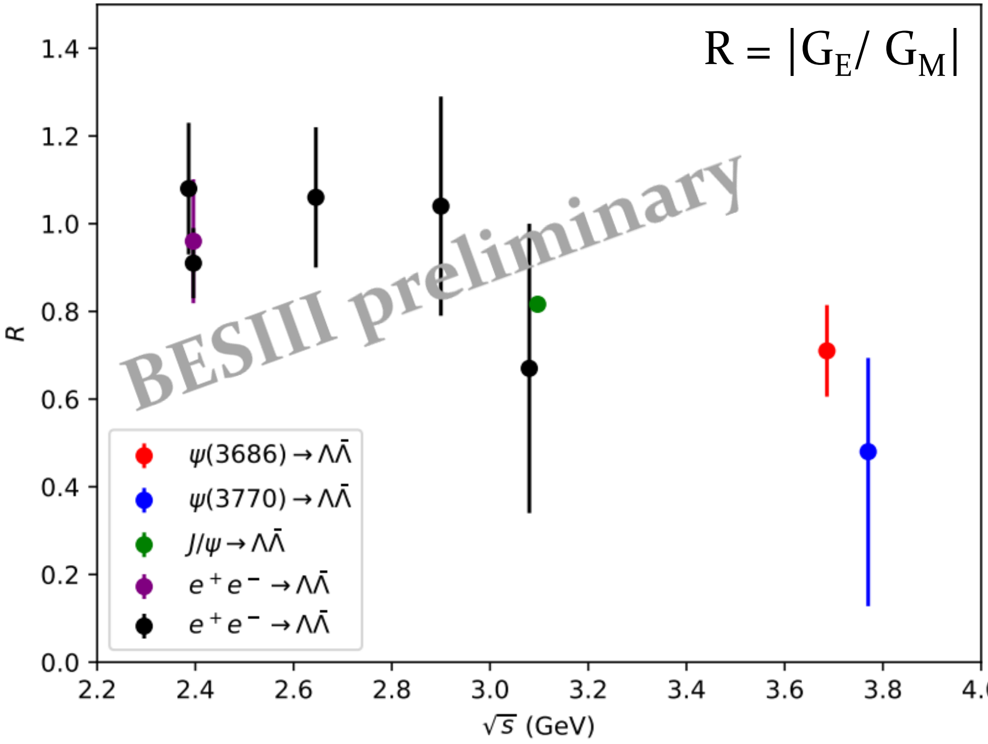
* arXiv[hep-ex]: 2307.15894, acc. by Phys. Rev. Lett.

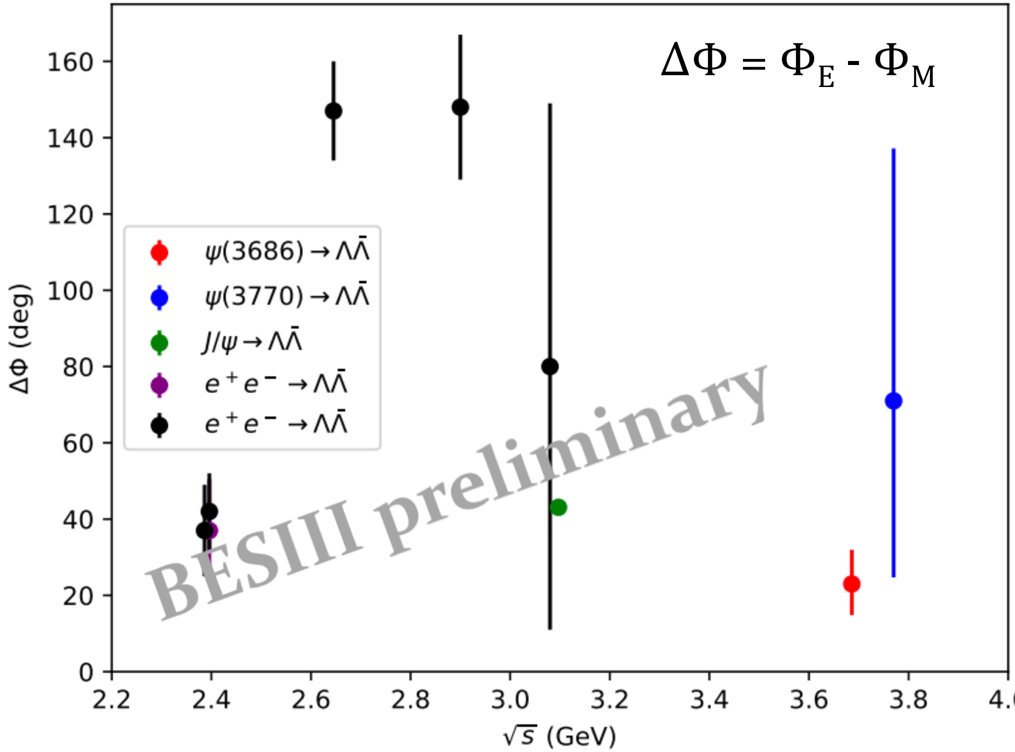
** Haidenbauer *et al.*, Phys. Rev. D 103, 014028 (2021)



Brand new: Complete Λ EMFFs

Spin analyses performed in the **continuum*** ** and at J/Ψ***, Ψ(3686)**** and Ψ(3773)*****

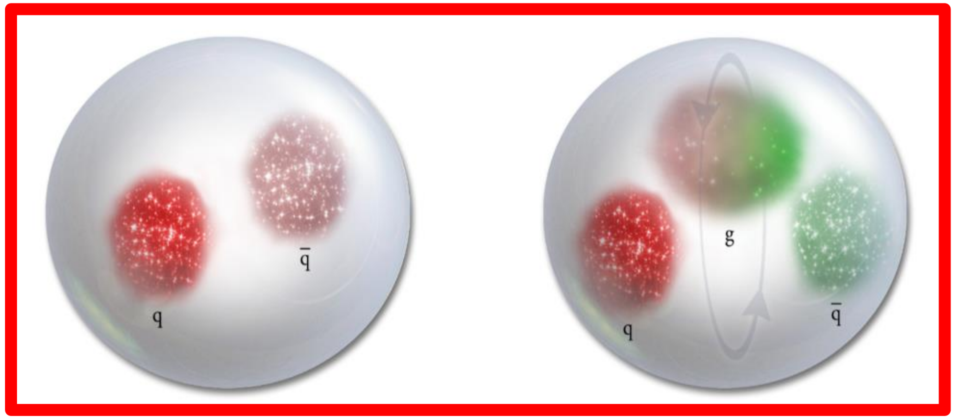




BESIII

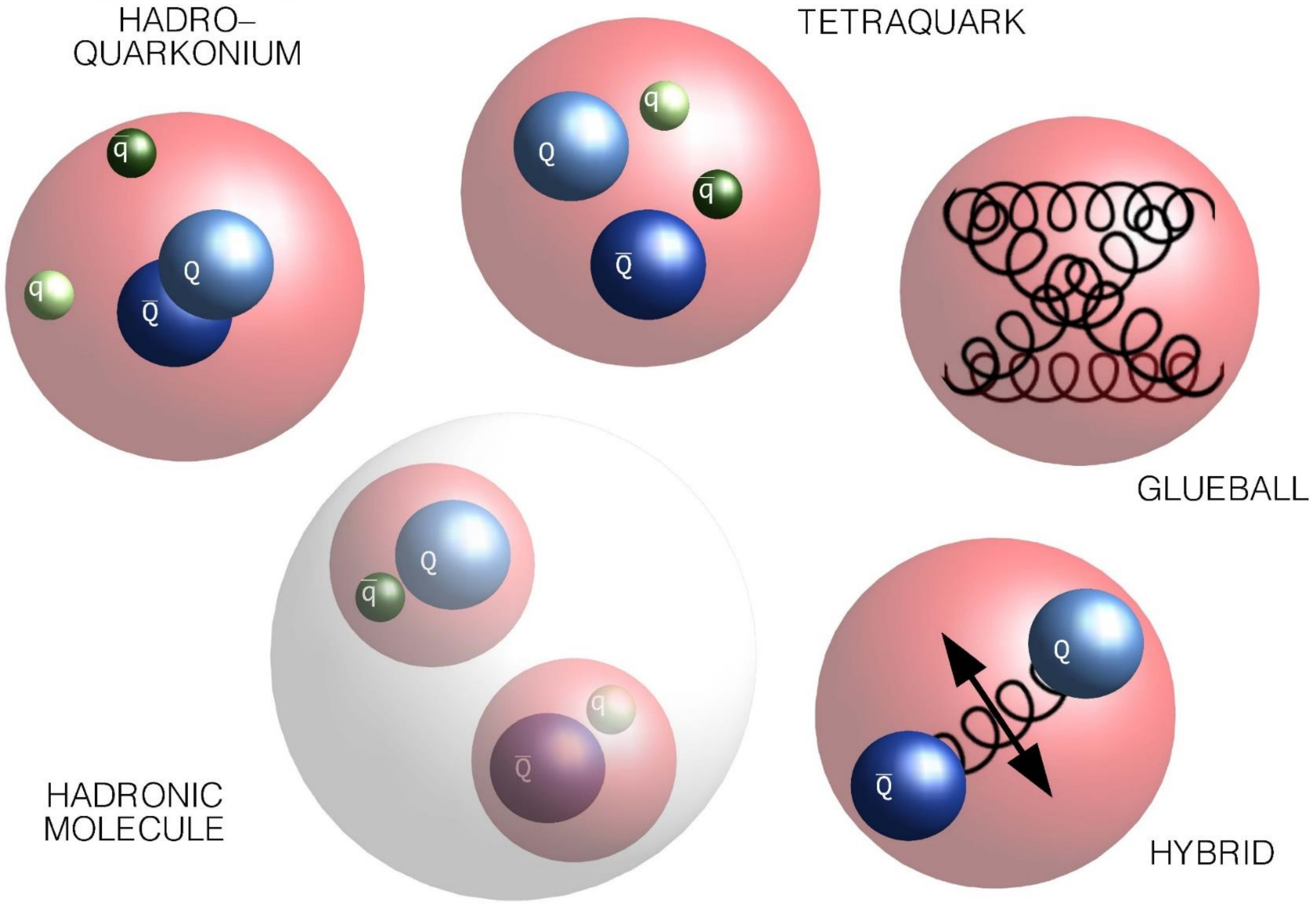
* Newly released from BESIII
**Phys. Rev. Lett. 123, 122003 (2019)
***Nature Phys. **15**, p. 631-634 (2019)

****JHEP10(2023)081
*****Phys. Rev. D 105, L011101 (2020)
Picture credit Michael Papenbrock

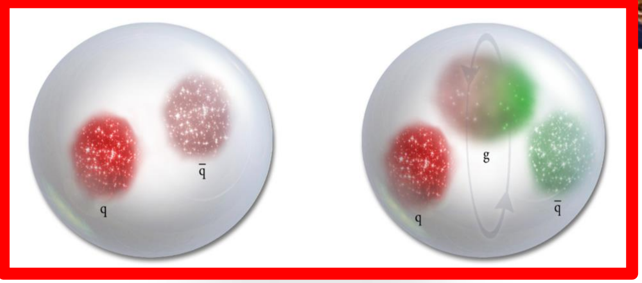


HADRON SPECTROSCOPY WITH BESIII

Hadron Spectroscopy



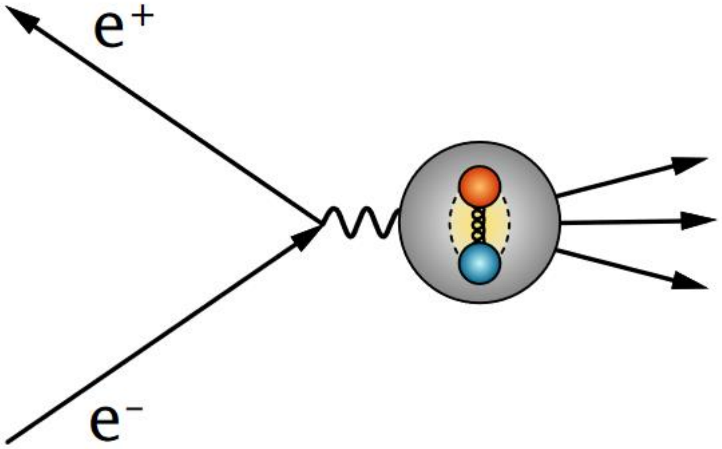
Unravelling the complexity of matter formed by the strong interaction…

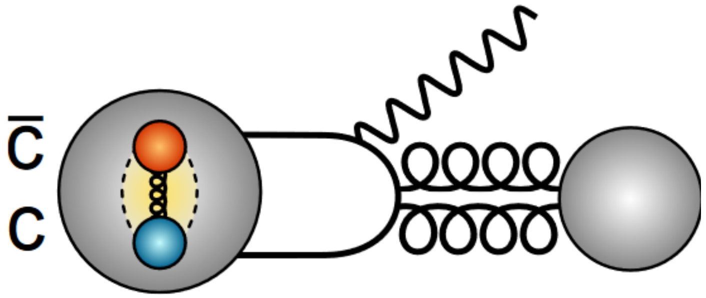


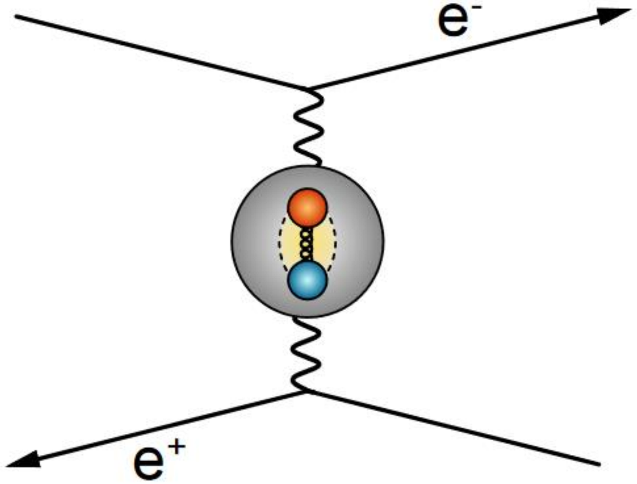
Meson spectroscopy at BESIII

Multiple ways to produce conventional and exotic mesons:

- Direct production of vector states
- Charmonium decays
- Two-photon scattering



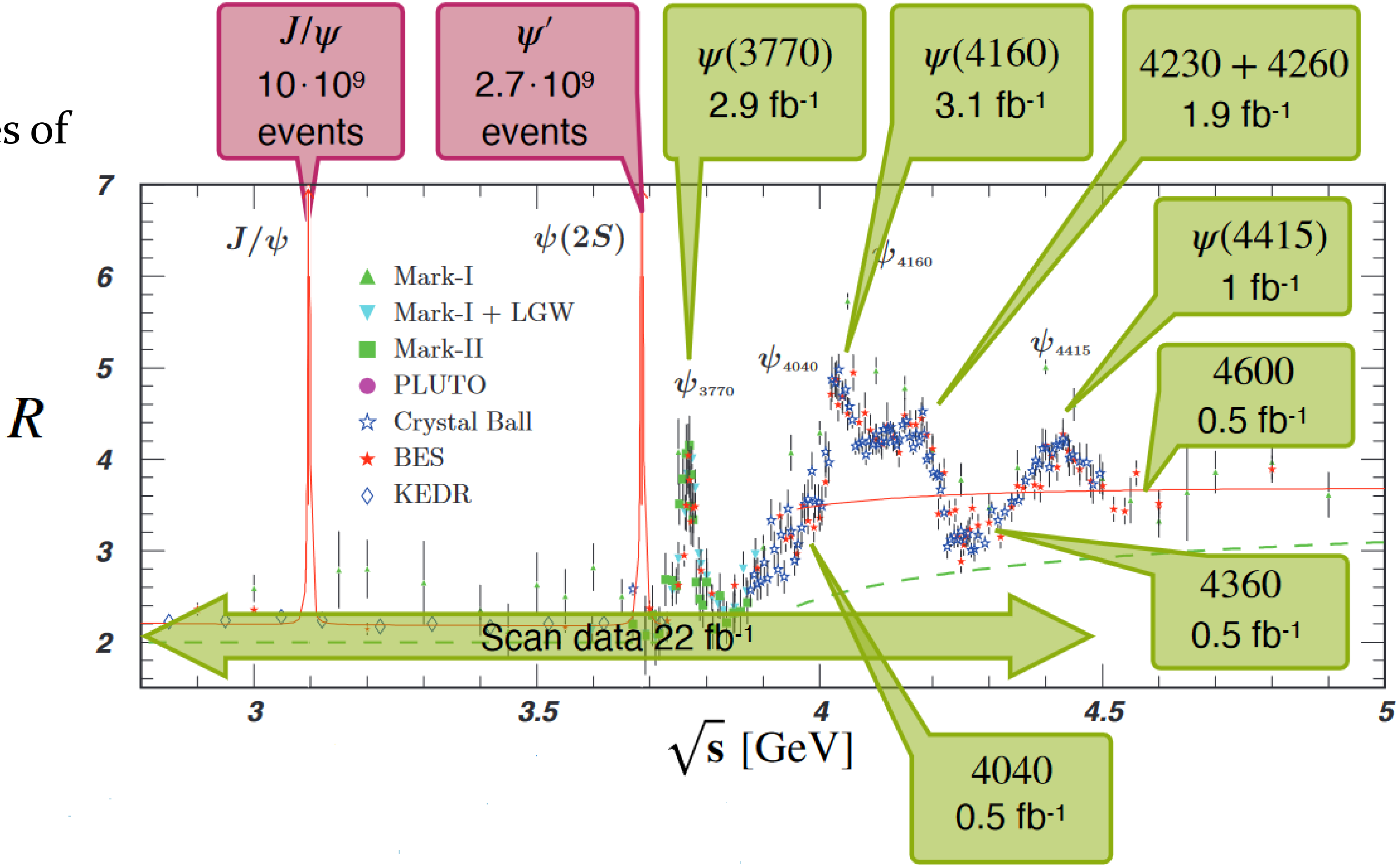




Picture cred: M. Kuessner

Meson spectroscopy at BESIII

- World-record samples of vector charmonia
- Energy scan in the continuum

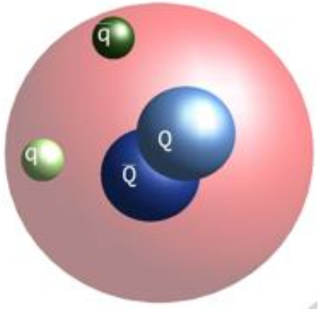


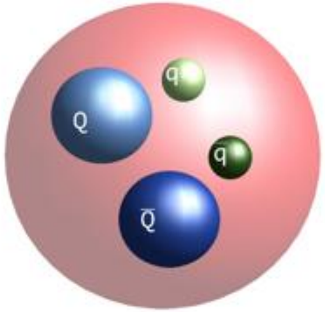
BESIII

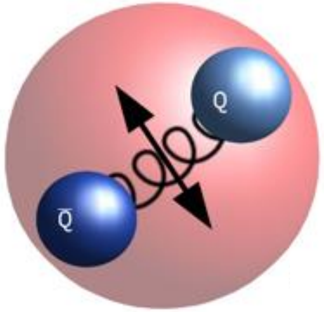
Charmonium spectroscopy

XYZ states do not fit into the naive quark model → searchground for exotica!

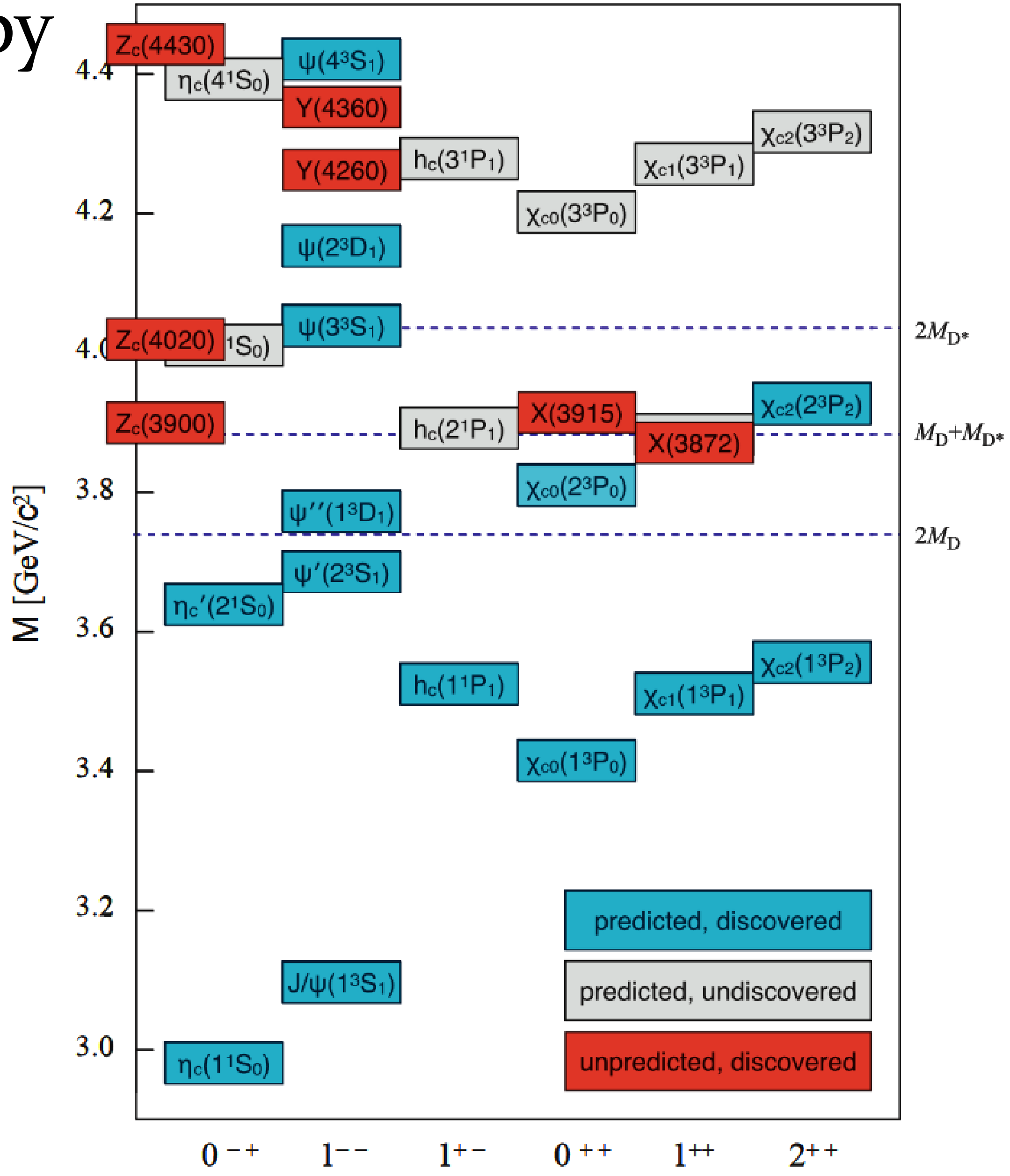
- X: neutral non-vector states
- Y: neutral vector states
- Z: charged, manifestly multiquark states





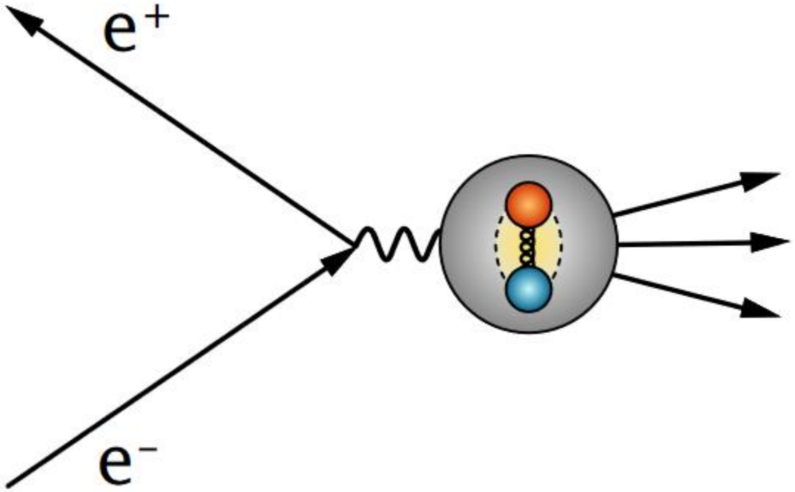


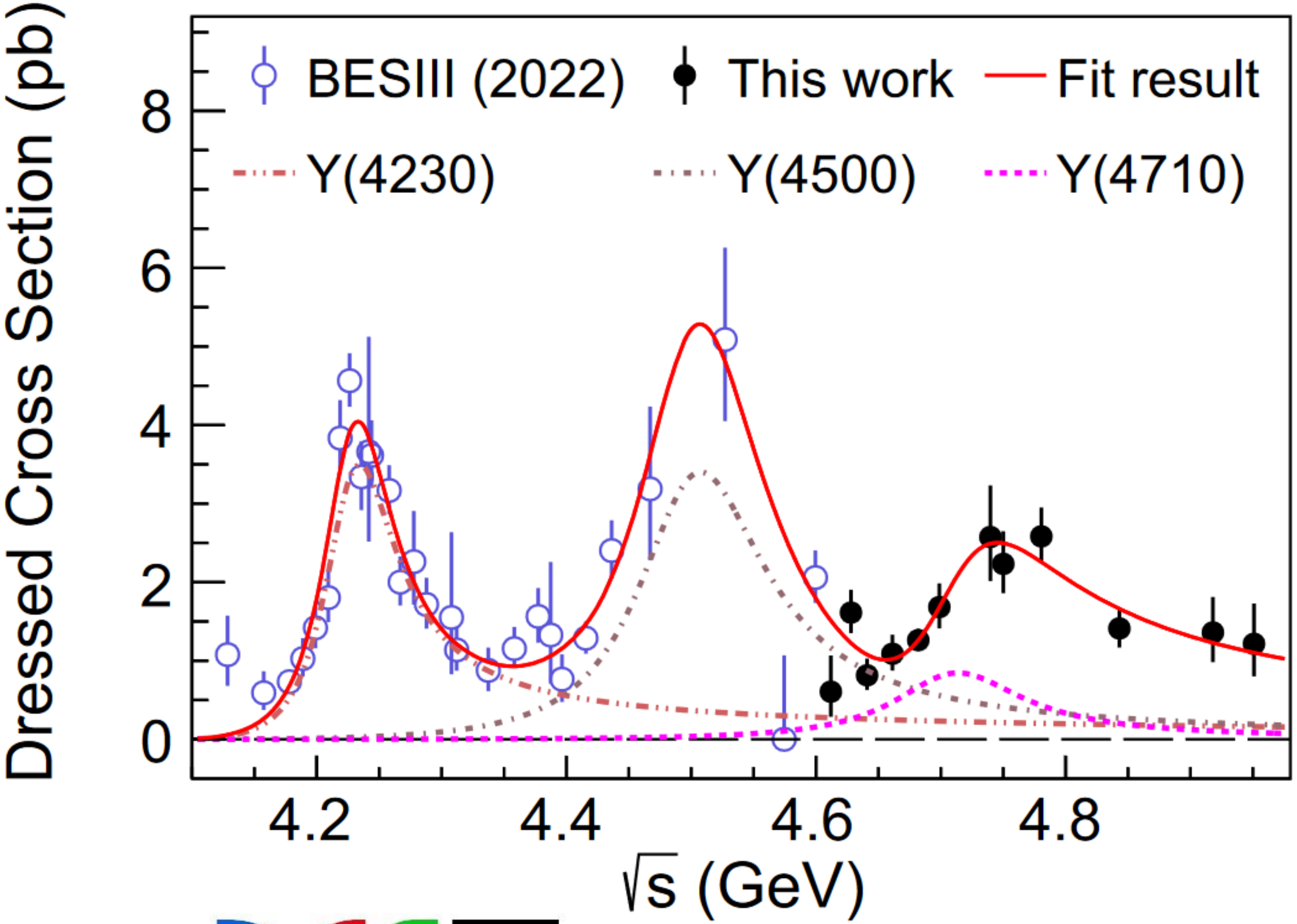
Picture cred: R. Mitchell and M. Kuessner



New: Observation of a resonance at 4.7 GeV/c²

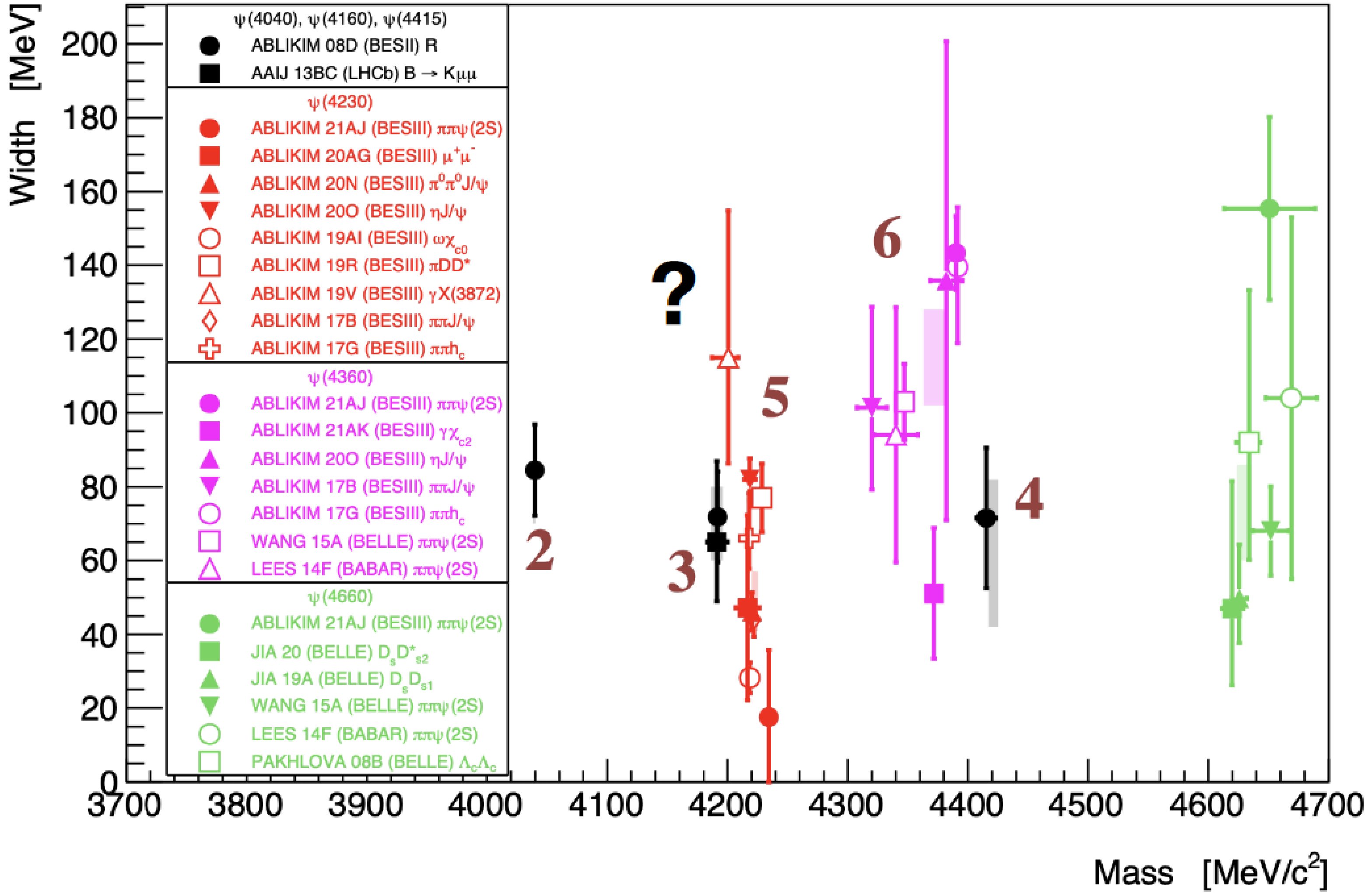
- Charmonium-like vector state
- Seen in $e^+e^- \to K^+K^-J/\Psi$*
- $M = 4708^{+17}_{-15} \pm 21$ MeV/c²
- $\Gamma = 126^{+27}_{-23} \pm 30$ MeV/c²
- Significance > 5 σ





* Phys. Rev. Lett. 131, 211902 (2023)

Vector charmonium-like Y states in PDG 2022



Picture credit:
R. Mitchell & M. Kuessner

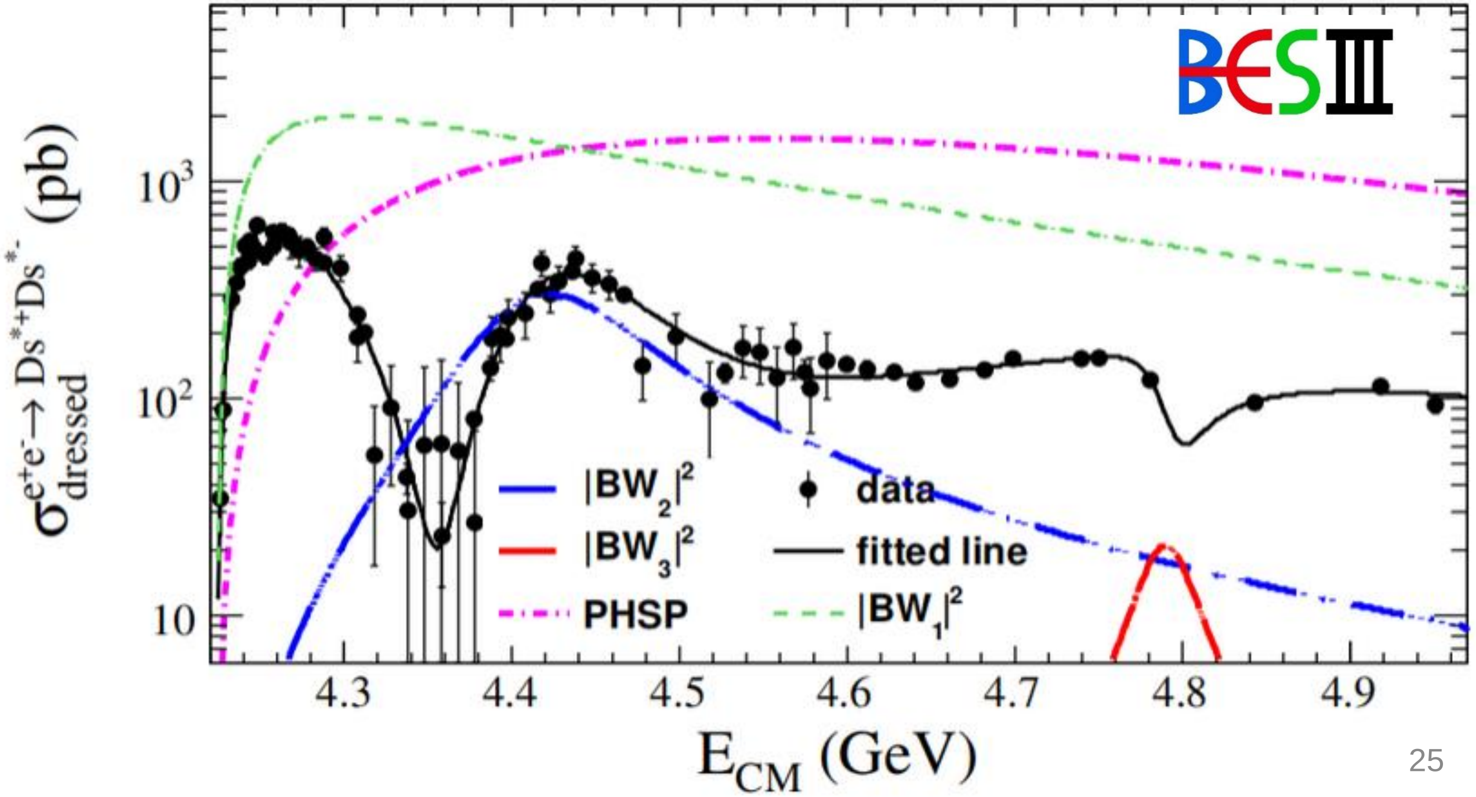
New: Precise line-shape measurement of $e^+e^- \to D_s^{*+}D_s^{*-}$

- Line-shapes provide important information on the nature of charmonium-like states
  $\rightarrow$ Many charmonium-like resonances coincide with thresholds of $D\bar{D}$, $D^*\bar{D}^*$ etc.

- BW fits yield masses at 4187 MeV/c² and 4414.6 MeV/c²

- First observation of $\Psi(4415) \rightarrow D_s^{*+}D_s^{*-}$

- A third BW necessary to describe structure at 4.79 GeV*.

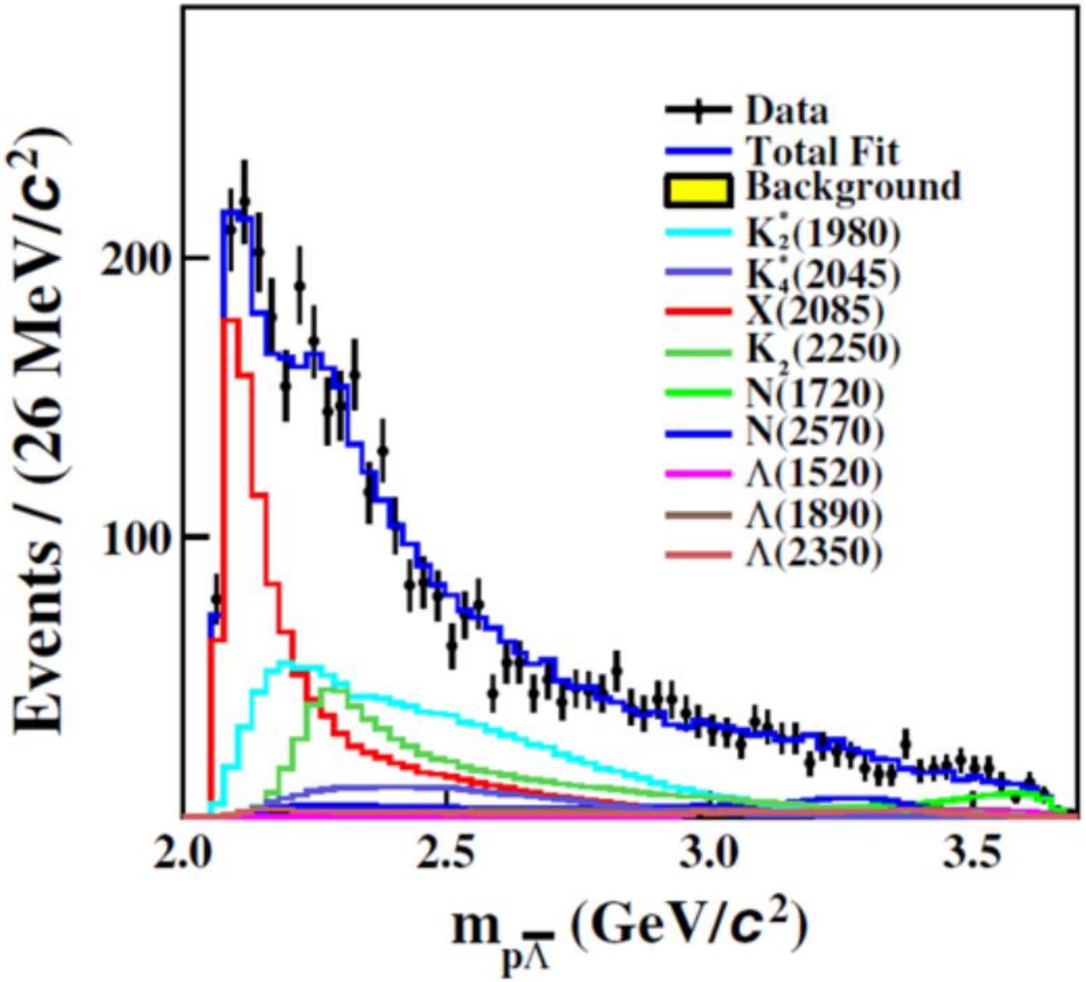


*Phys. Rev. Lett. 131, 151903 (2023)

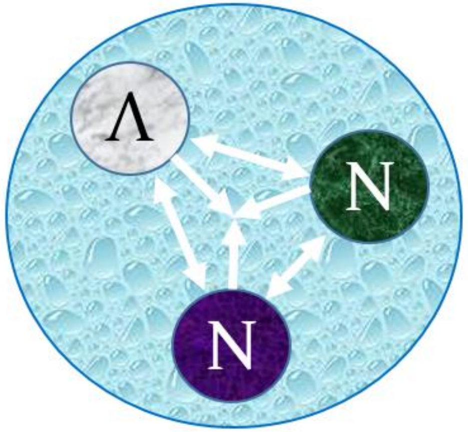
New: Observation of resonance near $p\bar{\Lambda}$ threshold

So-called X(2085) seen in $e^+e^- \to p\bar{\Lambda}K^- + c.c.$ *

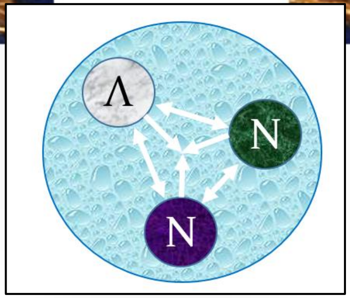
- $M = 2086^{+4}_{-2} \pm 9$ MeV/c²
- $\Gamma = 56^{+3}_{-3} \pm 25$ MeV/c²
- Favours $J^P = 1^+$
- Cannot be attributed to any known kaon.
- Not predicted by potential models.



*Phys. Rev. Lett. 131, 151901 (2023)



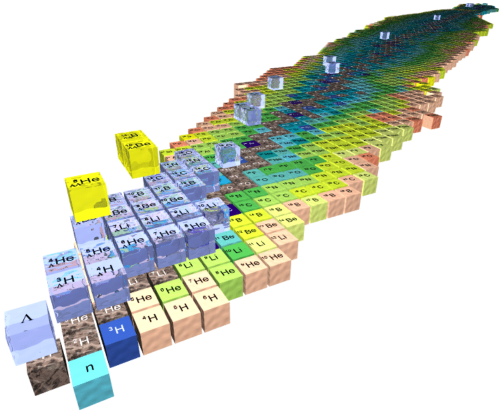
HADRON INTERACTIONS



Hyperon-nucleon (YN) interaction

Why?

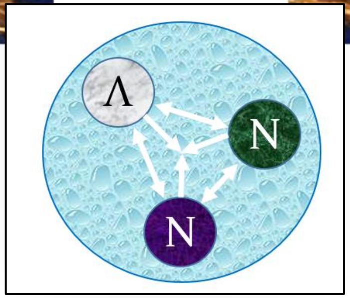
- Crucial component to predict properties of hypernuclei.
- Needed to understand the *hyperon puzzle* of neutron stars.



How?

- Hyperon femtoscopy
- Hypernuclear studies
- Secondary YN interactions

BESIII



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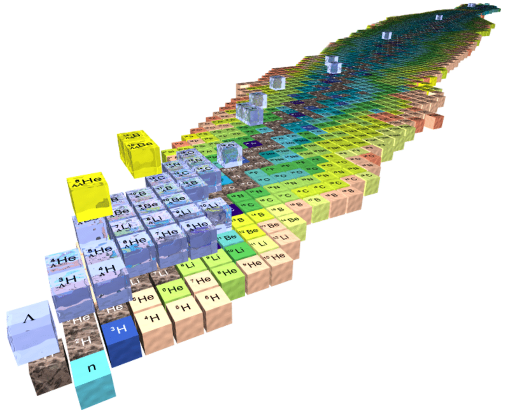

How?

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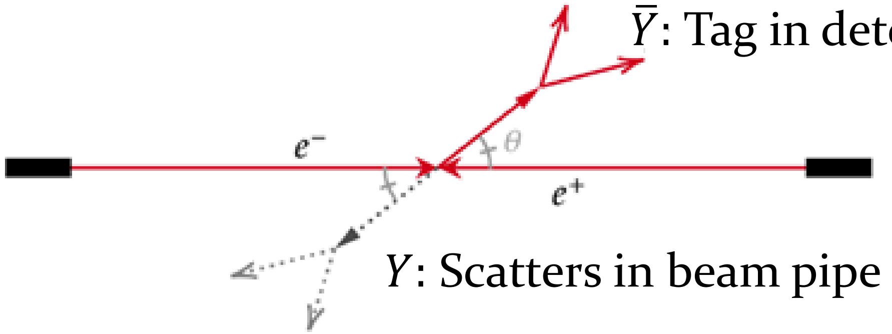
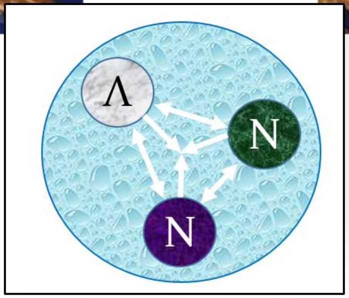
BESIII

– $e^+e^- \to J/\Psi \to Y\bar{Y}$

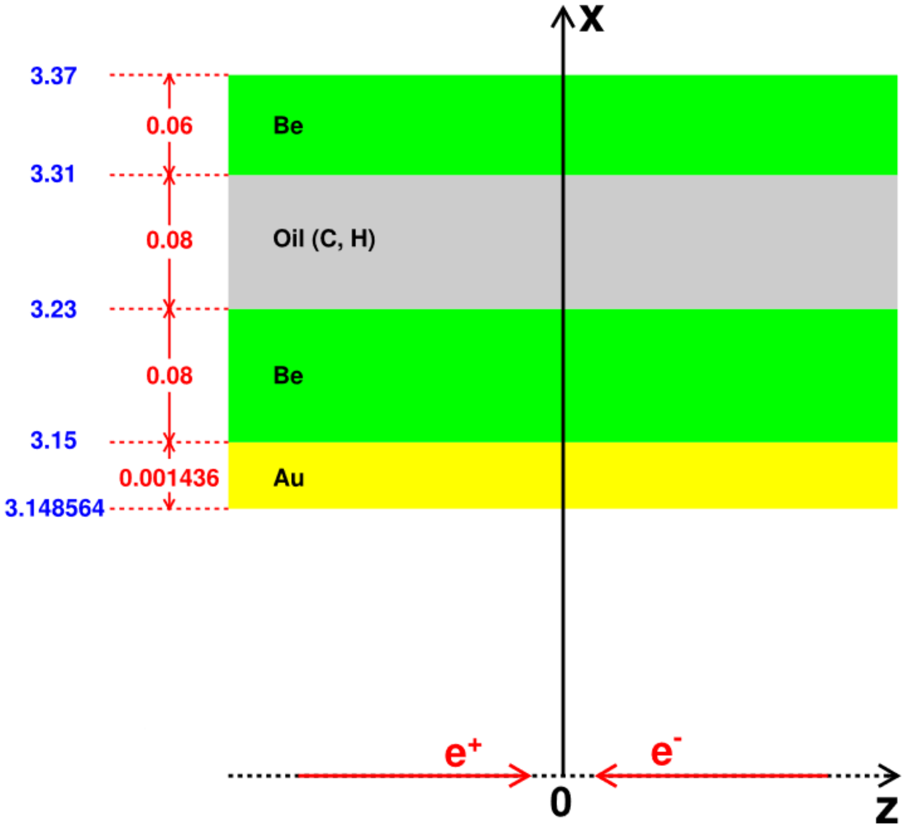


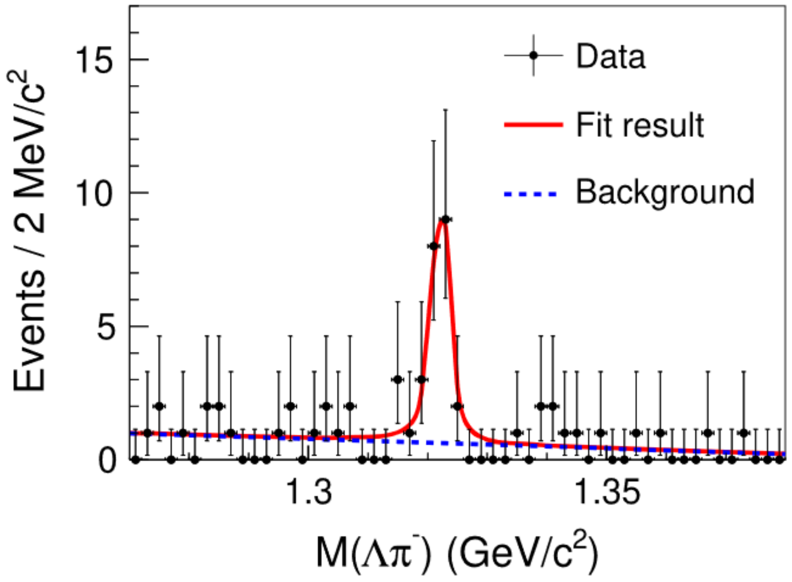
$\bar{Y}$: Tag in detector

Y: Scatters in beam pipe



New: First study of $\Xi^0 n \to \Xi^- p$ in an e^+e^- experiment





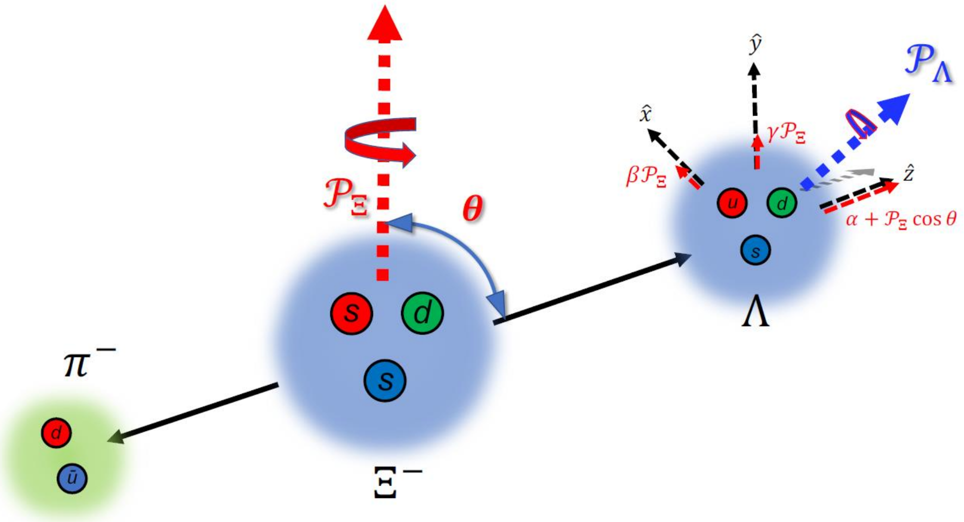
- Primary reaction $e^+e^- \to J/\Psi \to \Xi^0\bar{\Xi}^0$
- Secondary Ξ^0 beam with $p_\Xi = 0.818$ GeV/c
- Interaction mainly with ^{9}Be in beam pipe
- 20 events observed
- $\sigma(\Xi^0 + {}^9Be \to \Xi^- + {}^8Be + p)$ = 22.1 ±5.3 ±4.5 mb
- Assuming 3 effective reaction neutrons**:
  $\sigma(\Xi^0 n \to \Xi^- p)$ = 7.4 ±1.8 ±1.5 mb

*Phys. Rev. Lett. 130, 251902(2023)
**Phys. Lett. B 633, p 214-218 (2006)

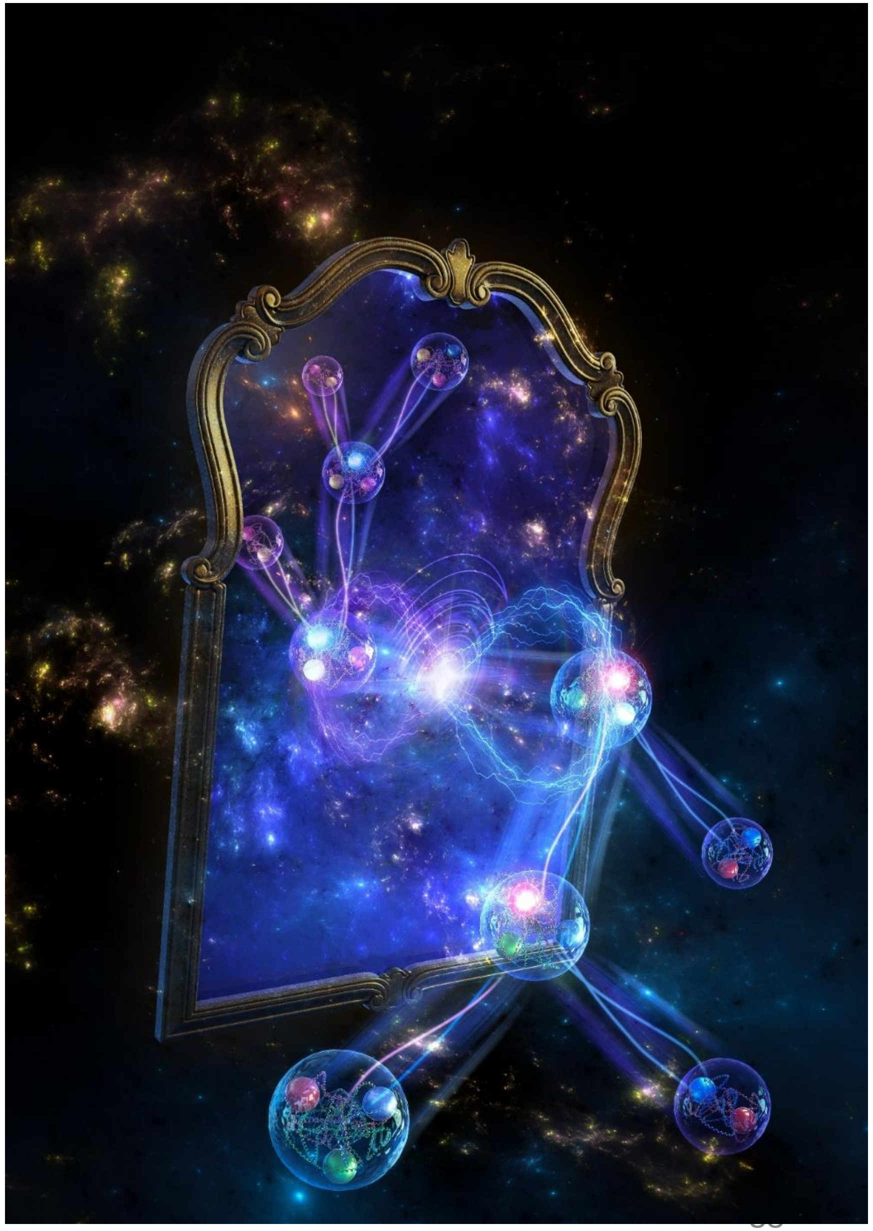
HADRONIC EFFECTS IN PRECISION AND RARE PROCESSES

Precision tests of the Standard Model

- SM predicts very small violations of charge conjugation and parity (CP) symmetry.
- Sizeable CP violations prerequisite for *Baryogenesis* ← Sakharov criterion.
- Spin-carrying hyperons precision probe of CP symmetry.



CP tests with BESIII



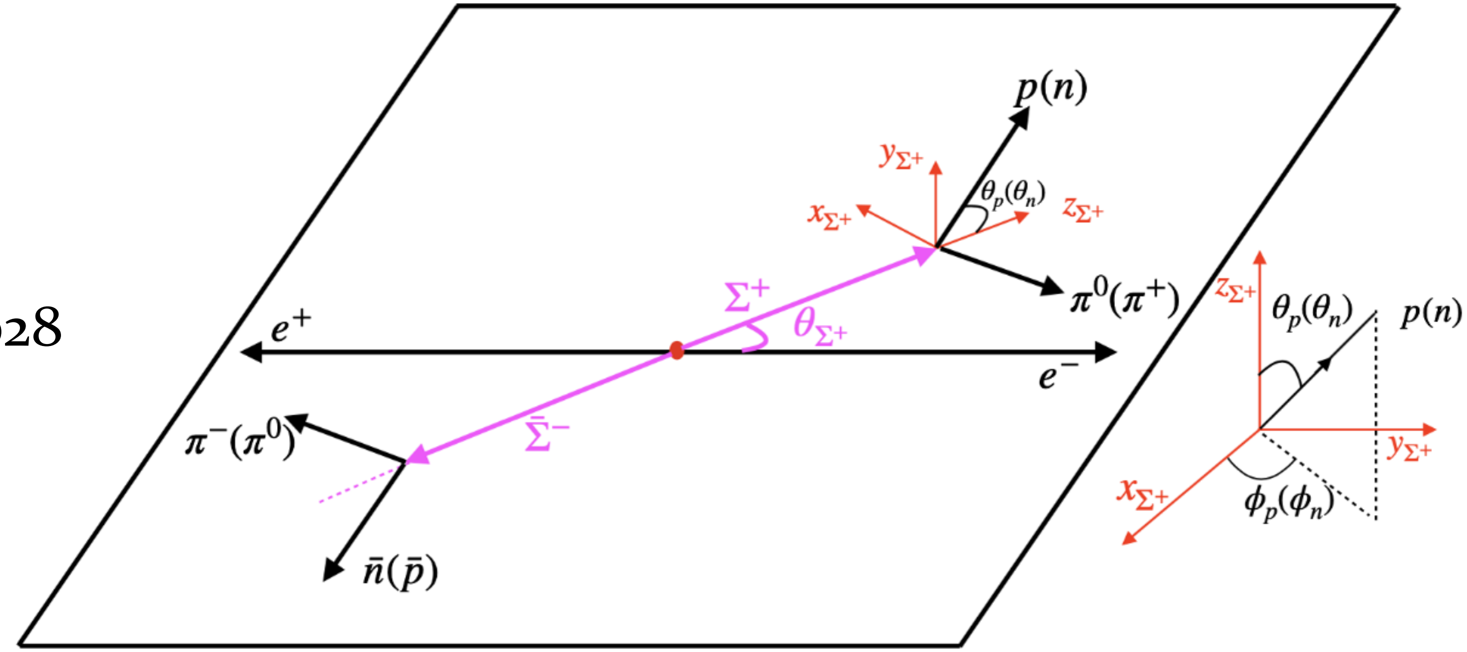
- **Polarised** and **entangled** hyperon-antihyperon pairs enable CP tests in hyperon decays
- **Sequentially decaying** multi-strange and charm hyperons enable
  - Production- and decay parameters
- A **combination** of the two approaches enables separation of strong and weak decay phases

→ More sensitive CP tests!

BESIII

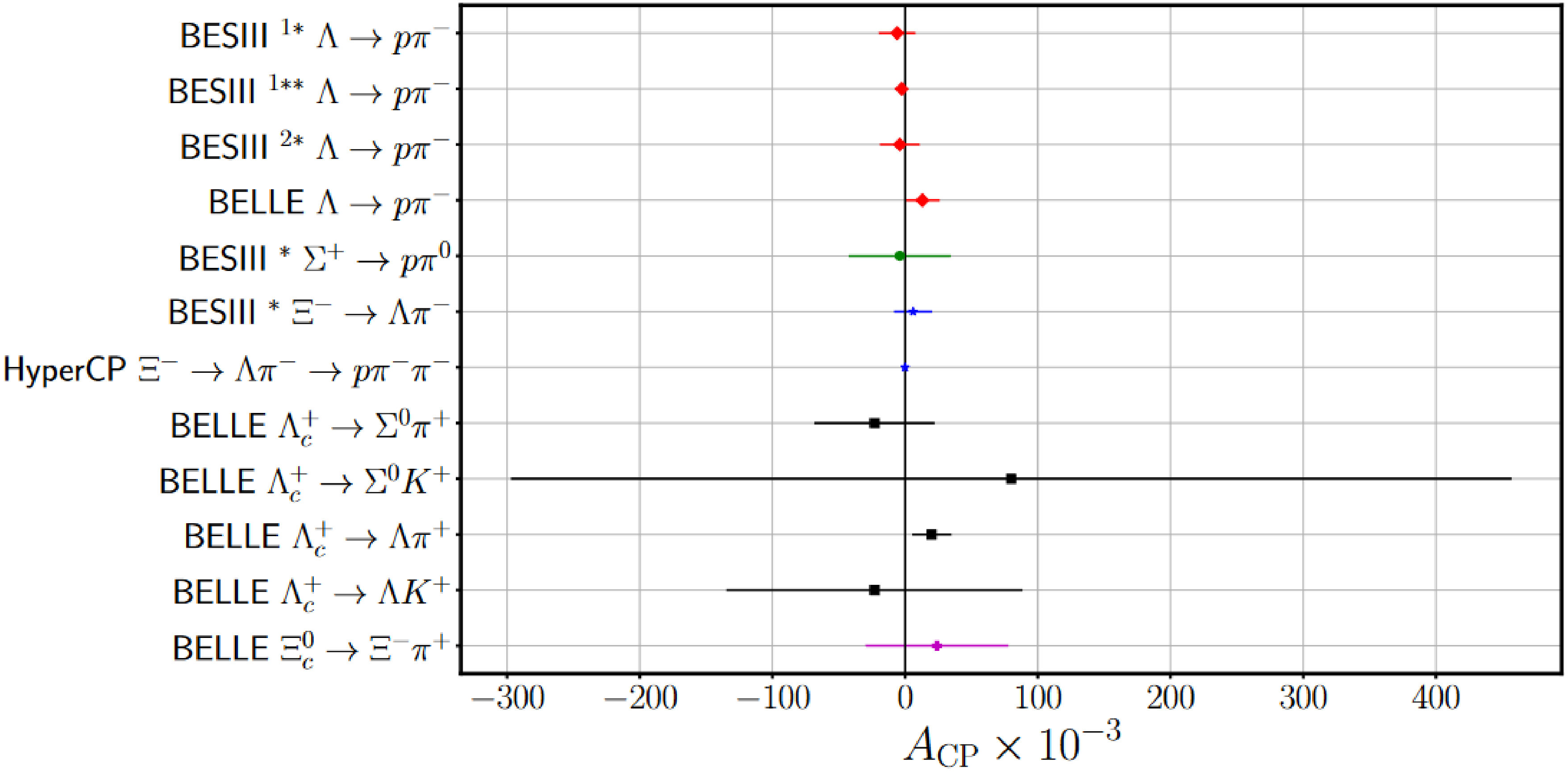
New: CP tests in decays into neutrons

- Polarised and entangled $\Sigma^+\bar{\Sigma}^-$ pairs J/Ψ decays*
- Select events where $\Sigma^+ \to n\pi^+, \bar{\Sigma}^- \to \bar{p}\pi^0$ or c.c.
- First CP precision test of any hyperon decaying into a neutron.
- Decay parameters α_+ $(\Sigma^+ \to n\pi^+)$ and $\bar{\alpha}_-$ $(\bar{\Sigma}^- \to \bar{n}\pi^-)$ measured.
- $A_{CP} = \frac{\alpha_+ + \bar{\alpha}_-}{\alpha_+ + \bar{\alpha}_-} = 0.080 \pm 0.052 \pm 0.028$



*Phys. Rev. Lett. 131, 191802 (2023)

CP tests, world data



BESIII:

Nature Phys. **15**, p 631-634 (2019)

Phys. Rev. Lett. 125, 052004 (2020)

Nature 606, 64-69 (2022)

Phys. Rev. Lett. 129, 131801 (2022)

Phys. Rev. D 108, L031106 (2023)

Belle:

Sci. Bull. 68, 583-592 (2023)

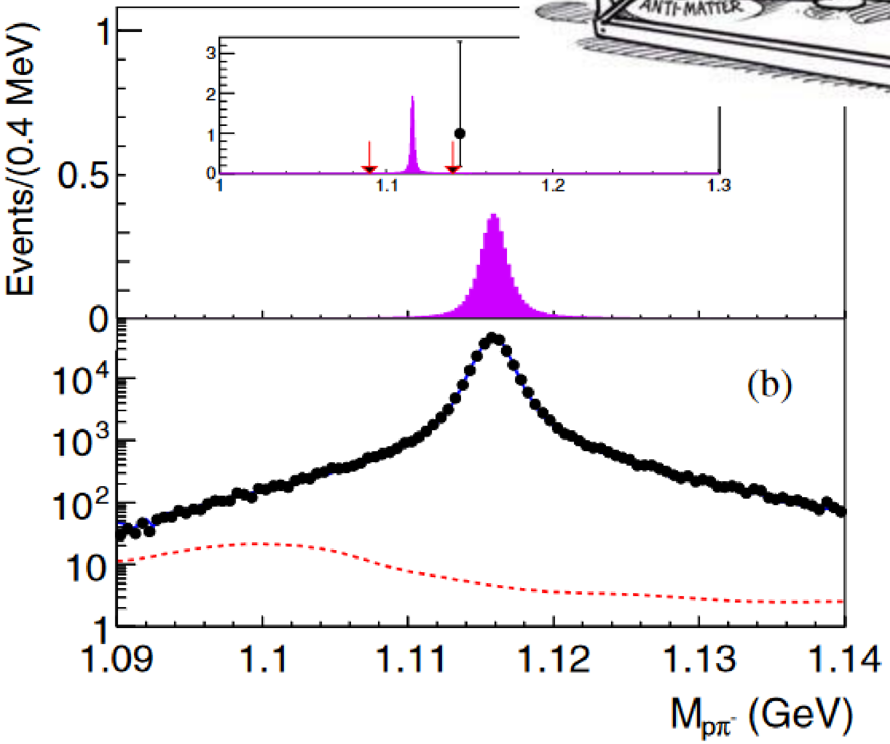
HyperCP:

Phys. Rev. Lett. 93, 262001, 2004.

New: Search for baryon number violating $\Lambda\bar{\Lambda}$ oscillations

- Baryon number violation (BNV) another Sakharov criterion for *Baryogenesis.*
- Protons insanely stable against BNV, what about neutral hyperons?
- BESIII looking for "wrong sign" events, *i.e.* $\Lambda \rightarrow p\pi^-$ in $J/\Psi \rightarrow pK^-\bar{\Lambda}$.
- $\frac{BR(J/\Psi \rightarrow pK^-\Lambda + c.c.)}{BR(J/\Psi \rightarrow pK^-\bar{\Lambda} + c.c.)} < 4.4 \cdot 10^{-6}$ (90% CL)

  $\rightarrow$ oscillation parameter $\delta m_{\Lambda\bar{\Lambda}} < 3.8 \cdot 10^{-18}$



*Phys. Rev. Lett. 131, 121801 (2023)

Summary

- BESIII i a multi-purpose experiment that covers the main four areas of hadron physics:
  - Hadron structure
  - Hadron spectroscopy
  - Hadron interactions
  - Precision and rare processes

The highlights presented here is a selection of last year's accomplishment – not exhaustive!

- Upgraded accelerator open new possibilities
- BESIII > 500 published papers
  - 98 in Physics Review Letters
  - 2 Nature Physics
  - 1 Nature

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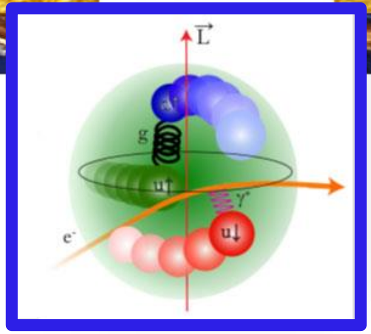
Thanks for your attention!

Knut and Alice Wallenberg Foundation

Swedish Research Council

STINT
The Swedish Foundation for International Cooperation in Research and Higher Education

Backup



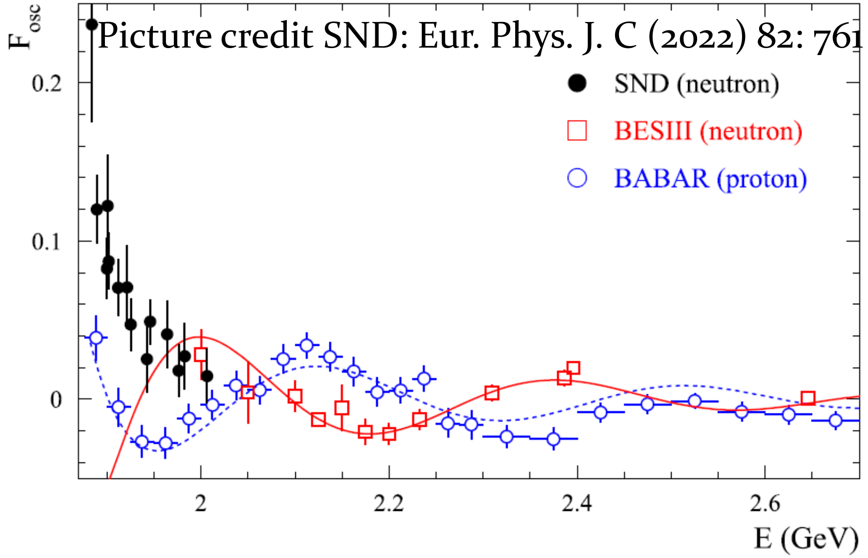
Proton and neutron EMFFs

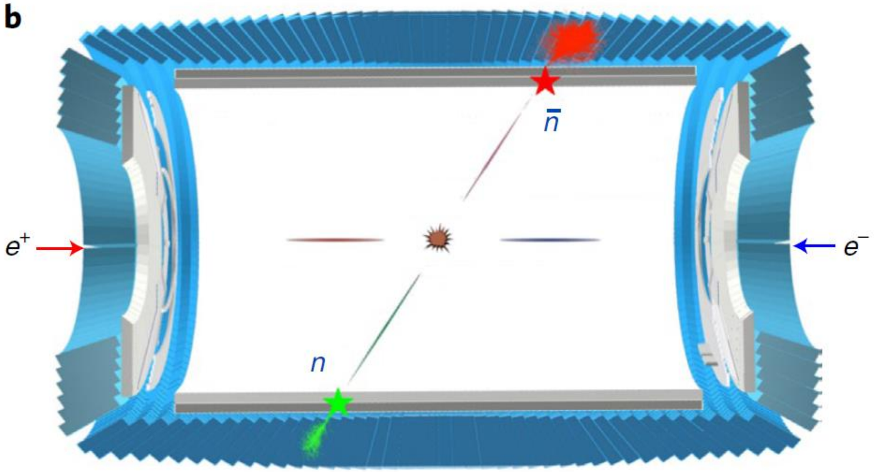
Energy dependence of G_{eff} :

$G_{eff} = G_0 + G_{osc}$

G_0 : Dipole-like

G_{osc}: Oscillations



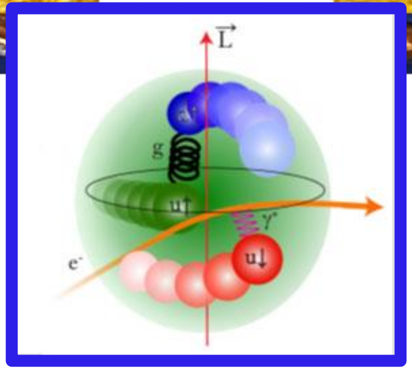


BESIII:

- $G_{osc}\ (p)^*$ and $G_{osc}\ (n)^*,\ ^{**}$: same frequency, different phase:
  $\Delta D = D_p - D_n = 125^{\circ} \pm 12^{\circ}$
- First separation of G_E and G_M

SND: Smaller frequency for neutron oscillations***.

BESIII proton EMFFs:
Phys. Rev. D 91, 112004 (2015)
Phys. Rev. D 99, 092002 (2019)
Phys. Rev. Lett. 124, 042001 (2020)
Phys. Lett. B 817, 136328 (2021)
BESIII neutron EMFFs:
BESIII, Nature Phys. **17**, p 1200–1204 (2021)
BESIII, Phys. Rev. Lett. 130, 151905 (2023)
SND: Eur. Phys. J. C (2022) **82**: 761



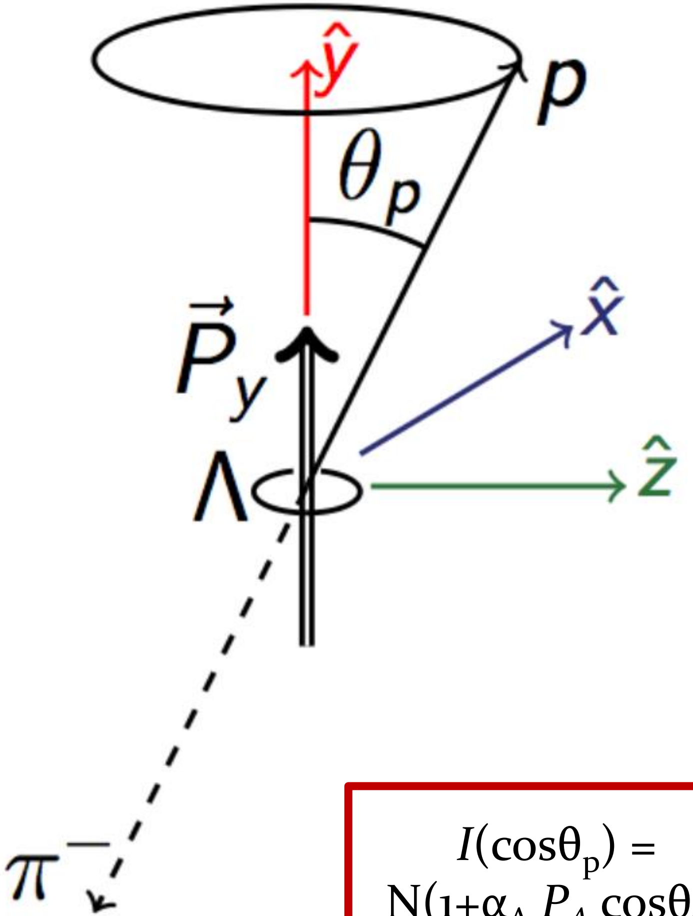
Time-like form factors

- Are complex:
  - $G_E(q^2) = |G_E(q^2)| \cdot e^{i\Phi_E}$, $G_M(q^2) = |G_M(q^2)| \cdot e^{i\Phi_M}$
  - Ratio $R = \frac{|G_E(q^2)|}{|G_M(q^2)|}$ accessible from baryon scattering angle.
  - $\Delta\Phi(q^2) = \Phi_M(q^2) - \Phi_E(q^2)$ = phase between G_E and G_M

  → Polarizes final state!

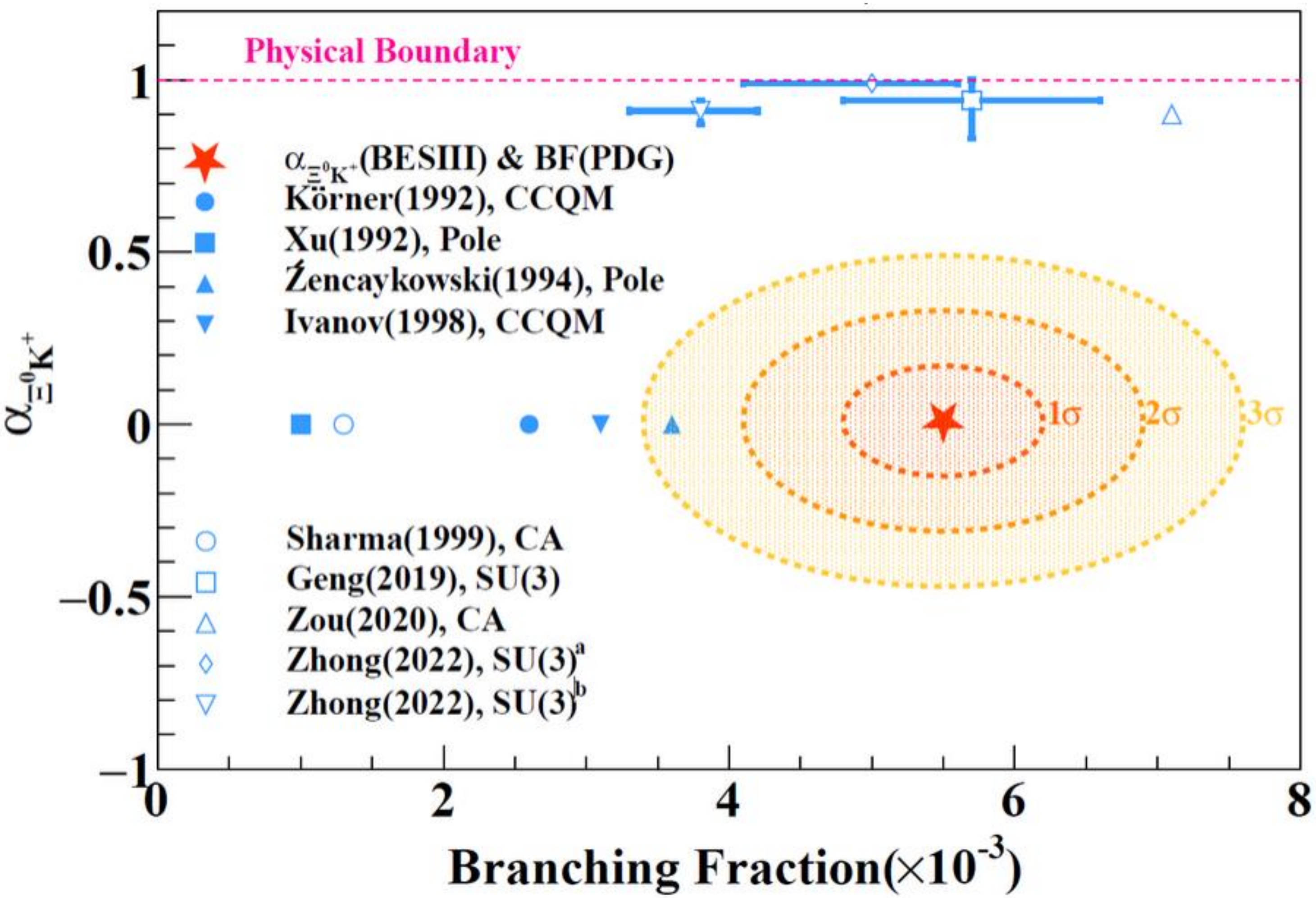
- Related to space-like EMFFs *via* dispersion relations.
  - Nucleons: SL and TL accessible.
  - Hyperons: Only TL accessible, but also phase!

    $\Delta\Phi(q^2) \rightarrow 0 \leftrightarrow$ SL = TL



$I(\cos\theta_p) =$
$N(1+\alpha_\Lambda P_\Lambda \cos\theta_p)$

Brand new: Decay asymmetry in $\Lambda_c^+ \to \Xi^0 K^+$



Phys. Rev. Lett. 132, 031801 (2024)