Recent highlights of the BESIII experiment

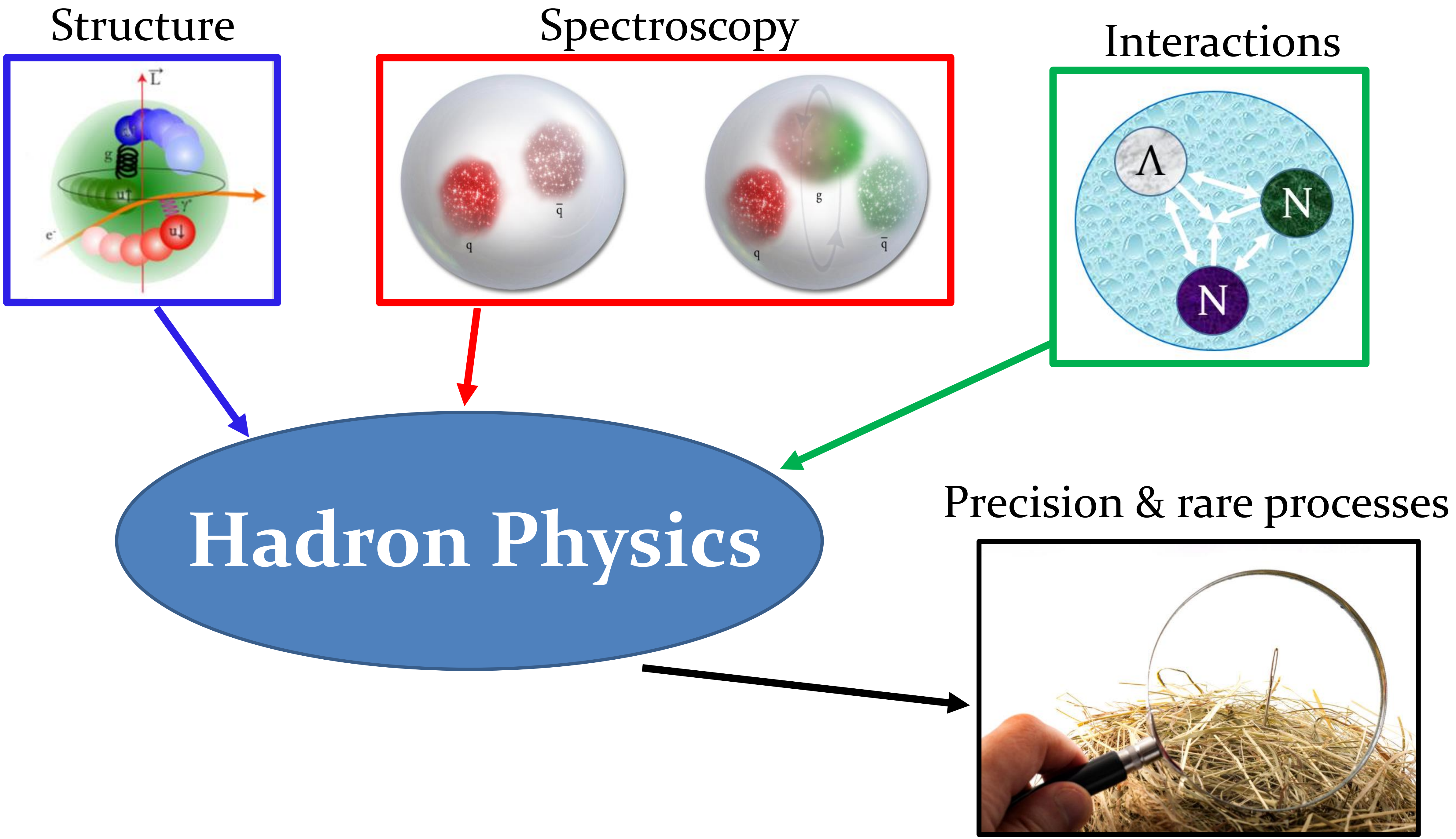
Swedish Nuclear Physics Meeting
Lund, October 30- November 1, 2024

Karin Schönning, Uppsala University

Outline

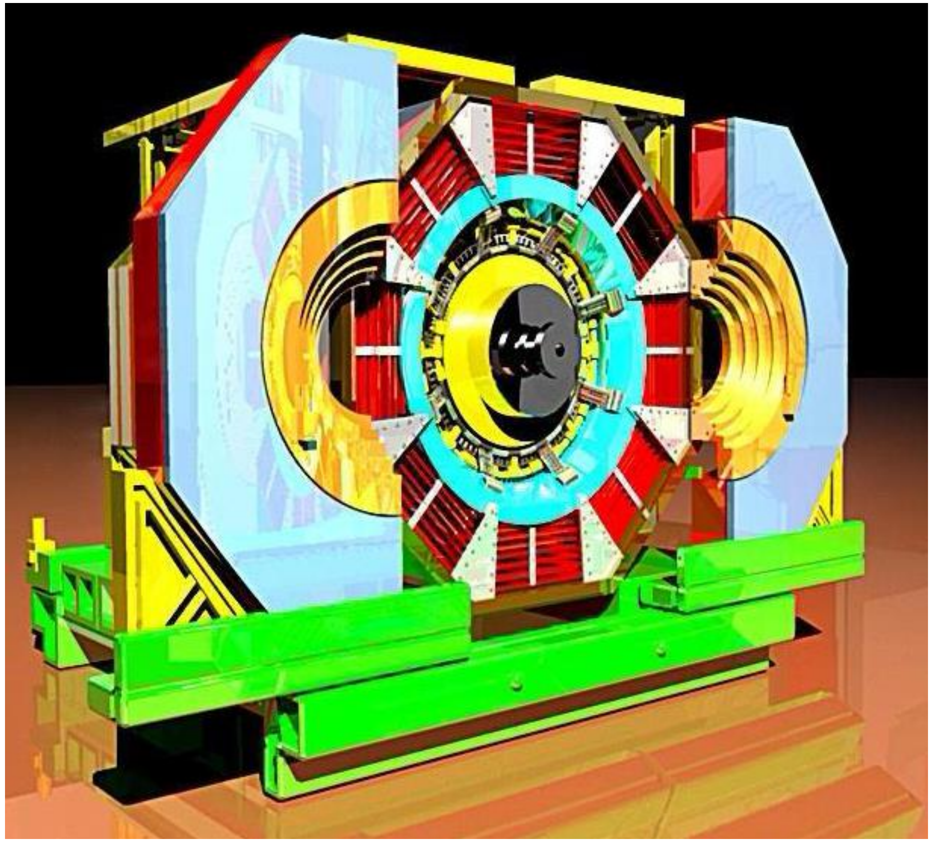
- BESIII at BEPC-II
- Recent highlights:
  - Hadron structure
  - Hadron spectroscopy
  - Hadron interactions
  - Precision and rare processes

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



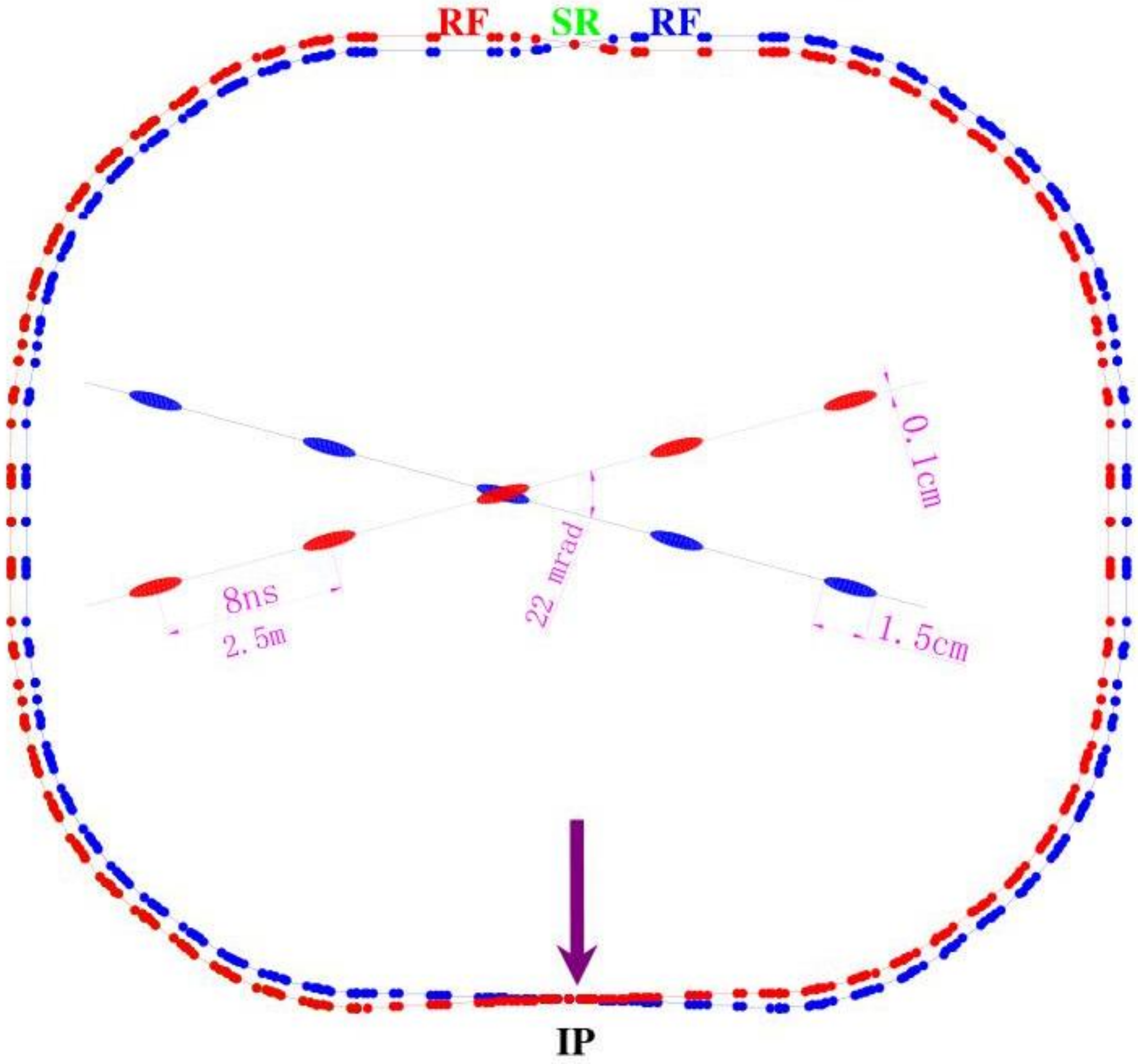
Structure
Spectroscopy
Interactions
Λ
N
N
Hadron Physics
Precision & rare processes

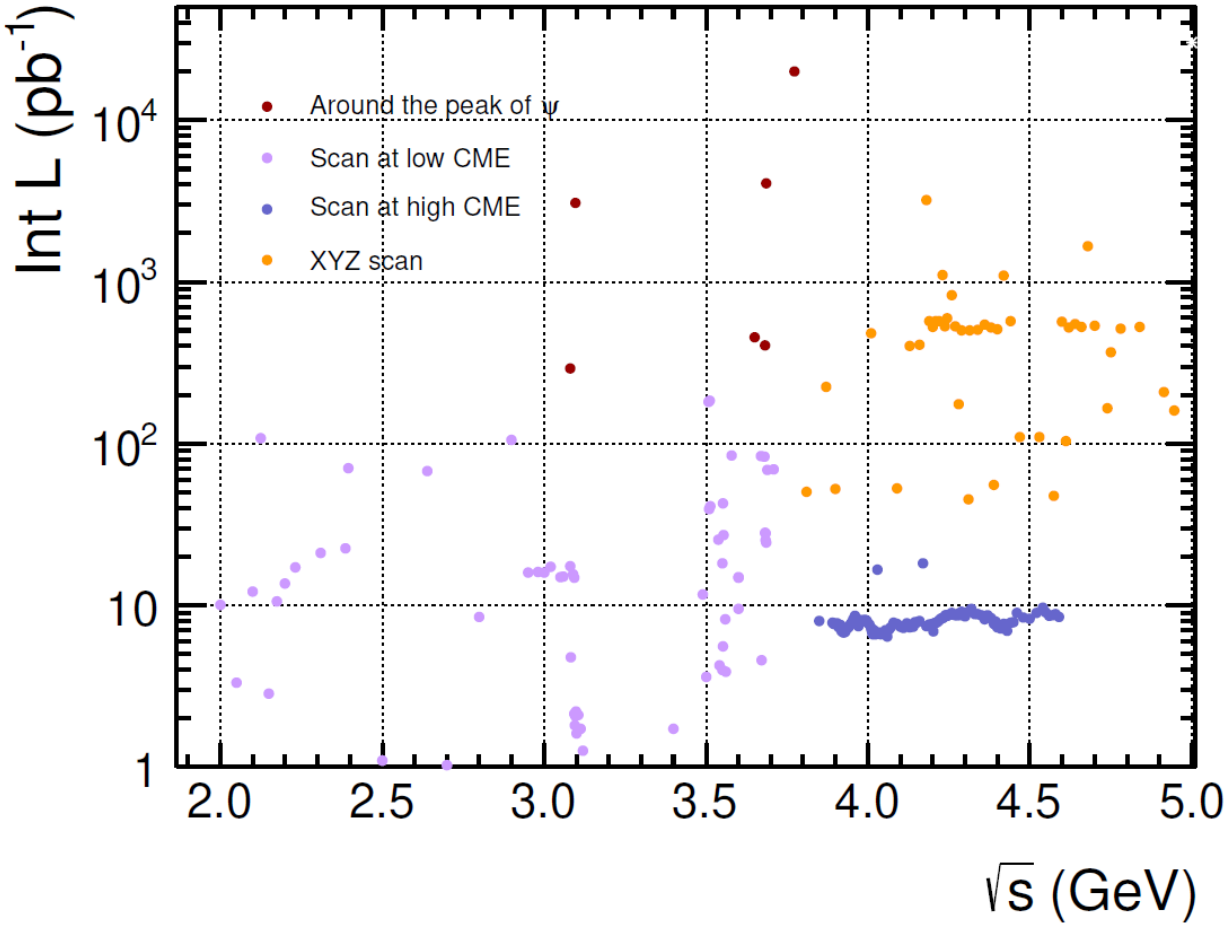
BESIII at BEPC-II



The Beijing Electron-Positron Collider (BEPC-II)

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

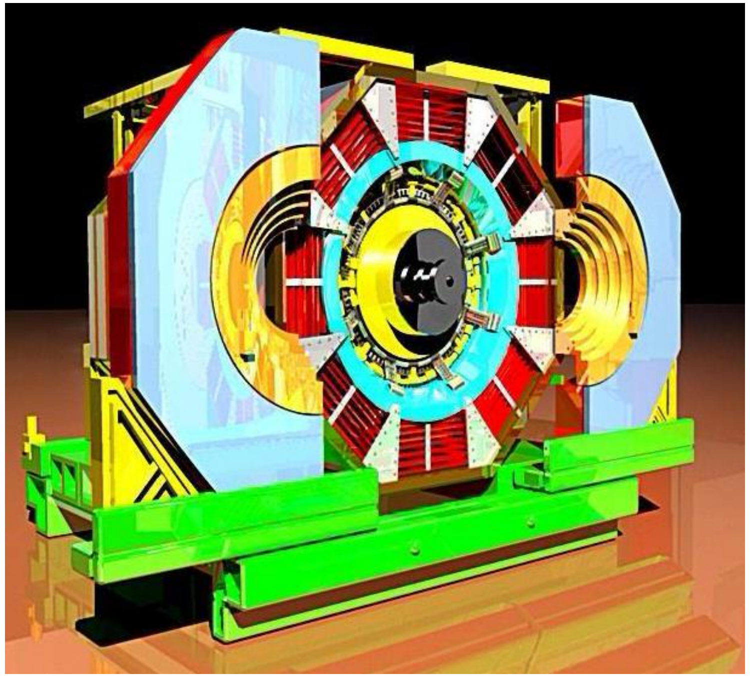


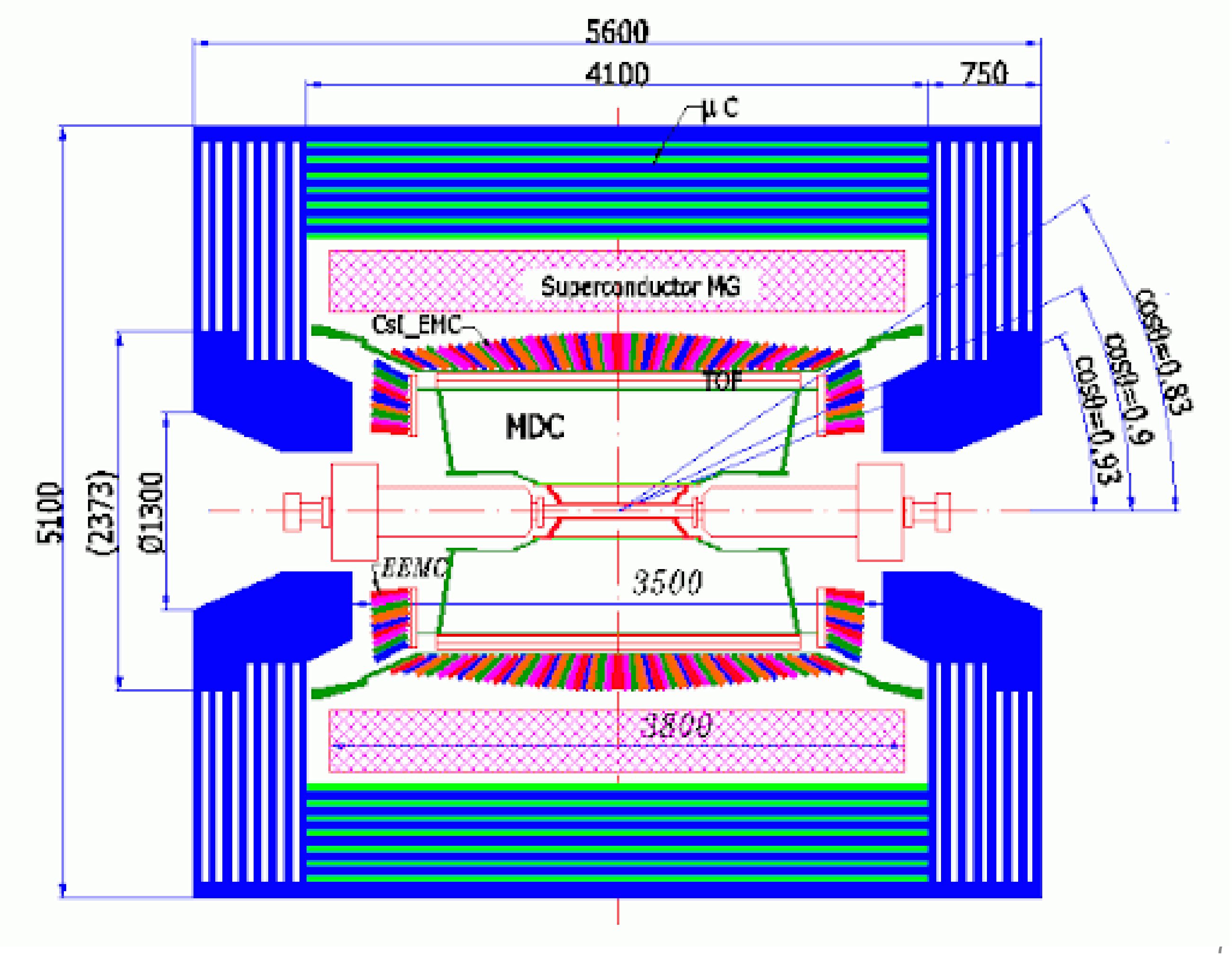


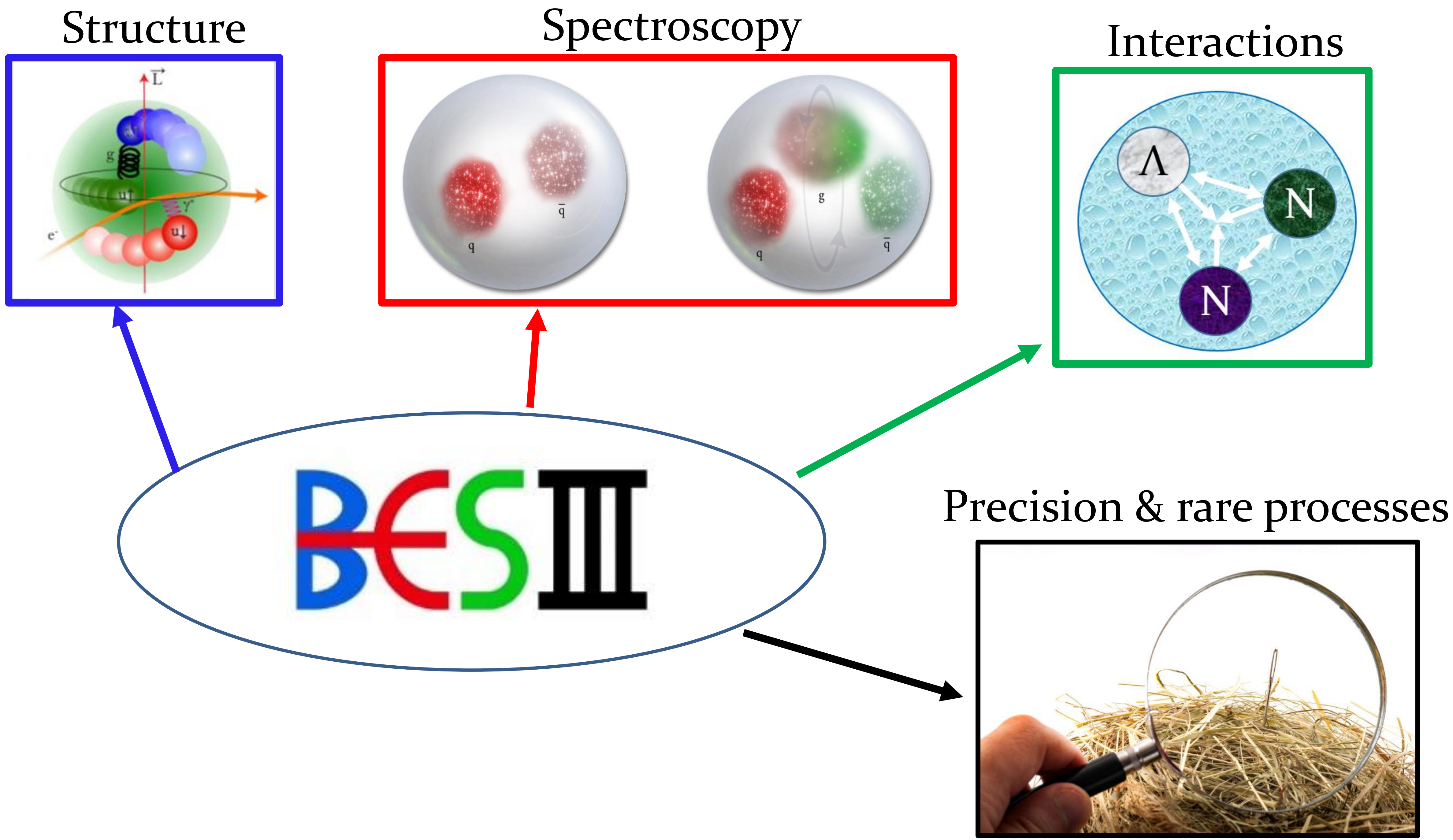
UPPSALA UNIVERSITET

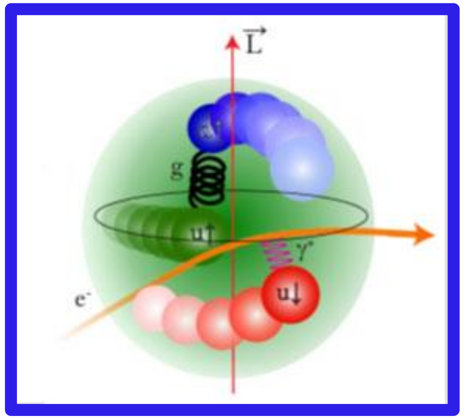
The Beijing Spectrometer (BESIII)

- Near 4π coverage
- Tracking, PID, Calorimetry

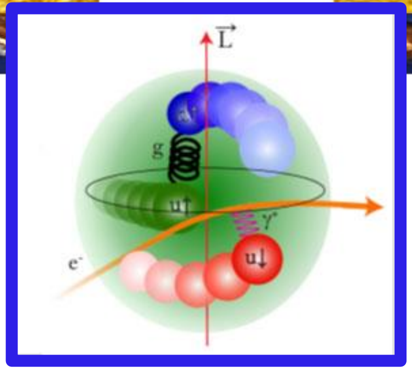





Structure
Spectroscopy
Interactions
Precision & rare processes
BESIII
q
q̄
g
Λ
N
N



HADRON STRUCTURE WITH BESIII



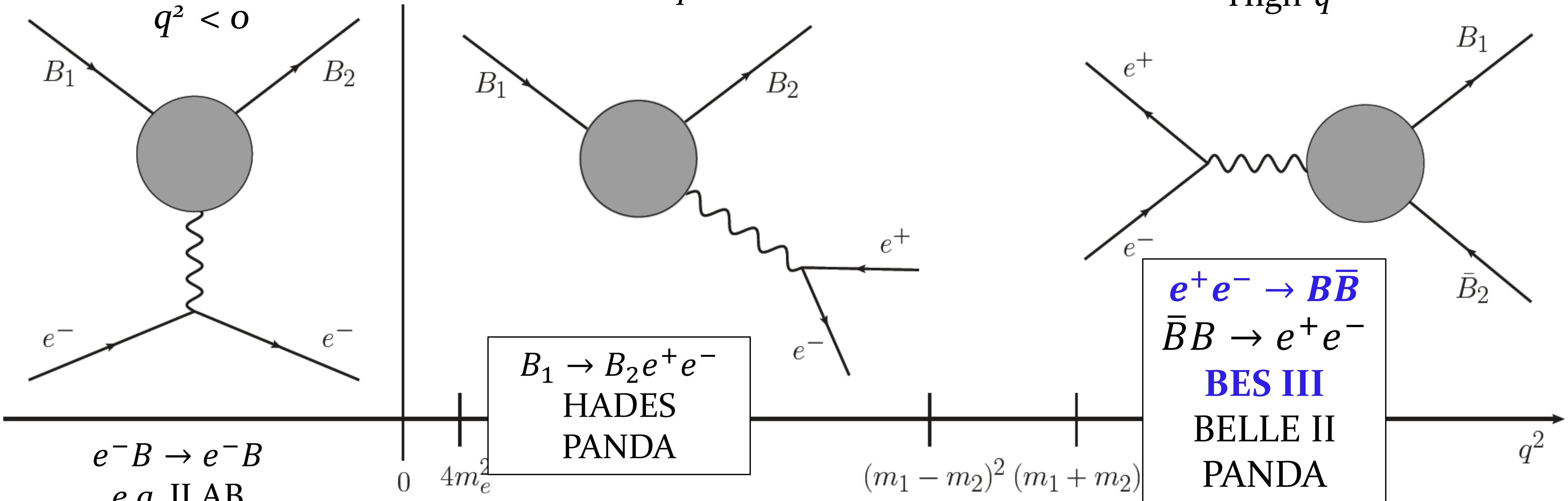
Electromagnetic Form Factors (EMFFs)

Space-like
$q^2 < 0$

Low-q^2

Time-like
$q^2 > 0$

High-q^2



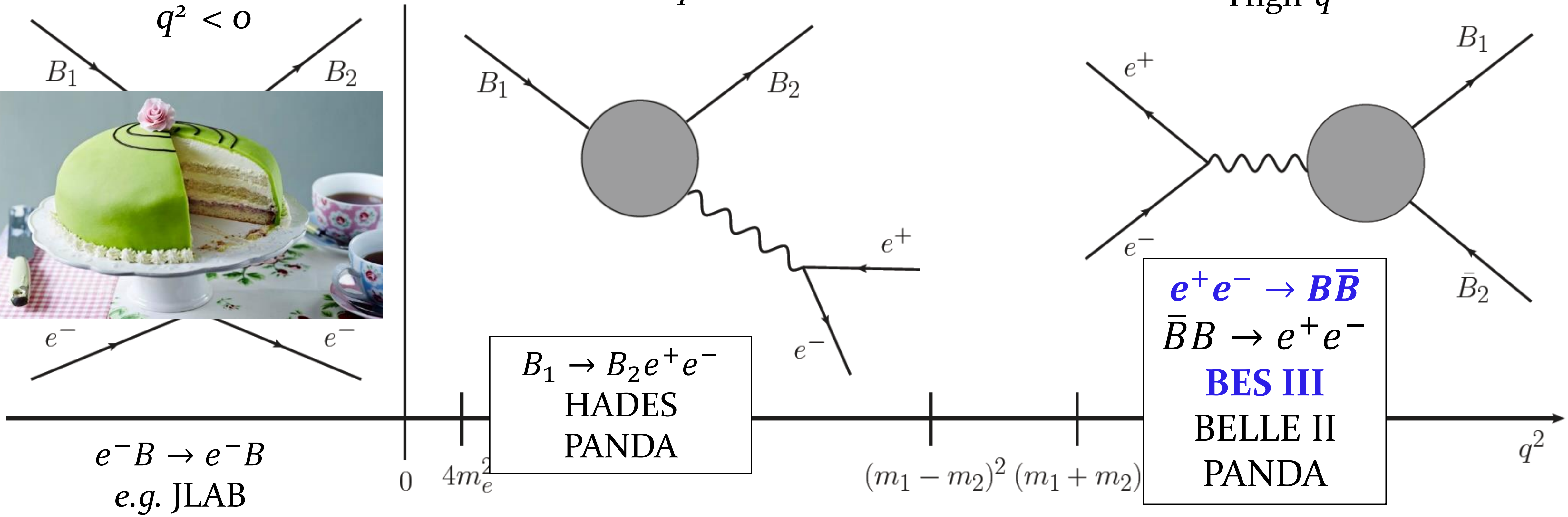
$B_1 \to B_2 e^+ e^-$
HADES
PANDA

$e^+ e^- \to B\bar{B}$
$\bar{B}B \to e^+ e^-$
BES III
BELLE II
PANDA

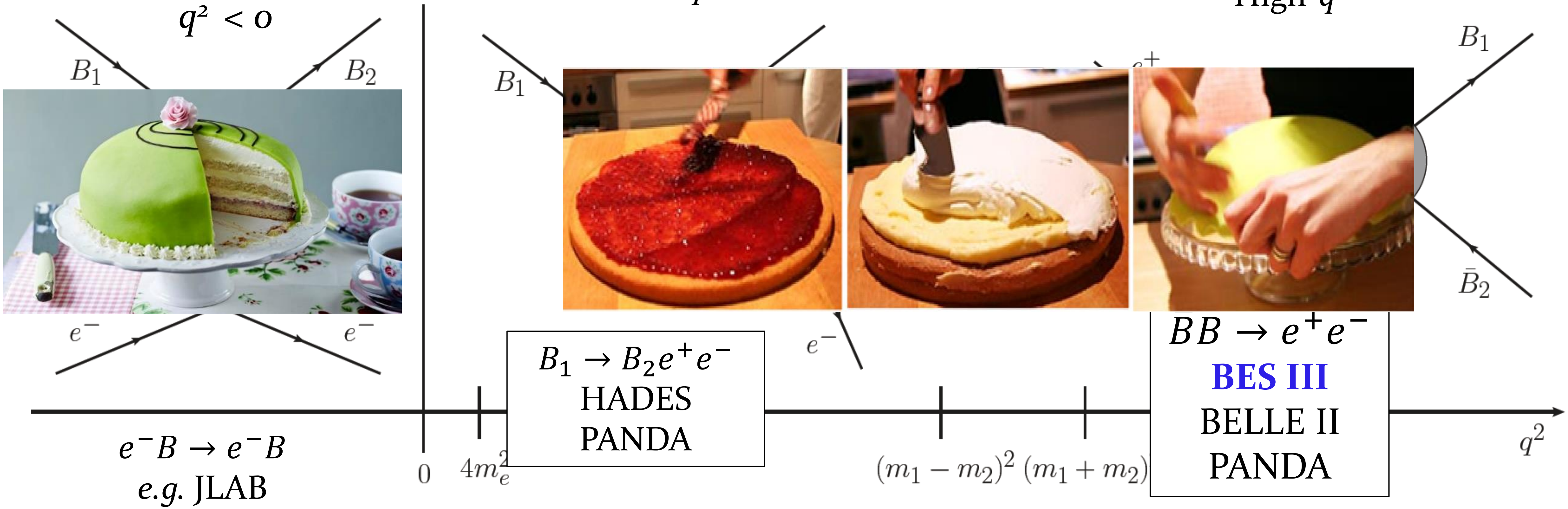
$e^- B \to e^- B$
e.g. JLAB

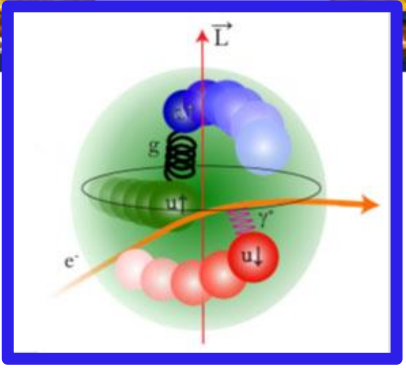
Picture cred. E. Perotti, PhD thesis (UU 2020)

Electromagnetic Form Factors (EMFFs)



Electromagnetic Form Factors (EMFFs)





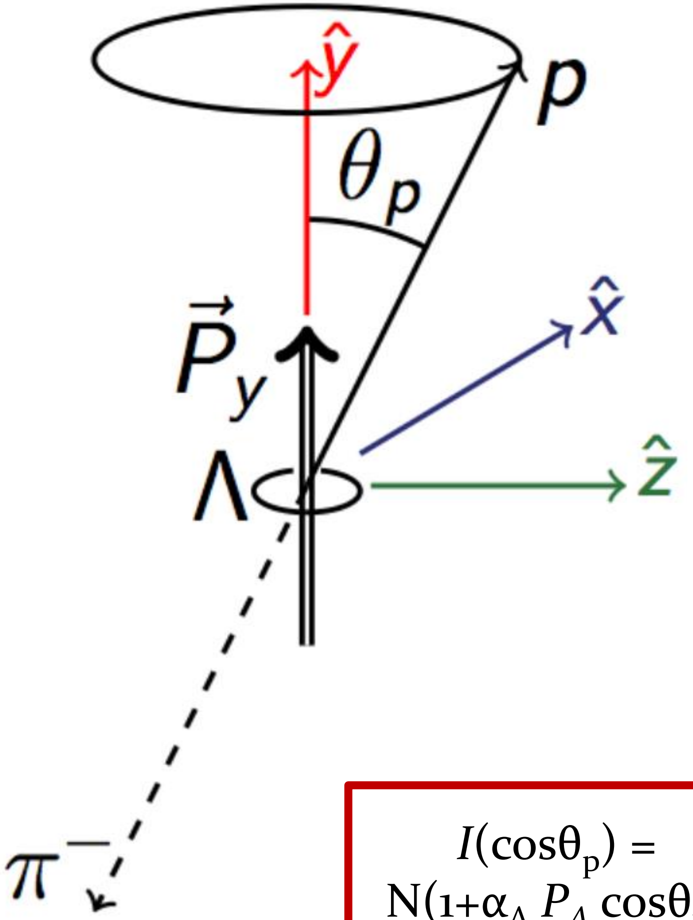
Time-like form factors

- 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



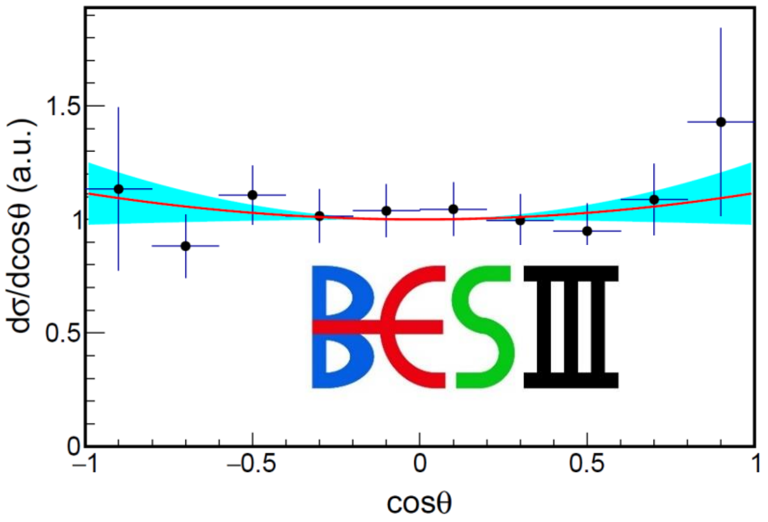
$I(\cos\theta_p) =$
$N(1+\alpha_\Lambda P_\Lambda \cos\theta_p)$

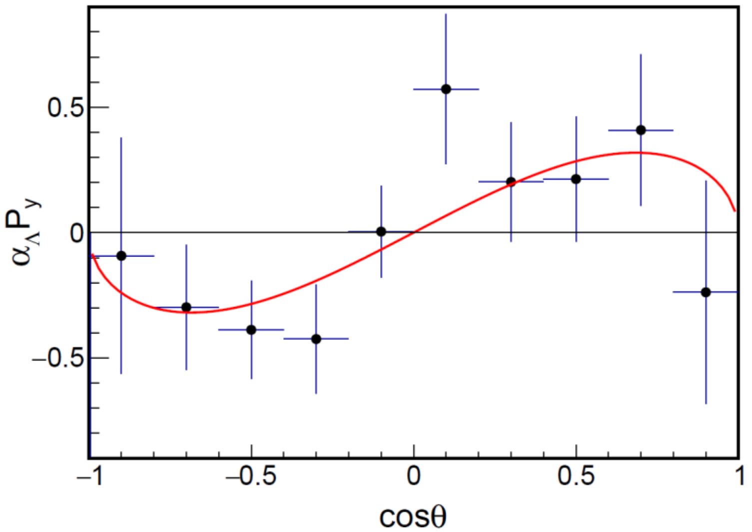
First complete measurement of Λ EMFF

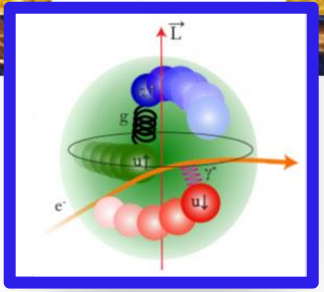
- New BESIII data at 2.396 GeV with 555 exclusive $\bar{\Lambda}\Lambda$ events in sample.
  - $R = |G_E/G_M| = \mathbf{0.96 \pm 0.14 \pm 0.02}$
  - $\Delta\Phi = \mathbf{37^o \pm 12^o \pm 6^o}$
  - $\sigma = 118.7 \pm 5.3 \pm 5.1$ pb

BESIII:
Phys. Rev. Lett. 123, 122003 (2019)

- Most **precise** result on R and σ
- **First** conclusive result on $\Delta\Phi$

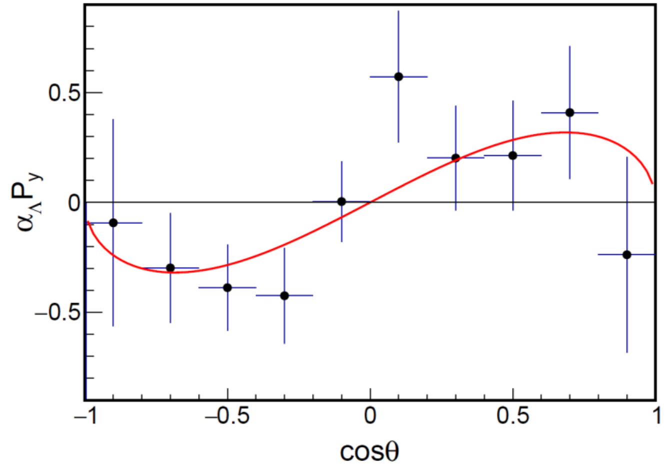


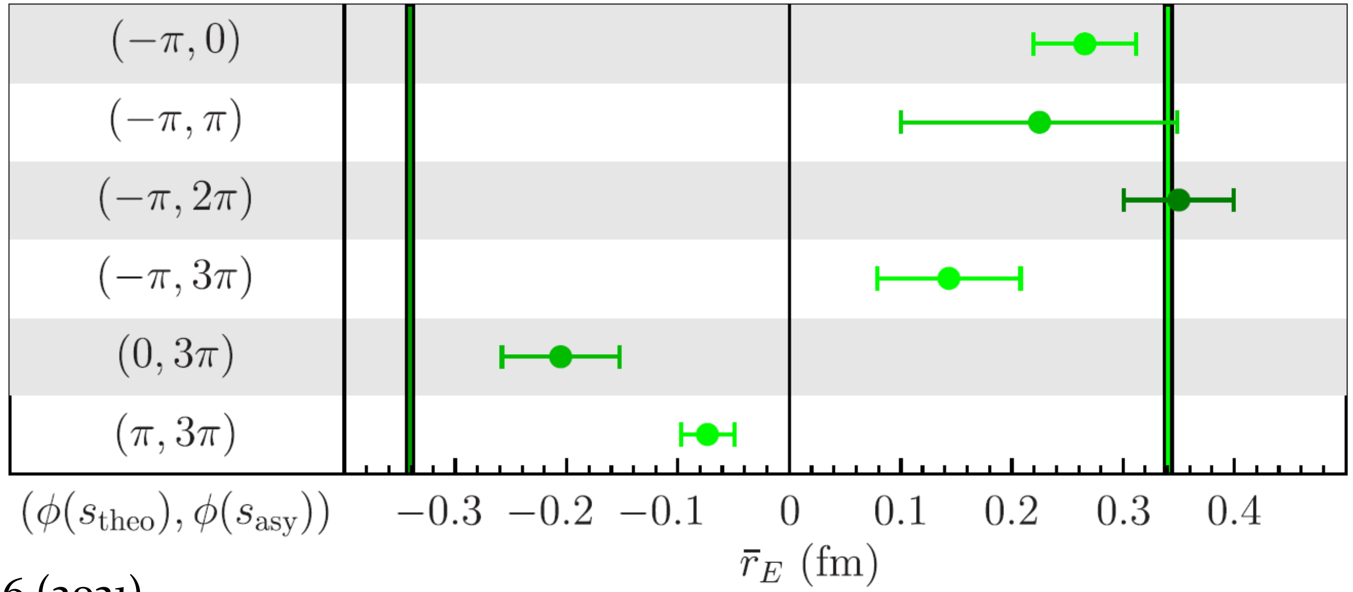




Complete decomposition of EMFFs

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



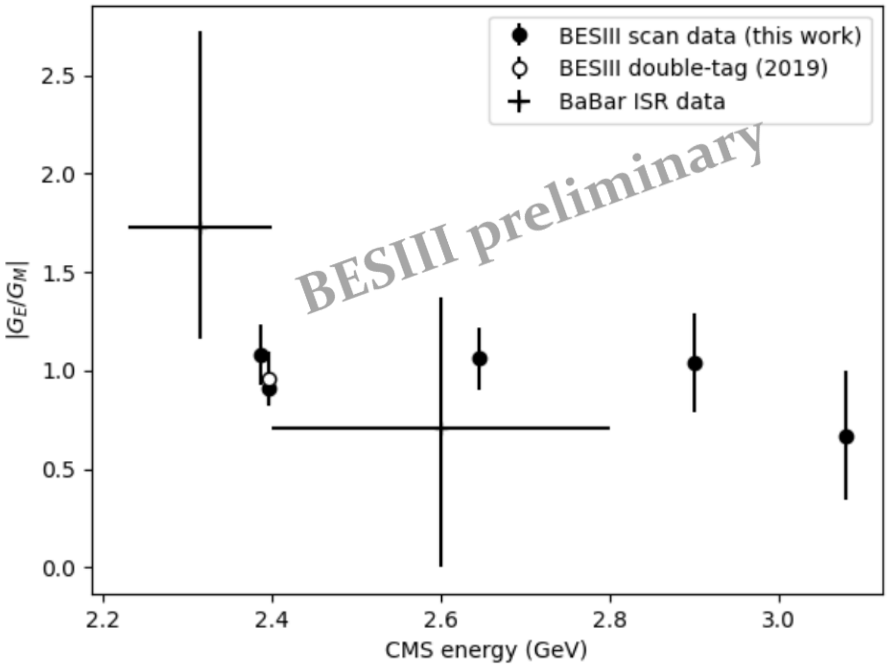


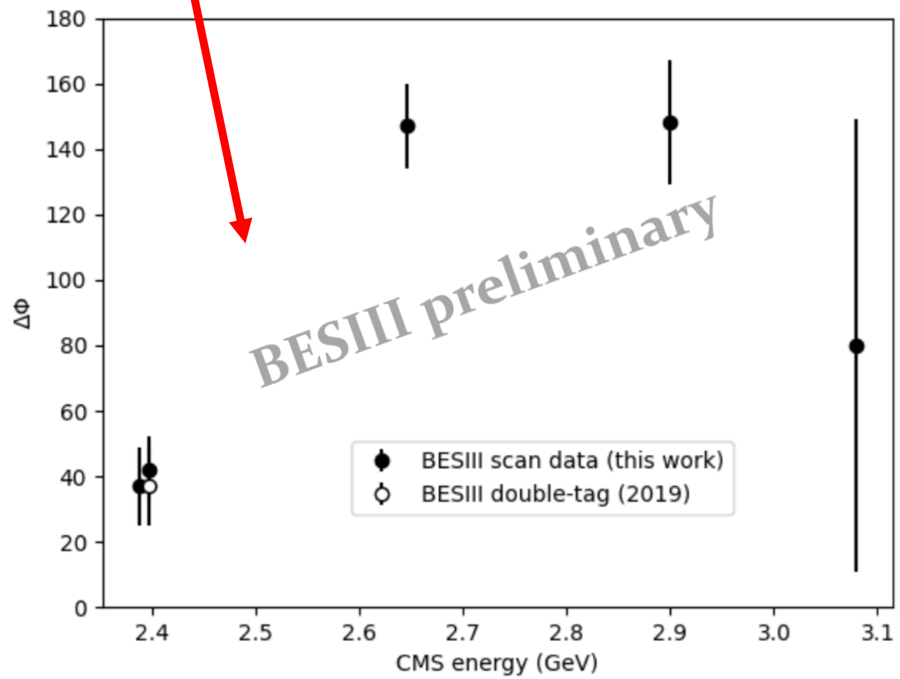
*Mangoni *et al.*, Phys. Rev. D 104, 116016 (2021)
**BESIII: Phys. Rev. Lett. 123, 122003 (2019)

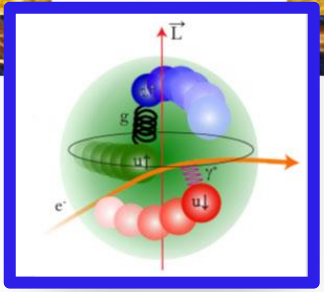
New: Energy-dependent Λ Spin Analysis

Five data points within 2.386 < q < 3.08 GeV.

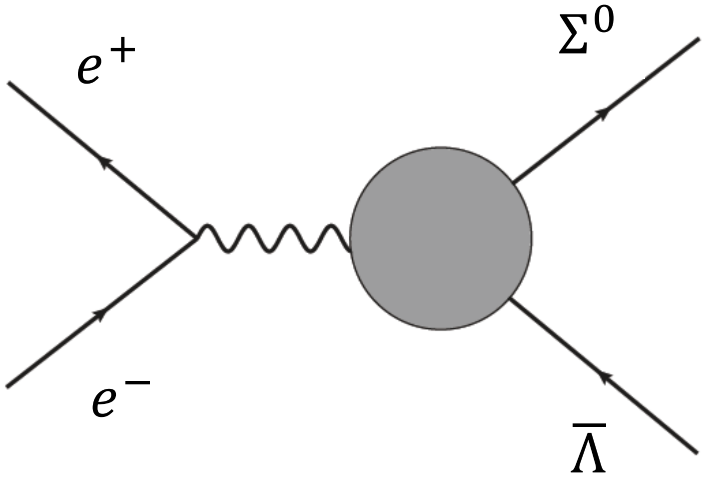
- The ratio $R = |\frac{G_E(q^2)}{G_M(q^2)}|$ fairly constant and consistent with 1.
- Rapid (~ 90°) change of the phase ΔΦ between q~2.4 GeV and 2.6 GeV.







First complete measurement of the $\Sigma^0\Lambda$ Transition EMFFs

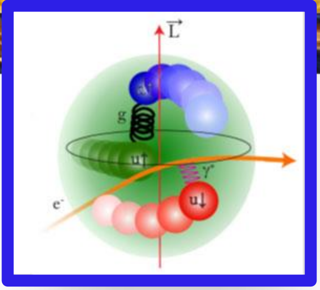


Article | Open access | Published: 11 October 2024

Extracting the femtometer structure of strange baryons using the vacuum polarization effect

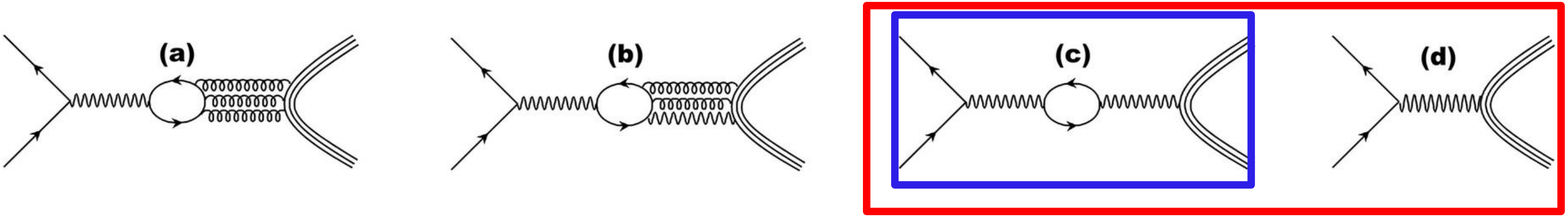
The BESIII Collaboration

Nature Communications **15**, Article number: 8812 (2024) | Cite this article



First complete measurement of the $\Sigma^0\Lambda$ Transition EMFFs

*BESIII, Nature Comm., 15, 8812 (2024)



At $q = M(J/\Psi)$, $e^+e^- \to \Sigma^0\overline{\Lambda} + c.c.$ process is predominantly **electromagnetic** (c, d), since

- Strong processes (a,b) are suppressed by $\frac{m_d - m_u}{q} \sim 10^{-3}$ due to isospin violation.
- Ratio between cross section at J/Ψ and at the continuum in agreement with expectations from EM processes, and with other EM transitions such as $e^+e^- \to \mu^+\mu^-$ and $e^+e^- \to \eta\pi^+\pi^-$.

At $q = M(J/\Psi)$, , the cross section is enhanced by **vacuum polarization**.

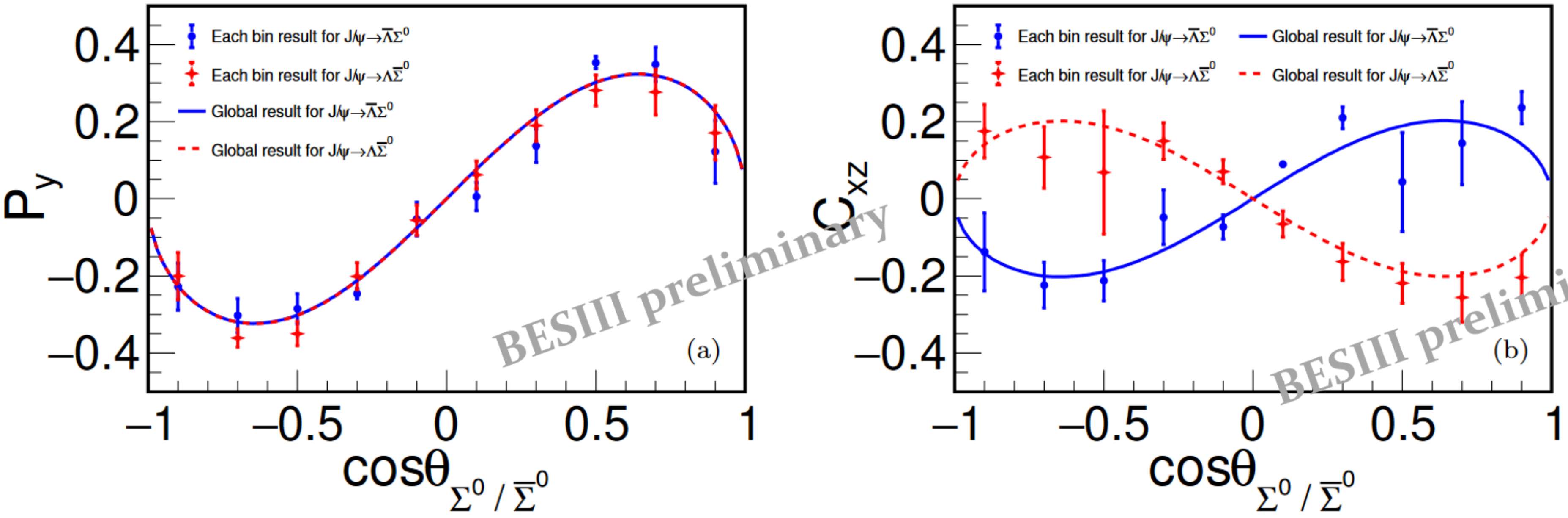
First complete measuerement of the $\Sigma^0\Lambda$ Transition EMFFs

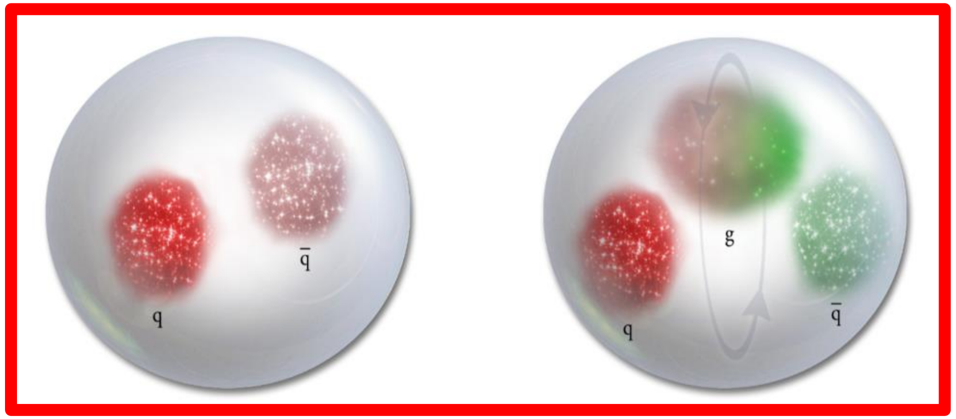
High-precision EMFF measurement:

- $R = |G_E/G_M| = 0.860 \pm 0.029 \pm 0.010$
- $\Delta\Phi_1(\bar{\Lambda}\Sigma^0) = 1.011 \pm 0.094 \pm 0.010$ rad
- $\Delta\Phi_2(\Lambda\bar{\Sigma}^0) = 2.128 \pm 0.094 \pm 0.010$ rad

*BESIII, Nature Comm., 15, 8812 (2024)

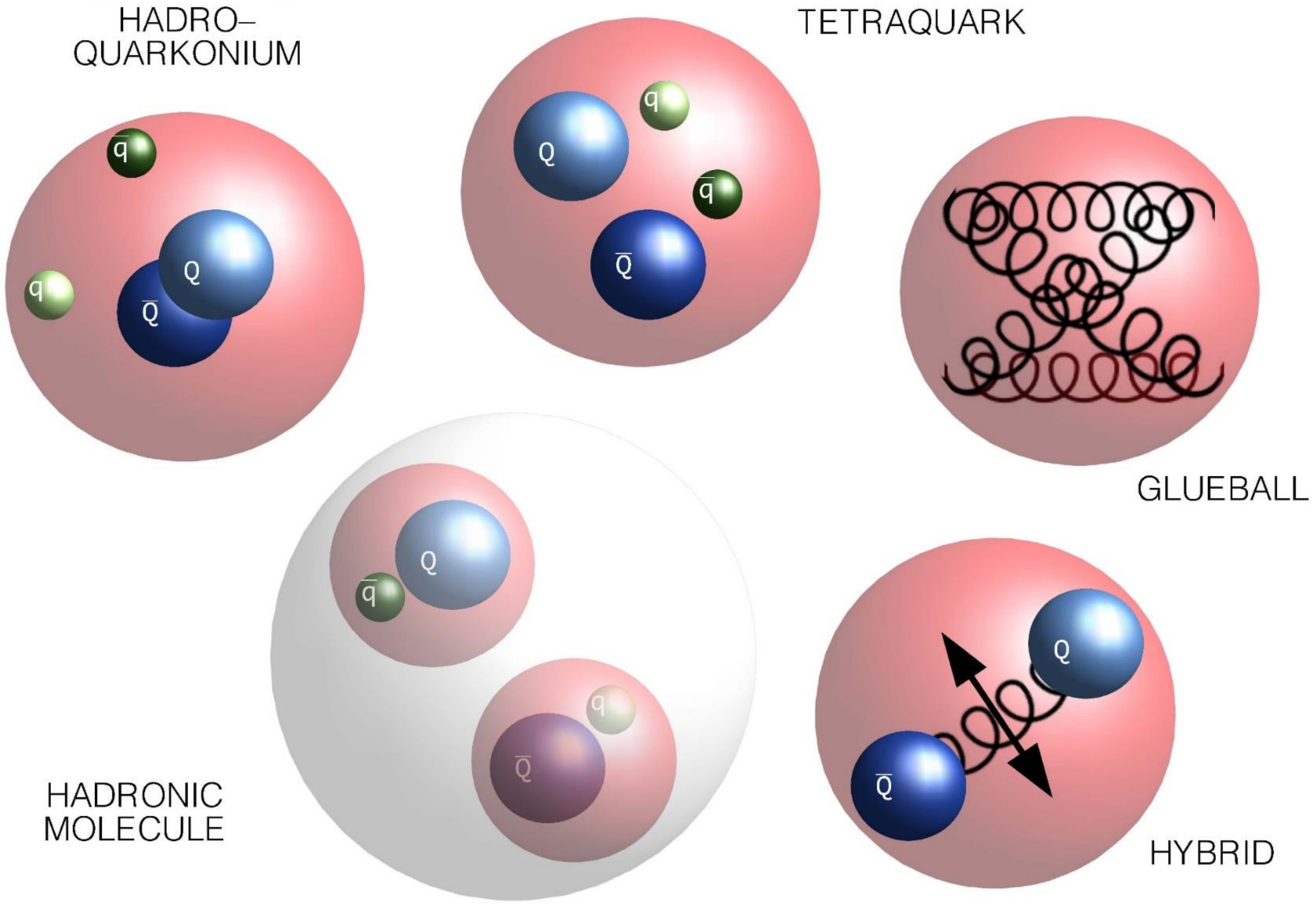
CP test: $\Delta\Phi_{CP} = |\pi - (\Delta\Phi_1 + \Delta\Phi_2)| = 0.003 \pm 0.133 \pm 0.014$ rad



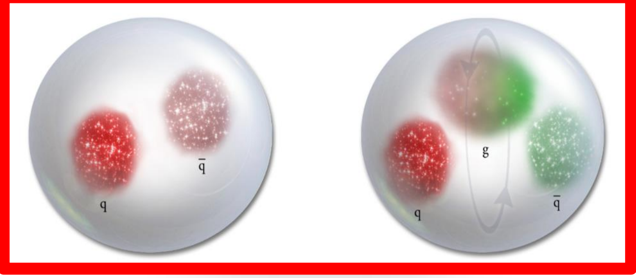


HADRON SPECTROSCOPY WITH BESIII

Hadron Spectroscopy



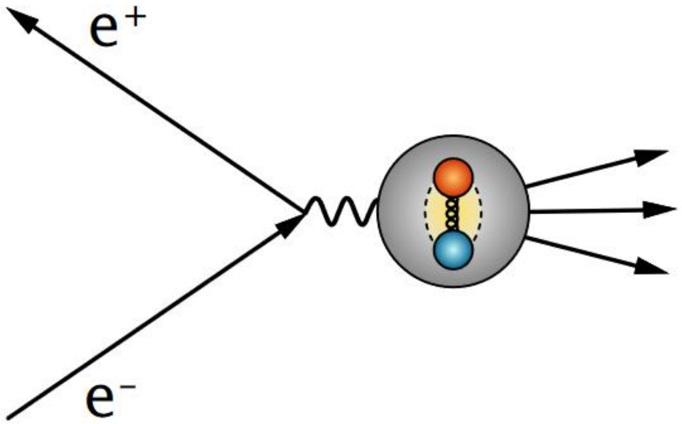
Unravelling the complexity of matter formed by the strong interaction...

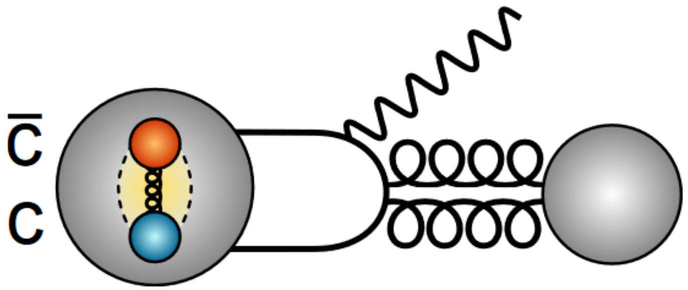


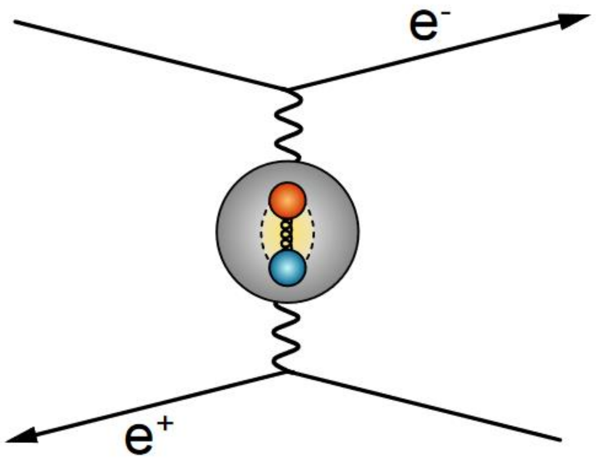
Meson spectroscopy at BESIII

Multiple ways to produce conventional and exotic mesons:

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



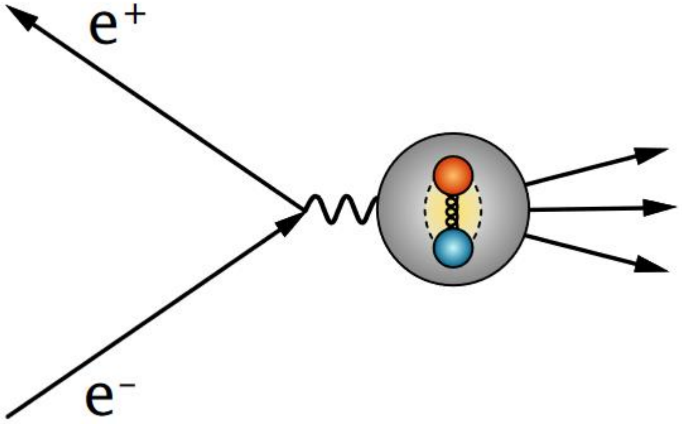


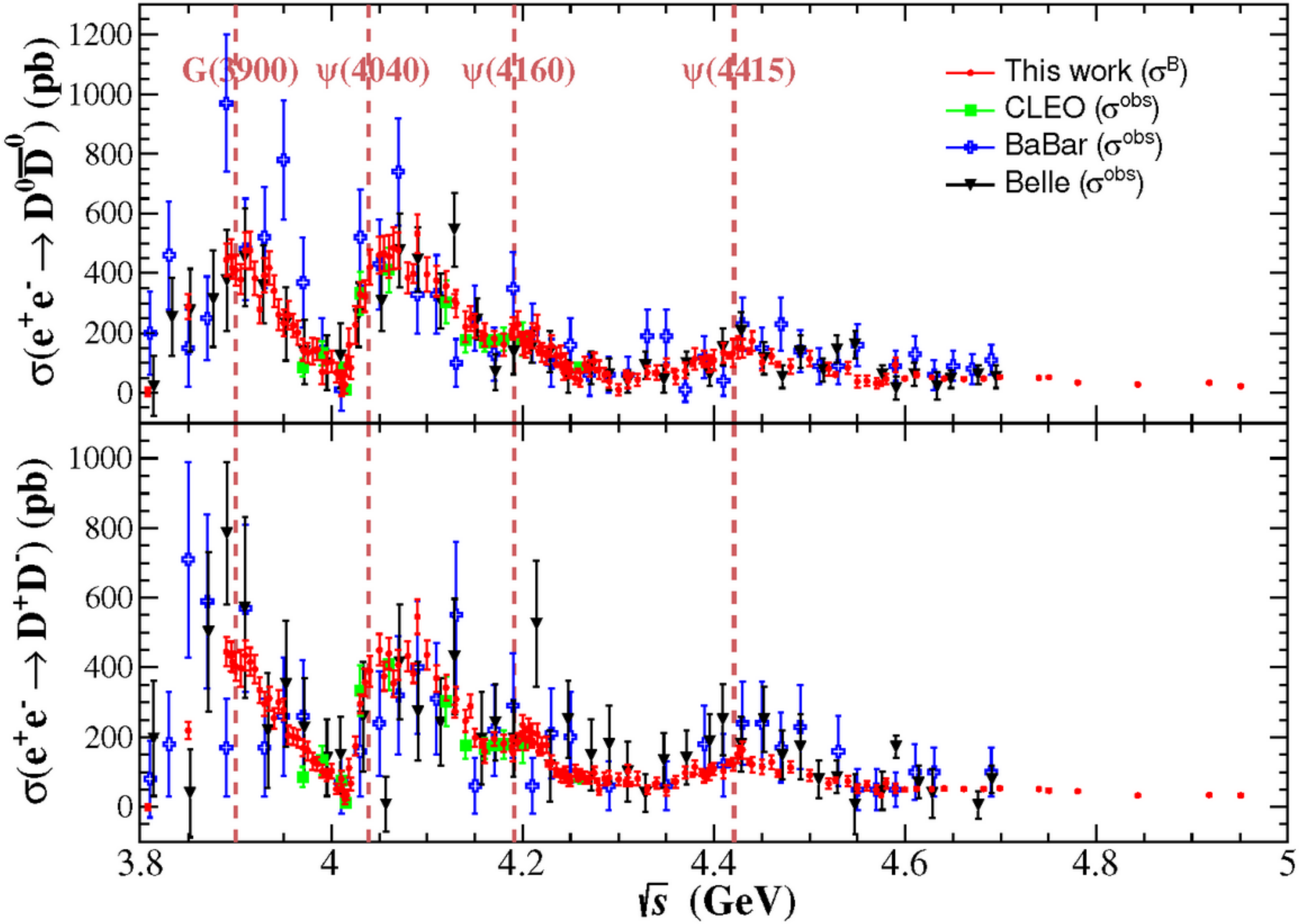


Picture cred: M. Kuessner

Precise line-shape measurement of $e^+e^- \to D\bar{D}$

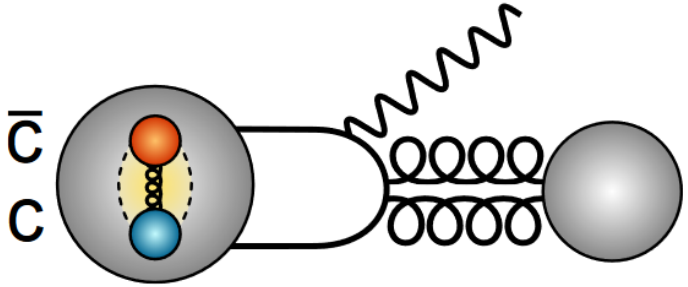
*Phys. Rev. Lett. 133 (2024) 081901

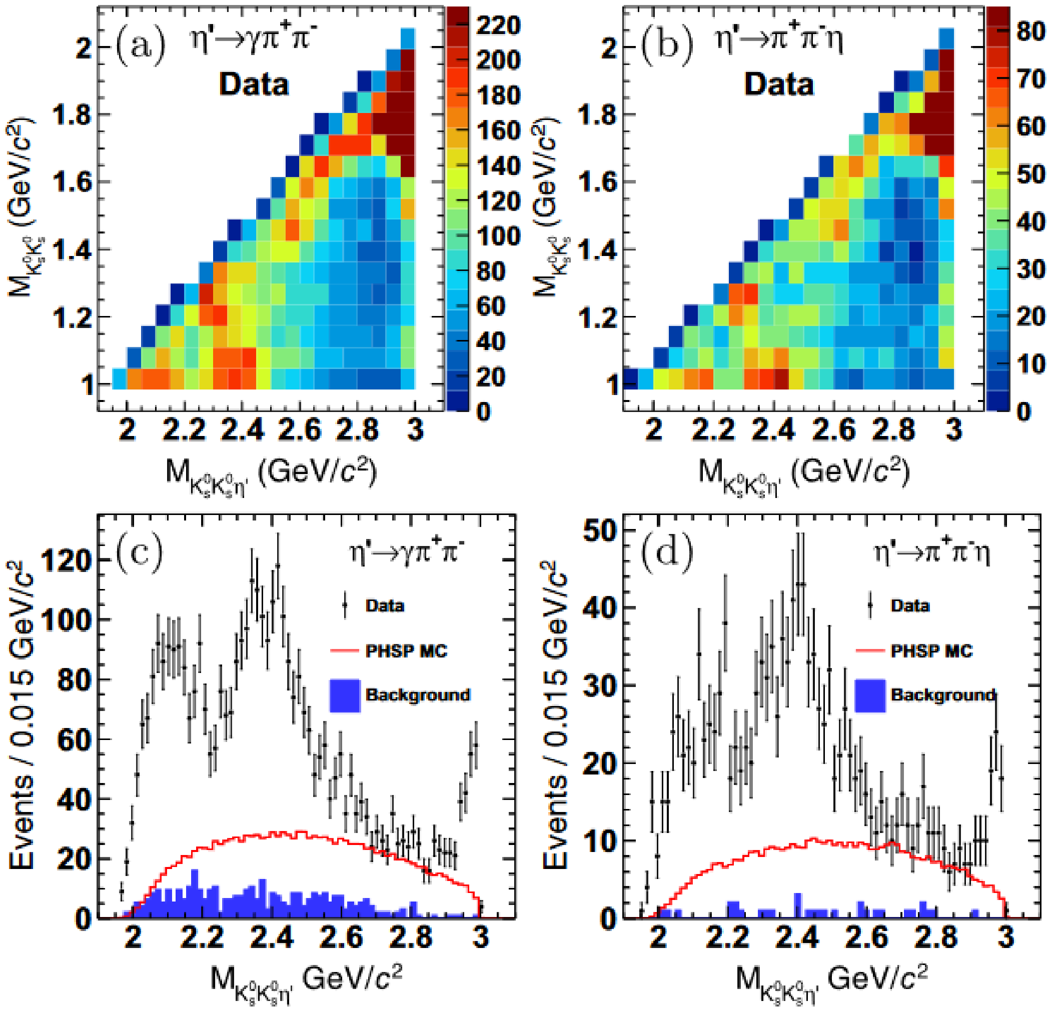




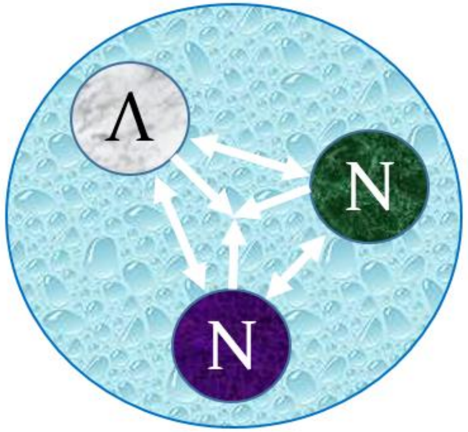
Spin-parity of the X(2370)

- Partial Wave Analysis of $J/\psi \to \gamma K_s K_s \eta'$
- Mass 2395 $\pm 11^{+26}_{-94}$ MeV/c², width $188^{+26+124}_{-94-33}$ MeV/c²
- Significance 11.7 σ
- $J^{PC} = 0^{-+}$ i.e. a pseudoscalar
- Produced in gluon-rich environment

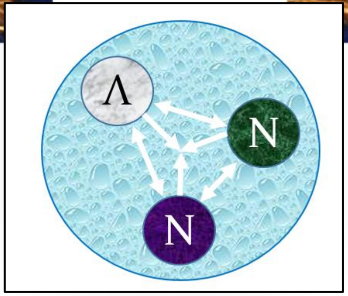




*Phys. Rev. Lett. 132 (2024) 181901



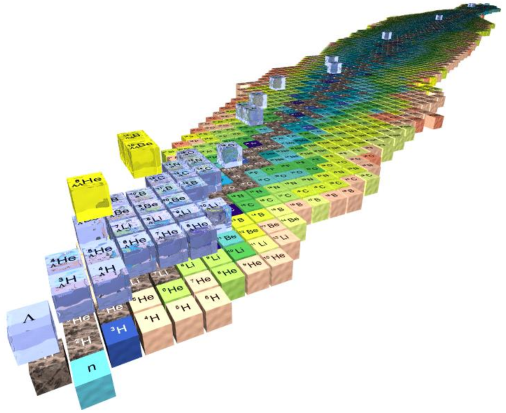
HADRON INTERACTIONS



Hyperon-nucleon (YN) interaction

Why?

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

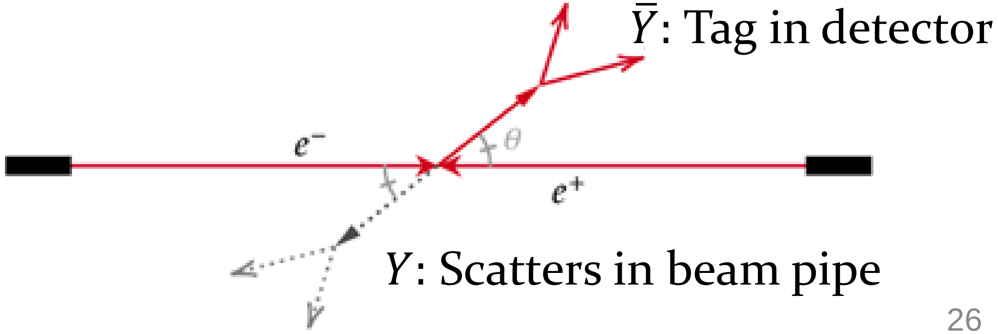


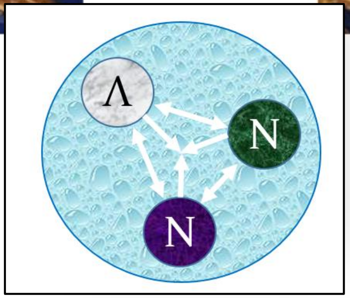
How?

- Hyperon femtoscopy
- Hypernuclear studies
- Secondary YN interactions

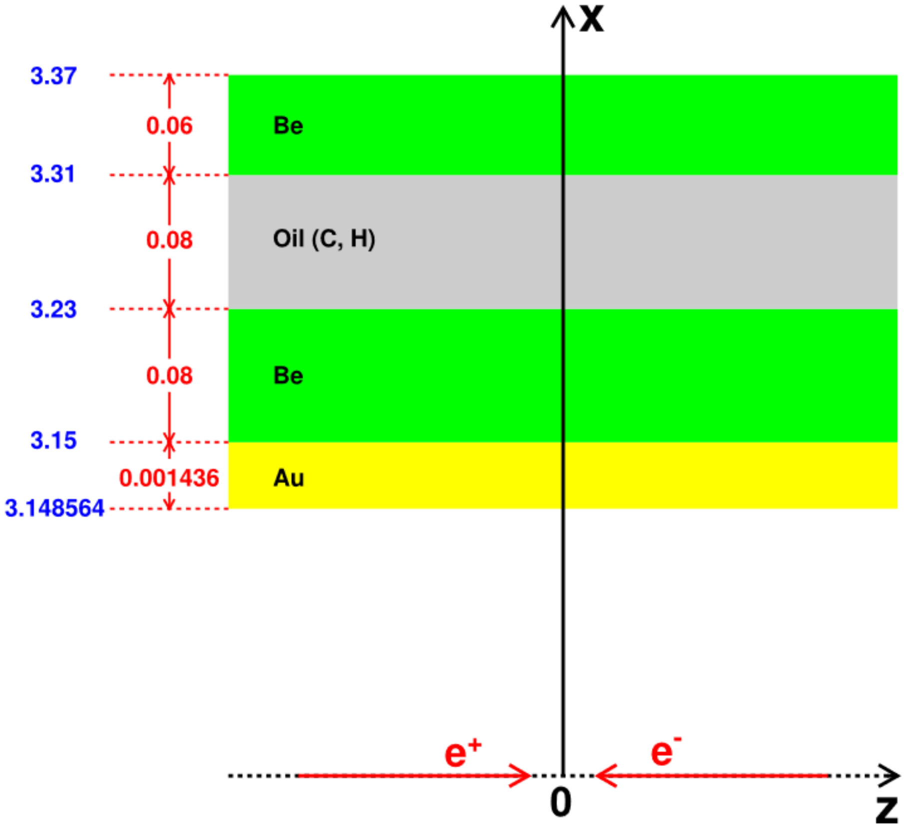
BESIII

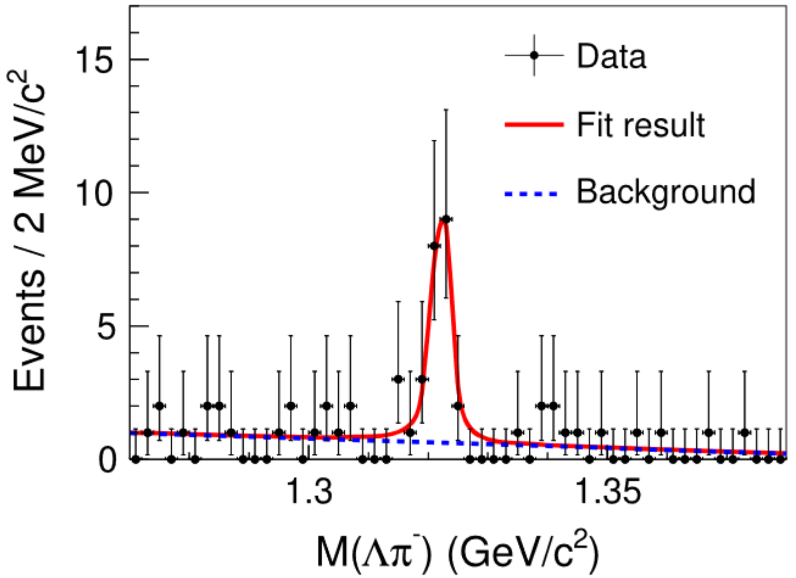
– $e^+e^- \to J/\Psi \to Y\bar{Y}$





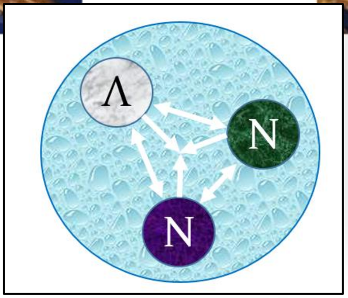
First study of $\Xi^0 n \to \Xi^- p$ in an e^+e^- experiment



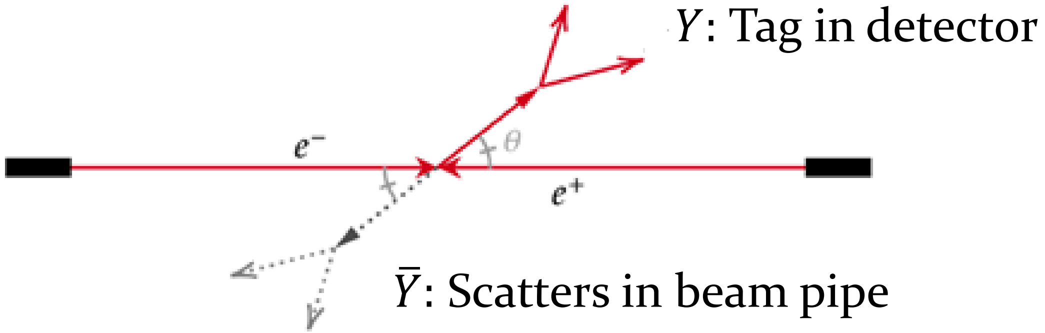


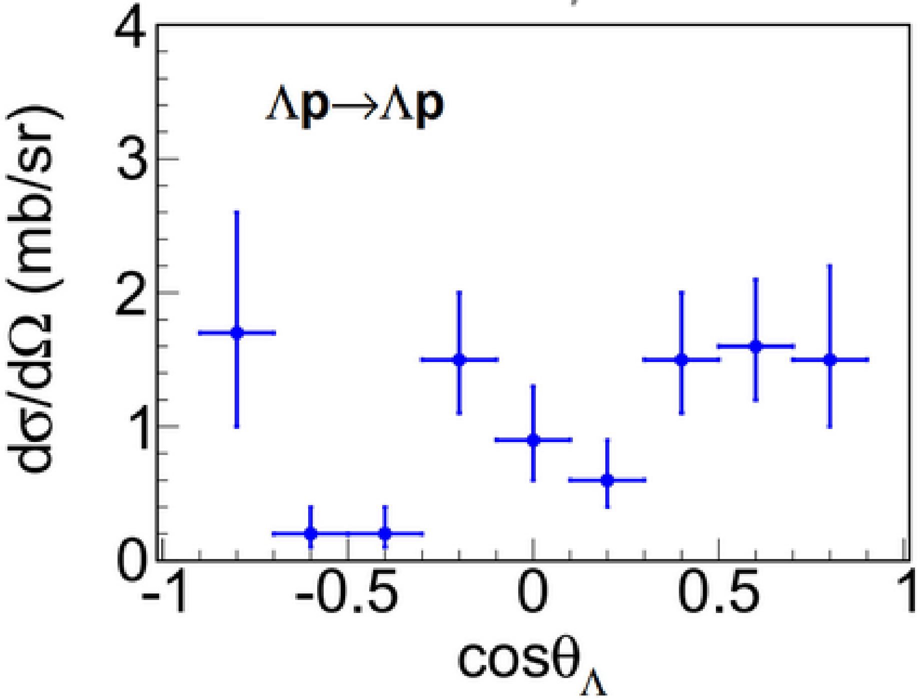
- Primary reaction $e^+e^- \to J/\Psi \to \Xi^0\bar{\Xi}^0$
- Secondary Ξ^0 beam with $p_\Xi = 0.818$ GeV/c
- Interaction mainly with ^{9}Be in beam pipe
- 20 events observed
- $\sigma(\Xi^0 + {}^9Be \to \Xi^- + {}^8Be + p)$ = 22.1 ±5.3 ±4.5 mb
- Assuming 3 effective reaction neutrons**:
  $\sigma(\Xi^0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

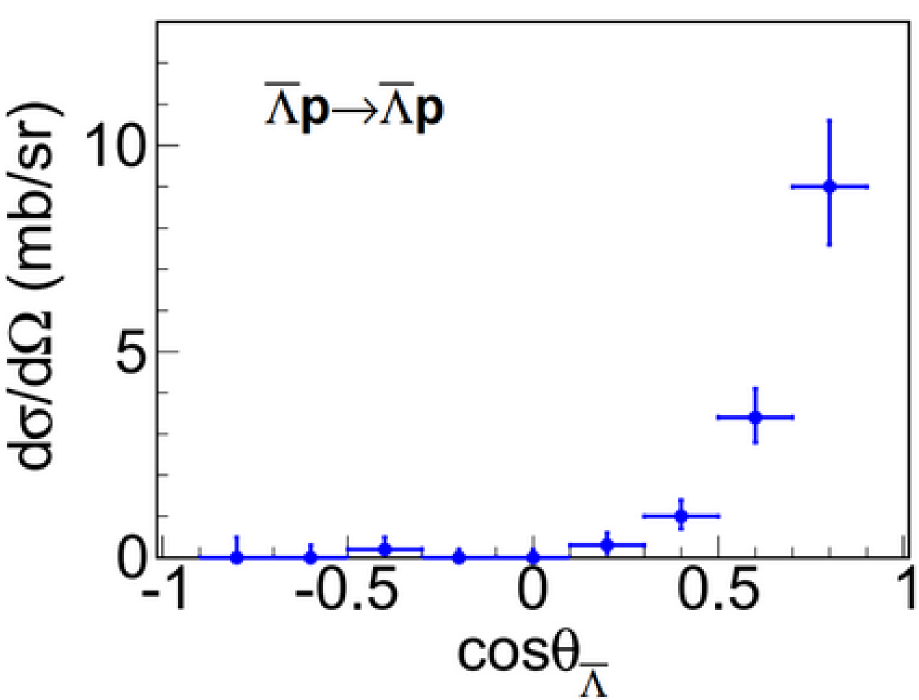
*Phys. Rev. Lett. 130, 251902(2023)
**Phys. Lett. B 633, p 214-218 (2006)



First study of $\bar{\Lambda}p$ scattering





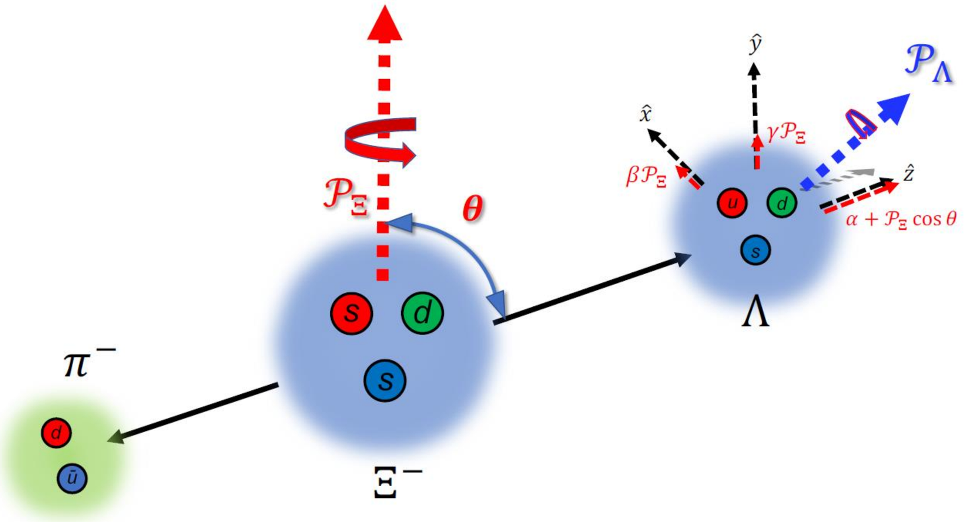


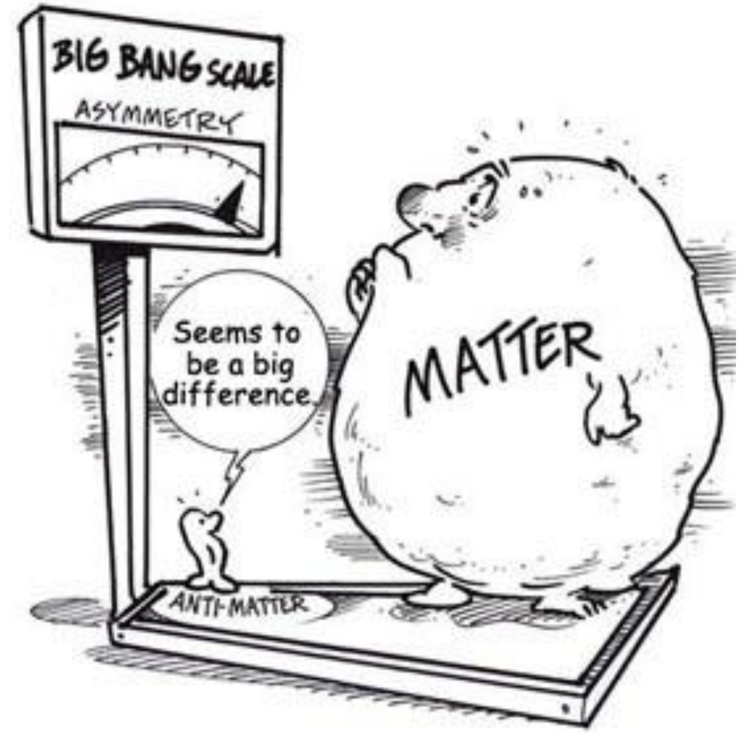
*Phys. Rev. Lett. 132, 231902 (2024)

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.



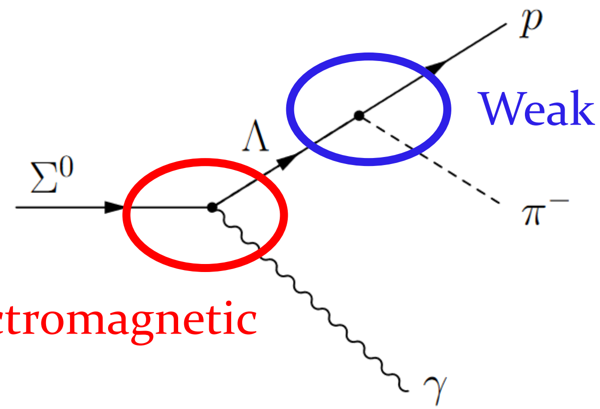


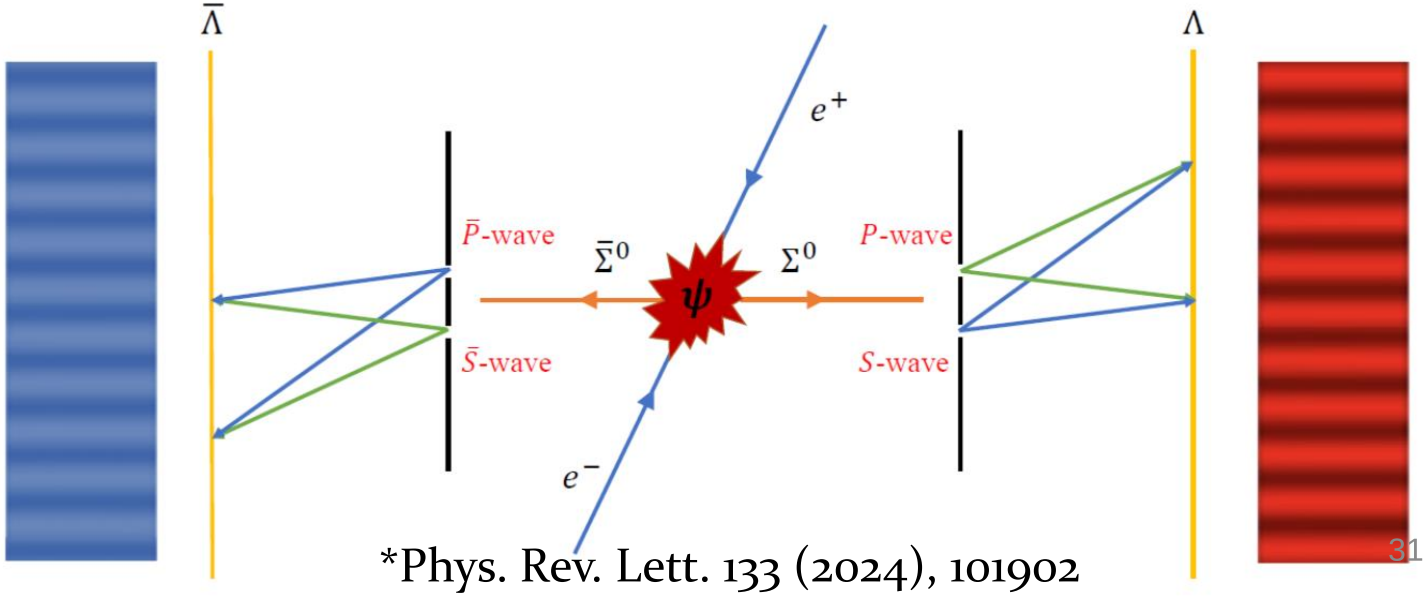
Strong and weak CP tests in Σ^0 hyperon decays

- The electromagnetic decay $\Sigma^0 \to \Lambda\gamma$ decay probes the interference between
  - The parity-conserving amplitude (magnetic transition moment) and
  - The parity-violating amplitude (electric dipole transition moment, related to the neutron EDM)

    $\rightarrow$ If non-zero, it can indicate strong CP violation.

- The weak decay $\Lambda \to \pi^- p$ probes the interference between
  - Parity-conserving p-waves and
  - Parity-violating s-waves



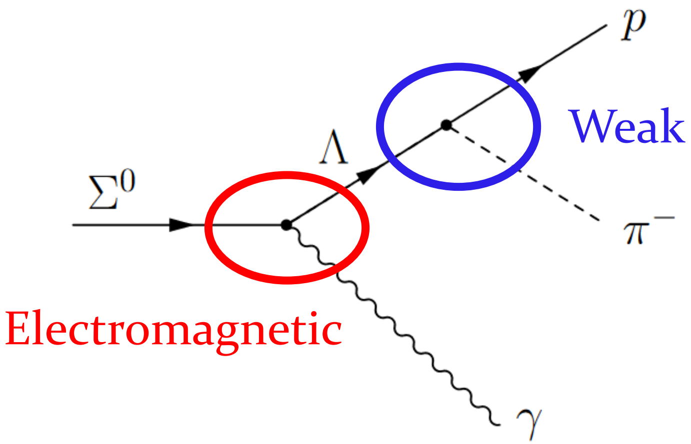


*Phys. Rev. Lett. 133 (2024), 101902

Strong and weak CP tests in Σ^0 hyperon decays

$$A_{CP}^{\Sigma} = \alpha_{\Sigma} + \bar{\alpha}_{\Sigma}$$

$$A_{CP}^{\Lambda} = \frac{\alpha_{\Lambda} + \bar{\alpha}_{\Lambda}}{\alpha_{\Lambda} - \bar{\alpha}_{\Lambda}}$$



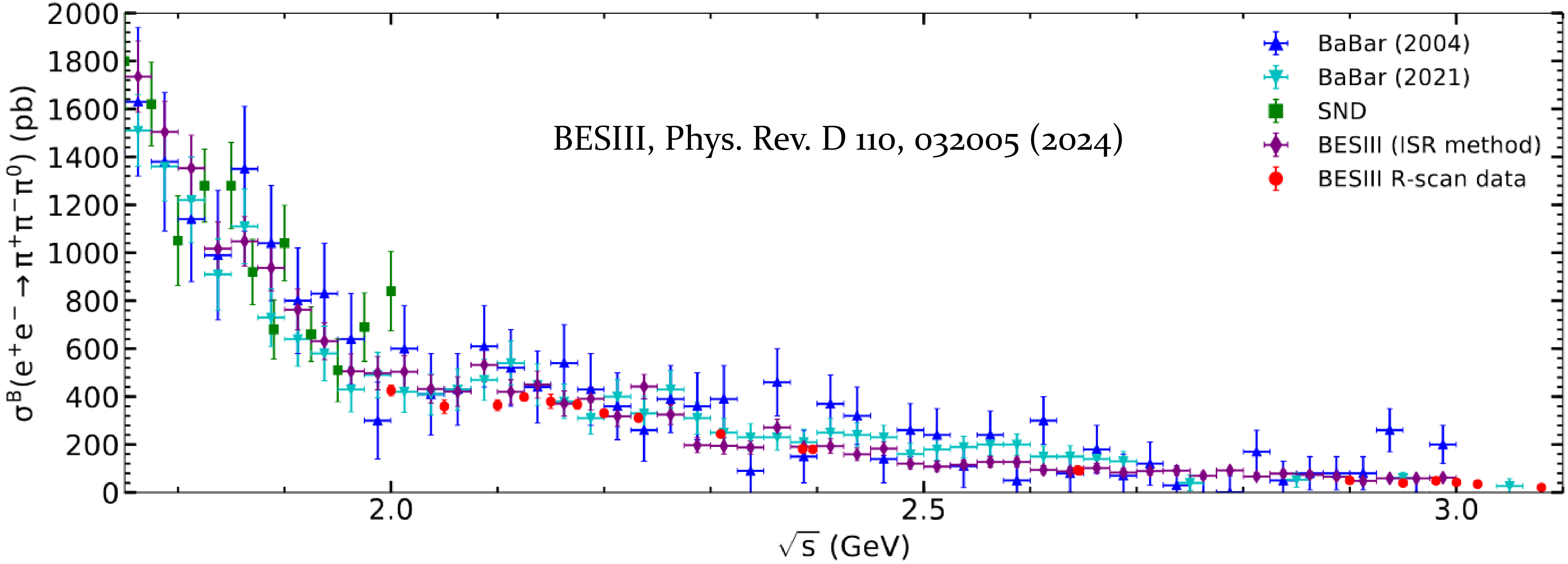
Parameter	This Letter	Previous results
$\alpha_{J/\psi}$	$-0.4133 \pm 0.0035 \pm 0.0077$	-0.449 ± 0.022 [52]
$\Delta\Phi_{J/\psi}$ (rad)	$-0.0828 \pm 0.0068 \pm 0.0033$	...
$\alpha_{\psi(3686)}$	$0.814 \pm 0.028 \pm 0.028$	0.71 ± 0.12 [52]
$\Delta\Phi_{\psi(3686)}$ (rad)	$0.512 \pm 0.085 \pm 0.034$	...
α_{Σ^0}	$-0.0017 \pm 0.0021 \pm 0.0018$	...
$\bar{\alpha}_{\Sigma^0}$	$0.0021 \pm 0.0020 \pm 0.0022$	...
α_{Λ}	$0.730 \pm 0.051 \pm 0.011$	0.748 ± 0.007 [44]
$\bar{\alpha}_{\Lambda}$	$-0.776 \pm 0.054 \pm 0.010$	-0.757 ± 0.004 [44]
A_{CP}^{Σ}	$(0.4 \pm 2.9 \pm 1.3) \times 10^{-3}$	...
A_{CP}^{Λ}	$(-3.0 \pm 6.9 \pm 1.5) \times 10^{-2}$	$(-2.5 \pm 4.8) \times 10^{-3}$ [2

*BESIII, Phys. Rev. Lett. 133 (2024), 101902

** Nair, Perotti & Leupold, Phys. Lett. B 788 (2019) 535-541.

Meson production cross sections

Experimental input to the Hadron Vacuum Polarization (HVP) term a_μ^{HVP} in the calculation of $(g\text{-}2)_\mu$.



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 > 600 published papers
  - 116 in Physics Review Letters
  - 1 Nature, 2 Nature Phys. 1 Nature Comm.

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Thanks for your attention!

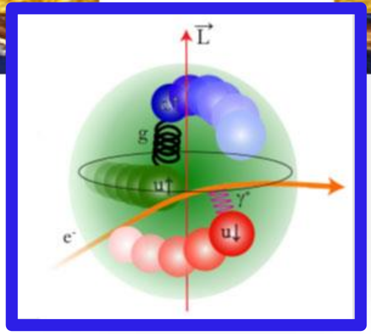
Knut and Alice Wallenberg Foundation

Swedish Research Council

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

Backup

Proton and neutron EMFFs

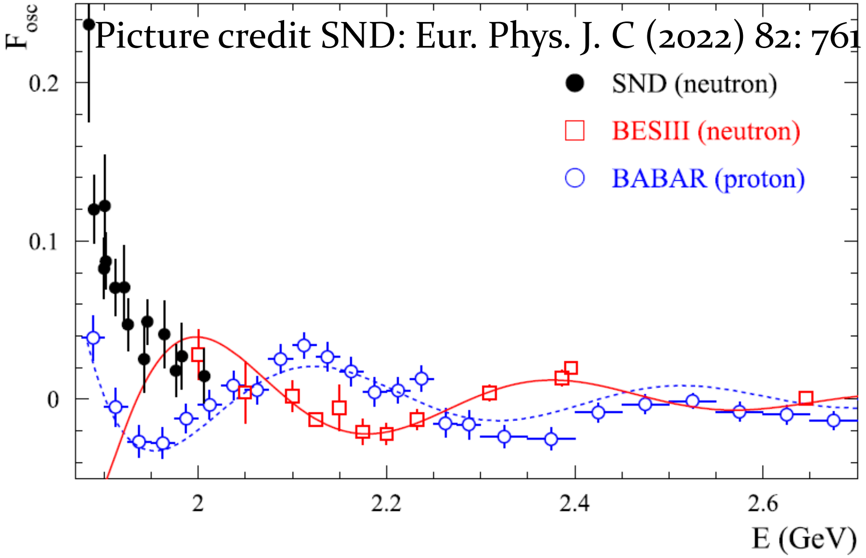


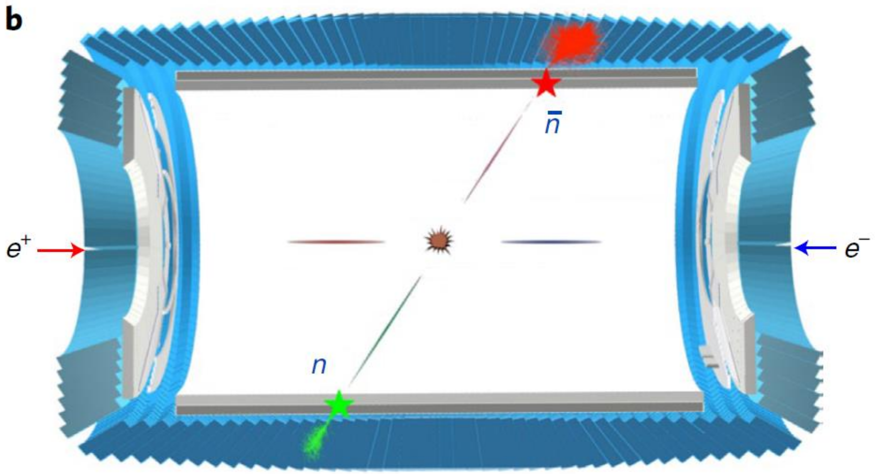
Energy dependence of G_{eff} :

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

G_0 : Dipole-like

G_{osc}: Oscillations



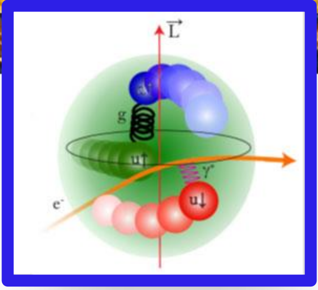


BESIII:

- 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



Complete decomposition of EMFFs

Production parameters of spin ½ baryons:

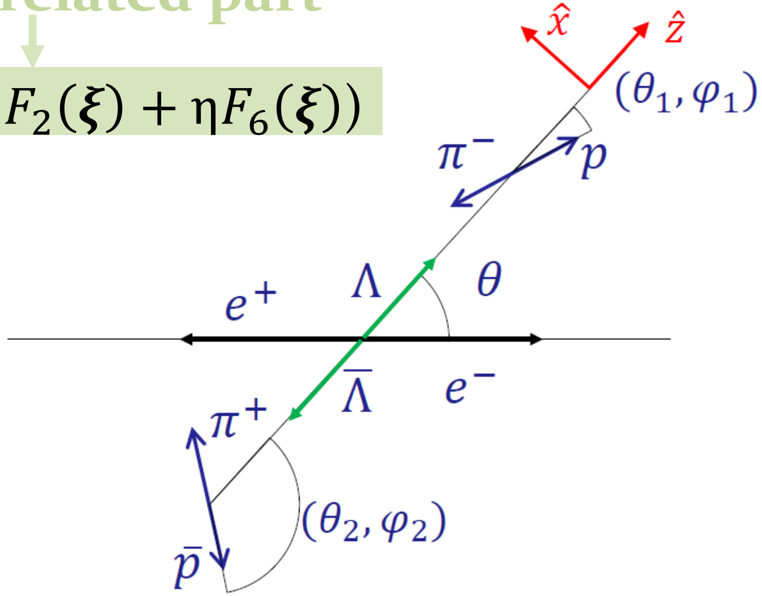
- Angular distribution parameter $\eta = \frac{\tau - R^2}{\tau + R^2}$ where $\tau = q^2/4M^2_B$
- Phase $\Delta\Phi$

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

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

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



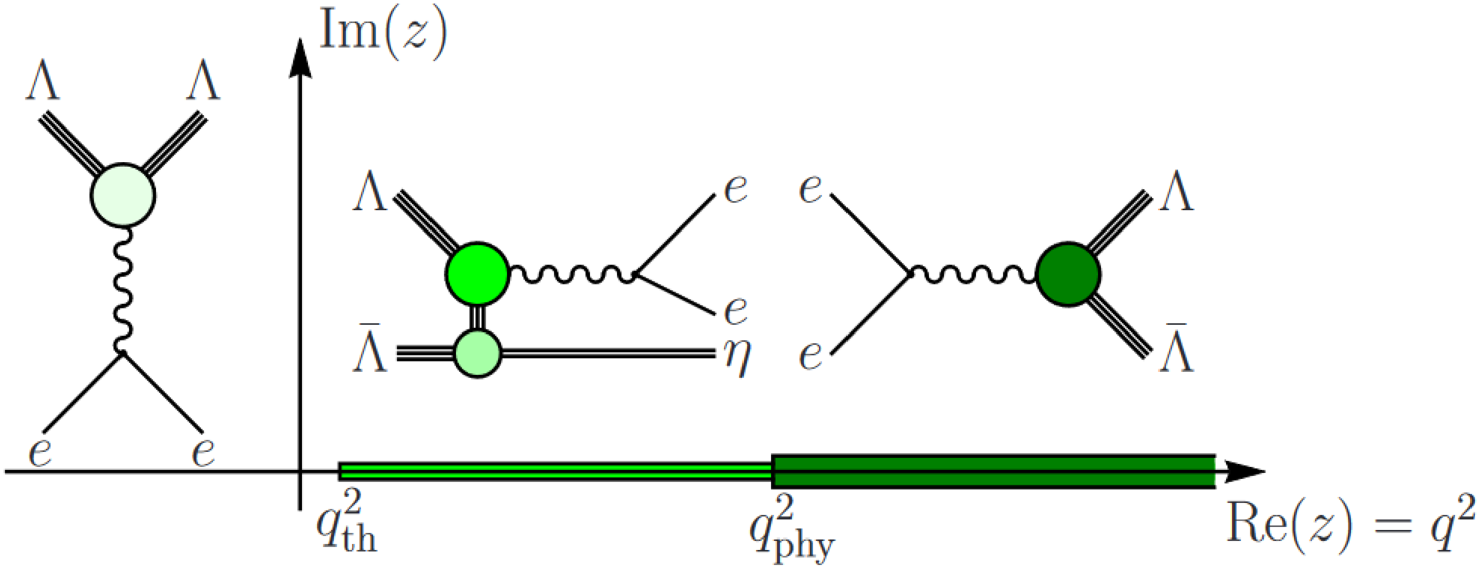
*Fäldt & Kupsc, PLB 772 (2017) 16.

Theory interpretation

Dispersive calculations by Mangoni, Pacetti & Tomasi-Gustafsson*:

- Few data points → ambiguous solution

  → scenarios for phase value at q^2_{th} and q^2_{asy}



Picture credit: *Mangoni *et al.*, Phys. Rev. D 104, 116016 (2021)