Stranger Things

– Investigating Hyperon Structure at the Femtometer Scale

25th European Conference on Few-body Problems in Physics
Mainz, Germany, 2023-08-04

Prof. Dr. Karin Schönning, Uppsala University

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Outline

- Prologue
- Electromagnetic Form Factors
- Recent results from BESIII
- Summary

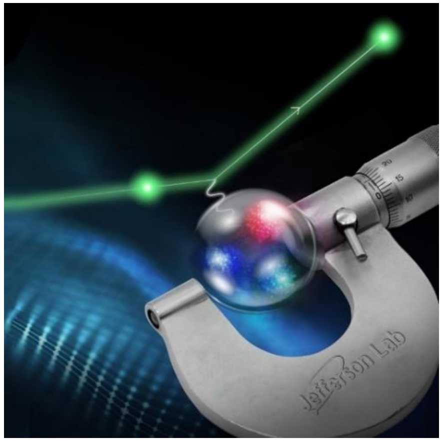
Prologue

Strong interactions manifest in *e.g.* hadron structure and size

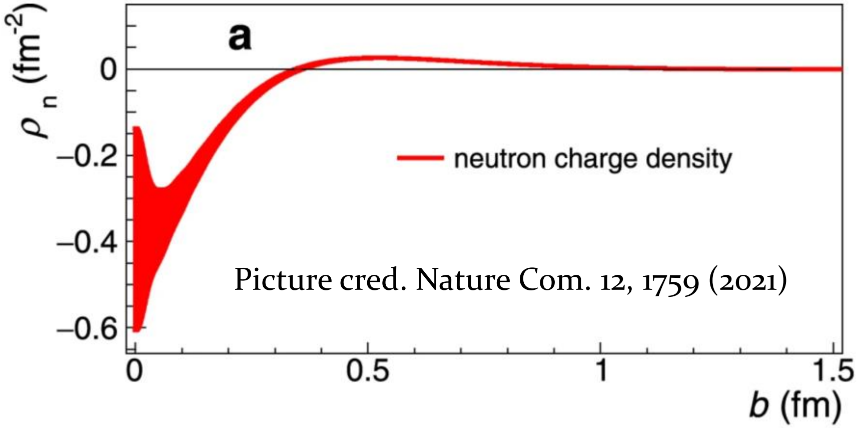
→ quantities at the femtometer scale!

Protons: rapid progress the last ~ 5 years!*

Neutrons: asymmetric distribution of *d* quarks and *u* quark results in a negative squared charge radius $< r_E^2 >$.**



Picture cred. Y-H Lin, U. Bonn



Picture cred. Nature Com. 12, 1759 (2021)

*Talk by U.G. Meissner (Monday)

**Atac *et al.*, Nature Com. 12, 1759 (2021)

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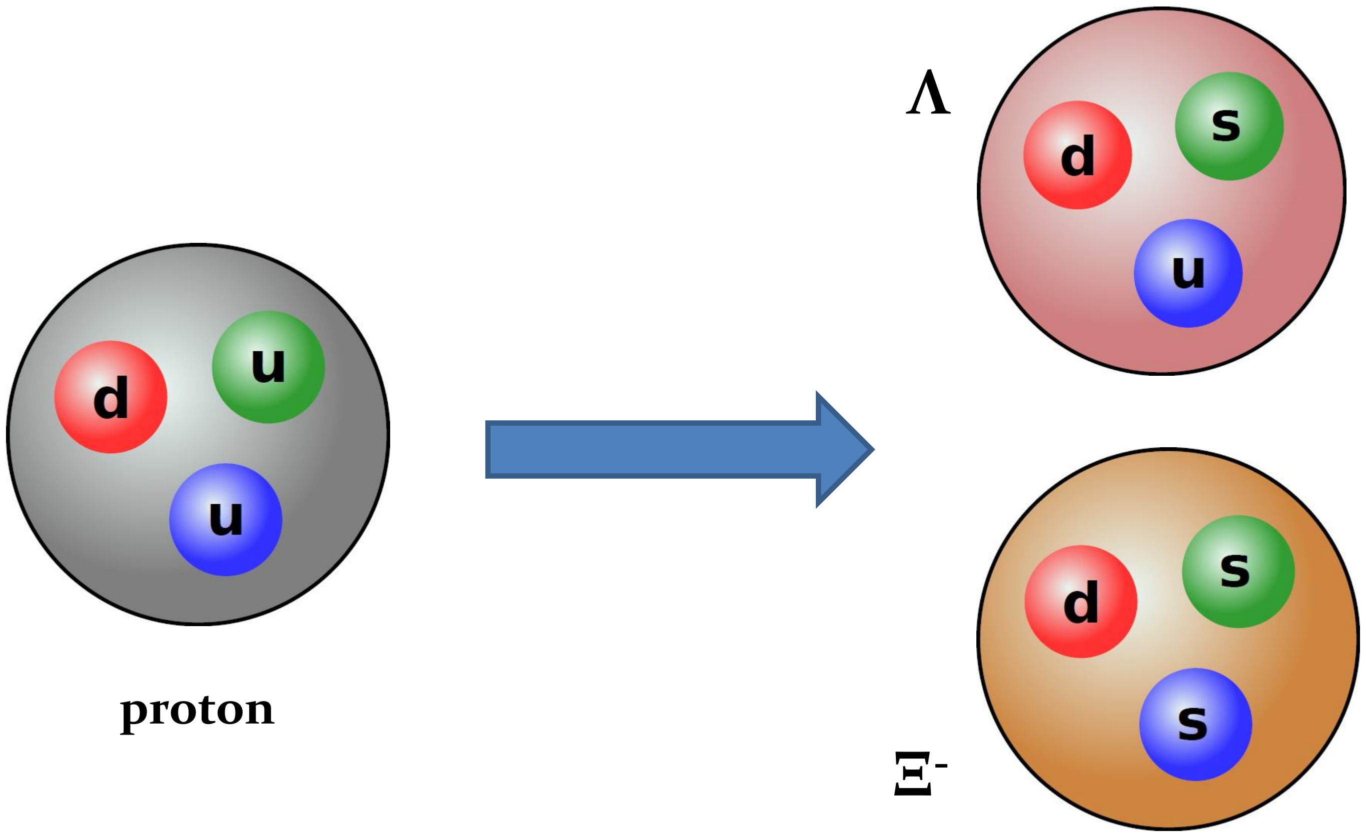
Prologue

FAQ1: *How does the presence of heavy strange and charm quarks affect the strong interaction dynamics?*



Prologue

To find out, we first need to answer **FAQ2:**

How can we study the structure of unstable hadrons?

Proton: $\tau > 10^{34}$ y

Neutron: $\tau \sim 15$ min

Strange hyperons: $\tau \sim 10^{-10}$ s

Charm hyperons: $\tau \sim 10^{-13}$ s

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Answer: By time-like electromagnetic form factors!

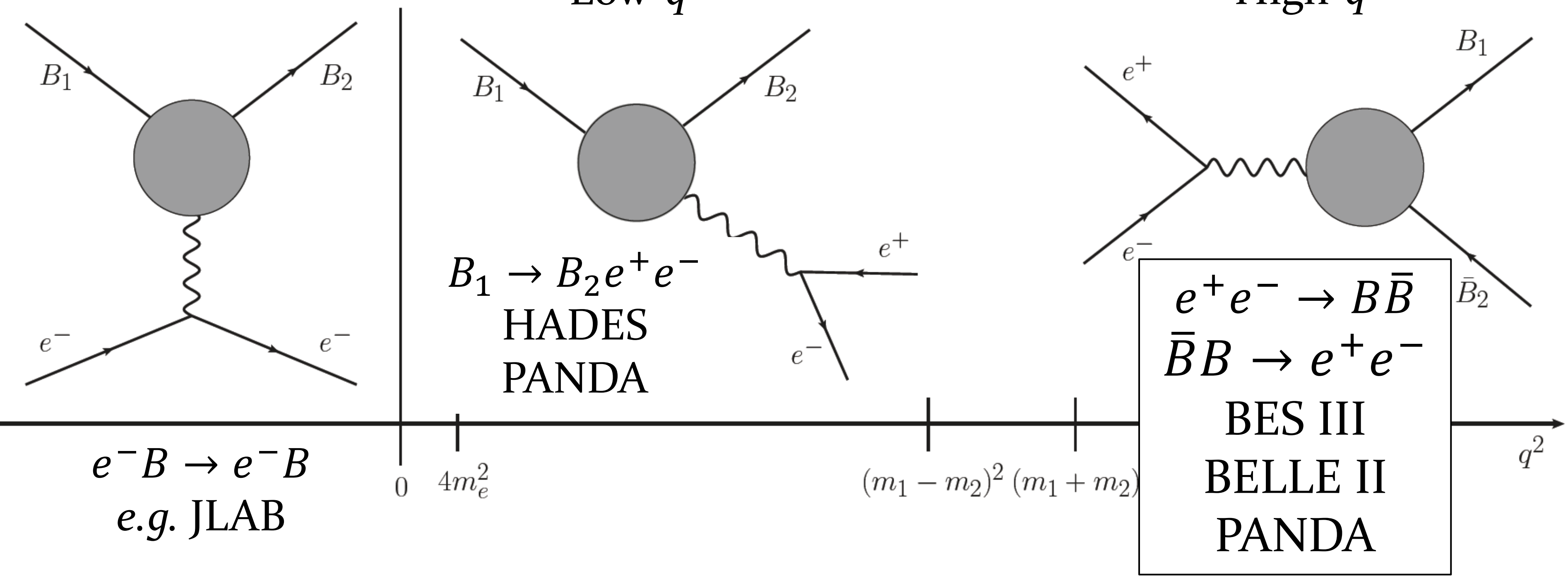
Space-like *vs.* time-like EMFF's

Space-like
$q^2 < 0$

Time-like
$q^2 > 0$

Low-q^2

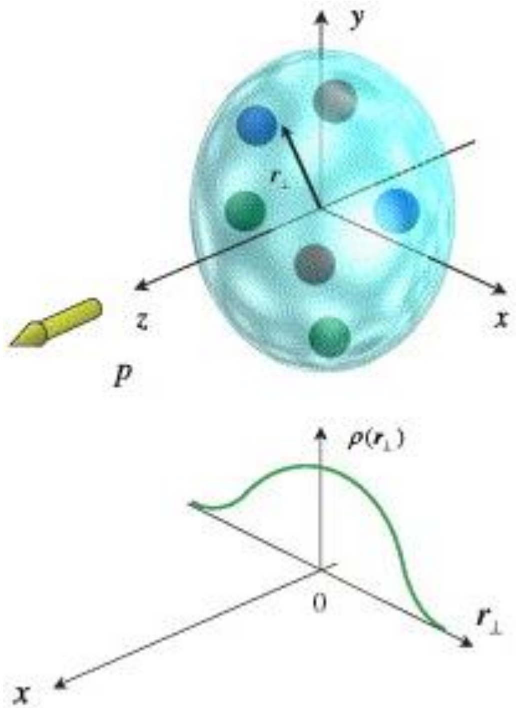
High-q^2



Cred. E. Perotti, PhD thesis (UU 2020)

Space-like form factors

- Number of EMFFs = 2*J*+1 → spin ½ baryons have 2.
- Sachs FFs: the electric G_E and magnetic G_M
  - Charge radius:
    $< r_E^2 > = 6 \frac{dG_E(q^2)}{dq^2}|_{q^2=0}$
  - Magnetic radius:
    $< r_M^2 > = \frac{6}{G_M(0)} \frac{dG_M(q^2)}{dq^2}|_{q^2=0}$



Space-like *vs.* time-like FF's

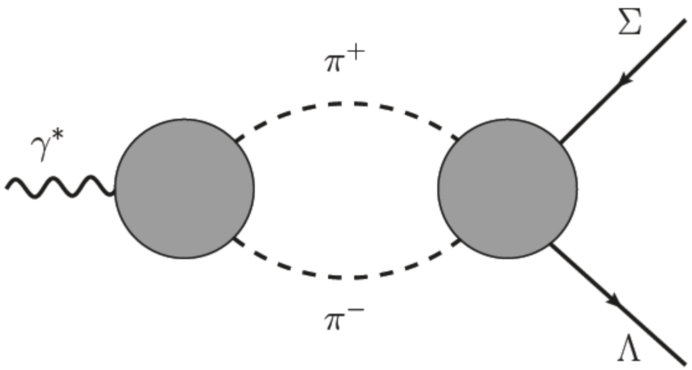
Space-like

Time-like

Time-like form factors

- Related to space-like EMFFs *via* dispersion relations.
- 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
  - Phase a reflection of intermediate fluctuations of the γ^* into *e.g.* $\pi\pi$.

→ Polarizes final state!



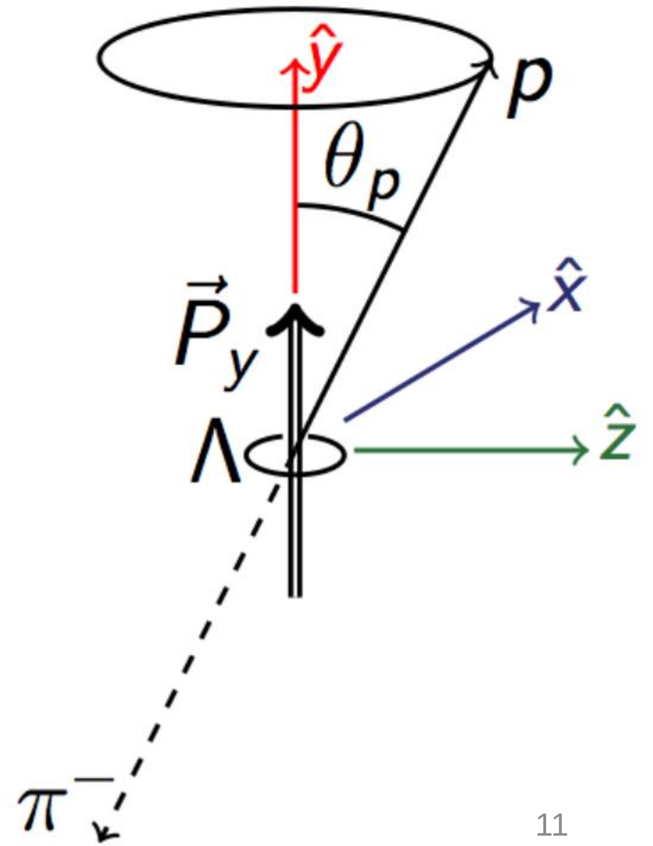
Picture credit:
Elisabetta Perotti, PhD Thesis,
UU (2020)

Advantage of hyperons

Polarization experimentally accessible by the weak, parity violating decay:

Example:

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



Space-like *vs.* Time-like EMFFs

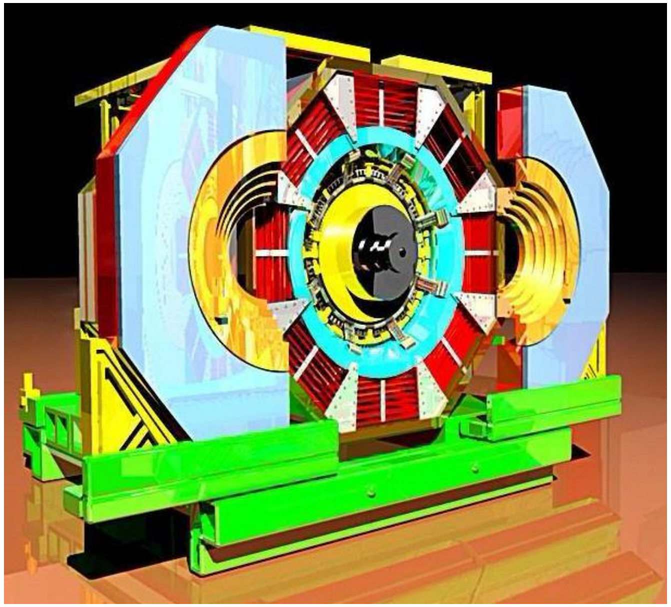
- **Onset of asymptotic scale** q^2_{asy} where SL = TL
  - Nucleons: SL and TL accessible.
  - Hyperons: Only TL accessible, but also phase!
    $\Delta\Phi(q^2) \to 0 \leftrightarrow$ SL = TL
- **Zero crossings***: Existence and location in the SL region from the TL behaviour!

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

The BESIII experiment

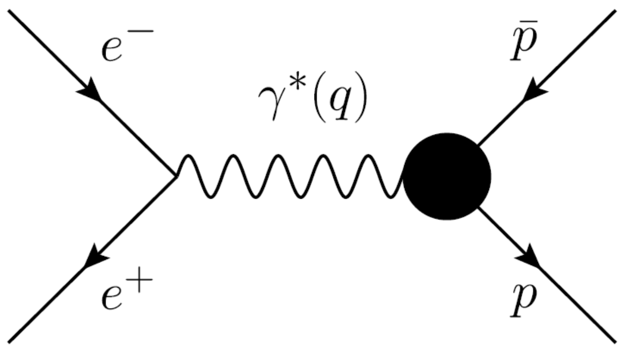
- Study $e^+e^- \to B\bar{B}$, where $B = p, n, \Lambda, \Sigma, \Xi, \Lambda_c^+$
- Beijing Electron Positron Collider (BEPC II):
  - e^+e^- collider within CMS range 2.0 – 4.95 GeV.
- Beijing Spectrometer (BES III):
  - Near 4π coverage
  - Tracking, PID, Calorimetry
  - Broad physics scope

BESIII



$B\bar{B}$ production in BESIII

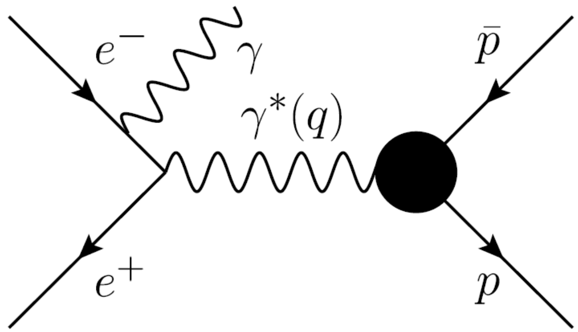
Energy Scan



$e^+e^- \to B\bar{B}$

- Simple final state
- ”Simple” formalism → Straight-forward to analyze
- Requires dedicated data campaigns

Initial State Radiation (ISR)



$e^+e^- \to e^+e^-\gamma_{ISR} \to \gamma_{ISR}B\bar{B}$

- ISR photon tagged or untagged
- Effective cross section much smaller than in direct $e^+e^- \to B\bar{B}$
- Possible to benefit from large data samples collected at *e.g.* J/Ψ

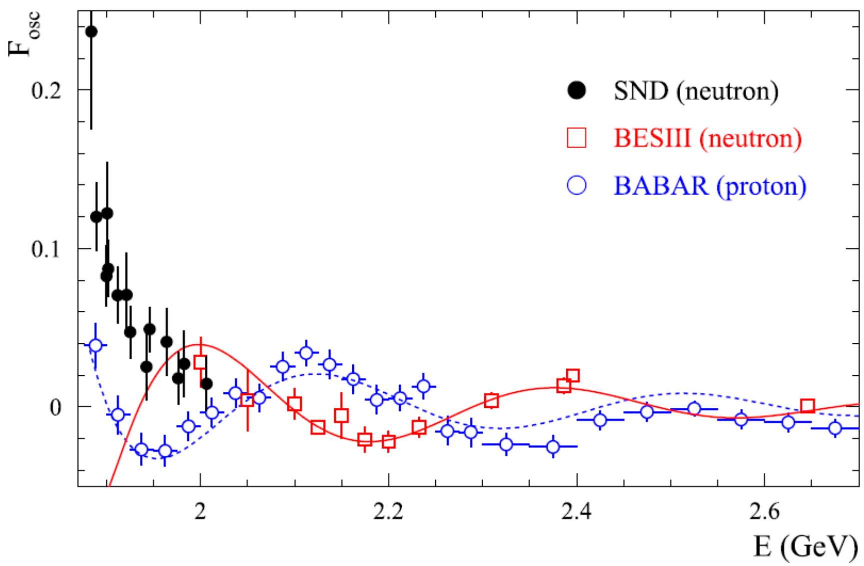
Production cross sections

- Energy dependence give information about the quark dynamics through
  - The *effective form factor:* $G_{eff} \propto \sqrt{\sigma}$
  - Di-quark correlations
  - Coupling to vector mesons and/or $B\bar{B}$ bound states

- Convenient for studies of
  - protons and (semi-) stable neutrons
  - small hyperon data samples

Proton and neutron EMFFs

Picture credit SND: Eur. Phys. J. C (2022) 82: 761



Energy dependence of G_{eff} :

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

G_0 : Dipole-like

G_{osc}: Oscillations

BESIII: $G_{osc}\ (p)^*$ and $G_{osc}\ (n)^{*\ **}$
have same frequency but different phase:

$\Delta D = D_p - D_n = 125^\circ \pm 12^\circ$

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

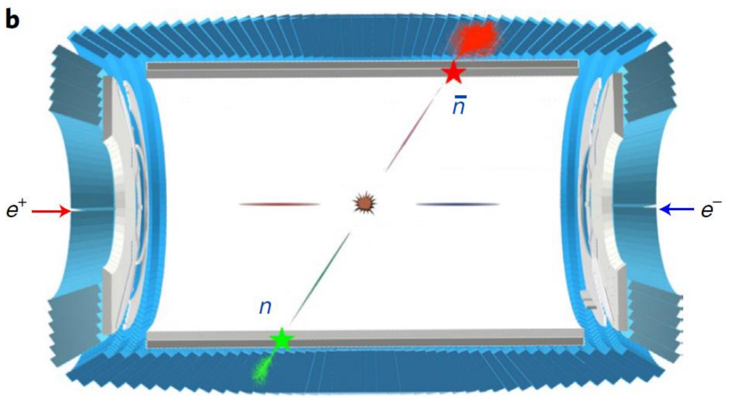
See also talk by U.G. Meissner

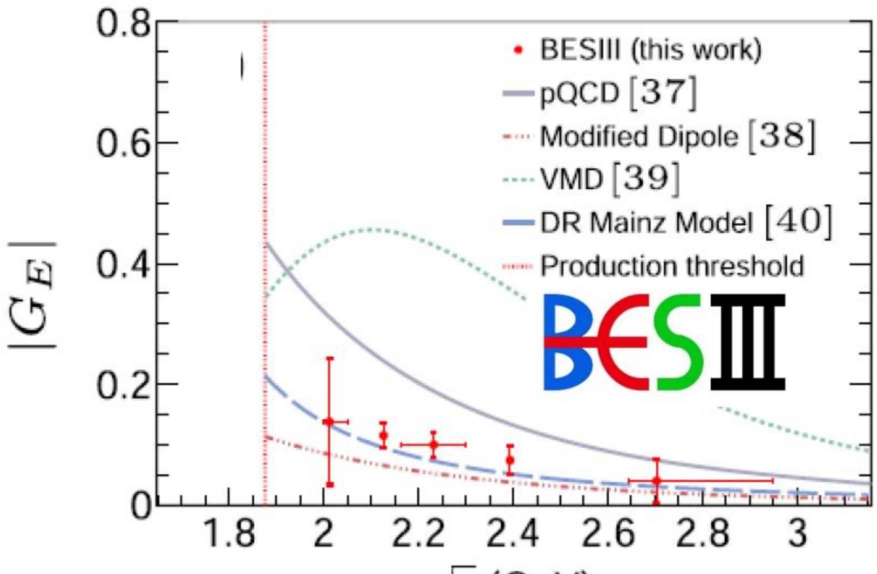
Neutron EMFFs

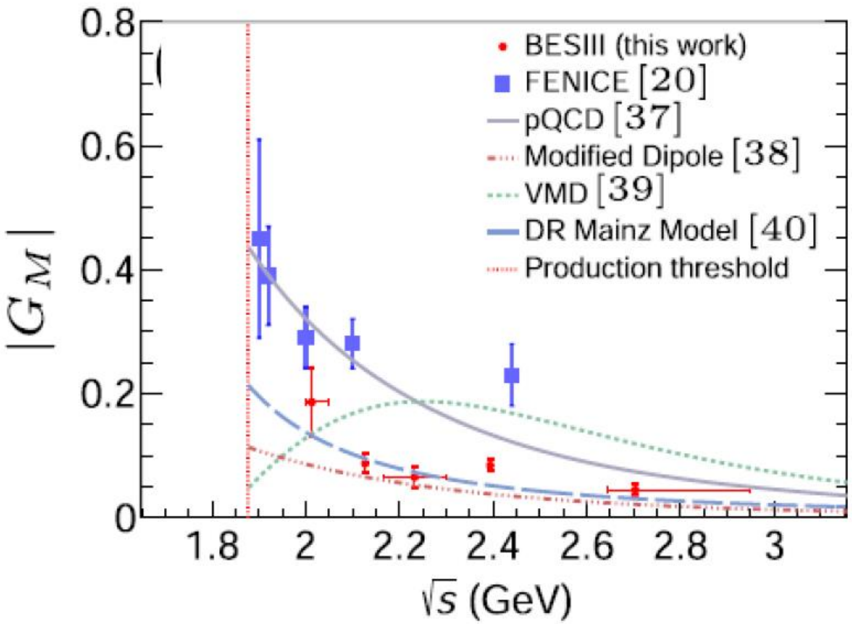
- New BESIII study*: Production angle distribution enables separation of electric G_E and magnetic G_M

  → First measured neutron time-like G_E !

  → Agreement with dispersive calculations, but not FENICE data.







BESIII, Phys. Rev. Lett. 130, 151905 (2023)

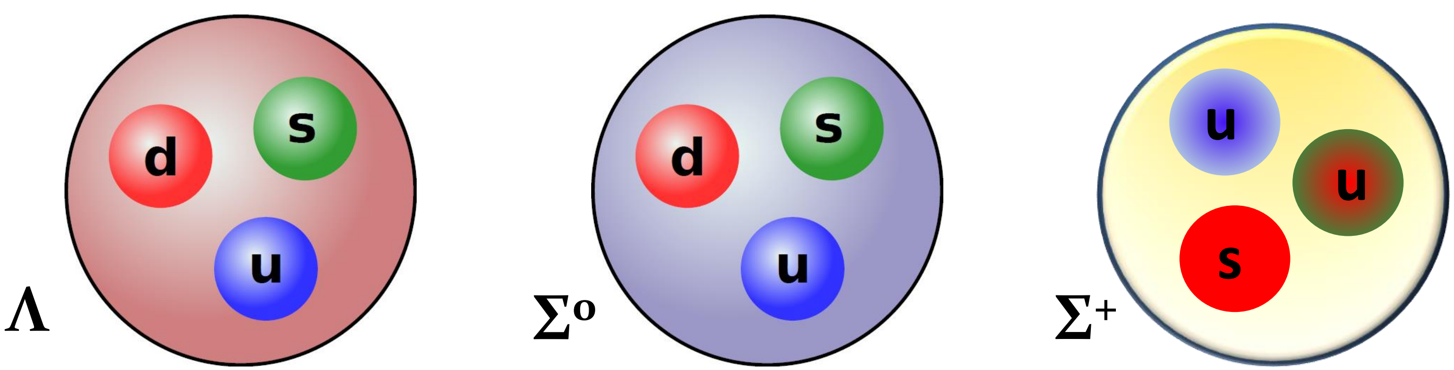
Single-strange hyperons

Diquark correlations in baryons?

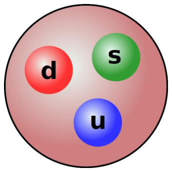
- The Σ^0 has isospin 1 whereas Λ has isospin 0
  - Strange quark has no isospin → difference is in the *ud* diquark

  → different spin structure

  → different cross sections expected.*
- In Σ^+, the *uu* should have same spin structure as the *ud* in Λ.
  - Similar cross sections expected.*

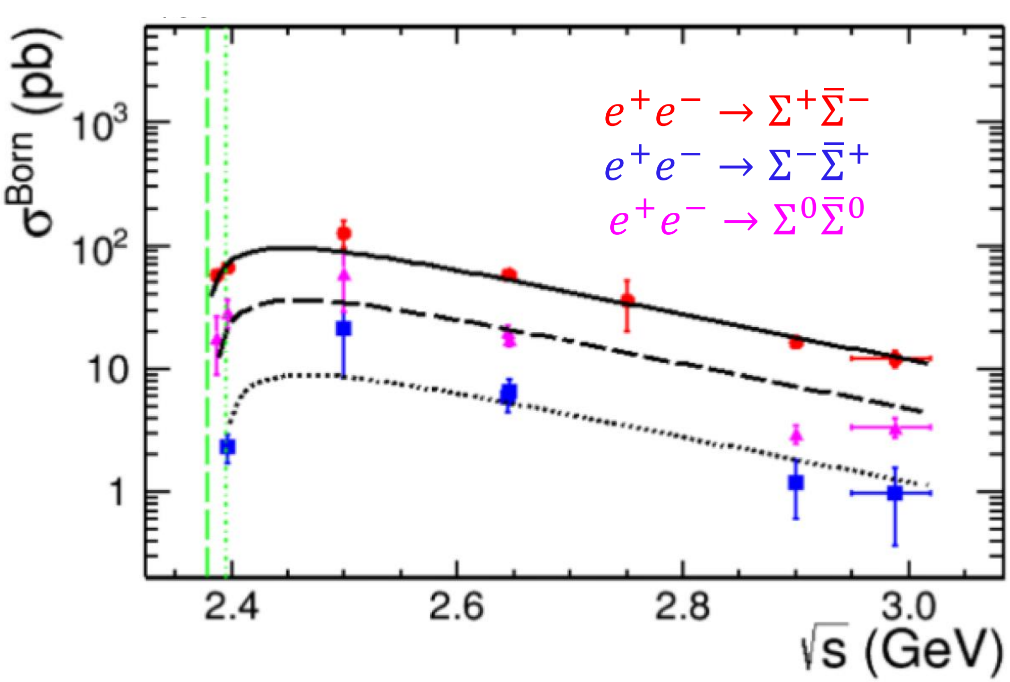


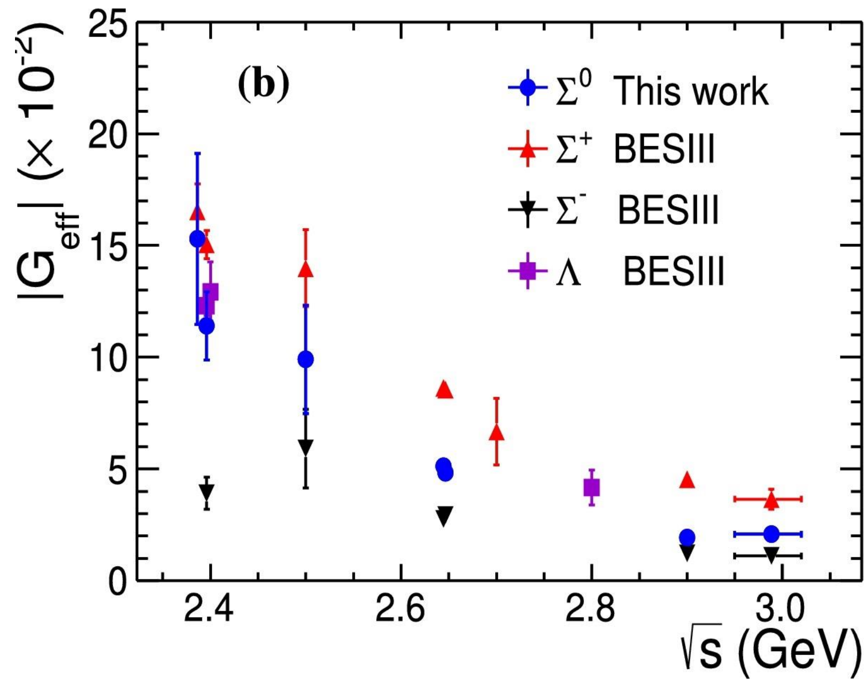
*Dobbs *et al.*,: Phys. Lett. B 739, 90 (2014)



Λ and Σ hyperons

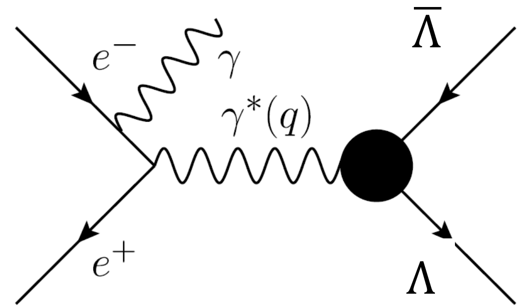
- Scan data between 2.386 GeV and 2.98 GeV.
- Λ/Σ^+ G_{eff} similar as expected from diquark correlations.*,**,***
- Σ^+/Σ^- cross section ratio ~ 9**



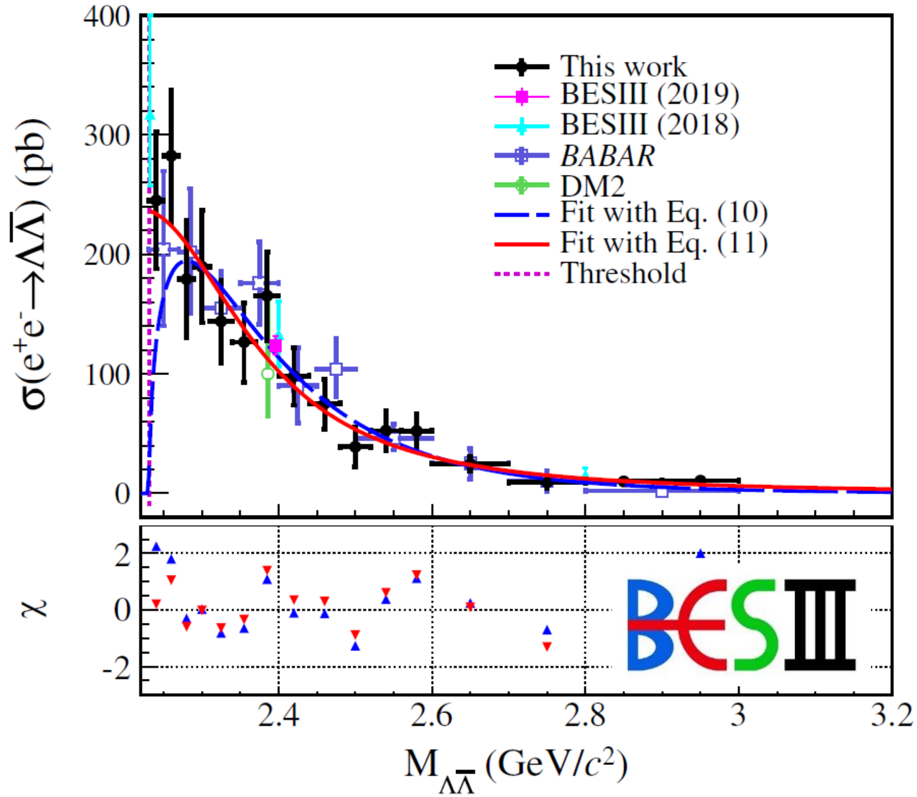


* BESIII: Phys. Lett. B 831, 137187 (2022)
** BESIII: Phys. Lett. B 814, 136110 (2021)
*** BESIII: Phys. Rev. D 97, 032013 (2018)

New: Λ production with ISR



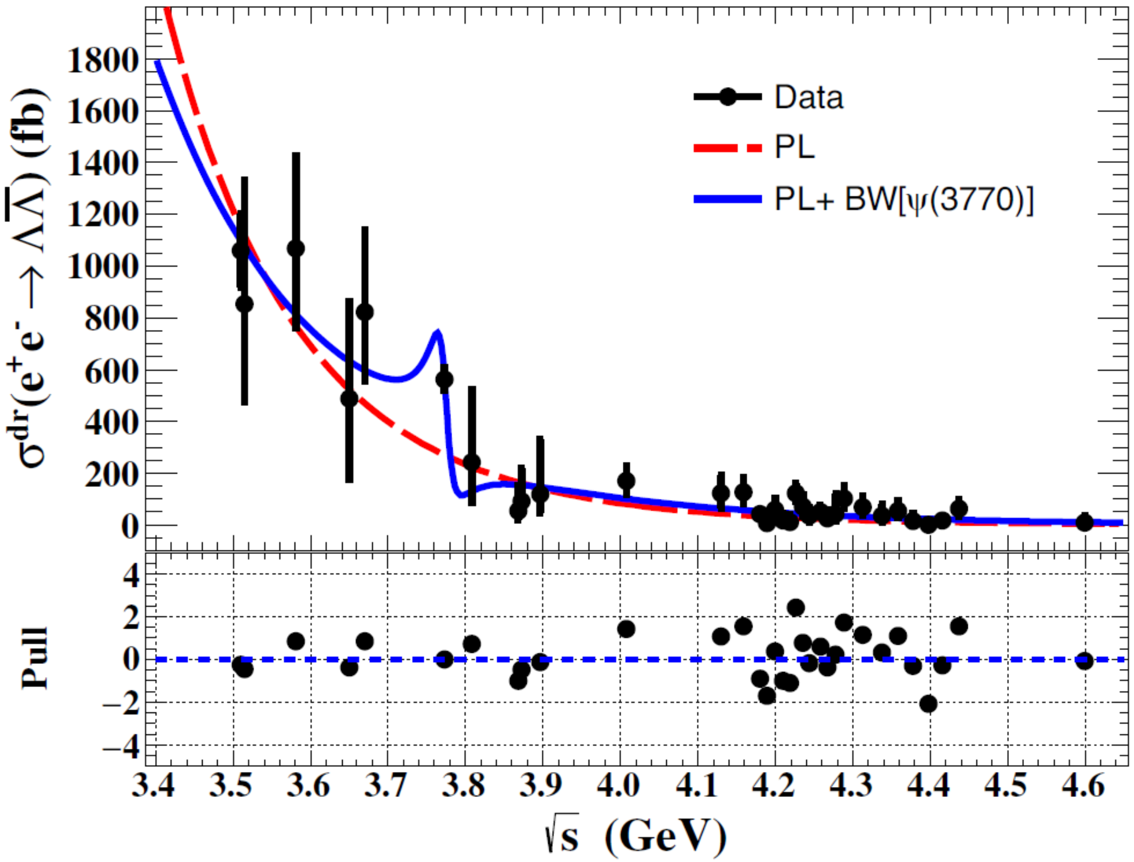
- ISR method applied on 12 fb^{-1} of data between 3.773 GeV and 4.258 GeV.*
- The $e^+e^- \to \Lambda\bar{\Lambda}$ cross section measured at 16 energies 2.231 3.0 GeV.
- Cross section enhancement at threshold confirmed.
- Fit accounting for the strong running coupling near threshold into give better agreement than a pQCD approach.



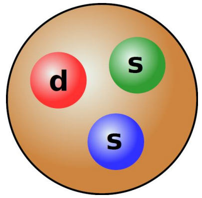
*BESIII, Phys. Rev. D 107, 072005 (2023)

Production of Λ at high q^2

- $\Lambda\bar{\Lambda}$ production near vector charmonia*,**
- $BR(\Psi \to \Lambda\bar{\Lambda})$ > 10 times larger than assumed in previous studies by CLEO-c***.

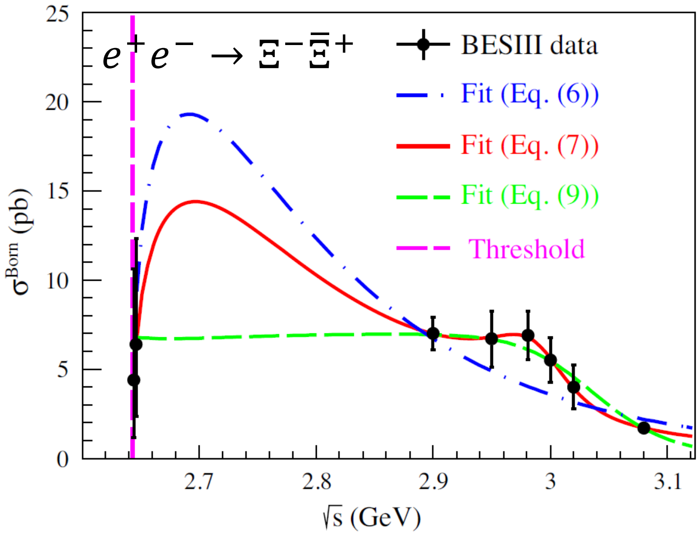


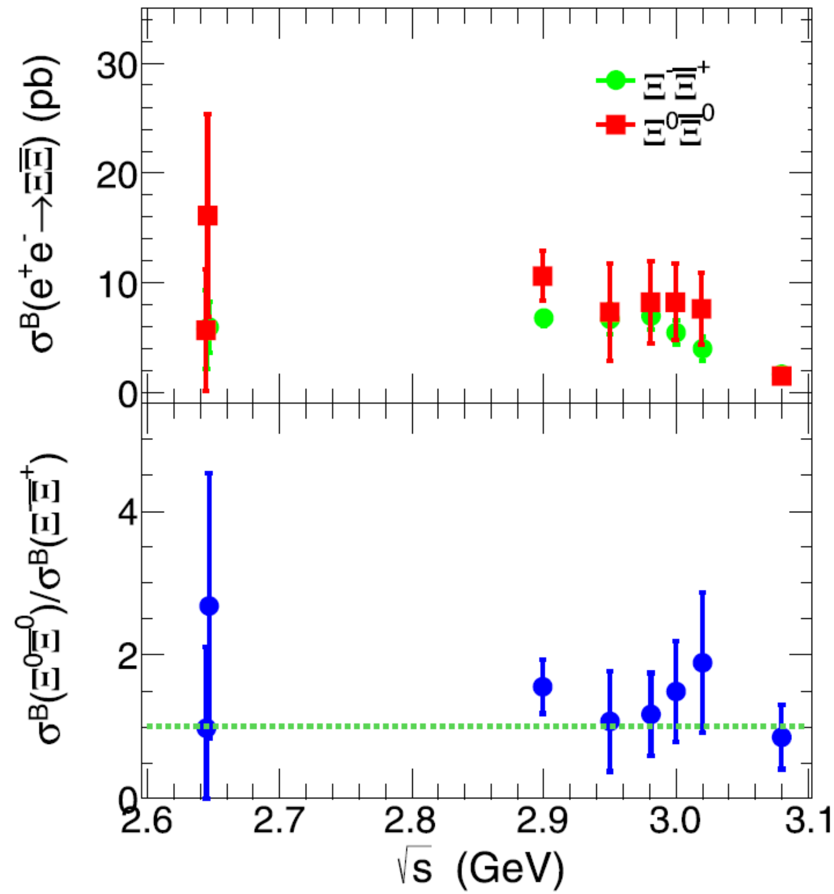
* BESIII: Phys. Rev. D 104, L091104 (2021)
** BESIII: Phys. Rev. D 105, L011101 (2022)
*** Dobbs *et al.*: Phys. Rev. D 96, 092004 (2017); Phys. Lett. B 739, 90 (2014)



Double-strange Ξ hyperons

- $e^+e^- \to \Xi^-\bar{\Xi}^+$ and $e^+e^- \to \Xi^0\bar{\Xi}^0$ studied for the first time.
- Possible resonance around 3 GeV.



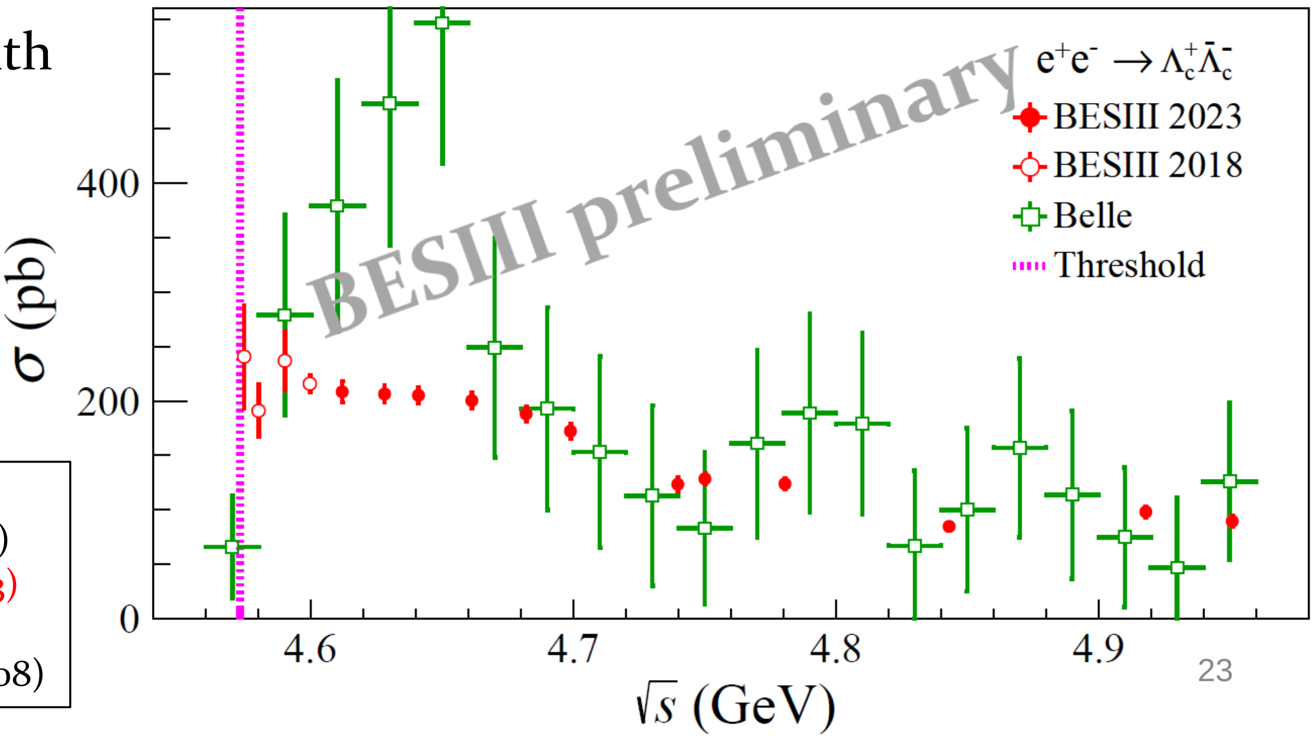


Ξ^- BESIII: Phys. Rev. D 103, 012005 (2021)
Ξ^0 BESIII: Phys. Lett. B 820, 136557 (2021).

New: Single-charm Λ_c^+ baryons

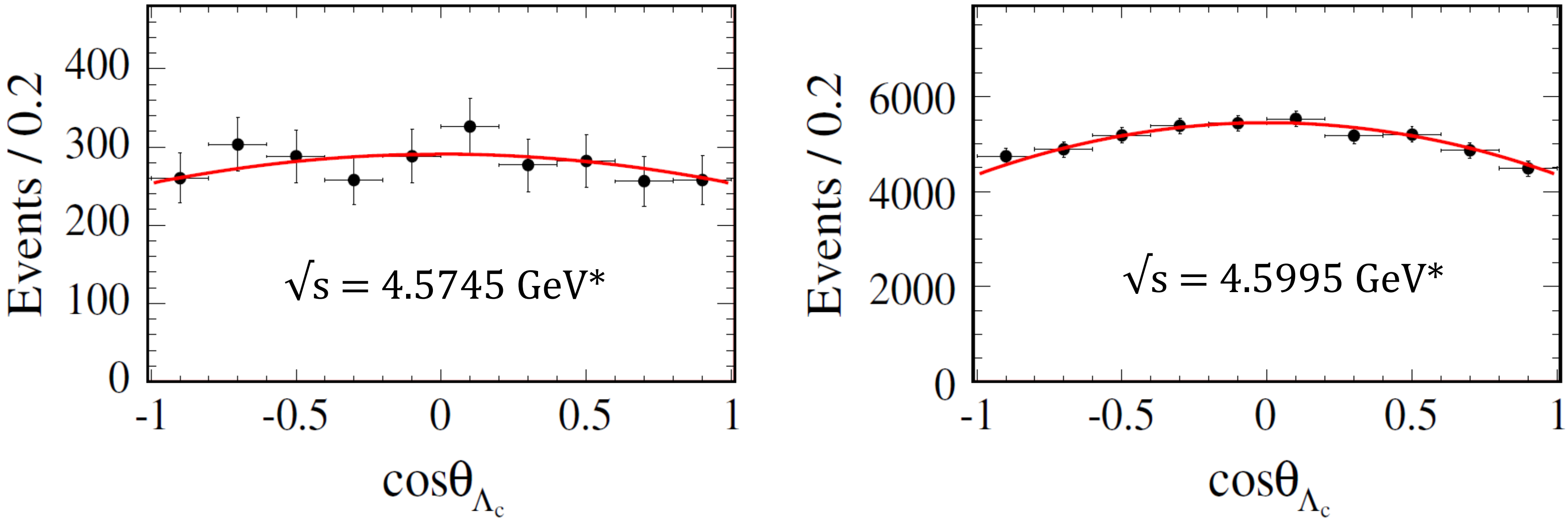
BESIII energy scans published in 2018* and 2023**

- Very precise cross section measurements
- First direct measurement of Λ_c^+ form factors
- Sharp rise in cross section near threshold
- Disagreement with Belle data*** near 4.6 GeV
- No discernible G_{eff} oscillations



BESIII:
*Phys. Rev. Lett. 120, 132001 (2018)
**arXiv[hep-ex]: 2307.07316 (2023)
Belle:
***Phys. Rev. Lett. 101, 172001 (2008)

Single-charm Λ_c^+ baryons



Angular distributions enable extraction of ratio R = $|G_E/G_M|$ of Λ_c^+ near threshold* and away from threshold**.

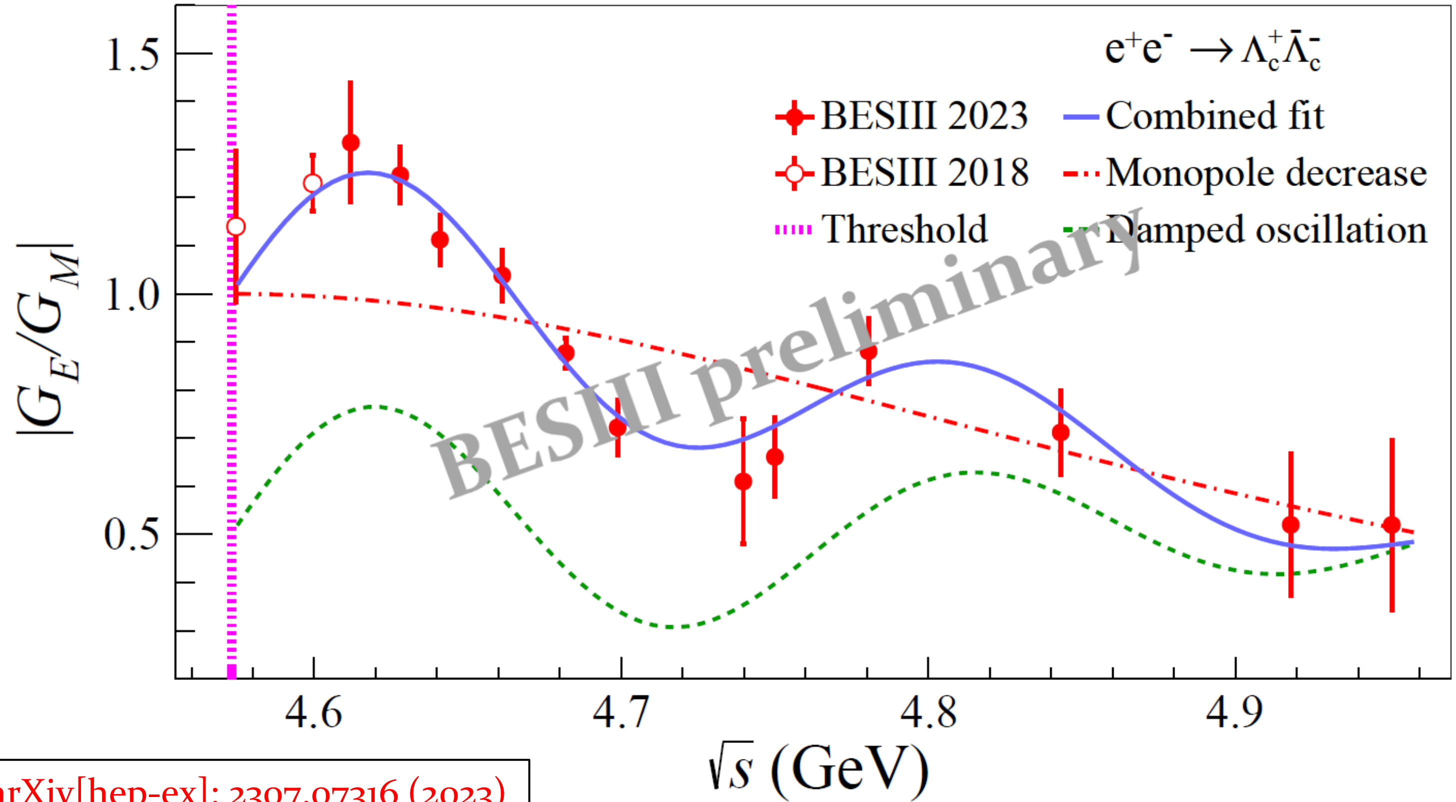
BESIII:
*Phys. Rev. Lett. 120, 132001 (2018)
**arXiv[hep-ex]: 2307.07316 (2023)

New: Single-charm Λ_c^+ baryons

Energy dependence of R = $|G_E/G_M|$* :

- Described by monopole model + damped oscillations

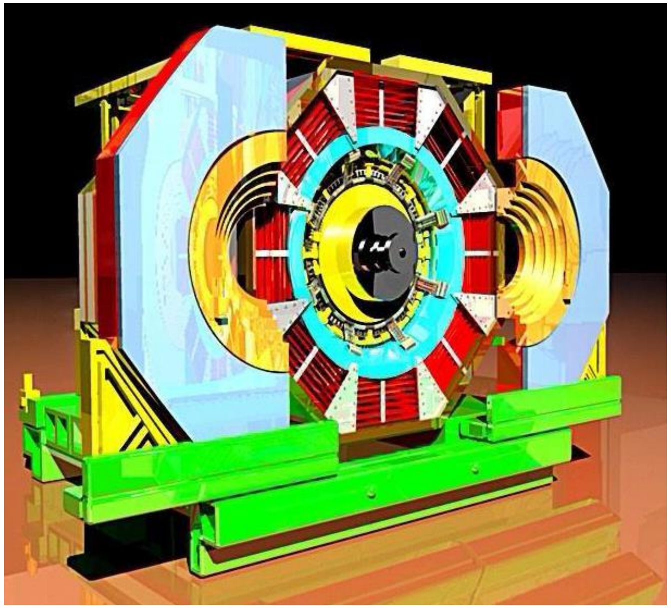
  → Oscillation frequency ~3.5 times larger than for the proton

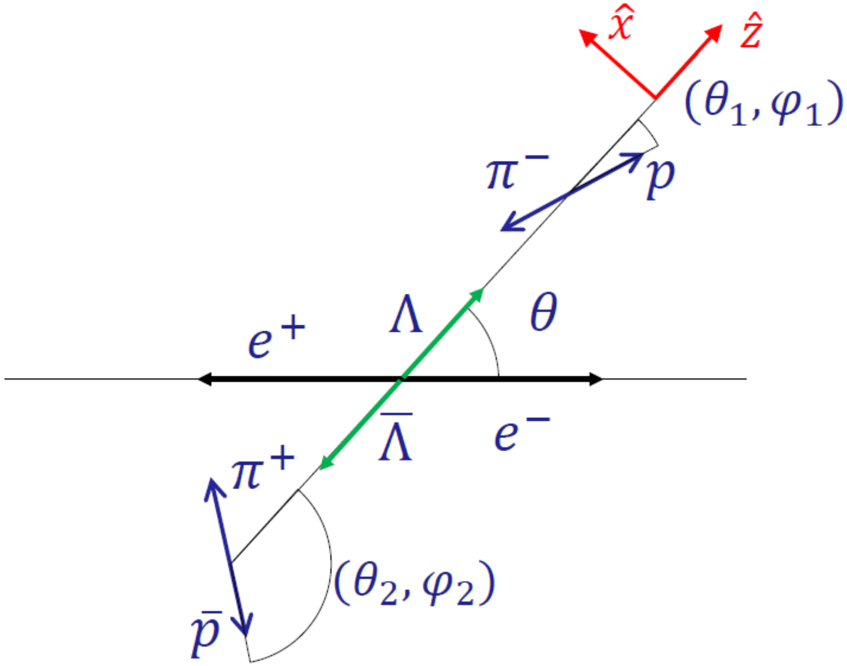


*BESIII:arXiv[hep-ex]: 2307.07316 (2023)

Spin Analysis

Consider $e^+e^- \to \bar{Y}Y, Y \to BM + c.c$





Spin Analysis

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

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

$$\mathcal{F}_0(\xi) = 1$$

$$\mathcal{F}_1(\xi) = \sin^2\theta \sin\theta_1 \sin\theta_2 \cos\phi_1 \cos\phi_2 + \cos^2\theta \cos\theta_1 \cos\theta_2$$

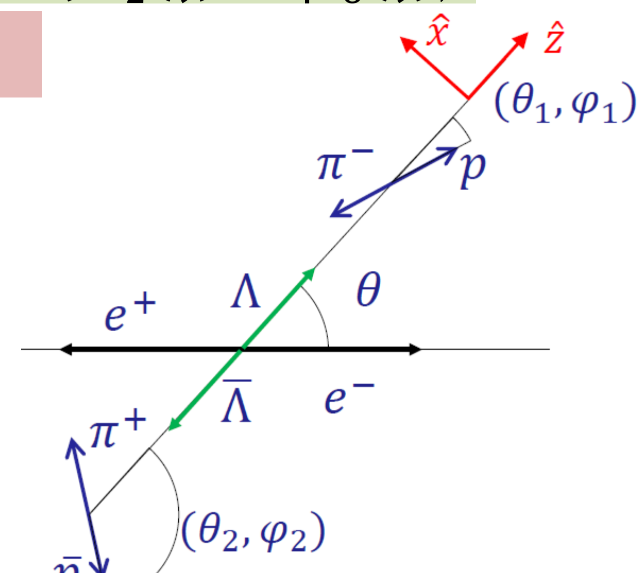
$$\mathcal{F}_2(\xi) = \sin\theta \cos\theta \left(\sin\theta_1 \cos\theta_2 \cos\phi_1 + \cos\theta_1 \sin\theta_2 \cos\phi_2\right)$$

$$\mathcal{F}_3(\xi) = \sin\theta \cos\theta \sin\theta_1 \sin\phi_1$$

$$\mathcal{F}_4(\xi) = \sin\theta \cos\theta \sin\theta_2 \sin\phi_2$$

$$\mathcal{F}_5(\xi) = \cos^2\theta$$

$$\mathcal{F}_6(\xi) = \cos\theta_1 \cos\theta_2 - \sin^2\theta \sin\theta_1 \sin\theta_2 \sin\phi_1 \sin\phi_2$$



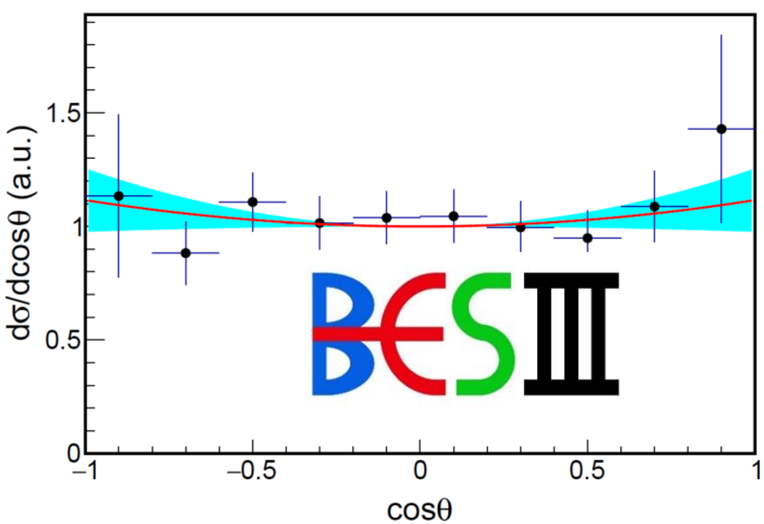
*Fäldt & Kupsc, PLB 772 (2017) 16.

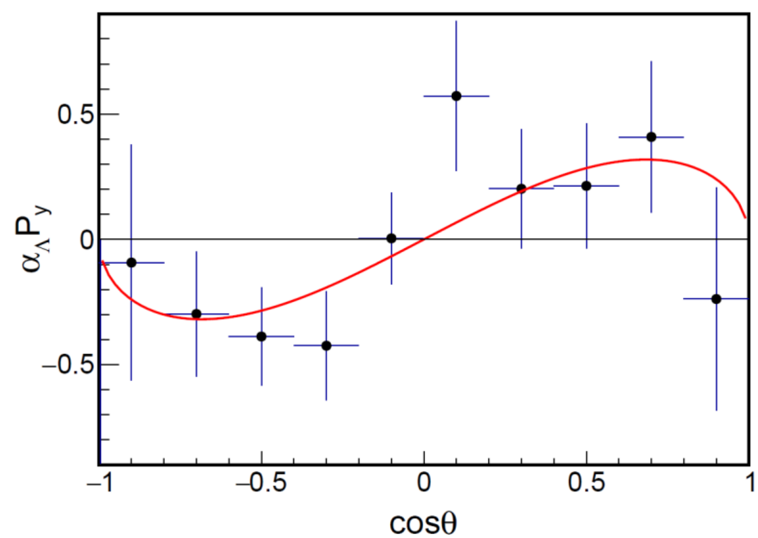
First complete measurement of Λ EMFF

- 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 $\Delta\Phi$

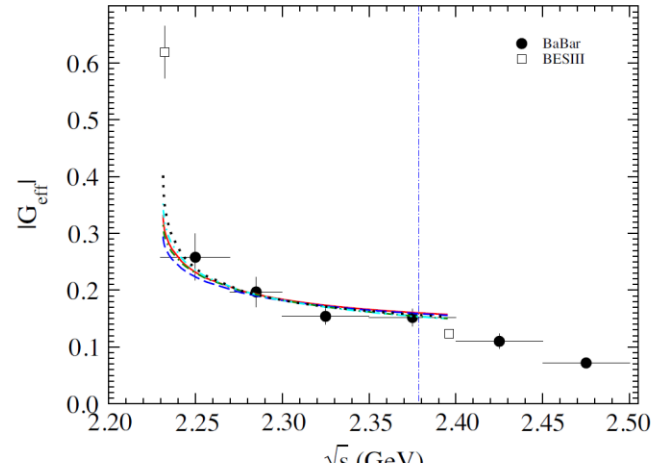


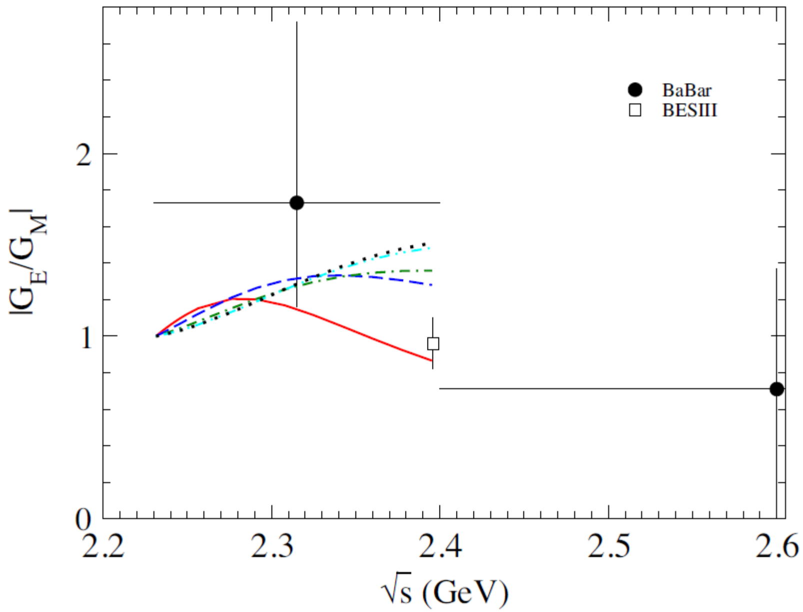


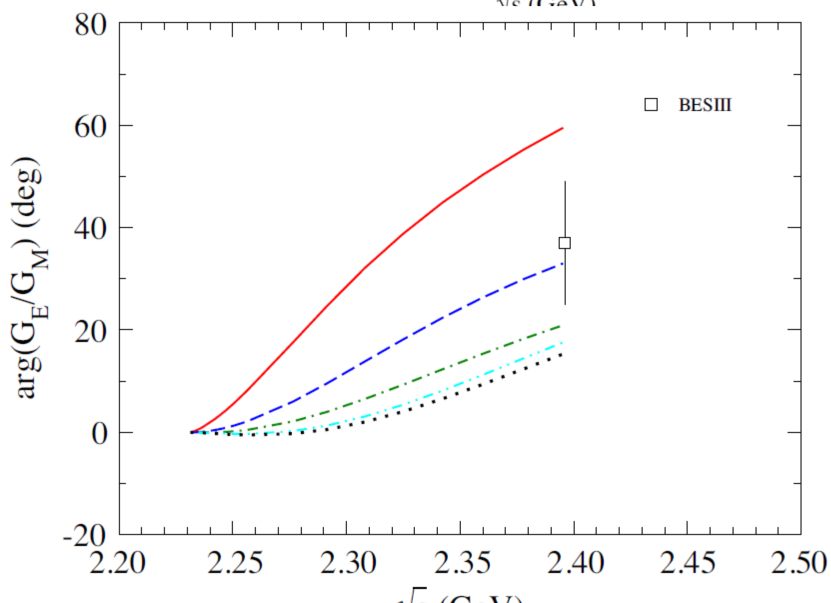
Theory Interpretation

Theoretical study of the $e^+e^- \to Y\bar{Y}$ by Haidenbauer, Meissner and Dai*

- $Y\bar{Y}$ potentials constructed from $\bar{p}p \to \bar{Y}Y$ data from PS185.
- Spin-dependent observables much more sensitive to the $Y\bar{Y}$ potential.
- Fairly good agreement with BESIII data.







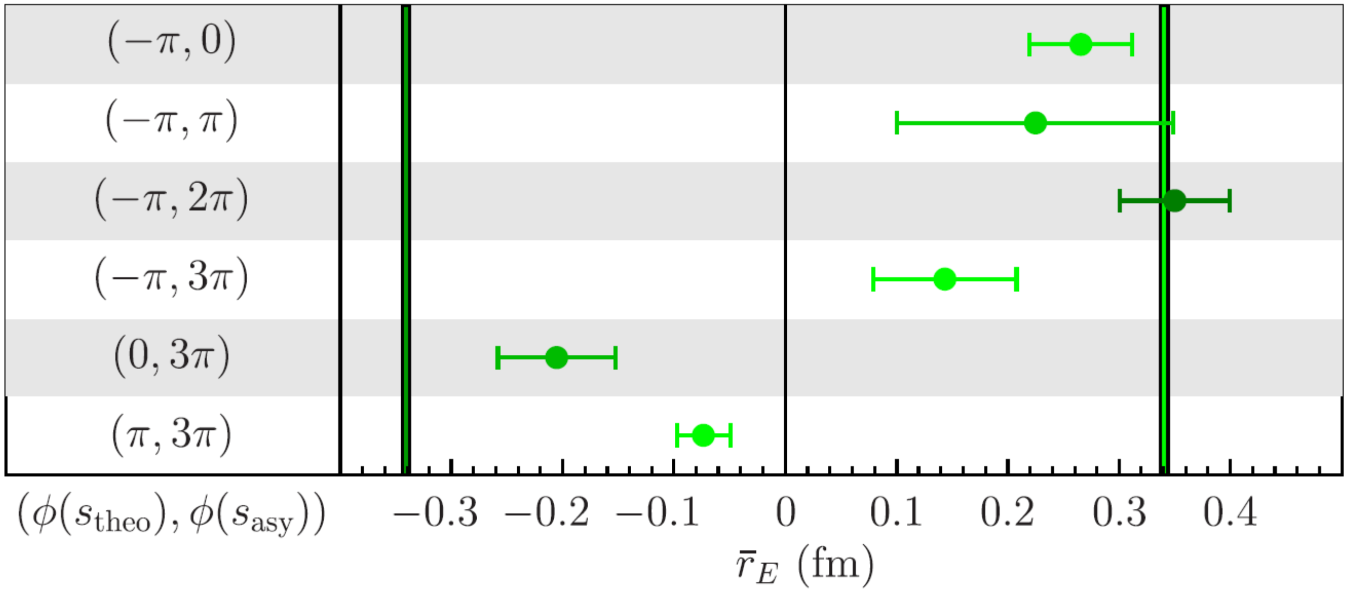
* Haidenbauer *et al.*, Phys. Rev. D 103, 014028 (2021)

Theory interpretation

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

- Study of the phase $\Delta\Phi$ – must be integer multiple of π at threshold *(N_{th})* and at the asymptotic scale q_{asy} *(N_{asy})*.
- Fit of different data from ** and *** to different scenarios of N_{th} and N_{asy}

  → calculations of charge radius!



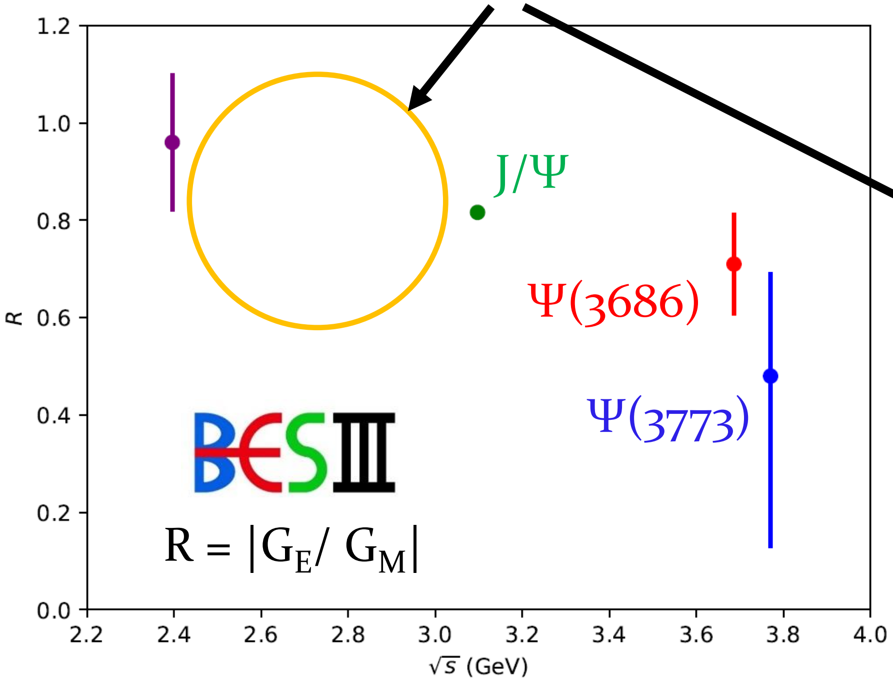
*Mangoni *et al.,* Phys. Rev. D 104, 116016 (2021)
**BESIII: Phys. Rev. Lett. 123, 122003 (2019)
***BaBar: Phys. Rev. D 76, 092006 (2007)

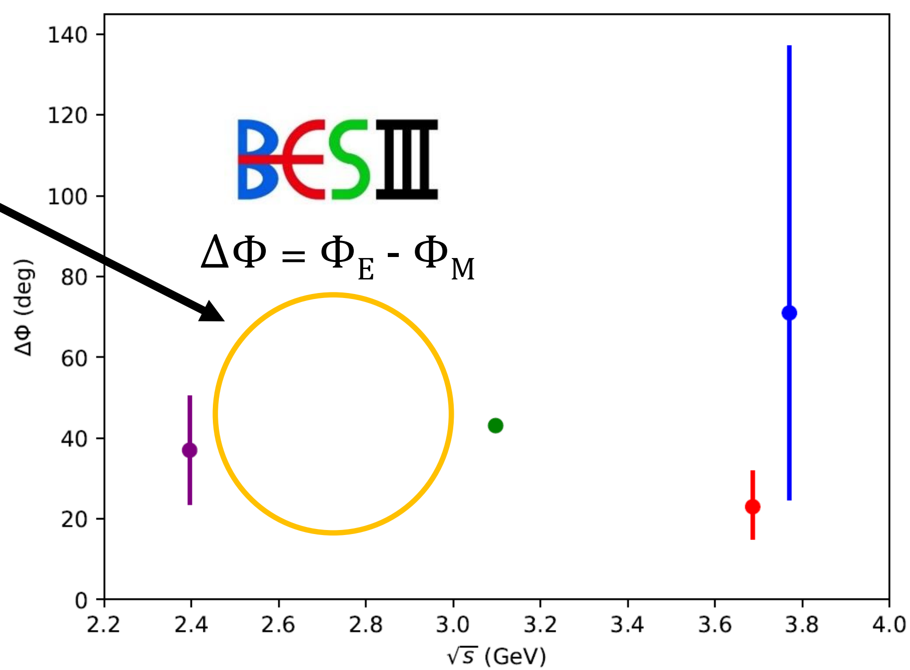
Λ Spin Analyses

Similar analyses performed at J/Ψ**, Ψ(3686)*** and Ψ(3773)****

- R and ΔΦ interpreted as *psionic* structure functions
- New off-resonance data underway

*Phys. Rev. Lett. 123, 122003 (2019)
Nature Phys. **15, p. 631-634 (2019)
***arXiv[hep-ex]: 2303.00271 (2023)
****Phys. Rev. D 105, L011101 (2020)



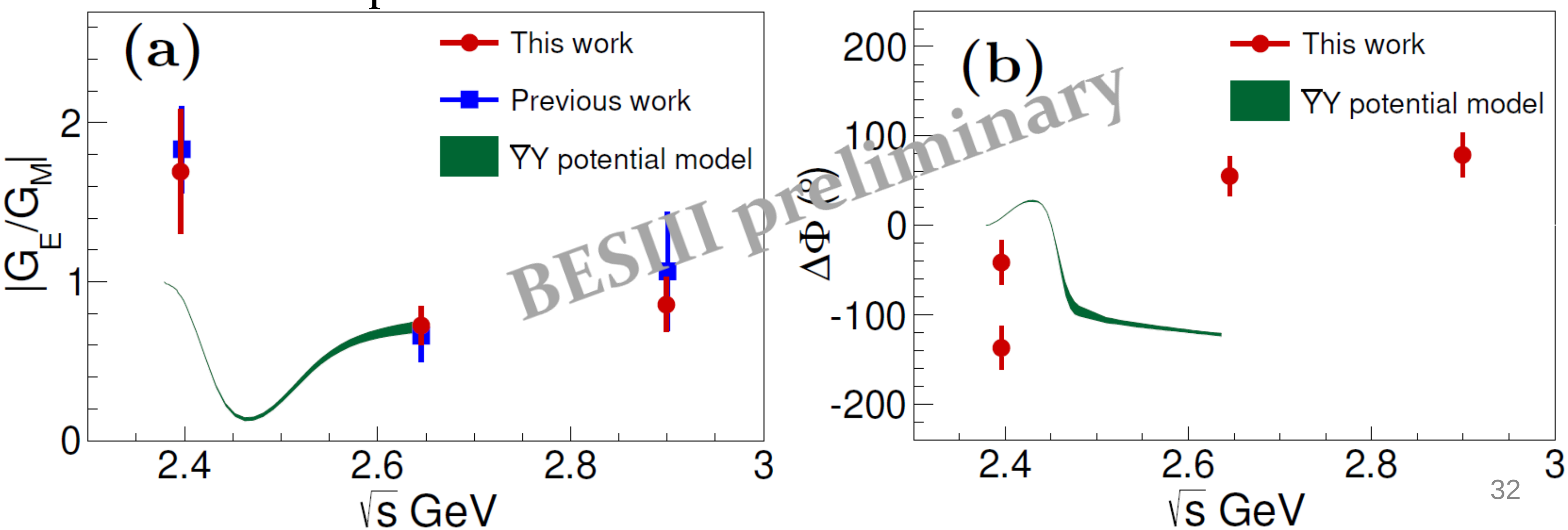


Picture credit Michael Papenbrock

New: Σ^+ Spin Analysis

- Energy dependence of R and ΔΦ in three different 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 $e^+e^- \to \Sigma^+\bar{\Sigma}^- \to p\pi^0X + c.c.$ at 2.396 GeV
    → ΔΦ / 180° – ΔΦ ambiguity
- Better precision than in previous work**.
- Worse agreement with $Y\bar{Y}$ potential model *** compared to Λ.

*BESIII, arXiv[hep-ex]:2307.15894 (2023)
** BESIII, Phys. Lett. B 814, 136110 (2021)
*** Haidenbauer *et al.*, Phys. Rev. D 103, 014028 (2021)



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Summary

- Time-like form factors a viable tool to study structure and femtometer sizes.
- Many new results from the BESIII experiment
  - single- and double strange hyperons
  - charm baryons
- Hyperon polarisation provide information about space-like structure *e.g.* charge radius.
- More data collected → STAY TUNED !!!

BESIII

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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

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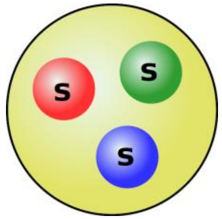
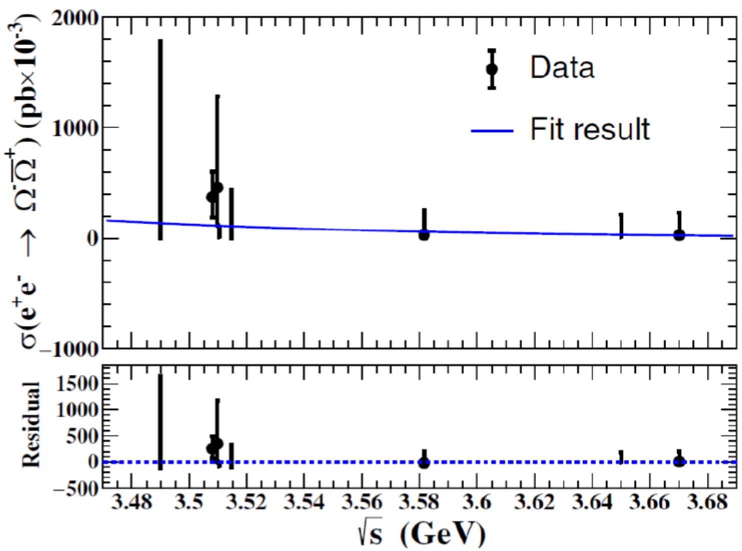
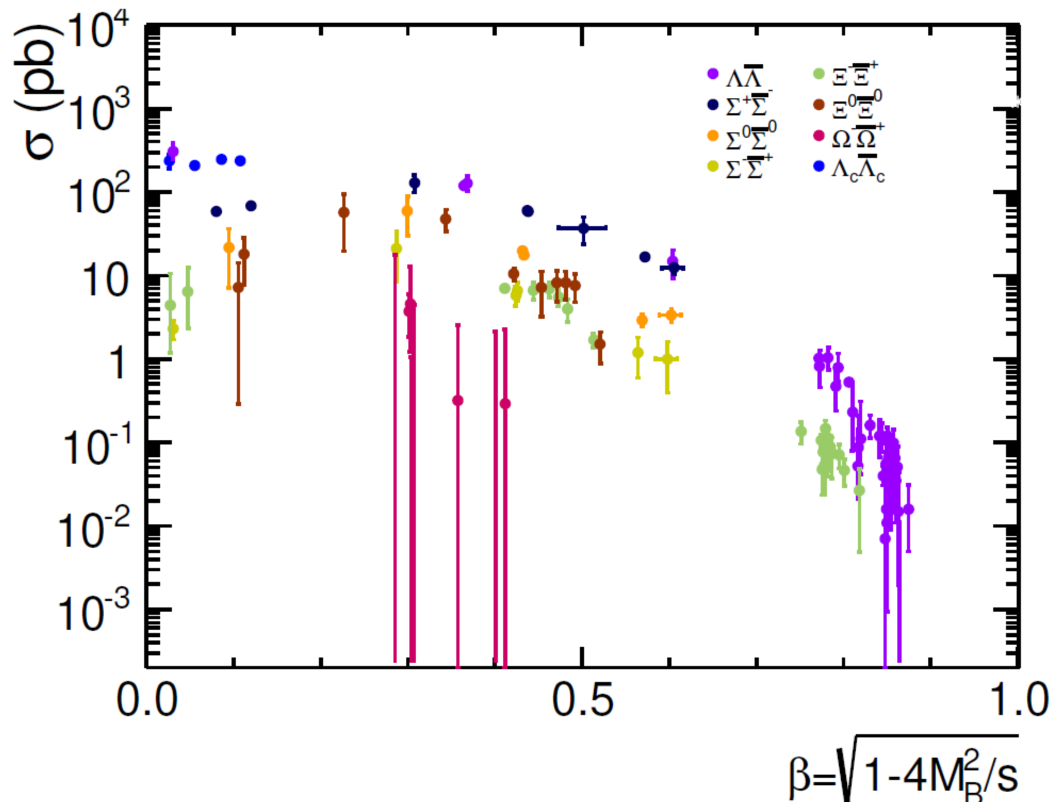
Backup



Triple-strange Ω hyperons

- New BESIII study: Search for $e^+e^- \to \Omega^-\bar{\Omega}^+$*
  - No signals seen → only upper limits determined.
  - Will need much larger luminosities to match other hyperon studies**



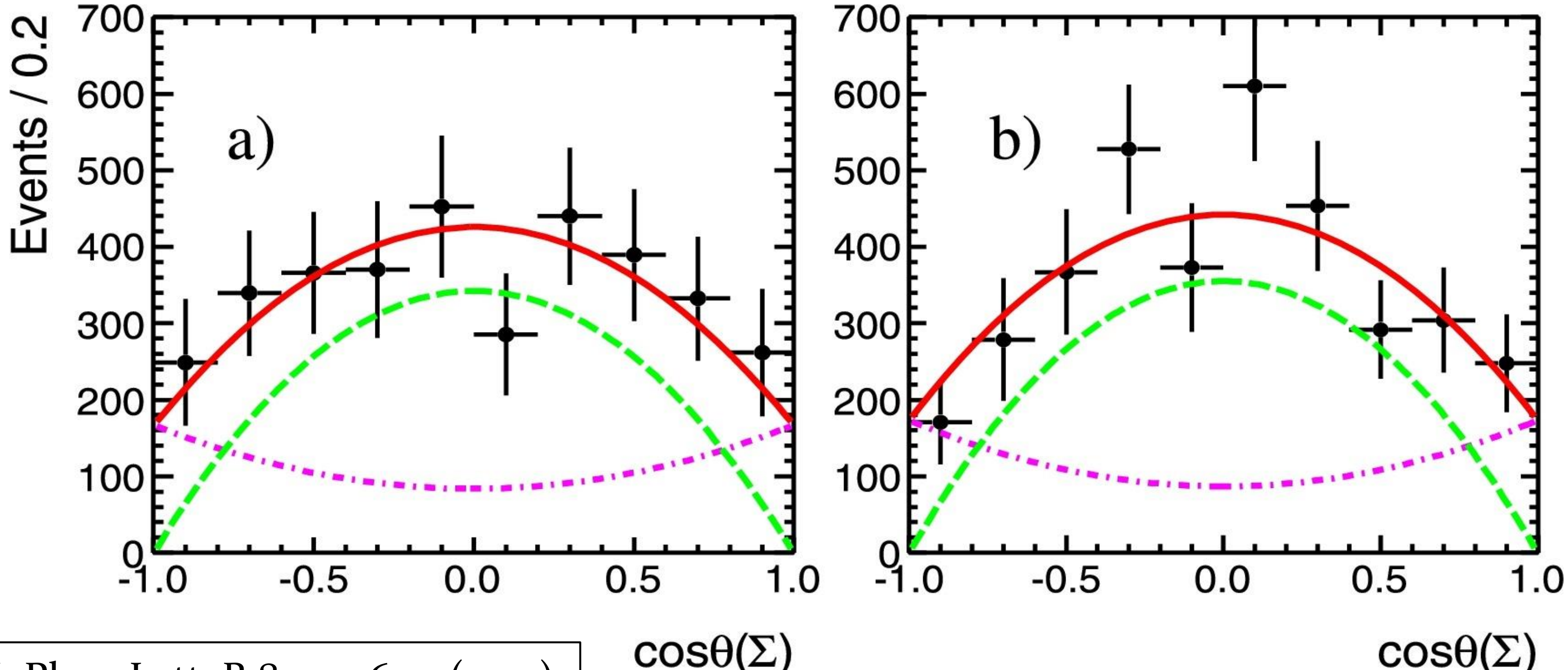


* BESIII: Phys. Rev. D 107, 052003, 2023
** Schönning et al., Chin. Phys. C 47, 5, 052002 (2023)

Single-strange hyperons

Σ^+ Form Factor Ratio:

$R = \frac{|G_E(q^2)|}{|G_M(q^2)|}$ measured at 2.396 GeV to be 1.83 ± 0.26



BESIII: Phys. Lett. B 814, 136110 (2021)