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Hyperon Structure with BESIII

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Kraków, Poland, 2022-06-08

Prof. Dr. Karin Schönning, Uppsala University

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Outline

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

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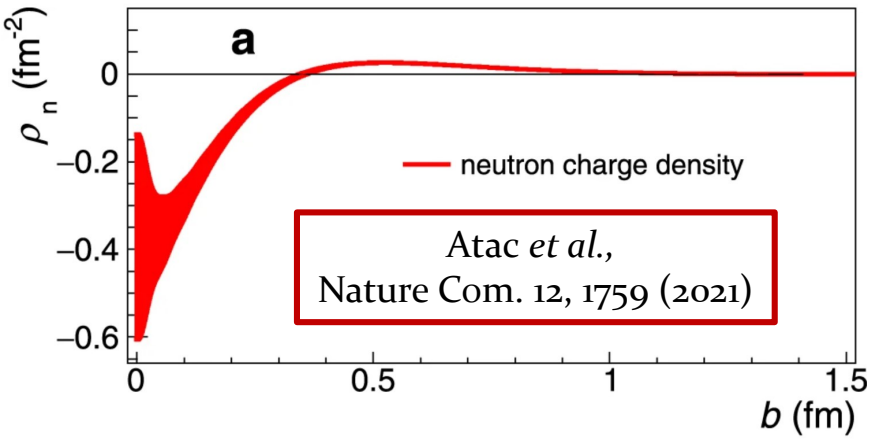
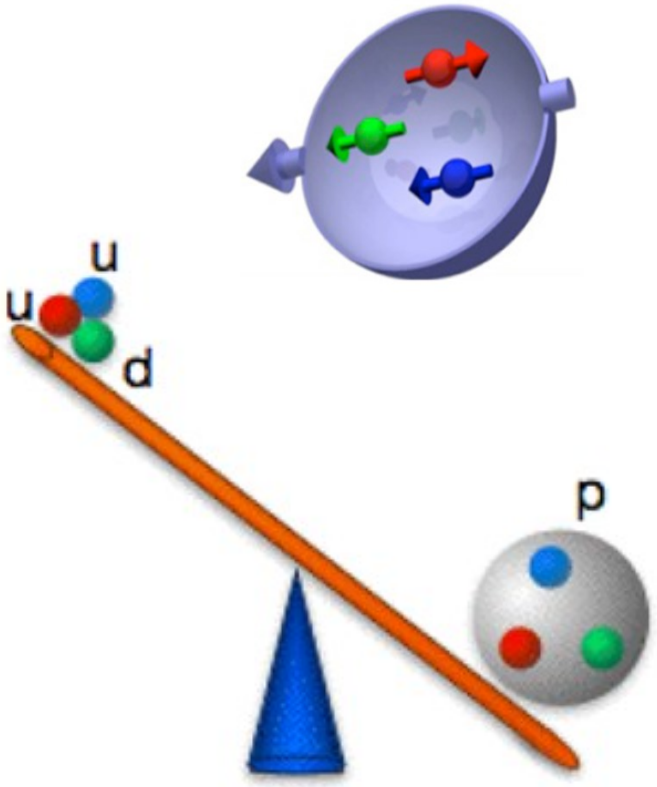
The Nucleon

The non-perturbative features of the strong interaction manifests in the **nucleon properties**:

- Mass
- Spin
- Structure





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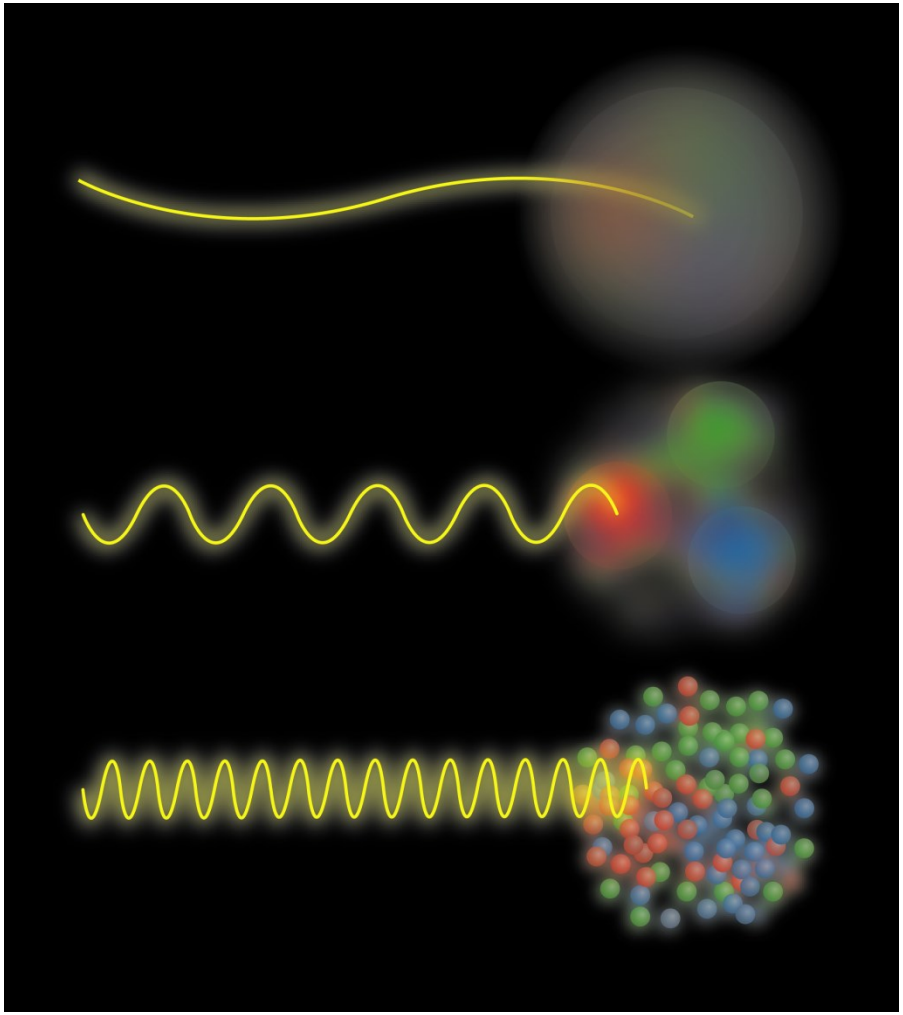
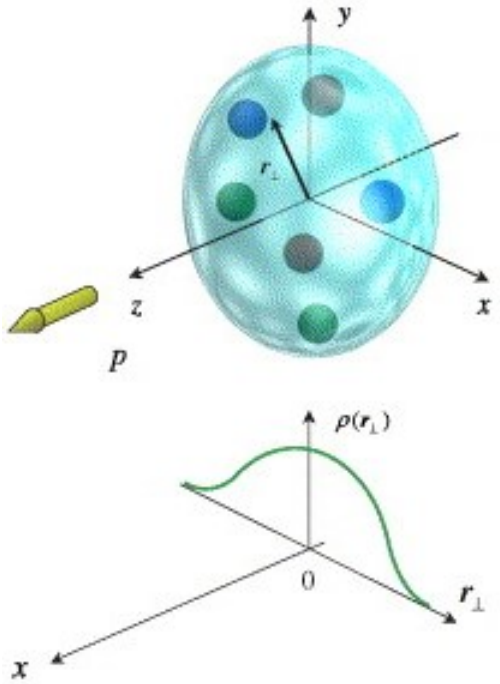
Electromagnetic Form Factors

- Probed in hadron - γ^* interactions:
- Scale governed by momentum transfer q^2.
- Can be elastic or inelastic.



Electromagnetic Form Factors

- EMFFs: Fundamental observable of the strong interaction.
- Quantify the deviation from point-like behaviour.
- Predictions from
  - LatticeQCD
  - ChPT
  - Dyson-Schwinger
  - Vector Meson Dominance



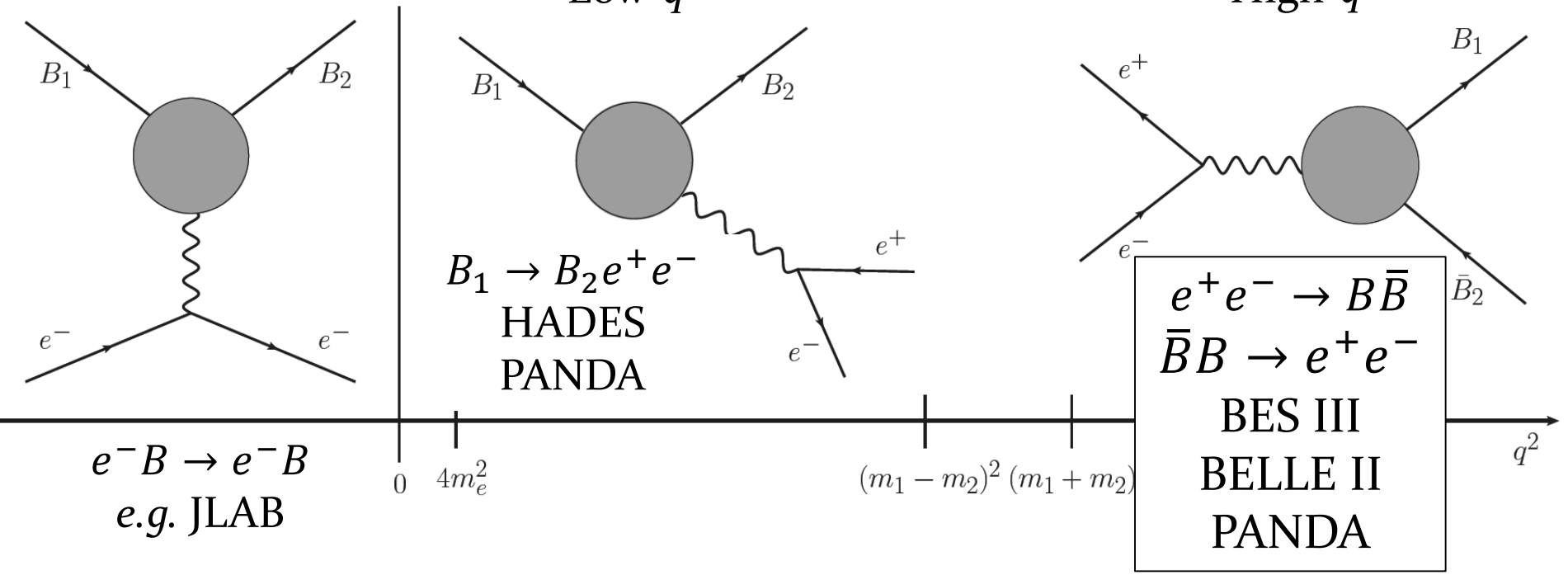
Space-like *vs.* time-like FF's

Space-like
$q^2 < 0$

Time-like
$q^2 > 0$

Low-q^2

High-q^2



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

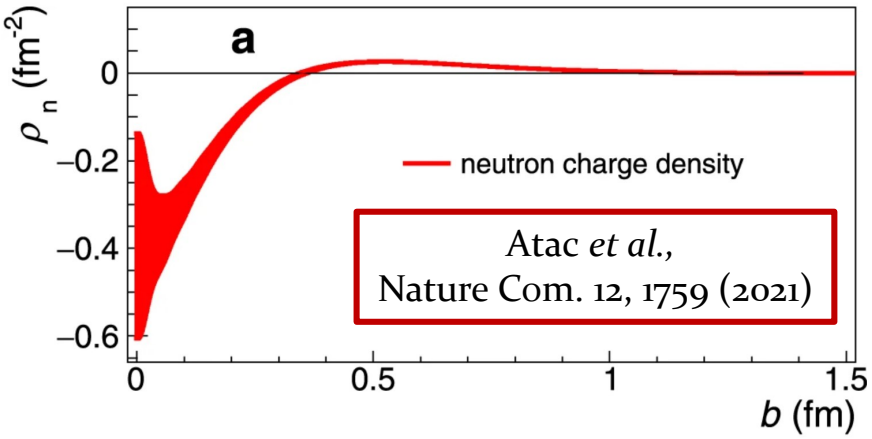
$e^+ e^- \to B\bar{B}$
$\bar{B}B \to e^+ e^-$
BES III
BELLE II
PANDA

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

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

Space-like form factors

- Number of EMFFs = $2J+1$ → spin ½ baryons have 2.
- Dirac and Pauli FFs F_1 (spin non-flip) and F_2 (spin flip).
- Sachs FFs G_E and G_M .
  - $G_E(q^2) = F_1(q^2) - \tau F_2(q^2)$
  - $G_M(q^2) = F_1(q^2) + F_2(q^2)$
  - $\tau = q^2/4M^2_B$

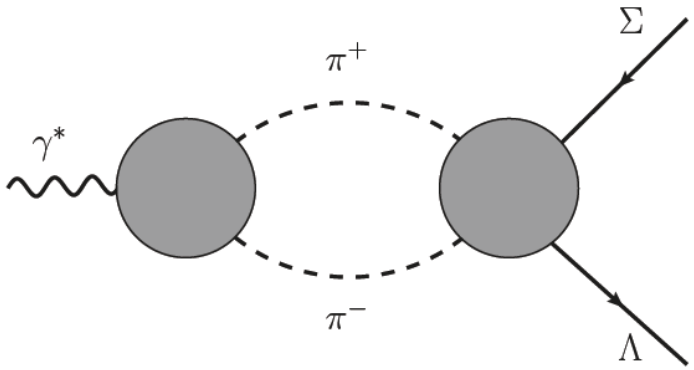


- Charge radius: $< r_E^2 > = 6 \frac{dG_E(q^2)}{dq^2}|_{q^2=0}$
- Magnetic radius: $< r_M^2 > = \frac{6}{G_M(0)} \frac{dG_M(q^2)}{dq^2}|_{q^2=0}$

Time-like form factors

- Related to space-like EMFFs *via* dispersion relations.
- Are complex:
  - $G_E(q^2) = |G_E(q^2)| \cdot e^{i\Phi_E}$, $G_M(q^2) = c \cdot e^{i\Phi_M}$
  - 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.* $\pi\pi$.

→ Polarises final state!



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

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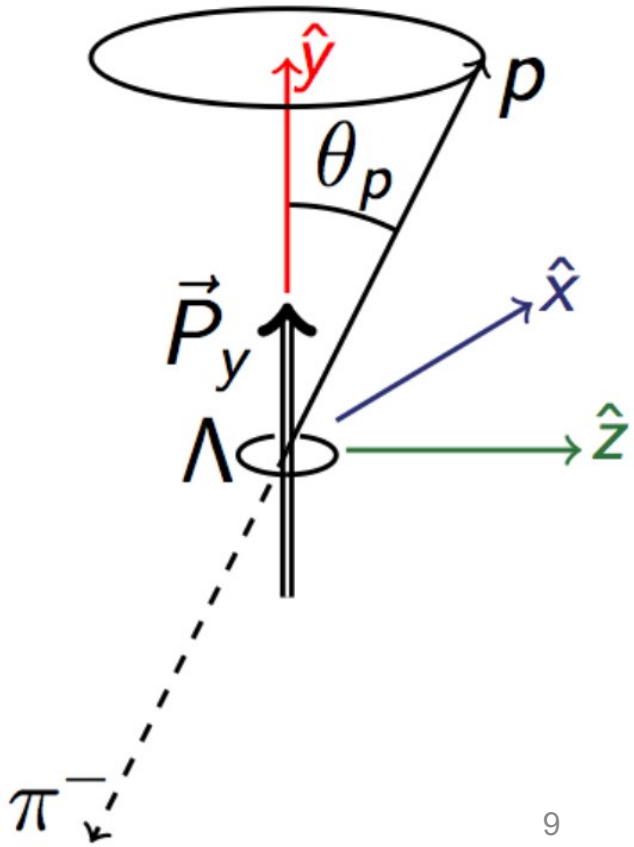
Advantage of hyperons

Polarisation experimentally accessible by the weak, parity violating decay:

Example:

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



Nucleon *versus* hyperon EMFFs

Asymptotic behaviour as $|q^2| \to \infty$: SL ~TL

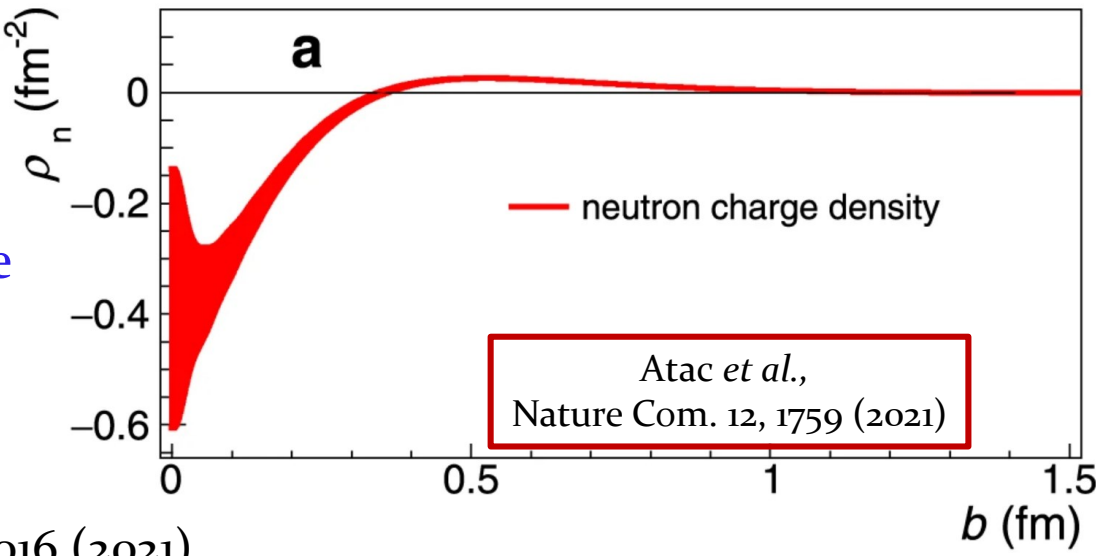
- Nucleons: SL and TL accessible.
- Hyperons: Only TL accessible, but also phase!

  SL = TL $\leftrightarrow \Delta\Phi(q^2) \to 0$ as $|q^2| \to \infty$ (or at $> q^2_{asy}$)

Baryon charge radius:

- Neutron: Found to be negative *,**
- Neutral hyperons: Can be calculated from q^2_{asy} and

  $Im(R(q^2)) = Im(\frac{G_E(q^2)}{G_M(q^2)})$



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

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

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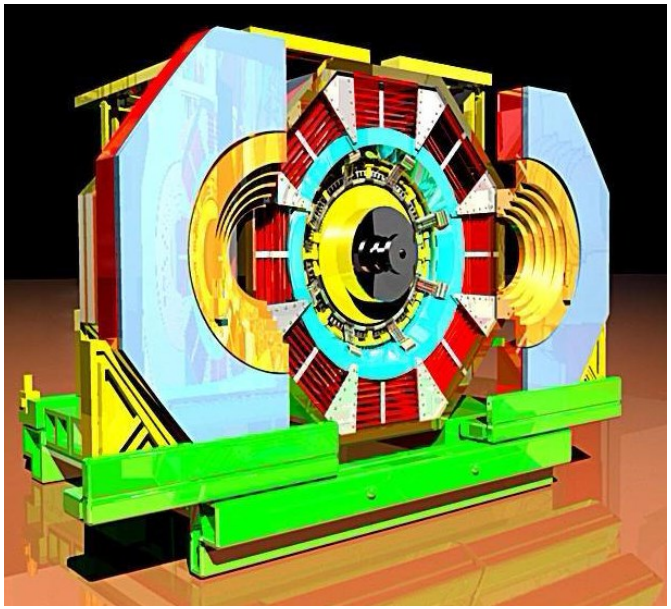
Recent measurements by BESIII

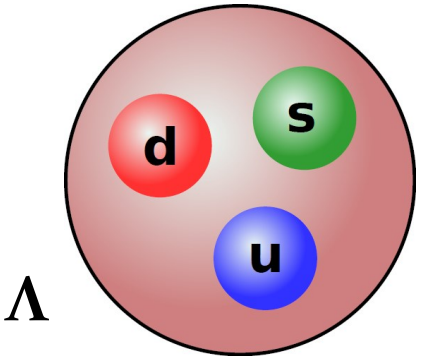
- Study the $e^+e^- \rightarrow B\bar{B}$, where $B = \Lambda, \Sigma, \Xi, \Lambda_c^+$
- Beijing Electron Positron Collider (BEPC II):
  - e^+e^- collider within CMS range 2.0 – 4.95 GeV.
  - Optimised in the τ-charm region.
- Beijing Spectrometer (BES III):
  - Near 4π coverage
  - Tracking, PID,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

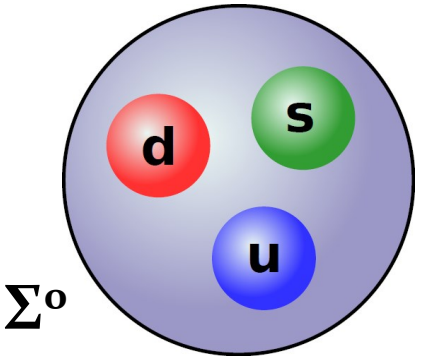


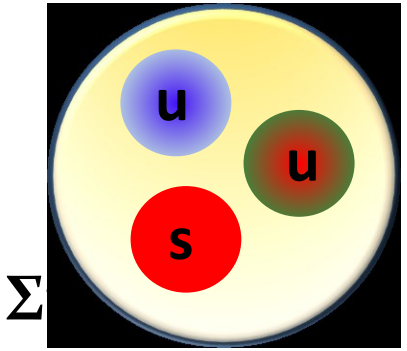
Single-strange hyperons

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



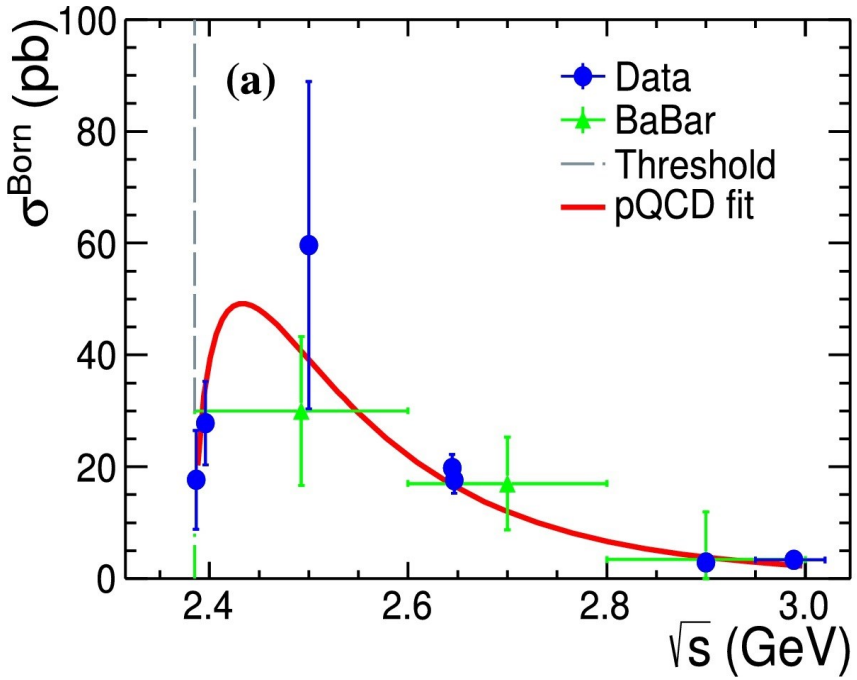


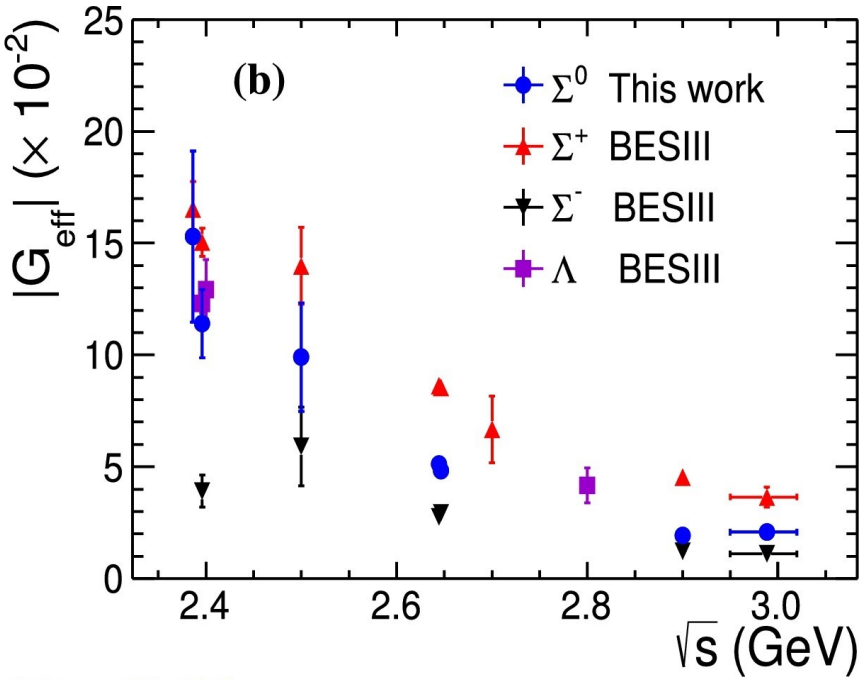


* PLB 739 (2014) 90.

Single-strange hyperons

- Λ/Σ^+ effective FFs similar as expected from diquark correlations.[*,**,***]
- Σ^+/Σ^- cross section ratio ~ 9[**] , in disagreement with the expected SU(3) symmetry breaking of 10-30% .



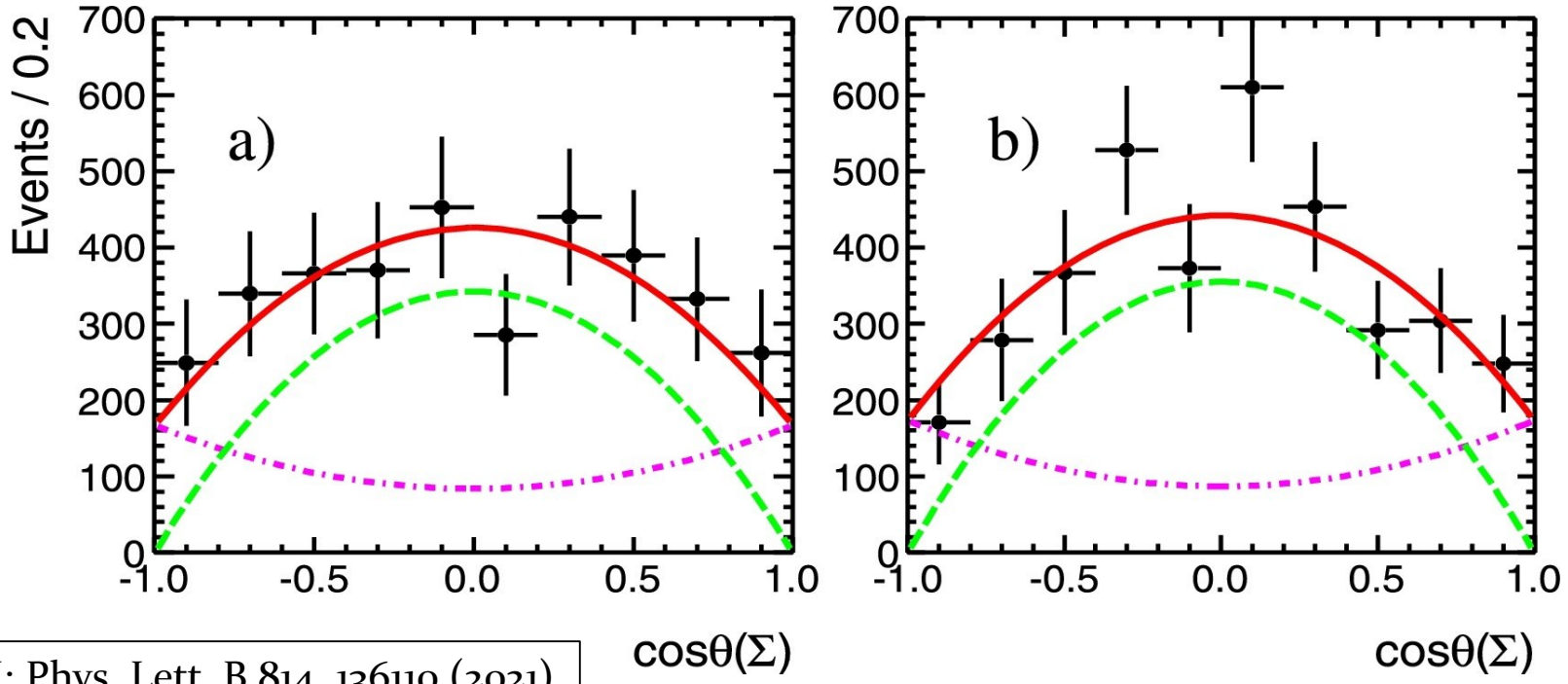


* BESIII: Phys. Lett. B 831, 137187 (2022)
** BESIII: Phys. Lett. B 814, 136110 (2021)
*** BESIII: Phys. Rev. D 97, 032013 (2018)

Single-strange hyperons

Σ^+ Form Factor Ratio:

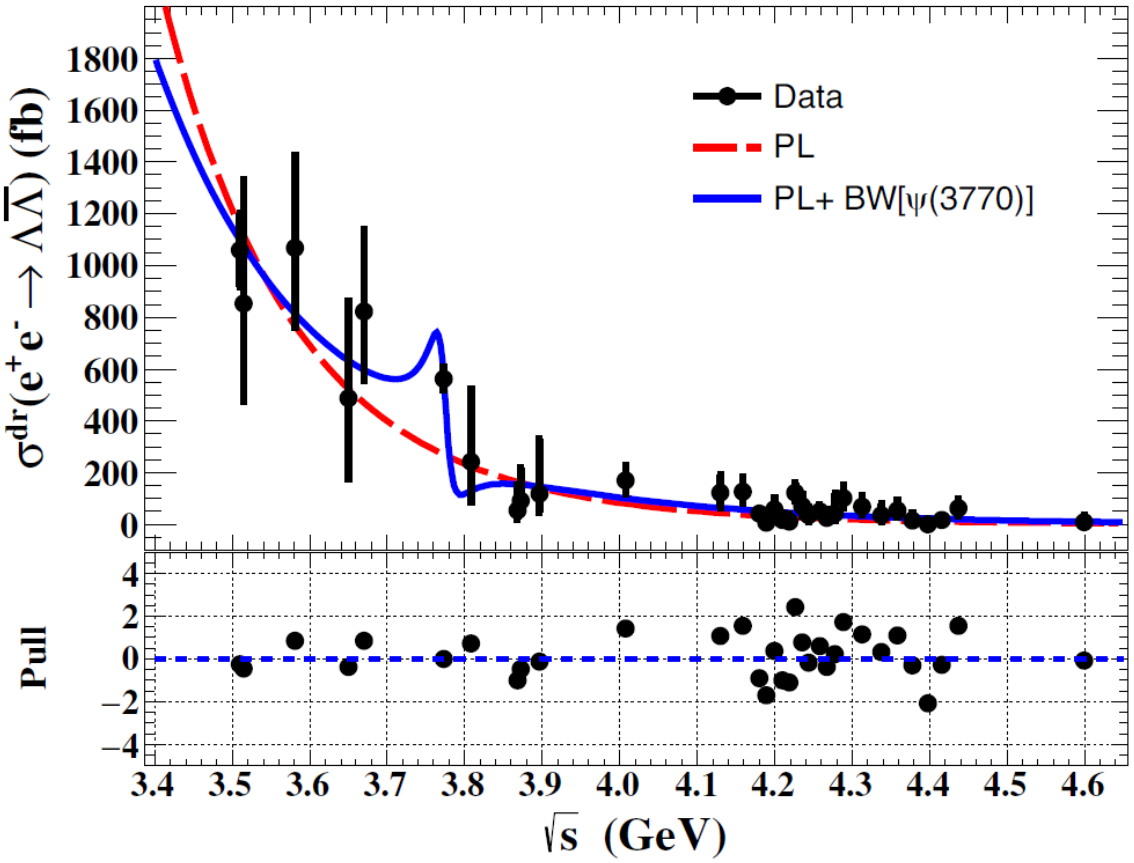
$R = \frac{|G_E(q^2)|}{|G_M(q^2)|}$ measured at 2.396 GeV to be 1.83±0.26



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

Production of Λ at high q^2

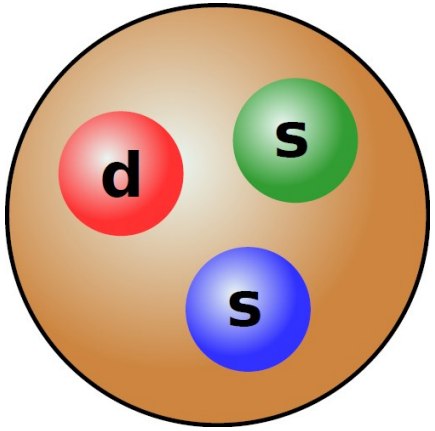
- $\Lambda\bar{\Lambda}$ production near vector charmonia*,**
- $BR(\Psi \to \Lambda\bar{\Lambda}) >$ 10 times larger than assumed in previous studies by CLEO-c***.

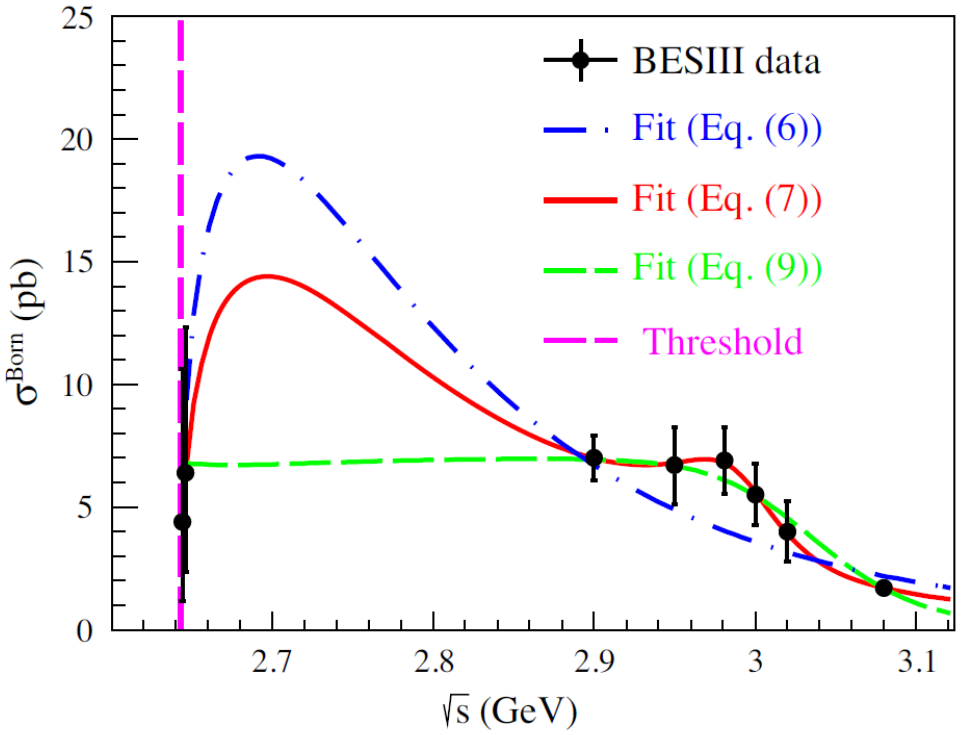


* BESIII: Phys. Rev. D 104, L091104 (2021)
** BESIII: Phys. Rev. D 105, L011101 (2022)
*** CLEO-c: Phys. Rev. D 96, 092004 (2017); Phys. Lett. B 739, 90 (2014)

Double-strange hyperons

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

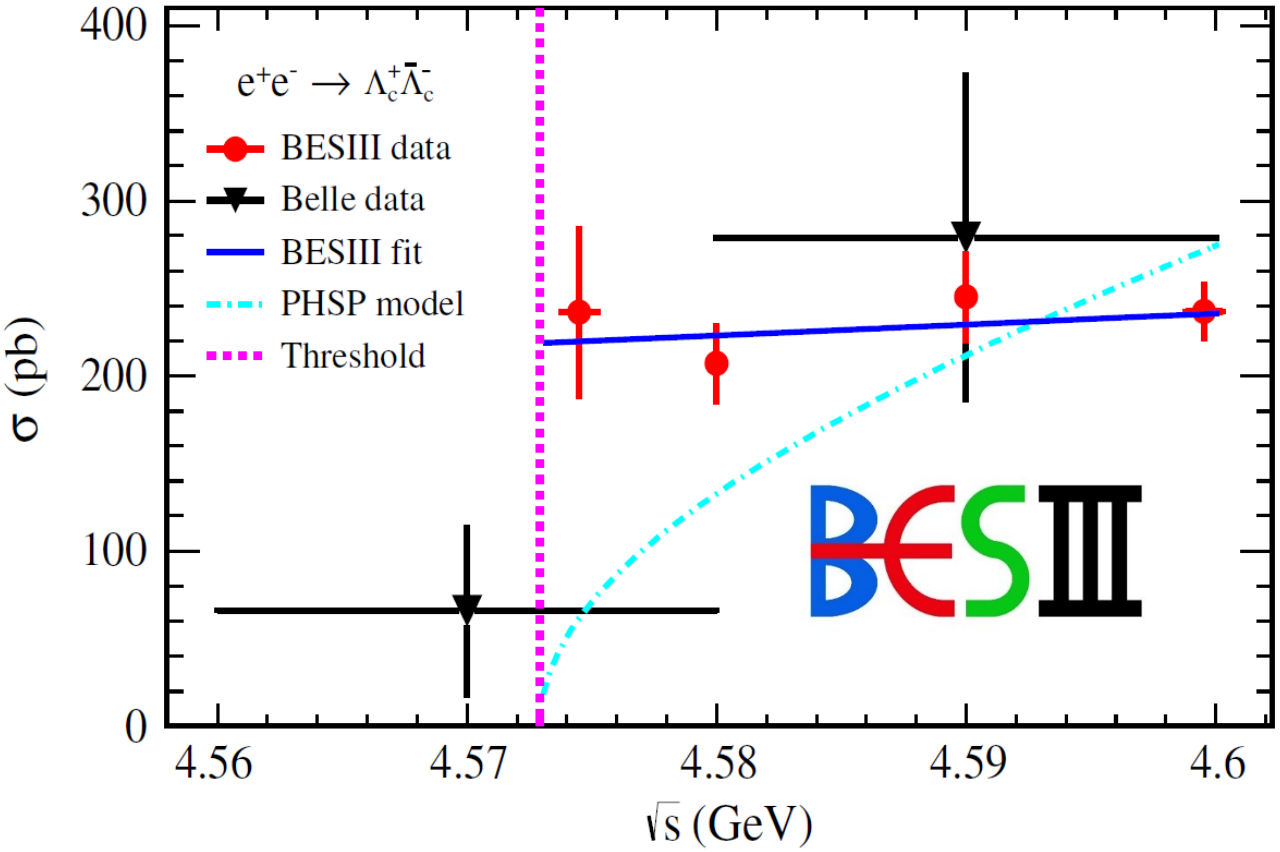




BESIII: Phys. Rev. D 103, 012005 (2021)

Single-charm Λ_c^+ baryons

The charm baryon Λ_c^+ EMFF's in $e^+e^- \to \Lambda_c^+\overline{\Lambda}_c^-$.*

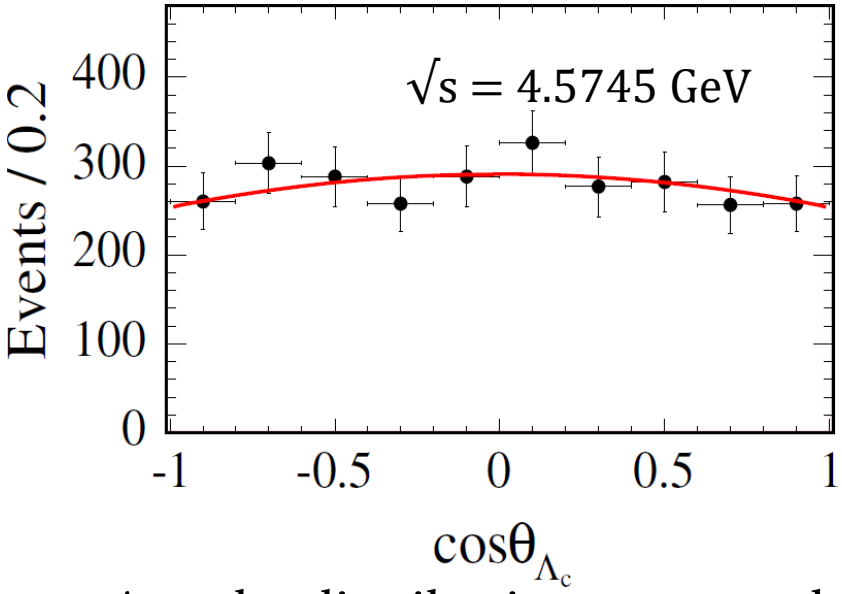


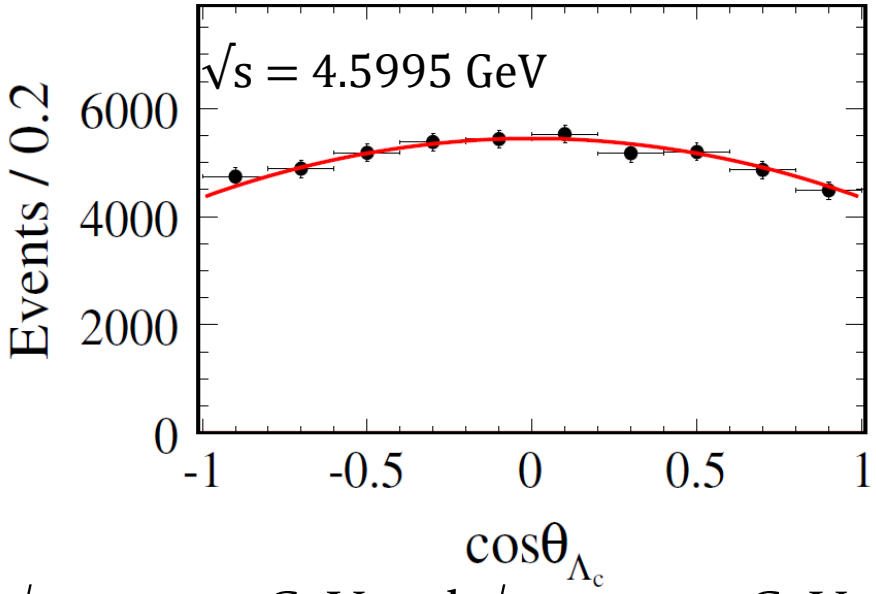
- First direct measurement of Λ_c^+ EMFF's.
- Most precise cross section measurement so far.
- Data very close to threshold.

BESIII: Phys.Rev.Lett. 120, 13, 132001 (2018)

Single-charm Λ_c^+ baryons

The charm baryon Λ_c^+ EMFF's in $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$



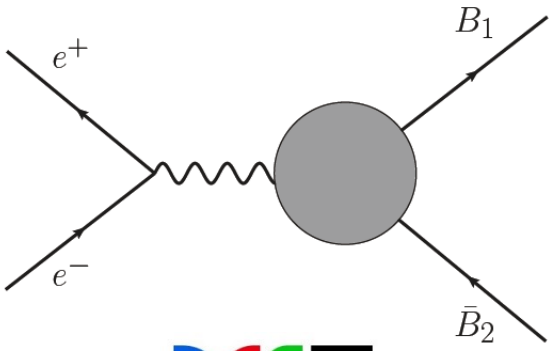


- Angular distributions extracted at √s = 4.5745 GeV and √s = 4.5995 GeV.
- Ratio $|G_E/G_M|$ of Λ_c^+ FF's measured for the first time.

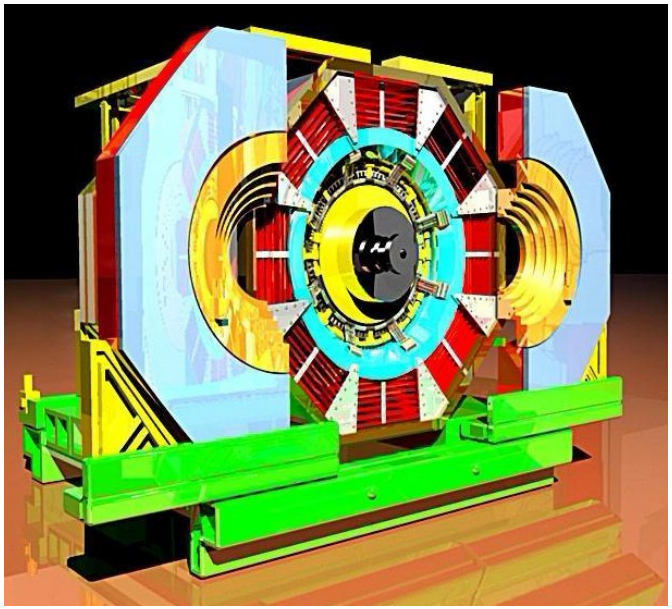
$\sqrt{s}$ MeV	$\lvert G_E/G_M \rvert$
4574.5	$1.10 \pm 0.14 \pm 0.07$
4599.5	$1.23 \pm 0.06 \pm 0.03$

BESIII: PRL 120, 13, 132001 (2018)

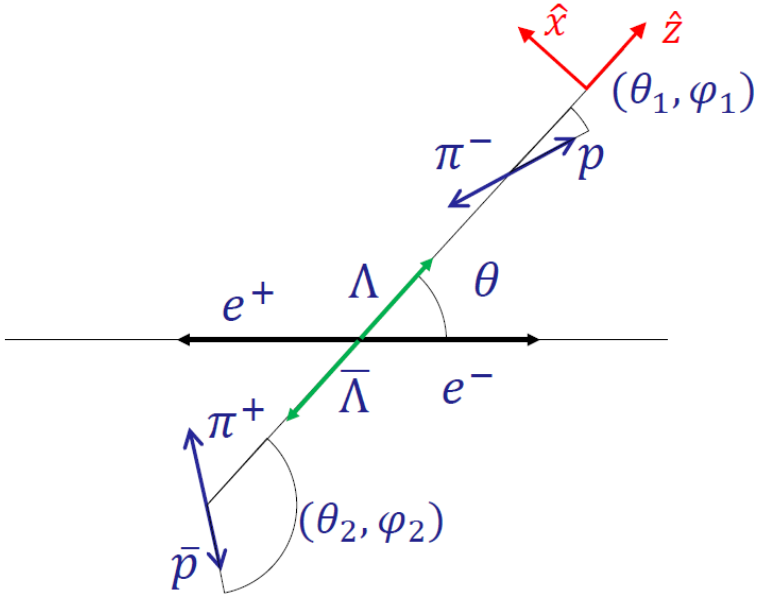
Spin Analysis



BESIII



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



Spin Analysis

Production parameters of spin ½ baryons:

- Angular distribution parameter η
- Phase ΔΦ

Decay parameters for 2-body decays: α_1 and α_2.

Unpolarized part Polarised part Correlated part

$$W(\xi) = F_0(\xi) + \eta F_5(\xi) - \alpha_1\alpha_2(F_1(\xi) + \sqrt{1-\eta^2}\cos(\Delta\Phi)\,F_2(\xi) + \eta F_6(\xi)) + \sqrt{1-\eta^2}\sin(\Delta\Phi)(\alpha_1 F_3(\xi) - \alpha_2 F_4(\xi))$$

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

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

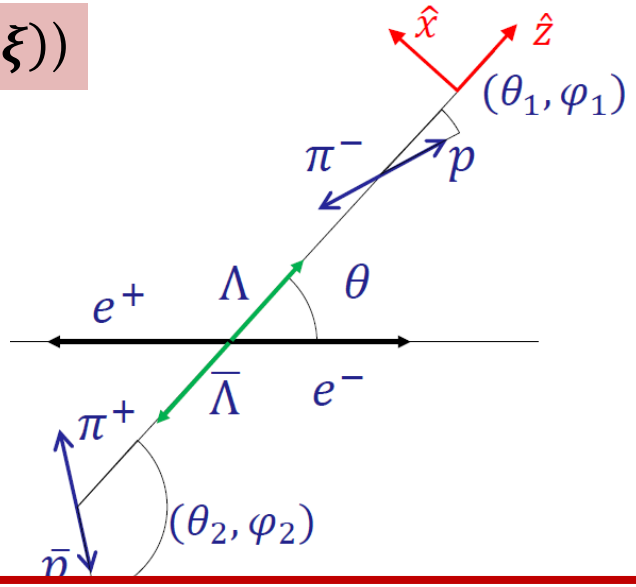
$$\mathcal{T}_2(\xi) = \sin\theta\cos\theta\,(\sin\theta_1 \cos\theta_2 \cos\phi_1 + \cos\theta_1 \sin\theta_2 \cos\phi_2)$$

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

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

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

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



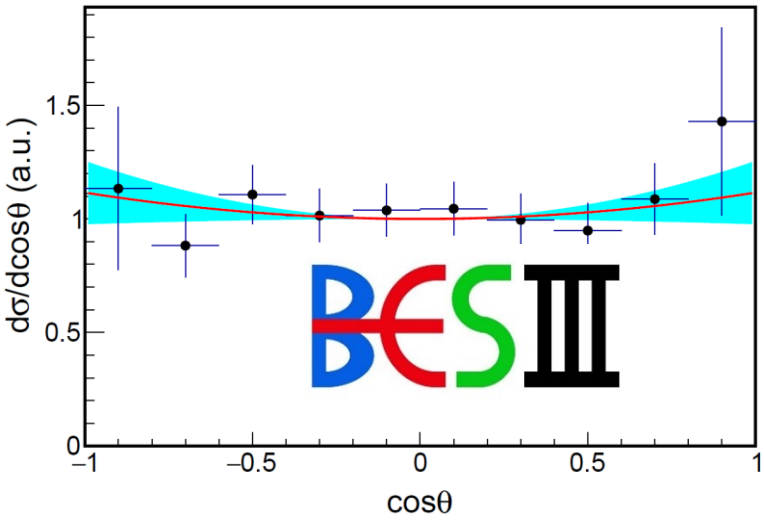
*Fäldt & Kupsc, PLB 772 (2017) 16.

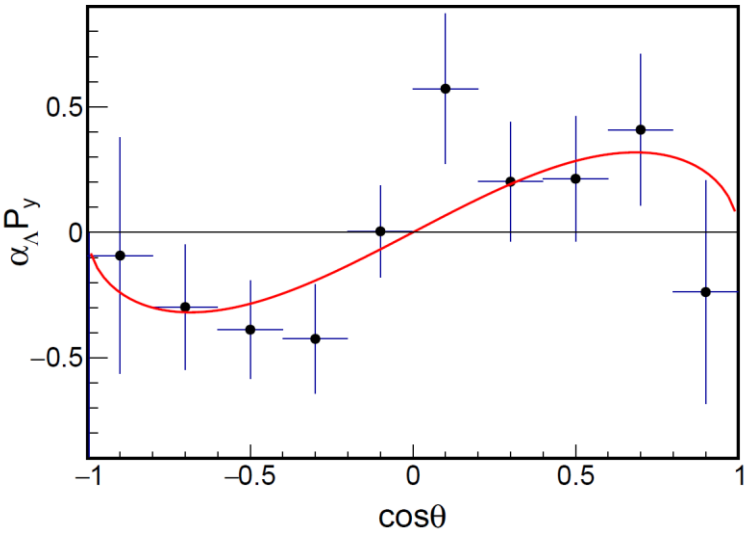
First complete measurement of Λ EMFF

- 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 $\Delta\Phi$





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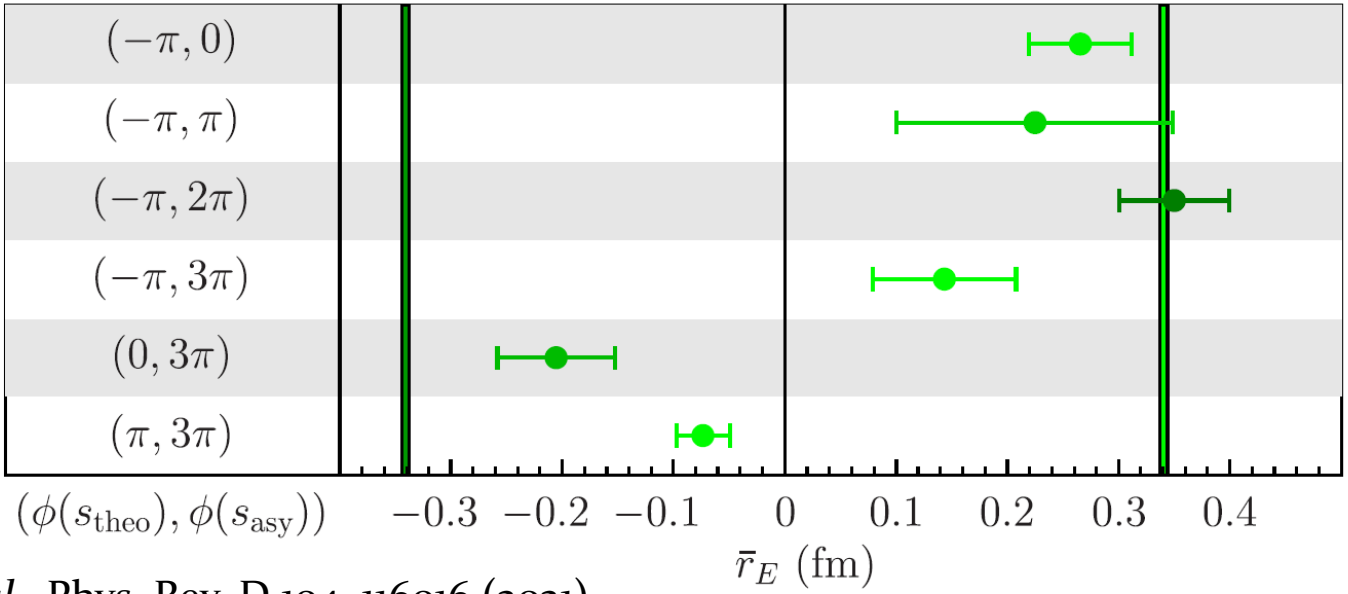
Theory interpretation

Mangoni, Pacetti & Tomasi-Gustafsson*:

- How many times does *sin*ΔΦ cross zero before approaching an integer multiple of π?
- Fit of different data from ** and *** to different scenarios

→ 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)

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Summary

- Hadron structure is a tool to understand the strong interaction.
- Time-like form factors most viable structure observable for hyperons.
- 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 !!!

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Thanks for your attention!

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