UPPSALA UNIVERSITET

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

Swedish Research Council

Knut and Alice Wallenberg Foundation

The Size of Strangeness
- New Perspectives on Hyperon Structure

EMMI Workshop
on *Meson and Hyperon Interactions with Nuclei*
September 14-16, 2022

Prof. Dr. Karin Schönning, Uppsala University

UPPSALA UNIVERSITET

Outline

- The Size of Protons and Neutrons
- The Size of Strangeness
  - Electromagnetic Form Factors
  - High q^2: Recent measurement by BESIII
  - Low q^2: Ongoing and future measurements at HADES and PANDA.

- Summary

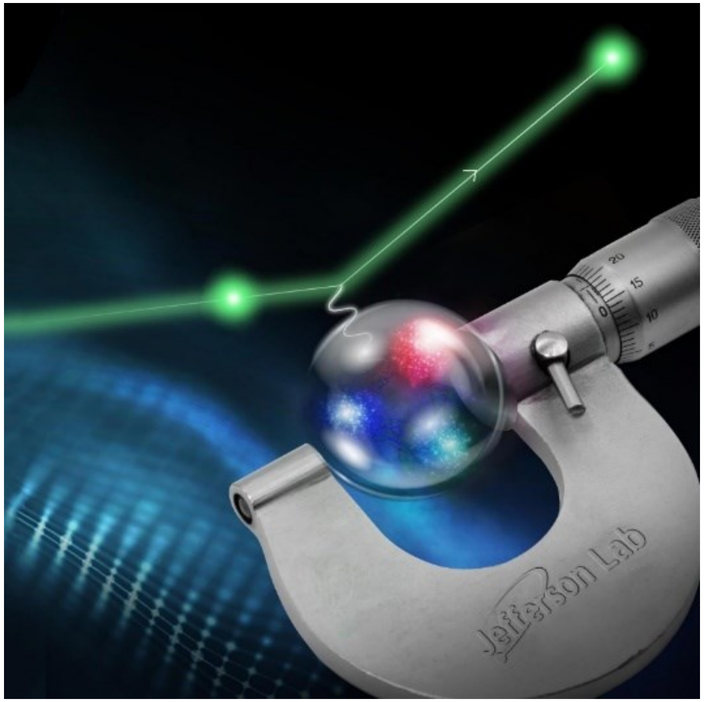
The Size of Protons

Strong interaction dynamics manifest in *e.g.*

- Charge distributions
- Charge radius

Proton radius:

Very rapidly progressing field!



Picture cred. Y-H Lin, U. Bonn

The Size of Protons

Ways to measure proton size:

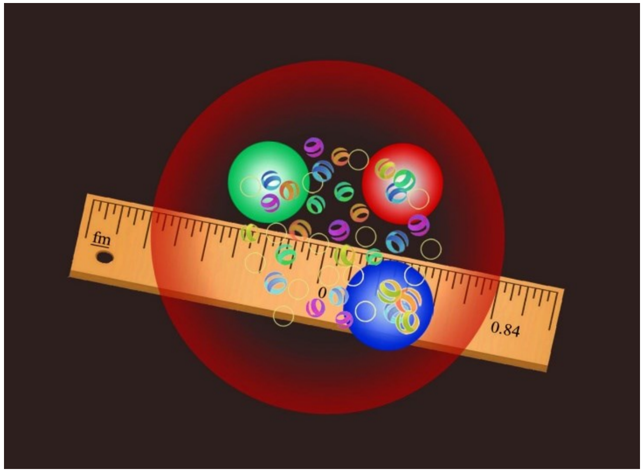
- Electron scattering
- Hydrogen spectroscopy

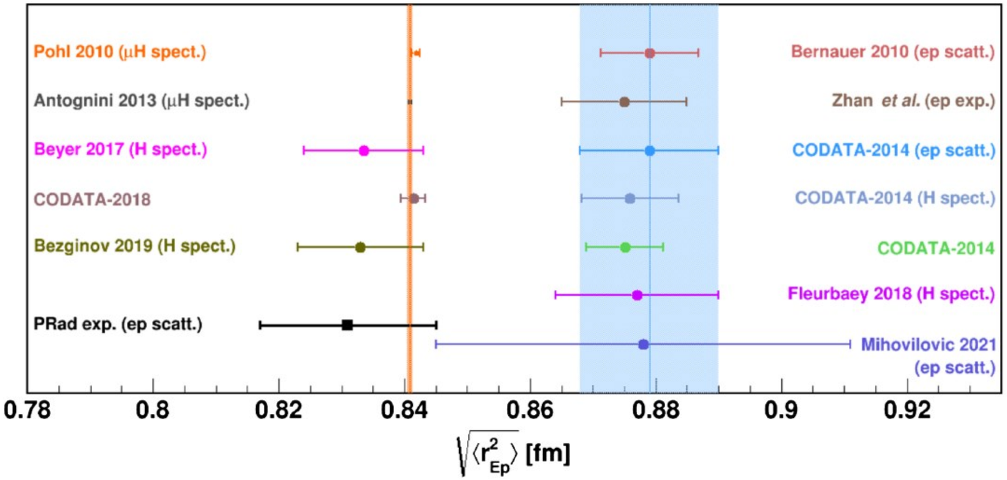
~0.88 fm

2010 – 2019:
Unexplained discrepancies
=*Proton radius puzzle**

- Muonic hydrogen spectroscopy

~0.84 fm





*Gao & Vanderhaegen Rev. Mod. Phys. 94, 015002 (2022)
Pictures from
- Y-H Lin, U. Bonn
- Rev. Mod. Phys. 94, 015002 (2022)

UPPSALA UNIVERSITET

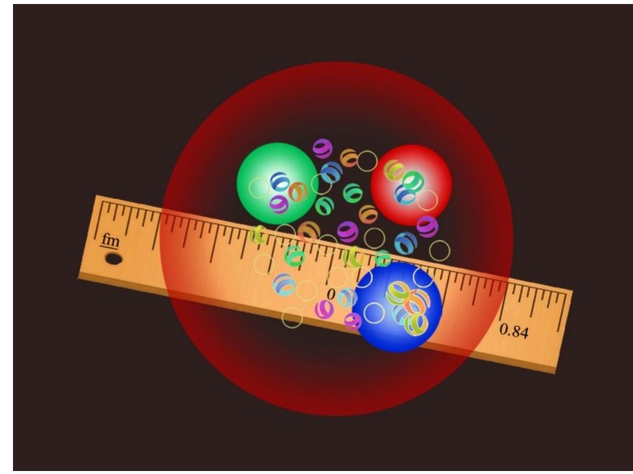
The Size of Protons

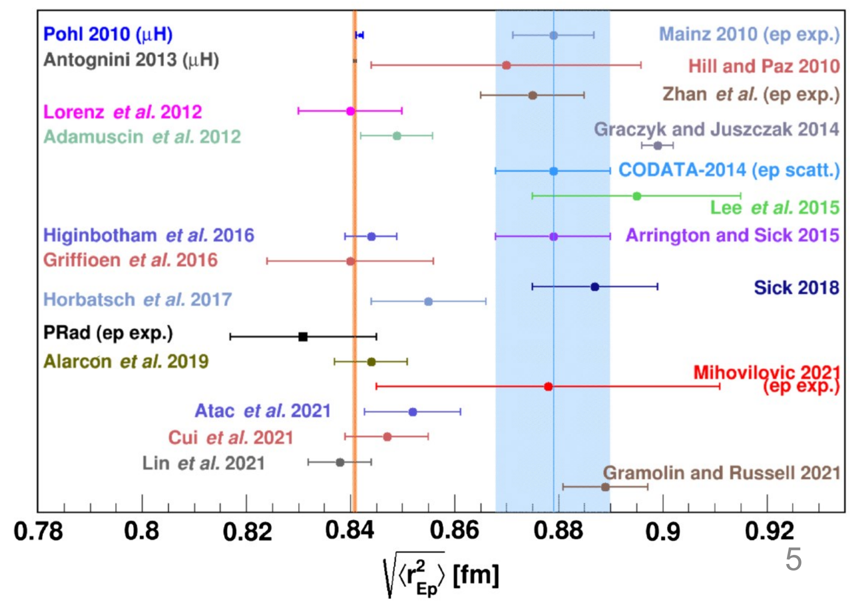
Ways to measure proton size:

- Electron scattering
- Hydrogen spectroscopy

Recently:
Dispersive calculations
Respecting analyticity and
unitarity give consistent results.*

- Muonic hydrogen spectroscopy





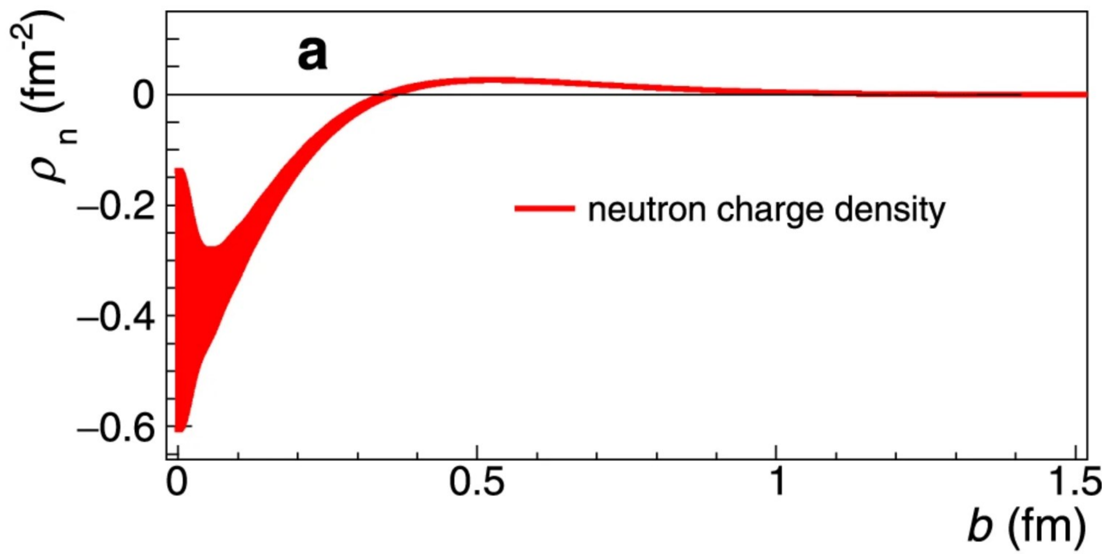
*Lin, Hammer & Meissner, Phys. Rev. Lett. 128, 052002 (2022).

Pictures from
- Y-H Lin, U. Bonn
- Gao & Vanderhaegen, Rev. Mod. Phys. 94, 015002 (2022)

The Size of Neutrons

Neutral and unstable (τ ~ 15 min) when "free":

- Atomic spectroscopy methods not suitable
- Electron scattering possible but difficult
  - Often based on low-energy scattering of bound neutrons
  - New calculation based on neutron EM form factor*.



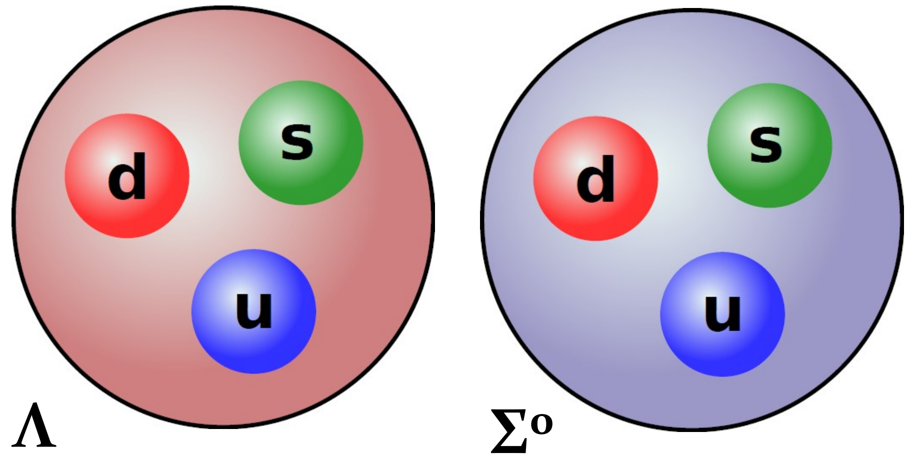
$\langle r_n^2 \rangle = -0.110 \pm 0.008$ fm²

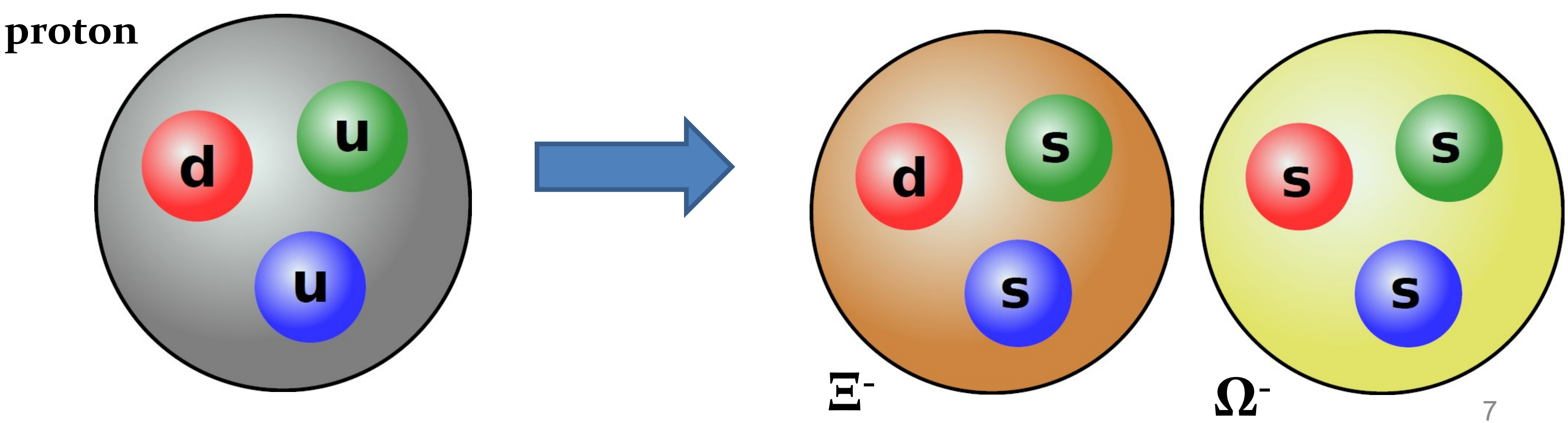
Negative = asymmetric quark distribution

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

The Size of Strangeness

What happens if we replace one of the light quarks in the proton with one - or many - heavier quark(s)?



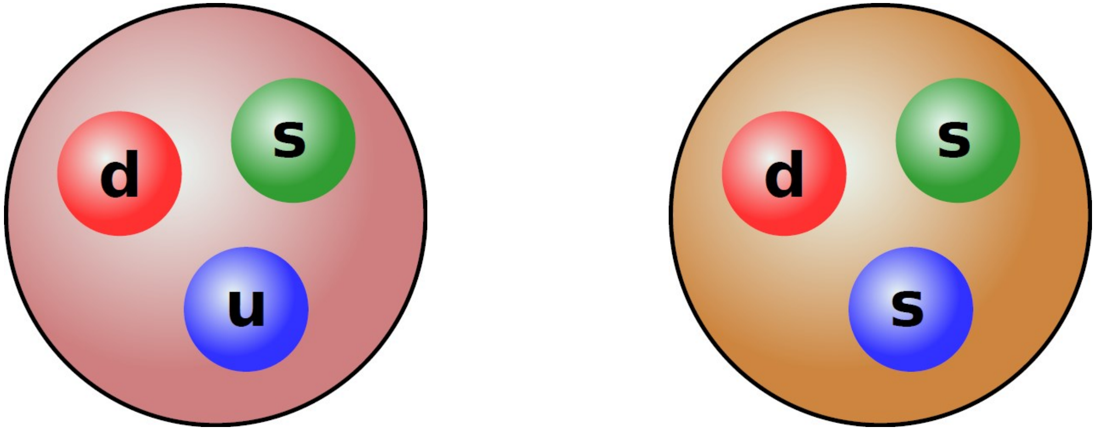


Picture cred. Lena Heijkenskjöld

The Size of Strangeness

- Hyperons are even less stable ($\tau \sim 10^{-10}$ s) than neutrons.
- Many of them are neutral or decay into neutrals.

Q: How can we study their size?



Picture cred. Lena Heijkenskjöld

The Size of Strangeness

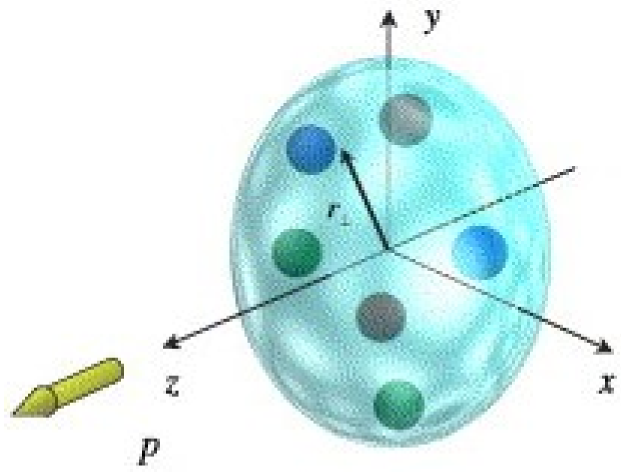
- Hyperons are even less stable ($\tau \sim 10^{-10}$ s) than neutrons.
- Many of them are neutral or decay into neutrals.

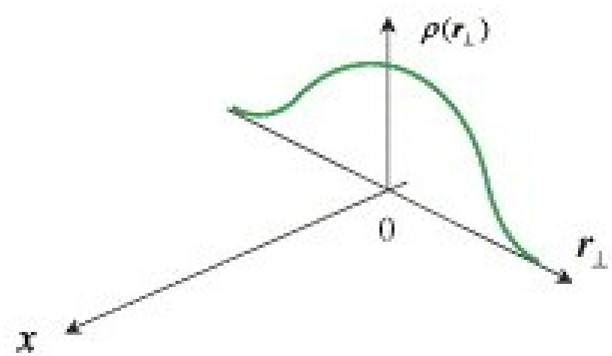
Q: How can we study their size?

A: By electromagnetic form factors!

Electromagnetic Form Factors

- Probed in hadron – photon interactions
- Functions of momentum transfer q^2
- Quantify the deviation from point-like behaviour.
- Predictions from
  - LatticeQCD
  - ChPT
  - Dyson-Schwinger
  - Vector Meson Dominance





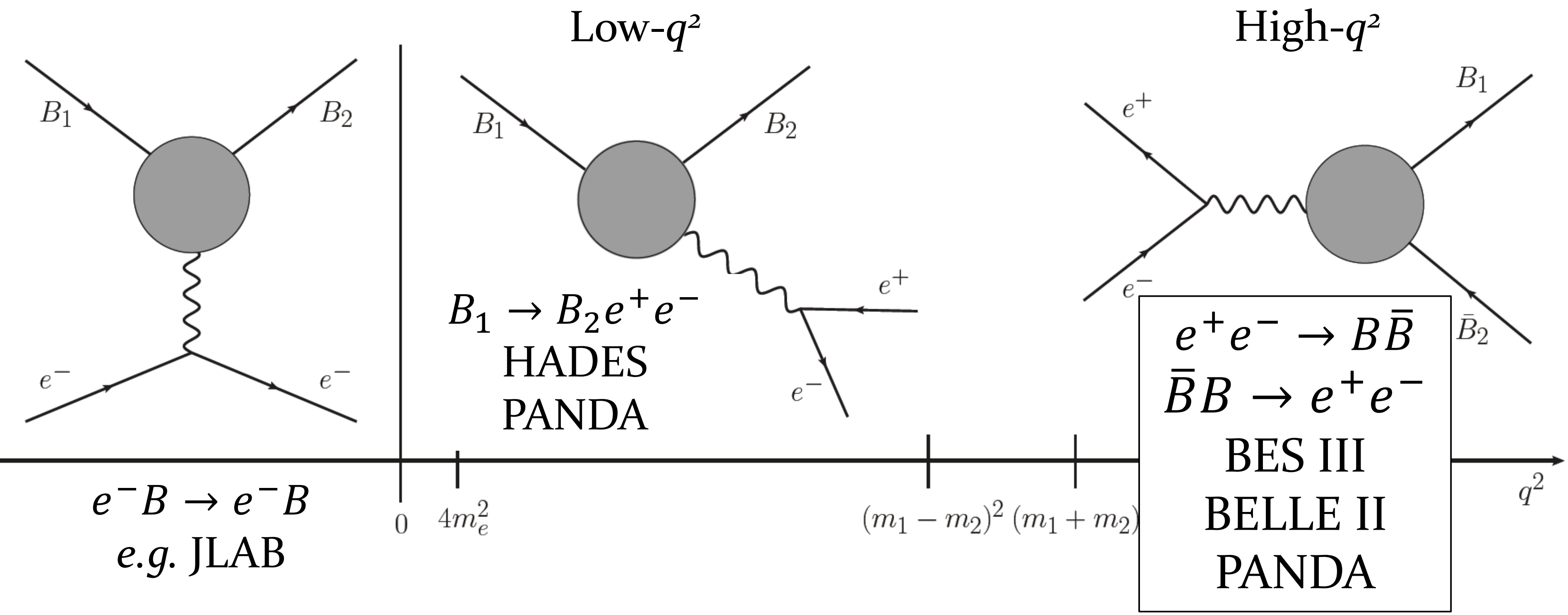
Space-like *vs.* time-like FF's

Space-like

$q^2 < 0$

Time-like

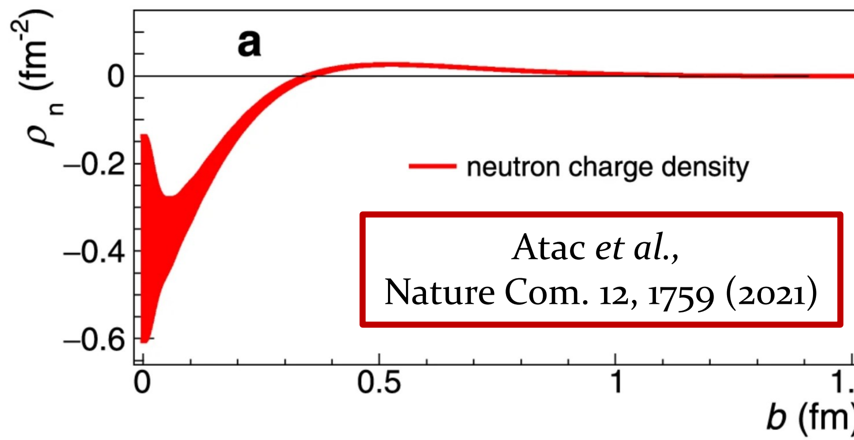
$q^2 > 0$



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 .
  - $G_E(q^2) = F_1(q^2) - \tau F_2(q^2)$
  - $G_M(q^2) = F_1(q^2) + F_2(q^2)$
  - $\tau = q^2/4M^2_B$

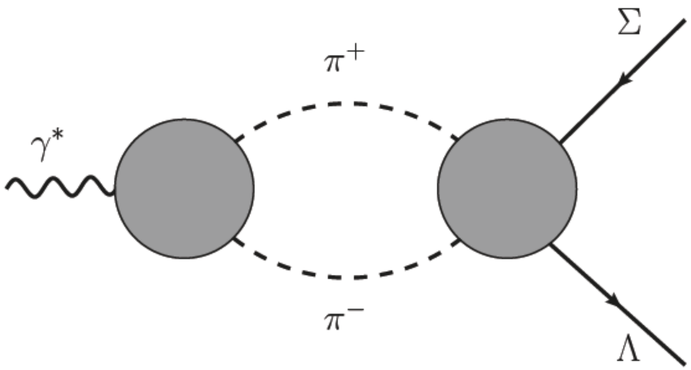


  - Charge radius: $< r_E^2 > = 6 \frac{dG_E(q^2)}{dq^2}|_{q^2=0}$
  - Magnetic radius: $< r_M^2 > = \frac{6}{G_M(0)} \frac{dG_M(q^2)}{dq^2}|_{q^2=0}$

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.* $\pi\pi$.

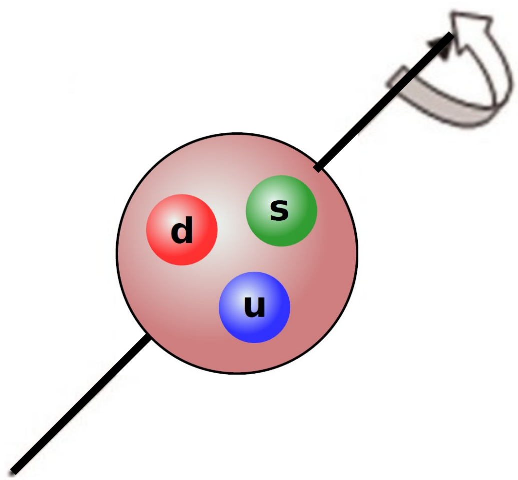
  → Polarises final state!

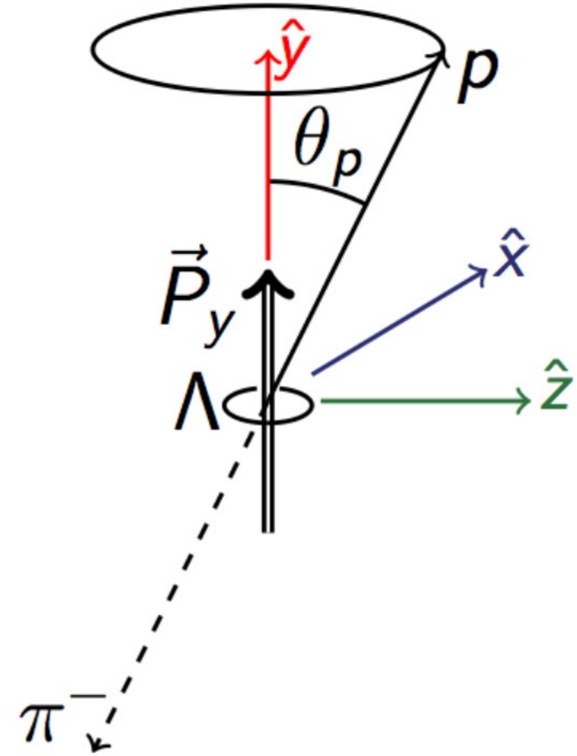


Picture credit:
Elisabetta Perotti, PhD Thesis,
UU (2020)

Advantage of hyperons

Polarisation experimentally accessible by the weak, parity violating decay:



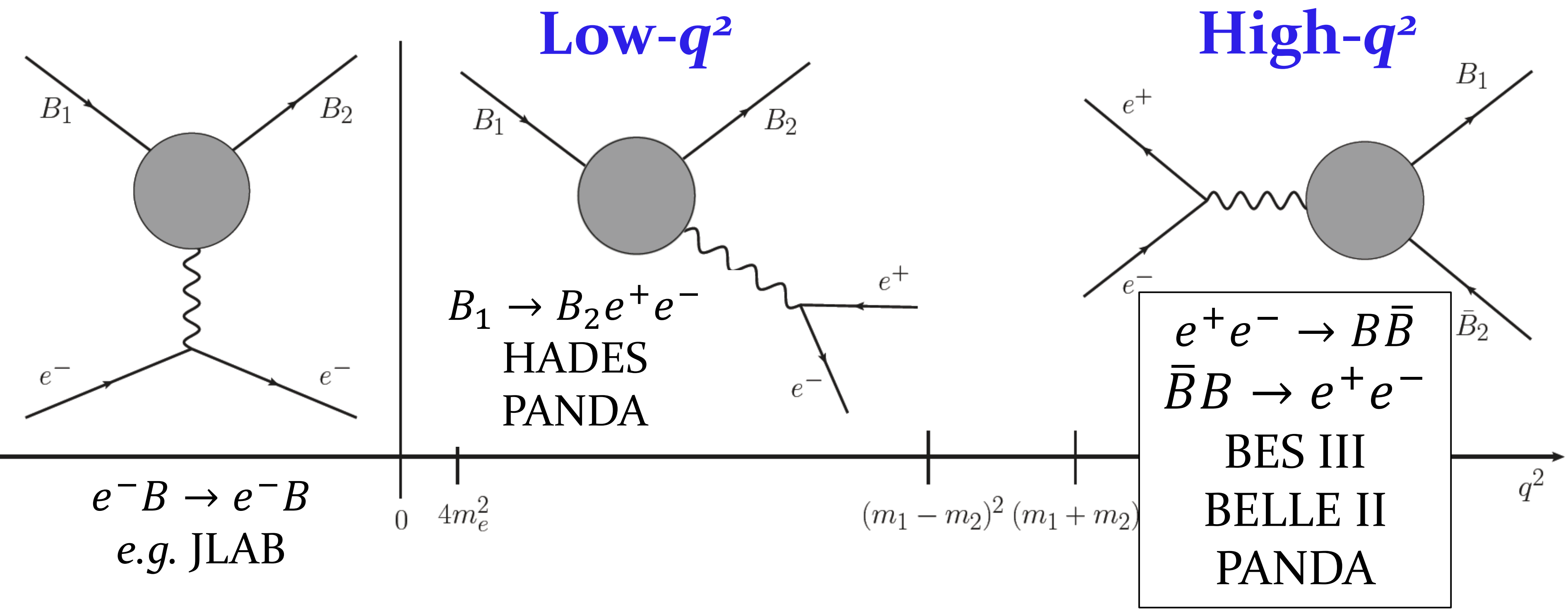


$$I(\cos\theta_p) = N(1+\alpha_\Lambda P_\Lambda \cos\theta_p)$$

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

Space-like
$q^2 < 0$

Time-like
$q^2 > 0$

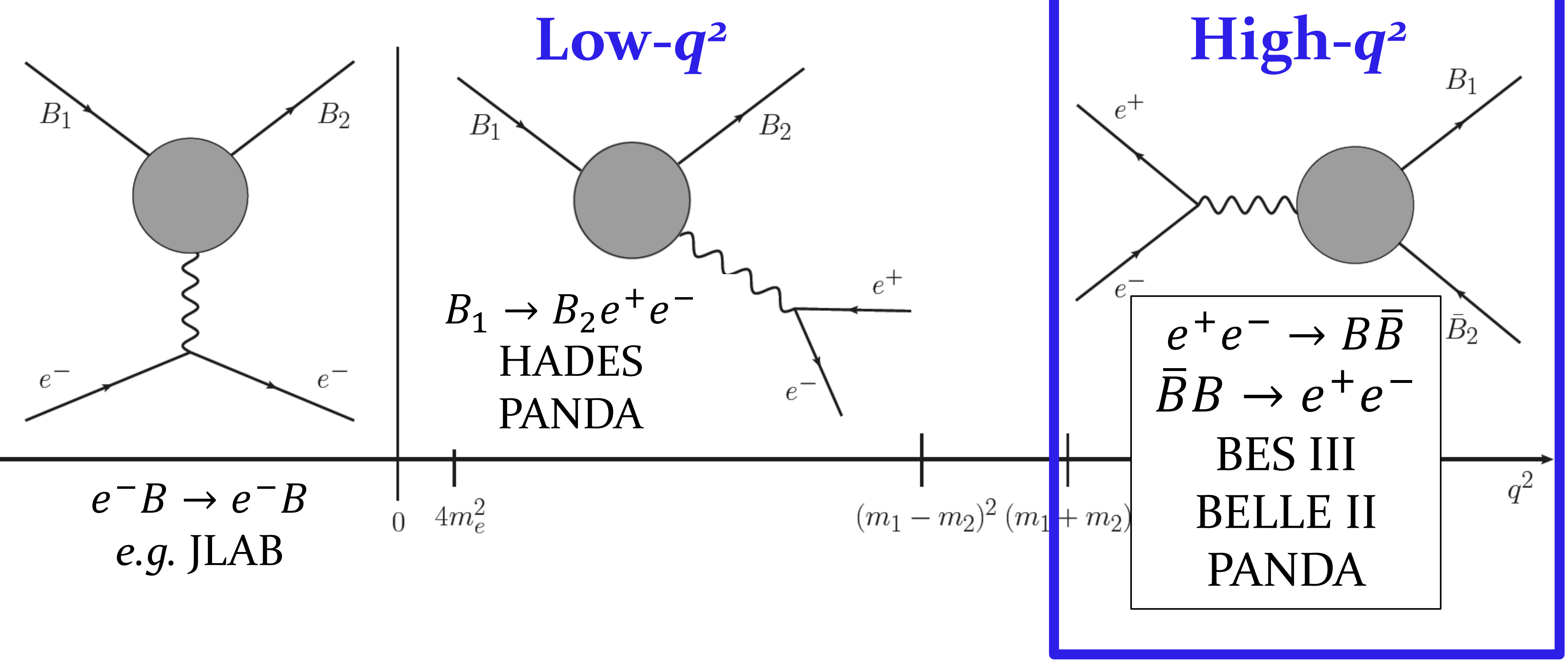


Cred. E. Perotti, PhD thesis (UU 2020)

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

Space-like $q^2 < 0$

Time-like $q^2 > 0$



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

Nucleon *versus* hyperon EMFFs

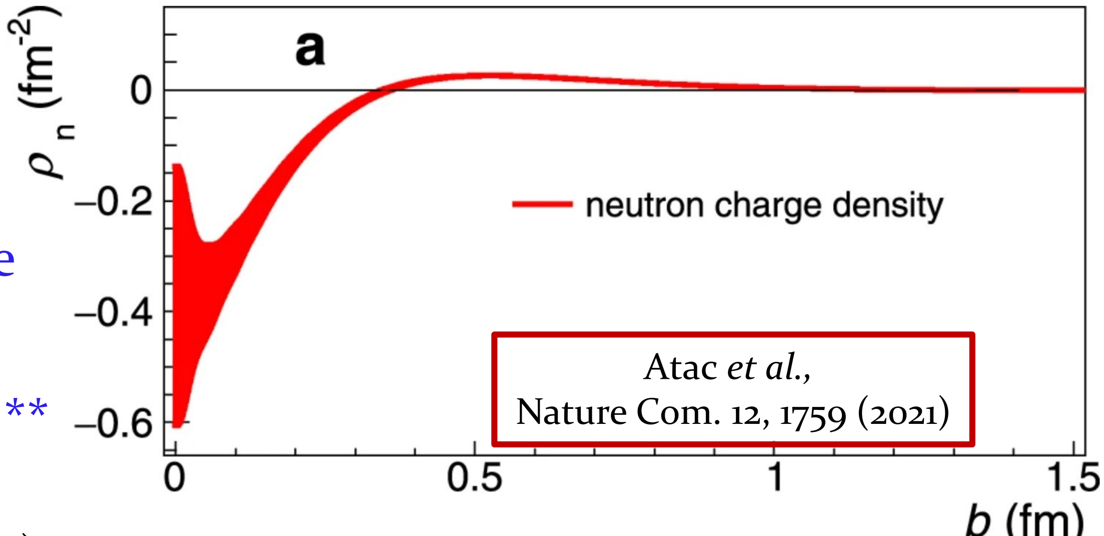
Asymptotic behaviour as $|q^2| \to \infty$: SL ~TL

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

  SL = TL ↔ $\Delta\Phi(q^2) \to 0$ 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 $Im(R(q^2)) = Im(\frac{G_E(q^2)}{G_M(q^2)})$ **



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

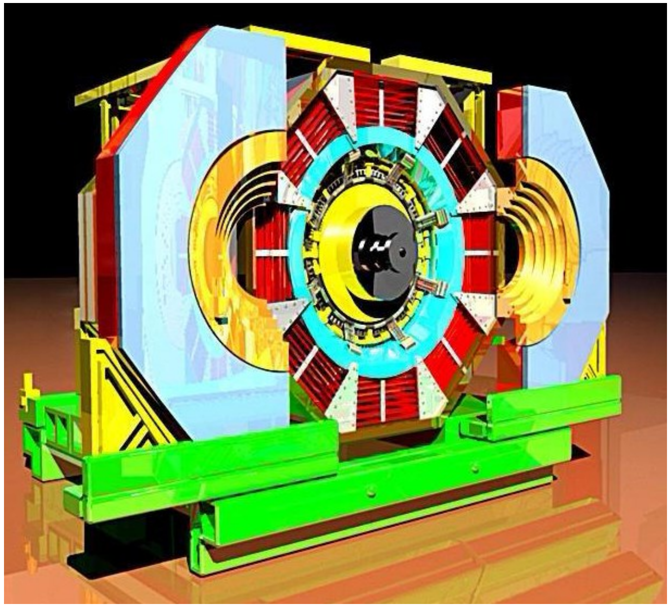
**Mangoni *et al.*, Phys. Rev. D 104, 116016 (2021)

UPPSALA UNIVERSITET

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

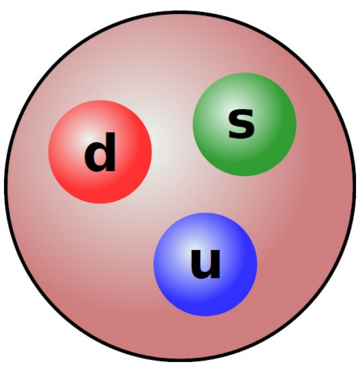
BESIII



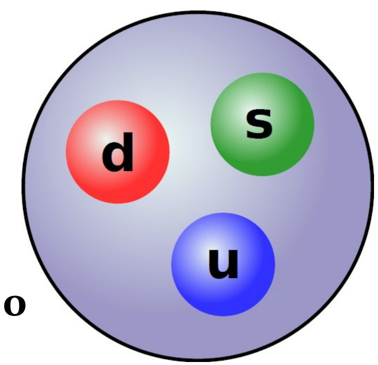
Single-strange hyperons

Diquark correlations in baryons?

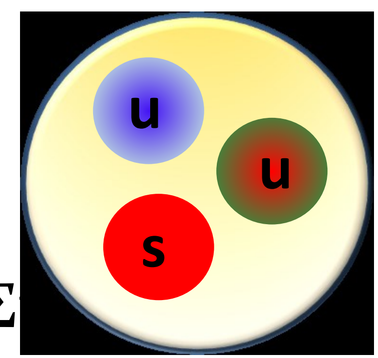
- The Σ^0 has isospin 1 whereas Λ has isospin 0
  - Strange quark has no isospin → difference is in the *ud* diquark.
  - Different isospin structure → different spin structure.
  - Difference in cross section and form factors expected.*
- In Σ^+, the *uu* should have same spin structure as the *ud* in Λ.
  - Similar cross sections expected.*



Λ



Σ^0



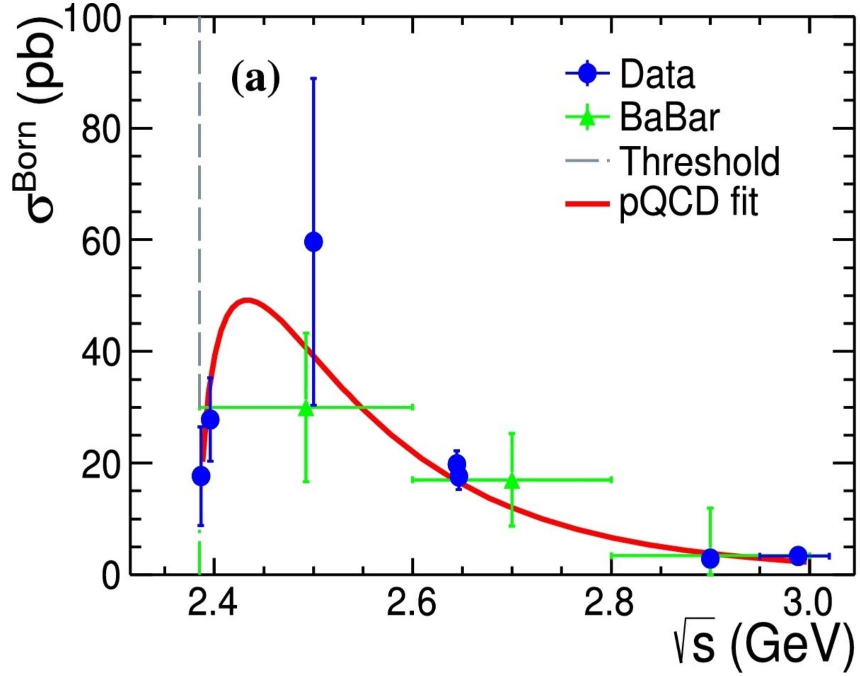
Σ

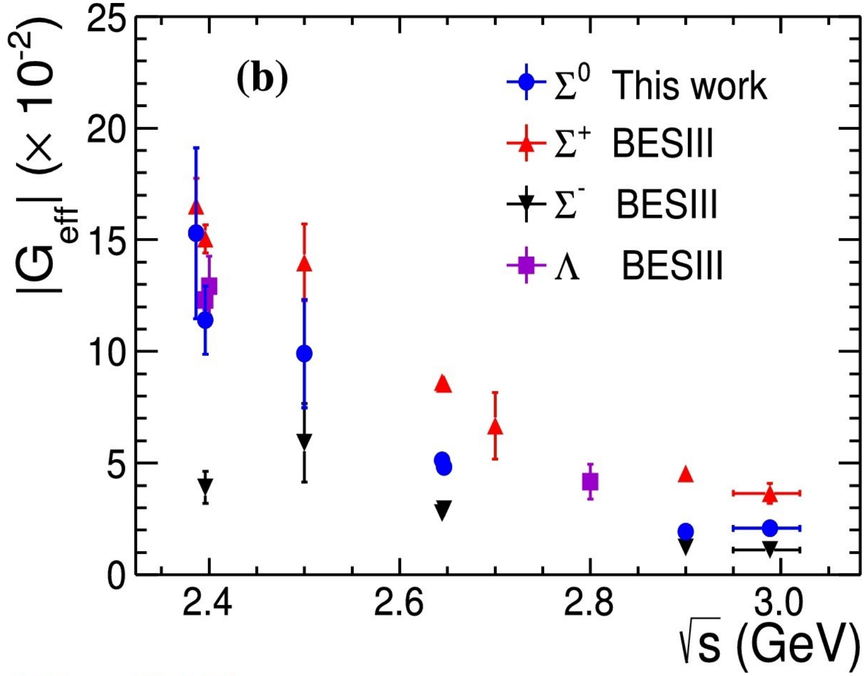
* PLB 739 (2014) 90.

UPPSALA UNIVERSITET

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% .





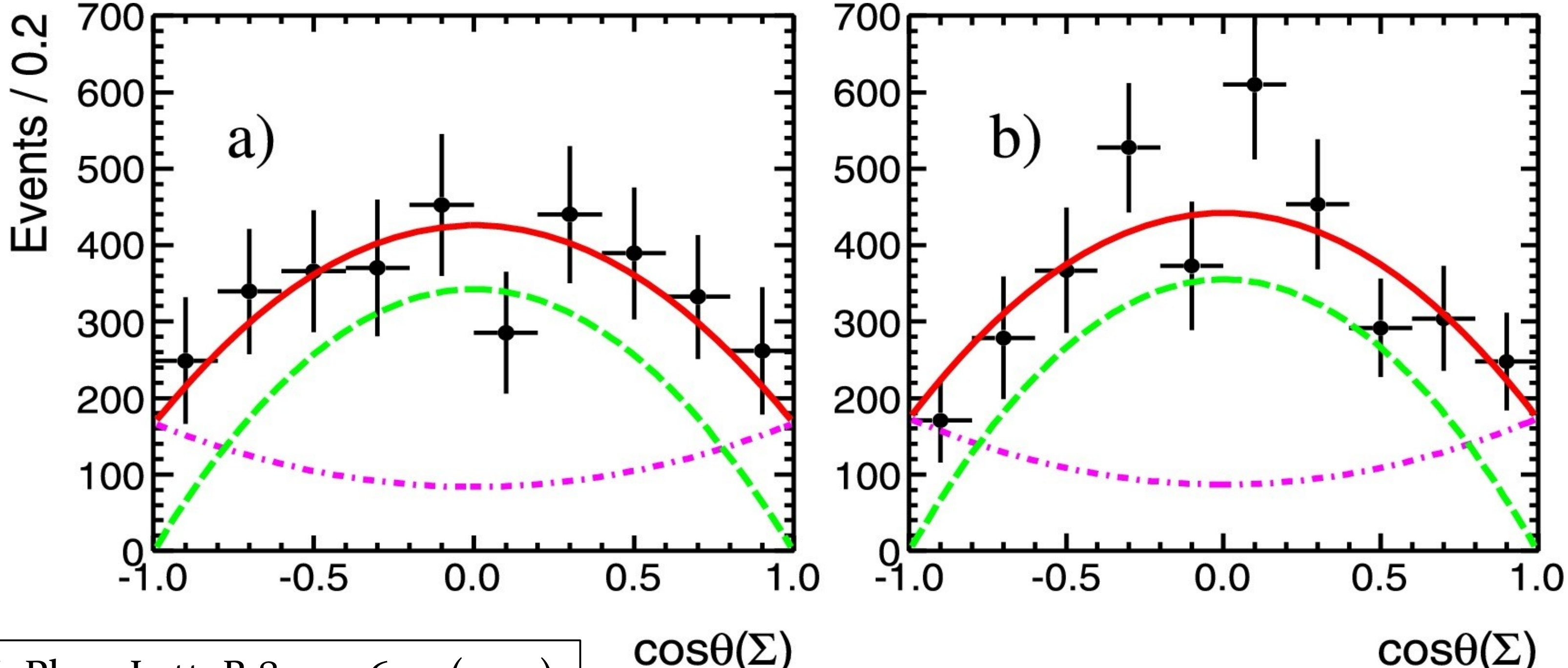
* BESIII: Phys. Lett. B 831, 137187 (2022)
** BESIII: Phys. Lett. B 814, 136110 (2021)
*** BESIII: Phys. Rev. D 97, 032013 (2018)

BESIII

Single-strange hyperons

Σ^+ Form Factor Ratio:

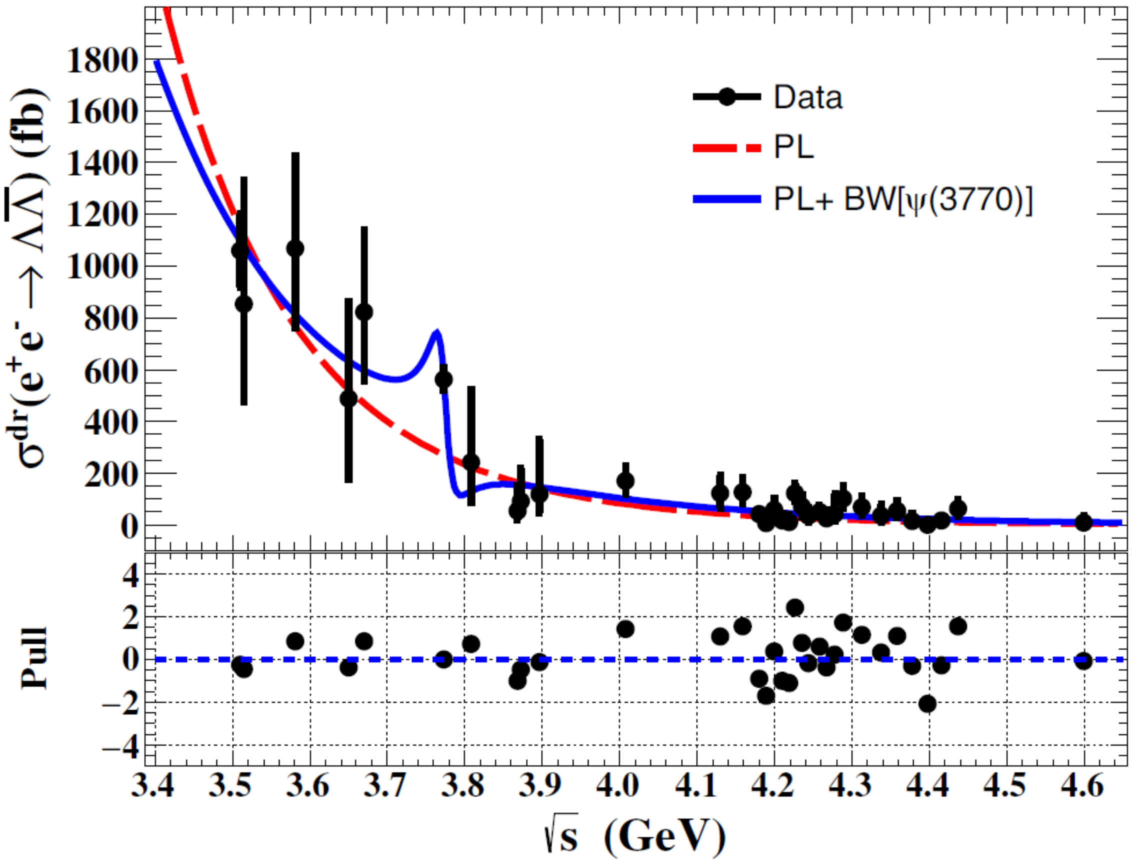
$R = \frac{|G_E(q^2)|}{|G_M(q^2)|}$ measured at 2.396 GeV to be 1.83 ± 0.26



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

Production of Λ at high q^2

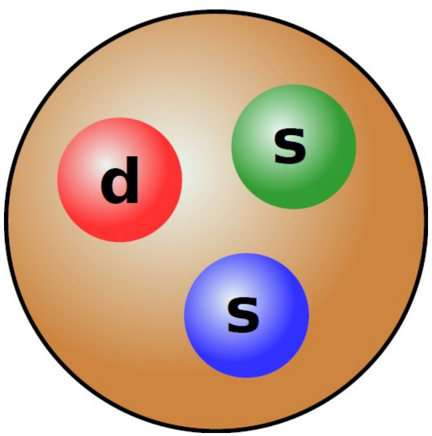
- $\Lambda\bar{\Lambda}$ production near vector charmonia*,**
- $BR(\Psi \rightarrow \Lambda\bar{\Lambda}) > 10$ times larger than assumed in previous studies by CLEO-c***.

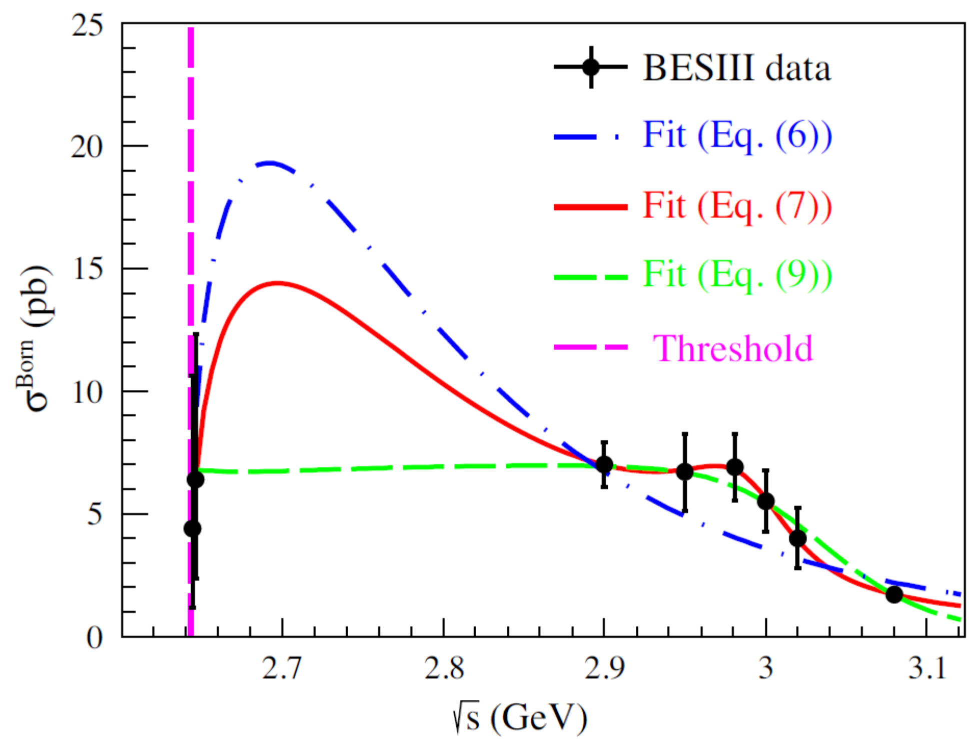


* BESIII: Phys. Rev. D 104, L091104 (2021)
** BESIII: Phys. Rev. D 105, L011101 (2022)
*** CLEO-c: Phys. Rev. D 96, 092004 (2017); Phys. Lett. B 739, 90 (2014)

Double-strange hyperons

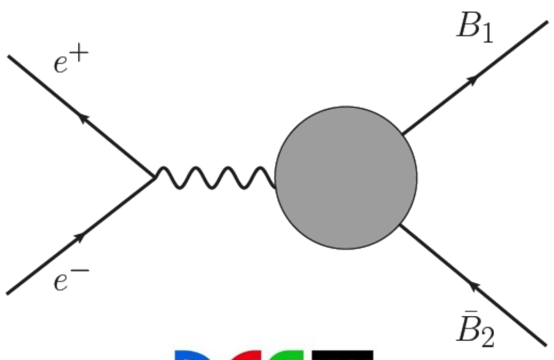
- $e^+e^- \to \Xi^-\bar{\Xi}^+$ studied for the first time.
- Possible resonance around 3 GeV.

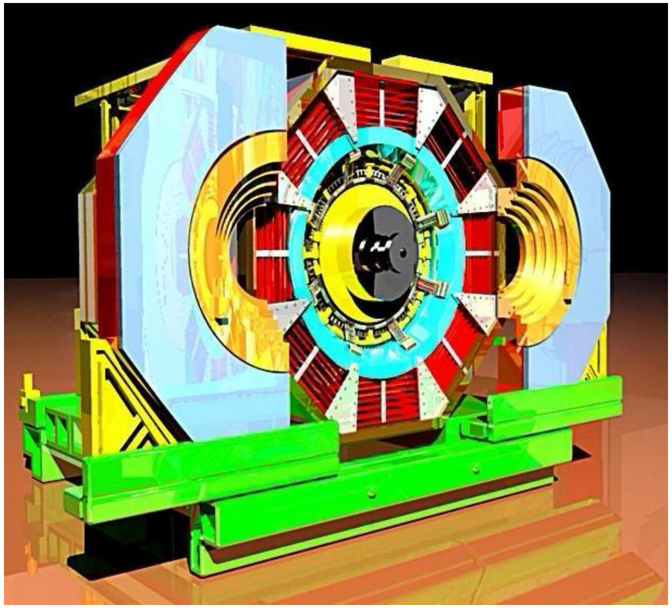




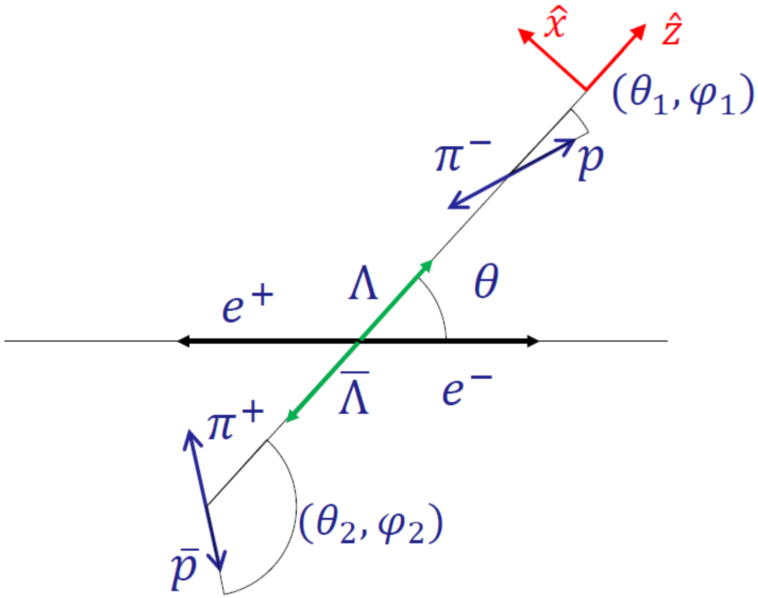
BESIII: Phys. Rev. D 103, 012005 (2021)

Spin Analysis





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



Formalism for $e^+e^- \rightarrow \bar{Y}Y, Y \rightarrow BM + c.c.$

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**

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

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

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

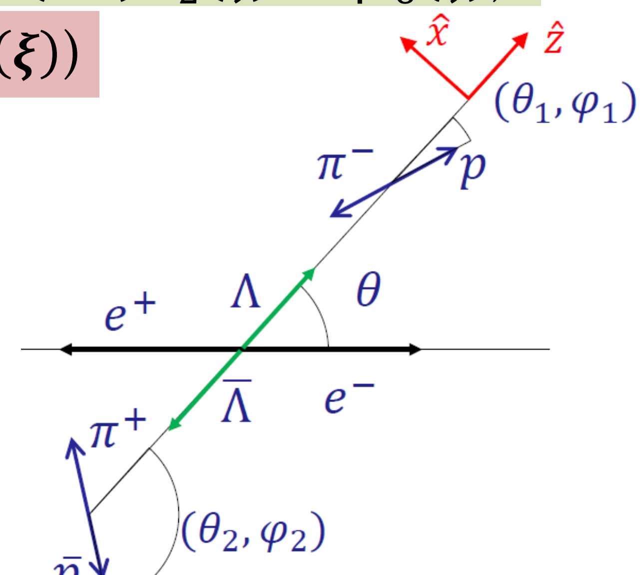
$$\mathcal{F}_2(\xi) = \sin\theta \cos\theta \left(\sin\theta_1 \cos\theta_2 \cos\phi_1 + \cos\theta_1 \sin\theta_2 \cos\phi_2\right)$$

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

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

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

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



*Fäldt & Kupsc, PLB 772 (2017) 16.

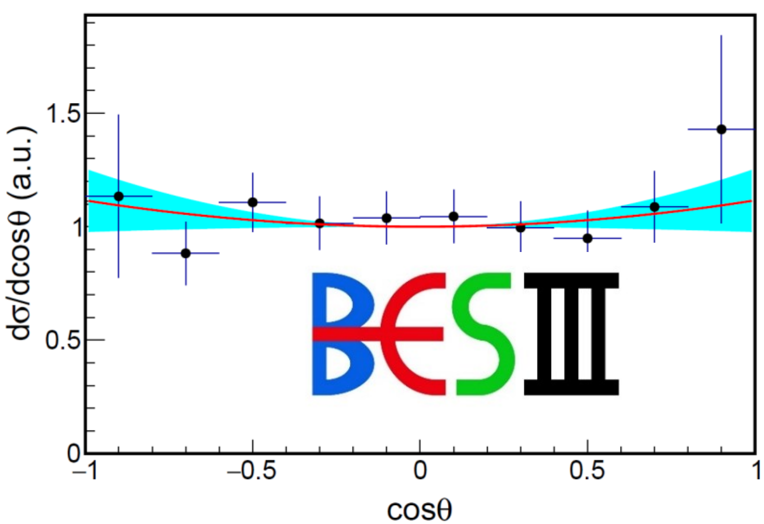
UPPSALA
UNIVERSITET

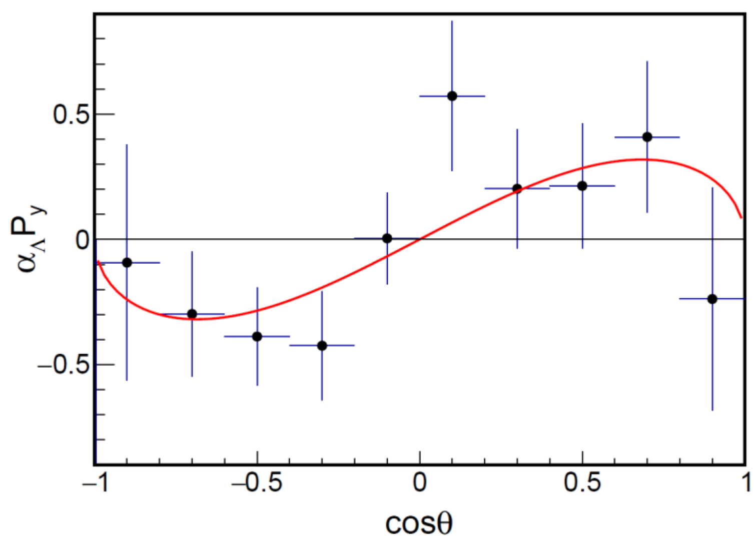
First complete measurement of Λ EMFF

- 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 $\Delta\Phi$

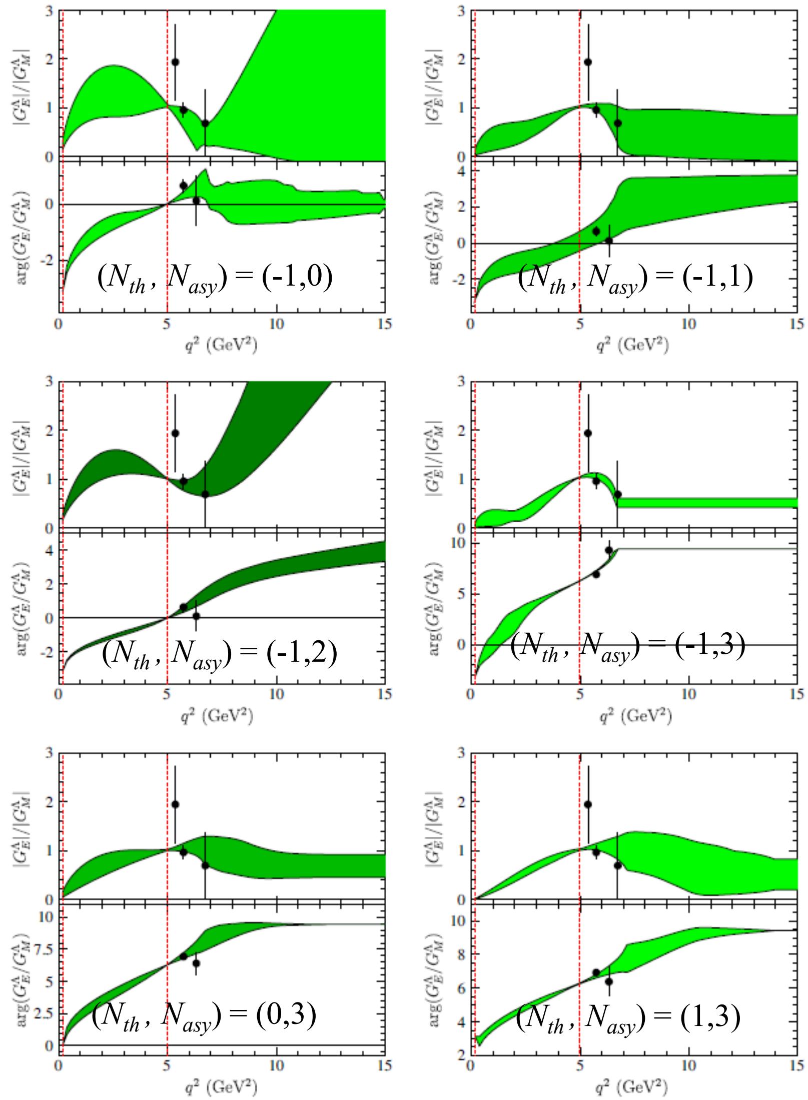




The Λ Charge Radius

Mangoni, Pacetti & Gustafsson*:

- Recall $< r_E^2 > = 6 \frac{dG_E(q^2)}{dq^2}|_{q^2=0}$
  - Neutrals: $\frac{dR(q^2)}{dq^2}\Big]_{q^2=0} = \frac{1}{\mu}\frac{<r_E>^2}{6}$
- Extract $\langle r_\Lambda^2 \rangle$ from
  - $N_{th} = \frac{1}{\pi}\arg(\frac{G_E^\Lambda(q_{th}^2)}{G_M^\Lambda(q_{th}^2)})$ and
  - $N_{asy} = \frac{1}{\pi}\arg(\frac{G_E^\Lambda(q_{asy}^2)}{G_M^\Lambda(q_{asy}^2)})$



Picture credit and results:
Mangoni, Pacetti & Tomasi Gustafsson, Phys. Rev. D 104, 116016 (2021)
Data:
BESIII: Phys. Rev. Lett. 123, 122003 (2019)
BaBar: Phys. Rev. D 76, 092006 (2007)

UPPSALA UNIVERSITET

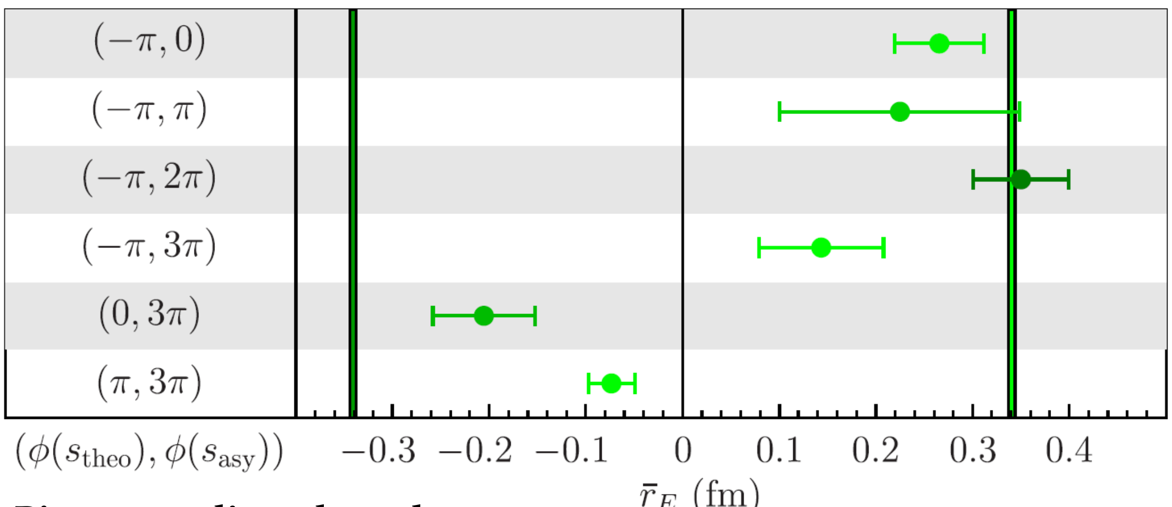
The Λ Charge Radius

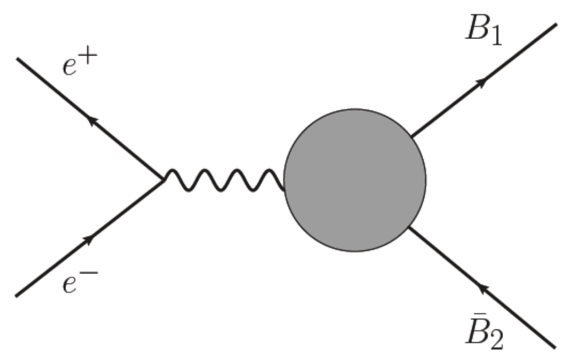
Mangoni, Pacetti & Tomasi-Gustafsson*:

- Fit of different data from ** and *** to different scenarios

→ pinpointing the radius requires data at more energies

”Snapshot → Movie”





Picture credit and results:

Mangoni, Pacetti & Tomasi Gustafsson, Phys. Rev. D 104, 116016 (2021)

Data:

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

BaBar: Phys. Rev. D 76, 092006 (2007)

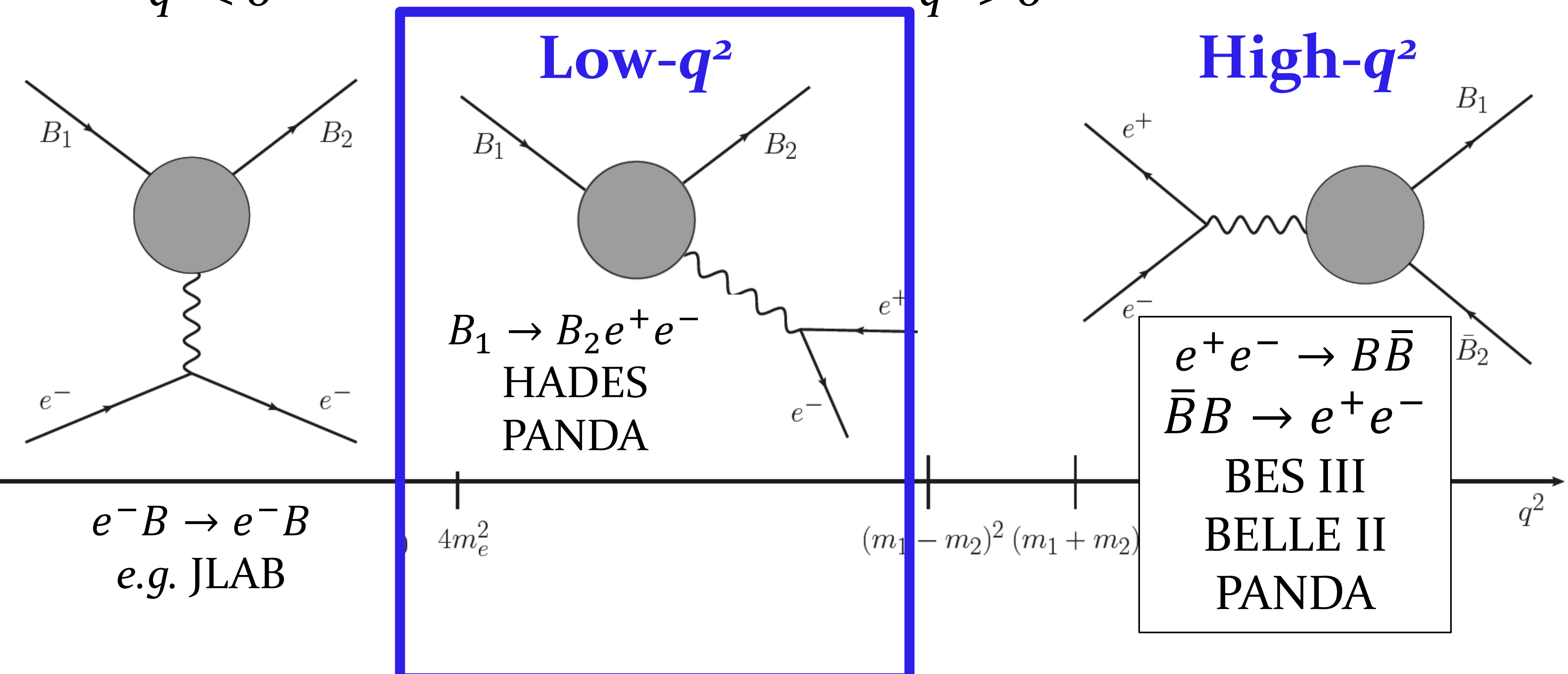
Space-like *vs.* time-like FF's

Space-like

$q^2 < 0$

Time-like

$q^2 > 0$

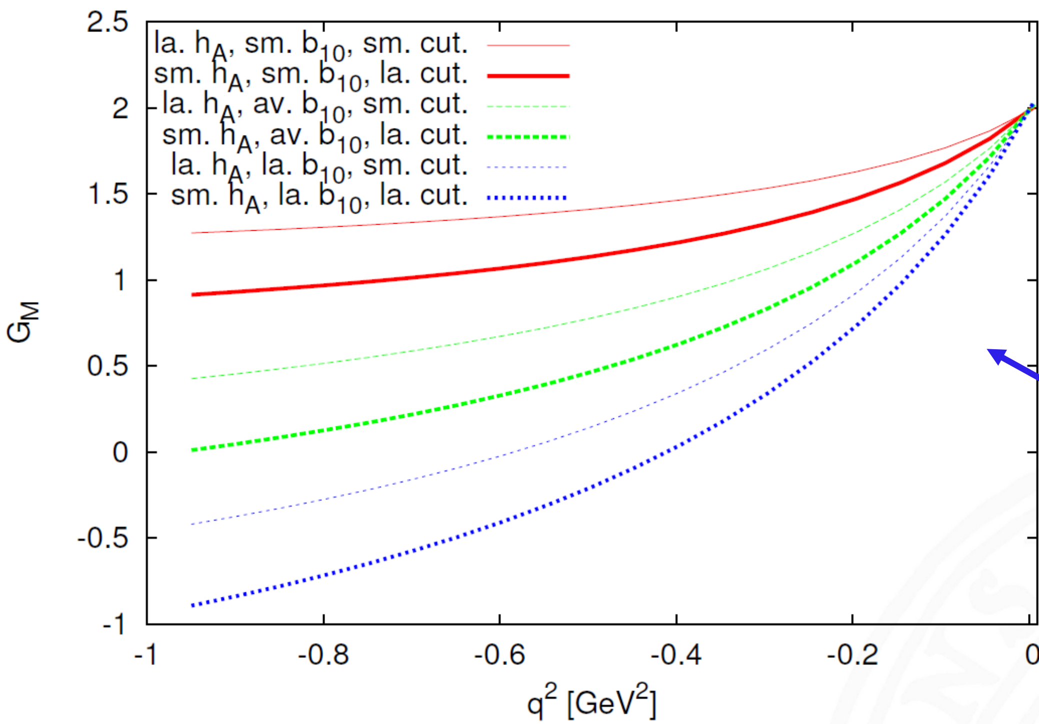


Cred. E. Perotti, PhD thesis (UU 2020)

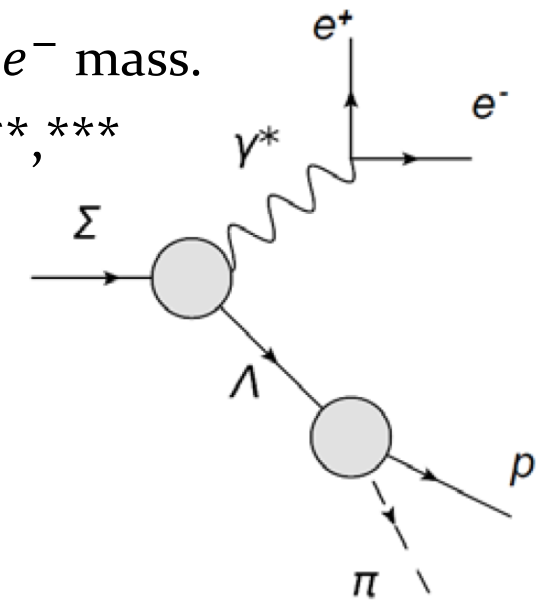
UPPSALA UNIVERSITET

Low-q^2 : Hyperon transition FF

- Can be measured in Dalitz decay with HADES and PANDA.
- Dispersive + ChPT framework* developed for $\Sigma^0\Lambda$
  $\rightarrow < r_M^2 >$ from the G_M dependence on the e^+e^- mass.
- Framework extended to other J^P hyperons **,***

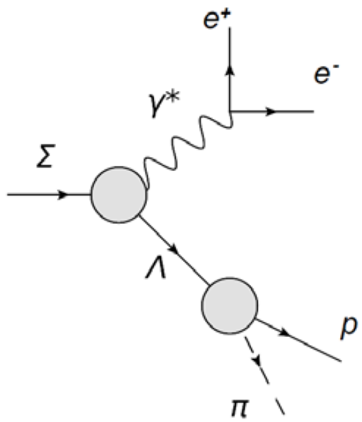


<

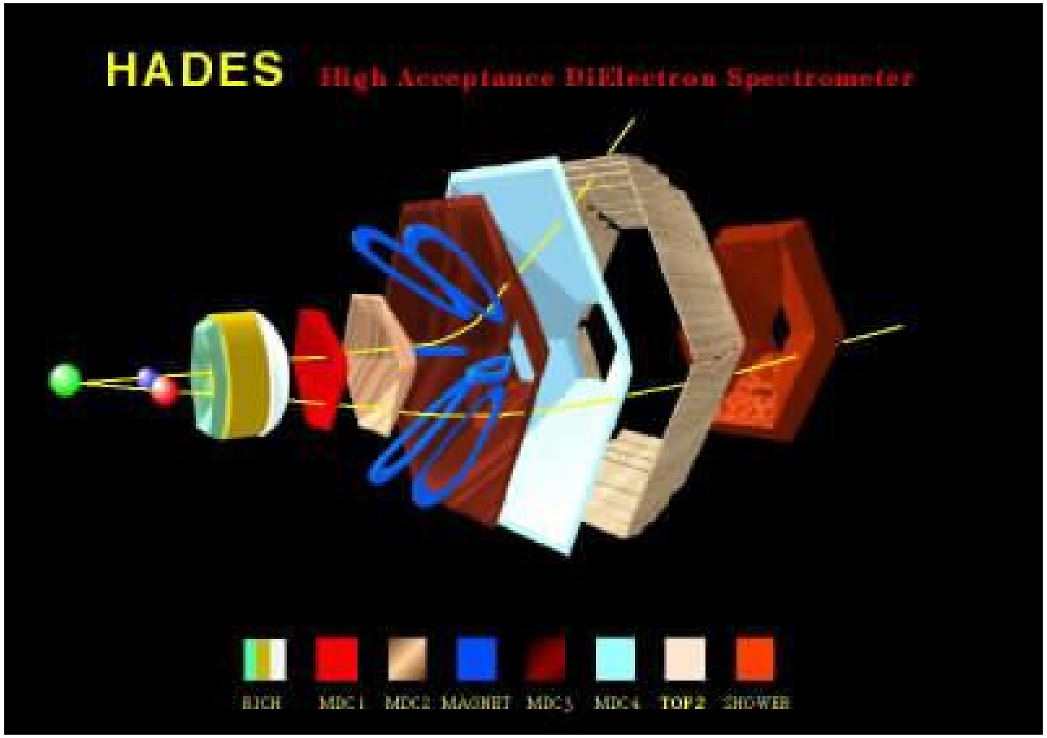


Leupold *et al.*:
* Eur. Phys. J A 53, 117 (2017)
** Phys. Rev. C 101, 015206 (2020)
*** Eur. Phys. J A 57, 183 (2021)

Low-q^2 Structure with HADES



* HADES + PANDA: Eur. Phys. J A **57**, 138 (2021)
** Rafal Lalik, see dedicated EMMI presentation
***Jenny Regina, PhD Thesis Uppsala U and EMMI poster (2022)
**** Jana Rieger, FAIRNESS talk (2022)



- Hyperons from *pp* collisions[*,**].
- Part of FAIR Phase 0
  → Forward trackers from PANDA
- Excellent for e^+e^- tagging.
- Hyperon reconstruction refined[***,****].
- First beam time February 2022.

UPPSALA UNIVERSITET

Low-q^2 Structure with PANDA

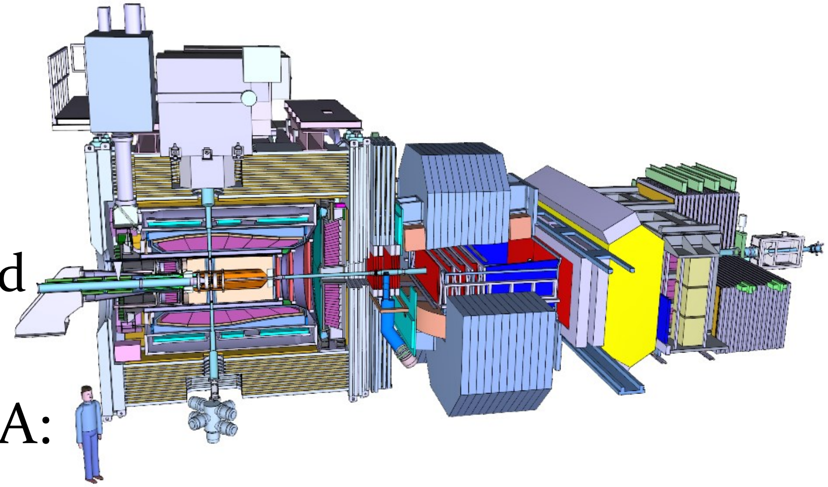
- Large expected Σ^0hyperon yields in $\bar{p}p$ annihilations!
- Beam momenta up to 15 GeV/c

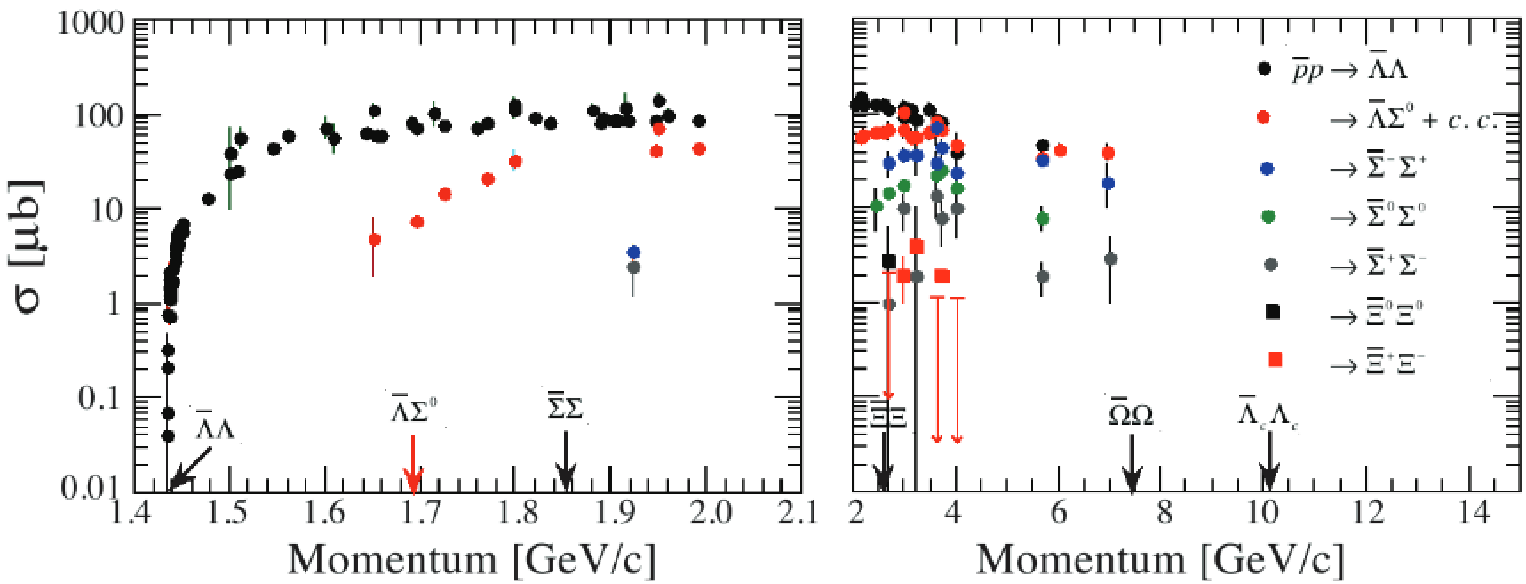
$\rightarrow e^+e^-$ from antihyperon decay boosted

$\rightarrow$ better chance to be detected?

- Hyperon reconstruction in PANDA:

Poster by A. Akram.





UPPSALA UNIVERSITET

Summary

- The strong interaction manifest in the structure and size of hadrons.
- Hyperon polarisation accessible by their self-analysing decays
  - New angle to structure and size!
- Recent progress from BESIII.
- Pioneering measurements possible at experiments world-wide.

UPPSALA UNIVERSITET

Thanks for your attention!

Knut and Alice Wallenberg Foundation

Swedish Research Council

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