Hyperon structure in e^+e^- annihilations

- past, present and future

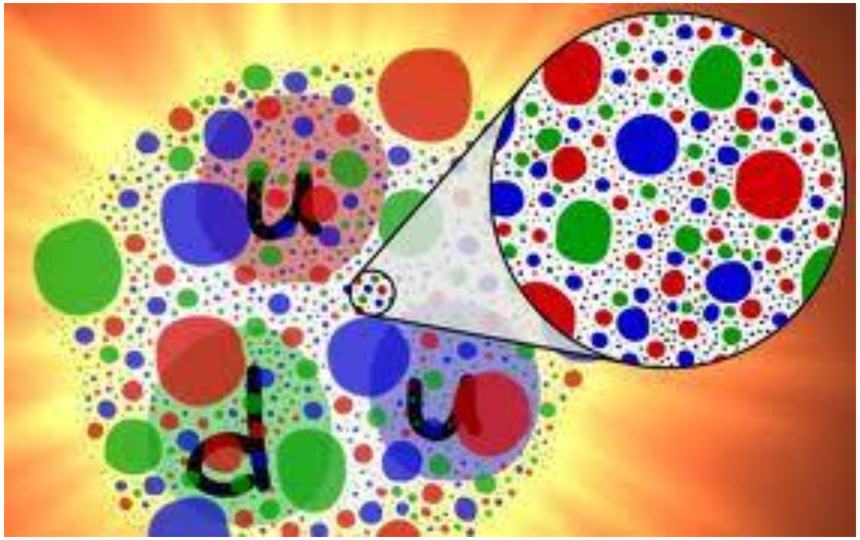
EMMI open symposium on hyperon form factors

GSI, October 22th 2018

Karin Schönning, Uppsala University

Outline

- The mysterious nucleon
- The hyperon – a charming stranger
- Electromagnetic Form Factors (EMFFs)
- EMFFs in e^+e^- annihilations
- Measurement of hyperon EMFFs
  - Past
  - Present
  - Future



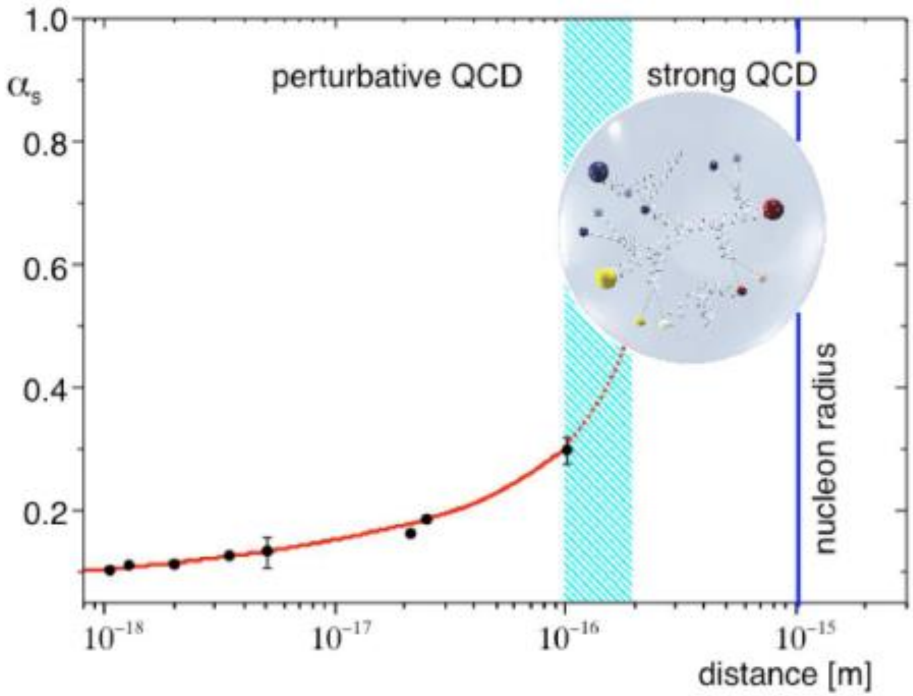
Prologue

Missing in the Standard Model of particle physics:

A coherent understanding of the strong interaction.

- Short distances / high energies: pQCD rigorously and successfully tested.

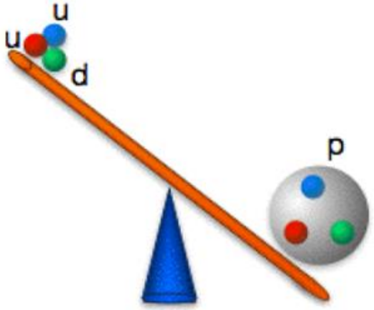
- Charm scale and below: pQCD fails, no analytical solution possible.

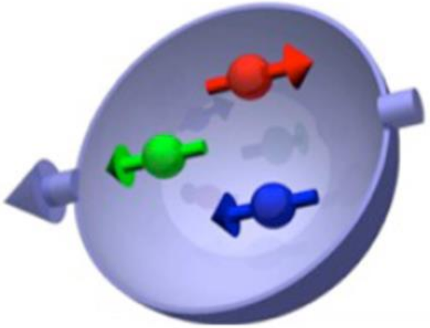


The mysterious nucleon

Strong interaction puzzle manifest in the **nucleon:**

- Proton discovered a century ago.
- Still, we don’t understand
  - Its abundance
  - Its mass
  - Its spin
  - It radius
  - Its inner structure





The mysterious nucleon

Abundance: matter-antimatter / nucleon-antinucleon asymmetry of the Universe.

Equal amounts in Big Bang (?)
→ Where did the anti-nucleons go?

Baryogenesis*: possible if
- Baryon number violation
- CP violation
- Processes outside thermal equilibrium.

Picture from Virginia Tech

*A. D. Sakharov, JETP 5 (1967) 24-27

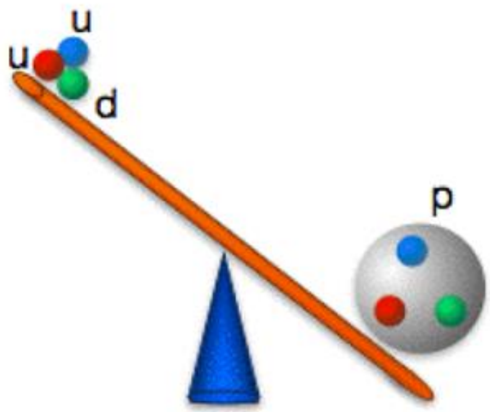
The mysterious nucleon

Mass:

- Summing quark masses: 1% of total proton mass.

→ ~99% of the visible mass in the Universe is dynamically generated by the strong interaction!

But how?

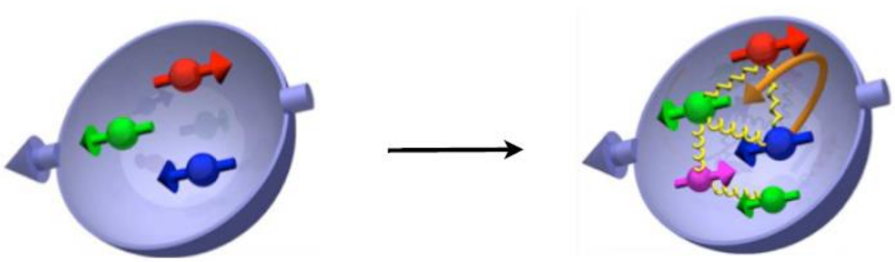


The mysterious nucleon

Spin:

- Valence quark spin only case ~1/2 of the total nucleon spin*.

- Proposed solution to *spin crisis:*
  - Sea quarks?
  - Gluons?
  - Relative angular momentum?



*C. A. Aidala *et al.*, RMP 85 (2013) 655-691.

The mysterious nucleon

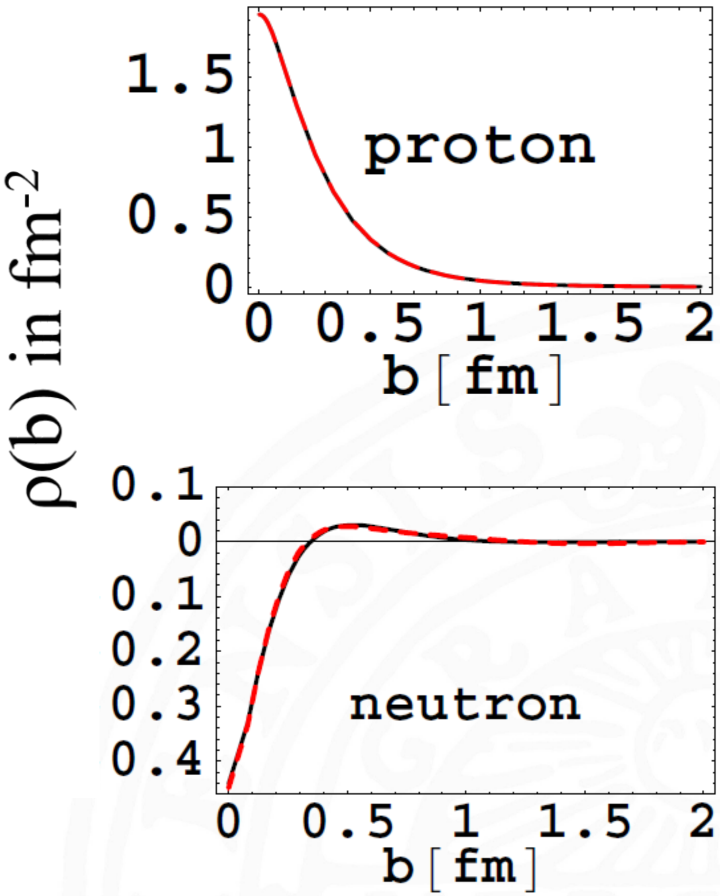
Radius: measured in

- Electron-nucleon scattering
- Electronic hydrogen spectrum
- Muonic hydrogen spectrum.

Results disagree.*

Inner structure:

- Neutron charge distribution intriguing.**



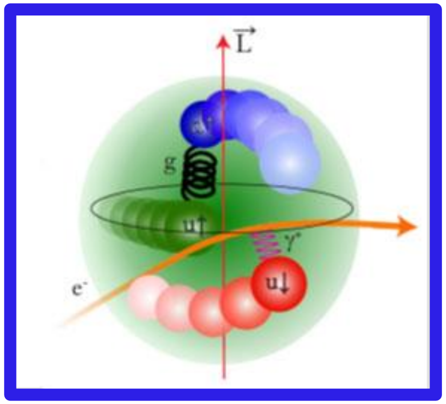
*R. Pohl, *Nature* 466 (2010)7303, 213-216.

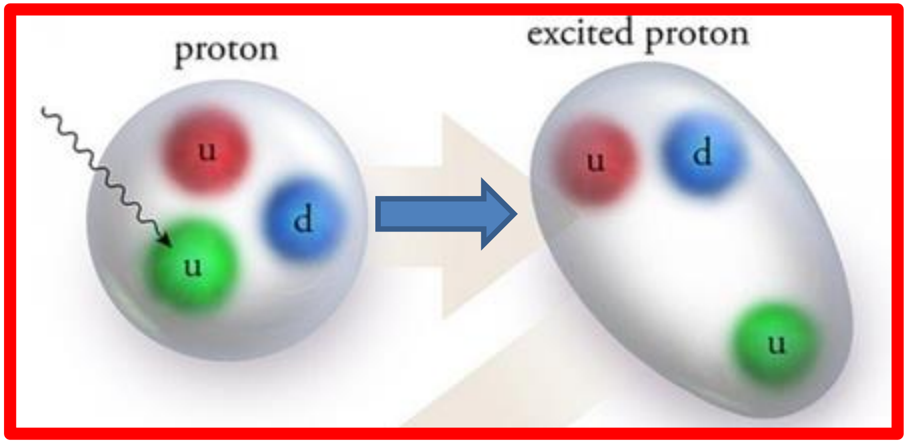
** G. A. Miller, PRL 99 (2007) 112001.

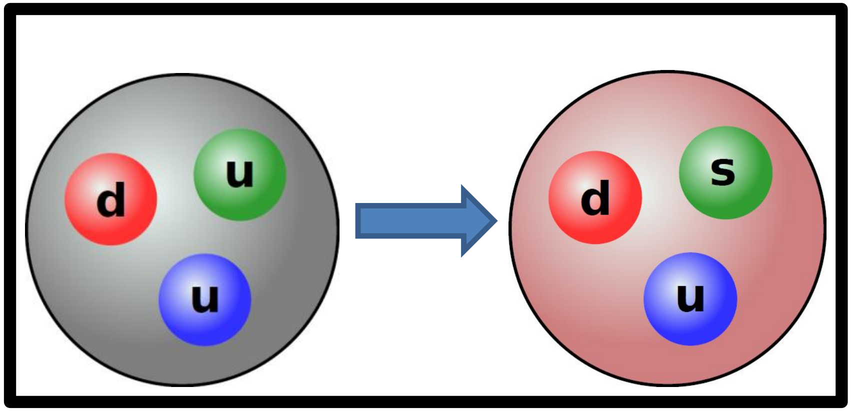
Approaches

When you don't understand a system, you can*

- Scatter on it
- Excite it
- Replace one of the building blocks



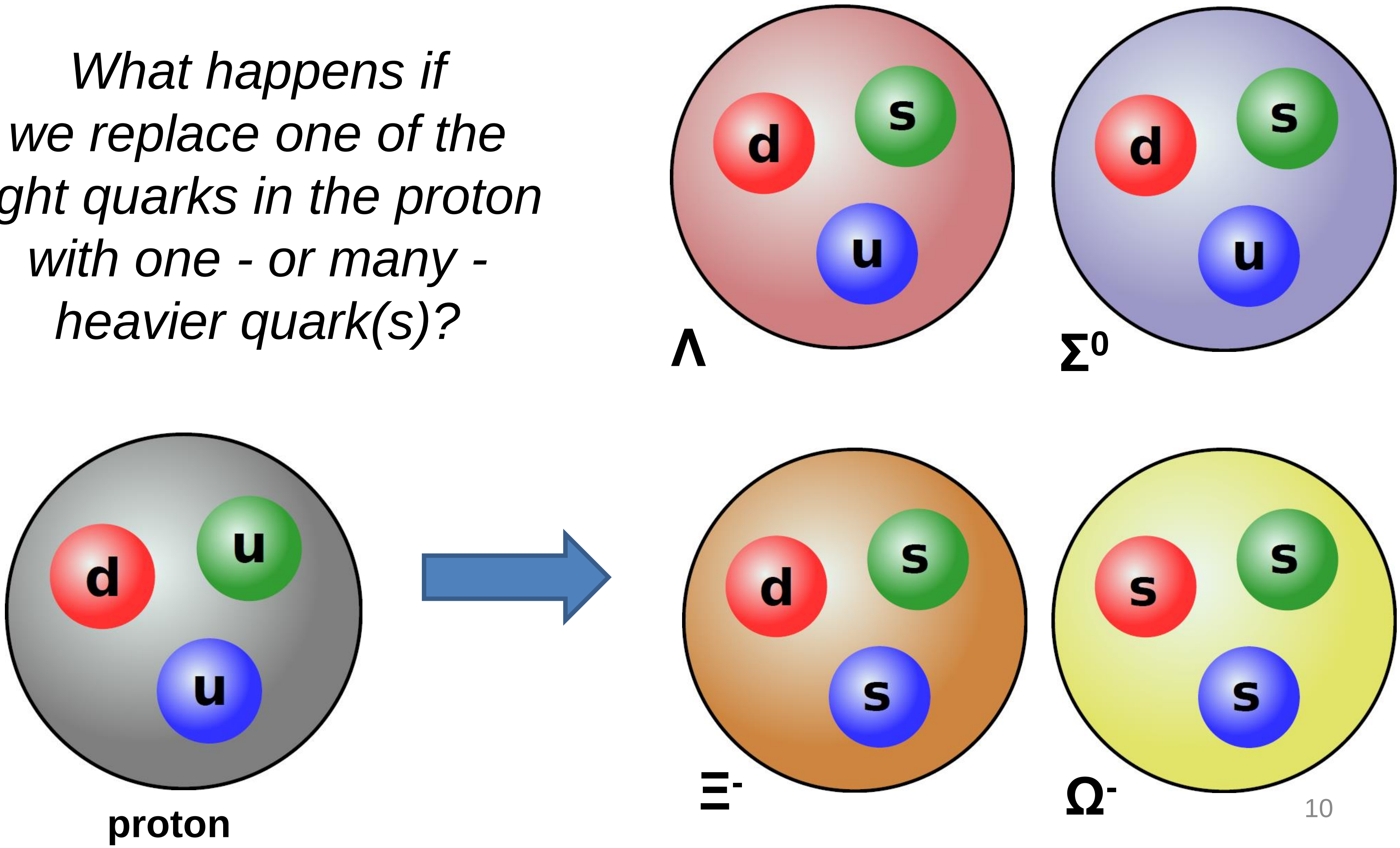




*C. Granados *et al.*, EPJA 53 (2017) 117

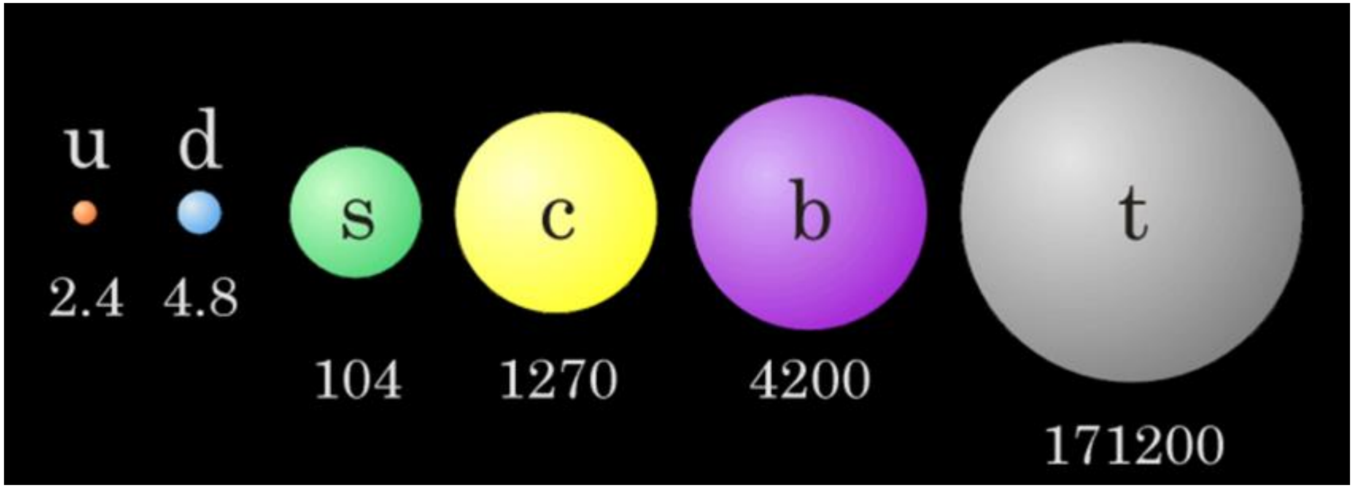
The hyperon – a charming stranger

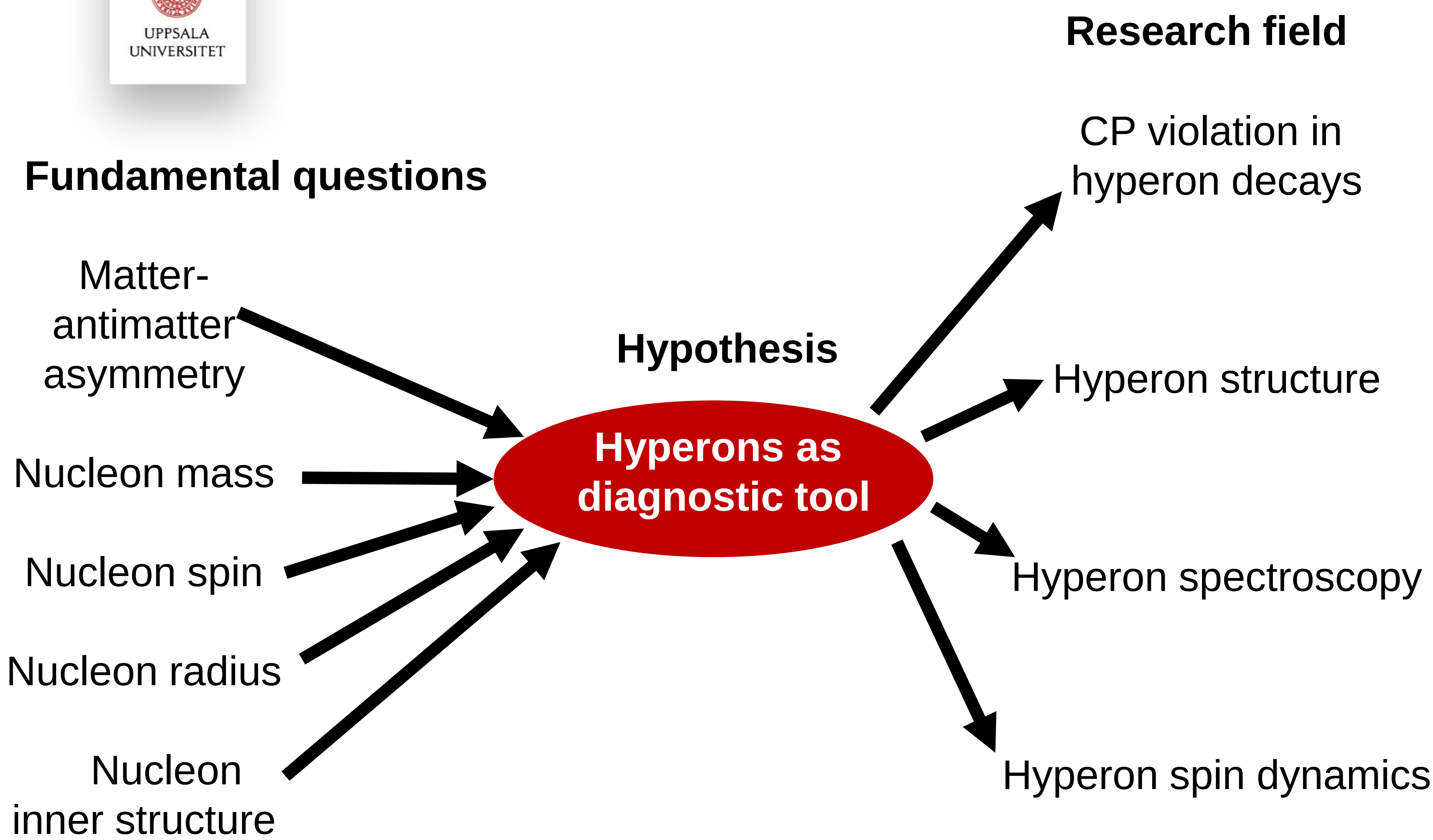
What happens if we replace one of the light quarks in the proton with one - or many - heavier quark(s)?

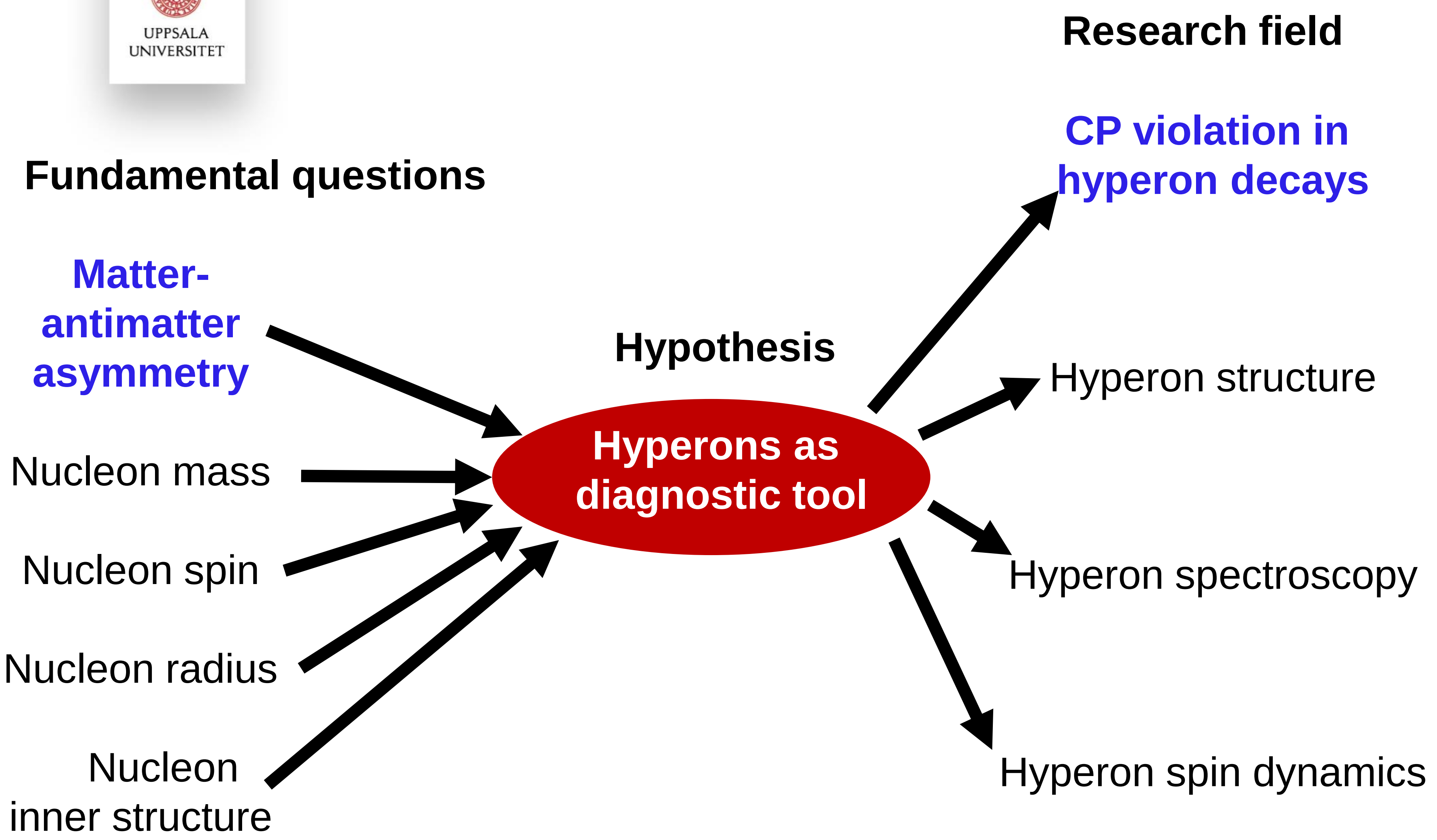


The hyperon – a charming stranger

- Systems with strangeness
  - Scale: $m_s \approx 100$ MeV ~ $\Lambda_{QCD} \approx 200$ MeV: Relevant degrees of freedom?
  - **Probes QCD in the confinement domain.**
- Systems with charm
  - Scale: $m_c \approx 1300$ MeV: Quarks and gluons more relevant.
  - **Probes QCD just below pQCD.**




Research field
Fundamental questions
Matter-antimatter asymmetry
Nucleon mass
Nucleon spin
Nucleon radius
Nucleon inner structure
Hypothesis
Hyperons as diagnostic tool
CP violation in hyperon decays
Hyperon structure
Hyperon spectroscopy
Hyperon spin dynamics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CP violation in hyperon decays

Hyperon structure

Hyperon spectroscopy

Hyperon spin dynamics

THIS TALK

Electromagnetic Form Factors

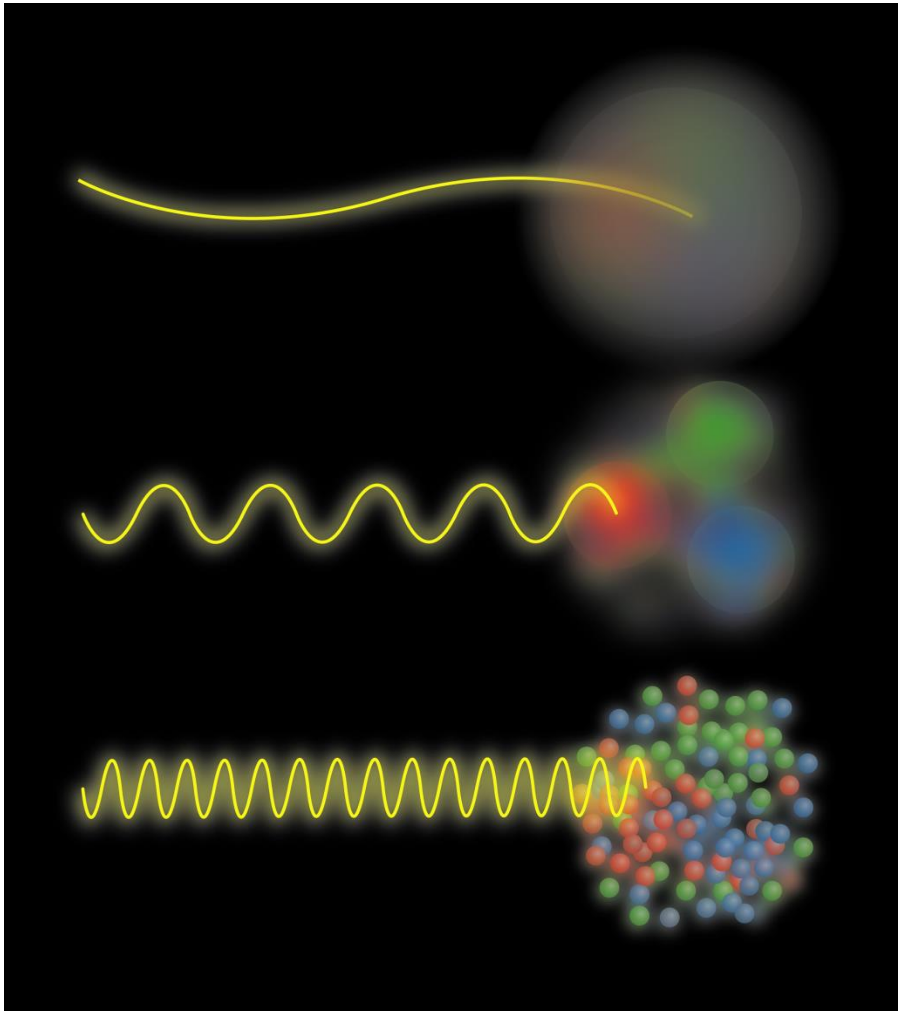
- Electromagnetic structure observable.

- Measured in interactions

  hadron – virtual photon γ^*.

- Quantify deviation from point-like case

  = depend on q^2 of γ^*.



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Electromagnetic 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).
- Elastic electron-baryon scattering parameterized by:

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \left\{ F_1^2(\mathrm{q}^2) + \tau \left[F_2^2(\mathrm{q}^2) + 2(F_1(\mathrm{q}^2) + F_2(\mathrm{q}^2))^2 \tan^2 \frac{\theta}{2} \right] \right\}$$

- In the limit $q^2 \rightarrow 0$:

  Proton $F_1(0) = 1$

  Neutron $F_1(0) = 0$

  Proton and neutron $F_2(0) = \mu_N$

  = anomalous magnetic moment.

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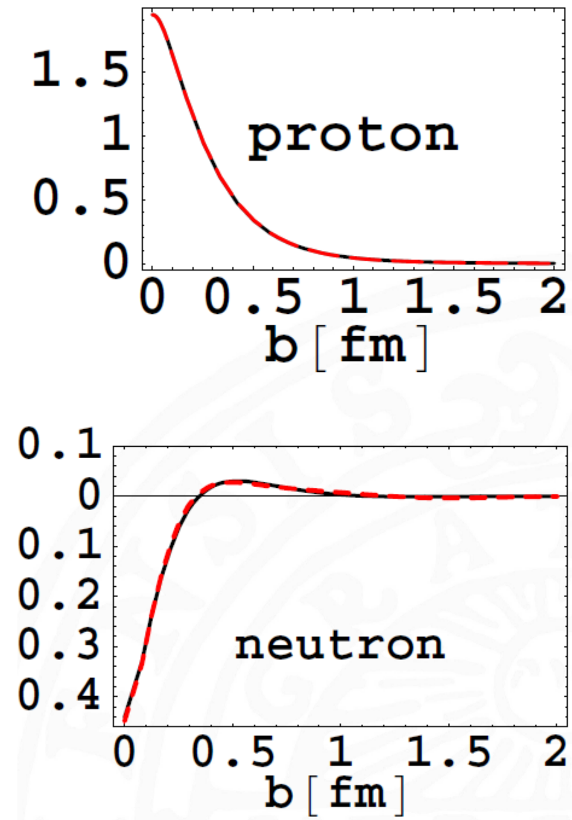
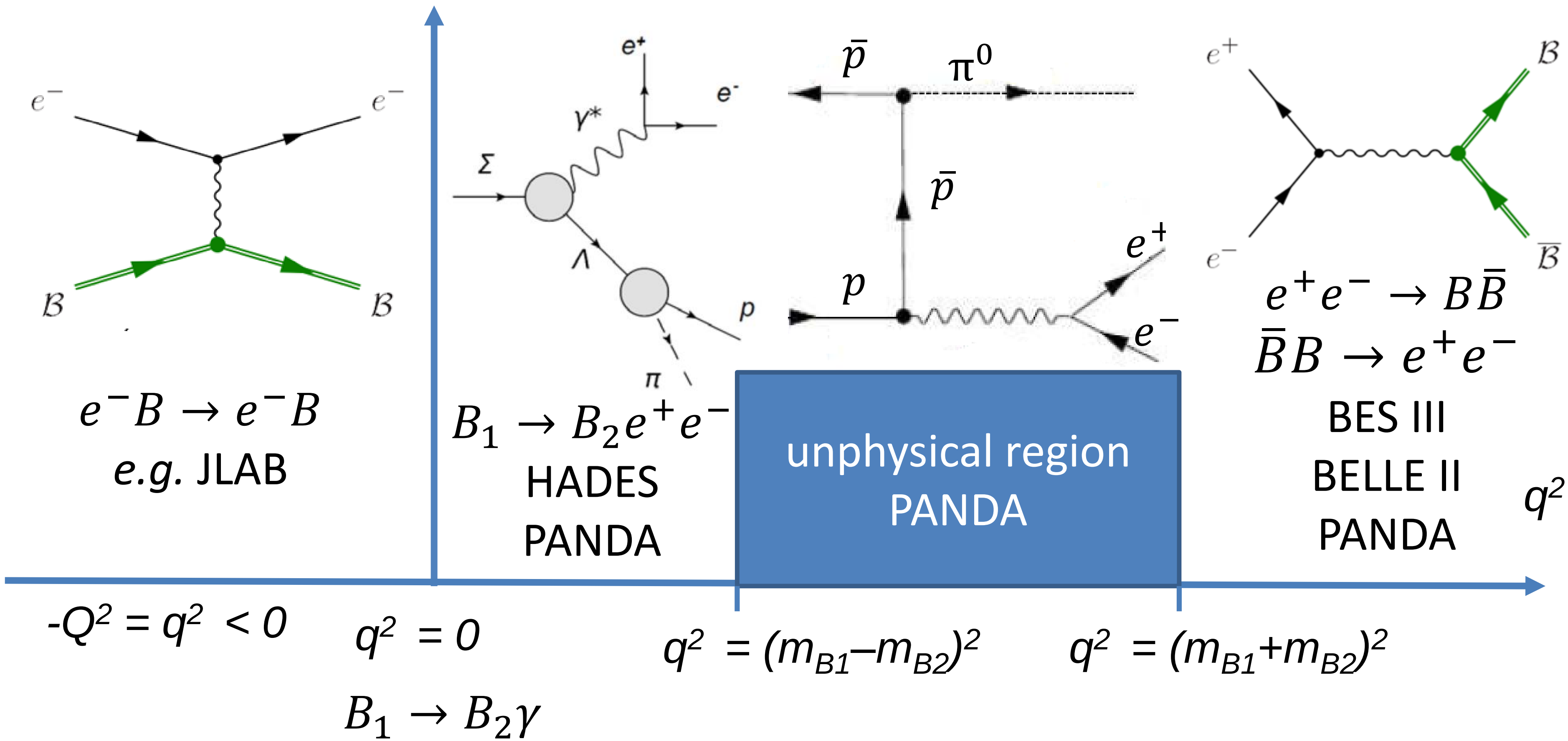
Electromagnetic Form Factors

- Sachs FFs G_E and G_M .
  - $G_E(q^2) = F_1(q^2) - \tau F_2(q^2), \quad G_M(q^2) = F_1(q^2) + F_2(q^2)$
  - $\tau = q^2/4M^2_B$
  - In the Breit frame, G_E and G_M are Fourier transforms of charge- and magnetization density.



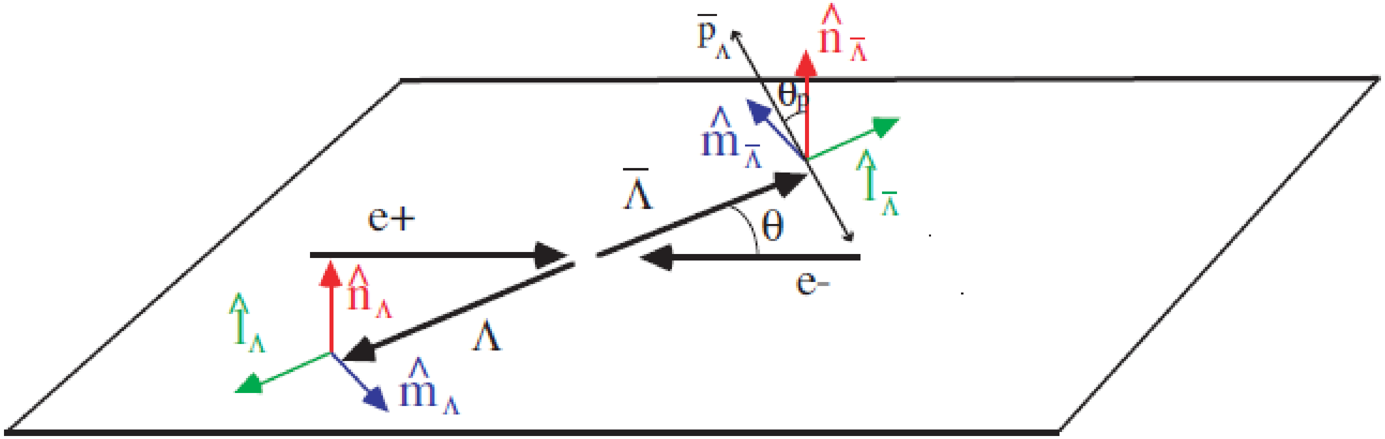
Space-like *vs.* time-like FF's



Time-like form factors

- Time-like FF's are complex:
  - $G_E(q^2) = |G_E(q^2)| \cdot e^{i\Phi_E}$
  - $G_M(q^2) = |G_M(q^2)| \cdot e^{i\Phi_M}$
  - $\Delta\Phi(q^2) = \Phi_M(q^2) - \Phi_E(q^2)$ = phase between G_E and G_M

- Phase between G_E and G_M – polarization effects on the final state even when the initial state is unpolarized *.



*Nuovo Cim. A 109 (1996) 241.

The EMFF phase

- Phase is **production related** and depends on q^2 .

- **Constraint 1:** Phase result of interfering amplitudes (*e.g. s-* and *d* partial waves)

  - $\Delta\Phi(q^2) = 0$ at threshold

- **Constraint 2:** Analyticity requires TL FF ~ SL FF as $|q^2| \to \infty$

  - $\Delta\Phi(q^2) \to 0$ as $|q^2| \to \infty$

Phase and polarisation

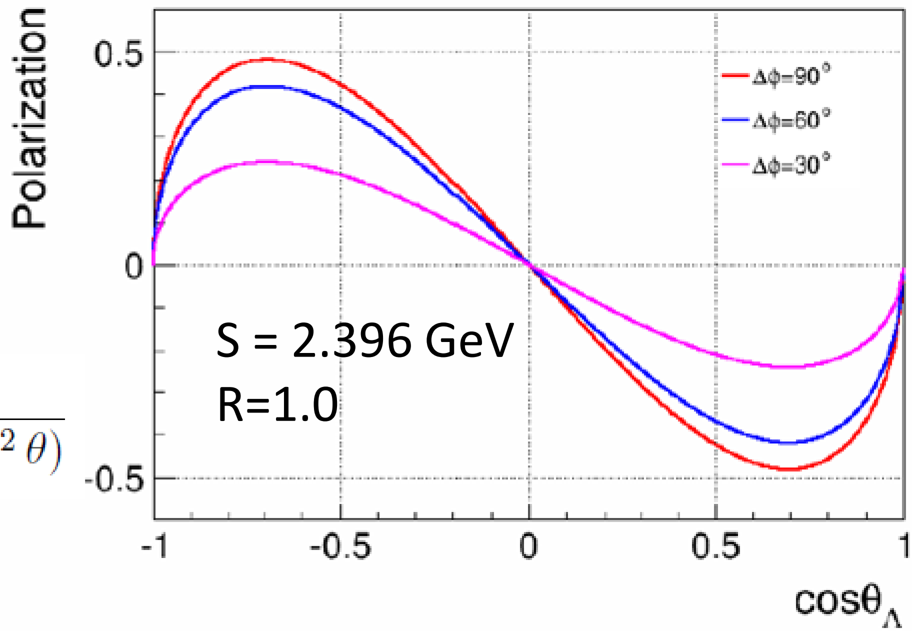
- Imaginary part polarizes the final state baryons*:

$$P_n = -\frac{\sin 2\theta Im[G_E(Q^2)G_M^*(Q^2)]/\sqrt{\tau}}{(|G_E(Q^2)|^2 \sin^2\theta)/\tau + |G_M(Q^2)|^2(1+\cos^2\theta)}$$ Eq. 1

- Real part related to the correlation between the baryon- and antibaryon spin:

$$C_{lm} = \frac{\sin 2\theta Re[G_E(Q^2)G_M^*(Q^2)]/\sqrt{\tau}}{(|G_E(q^2)|^2 \sin^2\theta)/\tau + |G_M(Q^2)|^2(1+\cos^2\theta)}$$

Eq. 2



*Nuovo Cim. A 109 (1996) 241.

Phase and polarisation

Advantage of hyperons:

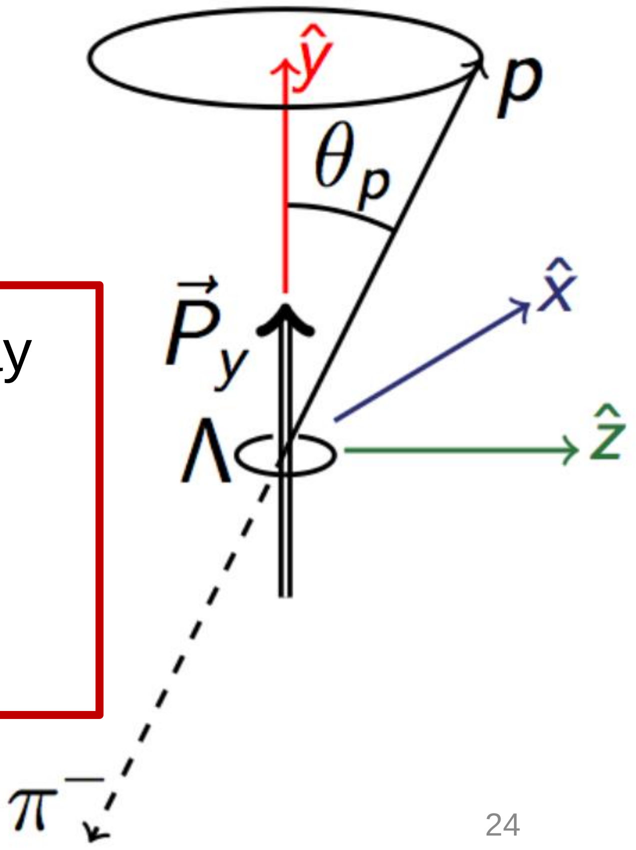
Polarization experimentally accessible by the weak, parity violating decay:

Example: Angular distribution of $\Lambda \rightarrow p\pi^-$ decay

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

P_Λ : polarisation

$\alpha = 0.64$ asymmetry parameter



Phase and polarisation

Challenges:

Polarisation depends on **energy** and **scattering angle** and has impact on **decay angles.**

- Formalism needs to take this into account.
- Acceptance depends on many variables.
- Large data samples required.

Phase and polarisation

Challenges:

Polarisation depends on **energy** and **scattering angle** and has impact on **decay angles.**

- Formalism needs to take this into account.
- Acceptance depends on many variables.
- Large data samples required.

→ **Until now, no conclusive phase measurements exist!**
Main focus so far on cross section / effective form factor.

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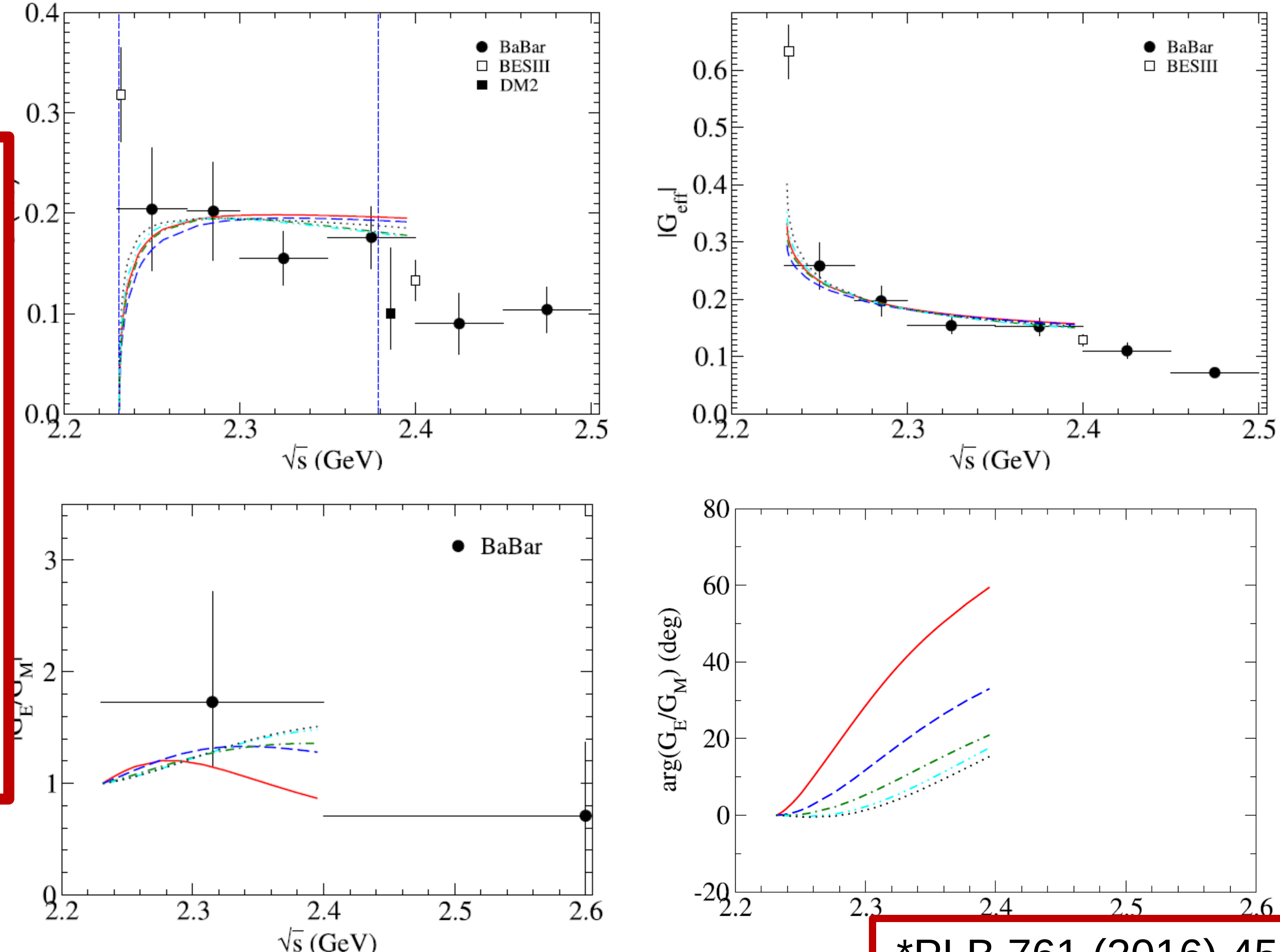
Why care about the phase?

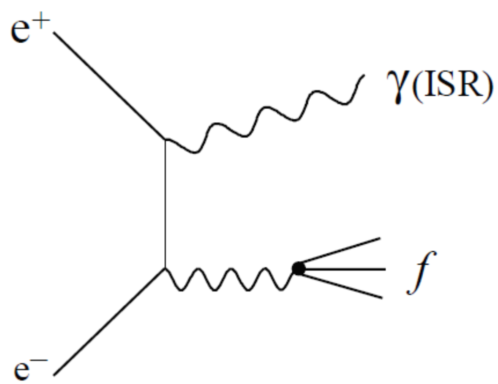
Phase and polarisation generally more sensitive to the underlying physics than cross section or scattering angle.

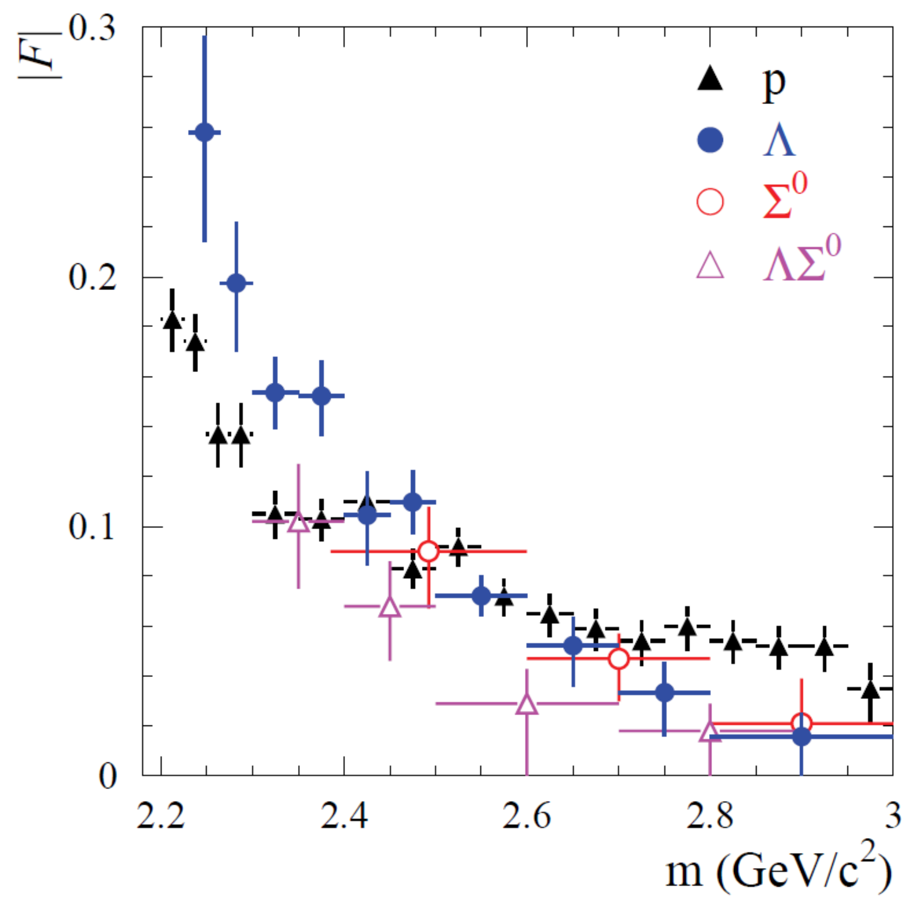


*PLB 761 (2016) 456.

Measurements: past

BaBar:





- Used the ISR technique on bottomium sample.
- Measured cross section and effective form factor.
- No conclusive separation between G_E and G_M.

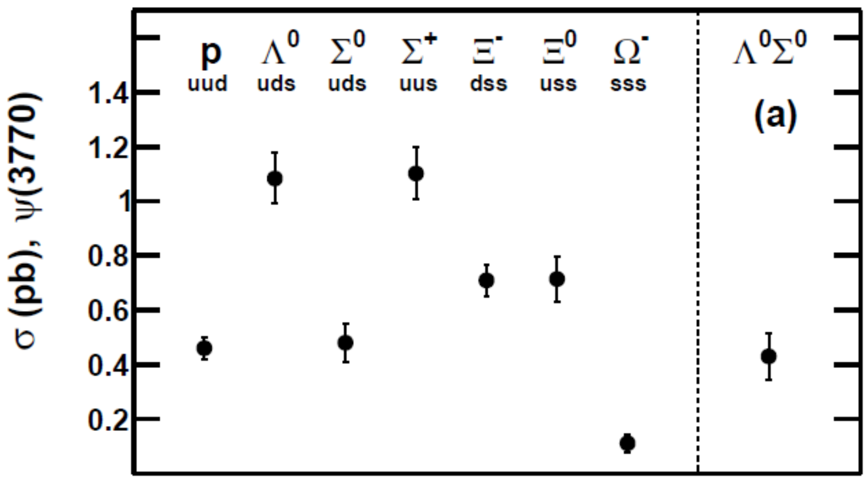
*PRD 76 (2007) 092006.

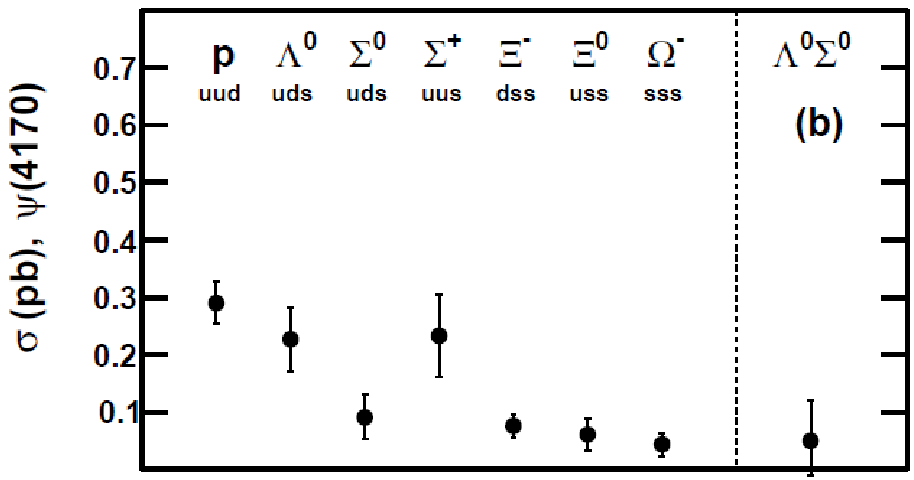
Measurements: present

CLEO-c:

– Cross sections in the high energy limit ($q = 3770$ MeV and $q = 4170$ MeV) of octet baryons and Ω^-.

– Claim evidence for effects from di-quark correlations*.



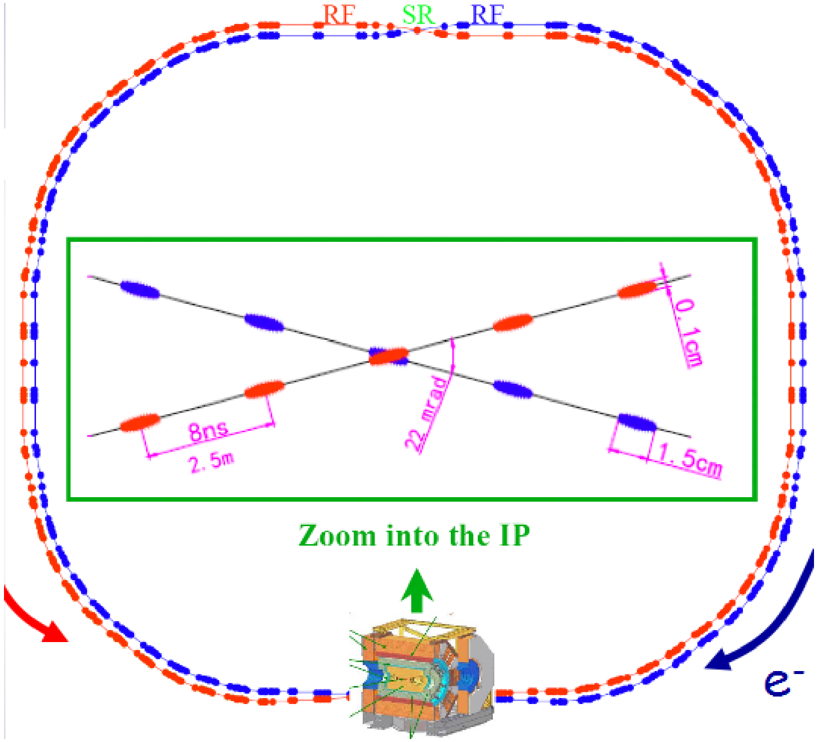


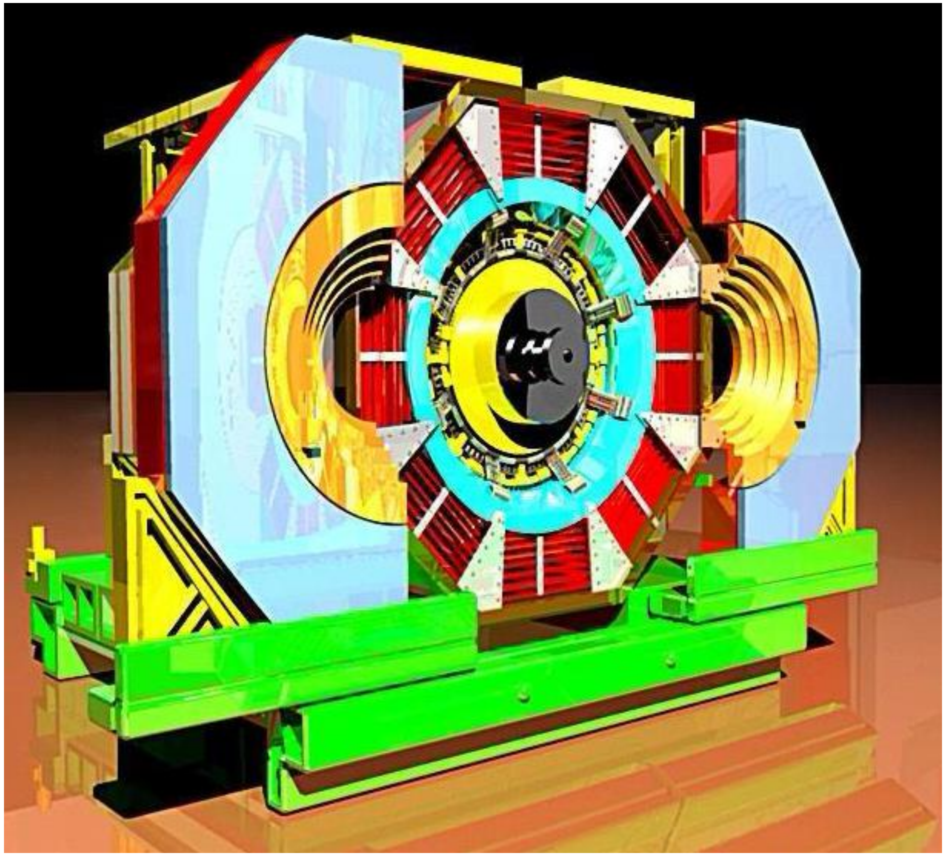
*PRD 96 (2017) 092004.

Measurements: present

BESIII@BEPC-II:

- BEPC = Beijing Electron Positron Collider.
- Operates in τ-charm mass region.



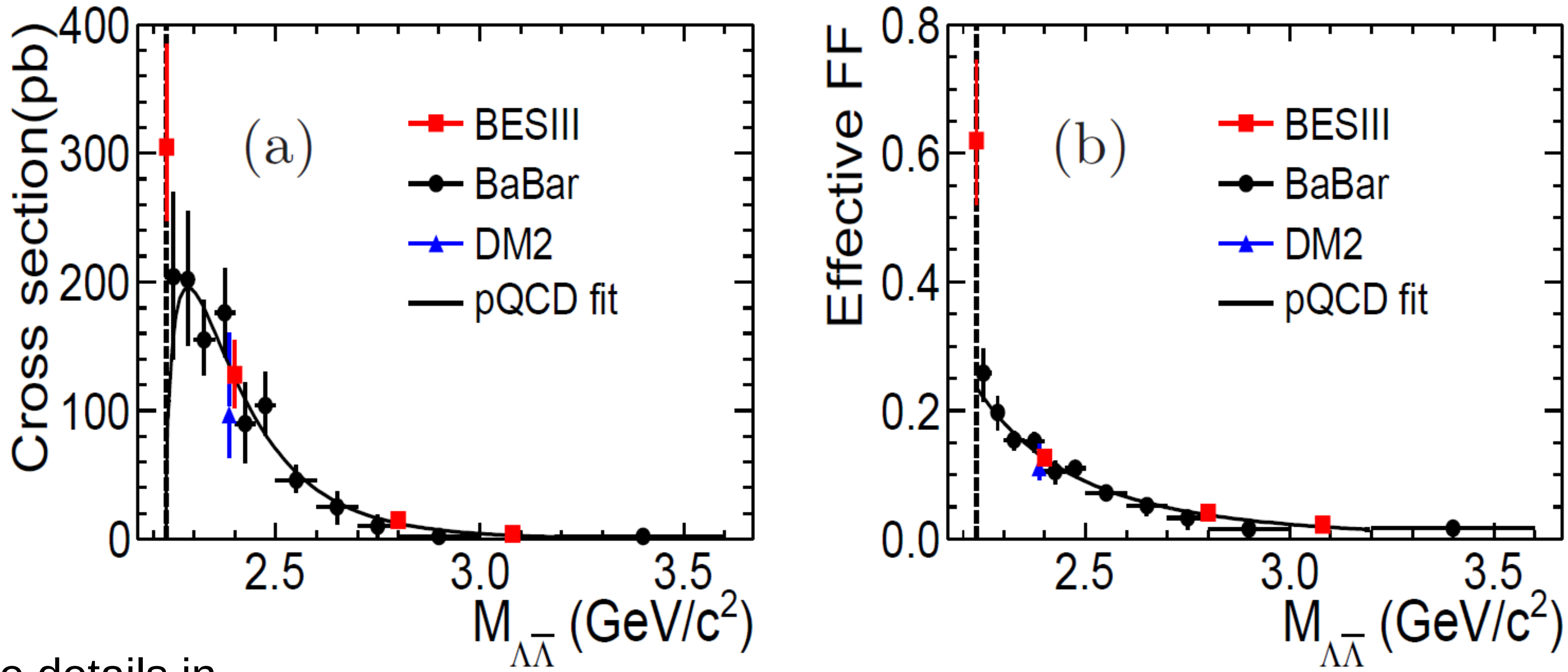


- BES III = Beijing Spectrometer
  - Wide physics scope

Measurements: present

BESIII:

- Four data points between threshold and $\sqrt{s} = 3.08$ GeV.
- Large cross section at threshold.

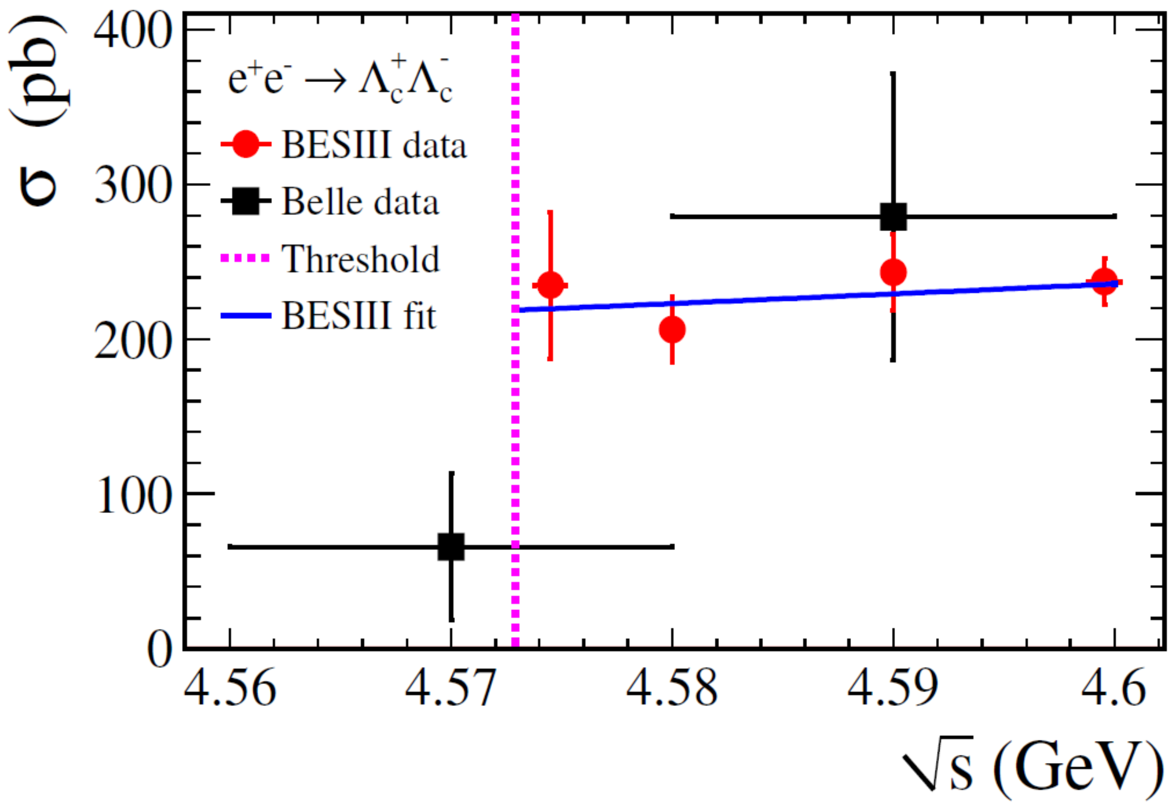


More details in talk by Y. Liang.

PRD 97 (2018) 032013.

Measurements: present

The charmed Λ_c^+ hyperon EMFF's in $e^+e^- \to \Lambda_c^+\overline{\Lambda}_c^-$

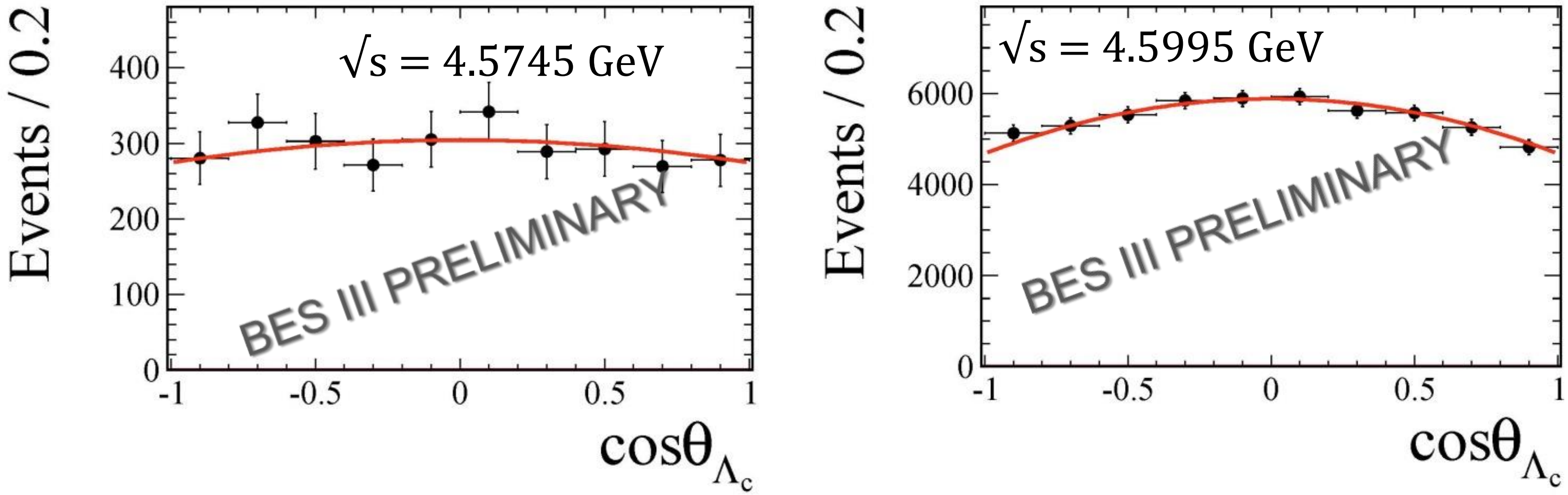


- First direct measurement of Λ_c^+ EMFF's.
- Most precise cross section measurement so far.
- Data very close to threshold.

PRL 120 (2018) 132001.

Measurements: present

The charmed Λ_c^+ hyperon EMFF's in $e^+e^- \to \Lambda_c^+\overline{\Lambda}_c^-$



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

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

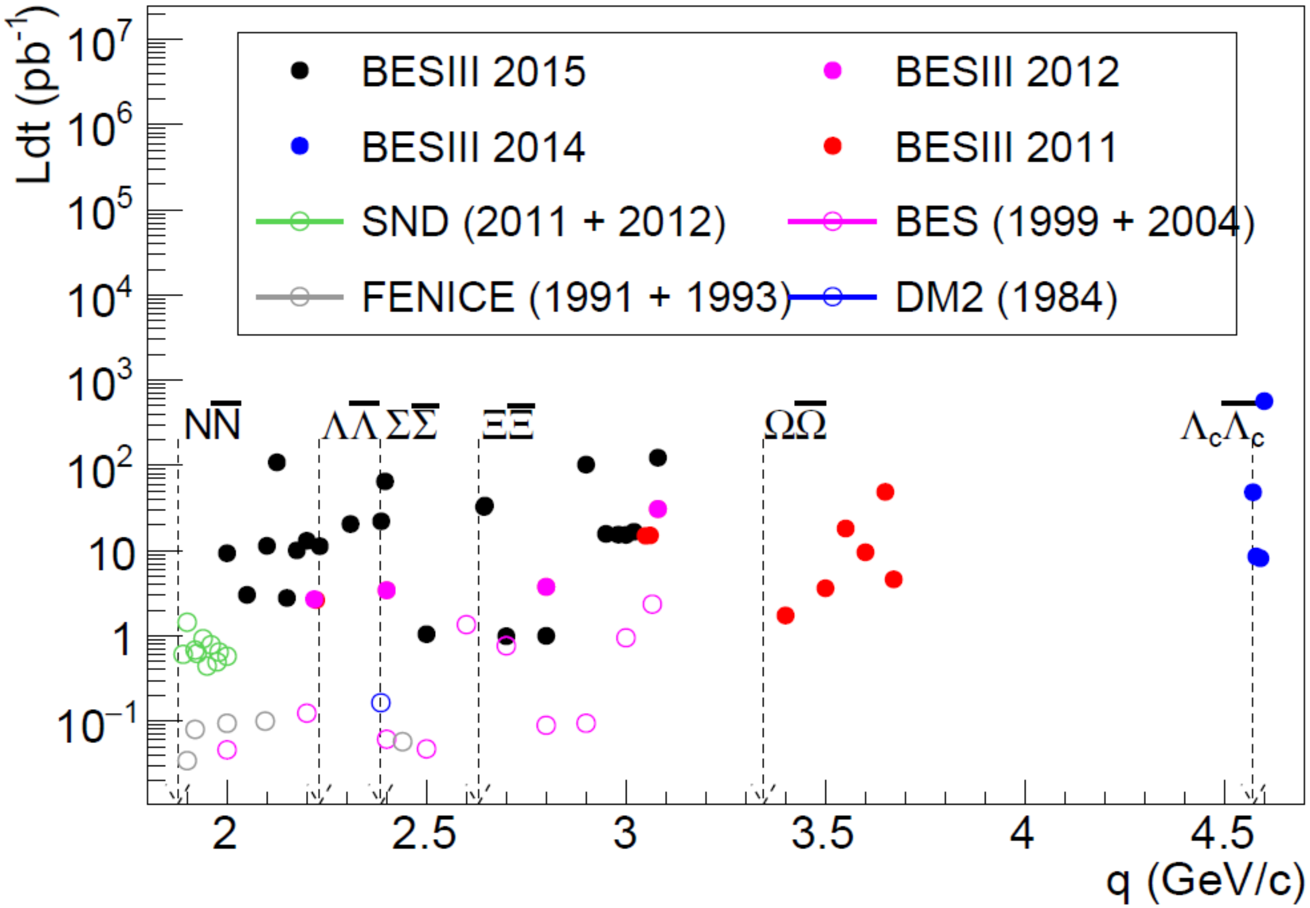
PRL 120 (2018) 132001.

THE FUTURE…

…is already here and it is full of phase measurements!

BESIII energy scan 2014-2015

- World leading data sample between 2.0 and 3.08 GeV.
- Nucleon and strange hyperons EMFF's available.

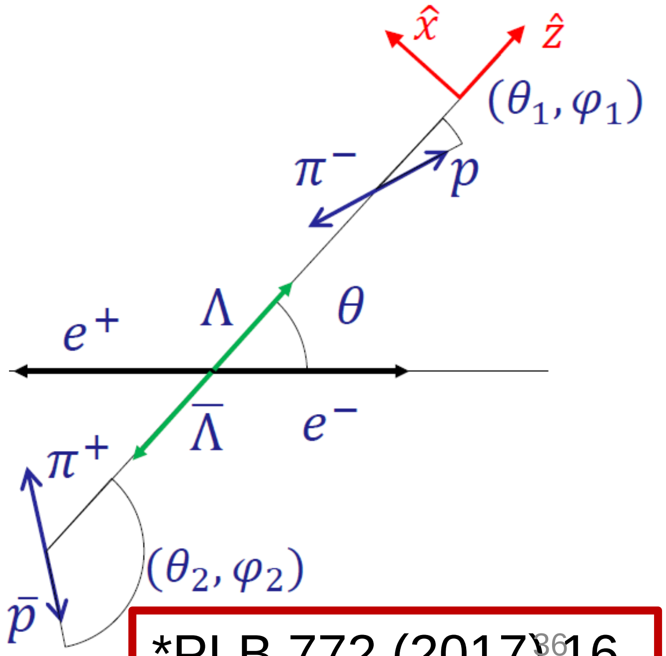


Measurement of Λ EMFF with BES III

For $R = |G_E/G_M|$ and $\Delta\Phi$, formalism for exclusive measurement derived*:

$$\begin{aligned}\mathcal{W}(\xi) = &\mathcal{T}_0(\xi) + \eta\,\mathcal{T}_5(\xi)\\ &-\alpha_\Lambda^2\left(\mathcal{T}_1(\xi) + \sqrt{1-\eta^2}\cos(\Delta\Phi)\,\mathcal{T}_2(\xi) + \eta\,\mathcal{T}_6(\xi)\right)\\ &+\alpha_\Lambda\sqrt{1-\eta^2}\sin(\Delta\Phi)\left(\mathcal{T}_3(\xi) - \mathcal{T}_4(\xi)\right).\end{aligned}$$

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



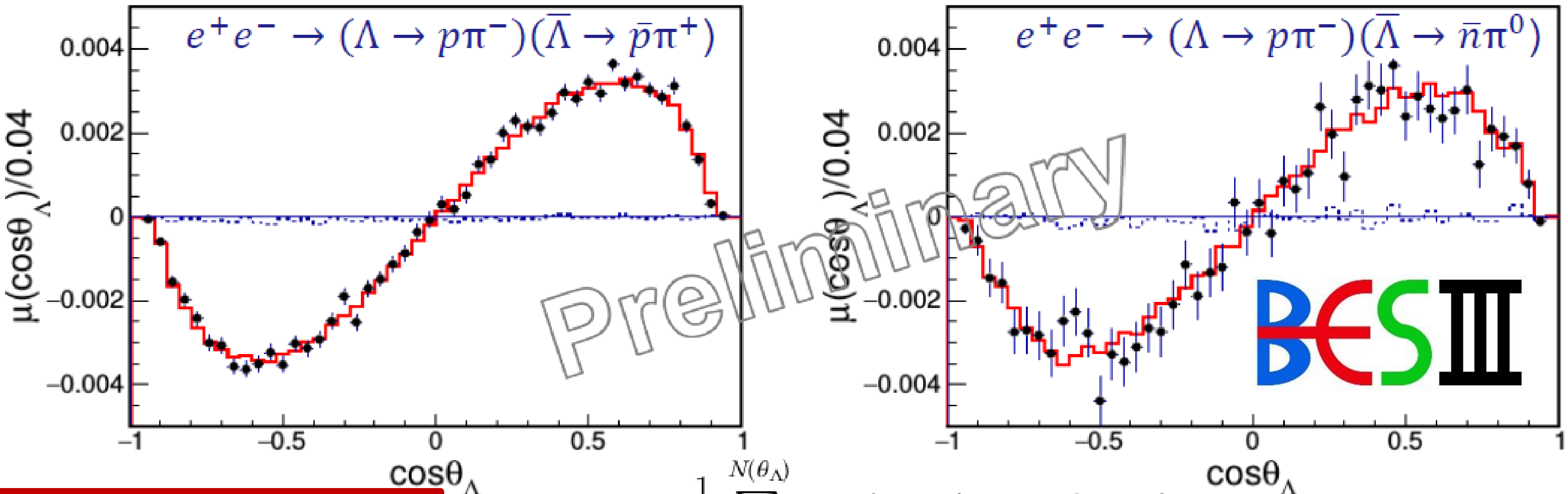
The $\eta = \frac{\tau - R^2}{\tau + R^2}$ is related to the angular distribution.

*PLB 772 (2017) 16.

The Λ phase in $e^+e^- \to J/\Psi \to \Lambda\bar{\Lambda}$

- > 400 000 $e^+e^- \to J/\Psi \to \Lambda\bar{\Lambda}$ events.
- "Hadronic" form factors (not EMFFs) accessible.
- Decay asymmetries α_-, α_0 and α_+ measured.
- Value of α_- $17 \pm 3\%$ > PDG value.
- Most precise CP test so far for Λ decay: $\frac{\alpha_- + \alpha_+}{\alpha_- - \alpha_+} = -0.006 \pm 0.012 \pm 0.007$

$\Delta\Phi = 42.3° \pm 0.6° \pm 0.5°$



$$\mu(\cos\theta_\Lambda) = \frac{1}{N} \sum_i^{N(\theta_\Lambda)} (\sin\theta_1^i \sin\phi_1^i - \sin\theta_2^i \sin\phi_2^i)$$

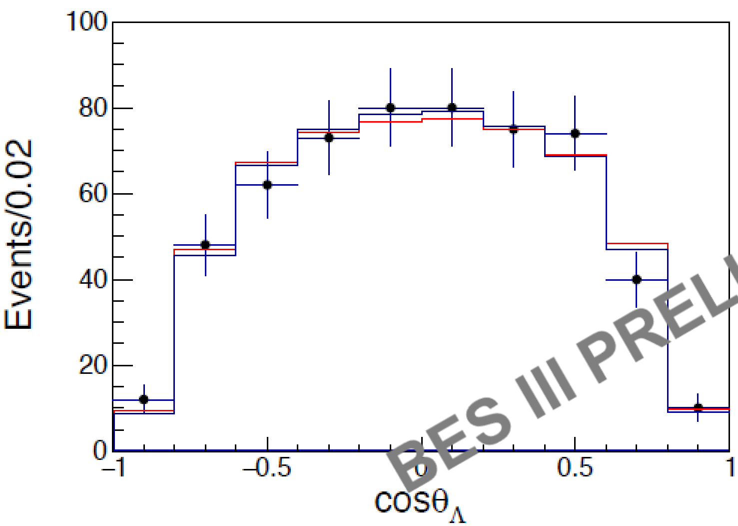
arXiv: hep-ex 1808.08917

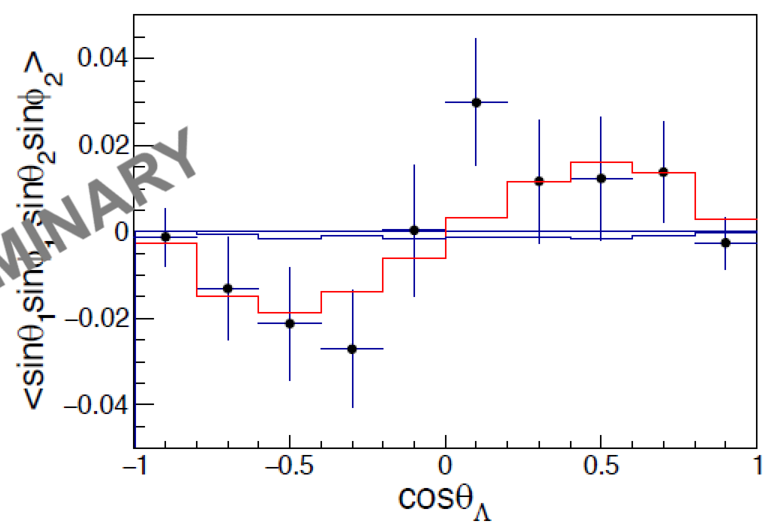
The Λ EMFF from $e^+e^- \to \gamma^* \to \Lambda\bar{\Lambda}$

- Same formalism as in J/Ψ case but with α_- and α_+ fixed to ± 0.75
- 555 exclusive events in sample.
  - $R = \mathbf{0.96 \pm 0.14 \pm 0.02}$
  - $\Delta\Phi = \mathbf{37^o \pm 12^o \pm 6^o}$

←**BES III PRELIMINARY**

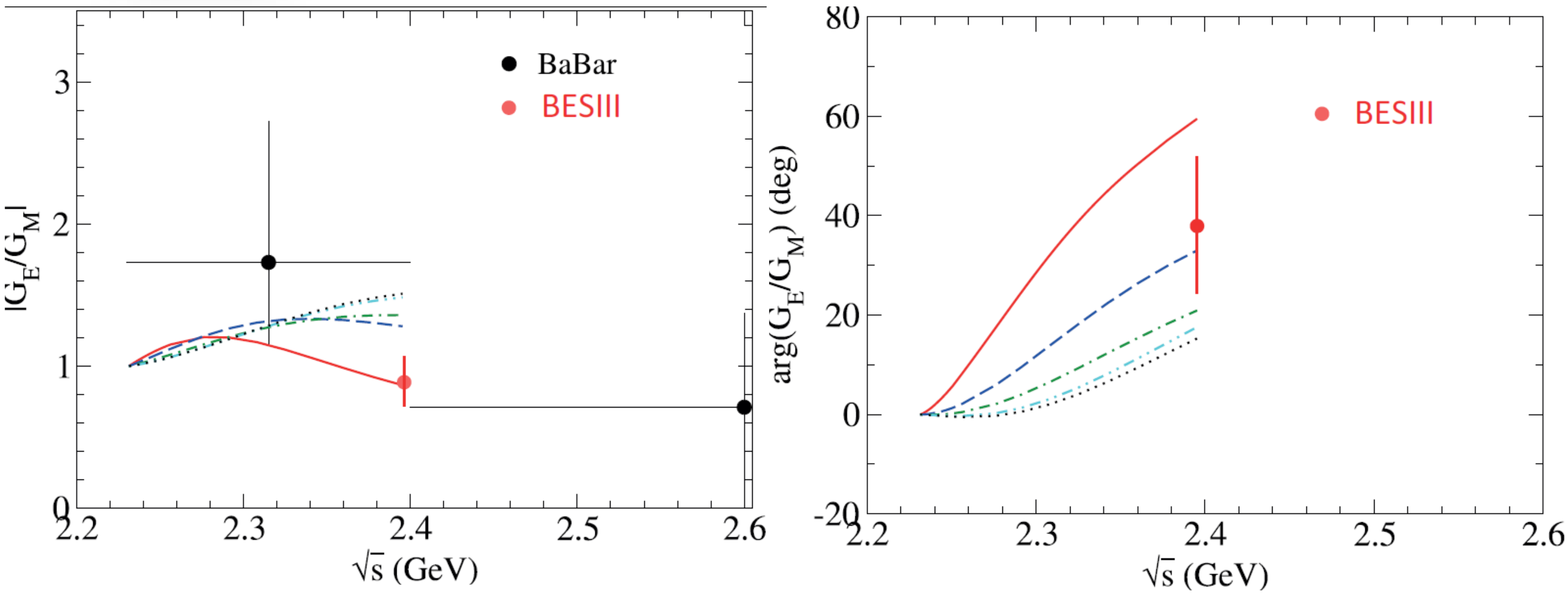
- Most **precise** result on *R*
- **First** conclusive result on $\Delta\Phi$





More details in talk by C. Li

The Λ EMFF from $e^+e^- \to \gamma^* \to \Lambda\bar{\Lambda}$



Model predictions by Haidenbauer and Meissner.*

*PLB 761(2016) 456, see also talk by Meissner
**BaBar: PRD 76 (2007) 092006
***BES III: Talk by C. Li, BEACH2018

Future

- **BESIII:** Possible to measure *R* and $\Delta\Phi$ for $\Sigma^0, \Sigma^+, \Xi^-$ and Λ_c^+:
  - Formalism available / under development.
  - A lot of data on tape.
  - More is coming!

- **Belle II:** High q^2 limit.

STAY TUNED!

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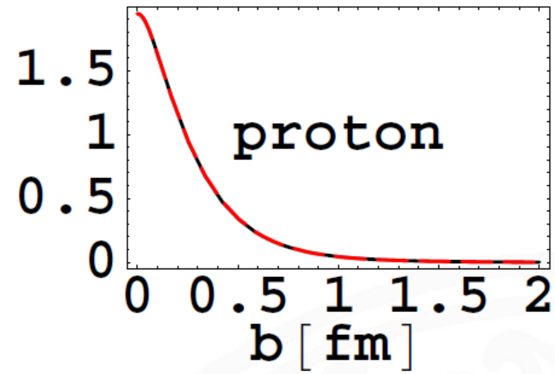
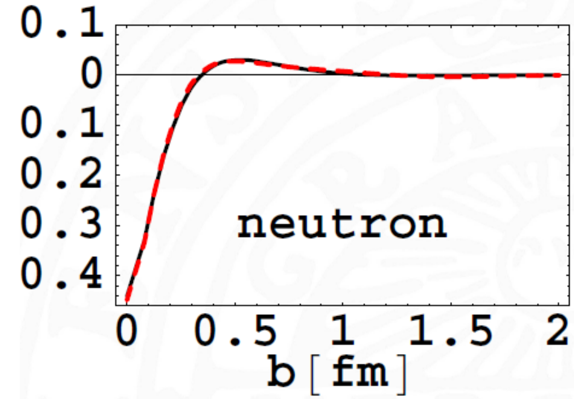
What can we learn from this?

- How does *F*, *R*, $\Delta\Phi$ change with q^2 ?
- What is $\Delta\Phi$ for other hyperons ↔ SU(3) symmetry?
- Role of $Y\bar{Y}$ final state interaction?
- Charge- and magnetization distribution of hyperons
  → time-like EMFFs + dispersion theory





Towards a coherent picture of octet baryons?

Summary

- Hyperons provide a new angle to hadron structure.
- Polarisation measurements give information about the EMFF phase.
- Measurements by BaBar, CLEO-c and BESIII.
- BESIII:
  - World-leading data samples for baryon EMFF measurements.
  - Λ : Ratio $R=|G_E/G_M|$ measured with unprecedented precision.
  - Λ : Relative phase $\Delta\Phi$ of G_E and G_M measured for the first time.
  - Can measure also $\Sigma^0, \Sigma^+, \Xi^-$ and Λ_c^+.

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Thanks for your attention!