Hyperon form factors
- present and future

WE-Heraeus Seminar on Baryon Form Factors:
Where do we stand?

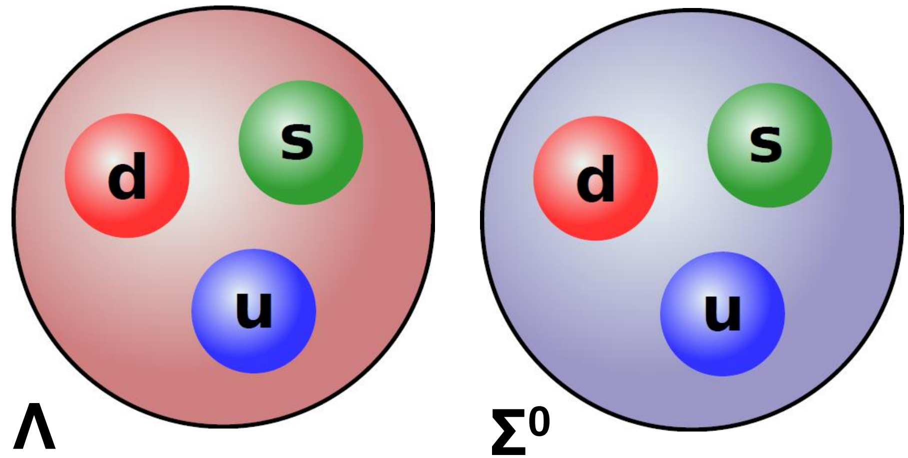
Karin Schönning for the BES III and PANDA collaborations

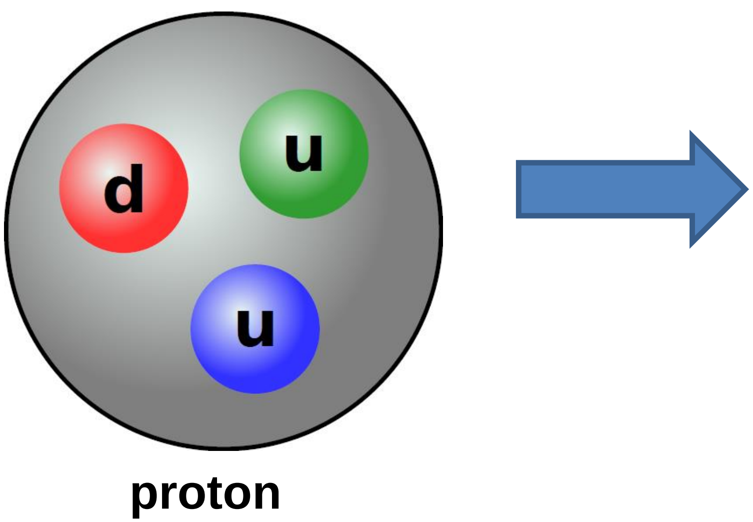
Outline

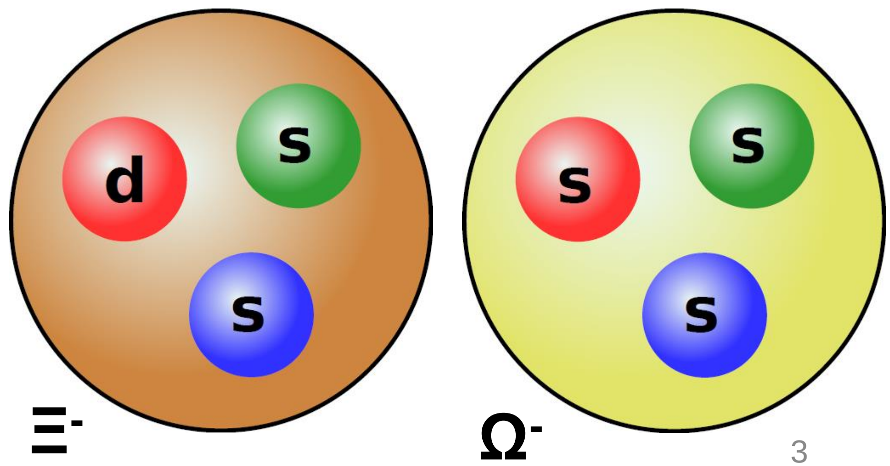
- Why hyperons?
- Space-like *versus* time-like EMFF’s
- The EMFF phase
- Recent theory predictions
- Recent experimental results
- BES III at BEPC-II
  - First EMFF’s phase measurement
- Possibilities with PANDA at FAIR
- Summary

Why hyperons?

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







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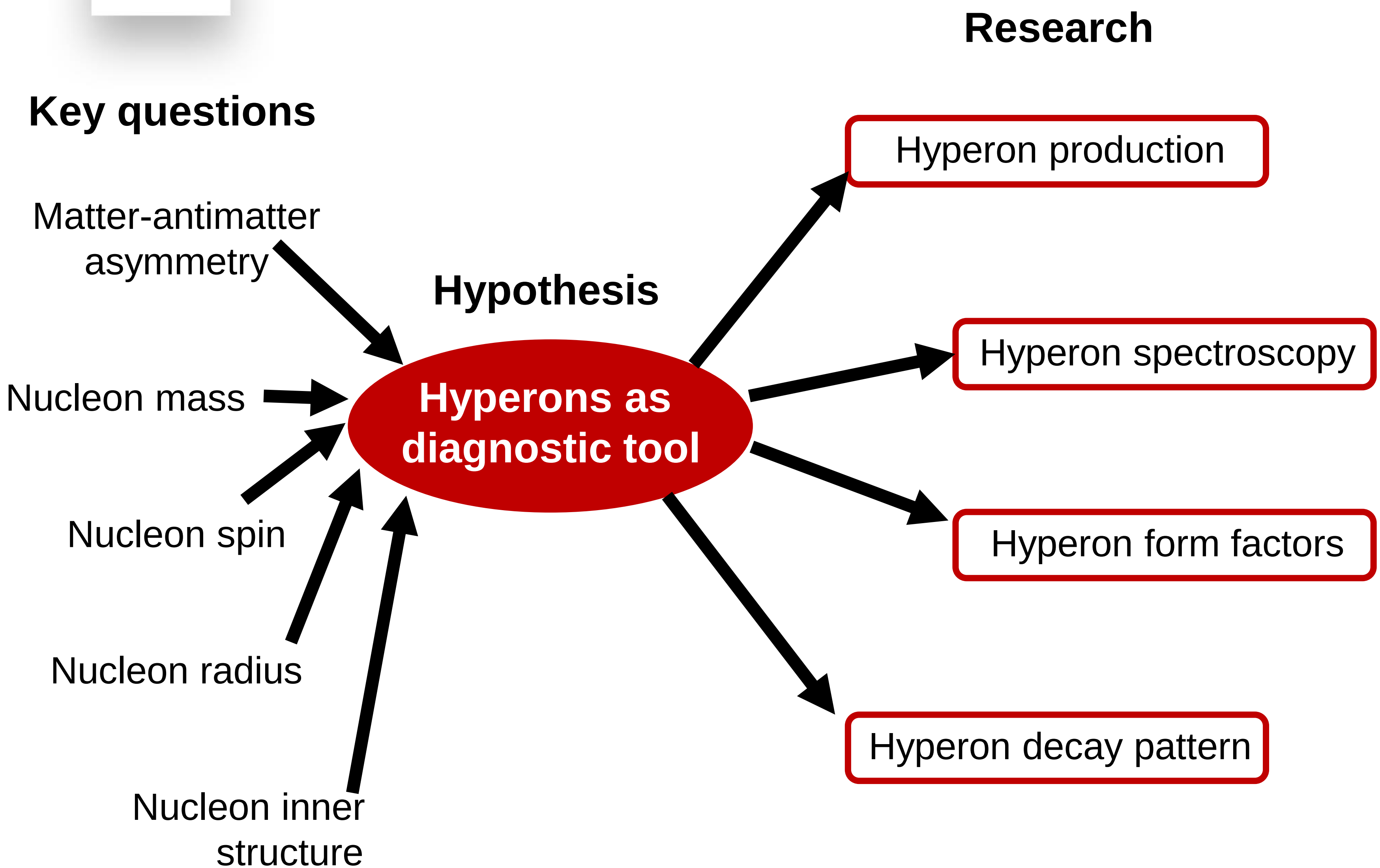
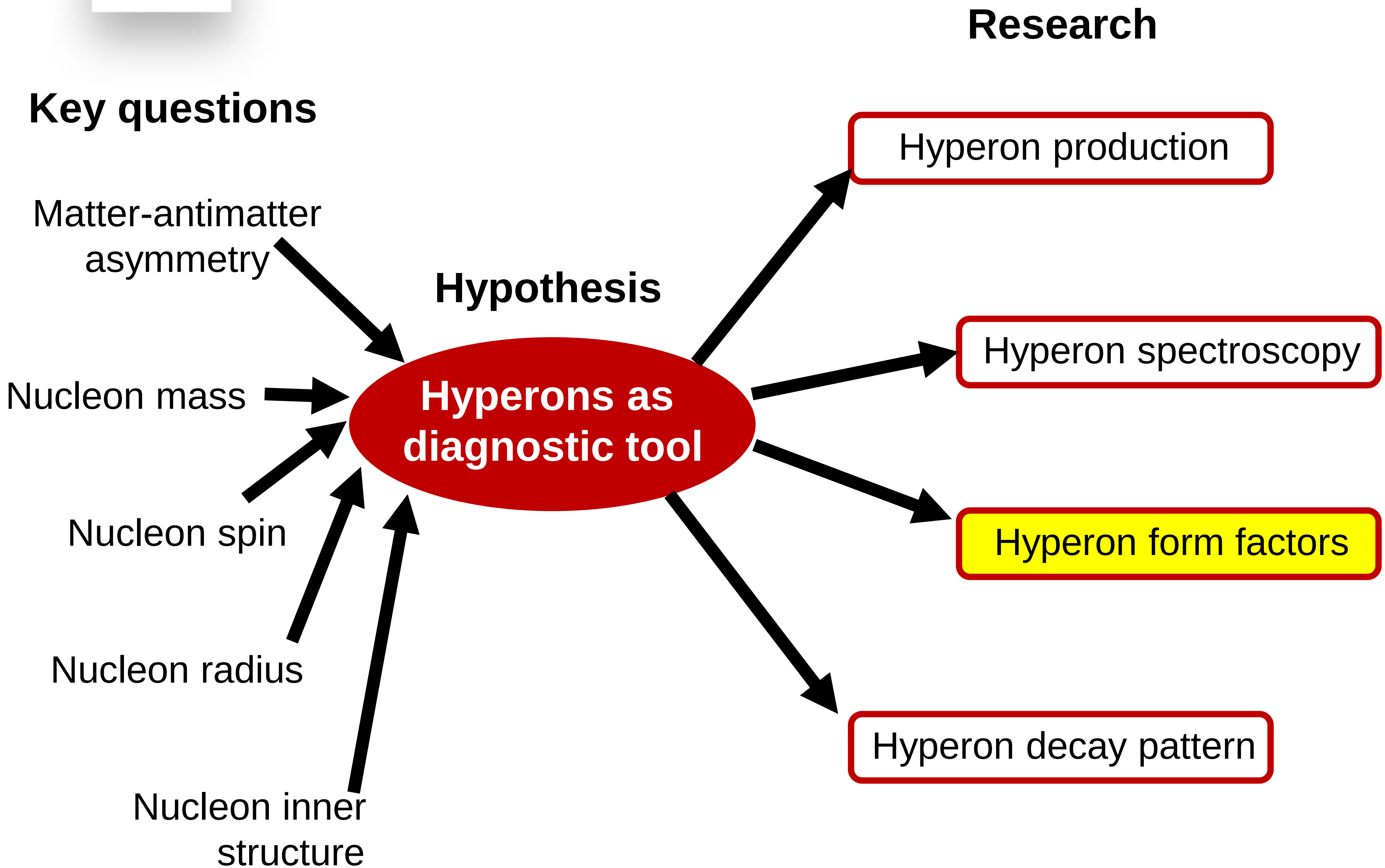
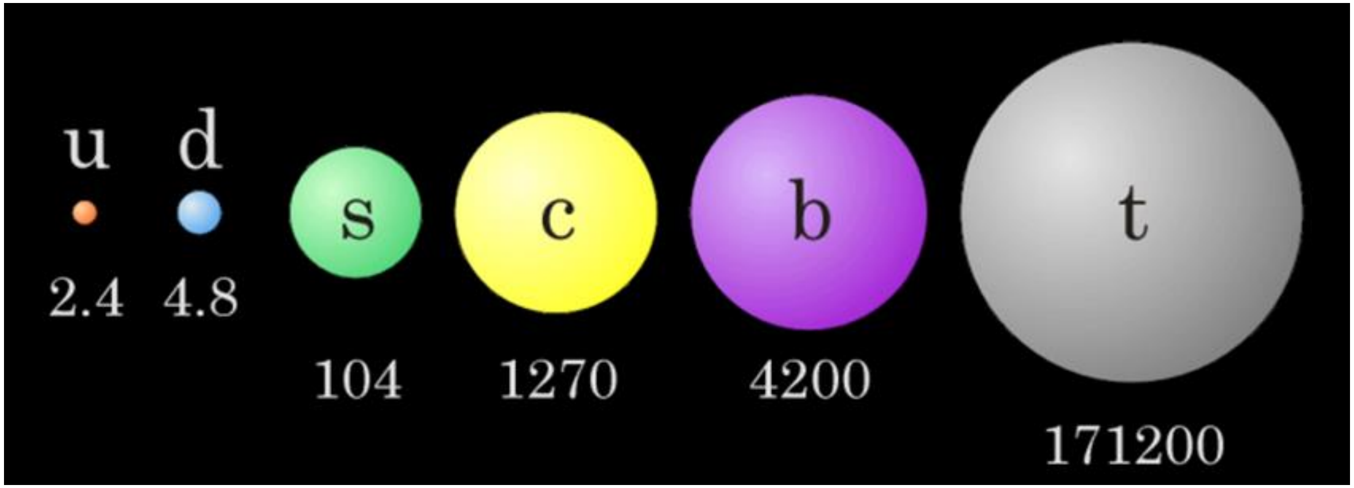



Research
Key questions
Hyperon production
Matter-antimatter asymmetry
Hypothesis
Hyperon spectroscopy
Nucleon mass
Hyperons as diagnostic tool
Hyperon form factors
Nucleon spin
Nucleon radius
Hyperon decay pattern
Nucleon inner structure

Why hyperons?

- 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.**



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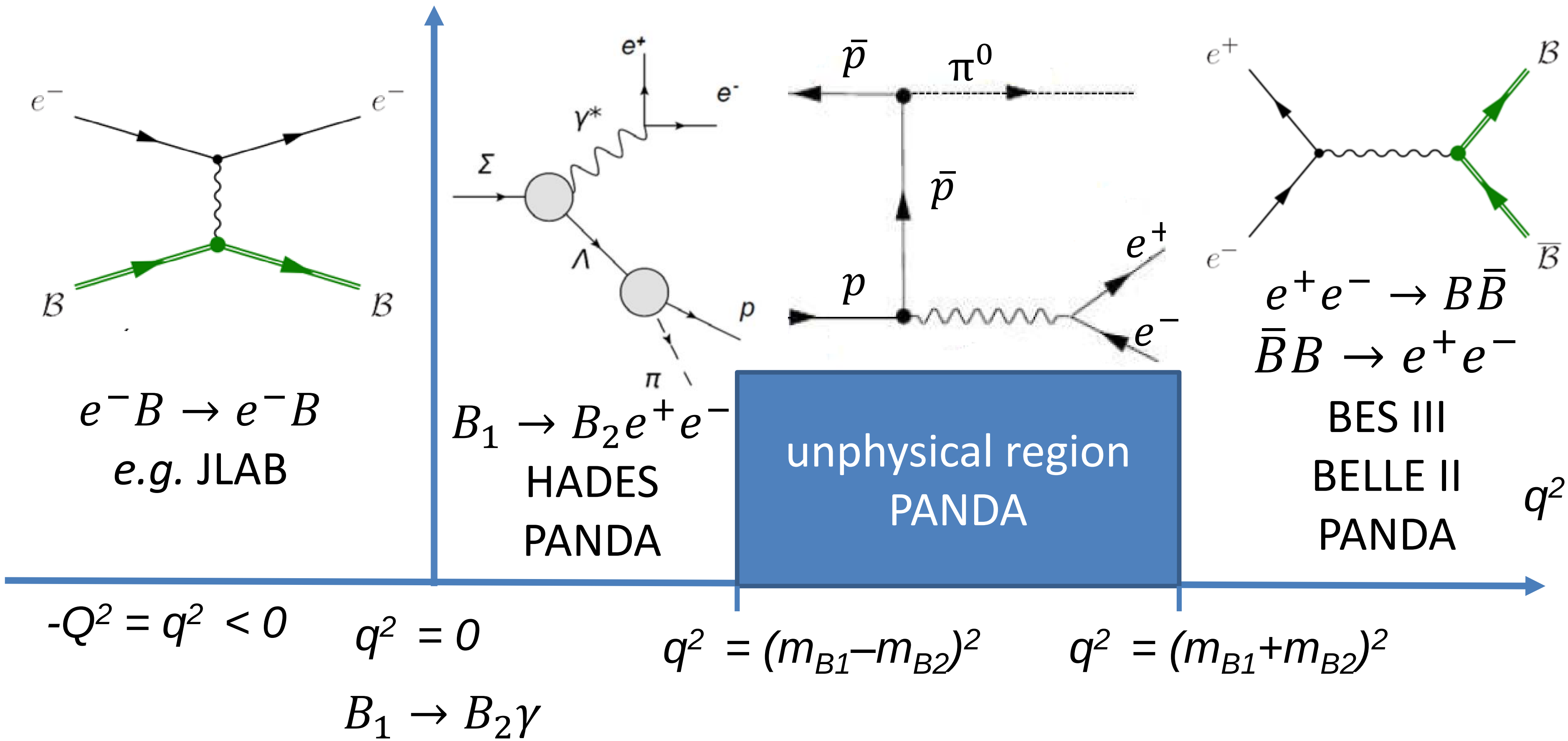
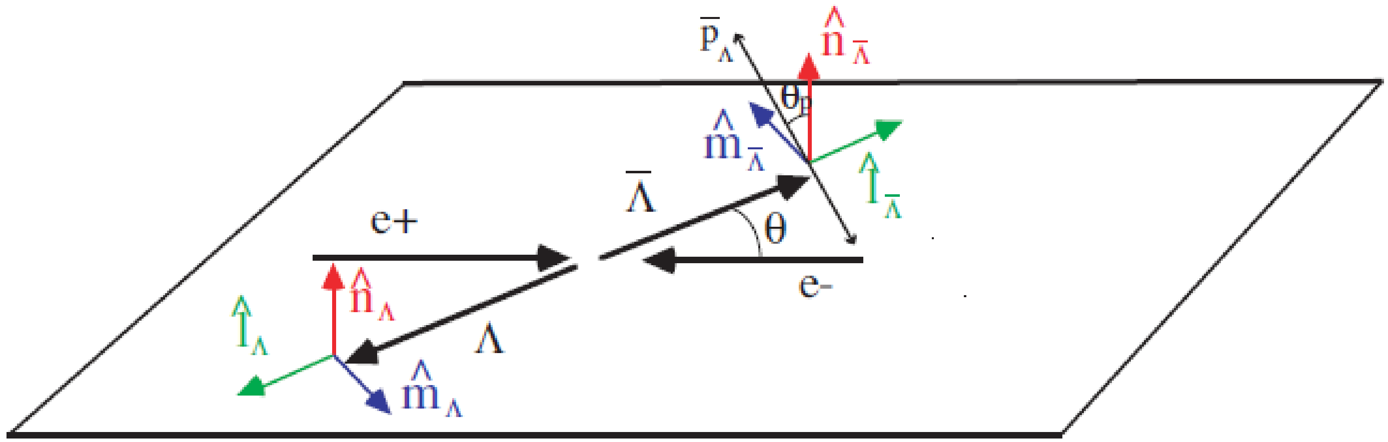
Space-like *vs.* time-like FF's



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 and scattering angle θ.
- **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 $|q^2| \to \infty$

The EMFF phase

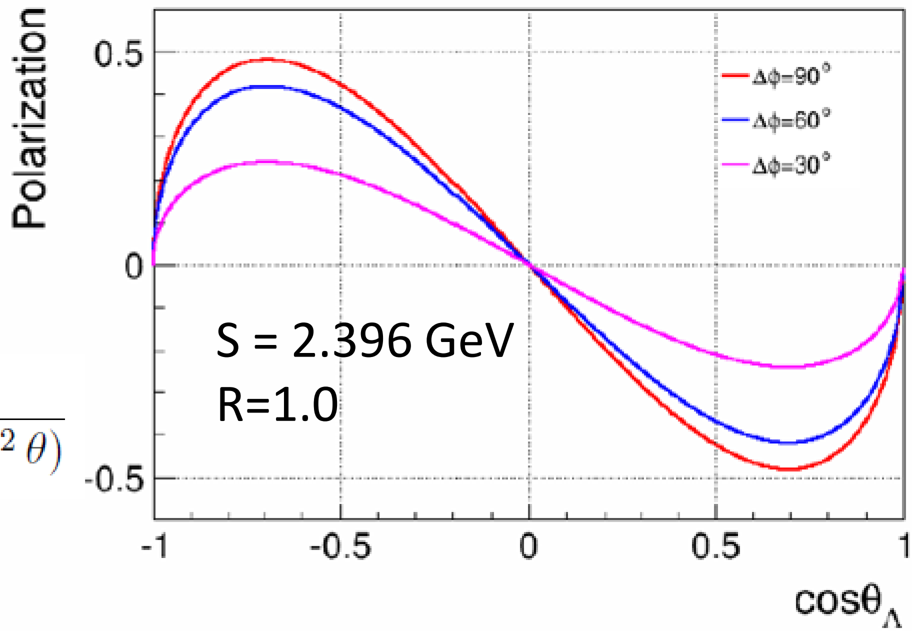
- Imaginary part polarizes the final state baryons*:

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

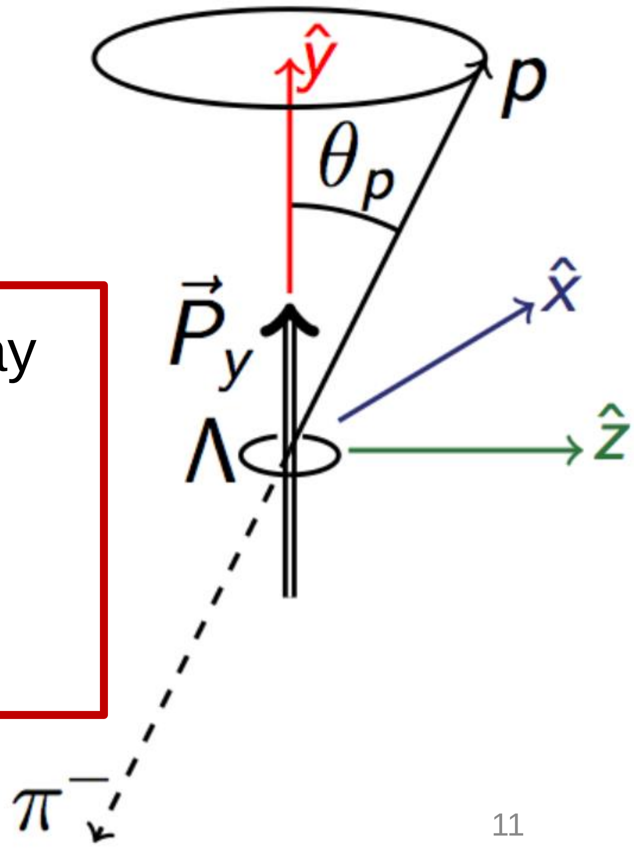
Polarization experimentally accessible by the weak, parity violating decay:

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

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

P_Λ : polarisation

α = 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 correctly.
- 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 correctly.
- 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.

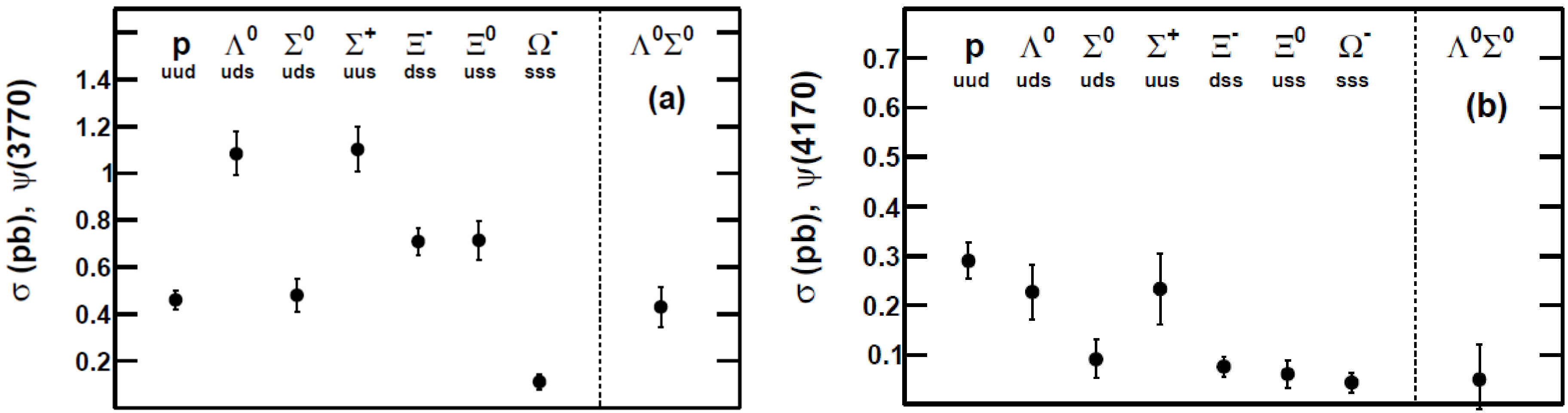
Recent experimental results

- See talks and posters by:
  - Monica Bertani (general time-like EMFF’s)
  - Rinaldo Baldini Ferroli (anomalies in baryon EMFF’s)
  - Xiaorong Zhou (EMFF’s of the strange Λ hyperon)
  - Weiping Wang (EMFF’s of the charmed Λ_c hyperon)

Recent experimental results

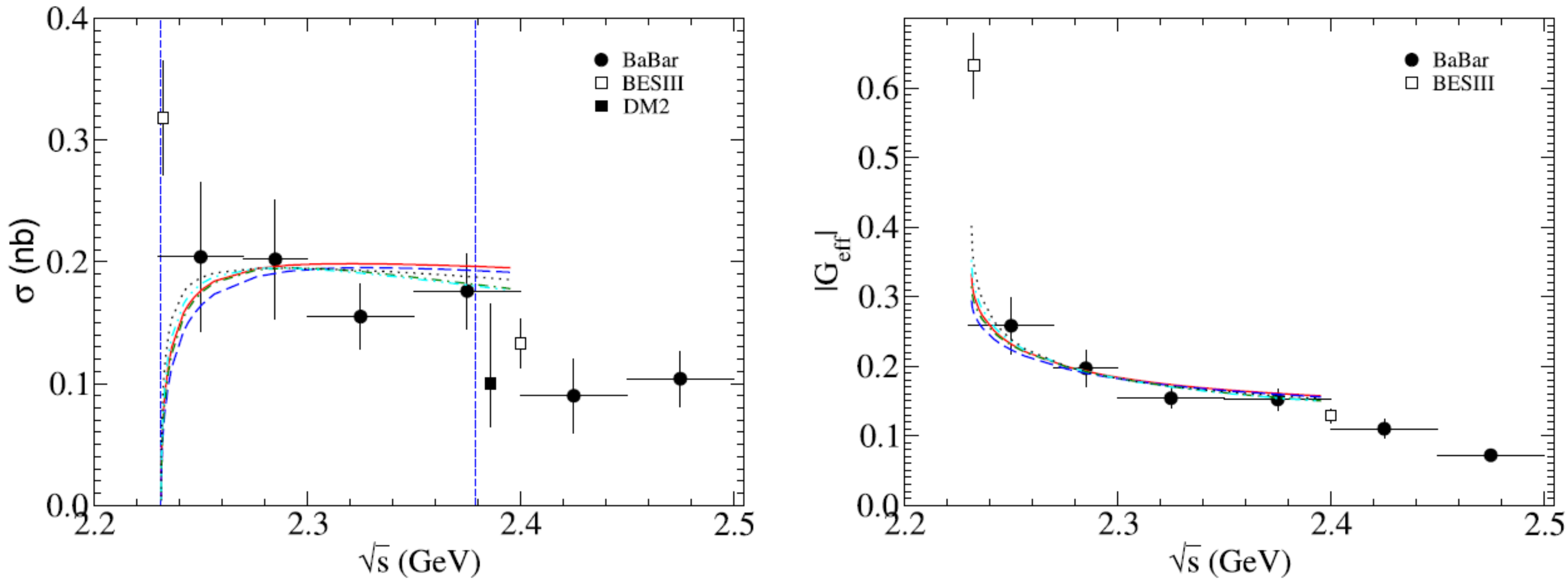
CLEO-c:

- 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.

Recent theory predictions



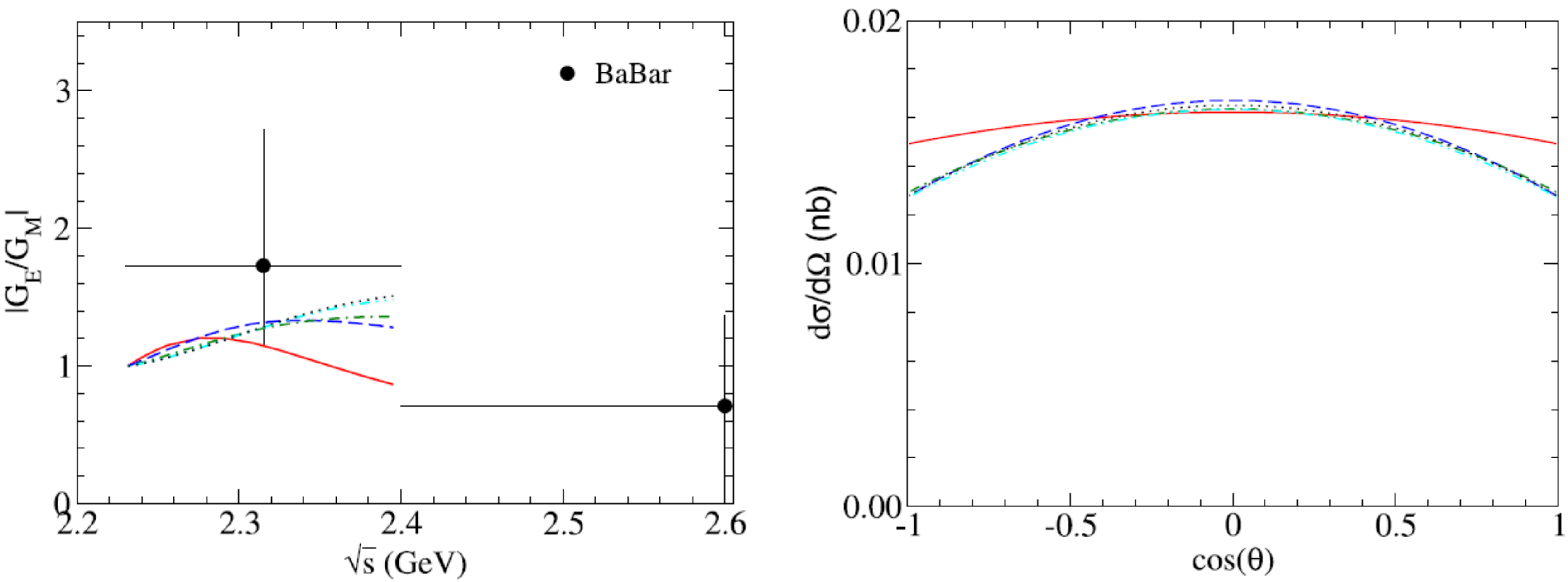
- Time-like EMFF's of Λ studied by Haidenbauer and Meissner*.
- Special focus on $\Lambda\bar{\Lambda}$ final state interaction.
- $\Lambda\bar{\Lambda}$ potentials fitted to $\bar{p}p \to \bar{\Lambda}\Lambda$ data from PS185**

Predictions for $\sigma(e^+e^- \to \Lambda\bar{\Lambda})$ and $|G_{eff}|$:

- Small difference between different $\Lambda\bar{\Lambda}$ potentials*.

*PLB 761 (2016) 456.
** Phys. Rep. 368 (2002) 119.

Recent theory predictions

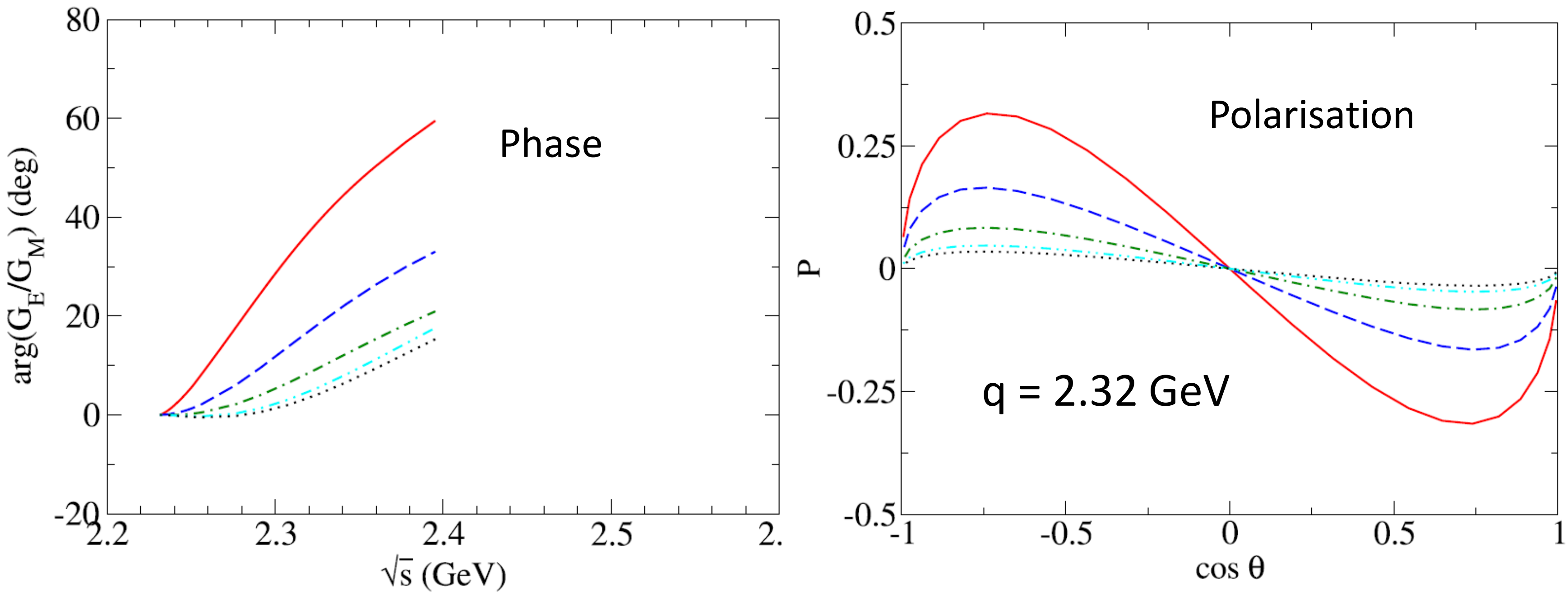


Predictions for $R = |G_E|/|G_M|$:

- Larger difference between different $\Lambda\bar{\Lambda}$ potentials*.
- Comparison to previous data* inconclusive.

*PLB 761 (2016) 456.
** PRD 76 (2007) 092006.

Recent theory predictions



- Different potential models give different values of the phase.
- What do data tell us?

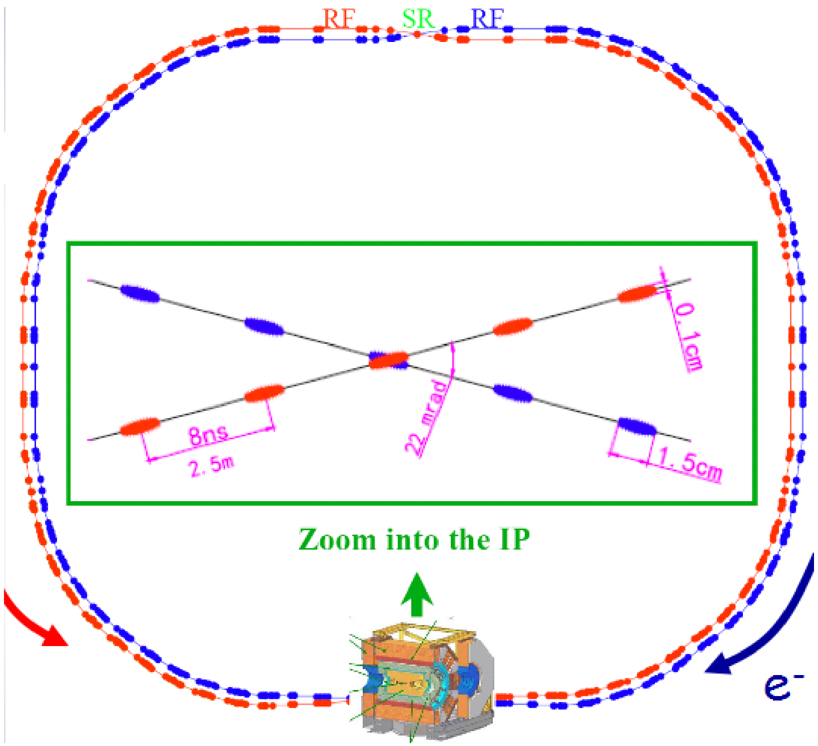
*PLB 761 (2016) 456.

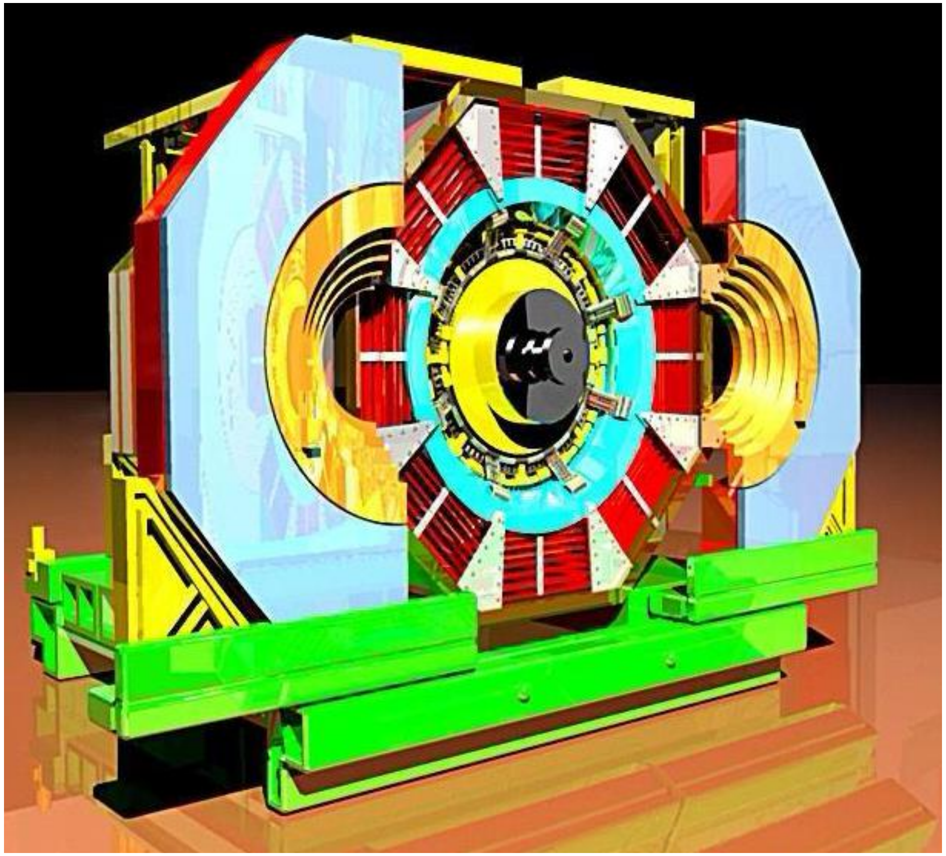
New data from BES III @ BEPC II

BES III in Beijing, China, excellent for baryon TL EMFF's!

BES III @ BEPC-II

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

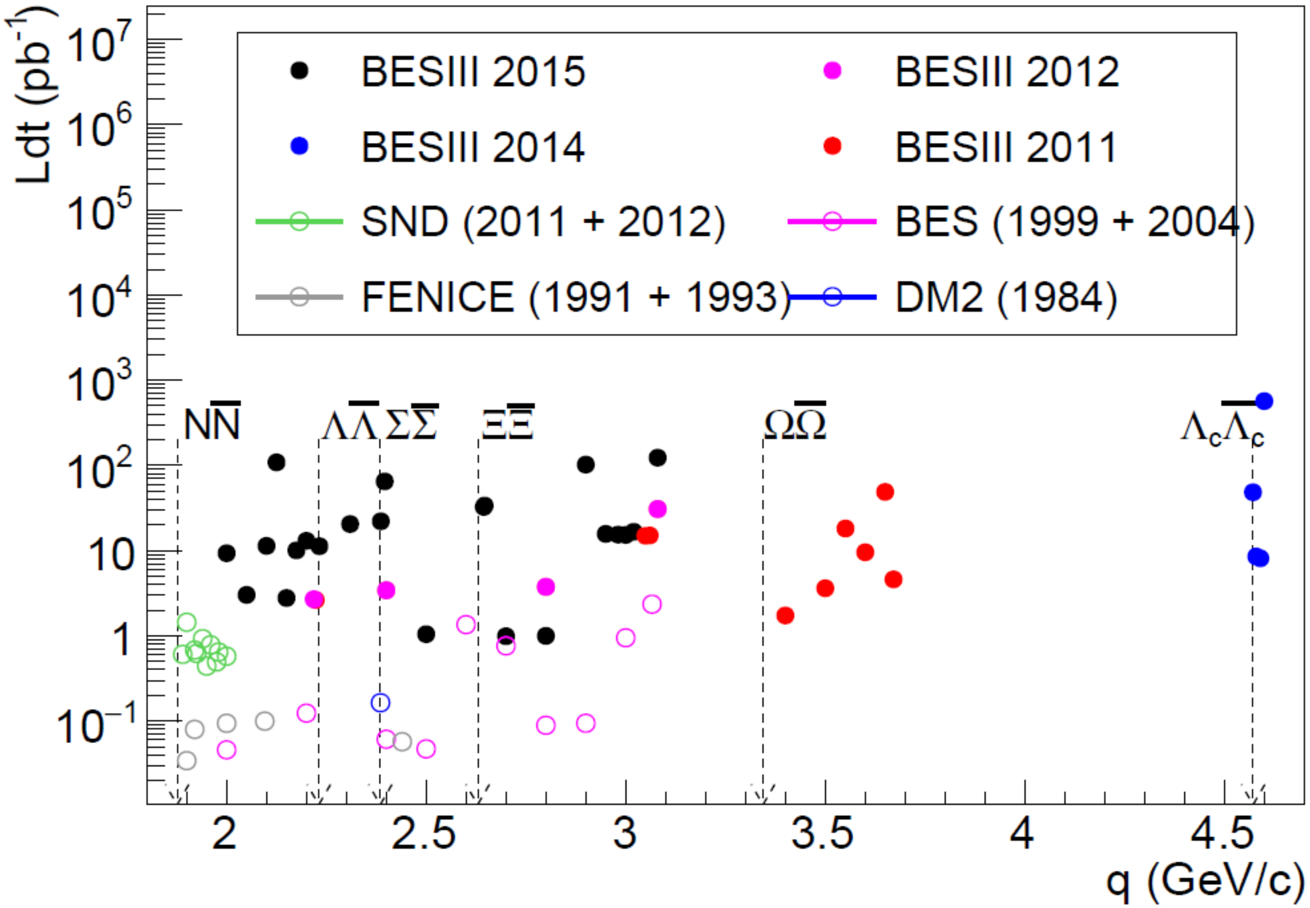




- BES III = Beijing Spectrometer
  - Wide physics scope
  - More details in talk by C. Rosner

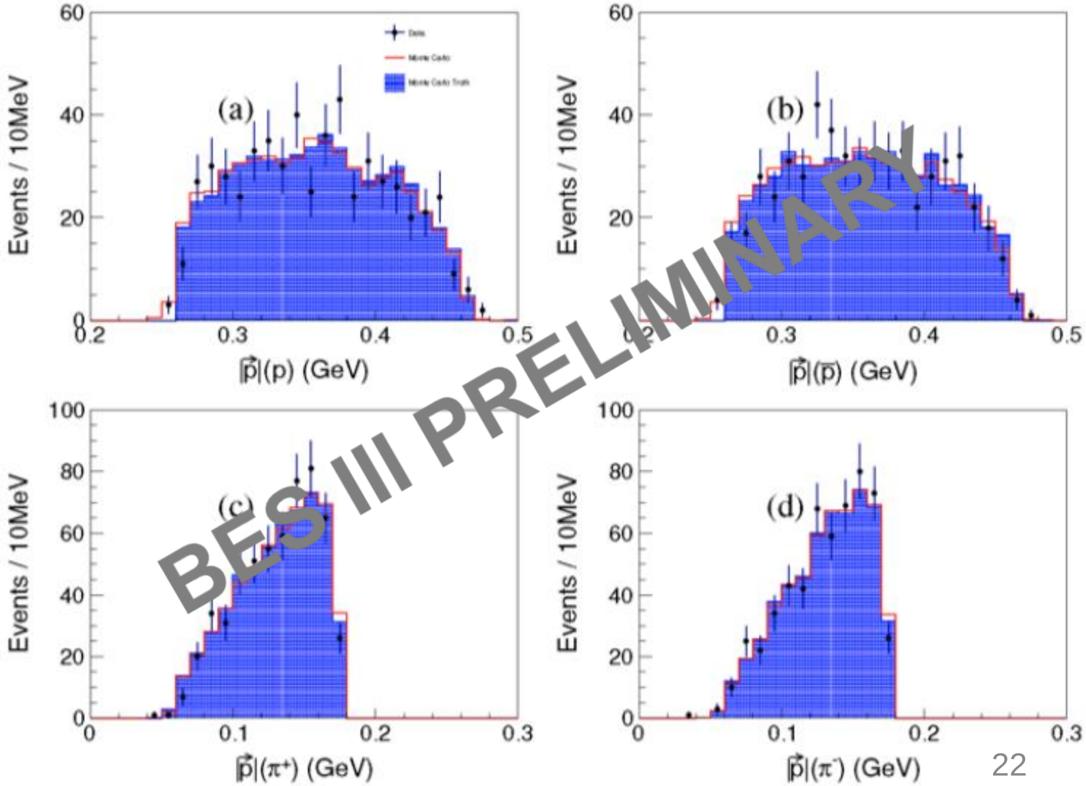
Energy scan 2014-2015

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



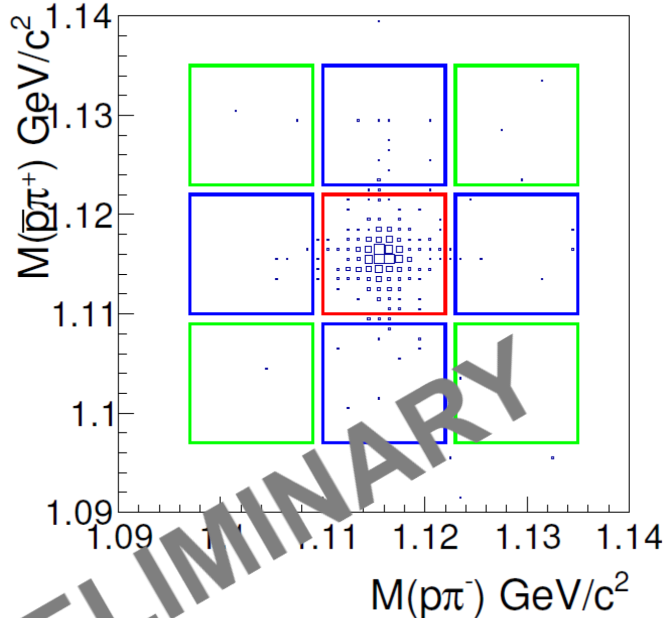
Measurement of Λ EMFF with BES III

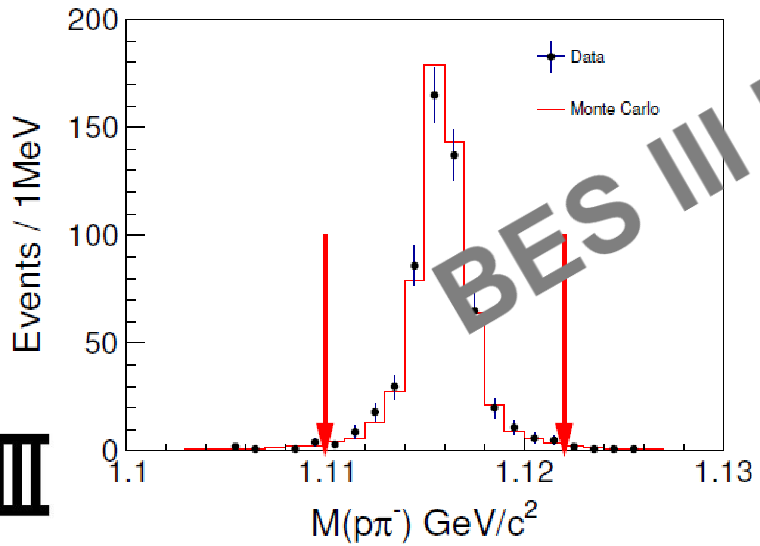
- Large data sample at 2.396 GeV.
- Exclusive event selection: $e^+e^- \to \Lambda\bar{\Lambda}, \Lambda \to p\pi^-, \bar{\Lambda} \to \bar{p}\pi^+$:
  - ≥ 4 tracks within the MDC
  - $p_p > 0.2$ GeV
  - $p_\pi < 0.2$ GeV
  - Vertex fit
  - 4C fit

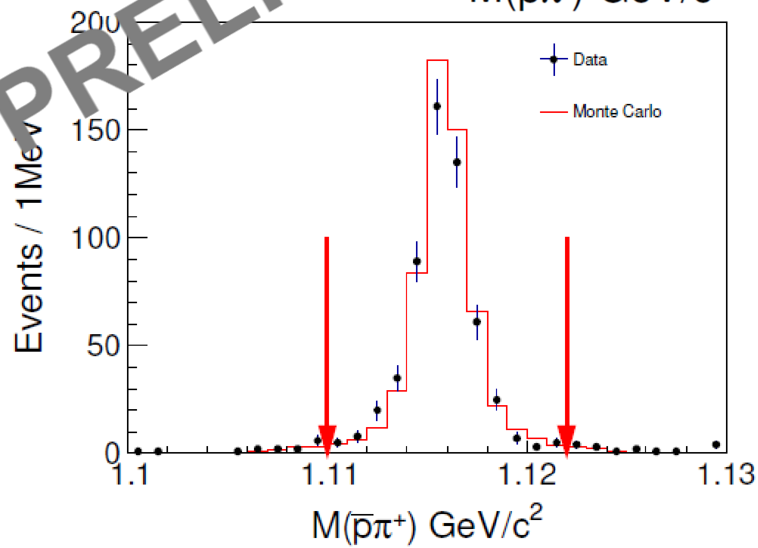


Measurement of Λ EMFF with BES III

- Invariant mass cut:
  $|M(p\pi) - M_{\Lambda}| < 0.006$ GeV/c²
- $N_{signal} = 555 \pm 24$
- $N_{sidebands} = 14 \pm 4$







Measurement of Λ EMFF with BES III

Cross section:

$$\sigma = \frac{N_{signal}}{L\varepsilon(1+\delta)BR(\Lambda \to p\pi^-)BR(\bar{\Lambda} \to \bar{p}\pi^+)} = \boxed{\mathbf{119.0 \pm 5.3 \pm 7.3\ pb}}$$

- $(1+\delta)$ ISR correction based on model by Czyz* *et al.*
- $\varepsilon = 17.7\%$
- $L = 66.9 \pm 0.02 \pm 0.5\ pb^{-1}$
- $BR(\Lambda \to p\pi^-) = BR(\bar{\Lambda} \to \bar{p}\pi^+) = 0.64\%$

Effective form factor:

$$|G(q^2)| = \sqrt{\frac{\sigma}{1+\frac{1}{2\tau}(\frac{4\pi\alpha^2\beta}{3q^2})}} = \boxed{\mathbf{0.123 \pm 0.003 \pm 0.004}}$$

- $\tau = \frac{q^2}{4m_\Lambda^2}$, $\beta = \sqrt{1-\frac{1}{\tau}}$, $\alpha = \frac{1}{137}$

*PRD 75 (2007) 074026

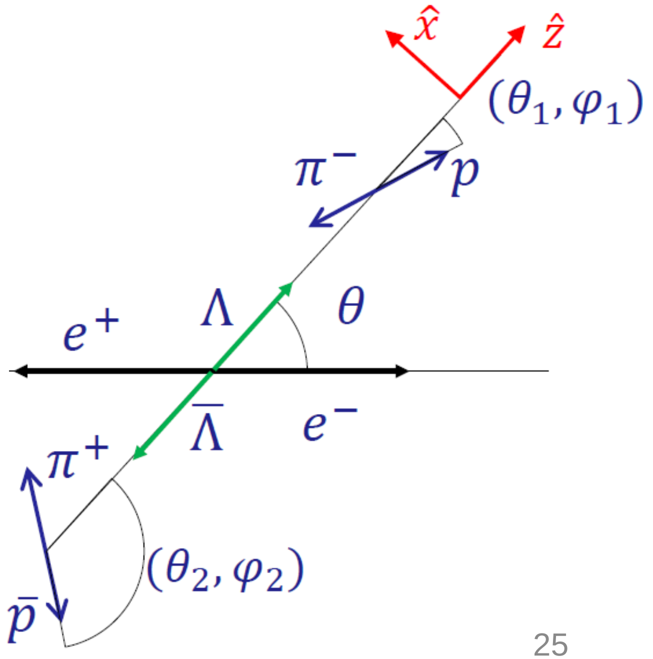
Measurement of Λ EMFF with BES III

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

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

Eq. 3

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



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

*PLB 772 (2017) 16.

Measurement of Λ EMFF with BES III

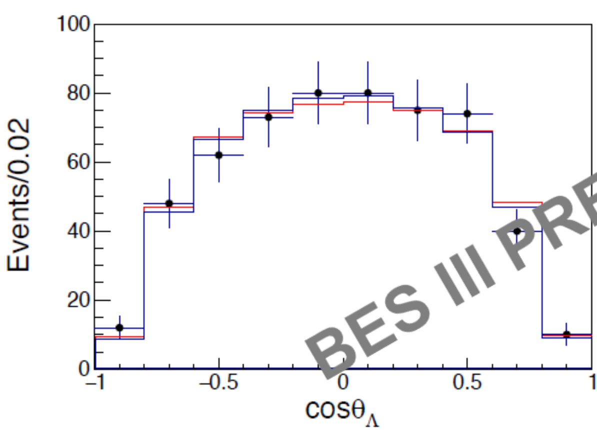
- Eq. 3 fitted to data using an unbinned Maximum Likelihood fit.
- Result:
  - $R = \mathbf{0.94 \pm 0.16 \pm 0.03}$ $(\pm 0.02\ \alpha_\Lambda)$
  - $\Delta\Phi = \mathbf{42^o \pm 16^o \pm 8^o}$ $(\pm 6^o\ \alpha_\Lambda)$

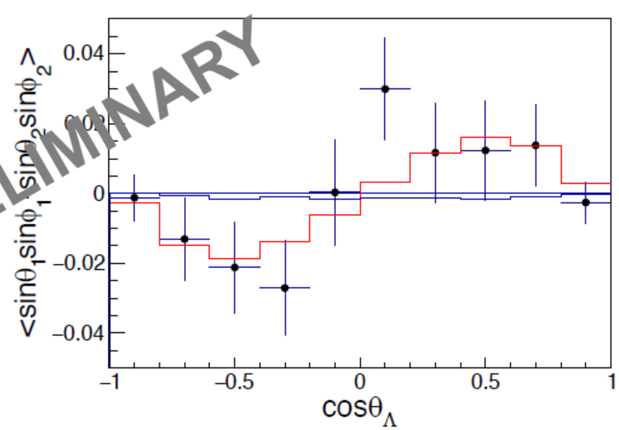
←**BES III PRELIMINARY**

- Most **precise** result on *R*

  (BaBar: $R = 1.73^{+0.99}_{-0.57}$ in $2.23 < q < 2.40$ GeV*)
- **First** conclusive result on $\Delta\Phi$

  (BaBar: $-0.76 < sin\Delta\Phi < 0.98$ in $2.23 < q < 2.80$ GeV*)





*PRD 76 (2007) 092006.

Measurement of Λ EMFF with BES III

Systematic uncertainties:

- New BES III results on $J/\Psi \to \Lambda\bar{\Lambda}$ suggest $\alpha_\Lambda = 0.64 \to \alpha_\Lambda = 0.75$

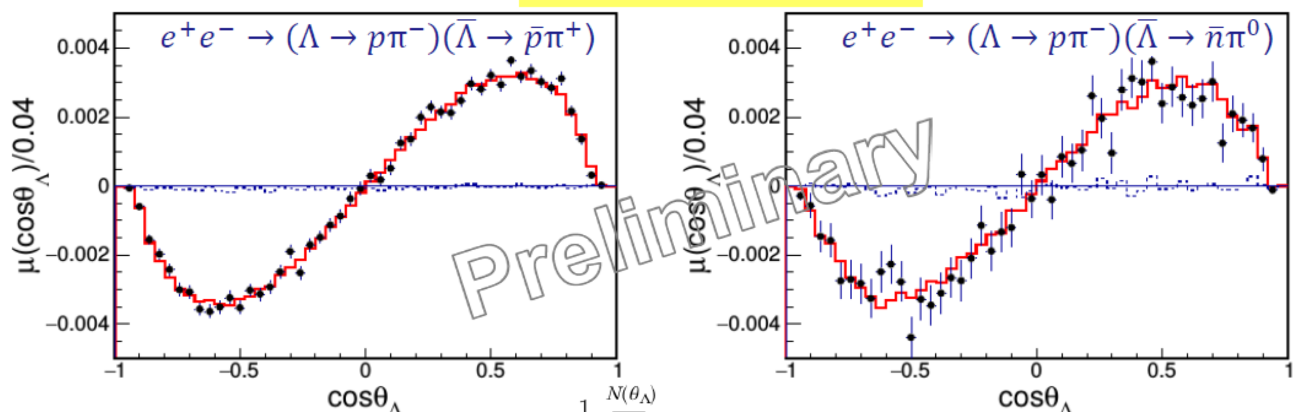
  $\to$ Impact on our $\Delta\Phi$ result.

NB: $\Delta\Phi$ result at J/Ψ consistent with our finding.

Source	$R(\%)$	$\Delta\Phi(\%)$
$\chi^2(4C)$ cut	2.8	16.8
mass window of $p\pi$	0.1	5.5
different range of $\cos\theta_\Lambda$	1.3	6.8
total	3.1	18.9
different α_Λ	2.0	13.7

BES III PRELIMINARY

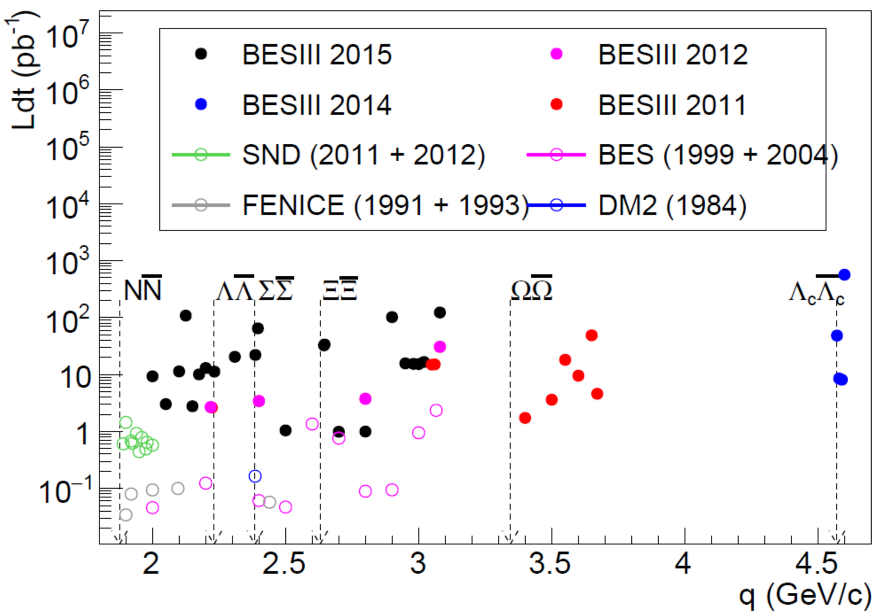
$\Delta\Phi = 42.3^\circ \pm 0.6^\circ \pm 0.5^\circ$



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

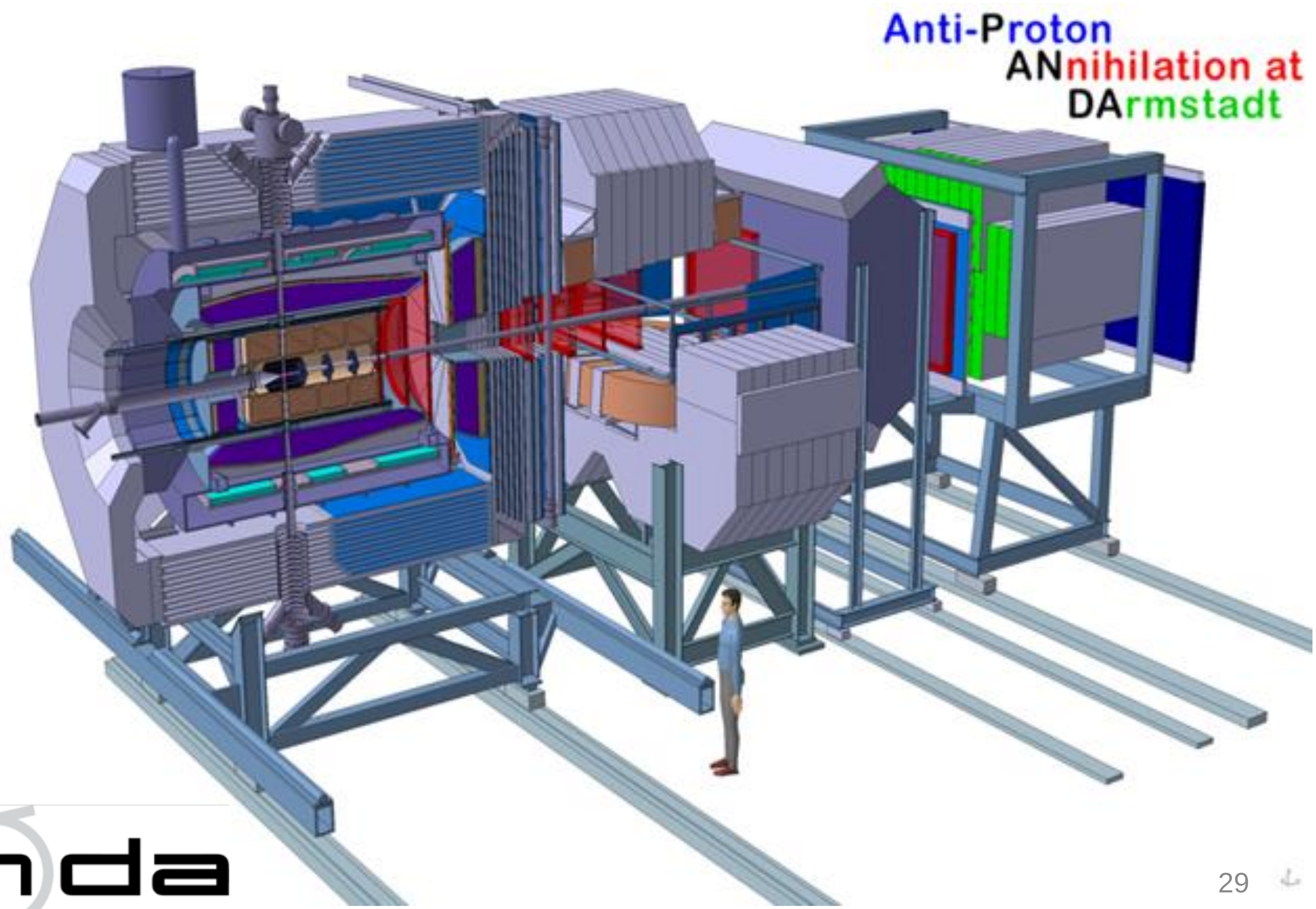
Future at BES III

- 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!

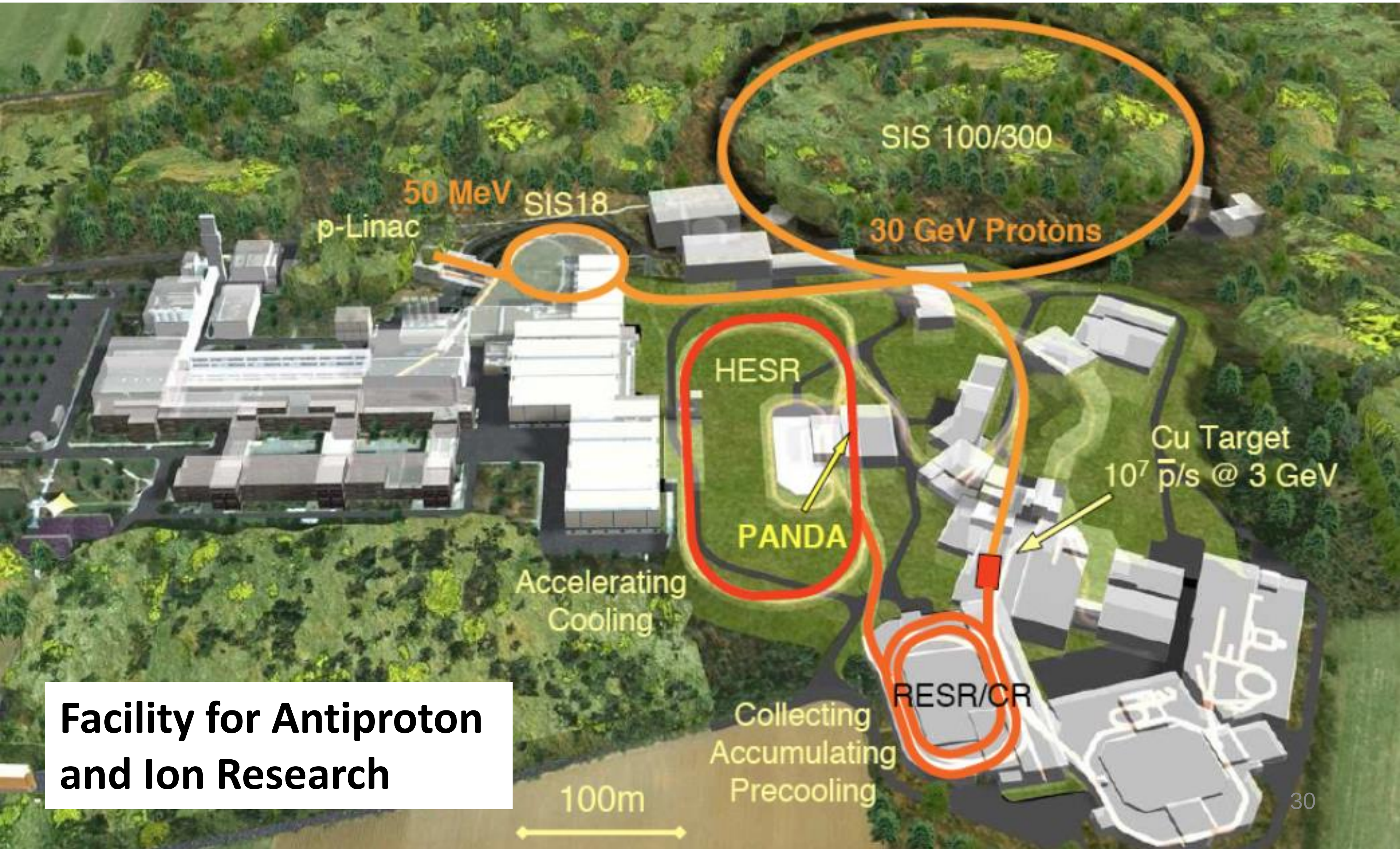


STAY TUNED!

Future at PANDA



The PANDA experiment at FAIR

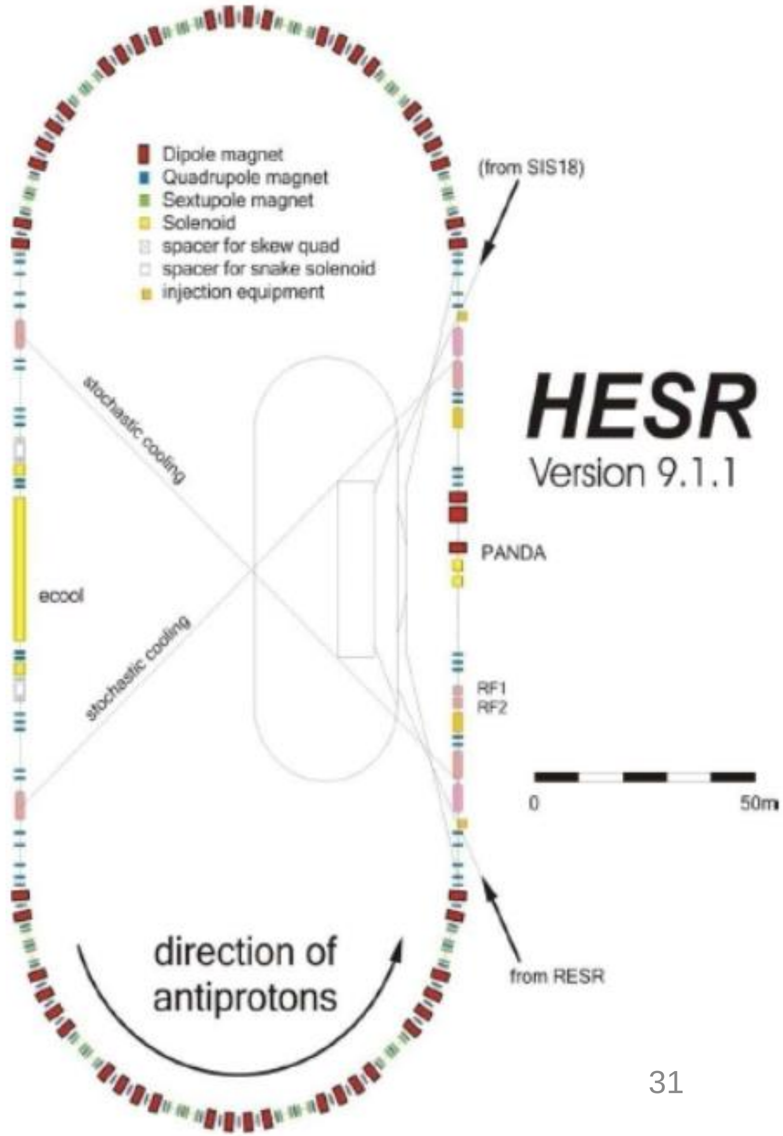


Facility for Antiproton and Ion Research

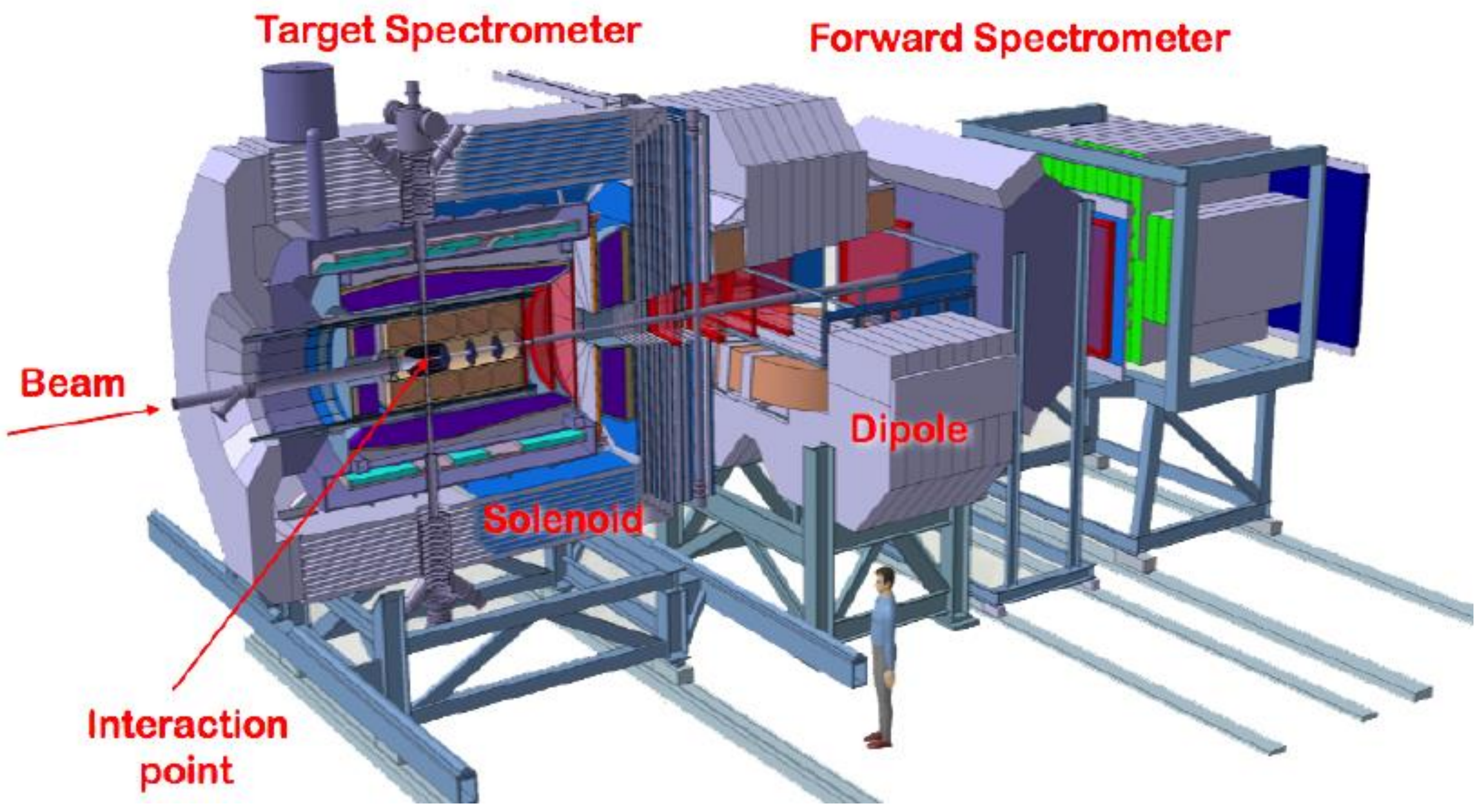
The PANDA experiment at FAIR

The High Energy Storage Ring (HESR)

- Anti-protons within
  1.5 GeV/c < p_{pbar} < 15 GeV/c
- Cluster jet or pellet targets
- *Day One* luminosity: 10^{31} $cm^{-2}s^{-1}$



The PANDA experiment at FAIR

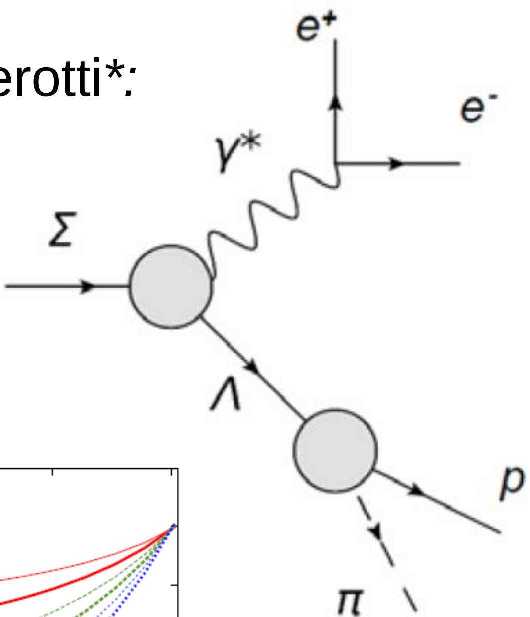


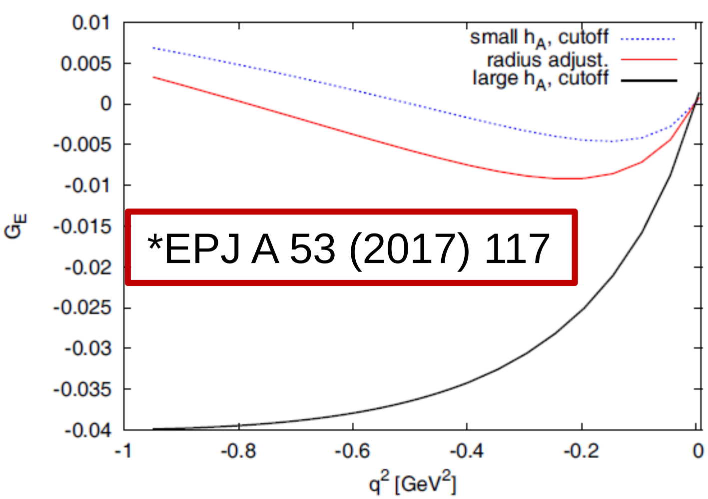
- 4π coverage
- Precise tracking
- PID
- Calorimetry

- Vertex detector
- Modular design
- Time-based data acquisition with software trigger

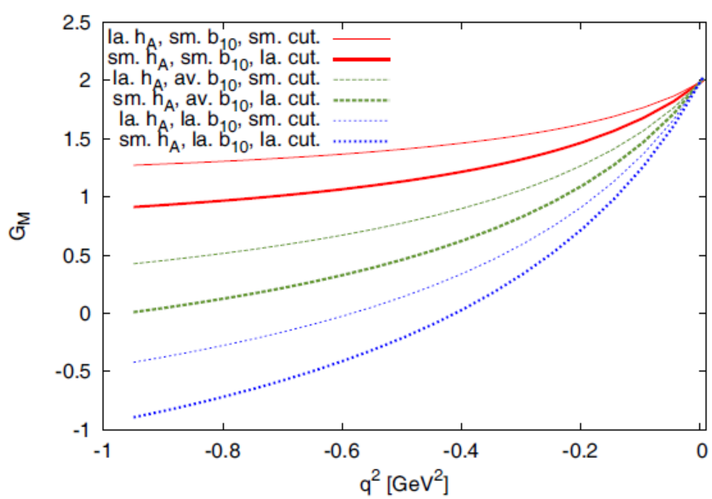
Possibilities with PANDA

- Transition form factors accessible from hyperon Dalitz decays.
- Possible in case of *e.g.* Σ^0 and $\Lambda(1520)$.
- Theory predictions by Granados, Leupold and Perotti*:
  - χPT and Dispersion Theory.
  - Comprehensive framework developing.
  - First calculations for $\Sigma^0 \to \Lambda e^+ e^-$.
  - Slope of G_M of special interest.





*EPJ A 53 (2017) 117

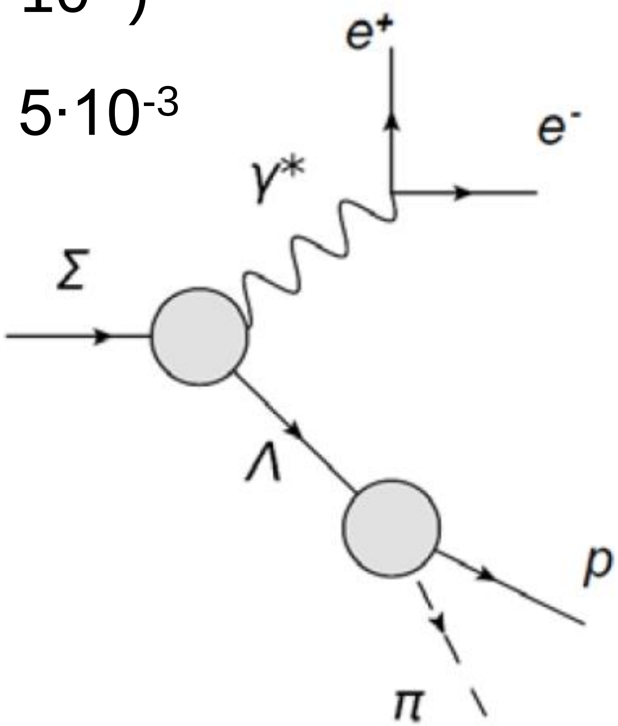


Possibilities with PANDA: Hyperons

Experimental challenge:

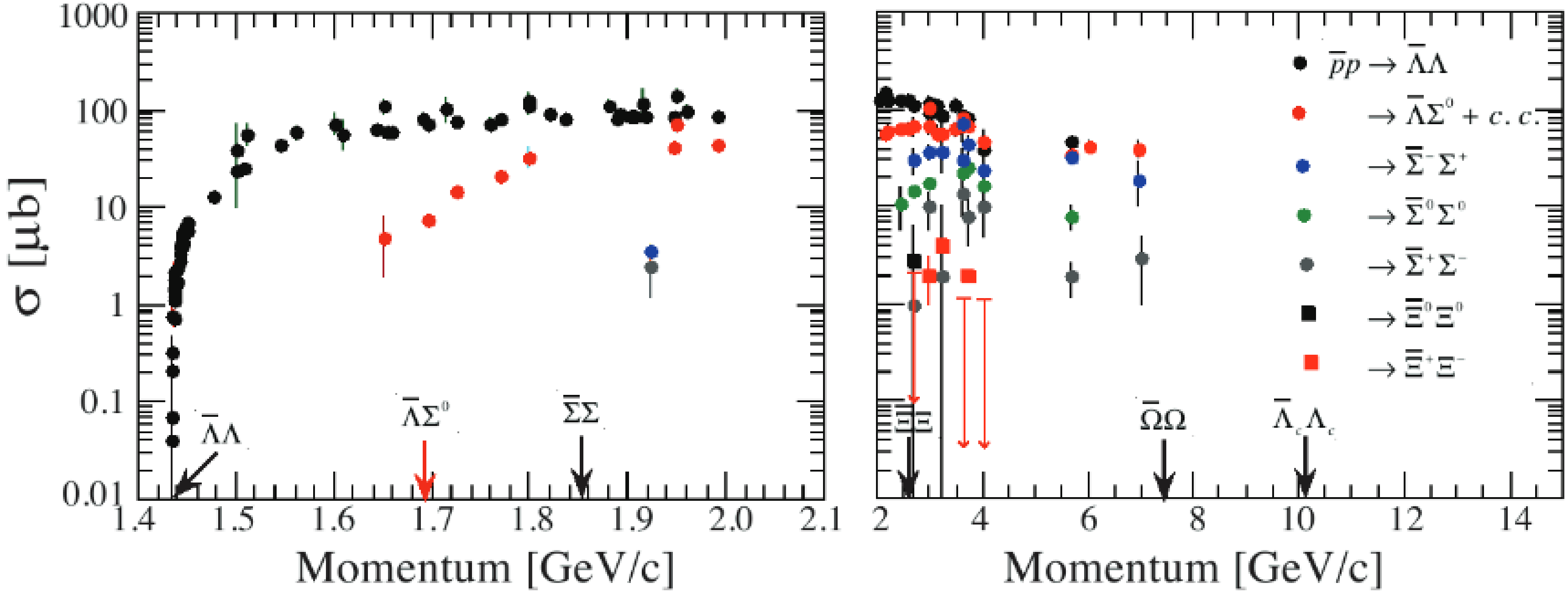
- Typically small predicted BR's (10^{-3} - 10^{-6})
- QED prediction for BR($\Sigma^0 \rightarrow \Lambda e^+ e^-$): $5 \cdot 10^{-3}$

$\rightarrow$ Need very high hyperon production rates!



Possibilities with PANDA: Hyperons

Figure from T. Johansson, AIP Conf. Proc. of LEAP 2003, p. 95.



- PANDA is a hyperon factory!
- Large cross sections of *e.g.* Σ^0 channels:
  - $\sigma(\bar{p}p \to \bar{\Lambda}\Sigma^0 + c.c.)$ ~40 *μb* at 4 GeV
  - $\sigma(\bar{p}p \to \bar{\Sigma}^0\Sigma^0)$ ~20 *μb* at 4 GeV

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Possibilities with PANDA: Hyperons

- Simulation study of $\bar{p}p \to \bar{\Lambda}\Sigma^0 + c.c., \Sigma^0 \to \Lambda\gamma$ by S. Grape (PhD thesis, UU 2009): Σ^0 production rates of

  - 30 s^{-1} at Day One luminosity
  - 600 s^{-1} at design luminosity

- Back-of-the-envelope calculation of the Dalitz decay rate:

$$\frac{dN_{\Lambda e^+e^-}}{dt} = \frac{dN_{\Lambda\gamma}}{dt} \bullet BR(\Sigma^0 \to \Lambda e^+e^-) \frac{\varepsilon(\Lambda e^+e^-)}{\varepsilon(\Lambda\gamma)}$$

$0.5 \cdot \varepsilon(\Lambda e^+e^-)\ s^{-1}$ with PANDA Day One

$10 \cdot \varepsilon(\Lambda e^+e^-)\ s^{-1}$ with HESR design luminosity

panda

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Possibilities with PANDA: Hyperons

With a $\Lambda e^+ e^-$ efficiency of 10% and Day One luminosity, we would get

➢ 1000 events per day!

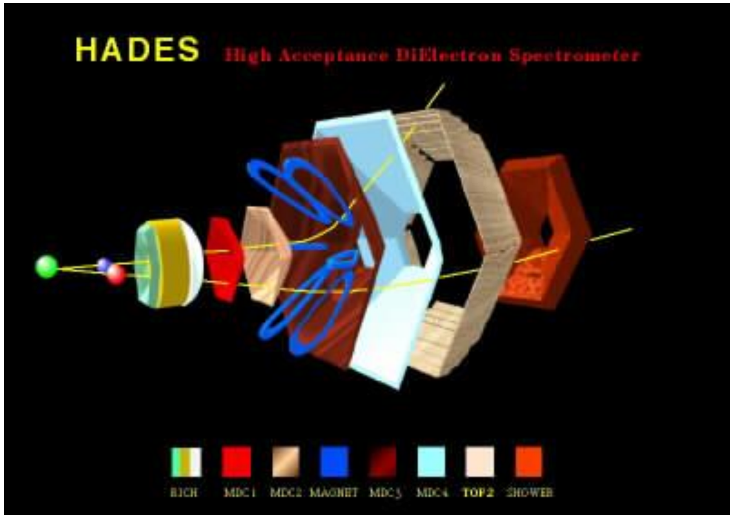
Simulation studies underway!

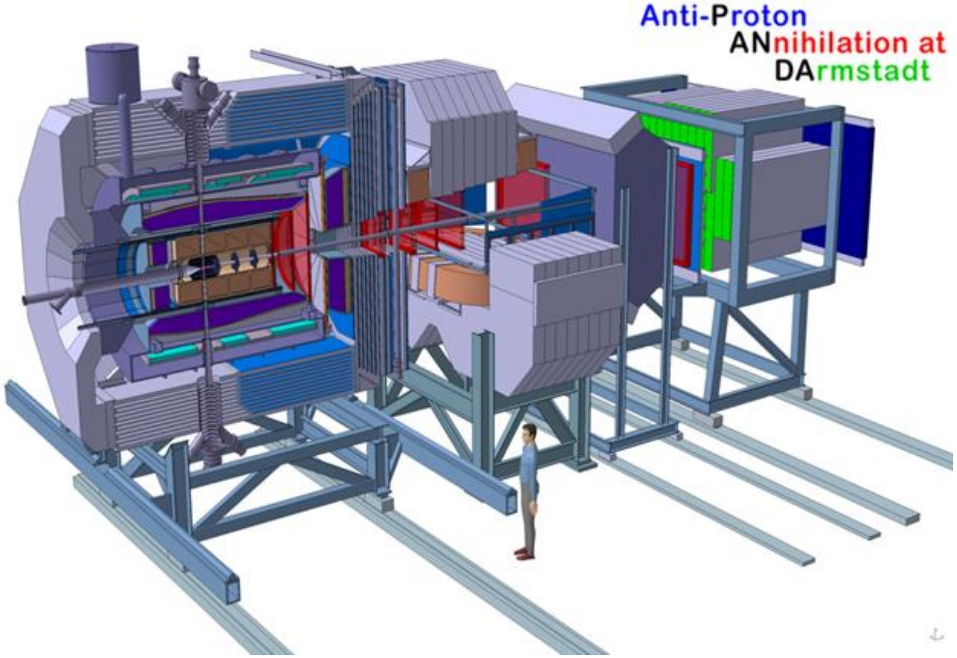
$$\frac{dN_{\Lambda e^+ e^-}}{dt} = \frac{dN_{\Lambda\gamma}}{dt} \bullet BR(\Sigma^0 \to \Lambda e^+ e^-) \frac{\varepsilon(\Lambda e^+ e^-)}{\varepsilon(\Lambda\gamma)}$$

$0.5 \cdot \varepsilon(\Lambda e^+ e^-)\ s^{-1}$ with PANDA Day One

$10 \cdot \varepsilon(\Lambda e^+ e^-)\ s^{-1}$ with HESR design luminosity

Possibilities with PANDA





While waiting for PANDA@HESR:
PANDA@HADES!

See talk by J. Ritman

Summary

- Hyperons provide a new angle to hadron structure.
- Polarisation measurements give information about the EMFF phase.
- BESIII:
  - Unique large-scale energy scan → 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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Summary

- PANDA:
  - Hyperon transition FF's accessible in Dalitz decays:

    PANDA a hyperon factory!
  - Until then: PANDA@HADES

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Thanks for your attention!