Hyperon form factors with BES III and PANDA

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PANDA collaboration meeting

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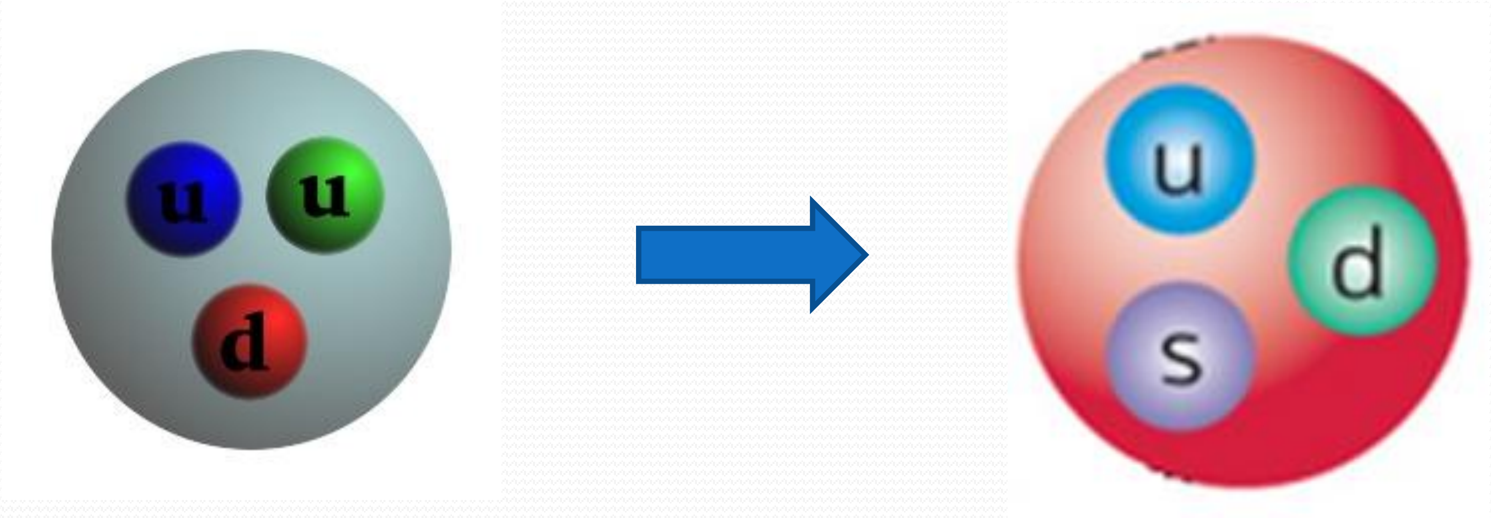
Outline

- Hyperons
- Electromagnetic Form Factors
- Measurement of TL FF's
- What can we do with BES III?
- What can we do with PANDA?

Hyperons

Key question:

What happens if we replace one of the light quarks in the nucleon with a heavier quark?

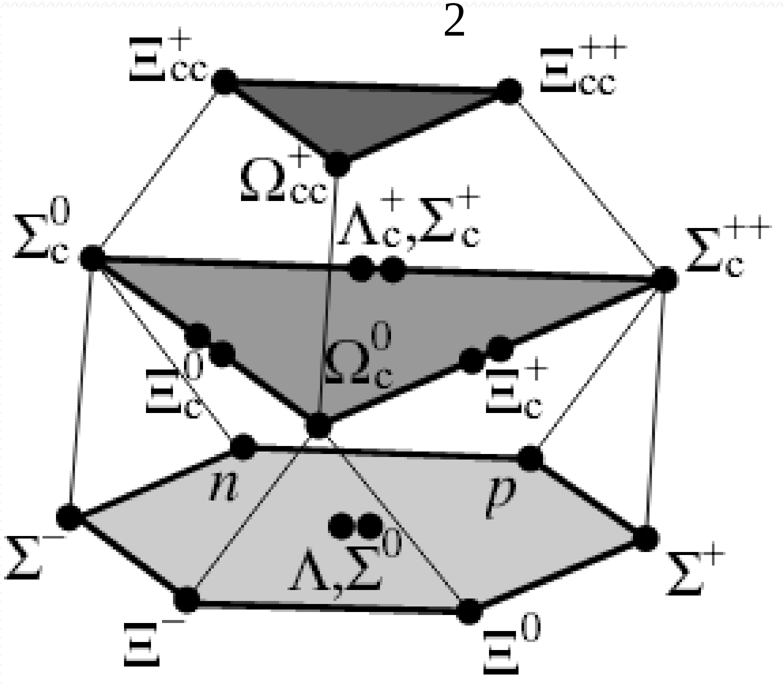


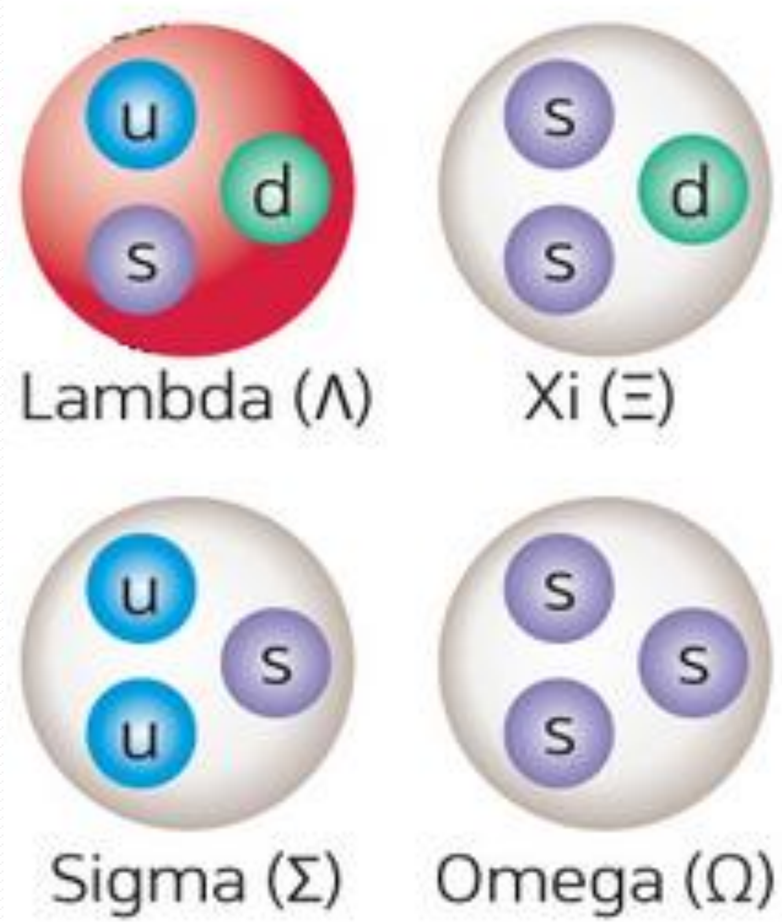
Hyperons

- **Hyperons** contain one or more *s*, *c* or *b* quarks instead of *u* or *d*.

This talk: focus on Λ hyperons.

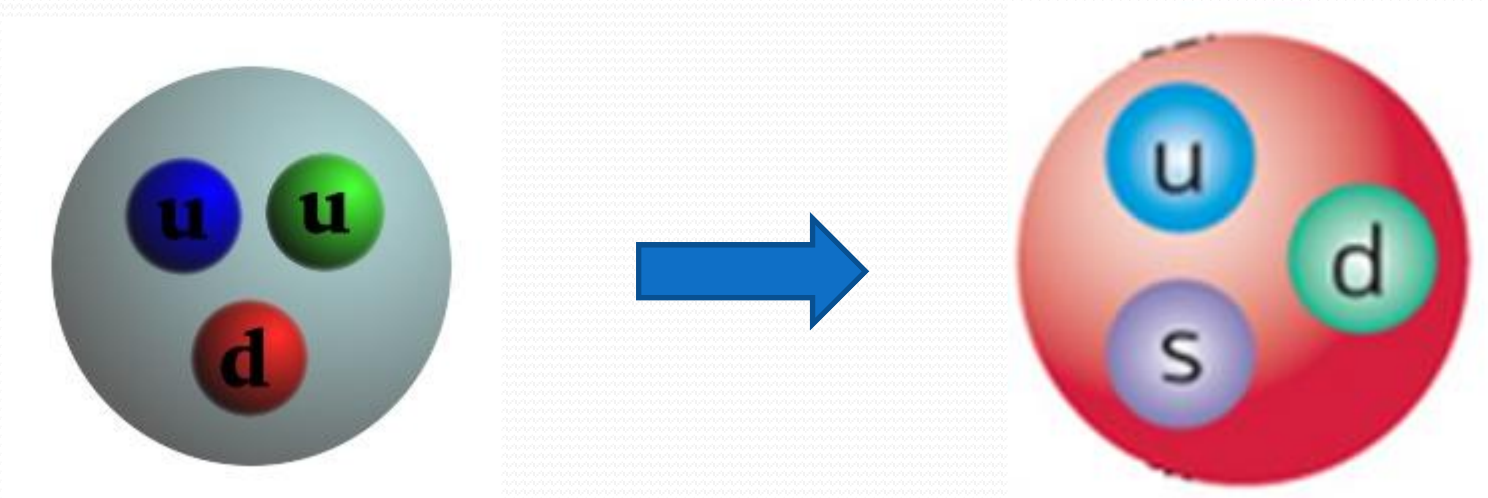
SU(4) Spin $\frac{1}{2}^{+}$ 20-plet





Hyperons

- Production mechanism
- Spin observables
- Structure



Hyperons

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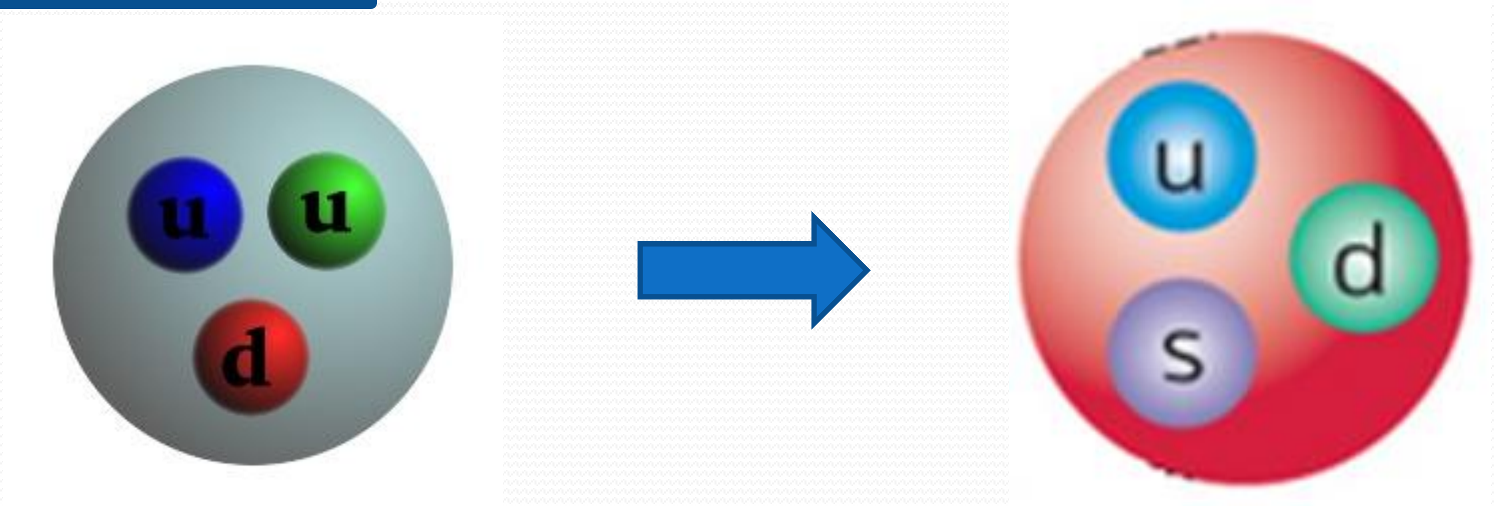
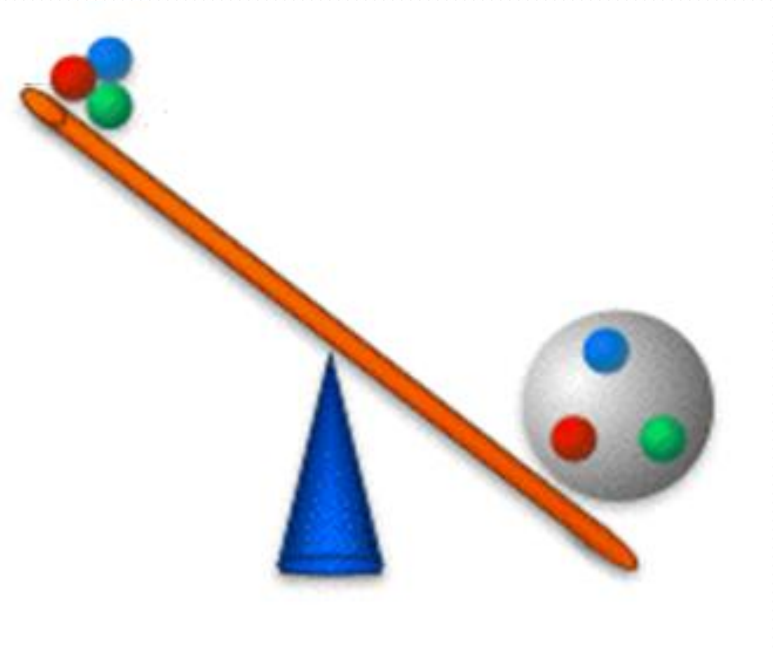


Hyperons

Baryon masses:



- $M(uud)/M(p) \sim 1\%$
- $M(uds)/M(\Lambda) \sim 15\%$
- $M(udc)/M(\Lambda_c) \sim 56\%$
- $M(udb)/M(\Lambda_b) \sim 75\%$

Comparing hyperons: SU(N) symmetry tests.

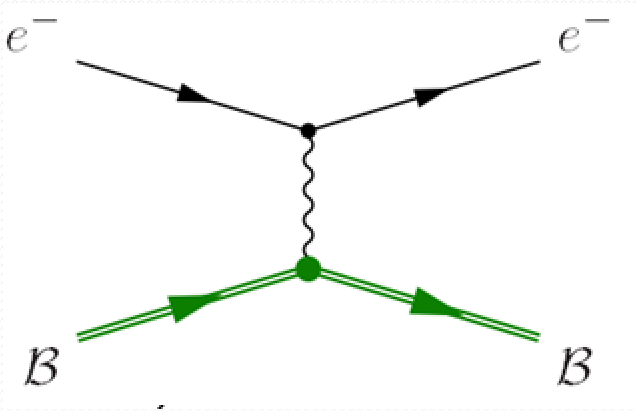
Electromagnetic form factors

- Fundamental hadron structure observable.
- Describes the deviation from the point-like case.
- Related to the charge- and magnetization density.

Time-like *vs.* space-like FF's

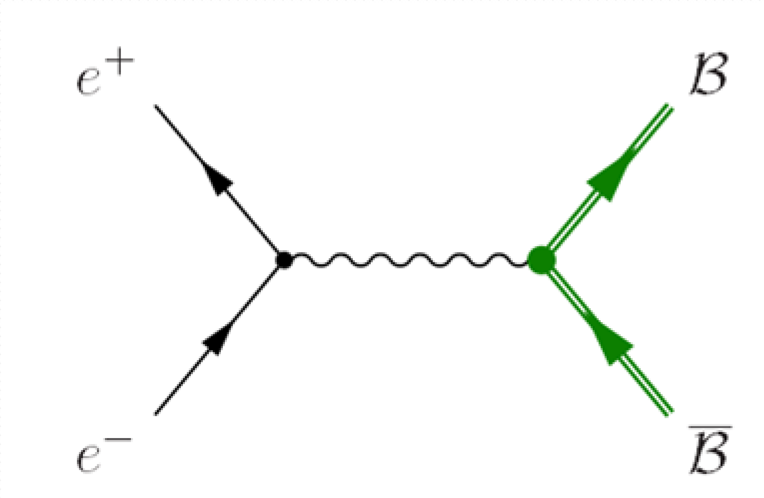
Space-like:

- Studied in $e^- N \rightarrow e^- N$ scattering.
- $q^2 = (p_{ie} - p_{fe})^2 < 0$.
- G_E and G_M real numbers.
- Nucleons studied since the 1960:s.

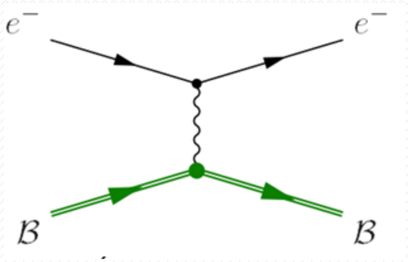


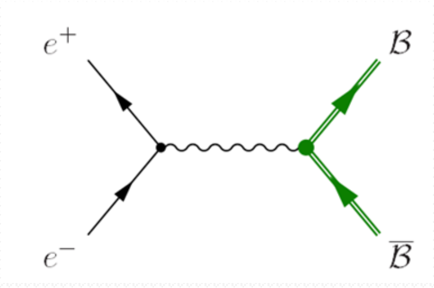
Time-like:

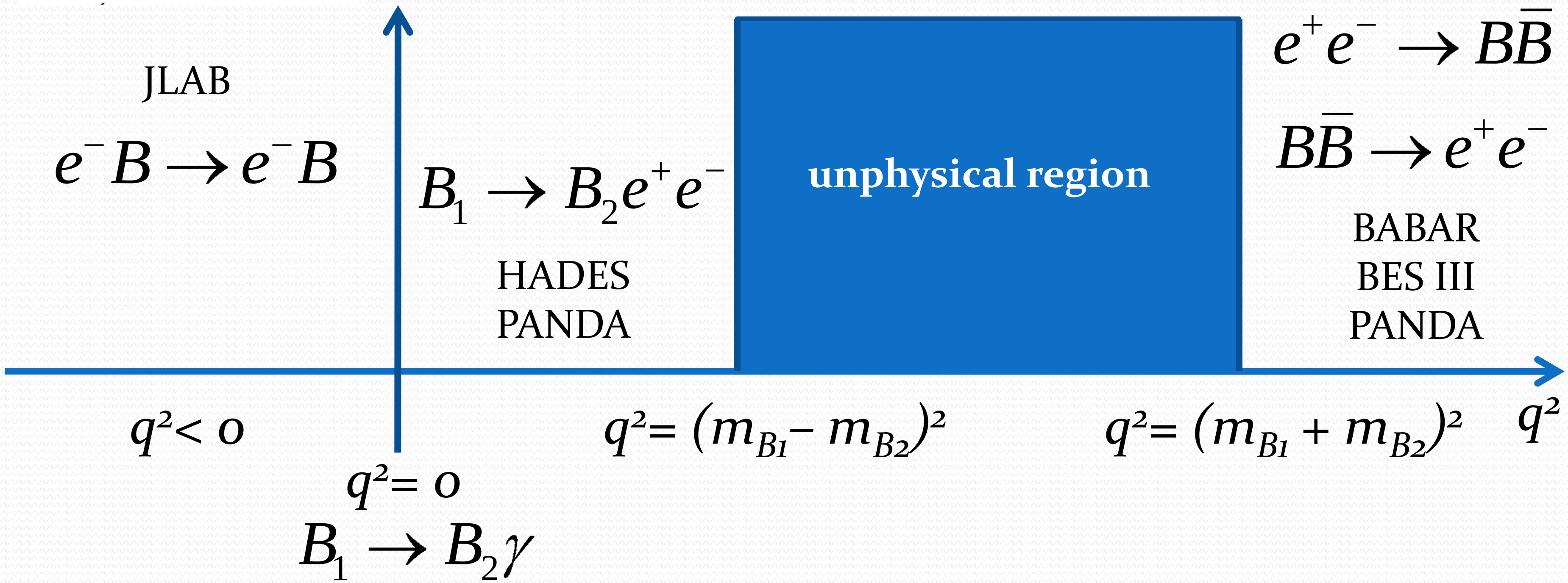
- $e^- e^+ \rightarrow B\bar{B}$
- $p\bar{p} \rightarrow e^- e^+$
- $Q^2 = M^2_{B\bar{B}}$
- G_E and G_M complex numbers.



Time-like *vs.* space-like FF's







Time-like form factors

- Time-like FF's are complex:
  - $Im[G_E(Q^2)\, G_M^*(Q^2)] = |G_E(Q^2)|\, |G_M^*(Q^2)| \sin\Delta\Phi$
  - $Re[G_E(Q^2)\, G_M^*(Q^2)] = |G_E(Q^2)|\, |G_M^*(Q^2)| \cos\Delta\Phi$

  $\Delta\Phi$ is the relative phase between G_E and G_M

- The phase between G_E and G_M – polarisation effects on the final state even when the initial state is unpolarised.

- Crucial for testing models, especially in the soft-hard transition region (Q^2 = 10-15 GeV^2)

- Space-like and time-like FF's can be related *via* dispersion relations.

Time-like form factors

- Protons and neutrons:
  - Synergy between space-like and time-like FF's.
  - Time-like FF's should coincide with space-like at high $|Q^2| = |q^2|$.
- Hyperons:
  - Difference between nucleon and hyperon FF – SU(3) symmetry?
  - Currently the best way to study hyperon structure.
  - Polarisation observables experimentally accessible.

Measurement of TL FF's

Energy dependence of the total cross section: Effective form factor

$$\sigma(B\bar{B}) \propto |F(Q^2)|^2 = \frac{2\tau |G_M(Q^2)|^2 + |G_E(Q^2)|^2}{2\tau + 1} \qquad \tau = Q^2/4M^2_B$$

Differential cross section:

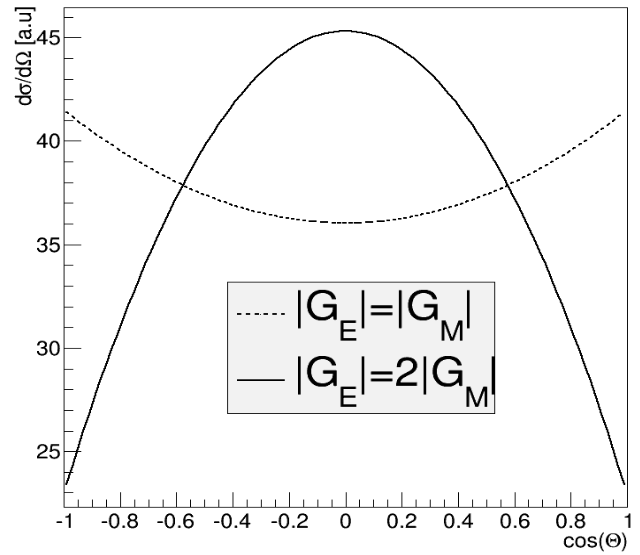
$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 \beta C}{4Q^2}\left[(|G_M(Q^2)|^2 (1+\cos^2\theta) + \frac{1}{\tau}|G_E(Q^2)|^2 \sin^2\theta)\right]$$

Angular dependence: Ratio $R=|G_E/G_M|$

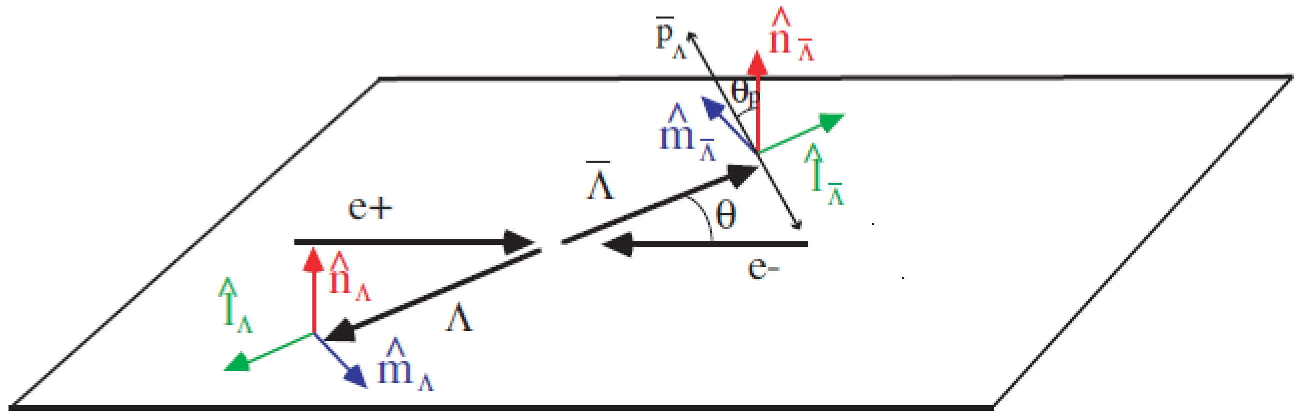
$$|G_M|^2 = \frac{2\tau+1}{2\tau+R^2}|\mathrm{F}|^2 \qquad |G_E|^2 = R^2 \frac{2\tau+1}{2\tau+R^2}|\mathrm{F}|^2$$

In terms of the moment of $\cos^2\theta$:

$$R = \sqrt{4\tau \frac{5 < \cos^2\theta > -2}{2 - 10 < \cos^2\theta >}}$$



Measurement of TL FF's



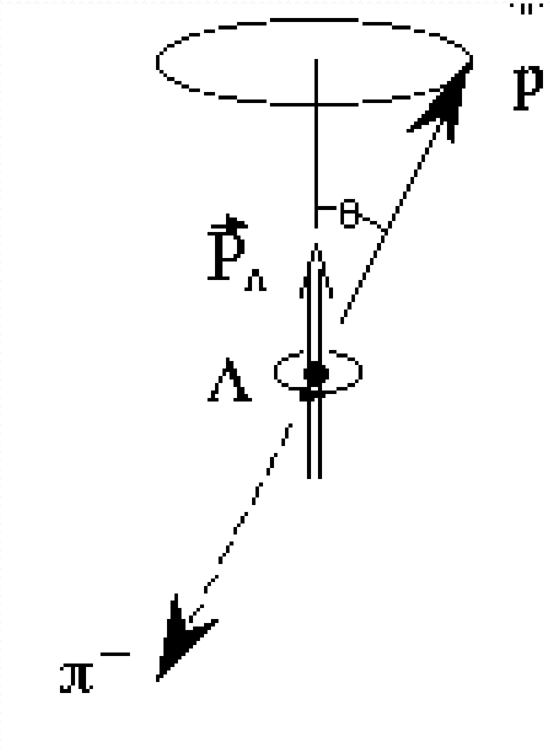
Time-like form factors: imaginary part polarises the final state baryons:

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

The real part is related to the correlation between the baryon- and antibaryon spin:

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

Measurement of TL FF's



Parity violating decay → the decay products are emitted according to the polarisation of the mother hyperon.

$$\frac{dN}{d\cos\theta_p} \propto 1 + \alpha_\Lambda P_n \cos\theta_p$$

In terms of the moment of the $\cos\theta_p$:

$$P_n = \frac{3}{\alpha_\Lambda}\langle\cos\theta_p\rangle$$

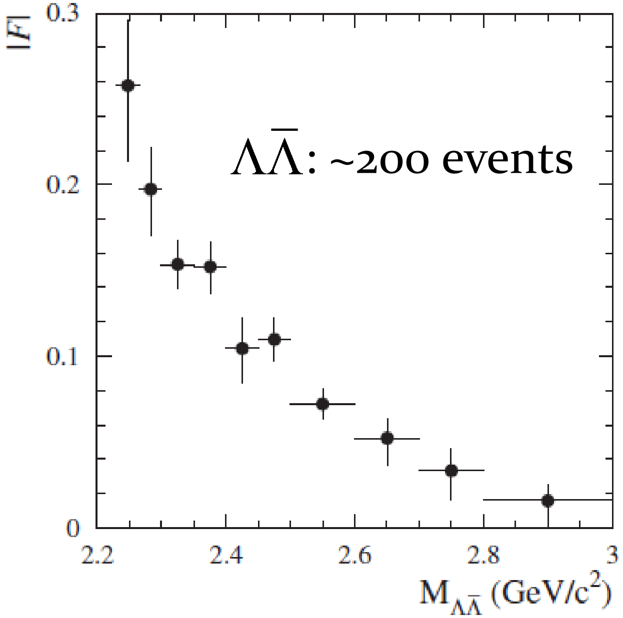
The spin correlation of the Λ and the $\bar{\Lambda}$:

$$C_{lm} = \left(\frac{9}{\alpha\bar{\alpha}}\right)\langle\cos\theta_{pl}\cos\theta_{\bar{p}m}\rangle$$

$Im(G_E G_M^*)$ and $Re(G_E G_M^*)$ depends on P_n , C_{lm}, R and F.

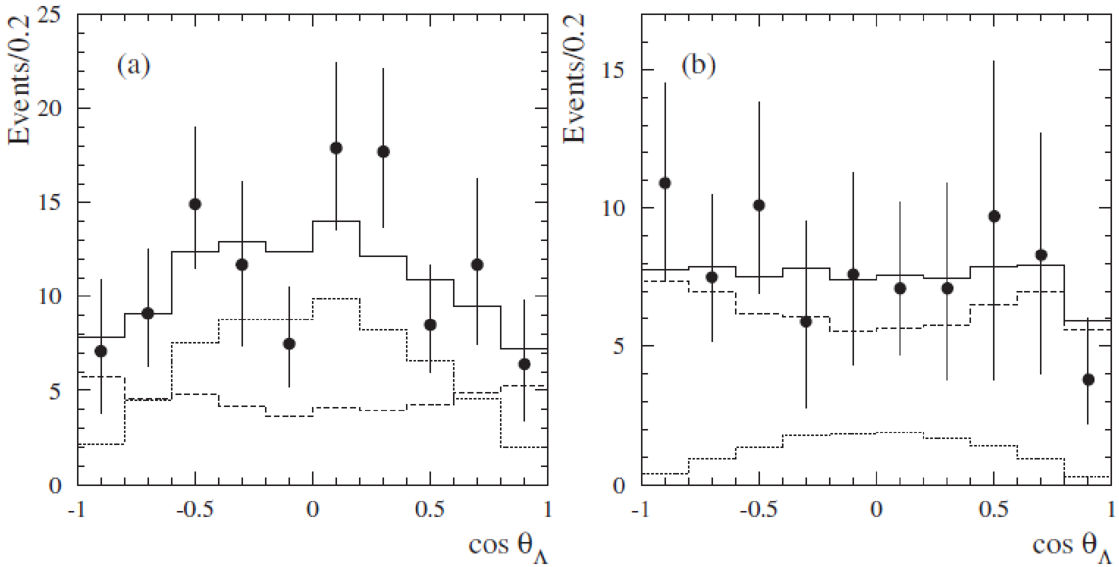
Hyperons: all experimentally accessible → TL FF's can be fully determined.

Experimental status of hyperon TL FF's



BABAR has measured the $\Lambda\bar{\Lambda}$, $\Sigma\bar{\Lambda}$ and $\Sigma\bar{\Sigma}$ FF's, but with very little data.

Total error on the $|G_E/G_M|$ ratio 33-100%



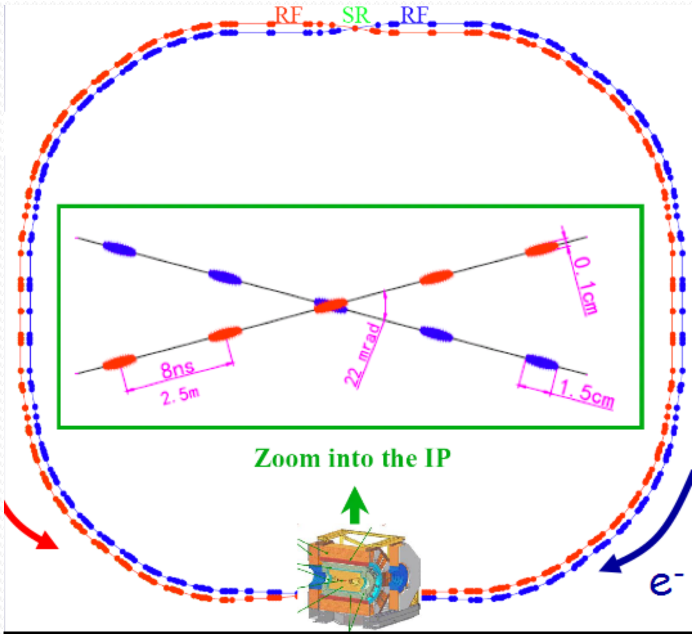
BABAR, PRD **76** (2007) 092006.

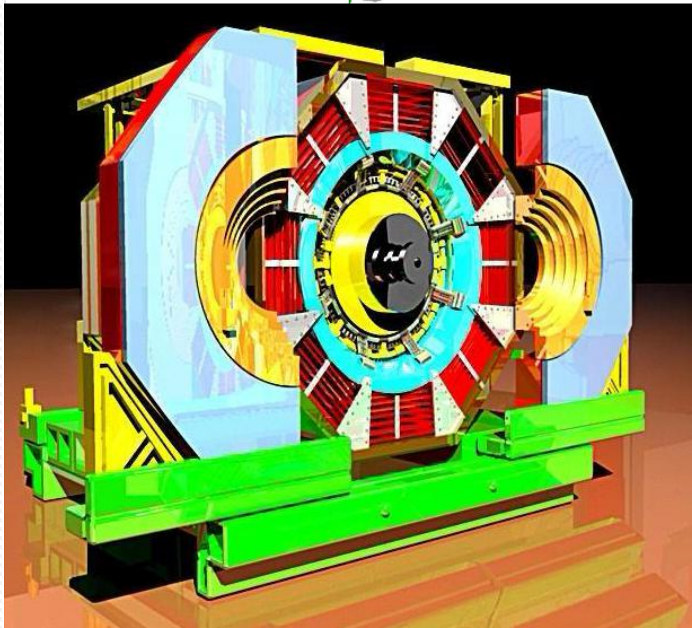
BES III @ BEPC II

BES III in Beijing, China is the only running experiment where hyperon TLFF's can be measured!

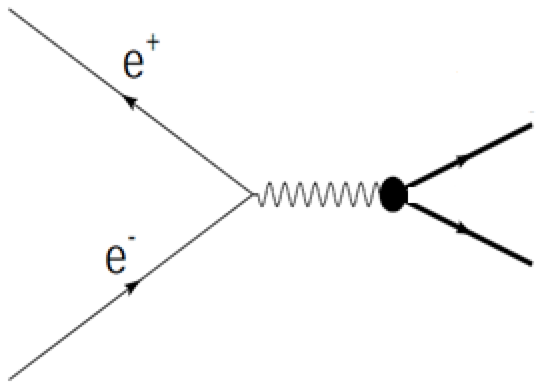
BES III @ BEPC-II

- BES = BEijing Spectrometer
- BEPC = Beijing Electron Positron Collider operates in charm-τ mass region
- $e^+ e^-$ annihilations
- Physics scope similar to PANDA

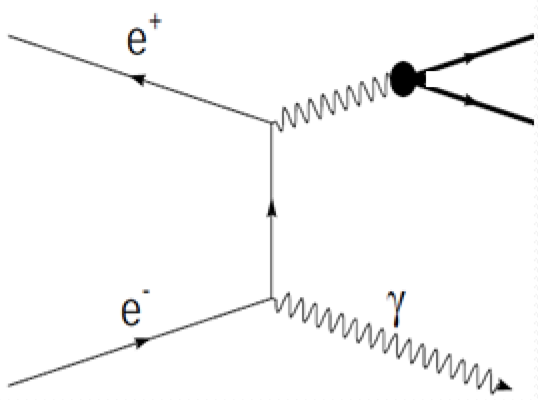




What can we do with BES III?



Direct production



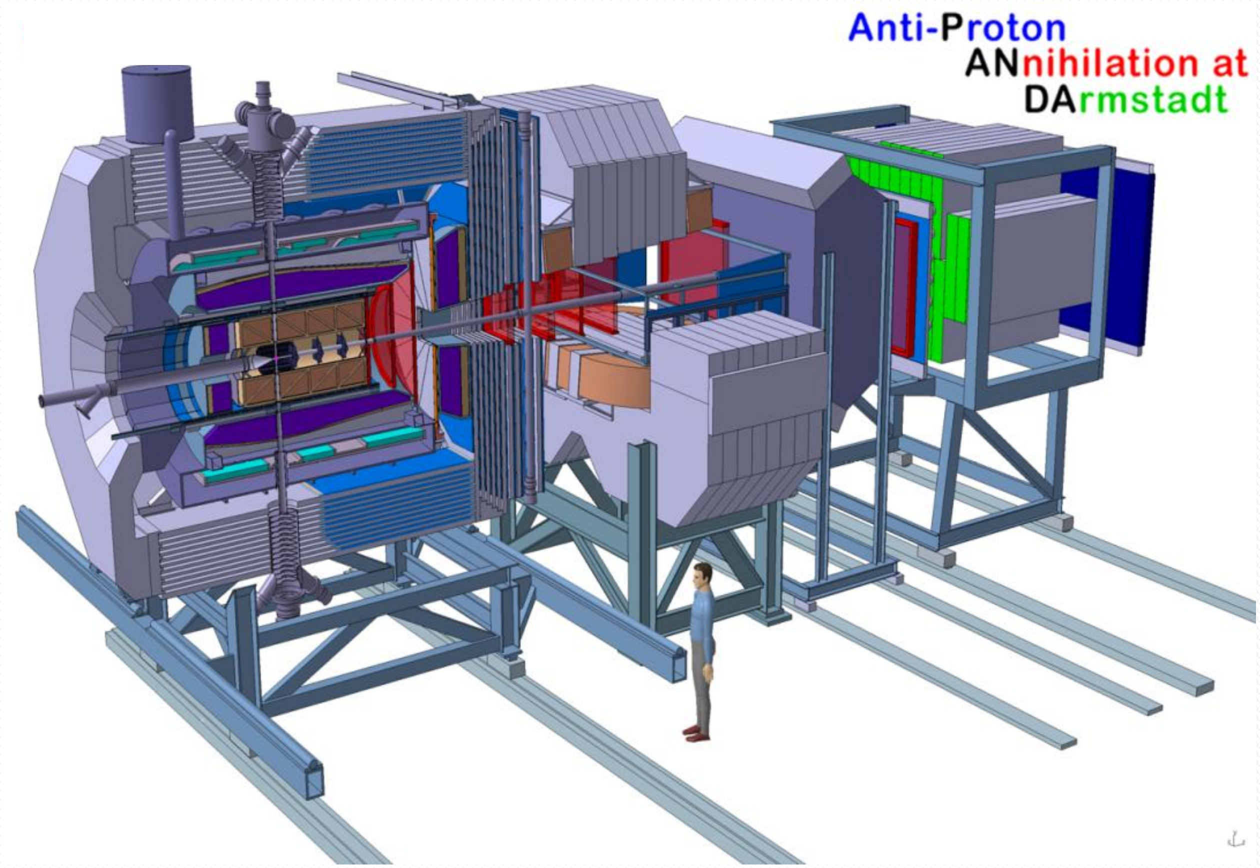
Initial state radiation (ISR)

- Measure $e^+e^- \to \Lambda\bar{\Lambda}$, $\Sigma\bar{\Lambda}$ and $\Sigma\bar{\Sigma}$ in direct e^+e^- annihilation in the continuum between $Q = 2$ and $Q = 3$ GeV
- Measure $e^+e^- \to \Lambda\bar{\Lambda}\gamma_{ISR}$, $\Sigma\bar{\Lambda}\gamma_{ISR}$ and $\Sigma\bar{\Sigma}\gamma_{ISR}$ with ISR at $Q = 3.773$ GeV

What can we do with BES III ?

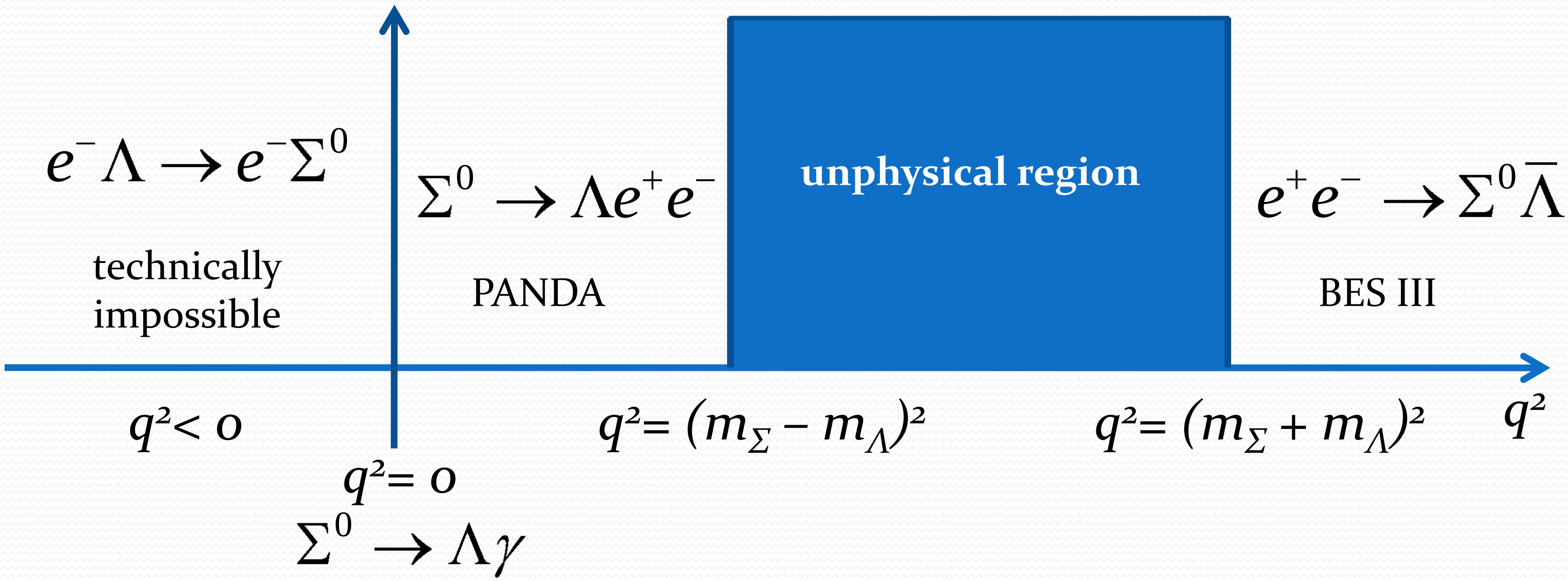
- Λ: With data already on tape: *F*
- Λ: With a few months of dedicated data taking:
  - *R*
  - P_n as a function of scattering angle $\theta \rightarrow Im(G_E G_M^*)$
  - C_{lm} as a function of scattering angle $\theta \rightarrow Re(G_E G_M^*)$
  - $Im(G_E G_M^*)$ and $Re(G_E G_M^*) \rightarrow$ relative phase $\Delta\Phi$
- Σ, Ξ: With a few months of dedicated data taking: *F*
- $\Lambda\Sigma^o$: Transition form factor

What can we do with PANDA?



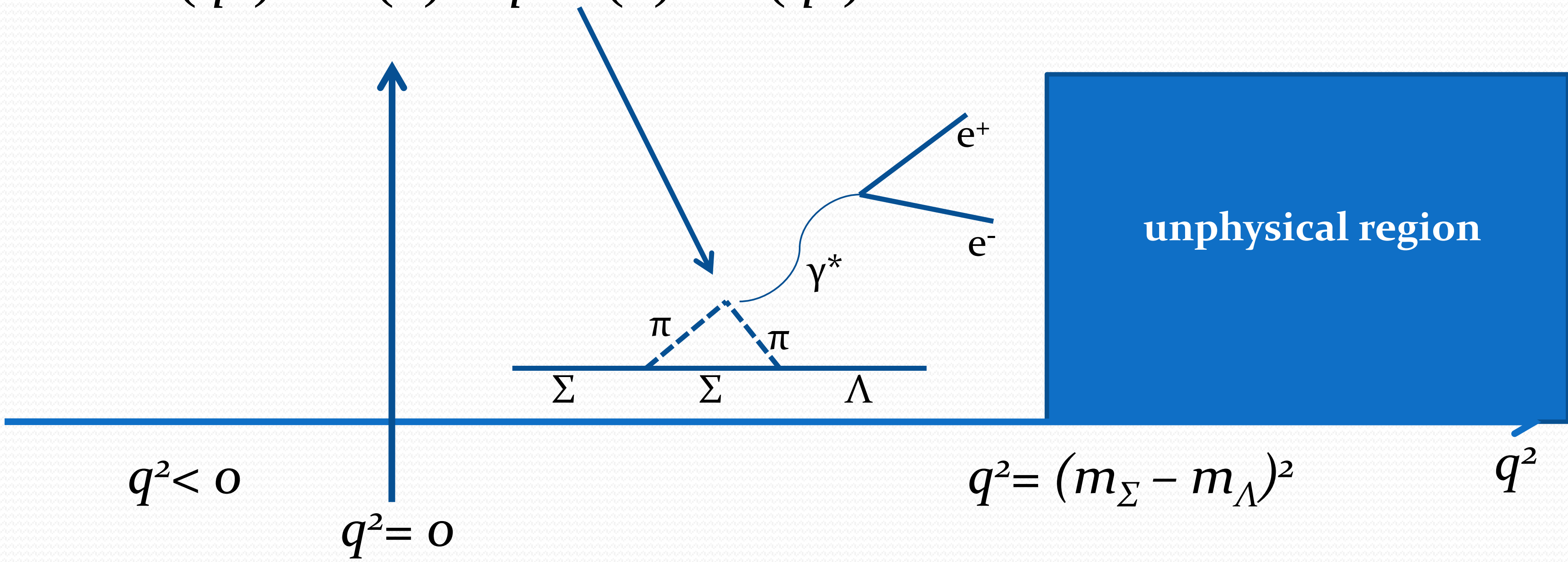
What can we do with PANDA?

Hyperon transition form factors?



What can we do with PANDA?

$$F(q^2) \approx F(0) + q^2 F'(0) + O(q^4)$$



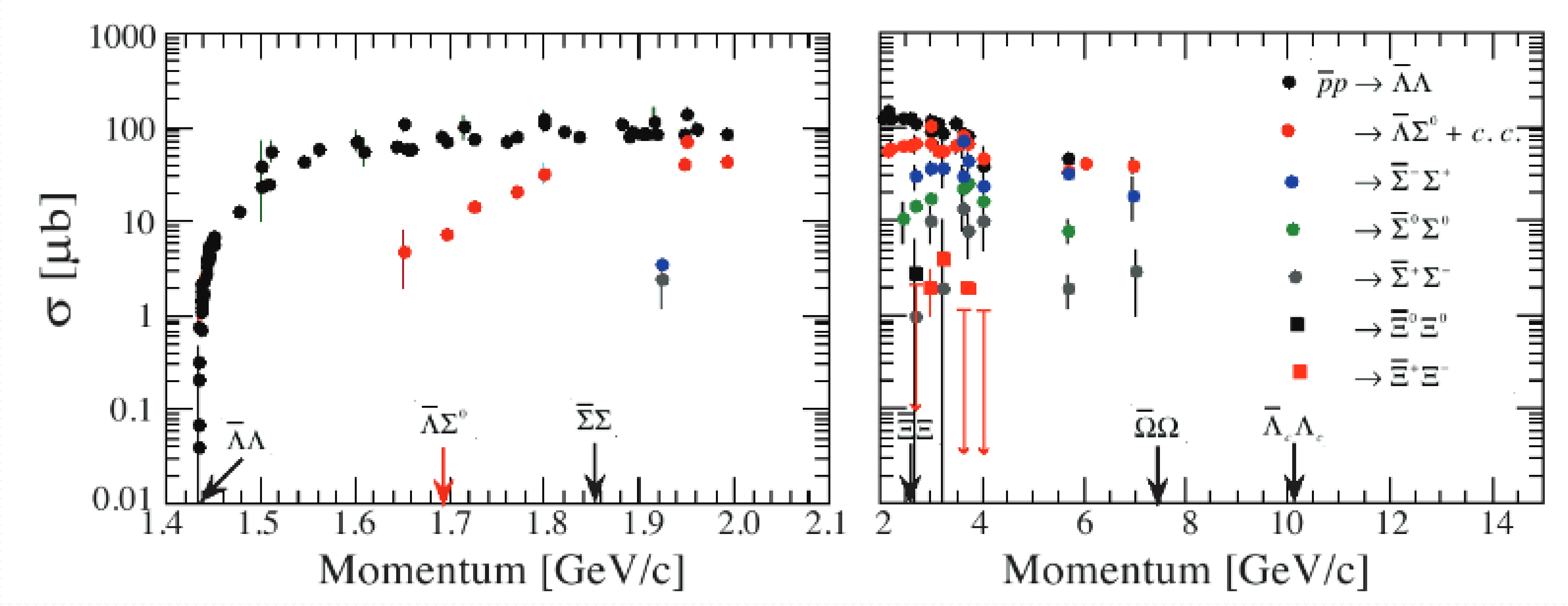
What can we do with PANDA?

Will we get enough data?

- Low branching ratio:

$$BR(\Sigma^0 \to \Lambda\gamma^*, \gamma^* \to e^+e^-) \approx 5{\bullet}10^{-3}$$

- High cross section for $\bar{p}p \to \bar{\Lambda}\Sigma^0 + c.c.$: σ ≈ 40 μb at 4 GeV/c



What can we do with PANDA?

Momentum (GeV/c)	Reaction	σ (μb)	Efficiency (%)	Rate at 2*10^{32} cm^{-2} s^{-1}
1.64	$\bar{p}p \rightarrow \bar{\Lambda}\Lambda$	64	11	580 s^{-1}
4	$\bar{p}p \rightarrow \bar{\Lambda}\Lambda$	~50	23	980 s^{-1}
15	$\bar{p}p \rightarrow \bar{\Lambda}\Lambda$	~10	14	120 s^{-1}
4	$\bar{p}p \rightarrow \bar{\Lambda}\Sigma^{o}$	~40	31	600 s^{-1}
4	$\bar{p}p \rightarrow \bar{\Xi}^{+}\Xi^{-}$	~2	19	30 s^{-1}
12	$\bar{p}p \rightarrow \bar{\Omega}^{+}\Omega^{-}$	~0.002	~30	~80 h^{-1}
12	$\bar{p}p \rightarrow \bar{\Lambda}_c^{-}\Lambda_c^{+}$	~0.1	~35	~25 day^{-1}

Thesis by Sophie Grape, Uppsala, 2009: 600 $\bar{p}p \rightarrow \bar{\Lambda}\Sigma^0, \Sigma^0 \rightarrow \gamma\Lambda$ per second .

How many $\bar{p}p \rightarrow \bar{\Lambda}\Sigma^0, \Sigma^0 \rightarrow e^+e^-\Lambda$?

What can we do with PANDA?

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

$$= 600s^{-1} \bullet 5 \cdot 10^{-3}\frac{\varepsilon(\Lambda e^+e^-)}{0.3} \approx 10 \bullet \varepsilon(\Lambda e^+e^-)s^{-1}$$

If enough data, it is straight-forward to extract

- Angular distribution of Λ/e^+e^- from Σ^0 decay
- Λ polarisation – but what does it mean?

Summary

- Key question of hyperon FF's: How does the structure change if light quark(s) are replaced with heavier?
- Time-like form factors is the best way to study hyperon structure.
- Rather unexplored territory.
- BES III is the only running experiment where this can be done.
- Excellent prospects for measurements of the $\Lambda\bar{\Lambda}$ effective form factor F, the ratio $R=G_E/G_M$ of and the phase $\Delta\Phi$ between G_E and G_M.
- We will be able to measure the effective form factor of heavier hyperons.
- Possibility to study Σ^0 Λ transition form factor with PANDA, if sufficient acceptance for Λ e^+e^- final state.
- Need to work out what kind of information we could get out from the foreseen PANDA data.