Hyperon Production in annihilation reactions

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Hyperons are a laboratory for strong interaction and baryon structure

- Form Factors BESIII *
- Spin observables BESIII panda †
- Spectroscopy panda
-
-

See talks from Paul Laurin (Monday)* for a more complete overview and Alaa Dbeyssi (Wednesday) †

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- Light quark (u,d) systems
  - Highly non-perturbative interactions.
  - Hadrons are relevant degrees of freedom.

- Systems with strangeness
  - Scale: $m_s \approx 100$ MeV $\Lambda_{QCD} \approx 200$ MeV.
  - Probes QCD in the confinement domain.

- Systems with charm
  - Scale: $m_c \approx 1300$ MeV
  - Quark-gluon degrees of freedom more relevant.

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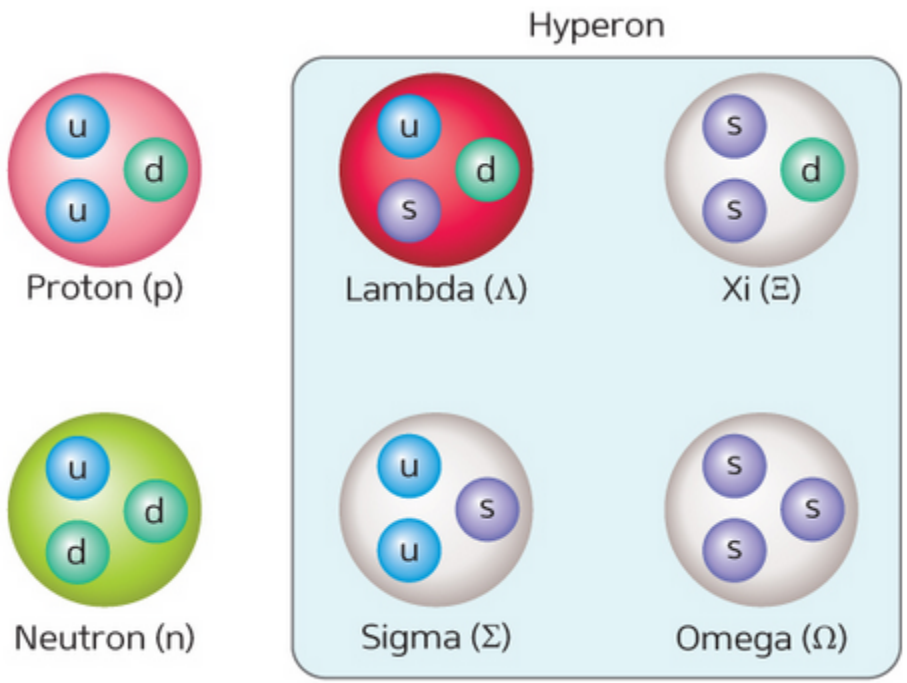
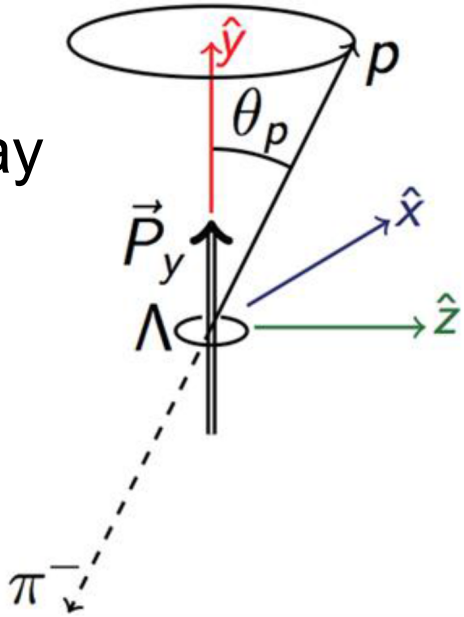
"How are baryons affected by replacing light quarks by strange quarks?"



Validity of $SU(3)_f$, SU(6)

"What is the role of spin?"

$$\Lambda \rightarrow p + \pi^-$$



The parity-violating weak hyperon decay gives access to spin observables.

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

Polarimeter

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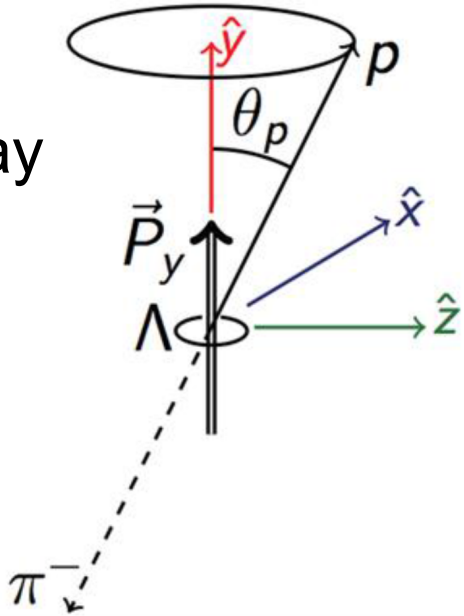
$$\Lambda \rightarrow p + \pi^-$$



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Polarimeter

without polarisation filter

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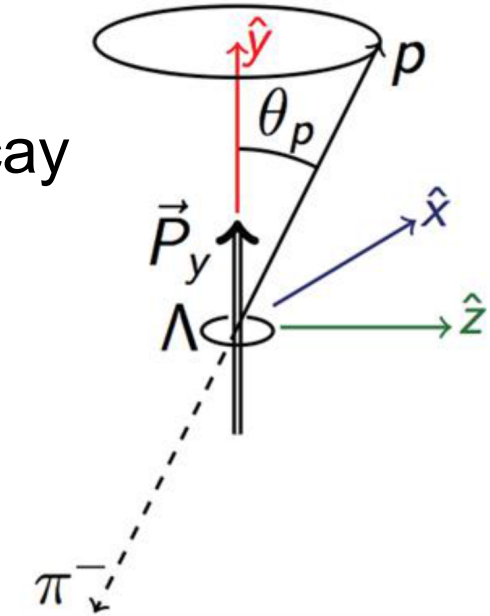


The parity-violating weak hyperon decay gives access to spin observables.

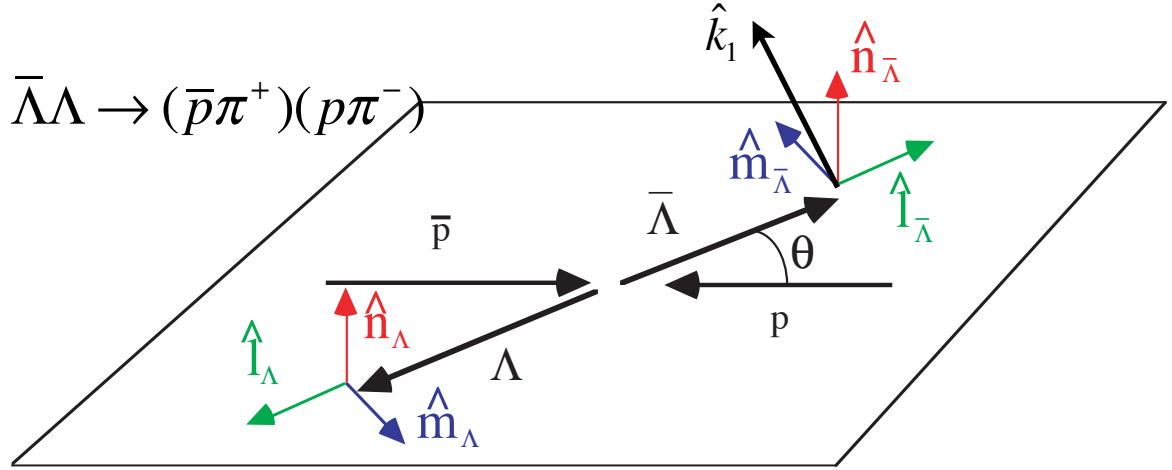
$$I(\cos\theta_p) = N(1 + \alpha_\Lambda P_\Lambda \cos\theta_p)$$

Polarimeter

without polarisation filter with polarisation filter

Spin observables, upolarised beam and target

$$e^+e^-, \bar{p}p \to \bar{\Lambda}\Lambda \to (\bar{p}\pi^+)(p\pi^-)$$



$$I_{\bar{\Lambda}\Lambda}\left(\theta, \hat{\boldsymbol{k}}_1, \hat{\boldsymbol{k}}_2\right) = \frac{I_0^{\bar{\Lambda}\Lambda}}{64\pi^3}\left[\begin{array}{l} 1 \\ +P_n\left(\bar{\alpha}k_{1n} + \alpha k_{2n}\right) \\ +C_{nn}\left(\bar{\alpha}\alpha k_{1n}k_{2n}\right) \\ +C_{mm}\left(\bar{\alpha}\alpha k_{1m}k_{2m}\right) \\ +C_{ll}\left(\bar{\alpha}\alpha k_{1l}k_{2l}\right) \\ +C_{ml}\left(\bar{\alpha}\alpha\left(k_{1m}k_{2l} + k_{1l}k_{2m}\right)\right) \end{array}\right]$$

$I_0 = \sigma_{tot}$

$I(\theta) = d\sigma/d\Omega$

P_n = Polarisation

C_{ij} = Spin correlations

Hyperon Electromagnetic Form Factors

- Electromagnetic Form Factors (EMFF) of hadrons are among the most basic quantities containing information about hadron internal structure. They provide access to the baryon spatial charge and magnetisation distributions.

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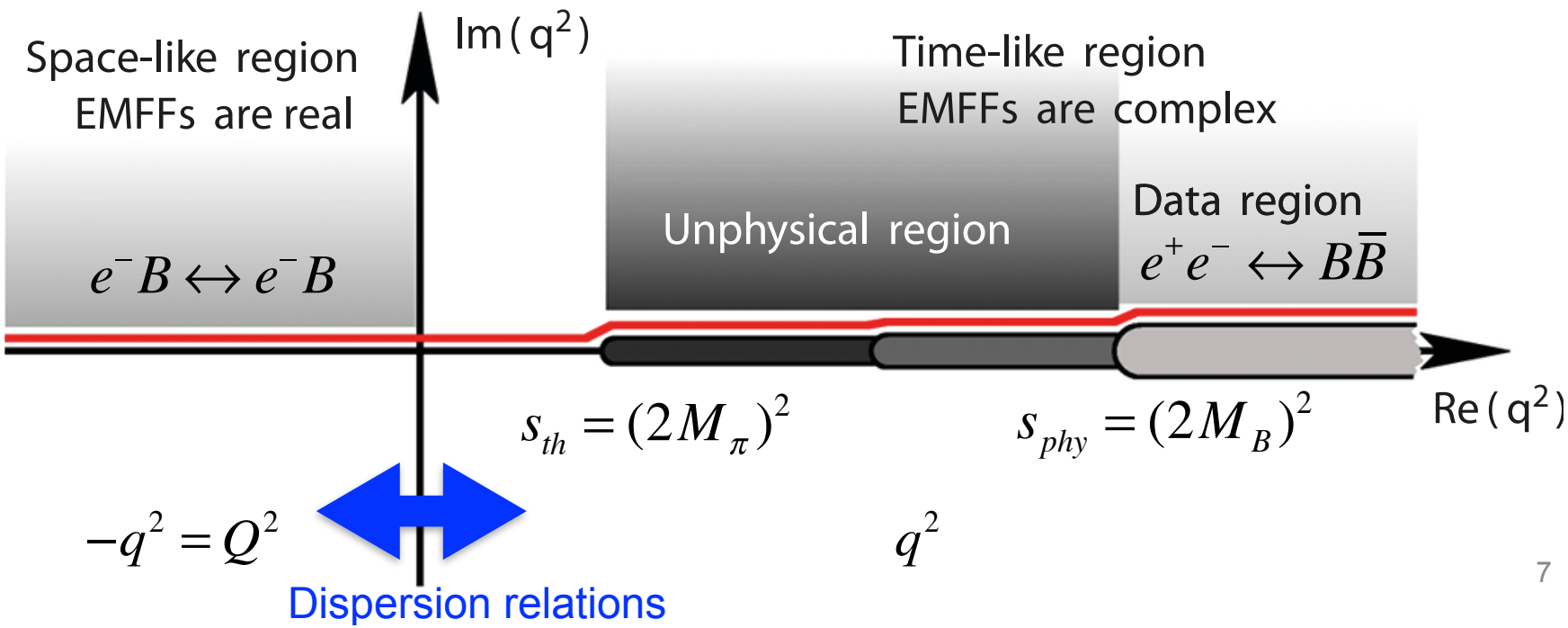

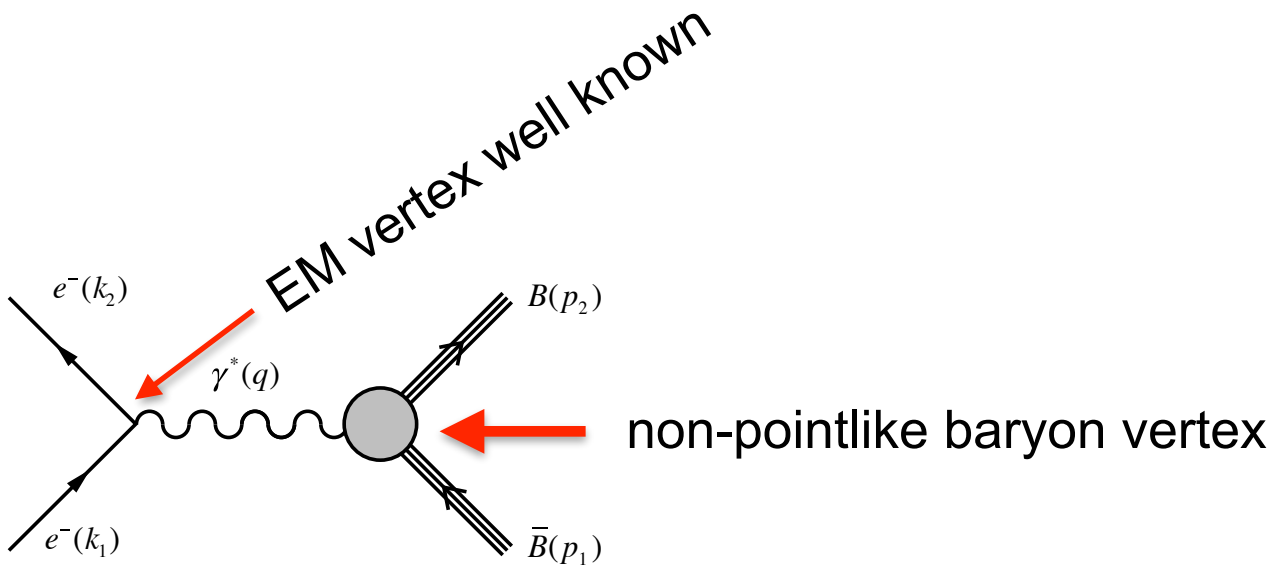

Baryon vertex matrix element: $$\Gamma^\mu = F_1^B(q^2)\gamma^\mu + \frac{\kappa}{2M_B}F_2^B(q^2)i\sigma^{\mu\nu}q_\nu$$

The Dirac ($F_1(q^2)$) and Pauli ($F_2(q^2)$) EMFF's is related to the charge (G_E) and magnetization (G_M) (Sachs) EMFF's via the relations:

$$G_E = F_1 - \tau F_2 \quad ; \quad \tau = \frac{q^2}{4M_B^2}$$

$$G_M = F_1 + F_2$$

$$G_E(0) = Z$$

$$G_M(0) = Z + \kappa = \mu_B$$

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- Time-like FF's are complex due to inelasticity:

$$\mathrm{Re}\left[G_E(q^2)G_M^*(q^2)\right] = \left|G_E(q^2)\right|\left|G_M(q^2)\right|\cos\Delta\phi$$

$$\mathrm{Im}\left[G_E(q^2)G_M^*(q^2)\right] = \left|G_E(q^2)\right|\left|G_M(q^2)\right|\sin\Delta\phi$$

$\Delta\phi$ = the relative phase between G_E and G_M.

➡ Three observables determine the Time-Like Form Factors.

- A relative phase between G_E and G_M gives polarisation effects on the final state even when the initial state is unpolarised.

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The differential cross section in the one-photon exchange picture is given by:

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

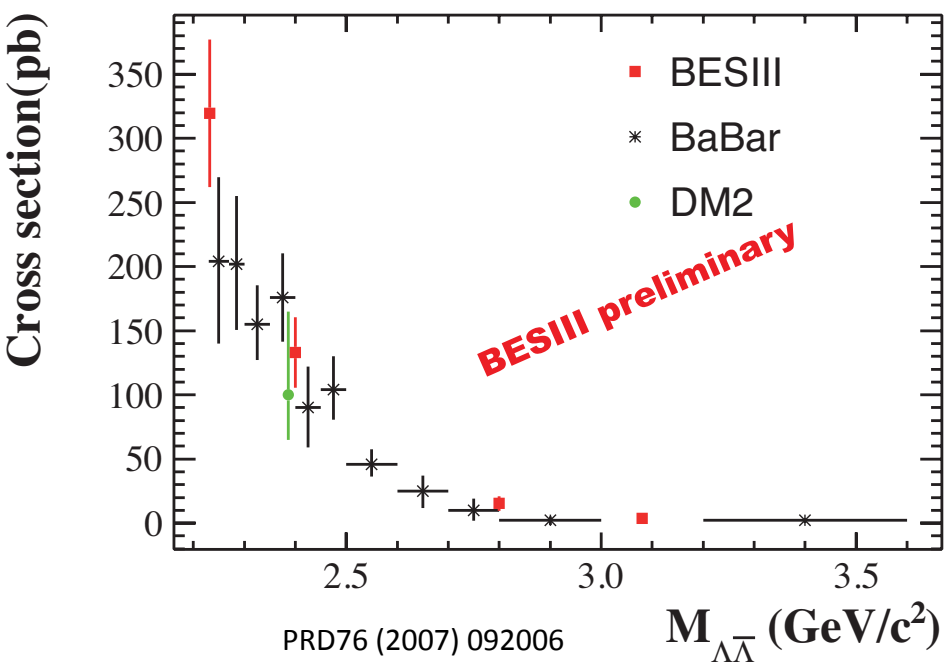
$$\tau = \frac{q^2}{4m_B^2},\ \beta = \sqrt{1-1/\tau},\ C = \text{Coulomb factor} = \text{y}/(1\text{-e}^{-y}), y = \pi\alpha/\beta$$

- The differential cross section at one energy is sufficient to extract the modulii of $|G_E|$ and $|G_M|$ 😊.

- Increasingly difficult to measure $|G_E|$ as q^2 increases due to the $1/\tau$ term ☹️.

Data (so far) has not allowed for a statistically significant extraction of the modulii of $|G_E|$ and $|G_M|$ for strange hyperons. One therefore defines an effective Form Factor from the total cross section:

$$\sigma_{tot} = \frac{4\pi\alpha^2\beta C}{3q^2}\left[|G_M|^2 + \frac{|G_E|^2}{2\tau}\right] \Rightarrow |G_{eff}| = \left(\frac{2\tau|G_M|^2 + |G_E|^2}{2\tau+1}\right)^{\frac{1}{2}}$$



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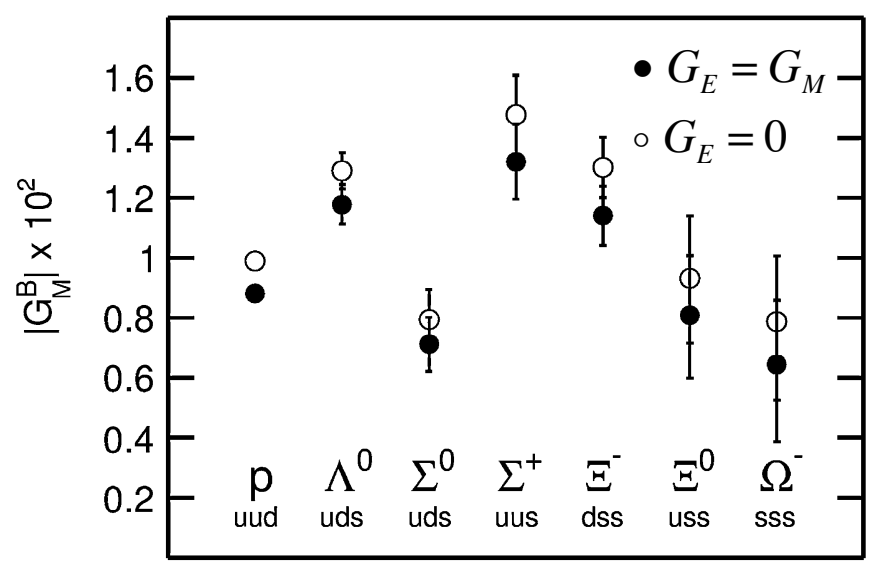
CLEO-C @ 3.77 GeV



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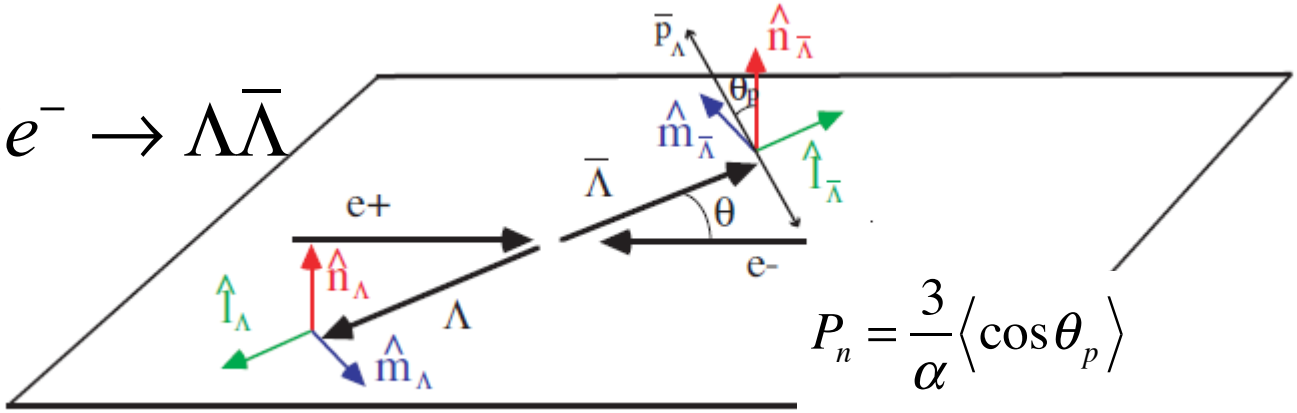
$$e^+e^- \to \Lambda\bar{\Lambda}$$



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

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

$$P_n = -\frac{\sin 2\theta \,\mathrm{Im}\left[G_E G_M^*\right]/\sqrt{\tau}}{\left(\left|G_E\right|^2 \sin 2\theta\right)/\tau + \left|G_M\right|^2\left(1+\cos^2\theta\right)} = -\frac{\sin 2\theta \sin\Delta\phi/\tau}{R\sin^2\theta + \left(1+\cos^2\theta\right)/R}; \quad R = \frac{\left|G_E\right|}{\left|G_M\right|}$$

=> gives modulus of the phase ϕ

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=> gives the sign of the phase ϕ

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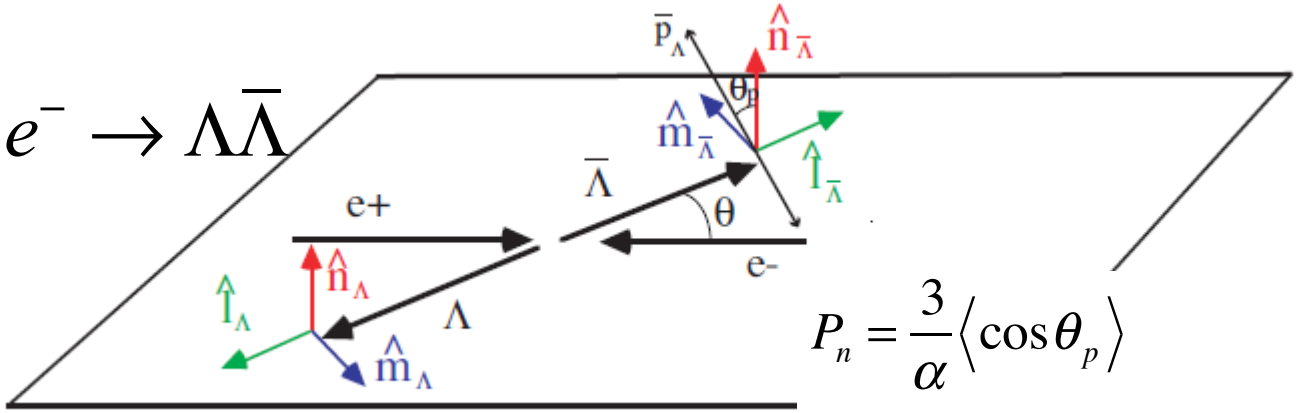
$$e^+e^- \to \Lambda\bar{\Lambda}$$



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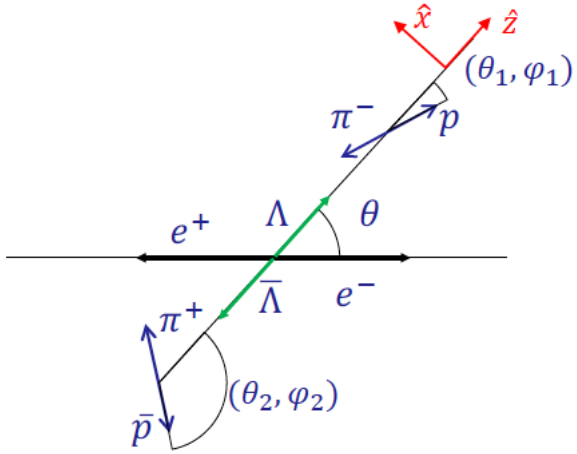
Nuov. Cim. A109(96)241

=> gives the sign of the phase ϕ

A complete determination of the Λ Time-Like Form Factor from $e^+e^- \to \Lambda\bar{\Lambda}$ is possible!

A multivariate parameterisation have been derived by G.Fäldt & A.Kupsc* to make maximum use of ***exclusive data***:

$$W(\xi) = F_0(\xi) + \alpha F_5(\xi)$$
$$+ \alpha_1\alpha_2\left(F_1(\xi) + \sqrt{1-\alpha^2}\cos(\Delta\Phi)F_2(\xi) + \alpha F_6(\xi)\right)$$
$$+ \sqrt{1-\alpha^2}\sin(\Delta\Phi)\left(\alpha_1 F_3(\xi) + \alpha_2 F_4(\xi)\right);\ \xi = (\theta, \theta_1, \phi_1, \theta_2, \phi_2)$$



$$F_0(\xi) = 1$$
$$F_1(\xi) = \sin^2\theta \sin\theta_1 \sin\theta_2 \cos\phi_1 \cos\phi_2 + \cos^2\theta \cos\theta_1 \cos\theta_2$$
$$F_2(\xi) = \sin\theta\cos\theta\left(\sin\theta_1\cos\theta_2\cos\phi_1 + \cos\theta_1\sin\theta_2\cos\phi_2\right)$$
$$F_3(\xi) = \sin\theta\cos\theta\sin\theta_1\sin\phi_1$$
$$F_4(\xi) = \sin\theta\cos\theta\sin\theta_2\sin\phi_2$$
$$F_5(\xi) = \cos^2\theta$$
$$F_6(\xi) = \cos\theta_1\cos\theta_2 - \sin^2\theta\sin\theta_1\sin\theta_2\sin\phi_1\sin\phi_2$$

- Allows for an unbinned ML fit.😊

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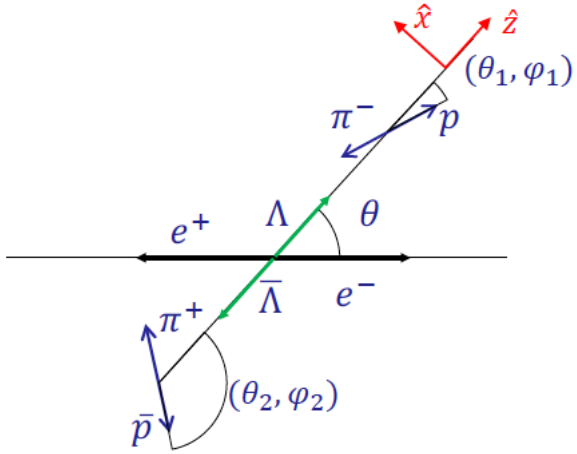

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- Allows for an unbinned ML fit.😊
- Allows for a simultaneous determination of α_1 and α_2 =>CP-tests. J/ψ-> $\Lambda\bar{\Lambda}$ @ BESIII. 😊

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BESIII has taken data at 10 energies from $\Lambda\bar{\Lambda}$ threshold to 2.9 GeV.

One high statistics point at $\sqrt{s}$ 2.39 GeV. Expectations:

=> statistical precision in $R = \frac{|G_E|}{|G_M|}$ ≈ 20 %

==> statistical precision in $\Delta\varphi$ ≈ 20 deg.

===> Determination of the phase, *including sign*, between |GE| and |GM| possible for the first time for any baryon!

(+ effective FF's for Σ^0, Σ^+, Ξ
transition FF for $\Lambda\Sigma^0$)

Stay posted!!

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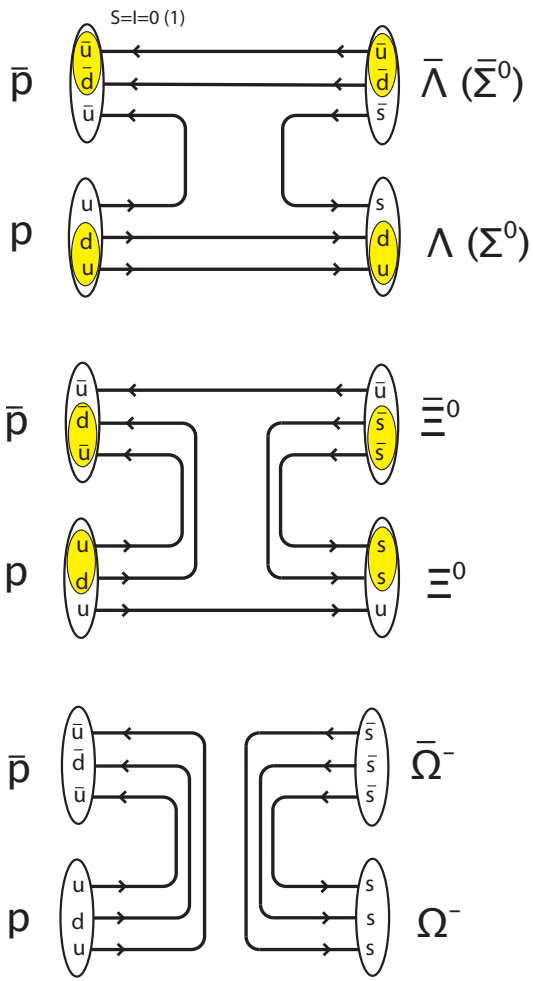
Antiproton-proton reactions are excellent entrance channels for hyperon studies using $\bar{p}p \rightarrow \bar{Y}Y$.



- Strong interaction processes ➪ High cross sections.
- Baryon number = 0 ➪ No extra kaons needed.
  ➪➪ Low energy threshold.
- Same pattern in Y and $\bar{Y}$ channels ➪ Consistency.

$\bar{p}$anda

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Hyperon Spin Dynamics

- Reaction mechanisms at different scales.
- The role of spin in strong interaction process.
- CP violation tests

Hyperon Spectroscopy

- Search for new baryon states
- Properties of already known states.
- Patterns in the observed spectrum.

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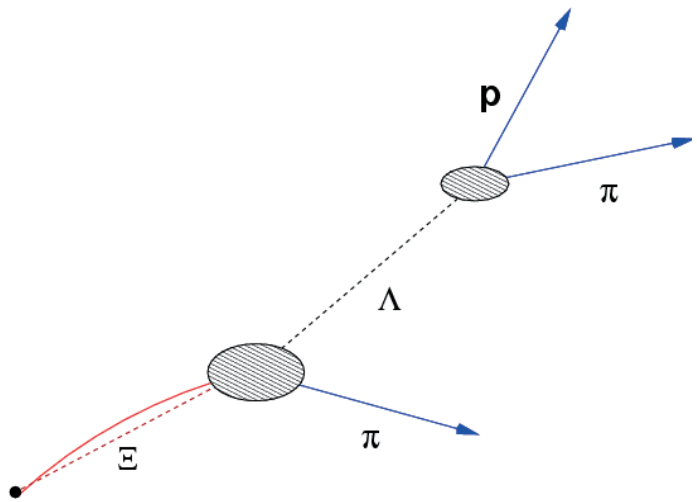
More info from sequential decays: $\frac{1}{2} \to \frac{1}{2} + 0 \quad (\Xi, \Lambda_c)$



Ξ rest frame:

$$(1+\alpha_\Xi P_\Xi \cos\theta_\Lambda) P_\Lambda = (\alpha_\Xi + P_\Xi \cos\theta_\Lambda)\hat{\boldsymbol{k}} + \beta_\Xi P_\Xi \hat{\boldsymbol{k}} \times \hat{\boldsymbol{n}} + \gamma_\Xi P_\Xi (\hat{\boldsymbol{k}} \times \hat{\boldsymbol{n}}) \times \hat{\boldsymbol{k}}$$

Λ rest frame:

$$\frac{dN}{d\cos\theta_{p\hat{\Lambda}}} = \frac{1}{2}\left(1 + \alpha_\Lambda \alpha_\Xi \cos\theta_{p\hat{\Lambda}}\right)$$

$$\left(\begin{aligned} \alpha &= \frac{2\,\mathrm{Re}\, S^* P}{|S|^2 + |P|^2} \\ \beta &= \frac{2\,\mathrm{Im}\, S^* P}{|S|^2 + |P|^2} \\ \gamma &= \frac{|S|^2 - |P|^2}{|S|^2 + |P|^2} \\ \alpha^2 &+ \beta^2 + \gamma^2 = 1 \end{aligned} \right)$$

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Sequential decay $\frac{3}{2} \rightarrow \frac{1}{2} + 0 \quad (\Omega)$

15 polarisation parameters. Total polarisation = $\sqrt{\sum_{L=1}^{2j} \sum_{M=-L}^{L} \left(r_M^L\right)^2}$

Parity conservation reduces this to 7 parameters

3 can be determined from the angular distributions of the $\Omega^- \rightarrow \Lambda K^-$ decay.

The 4 others can be extracted from the combined angular distributions of the $\Omega^- \rightarrow \Lambda K^-$ and $\Lambda \rightarrow p\pi$ decays.

The summed square of these 7 parameters gives the Ω polarisation.

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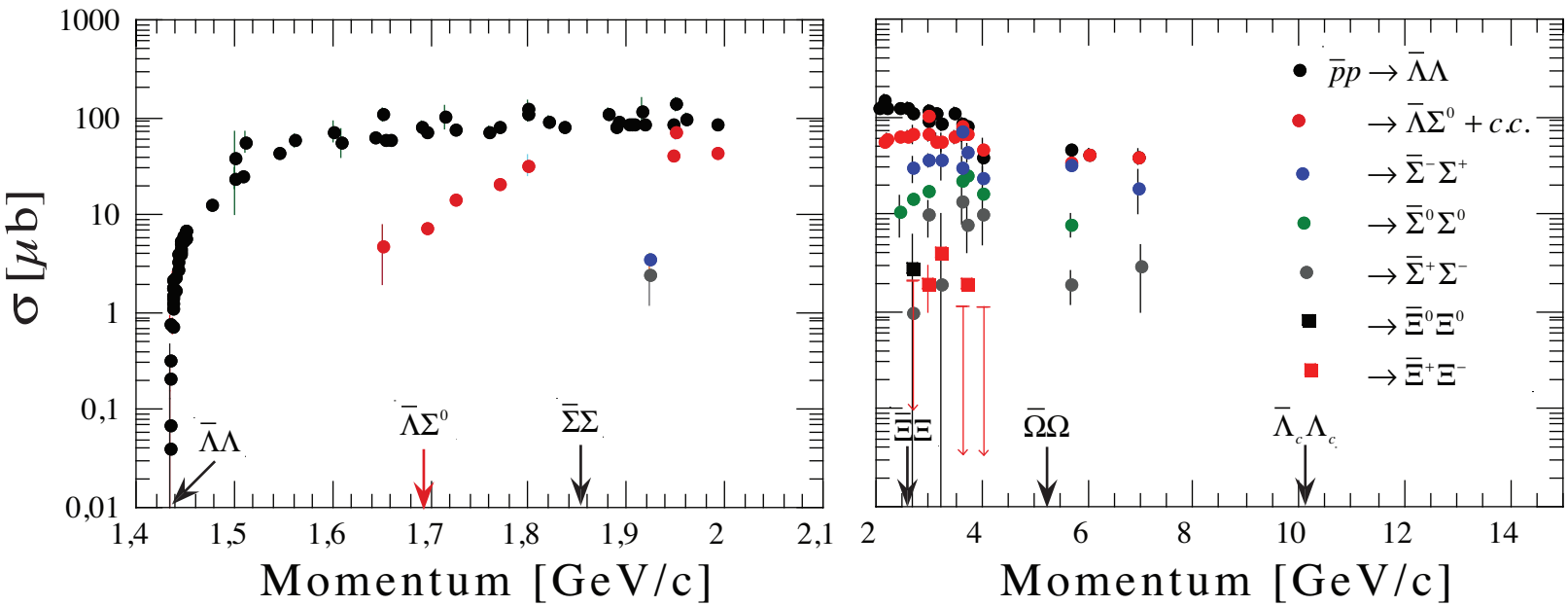
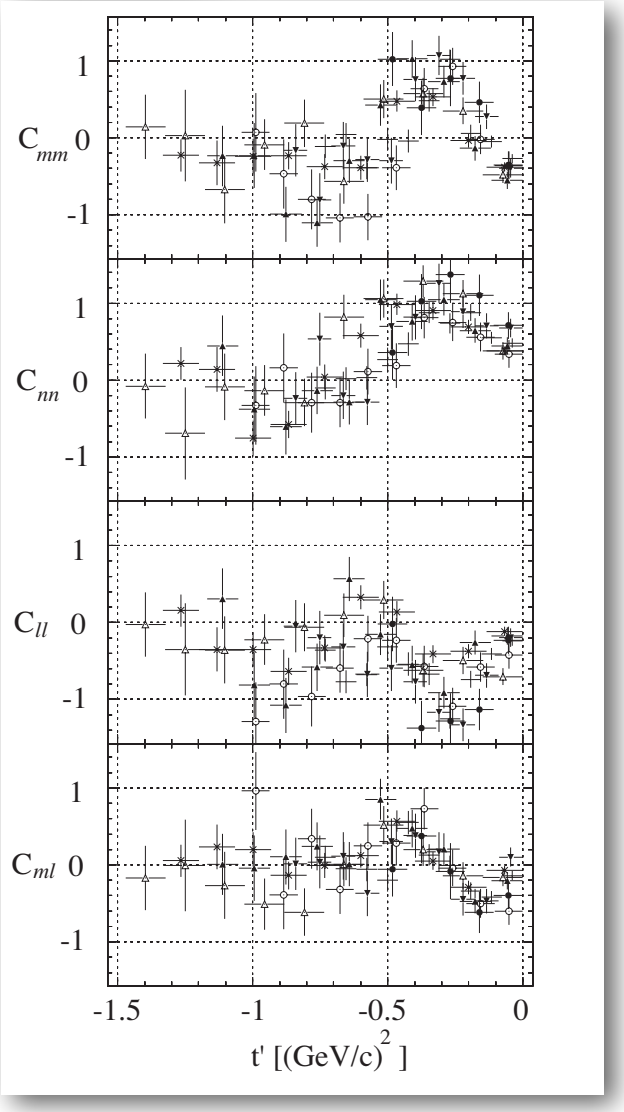
$\bar{p}p \to \bar{Y}Y$ experiments



$\bar{\Sigma}\Sigma$, $\bar{\Xi}\Xi$, $\bar{\Omega}\Omega$, $\bar{\Lambda}_c\Lambda_c$ terra incognita for spin obervables

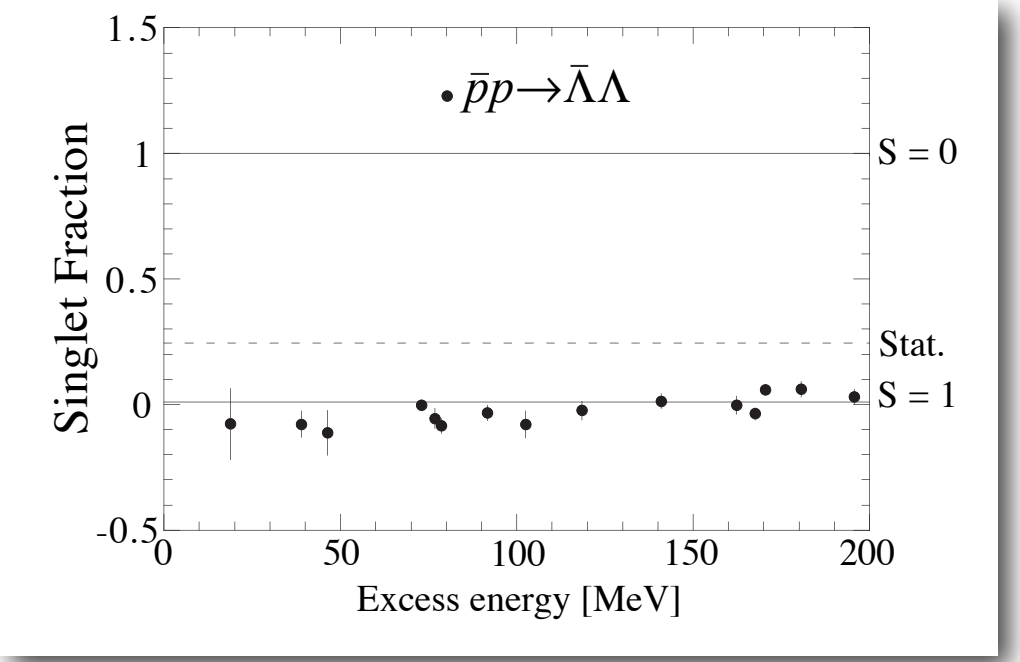
Spin correlations



The expectation value of the spin-singlet operator, "Singlet Fraction (F_S)":

$$F_S = \frac{\left(1-\langle\vec{\sigma}_1\cdot\vec{\sigma}_2\rangle\right)}{4} = \frac{\left(1+C_{mm}-C_{nn}+C_{ll}\right)}{4}$$

= 1 if singlet, = 0 if triplet, = 1/4 if uncorrelated.



$\bar{\Lambda}\Lambda$ $(\bar{s}s)$ -pairs are produced with parallel spin.

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Prospects Day 1

Momentum [GeV/c]	Reaction	σ [μb]	Efficiency [%]	Rate £=10^{31} $cm^{-2}s^{-1}$	
1.64	$\bar{p}p \rightarrow \bar{\Lambda}\Lambda$	64	10	≈ 30 s^{-1}	😊
4	$\bar{p}p \rightarrow \bar{\Lambda}\Sigma^0$	≈ 40	30	≈ 30 s^{-1}	😊
4	$\bar{p}p \rightarrow \bar{\Xi}^+\Xi^-$	≈ 2	20	≈ 1.5 s^{-1}	😊
12	$\bar{p}p \rightarrow \Omega^+\Omega^-$	(2×10^{-3})	30	(≈ 4 h^{-1})	😐
12	$\bar{p}p \rightarrow \bar{\Lambda}_c^-\Lambda_c^+$	(0.1×10^{-3})	35	(≈ 2 day^{-1})	?

First simulations show that these channels can be reconstructed free of background.

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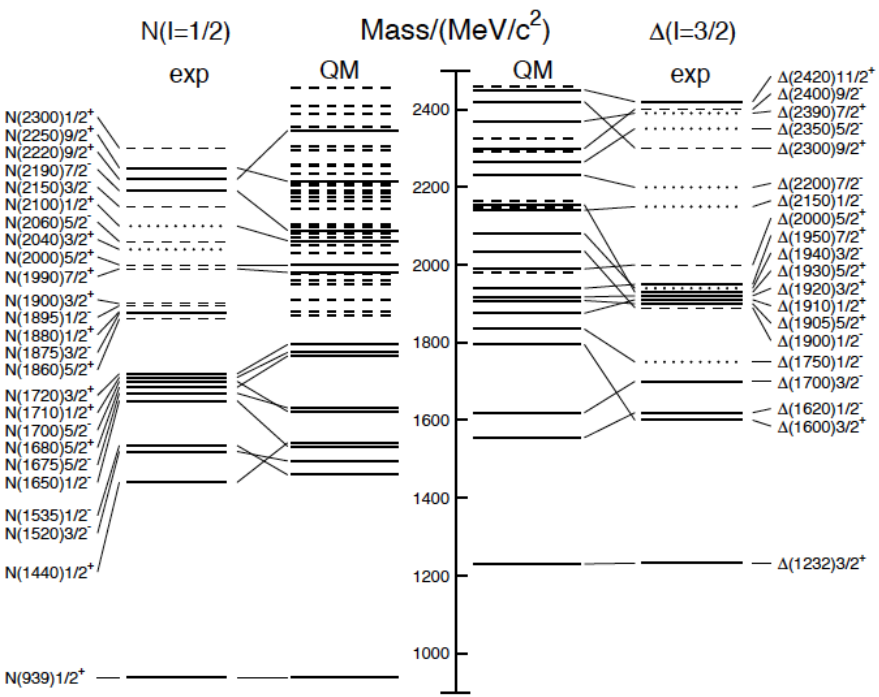
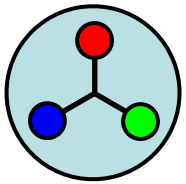
Gain of 100 with an inclusive measurement

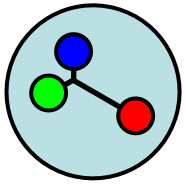
Spectroscopy

Understanding baryon spectra ⇔ Understanding strong QCD

- Level ordering of the light baryon spectra not understood.
- More states predicted than observed "missing resonances" (or the other way around).
- Effective degrees of freedom?
- Baryon-meson molecular systems?
- Testing Lattice QCD.







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PDG 2017:

Ξ RESONANCES

The accompanying table gives our evaluation of the present status of the Ξ resonances. Not much is known about Ξ resonances. This is because (1) they can only be produced as a part of a final state, and so the analysis is more complicated than if direct formation were possible, (2) the production cross sections are small (typically a few μb), and (3) the final states are topologically complicated and difficult to study with electronic techniques. Thus early information about Ξ resonances came entirely from bubble chamber experiments, where the numbers of events are small, and only in the 1980's did electronic experiments make any significant contributions. However, nothing of significance on Ξ resonances has been added since our 1988 edition.

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PDG 2017

Octet **Ξ*** partners of N* ?

Decuplet **Ξ*** and **Ω*** partners of Δ* ?

→ Ξ^*, Ω^* : *terra incognita*

Table 15.6: Quark-model assignments for some of the known baryons in terms of a flavor-spin SU(6) basis. Only the dominant representation is listed. Assignments for several states, especially for the Λ(1810), Λ(2350), Ξ(1820), and Ξ(2030), are merely educated guesses. † recent suggestions for assignments and re-assignments from Ref. 33. For assignments of the charmed baryons, see the "Note on Charmed Baryons" in the Particle Listings.

J^P	$(D, L_N^P)\,S$	Octet members				Singlets
$1/2^+$	$(56,0_0^+)$	$1/2\,N(939)$	$\Lambda(1116)$	$\Sigma(1193)$	$\Xi(1318)$	
$1/2^+$	$(56,0_2^+)$	$1/2\,N(1440)$	$\Lambda(1600)$	$\Sigma(1660)$	$\Xi(1690)^\dagger$	
$1/2^-$	$(70,1_1^-)$	$1/2\,N(1535)$	$\Lambda(1670)$	$\Sigma(1620)$	$\Xi(?)$	$\Lambda(1405)$
				$\Sigma(1560)^\dagger$		
$3/2^-$	$(70,1_1^-)$	$1/2\,N(1520)$	$\Lambda(1690)$	$\Sigma(1670)$	$\Xi(1820)$	$\Lambda(1520)$
$1/2^-$	$(70,1_1^-)$	$3/2\,N(1650)$	$\Lambda(1800)$	$\Sigma(1750)$	$\Xi(?)$	
				$\Sigma(1620)^\dagger$		
$3/2^-$	$(70,1_1^-)$	$3/2\,N(1700)$	$\Lambda(?)$	$\Sigma(1940)^\dagger$	$\Xi(?)$	
$5/2^-$	$(70,1_1^-)$	$3/2\,N(1675)$	$\Lambda(1830)$	$\Sigma(1775)$	$\Xi(1950)^\dagger$	
$1/2^+$	$(70,0_2^+)$	$1/2\,N(1710)$	$\Lambda(1810)$	$\Sigma(1880)$	$\Xi(?)$	$\Lambda(1810)^\dagger$
$3/2^+$	$(56,2_2^+)$	$1/2\,N(1720)$	$\Lambda(1890)$	$\Sigma(?)$	$\Xi(?)$	
$5/2^+$	$(56,2_2^+)$	$1/2\,N(1680)$	$\Lambda(1820)$	$\Sigma(1915)$	$\Xi(2030)$	
$7/2^-$	$(70,3_3^-)$	$1/2\,N(2190)$	$\Lambda(?)$	$\Sigma(?)$	$\Xi(?)$	$\Lambda(2100)$
$9/2^-$	$(70,3_3^-)$	$3/2\,N(2250)$	$\Lambda(?)$	$\Sigma(?)$	$\Xi(?)$	
$9/2^+$	$(56,4_4^+)$	$1/2\,N(2220)$	$\Lambda(2350)$	$\Sigma(?)$	$\Xi(?)$	
		Decuplet members				
$3/2^+$	$(56,0_0^+)$	$3/2\,\Delta(1232)$	$\Sigma(1385)$	$\Xi(1530)$	$\Omega(1672)$	
$3/2^+$	$(56,0_2^+)$	$3/2\,\Delta(1600)$	$\Sigma(1690)^\dagger$	$\Xi(?)$	$\Omega(?)$	
$1/2^-$	$(70,1_1^-)$	$1/2\,\Delta(1620)$	$\Sigma(1750)^\dagger$	$\Xi(?)$	$\Omega(?)$	
$3/2^-$	$(70,1_1^-)$	$1/2\,\Delta(1700)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$	
$5/2^+$	$(56,2_2^+)$	$3/2\,\Delta(1905)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$	
$7/2^+$	$(56,2_2^+)$	$3/2\,\Delta(1950)$	$\Sigma(2030)$	$\Xi(?)$	$\Omega(?)$	
$11/2^+$	$(56,4_4^+)$	$3/2\,\Delta(2420)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$	

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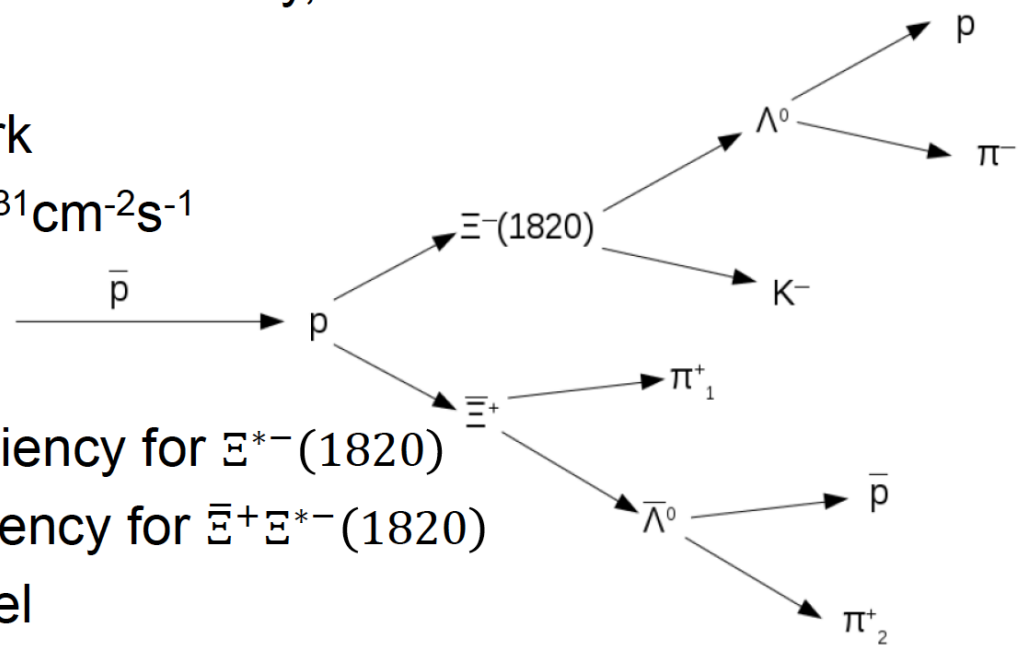
Feasibility study of $\bar{p}p \rightarrow \bar{\Xi}^{+}\Xi^{*-}(1820)$

- p_{beam} = 4.6 GeV/c
- Consider the $\Xi^{*-}(1820) \rightarrow \Lambda$ K decay, assume BR = 100%
- Assume σ = 1 μb
- Simplified MC framework
- *Day One* luminosity: 10^{31}cm^{-2}s^{-1}
- Results:
  - ~30 % inclusive efficiency for $\Xi^{*-}(1820)$
  - ~5 % exclusive efficiency for $\bar{\Xi}^{+}\Xi^{*-}(1820)$
  - Low background level
  - ~15000 exclusive events / day



J. Pütz, talk at FAIRNESS 2016

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Prospects Day 1

Momentum [GeV/c]	Reaction	σ [μb]	Efficiency [%]	Rate £=10^{31} $cm^{-2}s^{-1}$	
1.64	$\bar{p}p \rightarrow \bar{\Lambda}\Lambda$	64	10	≈ 30 s^{-1}	😊
4	$\bar{p}p \rightarrow \bar{\Lambda}\Sigma^0$	≈ 40	30	≈ 30 s^{-1}	😊
4	$\bar{p}p \rightarrow \bar{\Xi}^+\Xi^-$	≈ 2	20	≈ 1.5 s^{-1}	😊
12	$\bar{p}p \rightarrow \Omega^+\Omega^-$	(2x10^{-3})	30	(≈ 4 h^{-1})	😐
12	$\bar{p}p \rightarrow \bar{\Lambda}_c^-\Lambda_c^+$	(0.1x10^{-3})	35	(≈ 2 day^{-1})	😐

First simulations show that these channels can be reconstructed free of background.

Gain of 100 with an inclusive measurement

Cross sections for excited hyperons are expected to be of the same magnitude.

The Prospects of Hyperon Physics in annihilation reactions are good!!

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Backups

CP violation

- Has never been observed for baryons.
- The $\bar{p}p \rightarrow \bar{Y}Y$ process is suitable for tests of CP invariance (clean).
- CP invariance: $\alpha = \bar{\alpha}$ and $\beta = \bar{\beta}$.
- CP violation parameters:

$$A = \frac{\Gamma\alpha + \bar{\Gamma}\bar{\alpha}}{\Gamma\alpha - \bar{\Gamma}\bar{\alpha}} \simeq \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}}$$

PDG: 0.006±0.021 α_Λ

(0.0±5.1±4.4)x10^{-4} $\alpha_\Xi \alpha_\Lambda$

$$B = \frac{\Gamma\beta + \bar{\Gamma}\bar{\beta}}{\Gamma\beta - \bar{\Gamma}\bar{\beta}} \simeq \frac{\beta + \bar{\beta}}{\beta - \bar{\beta}}$$

$$B' = \frac{\Gamma\beta + \bar{\Gamma}\bar{\beta}}{\Gamma\alpha - \bar{\Gamma}\bar{\alpha}} \simeq \frac{\beta + \bar{\beta}}{\alpha - \bar{\alpha}}$$

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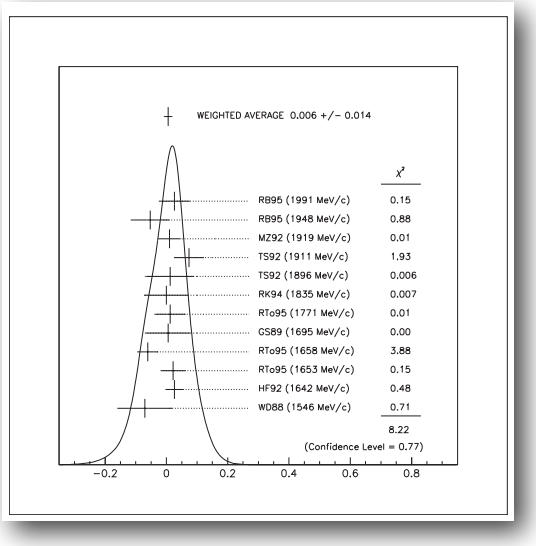
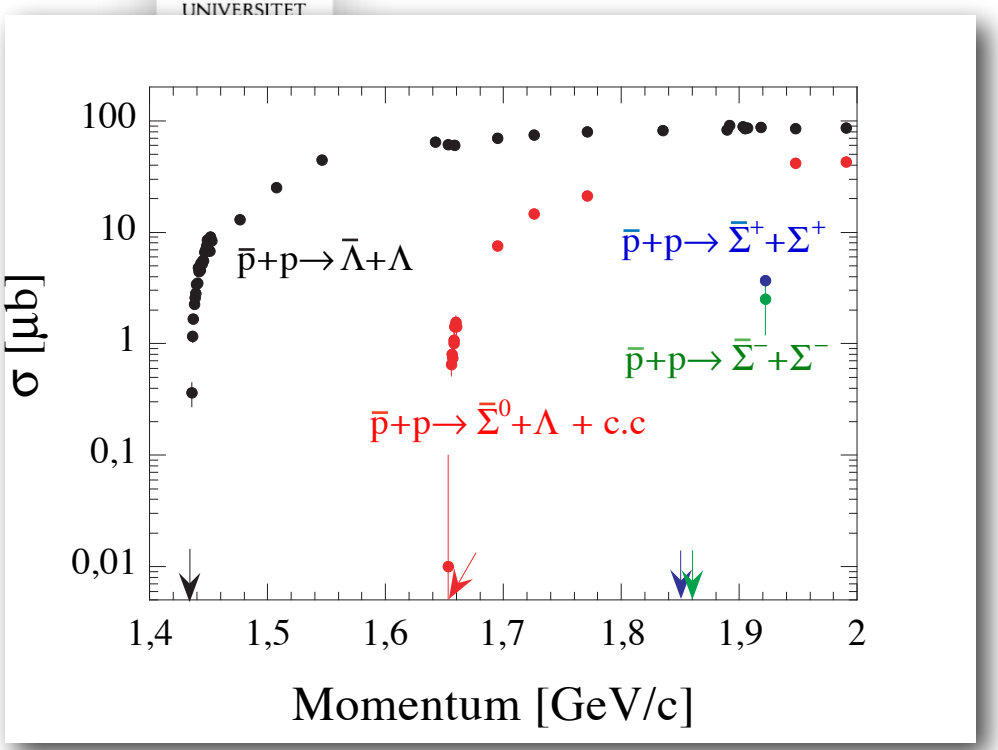
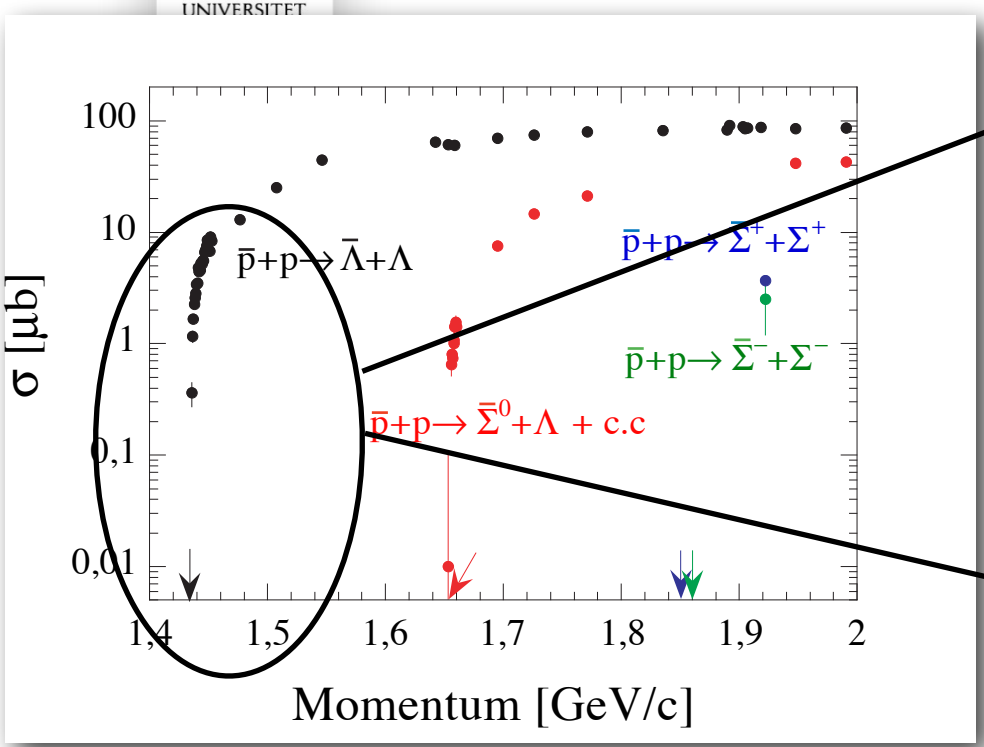


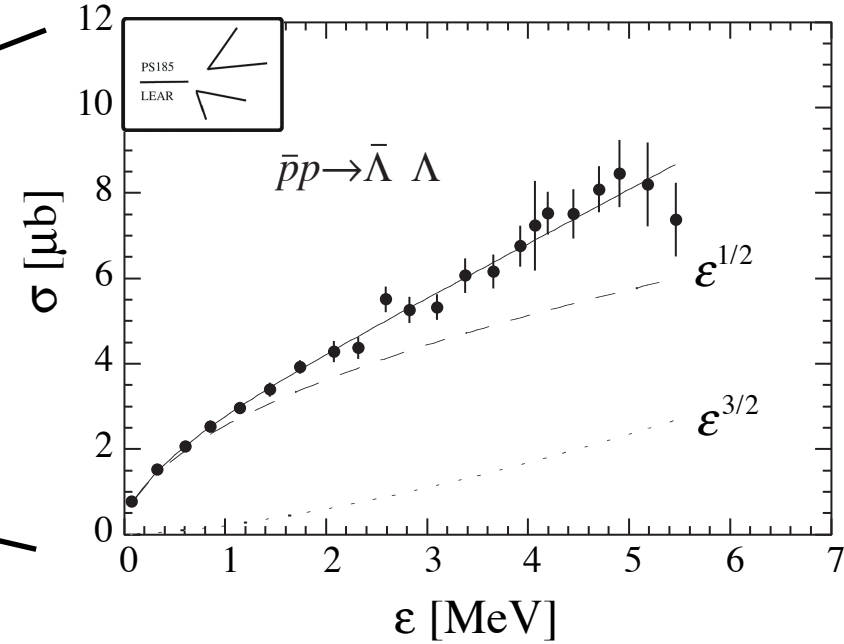
PS185 tot:
0.006±0.014
≈ 200000 events



Excess energy = $\varepsilon = \sqrt{s} - \sum m_{final}$

The phase space increases as $\varepsilon^{L+1/2}$





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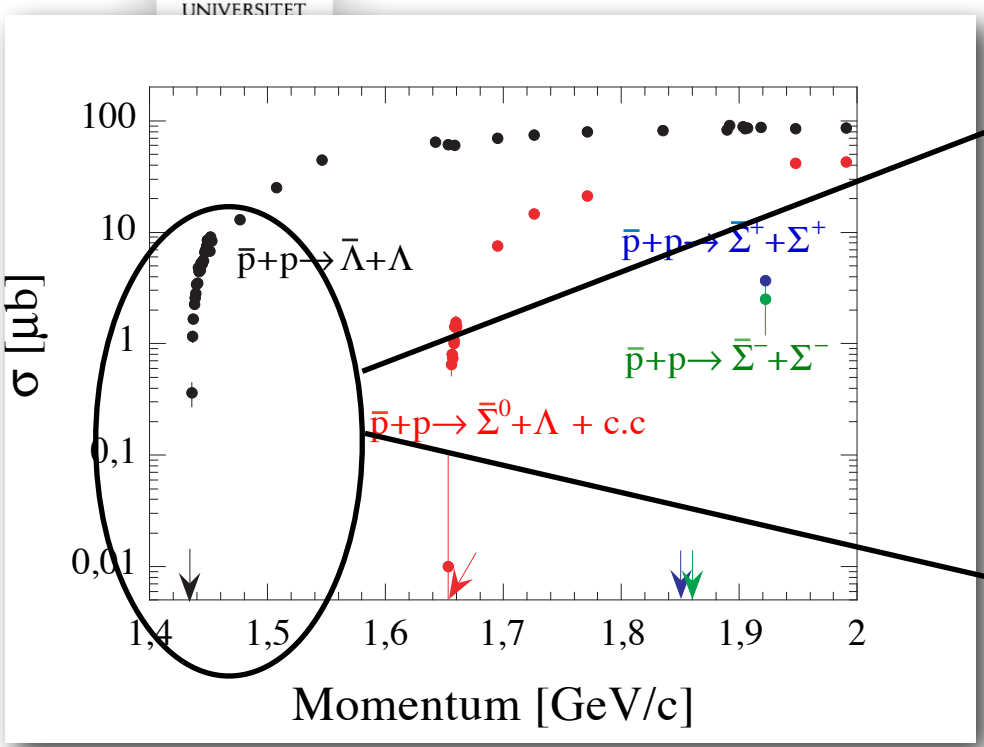

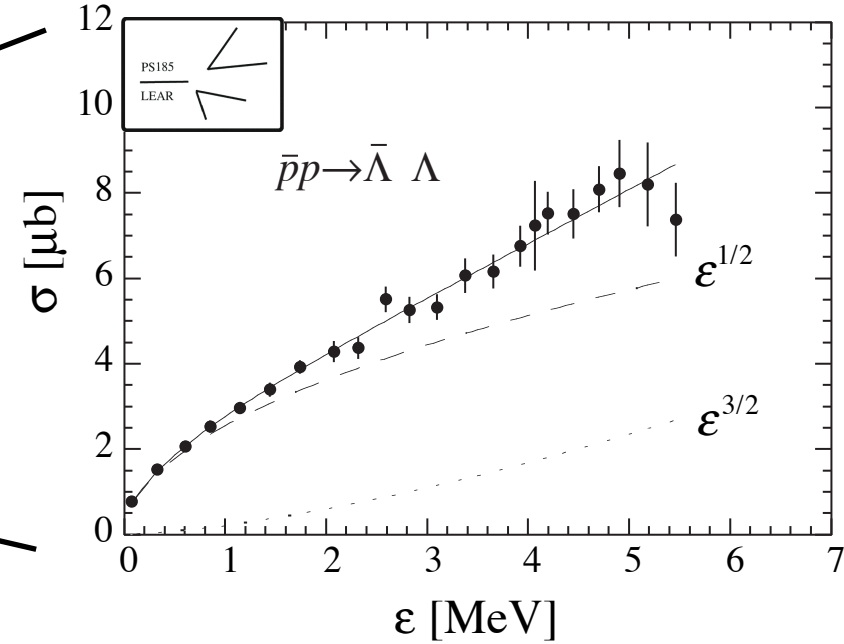

Excess energy = $\varepsilon = \sqrt{s} - \sum m_{final}$

The phase space increases as $\varepsilon^{L+1/2}$

P-waves already 1 MeV above threshold.