Prospects of Hyperon Physics with PANDA

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ICTP-SAIFR/FAIR Workshop on mass generation in QCD
São Paulo 2019

The PANDA experiment at FAIR

Collaboration

panda

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U Uppsala
U Valencia
SMI Vienna
U Visva-Bharati
NCBJ Warsaw

more than 460 physicists from
from more than 75 institutions in 20 countries

Focus on Day 1 antihyperon-hyperon pair production in antiproton-proton collisions.

- What do we know from experiments today?
- What new information will $\bar{\text{P}}$ANDA provide?
- + a little bit on EM Processes

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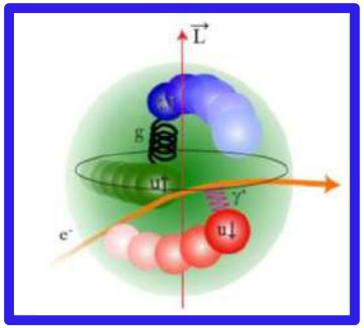
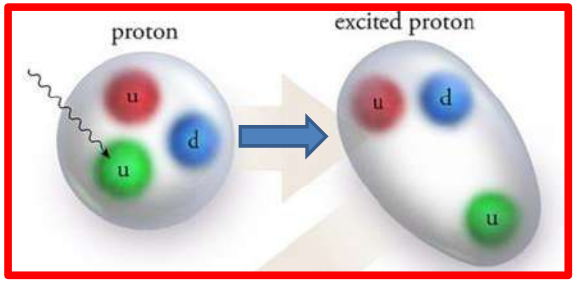
To learn about a system you can

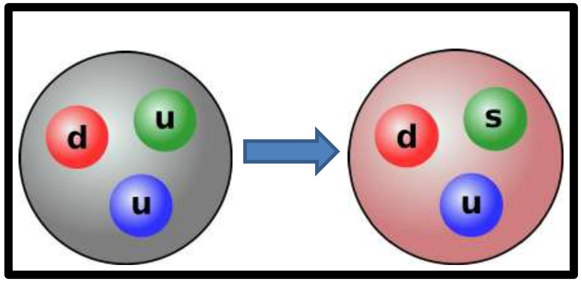
- Scatter on it



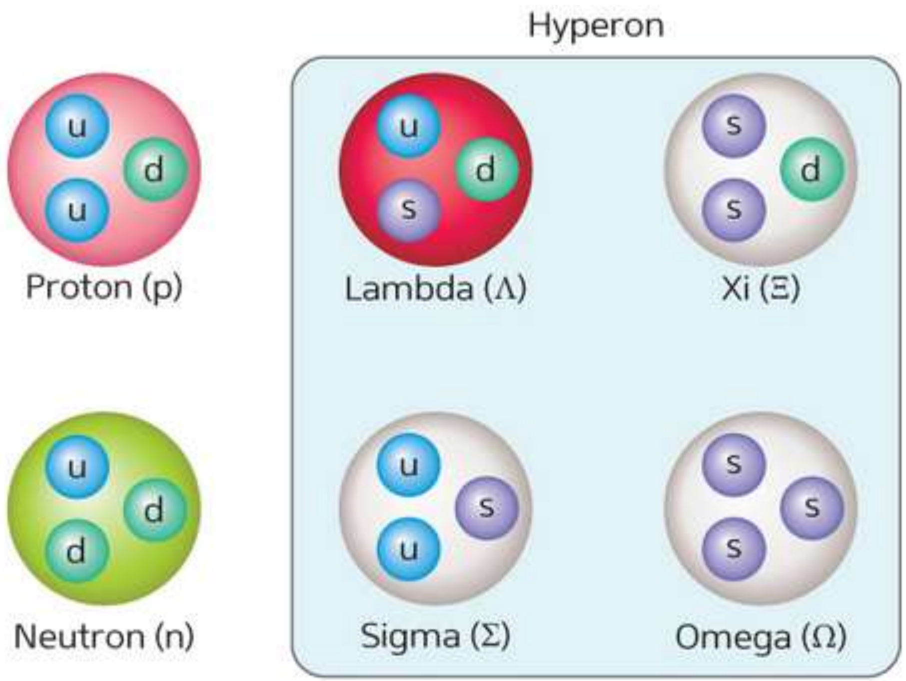
- Excite it



- Replace one of the building blocks



"How are baryon structure and interaction affected by replacing light quarks by strange quarks?"



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

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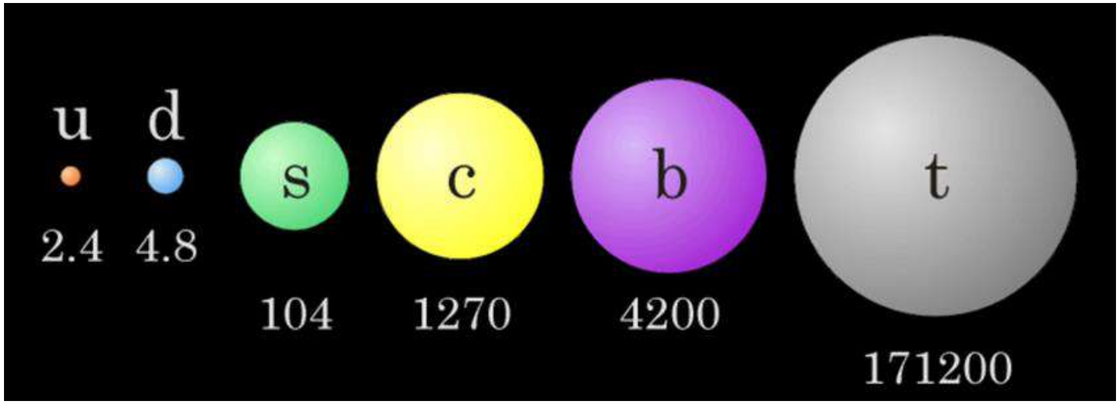
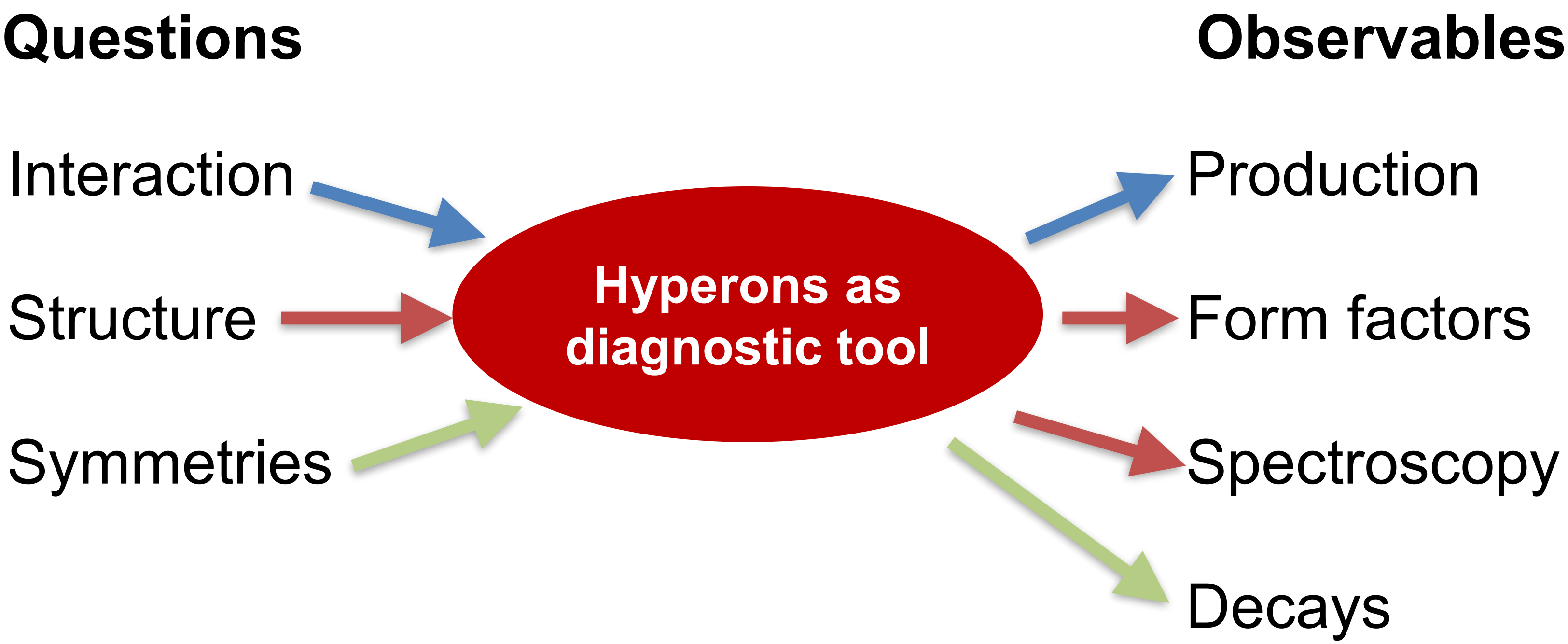
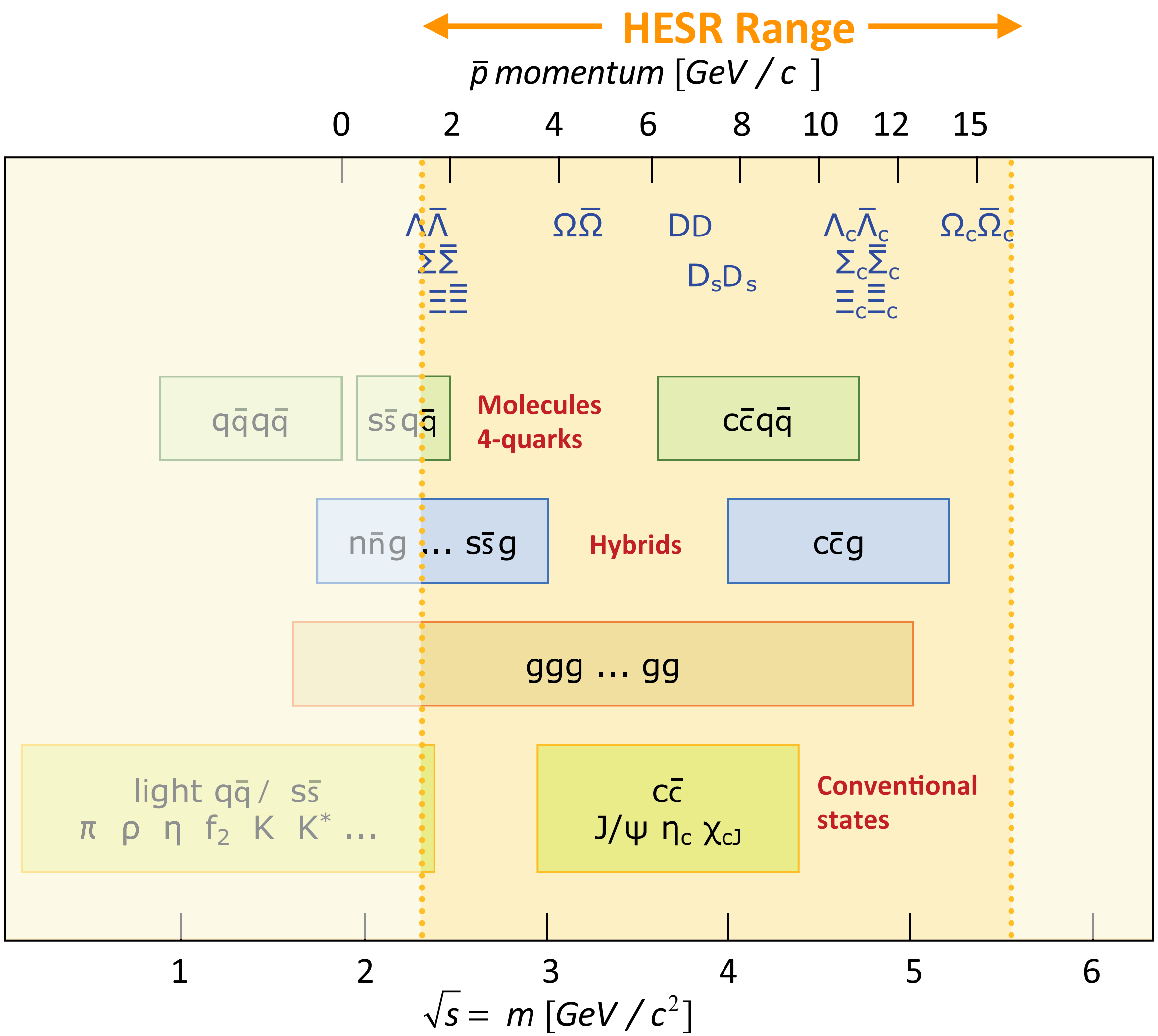
- Systems with strangeness
  - Scale: $m_s \approx 100$ MeV $\Lambda_{QCD} \approx 200$ MeV.
  - Probes QCD in the confinement domain.

- Systems with charm
  - Scale: $m_c \approx 1300$ MeV
  - Probes QCD approaching pQCD.



Hyperons are a laboratory for strong interaction and baryon structure

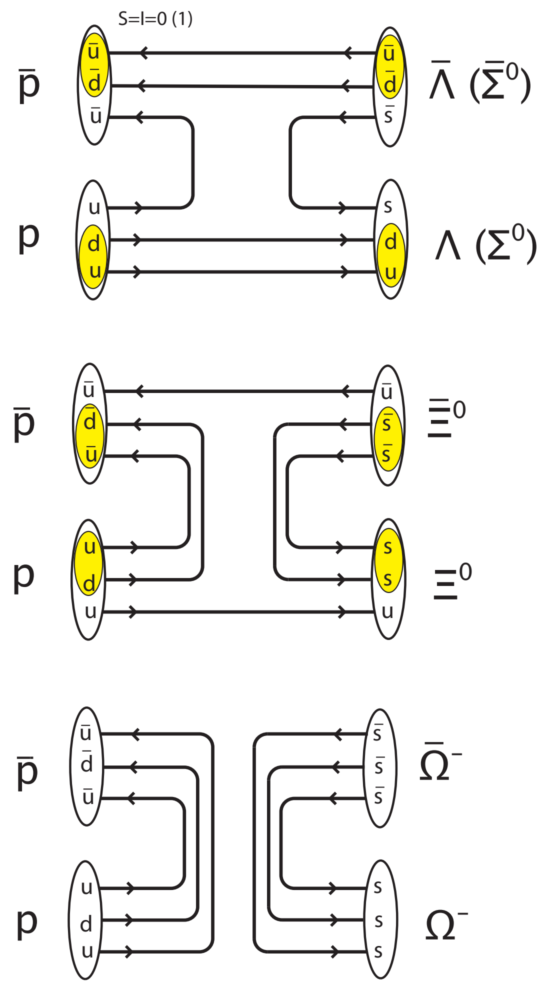


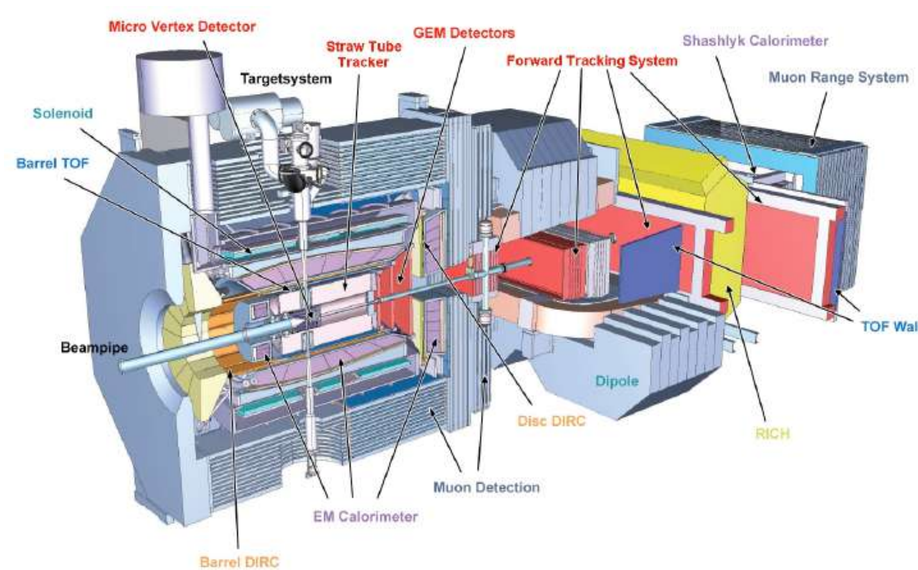


➪ Strange and charmed hyperons are accessible to $\bar{\text{P}}$ANDA

Antiproton-proton reactions are excellent entrance channels for hyperon studies: strong int. processes ➪ high x-sec's.

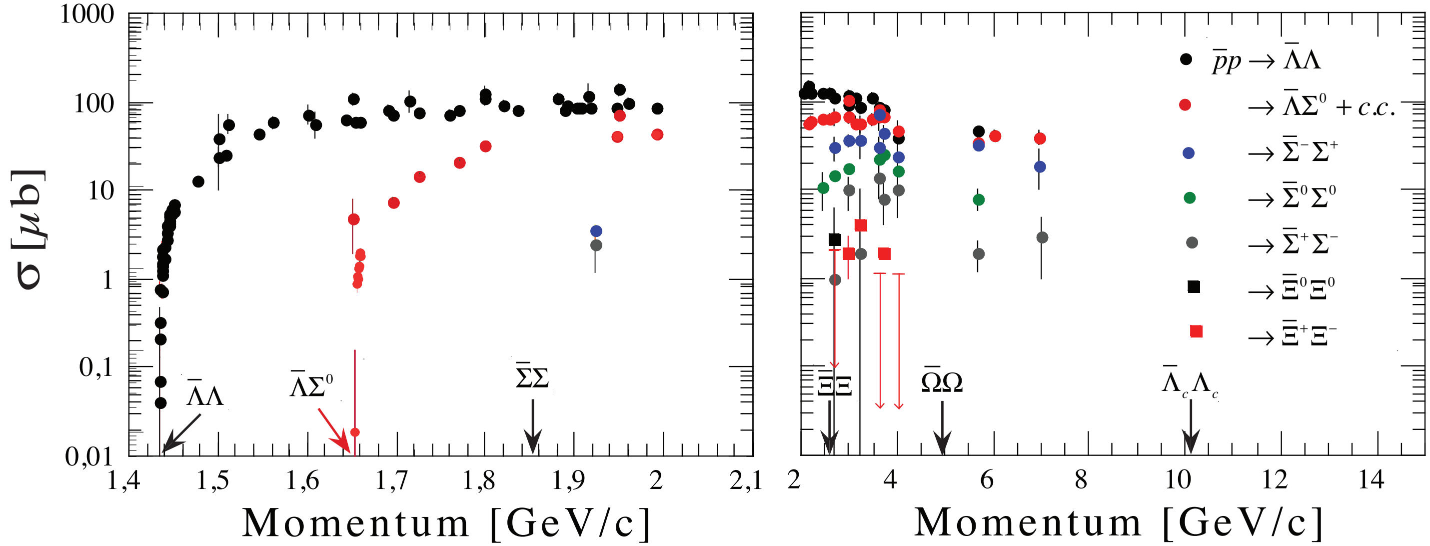
$$\bar{p}p \rightarrow \bar{Y}Y$$



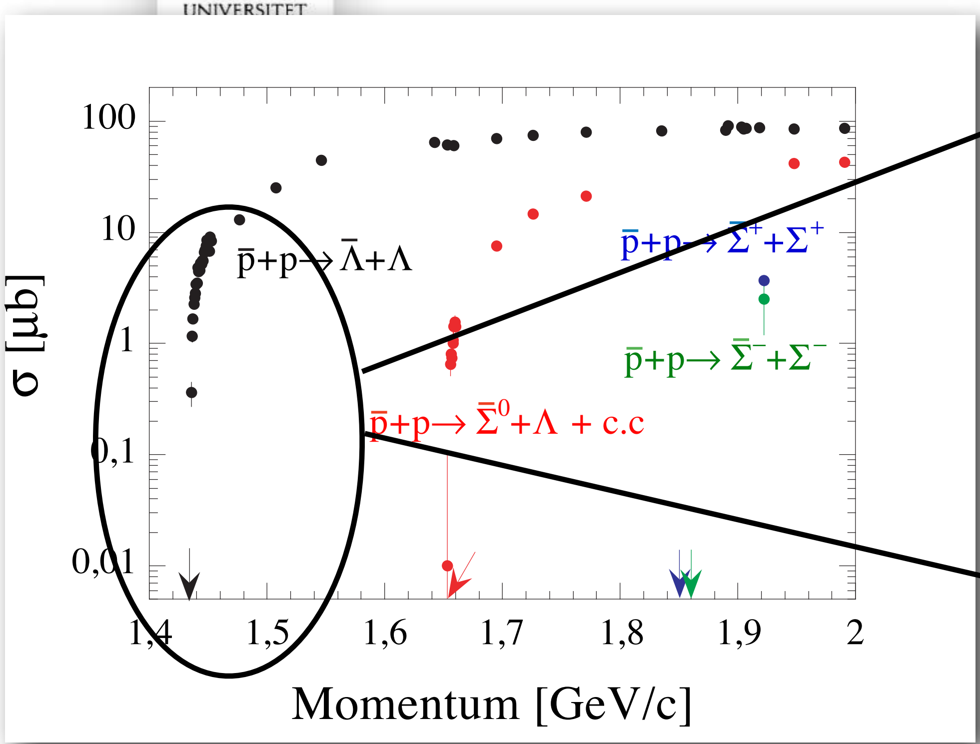


$\bar{p}p \rightarrow \bar{Y}Y$ experimental situation today

σ_{tot}



Threshold region for $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ is mapped out by PS185@LEAR. Handful of $\bar{\Xi}\Xi$ events from bubble chamber expt's, otherwise multiple strange and charmed hyperons are terra incognita.



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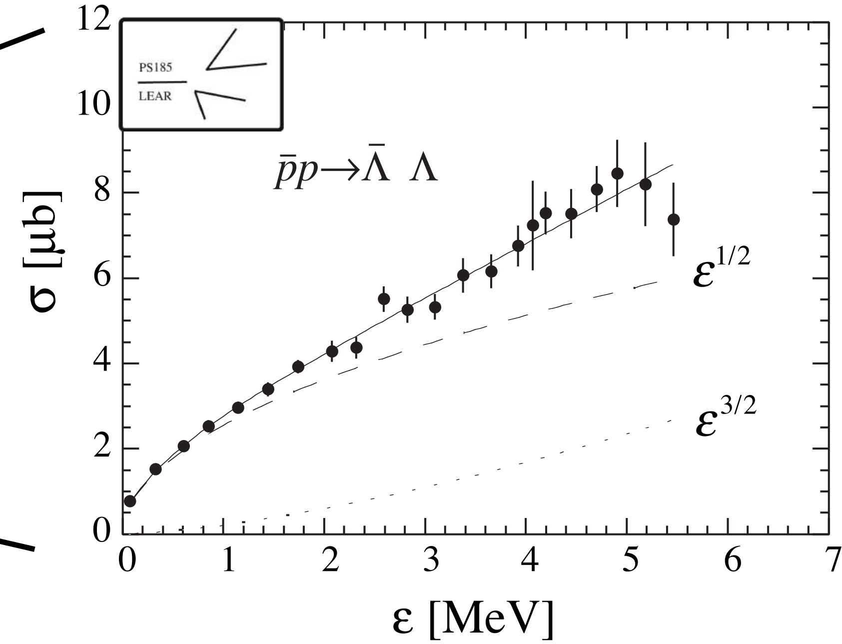
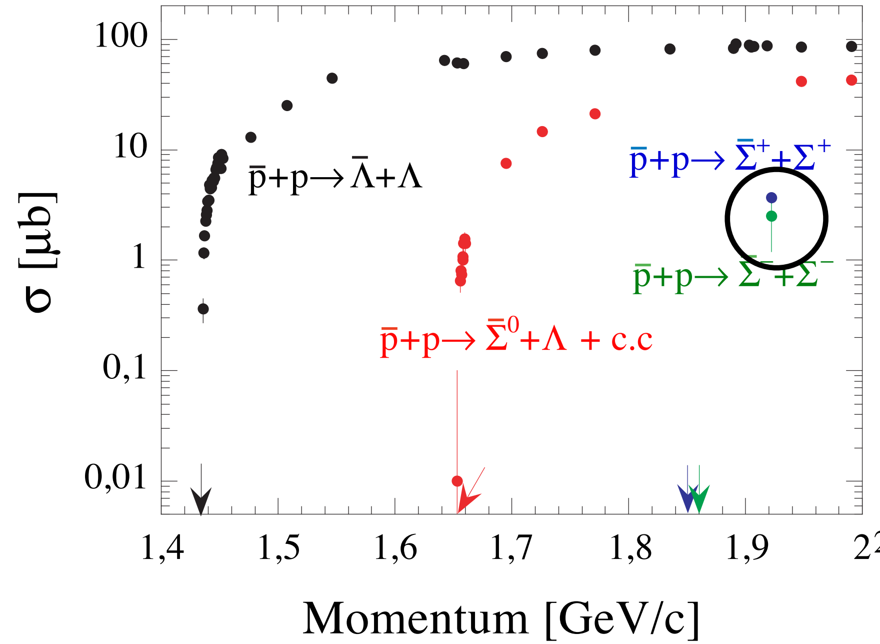
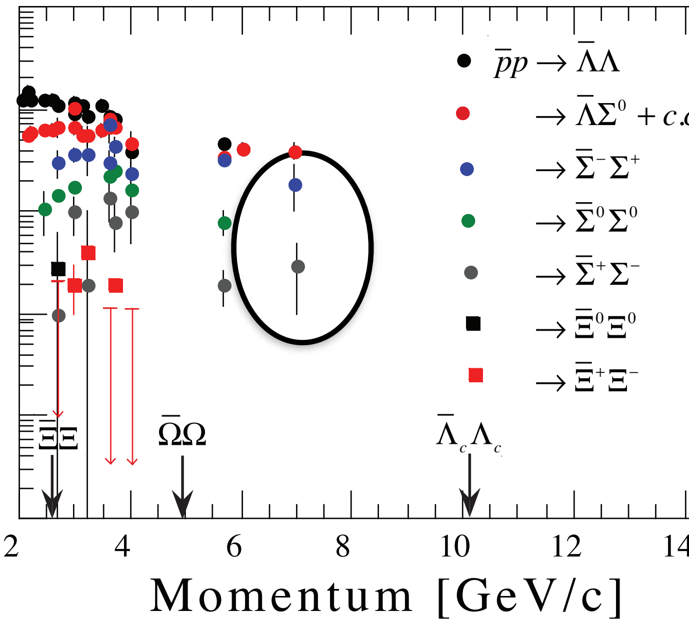


Excess energy = $\varepsilon = \sqrt{s} - \sum m_{final}$

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

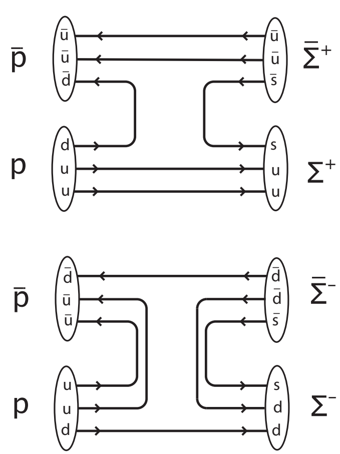
P-waves already at 1 MeV above threshold.
No sign of resonances near threshold.



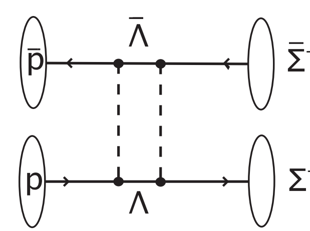


$$\sigma(\bar{p}p \to \bar{\Sigma}^{+}\Sigma^{+}) \approx \sigma(\bar{p}p \to \bar{\Sigma}^{-}\Sigma^{-})$$

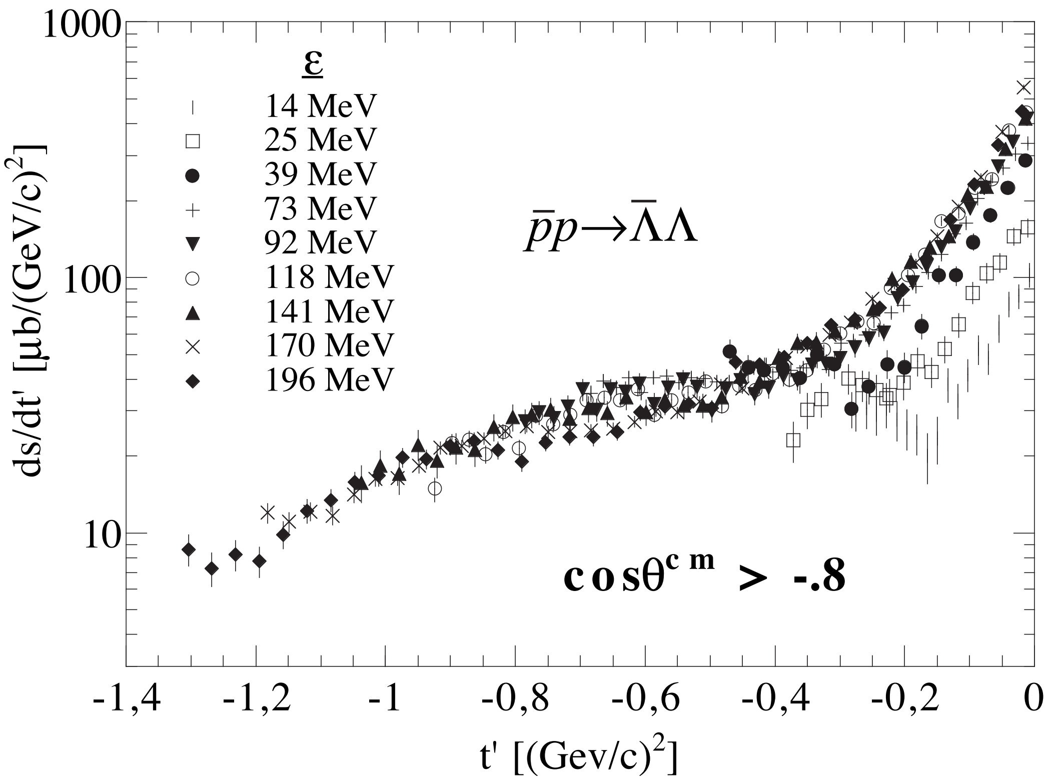
OZI rule violation?

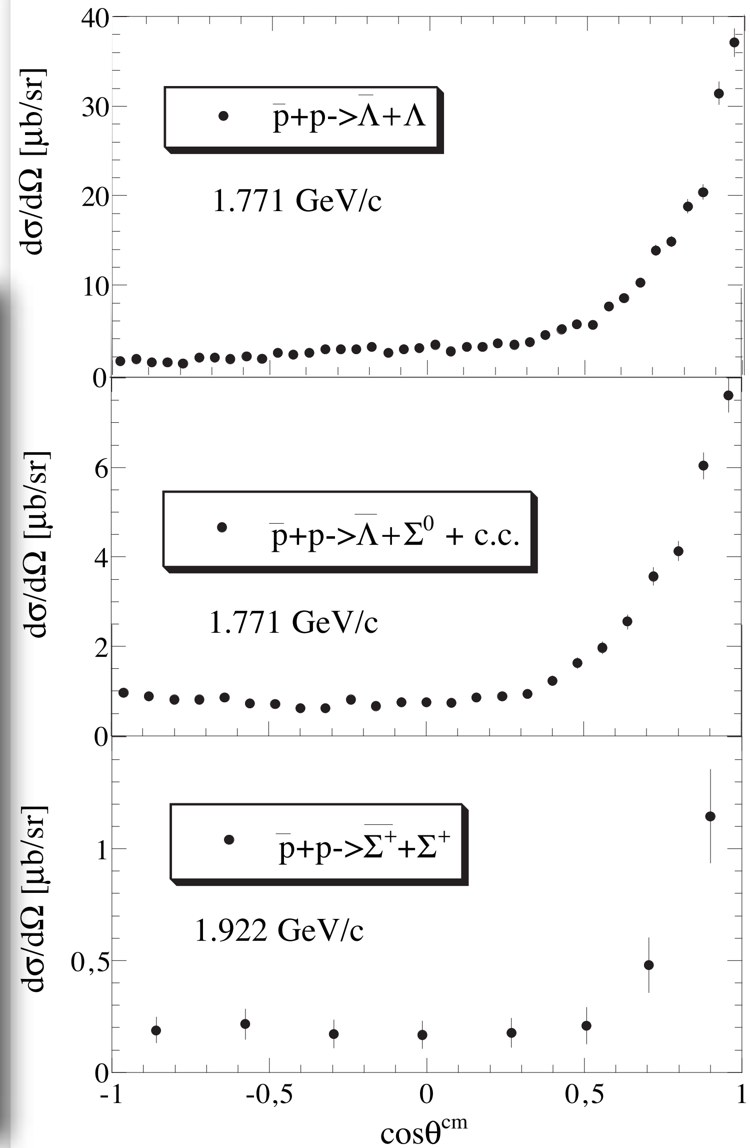


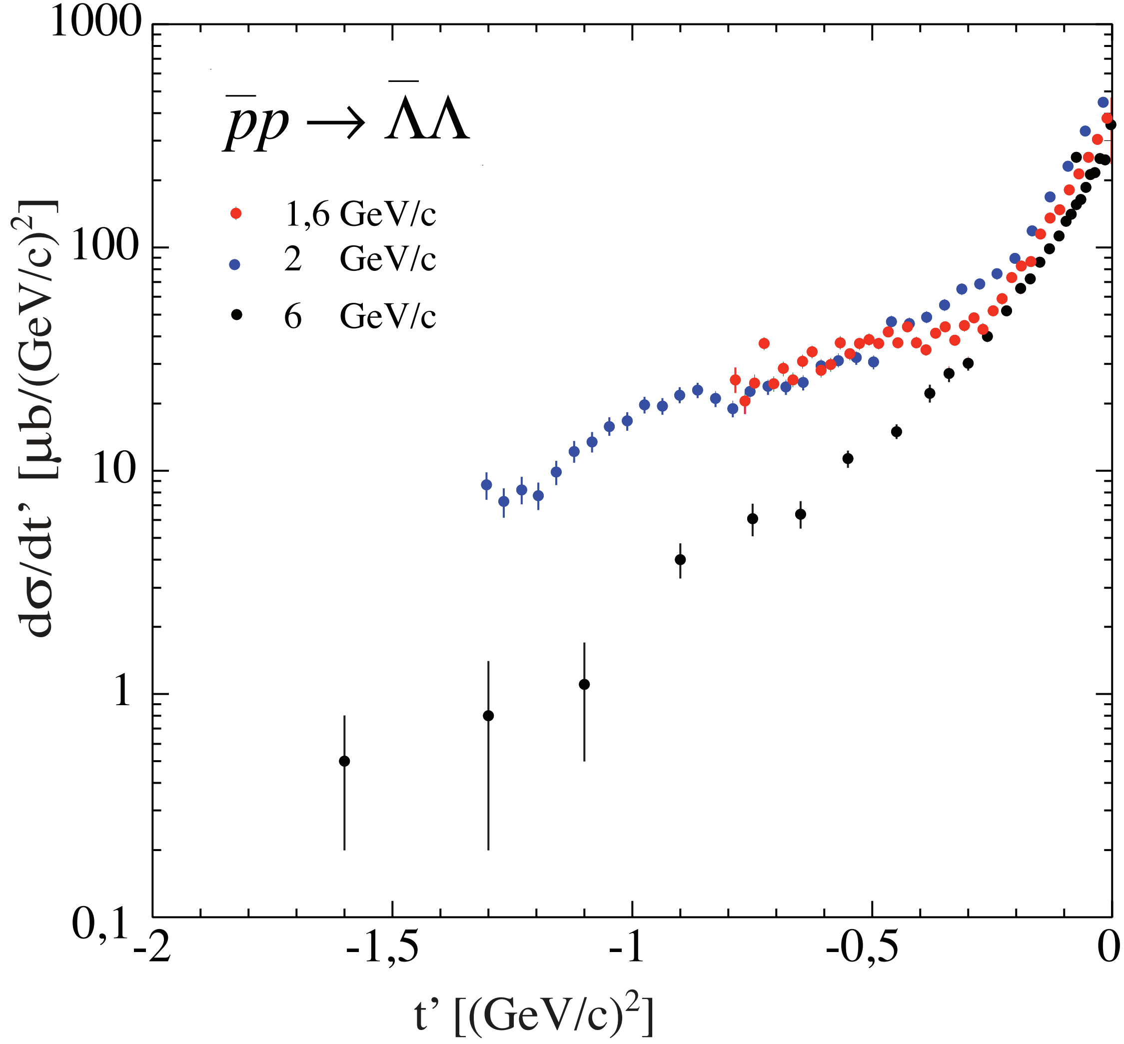
or coupled-channel effect?



$d\sigma / d\Omega$







$\bar{p}p \to \bar{\Lambda}\Lambda$
1,6 GeV/c
2 GeV/c
6 GeV/c
dσ/dt' [μb/(GeV/c)^2]
1000
100
10
1
0,1
-2
-1,5
-1
-0,5
0
t' [(GeV/c)^2]

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Observables

Quantity	Unpolarised beam Unpolarised target	Polarised beam Unpolarised target	Unpolarised beam Polarised target	Polarised beam Polarised target
Differential cross section	I_{0000}	A_{i000}	A_{ojoo}	A_{ij00}
Polarisaton of scattered particle	$P_{00\mu 0}$	$D_{i0\mu 0}$	$K_{0j\mu 0}$	$Mi_{j\mu 0}$
Polarisation of recoil particle	$P_{000\nu}$	$K_{i00\nu}$	$D_{0j0\mu}$	$N_{ij0\nu}$
Correlation of polarisations	$C_{00\mu\nu}$	$C_{i0\mu\nu}$	$C_{0j\mu\nu}$	$C_{ij\mu\nu}$

$I = d\sigma / d\Omega$

P = Polarisation

A = Asymmetry

D = Depolarisation

K = Polarisation transfer

C, M, N = Spin correlations

Indices refer to the spin projection of the beam, target, scattered and recoil particles (= 0 spin average)

256 observables!!

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Symmetries

- Parity conservation
- Charge conjugation invariance
- Geometrical identities
- $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$

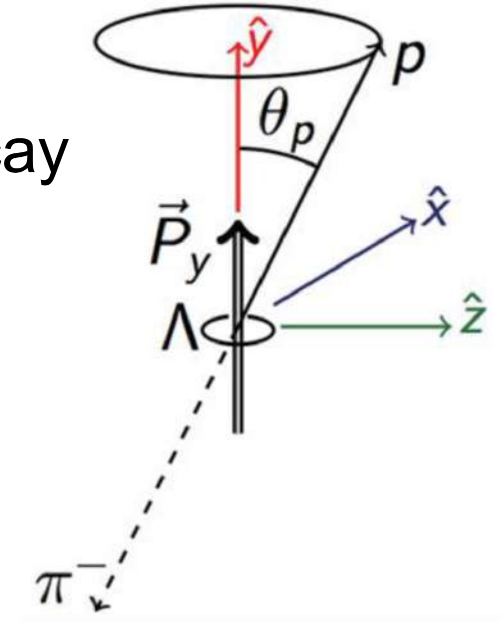
256 ➡ 40 independent observables

8 measurable with an unpolarised beam and target

24 measurable with an unpolarised beam and a transversely polarised target

Spin obsrevables

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



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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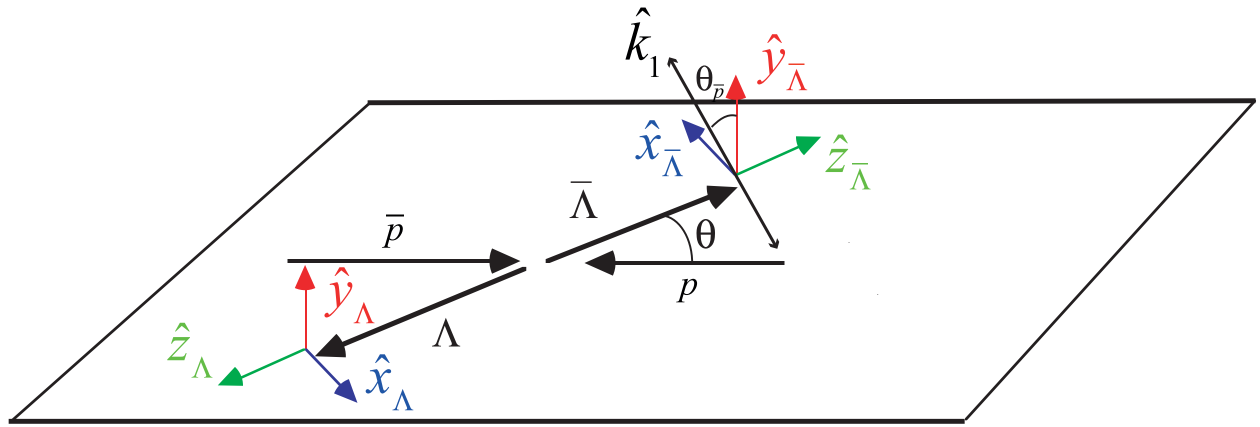
$$\bar{p}p \rightarrow \bar{\Lambda}\Lambda \rightarrow (\bar{p}\pi^{+})(p\pi^{-})$$

$$\hat{x} = \hat{y} \times \hat{z}$$

$$\hat{y} = \frac{\bar{p}_{beam} \times \bar{p}_{\Lambda}}{\left|\bar{p}_{beam} \times \bar{p}_{\Lambda}\right|}$$

$$\hat{z} = \hat{p}_{\Lambda}$$



Unpolarised beam and target

$$I_{\bar{\Lambda}\Lambda}\left(\theta, \hat{\boldsymbol{k}}_1, \hat{\boldsymbol{k}}_2\right) = \frac{I_0^{\bar{\Lambda}\Lambda}}{64\pi^3}\left[\begin{array}{l} 1 \\ +P_y\left(\bar{\alpha}k_{1y} + \alpha k_{2y}\right) \\ +C_{yy}\left(\bar{\alpha}\alpha k_{1y}k_{2y}\right) \\ +C_{xx}\left(\bar{\alpha}\alpha k_{1x}k_{2x}\right) \\ +C_{zz}\left(\bar{\alpha}\alpha k_{1z}k_{2z}\right) \\ +C_{xz}\left(\bar{\alpha}\alpha\left(k_{1x}k_{2z} + k_{1z}k_{2x}\right)\right) \end{array}\right]$$

I_0 = σtot

$I(\theta)$ = dσ/dΩ

P_n = Polarisation

C_{ij} = Spin correlations

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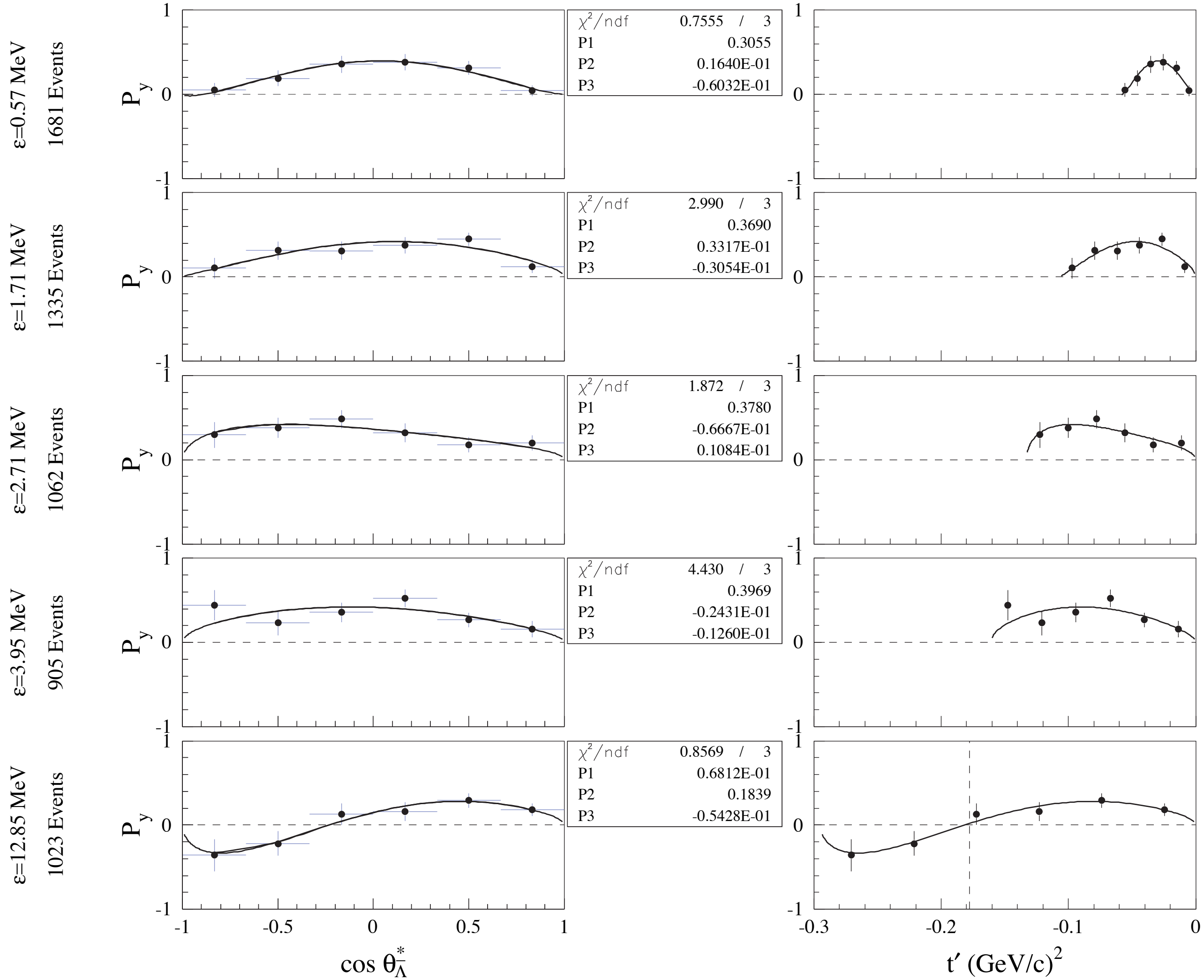
Hyperon	Quarks	cτ [cm]	α	Decay	B.R
Λ	uds	7.9	+0.64*	$p\pi^-$	.64
Σ^+	uus	2.4	-0.98	$p\pi^0$	.52
Σ^0	uds	2.2×10^{-9}	-	$\Lambda\gamma$	≈1.0
Σ^-	dds	4.4	-0.07	$n\pi^-$	≈1.0
Ξ^0	uss	8.7	-0.41	$\Lambda\pi^0$	≈1.0
Ξ^-	dss	4.9	-0.46	$\Lambda\pi^-$	≈1.0
Ω^-	sss	2.5	0.02	ΛK^-	.68
Λ^+_c	udc	6.0×10^{-3}	-0.91	$\Lambda\pi^+$	.01

* PDG 2018

Polarisation

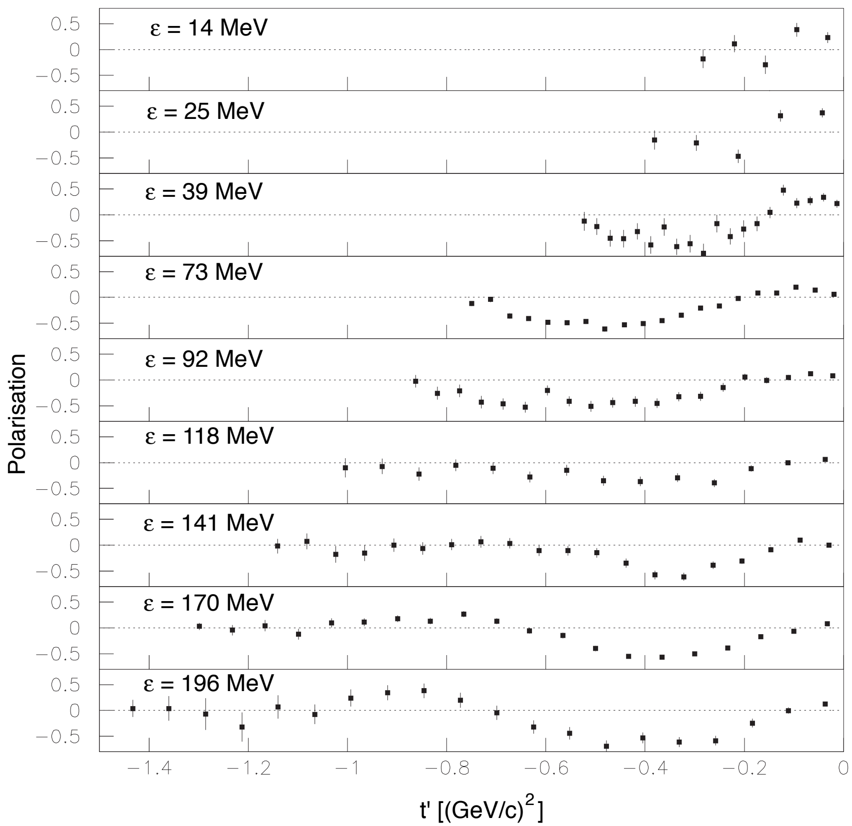
Interference between different partial waves

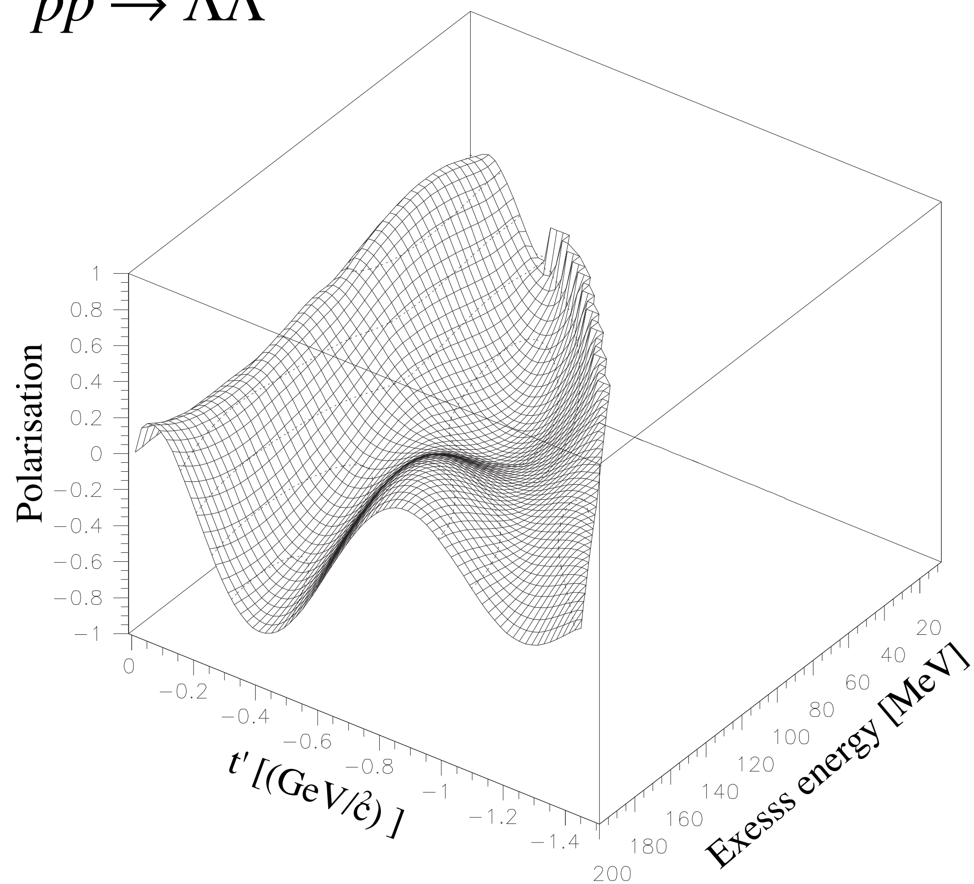


Polarisation

Interference between different partial waves

$\bar{p}p \rightarrow \bar{\Lambda}\Lambda$





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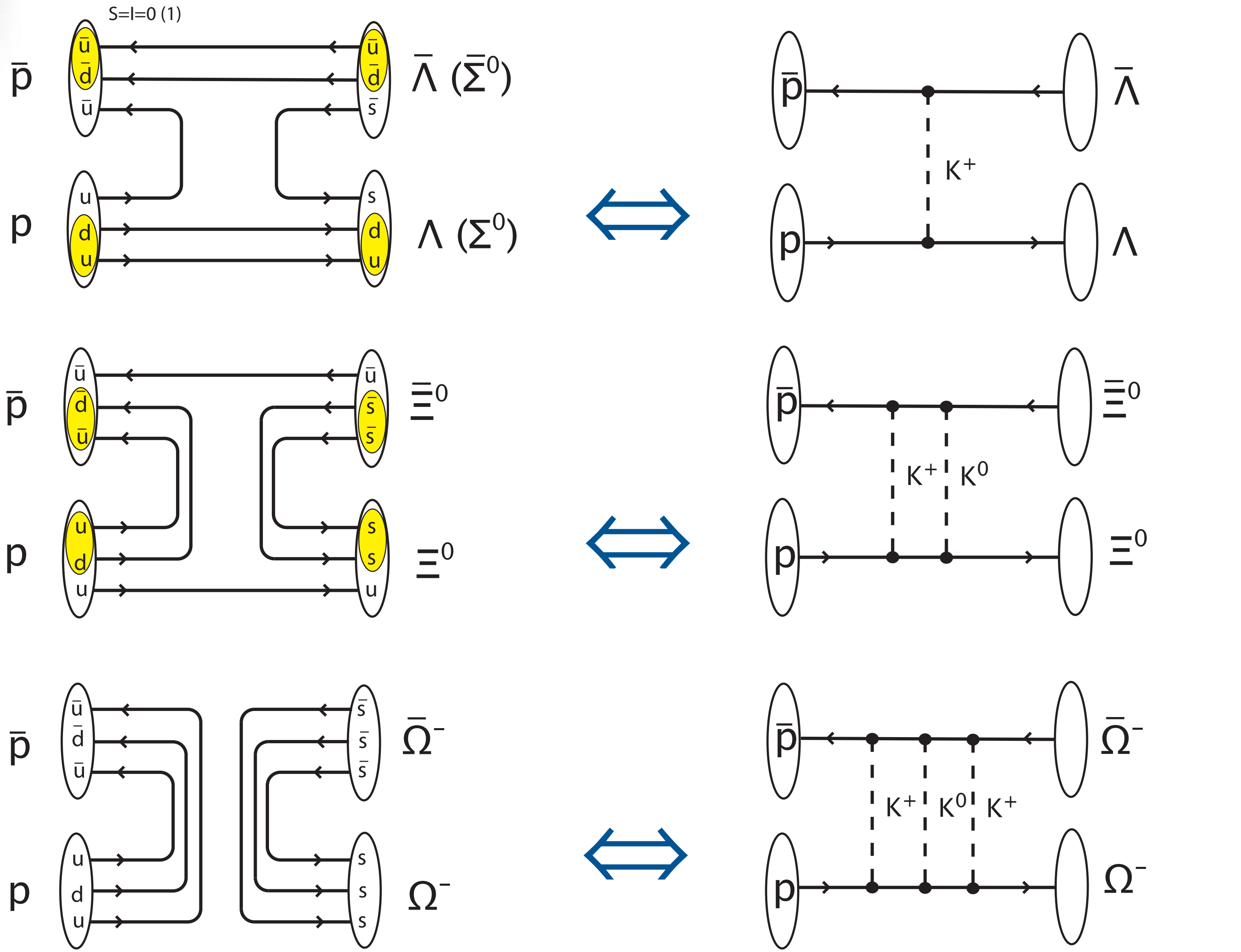
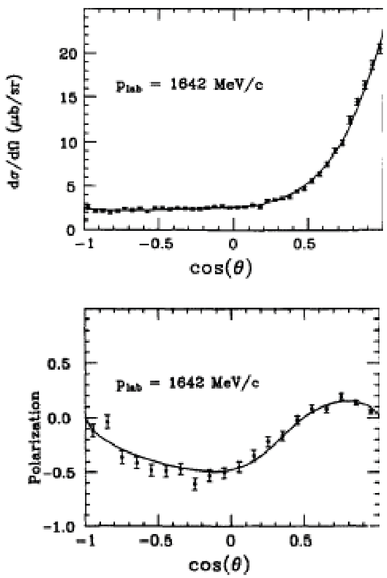
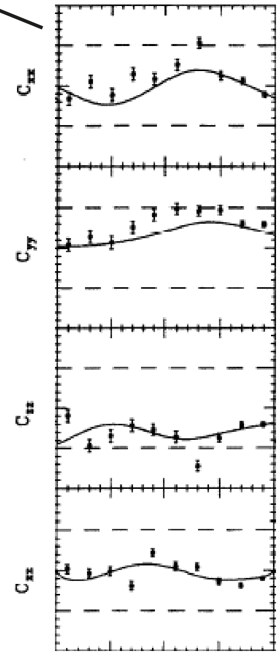
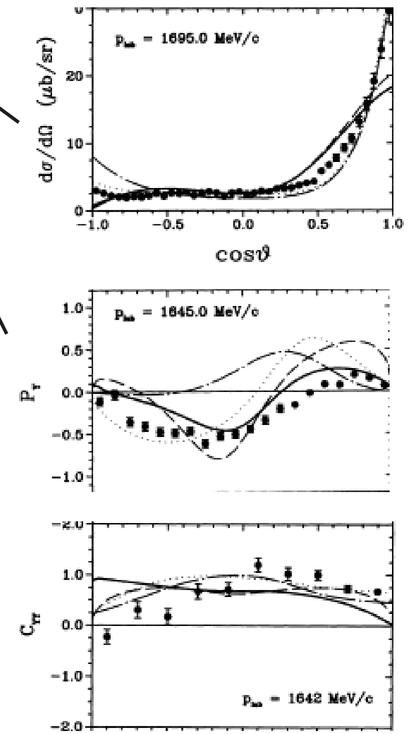
Constituent quark vs. meson exchange model

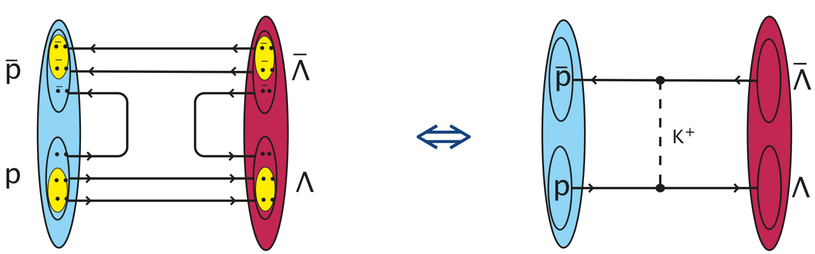


Both “Quark Inspired” and Meson Exchange models give reasonable FIT to data









Both approaches must include ISI and FSI.
ISI: not well know
FSI: unknown
➪ Much freedom in *fitting* the optical potential describing the FSI

Phys. Rep 368 (2002) 119 and refs. therein

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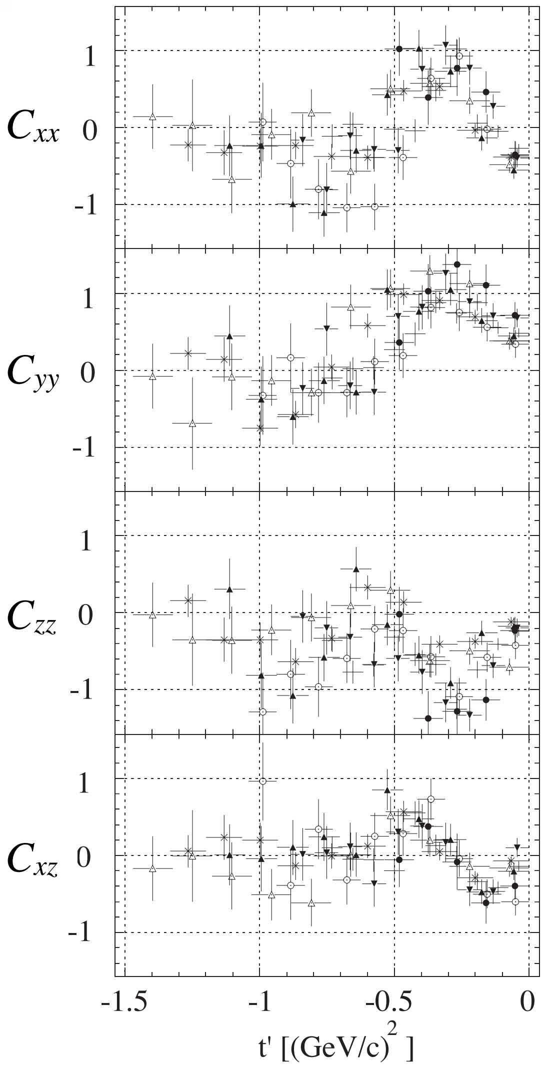
PS185 LEAR

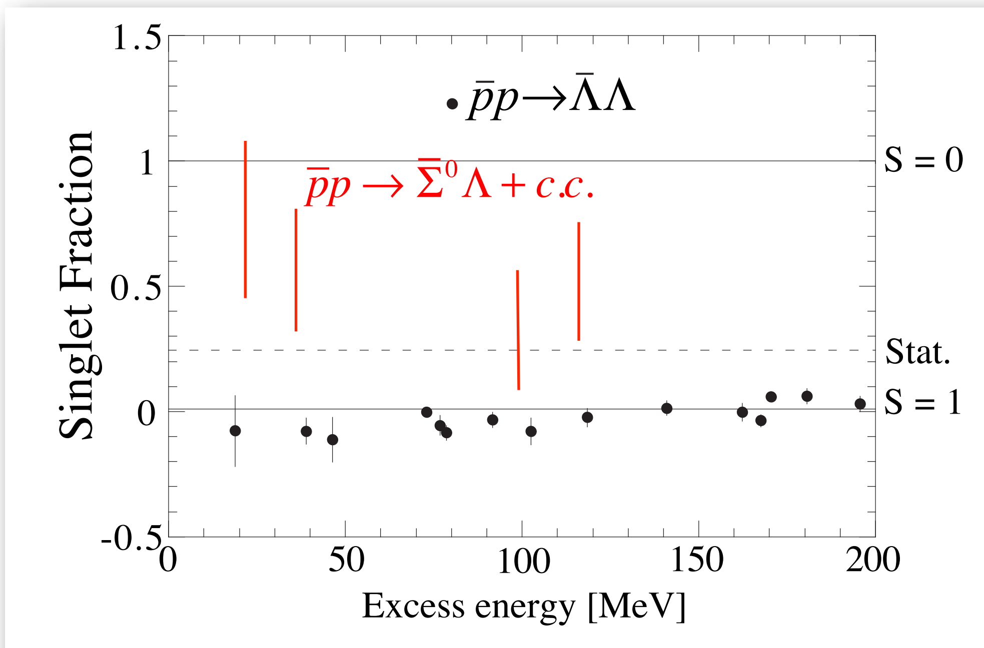
Spin correlations



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

$$F_S = \frac{\left(1 - \left\langle \vec{\sigma}_1 \cdot \vec{\sigma}_2 \right\rangle\right)}{4} = \frac{\left(1 + C_{xx} - C_{yy} + C_{zz}\right)}{4}$$

= 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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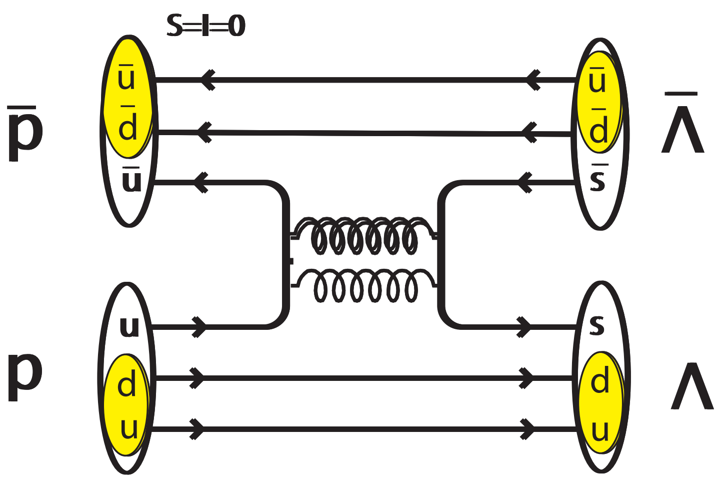
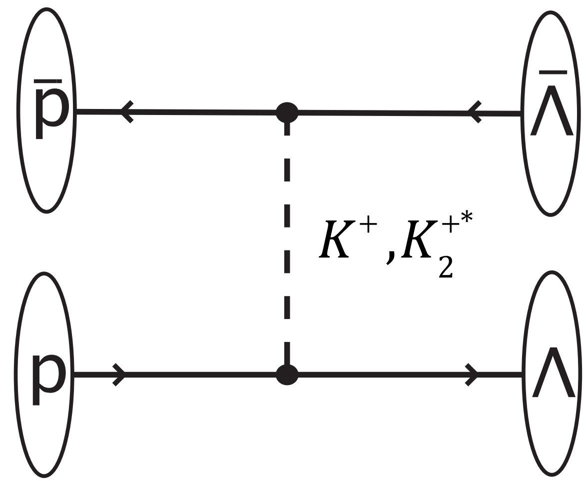
The $\bar{\Lambda}\Lambda$-pair is produced with parallel spin

- The spin of the Λ is essentially carried by the strange quark

➡ the parallel spins are related to the production mechanism





One gluon exchange: $^3S_{1^-}$ *vertex*

Two gluon exchange: $^3P_{0^+}$ *vertex*

➡ triplet $\bar{\Lambda}\Lambda$ spin

Including K_2^* exchange involves a $\Delta\ell = 2$ transition (spin-flip)

➡ triplet $\bar{\Lambda}\Lambda$ spin

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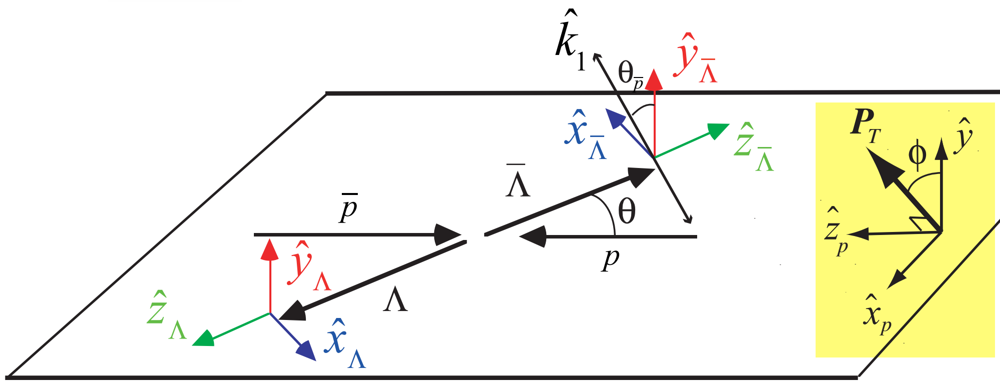
Unpolarised beam and transversely polarised target



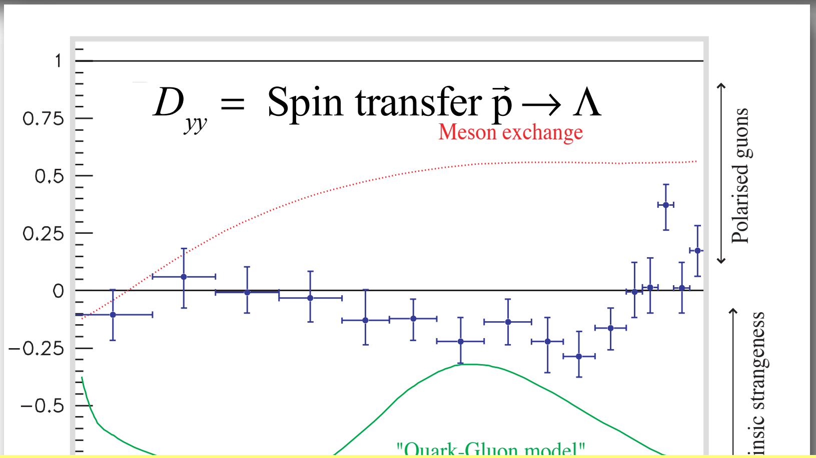
$$
I_{\bar{p}p}\left(\theta,\phi,\hat{\boldsymbol{k}}_1,\hat{\boldsymbol{k}}_2\right)=\frac{I_0^{\bar{\Lambda}\Lambda}}{64\pi^3}
\left[\begin{aligned}
&1\\
&+P_y\left(\bar{\alpha}k_{1y}+\alpha k_{2y}\right)\\
&+C_{00yy}\left(\bar{\alpha}\alpha k_{1y}k_{2y}\right)\\
&+C_{00xx}\left(\bar{\alpha}\alpha k_{1x}k_{2x}\right)\\
&+C_{00zz}\left(\bar{\alpha}\alpha k_{1z}k_{2z}\right)\\
&+C_{00xz}\left(\bar{\alpha}\alpha\left(k_{1x}k_{2z}+k_{1z}k_{2x}\right)\right)\\
&+A_{00y0}\left(P^T\cos\phi+\bar{\alpha}\alpha P^T k_{1y}k_{2y}\cos\phi\right)\\
&+K_{0yy0}\left(\bar{\alpha}P^T k_{1y}\cos\phi\right)\\
&+D_{0y0y}\left(\alpha P^T k_{2y}\cos\phi\right)\\
&+K_{0xx0}\left(\bar{\alpha}P^T k_{1x}\sin\phi\right)\\
&+K_{0xz0}\left(\bar{\alpha}P^T k_{1z}\sin\phi\right)\\
&+D_{0x0x}\left(\alpha P^T k_{2x}\sin\phi\right)\\
&+D_{0x0z}\left(\alpha P^T k_{2z}\sin\phi\right)\\
&+C_{0yxx}\left(\bar{\alpha}\alpha P^T\left(k_{1x}k_{2x}\cos\phi-k_{1z}k_{2z}\right)\right)\\
&+C_{0yxz}\left(\bar{\alpha}\alpha P^T k_{1x}k_{2z}\cos\phi\right)\\
&+C_{0yzx}\left(\bar{\alpha}\alpha P^T k_{1z}k_{2x}\cos\phi\right)\\
&+C_{0xxy}\left(\bar{\alpha}\alpha P^T k_{1x}k_{2y}\sin\phi\right)\\
&+C_{0xzy}\left(\bar{\alpha}\alpha P^T k_{1z}k_{2y}\sin\phi\right)\\
&+C_{0xyx}\left(\bar{\alpha}\alpha P^T k_{1y}k_{2x}\sin\phi\right)\\
&+C_{0xyz}\left(\bar{\alpha}\alpha P^T k_{1y}k_{2z}\sin\phi\right)
\end{aligned}\right]
$$

ϕ = angle between the normal of the scattering plane and target polarisation

D_{0y0y} : polarisation transfer from p to Λ

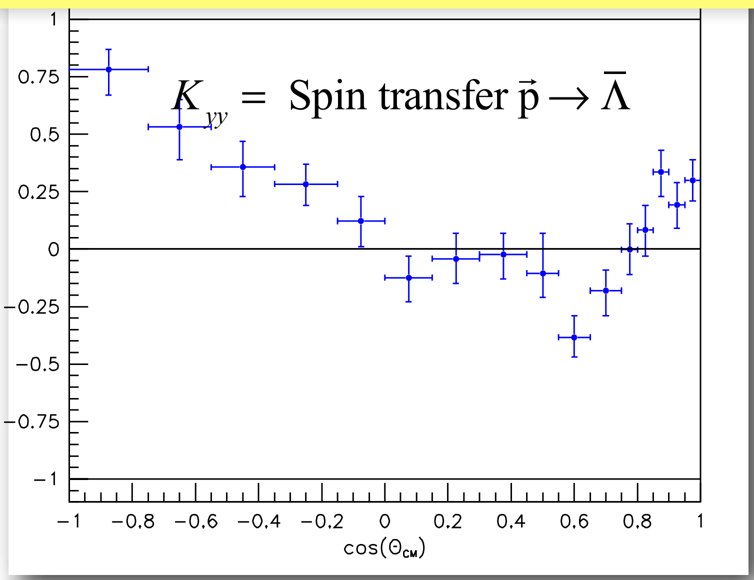
K_{0yy0} : polarisation transfer from p to $\bar{\Lambda}$

PS185/3: $\bar{p}\vec{p} \to \bar{\Lambda}\Lambda$ @ 1637 MeV / c



Practically no spin transfer from proton to Λ.

Spin transfer from proton to $\bar{\Lambda}$?



PRL 89 (2002) 212302-1

Transition matrix

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The spin structure of the transition matrix contains 16 complex amplitudes in terms of spin operators and momentum vectors.

Parity conservation and charge conjugation invariance brings this down to six complex amplitudes

$$M_{\bar{p}p\to\bar{\Lambda}\Lambda} = \frac{1}{2}\begin{bmatrix} (a+b)+(a-b)\vec{\boldsymbol{\sigma}}_1\cdot\hat{\boldsymbol{y}}\cdot\vec{\boldsymbol{\sigma}}_2\cdot\hat{\boldsymbol{y}} \\ +\,(c+d)\vec{\boldsymbol{\sigma}}_1\cdot\hat{\boldsymbol{x}}\cdot\vec{\boldsymbol{\sigma}}_2\cdot\hat{\boldsymbol{x}} \\ +\,(c-d)\vec{\boldsymbol{\sigma}}_1\cdot\hat{\boldsymbol{z}}\cdot\vec{\boldsymbol{\sigma}}_2\cdot\hat{\boldsymbol{z}} \\ +\,e\left(\left(\vec{\boldsymbol{\sigma}}_1+\vec{\boldsymbol{\sigma}}_2\right)\cdot\hat{\boldsymbol{y}}\right) \\ +\,g\left(\vec{\boldsymbol{\sigma}}_1\cdot\hat{\boldsymbol{x}}\cdot\vec{\boldsymbol{\sigma}}_2\cdot\hat{\boldsymbol{z}}+\vec{\boldsymbol{\sigma}}_1\cdot\hat{\boldsymbol{z}}\cdot\vec{\boldsymbol{\sigma}}_2\cdot\hat{\boldsymbol{x}}\right) \end{bmatrix}$$

The complex matrix parameters $\{a, b, c, d, e, g\}$ are functions of the polar scattering angle and contains the dynamics of the interaction.

24 measured observables relate to 11 real parameters + one arbitrary phase of the scattering matrix.

More observables than unknowns

The complete scattering matrix can be determined!

The knowledge of the scattering matrix can be used to extract unmeasured observables!

$$I_0 = \frac{1}{2}\left\{|a|^2+|b|^2+|c|^2+|d|^2+|e|^2+|g|^2\right\}$$

$$I_0 C_{00yy} = \frac{1}{2}\left\{|a|^2-|b|^2-|c|^2+|d|^2+|e|^2+|g|^2\right\}$$

$$I_0 D_{0y0y} = \frac{1}{2}\left\{|a|^2+|b|^2-|c|^2+|d|^2+|e|^2-|g|^2\right\}$$

$$I_0 K_{0yy0} = \frac{1}{2}\left\{|a|^2-|b|^2+|c|^2-|d|^2+|e|^2-|g|^2\right\}$$

$$I_0 P_{000y} = I_0 P_{00y0} = \mathrm{Re}\left(a^* e\right) - \mathrm{Im}\left(d^* g\right)$$

$$I_0 A_{0y00} = I_0 C_{0yyy} = \mathrm{Re}\left(a^* e\right) + \mathrm{Im}\left(d^* g\right)$$

$$I_0 C_{00xz} = I_0 C_{00zx} = \mathrm{Re}\left(a^* g\right) + \mathrm{Im}\left(d^* e\right)$$

$$I_0 C_{0yxx} = -I_0 C_{0yzz} = \mathrm{Re}\left(d^* e\right) + \mathrm{Im}\left(a^* g\right)$$

$$I_0 C_{00xx} = \mathrm{Re}\left(a^* d + b^* c\right) + \mathrm{Im}\left(e^* g\right)$$

$$I_0 C_{00zz} = \mathrm{Re}\left(-a^* d + b^* c\right) - \mathrm{Im}\left(e^* g\right)$$

$$I_0 C_{0yzx} = \mathrm{Re}\left(e^* g\right) + \mathrm{Im}\left(-a^* d + b^* c\right)$$

$$I_0 C_{0yxz} = \mathrm{Re}\left(e^* g\right) + \mathrm{Im}\left(-a^* d - b^* c\right)$$

$$I_0 D_{0x0x} = \mathrm{Re}\left(a^* b + c^* d\right)$$

$$I_0 C_{0xyz} = \mathrm{Im}\left(-a^* b + c^* d\right)$$

$$I_0 K_{0xx0} = \mathrm{Re}\left(a^* c + b^* d\right)$$

$$I_0 C_{0xzy} = \mathrm{Im}\left(-a^* c + b^* d\right)$$

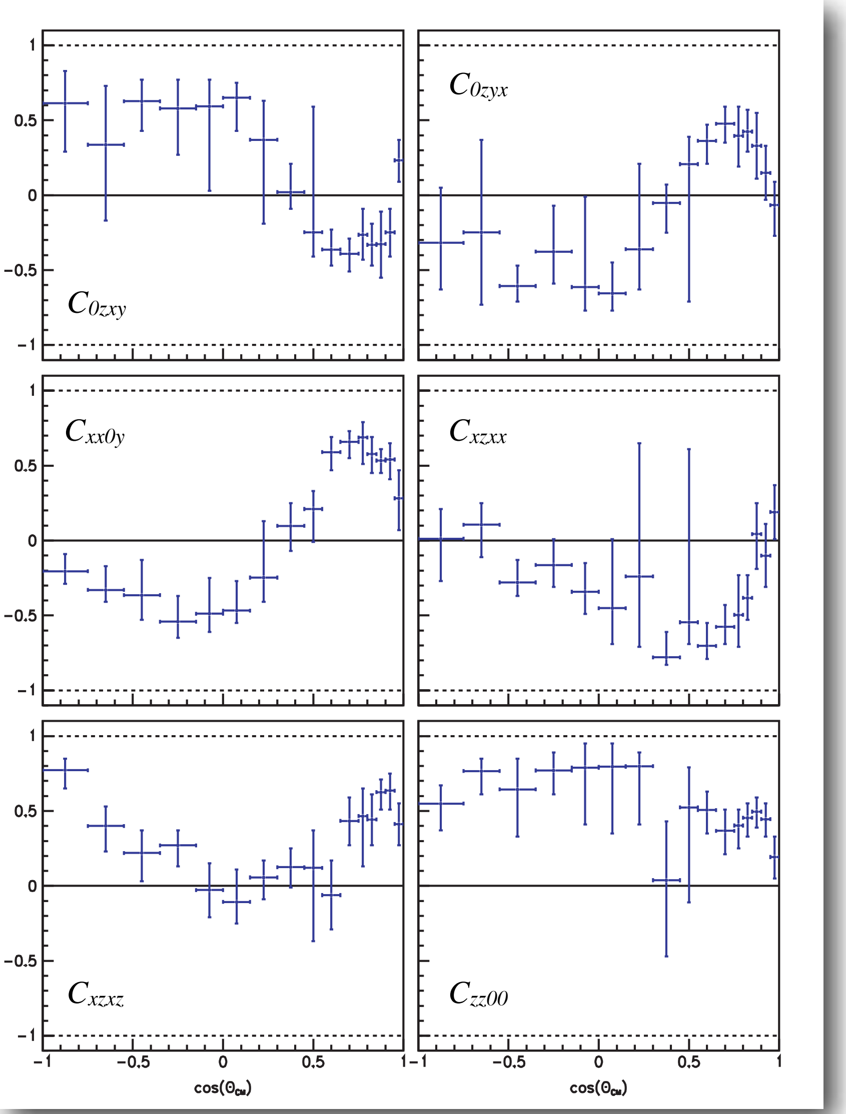
$$I_0 C_{0xyx} = \mathrm{Re}\left(b^* e\right) - \mathrm{Im}\left(c^* g\right)$$

$$I_0 D_{0x0z} = \mathrm{Re}\left(c^* g\right) + \mathrm{Im}\left(b^* e\right)$$

$$I_0 K_{0xz0} = \mathrm{Re}\left(b^* g\right) + \mathrm{Im}\left(c^* e\right)$$

$$I_0 C_{0xxy} = \mathrm{Re}\left(c^* e\right) - \mathrm{Im}\left(b^* g\right)$$

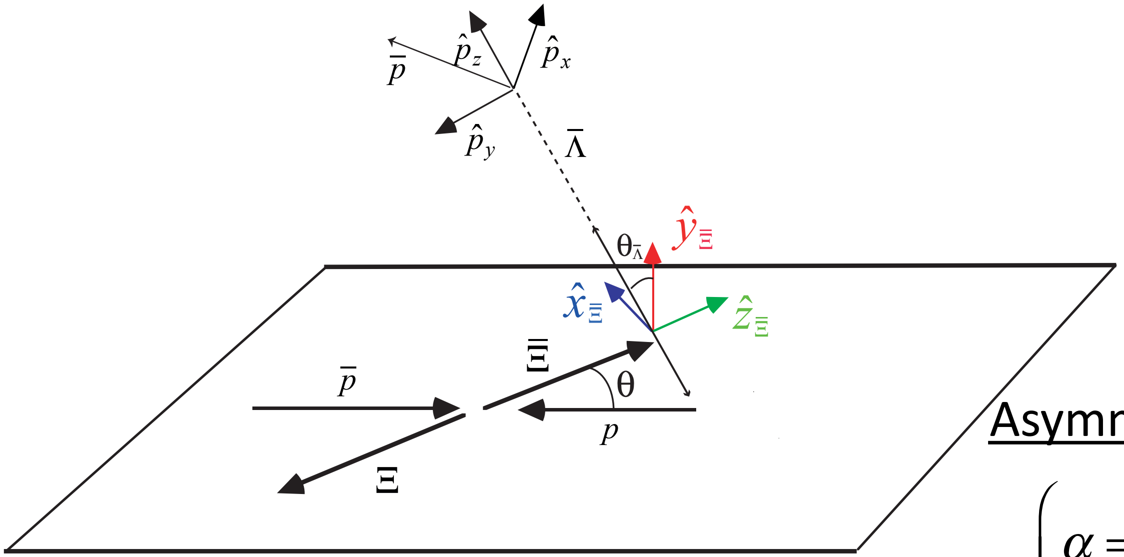
Extracted unmeasured spin observables



PRC 76 (2006) 015206

Multiple strange hyperons => sequential decays

$$e.g.\ \frac{1}{2} \to \frac{1}{2} + 0 \quad \left(\Xi \to \Lambda\pi \to (p\pi), \Lambda_c\right)$$



Ξ rest frame:

$$I(\theta_\Lambda) = 1 + \alpha_\Xi P_\Xi \cos\theta_\Lambda$$

Λ rest frame:

$$\hat{p}_x = \hat{p}_y \times \hat{p}_z \qquad I(\theta_{p,x}) = 1 - \frac{\pi}{4}\alpha_\Lambda \gamma_\Xi P_\Xi \cos\theta_{p,x} = 1 - \frac{\pi}{4}\alpha_\Lambda \gamma_\Xi P_\Xi \hat{p}_x$$

$$\hat{p}_y = \frac{\hat{y}_\Xi \times \bar{p}_\Lambda}{|\hat{y}_\Xi \times \bar{p}_\Lambda|} \qquad I(\theta_{p,y}) = 1 + \frac{\pi}{4}\alpha_\Lambda \beta_\Xi P_\Xi \cos\theta_{p,y} = 1 + \frac{\pi}{4}\alpha_\Lambda \beta_\Xi P_\Xi \hat{p}_y$$

$$\hat{p}_z = \hat{p}_\Lambda \qquad I(\theta_{p,z}) = 1 + \alpha_\Lambda \alpha_\Xi \cos\theta_{p,z} = 1 + \alpha_\Lambda \alpha_\Xi \hat{p}_z$$

<u>Asymmetry parameters.</u>

$$\begin{pmatrix} \alpha = \dfrac{2\,\mathrm{Re}\,S^* P}{|S|^2 + |P|^2} \\ \beta = \dfrac{2\,\mathrm{Im}\,S^* P}{|S|^2 + |P|^2} \\ \gamma = \dfrac{|S|^2 - |P|^2}{|S|^2 + |P|^2} \\ \alpha^2 + \beta^2 + \gamma^2 = 1 \end{pmatrix}$$

CP violation

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

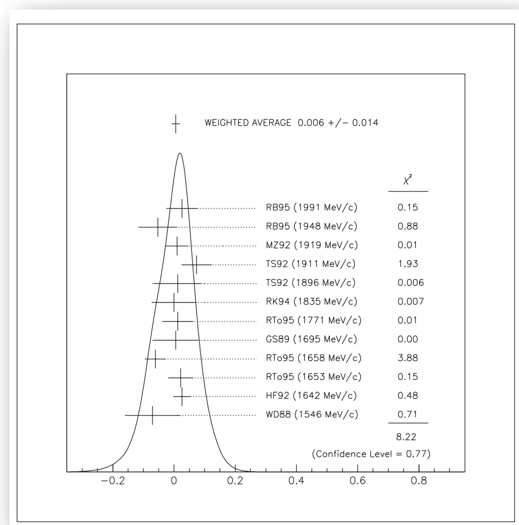
$$A = \frac{\Gamma\alpha + \bar{\Gamma}\bar{\alpha}}{\Gamma\alpha - \bar{\Gamma}\bar{\alpha}} \simeq \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}}$$

PDG: 0.006±0.021 α_Λ

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

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

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



PS185 tot:
0.006±0.014
≈ 200000 events

High statistics with PANDA !!

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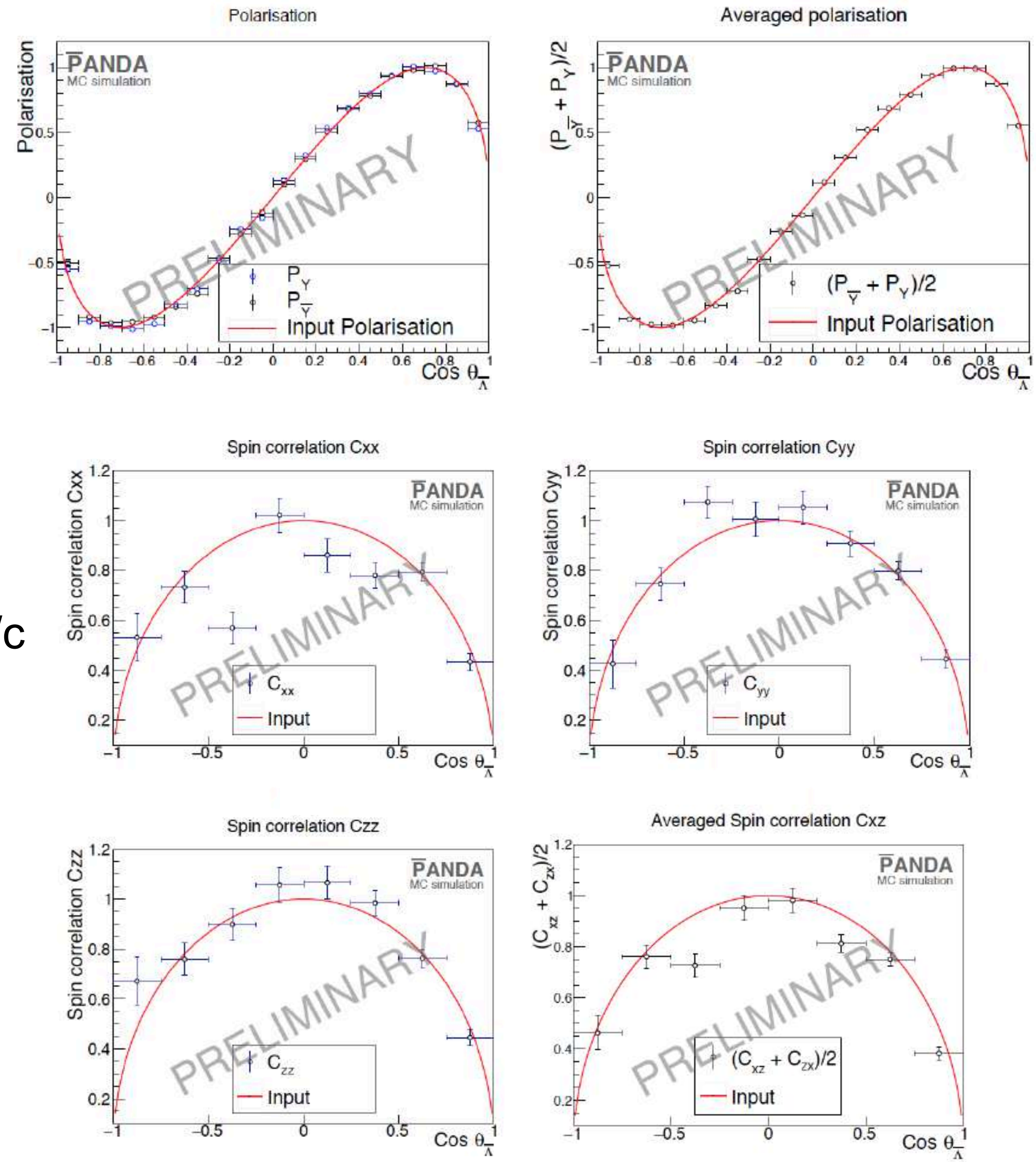
$$\bar{p}p \rightarrow \bar{\Lambda}\Lambda$$

Simulations @ 1.64 GeV/c
100k events



W. Ikegami Andersson

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panda

Prospects Day 1 luminosity

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

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

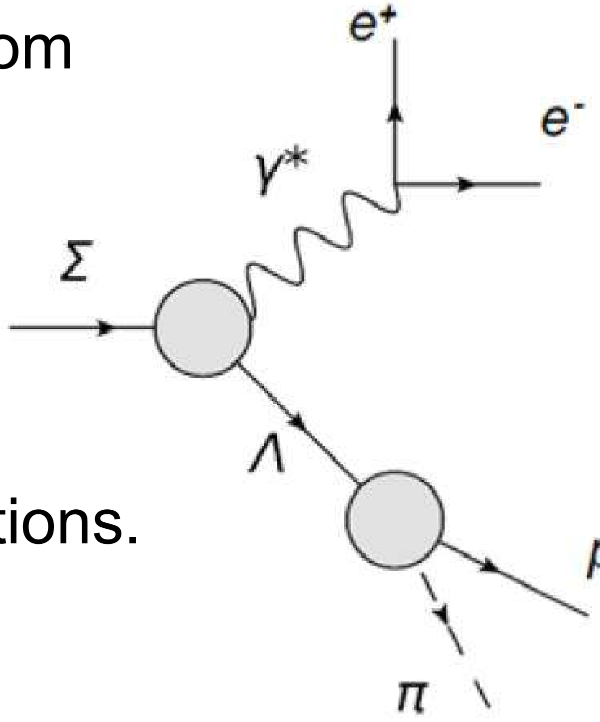
Gain of 100 with an inclusive measurement

- The weak hyperon decay gives access to polarisation and spin correlations.
  - ➪ Access to spin degrees of freedom in strange (charm) quark-pair creation.
  - ➪ Many observables
    - ➪ ➪ PWA of the data to extract relevant quantum numbers
    - ➪ ➪ high discriminating power between models (hadron vs. quark-gluon based)
  - ➪ CP-violation tests: $\bar{p}p \to \bar{\Lambda}\Lambda$, A-parameter
    $\bar{p}p \to \bar{\Xi}\Xi$, B-parameter

➡ $\bar{p}$anda

Hyperon Structure

Transitions Form Factors accessible from Dalitz decays, e. g. Σ^0, $\Lambda(1520)$.



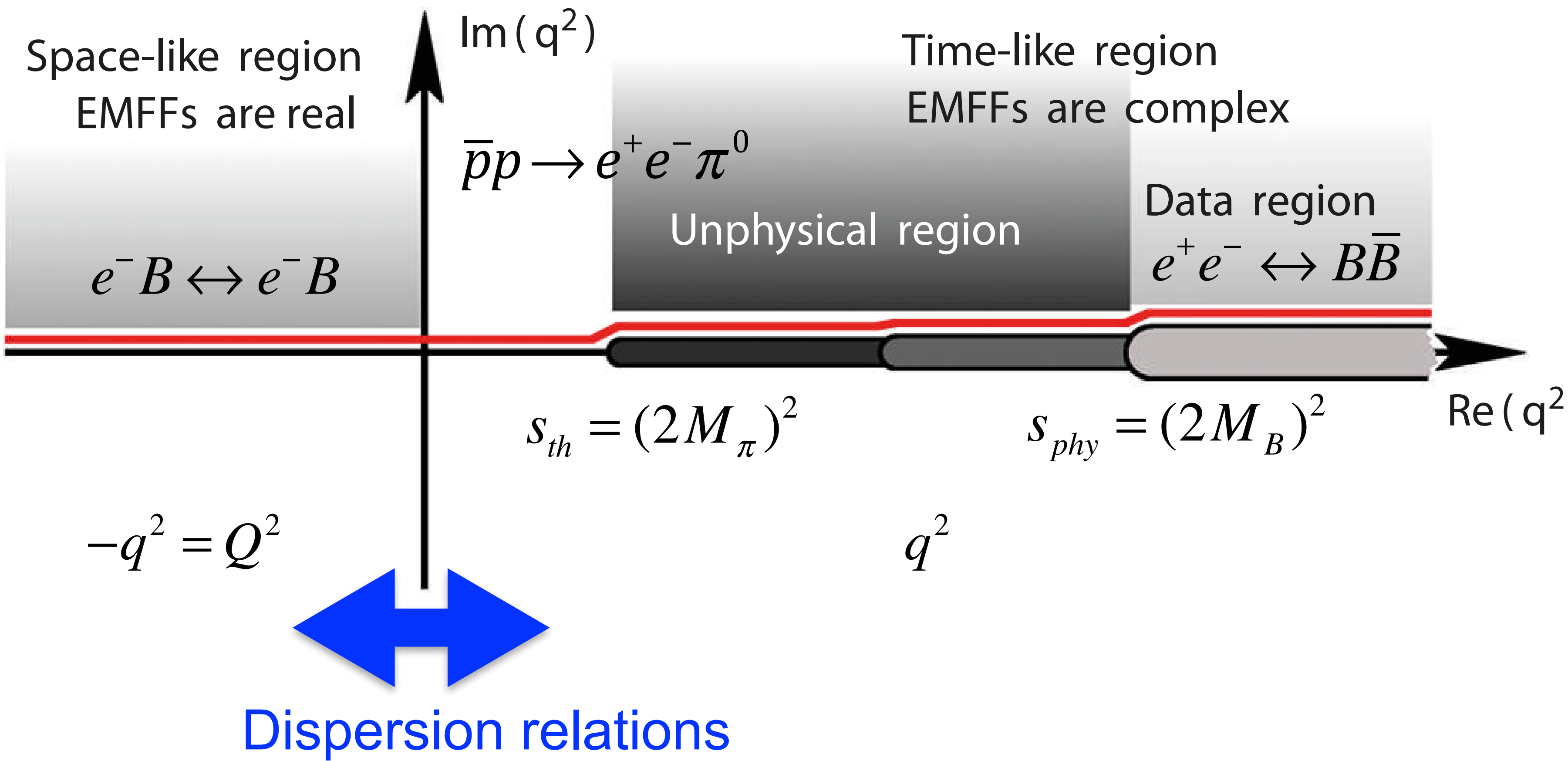
🙁 Small predicted BR's (10^{-3} - 10^{-6}). (No data exist)

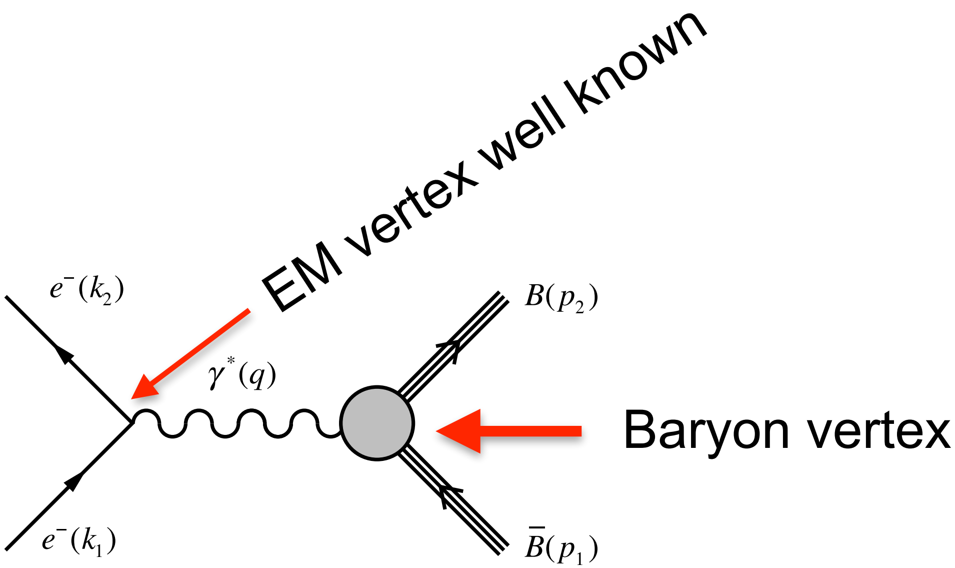
🙂 Large hyperon production cross sections.

→ PANDA

Electromagnetic Form Factors provide the most direct access to the spatial charge and magnetisation distributions.

This is given fot a hadron with spin *S* by *2S+1* Form Factors.





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:

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

$$G_M = F_1 + F_2$$

$$G_E(0) = Z$$

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

The Space-Like Sachs FF´s correspond to the Fourier transformations of the charge and magnetic spatial distributions in the Breit frame ($q = (0, \vec{q})$).
(The situation is more complicated.)

The Space-Like EEMFF is obtained from elastic electron scattering in terms of G_E^2 and G_M^2 (**Rosenbluth separation**) as:

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \frac{E_e}{E_{beam}} \frac{1}{1+\tau}\left(G_E^2 + \frac{\tau}{\varepsilon} G_M^2\right); \ \tau = \frac{Q^2}{4M_p^2}$$

$$\varepsilon = \frac{1}{1+2(1+\tau)\tan^2\theta_e/2}$$ = virtual photon polarisation

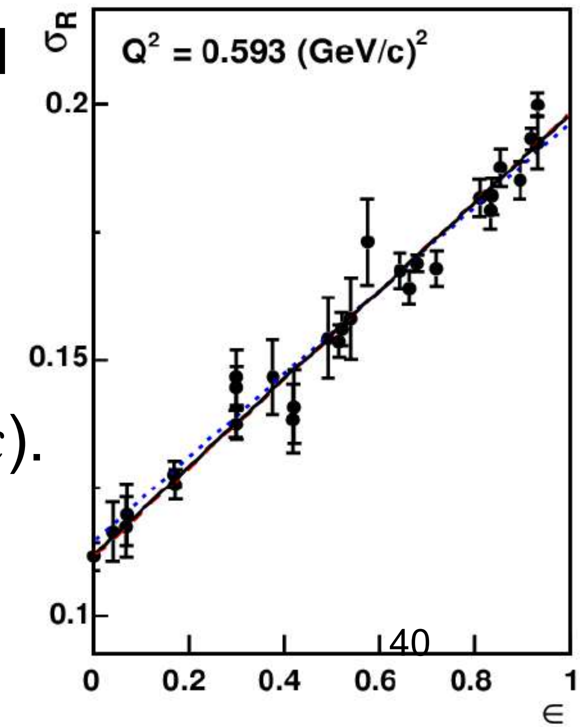
The linear dependence on τ in ε makes it possible to define a reduced cross section as

$$\sigma_{red} = \frac{\varepsilon(1+\tau)}{\tau}\frac{E_e}{E_{beam}}\frac{d\sigma}{d\Omega}/\left(\frac{d\sigma}{d\Omega}\right)_{Mott} = G_M^2 + \frac{\varepsilon}{\tau}G_E^2$$

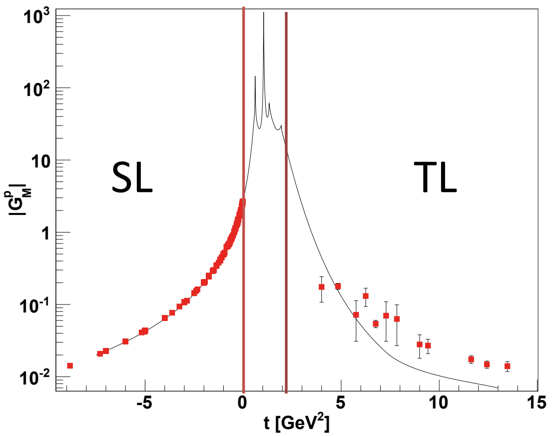
G_E^2 difficult to measure at high Q^2

=> σ_{red} is expected to have linear dependence on ε at a given Q^2 with a slope proportional to G_E^2 and with the intercept G_M^2.

G_E^2 and G_M^2 are extracted from fits to the data from measurements of the cross section at a given Q^2 at different energies (ε).

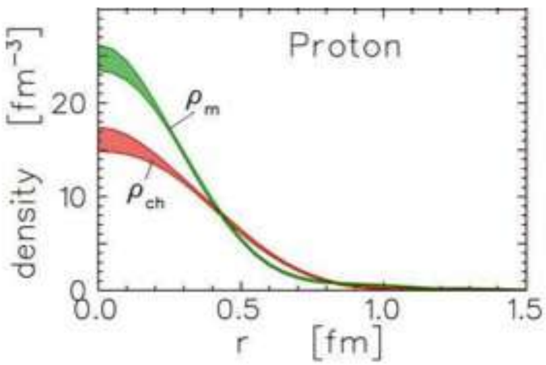


Proton EMFF



Bartos et al. NP 219-220 (2011) 166

Kelly PRC66 (2002)065203



G_E and G_M are analytical functions of q^2

- low q^2 probes the size of the baryon
- high q^2 tests perturbative QCD

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

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

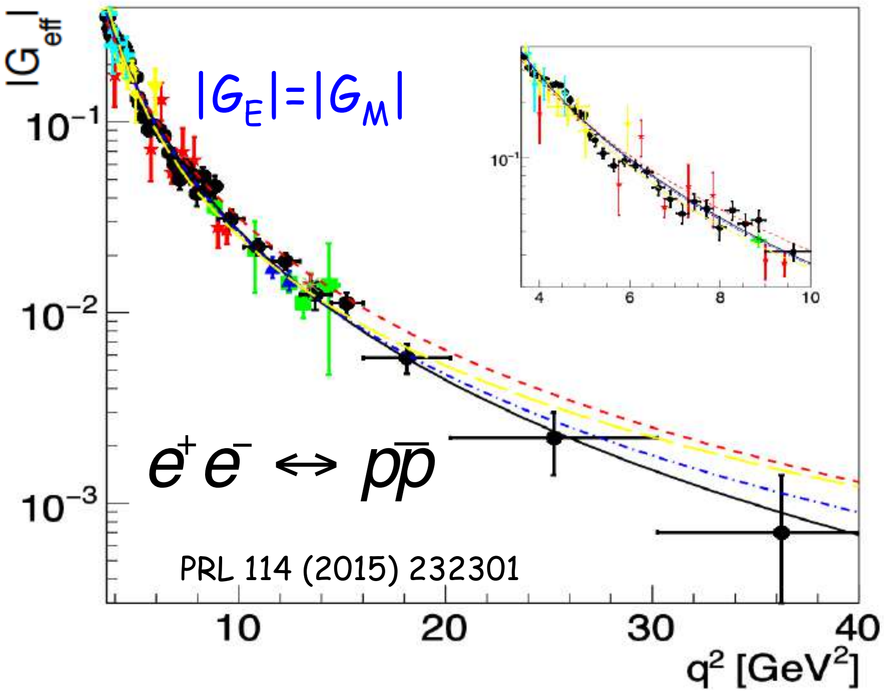
$$\tau = \frac{q^2}{4m_B^2},\ \beta = \sqrt{1-1/\tau},\ C = \text{Coulomb factor} = \mathrm{y/(1\text{-}e^{-y})}, y = \pi\alpha/\beta$$

- 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 ☹.

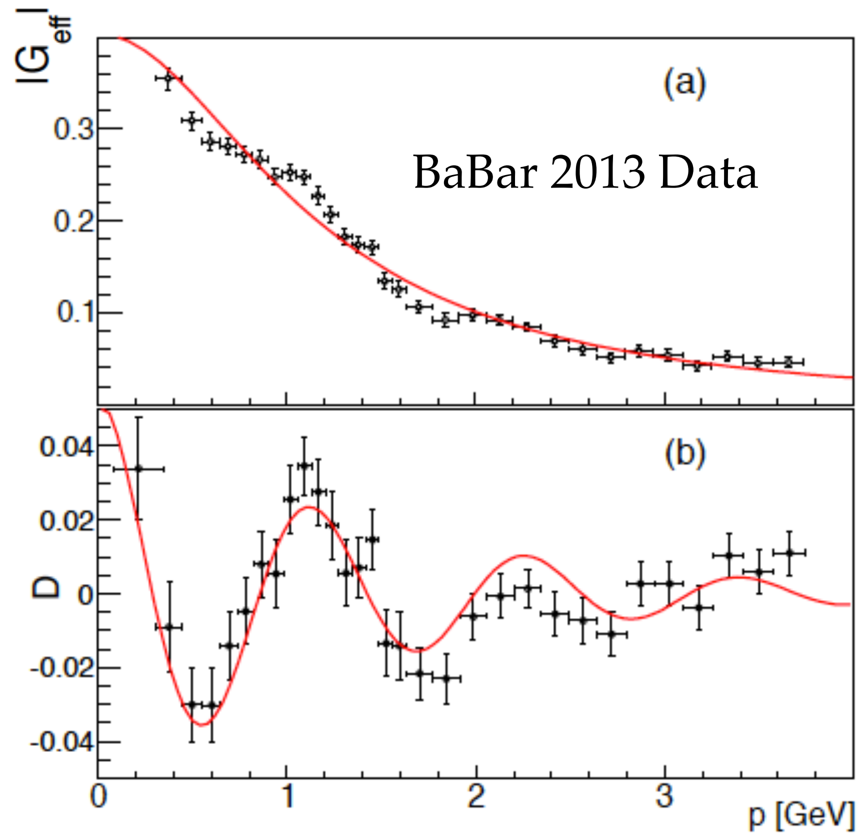
The total cross section is often rewritten as an effective form factor:

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

World data on the time-like (effective) proton form factor



Phys. Rev. Lett. 114,232301 (2015)

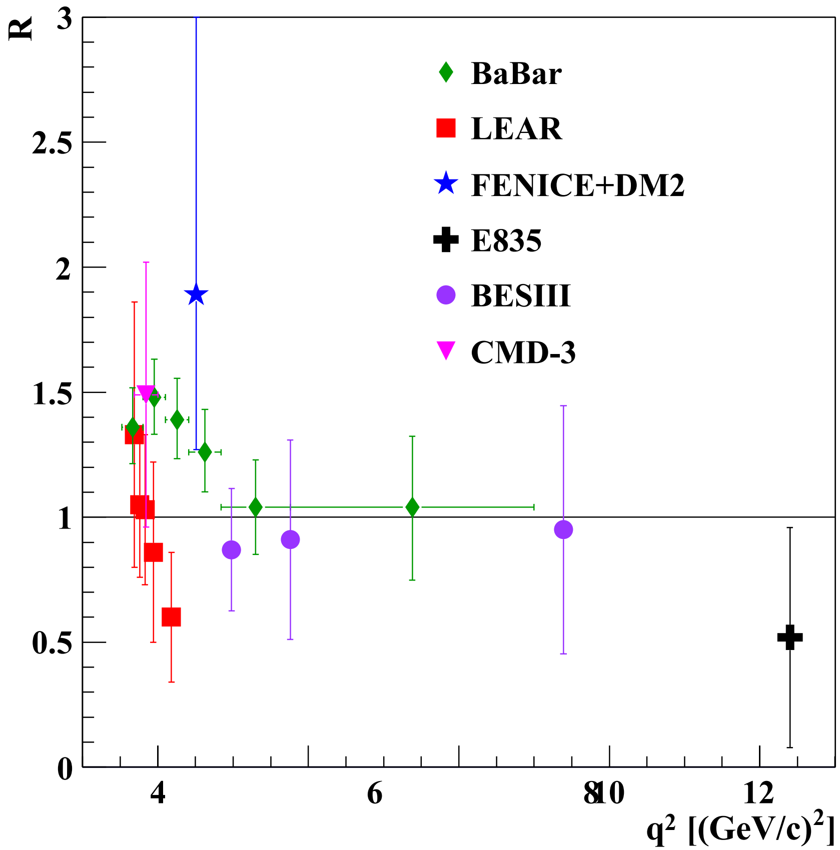


Structures seen in BaBar data

- Interference effect from rescattering processes in the final states.
  Phys. Rev. Lett. 114,232301 (2015)

- Independent resonant structures
  Phys. Rev. D 92, 034018 (2015)

World data on the time-like proton form factor ratio $R=|G_E|/|G_M|$



BaBar: Phys. Rev. D88 072009
LEAR: Nucl.Phys.J., B411:3-32. 1994
BESIII: arXiv:1504.02680. 2015
CMD-3: arXiv:1507.08013v2 (2015)

@ BaBar (SLAC): $e^+e^- \to \bar{p}p\gamma$

- data collection over wide energy range

@ PS 170 (LEAR): $\bar{p}p \to e^+e^-$

- data collection at low energies

Data from BaBar & LEAR show different trends

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

@ BESIII:

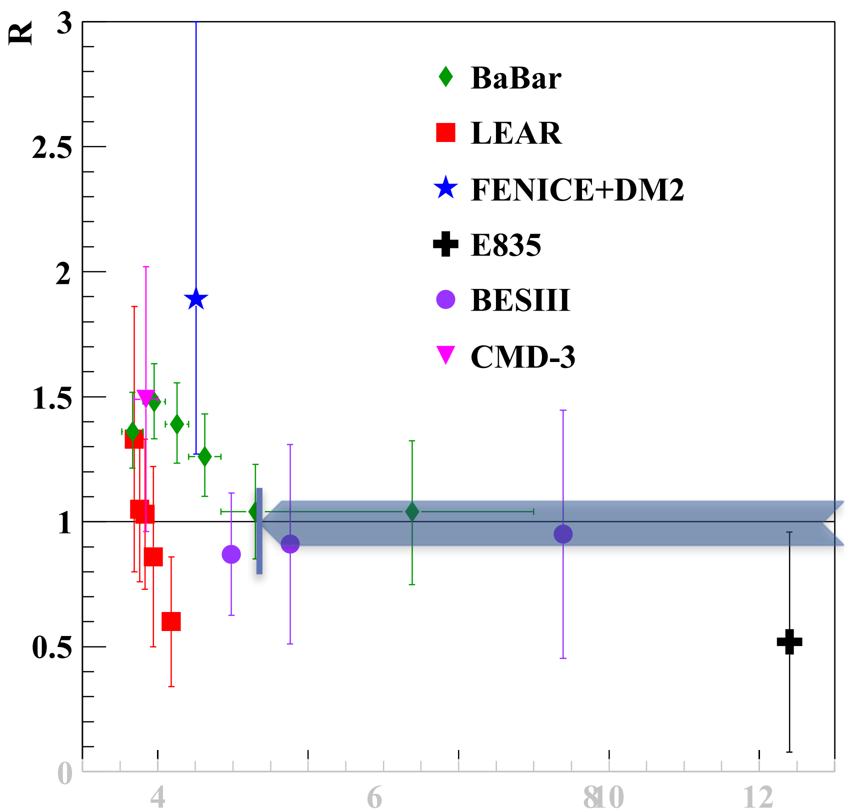
- Measurement at different energies
- Uncertainties comparable to previous experiments

$$\sqrt{s} = 1-2\ GeV$$

@ CMD-3 (VEPP2000 collider, BINP):

- Energy scan
- Uncertainty comparable to the existing data

World data on the time-like proton form factor ratio $R=|G_E|/|G_M|$



@ BaBar (SLAC): $e^+e^- \to \bar{p}p\gamma$

➢ data collection over wide energy range

@ PS 170 (LEAR): $\bar{p}p \to e^+e^-$

➢ data collection at low energies

Data
trenc

@ BE
➢ M
➢ U
ex

➢ E
➢ U
measurement by BaBar

More data needed with high precision!

- **Test of the theory, also at high q^2**
- **Data with high statistics increase the precision of Form Factors**
- **Existing data were obtained with electron channels**

PANDA: Measurement over wide range of q^2 with high precision

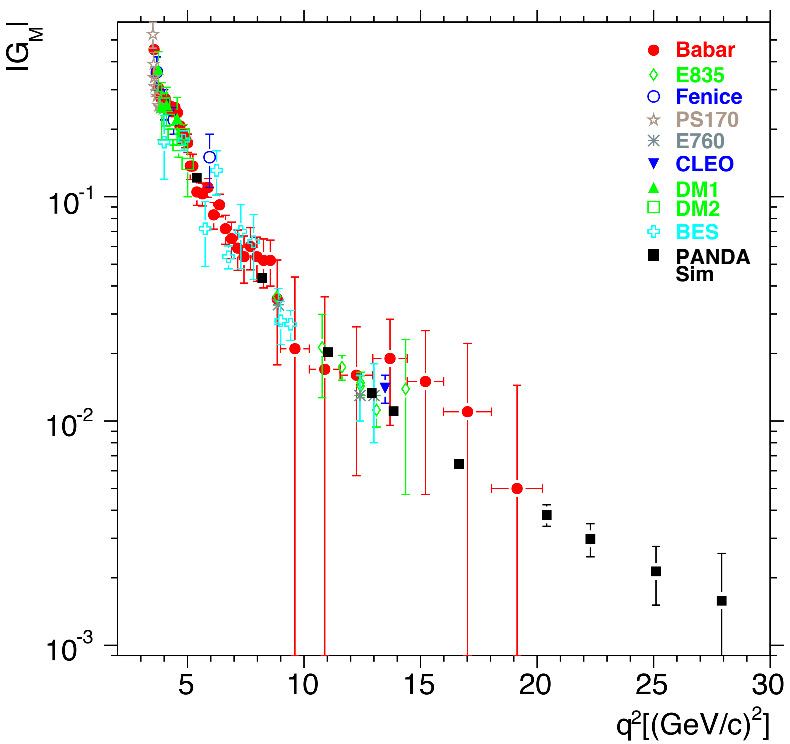
BESIII: arXiv:1504.02680, 2015

CMD-3: arXiv:1507.08013v2 (2015)

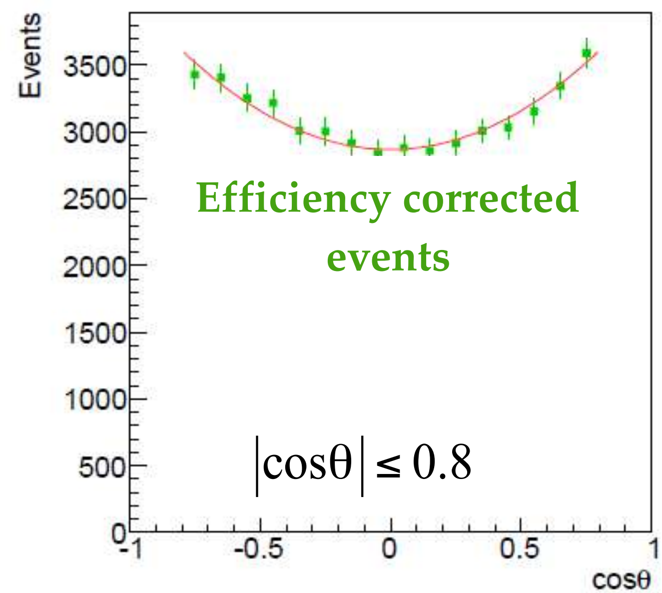
Feasibility studies: time-like proton form factors @ PANDA

The results

$\bar{p}p \rightarrow e^+e^-$



$|G_M|$ can be measured up to $q^2 \approx 30\ (GeV/c)^2$

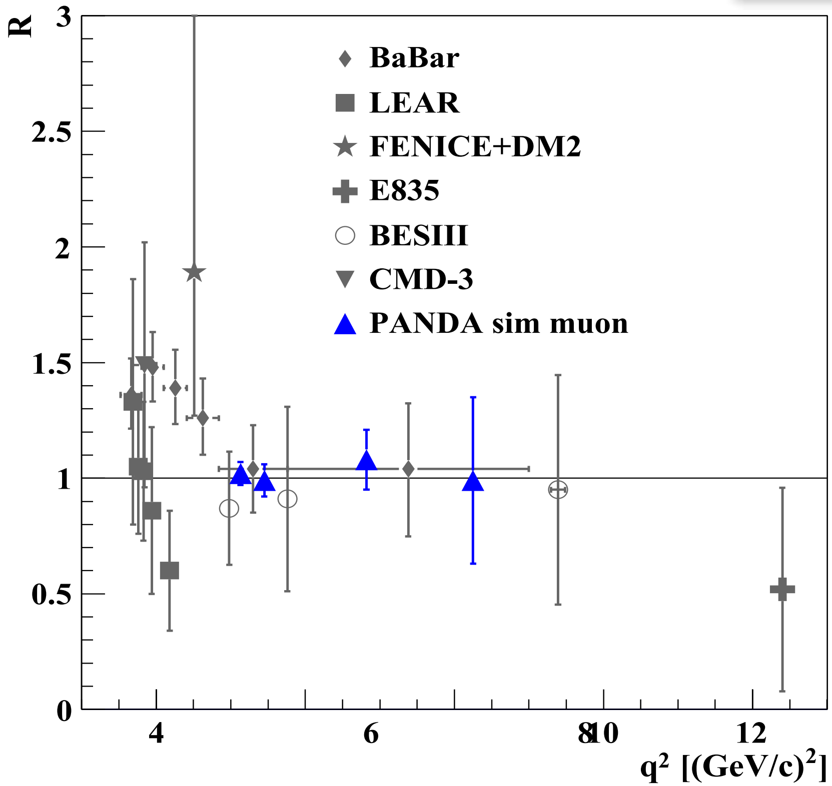


Precision on R=1, L= 2 fb^{-1}	
q^2 [$(GeV/c)^2$]	5.4 – 14
ΔR/R	3.3 % - 57%

Feasibility studies: time-like proton form factors @ PANDA

The results

$\bar{p}p \rightarrow \mu^+\mu^-$



p_{beam} [GeV/c]	Total signal efficiency ε	Background rejection [10^{-5}]	Expected S-B ratio
1.5	0.315	1.22	1:8
1.7	0.274	1.12	1:10
2.5	0.334	1.75	1:13
3.3	0.295	1.30	1:5

Precision on R=1, L= 2 fb^{-1}

q^2 [(GeV/c)^2]	5.1 – 8.2
ΔR/R	5.0 % - 37%

$\Delta\sigma/\sigma$: 4.1% - 4.9%

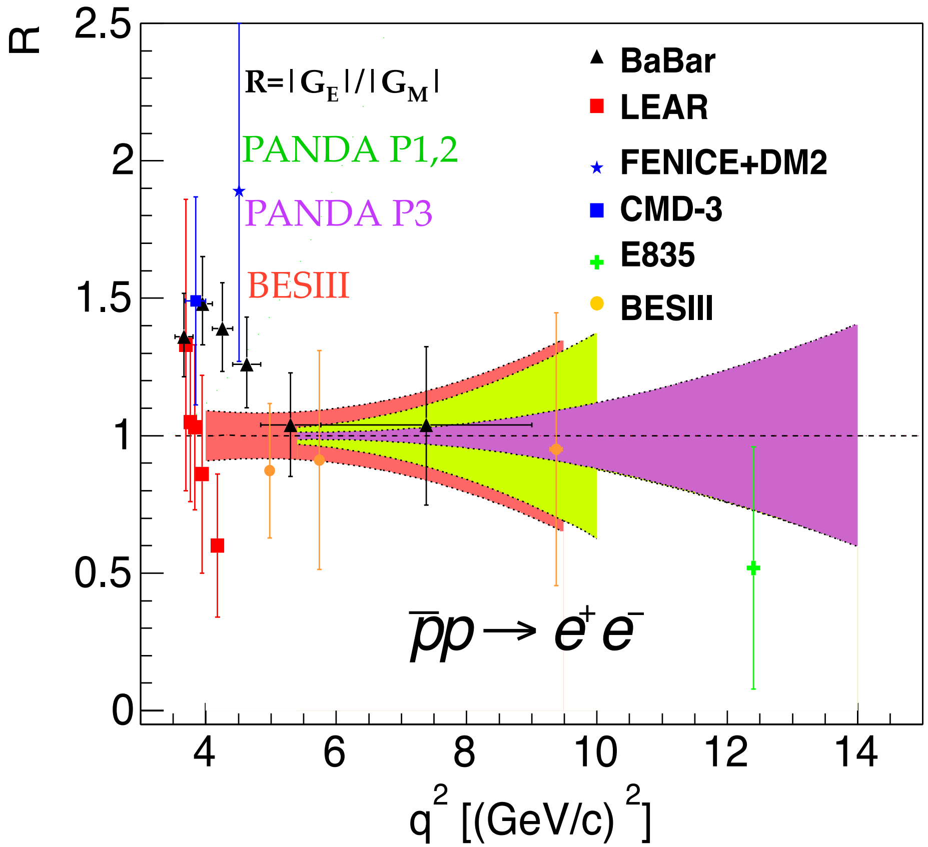
$\Delta|G_{eff}|/|G_{eff}|$: 2.03% - 2.44%

Systematic uncertainties

- Luminosity measurement: ΔL/L~4%
- Choice of cuts
- Choice of histogram bin width

Feasibility studies: time-like proton form factors @ PANDA

Phases 1,2,3



Phase-1,2 (L=10^{31} cm^{-2} s^{-1})

pbarp → e^+e^- @1.5 GeV/c ~ 220 /day

pbarp → e^+e^- @3.3 GeV/c ~ 10/day

ΔR/R: 4-26%, Δ|G_{eff}|/|G_{eff}|: 2.5% (stat. +syst.)

pbarp → $\mu^+\mu^-$ @1.5 GeV/c ~ 170/day

ΔR/R: 21%, Δ|G_{eff}|/|G_{eff}|: 2.5% (stat. +syst.)

pbarp → $e^+e^-\pi^0$ @1.5 GeV/c ~ 3,5k/day

- NO competition for first muon pair study
- Also first access to unphysical region

Time-Like EMFF:s @ PANDA Day 1

- First measurement with muons in the final state
- Consistency checks with e^+e^-
- TL EMFF:s ($|G_E|/G_M|$)over a large range of q^2

Hard exclusive processes at PANDA

- Generalised Distribution Amplitudes (GDAs)
- Transverse Momentum dependent Distributions (TDAs)
- Generalised Parton Distributions (GPDs)
- Drell-Yan processes
- More details on time-like form factors

➪ see uploaded talk on EMP by Frank Maas

- 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 if the initial state is unpolarised.

The polarisation arises from an $^3S_1$-$^3D_1$ interference.

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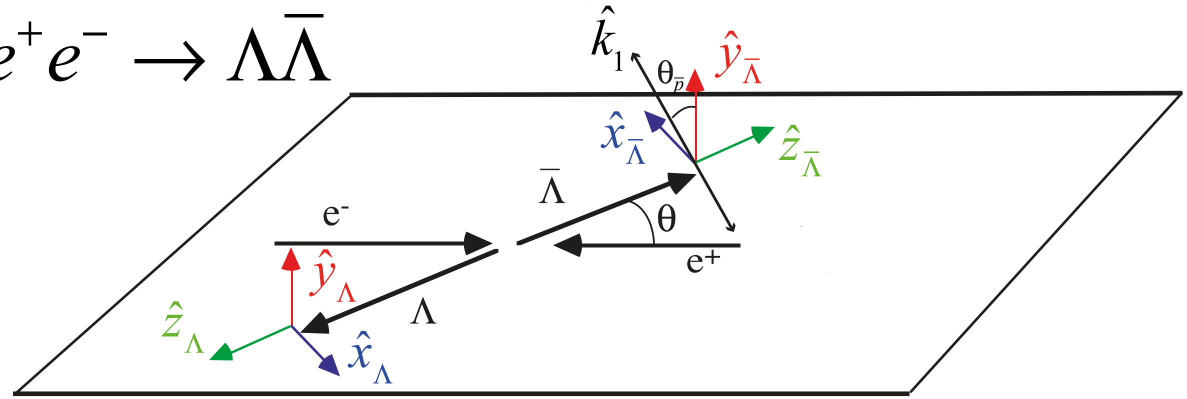
$e^+e^- \rightarrow \Lambda\bar{\Lambda}$



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

=> gives modulus of the phase ϕ

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

=> gives the sign of the phase ϕ

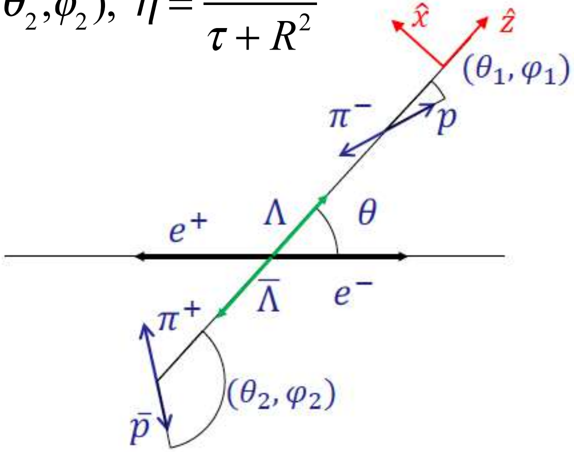
Nuov. Cim. A109(96)241

A complete determination of the Λ Time-Like Form Factor!

A multivariate parameterisation have been derived by G.Fäldt & A.Kupsc* to make **maximum use** of $e^+e^- \to \Lambda\bar{\Lambda}$ ***exclusive data***:

$$W(\xi) = F_0(\xi) + \eta F_5(\xi) + \sqrt{1-\eta^2}\sin(\Delta\Phi)\left(\alpha_\Lambda F_3(\xi) + \alpha_{\bar{\Lambda}} F_4(\xi)\right) + \alpha_\Lambda \alpha_{\bar{\Lambda}}\left(F_1(\xi) + \sqrt{1-\eta^2}\cos(\Delta\Phi) F_2(\xi) + \eta F_6(\xi)\right); \ \xi = (\theta,\theta_1,\phi_1,\theta_2,\phi_2), \ \eta = \frac{\tau - R^2}{\tau + R^2}$$

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



- Allows for an unbinned ML fit.😊
- No need for acceptance corrections.😊😊
  (except for an overall normalisation factor)

*PLB 772(2017) 16

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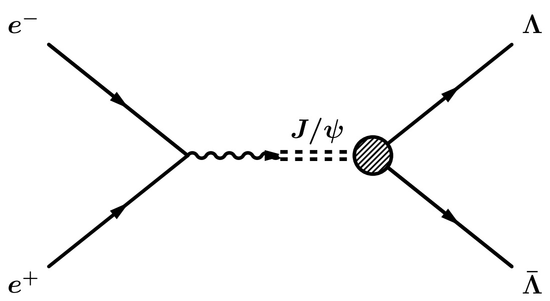
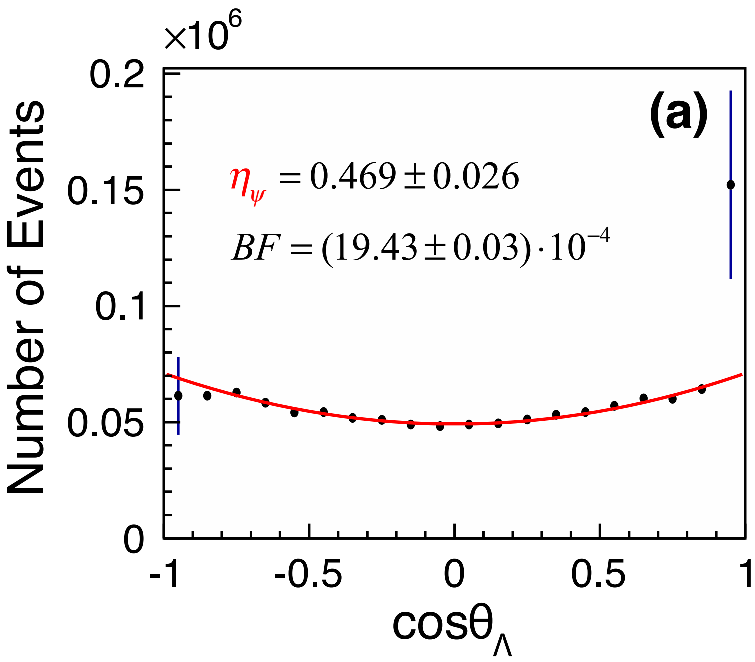
The formalism of Fäldt & Kupsc has been applied to BESIII data on

$$e^+e^- \to \gamma^* \to J/\psi \to \Lambda\bar{\Lambda}$$

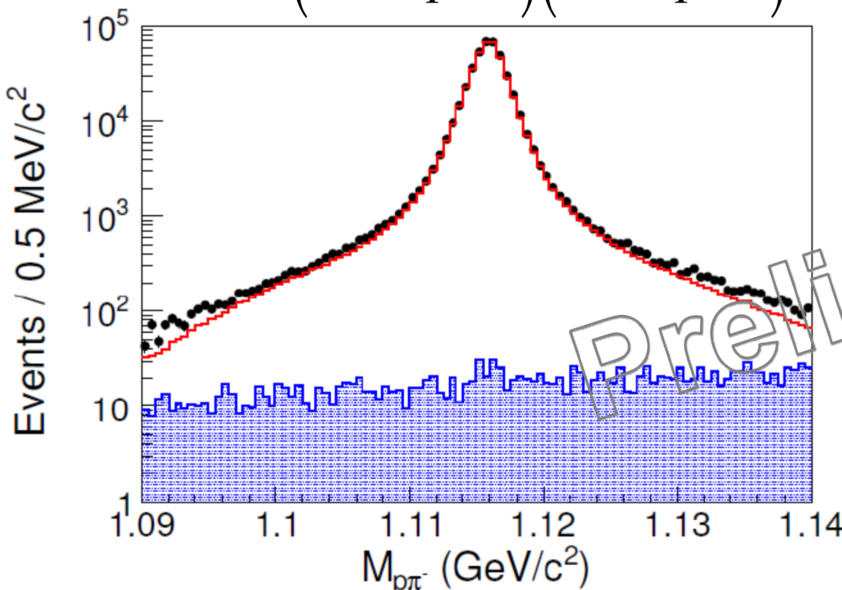


$$\frac{d\Gamma}{d\cos\theta} \propto 1 + \eta_\psi \cos^2\theta$$

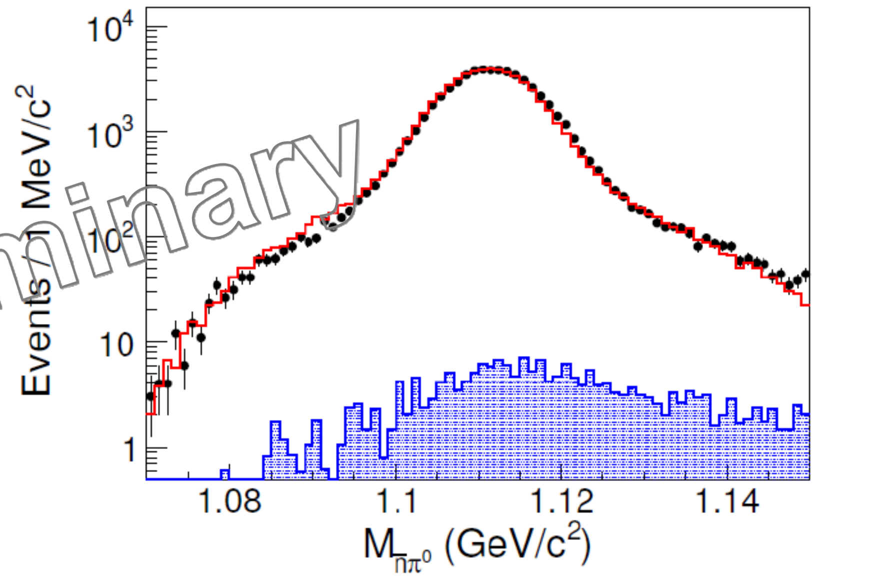


PRD 95 (2017) 052003

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



$$e^+e^- \to \left(\Lambda \to p\pi^-\right)\left(\bar{\Lambda} \to \bar{n}\pi^0\right)$$



$d\sigma / d\Omega$

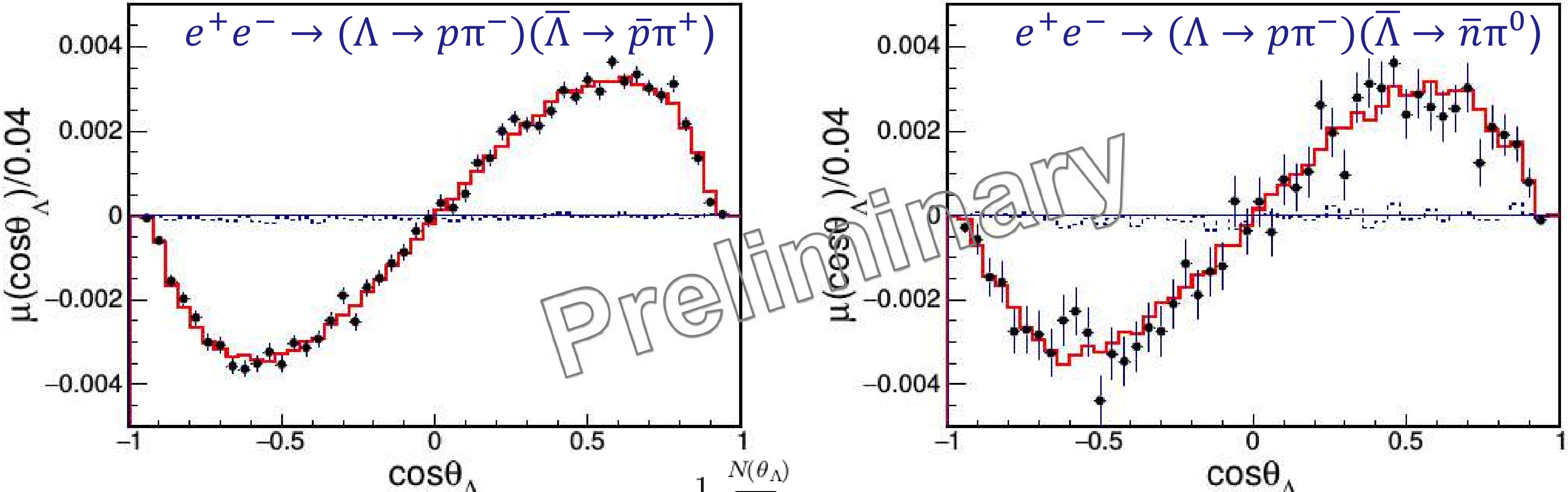
Polarisation

Spin correlation

$$W(\xi) = F_0(\xi) + \eta F_5(\xi) + \sqrt{1-\eta^2}\sin(\Delta\Phi)\left(\alpha_\Lambda F_3(\xi) + \alpha_{\bar{\Lambda}_{\bar{p},\bar{n}}} F_4(\xi)\right) + \alpha_\Lambda \alpha_{\bar{\Lambda}_{\bar{p},\bar{n}}}\left(F_1(\xi) + \sqrt{1-\eta^2}\cos(\Delta\Phi) F_2(\xi) + \eta F_6(\xi)\right);\ \xi = (\theta, \theta_1, \phi_1, \theta_2, \phi_2),\ \eta = \frac{\tau - R^2}{\tau + R^2}$$

Fit results

$\Delta\Phi$=42.3°±0.6°±0.5°



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

$\alpha_- = \alpha_{\Lambda\to p\pi^-}$

$\alpha_+ = \alpha_{\bar{\Lambda}\to\bar{p}\pi^+}$

$\bar{\alpha}_0 = \alpha_{\bar{\Lambda}\to\bar{n}\pi^0}$

Parameters	This work	Previous results	
η_ψ	**0.461 ± 0.006 ± 0.007**	0.469 ± 0.027	BESIII
$\Delta\Phi$ (rad)	**0.740 ± 0.010 ± 0.008**	–	
α_-	**0.750 ± 0.009 ± 0.004**	0.642 ± 0.013	PDG
α_+	**−0.758 ± 0.010 ± 0.007**	−0.71±0.08	PDG
$\bar{\alpha}_0$	**−0.692 ± 0.016 ± 0.006**	–	
A_{CP}	**−0.006 ± 0.012 ± 0.007**	0.006 ± 0.021	PDG
$\bar{\alpha}_0/\alpha_+$	**0.913 ± 0.028 ± 0.012**	–	

Preliminary

CP asymmetry:

$$A_{CP} = \frac{\alpha_- + \alpha_+}{\alpha_- - \alpha_+}$$

arXiv:1808.08917

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Parameters	This work	Previous results	
η_ψ	$\mathbf{0.461 \pm 0.006 \pm 0.007}$	0.469 ± 0.027	BESIII
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$\bar{\alpha}_0$	$\mathbf{-0.692 \pm 0.016 \pm 0.006}$	–	
A_{CP}	$\mathbf{-0.006 \pm 0.012 \pm 0.007}$	0.006 ± 0.021	PDG
$\bar{\alpha}_0/\alpha_+$	$\mathbf{0.913 \pm 0.028 \pm 0.012}$	–	

Preliminary

First: Phase measurement between G_M^ψ and G_E^ψ
$\bar{\alpha}_0$ decay asymmetry parameter

$\alpha_{\Lambda \to p\pi^-}$ decay parameter is measured to be (17±3)% larger than the PDG value (> 5σ)

Improved upper limit on A_{CP}

$\bar{\alpha}_0 / \alpha_+$ deviates 3σ from isospin symmetry prediction

PRELIMINARY

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$\alpha_{\Lambda \to p\pi^-}$ decay parameter is measured to be (17±3)% larger than the PDG value (> 5σ)

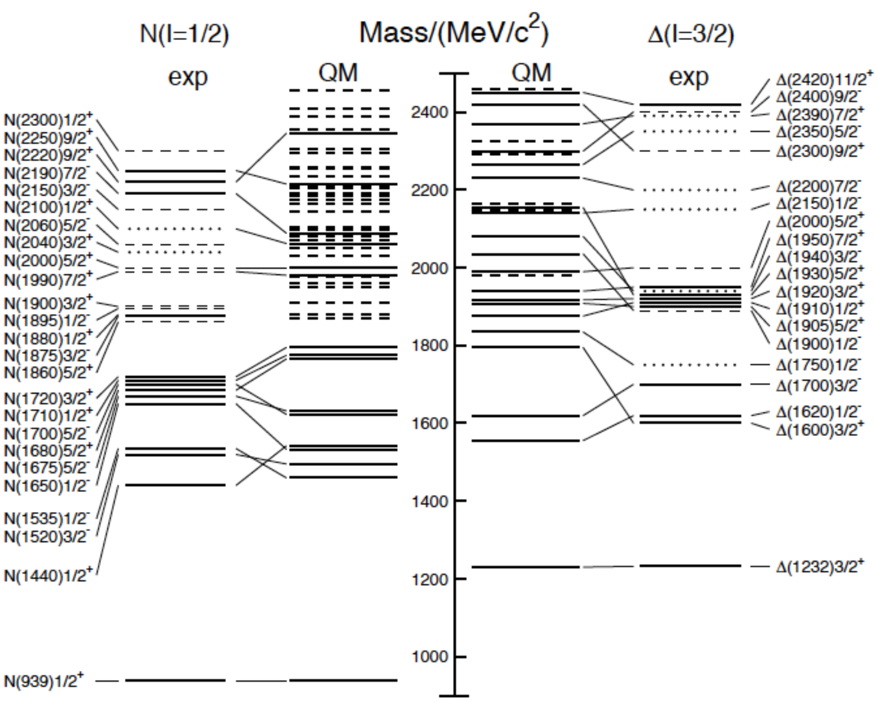
All published data on Λ and Σ^0 polarisation must be renormalised!

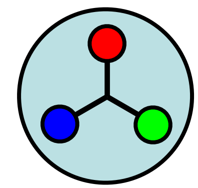
Decay asymmetry parameters of heavier hyperons must also be renormalised since most of them are determined via the product $\alpha_\Lambda \alpha_Y$! ➪ PDG!!

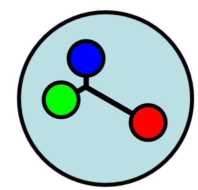
Spectroscopy

Understanding baryon spectra ⇔ Understanding strong QCD

- Level ordering of the baryon spectra not understood.
- More states predicted than observed “missing resonances” (or the other way around).
- Effective degrees of freedom?
- Dynamically generated baryon resonances?
- Testing Lattice QCD







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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 $\Lambda(1810)$, $\Lambda(2350)$, $\Xi(1820)$, and $\Xi(2030)$, are merely educated guesses. † recent suggestions for assignments and re-assignments from Ref. [28]. For assignments of the charmed baryons, see the "Note on Charmed Baryons" in the Particle Listings.

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

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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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Ξ^0 $I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$ Status: ∗∗∗∗

The parity has not actually been measured, but + is of course expected.

Ξ^- $I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$ Status: ∗∗∗∗

The parity has not actually been measured, but + is of course expected.

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Antiproton-proton reactions are excellent entrance channels for hyperon spectroscopy studies:

$$\bar{p}p \rightarrow \bar{Y}^{*}Y, \bar{Y}^{*}Y^{*}$$

- Strong interaction processes ➪ High cross sections.

- Baryon number = 0 ➪ No production of extra kaons needed.
  ➪➪ Low energy threshold.

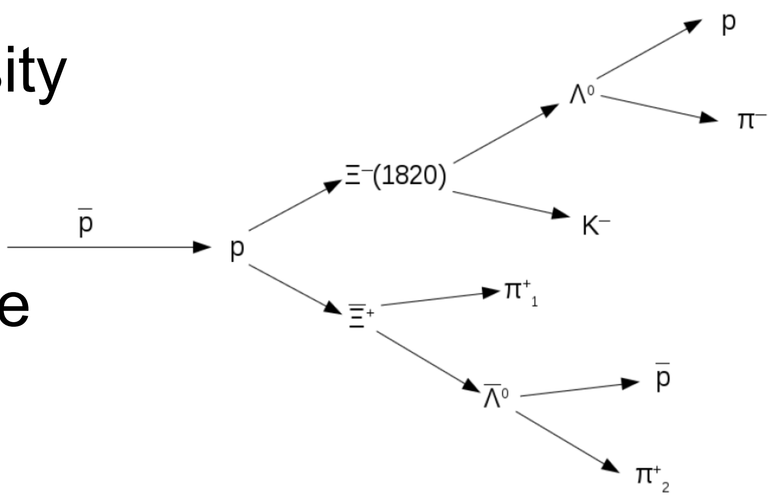
- Same pattern in Y and $\bar{Y}$ channels ➪ Consistency.

- No production of additional kaons required
  ➪ Threshold reduced

$\bar{Y}^{*}Y^{*}$ accessible for masses up to 2740 MeV/c^2, i.e $\bar{\Xi}_c^{*}\Xi_c^{*}$.

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

- Simplified P̄ANDA MC framework
- p_{beam} = 4.6 GeV/c
- σ = 1 μb assumed + Day 1 luminosity



- Results:
  - ≈ **15000** reconstructed exclusive events/day
  - Low background

J. Pütz, FAIRNESS 2016

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PANDA

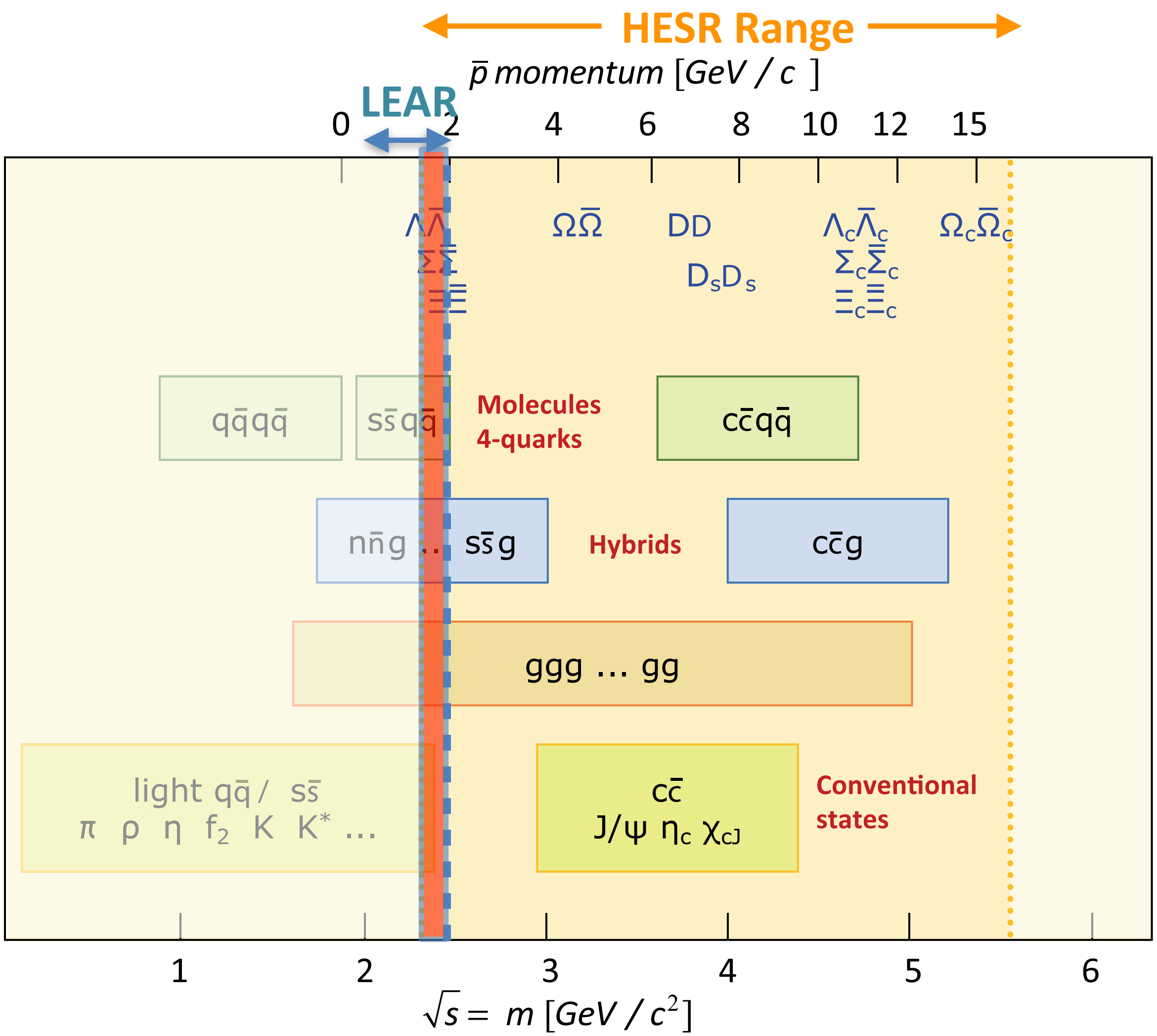
Prospects Day 1 luminosity

Momentum [GeV/c]	Reaction	σ [μb]	Efficiency [%]	Rate $\mathcal{L}=10^{31}$ 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 order of magnitude.


HESR Range
p̄ momentum [GeV / c]
LEAR
0
2
4
6
8
10
12
15
ΛΛ̄
ΣΣ̄
ΞΞ̄
ΩΩ̄
DD
D_sD_s
$\Lambda_c\bar{\Lambda}_c$
$\Sigma_c\bar{\Sigma}_c$
$\Xi_c\Xi_c$
$\Omega_c\bar{\Omega}_c$
qq̄qq̄
ss̄qq̄
Molecules
4-quarks
cc̄qq̄
nn̄g ...
ss̄g
Hybrids
cc̄g
ggg ... gg
light qq̄ / ss̄
π ρ η f_2 K K^* ...
cc̄
J/ψ η_c χ_{cJ}
Conventional
states
1
2
3
4
5
6
$\sqrt{s} = m\ [GeV / c^2]$

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Prospects of Hyperon Physics (and EM Physics) with $\bar{p}$anda from Day 1 are very good!