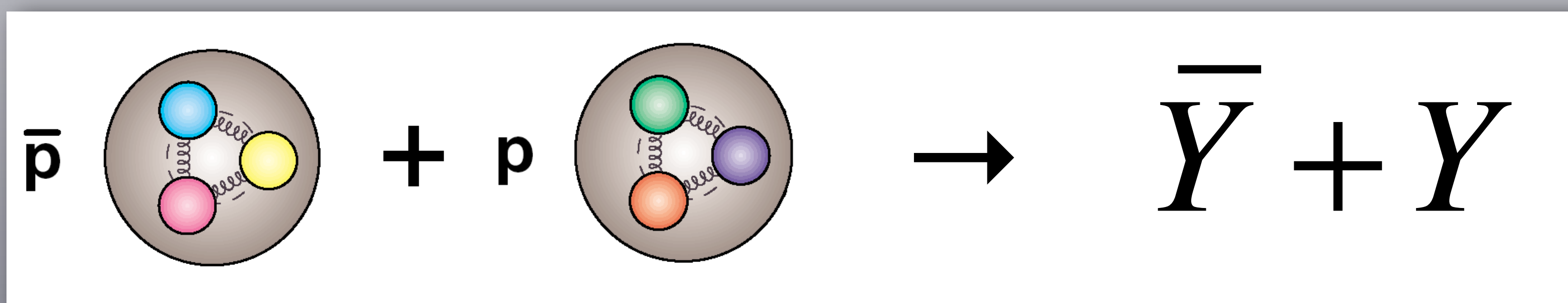
Polarisation Effects In Antiproton-Proton Interactions With Final State Hyperons

Tord Johansson, Uppsala University



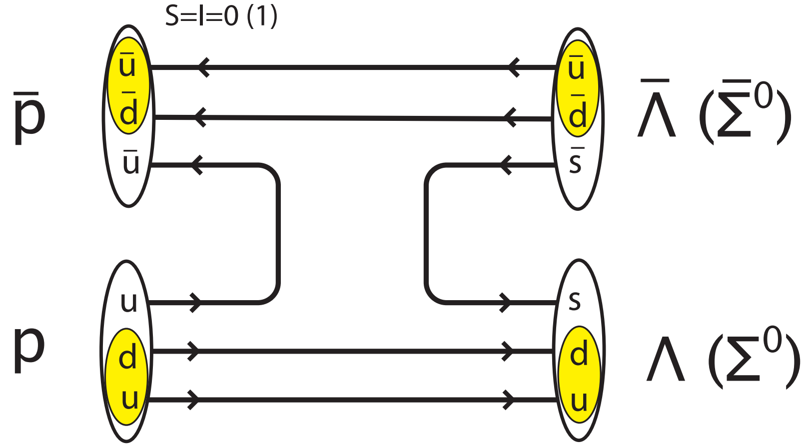
Outline

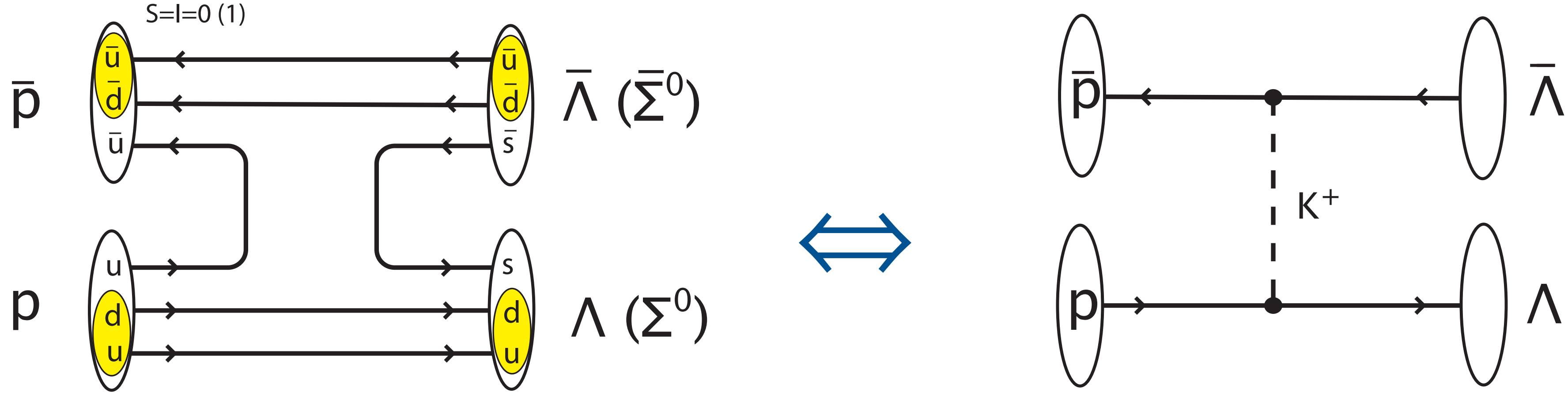
- Introduction
- Experimental status
- Future prospects @ HESR

Reactions with flavour change: $\bar{p}p \rightarrow \bar{Y}Y$

Focus on the strangeness sector:

- How is a $\bar{s}s$ quark pair created?
- Can we relate the observables to this process?
- What are the relevant degrees of freedom?
- What about charm?


S=I=0 (1)
p̄
p
ū
d̄
ū
u
d
u
ū
d̄
s̄
s
d
u
Λ̄ (Σ̄⁰)
Λ (Σ⁰)


S=I=0 (1)
p̄
ū
d̄
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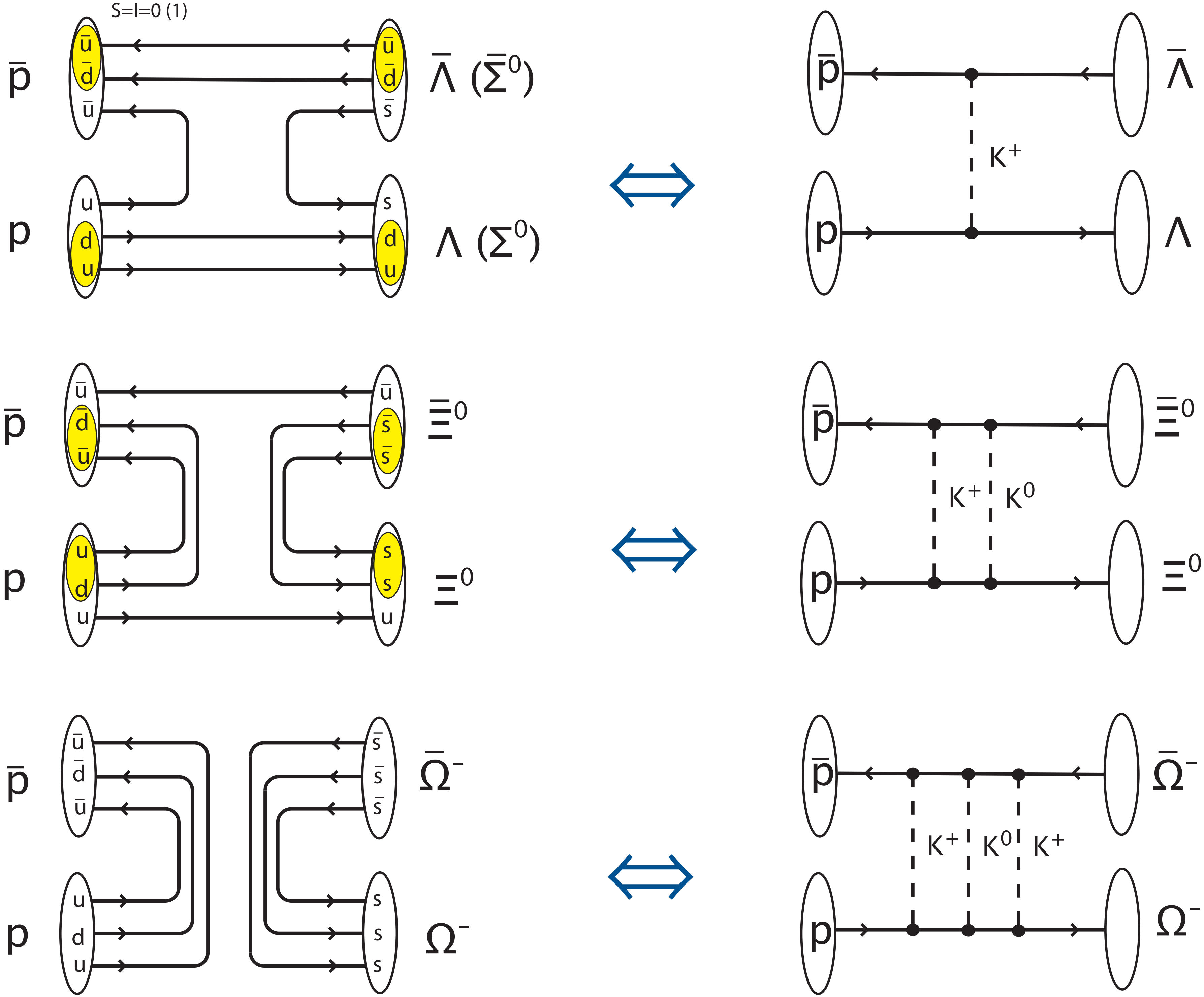
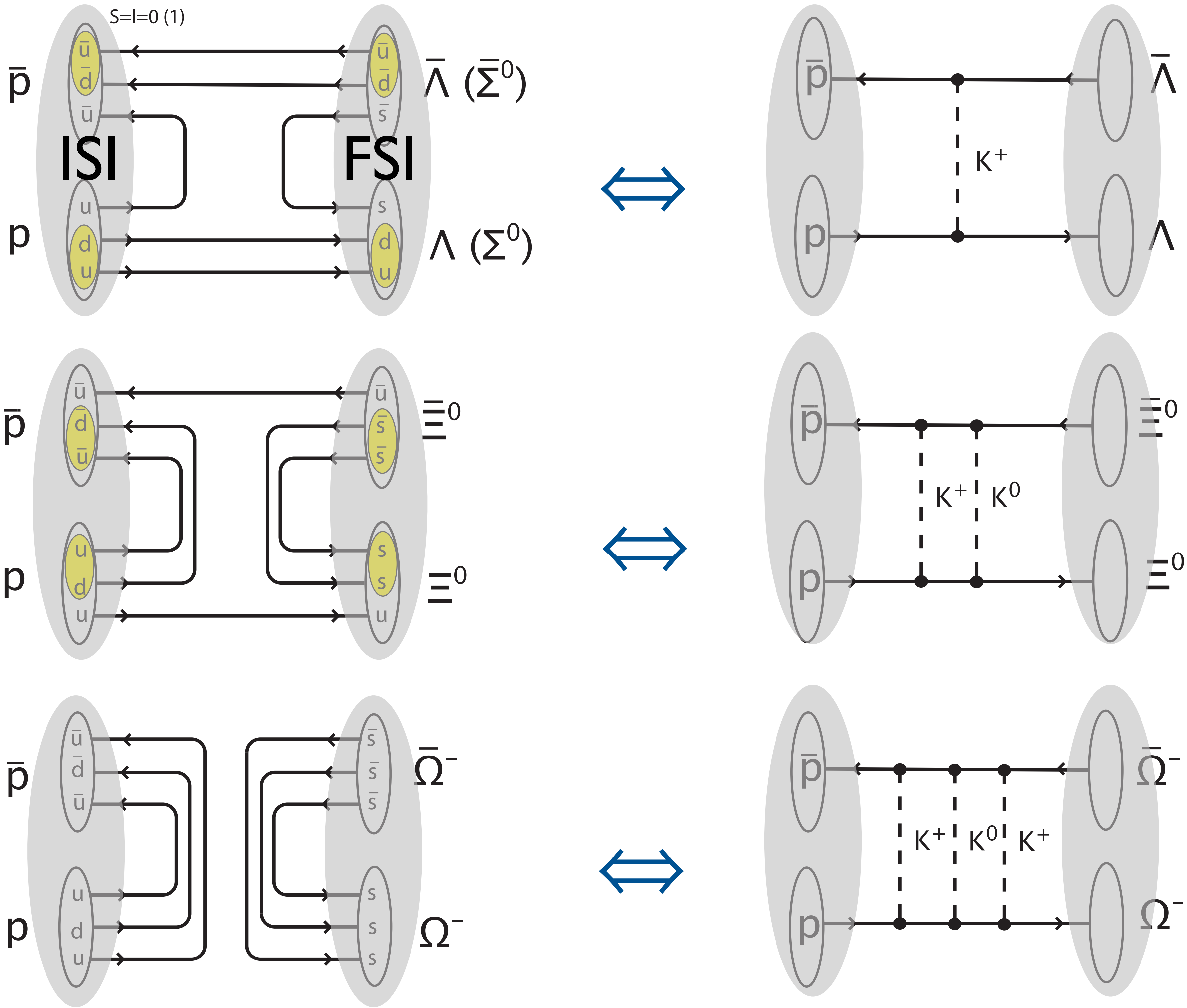
p
u
d
u
ū
d̄
s̄
Λ̄ (Σ̄⁰)
s
d
u
Λ (Σ⁰)
p̄
Λ̄
K⁺
p
Λ


S=I=0 (1)
p̄
p
Λ̄ (Σ̄⁰)
Λ (Σ⁰)
ū d̄ ū
u d u
ū d̄ s̄
s d u
K⁺
Ξ̄⁰
Ξ⁰
ū d̄ ū
u d u
ū s̄ s̄
s s u
K⁺ K⁰
Ω̄⁻
Ω⁻
s̄ s̄ s̄
s s s
K⁺ K⁰ K⁺


S=I=0 (1)
ISI
FSI
p̄
p
Λ̄ (Σ̄⁰)
Λ (Σ⁰)
K+
Ξ̄0
Ξ0
K+
K0
Ω̄−
Ω−
K+
K0
K+

The spin of the $\bar{\Lambda} / \Lambda$ is essentially carried by the $\bar{s} / s$ quark

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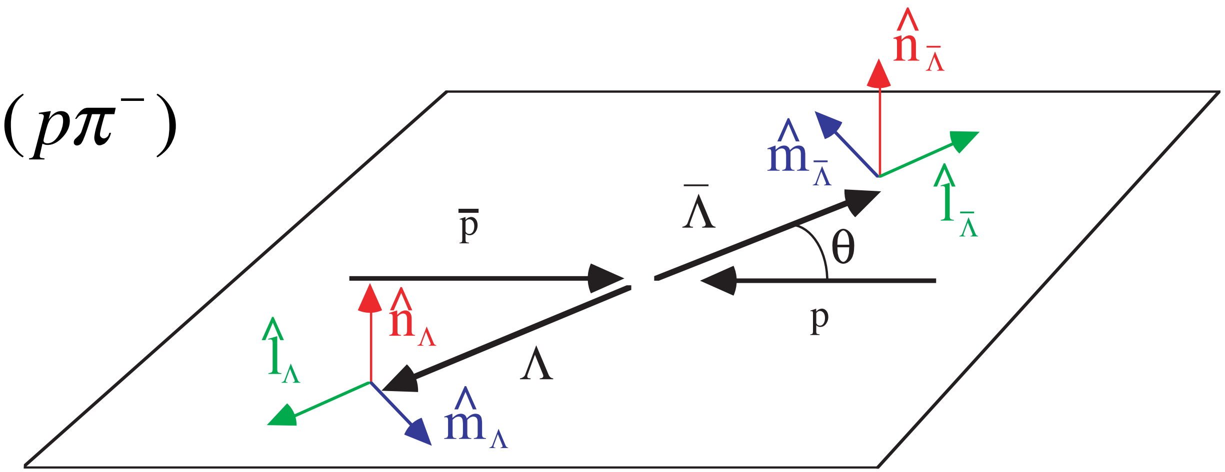
By studying spin observables in the $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ reaction one hopes to learn about the spin degrees of freedom in the $\bar{s}s$ quark pair production process

Strangeness production

Hyperon	Quarks	Mass [Mev/c^2]	$c\tau$ [cm]	α	Decay channel	B.R. [%]
Λ	uds	1116	8.0	+0.64	$p\pi^-$	64
Σ^+	uus	1189	2.4	-0.98	$p\pi^0$	52
Σ^0	uds	1193	2.2×10^{-9}	-	$\Lambda\gamma$	100
Σ^-	dds	1197	2.4	-0.07	$n\pi^-$	100
Ξ^0	uss	1315	8.7	-0.41	$\Lambda\pi^0$	99
Ξ^-	dss	1321	4.9	-0.46	$\Lambda\pi^-$	100
Ω^-	sss	1672	2.5	-0.03	ΛK^-	68

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



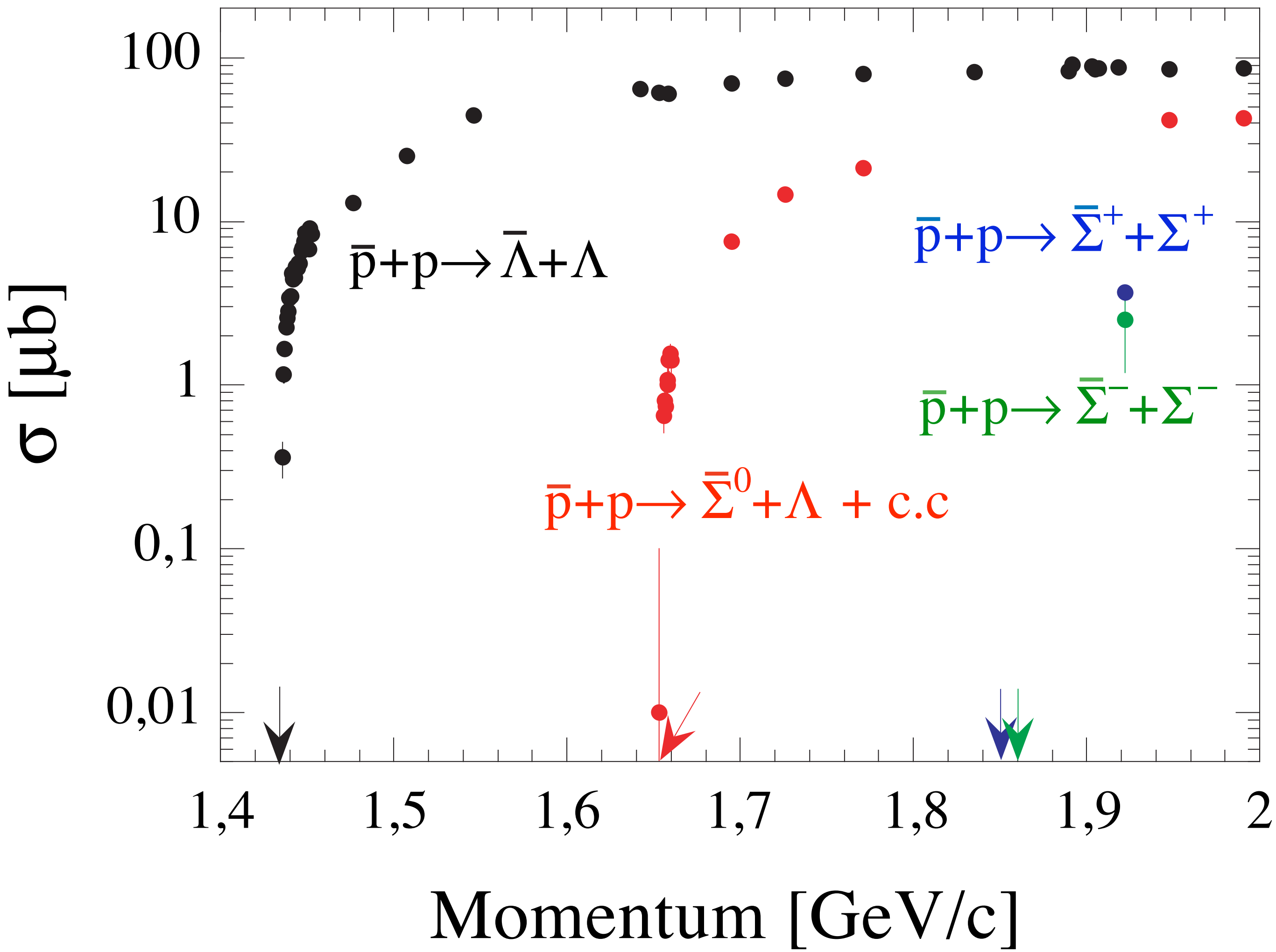
$$I_{\Lambda\Lambda}\left(\theta,\hat{k}_1,\hat{k}_2\right)=\frac{I_0^{\bar{\Lambda}\Lambda}}{64\pi^3}\left[\begin{array}{l}1\\ +P_n\left(\bar{\alpha}k_{1n}+\alpha k_{2n}\right)\\ +C_{00nn}\left(\bar{\alpha}\alpha k_{1n}k_{2n}\right)\\ +C_{00mm}\left(\bar{\alpha}\alpha k_{1m}k_{2m}\right)\\ +C_{00ll}\left(\bar{\alpha}\alpha k_{1l}k_{2l}\right)\\ C_{00ml}\left(\bar{\alpha}\alpha\left(k_{1m}k_{2l}+k_{1l}k_{2m}\right)\right)\end{array}\right]$$

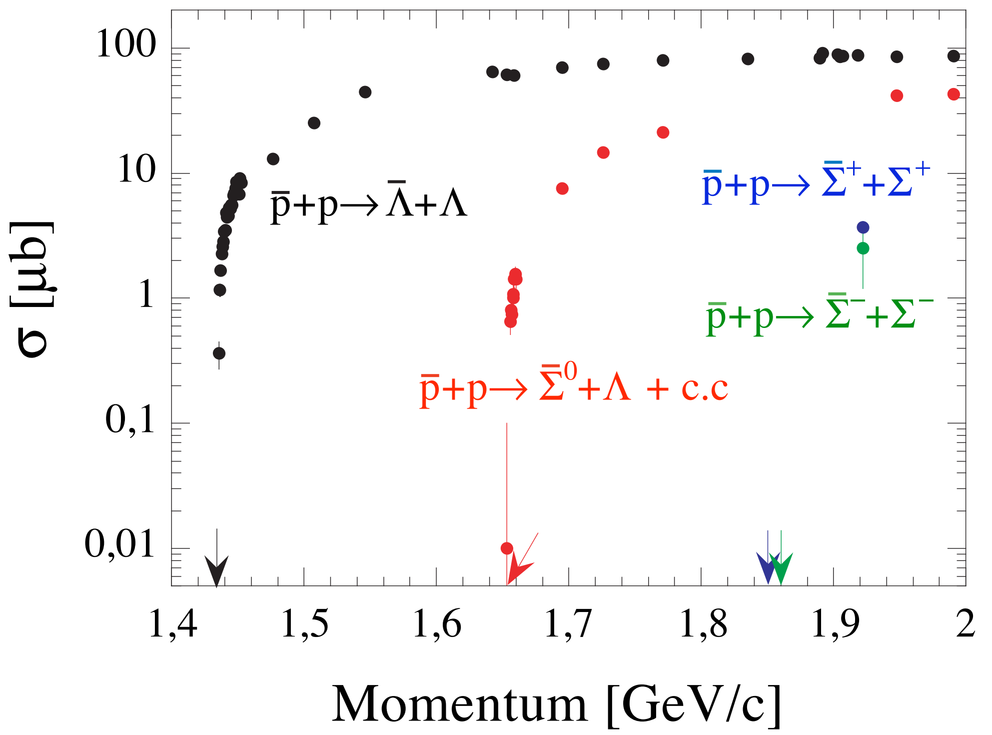
- Total X-sec
- Differential X-sec
- Polarisation
- Spin-correlations

θ = C.M. scattering angle

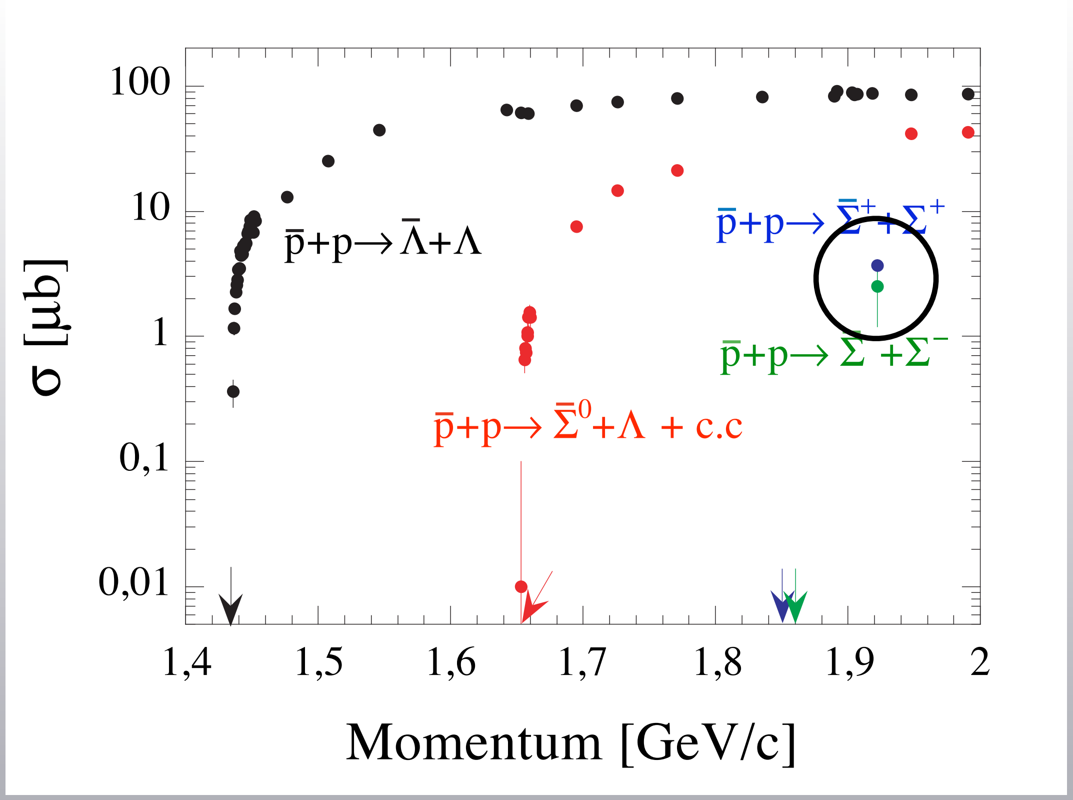
$\hat{k}_1,\hat{k}_2$ = directional vectors of decay nucleons

Total cross sections

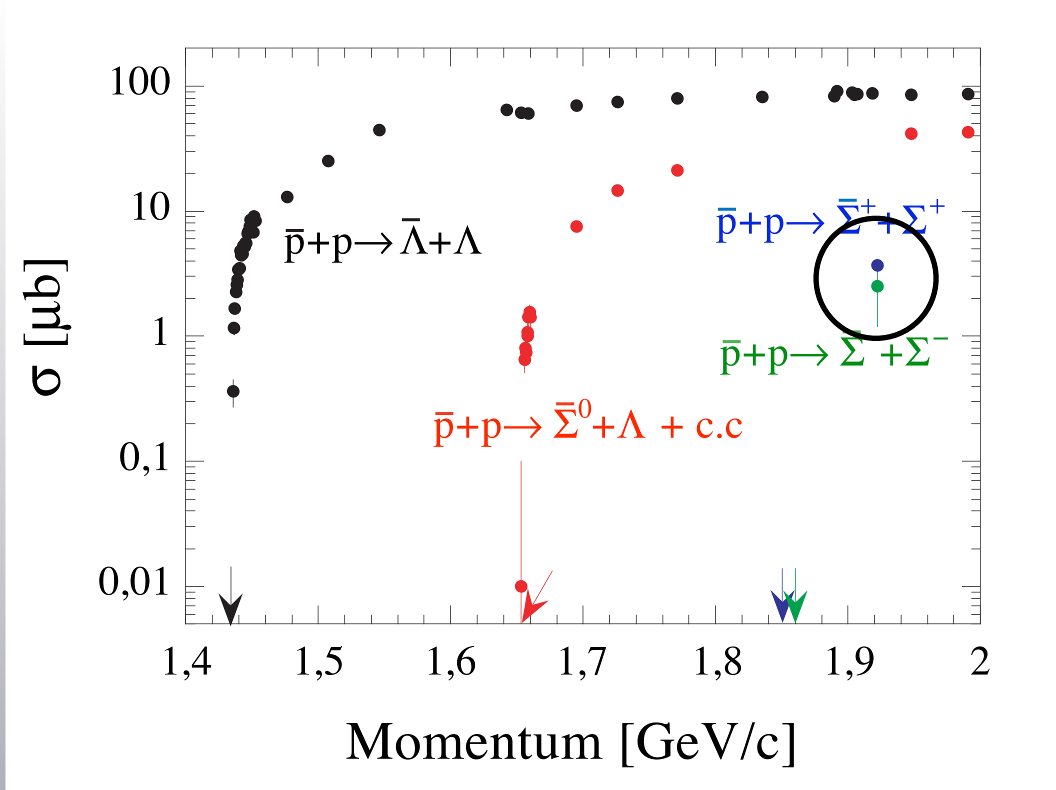




100
10
1
0,1
0,01
σ [μb]
1,4
1,5
1,6
1,7
1,8
1,9
2
Momentum [GeV/c]
p̄+p⟶ Λ̄+Λ
p̄+p⟶ Σ̄⁰+Λ + c.c
p̄+p⟶ Σ̄⁺+Σ⁺
p̄+p⟶ Σ̄⁻+Σ⁻



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



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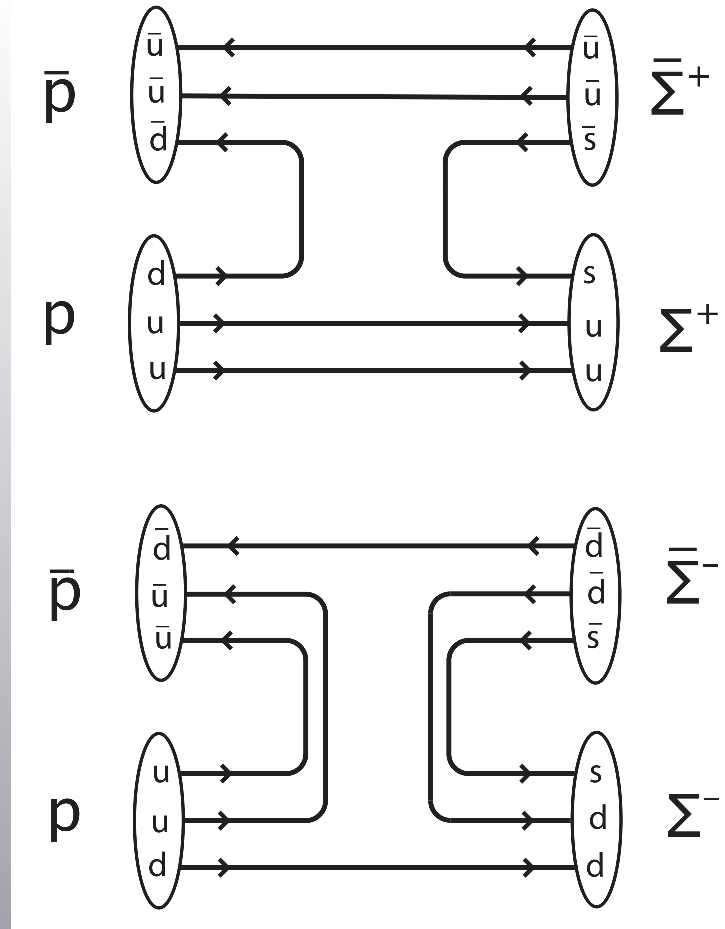
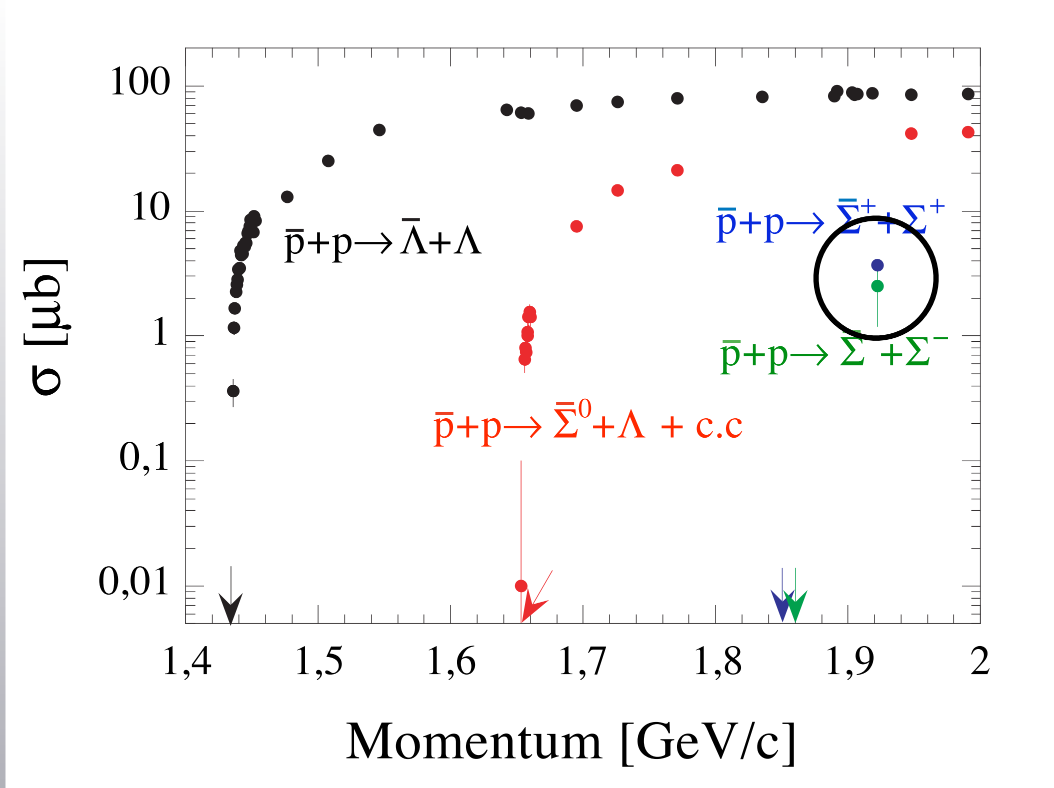
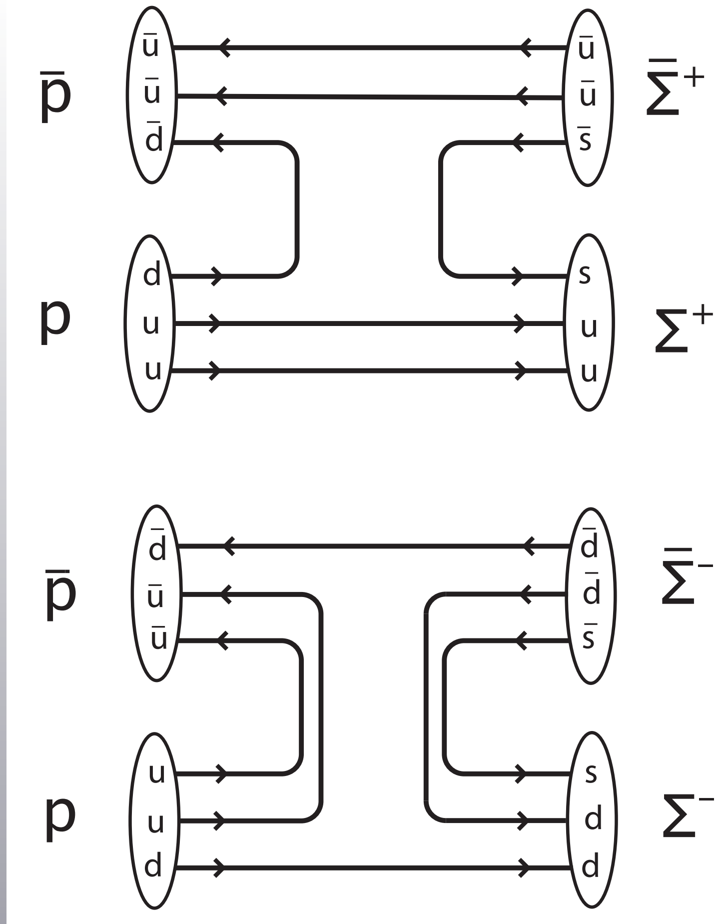


OZI rule violation?





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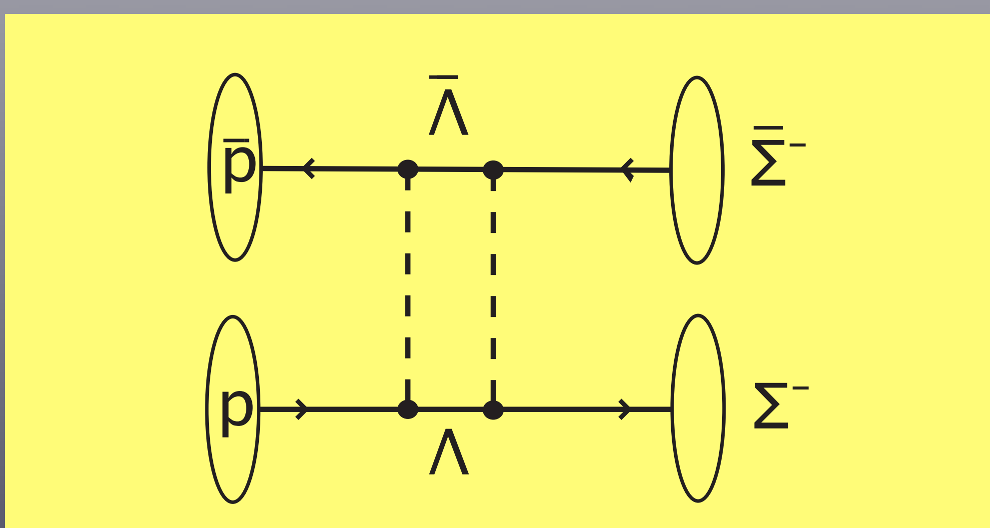
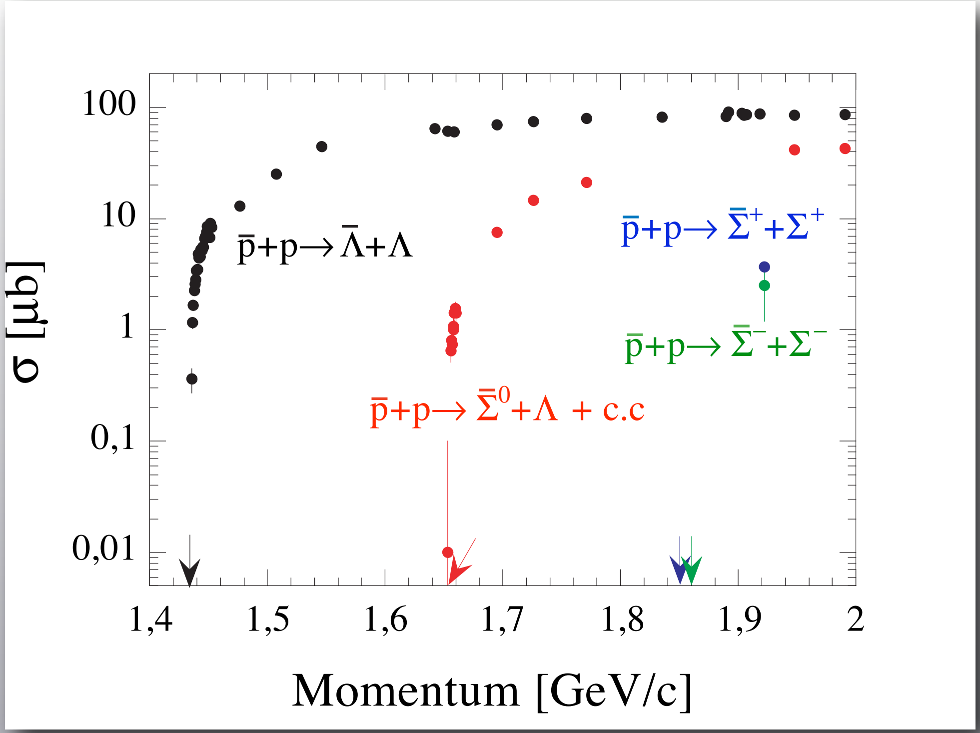


Close to threshold => Strong FSI



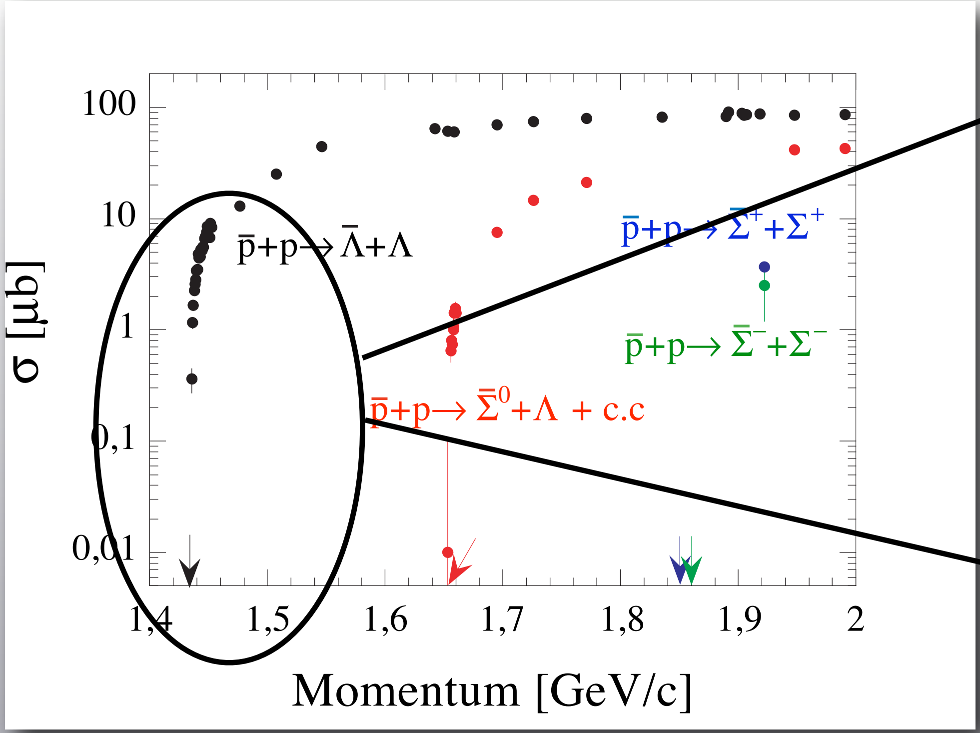
Excess energy = $\varepsilon = \sqrt{s} - \sum m_{final}$

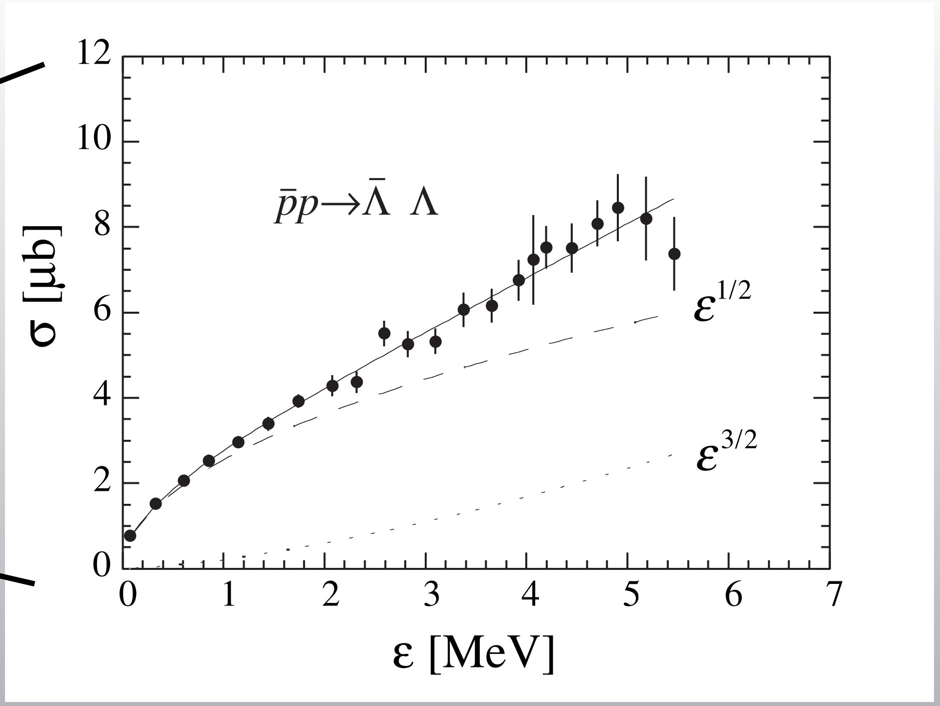
= Kinetic energy in CM-system

If the total cross section develops according to phase space then

$$\sigma_{tot}^{L}(\varepsilon) \propto \varepsilon^{L+1/2}$$

Near threshold: Expect *S*-waves to dominate.





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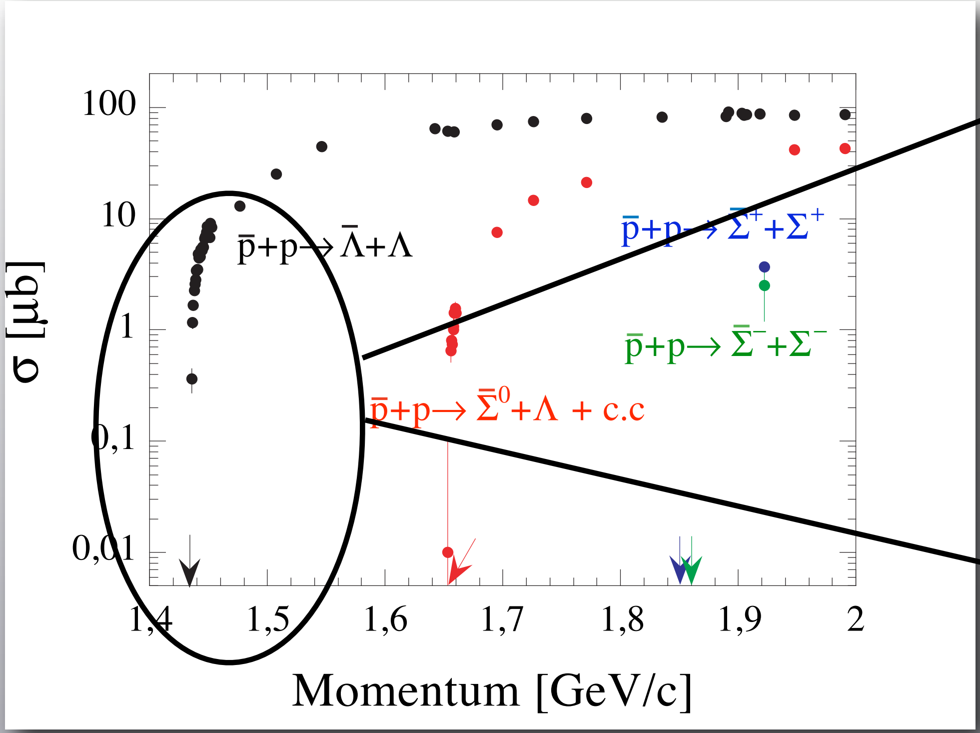

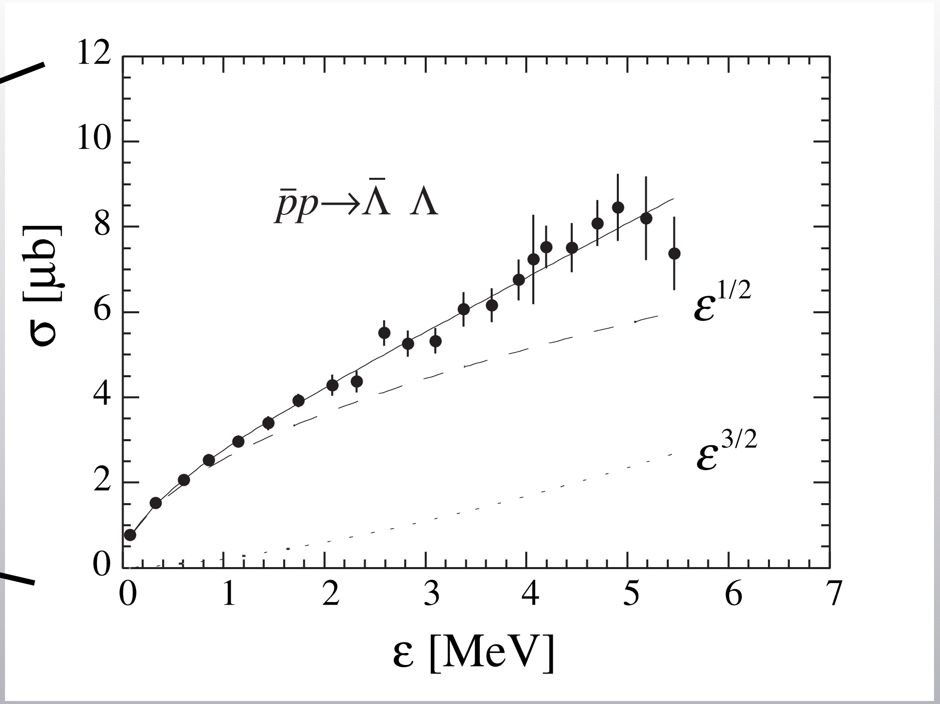

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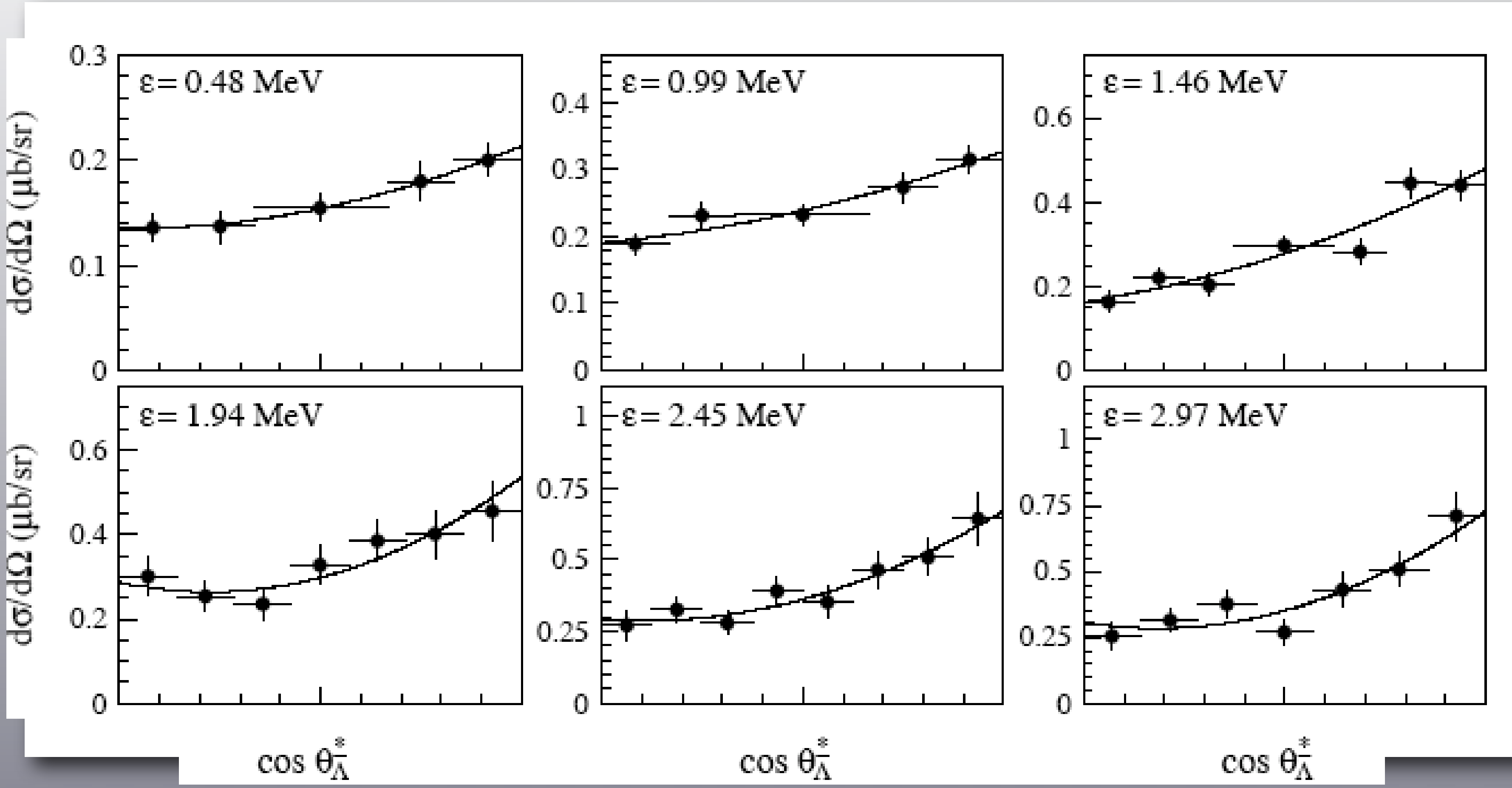
P-waves already 1 MeV above threshold.

Differential cross sections are sensitive different partial waves:



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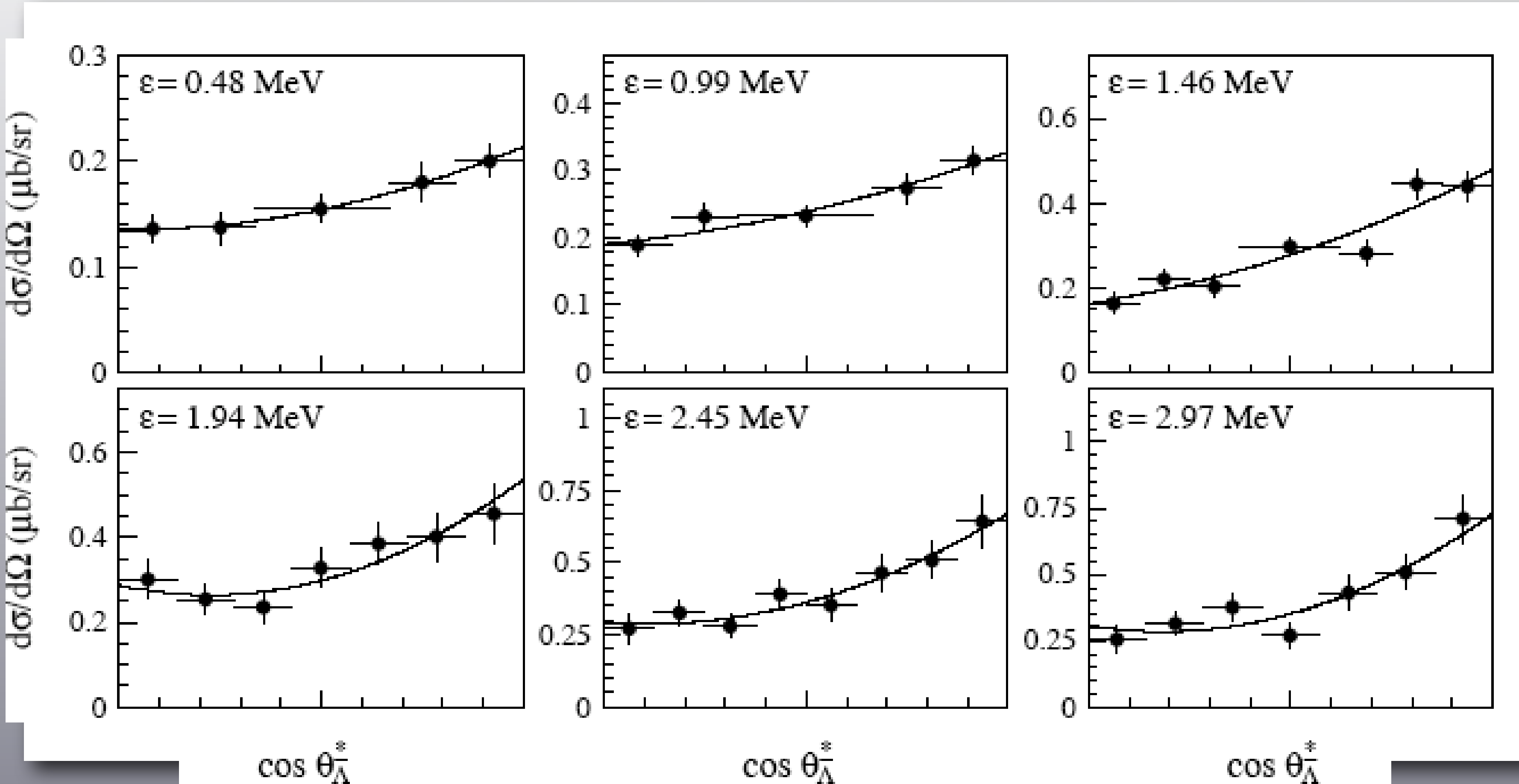

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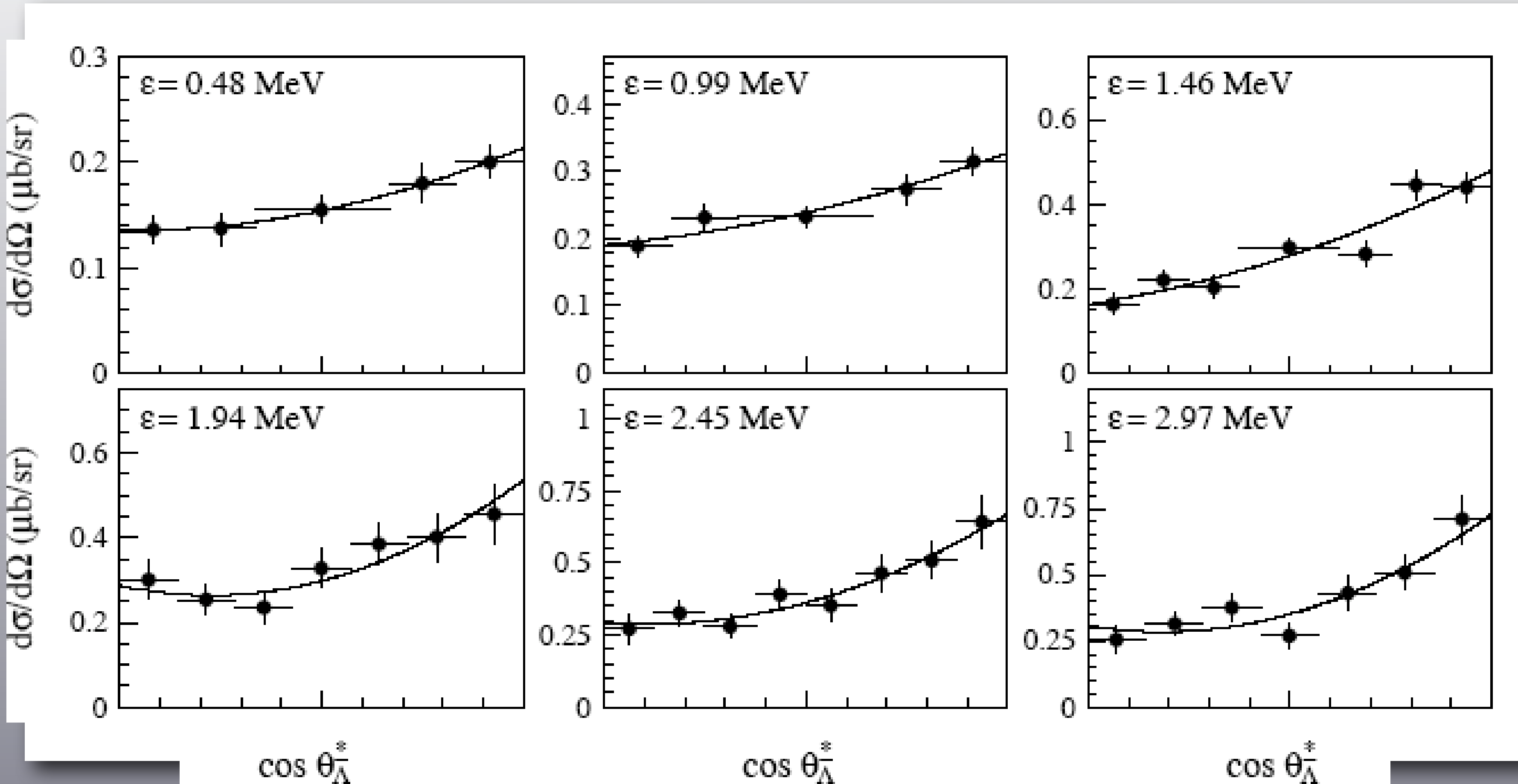

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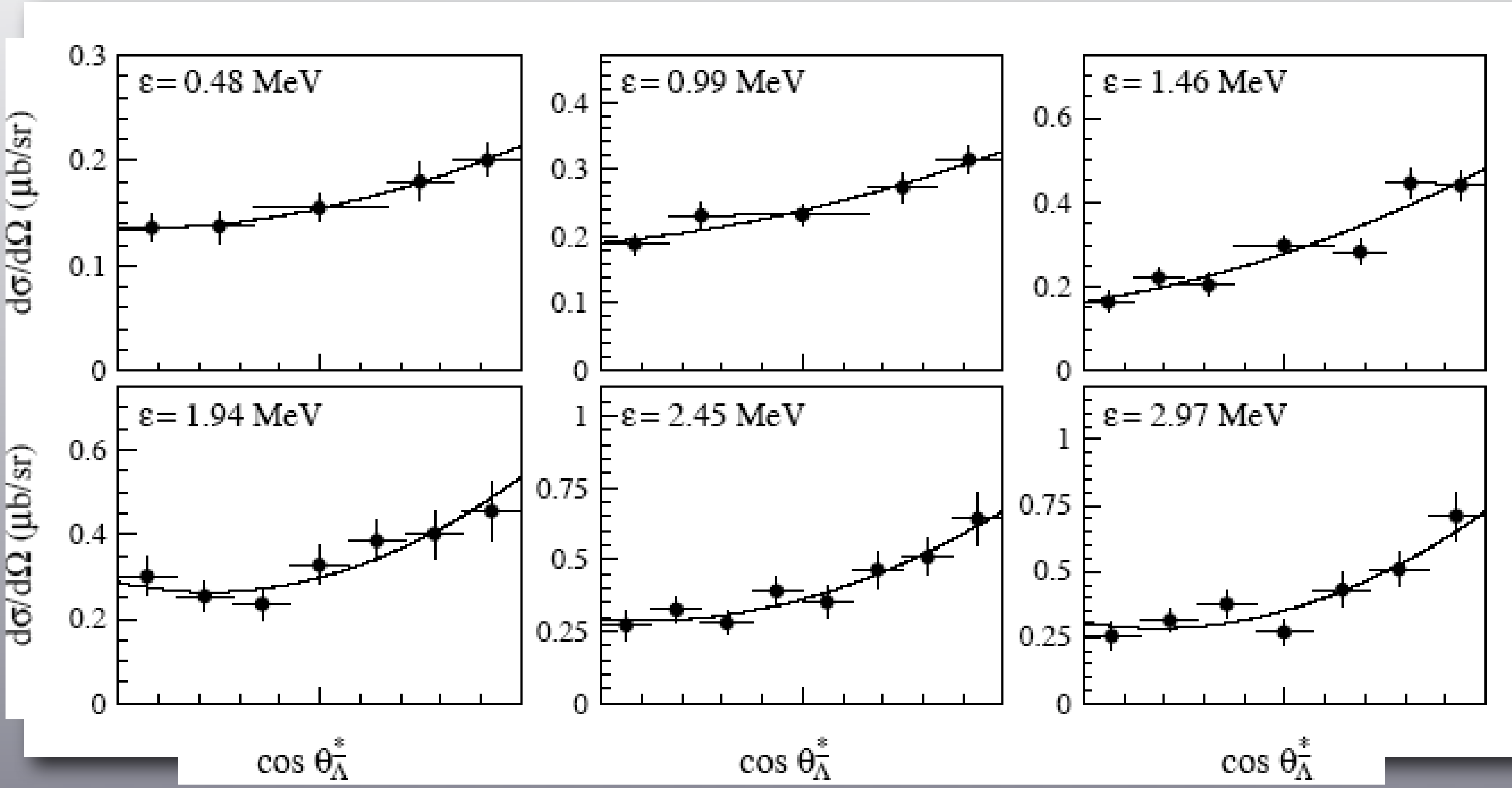
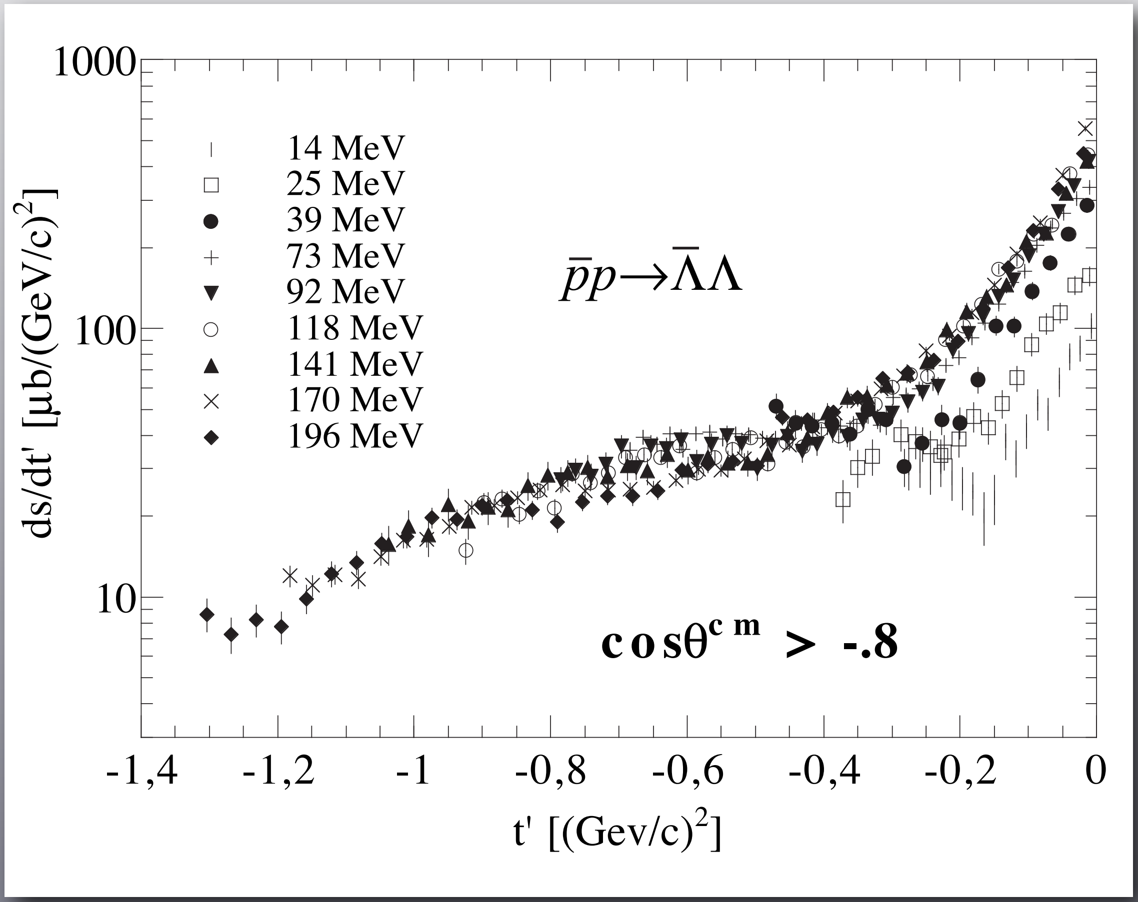


P-waves already below 1 MeV!

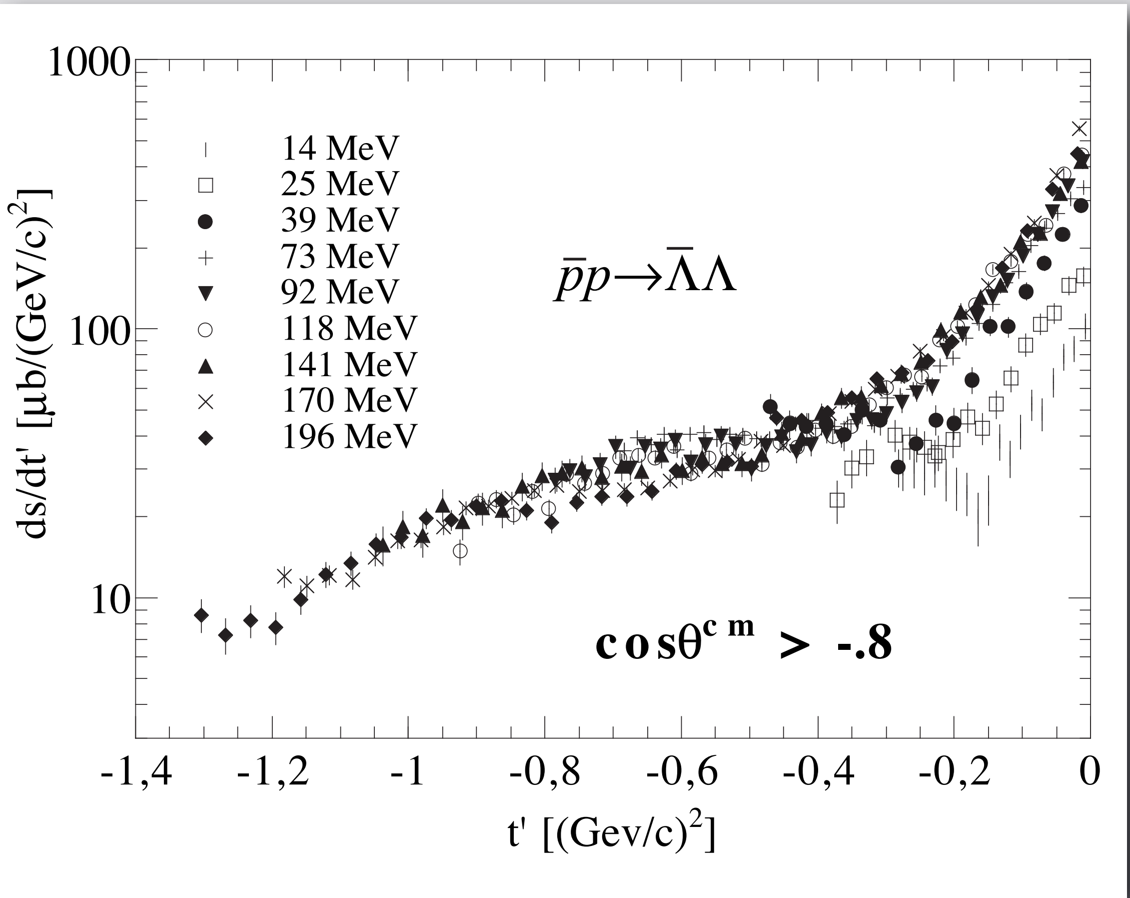
P-wave resonance below threshold?

Why?

Strong *s*-wave absorption in the initial $\bar{p}p$ state!



1000
100
10
ds/dt' [μb/(GeV/c)^2]
14 MeV
25 MeV
39 MeV
73 MeV
92 MeV
118 MeV
141 MeV
170 MeV
196 MeV
$\bar{p}p \rightarrow \bar{\Lambda}\Lambda$
cosθ^{cm} > -.8
-1,4
-1,2
-1
-0,8
-0,6
-0,4
-0,2
0
t' [(Gev/c)^2]


1000
100
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14 MeV
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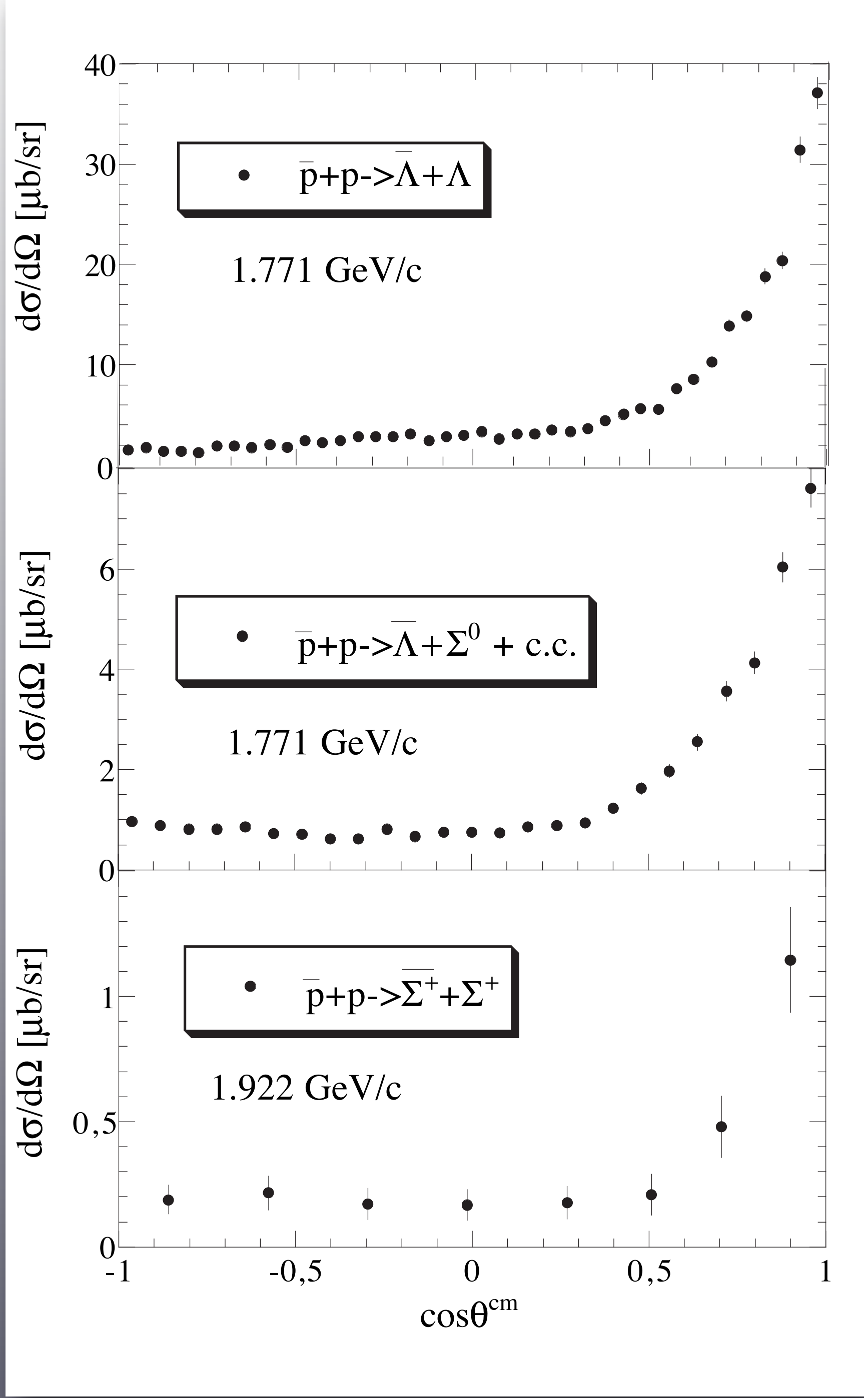
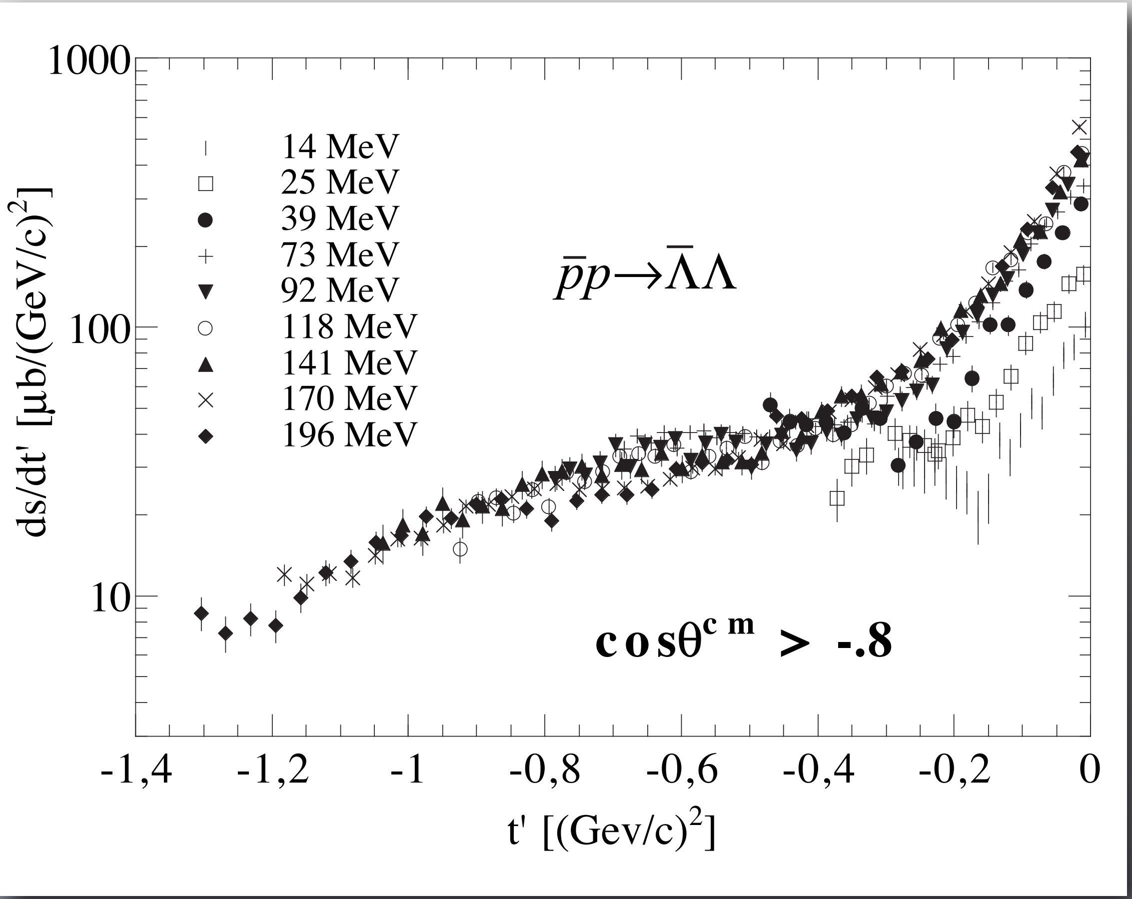
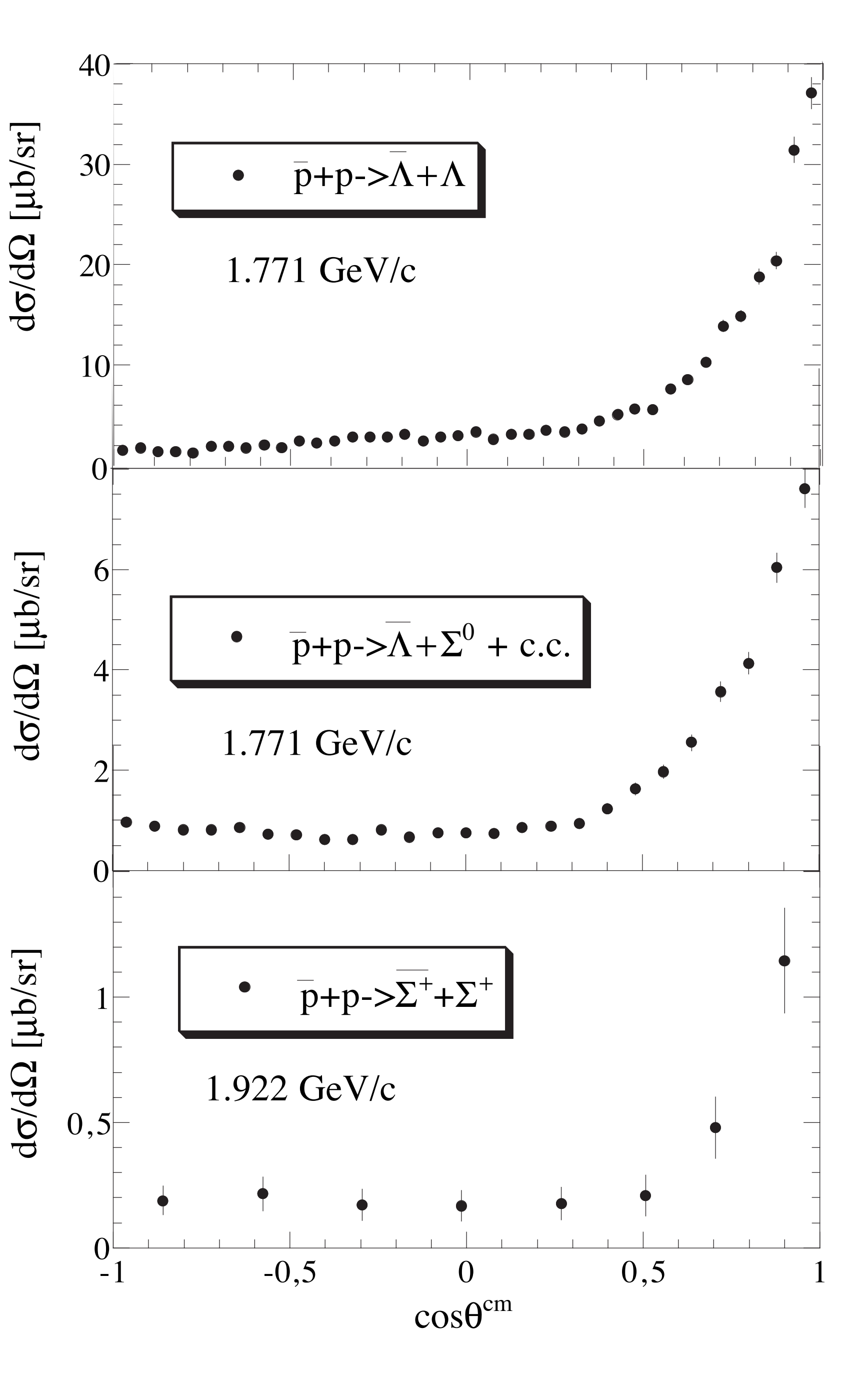
cosθ^c m > -.8
-1,4
-1,2
-1
-0,8
-0,6
-0,4
-0,2
0
t' [(Gev/c)^2]

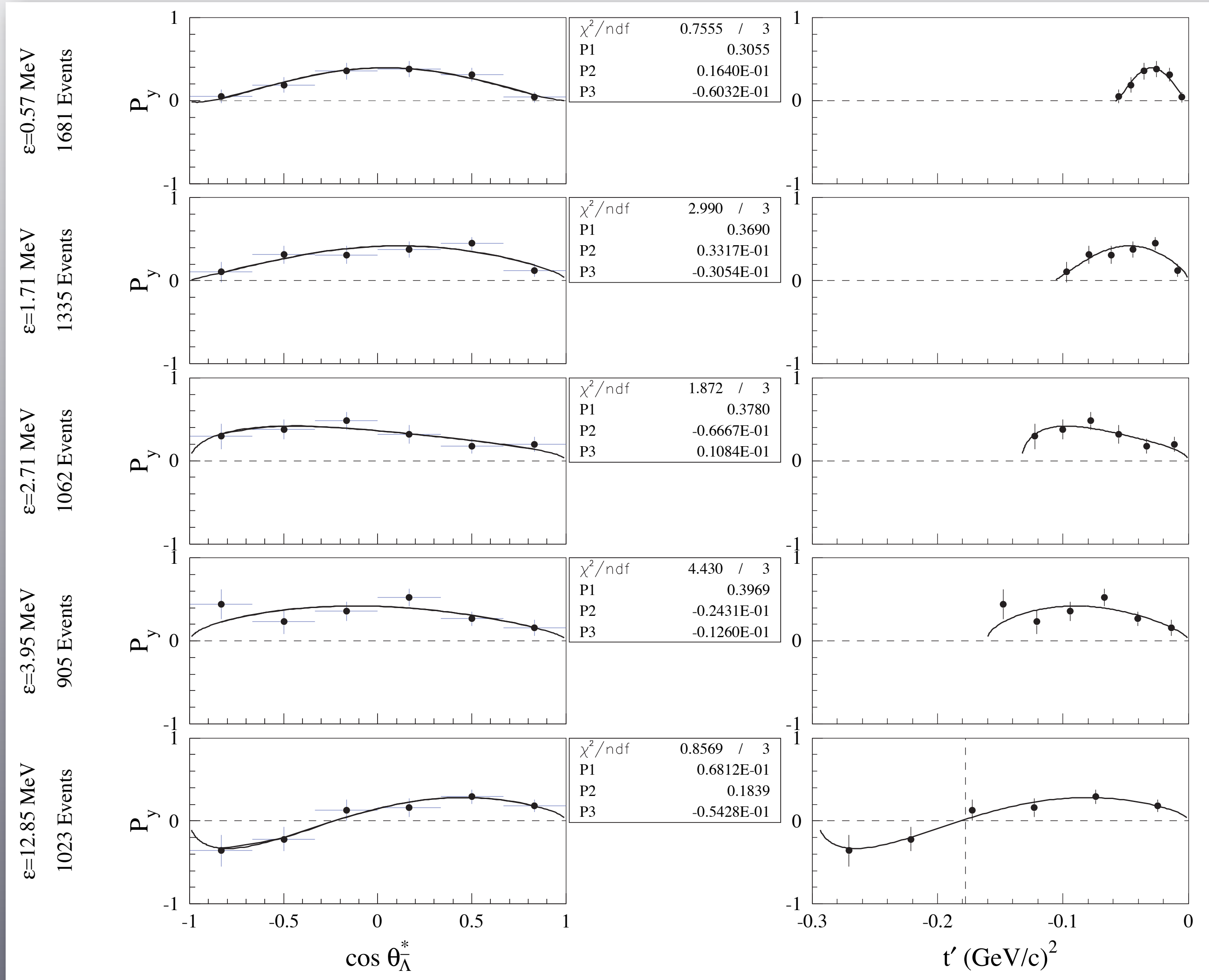

dσ/dΩ [μb/sr]
p̄+p->Λ̄+Λ
1.771 GeV/c
p̄+p->Λ̄+Σ^0 + c.c.
1.771 GeV/c
p̄+p->Σ̄^+ +Σ^+
1.922 GeV/c
cosθ^cm



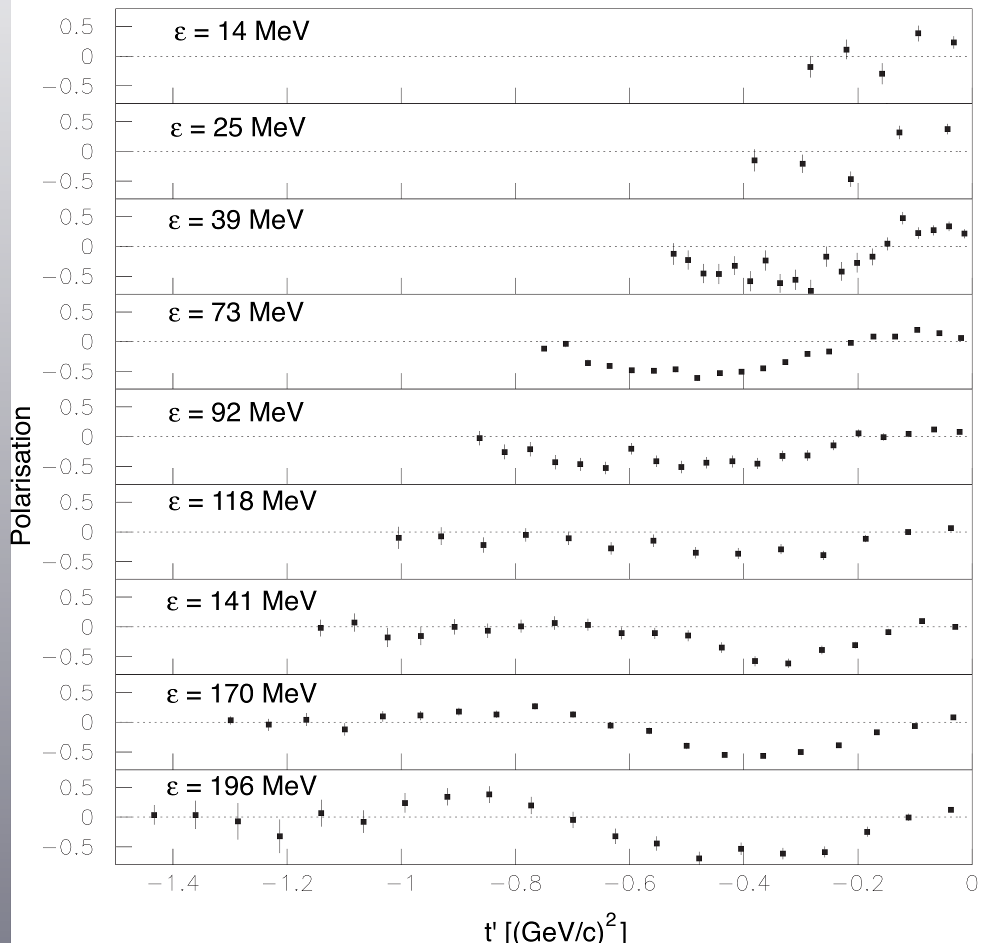


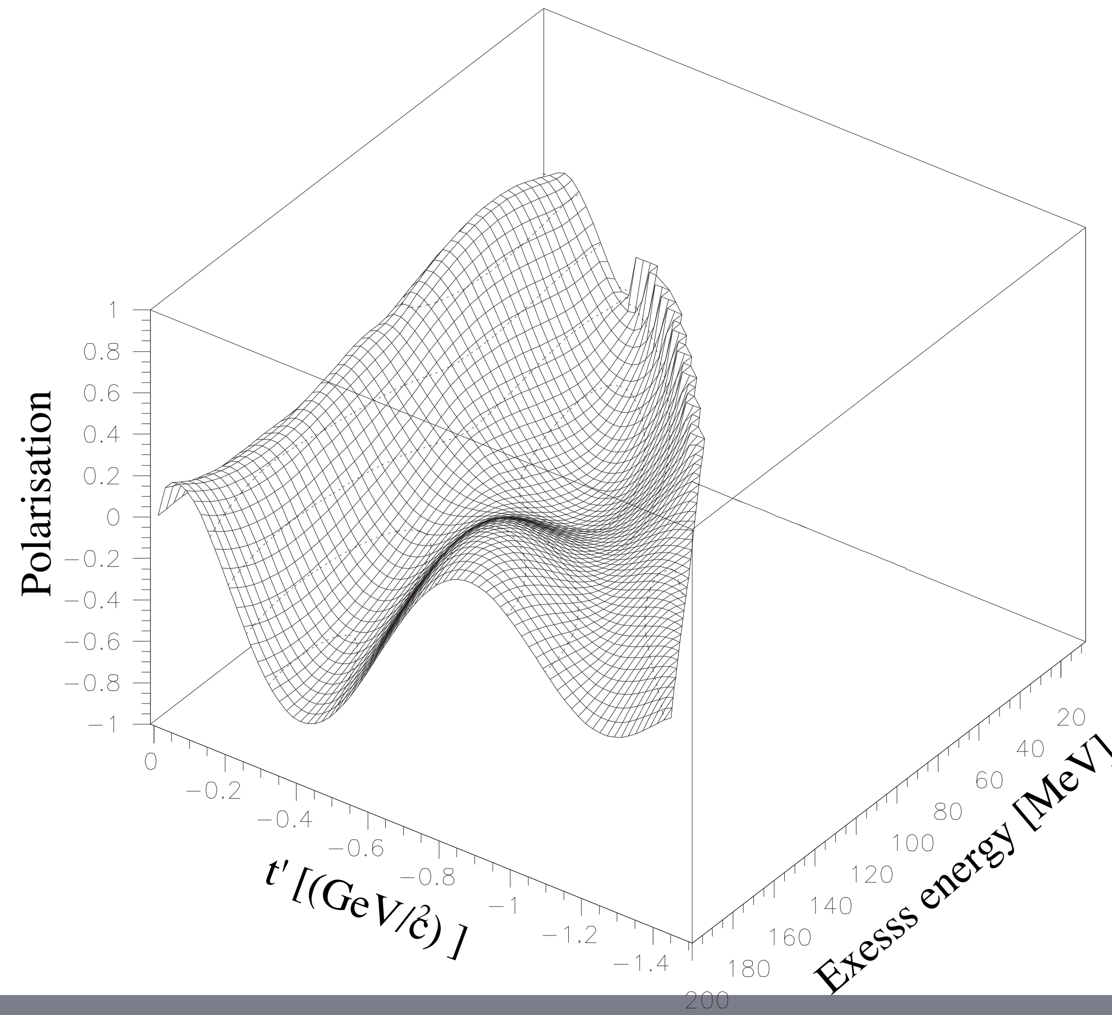
Forward rise a reflection of the interaction radius?

Polarisation



Polarisation





The polarisation show the interference between different partial waves

CP conservation requires that $\bar{\alpha} = -\alpha$

$$\Rightarrow \mathrm{A} = \frac{\bar{\alpha}+\alpha}{\bar{\alpha}-\alpha} = \frac{\bar{\alpha}P_{00n0}+\alpha P_{000n}}{\bar{\alpha}P_{00n0}-\alpha P_{000n}}$$

should be zero if CP is conserved

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☺ Observation of CP-violation in hyperon decay would be "a first" for baryons

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☹ "Expected" signal ≤ 10^{-4}

Feasibility study: ≈ 10^{-3} doable
$< 10^{-4}$ HARD

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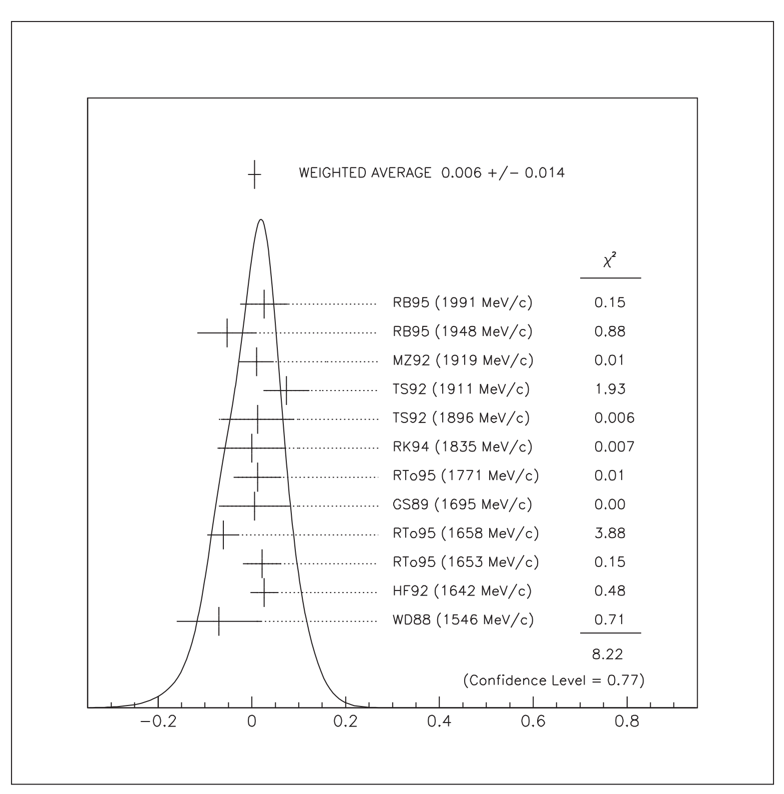
PS185 <A> = 0.006±0.014 (PDG 0.012±0.021)



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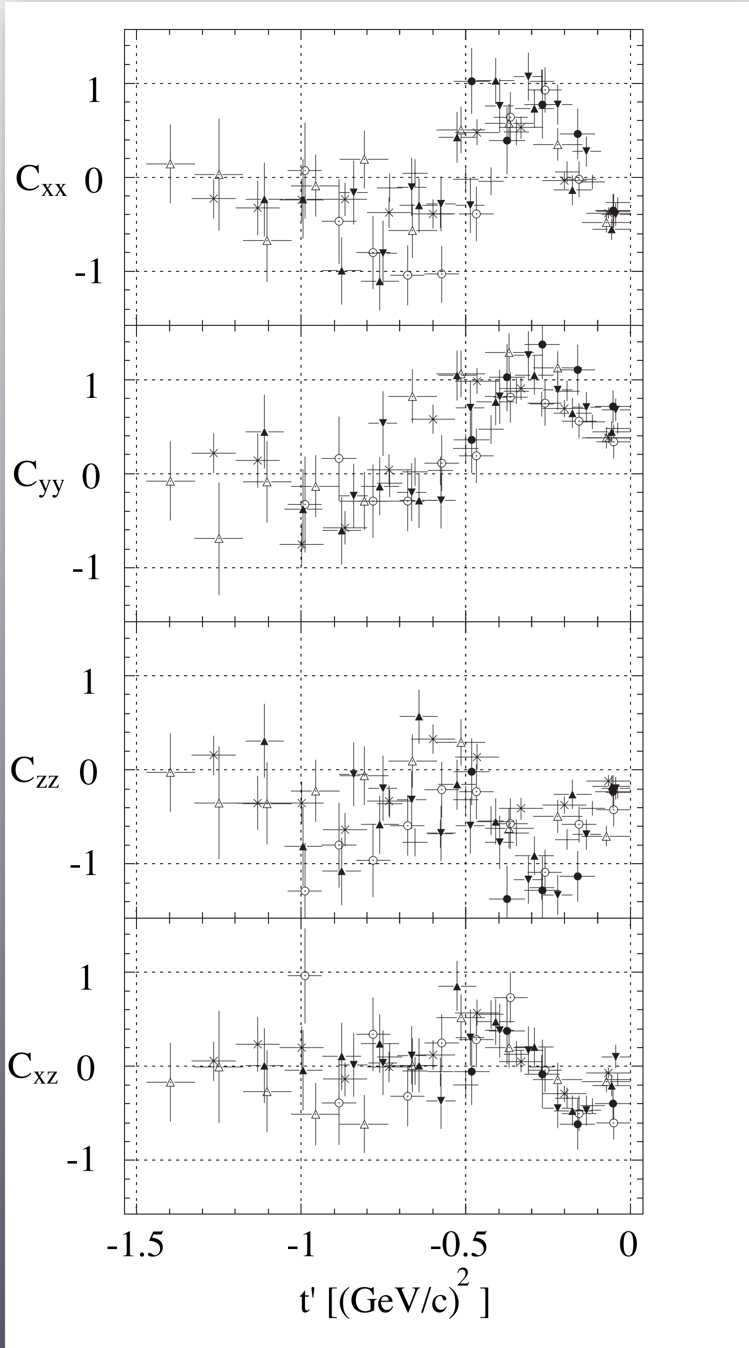
Spin correlations



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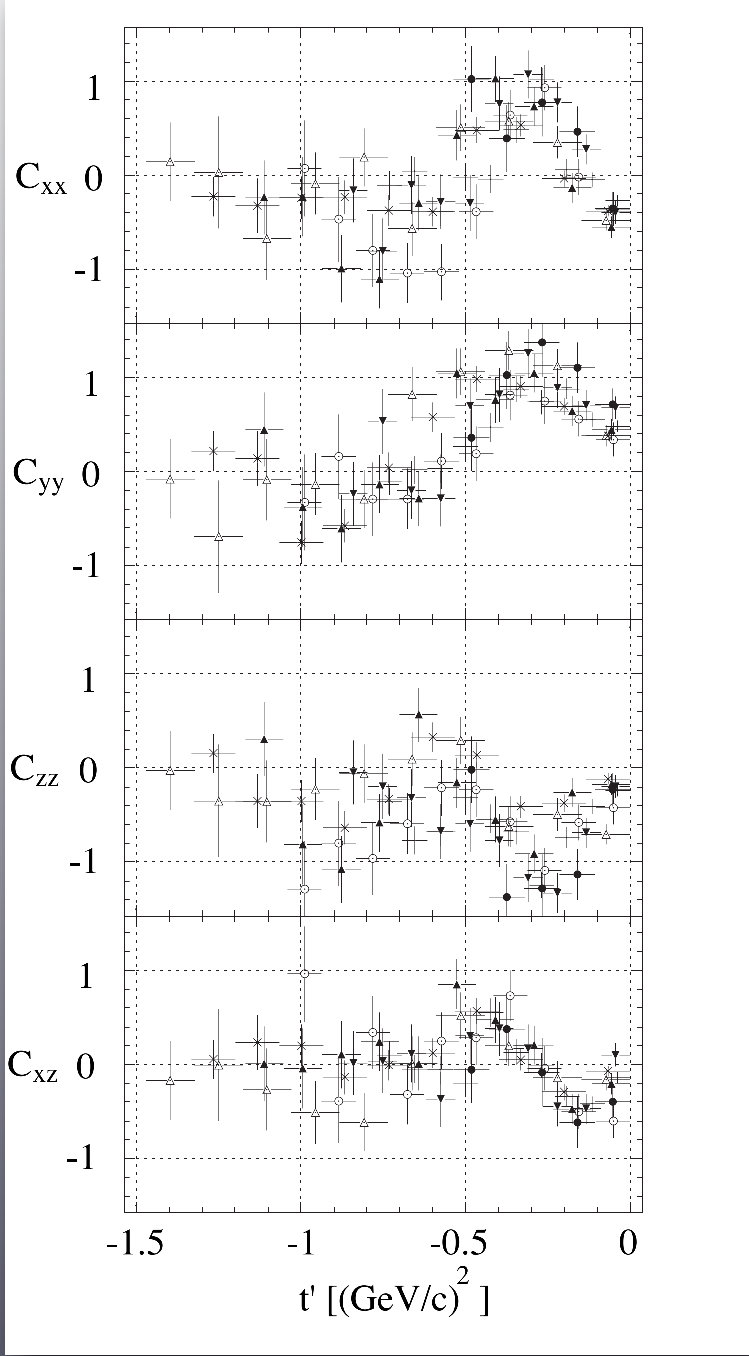
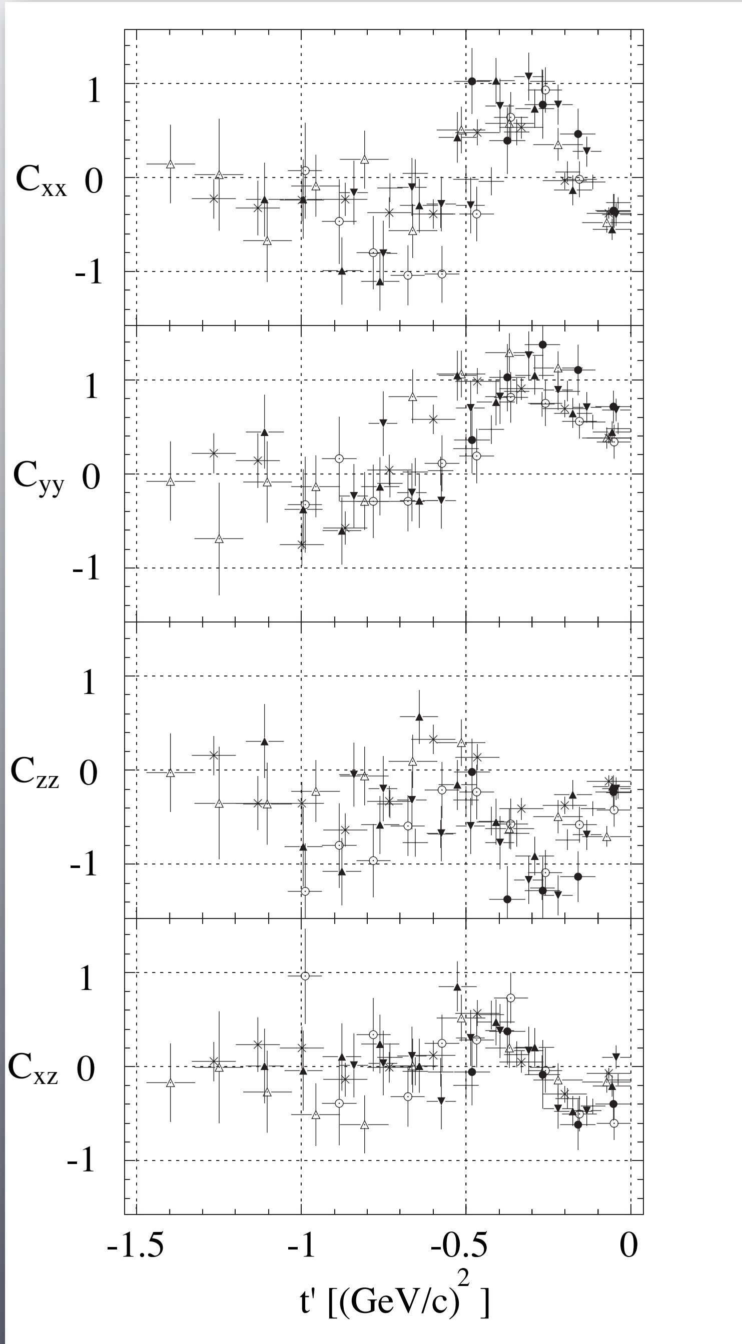


The expectation value of the spin-singlet operator, "Singlet Fraction (F_S)",

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

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

Spin correlations



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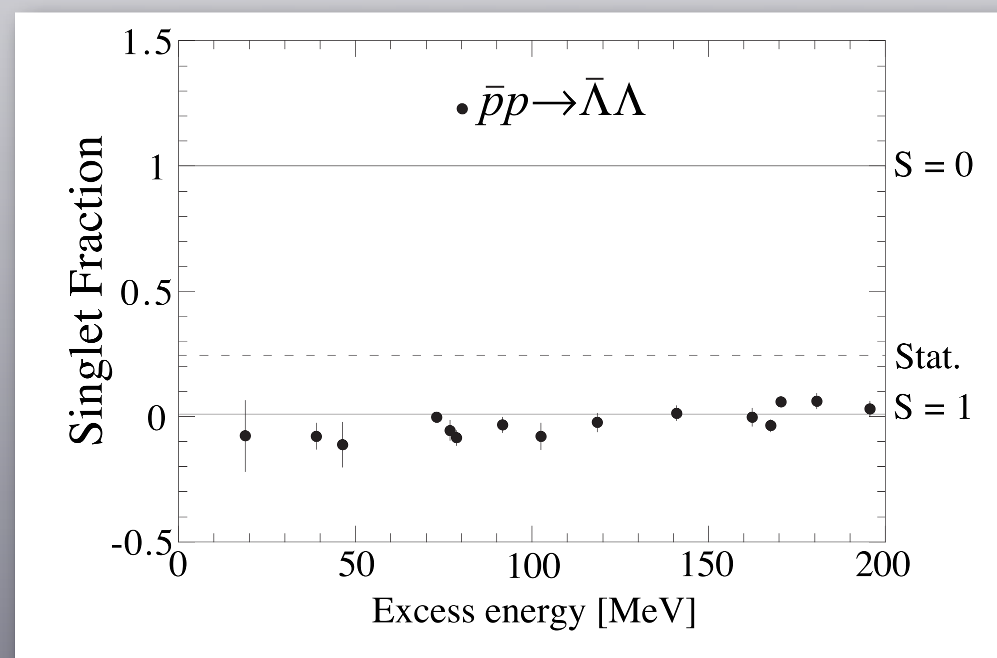
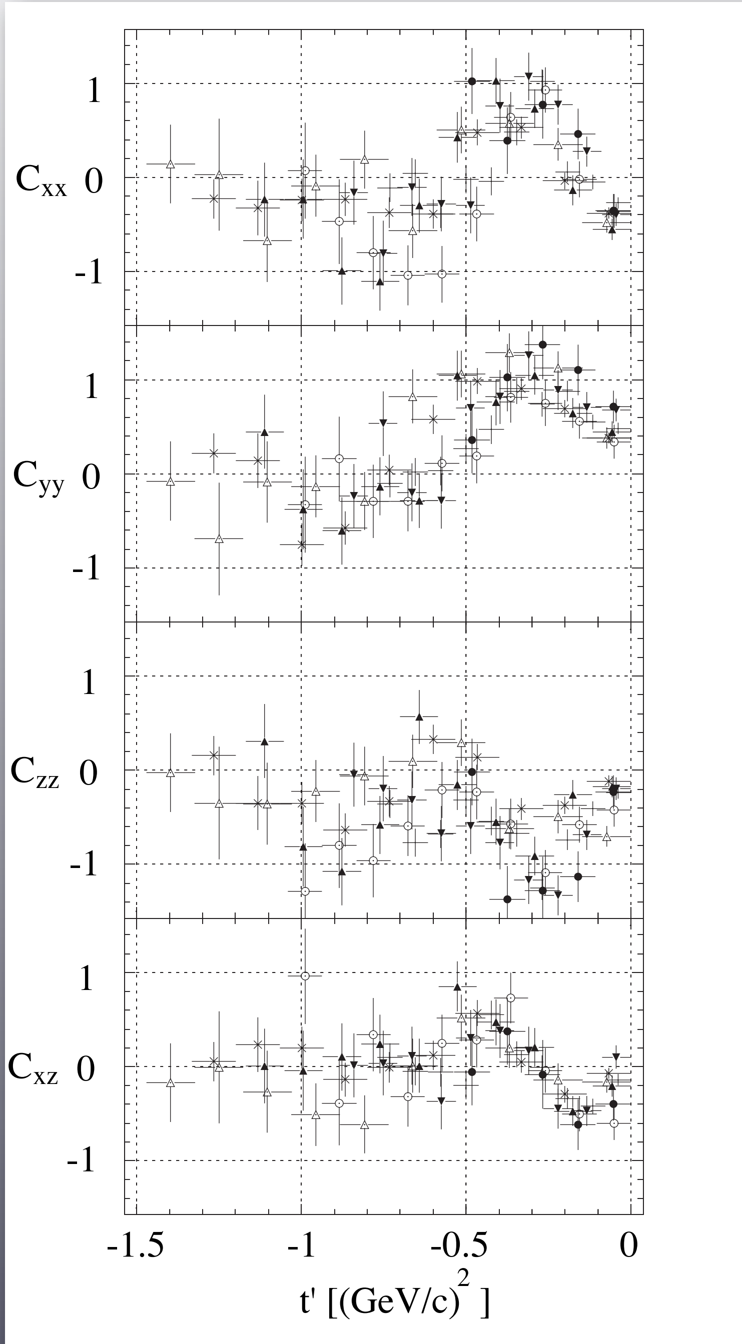


Spin correlations



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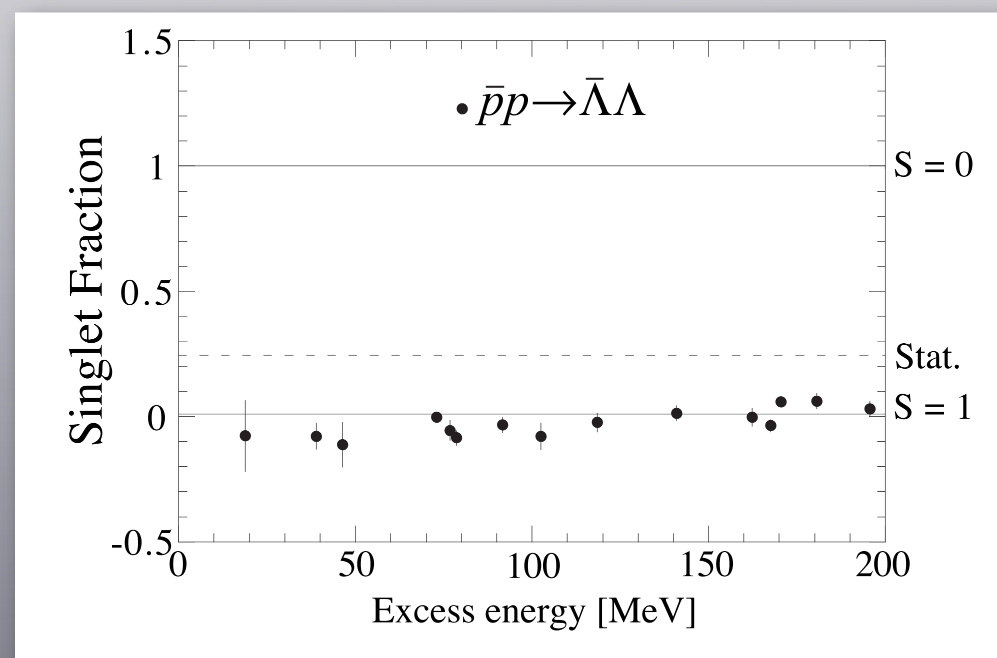
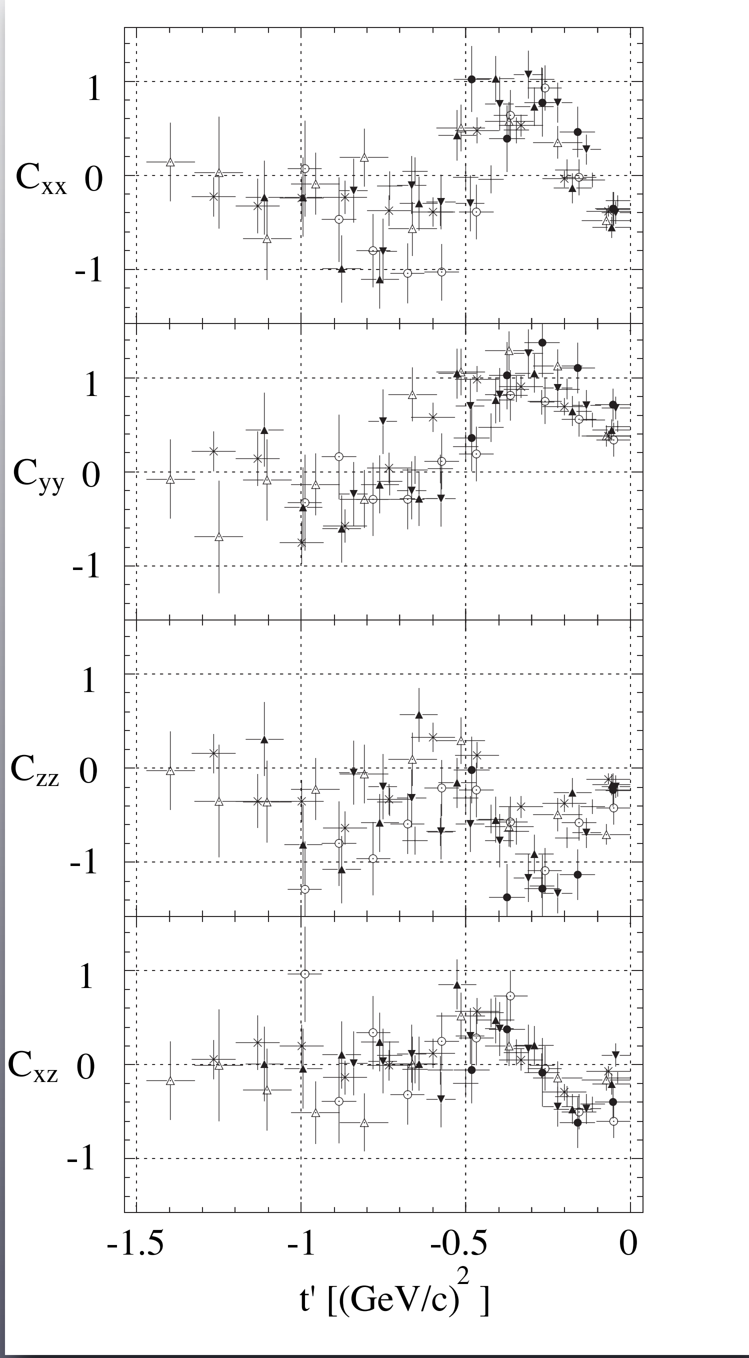


➡ $\bar{\Lambda}\Lambda$-pairs produced with parallel spin!

Spin correlations



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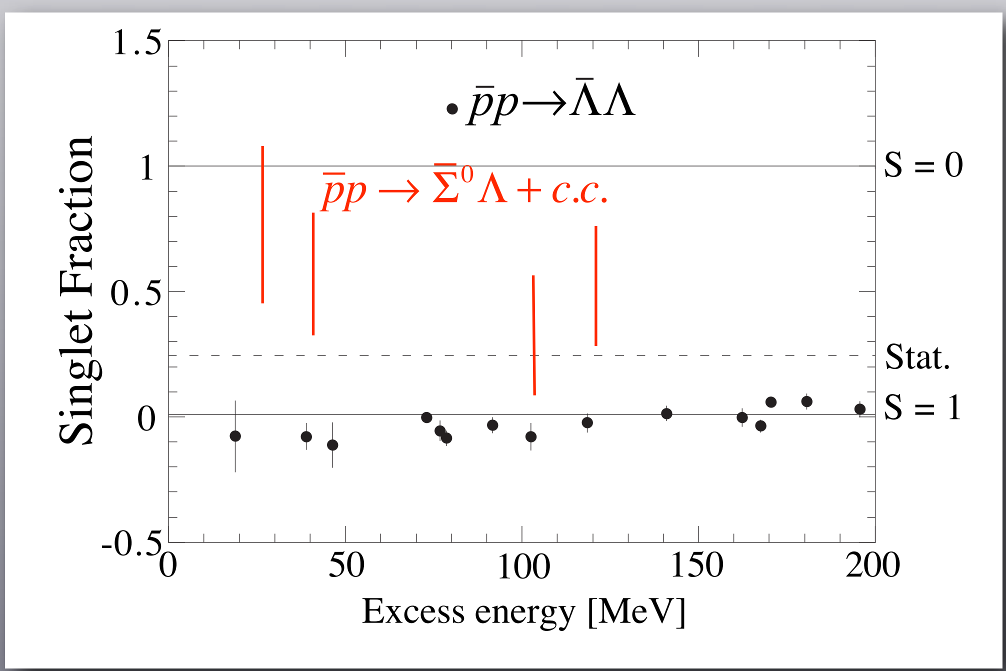

➡ $\bar{\Lambda}\Lambda$-pairs produced with parallel spin!

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

➡ the parallel spins are related to the $\bar{s}s$ production

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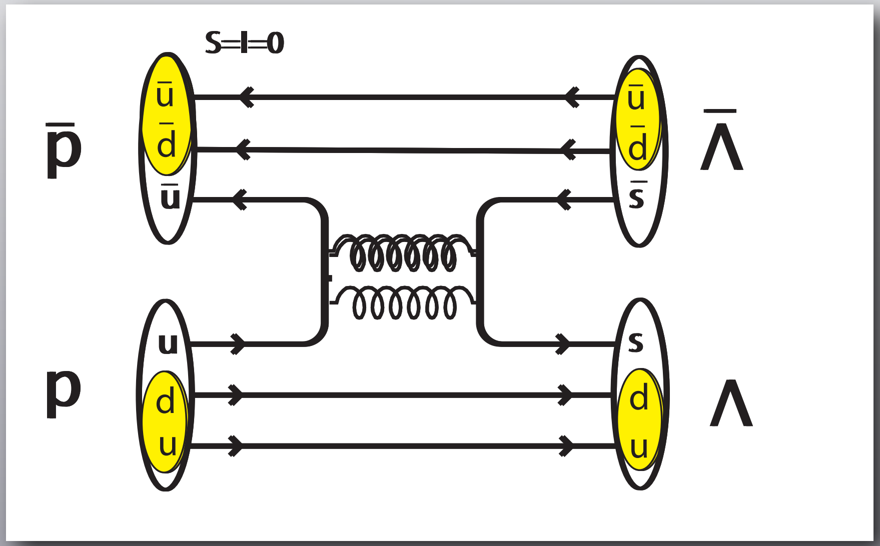

One gluon exchange: $^3S_{1^-}$ *vertex*

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

➡ triplet $\bar{s}s$ spin

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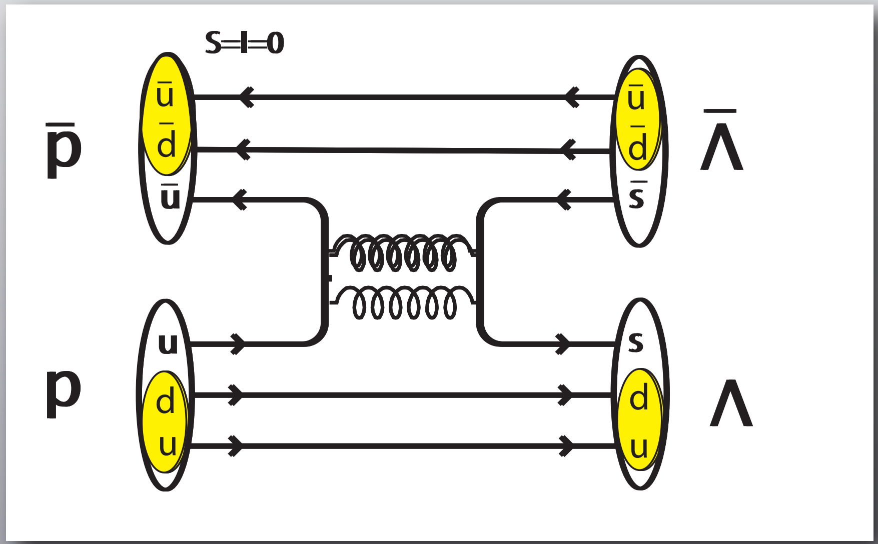

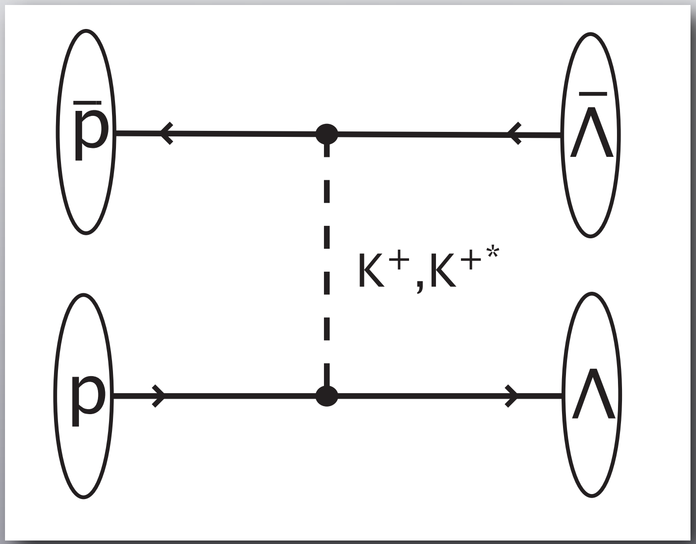

One gluon exchange: $^3S_{1^-}$ *vertex*

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➡ triplet $\bar{s}s$ spin

Including K_2^* allows for a $\Delta\ell = 2$ transition (spin flip)

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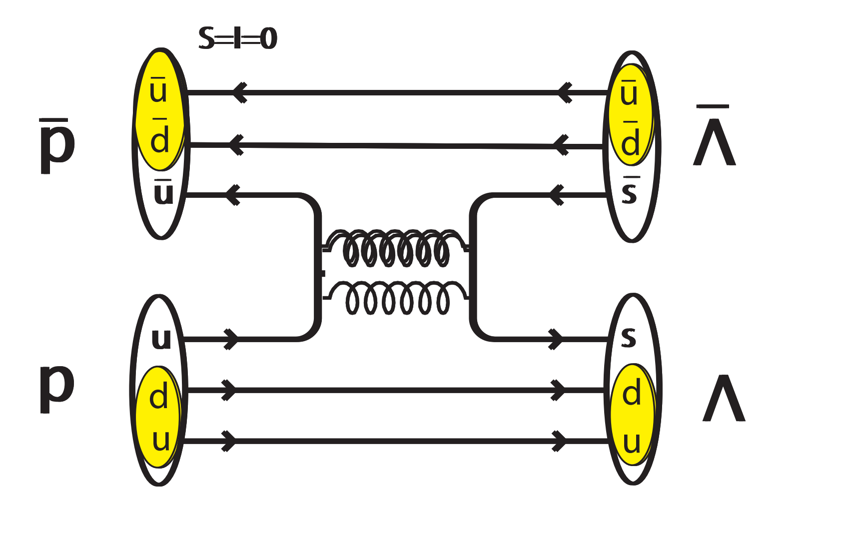
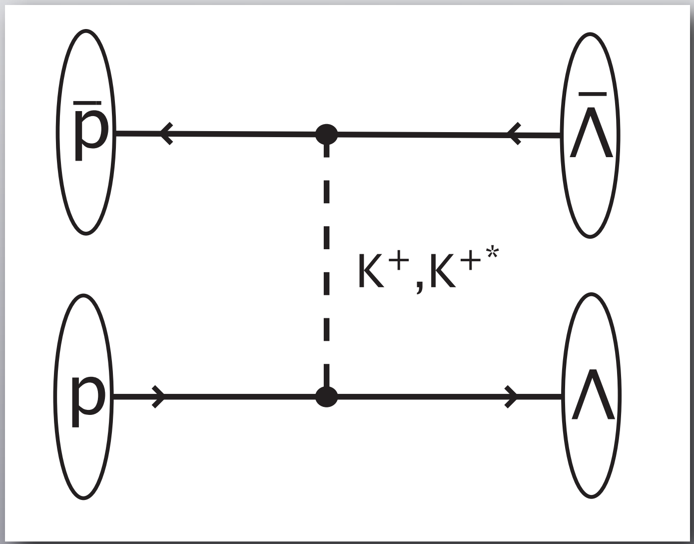
➡ the parallel spins are related to the $\bar{s}s$ production





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

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

➡ triplet $\bar{s}s$ spin

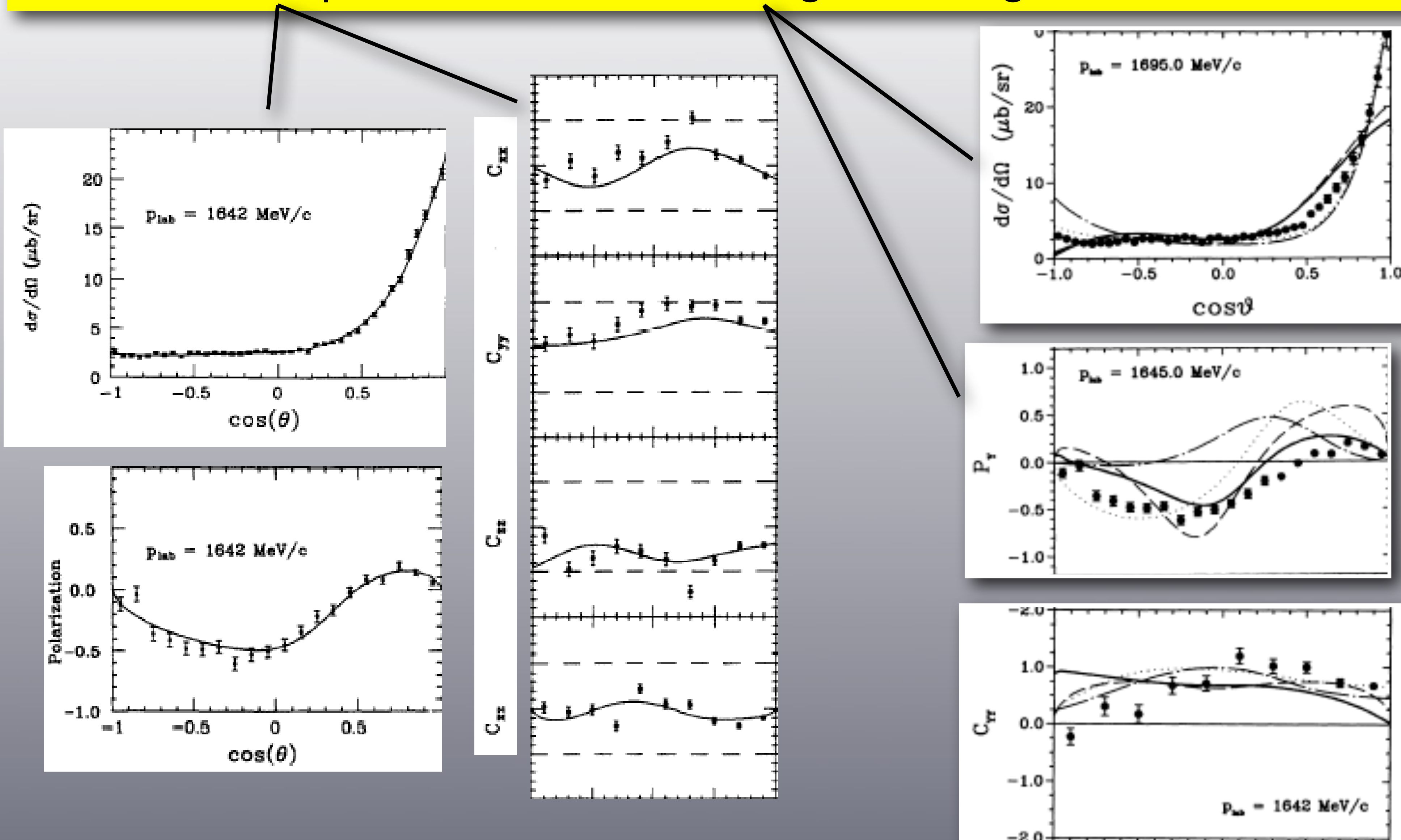
Including K_2^* allows for a $\Delta\ell = 2$ transition (spin flip)

➡ triplet $\bar{\Lambda}\Lambda$ spin

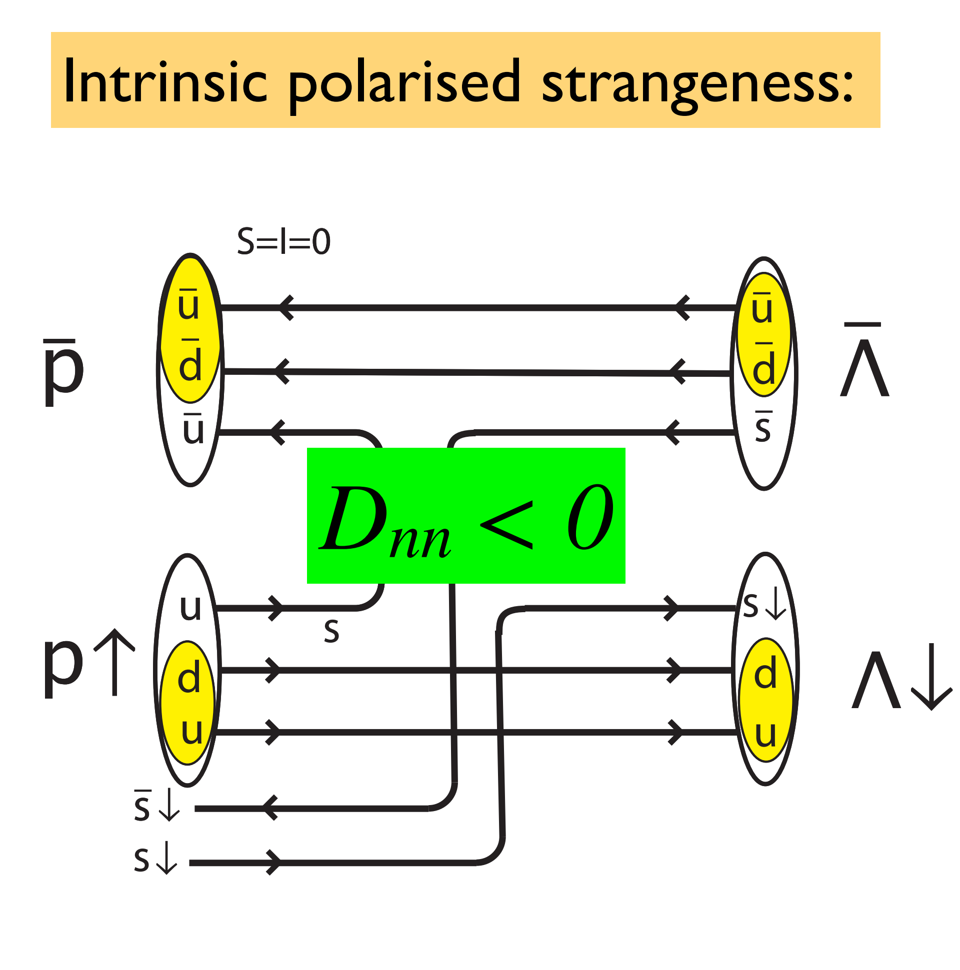
$D_{nn} > 0$

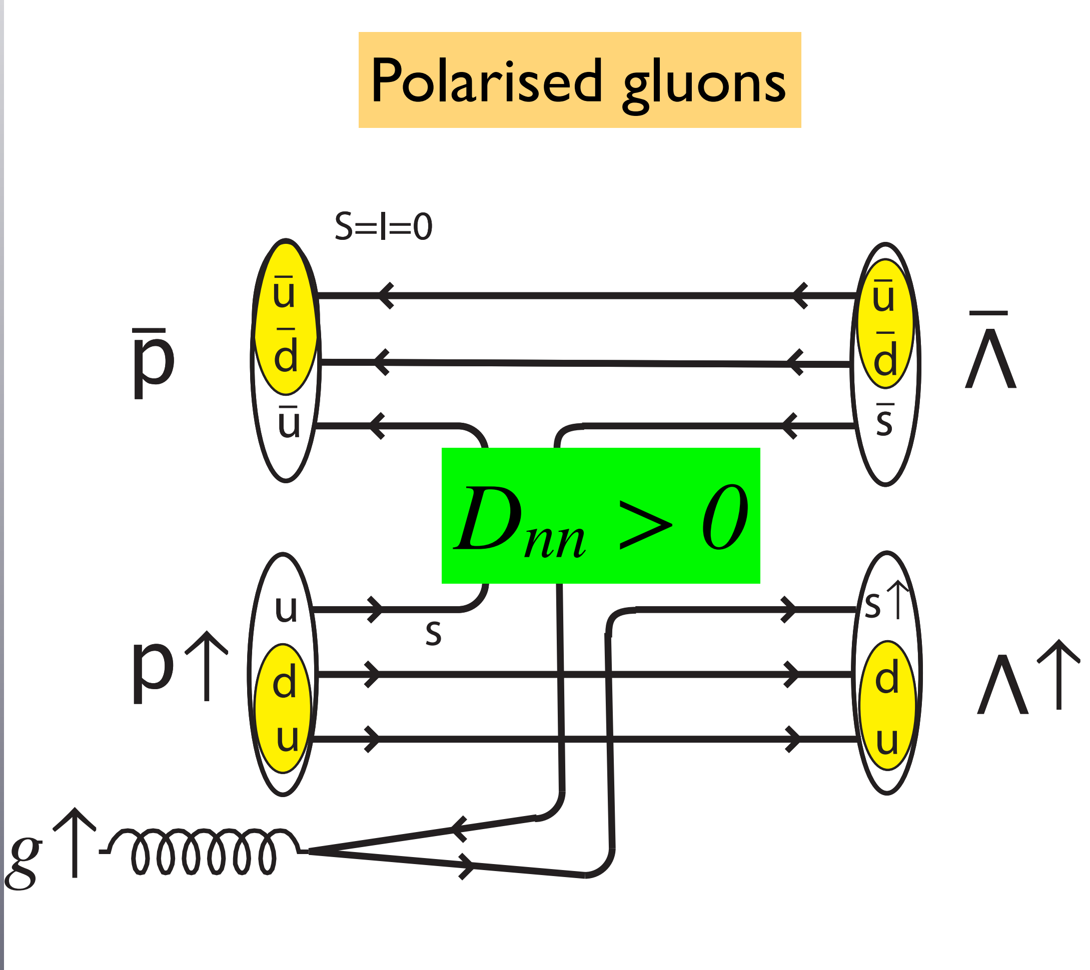
$D_{nn} < 0$

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

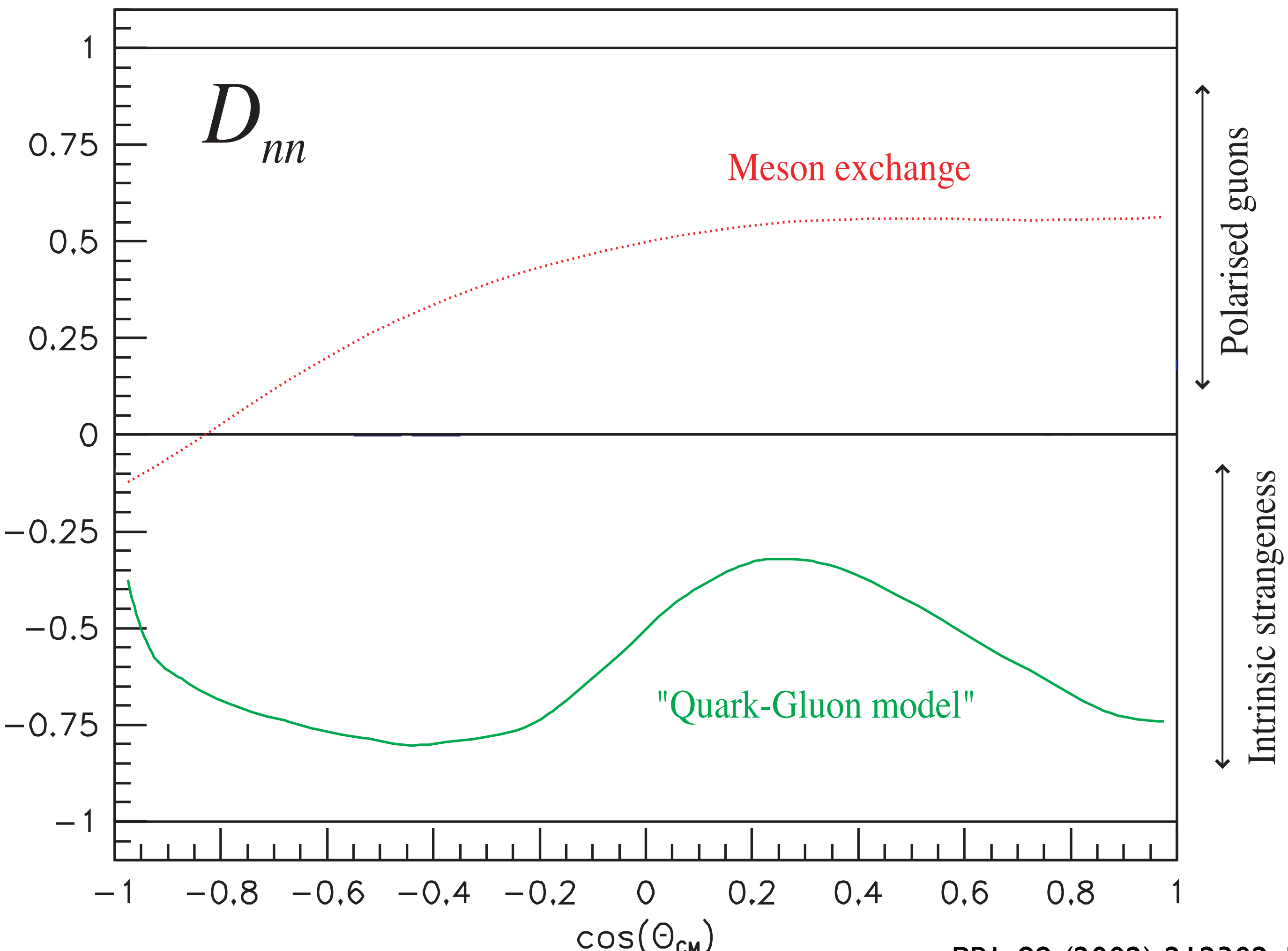


Intrinsic polarised strangeness or gluons?



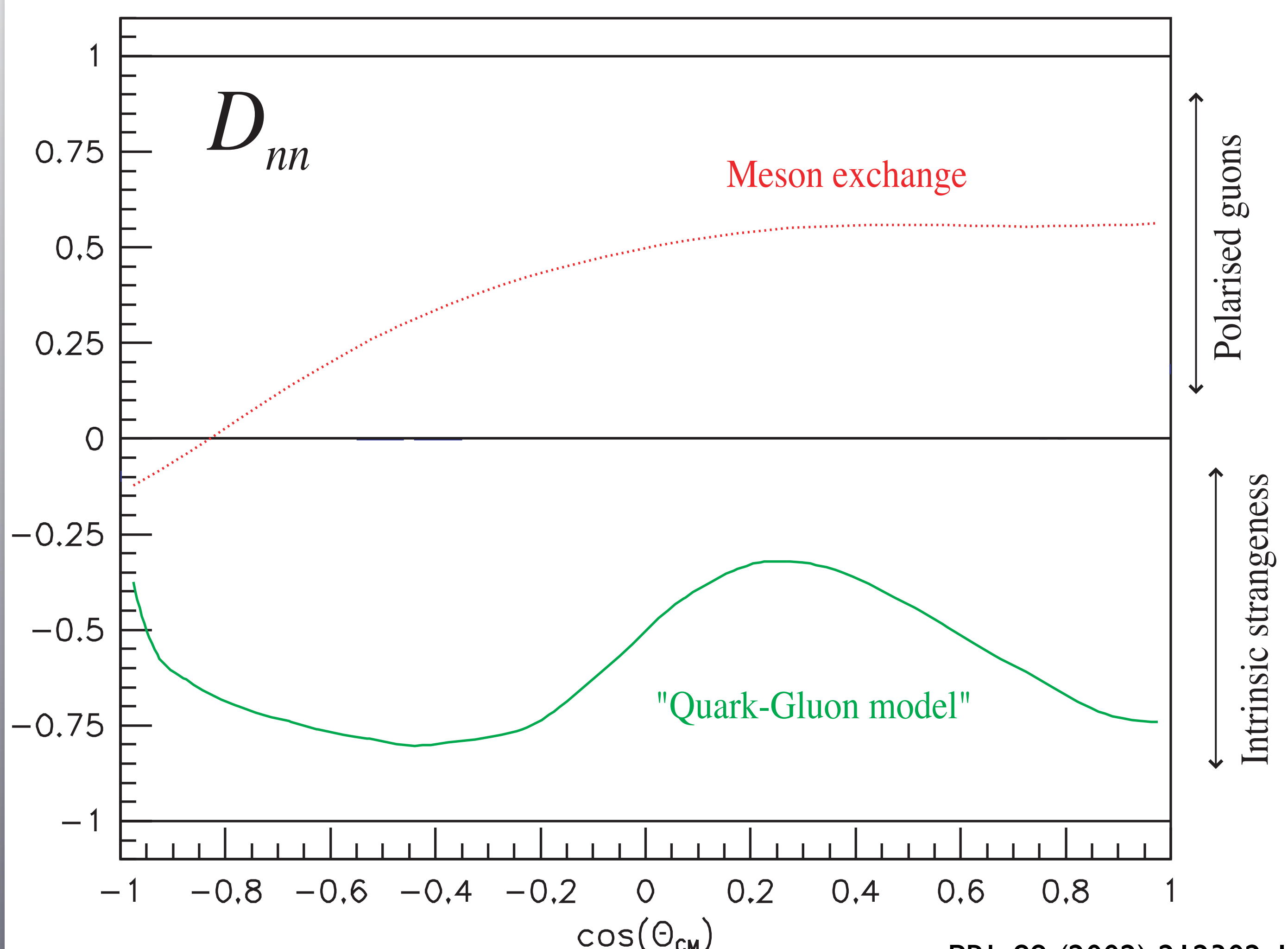


Alberg,Ellis,Kharzeev PLB 356(95)113



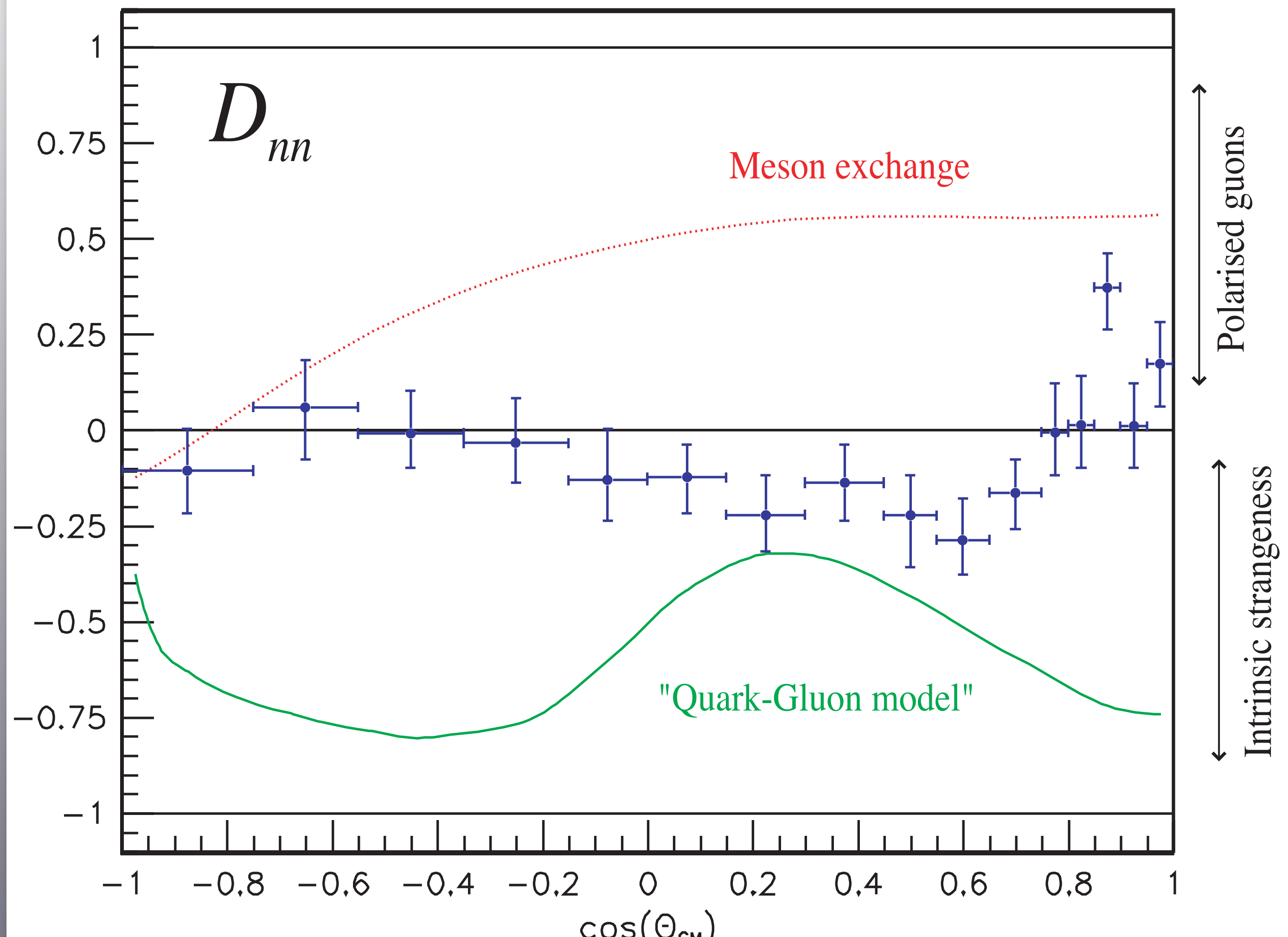
PRL 89 (2002) 212302-1

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



PRL 89 (2002) 212302-1

PS185/3: $\overline{p}\vec{p} \rightarrow \overline{\Lambda}\Lambda$ @ 1637 MeV / c



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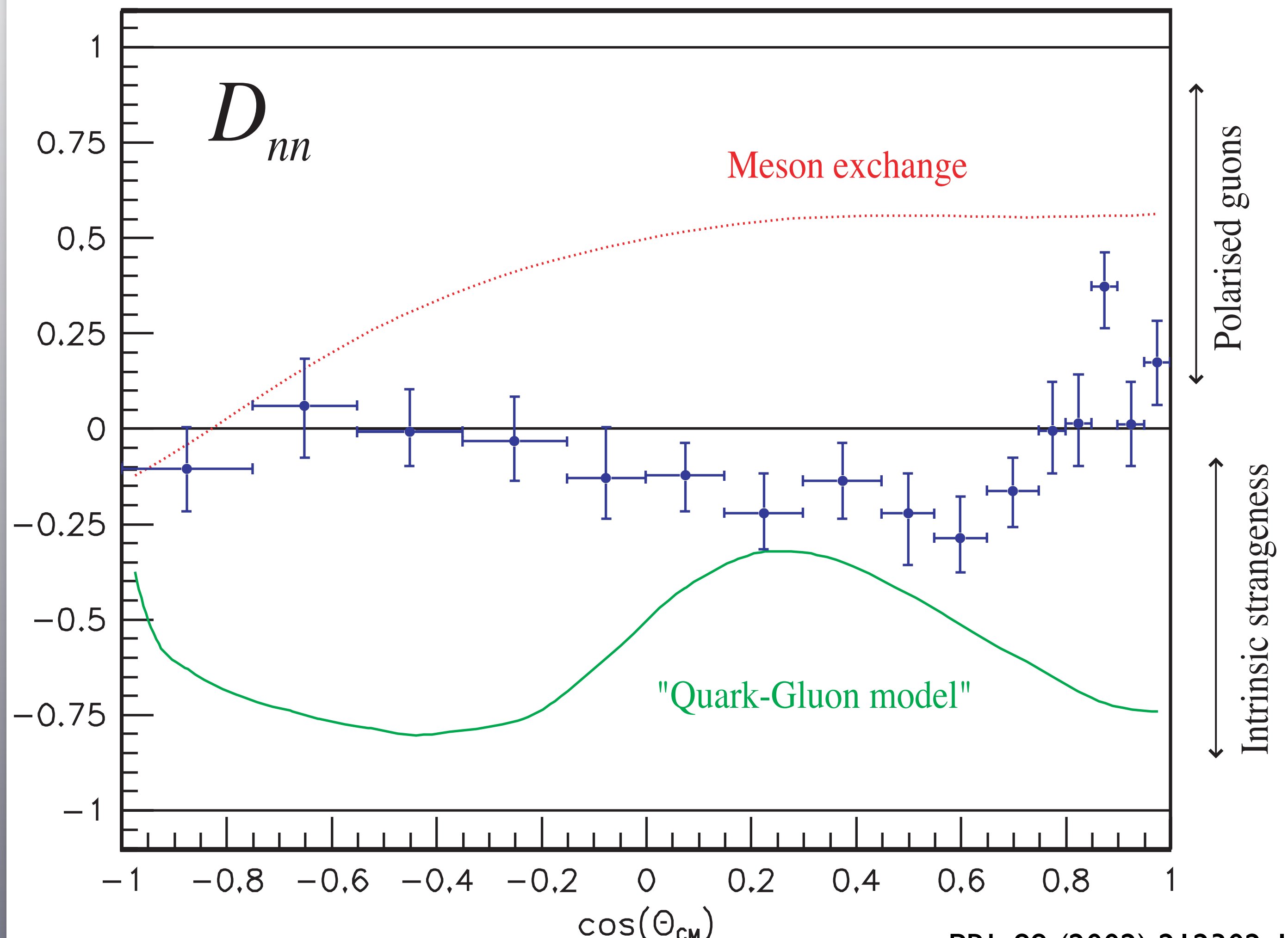
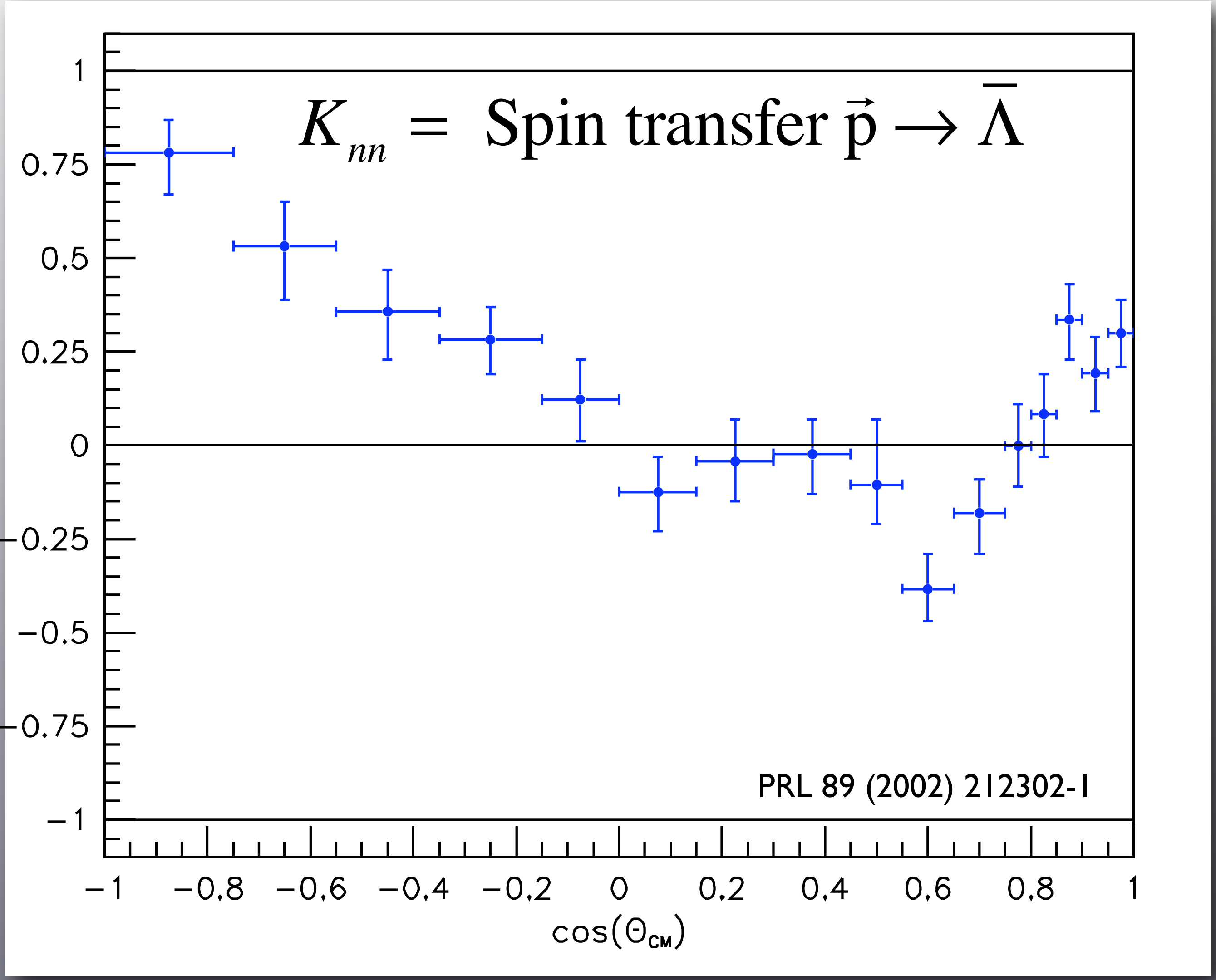


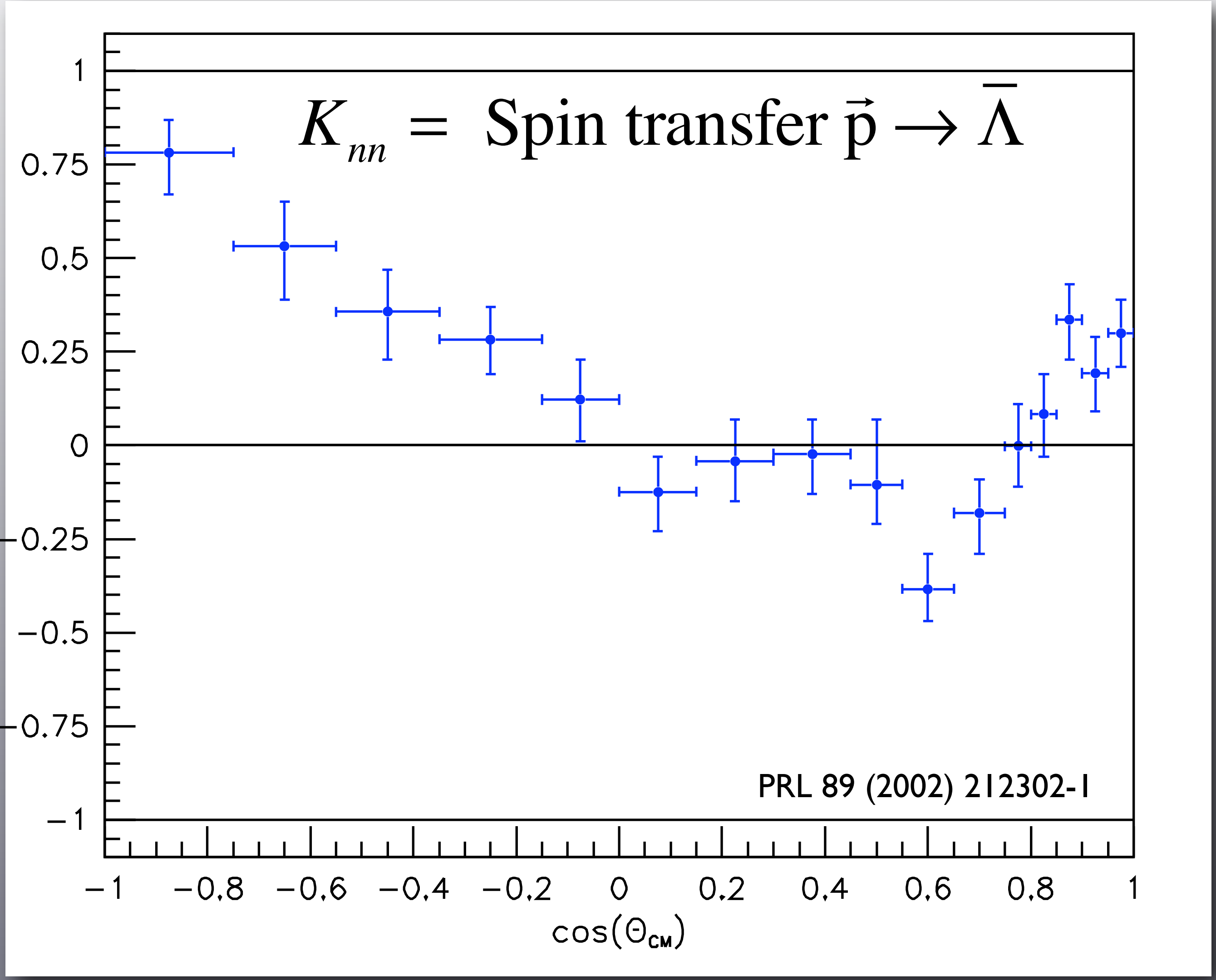
PRL 89 (2002) 212302-1

Practically no transfer of spin from proton to lambda!

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

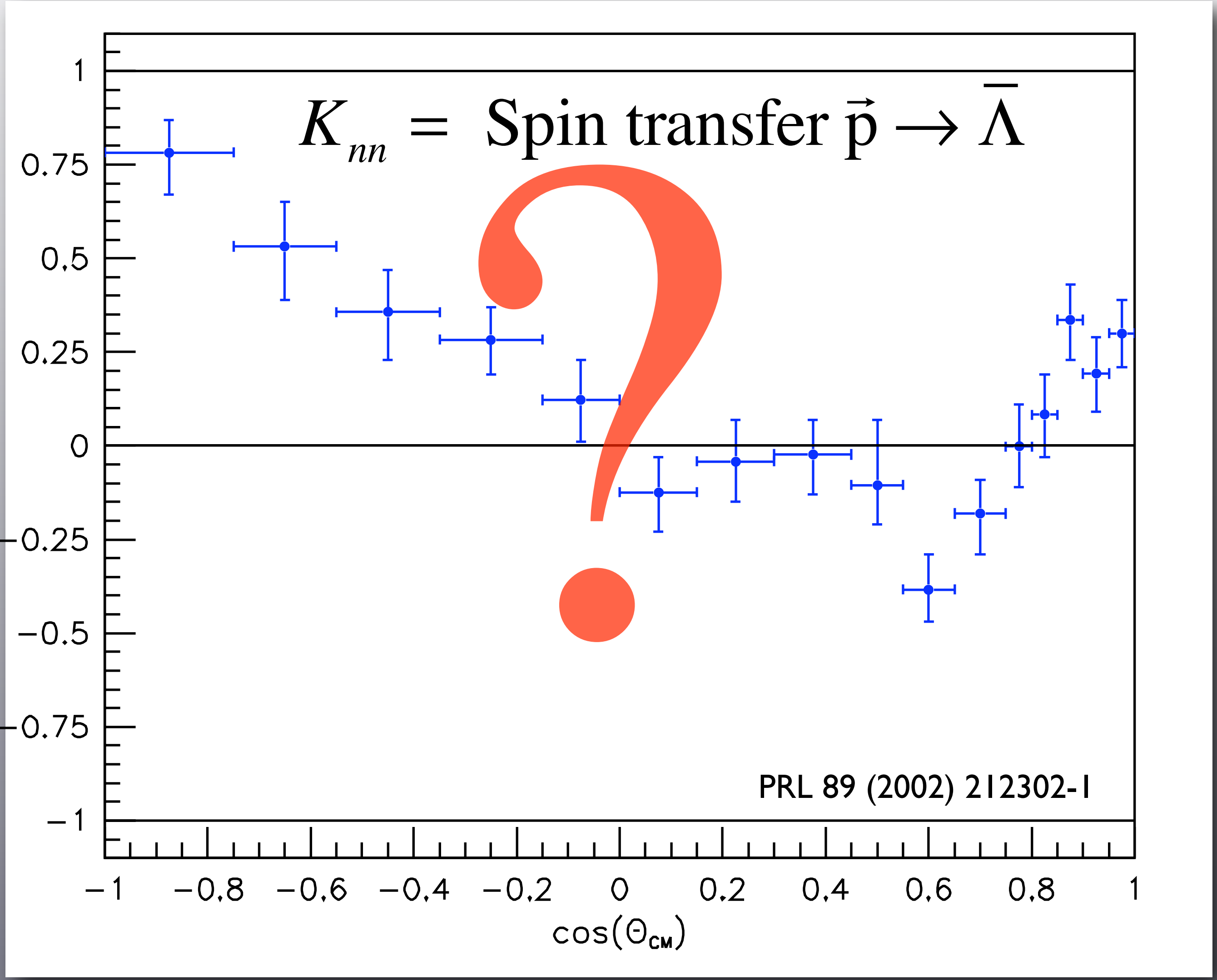


PS185/3: $\overline{p}\vec{p} \to \overline{\Lambda}\Lambda$ @ 1637 MeV / c



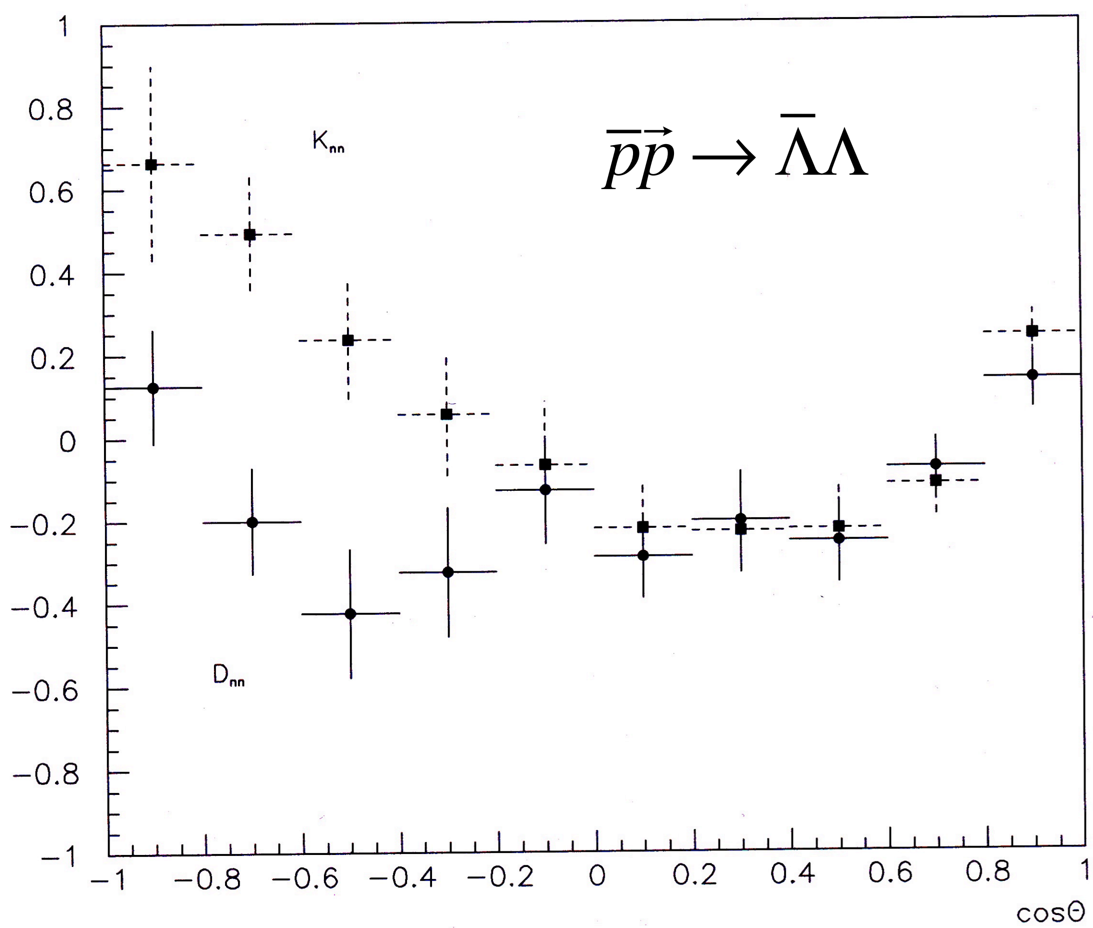
Transfer of spin from target proton to antilambda!

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



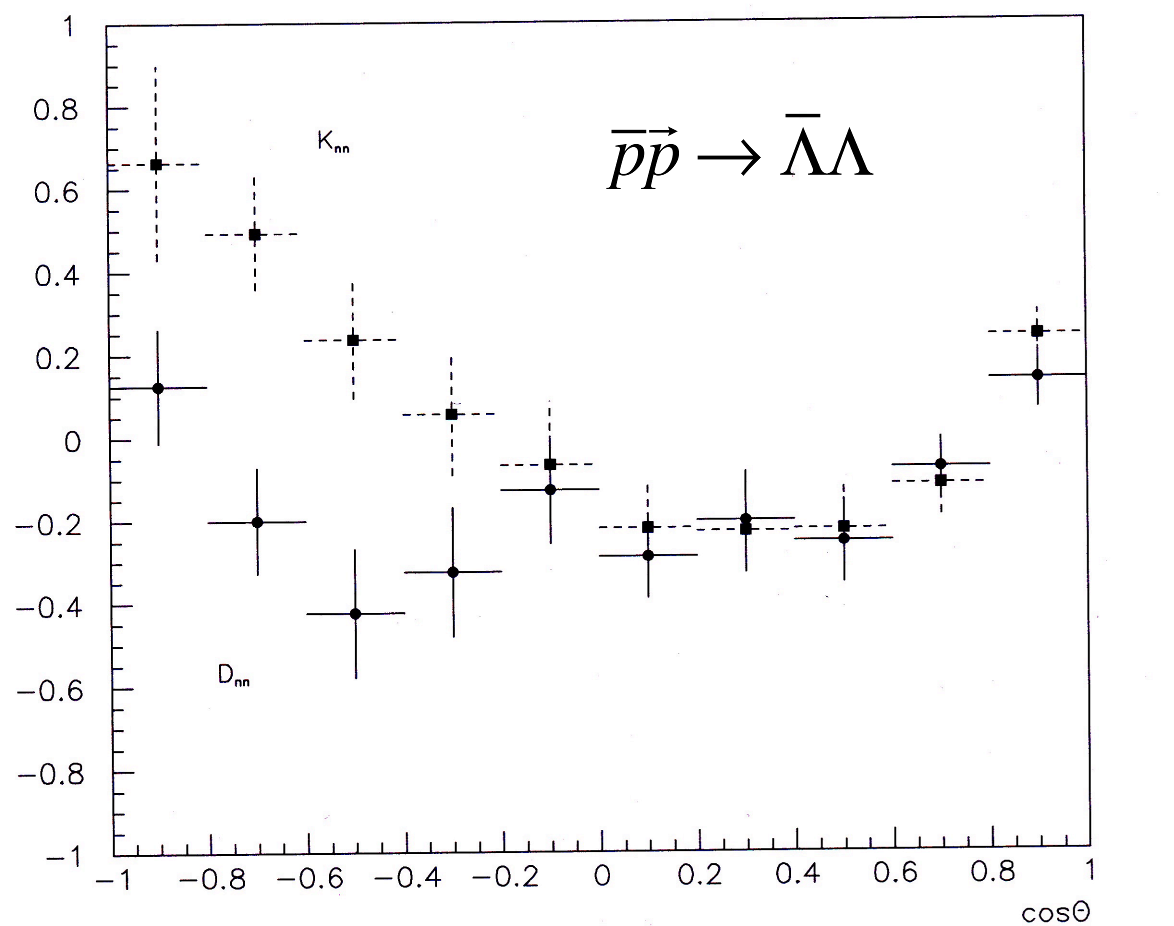
Transfer of spin from target proton to antilambda!

Results confirmed @ 1525 MeV/c



P. Kingsberry, Thesis, 2002

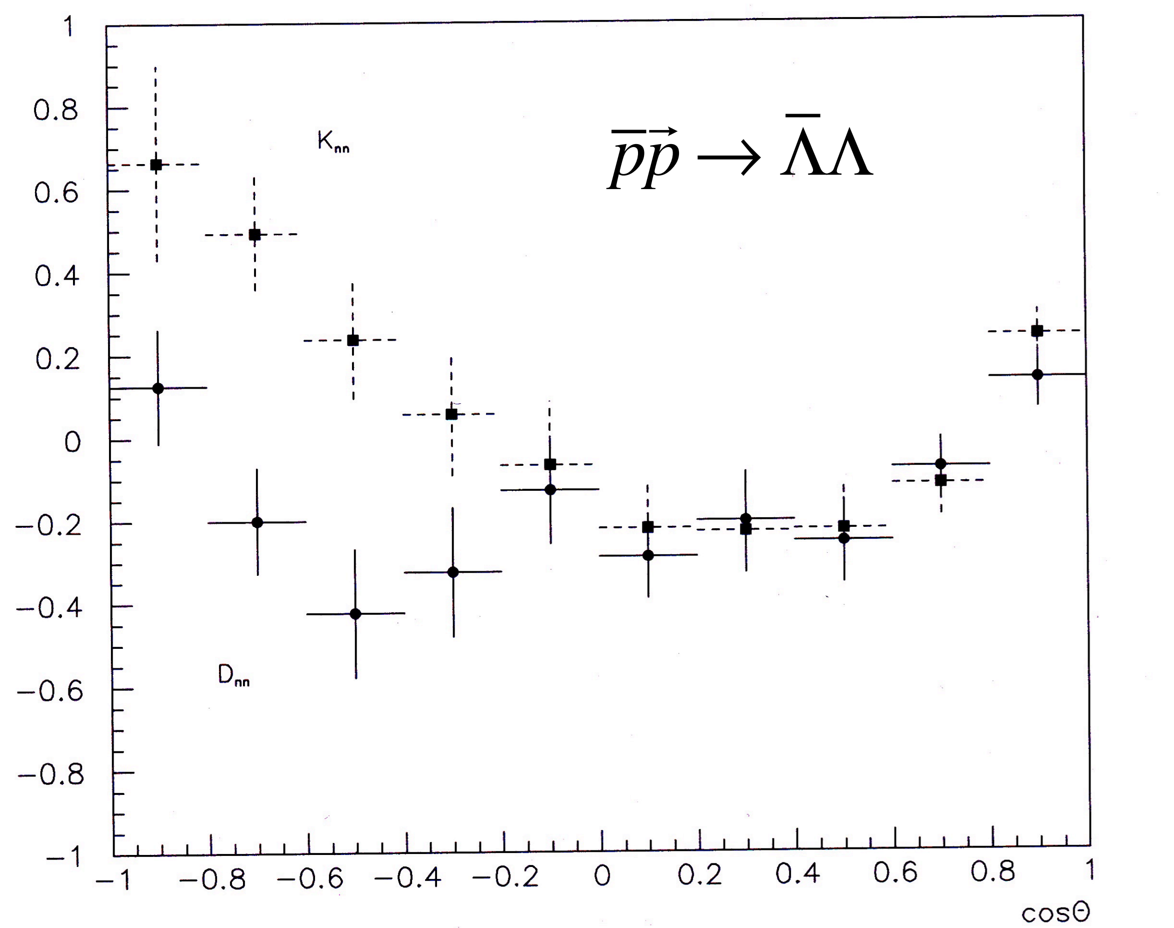
Results confirmed @ 1525 MeV/c



P. Kingsberry, Thesis, 2002

$\bar{\Lambda}\Lambda$ Triplet state ⟺ $D_{nn} = K_{nn}$

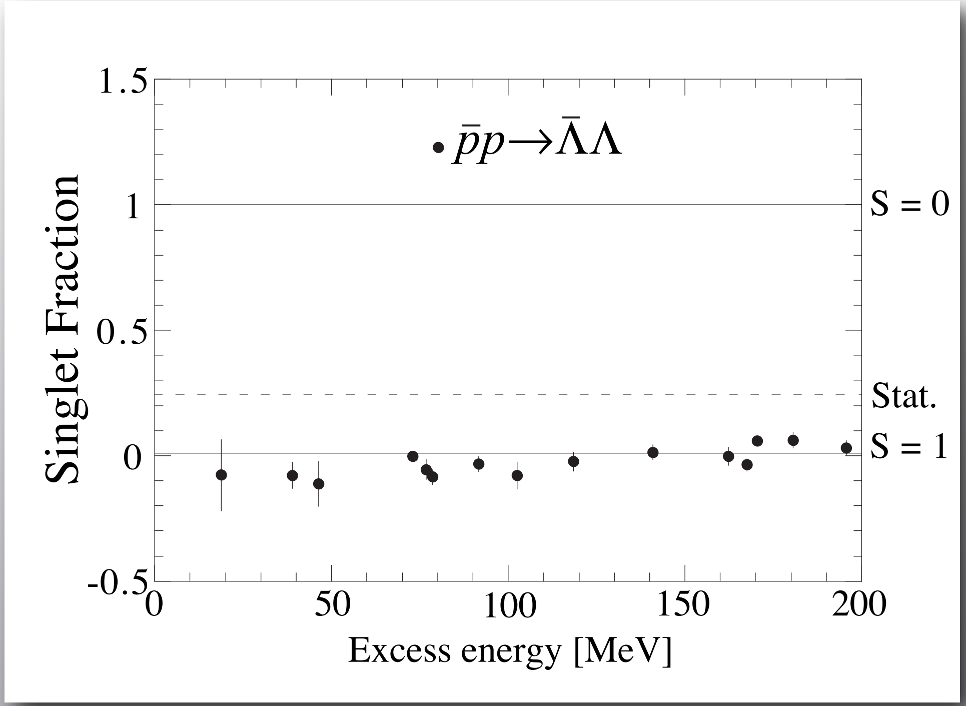
Results confirmed @ 1525 MeV/c



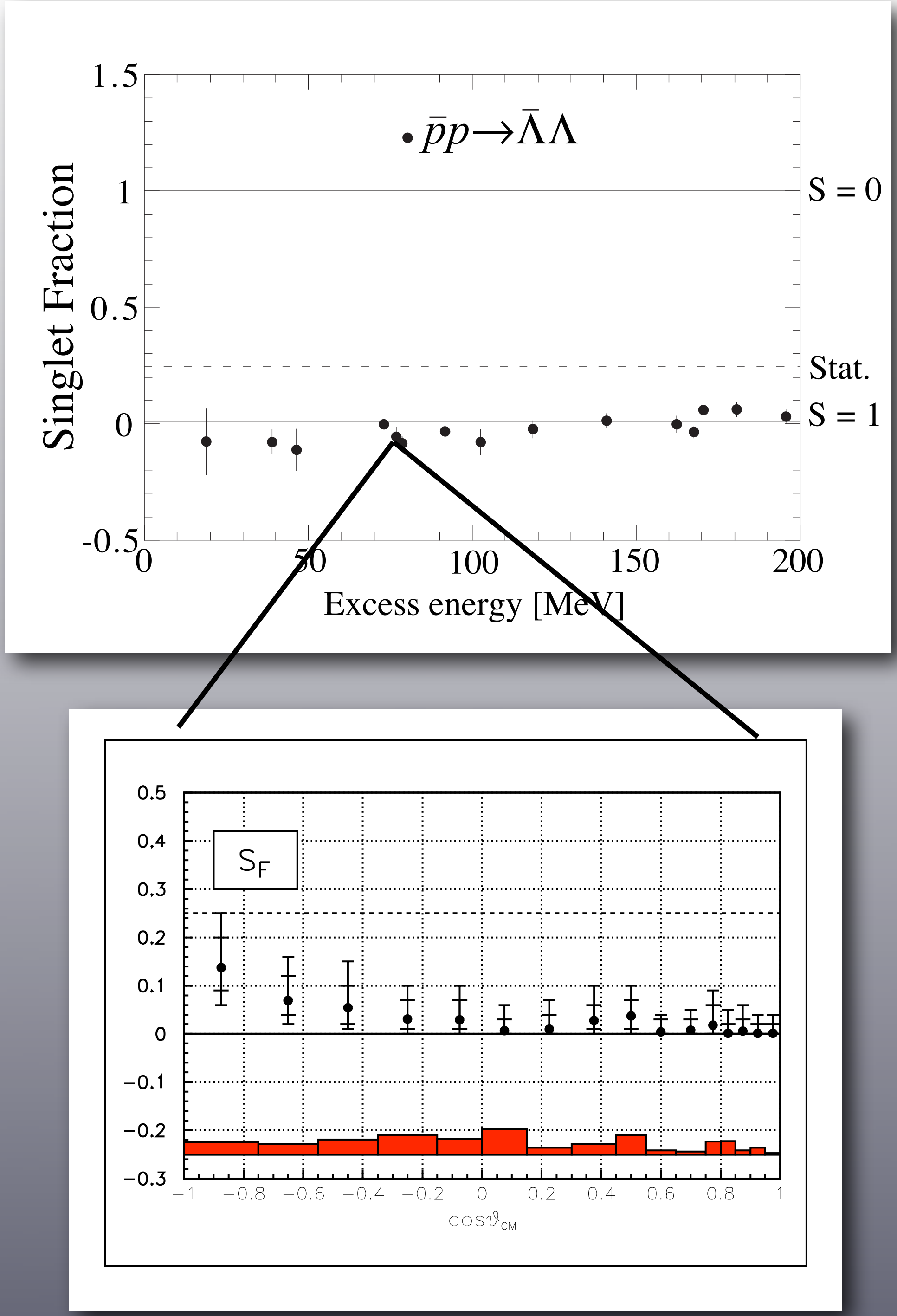
P. Kingsberry, Thesis, 2002

$\bar{\Lambda}\Lambda$ Triplet state ⟷ $D_{nn} = K_{nn}$

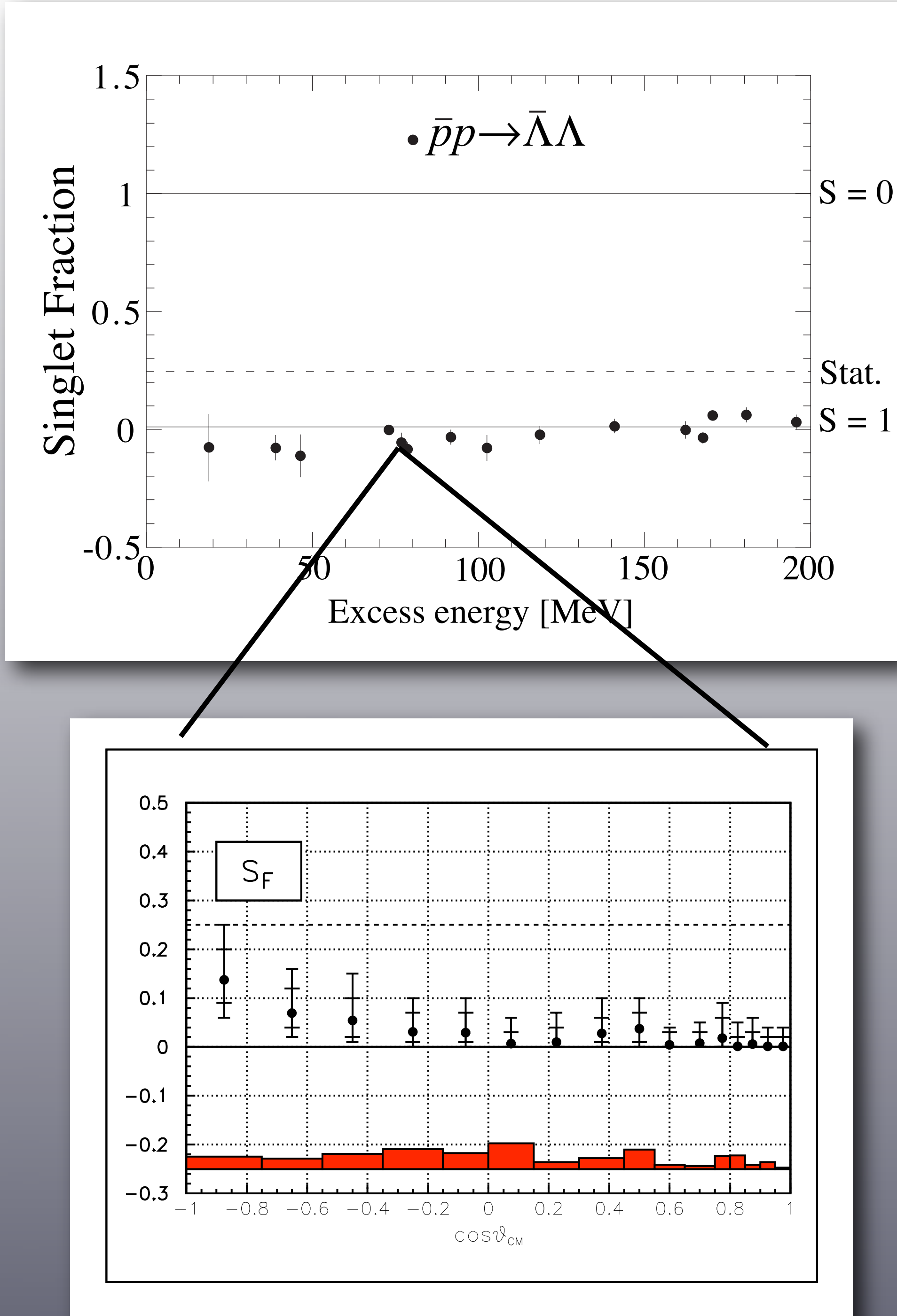
?

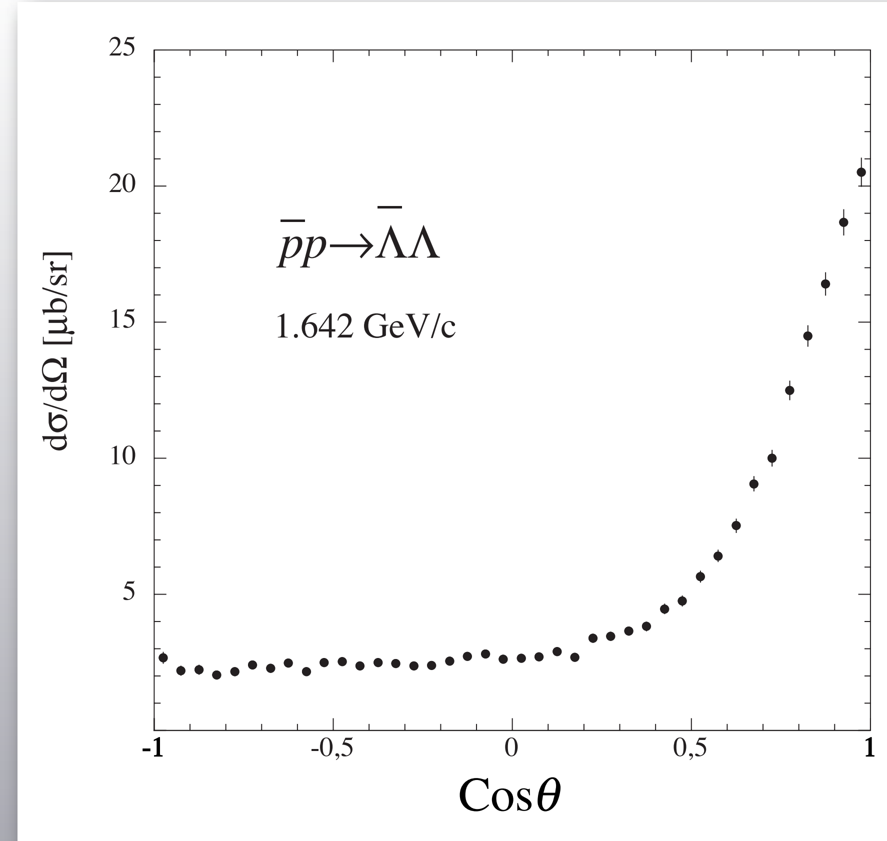


$\bullet\ \bar{p}p \rightarrow \bar{\Lambda}\Lambda$
Singlet Fraction
1.5
1
0.5
0
-0.5
S = 0
Stat.
S = 1
0
50
100
150
200
Excess energy [MeV]



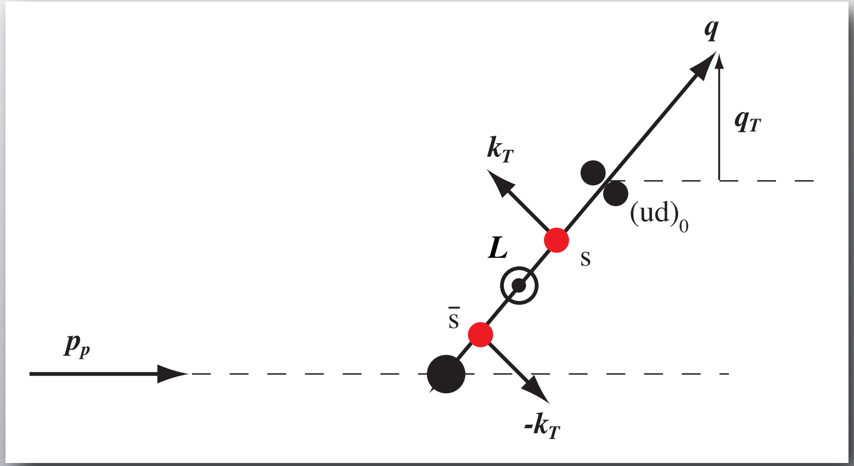
p̄p→Λ̄Λ
S = 0
Stat.
S = 1
Singlet Fraction
Excess energy [MeV]
S_F
cosϑ_CM



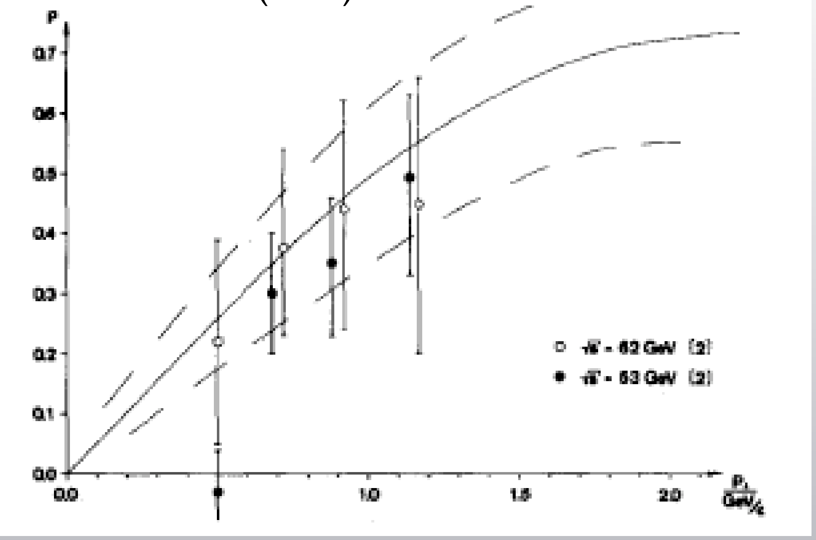


The high statistical weight of the forward angles gives an average Singlet Fraction of ≈ 0

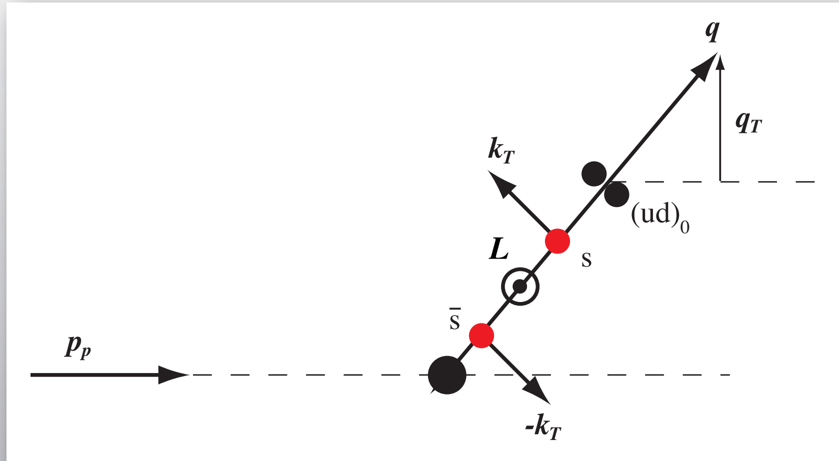
Lund model for Λ polarisation

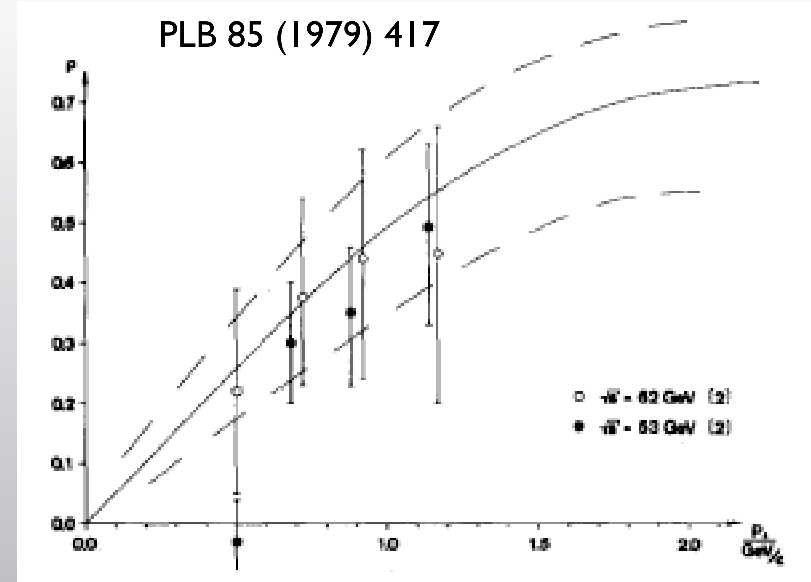


PLB 85 (1979) 417

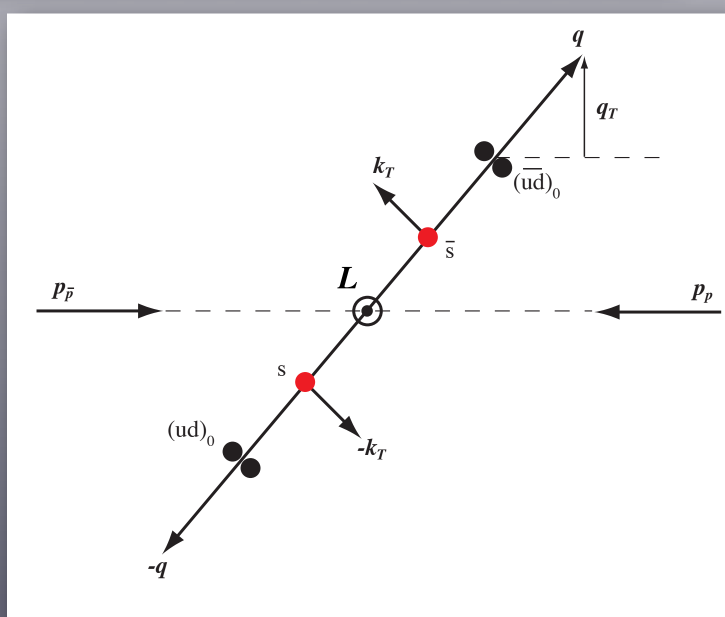


Lund model for Λ polarisation

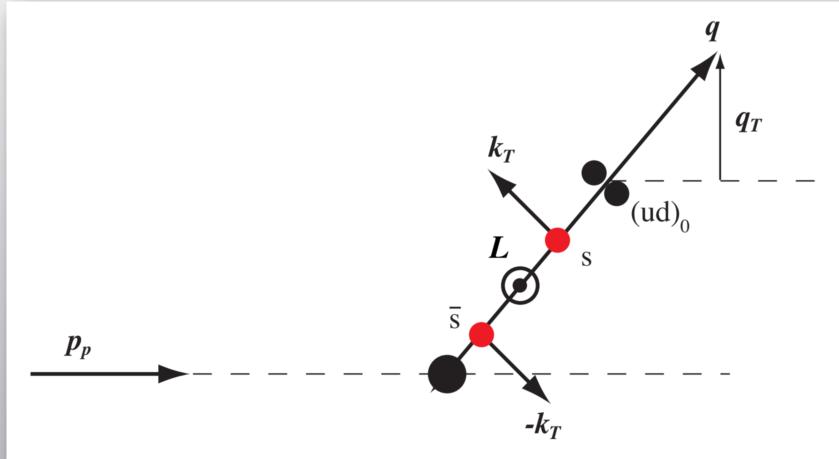


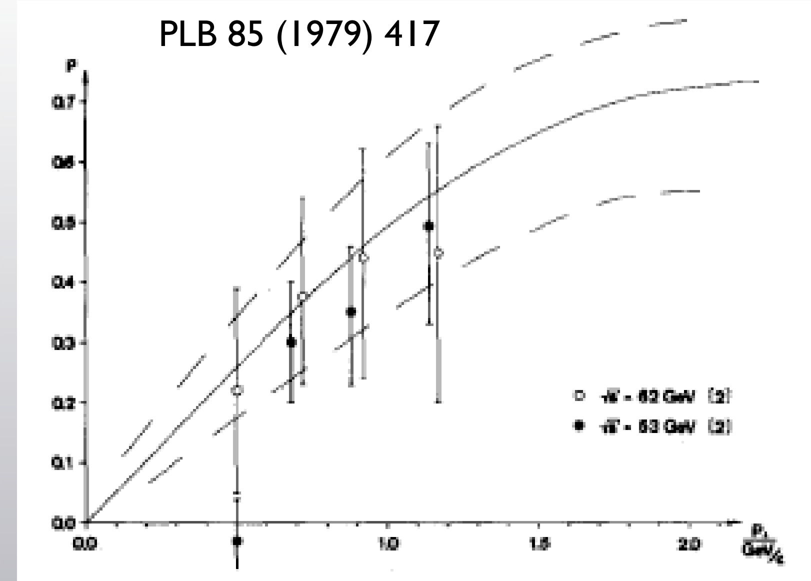


Lund model for $\bar{p}p \to \bar{\Lambda}\Lambda$

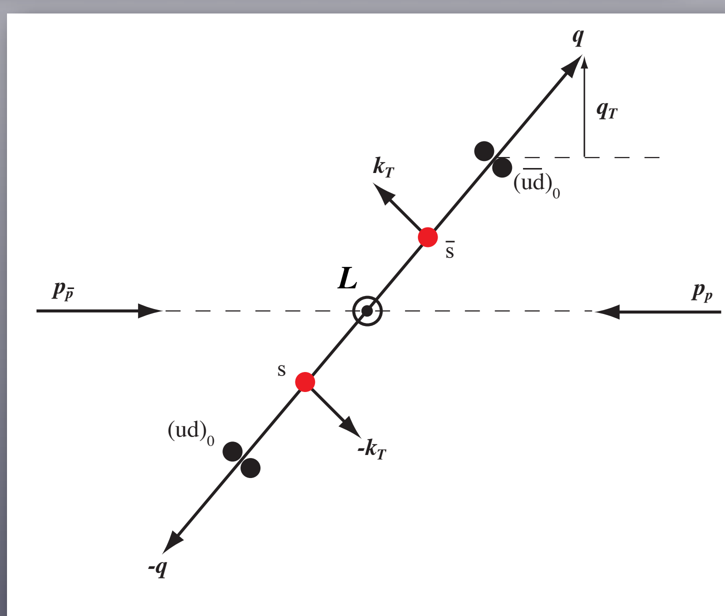


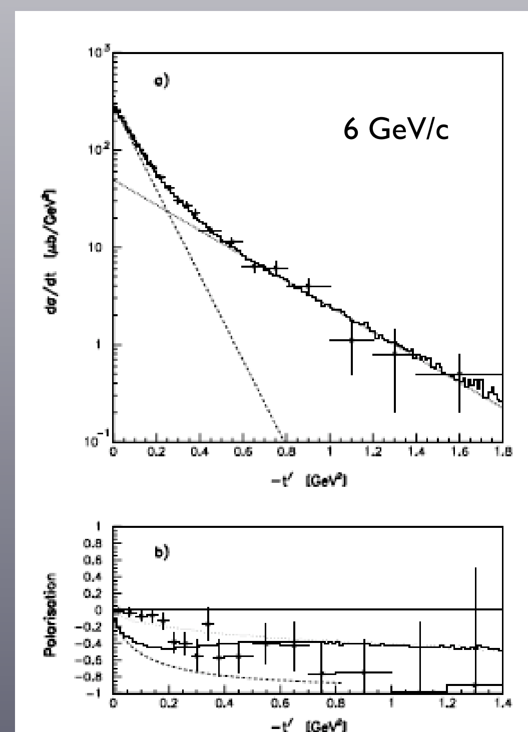
Lund model for Λ polarisation

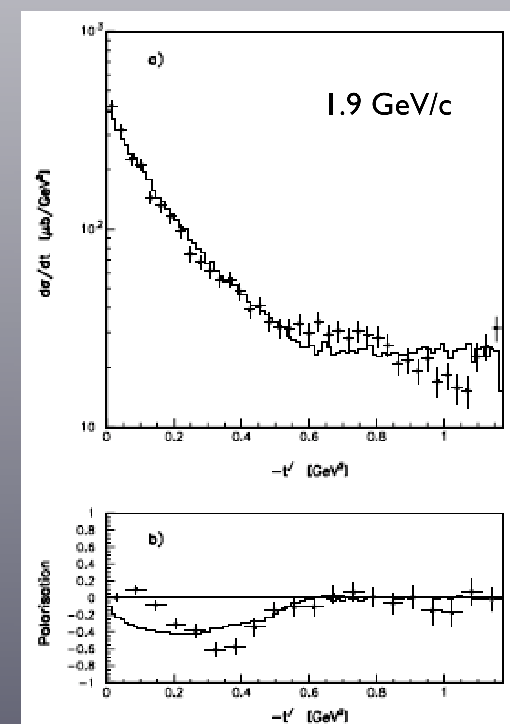




Lund model for $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$







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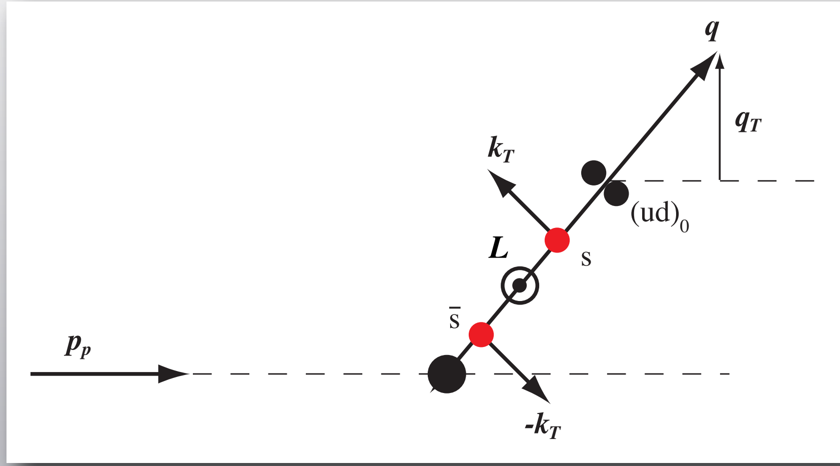
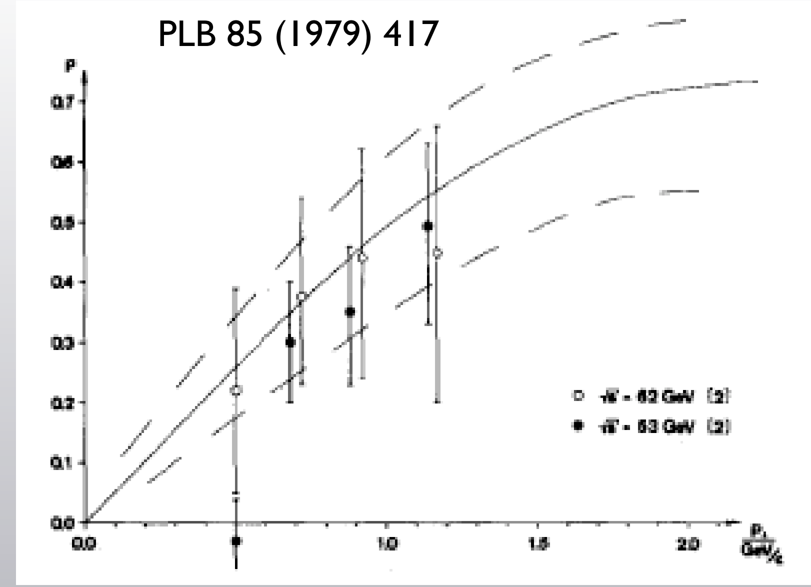
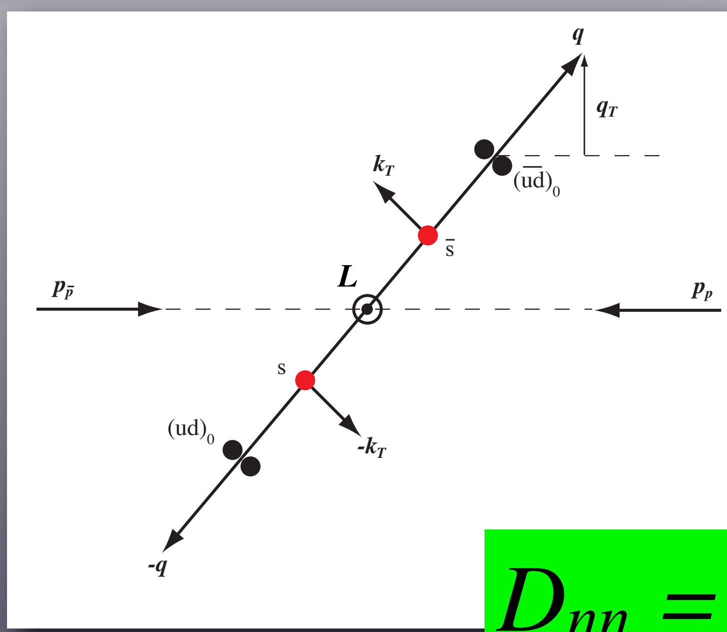
Lund model for Λ polarisation

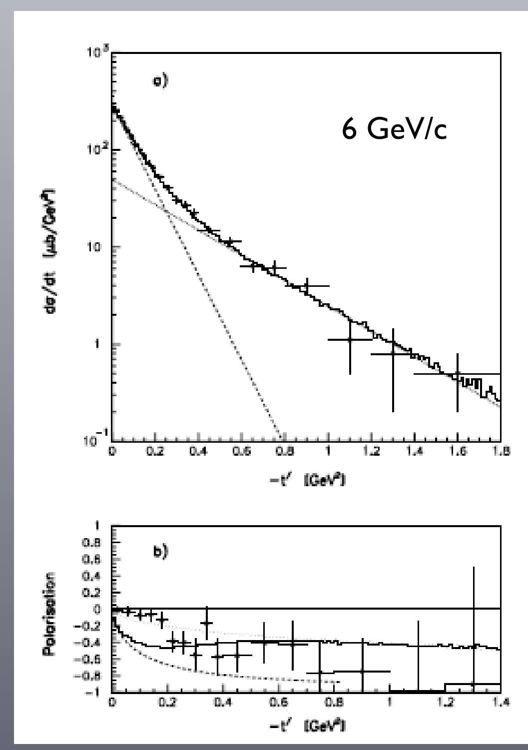


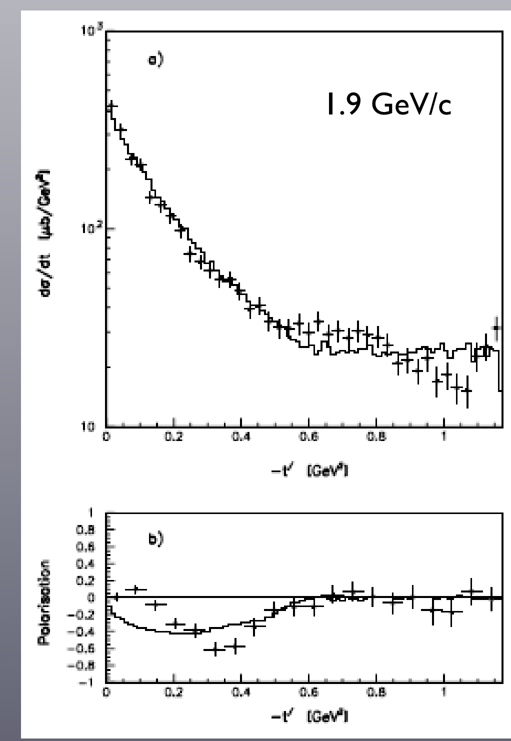


Lund model for $\bar{p}p \to \bar{\Lambda}\Lambda$



$D_{nn} = 0$





EPJA 15 (2002) 517

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_{0j00}	A_{ij00}
Polarisation of scattered particle	$P_{00\mu 0}$	$D_{i0\mu 0}$	$K_{0j\mu 0}$	$M_{ij\mu 0}$
Polarisation of recoil particle	$P_{000\nu}$	$K_{i00\nu}$	$D_{0j0\nu}$	$N_{ij0\nu}$
Correlations 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 paricles (= 0 spin average)

256 possible combinations

Symmetries

- Parity conservation
- Charge conjugation invariance
- Geometrical identities

256 ➔ 40 independent observables

8 accessible with an unpolarised beam and target

24 accessible with an unpolarised beam and a transversely polarised target

Symmetries

- Parity conservation
- Charge conjugation invariance
- Geometrical identities

256 ⇨ 40 independent observables

8 accessible with an unpolarised beam and target

24 accessible with an unpolarised beam and a transversely polarised target

Transition matrix

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

Taking all symmetries into account, the expression for $I_{\bar{p}p}$ with a tranversely polarised target becomes:

$$I_{\bar{p}p}\left(\theta,\phi,\hat{\boldsymbol{k}}_1,\hat{\boldsymbol{k}}_2\right)=\frac{I_0^{\bar{\Lambda}\Lambda}}{64\pi^3}\left[\begin{array}{l}
1\\
+\,P_n\left(\bar{\alpha}k_{1n}+\alpha k_{2n}\right)\\
+\,C_{00nn}\left(\bar{\alpha}\alpha k_{1n}k_{2n}\right)\\
+\,C_{00mm}\left(\bar{\alpha}\alpha k_{1m}k_{2m}\right)\\
+\,C_{00ll}\left(\bar{\alpha}\alpha k_{1l}k_{2l}\right)\\
+\,C_{00ml}\left(\bar{\alpha}\alpha\left(k_{1m}k_{2l}+k_{1m}k_{2l}\right)\right)\\
+\,A_{00n0}\left(P^T\cos\phi+\bar{\alpha}\alpha P^T k_{1n}k_{2n}\cos\phi\right)\\
+\,K_{0nn0}\left(\bar{\alpha}P^T k_{1n}\cos\phi\right)\\
+\,D_{0n0n}\left(\alpha P^T k_{2n}\cos\phi\right)\\
+\,K_{0mm0}\left(\bar{\alpha}P^T k_{1m}\sin\phi\right)\\
+\,K_{0ml0}\left(\bar{\alpha}P^T k_{1l}\sin\phi\right)\\
+\,D_{0m0m}\left(\alpha P^T k_{2m}\sin\phi\right)\\
+\,D_{0m0l}\left(\alpha P^T k_{2l}\sin\phi\right)\\
+\,C_{0nmm}\left(\bar{\alpha}\alpha P^T\left(k_{1m}k_{2m}\cos\phi-k_{1l}k_{2l}\right)\right)\\
+\,C_{0nml}\left(\bar{\alpha}\alpha P^T k_{1m}k_{2l}\cos\phi\right)\\
+\,C_{0nlm}\left(\bar{\alpha}\alpha P^T k_{1l}k_{2m}\cos\phi\right)\\
+\,C_{0mmn}\left(\bar{\alpha}\alpha P^T k_{1m}k_{2n}\sin\phi\right)\\
+\,C_{0mln}\left(\bar{\alpha}\alpha P^T k_{1l}k_{2n}\sin\phi\right)\\
+\,C_{0mnm}\left(\bar{\alpha}\alpha P^T k_{1n}k_{2m}\sin\phi\right)\\
+\,C_{0mnl}\left(\bar{\alpha}\alpha P^T k_{1n}k_{2l}\sin\phi\right)
\end{array}\right]$$

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

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

$$
\begin{aligned}
I_0 &= \frac{1}{2}\left\{|a|^2+|b|^2+|c|^2+|d|^2+|e|^2+|g|^2\right\}\\
I_0 C_{00nn} &= \frac{1}{2}\left\{|a|^2-|b|^2-|c|^2+|d|^2+|e|^2+|g|^2\right\}\\
I_0 D_{0n0n} &= \frac{1}{2}\left\{|a|^2+|b|^2-|c|^2+|d|^2+|e|^2-|g|^2\right\}\\
I_0 K_{0nn0} &= \frac{1}{2}\left\{|a|^2-|b|^2+|c|^2-|d|^2+|e|^2-|g|^2\right\}\\
I_0 P_{000n} = I_0 P_{00n0} &= \mathrm{Re}\left(a^* e\right)-\mathrm{Im}\left(d^* g\right)\\
I_0 A_{0n00} = I_0 C_{0nnn} &= \mathrm{Re}\left(a^* e\right)+\mathrm{Im}\left(d^* g\right)\\
I_0 C_{00ml} = I_0 C_{00lm} &= \mathrm{Re}\left(a^* g\right)+\mathrm{Im}\left(d^* e\right)\\
I_0 C_{0nmm} = -I_0 C_{0nll} &= \mathrm{Re}\left(d^* e\right)+\mathrm{Im}\left(a^* g\right)\\
I_0 C_{00mm} &= \mathrm{Re}\left(a^* d+b^* c\right)+\mathrm{Im}\left(e^* g\right)\\
I_0 C_{00ll} &= \mathrm{Re}\left(-a^* d+b^* c\right)-\mathrm{Im}\left(e^* g\right)\\
I_0 C_{0nlm} &= \mathrm{Re}\left(e^* g\right)+\mathrm{Im}\left(-a^* d+b^* c\right)\\
I_0 C_{0nml} &= \mathrm{Re}\left(e^* g\right)+\mathrm{Im}\left(-a^* d-b^* c\right)\\
I_0 D_{0m0m} &= \mathrm{Re}\left(a^* b+c^* d\right)\\
I_0 C_{0mnl} &= \mathrm{Im}\left(-a^* b+c^* d\right)\\
I_0 K_{0mm0} &= \mathrm{Re}\left(a^* c+b^* d\right)\\
I_0 C_{0mln} &= \mathrm{Im}\left(-a^* c+b^* d\right)\\
I_0 C_{0mnm} &= \mathrm{Re}\left(b^* e\right)-\mathrm{Im}\left(c^* g\right)\\
I_0 D_{0m0l} &= \mathrm{Re}\left(c^* g\right)+\mathrm{Im}\left(b^* e\right)\\
I_0 K_{0ml0} &= \mathrm{Re}\left(b^* g\right)+\mathrm{Im}\left(c^* e\right)\\
I_0 C_{0mmn} &= \mathrm{Re}\left(c^* e\right)-\mathrm{Im}\left(b^* g\right)
\end{aligned}
$$

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!

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

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

$$I_0 D_{0n0n} = \frac{1}{2}\left\{|a|^2+|b|^2-|c|^2+|d|^2+|e|^2-|g|^2\right\}$$

$$I_0 K_{0nn0} = \frac{1}{2}\left\{|a|^2-|b|^2+|c|^2-|d|^2+|e|^2-|g|^2\right\}$$

$$I_0 P_{000n} = I_0 P_{00n0} = \mathrm{Re}\left(a^* e\right) - \mathrm{Im}\left(d^* g\right)$$

$$I_0 A_{0n00} = I_0 C_{0nnn} = \mathrm{Re}\left(a^* e\right) + \mathrm{Im}\left(d^* g\right)$$

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

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

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

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

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

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

$$I_0 D_{0m0m} = \mathrm{Re}\left(a^* b + c^* d\right)$$

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

$$I_0 K_{0mm0} = \mathrm{Re}\left(a^* c + b^* d\right)$$

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

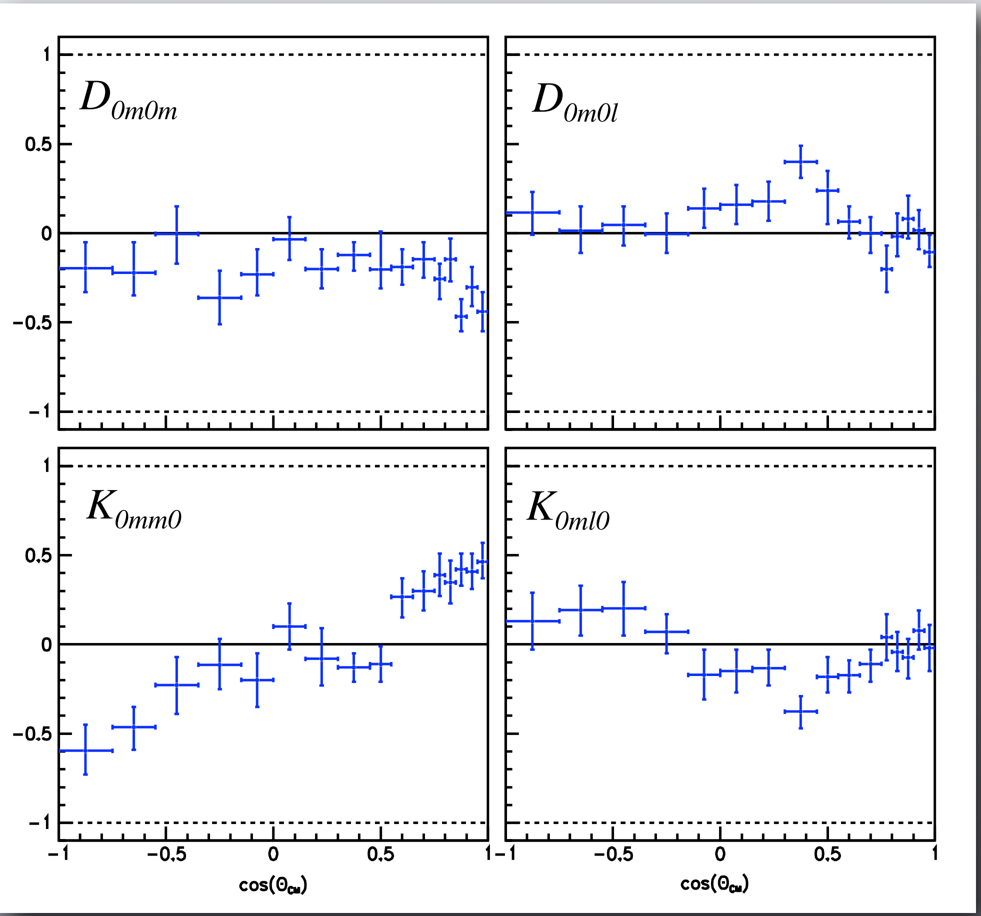
$$I_0 C_{0mnm} = \mathrm{Re}\left(b^* e\right) - \mathrm{Im}\left(c^* g\right)$$

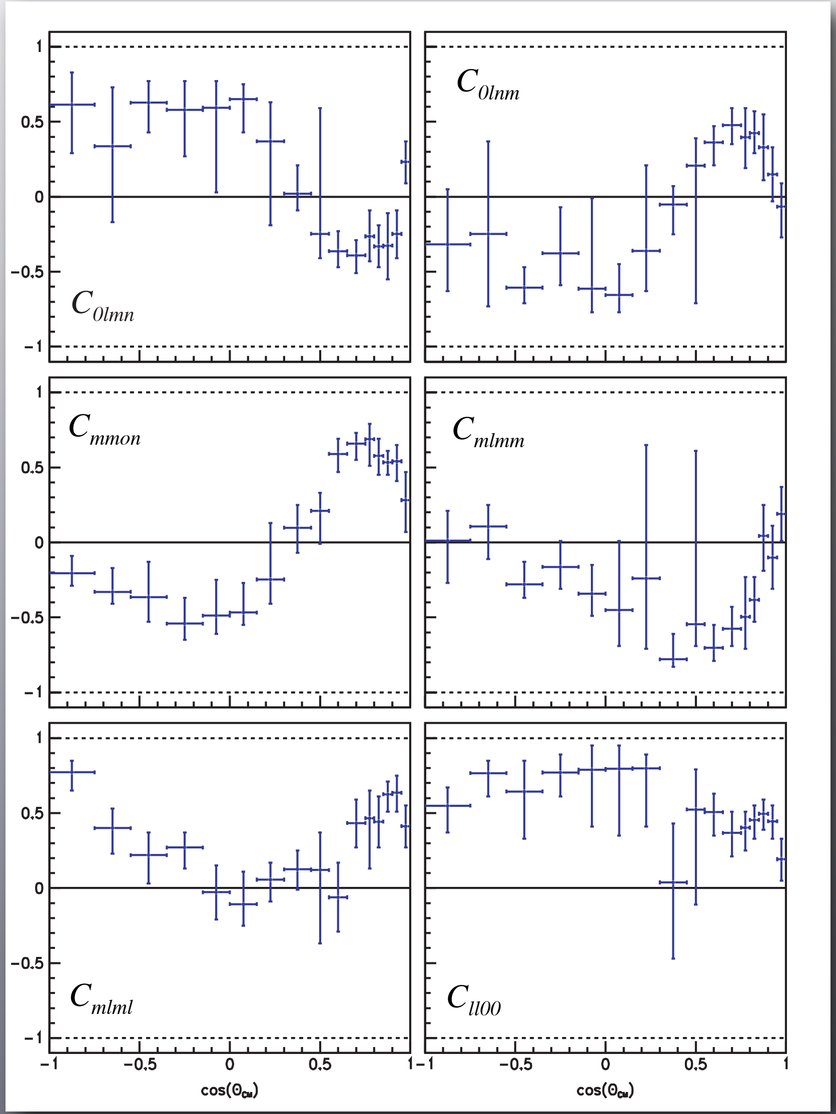
$$I_0 D_{0m0l} = \mathrm{Re}\left(c^* g\right) + \mathrm{Im}\left(b^* e\right)$$

$$I_0 K_{0ml0} = \mathrm{Re}\left(b^* g\right) + \mathrm{Im}\left(c^* e\right)$$

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

Indirectly measured spin observables





nucl-ex/0605025

Future prospects

→

HESR@FAIR

$\Lambda(1405)\ S_{01}$

$I(J^P) = 0(\frac{1}{2}^-)$

Mass $m = 1406 \pm 4$ MeV
Full width $\Gamma = 50.0 \pm 2.0$ MeV
Below $\overline{K}N$ threshold

Λ(1405) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\Sigma\pi$	100 %	152

$\Lambda(1405)\ S_{01}$

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$\Lambda(1405)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\Sigma\pi$	100 %	152

Structure of the $\Lambda(1405)$?

- Three quark state (uds)?

- Dynamically generated quasi-bound $N\bar{K}$ state?

$\Lambda(1405)\ S_{01}$ $\qquad I(J^P) = 0(\frac{1}{2}^-)$

Mass $m = 1406 \pm 4$ MeV
Full width $\Gamma = 50.0 \pm 2.0$ MeV
Below $\overline{K}N$ threshold

Λ(1405) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\Sigma\pi$	100 %	152

Structure of the $\Lambda(1405)$?

- Three quark state (uds)?

- Dynamically generated quasi-bound $N\bar{K}$ state?

Scan the $\bar{p}p \to \bar{\Lambda}(1405)\Lambda(1405)$ reaction over the $\bar{p}K^+pK^-$ threshold

Strangeness 2 and 3 sector accessible @ PANDA

Hyperon	Quarks	Mass [Mev/c^2]	cτ [cm]	α
Λ	uds	1116	8.0	+0.64
Σ^+	uus	1189	2.4	-0.98
Σ^0	uds	1193	2.2×10^{-9}	
Σ^-	dds	1197	2.4	-0.07
Ξ^0	uss	1315	8.7	-0.41
Ξ^-	dss	1321	4.9	-0.46
Ω^-	sss	1672	2.5	-0.03

Strangeness 2 and 3 sector accessible @ PANDA

Hyperon	Quarks	Mass [Mev/c^2]	cτ [cm]	α
Λ	uds	1116	8.0	+0.64
Σ^+	uus	1189	2.4	-0.98
Σ^0	uds	1193	2.2x10^{-9}	
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Ω^-	sss	1672	2.5	-0.03

$$\bar{p}p \rightarrow \bar{\Lambda}\Lambda,\ \bar{\Sigma}^+\Sigma^+,\ \bar{\Sigma}^0\Sigma^0,\ \bar{\Sigma}^+\Sigma^+,\ \bar{\Xi}^0\Xi^0,\ \bar{\Xi}^-\Xi^-,\ \bar{\Omega}^-\Omega^-$$

Λ	Σ^+	Σ^0	Σ^+	Ξ^0	Ξ^-	Ω^-
$\downarrow p\pi^-$	$\downarrow p\pi^0$	$\downarrow \Lambda\gamma$	$\downarrow n\pi^-$	$\downarrow \Lambda\pi^0$	$\downarrow \Lambda\pi^-$	$\downarrow \Lambda K^-$
64%	52%	≈ 100%	≈ 100%	≈ 100%	≈ 100%	68%

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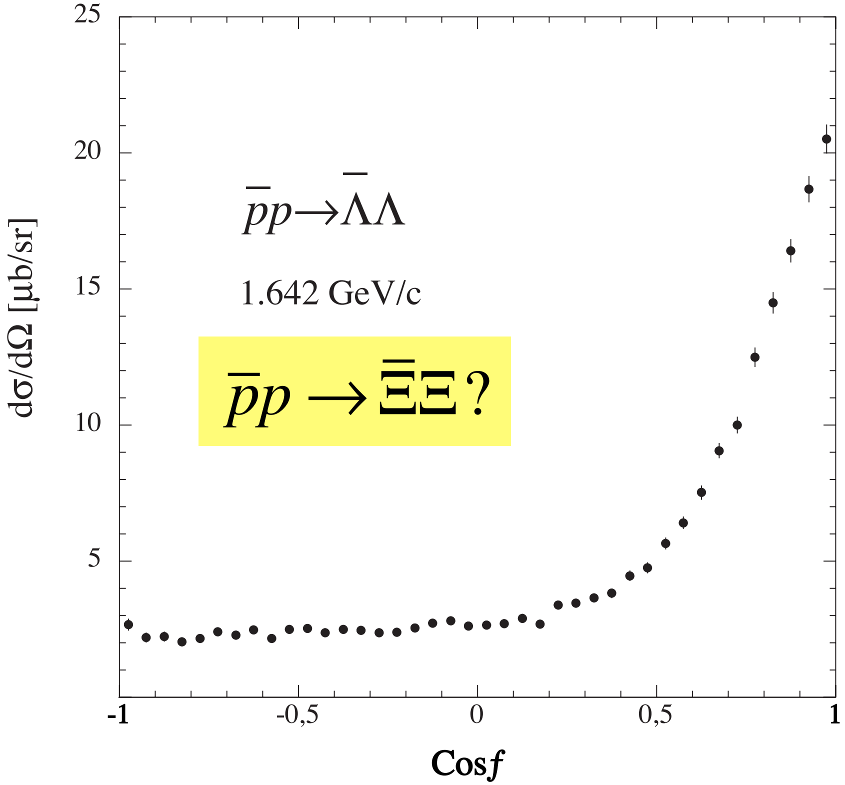
Λ	Σ^+	Σ^0	Σ^+	Ξ^0	Ξ^-	Ω^-
$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$
$p\pi^-$	$p\pi^0$	$\Lambda\gamma$	$n\pi^-$	$\Lambda\pi^0$	$\Lambda\pi^-$	ΛK^-
64%	52%	≈ 100%	≈ 100%	≈ 100%	≈ 100%	68%

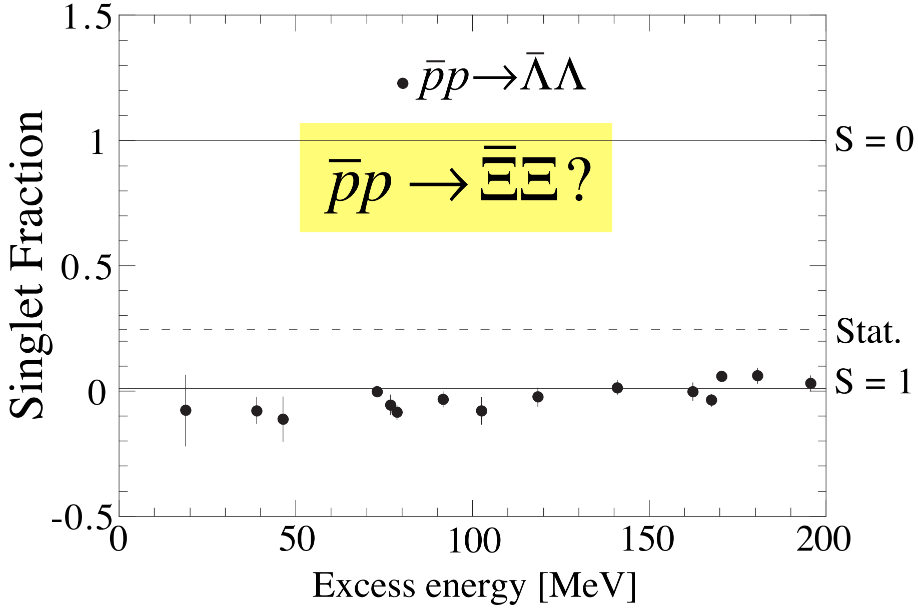
+

$$\bar{p}p \rightarrow \bar{Y}Y + \mathrm{n}\pi, \mathrm{n}K$$

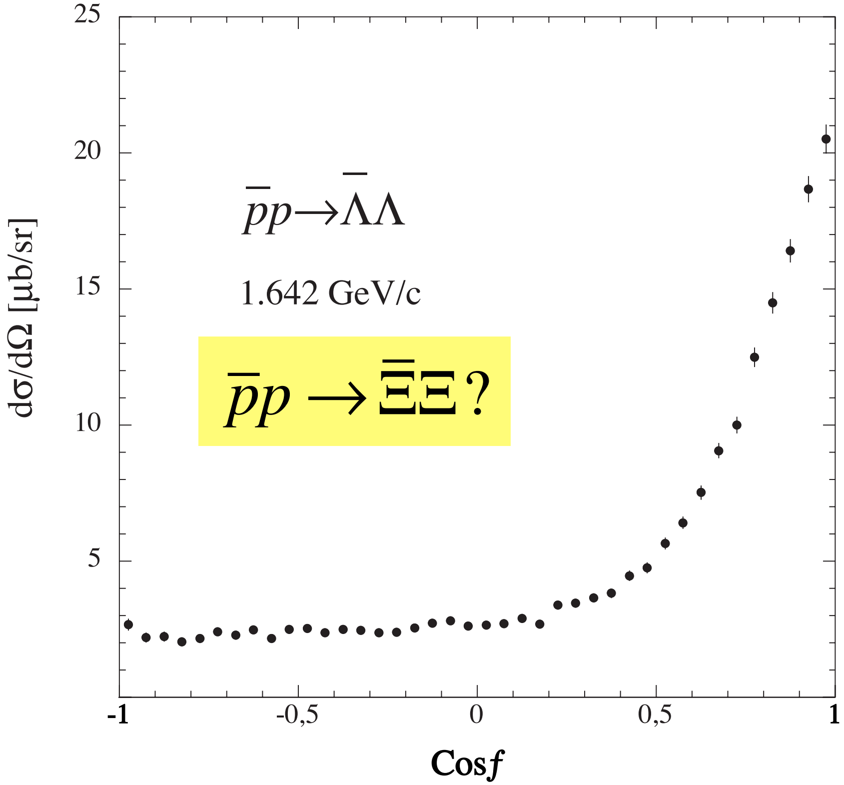
Excited hyperons,
hyperon-meson scattering

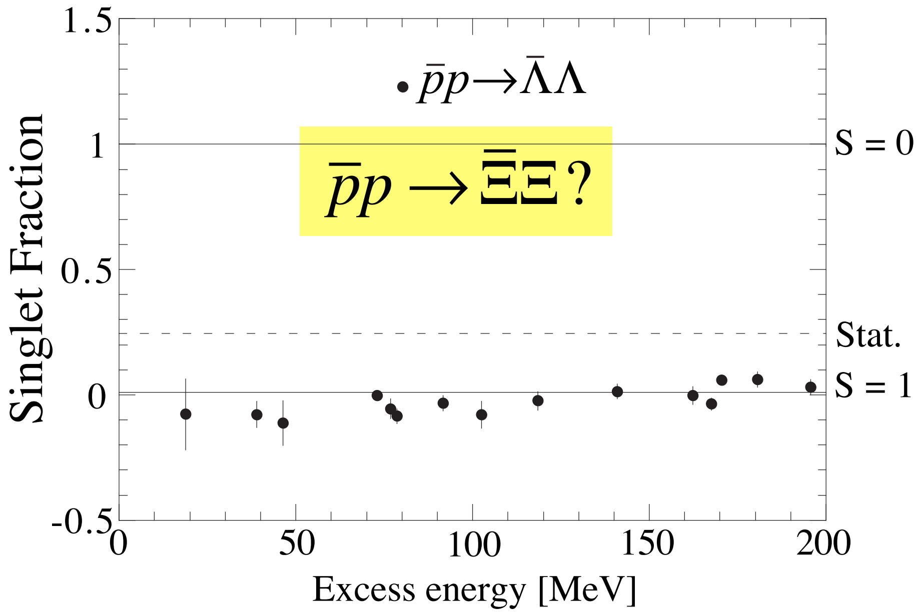


$\bar{p}p \rightarrow \bar{\Lambda}\Lambda$
1.642 GeV/c
$\bar{p}p \rightarrow \bar{\Xi}\Xi$?
dσ/dΩ [μb/sr]
Cos*f*
25
20
15
10
5
-1
-0,5
0
0,5
1



$\bar{p}p \rightarrow \bar{\Lambda}\Lambda$
$\bar{p}p \rightarrow \bar{\Xi}\Xi$?
S = 0
Stat.
S = 1
Singlet Fraction
Excess energy [MeV]
1.5
1
0.5
0
-0.5
0
50
100
150
200





The polarisation of the decay baryon, $\langle \boldsymbol{\sigma}_N \rangle$, gives additional information:

$$(1+\alpha P_Y \cos\theta)\langle \boldsymbol{\sigma}_N \rangle = (\alpha + P_Y \cos\theta)\hat{\boldsymbol{k}} + \beta P_Y \hat{\boldsymbol{k}} \times \boldsymbol{n} + \gamma P_Y \left(\hat{\boldsymbol{k}} \times \boldsymbol{n}\right) \times \hat{\boldsymbol{k}}$$

It has been suggested that the quantity

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

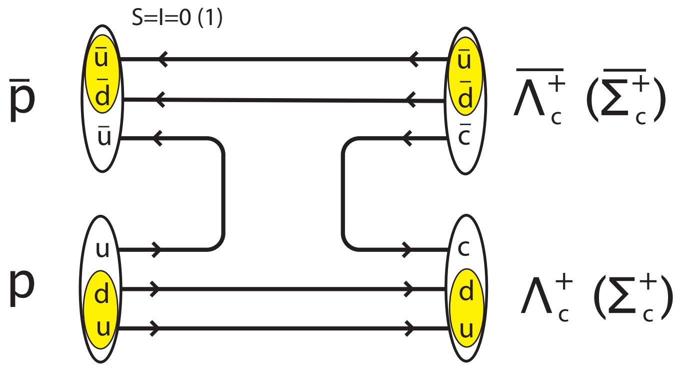
could has a 10x larger signal of CP violation than A

Charmed antihyperons/hyperons are accessible @ PANDA for masses < 2740 MeV

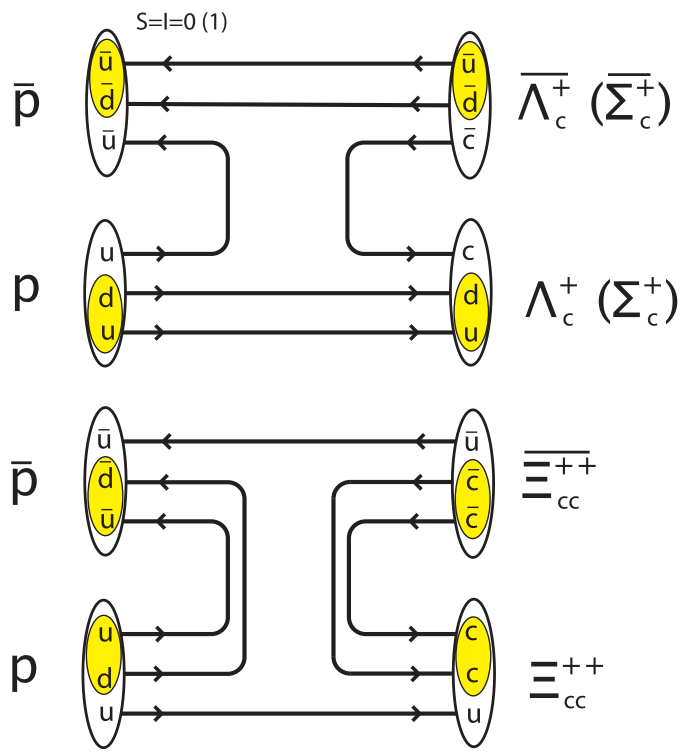
Hyperon	Quarks	Mass [Mev/c^2]	cτ [cm]	α	Decay channel	B.R. [%]
Λ	uds	1116	8.0	+0.64	$p\pi^-$	64
Σ^+	uus	1189	2.4	-0.98	$p\pi^0$	52
Σ^0	uds	1193	2.2×10^{-9}	-	$\Lambda\gamma$	100
Σ^-	dds	1197	2.4	-0.07	$n\pi^-$	100
Ξ^0	uss	1315	8.7	-0.41	$\Lambda\pi^0$	99
Ξ^-	dss	1321	4.9	-0.46	$\Lambda\pi^-$	100
Ω^-	sss	1672	2.5	-0.03	ΛK^-	68
Λ_c^+	udc	2285	6.0×10^{-3}	-.98(19)	$\Lambda\pi^+$	1
Σ_c^{++}	uuc	2453	.		$\Lambda_c^+\pi^+$	100
Σ_c^+	udc	2455	.		$\Lambda_c^+\pi^0$	100
Σ_c^0	ddc	2452	.		$\Lambda_c^+\pi^-$	100
Ξ_c^+	usc	2466	1.3×10^{-2}			
Ξ_c^0	dsc	2472	2.9×10^{-3}	-0.6(4)	$\Xi^-\pi^+$	seen
Ω_c^0	ssc	2697	1.9×10^{-3}			

Charmed antibaryon/baryon production in $\bar{p}p$ collisions

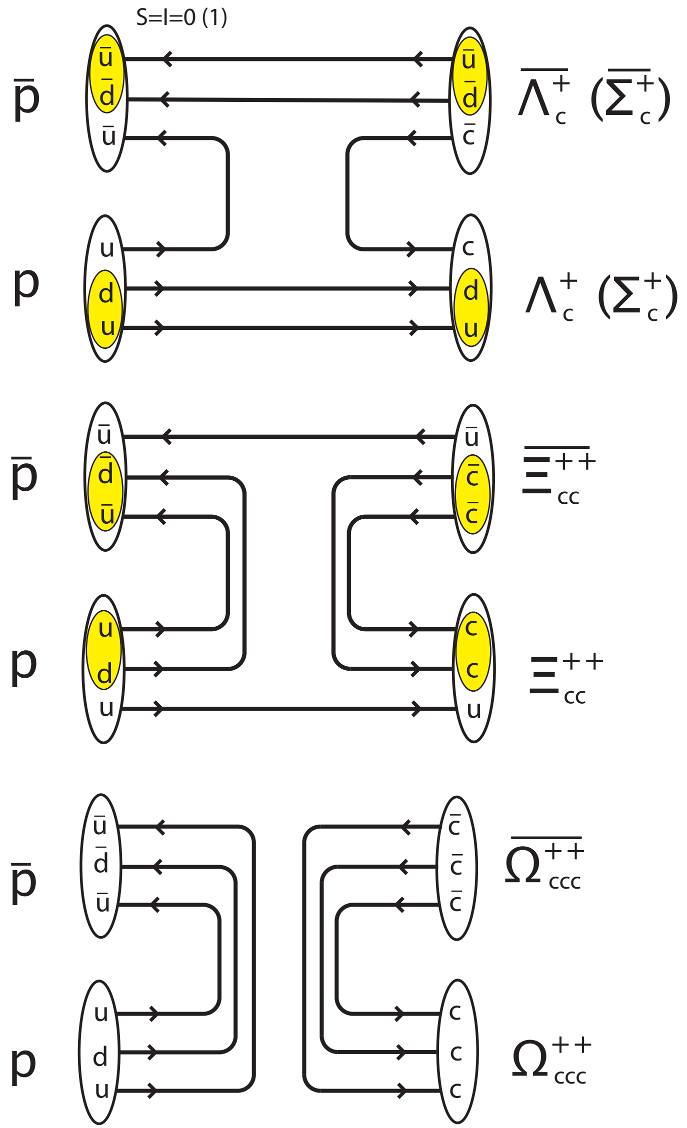
Charmed antibaryon/baryon production in $\bar{p}p$ collisions



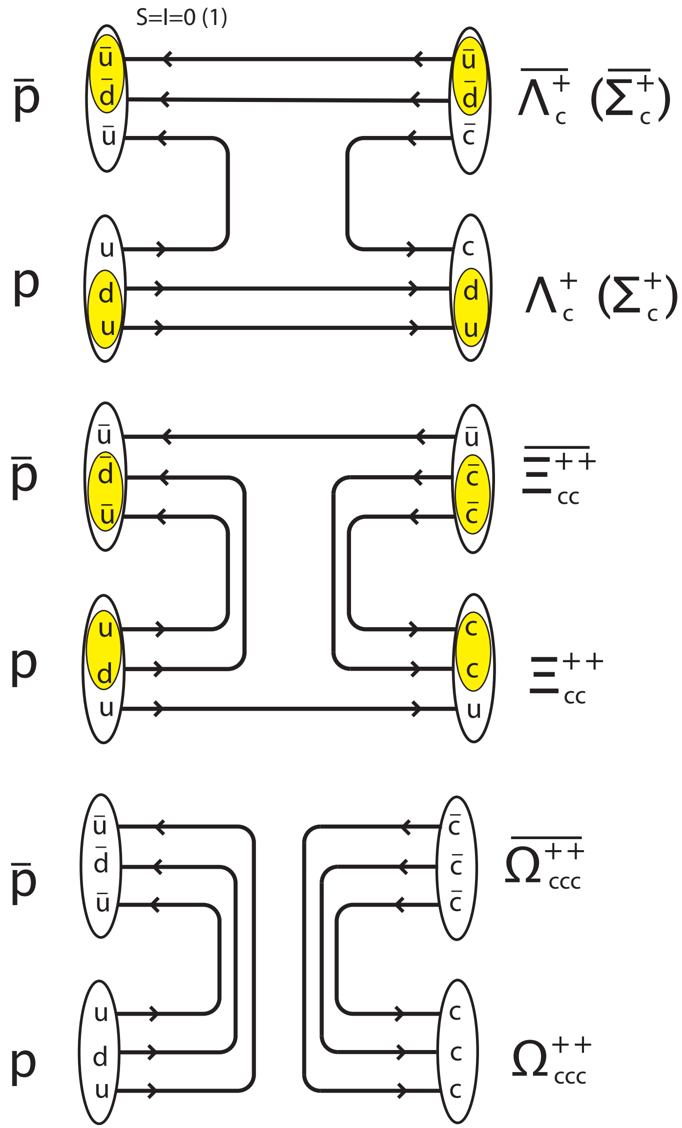
Charmed antibaryon/baryon production in $\bar{p}p$ collisions



Charmed antibaryon/baryon production in $\bar{p}p$ collisions



Charmed antibaryon/baryon production in $\overline{p}p$ collisions



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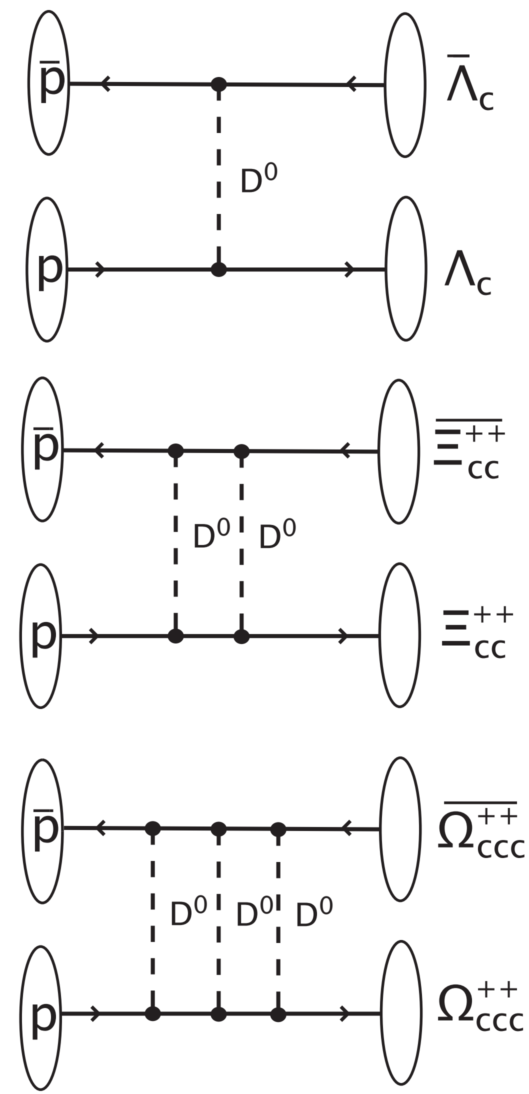
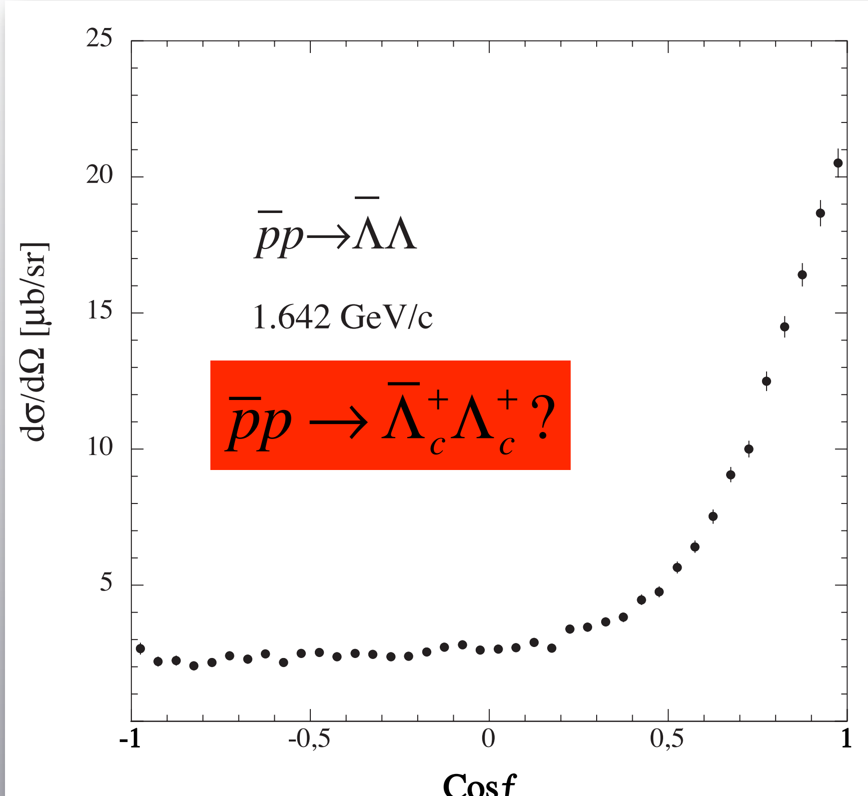
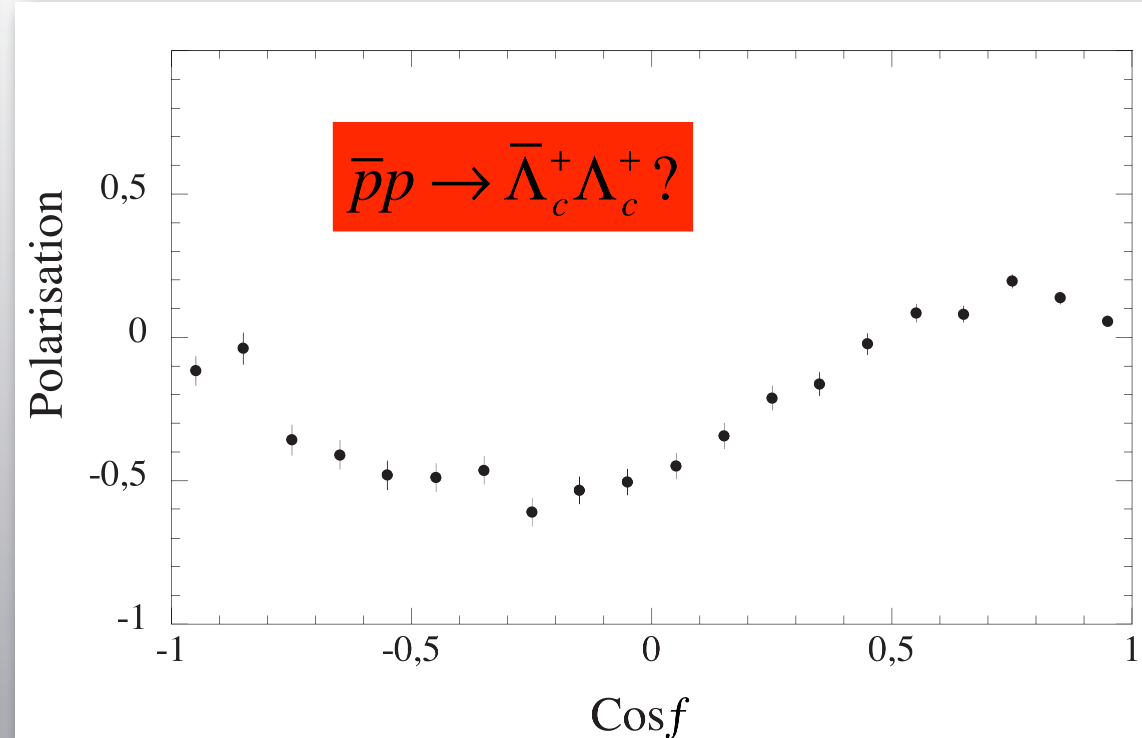


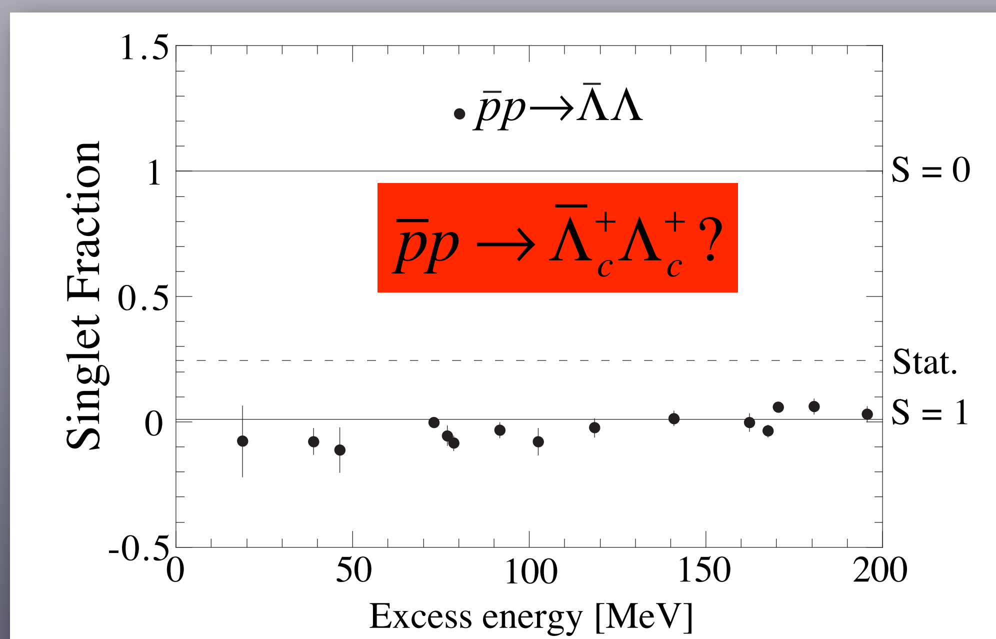
Λ_c^+ DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
Hadronic modes with a p: $S = -1$ final states				
$p\overline{K}^0$		(2.3 ± 0.6) %		872
$pK^-\pi^+$	[l]	(5.0 ± 1.3) %		822
$p\overline{K}^*(892)^0$	[m]	(1.6 ± 0.5) %		681
$\Delta(1232)^{++}K^-$		(8.6 ± 3.0) $\times 10^{-3}$		709
$\Lambda(1520)\pi^+$	[m]	(5.9 ± 2.1) $\times 10^{-3}$		626
$pK^-\pi^+$ nonresonant		(2.8 ± 0.8) %		822
$p\overline{K}^0\pi^0$		(3.3 ± 1.0) %		822
$p\overline{K}^0\eta$		(1.2 ± 0.4) %		567
$p\overline{K}^0\pi^+\pi^-$		(2.6 ± 0.7) %		753
$pK^-\pi^+\pi^0$		(3.4 ± 1.0) %		758
$pK^*(892)^-\pi^+$	[m]	(1.1 ± 0.5) %		579
$p(K^-\pi^+)_{\text{nonresonant}}\pi^0$		(3.6 ± 1.2) %		758
$\Delta(1232)\overline{K}^*(892)$		seen		416
$pK^-\pi^+\pi^+\pi^-$		(1.1 ± 0.8) $\times 10^{-3}$		670
$pK^-\pi^+\pi^0\pi^0$		(8 ± 4) $\times 10^{-3}$		676
Hadronic modes with a p: $S = 0$ final states				
$p\pi^+\pi^-$		(3.5 ± 2.0) $\times 10^{-3}$		926
$pf_0(980)$	[m]	(2.8 ± 1.9) $\times 10^{-3}$		621
$p\pi^+\pi^+\pi^-\pi^-$		(1.8 ± 1.2) $\times 10^{-3}$		851
pK^+K^-		(7.7 ± 3.5) $\times 10^{-4}$		615
$p\phi$	[m]	(8.2 ± 2.7) $\times 10^{-4}$		589
pK^+K^- non-ϕ		(3.5 ± 1.7) $\times 10^{-4}$		615
Hadronic modes with a hyperon: $S = -1$ final states				
$\Lambda\pi^+$		(9.0 ± 2.8) $\times 10^{-3}$		863
$\Lambda\pi^+\pi^0$		(3.6 ± 1.3) %		843
$\Lambda\rho^+$		< 5 %	CL=95%	638
$\Lambda\pi^+\pi^+\pi^-$		(3.3 ± 1.0) %		806
$\Lambda\pi^+\eta$		(1.8 ± 0.6) %		690
$\Sigma(1385)^+\eta$	[m]	(8.5 ± 3.3) $\times 10^{-3}$		569
$\Lambda K^+\overline{K}^0$		(6.0 ± 2.1) $\times 10^{-3}$		441
$\Xi(1690)^0K^+$, $\Xi(1690)^0 \to \Lambda\overline{K}^0$		(1.6 ± 0.8) $\times 10^{-3}$		286
$\Sigma^0\pi^+$		(9.9 ± 3.2) $\times 10^{-3}$		824
$\Sigma^+\pi^0$		(1.00 ± 0.34) %		826
$\Sigma^+\eta$		(5.5 ± 2.3) $\times 10^{-3}$		712
$\Sigma^+\pi^+\pi^-$		(3.6 ± 1.0) %		803
$\Sigma^+\rho^0$		< 1.4 %	CL=95%	578
$\Sigma^-\pi^+\pi^+$		(1.9 ± 0.8) %		798
$\Sigma^0\pi^+\pi^0$		(1.8 ± 0.8) %		802
$\Sigma^0\pi^+\pi^+\pi^-$		(1.1 ± 0.4) %		762
$\Sigma^+\pi^+\pi^-\pi^0$		—		766
$\Sigma^+\omega$	[m]	(2.7 ± 1.0) %		568
$\Sigma^+K^+K^-$		(2.9 ± 0.9) $\times 10^{-3}$		346
$\Sigma^+\phi$	[m]	(3.1 ± 1.0) $\times 10^{-3}$		292
$\Xi(1690)^0K^+$, $\Xi(1690)^0 \to \Sigma^+K^-$		(8.3 ± 3.5) $\times 10^{-4}$		286
$\Sigma^+K^+K^-$ nonresonant		< 7 $\times 10^{-4}$	CL=90%	346
Ξ^0K^+		(3.9 ± 1.4) $\times 10^{-3}$		652
$\Xi^-K^+\pi^+$		(4.9 ± 1.7) $\times 10^{-3}$		564
$\Xi(1530)^0K^+$	[m]	(2.6 ± 1.0) $\times 10^{-3}$		471
Hadronic modes with a hyperon: $S = 0$ final states				
ΛK^+		(6.7 ± 2.5) $\times 10^{-4}$		780
Σ^0K^+		(5.6 ± 2.4) $\times 10^{-4}$		734
$\Sigma^+K^+\pi^-$		(1.7 ± 0.7) $\times 10^{-3}$		668
Semileptonic modes				
$\Lambda\ell^+\nu_\ell$	[n]	(2.0 ± 0.6) %		–
$\Lambda e^+\nu_e$		(2.1 ± 0.6) %		870
$\Lambda\mu^+\nu_\mu$		(2.0 ± 0.7) %		866
Inclusive modes				
e^+ anything		(4.5 ± 1.7) %		–
pe^+ anything		(1.8 ± 0.9) %		–
p anything		(50 ± 16) %		–
p anything (no Λ)		(12 ± 19) %		–
n anything		(50 ± 16) %		–
n anything (no Λ)		(29 ± 17) %		–
Λ anything		(35 ± 11) %	S=1.4	–
$\Sigma^\pm$ anything	[o]	(10 ± 5) %		–
$\Delta C = 1$ weak neutral current ($C1$) modes, or Lepton number (L) violating modes				
$p\mu^+\mu^-$	$C1$	< 3.4 $\times 10^{-4}$	CL=90%	936
$\Sigma^-\mu^+\mu^+$	L	< 7.0 $\times 10^{-4}$	CL=90%	811



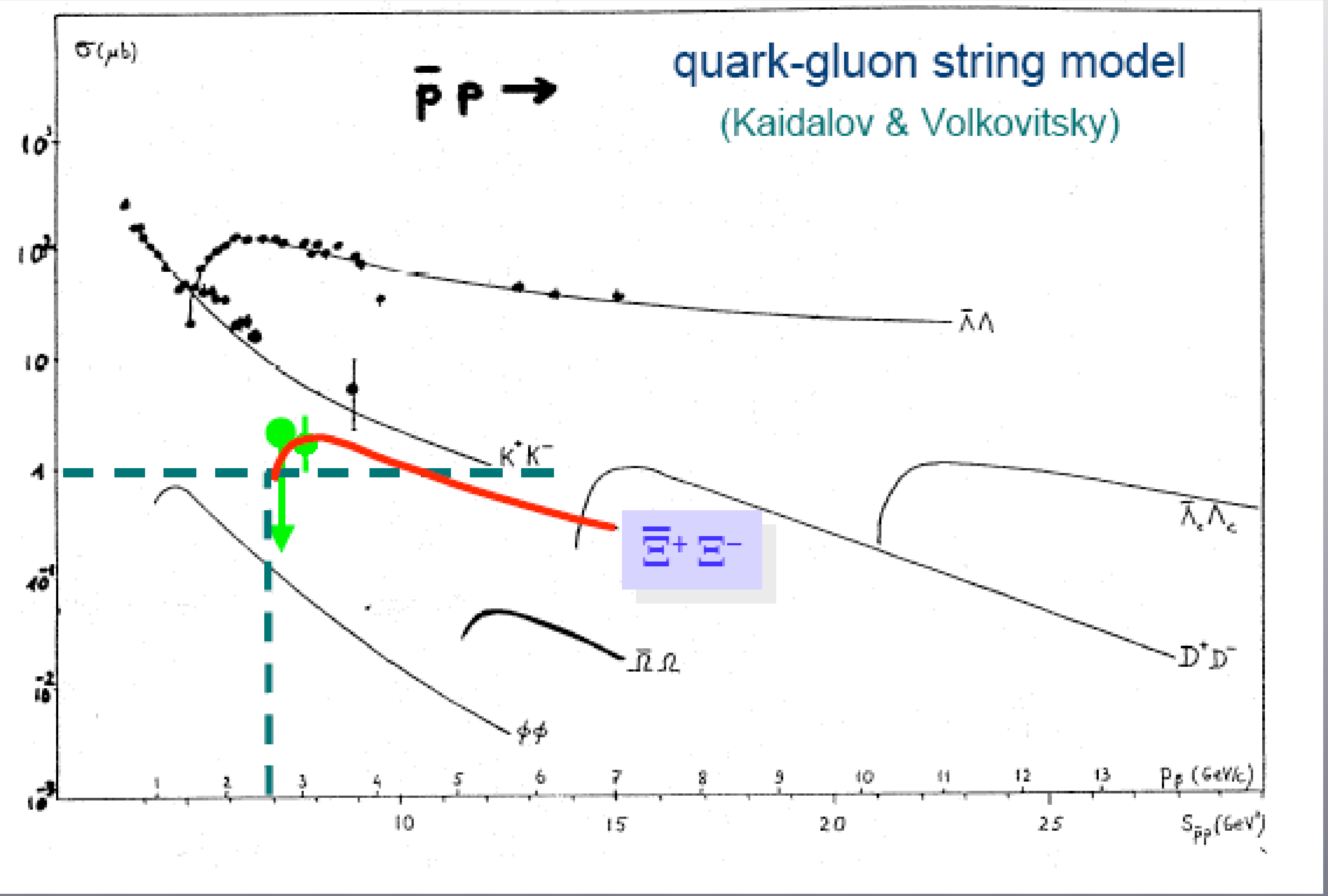
$\bar{p}p \rightarrow \bar{\Lambda}\Lambda$
1.642 GeV/c
$\bar{p}p \rightarrow \bar{\Lambda}_c^+ \Lambda_c^+$?
dσ/dΩ [μb/sr]
25
20
15
10
5
-1
-0,5
0
0,5
1
Cos*f*



$\bar{p}p \rightarrow \bar{\Lambda}_c^+ \Lambda_c^+$?
Polarisation
0,5
0
-0,5
-1
-1
-0,5
0
0,5
1
Cos*f*



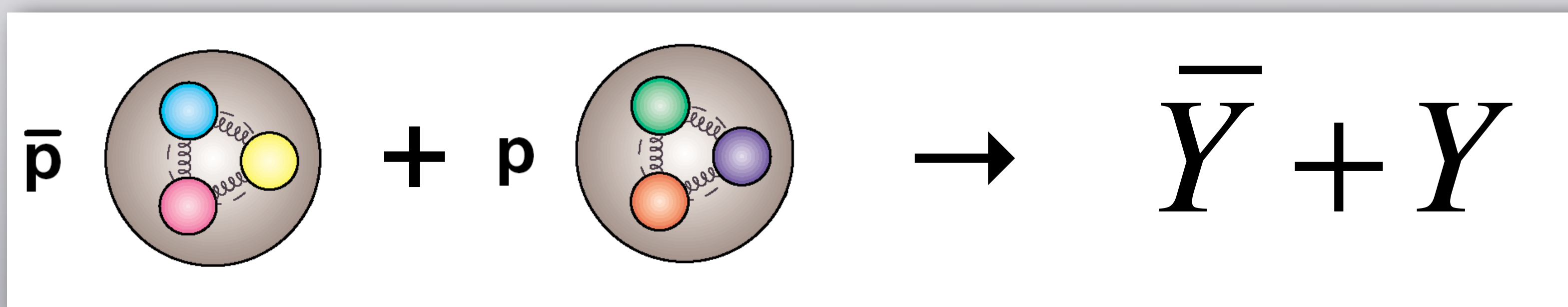
• $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$
$\bar{p}p \rightarrow \bar{\Lambda}_c^+ \Lambda_c^+$?
S = 0
Stat.
S = 1
Singlet Fraction
1.5
1
0.5
0
-0.5
0
50
100
150
200
Excess energy [MeV]


quark-gluon string model
(Kaidalov & Volkovitsky)
$\bar{p}p \rightarrow$
σ (μb)
$\bar{\Lambda}\Lambda$
K^+K^-
$\bar{\Xi}^+ \Xi^-$
$\bar{\Lambda}_c\Lambda_c$
$\bar{\Omega}\Omega$
D^+D^-
$\phi\phi$
$p_{\bar{p}}$ (GeV/c)
$s_{\bar{p}p}$ (GeV²)

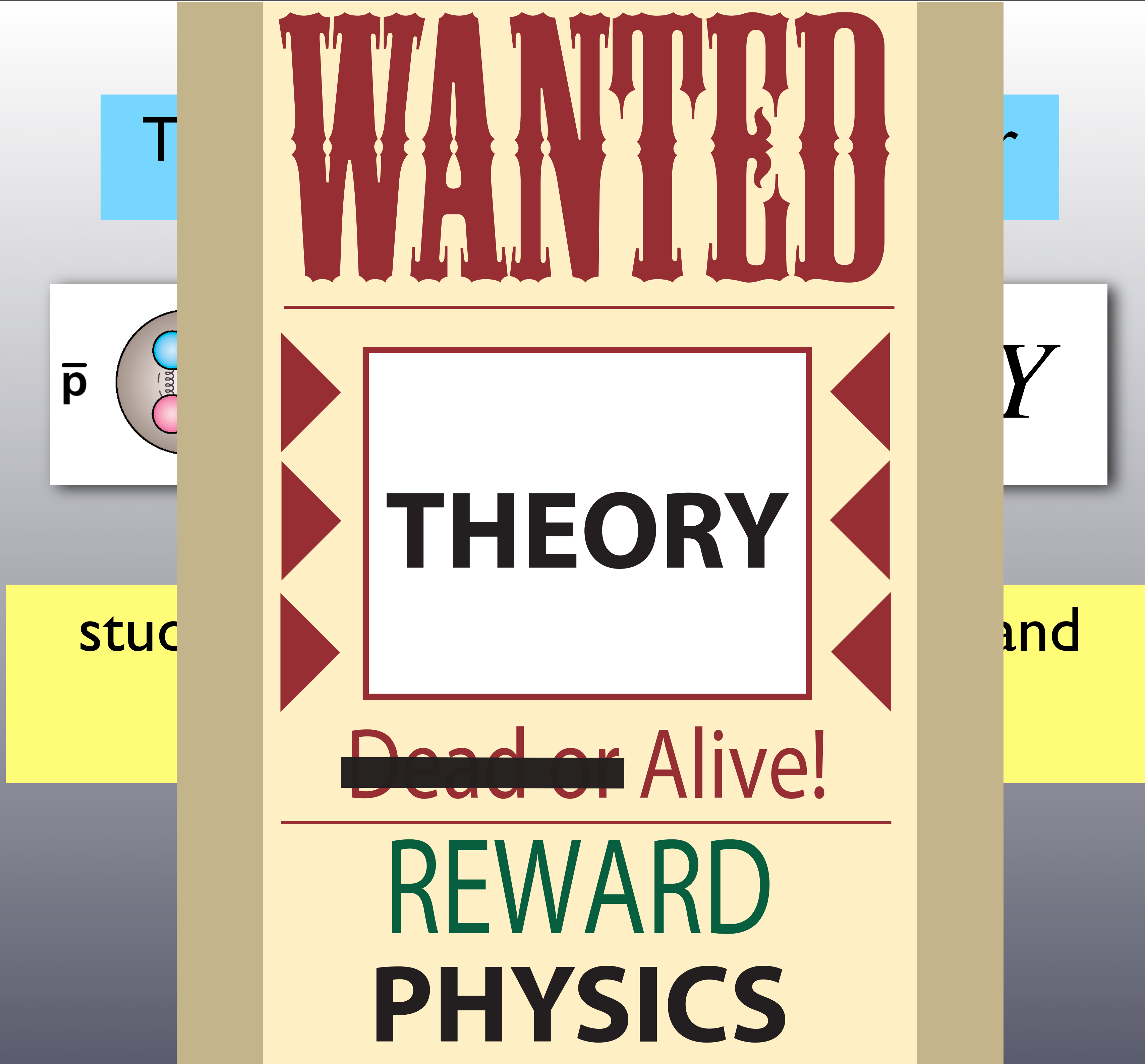
One year of data taking with PANDA ≈ 1-2 fb^{-1}

Final state	Cross section	# rec. events
$\bar{\Lambda}\Lambda$	50 μb	10^{10}
$\bar{\Xi}\Xi$	2 μb	10^{8}
$\bar{\Lambda}_c\Lambda_c$	20 nb	10^{7}
$\bar{\Omega}_c\Omega_c$	0.1 nb	10^{5}

There are excellent prospects for



studies in the multiple strangeness and charmed sector at FAIR!


WANTED
THEORY
~~Dead or~~ Alive!
REWARD
PHYSICS
p̄
and