Lecture 1: Hyperon Production and Spin Dynamics

PANDA lecture week, December 11-15, 2017

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Outline

- Introduction
- Strangeness production
- What we have learned from hyperons
- Hyperon spin dynamics
- Spin observables in $\bar{p}p \to \bar{Y}Y$
- The spin $\frac{1}{2}$
- Questions for discussion

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Introduction

Key questions

How is the visible mass of the universe generated?

What is the structure of matter?

Why and how are quarks confined into hadrons?

Matter-antimatter asymmetry of the universe?

Hypothesis

Hyperons as diagnostic tool

Topic

Hyperon spectroscopy

Hyperon production and spin dynamics

CP violation in hyperon decays

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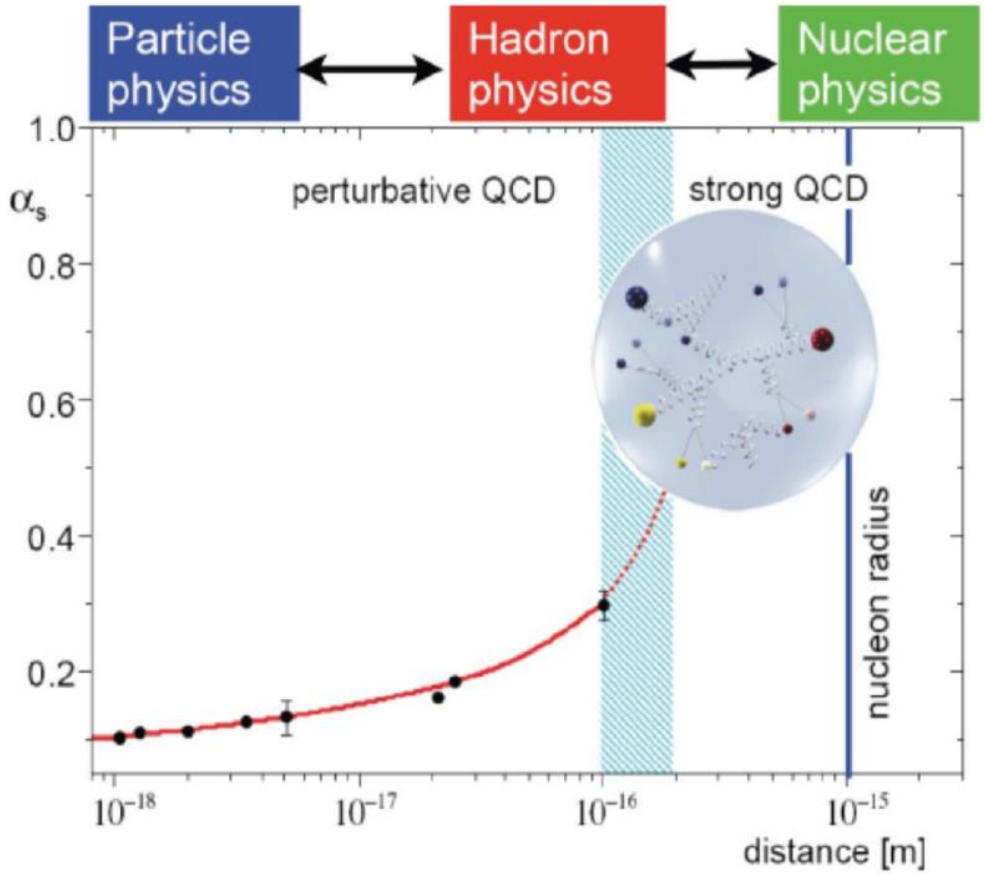
Introduction

Missing in the Standard Model of particle physics:

A complete understanding of the strong interaction.

- Short distances
  pQCD rigorously
  and successfully tested.

- Charm scale and above:
  pQCD fails, no analytical
  solution possible.

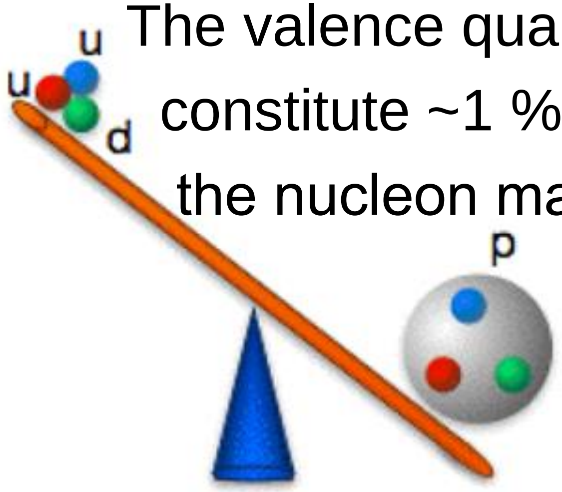


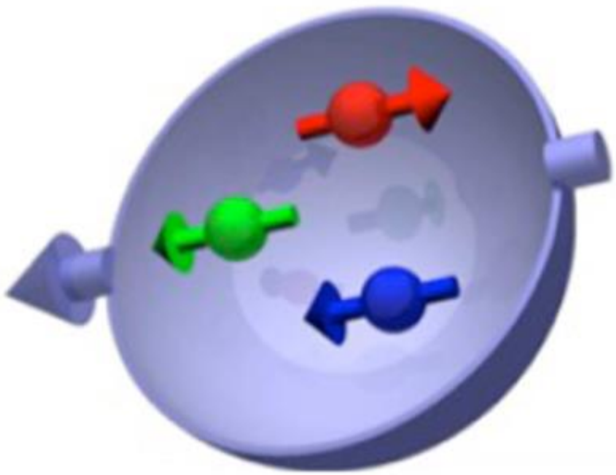
The mysterious nucleon

- Baryons are the simplest system for which the non-abelian nature of the strong interaction is manifest.
- Protons have been known for almost a century.
- Nucleons constitute the major part of the visible mass of the Universe.

- Yet, we don't understand them:

The valence quarks only constitute ~1 % of the nucleon mass…

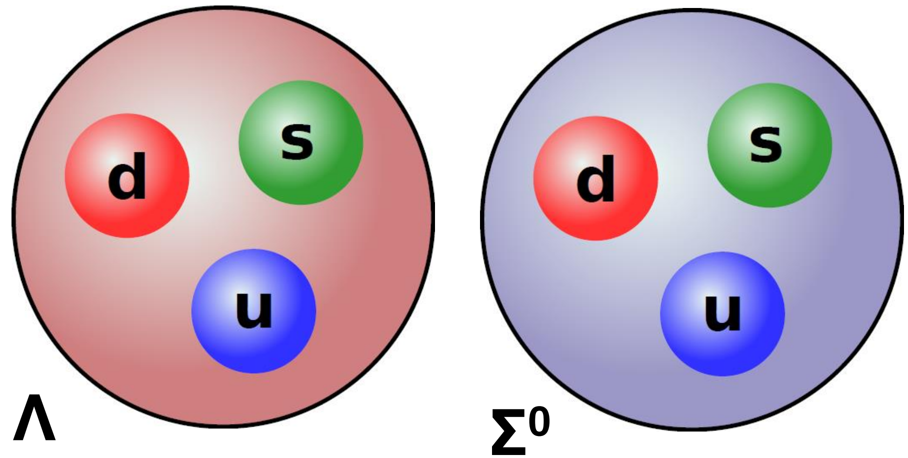


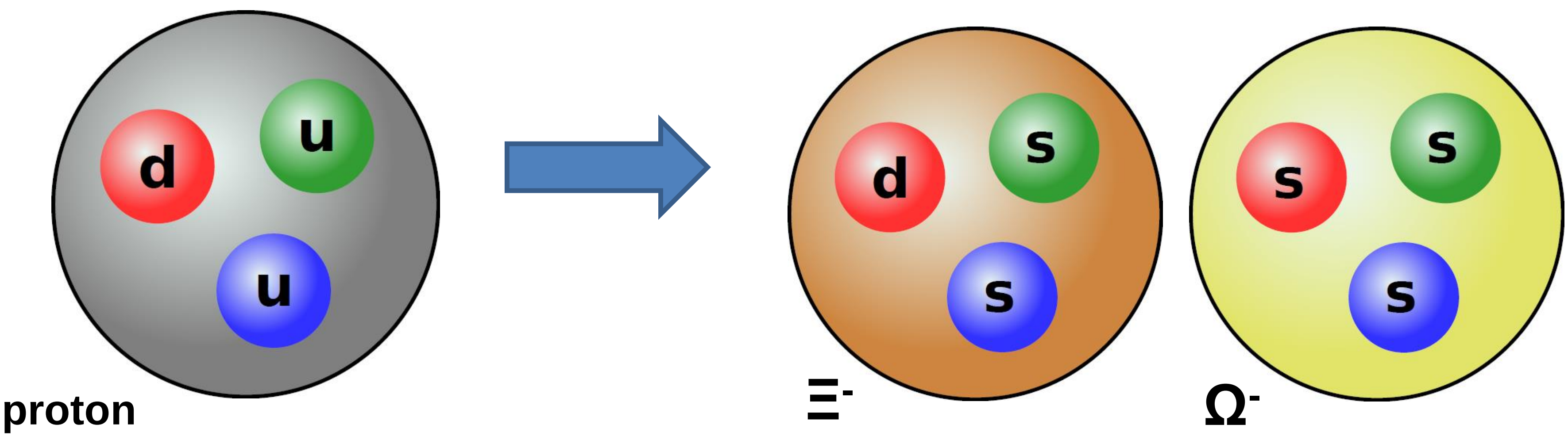


…and about 1/3 of the spin!

Key question in hyperon physics:

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





Strangeness production

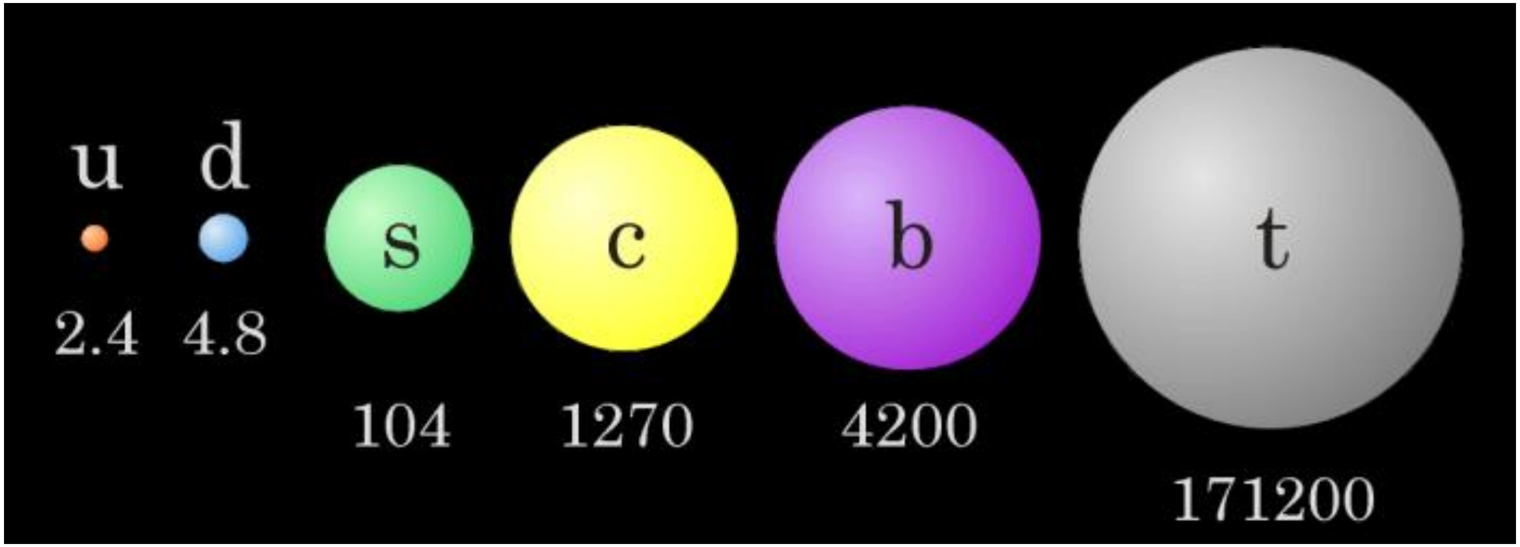
- u,d scale: Non-perturbative interactions → hadron degrees of freedom
- Strange scale: $m_s \approx 100$ MeV ~ $\Lambda_{QCD} \approx 200$ MeV

  → degrees of freedom unclear

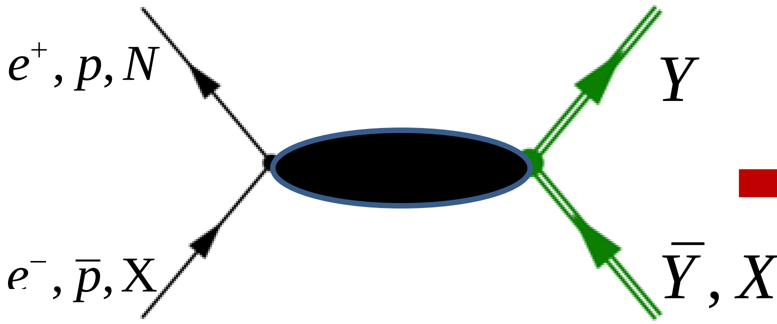
  → **Probes QCD in the intermediate domain.**
- Charm scale: $m_c \approx 1300$ MeV

  → Quark and gluon degrees of freedom

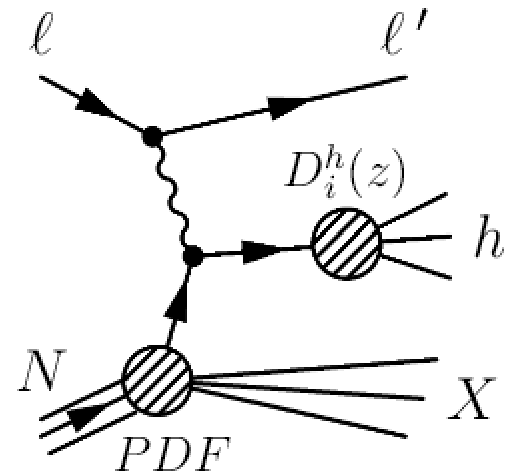
  → pQCD more relevant

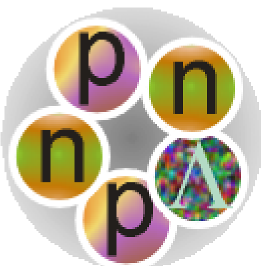


Hyperon production at
low/intermediate energies
-QCD in confinement domain
- CP test



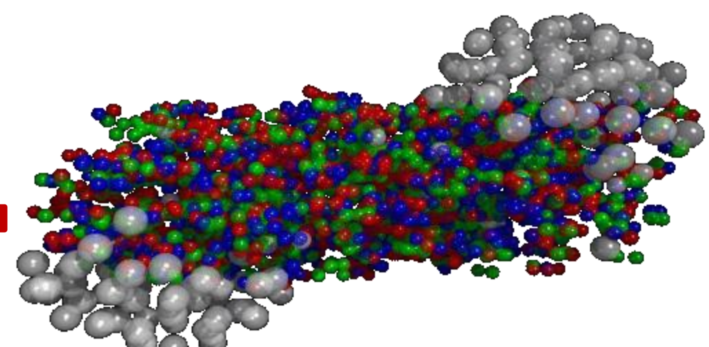
Inclusive hyperon production
at high energies
- spin and flavour
structure of nucleons and
hyperons

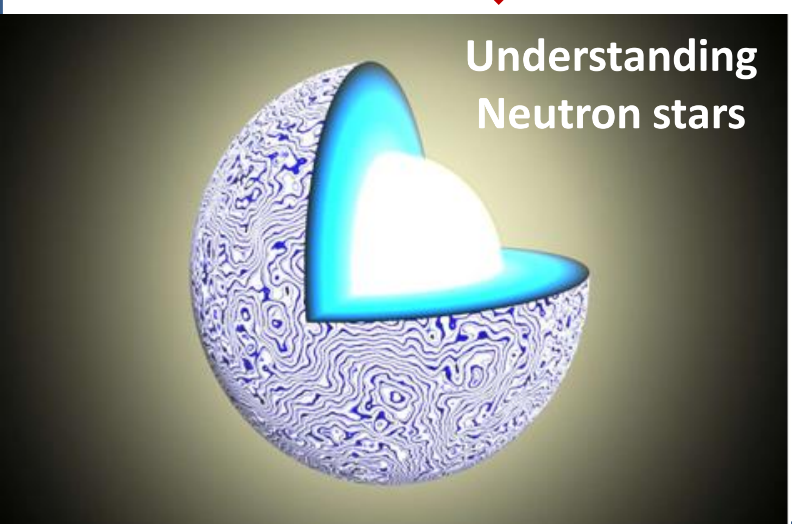




Hypernuclei
-probes nucleon-hyperon and
hyperon-hyperon potentials

Hyperon production in high energy
heavy ion collisions
- phase transition to quark-gluon plasma?





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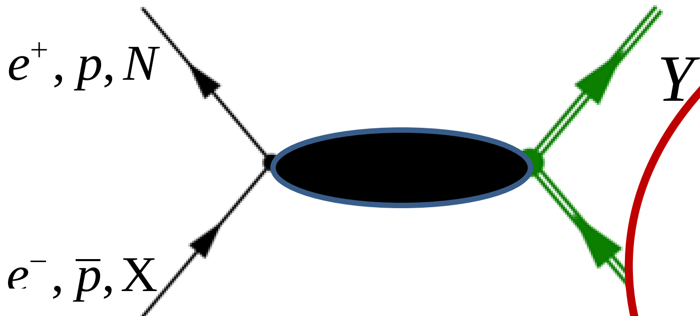
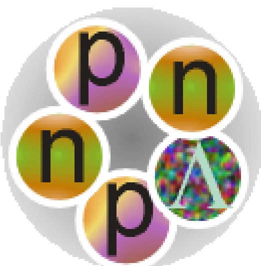


Inclusive hyperon production
at high energies
- spin and flavour
of nucleons and

Hyperons / Strangeness provides a diagnostic tool for various studies of (mainly) non-pQCD.



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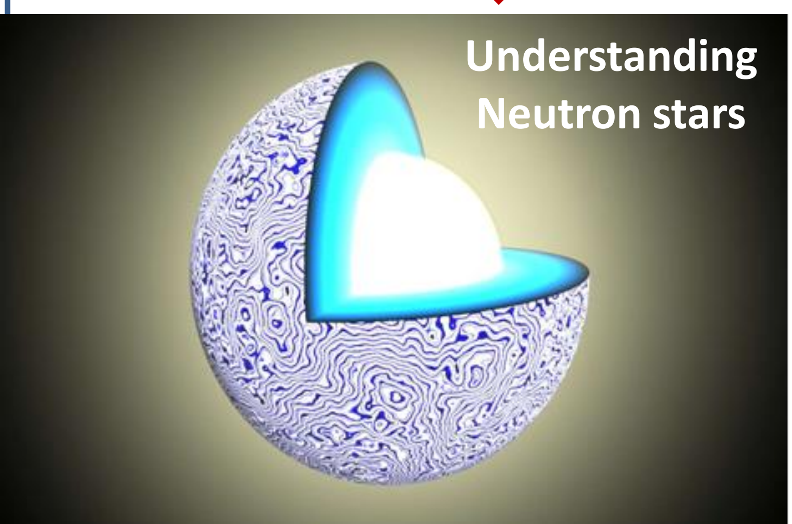

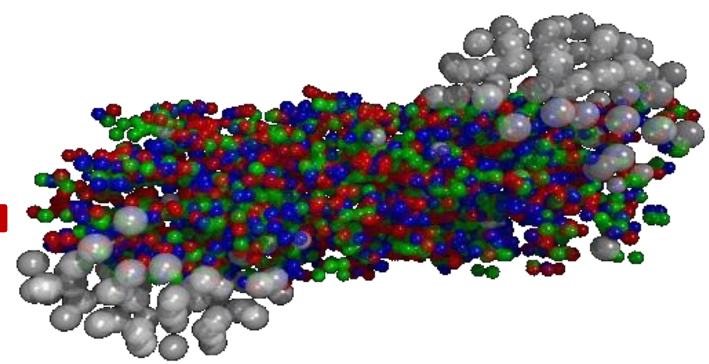

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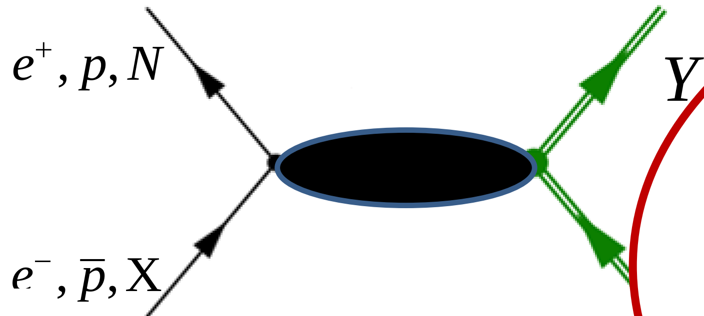

Inclusive hyperon production at high energies
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Hypernuclei
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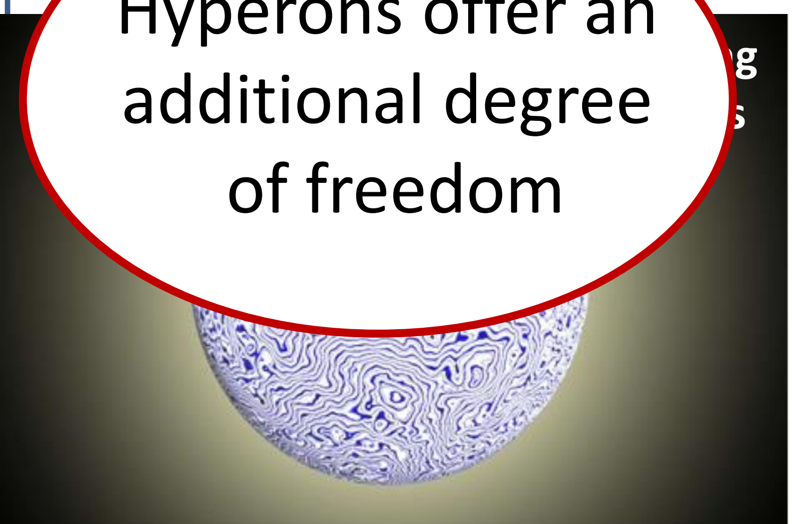
Hyperons offer an additional degree of freedom



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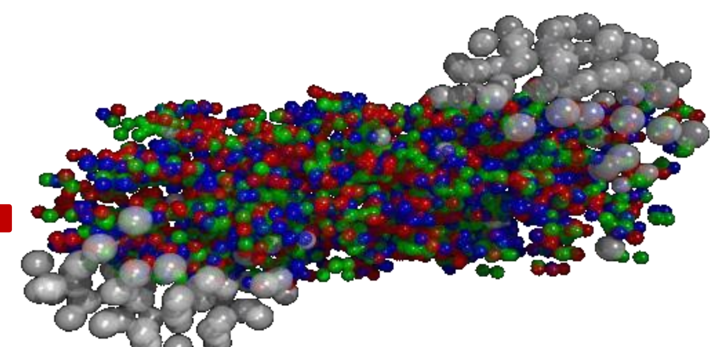
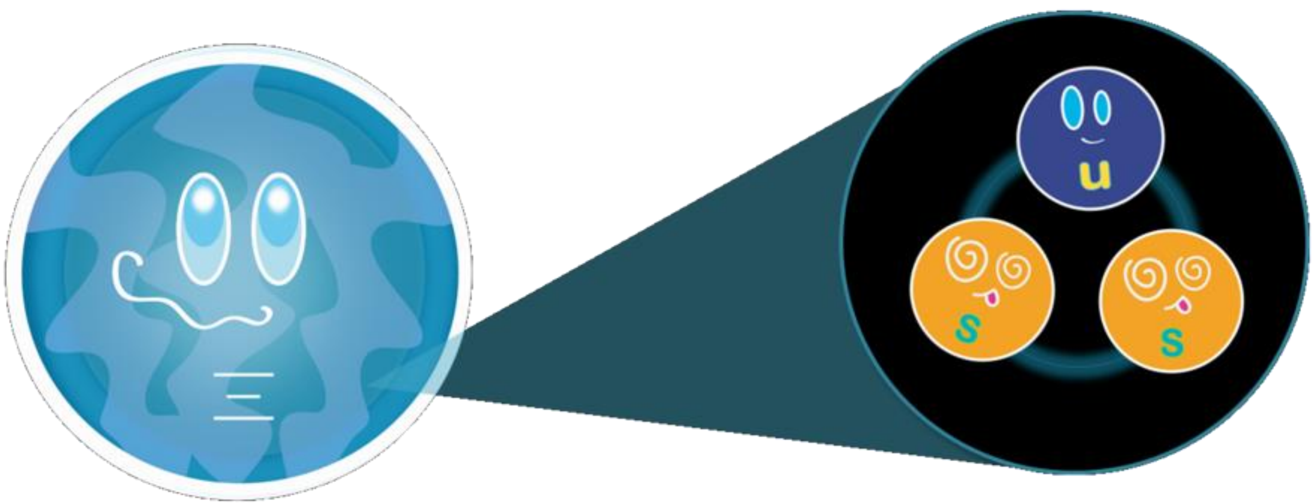
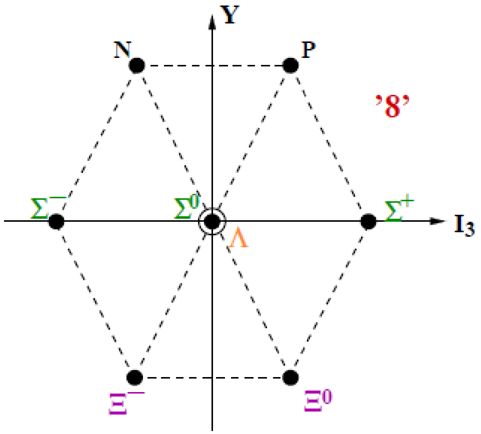


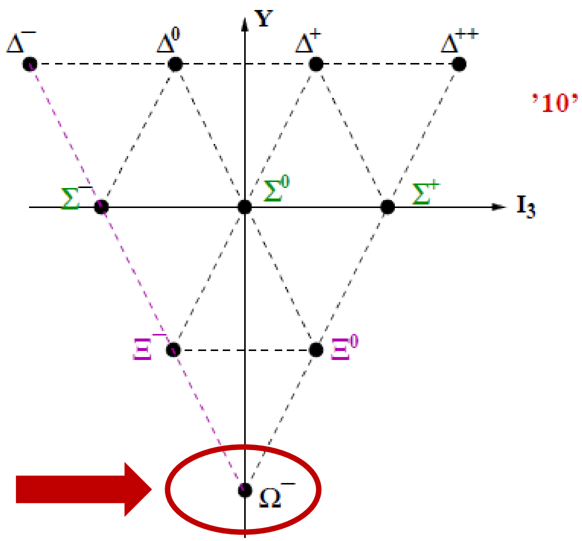
Past: what did we learn from hyperons?



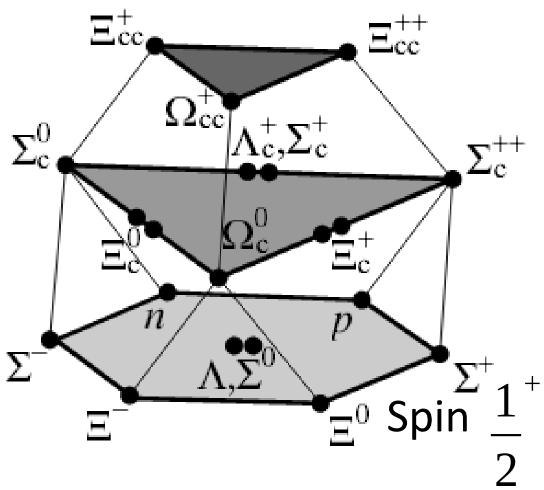
Hyperons and the quark model

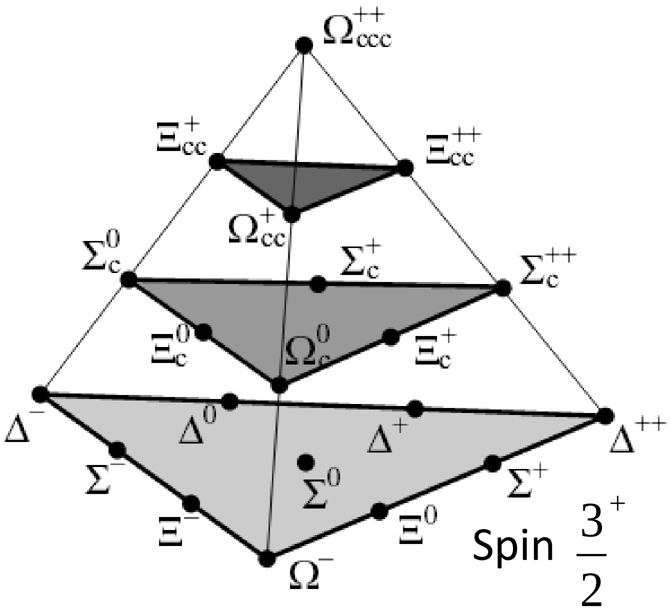
- 1950's and 1960's: a multitude of new particles discovered → obvious they could not all be elementary.
- 1961: Eight-fold way, organising spin $\frac{1}{2}$ baryons into octets and spin $\frac{3}{2}$ into a decuplet as a consequence of SU(3) flavour symmetry.
- 1962: Discovery of the predicted Ω^- demonstrates the success of the Eight-fold way.
- 1964: Quark model (Gell-Mann and Zweig)





Strange and charmed hyperons





SU(3):
- Approximately valid
- Octet and decuplet confirmed by experiment.

SU(4):
- Predicts two 20-plets
- Should not be a good symmetry ($m_c >> m_{s,u,d}$).
- Single charm (and one double) confirmed by experiment.

Hyperons and the quark model

- The simple (constituent) quark model* was successful in classifying hadrons and describing static properties of hadrons.

- Unable to explain *e.g.*
  – Mass of the nucleon
  – Spin structure of the nucleon.
  – Flavour asymmetry of the nucleon sea.
  – Certain features of the light baryon spectrum**.

*PR 125 (1962) 1067

**PRD 58 (1998) 094030

Hyperon spin dynamics

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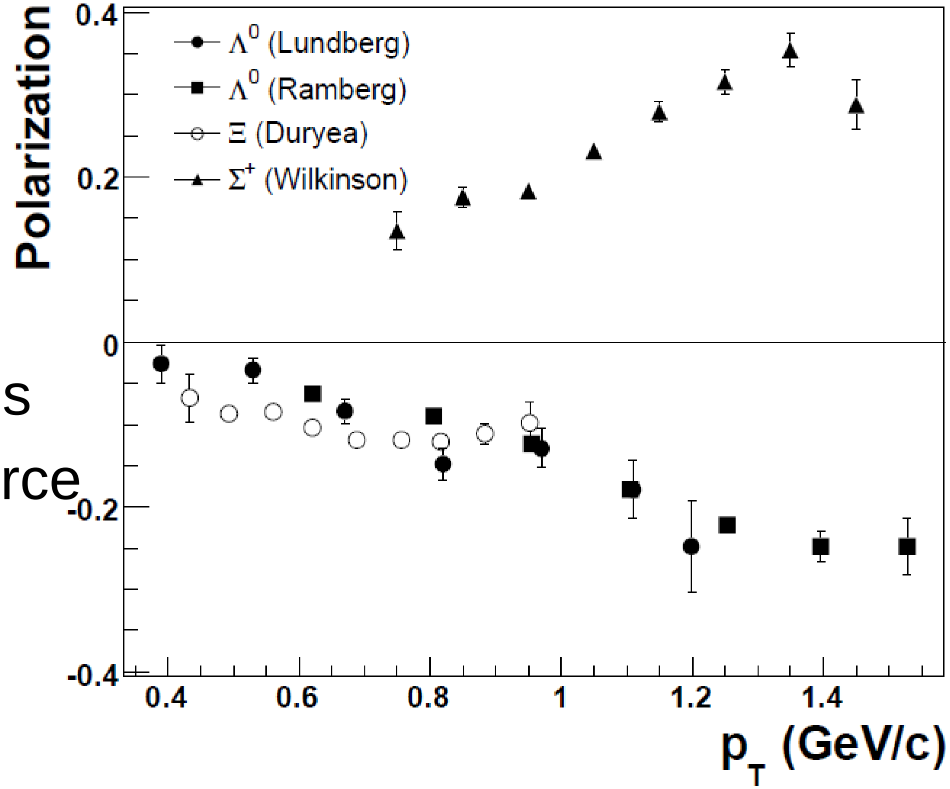
Or: what can we learn from looking into detail how known hyperons are produced?

Hyperons from *pp* and *pA* reactions

- Polarization a result of interfering amplitudes.
- In hadronic reactions, many contributing sub-processes.
- High energies: total polarization should be 0.
- Data: hyperons produced polarized at high energies → contrast to naïve expectations.
- Many contributing amplitudes → difficult to pinpoint the source of polarisation.



K. Heller, Colloque de Physique C6 (1990) 163

Hyperons from $\bar{p}p$ reactions

- Hyperons and anti-hyperons can be produced at low energies → fewer amplitudes contributing.
- Symmetry in hyperon and anti-hyperon observables.
- Polarisation + other spin observables powerful tools for testing models of production dynamics and structure.

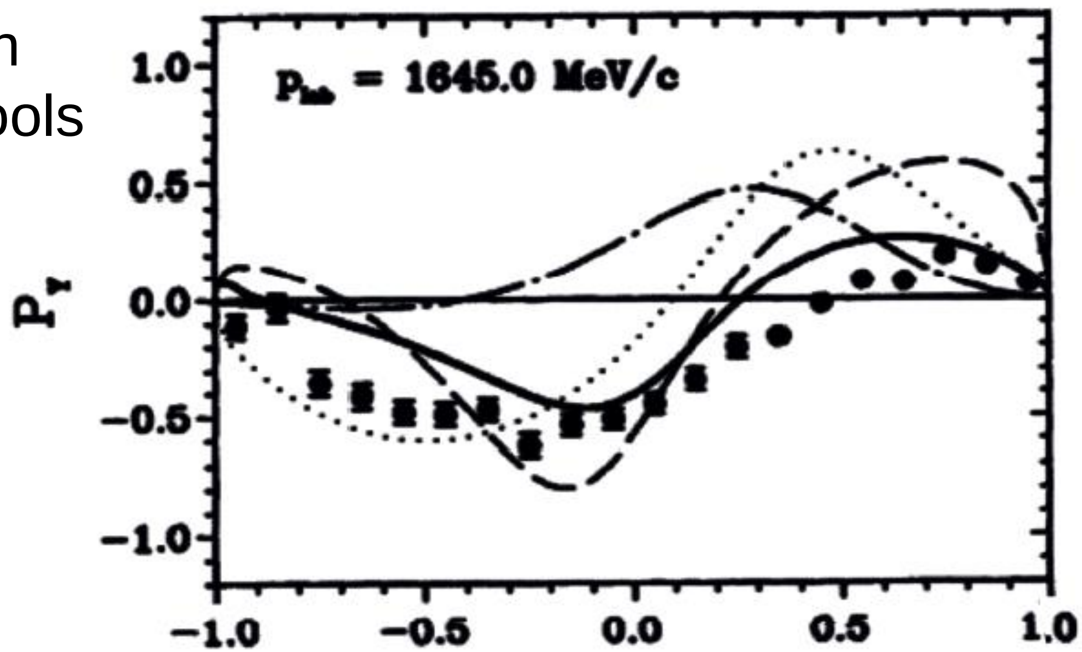
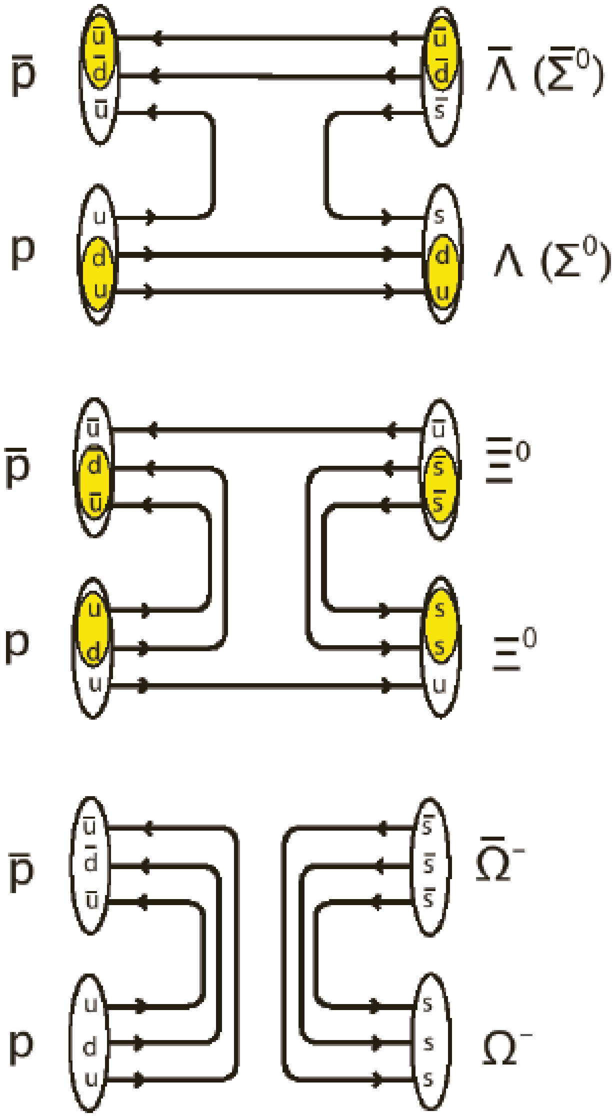
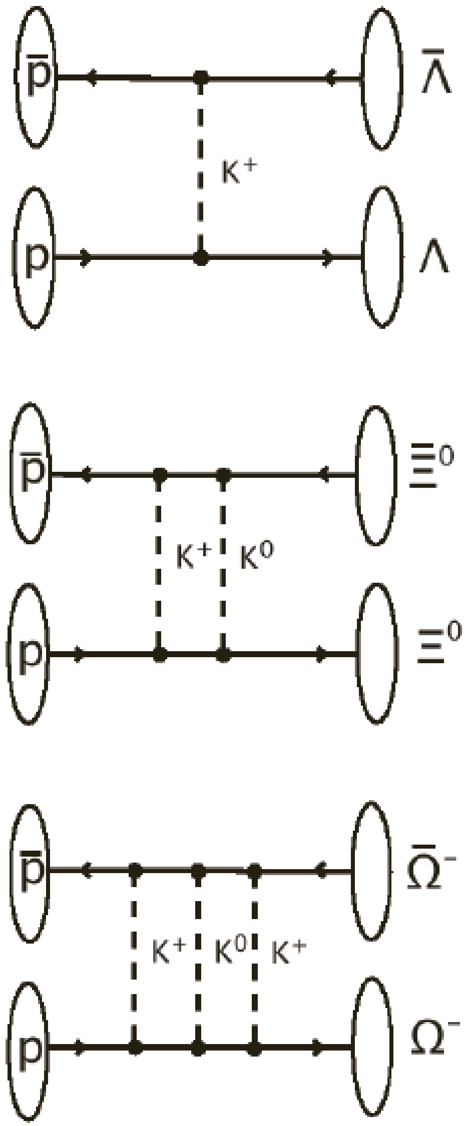


Figure from Phys. Rep. 368 (2002) 119.

Hyperons from $\bar{p}p$ reactions





Available models based on

i) constituent quark-gluons*

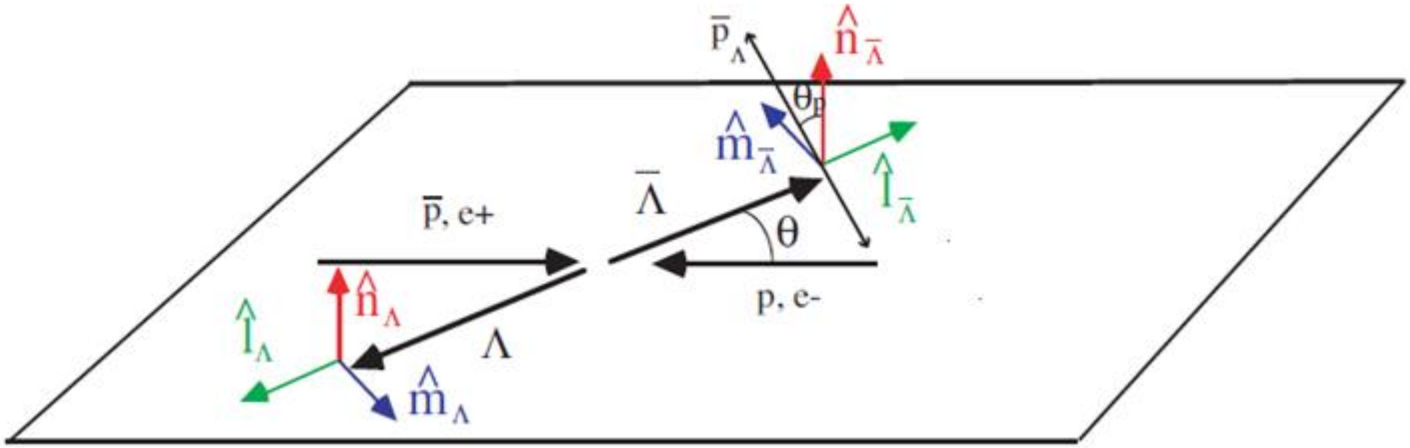
ii) hadrons**

ii) a combination ***

*PLB 179 (1986) 15; PLB 165 (1985) 187; NPA 468 (1985) 669;
** PR**C** 31(1985) 1857; PLB179 (1986) 15; PLB 214 (1988) 317;
*** PLB 696 (2011) 352.

Spin observables in $\bar{p}p \rightarrow \bar{Y}Y$

- The differential cross section of a $\bar{p}p \rightarrow \bar{Y}Y$ process can be described in terms of
  - Spin observables
  - Decay asymmetries
  - Angles



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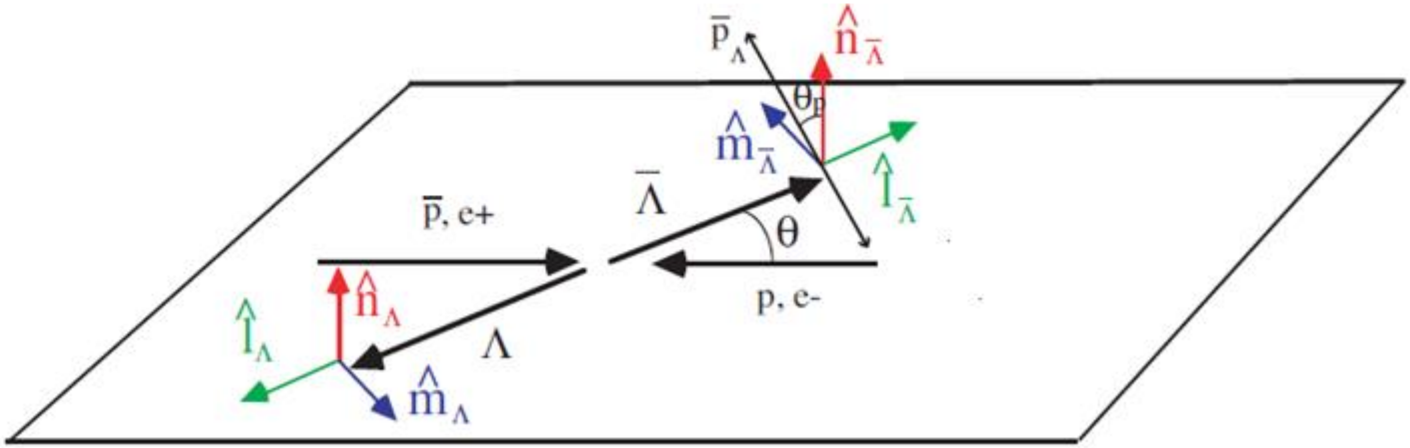
Related to production, Depend on energy and *Y* scattering angle θ.



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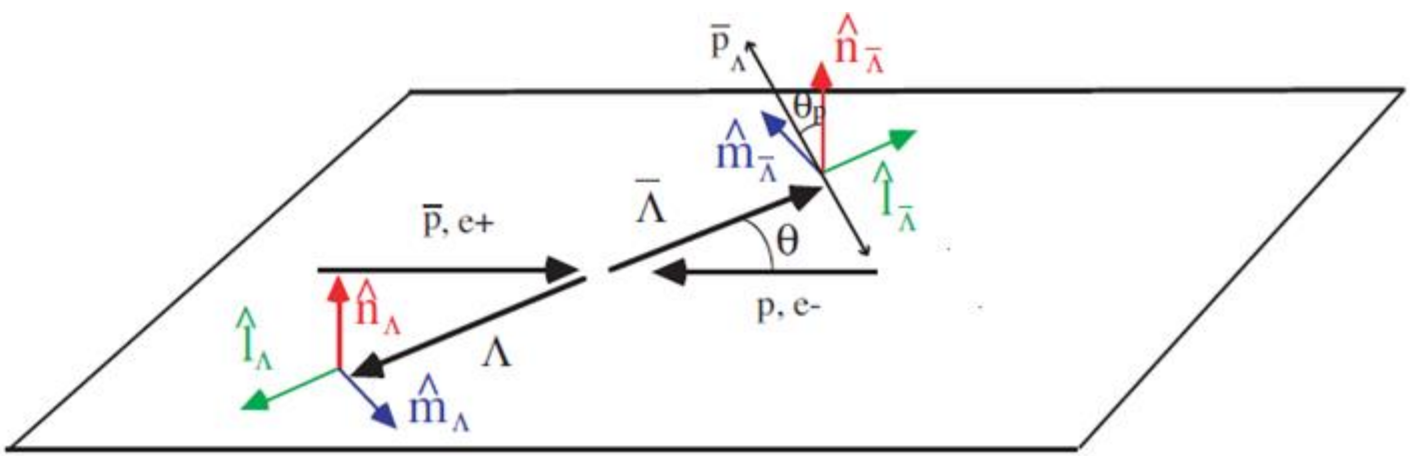
Related to decay, independent of energy and θ but depend on decay mode.



Spin observables in $\bar{p}p \to \bar{Y}Y$

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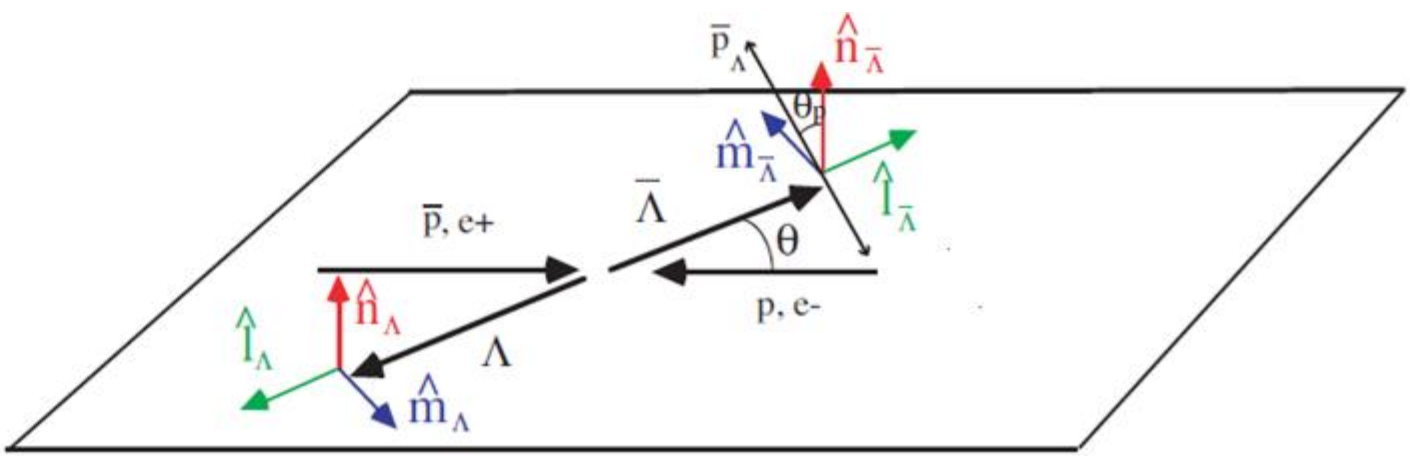
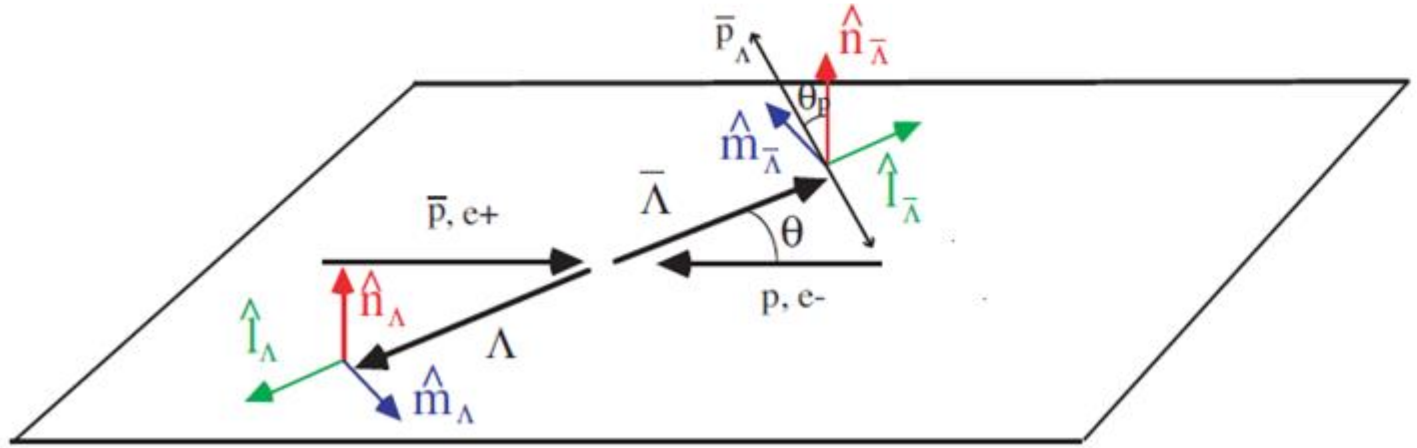
What we actually measure and estimate parameters (spin observables, decay asymmetries) from.



Spin observables in $\bar{p}p \rightarrow \bar{Y}Y$

- We need to find an expression that describes the full process
  - Production
  - Decay
- For this, we need the density matrix.



The density matrix

A pure ensemble in quantum mechanics is described by the same ket $|\Psi\rangle$

whereas a mixed sample is described by a sum of different kets, populated by amounts a_k : $\sum_k a_k \Psi_i$

The expectation value of an observable *E* for a pure state is given by

$$\langle E\rangle = \langle\Psi|E|\Psi\rangle$$

which in an orthonormal basis $\{|a_k\rangle\}$ can be written

$$\langle E\rangle = \langle\Psi|\left(\sum_k |a_k\rangle\langle a_k|\right) E|\Psi\rangle = \sum_k \langle\Psi|a_k\rangle\langle a_k|E|\Psi\rangle$$

$$= \sum_k \langle a_k|E|\Psi\rangle\langle\Psi|a_k\rangle = \mathrm{Tr}\left(E\,|\Psi\rangle\langle\Psi|\right)$$

The density matrix

The density matrix is defined as $\rho \equiv |\Psi\rangle\langle\Psi|$
meaning $\langle E\rangle = Tr(\rho E)$.

For a mixed state this can be generalized:

$$\rho \equiv \sum_i c_i \, |\Psi_i\rangle\langle\Psi_i|$$

$$\langle E\rangle = Tr(E \textstyle\sum_i c_i \, |\Psi_i\rangle\langle\Psi_i|).$$

Spin observables in $\bar{p}p \rightarrow \bar{Y}Y$

The density matrix of a particle with arbitrary spin *j* is given by

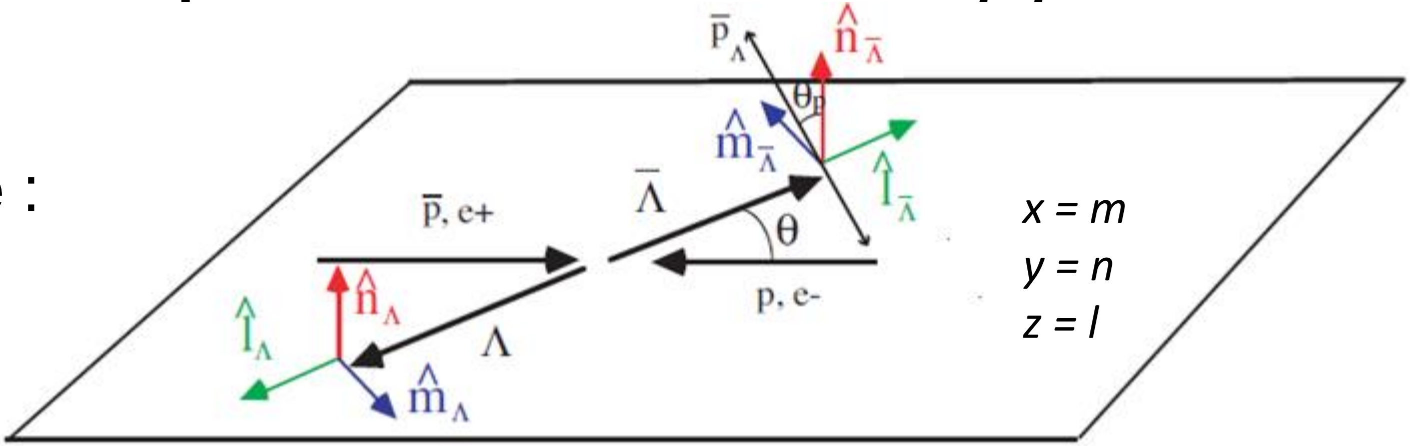
$$\rho = \frac{1}{2j+1}\mathscr{I} + \sum_{L=1}^{2j} \rho^L \quad \text{with} \quad \rho^L = \frac{2j}{2j+1}\sum_{M=-L}^{L} Q_M^L r_M^L$$

where Q_M^L are hermitian matrices and r_M^L polarisation parameters.

Spin $\frac{1}{2}$: 3 polarisation parameters (*L=1, -L < M < L)*

Spin $\frac{3}{2}$: 15 polarisation parameters (*L=1, 2, 3, -L < M < L)*

Spin observables in $\bar{p}p \to \bar{Y}Y$



x = m
y = n
z = l

Spin $\frac{1}{2}$ case :

$Q_M{}^L$ = Pauli matrices.

The spin density matrix of a spin $\frac{1}{2}$ particle is given by:

$$\rho(1/2) = \frac{1}{2}(\mathscr{I} + \bar{P}\cdot\bar{\sigma}) = \frac{1}{2}\begin{bmatrix} 1+P_z & P_x+iP_y \\ P_x-iP_y & 1-P_z \end{bmatrix}$$

Symmetry from parity conservation (strong production) requires $P_x = P_z = 0$, which gives:

$$\rho(1/2) = \frac{1}{2}\begin{bmatrix} 1 & iP_y \\ -iP_y & 1 \end{bmatrix}$$

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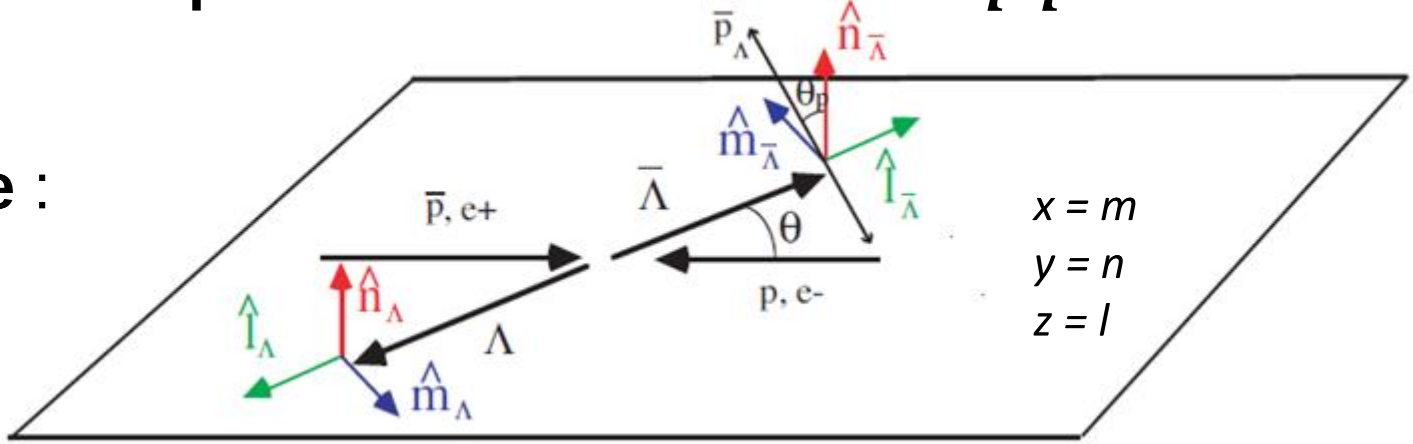

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Polarisation normal to the production plane!

Spin observables in $\bar{p}p \rightarrow \bar{Y}Y$

The spin observables of the full $\bar{p}p \rightarrow \bar{Y}Y$ process can be obtained from the angular distributions of decay baryons, using

$$\rho^{\bar{B}B} = \frac{I_0^{\bar{Y}Y}}{16\pi} \sum_{\mu,\nu=0}^{3} \sum_{i,j=0}^{3} P_i^{\bar{p}} P_j^{p} \chi_{ij\mu\nu} T_{\bar{Y}} T_{Y} \sigma_\mu^1 \sigma_\nu^2 T_{\bar{Y}}^\dagger T_{Y}^\dagger$$

where P_j^p is the polarisation vectors of the initial proton, and

$$\underbrace{\chi_{ij\mu\nu} = \frac{\mathrm{Tr}(\sigma_\mu^1 \sigma_\nu^2 M \sigma_i^1 \sigma_j^2 M^\dagger)}{\mathrm{Tr}(MM^\dagger)}}_{\text{256 spin variables}} \quad \text{and} \quad \underbrace{I_0^{\bar{Y}Y} = \frac{1}{4}\mathrm{Tr}(MM^\dagger)}_{\text{unpolarised angular distribution}}$$

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Polarised Particle	None	Beam	Target	Both
None	I_{0000}	A_{i000}	A_{0j00}	A_{ij00}
Scattered	$P_{00\mu0}$	$D_{i0\mu0}$	$K_{0j\mu0}$	$M_{ij\mu0}$
Recoil	$P_{000\nu}$	$K_{i00\nu}$	$D_{0j0\nu}$	$N_{ij0\nu}$
Both	$C_{00\mu\nu}$	$C_{i0\mu\nu}$	$C_{0j\mu\nu}$	$C_{ij\mu\nu}$

I – angular distribution
A – analysing power
P – polarisation
D – depolarisation
K – polarisation transfer
C – spin correlations
M, N – spin corr. tensor

Hyperon decays

- Define the *decay matrix T* such that:

$$|\Psi_f\rangle = T|\Psi_i\rangle$$

- Recall $\rho \equiv |\Psi\rangle\langle\Psi|$
- Then

$$\rho_f = T\rho_i T^\dagger$$

and the angular distribution is given by

$$I(\theta,\varphi) = Tr(T\rho_i T^\dagger)$$

Hyperon decays

For a spin $\frac{1}{2}$ hyperon decaying into a spin $\frac{1}{2}$ baryon and a spin 0 meson ($\frac{1}{2} \rightarrow \frac{1}{2}\, 0$):

- Parity violating S state: amplitude T_s
- Parity conserving P state: amplitude T_P

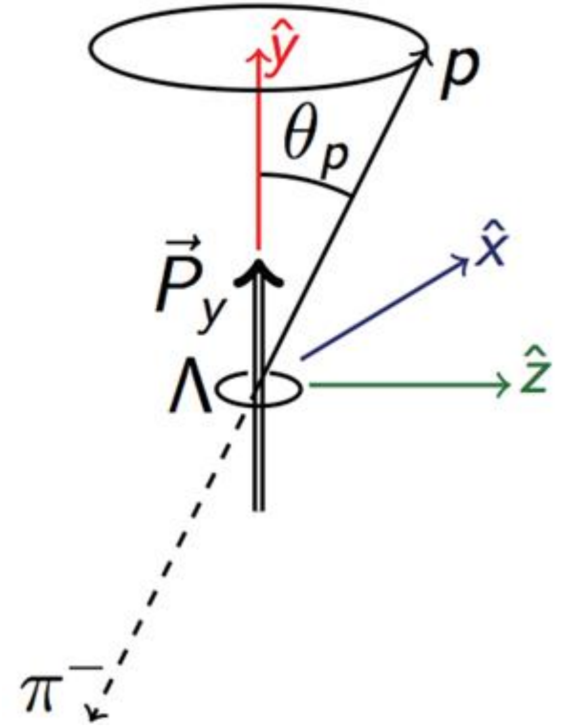
Spin density matrix:

$$T(1/2 \rightarrow 1/2, 0) = \frac{1}{\sqrt{4\pi}} \begin{bmatrix} (T_s + T_p)(\cos \frac{\theta_\mathrm{p}}{2}) & (T_s + T_p)e^{-i\phi_\mathrm{p}}(\sin \frac{\theta_\mathrm{p}}{2}) \\ (-T_s + T_p)e^{i\phi_\mathrm{p}}(\sin \frac{\theta_\mathrm{p}}{2}) & (T_s - T_p)(\cos \frac{\theta_\mathrm{p}}{2}) \end{bmatrix}.$$

Hyperon decays

Define *decay asymmetry parameters:*

$$\alpha = 2\mathrm{Re}(T_s^* T_p)$$
$$\beta = 2\mathrm{Im}(T_s^* T_p)$$
$$\gamma = |T_s|^2 - |T_p|^2$$



and by construction $\alpha^2 + \beta^2 + \gamma^2 = 1$

Then the decay angular distribution can be written

$$I(\theta, \phi) = \mathrm{Tr}(\rho(1/2)T^\dagger T(1/2 \to 1/2\ 0)) = \frac{1}{4\pi}(1 + \alpha P_y \sin\theta \sin\phi)$$

or if integrating over φ :

$$I(\cos\theta_\mathrm{p}) = \frac{1}{4\pi}(1 + \alpha P_y \cos\theta_\mathrm{p})$$

Questions for discussion

- At the kinematic threshold, the polarisation must be 0. Give an argument why.
- At the PS185 experiment, the $\bar{p}p \to \bar{\Lambda}\Lambda$ was studied with unpolarised beam and polarised target. Which spin observables could thus be extracted?
- With PANDA, we will have unpolarised beam and target. Which spin observables can then be extracted
  - If hyperons are studied inclusively?
  - If hyperons + antihyperons are studied exclusively?

Spin observables in $\bar{p}p \rightarrow \bar{Y}Y$

The angular distribution is obtained by the trace

$$I_0^{\bar{\mathrm{B}}\mathrm{B}} = \mathrm{Tr}(\rho^{\bar{\mathrm{B}}\mathrm{B}})$$

With an unpolarised beam and unpolarised taget this becomes

$$I_{\bar{B}B}(\Theta_{\bar{\mathrm{Y}}}, \hat{\bar{k}}, \hat{k}) = \frac{I_0}{64\pi^3} \begin{pmatrix} 1 \\ +P_{\bar{\mathrm{Y}},y}\bar{\alpha}\bar{k}_y + P_{\mathrm{Y},y}\alpha k_y \\ +C_{xx}\bar{\alpha}\alpha\bar{k}_x k_x \\ +C_{yy}\bar{\alpha}\alpha\bar{k}_y k_y \\ +C_{zz}\bar{\alpha}\alpha\bar{k}_z k_z \\ +C_{xz}\bar{\alpha}\alpha\bar{k}_x k_z \\ +C_{zx}\bar{\alpha}\alpha\bar{k}_z k_x \quad . \end{pmatrix}$$