Hyperon Physics – past, present and future

Karin Schönning, Uppsala University

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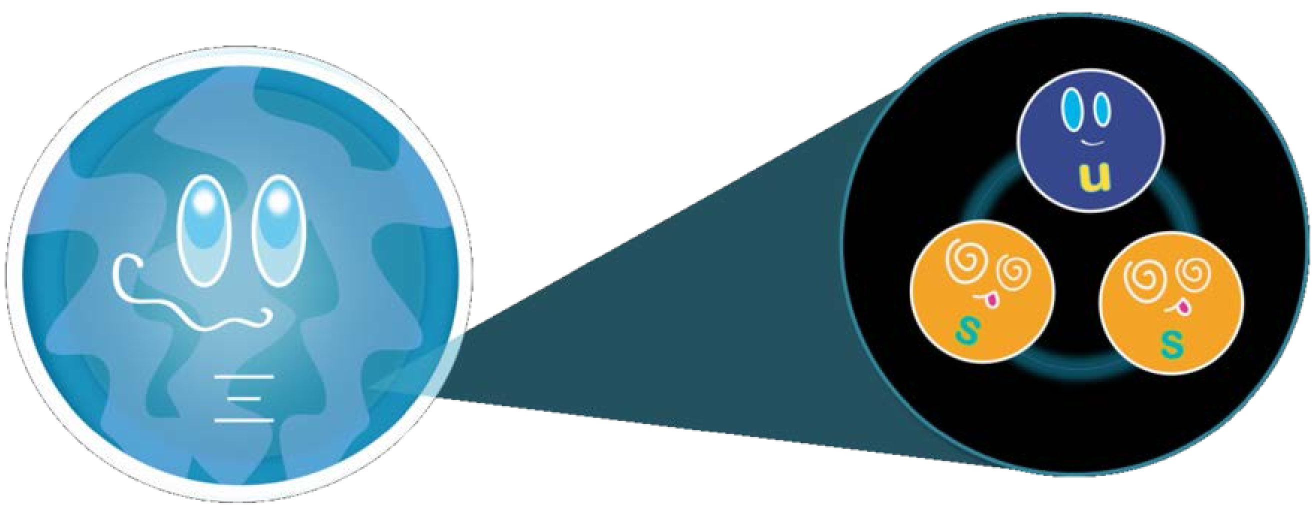
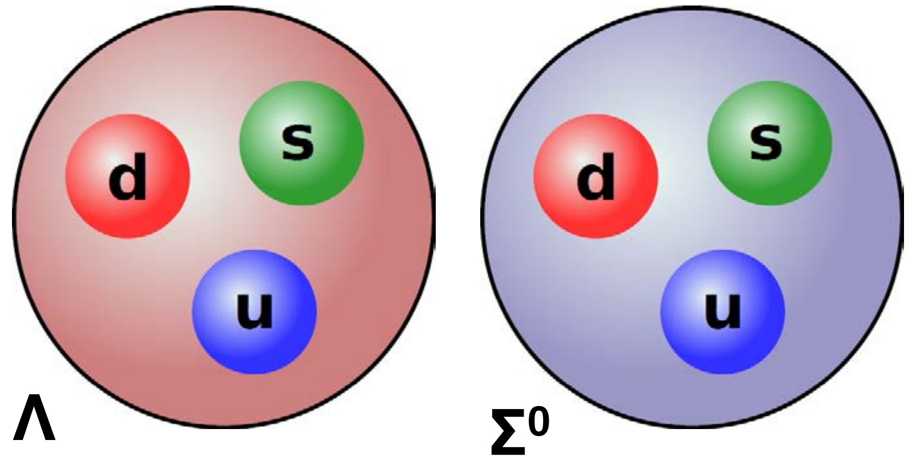


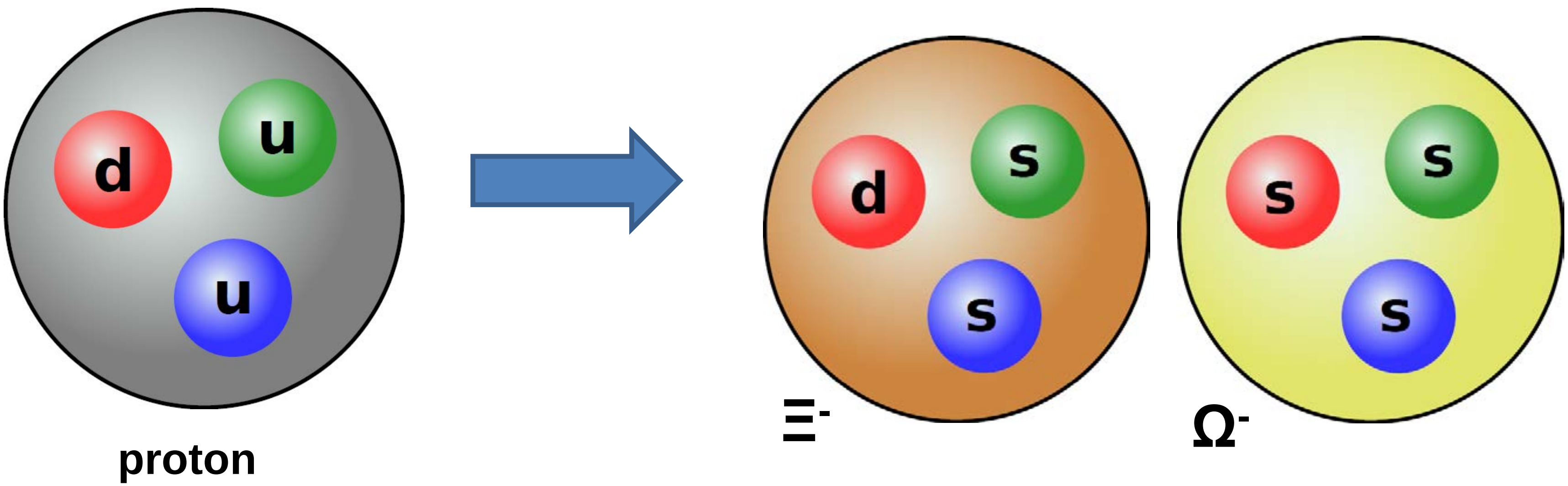
Outline

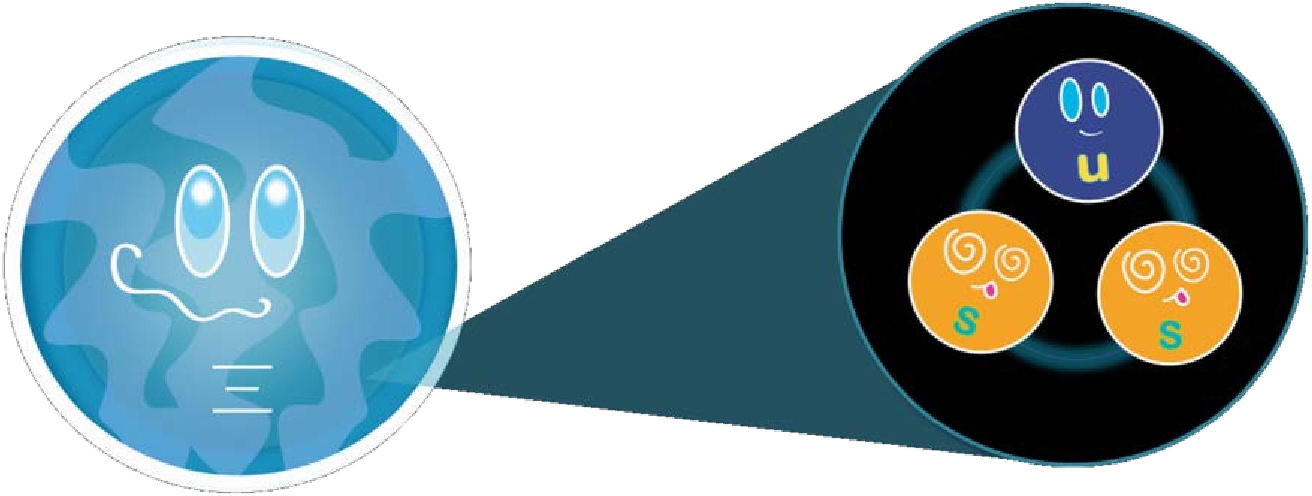
- Past: What did we learn from hyperons?
- Strangeness production
- Open questions in hadron physics
  - Can hyperons provide a key?
- Present: Recent highlights in hyperon physics.
- Future: Current and coming hyperon facilities

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)?



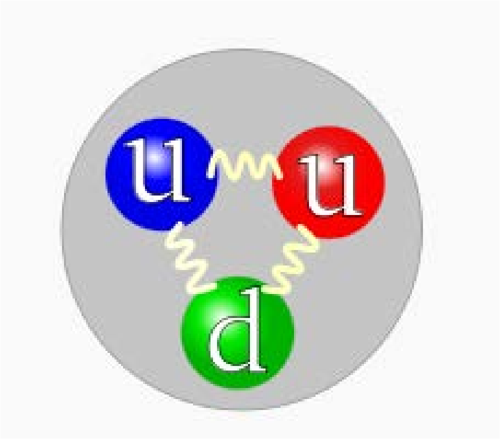


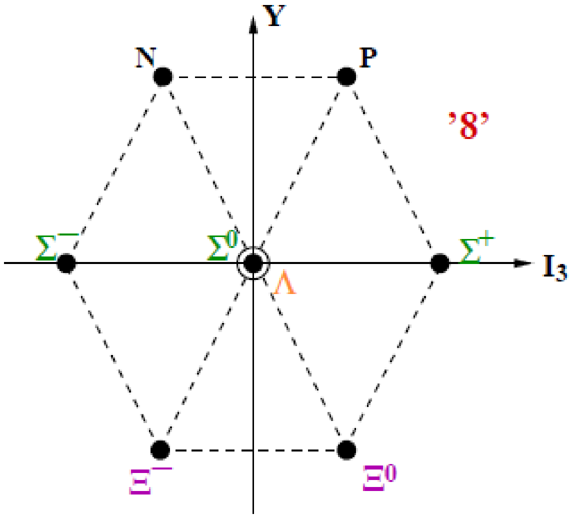


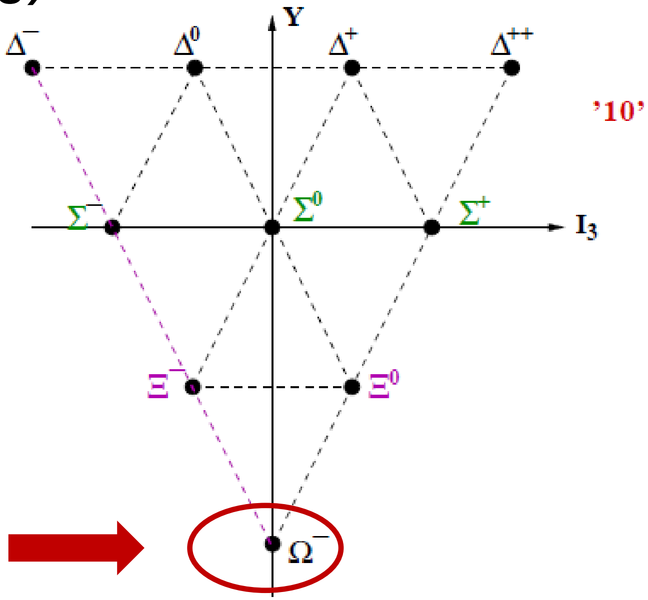
PAST: WHAT DID WE LEARN FROM HYPERONS?

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 from SU(3) flavour symmetry
  → Ω⁻ predicted
- 1962: Discovery of Ω⁻ : success of the Eight-fold way.
- 1964: Quark Model (Gell-Mann and Zweig)







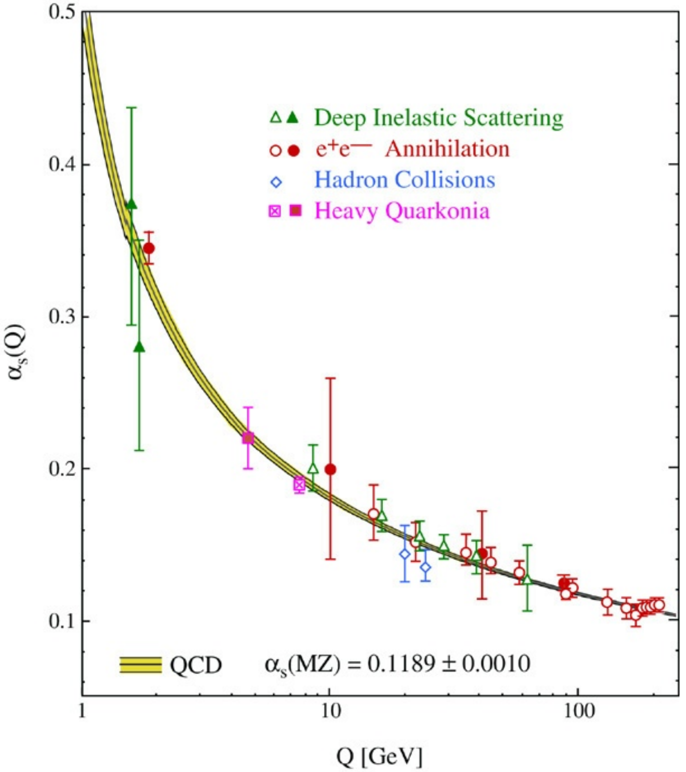
Hyperons and the Quark Model

The constituent Quark Model was a huge leap forward in our understanding of the microscopic world.

QM successful in classifying hadrons and describing their static properties.

QM + parton model → QCD

- high above the QCD cut-off Λ_{QCD} perturbative QCD (pQCD) successfully applied



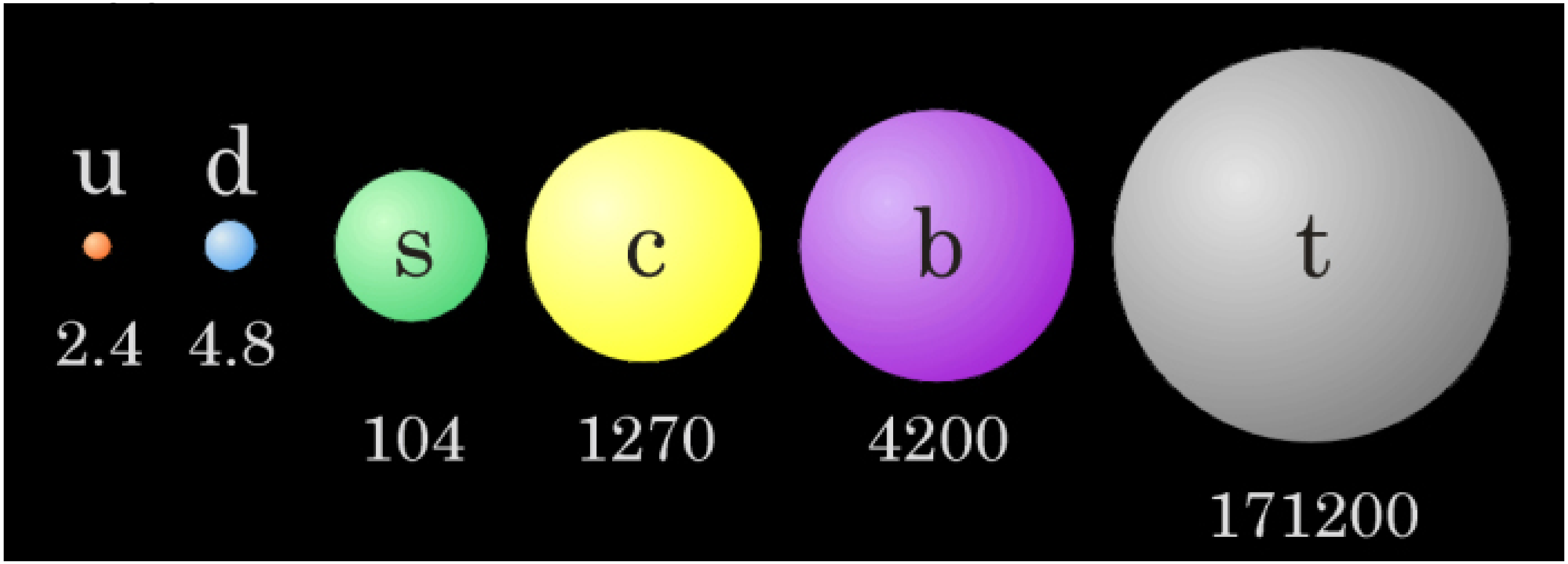
Strangeness production

- *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



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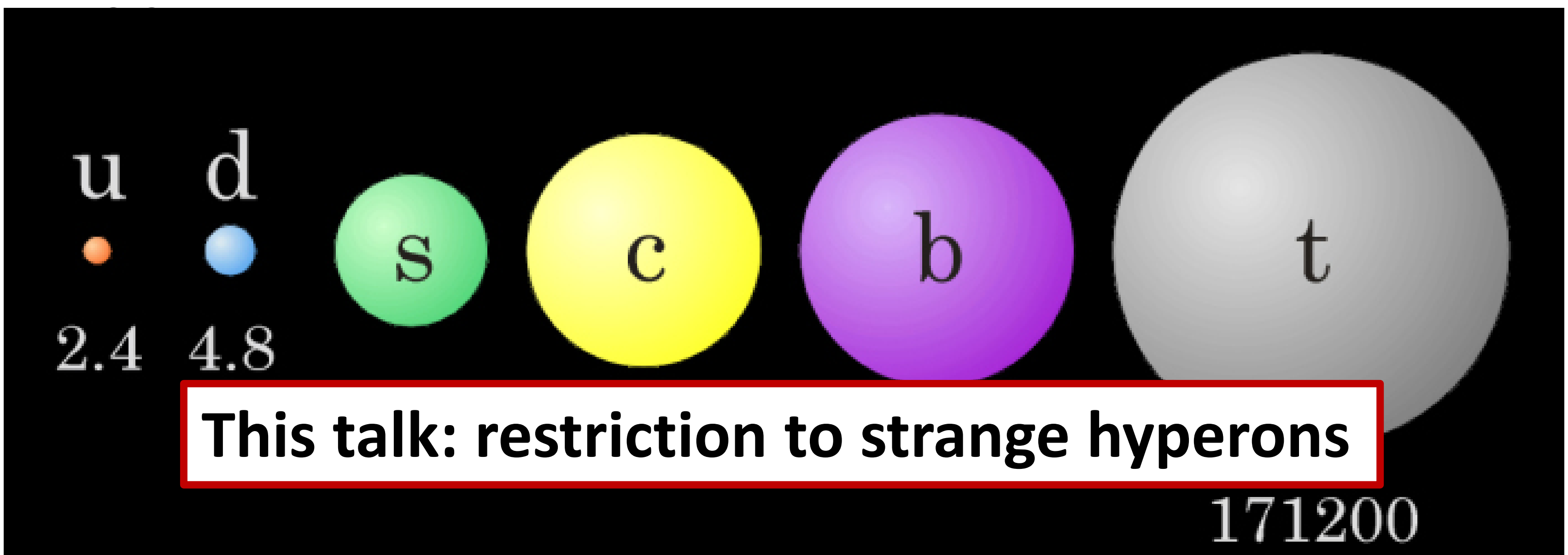

Open questions in hadron physics

- Why and how are quarks confined into hadrons?
  - Relevant degrees of freedom?
  - Mass generation from the strong interaction?

    (Higgs mechanism 1-2% of the visible mass in the Universe)
- Spin crisis of the nucleon?
- New state(s) of matter, like quark-gluon plasma?

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Theories need guidance from experiments

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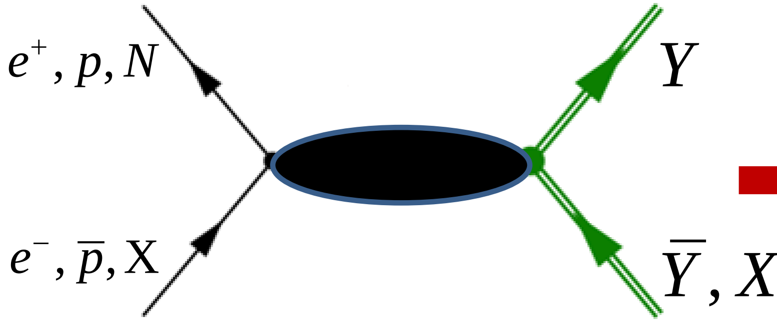
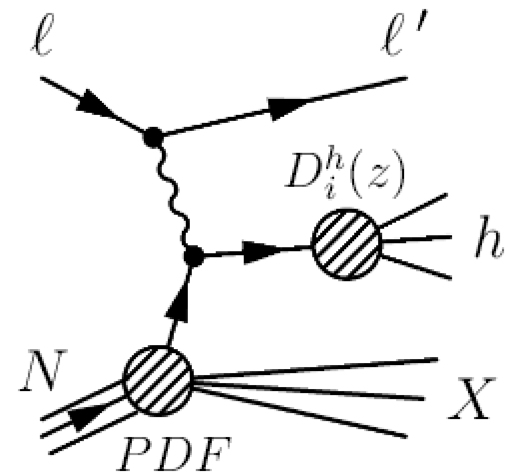
Can hyperons help us finding the answers here?

Hyperon production at
low/intermediate energies
-probes QCD in confinement domain
- Search for CP violation in baryon decays

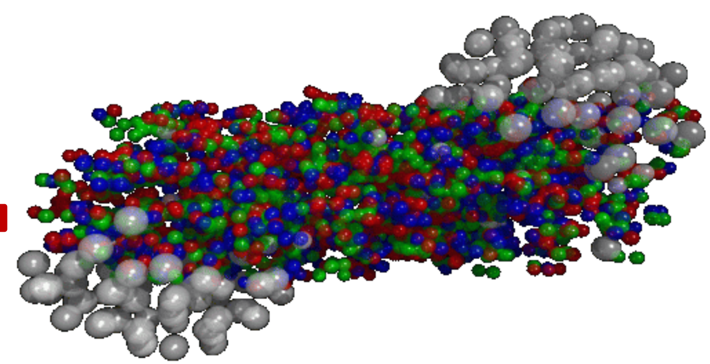


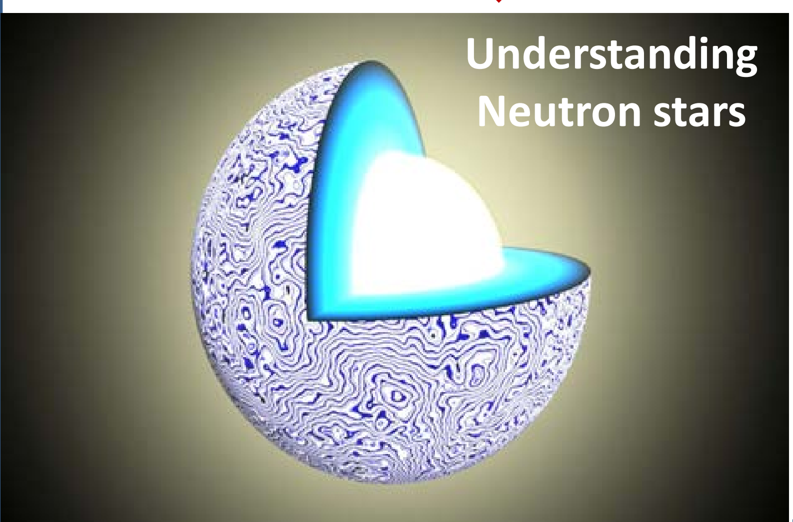
Inclusive hyperon production
at high energies
- probes spin and flavour
structure of nucleons and
hyperons



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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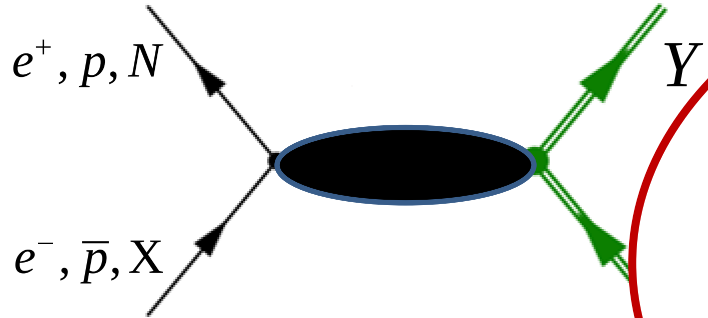

Hyperons / Strangeness provides a diagnostic tool for various studies of (mainly) non-pQCD.

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Hyperon production in high energy heavy ion collisions
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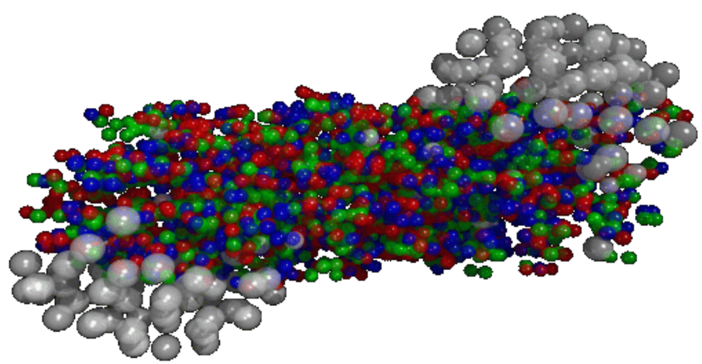

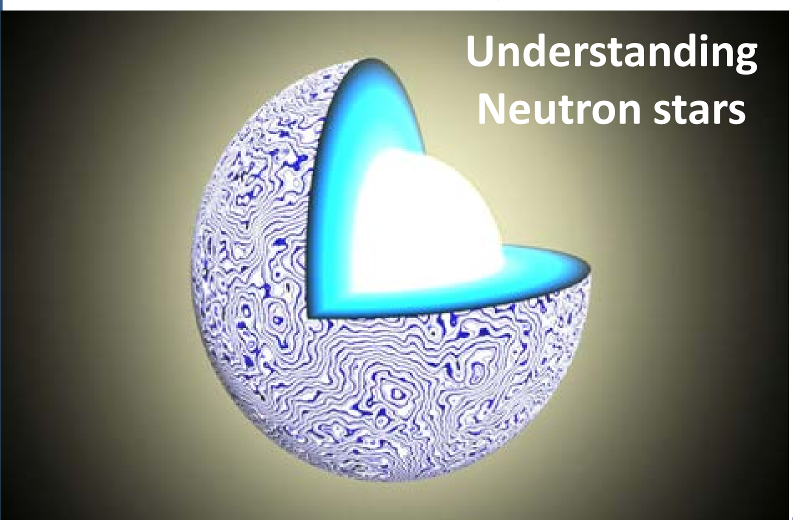

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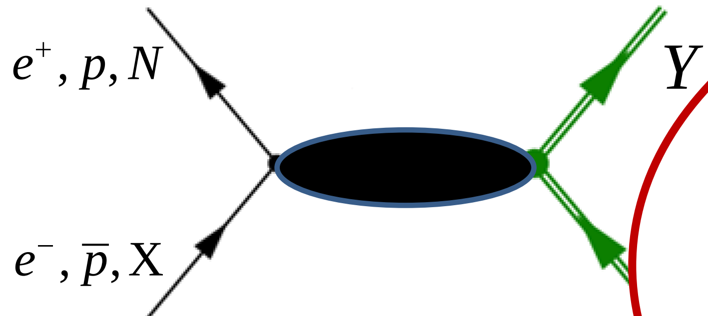

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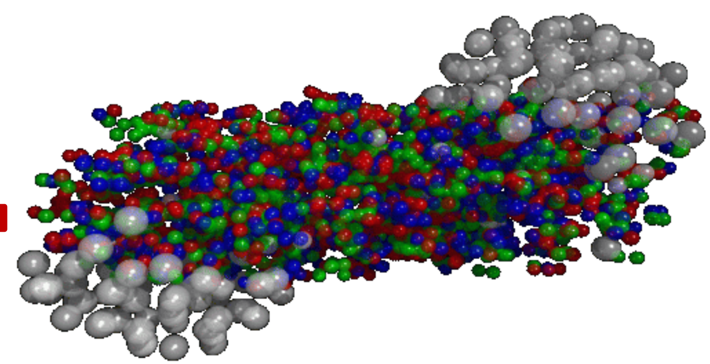
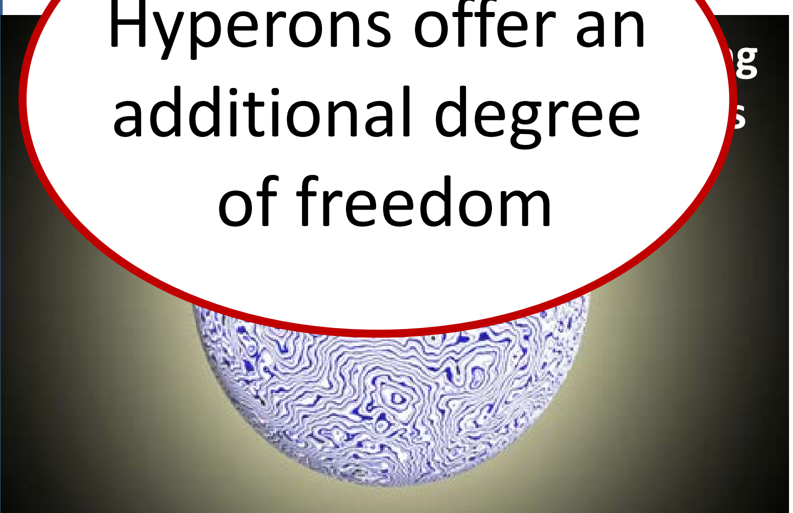


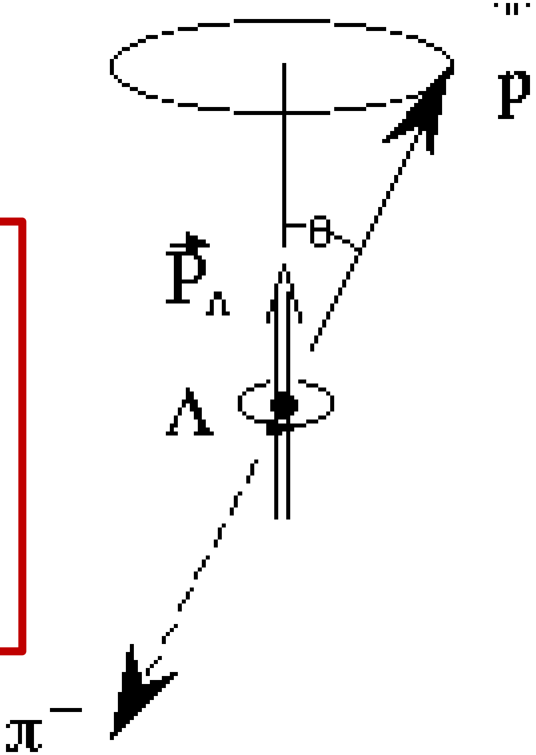


Hyperons offer an additional degree of freedom

Experimental properties

Con: Hyperons unstable → cannot serve as target.

Pro: **Polarisation** accessible by the parity violating, ”self-analysing” decay:

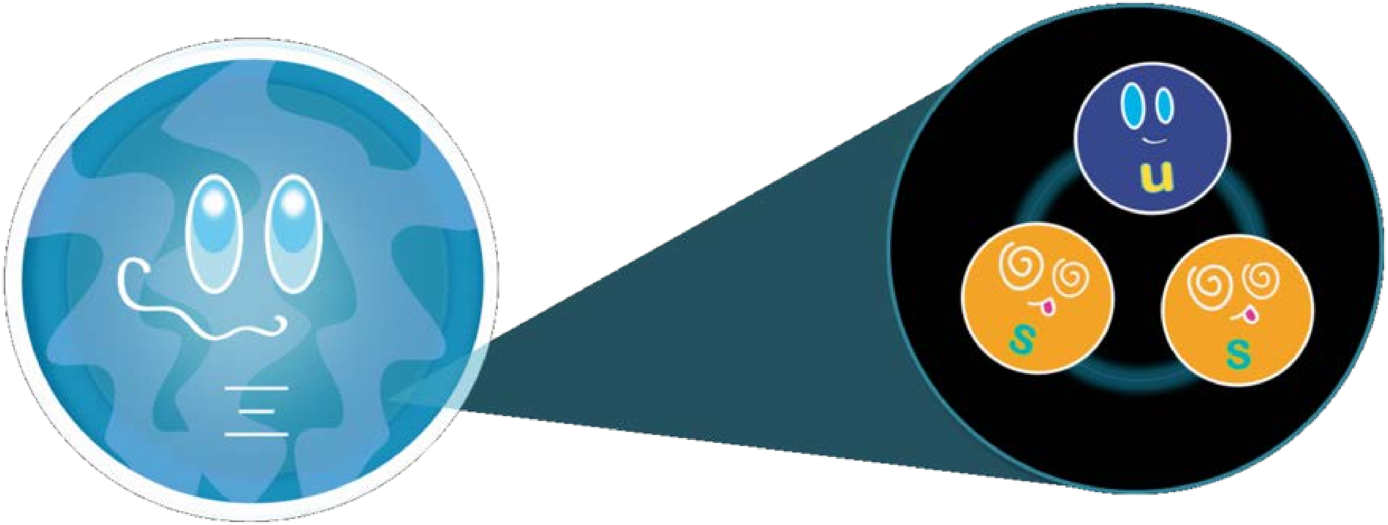


Example: Angular distribution of $\Lambda \rightarrow p\pi^-$ decay

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

P_Λ : polarisation

$\alpha = 0.64$ asymmetry parameter

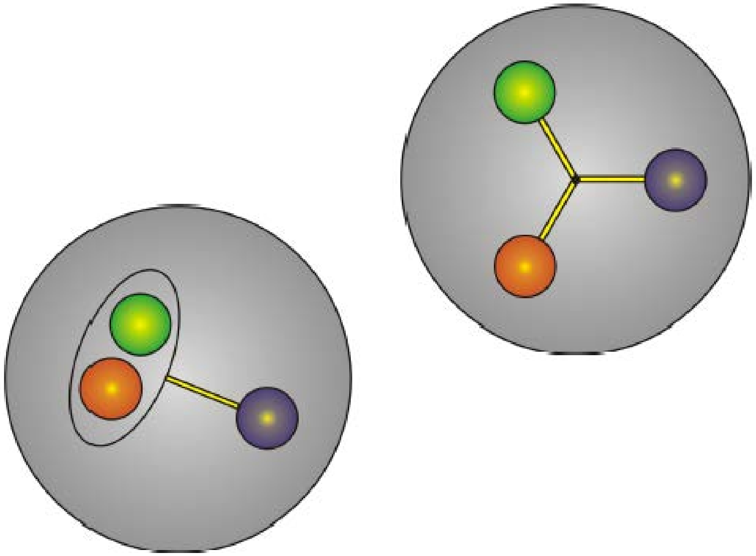


PRESENT: RECENT HIGHLIGHTS IN HYPERON PHYSICS

Hyperon spectroscopy

Many open questions reveal complicated reality

- Forces between quarks inside a hadron?
- Mass generation?
- Degrees or freedom?



Hyperon spectroscopy

Many open questions reveal complicated reality

- Forces between quarks inside a hadron?
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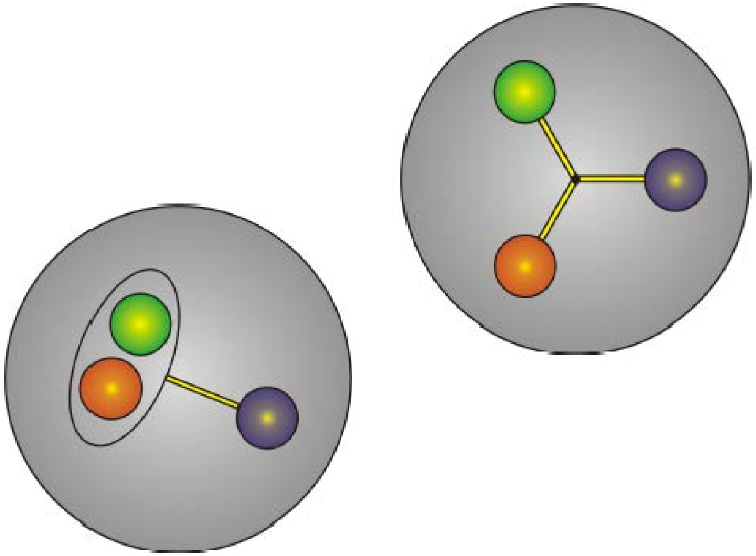
Excited hyperons can take our understanding of the quarks and the strong interaction
to the next level

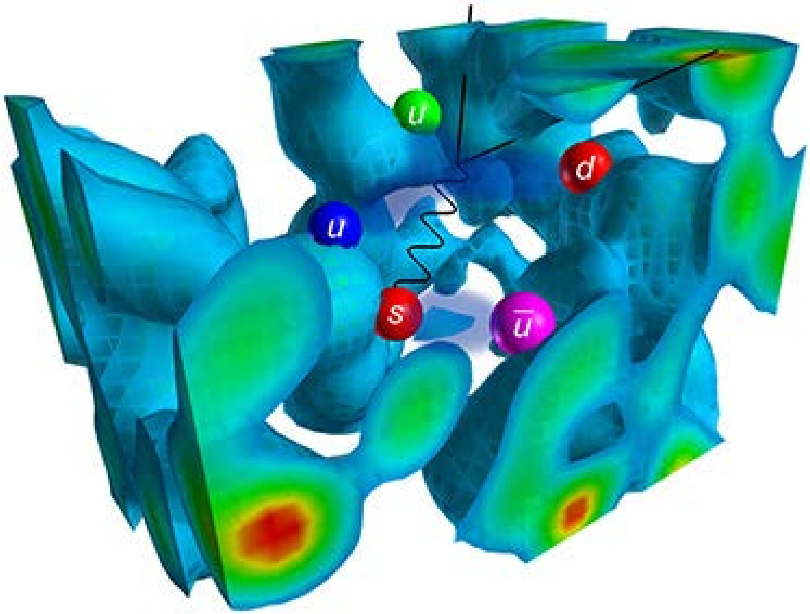


Highlight: The Λ(1405) hyperon

- Nature of Λ(1405) a puzzle for decades – wrong mass according to the simple Quark Model.

- Dynamically generated?
  - One or two poles?*
  - Subthreshold $N\bar{K}$ molecule?

- Assumed to have spin and parity $J^P = \frac{1}{2}^-$ but no direct measurement until now.

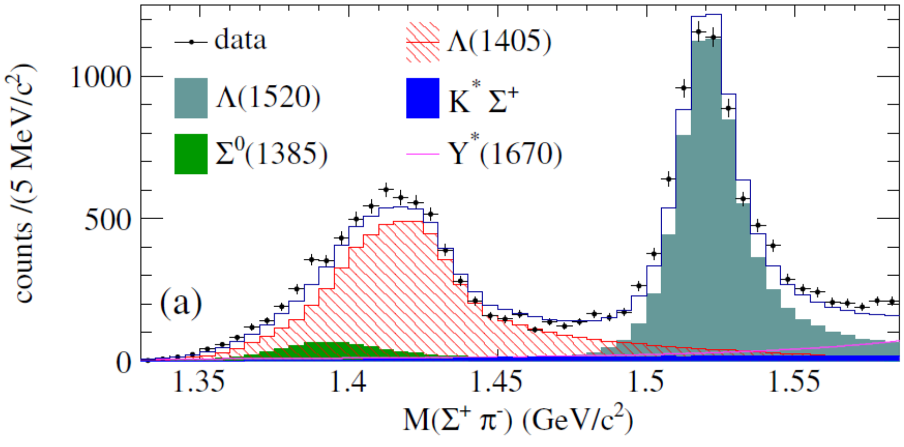


From Physics World, April 2015

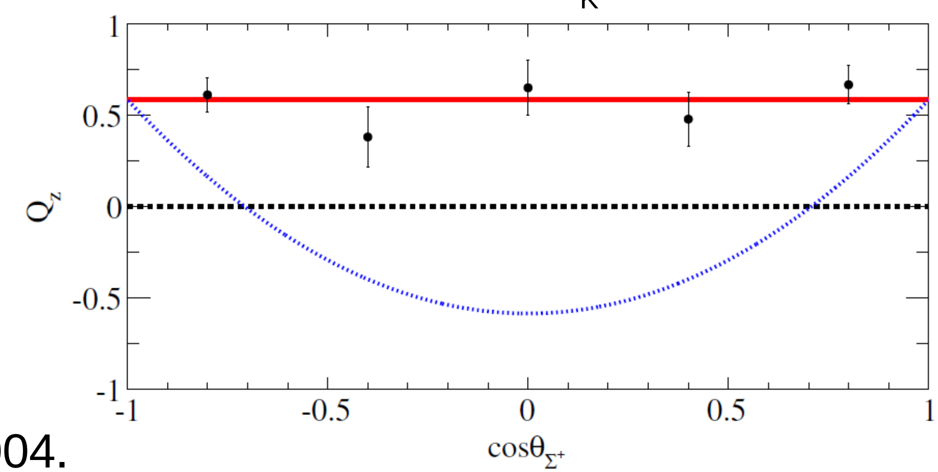
* Note on Λ(1405) in PDG 2014.

Highlight: The Λ(1405) hyperon

- The reaction $\gamma p \rightarrow K^{+}\Lambda(1405), \Lambda(1405) \rightarrow \Sigma^{+}\pi^{-}$ studied with CLAS at JLAB.
- Polarisation of Σ^{+} as a function of $cos\theta_{\Sigma}$ in bins of $cos\theta_{K}$ and CM energy studied.
  - Results consistent with $J^{P} = \frac{1}{2}^{-}$
  - $\frac{1}{2}^{+}$ and $\frac{3}{2}^{-}$ strongly disfavoured.



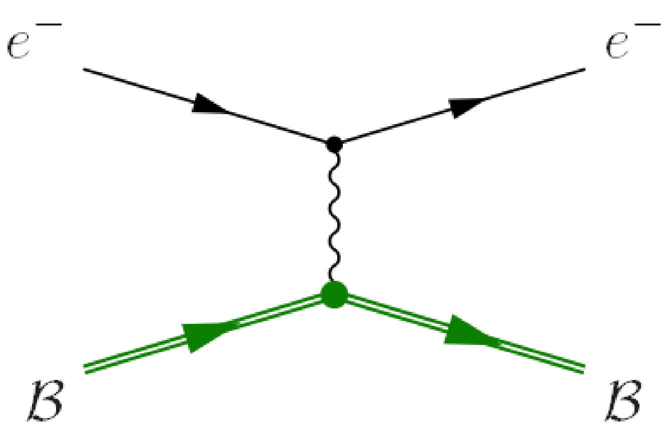
Polarisation of Σ for 2.65 < *W* < 2.75 GeV and 0.7 < $\cos\theta_K$ < 0.8.



Results and plots from PRL 112 (2014) 082004.

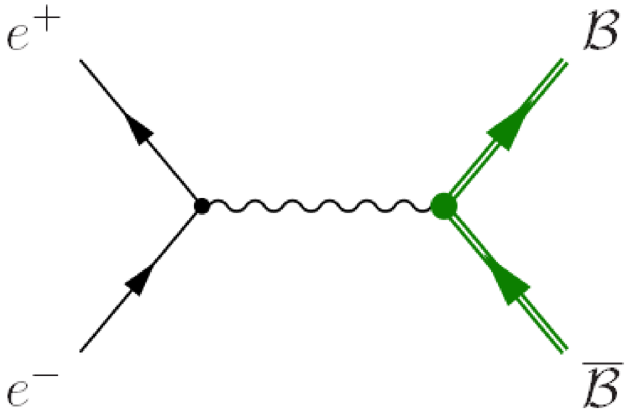
Electromagnetic form factors

- Describes the electromagnetic structure of hadrons.
- Fundamental observable of QCD.



Space-like EMFF's from elastic e^- *B* scattering.

→ Extensive measurements of proton EMFF's.



Time-like EMFF's: in e^+e^- annihilations

Time-like EM FF's

- Nucleons:
  - Time-like EMFF's should coincide with space-like at high Q^2.

- Hyperons:
  - Difference between nucleon and hyperon EMFF $\rightarrow$ test of SU(3) symmetry.
  - Currently the best way to study hyperon structure.
  - Polarisation observables experimentally accessible.

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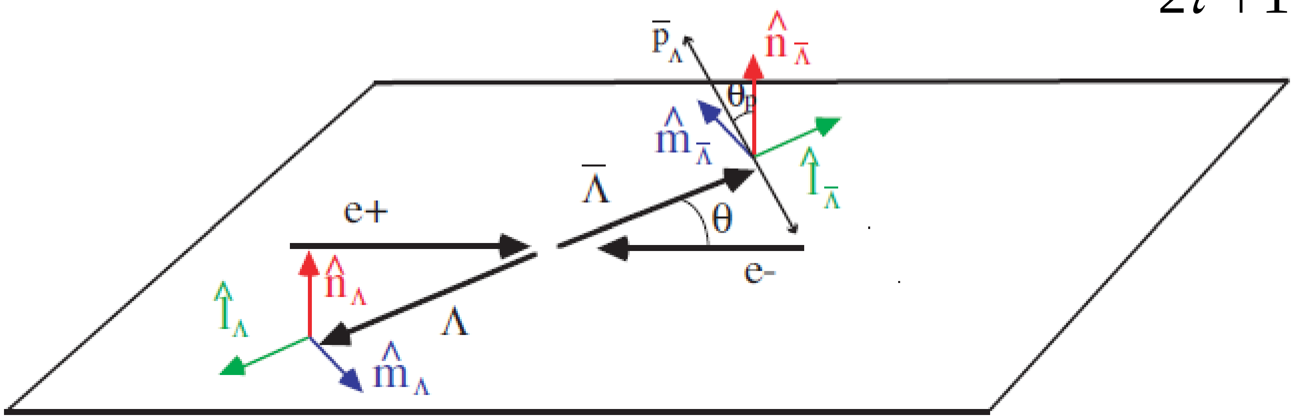
Time-like EM FF's

- Differential cross section for spin ½ particles in terms of EMFF's: $$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 \beta C}{4Q^2}\left[(|G_M(Q^2)|^2 (1+\cos^2\theta) + \frac{1}{\tau}|G_E(Q^2)|^2 \sin^2\theta) \right]$$
where G_E = electric FF, G_M = magnetic FF and $\tau = \frac{Q^2}{4M_B}$

- Effective form factor
$$|F(Q^2)|^2 = \frac{2\tau |G_M(Q^2)|^2 + |G_E(Q^2)|^2}{2\tau + 1} \propto \sigma(Q^2)$$



Time-like EM FF's

- Time-like EMFF's are complex:
  with a relative phase ΔΦ between G_E and G_M

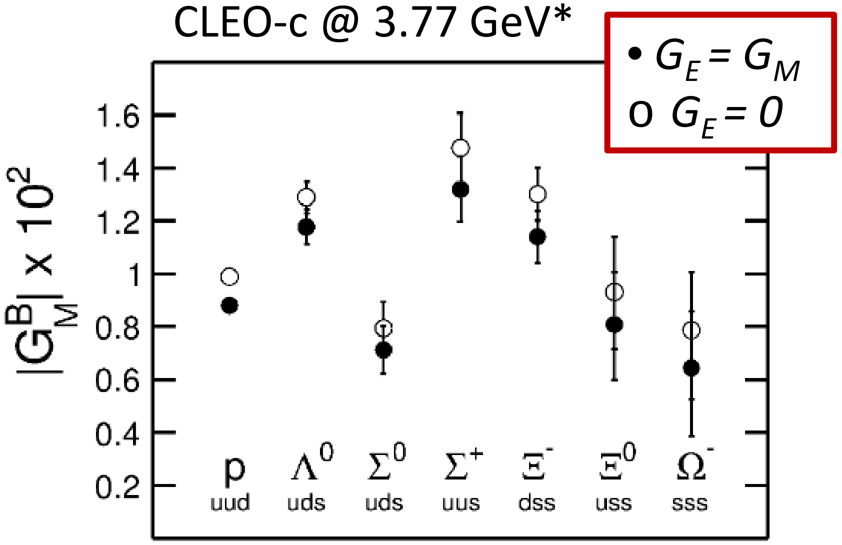
- The phase ΔΦ has a polarisation effect on the final state:

$$P_n = \frac{\sin 2\theta \,|G_E(Q^2)||G_M(Q^2)|\sin\Delta\Phi}{\frac{1}{\tau}|G_E(Q^2)|^2 \sin^2\theta + |G_M(Q^2)|^2 (1+\cos^2\theta)}$$

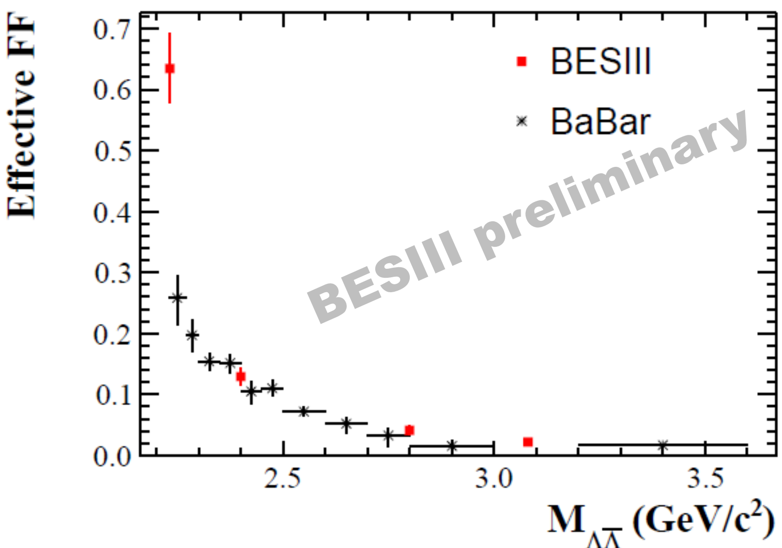
Highlight: Hyperon time-like FF's

- Effective EMFF of *p*, Λ, Σ^0, Σ^+, Ξ^- and Ω^- from CLEO-c* @ Cornell at *Q* = 3.77 GeV
- Effective EMFF of Λ from BESIII** @ BEPC-II at 2.23, 2.4, 2.8 and 3.09 GeV.
- Good consistency with previous BABAR*** data
- Threshold enhancement observed in BESIII.

CLEO-c @ 3.77 GeV*



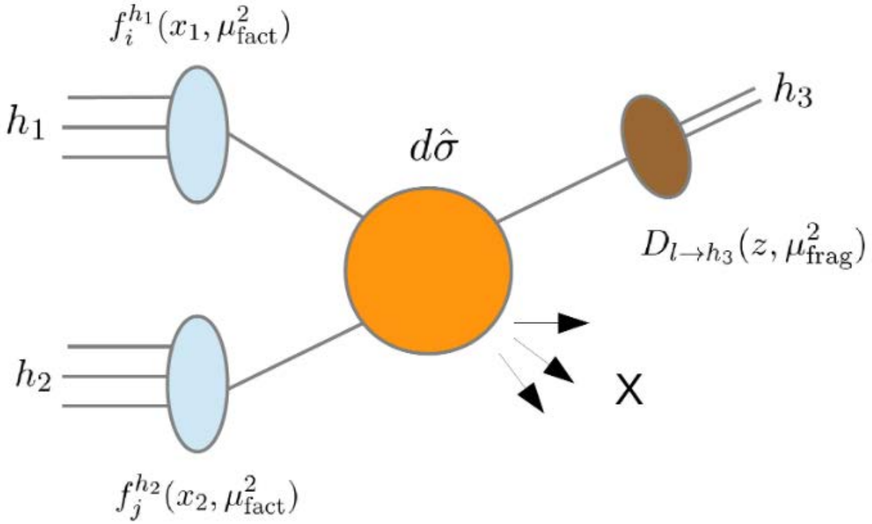
BES III scan data**



* PLB 739 (2014) 90, ** C.Li *et al.*, poster at EPS-HEP 2015, *** PRD 76 (2007) 092006

Inclusive hyperon production at high energies

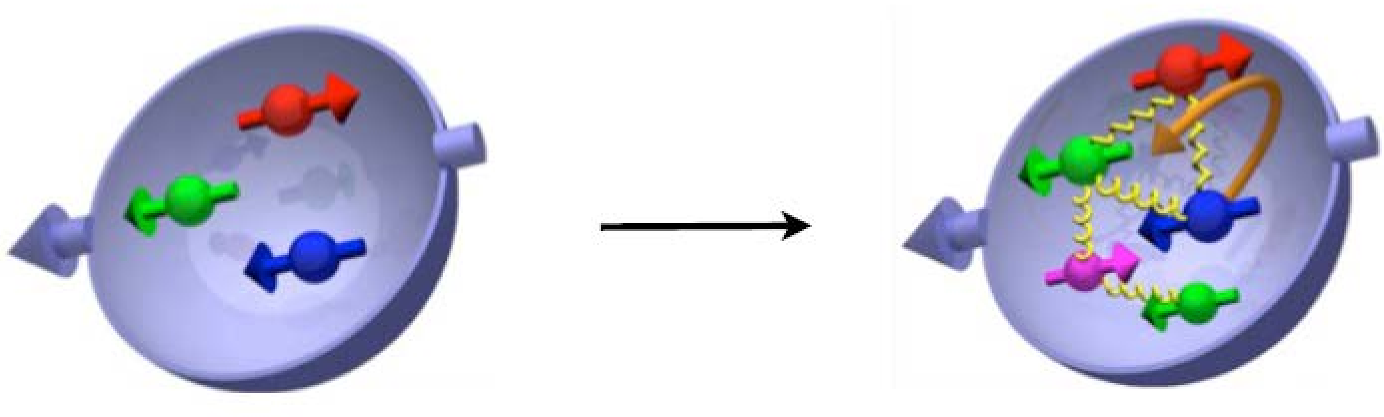
- Hyperon production in inclusive $e^+ e^-$, $e/\mu/\nu\ N$ and NN .
- Assumption: reactions can be factorised into universal soft (non-pQCD) and calculable hard (pQCD) processes.
- Parton distribution functions (PDF) and fragmentation functions (FF) described by non-pQCD.
  - PDF: spin and flavour structure of the nucleon.
  - FF: spin and flavour structure of produced hadron.



H. Paukkunen *et al.*,Proc. from DIS2014

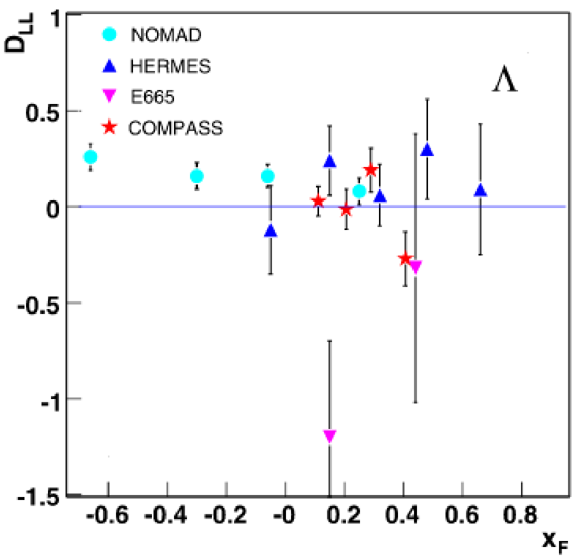
Inclusive hyperon production at high energies

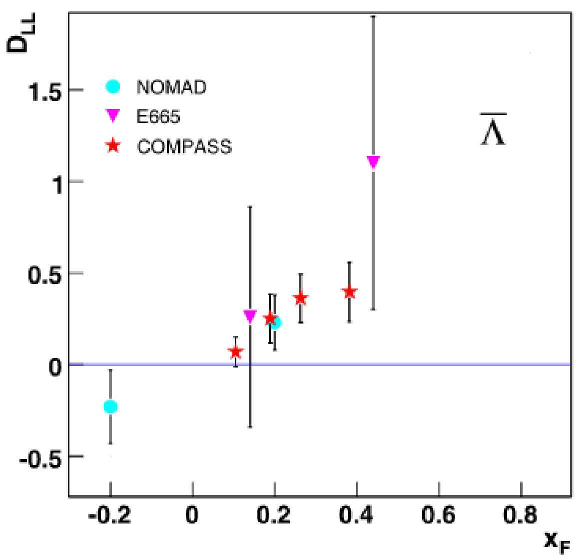
- Spin crisis of the nucleon: only small part of the nucleon spin comes from the valence quarks!
- Role of sea quarks in the nucleon?
- Is there a spin crisis also for hyperons?
  - Simple quark SU(6): Λ spin entirely from *s* quark.
  - Difficult to measure but spin observables provide tests of models.

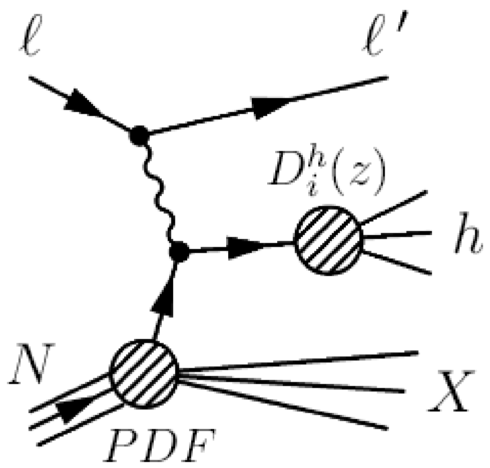


Highlight: hyperon production in polarised lepton DIS

- Longitudinal polarisation transfer D_{LL} from muons to Λ and $\bar{\Lambda}$ studied by COMPASS @ CERN.*
  - D_{LL} of Λ ~ 0, as in NOMAD**, E665*** and HERMES****.
  - D_{LL} of $\bar{\Lambda}$ increases with x_F → confirms importance of $\bar{s}$ distribution in the nucleon.
- Recent COMPASS paper: the role of heavy hyperons in the production of Λ in DIS*****







* EPJC 64 (2009) 171
** NPB 588 (2000) 3; NPB 605 (2001) 3
***EPJC 17 (2000) 263
****PRD 74 (2006) 74
*****EPJC 73 (2013) 2581

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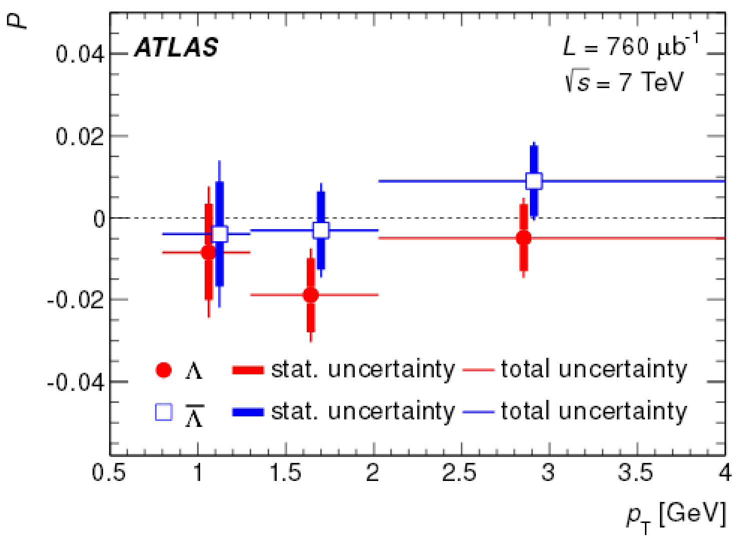
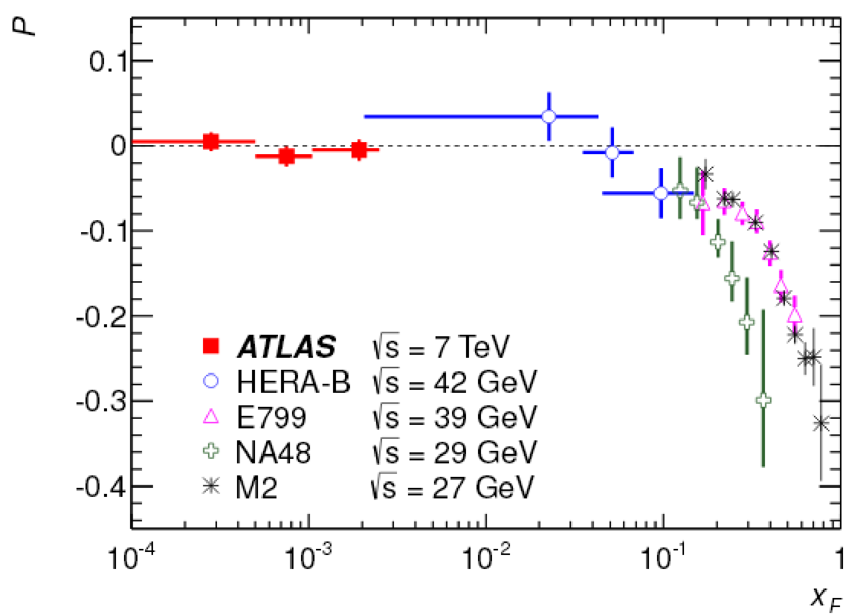
Highlight: hyperon polarisation in pp collisions on the TeV scale

- Λ hyperon polarisation observed at higher energies than expected in *pN* collisions in the √s~10-100 GeV range.
  - Does this effect remain at even higher energies?

- No polarisation observed by the ATLAS experiment.





* PRD 91 (2015) 032004

Hypernuclear Physics

An additional degree of freedom when a nucleon is replaced by a hyperon.

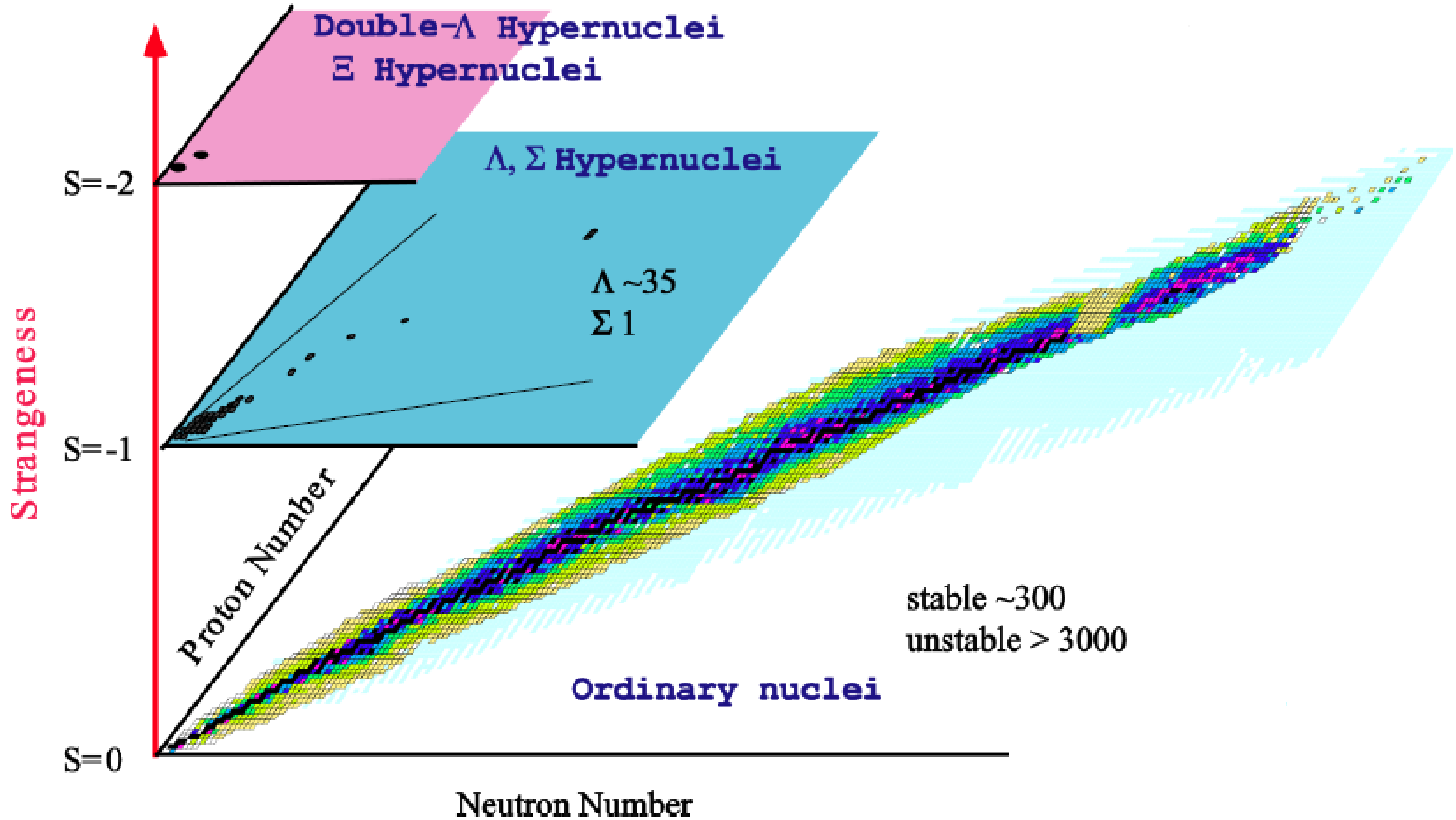


Fig. from E. Hiyama (RIKEN)

Hypernuclear physics

Why hypernuclei?

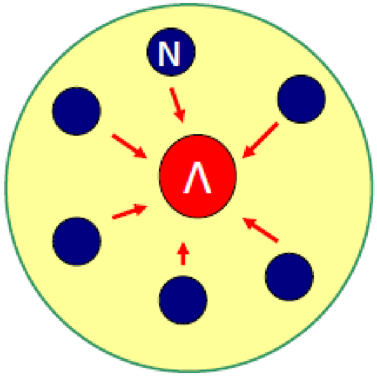
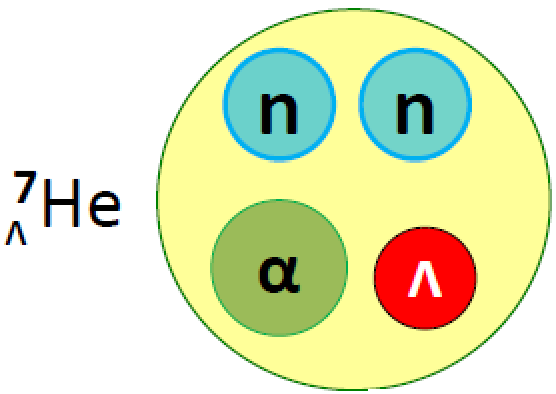


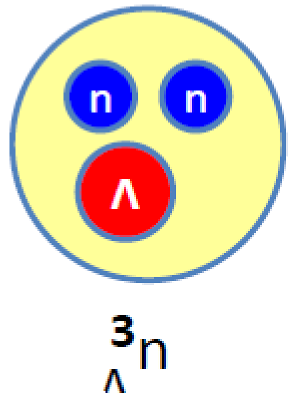
Fig. from E. Hiyama (RIKEN)

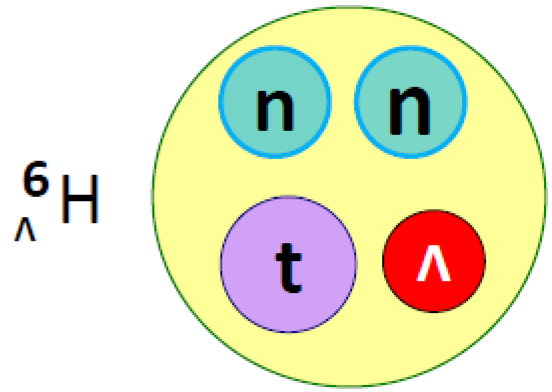
- Neutrons added to a nucleus prevented from reaching the inner core by the Pauli principle
- No Pauli principle between hyperons and nucleons
  → Hyperons reach deep inside the nucleus and attract surrounding nucleons
- Attractive ΛN potential gives stability against neutron decay.
- Hypernuclei a tool to understand neutron stars *.

* NPA 804 (2008) 309.

Highlight: Recently observed neutron-rich hypernuclei







$_{\Lambda}{}^{7}$He observed by E011 @ JLAB *.

$_{\Lambda}{}^{3}$n observed by HypHI @ GSI**.

$_{\Lambda}{}^{6}$H observed by FINUDA @ Frascati*** but not by E10 @ JPARC.****

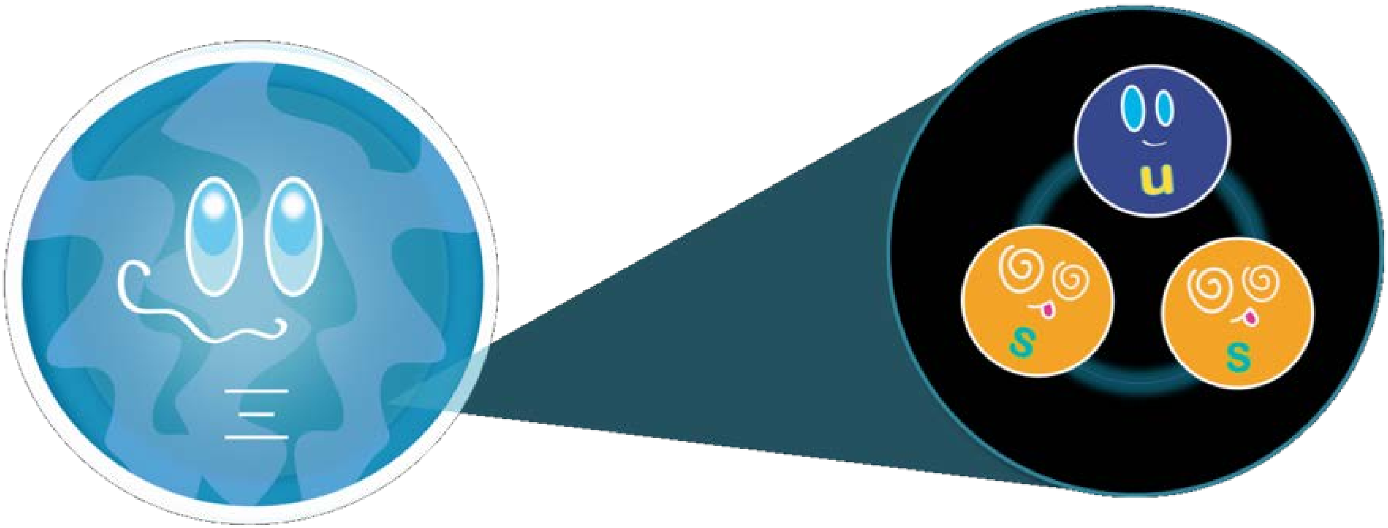
* PRL 110 (2013)12502,**PRC 88 (2013)R041001,***PRL108 (2012)042051,****PLB 729 (2014)39

Figs. From E. Hiyama

Not treated here…

Hyperon production in heavy ion collisions

→ Other related plenary talks and devoted parallel session



FUTURE – CURRENT AND COMING FACILITIES

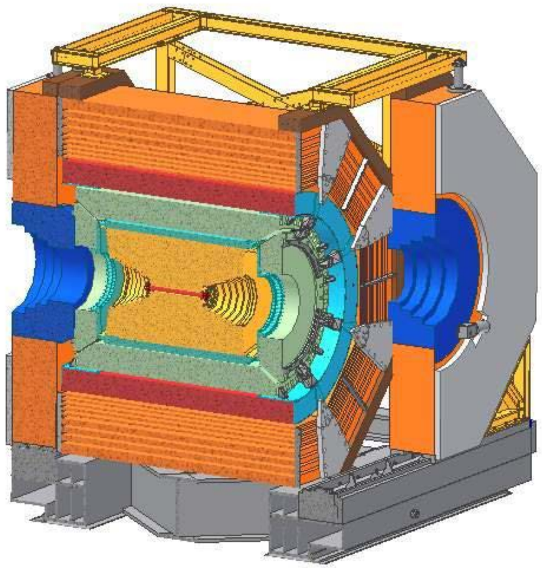
Running: BES III @ BEPC-II

- New data on tape for precision studies of hyperon form factors.
- Possible to extract Λ polarisation, angular distribution and $\Lambda\bar{\Lambda}$ spin correlation:

→ Complete determination of G_E and G_M : ratio R, phase ΔΦ.

→ Provides powerful constraint of theoretical models

→ Results coming soon!



Running: GlueX @ JLAB

Cascade hyperon spectroscopy

- Very few established excited Ξ states.
- Even fewer with known J^P

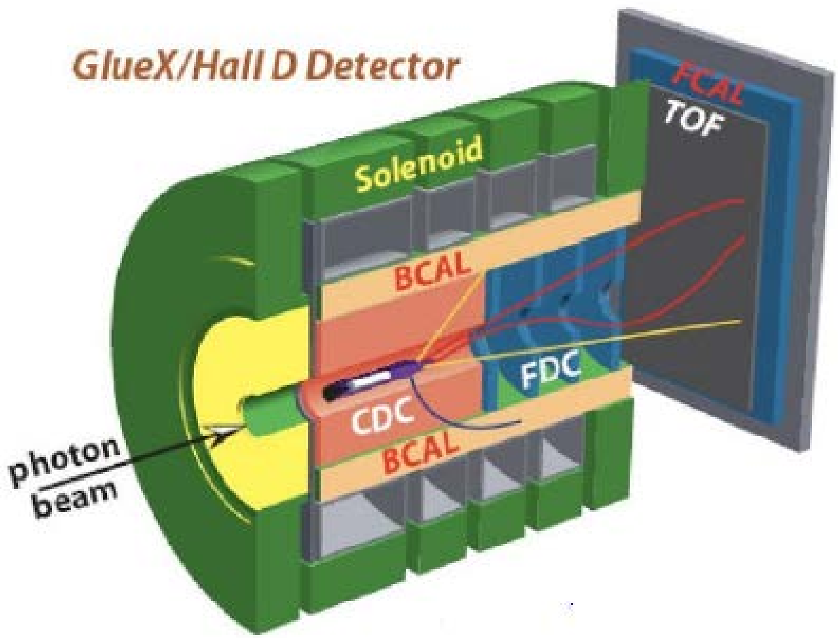
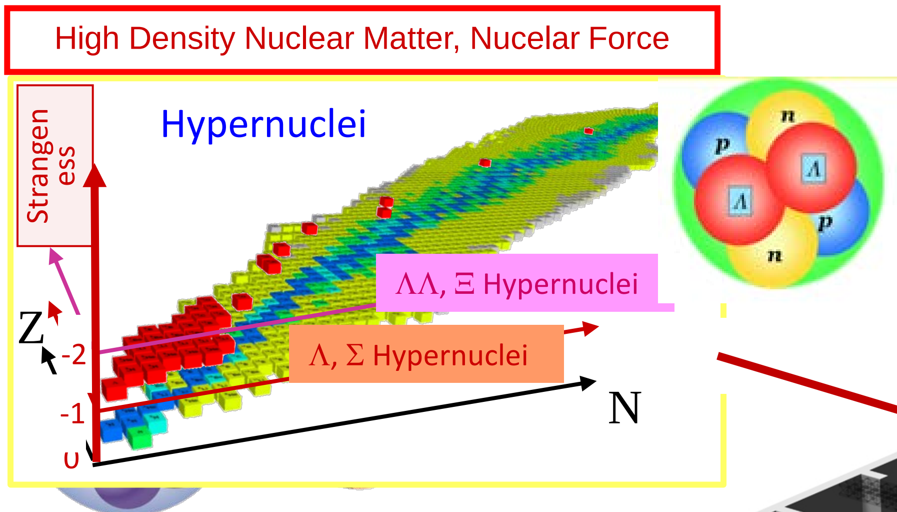


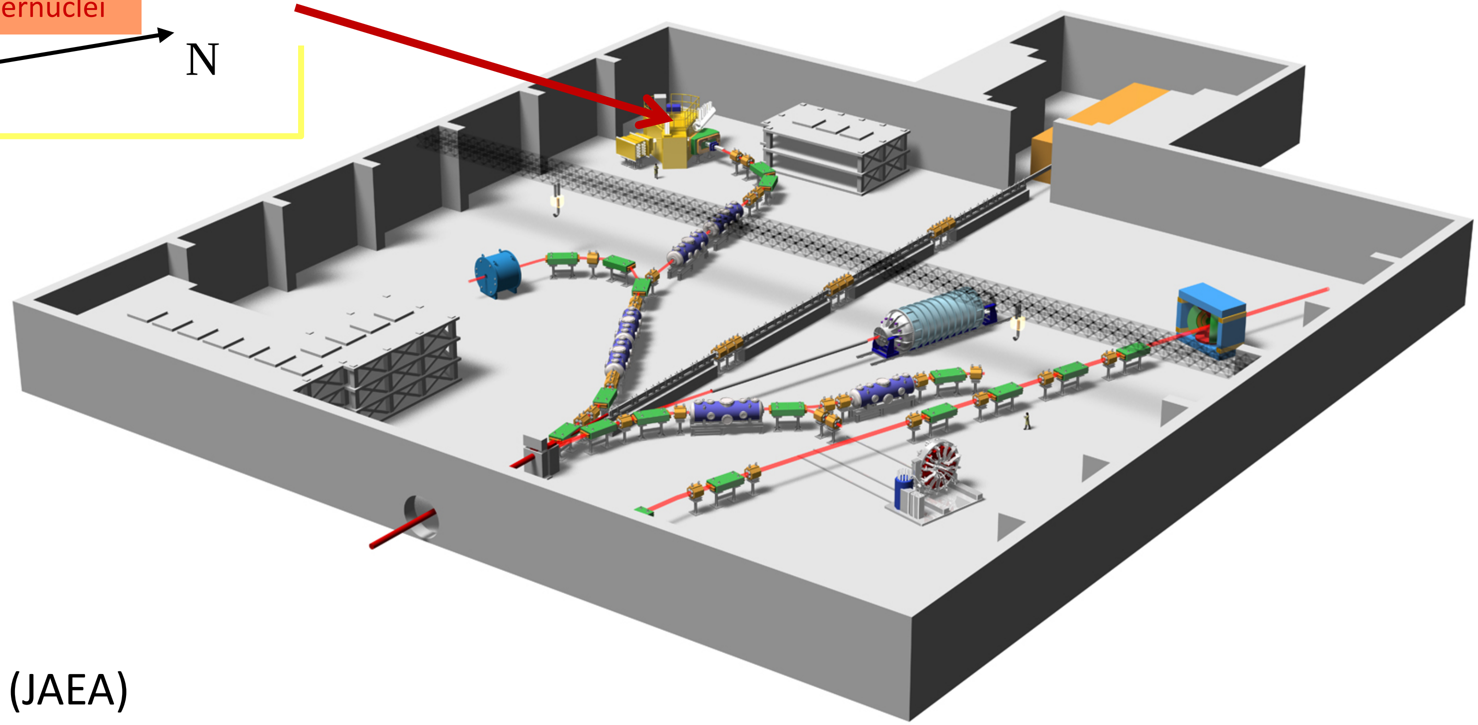
Fig. From V. Credé (GlueX)

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	$N(1440)$	$\Lambda(1600)$	$\Sigma(1660)$	$\Xi(?)$	
$1/2^-$	$(70,1^-_1)$	1/2	$N(1535)$	$\Lambda(1670)$	$\Sigma(1620)$	$\Xi(?)$	$\Lambda(1405)$
$3/2^-$	$(70,1^-_1)$	1/2	$N(1520)$	$\Lambda(1690)$	$\Sigma(1670)$	$\Xi(1820)$	$\Lambda(1520)$
$1/2^-$	$(70,1^-_1)$	3/2	$N(1650)$	$\Lambda(1800)$	$\Sigma(1750)$	$\Xi(?)$	
$3/2^-$	$(70,1^-_1)$	3/2	$N(1700)$	$\Lambda(?)$	$\Sigma(?)$	$\Xi(?)$	
$5/2^-$	$(70,1^-_1)$	3/2	$N(1675)$	$\Lambda(1830)$	$\Sigma(1775)$	$\Xi(?)$	
$1/2^+$	$(70,0^+_2)$	1/2	$N(1710)$	$\Lambda(1810)$	$\Sigma(1880)$	$\Xi(?)$	$\Lambda(?)$
$3/2^+$	$(56,2^+_2)$	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	$\Delta(1600)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$	
$1/2^-$	$(70,1^-_1)$	1/2	$\Delta(1620)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$	
$3/2^-$	$(70,1^-_1)$	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	$\Delta(2420)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$	

Running:J-PARC

- Hypernuclear physics
- H (ΛΛ) dibaryon search
- Role of Λ(1405) in Kpp interaction

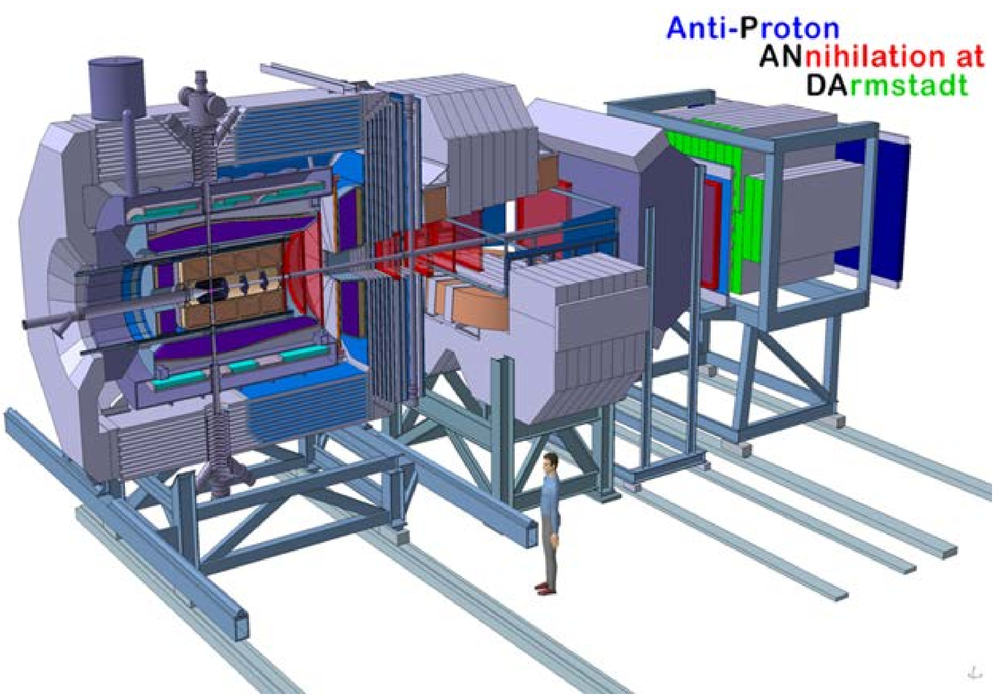




Figs. from K. Tanida (JAEA)

Next generation: PANDA

- Antiproton beam between 1-15 GeV/c
- Hyperon spectroscopy
- Spin observables in hyperon production
- Search for CP violation in
  hyperon decay
- Hypernuclear physics



Next generation: PANDA

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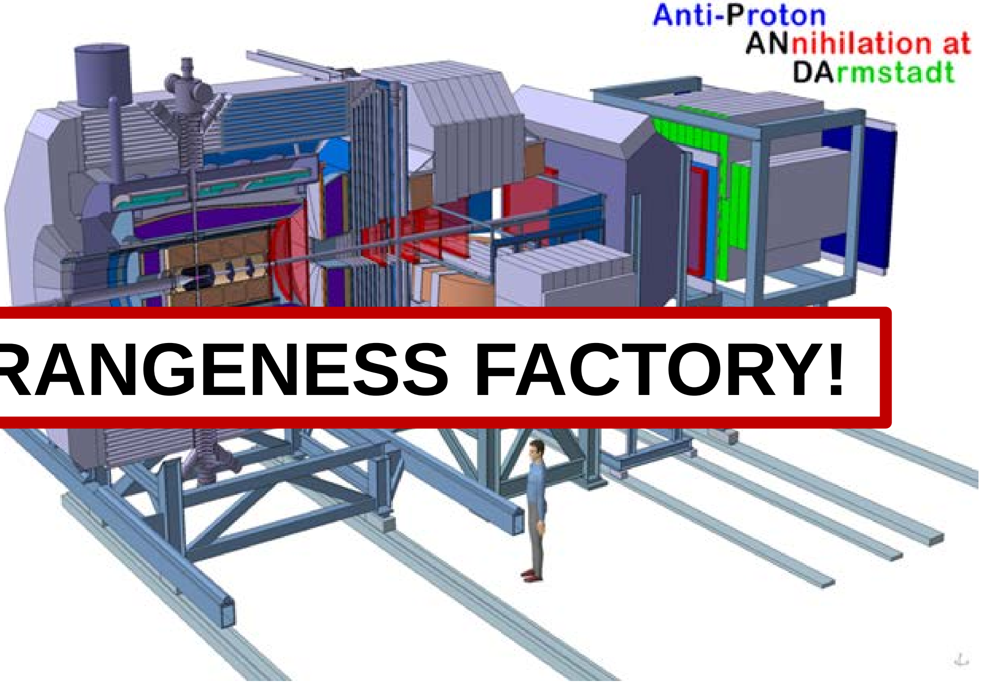

PANDA WILL BE A STRANGENESS FACTORY!

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Hyperon spectroscopy with PANDA

J^P	(D, L_N^P)	S	Octet members				Singlets
1/2$^+$	$(56,0_0^+)$	1/2	$N(939)$	$\Lambda(1116)$	$\Sigma(1193)$	$\Xi(1318)$	
1/2$^+$	$(56,0_2^+)$	1/2	$N(1440)$	$\Lambda(1600)$	$\Sigma(1660)$	$\Xi(?)$	
1/2$^-$	$(70,1_1^-)$	1/2	$N(1535)$	$\Lambda(1670)$	$\Sigma(1620)$	$\Xi(?)$	$\Lambda(1405)$
3/2$^-$	$(70,1_1^-)$	1/2	$N(1520)$	$\Lambda(1690)$	$\Sigma(1670)$	$\Xi(1820)$	$\Lambda(1520)$
1/2$^-$	$(70,1_1^-)$	3/2	$N(1650)$	$\Lambda(1800)$	$\Sigma(1750)$	$\Xi(?)$	
3/2$^-$	$(70,1_1^-)$	3/2	$N(1700)$	$\Lambda(?)$	$\Sigma(?)$	$\Xi(?)$	
5/2$^-$	$(70,1_1^-)$	3/2	$N(1675)$	$\Lambda(1830)$	$\Sigma(1775)$	$\Xi(?)$	
1/2$^+$	$(70,0_2^+)$	1/2	$N(1710)$	$\Lambda(1810)$	$\Sigma(1880)$	$\Xi(?)$	$\Lambda(?)$
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	$\Delta(1600)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$	
1/2$^-$	$(70,1_1^-)$	1/2	$\Delta(1620)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$	
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	$\Delta(2420)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$	

Excited states of

- double-strange hyperons (Ξ*)
- triple-strange hyperons (Ω*)
- single- and non-strange baryons (Λ*, Σ*, *N**)

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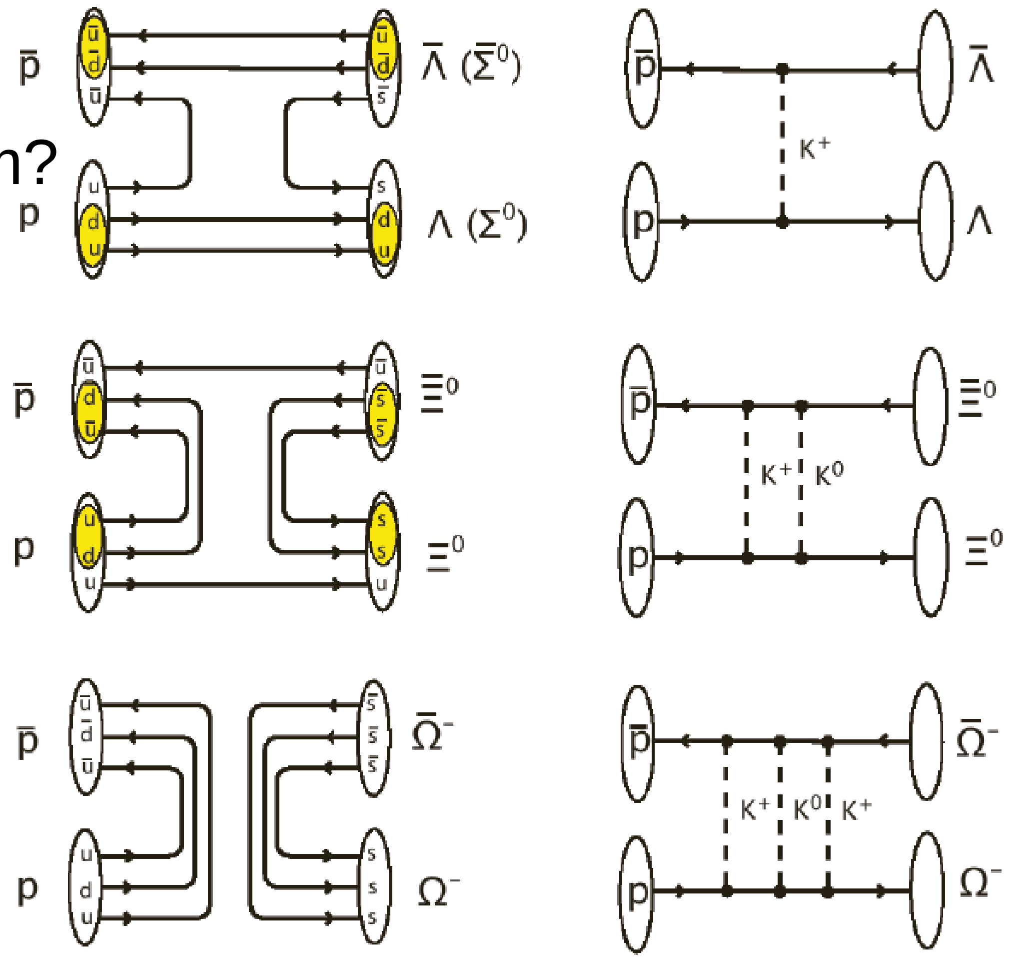
Spin observables in $Y\bar{Y}$ production

- Ballpark for non-perturbative QCD studies.
- Relevant degrees of freedom?
  - meson-baryon?
  - quark-gluon?
- Spin observables powerful test of models.
- PWA tools being developed in an Uppsala/Groningen collaboration.



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Search for CP violation in hyperon decays

- CP violation one of three necessary conditions to explain matter-antimatter asymmetry in the Universe.*
- Never observed for baryons.
- Asymmetry parameters in hyperon decays sensitive to CP violation.
- PANDA will provide the large yields of hyperons and antihyperons required for measurement.
- Feasibility studies show promising results.**

*Sakharov, JETP Lett. 5 (1976) 24.
**E. Thomé, Ph.D. Thesis, Uppsala U. (2012)

Hypernuclear physics with PANDA

- Double strange hypernuclei
- Anti-hyperon bound states

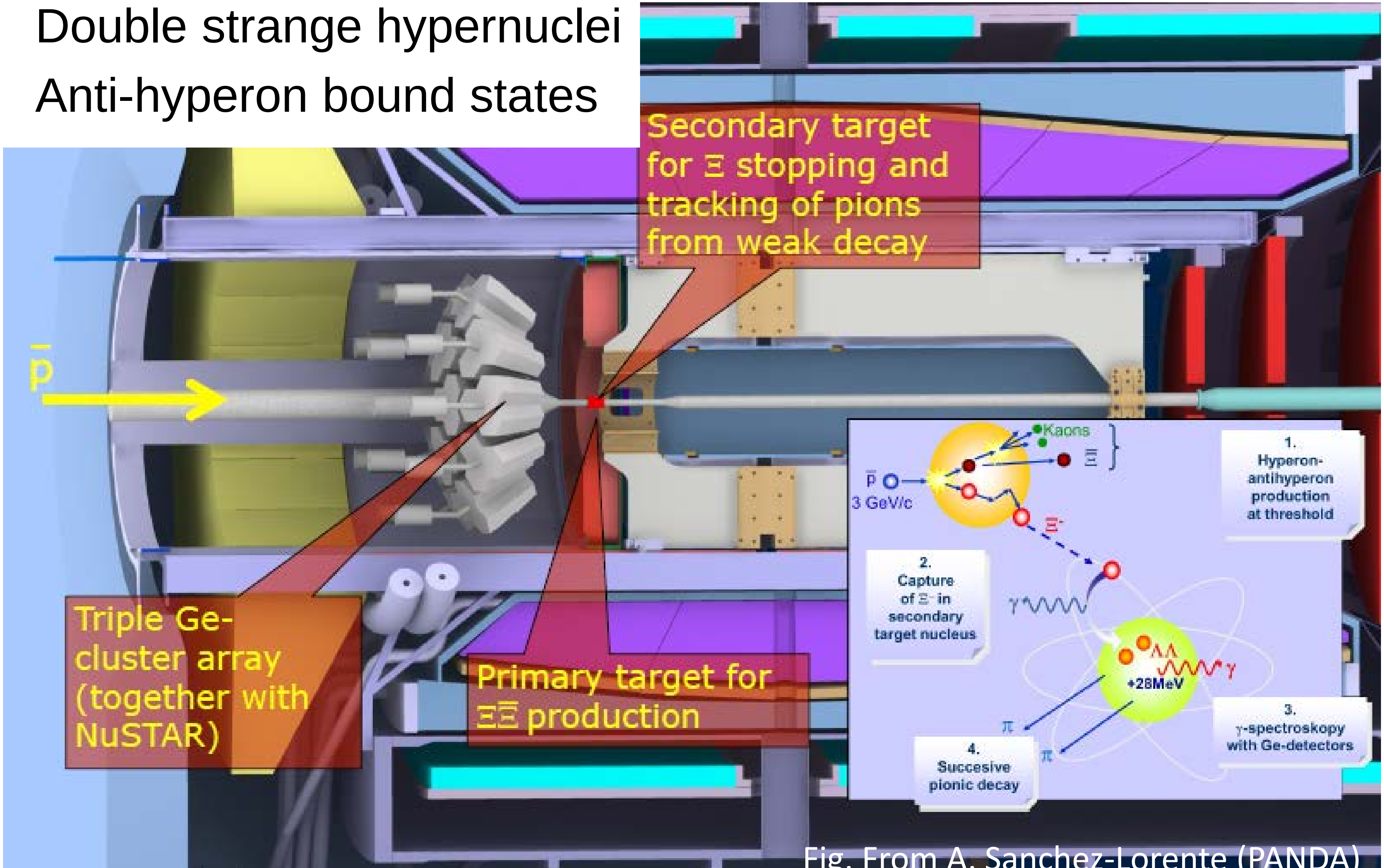

Fig. From A. Sanchez-Lorente (PANDA)

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Summary

- Strange hyperons help us to understand the world over several energy scales and many levels of complexity.
- The self-analysing decay enables studies of spin observables → provide powerful constraints for theoretical models.
- Ground state hyperons played an important part in formulating the quark model.
- Hyperons provide one key to CP violation tests.
- Many ongoing activities from GeV to TeV scale.
- Future strangeness facilities have potential to build a bridge from the low energy domain to pQCD.

Thanks for your attention!

...and special thanks to:

- the organisers of EuNPC for inviting me
- Stefan Leupold, Lena Heijkenskjöld and the hadron physics group at Uppsala University for valuable input