Hyperon Spectroscopy

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Hadronic Physics with Lepton and Hadron Beams
JLab, Newport News, VA
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Outline

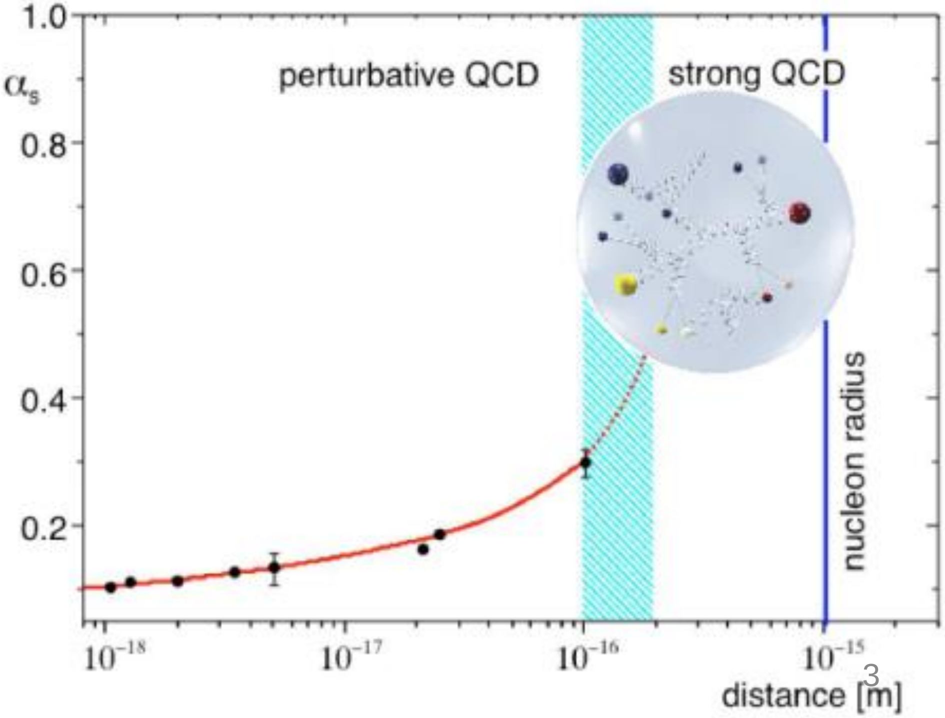
- Prologue
- Hyperons
- Spectroscopy
- Hyperons ♡ spectroscopy
- Experimental facilities
  - Past
  - Present
  - Future
- Summary

Prologue: The strong interaction

Missing in the Standard Model of particle physics:

A complete understanding of the strong interaction.

- Short distances / high energies: pQCD rigorously and successfully tested.
- Charm scale and below: pQCD fails, no analytical solution possible.

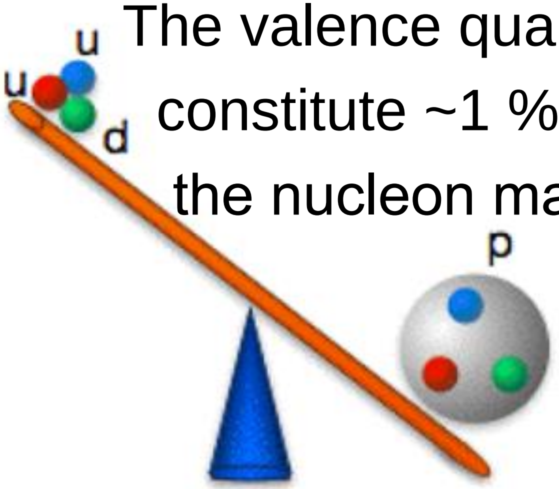


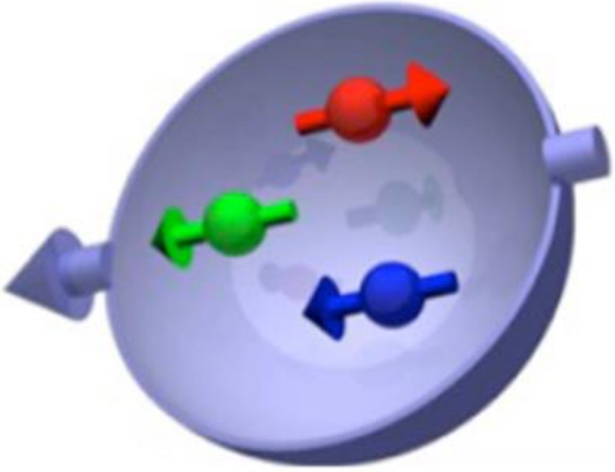
Prologue: The mysterious nucleon

- 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…



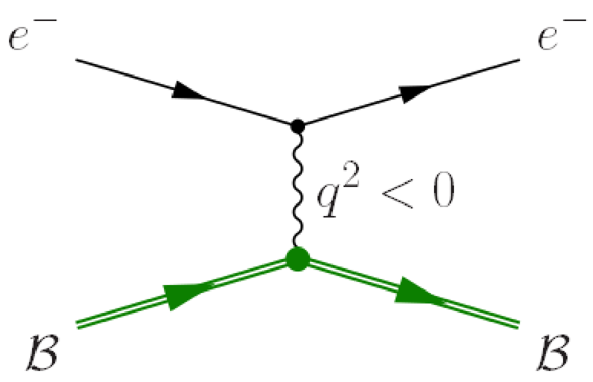


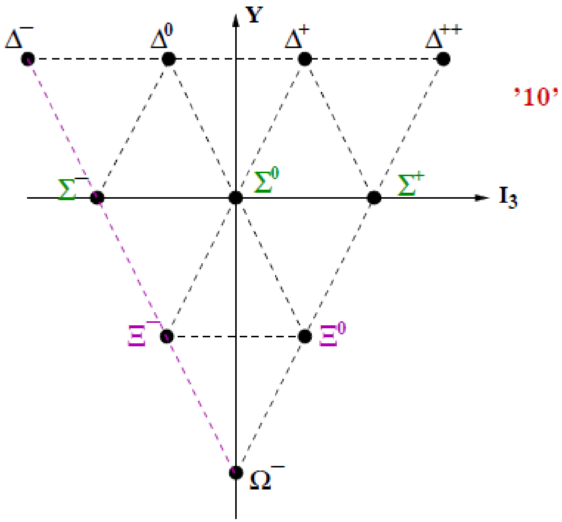
…and about 1/3 of the spin!

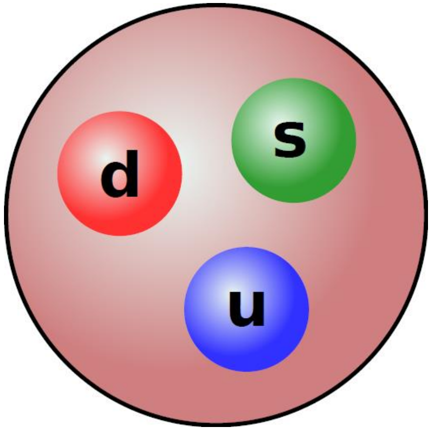
The mysterious nucleon

Common approaches (inspired by atomic physics)*:

- Scatter on it (EMFF's, GPD's, TMD's…)
- Excite it (spectroscopy)
- Replace one of the building blocks (hyperons)







*C. Granados et al., EPJA 53 (2017) 117

The mysterious nucleon

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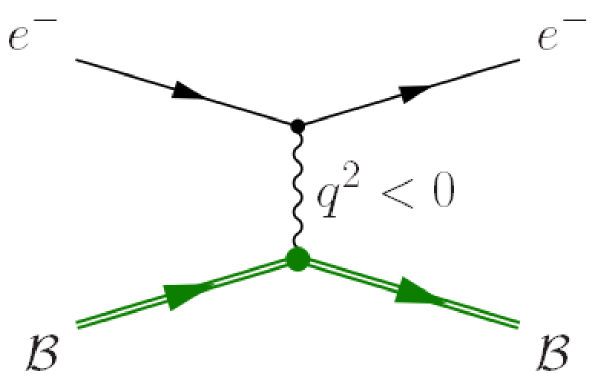

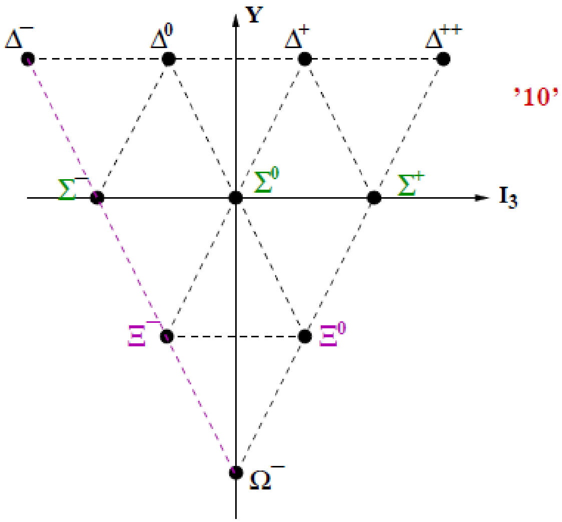

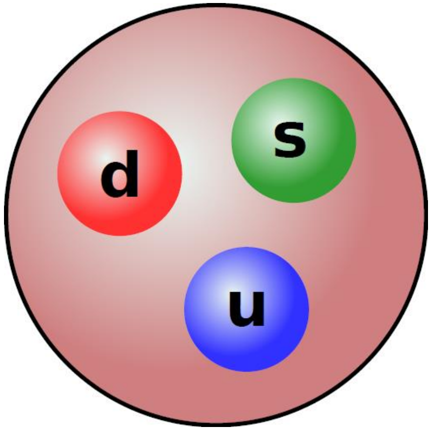

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Hyperons – probe of QCD

Scale probed by a system:

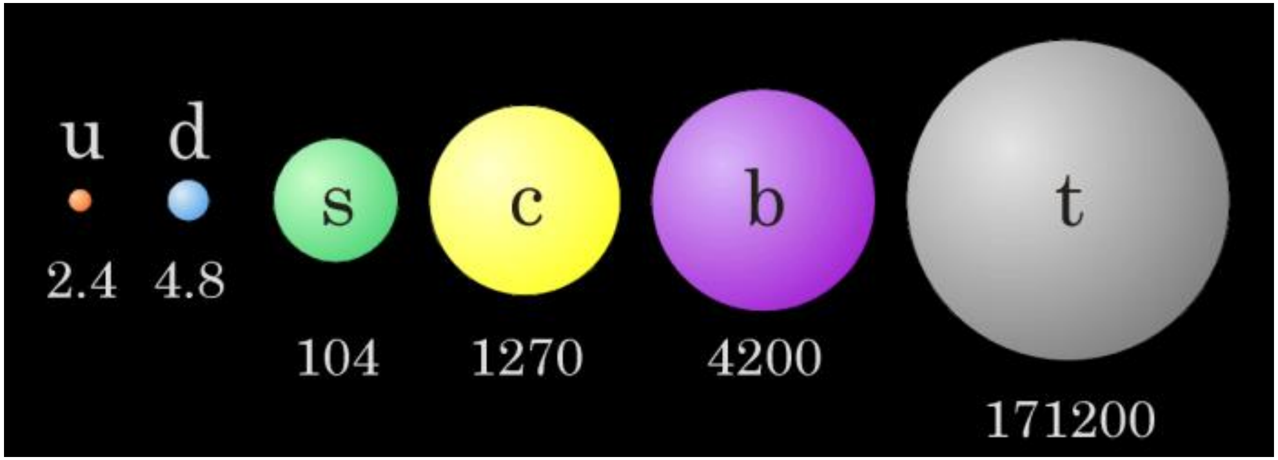
- *u,d*: Non-perturbative $\rightarrow$ hadron degrees of freedom.
- Strange: $m_s \approx 100$ MeV ~ $\Lambda_{QCD} \approx 200$ MeV

  $\rightarrow$ degrees of freedom unclear.

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

  $\rightarrow$ Quark and gluon degrees of freedom more relevant.

  $\rightarrow$ just below pQCD breakdown.



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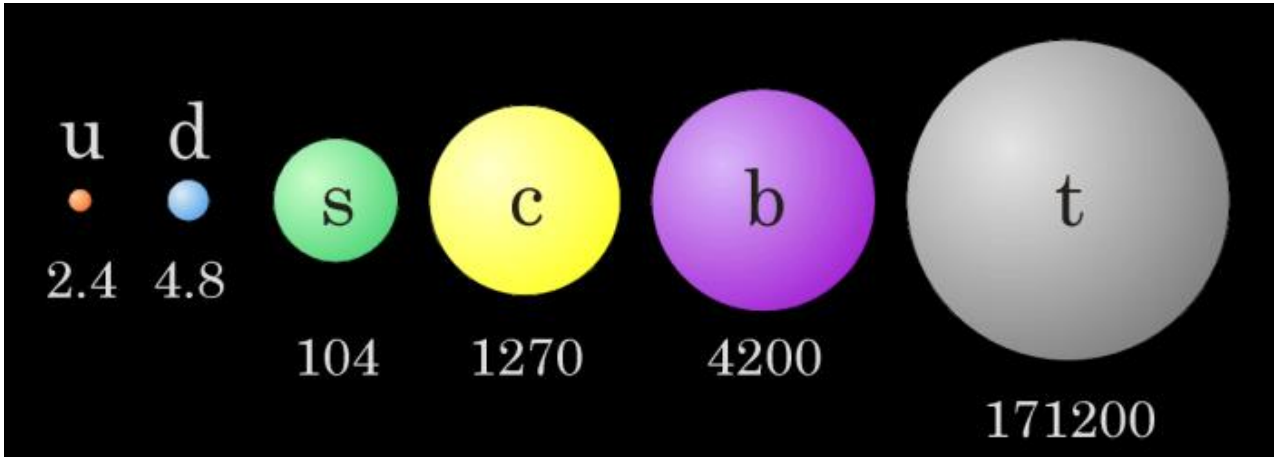
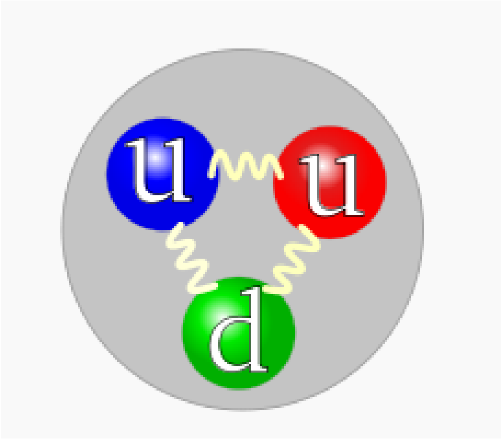
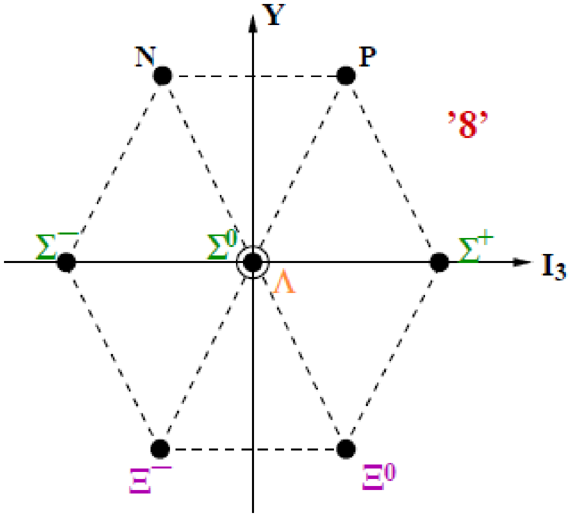


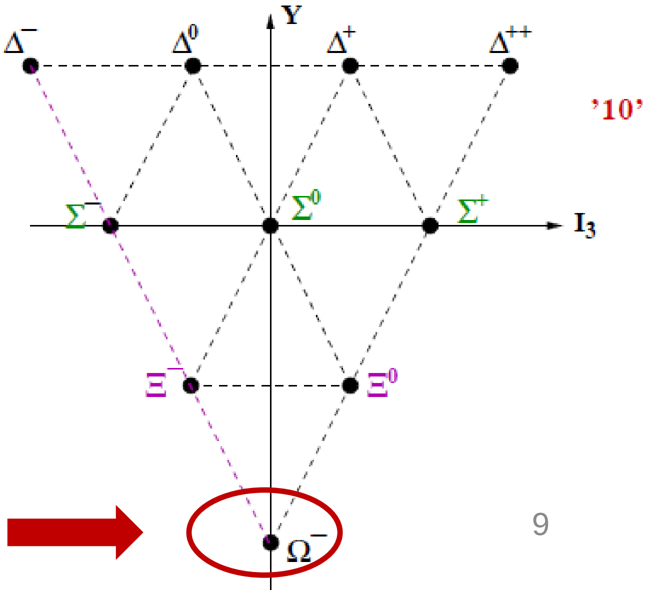
Hyperons – role in history

- 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)

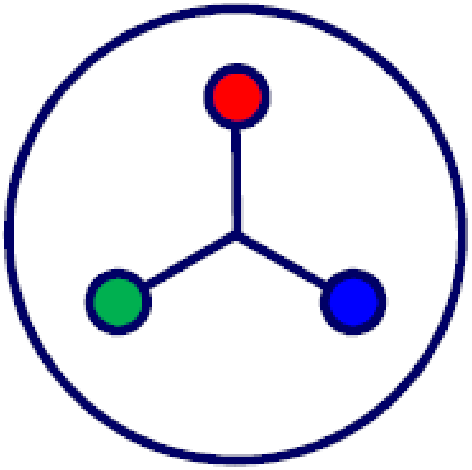






Spectroscopy

- Light baryon sector extensively explored, *e.g.* at
  - JLAB
  - MAMI
  - ELSA
  - Spring-8



- Classification scheme: SU(6) x O(3) (spin, flavour and *L*).
- Common theoretical approach: Symmetric quark models
  - See *e.g.* Löring *et al.,* EPJA 10 (2001) 395
  - Constituent quarks
  - Confinement potential
  - Residual interaction

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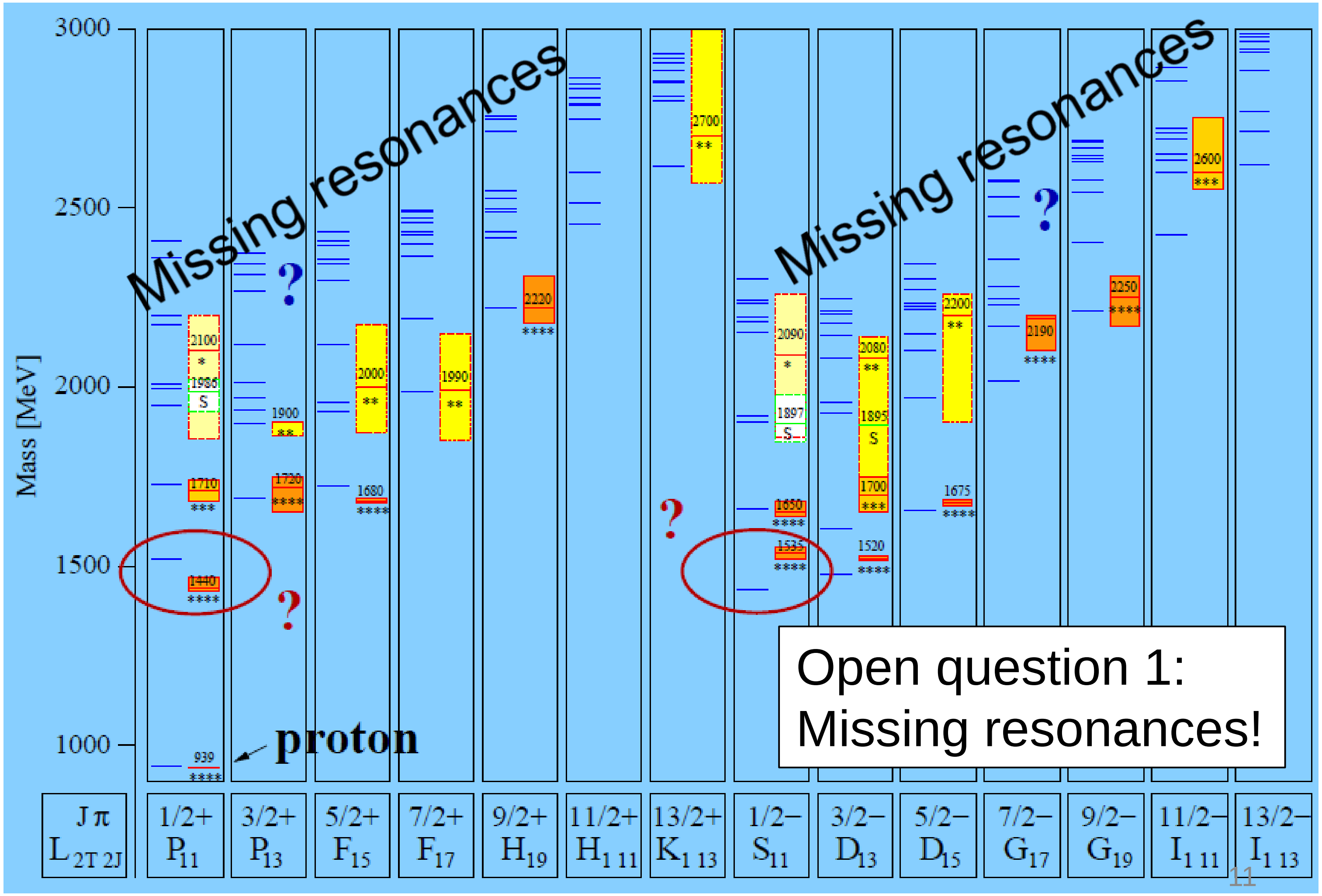
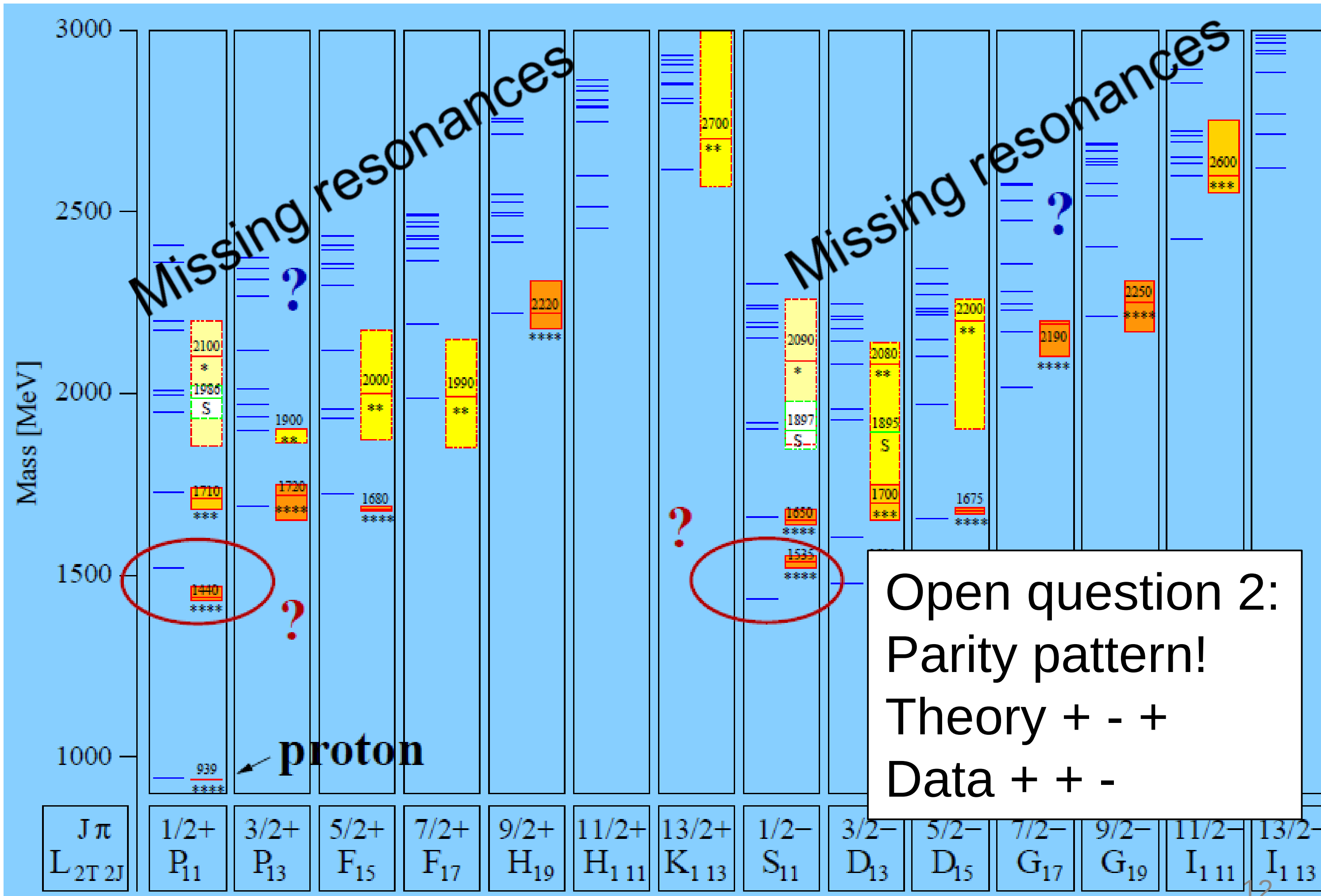
Light baryon spectroscopy



Löring *et al.*, EPJA 10 (2001) 395

Light baryon spectroscopy

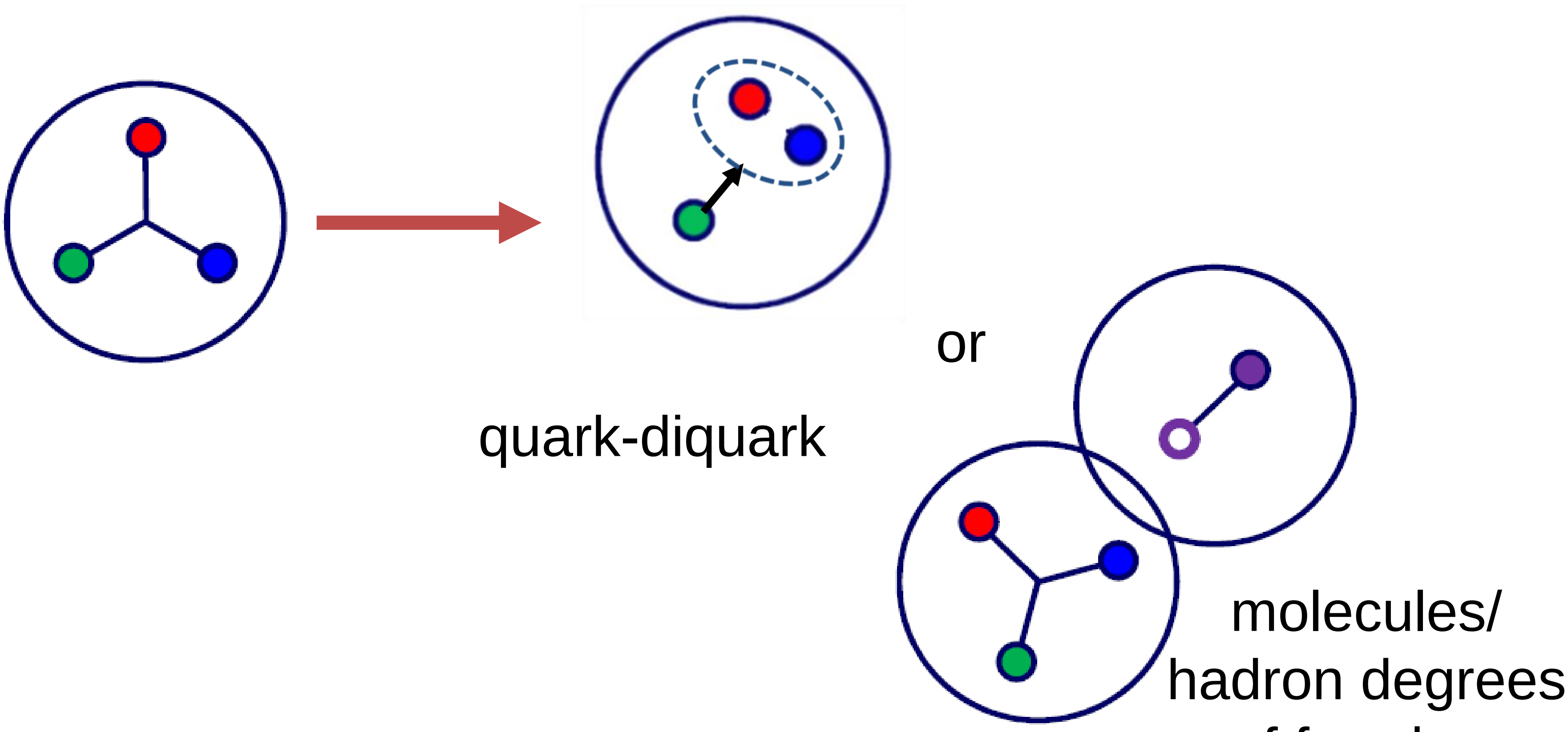


Open question 2:
Parity pattern!
Theory + - +
Data + + -

Löring *et al.*, EPJA 10 (2001) 395

Light baryon spectroscopy

Examples of alternatives to symmetric quark models:



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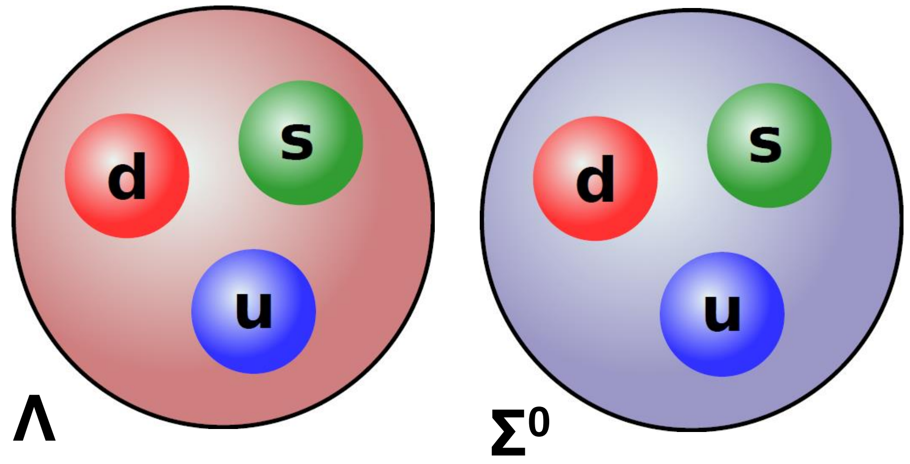
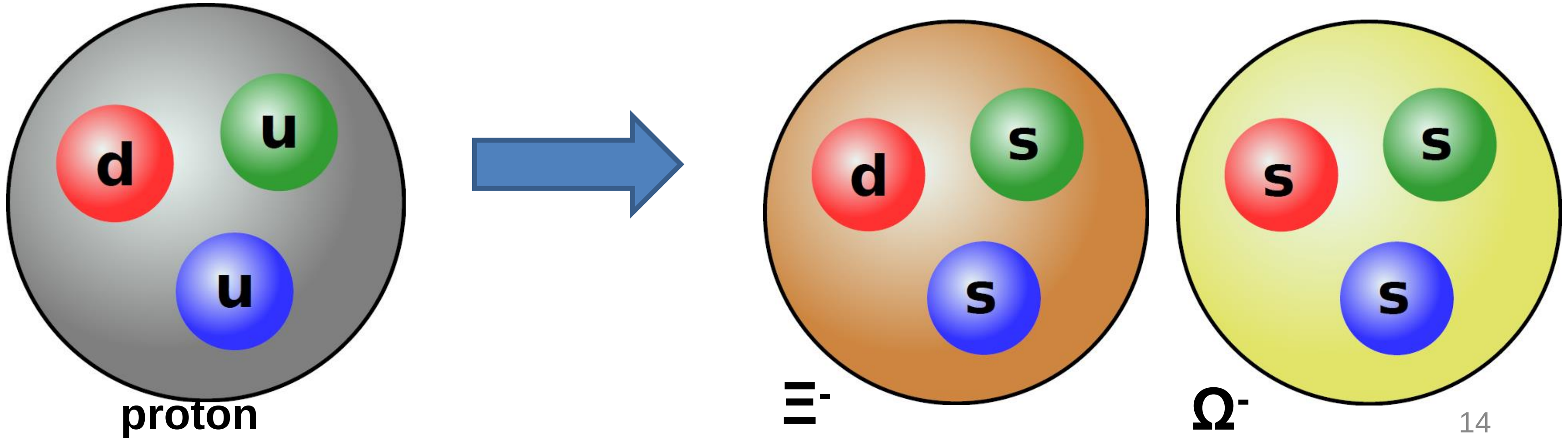
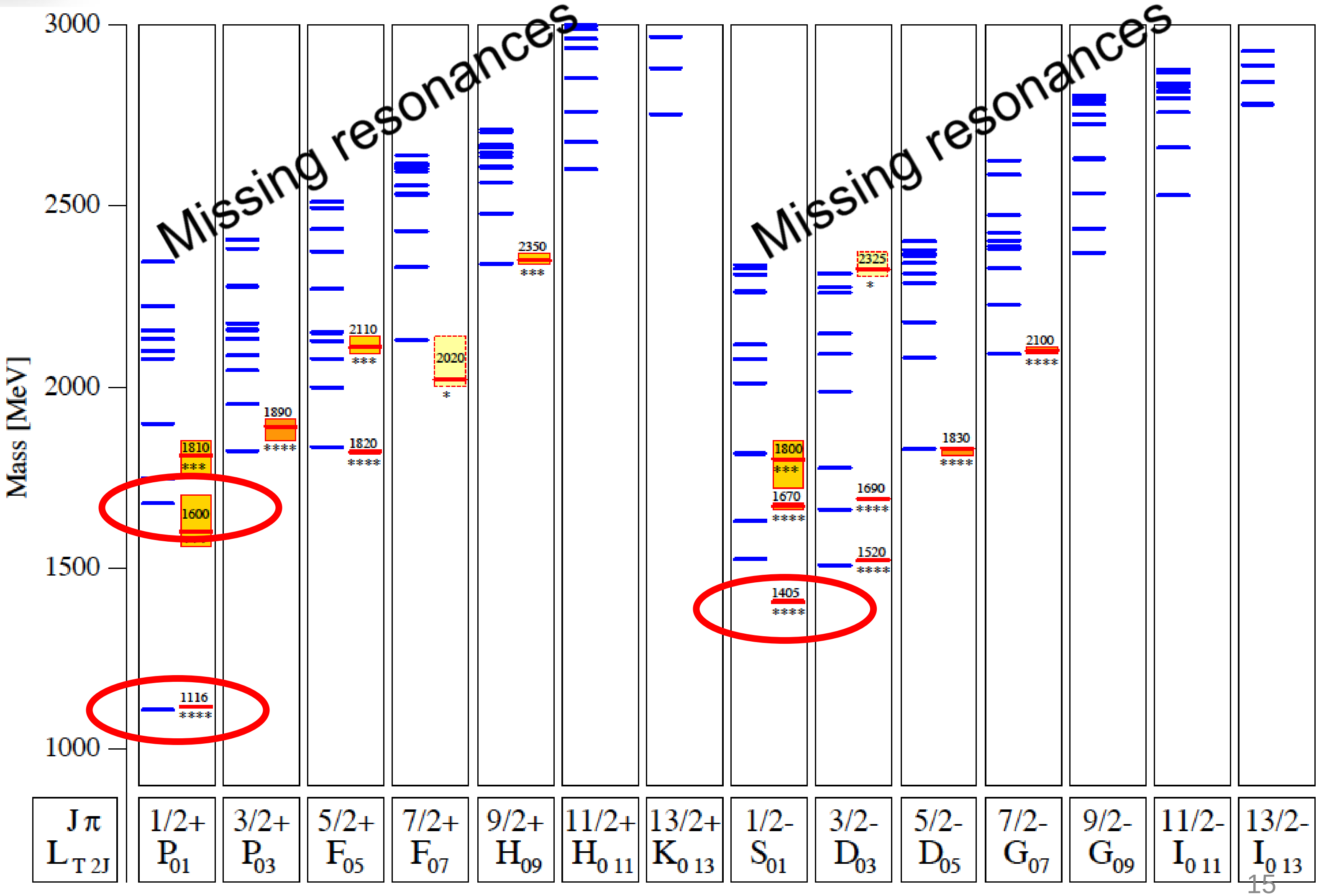
Hyperons ♡ spectroscopy

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





The Λ hyperon spectrum



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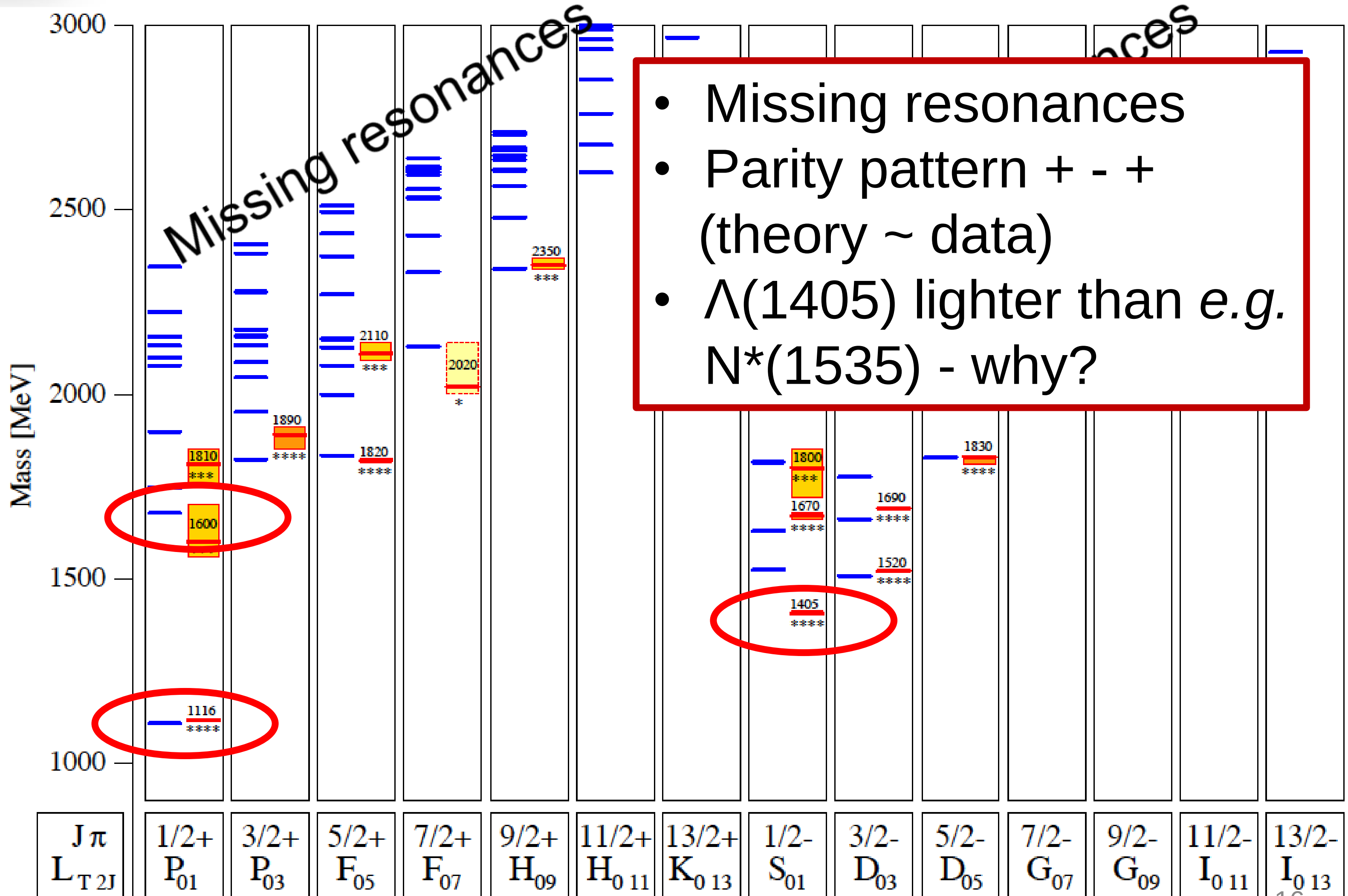
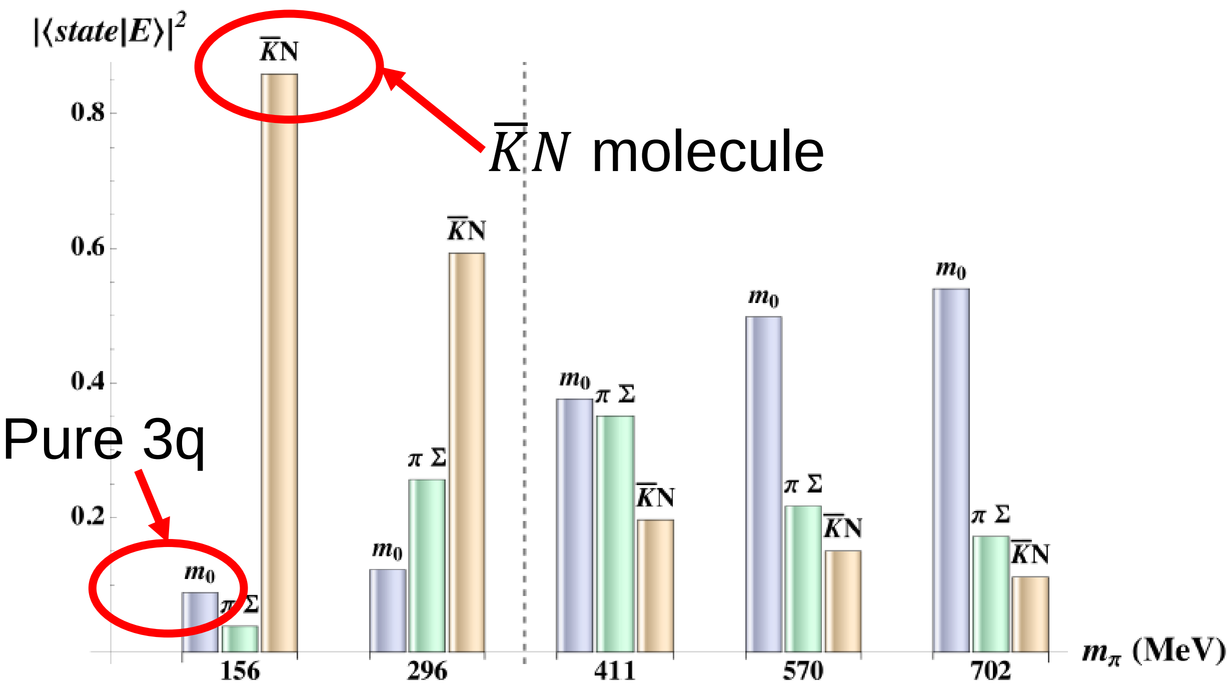


- Missing resonances
- Parity pattern + - + (theory ~ data)
- Λ(1405) lighter than *e.g.* N*(1535) - why?

The Λ(1405) hyperon

- Spin and parity measured by CLAS: $J^P = \frac{1}{2}^-$ *.
- Recent lattice calculations from the Adelaide group**: large $\bar{K}N$ molecule component.

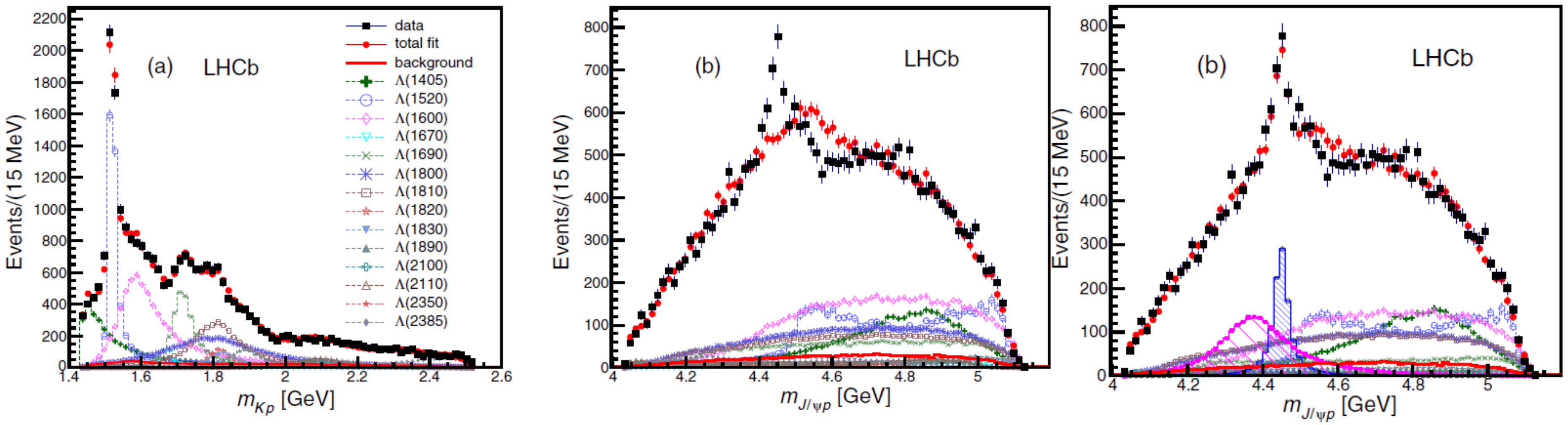


*CLAS coll. PRL 112 (2014) 082004

**Hall et al., PRL 114 (2015) 132002

The Λ hyperon spectrum

- Understanding the strange sector is crucial for understanding the charm sector!
- Example: The pentaquark candidate*.



Extended Λ* model

Extended Λ* model

Reduced Λ* model + pentaquark

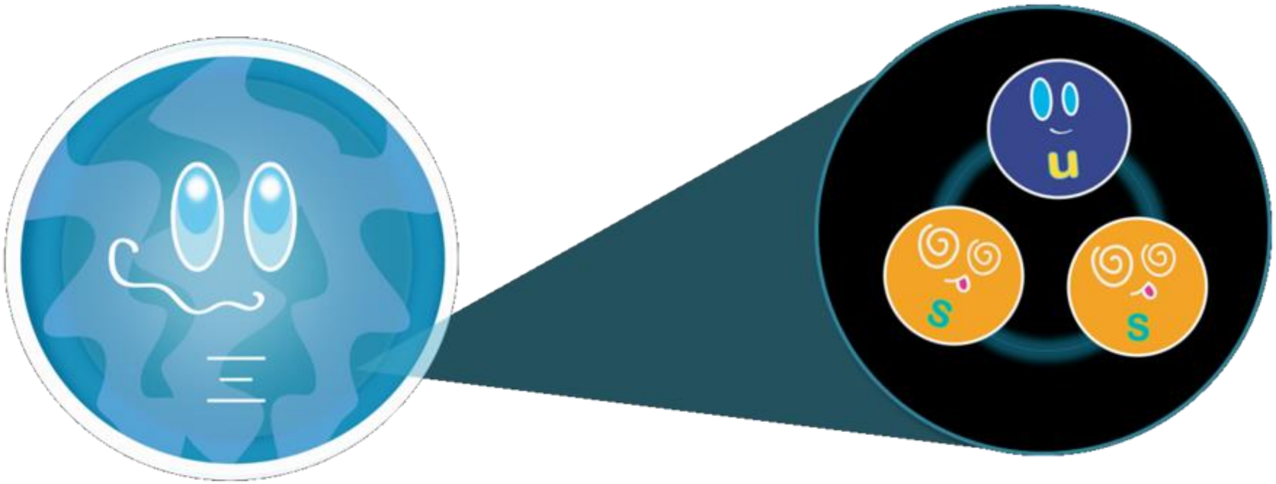
* Aaij *et al.*, PRL 115 (2015) 702001

From single- to multi-strange …

Test of SU(3) symmetry:

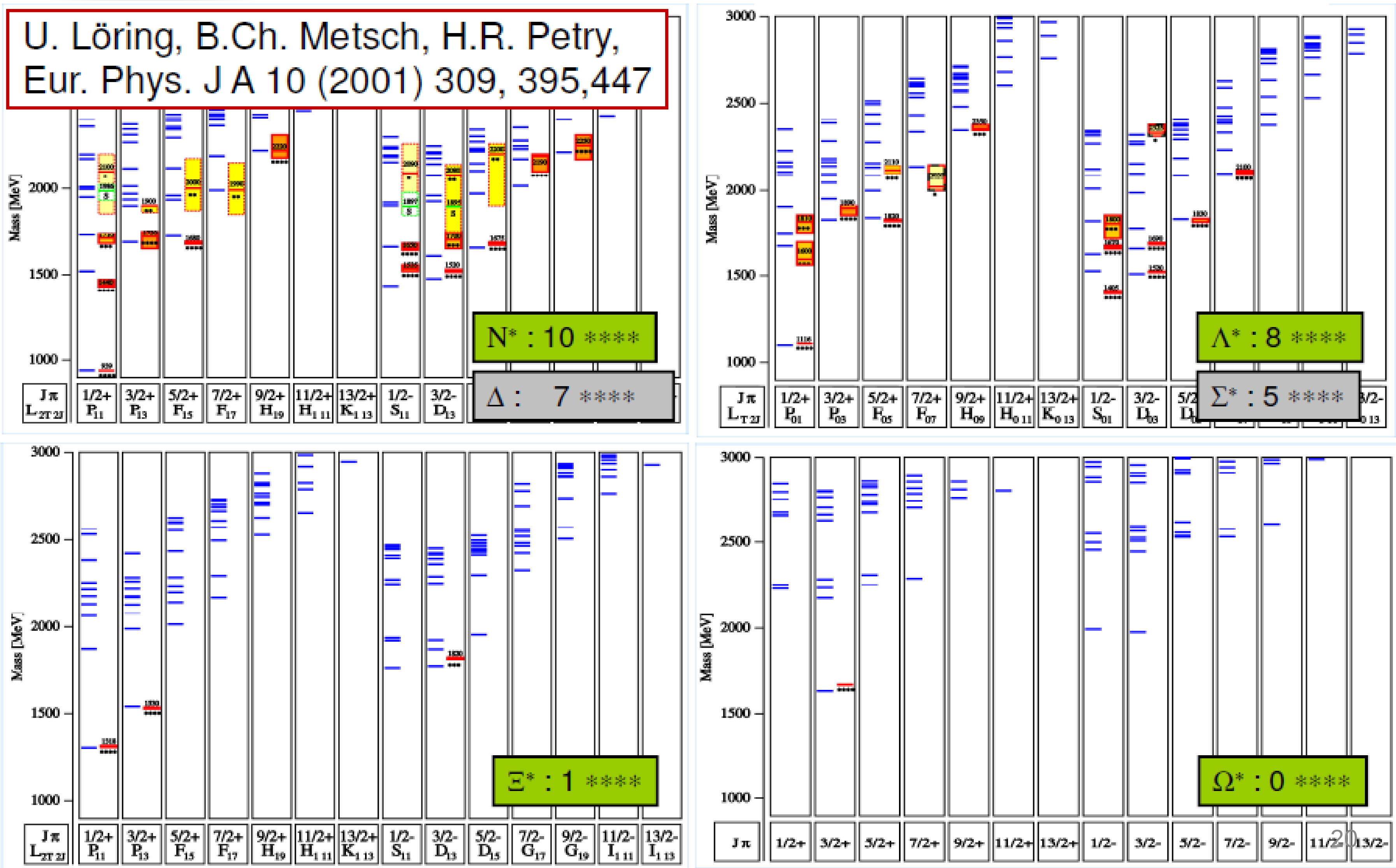
- N^* and Δ siblings in the strange sector
- Double- and triple strangeness (Ξ and Ω)
  - Should be as many Ξ^* as N^* and Δ^*.
  - Should be as many Ω^* as Δ^*.

But how does the excitation pattern really look like?



The Σ*, Ξ* and Ω* hyperon spectra

U. Löring, B.Ch. Metsch, H.R. Petry,
Eur. Phys. J A 10 (2001) 309, 395,447



Multi-strange hyperons

Multi-strange hyperon spectrum:

- Very scarce data bank*.
- Octet Ξ* partners of *N** ?
  - Only a few found
- Decuplet Ξ* and Ω* partners of Δ*?
  - Nothing found
- Parity not measured for ground-state Ξ and Ω.

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	$\Delta(2420)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$	

* PDG

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Multi-strange hyperons

- Are the states missing
  - Because they are not there (theoretical picture wrong)?
  - or because previous experiments haven't been optimal for multistrange baryon search?
- PDG note on Ξ hyperons:

  "…nothing of significance on Ξ resonances has been added since our 1988 edition."

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	$N(2220)$	$\Lambda(2350)$	$\Sigma(?)$	$\Xi(?)$	

J^P	(D, L_N^P)	S	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	$\Delta(1620)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$
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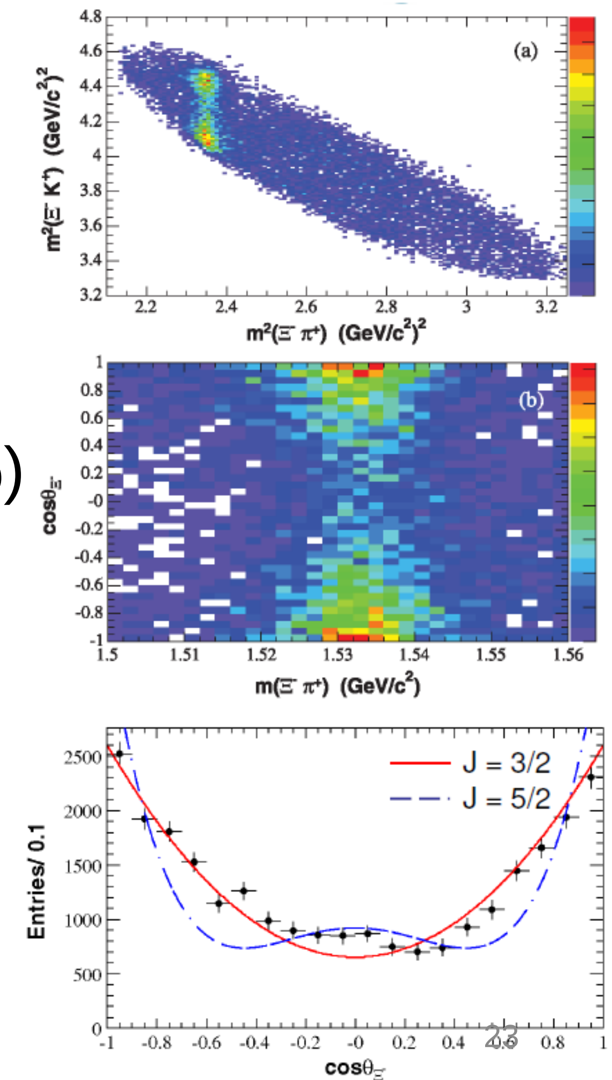
$5/2^+$	$(56,2_2^+)$	3/2	$\Delta(1905)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$
$7/2^+$	$(56,2_2^+)$	3/2	$\Delta(1950)$	$\Sigma(2030)$	$\Xi(?)$	$\Omega(?)$
$11/2^+$	$(56,4_4^+)$	3/2	$\Delta(2420)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$

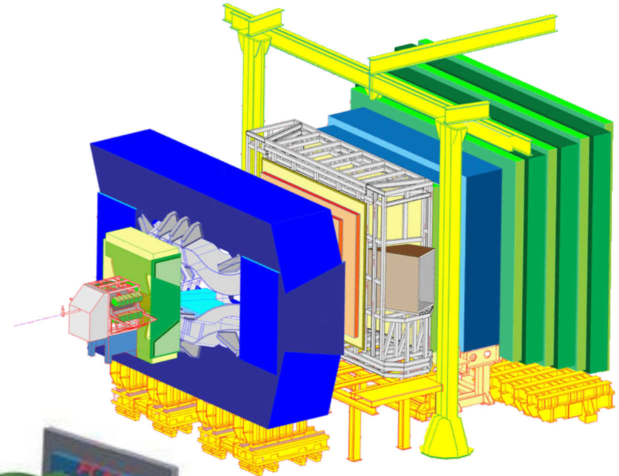
Multi-strange hyperons

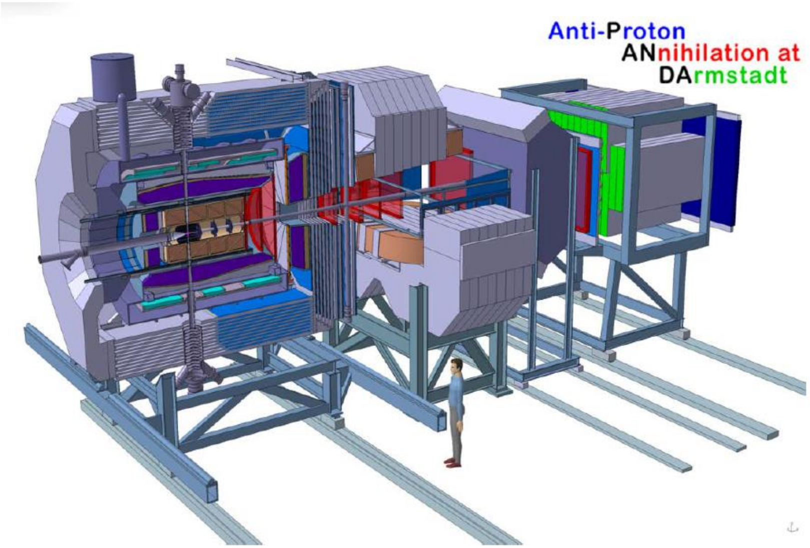
The Ξ*(1530) hyperon

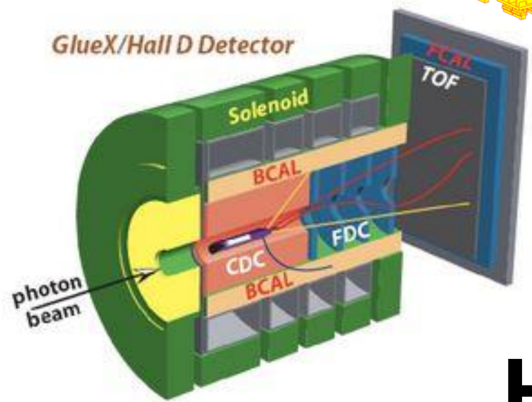
- Experimentally best known
- Width Γ ~ 10 MeV (compare to Δ…)
- Main decay Ξ*(1530) → Ξπ (BR ~100%)
- Predicted $J^P = \frac{3}{2}^+$
- Spin measured by BaBar to $J = \frac{3}{2}$ *.



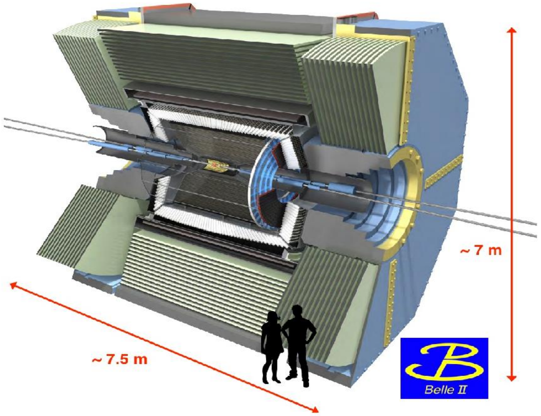
* Aubert *et al.*, PRD 78 (2008) 034008

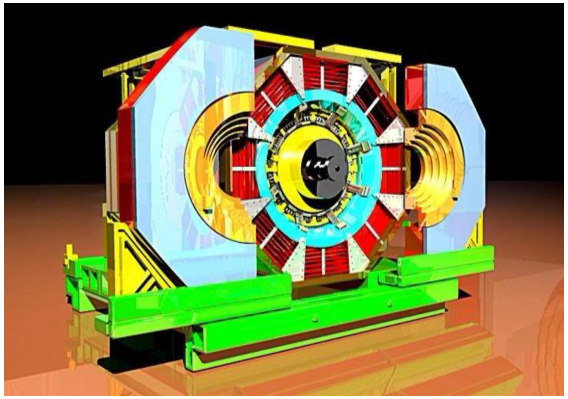






FACILITIES FOR HYPERON SPECTROSCOPY





Facilities: Past

- A lot of previous and ongoing activity in nucleon and Δ spectroscopy (*e.g.* CLAS @ JLAB, CBELSA/TAPS)

- Charmed hyperons often by-product at b-factories (BaBar, Belle, CLEO)

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- A lot of previous and ongoing activity in nucleon and Δ spectroscopy (*e.g.* CLAS @ JLAB, CBELSA/TAPS)

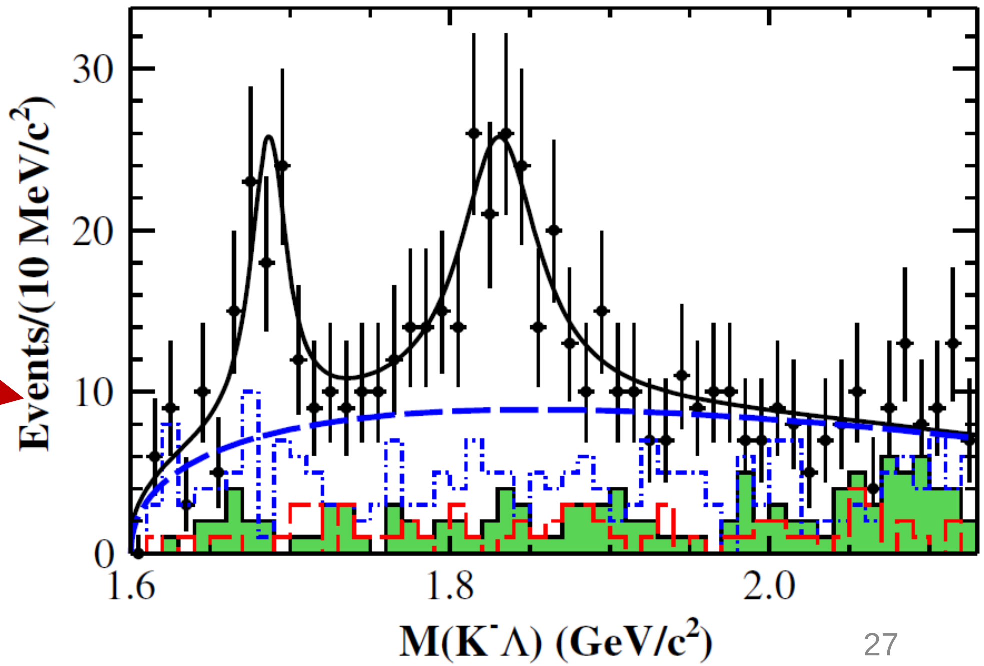
- Charmed hyperons often by-product at b-factories (BaBar, Belle, CLEO)

- Gap to fill in the strange sector!

Facilities: Present

BES III

- Hyperons from *e.g.* $e^+e^- \to J/\psi \to Y^*\bar{Y}^*$ and $\psi' \to Y^*\bar{Y}^*$
- First measurement of Ξ*(1690) and Ξ*(1820) in charmonium decays*.
- Large data sample for ground state hyperons.
- Excited, multi-strange hyperons: lower rates.
- Focus on decay patterns.

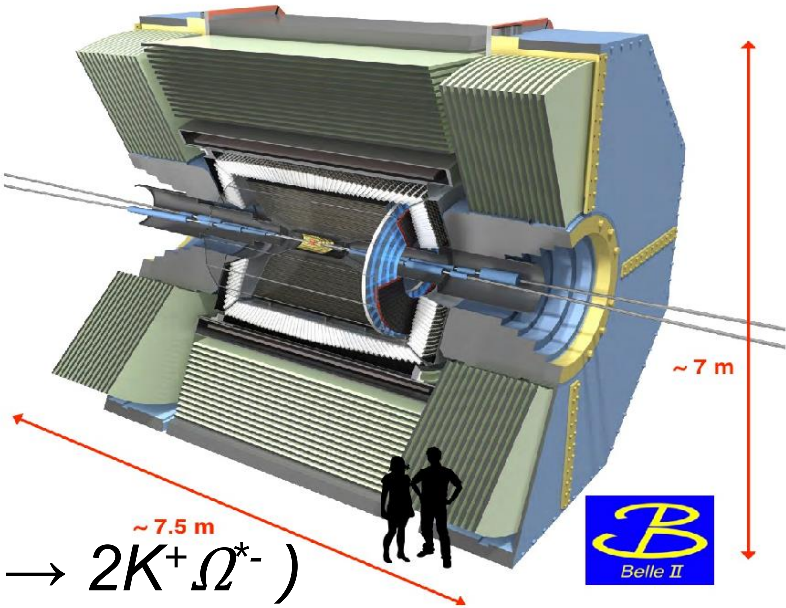


*PRD 91 (2015) 092006

Facilities: Present

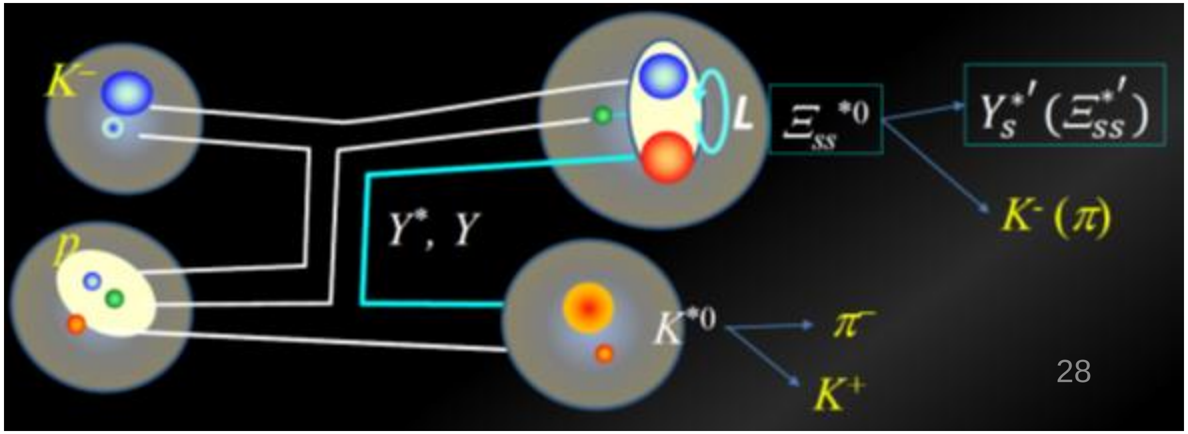
Belle II

- Hyperons from $\Upsilon(nS)$ decays
- Challenge: BR of $\Upsilon(nS) \rightarrow Y^{*}\bar{Y}^{*}$?
- Focus on charmed hyperons.



J-PARC

- Hyperons from $K^{-} p \rightarrow K^{+}\Xi^{*-}$ ($K^{-} p \rightarrow 2K^{+}\Omega^{*-}$)
- Identification by missing mass technique
- Large acc. detector under planning.

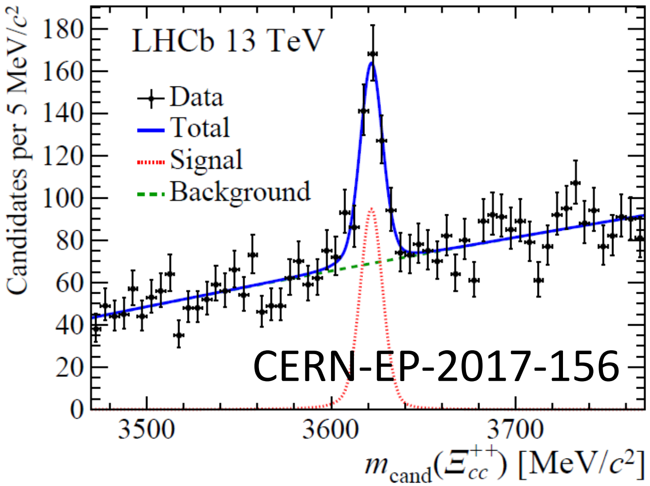


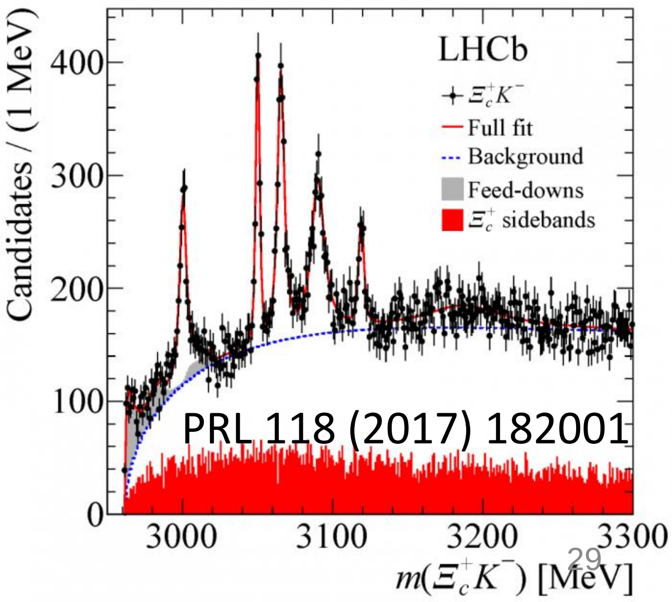
Pictures from Belle2@DESY and talk by H. Noumi at KL2016

Facilities: present

LHCb

- Charmed hyperons:
  - Double-charm candidate
  - Five strange-charmed baryons
- Strange hyperons:
  - Inclusive production in $pp \to Y^* X$
  - Spin & parity determination require known initial state
    $\to$ use Λ_b decays
    $\to$ lower rates

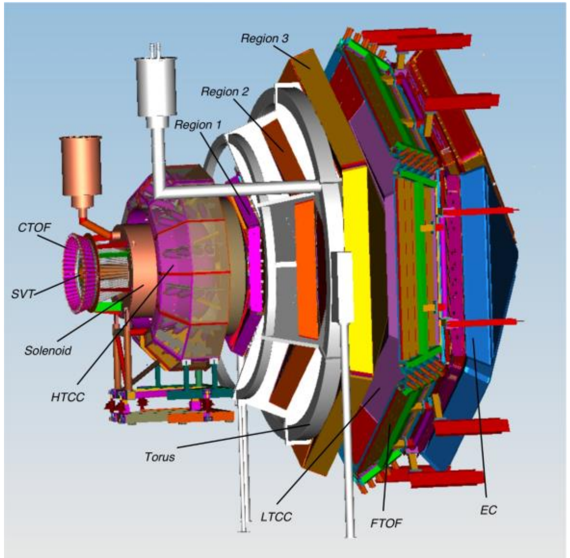




Facilities: Present

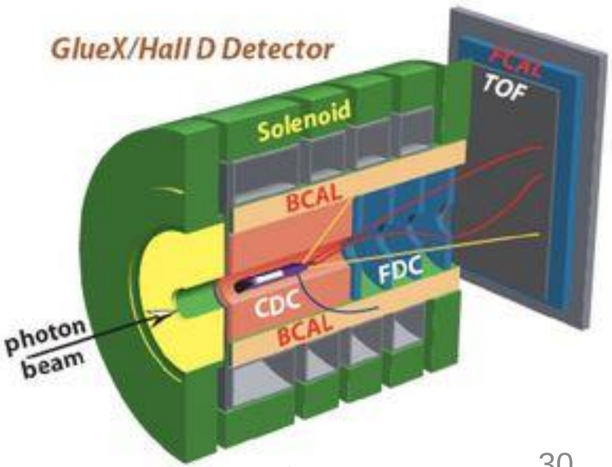
CLAS12 and GlueX @ JLAB:

- Hyperons from $\gamma p \rightarrow \Xi^{*} + 2K^{+}$ (See talk by V. Crede)
- Challenges:
  - Small cross sections
  - Many final state particles



Hall D K_L @ JLAB

- Hyperons from $K_L\, p \rightarrow K^{+}\Xi^{*-}$.
- Ξ^* in two-body final state.
- Challenge:
  - Mixed strangeness in initial state $\rightarrow$ background from $K^{+}X$ from charge exchange

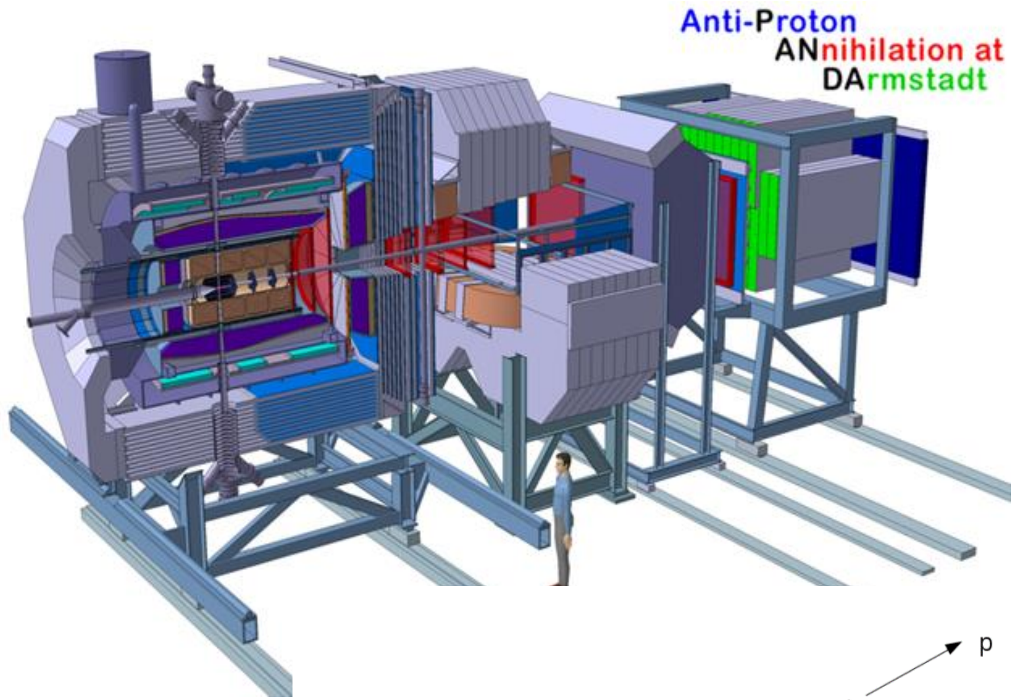


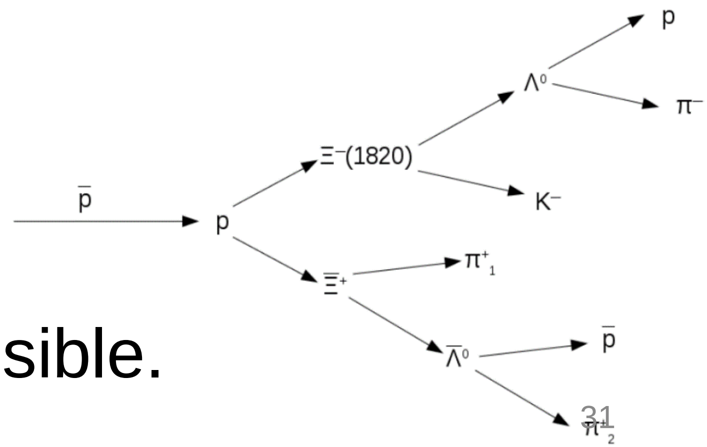
Pictures from JLAB webpage

Facilities: Future

PANDA @ FAIR:

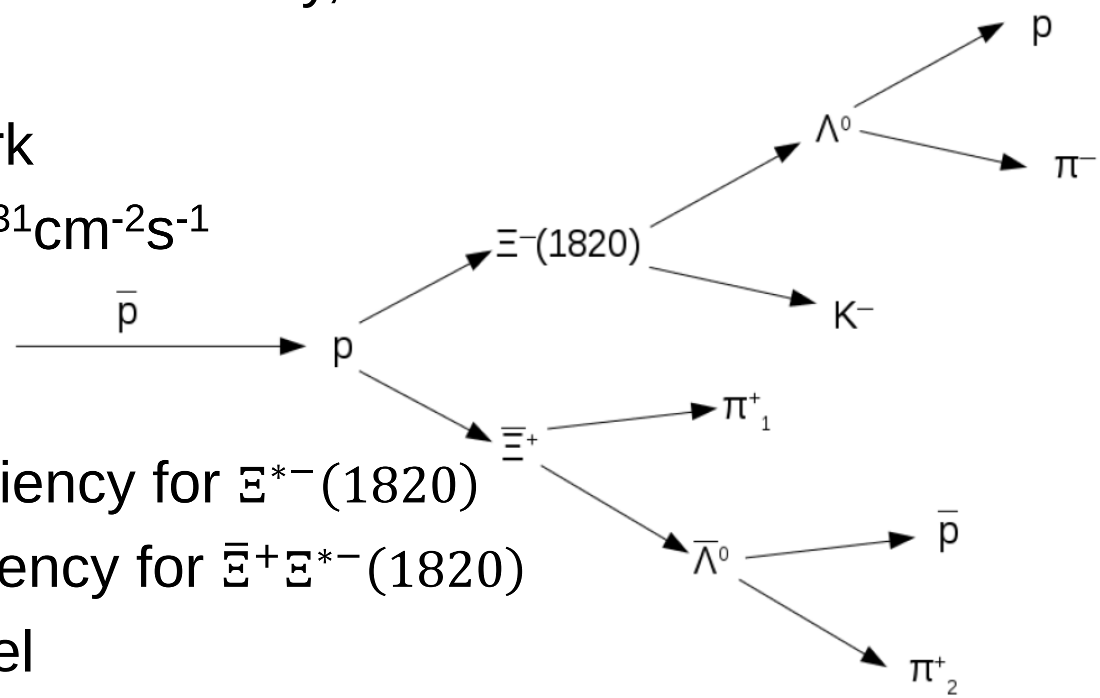
- Hyperons from $\bar{p}p \to \bar{Y}^{*}Y, \to \bar{Y}Y^{*}$.
- Cross sections *nb – μb.*
- Two-body final state.
- Symmetry in hyperon-antihyperon observables.
- Exclusive measurements
- Charged and neutral modes accessible.





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

- p_{beam} = 4.6 GeV/c
- Consider the $\Xi^{*-}(1820) \rightarrow \Lambda$ K decay, assume BR = 100%
- Assume σ = 1 μb
- Simplified MC framework
- *Day One* luminosity: $10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$



- Results:
  - ~30 % inclusive efficiency for $\Xi^{*-}(1820)$
  - ~5 % exclusive efficiency for $\bar{\Xi}^{+}\Xi^{*-}(1820)$
  - Low background level
  - ~15000 exclusive events / day

J. Pütz, talk at FAIRNESS 2016

Summary

- Baryons crucial for understanding the strong interaction.

- Open questions on light baryons:
  - Missing states?
  - Parity pattern?
  - Degrees of freedom?

- What happens if light quarks are replaced with heavier?

Summary

- Past experimental efforts focus on *N** and *Δ*.*
- Almost nothing on multi-strange hyperons:

How does the pattern obserbed in the N* and Δ* carry over to the strange sector?

- Interesting opportunities at current facilities world-wide.
- Next generation: PANDA at FAIR.

Thanks to:

Albrecht Gillitzer and Stefan Leupold