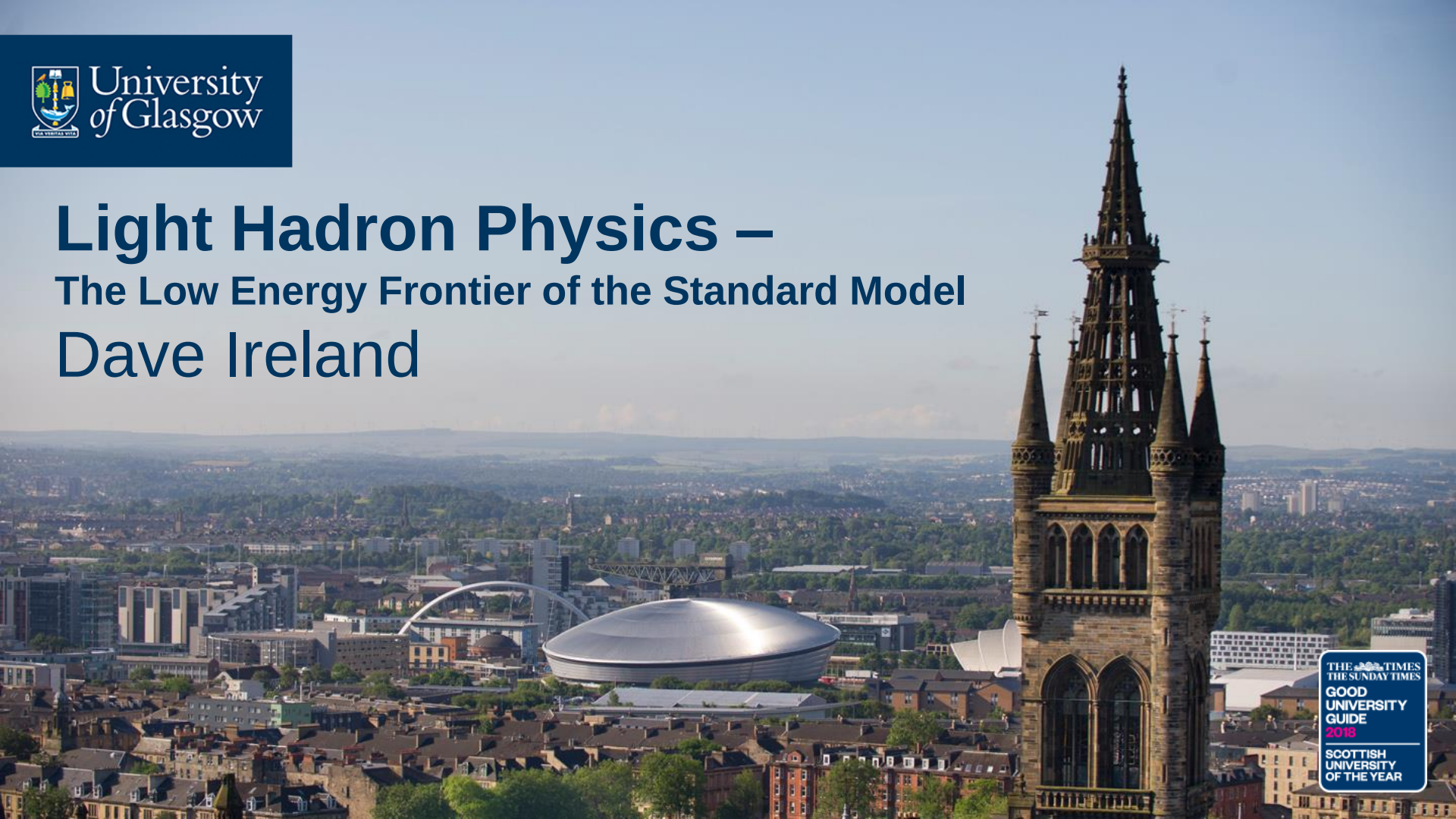
University of Glasgow

Light Hadron Physics –

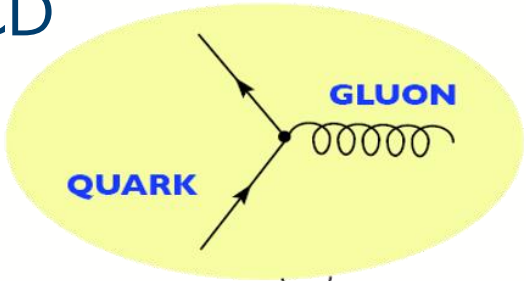
The Low Energy Frontier of the Standard Model

Dave Ireland



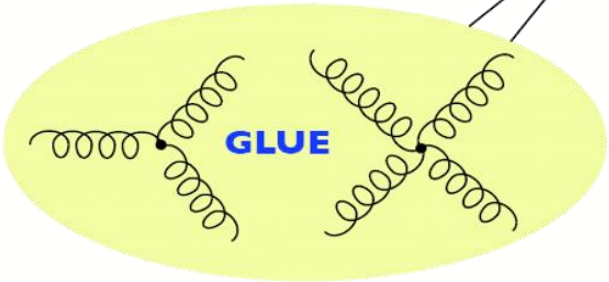
(Fritzsch, Gell-Mann, Leutwyler 1973)

QCD



QUARK MASSES

$$\mathcal{L}_{\mathrm{QCD}} = \bar{\psi}\left(i\gamma_\mu \mathcal{D}^\mu - \mathbf{m}\right)\psi - \frac{1}{4}\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu}$$

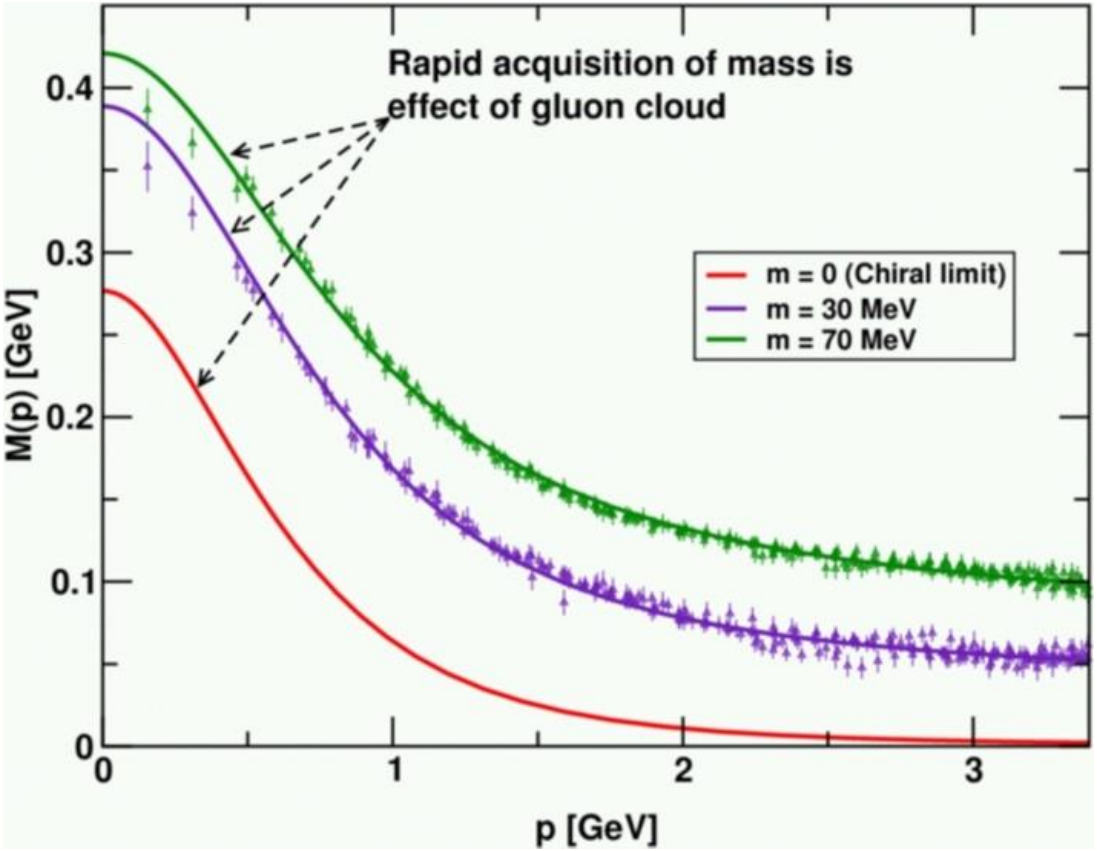


Quarks and Gluons carry "**COLOR**" charges:
Sources of the **STRONG FORCE**

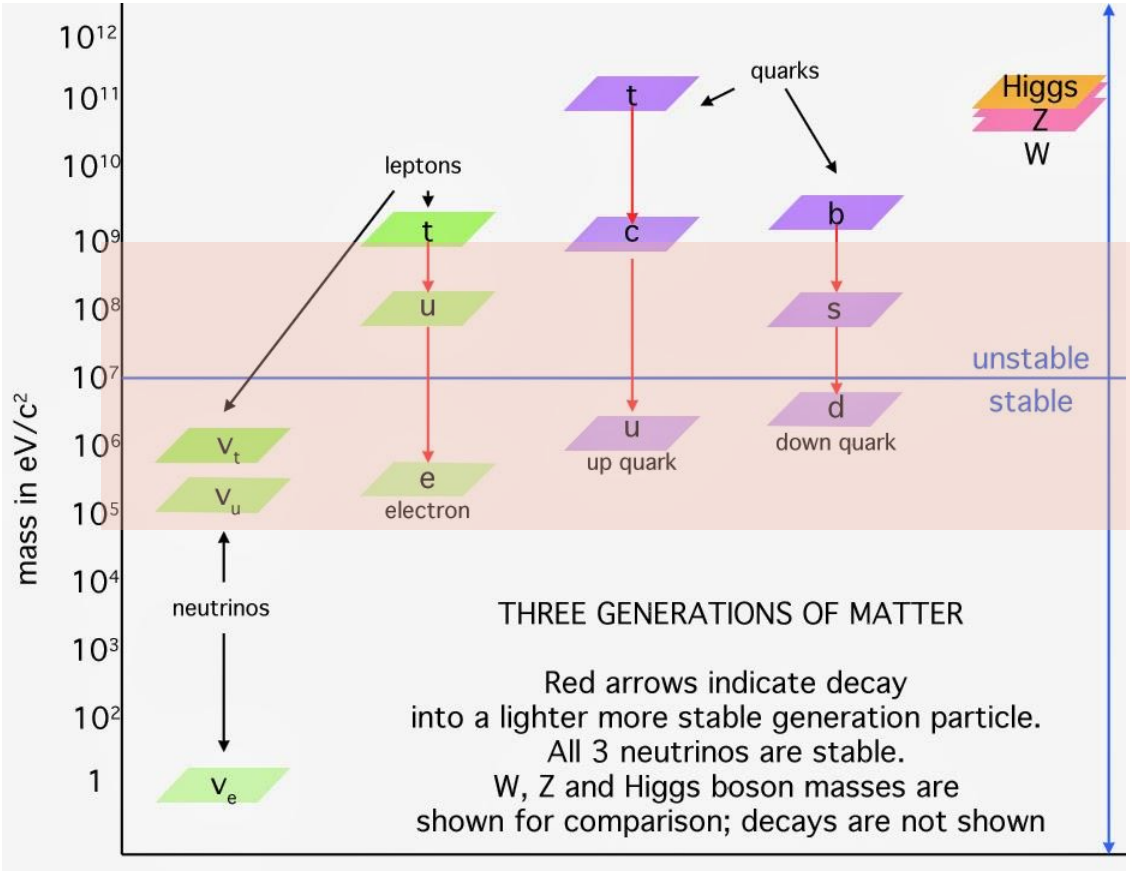
Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

Gauge **BOSON** of the **STRONG FORCE** spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

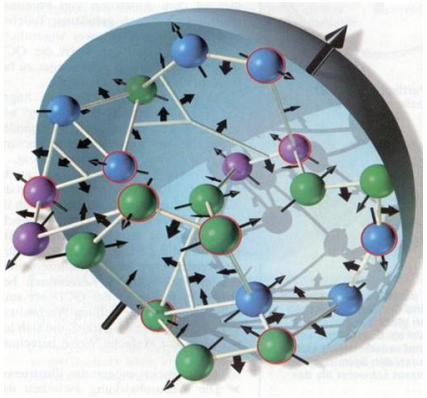
Origin of Hadronic Mass

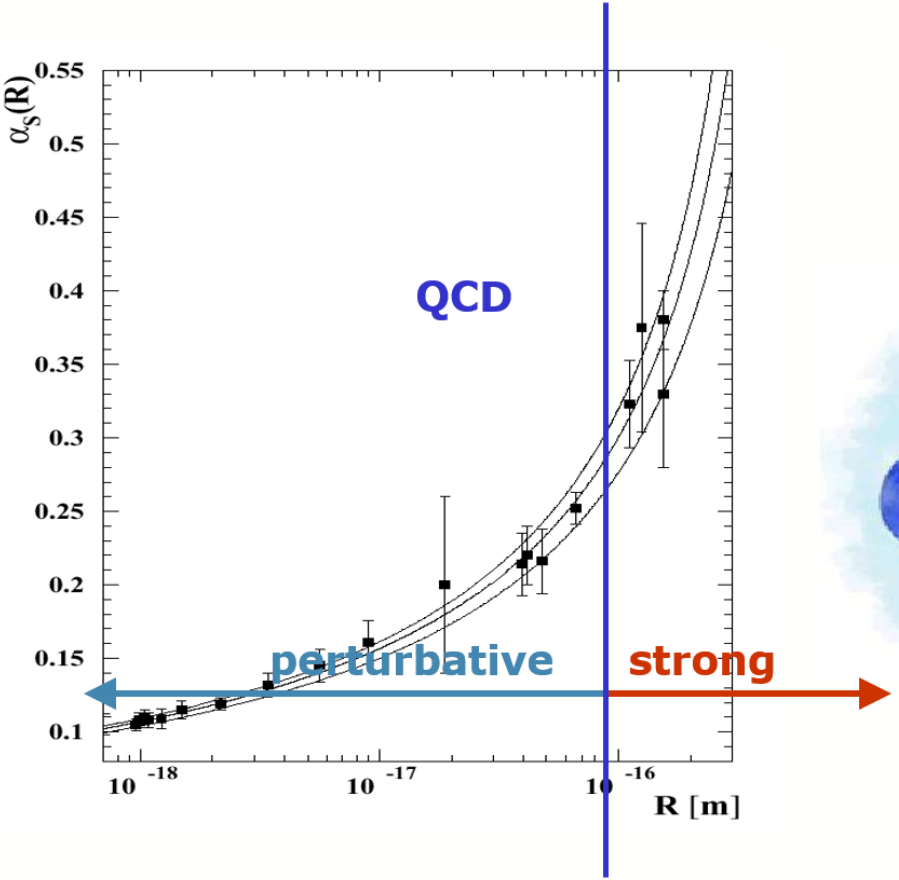


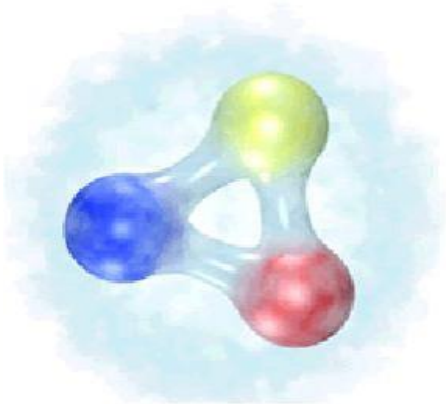
Light and Heavy Hadrons



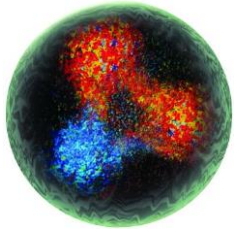
Low and High Q^2 Regimes



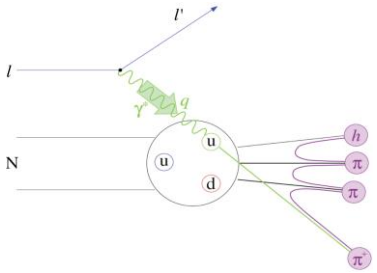




Images of the nucleon



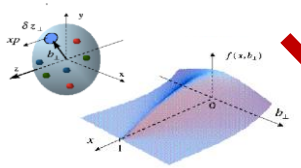
Wigner function:
full phase space parton distribution of the nucleon

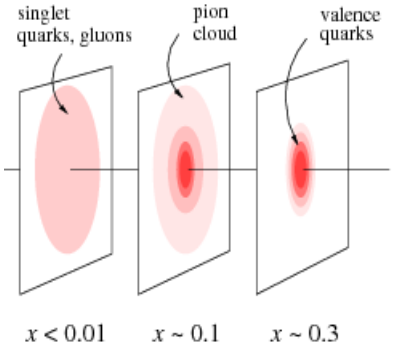


$$\int d^2k_T$$

$$\int d^2b_T$$

Generalised Parton Distributions (GPDs)

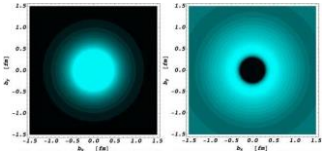




Transverse Momentum Distributions (TMDs)

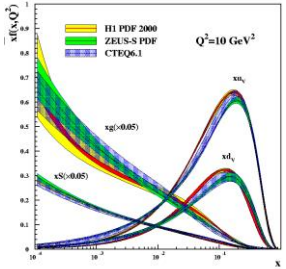
$$\int dx$$

$$\int d^2k_T$$

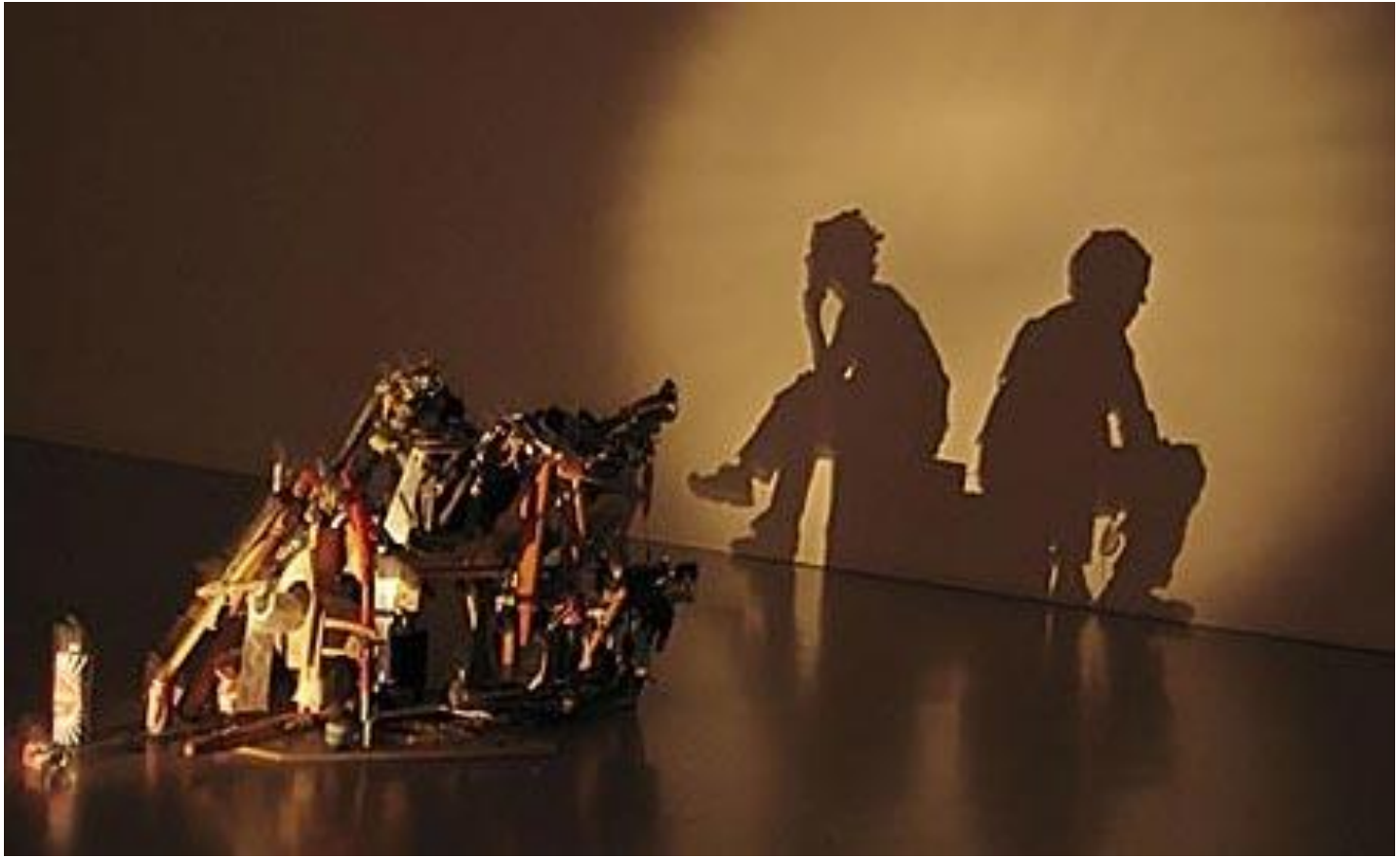


Form Factors
eg: G_E, G_M

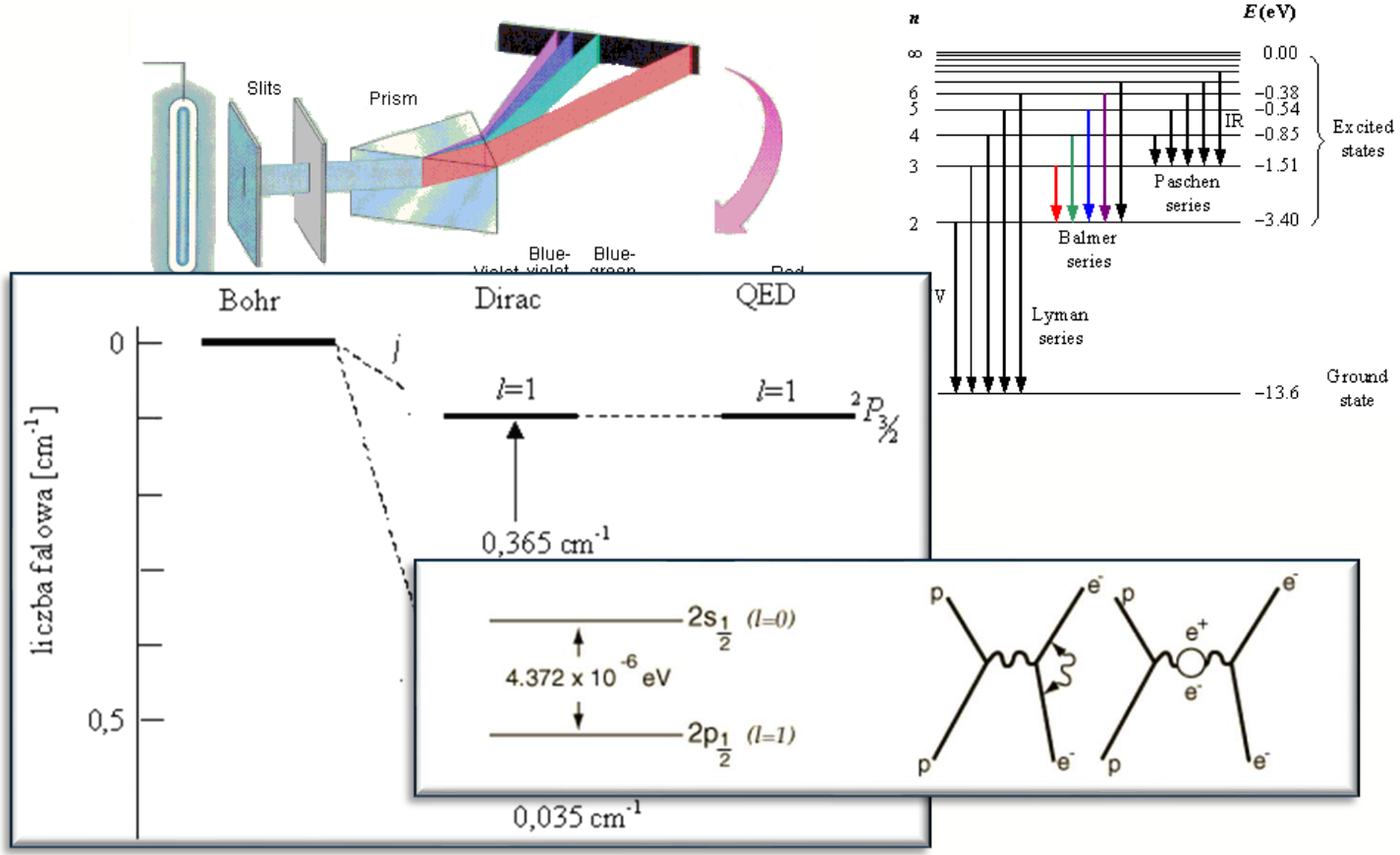
Parton Distribution Functions (PDFs)



Interpreting results from one point of view



Why spectra matter…



University of Glasgow

Outline

1. Light Baryon Spectrum
2. Exotic Mesons
3. Λ Weak Decay Parameter
4. Outlook

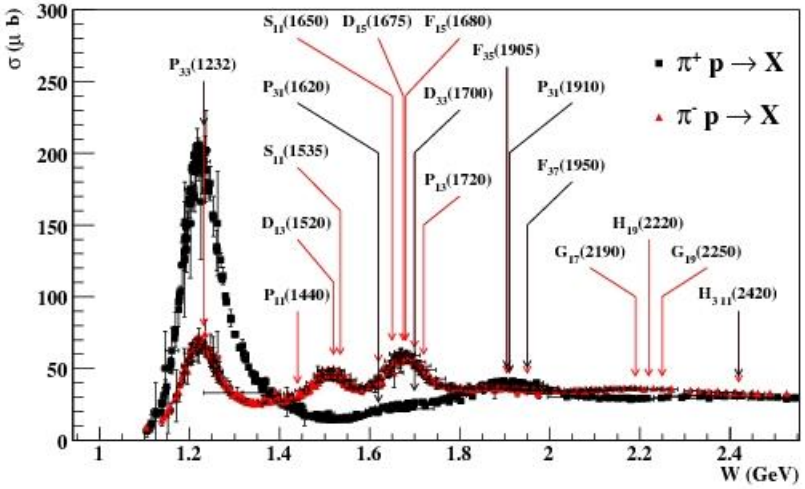
University of Glasgow

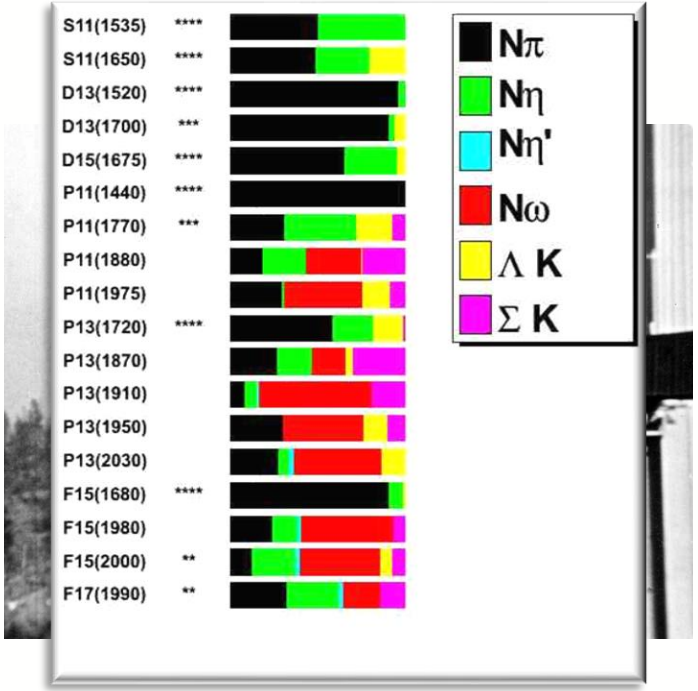
Outline

1. **Light Baryon Spectrum**
2. Exotic Mesons
3. Λ Weak Decay Parameter
4. Outlook

Resonance Hunting…

Total Cross-sections
+ differential cross-sections
+ Partial Wave Analysis + …





- Mostly done with πN scattering
- Missing resonances may decay through other channels

PHYSICS REPORTS (Review Section of Physics Letters) 96, Nos. 2 & 3 (1983) 71–204. North-Holland Publishing Company

BARYON SPECTROSCOPY

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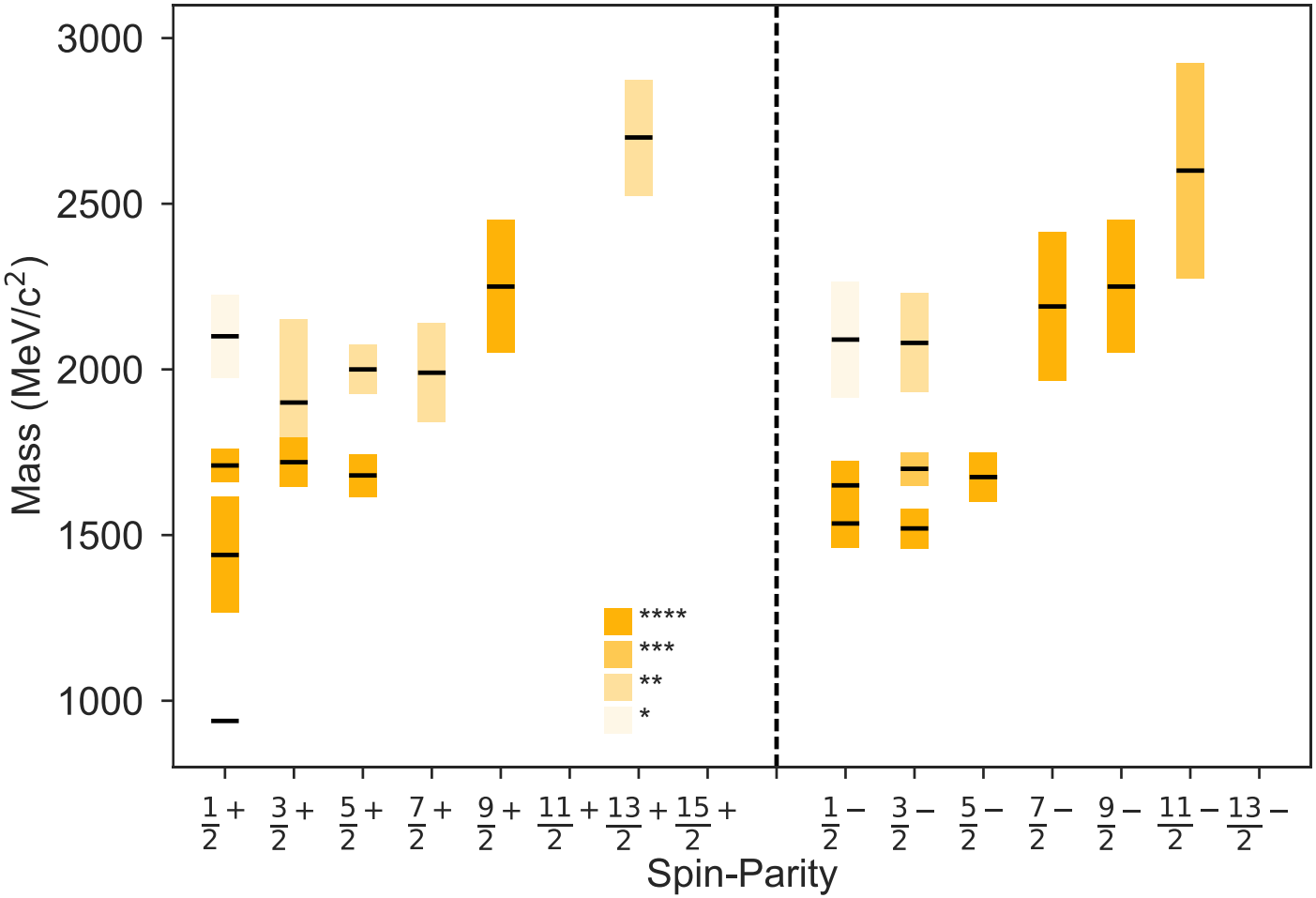
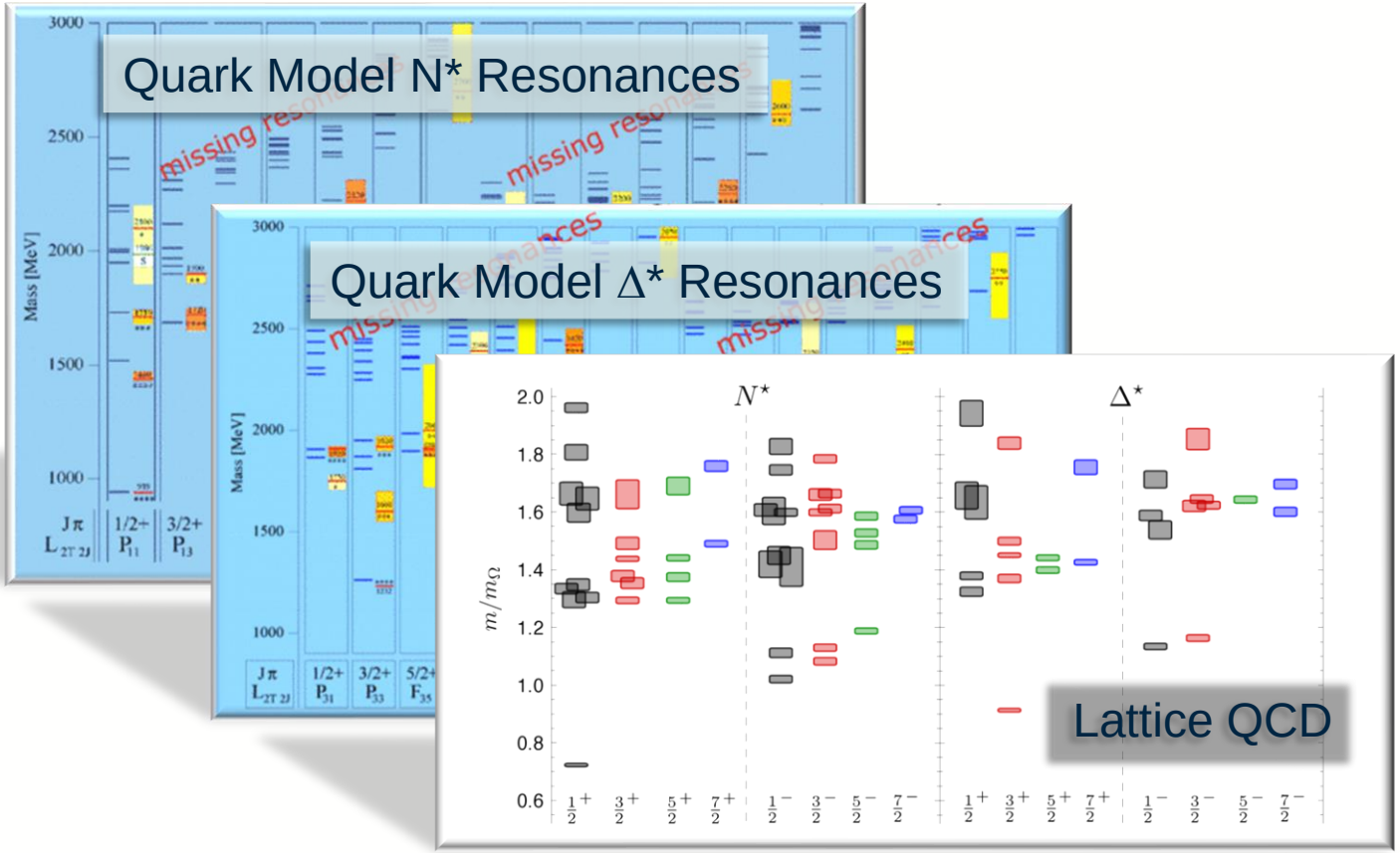
Received 29 September 1982

In 1952 Fermi and coworkers (Andersen et al. [1952]) discovered the first baryon resonance – the $\Delta(1238)$. Since then, hundreds of resonances have been identified and nuclear democracy has given way to fundamental quarks. Baryon spectroscopy is now thirty years old and perhaps approaching a mid-life crisis. For it is inevitable in such a fast-moving field as high energy particle physics, that experiments have moved on beyond the resonance region to higher energies and different priorities. Thus it is probably no exaggeration to say that we now have essentially *all* the experimental data relevant to the low-energy baryon spectrum, that we are *ever* likely to obtain. It is therefore timely to review both the accumulated mass of resonance data, together with the techniques used in its analysis, and also our theoretical framework for understanding the results. The latter is inevitably based on quarks and, by and large, on a

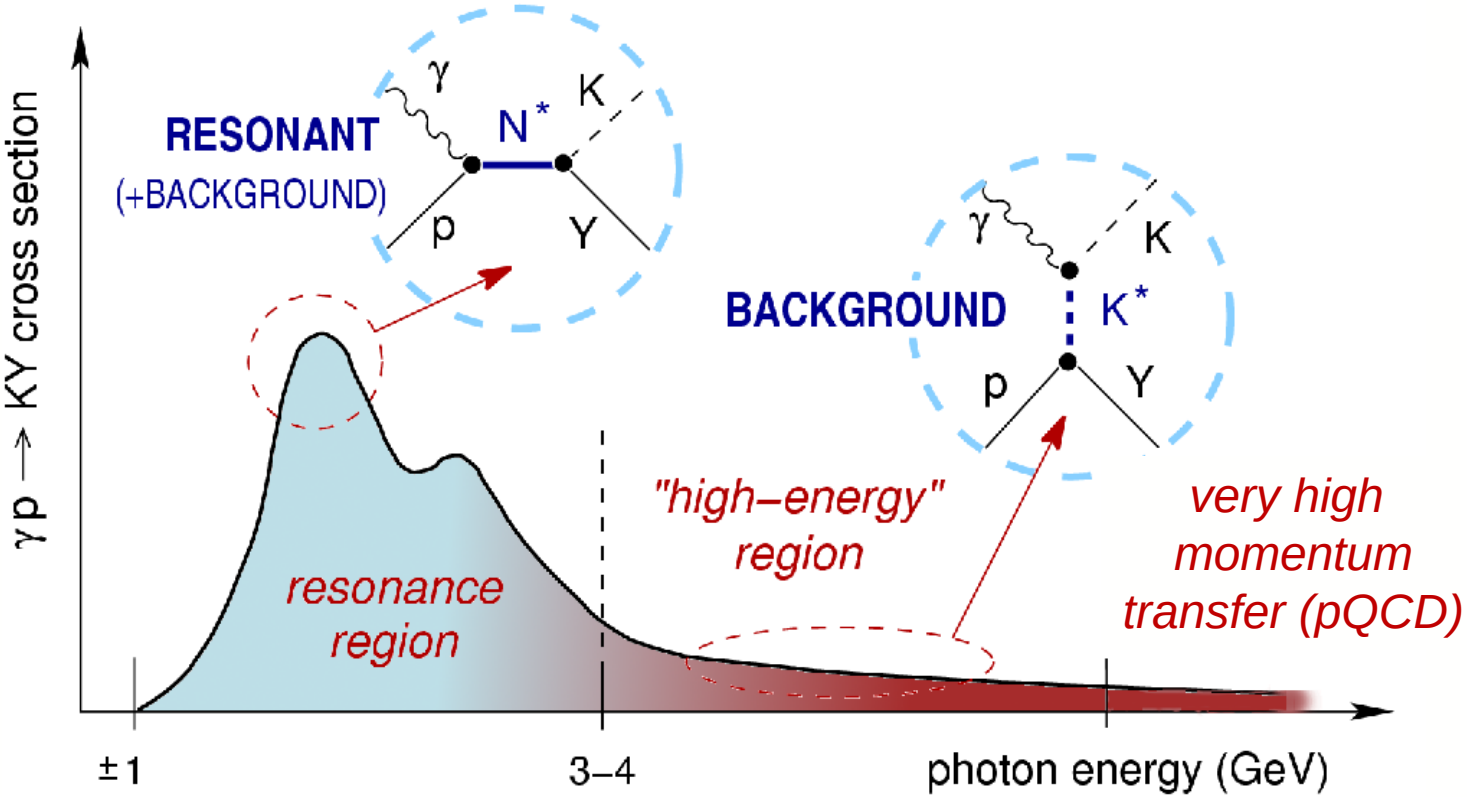
N* Resonances: PDG 1996



But…


Quark Model N* Resonances
missing resonances
Mass [MeV]
Quark Model Δ* Resonances
missing resonances
Mass [MeV]
$N^\star$
$\Delta^\star$
m/m_Ω
Lattice QCD

Pseudoscalar Meson Photoproduction

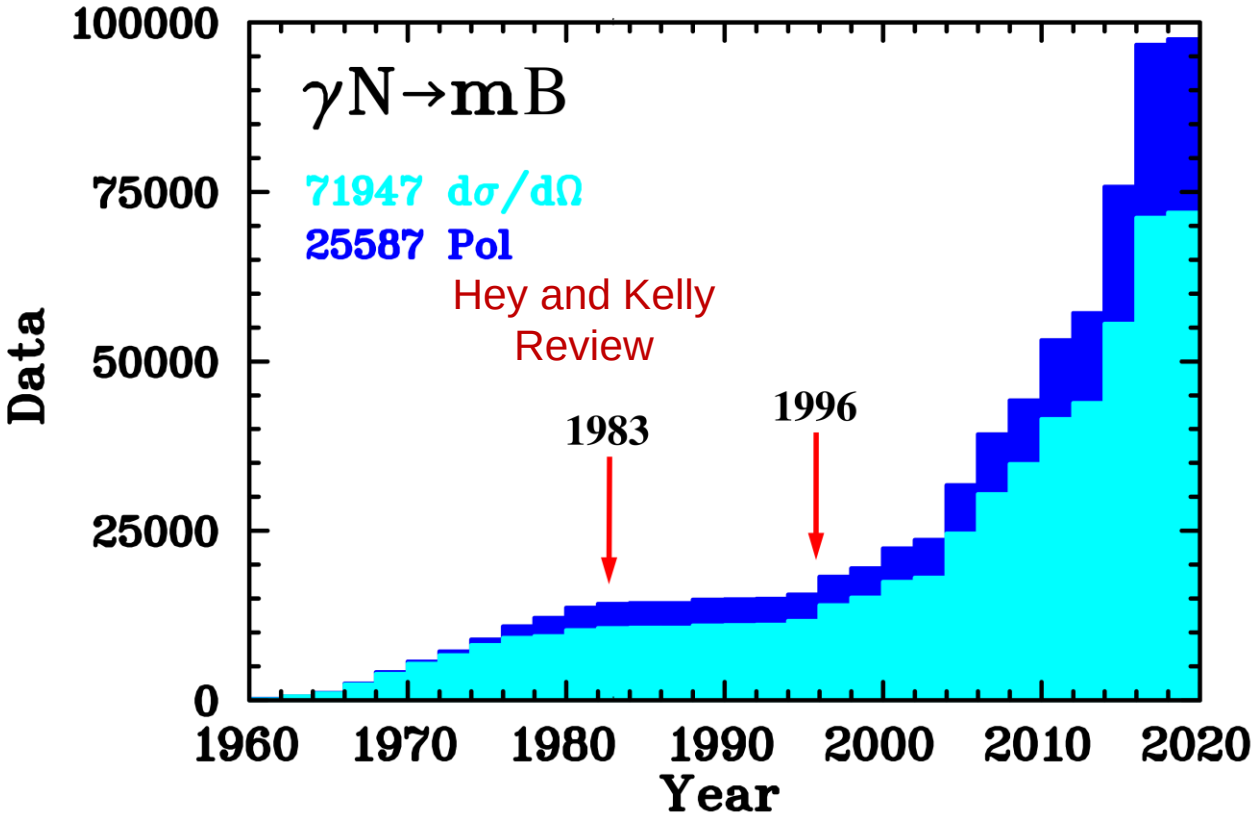


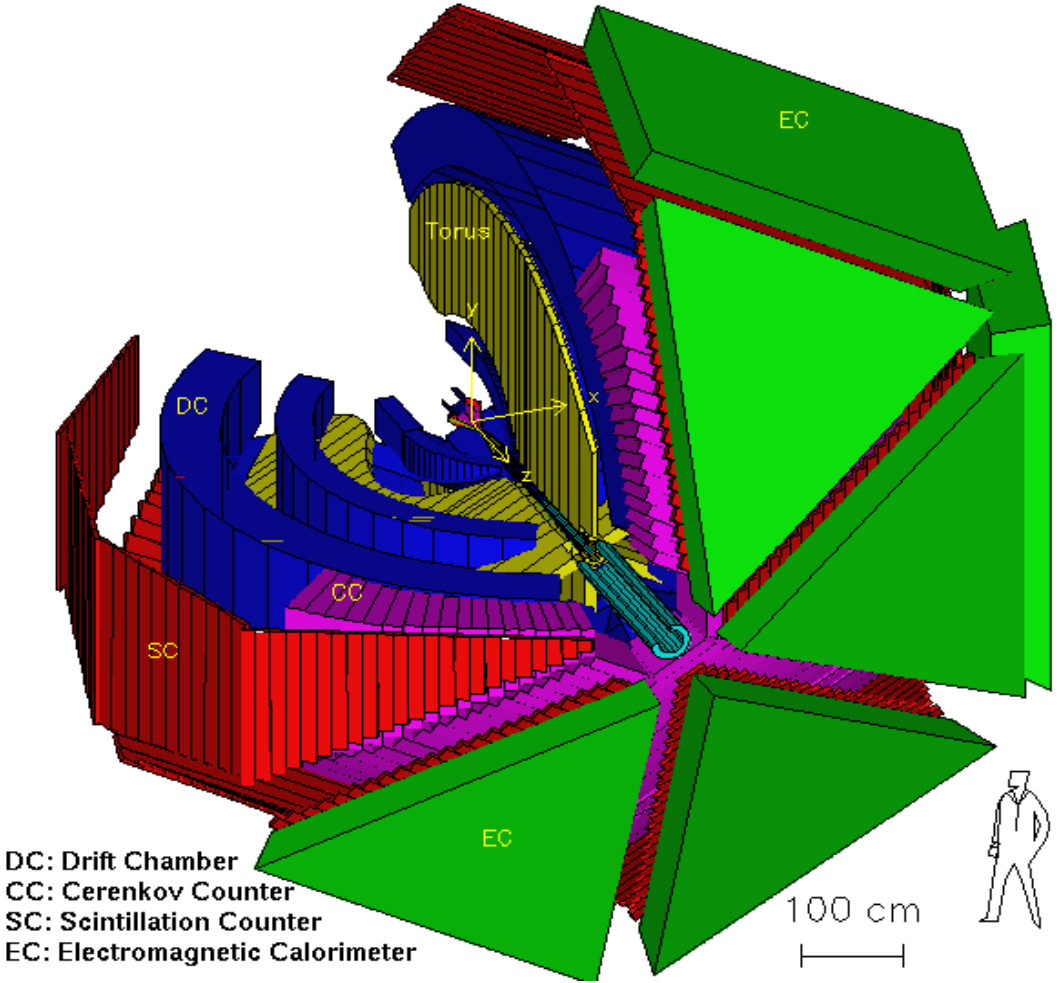
Jefferson Lab

Other facilities…

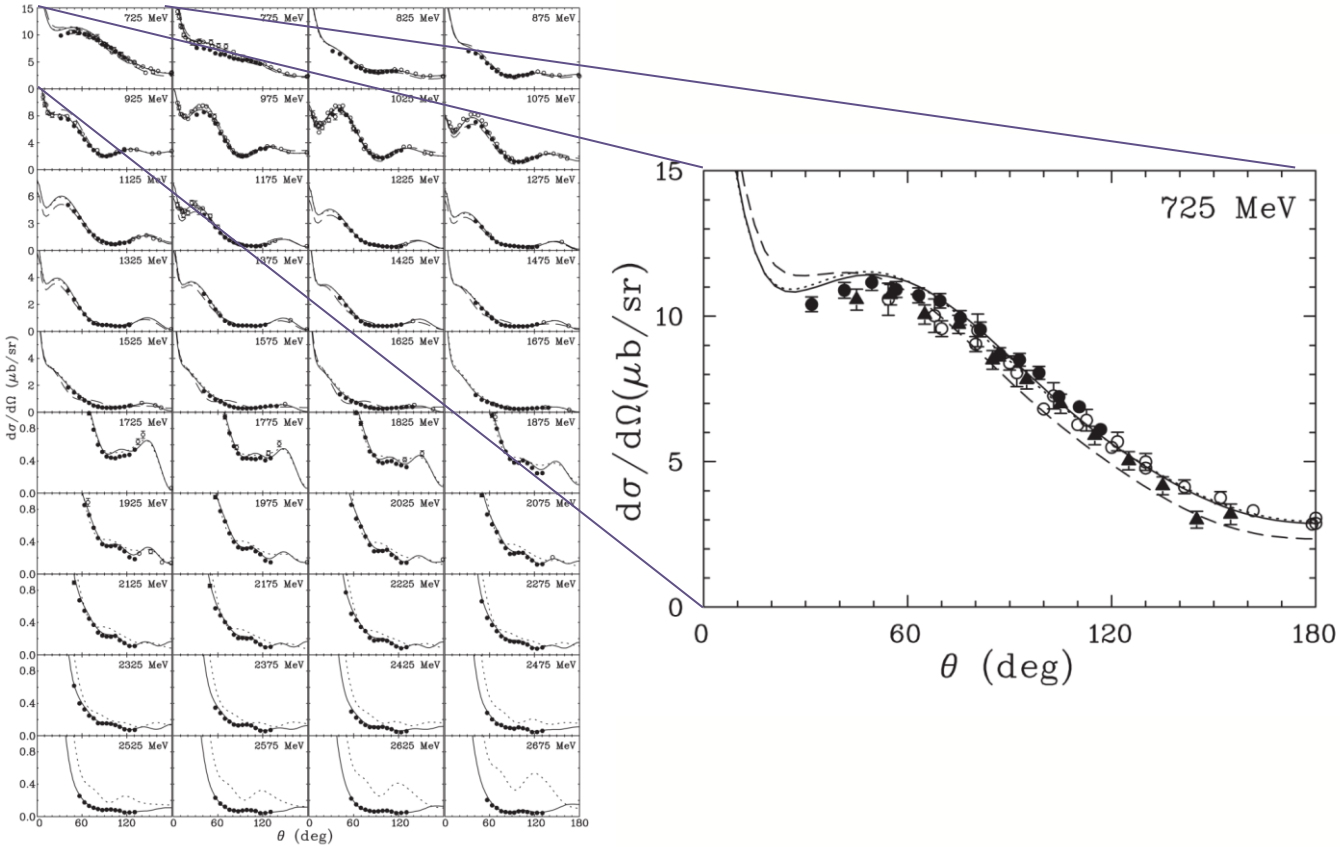
- ELPH (Tohoku, Japan)
- ELSA (Bonn, Germany)
- GRAAL (Grenoble, France)
- LEPS (SPRing-8, Japan)
- MAMI (Mainz, Germany)
- +…

Data Accumulation



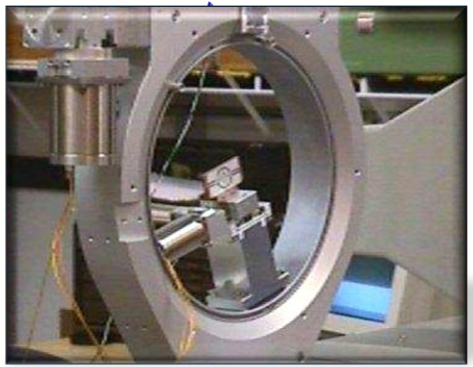

EC
Torus
y
x
z
DC
CC
SC
EC
100 cm
DC: Drift Chamber
CC: Cerenkov Counter
SC: Scintillation Counter
EC: Electromagnetic Calorimeter

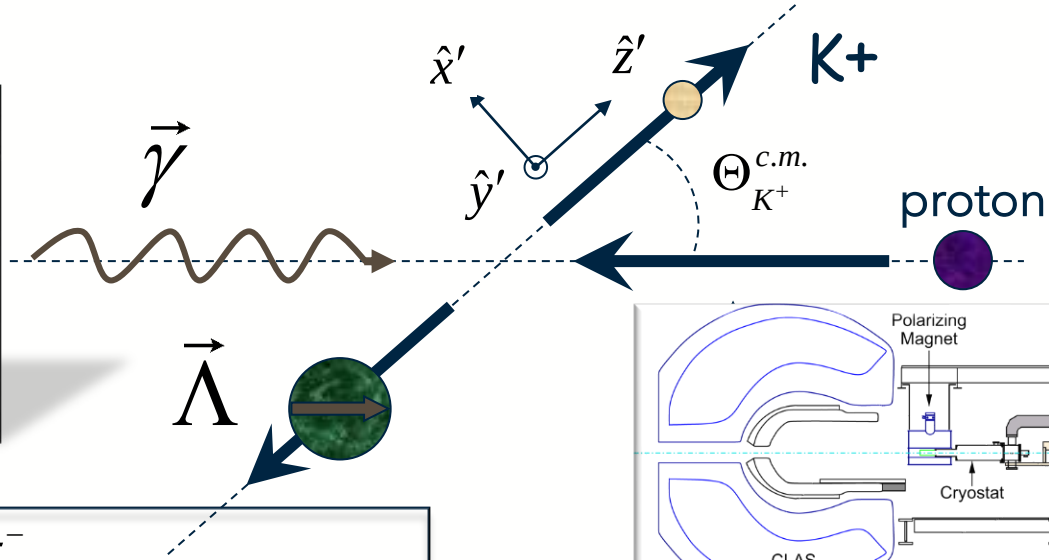
Channel: $\gamma + p \rightarrow \pi^+ + n$;Cross-section

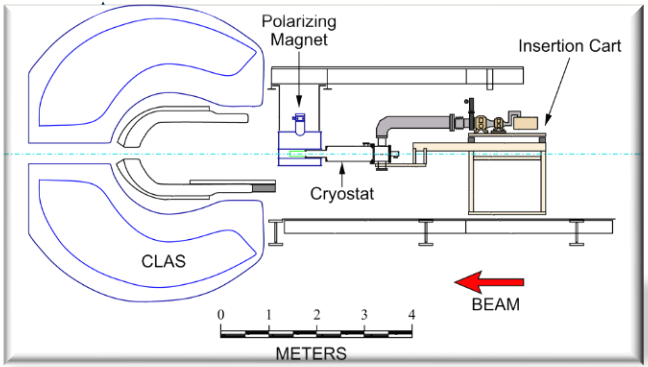


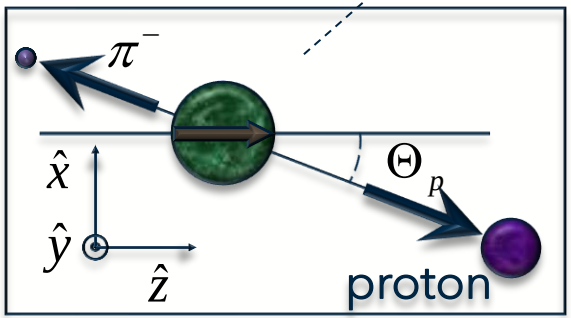
M. Dugger et al. (CLAS), Phys. Rev. C 79, 065206, 2009

Pseudoscalar Meson Photoproduction







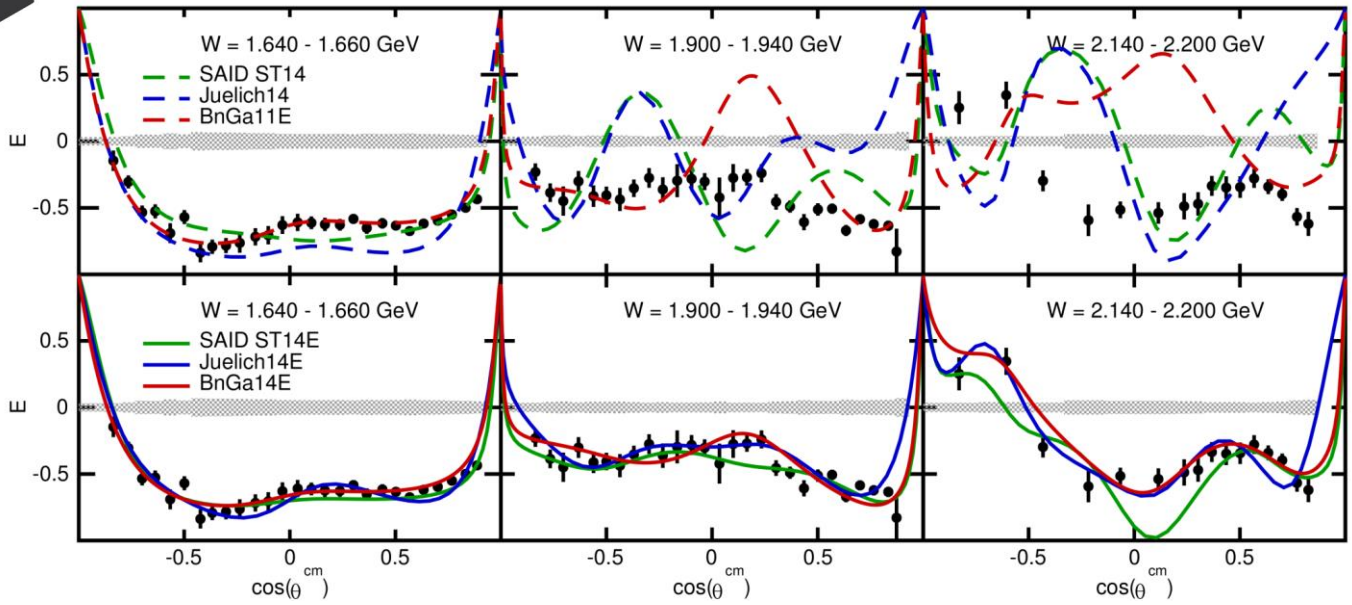


In praise of polarisation…

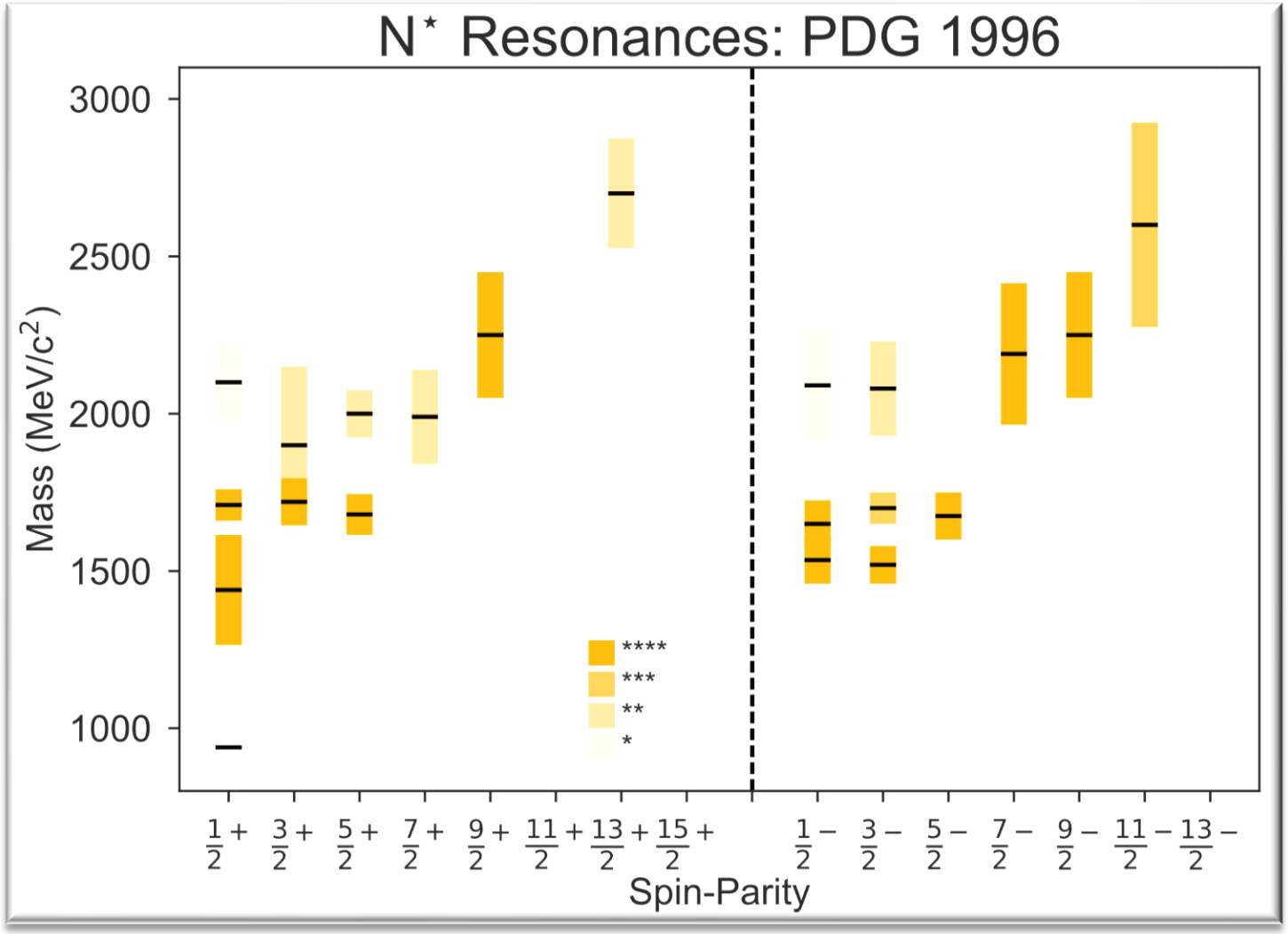
Without Polarizer

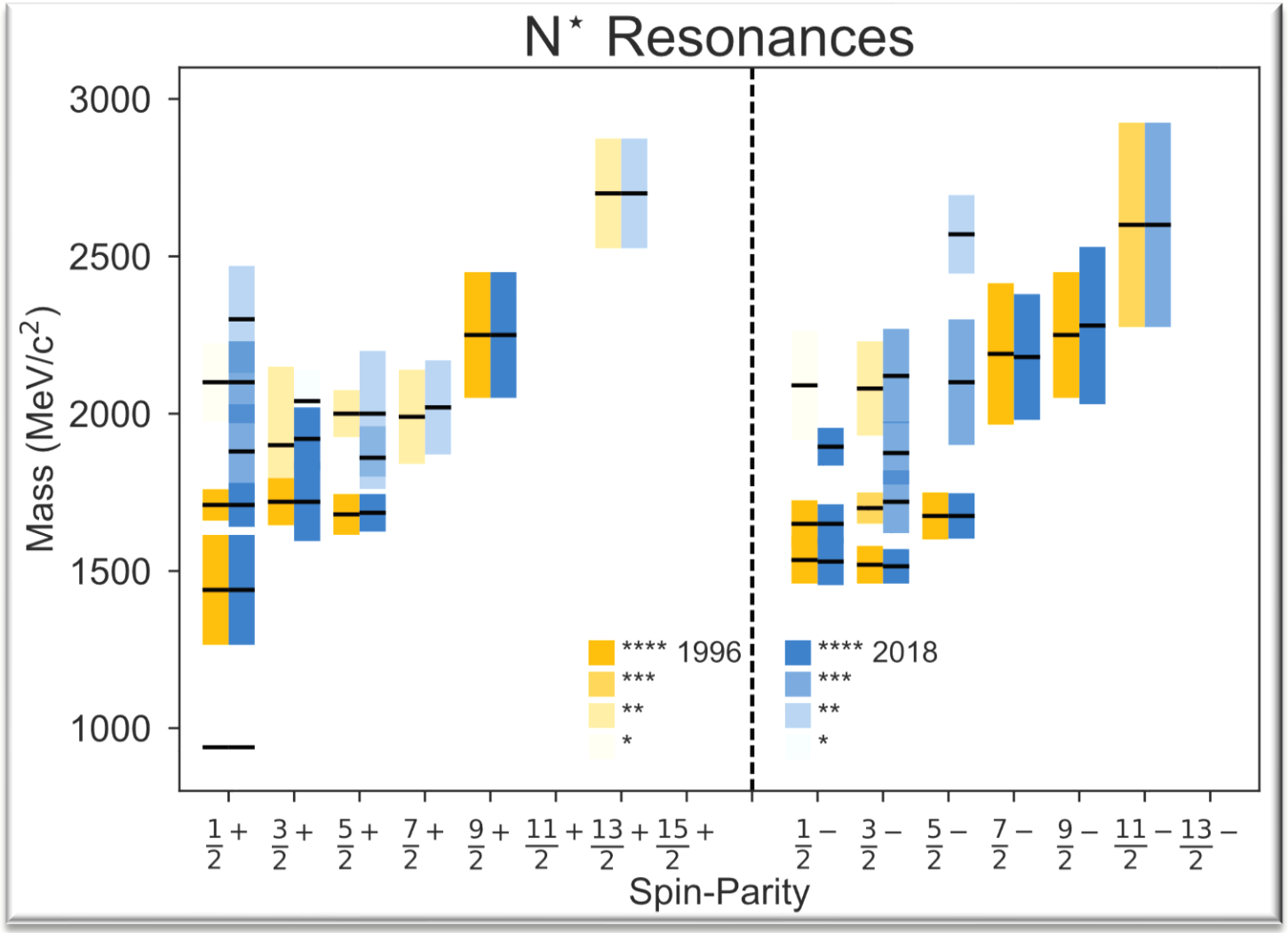
…you'll see more!

Channel: $\vec{\gamma} + \vec{p} \rightarrow \pi^+ + n$;Observable: E

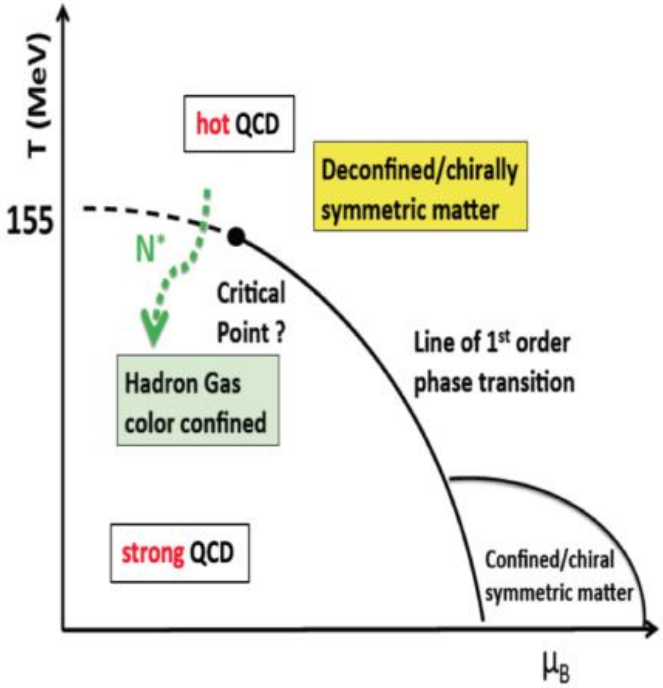


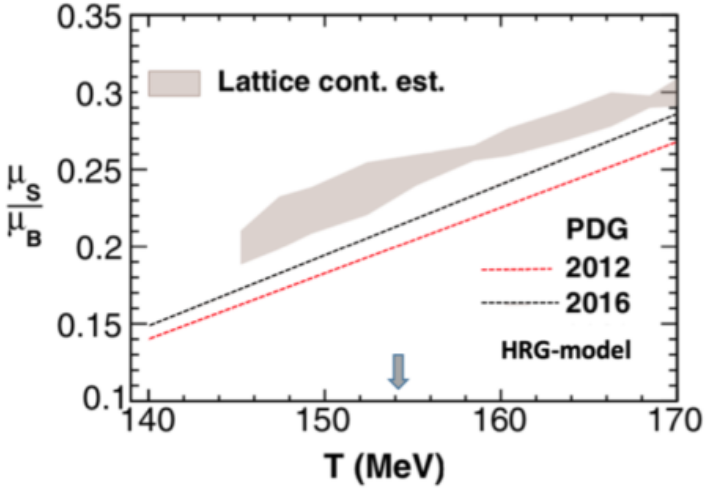
S. Strauch et al. (CLAS), http://arxiv.org/abs/1503.05163 , Phys. Lett. B 750, 53 (2015) .


N* Resonances: PDG 1996
Mass (MeV/c²)
3000
2500
2000
1500
1000
****
***
**
*
1/2 +
3/2 +
5/2 +
7/2 +
9/2 +
11/2 +
13/2 +
15/2 +
1/2 −
3/2 −
5/2 −
7/2 −
9/2 −
11/2 −
13/2 −
Spin-Parity


N* Resonances
Mass (MeV/c²)
3000
2500
2000
1500
1000
**** 1996
***
**
*
**** 2018
***
**
*
1/2 + 3/2 + 5/2 + 7/2 + 9/2 + 11/2 + 13/2 + 15/2 +
1/2 − 3/2 − 5/2 − 7/2 − 9/2 − 11/2 − 13/2 −
Spin-Parity

Baryon resonances and chemical potential



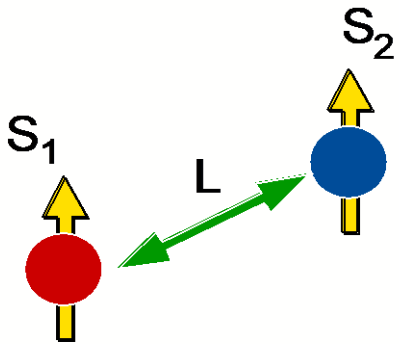


University of Glasgow

Outline

1. Light Baryon Spectrum
2. **Exotic Mesons**
3. Λ Weak Decay Parameter
4. Outlook

"Real" Meson States



$$S = S_1 + S_2$$

$$J = L + S$$

$$P = (-1)^{L+1}$$

$$C = (-1)^{L+S}$$

$q\bar{q}$

+

$(q\bar{q})(q\bar{q})$

+

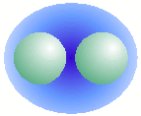
$(q\bar{q})g$

+

gg

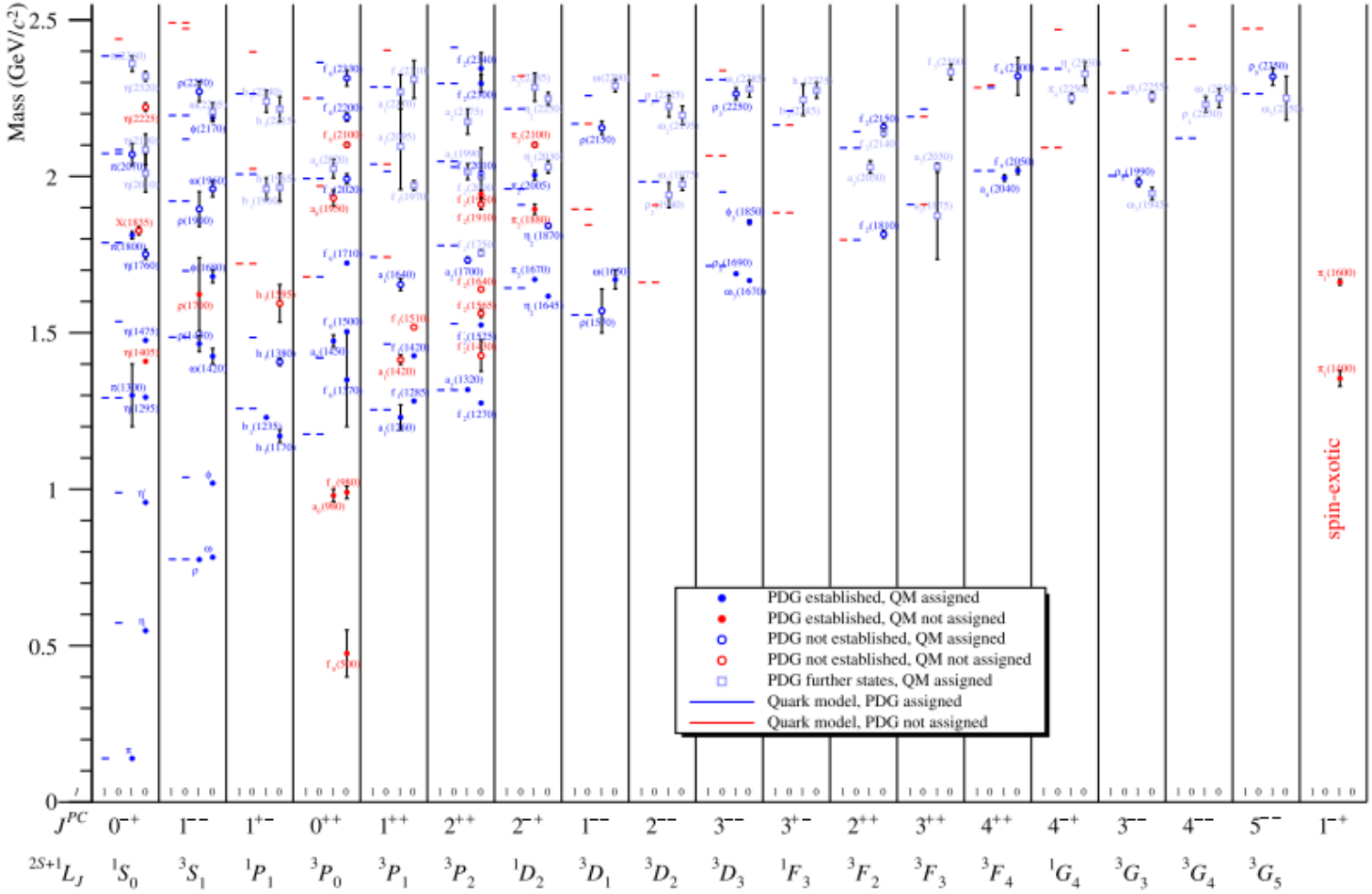
+

.....

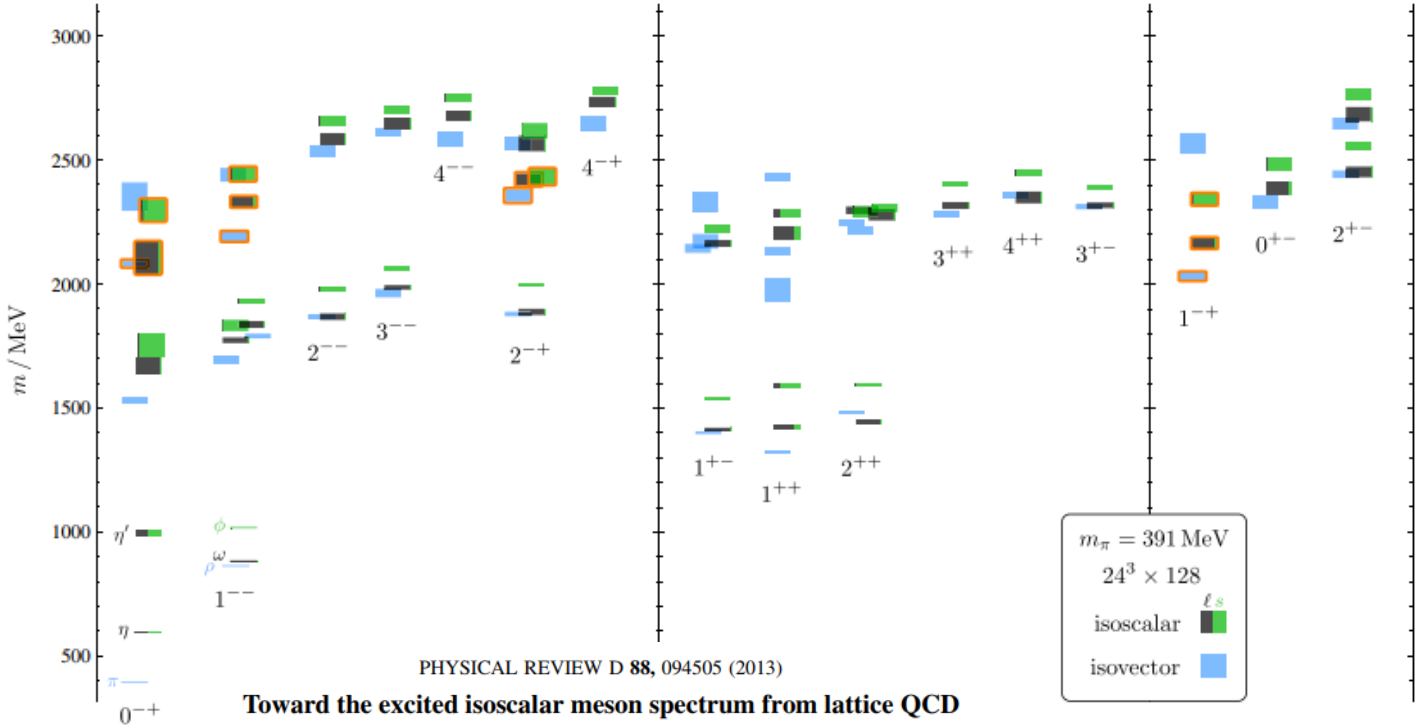


$= \Sigma_i (q\bar{q})_i \Sigma_j g_j$

"Real" Meson States



Lattice Calculations of Light Meson Spectrum



PHYSICAL REVIEW D **88,** 094505 (2013)

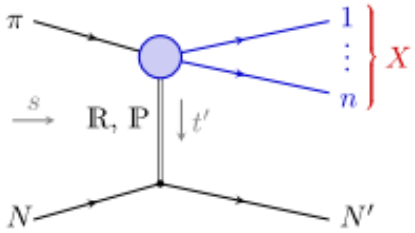
Toward the excited isoscalar meson spectrum from lattice QCD

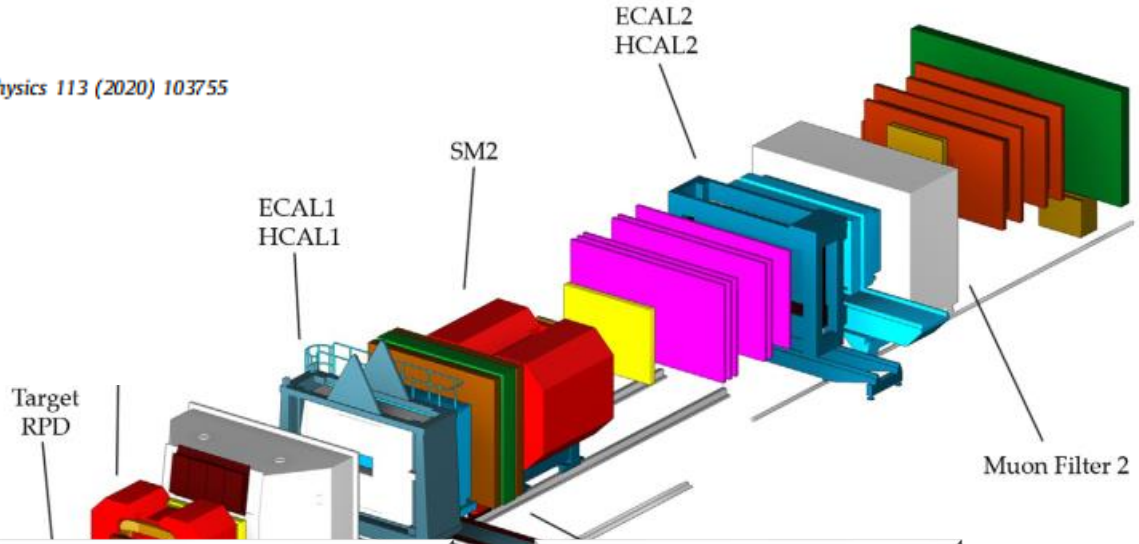
Jozef J. Dudek,[1,2,*] Robert G. Edwards,[1] Peng Guo,[1] and Christopher E. Thomas[3]

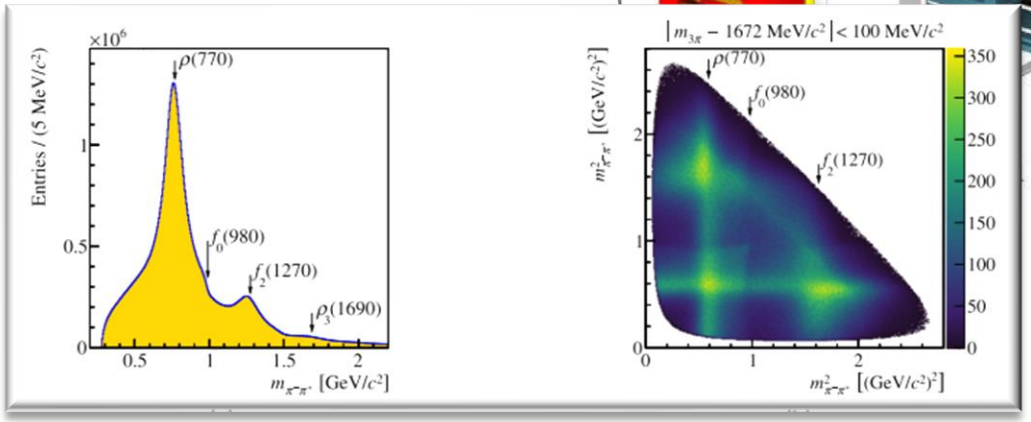
(for Hadron Spectrum Collaboration)

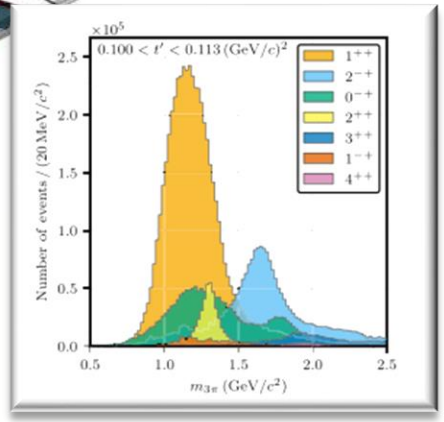
COMPASS results

B. Ketzer, B. Grube and D. Ryabchikov / Progress in Particle and Nuclear Physics 113 (2020) 103755

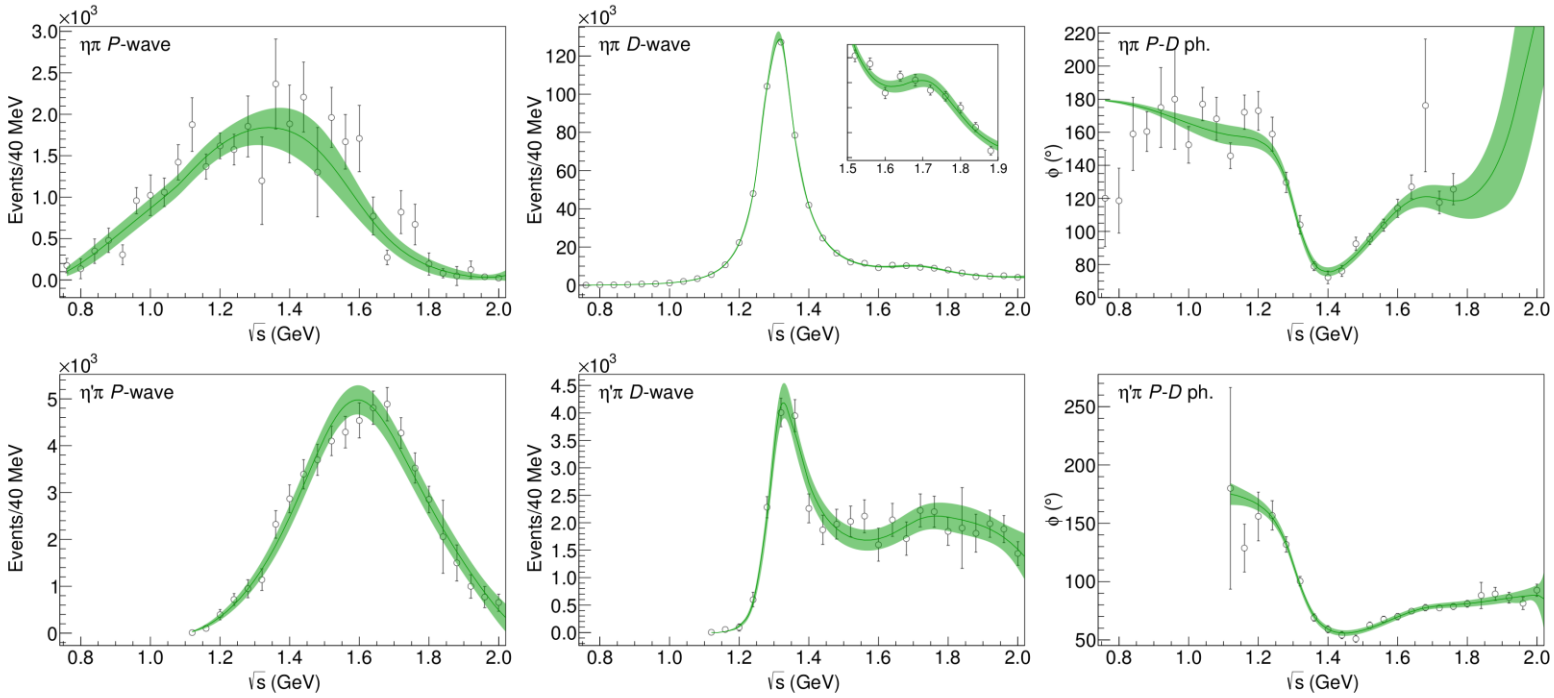






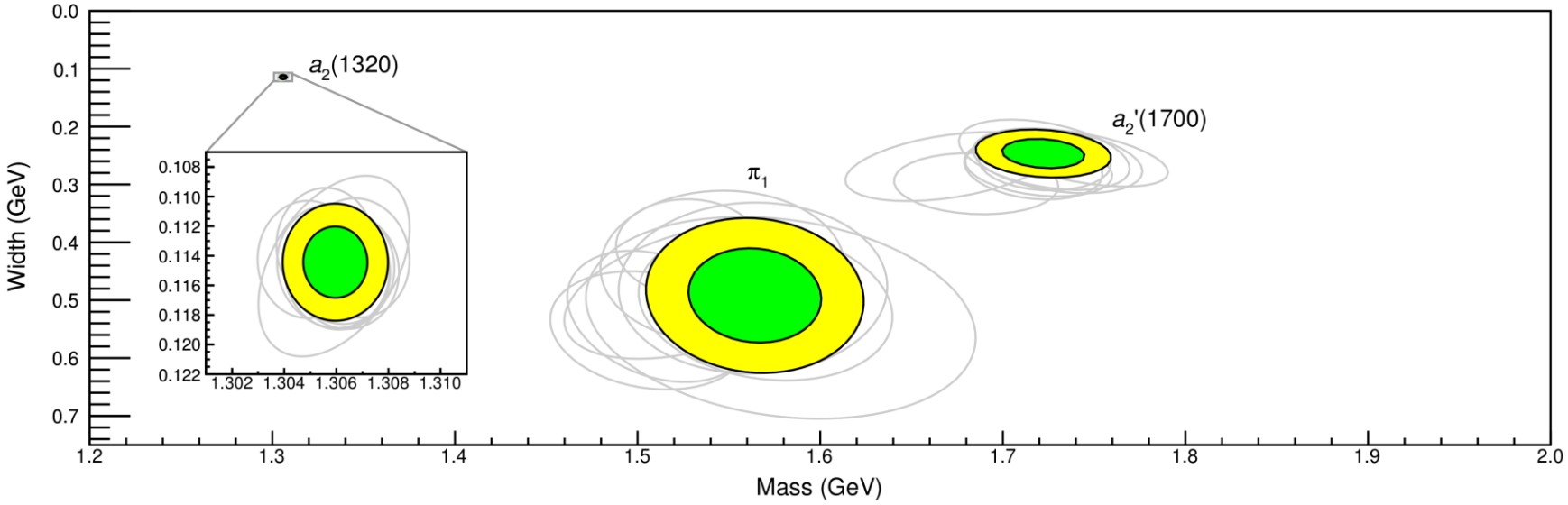


Pole position(s) of the lightest hybrid meson(s)?



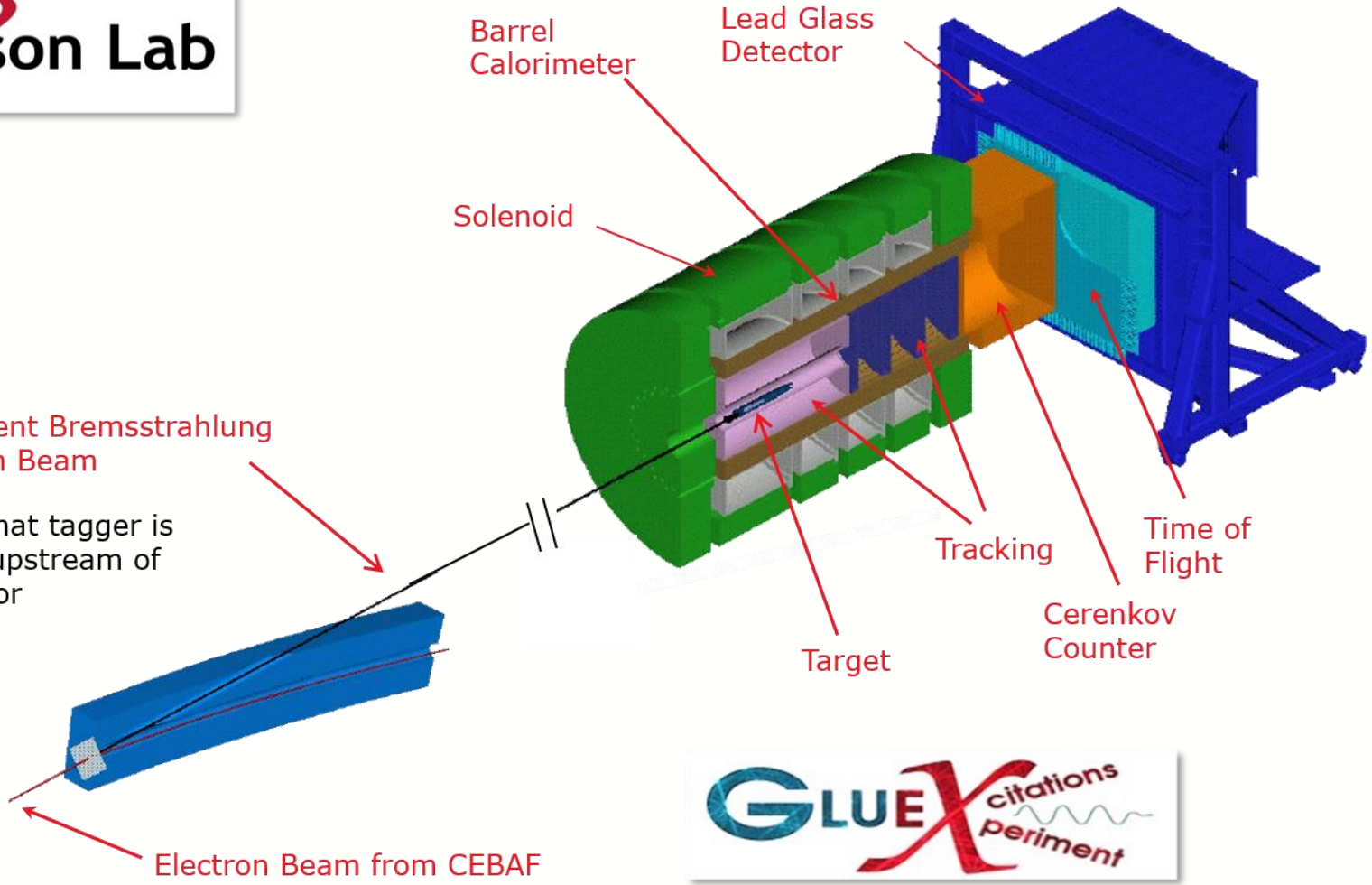
JPAC Collaboration: A. Rodas, et al, Phys. Rev. Lett. 122, 042002 (2019)

Pole position(s) of the lightest hybrid meson(s)?



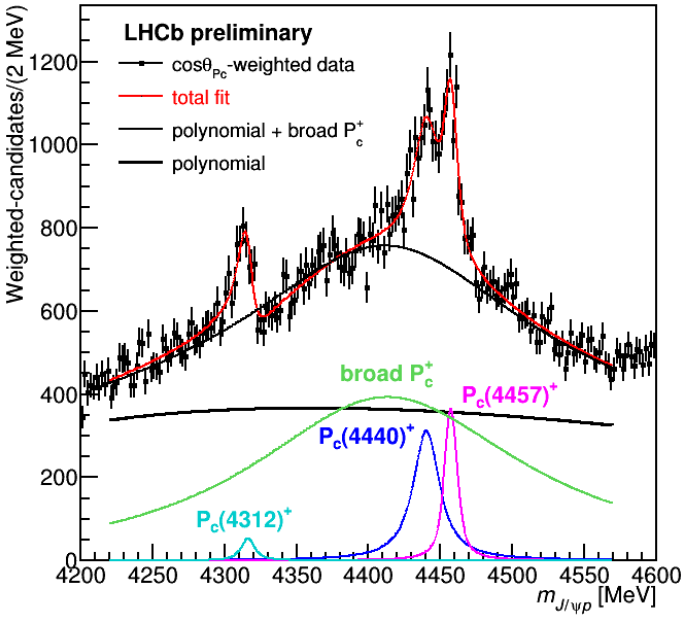
- extracted single exotic π_1 resonant pole
- mass and width 1564 +- 24 +- 86 MeV and 492 +- 54 +- 102 MeV
- couples to both $\eta(')\pi$ channels
- no evidence for a second exotic state.

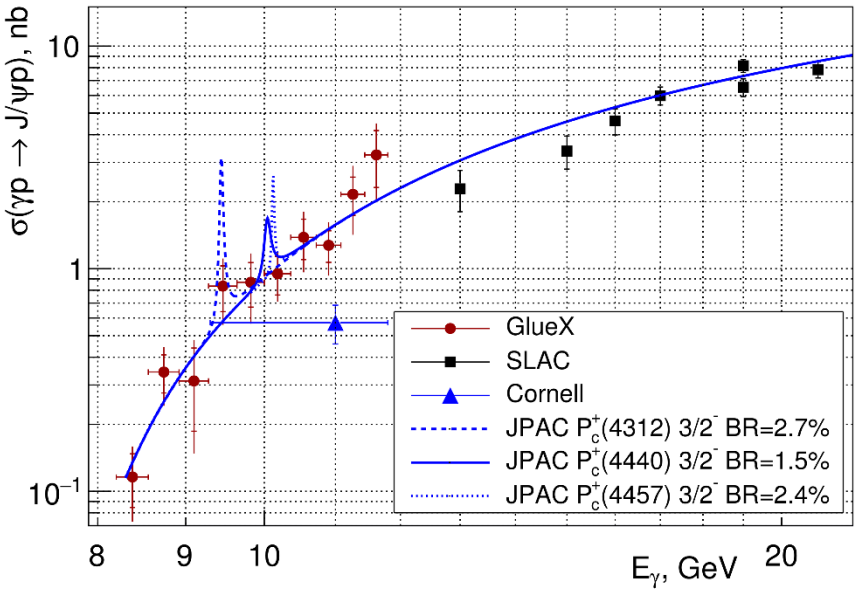
Jefferson Lab



GlueXcitations Experiment

http://dustbunny.physics.indiana.edu/HallD





https://arxiv.org/abs/1905.10811

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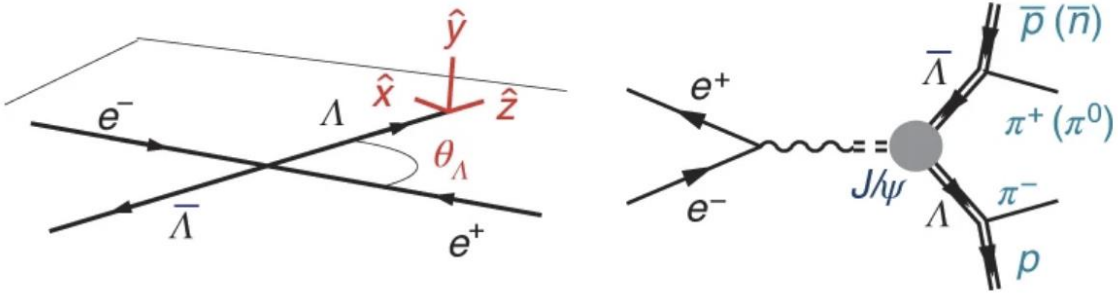
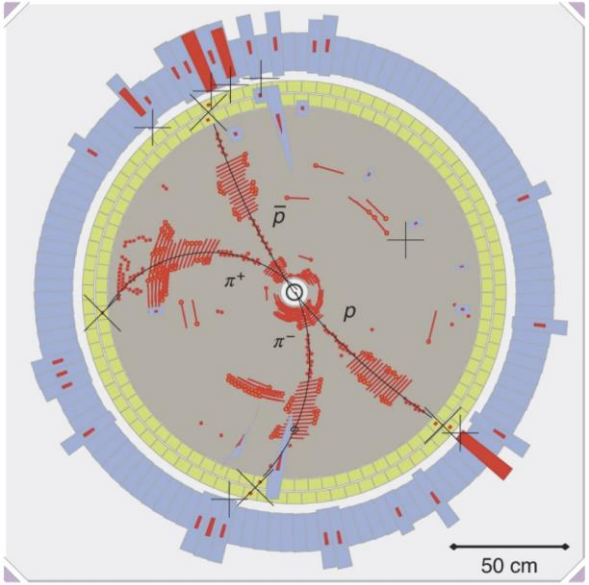
nature physics

Letter | Published: 06 May 2019

Polarization and entanglement in baryon–antibaryon pair production in electron–positron annihilation

The BESIII Collaboration



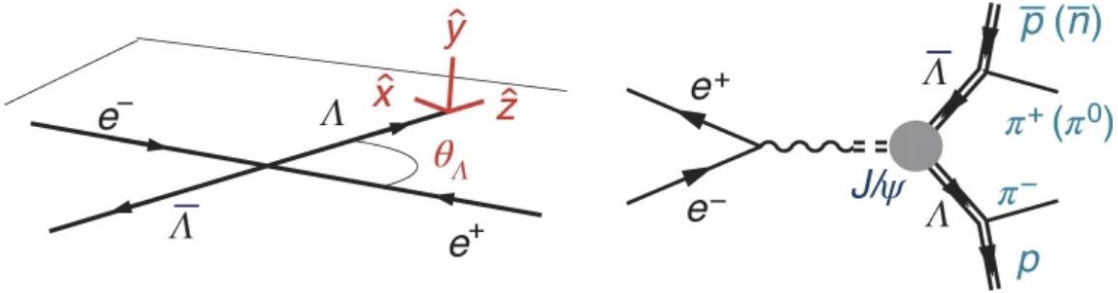


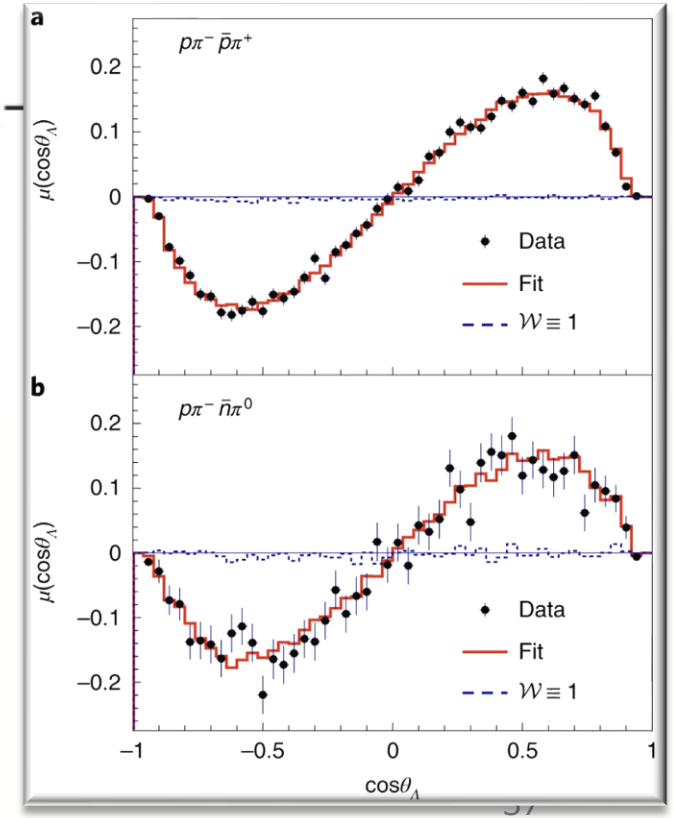
nature physics

Letter | Published: 06 May 2019

Polarization and entanglement in baryon–antibaryon pair production in electron–positron annihilation

The BESIII Collaboration





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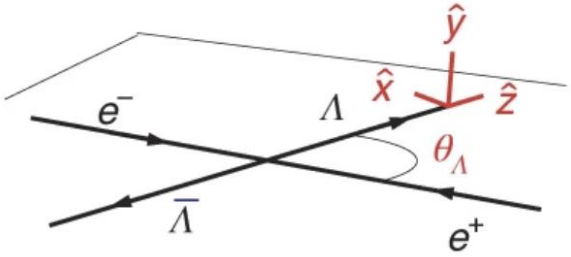


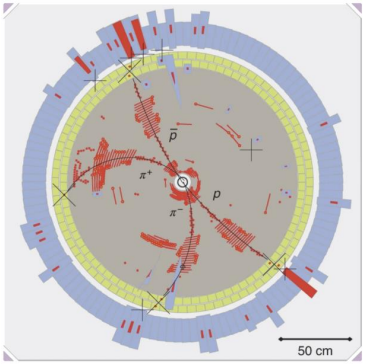
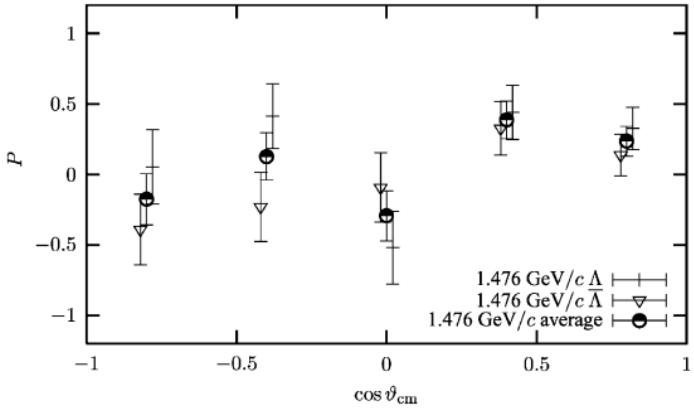


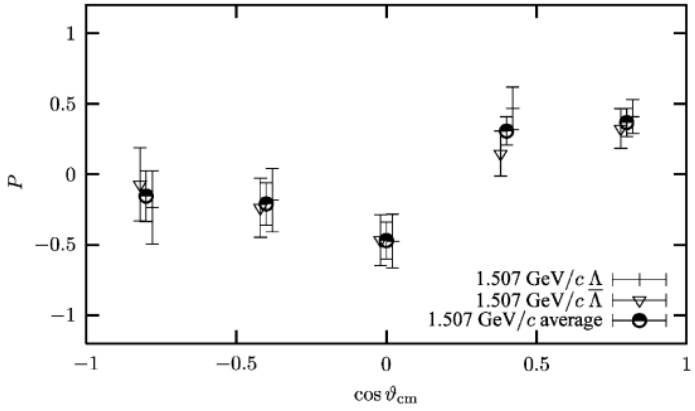
Table 1 | Summary of the results

Parameters	This work	Previous results
α_ψ	$0.461 \pm 0.006 \pm 0.007$	0.469 ± 0.027 (ref. [14])
$\Delta\Phi$	$42.4 \pm 0.6 \pm 0.5°$	-
α_-	$0.750 \pm 0.009 \pm 0.004$	0.642 ± 0.013 (ref. [6])
α_+	$-0.758 \pm 0.010 \pm 0.007$	-0.71 ± 0.08 (ref. [6])
$\bar{\alpha}_0$	$-0.692 \pm 0.016 \pm 0.006$	-
A_{CP}	$-0.006 \pm 0.012 \pm 0.007$	0.006 ± 0.021 (ref. [6])
$\bar{\alpha}_0/\alpha_+$	$0.913 \pm 0.028 \pm 0.012$	-

So what?

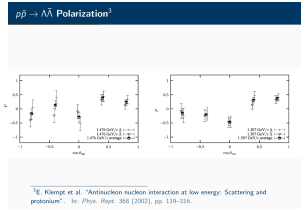
$p\bar{p} \to \Lambda\bar{\Lambda}$ Polarization[3]





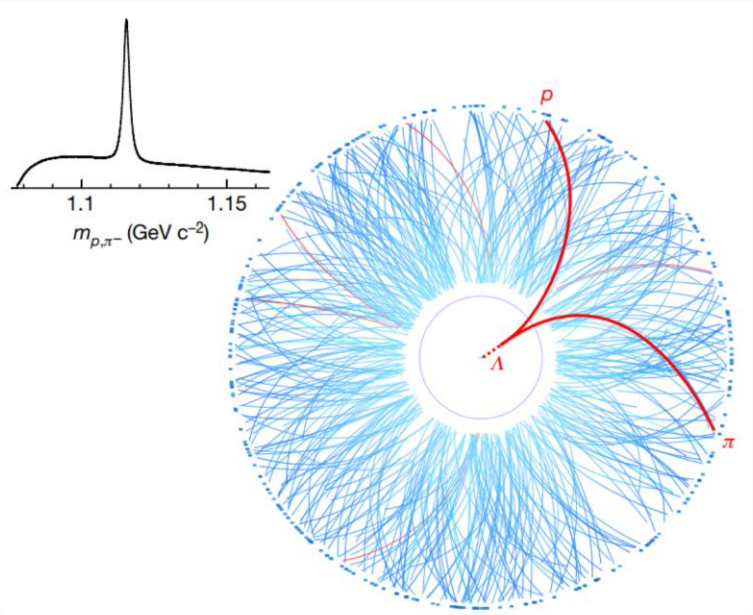
[3] E. Klempt et al. "Antinucleon nucleon interaction at low energy: Scattering and protonium". In: *Phys. Rept.* 368 (2002), pp. 119–316.

So what?

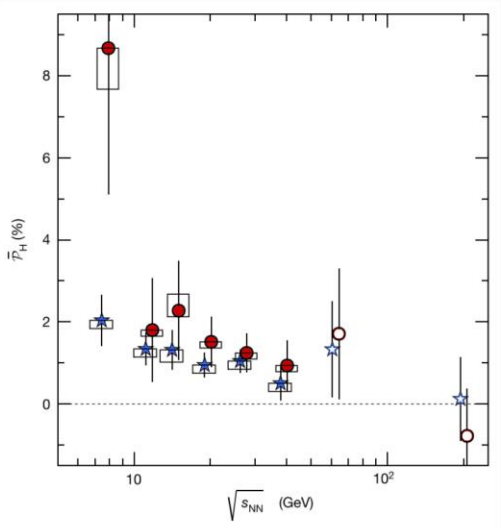


Global Λ hyperon polarization in nuclear collisions[4]

STAR Au-Au collision

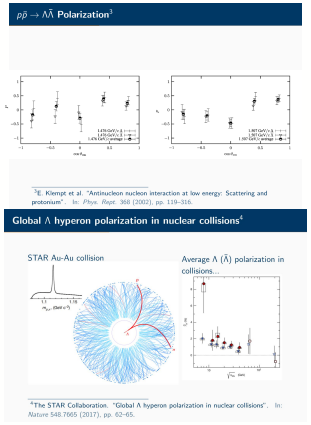


Average Λ ($\bar{\Lambda}$) polarization in collisions...

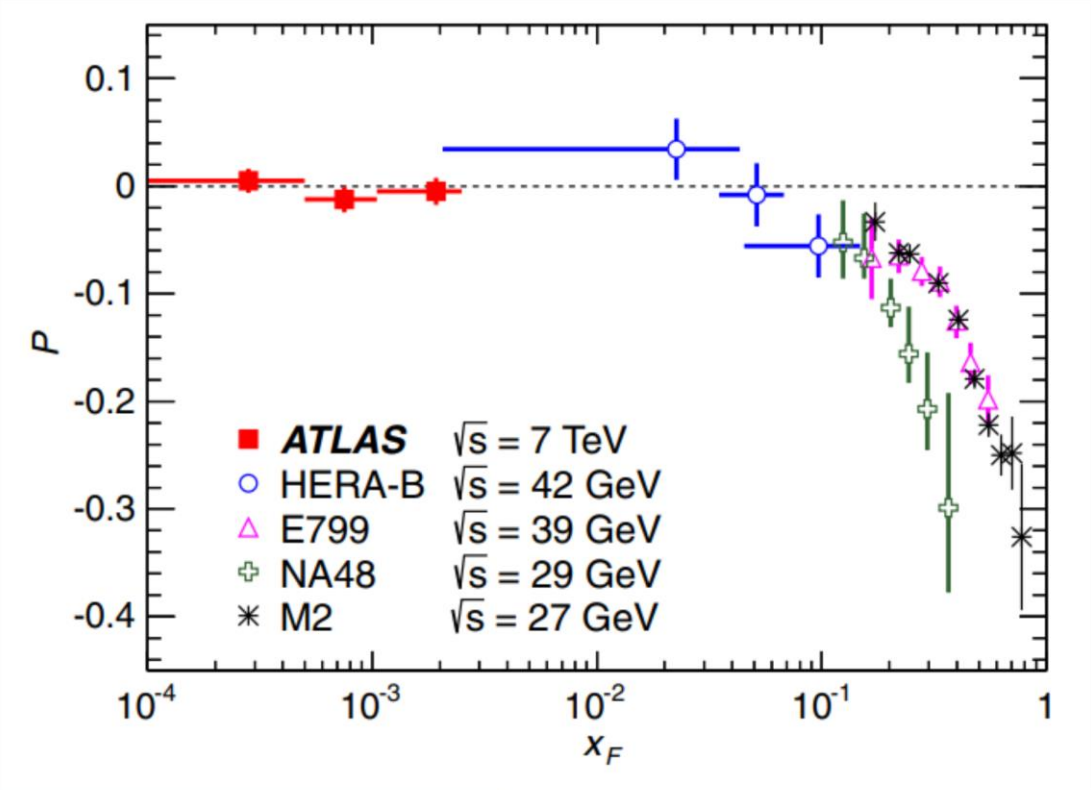


[4] The STAR Collaboration. "Global Λ hyperon polarization in nuclear collisions". In: *Nature* 548.7665 (2017), pp. 62–65.

So what?



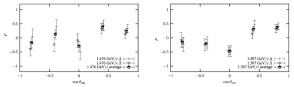
$\Lambda(\bar{\Lambda})$ Transverse Polarization with ATLAS[5]



[5] ATLAS Collaboration, G. Aad, et al. "Measurement of the transverse polarization of Λ and $\bar{\Lambda}$ hyperons produced in proton-proton...". In: *Phys. Rev. D* 91 (2015),

So what?

$p\bar{p} \to \Lambda\bar{\Lambda}$ Polarization[3]



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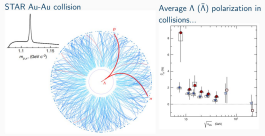

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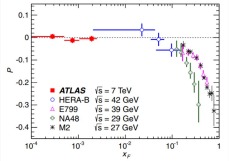

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10

Decay Parameters of Higher Mass States[6]

Ω^- DECAY PARAMETERS

$\alpha(\Omega^-)\ \alpha_-(\Lambda)$ FOR $\Omega^- \to \Lambda K^-$

Some early results have been omitted.

VALUE	*EVTS*
0.0115 ± 0.0015	**OUR AVERAGE**

Ξ^0 DECAY PARAMETERS

See the ``Note on Baryon Decay Parameters'' in

$\alpha(\Xi^0)\ \alpha_-(\Lambda)$

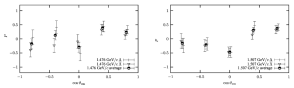
This is a product of the $\Xi^0 \to \Lambda\pi^0$ and $\Lambda \to p\pi^-$ asy

VALUE	*EVTS*
-0.261 ± 0.006	**OUR AVERAGE**

[6] (Particle Data Group) Tanabashi, M. et al. "Review of Particle Physics". In: *Phys. Rev. D* 98.3 (Aug. 2018), p. 030001.

So what?

$p\bar{p} \to \Lambda\bar{\Lambda}$ Polarization[3]



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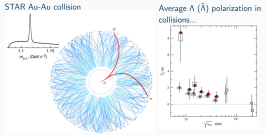

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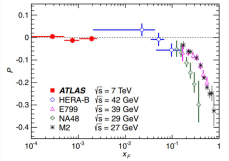

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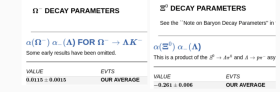
Decay Parameters of Higher Mass States[6]



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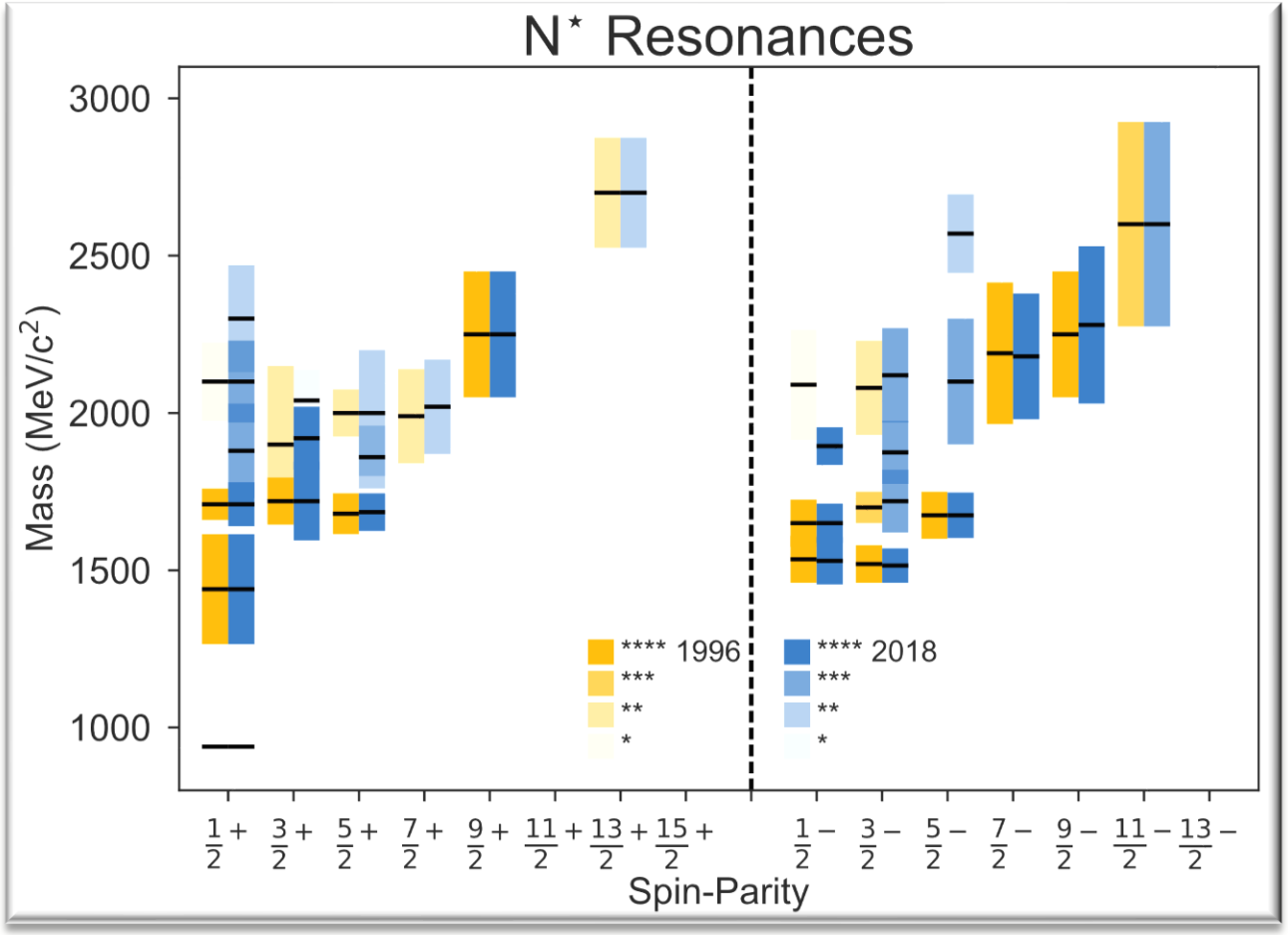
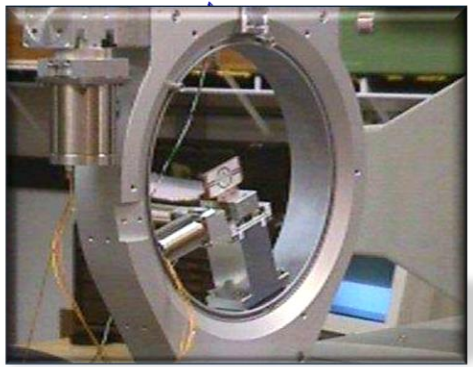
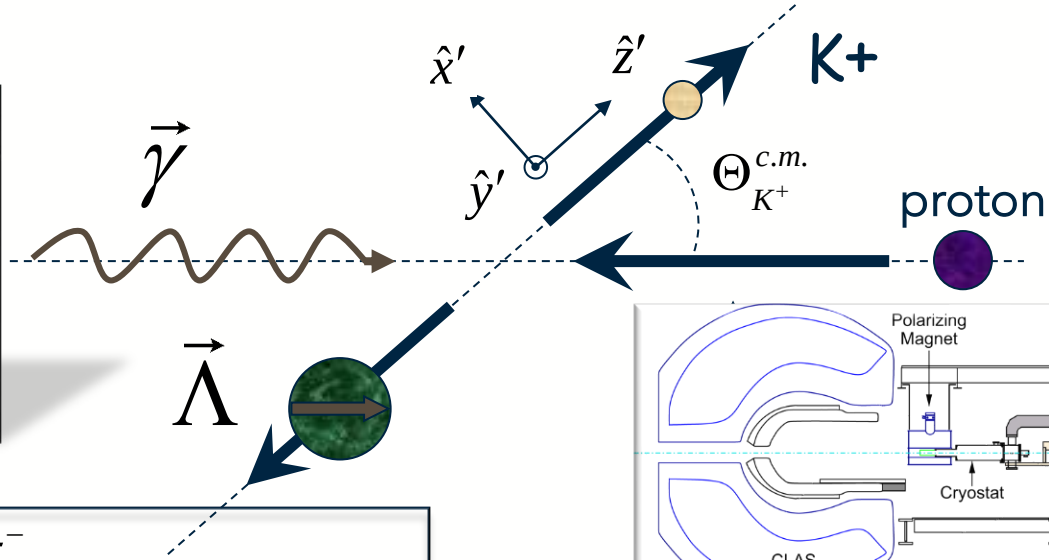
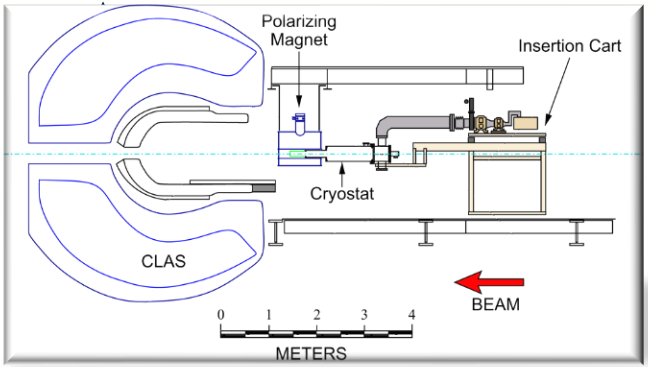
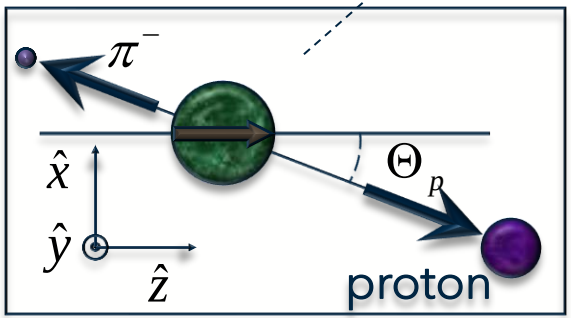


Pseudoscalar Meson Photoproduction

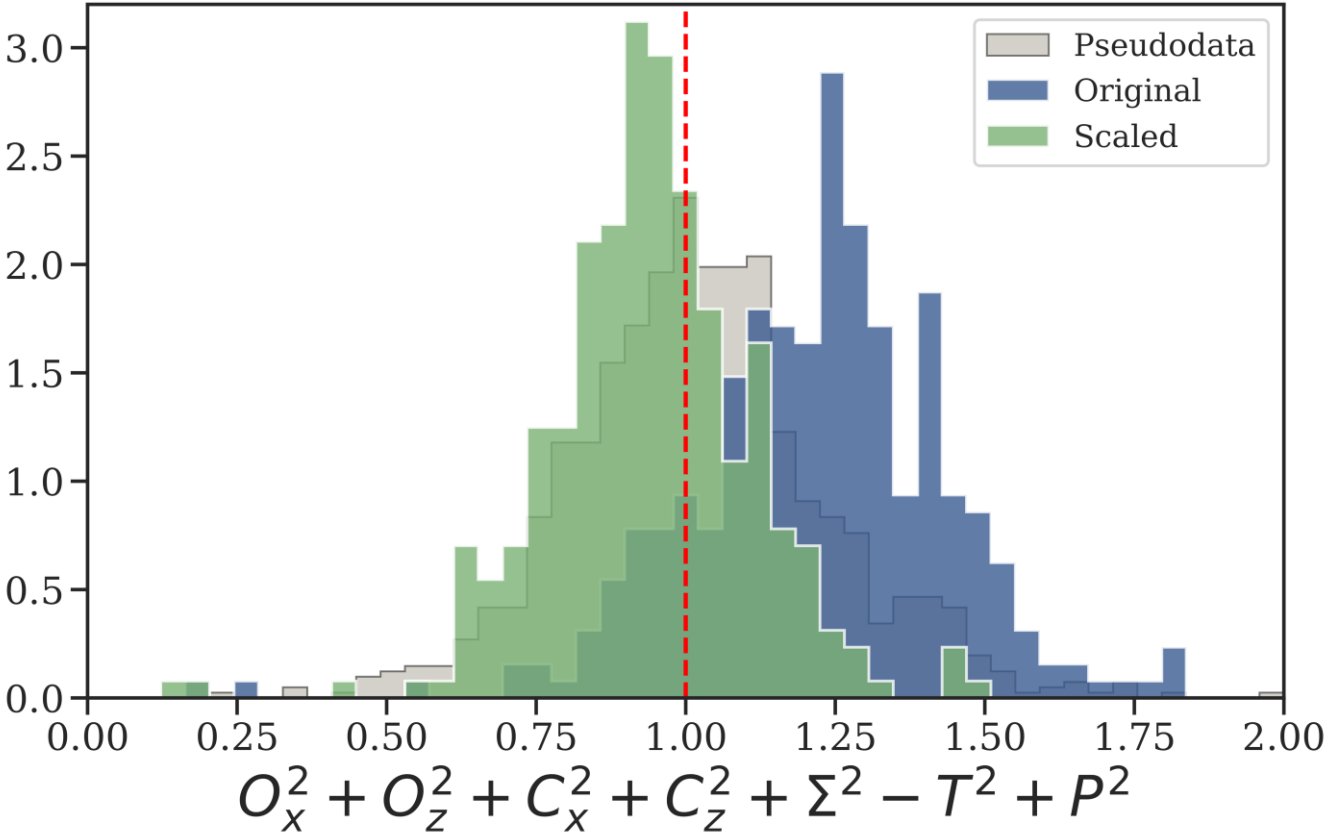




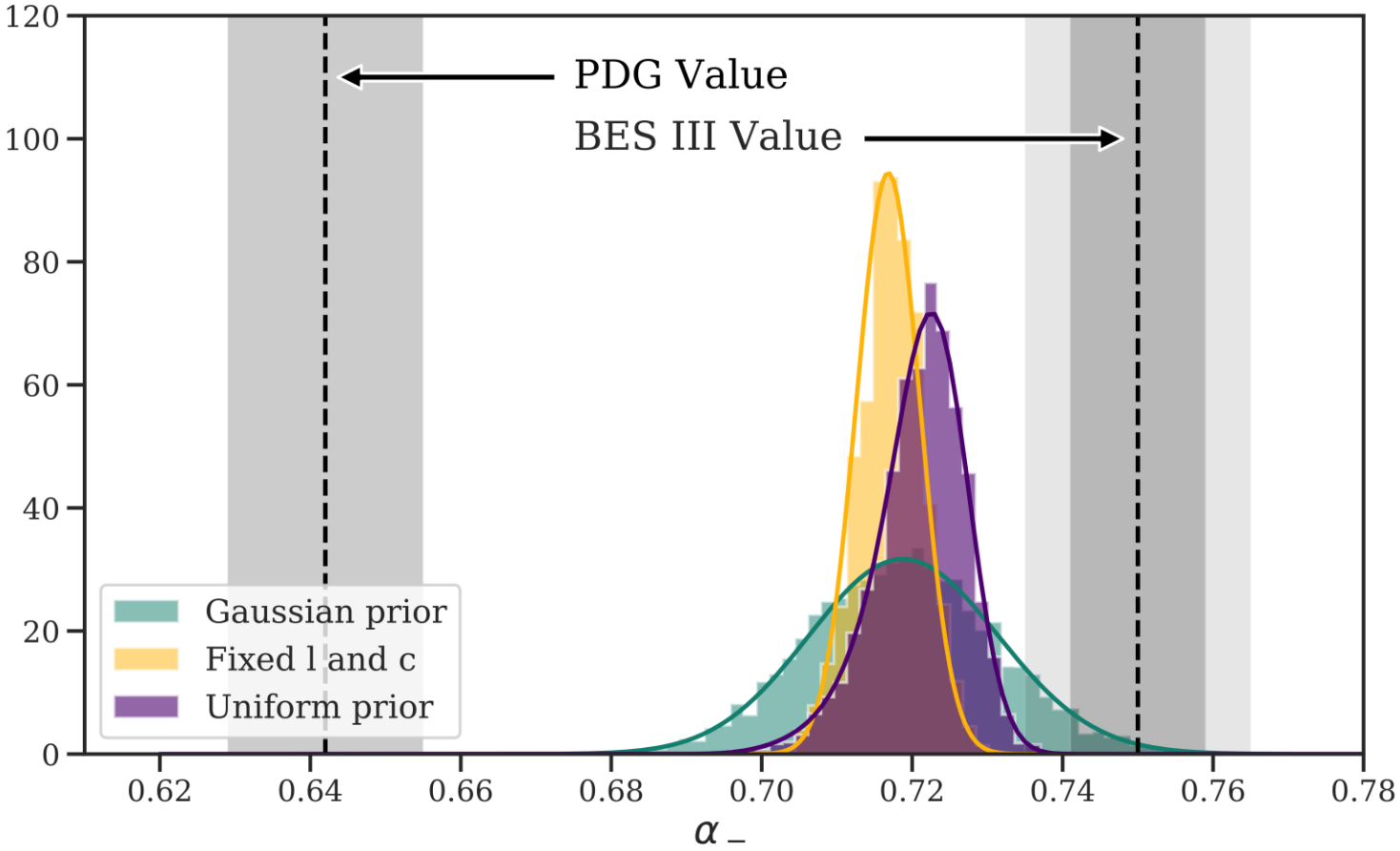




Kaon Photoproduction (@CLAS)



MCMC Parameter Estimate of α_-



2020 Review of Particle Physics.
P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020)

Λ DECAY PARAMETERS

See the ``Note on Baryon Decay Parameters'' in the neutron Listings. Some early results have been omitted.

α_- FOR $\Lambda \to p\pi^-$

INSPIRE search

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.732 ± 0.014	**OUR AVERAGE**	Error includes scale factor of 2.3.			
0.750 ±0.009 ±0.004	420k	ABLIKIM	2019BJ	BES3	J/ψ to $\Lambda\bar{\Lambda}$
0.721 ±0.006 ±0.005		[1] IRELAND	2019	CLAS	K production
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.584 ±0.046	8500	ASTBURY	1975	SPEC	
0.649 ±0.023	10325	CLELAND	1972	OSPK	
0.67 ±0.06	3520	DAUBER	1969	HBC	From Ξ decay
0.645 ±0.017	10130	OVERSETH	1967	OSPK	Λ from $\pi^- p$
0.62 ±0.07	1156	CRONIN	1963	CNTR	Λ from $\pi^- p$

[1] This is a new analysis based on existing kaon photoproduction data of the CLAS collaboration and using spin algebra constraints.

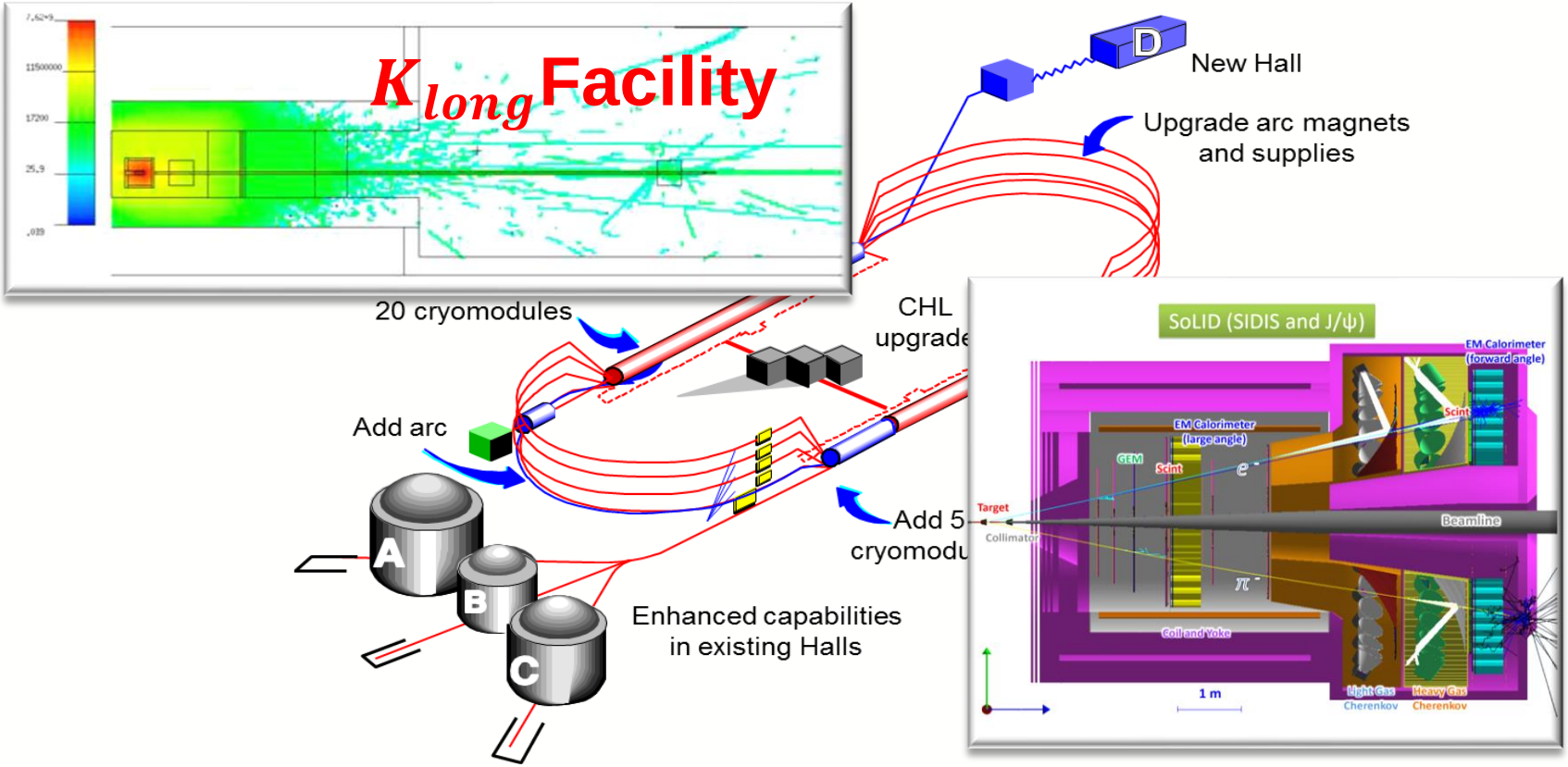
University of Glasgow

Outline

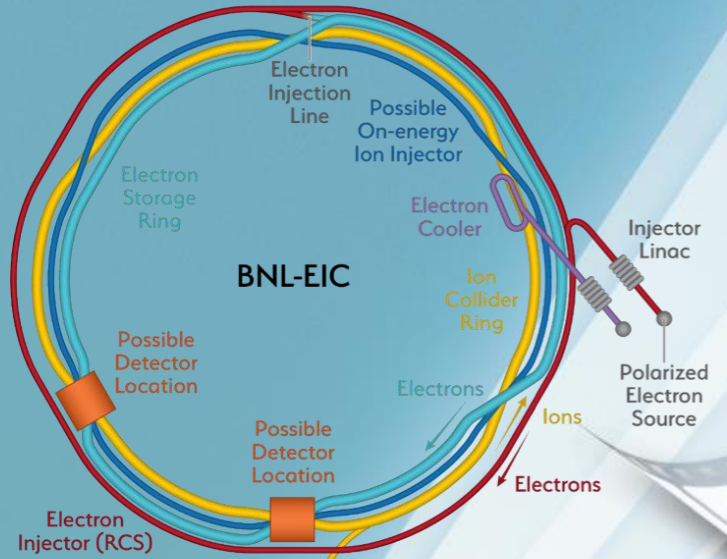
1. Light Baryon Spectrum
2. Exotic Mesons
3. Λ Weak Decay Parameter
4. **Outlook**

Jefferson Lab

K_{long} Facility



Electron-Ion Collider



EIC: Current UK involvement / interest

University of Glasgow

Lancaster University

THE UNIVERSITY of LIVERPOOL

Brunel University London

UNIVERSITY OF DERBY

The Cockcroft Institute of Accelerator Science and Technology

UNIVERSITY OF BIRMINGHAM

UNIVERSITY of York

UNIVERSITY OF OXFORD

Science & Technology Facilities Council Rutherford Appleton Laboratory

Science & Technology Facilities Council Daresbury Laboratory

UCL

Plus interest from other groups (Cambridge, Manchester, QMUL)…

Summary

1. Light Baryon Spectrum
   - Progress, but not complete
2. Exotic Mesons
   - Focus of JLab campaigns (GlueX,CLAS12)
3. Λ Weak Decay Parameter
   - Updated value
4. Outlook
   - Exploitation and new facilities

- Updated value