Preparations for CLAS12 and Connections Between Nuclear and Particle Physics

Derek Glazier

University of Glasgow

In Collaboration with :
CLAS, HASPECT

Workshop : Exotic Hadron Spectroscopy
Higgs Centre for Theoretical Physics
Edinburgh, 26-27th September 2016

Aim of the Workshop

The aim of the workshop is to bring together the nuclear and particle physics communities to discuss experimental searches for exotic hadronic resonances (tetra, penta, hexaquarks etc); the latest data analysis methods used; the theoretical interpretation of these states and the potential for future searches at current experimental facilities (CERN, JLab, Mainz). It is hoped that this workshop will facilitate information exchange between the different communities involved and lead to new search strategies for exotic states to be developed.

What is the difference between nuclear and particle?

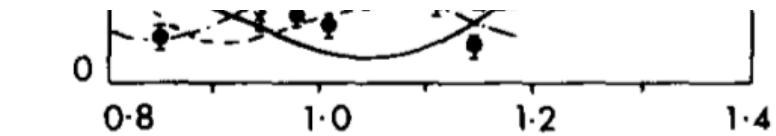
What is the difference between nuclear and particle?

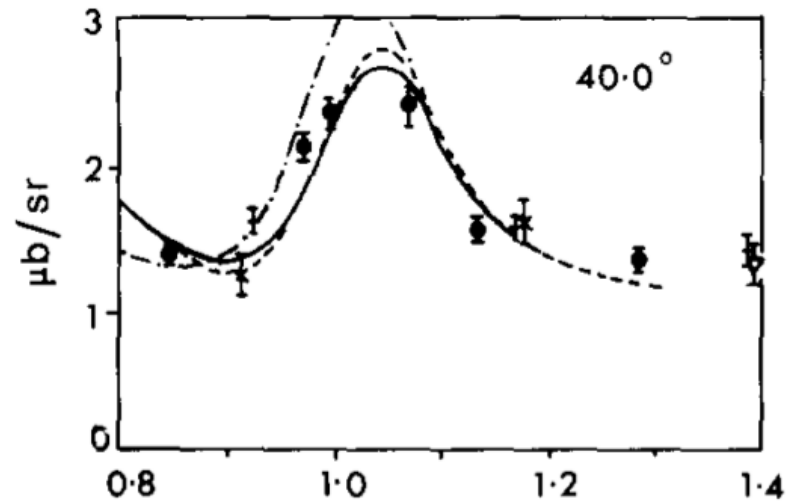
THE PHOTOPRODUCTION OF NEUTRAL PIONS FROM PROTONS AT FORWARD ANGLES IN THE RESONANCE REGION

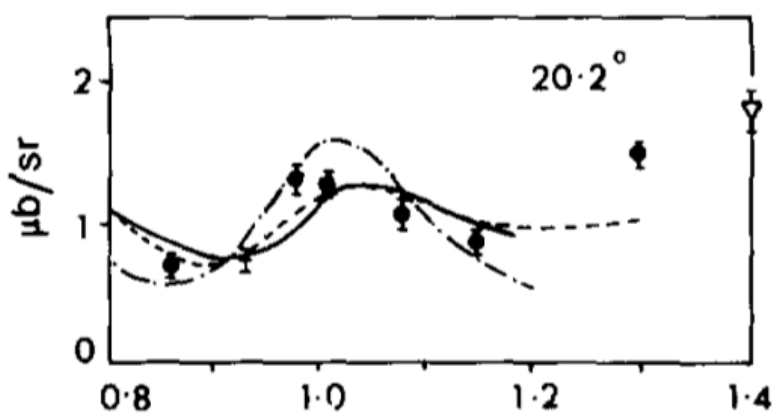
P.S.L. BOOTH, L.J. CARROLL, J.R. HOLT, J.N. JACKSON, W.H. RANGE, K.A. SPRAKES and J.R. WORMALD
University of Liverpool

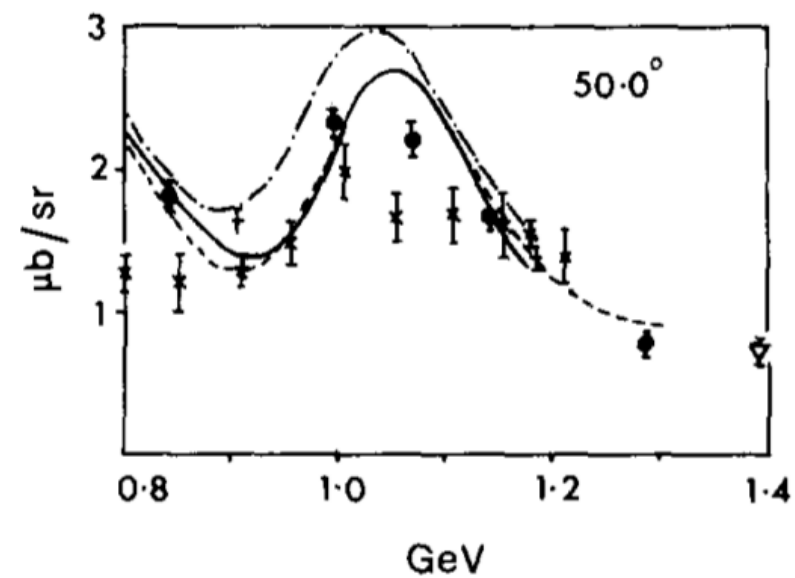
Received 8 August 1974

Abstract: Differential cross sections for the photoproduction of pi-zero mesons from protons have been measured at angles between 10° and 70° c.m. in the energy range 0.85 GeV to 1.30 GeV. The values are compared with the fits to pion photoproduction data from three recent partial-wave analyses.









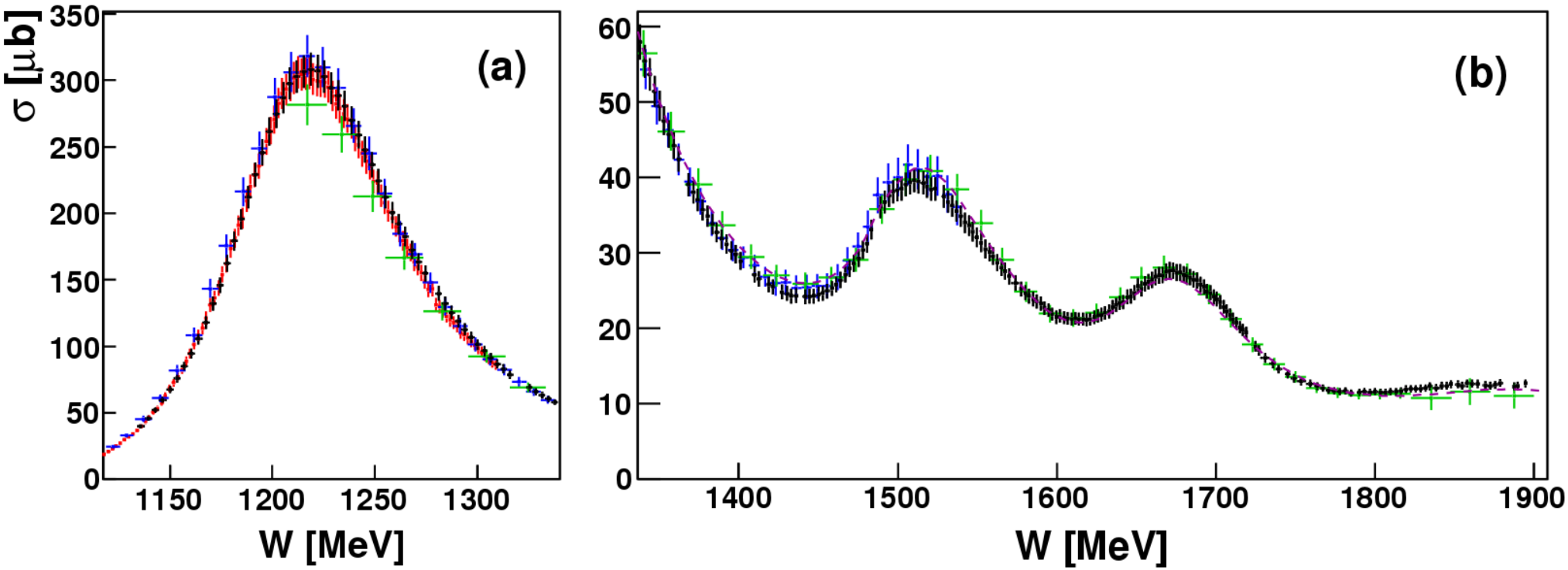
What is the difference between nuclear and particle?

Around 40 years....

Measurement of π^0 photoproduction on the proton at MAMI C

(Dated: August 21, 2015)

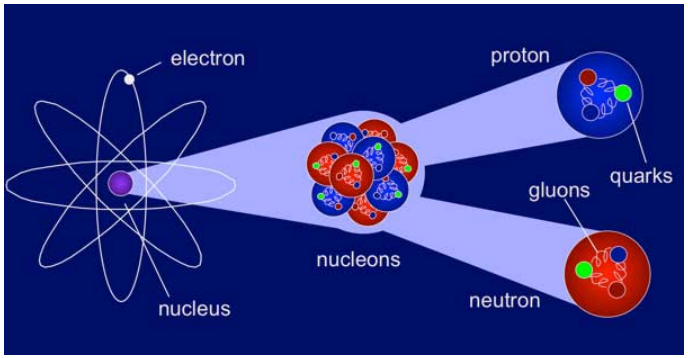
Differential cross sections for the $\gamma p \to \pi^0 p$ reaction have been measured with the A2 tagged-photon facilities at the Mainz Microtron, MAMI C, up to the center-of-mass energy $W = 1.9$ GeV. The new results, obtained with a fine energy and angular binning, increase the existing quantity of π^0 photoproduction data by $\sim 47\%$. Owing to the unprecedented statistical accuracy and the full angular coverage, the results are sensitive to high partial-wave amplitudes. This is demonstrated by the decomposition of the differential cross sections in terms of Legendre polynomials and by further comparison to model predictions. A new solution of the SAID partial-wave analysis obtained after adding the new data into the fit is presented.



But look, it is much more precise!

UK Nuclear Physics & STFC

A nucleus is a system of protons and neutrons, themselves composed of further sub-constituents (quarks), held together by the strong force.



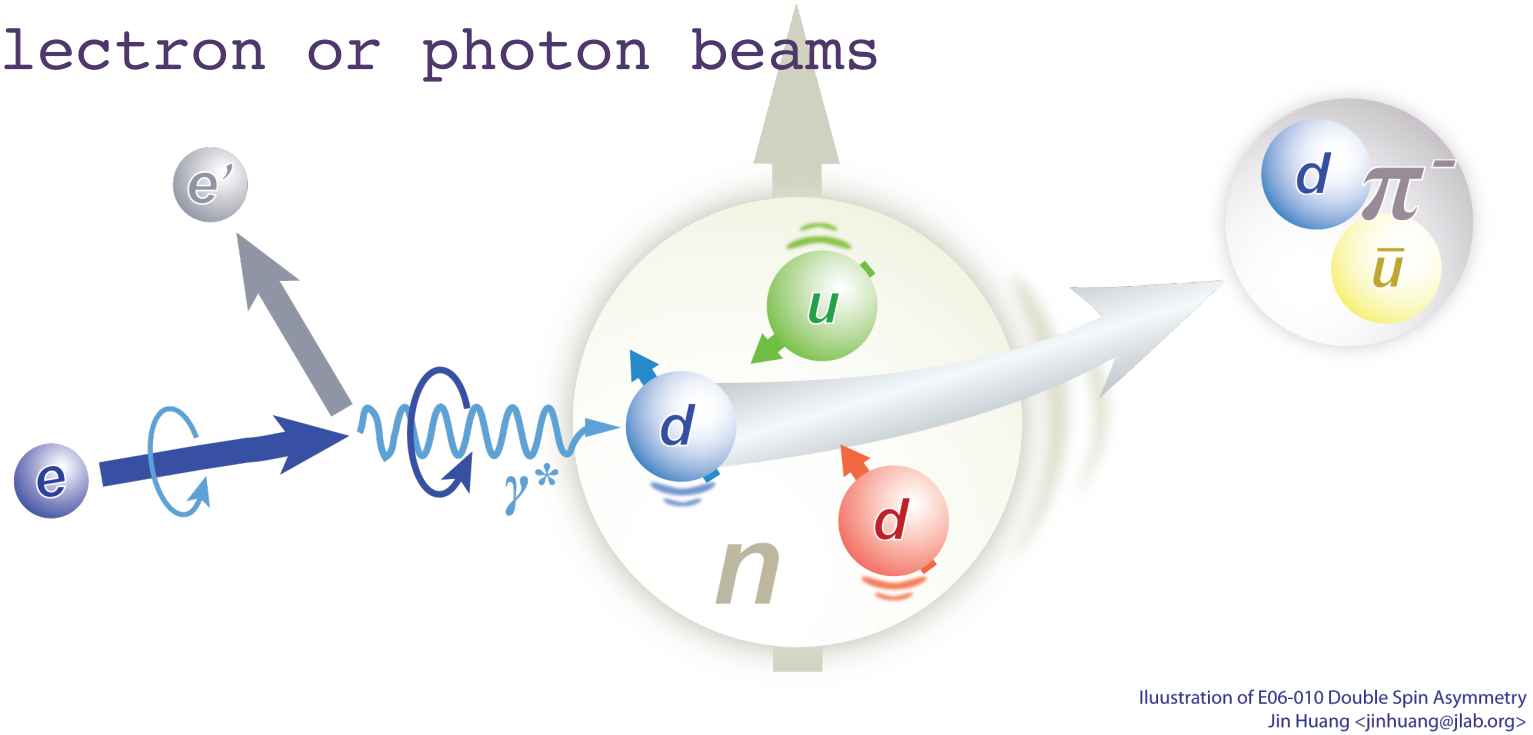
The broad aim of Nuclear Physics research is to study the properties and structure of nuclei, and the mechanisms involved in their creation. This poses questions about the limits of nuclear stability, the fundamental physical processes which governed the formation of light nuclei in the first moments after the Big Bang, and the subsequent synthesis of heavier nuclei within stars.

The Nuclear Physics programme can be divided into four broad areas of research:

- Nuclear structure
- Nuclear astrophysics
- Hadron physics
- Phases of strongly interacting matter

UK Nuclear Hadron Spectroscopy

Use electron or photon beams



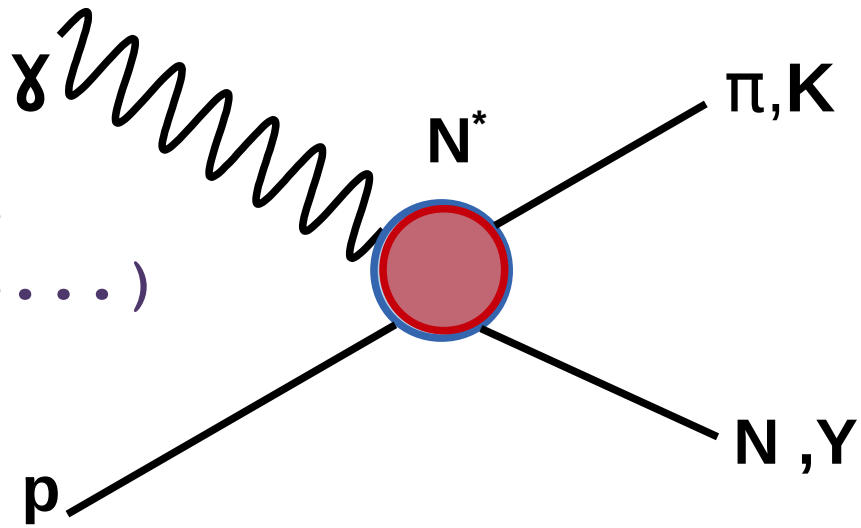
Detect final states from elastic scattering and Meson production reactions

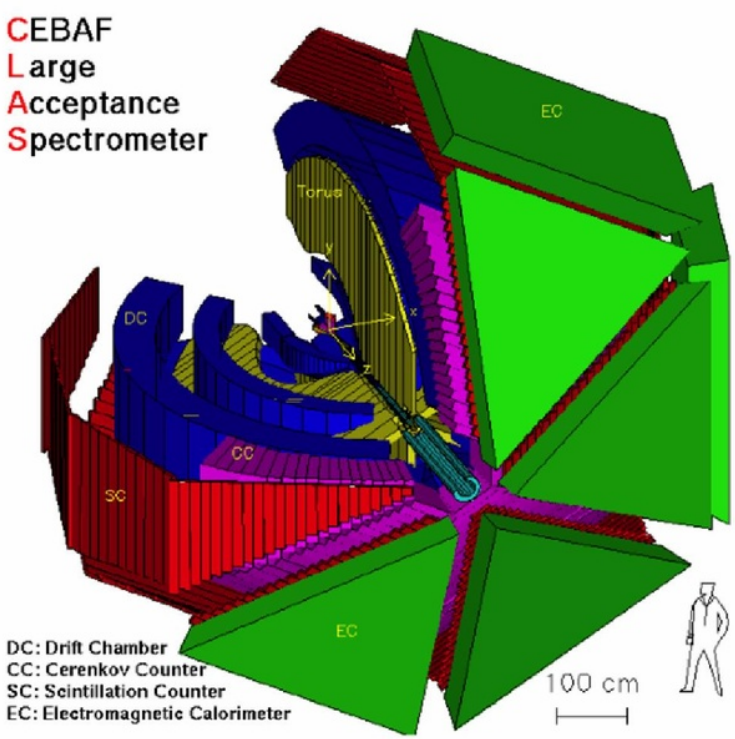
Hadron Structure : Imaging the nucleon's internal mass, spin and momenta. Parton distributions...

Hadron Spectrocopy : What states can be made from quarks/ strong interaction?

Baryon Spectroscopy (<3GeV)

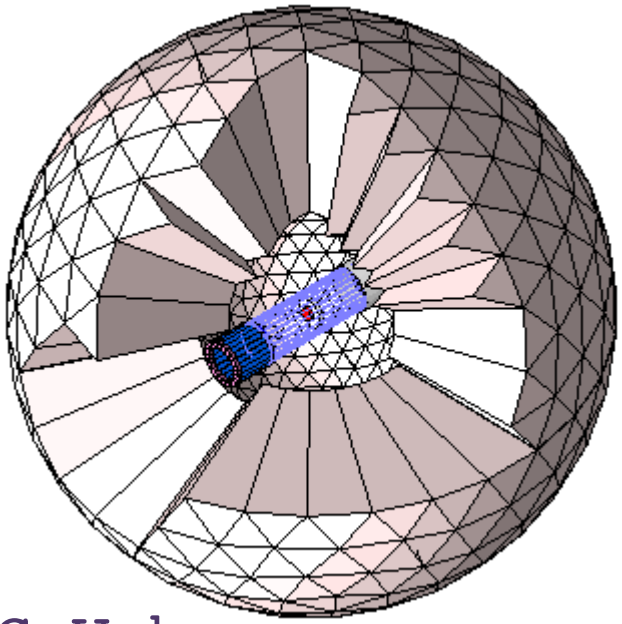
Establish spectrum of N* states from experiment and determine their properties (pole position, photocouplings...)





6 GeV beam

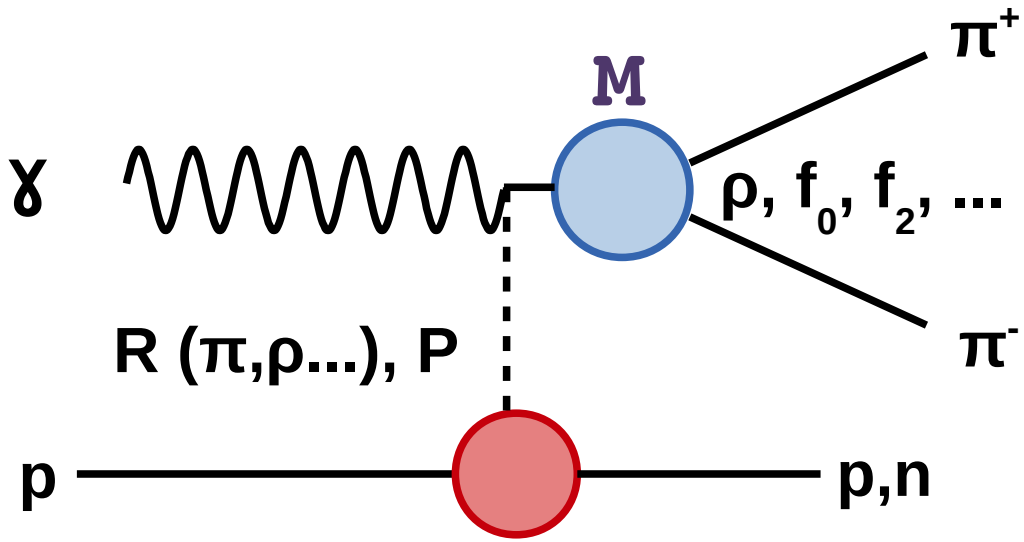
Crystal Ball at MAMI



1.6GeV beam

Next : Meson Spectroscopy (<3GeV)

t-channel exchange production mechanism

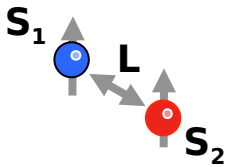


Or many other decay modes

Where **M** can contain u,d,s quarks

Want to identify many different types of **M**eson

Light Quark Meson Spectroscopy



$S = S_1 + S_2$ $\quad$ $J = L + S$

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

Not all the J^{PC} combinations are allowed:

0^{++} 0^{+-} 0^{-+} 0^{--} 1^{++} 1^{+-} 1^{-+} 1^{--} 2^{++} 2^{+-} 2^{-+} 2^{--} 3^{++} ...

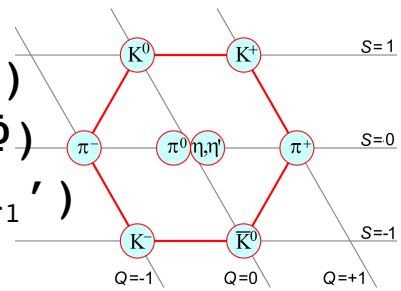
Each J^{PC} decomposed into nonet of degenerate states

$J^{PC} = 0^{-+} \Rightarrow (\pi, K, \eta, \eta')$

$1^{--} \Rightarrow (\rho, K^*, \omega, \Phi)$

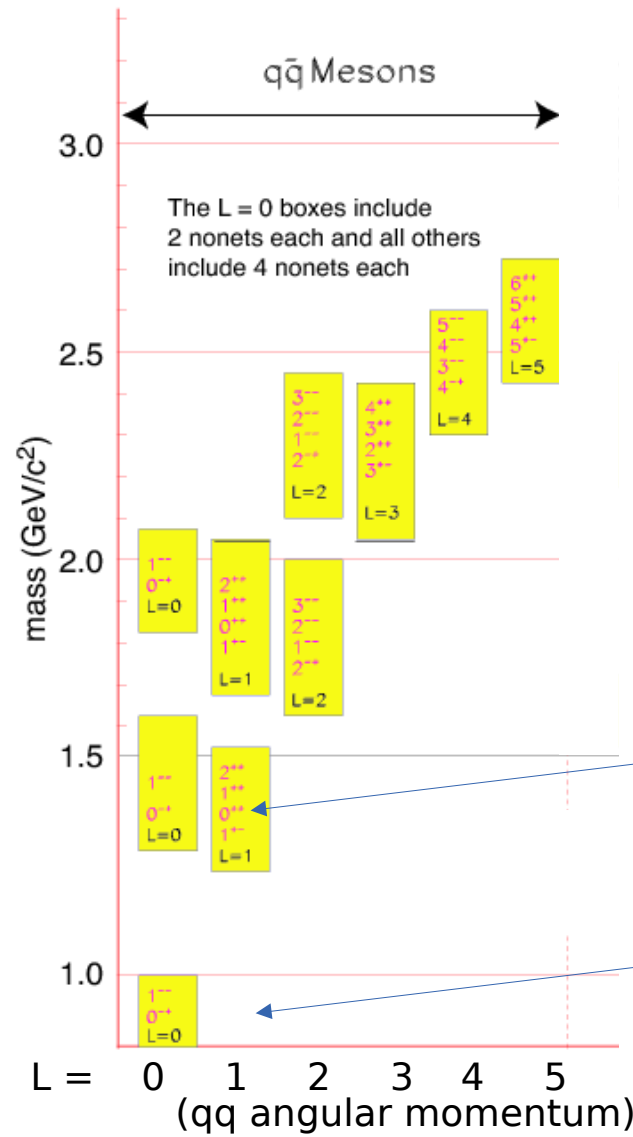
$1^{+-} \Rightarrow (b_1, K_1, h_1, h_1')$

...



- Quark model explains much of the observed states
- Some states not well established or not definitively assigned (where are 2--?)
- Some additional unassigned states
- Particular ?? with 0++ scalars

Consider light quarks: u,d,s



a,K,f,f'
b,K,h,h'

ρ,K*,ω,φ
π,K,η,η'

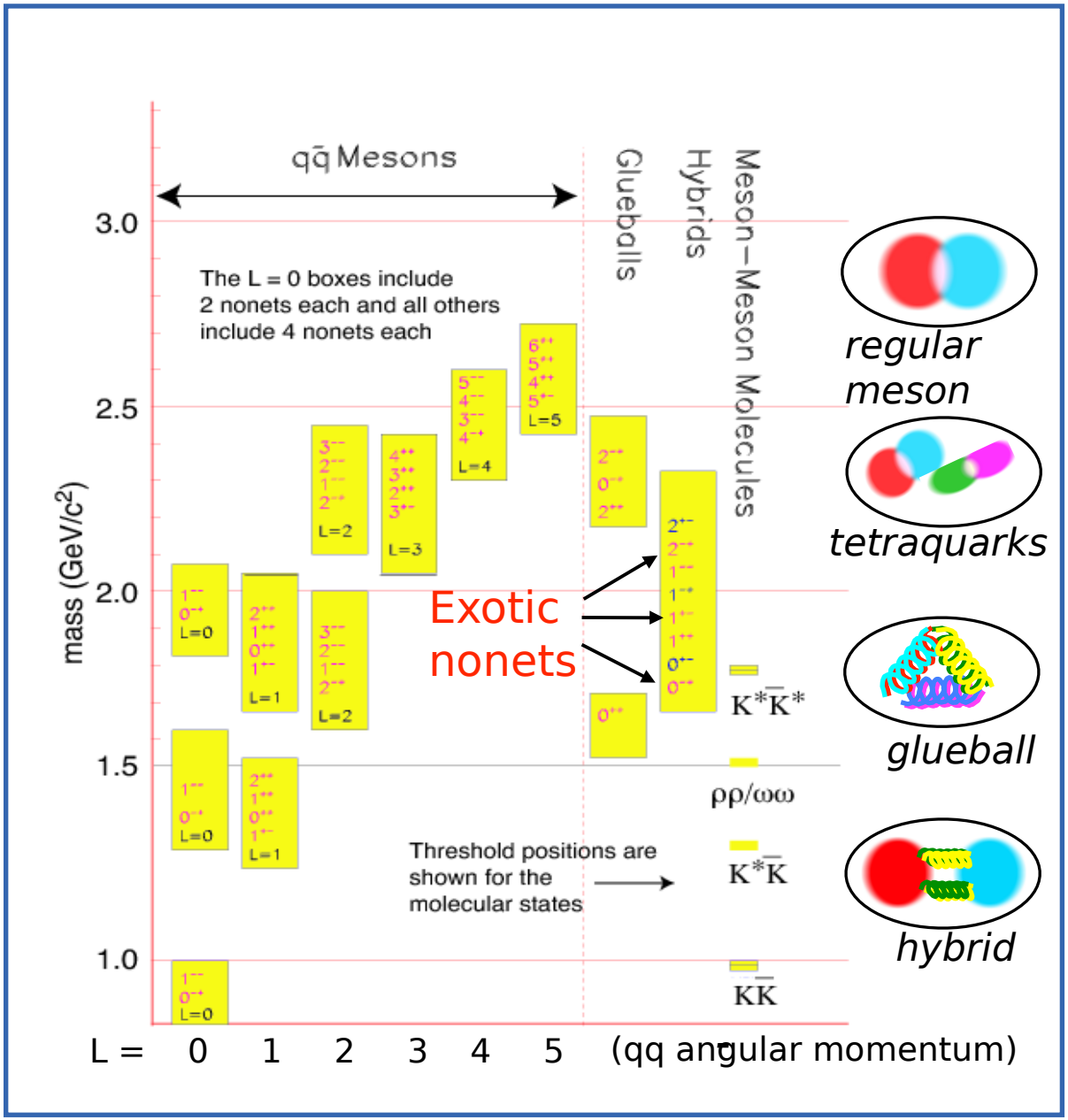
What else might we find?

QCD does not forbid other compositions

Some states predicted by theory (including LatticeQCD)

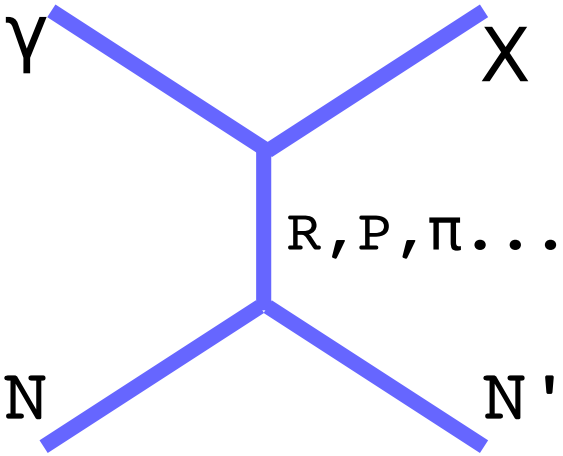
Evidence for some states found experimentally (but not conclusive)

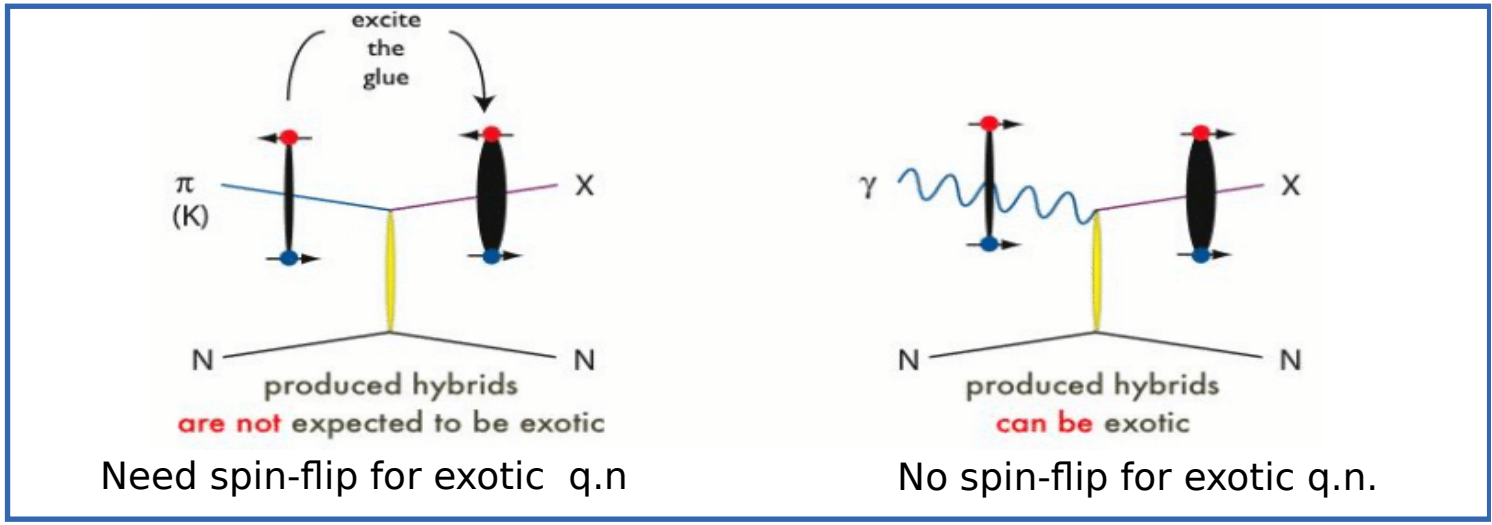
Hybrids include states of exotic Q.N.



Why Photoproduction?

Photoproduction: exotic J^{PC} are more likely produced by S=1 probe

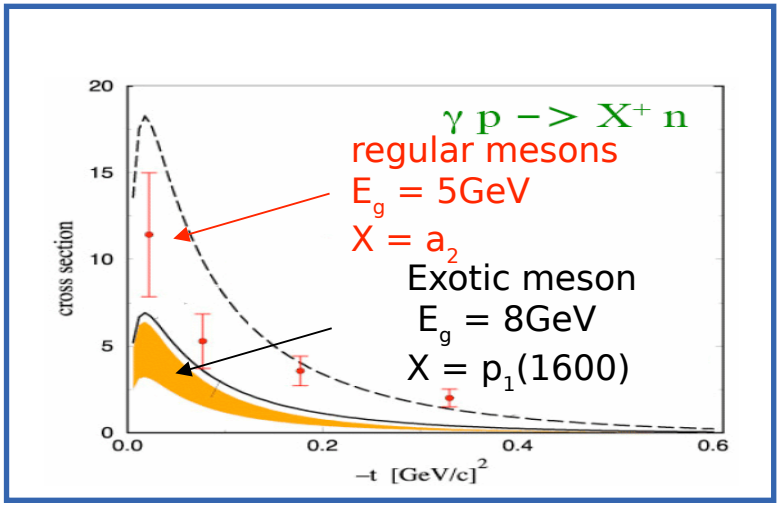




A. Afanasev and P. Page et al. PR A5 1998 6771

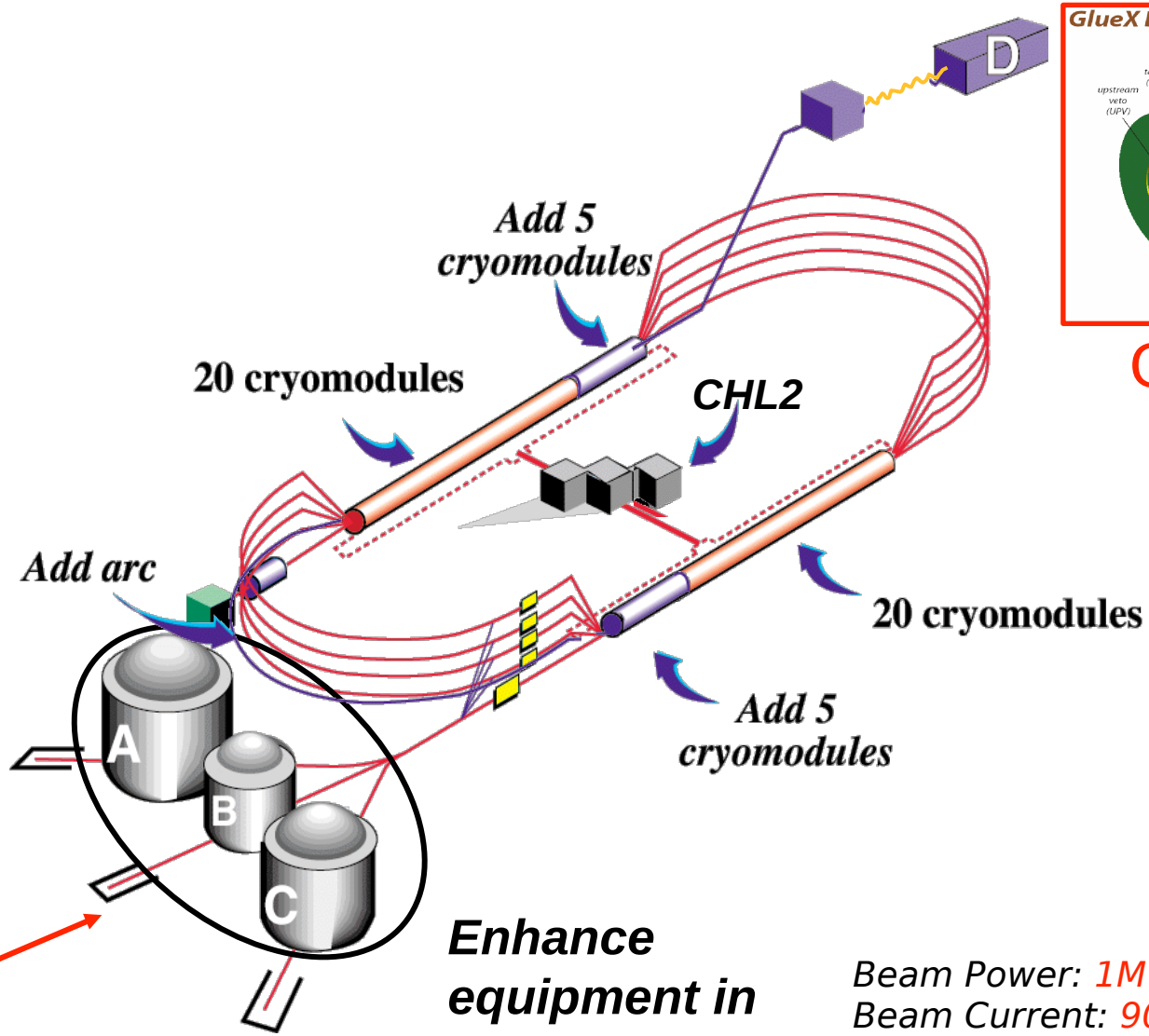
Linear polarization acts like a filter to disentangle the production mechanisms

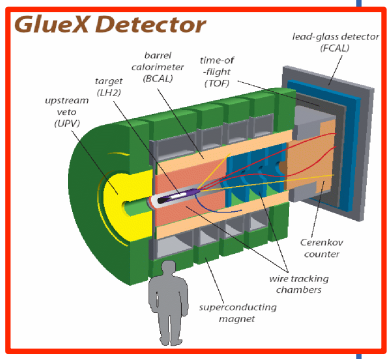
Production rate for exotics is expected comparable as for regular mesons



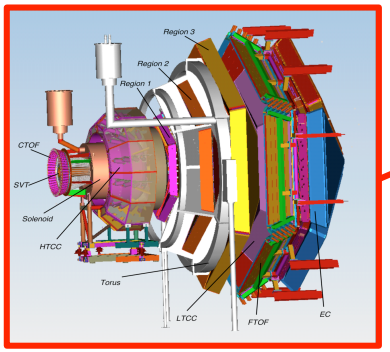
A. Szczepaniak and M. Swat PLB 516 2001 72

Spectroscopy:Jefferson Lab at 12 GeV





GLUEX



CLAS12

Enhance equipment in existing halls

Beam Power: 1MW
Beam Current: 90 μA
Max Pass energy: 2.2 GeV
Max Enery Hall A-C: 10.9 GeV
Max Energy Hall D: 12 GeV

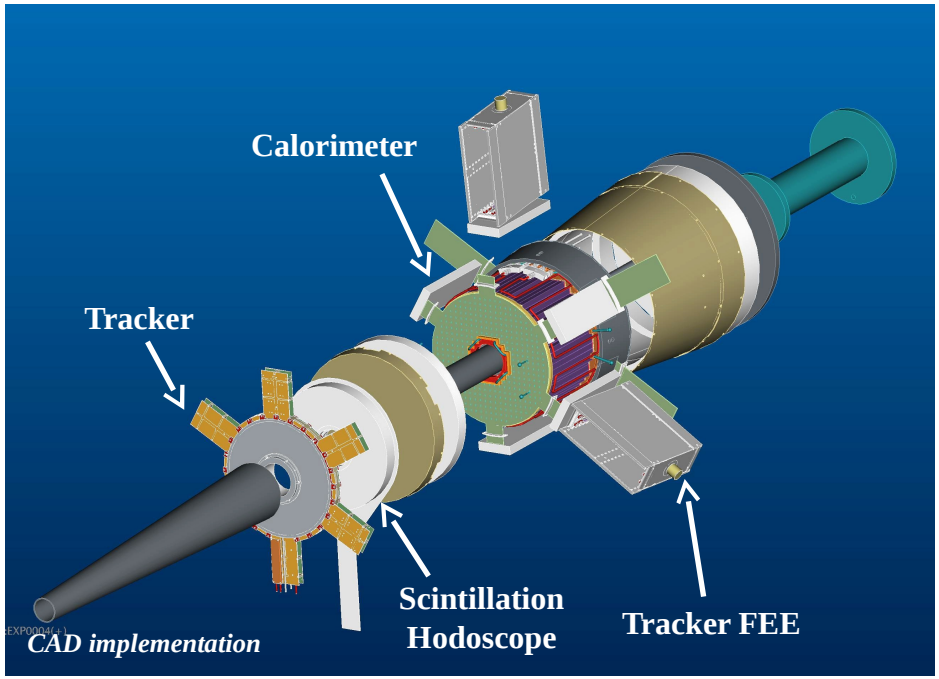
CLAS12 - Forward Tagger

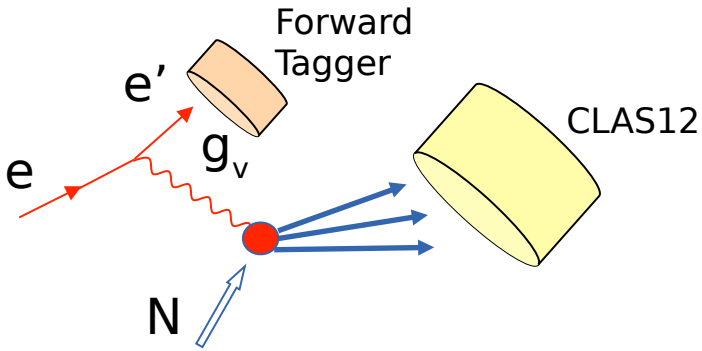
Detect electrons at small angle to perform quasi-real photo-production experiments.

Calorimeter: electron energy/momentum
Photon energy (ν=E-E')
Polarization $\varepsilon^{-1} \approx 1 + \nu^2/2EE'$
$PbWO_4$ crystals with APD/SiPM readout

Scintillation Hodoscope: veto for photons
Scintillator tiles with WLS readout

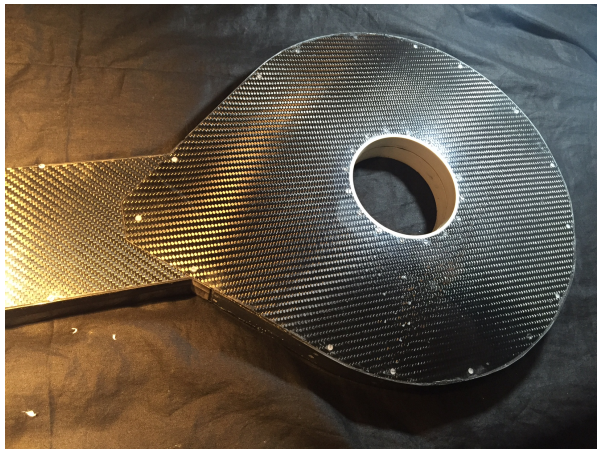
Tracker: electron angles, polarization plane
MicroMegas detectors





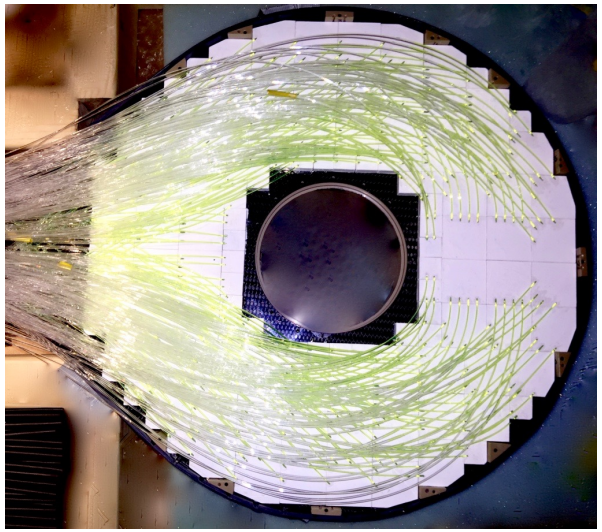
$E_{scattered}$	0.5 - 4.5 GeV
θ	2.5^o - 4.5^o
ϕ	0° - 360°
ν	6.5 - 10.5 GeV
Q^2	0.01 - 0.3 GeV^2 ($< Q^2 >$ 0.1 GeV^2)
W	3.6 - 4.5 GeV

Edinburgh Hodoscope

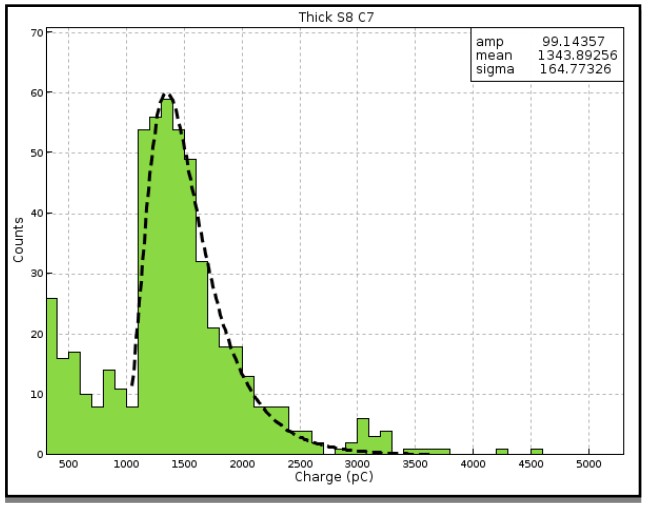


Hodoscope carbon fibre enclosure

- scintillation detector for charged particles (MIPs)
- used for hadron spectroscopy
- provides electron / photon discrimination for fast trigger decision
- two layers (7 mm,15 mm thick) of 116 tiles coupled to 6 meter long optical fibres
- light readout with wavelength-shifting fibres embedded in plastic scintillator tile arrays

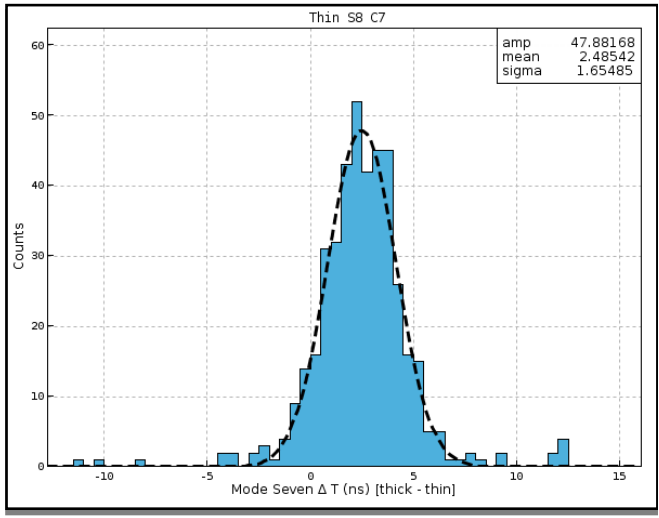


Painted plastic scintillation tiles with wavelength-shifting fibres



Example energy deposited

Example timing ($\Delta t = t_{thick} - t_{thin}$)



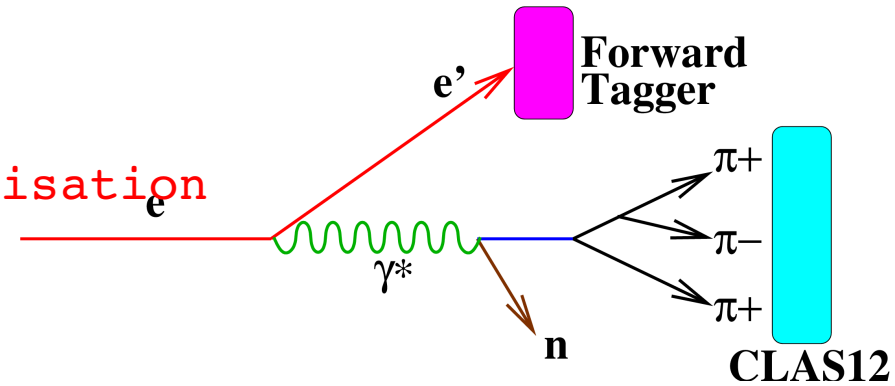
NB offset uncalibrated

CLAS12 MesonEx Experiment (Glasgow,Edinburgh)

11 GeV e- scattering in 5cm lH_2 target

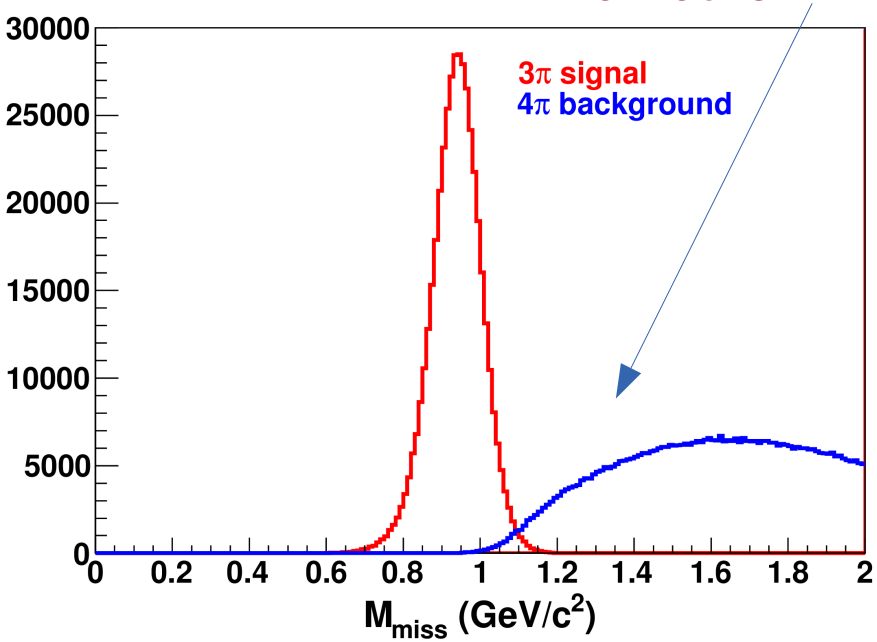
Luminosity ~ $10^{35} cm^{-2} s^{-1}$

e' detected in forward tagger
→γ energy (7-10.5 GeV) and polarisation
- σ_E= 0.02-0.07 GeV



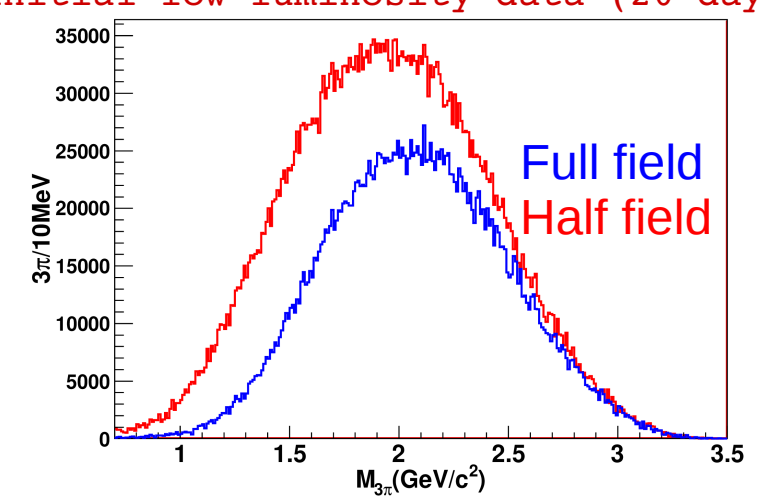
3π detected in CLAS12
- σ_p=0.5 %, σ_θ=1 mrad , σ_φ=3 mrad

Resolution allows good discrimination from other final states (simulation)



Neutron reconstructed by missing mass

Expected number of reconstructed events from initial low luminosity data (20 days)



80 day experiment with full luminosity
80 X more events or 10^6/10MeV

Amplitude Analysis
Extended Maximum Likelihood
IUAmpTools :

Calculate Intensity in terms of production and decay amplitudes

kinematics derived from 4-vectors

decay amplitudes (from theory) ← Constructed by user

$$I(\Omega) = \sum_{\alpha} \left| \sum_{\beta} V_{\alpha\beta} A_{\alpha\beta}(\Omega) \right|^2$$

E.g Helicity Amplitudes

incoherent sum

coherent sum

production amplitudes (complex fit parameters)

Minimise :

From data

From Simulation

$$-2 \ln L = -2 \sum_{i=1}^{N_{\text{observed}}} \ln(I'(\Omega_i)) + \frac{2}{N^{\text{MC}}_{\text{generated}}} \sum_{i=1}^{N^{\text{MC}}_{\text{accepted}}} I'(\Omega_i)$$

i.e. Same as LHCb “pentaquark” analysis

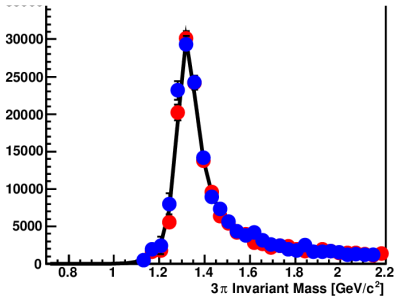
Simulated Amplitude Analysis

Search for $\pi_1(1600)$ exotic in 3π final state

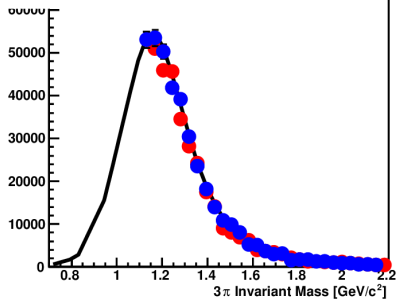
Detector response capable of reconstructing signals <1%

But are our amplitude analysis techniques sufficient to understand such small signals?

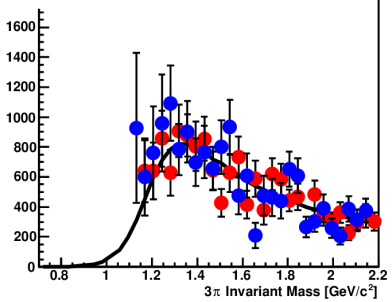
a_2 to $\rho\pi$ S wave



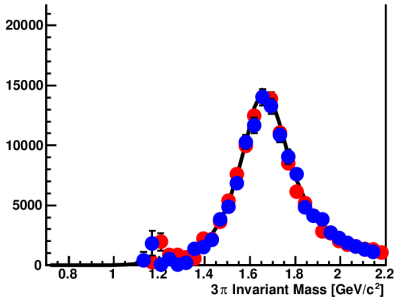
a_1 to $\rho\pi$ S wave



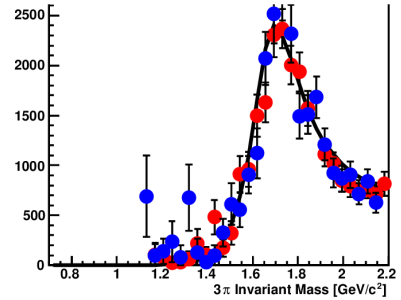
a_1 to $\rho\pi$ D wave



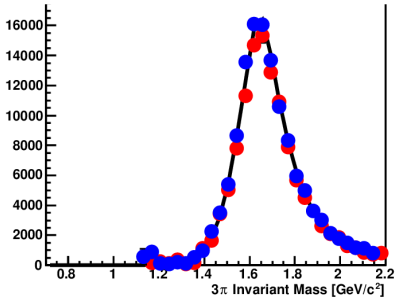
π_2 to $\rho\pi$ P wave



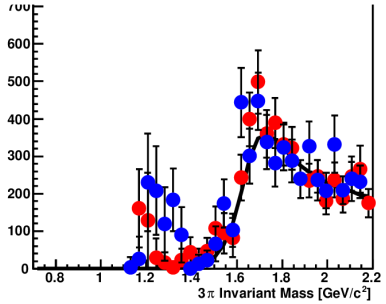
π_2 to $\rho\pi$ F wave



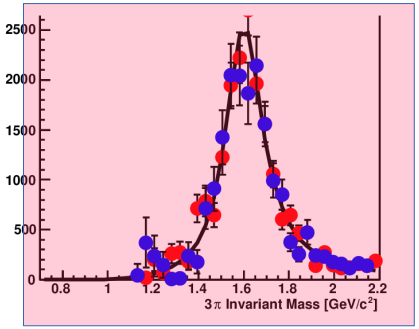
π_2 to $f_2\pi$ S wave



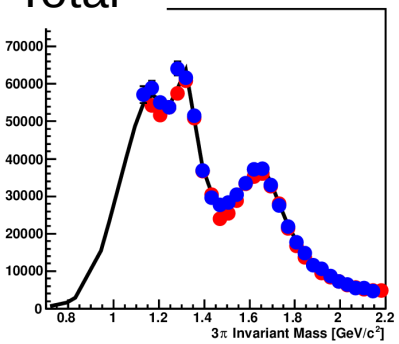
π_2 to $f_2\pi$ D wave



π_1 to $\rho\pi$ P wave



Total



Most recent hybrid search

π_1 hybrid candidate seen in several experiments

Most recent COMPASS (pion beam) result :

Highlights from the COMPASS experiment at CERN -- Hadron spectroscopy and excitations arXiv:1601.05025

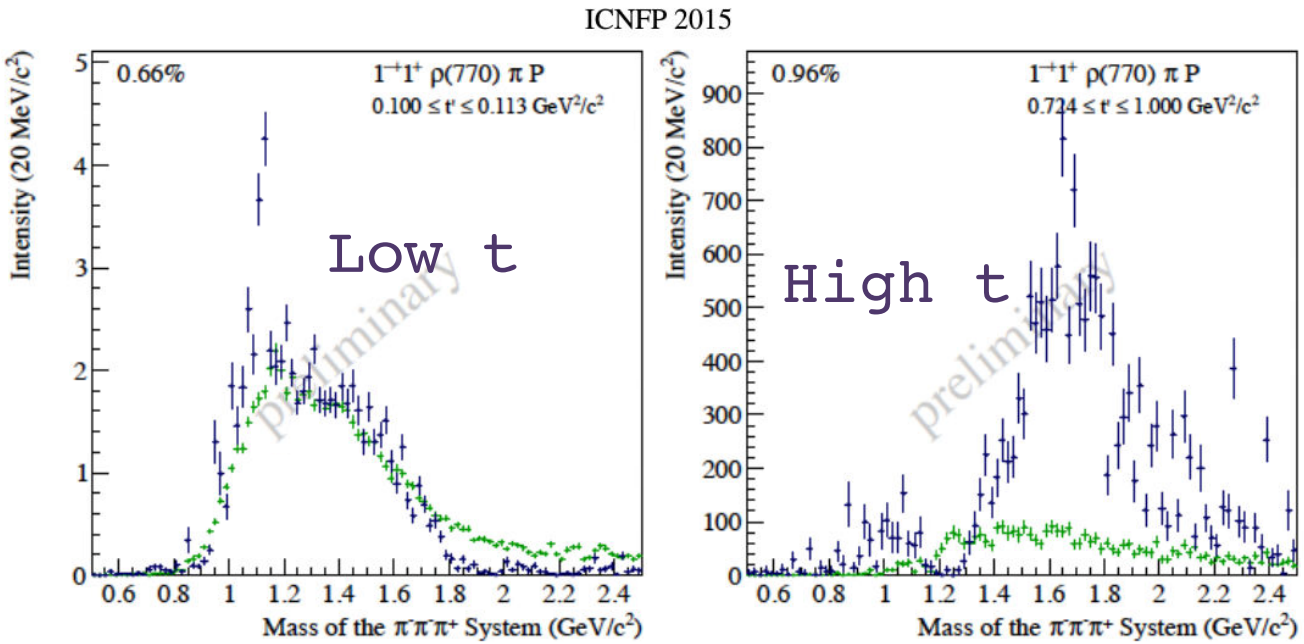


Figure 8. First step PWA result for the intensity of the exotic $1^{-+}1^{+}$ $\rho(770)\,\pi$ P-wave for the charged decay mode (blue) overlaid with a projection of a simulated Deck-effect in this wave (green), shown for the range of lowest *(left)* and highest *(right)* values of t' [16].

Blue – data
Green - Background(Deck)

Signal seems to increase above background at higher t

Recent example COMPASS : a1(1420)

Total 46M 3π events,

Fit with Isobar model

A new state!

Possible tetraquark or molecular Nature

0.25% of signal

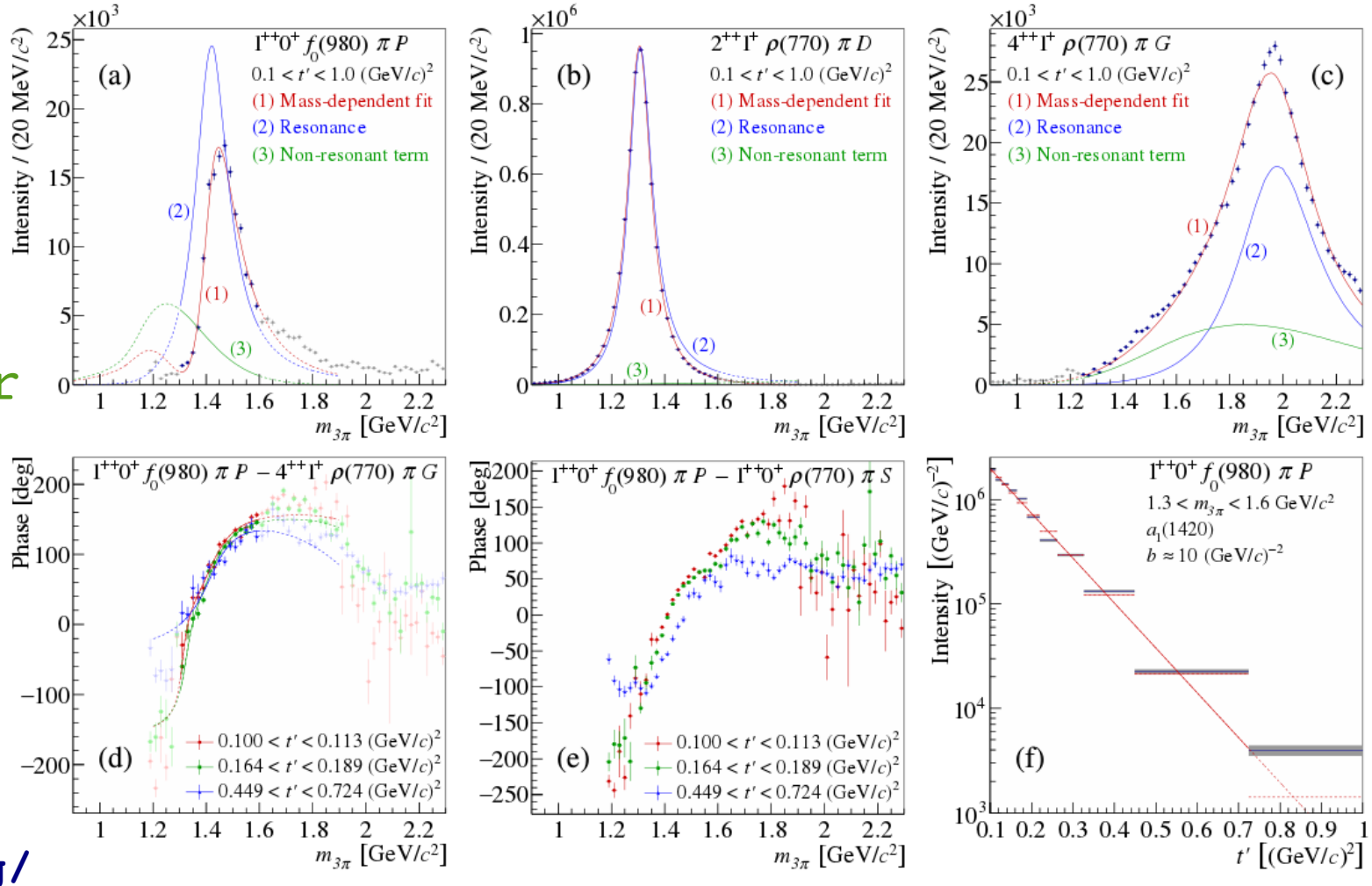


Figure 1: (Color online) Results of the PWA in 3π mass bins of $20\,\mathrm{MeV}/c^2$ width (data points with statistical errors only) showing the intensity of the three waves $1^{++}0^+ f_0(980)\,\pi P$ (a), $2^{++}1^+\rho(770)\,\pi D$ (b), and $4^{++}1^+$

http://arxiv.org/Abs/1501.05732
Jan 2015

Alternative dynamic interpretation

On the nature of $a_1(1420)$

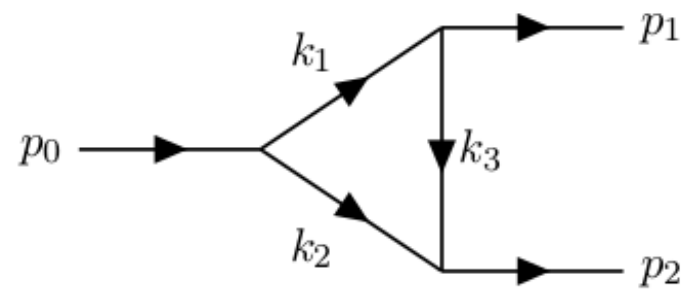
M. Mikhasenko,[1] B. Ketzer,[1] and A. Sarantsev[1,2]

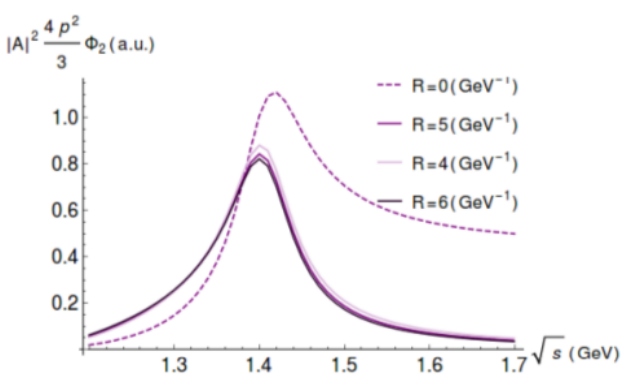
[1] *Universität Bonn, Helmholtz-Institut für Strahlen- und Kernphysik, 53115 Bonn, Germany*

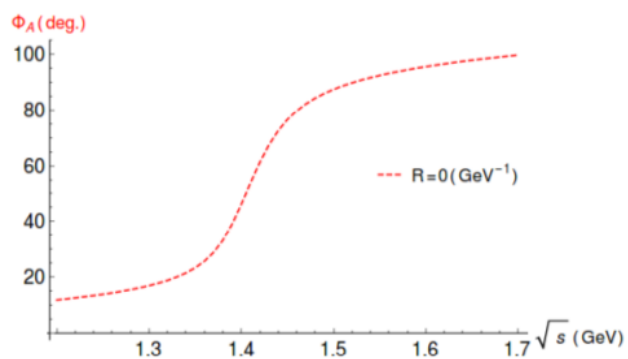
[2] *Petersburg Nuclear Physics Institute, Gatchina, Russia*

The resonance-like signal with axial-vector quantum numbers $J^{PC} = 1^{++}$ at a mass of 1420 MeV and a width of 140 MeV, recently observed by the COMPASS and VES experiments in the $f_0(980)\pi$ final state and tentatively called $a_1(1420)$, is discussed. Instead of a genuine new meson, we interpret this signal as a dynamical effect due to a singularity (branching point) in the triangle diagram formed by the processes $a_1(1260) \to K^\star \bar{K}$, $K^\star \to K\pi$, and $K\bar{K} \to f_0(980)$ (+ c.c). The amplitude

arXiv.1501.07023
Jan 15







See also

Peak Locations and Relative Phase of Different Decay Modes of the a_1 Axial Vector Resonance in Diffractive Production

Jean-Louis Basdevant and Edmond L. Berger
Phys. Rev. Lett. **114**, 192001 – Published 12 May 2015

In general, the large data samples available nowadays both for light and heavy hadrons allow us to revisit effects which were already discussed more than 30 years ago, but were almost forgotten since then because data were too scarce to test them. These may play an important role in our understanding of the hadron spectrum.

Scattering Theory Summer School, Indiana, June 15
http://www.indiana.edu/~jpac/Resources.html

Joint Physics Analysis Center (JPAC)

JPAC members

Mike Pennington (JLab)
Adam Szczepaniak (IU/JLab)
Tim Londergan (IU)
Geoffrey Fox (IU)
Emilie Passemar (IU/JLab)
Peng Guo (Cal. St.)
Cesar Fernandez-Ramirez (JLab)
Ron Workman (GWU)
Michael Döring (GWU)

Vladyslav Pauk (JLab)
Alessandro Pilloni (JLab)
Igor Danilkin (Mainz)
Lingyun Dai (Bonn)
Meng Shi (Beijing)
Astrid Blin (Valencia)
Andrew Jackura (IU)
Vincent Mathieu (IU)
…

CLAS collaboration

Diane Schott (GWU/JLab)
Viktor Mokeev (JLab)

HASPECT:

Marco Battaglieri (Genova)
Derek Glazier (Glasgow)
… Edinburgh

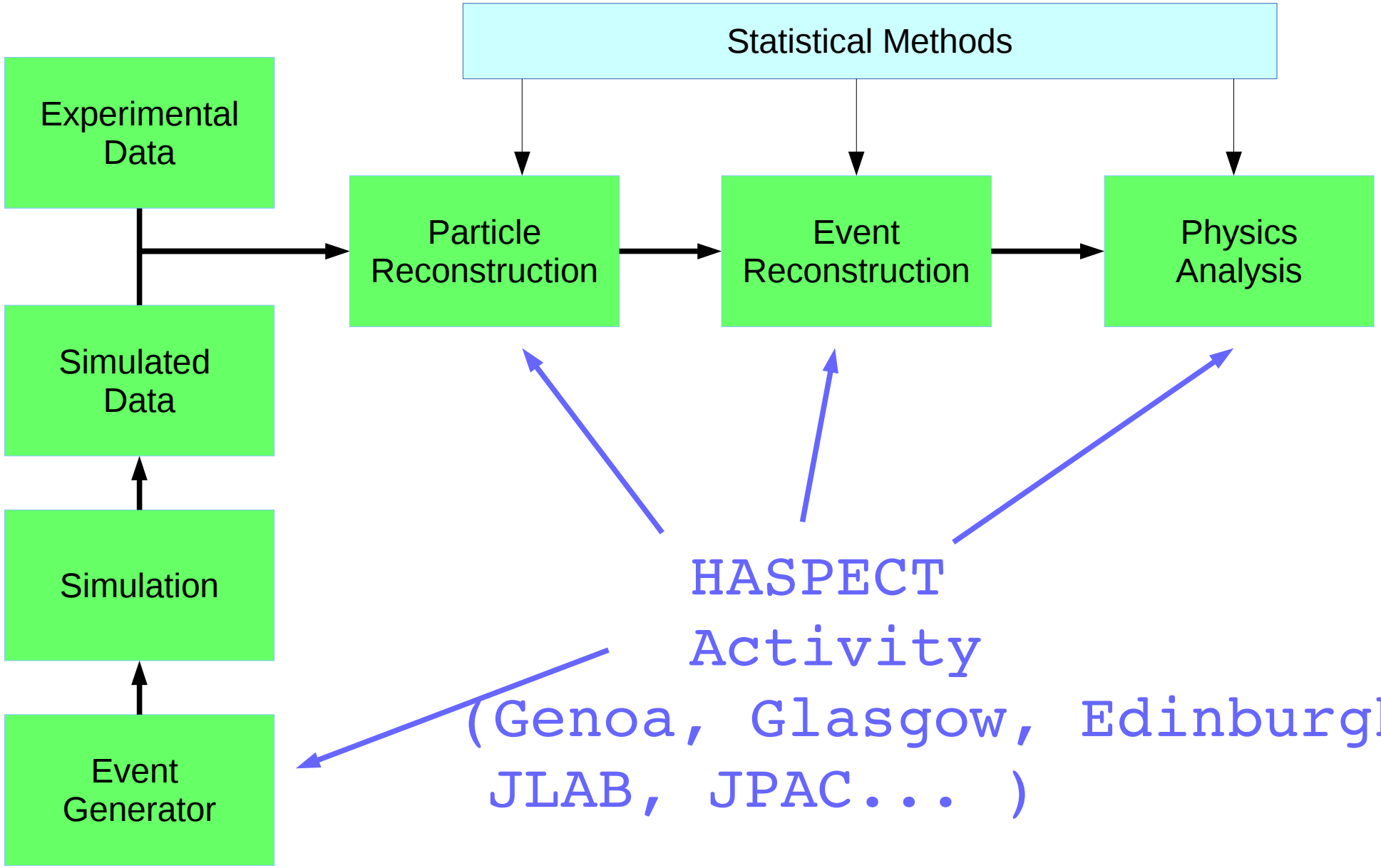
GlueX collaboration

Matthew Shepherd (IU)
Justin Stevens (JLab)
…

COMPASS collaboration

Mikhail Mikhasenko (Bonn)
Fabian Krinner (TUM)
Boris Grube (TUM)
…

Use of Software in hadron physics



Event Reconstruction : sWeights

M. Pivk,F.R. Le Diberder,Nucl.Inst.Meth.A 555, 356-369, 2005

Given discriminatory PDF for signal and background calculates weight :

$$ {}_s\mathcal{P}_n(y_e) = \frac{\sum_{j=1}^{N_S} \mathbf{V}_{nj} f_j(y_e)}{\sum_{k=1}^{N_S} N_k f_k(y_e)} $$

N_s = Number of species

f_k = PDF for species k

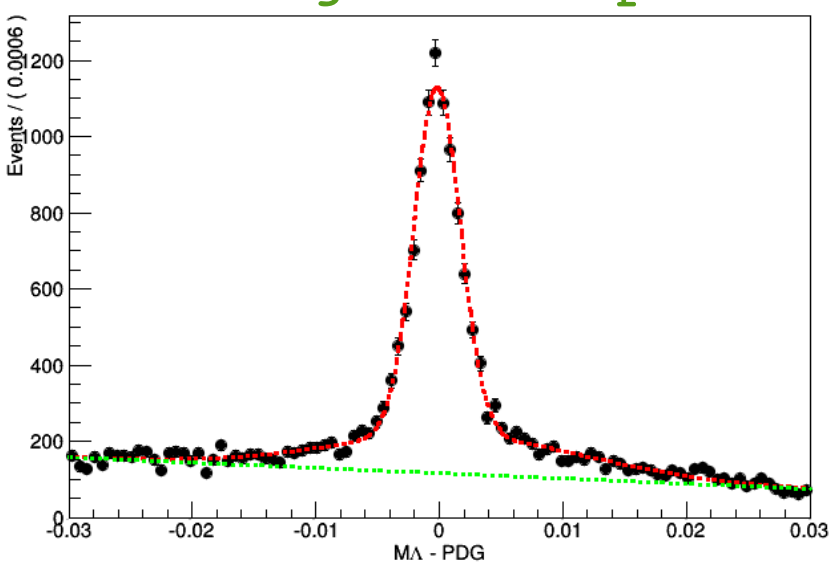
N_k = Yield for species k

V = covariance matrix

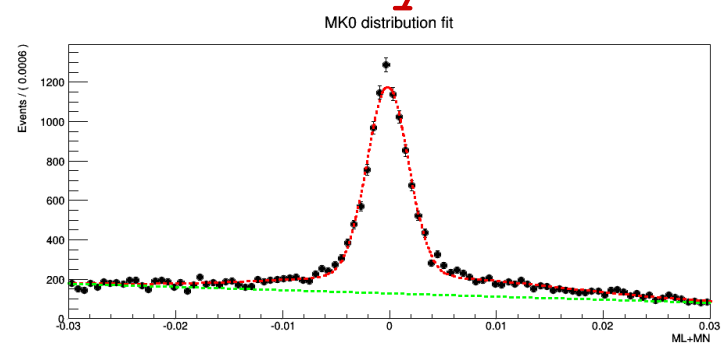
Part of RooStats(used here)

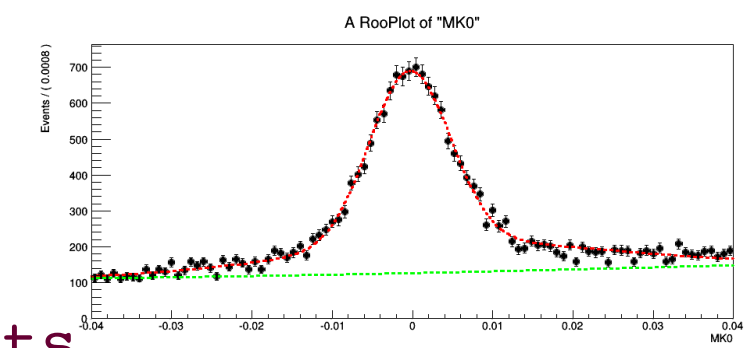
Can include multiple signal and background species

Can fit multidimensional discriminatory PDF



Only as good as fit model...



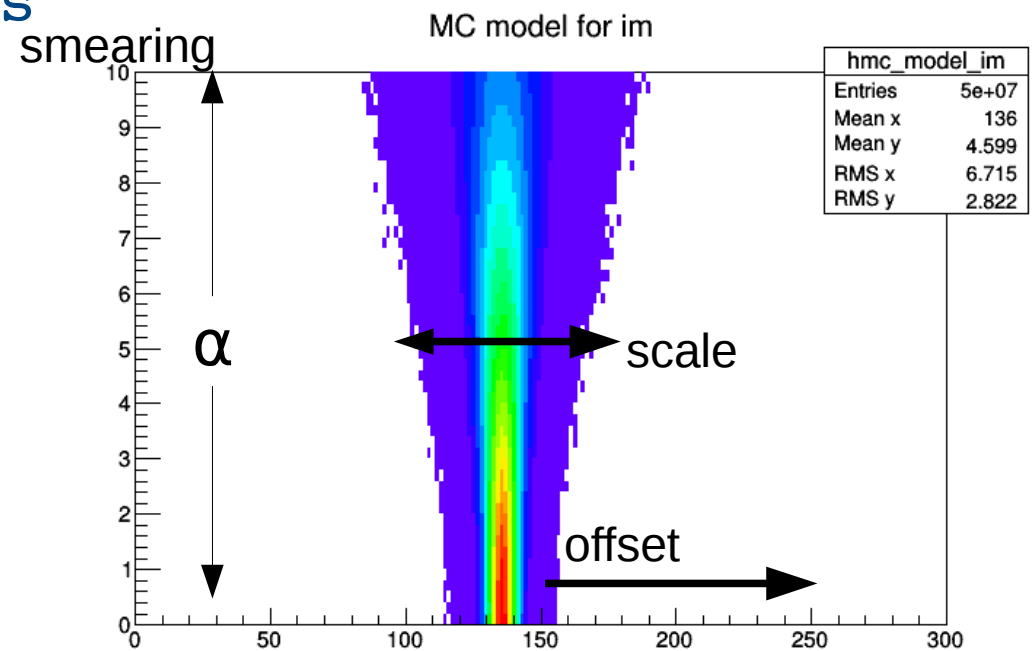


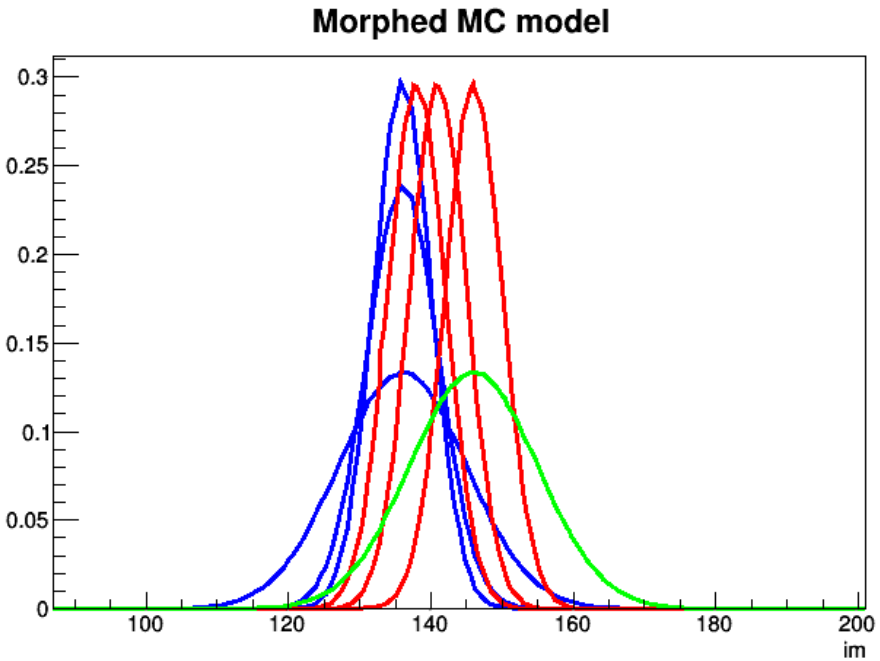
Can use directly in likelihood fits

Event Reconstruction : Simulated Models

Signal shapes are not always well described by parameteric functions
⇒Simulated PDFs
systematic uncertainty in shape accounted for via morphing with additional nuisance parameters
i.e Profile Likelihood

Construct new RooFit PDF
Supply simulated events
Sequential 1D histograms
Smoothed and interpolated
Adding greater additional smearing with morphing parameter α
Additional offset parameter
(Also RooFit HistFactory...)





sWeight Event Selection : $\pi^+\pi^-p$

Just Phase Space

g11 dataset, detect π^+ and p

Model from simulated $\pi^+\pi^-p$ and $\pi^+\pi^-\pi^0p$ events

Signal BG

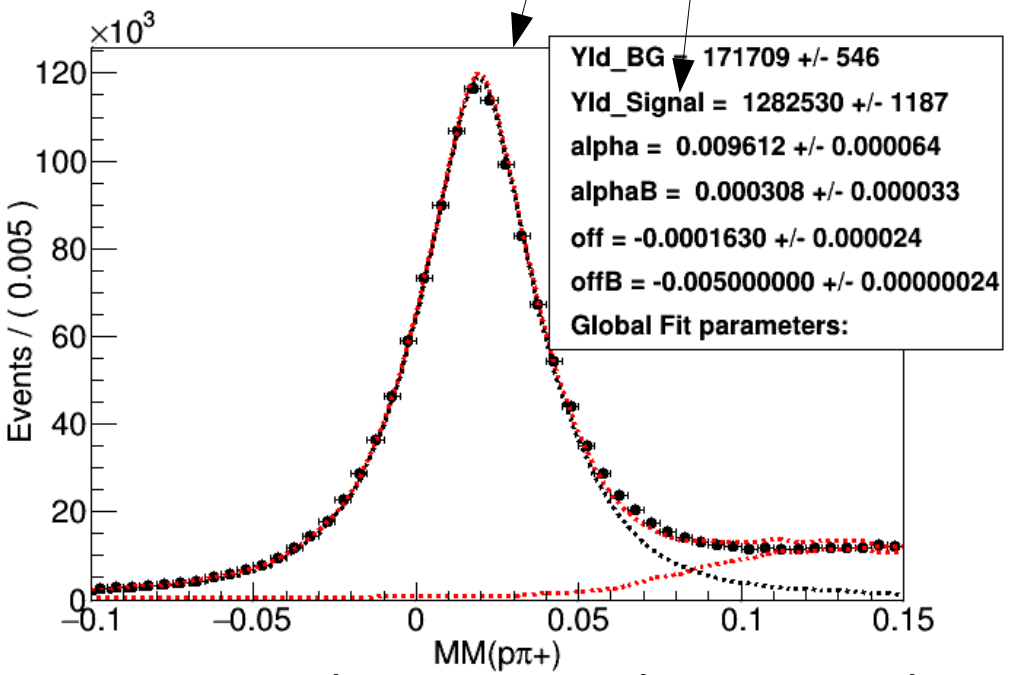
RooFit Extended Maximum likelihood fit

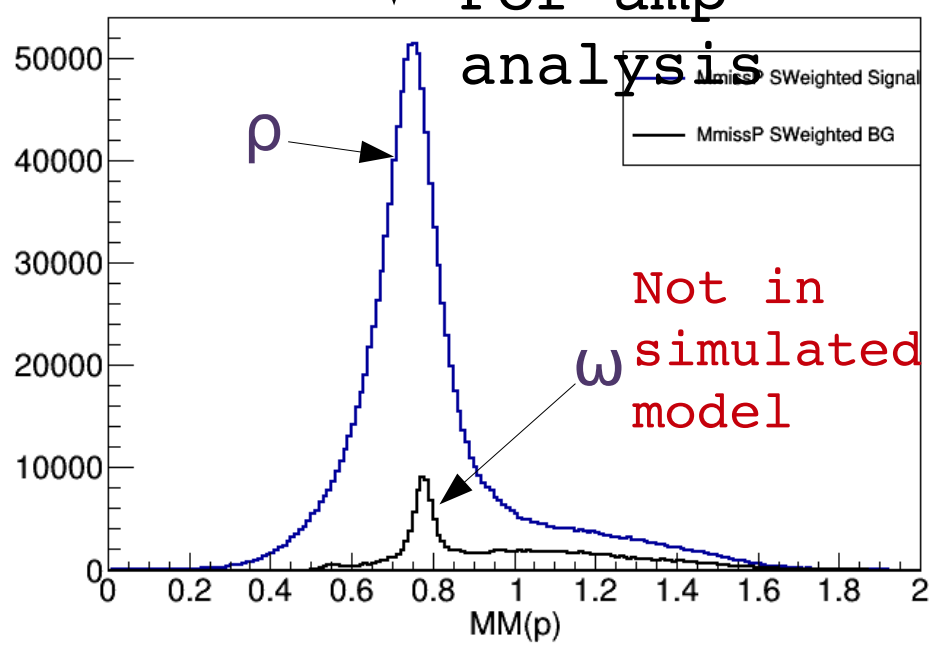
RooStats sWeight calculation

⇒Disentangle distributions

For Cross section

For amp analysis



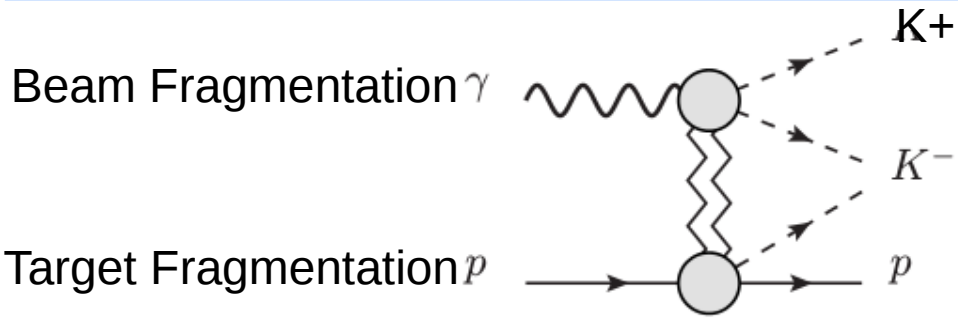


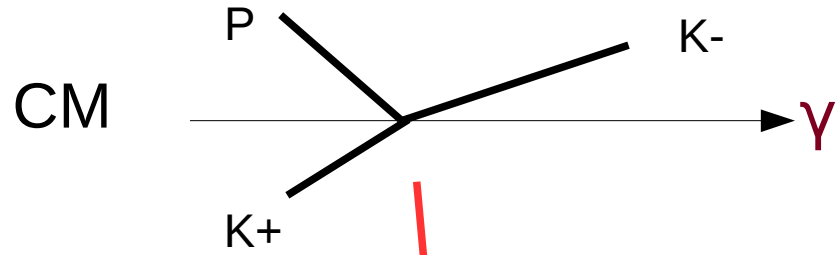
Note 2 fits required. First fixes alpha and off.

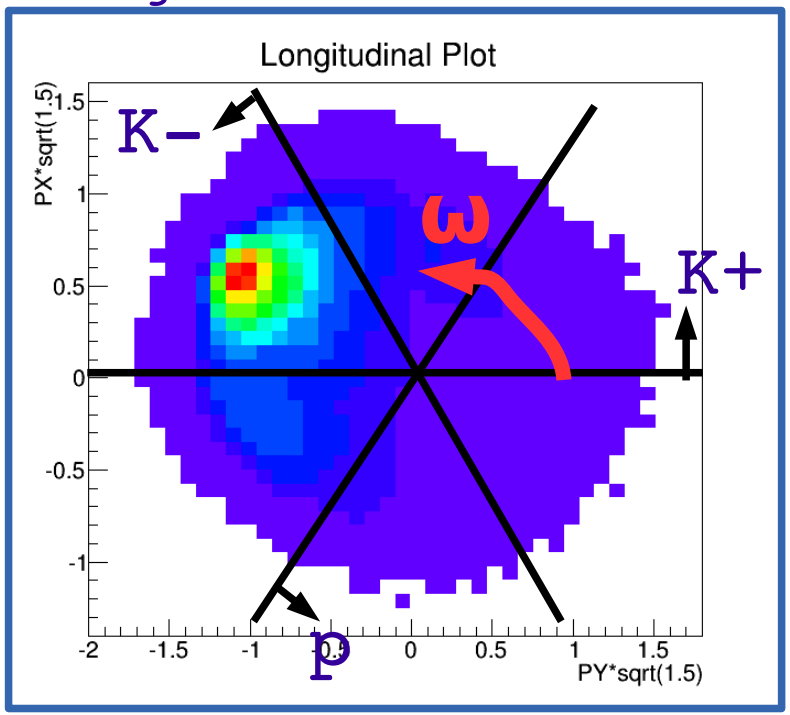
Second, only Yields free => Covariance matrix

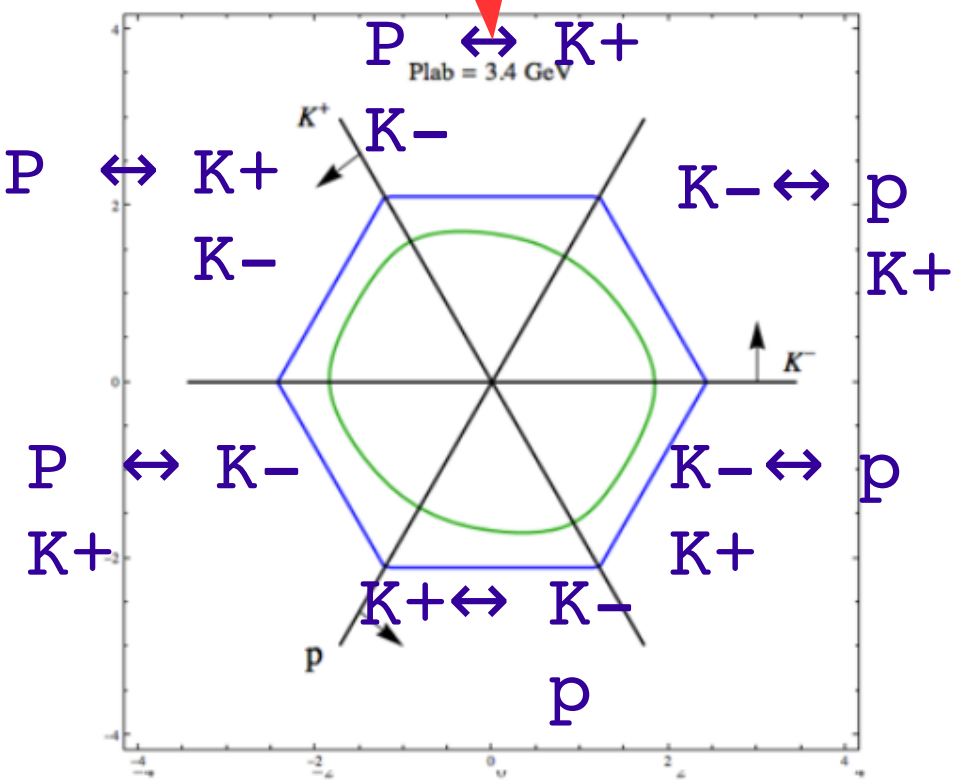
Van Hove Plots (Longitudinal)

Example 3-3.8GeV γp→K+K-p
CLAS g11 dataset







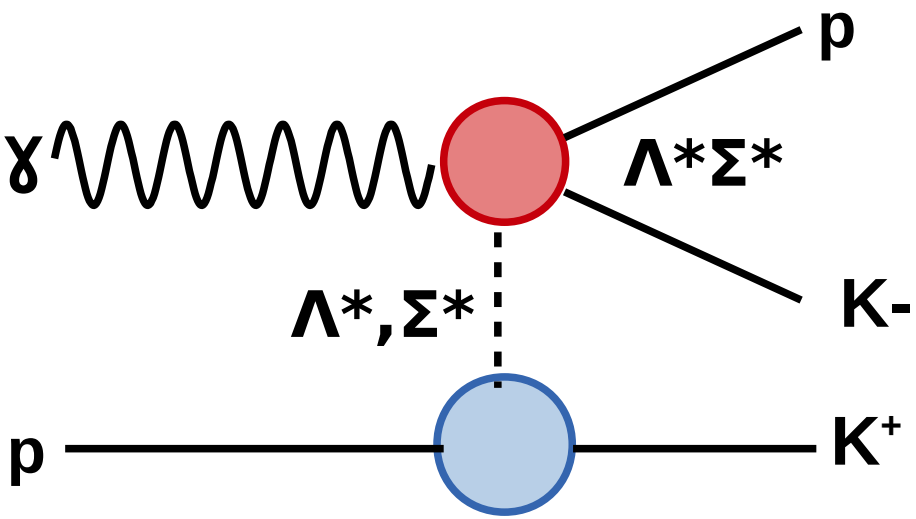


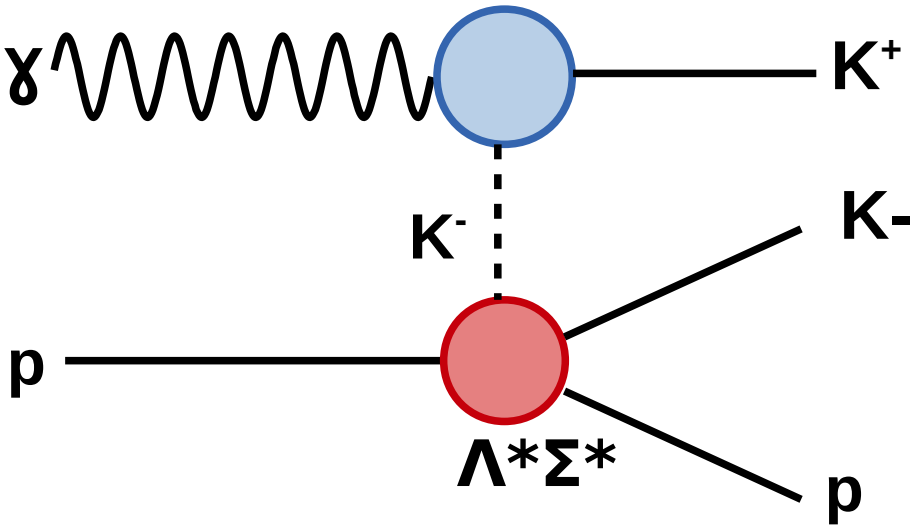
$$p_{K^+L} = \sqrt{\frac{2}{3}} q \sin\omega,$$

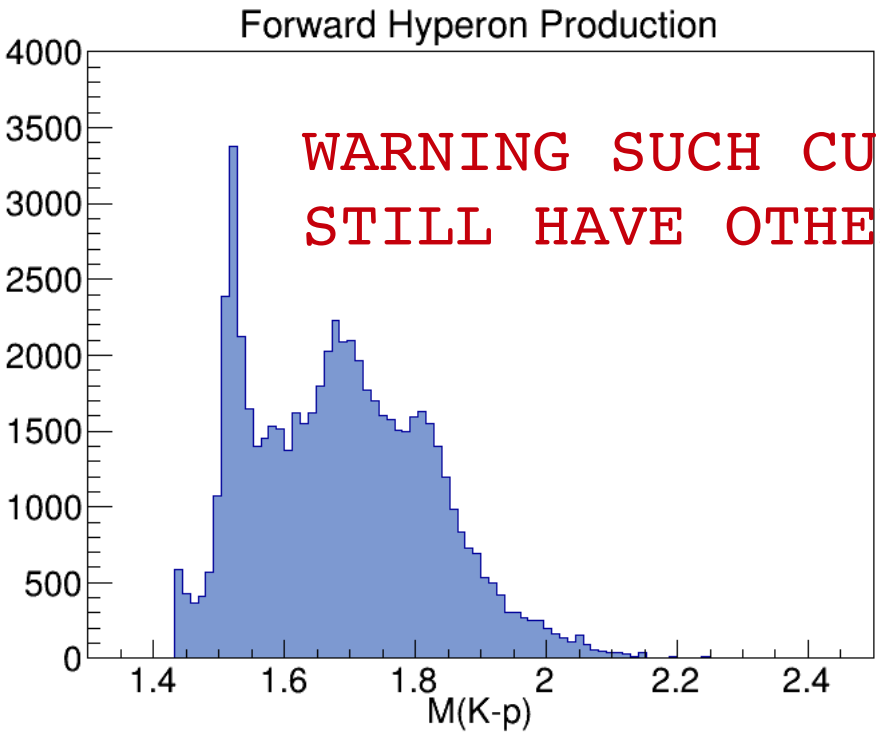
$$p_{K^-L} = \sqrt{\frac{2}{3}} q \sin\left(\frac{2}{3}\pi + \omega\right),$$

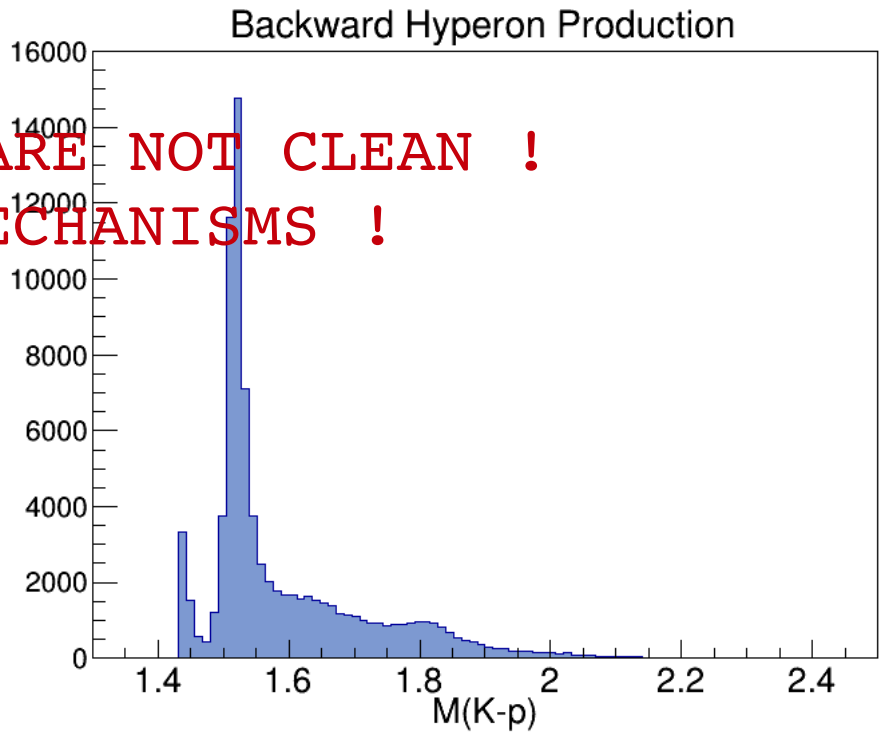
$$p_{PL} = \sqrt{\frac{2}{3}} q \sin\left(\frac{4}{3}\pi + \omega\right).$$

Using Longitudinal Phase Space to seperate mechanisms





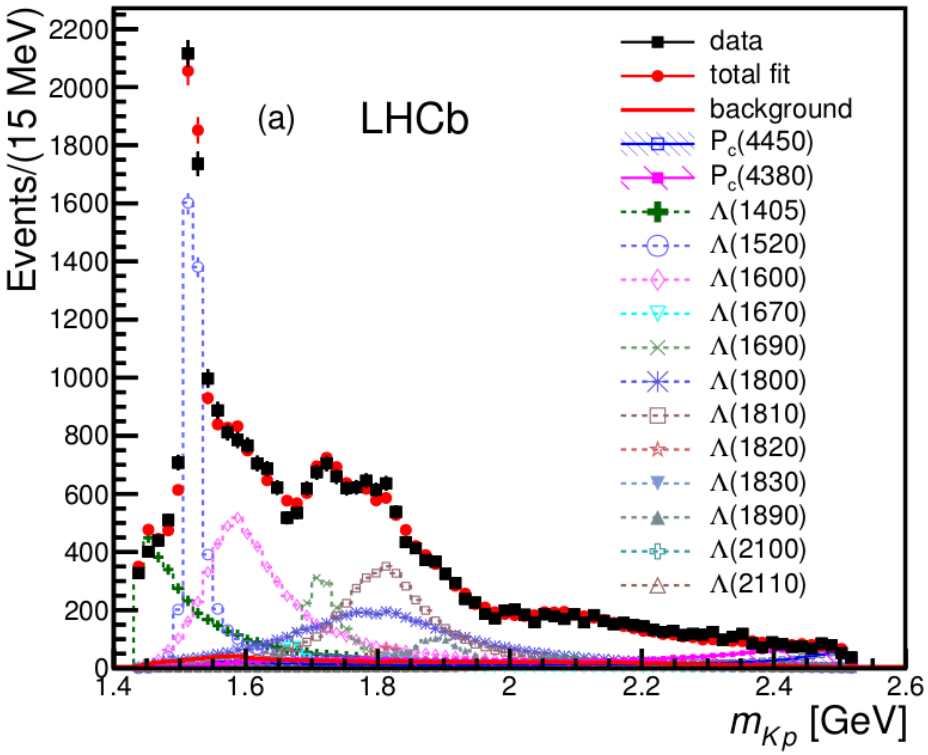




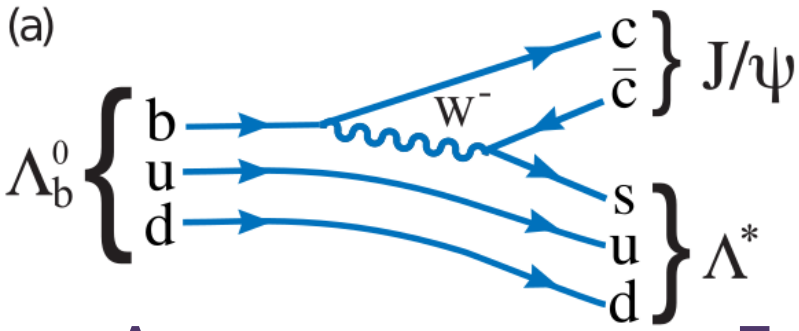
WARNING SUCH CUTS ARE NOT CLEAN !
STILL HAVE OTHER MECHANISMS !

Observation of $J/\psi p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \to J/\psi K^- p$ Decays

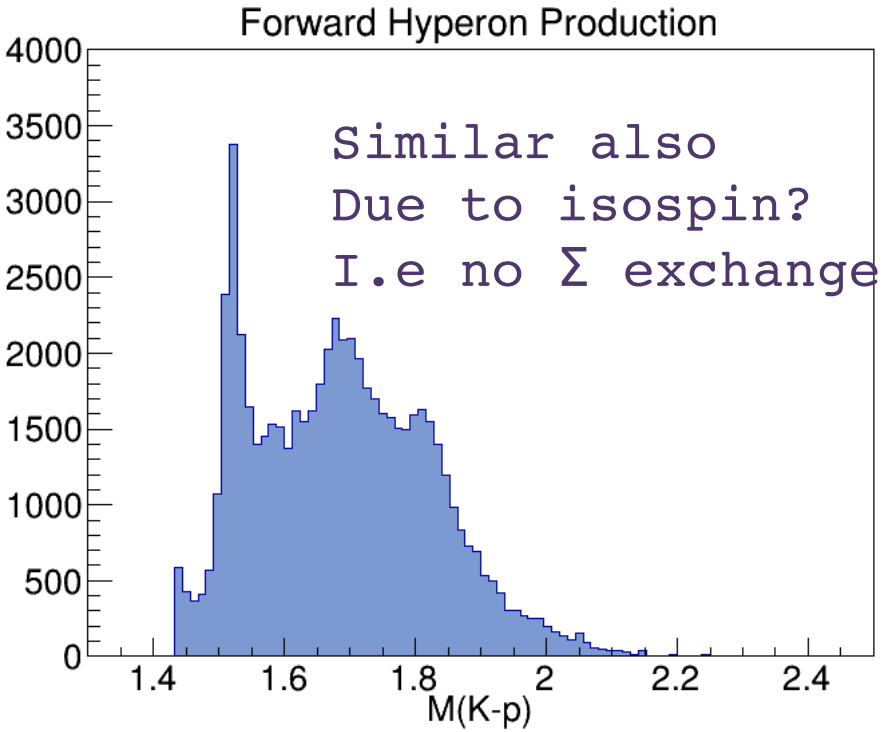
R. Aaij *et al.* (LHCb Collaboration)
Phys. Rev. Lett. **115**, 072001 – Published 12 August 2015



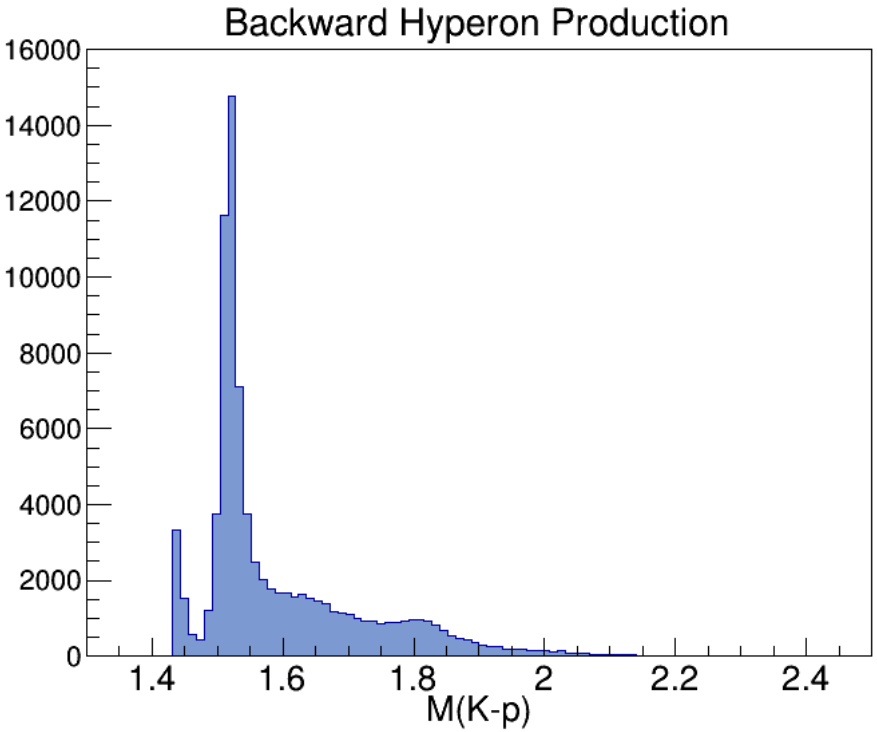
"Particle" physics spectra
≃"Nuclear" physics spectra



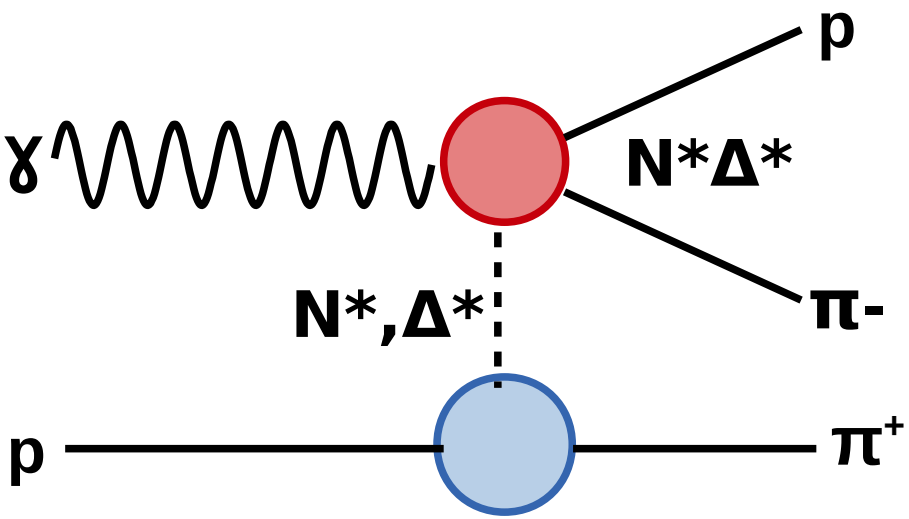
Note Λ prefered over Σ as ΔI=0 ?

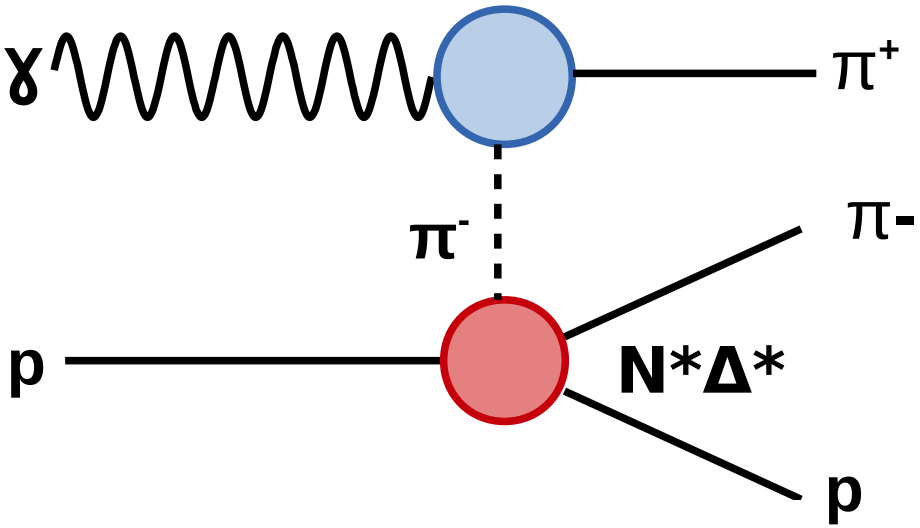


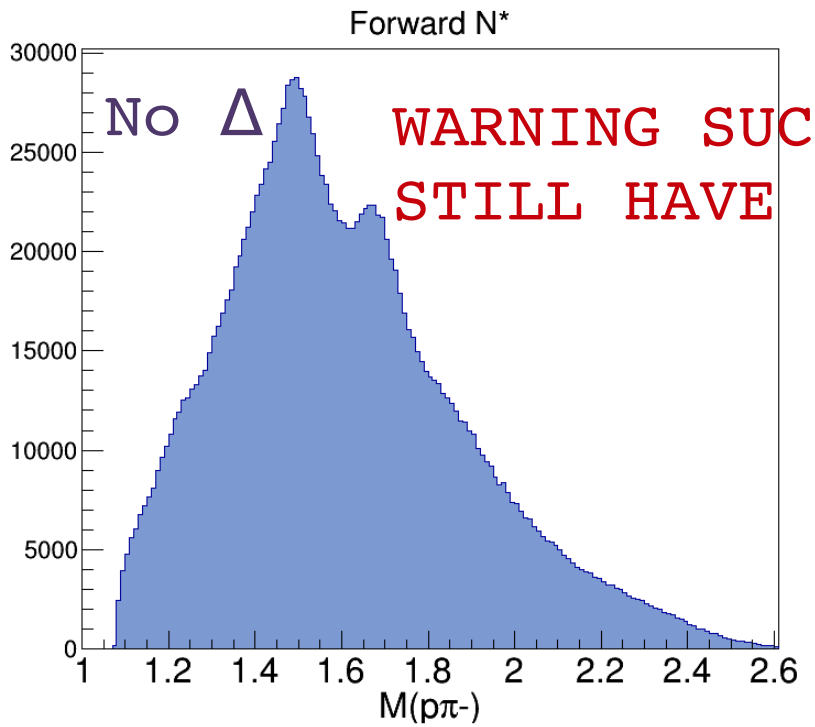
Similar also
Due to isospin?
I.e no Σ exchange

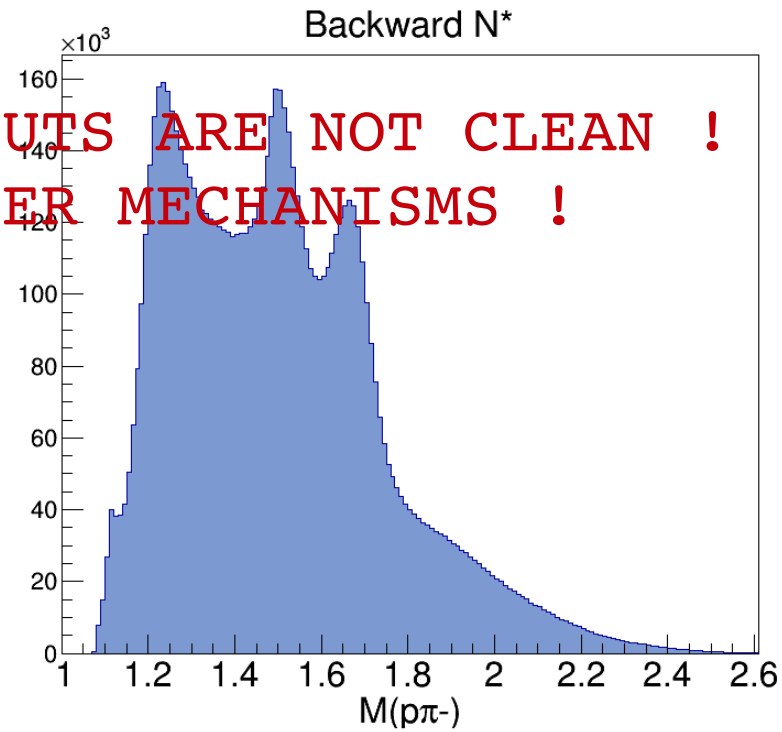


Using Longitudinal Phase Space to seperate mechanisms









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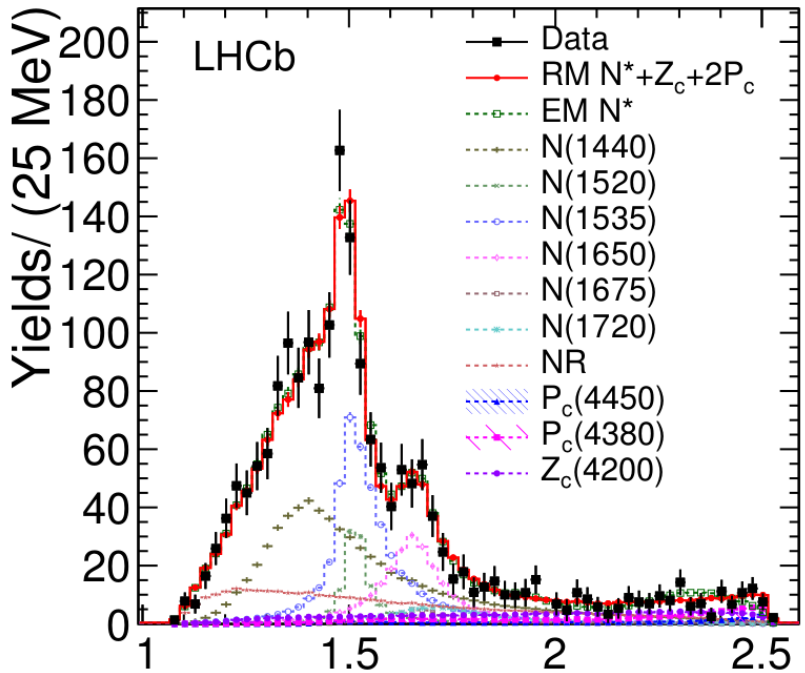
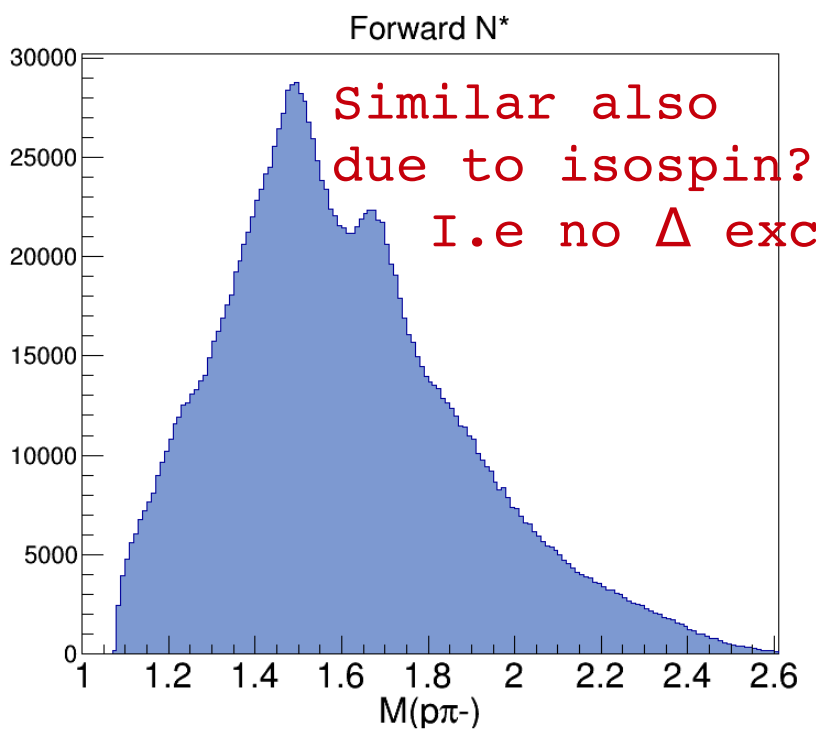
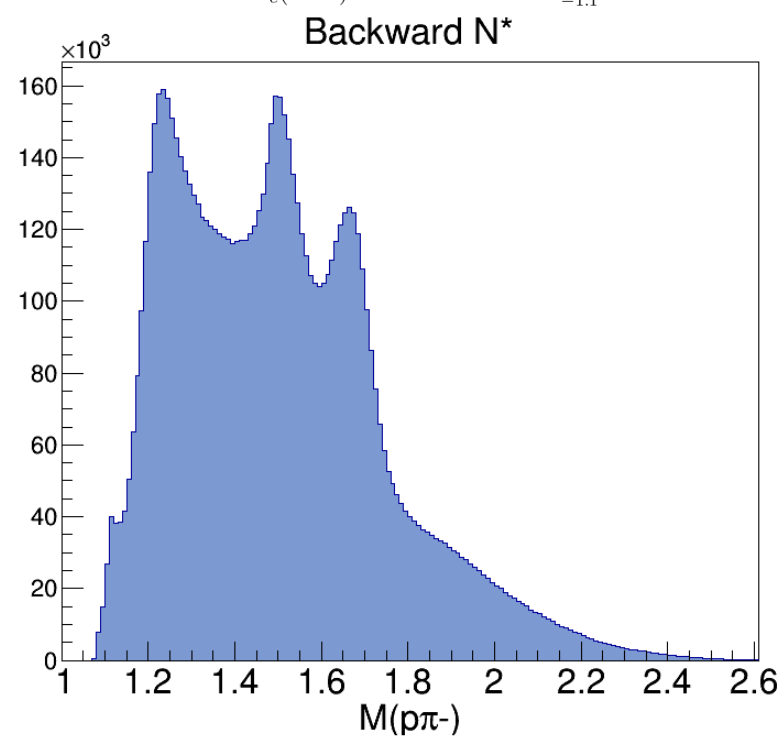


Publisher's Note: Evidence for Exotic Hadron Contributions to $\Lambda_b^0 \to J/\psi p \pi^-$ Decays [Phys. Rev. Lett. **117**, 082003 (2016)]

R. Aaij *et al.* (LHCb Collaboration)
Phys. Rev. Lett. **117**, 109902 – Published 2 September 2016

State	RM	EM
NR $p\pi$	18.6 ± 3.2	16.0 ± 3.3
$N(1440)$	34.0 ± 4.9	43.9 ± 5.7
$N(1520)$	7.6 ± 2.2	1.9 ± 3.9
$N(1535)$	25.4 ± 5.9	34.4 ± 6.5
$N(1650)$	10.5 ± 5.1	9.5 ± 4.1
$N(1675)$	$3.4^{+2.2}_{-1.0}$	4.2 ± 1.6
$N(1680)$	-	3.0 ± 1.6
$N(1700)$	-	1.7 ± 3.0
$N(1710)$	-	2.1 ± 1.6
$N(1720)$	$3.9^{+1.8}_{-1.3}$	9.6 ± 3.2
$N(1875)$	-	2.3 ± 1.9
$N(1900)$	-	3.0 ± 1.7
$N(2190)$	-	0.5 ± 0.4
$N(2300)$	-	4.9 ± 2.2
$N(2570)$	-	0.3 ± 0.5
$P_c(4380)$	5.1 ± 1.5	4.1 ± 1.7
$P_c(4450)$	$1.6^{+0.8}_{-0.6}$	$1.5^{+0.8}_{-0.6}$
$Z_c(4200)$	7.7 ± 2.8	$4.1^{+4.3}_{-1.1}$





Conclusions

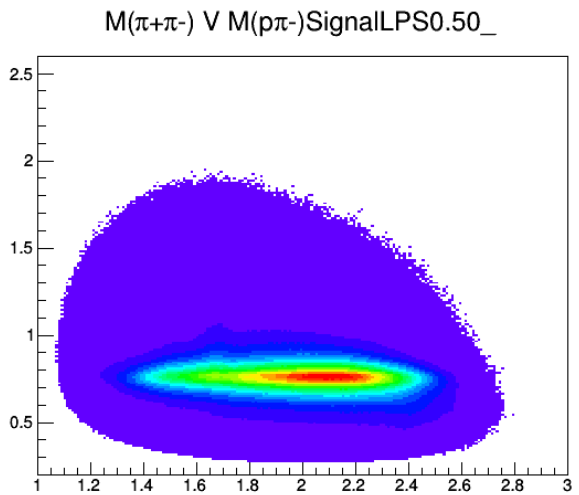
There are many connections between UK Particle and Nuclear hadron physics communities :

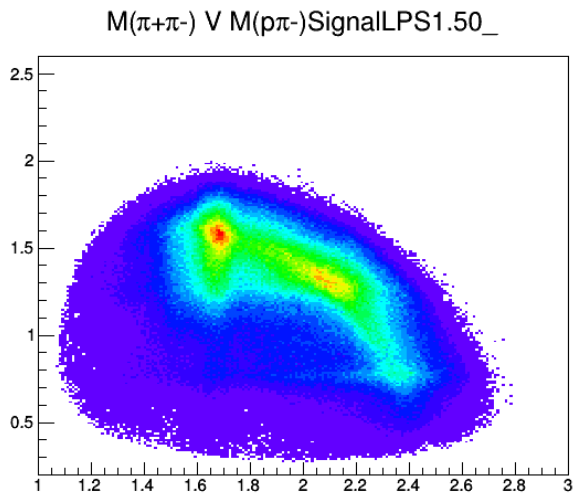
Data Analysis Techniques

Data Spectra

The need to apply more advanced theoretical methods to data

Hopefully this workshop can help bring the communities together!


M(π+π-) V M(pπ-)SignalLPS0.50_
2.5
2
1.5
1
0.5
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8
3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2
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1
1.2
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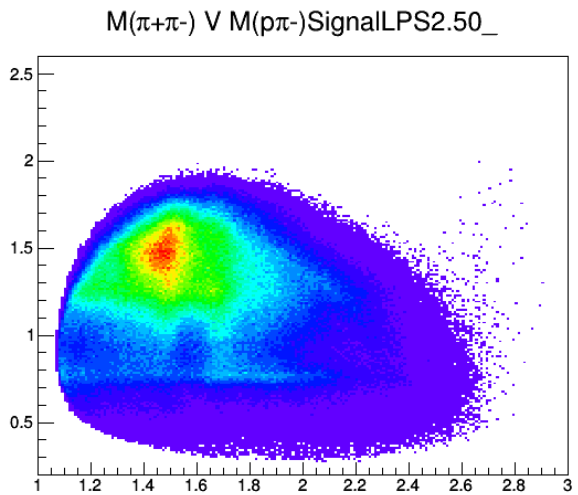
1.6
1.8
2
2.2
2.4
2.6
2.8
3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1.2
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1.6
1.8
2
2.2
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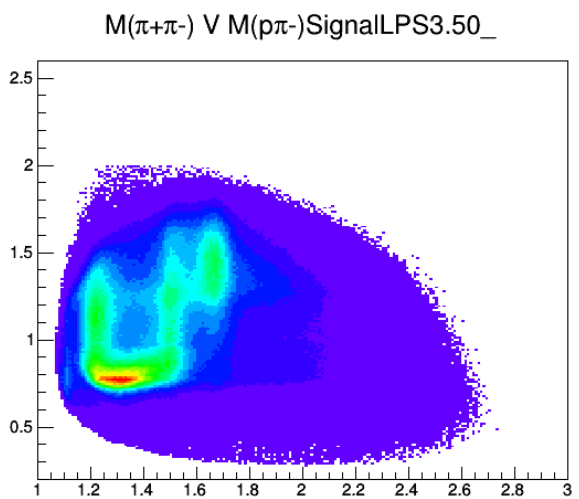
2.6
2.8
3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1.8
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2.2
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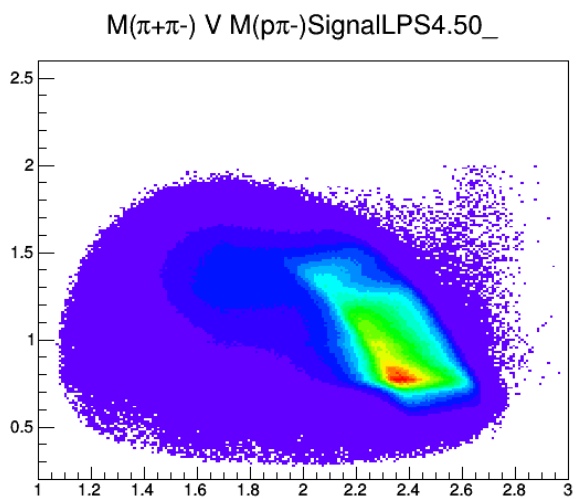
2.6
2.8
3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2.2
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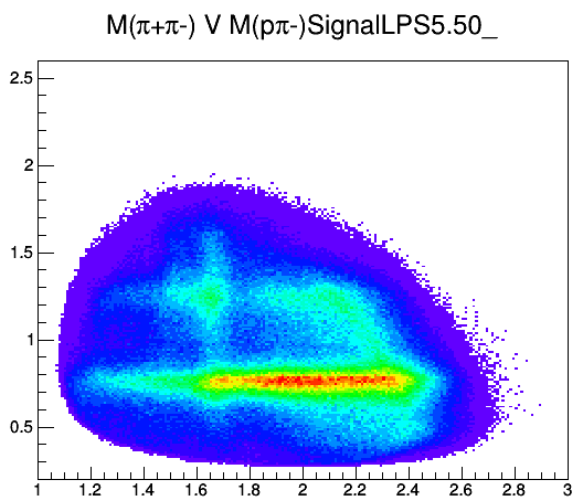
2.6
2.8
3


M(π+π-) V M(pπ-)SignalLPS5.50_
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1
1.2
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1.6
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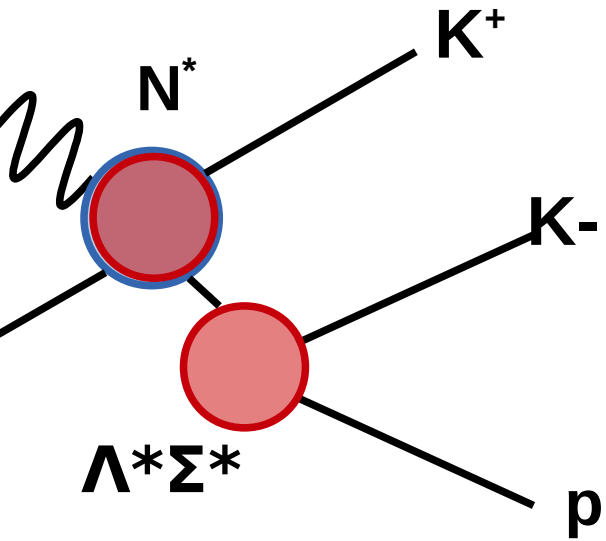
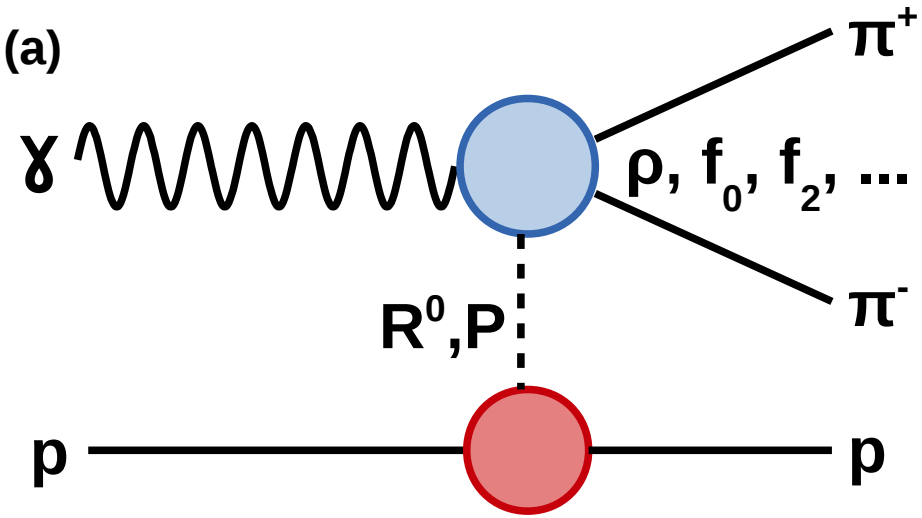
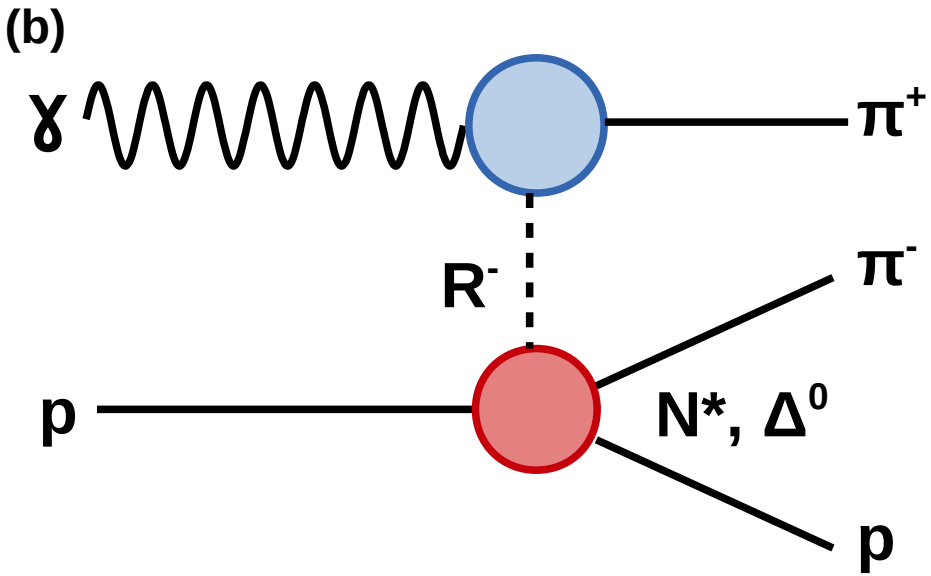
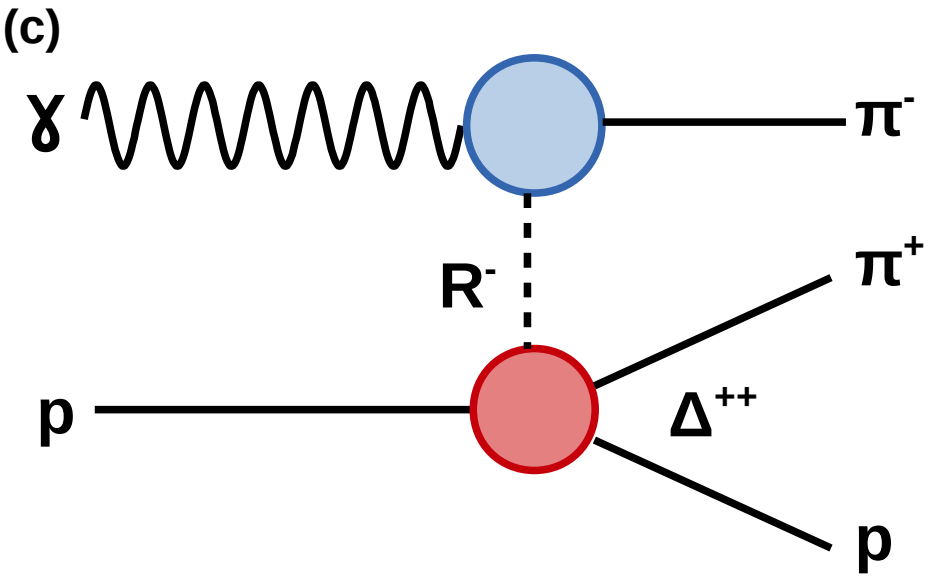
2.6
2.8
3


N*
K+
K-
Λ*Σ*
p


(a)
γ
π+
ρ, f0, f2, ...
π-
R0,P
p
p


(b)
γ
π+
R-
π-
p
N*, Δ0
p


(c)
γ
π-
R-
π+
p
Δ++
p