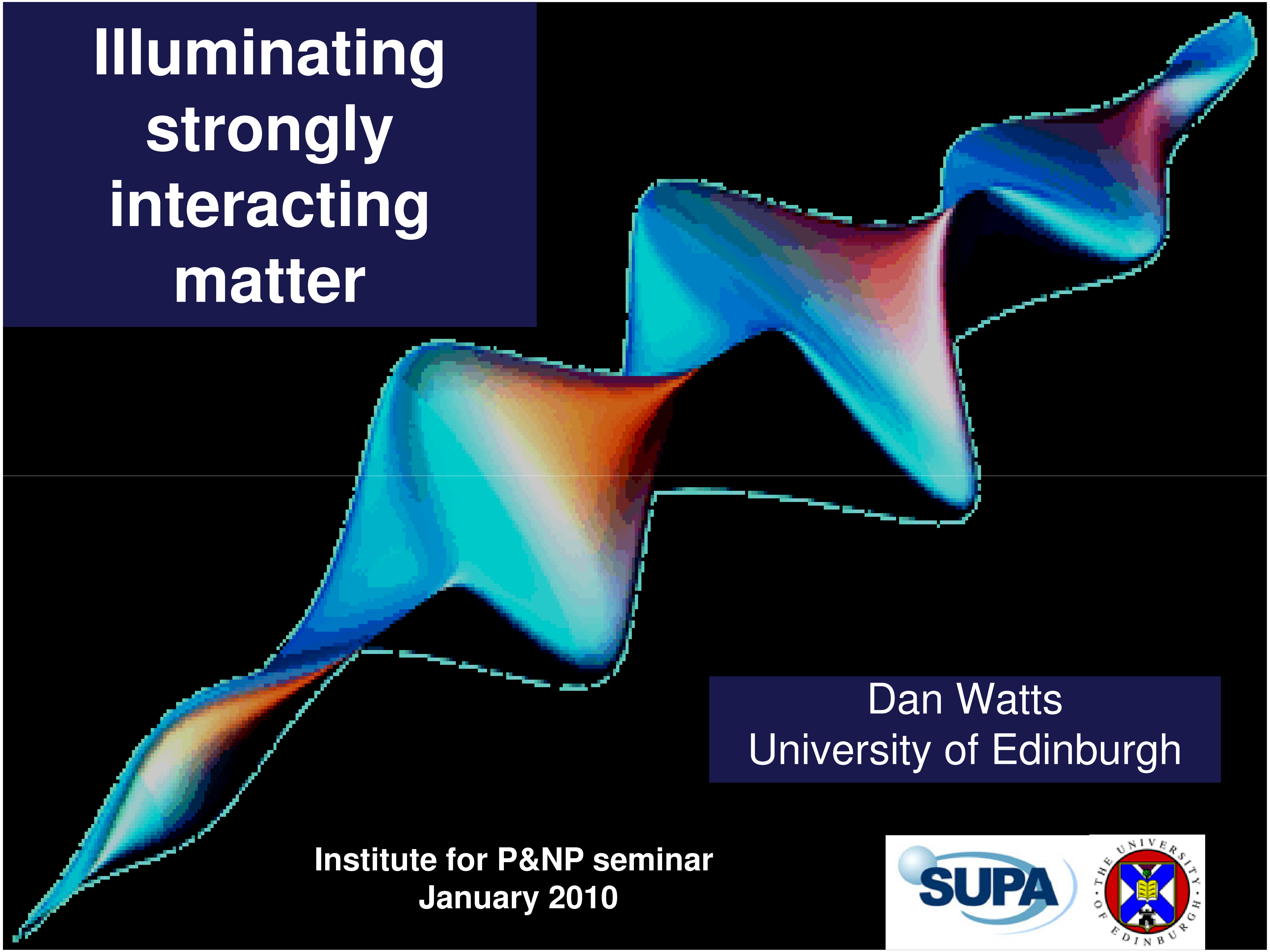
Illuminating strongly interacting matter



Dan Watts
University of Edinburgh

Institute for P&NP seminar
January 2010

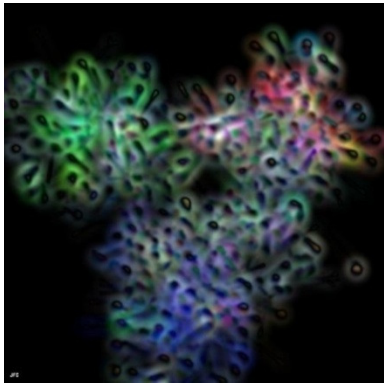
Lecture outline

- Generating intense photon beams
- Current facilities

Two selected physics topics

The equation of state
for neutron rich matter

The excitation spectrum
of the nucleon



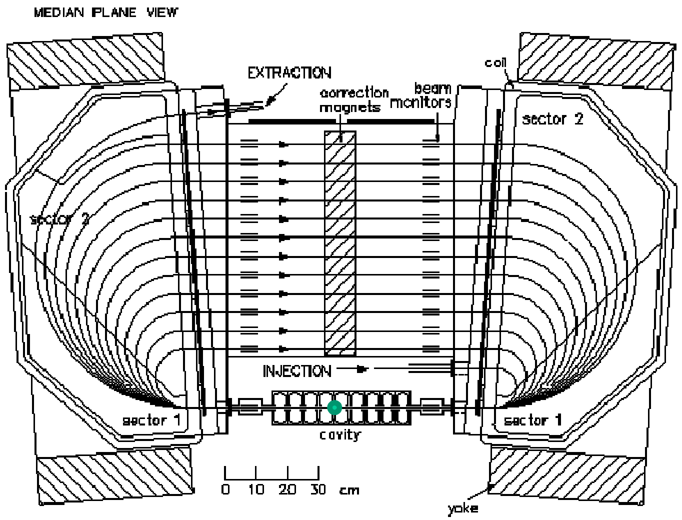
Forward Look - probing quark confinement in the light quark sector with meson spectroscopy

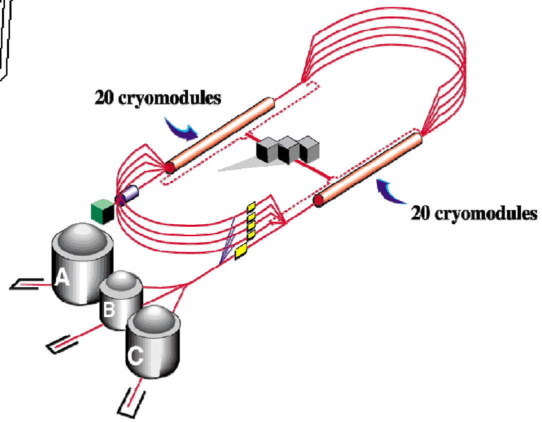
High intensity electron beams

Microtron technique

(MAMI, Jefferson Lab)

- e^- beam accelerated by rf cavities
- Tune magnetic field to ensure path through magnets multiple of λ of accelerating field.
- e^- arrive back in phase → "Continuous" beam (high d.f.)





Strecher ring technique

(Spring8, Bonn, Frascati, GRAAL)

- e^- beams fed in from linac
- Accelerated and stored in ring.
  - Useable beam bled off slowly
- Many built for synchrotron radiation – can exploit !!
- Tend to have poorer duty factors beam properties and less stable operation than microtrons

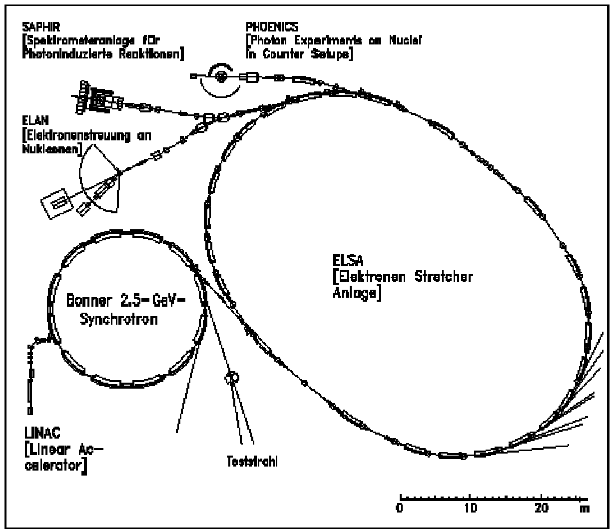
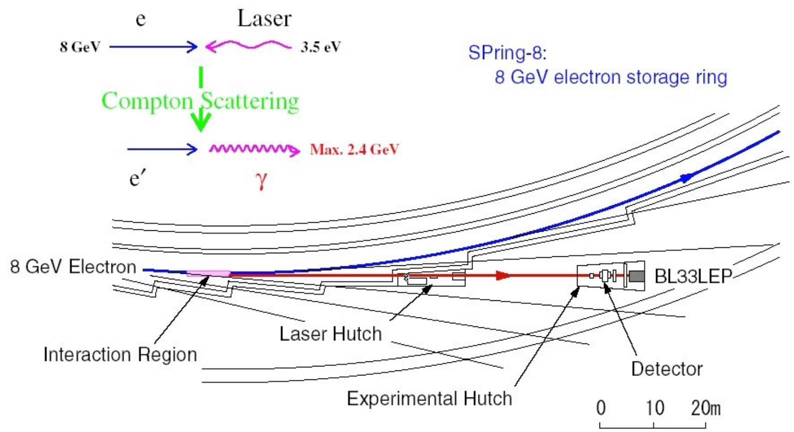


Abb. 1: Die Bonner Beschleunigeranlage ELSA mit den angeschlossenen Experimenten. Die Elektronenquelle befindet sich im Bild links unten. Von hier aus werden die Elektronen im LINAC vorbeschleunigt, über das Synchrotron in ELSA eingespeist, wo sie an den dargestellten Experimenten extrahiert werden können.

Real photon beams from electron beams

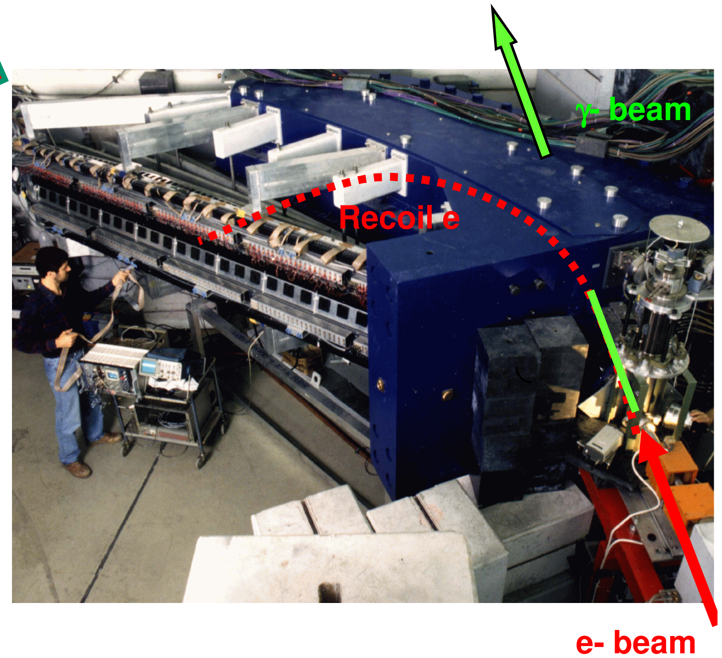
Laser back-scattering

(LEGS, FRASCATI, DUKE, Spring8)
E_γ smaller than beam energy
Facilities up to 4 GeV

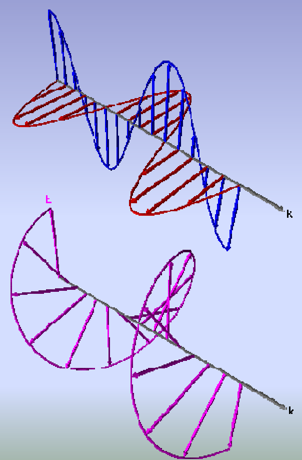


Tagged Bremsstrahlung

(MAMI, Bonn, Lund, Jlab)
Eγ up to ~beam energy
Facilities up to 6 GeV (9GeV ~ Yr 2012)



Both techniques can produce *polarised* γ beams



Transverse polarisation
(Electric field vector
oscillates in a plane)

Circular polarisation
(Electric field rotates
Clockwise or anticlockwise)

Photon beam facilities

	E_γ^{max} (GeV)	I_γ^{max} ($s^{-1}MeV^{-1}$)	ΔE_γ (FWHM) (MeV)	Pol_γ^{lin} (%)	Pol_γ^{circ} (%)
ELSA	3.5	$\approx 10^4$	5	70	80
Graal	1.5	$\approx 10^3$	15	100	100
Jefferson Lab	5.4 12	$\approx 10^4$	5	70	80
Legs	0.45	$\approx 10^3$	5	100	100
mami MAINZER MIKROTRON B C	0.8 1.6	$\approx 10^5$	1	70	80
SPring-8	3.0	$\approx 10^3$	30	100	100

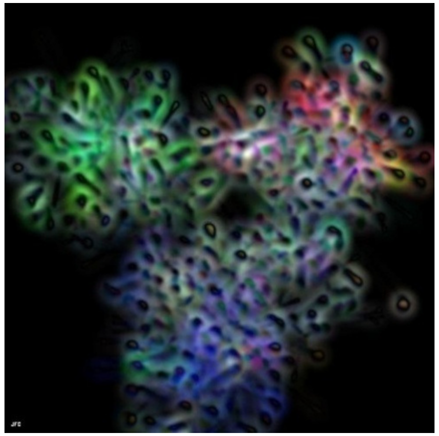
Two selected physics topics

The equation of state
for neutron rich matter

Coherent pion
photoproduction to measure
matter form factor

Transition matter FF's

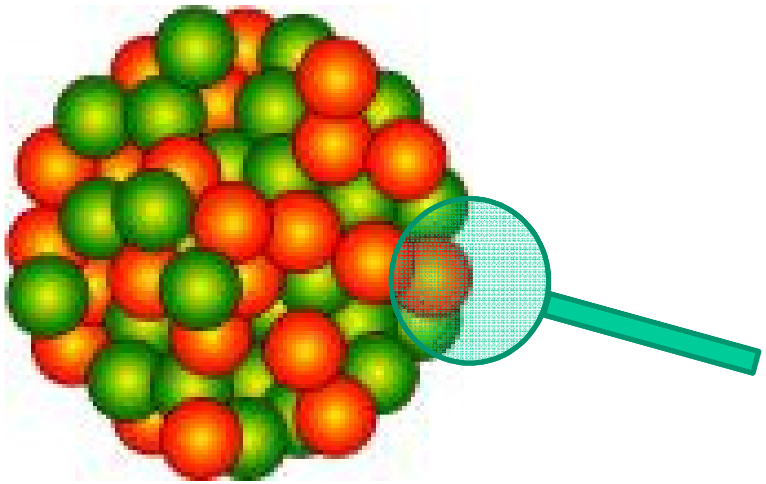
The excitation spectrum
of the nucleon

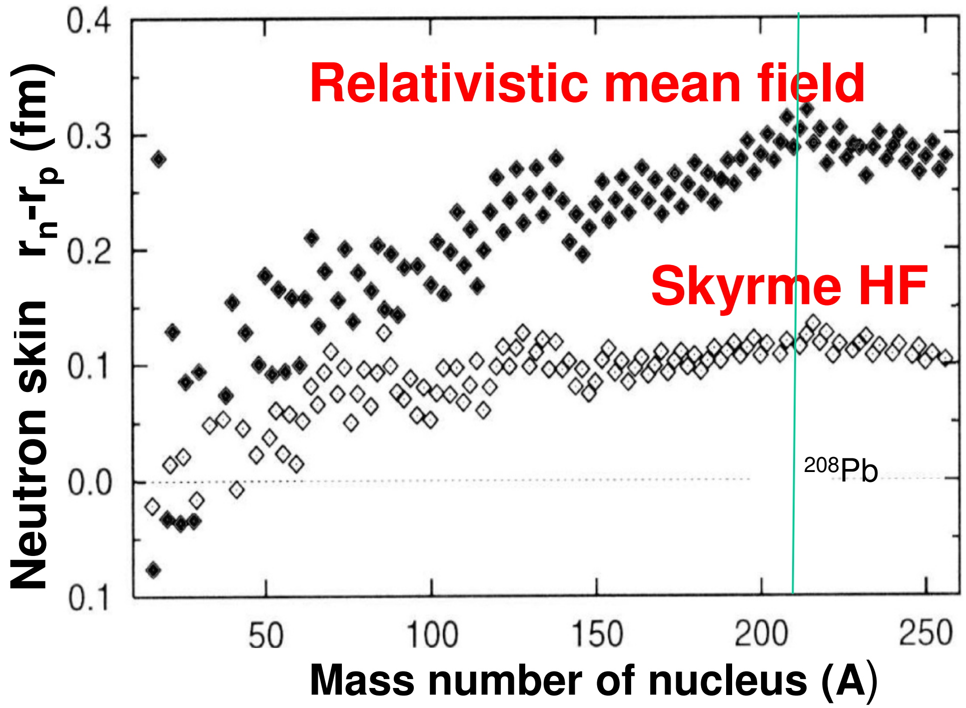


"Complete measurement"
of meson photoproduction
from the nucleon

Matter form factor and the neutron skin

- Our knowledge of the shape of stable nuclei is presently incomplete





- e.g. ^{208}Pb RMS charge radius accuracy < 0.001 fm
  RMS neutron radius accuracy ~0.2 fm !!

Horowitz et al. PRC63 025501 (2001)
Piekarewicz et al. NPA 778 (2006)

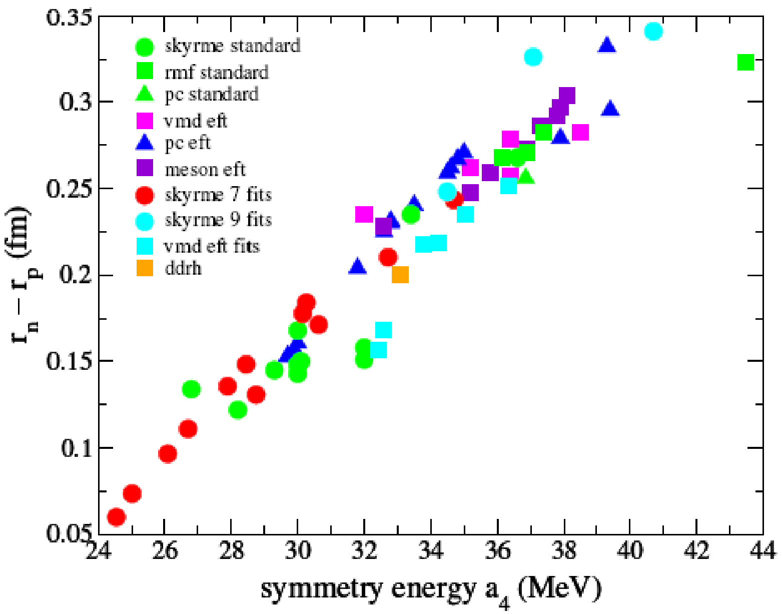
Neutron skin and the equation of state

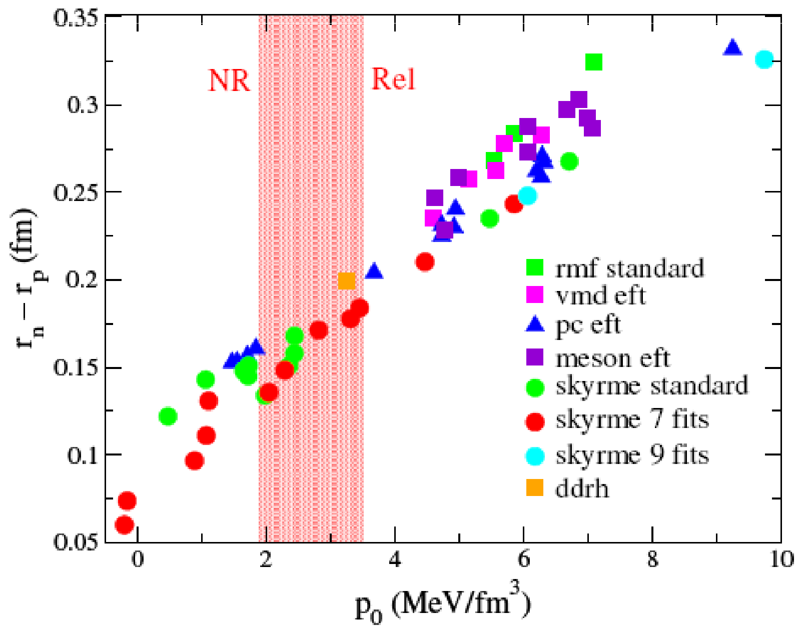
$$E(n,\alpha) = E(n,0) + S_2(n)\alpha^2 + S_4(n)\alpha^4 + \cdots$$

negligible

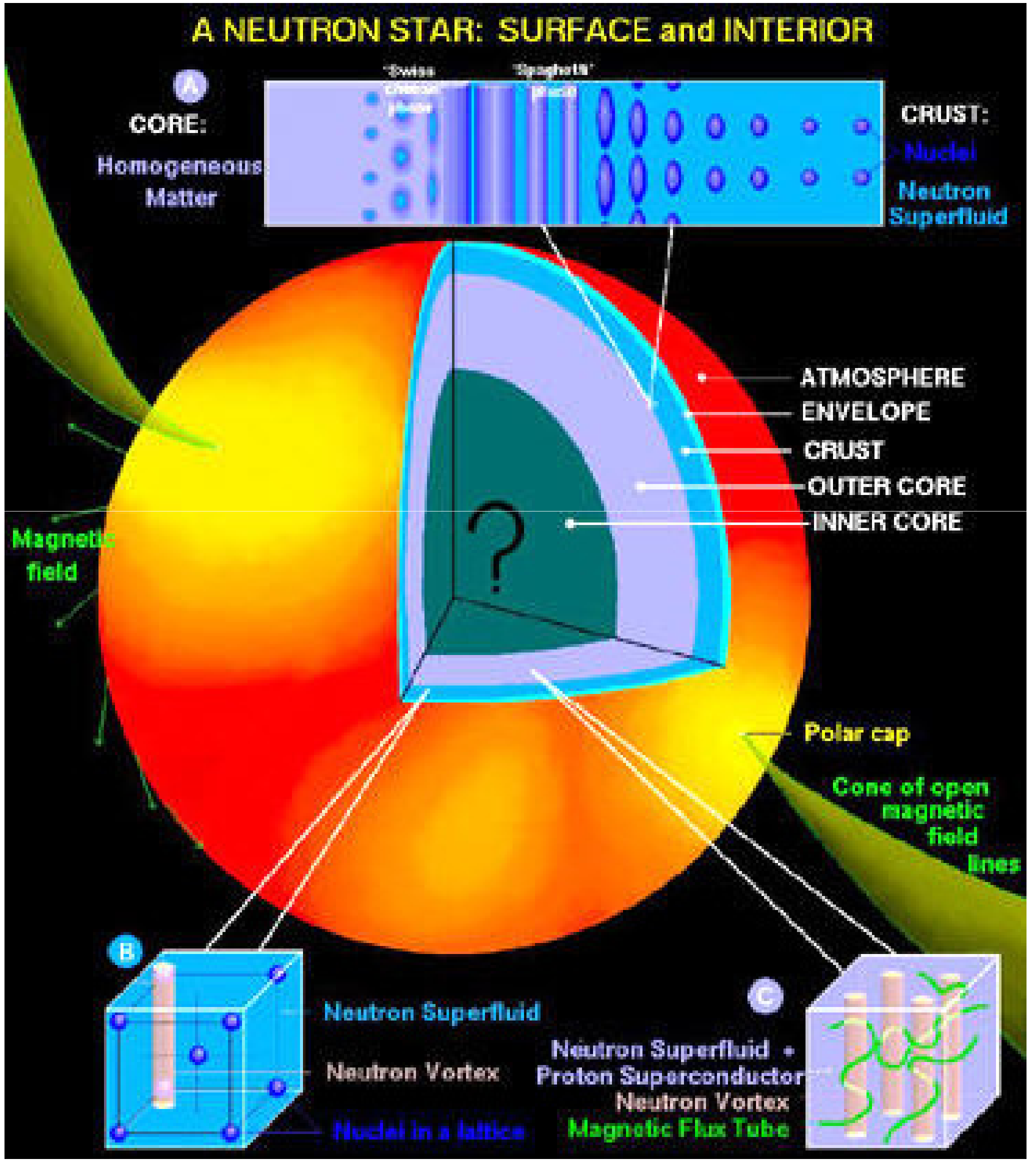
n = density (fm^{-3})
α = (N-Z)/A
n_0 = nuclear density

$$S_2(n) = a_{\text{sym}} + \frac{p_0}{n_0^2}(n-n_0) + \frac{\Delta K_0}{18 n_0^2}(n-n_0)^2 + \cdots$$

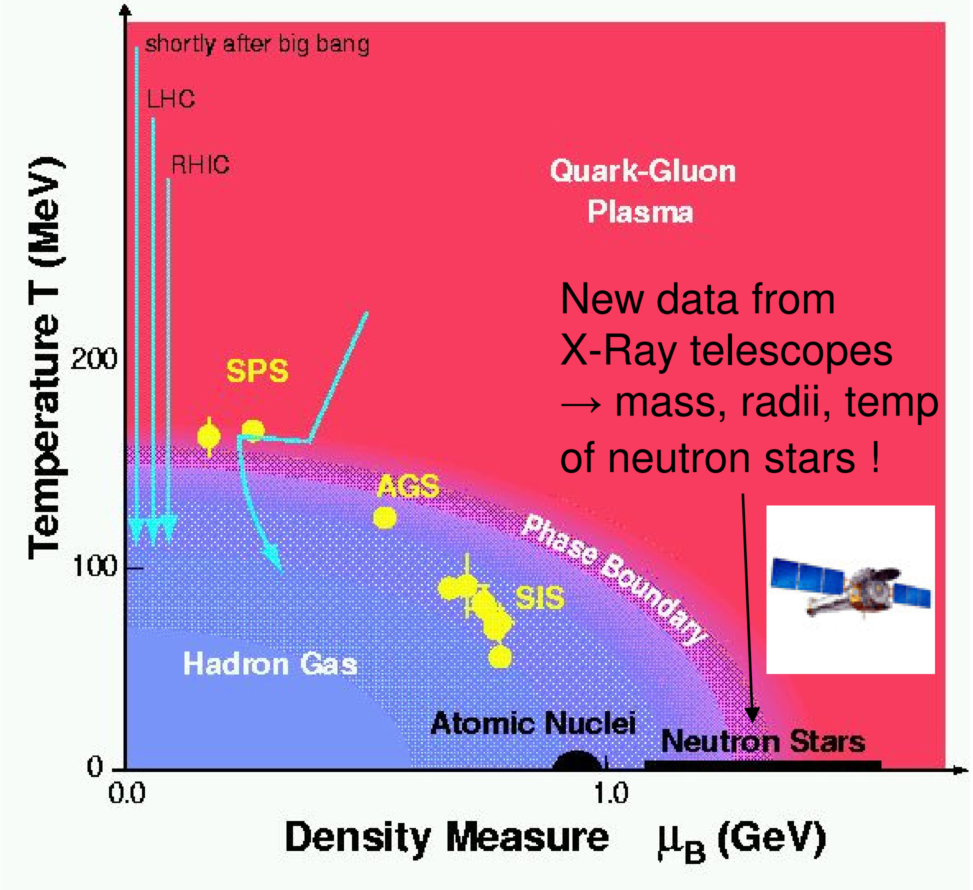




Neutron stars

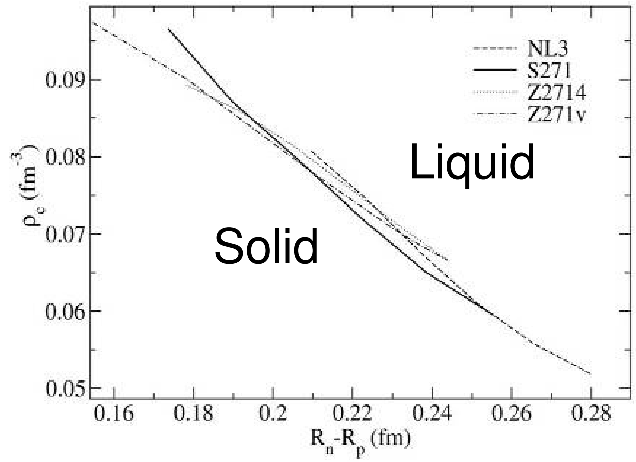


Neutron skin and neutron stars

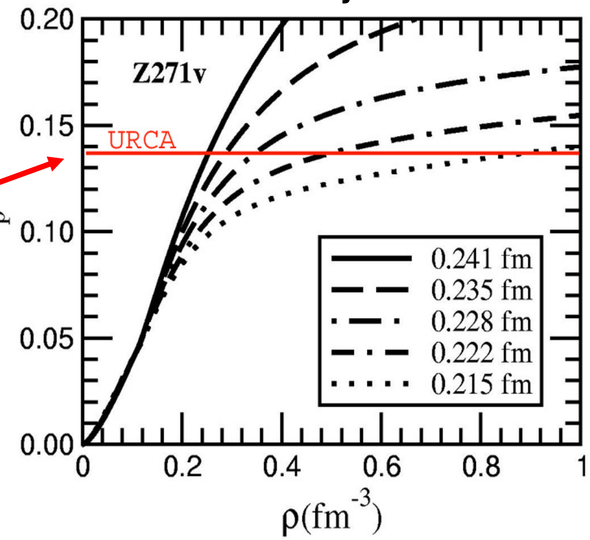


Rutel et al, PRL 95 122501 (2005)
Horowitz, PRL 86 5647 (2001)
Horowitz, PRC 062802 (2001)
Carriere, Astrophysical Journal 593 (2003)
Tsuruta, Astrophysical Journal Lett. 571 (2002)

Thick neutron skin
→ Low transition density in neutron star



Proton fraction as a function of density in neutron star



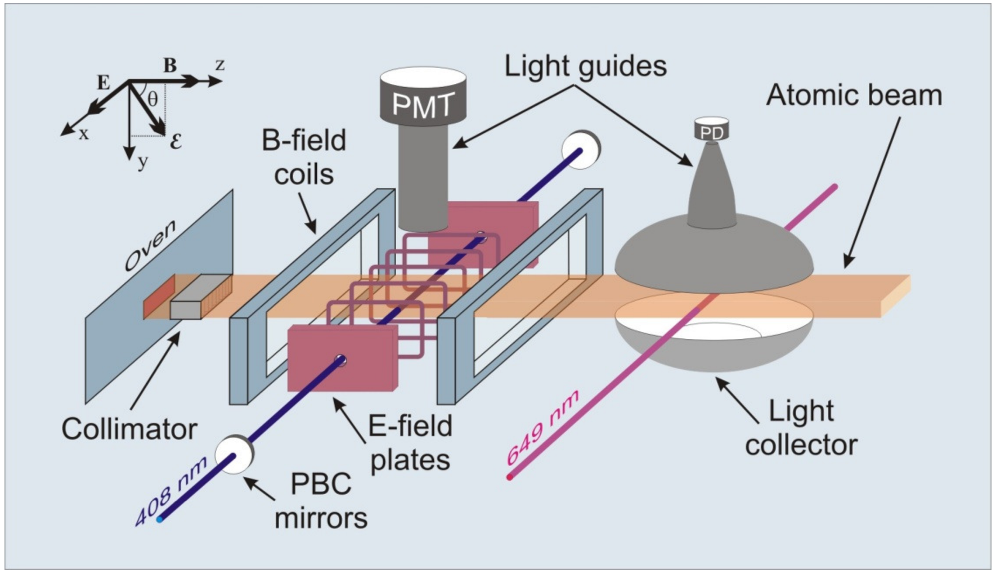
Direct URCA Cooling

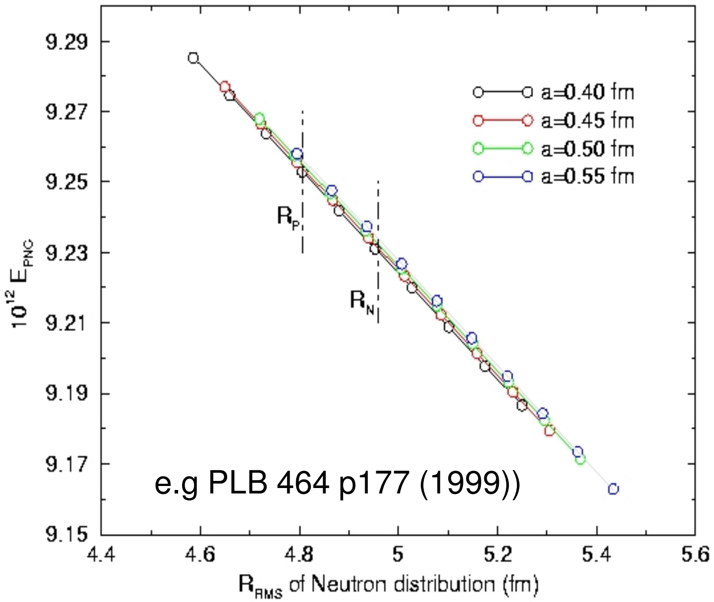
$n \rightarrow p + e^- + \bar{\nu}$

$e^- + p \rightarrow n + \nu$

Constrains gravitational wave emission from neutron stars – Frequency and damping modes!! arXiv:0902.4702 (2009)

Further need for neutron skins

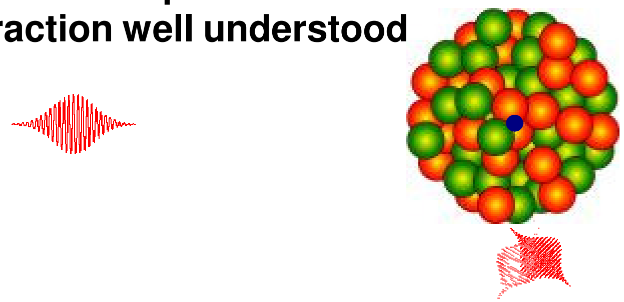




- Atomic Parity Non Conserving transitions
- Direct measure of weak nuclear charge
- $Q_w = (1 - 4\sin^2\theta_W)Z - N$
- One of most accurate low energy tests of standard model
- Uncertainty in neut. radii one of largest systematic uncertainties

Coherent pion photoproduction

Photon probe ✓
Interaction well understood



π^0 meson – produced with ~equal probability on protons *AND* neutrons.

Select reactions which leave nucleus in ground state

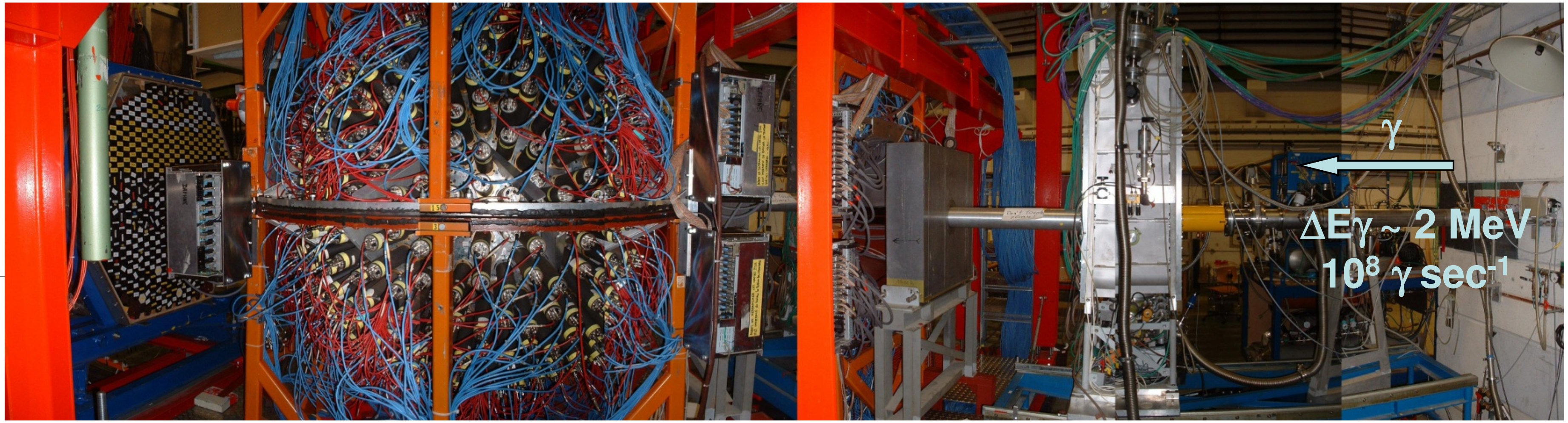
Reconstruct π^0 from $\pi^0 \rightarrow 2\gamma$ decay

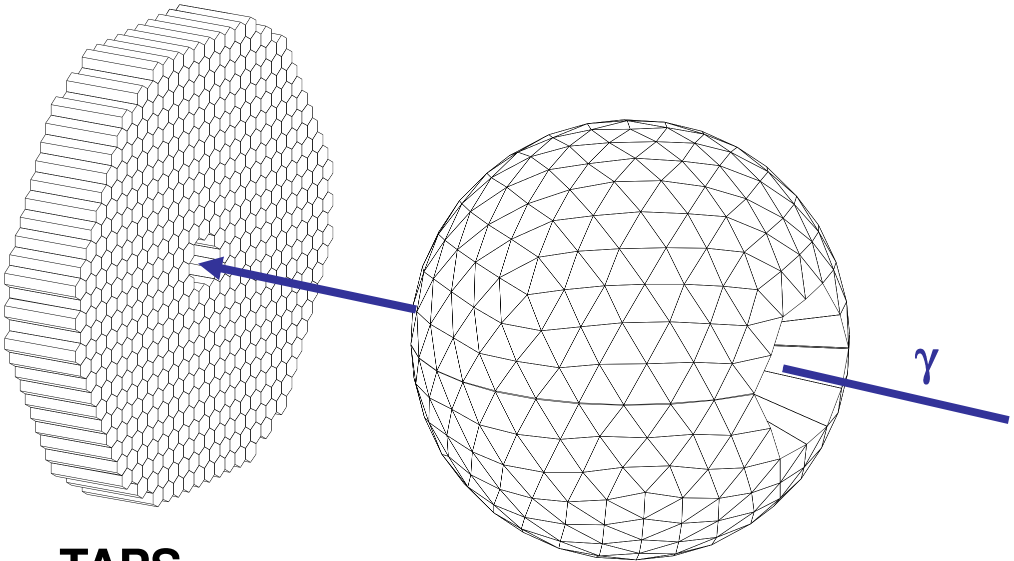
- Angular distribution of π^0 $\rightarrow$ PWIA contains the matter form factor

$$d\sigma/d\Omega(\mathrm{PWIA}) = (s/m_N^2)\, A^2\, (q_\pi^*/2k_\gamma)\, F_2(E_\gamma^*,\theta_\pi^*)^2\, |F_m(q)|^2 \sin^2\theta_\pi^*$$

- π^0 final state interactions - use latest complex optical potentials tuned to π-A scattering data. Corrections modest at low pion momenta

Crystal Ball at MAMI

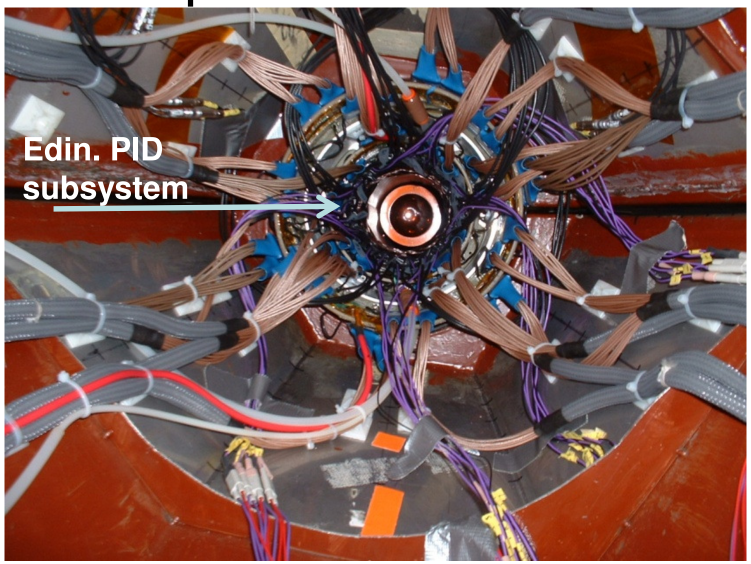




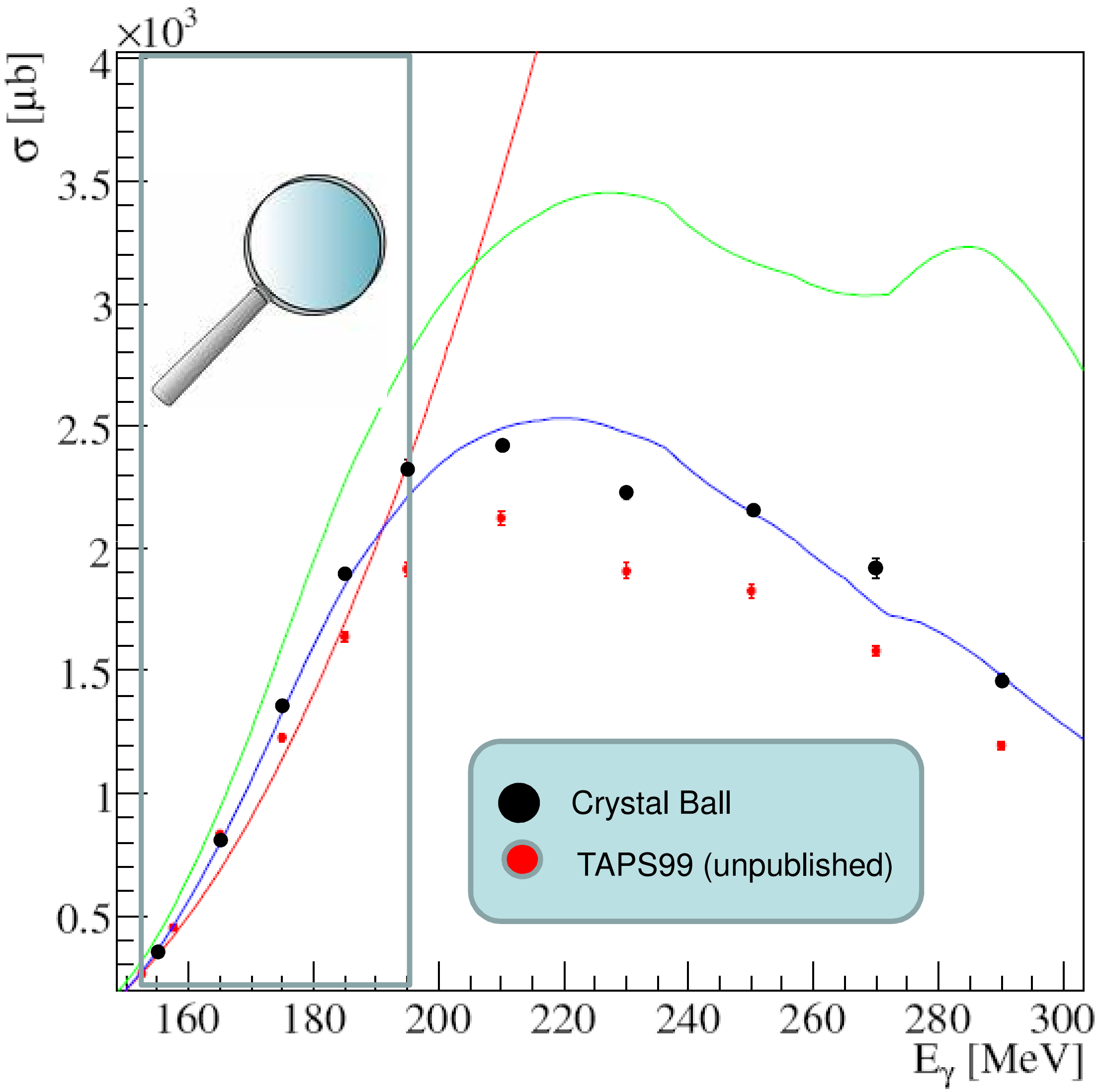
TAPS
528 BaF_2 crystals

Crystal Ball
672 NaI crystals

Upstream view into the ball



^{208}Pb Coherent pion photoproduction – total σ

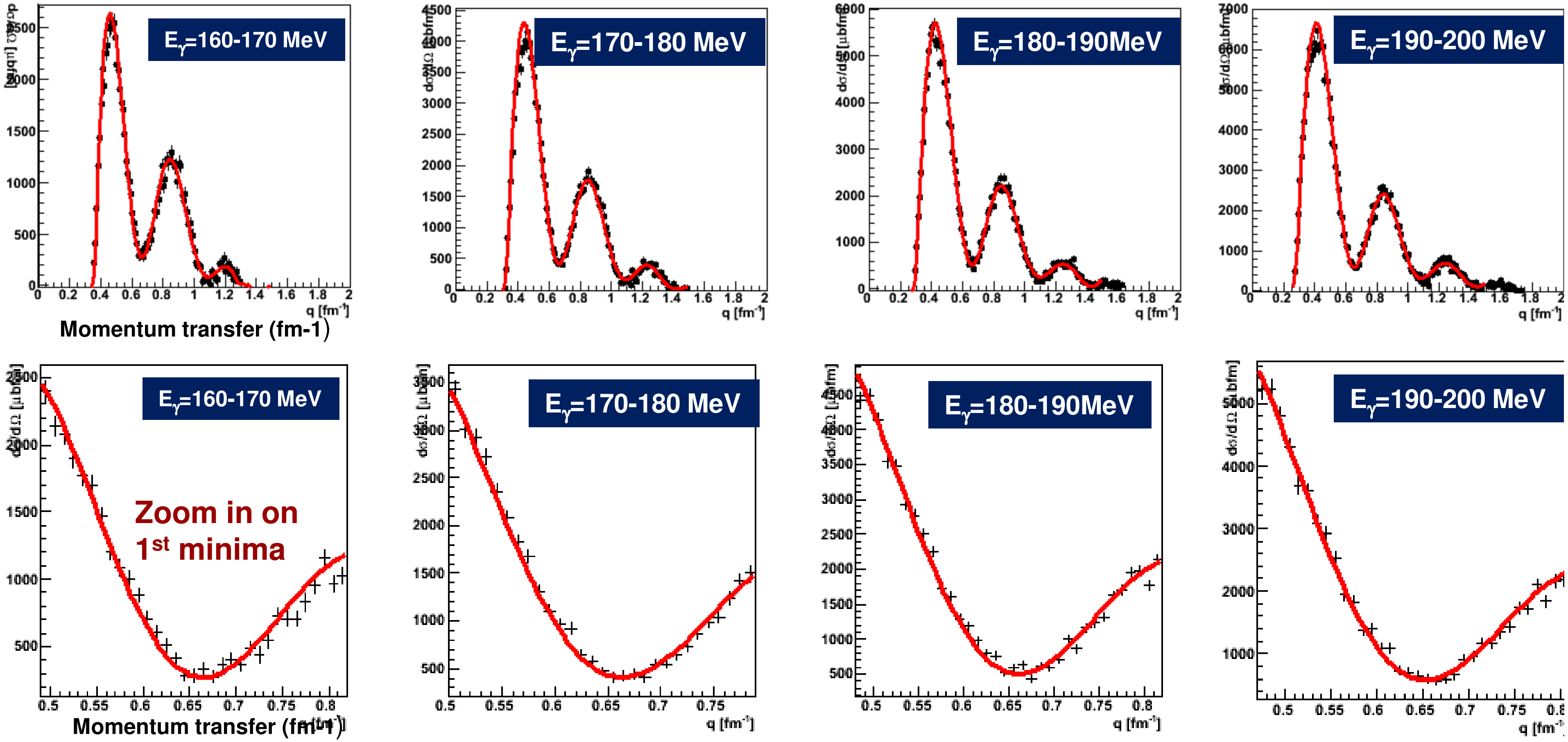


Theoretical calculations:
Unitary isobar model with complex π^0-A interaction

PWIA
DWIA
FULL (+ Δ–self energy)

- Eγ from threshold to ~190 MeV is the "window" to get best access to FF

^{208}Pb Coherent pion photoproduction – analysis for neutron skin

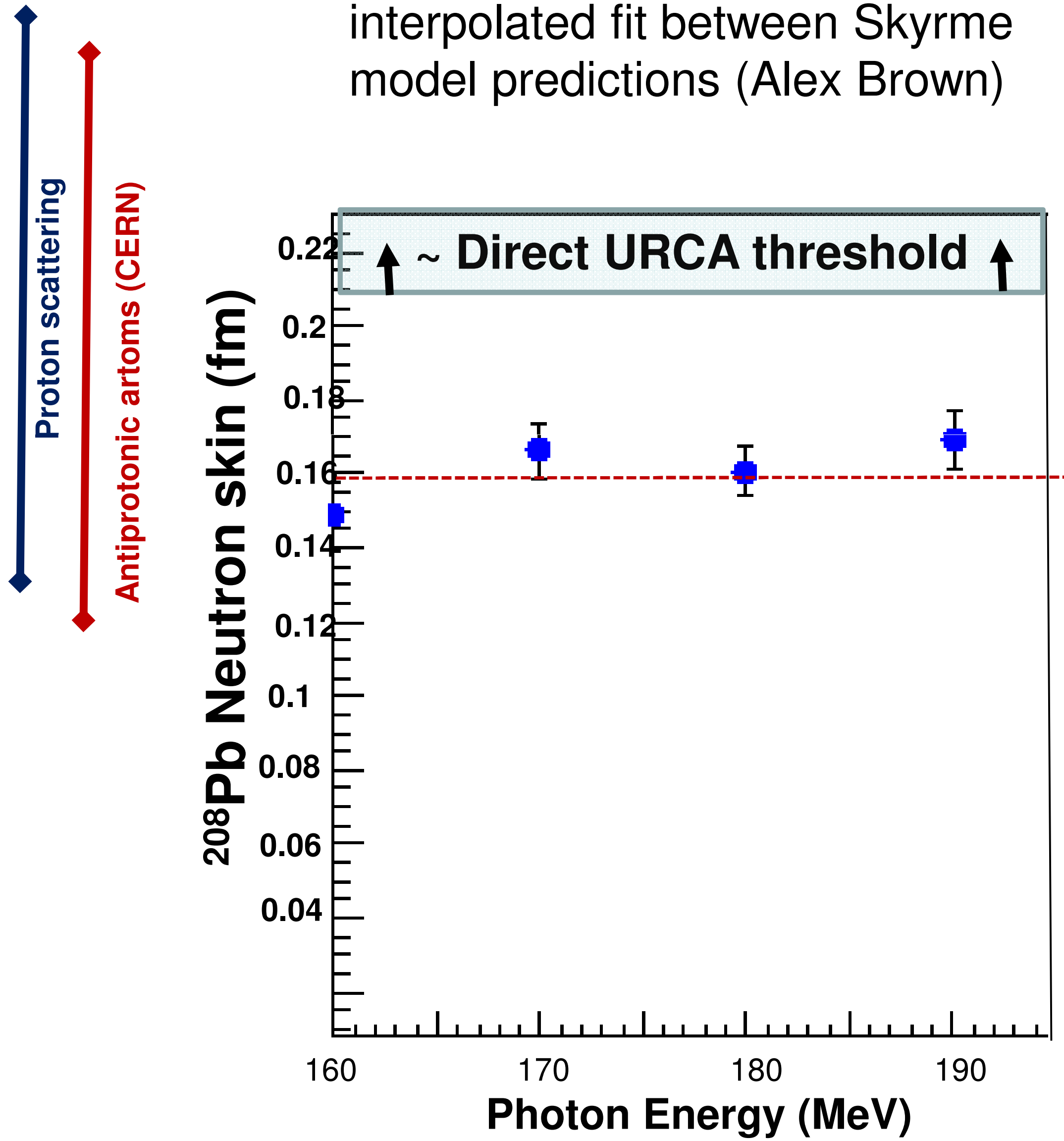


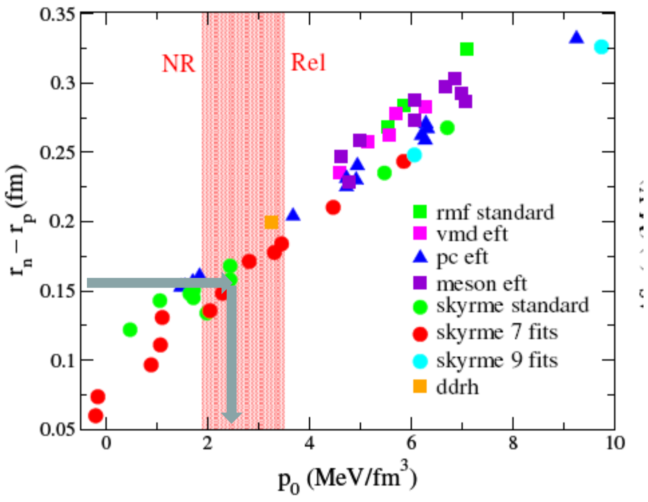
- Red line – Coh pi model plus detector resolution (G4)
- Skin extraction - Linear interpolation between predicted distributions for different skin thicknesses – $\chi 2$ minimising fit to the data
- 2 parameter Fermi Fn. → Charge radii = e^- scattering; ntn radii interval 0 - 0.5 fm

Neutron skins extracted from fit

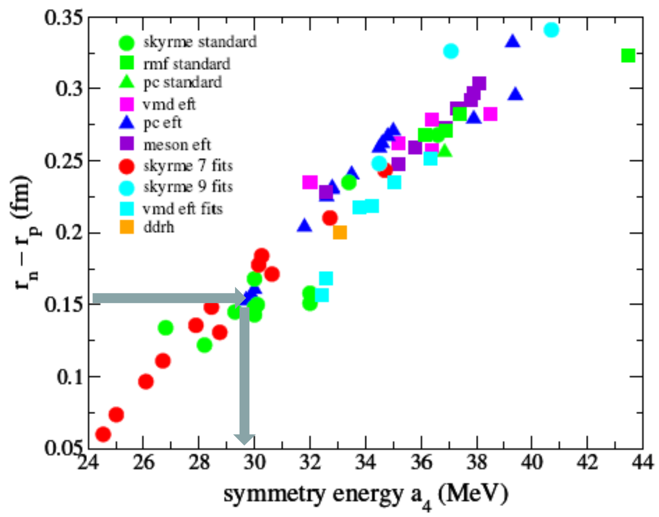
(p,d) pickup

- Further work in progress – interpolated fit between Skyrme model predictions (Alex Brown)

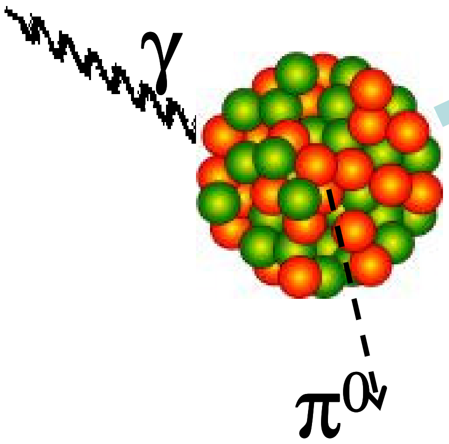




Preliminary results rule out direct URCA cooling in neutron stars!

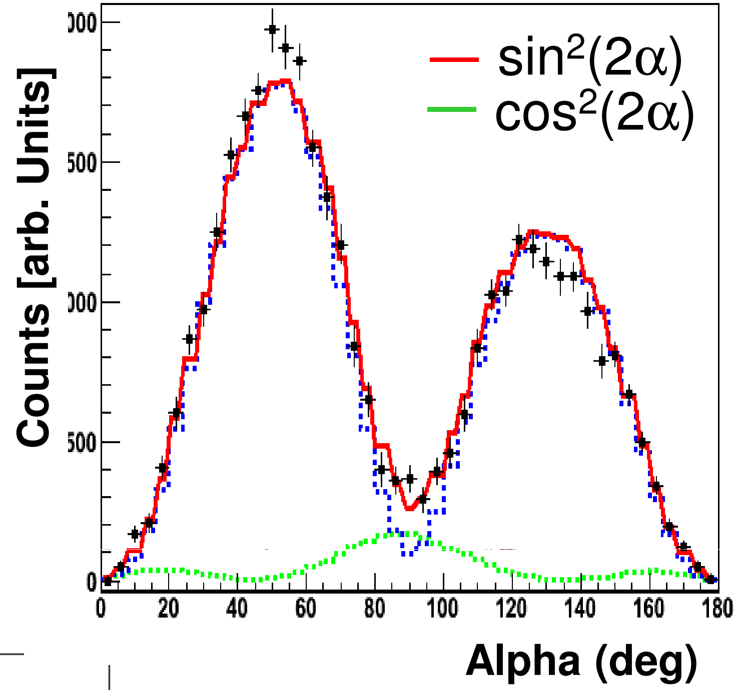


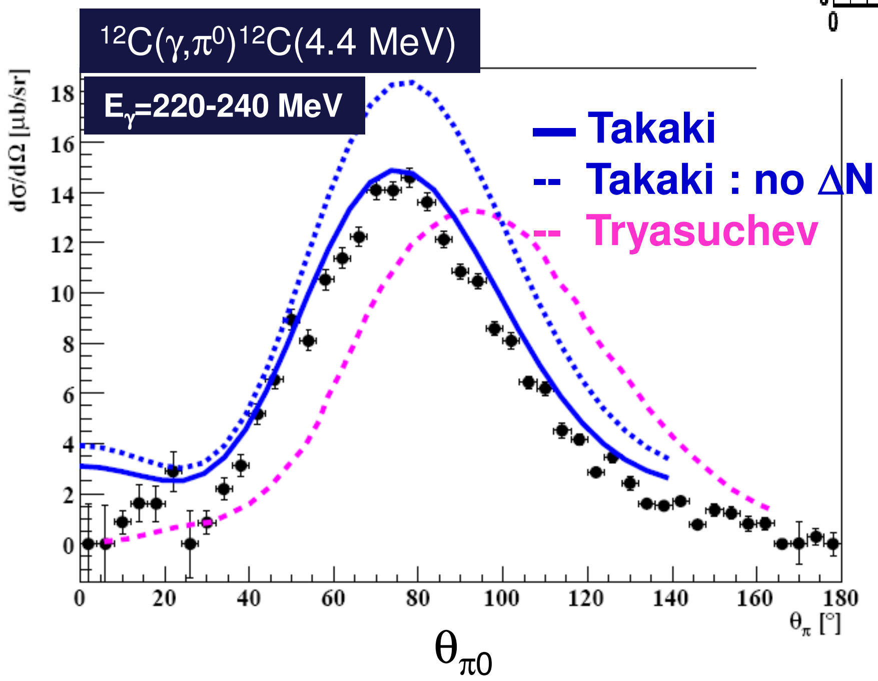
Transition matter form factors



E_x, q

→ Detect nuclear decay photon *in the same detector* as the π^0 decay photons

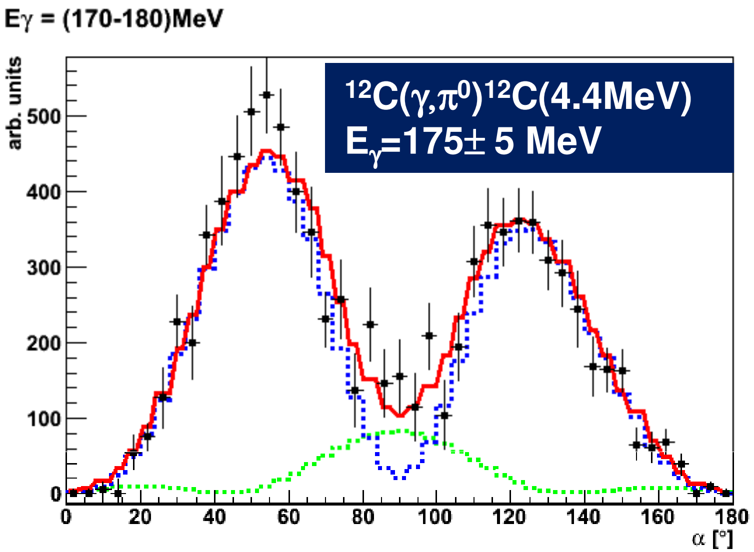


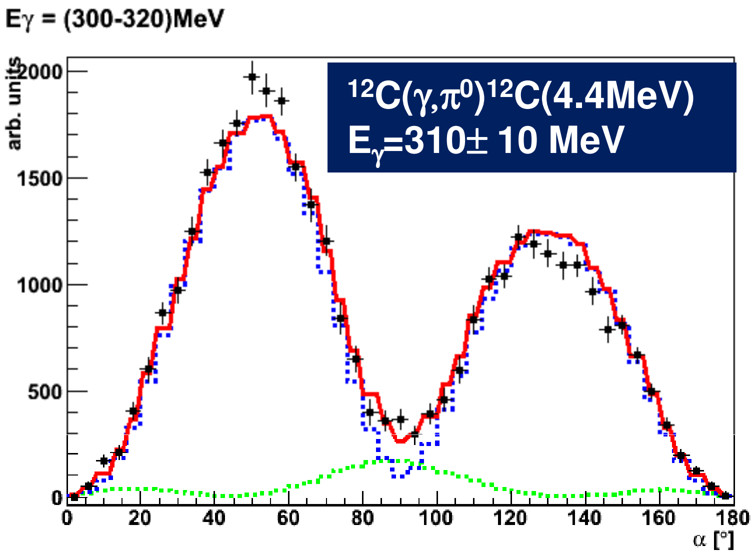


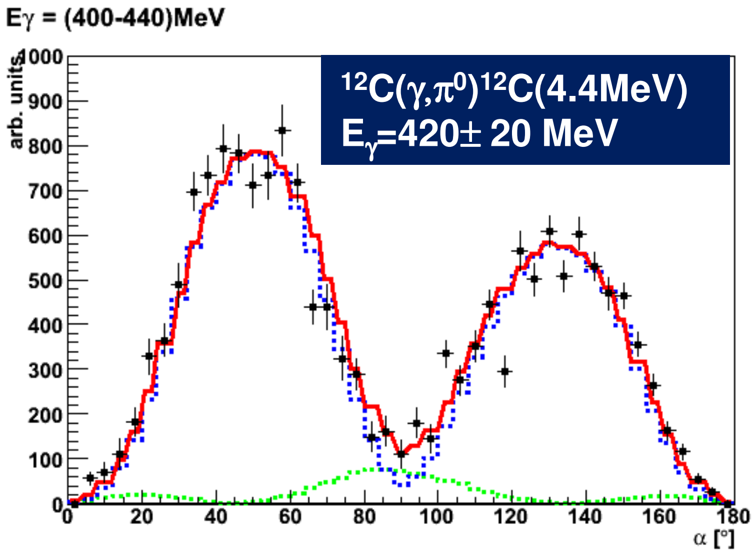
Transition matter form factor with an EM probe !

CM Tarbert, DP Watts et. al.
Phys. Rev. Lett 100 132301 (2008)

Eγ dependence of spin dependent / independent in medium







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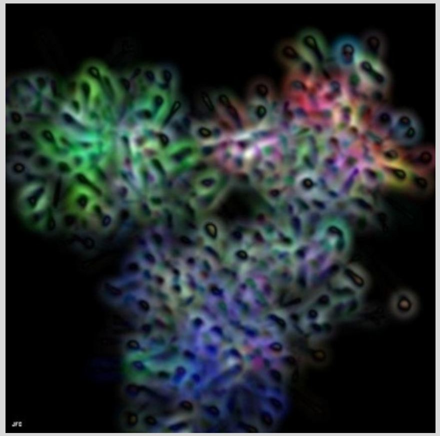
photoproduction to measure
matter form factor

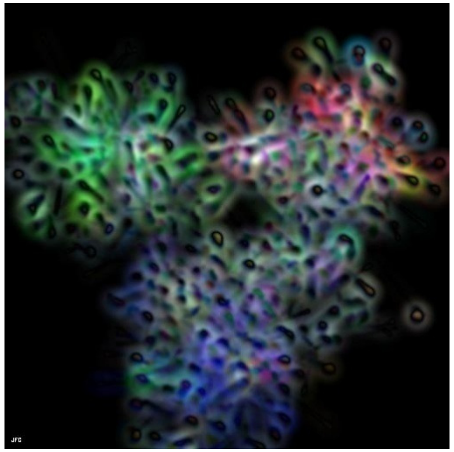
Incoherent – transition matter
form factors

The excitation spectrum
of the nucleon



"Complete measurement"
of meson photoproduction
from the nucleon

Excitation spectrum of nucleon



- Nucleon: 3 light quarks existing in a sea of virtual gluons and $\bar{q}q$ pairs
- Excitation spectrum → fundamental information on interactions/dynamics of constituents.
- Predicted by various theories using different approaches

  Constituent quark models (e.g. Capstick & Roberts, FSU)

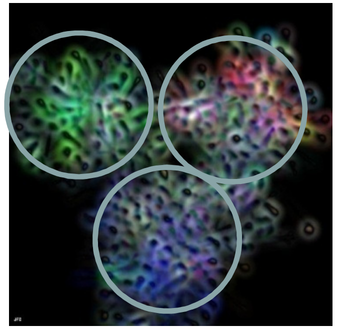
  Lattice QCD (fast developing) (e.g. Jefferson Lab, UKQCD, Morningstar)

  Dyson Schwinger approaches – near future e.g. Chris Robert Argonne)

  Conformal holographic dual of QCD (e.g. Brodsky, SLAC)

  Soliton models (e.g. Polyakov, Juelich)

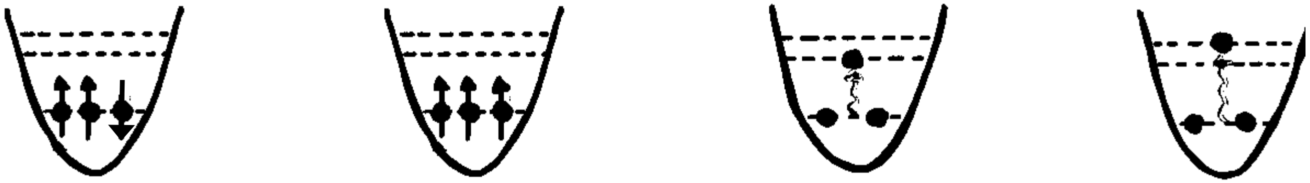
I - Constituent quark model



- Nucleon - assume comprised of 3 heavy quarks (~1/3 M_N)
- Earliest models used simple harmonic oscillator
  Subsequent refinements in CQ interaction
- General form:
  Confining interaction (longer range + spin independent)
  Spin dependent interaction – shorter range modelled after effects of gluon exchange
- Get better agreement with data with strong S.S component in CQ interaction
  → Small L.S component e.g. Isgur model

$$H = \sum_{i=1}^{3}(m_i + \vec{p}_i/2m) + \frac{K}{2}\sum_{i<j} r_{ij}^2 + \sum_{i<j} U(\vec{r}_{ij}) + V_{ij}^{hyp})$$

Function of **spin-spin** and **tensor** (**s.r**) only



S_{11}(938)
J^π=1/2$^+$
"Nucleon"

P_{33}(1232)
J^π=3/2$^+$
" Δ resonance"

D_{13}(1520)
J^π=3/2$^-$

S_{11}(1535)
J^π=1/2$^-$

Independent model (3q)
Also diquark model (2q+q)

II - excitation spectrum from Lattice QCD

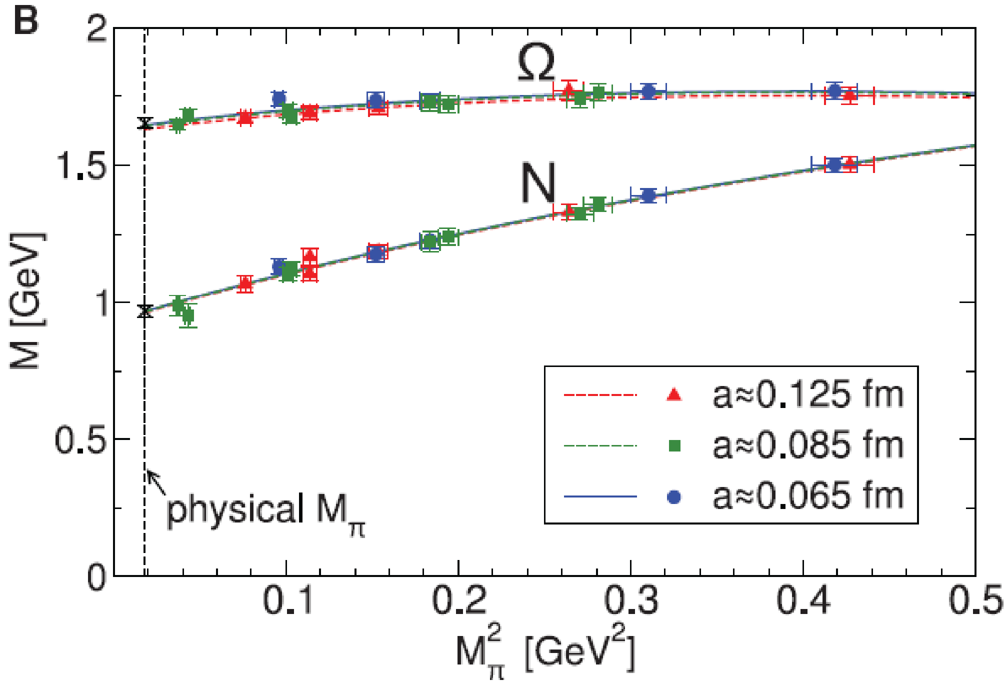
- Formulation of QCD on discrete rather than continuous space-time
  → q's and gluons reside on lattice points
  → Travel along lines between lattice points

- Approaches continuum QCD as lattice space reduced – but limited by CPU power

- Computation cost also increases rapidly for ight quark masses

- Mass of proton determined to within 2% - approaching realistic quark masses!

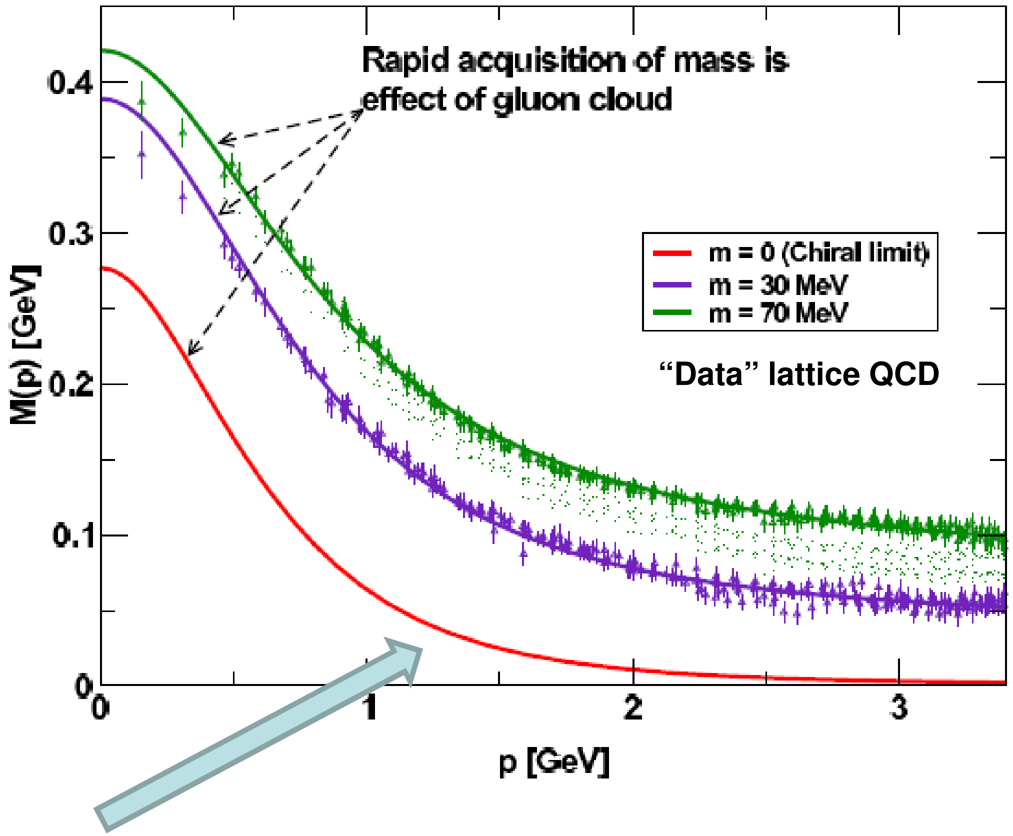
S. Durr, Science 322:1224 (2009)



- First work on excitation spectrum coming from lattice in past few years!!

III- Dyson Schwinger approach

- Links the constituent quark approach more directly to QCD
- Accounts for mass magnification of current quark masses - dynamical chiral symmetry breaking
- Allows calculation of "dressed quark" mass function – agree with lattice results ✔
- Mass of quark depends on its momentum – pivotal to the properties of hadrons
- Faddeev approach to calculate baryon properties from dressed quarks – excitation spectrum in progress



DχSB really can create mass from nothing!!

e.g. C. Roberts, Argonne

IV - Hadronic spectrum of a holographic dual of QCD

- Approach based upon the higher dimensionality of string theories
- Hadron masses extracted as solutions of wave equation with boundary conditions in higher dimensional space
- Works with any number of quarks , gluons, any L
- Only one parameter! – QCD scale Λ_{QCD}
- Predicts many states expected from quark model – plus some that are not !

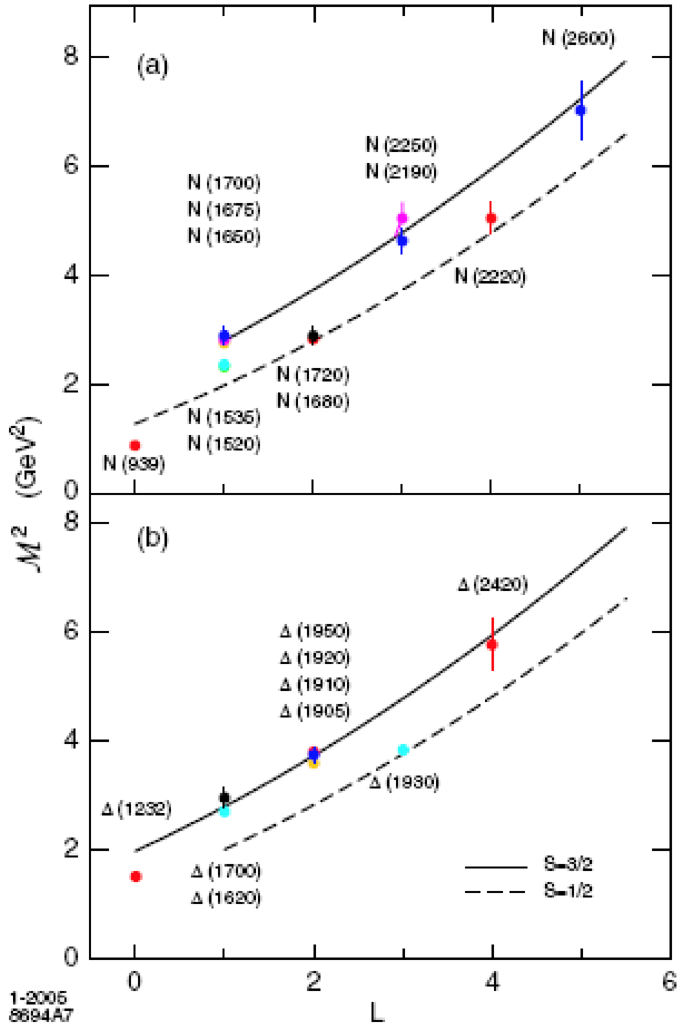
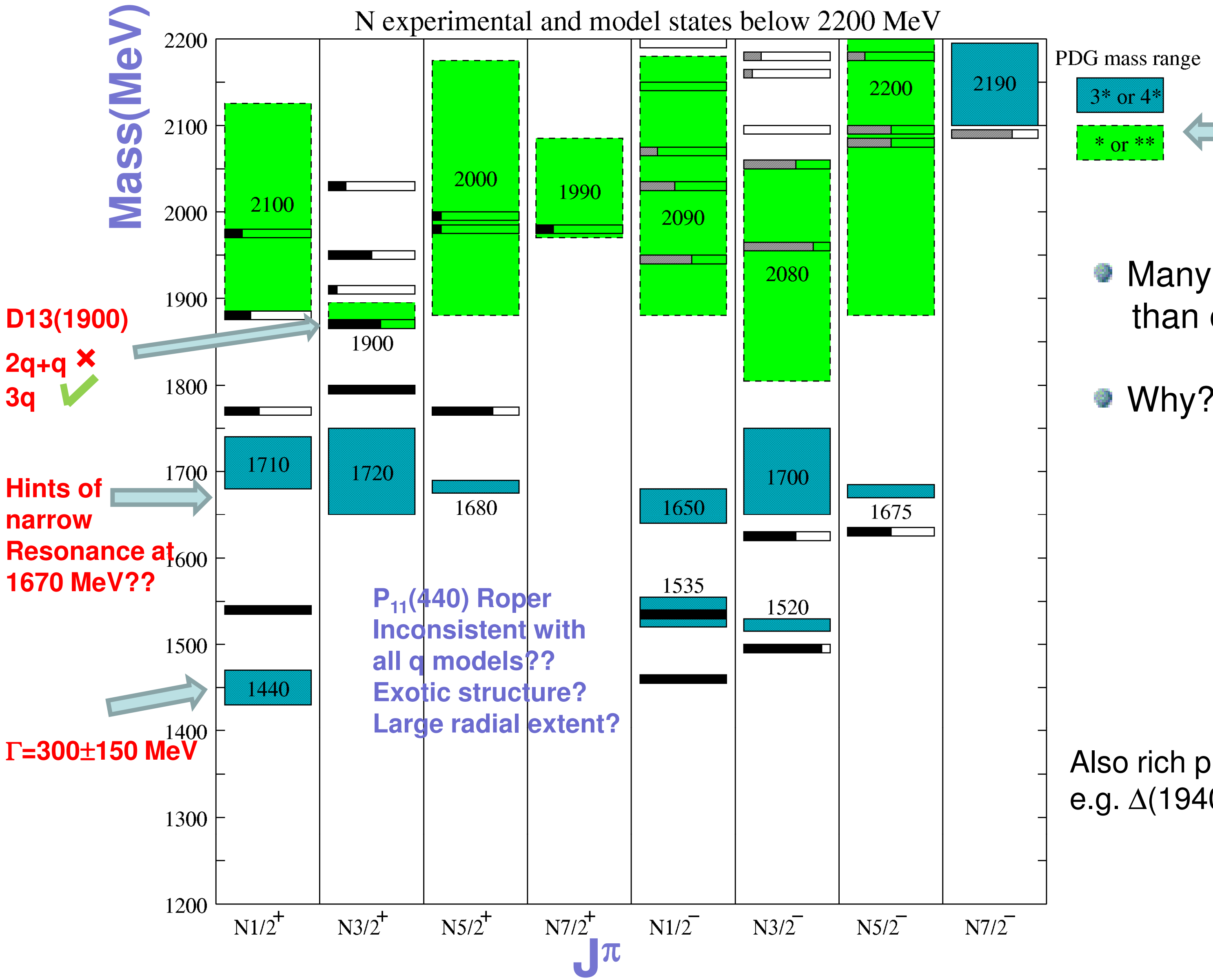


FIG. 2 (color online). Light baryon orbital spectrum fo Λ_{QCD} = 0.22 GeV. Predictions for the nucleons are shown i (a) and for the Δ trajectories in (b). The lower dashed curve correspond to baryon states dual to spin-$\frac{1}{2}$ modes in the bulk an the upper continuous curve to states dual to spin-$\frac{3}{2}$ modes.

Brodsky et. al. PRL **94, 201601 (2005)**

T=1/2 excited states compared to quark model

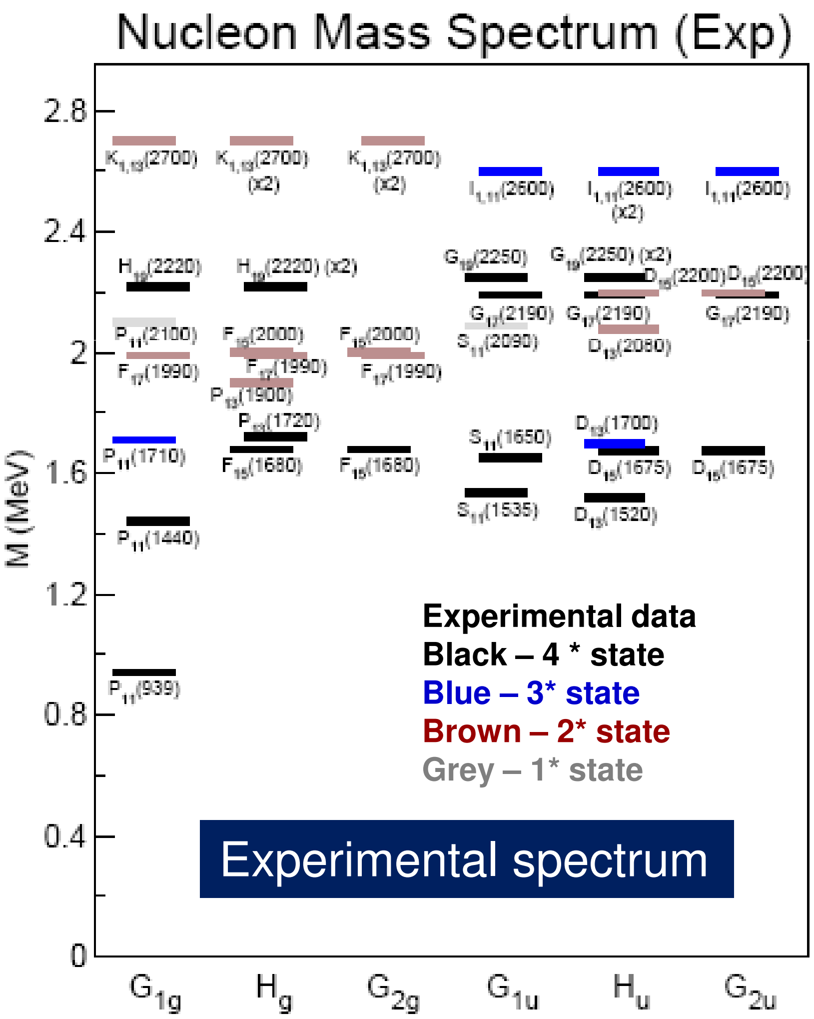


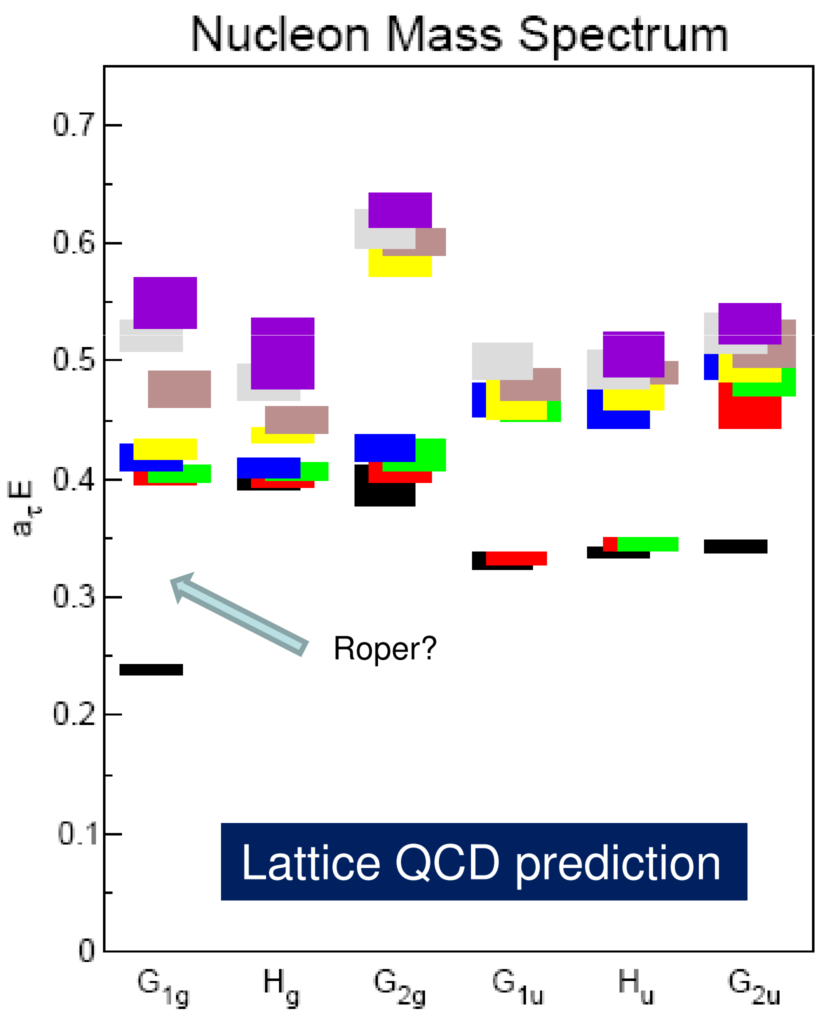
- Many more states predicted than observed ?
- Why? Too many d.o.f, ? insensitive data ?

Also rich pickings for T=3/2 (Δ's)
e.g. Δ(1940) 1* resonance!!
Holographic dual ✓
Quark model ✗

Excitation spectrum from Lattice QCD

- Recent calculations : m_π=700 MeV (C. Morningstar et. al. Carnegie Mellon)
- First "ab-initio" calculations of excitation spectrum from QCD!!





Polarisation observables in meson photoproduction

- *16 experimental observables* - Can ***fully*** constrain reaction amplitudes with 8 measurements

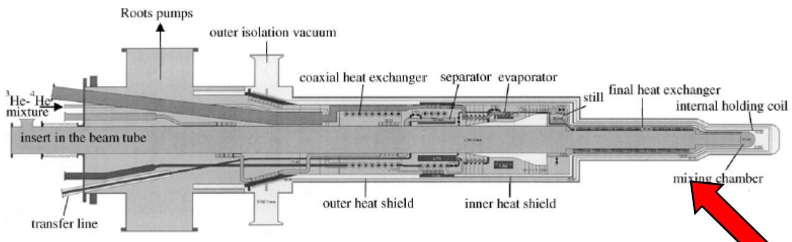
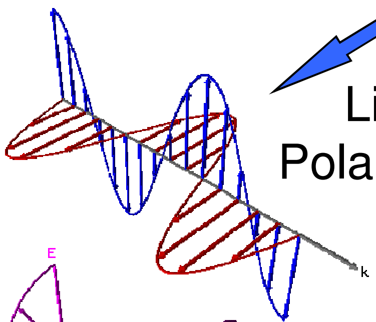


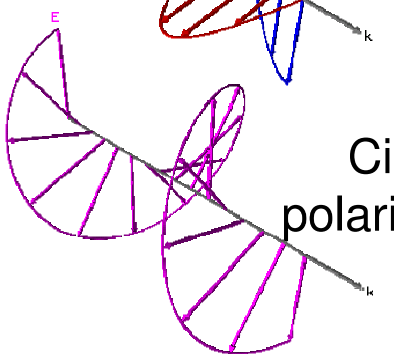
Fig. 4. Schematic diagram of the dilution refrigerator.

Longitudinally polarised proton target ✓
Transversely polarised ✓

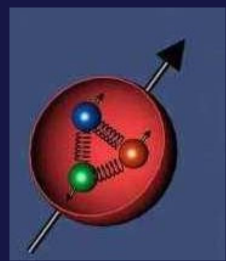
$$\gamma + N \longrightarrow N^* \longrightarrow N + meson$$



Linear Polarisation ✓



Circular polarisation ✓

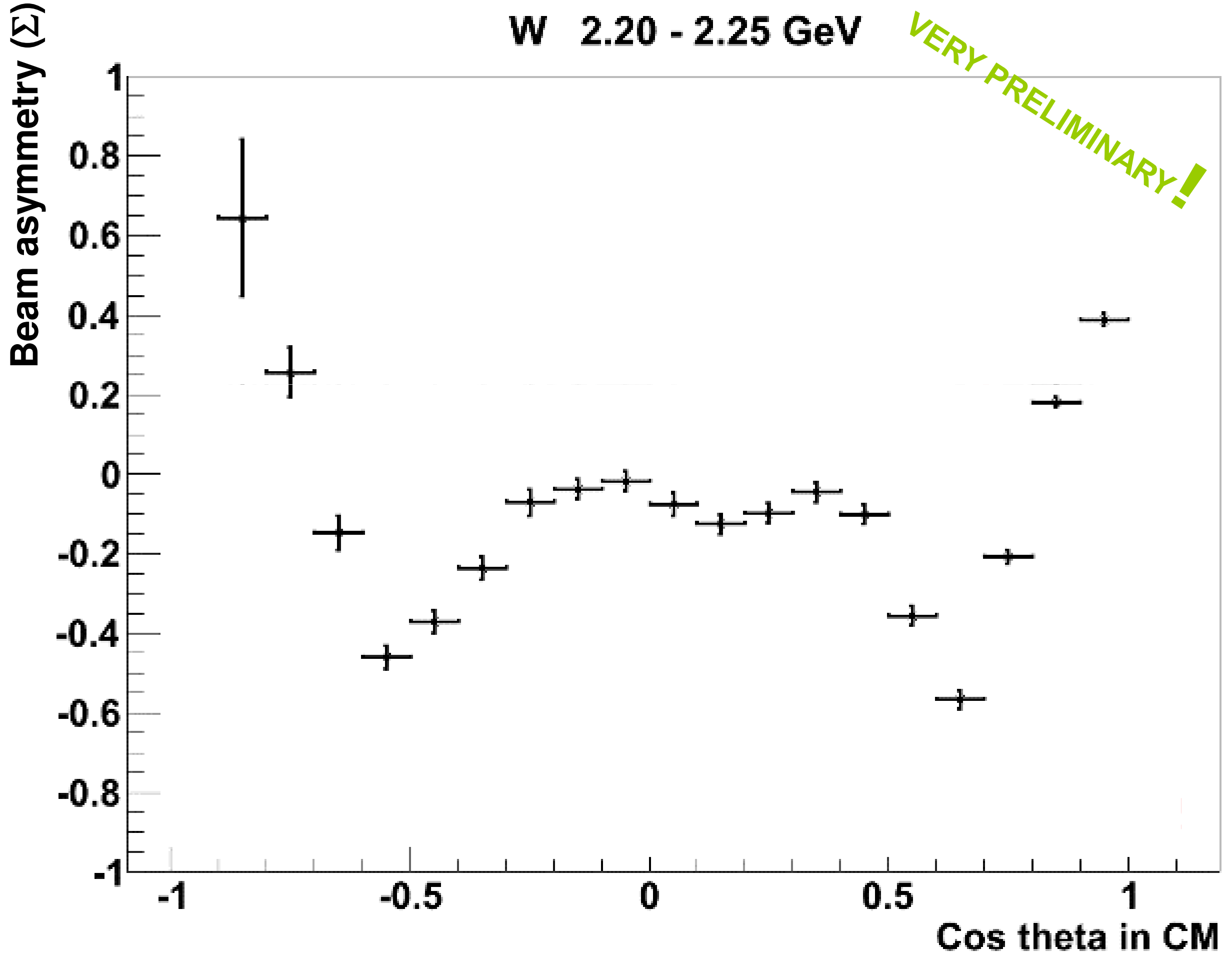


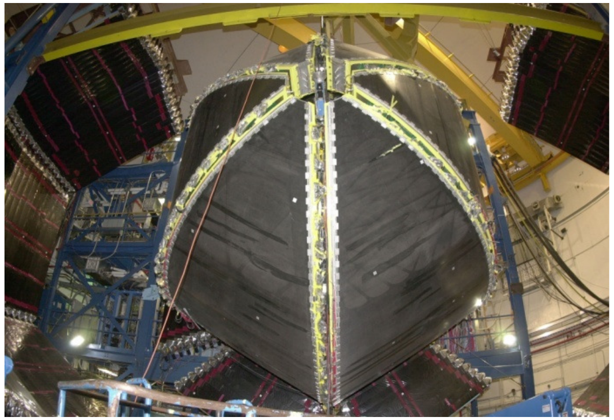
Cannot fully constrain the reaction amplitudes without recoil polarimeter - provides 4 additional observables & enables the first complete measurement

The way forward – First “Complete measurement”

	Observable	Polarisation of: γ	target	recoil	
1.	$\{d\sigma/d\Omega\}/\mathcal{N}$				$= \lvert b_1\rvert^2 + \lvert b_2\rvert^2 + \lvert b_3\rvert^2 + \lvert b_4\rvert^2$
	Single polarization				
2.	P			↑	$= \lvert b_1\rvert^2 - \lvert b_2\rvert^2 + \lvert b_3\rvert^2 - \lvert b_4\rvert^2$
3.	Σ	→			$= \lvert b_1\rvert^2 + \lvert b_2\rvert^2 - \lvert b_3\rvert^2 - \lvert b_4\rvert^2$
4.	T		→		$= \lvert b_1\rvert^2 - \lvert b_2\rvert^2 - \lvert b_3\rvert^2 + \lvert b_4\rvert^2$
	Double polarizaton				
	Beam-target				
5.	E	●	●		$= 2\,\mathrm{Re}(b_1 b_3^* + b_2 b_4^*)$
6.	F	●	→		$= 2\,\mathrm{Im}(b_1 b_3^* - b_2 b_4^*)$
7.	G	→	●		$= 2\,\mathrm{Im}(b_1 b_3^* + b_2 b_4^*)$
8.	H	→	→		$= -2\,\mathrm{Re}(b_1 b_3^* + b_2 b_4^*)$
	Beam-recoil				
9.	C_x	●		→	$= -2\,\mathrm{Im}(b_1 b_4^* - b_2 b_3^*)$
10.	C_y	●		●	$= 2\,\mathrm{Re}(b_1 b_4^* + b_2 b_3^*)$
11.	O_x	→		→	$= 2\,\mathrm{Re}(b_1 b_4^* - b_2 b_3^*)$
12.	O_z	→		●	$= 2\,\mathrm{Im}(b_1 b_4^* + b_2 b_3^*)$
	Target-recoil				
13.	T_x		→	→	$= 2\,\mathrm{Re}(b_1 b_2^* - b_3 b_4^*)$
14.	T_z		→	●	$= 2\,\mathrm{Im}(b_1 b_2^* - b_3 b_4^*)$
15.	L_x		●	→	$= -2\,\mathrm{Im}(b_1 b_2^* + b_3 b_4^*)$
16.	L_z		●	●	$= 2\,\mathrm{Re}(b_1 b_2^* + b_3 b_4^*)$

CLAS@JLab – Beam asymmetry (Σ) in n(γ,π⁻)p





CLAS spectrometer at JLAB

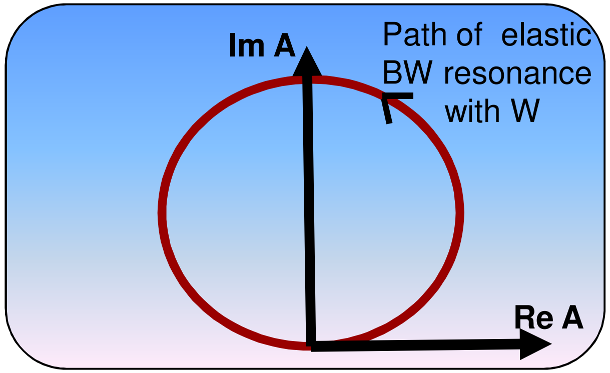
~**30 %** of available data set

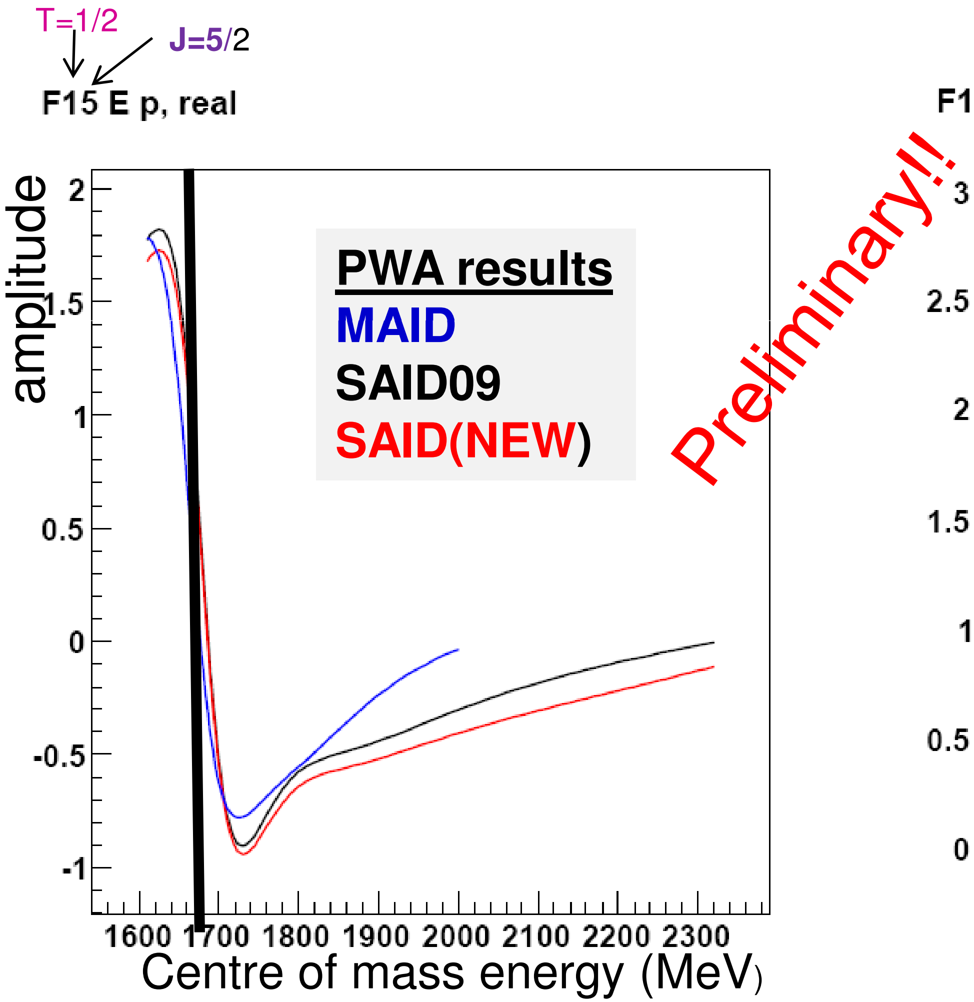
Existing data:

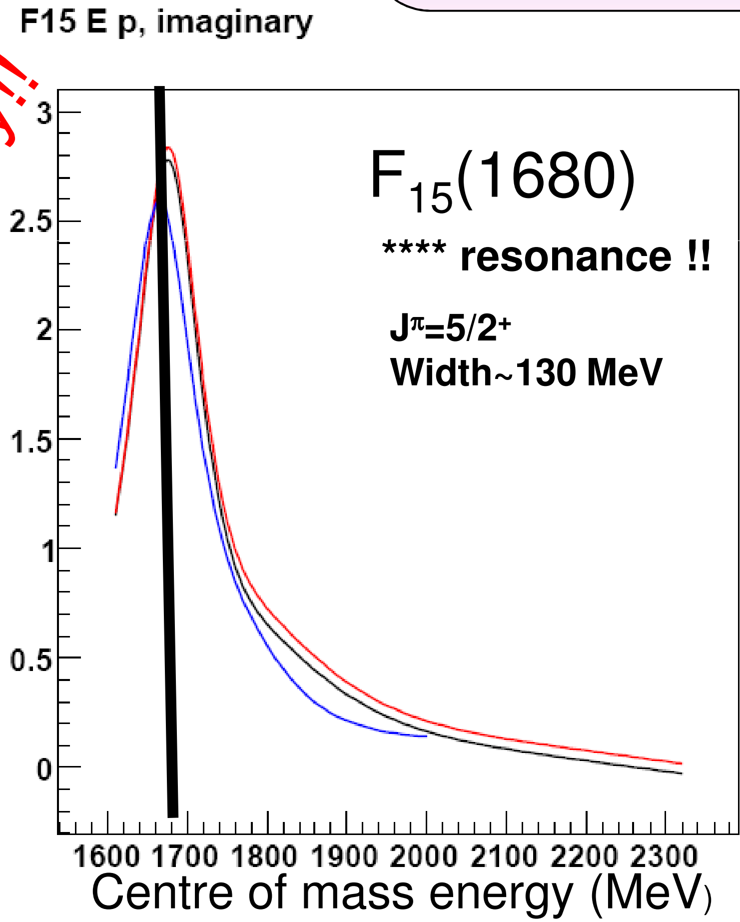
- Alspector, PRL **28**, 1403 (1972).
- Abrahamian,SJNP 32, 69 (1980).
- Adamyan, JPG **15,** 1797 (1989).

Effect of new Σ data on PWA amplitudes

- Partial wave amplitudes contain information on resonances with given J^{π}
- Some resonances stick out like a sore thumb!!

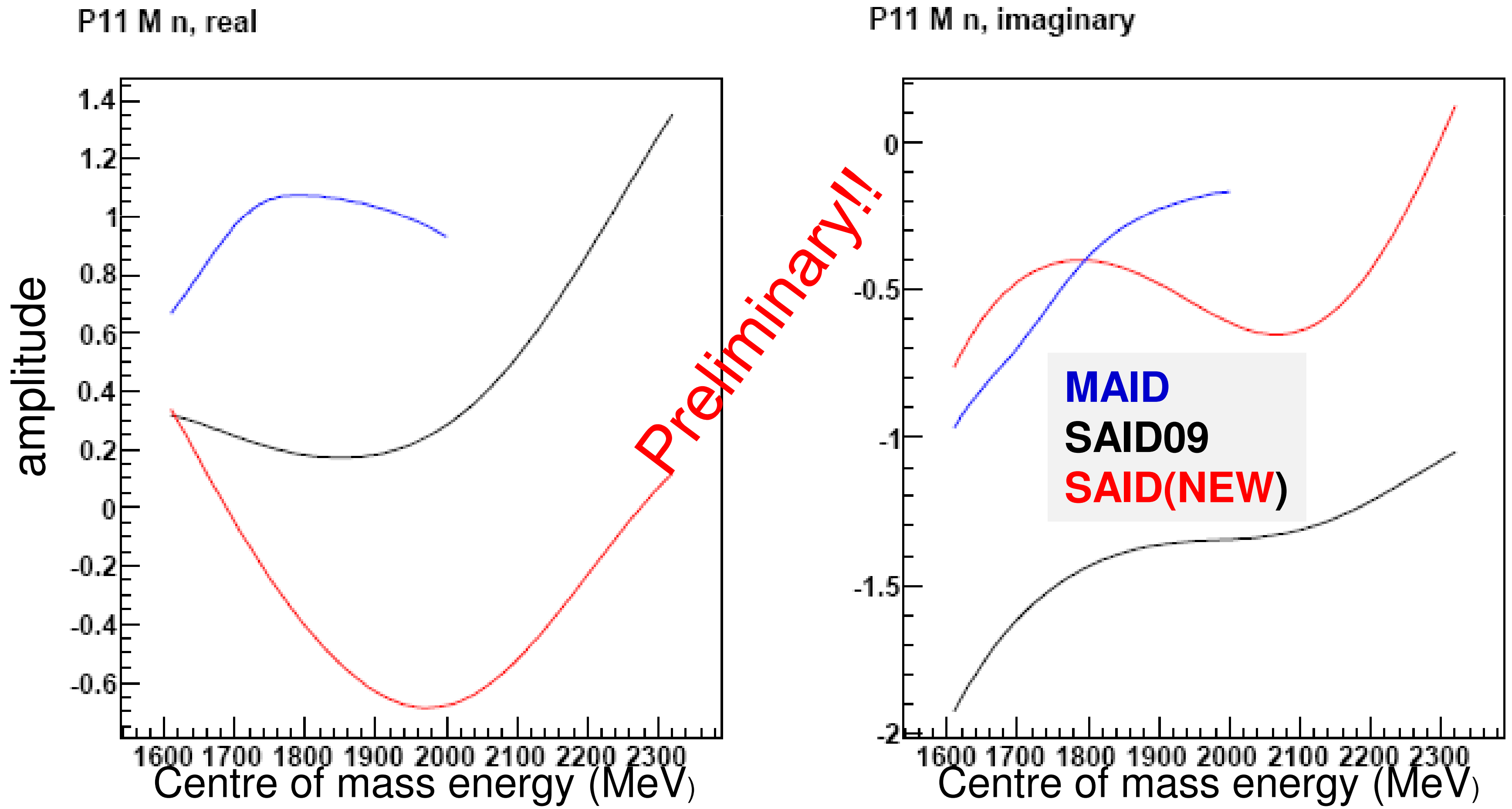




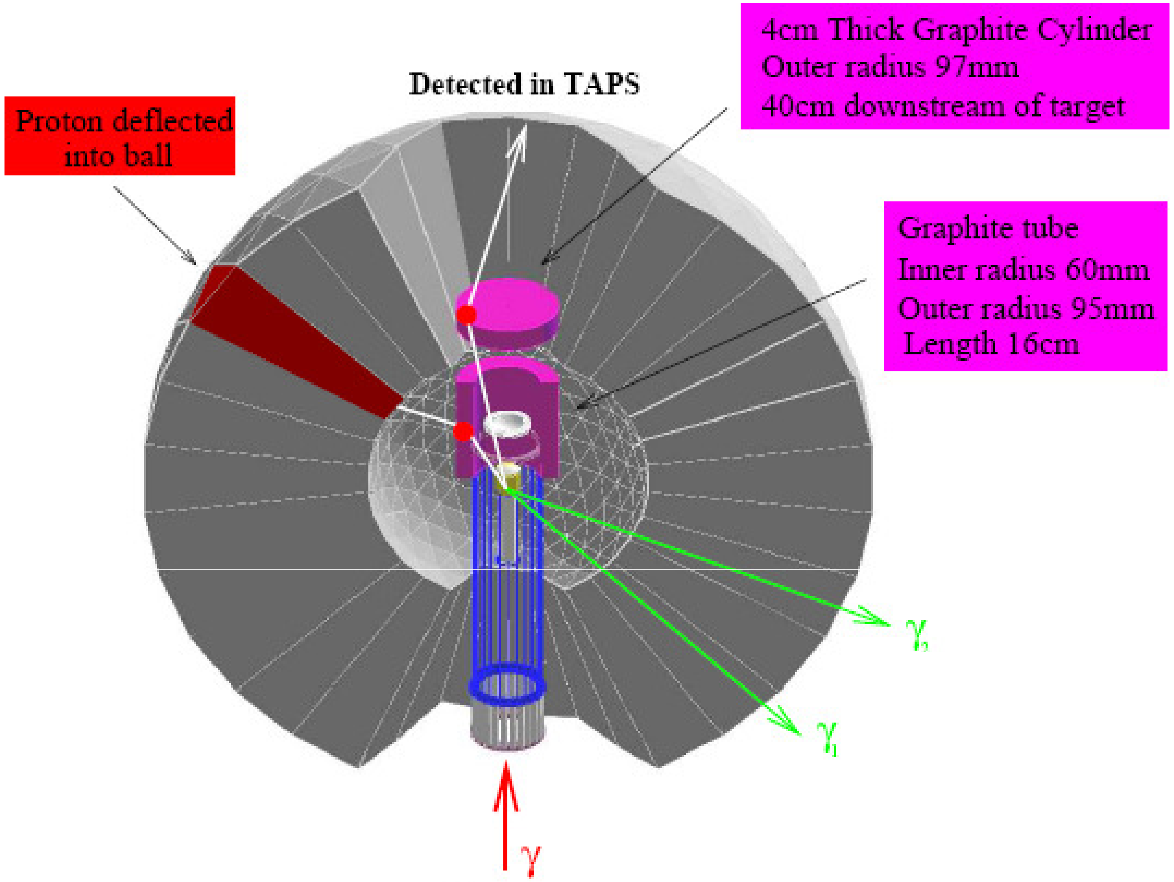


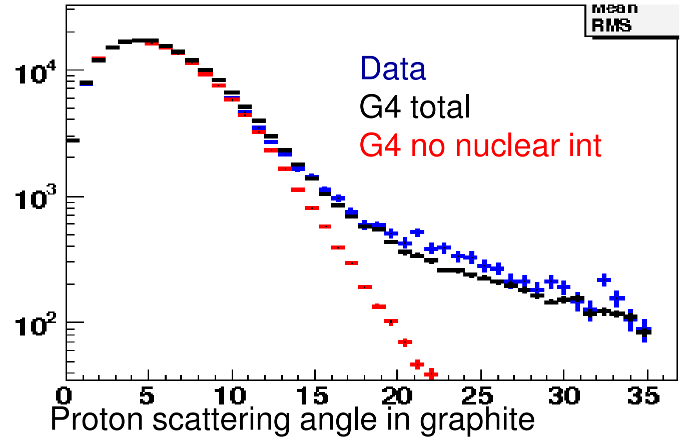
Effect of new Σ data on PWA amplitudes

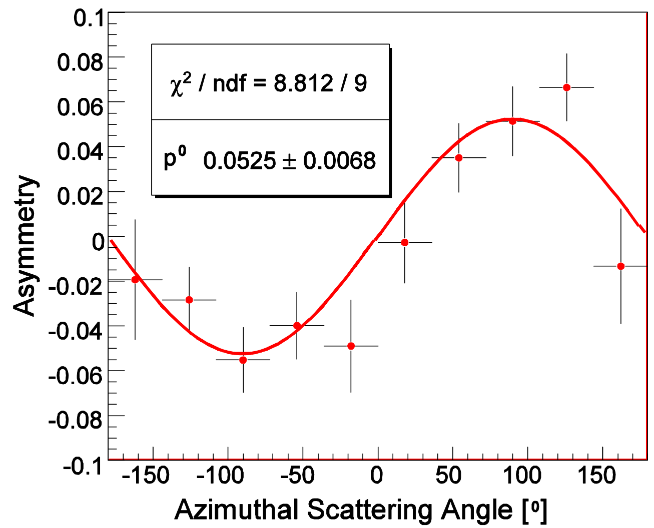
- Situation in other partial waves can be more subtle - require more detailed analysis
- But – new data clearly change the partial waves – as we get closer to complete measurement → convergence !!



Recoil polarimeter at MAMI – First phase (proton target)







$$n(\theta,\phi) = n_o(\theta)\{1 + A(\theta)[P_y \cos(\phi) - P_x \sin(\phi)]$$

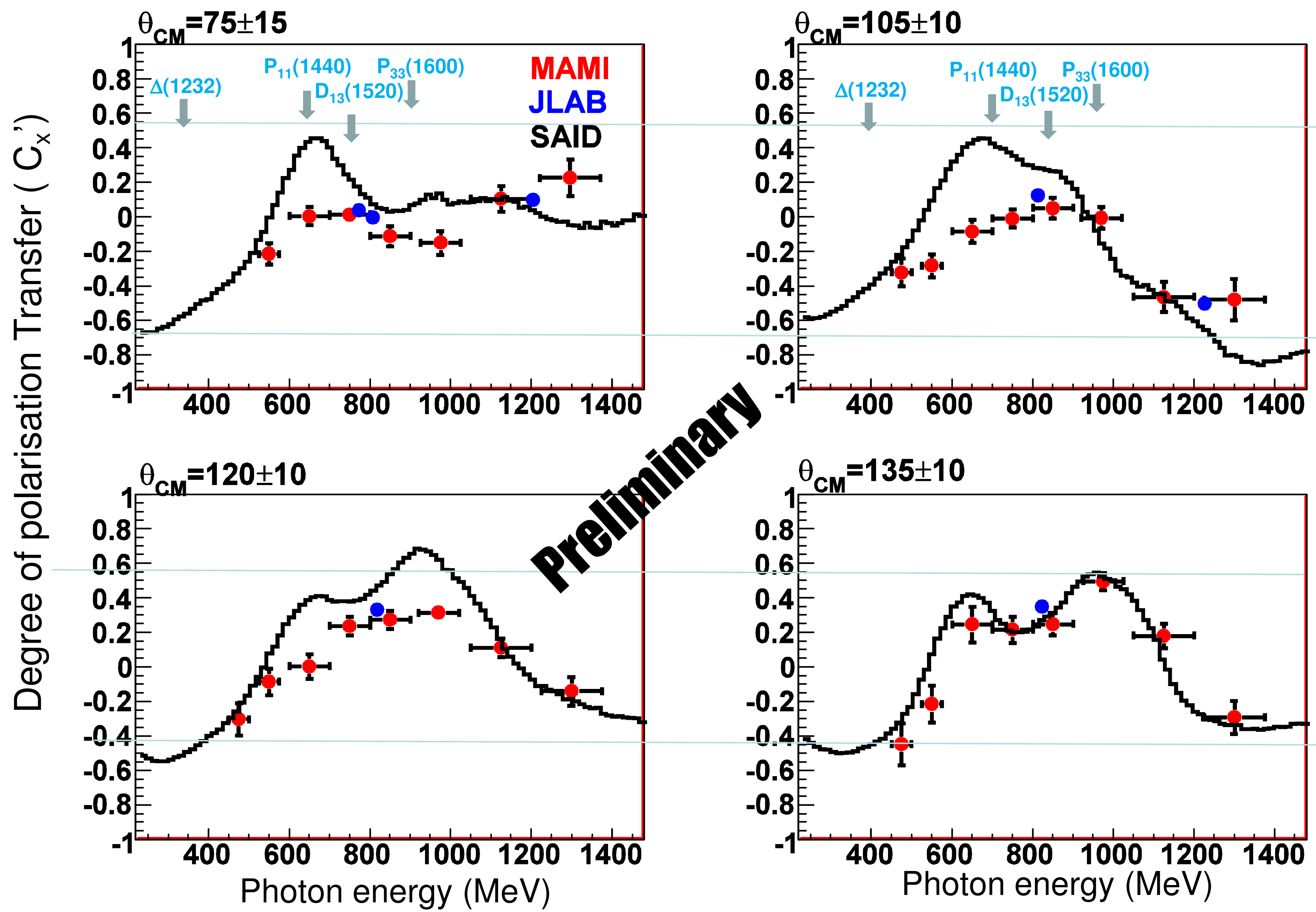
No. nucleons scattered In the direction θ, ϕ

Unpolarised polar angle distributiion

Analysing power of scatterer

x and y (transverse) components of nucleon polarisation

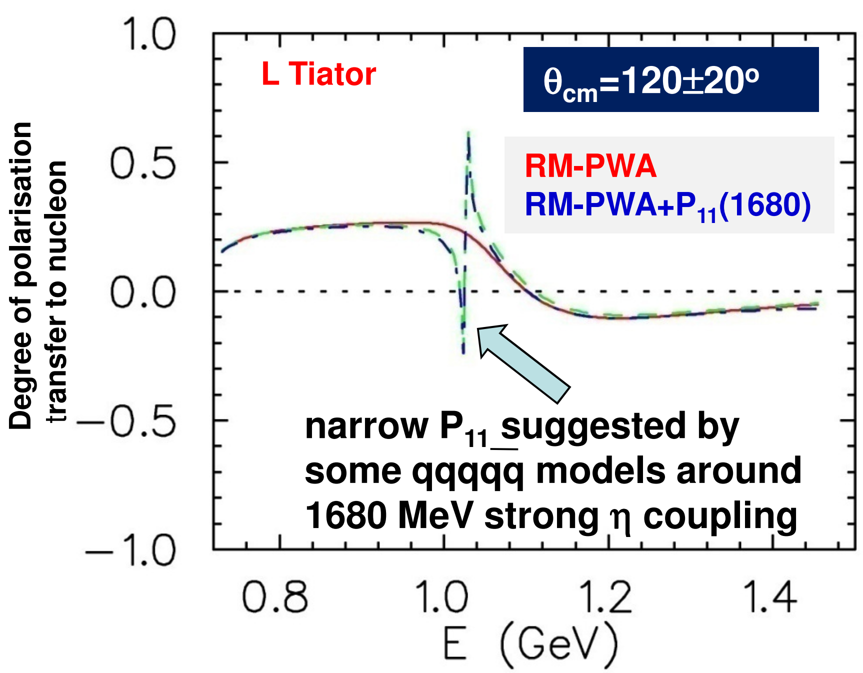
$p(\gamma,\pi^0)p$ polarisation transfer: Circ. polarised beam to recoil proton



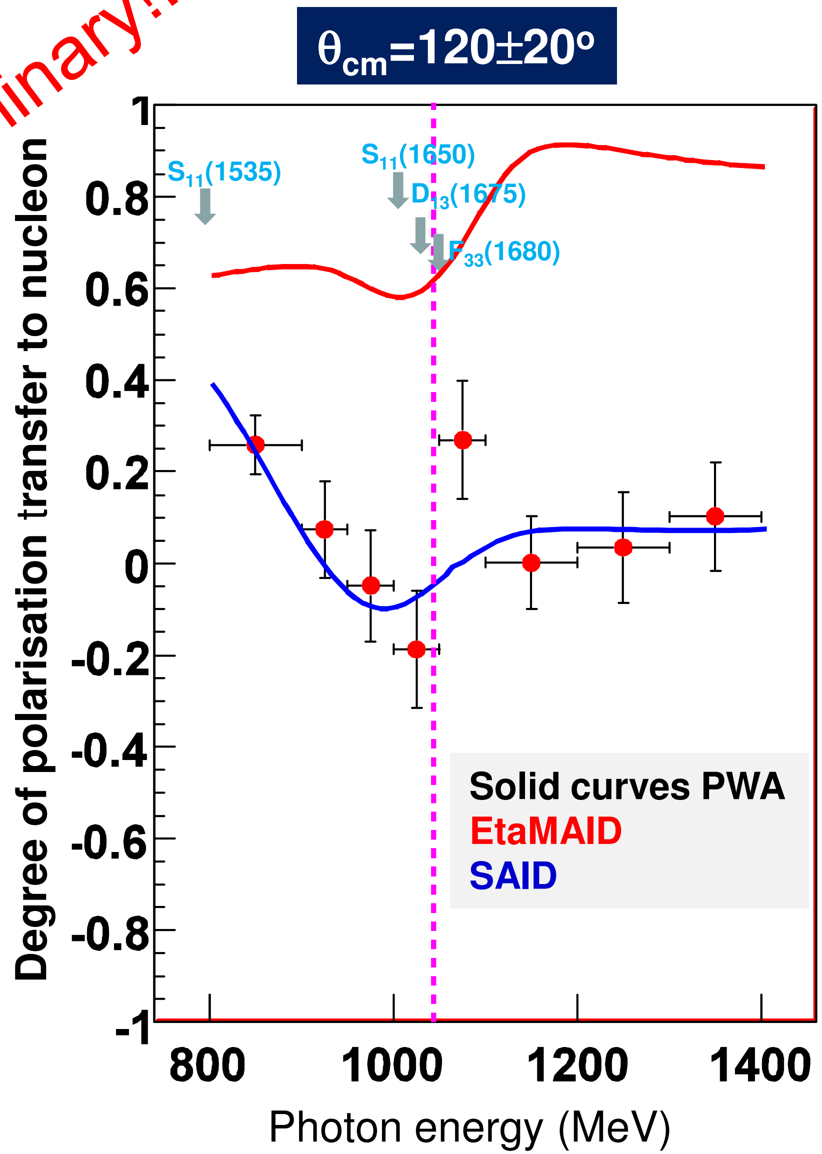
- Also P,T,O_x. Final states: η (N^* only!!), 2π, ηπ (selective in contr. Res.):

Polarisation transfer in η photoproduction

- $\gamma + p \rightarrow N^* \rightarrow p + \eta$
- η meson has isospin zero
  only T=1/2 resonances

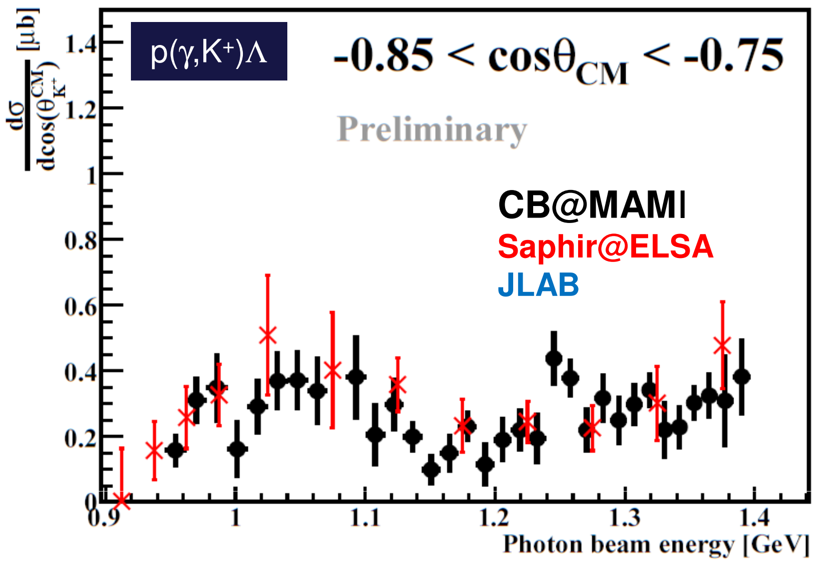


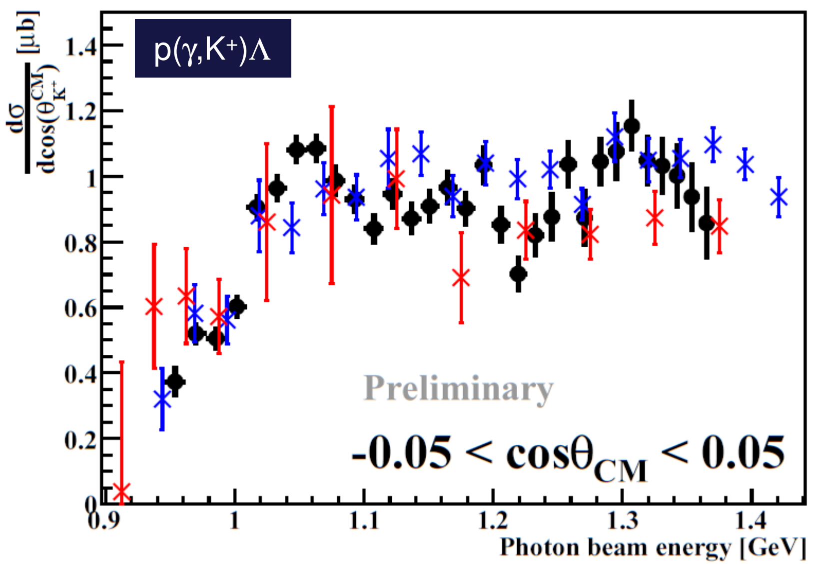
Preliminary!!



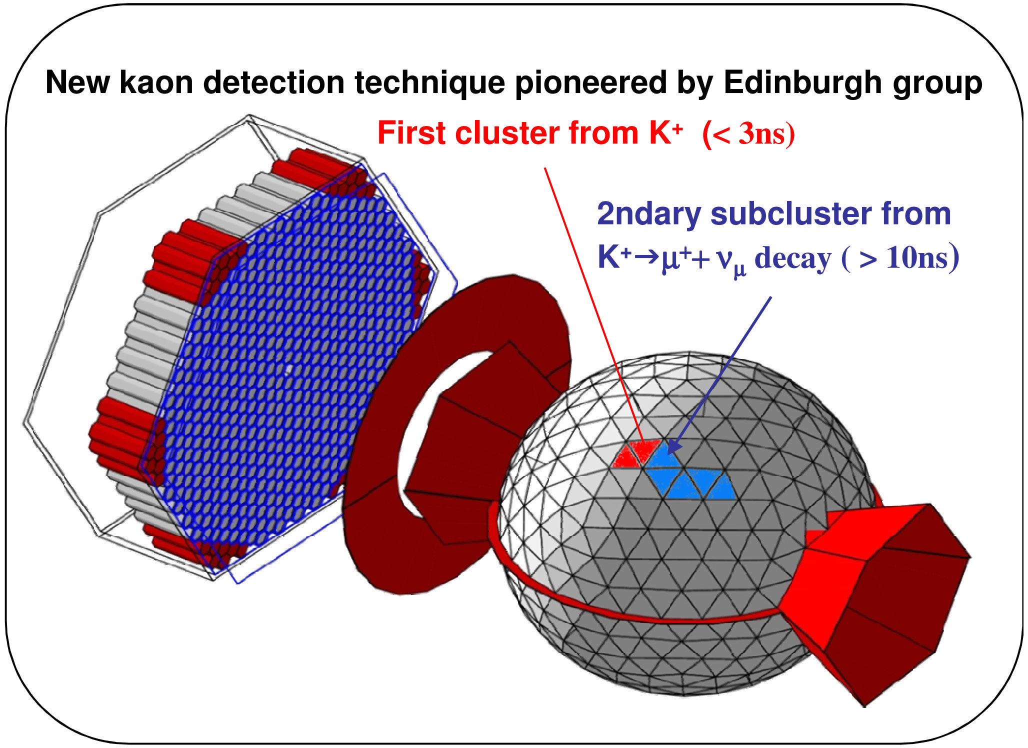
Thesis work of Mark Sikora

Strange meson photoproduction - $p(\gamma,K^+)\Lambda$





< ½ of available data!



Forward look

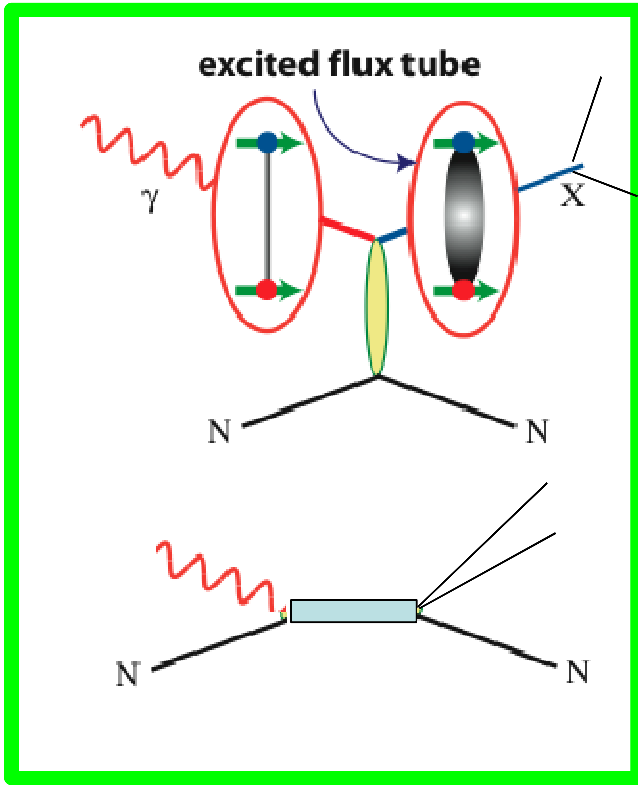
- JLAB upgrade to 12 GeV – challenge our understanding of confinement between light quarks
  → underpins hadron and nuclear physics

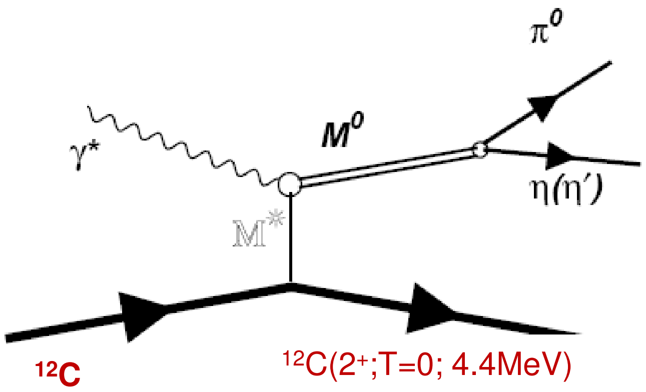
- Excite the flux tube which forms between quarks
  → Hybrid meson with additional d.o.f
  Smoking gun signals in "exotic" partial waves

- Meson spectroscopy complicated by the large background of nucleon resonance decays – complicates the PWA

- Get a clean mesonic decay sample by nuclear decay tagging!

- Also use quantum numbers of residual state to emphasize mechanisms favourable to hybrid production





Also use in nuclear DVCS? Hypernuclei?

Summary

- New experiments using electromagnetic probes will give valuable and timely constraints on the structure of the nucleus, the nucleon and neutron stars