Outlook

Pions: Experimental Tests of Chiral Symmetry Breaking
A.M. Bernstein
Chiral Dynamics : 2012

- Spontaneous Chiral symmetry hiding

$\Rightarrow$Nambu-Goldstone Bosons π, η, K

$\Rightarrow$ ChPT $\Rightarrow$ Low energy theorems

- compare $\pi\,\pi$ and π N scattering   a($\pi\,\pi$), a(π N)

- testing ChPT in photo pion production

- quark mass effects- Isospin breaking

- Open problems

Spontaneous Chiral Symmetry Hiding in QCD

1. mass gap below chiral symmetry breaking scale
   $\Lambda_x \simeq 1$ GeV

2. three families of Nambu-Goldstone Bosons π, η
   K are in the gap

3. $m_\pi^2, m_\eta^2, m_K^2 \propto m_u, m_d, m_s$
   explicit chiral symmetry breaking

4. $m_\pi \simeq 140$ MeV, the lightest hadrons

5. **pion properties, interactions the most accurately calculated in ChPT and lattice the best tests of confinement scale QCD**

$\tau(\pi^0)$ and QCD

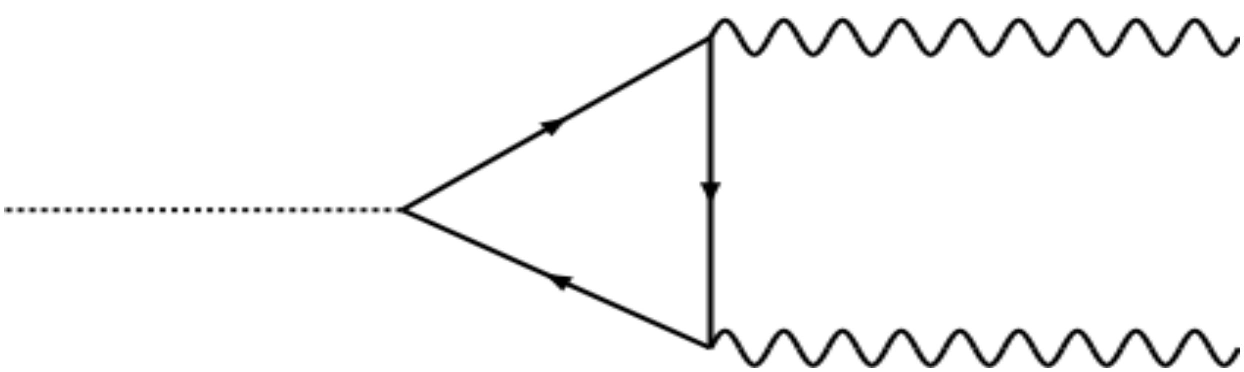
Axial Anomaly   Bell and Jackiw, Adler 1969

Chiral Symmetry exact in Lagrangian

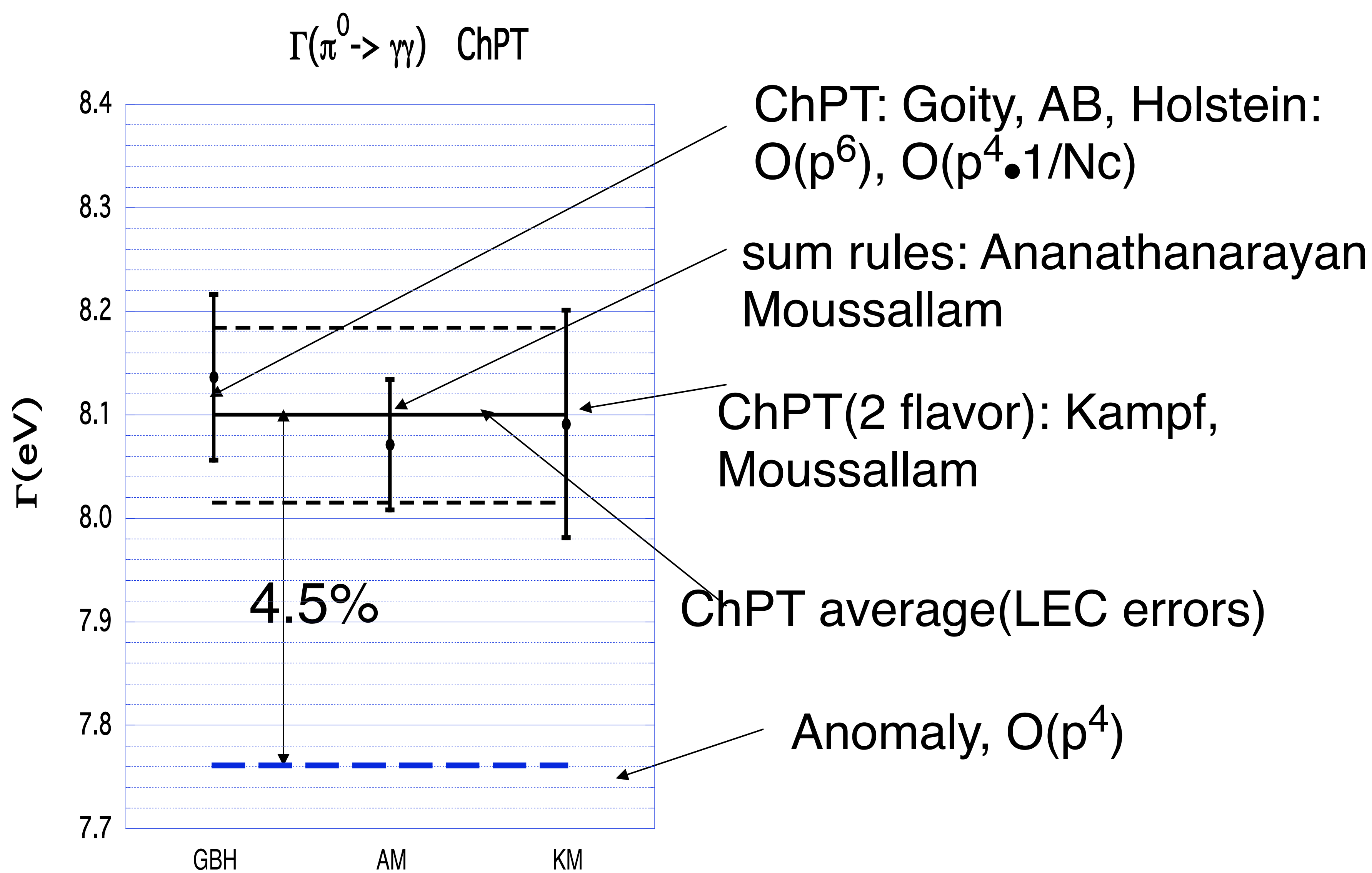
massless up, down quarks

lost in quantization

- $\Gamma(\pi^0 \to \gamma\,\gamma) = (m_\pi/4\pi)^3\,(\alpha\,/F_\pi)^2 = 7.76$ eV
- exact in the chiral limit m_u, m_d, $m_\pi \to 0$
- no adjustable constants
- chiral corrections ~ $(m_\pi\,/\,4\pi\,F_\pi\,)^2$ ~ 2 %

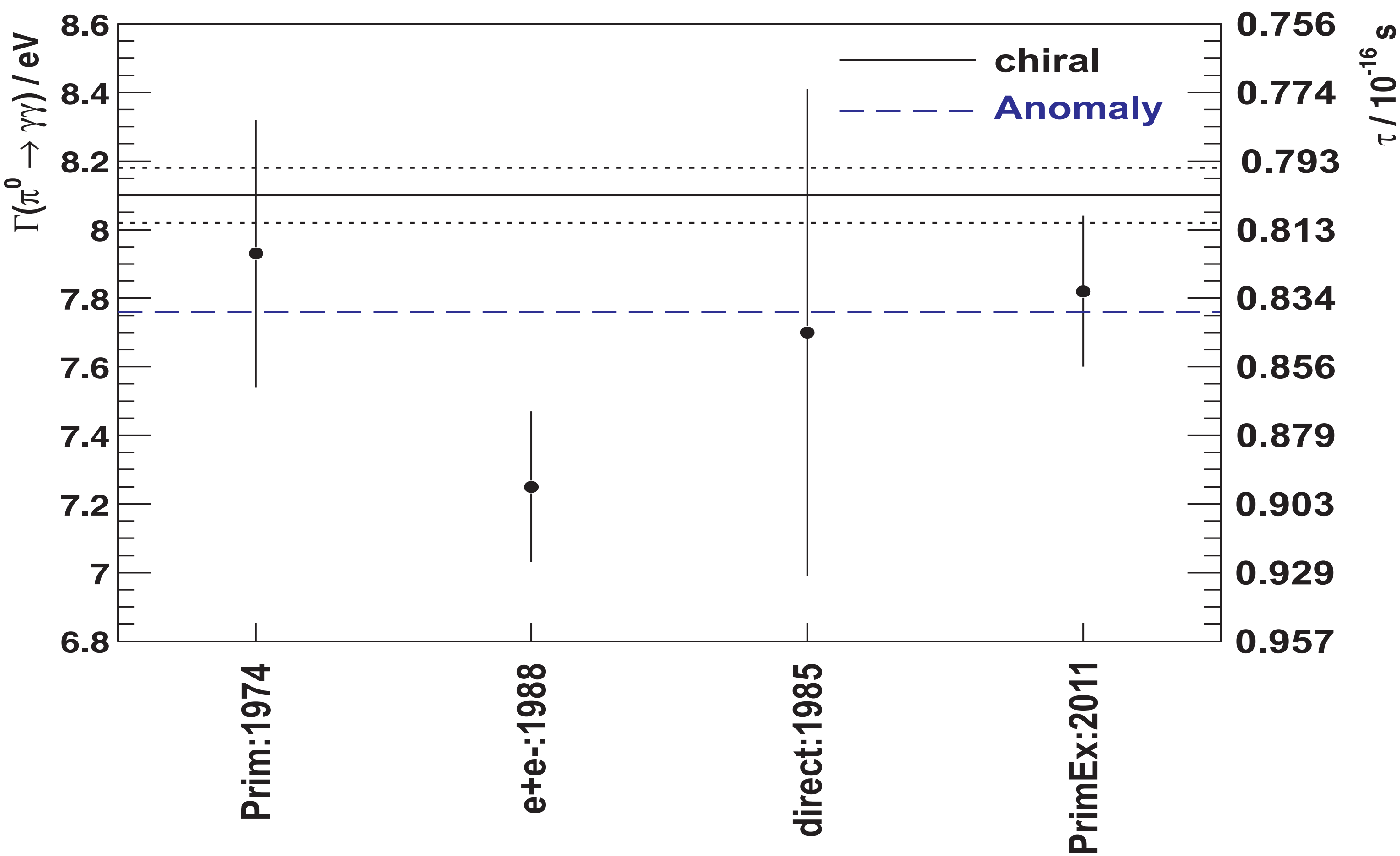


Chiral calculations $\Gamma(\pi^0 \rightarrow \gamma\gamma)$: π,η,η'

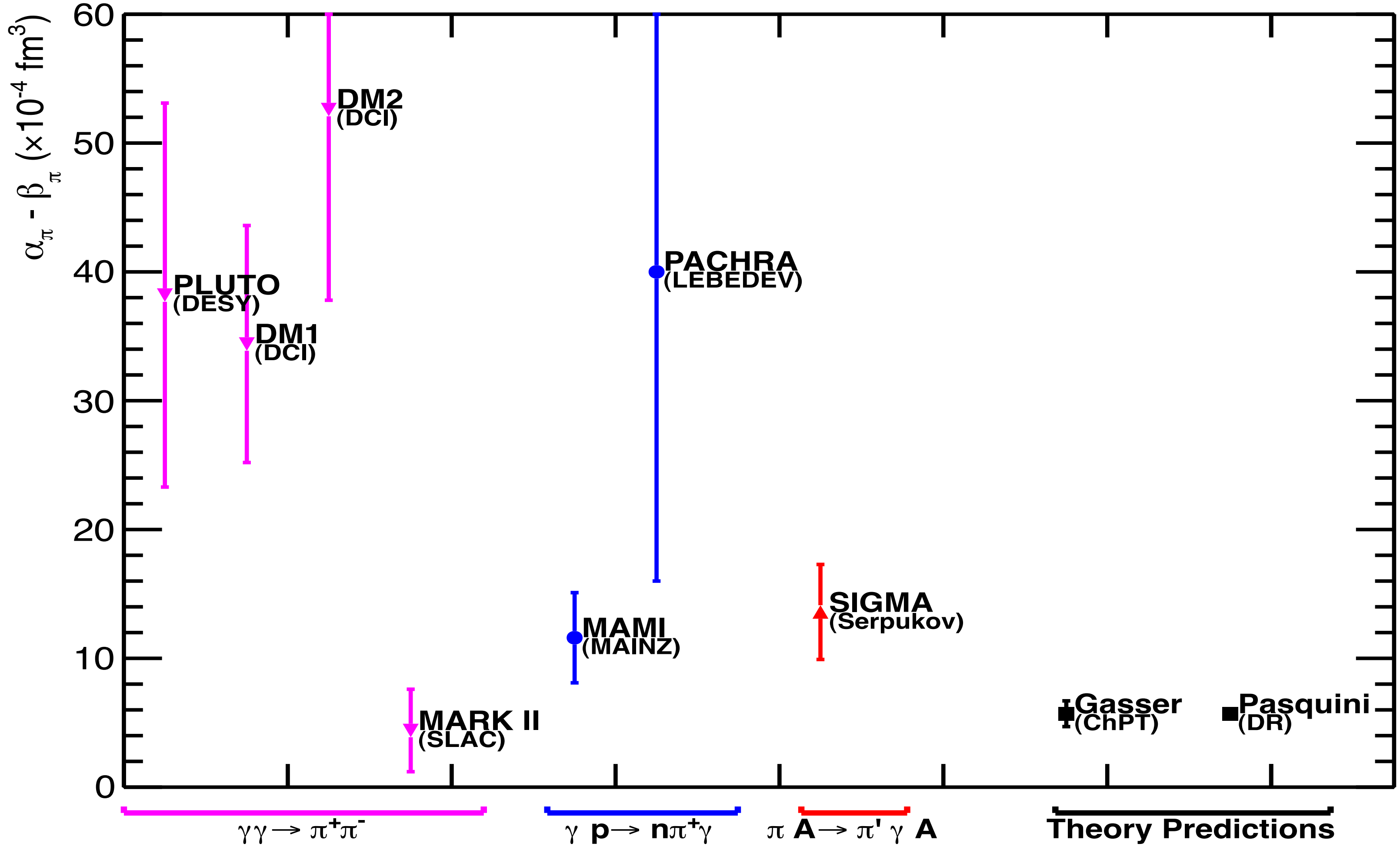


π^0 lifetime

- dominated by axial anomaly
- chiral corrections 4.5%, isospin breaking ~ m_d-m_u accurate to 1%
- commissioned article for the Reviews of Modern Physics with B. Holstein completed
- R.Miskimen Annual Reviews



π polarizability predicted; experiments needed
Compass Jlab LOI: Miskimen, Lawrence



π-Hadron Scattering Lengths

Weinberg PCAC Calculation (1966)

$$a^I_{\pi-h} = -\vec{I_\pi} \cdot \vec{I_h} \; L$$

$$\vec{I} = \vec{I_\pi} + \vec{I_h} \qquad \text{isospin}$$

$$L = \; m_\pi/(8\pi F_\pi^2) \simeq \mathbf{0.1\ fm}$$

$F_\pi \simeq$ **92 MeV** **pion decay constant**

$$a^{I=0}_{\pi-\pi} = (7/4)L$$

$a^I_{\pi-h} \rightarrow$ **0 in chiral limit** $m_\pi \rightarrow$**0**
measures chiral symmetry breaking

this is the first term in the chiral series

Experimental Challenge: $a_{\pi\pi}, a_{\pi N}$

1. final state interaction in $K^{\pm} \longrightarrow \pi^{+}\pi^{-}e^{\pm}\nu$
2. unitary cusp in $K^{\pm} \longrightarrow \pi^{\pm}\pi^{0}\pi^{0}$
3. pionic H and D: 1s state energy, decay width
4. unitary cusp in $\gamma p \longrightarrow \pi^{0}p$

unitary cusps can appear when a new threshold opens up and flux is either diverted or added

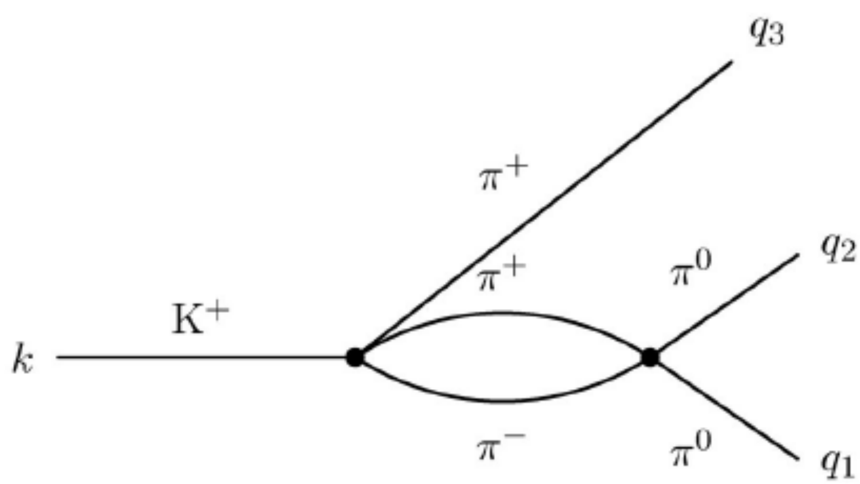
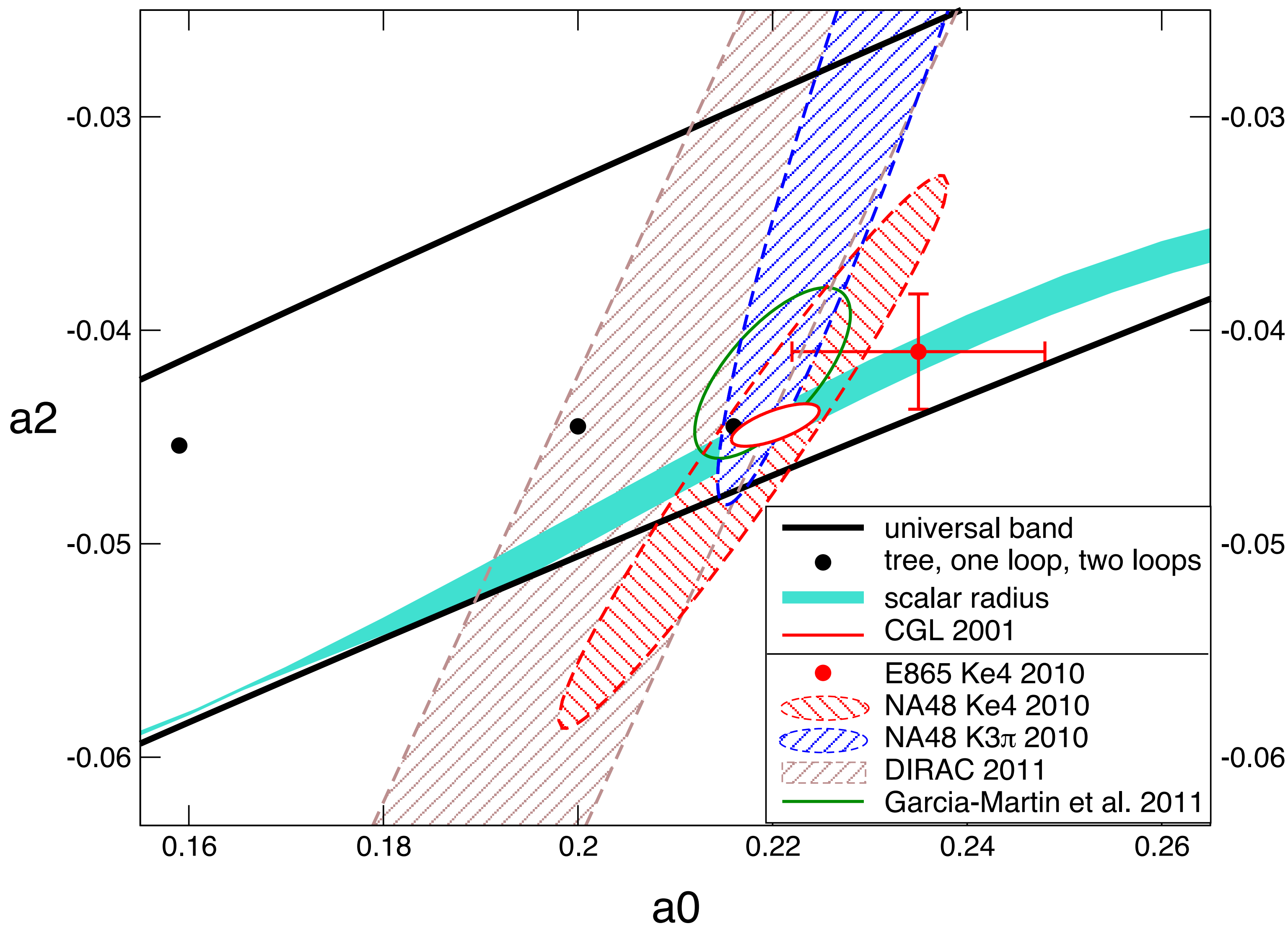


FIG. 1. The $\pi\pi$ rescattering diagram.

π π scattering lengths



ChPT Low Energy Constants

1. chiral symmetry
   $\Rightarrow L_{eff}$ structure
2. magnitudes(LEC)
   $\Rightarrow$ fitting data
3. limits predictive power
4. mask higher order contributions?
5. $a_{\pi\pi}(\bar{l_3}, \bar{l_4})$
6. $m_\pi \Rightarrow \bar{l_3}$
   $F_\pi, < r^2_{S,\pi} > \Rightarrow \bar{l_4}$

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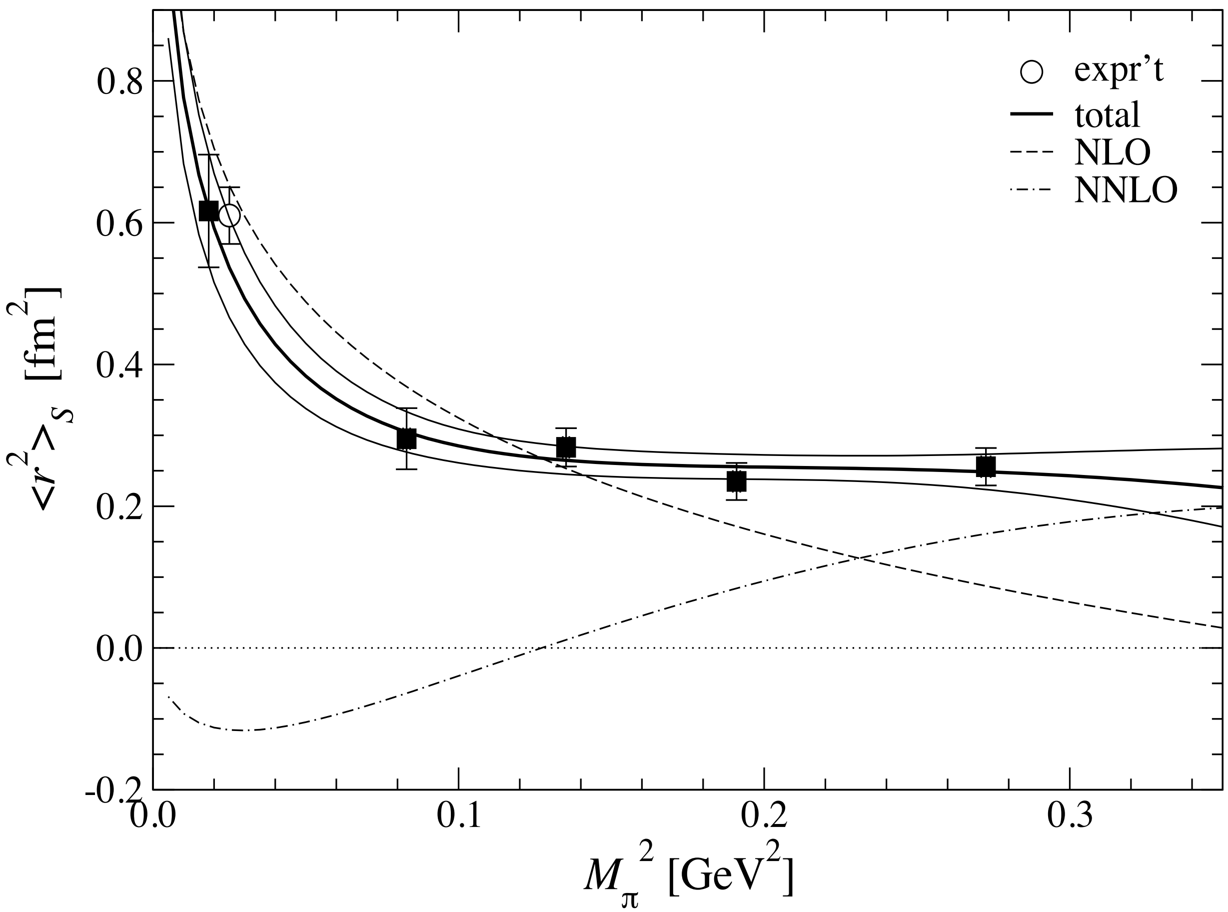
π scalar radius
lattice Aoki PRD (2009)



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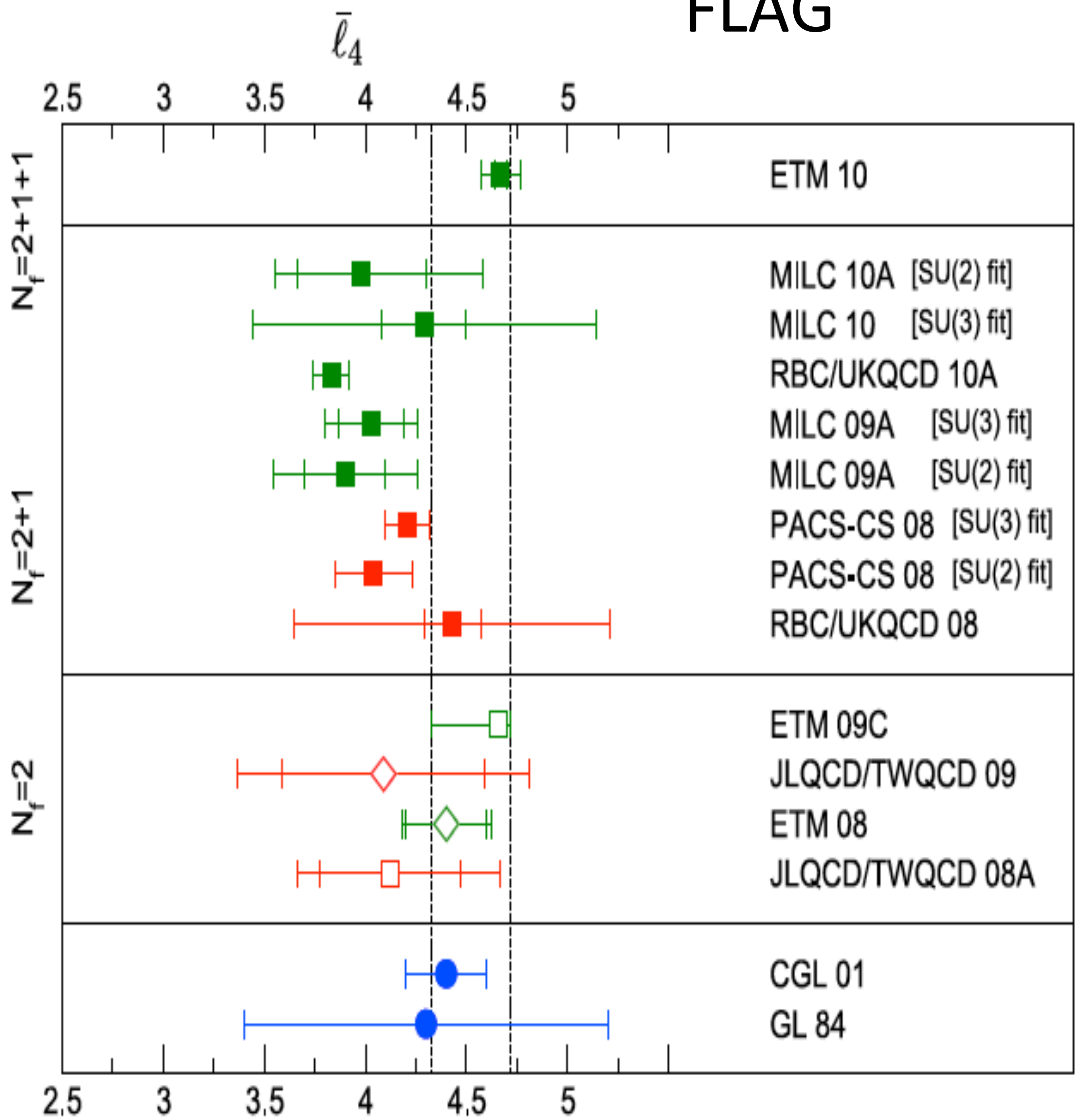
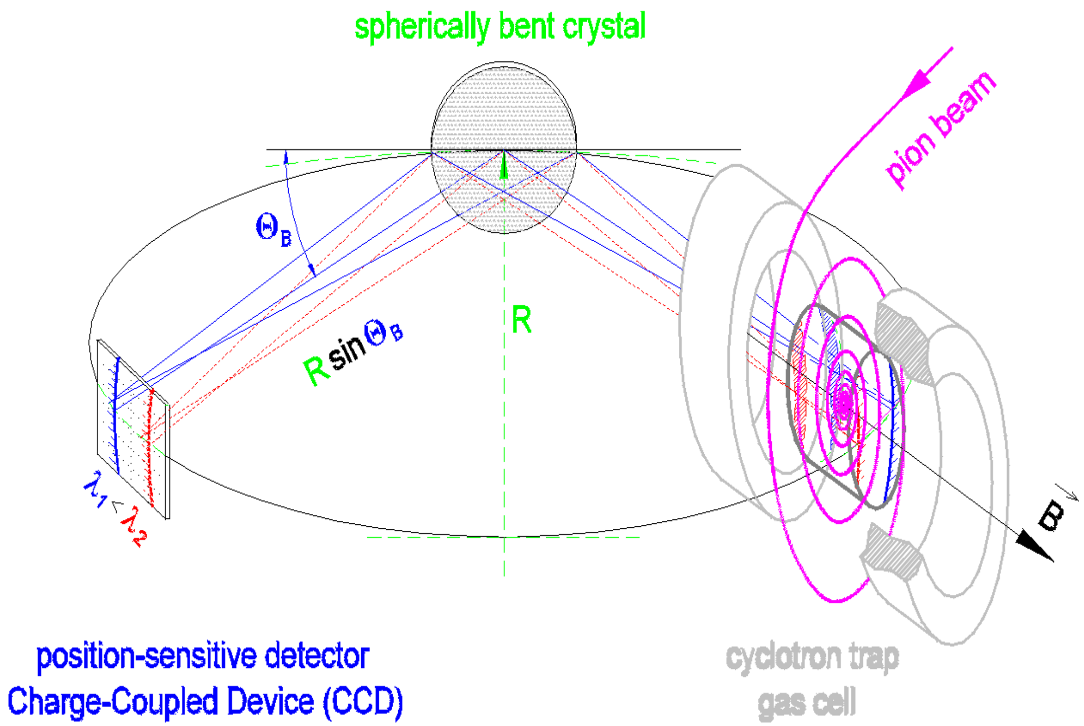
FLAG

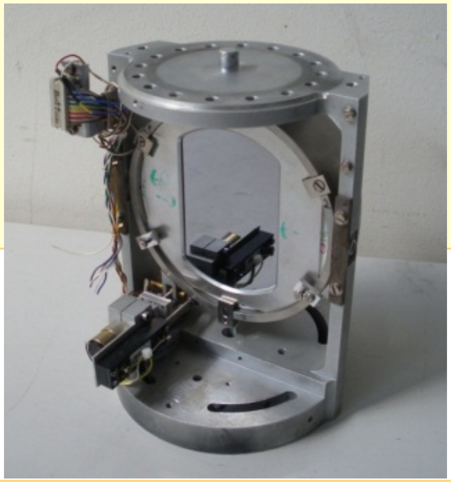


PIONIC HYDROGEN – PSI   D. Gotta, Jülich

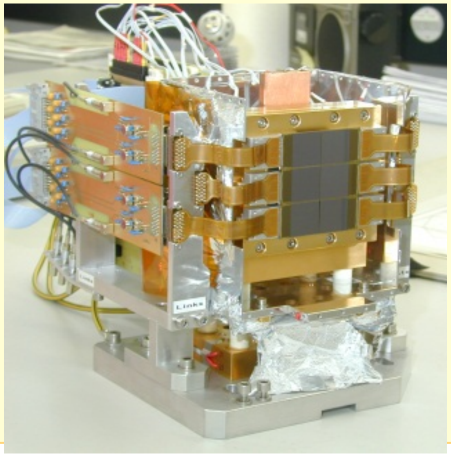
measurements   **πH(n=2,3,4-1), πD(3-1), µH(3-1)**



BRAGG CRYSTAL

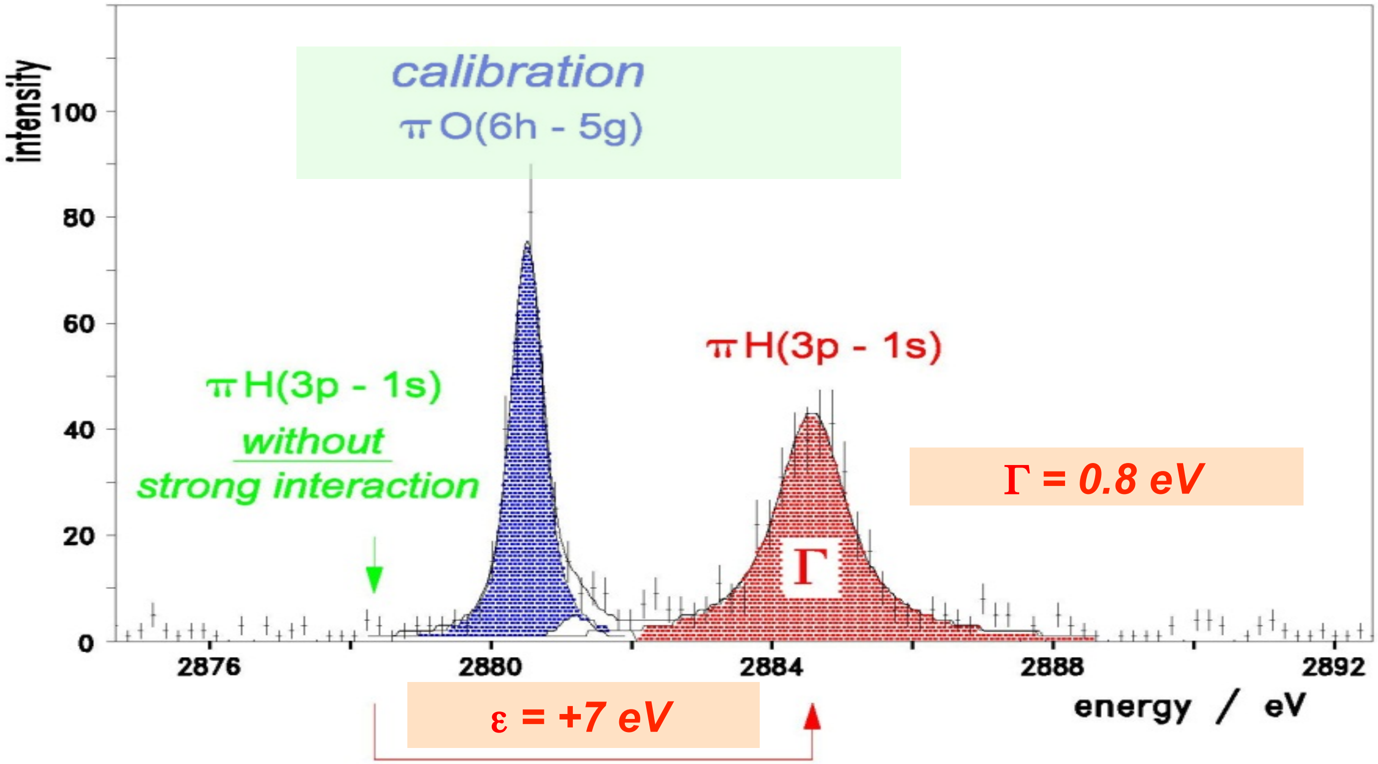


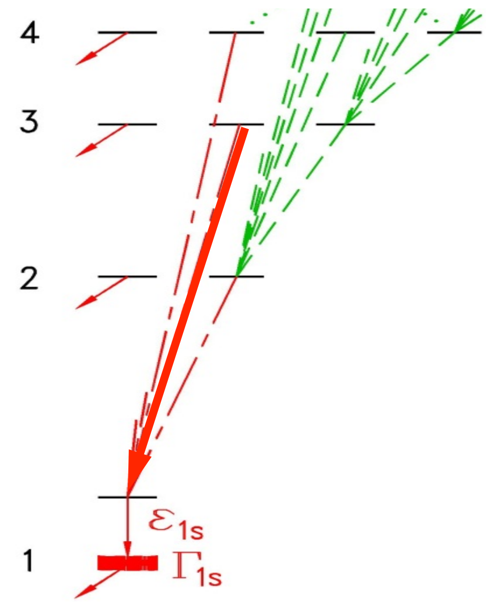
FOCAL PLANE *CCD* DETECTOR



PIONIC HYDROGEN 3p-1s transition

D. Gotta, Jülich

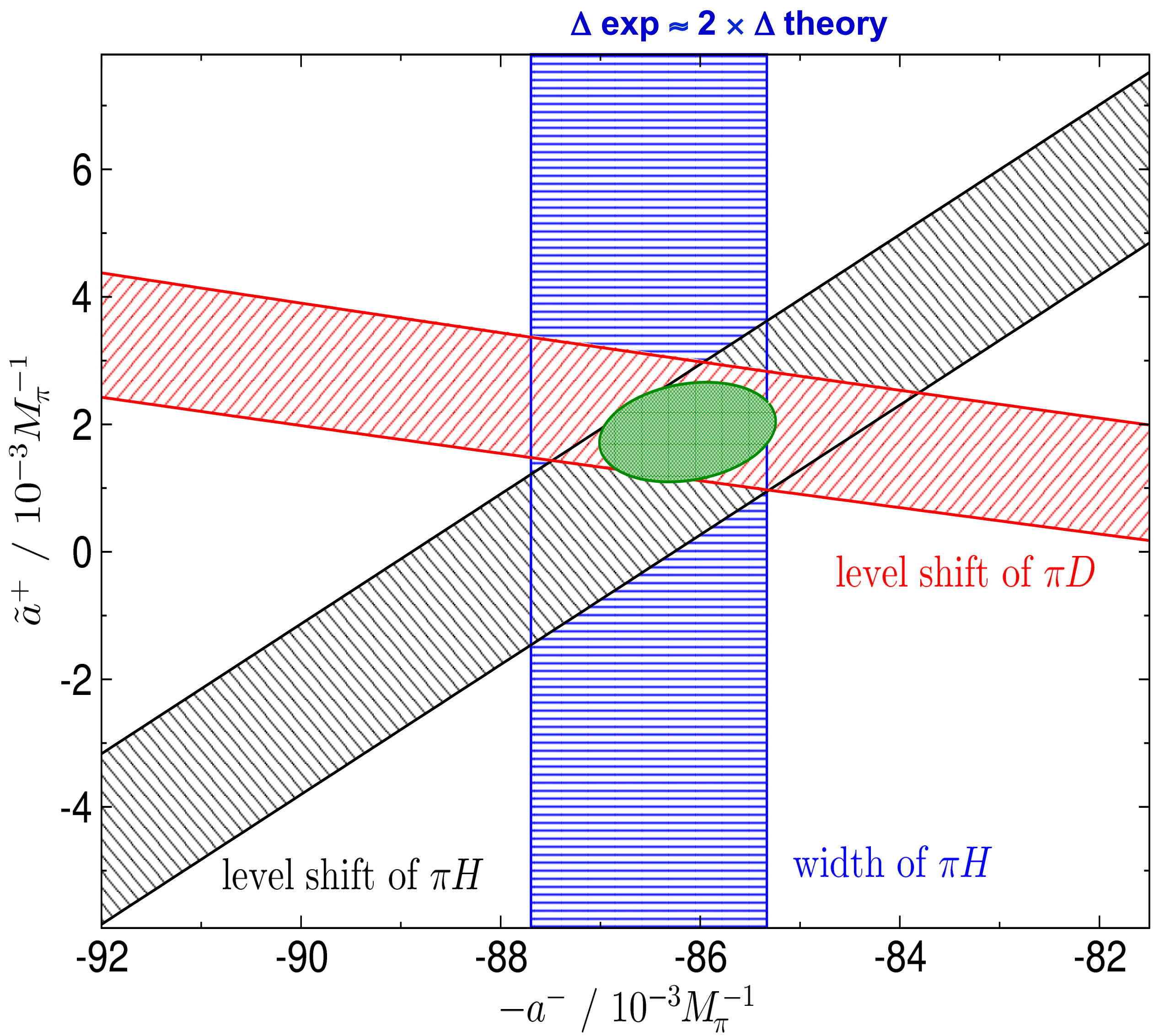




scattering lengths

				experiment	χPT
πH	$\varepsilon_{1s} \propto a_{\pi\text{-}p \rightarrow \pi\text{-}p}$	$\propto a^{+} + a^{-}$	+ …	± 0.2%	± 3.0%
	$\Gamma_{1s} \propto (a_{\pi\text{-}p \rightarrow \pi^{0} n})^{2}$	$\propto (a^{-})^{2}$	+ …	± 2.5%	± 1.0%
πD	$\varepsilon_{1s} \propto a_{\pi\text{-}d \rightarrow \pi\text{-}d}$	$\propto 2 \cdot a^{+}$	+ …	± 1.3%	± 4%

πN scattering lengths



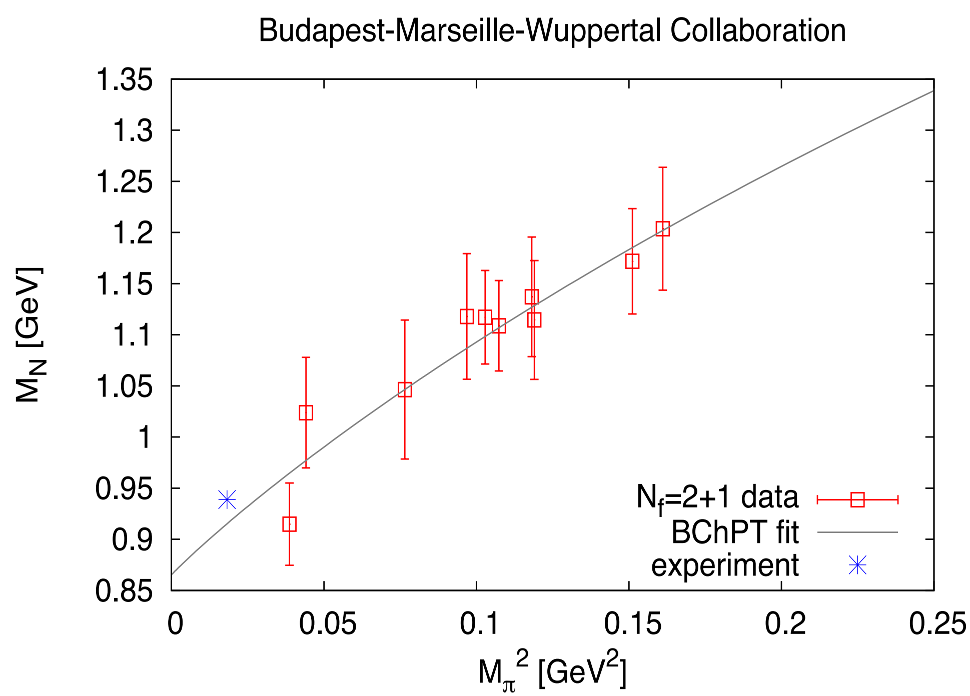
Δ exp << Δ theory

Δ exp << Δ theory

✔

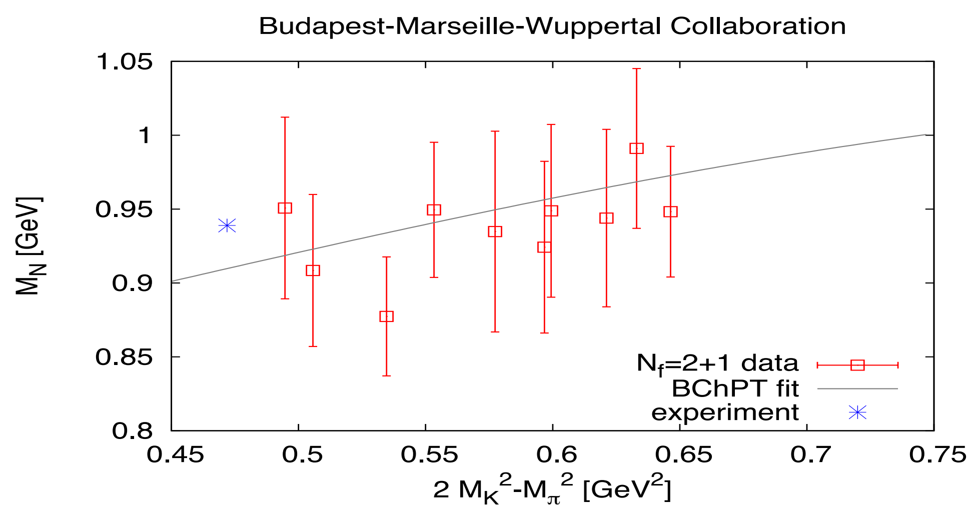
- $a^+ > 0$!

πN σ term: u,d,s quarks mass contributions



lattice calc: S. Durr PRD85 (2012)
careful error estimates
3 lattice spacings
m_π > 190 MeV
ChPT fits to N, Λ, Σ, Ξ mass

f_ud = u,d fraction of N mass
= 0.042(5) (+21, -4)

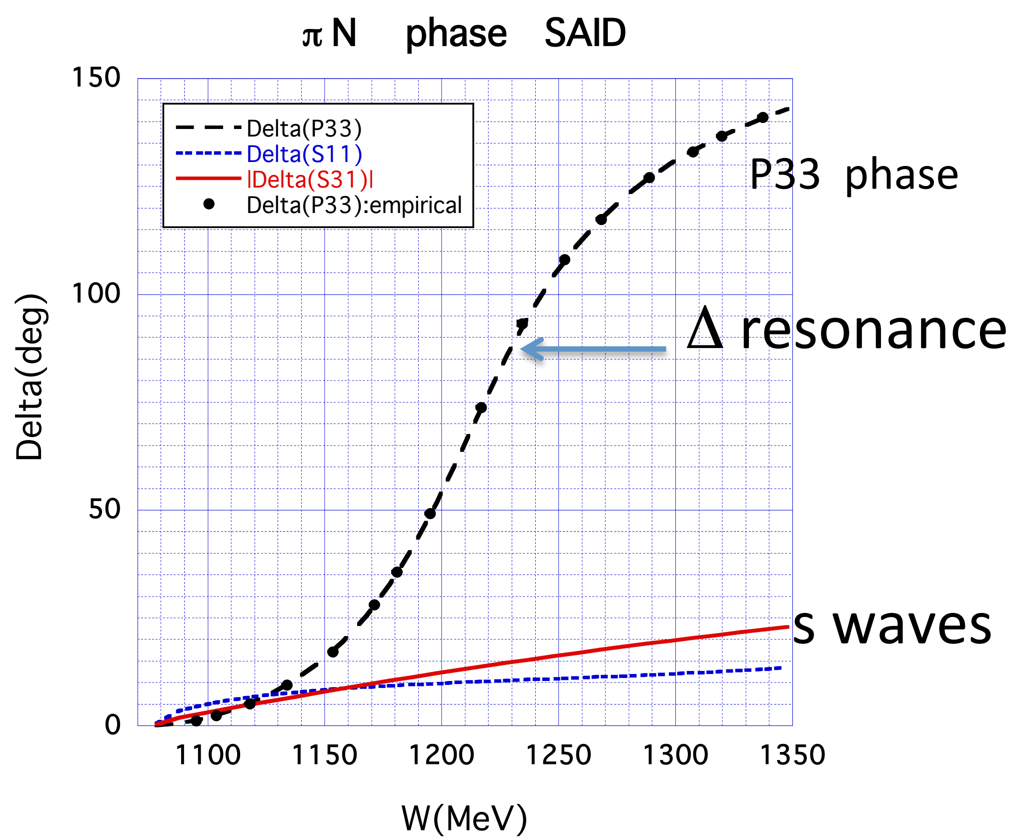


f_s = 0.036(14) (+30, -23)

$\pi - \pi,\ \pi - N$ scattering

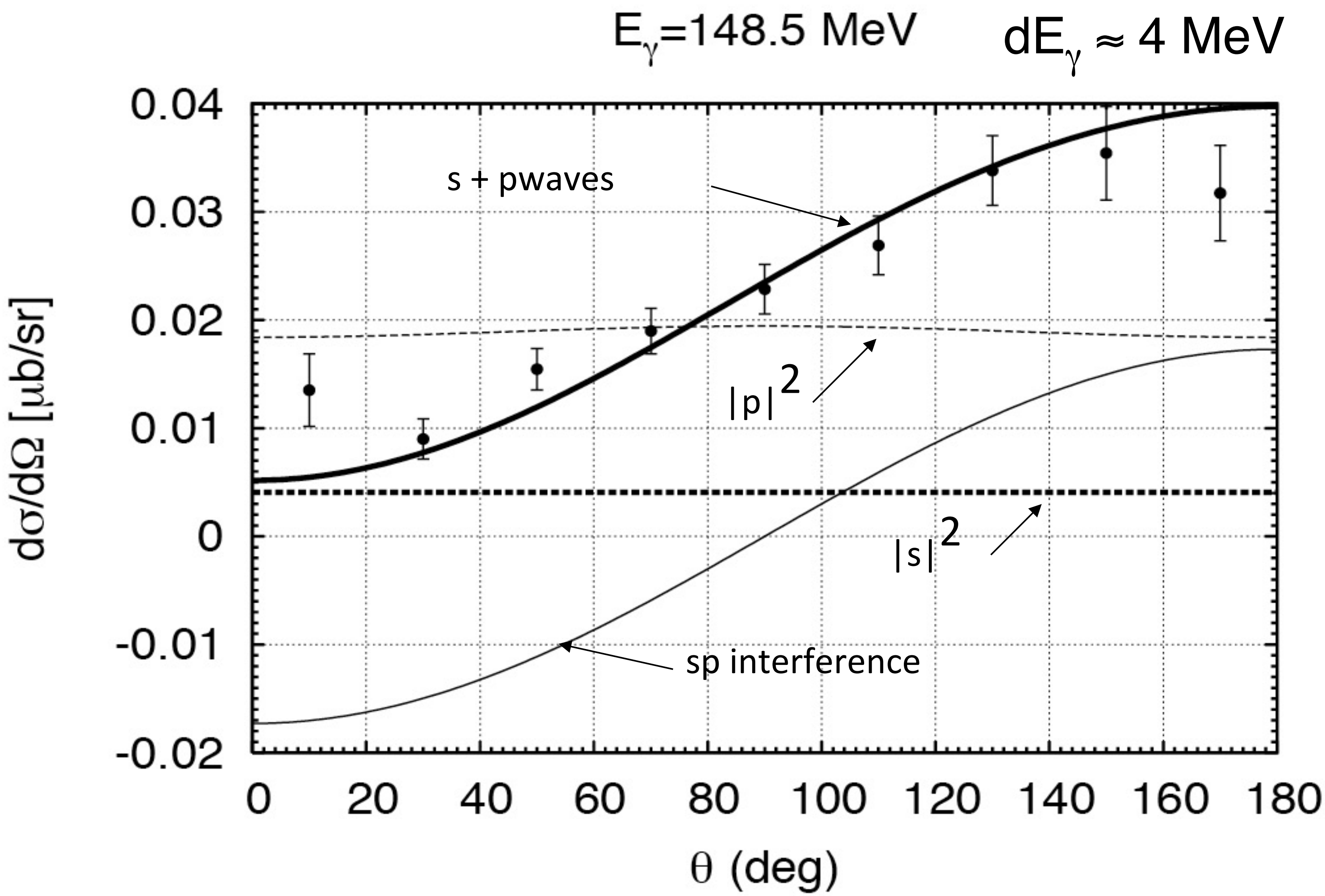
1. chiral symmetry requires weak threshold s wave measures explicit chiral symmetry breaking

2. strong p wave



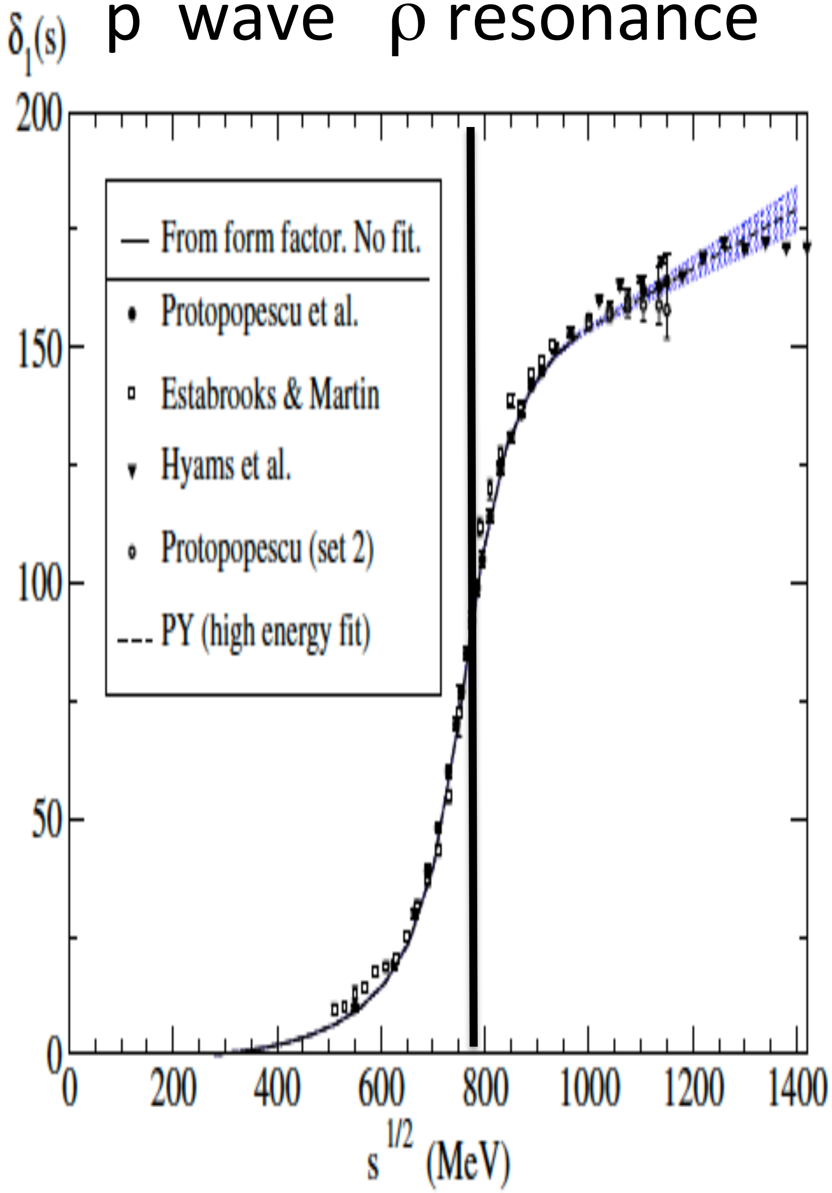
πN phase SAID
Delta(P33)
Delta(S11)
|Delta(S31)|
Delta(P33):empirical
P33 phase
Δ resonance
s waves
Delta(deg)
W(MeV)
150
100
50
0
1100
1150
1200
1250
1300
1350

$\gamma p \rightarrow \pi^0 p$: s wave weak even close to threshold



π π scattering phase shifts

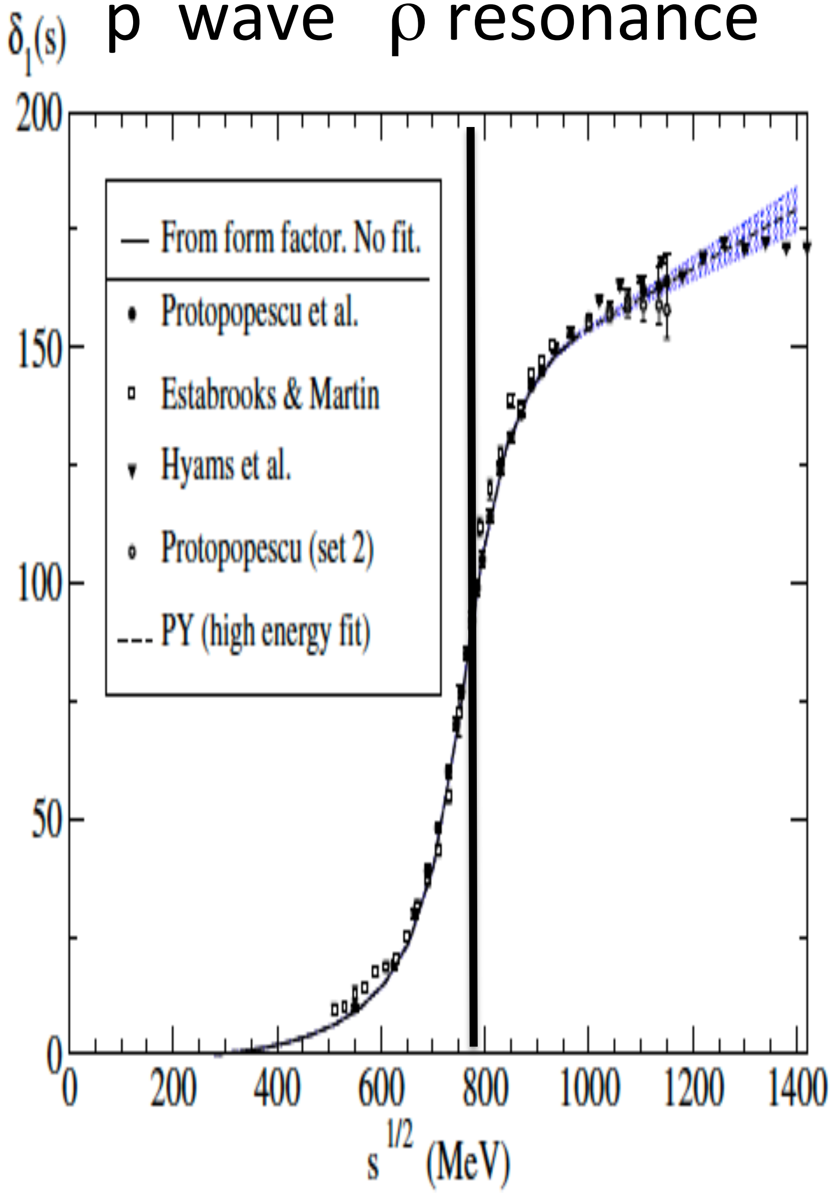
p wave ρ resonance

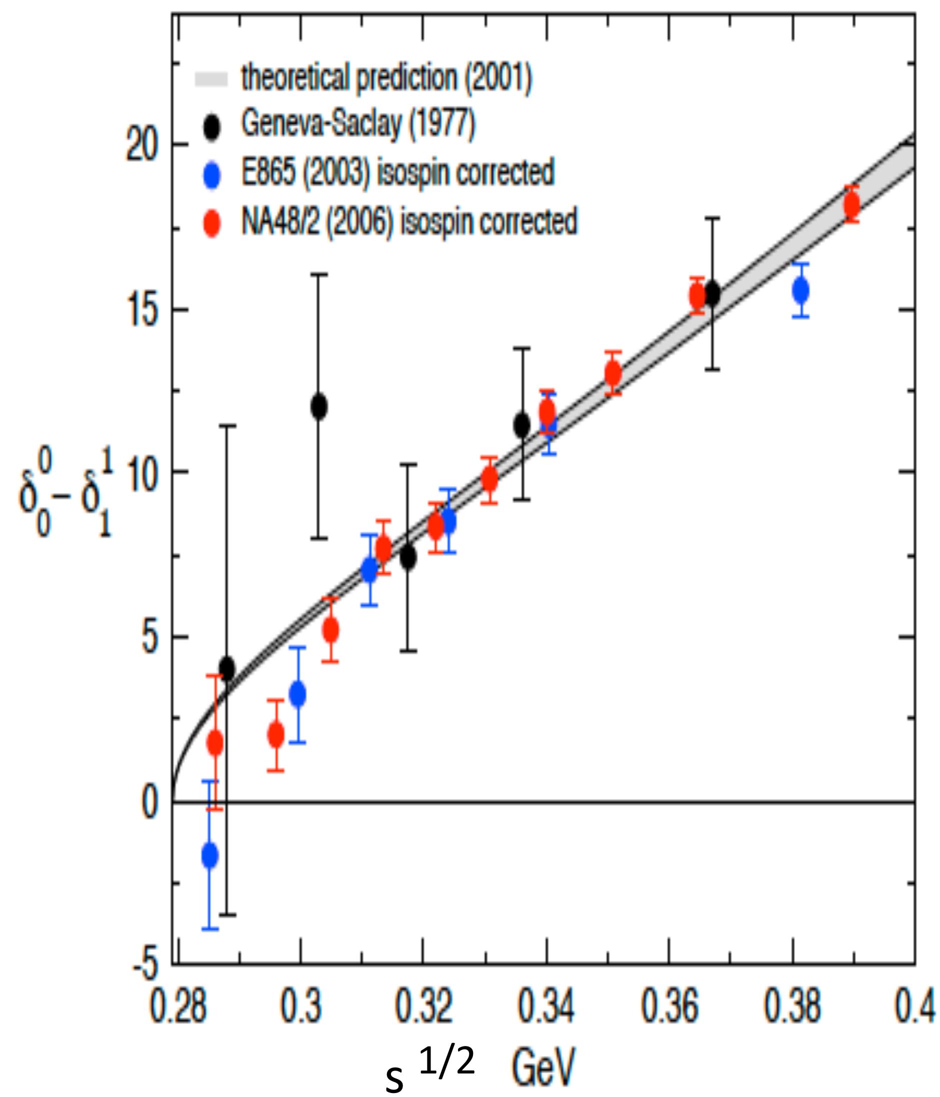


π π scattering phase shifts

p wave ρ resonance

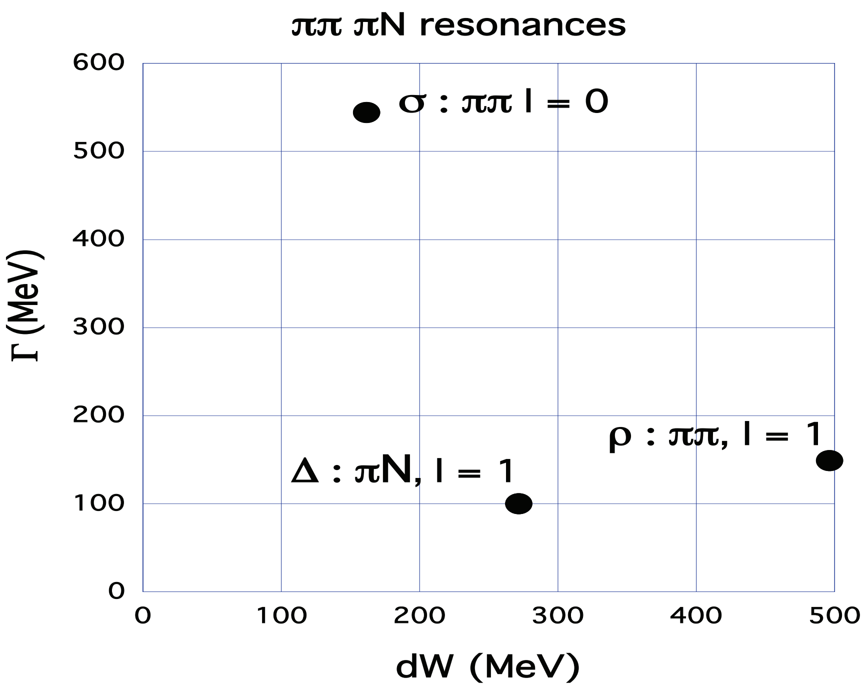
s- p wave phases





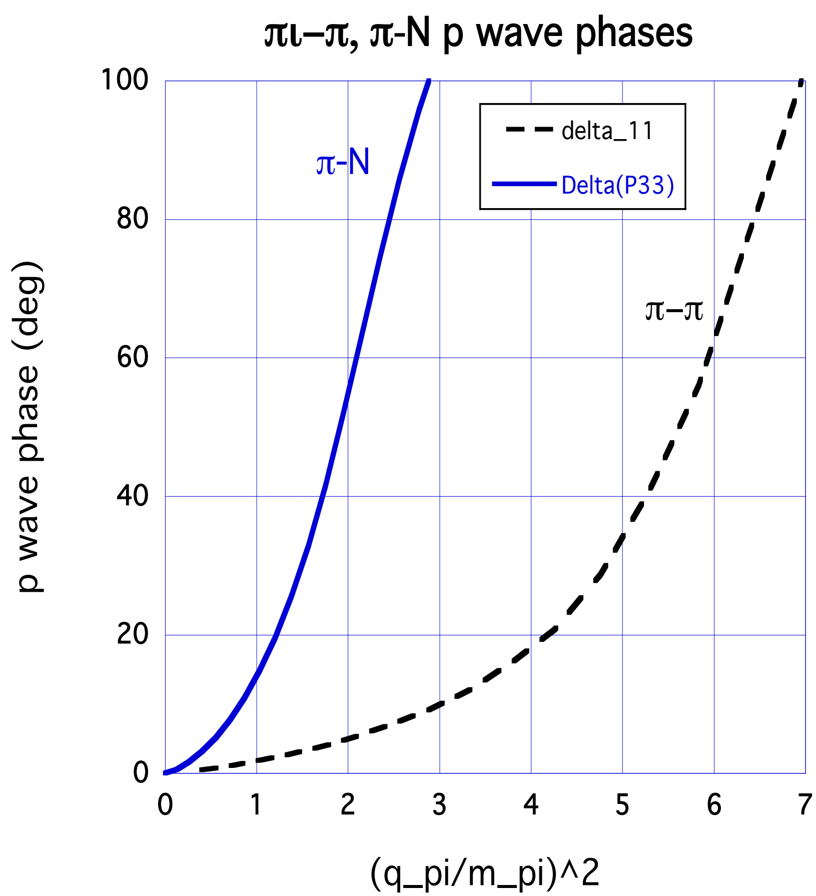
$\pi - \pi, \ \pi - N$ scattering

1. chiral symmetry requires weak threshold s wave measures explicit chiral symmetry breaking
2. strong p wave
3. resonances create differences



ππ πN p wave phases versus q^2

absolute q values



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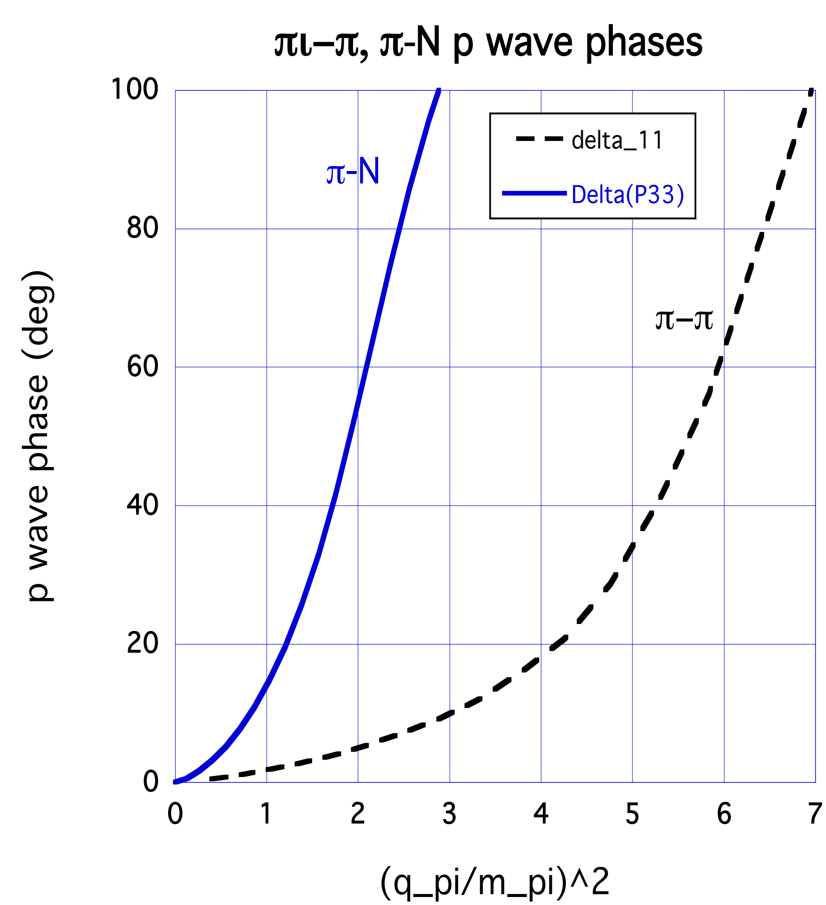
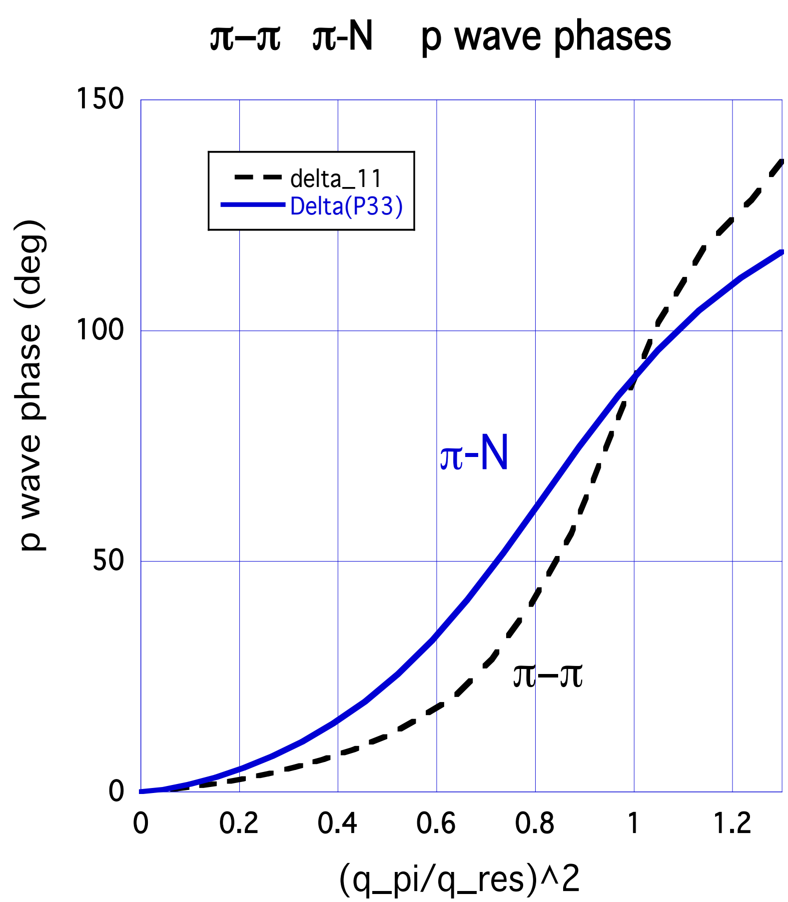
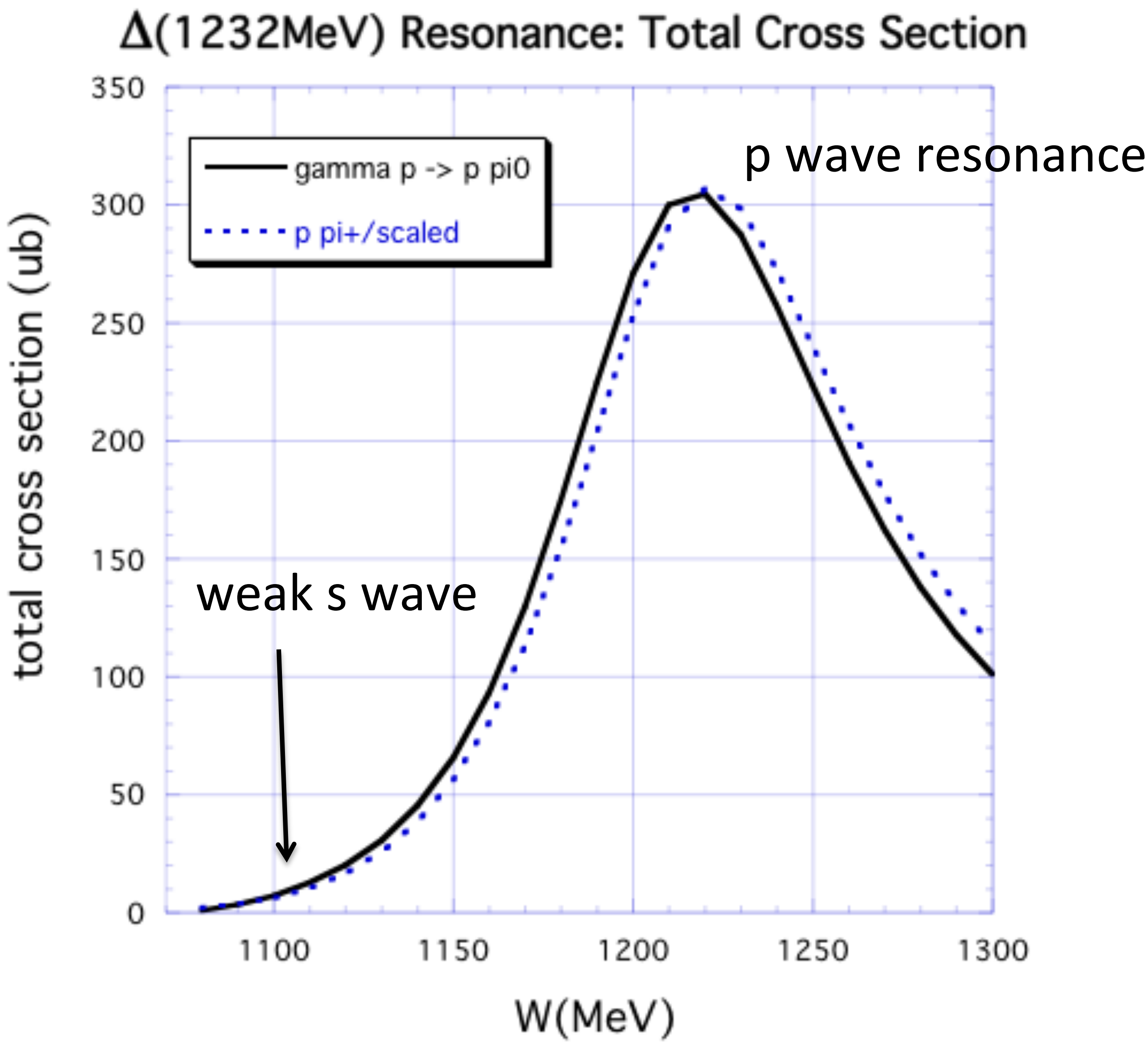
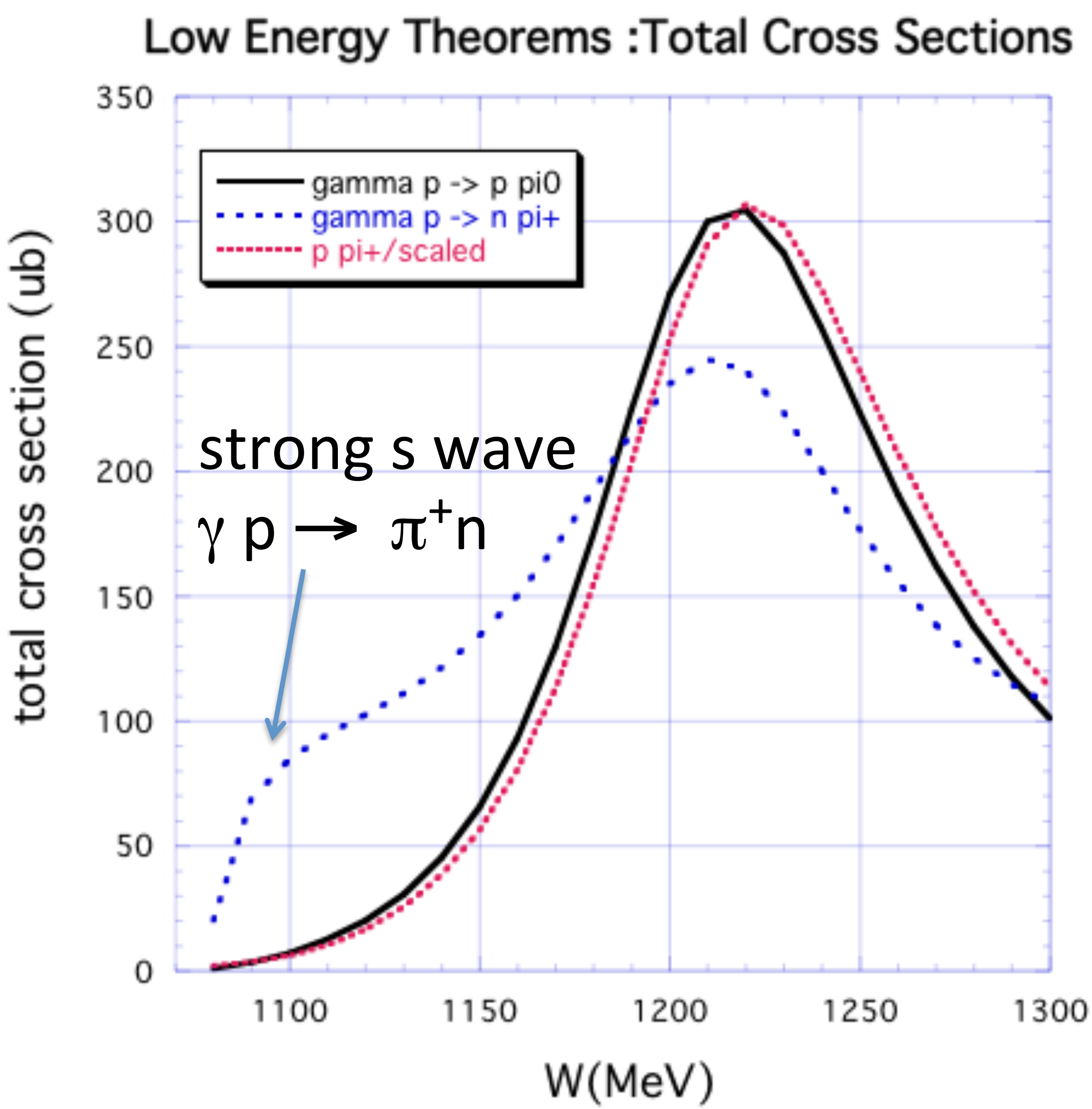


relative to resonance q values



πN scattering: chiral dynamics → resonance shape




Low Energy Theorems :Total Cross Sections
total cross section (ub)
W(MeV)
gamma p -> p pi0
gamma p -> n pi+
p pi+/scaled
strong s wave
γ p → π+n
350
300
250
200
150
100
50
0
1100
1150
1200
1250
1300

$\vec{\gamma}\vec{p} \longrightarrow \pi N$: A New Era

1. Mainz: $\simeq 4\pi$ detector
   polarized beams and targets
   continuous energy coverage

2. new, stringent tests of ChPT
   sensitive polarization observables

3. first determination of accurate energy range

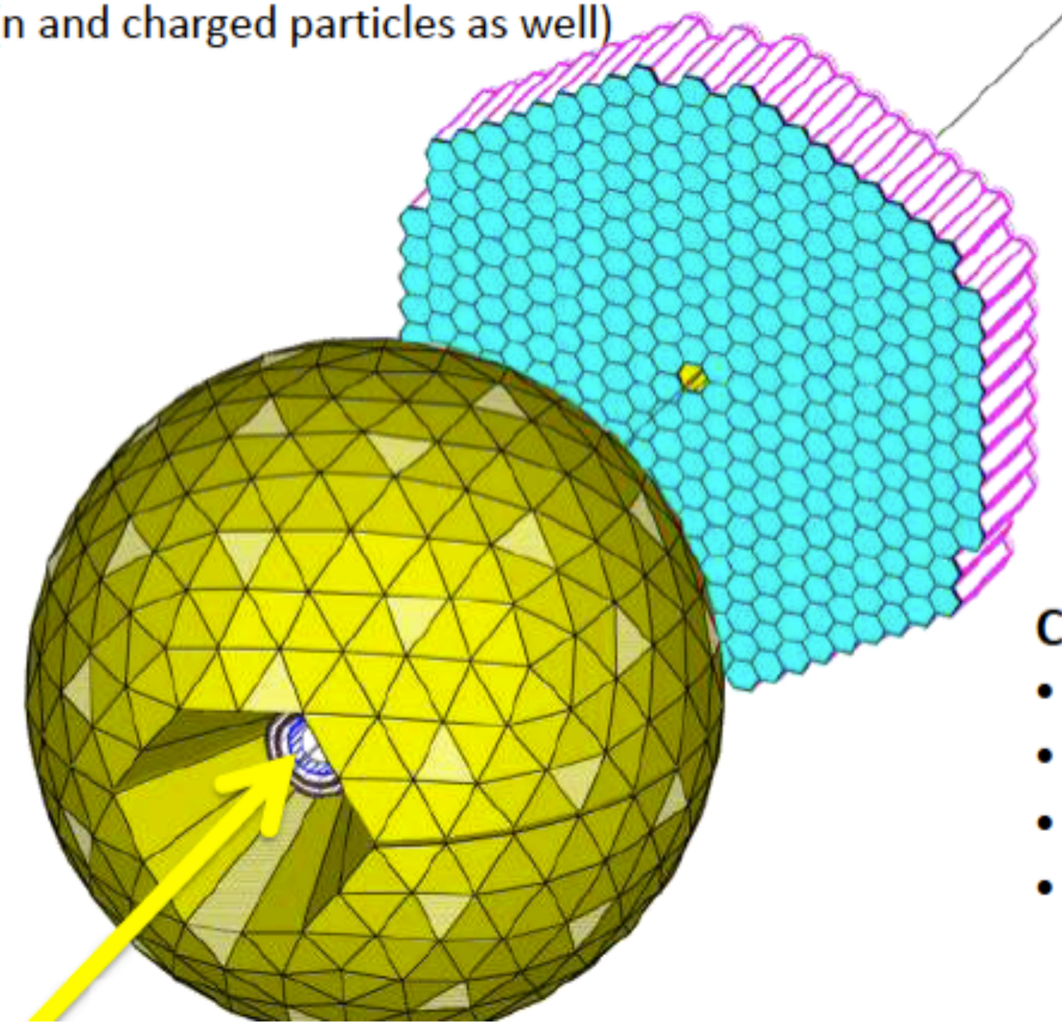
4. transverse polarized target $\rightarrow$
   sensitive to final $\pi^0 p, \pi^+ n$ state $\rightarrow$
   previous $\pi^\pm p$ experiments: isospin tests(?)

5. experimental challenge
   small cross sections; accurate data
   new techniques(?):HIγS,virtual photon tagging

6. theoretical challenge
   ChPT(heavy Baryon, relativistic, Δ)
   subtracted dispersion relations. lattice

crystal ball at Mainz

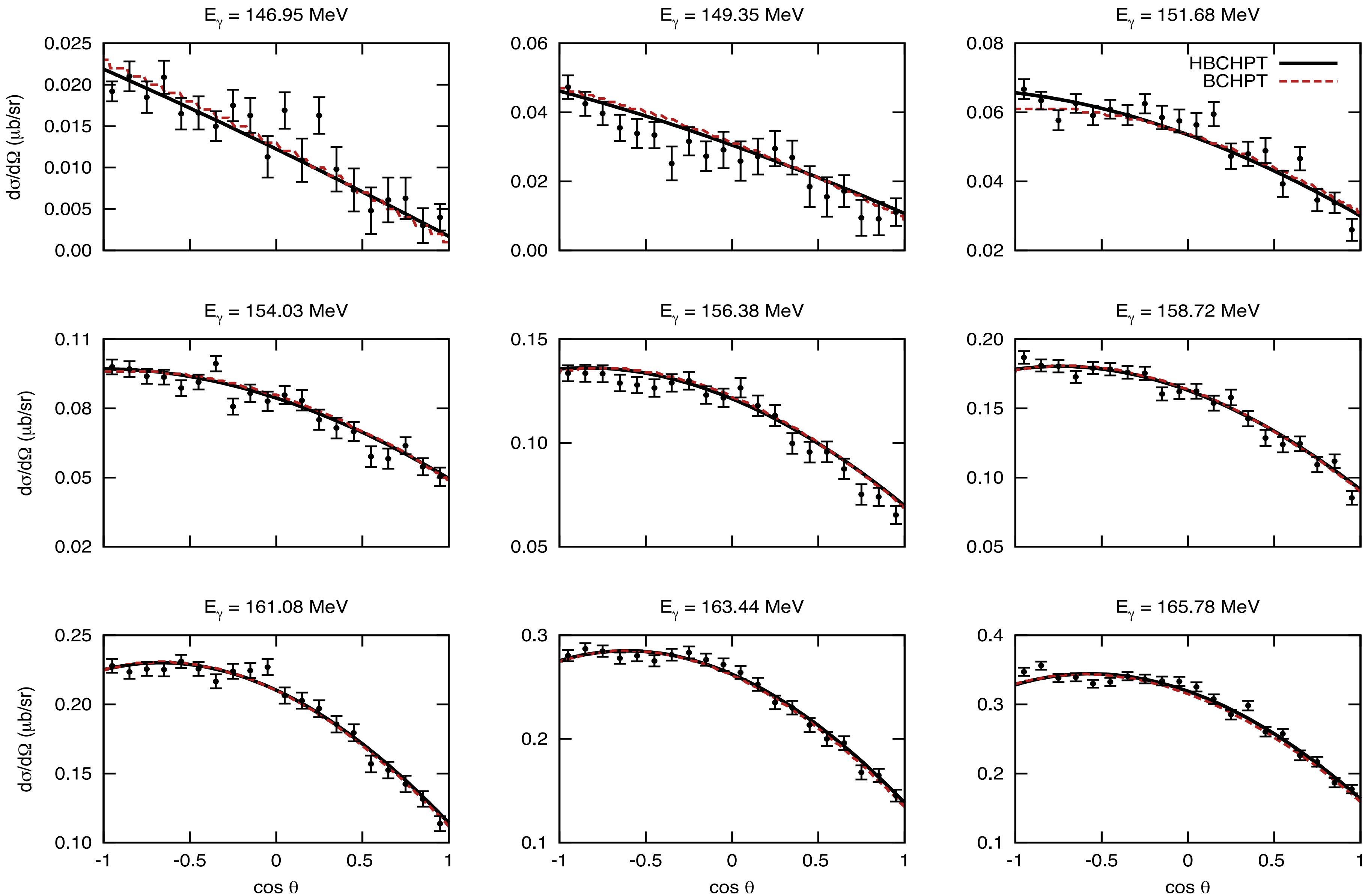
- 4π photon spectrometer
  (n and charged particles as well)



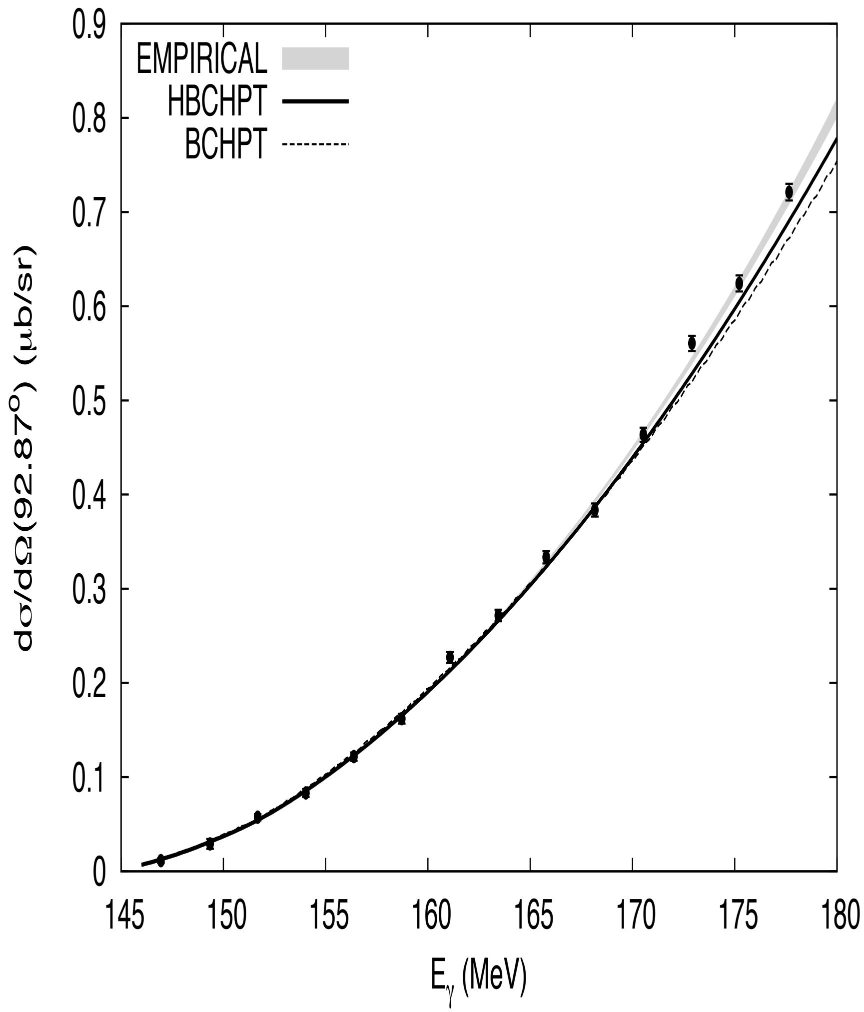
TAPS
- 366 BaF_2 crystals
- 12 radiation lengths
- $1° < \theta < 20°$ (3%)

Crystal Ball
- 672 NaI(Tl) crystals
- 16 radiation lengths
- $20° < \theta < 160°$ (94%)
- $\sigma \approx 2\text{-}3°$

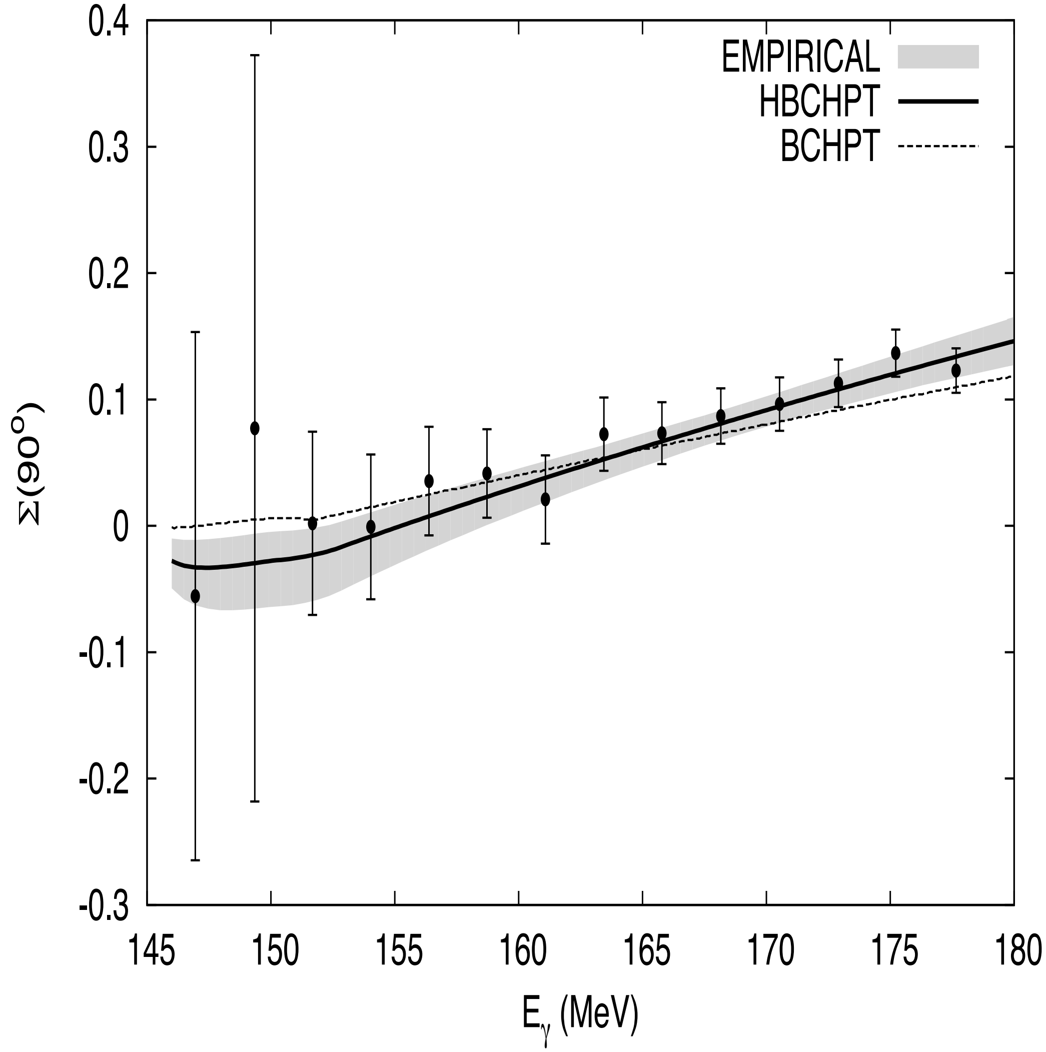
$\gamma\, p \rightarrow \pi^0\, p$ Mainz data: Hornidge..;
HBChPT: BKM O(p^4): Fernandez-Ramirez, AB, relativistic BCHPT Hilt, Scherer, Tiator



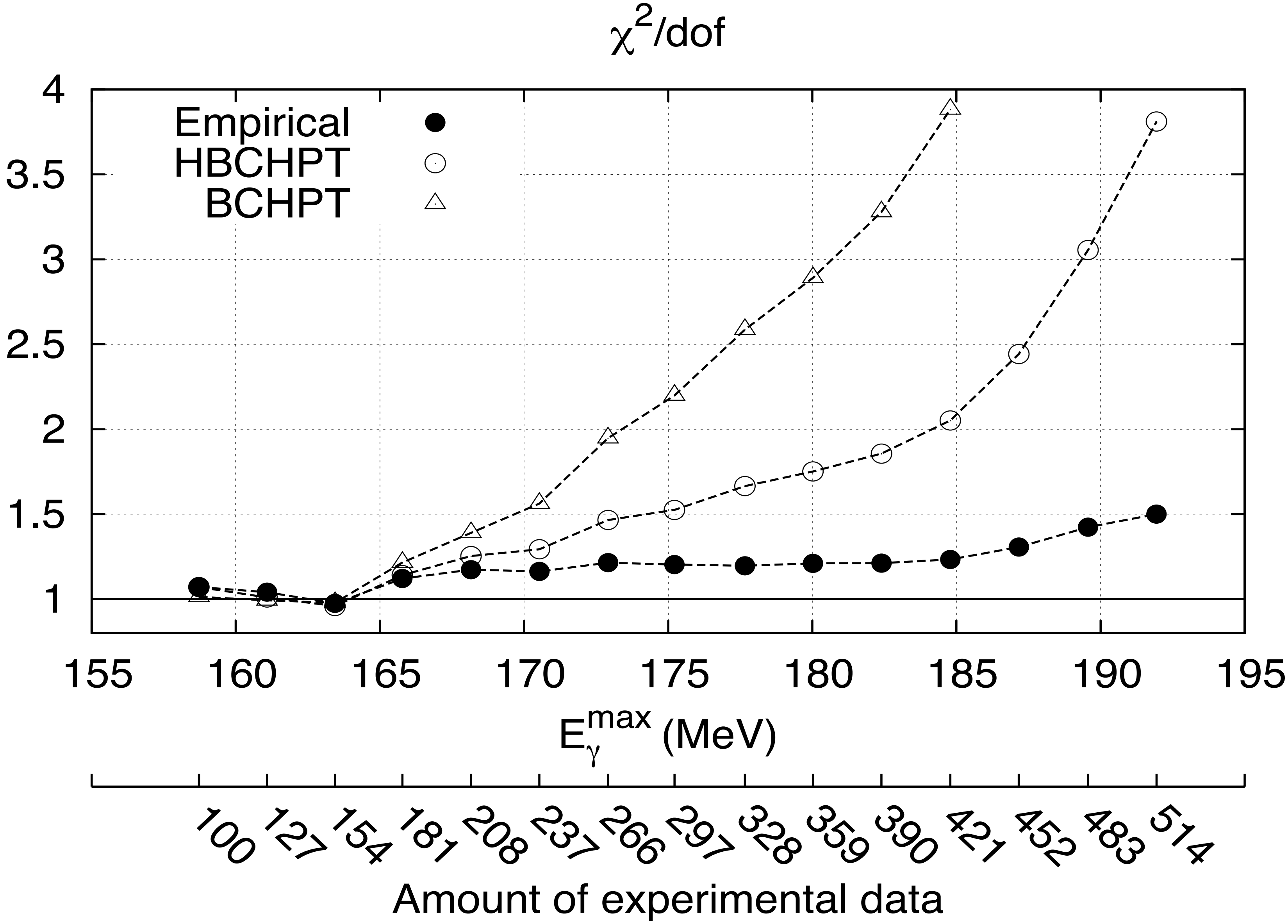
cross section
→ s, p wave amplitudes



polarized photon asymmetry
→ p wave amplitudes



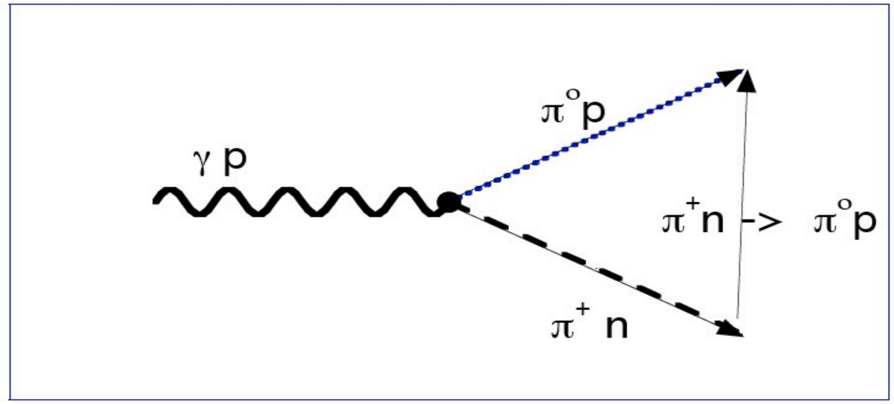
ChPT works to ≤ 170 MeV



Unitary Cusp $\gamma p \rightarrow \pi^0 p$

$\beta = E_{0+}(\gamma p \rightarrow \pi^+ n)\, a_{cex}(\pi^0 p \leftrightarrow \pi^+ n)$

cusp sign and magnitude



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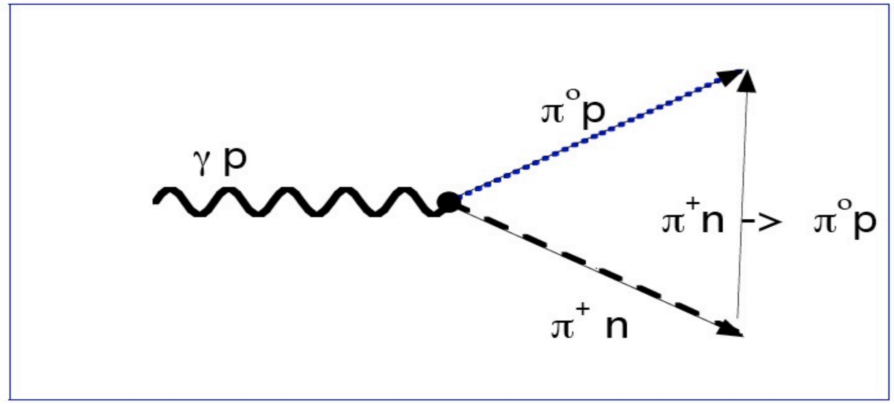
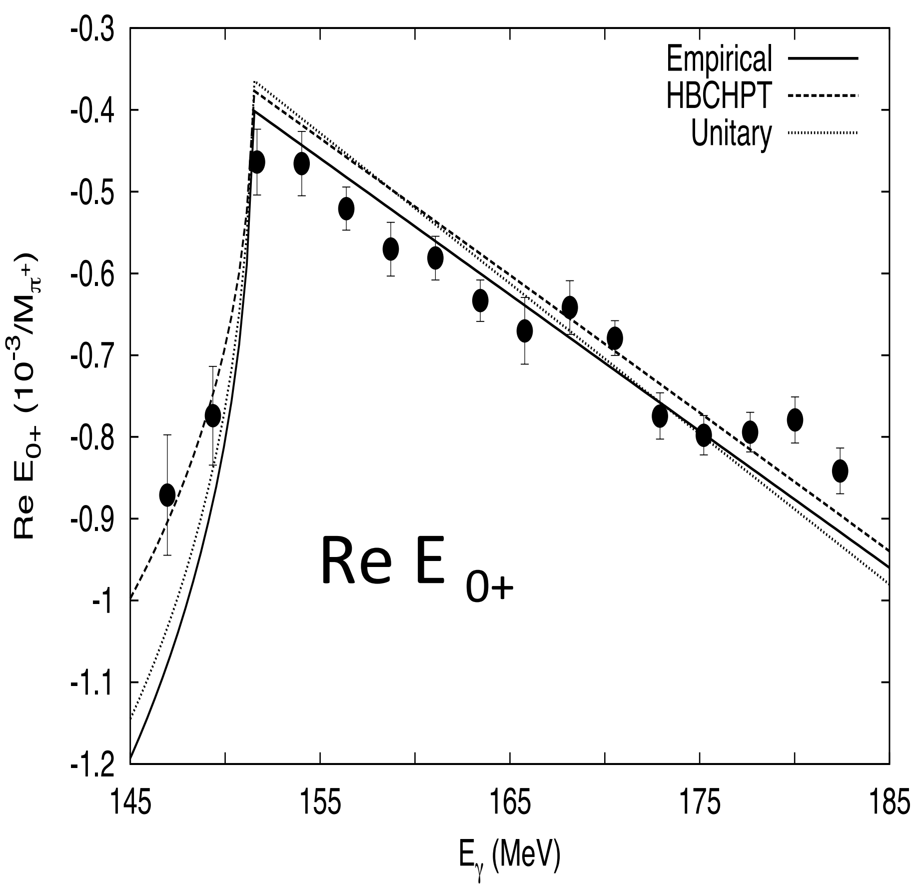
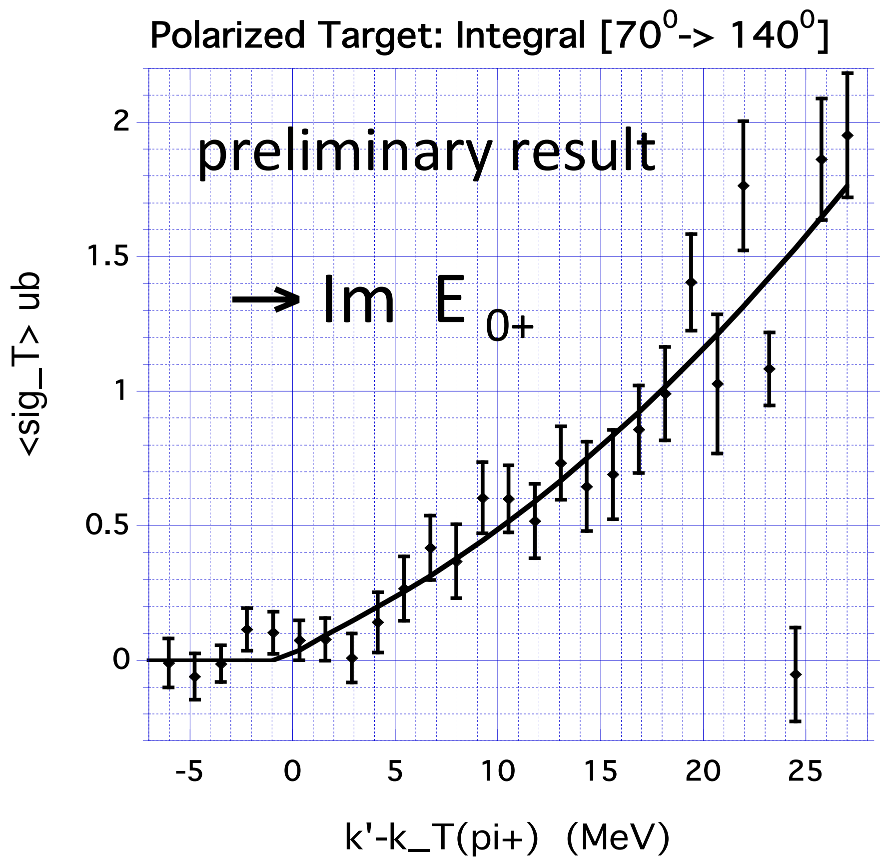






testing isospin symmetry

$L_{QCD} = L_0\ (m_q \rightarrow 0) + L_m$ (quark mass term)

L_0 has chiral symmetry; spontaneously broken

$\Rightarrow$ Nambu-Goldstone Bosons (π, η, K)

$\Rightarrow$ ChPT: effective theory of QCD

$L_m = A(m_u + m_d) + B\,(m_u - m_d)$

explicitly breaks chiral symmetry

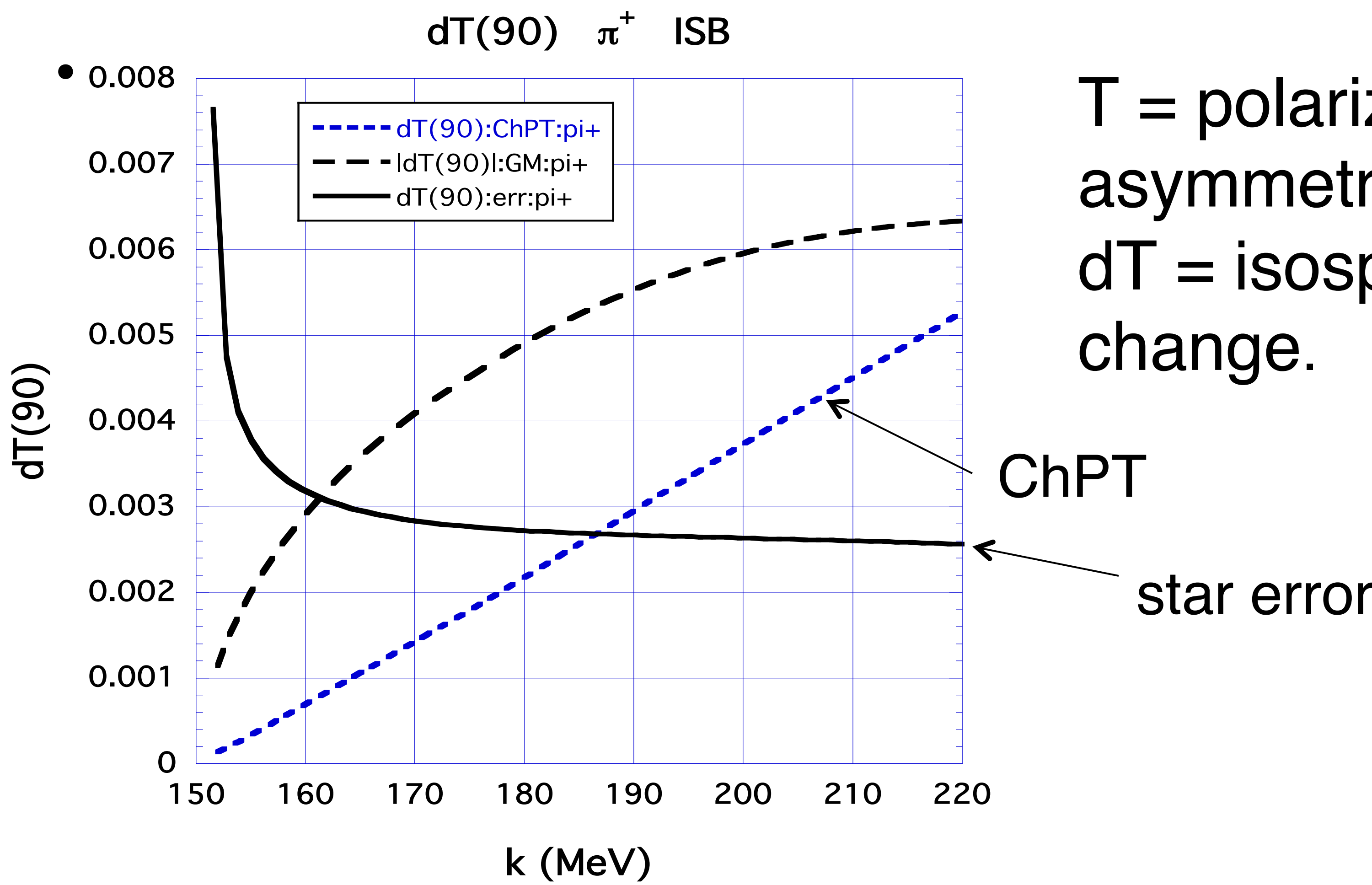
isospin symmetry broken: EM interaction

$(m_d - m_u)/\Lambda_{QCD} \approx 2\%$

exp. tests needed

$\gamma p \rightarrow \pi^+ n, \pi^0 p$ transverse polarized target

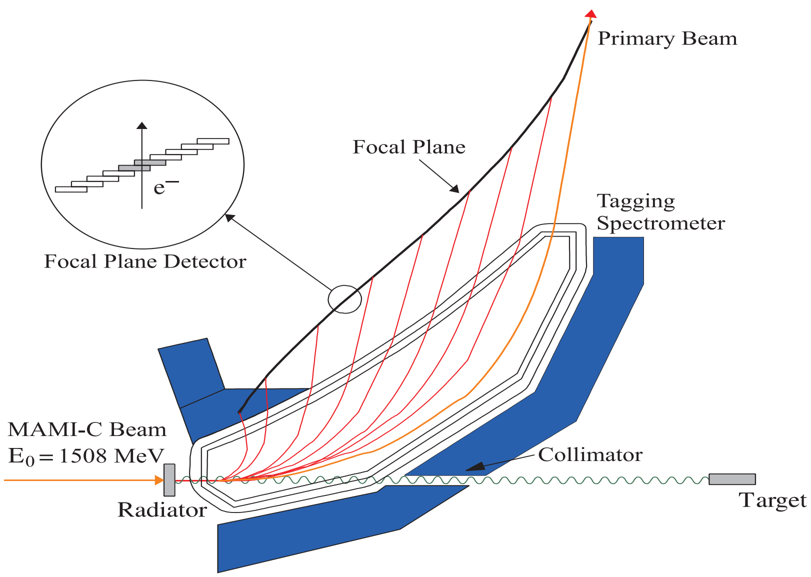
- $\Rightarrow \pi$ N interaction neutral charge states.
- predicted sign change for π^0, π^+ production

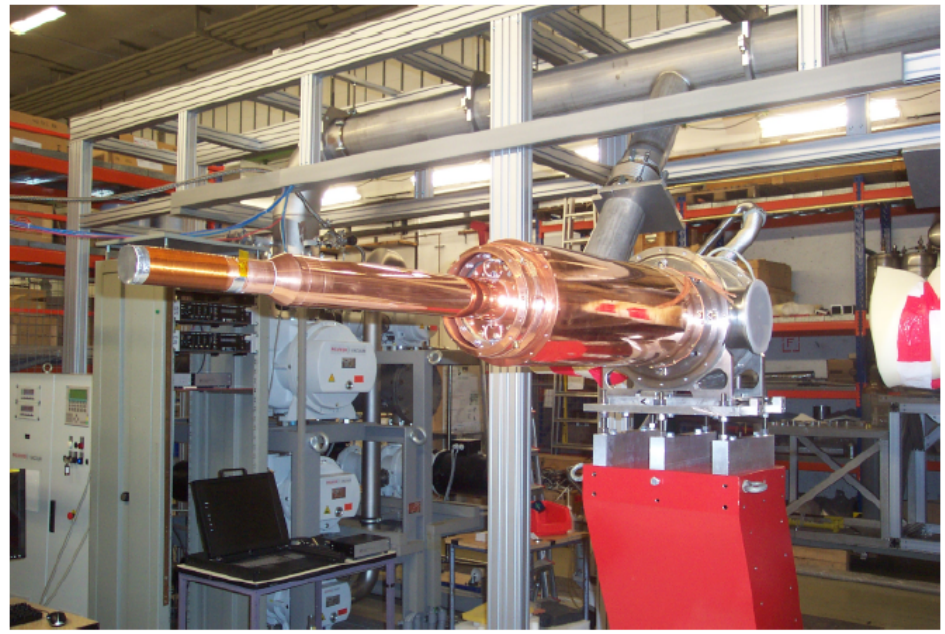


T = polarized target asymmetry
dT = isospin breaking change.

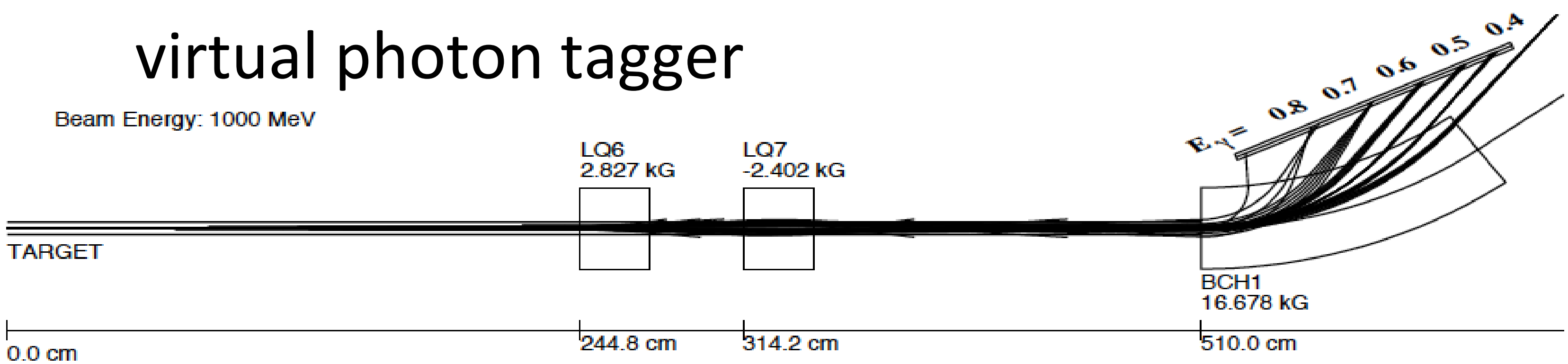
need improved techniques for threshold energies

Mainz

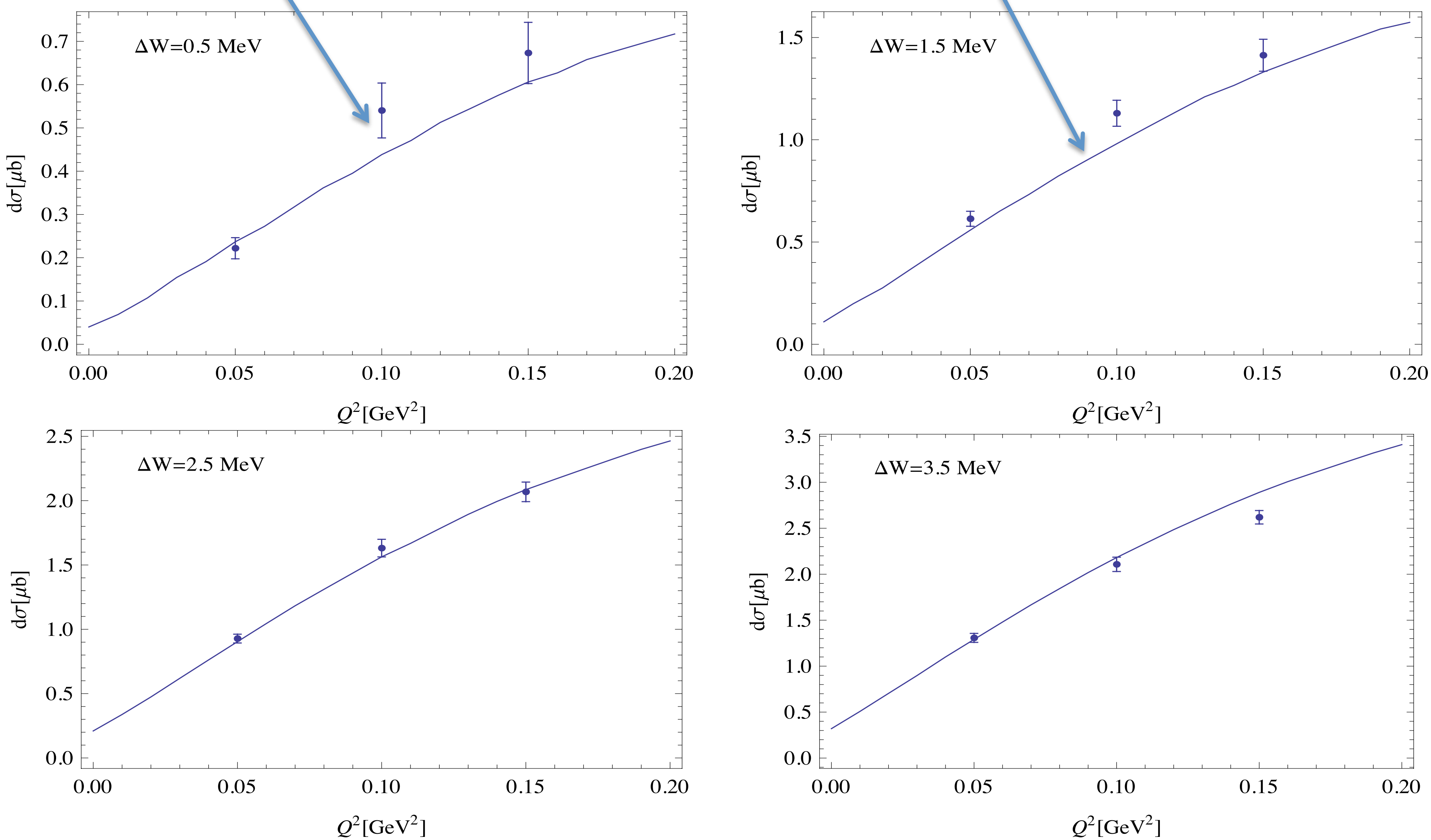




virtual photon tagger



ep → e'p π^0 Q2 dependence
new Mainz , Jlab data HBChPT, relativistic ChPT



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- It has been a stimulating week
- Let's look forward to the CD2015 conference
- let's thanks Jefferson Lab
  the participants
  the working group organizers

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- **last but not least**
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