From the deuteron to the TeV region:

How well do we know the nucleon-nucleon interaction?

R. Machleidt
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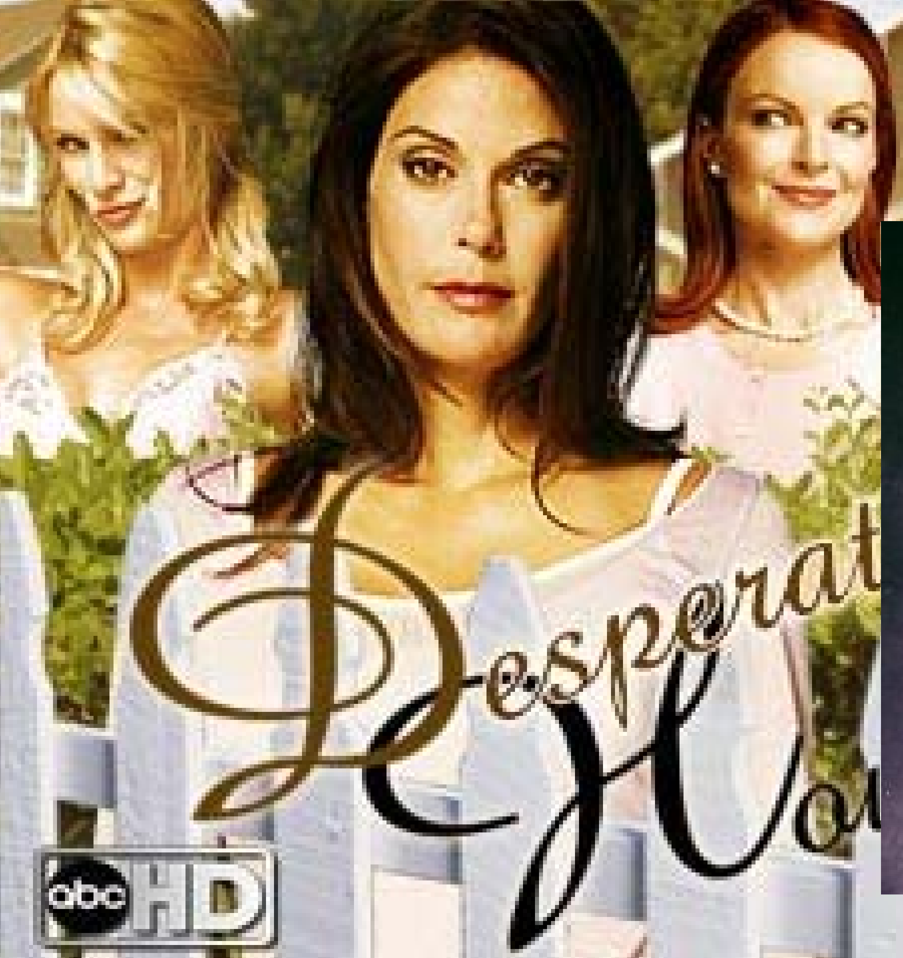
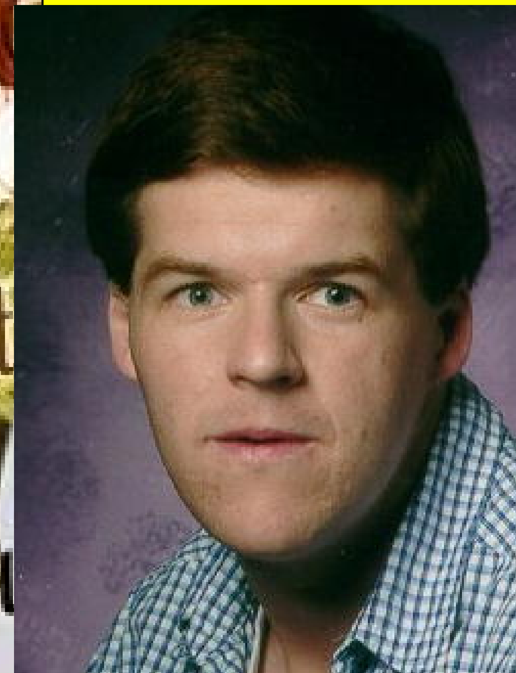
Desperate Physicists

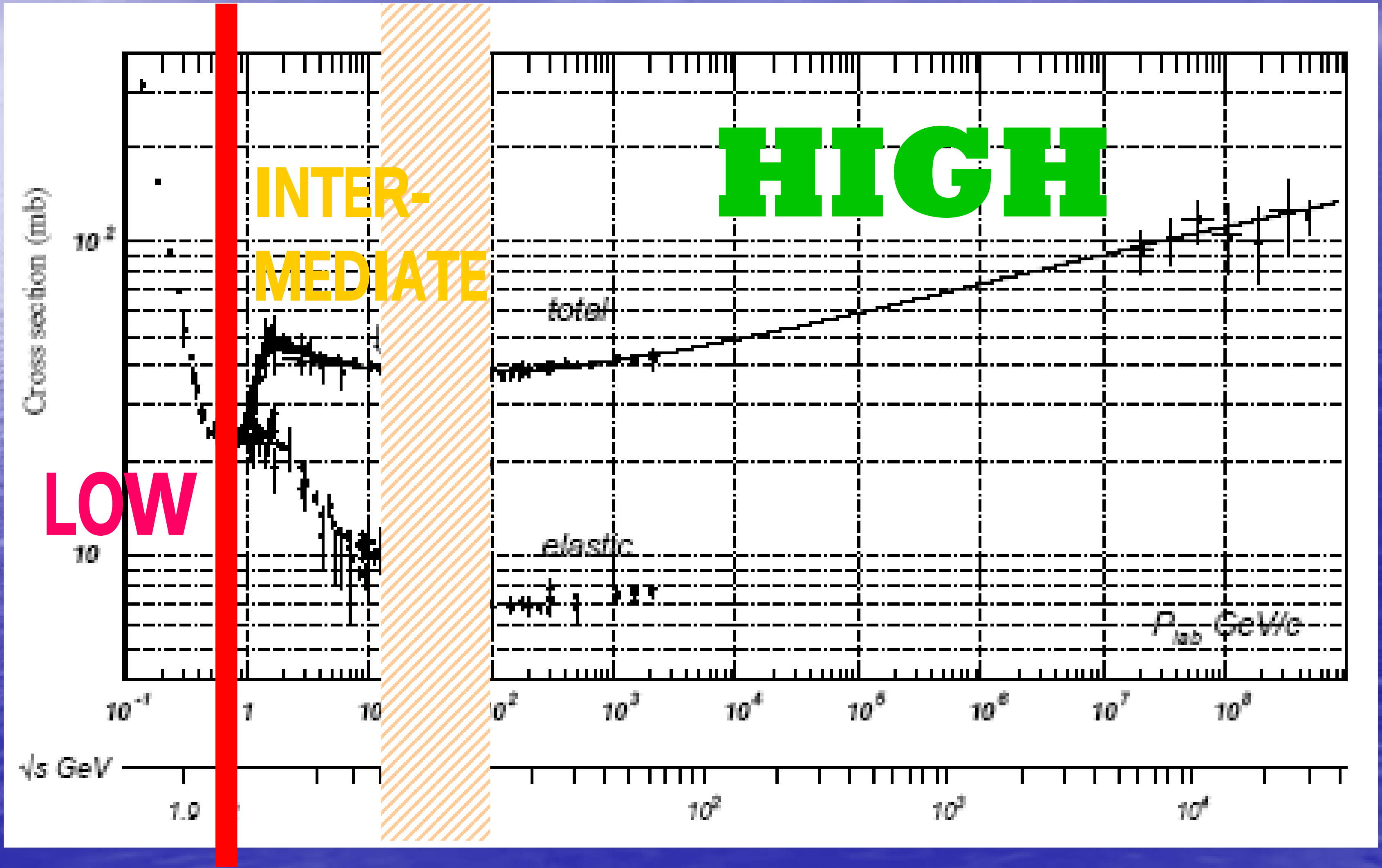




Outline

- Motivation
- Overview: pp scattering from zero to infinity
- The low-energy region
- Intermediate energies
- High energy
- Conclusions

pp TOTAL CROSS SECTIONS



LOW ENERGIES

Low-energy QCD

- QCD for u and d quarks: approx. chirally symmetric

- Spontaneously broken:
$$SU(2)\times SU(2)\rightarrow SU(2)_V$$

- Goldstone bosons: 3 pions

Effective Field Theory (EFT)

- Effective DOF: Pions and Nucleons
- Heavy mesons frozen, static sources, "contact interactions"
- All relevant symmetries; particularly, **spontaneously broken Ch. Sym.**
- Lagrangian: **non-linear realization**

$$L_{eff} = L_{\pi\pi} + L_{\pi N} + L_{NN}$$

Power Counting

(Weinberg, van Kolck)

Chiral Perturbation Theory

- **Organize contributions in terms of**

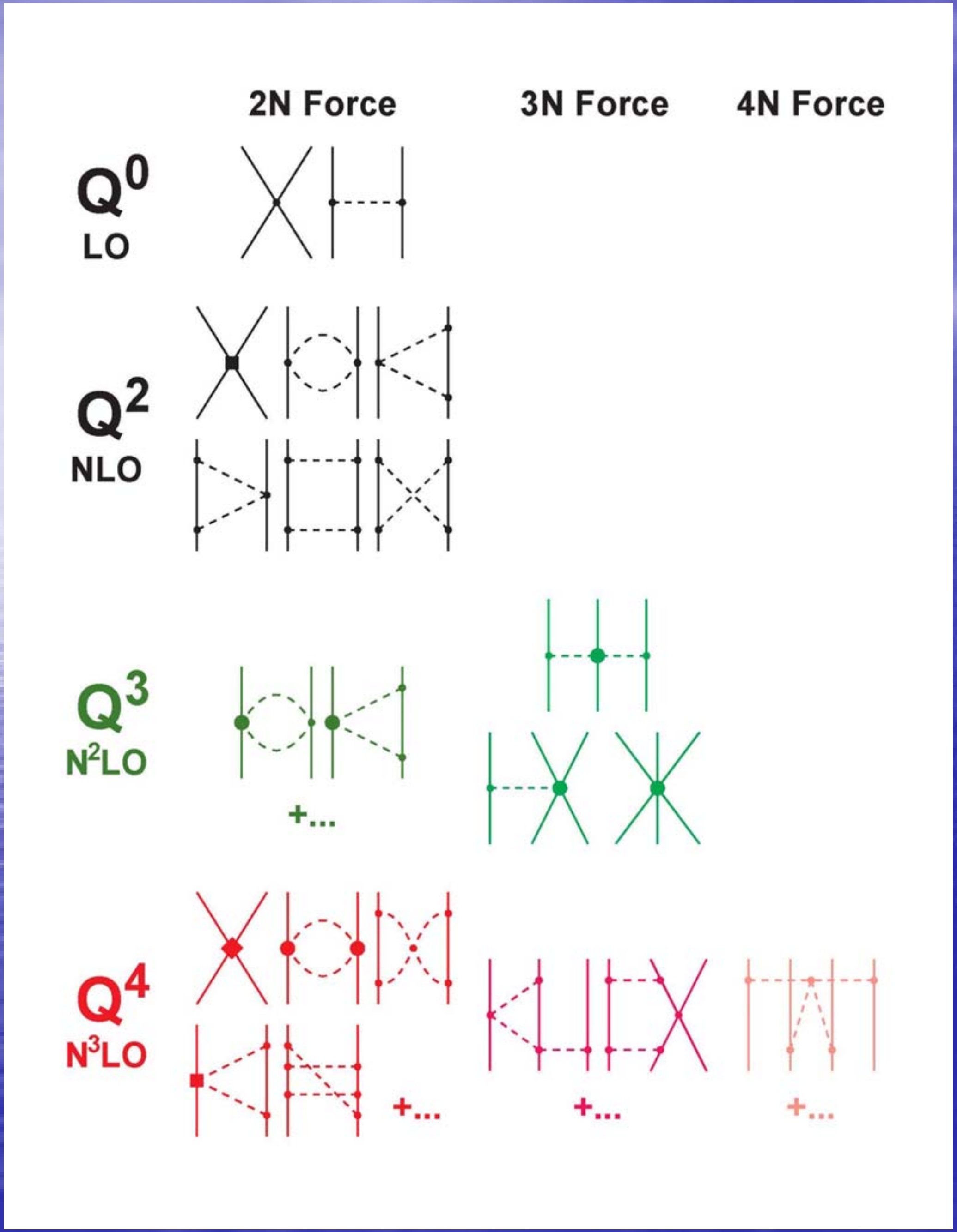
$$\left(Q/\Lambda\right)^{\nu}, \quad with \;\; \nu \geq 0$$

- **For just two nucleons:**

$$\nu = 2 \times Loops \;\; + \sum_{all\ vertices\ j} \Delta_j$$

$$\Delta_j = d_j + \frac{n_j}{2} - 2 \geq 0$$

Hierarchy of Nuclear Forces



How to define a potential?

$$\bar{V}(\vec{p}\,',\vec{p}) \equiv \left\{ \begin{array}{c} \text{sum of irreducible} \\ \pi + 2\pi \text{ diagrams} \end{array} \right\} + \text{ contacts}$$

Define

$$V(\vec{p}\,',\vec{p}) \equiv \sqrt{\frac{M}{E_{p'}}}\,\bar{V}(\vec{p}\,',\vec{p})\,\sqrt{\frac{M}{E_p}}$$

and apply in Lippmann-Schwinger Equation

$$T(\vec{p}\,',\vec{p}) = V(\vec{p}\,',\vec{p}) + \int d^3p''\,V(\vec{p}\,',\vec{p}\,'')\,\frac{M}{p^2 - p''^2 + i\epsilon}\,T(\vec{p}\,'',\vec{p})$$

Iteration of V in the LS Eq. (ladder-diagram loops) requires cutting V for high momenta, therefore

$$V(\vec{p}\,',\vec{p}) \longmapsto V(\vec{p}\,',\vec{p})\, e^{-(p'/\Lambda)^{2n}}\, e^{-(p/\Lambda)^{2n}}$$
$$\approx V(\vec{p}\,',\vec{p}) \left\{ 1 - \left[\left(\frac{p'}{\Lambda}\right)^{2n} + \left(\frac{p}{\Lambda}\right)^{2n} \right] + \ldots \right\}$$

$\Lambda = 0.5$ GeV

"Weinberg Power Counting"

History of chiral NN potential development

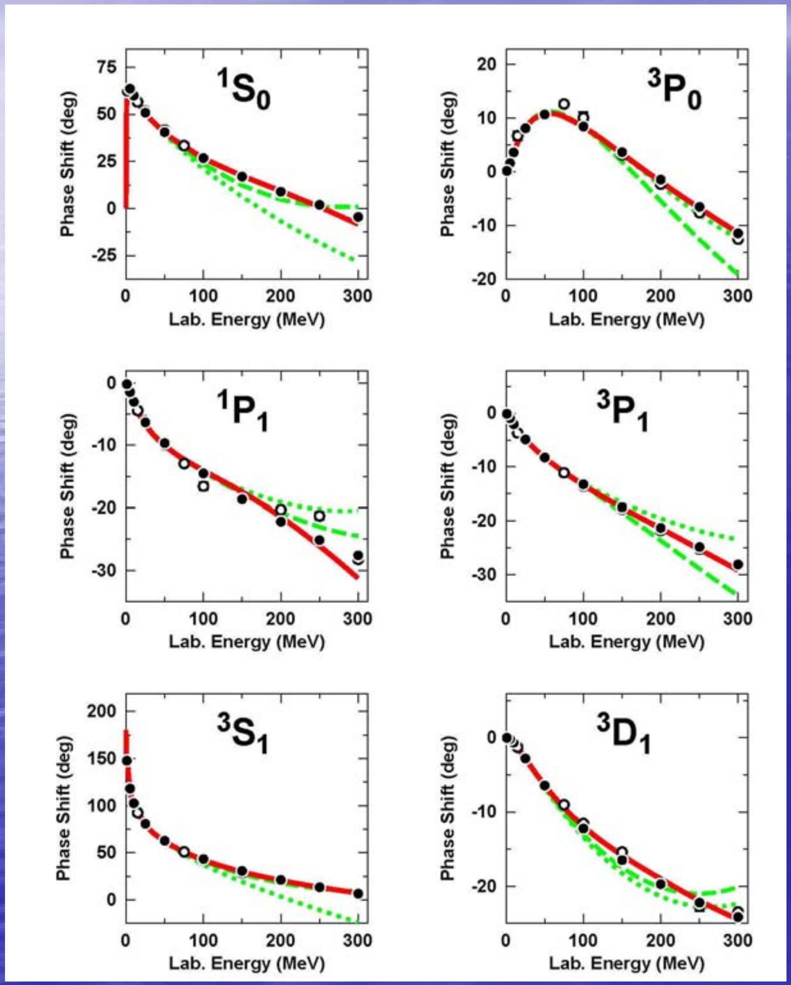
- 1994/96: Ordonez, Ray & van Kolck
  N2LO potential in r-space

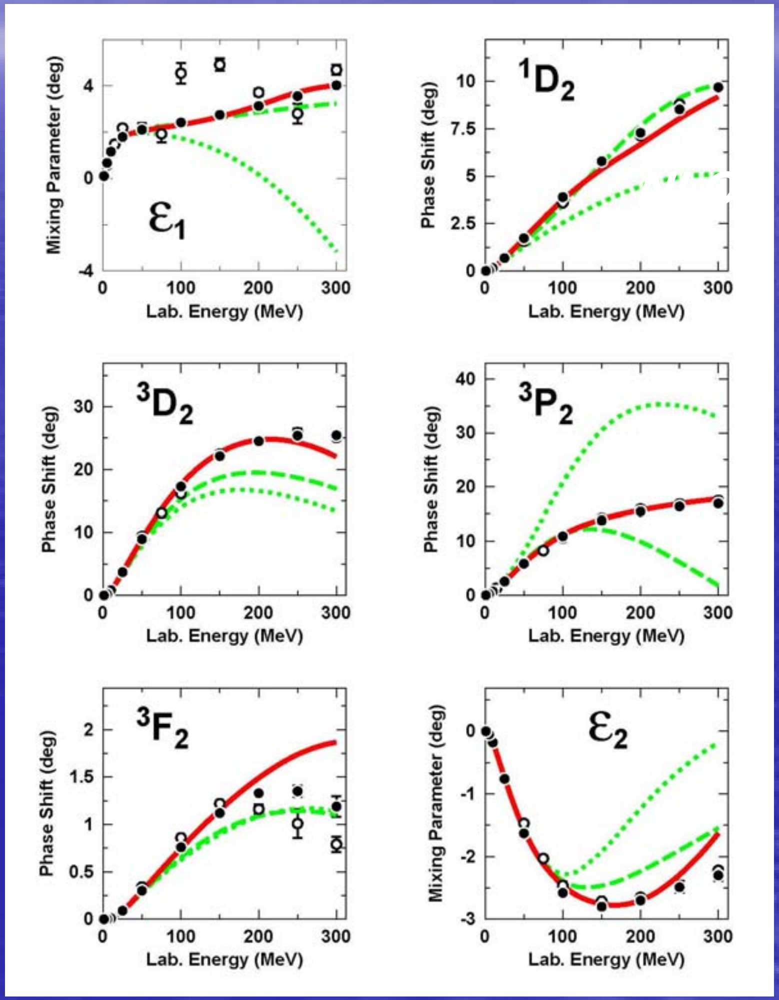
- … … … …

- 2003: Entem & Machleidt
  N3LO potential in momentum space
- 2005: Epelbaum et al.
  N3LO potential in momentum space

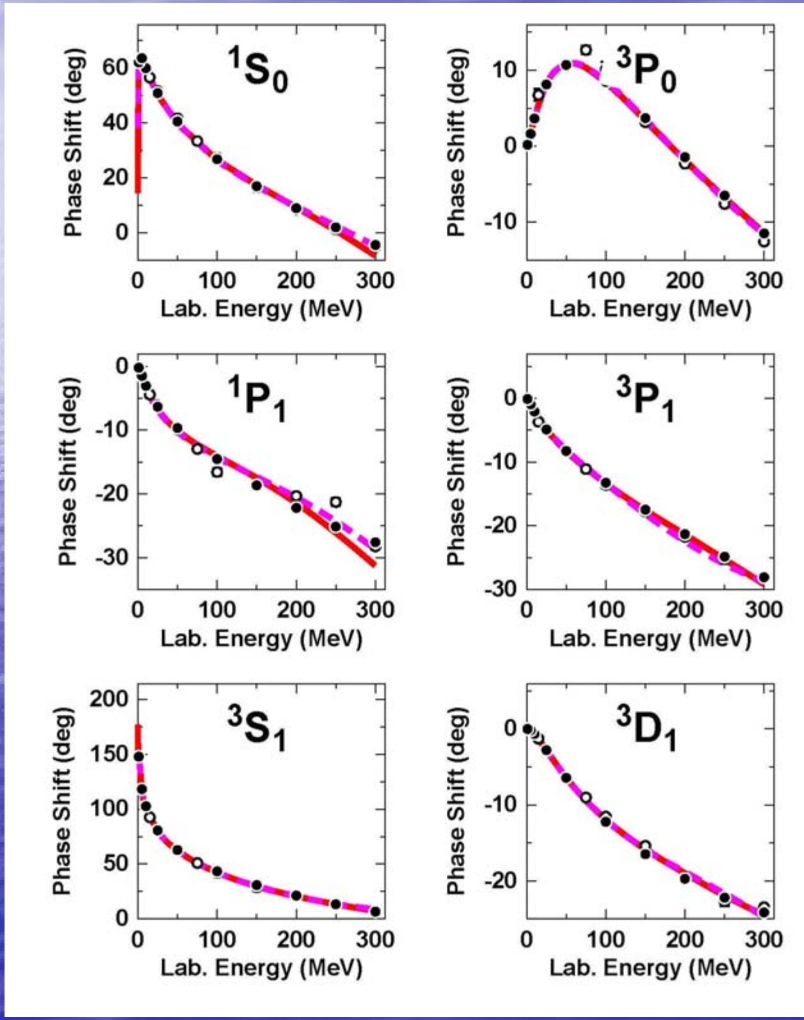
Phase shifts up to 300 MeV

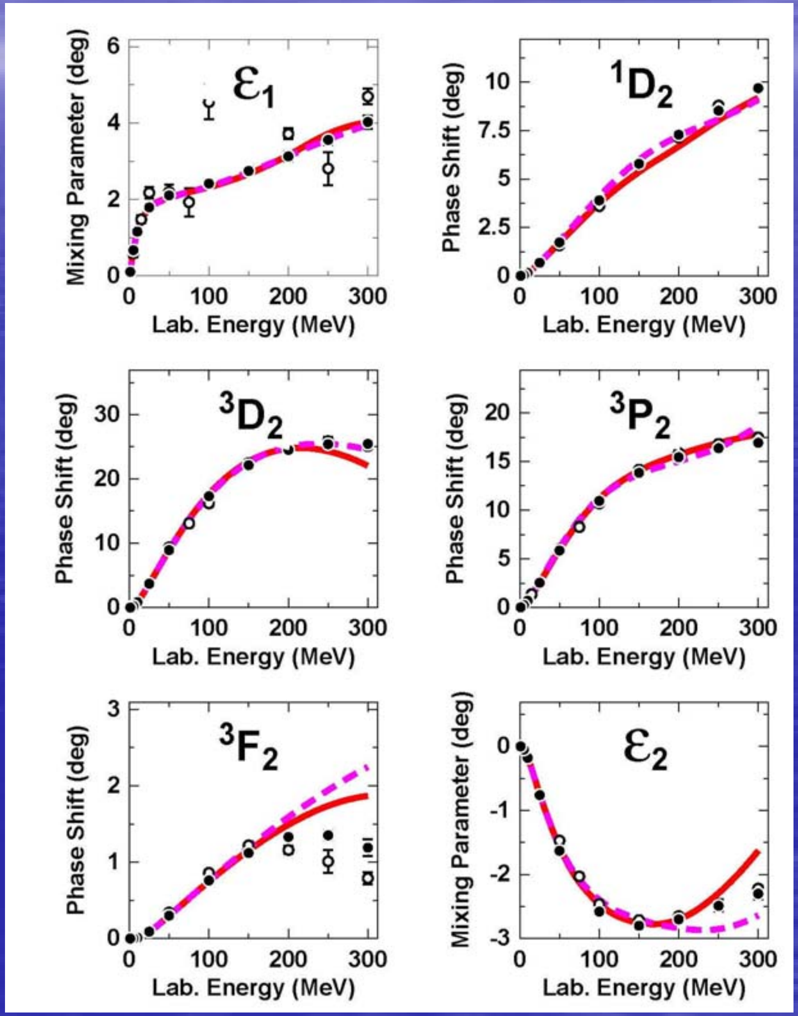
Red Line: N3LO by Entem & Machleidt





Variations of the Cutoff (500-600 MeV)





χ^2/datum for the reproduction of the 1999 *np* database

Bin (MeV)	# of data	N^3LO	NNLO	NLO	AV18
0–100	1058	1.06	1.71	5.20	0.95
100–190	501	1.08	12.9	49.3	1.10
190–290	843	1.15	19.2	68.3	1.11
0–290	2402	1.10	10.1	36.2	1.04

N3LO by Entem & Machleidt

Deuteron Properties

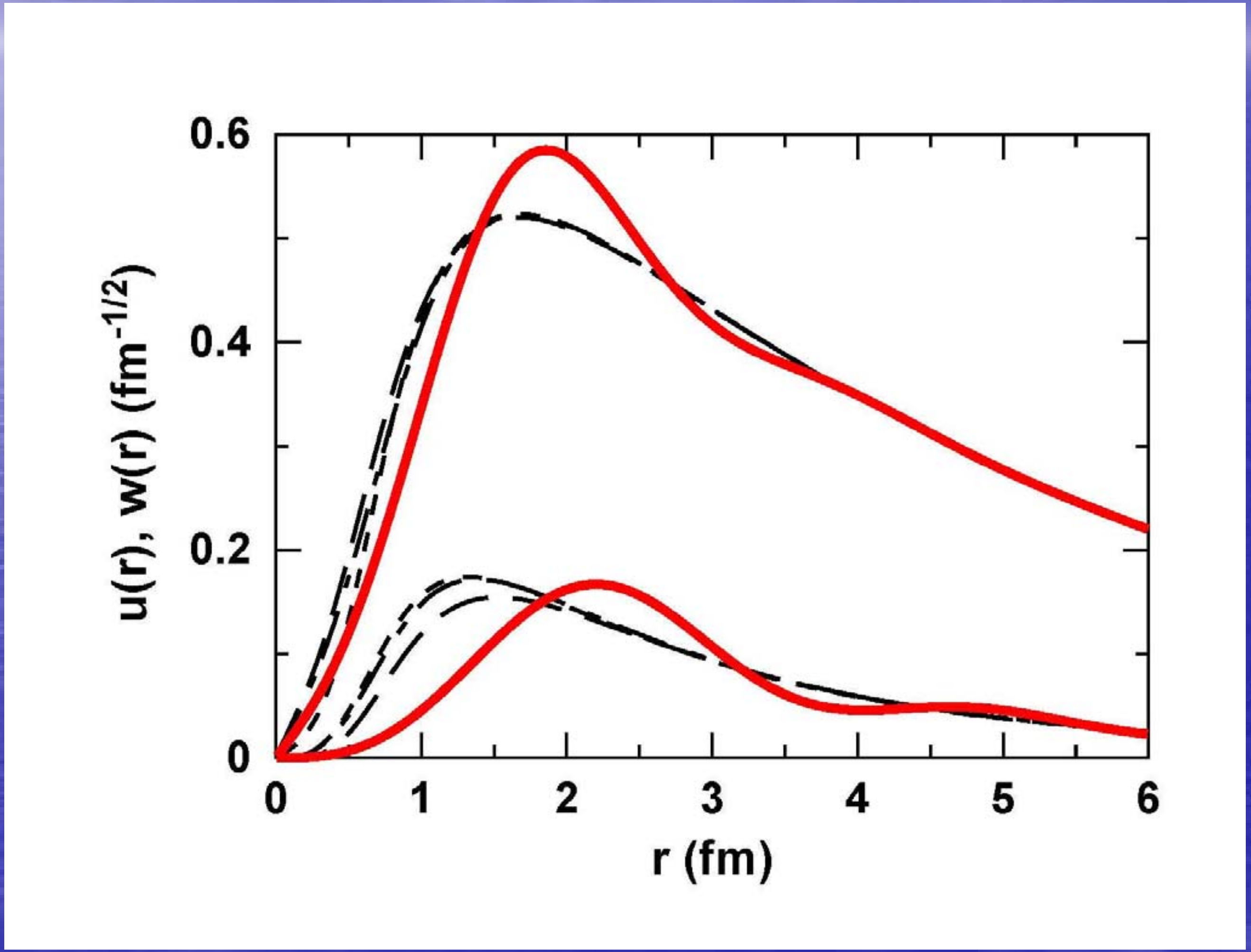
	N3LO	CD-Bonn	AV18	Empirical
Binding energy B_d (MeV)	2.224575	2.224575	2.224575	2.224575(9)
Asymptotic S state A_S ($\mathrm{fm}^{-1/2}$)	0.8843	0.8846	0.8850	0.8846(9)
Asymptotic D/S state η	0.0256	0.0256	0.0250	0.0256(4)
Matter radius r_d (fm)	1.978^a	1.970^a	1.971^a	1.9754(9)
Quadrupole moment Q_d (fm^2)	0.285^b	0.280^b	0.280^b	0.286(1)
D-state probability P_D (%)	4.51	4.85	5.76	

^{a} With MEC and rel. corrections (Friar, Martorell & Sprung).

^{b} Including MEC and rel. corrections in the amount of 0.010 fm^2 (Henning).

Deuteron Wave Functions

Red Line: N3LO



Summary
Status of NN at low energies

- Substantial progress in the past decade in terms of EFT
  for which this series of workshops has played a stimulating and crucial role
- A quantitative QCD-based theory;
  quantitative NN potentials - at N3LO
- Two- and many-body forces on an equal footing;
  at 3NF N2LO known, at N3LO under construction
- But there are **Open Questions:**

Renormalization

"I about got this one renormalized"

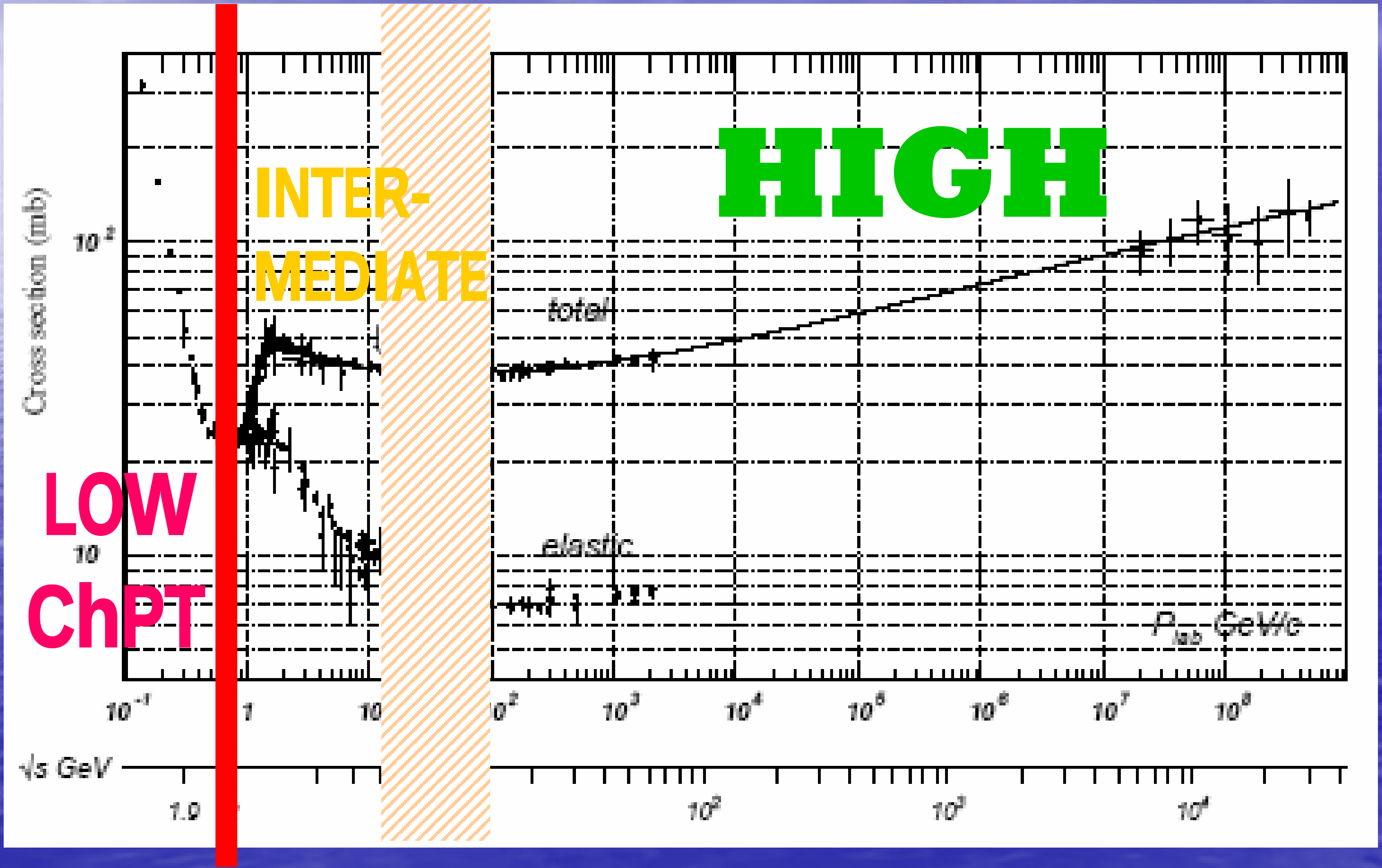
THE SINGLE MOST IMPORTANT OPEN QUESTION

Weinberg counting

or

Nogga counting?

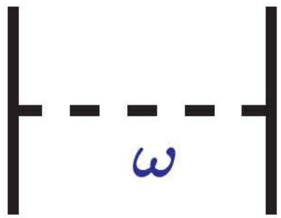
pp TOTAL CROSS SECTIONS



INTERMEDIATE ENERGIES
above about 0.4 MeV

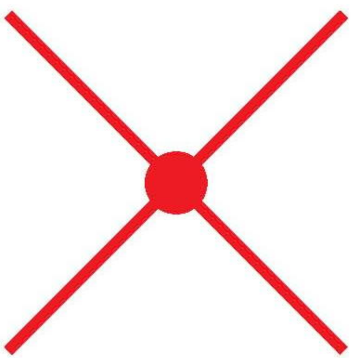
- Too high for ChPT
- Too low for perturbative QCD (pQCD)
- Lattice QCD
  … not very practical
- Build a model –
  a relativistic meson model (Franz Gross)

Resonance Saturation



$$\frac{1}{m_\omega^2+Q^2} \approx \frac{1}{m_\omega^2}\left[1 - \frac{Q^2}{m_\omega^2} + \frac{Q^4}{m_\omega^2} - \ldots\right.$$

χPT



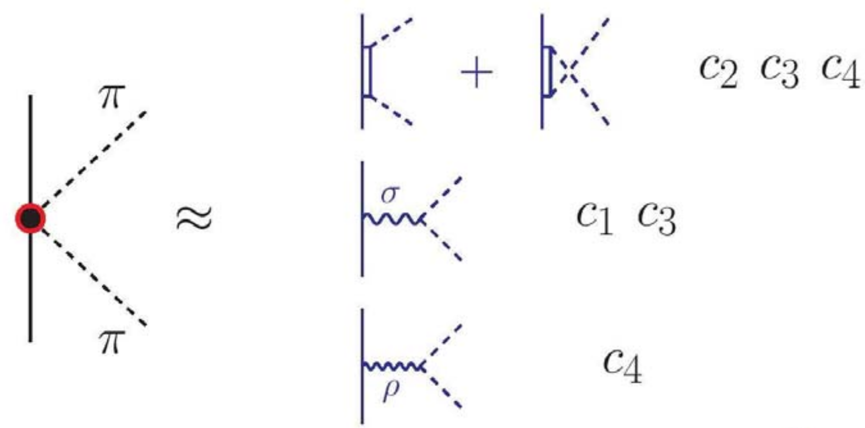
$$\equiv (Q^0, Q^2, Q^4, \ldots) \times \text{OPERATORS}$$

24 up to Q^4

Contact Terms

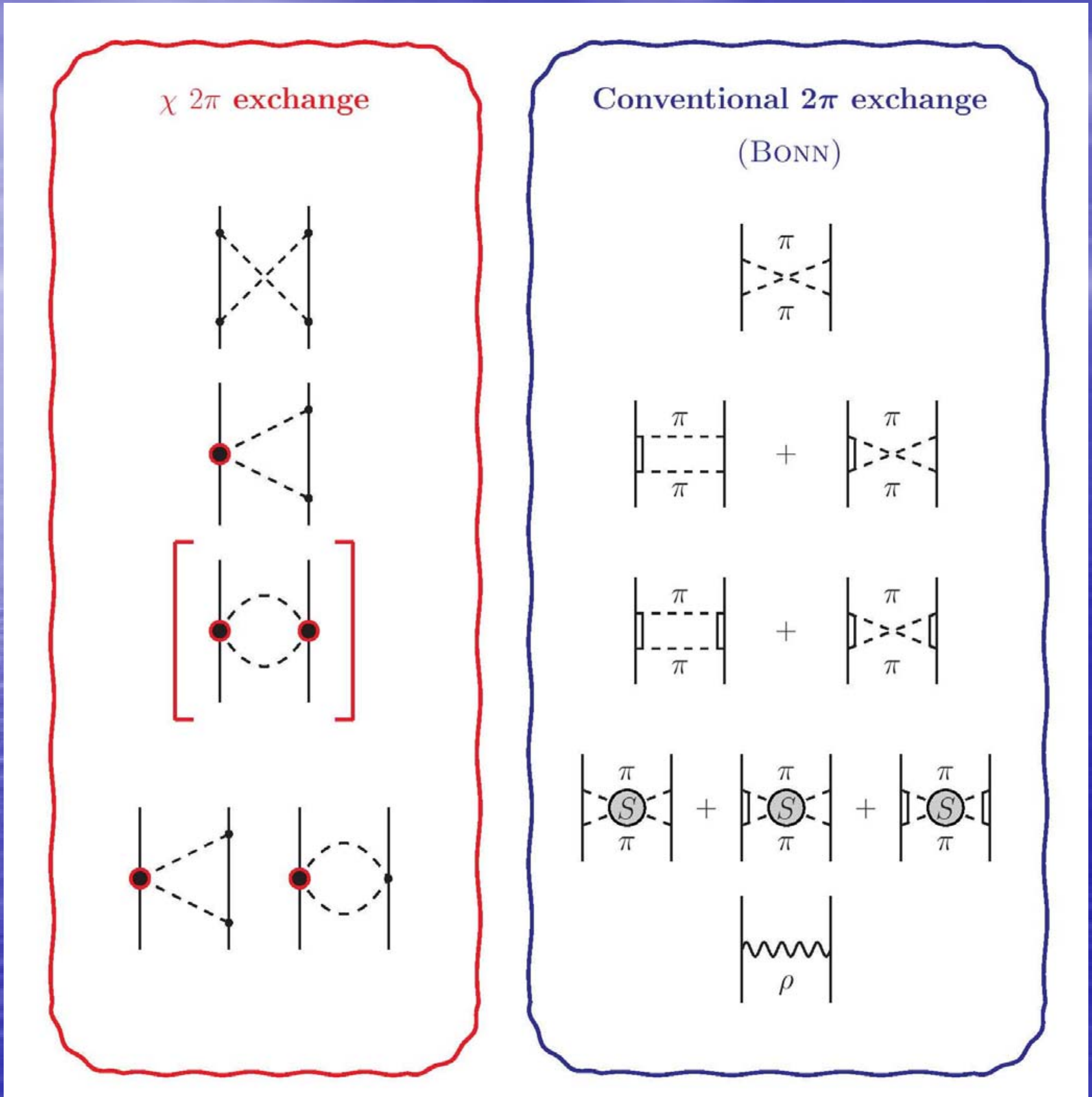
— The Lagrangian — two derivatives —

$$\mathcal{L}^{(2)}_{\pi N, c_i} = \bar{N}\Big[2\,c_1\,m_\pi^2\,(U+U^\dagger) + \left(c_2 - \frac{g_A^2}{8M_N}\right) u_0^2 + c_3\,u_\mu\,u^\mu + \frac{i}{2}\left(c_4 + \frac{1}{4M_N}\right)\vec{\sigma}\cdot(\vec{u}\times\vec{u})\Big] N$$



Bernard, Kaiser & Meißner

Resonance Saturation


χ 2π exchange
Conventional 2π exchange
(Bonn)
π
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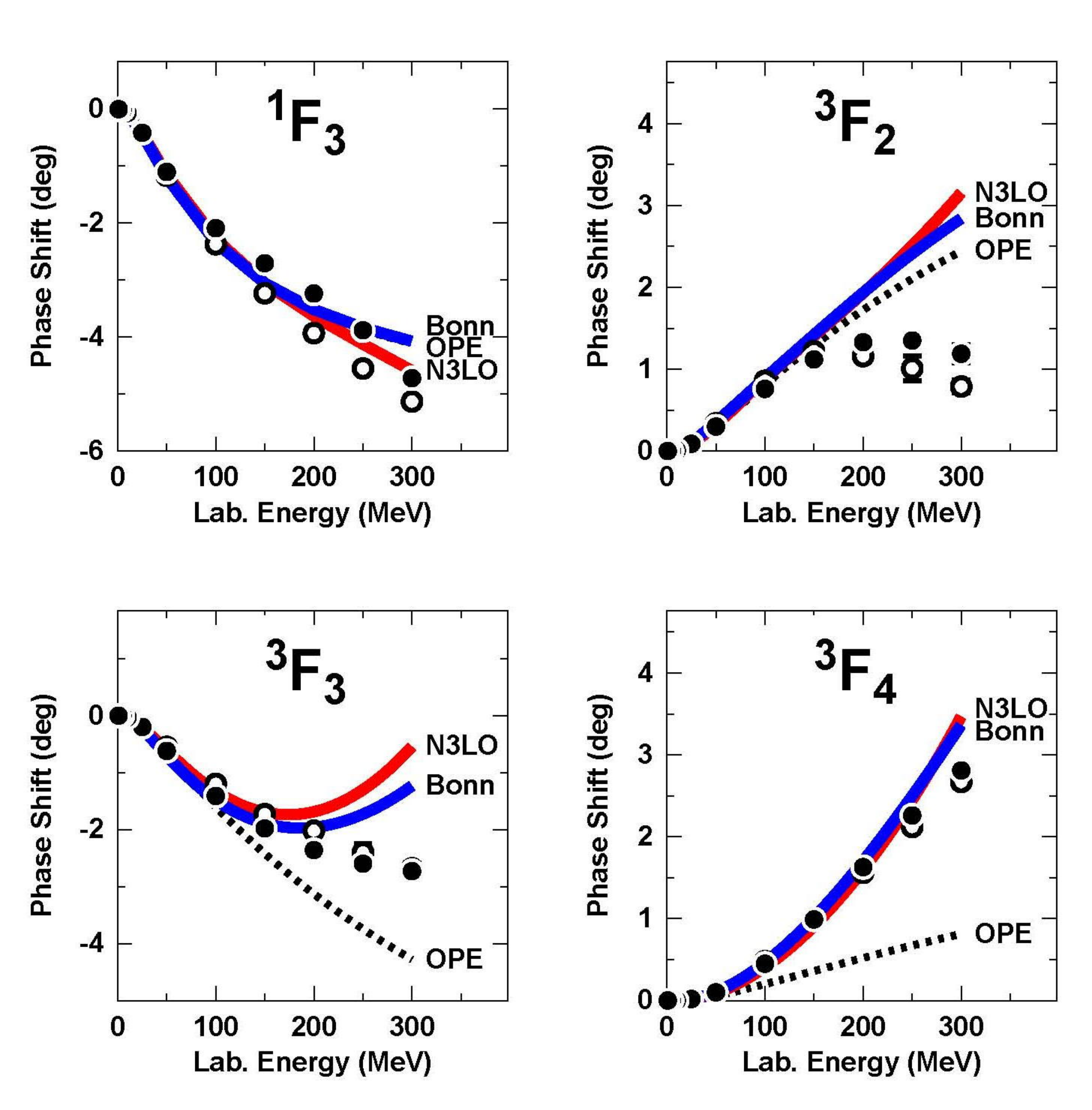
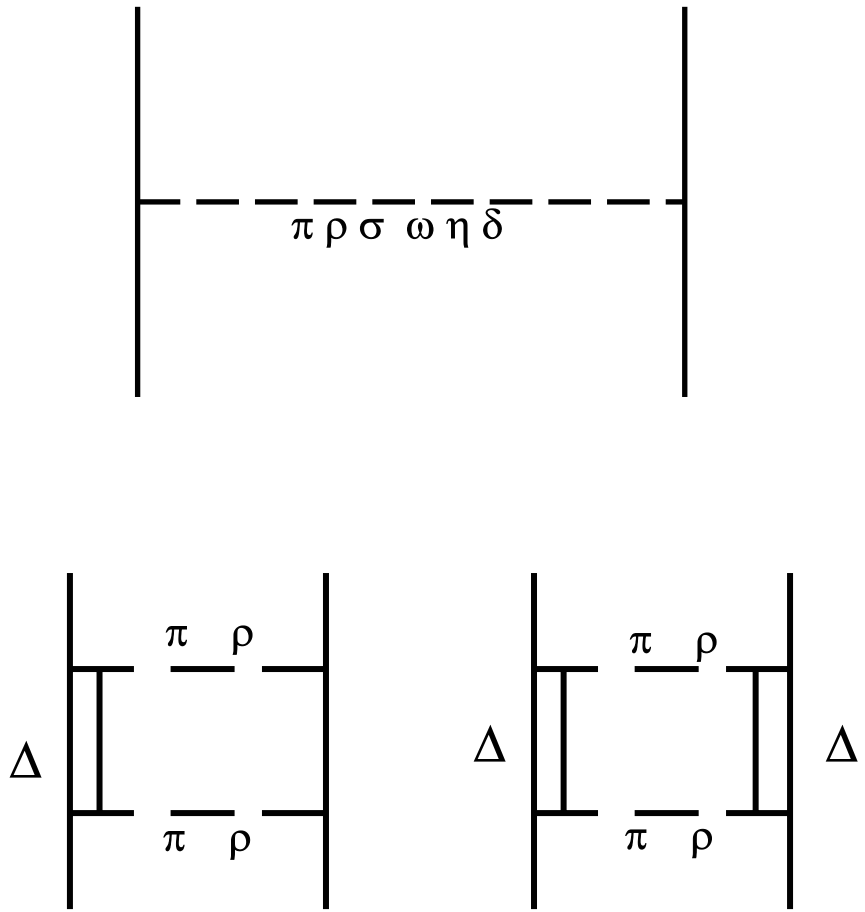
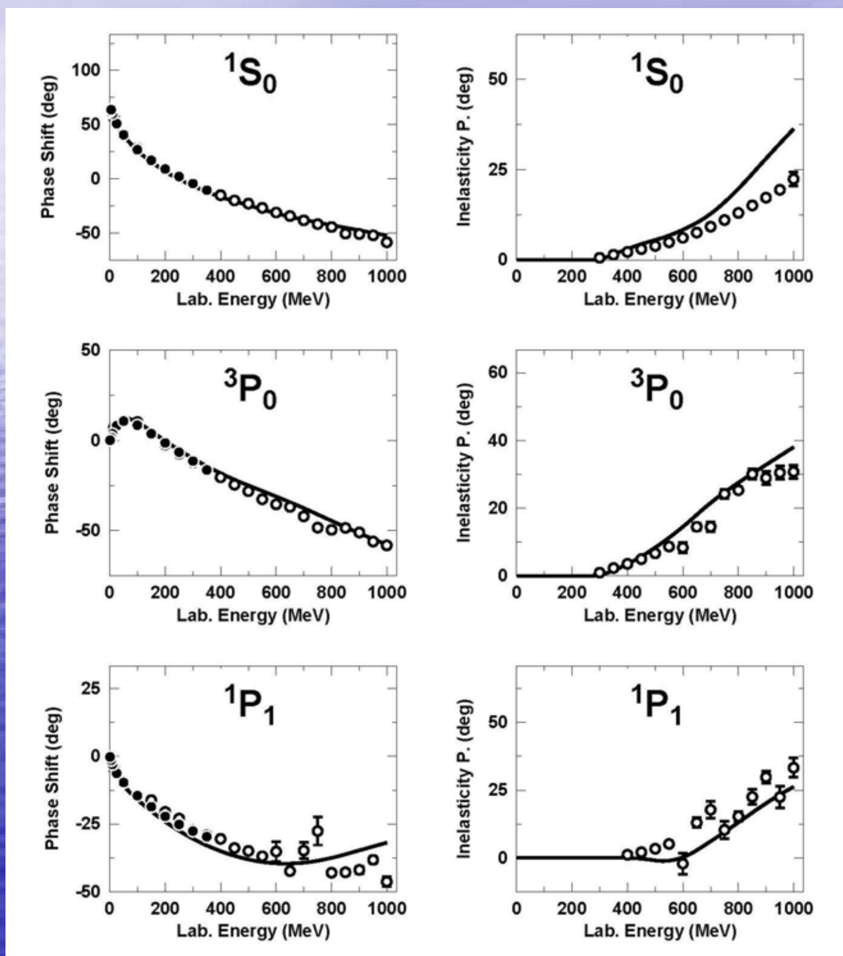


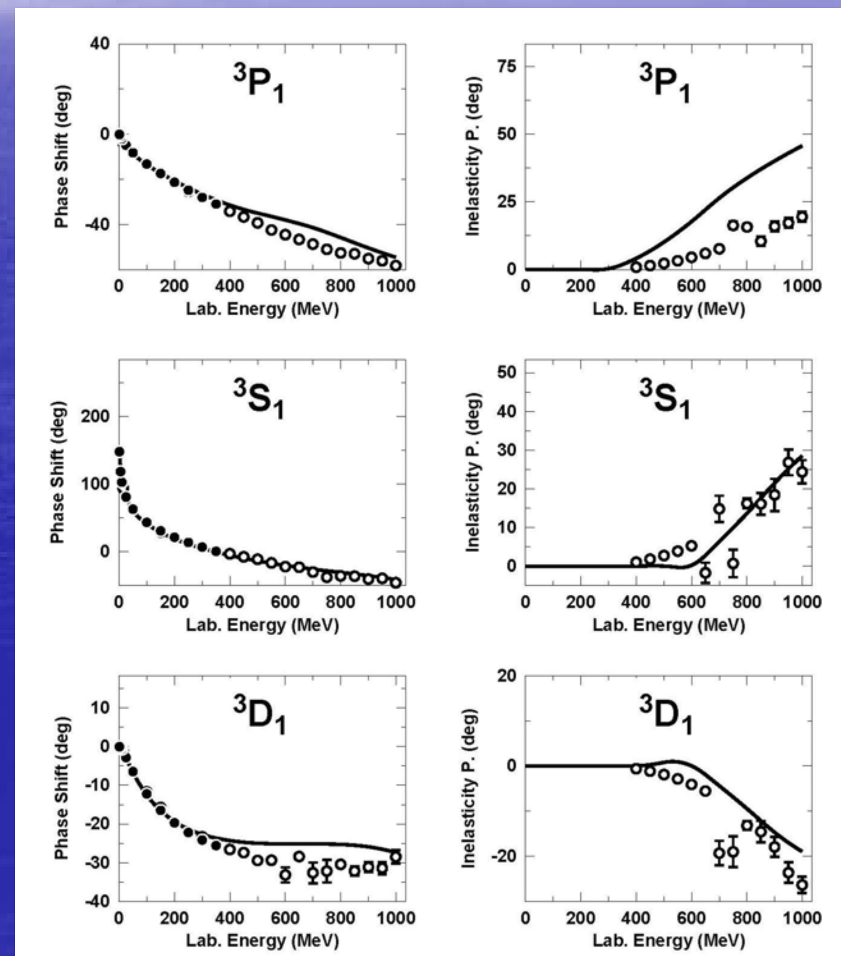
$^1F_3$
Bonn
OPE
N3LO
$^3F_2$
N3LO
Bonn
OPE
$^3F_3$
N3LO
Bonn
OPE
$^3F_4$
N3LO
Bonn
OPE
Phase Shift (deg)
Lab. Energy (MeV)

Meson model for intermediate energies

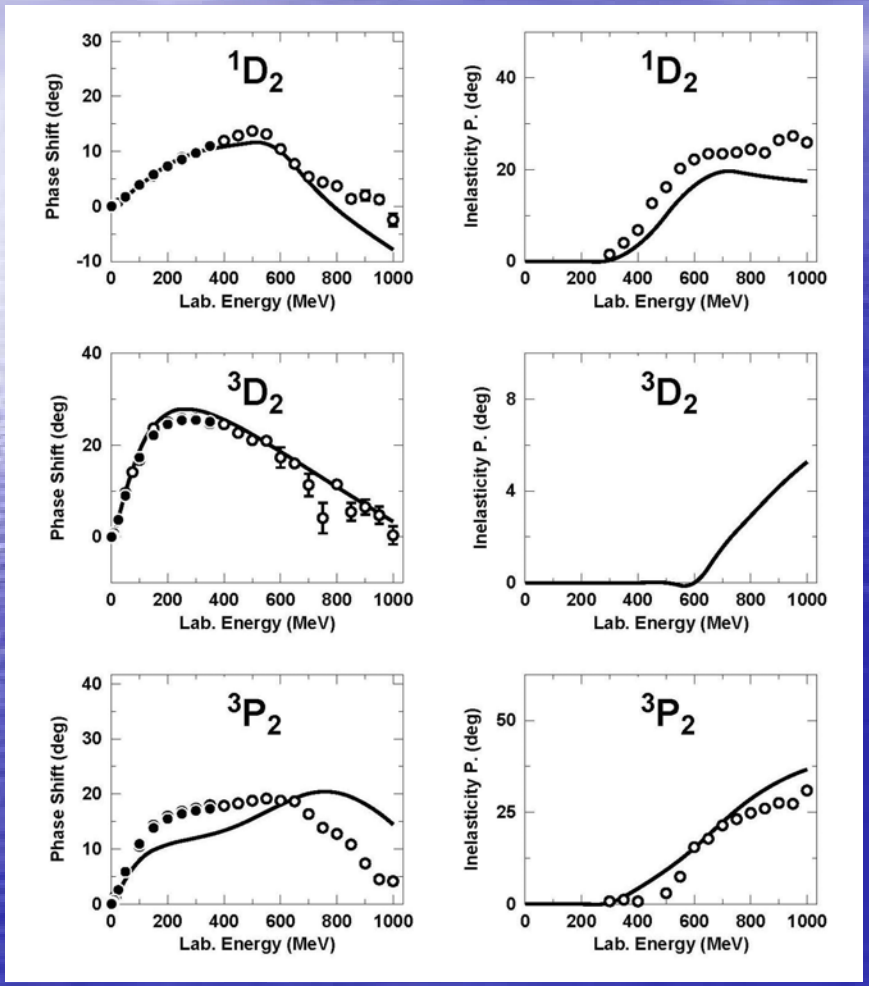


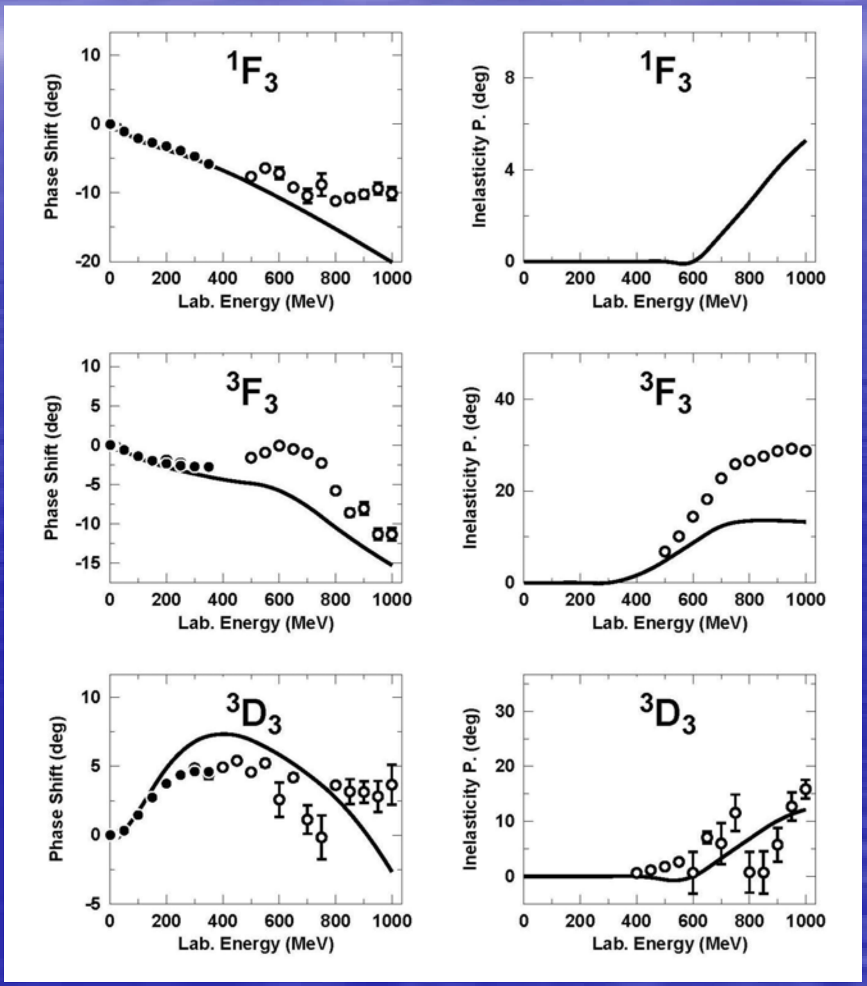
NN Phase shifts up to 1 GeV





Phase shifts, cont'd



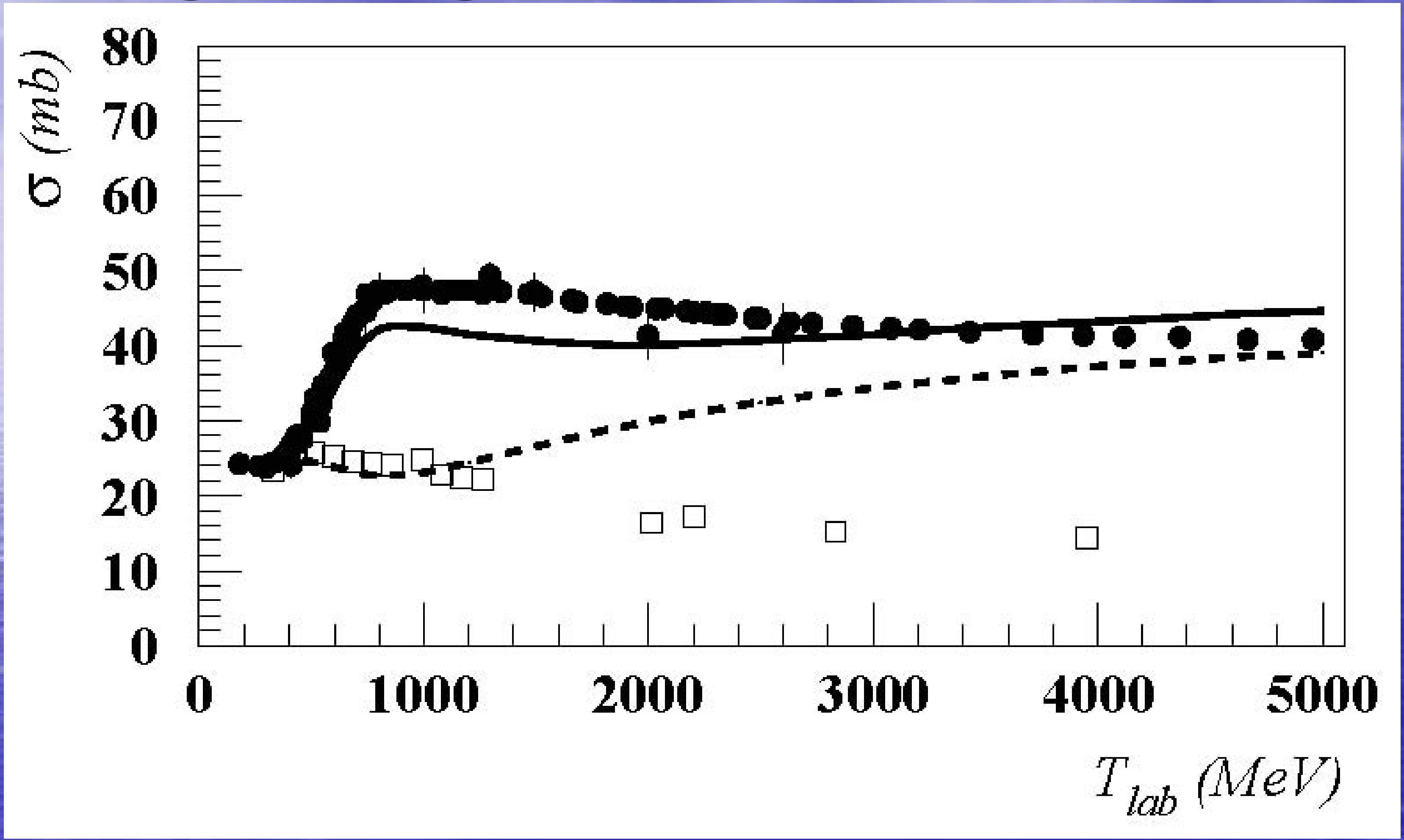


Summary up to about 1 GeV

Relativistic Meson Model quite adequate!

How about energies above 1 GeV?

Energy regime above 1 GeV.



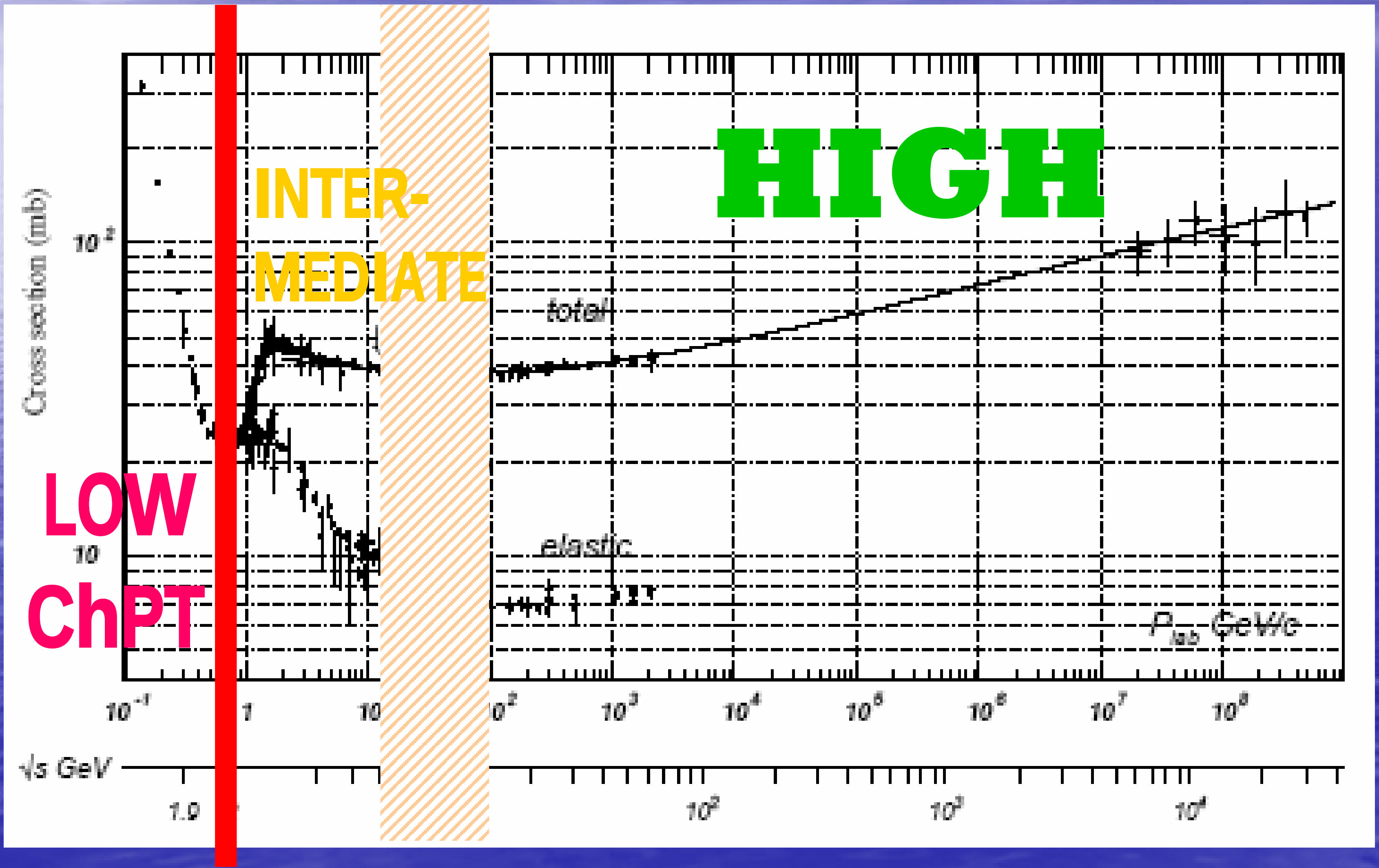
___ Total cross-section,

------- Total elastic cross-section

● Experimental data total cross-section,

□ Experimental data total elastic cross-section

pp TOTAL CROSS SECTIONS



Fixing the elastic cross-section

- The basic mathematical structure for one meson exchange is:

$$\bar{V}_\alpha \propto \frac{s^J}{t - m_\alpha^2}$$

S: total energy squared in the C.M.
J: spin of the exchange particle
t: square of four-momentum transfer

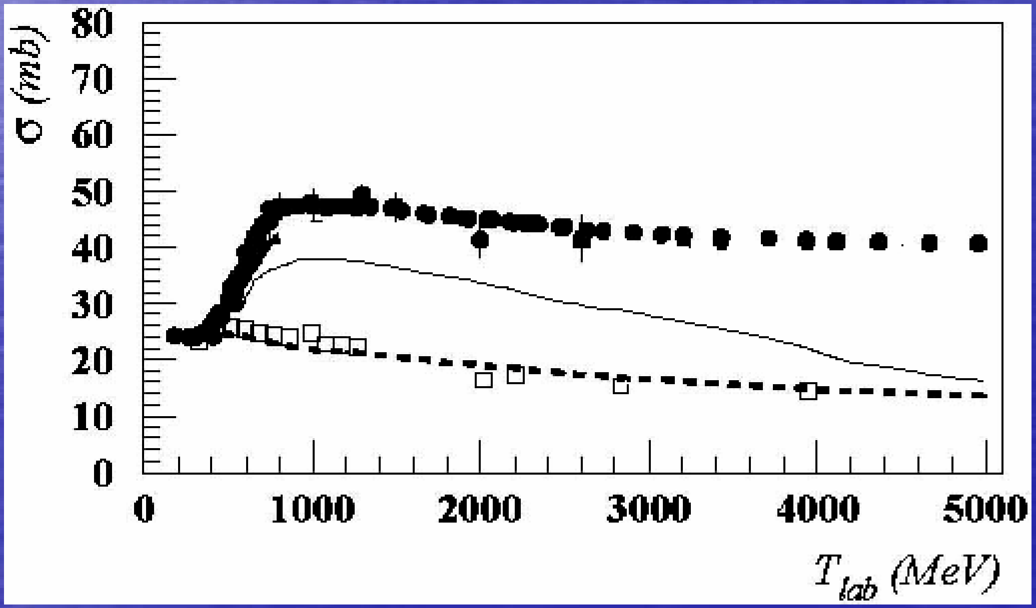
The vector mesons ρ and ω have J=1 which creates a rising cross-section with S, which is the basic reason for the rising cross-sections in the previous figure.

In the spirit of Regge theory: divide out the wrong s dependence

$$\overline{V}_\alpha \mapsto \frac{s_0}{s}\overline{V}_\alpha$$

$\alpha=\rho,\omega$

$s_0 \approx 4M^2$



Fixing the inelastic total cross-section

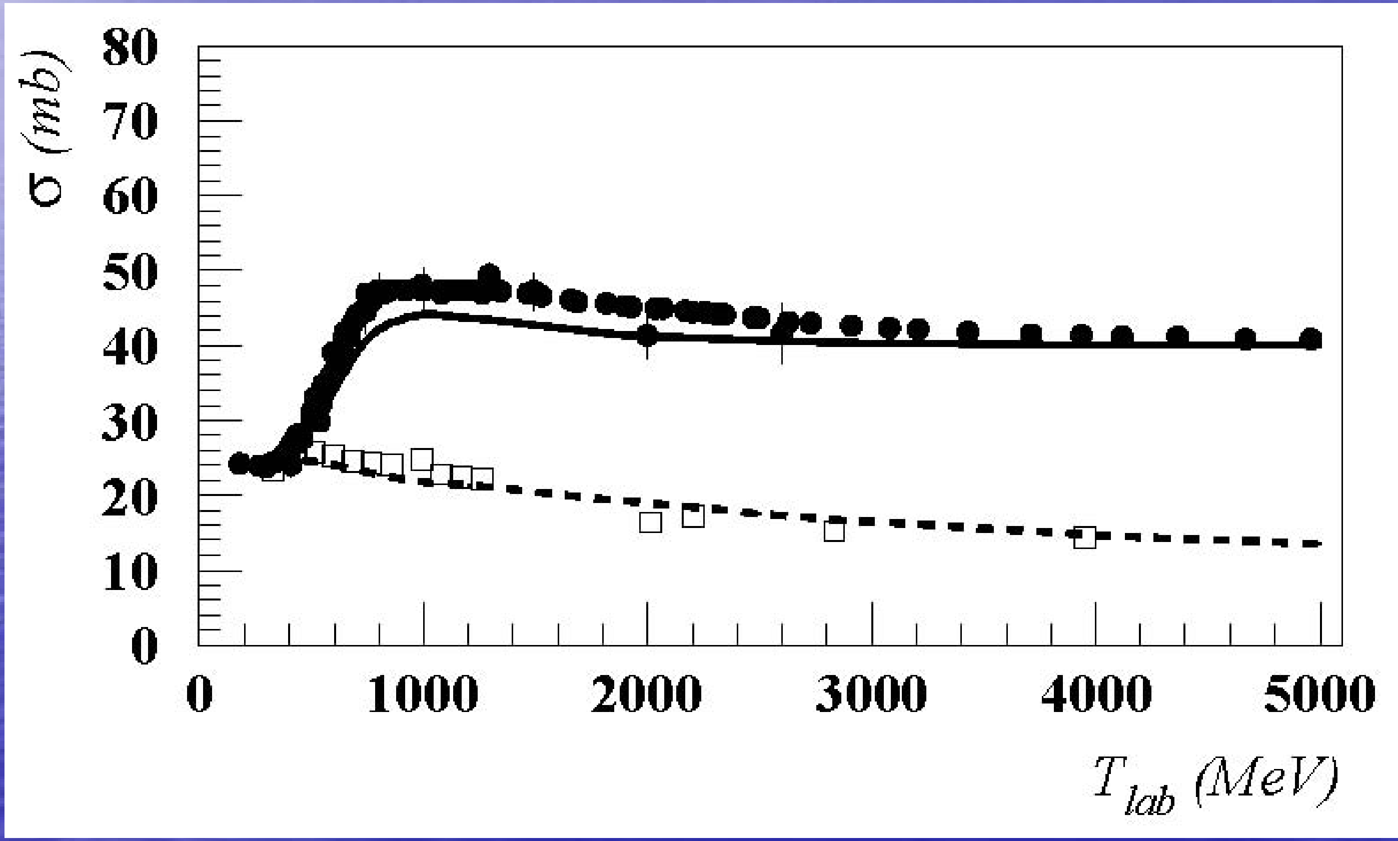
- For Tlab>1GeV the lack of inelasticity is not unexpected since other processes come into play which are not included in the present model.

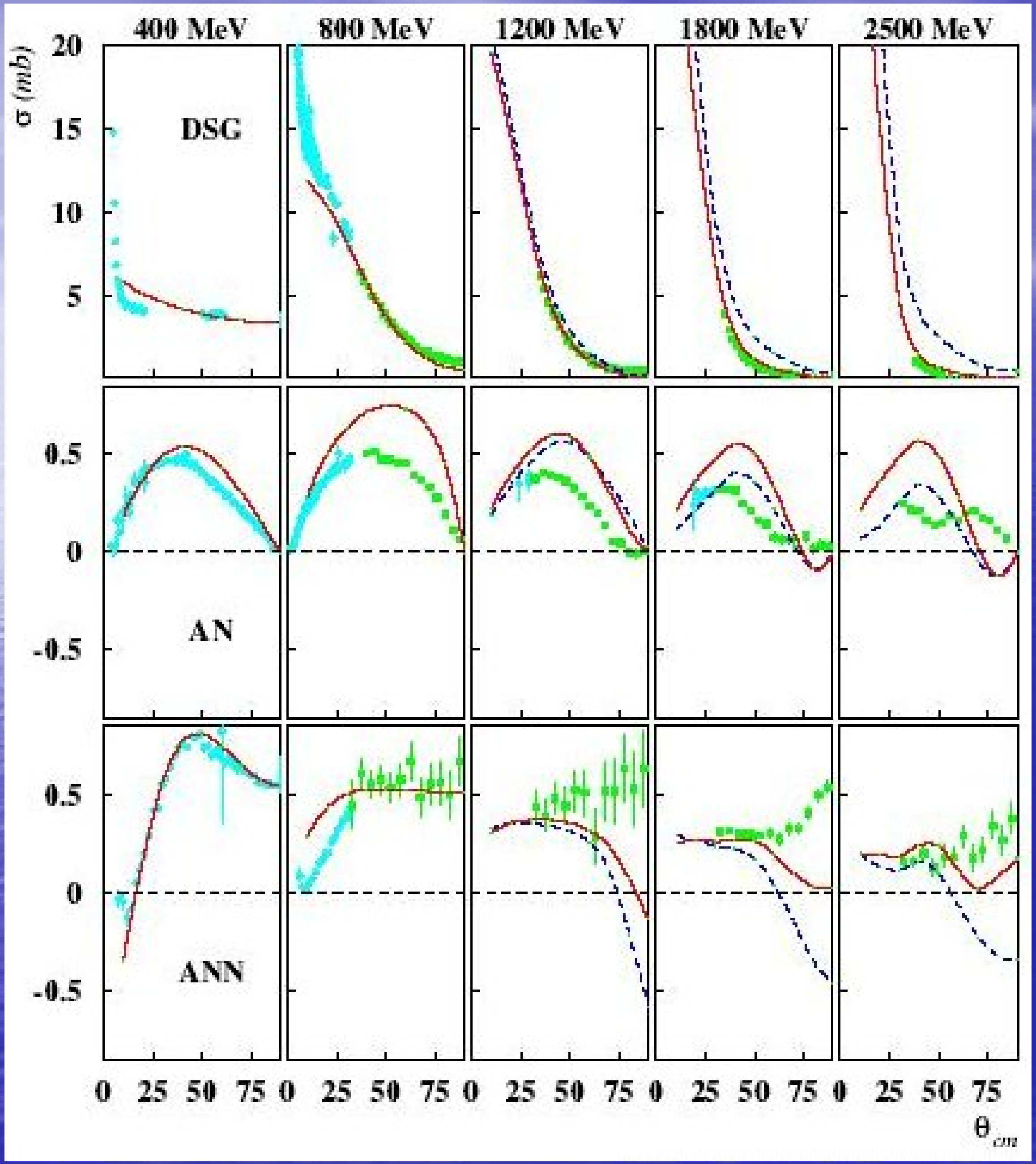
- It would be inefficient to take into account all the meson-nucleon resonances which open up above 1GeV since there are many.

- Since the inelastic cross-section is smooth and does not show any structures, a picture of many overlapping resonances and inelastic channels emerges. This suggests that further inelasticity can described by a smooth optical potential

$$\bar{V}_{opt}(r,s) = \left[\tilde{V}(s) + i\tilde{W}(s)\right]\exp\left(-\frac{r^2}{a^2}\right)$$

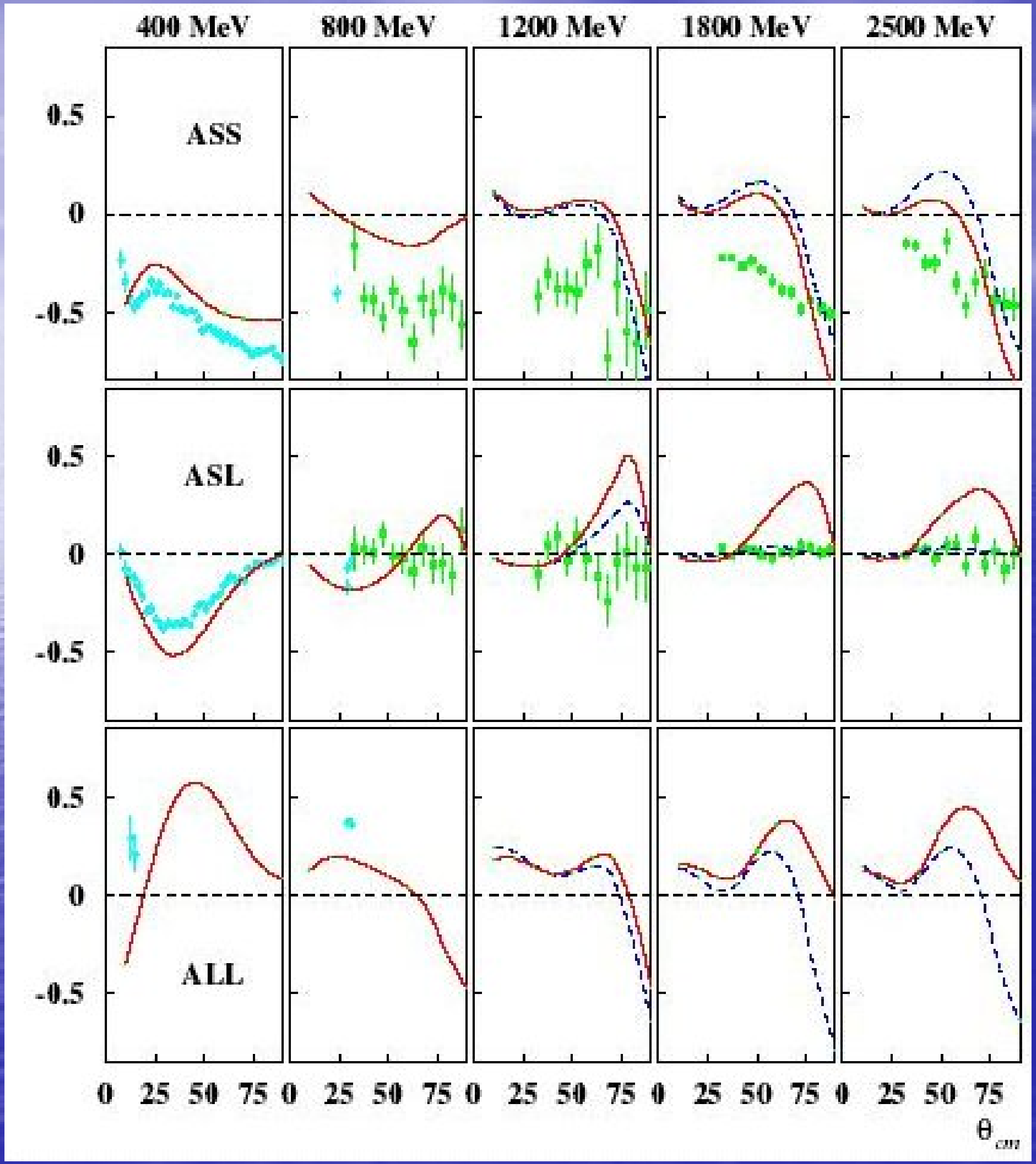
The modified meson model





Analyzing Power

Spin Correlation Coefficient



more **Spin Correlation Coefficients**

Green Data by EDDA Group COSY, Juelich Germany

Summary for intermediate energies

- Total cross sections easy to explain.
- Spin observables: Big Problems!
- Meson models inadequate above 1 GeV.
- **Perturbative QCD (pQCD)?**

  pQCD predicts vanishing Analyzing Power, but we observe large spin effects up to high energies!

  Non-perturbative, but we do not know how to model it

Analyzing Powers at 11.75, 18.5, and 28 GeV/c

(Alan Krisch & Co, 1980's)

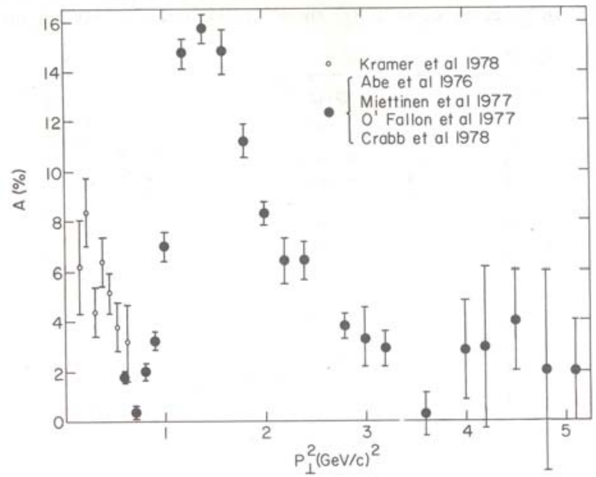


Figure 10 The analyzing power A for p-p elastic scattering at 11.75 GeV/c is plotted against $P_\perp^2$.

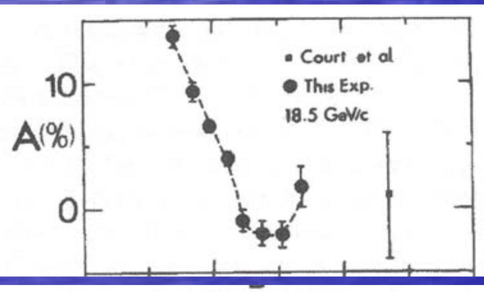


FIG. 2. Plot of the analyzing power A and the spin-spin correlation parameter A_{nn} as functions of momentum transfer squared for proton-proton elastic scattering at 18.5 GeV/c. The error bars include both statistical and systematic errors. The dashed lines are hand-drawn curves to guide the eye.

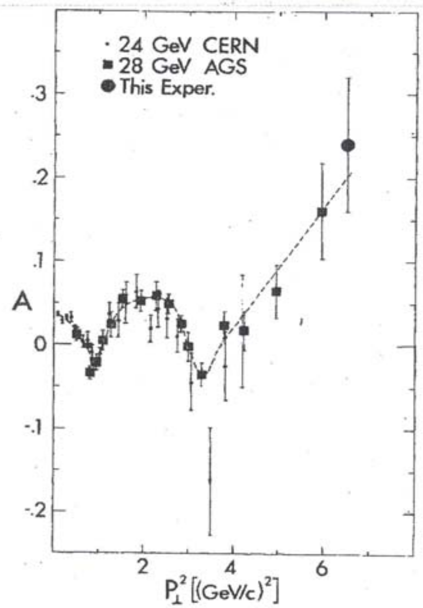


FIG. 2. Analyzing power for proton-proton elastic scattering plotted as a function of $P_\perp^2$. Some adjacent AGS data points have been combined. The curve is a hand-drawn line to guide the eye.

Spin correlation coefficient

A_{NN}

2 to 18.5 GeV/c

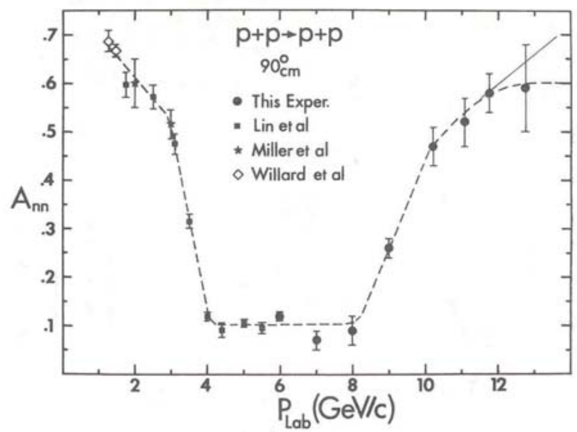


Figure 11 The spin-spin correlation parameter A_{nn} for p-p elastic scattering at 90° in the center of mass is plotted against the incident lab momentum. The curve is hand-drawn to guide the eye. Circles refer to the data of Crosbie et al (1981).

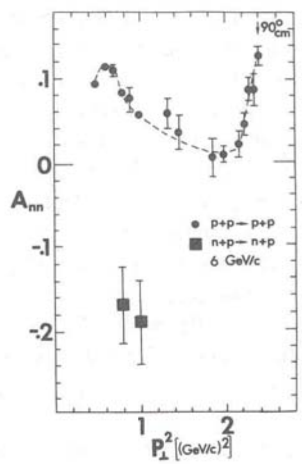


Figure 15 The spin-spin correlation parameter A_{nn} for n-p and p-p elastic scattering at 6 GeV/c is plotted against $P_{\perp}^2$.

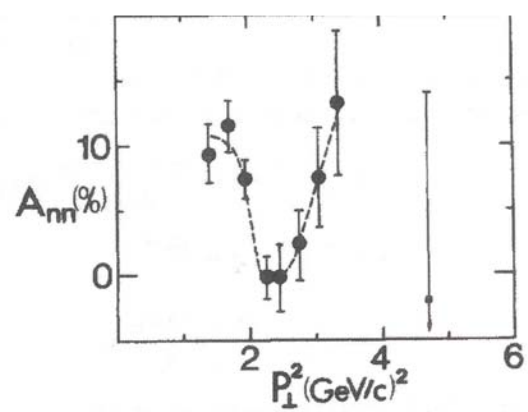
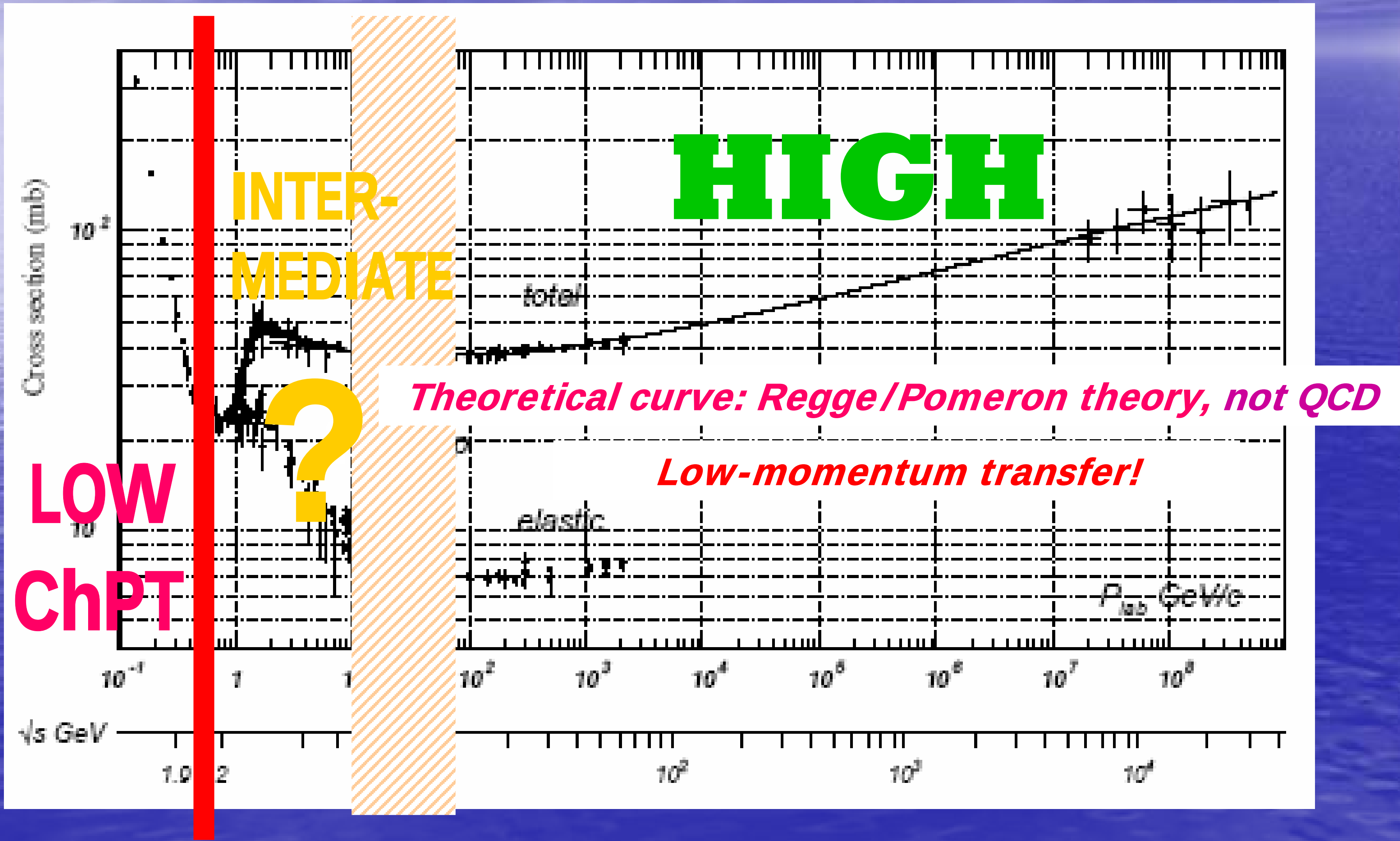


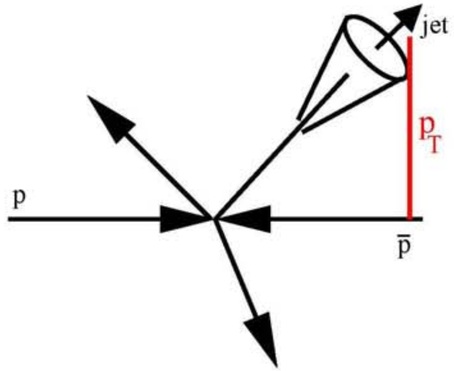
FIG. 2. Plot of the analyzing power A and the spin-spin correlation parameter A_{nn} as functions of momentum transfer squared for proton-proton elastic scattering at 18.5 GeV/c. The error bars include both statistical and systematic errors. The dashed lines are hand-drawn curves to guide the eye.

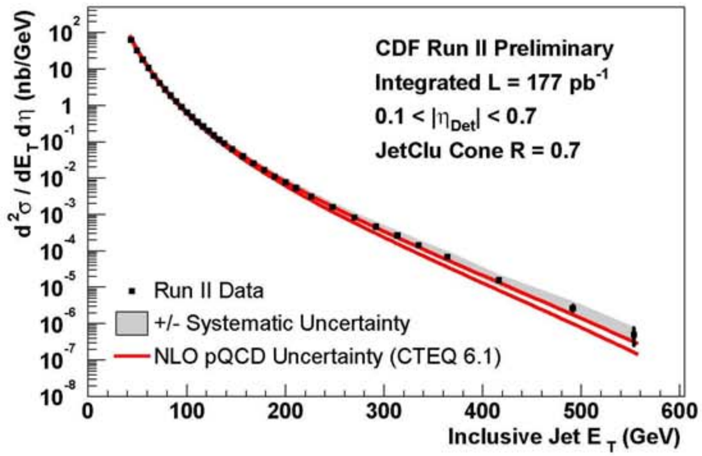
Summary up to intermediate energies

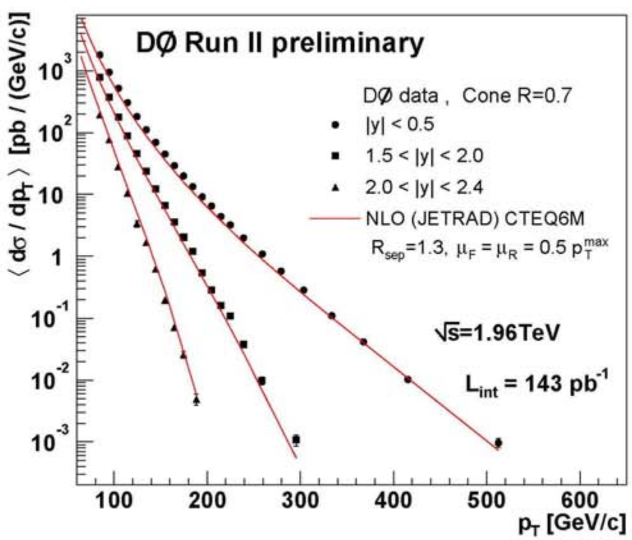


Does pQCD ever apply?

Fermilab's TeVatron: Jet Production







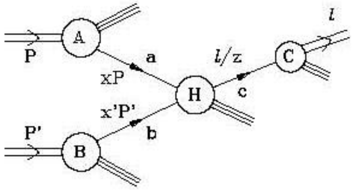
- jet cross section in agreement with expectations from pert. QCD calculations
- similar for other processes: heavy flavors, prompt photons, electroweak bosons, . . .

RHIC and A_N

A_N in brief:

- exciting observable, goes back to the early days of spin:

$$A(p, \vec{s}_T) + B(p') \to C(l) + X \text{ with } C \text{ '=' high-}p_T\ \pi, \gamma, \ldots$$

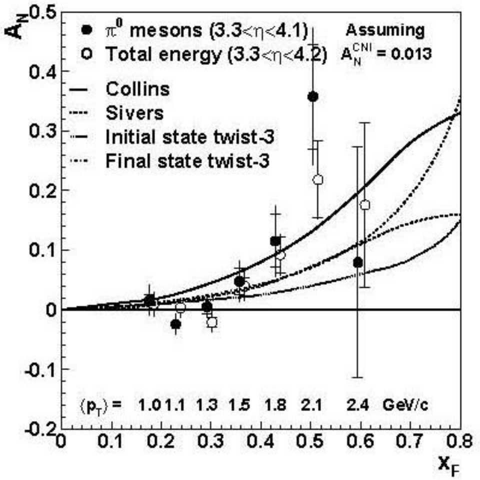


$$\text{measure}: \ A_N = \frac{\Delta_N \sigma}{\sigma} \equiv \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}$$

- leading-twist pQCD: $A_N = 0$ but large A_N found experimentally ever since

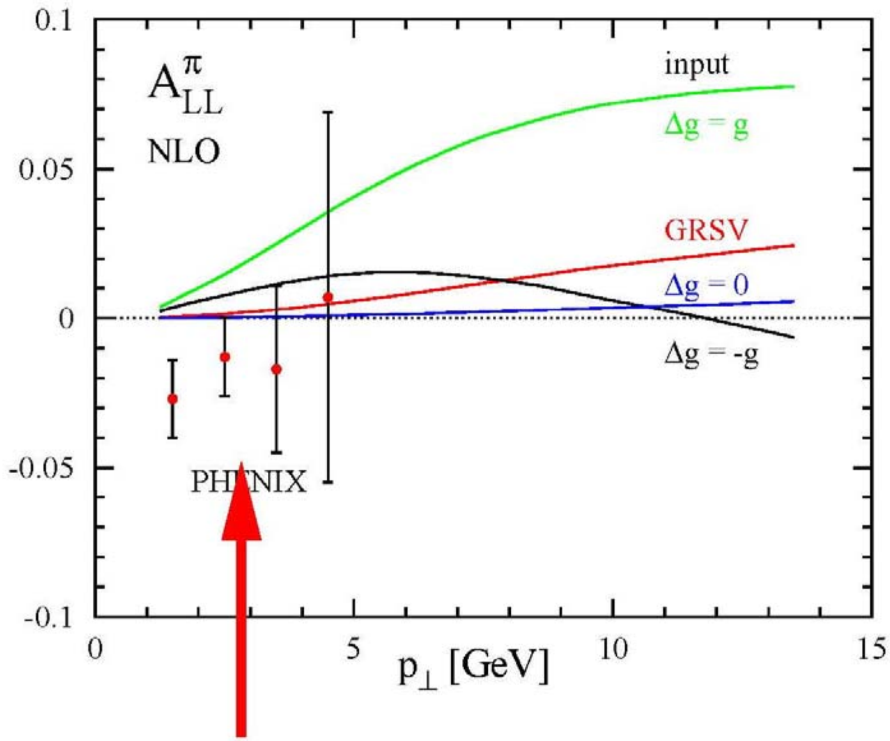
$\rightarrow$ explanation requires new non-perturbative objects

for the 1^{st} time also seen at $\sqrt{S} = 200\,\text{GeV}$ by STAR



RHIC: π_0 production in $\vec{p}\vec{p}$ at $\sqrt{s} = 200\,GeV$

recent exciting development: first results on A_{LL} by PHENIX

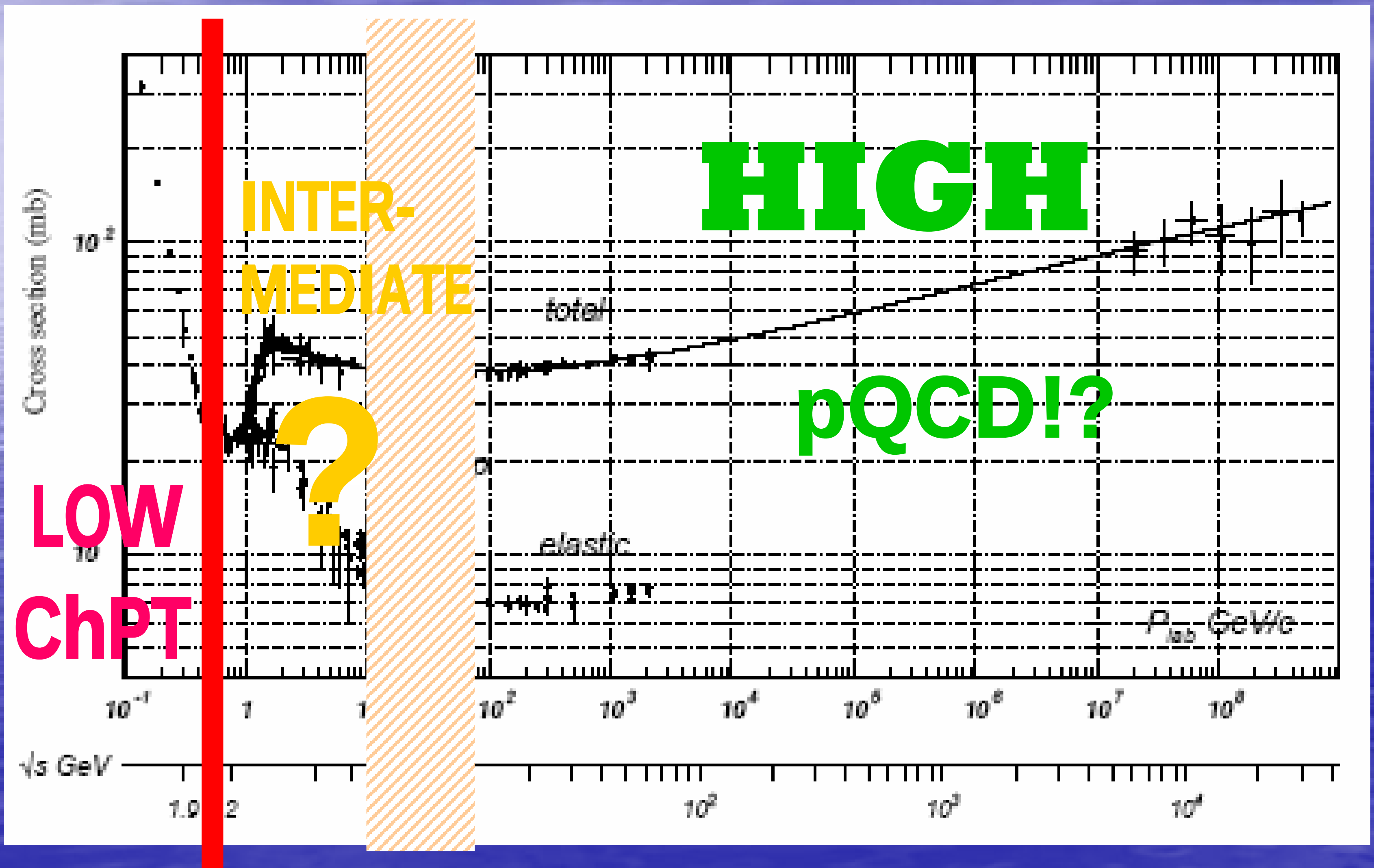


trend for $A_{LL} < 0$ at small p_T contrary to expectations

“pp2pp” proposal for RHIC

Measure polarized pp elastic between 50 and 500 GeV

Summary



HIGH
pQCD!?
INTER-
MEDIATE
?
LOW
ChPT
Cross section (mb)
total
elastic
P_{lab} GeV/c
√s GeV

Conclusion 1

In contrast to common perception:

The NN interaction at low energies is understood best!

Conclusion 2

The question

“Nuclear Forces and QCD: Never the Twain Shall Meet?”

can rightfully be raised at

all energies.

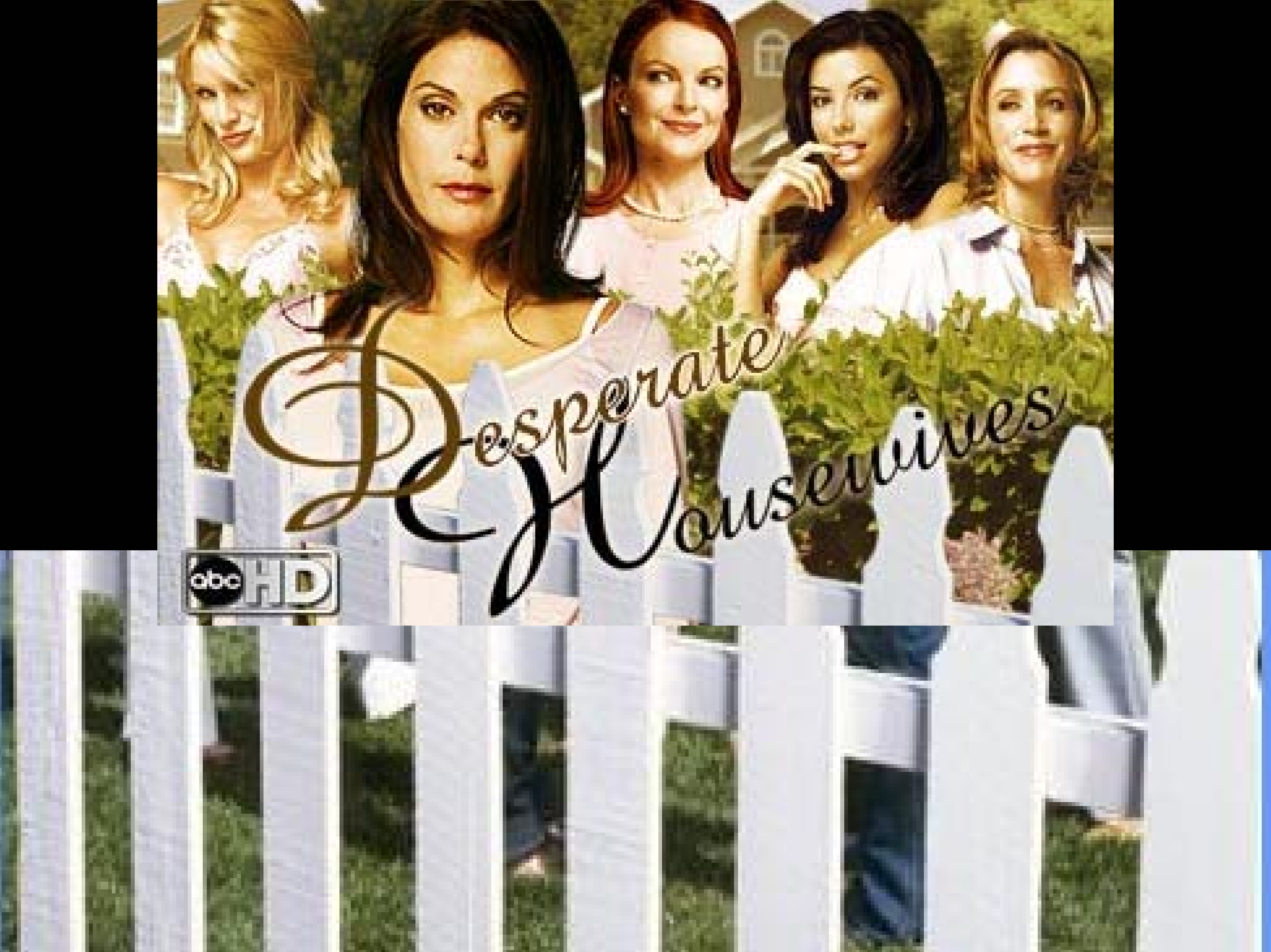
… and the ultimate conclusion

The world behind the fence of your backyard is

attractive,

but not under control,

quite like …


Desperate Housewives
abc HD