The Past and the Future: This talk will give a broad overview, incl. role of hadrons, hadron reaction phenomenology, past achievements and future goals

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http://www.indiana.edu/~ssrt/

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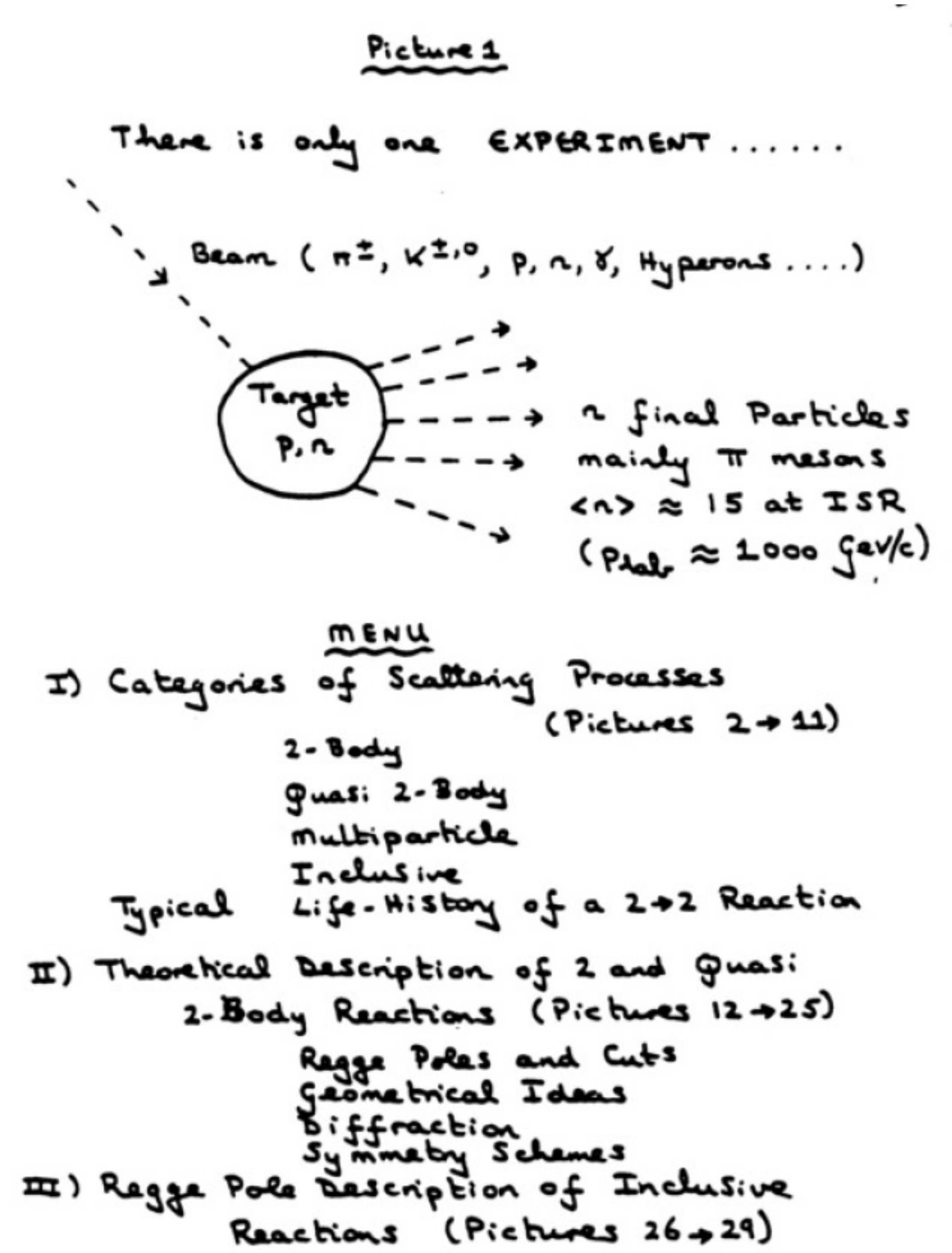
LOW TRANSVERSE MOMENTUM SCATTERING



Picture 1

There is only one EXPERIMENT ......

Beam ($\pi^{\pm}$, $K^{\pm,0}$, p, n, γ, Hyperons ....)

Target

p, n

n final Particles

mainly π mesons

$\langle n \rangle \approx 15$ at ISR

($P_{lab} \approx 1000$ GeV/c)

MENU

I) Categories of Scattering Processes

(Pictures 2 → 11)

2-Body

Quasi 2-Body

Multiparticle

Inclusive

Typical Life-History of a 2→2 Reaction

II) Theoretical Description of 2 and Quasi 2-Body Reactions (Pictures 12→25)

Regge Poles and Cuts

Geometrical Ideas

Diffraction

Symmetry Schemes

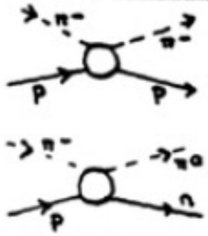
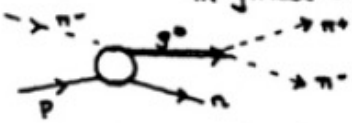
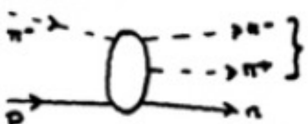
III) Regge Pole Description of Inclusive Reactions (Pictures 26→29)

PICTUREBOOK 1975

- Interesting that my classification ignored the dominant experiments in following 30 years that focused on "hard" not "soft" low transverse momentum physics
- At this time I was working on three Fermilab experiments E110, E260, E350 where I wrote most of analysis and Monte Carlo software
- Around 1981 I switched to "computer science" although data analysis continued till 1984
- My dream "E110" essentially failed as not enough data

SCATTERING PROCESSES

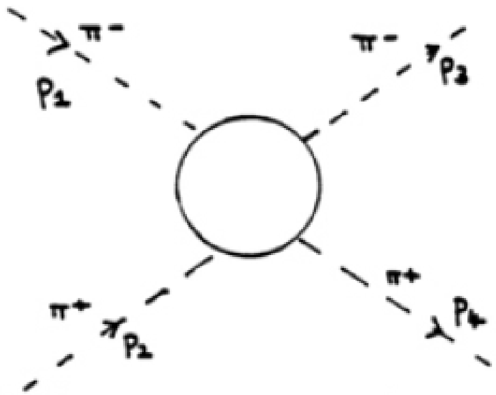
Picture 2

Scattering Process	Observables	Approx. Number of Species measured	% of Cross-Section: Low Energy	% of Cross-Section: 2 GeV/c	% of Cross-Section: High Energy
2 → 2 (Stable)  roughly constant with energy; falls like 1/energy$^{1.5}$	σ_{total}, $d\sigma/dt$, Polarization, R and A	40	ALL	25 %	20 %
2 → Quasi 2 (Resonances in final state)  most Fall with Energy	$d\sigma/dt$, Decay Density matrix elements	400	NONE	75 %	ZERO To 20 %
Genuine Multiparticle Events (2 → n)  most Fall with Energy	Production Cross-Section, Differential Cross-Section Has 3n−4 Variables	2000	NONE	NONE	60 % to 80 %
Inclusive Reactions (Roughly constant with energy) 	$\frac{d^2\sigma}{dp_L\, d(p_T^2)}$	40	ALL	ALL	ALL

- The original Picturebook was part of a series produced by Caltech particle physics group
  - I don't have others
- I started as a theorist or phenomenologist but decided to join experiments "for real" as I though best to analyze raw events rather than let experimentalists make a model which was often different from what I would expect and then present "experimental" results based on model

<u>Picture 3 : SPINLESS SCATTERING</u>

e.g. $\pi^+\pi^- \to \pi^+\pi^-$



is described by one complex amplitude $A(s,t)$

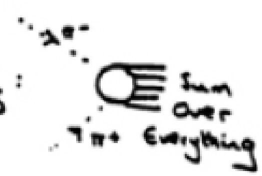
(π^+'s are not available as a target - this is only a theorists dream of a reaction !)

$s = (p_1+p_2)^2$ corresponds to laboratory momentum of incident beam

$t = (p_1-p_3)^2$ corresponds to laboratory Scattering angle of particle 1 to 3.

<u>OBSERVABLES</u>

Total Cross-Section $(\sigma_{total}) \propto \operatorname{Im} A(s,t=0)/s$:



Differential Cross-Section $d\sigma/dt \propto \frac{1}{s^2}\{\operatorname{Re} A(s,t)^2 + \operatorname{Im} A(s,t)^2\}$

<u>TODAYS PROBLEM</u>

WHAT (Experimental) and WHY (Theoretical) is dependence of Re A and Im A on S and t.

AMPLITUDES FOR SPINLESS SCATTERING

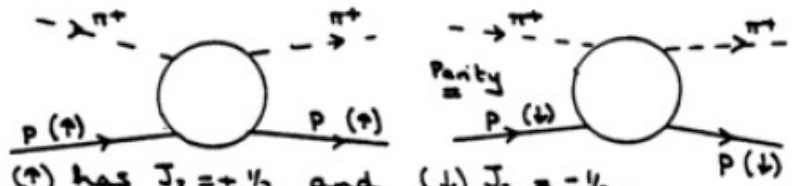
- At time QCD calculations only just starting and we had no realistic expectation of calculating amplitudes from first principles
- We could hope to derive some features (constraints) from first principles
- S-matrix theory hoped that constraints would be enough to define a "unique" answers

Picture 4: Spin ½, Spin 0 Elastic Scattering

e.g. $\pi^+ p \to \pi^+ p$

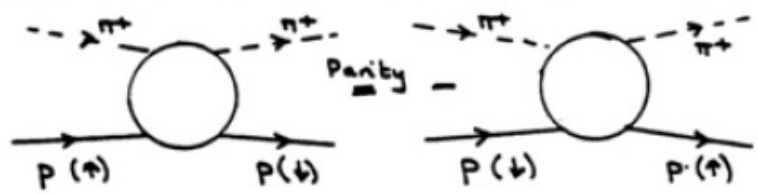
Two Complex Amplitudes $N(s,t)$ and $F(s,t)$ describe process:

$N(s,t)$ is Spin Nonflip Amplitude



where spin state (↑) has $J_3 = +\frac{1}{2}$ and (↓) $J_z = -\frac{1}{2}$.

$F(s,t)$ is Spin Flip Amplitude



OBSERVABLES

$\sigma_{total} \propto \mathrm{Im}\, N(s,t=0)/s$ as simple as spinless case

$d\sigma/dt \propto \{\mathrm{Re}N^2 + \mathrm{Im}N^2 + \mathrm{Re}F^2 + \mathrm{Im}F^2\}/s^2$ which is twice as complicated as spinless example. There are extra observables which use polarized targets and/or observe the polarization (spin) of the final nucleon.

$P\, d\sigma/dt \propto 2\,\mathrm{Im}(NF^*)$: data good for elastic scattering : reasonable for charge exchange processes.

Polarize one particle to get P.

$R\, d\sigma/dt \propto 2\,\mathrm{Re}(NF^*)$: data poor and only exists for elastic scattering.

$A\, d\sigma/dt \propto (|N|^2 - |F|^2)$

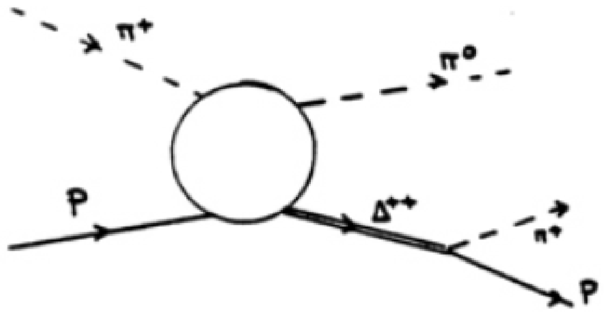
R and A measurements require measuring spins of initial and final particles.

SPIN, THE ESSENTIAL COMPLICATION

- Spin is always present and we discussed role of polarization
- Fox, G. C. and Berger, E. L., ``High Energy Physics with Polarized Proton Beams,"
- Fox, G. C., ``The Importance of Being an Amplitude,"
- Density matrices ρ(i,j) of especially rho mesons were used effectively

<u>Picture 5: Plague of Resonance Reactions</u>

Simplest is perhaps:



Amplitude	Δ^{++} Spin
A_1	$-3/2$
A_2	$-1/2$
A_3	$1/2$
A_4	$3/2$
all for proton Spin $= 1/2$ (↑)	

Even more horrible: four complex amplitudes corresponding to the four (2.Spin+1) Spin States of Spin $3/2$ Δ^{++}. However more observables:

$$d\sigma/dt \propto [\,|A_1|^2 + |A_2|^2 + |A_3|^2 + |A_4|^2\,]$$

$$\rho_{3,3}\, d\sigma/dt \propto |A_1|^2 + |A_4|^2$$

$$\rho_{3,-1}\, d\sigma/dt \propto \mathrm{Real}\,(A_1 A_3^* + A_2 A_4^*)$$

$$\rho_{3,1}\, d\sigma/dt \propto \mathrm{Real}\,(A_3 A_4^* - A_1 A_2^*)$$

where last 3 are obtained "free" (i.e. without special polarization expts) from decay distribution of $p(\pi^+)$ from Δ^{++} decay.

i.e.
$$W(\theta,\varphi) \propto 1/6 + 2\rho_{33}/3 + \cos^2\theta\,(1-4\rho_{33})/2$$
$$- 2/\sqrt{3}\;\rho_{3,-1}\,\sin^2\theta\cos 2\varphi$$
$$- 2/\sqrt{3}\;\rho_{3,1}\,\sin 2\theta\cos\varphi$$

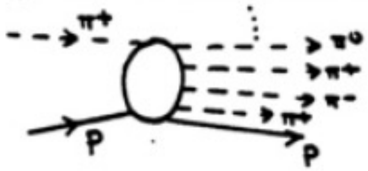
where θ and φ are polar angles of final proton in Δ^{++} rest frame.

QUASI TWO BODY REACTIONS

- I claim there are 400 such reactions in 1975 and they some **disadvantages**
- Need to be identified from background
- Complex Spin
- **Advantages**
- Some large Regge couplings e.g. Δ++ → πp which does not vanish at t=0 for π trajectory
- p → π n does vanish

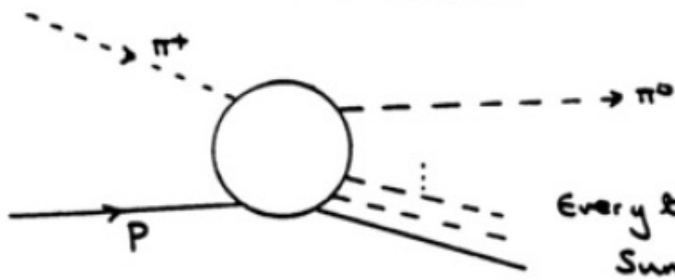
Picture 6: Most of the Cross-section

GENUINE MULTIPARTICLE REACTIONS



Too Many Variables
Cant even display data!

INCLUSIVE REACTIONS



Everything Else
Summed Over

(i) Only 2 (3) continuous variables s, p_L, ($p_\perp^2$) to specify momenta of $\pi^+ p, \pi^0$. Theoretical description technically simple.

(ii) Scaling (Come and listen to Feynman)

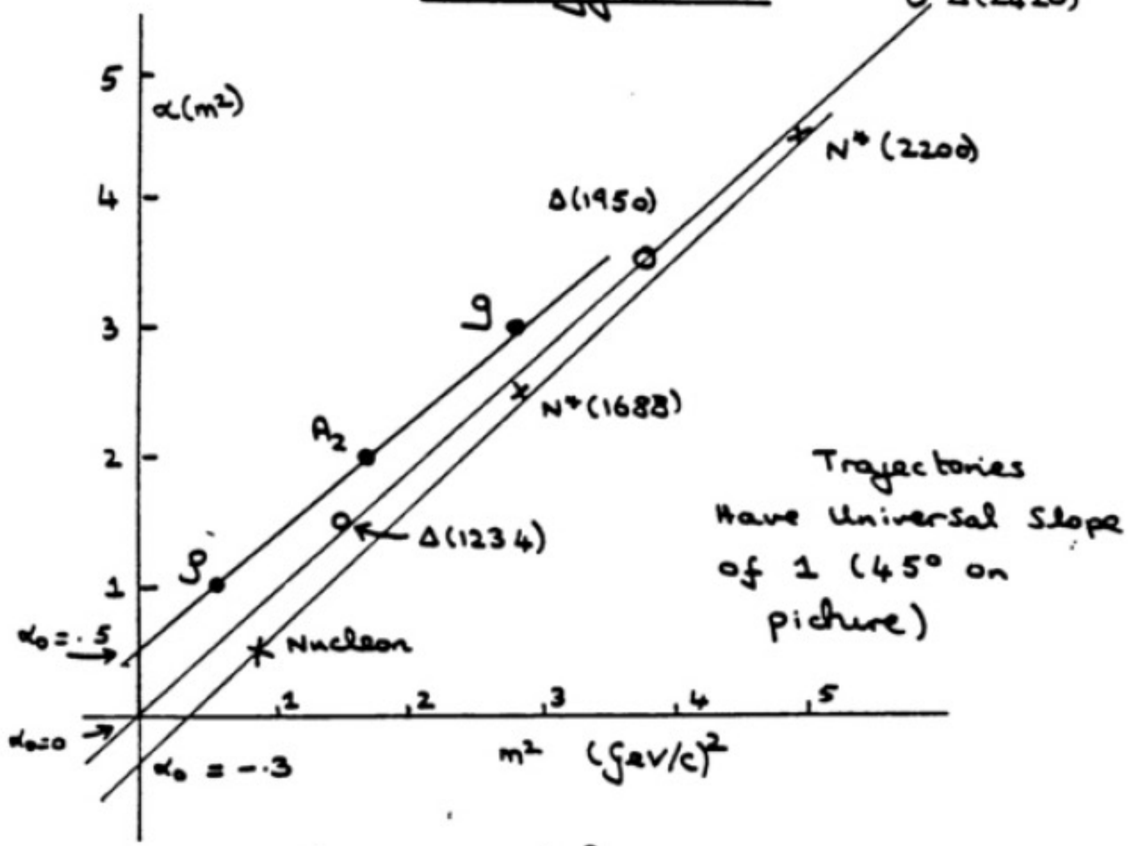
(iii) Cross-sections are large as you use all events : thus early NAL and ISR results are dominantly in this field. At current accelerators, bubble chambers are doing well.

(iv) Recent Mueller formalism ties together theories of inclusive and exclusive reactions. (tests of this require better data - see pictures 26 - 29).

MULTIPARTICLE FINAL STATES

- I thought there were 2000 of these in 1975.
- The slide references Feynman's parton model as in
- "Quantum-chromodynamic approach for the large-transverse-momentum production of particles and jets", RP Feynman, RD Field, GC Fox, Physical Review D 18 (9), 3320 (1978)

Picture 7: Third Time Lucky on Regge Poles



$$\alpha(m^2) = \alpha_0 + \alpha' m^2$$

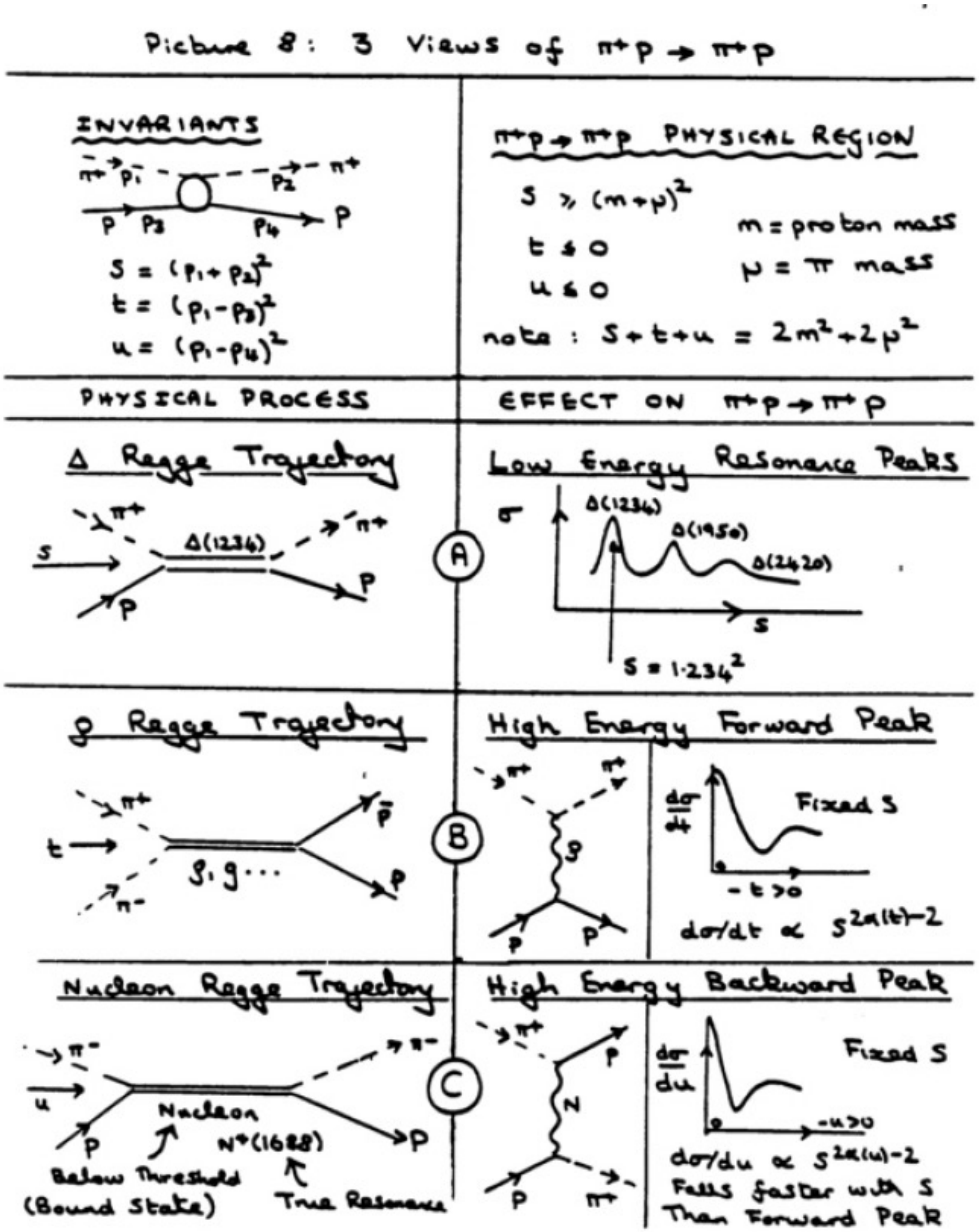
α_0 varies

α' universal

One gets real live particles, for $\alpha =$ integer (mesons) and half odd integer (baryons). Forces are exchange degenerate for mesons and So there is a resonance for each Spin : usually on gets only every other resonance i.e. as in Δ and Nucleon trajectories, Spacing in Spin 2 units.

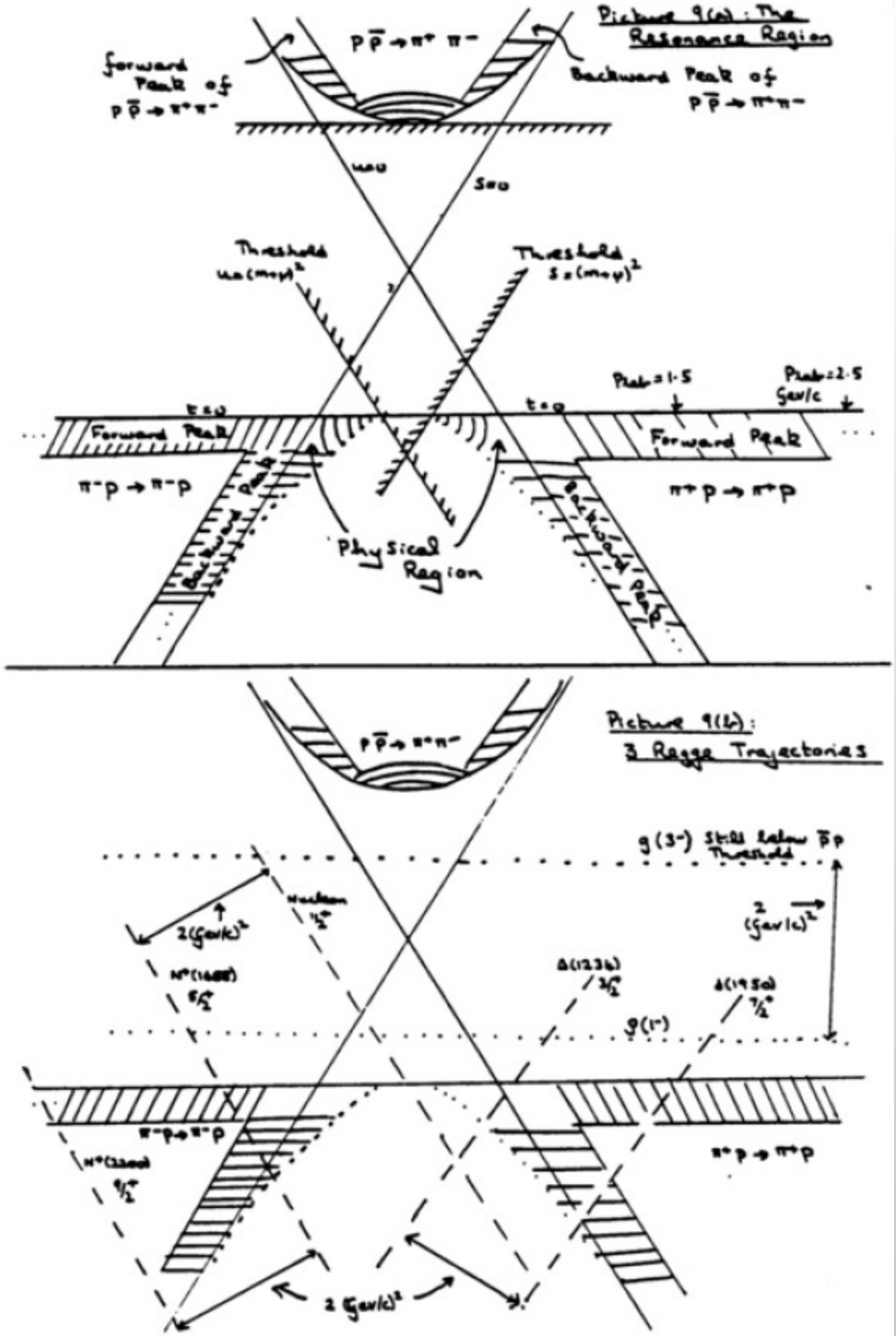
REGGE THEORY

- Observed particles lie on Regge trajectories and these control scattering in "crossed channels"
- Lost papers
- Fox, G.C., "Veni, Vidi, Vici Regge theory",
- Fox, G. C. ``Skeletons in the Regge Cupboard,"
- Fox, G. C., ``π-exchange," in Planning for the Future, ANL/HEP-7208



FOR EVERY WORLD, THERE ARE TWO MORE TWISTED ONES

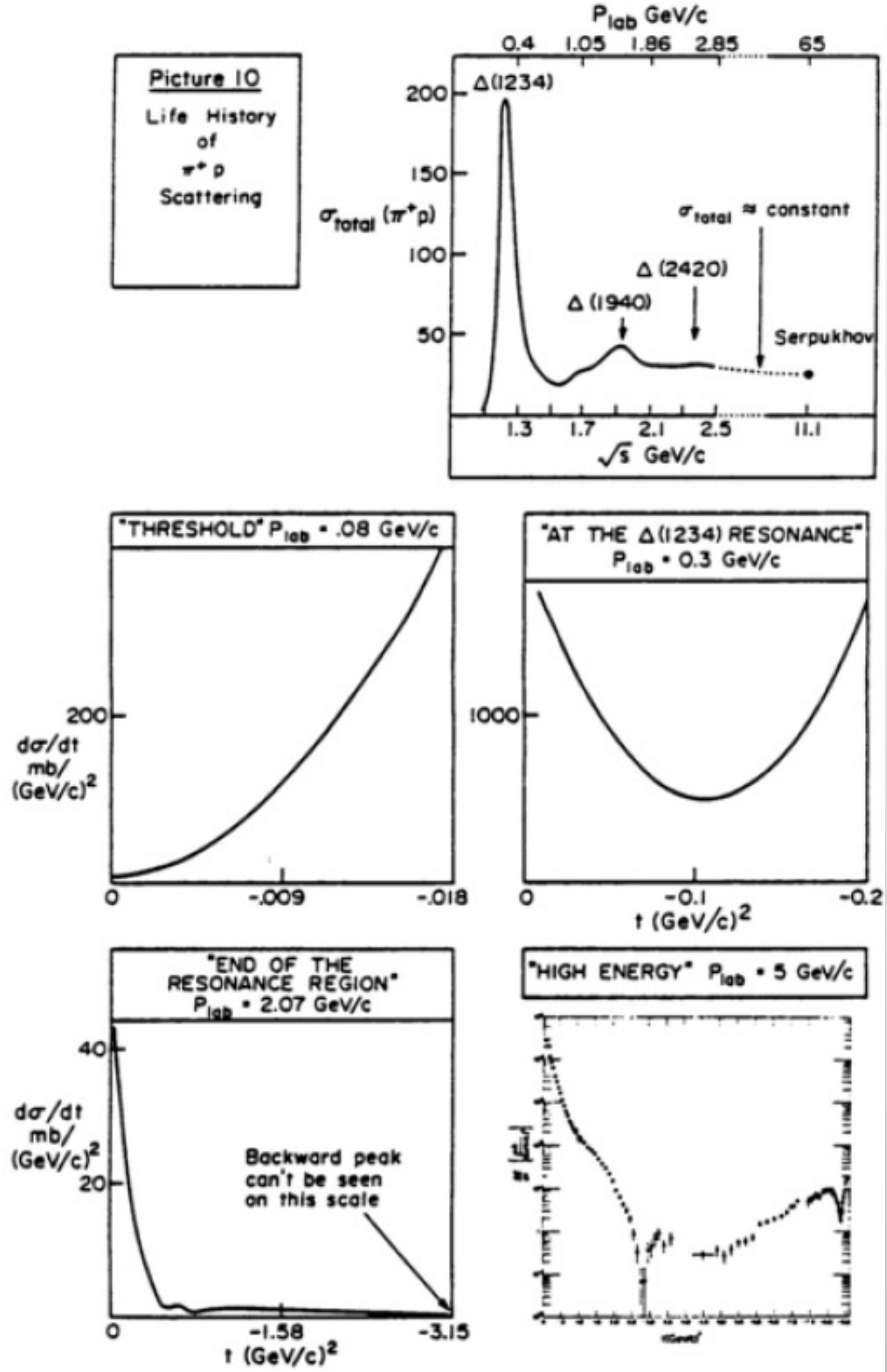
- $\pi^+ p \rightarrow \pi^+ p$ has two reactions related by "crossing"
- A key feature of relativistic field theories not present in potential theories
- t channel
  $\pi^+ \pi^- \rightarrow \bar{p}\, p$
- u channel
  $\pi^- p \rightarrow \pi^- p$
- Next slide will show in s, t, u plane with
  $s + t + u = 2m^2 + 2\mu^2$



LET THERE BE REGGE POLES AND THERE AND IT WAS GOOD

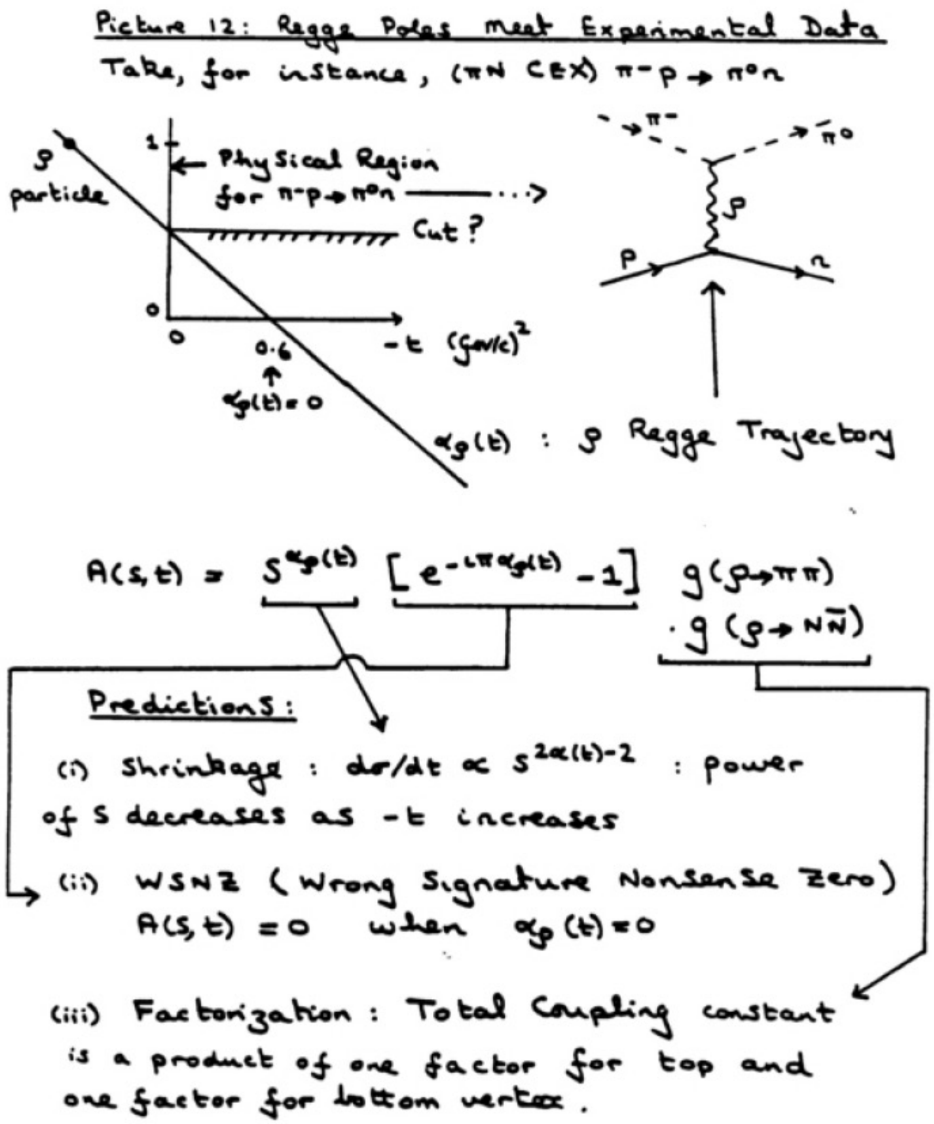
- The physical regions of the 3 related reactions described by same analytic function.
- 9(b) show the Regge Poles
- 9(a) shows key parts of of scattering regions.
- In bottom right of 9(a), we see s-(direct-) channel resonances for $\pi^+ p \to \pi^+ p$
- As s increases, the scattering is concentrated on forward and backward peaks with s behavior $d\sigma/d(t,u) \propto s^{2\alpha(t,u)-2}$

PROGRESS IN ΠN SCATTERING



- πN scattering starting at threshold
- Moving to resonance region
- And then settling down to a dominant forward peak and some backward peak
- Nature has a range ~s in t but only uses a fraction of a (Gev/c)^2

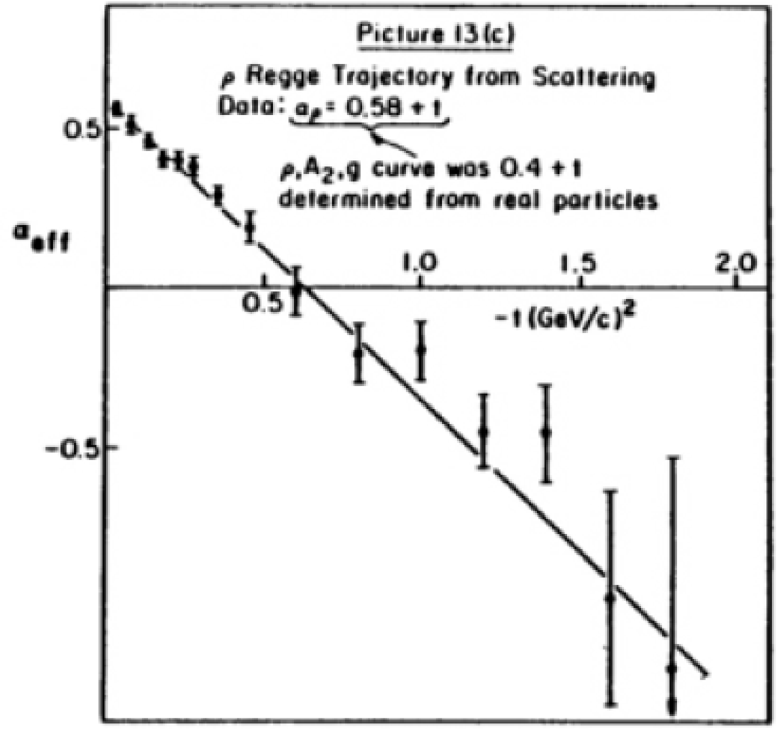
REGGE THEORY

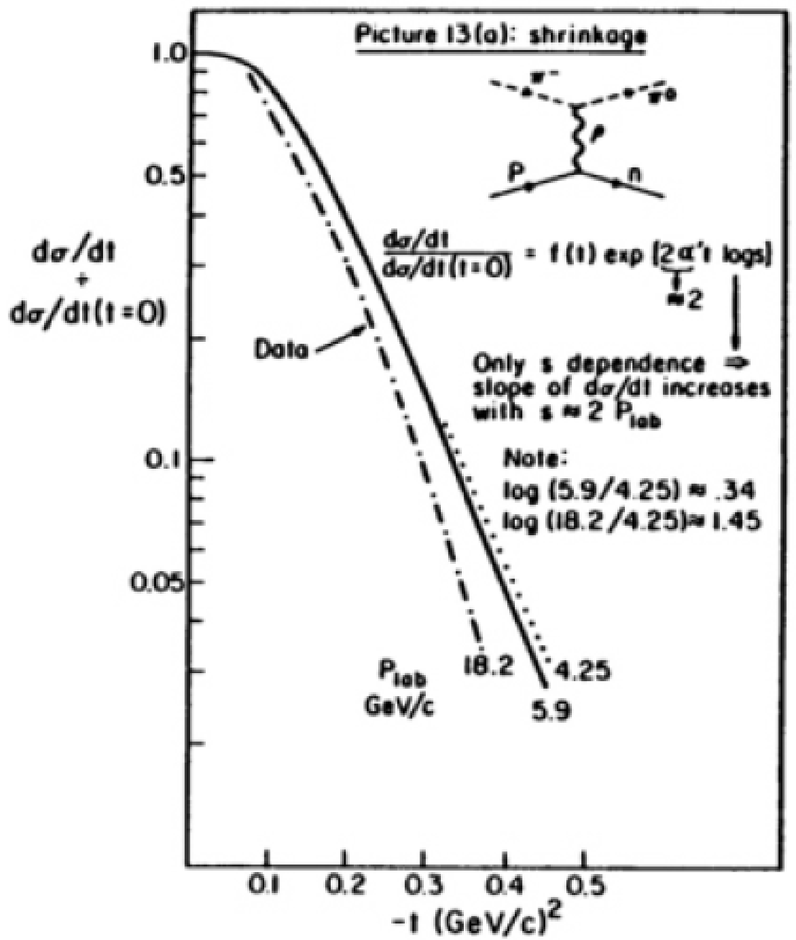


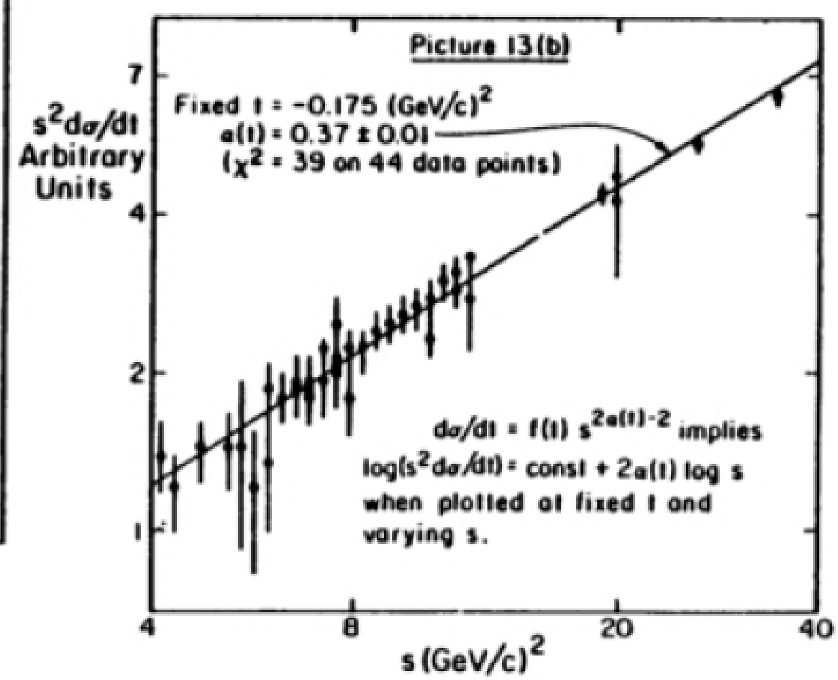
REGGE THEORY FOR $\Pi^- P \to \Pi^0 N$

- Regge Theory has (at least) three distinctive predictions
- **Shrinkage** – power of s in $s^{2\alpha(t)-2}$ decreases as –t decreases so peaks get sharper as energy increases
- **WSNZ** Wrong Signature Nonsense zeroes. Trajectory and amplitude vanishes at $\alpha = 0$.
- **Factorization.** Total coupling constant product of those at "top" and "bottom" vertex
- Corrections due to "cuts"

PICTURE 13







The first universal success for Regge theory. Excellent data. Simple theory Confirmed with later data

How α(t) determined at each t

E111 $\pi^- p \rightarrow \pi^0 n$

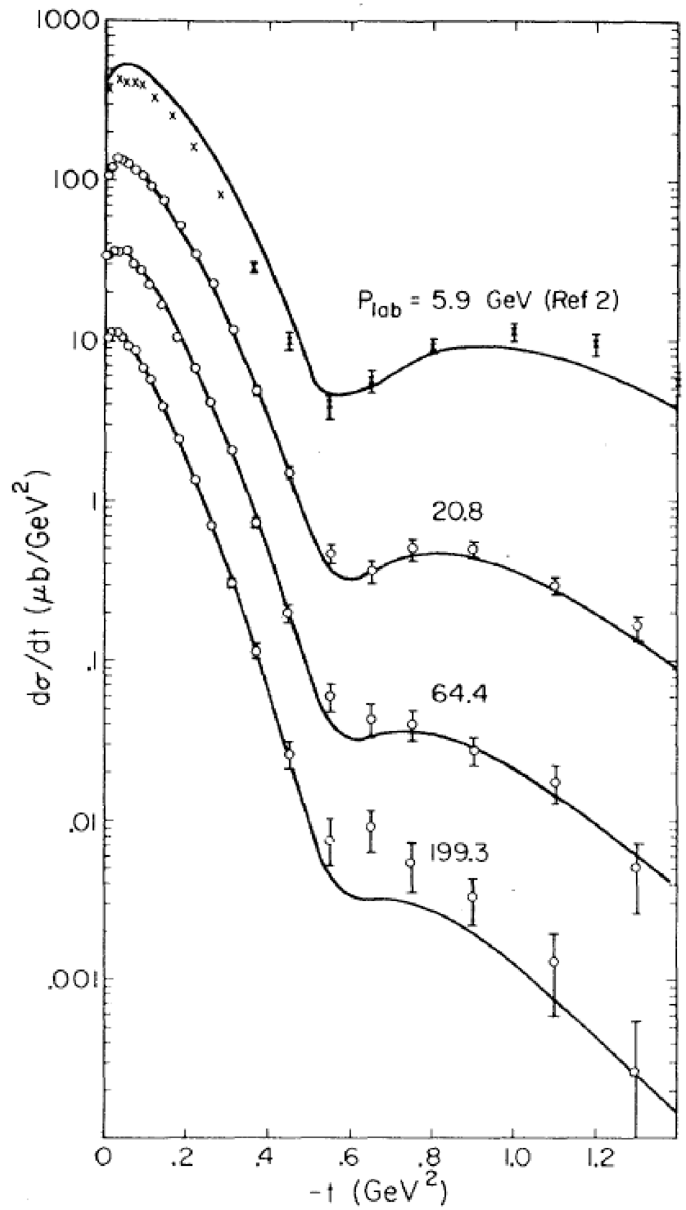


FIG. 1. Differential cross sections at 20.8, 64.4, and 199.3 GeV from this experiment, and at 5.9 GeV from Ref. 2. The curves are the result of a fit described in the text.

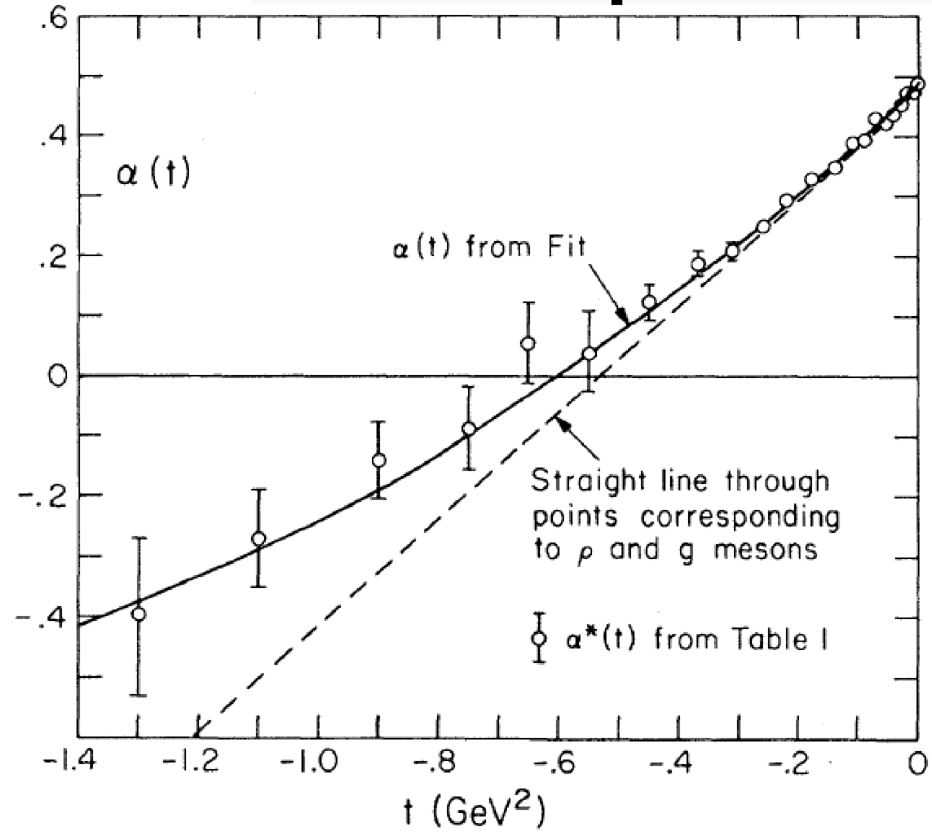


FIG. 3. The effective trajectory $\alpha(t)$.

Best data and best success of Regge Theory?

E111 $\pi^- p \rightarrow \eta\, n$

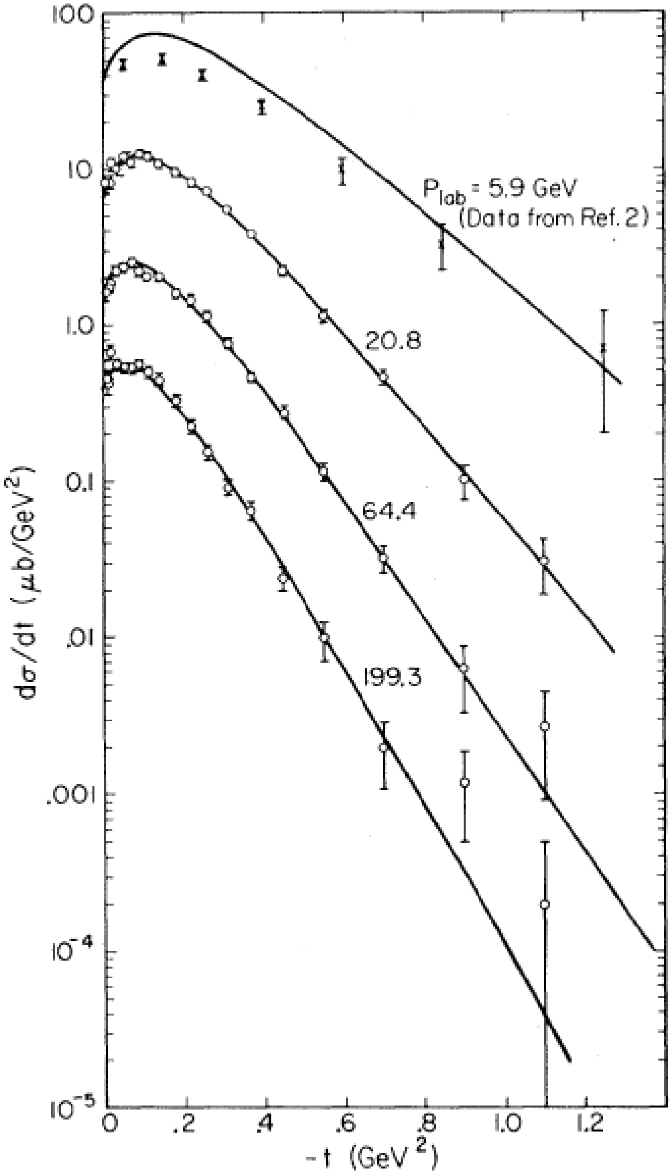


FIG. 3. Differential cross sections for the reaction $\pi^- p \rightarrow \eta n$ with $\eta \rightarrow 2\gamma$ at 20.8, 64.4, and 199.3 GeV from this experiment and 5.9 GeV from the experiment of Ref. 2. The curves are the result of a fit described in the text.

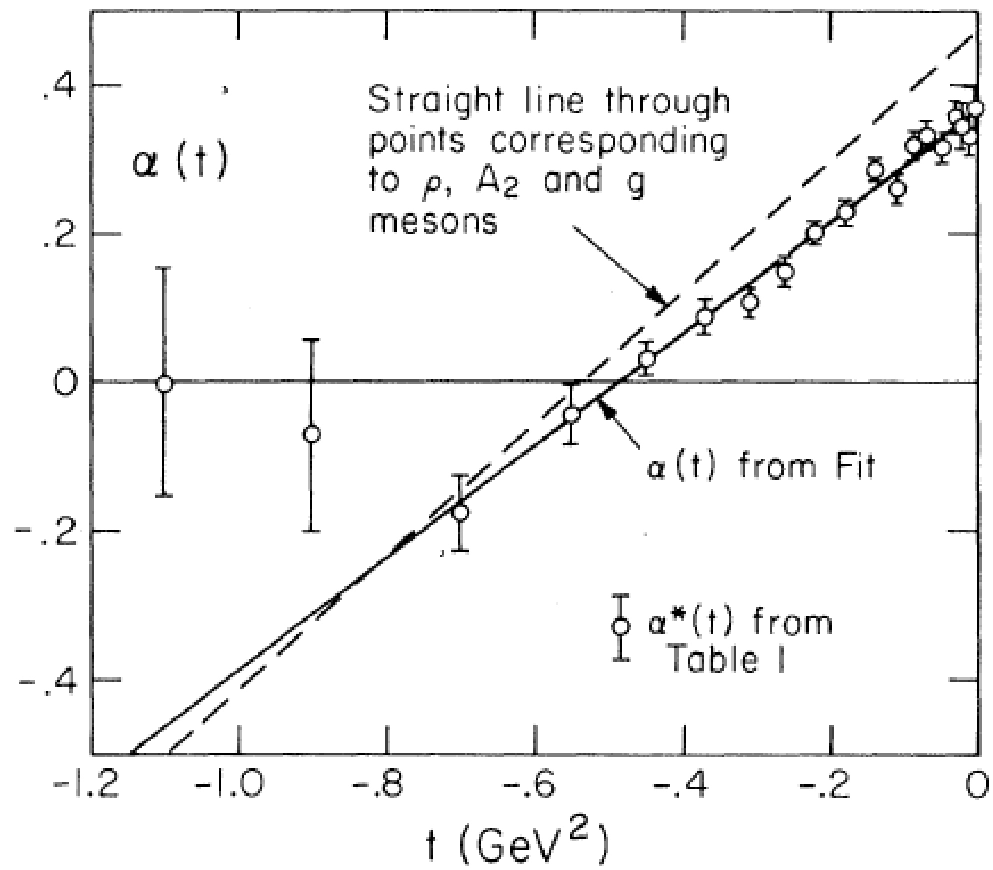
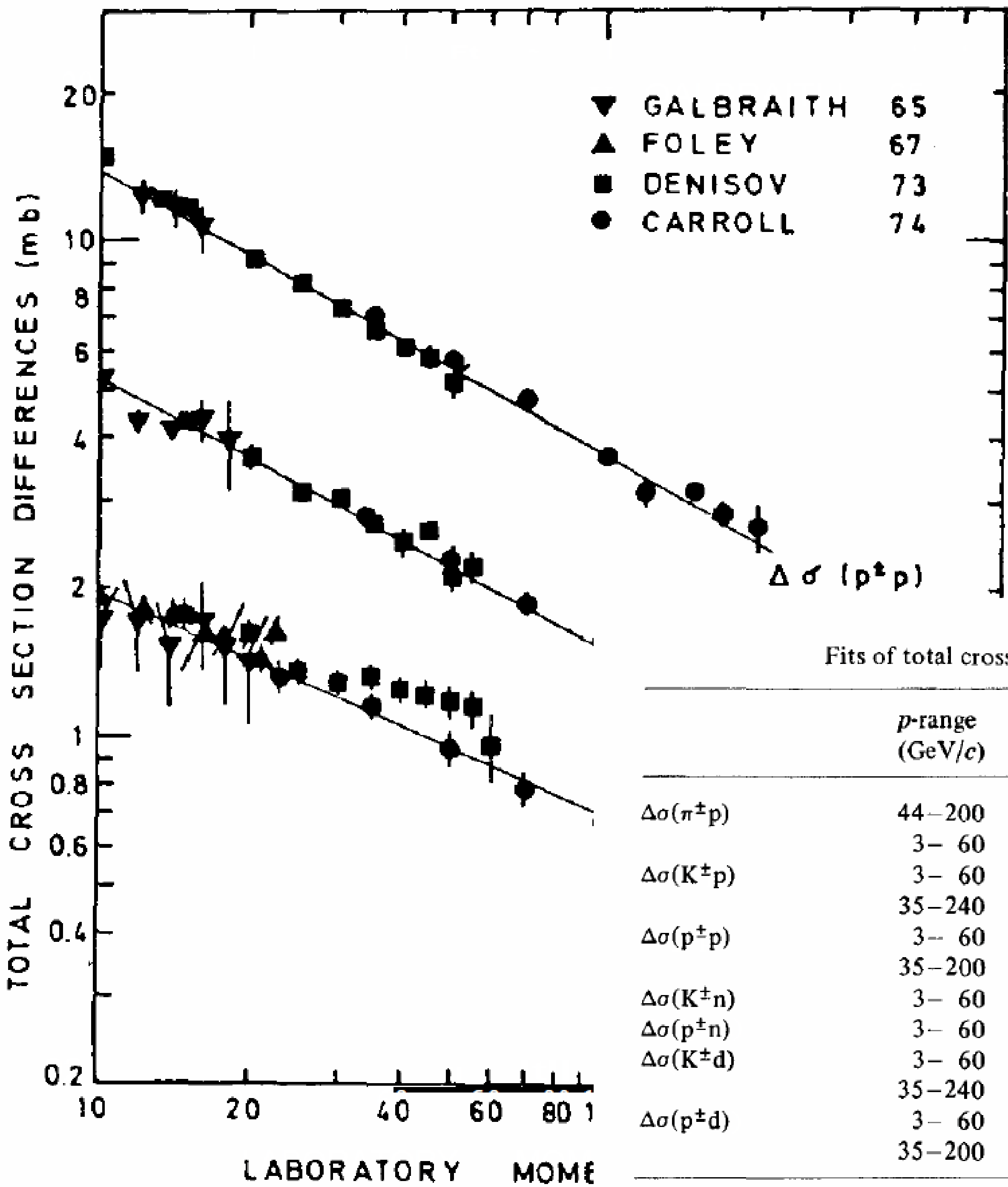


FIG. 4. The effective trajectory $\alpha(t)$.

No dip near t=-0.6 (GeV/c)^2 as predicted by theory

TOTAL CROSS SECTION DIFFERENCES



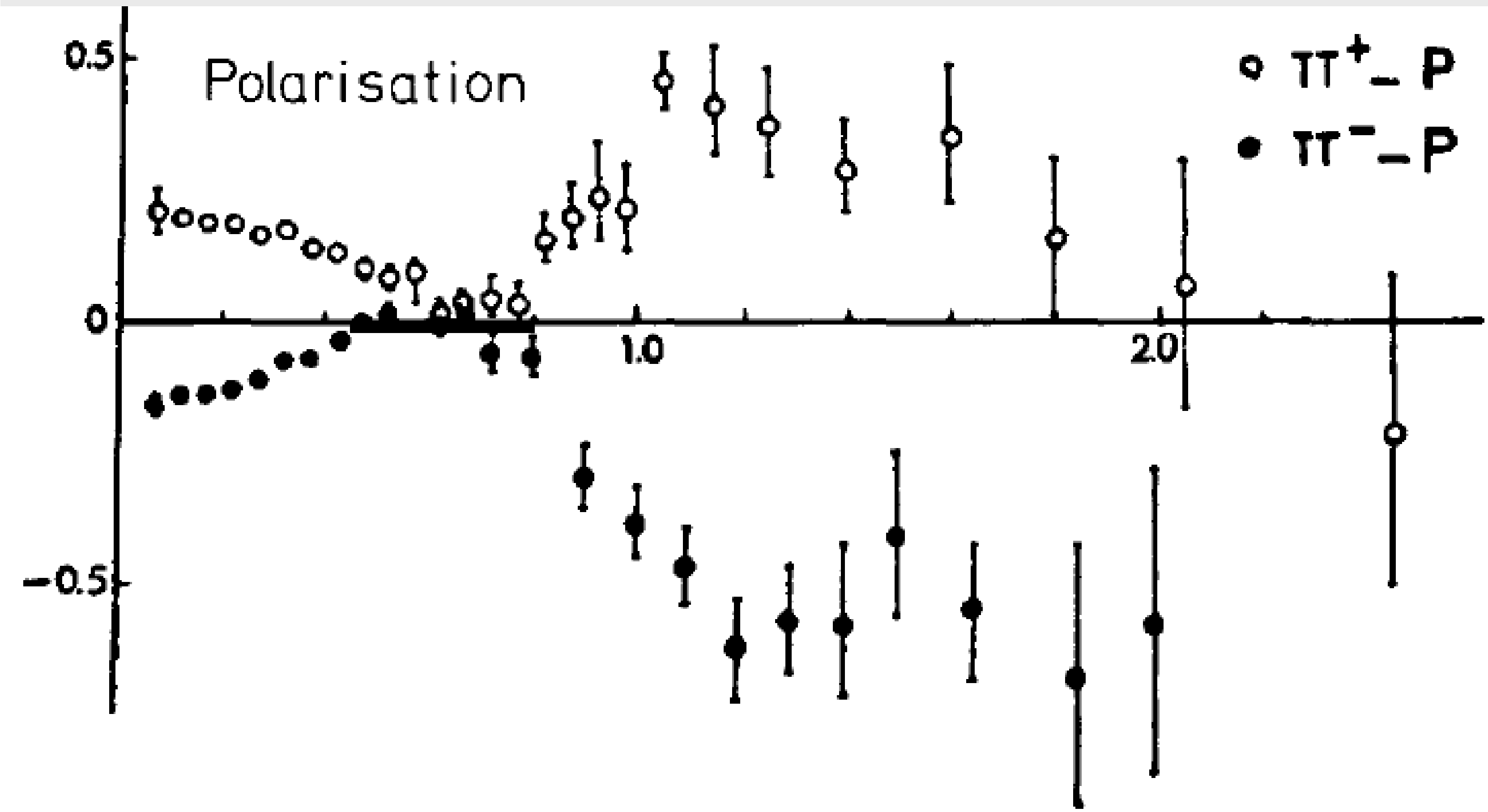
- Irving & Worden fig. 2.5
- $\Delta\sigma \propto p_{lab}^{(\alpha(0)-1)}$ as no Pomeron exchange
- ρ or ω exchange term

Table 4.5
Fits of total cross-section differences to formula (4.29).

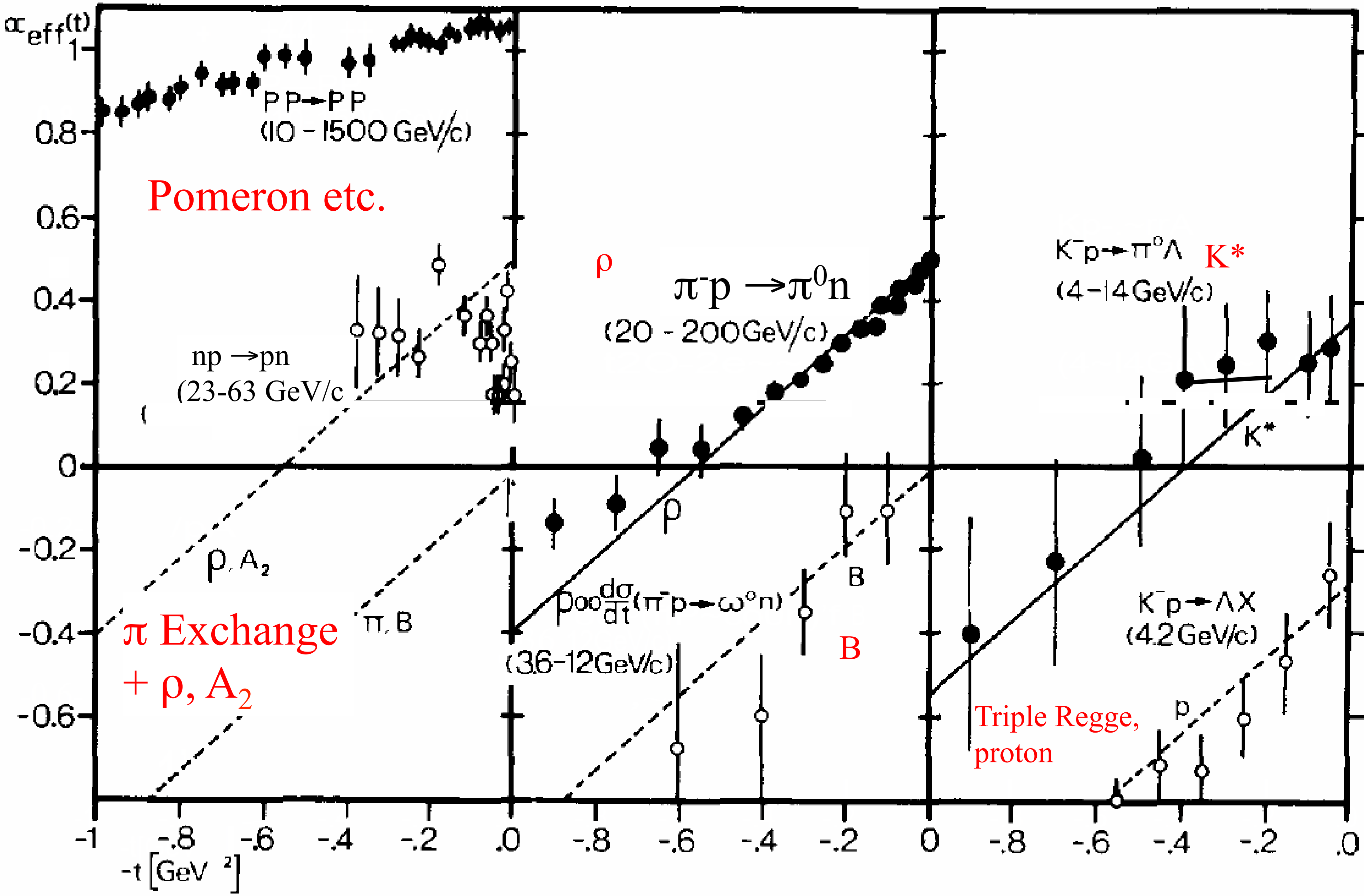
	p-range (GeV/c)	A (mb)	$1-\alpha(0)$ n
$\Delta\sigma(\pi^{\pm}p)$	44–200	5.24 ± 0.10	0.43 ± 0.01
	3– 60	4.0 ± 0.30	0.32 ± 0.02
$\Delta\sigma(K^{\pm}p)$	3– 60	18.1 ± 0.3	0.54 ± 0.02
	35–240	21.7 ± 3.9	0.58 ± 0.04
$\Delta\sigma(p^{\pm}p)$	3– 60	63 ± 2	0.64 ± 0.02
	35–200	58 ± 4	0.59 ± 0.02
$\Delta\sigma(K^{\pm}n)$	3– 60	13.0 ± 0.4	0.67 ± 0.02
$\Delta\sigma(p^{\pm}n)$	3– 60	49 ± 7	0.61 ± 0.05
$\Delta\sigma(K^{\pm}d)$	3– 60	29.0 ± 0.5	0.58 ± 0.02
	35–240	32 ± 5	0.58 ± 0.04
$\Delta\sigma(p^{\pm}d)$	3– 60	106 ± 8	0.64 ± 0.04
	35–200	95 ± 7	0.54 ± 0.02

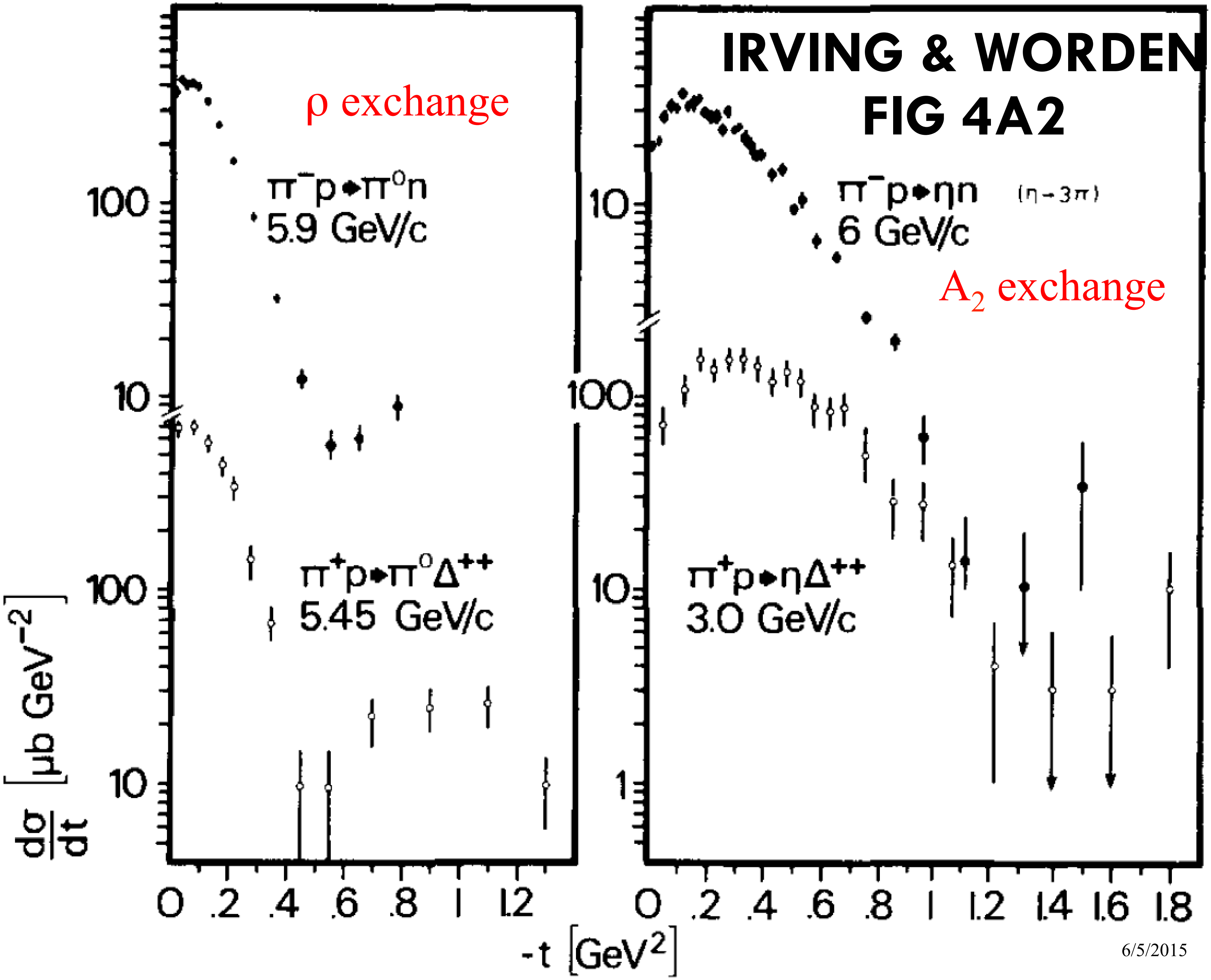
Π^+P Π^-P POLARIZATIONS

- Irving and Worden Fig. 4A1
- The π^+p π^-p polarizations are mirror-symmetric showing the dominance of ρ exchange over f exchange in the helicity-flip amplitude, and have a double zero at *t* = —*0.5*, as expected from a ρ pole amplitude (with WSNZ)

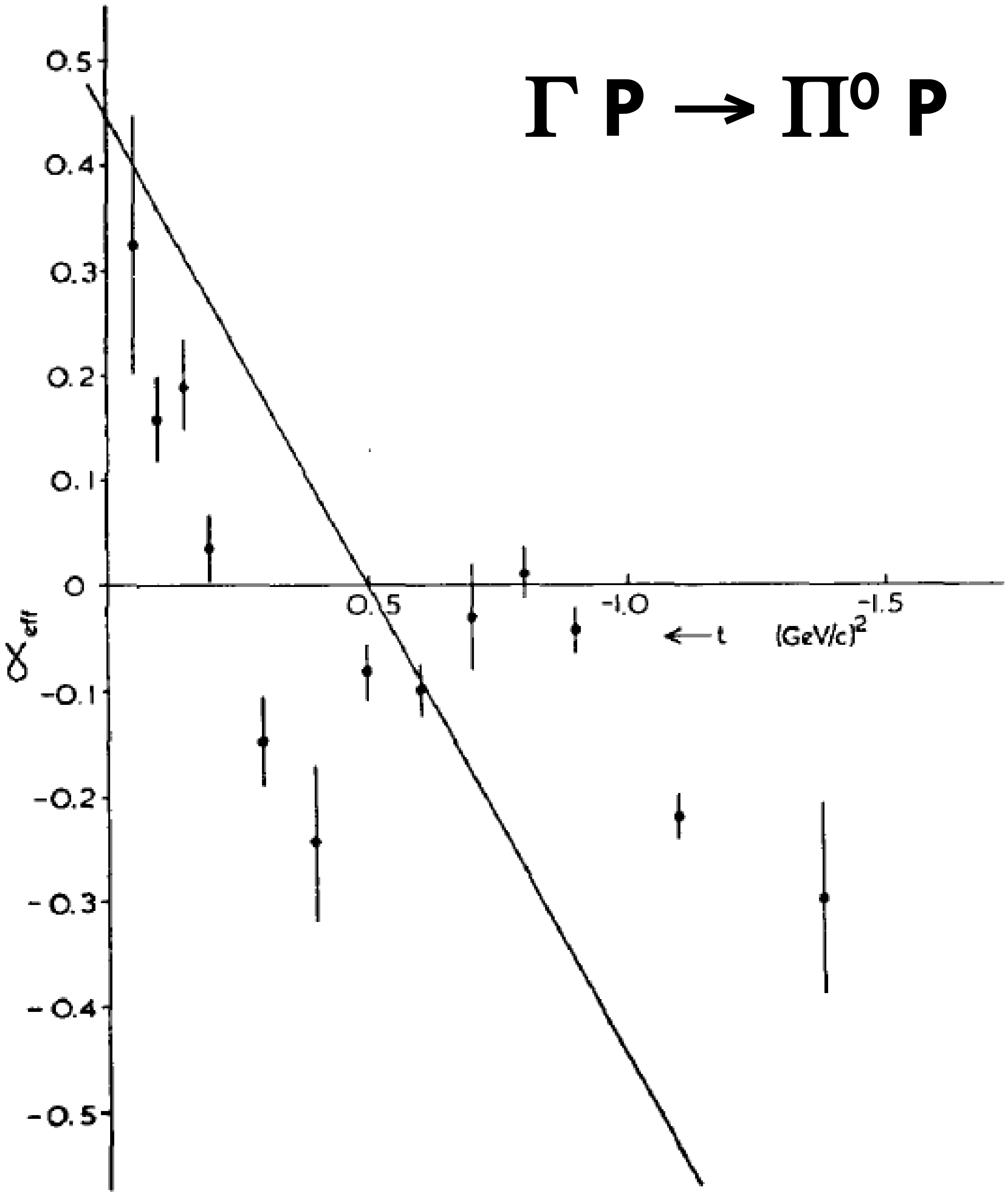


IRVING & WORDEN FIG. 2.7





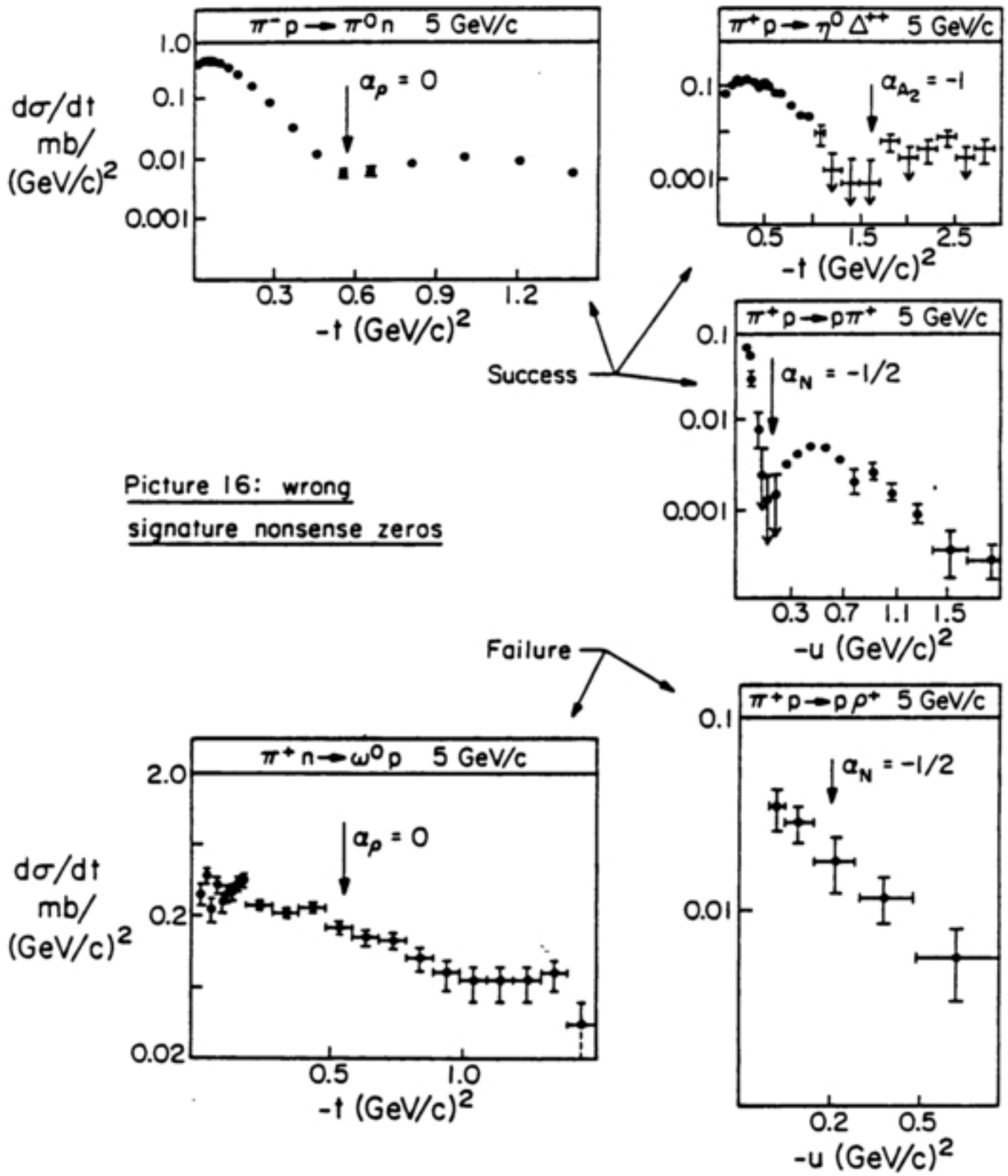
IRVING & WORDEN
FIG 4A2
ρ exchange
π⁻p→π⁰n
5.9 GeV/c
π⁺p→π⁰Δ⁺⁺
5.45 GeV/c
π⁻p→ηn (η→3π)
6 GeV/c
A₂ exchange
π⁺p→ηΔ⁺⁺
3.0 GeV/c
dσ/dt [μb GeV⁻²]
-t [GeV²]
100
10
100
10
10
100
10
1
0 .2 .4 .6 .8 1 1.2
0 .2 .4 .6 .8 1 1.2 1.4 1.6 1.8



Γ P → Π⁰ P

The effective trajectory for $d\sigma/dt$ ($\gamma p \to \pi^0 p$) is compared with a linear ω Regge pole trajectory

- The α_{eff} for $d\sigma/dt$ ($\gamma\ p \to \pi^0\ p$)
- Also shown is the trajectory of the Regge pole which is expected to dominate this process (in a helicity-flip amplitude).
- The $\alpha_{eff}(t)$ is much more reminiscent of a pole + strong cut than of a simple Regge pole.
- The feature, $\alpha_{eff}(t) \approx 0$ for $-t \geq 0.6$, is common to most photo-production cross-sections.
- Irving & Worden fig. 4A2



Picture 16: wrong signature nonsense zeros

ΠN BACKWARD SCATTERING

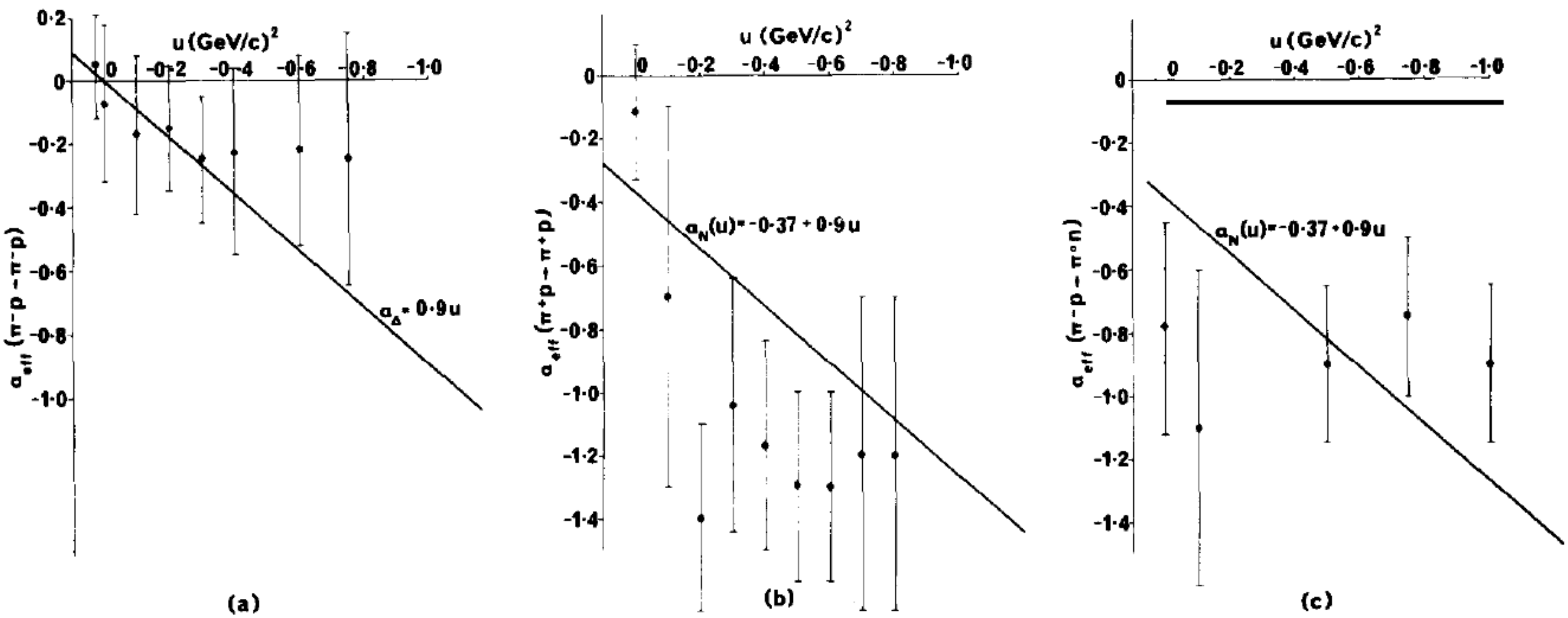
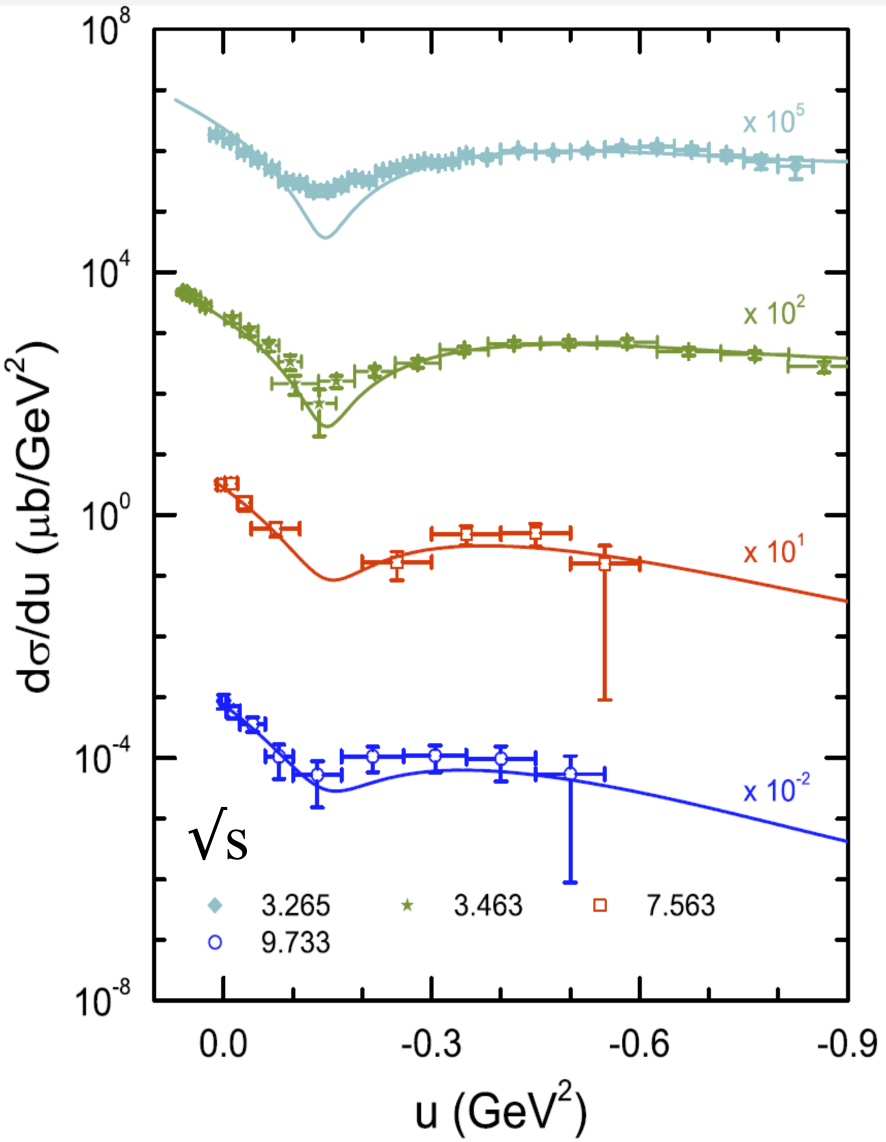


Fig. 4I.4. Effective trajectories for backward πN scattering, (a) $\pi^-p \to p\pi^-$, (b) $\pi^+p \to p\pi^+$ and (c) $\pi^-p \to n\pi^0$ [181].

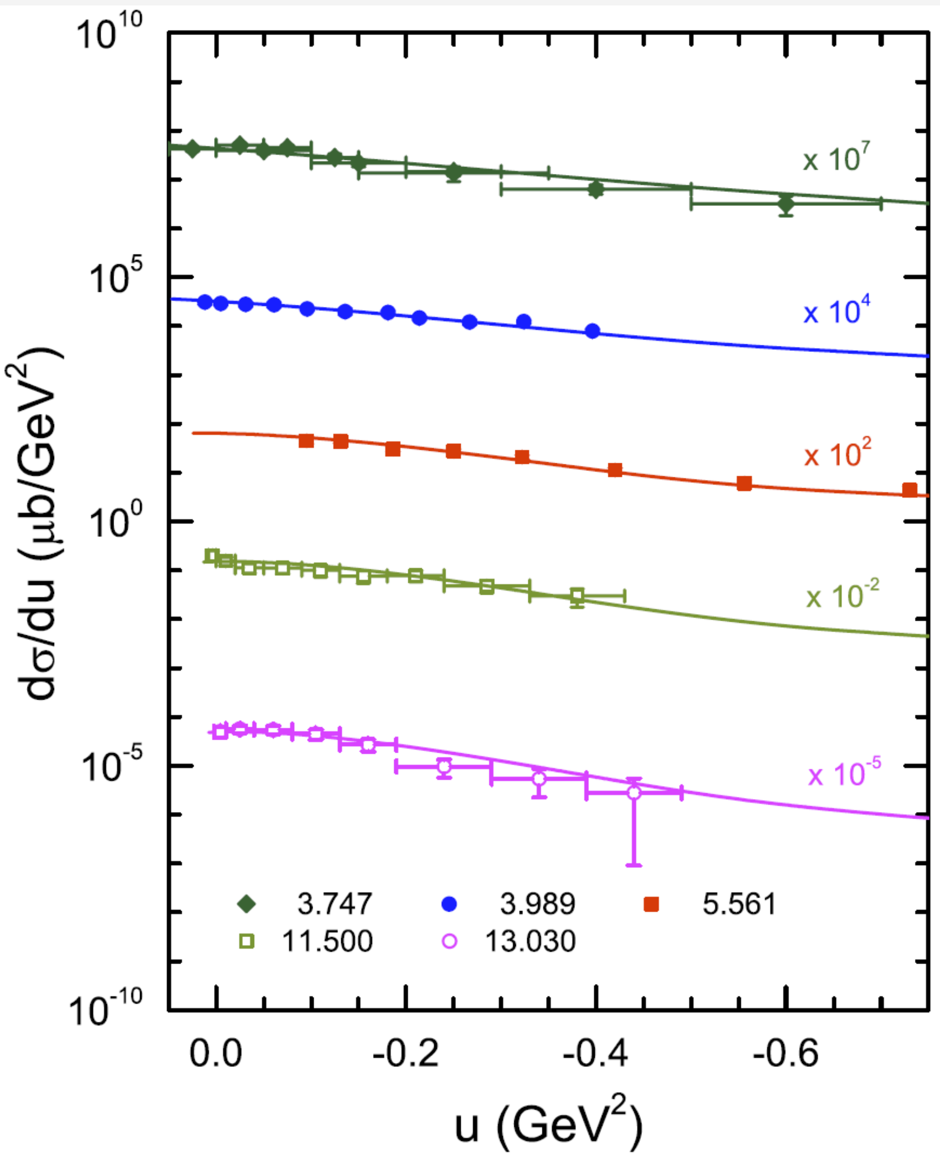
- Old data πN Backward Scattering
- Irving & Worden fig, 4.14

2010 REGGE FITS

π^+ p backward scattering
Nucleon Exchange with WSNZ



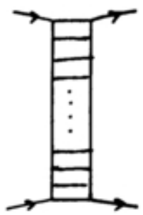
π^- p backward scattering
Δ^{++} Exchange without WSNZ



Π EXCHANGE
REGGE CUTS AND PROBLEMS

Regge Cuts

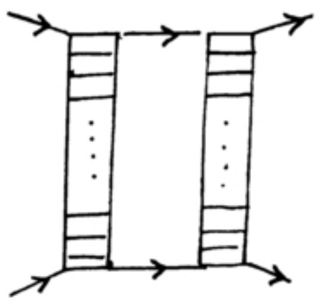
Summing ladders gives Regge poles, i.e.,



and generally no cuts - which is simple analytic structure in ℓ plane found in potential scattering.

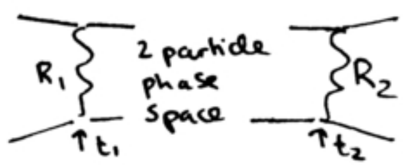
Unfortunately, it was soon realized that one could combine Regge poles

as



or

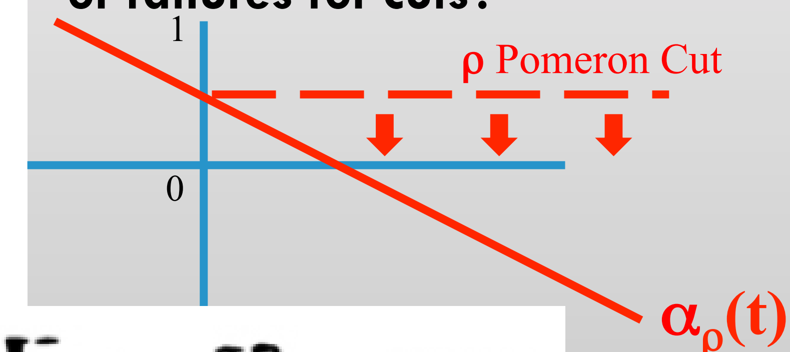
Putting the intermediate particles "on shell", i.e,

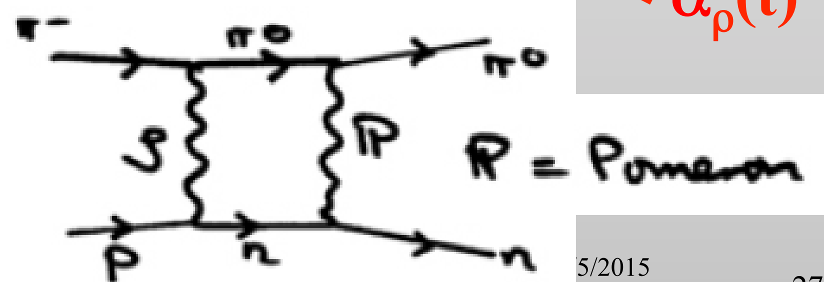


These box diagrams may be included in dynamically generated pole. The ρ trajectory is not a Born term

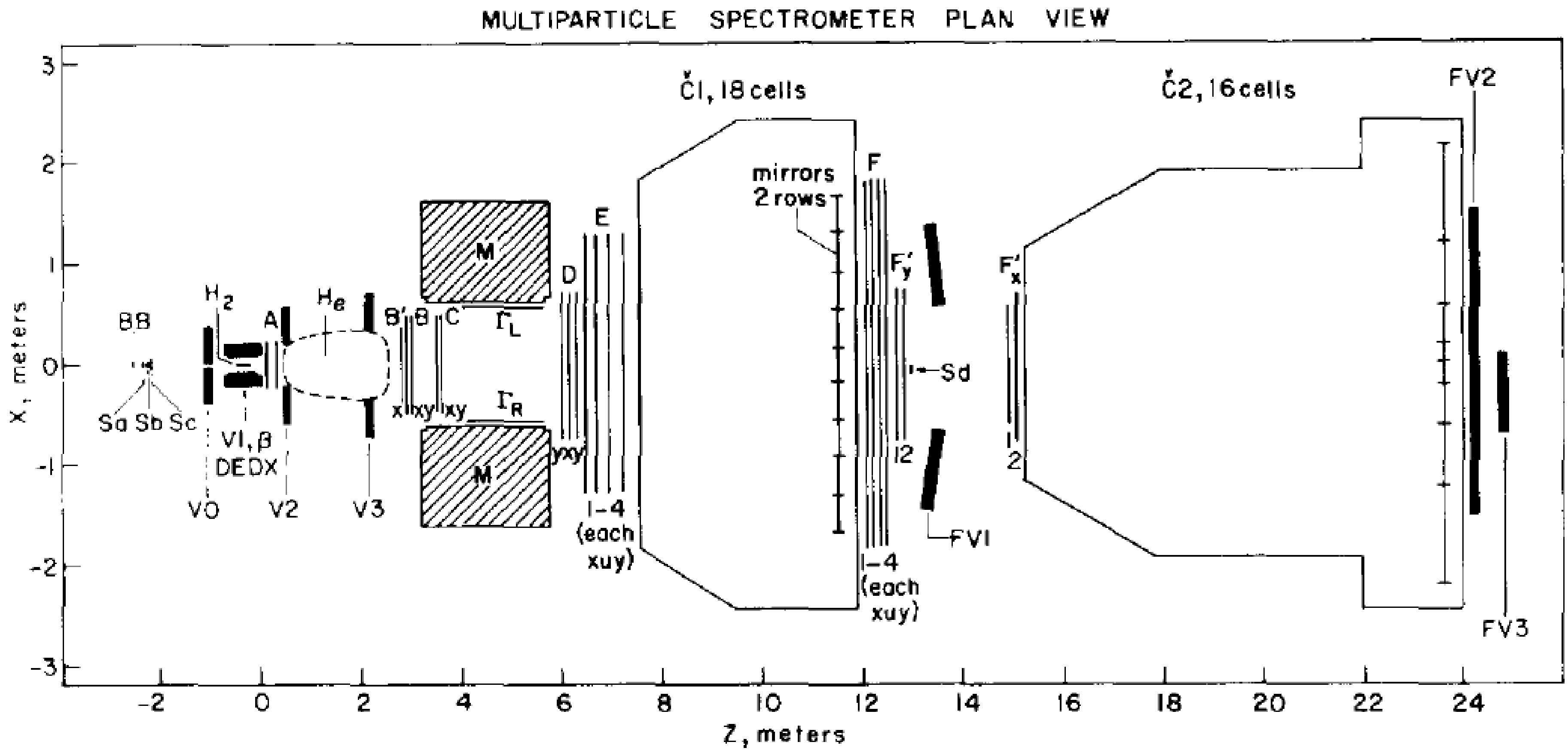
REGGE CUTS

- Regge Pole Cross Section $s^{2\alpha(t)-2}$
- Regge Cut
- $\alpha_{cut}(t) <= \alpha_1(t_1) + \alpha_2(t_2) - 1$
- $\alpha_2(t) = 1$ gives simplest result
  $\alpha_{cut}(t) <= \alpha_1(0)$
- Plenty of deviations from Regge theory but no striking successes or failures for cuts?





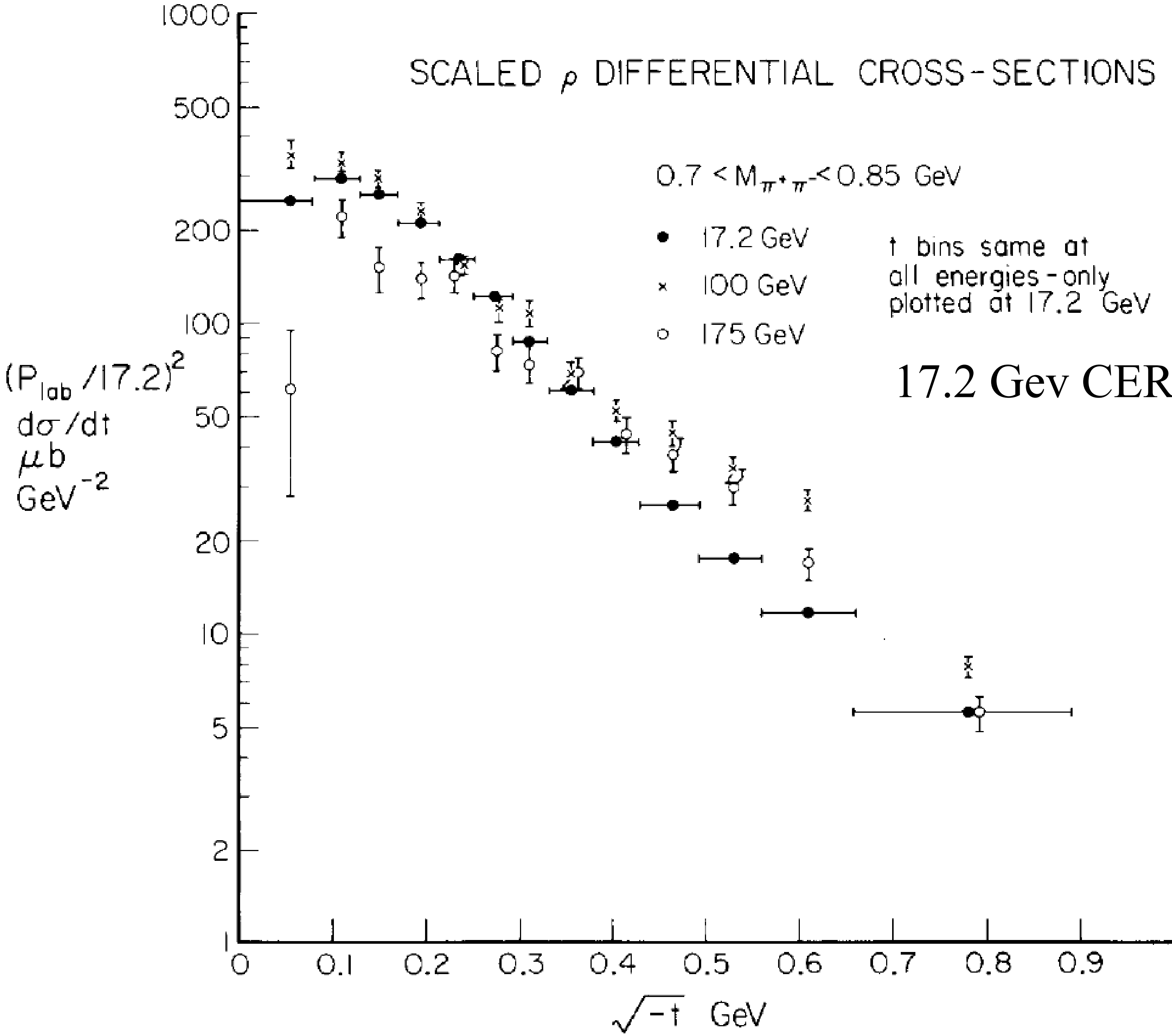
FERMILAB E110 MULTIPARTICLE SPECTROMETER



Highlights of the reaction $\pi^- p \rightarrow \pi^- \pi^+ n$ at 100 and 175 GeV/c

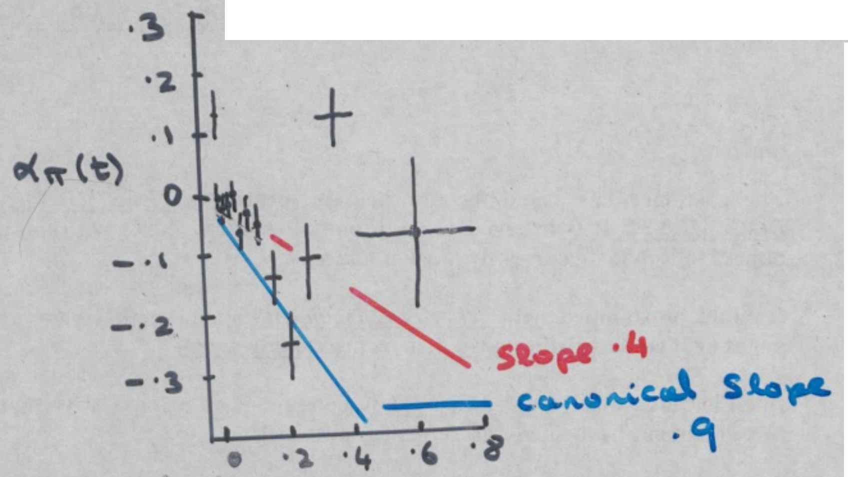
Nuclear Physics B232 (1984) 189-235 **Cited by (only) 5**

E260 AND E110



17.2 Gev CERN

Π TRAJECTORY



Fits of $\rho_{00}\, d\sigma/dt$ for $\pi^- p \to \rho^0 n$

at p_{lab} = 17, 100, 175 GeV

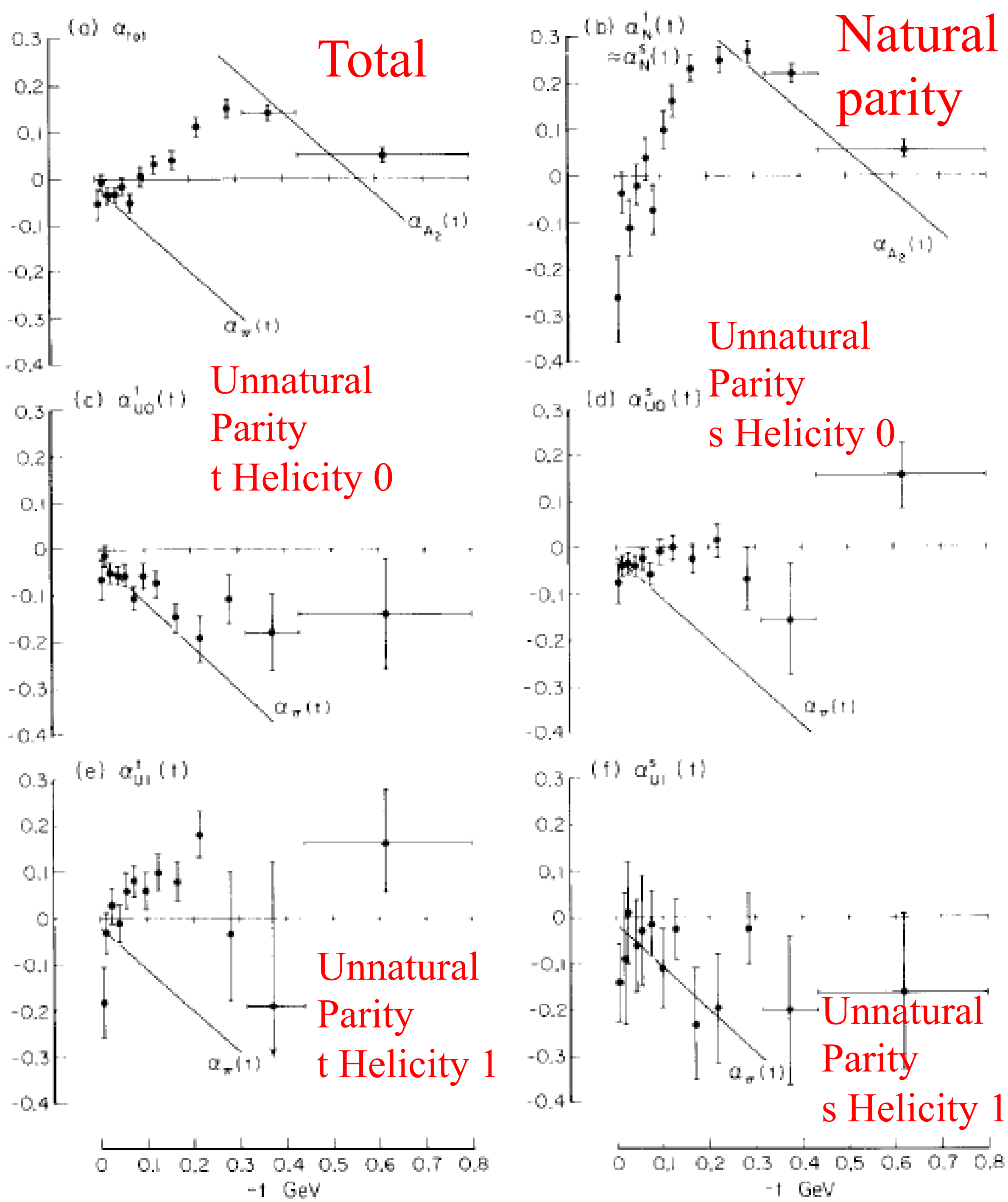
CERN-MUNICH   E110

(1) π only important trajectory

(2) Spin flip amplitude which folk lore (now 10 years old!) suggests should have small cuts.

Written 1980

- Pretty scruffy slide standards in those days
- $\rho_{(0,0)}\ d\sigma/dt\ \pi^- p \to \rho^0 (\to \pi^+ \pi^-)\ n$
- $\rho_{(0,0)}$ projects out helicity nonflip (must be unnatural parity) at $\pi^- \to \rho^0$ vertex and always spinflip at $p \to n$ vertex
- Net is total Spin flip π exchange with no conspiracy issues
- Special as π pole so near physical region that cross-section large
- One can project out natural and unnatural parity in “helicity flip” at $\pi^- \to \rho^0$ vertex
- Helicity flip has π and A_2 exchange and Regge cuts



E110

Excluding special alignment and calibration runs, the first run recorded 1.058 million events from all triggers at 100 GeV/c with 280 000 events in the $\pi\pi n_T$ trigger.

The second run had 1.680 million events at 175 GeV/c of which 481000 were from $\pi\pi n_T$. Final samples used for decay distributions are 10577 events at 100 GeV/c and 9895 events at 175 GeV/c

Regge Trajectory for the ρ Region

Helicity Frame

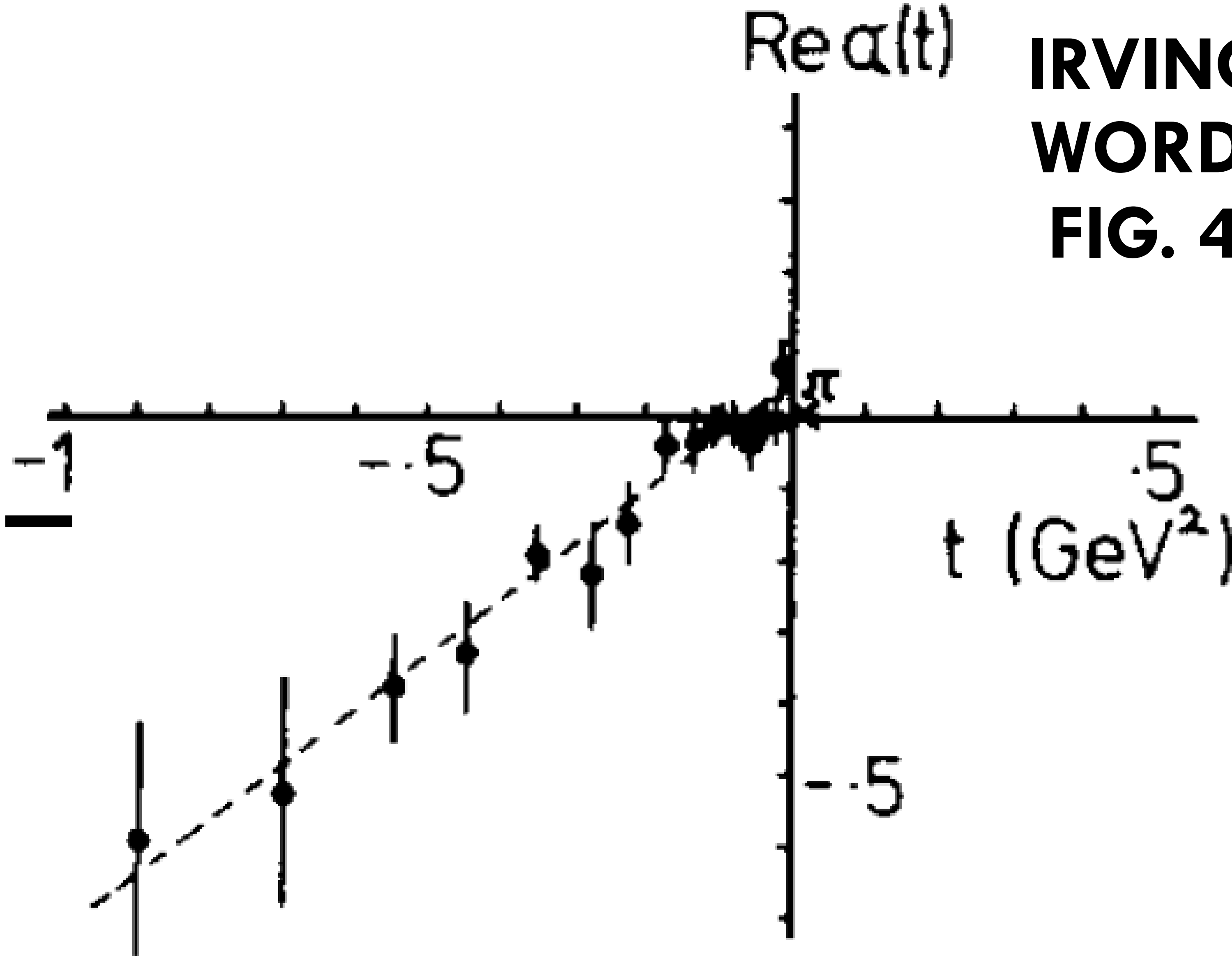
Gottfried Jackson Frame

Natural Parity Exchange

Unnatural Parity Exchange — Helicity 0

Unnatural Parity Exchange — Helicity 1

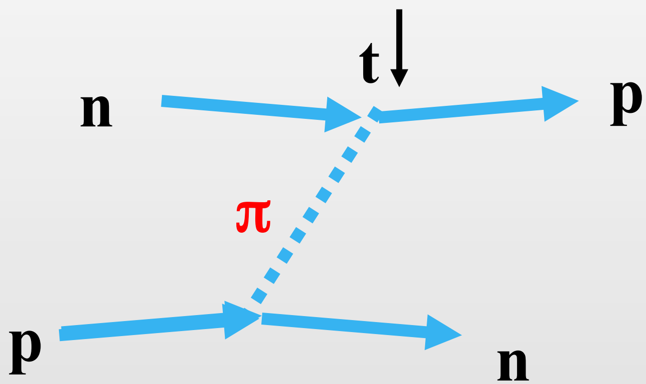
IRVING & WORDEN FIG. 4E1



$\pi^- p \rightarrow \pi^0 \pi^0 n$ data in the range 2 to 50 GeV/c

Π CONSPIRACY I

- **Problems with double spin flip amplitudes**



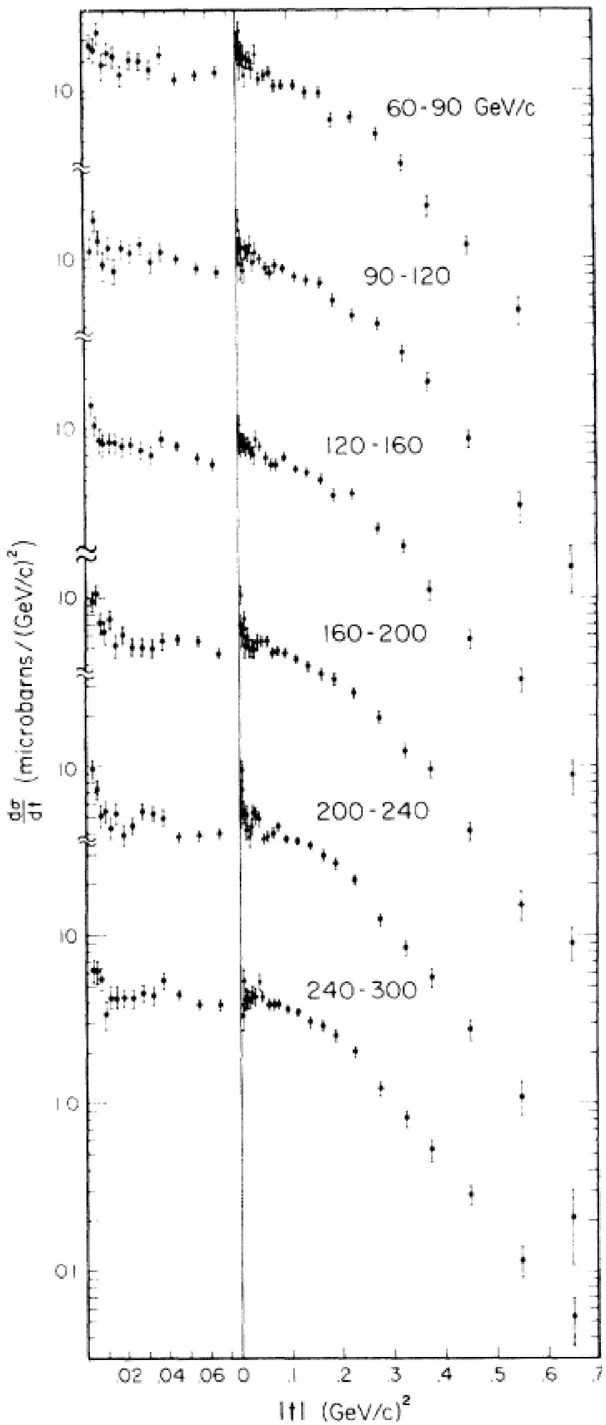
- In np → p n, π exchange is large due to nearby pole and as spin flip at BOTH vertices the Regge formula is proportional to
- $\pi\, \bar{p}\, n$ vertex vanishes at t=0 as spin flip=0
- So amplitude is
  Coupling Constant . $(t/m_\pi^2)/(m_\pi^2 - t)$ (*)
  with $\alpha_\pi(0) \sim 0$

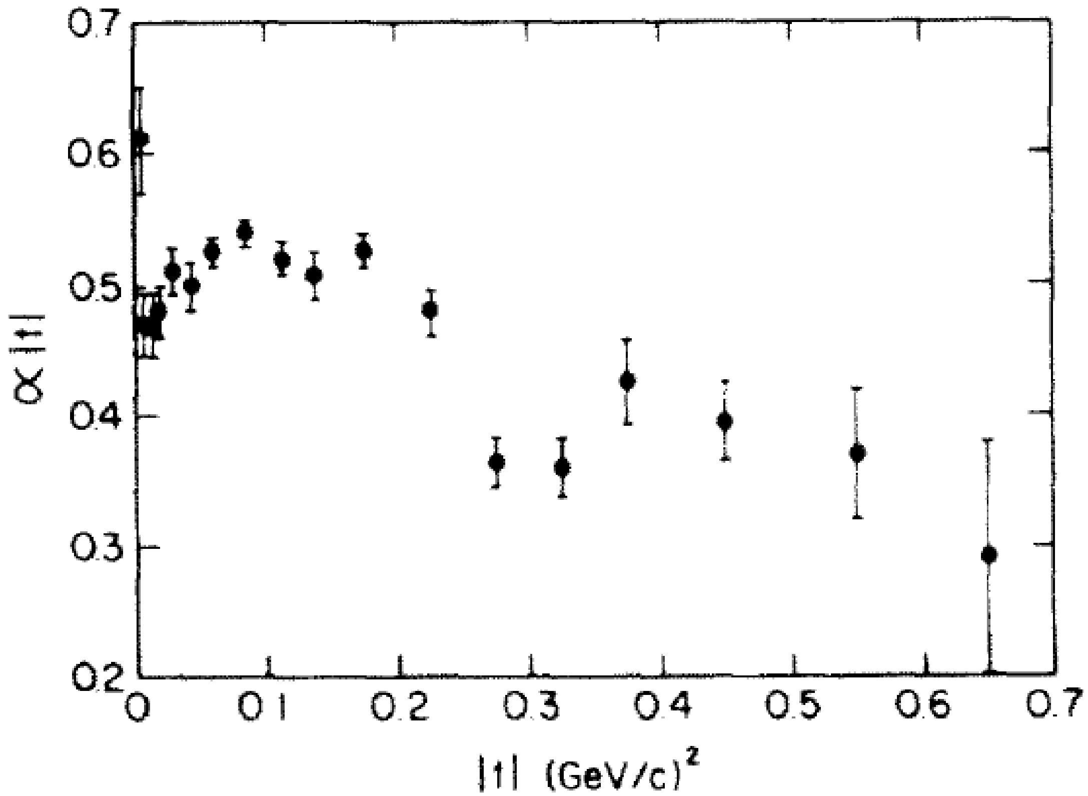
- Factorization requires full amplitude to vanish at t = 0 whereas general principles only require amplitude where there is a double spin flip to vanish e.g. (½ , ½ → -½ , -½) helicity states
- π exchange data like this looks as double spin flip amplitude is just like (*) but non flip amplitudes like (½ , ½ → ½ , ½) are just what you would get from smooth AMPLITUDE approximation

Coupling Constant . $(m_\pi^2/m_\pi^2)/(m_\pi^2 - t)$ (**)

NP CHARGE EXCHANGE

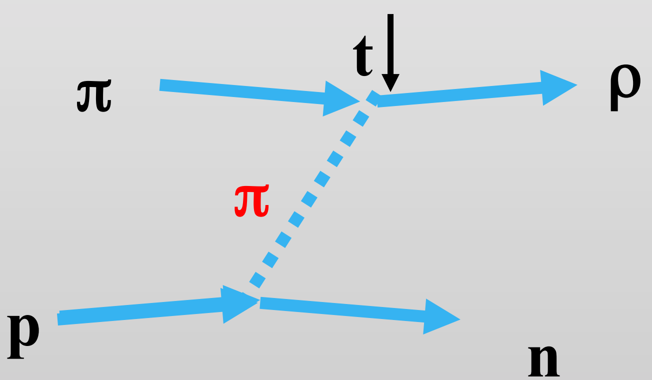
- Agrees better with ρ, A_2 exchange at highest energies
- See paper by Farmelo and Irving 1977



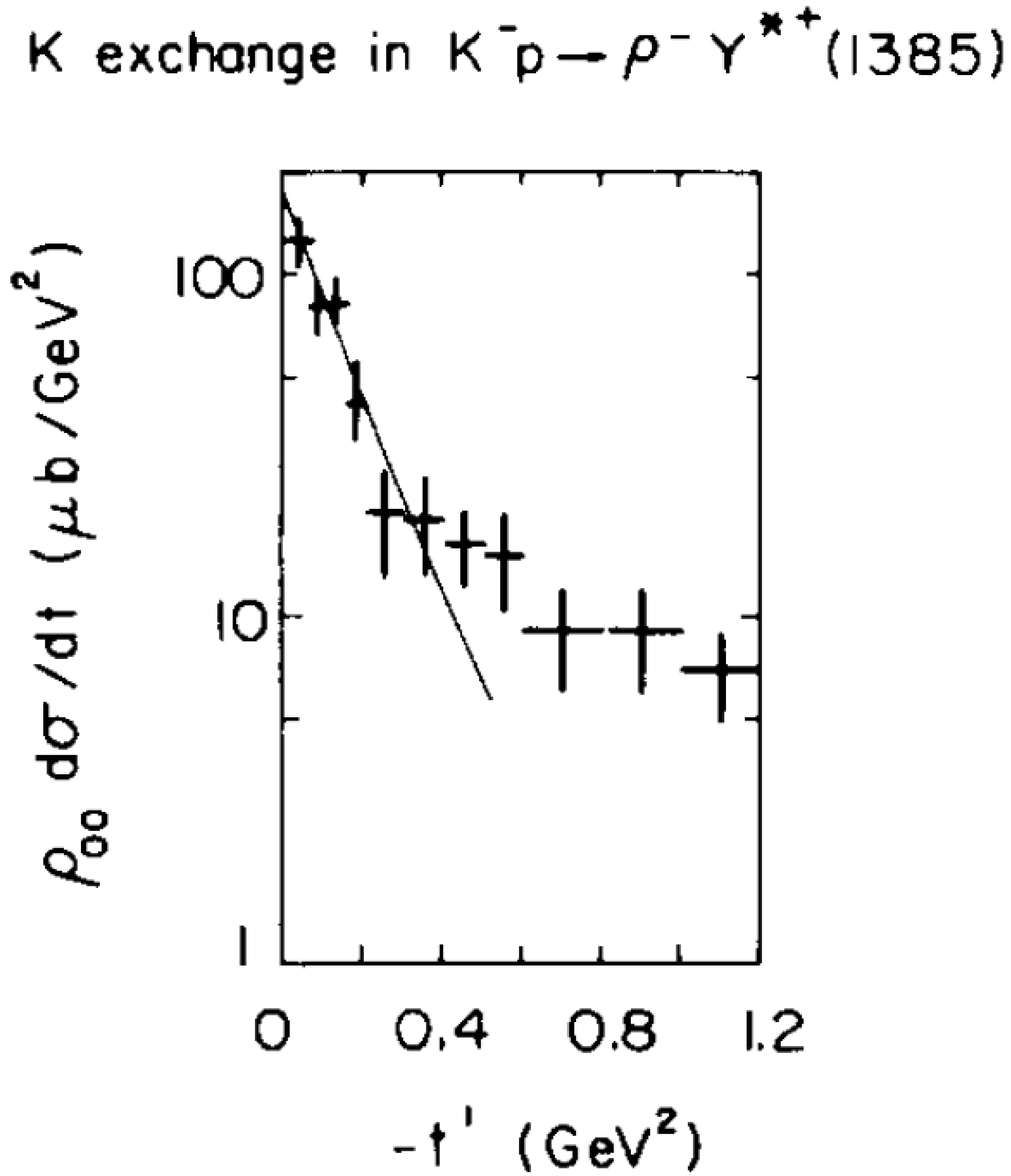


Π CONSPIRACY II

- You can explore these issues more clearly with $\pi^- p \rightarrow \rho^0 n$ as you can project out rigorously unnatural parity part where π is leading trajectory
- Interesting to compare with Δ production at target vertex as $\pi\ \bar{p}\ \Delta$ does not vanish at $t=0$
- $\pi^+ p \rightarrow \rho^0 \Delta^{++}$ and $p\ p \rightarrow n\ \Delta^{++}$



- OK with helicity 0 ρ but naïve factorizable π exchange vanishes when ρ helicity 1 – not seen experimentally in any π exchange reaction
- See E110 data



IRVING AND WORDEN FIG 4E.2

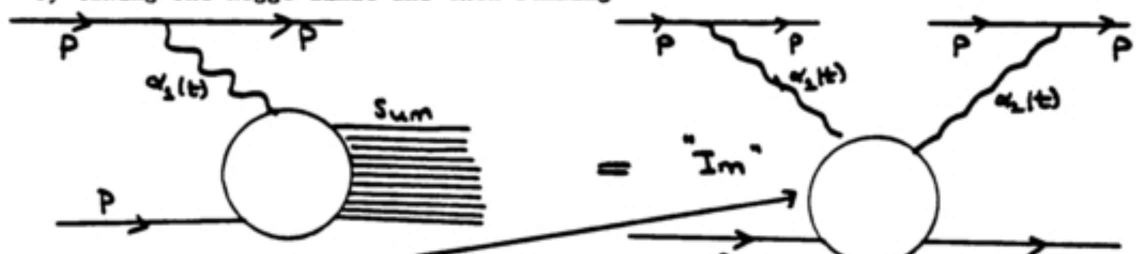
Broken SU(3) from π exchange in $\pi^+ p \to \rho^0 \Delta^{++}$. Unknown Energy

Note unnatural parity part extracted

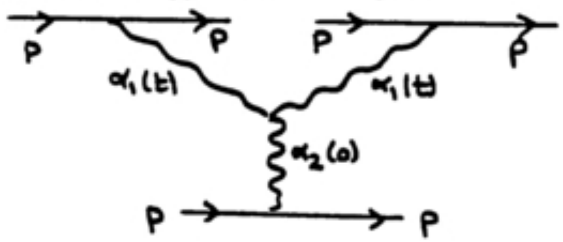
TRIPLE REGGE THEORY

Picture 29: Mr. Regge, All Dolled-up, Meets Medusa But Comes Out Pretty Well

The final limit is called the Triple Regge limit. This is achieved by taking one Regge limit and then summing



Another Regge limit here gives us



$\alpha_1(t)$ can be Pomeron, ρ...
see $\alpha_1(t)$ for all t

α_2 = Pomeron for scaling: see $\alpha_2(0)$ only

For x near 1, $d^3\sigma/d^3p \propto (1-x)^{\alpha_2(0)-2\alpha_1(t)}$ and one can hope to see "shrinkage" in t-dependence of $(1-x)^{n(t)}$.

This is particularly interesting as it allows us to use Regge theory away from t = 0 and perhaps see not only shrinkage, but absorption dips (?), WSNZ, etc.!

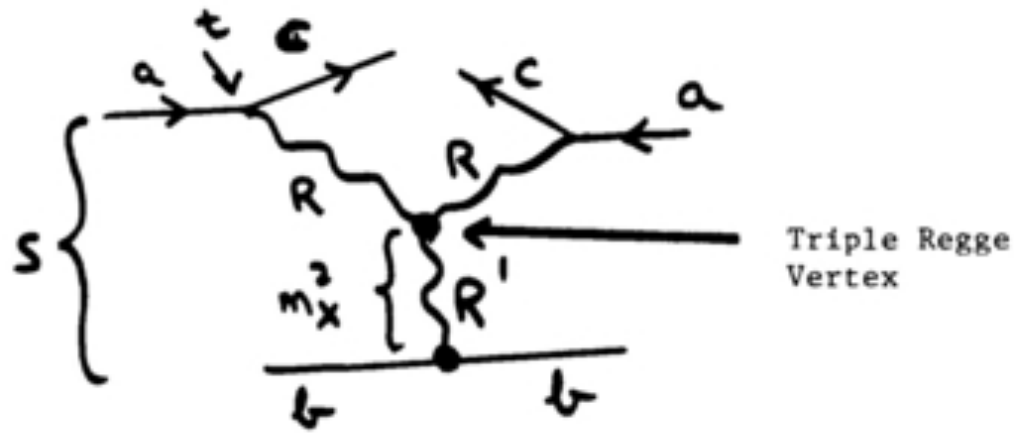
Picture 29 shows some fine data from the ISR. As illustrated, it can be fitted by the sum of two triple Regge terms

(i) α_2 = Pomeranchuk, $\alpha_1 = f^0$ where the data shows shrinkage of f^0!

(ii) $\alpha_2 = f^0$, α_1 = Pomeranchuk to give the striking peak near x = 1 in proton distribution. (This can also be fitted by $\alpha_1 = \alpha_2$ = Pomeranchuk; a so-called triple Pomeron coupling which terrifies theorists as it is meant to be zero.)

This particular application will advance quickly as NAL/ISR pour data in our eager hands.

TRIPLE REGGE THEORY



which describe (35) when t is small and s, m_X^2 are large.

The theory predicts

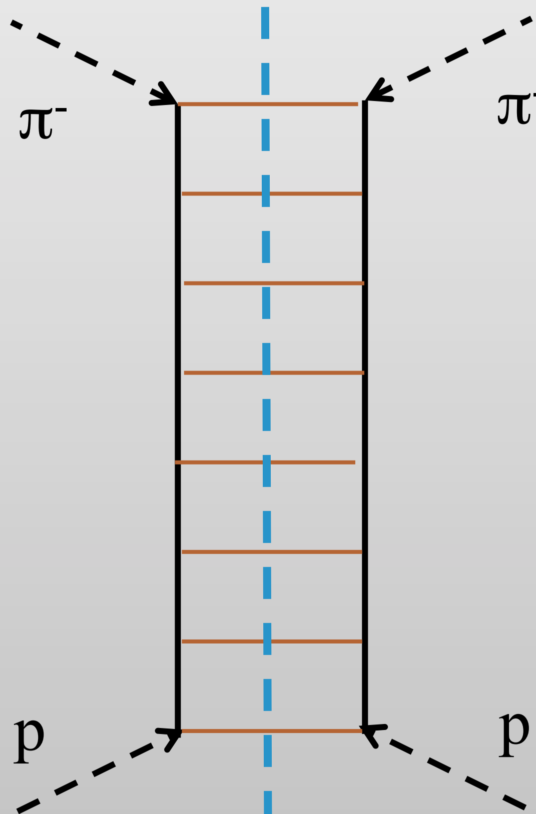
$$\frac{d\sigma}{dtdx} \propto \frac{(1-x)^{\alpha'-2\alpha(t)}}{s^{1-\alpha'}} \tag{36}$$

(α' is intercept at momentum transfer 0 or Reggeon R', $\alpha(t)$ is trajectory of R) or for $\alpha' = 1$ (the Pomeron) one finds the energy independent inclusive cross section

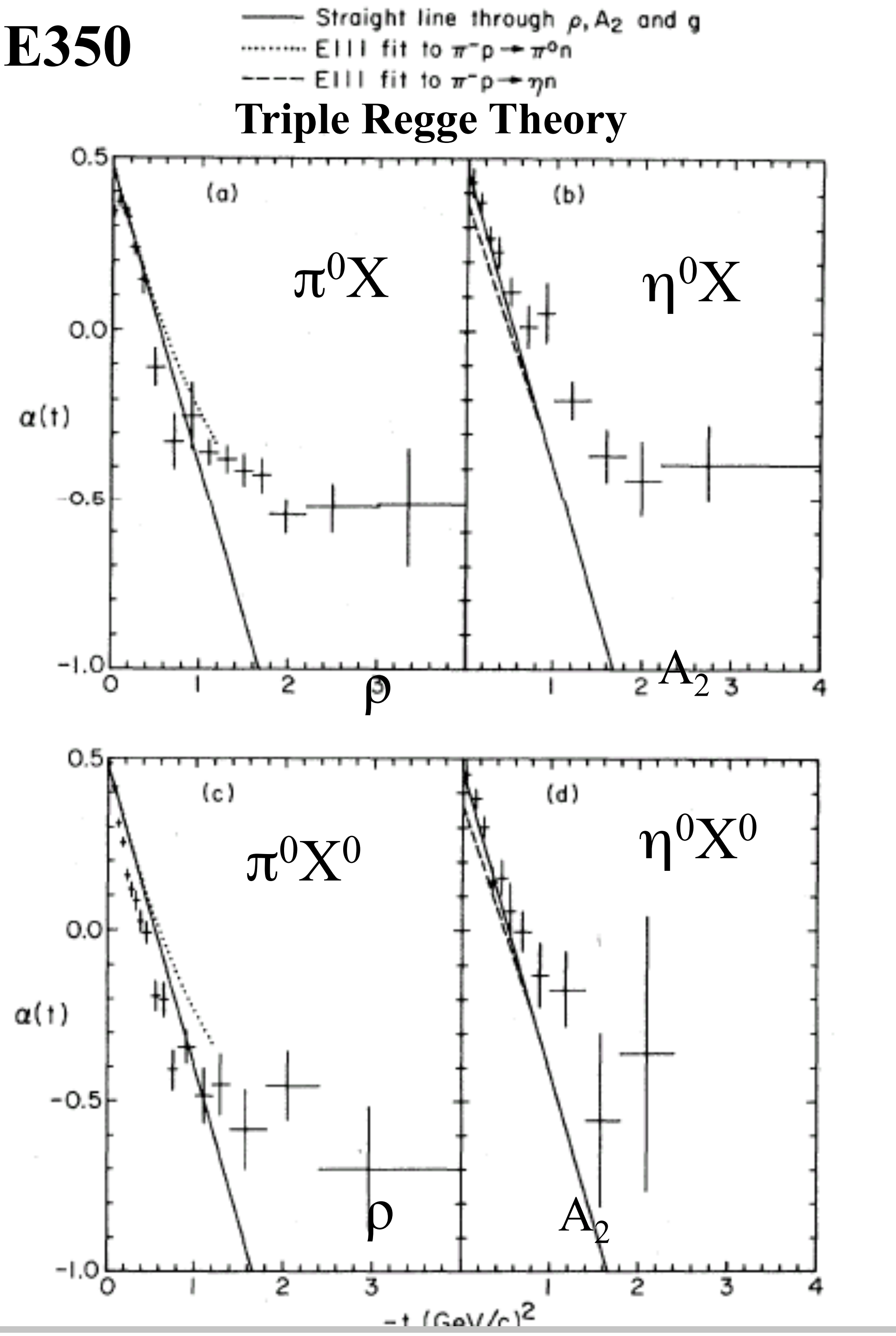
$$\frac{d\sigma}{dtdx} \propto (1-x)^{1-2\alpha(t)}. \tag{37}$$

4 TRIPLE REGGE REACTIONS

- The cut "all" or "all neutrals" both sum ladder diagrams and one expects "all neutral Regge pole" controlling all neutral total cross section
- $\alpha_{\text{All Neutral}}(0) = -0.08$



E350



All that remains from that work are papers and a good fitting program!

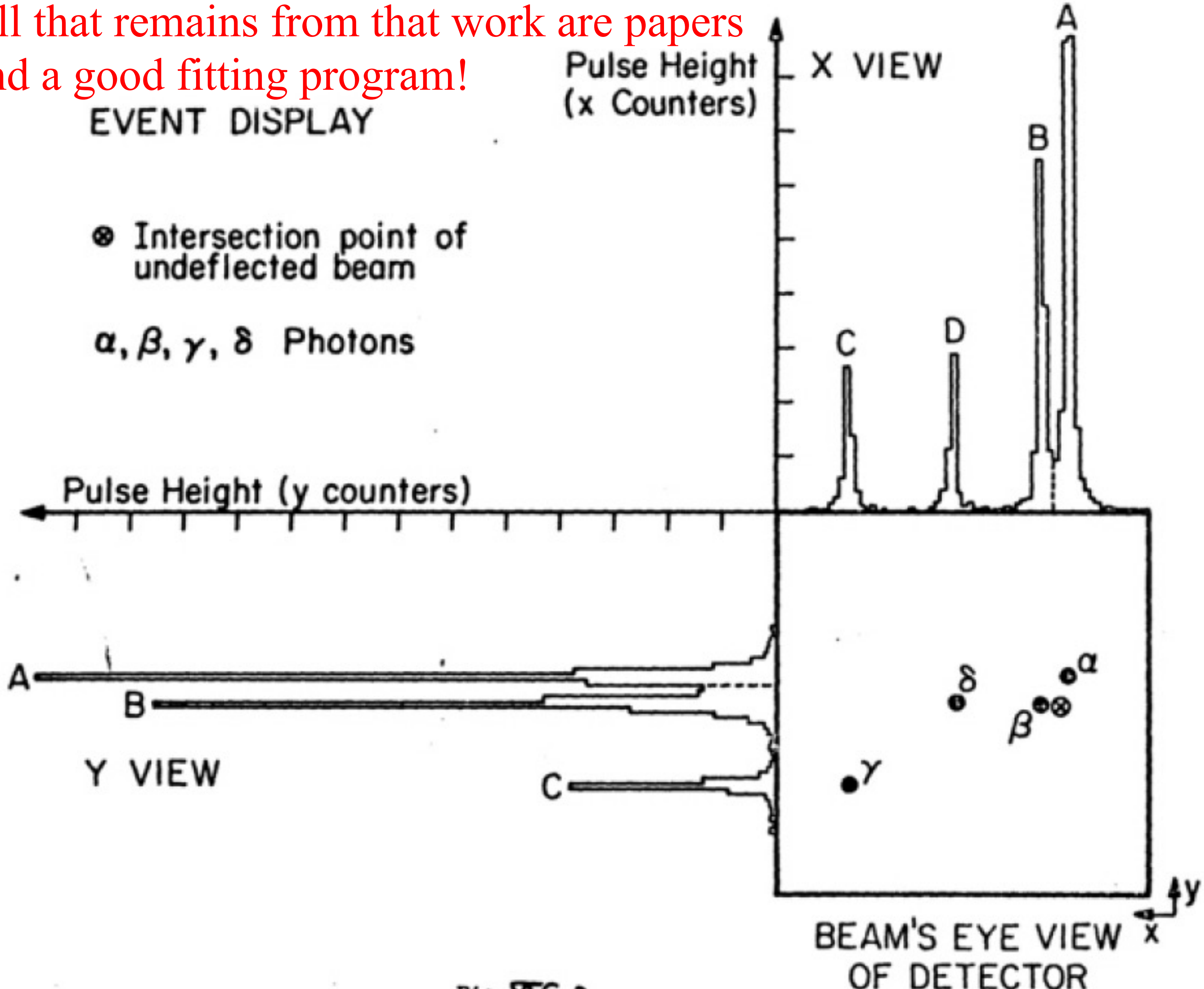
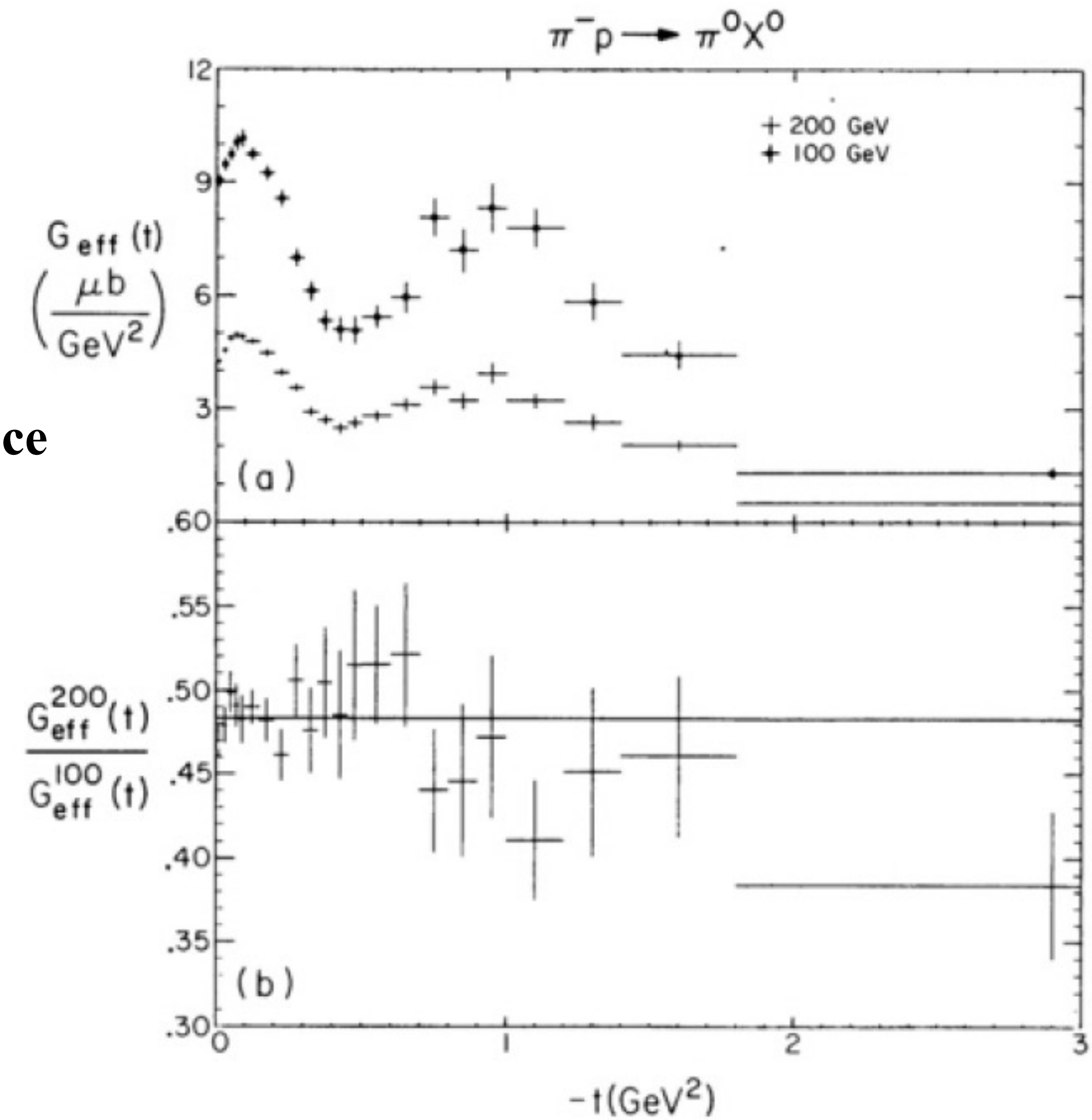
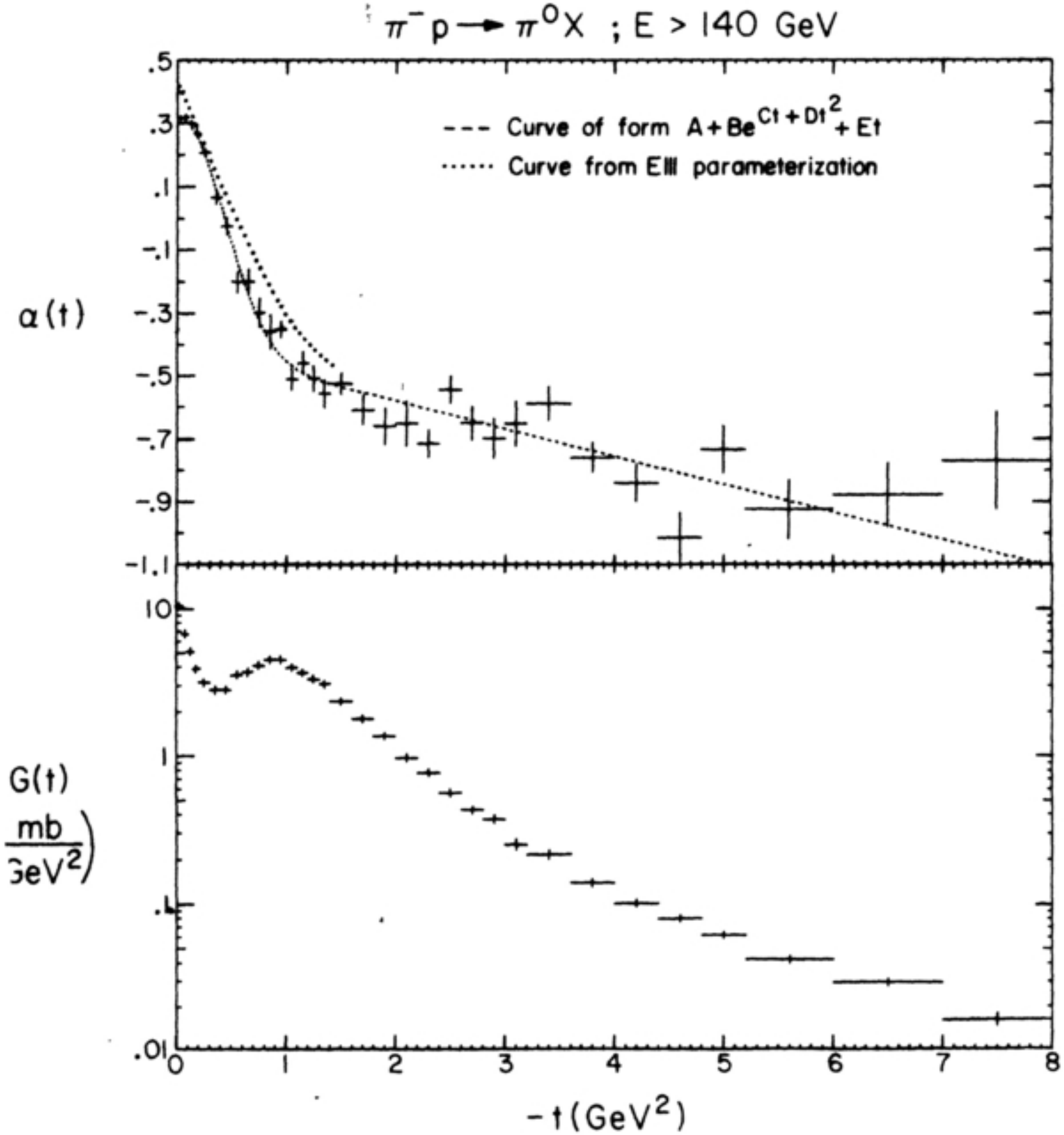


Fig. VI.2

$s^{-1.08}$ **dependence in G due to all neutral pseudopole**





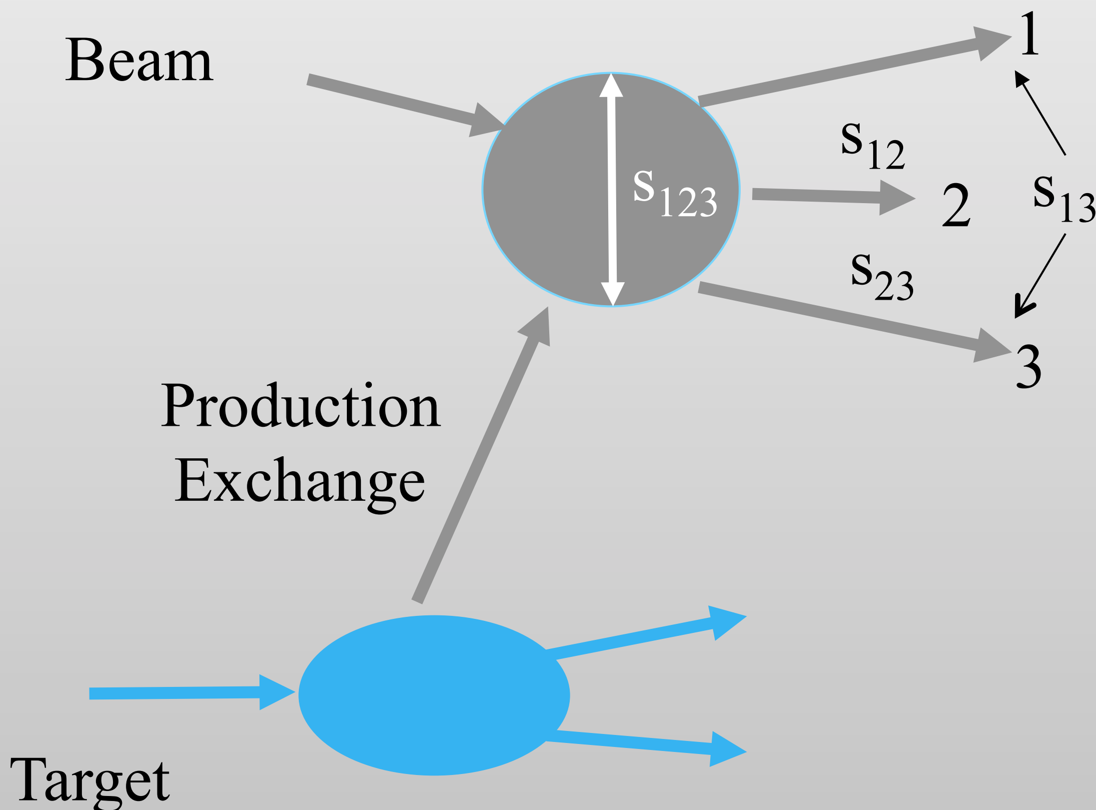
E350: Triple Regge Data

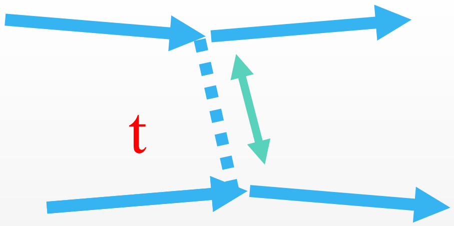
- Note get good agreement with ρ trajectory from E111 $\pi^- p \rightarrow \pi^0 n$
- WSNZ very clear
- Extend trajectory measurement to t = - 8 $(GeV/c)^2$
- Agreement between π^0 and η inclusive
- Full and all neutral final states

PERIPHERAL PARTIAL WAVE ANALYSIS

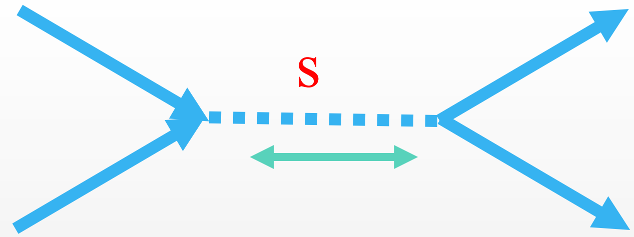
ISSUES IN PARTIAL WAVE ANALYSIS

- **Goal:** Extract clear evidence for resonances; determine masses, widths and their decay modes; compare with theoretical models; especially in areas that extend understanding of quark model (exotics, glueballs)
- **Peripheral Production** should be cleanest; Goal of E110 at Fermilab but never ran for long enough!





SOME LESSONS FROM THE PAST I



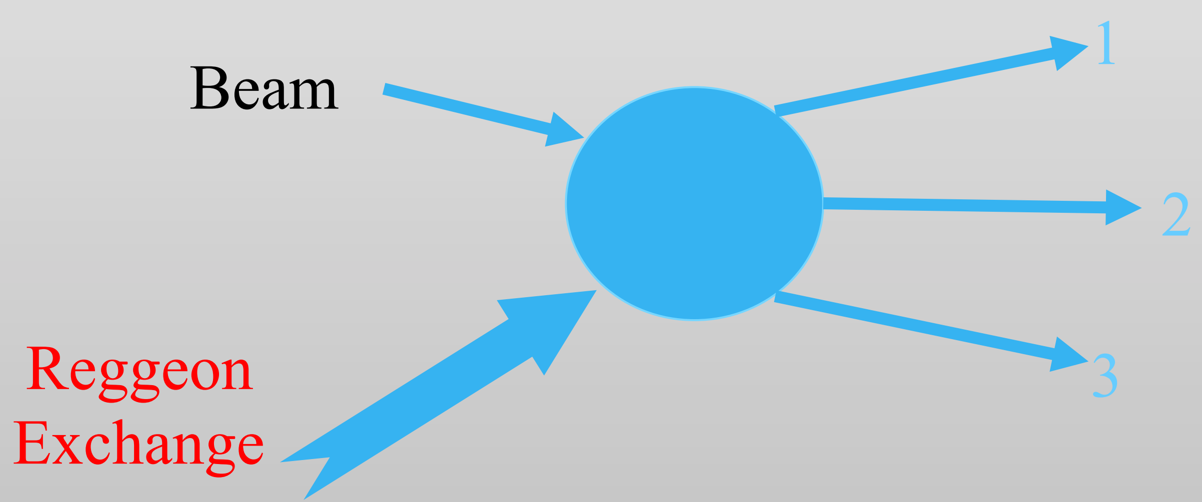
- Amplitudes exhibit many features for which there is no clear formalism that expresses in an integrated "additive" fashion
  - We found a lot of "true" results but little that was quantitative
- Analytic Structure as in S matrix with poles and cuts
  - Poles correspond to particles and resonances
  - Cuts to multiple exchanges (box and more complex diagrams)
  - Need to look at all channels to get full analytic structure
- Unitarity as a well understood (but difficult in multi-particle case to implement) constraint in every direct sub-channel
  - Constraint only strong at low channel energy when one or a few possible intermediate states and not clearly useful in production processes
- Spin formalism (Lorenz invariance) is of course well understood and uncontroversial
- Field Theory (Quark Model) can suggest quantum numbers, coupling constants, symmetries, chiral limits etc.
- Calculable field theories may not embody all known constraints

SOME LESSONS FROM THE PAST II

- Spin Formalism well understood both for full, decay, and Regge exchange amplitudes
  - Extremely complex
- Analytic structure of amplitudes well understood for t-channel (Jackson-Gottfried), s-channel frame helicity and transversity amplitudes
  - Transversity amplitudes have nice selection rules and invariance under rotations
  - But poor analyticity structure
- s-channel frame has particularly good analyticity and well understood “zero” structure at $t=0$

DENSITY MATRIX OR AMPLITUDE?

- Density Matrices will find dominant high spin resonances
- Amplitudes are more or less essential to find anything "not immediately obvious"
  - enforces rank and positivity conditions on density matrix
  - have well defined analyticity properties
  - But must be parameterized to reflect both unknowns and "what we know" – this bound to be wrong at some level?
  - Minimize and more realistically find ways to estimate error in amplitude approximations



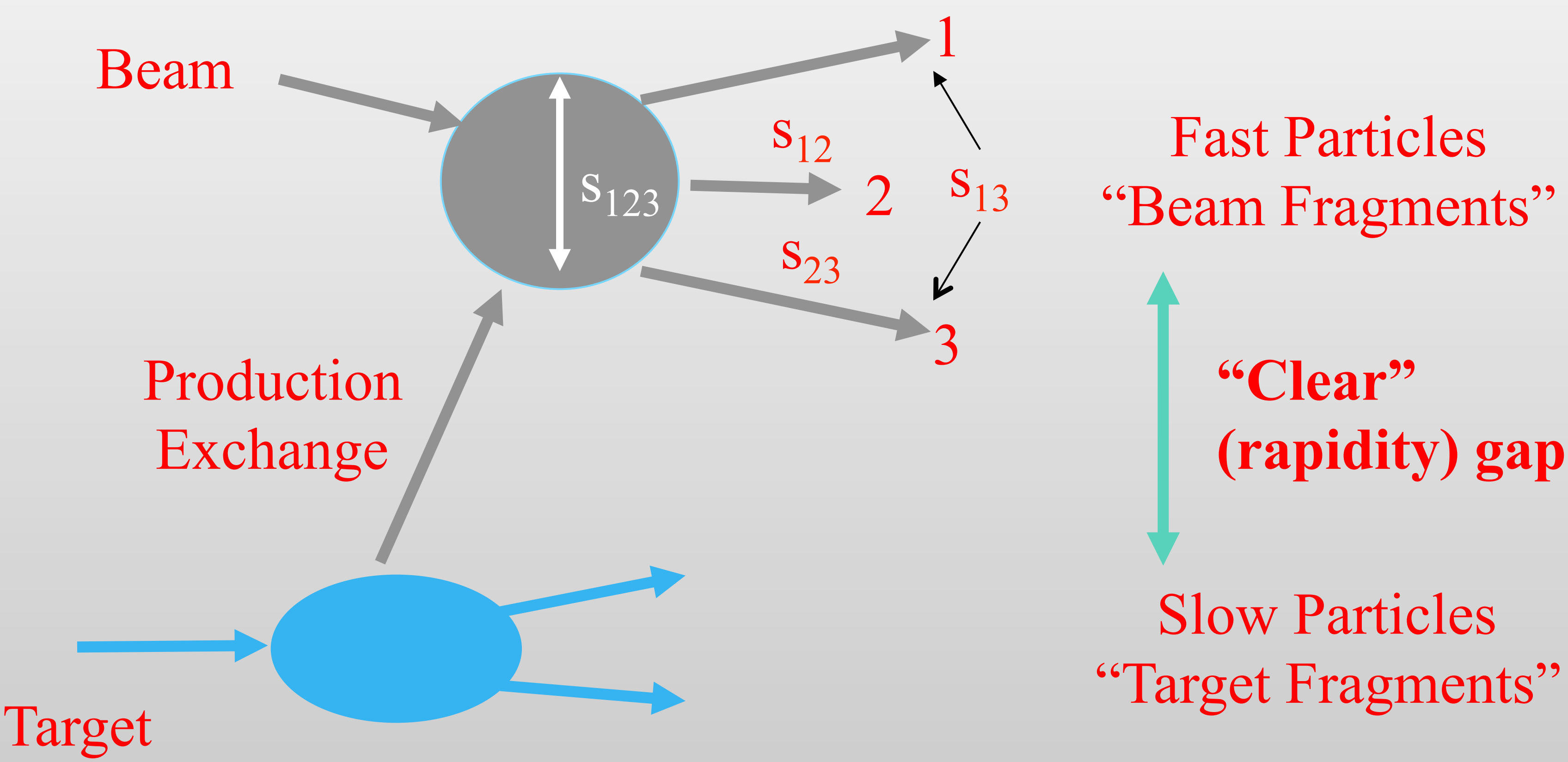
BREAK AMPLITUDE MODEL INTO 2 PIECES

- 1) Model for Exchange
  - In nearly all interesting cases exchanged particle should be a well known Reggeon (possibly the Pomeron) as these have highest intercept and will dominate in high energy region and this is only place reaction clean and distinguishable from background
  - Exchange is Pomeron, ρ ω π and exchange degenerate A_2 f_2 B_1
- 2) Model for

  Beam plus Exchange → "top vertex" final state
  - This is similar (how accurate is this?) to that for case where Exchange (Reggeon) replaced by "real particle" as critical symmetry, analyticity, duality, relevant unitarity constraints are qualitatively unchanged

PROTOTYPICAL REACTION

- We are studying the sub-Reaction,
  Beam + "Production Exchange" gives 1 + 2 or 1 + 2 + 3

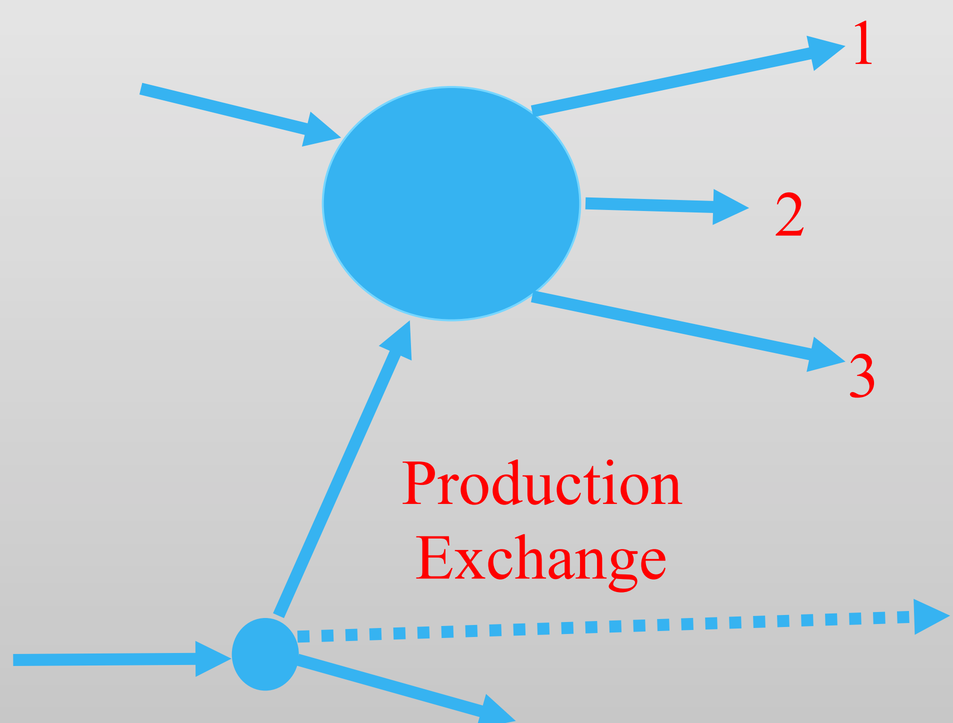


WHAT DO WE KNOW ABOUT PRODUCTION?

- Exchanged Reggeons are pretty phenomenological – mixtures of multiple poles and cuts – so exact status of a say Pomeron is not important – can use $\alpha_{\text{Pomeron}}(0) \approx 1.0$ style fits agreeing naturally with flat pp total cross section at intermediate energies
- There are well understood difficulties with π exchange as a simple factorizable Regge pole (in case of helicity flip at top vertex)
  - More study useful here
- So we know how to do exchanges and this will be more or less accurate for overall beam momentum dependence, quark model structure of exchange, production t dependence and aspects of the exchanged Reggeon helicity structure

FACTORIZATION USEFUL?

- As in Triple Regge experiments with full or all neutral, we got essentially identical dynamics from $\pi^- p \rightarrow \pi^0 n$; $\pi^- p \rightarrow \pi^0$ inclusive ; $\pi^- p \rightarrow \pi^0$ plus any neutral
- So at least in cases where clear Reggeon exchange involved, doesn't really matter if "target vertex" reaction clean

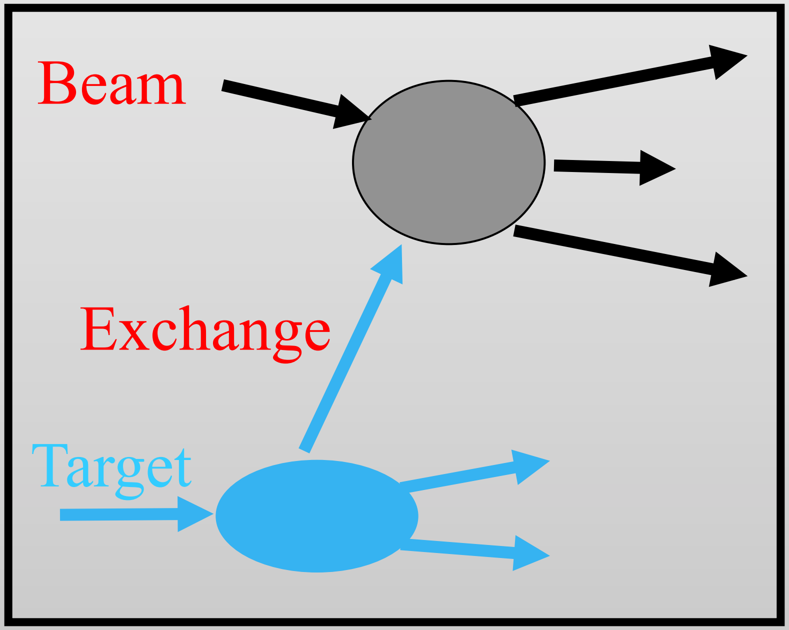


Add anything you like at bottom vertex

WHAT'S THE PROBLEM AGAIN?

- The understanding of exchange part is roughly right and we will use a roughly right model in PWA
- But in trying to find new resonances, we are looking at non dominant effects in Beam Reggeon → 2 or 3 (or more) particles
- How can we sure that approximations do not affect our partial wave analysis
- Answer:

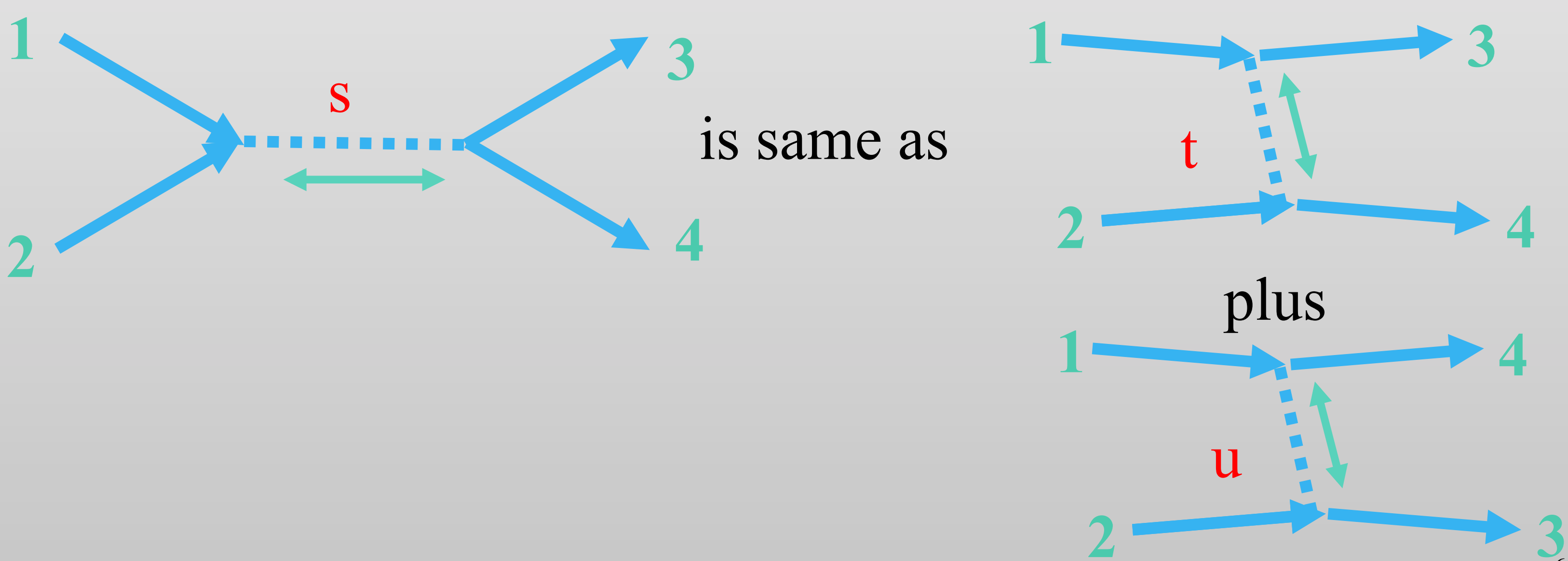
  - **Need to include all important effects and evaluate uncertainties they cause?**



Lets examine other approximations
In the
Beam Reggeon → 2 or 3 (or more) particles reaction

LESSONS FROM DUALITY I

- t(u)-channel exchanges are "classically" the forces that create the s-channel particles
- Thus it is not trivially "wrong" that same effect (e.g. diffractively produced a_1) can be "explained from direct or cross channel point of view
- Veneziano model illustrates this



LESSONS FROM DUALITY II

- It appears that ρ ω A_2 f g N Δ … particles form Regge trajectories having party line characteristics
  - Exchange degeneracy of mesons reflecting exotic channels
  - Daughters
- Presumably this extends to π B a_1 but study here could be improved
- Exchange Degenerate $\alpha_\rho = \alpha_f = \alpha(0) + \alpha' t$

  Veneziano formula for $\pi^- \pi^+ \rightarrow \pi^- \pi^+$ is

  $A(s,t) = \Gamma(1-\alpha_\rho(s))\, \Gamma(1-\alpha_\rho(t)) / \Gamma(1-\alpha_\rho(s)-\alpha_\rho(t))$
- This has Regge poles in s and t channels, no poles in u channel and residue proportional to $\alpha(0) + \alpha' t$ at $\alpha_\rho(s)=1$
  - **$\alpha(0) + \alpha' t$ is a mixture of spin 0 and spin 1 i.e. requires** $\rho + \varepsilon$

LESSONS FROM DUALITY III

- Partial Wave Analyses of π N elastic scattering suggested an important additive model of two component duality
  - $A_{\pi N \to \pi N}(s,t,u) = A_{\text{Particle Regge}}(s,t,u) + A_{\text{Pomeron}}(s,t,u)$
- The classic nucleon resonances in the s channel sum to an amplitude $A_{\text{Particle Regge}}(s,t,u)$ corresponding to the classic meson Reggeons in t channel plus classic nucleon Reggeons in u channel
- The background in the s channel corresponds to an amplitude $A_{\text{Pomeron}}(s,t,u)$ corresponding to the Pomeron in the t channel
  - Pomeron component in meson scattering can be estimated from

    $\pi^+ \pi^+ \to \pi^+ \pi^+$?
- **Regge Pole for high partial waves plus "s-channel" (resonances) guided by 2-component duality is natural model**

FINITE ENERGY SUM RULES

- In π N elastic scattering, duality worked well to low energies as shown by for example
  - Persistence of Regge zeros (such as ρ exchange zero at t = -0.6 Gev^2) to low energies
  - Suppression of backward peaks corresponding to nucleon and not meson exchange)
- We need to convert sloppy S-matrix arguments into more precise constraints wherever possible
- Finite energy sum rules FESR of form

$$\int_{\text{Threshold}}^{\text{Cutoff}} \nu^n \, \text{Im}\, A(\nu,t)\, d\nu = \text{Regge Contribution} \qquad [\, \nu = s\text{-}u \,]$$

were successful in π N scattering and should be also be applicable in Beam (Reggeon) scattering (see Indiana University work on $\pi^- p \to \eta \, \pi^- p$ with Pomeron at $p \to p$ vertex)

- A is the low energy amplitude from the partial wave analysis

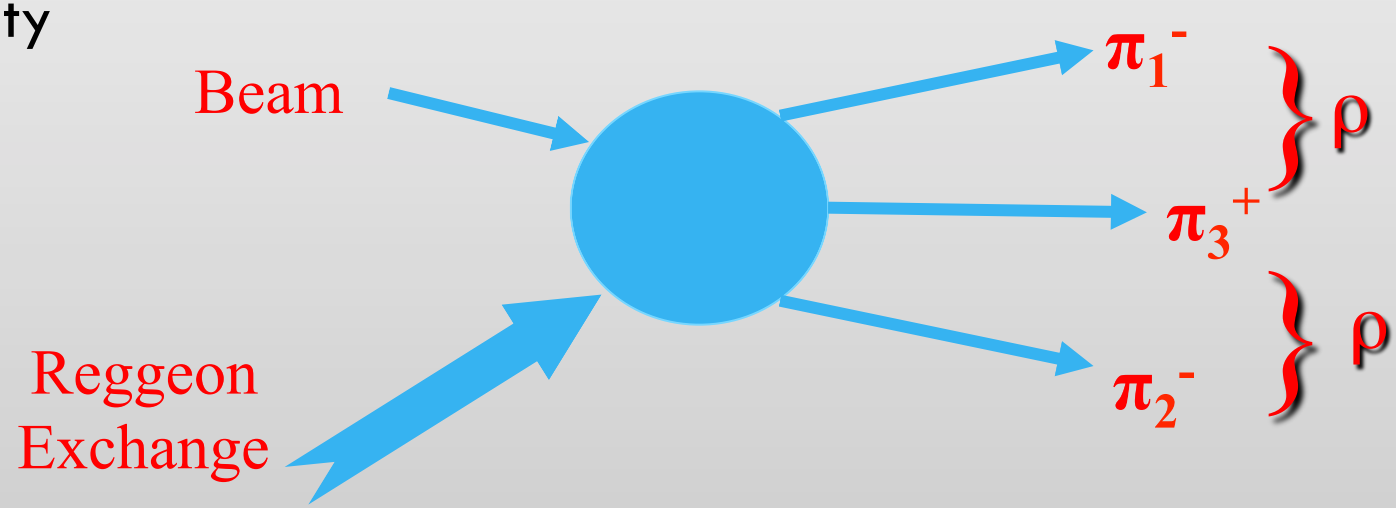
SOURCE OF ERROR IN PERIPHERAL PARTIAL WAVE ANALYSIS

SOURCES OF ERRORS IN PWA

- We will need to study final state interactions although these are partly included as
- Duality says direct (resonances) and exchange effects (forces) are the same not different dynamics
  - An effect being "final state interactions" does not mean it is or is not a resonance ….
- One will be looking at 2 3 and higher particle final states at the top vertex and realistically one will need the "Quasi 2-body" approximation to do a practical amplitude based partial wave analysis.
  - This sometimes can be done reliably and independently in different sub-channels

QUASI 2-BODY APPROXIMATION I

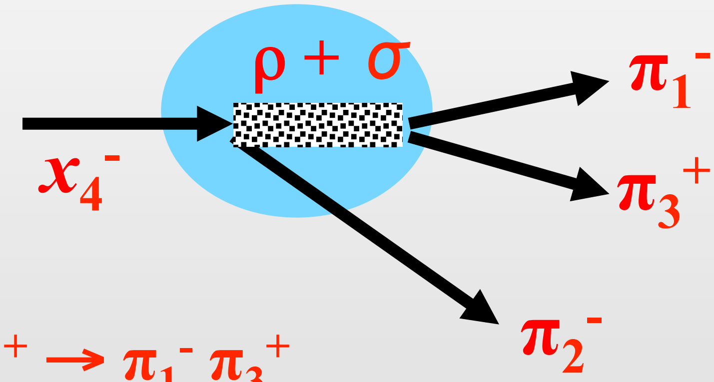
- The "Quasi 2-body" approximation says that $\pi_1^- \pi_2^- \pi^+$ final state can be thought of as $\pi_1^- \rho$ plus $\pi_2^- \rho$ and has proven to be reliable at least when resonances are well established like the ρ which appears to have similar dynamics to "real particles" like the π
- However there are subtle amplitude interference effects required by duality

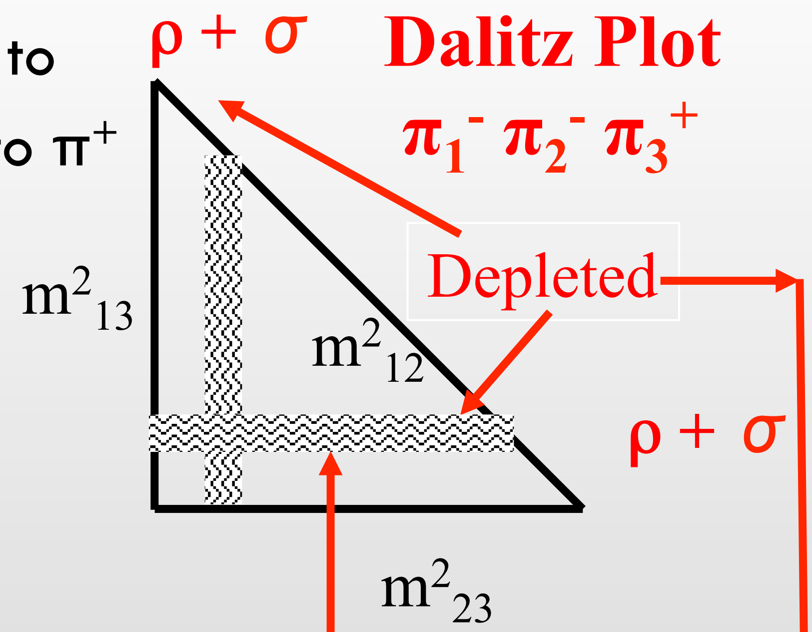


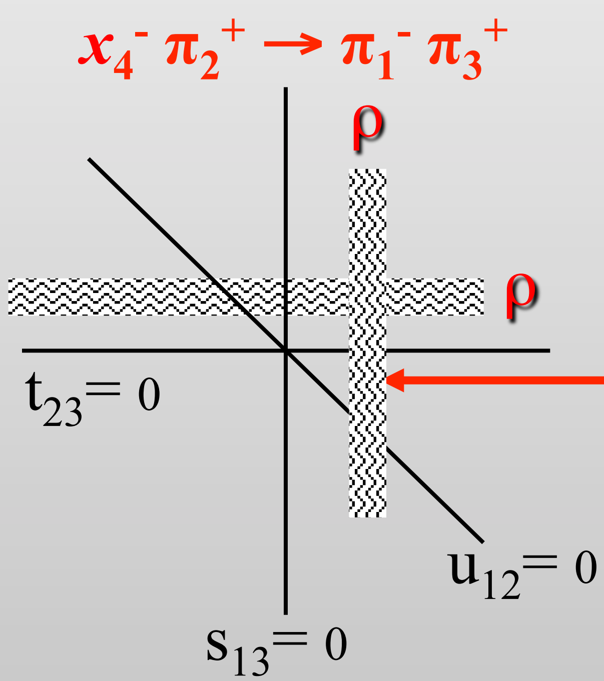
- Note the spin 0+ f0(600) or σ must exist by duality as daughter of ρ. It can be arbitrarily distorted by threshold effects and mixing

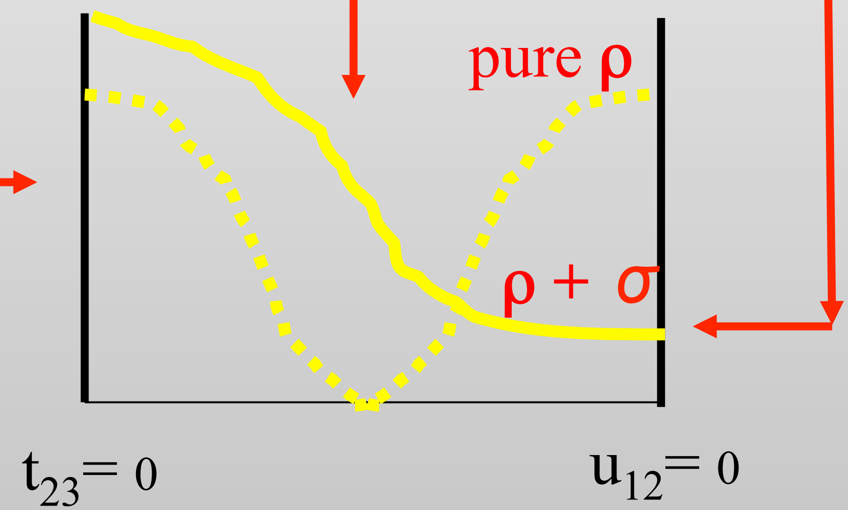
QUASI 2-BODY APPROXIMATION II

- The ρ and σ must interfere coherently to suppress double charge exchange x^- to π^+









PLAN GOING FORWARD

SOME LESSONS I

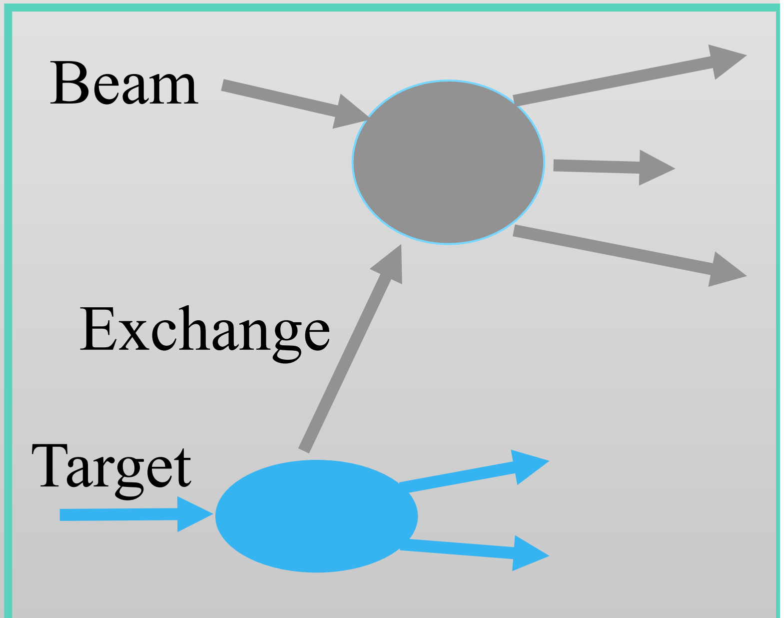
- All confusing effects exist and no fundamental (correct) way to remove. So one should:
  - Minimize effect of the hard (insoluble) problems such as “particles from wrong vertex”, “impossible to estimate exchange effects” sensitive to slope of unclear Regge trajectories, absorption etc.
- Note many of effects (exchanges) are intrinsically MORE important in multiparticle case than in relatively well studied $\pi N \Rightarrow \pi N$
- Try to estimate impact of uncertainties from each effect on results
  - Need systematic very high statistic studies of relatively clean cases where spectroscopy may not be most interesting issue but one can examine uncertainties
  - Possibilities are A_1 A_2 A_3 B_1 peripherally produced and even $\pi N \Rightarrow \pi \pi N$

SOME LESSONS II

- Theory failed to provide convincing parameterizable amplitudes one could use to fit/explain data
- Theory provided some quantitative constraints (π pole, unitarity, kinematics, …), many qualitative truths (two-component duality) which overlap and whose effect can be estimated with errors from 10 to 100%
- Now we must take a factor of 100 or so more data to tackle problem phenomenologically
- First step is to clarify and test technique
- Next step is to use technique to do new physics
- Put everything on the web! http://www.indiana.edu/~jpac/index.html

EFFECTS TO INCLUDE I

- We need to develop reasonable Regge phenomenology for production amplitudes
  - Update Irving, A. C.; Worden, R. P. (1977). "Regge phenomenology". *Phys. Rep.* 34 (3): 117–231 (Worden was my student)
- Identifying reliably quantum numbers (including naturality) of exchanged particles will be essential if we want to make reliable PWA models
- We do not expect previous fits to give quantitative predictions in many cases but good start



EFFECTS TO INCLUDE II

- Include Regge cuts as phenomenological poles?
- Spin Formalism: Must use
  - Amplitude Parameterization – polarization needed with photon beams to determine the different amplitudes with different photon helicities
  - With some checks using a Density Matrix Formalism – but this can't cope with explicit contributions, analyticity etc. Only likely to show clearly "blatant" effects.
  - Transversity versus helicity formalism is trade-off of analyticity versus selection rules; I always preferred helicity amplitudes

EFFECTS TO INCLUDE III

- Regge exchange contributions in top vertex: Identify all allowed (by normal Regge phenomenology) exchanges and catalog where expected to be large due to coupling constants and/or values of $\alpha(t,u)$
- Use usual duality type arguments to identify related s_{13} t u exchanges i.e. where you might expect the direct and crossed descriptions to be related
- Develop models for exchange contributions using simple phenomenological Regge theory
  - Determine parameter either by fitting higher mass data or iteratively through finite energy sum rules
  - Identify all π exchange contributions and expect these to be reliable (with "conspirator) near t=0 but unreliable away from there -- π as a Regge pole problematic
  - Parameterize cuts as poles?

EFFECTS TO INCLUDE IV

- Dispersion Relations and other Analyticity
  - Check FESR's and look for zeros
  - Present data and fits in a way to display effect (e.g. fixed u cross sections for reactions with no u channel exchanges) – check qualitatively reasonable
- Coupled Multichannel analysis (at top vertex) is useful and could reduce parameters and check results
  - but will not be as powerful as in π N case as unitarity will rarely be applicable in same fashion (as don't have any elastic amplitudes except for case of π exchange in production case)

INVESTIGATE UNCERTAINTIES

- There are several possible sources of error
  - Unitarity (final state interactions)
  - Errors in the two-component duality picture
  - Exotic particles are produced and are just different
  - Photon beams, π exchange or some other "classic effect" not present in original πN analyses behaves unexpectedly
  - Failure of quasi two body approximation
  - Regge cuts cannot be ignored
  - Background from other channels
- Develop tests for these in "easy" cases such as π π Scattering
  - Investigate all effects on any interesting result from PWA