Double Pomeron Exchange: The early years
or
A Brief History of the Pomeron: Chapter 1(experimental)

Michael Albrow (Fermi National Accelerator Laboratory)

Mike Albrow HERAUS 2015 *Bad Honnef*

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A Brief History of the Pomeron: Chapter 1

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This talk is mainly for people:

Under 55,
as you think "ISR" means Initial State Radiation, or only worked at LEP or HERA

Over 75,
because you are rapidly forgetting things and this might remind you (briefly)

Double Pomeron Exchange: The early years

Intersecting Storage Rings (ISR)
SuperProton Synchrotron (SPS) and Tevatron (Fixed target) (& RHIC)

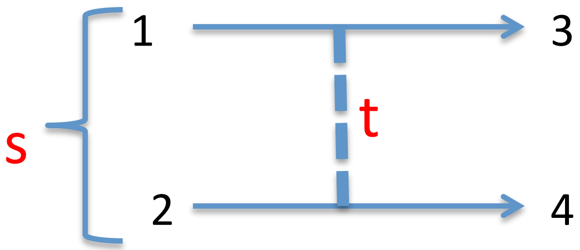
Growth of an idea
Early experimental searches
The ISR and the first observations
The Omega spectrometer (SPS-FT) studies
The Tevatron (fixed target)
RHIC pp2pp (200 GeV)

Very incomplete!
Highlights only!

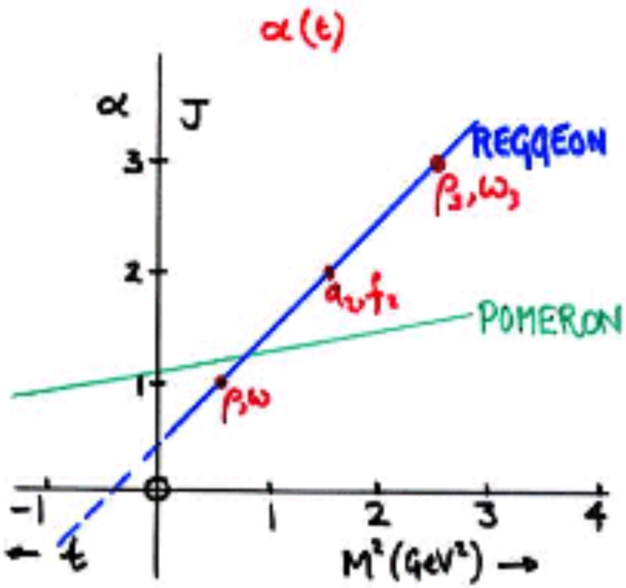
++++++++++++++++++++++++++++++++

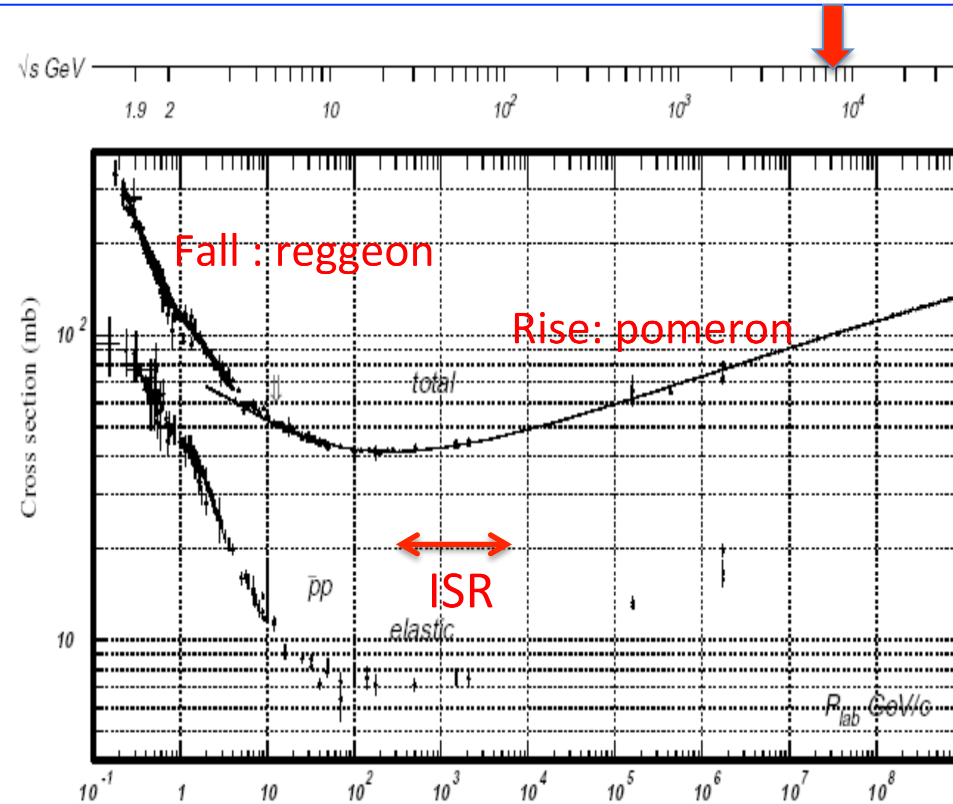
Later (not here): CDF (900+1960), LHC (7000, 8000)

Late 1960's : No QCD yet. Interactions described in terms of Regge trajectories.
Regge theory based on scattering amplitudes: A (1 + 2 → 3 + 4)
A(s,t) compex, where s,t,u are Mandelstam variables (invariants): $s + t + u = \Sigma m^2$
s = CM energy squared, t = four-momentum transfer² from 1 → 3



Attention: exchange not a particle, but carries 4-momentum.
Not "emitted" from 1 or from 2 (frame-dependent)
In C.M. (only) transfers no energy, only momentum.





Rise in total and elastic cross sections : "discovery" of pomeron (Pomeranchuk-on)

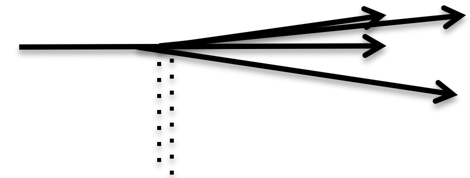
Small Angle Spectrometer R201 (CERN-Holland-Lancaster-Manchester)

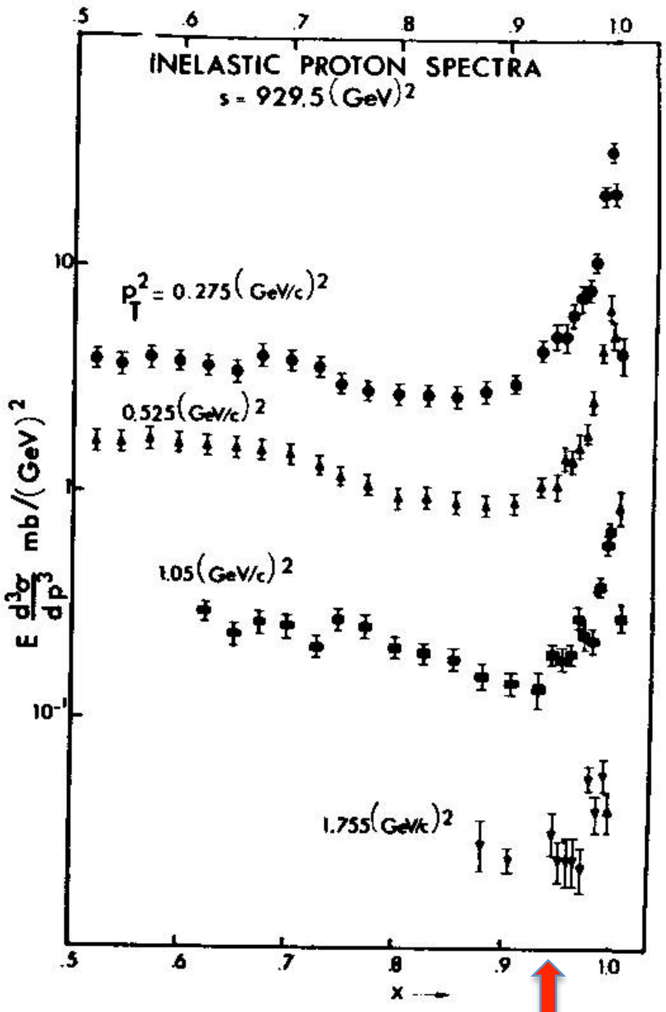
Observed Feynman scaling $\sigma(x_F,p_T)$ and discovered **high-mass (M > 2 GeV) diffraction**

Previously knew p → pππ, ΛK etc, resonances.

At ISR scaling peak $x_F > 0.95$ showed diffraction to M ~ 15 GeV

Note: at $x_F = 0.90$ have P & R each ~ 50%, not P-dominated





$$x_F = x_{Feynman} = \frac{p_z}{p_{Beam}} \geq\sim 0.95$$

$$\frac{M^2}{s} = (1 - x_F) \Rightarrow M_{\max} \sim \sqrt{0.05}\sqrt{s}$$

$$M_{\max} \sim 0.22\sqrt{s}$$

Proton $X_F > 0.95$ ≅ rapidity gap Δy > 3

If **both** protons diffractively scattered with $x_F > 0.95$, central mass M(X) < 0.05 √s (3 GeV at ISR, 100 GeV at Tevatron)

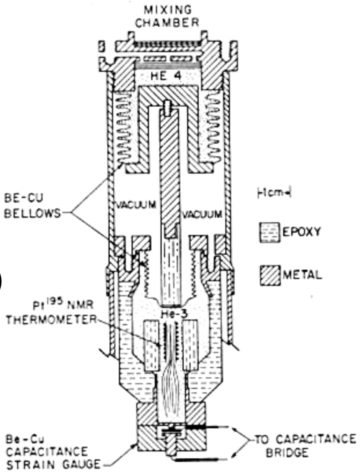
My *rule-of-thumb* for P-dominance: **$x_F > 0.95$ or Δy > 3**

Large (>~4) rapidity gaps ~ only "possible" by (t) exchange of 4-momentum with:
No color or charge, and effective spin at t ~ 0 >= 1. **J = 1, α(0) >=1**.
But (a) we **do** have such large gaps in strong interactions
(b) QCD is the theory of strong interactions. Unlike QED, there is no elementary (q,g) object with these properties.
(c) In QCD, with Regge theory to describe exchanges of states in the t-channel, only >= 2 g exchange can work.
Leading order P = gg C = +1 (Low, Nussinov)

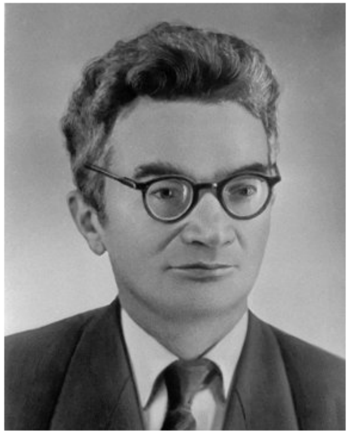
Scattering amplitudes must obey analyticity, crossing symmetry & unitarity.
Allow complex angular momenta → Regge theory

Tullio Regge

Experimenter Pomeranchuk cooling cell (1950) → 1 mK

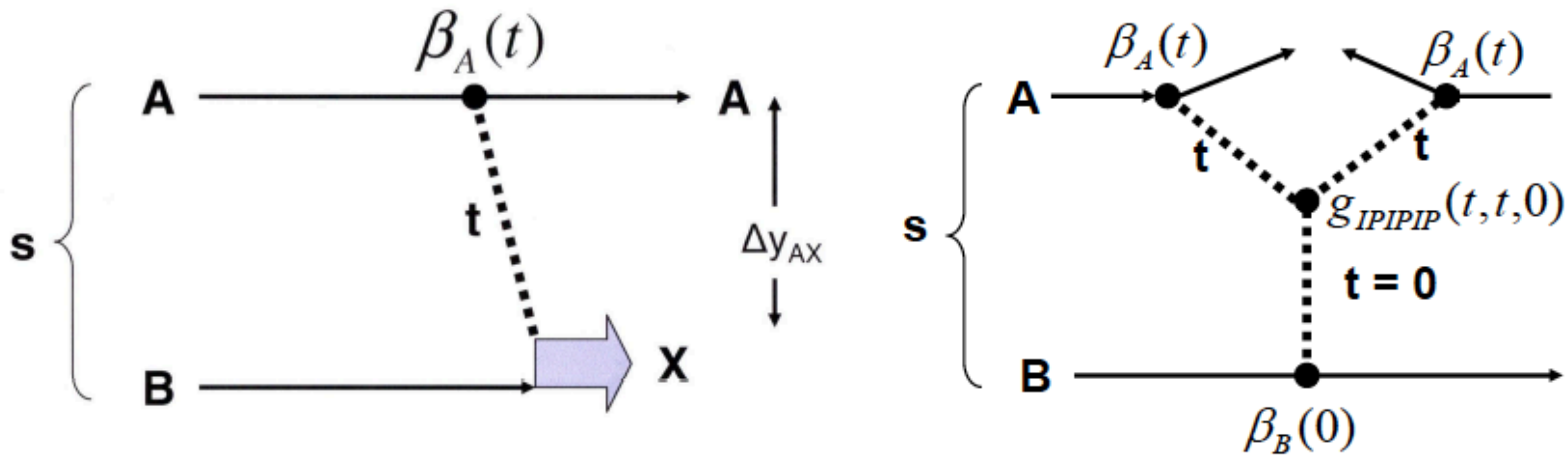


The Pomeranchuk cell used for cooling and measuring

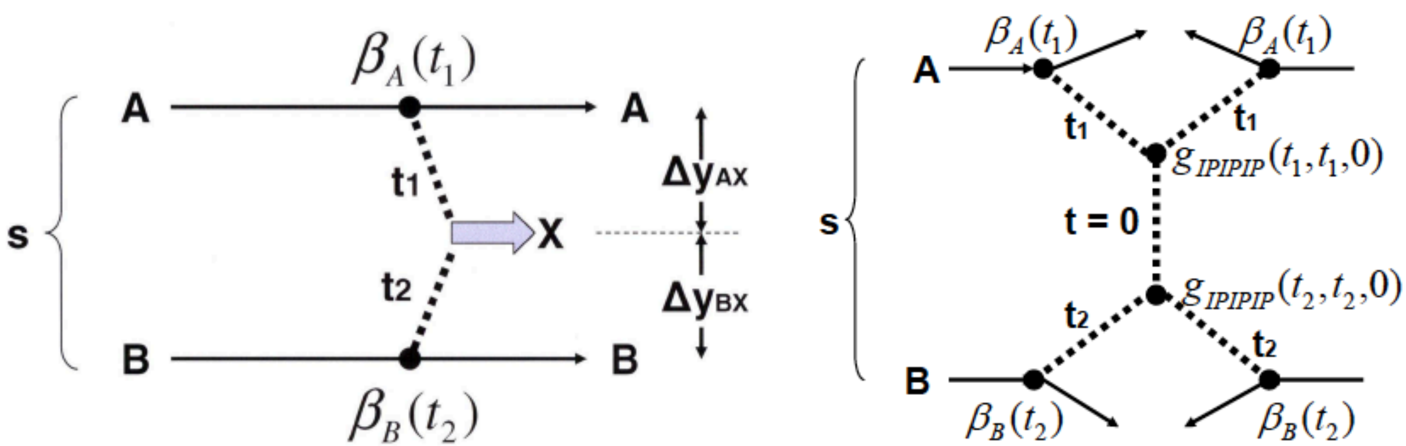


Isaak Pomeranchuk
1913 - 1966

The triple-Regge diagram:



Can the pomeron be exchanged more than once?



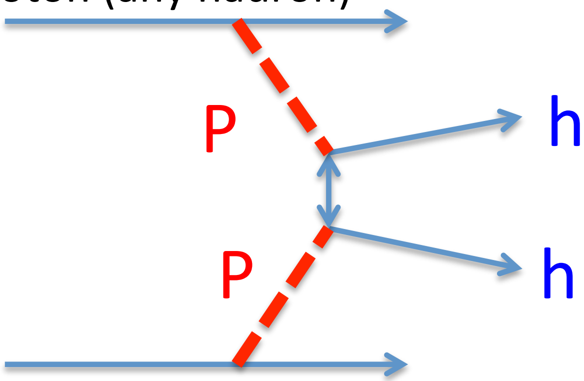
Pomeron ?
Yes at high M
At low M(X)?

Figure 3: (a) Diagram for double pomeron exchange. (b) The corresponding cut diagram in the limit of large M_X.

Figures from Albrow, Coughlin, Forshaw, CEP review: Prog.Part.Nucl.Phys 65 (2010) 149

Low masses, hadron pairs

Proton (any hadron)



Proton (any hadron)

$\mathbf{h}$ = any hadron

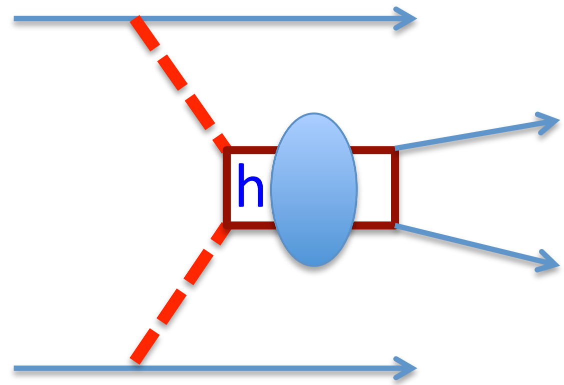
Different hadron pairs (full set)?

Flavor democracy?

Size dependence … B_c tiny!

Gluey hadron pairs preferred

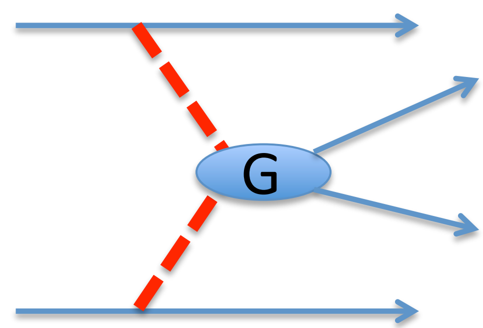
With final state interactions and resonances



Strong final state interactions

(Au, Morgan, Pennington: PR D35, 1633 (1987))

S-channel resonances $f_{0,2}$



The experimental progression (apologies to theorists, that would be another talk)

First search for DPE: Lipes, Zweig (*the* Zweig) and Robertson PRL 22 (1969) p22
π- p → π- (π+π-) p in BNL 80" bubble chamber with 25 GeV/c π-
250 events looking like "multi-regge exchange" but not DPE (ρ, ω etc dominate)

1974 Derrick et al 205 GeV/c p-beam PRL 32 (1974) 80
p p → p (π+π-) p … Fermilab BC 191 events/50,000 pictures σ(DPE) < 44 μb

1975 France-Sov.U 69 GeV/c p-beam on H-target Nucl. Phys. B98 (1975) 189
Dominated by SDE, σ(DPE, M < 700 MeV) < 20 μb

ISR Observation (1976)
R407/8 at Split Field Magnet
PL 65B (1976) 394

Brick et al : Fermilab-Pub-80-112E (1980) H_2 BC 147 GeV/c π, K, p beams
47 candidates in 500,000 pictures … σ ~ 20-50 μb

So: Study of double pomeron exchange needs the higher √s of colliding p-beams and electronic detectors, forget bubble chambers.

The Intersecting Storage Rings ISR led the way

But the Ω-detector at 450 GeV/c, √s = 29 GeV, did many studies at threshold of DPE dominance

DPE spectroscopy is mostly to do with isoscalar J = 0, 2 mesons

Mini-review on scalar mesons from Particle Data Group "bible"

NOTE ON SCALAR MESONS

Revised April 2010 by C. Amsler (University of Zurich), T. Gutsche (University of Tübingen), S. Spanier (University of Tennessee) and N.A. Törnqvist (University of Helsinki).

I. Introduction: The scalar mesons are especially important to understand because they have the same quantum numbers as the vacuum ($J^{PC} = 0^{++}$). Therefore they can condense into the vacuum and break a symmetry such as a global chiral $U(N_f) \times U(N_f)$. The details of how this symmetry breaking is implemented in Nature is one of the most profound problems in particle physics.

In contrast to the vector and tensor mesons, the identification of the scalar mesons is a long-standing puzzle. Scalar resonances are difficult to resolve because of their large decay

J. Pumplin, F. Henyey, Double pomeron exchange in the reaction $pp \to pp\pi^+\pi^-$, Nucl. Phys. B117 (1976) 377.

At low √s Regge Non-P decreases

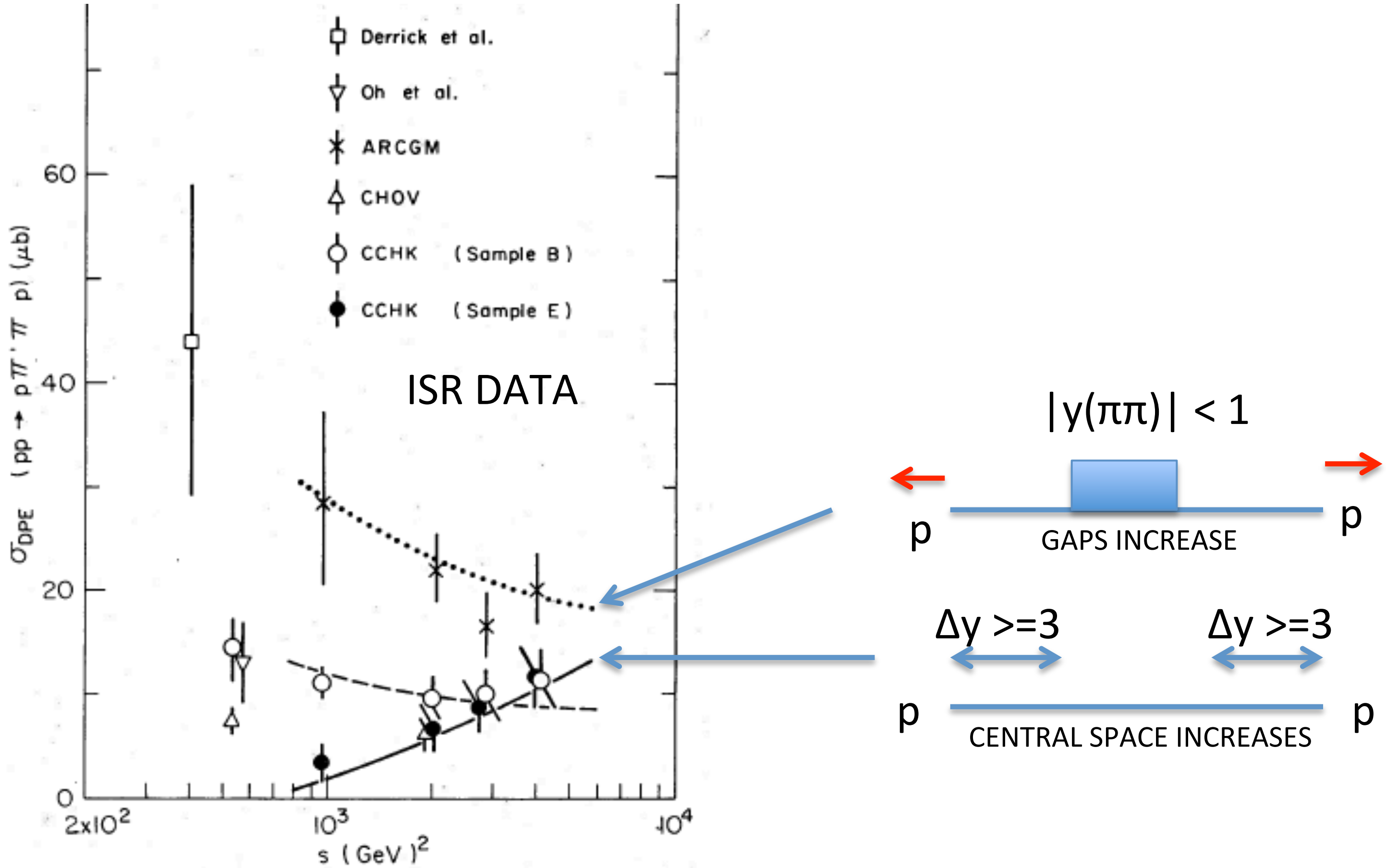
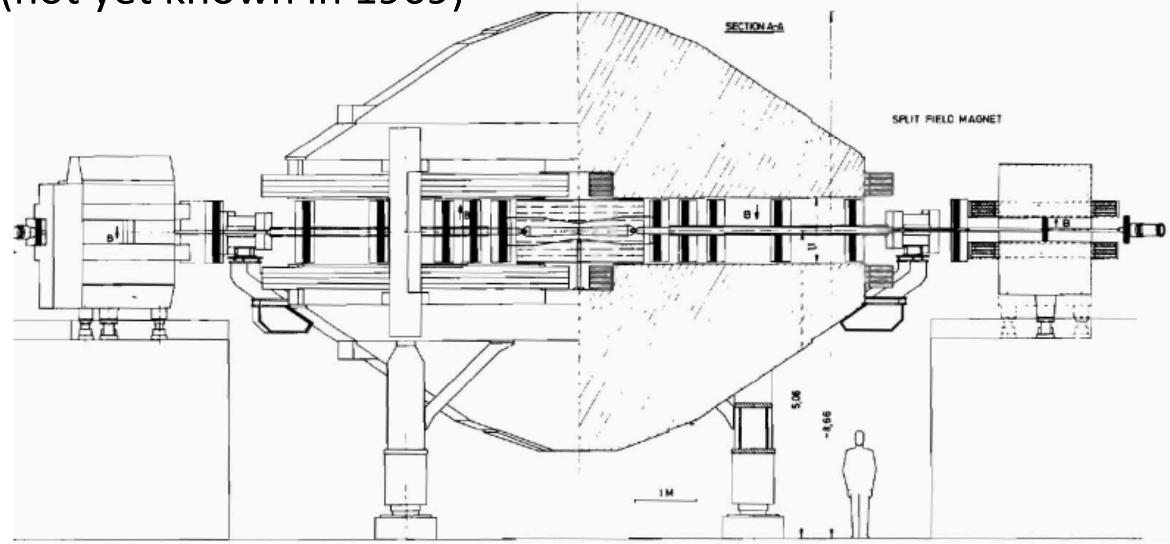


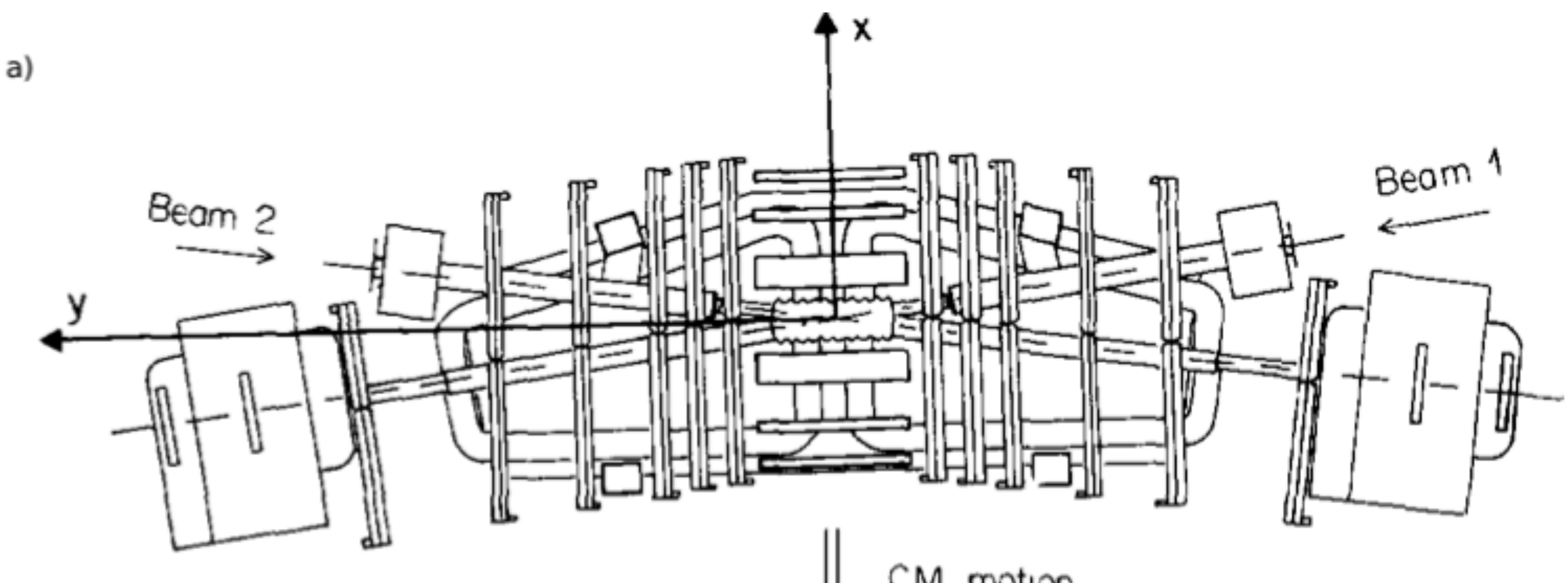
Figure 7: Experimental *DIPE* cross sections (μb) versus s (GeV^2) at the ISR together with the Regge calculations of Ref [26]. The full circles and the rising solid line are for two gaps with $\Delta y > 3$. The dashed line is for $|y_\pi| < 1.0$ and the dotted line for $|y_\pi| < 1.5$. Figure from Ref. [26].

The Split Field Magnet Facility at the ISR

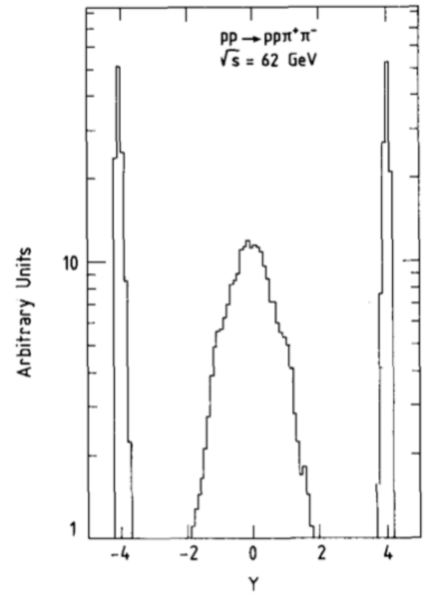
Good for forward particles (low mass diffraction e.g. p → pππ)

Bad for central and high-p_T physics (not yet known in 1969)

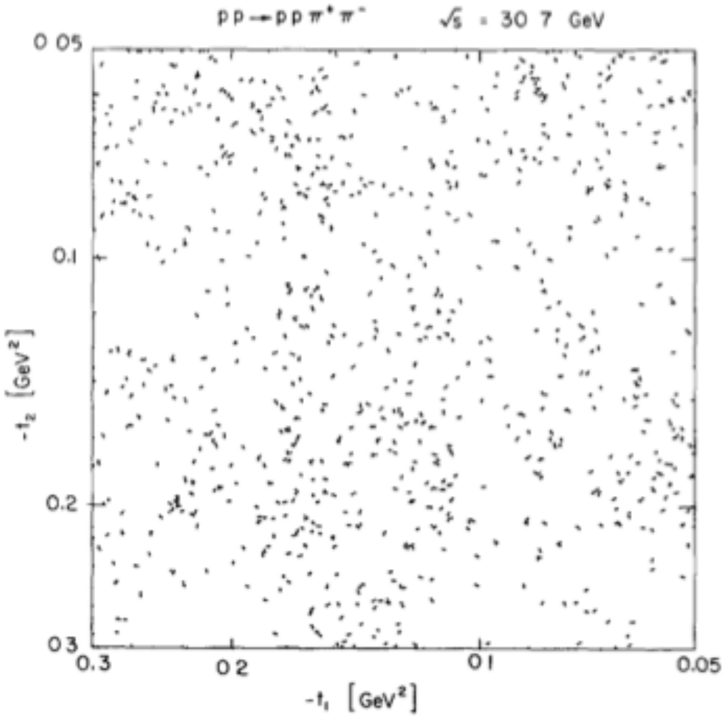


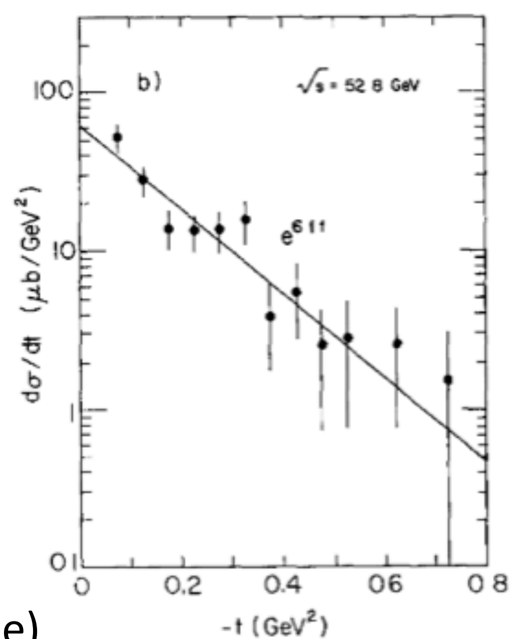


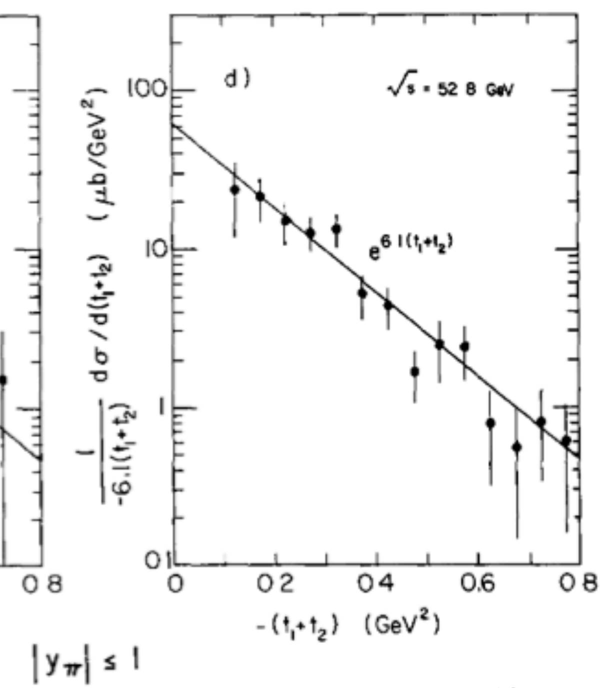
Breakstone et al., (SFM) Z.Phys.C 31 (1986) 185
4-track events, 2 gaps $\Delta y > 2$
4C fit to p + ππ + p   Rapidity distribution →



Beam rapidity =
$\ln(\sqrt{s} / m_p) = 4.2$



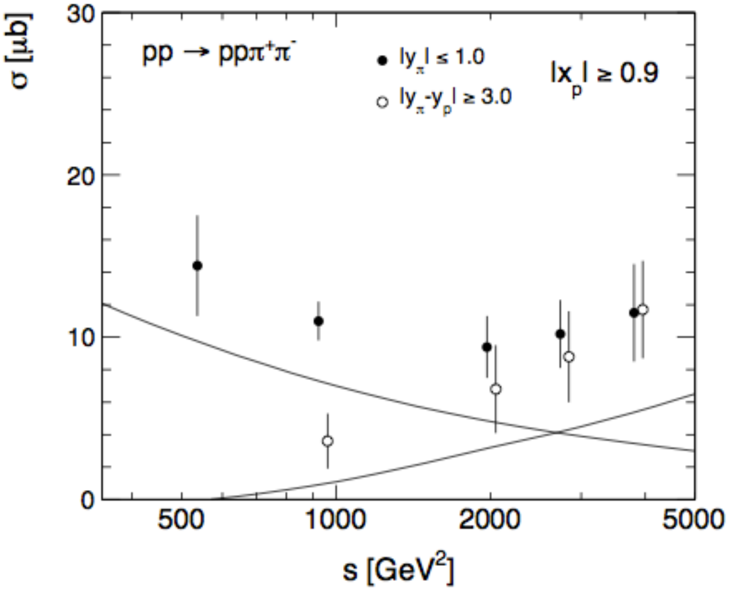




t1 and t2 are uncorrelated,
(and so no elastics)
and dσ/dt and dσ/d(t1+t2) both
exp (- 6.1 t,Σt) (half the elastic slope)
As expected for DPE

SFM Breakstone et al (1988)

Cross section (fn. Cuts!) through ISR range:



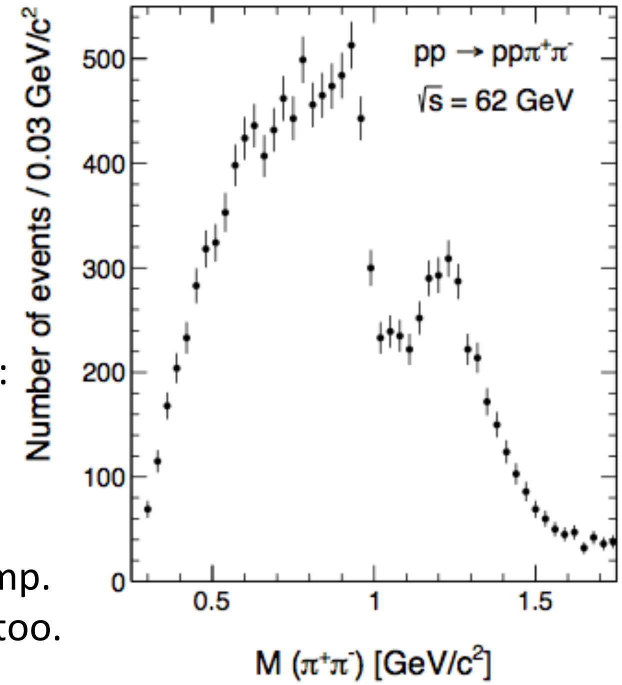
M(ππ) spectrum

Not acceptance corrected:

No ρ, f0(980)/KK cusp

Looks like f2(1270) signal.

But S-wave/D-wave decomp. shows scalar bump there too.



Cf AFS data at about same time

f2(1270) events show non-factorization:
ϕ1 and ϕ2 are correlated:
more Δϕ > 90° (at SPS also)

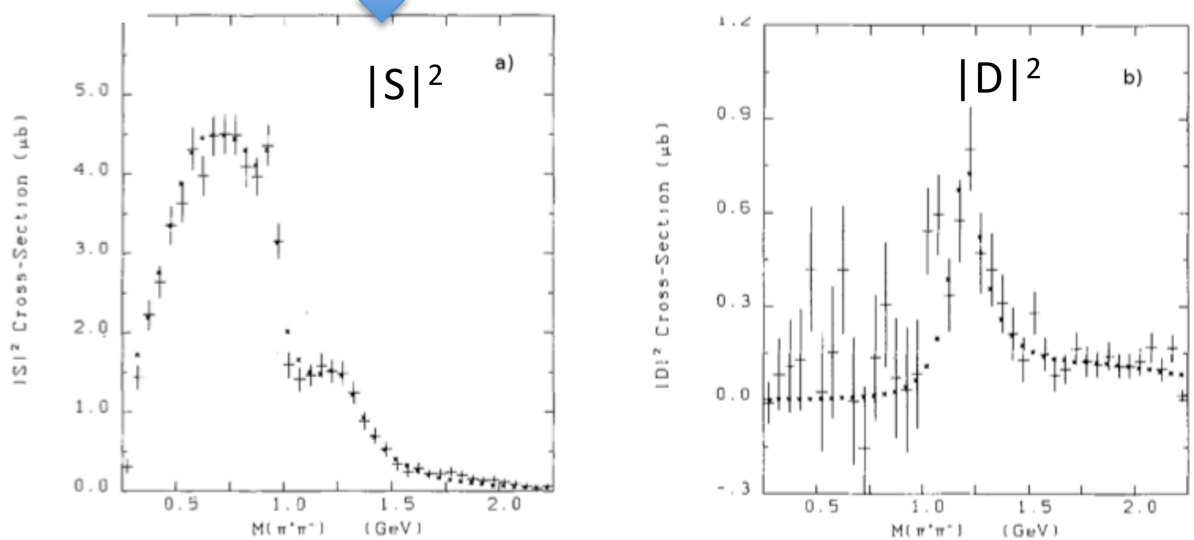


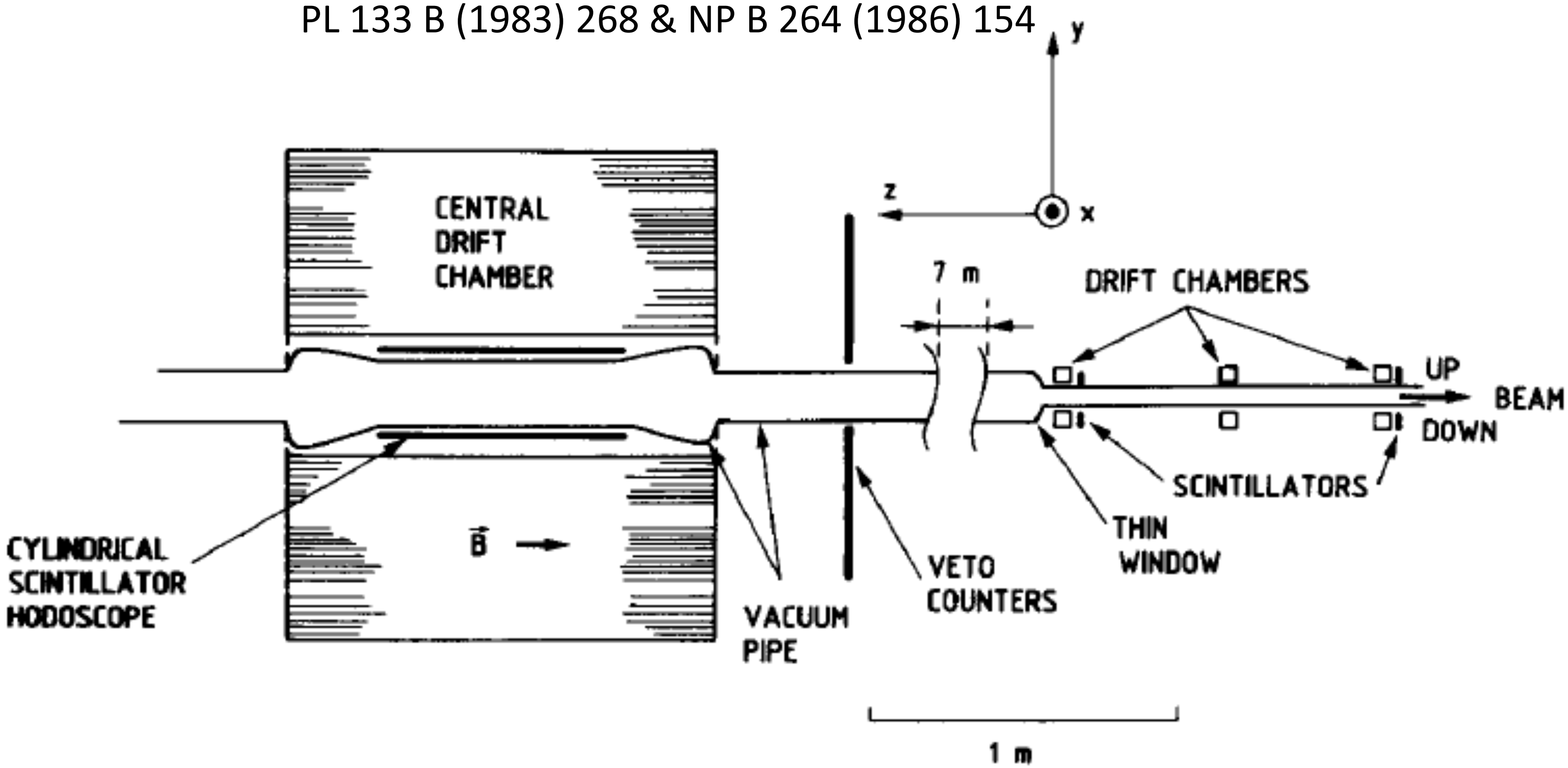
Fig. 14. Cross sections for a) s-wave and b) *d*-wave contributions to the mass spectrum as a function of the two-pion mass

The Axial Field Spectrometer

AFS was for high-E_T physics, with $\Delta\Omega = 4\pi$ uranium scintillator calorimeter, co-discovered jets etc

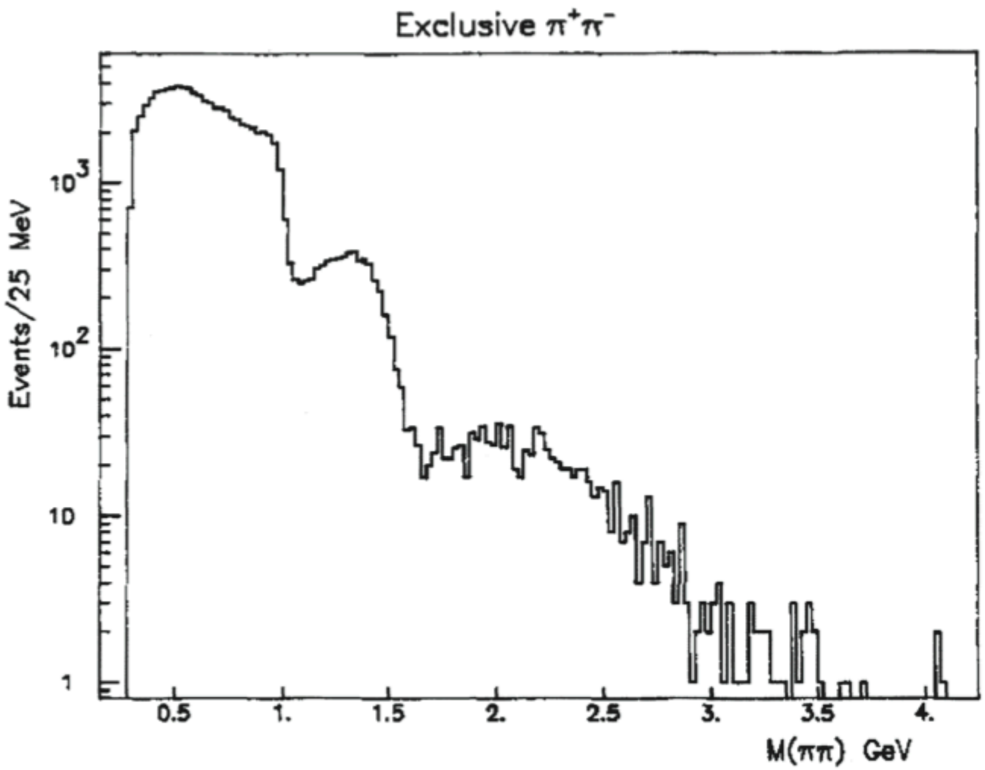
156 *T. Åkesson et al. / Search for glueballs*

PL 133 B (1983) 268 & NP B 264 (1986) 154

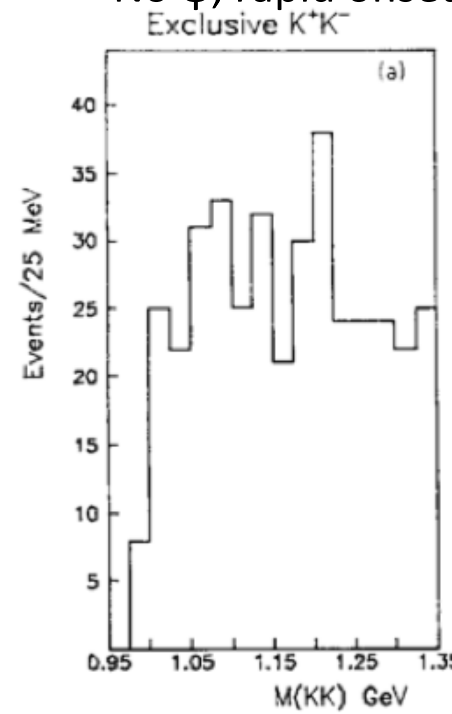


We added very forward drift chambers and scints, and medium angle veto counters to study DPE in pp at √s = 45 and 63 GeV, and αα at 126 GeV.
Trigger on 2 forward protons (α), medium-η vetos and > = 2 barrel hodoscope hits.
dE/dx on 42 wires in central drift chamber → π / K / p separation at low momenta.

$\text{AFS } \sqrt{s} = 63$ GeV. Exactly two tracks Q = 0, 2C constraint with 2 forward p's $x_F > 0.95$
p's non-colinear (UP*UP or DN*DN) $-t = 0.01 – 0.06\ \text{GeV}^2$ $|y(\pi\pi)| < 1$
➔ 87,000 π+π- & 523 K+K- & 64 p-pbar events.

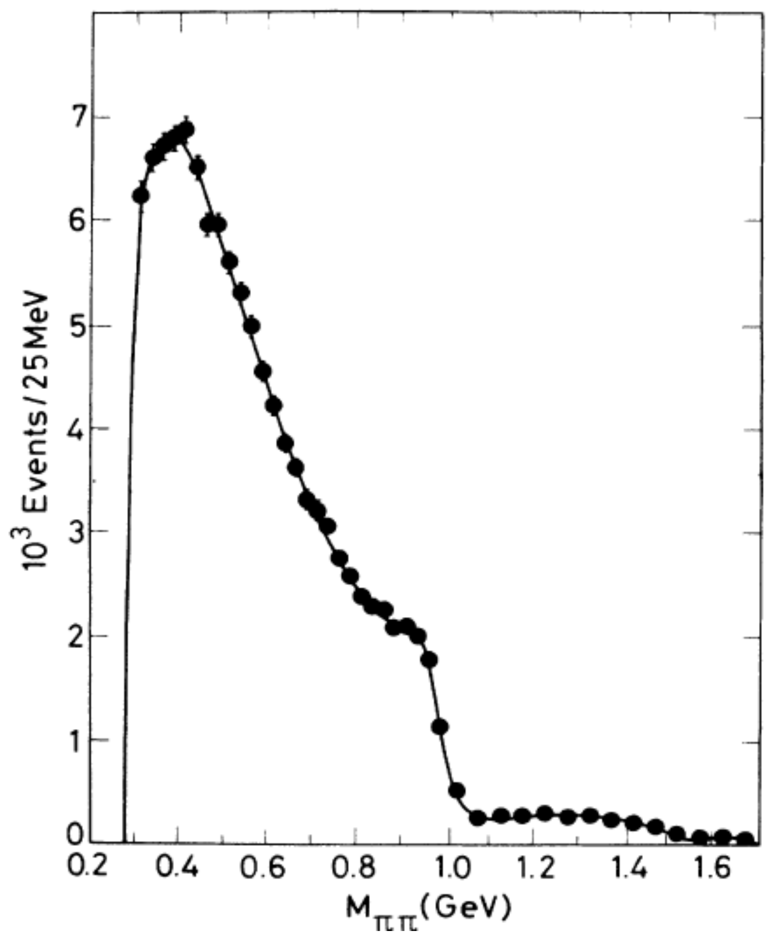


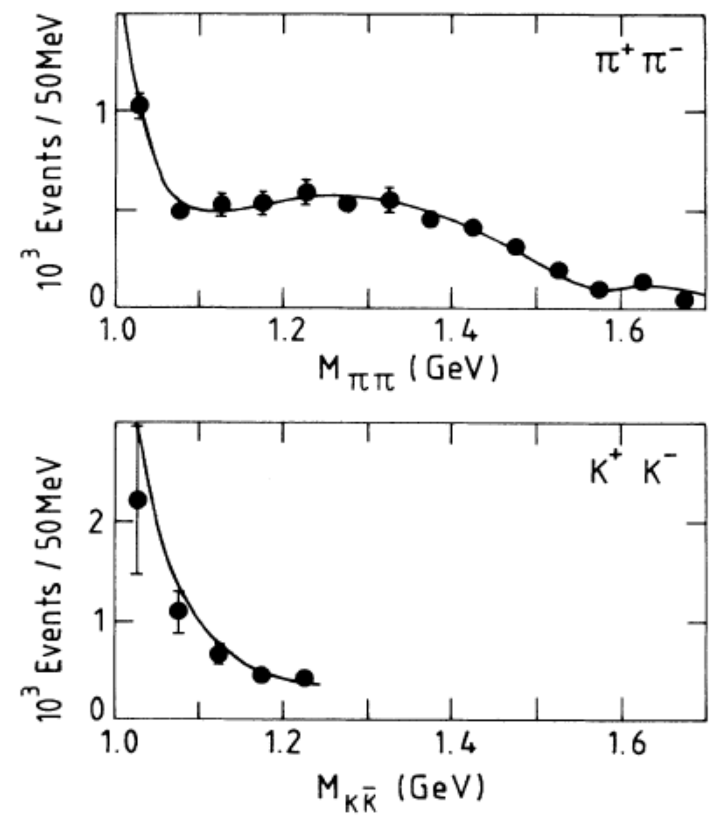
No ϕ, rapid onset



High statistics and good mass resolution (< 20 MeV at 1 GeV)
Unexpected structures, watched them build up over months of data taking!
Sharp drop at 1 GeV where $f_0(980)$ and K^+K^- threshold coincide.
Broad bump more like $f_0(1370)$ than $f_2(1270)$ from PWA (S-U. Chung) … p's seen
Mini-dip at ~ 1600 MeV followed by broad bump.
No sign of ρ(770) so Pomeron-Regge(ρ*) exchange absent. (unlike in lower √s expts)

Interpretation of data (+ other data) by Au, Morgan and Pennington (Durham)
PL B 167 (1986) 229 and PR D 35 (1987) 1633
Coupled channel analysis of final state interactions including ππ ⟷ KK etc
After correcting for acceptance (P.Cecil thesis) gave good fits to spectra to 1500 MeV.





AMP paper has lots of fits/phase shift solutions, including other ππ, KK data
.... and has 364 citations now.

This is the amplitude, Re + Im, of
S-wave (J = 0) Isospin = 0 ππ scattering
→ Argand diagram

√s (GeV) on points
When purely elastic, on Unitarity Circle
σ as big as allowed.
Slow motion threshold –to- 940 MeV/c2
Then rapid motion → drop in σ at KK thresh.

No scalar glueball with 400 < M < 900 MeV
Would cause narrow **dip** in DPE ππ
mass spectrum.

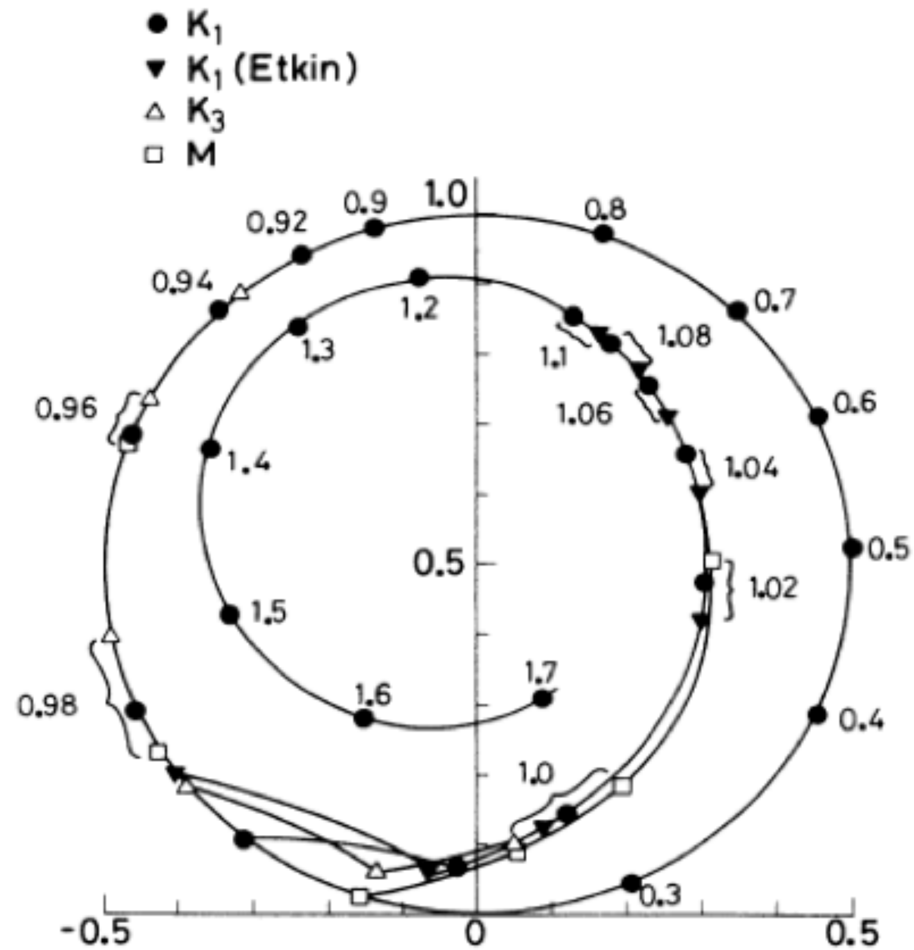


FIG. 5. The ππ $I=0$ S-wave amplitude $\rho_1 \mathscr{T}_{11}$ shown in an Argand plot comparing the solutions K_1 (●), K_1 (Etkin) (▼), K_3 (△), and M (□). The last three are only shown where they differ from solution K_1. The corresponding energies in GeV are displayed on the plot.

November 1985 RAL-85-099

Some excitement:

DISCOVERY OF THE LOWEST MASS SCALAR GLUEBALL?

K.L. Au*, D. Morgan+ and M.R. Pennington*

*Physics Department, University of Durham, Durham, U.K.
+Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, UK

Abstract: Incorporating new data on $pp \to pp\pi\pi(K\bar{K})$, we have performed a coupled channel analysis of results on $\pi\pi$, $K\bar{K}$ final state interactions with $I = 0$ 0^{++} quantum numbers below 1.6 GeV. We show that though no poles are imposed on these data at least 3 and probably 4 distinct resonances emerge, when the naive quark model requires but two. This we claim constitutes definite evidence for new dynamics in the 0^{++} channel.

MGA CERN Seminar 1985: "Have we discovered the lightest scalar glueball?"

Answer: No

AFS M(ππ) = !.0 -2.2 GeV/c^2 region
Angular distribution moments → J = 0, 2 (Su-Urk Chung)

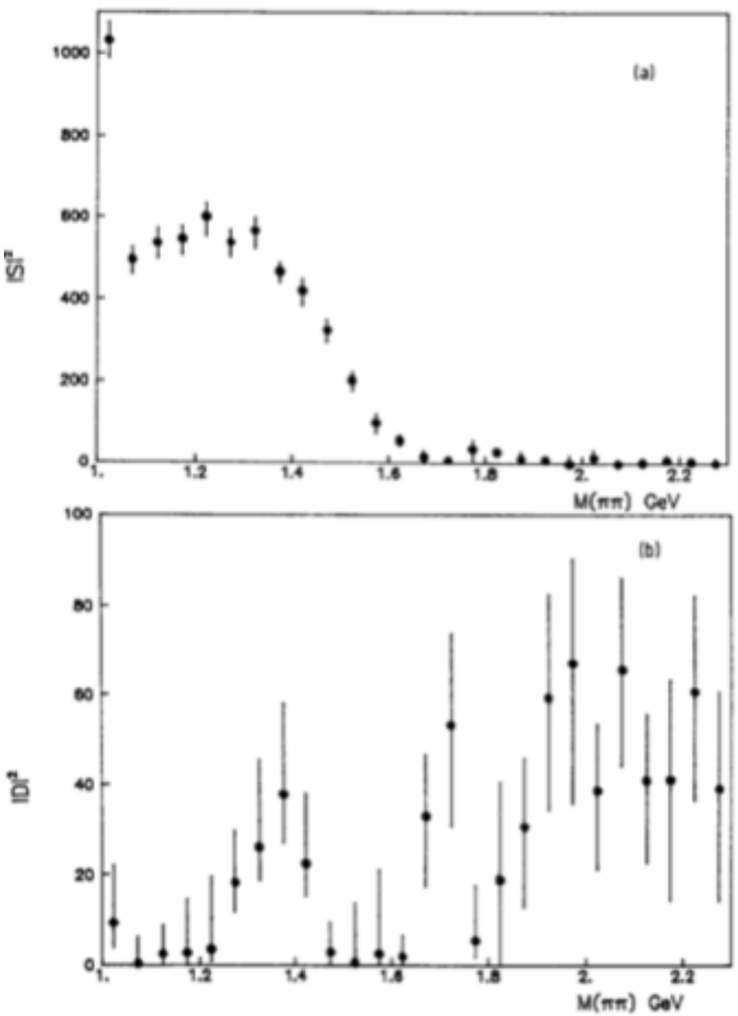


Fig. 11. The relative S- and D-wave cross-sections. (a) $|S|^2$. (b) $|D|^2$.

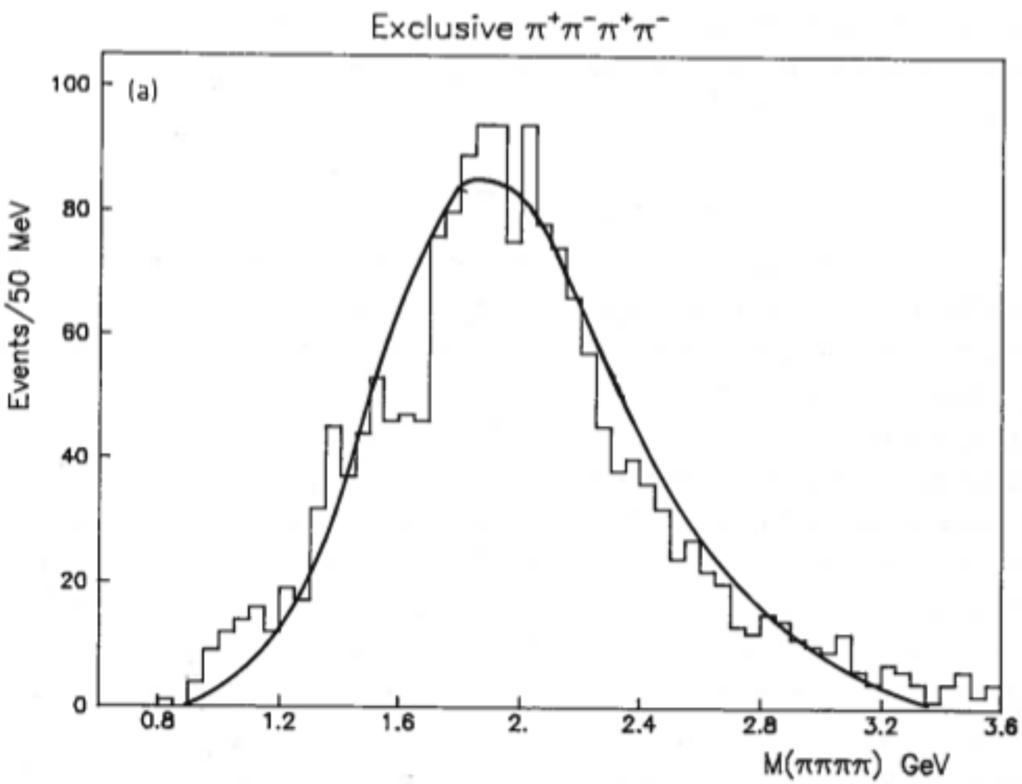
Most of 1000 – 1500 MeV/c^2 bump is S-wave

Only PDG state is f0(1370) $I^G JPC = 0^+0^{++}$
M = 1200 – 1500 MeV/c^2 , Γ= 150-250 MeV

D-wave J = 2 shows probable f_2(1270) but systematically high and sub-dominant.

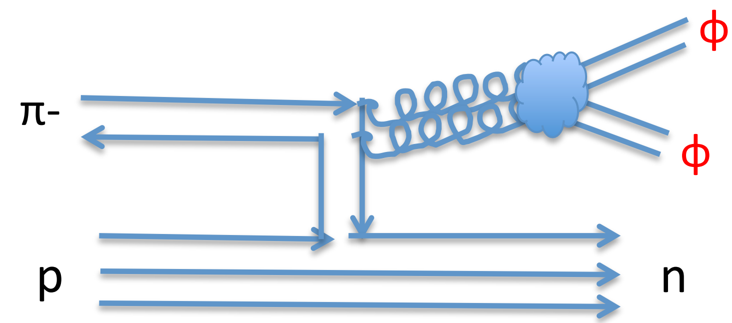
Not like higher √s (CDF) Gap-ππ-Gap data
Maria Zurek talk.

AFS also had some π+π-π+π- data



Empirical fit, not theory, poor
Not corrected for acceptance
(need to assume decay dynamics)

M(ππ) from this sample shows a ρ
Selecting one ρ → ππ see other ρ
So DPE → ρρ
Would have especially liked ϕϕ
Cf with three f_2 states seen at BNL
In π- p → (ϕϕ) n (gluey production)



More like a broad peak 1800-2200 MeV
on non-resonant background ??

The Omega Spectrometer (SPS fixed target)

Later than the ISR experiments and at lower √s, but higher statistics, more channels and a large dedicated group (not peripheral)

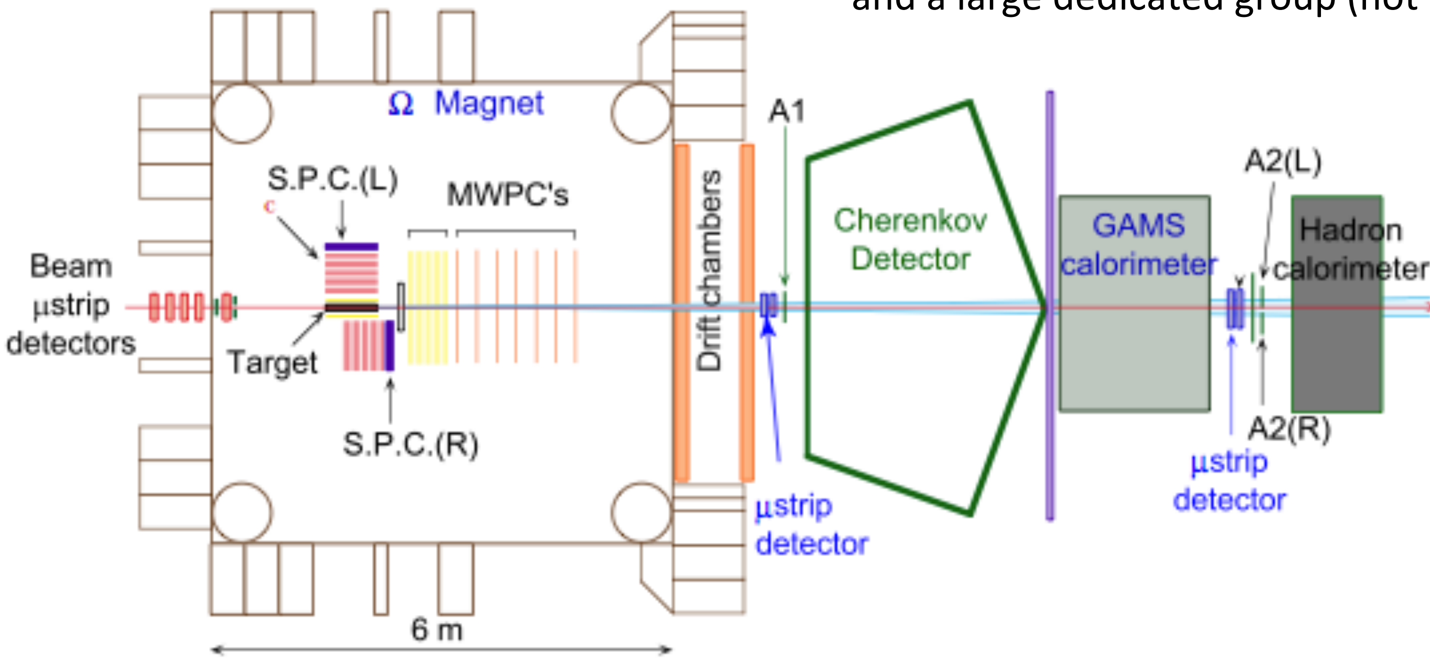


Fig. 1. Layout of the Ω spectrometer for the 1996 run of experiment WA102.

Series of experiments with changing configurations of the "facility"
WA76, WA91 & WA102 (WA = West Area)

WA76 and WA102 at CERN Ω facility : pp → $p_{slow} + X + p_{fast}$

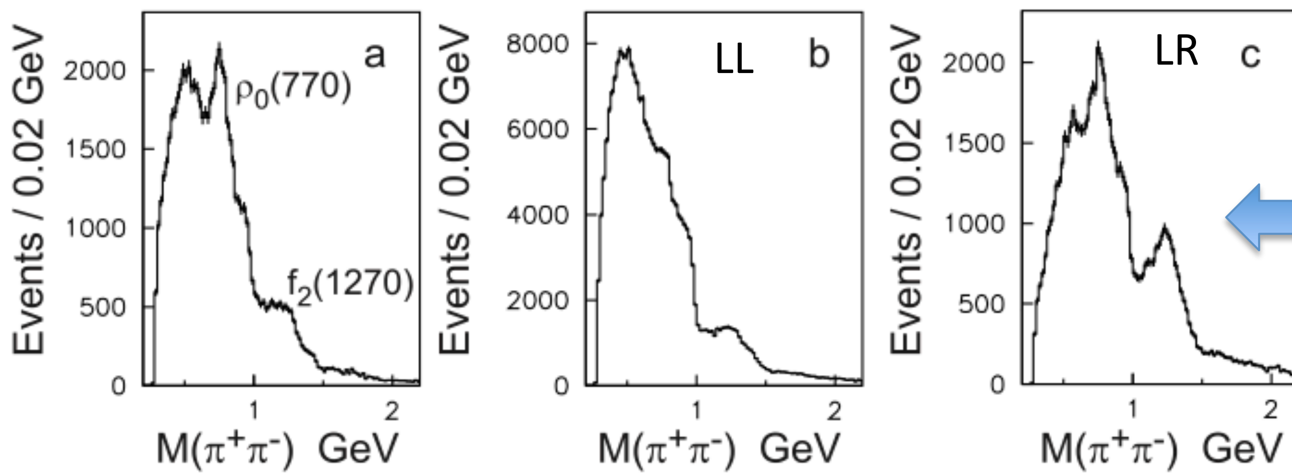
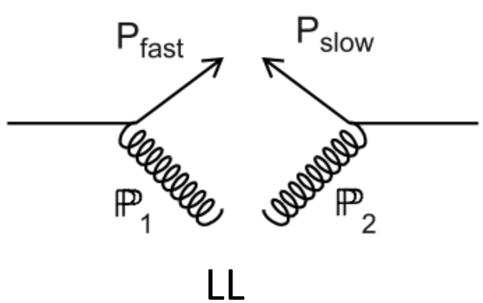


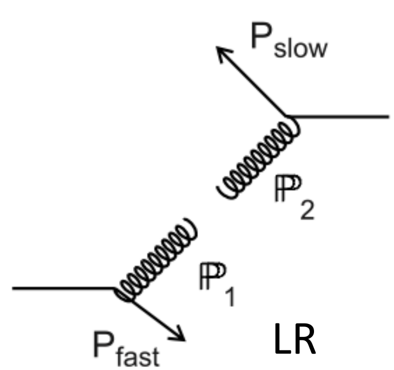
Fig. 2. The centrally produced $\pi^+\pi^-$ effective mass spectrum at $\sqrt{s}$ = a) 12.7 GeV and b) 29 GeV using a LL trigger and c) at 29 GeV from a LR trigger.

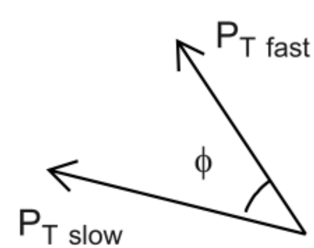
Δϕ (pp) dependence

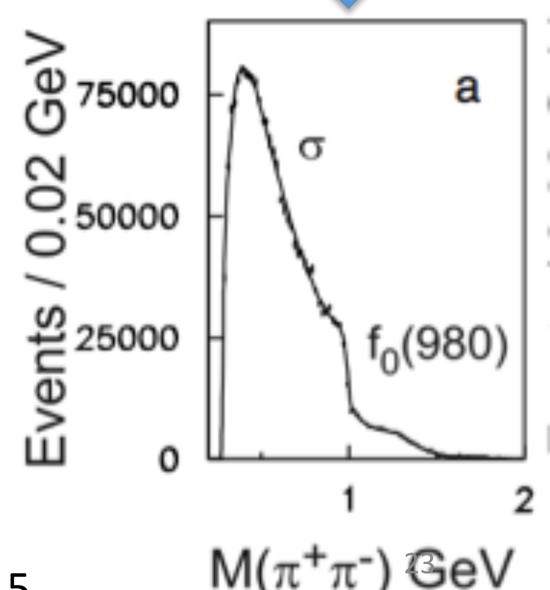
Spin-parity analysis
S-wave J = 0
Very like ISR

Note large ρ signal at √s = 12.7 (forbidden in DPE, can be RP exchange)
Much smaller at √s = 29 GeV (will be gone by √s = 63 GeV (ISR)).
σ (Photoproduction of ρ) << σ (DPE at M(ππ) = M(ρ))

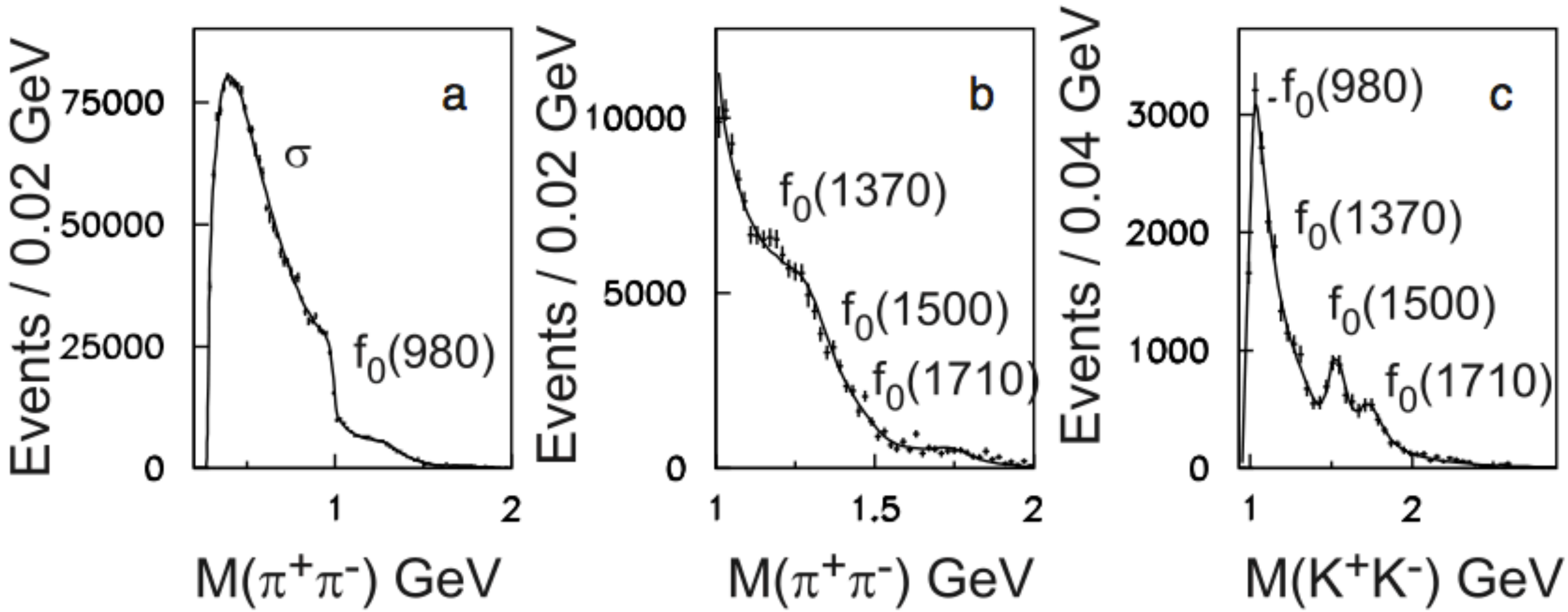


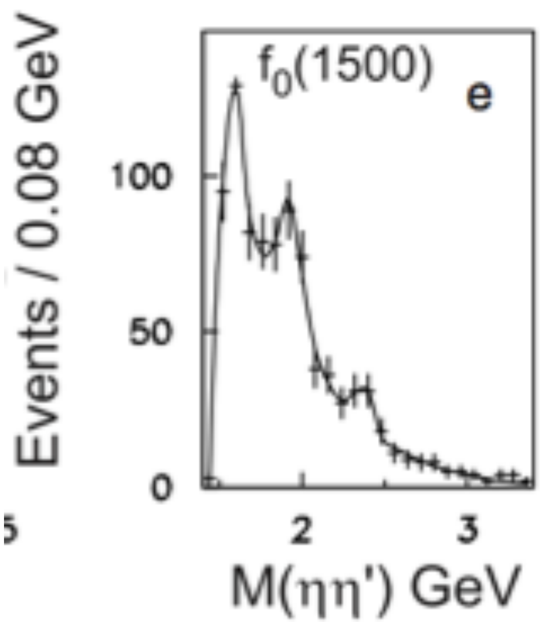






WA102 Spin-parity analysis projects out J = 0 (S-wave) spectra:





η and esp. η'
Have high glue content.

Durham group (much later):
In p + X + p at high M(X):
$\eta'\eta' \gg \eta\eta \gg \pi^0\pi^0$

+other channels

Δϕ (pp) distributions very different for different central resonances
Close, Kirk and Schuler : **"glueball filter",** Pomeron transforms as non-conserved vector current

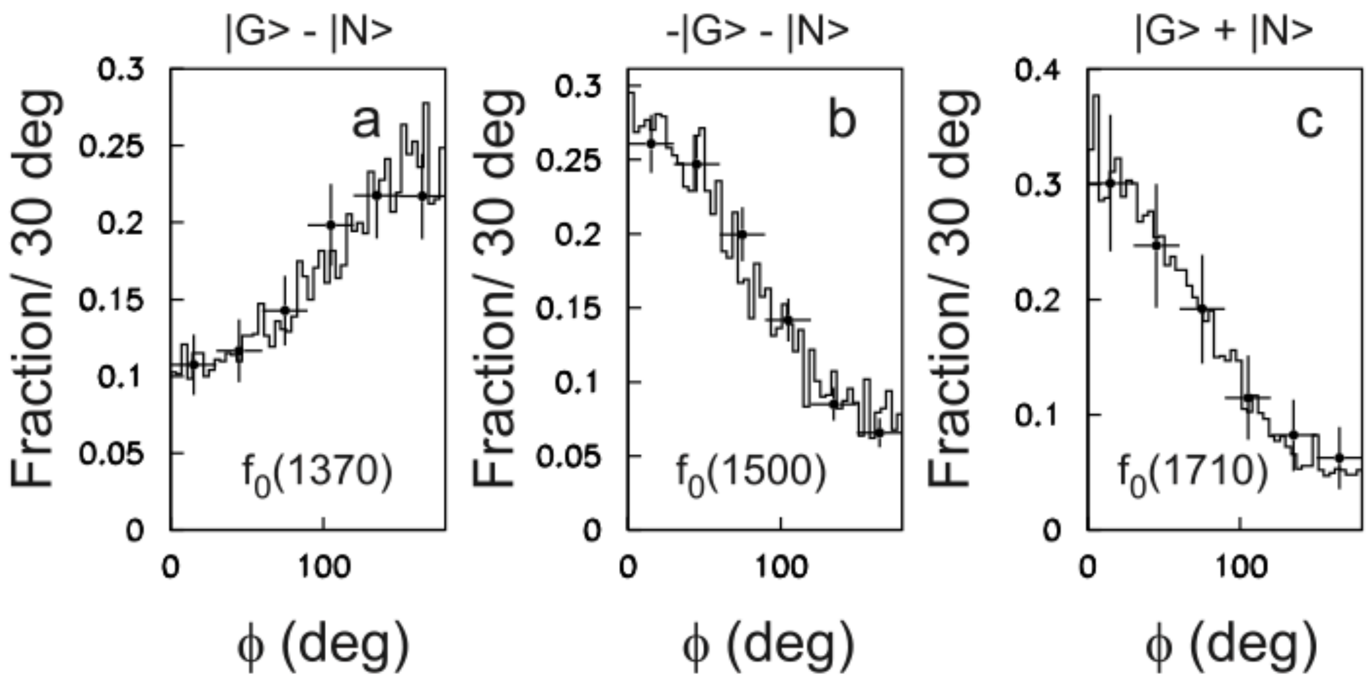


Fig. 6. The ϕ dependence for a) $f_0(1370)$, b) $f_0(1500)$ and c) $f_0(1710)$ for the data (dots) and the model (histogram).

Different J=2 states $f_2(1910)$, $f_2(1950)$ and $f_2(2150)$ also show different ϕ = Δϕ distributions.
Ω made a major contribution high many channels, high statistics, but significant non-DPE.

To do this at higher √s (with p's measured, particle ID, high statistics …) who and where?
RHIC ? Give **CMS+TOTEM** two dedicated weeks? Add proton spectrometers to **LHCb**?

Fermilab Tevatron Fixed Target, p(beam) = 800 GeV/c
Liquid hydrogen target, $\sqrt{s}$ = 40 GeV Expt **E690 & E710**
Beam spectrometer to measure leading proton.
Recoil proton usually stays in Liquid H_2 target : require missing mass = m(p)

→ Fully exclusive reactions p + (X = ππ, $K^0_s K^0_s$, ϕϕ) + p

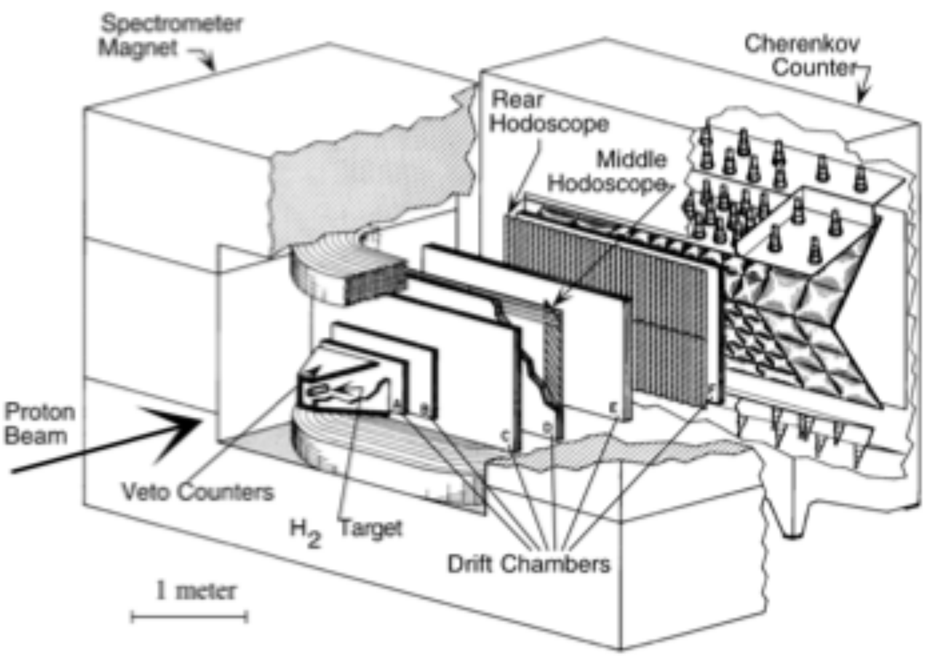
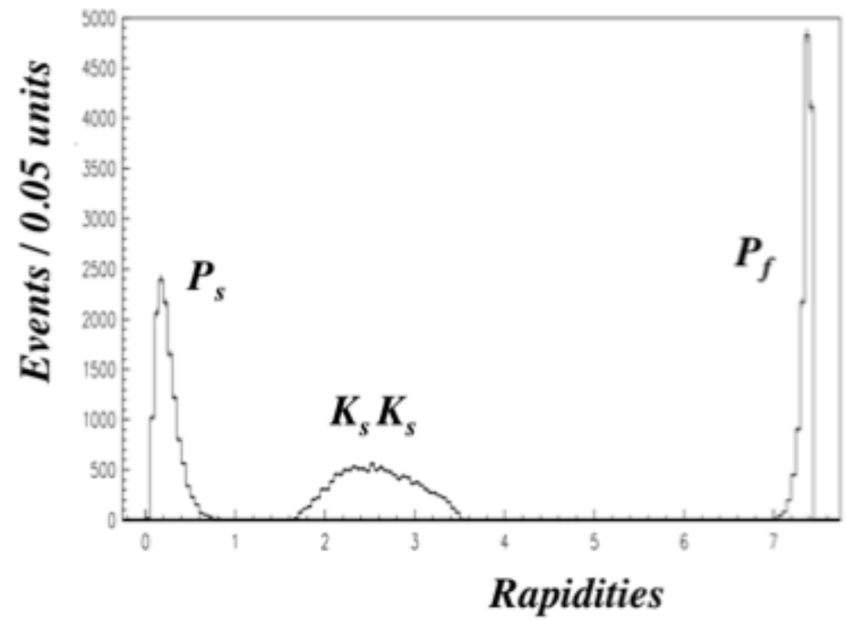
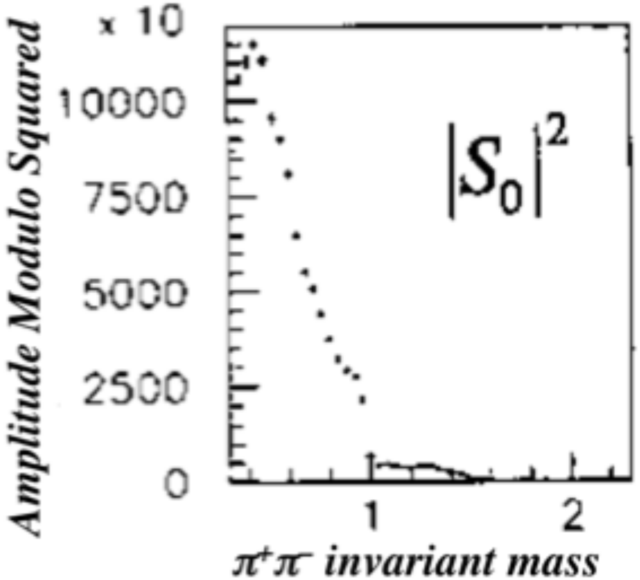


Fig. 1. The E690 main Spectrometer.

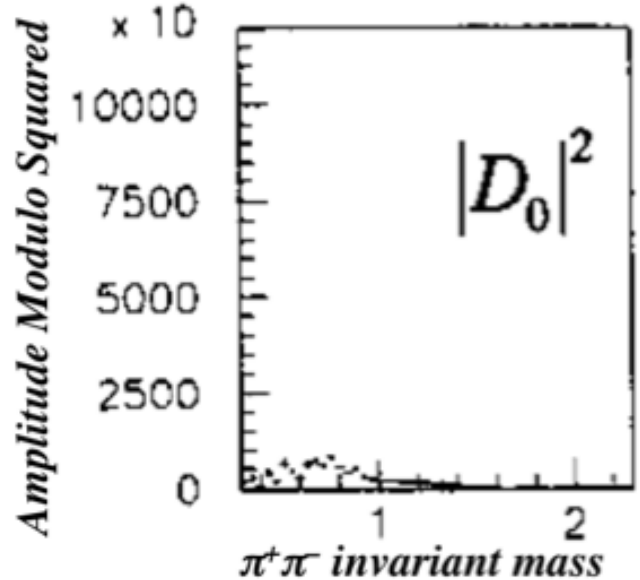
Keep in mind : one gap not large enough for pomeron dominance

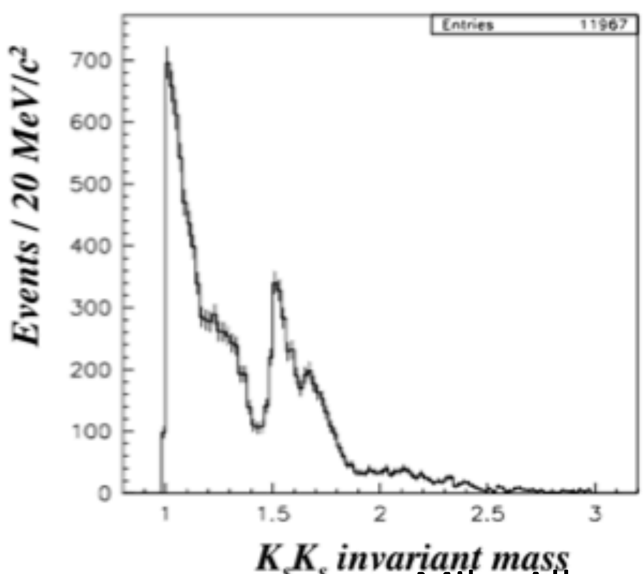


Partial Wave analysis. S-wave “classic” features

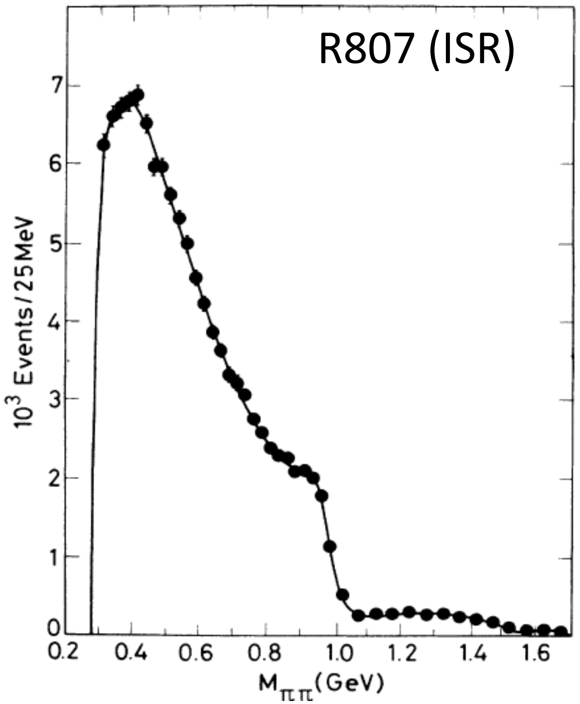


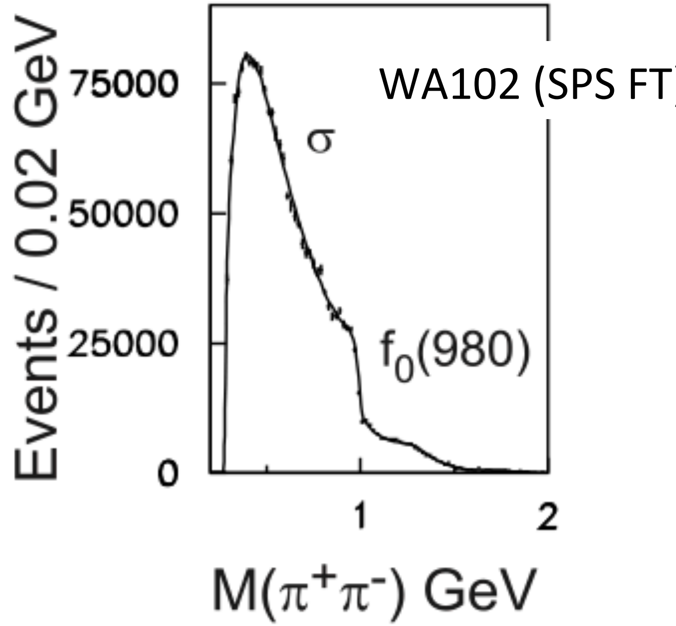
Very small D-wave component

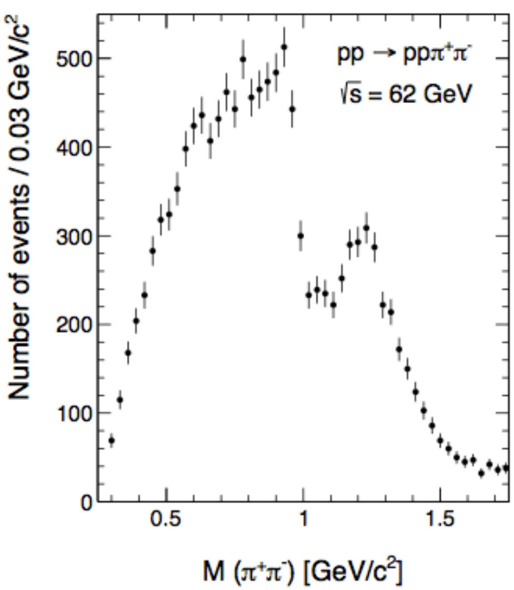




K^+K^- shows rich structure!
PWA analysis next slide →

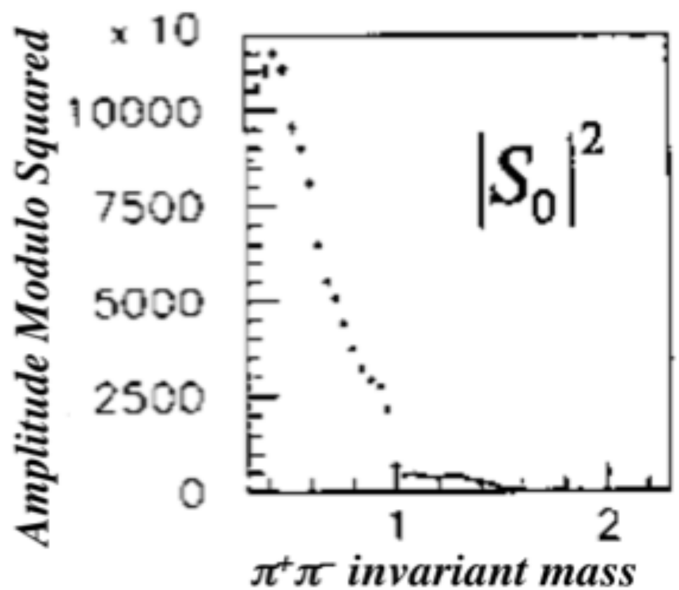






SFM (ISR)
Not corr for A

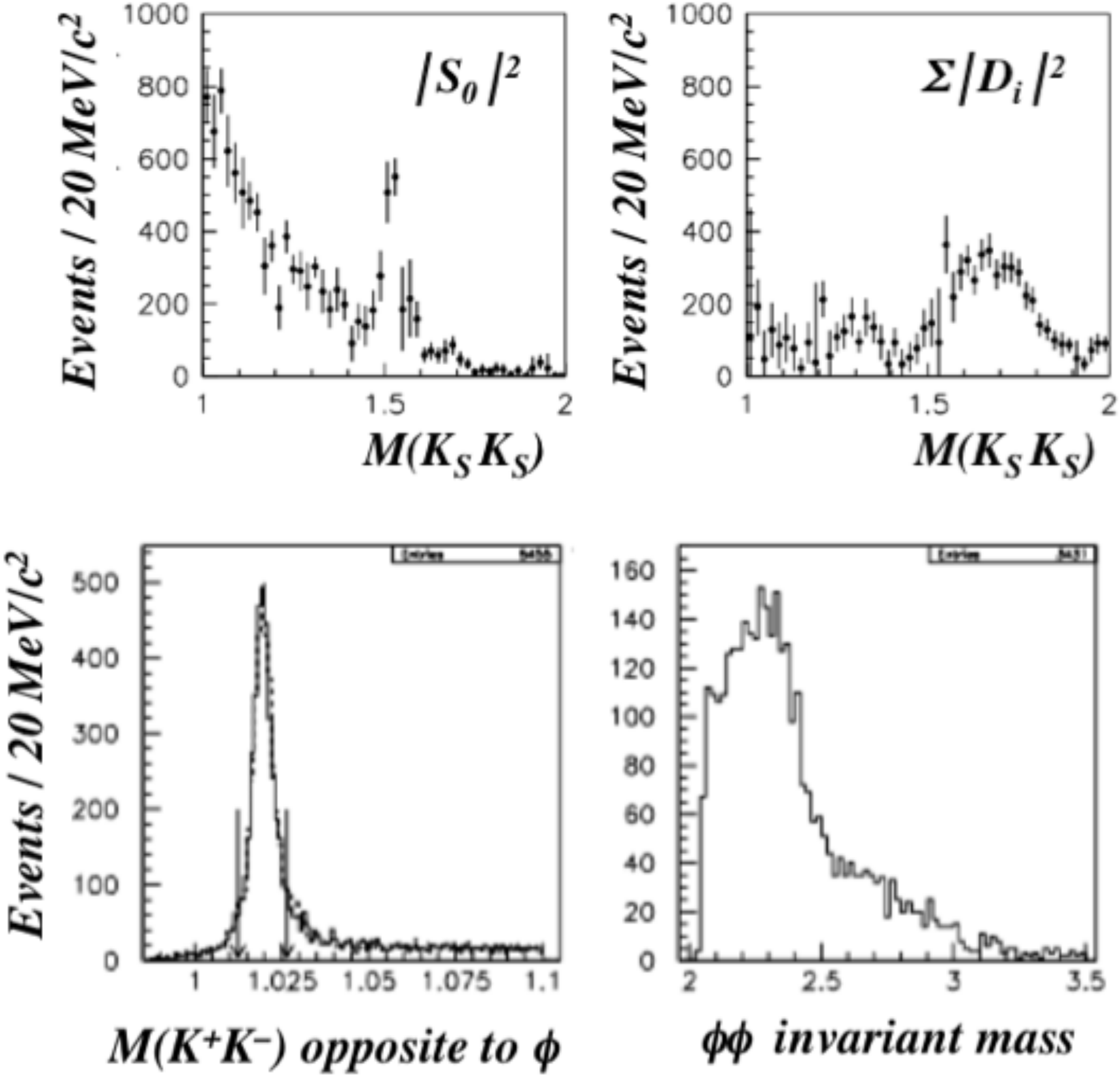
E710 (Fermilab FT)



ke Albrow HERAU

E690 + E710

Tail of $f_0(980)$ $f_0(1500)$



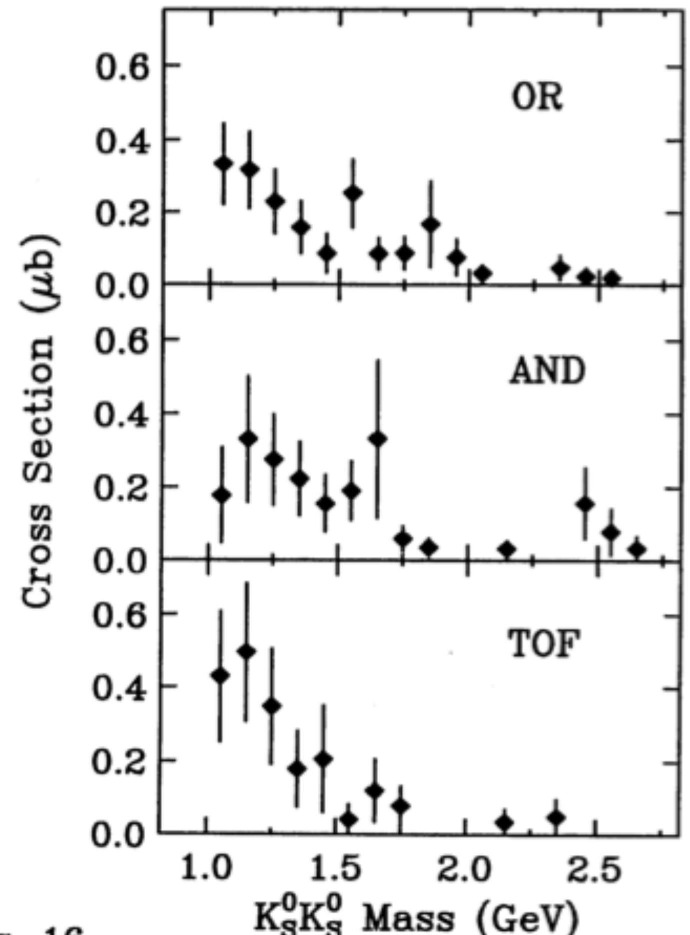
φφ

Fits $f_2(2243)$
Γ = 368 MeV)
+ state just
Below threshold

ABCDHW (SFM) Collaboration: neutral strange particle prodn. in DPE at √s = 62 GeV (1990)

Table 4 Total cross sections for reactions 3.1-3.4; the quoted errors do not include an overall systematic error factor of 1.54 which results from an uncertainty in acceptance and luminosity calibrations.

Reaction	Raw Events	Background	Real Events	Cross Section (μb)
$pp \to pp(K^0_S K^0_S)$	138	15%	117	$1.57 \pm .27$
$pp \to pp(K^0_S K^{\pm}\pi^{\mp})$	56	10%	50	$.72 \pm .22$
$pp \to pp(\Lambda^0 \bar{\Lambda}^0)$	13	$\geq$ 54%	≤ 6	$\leq .56$
$pp \to pp(\Lambda^0 \bar{\Lambda}^{0*})$	30	43%	17	$.15 \pm .055$



ɀ. 16

Protons measured but $x_F > 0.7$ (weak)
and gaps $\Delta y > 2$ (weak) required.
4C fits selected exclusive events

Different triggers shown on right plot.
Speculate about a 1.15 GeV enhancement,
Different from $\gamma + \gamma \to K^0_s K^0_s$.

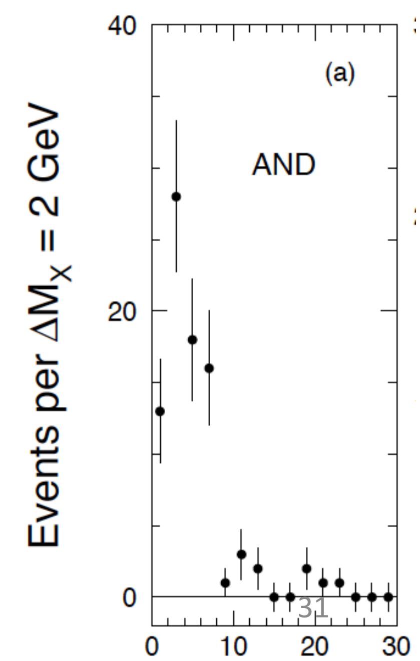
The SppS Collider : UA1 and UA8

Proton-antiproton collider: √s = (300) – 540 & 630 – (900) GeV
Expts UA1 and UA2 designed to find **W- and Z-bosons**, and did so (1982)
UA2 (and AFS) then UA1 discovered **high-E_T jets** in hadron-hadron collisions.
GAP-X-GAP study done in UA1 (post-end)   PR D 48 1943 (1993)

UA1: Rap. Gaps $3 < |\eta| < 6$, ΣE_T(central) > 1.4 GeV & (EM E_T > 1.2 GeV + Jet > 3 GeV)
So bias towards jetty events. M(X) = 4 – 100 GeV. For M(X) > 63 GeV x_F(min) < 0.90 so not P.
Events not like pp or e+e- at same M(X).   5% of events have >= 1 jet with ET > 10 GeV.

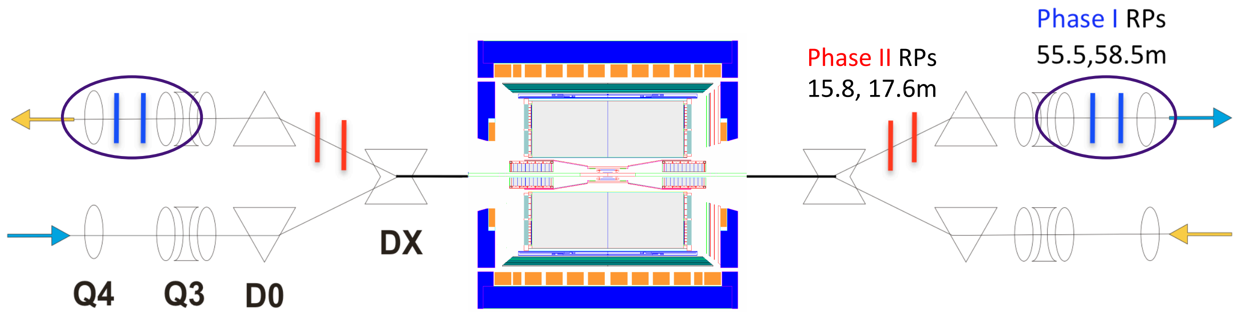
UA8 was addition of Roman pots to UA2 for SDE and DPE Eur.Phys.J C 25 361 (2002)
Quadrupoles → p and M(X) but resolution only 1.8 GeV.
Had **107 events with MM(pp) = M(X) i.e. Σ(E) ~ 630 GeV** thus exclusive

Not good for spectroscopy (no central track momenta) but
UA8 claimed higher than expected σ(DPE) may be due to gluey states.



RHIC: Relativistic Heavy Ion Collider at Brookhaven Nat Lab

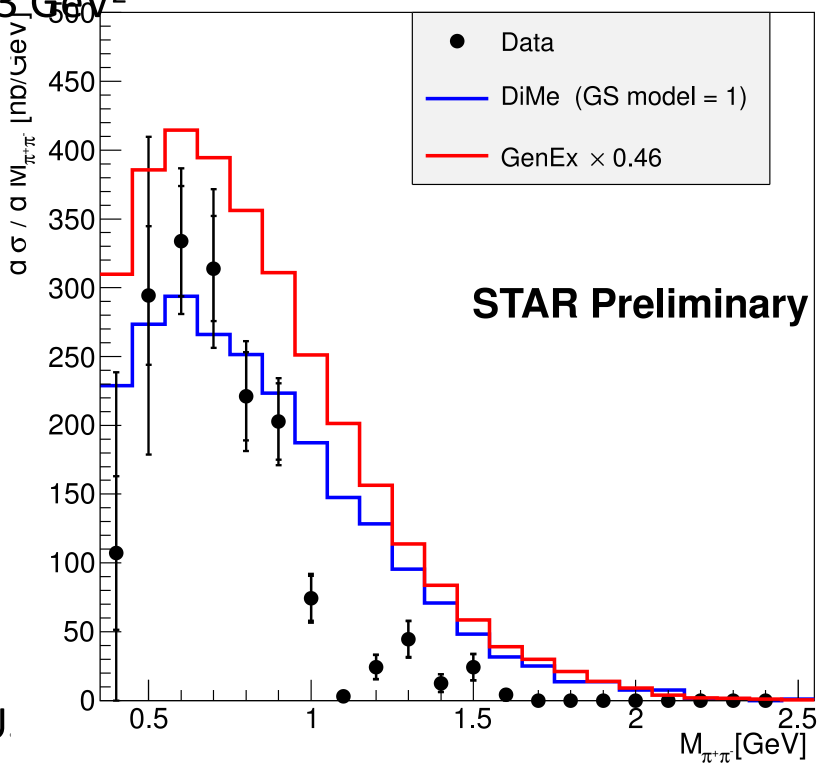
STAR Experiment with pp collisions at √s = 200 GeV : p + p ⟶ p + (π+π-) + p



Central π+π- measured in TPC with |η| < 1.0

Protons measured in Roman pots, |t| = 0.005 – 0.03 GeV^2

Early results as of Nov 2014



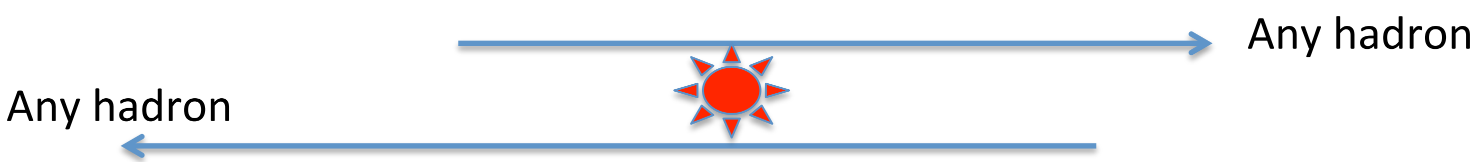
Note:
As always, rapid drop at 950-1000 MeV
Bump at ~ 1300 MeV
Not described in generators DiMe, GenEx
Which do not incorporate resonances.

f_0(600), f_0(980) and f_2(1270) important!

After ISR and Fixed target experiments, we could conclude:

If there is a hadron with no valence quarks, only gluons, to first order
i.e. glueball G
Its mass exceeds 1000 MeV/c2 (unless the f0(600)/σ is such a state)
and will have a large width = very short lifetime.
(String model of hadrons: G = closed loop different from q qbar open string.)
If produced inclusively it will decay before emerging as an isolated hadron.

It can occur in isolation as a fluctuation in the vacuum : $\Delta E . \Delta t > \hbar$
Double pomeron exchange ***is*** vacuum excitation:



Vacuum quantum numbers
Scalar glueball or Higgs boson at LHC!

Keep at it! Want mass spectra and PWA in clean DPE data (LHC) of all (!) channels:
ππ, KK, ρρ, φφ, ηη, η'η', …. Not forgetting pair production G1 G2… Q #s not restricted.
In 2 weeks = 200 hours with <n> = 1 and special triggers 200,000 × ε events per nb !!

LHCb & CMS-TOTEM

18 papers on arXiv with "glueball" in title in 2013.
Including review "The Status of Glueballs" by Wolfgang Ochs J.Phys G40 (2013) 043001.

ADVERTISEMENT: November 2014

Special edition of Int. J.Mod.Phys A *"Central Exclusive Production in Hadron-Hadron Collisions"*

Eds MGA, Khoze, Royon

Complete bibliography of all DPE expts !?

Contributed papers:

DPE with SFM at ISR (Fischer, Geist and Makariev)
Central Production at CERN Ω spectrometer (Kirk)
DPE at CERN ISR and SppS Collider (Albrow)
Tevatron fixed target expts (Gutierrez and Reyes)

Helped with this talk

Introduction to CEP volume (Albrow)
CEP and the Durham model (Harland-Lang, Khoze, Ryskin)
Double diffraction at zero impact parameter (Bjorken)
Central soft hadron production (Donnachie and Landshoff)
Central exclusive production at the Tevatron (Albrow)
Central exclusive dijet production at the Tevatron (Goulianos)
CEP at RHIC (Adamczyk, Guryn and Turnau)
Exclusive production in CMS (Hollar)
CEP in LHCb (McNulty)
Physics with FSC (Albrow, Collins and Penzo)
CEP with CMS-TOTEM (Osterberg)
CEP in ALICE (Schicker)
Photon-induced CEP (Royon and Saimpert)
AFP and CT-PPS projects (Royon and Cartiglia)
CEP of Higgs BSM (Tasevsky)
Holographic double diffraction of Higgs and AdS/CFT (Brower, Djuric and C-I Tan)

Epilogue

Thank you

Tevatron : other talks.

Roman pots added to CDF at very start (Run 0) for elastic, total, and SDE (not DPE)
Removed for most of Run 1, then new pots at end Run 1 for Run 2 on pbar side only.

Central exclusive production had to use rapidity gaps $\Delta\eta$ on both sides, with added Beam Shower Counters BSC for gaps y = 5 – 7.4 (~ beam y)

CEP program in CDF (all 1st obs. in hadron collisions):

Exclusive **$\gamma\gamma \rightarrow e^+e^-$, $\mu^+\mu^-$, $\gamma P \rightarrow J/\psi$, $\psi(2S)$, $PP \rightarrow \gamma\gamma$, χ_c, JJ**

but without protons detected, gaps $\Delta\eta > 4.6$ both sides. Dissociation allowed ← effects?

Now: DPE → $\pi^+\pi^-$ (Maria Zurek's talk at this meeting)

In progress : DPE → K^+K^-, $K^0_sK^0_s$, p pbar, ΛΛbar (?) …