Exclusive Photoproduction of Mesons Decaying to Purely Photonic Final States at HERA: Seeing the Pomeron, and Looking for the Odderon

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The Origin of the Odderon Concept: pp vs $\bar{p}p$ cross sections

- At low energies (but above the annihilation regime) large difference between pp and $\bar{p}p$ total cross sections, due to (I = 0) - Reggeon (ω, f) exchanges: ω (C = -1) contributes with different signs to pp and $\bar{p}p \rightarrow$

$$\sigma(pp) < \sigma(\bar{p}p).$$

- At high energies where Pomeron ($I\!P$) exchange dominates, the Pomeranchuk theorem states that

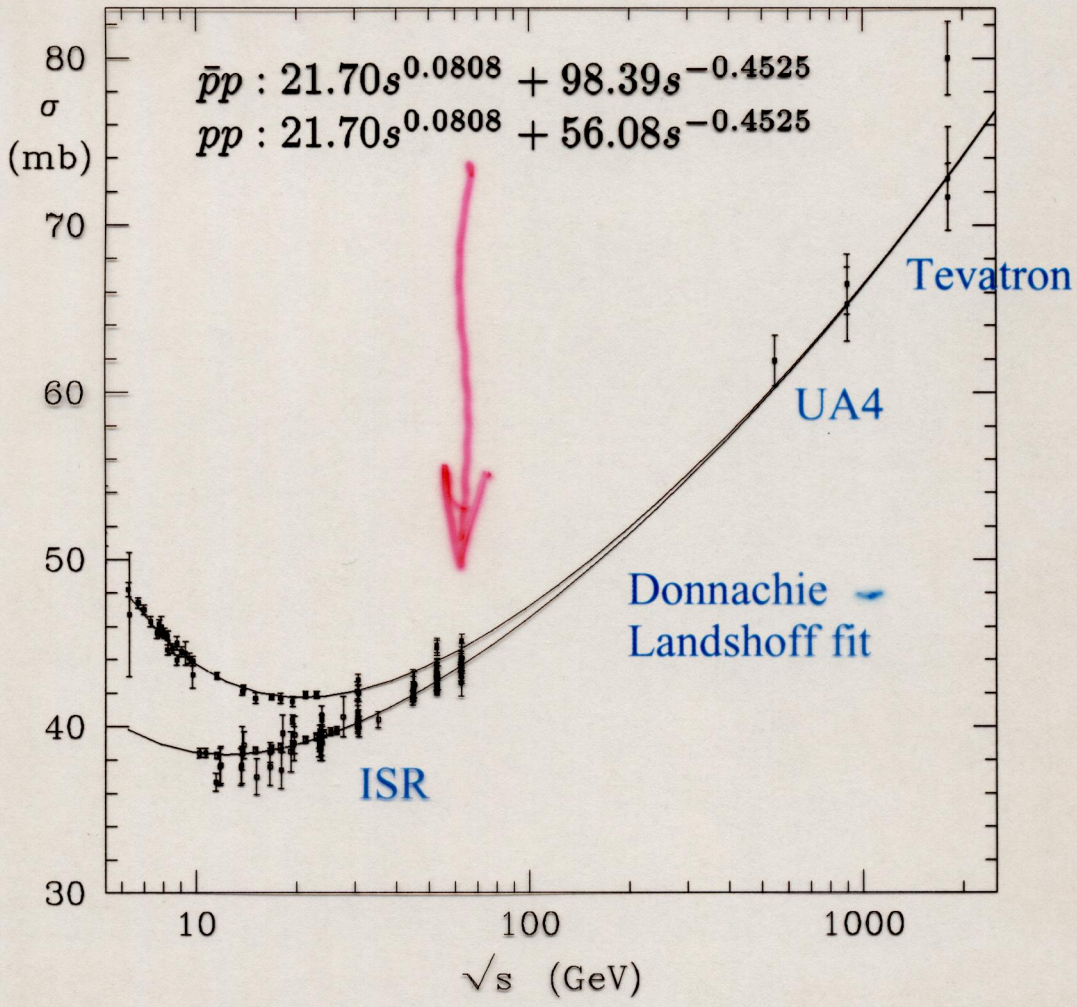
$$\sigma(\bar{p}p) - \sigma(pp) \rightarrow 0 \qquad \text{for } s \rightarrow \infty.$$

- But: Quantum Field Theory allows for a finite difference, e.g. due to presence of an "odd under crossing" amplitude which (as the ω does at low energies) contributes with different signs at high energies to pp and $\bar{p}p \rightarrow$

  The (non - perturbative) Odderon ($I\!O$) - the $I\!O$ trajectory - enters the stage:

  The (P = C = -1) partner of the Pomeron.

No pp - data above here!



A world without

an Odderon!

The Starting Point:

- Pioneering theoretical work by:

  L. Łukaszuk and B. Nicolescu (1973)

  D. Joynson, E. Leader, C. Lopez, B. Nicolescu (1975)
  (This paper coined the term "Odderon"!)

  K. Kang and B. Nicolescu (1975)

- But: No indication of $\mathcal{O}$ - induced effects visible up to now in high energy pp / $\bar{p}p$ scattering, neither in $\sigma(\bar{p}p) - \sigma(pp)$ nor in $\rho(\bar{p}p) - \rho(pp)$ with e.g. $\rho(pp) = \frac{Re\ F_{pp}(t=0)}{Im\ F_{pp}(t=0)}$
  = phase of elastic forward scattering amplitude.

- $\rightarrow$ New theoretical investigations triggered, e.g.:

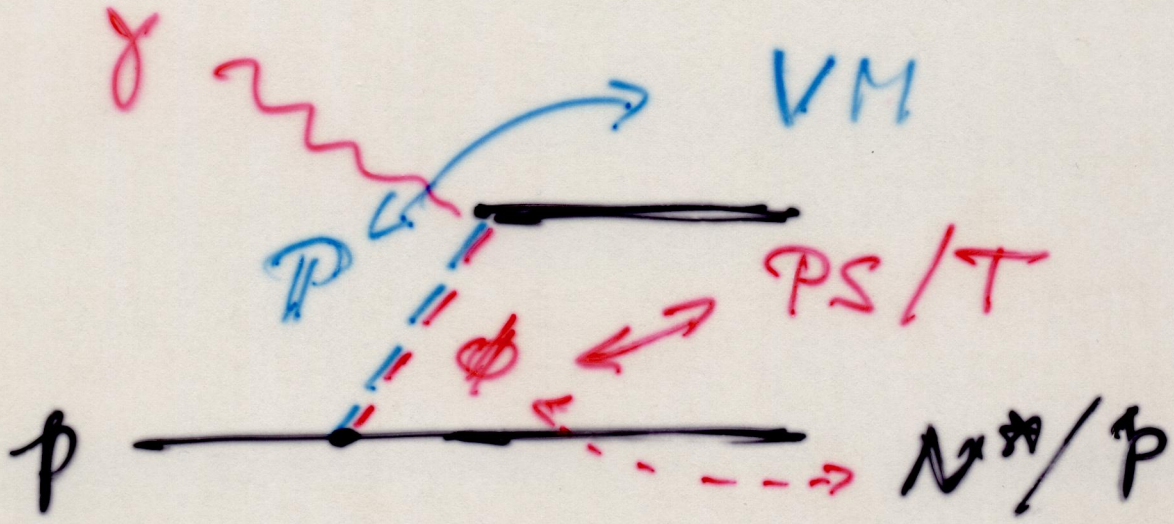
  M. Rüter, H. G. Dosch, O. Nachtmann (1998):

  $\mathcal{O}$ - contribution suppressed by quark - diquark shape of the proton, due to parity arguments (see talk by H. G. Dosch).

- $\rightarrow$ No chance for the Odderon to reveal its existence?

The Odderon at HERA:

- There IS a chance: A new window opened at HERA.
  Basic idea: Look at "classical" graph for vector meson (VM) photoproduction



and replace $I\!P$ with $O\!\!\!/$ (P = C = -1) → generate pseudoscaler and tensor mesons (C = +1) instead of vectors (C = -1).

Note: $O\!\!\!/$ - exchange in photoproduction principally competes with Primakoff - effect ($\gamma - \gamma$ - fusion).

The Experimental Strategy:

- Look for the elusive Odderon - induced reactions while - at the same time - measuring well established Pomeron - mediated processes (vector meson and axial vector meson (AVM) production).

- Look for exclusive meson production and look for purely photonic final states only (i.e. all mesons cascade down to photons - the products of branching ratios are finite).

- Advantage: The number of final state photons determines the charge conjugation eigenvalue C and thus

  tags $I\!P$ or $\mathcal{O}$ exchange !

The Odderon at HERA:

- Overcome the suppression of the ($\mathbb{O}$ - proton) - coupling due to the quark - diquark structure of the proton by diffractive excitation / breakup:
  e.g. $p \to N^*(1520, 1535, ..)$ or to continuum states with negative parity $\to$

  No longer suppression due to parity arguments.

- Calculations based on the "Stochastic Vacuum Model (SVM)", a model of non-perturbative QCD:

  H. G. Dosch and Yu. A. Simonov (1988)
  O. Nachtmann (1991)
  E. R. Berger, A. Donnachie, H. G. Dosch, W. Kilian, O. Nachtmann, M. Rüter (1999 + 2000)

  The model starts at $W = \sqrt{s_{\gamma p}} = 20$ GeV; the intercept of the Odderon trajectory is assumed as $\alpha_{\mathbb{O}}(0) = 1$, i.e. no energy dependence when moving towards HERA energies, namely $< W >= 200$ and 215 GeV.

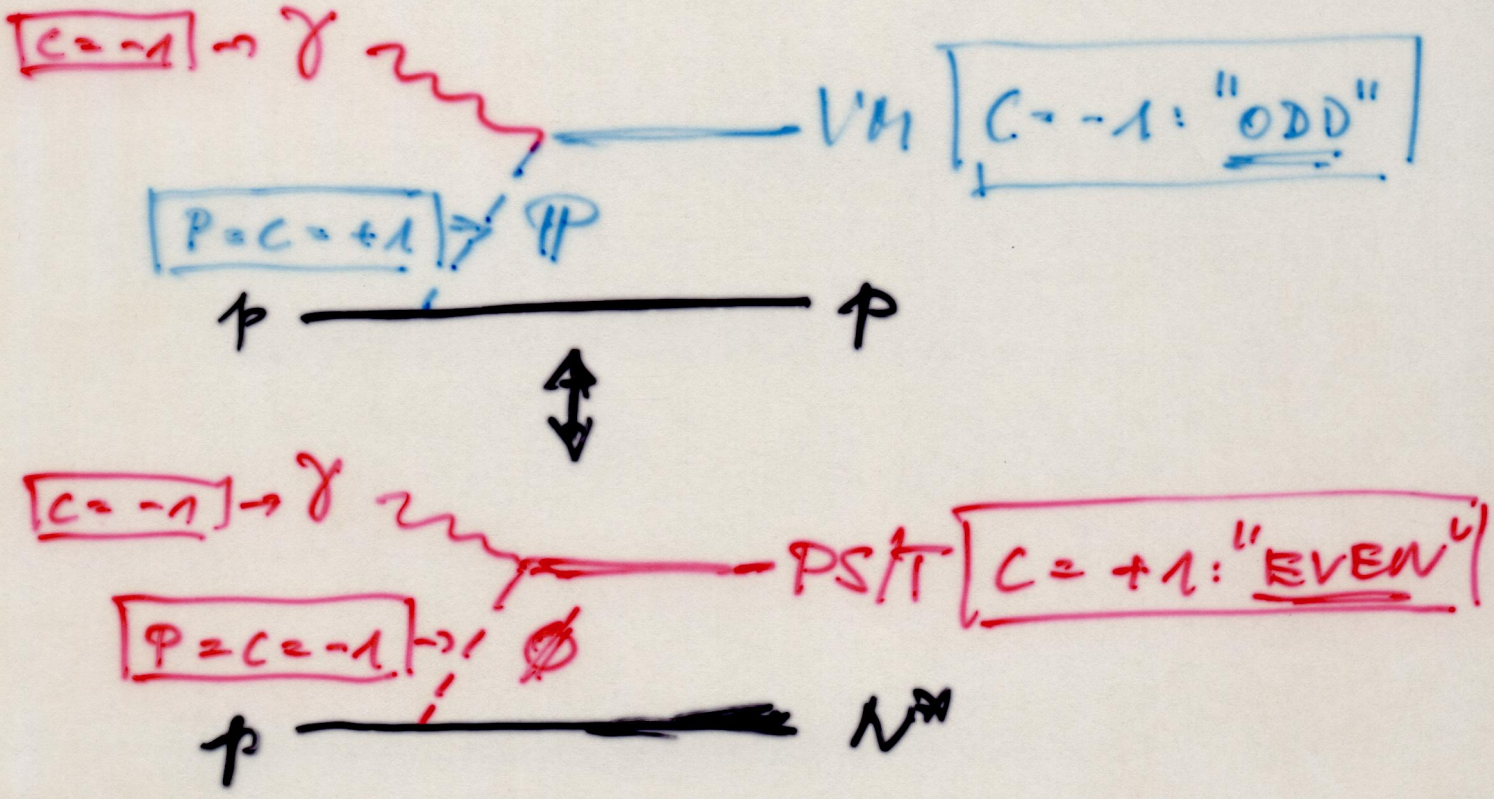
  Note that the authors state an uncertainty of the order of a factor 2 on their calculations.

- The SVM was successfully applied to diffractive ($\mathbb{P}$ - exchange dominated) reactions such as $\gamma\, p \to \rho^0\, p$
  (see e.g. M. Rüter, Eur. Phys. J. **C8** (1999) 233).

  $\to$ It is expected to work with the Odderon, too.

The Experimental Strategy:

- To illustrate what is meant by "experimental strategy", the "Pomeronic" and "Odderonic" graphs are sketched and confronted to each other below:

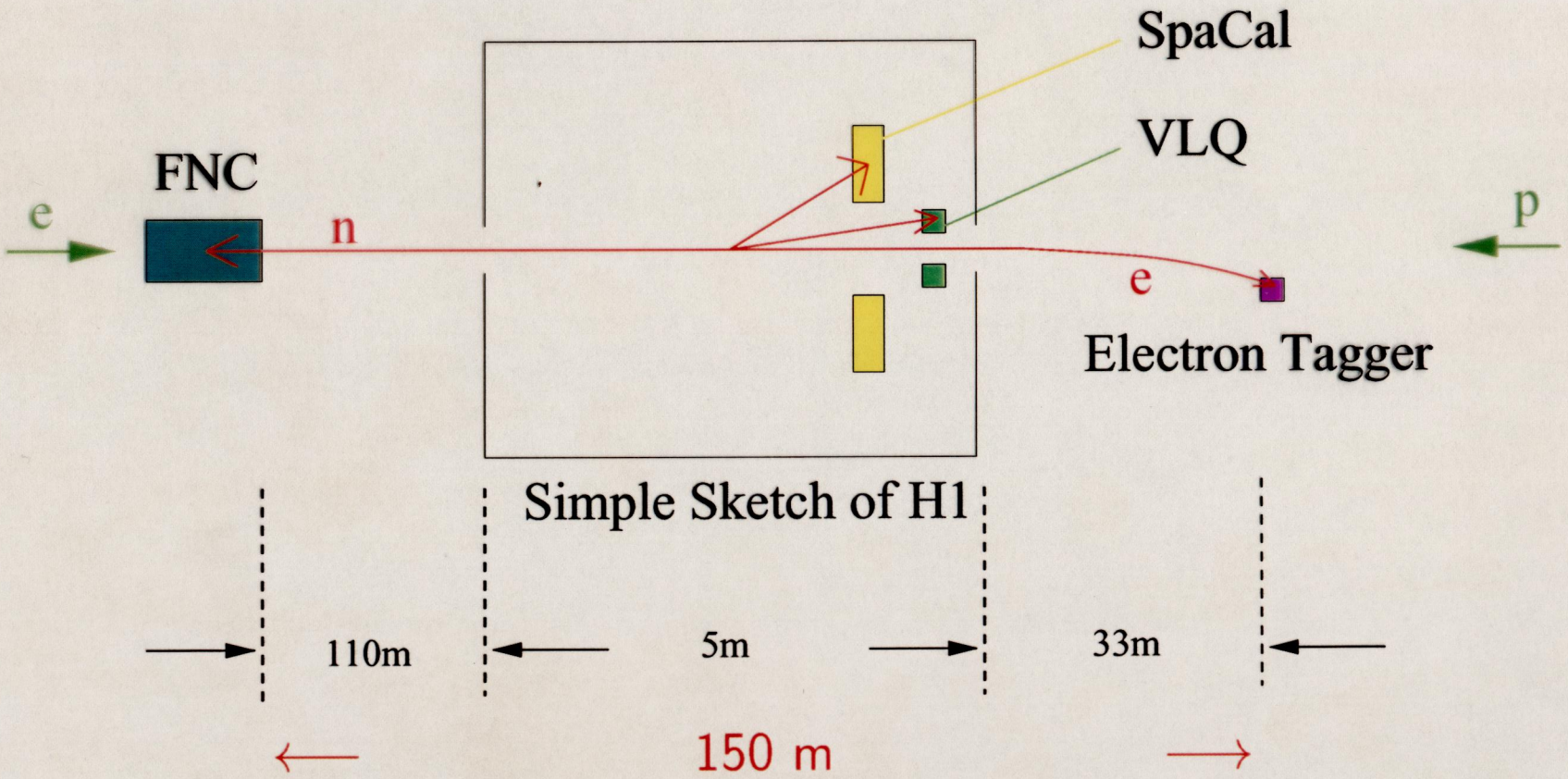


→ An even number of final state (i.e. meson daughter and granddaughter) photons "tags" photoproduction via $\mathbb{O}$ exchange, an odd number tags $\mathbb{P}$ exchange.

THE SIGNATURE

$$ep \to e + \pi^0 + N^*$$

$N^* \to n\pi(\pi)$ $\qquad$ $\pi^0 \to \gamma\gamma$



The Experimental Signature:

- Purely "photonic" final states: No tracks → no vertex. This is a purely calorimetric measurement!

- Photoproduction (i.e. HERA's electron emits a quasi - real photon): Find scattered electron in small angle electron detector.

- Decay "photons": "Good" clusters in backward calorimeters VLQ and SpaCal.

- "Exclusive" reactions: Energy - momentum conservation verified by so called (HERA - specific) "$E - p_z$ - cut". This cut excludes also overlapping events.

- (Only) in case of π^0 N^* photoproduction: The leading neutron from the isobar decay has to be seen in the Forward Neutron Calorimeter FNC.

- plus: Cuts against Bethe - Heitler events..

The Menu:

- The Pomeron mediated reactions investigated are

  $\gamma\, p \to \omega\, p \to (\pi^0\, \gamma)\, p \to (3\, \gamma)\, p$

  and $\gamma\, p \to (\omega\, \pi^0)\, X \to (\pi^0\, \gamma\, \pi^0)\, X \to (5\, \gamma)\, X$

  with a possible resonant $b_1(1235) \to \omega\, \pi^0$ (BR $\approx$ 100 %) contribution.

- The Odderon mediated reactions searched for are

  $\gamma\, p \to \pi^0\, N^* \to (\gamma\, \gamma)\, N^*$

  $\gamma\, p \to f_2(1270)\, X \to (\pi^0\, \pi^0)\, X \to (4\, \gamma)\, X$

  and $\gamma\, p \to a_2(1320)\, X \to (\pi^0\, \eta)\, X \to (4\, \gamma)\, X$

  $\to$ (Quasi -) elastic photoproduction reactions with nothing but photons in the "backward hemisphere" of the detector, i.e. the phase space region populated by the fragments of the incoming photon - therefore also called "photon hemisphere".

Dominant Backgrounds:

- Feed - down from many - photon final states to fewer - photon final states due to loss of photon(s), e.g.:

  $\gamma\, p \rightarrow (\omega\, \pi^0)\, X \rightarrow (5\, \gamma)\, X$

  feeds, after loss of one photon e.g. in beam pipe,

  $\gamma\, p \rightarrow (\pi^0\, \pi^0)\, X \rightarrow (4\, \gamma)\, X.$

- "Leakage" from low multiplicity inclusive reactions due to finite resolution of cuts.

- (Note: Background from $\gamma - \gamma$ - fusion (Primakoff effect) is negligible.)

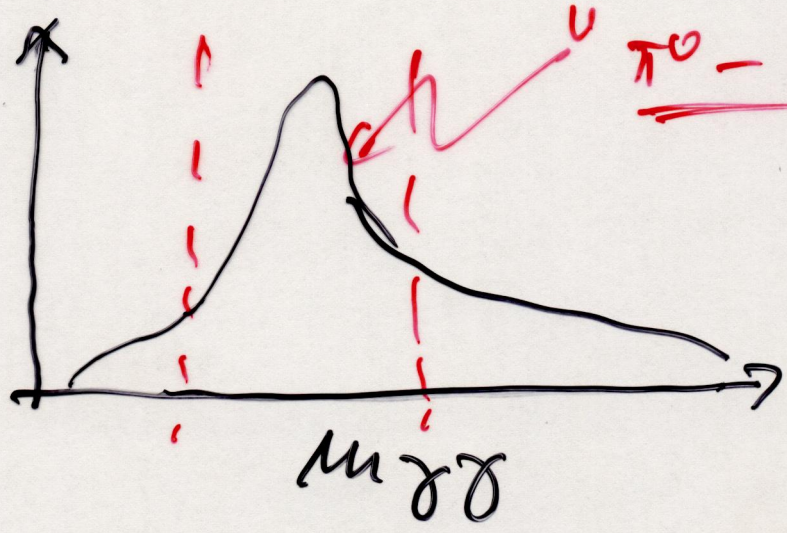
- Also background from Reggeon (ω - trajectory) exchange can be neglected.

THE FOLLOWING PLOTS SHOW $(2\gamma), \ldots (5\gamma)$ -

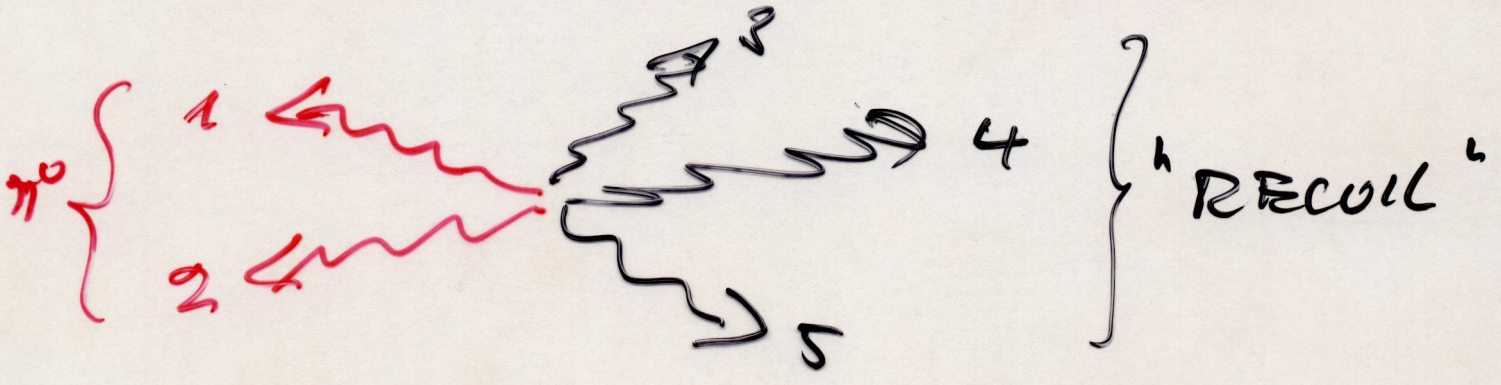
INVARIANT MASS SPECTRA

$\Rightarrow$ DEFINE "MASS WINDOWS"

e.g.



DEFINITION OF RECOIL:



IF γ_1, γ_2 INSIDE e.g. π^0 - WINDOW, CALL $(\gamma_3, \gamma_4, \gamma_5)$ "RECOIL SYSTEM" AGAINST π^0.

THE FOLLOWING MASS PLOTS SHOW

DATA

AND

MODEL - BACKGROUND } PREDICTIONS

The Experimental Evidence: $I\!P$ Exchange

- The analyses presented here are based on two data taking periods, namely

  the 1996 period with an integrated luminosity of 4.5/pb - these are "SpaCal only / no VLQ" data -, and

  the 1999 and 2000 periods with an integrated luminosity of 30/pb - these are the "VLQ and SpaCal" data.

- Let us start with "well known" diffractive / $I\!P$ mediated reactions, first:

  $\gamma\, p \to \omega\, p \to (\pi^0\, \gamma)\, p$

  $\to$ look at the spectra:

Result:

$\sigma(\gamma\, p \to \omega\, p,\ W\ =\ 200\ GeV) = (1.25 \pm 0.18 \pm 0.22)\ \mu$b,

as expected e.g. from $\gamma\, p \to (\omega \to 3$ pions$)\, p$ at HERA (ZEUS): $\sigma = (1.21 \pm 0.12 \pm 0.23)\ \mu$b.

The Experimental Evidence: $I\!P$ Exchange

- The second Pomeron mediated reaction is

  $\gamma\, p \to (\omega\, \pi^0)\, X \to (\pi^0\, \gamma\, \pi^0)\, X \to (5\, \gamma)\, X,$

  with a possibly dominant resonant contribution from $b_1(1235) \to \omega\, \pi^0$.

  The first measurement of axial vector meson production at HERA!

→ look at the spectra:

Result:

$\sigma(\gamma\, p \to (\omega\, \pi^0)\, X) = (980 \pm 200 \pm 200)\ nb.$!

- A comparison with PYTHIA (which does NOT model resonant b_1 production, but predicts a cross section of 190 nb for non - resonant $(\omega\, \pi^0)$ - production) suggests a sizeable b_1 contribution.

  This is in agreement with results from experiments at low energies. e.g The Omega Photon Collaboration (1984): Extrapolating their b_1 - cross section to HERA energies gives

  $\sigma(\gamma\, p \to b_1\, p) = 660\ (\pm 30\%)$ nb. ⇒ compare:

Δ = (H1 - PYTHIA) =

(980 - 190) nb = 790 (±35%) nb

The Experimental Evidence: $I\!P$ Exchange

- A spin - parity analysis in order to pin down the resonant b_1 - state could not be performed, due to lack of acceptance in some relevant phase space regions.

- $\rightarrow$ Two Pomeron induced reactions with purely photonic final states measured, results fit in "traditional" pattern known from previous experiments

  $\rightarrow$ Have confidence in this particular strategy, and look for the Odderon!

The Experimental Evidence: $\mathcal{O}$ Exchange

- Start with pseudoscalar (here: π^0) production and compare with SVM prediction:

  $\gamma\, p \to \pi^0\, N^* \to (\gamma\, \gamma)\ (n\ +\ \text{pions})$

  The neutron is needed to indicate the break - up of the proton → detect neutron in Forward Neutron Calorimeter FNC.

  The acceptance is small due to small solid angle covered by VLQ and FNC; anyhow:

  Compare 13 events observed with 110 events expected

→ look at the spectra:

Result: Quote cross section as upper limit:

$\sigma(\gamma\, p \to \pi^0\, N^*) < 39$ nb (95 % CL),

to be compared with the SVM prediction of 200 nb → model excluded even after "safety" factor 2.

The Experimental Evidence: $\mathcal{O}$ Exchange

- Turn to tensor mesons, look for

  $\gamma\, p \to a_2(1320)\, X \to (\pi^0\, \eta)\, X \to (4\, \gamma)\, X.$

  Look for four photons in SpaCal

  $\to$ look at the spectra:

  Result:

  $\sigma(\gamma\, p \to a_2\, X) < 96$ nb (95 % CL),

  to be compared with the SVM model prediction of 190 nb.

- Finally, look for the second four photon final state:

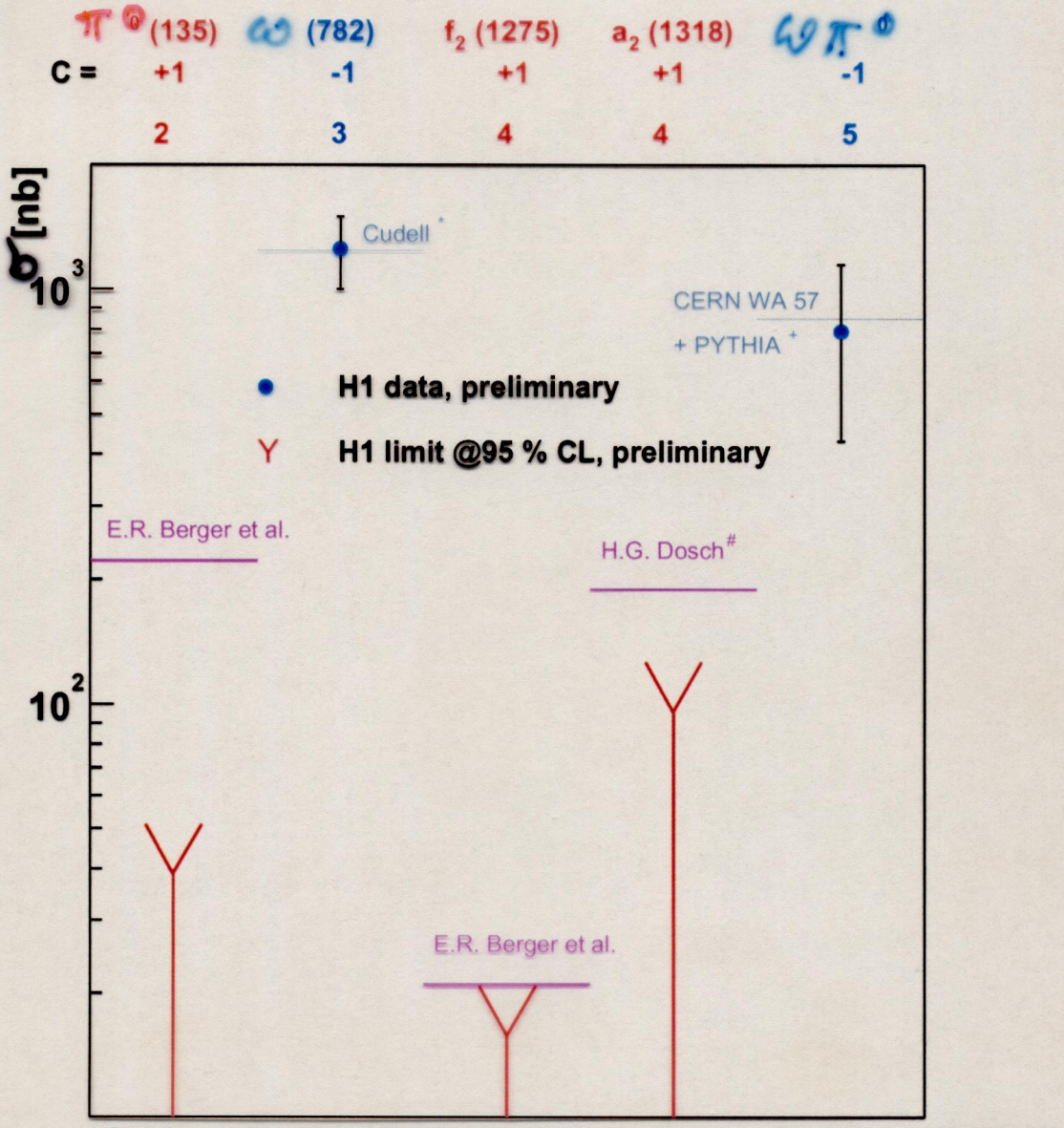
  $\gamma\, p \to f_2(1270)\, X \to (\pi^0\, \pi^0)\, X \to (4\, \gamma)\, X.$

  Result:

  $\sigma(\gamma\, p \to f_2\, X) < 16$ nb (95 % CL),

  to be compared with the SVM model prediction of 21 nb.

  Here, the situation is much less conclusive than in the case of the a_2 or π^0. This is mostly due to the unsatisfactorily poor statistics, but might have physical reasons: The Odderon, if existent, might distinguish between pseudoscalar and tensor mesons and prefer the latter.



* Cudell et al.: Phys.Rev. D61 (00), 034019; Schuler, Sjoestrand: Nucl.Phys. B407 (93), 539

+ CERN WA 57: Nucl.Phys. B243 (84), 1; extrapolated to HERA energies

private communication

Summary:

- (Known for long) Pomeron induced reactions, investigated in purely photonic final states, have been measured in agreement with previous experiments

  $\rightarrow$ The "photonic tag" works.

- The search for Odderon - induced reactions tells us:

  The limit on $\sigma(\gamma\, p \rightarrow \pi^0\, N^*)$ clearly rules out the SVM prediction. Also the a_2 - limit excludes the model, but less strictly due to the "safety" factor 2 in the calculations. The f_2 situation is inconclusive.

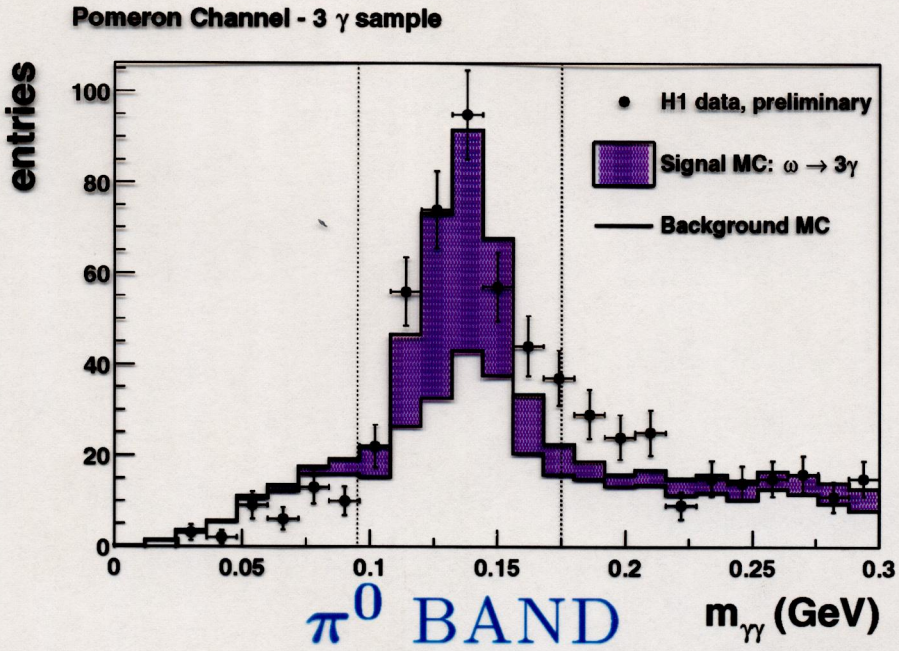
  We do not understand the non - observation of the Odderon at present. There are, perhaps, two - faint - explanations:

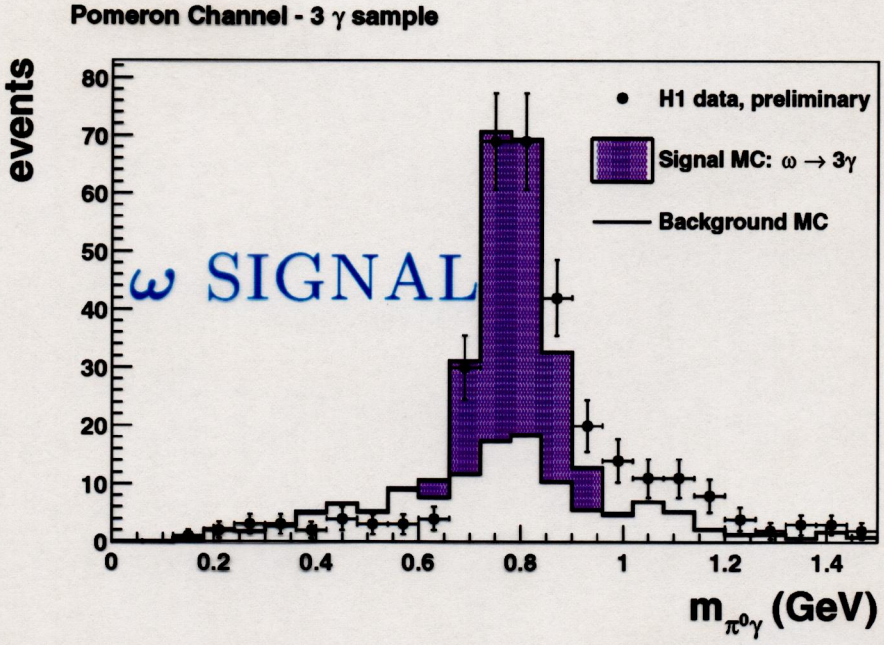
- The Odderon might prefer tensor mesons to pseudoscalars, especially to pions - if pions turn out to be Goldstone bosons.

  And / or: Theorists generally assume that the $\mathbb{O}$ - trajectory resembles very much the $\mathbb{P}$ - trajectory, both in intercept and slope. But perhaps, the Odderon has a trajectory completely different.

- Therefore: The elusive Odderon, up to now, keeps its secrets. For a further pursuit, we need statistics AND acceptance. Given these, and detailed measurements at different energies, would enable us to determine the parameters of its trajectory, and to establish firmly the Pomeron's "odd" partner.

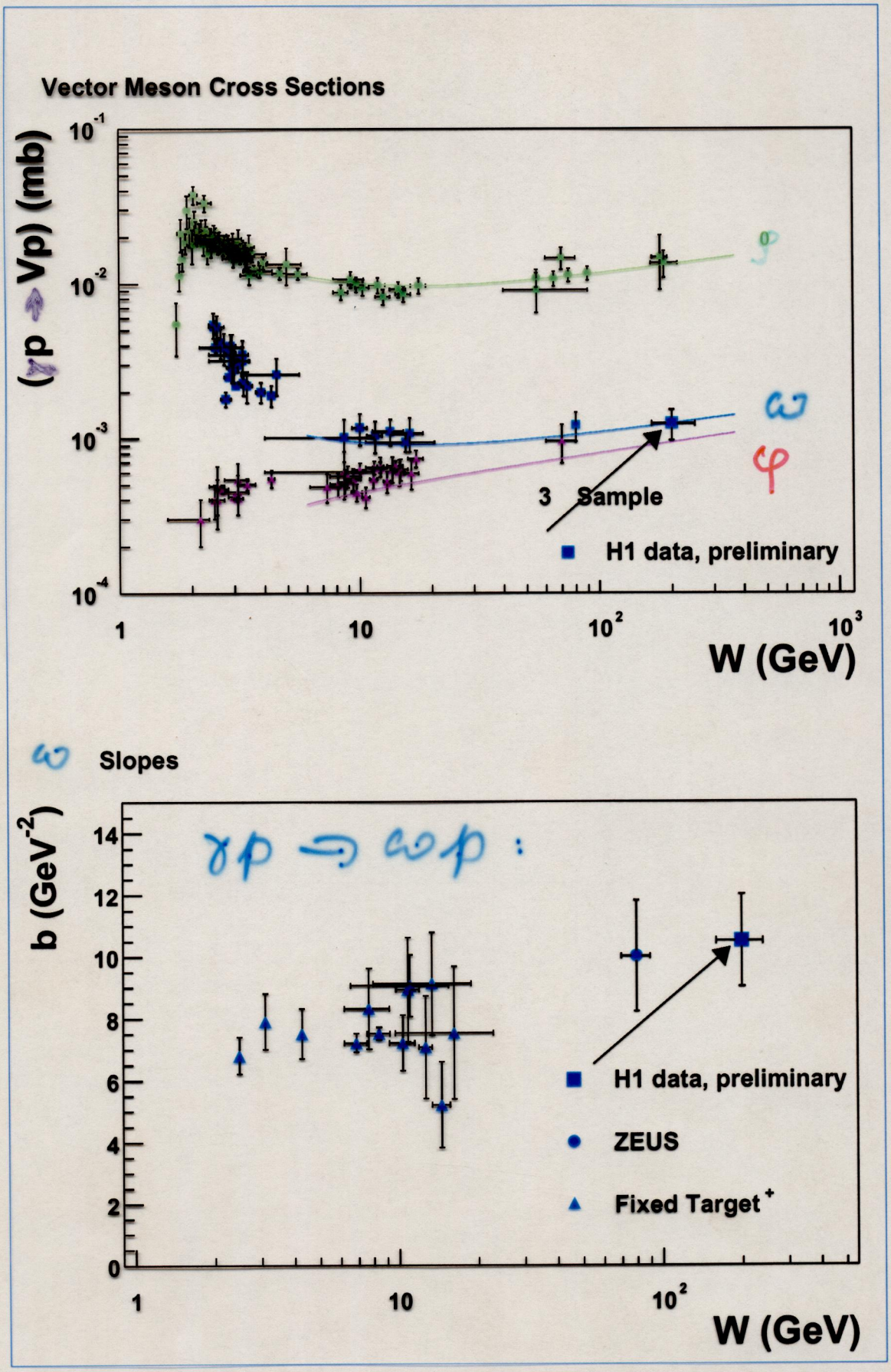
THE 3 γ SAMPLE $C = -1$ $\mathbb{P}$ EXCHANGE



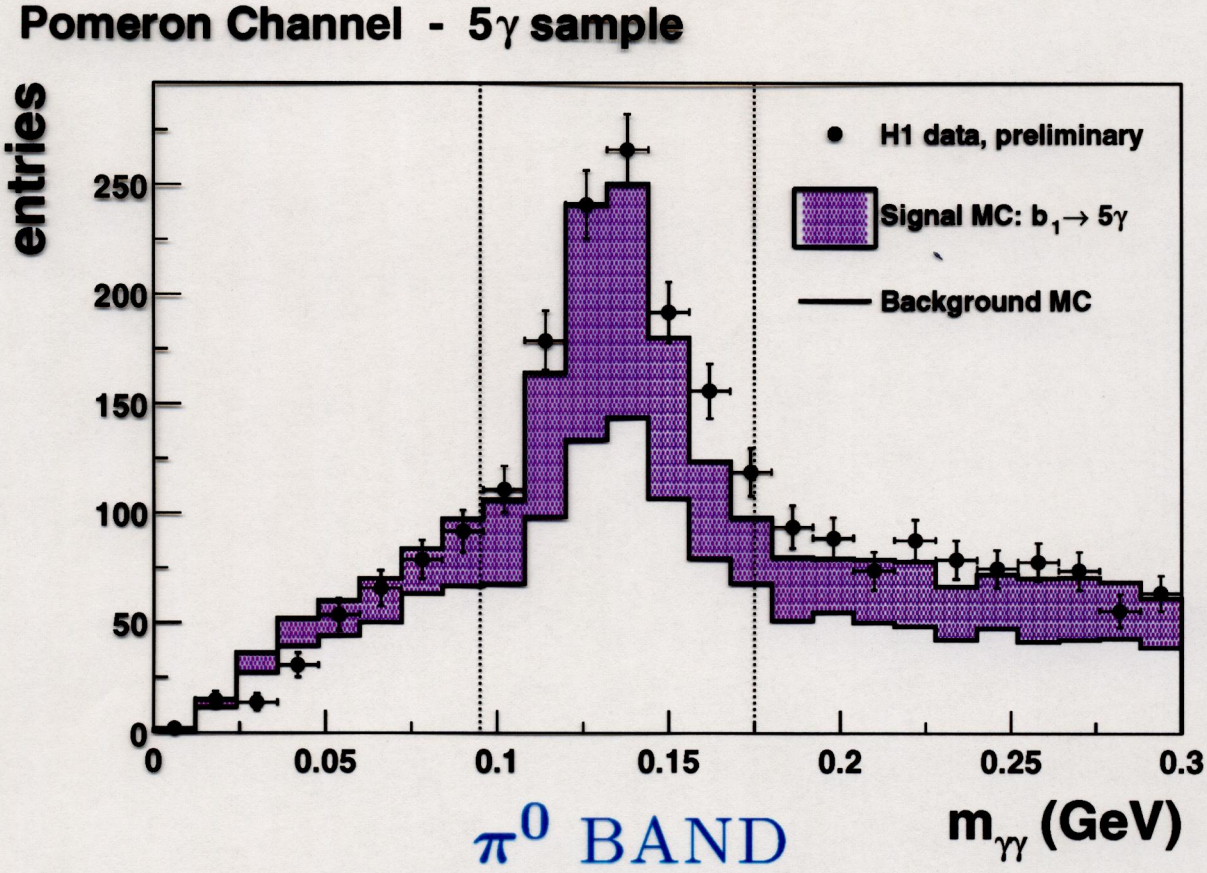


$$\sigma(\gamma p \to \omega p) = (1.25 \pm 0.17 \pm 0.22)\ \mu\text{b}$$

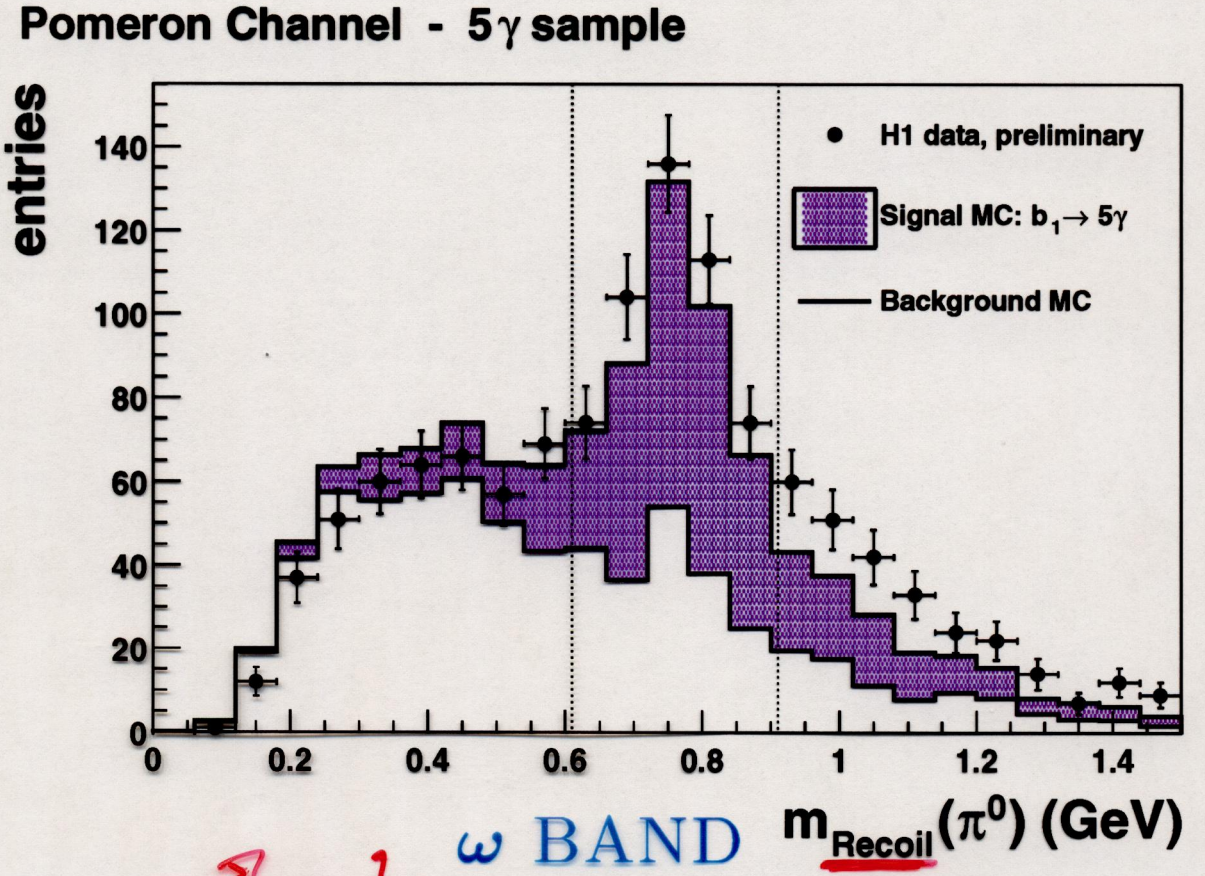
$$b = (10.5 \pm 1.2 \pm 0.5)\ \text{GeV}^{-2}$$


Vector Meson Cross Sections
(γp → Vp) (mb)
10^-1
10^-2
10^-3
10^-4
1
10
10^2
10^3
W (GeV)
ρ
ω
φ
3 Sample
H1 data, preliminary
ω Slopes
b (GeV^-2)
γp ⇒ ωp :
14
12
10
8
6
4
2
0
1
10
10^2
W (GeV)
H1 data, preliminary
ZEUS
Fixed Target +

THE 5 γ SAMPLE $C = -1$ $\mathbb{P}$ EXCHANGE



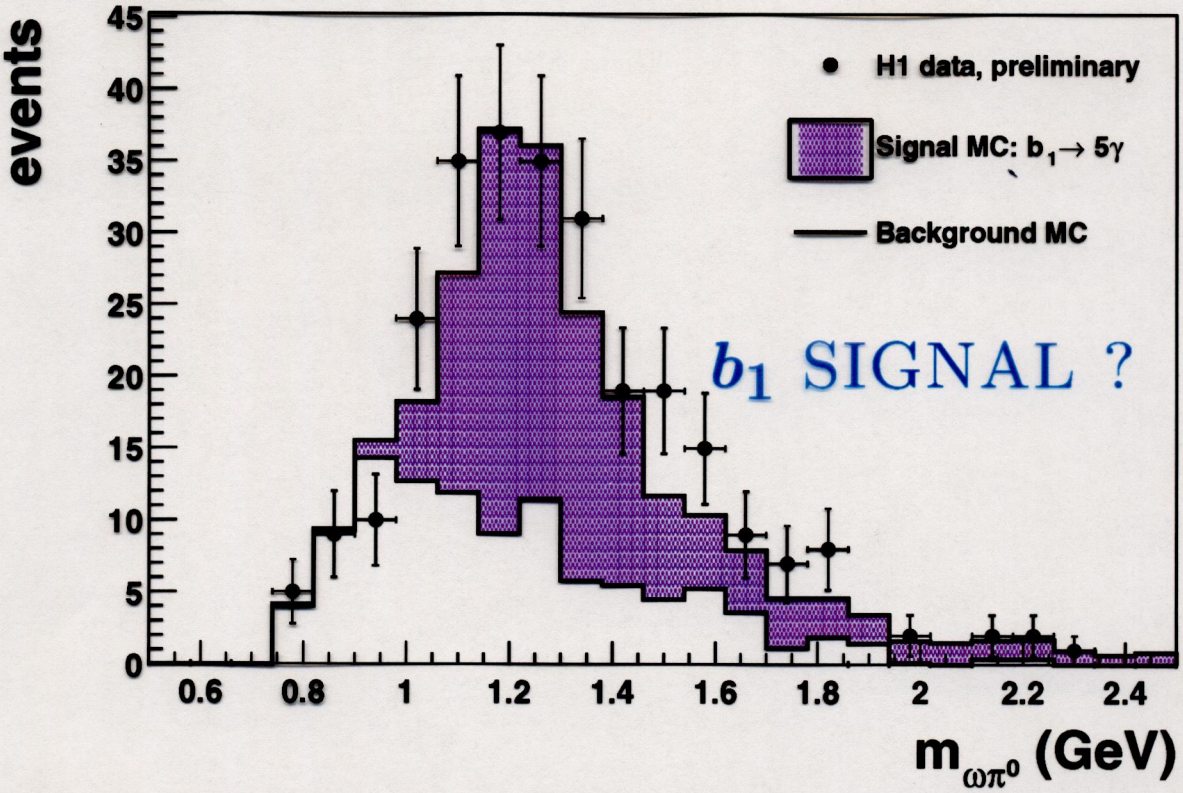
π^0 BAND



ω BAND

$\omega\pi^0$ Cross Section $C = -1$ $I\!P$ exchange

Pomeron Channel - 5γ sample



$\sigma(\gamma p \to \omega\pi^0 X) = (980 \pm 200\ (\text{stat}) \pm 200\ (\text{syst}))$ nb

to be compared with

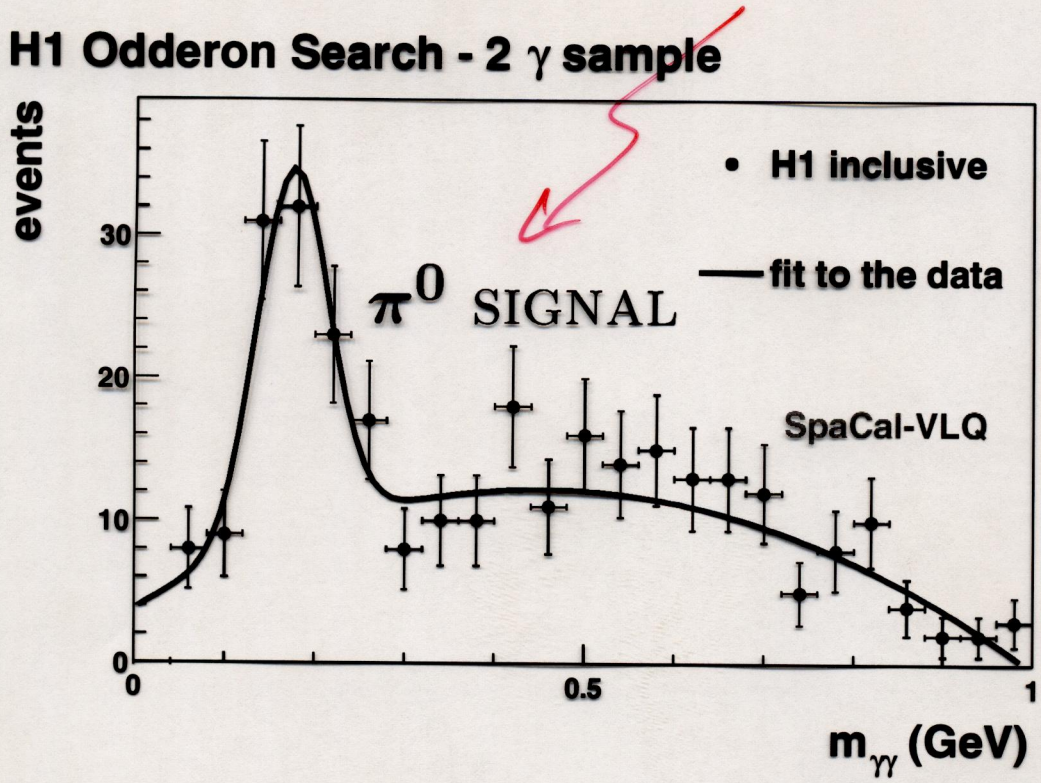
$\sigma_{\text{PYTHIA}}(\gamma p \to \omega\pi^0 X) = 190$ nb

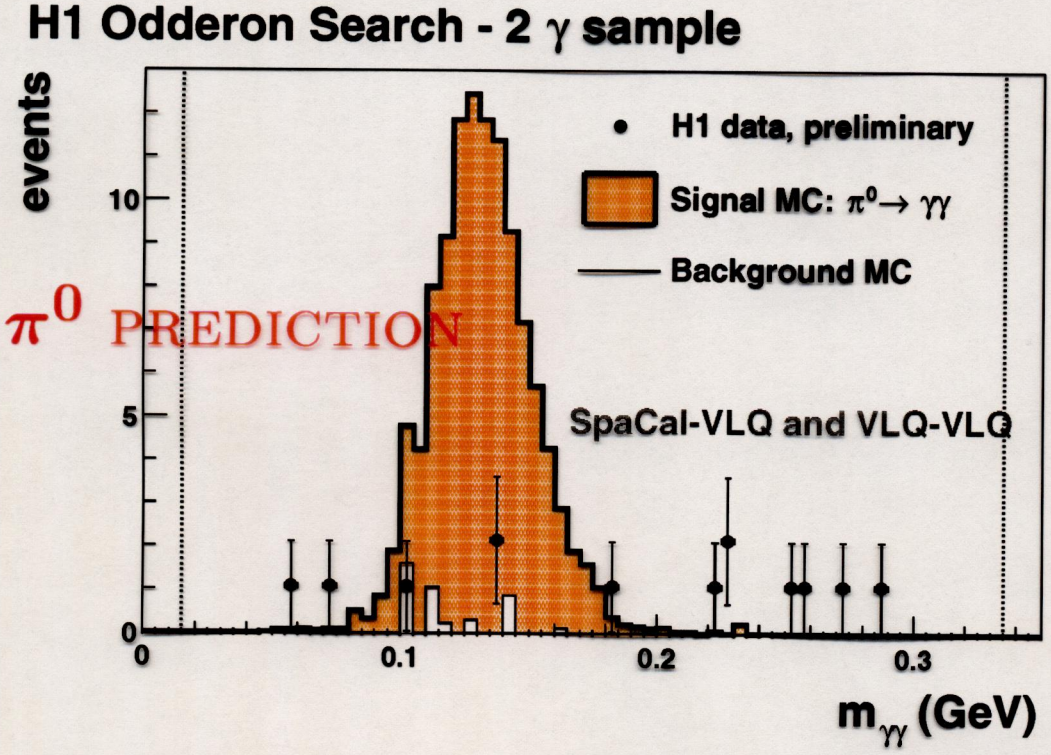
$\sigma_{\text{extrapolated}} * (\gamma p \to b_1(1235) X) = 660$ nb

at $\langle W_{\gamma p} \rangle = 200$ GeV

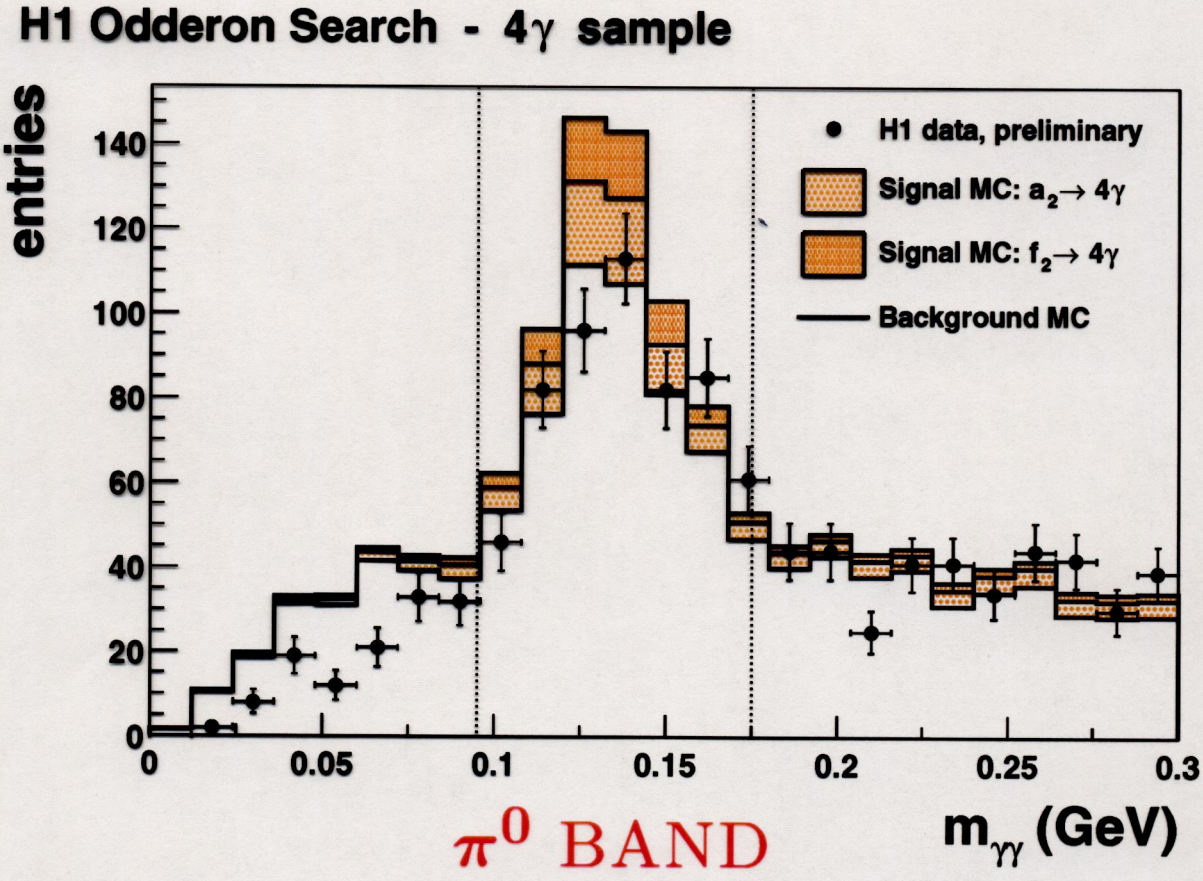
* $b_1(1235)(J^{PC} = 1^{+-})$ measurement by the Omega Photon collaboration and extrapolated to HERA energies:
Nucl. Phys. **B243** (1984) 1.

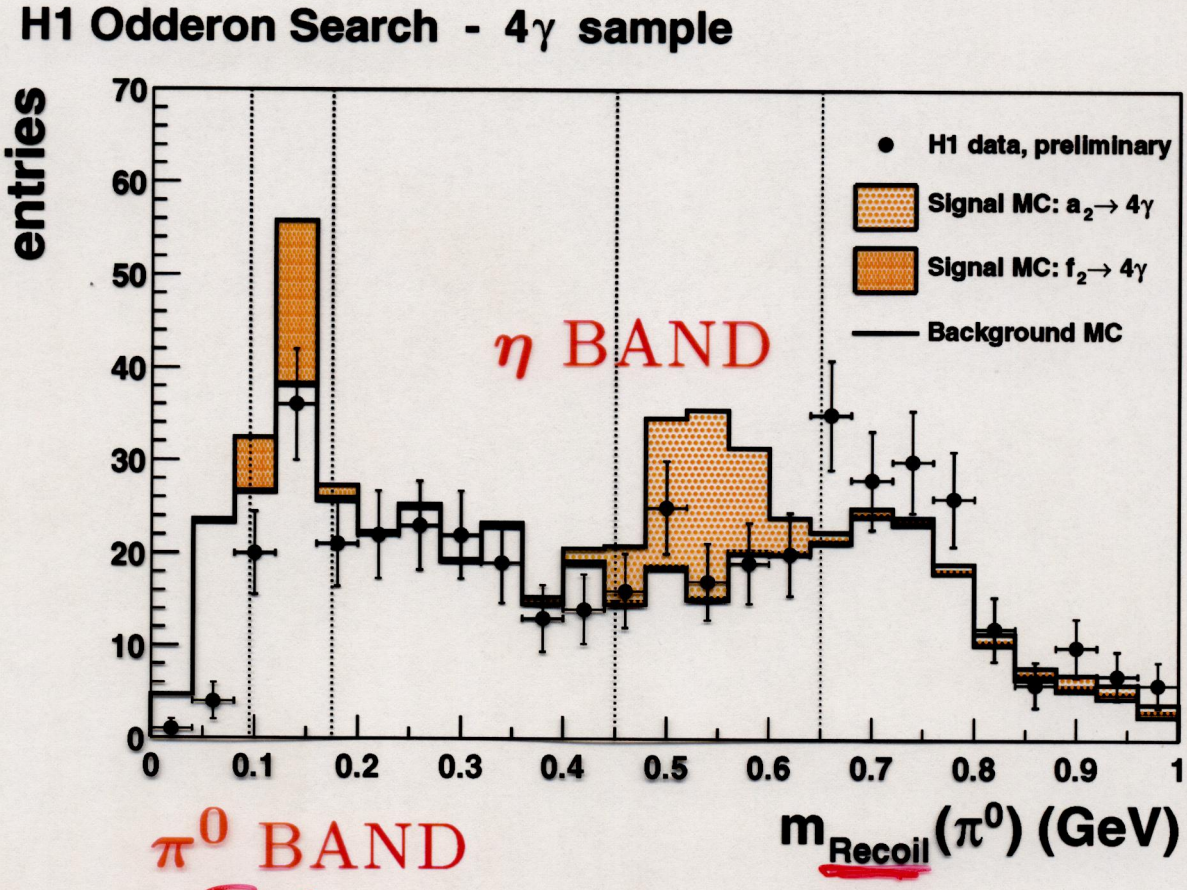
CUTS RELEASED





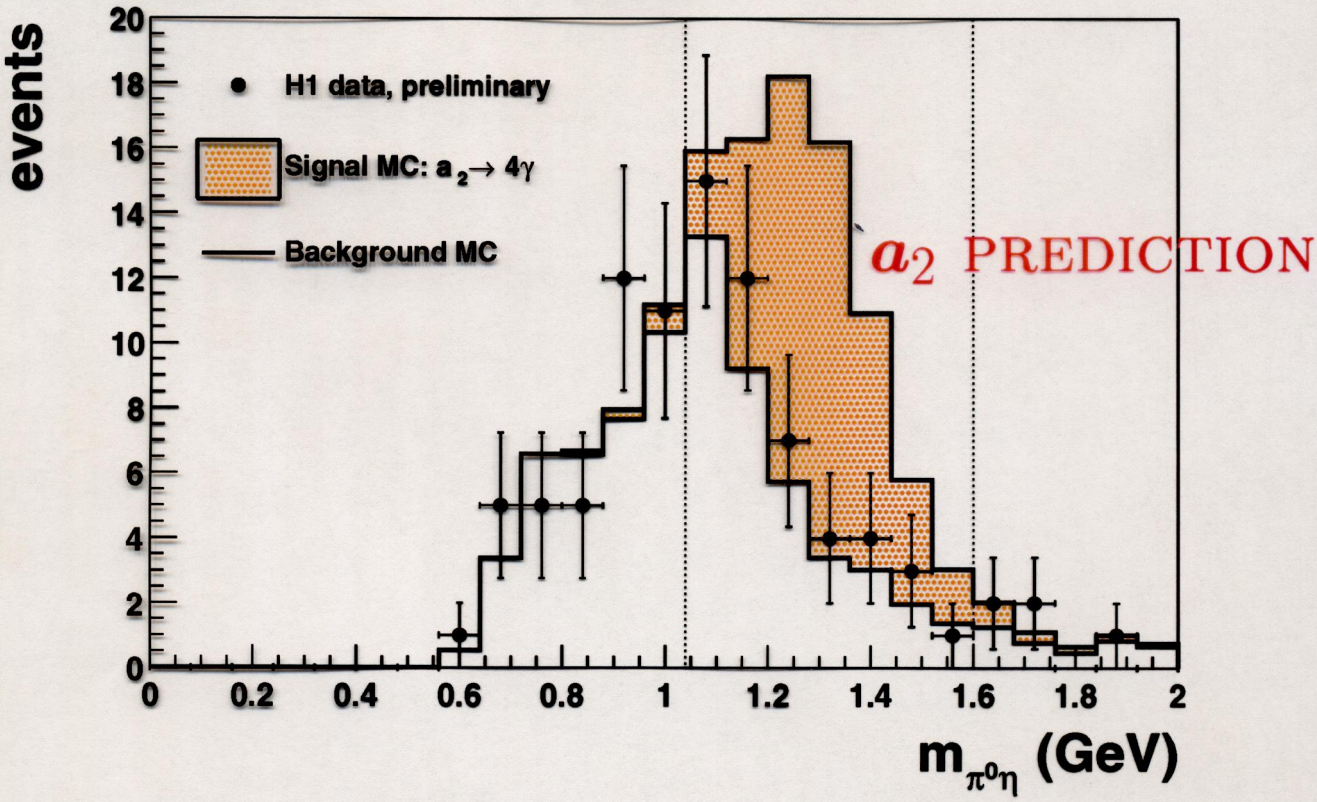
THE 4 γ SAMPLE $C = +1$ $\mathbb{O}$ EXCHANGE





π⁰ ⟷ } 'RECOIL'

H1 Odderon Search - 4γ sample



H1 Odderon Search - 4γ sample