How Omega helped to establish the existence of non-$q\bar{q}$ mesons

Andrew Kirk

How Orlando helped to establish the existence of non-qq̄ mesons

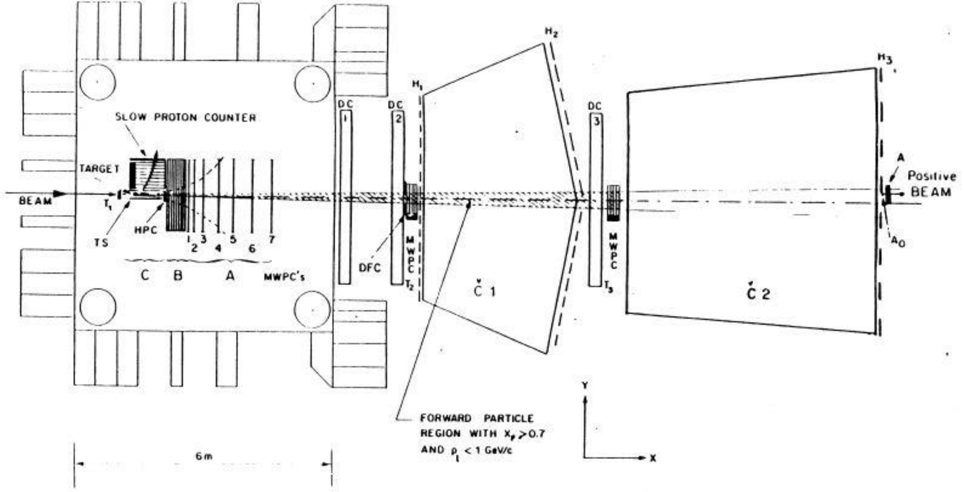
Andrew Kirk

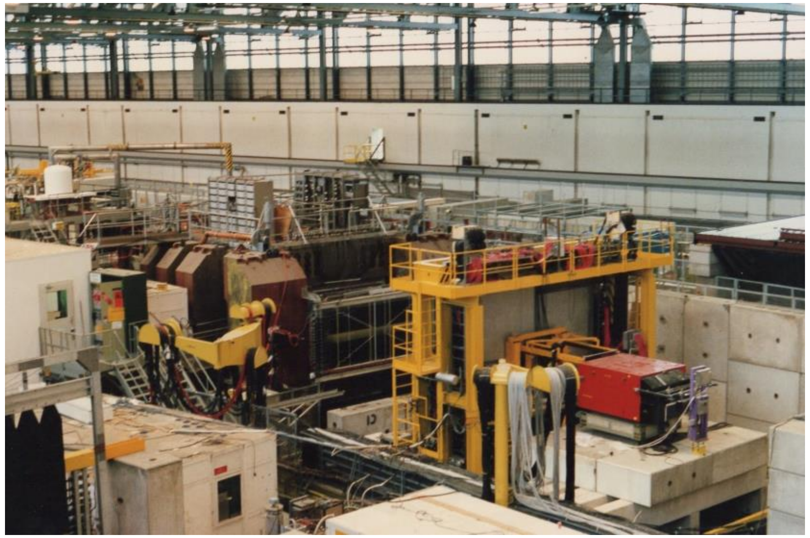
The Omega experiments Orlando was involved in

WA76 WA91 WA102	**non-$q\bar{q}$ mesons**
WA77	**Higher twist QCD processes**
WA83	**Soft photons**
WA85 WA97	**Heavy ions**

The search for non-$q\bar{q}$ mesons at the Omega Spectrometer

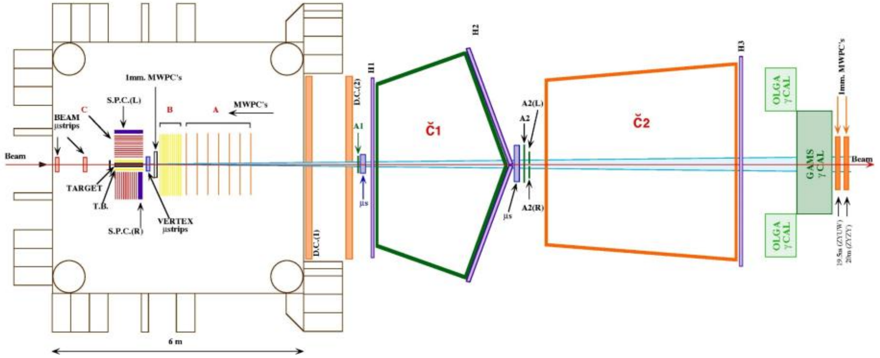
WA76 (1982-1986)



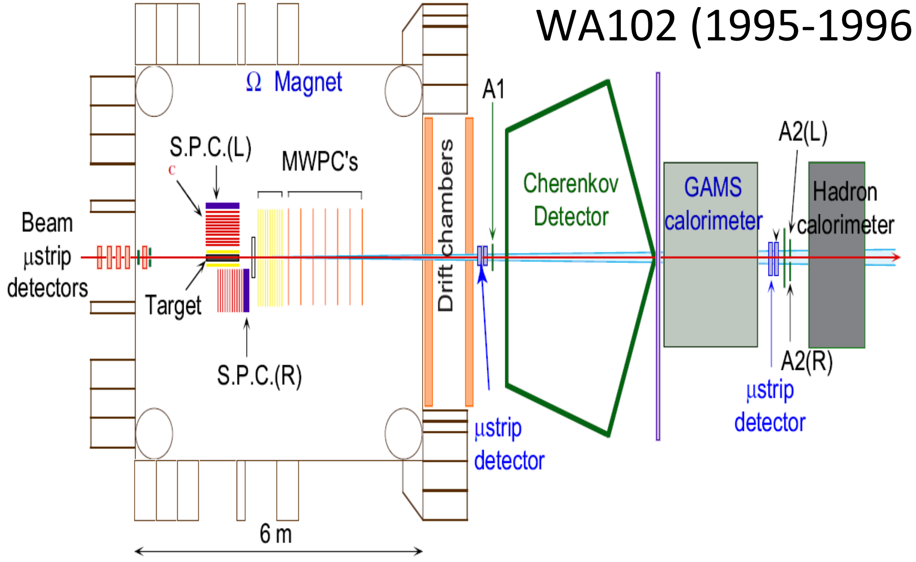


Ω LAYOUT FOR WA91 (1994 RUN)

WA91 (1992-1994)



V. Lenti 2/9/1993



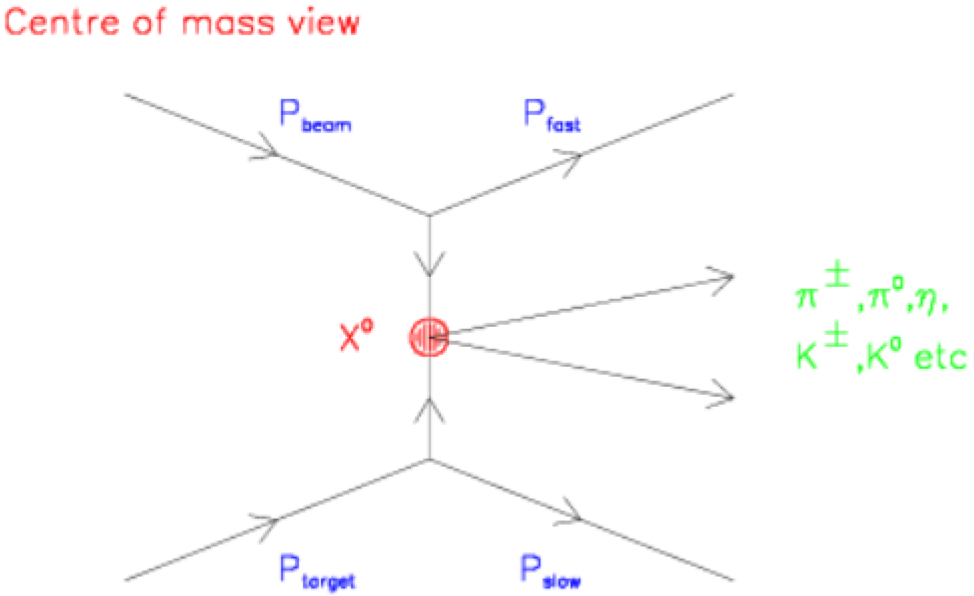
WA102 (1995-1996)

Experiments at the CERN Omega Spectrometer

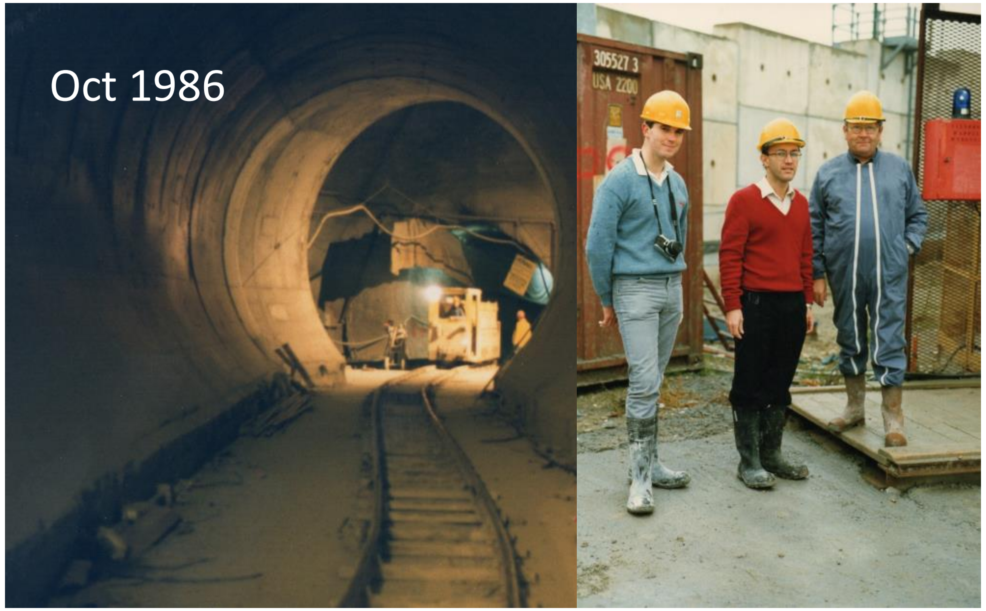
Fixed target experiments WA76, WA91 and WA102 have studied exclusive final states formed in the reaction

$$pp \rightarrow p_f p_s (X^0)$$

at 85, 300 and 450 GeV/c
(√s =12.7, 23.8 and 29 GeV)



Personal Memories

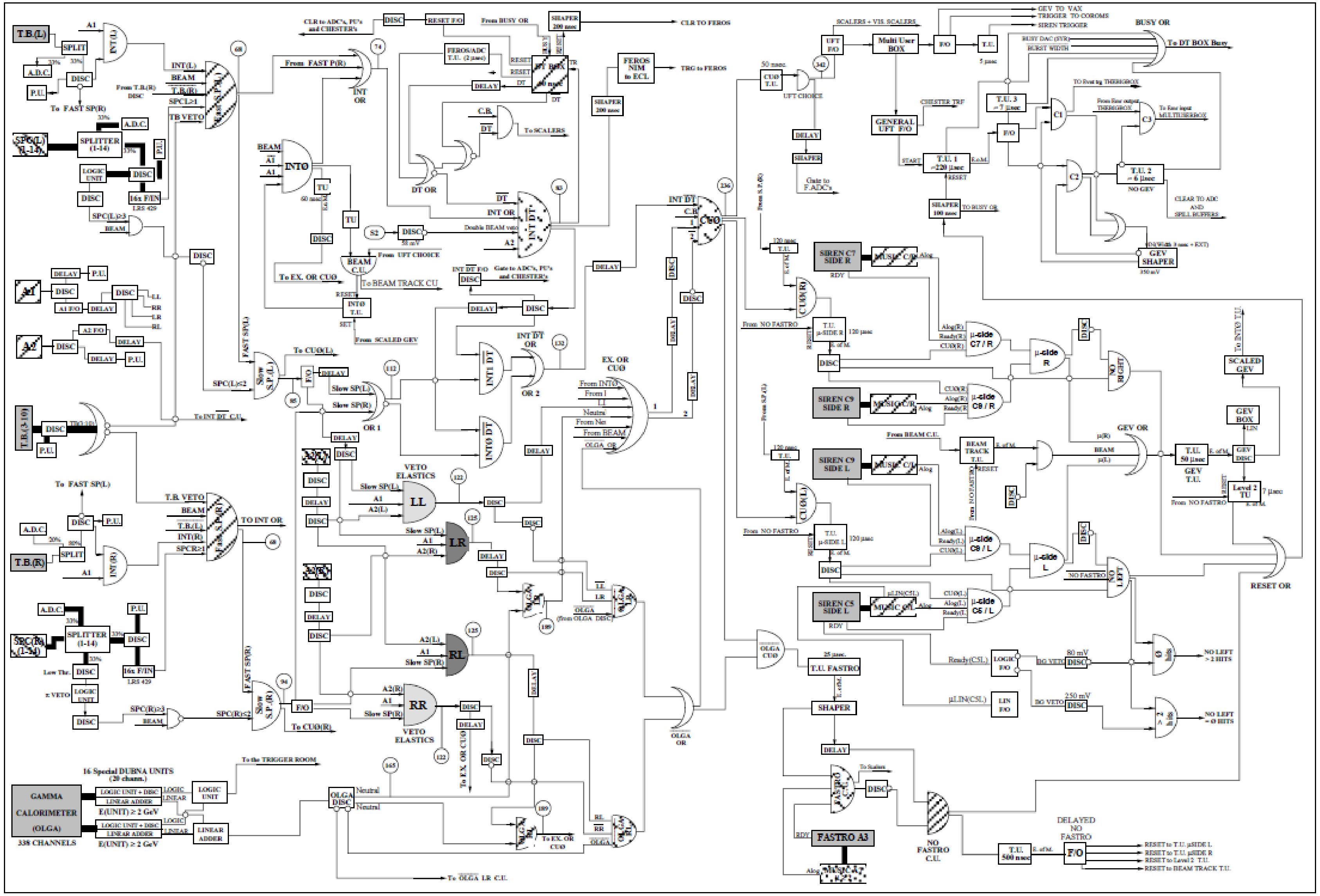

Oct 1986


July 1988


July 1988


Jan 1987

Orlando’s contributions

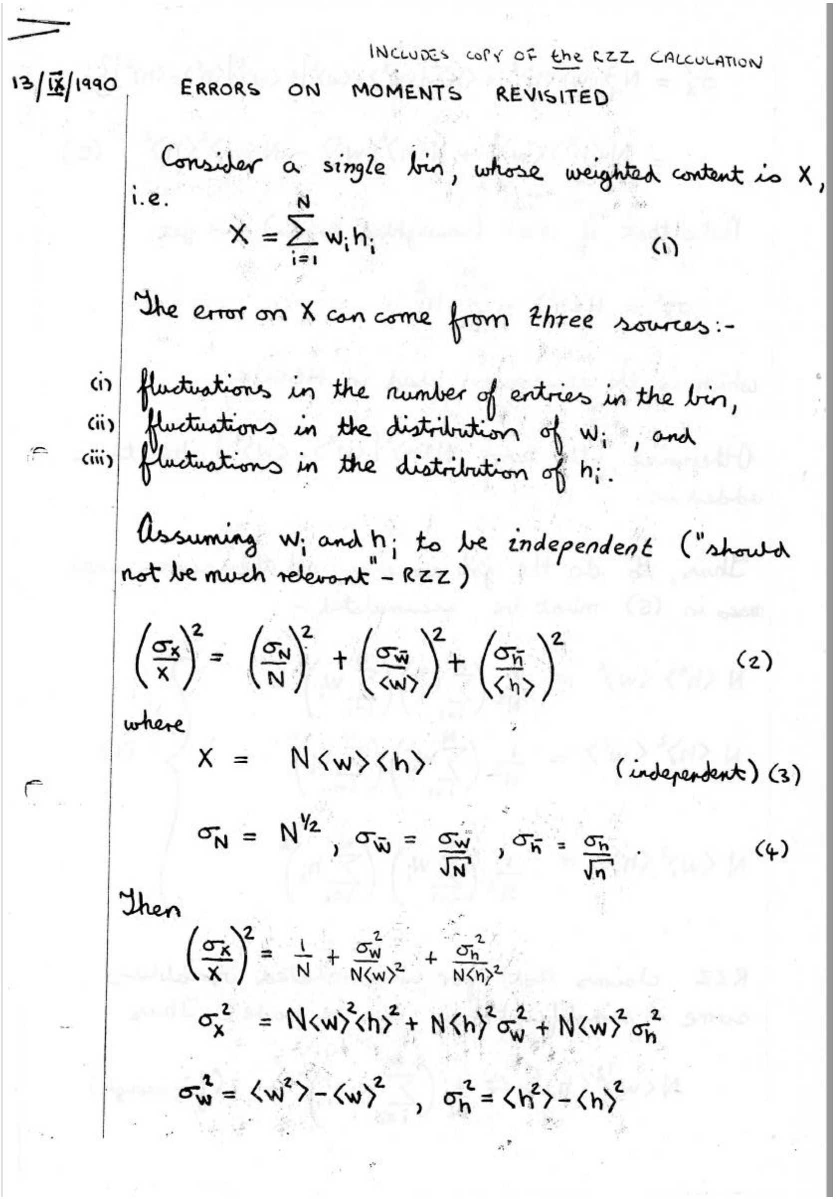

WA91 TRIGGER LOGIC (1993/P2)

Orlando played a major role in setting up the triggers for these experiments

In particular the L2 trigger which triggered on the centrally produced particles

More on the importance of that later….

Orlando’s contributions



INCLUDES COPY OF the RZZ CALCULATION

13/IX/1990 ERRORS ON MOMENTS REVISITED

Consider a single bin, whose weighted content is X, i.e.

$$X = \sum_{i=1}^{N} w_i h_i \qquad (1)$$

The error on X can come from three sources:-

(i) fluctuations in the number of entries in the bin,
(ii) fluctuations in the distribution of w_i, and
(iii) fluctuations in the distribution of h_i.

Assuming w_i and h_i to be independent ("should not be much relevant" - RZZ)

$$\left(\frac{\sigma_X}{X}\right)^2 = \left(\frac{\sigma_N}{N}\right)^2 + \left(\frac{\sigma_{\bar{w}}}{\langle w\rangle}\right)^2 + \left(\frac{\sigma_{\bar{h}}}{\langle h\rangle}\right)^2 \qquad (2)$$

where

$$X = N\langle w\rangle\langle h\rangle \qquad \text{(independent)} \ (3)$$

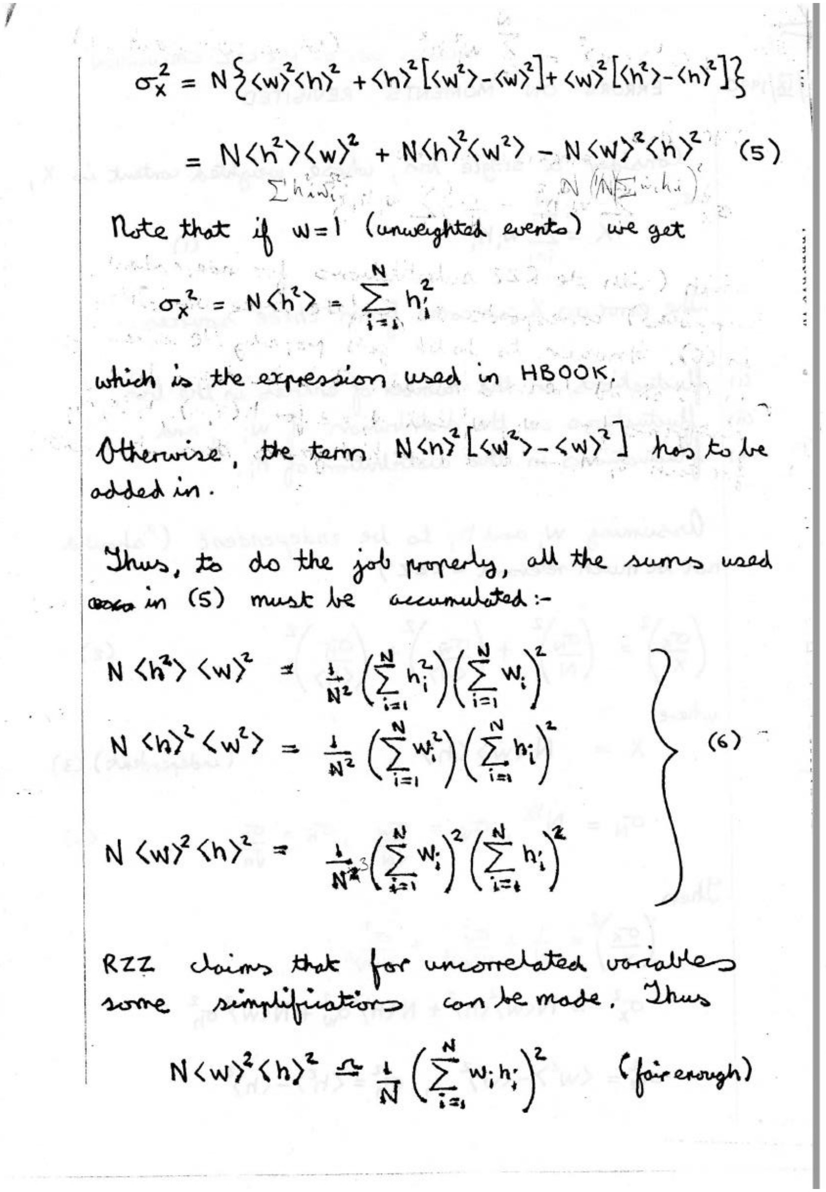
$$\sigma_N = N^{1/2}, \quad \sigma_{\bar{w}} = \frac{\sigma_w}{\sqrt{N}}, \quad \sigma_{\bar{h}} = \frac{\sigma_h}{\sqrt{n}}. \qquad (4)$$

Then

$$\left(\frac{\sigma_X}{X}\right)^2 = \frac{1}{N} + \frac{\sigma_w^2}{N\langle w\rangle^2} + \frac{\sigma_h^2}{N\langle h\rangle^2}$$

$$\sigma_X^2 = N\langle w\rangle^2\langle h\rangle^2 + N\langle h\rangle^2\sigma_w^2 + N\langle w\rangle^2\sigma_h^2$$

$$\sigma_w^2 = \langle w^2\rangle - \langle w\rangle^2, \quad \sigma_h^2 = \langle h^2\rangle - \langle h\rangle^2$$



$$\sigma_X^2 = N\left\{\langle w\rangle^2\langle h\rangle^2 + \langle h\rangle^2\left[\langle w^2\rangle - \langle w\rangle^2\right] + \langle w\rangle^2\left[\langle h^2\rangle - \langle h\rangle^2\right]\right\}$$

$$= N\langle h^2\rangle\langle w\rangle^2 + N\langle h\rangle^2\langle w^2\rangle - N\langle w\rangle^2\langle h\rangle^2 \qquad (5)$$

$\sum h_i^2 w_i^2$ $N\left(\frac{1}{N}\sum w_i h_i\right)^2$

Note that if $w=1$ (unweighted events) we get

$$\sigma_X^2 = N\langle h^2\rangle = \sum_{i=1}^{N} h_i^2$$

which is the expression used in HBOOK.

Otherwise, the term $N\langle h\rangle^2\left[\langle w^2\rangle - \langle w\rangle^2\right]$ has to be added in.

Thus, to do the job properly, all the sums used in (5) must be accumulated:-

$$\left.\begin{aligned} N\langle h^2\rangle\langle w\rangle^2 &= \frac{1}{N^2}\left(\sum_{i=1}^{N} h_i^2\right)\left(\sum_{i=1}^{N} w_i\right)^2 \\ N\langle h\rangle^2\langle w^2\rangle &= \frac{1}{N^2}\left(\sum_{i=1}^{N} w_i^2\right)\left(\sum_{i=1}^{N} h_i\right)^2 \\ N\langle w\rangle^2\langle h\rangle^2 &= \frac{1}{N^{\cancel{2}3}}\left(\sum_{i=1}^{N} w_i\right)^2\left(\sum_{i=1}^{N} h_i\right)^2 \end{aligned}\right\} \qquad (6)$$

RZZ claims that for uncorrelated variables some simplifications can be made. Thus

$$N\langle w\rangle^2\langle h\rangle^2 \simeq \frac{1}{N}\left(\sum_{i=1}^{N} w_i h_i\right)^2 \qquad \text{(fair enough)}$$

But always took the time to answer any question you had

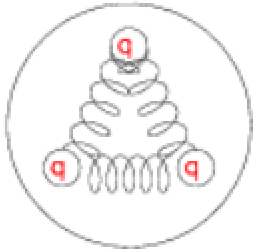
An introduction to $q\bar{q}$ mesons

Originally the quark model predicted that only two types of quark configurations were required to account for all strongly interacting particles

This description was found to be very successful in grouping the particles into multiplets of a given spin parity

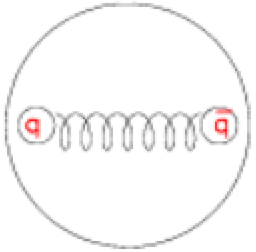
Baryons

qqq

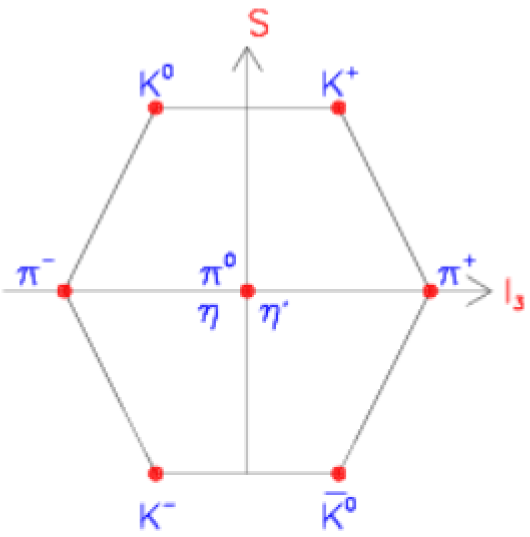


Mesons

$q\bar{q}$



For example the ground state 0^{-+} meson nonet



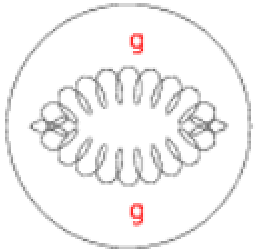
An introduction to non-$q\bar{q}$ mesons

Quantum Chromo Dynamics the field theory describing strong interactions not only describes how quarks and antiquarks interact by the exchange of gluons to form mesons

- it also predicts a rich spectrum of non-$q\bar{q}$ states

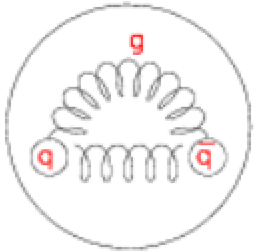
Glueballs

gg, ggg



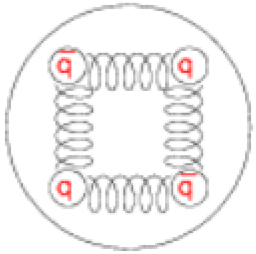
Hybrids

$q\bar{q}g$



4-quark states etc

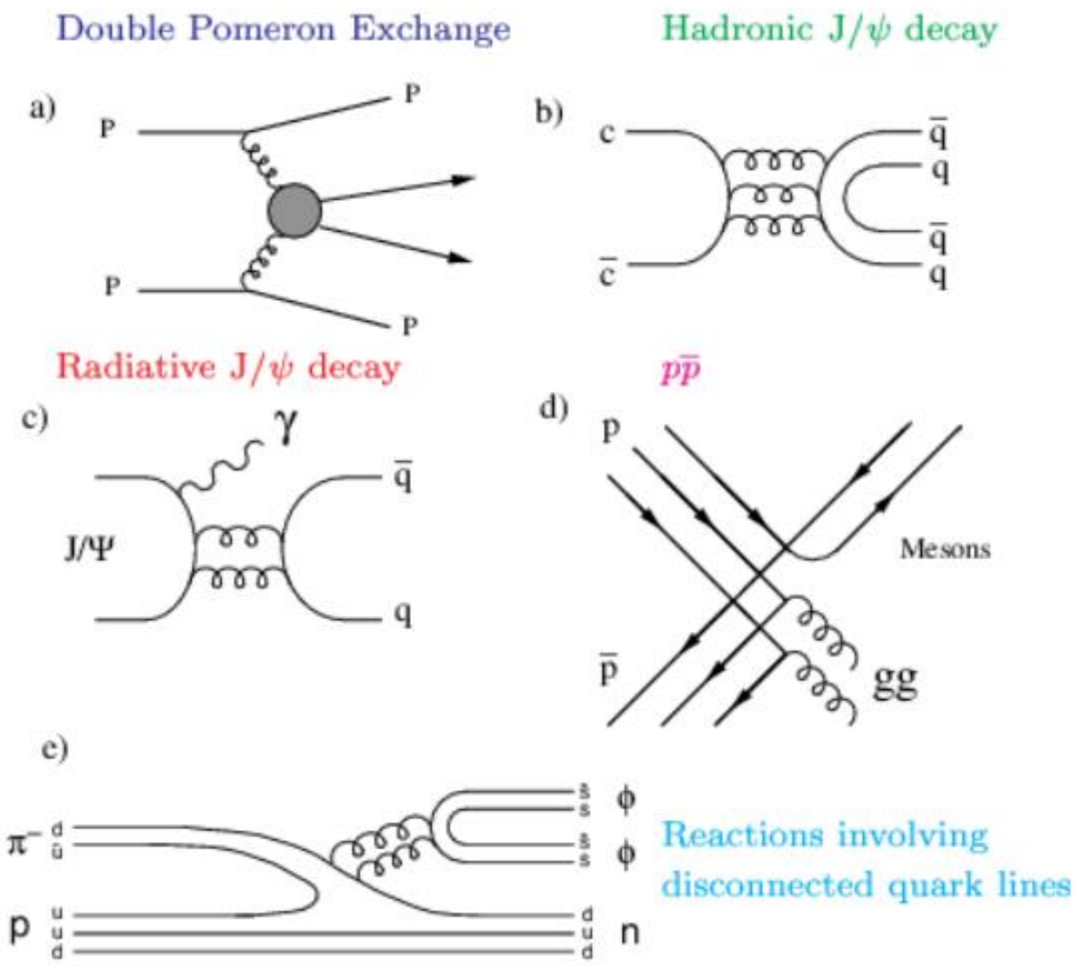
$q\bar{q}q\bar{q}$



How to look for non-$q\bar{q}$ mesons

1) Look for Oddballs
    - states with J^{PC} not allowed for $q\bar{q}$ states i.e. 1^{-+}
2) Look for extra states
    - states with quantum numbers of an already completed nonet
3) Look for states with unusual branching ratios
4) Look for states preferentially produced in gluon rich processes

Gluon rich processes



Mass estimates

Naive estimates from the Bag model in the late 1980s predicted the lightest glueball

$M_{gg}(0^{++}) = 1$ GeV

$M(2^{++})/M(0^{++}) = 1.5$

However, Lattice Gauge calculations that began producing results in the mid-90’s predicted

and that depending on the choice of constants

$M(0^{++}) = 1500 - 1750$ MeV

The ggg states are higher in mass
and the lightest $q\bar{q}$ hybrid had

$M(q\bar{q}g) > 1.9$ GeV

So the lightest glueball was predicted to be in the middle of the ground state $q\bar{q}$ nonet

Progress in the search for glueballs and new understanding

In the 1990s theoretical progress was made on understanding how the bare $q\bar{q}$ states mix with glueballs to give the observed mesons

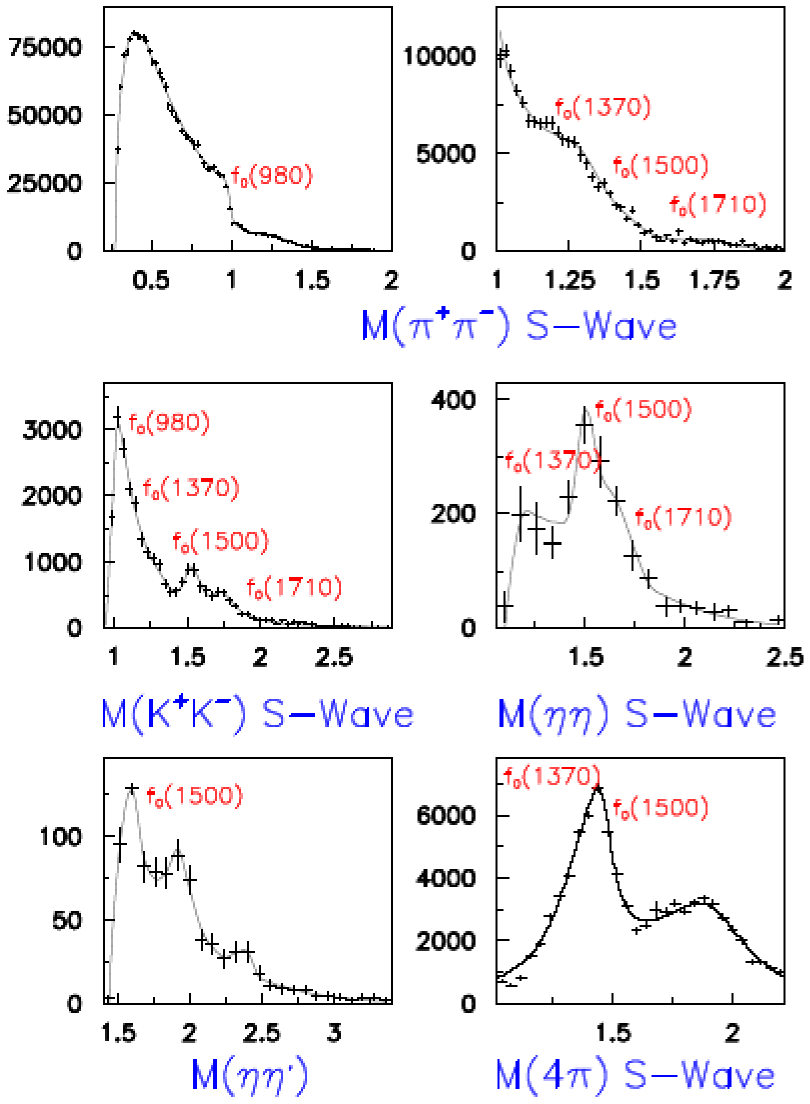
The original picture was

However glueballs with the same J^{PC} as nearby $q\bar{q}$ states will mix

Depending on the mass difference the observed states will be a mixture of $u\bar{u} + d\bar{d}$, $s\bar{s}$ and gg - hence flavour blind decays are no longer expected BUT an excess of states was

Need to measure the states and their dominant decay modes

Observation of scalar mesons around 1.5 GeV/c^2 by Omega



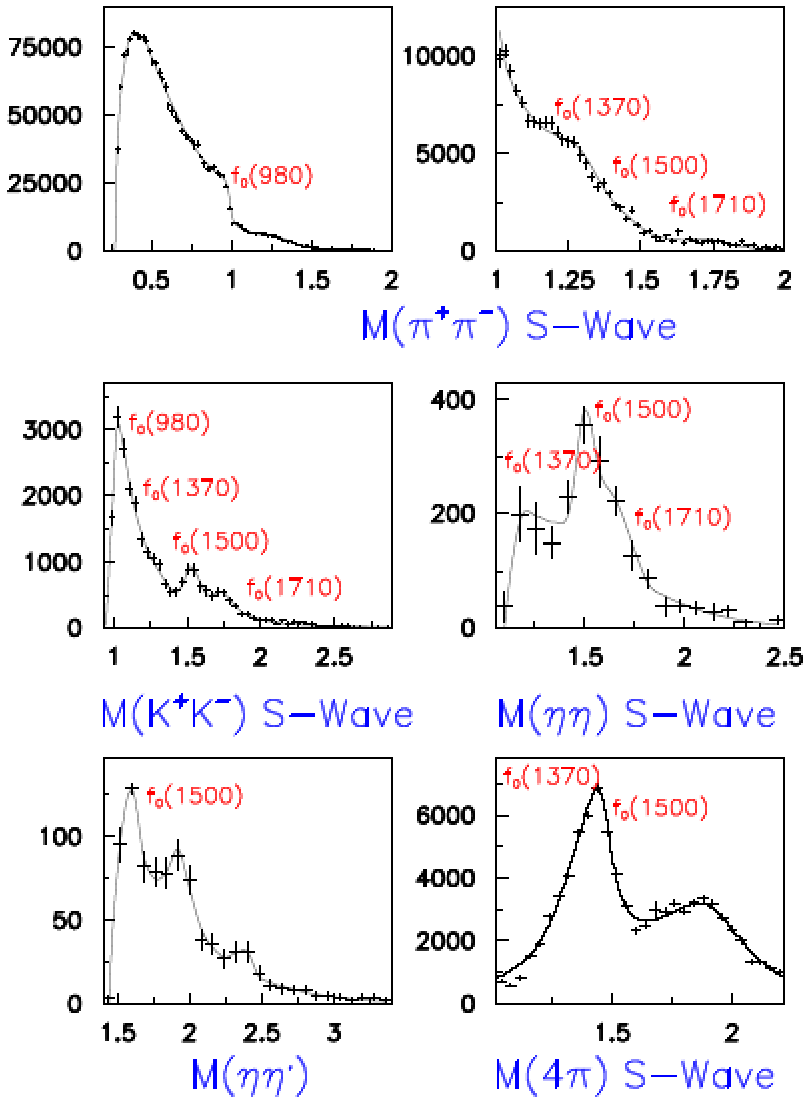
The Omega experiments helped to establish the $J^{PC}=0^{++}$ states in the glueball region and measure their decay parameters

$f_0(1370)$ $f_0(1500)$ $f_0(1710)$

3 states observed

2 $q\bar{q}$ states predicted

Observation of scalar mesons around 1.5 GeV/c^2 by Omega



Assuming the missing is strongest between the glueball and nearest $q\bar{q}$ states

The three physical states can be expressed as:

$$\begin{pmatrix} |f_0(1710)\rangle \\ |f_0(1500)\rangle \\ |f_0(1370)\rangle \end{pmatrix} = \begin{pmatrix} x_1 & y_1 & z_1 \\ x_2 & y_2 & z_2 \\ x_3 & y_3 & z_3 \end{pmatrix} \begin{pmatrix} |G\rangle \\ |S\rangle \\ |N\rangle \end{pmatrix}$$

Where x,y and z can be determined from a fit to the partial widths

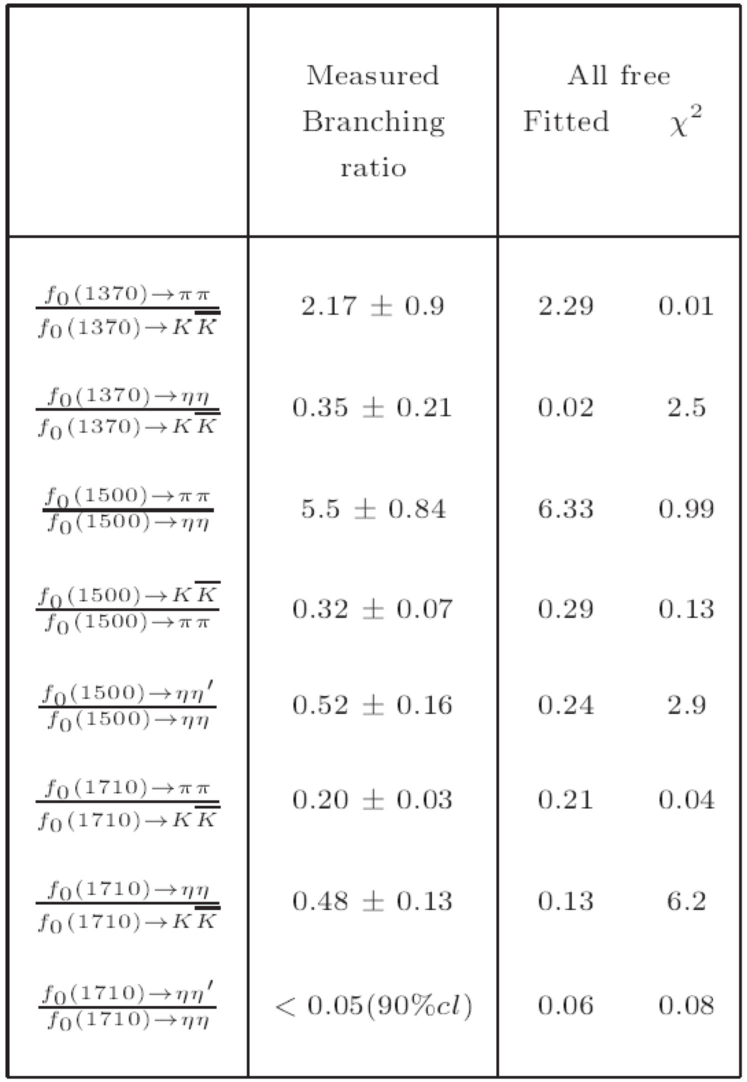
Gluonic content of scalar mesons around 1.5 GeV/c^2

The parameters determined by the fit were:

M_G	1446±16	MeV
M_S	1664±9	MeV
M_N	1374±28	MeV

With the physical states being

|f0(1370)> = (0.65±0.08)|G> - (0.15±0.04)|S> - (0.73±0.09)|N>
|f0(1500)> =-(0.61±0.07)|G> + (0.37±0.06)|S> - (0.69±0.08)|N>
|f0(1710)> = (0.42±0.14)|G> + (0.89±0.12)|S> - (0.17±0.08)|N>



	Measured Branching ratio	All free	
		Fitted	χ^2
$\frac{f_0(1370)\to\pi\pi}{f_0(1370)\to K\overline{K}}$	2.17 ± 0.9	2.29	0.01
$\frac{f_0(1370)\to\eta\eta}{f_0(1370)\to K\overline{K}}$	0.35 ± 0.21	0.02	2.5
$\frac{f_0(1500)\to\pi\pi}{f_0(1500)\to\eta\eta}$	5.5 ± 0.84	6.33	0.99
$\frac{f_0(1500)\to K\overline{K}}{f_0(1500)\to\pi\pi}$	0.32 ± 0.07	0.29	0.13
$\frac{f_0(1500)\to\eta\eta'}{f_0(1500)\to\eta\eta}$	0.52 ± 0.16	0.24	2.9
$\frac{f_0(1710)\to\pi\pi}{f_0(1710)\to K\overline{K}}$	0.20 ± 0.03	0.21	0.04
$\frac{f_0(1710)\to\eta\eta}{f_0(1710)\to K\overline{K}}$	0.48 ± 0.13	0.13	6.2
$\frac{f_0(1710)\to\eta\eta'}{f_0(1710)\to\eta\eta}$	$< 0.05(90\%cl)$	0.06	0.08

Gluonic content of scalar mesons around 1.5 GeV/c^2

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$|f0(1500)\rangle = -(0.61\pm0.07)|G\rangle + (0.37\pm0.06)|S\rangle - (0.69\pm0.08)|N\rangle$
$|f0(1710)\rangle = (0.42\pm0.14)|G\rangle + (0.89\pm0.12)|S\rangle - (0.17\pm0.08)|N\rangle$

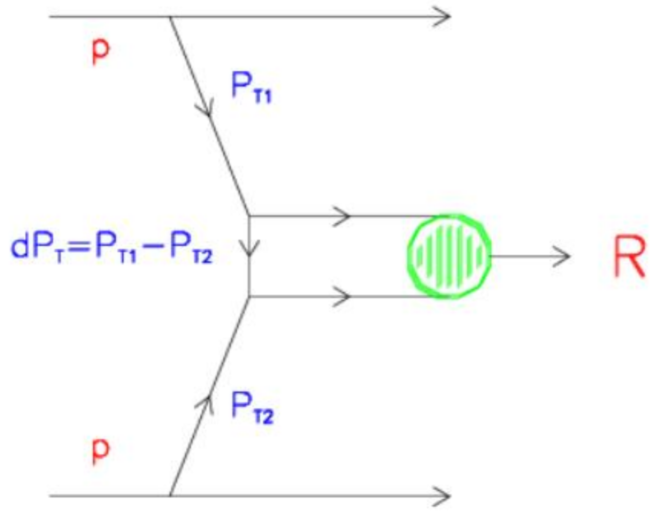
Gave predictions for relative productions rates in $\gamma\gamma$, $p\bar{p}$ and J/Ψ decays

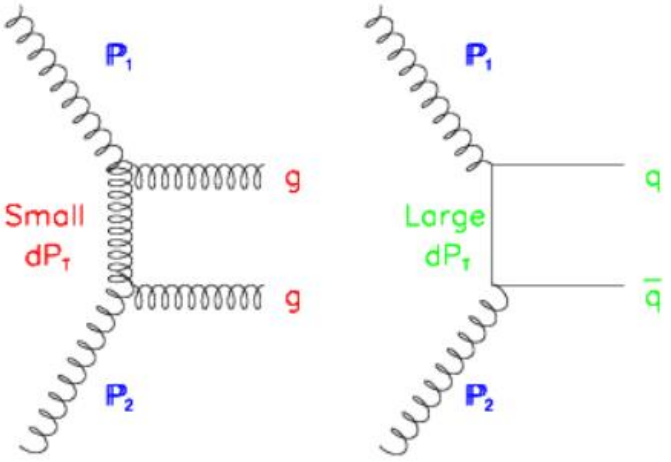
All the data that was available was consistent with the proposed mixing

Glueball-$q\bar{q}$ filter

Of course what you would really like is a filter that selected out states with high glue content from the $q\bar{q}$ states

i.e. a way of coupling the pomerons to the gluon component



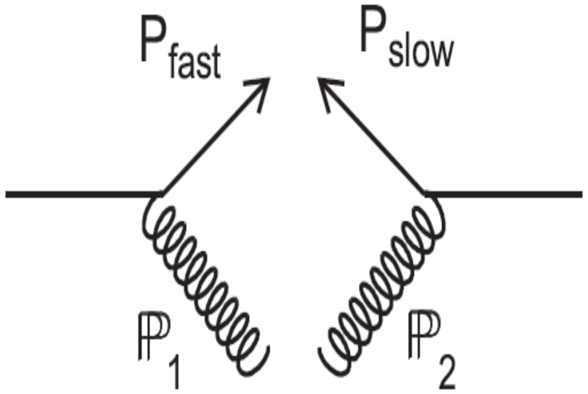


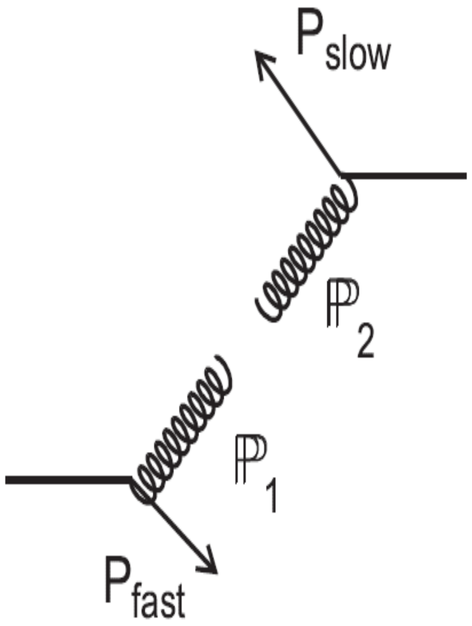
Glueball $q\bar{q}$ filter

Actually we stumbled across such an effect with the way the trigger was arranged with either like or opposite sided protons

Small dP_T
(like sided protons)

Large dP_T
(opposite sided protons)





Enabled by the new L2 triggers implemented in WA91/WA102 to increase the statistics

Glueball $q\bar{q}$ filter

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Small dP_T
(like sided protons)

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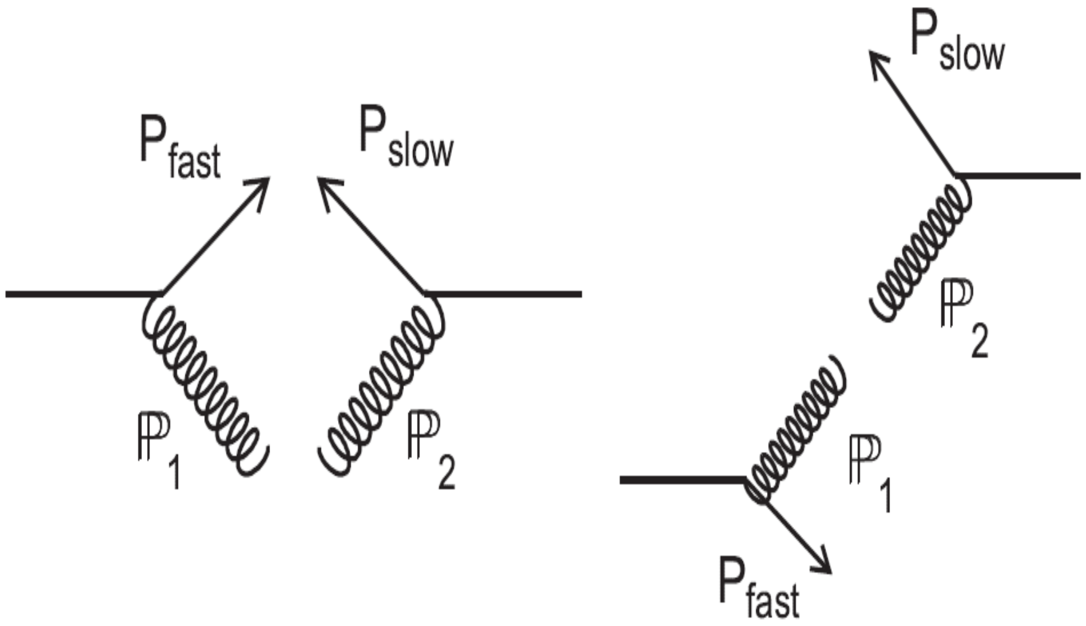
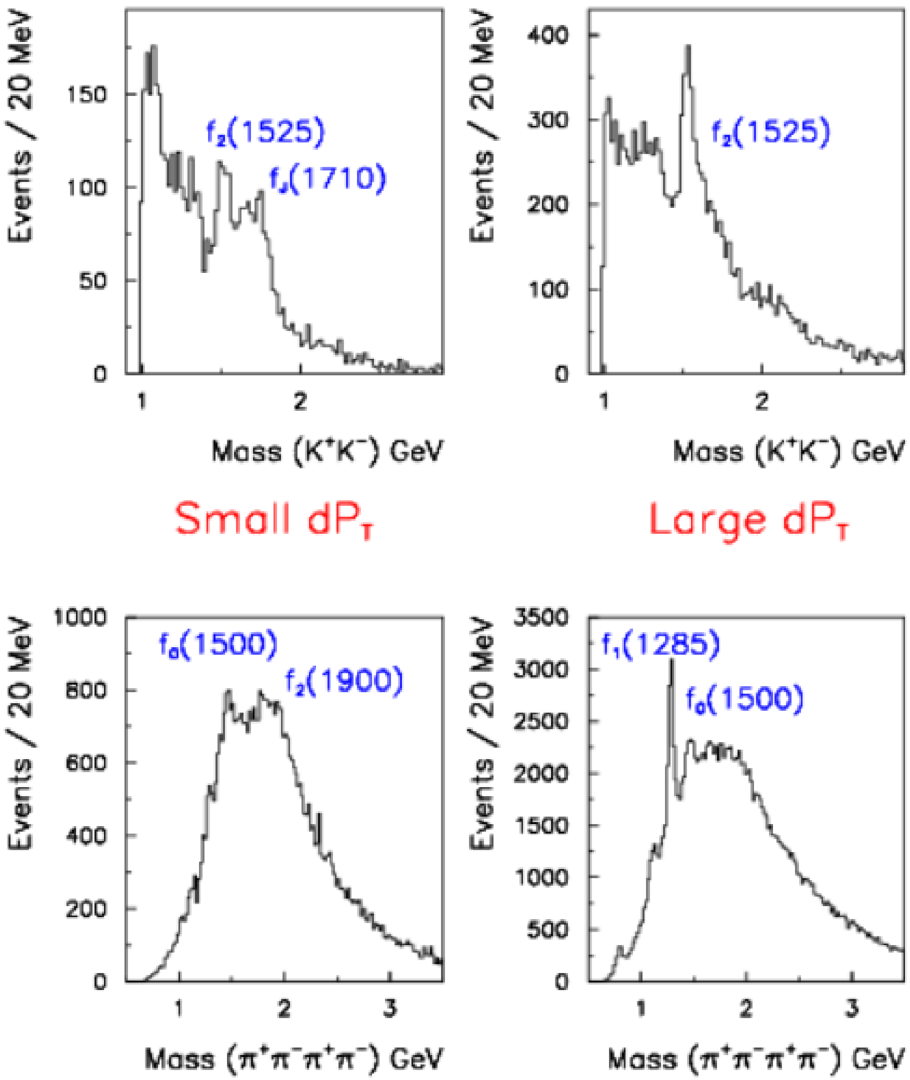


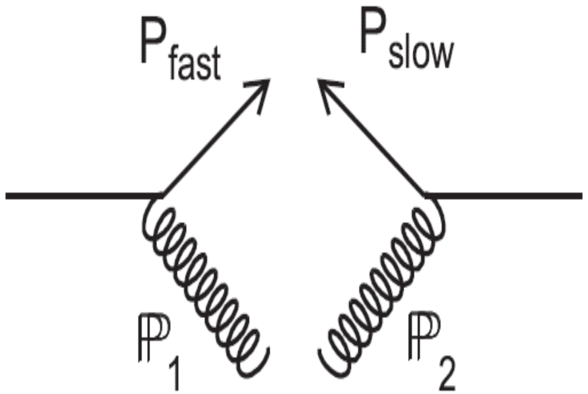
The known $q\bar{q}$ states were at high dP_T



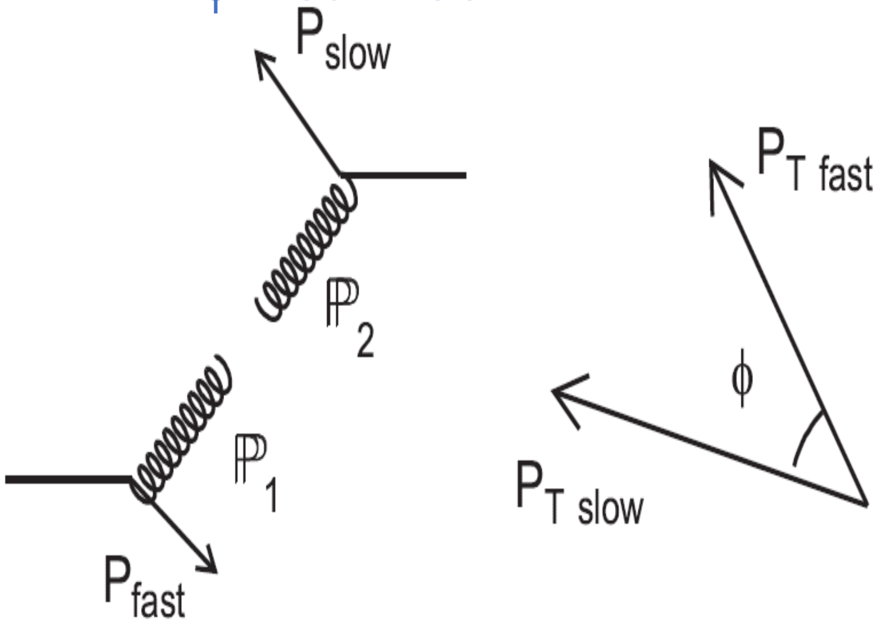
Glueball $q\bar{q}$ filter

It was realised that another way to look at dP_T is in terms of the angle ϕ between the protons but the pomeron was traditionally spoken about as being a scalar particle
if J=0 then the ϕ would be flat

Small dP_T
(like sided protons)
ϕ Near 0



Large dP_T
(opposite sided protons)
ϕ Near 180

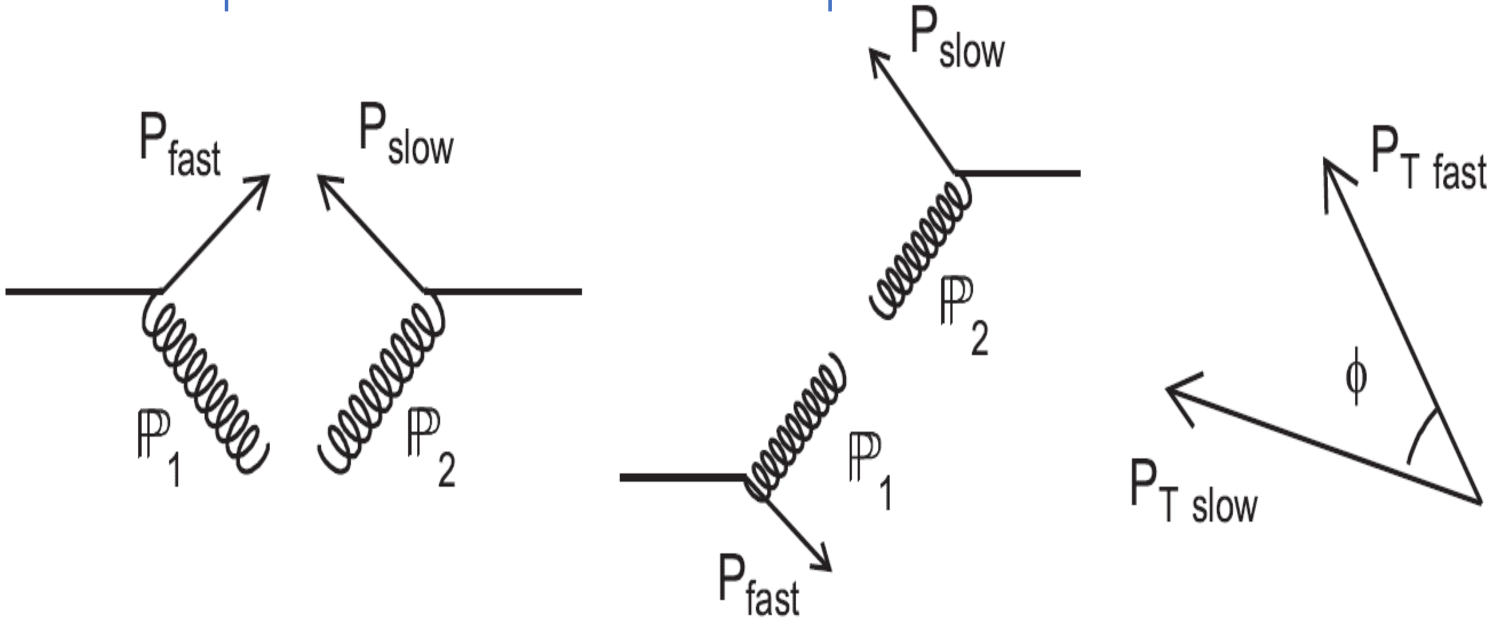


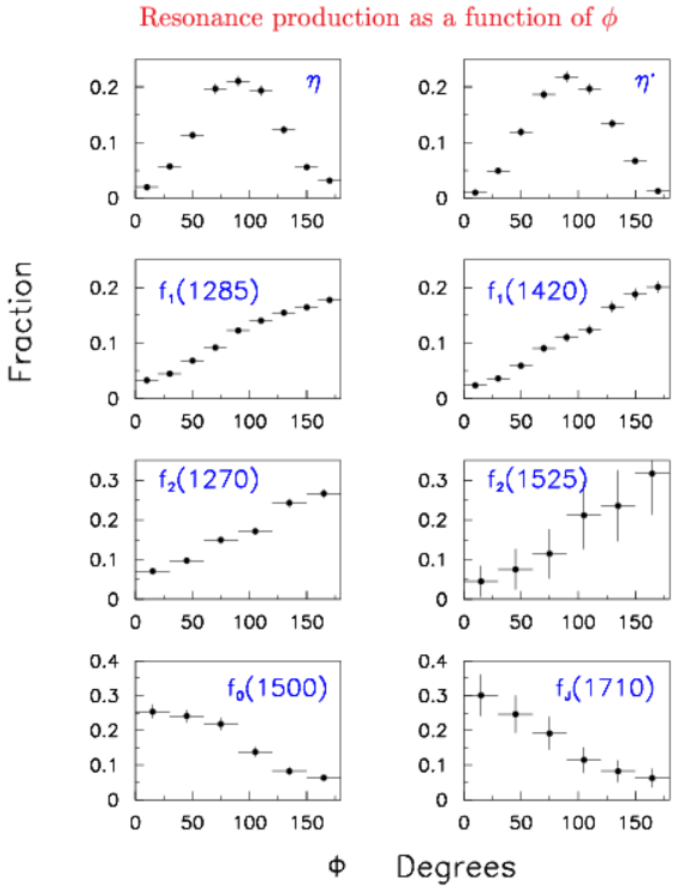
Glueball q$\bar{q}$ filter

But the observed ϕ distributions were anything but flat and were resonant dependent

Small dP$_T$
(like sided protons)
ϕ Near 0

Large dP$_T$
(opposite sided protons)
ϕ Near 180

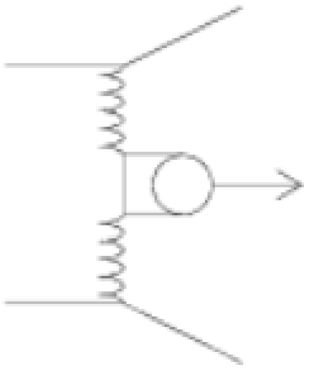




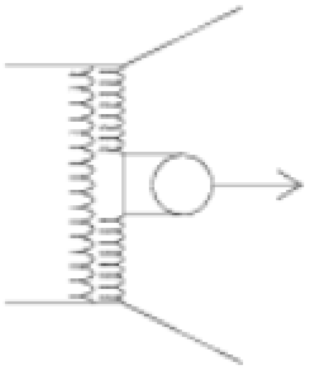
The pomeron as a vector particle

Using γ*γ* as an analogy Close and Schuler developed a model for pomeron exchange based on the pomeron transforming as a non-conserved vector current

$e^+e^- \rightarrow e^+e^-R$



$pp \rightarrow ppR$



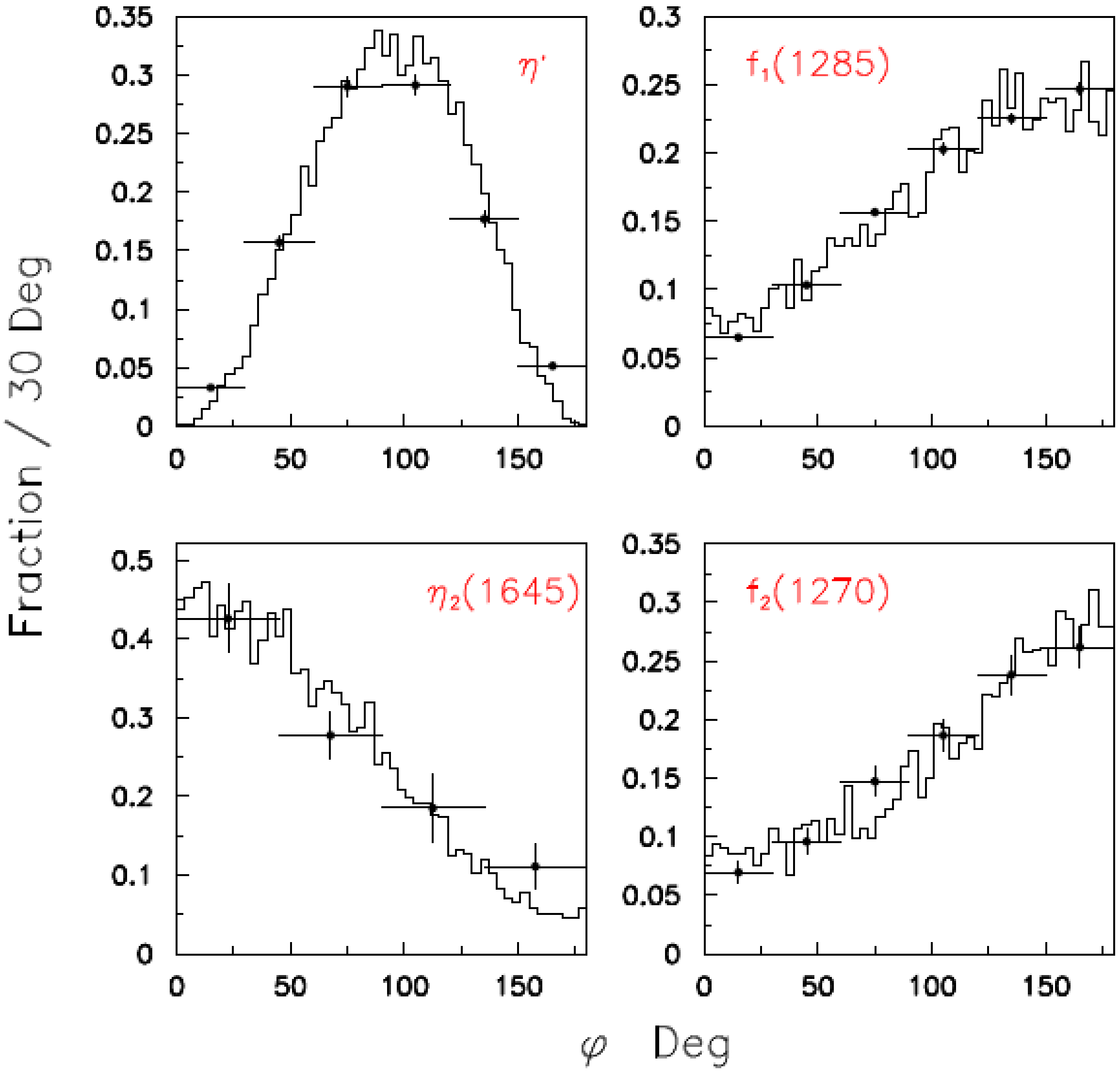
$$\frac{d\sigma}{dt_1 dt_2 d\phi'} \sim G_E^{p\,2}(t_1) G_E^{p\,2}(t_2) F^2(t_1, t_2, M^2) A(t_1, t_2, \phi')$$

where $G_E(t)$ is the proton- $\mathbb{P}$ form factor

$A(t_1, t_2, \phi')$ is the prediction for the interaction of two Pomerons acting like non-conserved vector currents

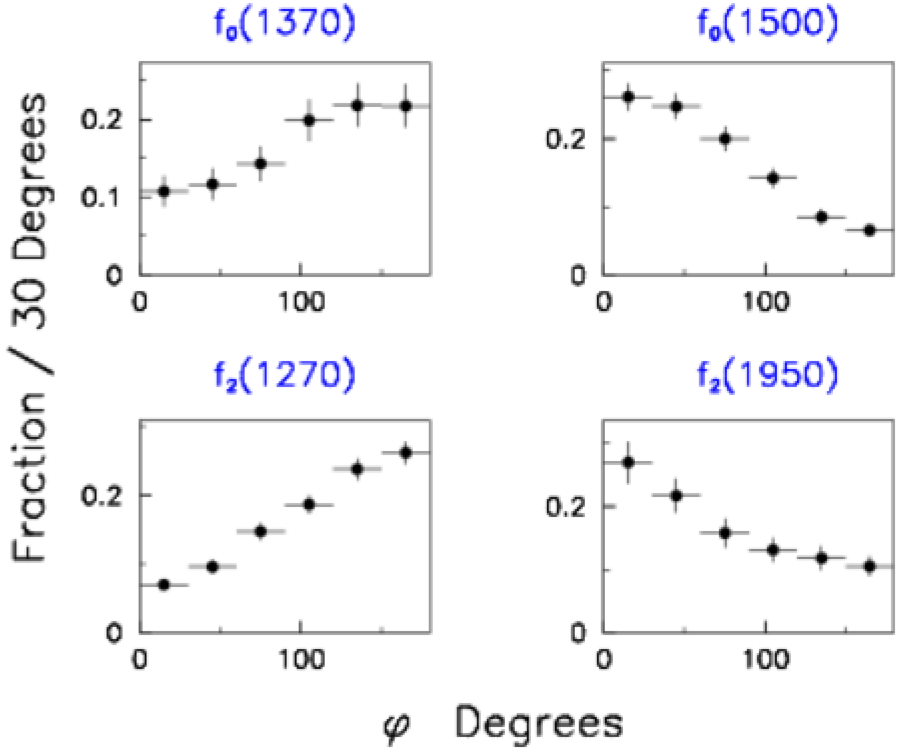
and $F^2(t_1, t_2, M^2)$ is the $\mathbb{P}$- $\mathbb{P}$-Meson form factor

Data and model predictions for known $q\bar{q}$ states



All the effects are consistent with a vector like behaviour of the exchanged pomeron with $J_Z=1$

But its not just a J^{PC} of the meson effect

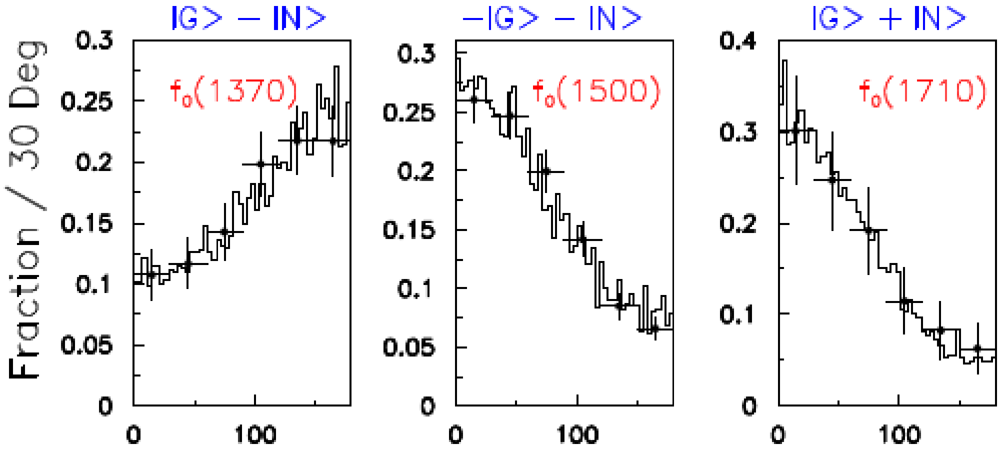


In addition to the properties of the Pomeron the distributions are sensitive to the underlying constituents of the mesons

In particular the coupling of the Pomeron to either the $n\bar{n}$ or gg component of the meson

Pomeron coupling to glue

The scalar sector



In particular the coupling of the Pomeron to either the $n\bar{n}$ or gg component of the meson

Consistent with the previously determined constituents of these mesons determined from their decay properties

Summary: How Omega helped to establish the existence of non-$q\bar{q}$ mesons

The Omega experiments WA76, WA91 and WA102 played a vital roles in establishing the existence of the scalar mesons

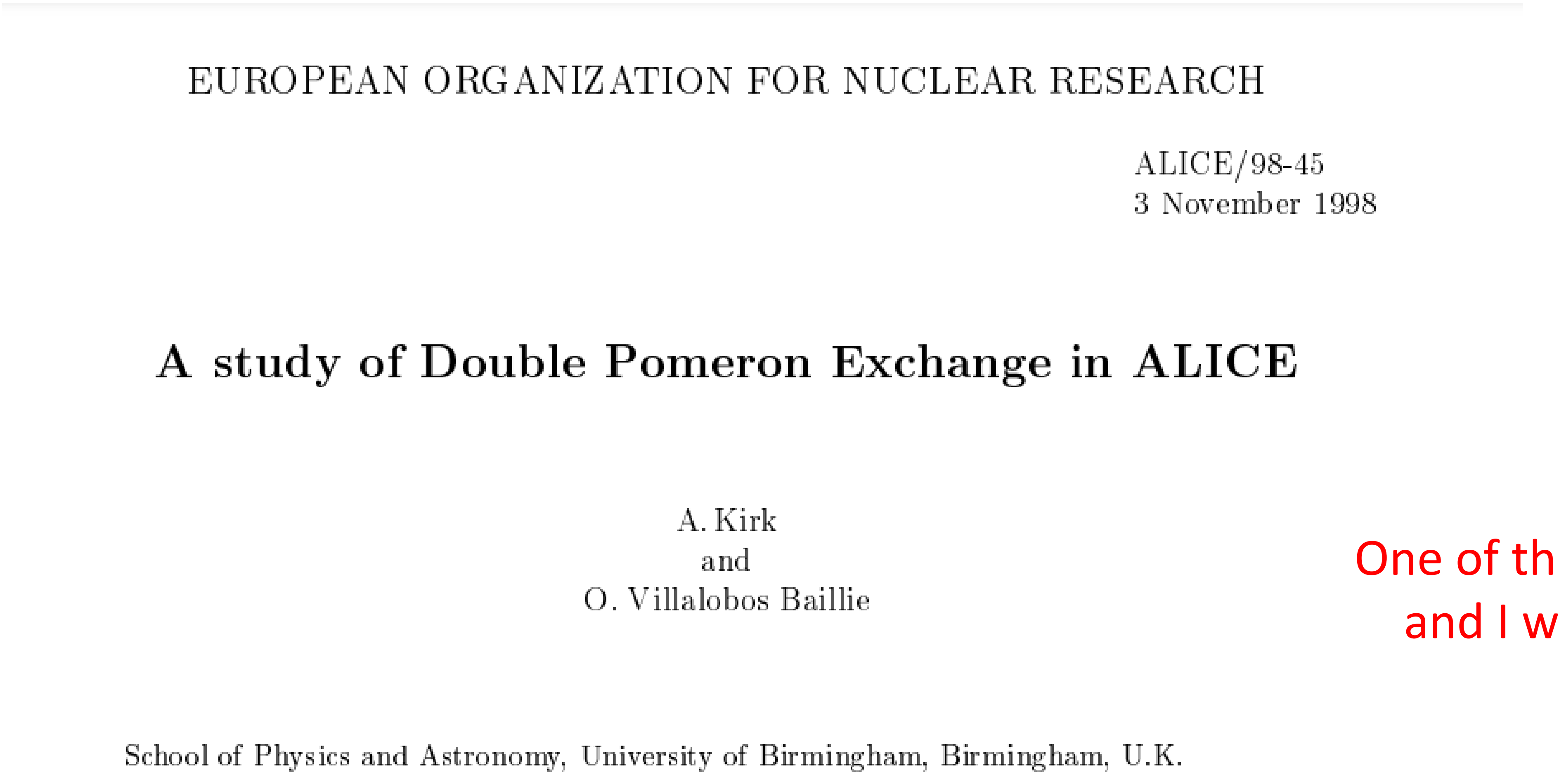
$f_0(1370)$, $f_0(1500)$ and $f_0(1710)$

and accurately measured their decays

The results showed that these states are consistent with being due to mixing between the scalar $q\bar{q}$ nonet and the scalar glueball

The solution found was consistent with other known measurements

An interesting kinematic filter was discovered due to the new triggers implemented which led to information on the nature of the Pomeron and how it couples to the $n\bar{n}$ or gg components of the central states



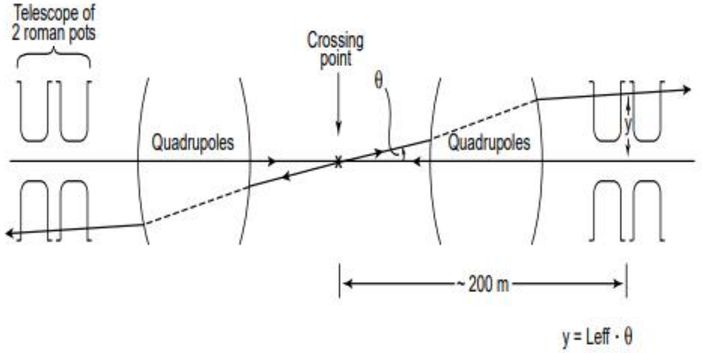
EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

ALICE/98-45
3 November 1998

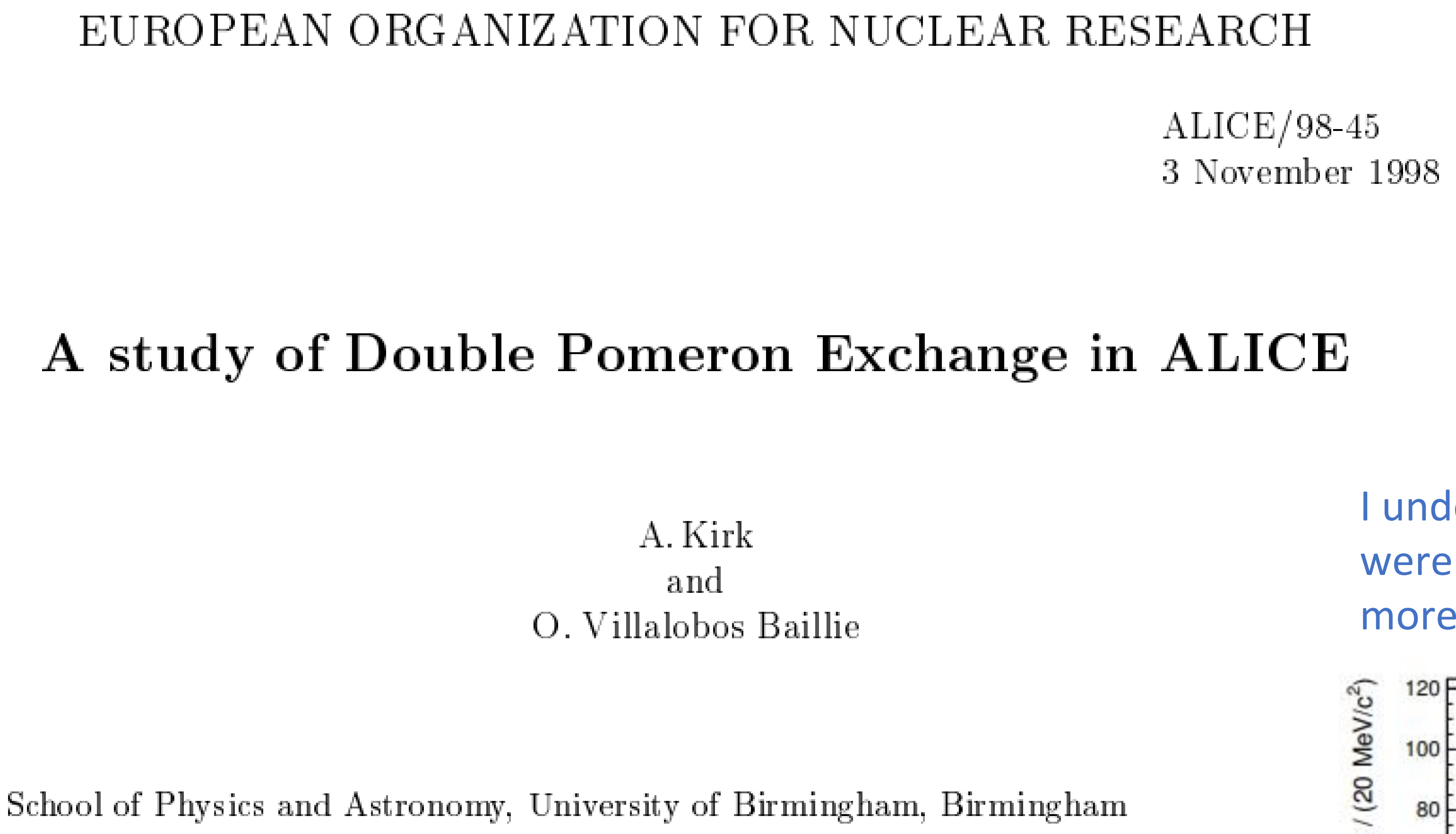
A study of Double Pomeron Exchange in ALICE

A. Kirk
and
O. Villalobos Baillie

School of Physics and Astronomy, University of Birmingham, Birmingham, U.K.



One of the last things Orlando and I worked on together



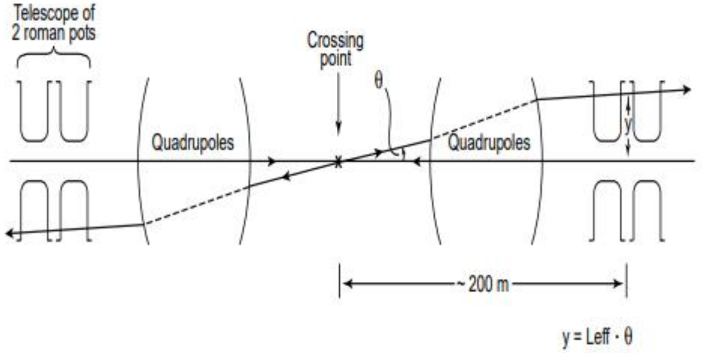
EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

ALICE/98-45
3 November 1998

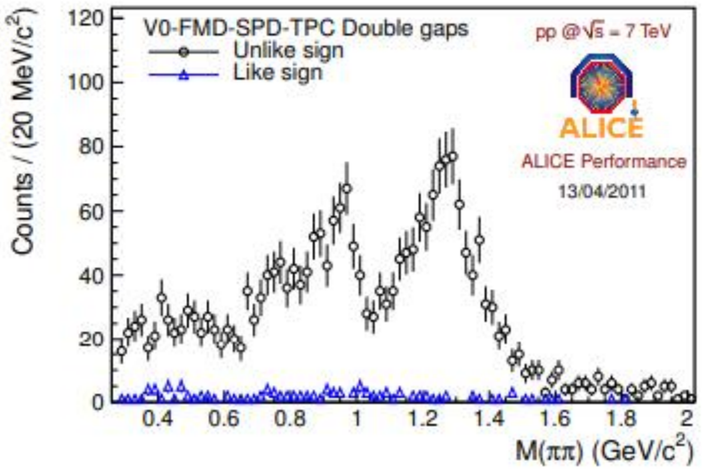
A study of Double Pomeron Exchange in ALICE

A. Kirk
and
O. Villalobos Baillie

School of Physics and Astronomy, University of Birmingham, Birmingham



I understand some measurements were made and Id like to know more….



https://doi.org/10.48550/arXiv.1110.3693

The Omega experiments Orlando was involved in:

WA76 WA91 WA102	**non-$q\bar{q}$ mesons**
WA77	**Higher twist QCD processes**
WA83	**Soft photons**
WA85 WA97	**Heavy ions**

It was a pleasure to work with Orlando and even 25 years on I fondly remember the times we spent working together

Thank you for all your advice, help and support through those years and best wishes for your retirement