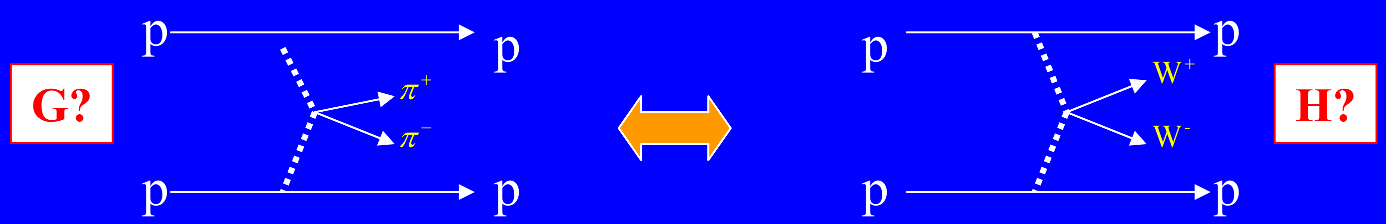
Exclusive Central Production in Proton-Proton Collisions:
from the ISR to the Tevatron to the LHC

Mike Albrow
Fermilab

Exclusive Central Production in Proton-Proton Collisions: from Glueballs to Higgs Bosons

Mike Albrow (Fermilab)

ISR – Tevatron -- LHC



1) Introduction

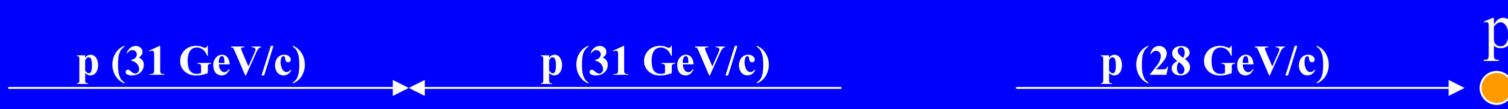
2) Diffractive Excitation of High Masses (Jets,W,Z) – CDF/D0

3) Central Exclusive Production:

$$(\pi^+\pi^-, K^+K^-, p\bar{p}) \longrightarrow e^+e^-, \mu^+\mu^-, J/\psi/\psi(2S), Y, JJ$$

4) LHC: Study of Higgs through p+H+p, WW and ZZ, Excl.Z? FP420: R&D project; proposing extensions to ATLAS & CMS.

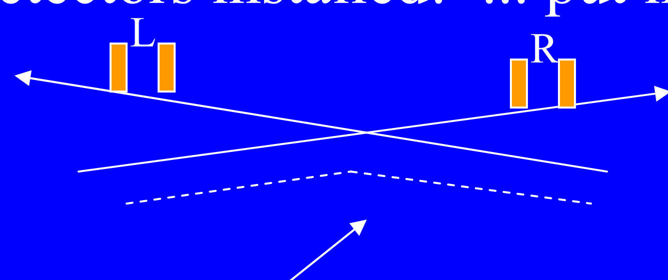
ISR = Intersecting Storage Rings, started 1971
First colliding proton beams.

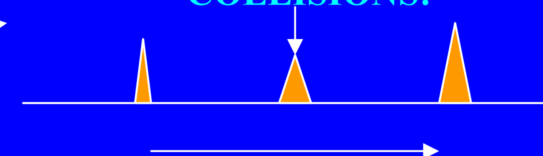


Centre of Mass Energy = 63 GeV **Centre of Mass Energy = 7.4 GeV**

Equivalent to beam of 2110 GeV + fixed p target
"Into the realm of cosmic rays!"

First collisions ... no detectors installed! ... put in 4 counters!





Experiment 101

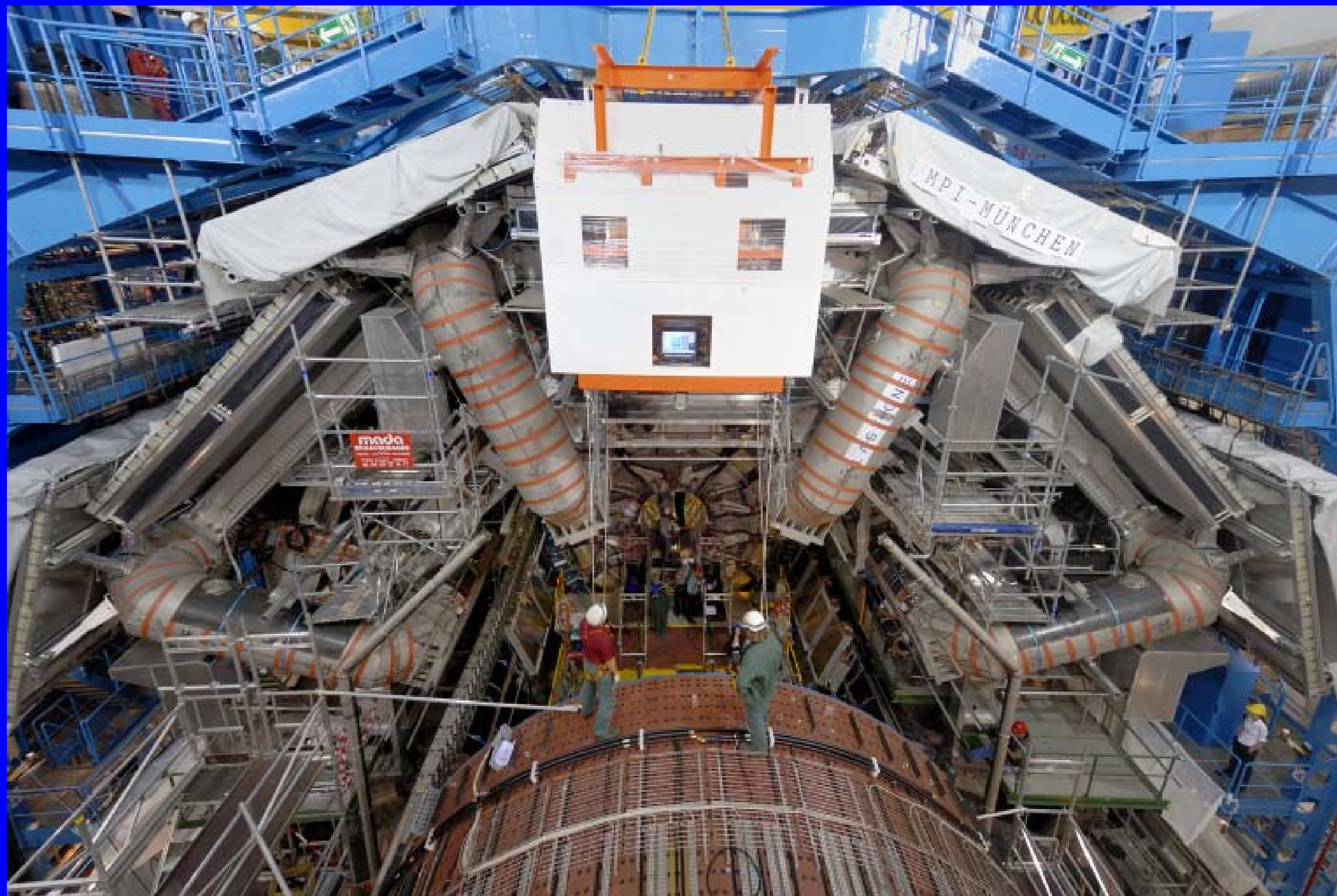
Emulsions on a toy train set!

2008: LHC = Large Hadron Collider

$\equiv 10^{8}\,\text{GeV} = 10^{17}\,\text{eV}$

7 TeV = 7000 GeV → ← 7 TeV = 7000 GeV

cf. cosmic cut off $\approx 10^{20}$ eV

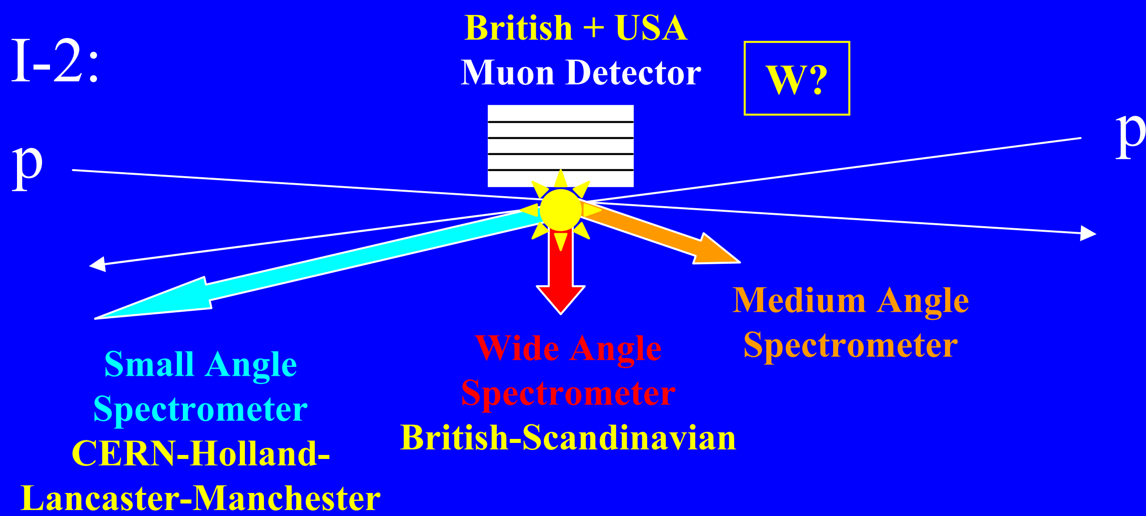


ATLAS ~ 2500 physicists!

One of four experiments.

Meanwhile, back at the ISR in 1972 ...

Intersection I-2:



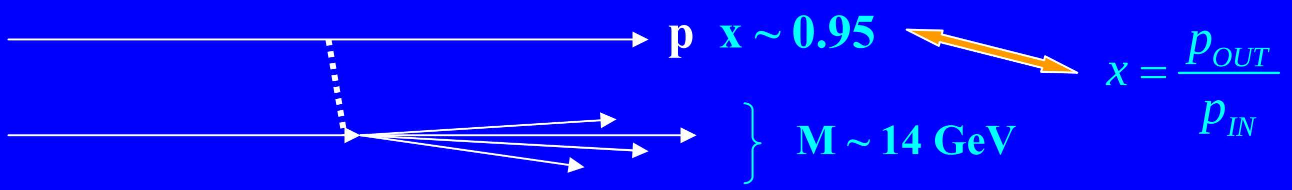
Nobody knew what to do with complete multi-particle (~ 10+) final states.

Study "inclusive" particle production: pp → e, μ, π, K, p ...+ "anything".

Muon Detector: Looking for W(~3-4 GeV!) ... missed J/ψ

Wide Angle Spectrometer: co-discovered high p_T (quark scattering)

Small Angle Spectrometer: discovered high mass (14 GeV) diffraction



Small Angle Spectrometer: Forward proton spectra

$$x_{Feynman} = \frac{p_L}{p_{beam}}$$

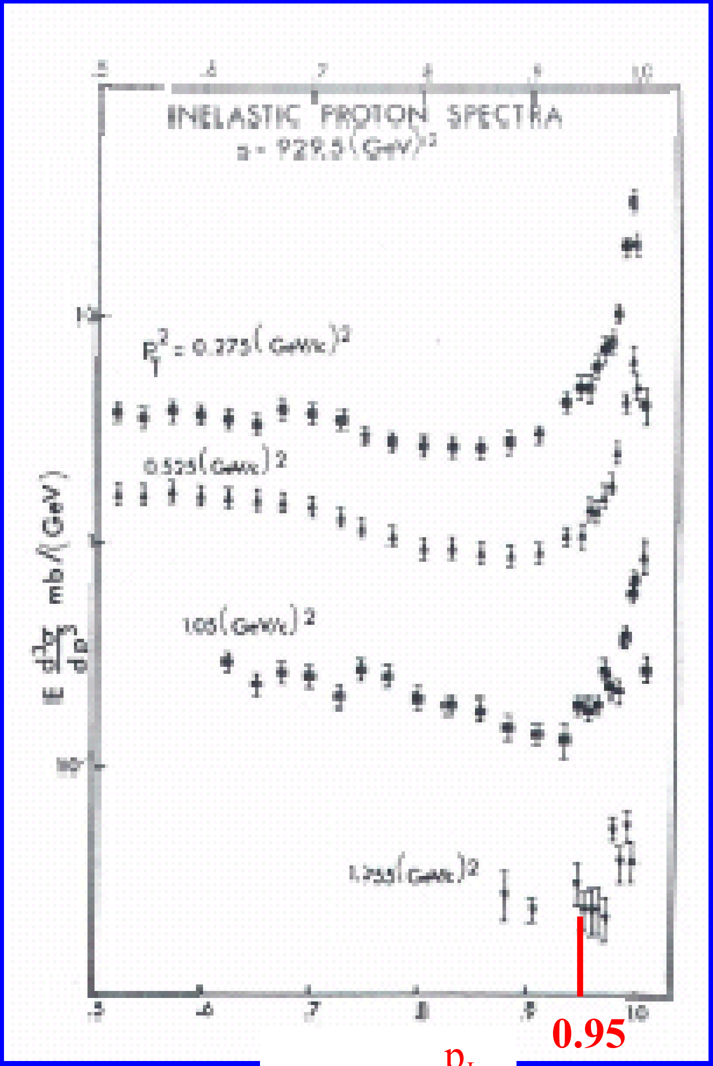
Feynman scaling:

$$E\frac{d^3\sigma}{dp^3} = f(x_F, p_T) \text{ not } \sqrt{s}$$

Discovery of high-x, scaling peak

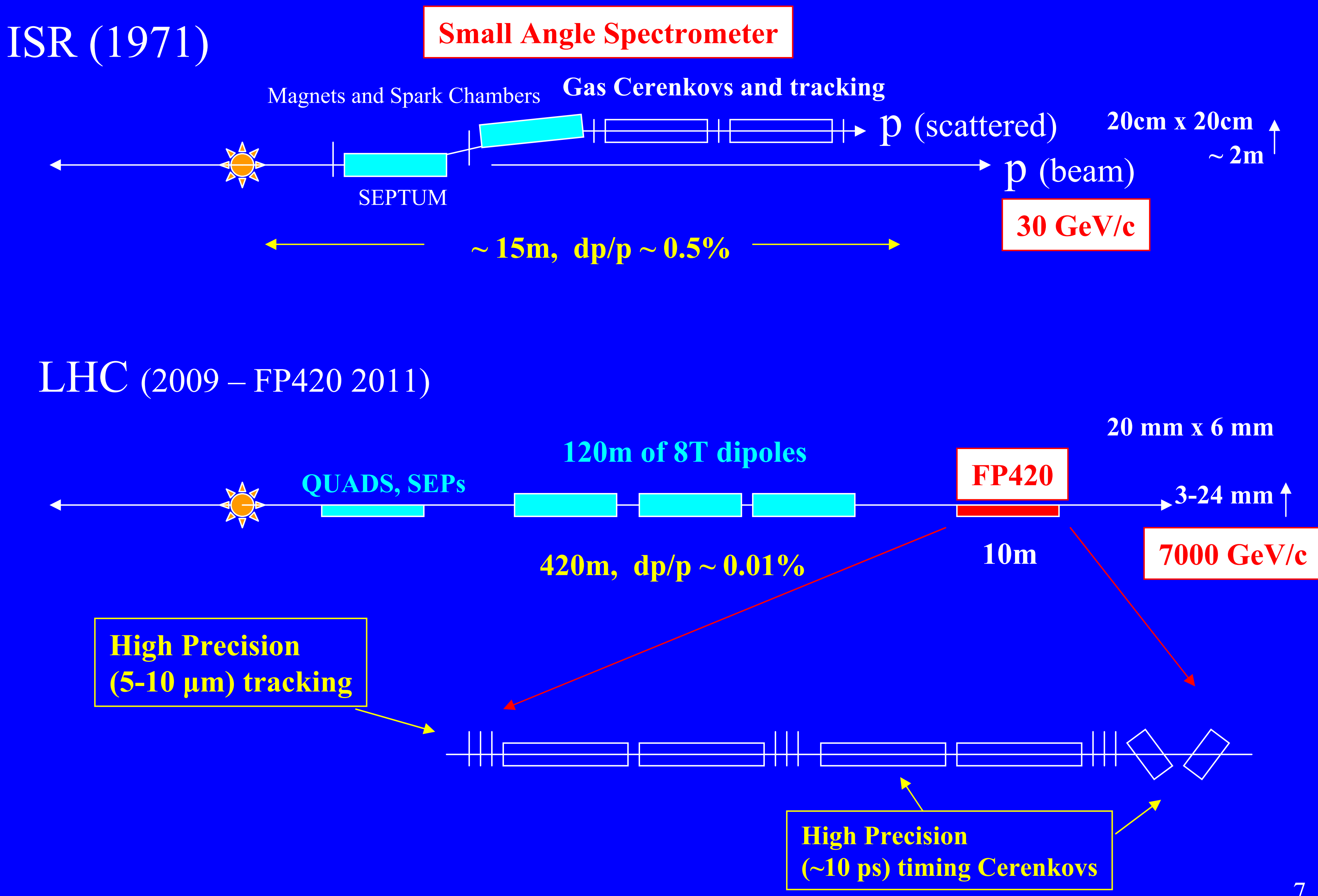
$M < \sqrt{0.05}\sqrt{s} = 0.22\sqrt{s}$

M up to about 1.6 GeV at AGS/PS
14 GeV at ISR
440 GeV at Tevatron
3100 GeV at LHC



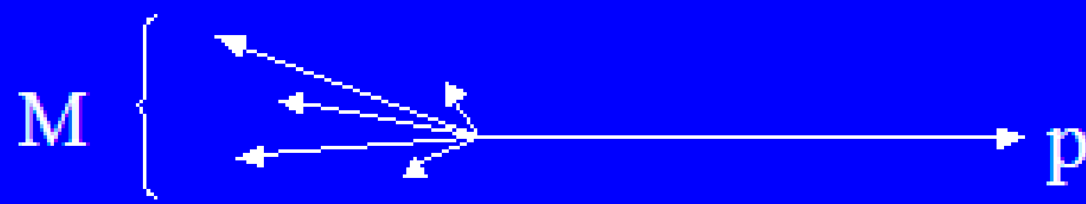
$$x_{Feynman} = \frac{p_L}{p_{beam}}$$

Forward Proton Spectrometers: ISR → LHC



Central Diffractive Excitation

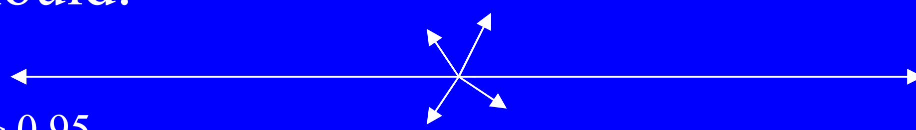
Theoretically
(Regge theory)
if:



$M < \sqrt{0.05}\sqrt{s} = 0.22\sqrt{s}$

$x > 0.95$

happens, so should:

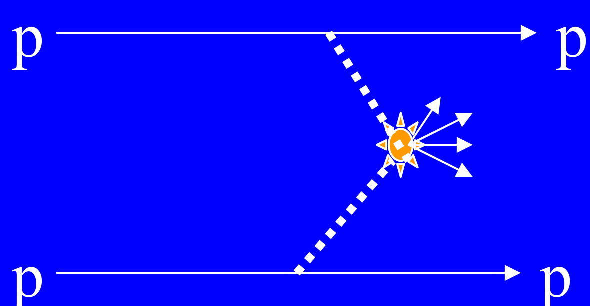


$x > 0.95$ $x > 0.95$

$M < 0.05\sqrt{s}$

… both protons coherently scattered

H,WW → **M up to about 3 GeV at ISR**
100 GeV at Tevatron
700 GeV at LHC



"Vacuum Excitation"

Exchanged 4-momentum must
have no electromagnetic charge
or strong charge (colour), **& spin >=1**

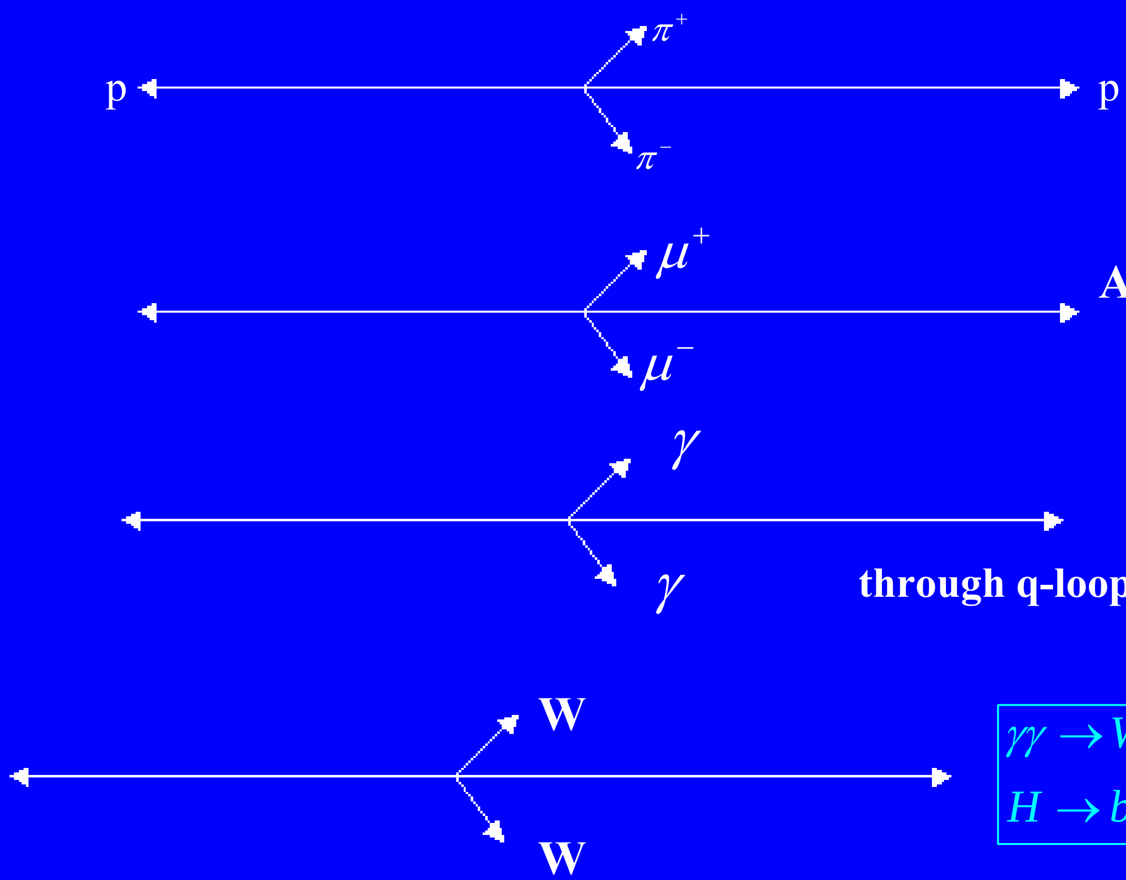
γ or $g\ (+g,\ gg)$ = **IP (pomeron)**

Central state Quantum Numbers restricted.

W/Z exchange allowed, but p would break up

Central Exclusive Production

pp → p X p where X is *a simple system completely measured*



At CERN ISR
Glueball Search

At Tevatron & LHC

$$\gamma\gamma \rightarrow \mu^+\mu^-$$

$$\gamma\, IP \rightarrow \psi, \Upsilon \rightarrow \mu^+\mu^-$$

$$gg \rightarrow \gamma\gamma$$

through q-loops (box) + colour bleaching (g)

$$\gamma\gamma \rightarrow WW;\ H \rightarrow WW,\ H \rightarrow ZZ$$
$$H \rightarrow b\bar{b};\ BSM \rightarrow WW,\ SUSY\ etc$$

Central Exclusive Production in Different Machines

In e^+e^- collisions (through LEP energies → I L C) :
$\gamma\gamma \to l^+l^-, q\bar{q}$ → hadrons, and at high (ILC) energy:
WW → WW, WW → Z,H ; WZ → W

....

In ep collisions (HERA) :
gamma-IP → vector mesons $\rho, \phi, J/\psi, \Upsilon$
$\gamma\gamma \to l^+l^-$ ($q\bar{q}$ too but buried?)

....

In pp ($p\bar{p}$) (ISR → Tevatron and LHC) :
IP IP → hadrons (can be single hadron), q-loop →Higgs, γ γ
γ -IP → vector mesons (.. ψ, ψ' ,Y, Z(allowed but tiny)?)
γ γ → **l+l-** ($q\bar{q}$ too but buried?)

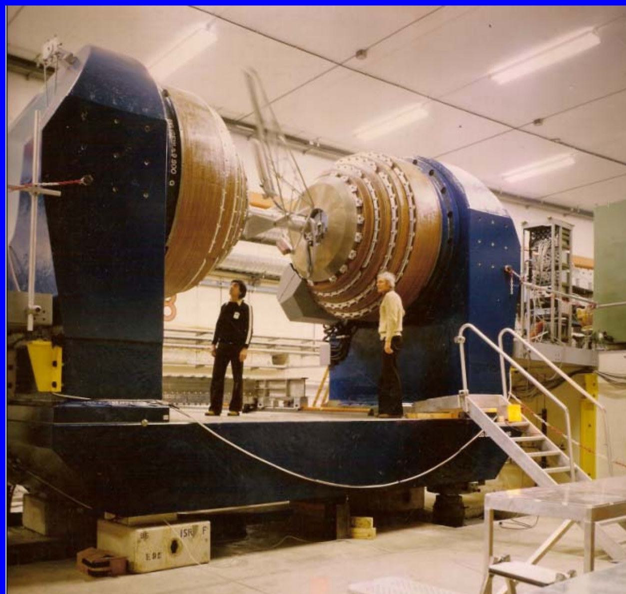
New in CDF

....

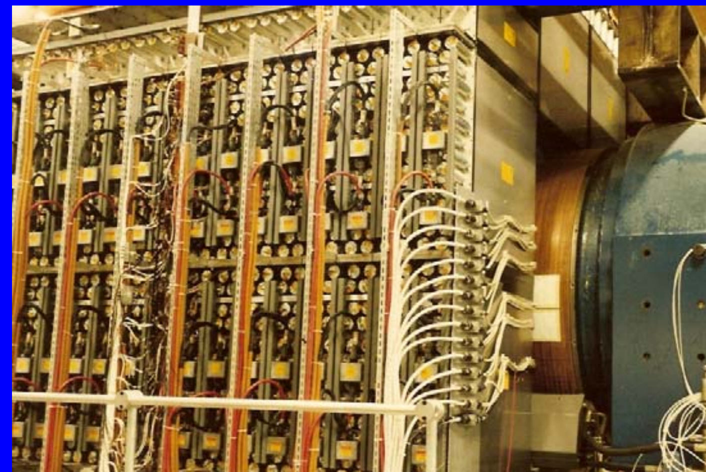
In AA (RHIC, LHC) mainly $\gamma\gamma \to l^+l^-$ (E-fields)
γ -IP and IP+IP

ISR: Axial Field Spectrometer (R807)

First sophisticated high-pT spectrometer in pp. Forerunner of p-pbar collider experiments.



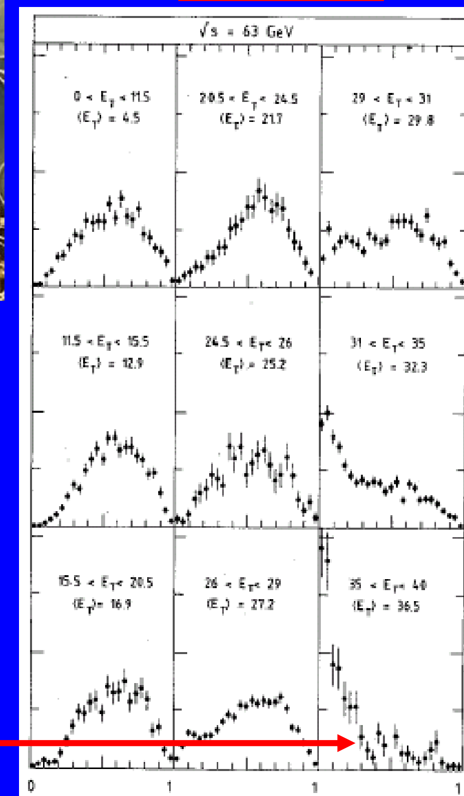
Axial Field Magnet
(~Helmholtz coils)



Uranium-scintillator
full-azimuth calorimeter
37%/sqrt(E) hadron showers

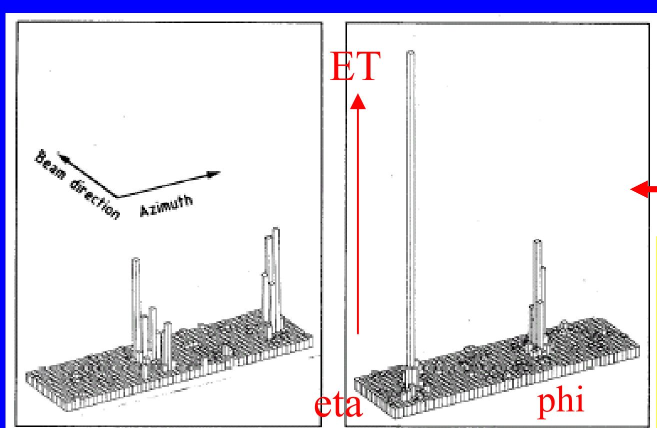
|eta| <~ 1

ET = 0-11.5/63 GeV



Circularity (2D-sphericity)
Phys.Lett B128 (1983) 354

ET = 35-40/63 GeV



Jets in hadron-hadron
co-discovered
with UA2,UA1 (1982 Paris)

Low Mass Central Exclusive Production

pp → p X p
X fully measured

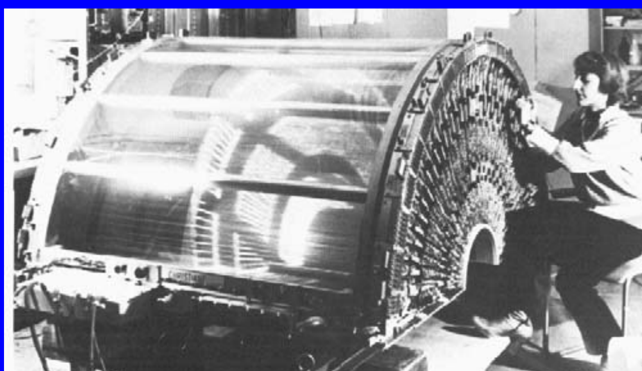
ISR $\sqrt{s}$ **= 63 GeV**

Search for "Glueballs"

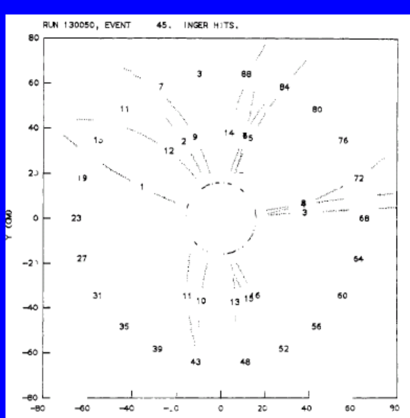
$\{gg\}$ as distinct from $\{q\bar{q}\}$

p ← → p, π^+, π^-

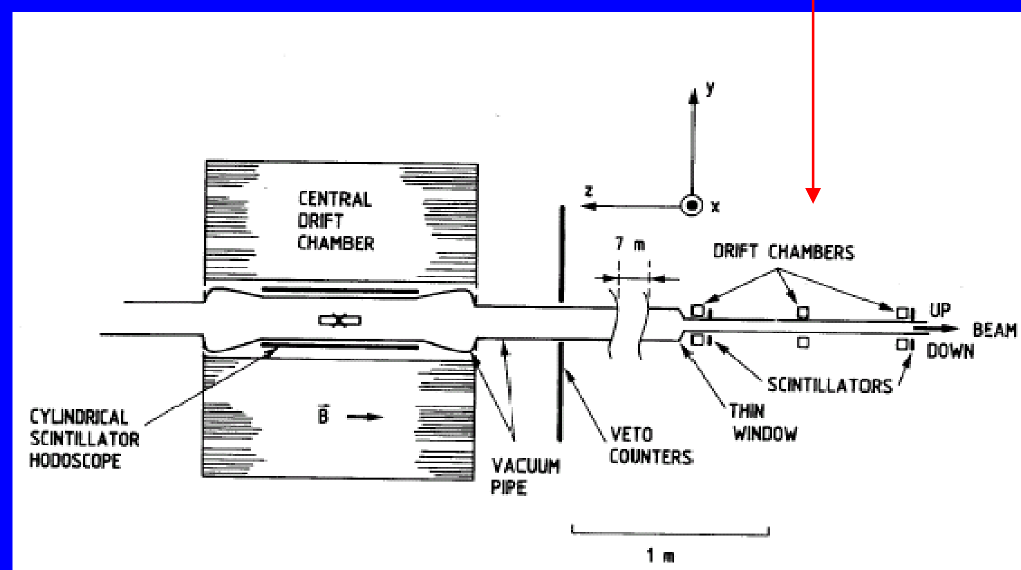
+ nothing else



Central drift chamber half

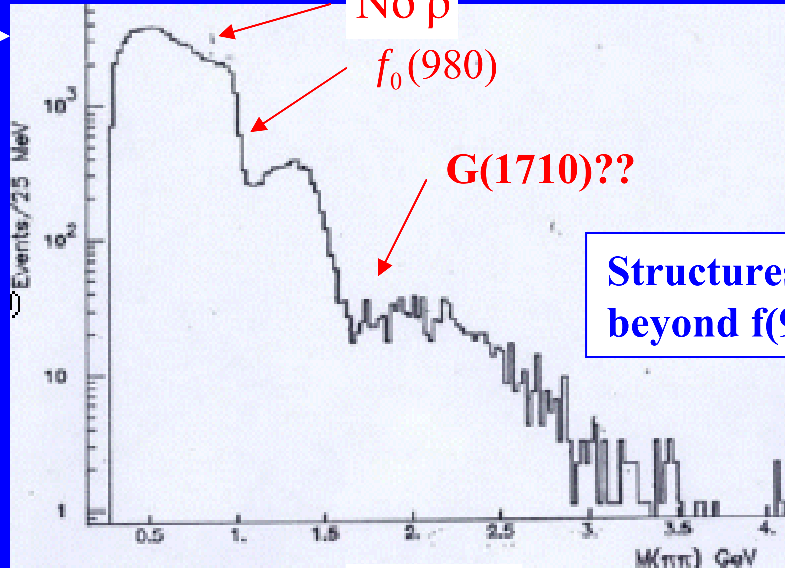


Axial Field Spectrometer (R807)
Added very forward drift chambers



Central Exclusive $\pi^+\pi^-$ Production (AFS)

3500 events/25 MeV



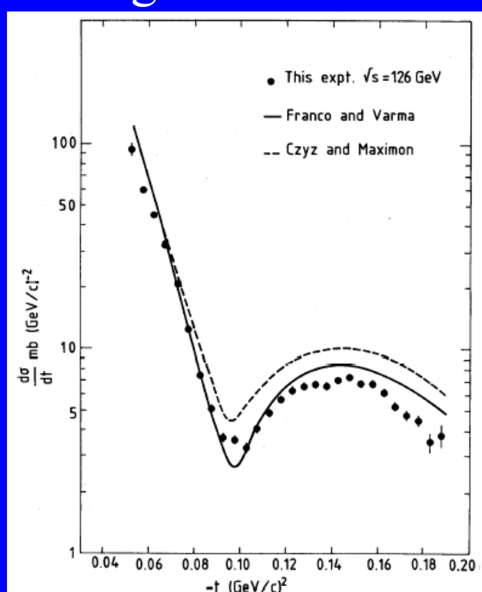
$M(\pi^+\pi^-)$

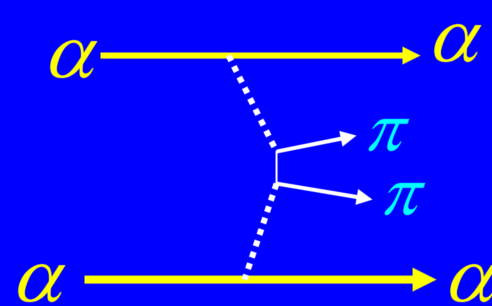
Structures not well understood beyond f(980). Not studied at higher $\sqrt{s}$

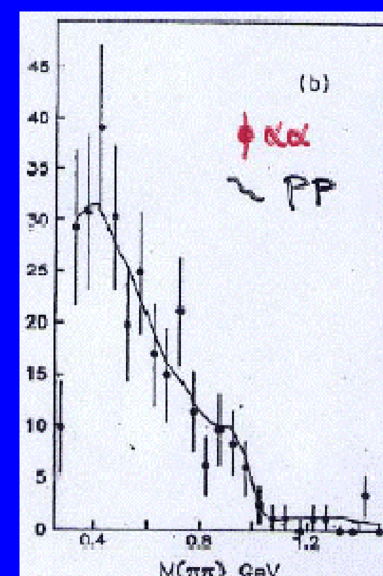
Pity: $\phi\phi$ would be great for G-spectroscopy

Also K^+K^- and $p\bar{p}$

$\alpha\alpha$ elastic scattering on-line dip!







Exclusive Central Hadron States at ISR

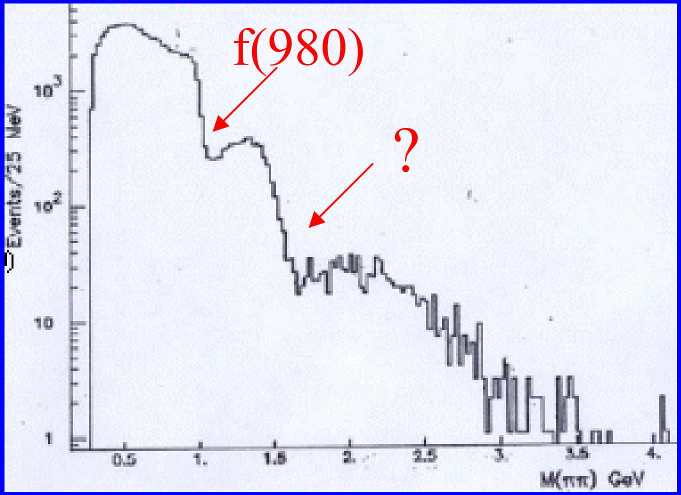
Birmingham did much of this at Omega facility, lower $\sqrt{s}$

Axial Field Spectrometer:

$$\sqrt{s} = 63\ \mathrm{GeV},\ \Delta y \leq 3$$

$$\pi^+\pi^-, K^+K^-, p\bar{p}, 4\pi$$

Q.No. Filter: $I^G J^{PC} = 0^+ \mathrm{even}^{++}$



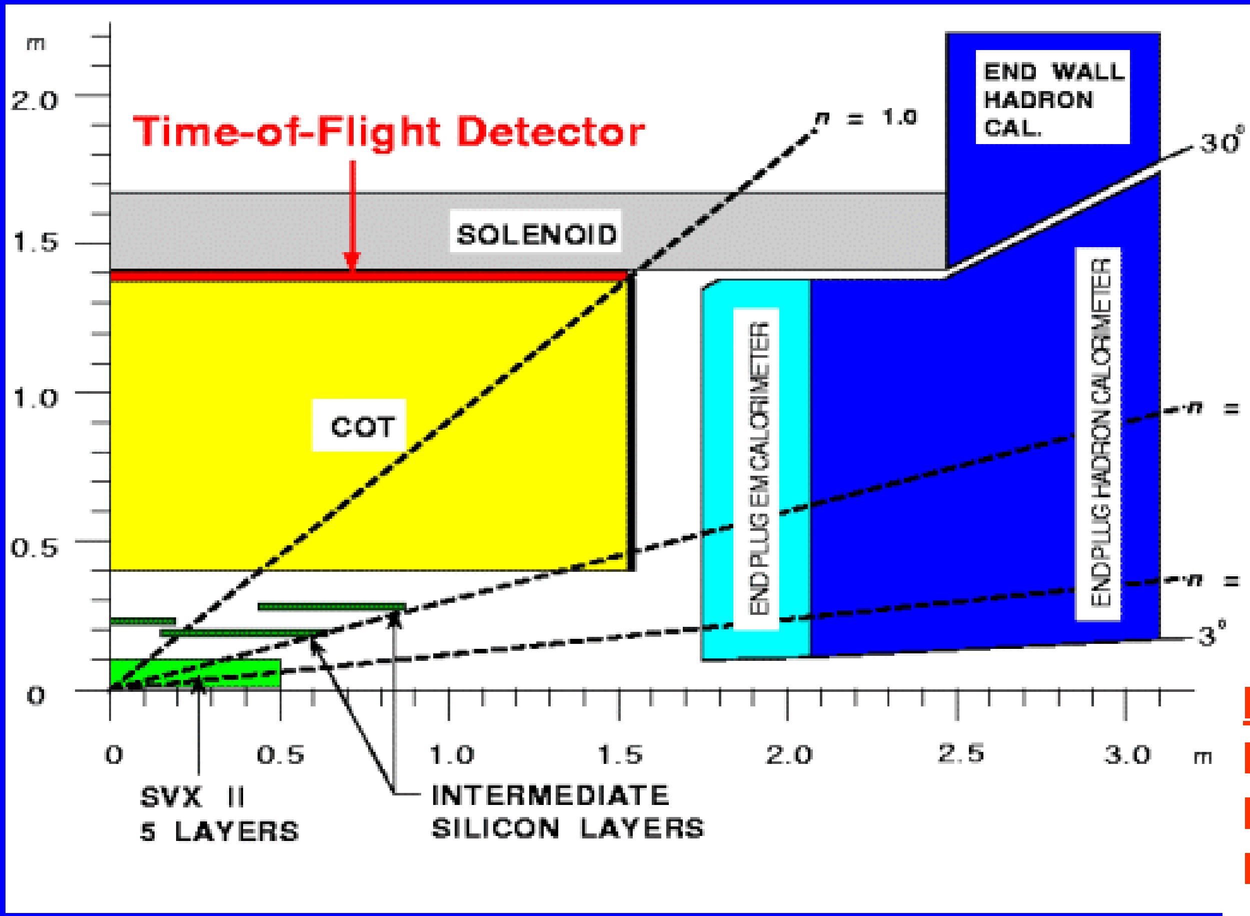
$M(\pi^+\pi^-)$

What about, among others:

$$K_S^0 K_S^0, D^0\overline{D}^0, D_S\overline{D}_S, \ldots \Lambda\overline{\Lambda}, \Sigma\overline{\Sigma}, \Omega\overline{\Omega}, \ldots!$$

Pomeron ~ gg is flavor-blind, mostly depends on masses.
CDF detector equal to best in world, Tevatron to best place!
Hope to do it, but …

CDF Detector at Fermilab Tevatron



BEYOND 3 deg :

Luminosity Counters

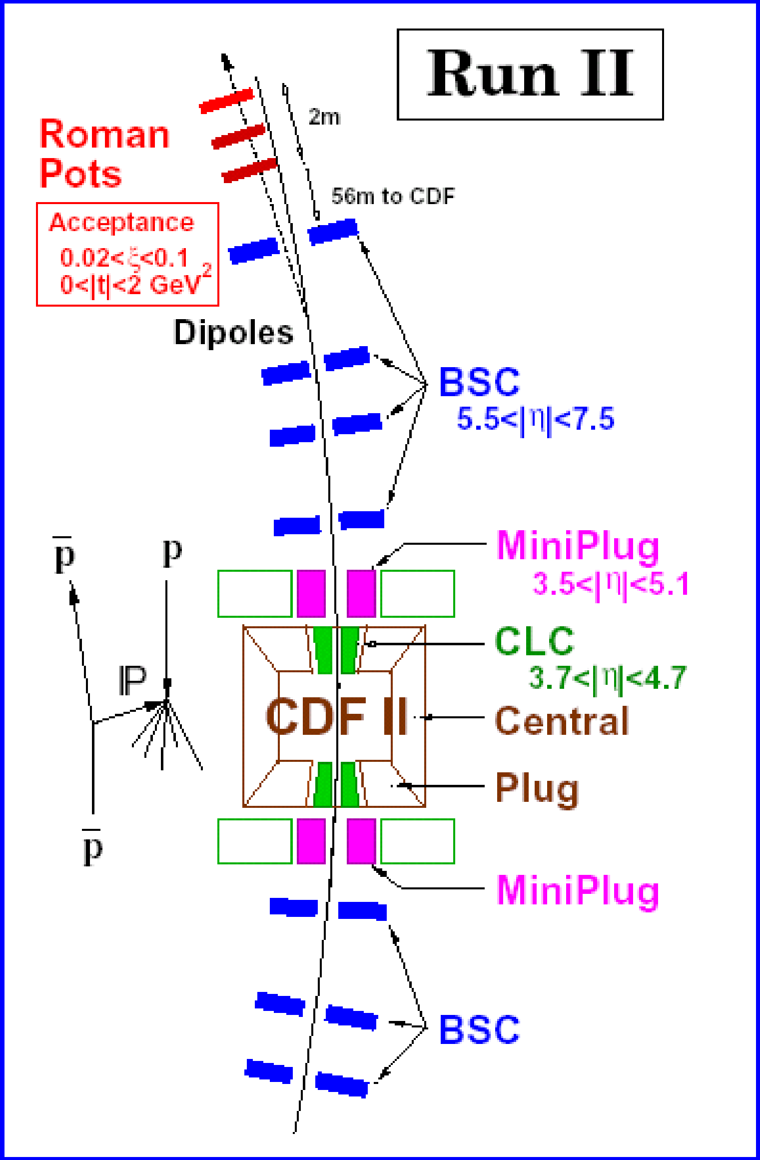
Beam Shower Counters

Roman Pots

MiniPlugs

980 GeV pbar → ← 980 GeV p

Installed very forward Beam Shower Counters (BSC) for rapidity gaps and scintillating fiber trackers in Roman pots for pbar detection



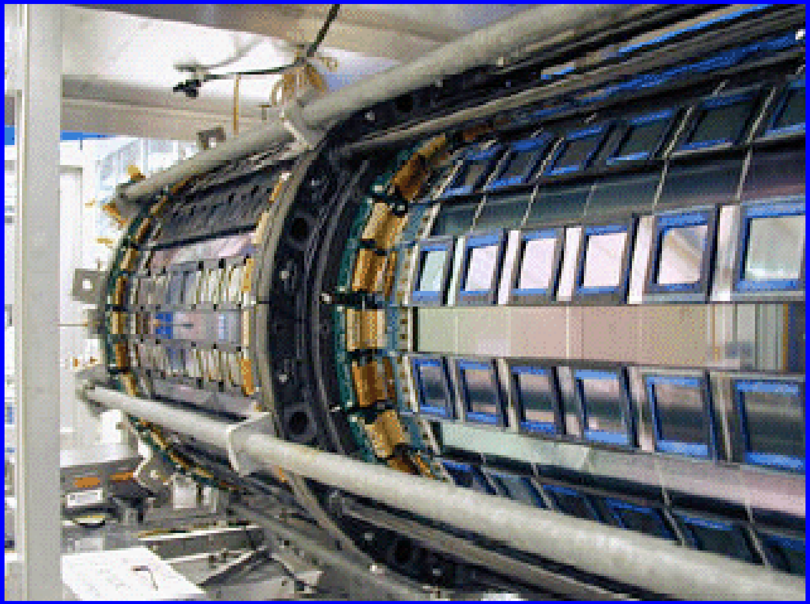
Not at all to scale!

Roman pot detectors 20mm x 20mm
55 m downstream.
Not used for most of this (acceptance).

Beam Shower Counters BSC tight around pipe.
Full coverage $-7.4 < \eta < +7.4$

$p \to n\pi;\ p\pi\pi,$ etc vetoed

Central tracking: Silicon strips & Drift Chamber

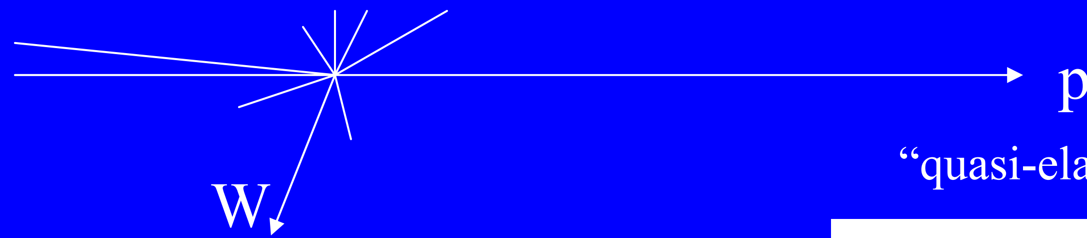


~ 720,000 strips,
25 μm with 50 μm readout

Drift chamber
96 layers → 30,240 sense wires
40 μm gold-plated tungsten
ADC and TDC each end
Resolution ~ 150 μm/wire

Surrounded by lead/iron scintillator sandwich calorimeter for energy measurement

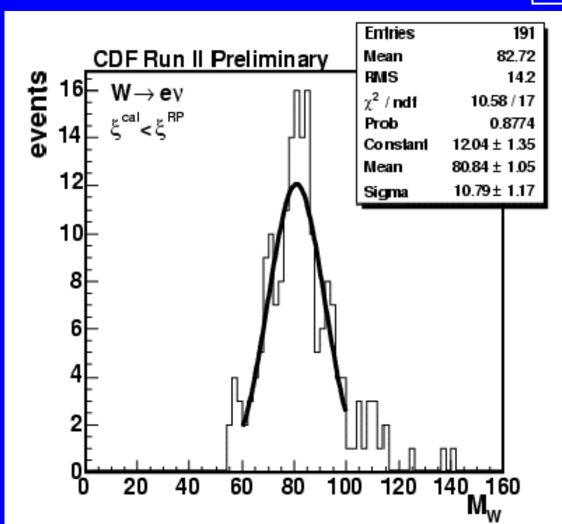
Diffractive W and Z Production



"quasi-elastic"

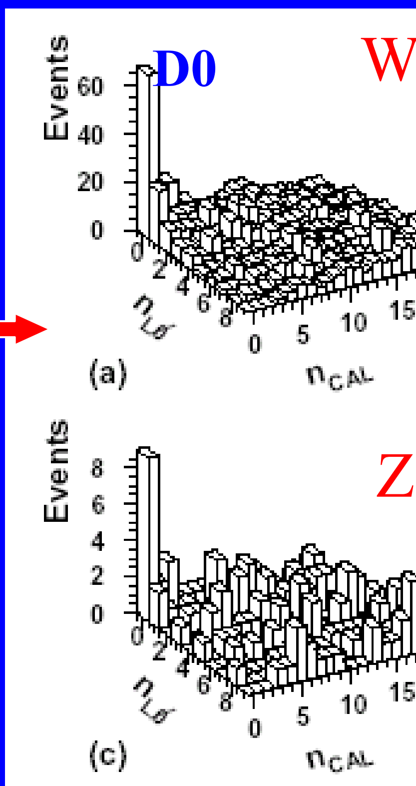
W produced but p "stays intact"

CDF: $\frac{\text{Diff. W}}{\text{Non-Diff W}} = (1.15 \pm 0.55)\%$



$M(\mu\nu)$: no $p_z(\nu)$ ambiguity

D0 also sees diffractive W and Z all consistent with 1% diffractive



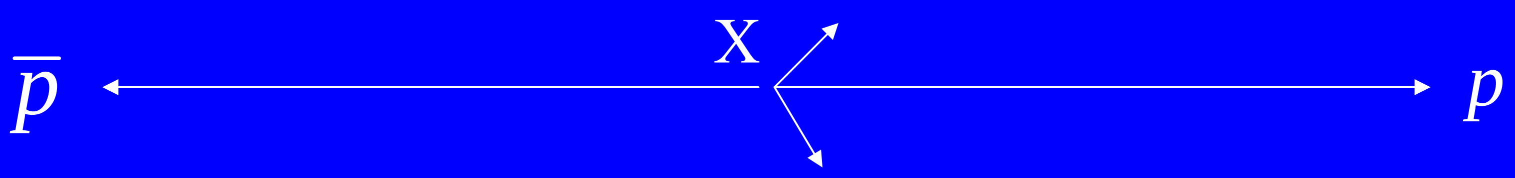
$\eta(LO) = 2.3 - 4.3$

$\eta(CAL) = 3.0 - 5.2$

Should be much larger at LHC

Central Exclusive Production in CDF

pp → p X p where X is ***a simple system completely measured***

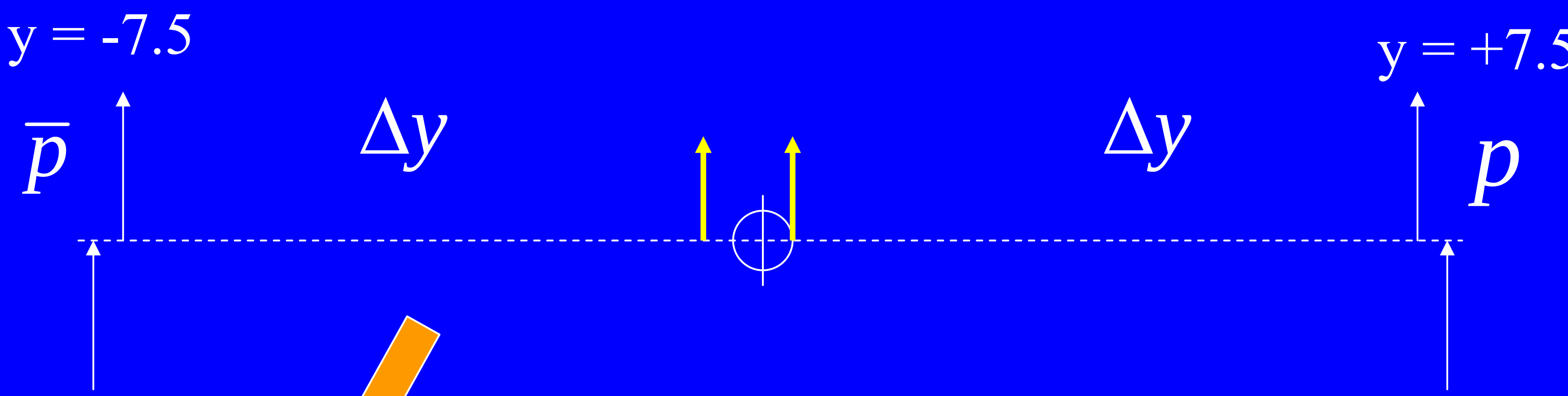


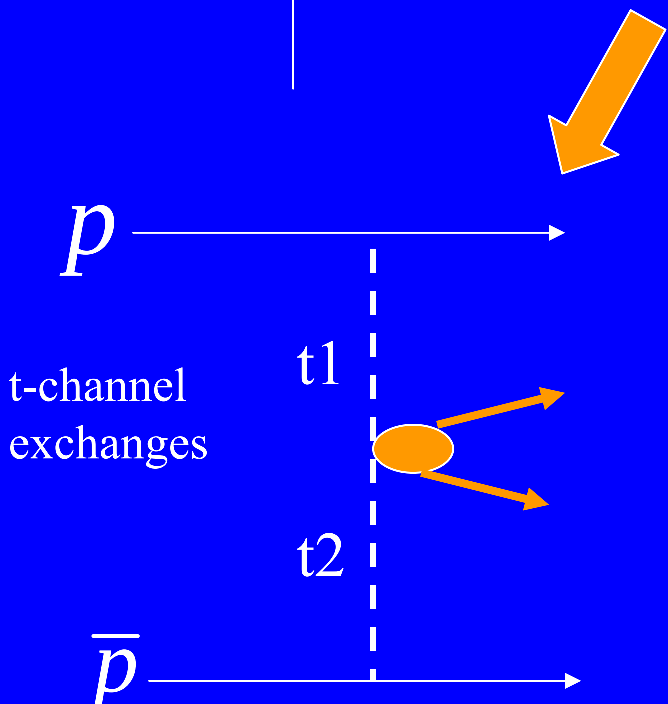
$\sqrt{s}$ =	63	1960	14000	GeV
$\Delta y = 2\ln\frac{\sqrt{s}}{m_p}$ =	8.4	15.3	19.2	(- 6 for gaps)
	3	100	700	GeV M(cen)

CDF : e+e-, γγ, μ+μ-, J/ψ, ψ(2S), χ_c, Y …. Z? JJ

LHC: Z, H, W+W-, $\tilde{l}\,\tilde{l}$ **.….**

Rapidity (Tevatron)





$\sigma \approx \Delta y^{\alpha(t)-1}$, where $\alpha(t)$ is (complex) spin of exchange.

$\alpha(0) \equiv$ spin J for massless exchange:

$\Rightarrow J \geq 1$ for large $\Delta y \Rightarrow$ only photon or "pomeron" IP

$\alpha(0) \sim 1.1$ for IP $\rightarrow$ rising elastic and σ(tot).

IP modeled as gg for many situations.

+(?) O = ggg

3 possibilities : $\gamma + \gamma,\ \gamma + \mathrm{IP},\ \mathrm{IP} + \mathrm{IP}$

We have now seen all 3 in h-h! $t(\gamma) << t(\mathrm{IP})$

Also in e+e- and ep | **Also in ep** | **Only in hadron-hadron**

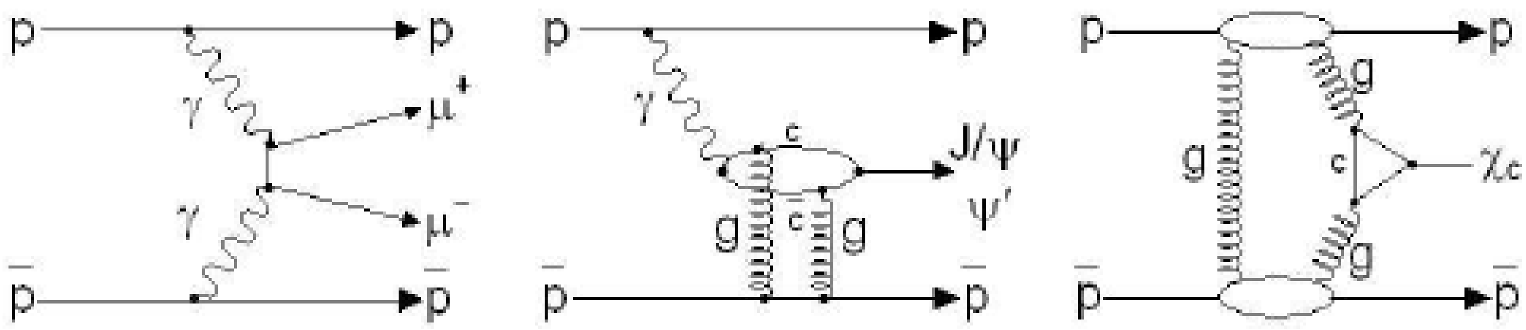


FIG. 1: Feynman diagrams for (a) $\gamma\gamma \to \mu^+\mu^-$, (b) $\gamma I\!P \to J/\psi(\psi(2S))$, and (c) $I\!P\, I\!P \to \chi_c$.

$$J/\psi/\psi'(2S) \to \mu^+\mu^-$$

$$\chi_c \to J/\psi + \gamma \to \mu^+\mu^- + \gamma$$

Odderon can replace photon in p+pbar, not in e+p

We cannot detect p and pbar … require all CDF in noise, to |eta| =7.4

Exclusive Electron-Positron Production

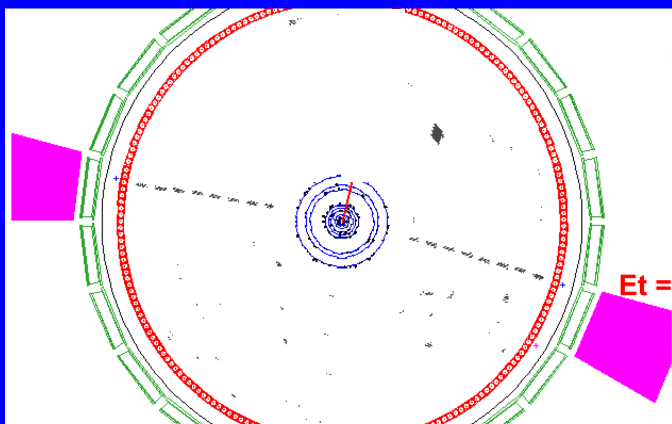
$E_T(e^{\pm}) > 5$ GeV; $|\eta(e^{\pm})| < 2.0$

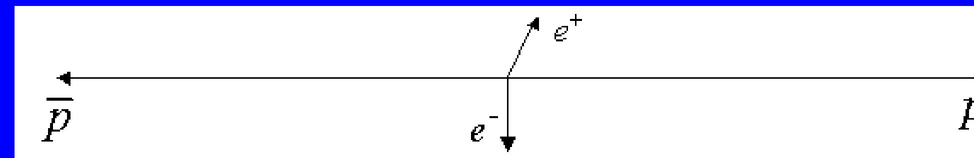
Phys.Rev.Lett 98,112001(2007)

e^+e^- : $\Delta\phi = 180^0 \pm 2^0$

$M(e^+e^-)\ 10 \rightarrow 38$ GeV

Δp_T small ($\cong$ resolution)





16 events

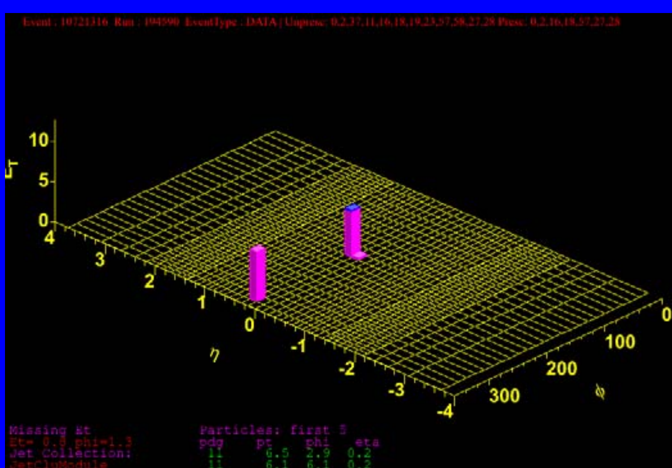
Estimated background = 1.9 ± 0.3 (mostly p-dissociation)

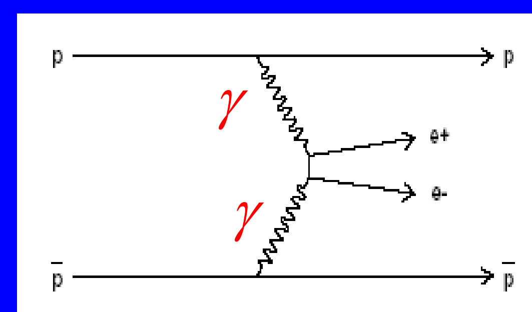
$\sigma_{MEAS.} = 1.6\ ^{+0.5}_{-0.3}$ (stat) $\pm\ 0.3$ (syst) pb

p-value = 1.3×10^{-9} ($> 5\sigma$)

$\sigma_{QED} = (1.711 \pm 0.008)$ pb

QED process : $\gamma\gamma$ collisions in pp



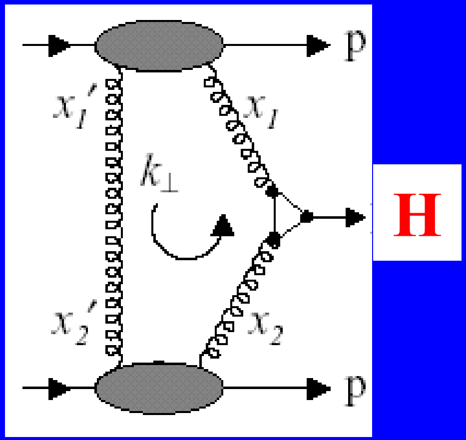


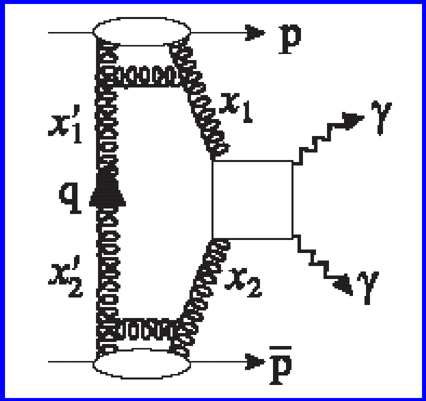
Monte Carlos : LPAIR, GRAPE, STARLIGHT

Exclusive 2-Photon Production

MGA et al. (2001) hep-ex/0511057

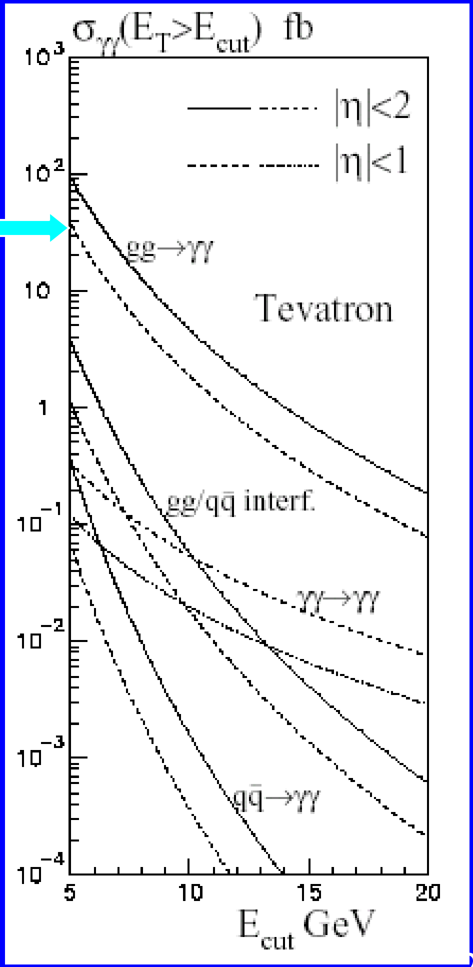
Khoze, Martin and Ryskin, hep-ph/0111078, Eur.Phys.J. C23: 311 (2002)
KMR+Stirling hep-ph/0409037





Tevatron

36 fb

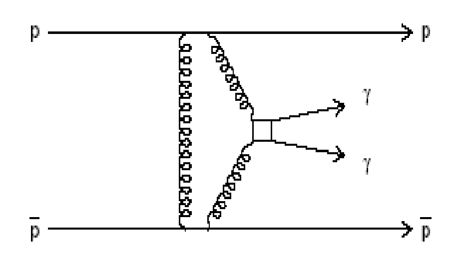


~ 40 events per fb^{-1} with $p_T(\gamma) > 5$ GeV/c & $|\eta| < 1.0$

Claim factor ~ 3 uncertainty ; Correlated to p+H+p

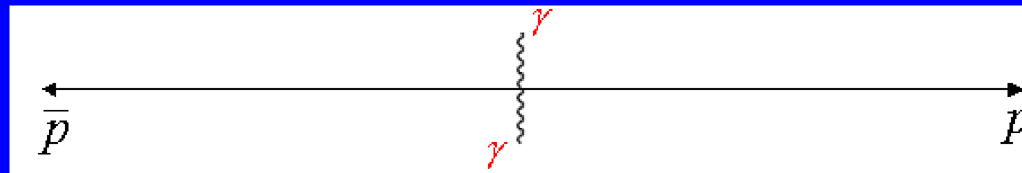
$\gamma\gamma \to \gamma\gamma$ & $q\bar{q} \to \gamma\gamma$ much smaller

Exclusive $\gamma\gamma$ Production in Hadron-Hadron Collisions

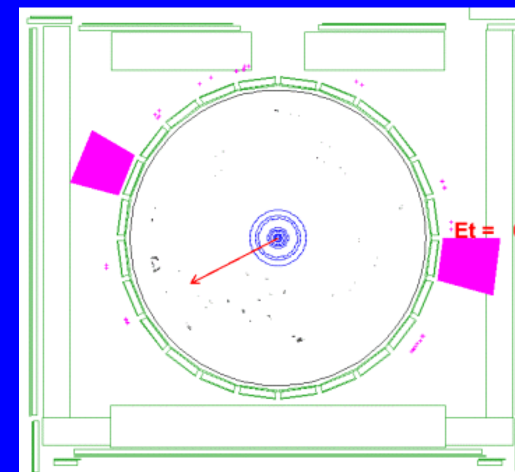


$gg \rightarrow \gamma\gamma$

Phys.Rev.Lett. 99,242002 (2007)



3 candidates observed: $E_T(\gamma) > 5\ \text{GeV}; |\eta(\gamma)| < 1.0$



2 events are "perfect" γγ candidates and 1 may be a $\pi^o\pi^o$

Prediction V.A.Khoze et al. Eur. Phys. J C38, 475 (2005)
σ (our cuts) = (36 +72 – 24) fb = 0.8 +1.6 –0.5 events.
Cannot yet claim "discovery" as b/g study *a posteriori*, 2 events corresponds to σ ~ 90 fb, agreeing with Khoze *et al.*

If really γγ →

It means exclusive H must happen (if H exists) and probably σ ~ 5 fb within factor ~ 3.
σ is higher in MSSM

$$\text{Note}: \sigma_{MEAS} \approx 2\times10^{-12}\,\sigma_{INEL}\ !$$

Central Exclusive $\mu^+\mu^-$ Production

Why interesting?

Among other things:

Two-photon production: $\gamma\gamma \rightarrow \mu^+\mu^-$ continuum (QED + FF).

Cross section very well known (QED) so can calibrate LHC luminosity (?).
Can come through photo-production of $\psi, \psi', \Upsilon, \Upsilon', \Upsilon''$

Forward proton momenta precisely known: calibrate momentum scale of forward spectrometers for p + p → p + H + p at LHC .

New Results "approved" Sept 4th :

$$p + \bar{p} \rightarrow p + \mu^+\mu^- + \bar{p}$$

$$3\ \mathrm{GeV/c^2} < M_{\mu\mu} < 4\ \mathrm{GeV/c^2}$$

Region rich in physics.
First observations in (elastic) hadron-hadron:

1) $\gamma + \gamma \rightarrow \mu^+\mu^-$

2) $\gamma + IP \rightarrow J/\psi\ \&\ \psi(2S)$

3) $IP + IP \rightarrow \chi_c$

1 & 2) Forward proton momenta precisely known: calibrate momentum scale of forward spectrometers for p + p → p + H + p at LHC.
3) Calibrate theory (x-sn) of p + H + p

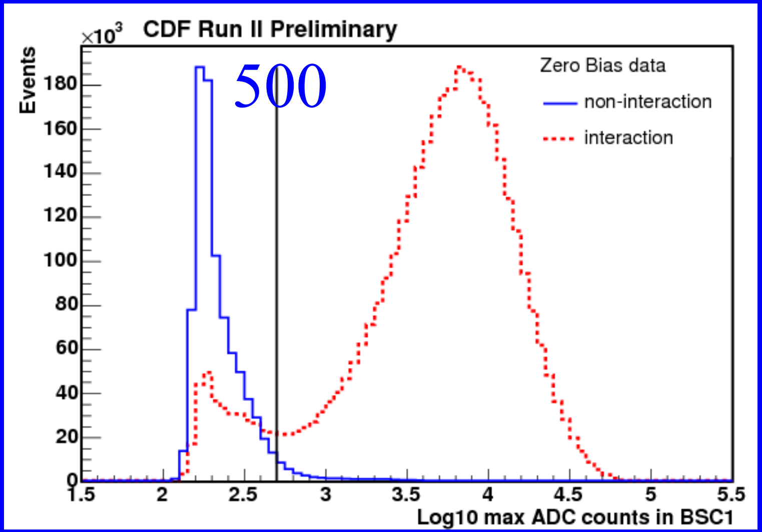
Luminosity (Good Runs) = 1.48/fb (+/- 6%)
Trigger = muon + track +BSC1 gaps → 2 muons
Number of events on tape: ~ 1.6 million

Fiducial "box" :

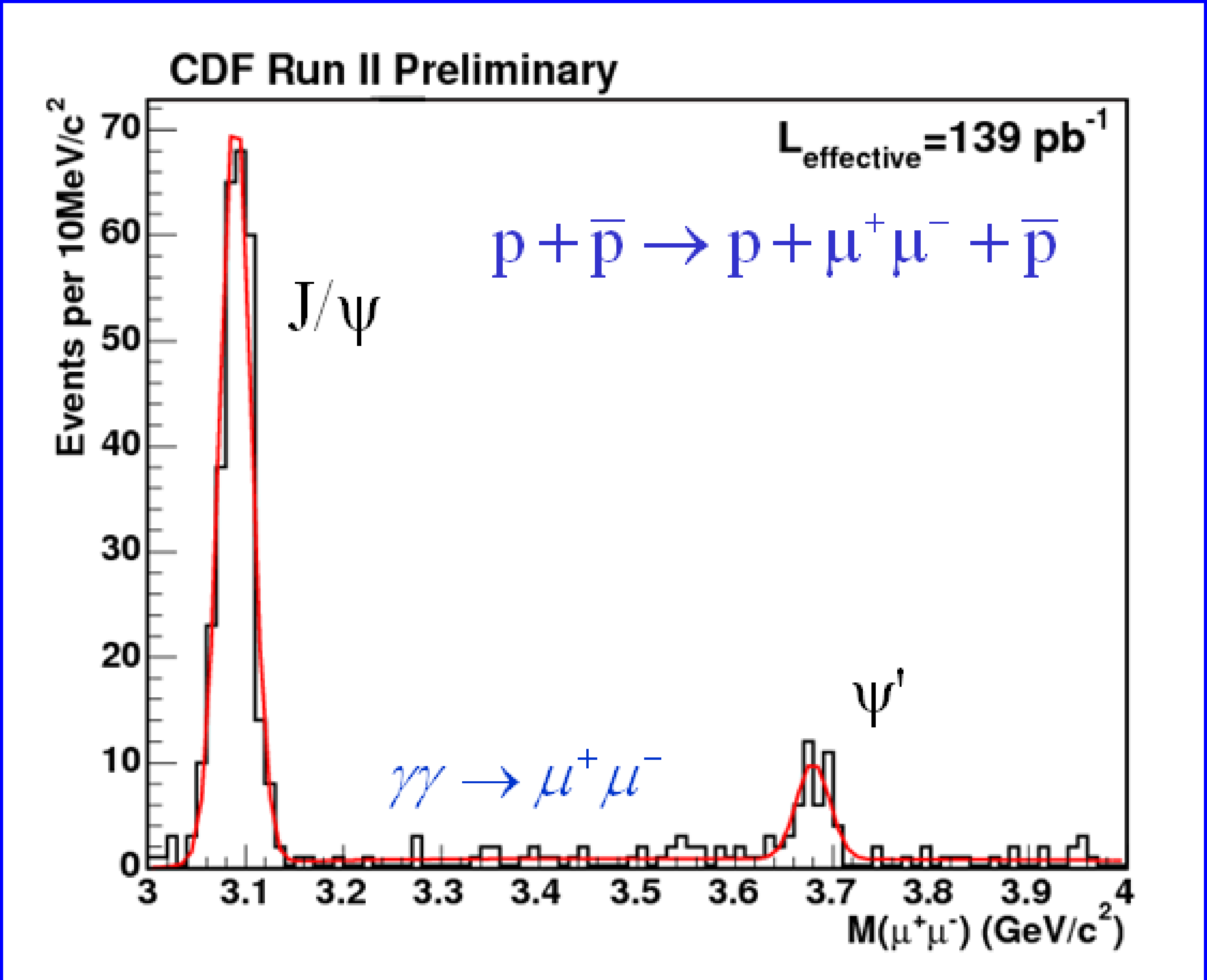
$$|\eta(\mu)| < 0.6\ ,\ p_T(\mu) > 1.4\ \text{GeV/c},\ 3.0 < M(\mu^+\mu^-) < 4.0\ \text{GeV/c}^2$$

Reject cosmic ray events (ToF, colinearity) … 100% efficient
Exclusivity: Require *all* detectors < noise cuts
except in and around muons.

Example, BSC1, Period 9:



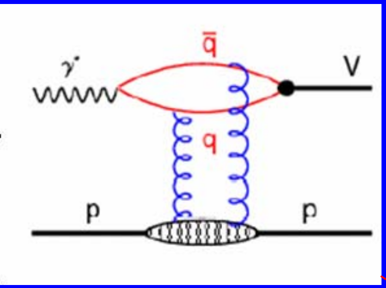
402 events, final sample

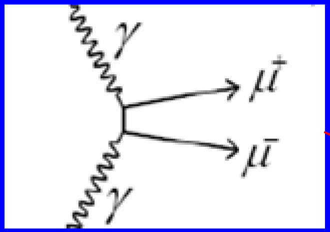


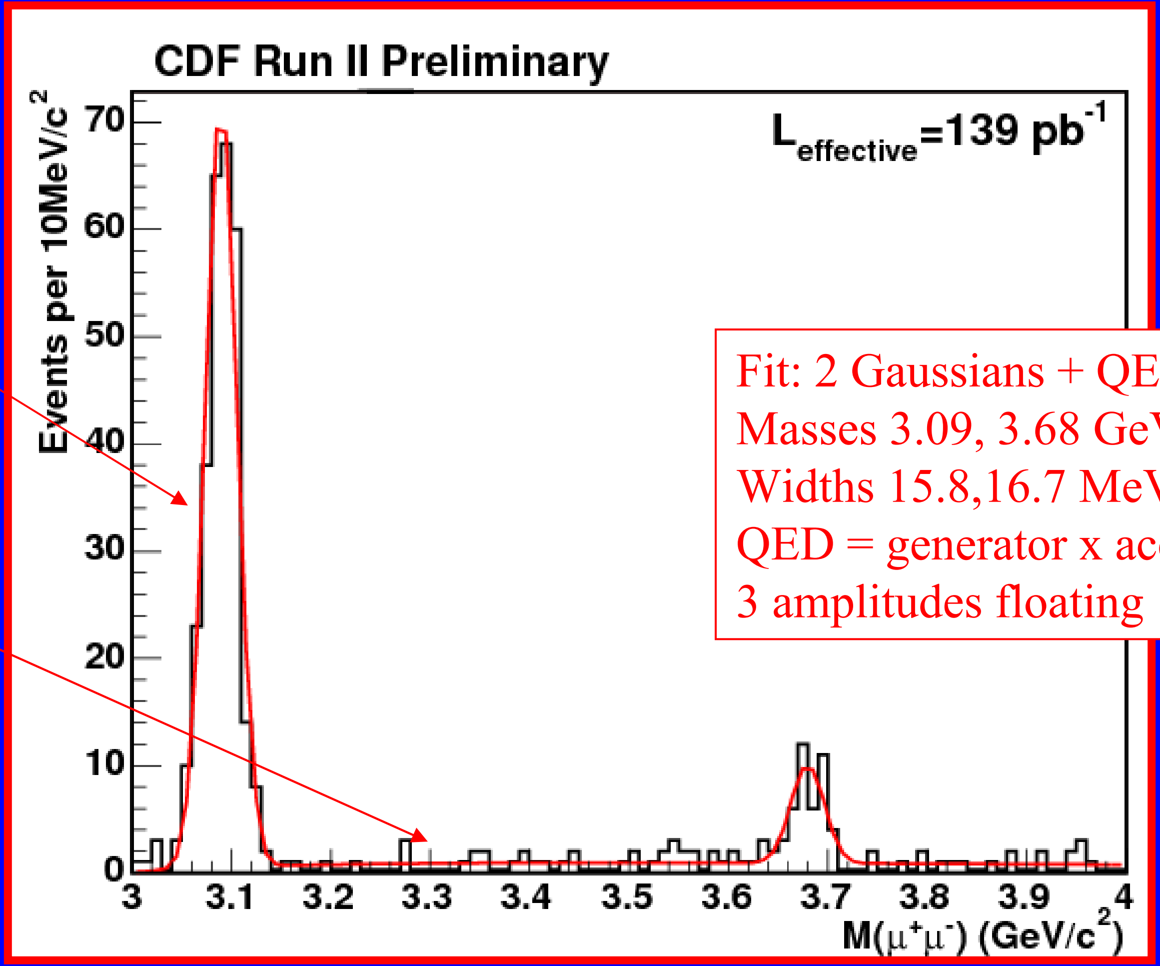
Observation of Exclusive Charmonium Production and $\gamma\gamma \rightarrow \mu^+\mu^-$ in $p\bar{p}$ Collisions at $\sqrt{s}$=1.96 TeV.

$$p + \overline{p} \rightarrow p + \mu^+\mu^- + \overline{p}$$

PRL under internal review



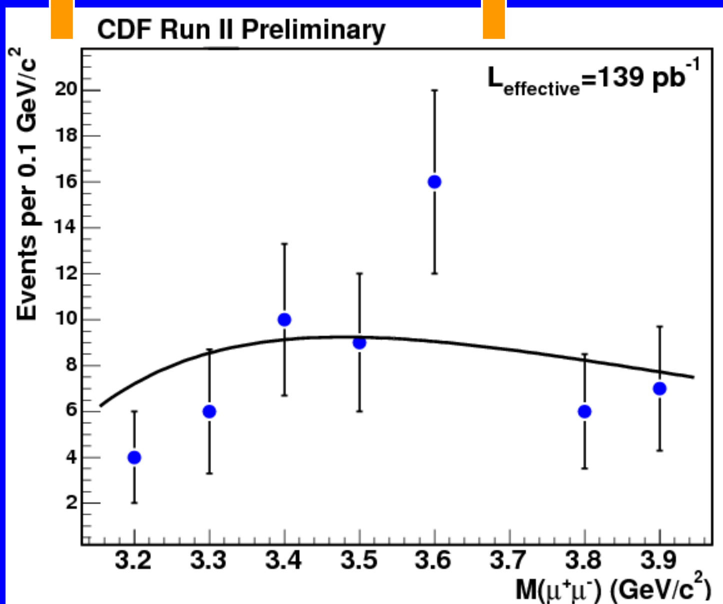


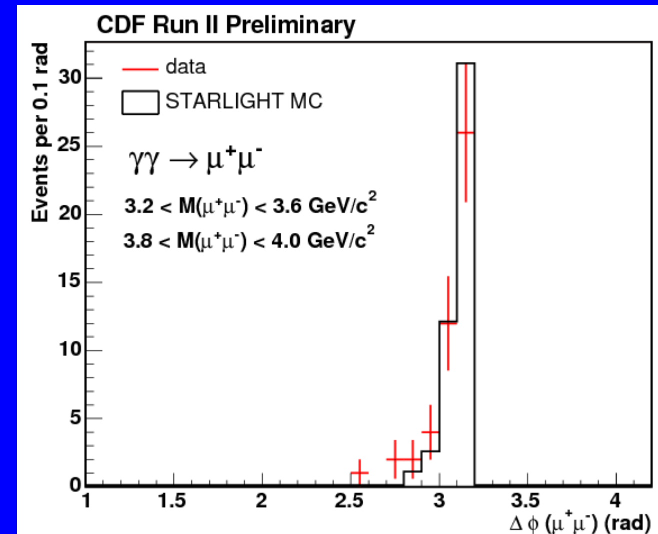


Fit: 2 Gaussians + QED continuum.
Masses 3.09, 3.68 GeV == PDG
Widths 15.8,16.7 MeV=resolution.
QED = generator x acceptance
3 amplitudes floating

J/ψ $\psi(2S)$

QED continuum : $\gamma + \gamma \rightarrow \mu^+\mu^-$



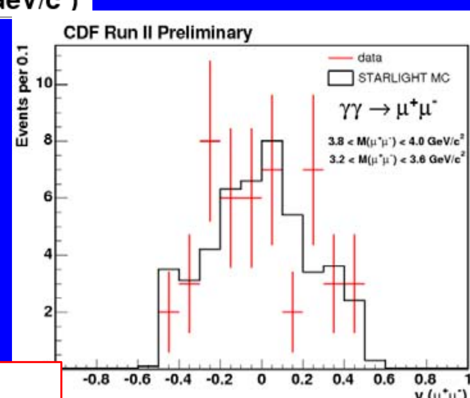


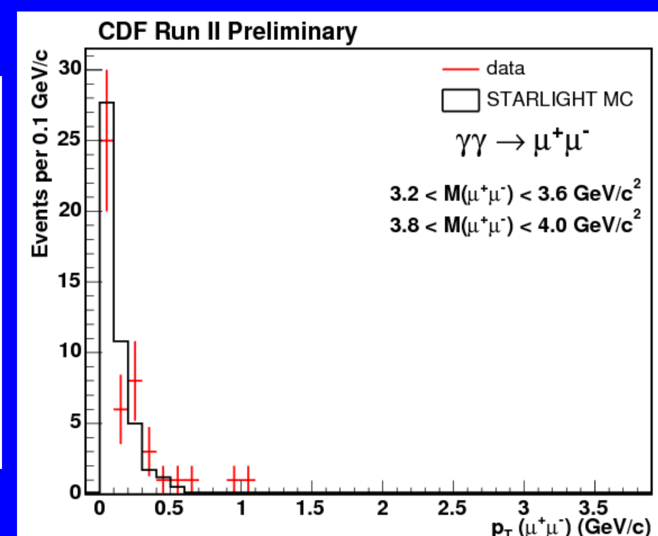
$F_{AE} = 0.6 - 0.5.e^{-3.22.(M-3.05)}$

x QED spectrum

$\sim \; F_{QED} = A.e^{-0.852 \times M}$

Only normalization A floating





$A \rightarrow \sigma(\gamma\gamma \rightarrow \mu^+\mu^-)$:

$\sigma(|\eta| < 0.6, 3\ GeV/c^2 < M_{\mu\mu} < 4\ GeV/c^2)$

$= 2.6 \pm 0.5$ pb

STARLIGHT & LPAIR QED : 2.18 pb

STARLIGHT & LPAIR MCs

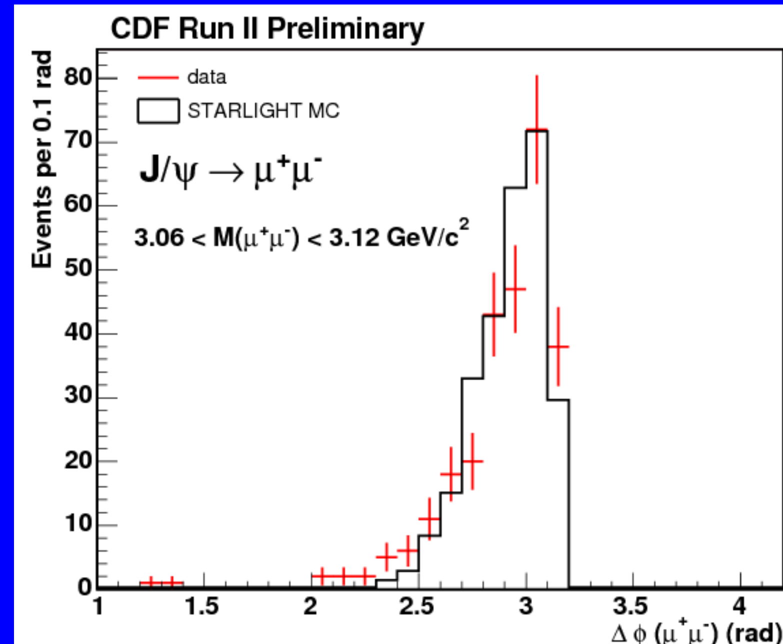
Good description: v.low pT

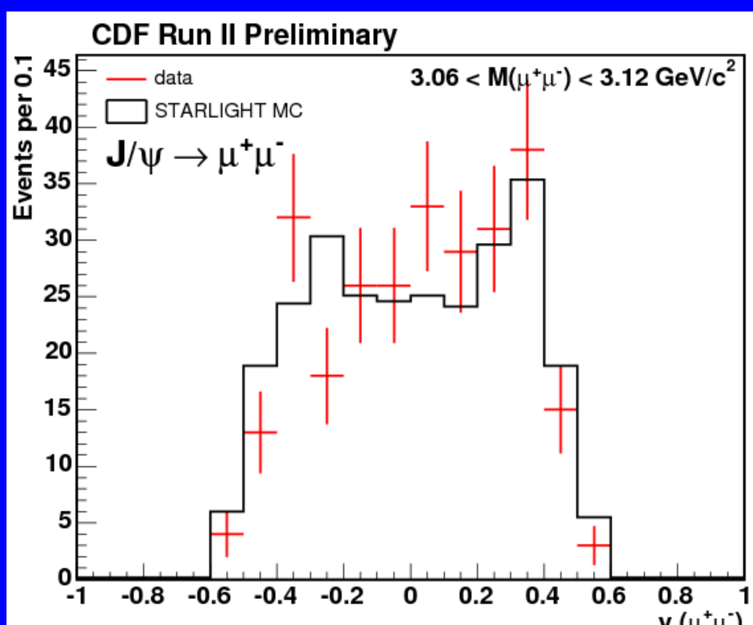
J/ψ Photoproduction
(or possible odderon exchange)

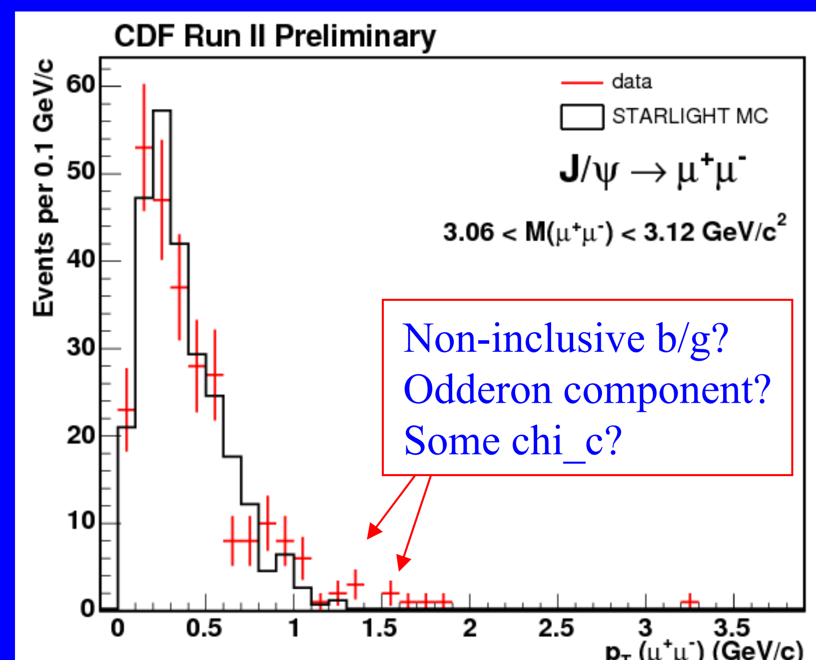
Kinematics well described by
STARLIGHT MC
also $\psi(2S)$
Much broader

$\Delta\phi(\mu-\mu), p_T(\mu^+\mu^-)$ **than**

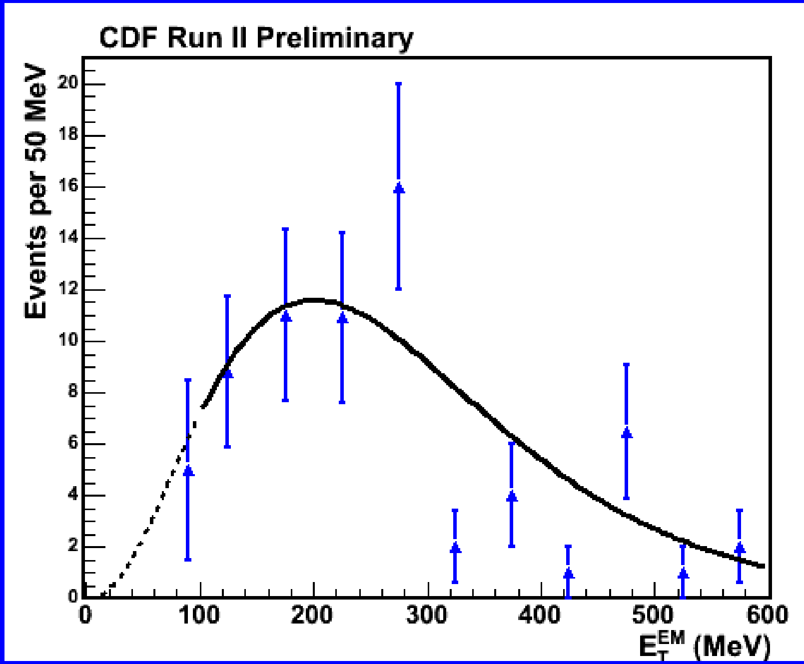
QED continuum : $\gamma + \gamma \rightarrow \mu^+\mu^-$







Now allow photons: EmEt spectrum with J/psi mass cut:



J/ψ have photons : $286 \rightarrow 352$

$\psi(2S)$ do not : $39 \rightarrow 40$

$$\chi_c \rightarrow J/\psi + \gamma$$

Empirical functional form

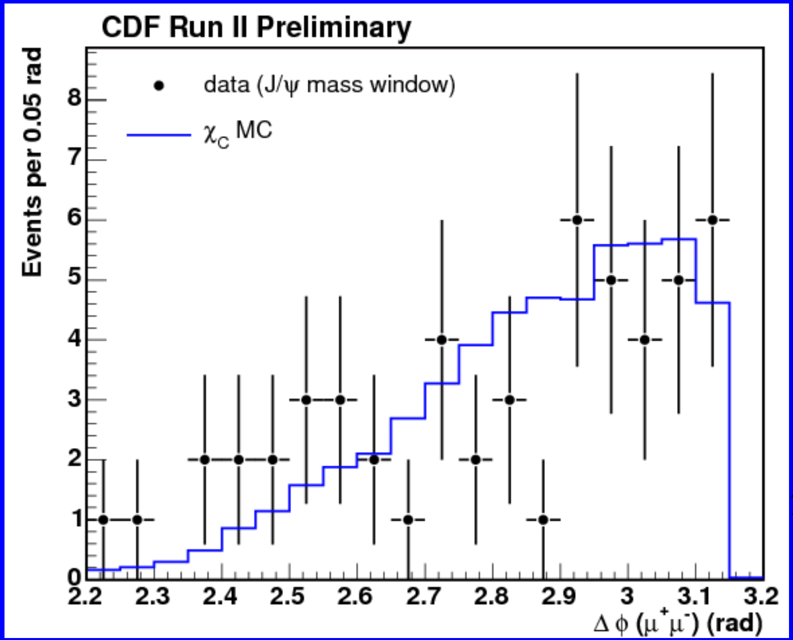
65 events above 80 MeV cut.
3 events below (estimated from fit)
→1% background under J/psi
→# χ_c = 68 +/- 8

MC also estimates only few % of $\chi_c \rightarrow J/\psi + \gamma$ under the cut

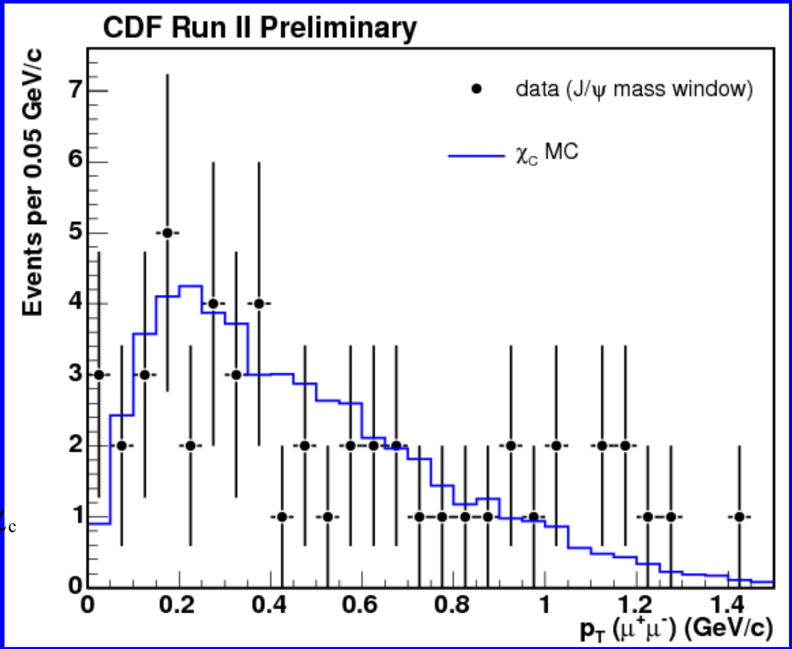
(But CDFSIM not reliable for such low ET)

Kinematic fits on J/ψ : $\Delta\phi(\mu\mu)$ and $p_T(J/\psi)$

Events *with* EM shower



χc



Good fits to $\mu^+\mu^-$ kinematics with only χ_c , if EM shower

⇒ No photoproduced J/ψ above 80 MeV cut

Confirms χ_c assignment

Summary of Results

$$p + \overline{p} \to p + \mu^{+}\mu^{-} + \overline{p}$$

M = 3-4 GeV/c2

Quantity	This analysis	Theory
$\frac{d\sigma}{dy}(y=0) J/\psi$ (nb)	3.96±0.64	(3.0 ± 0.8) nb
$\frac{d\sigma}{dy}(y=0) \psi(2S)$ (nb)	0.53±0.15	$0.46^{+0.11}_{-0.04}$
$\frac{d\sigma}{dy}(y=0) \chi_c^{\circ}$ (nb)	66±13	130± ≈50
$\sigma(box, QED, pb)$	2.6±0.5	2.18 ± 0.02
$\frac{O}{\gamma}$	< 0.38(95% c.l.)	0.3 - 0.6
$\frac{OP \to J/\psi}{PP \to \chi_c}$	<0.06 (95% c.l.)	No Prediction

Assumed

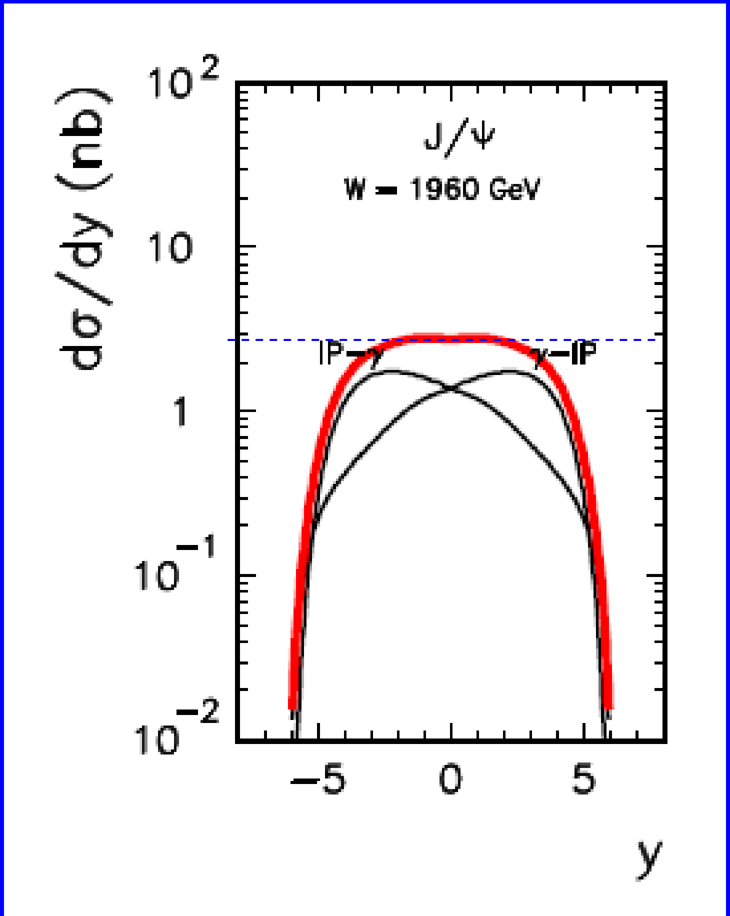
$$\chi_c(3415), \mathrm{J} = 0, \mathrm{B} \to (\mathrm{J}/\psi + \gamma) = 0.013$$

$$\chi_c(3516), \mathrm{J} = 2, \mathrm{B} \to (\mathrm{J}/\psi + \gamma) = 0.202$$

Suppressed by J_z=0 rule

Some predictions for J/psi photoproduction:

e.g. Schafer and Szczurek:
arXiv:0705.2887 [hep-ph]



Take 3.0 +- 0.8

Machado,Goncalves 3.0 nb

Motyka and Watt: 3.4 nb

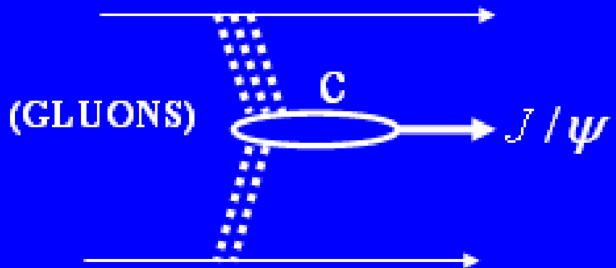
Schafer & Szczurek ~ 2.8 nb

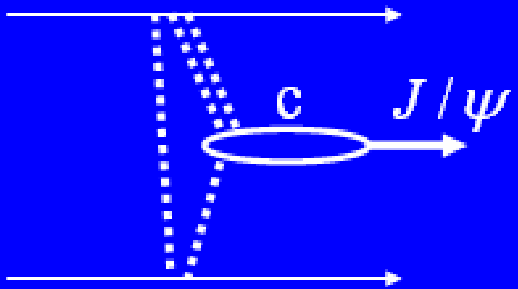
Nystrand 2.2 nb

Our result: 3.96 +- 0.64 nb

We are consistent, & so
we can put a limit on odderon exchange.
If theory gets more precise, our limit can change

Odderon Limits and ratios





In QCD but not yet observed.

$$R\left(\frac{data}{theory}\right)(J/\psi) = 1.32 \pm 0.41$$

$$R\left(\frac{data}{theory}\right)(\psi') = 1.15 \pm 0.21$$

$$R\left(\frac{data}{theory}\right)(V,\text{combined}) = 1.19 \pm 0.19$$

$$\left(\frac{O\ IP \rightarrow V}{\gamma\ IP \rightarrow V}\right) < 0.38\ (95\%\ \text{c.l.})$$

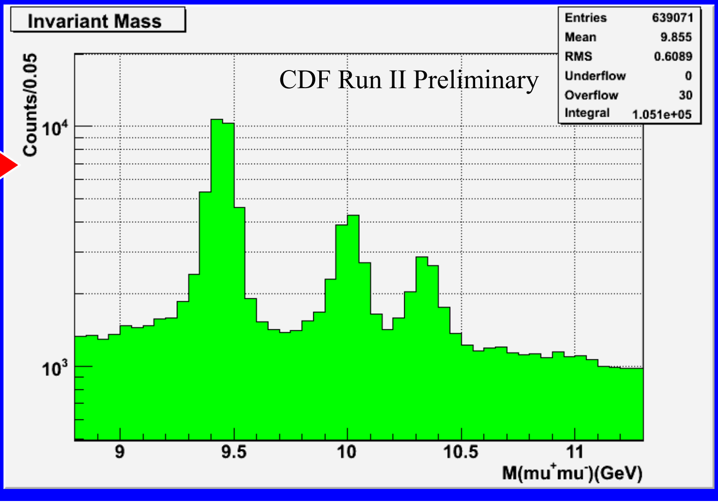
$$\left(\frac{(O+\gamma)\ IP \rightarrow J/\psi}{IP + IP \rightarrow \chi_{c0}(3415)}\right) = 0.060 \pm 0.015$$

Our limits on O-exchange are close to, and constrain, theoretical predictions

Dimuons: Upsilon Region

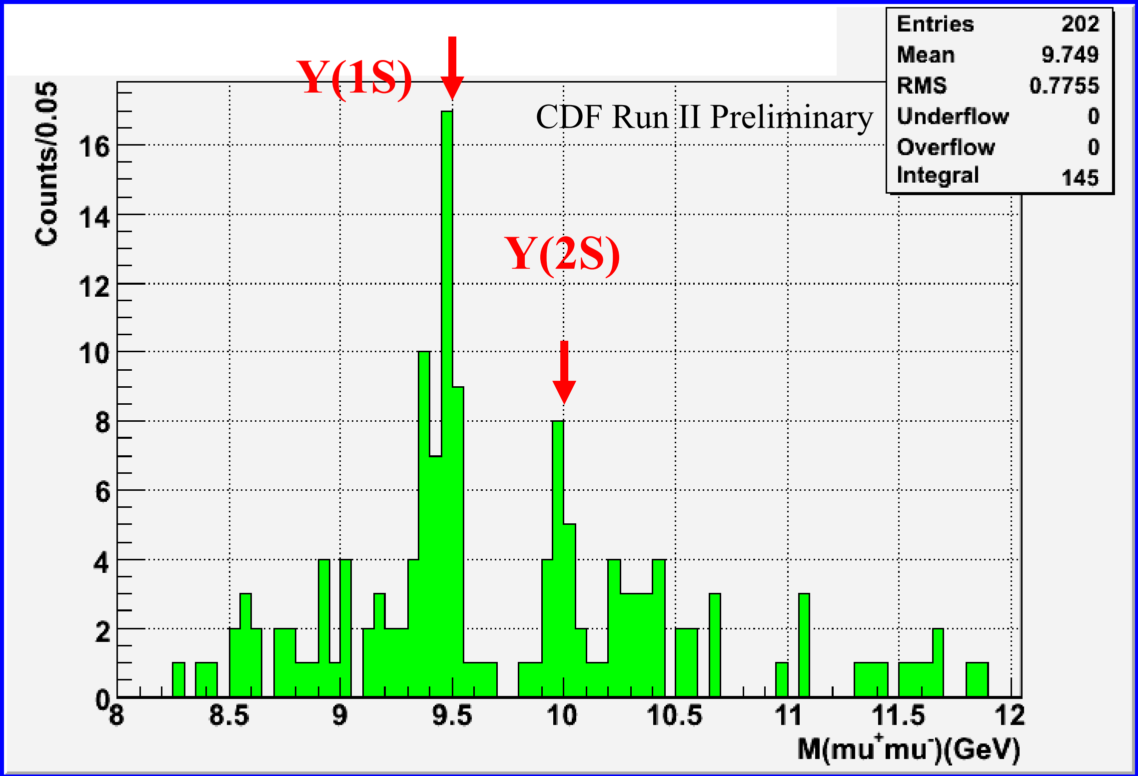
Trigger: μ+μ-
|η|<0.6 , pT(μ) > 4 GeV/c

Inclusive



Search for/measurement of photo-production of Y, Y'
(not before seen in hadron-hadron)

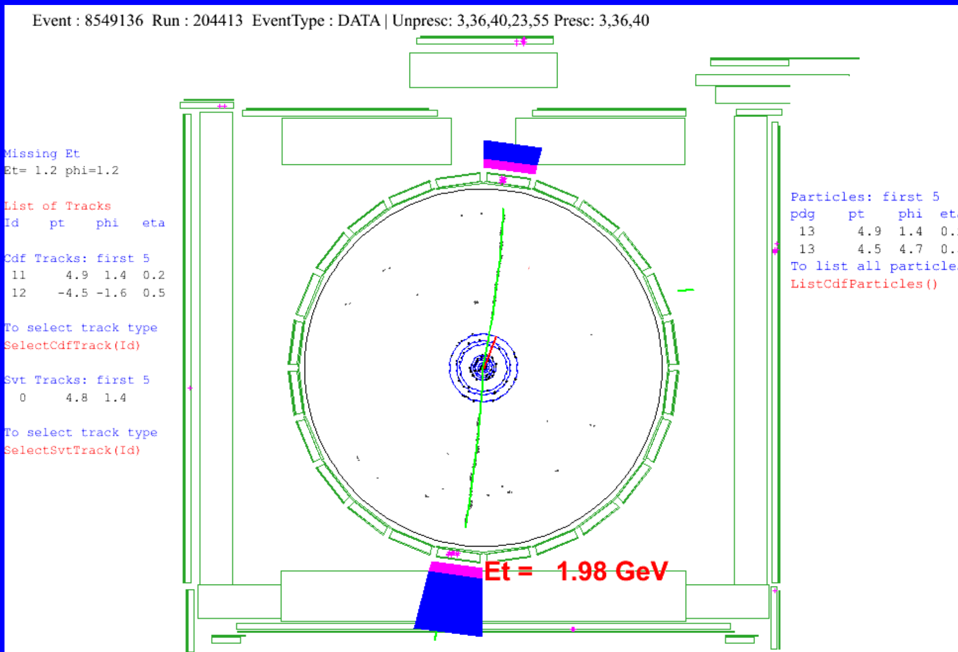
Invariant Mass
(n_{assoc_tracks} = 0)
pT(μμ) < 6GeV/c



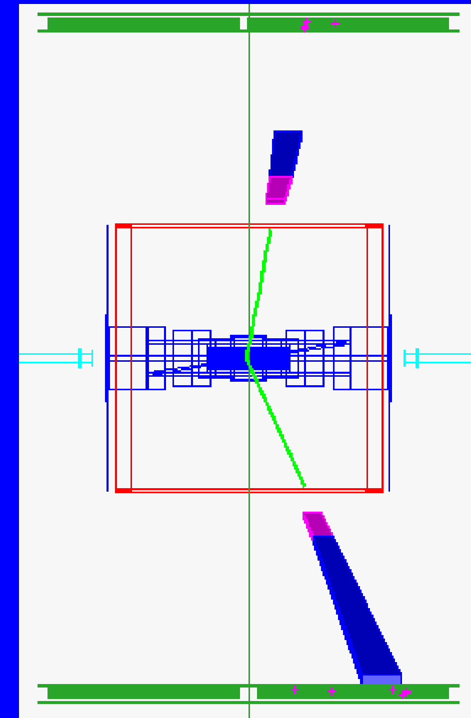
Status: have data, analysis in progress.

Exclusive Upsilon(1S) candidate

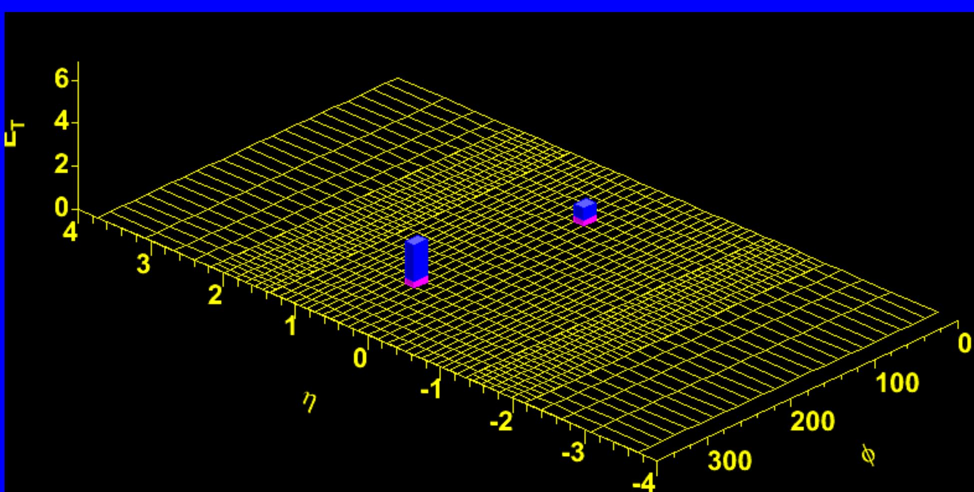
Run/Event: 204413/8549136



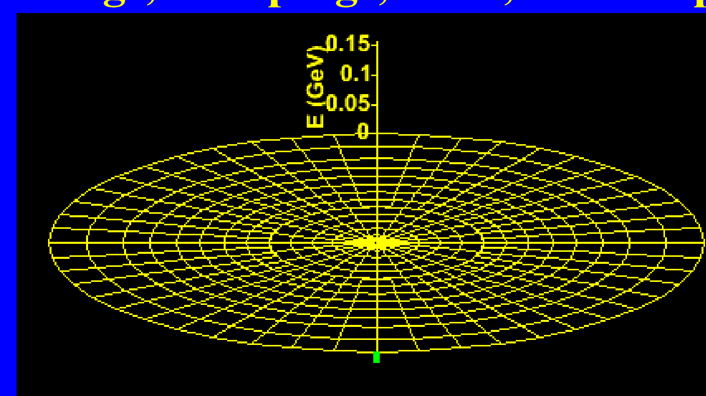
M ~ 9.4 GeV



R-z, Muon hits

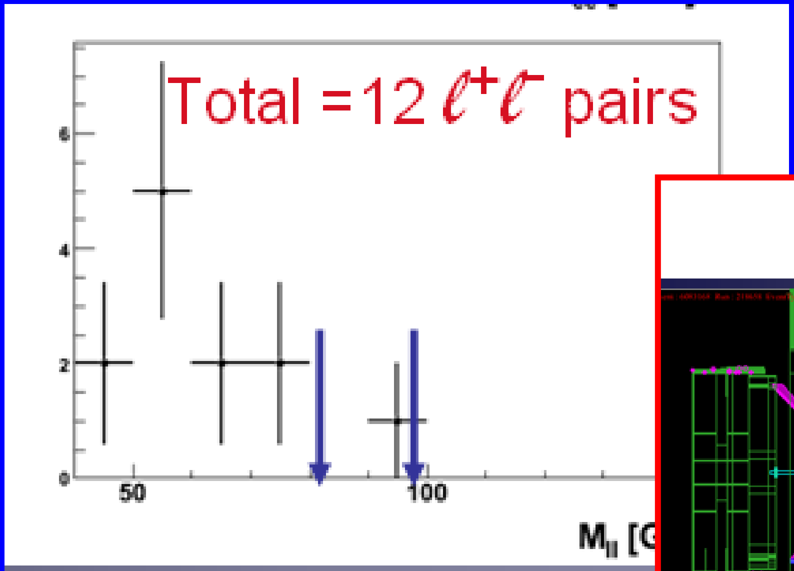


Plugs, Miniplugs, CLC, BSC empty

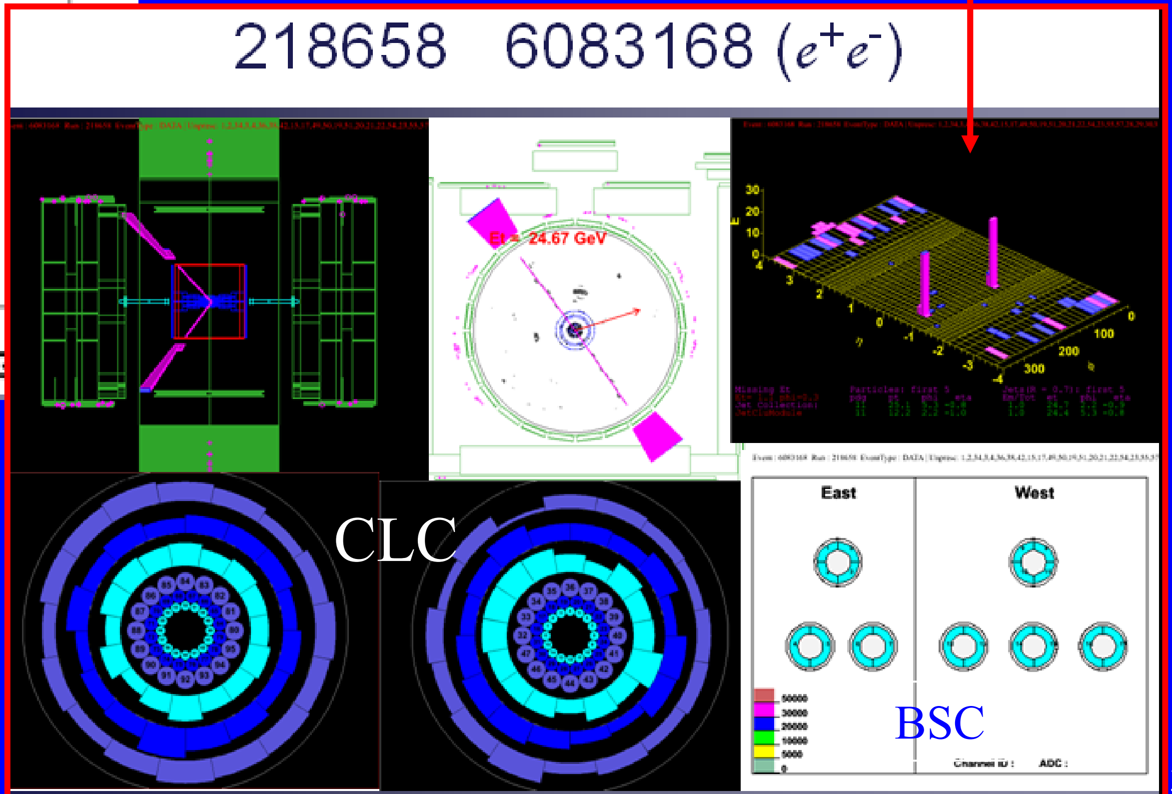


Search for Exclusive Z, and observation of high mass lepton pairs.

Have 12 exclusive candidate events e+e- and $\mu^+\mu^-$ M = 40 – 91 GeV2
11 have dphi < 0.02 rad and good QED candidates. Cross section ~ right.
91 GeV2 = M(Z) has larger dphi & pT … may be non-exclusive b/g (?)

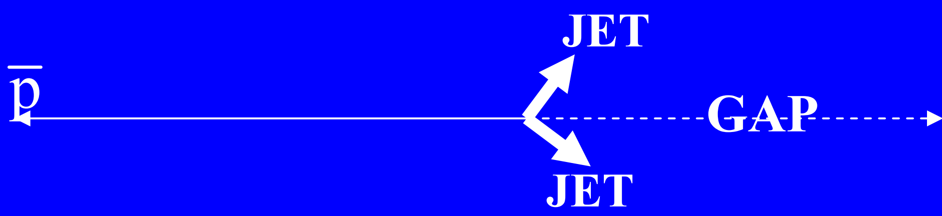


E not ET!

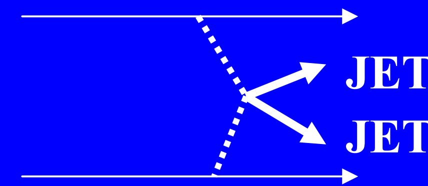


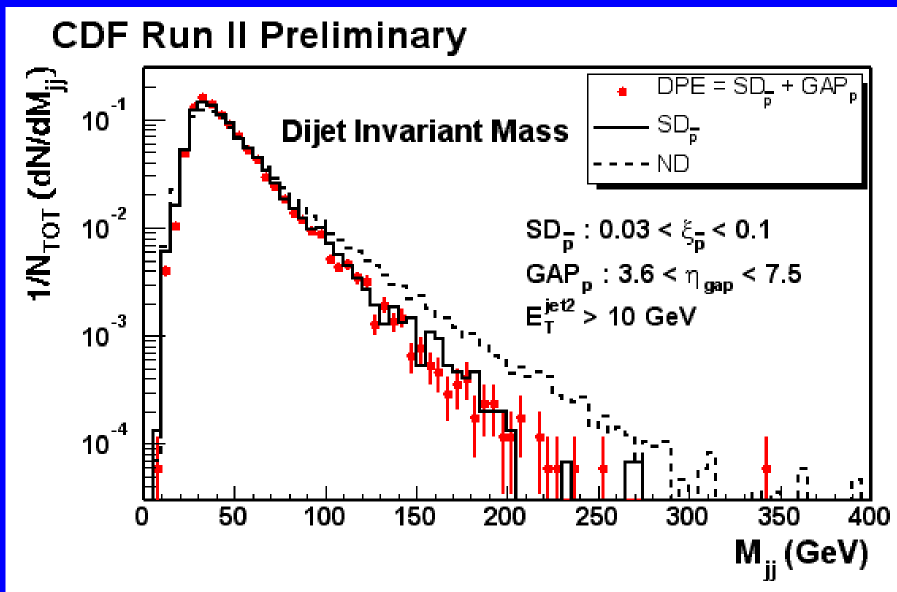
CLC and BSC empty in 8/12 events, others p→p* dissociation.
Paper in draft.

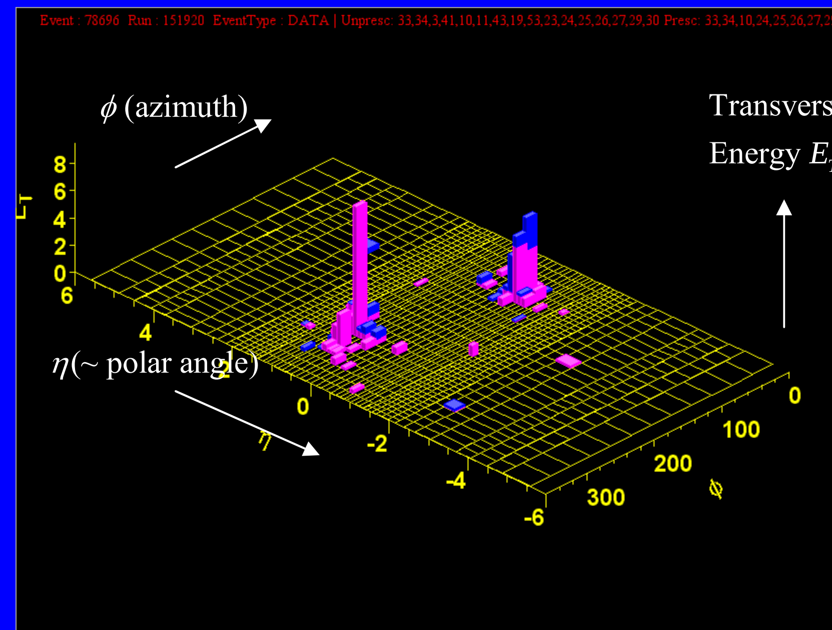
Double Diffractive Di-Jets in CDF



(p not seen)







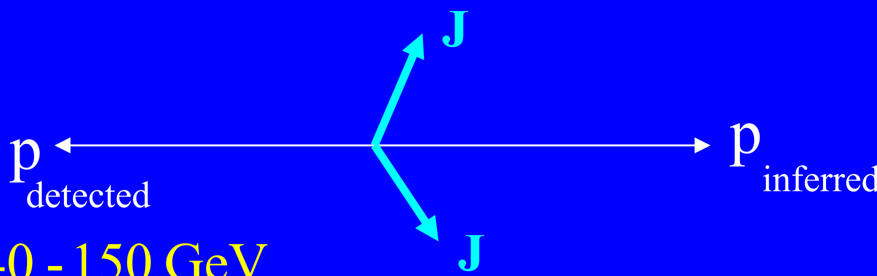
Jet <ET> spectra ~ same in SD and DPE

"Almost" exclusive di-jet,
Two jets and nothing else

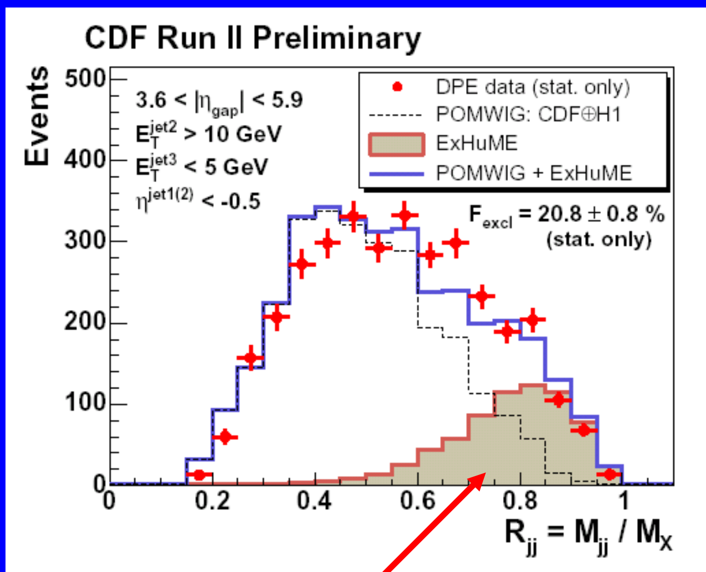
$$\frac{M_{JJ}}{M_{CEN}} > 0.8$$

Exclusive Dijets (2 central jets + "nothing") : CDF

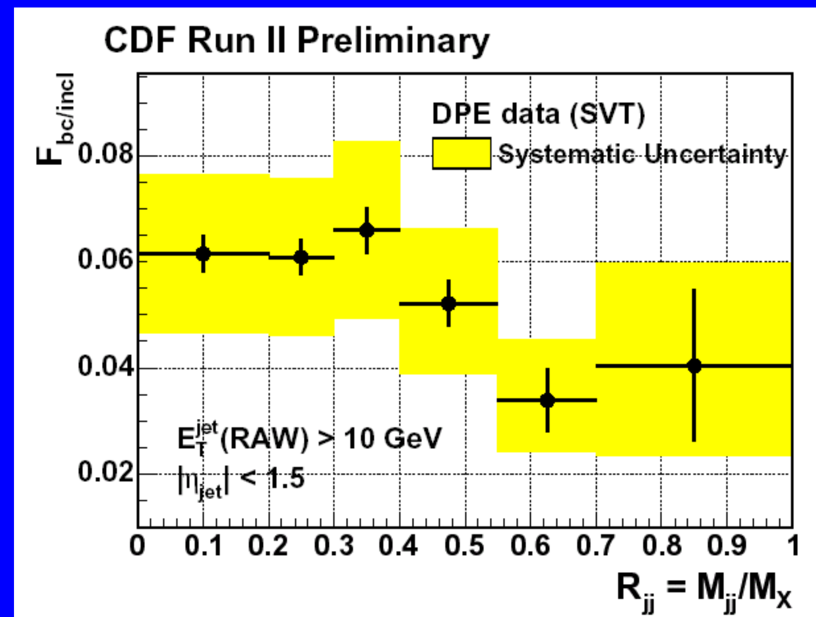
$$R_{JJ} = \frac{M_{JJ}}{M_X} \approx 1.0$$



M_X = total central mass $\quad M_{JJ} \approx 40 - 150$ GeV



ExHuME: MC with exclusive di-jets.

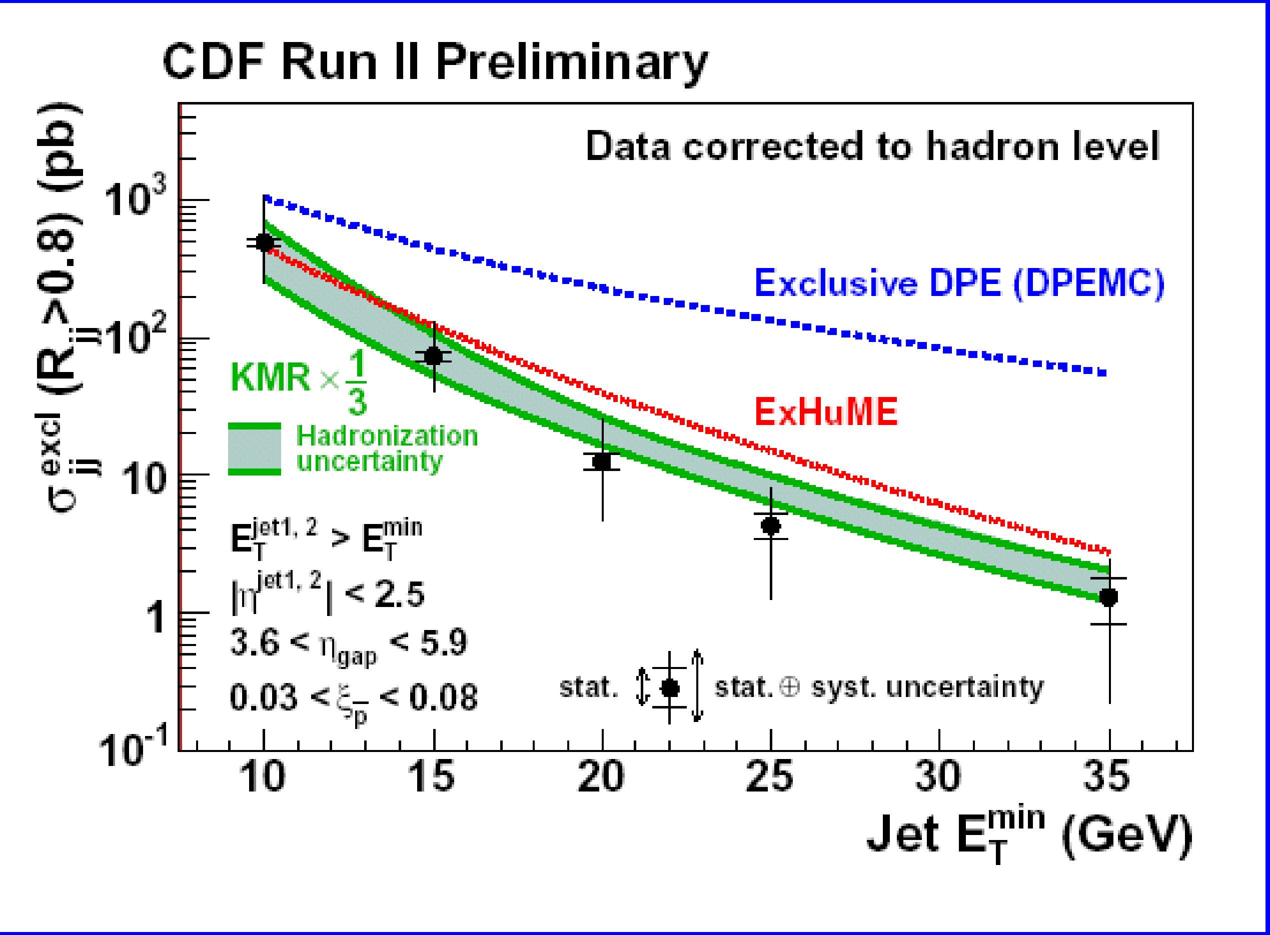


Cross section comparison not yet done

Apparent b-jet suppression as they become exclusive ?
(Theoretically → 0 as Rjj → 1, Jz=0 rule)
Greatly reduces QCD background

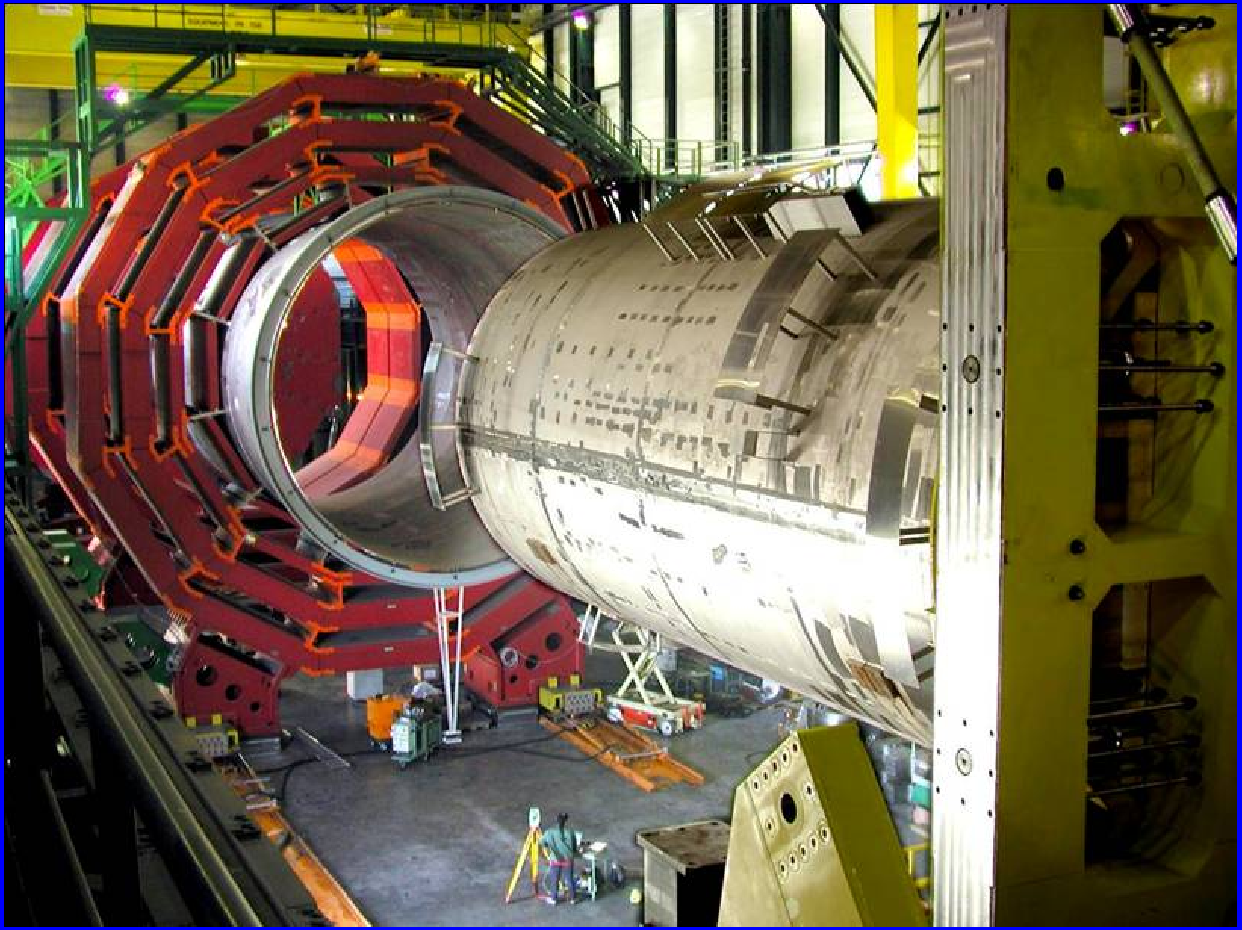
Exclusive DiJet cross section

$$p + \overline{p} \rightarrow p + JJ + \overline{p} + \sim \text{nothing else}$$



Cross section agrees with ExHuME / 3 (inside uncertainty)

FP420 : Forward Protons 420m downstream of CMS & ATLAS



CMS: Inner Vacuum Tank insertion

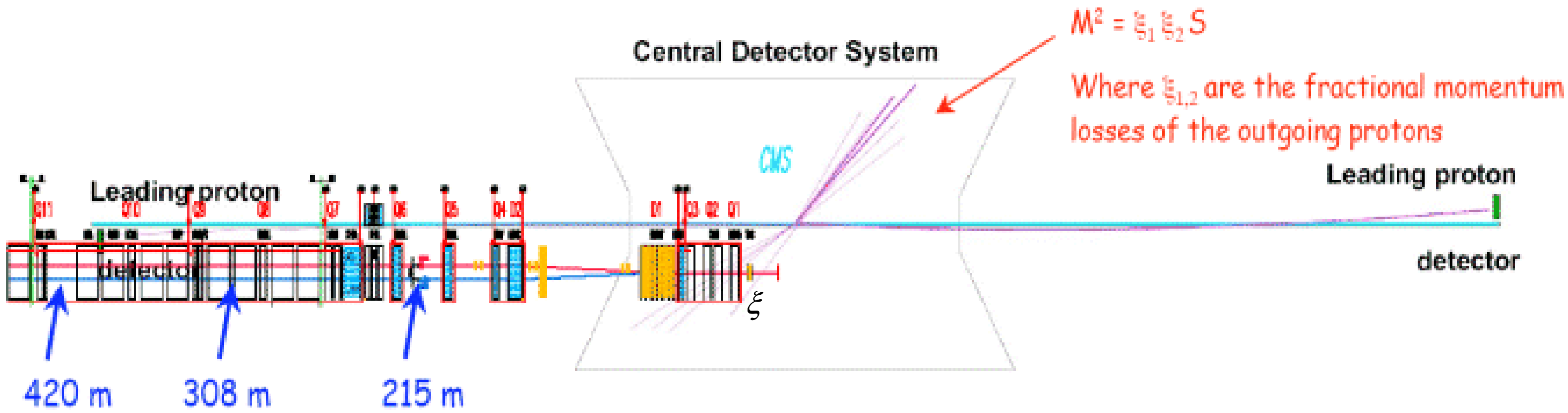
420 & 220m **CMS** **220 & 420m**

ATLAS

Very Forward Proton Detectors (& Momentum Measurement)

& FP420

Roman pot acceptances



ξ= fractional momentum loss

Straight Section

Low β^*: (0.5m): Lumi 10^{33}-10^{34} cm^{-2}s^{-1}

220m: $0.02 < \xi < 0.2$

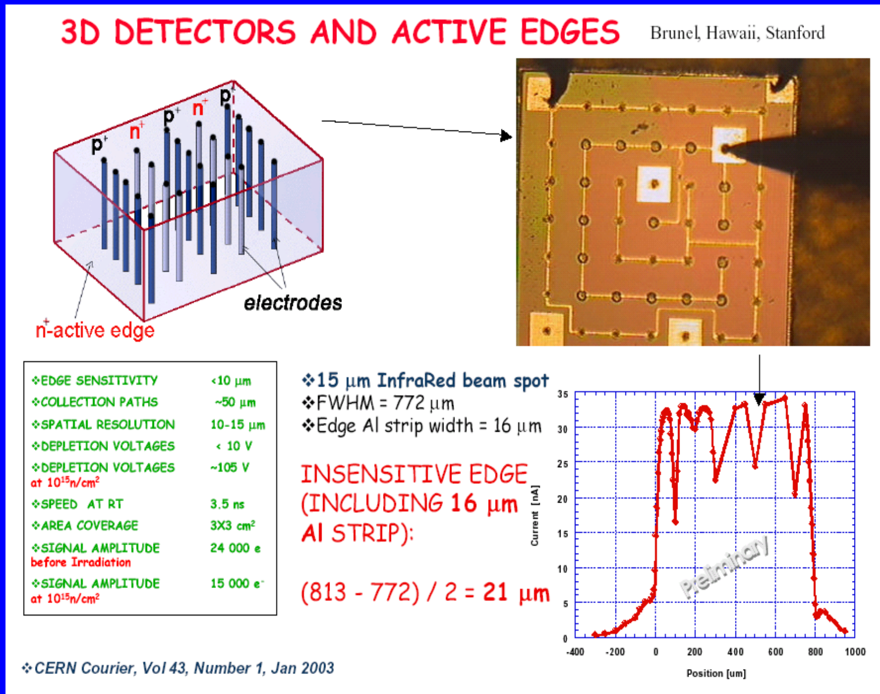
300/400m: $0.002 < \xi < 0.2$

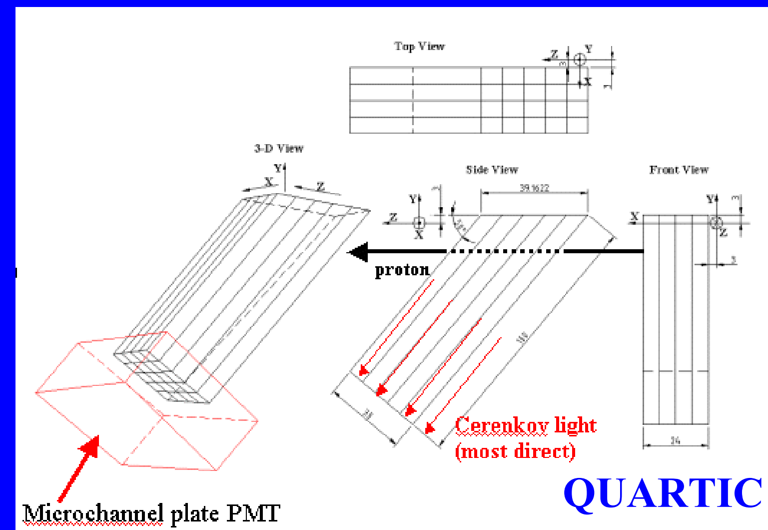
3D Si Tracking, Cerenkov Fast Timing

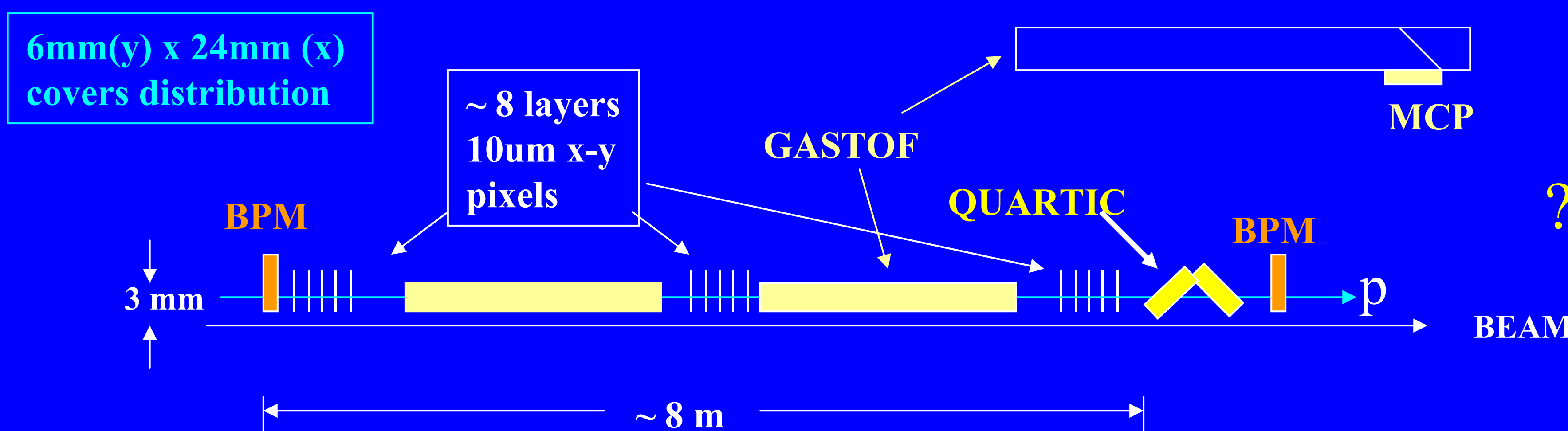
Resolution
Rad hardness
Edgelessness
Speed, S/N
Availability
Enthusiasts!

$\sigma_{TOF}(z) \approx 4.2 \rightarrow 2.1$ mm

cf $\sigma_z(\text{interactions}) \approx 52$ mm





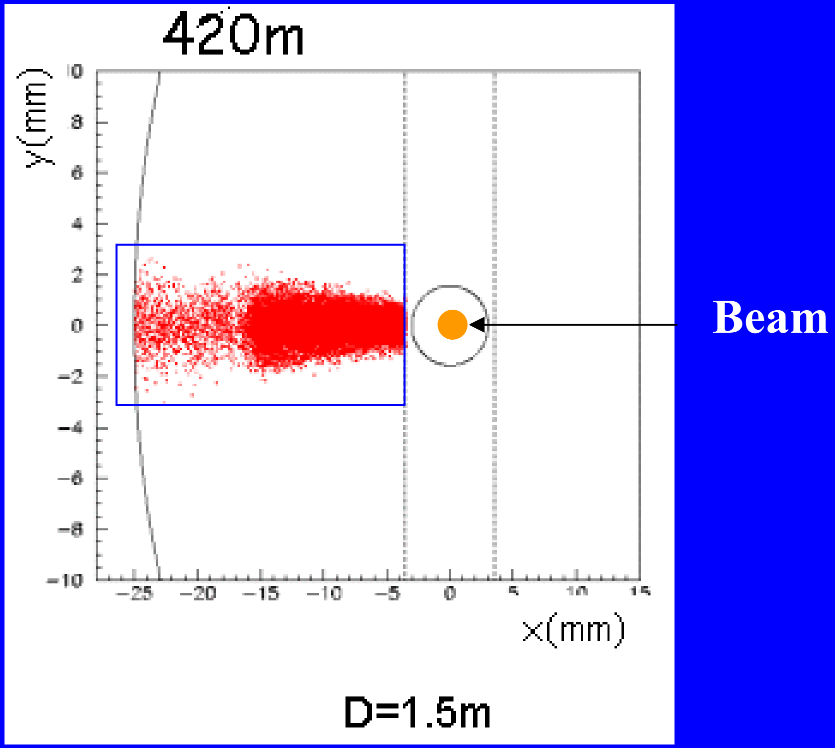


Measure distance of track from beam (5-10 um) and slope (~5-10 um over 10 m) → fractional momentum loss ξ

Protons, in x and y at detector

Normal Low-β operation

Note: detector 6mm(y) x 24mm (x) covers distribution.



Fast Timing Counters: GASTOFs and QUARTICs

Pile-Up background: p's, JJ or WW from different collisions

Counters with ~ 10 ps timing resolution behind tracking

10 ps = 3 mm

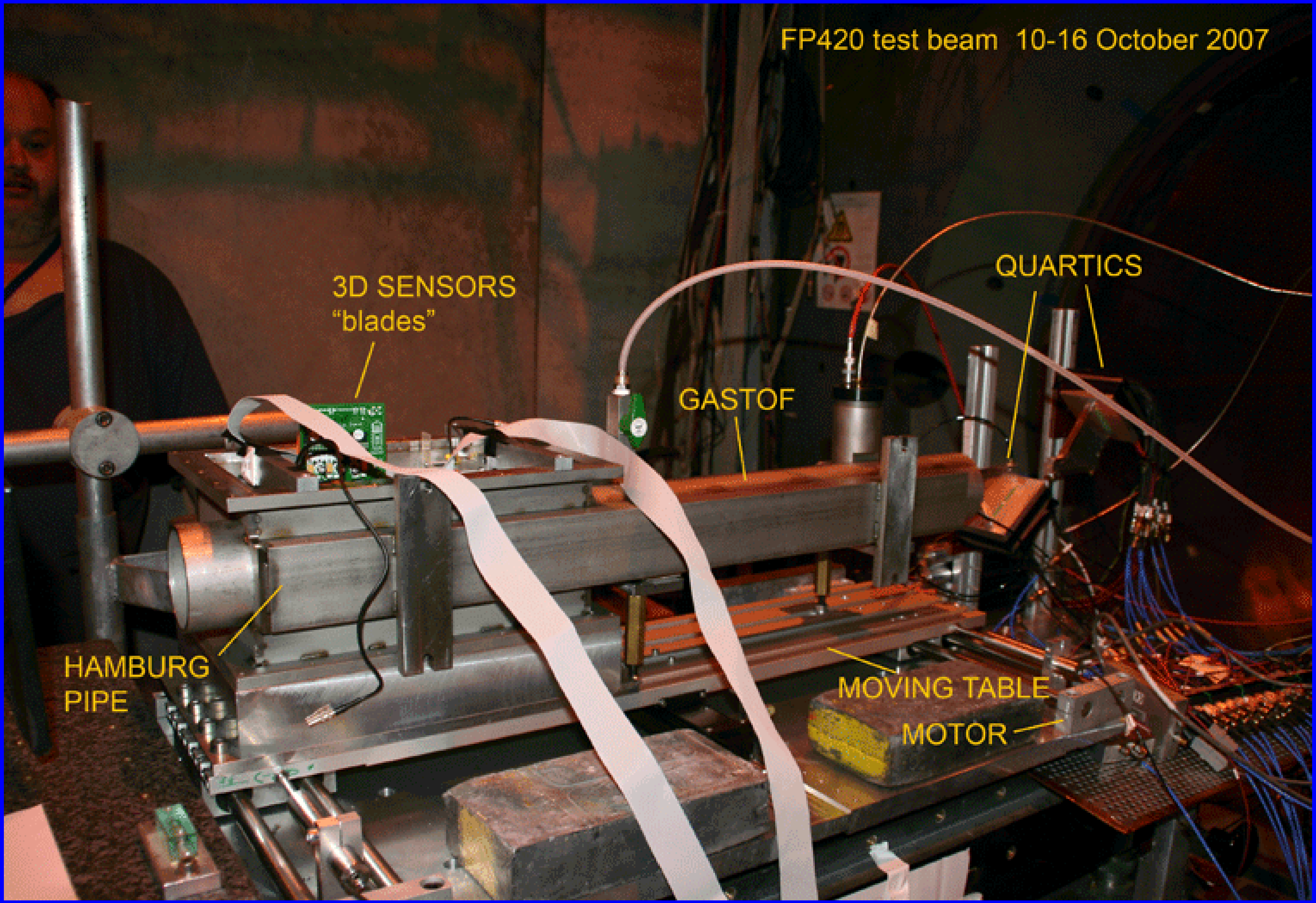
$$\frac{3mm}{\sqrt{2}} = 2.1mm$$

1) Check both p's from same collision (reduce background)
2) Get z(vertex) to match with central track vertex
3) Tell what part of bunches interacting protons were (F-M-B)

Solution:
Cerenkov light in gas or quartz (fused silica) bars →
MCP-PMT (Micro-Channel Plate PMT)

Oct 07 test beam at CERN:

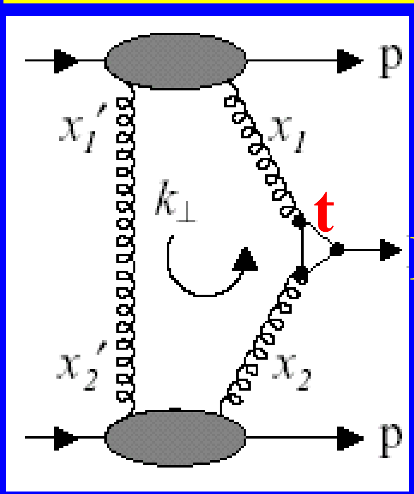
"Hamburg pipe", 3D Si tracking, GASTOF & QUARTIC timing



Central Exclusive Production of Higgs

Higgs has vacuum quantum numbers, vacuum has Higgs field.
So pp → p+H+p is possible.
Allowed states: $I\ J^{PC} = 0\ \text{even}^{++}$

u-loop : γγ   c-loop : χ_c^0
b-loop : χ_b^0 t-loop: H



J >= 2 strongly suppressed at small p angle (t)

Process is gg → H through t-loop as usual with another g-exchange to cancel color and even leave p's in ground state.
If measure p's:

4-vectors

$$M_{CEN} = \sqrt{(p_1 + p_2 - p_3 - p_4)^2} \longrightarrow \sigma(M_H) \approx 2\ \text{GeV per event}$$

Even for $H \rightarrow W^+W^- \rightarrow l^{\pm}\nu JJ$!

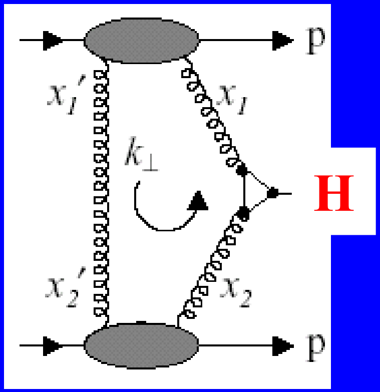
MGA+Rostovtsev: hep-ph/0009336

and $\gamma\gamma \rightarrow \tilde{l}\,\tilde{l}$ etc...

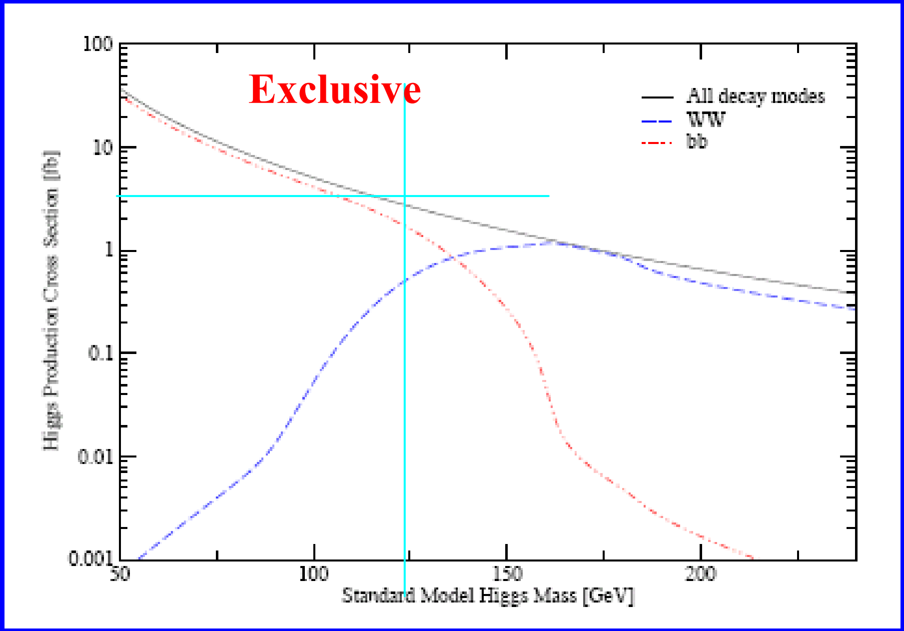
http://www.fp420.com

What is exclusive H cross section?

$$\sigma[pp \to p + H + p](M_H), \sqrt{s} = 14\ \mathrm{TeV}$$



Calculation involves:
gg → H (perturbative, standard, NLO)
Unintegrated gluon densities $g(x_i).g(x_i')$
Prob.(no other parton interaction) ("Gap survival")
Proton form factor
Prob.(no gluon radiation → no hadrons) ***Sudakov Suppression***



Durham Gp: Khoze, Martin, Ryskin, Stirling
hep-ph/0505240 ++

σ ~ 3 fb (M(H)=125 GeV)
"factor ~ 3 uncertainty"

➡ 30 fb^-1 → ~ 100 Ae events
(Ae = acceptance, efficiency)

But other estimates differ by "large" amounts!
Need to "calibrate" theory!

What is H Signal:Background? (not pile-up)

$H(120-135\ \mathrm{GeV}) \to b\bar{b}$

$H \to b\bar{b},\ W^{+}W^{-},\ ZZ$

Inclusively, $gg \to b\bar{b}$ background overwhelming

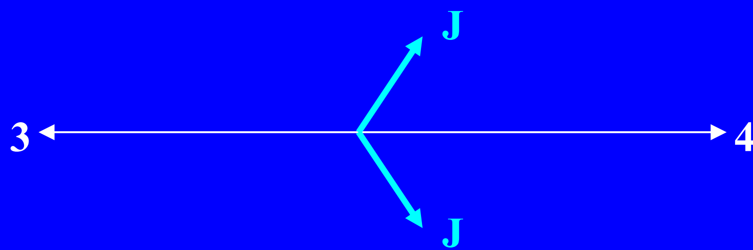
Exclusively, $pp \to p + qq + p$ (q = quark jet)

strongly suppressed at LO $\left(\sim \frac{M_q^2}{M_H^2}\right)$ by

spin selection rule $J_Z = 0$.

Most "exclusive dijets" are gg

Need b-tagging, then $\frac{S}{B}(\mathrm{SMH}) \sim 3 \times \frac{1\ \mathrm{GeV}}{\sigma(M)}$



> $q\bar{q}$ dijets strongly suppressed
> $J = 1$ forbidden, J=0 strongly favored
> $J = 0,2$ discrimination possible

Kinematic constraints:

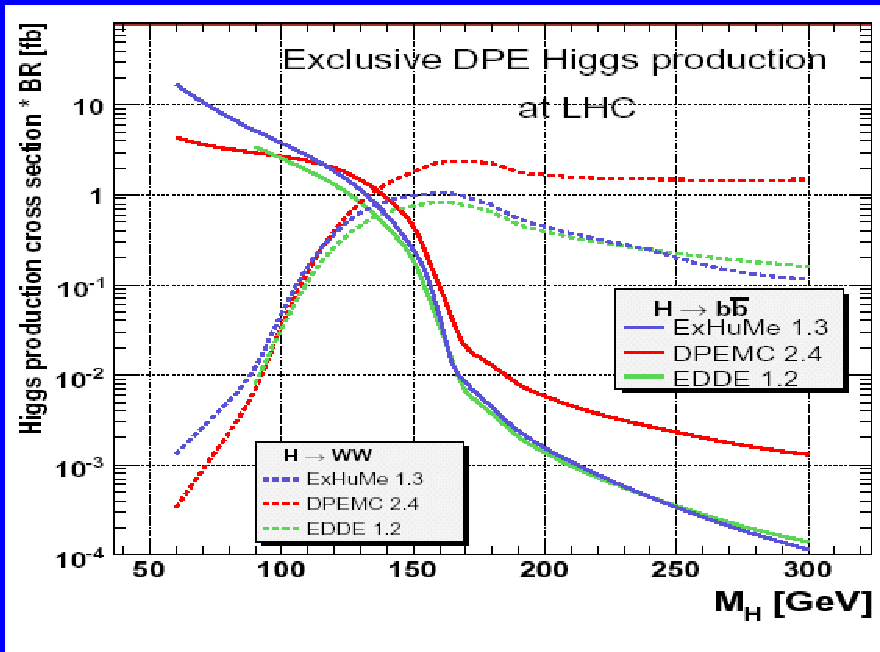
$E_{T,1} \approx E_{T,2};\ \phi_1 = -\phi_2$

$$\xi_{3(4)} = \frac{1}{\sqrt{s}} \sum_{1,2} E_T e^{-(+)\eta}$$

Trigger is issue:
Probably need asymmetric
220m + 420m and:
Eventual trigger upgrade??

$$\left(\xi = 1 - \frac{p_{\mathrm{out}}}{p_{\mathrm{beam}}}\right)$$

Cross section for p+p $\rightarrow$ p + SMH + p at LHC, x branching fractions:



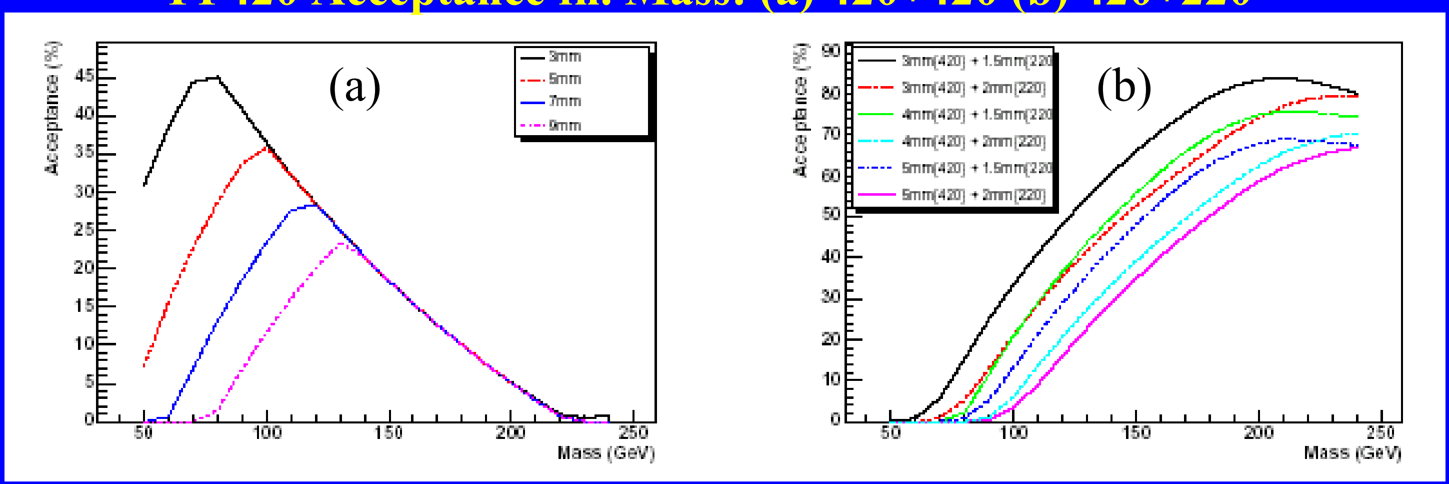
Small (~ fb) but S:B can be high.

ExHuMe “verified” by 2-photon, χ_c & JJ

< 140 GeV : bbar,

> 140 GeV, WW(*)

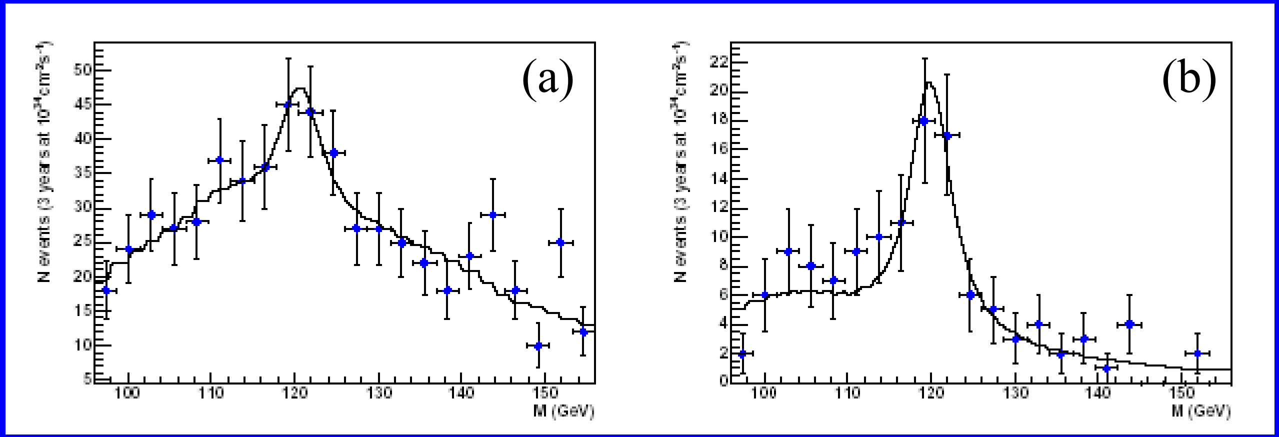
FP420 Acceptance fn. Mass: (a) 420+420 (b) 420+220



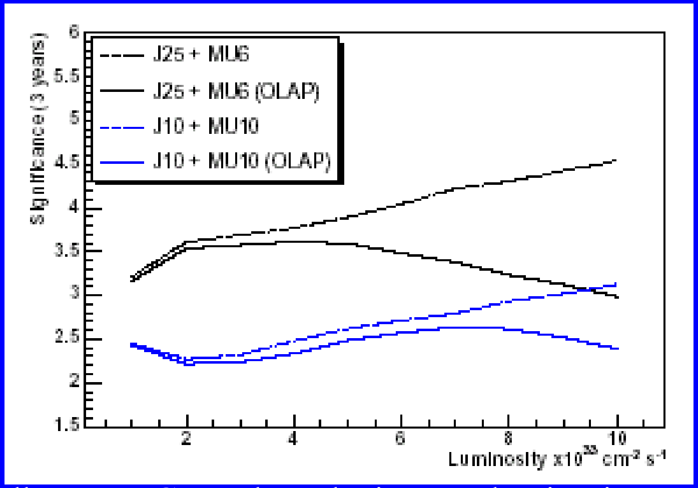
Simulations of SMH → b-bbar signals & background

Cox, Loebinger and Pilkington arXiv:0709.3035 (JHEP t.b.p.)

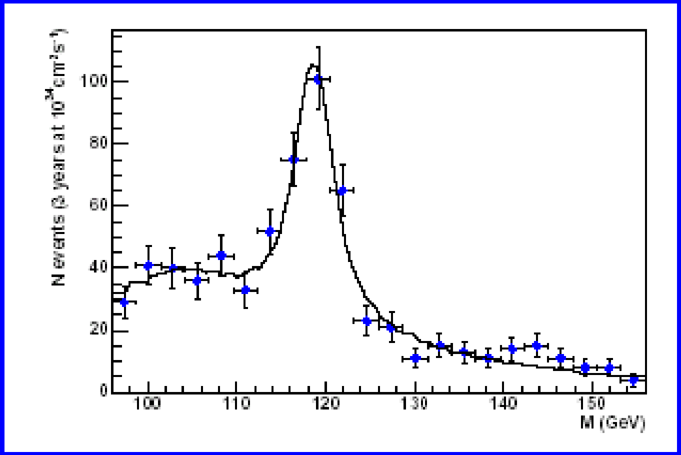
(a) 300/fb = 3 years at 10^34, 420+420, L1 trigger on jets, muons, 25 kHz
(b) Same with no pile-up background – super-high resolution p-timing



SMH significance, 120 GeV SMH, vs L(E33)
3 years with no pile-up b/g. JET + mu trigs



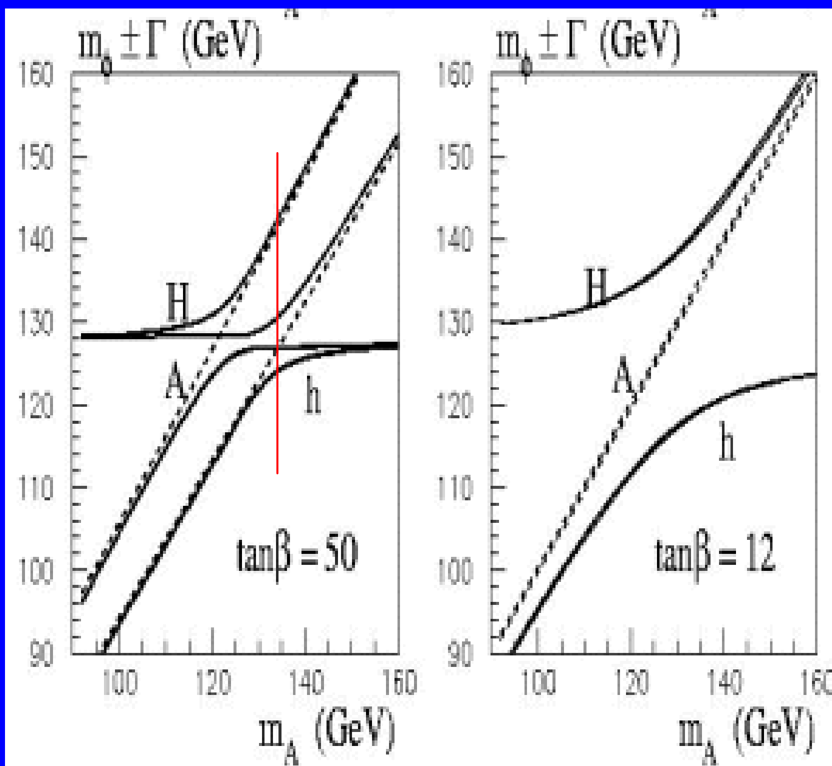
... and if 420+420 in L1 trigger



future upgrade in latency?

MSSM

Can have {h, A, H} close together in mass (few GeV)
Hard to resolve by inclusive production.
Exclusive advantages: higher production than SM, A highly suppressed
Excellent mass resolution could separate h and H (unique)
Excellent mass resolution might even measure H widths (if ~ few GeV)



Durham Group (KMRS)

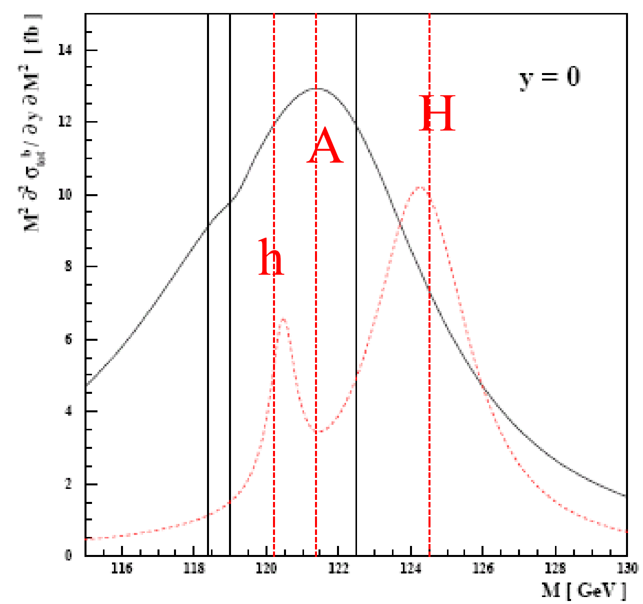


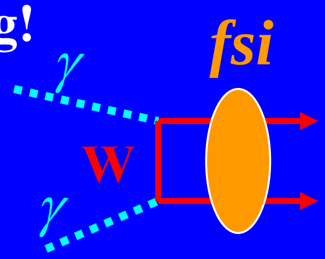
Figure 4: *The hadronic level cross section* $M^2 \frac{\partial^2 \sigma^b_{tot}}{\partial y \partial M^2}(y = 0)$ *when the produced Higgs bosons decay into b quarks, calculated using CTEQ6M PDFs. Tri-mixing scenarios have been taken with* $\Phi_3 = -90°$ *(solid lines) and* $\Phi_3 = -10°$ *(dotted lines). The vertical lines indicate the three Higgs-boson pole-mass positions.*

J.Ellis, J.S.Lee and A.Pilaftsis, PRD71:075007, hep-ph/0502251

Non-SM cases : no Higgs? MSSM Higgses?

1) **No SMH? Can we exclude? Suppose measure 100 exclusive $\gamma\gamma$ in CMS.**
(~ 0.1 fb^-1 effective S.I.Lum) → predict p+SMH+p to ~ 20%
Expect (say) 100 pHp events in 30 fb^-1, see < 50. Conclusion?

2) **No SMH or MSSM-Hs? WW physics becomes very interesting!**

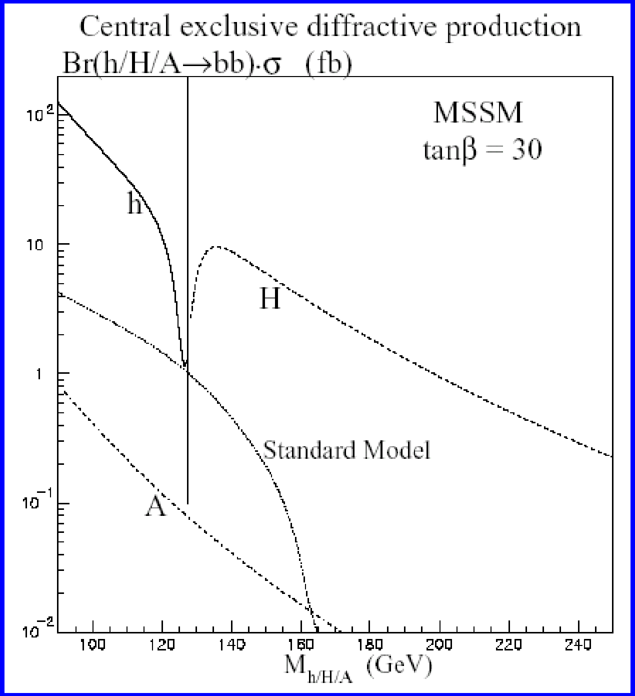


$pp \rightarrow p + W^+W^- + p$ via $\gamma\gamma \rightarrow W^+W^-$ $\quad \sigma \approx 50$fb (precisely known in SM)

W^+W^- Final State Interactions distort $\frac{d\sigma}{dM_{WW}}$, visibly? New physics?

Preview of ILC physics!

3) **In case of SUSY, Forward p-tagging can be crucial! Cross section can be *much* higher than SMH. Decays to $b\bar{b}$ enhanced. A(CP –ve) highly suppressed.**

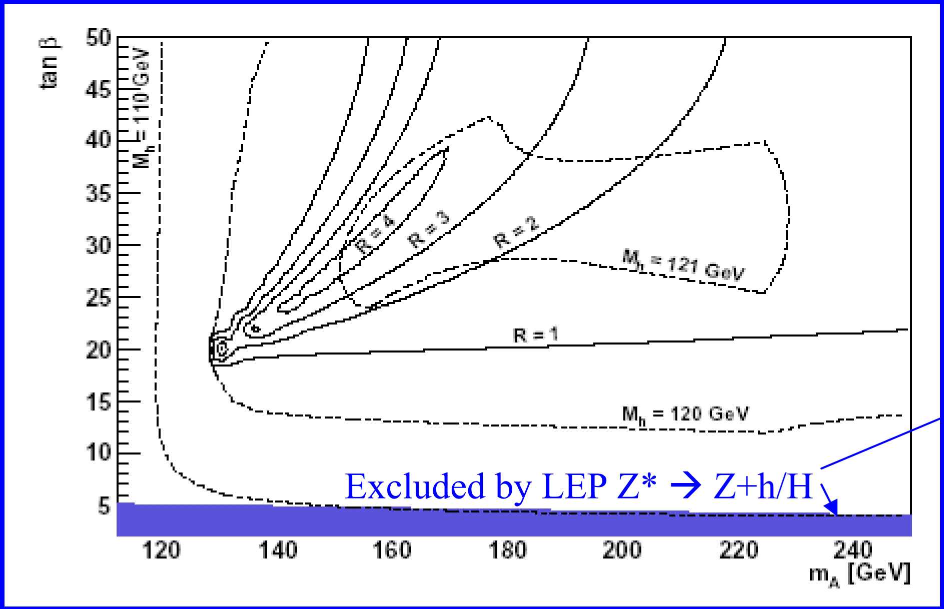


Kaidalov Khoze Martin Ryskin
hep-ph/0307064

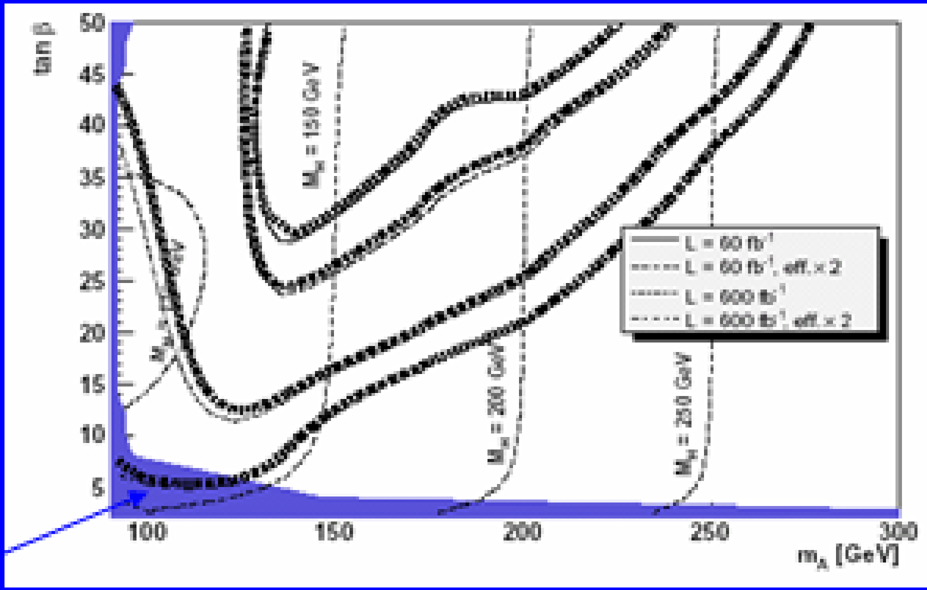
MSSM SUSY: cross section x BR → b-bbar larger than SM

Heinemeyer et al., arXiv:0708.3052

Ratio (MSSM/SM) h → WW(*) vs M(A) and tan(beta). M(h) ~ 120 GeV.



60/fb 600/fb



In [tan β : M_A] plane, 5σ contours (top) and 3σ (bottom); $H \to b\bar{b}$, 60/fb & 600/fb

M(H) contours : dashed lines

Exclusiveness brings many rewards. H → Jet Jet case

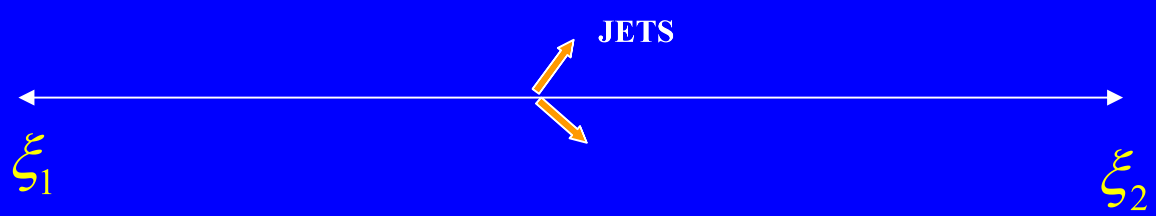
$$M_{CEN} = \sqrt{(p_1 + p_2 - p_3 - p_4)^2}$$

Two jets' E_T are the same to ~ 1 GeV, $\Delta\phi = 180^0$
and, knowing that and η_1, η_2 and ξ_1(220)
in L1 trigger (fast look-up) can use correlation
to reduce L1 trigger rate.

$$\xi = 1 - \frac{p_z(out)}{p_z(beam)}$$

(fractional momentum loss)

$$\xi_{1(2)} = \frac{1}{\sqrt{s}} \sum_{jets} E_{Ti} e^{+(-)\eta_i}$$



420m just too far for L1 trigger. 420 + 220 + Jet info.

What is Signal:Background? H(135-200) (not pile-up)

$\mathrm{H}(135-200\ \mathrm{GeV}) \rightarrow \mathrm{W}^{+}\mathrm{W}^{-}$

$\sigma_{\mathrm{incl}}(\mathrm{W}^{+}\mathrm{W}^{-}\ \text{non-H}) \sim 100\ \mathrm{pb};\ \sigma(\mathrm{H}) \sim 20\ \mathrm{pb}$

& M(WW) resolution v.poor ($\nu(s)$ and/or jets)

Exclusive B/G is $\gamma\gamma \rightarrow \mathrm{W}^{+}\mathrm{W}^{-}, \sigma \sim 50\ \mathrm{fb}$, continuum

Mass resolution $\sigma_{\mathrm{M}}(\mathrm{WW}^{(*)}) \sim 2\ \mathrm{GeV}$ *any decay*

Exclusive $\mathrm{H} \rightarrow ZZ$, negligible B/G

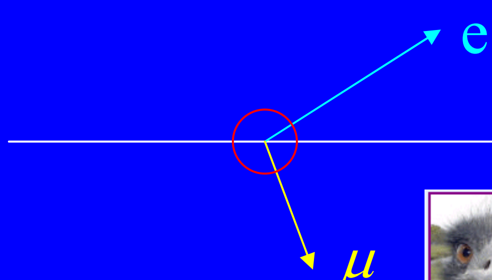
Examples: $WW \rightarrow l\nu l\nu, l = e, \mu$

NO OTHER TRACKS ON VERTEX!

(But only 4.6% of WW)

$\mathrm{H}(160) \rightarrow \mathrm{W}^{+}\mathrm{W}^{-} \rightarrow \mathrm{p}\ \ e^{+}\mu^{-}\ \not{E}_{T}\ \ \mathrm{p}$

$\mathrm{MM}^{2} = (p_{1} + p_{2} - p_{3} - p_{4})^{2} = \mathrm{M}_{\mathrm{H}}^{2}$



$\text{Always}: \sigma(M_{WW} \approx 2\ \mathrm{GeV})!$

Prob. ZERO BACKGROUND in ZZ!
~ 4 events ➔ DISCOVERY!

What is Signal:Background? H(135-200) → WW(*)

$$WW \rightarrow l\nu JJ, l = e, \mu, \tau$$

Durham Gp: Khoze, Martin, Ryskin, Stirling hep-ph/0505240

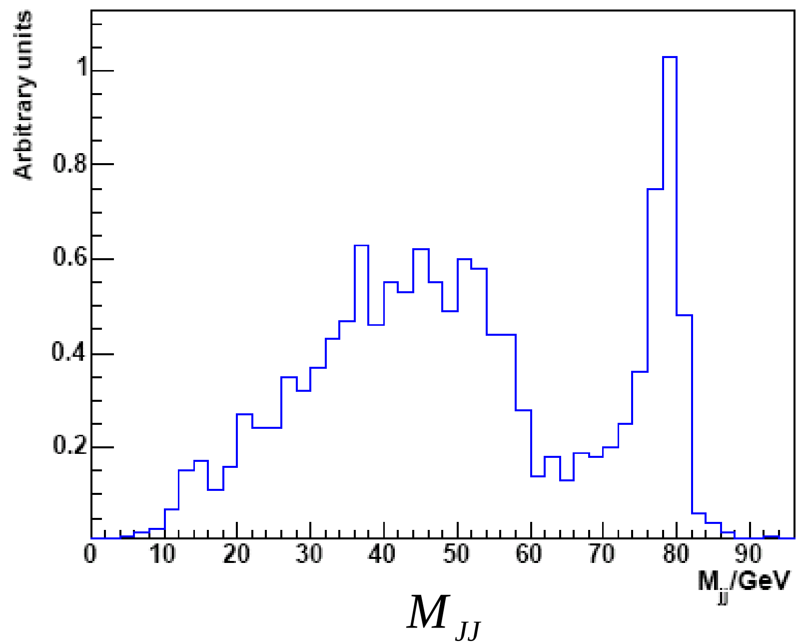
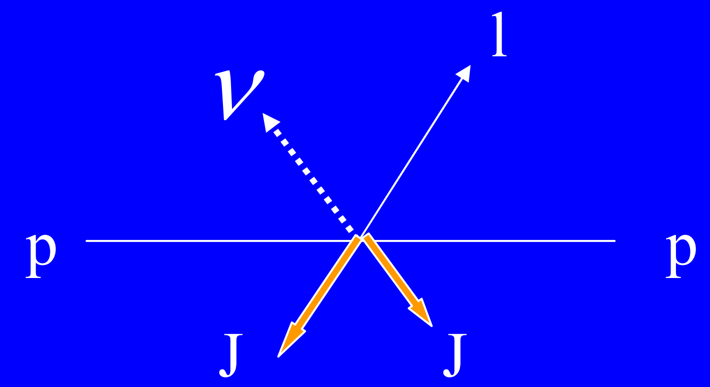


Fig. 6: The di-jet invariant mass distribution dN/dM_{jj} in the semi-leptonic decay channel $H \rightarrow WW^* \rightarrow l\nu jj$ for M_H = 140 GeV.



$$MM(12-34JJl) \approx 0(M_\nu)$$

$$MM(12-34JJ) = M_W^{(*)} \text{(even for } \tau\nu)$$

$$M(JJ) = M_W^{(*)}$$

Can use ~ 50% of WW (all but JJJJ)

$$\text{H}(180) \rightarrow \text{ZZ} \rightarrow l^+l^-\nu\bar{\nu} \ (\text{BR} \sim 10 \times l^+l^-l^+l^-)$$

$$MM(12-34l^+l^-) = M(Z_{\nu\bar{\nu}}), \ \sigma_M \sim 2 \text{ GeV!}$$

!! **Unfortunately very few events (SM)**

In WW/ZZ case, central trigger effective (420+420 OK)

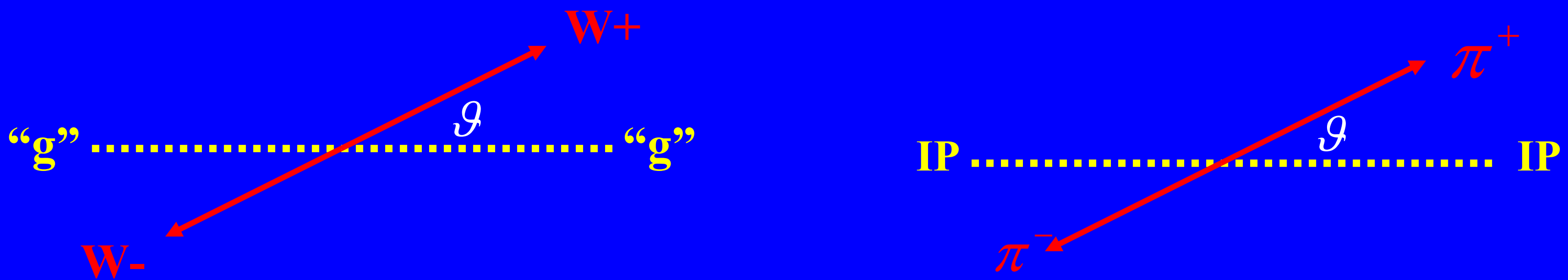
Determining Quantum Numbers of Central State (H?)

Is it J = 0, CP = ++?

In gg → X only **CP = ++** is allowed.
(a CP –ve A (MSSM) is highly suppressed)

gg → vector (J = 1) forbidden, Yang's theorem.

J = 0, 2 can be distinguished by angular distributions
→partial wave analysis. Can even see states hidden in overall M distribution!
Of course this needs many events.



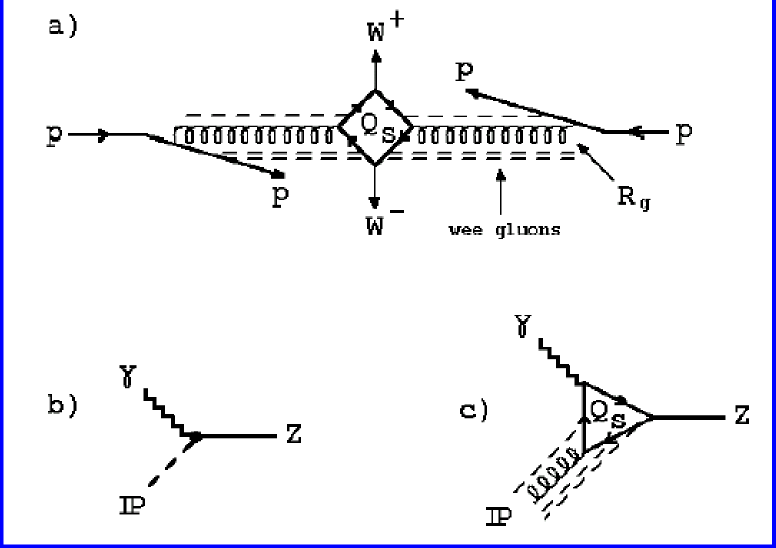
Moments H(LM) of the cos(ϑ) distributions → M(J=0), M(J=2).

e.g. ISR/R807 glueball search in $pp \to p + \pi^+\pi^- + p$ **NPB264 (1986) 154**

BSM: The White Pomeron

Alan White (ANL)

BFKL Pomeron = 2 reggeized gluons / ladder
White Pomeron = 1 reggeized gluon + sea wee g's



Asymptotic freedom → 16 color triplet q's
Only 6 known (duscbt)
But (!) 1 color sextet Q counts 5 times, so
{ud}+{cs}+{tb} + {UD} works!

$\Pi = U\bar{D}$ etc, η_6 ....EWSB, role of Higgs ***"composite higgs"***

Can be dark matter (N = DDU ~ TeV)

Pomeron couples strongly to WW through U,D loops

→Anomalous (quasi-diffractive) production of WW, ZZ (not WZ) production at LHC **(M(DPE@LHC) <~ 700 GeV).**

Dramatic effects at LHC, especially in pp → p + WW/ZZ + p
& pp → p + Z + p

Summary

Any states with vacuum quantum numbers and strong or electromagnetic couplings can be produced at LHC by

Central Exclusive Production

CDF: $e^+e^-, \mu^+\mu^-, J/\psi/\psi'(2S), \chi_c, Y1,2$(cand.) **+ JJ**

This includes *Higgs boson(s), W-pairs*, lepton and photon pairs.
Cross section pp → p+SMH+p known to factor ~ 3 (~ 5 fb)
If protons well measured, can get mass of central state to ~ 2 GeV per event, Quantum numbers (J, CP) and couplings to gg.
need both 220m and 420m detectors.
R&D on S:B can be good – excellent in BSM scenarios.
For good acceptance/resolution FP420:
tiny but v.high precision tracking, timing, BPM
Best particle spectrometer ever, using part of LHC

We have proposed this as extensions to CMS and ATLAS for installation in 2010-2011 shutdown

BACK-UPs

$\psi(2S)$ photoproduction
(or possible odderon exchange)

Kinematics well described by STARLIGHT MC

Again much broader

$\Delta\phi(\mu-\mu), p_T(\mu^+\mu^-)$ **than**

QED continuum : $\gamma + \gamma \rightarrow \mu^+\mu^-$