Exclusive Central Production at the Tevatron (→ LHC)

+ some diffraction

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for the CDF Collaboration

Introduction, definitions, prehistory & other places

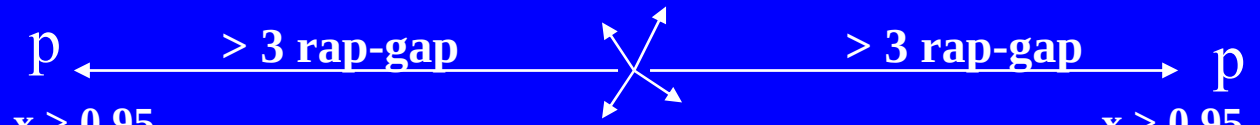
Exclusive lepton pairs: $\gamma\gamma \to e^+e^-, \mu^+\mu^- (QED)$

Photoproduction, γ+ IP → $J/\psi, \psi', \Upsilon(1S,2S,3S)....Z(LHC\ ??)$

D IP E : IP + IP → χ_c, χ_b
IP + IP → $\gamma\gamma$
IP + IP → J+J, bJ + bJ
IP + IP → H → $b\bar{b}$ or WW/ZZ

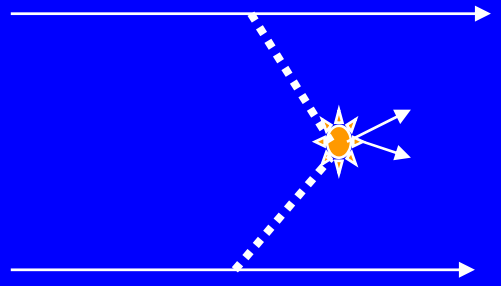
Central Exclusive Production

"Vacuum Excitation"



$M < 0.05\sqrt{s}$ $\xi < 0.05$

… both protons coherently scattered. Central state fully specified and measured.
As distinct from "inclusive" production: e.g. J/psi + "anything"



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

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

γ or g $(+g, gg)$ (W,Z allowed, but from q's)

Central state Quantum Numbers restricted:

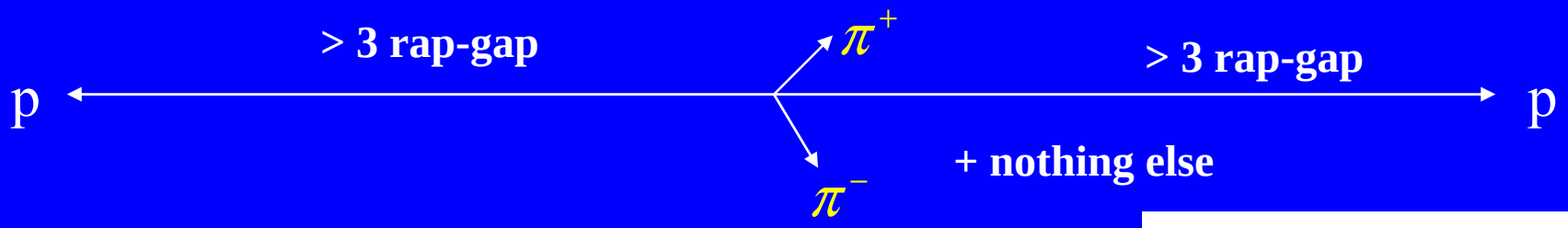
$I^G J^{PC}(\mathrm{D\ IPE}) = 0^+0^{++}, 0^+2^{++}$

$J^{PC}(\gamma - \mathrm{IP}) = 1^{--}$

Low Mass Central Exclusive Production

pp → p X p
X fully measured

ISR $\sqrt{s}$ = 63 GeV ... then SPS at lower $\sqrt{s}$



(rho just visible in moment analysis)

No ρ, broad $\sigma(600)$?

Search for "Glueballs"

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

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

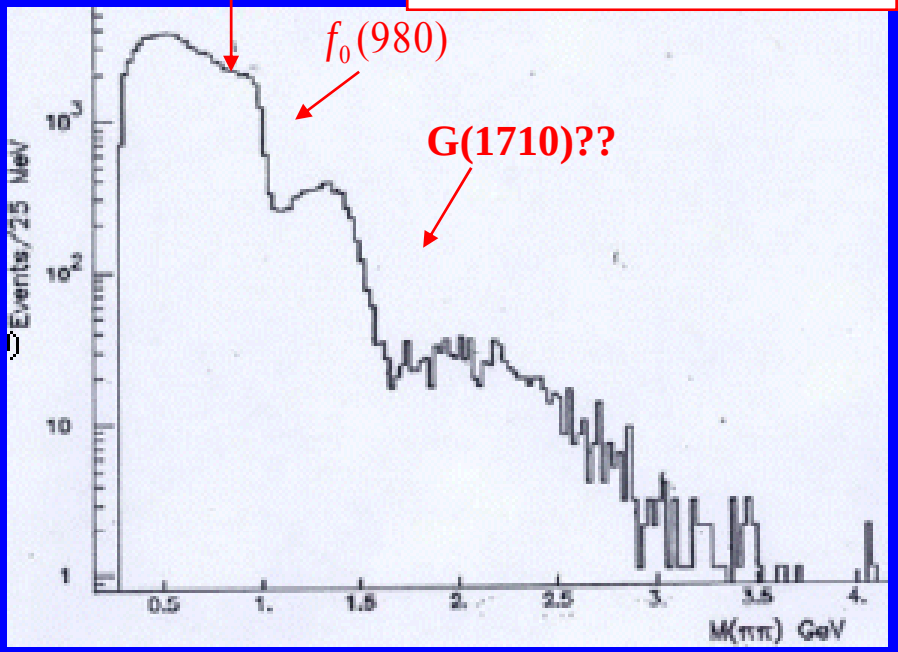
… and

$\alpha\alpha \rightarrow \alpha + \pi^+\pi^- + \alpha$

coherence!

Angular correlations → spins

R807: NP B264 (1987) p.154



Central Exclusive Production in Different Machines

In e^+e^- collisions (LEP energies → I L C) :

$\gamma\gamma \to l^+l^-, q\bar{q}$ → hadrons, and at high energy:

WW → WW, WW → Z , 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), Higgs, $\gamma\gamma$

New in CDF

γ-IP → vector mesons (... Υ, Z(allowed but tiny)?)

$\gamma\gamma$ → l+l- ($q\bar{q}$ too but buried?)

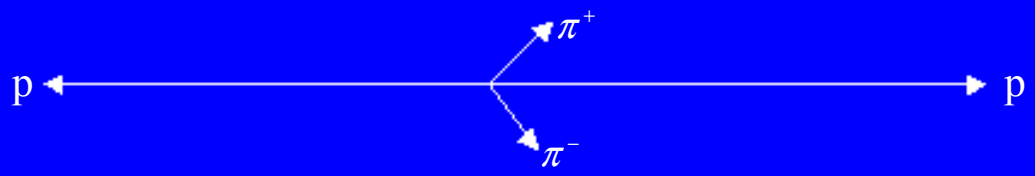
.....

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

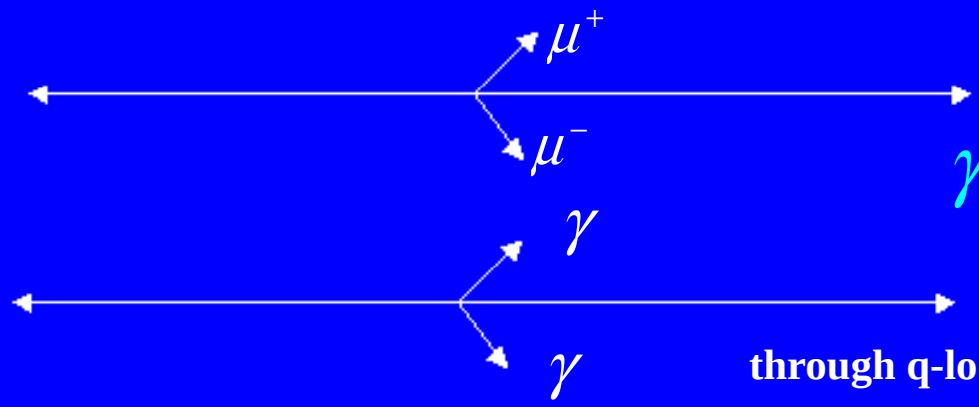
γ -IP and IP+IP

Central Exclusive Production

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



At CERN ISR
Glueball Search

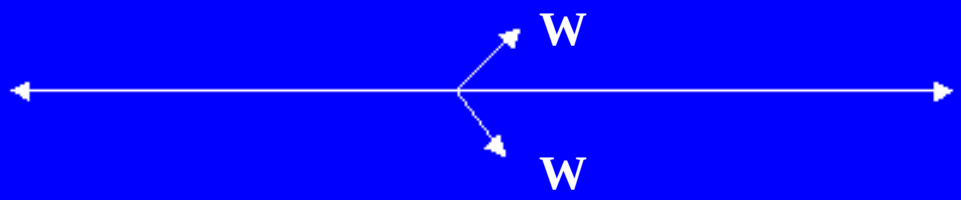


At Tevatron & LHC

$\gamma\gamma \to \mu^+\mu^-, e^+e^-$

$gg \to \gamma\gamma$

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



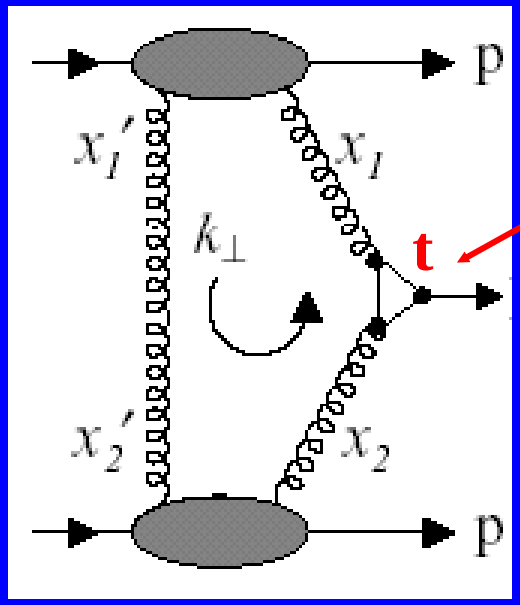
$\gamma\gamma \to WW; H \to WW, H \to ZZ$

$H \to b\bar{b}; BSM \to WW, SUSY\ etc$

Central Exclusive Production of Higgs Bosons (LHC)

Gluon-gluon fusion + bleaching gluon exchange

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



q – loop : γγ c – loop : χ_c

b – loop : χ_b t – loop : H

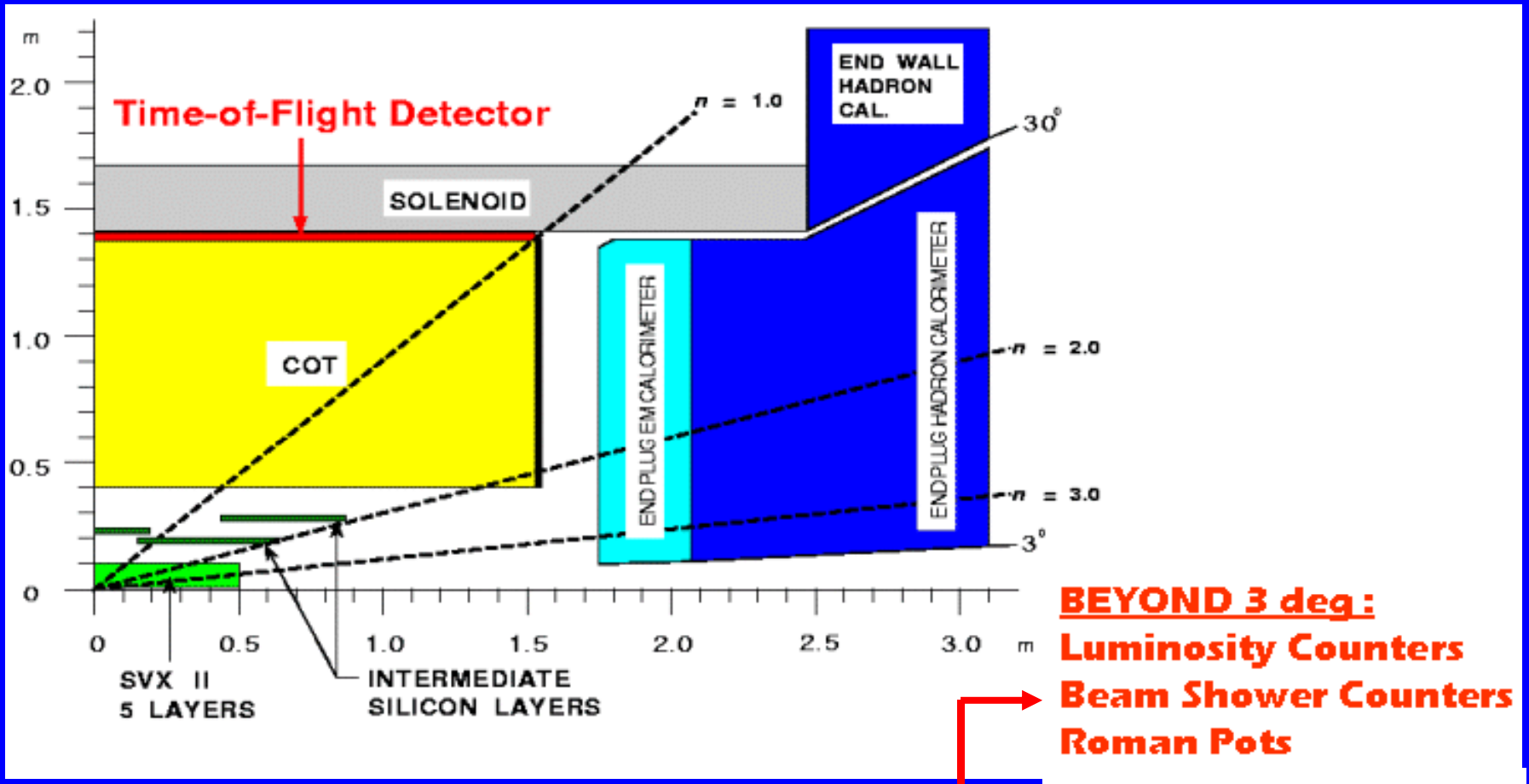
Theory can be tested, low x gluonic features of proton measured with exclusive γγ, χ_c^0 and χ_b^0 production.

Advantage: F.S. not strongly interacting
Disadvantage: v.small cross section, experimentally difficult.

Hadrons with same quantum numbers as Higgs.

CDF Detector at Fermilab Tevatron

980 GeV pbar → ← 980 GeV p



BEYOND 3 deg :

Luminosity Counters

Beam Shower Counters

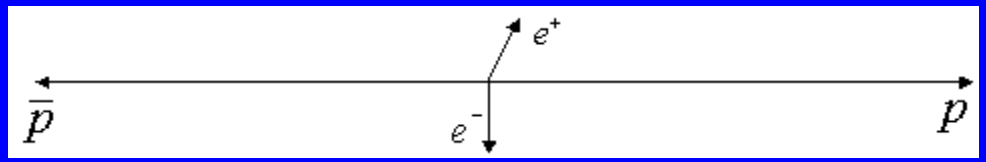
Roman Pots

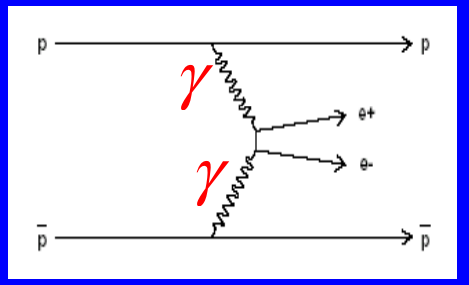
MiniPlug calorimeters

Roman pots not used in the data in this talk (acceptance) except exclusive di-jets

Coverage $-7.5 < |\eta| < +7.5$

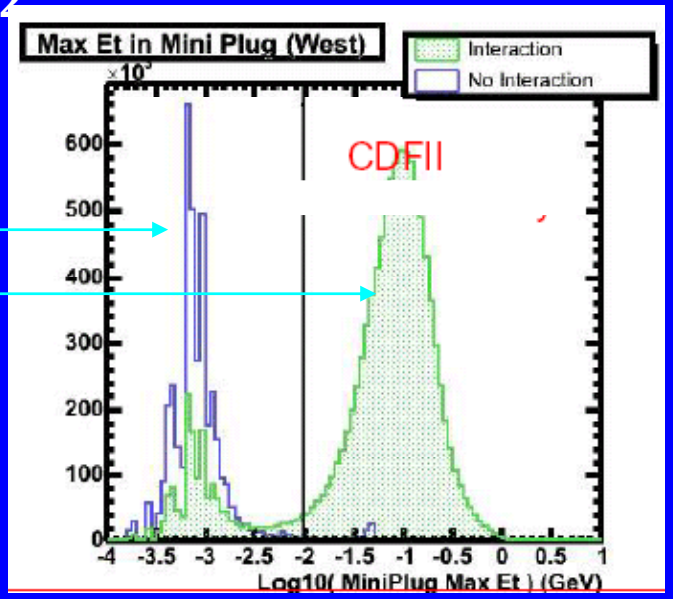
Search for Exclusive Lepton Pairs I : e+e-





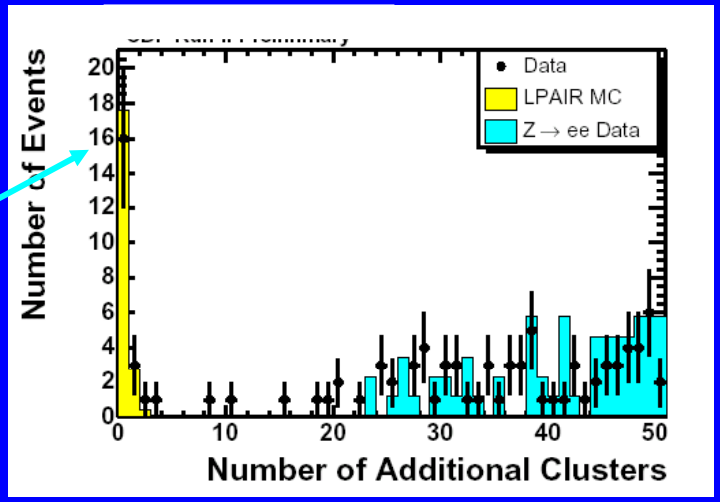
Motivation was search for exclusive $\gamma\gamma$ (cf H)
Trigger: 2 EM showers + forward BSC veto (p not visible) ~ 1M on tape
Off-line, exactly 2 showers, ET > 5 GeV and |eta| < 2
All CDF calorimetry and counters in "noise"

Example: Miniplug, hottest tower ET < 10 MeV
Empty events
Active events



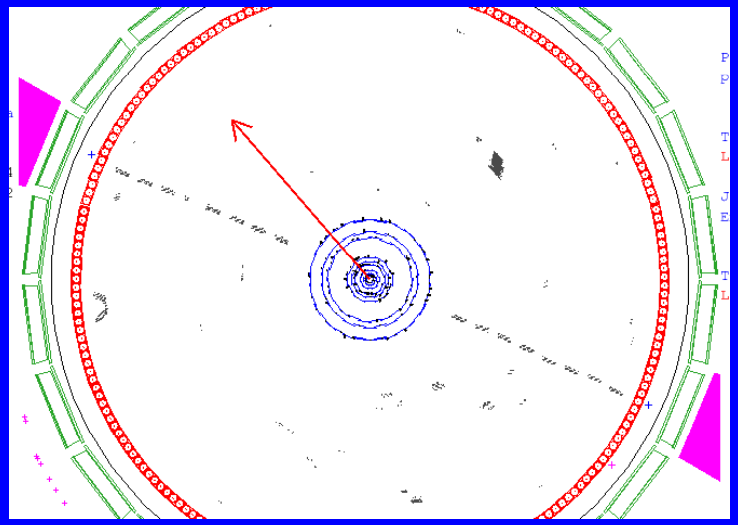
19 superclean events,
16 had exactly 2 (+-) tracks (e+e-)

Exclusive signature

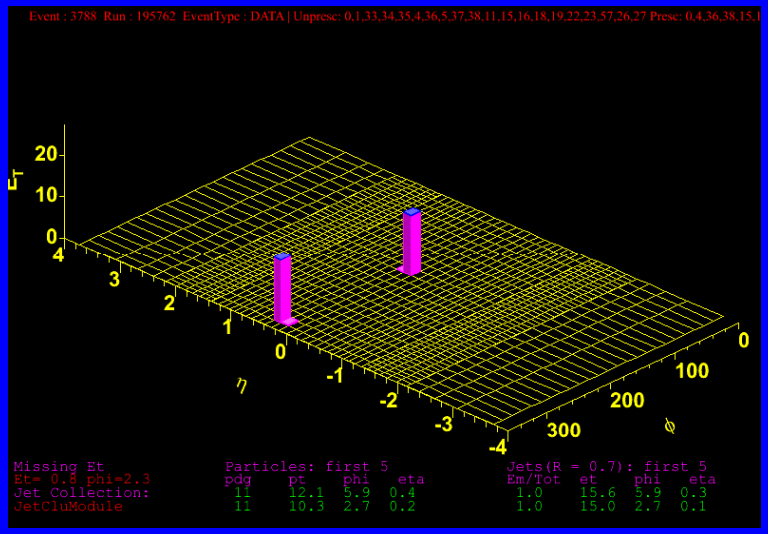


Exclusive Two Electron Event

Run/Event 195762/3788

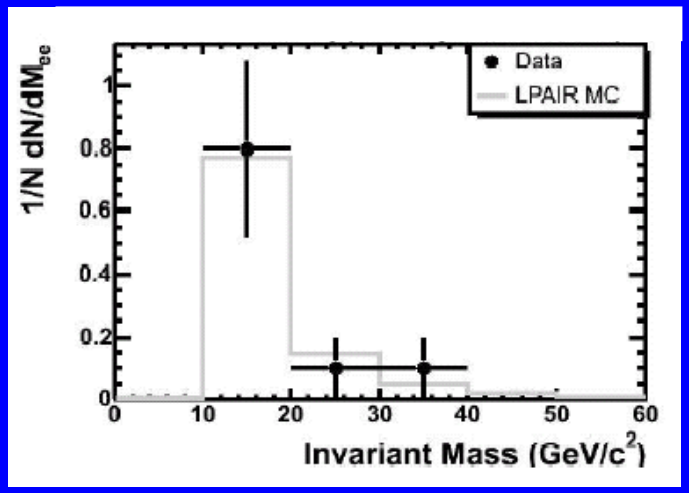


Central track chamber hits



Calorimeter "lego plot"

M(ee) = 30 GeV!
(another has M = 38.4 GeV!)



LPAIR: MC, QED + p form factors

$M(e^+e^-)$, $\Delta\phi$, $p_T(e^+e^-)$ distributions agree

$$\sigma(\text{LPAIR}) = 1.71 \pm 0.01 \text{ pb}$$

$$\sigma(\text{CDF}) = 1.6^{+0.5}_{-0.3} \pm 0.3 \text{ pb}$$

16 events b/g = 2.1+07-.3

First observation of $\gamma\gamma \to X$ in had had

Phys Rev Lett 98, 112001 (2007)

Search for Exclusive Lepton Pairs II : $\mu^+\mu^-$

Continue study of $\gamma\gamma$ collisions :
QED and luminosity calibration at LHC, $\mu^+\mu^-$easier than e+e- (?)
(must be done with pile-up).
Forward p-spectrometer calibration if p detected (FP420!)
Look for exclusive vector mesons (photoproduction γ-IP → V)

Two triggers in CDF:

(1) $\mu^+\mu^-(p_T > 1.5\ \text{GeV/c}), M(\mu^+\mu^-) = 3.0 - 4.0\ \text{GeV}$, BSC - veto

(2) $\mu^+\mu^-(p_T > 4.0\ \text{GeV/c}), M(\mu^+\mu^-) > 8.0\ \text{GeV}$

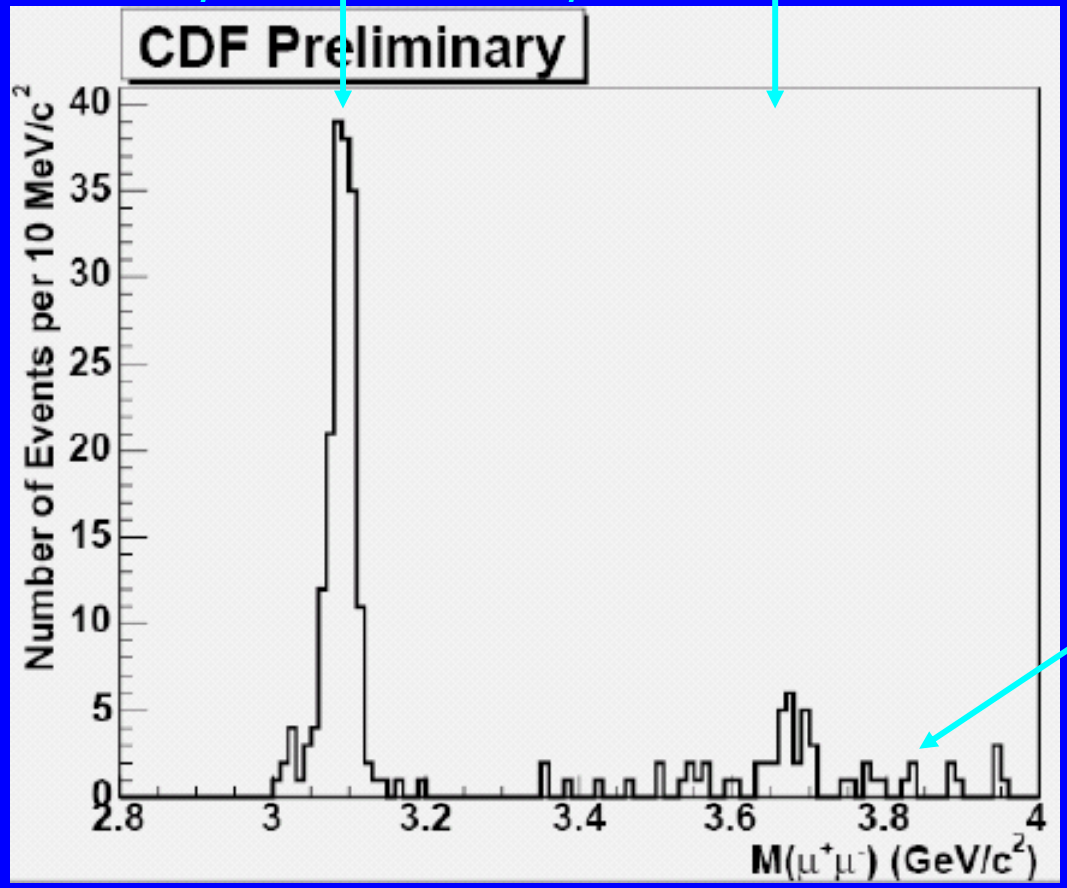
Low mass: continuum & $J/\psi, \psi'$, superclean (no pile-up)
High mass: continuum & Y(1S), Y(2S), Y(3S) ... allow pile-up
Can we select exclusive events among others?
Does final sample contain "supercleans" (4% - 8% expected)?

Exclusive $\mu^+\mu^-$ candidates (Low mass)

Photoproduction
(1st time in hadron-hadron)

$J/\psi, \psi'$

ψ(1S)(3097) ψ(2S)(3686)



Continuum

$\gamma\gamma \to \mu^+\mu^-$

Acceptance rising strongly through mass range
Calculations of acceptance, and possible background from $\chi_c \to J/\psi + \gamma$ underway.

Exclusive $\mu^+\mu^-$ candidates (High mass)

Y Photo-production and exclusive $\gamma\gamma \rightarrow \mu^+\mu^-$ pairs

Q: Can exclusives be found using $n_{assoc\_tracks} = 0$ & kinematics ?

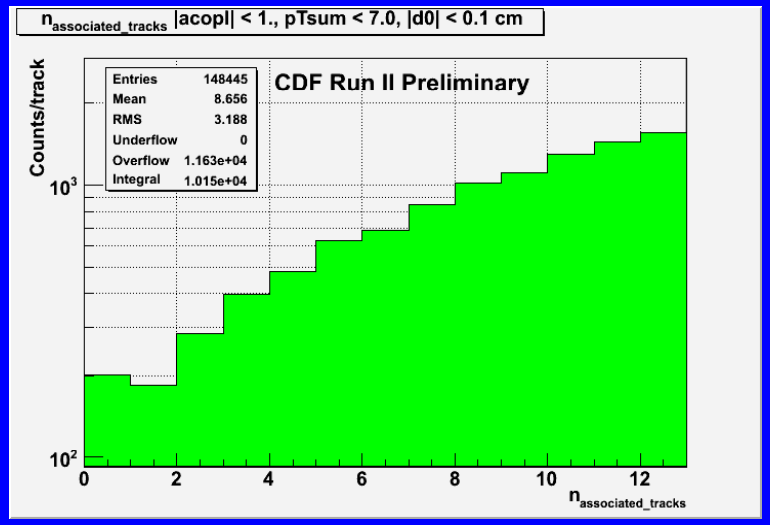
$$\Delta\phi \approx 180^0, \Delta p_T \approx 0 \quad (\text{or } \Sigma\vec{p}_T \approx 0)$$

Trigger: 2 central muons with pT > 4 GeV/c L = 890/pb

~ 2.3 M events. Remove cosmic rays (timing + colinearity)

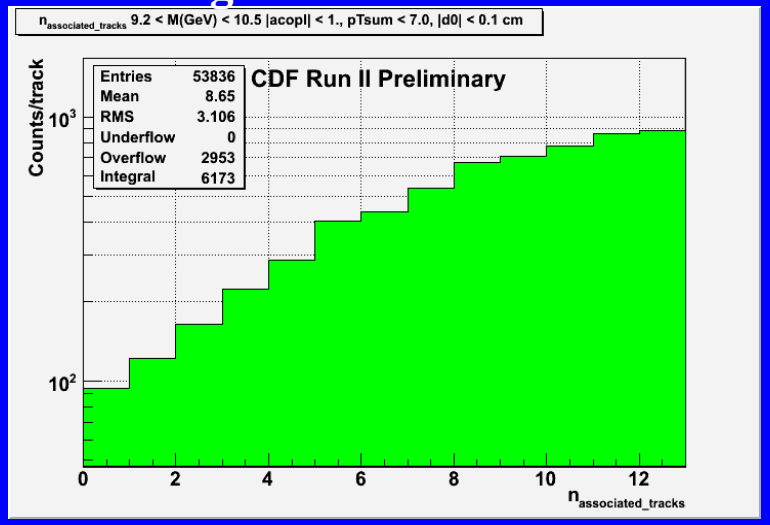
Require on beam-line. Count additional (associated) tracks n_ass within 5 cm of $\mu^+\mu^-$ vertex.

All masses



n_ass →

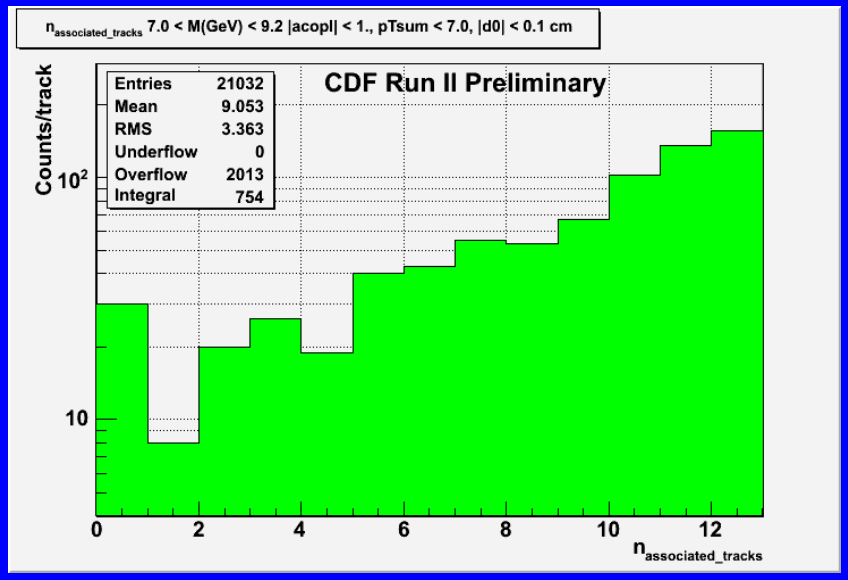
Y region 9.2 – 10.5 GeV



n_ass →

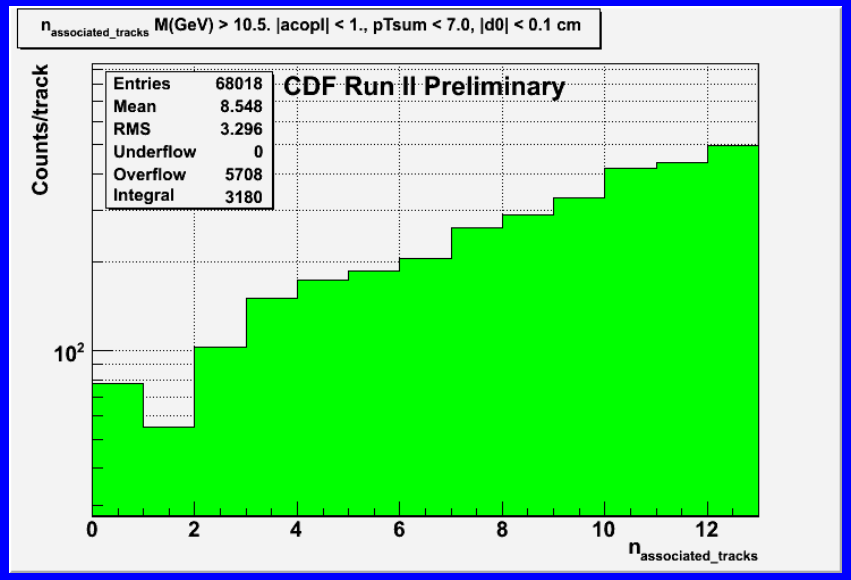
Number of associated tracks on mumu vertex

7.0 < M(μ+μ-) (GeV/c²) < 9.2
Below Upsilon region



n_ass →

M(μ+μ-) (GeV/c²) > 10.5
Above Upsilon region

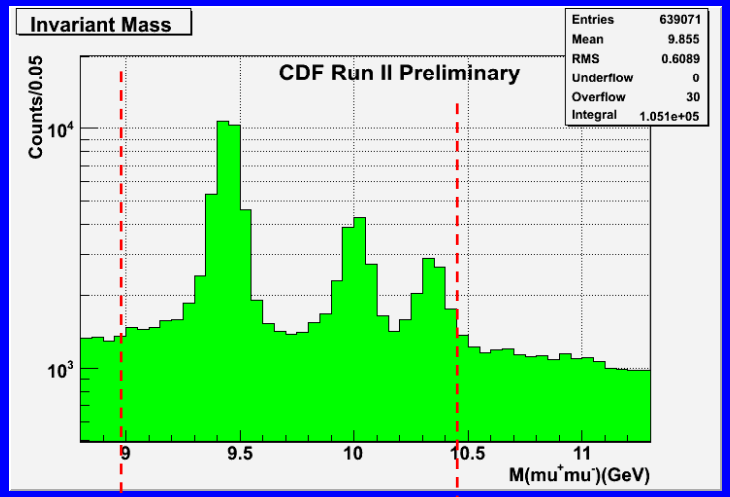


n_ass →

Excesses in bin 0 : candidates for $\gamma\gamma \to \mu^+\mu^-$
Cleanliness, backgrounds and acceptances being studied.
Number of events "reasonable" for QED process, Luminosity.

Invariant Mass Distribution - Upsilon Region

All (inclusive)
in sample in Y region



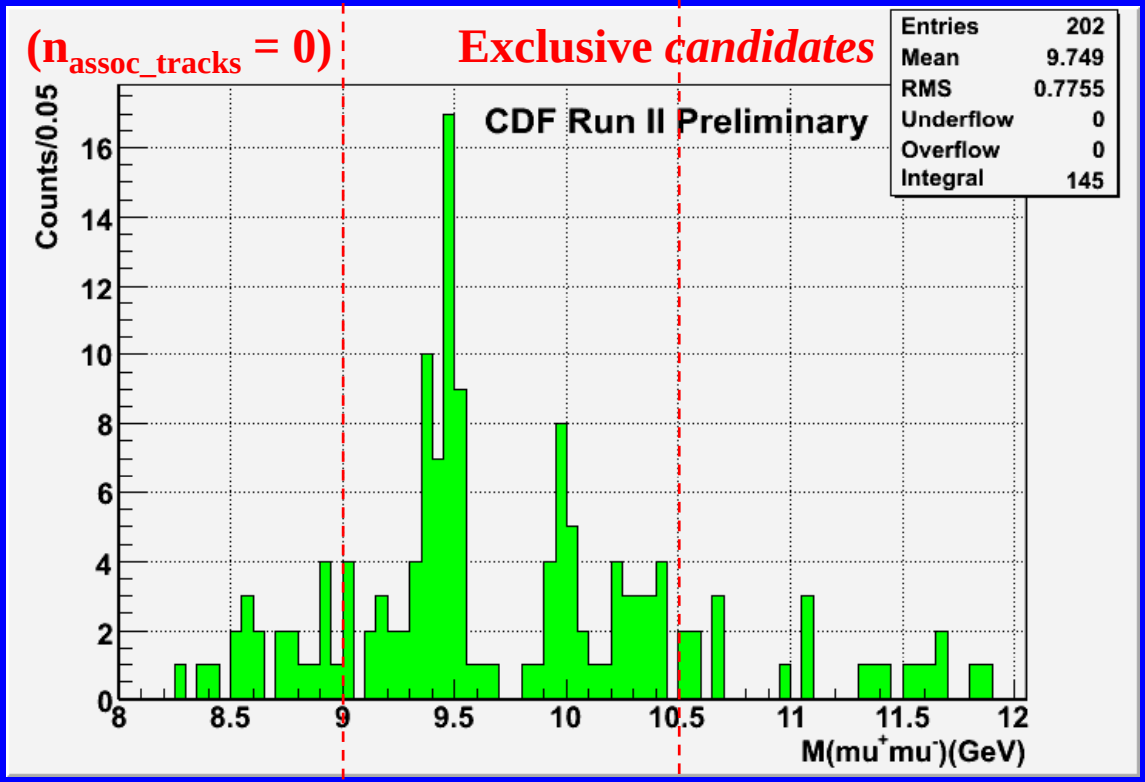
Branching ratios for μ+μ- channels:

Y(1s)[9.46 GeV] : 2.5%

Y(2s)[10.02 GeV] : 1.3%

Y(3s)[10.36 GeV] : 1.8%

$\Delta\phi > 120^0, p_T(\mu^+ + \mu^-) < 7$ GeV/c



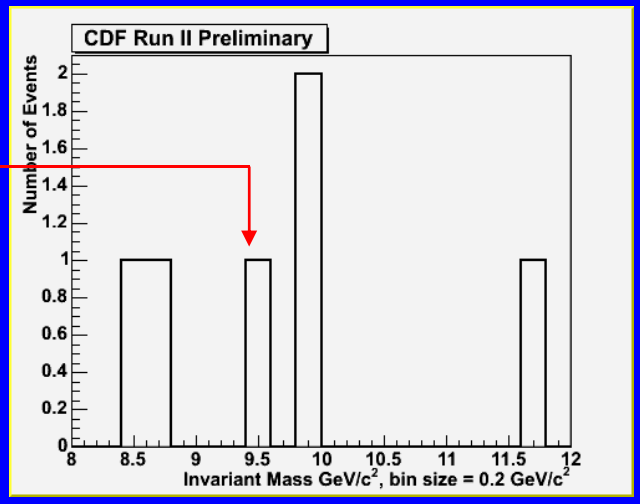
Clearly visible peaks Y(1s) and Y(2s), perhaps Y(3S) too. + continuum

Now apply "superclean" exclusivity cuts as in ee and low mass $\mu^+\mu^-$ i.e. no pile-up, and no detected particles except $\mu^+\mu^-$

145 events in 8 GeV – 12 GeV region →

6 events + 4 M($\mu^+\mu^-$) > 12 GeV.

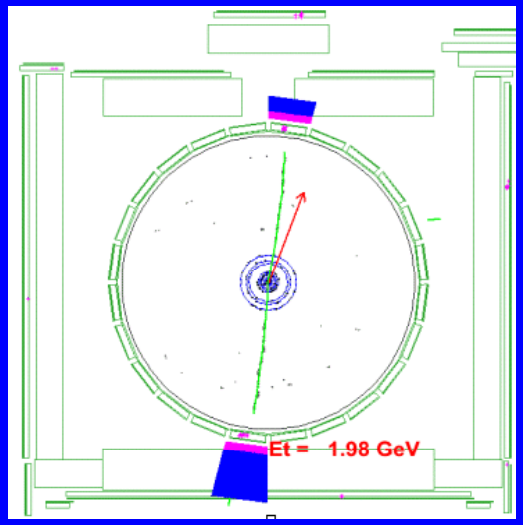
(Most of reduction is killing pile-up)

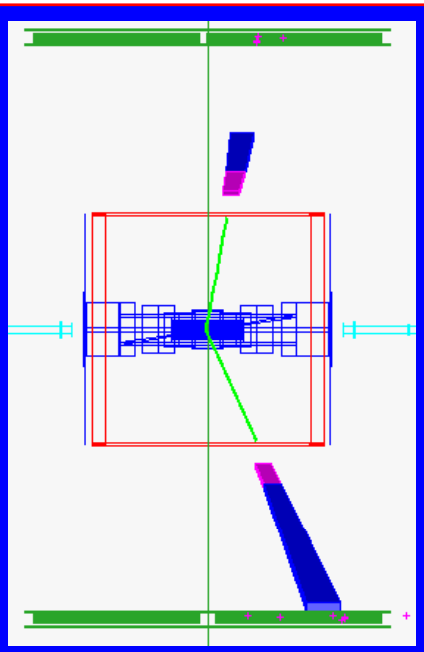


Use these to understand backgrounds of full (pile-up) sample.

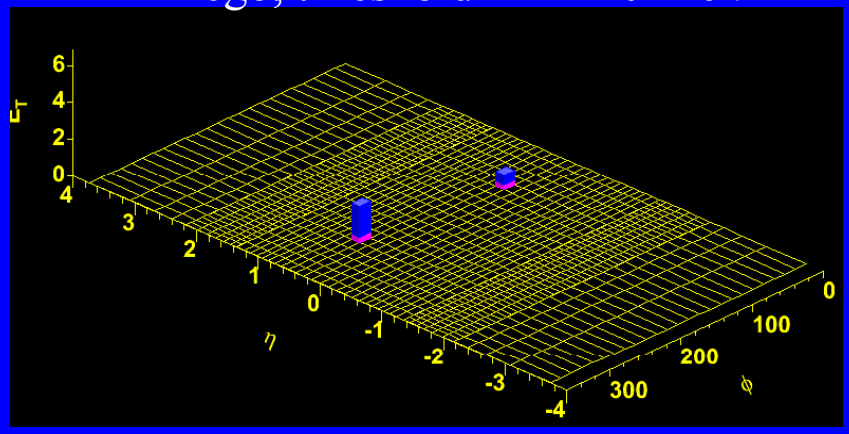
Superclean Upsilon

M ~ 9.4 GeV





Lego, threshold ET > 10 MeV



Run/Event: 204413/8549136

Exclusive χ_c search: $p\,\bar{p} \rightarrow p\quad \chi_c\quad \bar{p}$

Predictions for Tevatron

F.Yuan ds/dy ~ 150 nb

In reality: $BR(\chi_c^o \rightarrow J/\psi\,\gamma \rightarrow \mu^+\mu^-\gamma)$

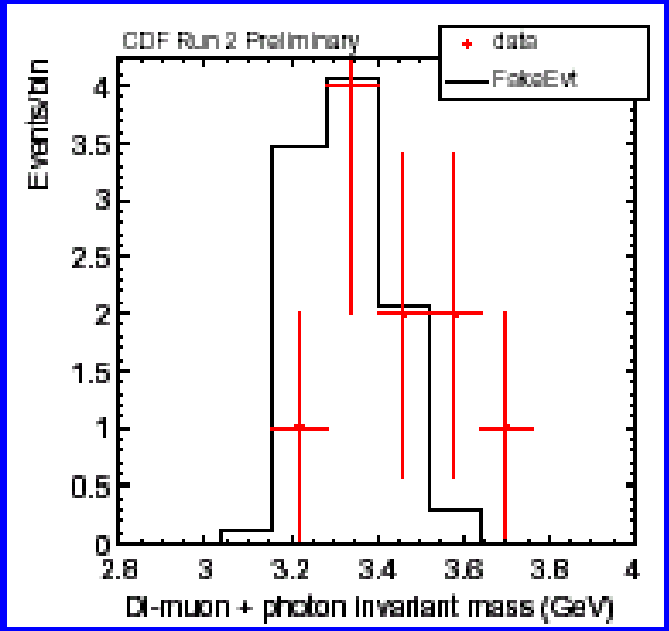
$\times$ no other interaction $\times$ acceptance(trig)

$\Rightarrow$ few pb (1000's in 1 fb^{-1})

M.Rangel et al **(+Royon,Peschanski)**

60 pb with CDF cuts

Difficulty is soft photons, and "background" from photoproduction: $\gamma + IP \rightarrow J/\psi$



Candidate events

{Measuring forward p → central quantum numbers

2+ forbidden at t=0 for $q\bar{q}$ state}

$I^G J^P = 0^+ 0^+$ ← Isotopic spin, spin, G-parity, parity same as Higgs boson

Central Exclusive 2-Photon Production

Cleanest test of p+H+p theory

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

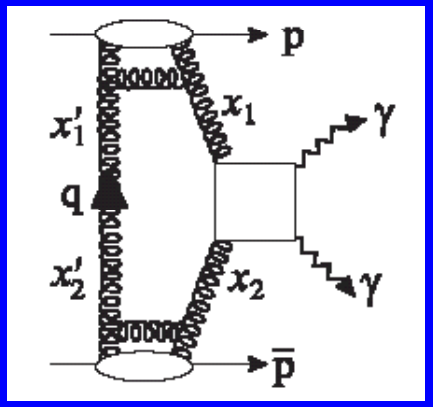
Khoze, Martin and Ryskin, hep-ph/0111078, Eur.Phys.J. C23: 311 (2002)
KMR+Stirling hep-ph/0409037

QCD diagram identical to pHp

$M(\gamma\gamma) \sim 10 - 20$ GeV

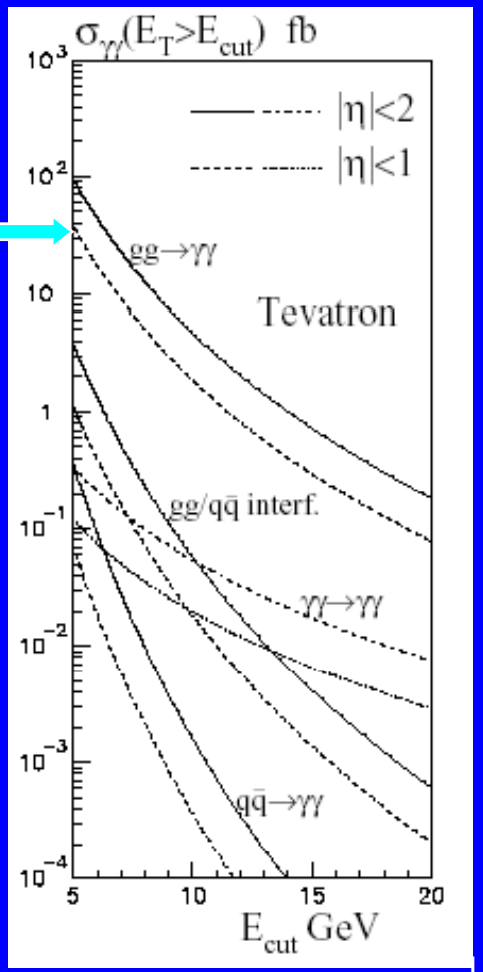
x_1, x_2 similar, Q^2 lower

top $\rightarrow$ u,c (mainly)



Tevatron

38 fb



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

Claim factor ~ 4 uncertainty

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

Exclusive 2-photon Search in CDF

$$p\bar{p} \rightarrow p + \gamma\gamma + \bar{p}$$

Exactly as in exclusive e+e- observation:

Cannot detect protons. Need to look for $\gamma\gamma$ + nothing.
Trigger on 2 EM4 showers + forward BSC1veto. $(5.4 < |\eta| < 5.9)$
Require all calorimetry and Beam Shower Counters $(-7.4 < \eta < +7.4)$
in pedestals except 2 EM showers > 5 GeV. (1.2 mrad)

Can only use events with no other collisions in bunch crossing.
→ "exclusive efficiency" = 0.086

$\sim 2.10^6$ triggers in 532 pb^{-1} delivered, $L_{eff} = 46\ pb^{-1}$

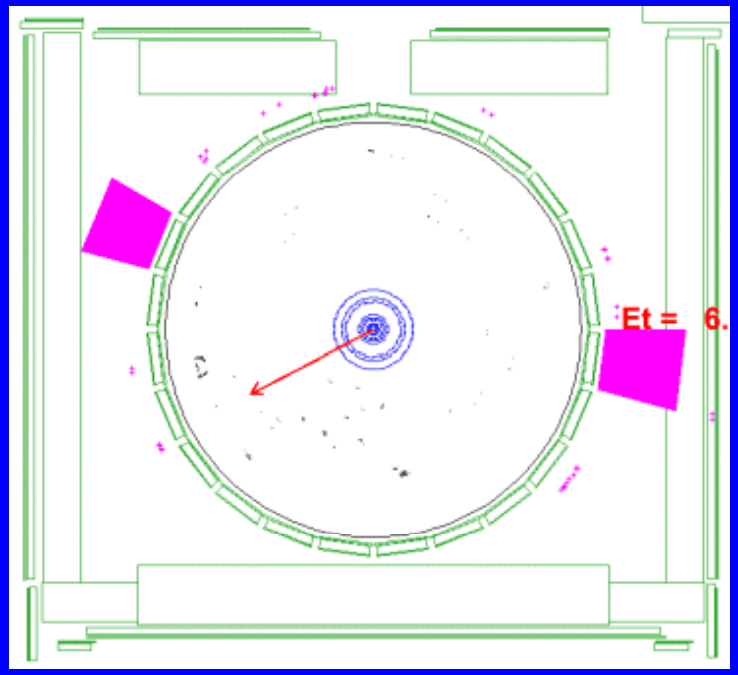
19 events have 2 EM showers with

$E_T > 5$ GeV and $|\eta| < 2.0$ + nothing else

16 were the 2-photon → e+e- events (presented earlier).
3 were not, no tracks. $\gamma\gamma$ or $\pi^0\pi^0$
Detailed study: 1 had characteristics of $\pi^0\pi^0$, 2 of $\gamma\gamma$
-- single narrow showers on each side.

2 $(+1\pi^0\pi^0)$ events were like this:

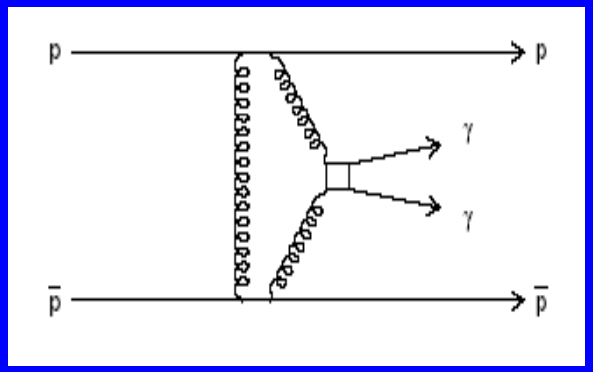
$E_T(\gamma) > 5$ GeV; $|\eta(\gamma)| < 1.0$



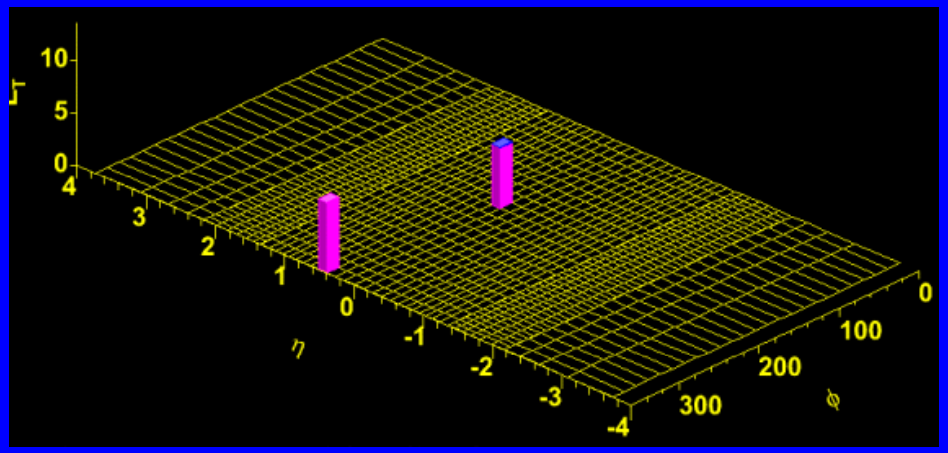
$\Delta\phi > 175^0$; Δp_T small

$M(\gamma(\gamma = 10 - 12$ GeV

QCD +QED process



$gg \to \gamma\gamma$



$\sigma(2 \text{ events}) = (90^{+120}_{-30} \pm 16)$ fb

KMR : 38/fb (x4/4)

ExHuME Monte Carlo

Durham Gp, James Monk & Andy Pilkington

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

arXiv:0707.2374 submitted to PRL

Conclusion: We have observed:

3 candidates for exclusive $(\gamma\gamma + \pi^0\pi^0 + \eta\eta)$ production

May be mixture

$B/G = 0.09 \pm 0.04;\ P(\geq 3) = 1.7 \times 10^{-4} \equiv 3.7\sigma$

$\sigma(\gamma\gamma) < 410$ fb (95% c.l.)

A, B favor $\gamma\gamma$ and C favors $\pi^0\pi^0$

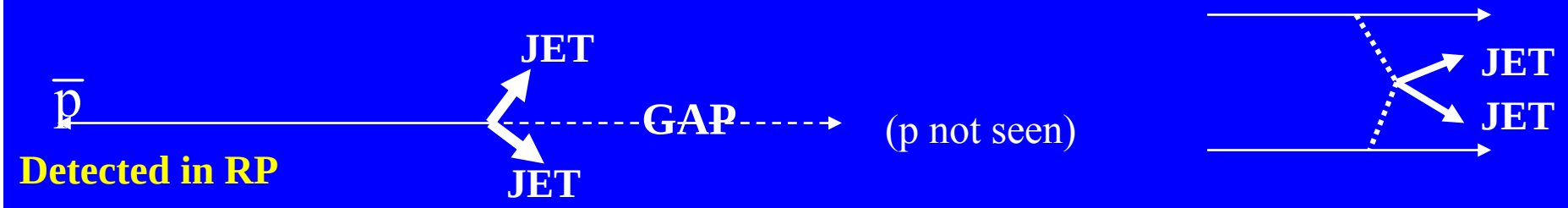
If 2 of the 3 candidates are $\gamma\gamma$ events we obtain a cross section: $\sigma(2 \text{ events}) = (90^{+120}_{-30} \pm 16)$ fb

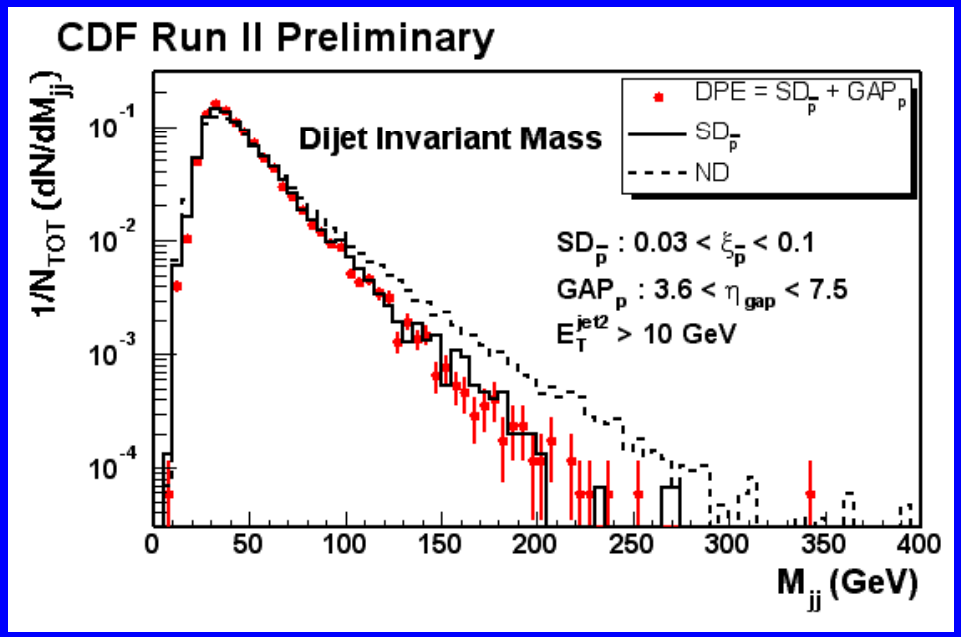
cf **Durham Group Khoze, Martin, Ryskin & Stirling hep-ph/0507040 Eur.Phys.J C38 (2005) 475 : 38 fb with factor ~ 3 uncertainty**

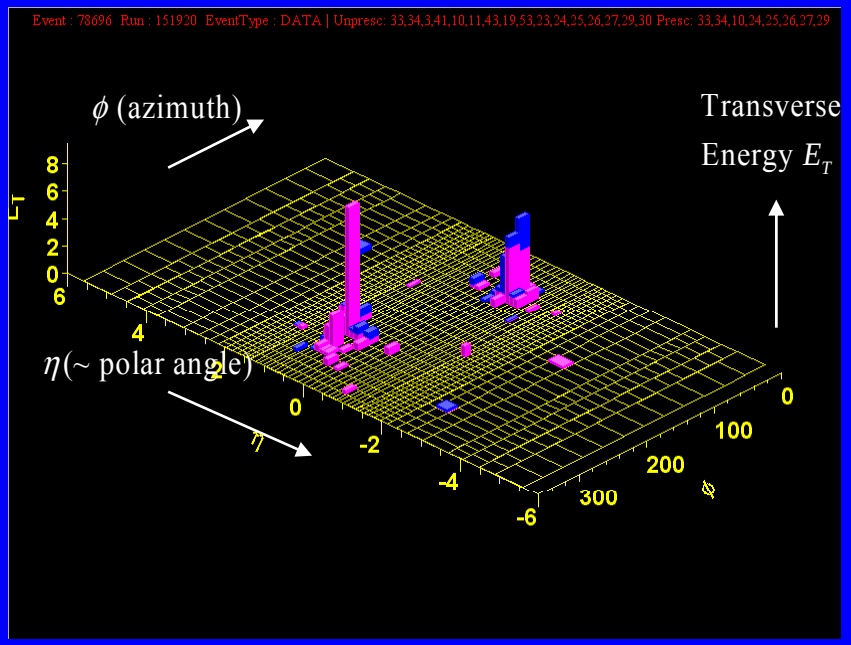
Existence of exclusive $\gamma\gamma$ implies that exclusive H must exist (if H exists)

Agreement with Durham group suggests H cross section at LHC in reach

Double Pomeron Exchange Di-Jets in CDF







Jet <ET> spectra ~ same in SD and DPE

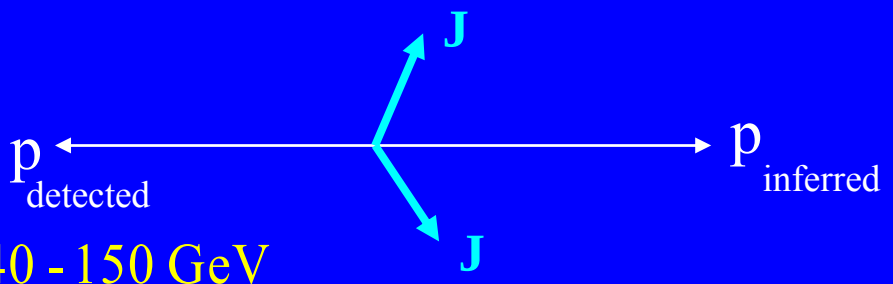
"Almost" exclusive di-jet,
Two jets and nothing else

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

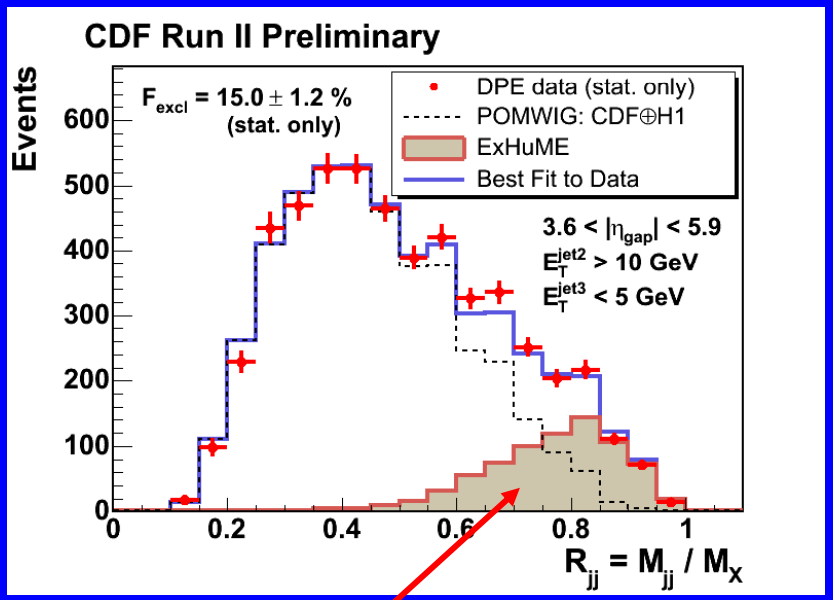
No pile-up essential; low-L
(at LHC if both p detected, some PU allowed)

CDF Search for Exclusive Dijets (2 central jets + "nothing")

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

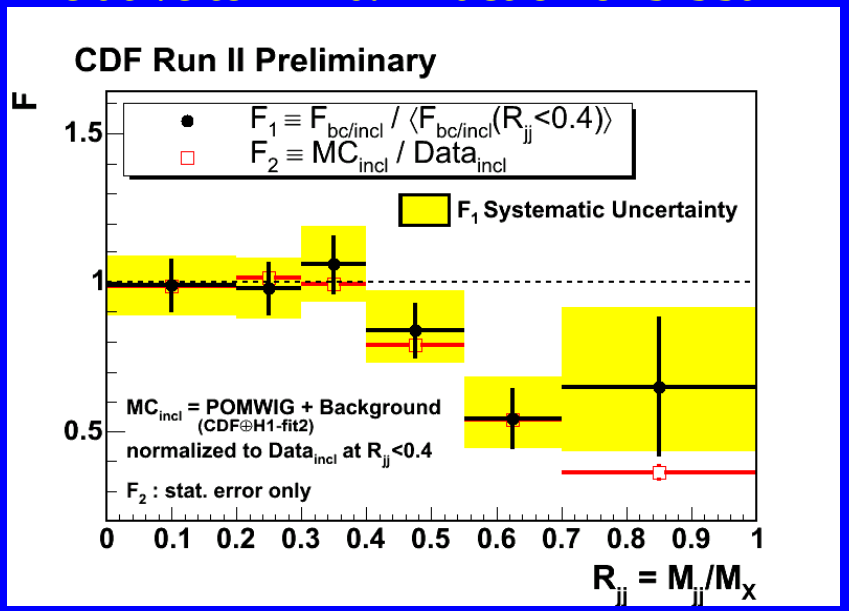


M_X = total central mass $M_{JJ} \approx 40 - 150$ GeV



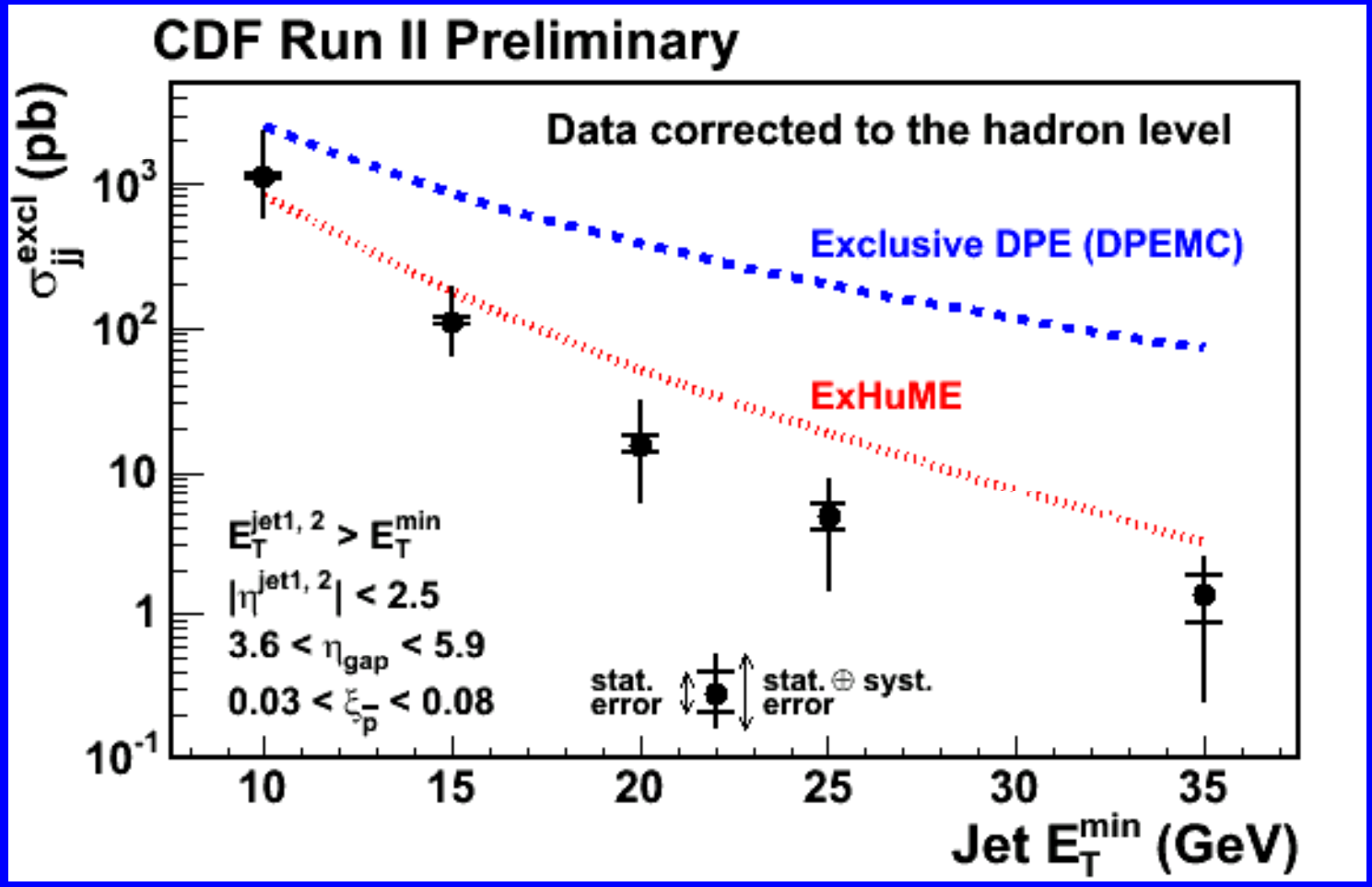
ExHuME: MC with exclusive di-jets.

Relative to R < 0.4 fraction of b-bbar



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

Exclusive di-jet Cross section (integral)



Value of CDF Central Exclusive Program for p+H+p at LHC

1) Exclusive $\gamma\gamma$ **(if confirmed ... more data being analysed)** implies that exclusive Higgs must happen (if H exists) at ~ KMR level. Cross section > 10x higher at LHC, but still difficult.

2) $\gamma\gamma \to e^+e^-, \mu^+\mu^-$. Luminosity calibration will be very hard, but p-calibration of p-spectrometers will work as long as have trigger in good kinematic region (high M, forward).

3) Photoproduction of Y,Y',Y" : cross section higher than continuum and good p-calibration tool (pile-up allowed).

4) Can exclusive χ_b states be measured (Y+γ) as another calibration of p+H+p cross section? Low-L, no pile-up, $\mu^+\mu^-\gamma$

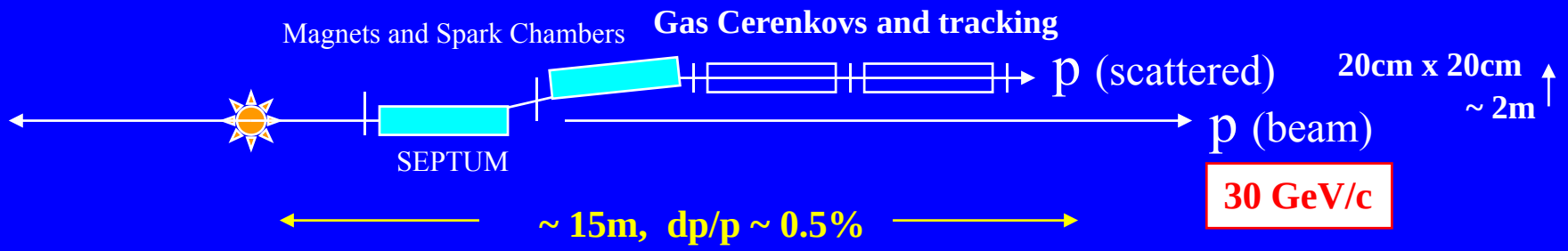
5) Evidence for exclusive di-jets, with suggestion of depletion of exclusive b-bbar dijets as expected.

This field started with $\pi^+\pi^-$ at ISR, motivation glueball search.
→striking structures, narrow scalars, glueball nature still unclear.
Analogue for LHC is W+W- : guaranteed from 2-photon collisions,
→hopefully striking structures, narrow scalars, Higgs or even not.

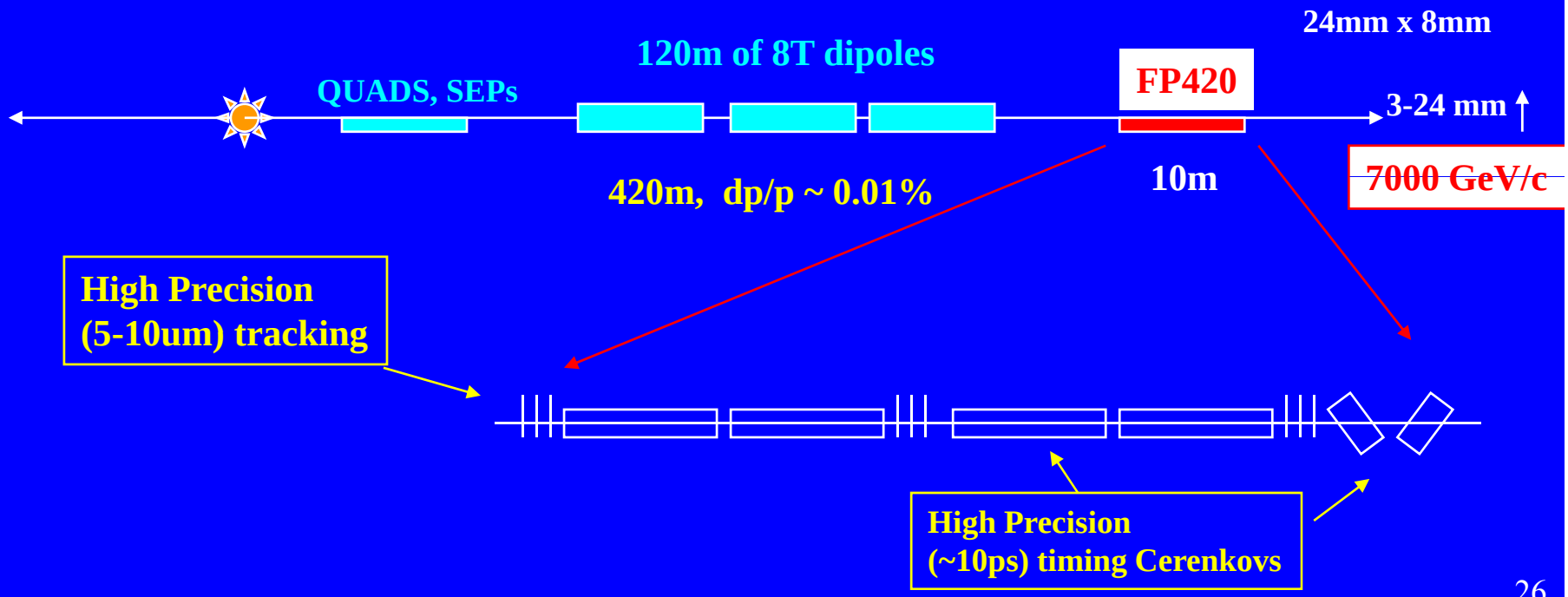
Note: pp → p+(W+W-)+p
measures M(WW) even with 1(2) neutrinos and jets (UNIQUE)
as well as (WW) quantum numbers (spin) if enough statistics.
For pp → p+(ZZ)+p 2-photon continuum absent, only "H"-like states

Forward Proton Spectrometers: ISR → LHC

ISR (1971)



LHC (2009?)



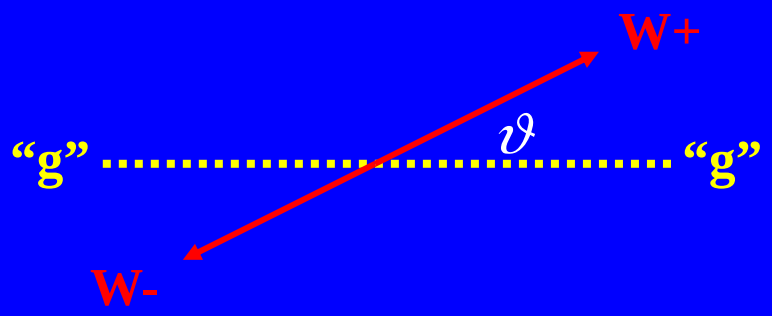
Determining Quantum Numbers of Central State (H?)

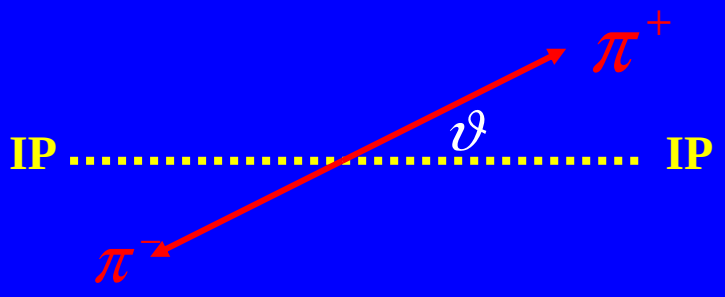
Is it J = 0, CP = ++?

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!

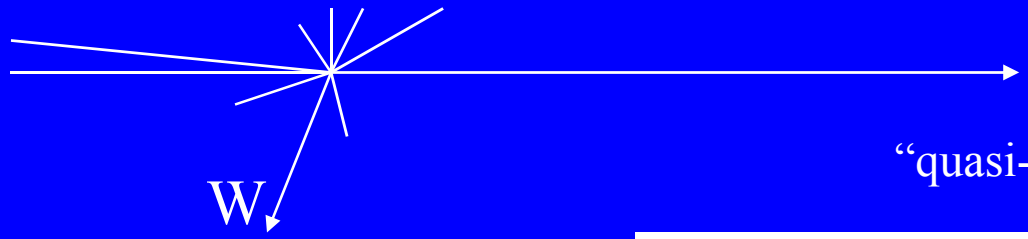




Moments H(LM) of the cos(ϑ) distributions → M(J=0), M(J=2).

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

Not Central Exclusive, but : Diffractive W and Z Production : Run 1



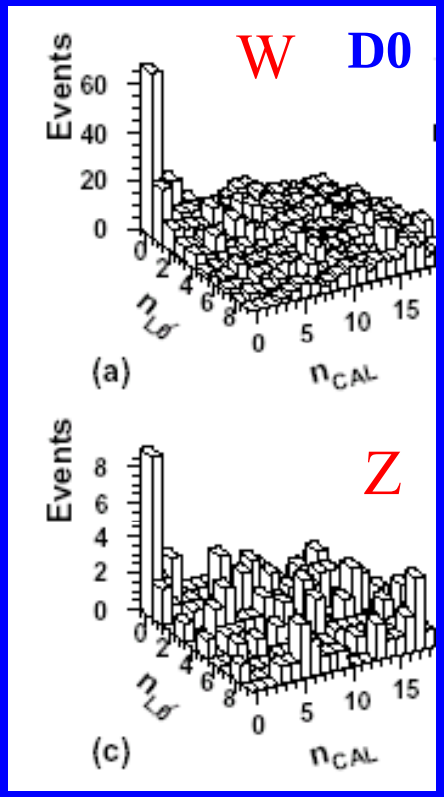
"quasi-elastic"

W produced but p "stays intact"

CDF:

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

D0 sees diffractive W and Z
all consistent with 1% diff./ND



$\eta(LO) = 2.3 - 4.3$

$\eta(CAL) = 3.0 - 5.2$

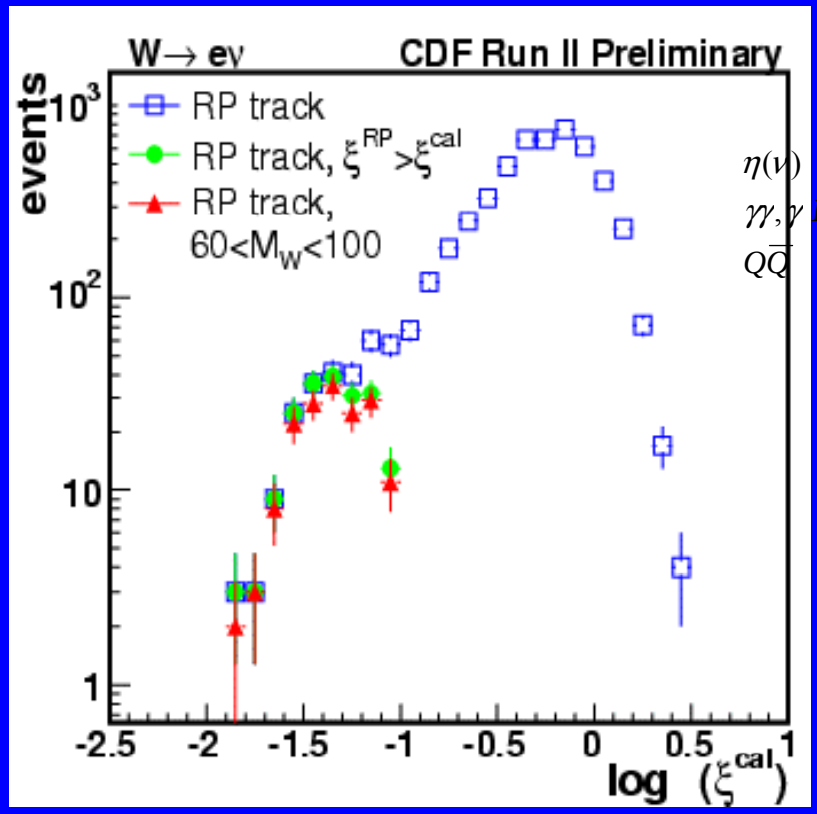
Update (Run 2) on CDF diffractive W,Z

Events with Roman Pot $\bar{p}$ ($\xi^{RP} < 0.1$) and central W
Calculate from full calorimetry ξ^{CAL}. Only "agree" if no PU
Very small fraction of all events. Cannot use PU events.

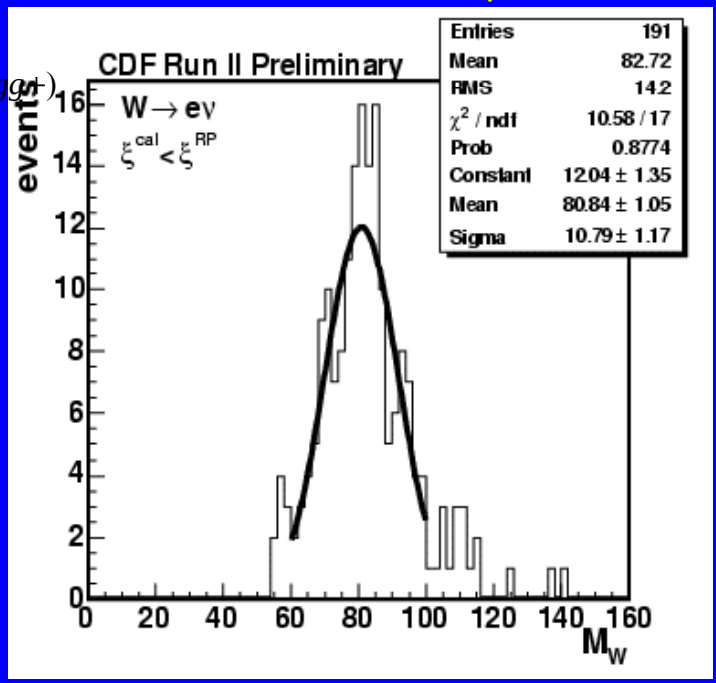
$$\xi^{cal} = \sum_{towers} \frac{E_T}{\sqrt{s}} e^{-\eta}$$

For no PU events, can find $\eta(\nu)$
by balancing ξ^{RP} and ξ^{CAL}(unique in pp)

$$\xi^{RP} - \xi^{cal} = \sum_{towers} \frac{\not{E}_T}{\sqrt{s}} e^{-\eta_\nu}$$



$\eta(\nu)$
$\gamma\gamma, \gamma$ *IP*, *IPIP* (gg+)
$Q\overline{Q}$



+ Some Diffractive Z candidates

M(W) (not transverse mass!)

Conclusions

Central Exclusive Production in hadron-hadron collisions is a rich field, with very clean initial and final states.

Initial: $\gamma\gamma, \gamma\ IP, IP\,IP\ (gg+)$
Final: lepton pairs, vector mesons, scalar $Q\overline{Q}$ states, H, WW.

CDF studies of all above CE processes (except H,WW !) are an important stepping stone. First observation of $\gamma\gamma \to l^+l^-$, likely first observation of photoproduction in had-had of onium states, Candidates for exclusive $\gamma\gamma$ production, 2-jet production.

Goal of FP420/220 of studying electroweak physics (H etc) in a unique situation looks feasible.