# *Observation of Exclusive γγ Production in CDF (and other exclusive states)*

Mike Albrow (Fermilab)

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

**3 Classes of Hadron-Hadron Collisions:**

**>> Elastic Scattering : no particles produced**
**>> Inelastic : multi- hadron production**
**>> Inelastic, with no hadrons produced**

**ALMOST ELASTIC**

Introduction $\boxed{p+\bar{p} \to p+X+\bar{p}}$

X = $e^+e^-$, $\mu^+\mu^-$, J/$\psi$, $\psi$(2S), $\chi_c$, $\gamma\gamma$

CDF Detectors, Triggers & Data

Selection of Exclusive Events: $\boxed{p+\bar{p} \to p+\{2EM\ showers\}+\bar{p}}$

e+e-, $\gamma\gamma$ , or $\pi^0\pi^0$ background ?, Cross sections

Other exclusive channels: $\mu^+\mu^-$, J/$\psi$, $\psi$(2S), $\chi_c$, JJ

Summary & Conclusions

Implications for Exclusive Higgs at LHC

# Executive Summary

In CDF we have observed ( >> 5 σ) the new clean process:

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

**Photons central, $E_T$ > 2.5 GeV**

The cross section is about 2.5 pb, i.e. 1 per 25 billion inelastic collisions

Needed:

A good level 1 trigger (EM showers + Forward gap-seeds)

Extended rapidity coverage of CDF to $\eta = \pm 7.4$

Understand noise levels in all calorimeters and counters.

Demonstrate we understand "empty events" (non-interaction in 0-bias)

Use $\boxed{p + \bar{p} \rightarrow p + e^+e^- + \bar{p} \text{ via } \gamma\gamma \text{ (QED)}}$ as a control (σ known)

Show that EM showers are from γ and not $\pi^0$

# High Energy Hadron-Hadron Collisions

**TWO DISTINCT CLASSES:**

Elastic

$\sigma$(elastic) ~ 20 mb

Inelastic, multi-hadron production

$\sigma$(inelastic) ~ 60 mb (at Tevatron)

**<u>NOT</u> DISTINCT CLASSES:**

Diffractive

Non-diffractive

**A "NEW" 3rd DISTINCT CLASS:**

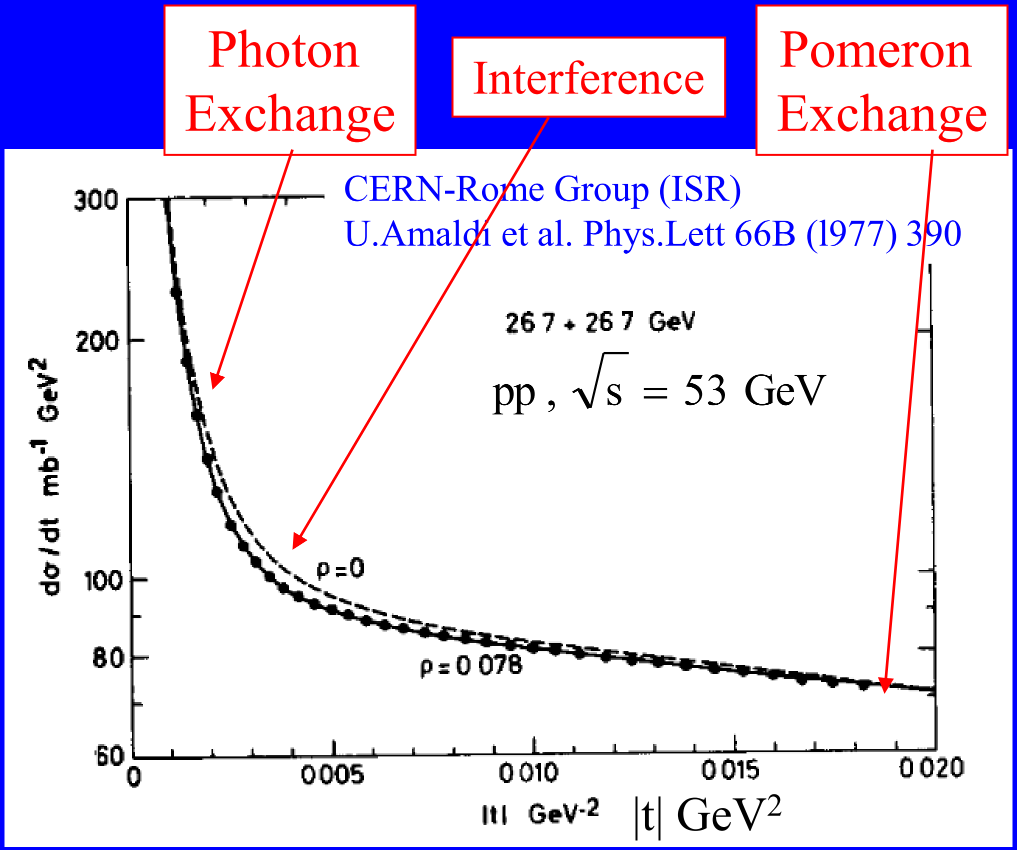
**<u>Almost</u> elastic (99%), <u>no hadrons</u> produced:**

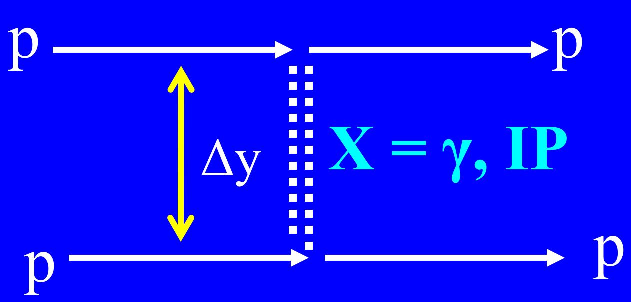
**e+e- μ+μ- γ+γ & at LHC: W+W- H**

Observed in CDF, $\sigma$ ~ pb

Observable at LHC, $\sigma$ ~ 10's fb

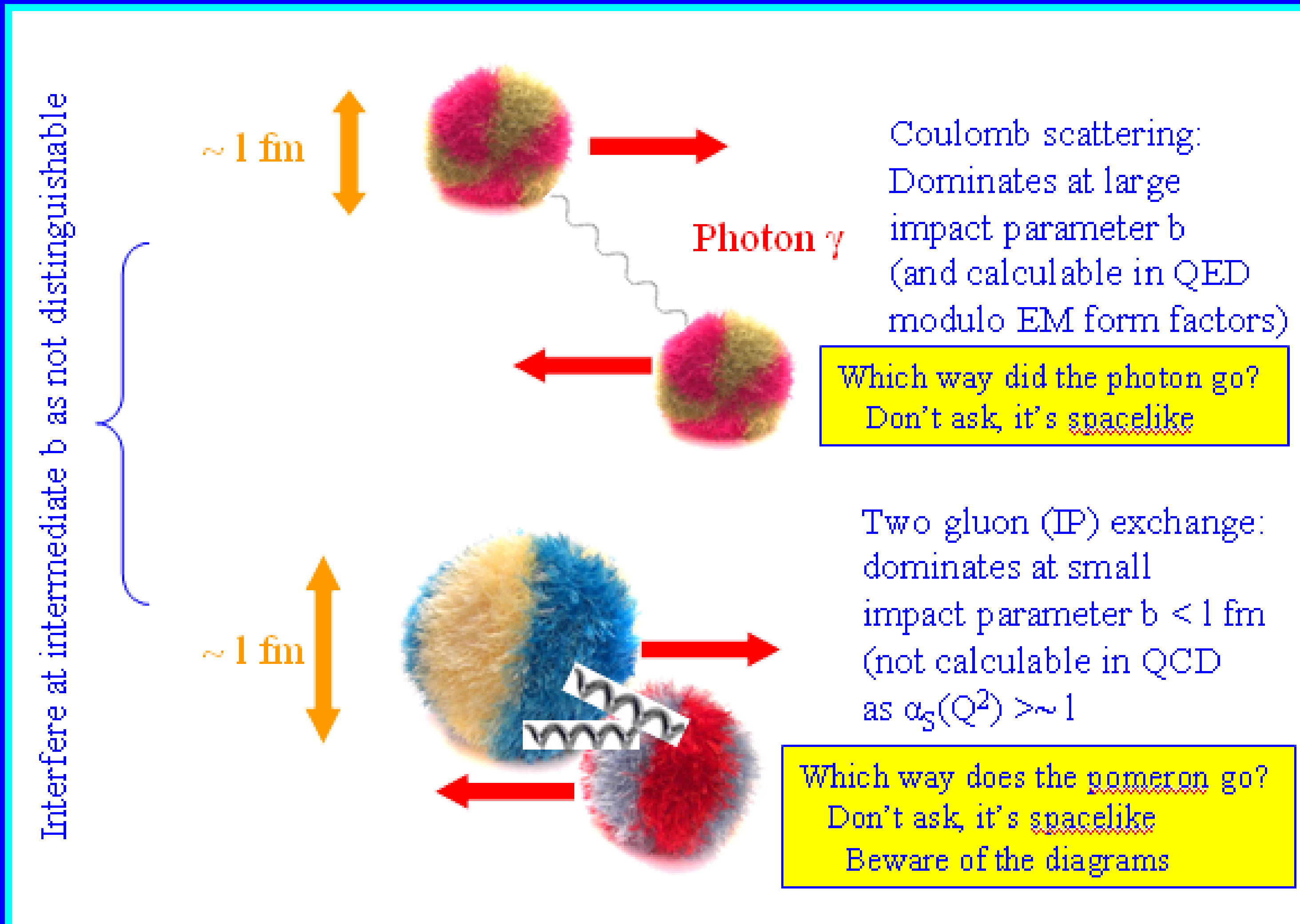
# Elastic pp scattering at very small angles == large distances



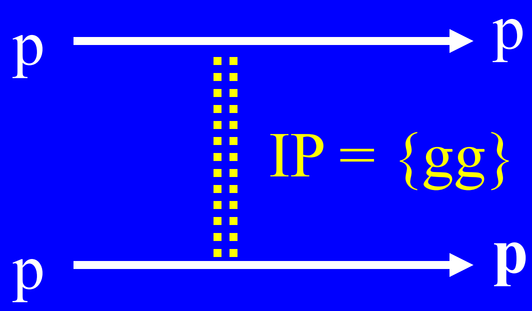

The only allowed t-channel exchanges have Q = 0, Color = 0
and at high energy (Large Δy) spin J >= 1.
**Photon** dominates at small $|t| \sim p_T^2$
**Strong Interaction: 2-gluons is simplest**. Called the **pomeron** IP
Effective spin $\alpha(t=0) > 1$ … that's why total cross section $\sigma_{TOT}$ rises.

# Elastic Scattering by Electromagnetic and Strong Interactions



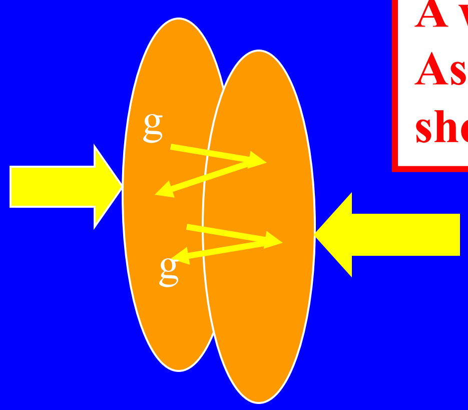
# *Elastic Scattering by strong interaction*

**MISLEADING PICTURE**




Unlike the QED case, do not imagine this as the emission from one proton of a color singlet {gg} state (glueball) propagating freely like a hadron.

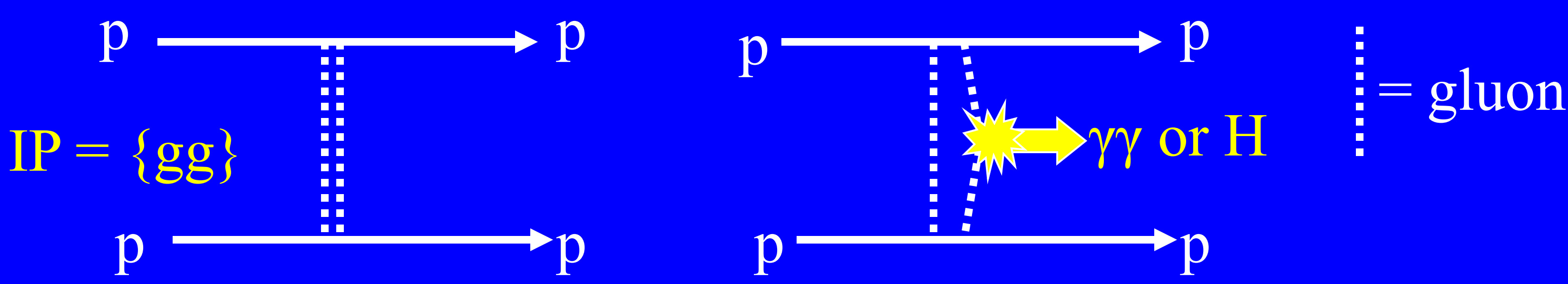
**ANOTHER (BETTER) VISUALIZATION:**




**A wee $x_{Bj}$ gluon is turned around.**
**As the p separate … color field …**
**shorted out by a 2nd exchange**

**Or: a pair of gluons annihilate ( → H e.g.).**
**As the p separate … color field …**
**shorted out by a 2nd exchange (rarely)**

# From elastic scattering to exclusive γγ or H production



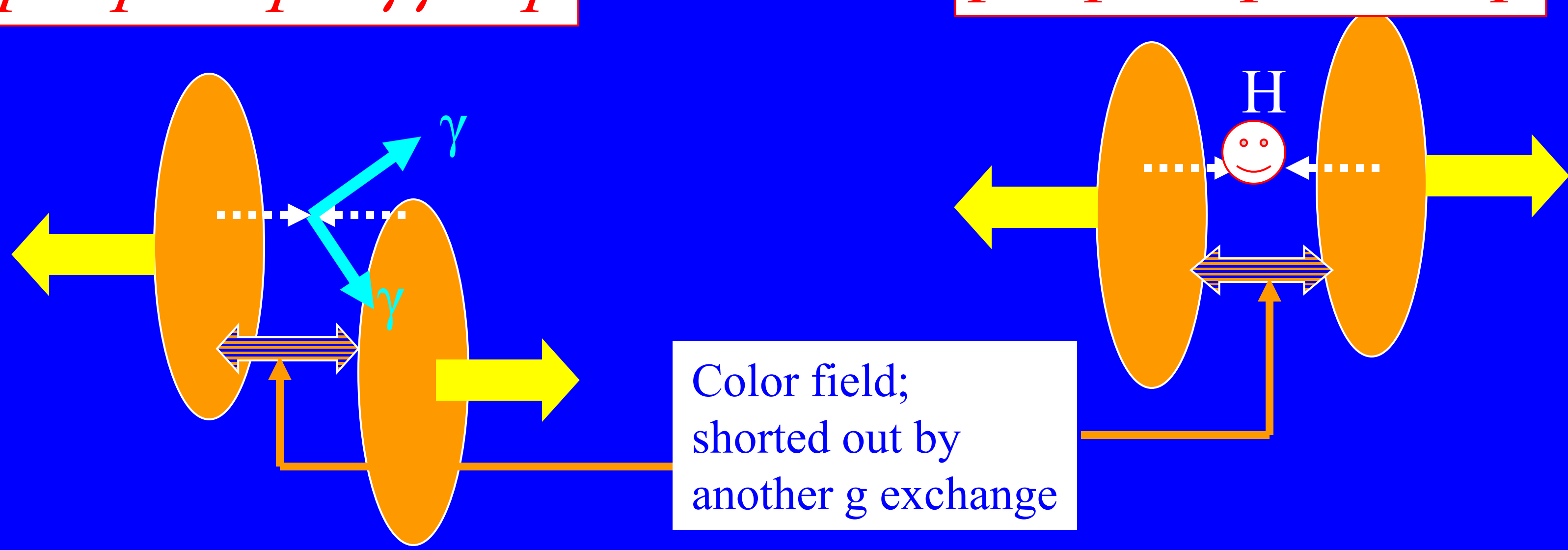

About 25% of $\sigma_{TOT}$

About $10^{-11} - 10^{-13}$ of $\sigma_{TOT}$

These are related processes!

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

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



# CDF: The Collider Detector at Fermilab

$\text{Tevatron}: p\bar{p}\ \sqrt{s} = 1.96\ \text{TeV}$

## CENTRAL:

Silicon tracker

**Drift chamber tracker** ← **COT**

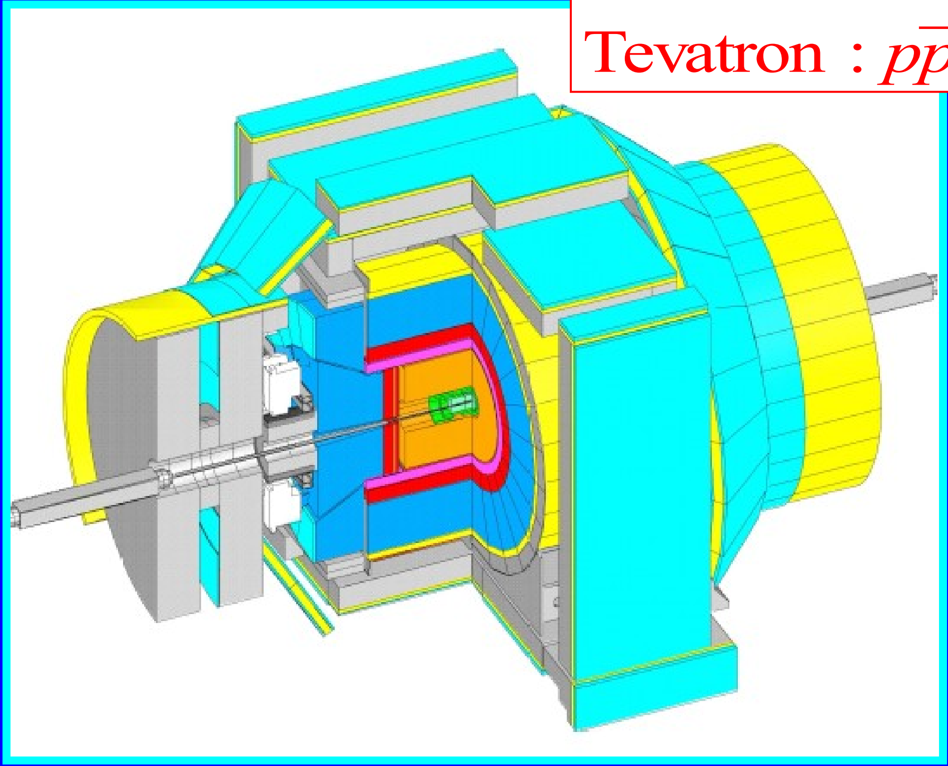
Time-of-Flight barrel

**EM calorimeters w/**

**CES shower max PC**

Hadron Calorimeters

Muon chambers



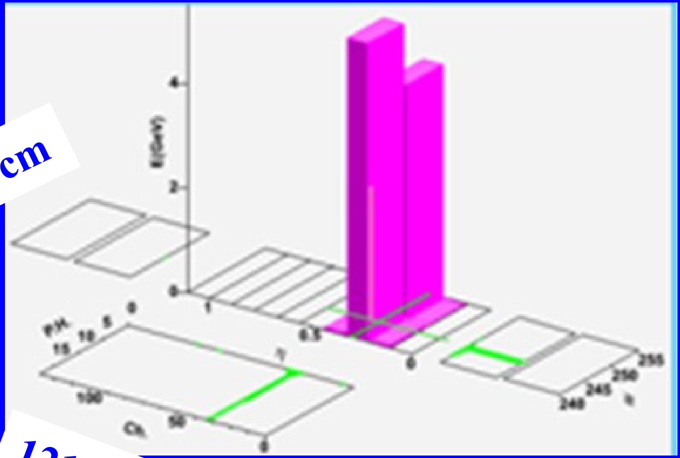
**FORWARD**

**NEXT slides**

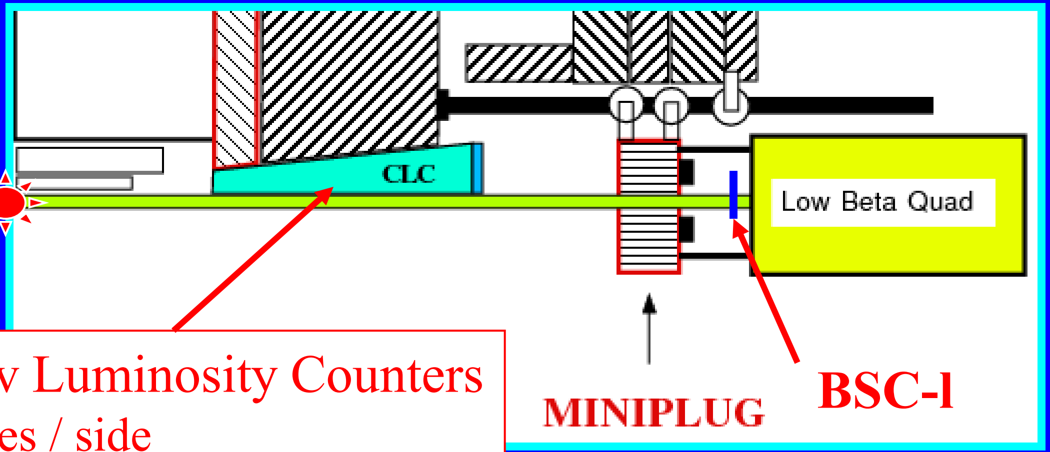
**(Important)**

CES shower maximum
proportional chambers
at 6 $X_0$
1.5 cm anode wires in $\varphi$
1.7 – 2.0 cm strips in $\eta$
92% active over $|\eta| < 1.1$

10 GeV electron



# Forward Detectors in CDF I: Cherenkov Luminosity Counters



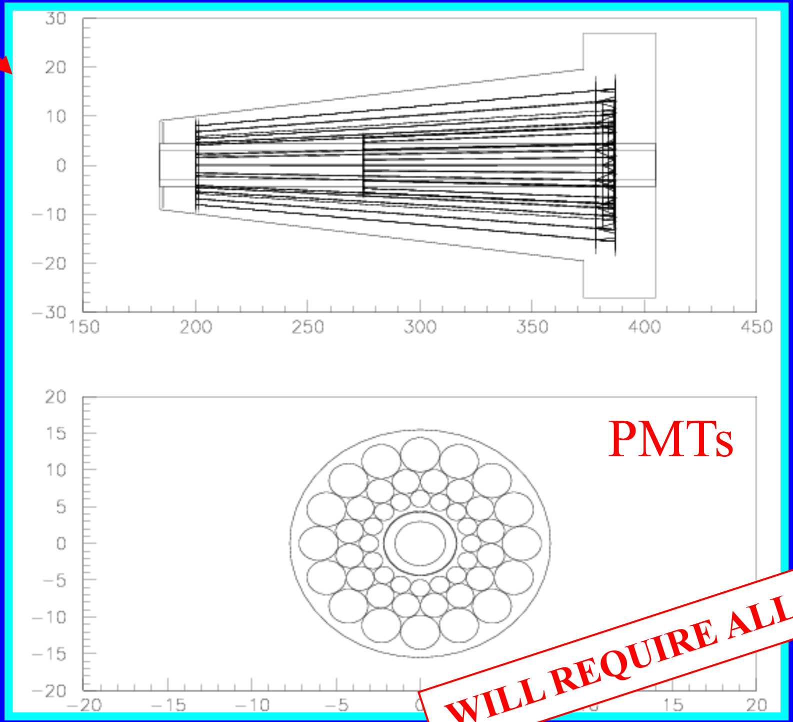

55 m

BSC-2, -3

**CLC** = Cherenkov Luminosity Counters
48 PMT + Gas cones / side

$3.7 < |\eta| < 4.7$

Univ. Florida

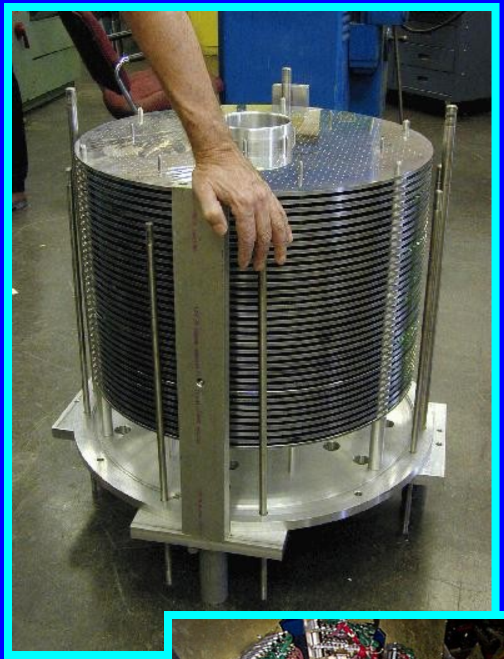



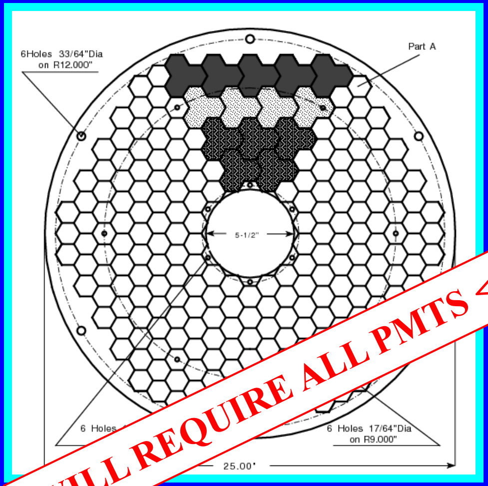

WILL REQUIRE ALL PMTS < NOISE CUT

# Very Forward Detectors in CDF  II : MiniPlugs

MiniPlug Calorimeters: $3.6 < |\eta| < 5.1$
Lead + Liquid Scintillator + WLS Fibers

Rockefeller Univ.



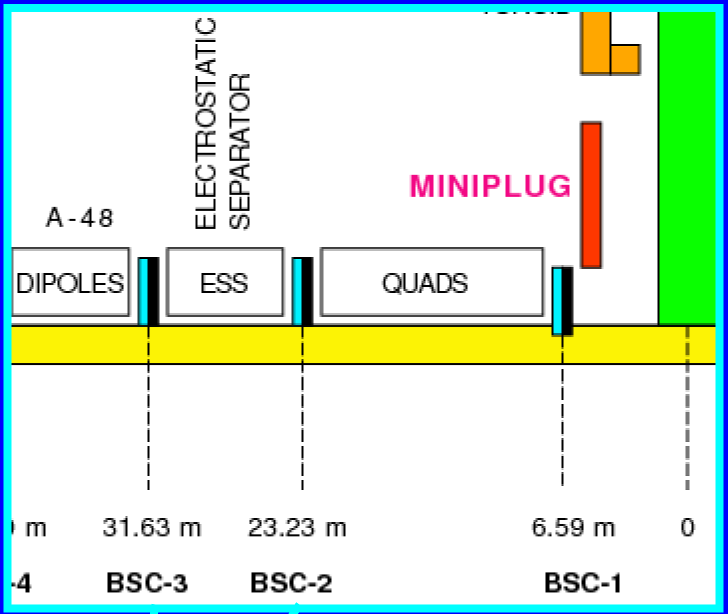



WILL REQUIRE ALL PMTS < NOISE CUT

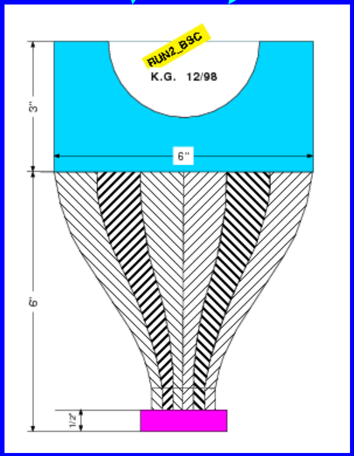
Beam Shower Counters (BSC)

$5.5 < |\eta| < 7.4$ (Scintillators + PMT)

Rockefeller Univ.




BSC-1 (4 PMTs)




2 PMTs / station

WILL REQUIRE ALL PMTS < NOISE CUT

# Central Exclusive Production, examples:

**p + p → p + X + p**

where + = true rapidity gap, **no hadrons**
and X = "simple" system fully measured.

→ *γ or IP exchange*

## States observed in CDF for first time in hadron-hadron collisions:

| Quantum Number restrictions | | |
|---|---|---|
| | γ + γ | $e^+e^-, \mu^+\mu^-$ |
| | γ + IP | $J/\psi, \psi(2S)$ |
| | IP + IP | $f_0(600)/\sigma, f_0(980), \ldots \chi_c, JJ, +\gamma\gamma$ |

**Observed at CERN ISR**

**NEW**

Previous exclusive γγ search paper, 3 candidates $E_T > 5$ GeV: PRL 99 (2007) 242002

# Central Exclusive Production Diagrams

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

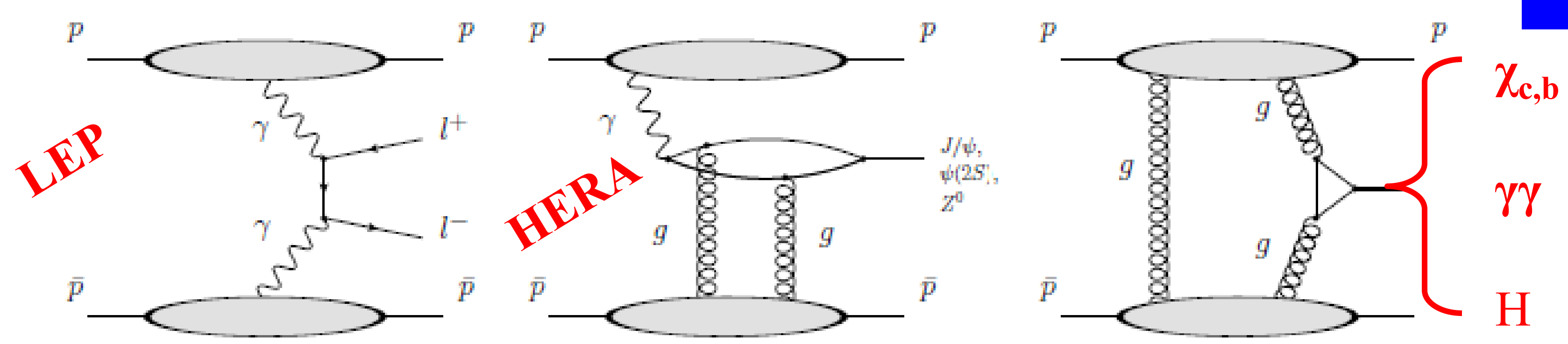



Figure 10: Feynman diagrams for processes contributing to the exclusive di-lepton signal. (a) $\gamma\gamma \to l^+l^-$, (b) $\gamma I\!\!P \to J/\psi, \psi(2S), Z^0$, and (c) $I\!\!P I\!\!P \to \chi_{c0}$.

**LPAIR MC:**
**J.A.M.Vermaseren, Nucl.Phys.B229 (1983) 347**

**Photoproduction**

**SuperCHIC MC:**
**L.Harland-Lang et al, arXiv:1005.0695 [hep-ph]**

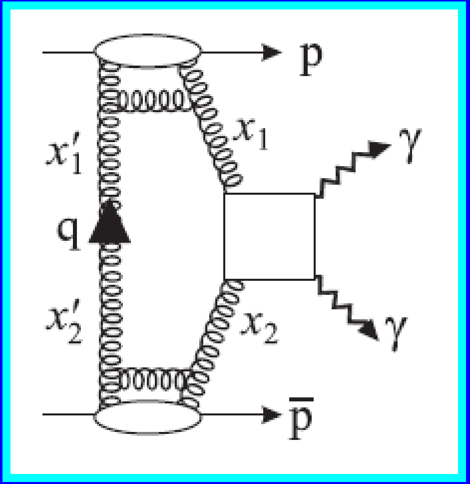
>>> Not essential to detect protons; can require all forward detectors to be at noise levels, for $|\eta| < \sim 7.4$

>>> Quasi-elastic protons inferred.

>>> No pile-up interactions allowed.

# Theoretical prediction for exclusive γγ

Khoze, Martin, Ryskin & Stirling
Eur.Phys. J.C38 (2005) p.475

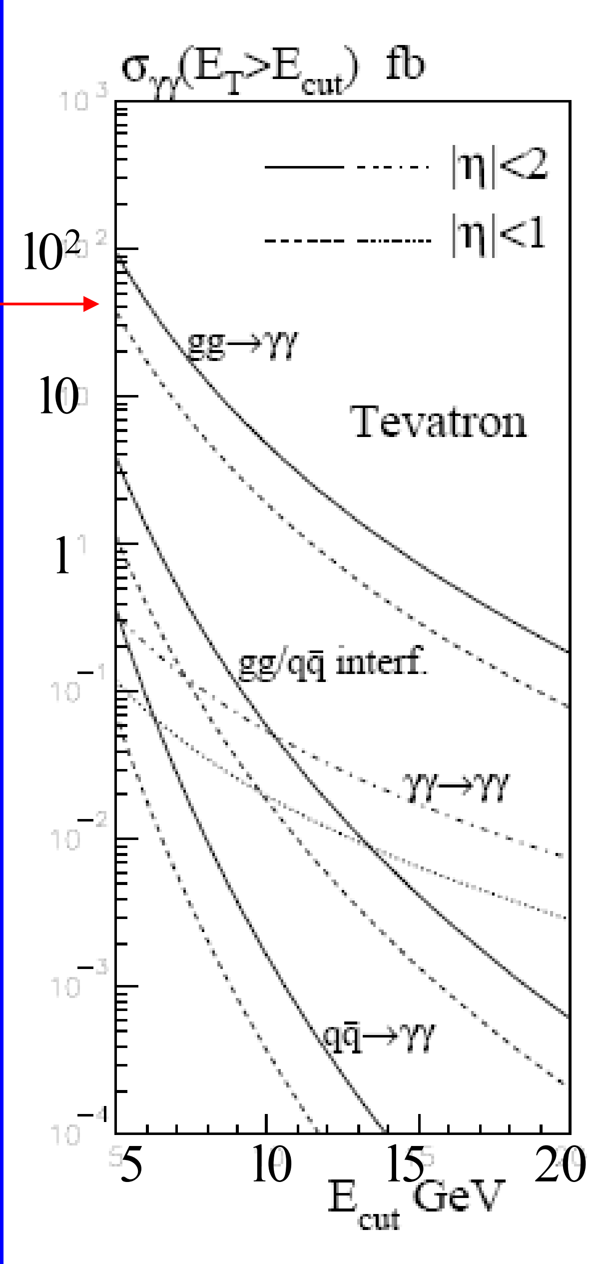



$E_T(\gamma)_{min} = 5$ GeV

$|\eta(\gamma)| < 1$

$\sim 38\ ^{\times 3}_{\div 3}$ fb @ 1.96 TeV

Factor 3 claimed
> 0.8 events pred.
3 candidates seen '07




Ingredients:

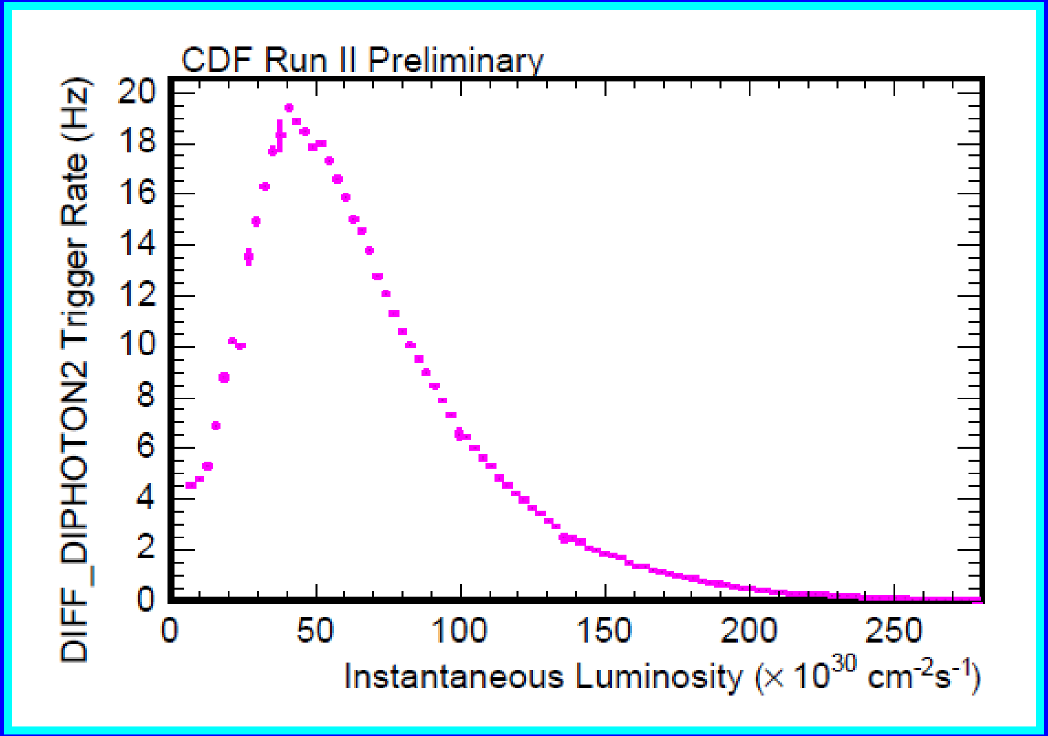
$\sigma(g + g \to \gamma + \gamma)$
Unintegrated g(x,x') $\sigma \sim g^4$
Loop integral
No gluon/hadron radiation
No other parton-parton interaction
(Gap survival factor)

Later extended down to 2 GeV: L.Harland-Lang et al.

# Trigger and Data Taking

2 EM towers ET > 2 GeV * BSC1 veto (kills P-U & many singles
HAD/EM < 0.125 ; No prescale ; 2 x $10^8$ triggers recorded

One year 2006-2007, Integrated luminosity 1.11 +/- 0.7 /fb
Trigger rate peaks when $\boxed{\bar{n}e^{-\bar{n}}}$ is maximum, L = 40 x $10^{30}$cm$^{-2}$s$^{-1}$

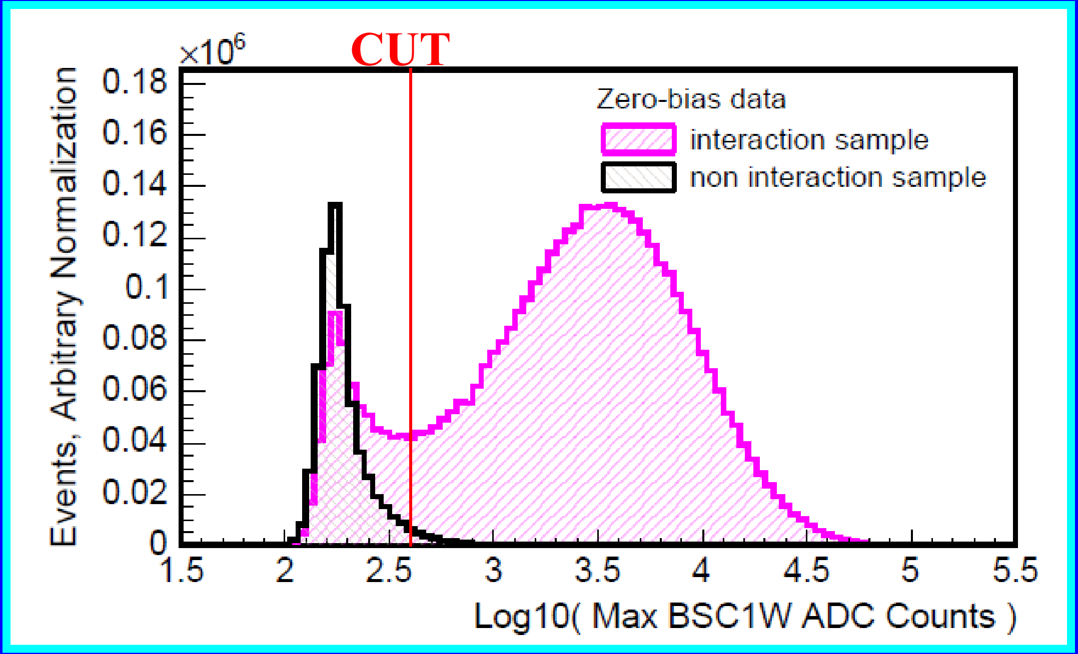



"Exclusive efficiency" = Prob. event not killed by P-U, calculated bunch x bunch.

# Selection of Exclusive Events

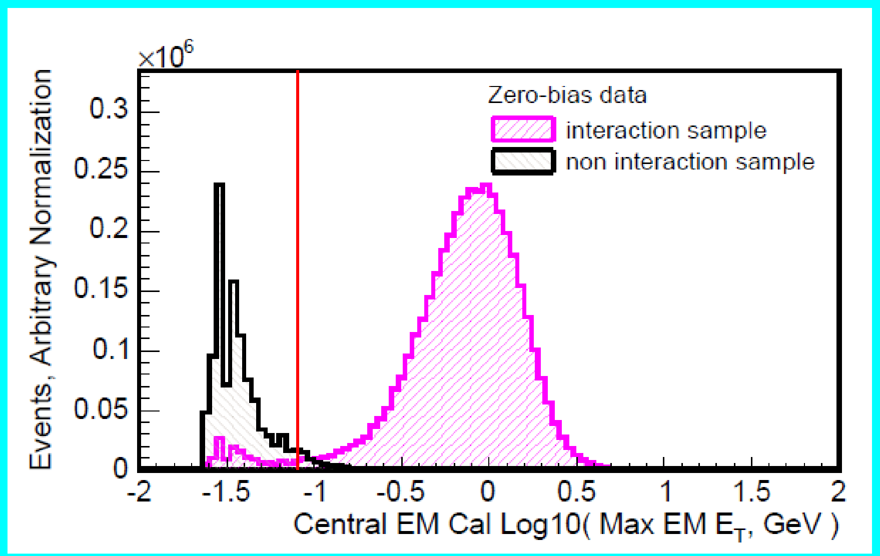
Require no other particles detected in entire CDF, including forward to $|\eta| = 7.4$
p & pbar are not detectable: stay in beam pipe.
Study noise levels: ZERO-BIAS (bunch crossing) trigger (crucial).
Make 2 classes: No COT tracks, no CLC hits, no muon stubs : **NON-INTERACTION**
All other events : **INTERACTION** (or several interactions)
For each sub-detector, plot "hottest" PMT signal or $E_T$ signal ($Log_{10}$ scale handy)
Choose cut separating noise from signals.

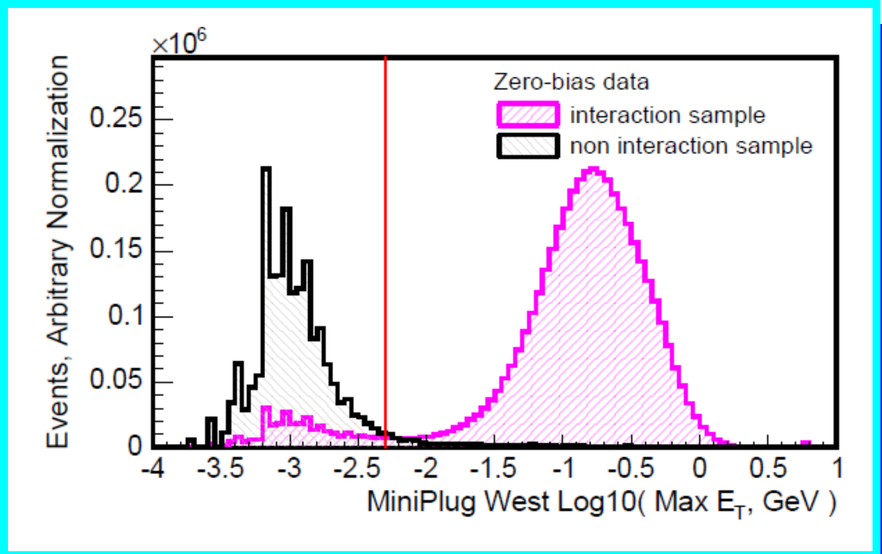
EXAMPLE:




INTERACTION events below cut : interactions having no particles in BSC-1

# Two more examples of noise studies and exclusive cuts:




Exclusive Filter Cuts

| Detector Part | max. Signal | $\|\eta\|$ coverage |
|---|---|---|
| Central EM Calorimeter ($E_T$): | 80 MeV | 0 - 0.66 |
| Central HAD Calorimeter ($E_T$): | 200 MeV | 0 - 0.66 |
| End Wall EM Calorimeter ($E_T$): | 80 MeV | 0.66 - 1.32 |
| End Wall HAD Calorimeter ($E_T$): | 200 MeV | 0.66 - 1.32 |
| Mid Plug Calorimeter ($E_T$): | 80 MeV | 1.32 - 2.11 |
| Forward Plug Calorimeter ($E_T$): | 30 MeV | 2.11 - 3.64 |
| Mini Plug Calorimeter ($E_T$): | 5 MeV | 3.6 - 5.2 |
| BSC-1 (ADC): | 400 counts | 5.4 - 5.9 |
| BSC-2 (ADC): | 300 counts | 6.4 - 7.1 |
| BSC-3 (ADC): | 400 counts | 6.7 - 7.4 |
| CLC (Sum of West and East) (ADC): | 6300 | 3.7 - 4.7 |

Apart from 2 EM towers, events pass all exclusive cuts

# Exclusive Efficiency, and Empty Detector

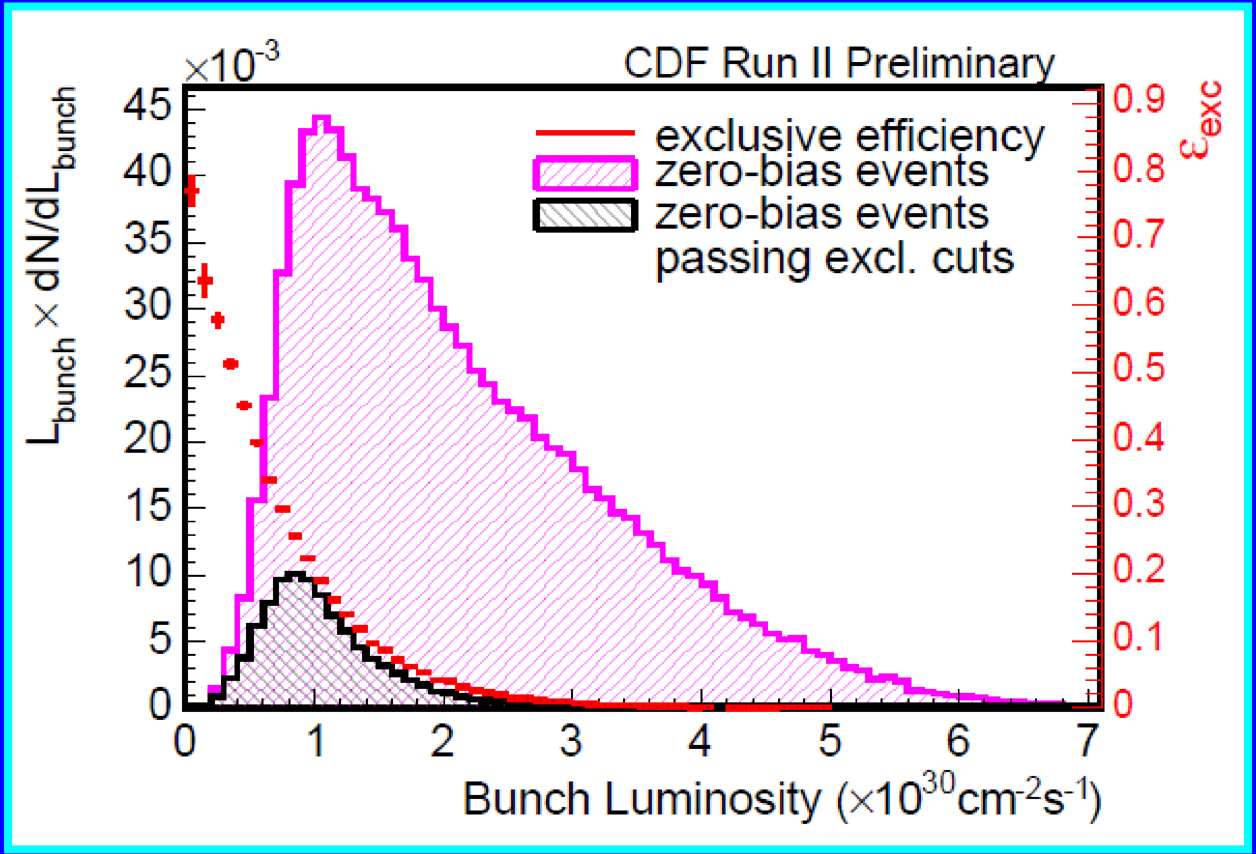
Exclusive efficiency $\varepsilon_{excl}$ :

Prob. good event not spoiled by another inelastic interaction (Pile-Up)

Apply all noise cuts to **ZERO-BIAS** events (no EM towers).

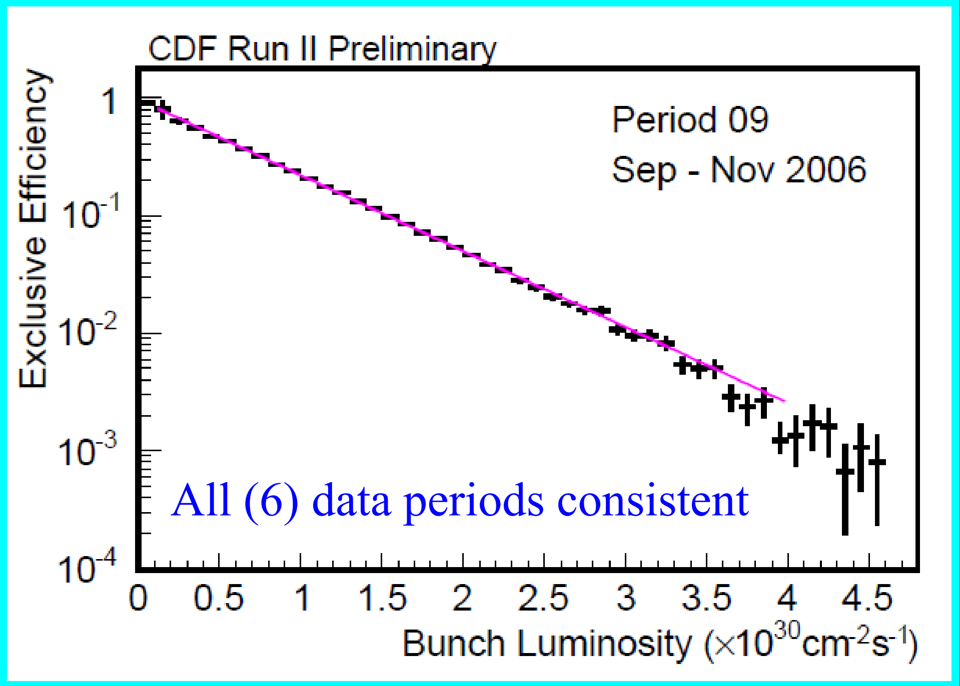
Measure P(0) = Prob(empty) vs Bunch luminosity (B x B)

[Not all the 36 bunch crossings have same Luminosity]




Red points:
Right scale
Ratio black:**pink**
(exponential)

# Probability all CDF empty vs bunch luminosity = exclusive efficiency




$$P(0) = \bar{n}.e^{-\bar{n}}$$

$$\bar{n} = \left(\frac{L_{bunch}}{46{,}500}\right) \times \sigma_{inel}$$

$$46{,}500 = \text{orbits / sec}$$

$$\Rightarrow \sigma_{\text{inel}}$$

Intercept should be 1.0
→at L = 0 all should pass
unless noise kills event

Total L = 1114 pb$^{-1}$ Intercept = 0.98±0.02,
Slope = 67±4 mb
$\varepsilon_{excl}$ = 0.068±0.004 ; Leff = 75.8 pb$^{-1}$

**Slope ~ "Inelastic Cross section": Not missing inelastic interactions**

$$CDF : \sigma_{TOT} = 80.0 \pm 2.2 \text{ mb at } \sqrt{s} = 1800 \text{ GeV}$$

$$\sigma_{\text{ELASTIC}} = 19.7 \pm 0.9 \text{ mb}$$

$$\Rightarrow \sigma_{INEL} = 60.3 \pm 2.4 \text{ mb at} \sqrt{s} = 1800 \text{ GeV}$$

$$\text{We are at } \sqrt{s} = 1960 \text{ GeV}$$

➡ Confidence that exclusive efficiency method and normalization are good

# Numbers of events, after all exclusive cuts:

| | |
|---|---|
| 2 EMO Central $\|\eta\|$ <1.0 and $E_T$ > 2.5 GeV | 82 |

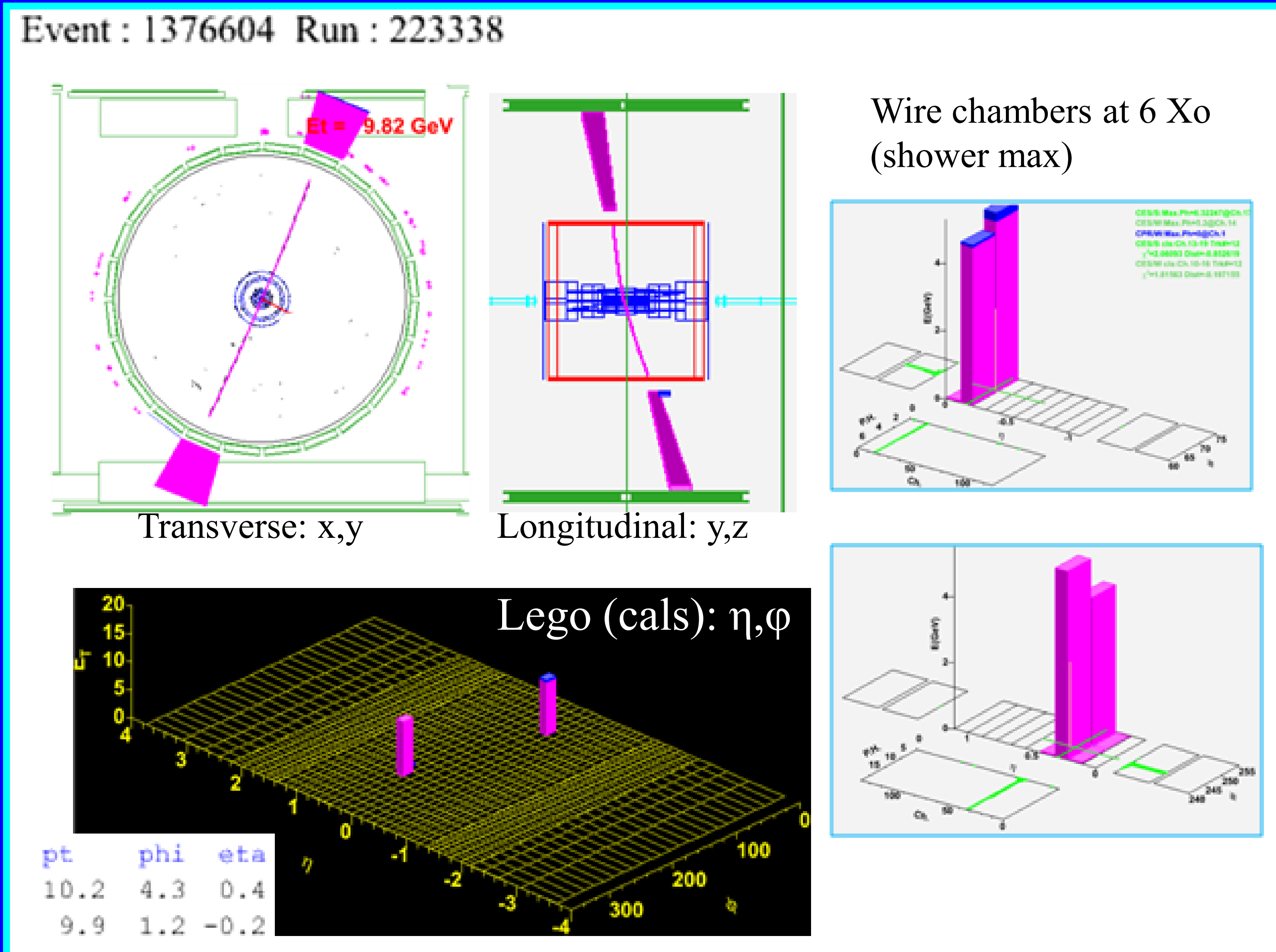
Up to now NO TRACK REQUIREMENTS:
Blind to COT Drift Chamber (& Silicon, Muons).
Now look at COT tracker:

2 Opposite charge tracks ($e^+e^-$) : 34

No tracks at all ( $\gamma\gamma$, or $\pi^0\pi^0$?) : 43

Ambiguous : 5 ( scan $\Rightarrow$ 2 + 2 + 1)

# Event display: the highest mass $e^+e^-$ event: $M(e^+e^-) = 20\ GeV/c^2$

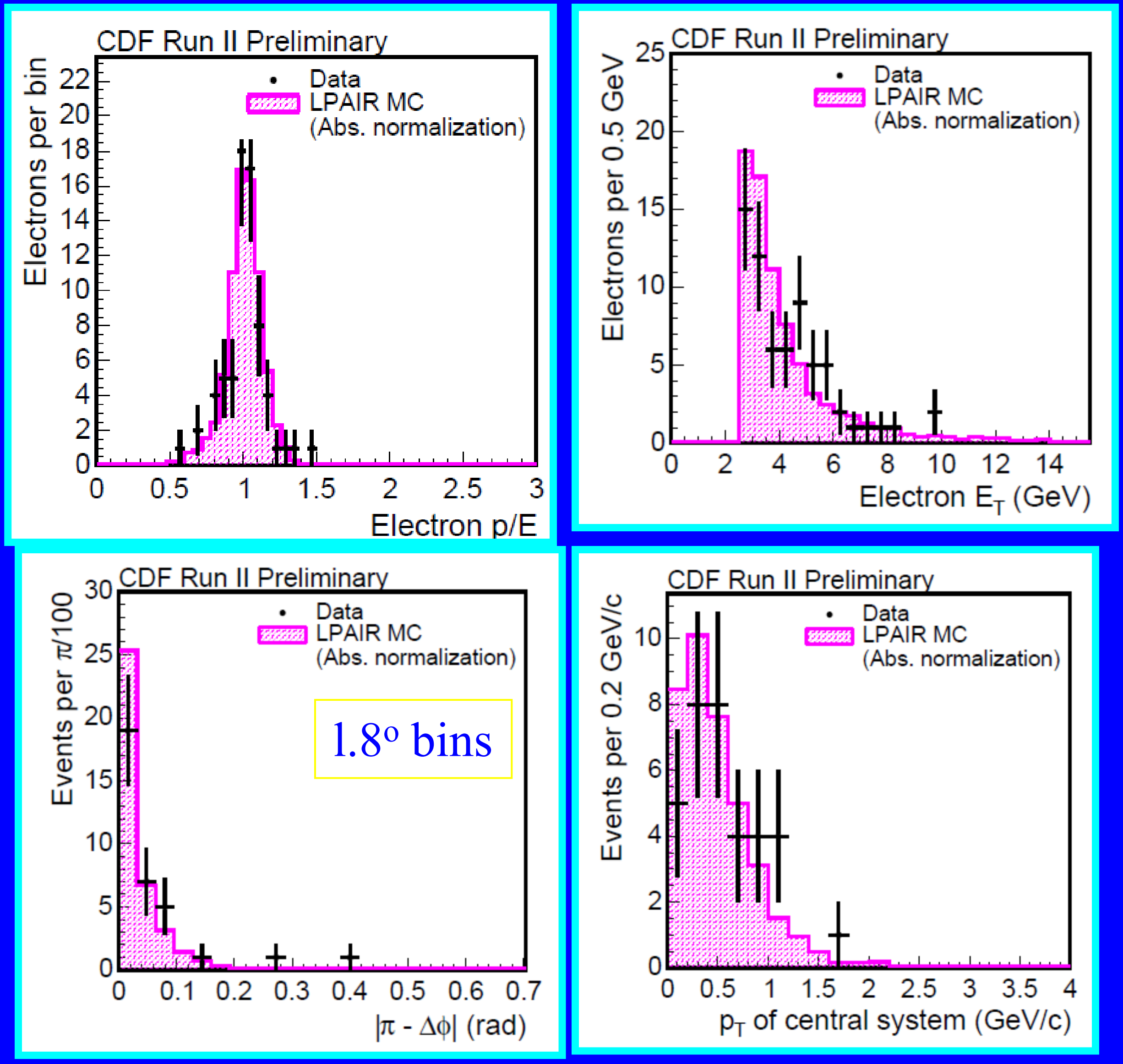



**Tracking efficiency very high: hard to miss an isolated high $p_T$ central track**

# Properties of e+e- events cf LPAIR e+e- MC simulation + CDFSIM
# Absolute normalization!

$E_T(e) > 2.5$ GeV
$\eta(e) < 1.0$
34 events,
>> 68 e's

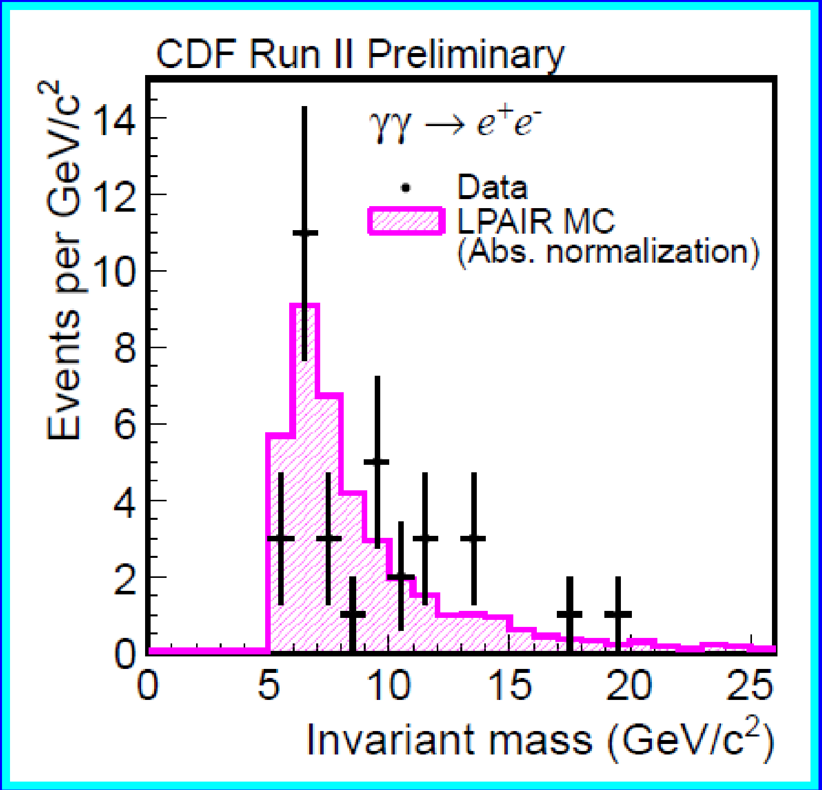
$$\gamma + \gamma \rightarrow e^+ + e^-$$




Photons … Coulomb..
$\langle p_T \rangle$ very small.
Detector resln (and FSR)
dominates spread.

# Mass spectrum (e+e-)

$\gamma + \gamma \rightarrow e^+ + e^-$




$$\sigma_{e^+e^-\,excl.}^{|\eta|<1, E_T>2.5\mathrm{GeV}} = 2.88 \pm 0.59(\mathrm{stat}) \pm 0.62(\mathrm{sys})\,\mathrm{pb}$$

$$\sigma_{\mathrm{LPair}}^{|\eta|<1, E_T>2.5\mathrm{GeV}} = 3.25 \pm 0.07\,\mathrm{pb}$$

**AGREE**

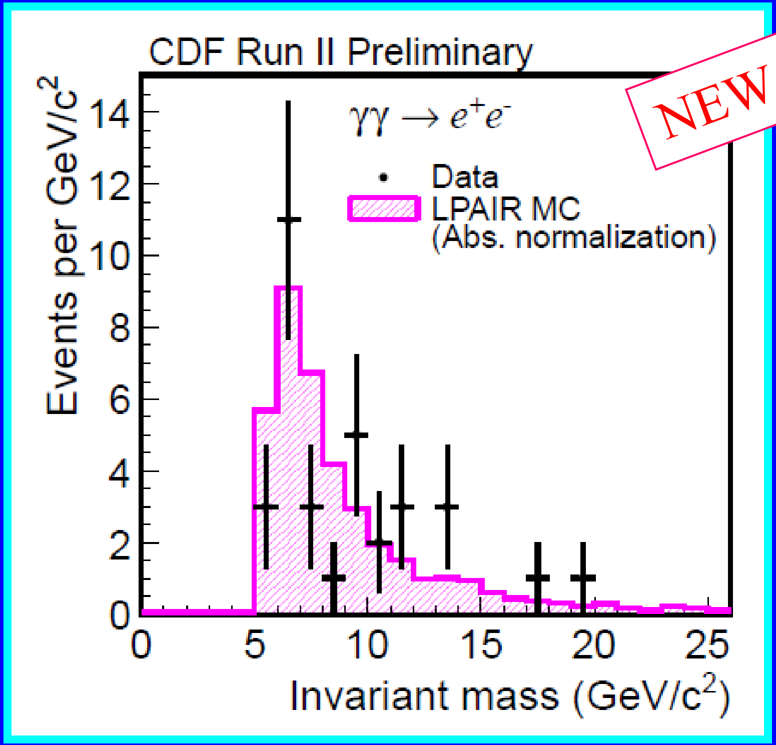
$$\sigma_{e^+e^-\,excl.}^{|\eta|<1, E_T>5.0\mathrm{GeV}} = 0.60 \pm 0.28(\mathrm{stat}) \pm 0.14(\mathrm{sys})\,\mathrm{pb}$$

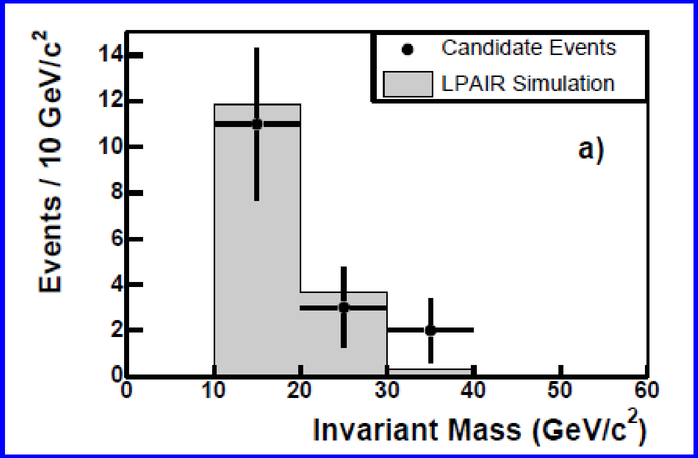
$$\sigma_{\mathrm{LPair}}^{|\eta|<1, E_T>5.0\mathrm{GeV}} = 0.58 \pm 0.003\,\mathrm{pb}$$

**AGREE**

Systematic uncertainties in back-ups

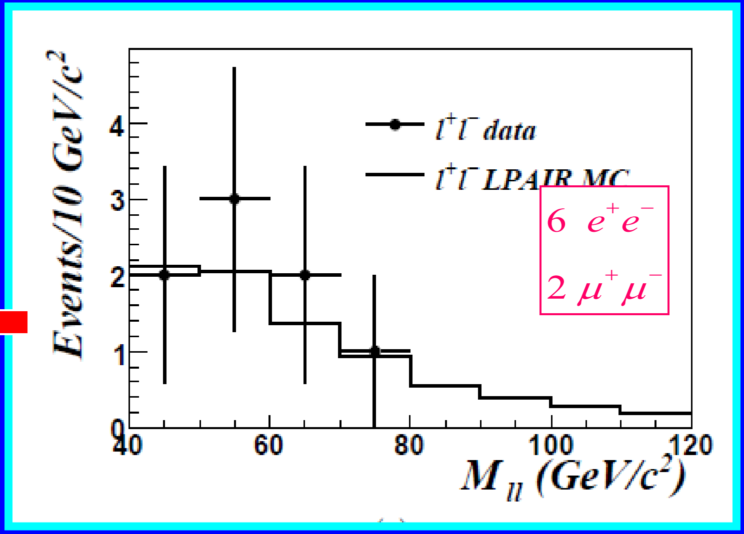
# Mass spectra (e+e-): Other CDF results cf QED (LPAIR)




CDF Phys.Rev.Lett. 98 (2007) 112001 (lst observation.)

All pairs have 180° – Δφ < 1°




AGREEMENT With LPAIR

CDF: Phys.Rev.Lett. 102 (2009) 222002
(Search for exclusive Z photoproduction)

# 43 Events with no tracks in COT ($\gamma\gamma$ candidates: $\pi^0\pi^0$ ?)

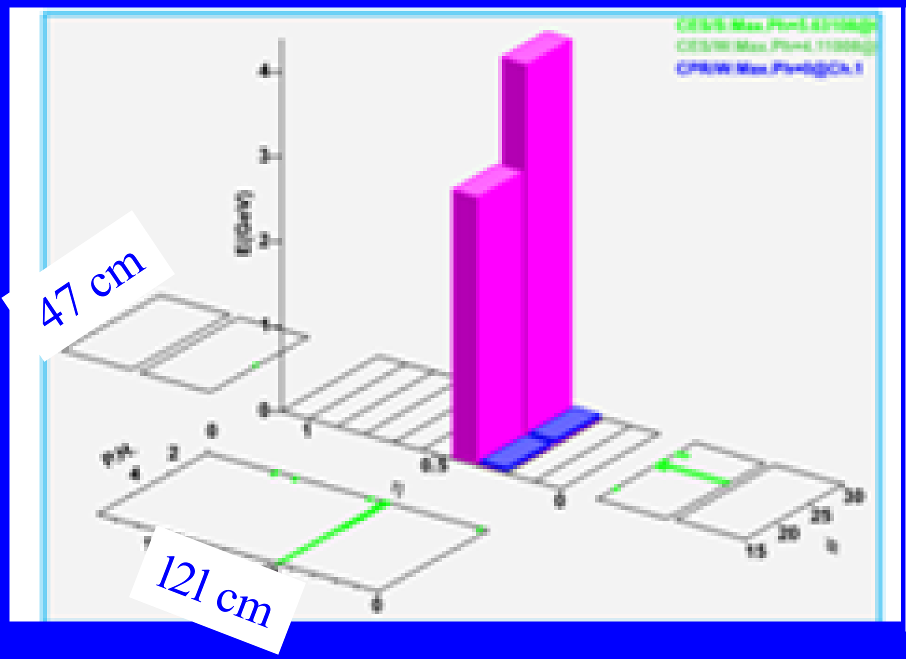
How do we know if they are $\gamma\gamma$ or $\pi^0\pi^0$ ?

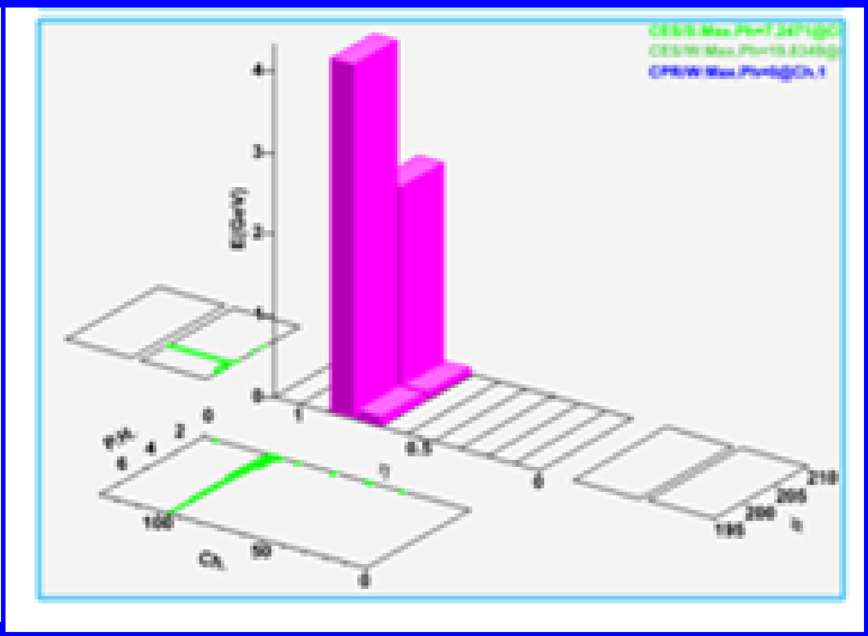
Note that exclusive **p + $\gamma$ $\pi^0$ + p** is forbidden (e.g. parity P)

Count showers in CES strip chambers. **Wires 1.45 cm, strips ~ 1.8 cm**

Two photons cannot merge:

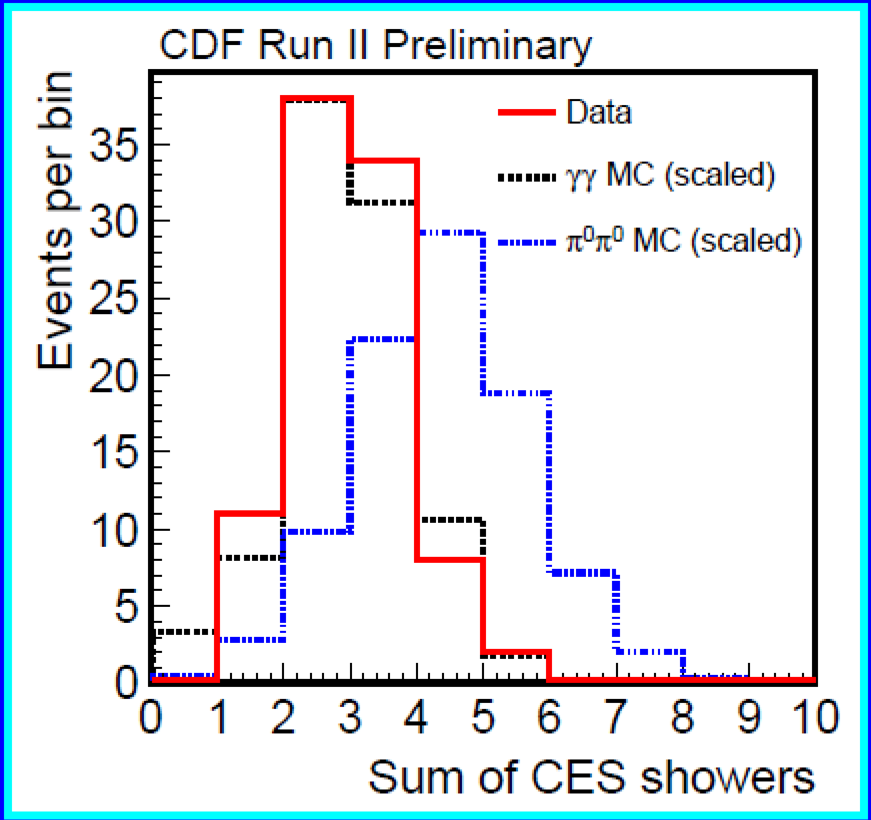
$$\theta(\gamma\gamma)_{min} = 2\times\left(\frac{m_\pi}{p_\pi}\right) = 3.2^0 \text{ for } p_\pi = 5 \text{ GeV/c}$$
$$= 11.2 \text{ cm at 2 m.}$$

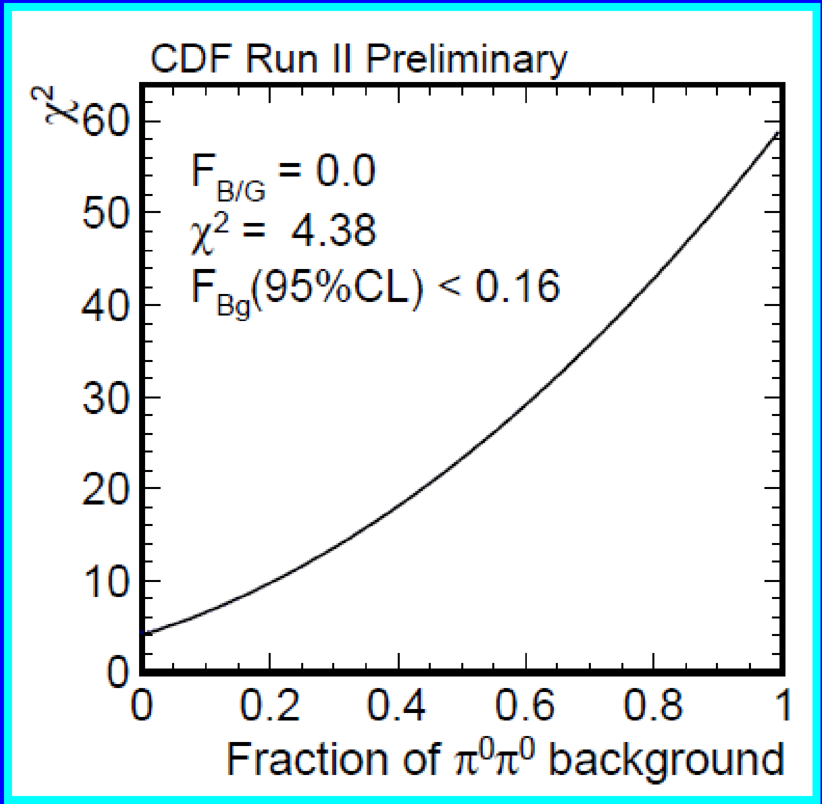


# Are any events not $\gamma\gamma$ but $\pi^0\pi^0$ ?

Add # showers on both sides (there is no correlation)




Result: Best fit is with ZERO background from $\pi^0\pi^0 \rightarrow 4\,\gamma$

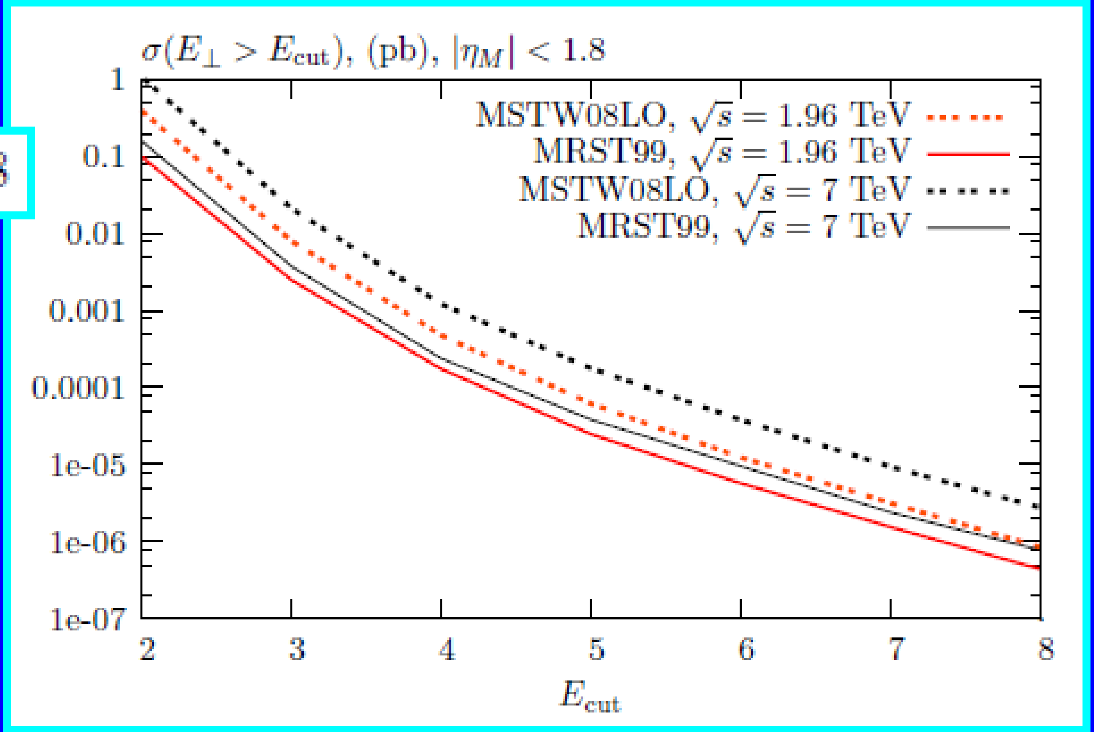
Pearson's $\chi^2$ test: fraction of $\gamma\gamma$ events in sample < 16% (95% C.L.)

# Theoretical Prediction of $p + \pi^0\pi^0 + p$ (After our conclusion)

L.Harland-Lang, V.Khoze, M.Ryskin and W.J.Stirling, arXiv:1105.1626

$\sigma(p + \pi^0\pi^0 + p)$

$\sigma(E_\perp > E_{\rm cut})$, (pb), $|\eta_M| < 1.8$




$\sqrt{s} = 1960\ GeV$

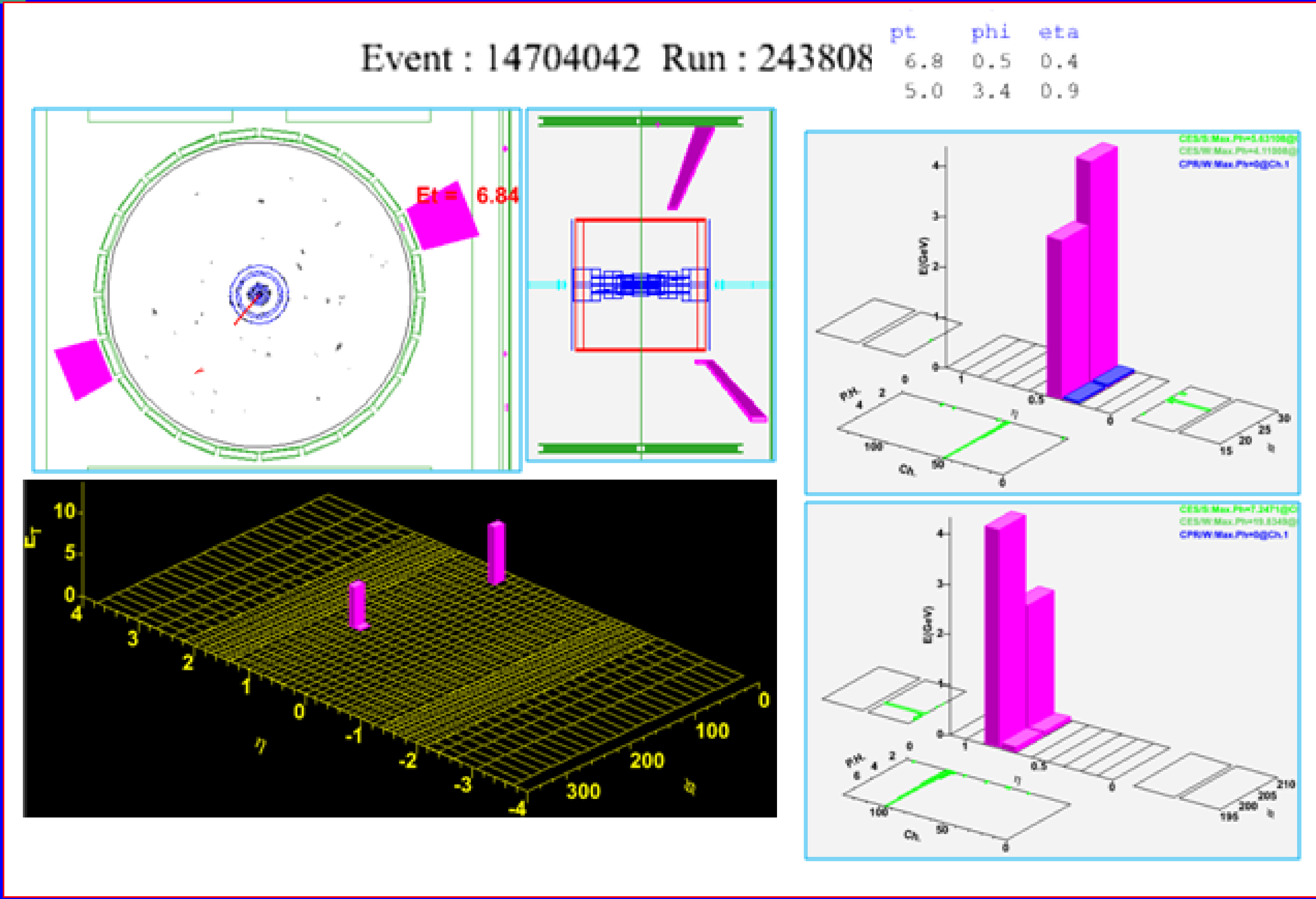
$|\eta| < 1.0$, $E_T > 2.5$ GeV

6 – 24 fb … < 1%

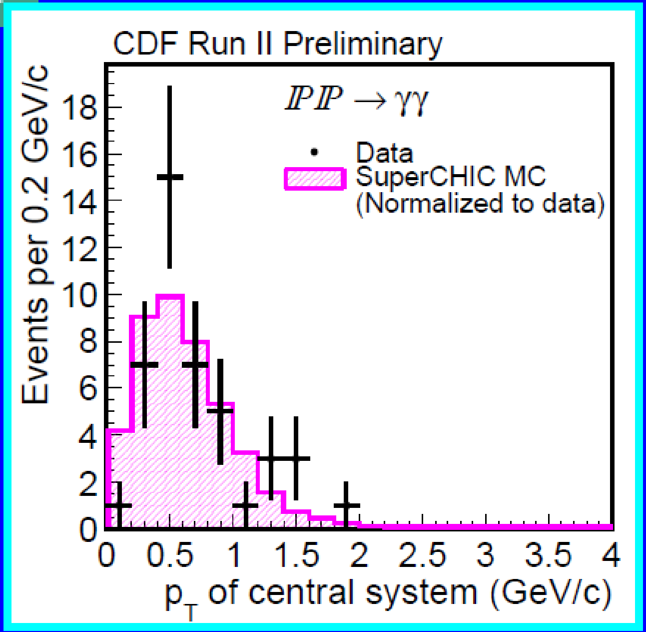
$\eta^0\eta^0$ also negligible.

Theoretically exclusive $\pi^0\pi^0$ falls <u>much</u> faster with $E_T$ or M than $\gamma\gamma$

# Example of γγ event

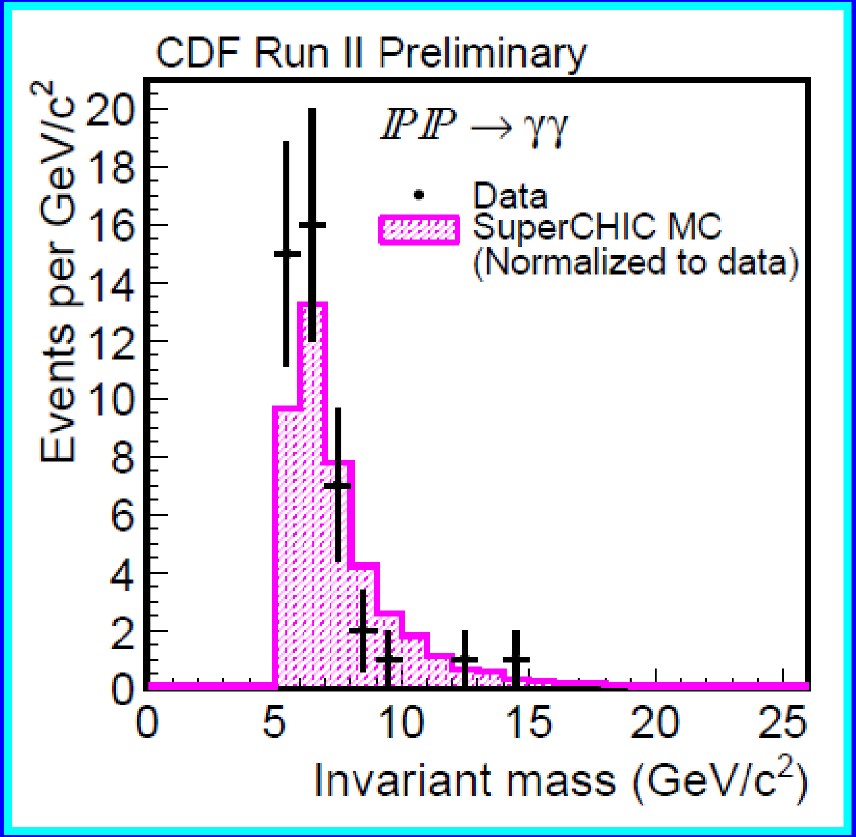


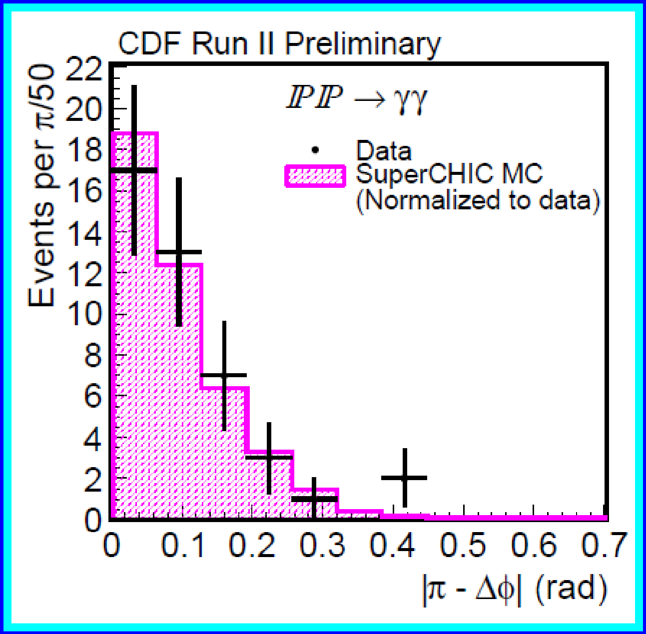
# Kinematic distributions of photon pairs




Normalization to equal area (shape comparison)

Note differences: γ+γ vs IP+IP



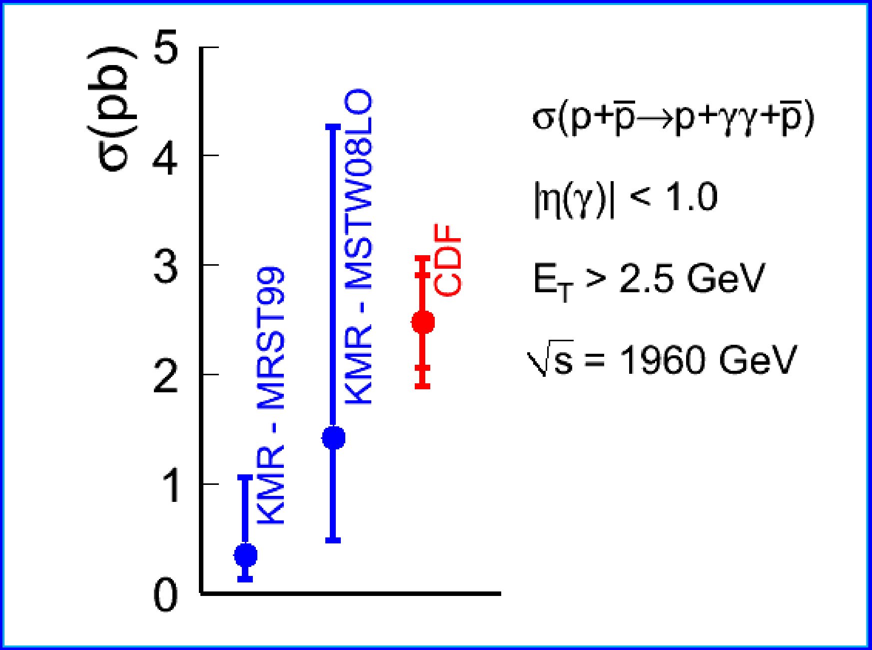
## Final results on $p+\bar{p} \rightarrow p+\gamma\gamma+\bar{p}$ via $IP+IP$ (QCD)

$$\sigma_{\gamma\gamma excl.}^{|\eta|<1, E_T>2.5GeV} = 2.48 \pm 0.42(stat) \pm 0.41(sys)\ pb$$

$$\sigma_{SuperCHIC\ (MSTW08LO)}^{|\eta|<1, E_T>2.5GeV} = 1.42^{\times 3}_{\div 3}\ pb$$

$$\sigma_{SuperCHIC\ (MRST99)}^{|\eta|<1, E_T>2.5GeV} = 0.35^{\times 3}_{\div 3}\ pb$$

Systematic uncertainties in back-ups




Only prediction (Durham Group) has ~ x 3 uncertainties + PDF's : $g(x)^4$

# Summary of Exclusive γγ

We have observed (43 events, >> 5 σ) the new clean process:

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

<u>We needed:</u>

A good level 1 trigger (EM showers + Forward gap-seeds with BSC-1)

Extended rapidity coverage of CDF to η = ± 7.4

Understood noise levels in all calorimeters and counters.

Demonstrated understanding of "empty events" (non-interaction in 0-bias)

Used $\boxed{p + \bar{p} \rightarrow p + e^+e^- + \bar{p} \text{ via } \gamma\gamma \text{ (QED)}}$ as a control (σ known)

Showed that EM showers are from γ and not $\pi^0$ as theoretically expected

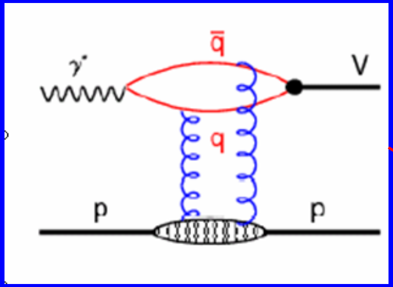
---

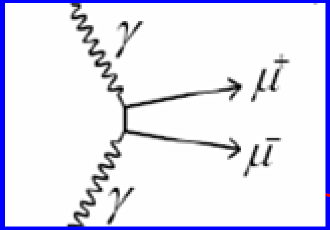
Result ~ background – free, agrees with Durham prediction (on high side)

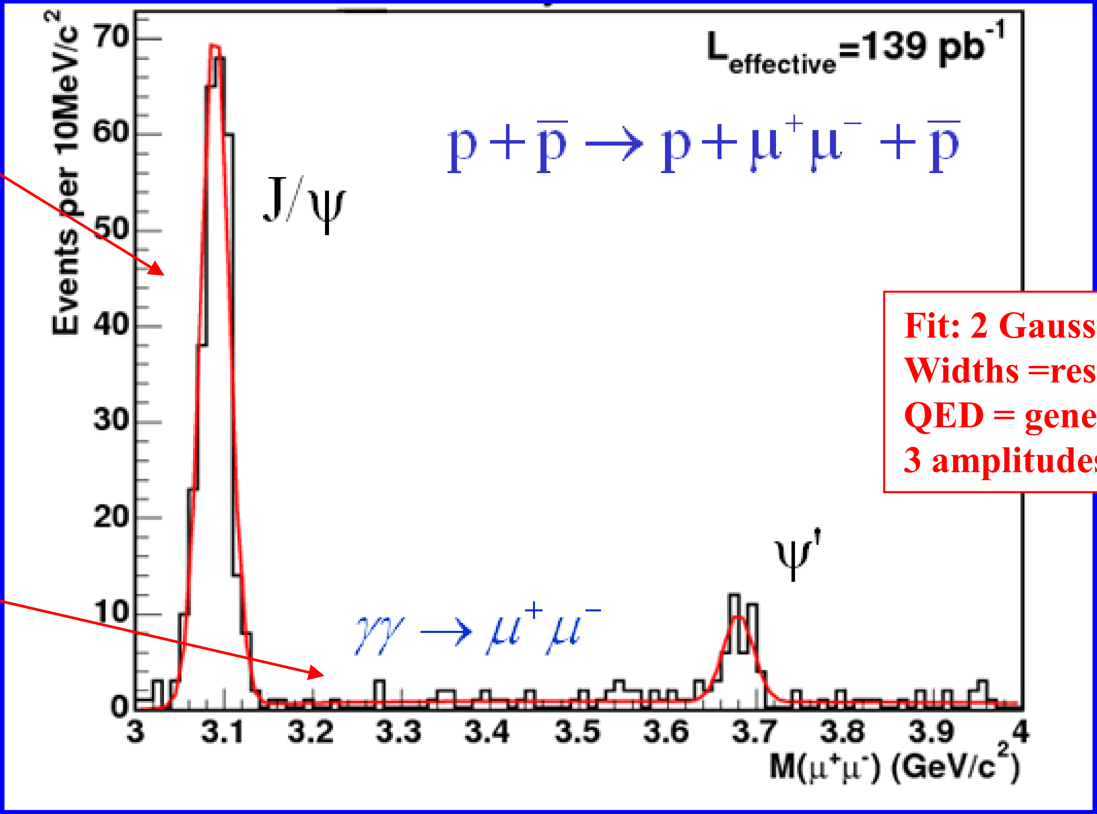
Observation of Exclusive Charmonium Production and $\gamma\gamma \to \mu^+\mu^-$ in $p\bar{p}$ Collisions at $\sqrt{s}$=1.96 TeV.

CDF: PRL 102, 242001 (2009)

$p+\bar{p} \to p+\mu^+\mu^- + \bar{p}$   $3\ \mathrm{GeV/c^2} < M_{\mu\mu} < 4\ \mathrm{GeV/c^2}$   **402 events**



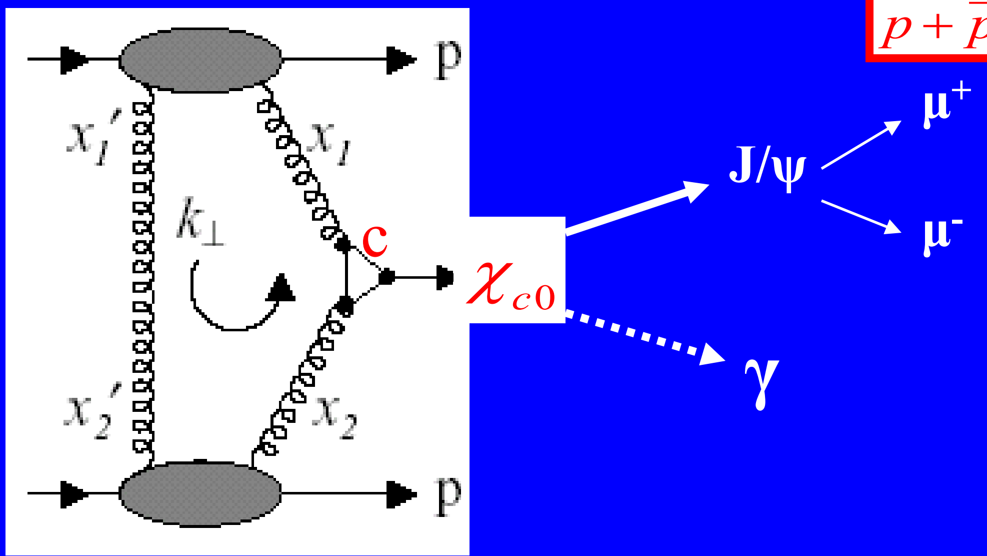




Fit: 2 Gaussians + QED continuum
Widths =resolution.
QED = generator x acceptance
3 amplitudes floating

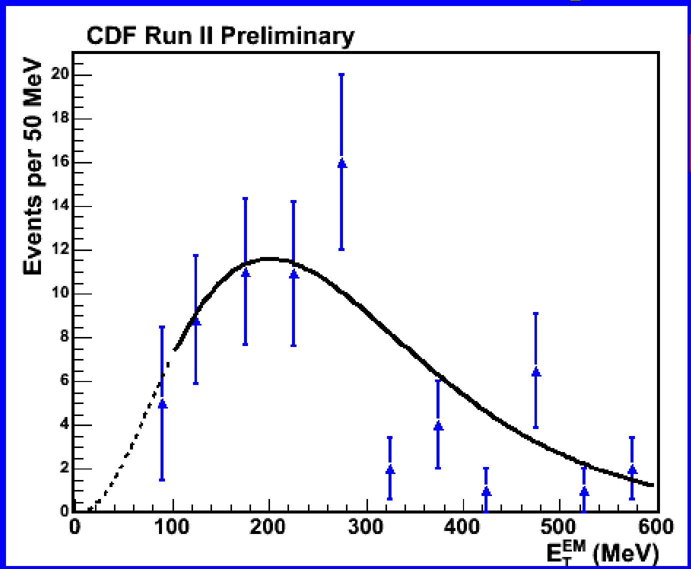
# Exclusive $\chi_c \rightarrow J/\psi + \gamma \rightarrow \mu^+\mu^- \gamma$

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




**& nothing else in all CDF -7.4 < |η| < + 7.4**

Now allow photons: EM $E_T$ spectrum with J/ψ mass cut:




J/ψ have photons : 286 → 352

ψ(2S) do not : 39 → 40

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

Kinematic fits of Δφ(μ+μ-) and pT(μ+μ-) for events with γ shower agree with $\chi_c$ simulations.

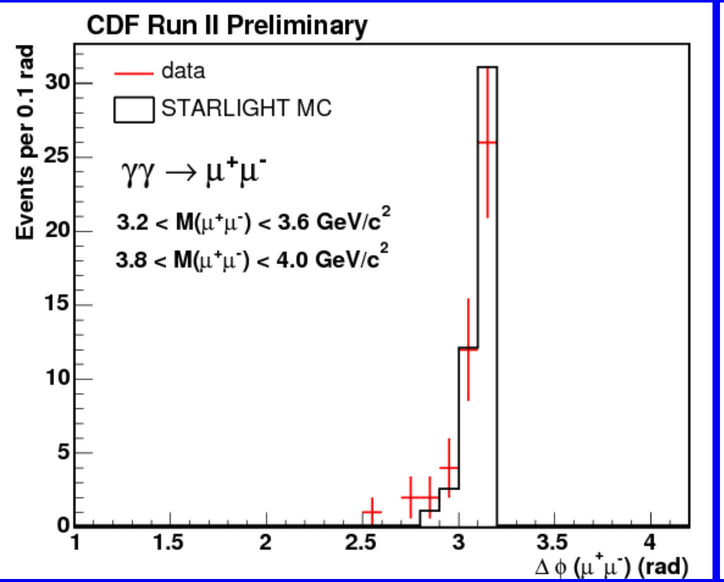
# $\chi_c$ = 65 +/- 8

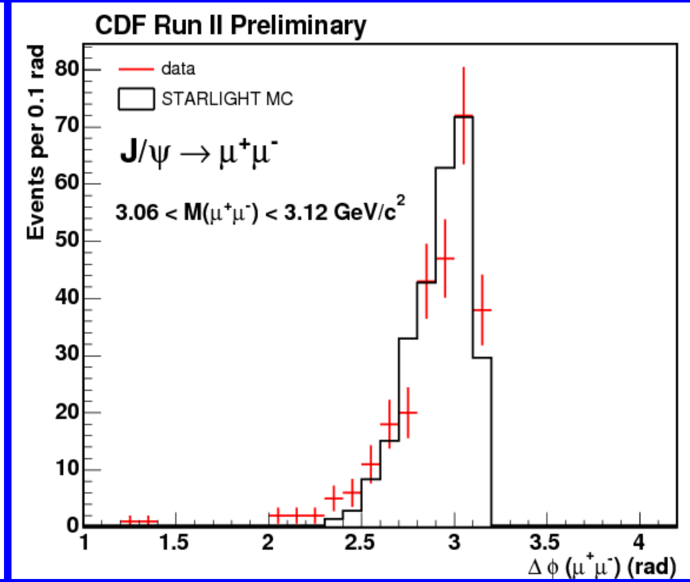
# Summary of Results from $p + \bar{p} \rightarrow p + \mu^+\mu^- + \bar{p}$ M = 3-4 GeV/c2

| Quantity | This analysis | Theory |
|---|---|---|
| $\frac{d\sigma}{dy}(y=0)J/\psi$ (nb) | $3.92\pm0.62$ | $3.0\pm0.3$ |
| $\frac{d\sigma}{dy}(y=0)\psi(2S)$ (nb) | $0.53\pm0.14$ | $0.46^{+0.11}_{-0.04}$ |
| $\frac{d\sigma}{dy}(y=0)\chi_c^\circ$ (nb) | $76\pm14$ | $130\pm\approx50$ |
| $\sigma(box, QED, pb)$ | $2.7\pm0.5$ | $2.18\pm0.02$ |
| $\frac{d\sigma}{dy}(y=0)O\mathbb{P}\rightarrow J/\psi$ | <2.3 nb (95% C.L.) | |
| $\frac{J/\psi}{\chi_c}$ | $0.052\pm0.015$ | No Prediction |

90 nb

No evidence for odderon




$\langle p_T(\gamma\gamma)\rangle < \langle p_T(I\!P)\rangle$

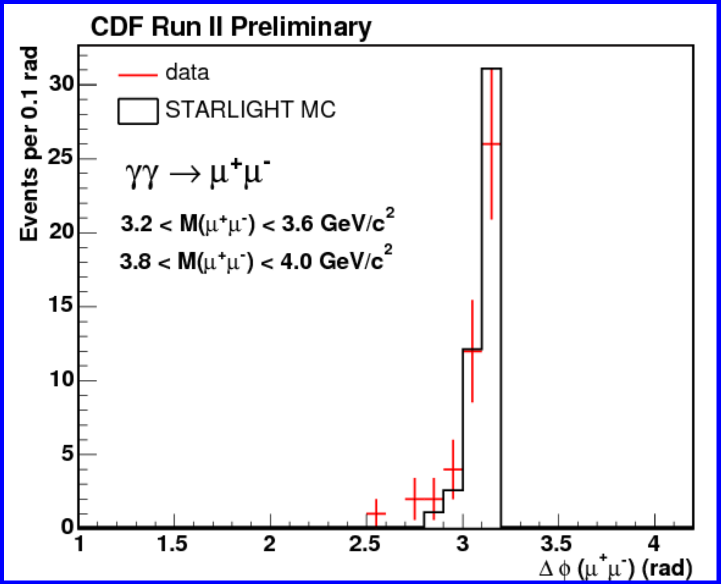
# Summary of Results

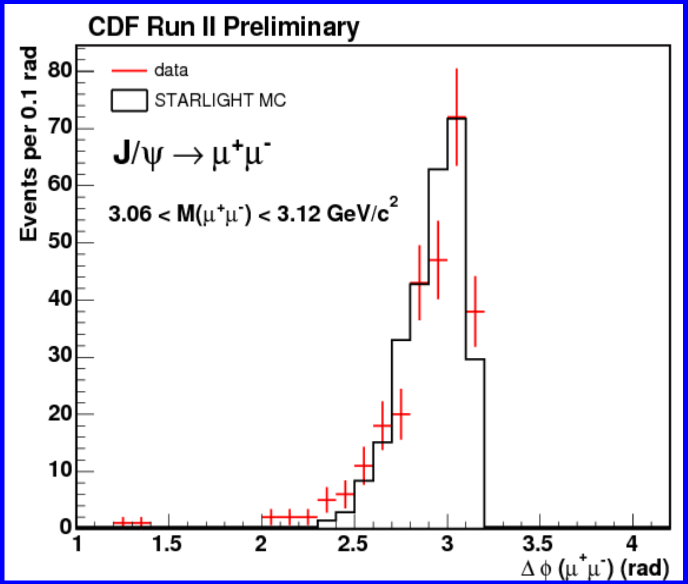
$p+\bar{p} \rightarrow p+\mu^+\mu^-(\gamma)+\bar{p}$

**M = 3-4 GeV/c2**

| Quantity | This analysis | Theory |
|---|---|---|
| $\frac{d\sigma}{dy}(y=0)J/\psi$ (nb) | 3.92±0.62 | 3.0±0.3 |
| $\frac{d\sigma}{dy}(y=0)\psi(2S)$ (nb) | 0.53±0.14 | $0.46^{+0.11}_{-0.04}$ |
| $\frac{d\sigma}{dy}(y=0)\chi_c^\circ$ (nb) | 76±14 | 130± ≈50 |
| $\sigma(box, QED, pb)$ | 2.7±0.5 | 2.18 ± 0.02 |

90 nb



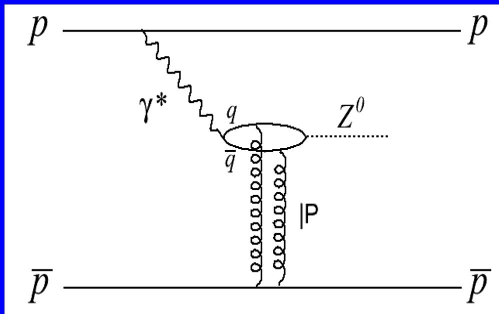




$\langle p_T(\gamma\gamma) \rangle < \langle p_T(IP) \rangle$

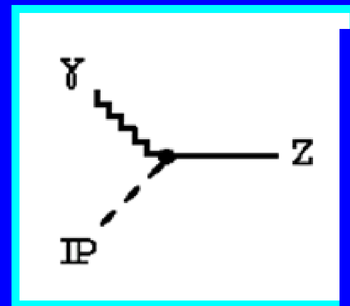
# Search for Exclusive Z production

PRL 102,222002 (2009)

**Allowed in SM (like V)**
**but $\sigma \sim 0.3$ fb (Motyka+Watt)**

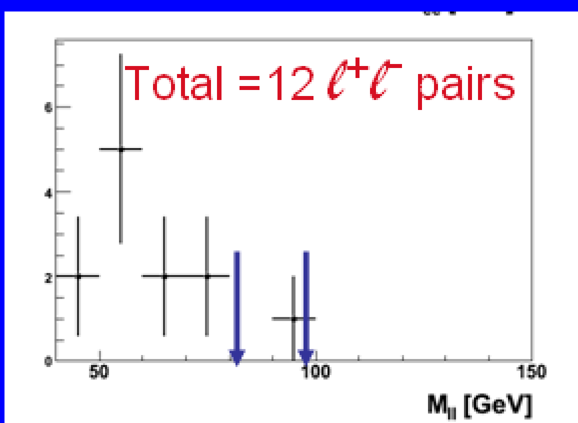


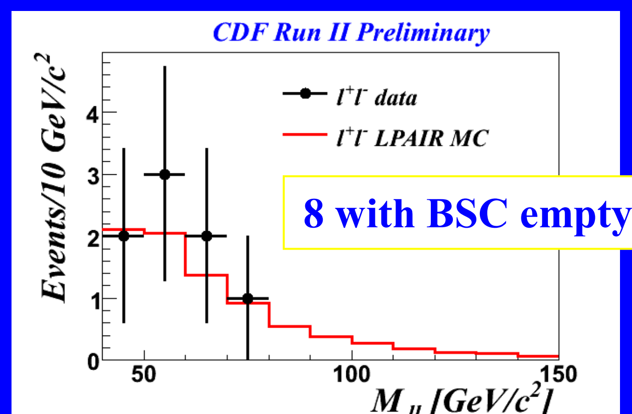

**Could be enhanced by BSM loops**




**Interesting?!**
**γ-IP-Z eff.coupling.**
**ZOOM IN to see how!**

$e^+e^-$ and $\mu^+\mu^-$, M > 40 GeV; 2.2fb-1, 31K, 183K in Z window 82-98 GeV
Require no other interaction, no additional tracks, all calorimeters in noise (E)




$\sigma(Z_{excl}) < 0.96$ pb (95% C.L.)
$\sigma(Z_{excl})$ Theory $= 0.3$fb
(13fb @ LHC)

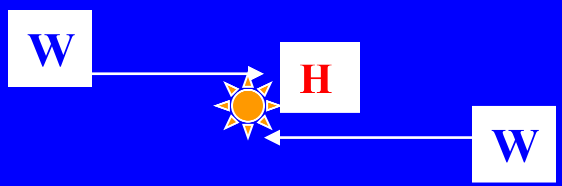
Search was in “no-PU” events.
Have 10 x data if PU allowed.
Great LHC topic!

# The Ultimate Vacuum Excitation

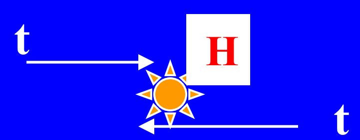
Above the $\chi_b$, the only "known" heavier particle with vacuum Q.Nos. is the Higgs.

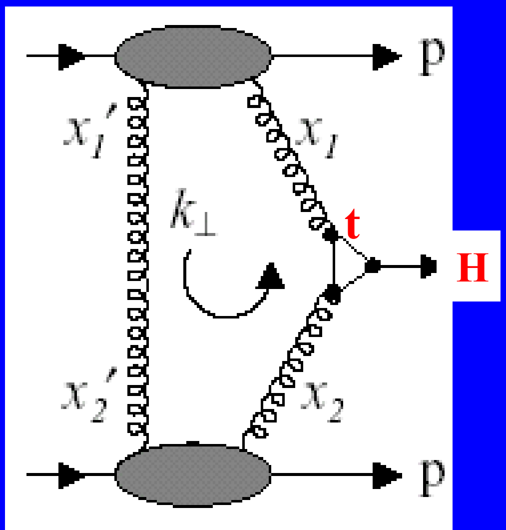
Vacuum is everywhere = Higgs field.

Hit the vacuum hard with a pair of weak probes, and you can promote them from Virtual → Real




**Top quarks work too**
**(they have weak charges)**




u-loop : $\gamma\gamma$ c-loop : $\chi_c^0$
b-loop : $\chi_b^0$ t-loop: H

gg→H is the main production process at LHC

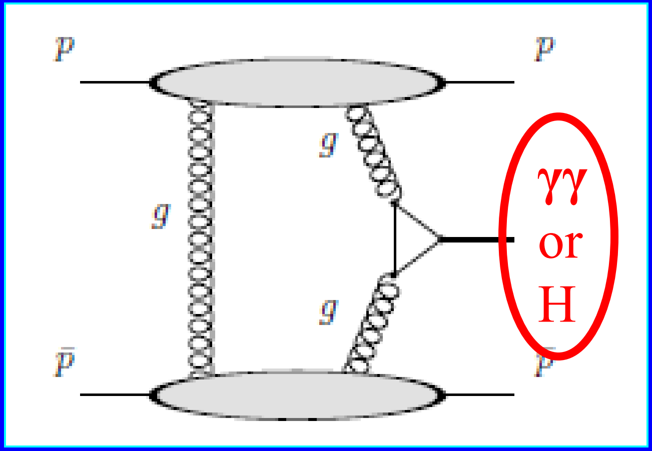
Sometimes : Another gluon cancels the color
No other parton-parton collisions occur
All gluon radiation is suppressed (Sudakov)

**Price ~ 1/2000 – 1/10000**
**σ (excl) ~ 1 – 10 fb cf ~ 20 pb**

**But if you see them, and measure both p, powerful benefits**

$$M_{CEN} = \sqrt{(p_1 + p_2 - p_3 - p_4)^2}$$ ⇒ $\sigma(M_H)$ ~ 2 GeV/event

**J,C,P,Γ?**




Same process from QCD perspective.
u,d,s,c,b loops → (b and) t loops
$Q^2$ different. x(g) similar

& $\chi_c$, $\chi_b$

σ(SMH ~ 120 GeV) ~ 10 fb (MSSM bigger)

Measuring both protons at 240m & 420m : σ(M) ~ 2 GeV/event
S:B only a few. → J=0, CP = ++, Γ(H), Γgg.

Technical Proposal being prepared to add very forward proton spectrometers to CMS & ATLAS in 2014

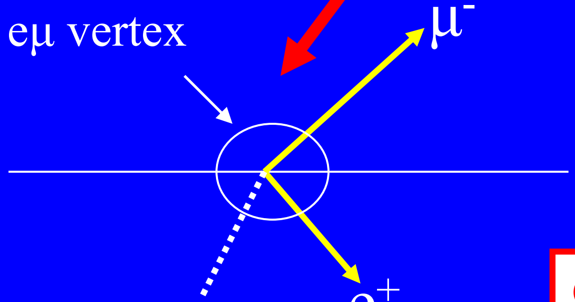
# The cleanest, simplest inelastic pp collisions.

Class 3 Interactions at the LHC:
"Inelastic, with no hadrons produced"

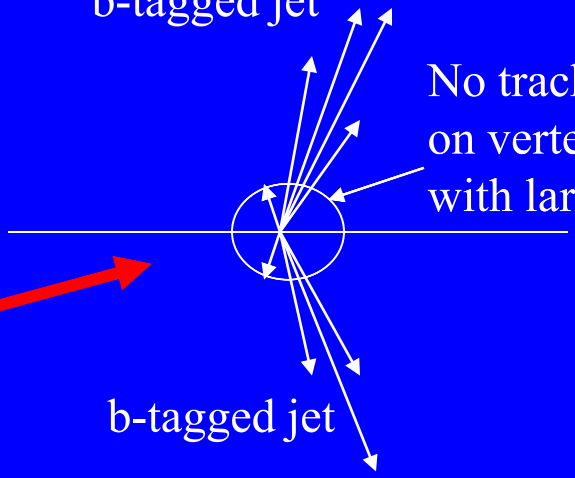
Consider WW + nothing (p's go down pipe, small $p_T$)
$\sigma(\gamma\gamma \rightarrow W^+W^-) \sim 50$ fb … or H + nothing

Could be H→WW.
Know M(WW) if measure p's

No other tracks on eμ vertex




or



b-tagged jet

No tracks on vertex with large $p_T$(rel)

b-tagged jet

Could be H→$b\bar{b}$.
Know M($b\bar{b}$) if measure p's

Missing $E_T$
$E_z$ too if measure p's

# Conclusions: I

In CDF we have observed exclusive 2-photon production,
i.e. $\boxed{p + \bar{p} \rightarrow p + \gamma\gamma + \bar{p}}$ with $E_T(\gamma) > 2.5$ GeV and with no hadrons.

43 events with background consistent with zero, and < 8 events (95% CL)

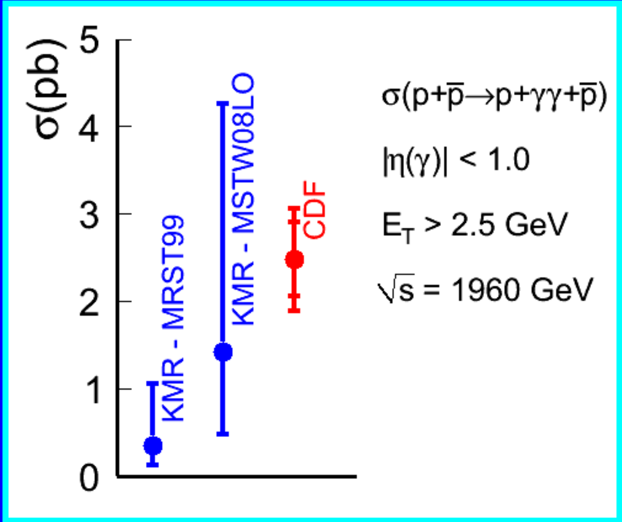
The cross section is ~ 2.5 pb, consistent with a theoretical prediction.

This confirms the picture of a hard pomeron as {gg}.

This is the first OBSERVATION of exclusive 2-photon production in hadron-hadron collisions.

| Exclusive Photon-Pair Production | |
|---|---|
| Theoretical | $\sigma_{\text{SuperCHIC}}^{\|\eta\|<1, E_T>2.5\text{GeV}} = 0.35^{\times 3}_{\div 3}\text{pb}$ (MRST99) |
| | $\sigma_{\text{SuperCHIC}}^{\|\eta\|<1, E_T>2.5\text{GeV}} = 1.42^{\times 3}_{\div 3}\text{pb}$ (MSTW08LO) |
| Measured | $\sigma_{\gamma\gamma\text{excl.}}^{\|\eta\|<1, E_T>2.5\text{GeV}} = 2.48 \pm 0.42(\text{stat}) \pm 0.41(\text{sys})\ \text{pb}$ |

Note: This corresponds to 1 in 25 billion inelastic collisions!



# Conclusions: II

We have also (earlier) observed:
Exclusive e+e- and μ+μ- pairs (QED: $\gamma\gamma \longrightarrow$ )
Exclusive J/ψ and ψ(2S) ... photoproduction
Exclusive IP + IP $\longrightarrow \chi_c$ (through c-quark loop)
Exclusive IP + IP $\longrightarrow$ Jet + Jet

These processes, especially $\chi_c$ and $\gamma\gamma$, confirm that at the LHC, if there is a Higgs boson, $p + p \longrightarrow p + H + p$ exclusive must happen, with σ(SMH-120) ~ 10 fb. More in MSSM scenarios...

→ 1000 x Acc. x Eff. events /year at $10^{34}$ cm$^{-2}$s$^{-1}$.
A few dozen events : M ($\sigma < 1$ GeV), J, CP, $\Gamma_{gg}$)

Need to install high precision spectrometers at 240m >>> 420 m from IP

**Thank you for your attention**

# Numbers of events, after sequential cuts:

| Number of events after exclusive cuts | |
|---|---|
| Trigger: | 200,143,239 |
| Presel: (2EMO > 2 GeV, $\|\eta\| < 1.8$): | 93,976,483 |
| Empty BSC counters (all): | 39,099,062 |
| Empty Miniplug and CLC: | 136,914 |
| Empty Forward Plug Calorimeter: | 13,974 |
| Empty Mid Plug: | 5,254 |
| Empty Low Plug: | 1,359 |
| Empty Central Calorimeter: | 421 |
| 2 EMO Central $\|\eta\| < 1.0$: | 180 |
| 2 EMO Central $\|\eta\| < 1.0$ and $E_T > 2.5$ GeV | 82 |

Up to now NO TRACK REQUIREMENTS:

Blind to COT Drift Chamber (& Silicon, Muons). Now look at COT tracker:

2 Opposite charge tracks ($e^+e^-$) : 34

No tracks at all ( $\gamma\gamma$, or $\pi^0\pi^0$?) : 43

Ambiguous : 5 ( scan $\Rightarrow$ 2 + 2 + 1)

# Final Results on $p+\bar{p} \rightarrow p+e^+e^- +\bar{p}\ via\ \gamma+\gamma\ (QED)$

Table: Statistics summary of all relevant parameters for the measurement of the exclusive $e^+e^-$ for an $E_T$ cut of 2.5 GeV and $|\eta| < 1.0$.

| | Value | Stat. error | Syst. error |
|---|---|---|---|
| $\mathcal{L}_{int}$ | 1.11 $fb^{-1}$ | $\pm 0.7 pb^{-1}$ | |
| $e^+e^-$ (events) | 34 | | |
| Trigger efficiency | 0.920 | $\pm 0.009$ | $\pm 0.018$ |
| Reconstruction efficiency | 0.508 | $\pm 0.007$ | $\pm 0.016$ |
| Identification efficiency | 0.912 | $\pm 0.017$ | $\pm 0.013$ |
| Tracking efficiency | 0.963 | 0.003 | |
| Radiative acceptance | 0.419 | $\pm 0.001$ | $\pm 0.077$ |
| Exclusive efficiency | 0.0680 | negligible | 0.004 |
| Dissoc. B/G (events) | 3.8 | 0.4 | 0.9 |

$$\sigma^{|\eta|<1, E_T>2.5\text{GeV}}_{e^+e^- \text{excl.}} = 2.88 \pm 0.59(\text{stat}) \pm 0.62(\text{sys})\ \text{pb}$$

$$\sigma^{|\eta|<1, E_T>2.5\text{GeV}}_{\text{LPair}} = 3.25 \pm 0.07\ \text{pb}$$

**AGREE**

$$\sigma^{|\eta|<1, E_T>5.0\text{GeV}}_{e^+e^- \text{excl.}} = 0.60 \pm 0.28(\text{stat}) \pm 0.14(\text{sys})\ \text{pb}$$

$$\sigma^{|\eta|<1, E_T>5.0\text{GeV}}_{\text{LPair}} = 0.58 \pm 0.003\ \text{pb}$$

**AGREE**

**Confidence that exclusive efficiency method and normalization are good**

# Final results on $p+\bar{p} \rightarrow p+\gamma\gamma+\bar{p}$ via $IP+IP$ (QCD)

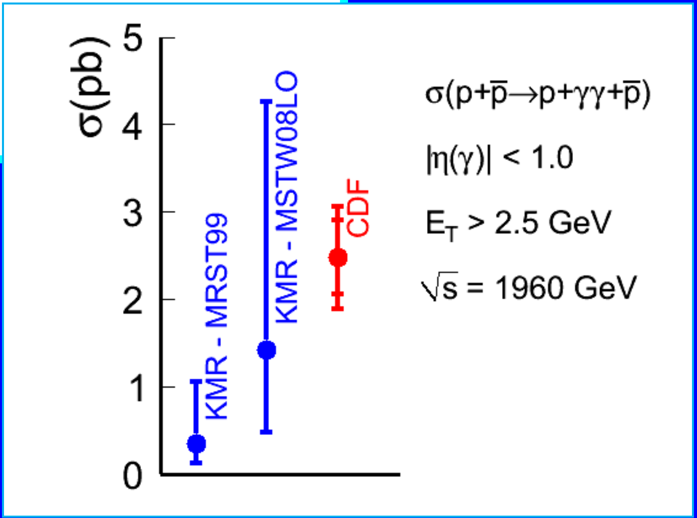
Table: Statistics summary of all relevant parameters for the measurement of the exclusive photon pair cross section for an $E_T$ cut of 2.5 GeV and $|\eta| < 1.0$.

| | Value | Stat. error | Syst. error |
|---|---|---|---|
| $\mathcal{L}_{int}$ | 1.11 fb$^{-1}$ | | $\pm$0.7pb$^{-1}$ |
| $\gamma\gamma$ (events) | 43 | | |
| Trigger efficiency | 0.918 | $\pm$0.005 | $\pm$0.018 |
| Reconstruction efficiency | 0.553 | $\pm$0.005 | $\pm$0.029 |
| Identification efficiency | 0.927 | $\pm$0.017 | $\pm$0.013 |
| Exclusive efficiency | 0.0680 | negligible | 0.004 |
| Conversion acceptance | 0.568 | $\pm$0.001 | $\pm$0.063 |
| $\pi^0$ background | 0.0 | | <16% (95% C.L.) |
| Dissoc. B/G (events) | 0.14 | | 0.14 |

$$\sigma^{|\eta|<1,E_T>2.5\text{GeV}}_{\gamma\gamma\text{excl.}} = 2.48 \pm 0.42(\text{stat}) \pm 0.41(\text{sys})\ \text{pb}$$

$$\sigma^{|\eta|<1,E_T>2.5\text{GeV}}_{\text{SuperCHIC (MSTW08LO)}} = 1.42^{\times 3}_{\div 3}\ \text{pb}$$

$$\sigma^{|\eta|<1,E_T>2.5\text{GeV}}_{\text{SuperCHIC (MRST99)}} = 0.35^{\times 3}_{\div 3}\ \text{pb}$$



# Checks and Efficiencies: Summary

**Rate** of final events (per effective luminosity) independent of run period.
**Trigger** efficiency (~ 92%)
Efficiency of **HAD/EM** cut vs E(e) (~ 93%)
Efficiency of **track finding/fitting** independent of $\eta$, $p_T$ (~ 96%) : Using J/$\psi$ data +MC
Efficiency of event not being lost by **radiation** (CDFSIM, ~ 40%)

**Reconstruction** efficiency: Full Monte Carlo simulation including reconstruction of electrons or photons.
Values are low and more dependent on $E_T$ and $\eta$ ( 1 – 2 )
because of bremstrahlung, conversions, $\delta$-rays.
Decided to select **$|\eta| < 1.0$** to minimize such dependence.
Scanning events confirmed more ambiguities there: "e $\rightarrow$ $\gamma$" and "$\gamma$ $\rightarrow$ e"

Reconstruction efficiency:

Electron pairs (LPAIR)

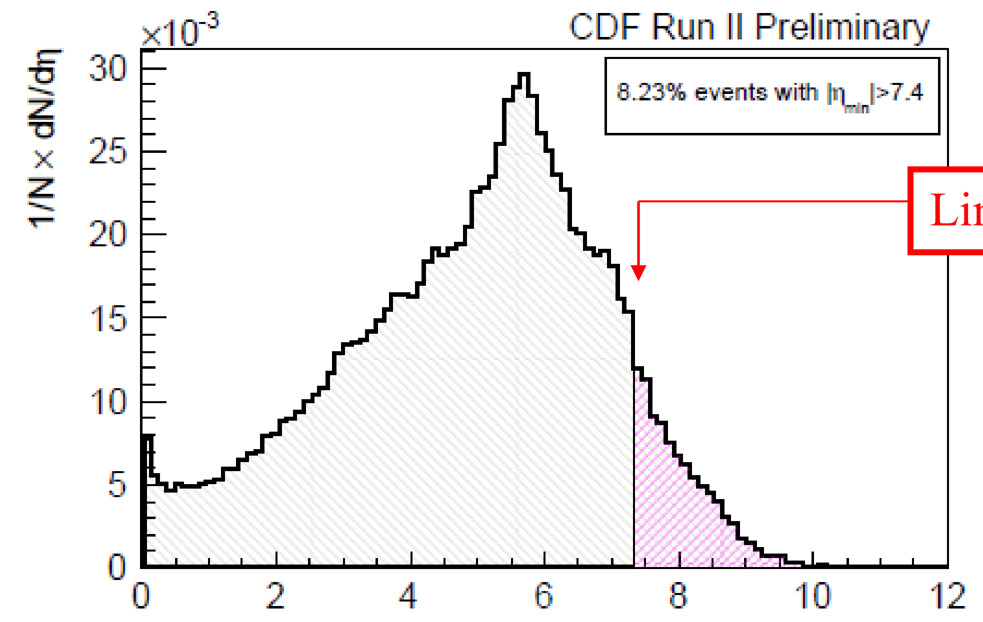
| $E_T$ cut (GeV) | 2.5 | 5.0 |
|---|---|---|
| $\varepsilon_{rec}^{e^+e^-}$ | 0.508 | 0.802 |
| Stat Err | $\pm$0.007 | $\pm$0.017 |
| Syst Err | $\pm$0.016 | $\pm$0.037 |

Photon pairs (SuperCHIC)

| $E_T$ cut (GeV) | 2.5 |
|---|---|
| $\varepsilon_{rec}^{\gamma\gamma}$ | 0.553 |
| Stat Err | $\pm$0.005 |
| Syst Err | $\pm$0.029 |

# Undetected p-dissociation e.g. $p \rightarrow p\, \pi^+ \pi^-$

Still γ+γ or IP + IP but not truly exclusive. Consider as B/G




η(min) of dissociating cluster particles

MinBias Rockefeller (MBR) Monte Carlo

~ 10 % for e+e-
< 1 % for γγ

e+e-

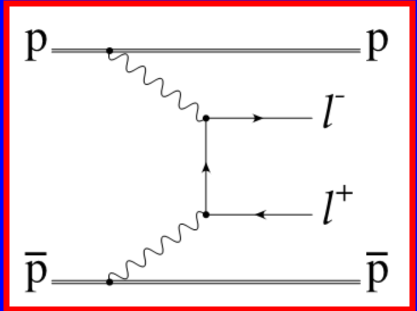
Dissociation Background (events)

| $E_T$ cut [GeV] | Fraction | Background |
|---|---|---|
| 2.5 | 0.12±0.01(stat)±0.03(sys) | 3.8±0.4(stat)±0.9(sys) |
| 5.0 | 0.13±0.02(stat)±0.03(sys) | 1.3±0.2(stat)±0.3(sys) |

For γγ

- Durham estimation using our selection rules with large rapidity gaps.
- Dissociation background estimate for $E_{T,min} = 2.5$ GeV: $0.14 \pm 0.14$(syst) events

# All our $e^+e^-$ and $\mu^+\mu^-$ measurements agree with QED: So what?




1) It shows we know how to select rare exclusive events in hadron-hadron environment
2) No other h-h cross section is so well known theoretically except Coulomb elastic (inaccessible).
3) Outgoing p-momenta extremely well-known (limited by beam spread). Calibrate forward proton spectrometers.
4) Practice for other $\gamma\gamma$ collisions at LHC:

$$\gamma\gamma \rightarrow W^+W^-, \tilde{l}^+\tilde{l}^-, \ldots$$

**<u>At</u> LHC**

Has been considered as a calibration of luminosity monitors at LHC. Theory precise but acceptance, efficiencies and background (including p-dissociation) probably limit uncertainty to ~ 2-3%

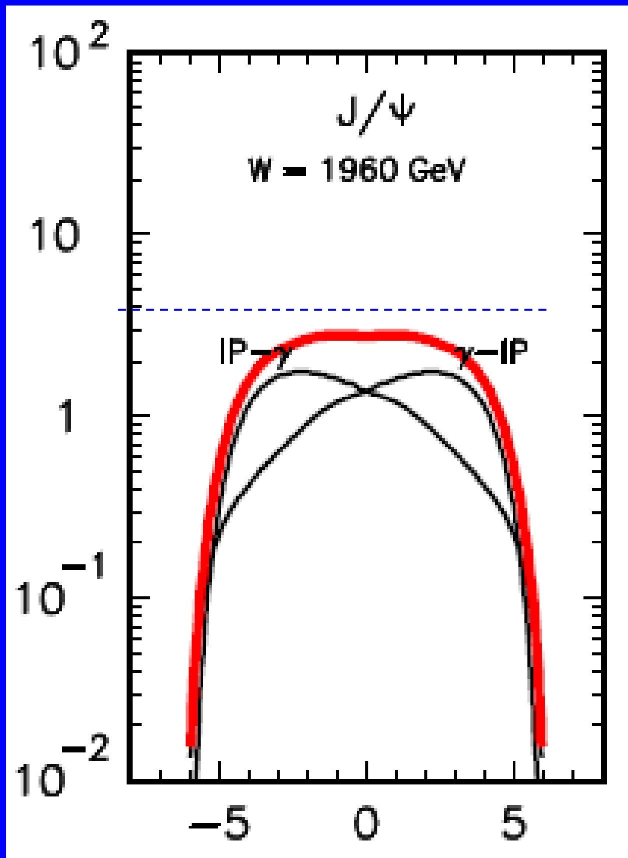
8800 events in 1 $fb^{-1}$ with $M(\mu^+\mu^-) > 10$ GeV and $|\eta| < 2$

Van der Meer scans can probably reach that with improvements

Some predictions for J/ψ photoproduction:

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

dσ/dy (nb)




y

Take 3.0 +- 0.3

**Machado,Goncalves 3.0 nb**
**Motyka and Watt: 3.4 +- 0.4 nb**
**Schafer & Szczurek ~ 2.8 nb**
**Nystrand 2.7+0.6-0.2 nb**

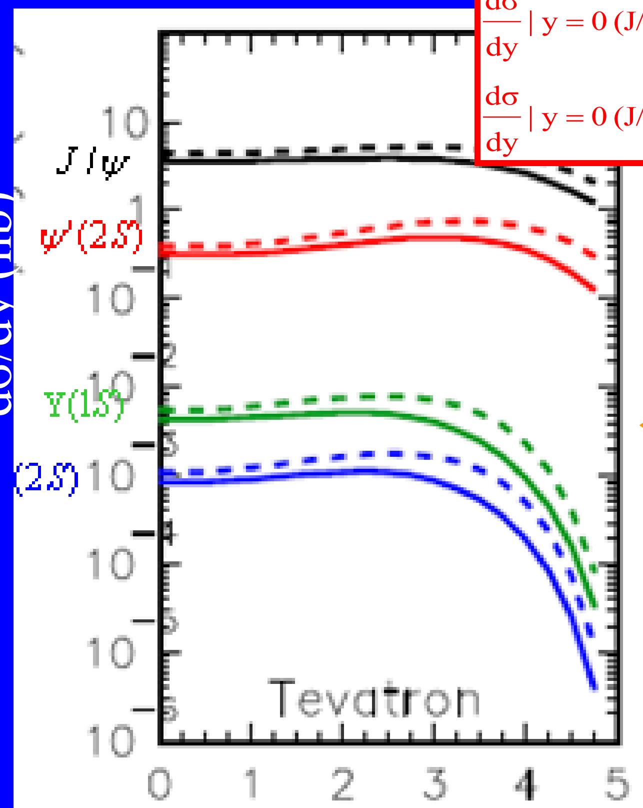
**Our result: 3.92 +- 0.62 nb**

$\frac{d\sigma}{dy}|\, y=0\, (J/\psi) = 3.0 \pm 0.3$ nb (theory, average)

$\frac{d\sigma}{dy}|\, y=0\, (J/\psi) = 3.92 \pm 0.62$ nb (CDF)

$\frac{d\sigma}{dy}|\, y=0\, (J/\psi) < 2.3$ nb for $OIP \to J/\psi$ (95%)

dσ/dy (nb)

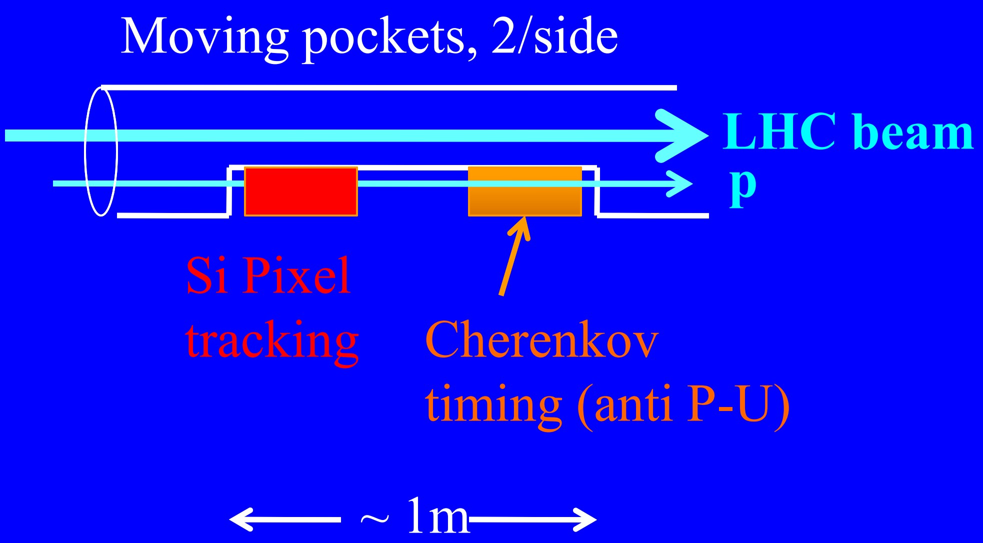



y

**Υ is much lower.**

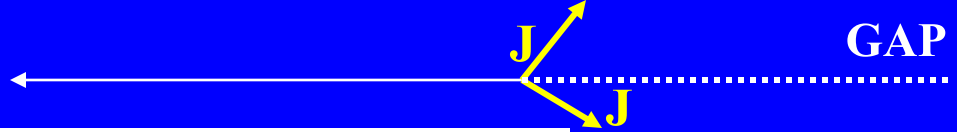
Technical proposals under development to add precision p-detection:
ATLAS : AFP = Atlas Forward Protons +/- 220m later 420m
CMS : HPS = High Precision Spectrometers +- 240m (2014), 420m (2018)
(Joint R&D was called FP420 ... many common solutions)

@ 240m: clear pipes. Moving pipe

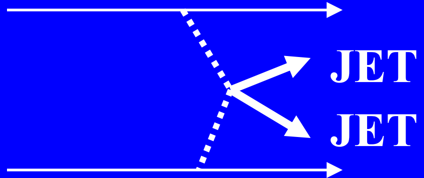



Tracking: 1 μrad = 8 μm/8 m, Rad hard, edgeless, 2 $cm^2$ ~ 16 layers
Timing: $\sigma(t) \sim 10$ ps: Cherenkov : gas with MCP-PMT; quartz with SiPMs.
Precision mechanics, BPMs, reference time signals, ...
$\sigma(t) = 10$ ps $\rightarrow$ $\sigma(z) = 2.1$ mm cf $\sigma(z, \text{interactions}) \sim 50$ mm

# *Exclusive Di-Jets*

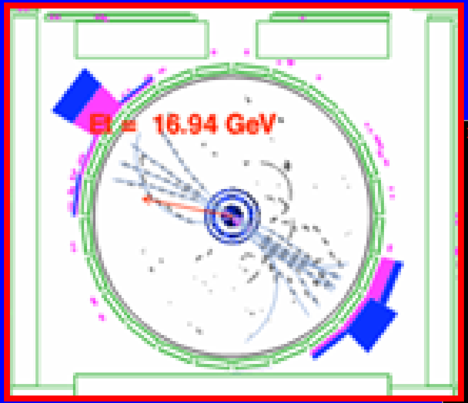



$p+\bar{p} \rightarrow p+JJ+\bar{p}+\sim \text{nothing else}$

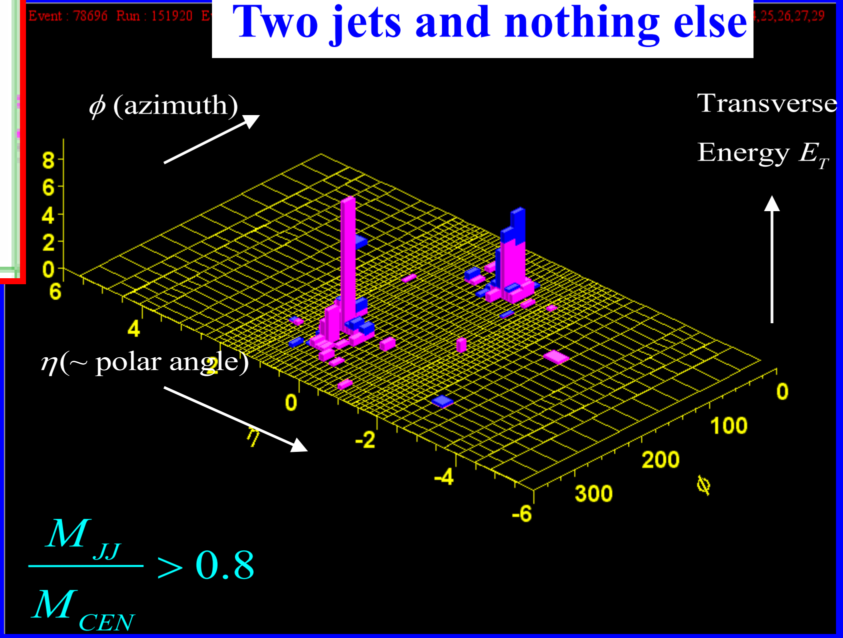



**Observed in CDF, QCD tests & related to p+H+p**

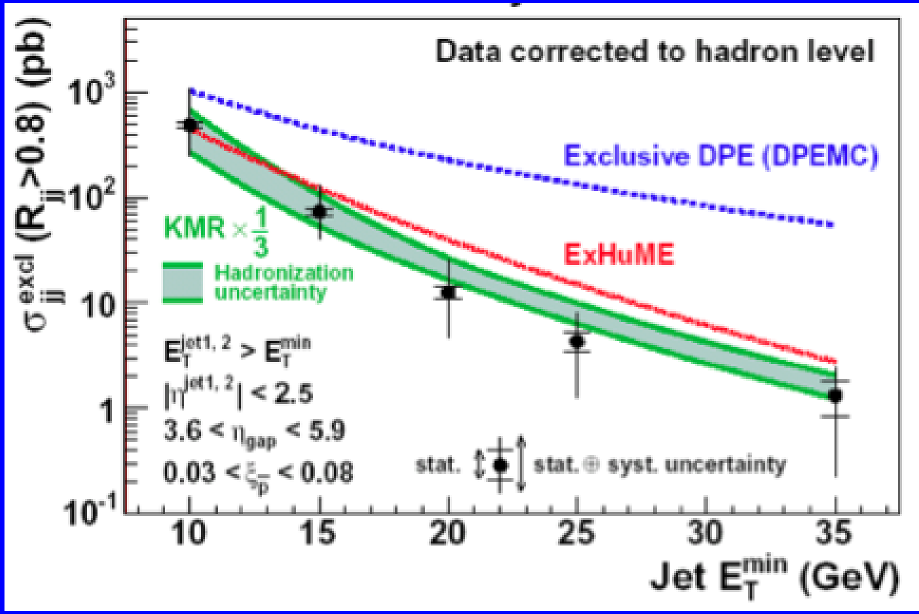
$R_{JJ} = \frac{M_{JJ}}{M_X} \approx 1.0$




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




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




Interesting QCD: gap survival, Sudakov factor
Nearly all jets should be gg …. qq suppressed by M(q)/M(JJ) (Jz=0 rule)

Gluon jet physics.