Observation of Exclusive γγ Production in CDF

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Ph.D. thesis of Erik Brucken (U. Helsinki)

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

3 Classes of Hadron-Hadron Collisions:

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

ALMOST ELASTIC

Observation of Exclusive γγ Production in CDF

Introduction

$p + \bar{p} \rightarrow p + X + \bar{p}$ X = e^+e^-, $\mu^+\mu^-$, J/ψ, ψ(2S), χ_c, **γγ**

CDF Detectors, Triggers & Data

Selection of Exclusive Events:

$p + \bar{p} \rightarrow p + \{2EM\ showers\} + \bar{p}$

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

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

Summary & Conclusions

Implications for Exclusive Higgs at LHC

Executive Summary

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

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

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

Show that EM showers are from γ and not π^0

High Energy Hadron-Hadron Collisions

TWO DISTINCT CLASSES:

Elastic

σ(elastic) ~ 20 mb

Inelastic, multi-hadron production

σ(inelastic) ~ 60 mb (at Tevatron)

NOT DISTINCT CLASSES:

Diffractive

Non-diffractive

A "NEW" 3rd DISTINCT CLASS:

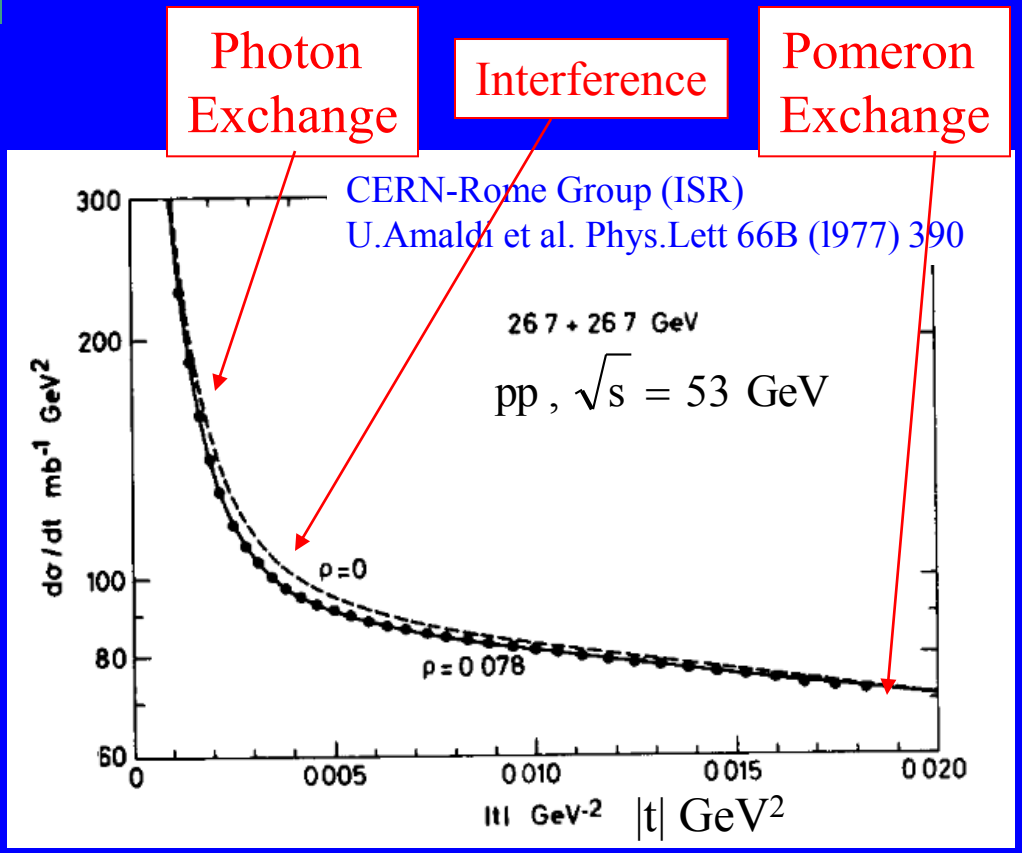
Almost elastic (99%), no hadrons produced:

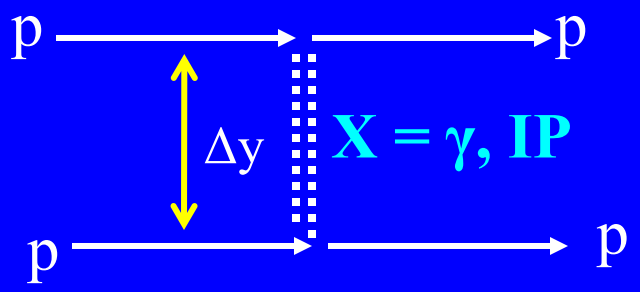
e+e- μ+μ- γ+γ & at LHC: W+W- H

Observed in CDF, σ ~ pb

Observable at LHC, σ ~ 10's fb

Elastic pp scattering at very small angles == large distances





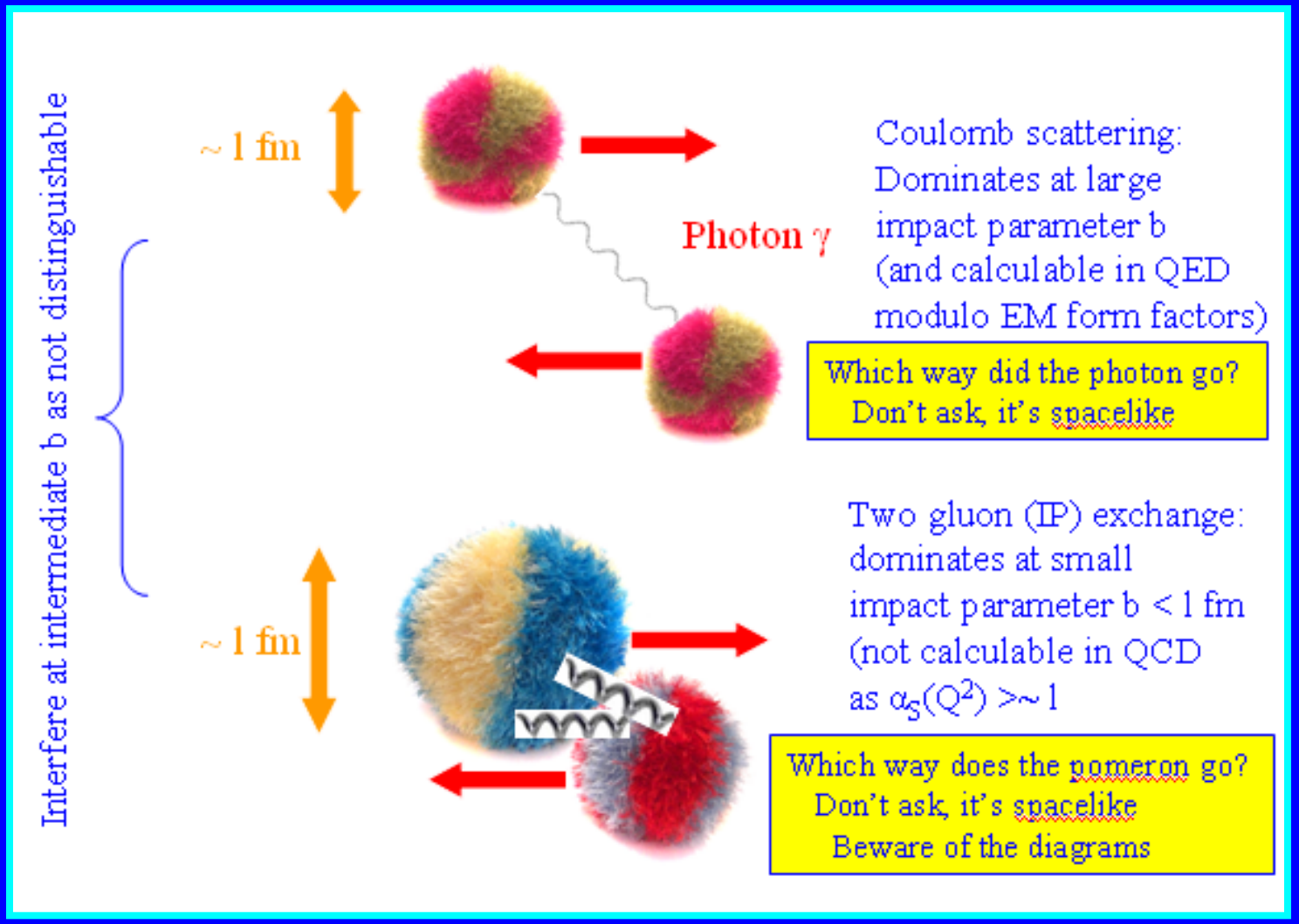
The only allowed t-channel exchanges have Q = 0, Color = 0
and at high energy (Large Δy) spin J >= 1.

Photon dominates at small $|t| \sim p_T^2$

Strong Interaction: 2-gluons is simplest. Called the **pomeron** IP

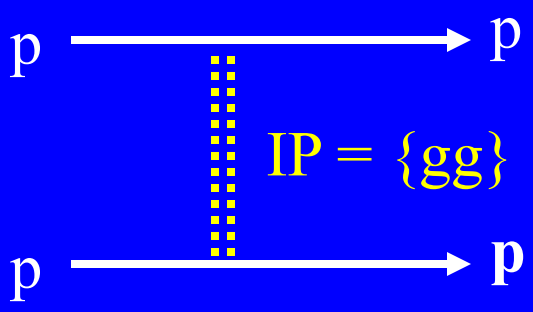
Effective spin $\alpha(t=0) > 1$ … that's why total cross section σ_{TOT} rises.

Elastic Scattering by Electromagnetic and Strong Interactions



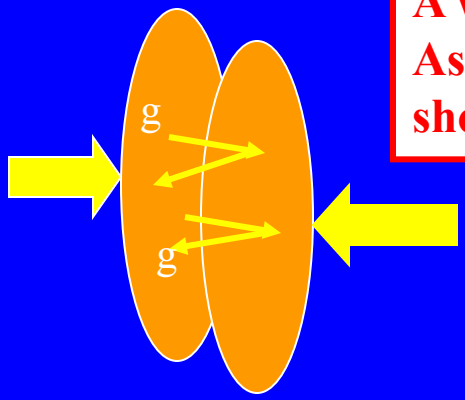
Elastic Scattering by strong interaction

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.

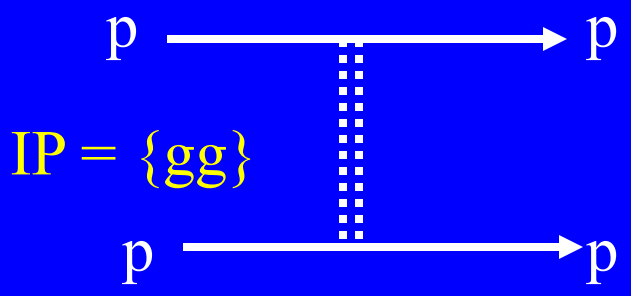
ANOTHER (BETTER) VISUALIZATION:

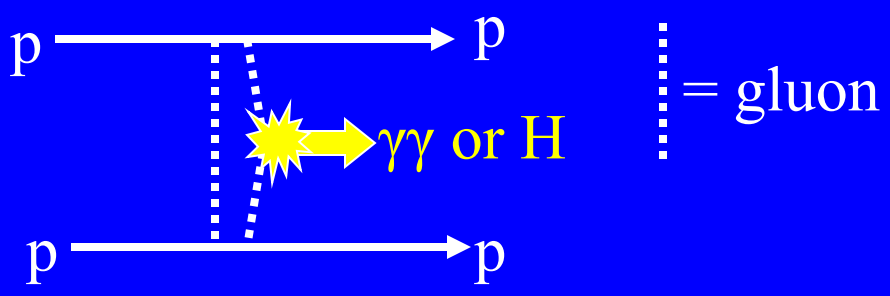


A wee x_{Bj} gluon is turned around. As the p separate … color field … shorted out by a 2nd exchange

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



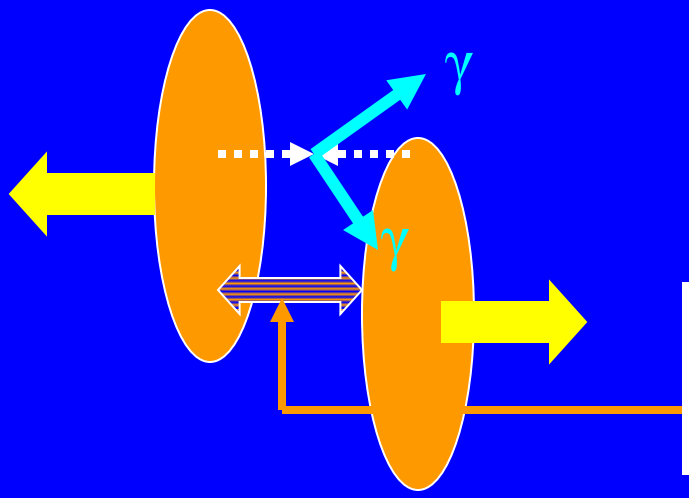


About 25% of σ_{TOT}

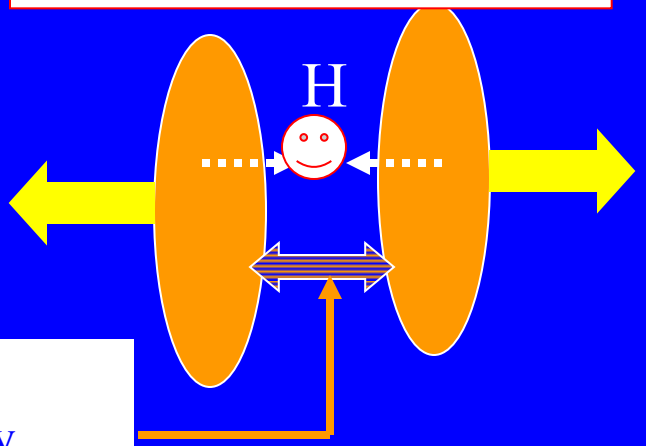
About 10^{-11} – 10^{-13} of σ_{TOT}

These are related processes!

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



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

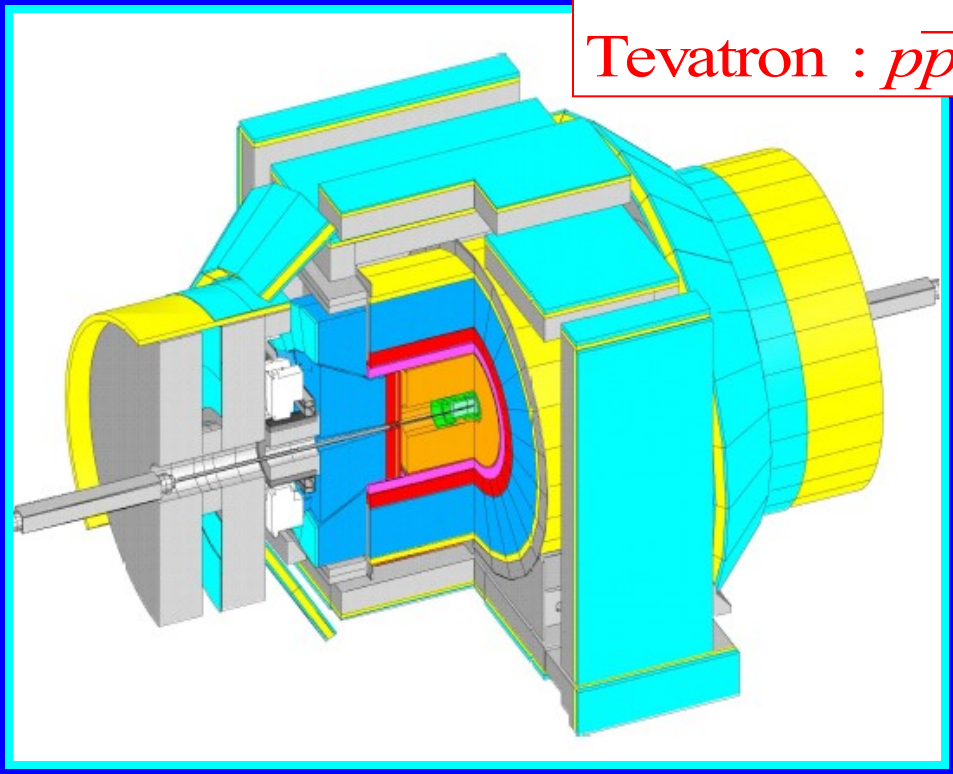


Color field;
shorted out by
another g exchange

CDF: The Collider Detector at Fermilab

CENTRAL:

Silicon tracker
Drift chamber tracker ← COT
Time-of-Flight barrel
EM calorimeters w/
CES shower max PC
Hadron Calorimeters
Muon chambers

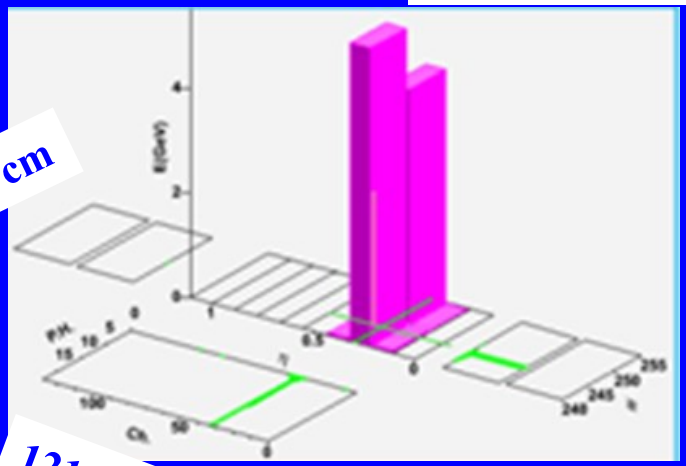


Tevatron : $p\bar{p}$ $\sqrt{s} = 1.96$ TeV

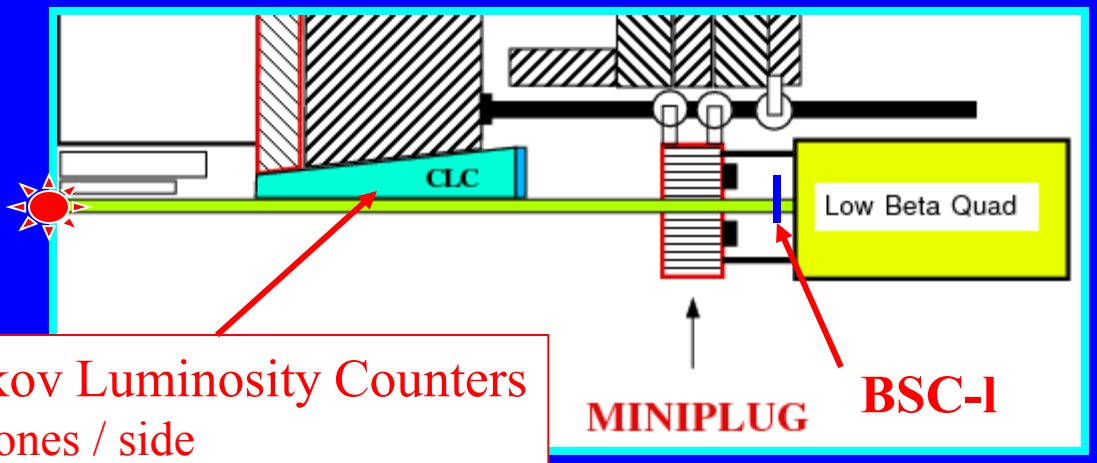
FORWARD
NEXT slides
(Important)

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

10 GeV electron



Forward Detectors in CDF I: Cherenkov Luminosity Counters



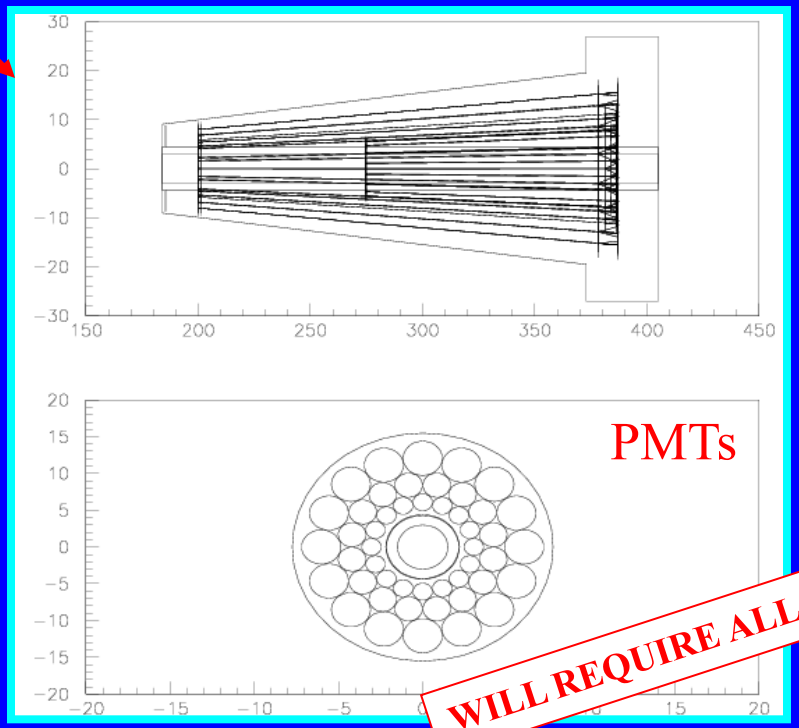
55 m

BSC-2, -3

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

$3.7 < |\eta| < 4.7$

Univ. Florida

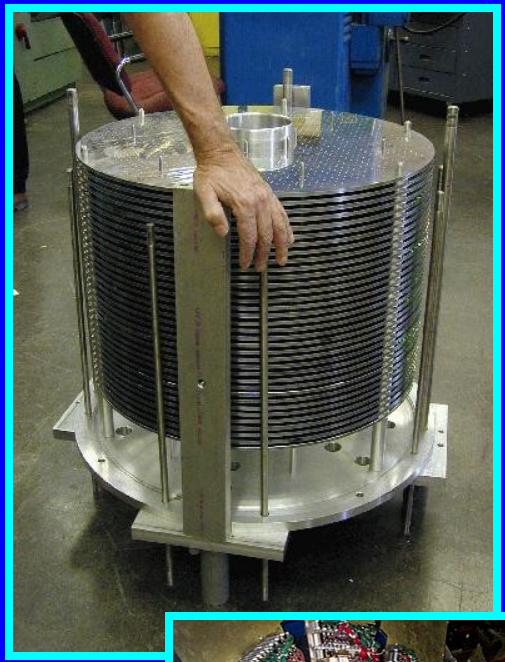


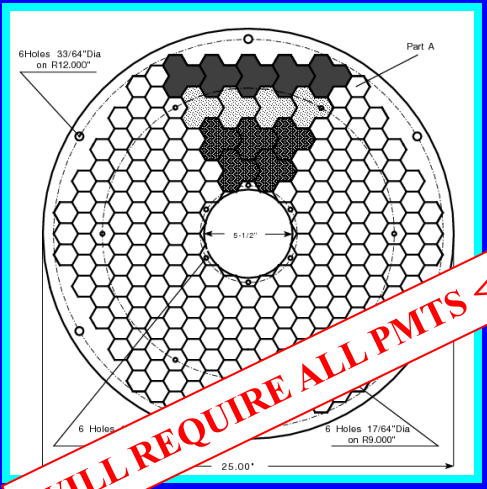
WILL REQUIRE ALL PMTS < NOISE CUT

Very Forward Detectors in CDF II : MiniPlugs

Rockefeller Univ.

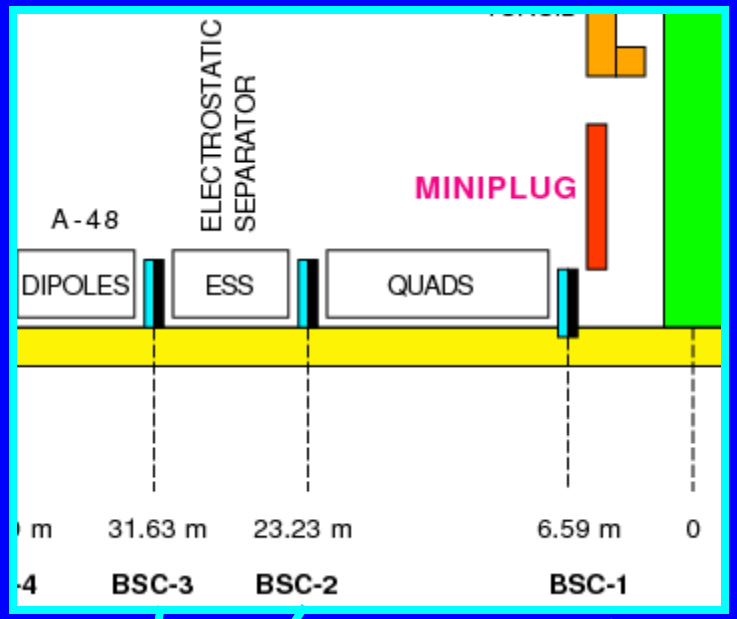
MiniPlug Calorimeters: $3.6 < |\eta| < 5.1$
Lead + Liquid Scintillator + WLS Fibers





WILL REQUIRE ALL PMTS < NOISE CUT

Very Forward Detectors in CDF III: BSC



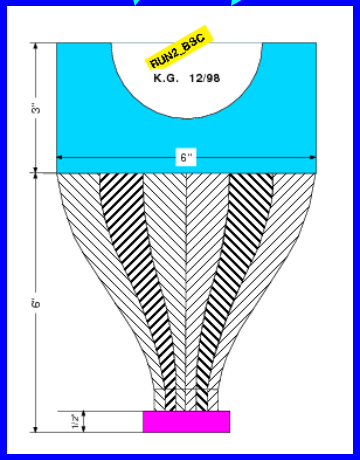
Beam Shower Counters (BSC)

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

Rockefeller Univ.

BSC-1 (4 PMTs)

WILL REQUIRE ALL PMTS < NOISE CUT



2 PMTs / station

Central Exclusive Production, examples:

$p + p \rightarrow p + X + p$

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

$\gamma + \gamma$	$e^+e^-, \mu^+\mu^-$
$\gamma + \mathrm{IP}$	$J/\psi, \psi(2S)$
$\mathrm{IP} + \mathrm{IP}$	$f_0(600)/\sigma, f_0(980), \ldots \chi_c, JJ, +\gamma\gamma$

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**

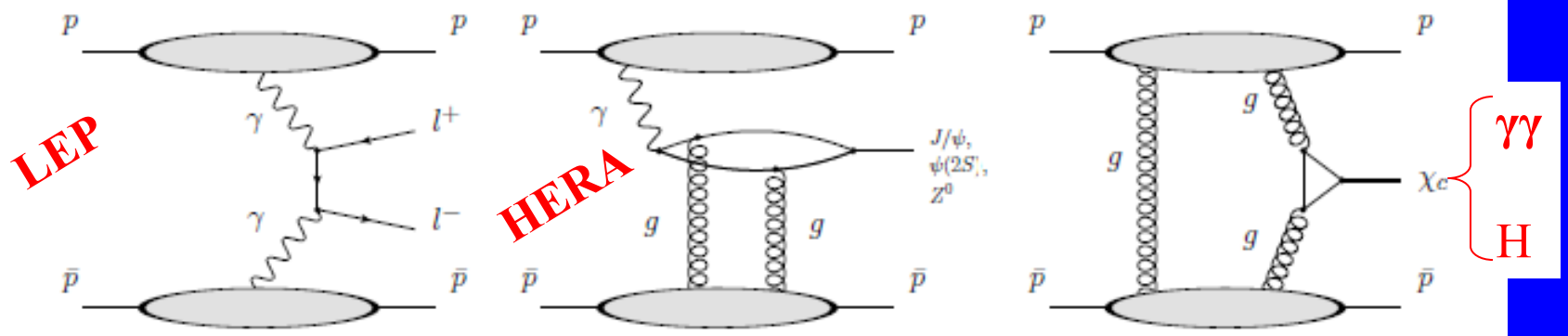


Figure 10: Feynman diagrams for processes contributing to the exclusive di-lepton signal. (a) $\gamma\gamma \to l^+l^-$, (b) $\gamma I\!P \to J/\psi, \psi(2S), Z^0$, and (c) $I\!P I\!P \to \chi_{c0}$.

LPAIR MC:
J.A.M.Vermaseren, Nucl.Phys.B229 (l983) 347

Photoproduction

SuperCHIC MC:
L.Harland-Lang et al, arXiv:l005.0695 [hep-ph]

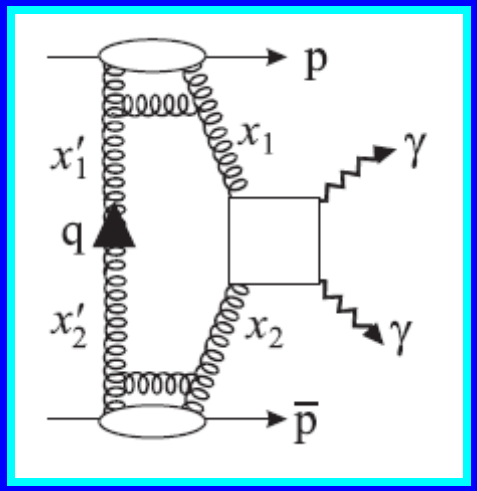
>>> Not essential to detect protons; can require all forward detectors to be at noise levels, for $|\eta| < \sim 7.4$

>>> Quasi-elastic protons inferred.

>>> No pile-up interactions allowed.

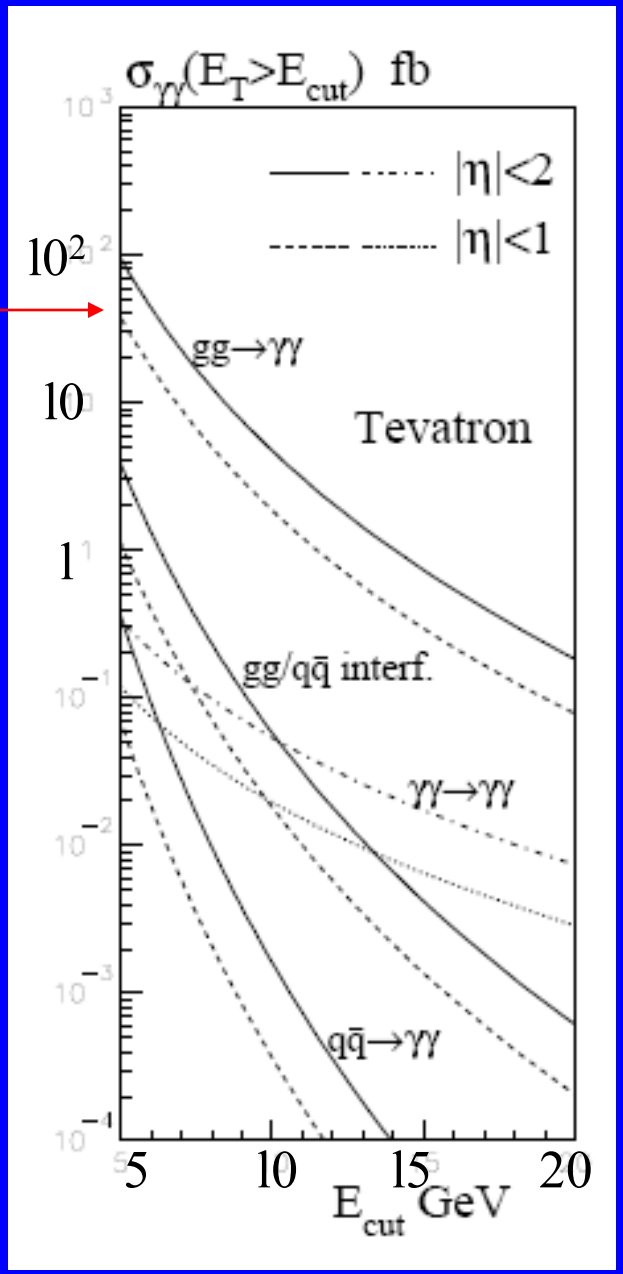
Theoretical prediction for exclusive γγ

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



$$E_T(\gamma)_{min} = 5\ \text{GeV}$$
$$|\eta(\gamma)| < 1$$
$$\sim 38\ ^{\times 3}_{\div 3}\ \text{fb}\ @\ 1.96\ \text{TeV}$$

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



Ingredients:

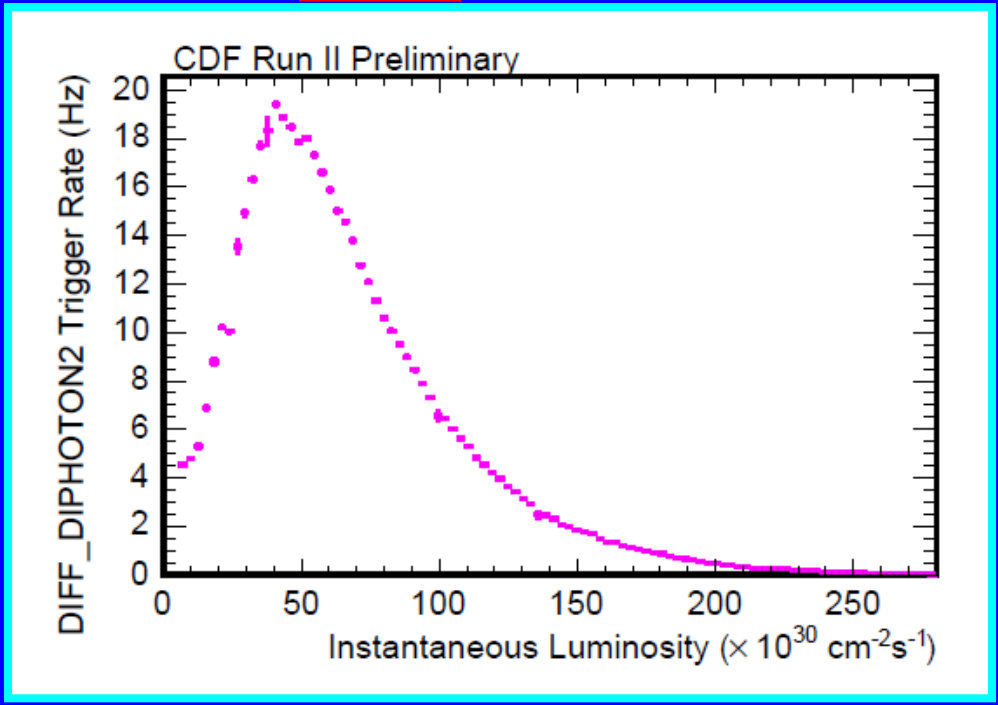
$\sigma(g + g \rightarrow \gamma + \gamma)$
Unintegrated g(x,x') $\sigma \sim g^4$
Loop integral
No gluon/hadron radiation
No other parton-parton interaction
(Gap survival factor)

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

Trigger and Data Taking

Level l trigger : [l EM Tower C&P > 2 GeV] * [BSC-l (E & W) veto]
No prescale needed: Veto kills pile-up and most single interactions
Level 2+3 : 2 EM Towers > 2, Clean up, e.g. Ratio (HAD/EM) < 0.l25

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

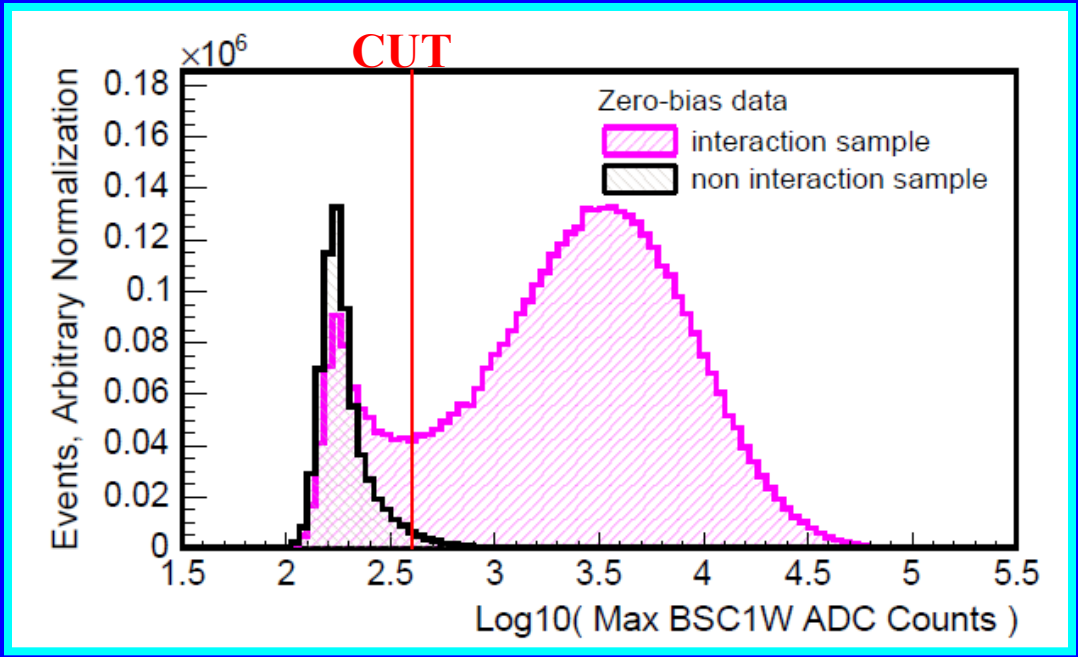


"Exclusive efficiency" = Prob. event not killed by P-U, calculated bunch x bunch.

Selection of Exclusive Events

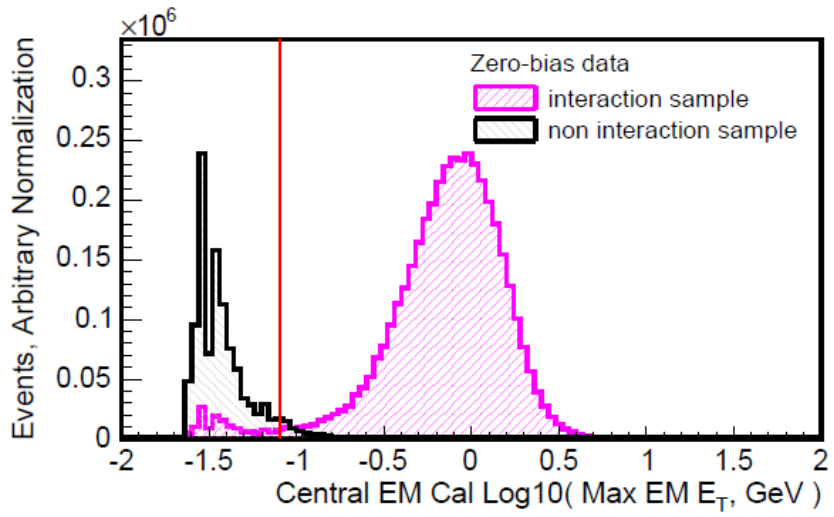
Require no other particles detected in entire CDF, including forward to $|\eta| = 7.4$
p & pbar are not detectable: stay in beam pipe.
Study noise levels: ZERO-BIAS (bunch crossing) trigger (crucial).
Make 2 classes: No COT tracks, no CLC hits, no muon stubs : **NON-INTERACTION**
All other events : **INTERACTION** (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.

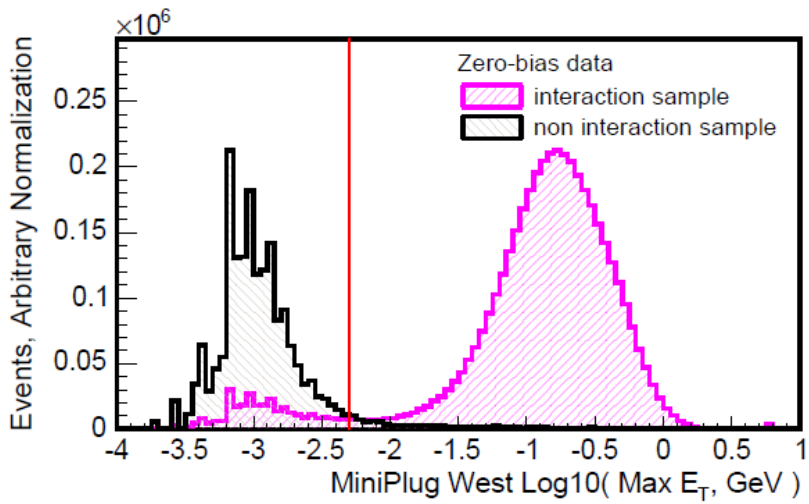
EXAMPLE:



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

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

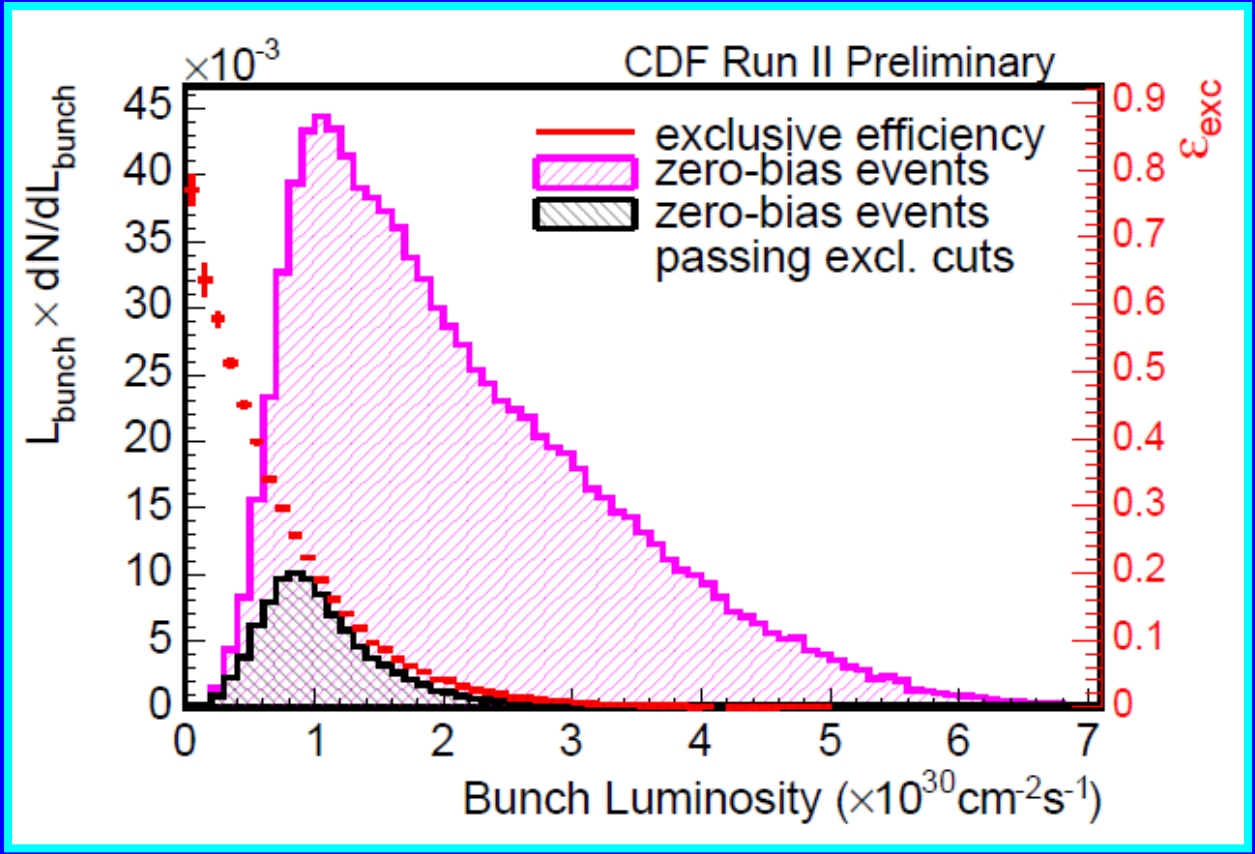
Exclusive efficiency ε_{excl} :

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

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

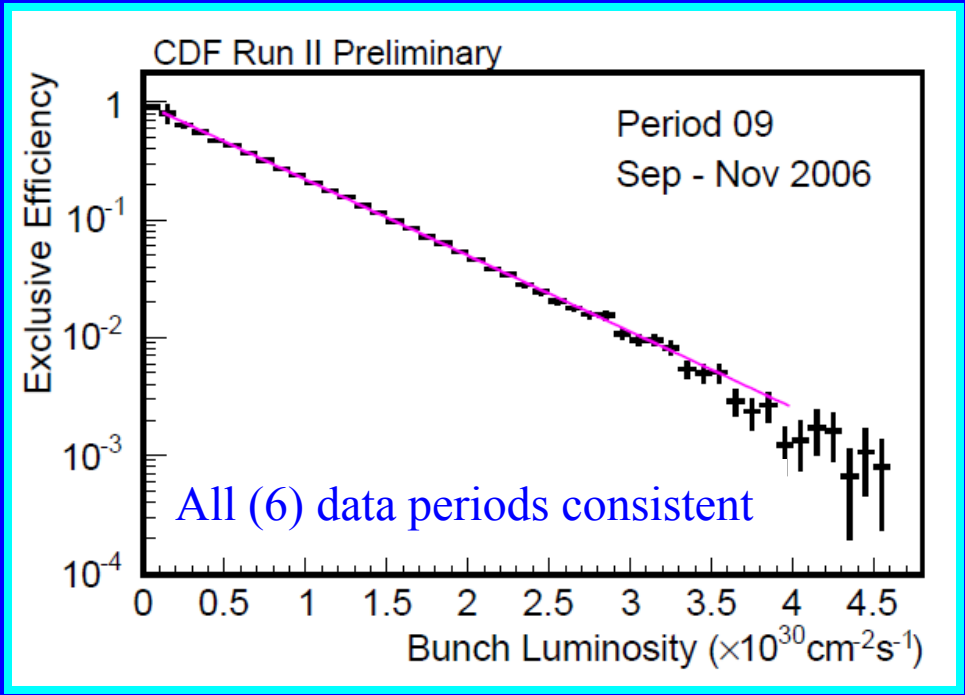
Measure P(0) = Prob(empty) vs Bunch luminosity (B x B)

[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
ε_{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 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:

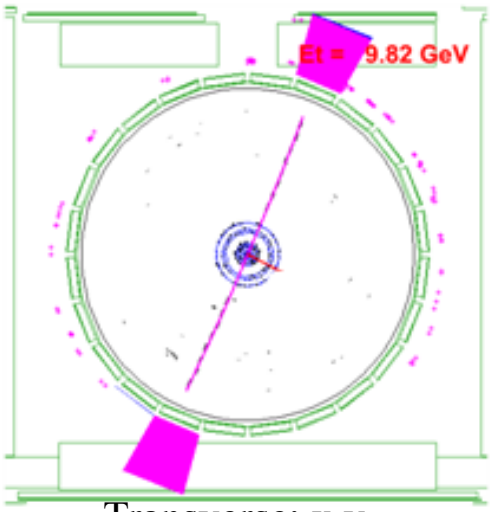
2 Opposite charge tracks (e^+e^-) : 34

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

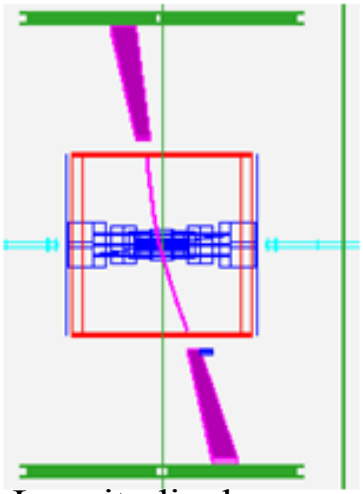
Ambiguous : 5 (scan $\Rightarrow$ 2 + 2 + 1)

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

Event : 1376604 Run : 223338

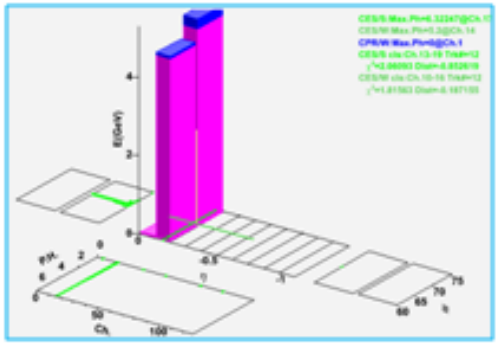


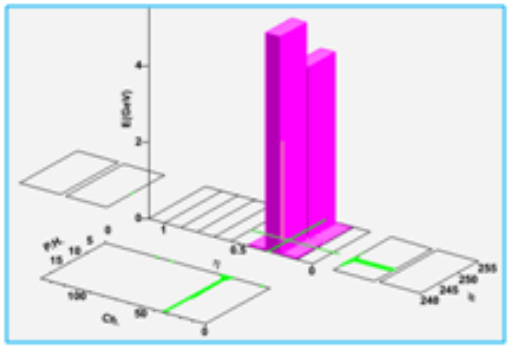
Transverse: x,y

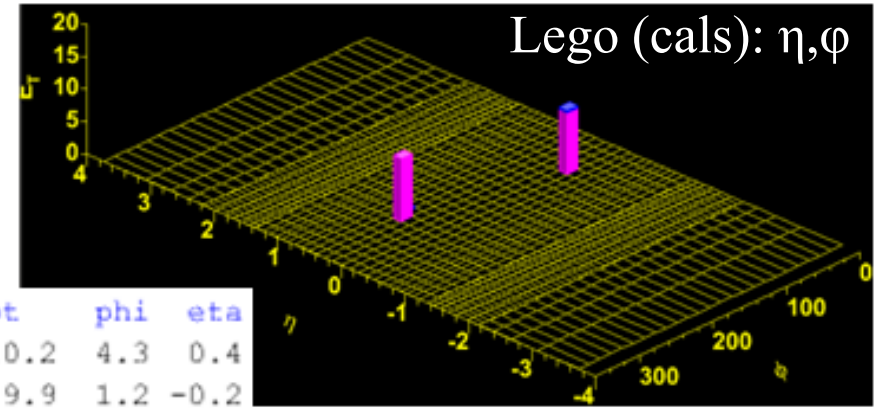


Longitudinal: y,z

Wire chambers at 6 Xo (shower max)

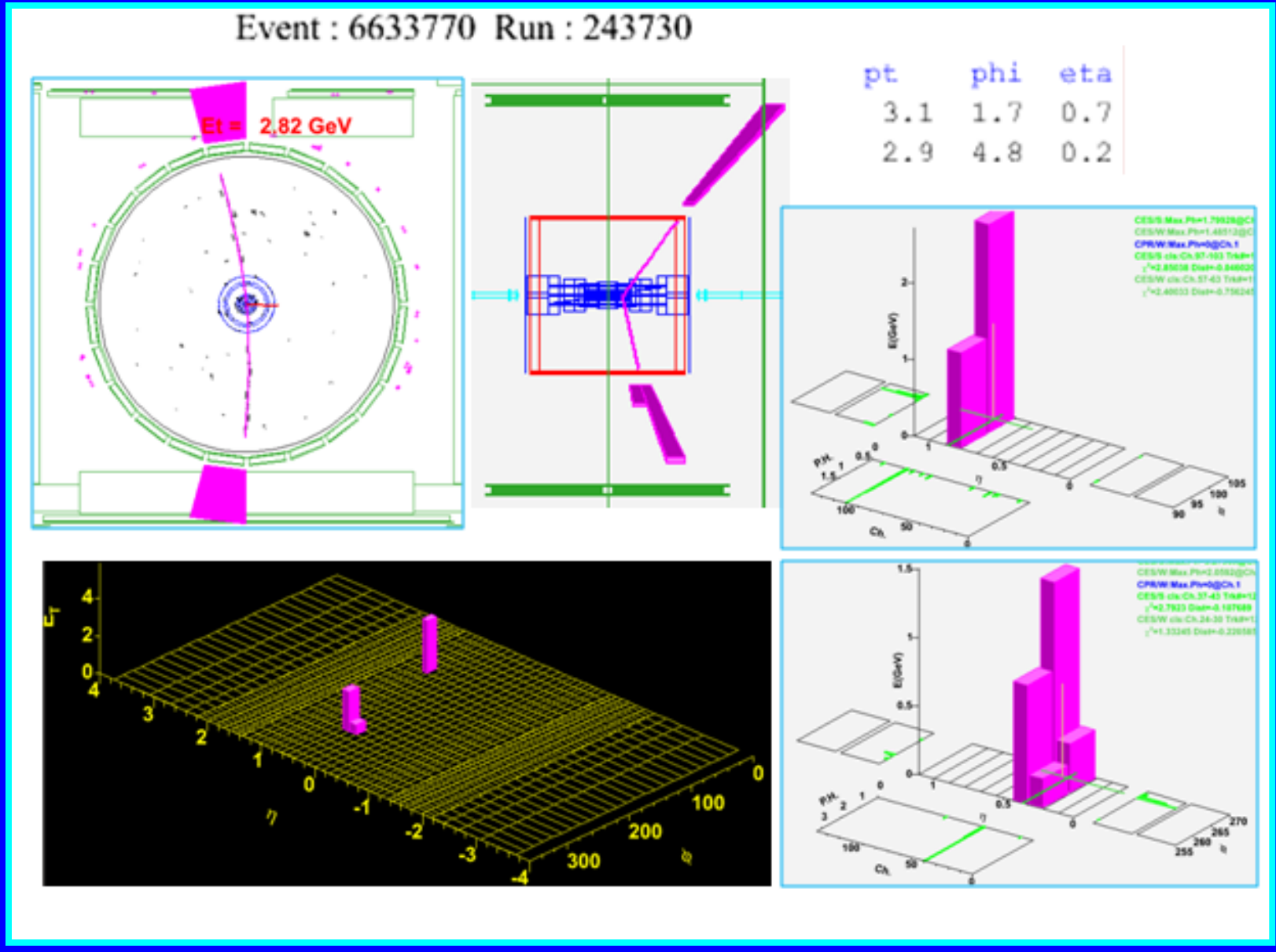






Tracking efficiency very high: hard to miss an isolated high p_T central track

Event display: a typical e^+e^- event: $M(e^+e^-) \sim 6$ GeV



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 η, p_T (~ 96%) : Using J/ψ 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 η (1 – 2)
because of bremstrahlung, conversions, δ-rays.
Decided to select **|η| < 1.0** to minimize such dependence.
Scanning events confirmed more ambiguities there: "e → γ" and "γ → e"

Reconstruction efficiency:

Electron pairs (LPAIR)

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

Photon pairs (SuperCHIC)

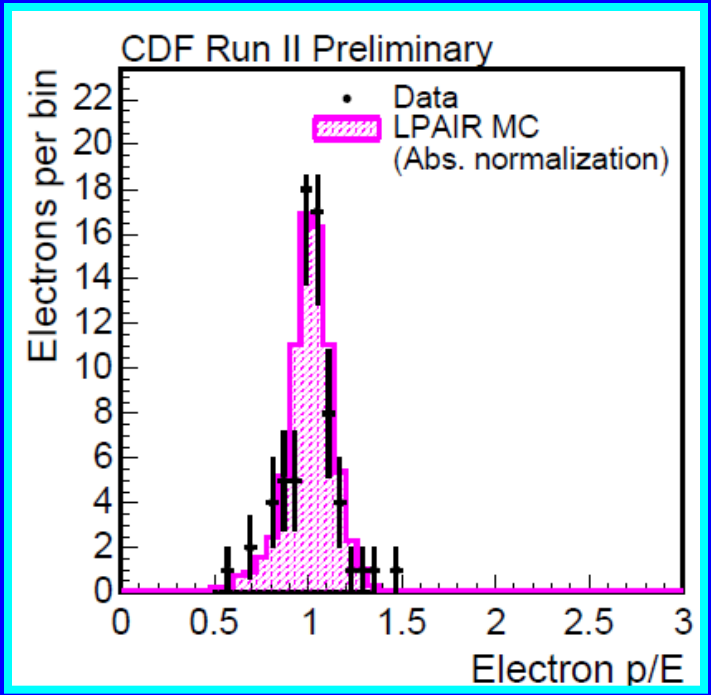
E_T cut (GeV)	2.5
$\varepsilon_{rec}^{\gamma\gamma}$	0.553
Stat Err	±0.005
Syst Err	±0.029

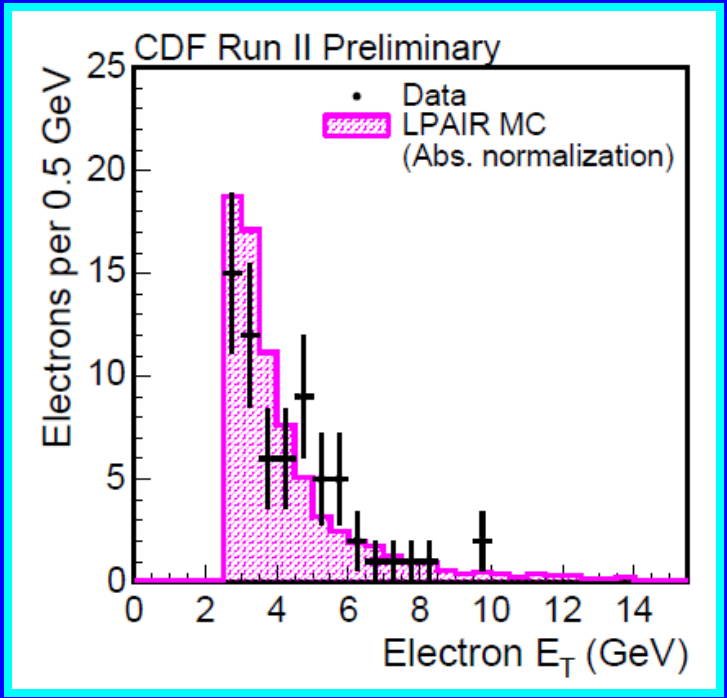
Properties of single tracks cf LPAIR e+e- simulation + CDFSIM

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

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

Absolute normalization (to LPAIR/QED σ)

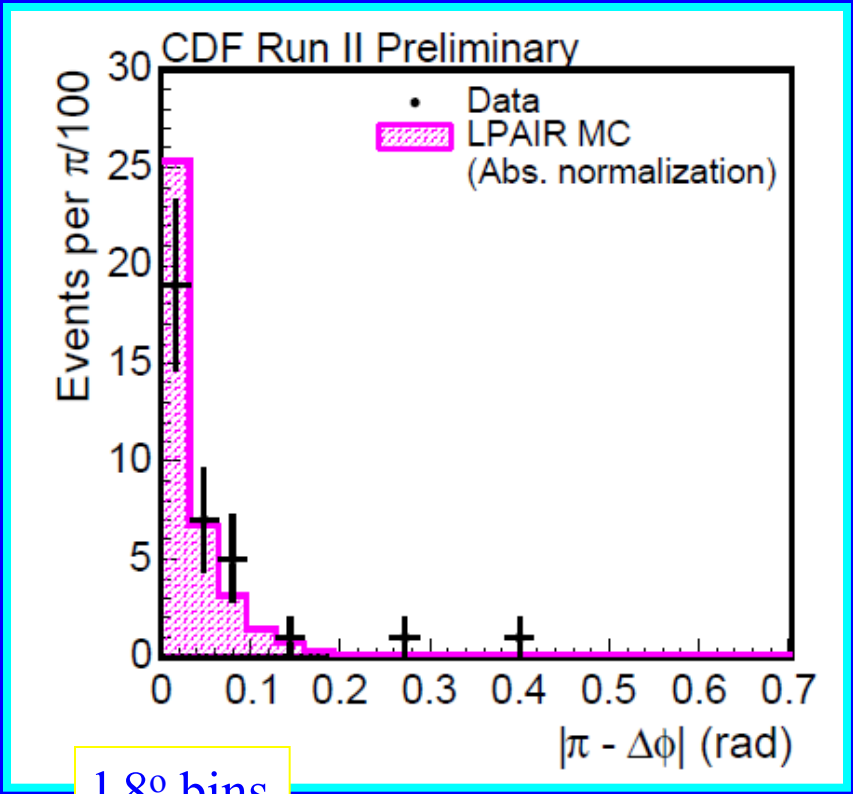




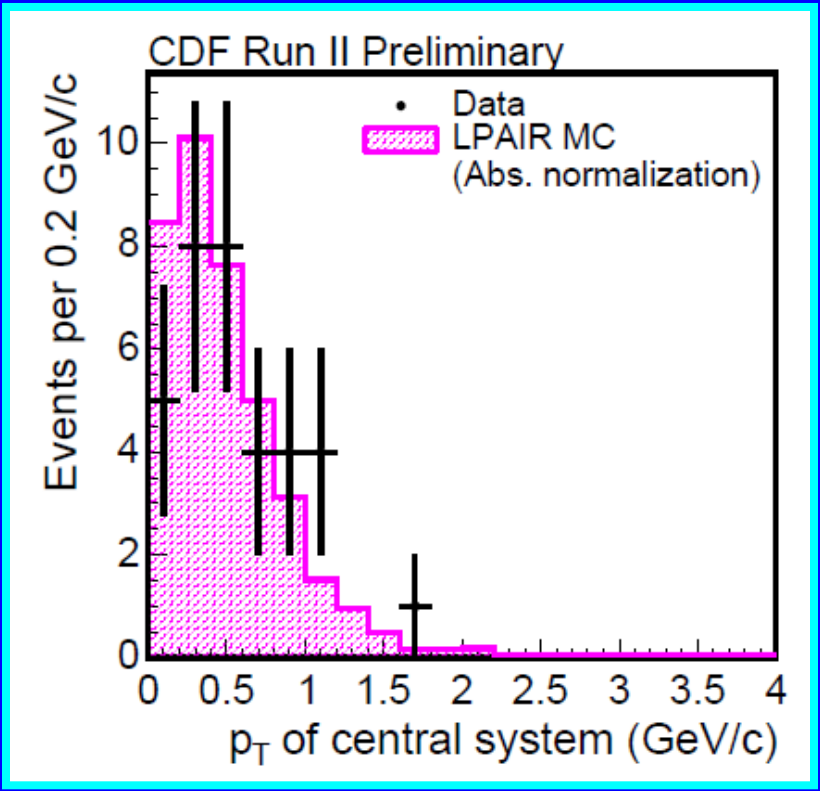
Distributions in η(e) and φ(e) … flat … also agree well with LPAIR + CDFSIM

Electron pair properties (34 events)

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



1.8° bins

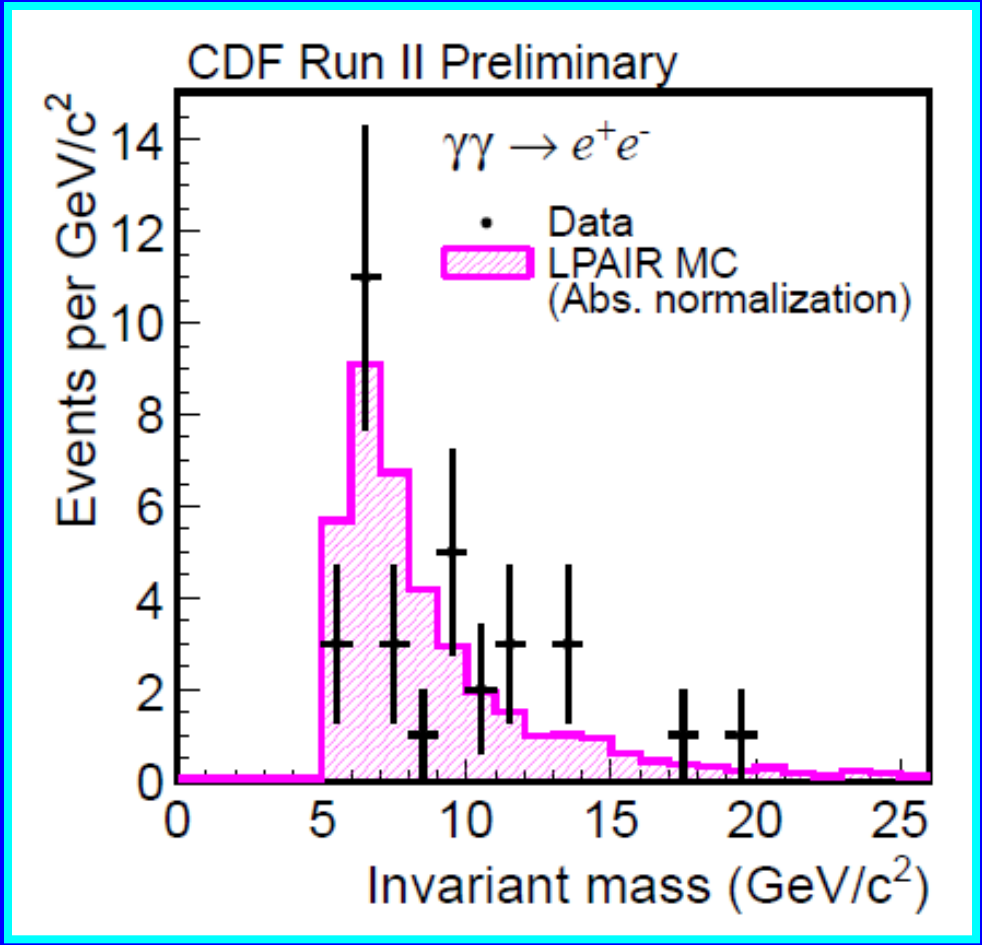


Photons … Coulomb.. <p_T> very small.

Detector resolution (and Final State Radiation) dominates spread.

Mass spectrum (e+e-)

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



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}	±0.7pb^{-1}	
e^+e^- (events)	34		
Trigger efficiency	0.920	±0.009	±0.018
Reconstruction efficiency	0.508	±0.007	±0.016
Identification efficiency	0.912	±0.017	±0.013
Tracking efficiency	0.963	0.003	
Radiative acceptance	0.419	±0.001	±0.077
Exclusive efficiency	0.0680	negligible	0.004
Dissoc. B/G (events)	3.8	0.4	0.9

$$\sigma^{|\eta|<1, E_T>2.5\text{GeV}}_{e^+e^-\text{excl.}} = 2.88 \pm 0.59(\text{stat}) \pm 0.62(\text{sys})\ \text{pb}$$
$$\sigma^{|\eta|<1, E_T>2.5\text{GeV}}_{\text{LPair}} = 3.25 \pm 0.07\ \text{pb}$$

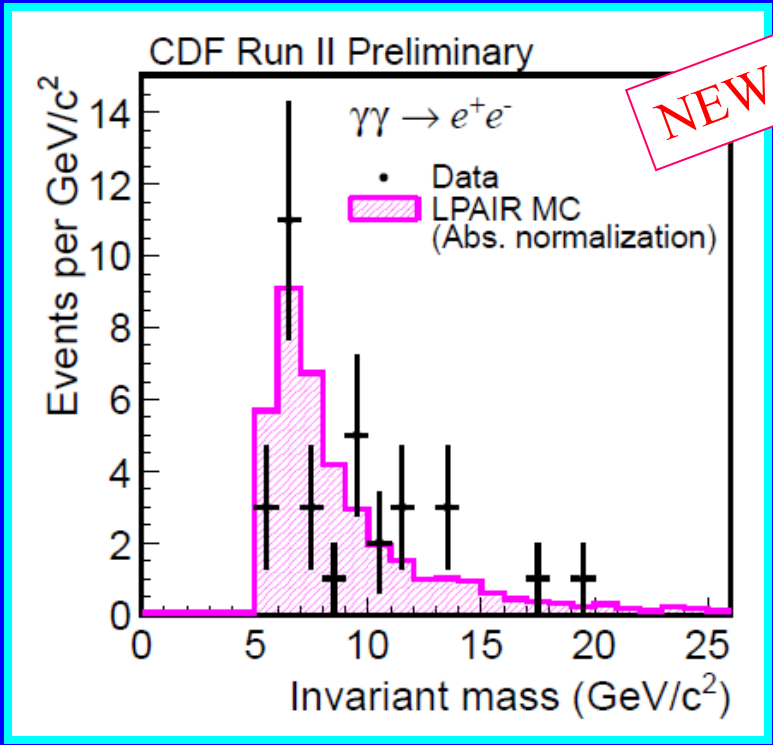
AGREE

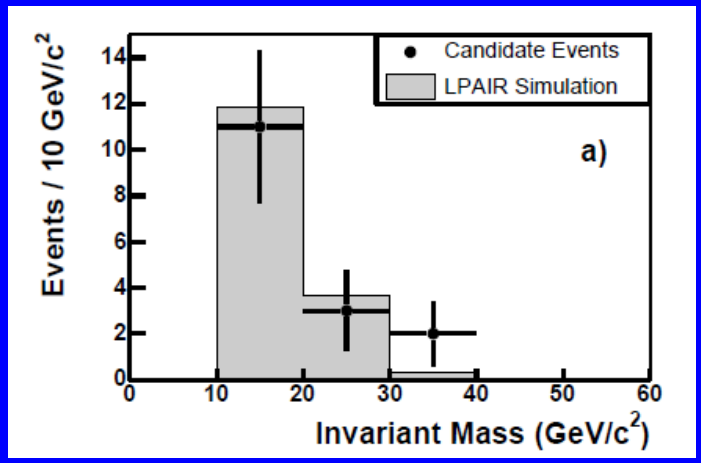
$$\sigma^{|\eta|<1, E_T>5.0\text{GeV}}_{e^+e^-\text{excl.}} = 0.60 \pm 0.28(\text{stat}) \pm 0.14(\text{sys})\ \text{pb}$$
$$\sigma^{|\eta|<1, E_T>5.0\text{GeV}}_{\text{LPair}} = 0.58 \pm 0.003\ \text{pb}$$

AGREE

Confidence that exclusive efficiency method and normalization are good

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

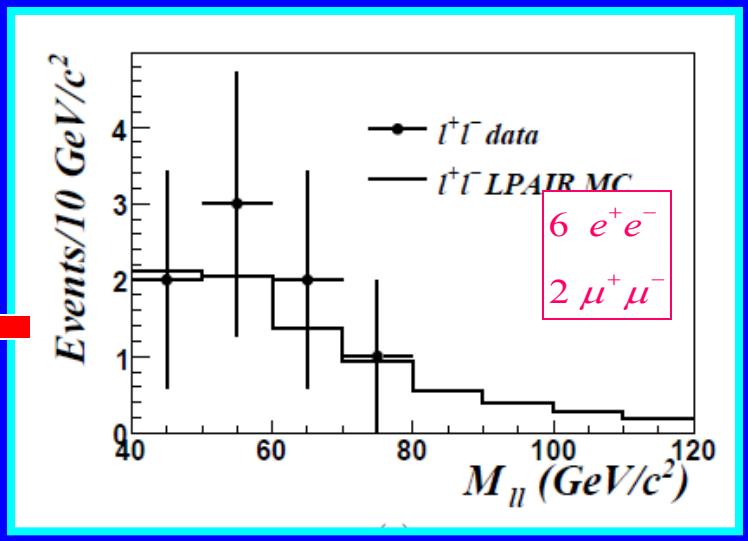




CDF Phys.Rev.Lett. 98 (2007) 112001 (lst observation.)

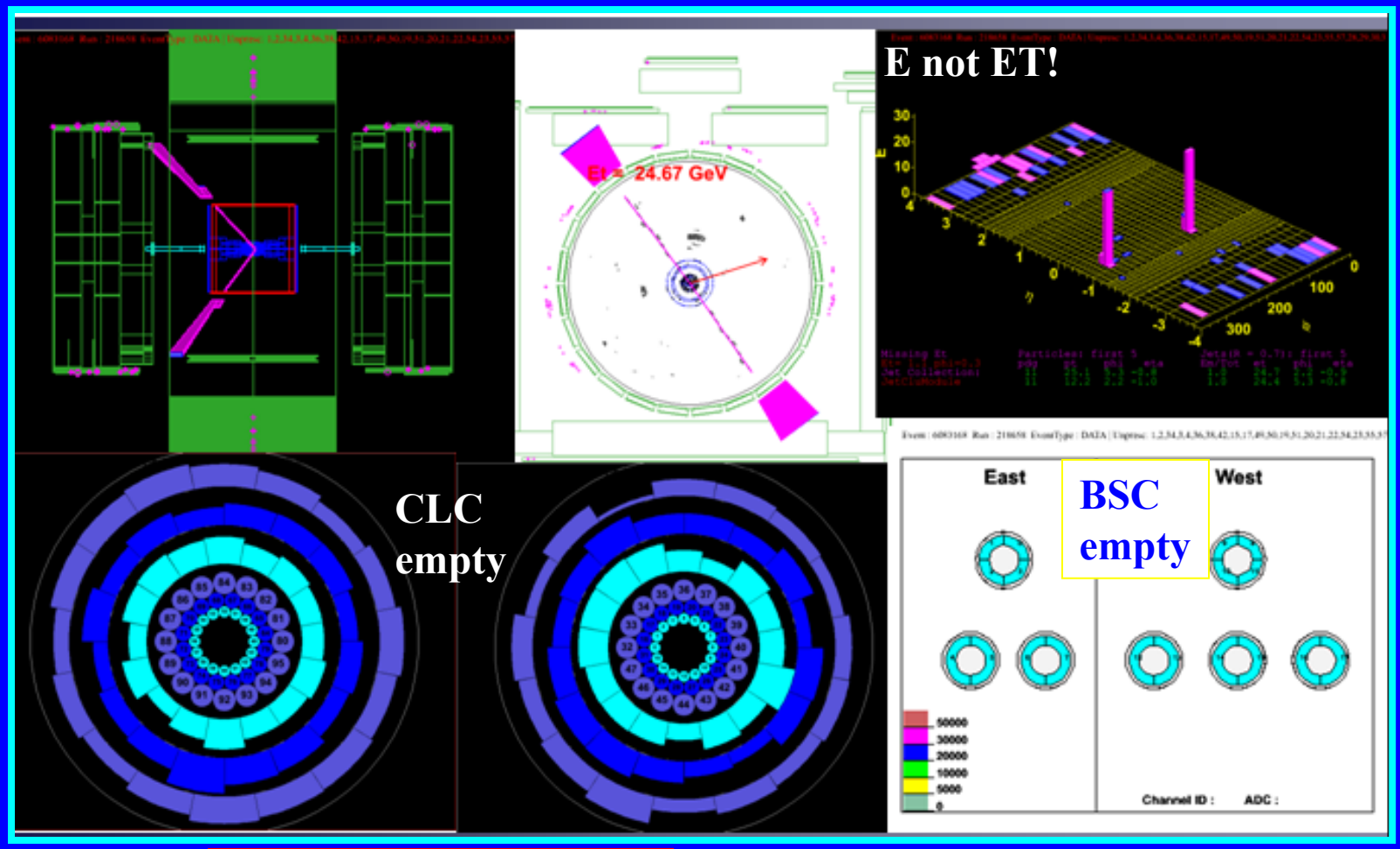
All pairs have $180^o - \Delta\varphi < 1^o$

AGREEMENT With LPAIR



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

$M(e^+e^-) = 49.3\ \text{GeV}/c^2$ $|\Delta\varphi - \pi| = 6\ \text{mrad} = 0.34\ \text{deg}$, $p_T(e^+e^-) = 210\ \text{MeV}$



$$\sigma(p + \bar{p} \rightarrow p + e^+e^- + \bar{p}) \text{ or } \mu\mu$$

$$M > 40\ \text{GeV}/c^2, |\eta| < 4$$

$$= 0.24^{+0.13}_{-0.10}\ \text{pb}$$

$$\text{cf QED}_{(\text{LPAIR})} = 0.256\ \text{pb}$$

Mass reach Tevatron
>~ HERA, LEP !
At LHC: Allow pile-up:
N_{ass}=0, $\Sigma p_T \sim 0$, $\Delta\varphi \sim 180^o$

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

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

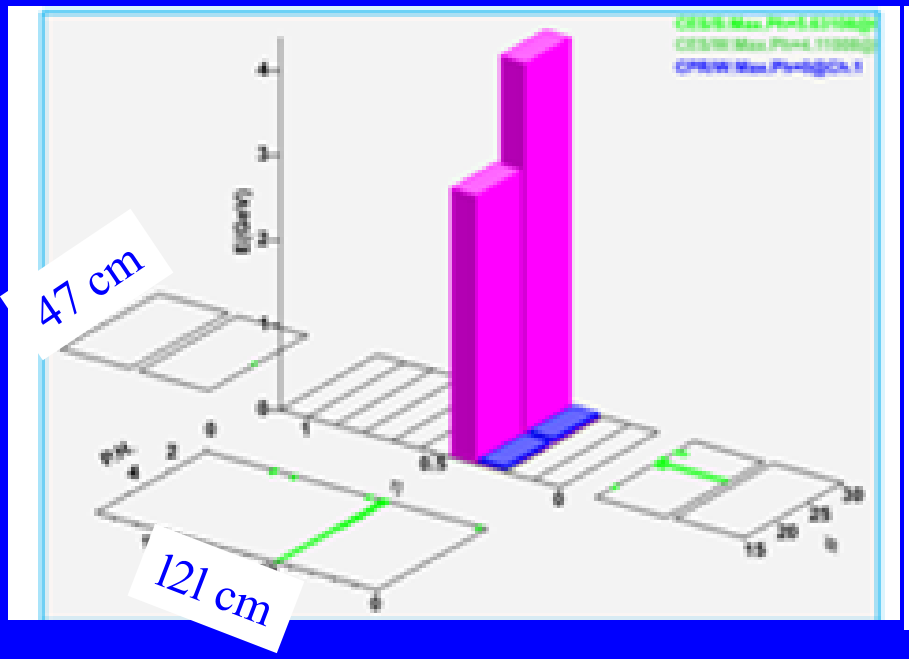
Note that exclusive **p + γ π^0 + p** is forbidden (e.g. parity P)

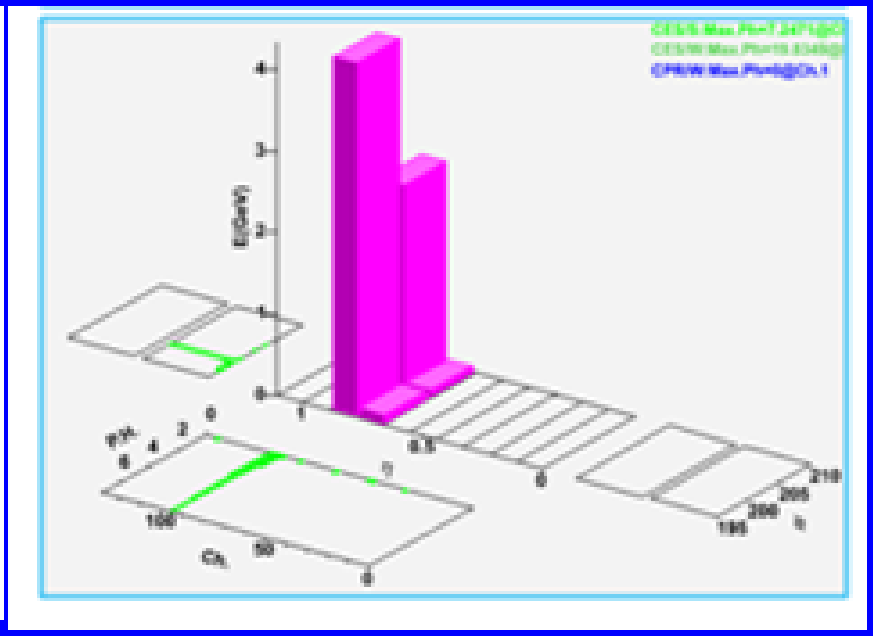
Count showers in CES strip chambers. **Wires 1.45 cm, strips ~ 1.8 cm**

Two photons cannot merge:

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

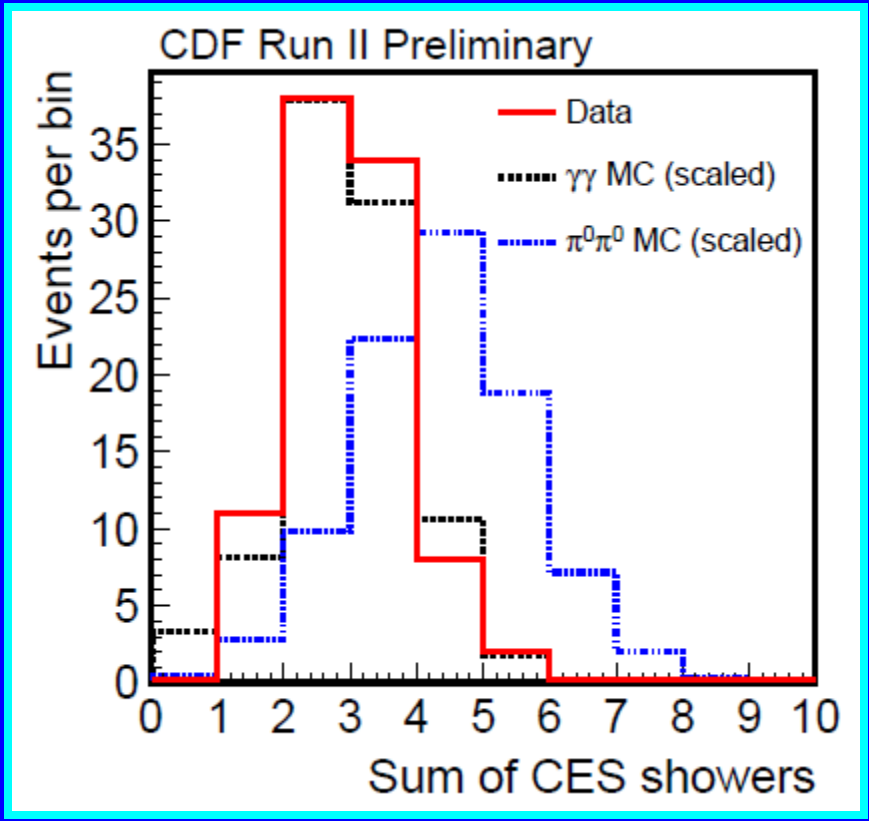
$$= 11.2 \text{ cm at 2 m.}$$

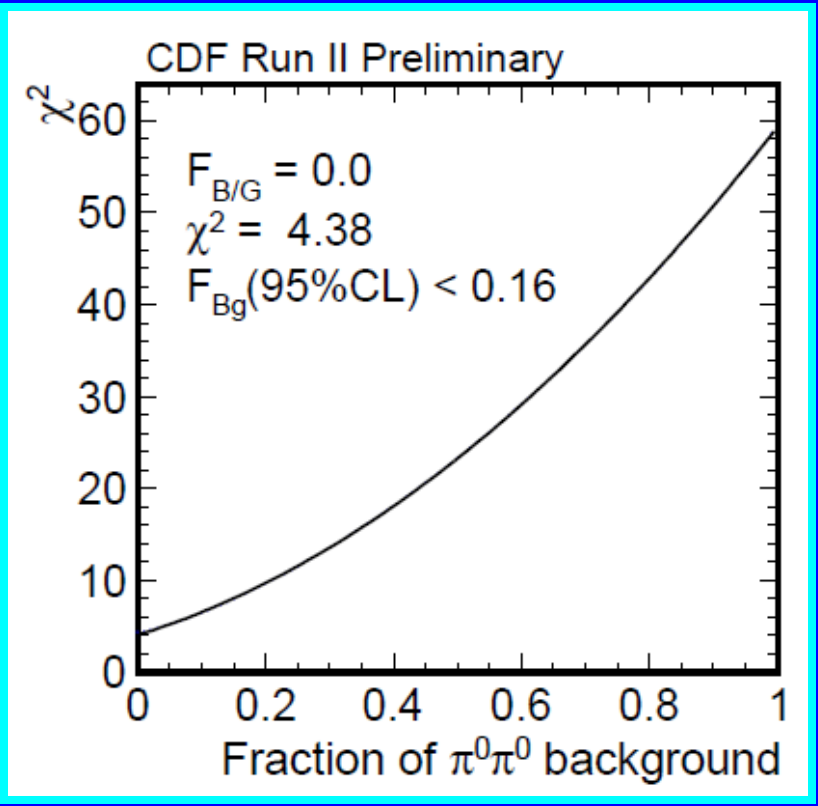




Are any events not γγ but $\pi^0\pi^0$?

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





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

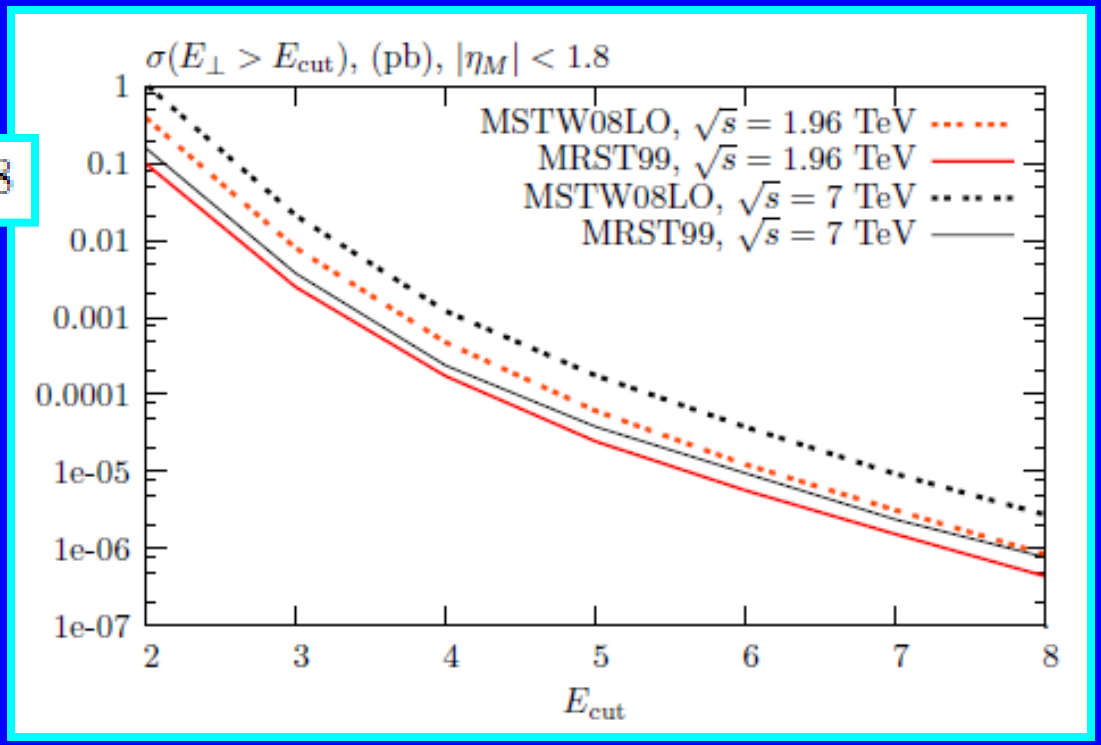
Pearson's χ^2 test: fraction of γγ events in sample < 16% (95% C.L.)

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

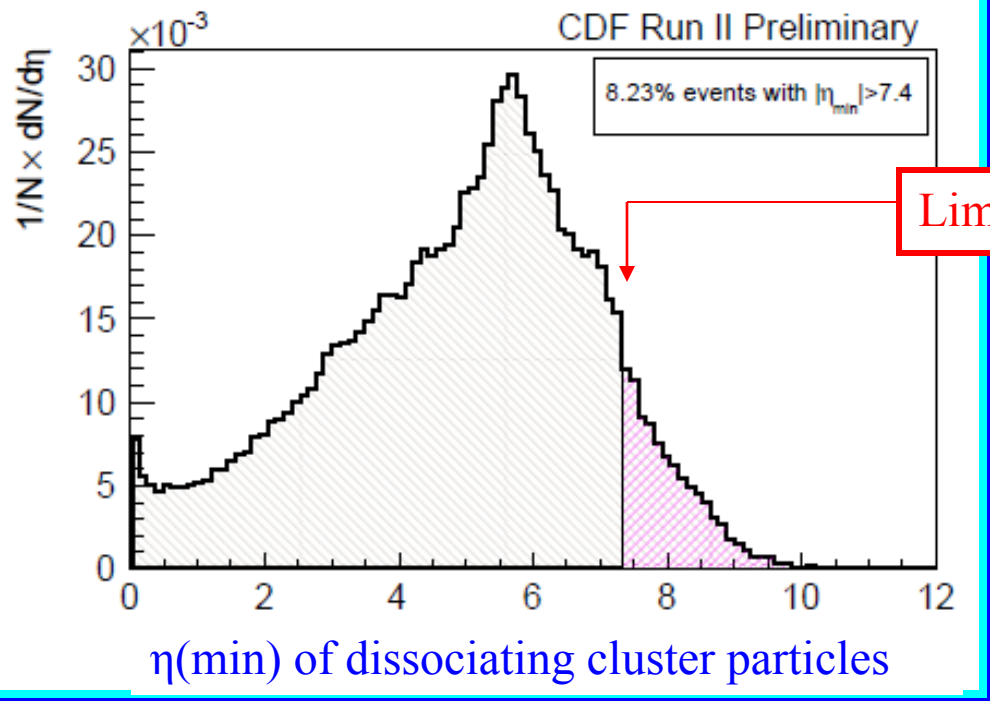
6 – 24 fb … < 1%

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

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

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

Still $\gamma+\gamma$ or IP + IP but not truly exclusive. Consider as B/G



MinBias Rockefeller (MBR) Monte Carlo

Limit of BSC counters

~ 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)

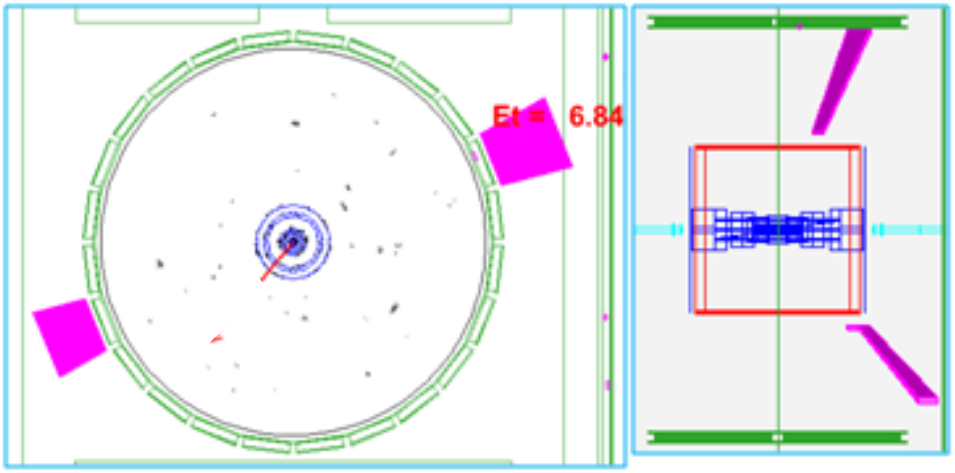
For γγ

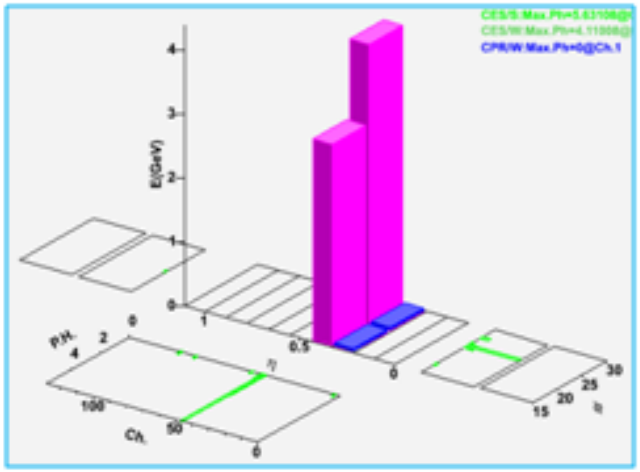
- Durham estimation using our selection rules with large rapidity gaps.
- Dissociation background estimate for $E_{T,min} = 2.5$ GeV:
  0.14 ± 0.14(syst) events

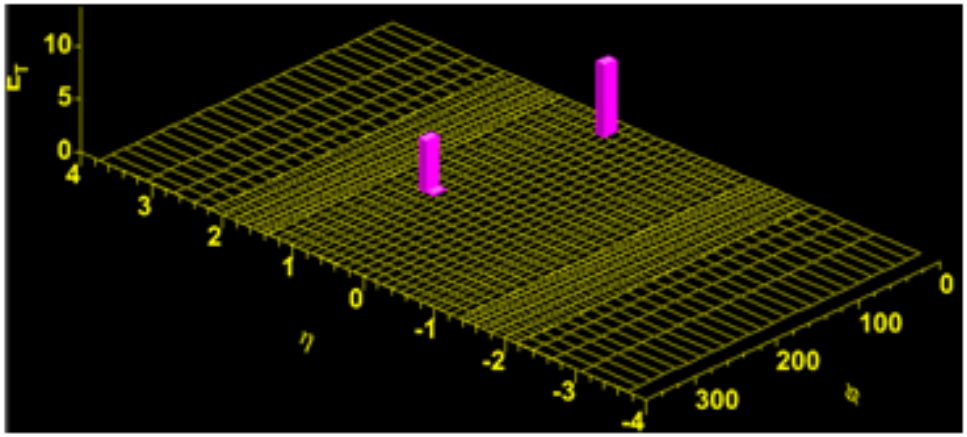
Example of γγ event

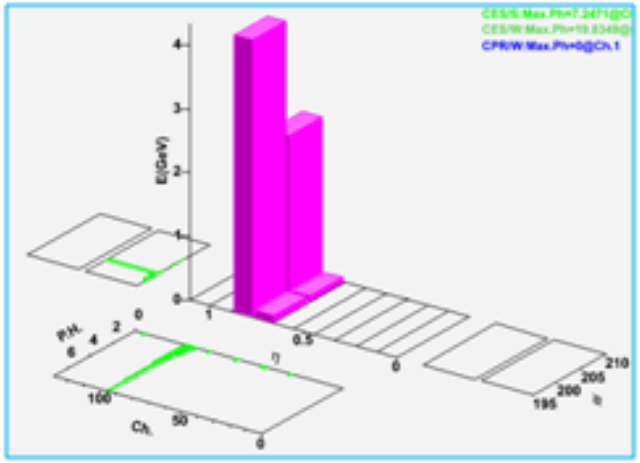
Event : 14704042 Run : 243808

pt	phi	eta
6.8	0.5	0.4
5.0	3.4	0.9

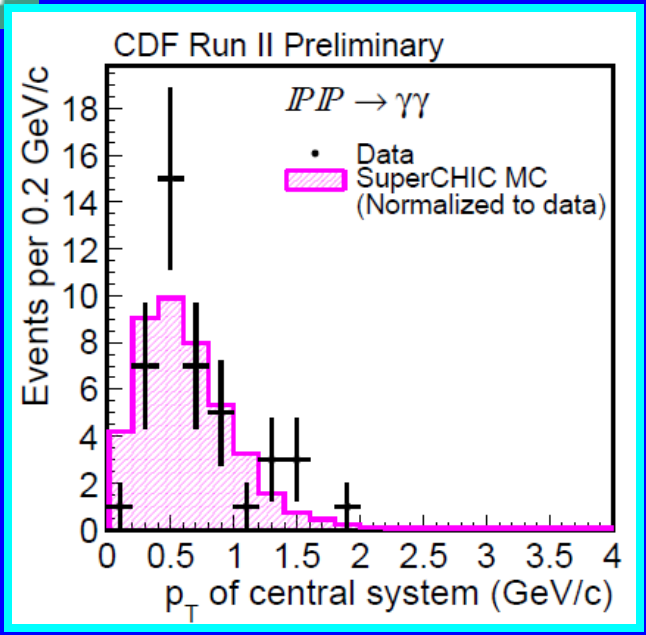


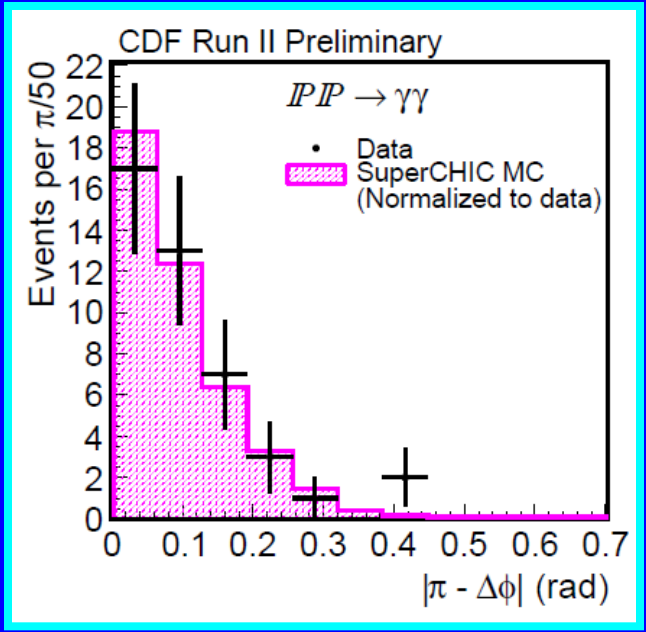




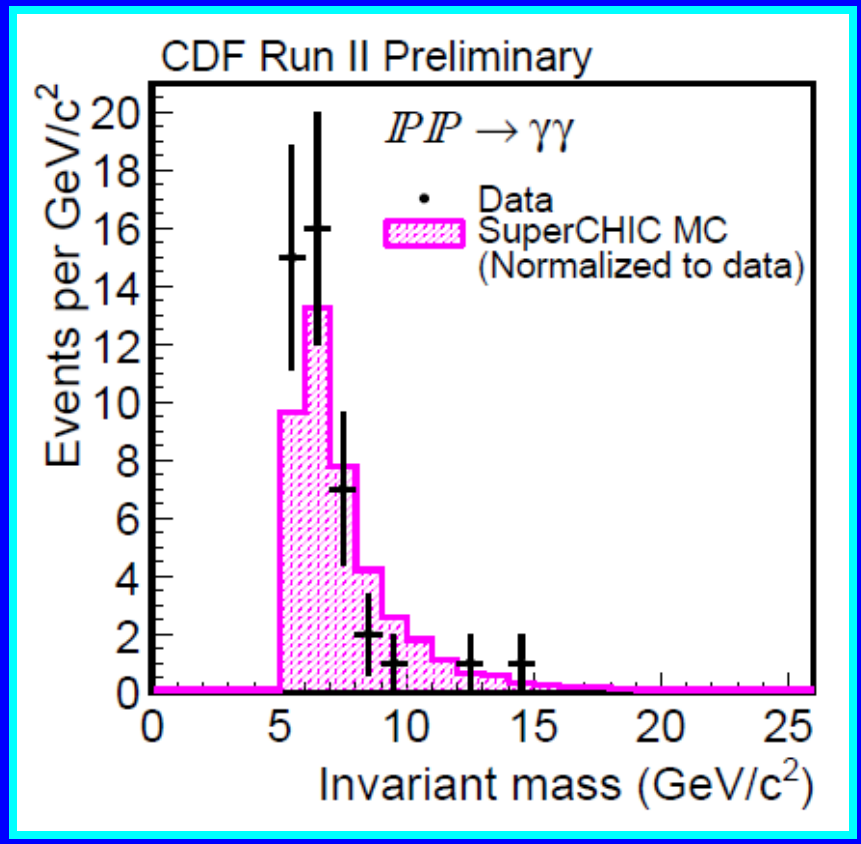


Kinematic distributions of photon pairs





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)

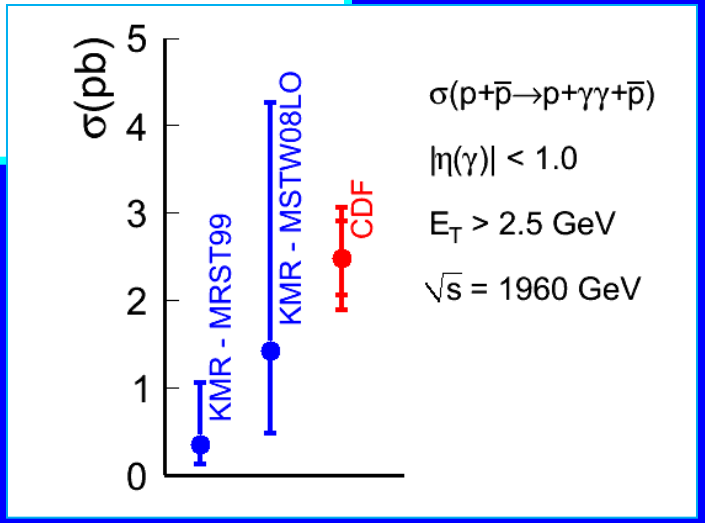
Table: Statistics summary of all relevant parameters for the measurement of the exclusive photon pair cross section for an E_T cut of 2.5 GeV and $|\eta| < 1.0$.

	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
π^0 background	0.0		$<$16% (95% C.L.)
Dissoc. B/G (events)	0.14		0.14

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

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

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



Summary of Exclusive γγ

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

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

We needed:

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

Extended rapidity coverage of CDF to η = ± 7.4

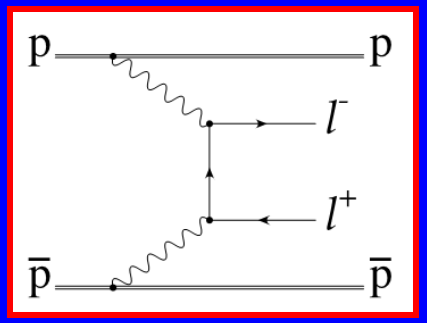
Understood noise levels in all calorimeters and counters.

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

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

Showed that EM showers are from γ and not π^0 as theoretically expected

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 $|\eta| < 2$

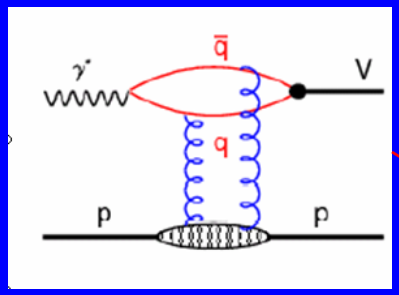
Van der Meer scans can probably reach that with improvements

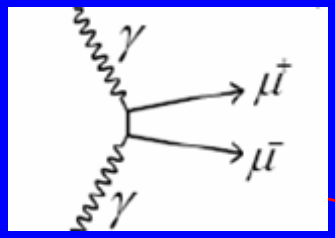
Observation of Exclusive Charmonium Production and $\gamma\gamma \to \mu^+\mu^-$ in $p\bar{p}$ Collisions at $\sqrt{s}$=1.96 TeV.

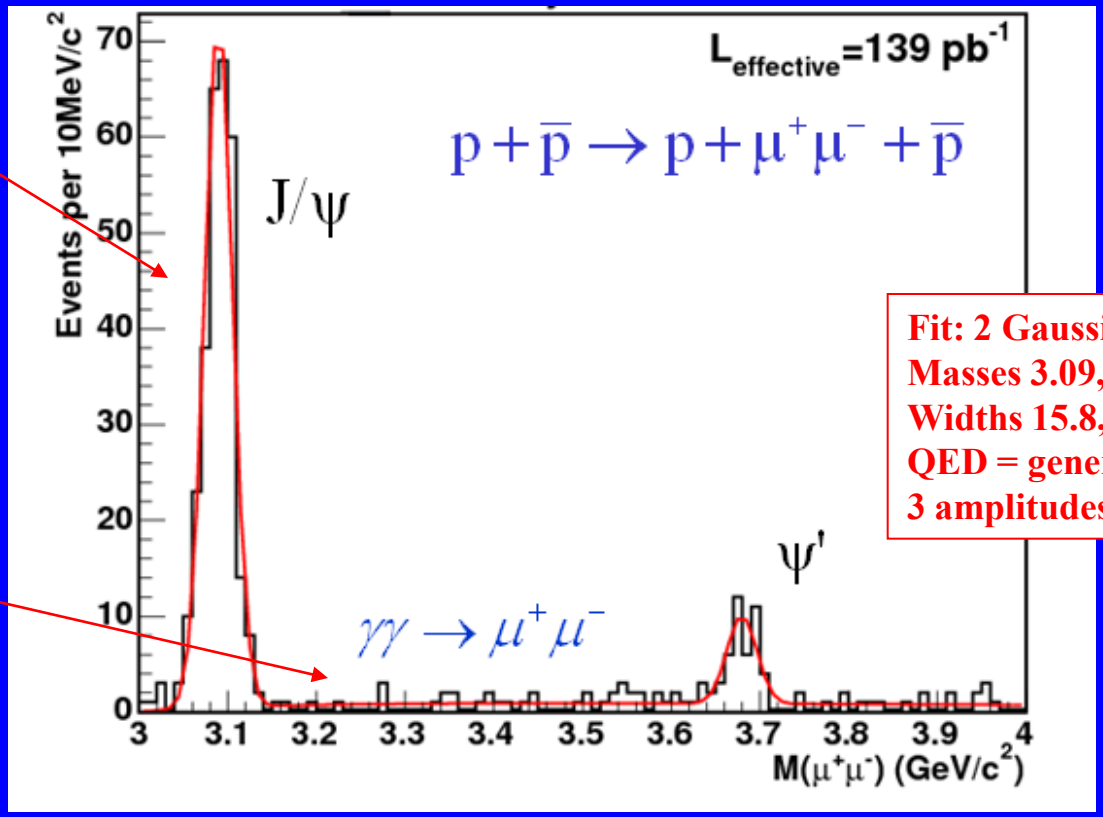
CDF: PRL 102, 242001 (2009)

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

402 events



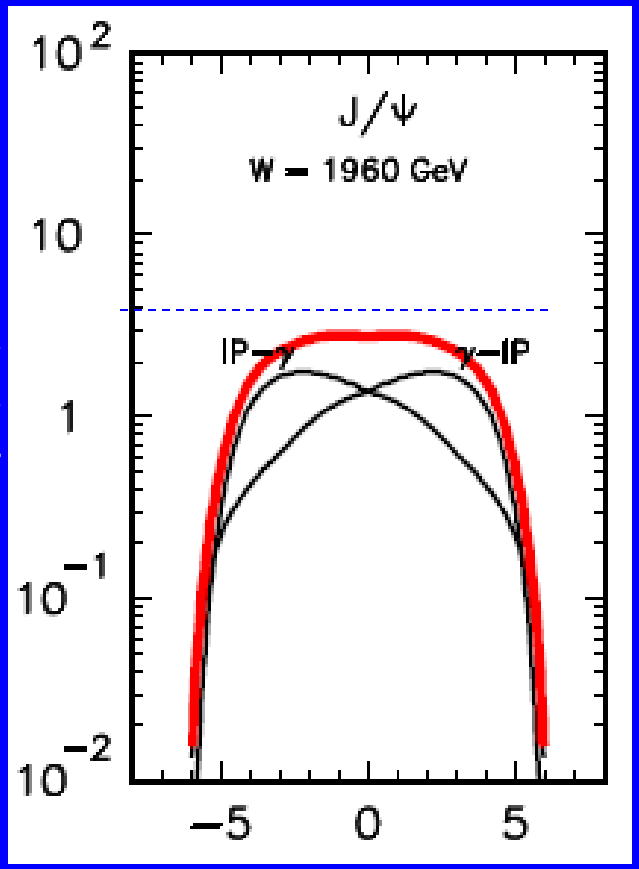




Fit: 2 Gaussians + QED continuum
Masses 3.09, 3.68 GeV == PDG
Widths 15.8,16.7 MeV=resolution.
QED = generator x acceptance
3 amplitudes floating

Some predictions for J/ψ photoproduction:

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



Take 3.0 +- 0.3

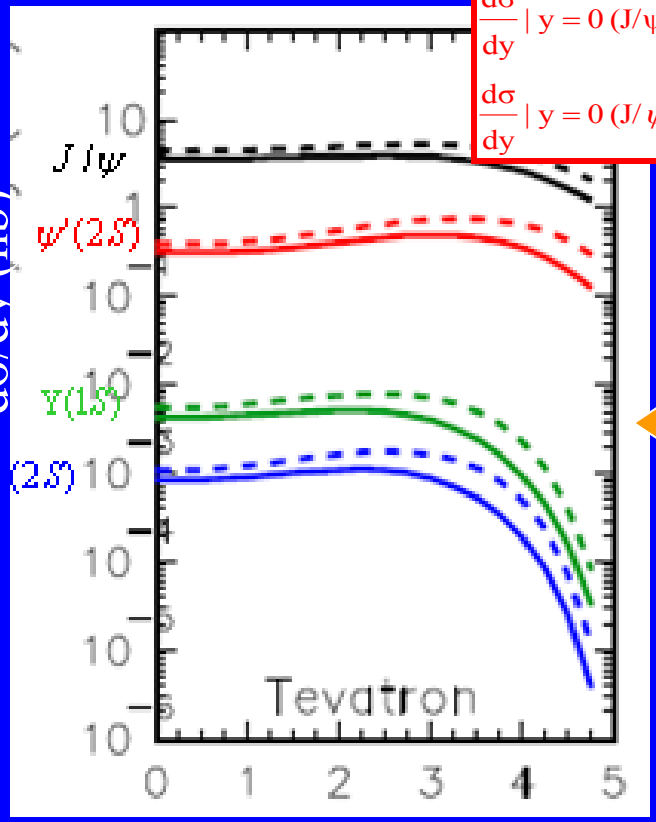
Machado,Goncalves 3.0 nb
Motyka and Watt: 3.4 +- 0.4 nb
Schafer & Szczurek ~ 2.8 nb
Nystrand 2.7+0.6-0.2 nb

Our result: 3.92 +- 0.62 nb

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

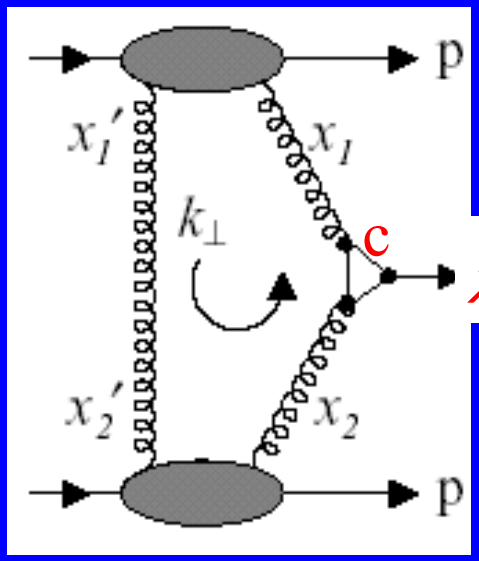
$\frac{d\sigma}{dy} | y = 0 (J/\psi) = 3.92 \pm 0.62$ nb (CDF)

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



Υ is much lower.

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



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

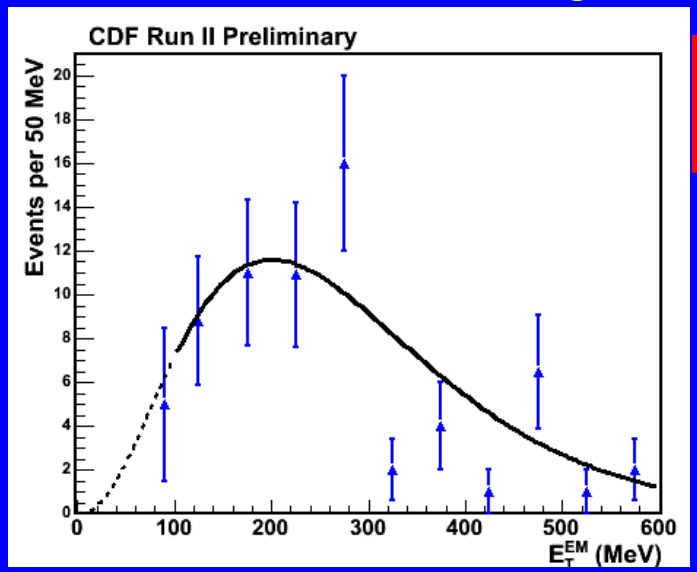
$J/\psi \rightarrow \mu^+$

$J/\psi \rightarrow \mu^-$

$\chi_{c0} \rightarrow \gamma$

& nothing else in all CDF $-7.4 < |\eta| < +7.4$

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



J/ψ have photons : 286 → 352

ψ(2S) do not : 39 → 40

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

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

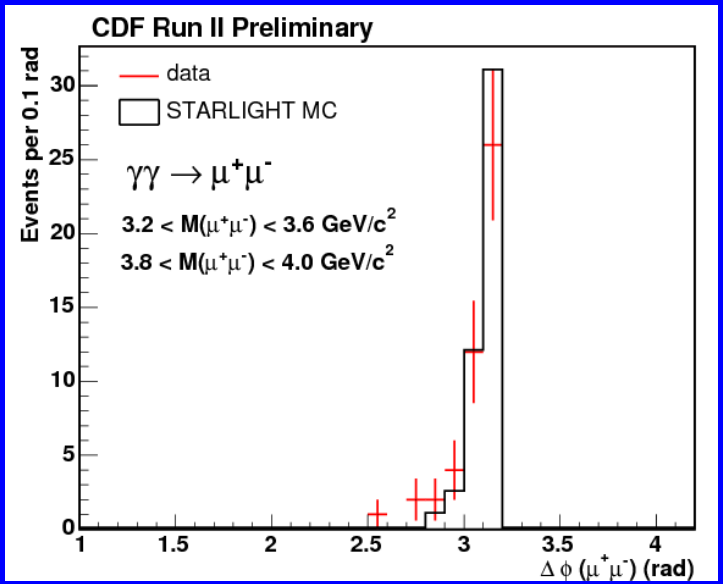
χ_c = 65 +/- 8

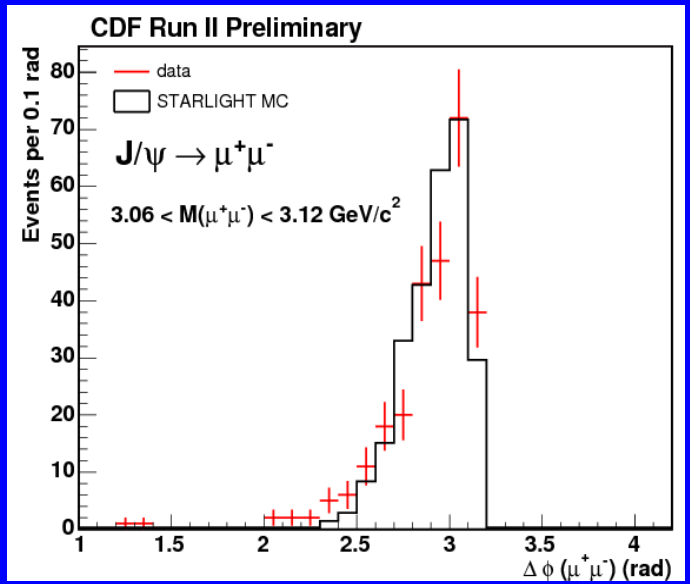
Summary of Results from $p + \bar{p} \rightarrow p + \mu^+\mu^- + \bar{p}$

M = 3-4 GeV/c2

Quantity	This analysis	Theory
$\frac{d\sigma}{dy}(y=0) J/\psi$ (nb)	3.92±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 → 90 nb
$\sigma(box, QED, pb)$	2.7±0.5	2.18 ± 0.02
$\frac{d\sigma}{dy}(y=0) O\!P \rightarrow J/\psi$	<2.3 nb (95% C.L.)	
$\frac{J/\psi}{\chi_c}$	0.052±0.015	No Prediction

No evidence for odderon



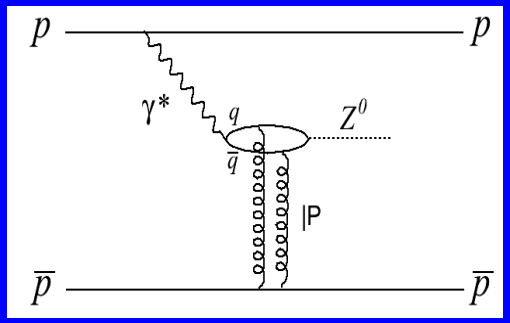


$\langle p_T(\gamma\gamma) \rangle < \langle p_T(IP) \rangle$

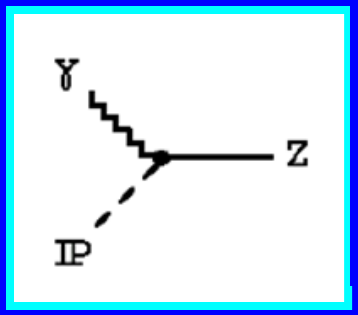
Search for Exclusive Z production

PRL 102,222002 (2009)

Allowed in SM (like V)
but σ ~ 0.3 fb (Motyka+Watt)

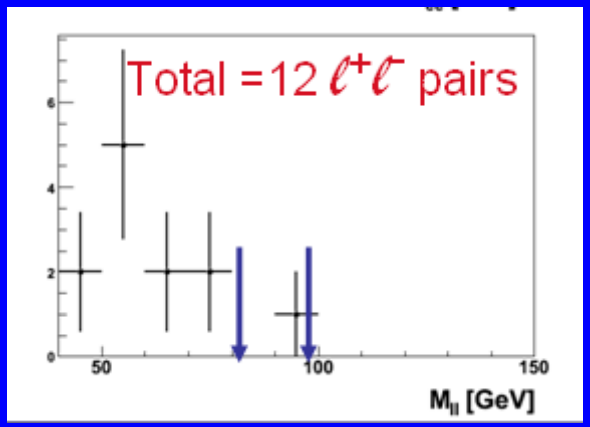


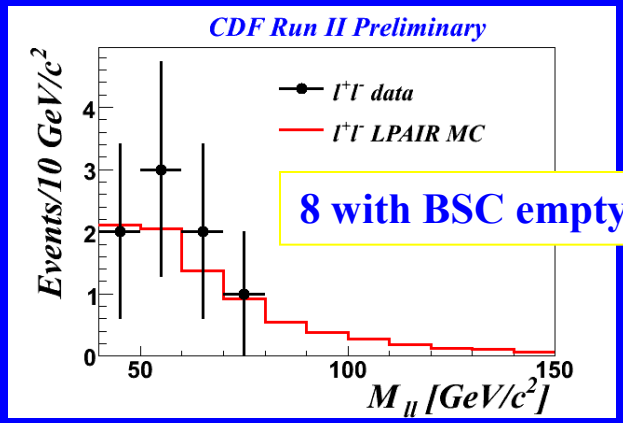
Could be enhanced by BSM loops

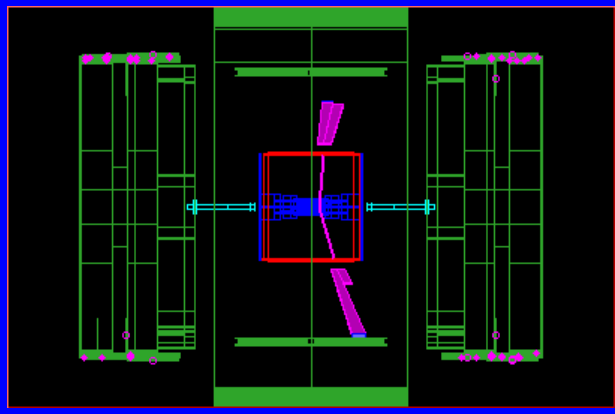


Interesting?!
γ-IP-Z eff.coupling.
ZOOM IN to see how!

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)





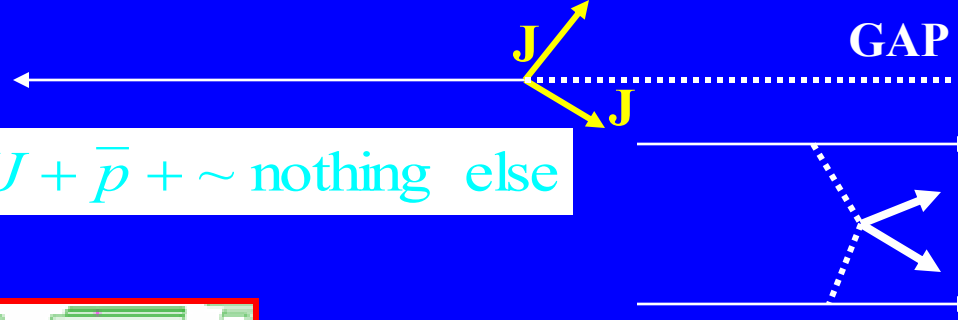


$\sigma(Z_{excl}) < 0.96$ pb (95% C.L.)
$\sigma(Z_{excl})$ Theory $= 0.3$fb
(13fb @ LHC)

~ record E(γγ)

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

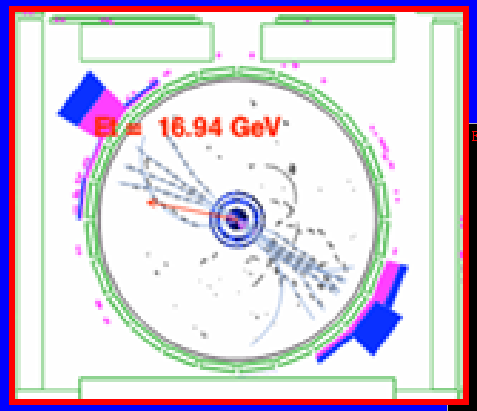
Exclusive Di-Jets



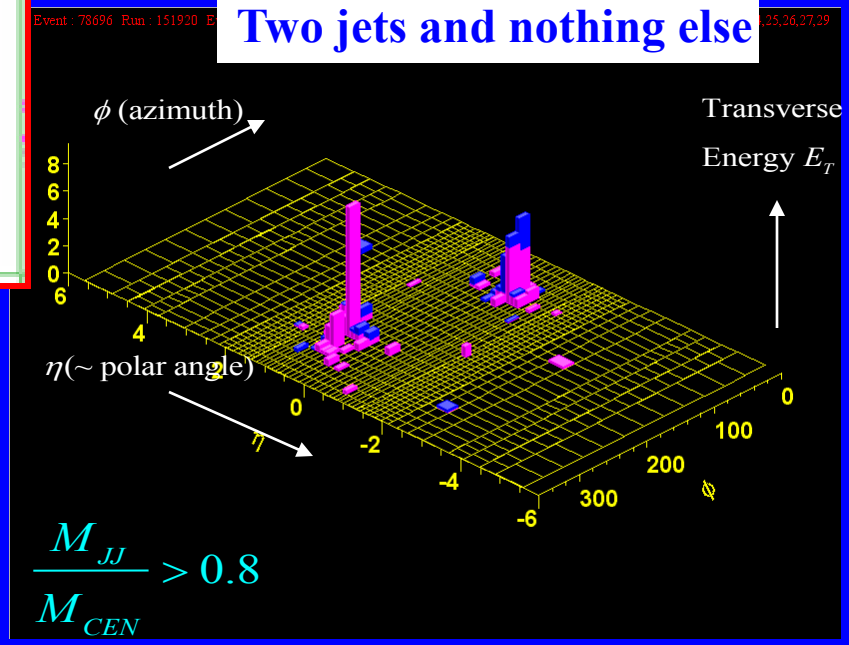
$$p + \bar{p} \rightarrow p + JJ + \bar{p} + \sim \text{nothing else}$$

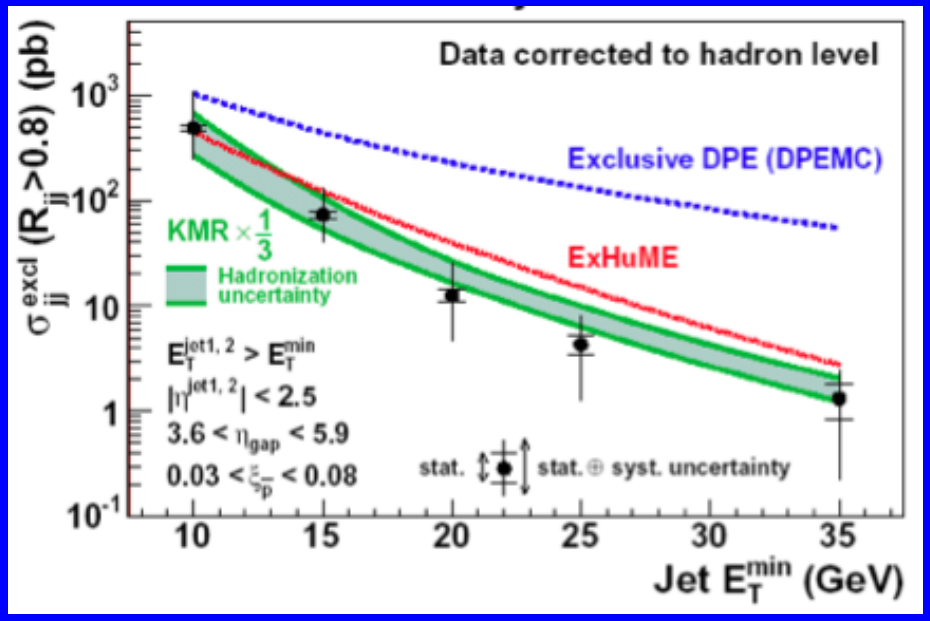
Observed in CDF, QCD tests & related to p+H+p

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



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





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

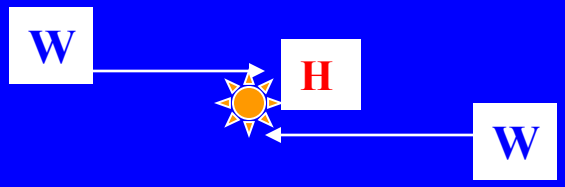
Gluon jet physics.

The Ultimate Vacuum Excitation

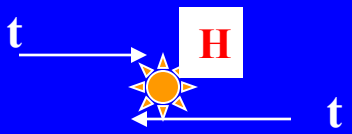
Above the χ_b, the only "known" heavier particle with vacuum Q.Nos. is the Higgs.

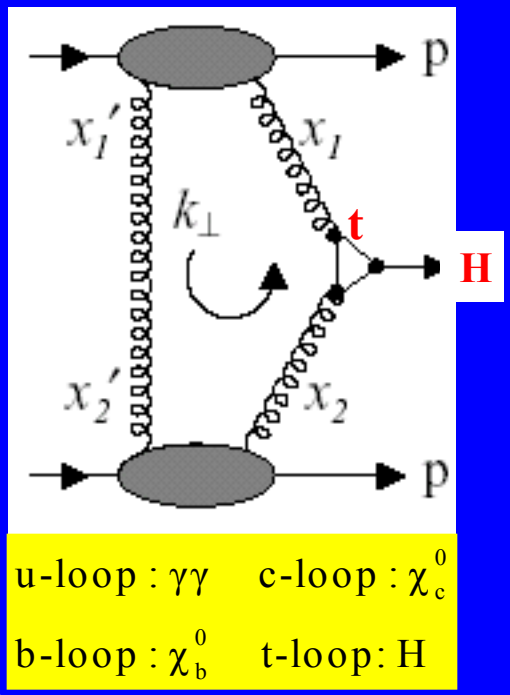
Vacuum is everywhere = Higgs field.

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)





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

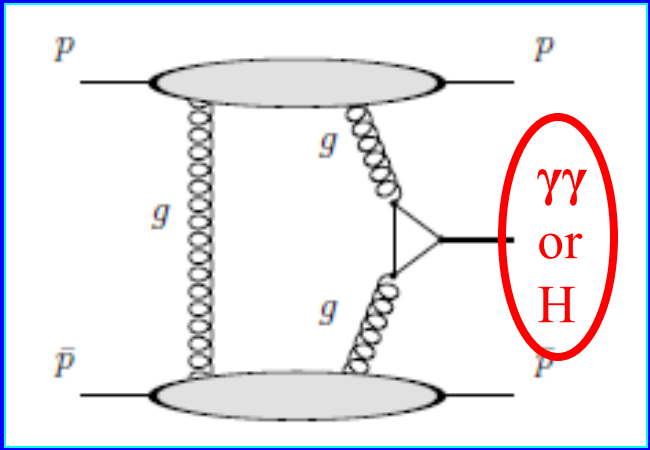
But if you see them, and measure both p, powerful benefits

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

→ $\sigma(M_H) \sim 2$ GeV/event

J,C,P,Γ?

Exclusive Higgs at LHC : Implications



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

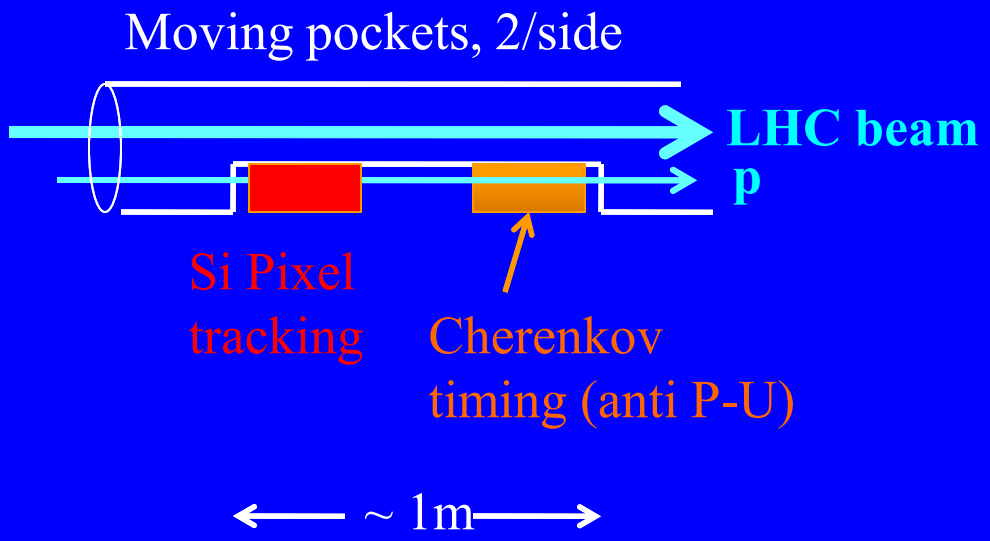
σ(SMH ~ 120 GeV) ~ 10 fb (MSSM bigger)

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

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

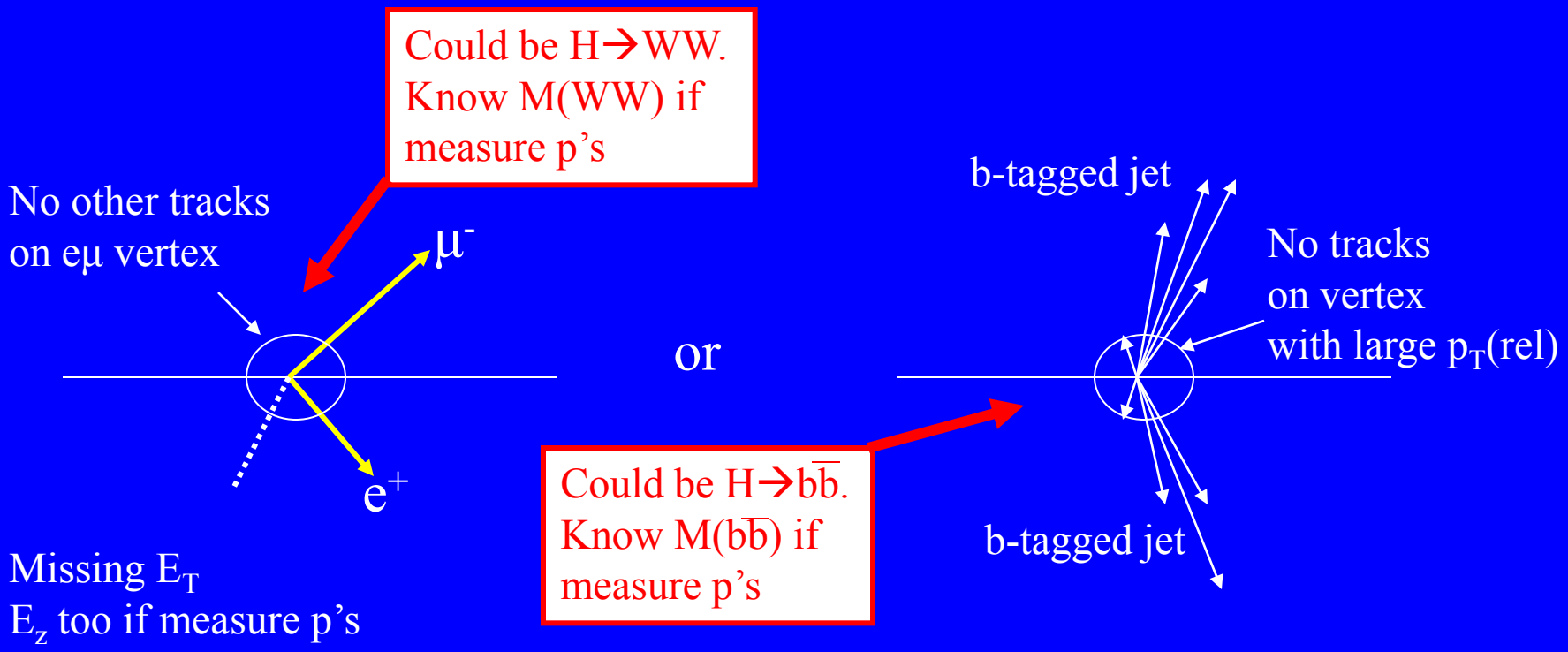


Tracking: 1 μrad = 8 μm/8 m, Rad hard, edgeless, 2 cm^2 ~ 16 layers
Timing: σ(t) ~ 10 ps: Cherenkov : gas with MCP-PMT; quartz with SiPMs.
Precision mechanics, BPMs, reference time signals, ...
σ(t) = 10 ps → σ(z) = 2.1 mm cf σ(z, interactions) ~ 50 mm

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



Conclusions: I

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

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

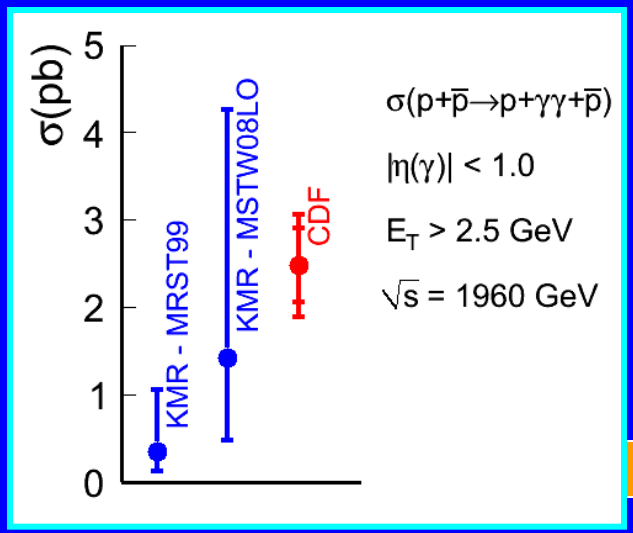
The cross section is ~ 2.5 pb, consistent with a theoretical prediction.

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	$\sigma_{\text{SuperCHIC}}^{\|\eta\|<1, E_T>2.5\text{GeV}} = 0.35^{\times 3}_{\div 3}$ pb (MRST99)
	$\sigma_{\text{SuperCHIC}}^{\|\eta\|<1, E_T>2.5\text{GeV}} = 1.42^{\times 3}_{\div 3}$ pb (MSTW08LO)
Measured	$\sigma_{\gamma\gamma\text{excl.}}^{\|\eta\|<1, E_T>2.5\text{GeV}} = 2.48 \pm 0.42(\text{stat}) \pm 0.41(\text{sys})$ 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: γγ ⟶)
Exclusive J/ψ and ψ(2S) ... photoproduction
Exclusive IP + IP ⟶ χ_c (through c-quark loop)
Exclusive IP + IP ⟶ Jet + Jet

These processes, especially χ_c and γγ, confirm that at the LHC, if there is a Higgs boson, p + p ⟶ 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 (σ < 1 GeV), J, CP, Γ_{gg})

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

Thank you for your attention

Rate of γγ Events is constant over the data year

Table: γγ candidates

		E_T> 2.5 GeV	
Period	$\mathcal{L}_{eff}$[pb^{-1}]	γγ	÷$\mathcal{L}_{eff}$[pb]
8	11.7	7	0.60
9	11.8	9	0.76
10	16.5	11	0.67
11	11.7	5	0.43
12	6.4	3	0.47
13	17.7	8	0.45
Tot:	75.8	43	

Rate consistent over time

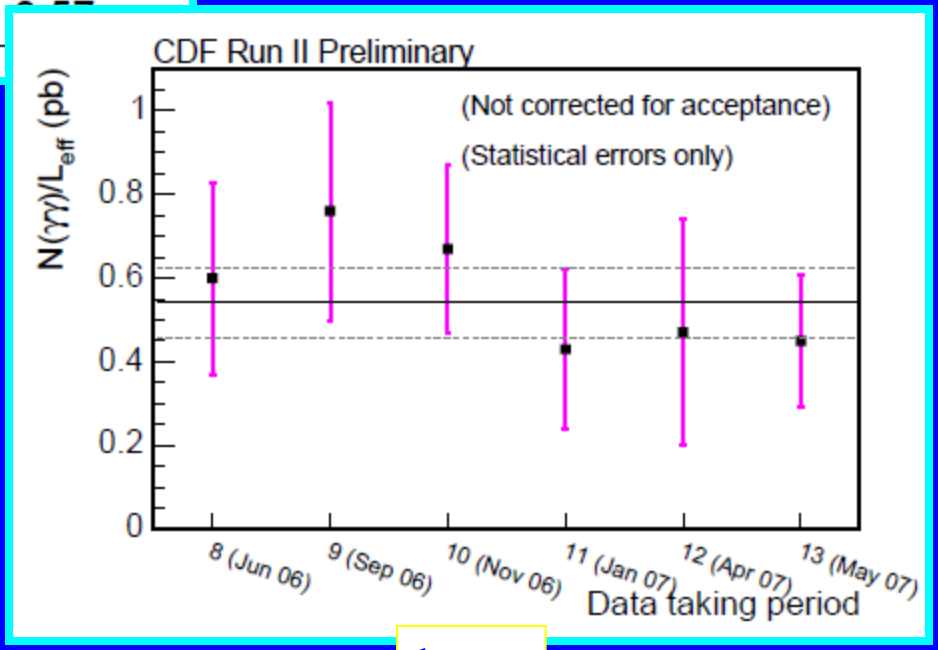


Table: Conversion Acceptance

E_T cut (GeV)	2.5
Acceptance$_{conv}$	0.568
Stat Err	±0.001
Syst Err	±0.063

1 year