



Exclusive Production at the TEVATRON and the LHC

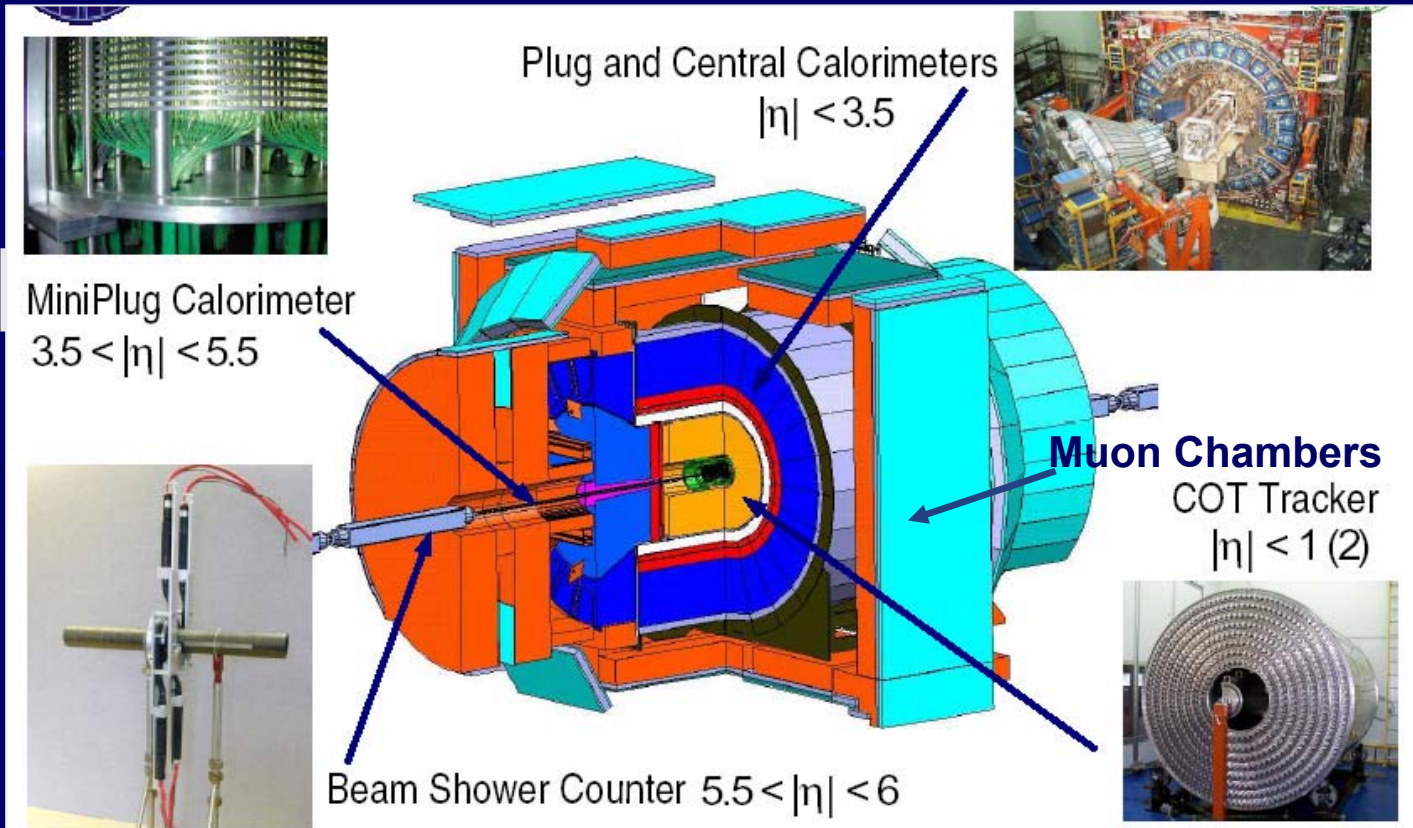
Meson 2008

See talks by Antoni Szczurek & Wolfgang Schäfer on Saturday

James L Pinfold

University of Alberta

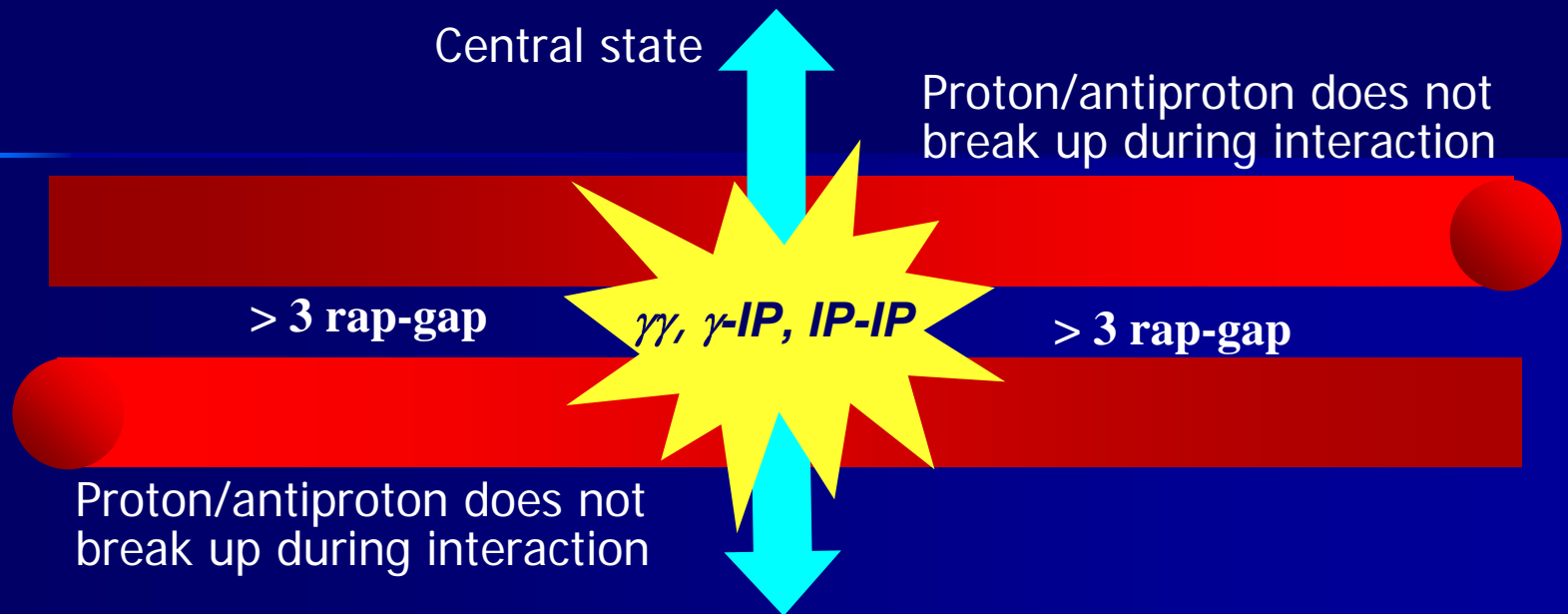
CDF Detector



Region	η range
Central	0.00 – 0.66
End Wall	0.66 – 1.32
Mid Plug	1.32 – 2.11
Fwd Plug	2.11 – 3.64
Mini Plug	3.6 – 5.2
BSC 1	5.4 – 5.9
BSC 2	6.4 – 7.1
BSC 3	6.7 – 7.4

- *A Roman Pot deployed detector is placed on one side of CDF at 60m from the IP. (RPS acceptance ~80% for $0.03 < x < 0.1$ and $|t| < 0.1$)*

Central Exclusive Physics

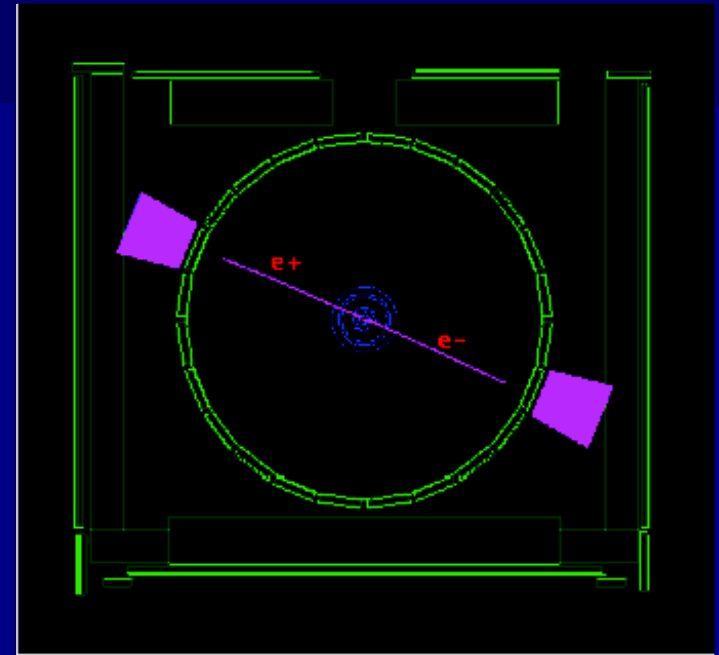
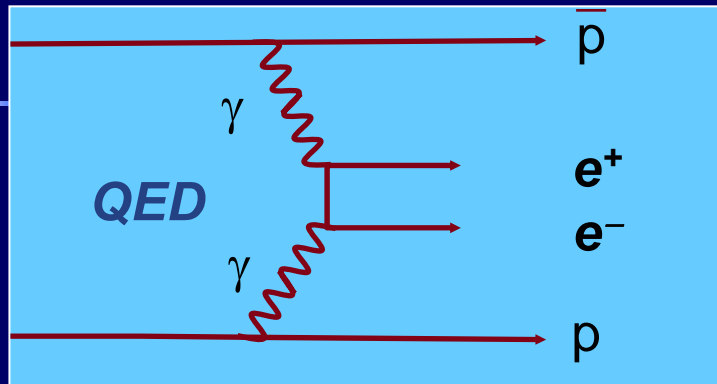


... both protons coherently scattered. Central state fully specified and measured, unlike "inclusive" production:

Forward tagging of the p 's at the LHC with FP420/RP220m allows full reconstruction of the central state

Mass to ~ 3 GeV at ISR, ~ 100 GeV at Tevatron, ~ 700 GeV at LHC

Exclusive e^+e^- Production (1)



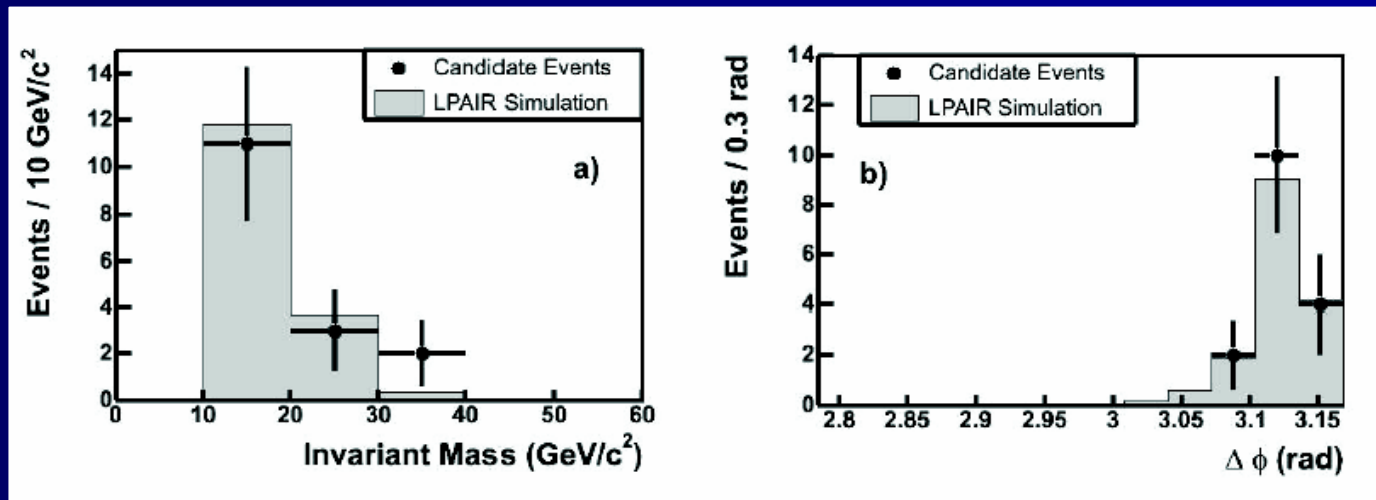
- **Central state produced via QED $\gamma\gamma \rightarrow e^+e^-$**
- **Protons do not dissociate**
- **Only e^+e^- are produced \rightarrow nothing else**

Exclusive e^+e^- Production (2)

- **Integrated luminosity** $\rightarrow 532 \pm 32 \text{ pb}^{-1}$
- **DIFF_DIPHOTON Trigger:**
 - 2 EM clusters with $E_T > 4 \text{ GeV}$ plus a veto on BSC 1 (E+W)
- **Exclusive e^+e^- events are selected by:**
 - Reconstructing the e^+e^-
 - Requiring that there is no other activity in $|\eta| < 7.4$
 - For the two EM showers we have $E_T > 5 \text{ GeV}$ and $|\eta| < 2$
 - 16 e^+e^- candidates selected
- **Backgrounds 1.9 ± 0.3 events:**
 - dijet fake ($0.0 +0.1 -0.0$)
 - cosmic (negligible)
 - inclusive distribution (0.3 ± 0.1)
 - dissociation (1.6 ± 0.3) (these are also $gg \rightarrow e^+e^-$) where one (or both) proton(s) dissociate)

Exclusive e^+e^- Production (3)

- Kinematics of 16 event candidate sample match the predictions of the LPAIR signal MC (J.Vermaseren. Nucl. Phys., B229 347-371, 1983)- e^+e^- are collinear in ϕ and have matching E_T**



- Cross-section for $\gamma\gamma \rightarrow e^+e^-$ LPAIR theory:**

$$\sigma_{LPAIR} = 1.71 \pm 0.01 \text{ pb}$$

Exclusive e^+e^- Production (4)

$$\sigma_{MEASURED} = 1.6^{+0.5}_{-0.3} \text{ (stat)} \pm 0.3 \text{ (sys) pb}$$

- **Agrees with LPAIR theory:** $\sigma_{LPAIR} = 1.71 \pm 0.01 \text{ pb}$
- **Prob. of $1.9 \rightarrow \geq 16 = 1.3 \times 10^{-9}$ - a 5.5σ “observation”**
- **This is the first observation of exclusive two-photon produced e^+e^- interactions in p - $p(\bar{p})$ collisions (also seen at RHIC – Phys. Rev C70:031902, 2004; nucl-ex/0601001)**
- **The LHC can rely on measuring such processes for luminosity measurement, etc.**

PRL 98, 112001 (2007)

PHYSICAL REVIEW LETTERS

week ending
16 MARCH 2007

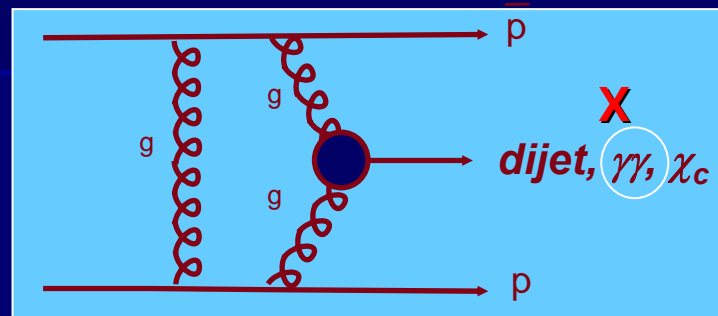
Observation of Exclusive Electron-Positron Production in Hadron-Hadron Collisions

A. Abulencia,²³ J. Adelman,¹³ T. Affolder,¹⁰ T. Akimoto,⁵⁵ M. G. Albrow,¹⁶ D. Ambrose,¹⁶ S. Amerio,⁴³ D. Amidei,³⁴
A. Anastassov,⁵² K. Anikeev,¹⁶ A. Annovi,¹⁸ J. Antos,¹ M. Aoki,⁵⁵ G. Apollinari,¹⁶ J.-F. Arguin,³³ T. Arisawa,⁵⁷

We have many more candidates in new data with dedicated 2-EM shower trigger

CDF $e^+e^- \gamma\gamma$ $\mu\mu, J/\psi, \psi', \chi_c$ Y Di-jets LHC, FP420/220 Conclusions

Exclusive $\gamma\gamma$ Study (1)

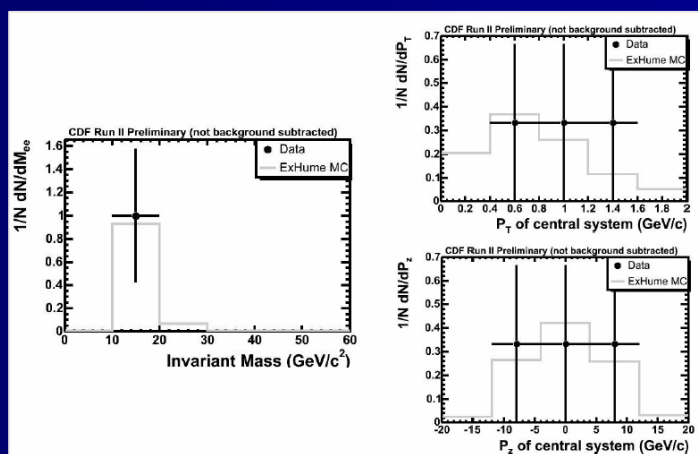


where X has $J^{PC} = 0^{++}$

- **Exclusive $\gamma\gamma$ events:**
 - selected in the same way as e^+e^- (except tracking)
- **Selected in the same way as $\gamma\gamma \rightarrow e^+e^-$ (except tracks)**
agreement of $\gamma\gamma \rightarrow e^+e^-$ cross section gives confidence in analysis methodology

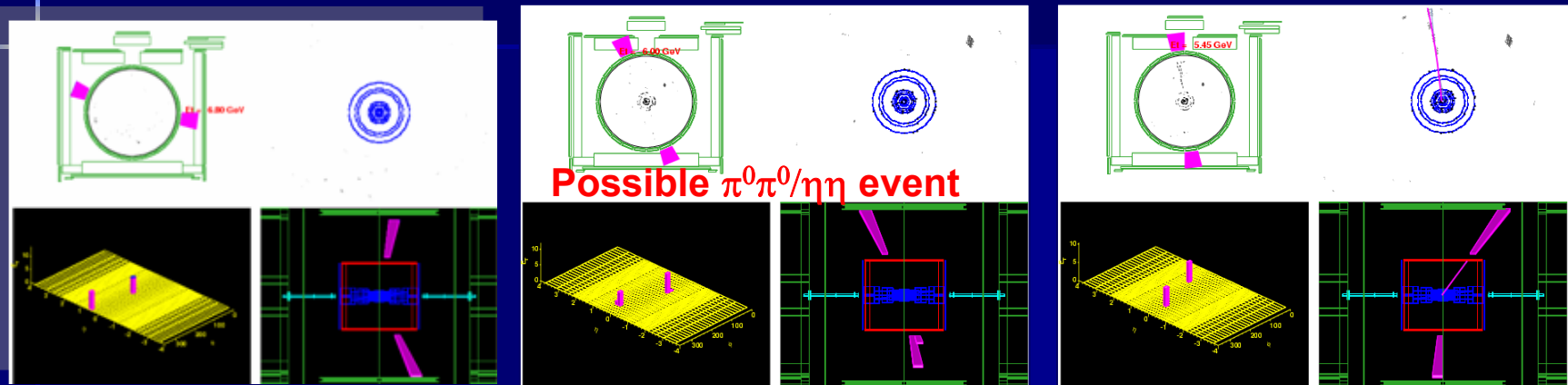
Exclusive $\gamma\gamma$ Study (2)

- **3 candidate events found in 532 pb⁻¹ of Run II data.**
- **Background 0.09 ± 0.04 events (mostly misid. of excl.)**
- **Good agreement on kinematics with ExHume MC (Monk & Pilkington. hep-ph/0502077)**



- **$0.8^{+1.6}_{-0.5}$ events predicted from ExHuME MC**

Exclusive $\gamma\gamma$ Candidates (1)



- *2 candidates are almost certainly $\gamma\gamma$ but the $\pi^0\pi^0/\eta\eta$ hypotheses cannot be excluded*

We have found >10 more candidates in data with new di-EM shower trig.

Exclusive $\gamma\gamma$ Candidates (2)

- *The upper limit of the cross-section $pp \rightarrow p \gamma\gamma p$ is set at 410 fb with 95% confidence level (taking into account the background + its uncertainty, signal selection efficiency, & L_{int})*
- *If 2 of the 3 candidates are $\gamma\gamma$ events we obtain a cross section:*

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

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

PRL 99, 242002 (2007)

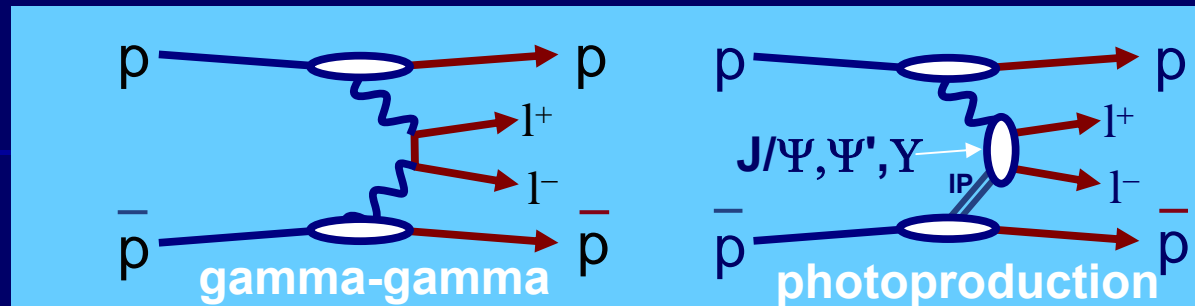
PHYSICAL REVIEW LETTERS

week ending
14 DECEMBER 2007

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

T. Aaltonen,²³ A. Abulencia,²⁴ J. Adelman,¹³ T. Affolder,¹⁰ T. Akimoto,⁵⁵ M. G. Albrow,¹⁷ S. Amerio,⁴³ D. Amidei,³⁵
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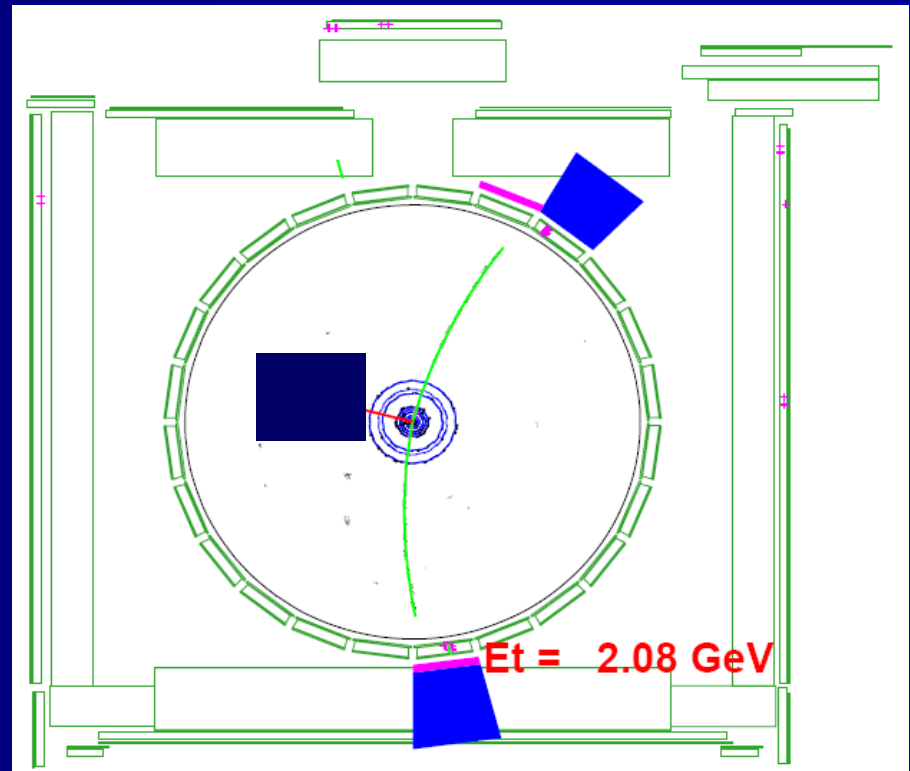
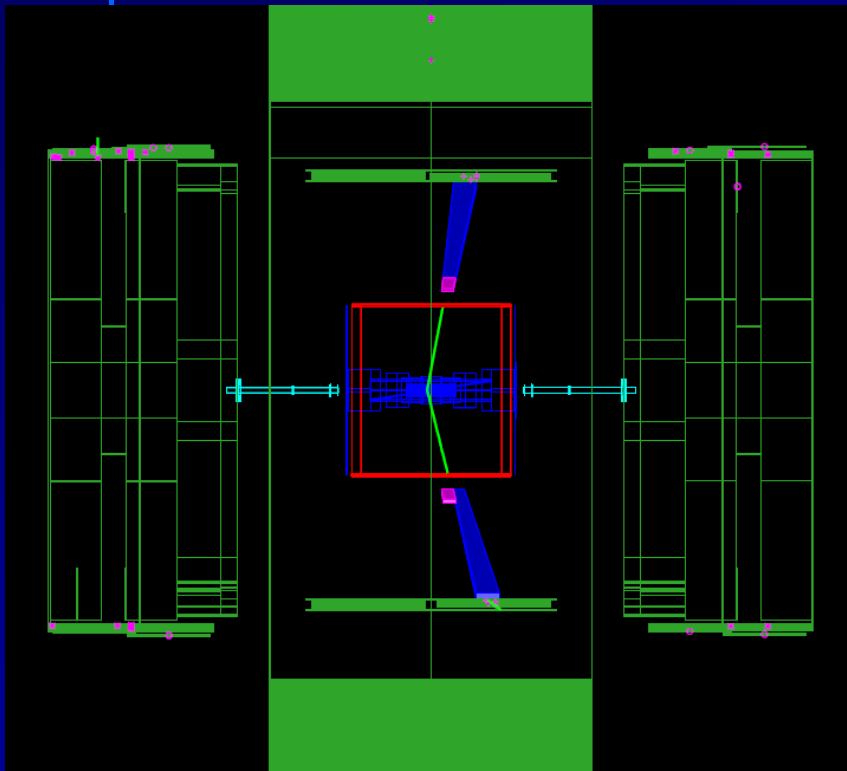
Exclusive $\mu^+\mu^-$ Production (1)



- **Trigger (*DIFF_CHIC_CMU1.5_PT1.5_TRK*):**
 - BSC Gap, east & west
 - muon + track ($p_t > 1.3$; $|\eta| < 1.2$)
 - $2.7 < M(\text{muon} + \text{track}) < 4.0 \text{ GeV}c^2$
- **The existing sample corresponds to a lumi of 1.48 fb^{-1}**
- **Also higher mass muons have just been stripped, (trigs with $p_t(\mu) > 4 \text{ GeV}$, 2 muons, no $\Delta\phi$ requirement).**
- **Should be very efficient for dimuons, with $M > \sim 9 \text{ GeV}$, covering the Upsilon region and above.**

Exclusive $\mu^+\mu^-$ Production (2)

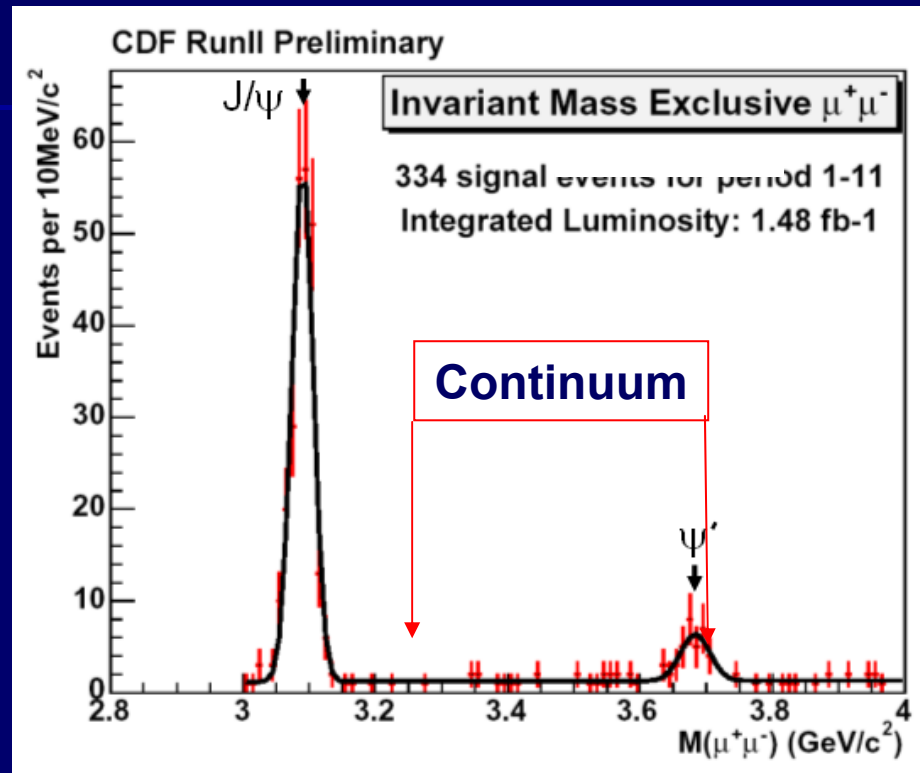
*Example exclusive $\mu^+\mu^-$ event:
Run 199559, Event 13120174*



Exclusive $\mu^+\mu^-$ Production (3)

- **Integrated luminosity – 1.48 fb⁻¹**
- **Offline cuts**
 - Loose quality cuts
 - No other activity in the events (to an $|\eta|$ of 7.4)
 - $P_T(\mu) > 1.4 \text{ GeV}/c$ & $|\eta(\mu)| < 0.6$
 - Cosmic ray cuts ($\text{abs}(\text{delta_TOF}) < 3 \text{ ns}$)
 - Exclusivity cuts (same as for the e^+e^- paper)
- **Analysis of cuts is underway**
 - Acceptance
 - Efficiency
 - Effective luminosity
- **STARLIGHT Monte Carlo simulation employed (S. Klein & J. Nystrand)**

Exclusive $\mu^+\mu^-$ Candidates (1)

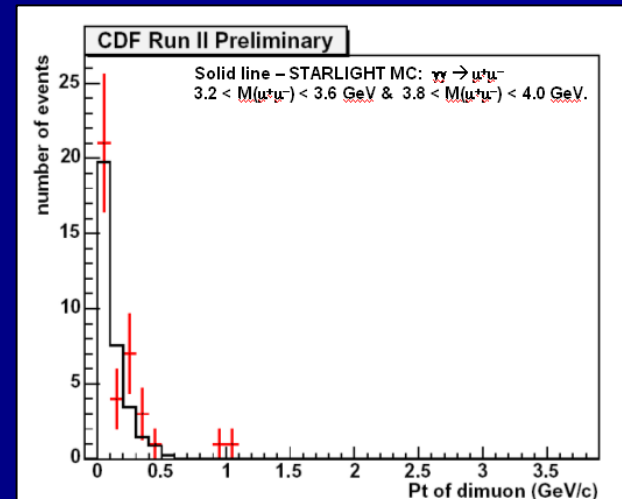
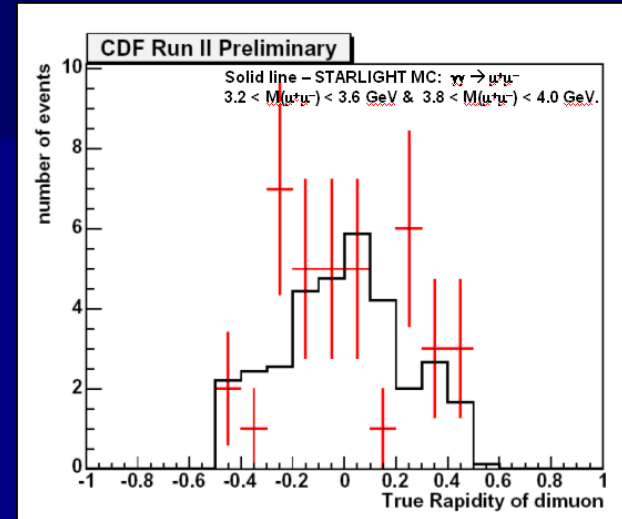
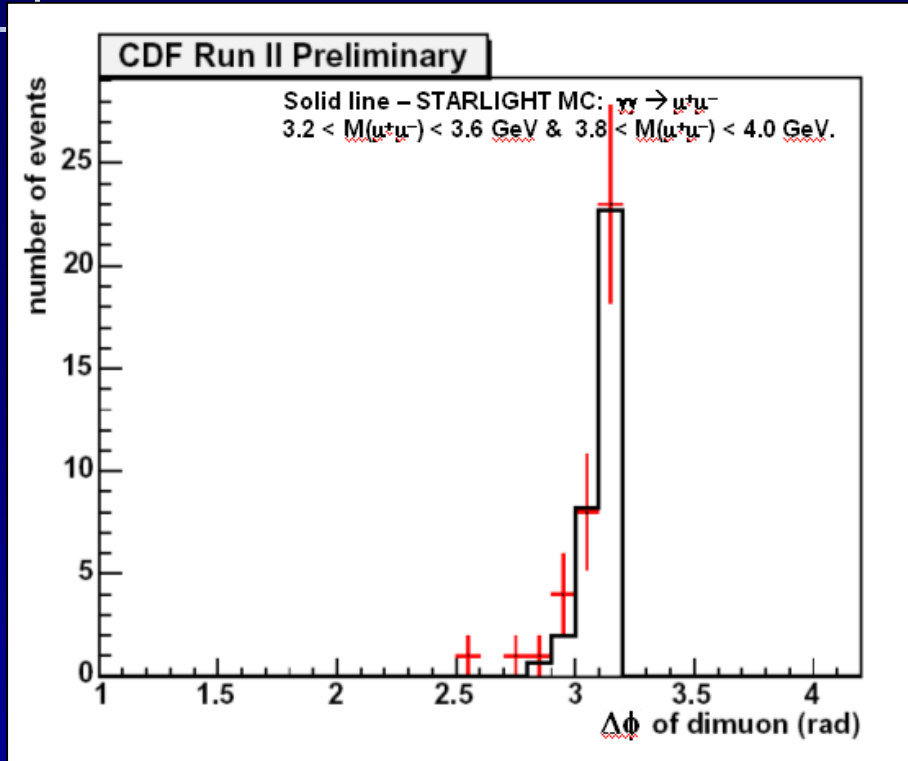


Many candidate events (334) have been found (CDF-II Preliminary)

We now have a ~25% increase of the signal due to a more efficient cosmic ray cut. – we await the blessing of the requisite plot.

Exclusive $\mu^+\mu^-$ Candidates (2)

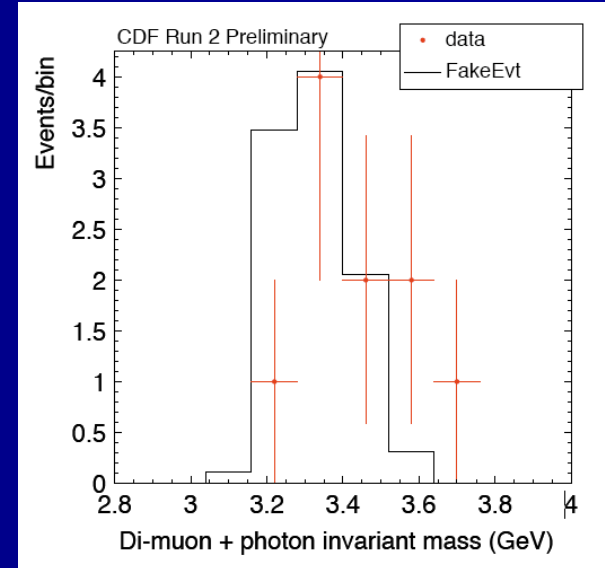
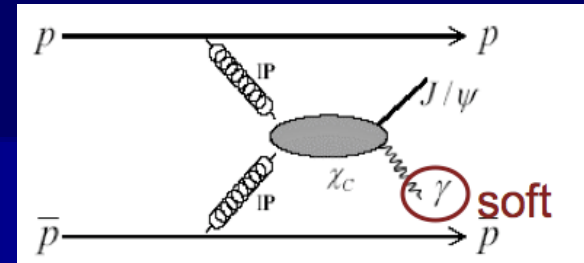
The $\gamma\gamma \rightarrow \mu^+\mu^-$ continuum



- *Good agreement on kinematics with STARLIGHT MC (Klein & Nystrand)*

Exclusive χ_c Production “Background”

- **Similar selection as $\mu^+\mu^-$ search with additional isolated EM shower req.**
- **10 candidates in 93 pb^{-1} of data from an old analysis**
- **New ChicMC (James Stirling)**
- **Problem is - understanding low energy photon from the χ_c decay**
- **Many more events with new trigger**
- **We estimate that there is a ~10% cont. of χ_c to the $J/\psi \rightarrow \mu^+\mu^-$ peak - with excl. cuts (using fits to E_t & $\Delta\phi$ dists)**
- **We are working on this ...watch this space**



$BR(\chi_c^0 \rightarrow J/\psi + \gamma \rightarrow \mu^+\mu^-\gamma)$
 \times no other interaction \times
 acceptance (tria) \Rightarrow few pbs

Exclusive $\mu^+\mu^-$ Candidates (High Mass) (1)

- **Find Exclusive events using**
 - Number of associated tracks = 0
 - Kinematics: $\Delta\phi \approx 180^\circ$, $\Delta p_T \approx 0$, (or $\Sigma P_T \approx 0$)
- **Trigger: 2 central muons with $p_T > 4$ GeV/c**
- **$L = 890/\text{pb}^{-1} \sim 2.3$ M events.**
- **Remove cosmic rays (timing + colinearity)**
- **Require on beam-line. Count additional (associated) tracks (n_{ass}) within 5 cm of $\mu^+\mu^-$ vertex.**
- **Cleanliness, backgrounds & acceptances being studied.**
- **Number of events “reasonable” for QED process & Lumi.**

Exclusive $\mu^+\mu^-$ Candidates (High Mass) (2)

Invariant Mass - Upsilon Region

$\Delta\phi > 120^\circ$, $p_T(\mu^+ + \mu^-) < 7 \text{ GeV}/c$ + no add. tracks

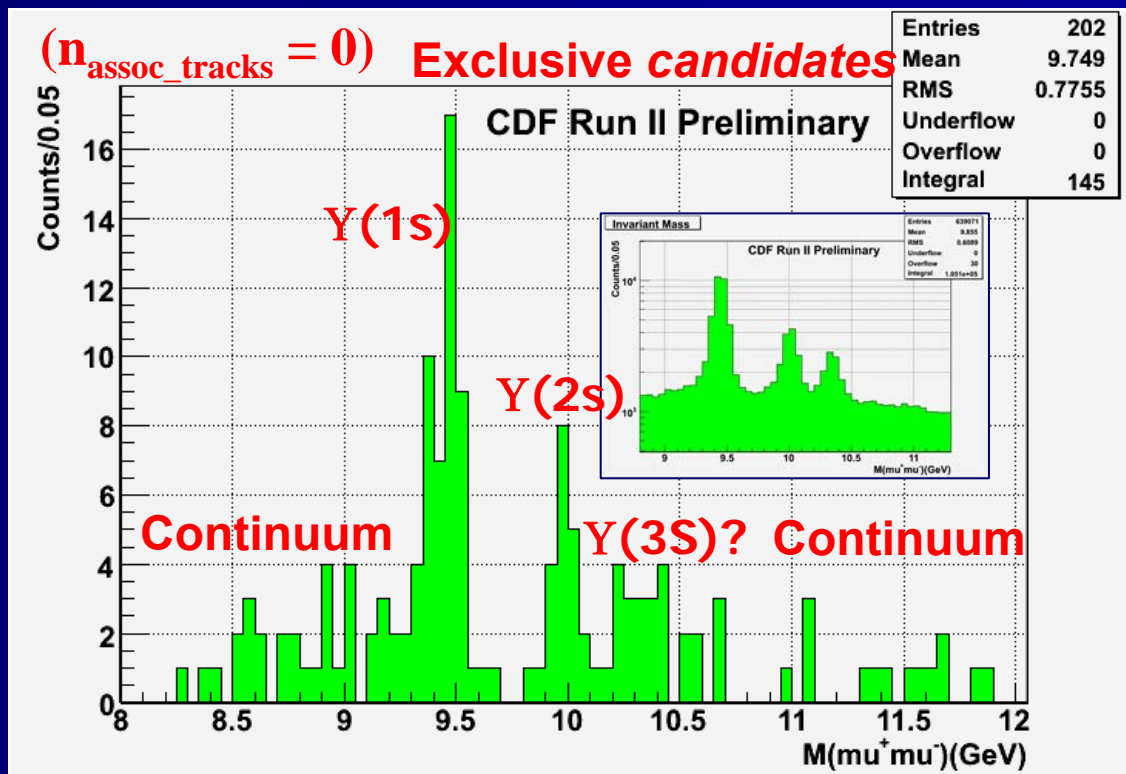
Branching ratios for $\mu^+\mu^-$ channels:

$Y(1s) | 9.46 \text{ GeV} | : 2.5\%$

$Y(2s) | 10.02 \text{ GeV} | : 1.3\%$

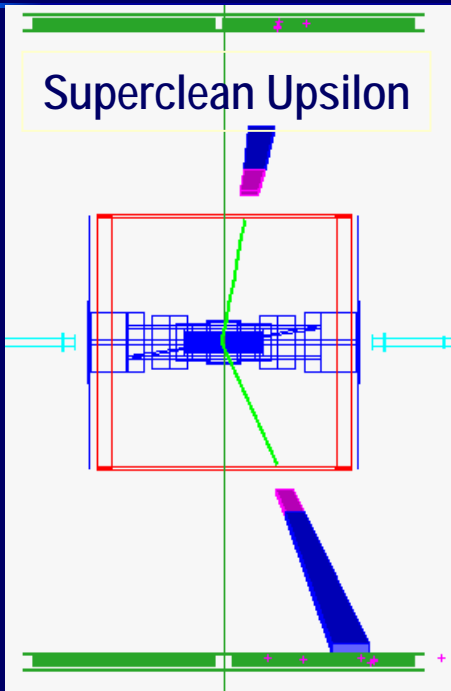
$Y(3s) | 10.36 \text{ GeV} | : 1.8\%$

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

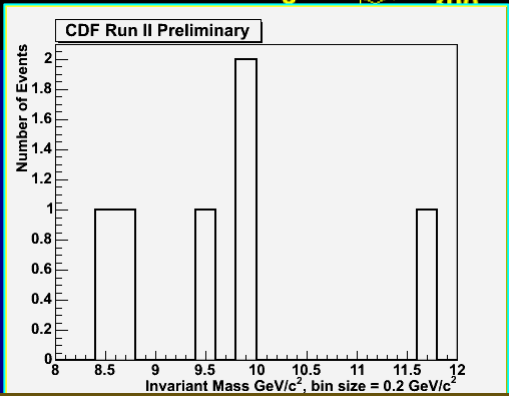
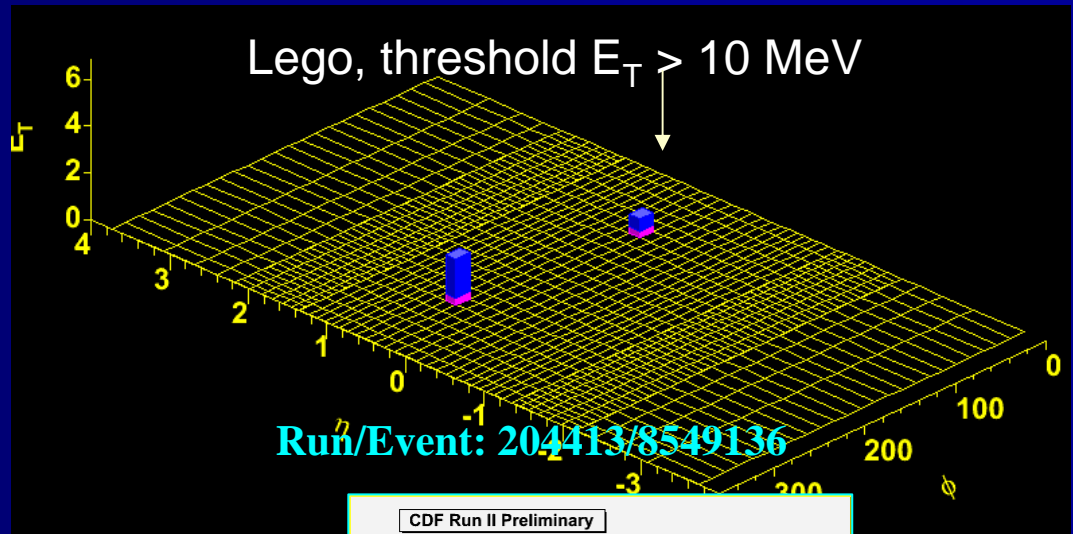


Exclusive $\mu^+\mu^-$ Candidates (High Mass) (3)

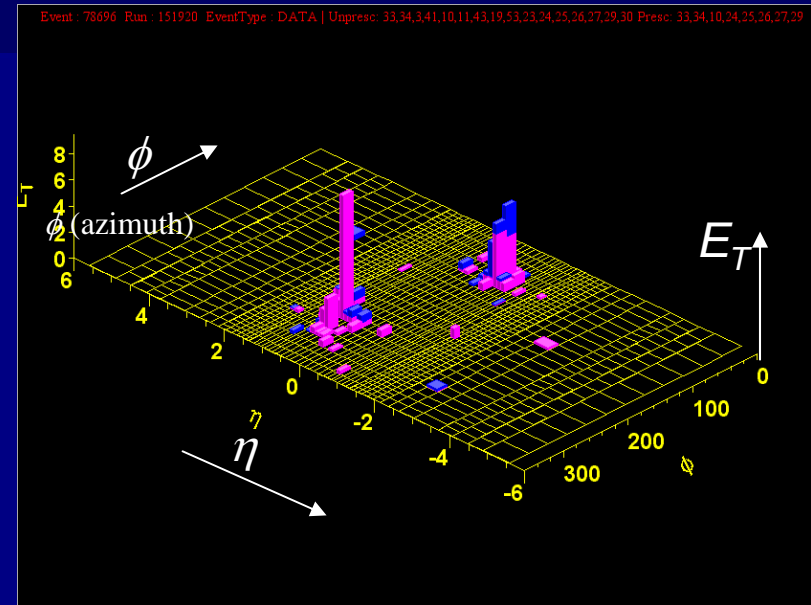
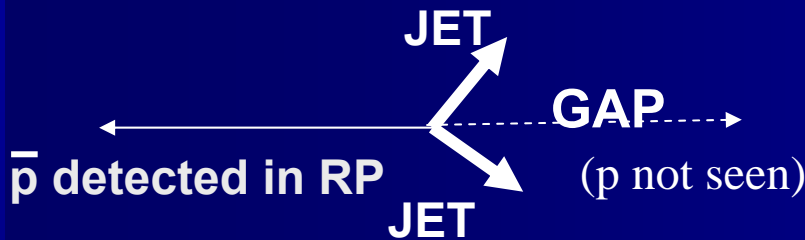
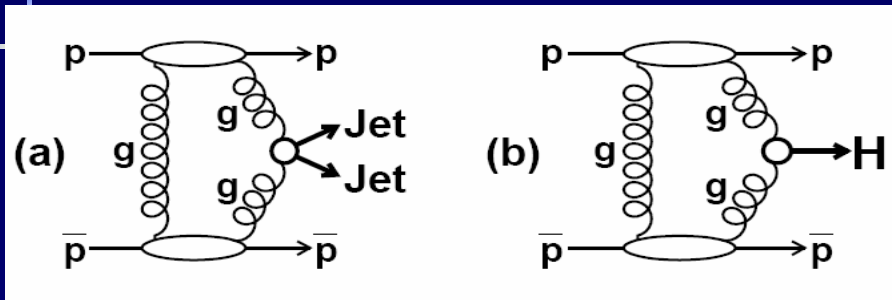
Now apply "super clean" exclusivity cuts as in low mass l -pair mass i.e. no pile-up, and only μ -pairs detected



145 events in 8 – 12 GeV region
→ 6 events + 4 $M(\mu^+\mu^-) > 12$ GeV.
(Most of reduction is killing pile-up)



Exclusive Di-jet Search



- **Exclusive di-jets 2 jets + nothing else - no pile-up essential thus lower lumi running**
- **Initial sample includes two high E_T ($>10 \text{ GeV}/c^2$) jets with a 3rd jet with $E_T < 5 \text{ GeV}/c^2$ with $3.6 < \eta_{\text{gap}} < 5.9$**

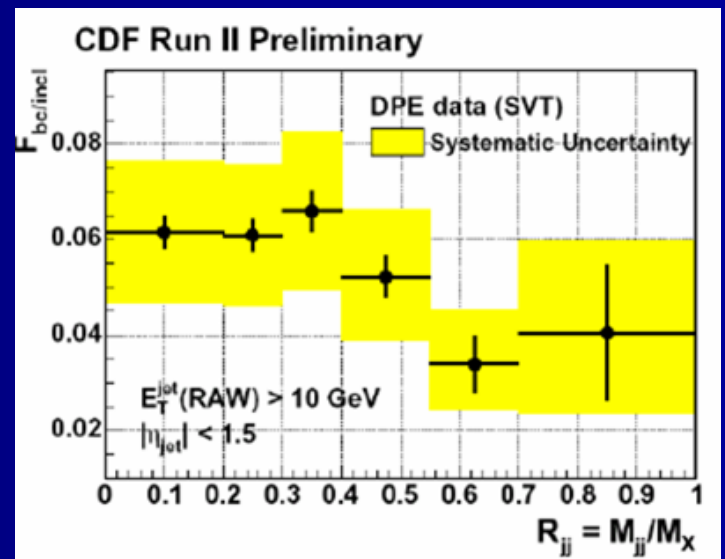
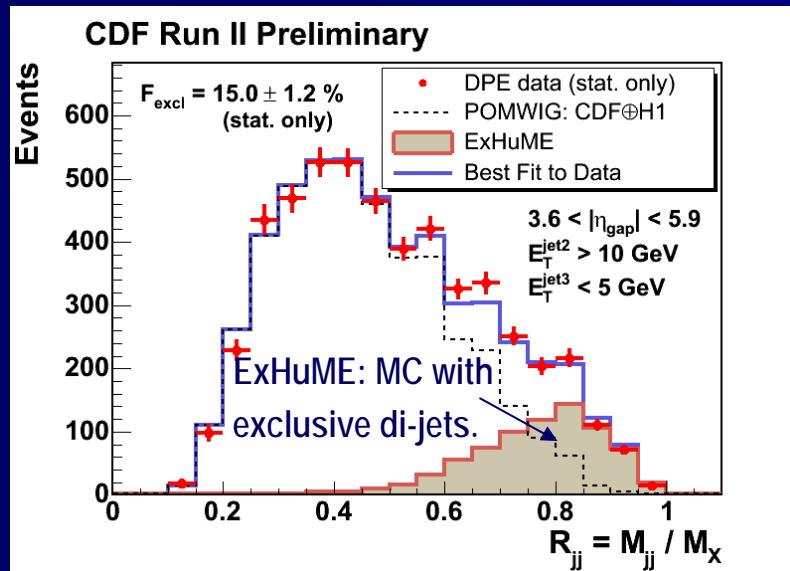
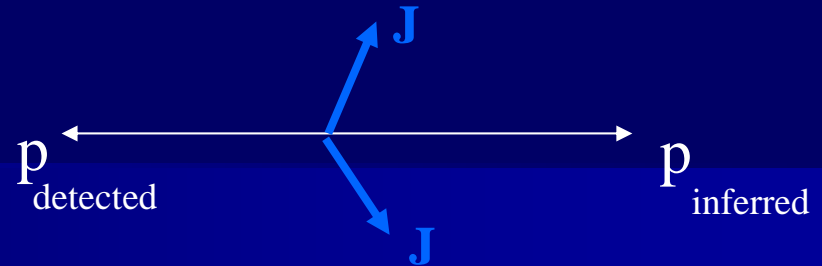
CDF e^+e^- $\gamma\gamma$ $\mu\mu, J/\psi, \psi', \chi_c$ Y **Di-jets** LHC, FP420/220 Conclusions

Exclusive Di-jet Search

$$R_{jj} = M_{jetjet} / M_{CENTRAL} > 0.8$$

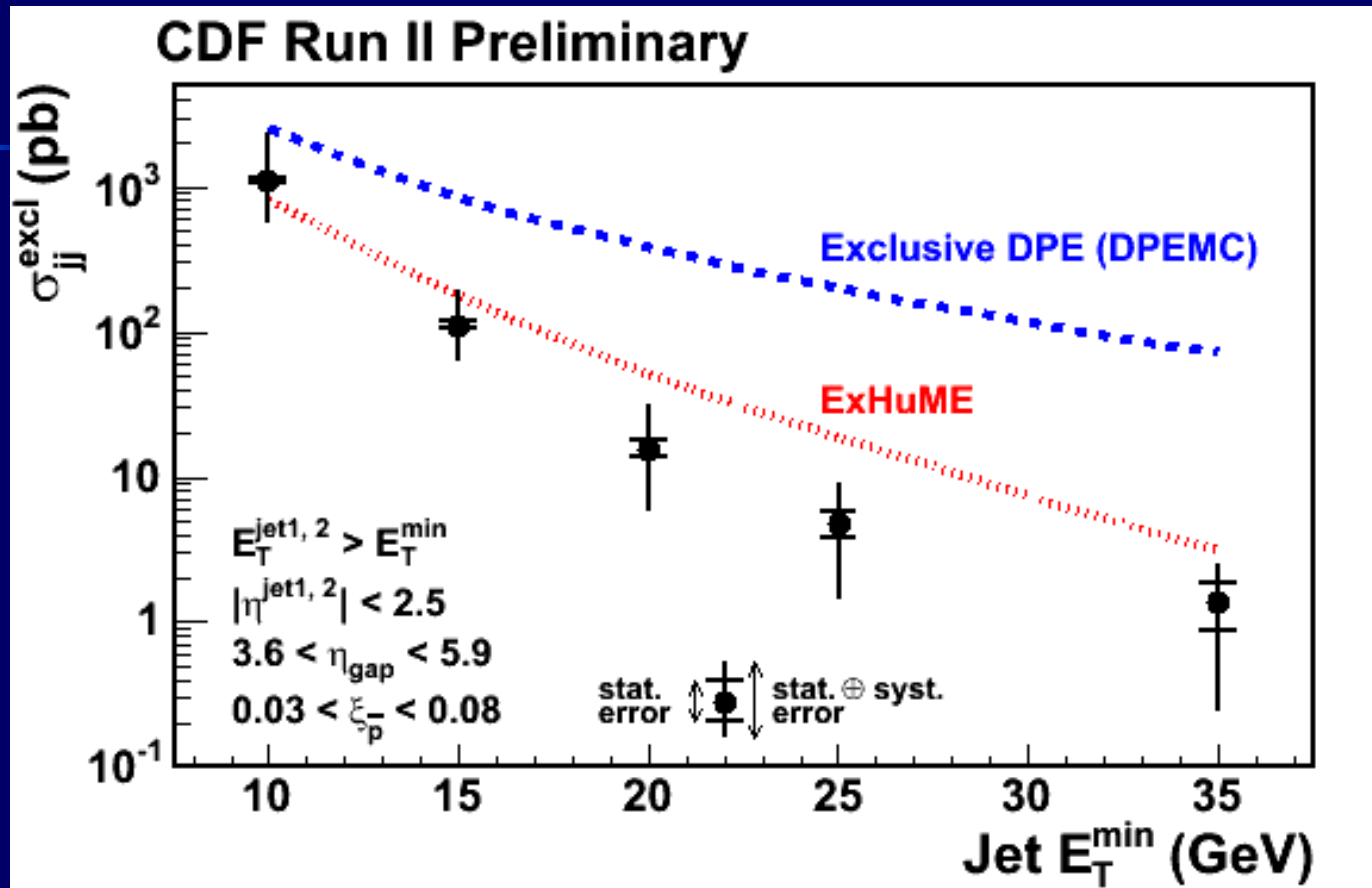
(to be "exclusive")

$$M_{jetjet} \approx 40-150 \text{ GeV}/c^2$$



Apparent *b*-jet suppression as di-jets become exclusive
 (Theoretically $\Rightarrow 0$ as $R_{jj} \Rightarrow 1$, $J_z=0$ rule)

Exclusive Di-jet Cross-section



ExHuME (KMR): based on LO pQCD

DPEMC: based on Regge theory

The LHC Startup

Month	Phase	Days physics	Efficiency factor	Peak luminosity	Delivered luminosity	
Jan	Cooldown and Hardware Commissioning and Machine checkout					
Feb						
Mar						
Apr						
May						
June						
Jul						
Aug	Beam Commissioning					
Sep						
Oct	Physics run					
Nov						
Dec	Shutdown					
Jan						
Feb						
Mar	Machine checkout					
Apr	75ns Commissioning					
May	Physics run					
June						
Jul						
Aug			140	0.2	10^{33}	2.4 fb^{-1}
Sep						
Oct						
Nov						
Dec						

5TeV in 2008

7TeV in 2009

Cross check

1 * 10h fill per day over 140 days
1400h = $5 \cdot 10^6$ seconds

Peak luminosity $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$
 $\langle L \rangle 5 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$

Integrated luminosity 2.5 fb^{-1}

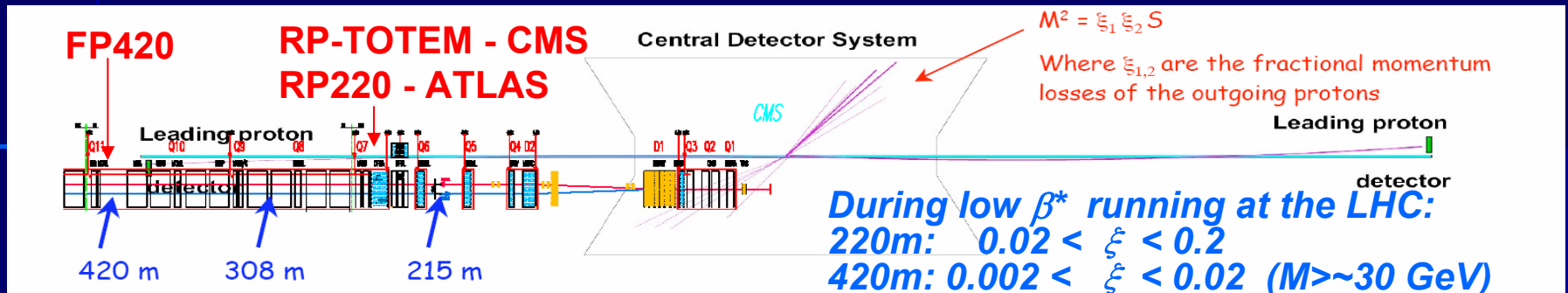
CDF e^+e^- $\gamma\gamma$ $\mu\mu, J/\psi, \psi', \chi_c$ Y Di-jets **LHC, FP420/220** Conclusions

Forward Detectors at the LHC



CDF e^+e^- $\gamma\gamma$ $\mu\mu, J/\psi, \psi', \chi_c$ Y Di-jets **LHC, FP420/220** Conclusions

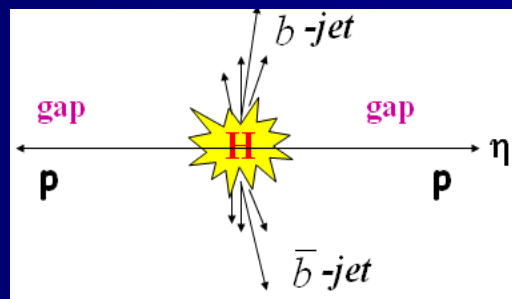
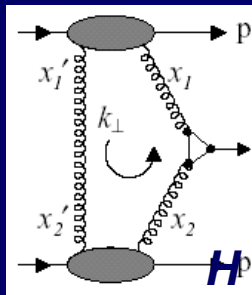
Proton Tagging with FP420 & RP220



- **Main physics aim is Exclusive Central Production - $pp \rightarrow p + X + p$**
 - Higgs boson by DPE, New (SUSY) physics, QCD/Diffractive Physics studies, photon photon physics, photoproduction
- **Detector Requirements:**
 - Detectors close to the beam – edgeless (Si) detectors & rad. hard
 - Resolution $5\mu\text{m}$ for track displacement, $1\mu\text{rad}$ for angle to beam
 - Suppress pile-up background with UF ToF detectors ($\sim 10\text{ps}$ res.)
- **R&D advanced – all TDRs submitted by the end 2008**

EG - Exclusive Higgs Production at the LHC

- **Exclusive central production at the LHC is a glue – glue collider with known beam energy**
- **Selection rules mean that central system is 0^{++}**
- **Tagging the protons gives central mass resolution $\sim \text{GeV}$**
- **Exclusive production of the Higgs is a benchmark.**



$$\sigma(pp \rightarrow p H p) : \\ \sim 2-10 \text{ fb (SM)} \\ \sim 10-100 \text{ fb (MSSM)}$$

- **CP violation in the Higgs sector studied using azimuthal correlation between the tagged protons**
- **Proton tagging may be the discovery channel in certain regions of the MSSM.**

Conclusion

- **At CDF** we have observed exclusive production via:
 - Two-photon interactions (e^+e^- , $\mu^+\mu^-$)
 - QCD Central Exclusive Production (DPE) ($\gamma\gamma$, jetjet)
 - Photoproduction (γ -IP fusion) (J/ψ , ψ' , Y)
- **The 2-photon results** agree with LPAIR Monte Carlo
 - The way is open to use such events in the luminosity measurement at the LHC as well as the calibration of FP420/220
- **The TEVATRON results for $\gamma\gamma$ & jet jet** “agree” (~ 2) with Durham group predictions, leading credence to their predictions for the LHC Higgs X-sec
- **The LHC will not only be a p-p collider**, but also a: γ - γ collider; g-g (IP-IP) collider and a γ -IP collider
- **Proton tagging at the LHC with FP420+RP220/RP-TOTEM** promises an exciting exclusive physics program

Extra Slides

Tevatron Performance



$p\bar{p}$ collisions @ $\sqrt{s} = 1.96 \text{ TeV}$

$\mathcal{L}_{\text{inst}} = 20 \text{ to } 160 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$

$\overline{\Delta t}_{\text{bunch}} = 580 \text{ ns}$ radius = 1 km
36 bunches

$\sigma_{\text{inel}} = 60 \text{ mb}$

$\bar{n} = \sigma_{\text{inel}} \mathcal{L}_{\text{inst}} \overline{\Delta t}_{\text{bunch}}$

~ 1 to 6 interactions per crossing

**~25 interactions per crossing
at high lumi LHC**

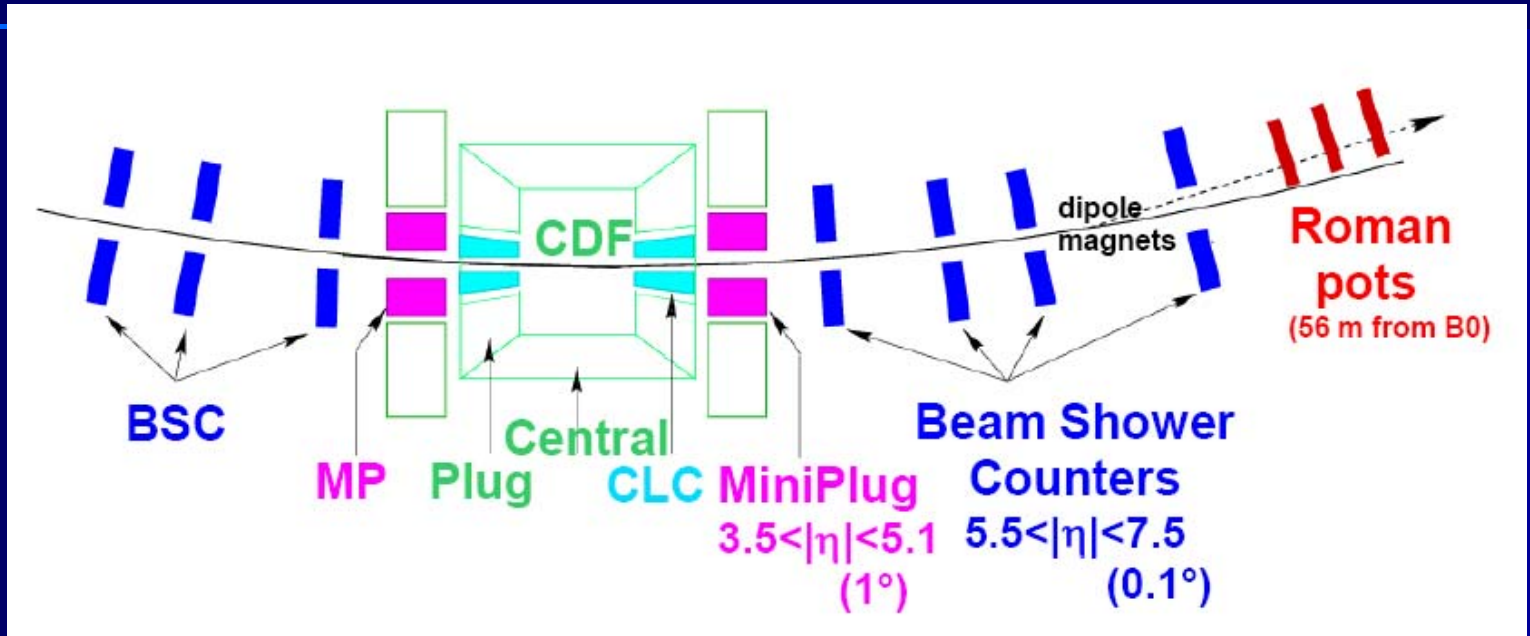
very important when searching for exclusive states without proton taggers

Collider Run II – anticipated $6 \rightarrow 7 \text{ fb}^{-1}$ by end FY09

Lumi delivered to CDF - 3.7 fb^{-1} about 3 fb^{-1} of data to tape

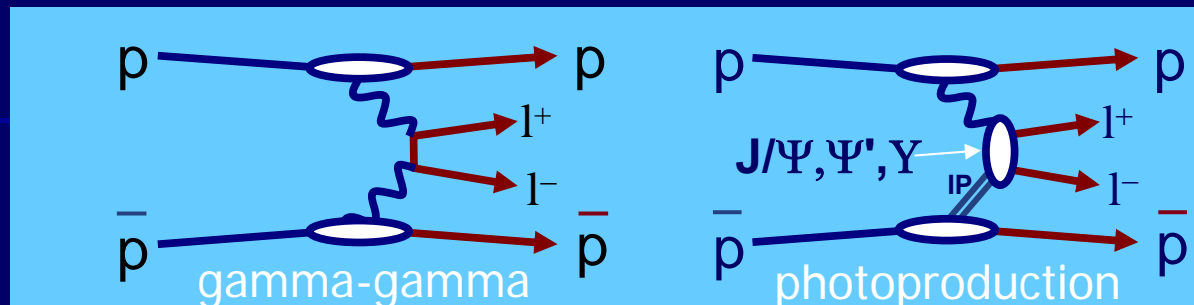
TEVATRON e^+e^- $\gamma\gamma$ $\mu\mu, J/\psi, \psi', \chi_c$ Y Di-jets LHC, FP420/220 Conclusions

CDF Forward Detector



RPS acceptance $\sim 80\%$ for $0.03 < x < 0.1$ and $|t| < 0.1$

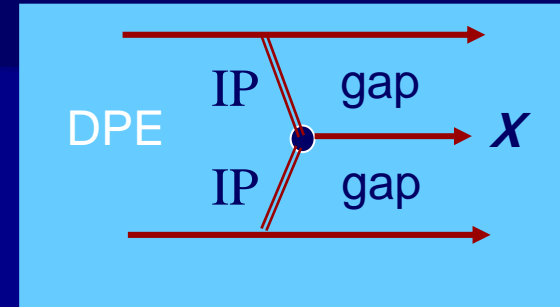
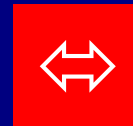
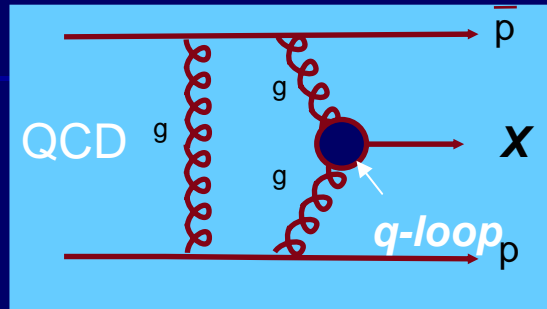
Motivation: for Exclusive Studies



■ Motivations to study exclusive lepton pair production at the Tevatron:

- Potential to make measure luminosity at the LHC with precision ~5 % or better as we have a relatively well known QED cross-section
- Can be used as a control sample for exclusive processes whose cross- sections are not well predicted ($\gamma\gamma$, χ_c , Higgs, ...)
- Used to calibrate forward proton spectrometers (FP420) at LHC
- Good place to search for the odderon
-

Motivation: for Exclusive Studies

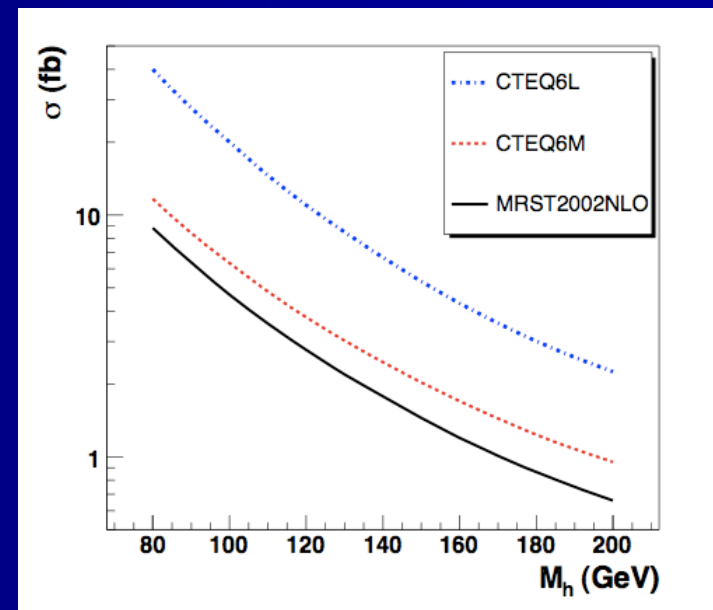


■ Motivations to study QCD Central Exclusive Production at the Tevatron:

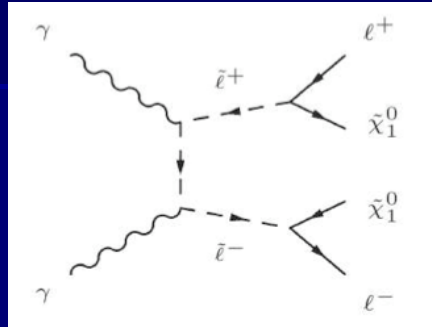
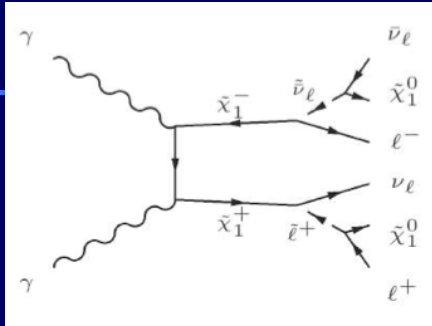
- Study exclusive di-jets
- Study χ_c (c -loop), χ_b (b -loop) production
- Study $\gamma\gamma$ production - the cleanest test of the theory of diffractive Higgs production
- Good training ground for LHC exclusive physics at higher masses

More on the Exclusive Higgs

- **Main uncertainties in the exclusive Higgs cross-section:**
 - Proton survival probability (Tevatron \rightarrow LHC) that could be pinned down with early LHC data on $pp \rightarrow p WW p$
 - PDF uncertainty
- **The Durham Group's (DG's) predictions for dijets & diphotons are confirmed within a factor of ~ 2 by CDF**
- **NB these processes are standard candles for exclusive Higgs production lending credence to the DG's predictions for the exclusive x-sec at the LHC**



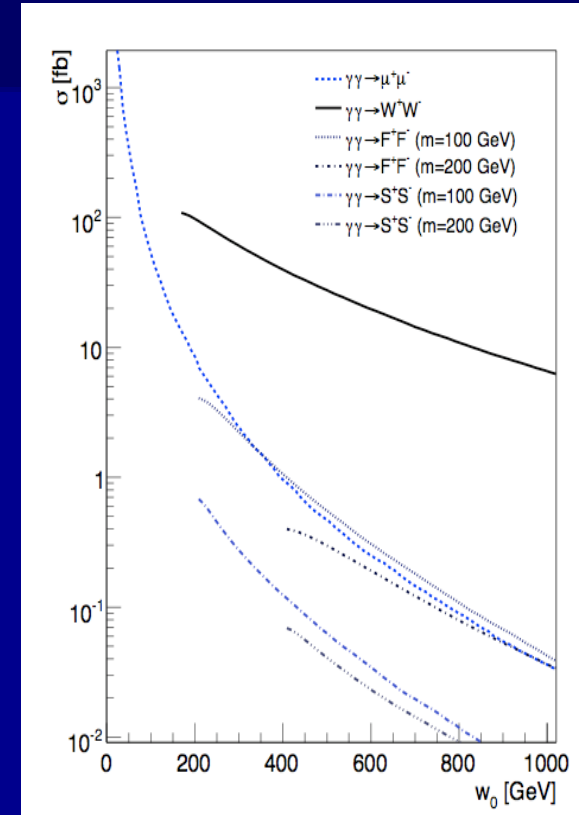
Photon-Photon Physics



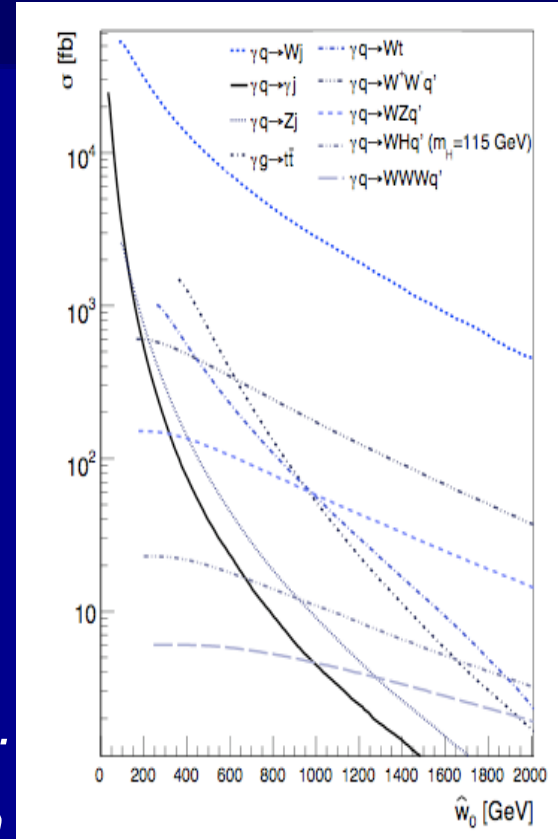
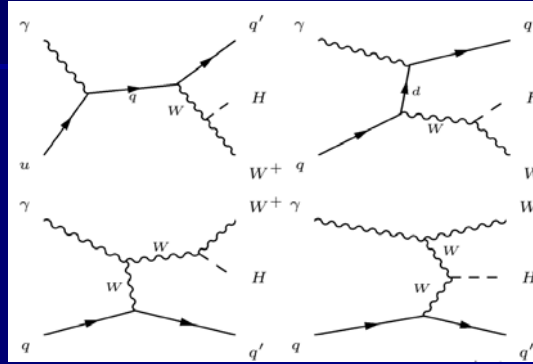
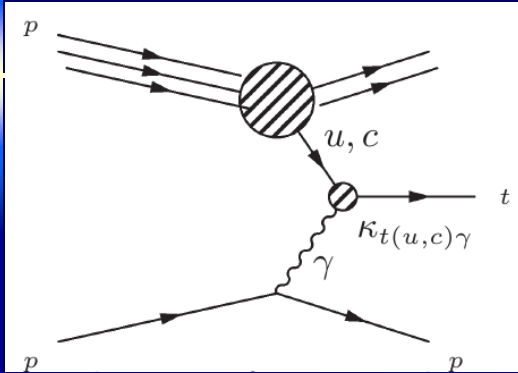
■ Extensive program of $\gamma\gamma$ -physics

- $\gamma\gamma \rightarrow \mu\mu, ee$ QED processes
- $\gamma\gamma \rightarrow$ QCD (jets..)
- $\gamma\gamma \rightarrow ZZ/WW$ anom. couplings
- $\gamma\gamma \rightarrow$ top pairs
- $\gamma\gamma \rightarrow$ Higgs
- $\gamma\gamma \rightarrow$ Charginos....

■ There is also an photoproduction study program.....



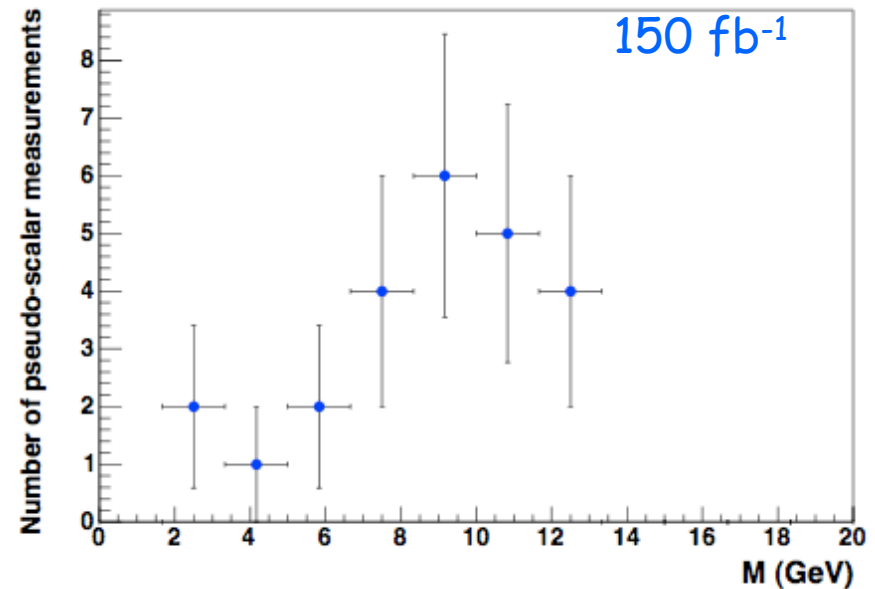
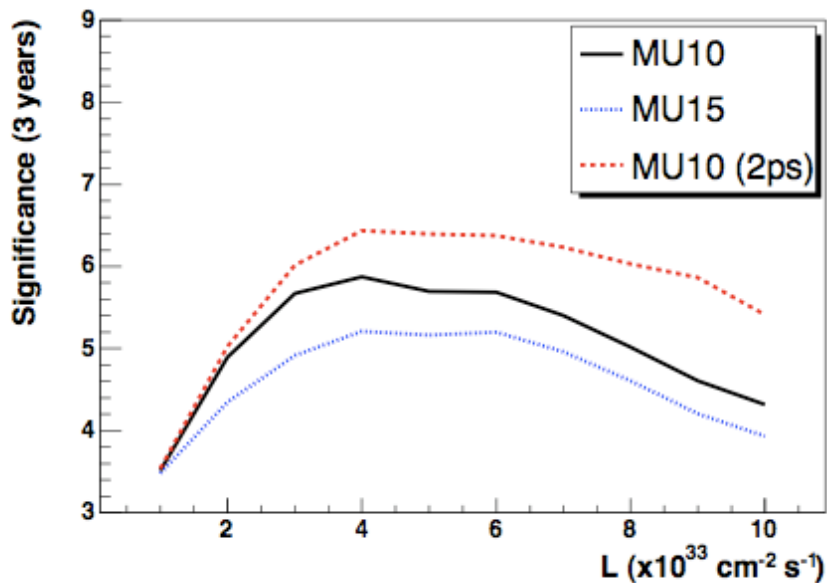
Photoproduction



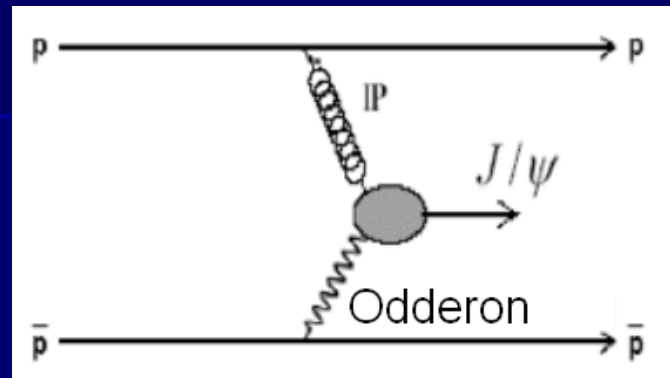
- **In photon-proton scattering eg:**
 - *WH mechanism in SM can be enhanced in some models – probably not a discovery channel.*
 - *Look for anomalous single top via FCNC.*
- **Exclusive photon-pomeron fusion studies will continue at higher mass**

$h \rightarrow aa \rightarrow \tau\tau\tau\tau$

Low mass higgs in NMSSM: If $m_a < m_b$ difficult (impossible) at standard LHC
J. Gunion: FP420 may be the only way to see it at the LHC

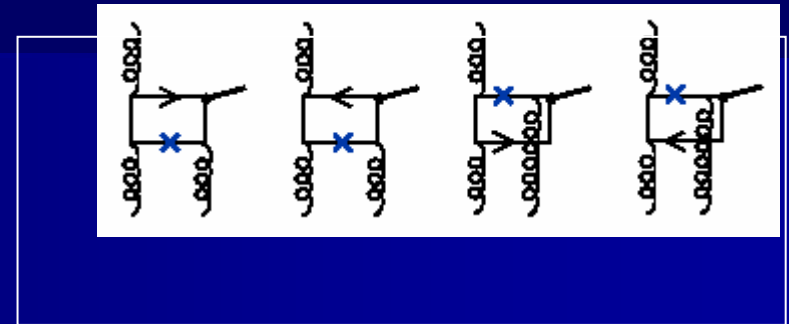
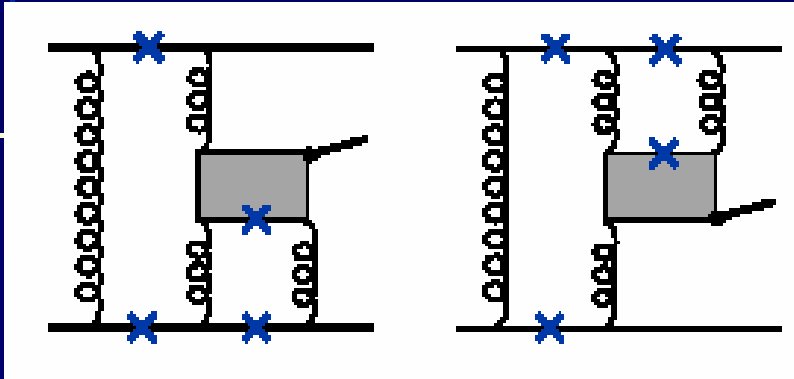


Exclusive Di-leptons – a Good Place to Search for the Odderon



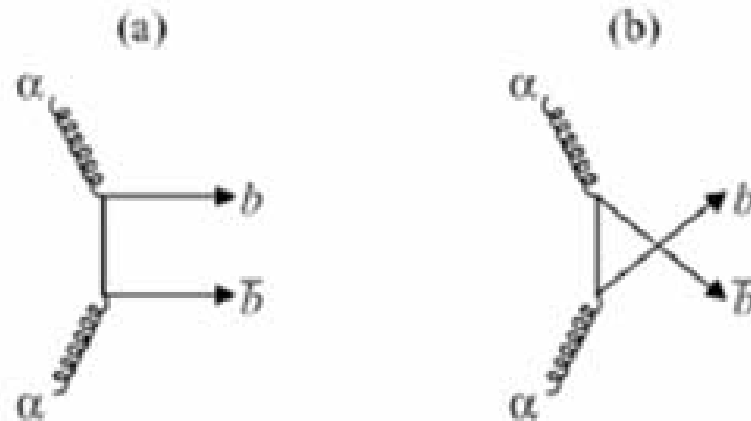
- *In perturbative QCD the lowest order prototype of the pomeron is the color neutral system of two gluons.*
- *The odderon is the C-odd partner of the pomeron - the hard odderon skeleton consists of three gluons in a color neutral state.*
- *Global fits of the available hh and $h\bar{h}$ data seem to establish that HE scattering dominated by exchange of the $C = P = +1$ Pomeron.*
- *If the Odderon exists it would contribute to the exclusive J/Ψ and Ψ' signal and be part of our signal*
- *The Odderon would contribute to J/Ψ , Ψ' , Y peaks unlike the χ_c background*

The Odderon



- *The color neutral gluon systems, exchanged at high energy scattering processes, can be classified wrt their C parity. The most important one is C-even system with quantum numbers of vacuum i.e. the pomeron.*
- *In perturbative QCD the lowest order prototype of the pomeron is the color neutral system of two gluons.*
- *The odderon is the C-odd partner of the pomeron - the hard odderon skeleton consists of three gluons in a color neutral state.*
- *One would naively expect a suppression by a power of the coupling constant s for the additional gluon). It is not clear, however, why the contribution of the odderon is so small that it has not been definitely observed by any experiment.*

b-jet Suppression



$J_2=0 \rightarrow$ for colour singlet $b\bar{b}$ production, the born level contributions of a) and b) cancel in the limit $m_b \rightarrow 0$