Exclusive Leptonic & Photonic Final States at the TEVATRON

Low-x Meeting, Crete
July 2008

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Tevatron Performance

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

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

$\overline{\Delta t}_{bunch} = 580$ ns

radius = 1 km
36 bunches

$\sigma_{inel} = 60$ mb

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

~ 1 to 6 interactions per crossing
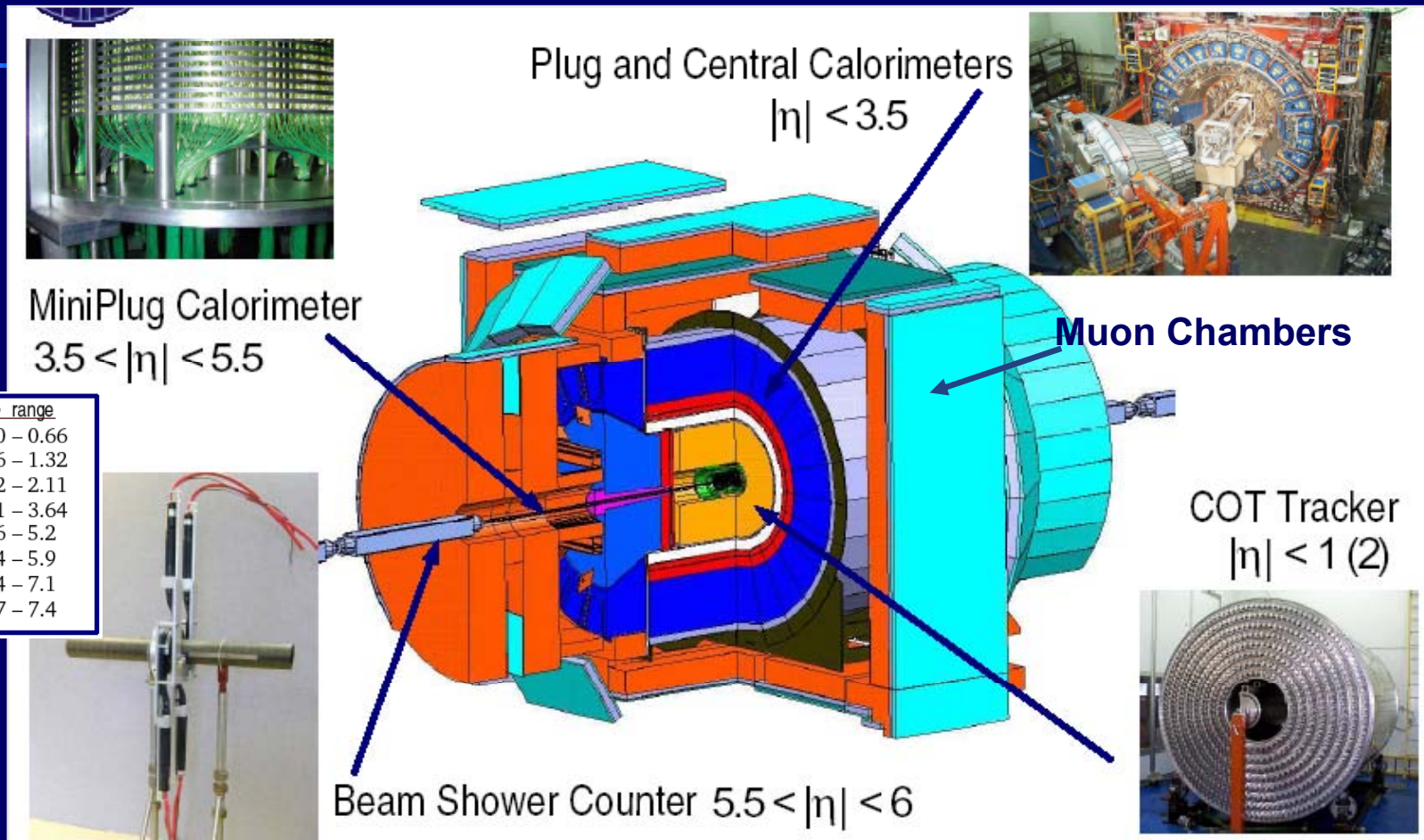
~25 interactions per crossing at high lumi LHC

very important when searching for exclusive states without proton taggers

Collider Run II – anticipated 6$\rightarrow$7 fb^{-1} by end FY09
Lumi delivered to CDF - 3.7 fb^{-1} about 3 fb^{-1} of data to tape

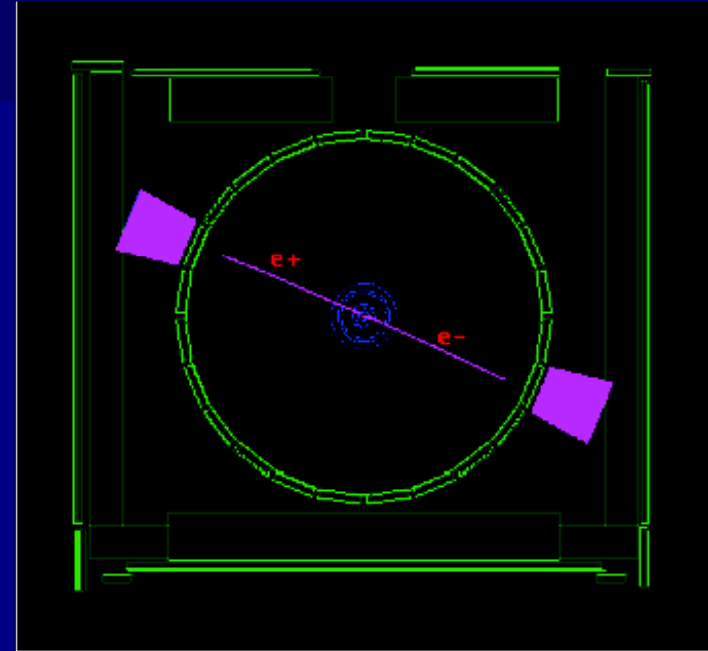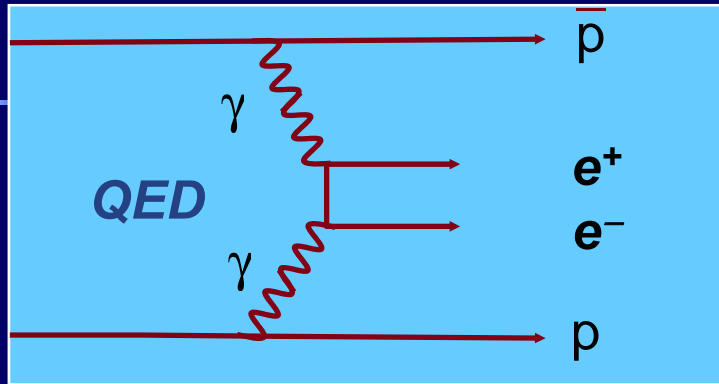CDF e^+e^- $\gamma\gamma$ $\mu^+\mu^-$/ **Charmonium   Bottomonium   Conclusions**

CDF Detector

MiniPlug Calorimeter
$3.5 < |\eta| < 5.5$

Plug and Central Calorimeters
$|\eta| < 3.5$

Muon Chambers

COT Tracker
$|\eta| < 1 (2)$

Beam Shower Counter $5.5 < |\eta| < 6$

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

Exclusive e⁺e⁻ Production (1)

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

Exclusive e^+e^- Production (2)

- **Integrated luminosity → 532 $\pm$ 32 pb^{-1}**
- **DIFF_DIPHOTON Trigger:**
  - *2 EM clusters with E_T>4GeV 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 GeV and $|\eta|$ < 2*
  - *16 e^+e^- candidates selected*
- **Backgrounds 1.9 $\pm$ 0.3 events:**
  - *dijet fake (0.0 +0.1 -0.0)*
  - *cosmic (negligible)*
  - *inclusive distribution (0.3+/-0.1)*
  - *dissociation (1.6 $\pm$ 0.3) (these are also gg →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***
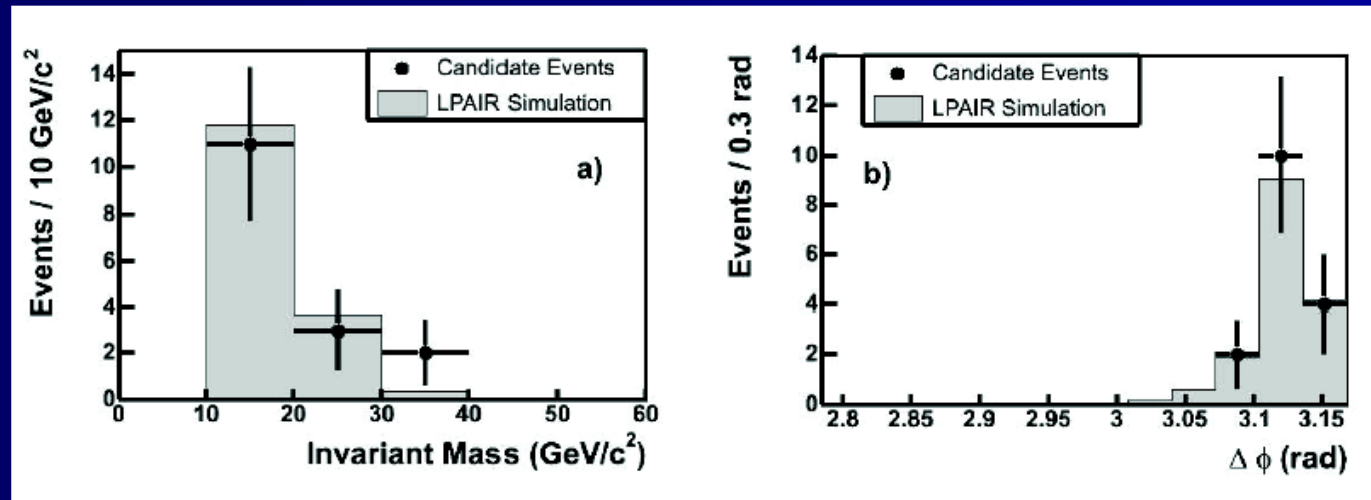
- ***Cross-section for $\gamma\gamma \rightarrow$ e⁺e⁻ LPAIR theory:***
$$\sigma_{LPAIR} = 1.71 \pm 0.01 \ pb$$

Exclusive e⁺e⁻ Production (4)

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

- **Agrees with LPAIR theory:** $\sigma_{LPAIR} = 1.71 \pm 0.01\ pb$

- **Prob. of 1.9 → ≥16 = 1.3×10⁻⁹ - a 5.5σ "observation"**

- **This is the first observation** of exclusive two-photon produced e⁺e⁻ interactions in p-p(bar) 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
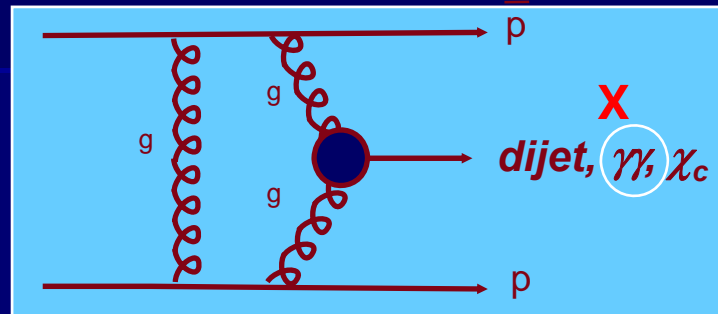
# Exclusive $\gamma\gamma$ Study (1)

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**
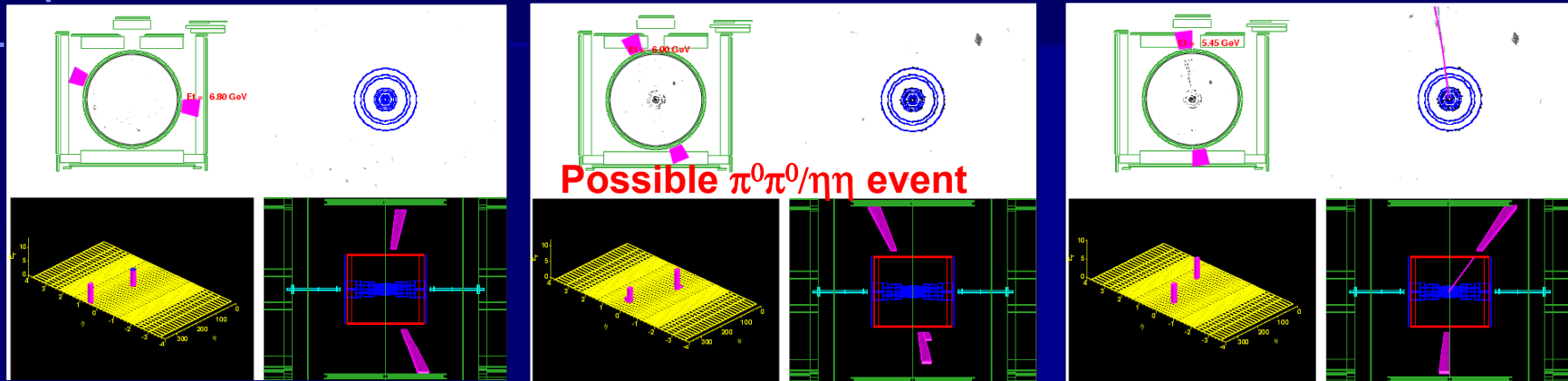
Exclusive $\gamma\gamma$ Study (2)

- **3 candidate events found in 532 pb^{-1} of Run II data.**

- **Background 0.09 $\pm$ 0.04 events** *(mostly misid. of excl.)*

- **Good agreement on kinematics with ExHume MC**
  (Monk & Pilkington. hep-ph/0502077)
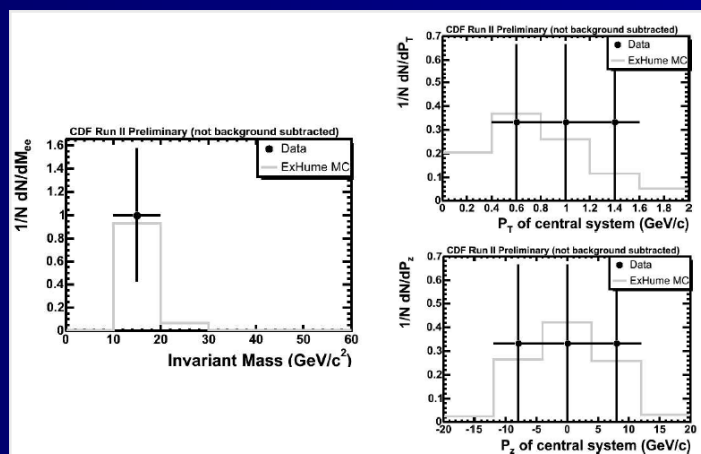
- **0.8 $^{+1.6}_{-0.5}$ events predicted from ExHuME MC**

Exclusive $\gamma\gamma$ Candidates (1)

Possible $\pi^0\pi^0/\eta\eta$ event

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

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

Exclusive $\gamma\gamma$ Candidates (2)

- **The upper limit of the cross-section pp --> 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] A. Anastassov,[52] K. Anikeev,[17] A. Annovi,[19] J. Antos,[14] M. Aoki,[55] G. Apollinari,[17] T. Arisawa,[57] A. Artikov,[15]

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

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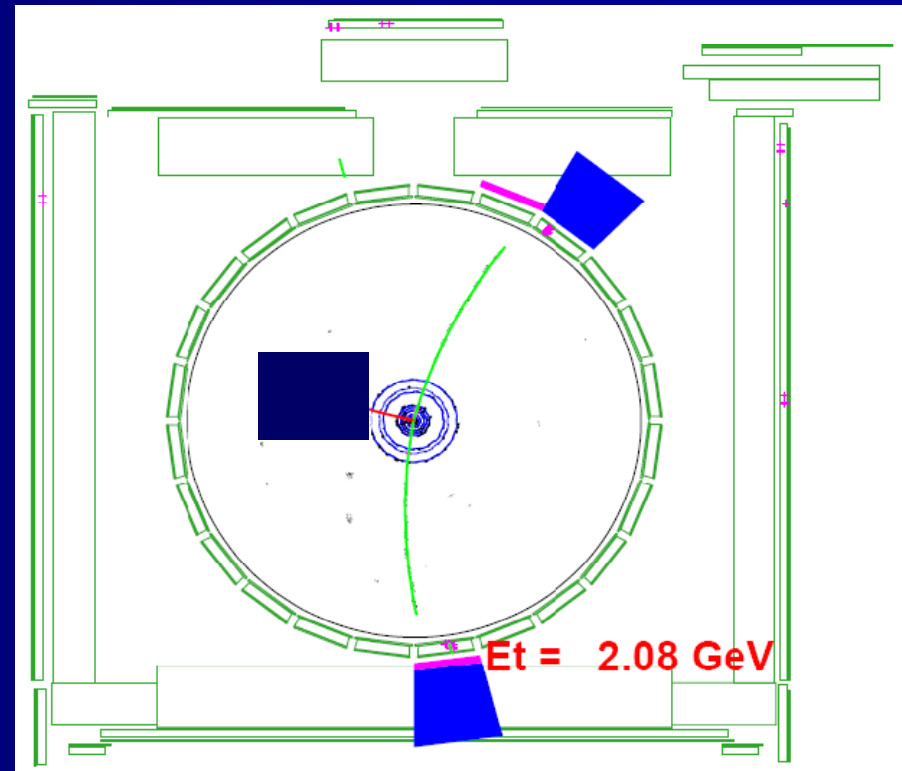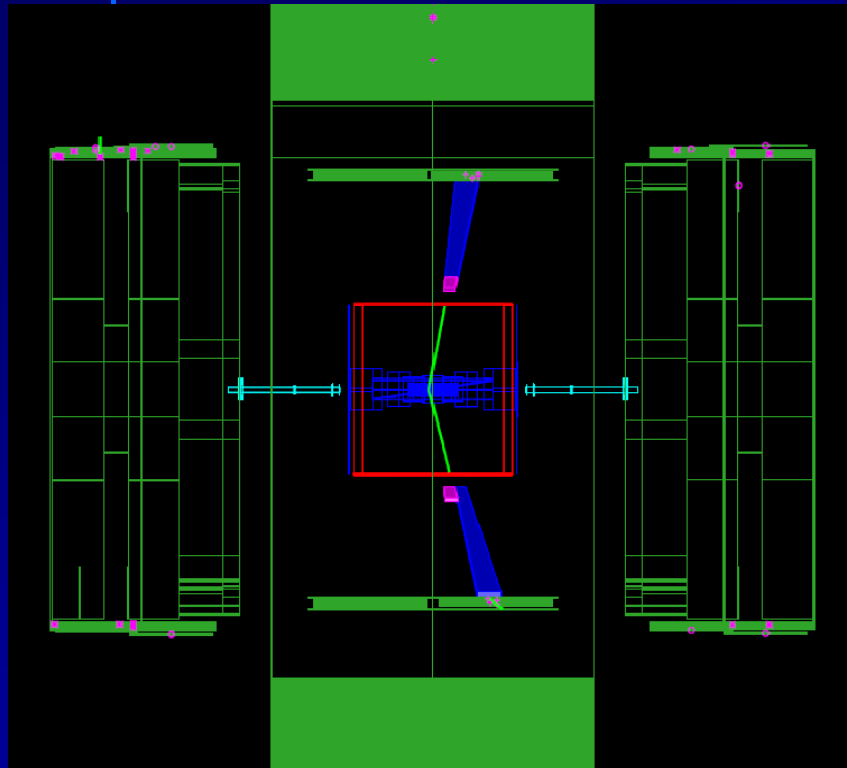
- **Trigger (DIFF_CHIC_CMU1.5_PT1.5_TRK):**
  - *BSC Gap, east & west*
  - *muon + track ($p_t > 1.3$; $|\eta| < 1.2$)*
  - *$2.7 < M(muon + track) < 4.0$ GeVc^2*
- **The existing sample** *corresponds to a lumi of 1.48 fb^{-1}*
- **Also higher mass muons have just been stripped**, *(trigs with $p_t(\mu)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

CDF e^+e^- $\gamma\gamma$ $\mu^+\mu^-$/ **Charmonium**   **Bottomonium**   **Conclusions**

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

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

Et = 2.08 GeV

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

- ***Integrated luminosity – 1.48 fb⁻¹***

- ***Offline cuts***
  - *Loose quality cuts*
  - *No other activity in the events (to an |η| of 7.4)*
  - *$P_T(\mu) > 1.4$ GeV/c & $|\eta(\mu)| < 0.6$*
  - *Cosmic ray cuts (abs (delta_TOF) < 3 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 μ⁺μ⁻ Candidates (1)

CDF RunII Preliminary

Invariant Mass Exclusive μ⁺μ⁻

334 signal events for period 1-11
Integrated Luminosity: 1.48 fb-1

Continuum

J/ψ

ψ'

Events per 10MeV/c²

M(μ⁺μ⁻) (GeV/c²)
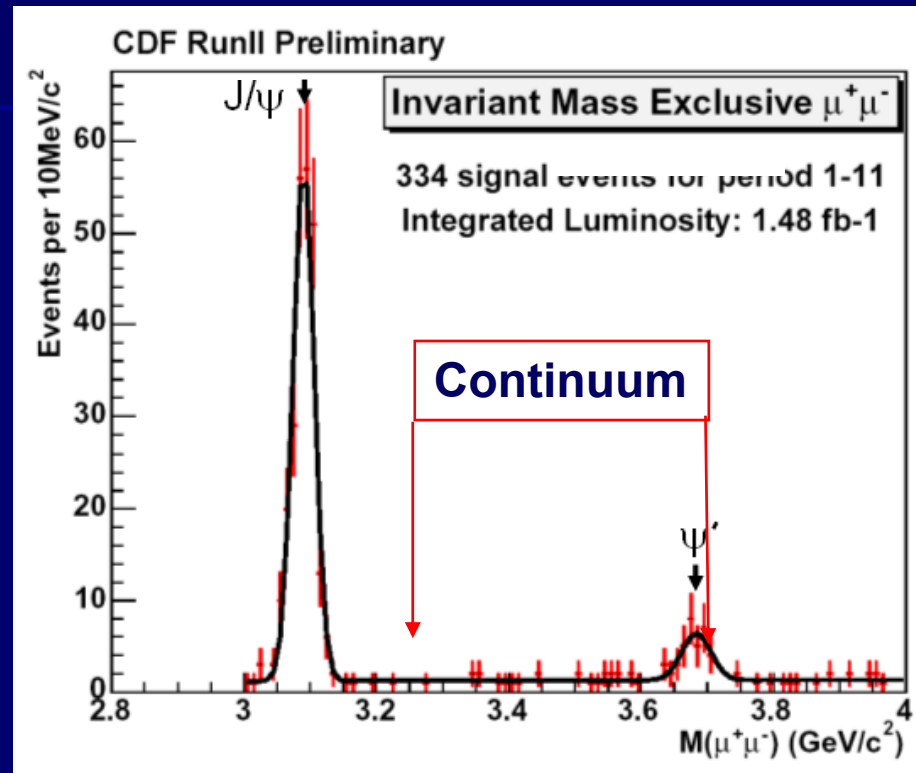
Many candidate events (334) have been found (CDF-II Preliminary)

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.

CDF   e⁺e⁻   γγ   μ⁺μ⁻/ **Charmonium**   **Bottomonium**   **Conclusions**

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

The $\gamma\gamma \to \mu^+\mu^-$ continuum
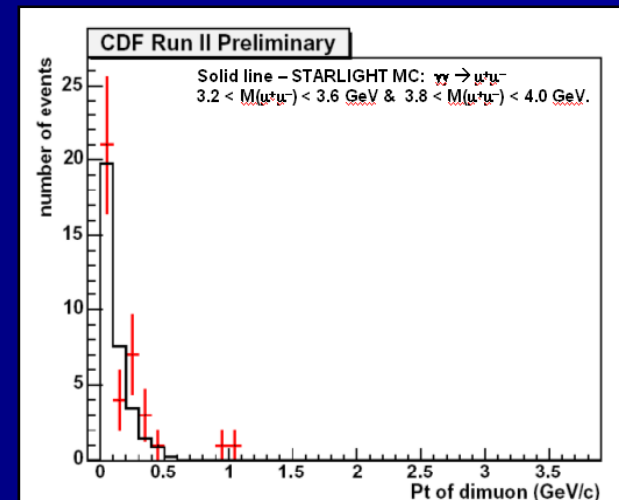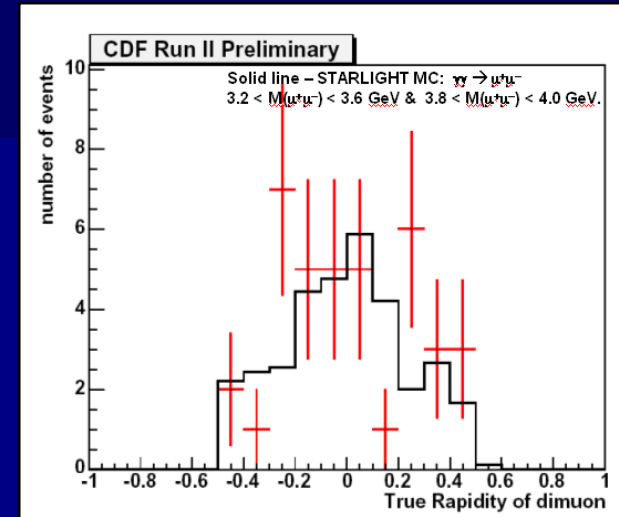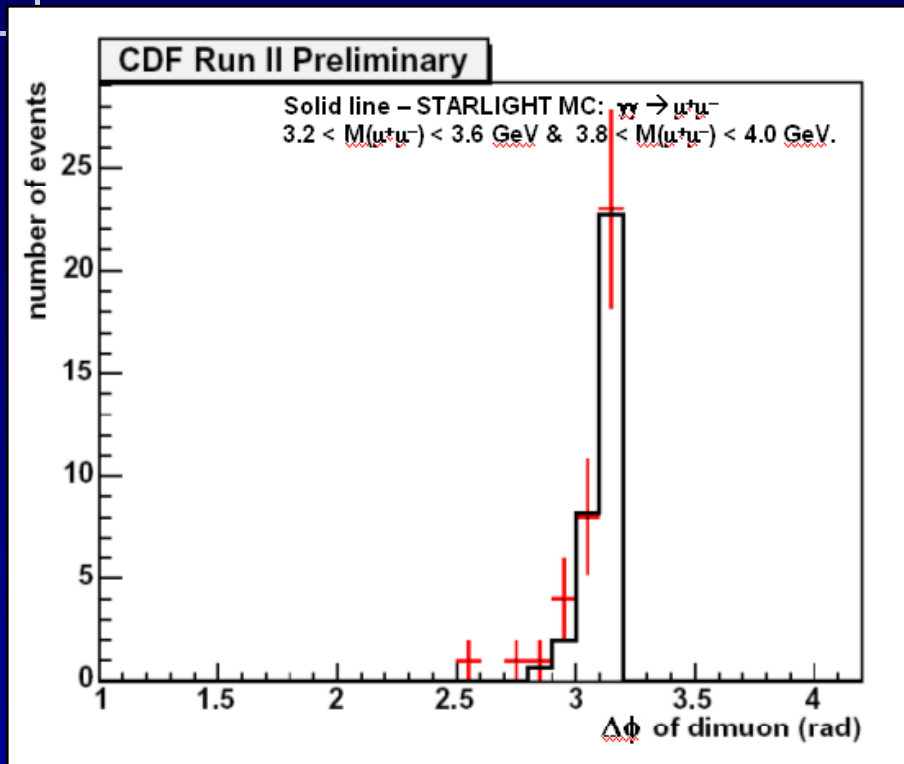
- *Good agreement on kinematics with STARLIGHT MC (Klein & Nystrand)*

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/ψ** $\rightarrow$ $\mu^+\mu^-$ **peak** - *with excl. cuts (using fits to E_t & $\Delta\phi$ dists)*

- *We are working on this …watch this space*
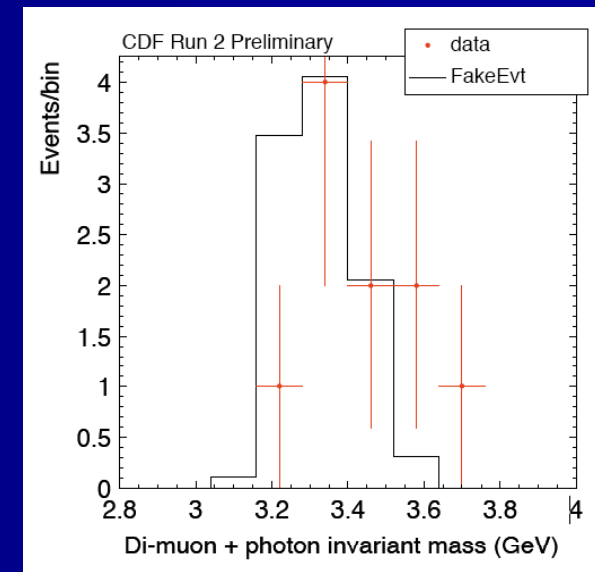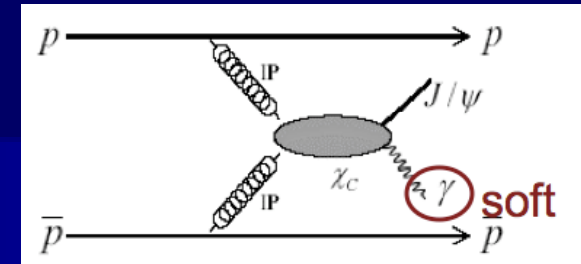
BR ($\chi_c^0 \rightarrow J/\psi + \gamma \rightarrow \mu^+\mu^-\gamma$

x no other interaction x acceptance (trig) $\Rightarrow$ *few pbs*

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

- **Find Exclusive events using**
    - *Number of associated tracks = 0*
    - *Kinematics: $\Delta\phi \approx 180^o$, $\Delta p_T \approx 0$, (or $\Sigma P_T \approx 0$)*

- **Trigger: 2 central muons with p_T > 4 GeV/c**

- **L = 890/pb^{-1} ~ 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.*

Invariant Mass - Upsilon Region

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

Branching ratios for μ+μ- channels:

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

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

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

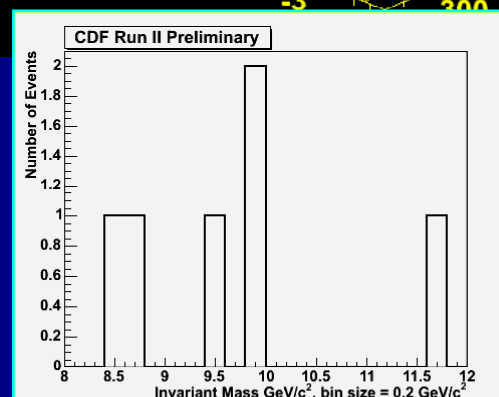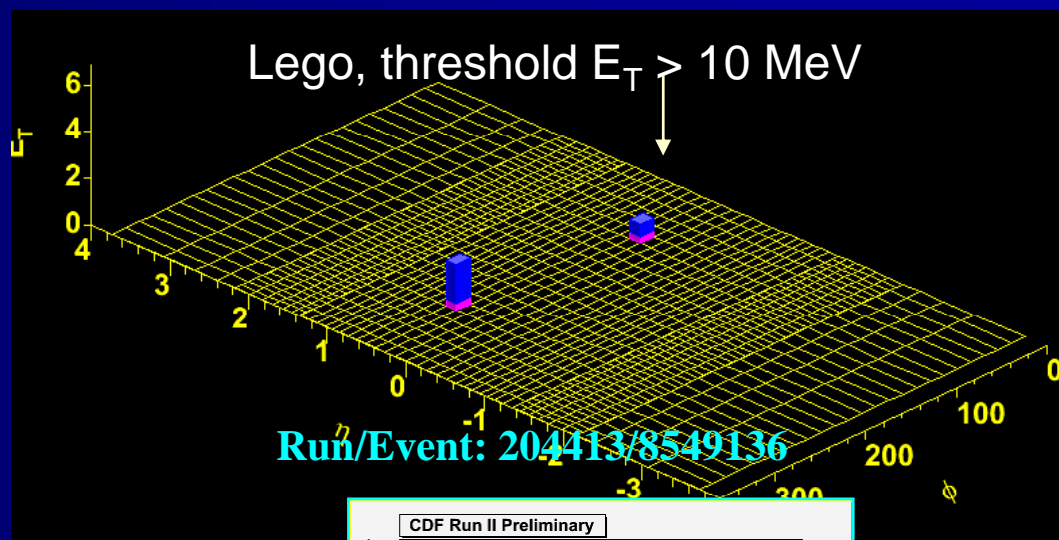Clearly visible peaks
Y(1s) and Y(2s),
perhaps Y(3S) too.
+ continuum

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

Superclean Upsilon

Lego, threshold $E_T > 10$ MeV

Run/Event: 204413/8549136

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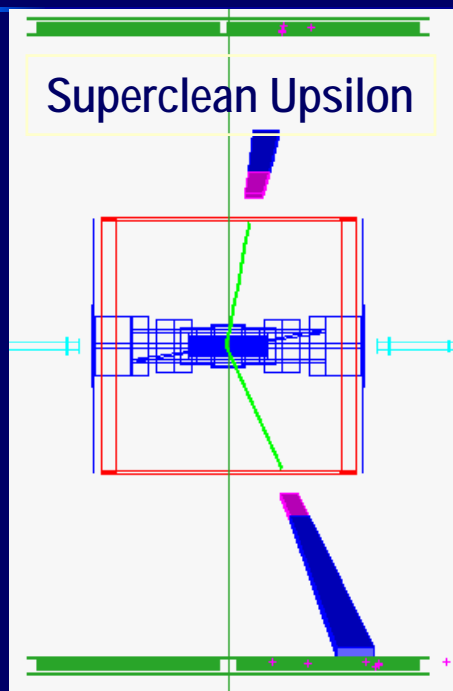
145 events in 8 – 12 GeV region
→6 events + 4 M($\mu^+\mu^-$) > 12 GeV.
(Most of reduction is killing pile-up)

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, lending 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

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

Plug and Central Calorimeters $|\eta| < 3.5$

MiniPlug Calorimeter $3.5 < |\eta| < 5.5$

Muon Chambers

COT Tracker $|\eta| < 1\ (2)$

Beam Shower Counter $5.5 < |\eta| < 6$
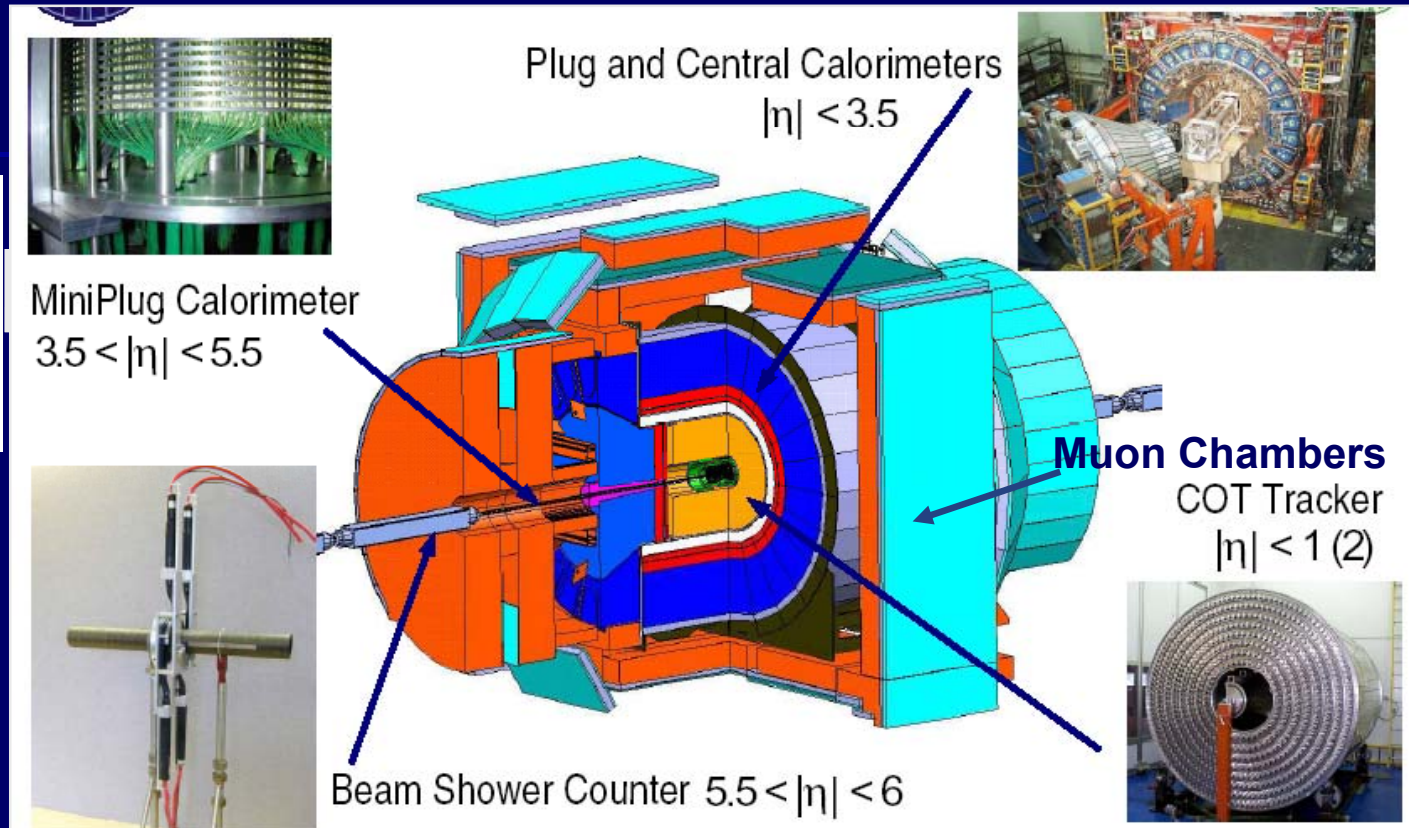
- **A Roman Pot deployed detector** is placed on one side of CDF at 66m from the IP. (RPS acceptance ~80% for 0.03 < x < 0.1 and |t| < 0.1)

Central Exclusive Physics

Central state

Proton/antiproton does not break up during interaction

> 3 rap-gap

$\gamma\gamma$, γ-IP, IP-IP

> 3 rap-gap

Proton/antiproton does not break up during interaction
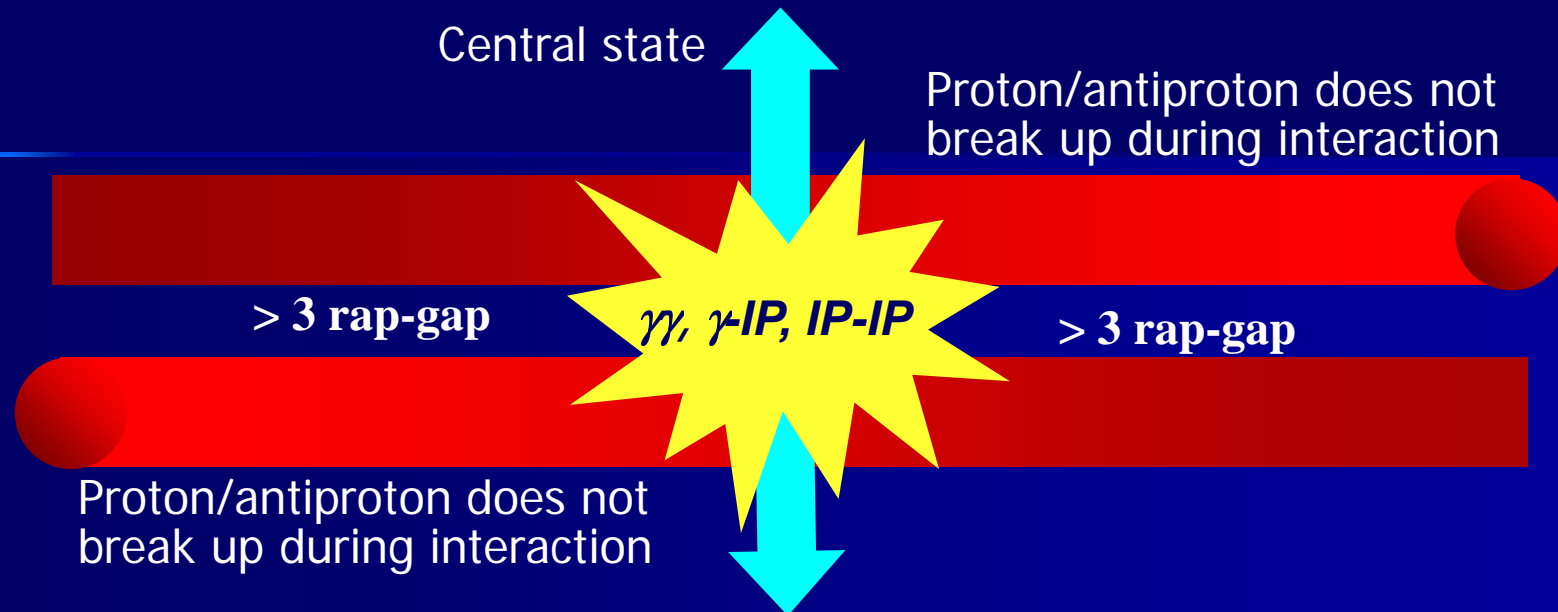
… both protons coherently scattered. Central state fully specified and measured, unlike "inclusive" production:

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

CDF   e⁺e⁻ $\gamma\gamma$ $\mu^+\mu^-$/ **Charmonium**   **Bottomonium**   **Conclusions**

Exclusive Di-jet Search
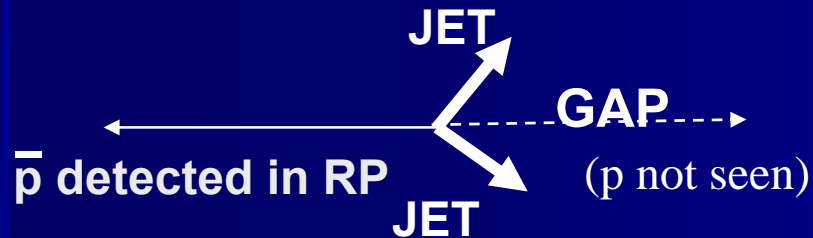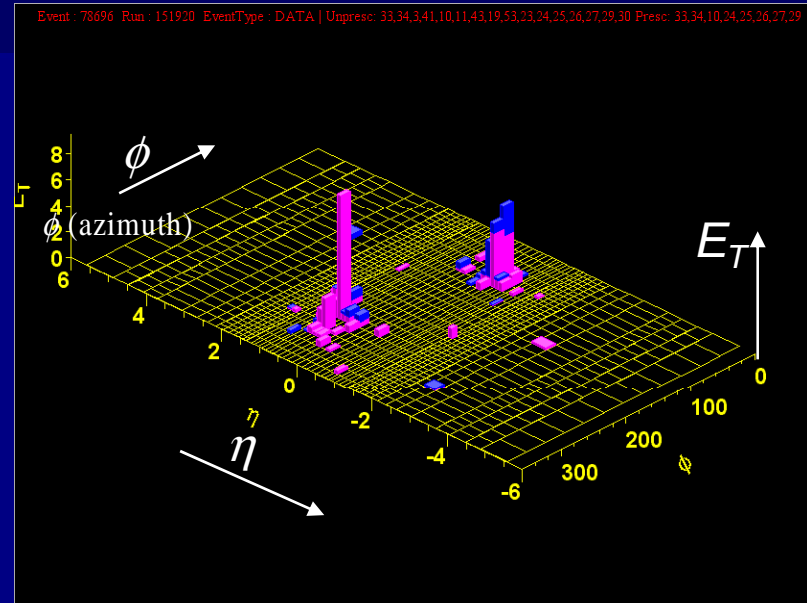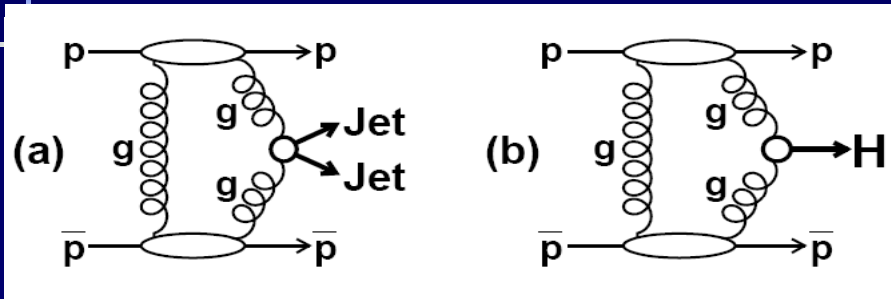
- **_Exclusive di-jets 2 jets + nothing else_** - *no pile-up essential thus lower lumi running*

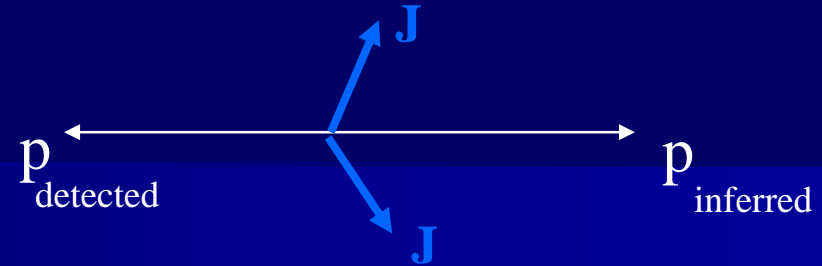- **_Initial sample includes_** *two high E_T (>10 GeV/c²) jets with a 3rd jet with E_T< 5 GeV/c² with 3.6 < η_{gap} < 5.9*

Exclusive Di-jet Search

$R_{jj} = M_{jetjet}/M_{CENTRAL} > 0.8$
(to be "exclusive")

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

J

$p_{detected}$ $p_{inferred}$

J

CDF Run II Preliminary

$F_{excl} = 15.0 \pm 1.2 \%$
(stat. only)

- DPE data (stat. only)
- POMWIG: CDF⊕H1
- ExHuME
- Best Fit to Data

$3.6 < |\eta_{gap}| < 5.9$
$E_T^{jet2} > 10 \text{ GeV}$
$E_T^{jet3} < 5 \text{ GeV}$

ExHuME: MC with exclusive di-jets.

$R_{jj} = M_{jj} / M_X$

CDF Run II Preliminary

DPE data (SVT)
Systematic Uncertainty

$E_T^{jet}(\text{RAW}) > 10 \text{ GeV}$
$|\eta_{jet}| < 1.5$

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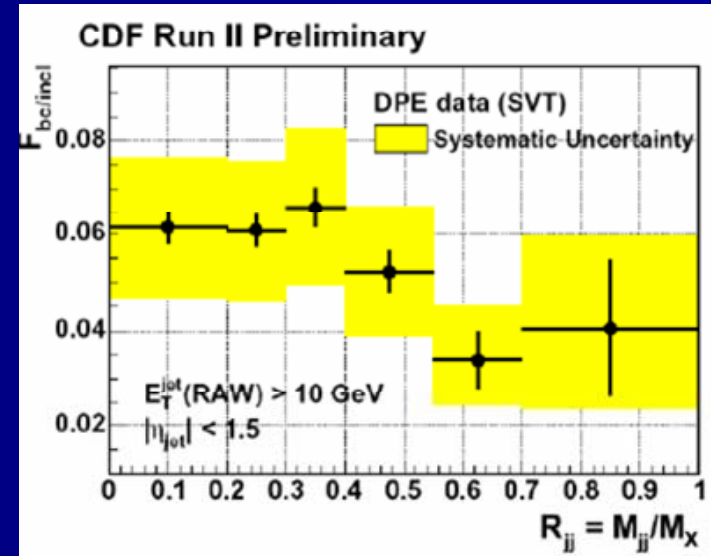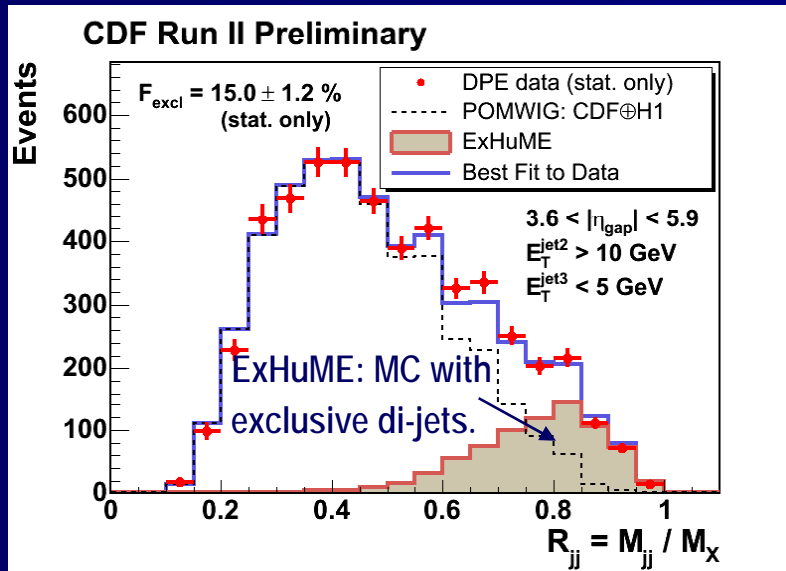
***Apparent b-jet suppression** as di-jets become exclusive
(Theoretically $\Rightarrow$ 0 as Rjj $\Rightarrow$ 1, J_z=0 rule)*

Exclusive Di-jet Cross-section
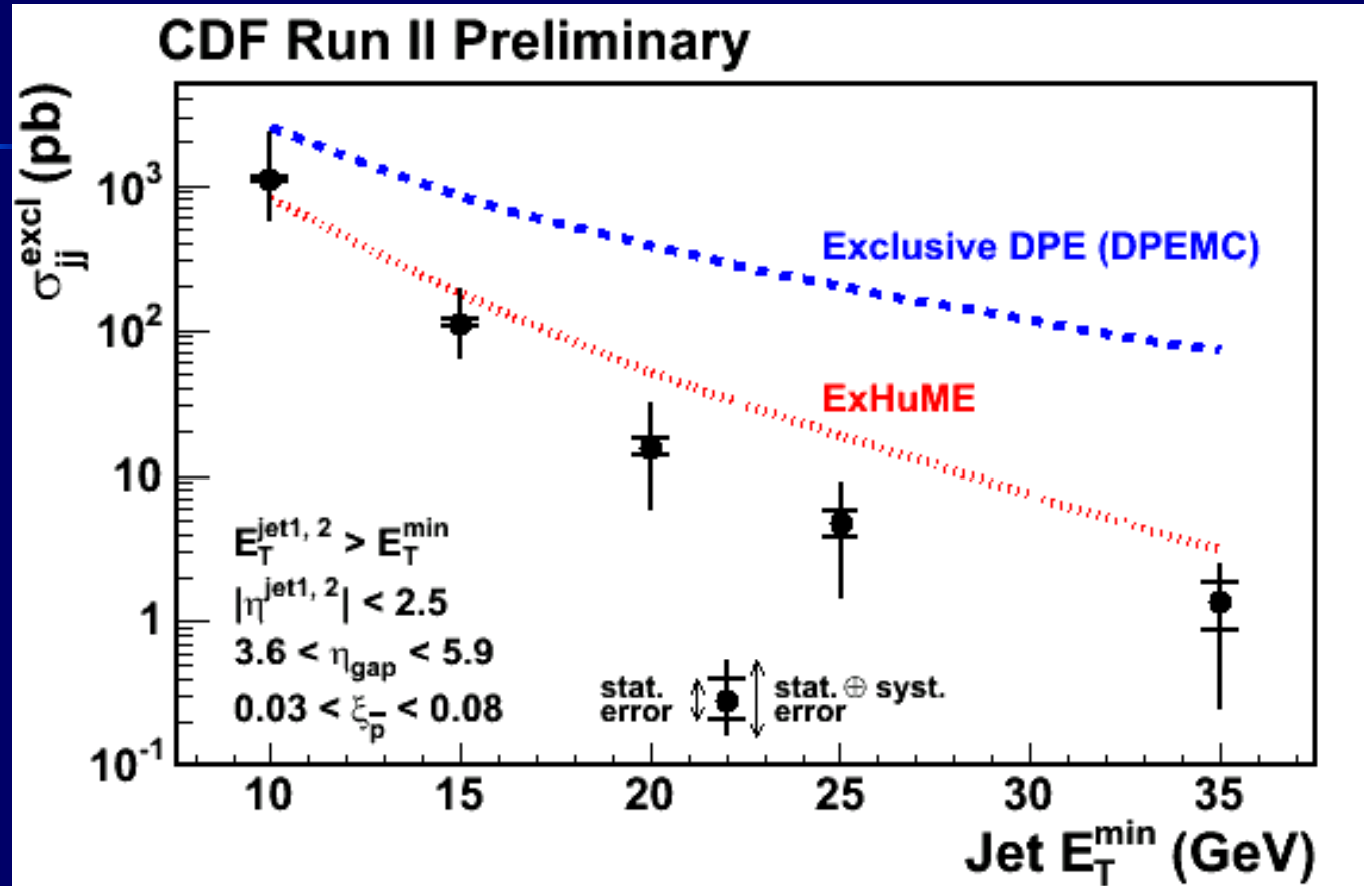
ExHuME (KMR):based on LO pQCD)   DPEMC: based on Regge theory

The LHC Startup

Forward Detectors at the LHC

Proton Tagging with FP420 & RP220

FP420

RP-TOTEM - CMS
RP220 - ATLAS

Central Detector System

$M^2 = \xi_1 \xi_2 S$

Where $\xi_{1,2}$ are the fractional momentum losses of the outgoing protons

Leading proton

CMS

detector

Leading proton

detector

During low β^* running at the LHC:
220m: 0.02 < ξ < 0.2
420m: 0.002 < ξ < 0.02 (M>~30 GeV)

420 m   308 m   215 m
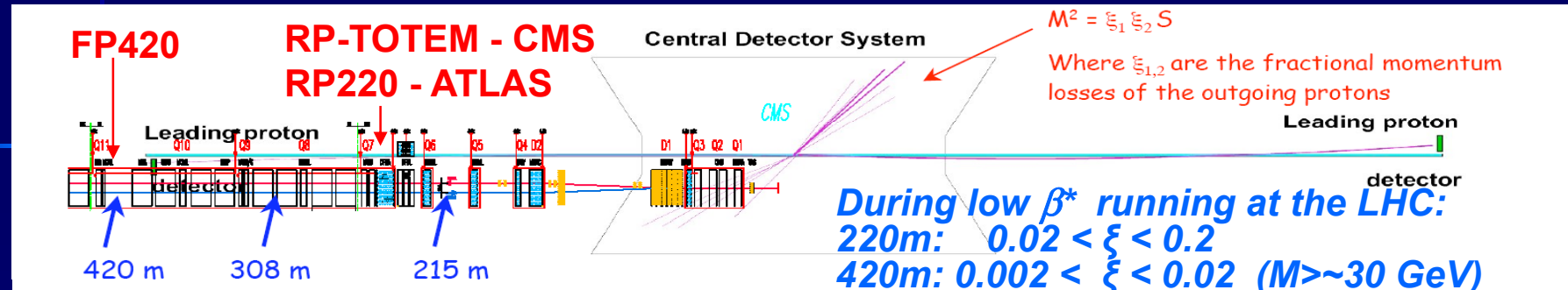
- **Main physics aim is Exclusive Central Production -**
  pp → p + X + p
  - *Higgs boson by DPE , New (SUSY) physics, QCD/Diffractive Physics studies, photon photon physics, photoproduction*

- **Detector Requirements:**
  - *Detectors close to the beam – edgeless (Si) detectors & rad. hard*
  - *Resolution 5μm for track displacement, 1μrad for angle to beam*
  - *Suppress pile-up background with UF ToF detectors (~10ps res.)*

- **R&D advanced – all TDRs submitted by the end 2008**

CDF   e⁺e⁻   γγ   μμ,J/ψ,ψ',χc   Υ   Di-jets   LHC,FP420/220   Conclusions
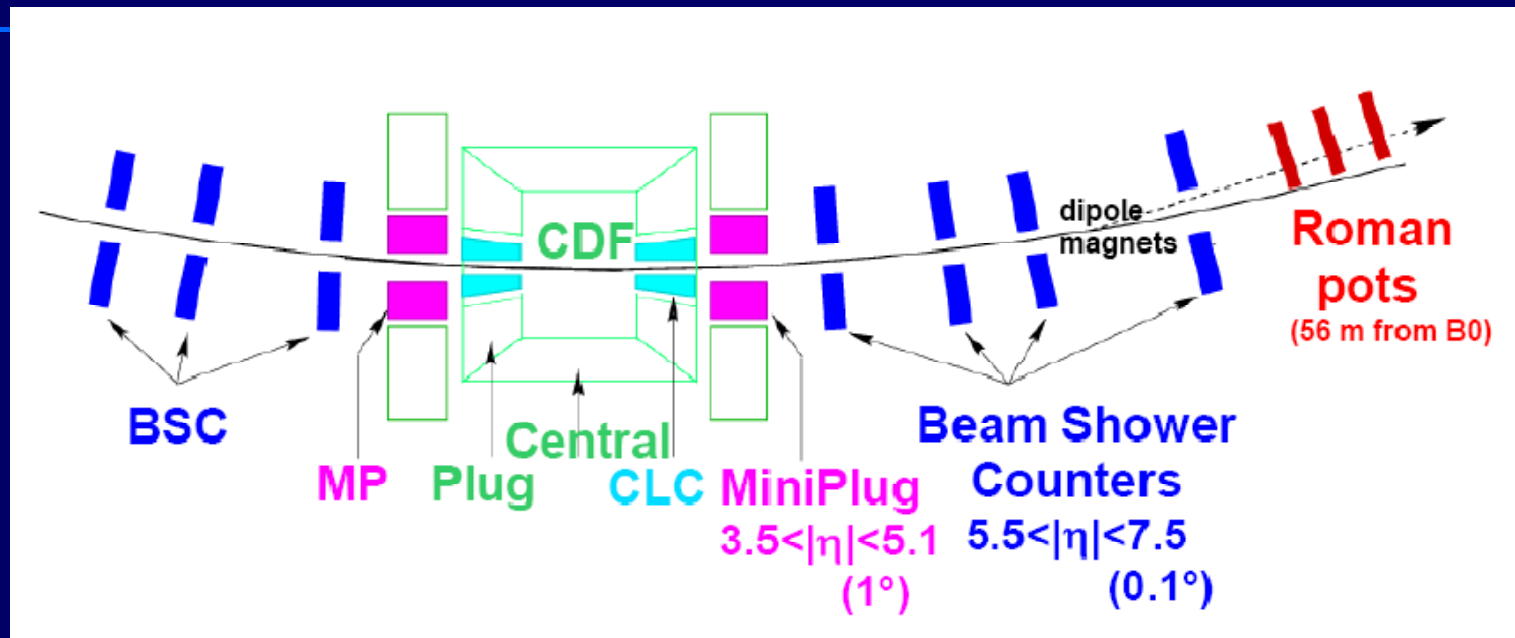
EG - Exclusive Higgs Production at the LHC

- **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 ~GeV*

- **Exclusive production of the Higgs** *is a benchmark.*
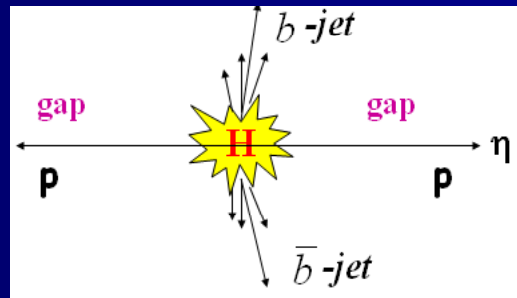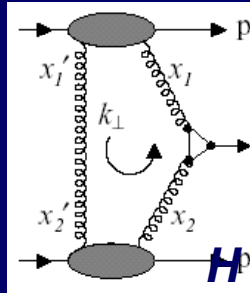
$\sigma(pp \to p\, H\, p) :$
~ 2-10 fb (SM)
~10-100 fb (MSSM)

- **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.*

CDF Forward Detector

RPS acceptance ~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
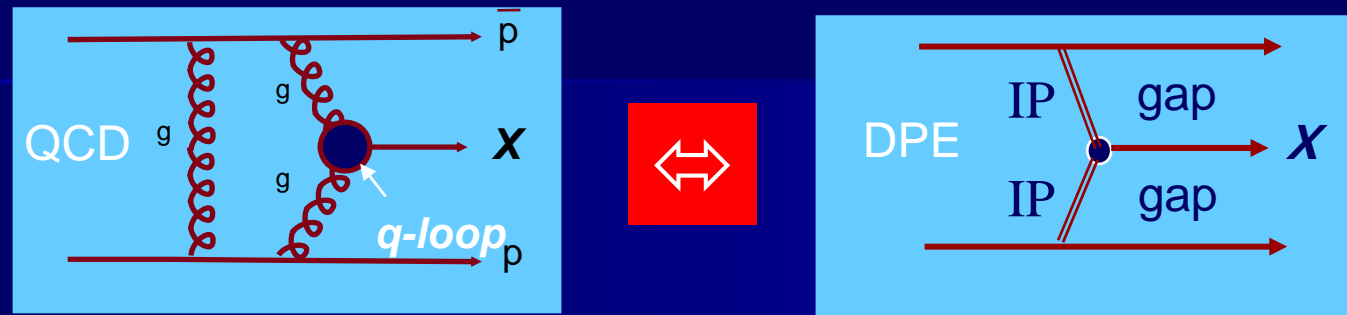
- **Motivations to study QCD Central Exclusive Production at the Tevatron:**

  - 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

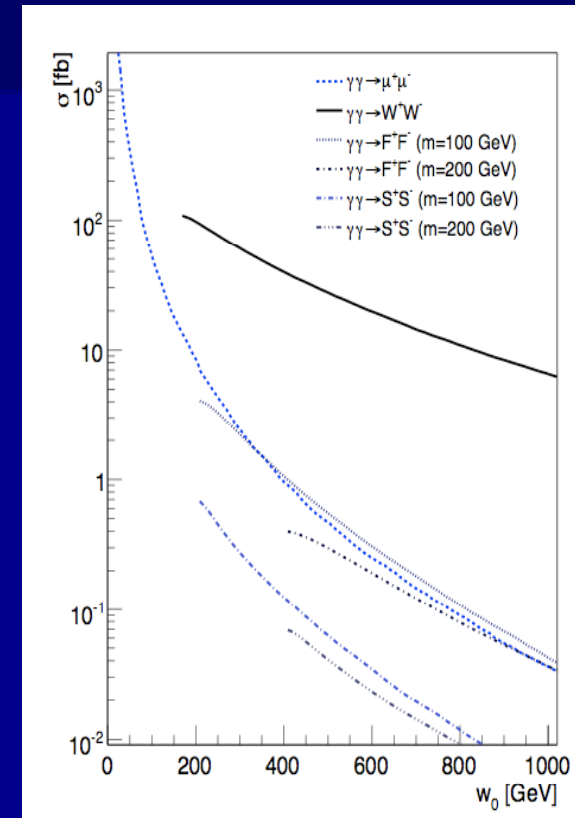- **NB these processes are standard candles** for exclusive Higgs production lending credence to the DG's predictions for the exclusive x-sec at the LHC
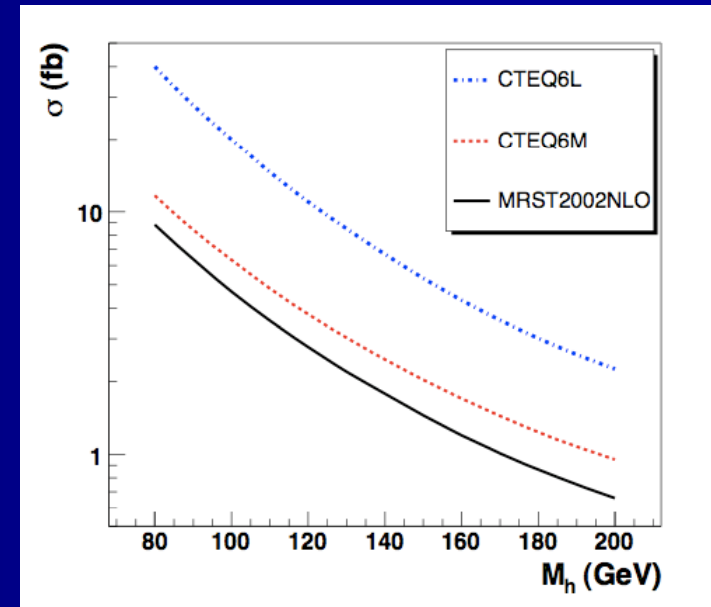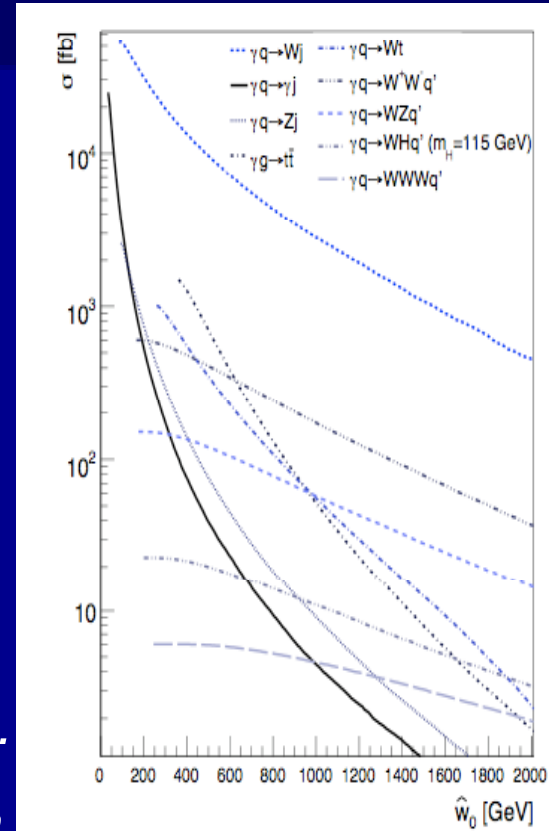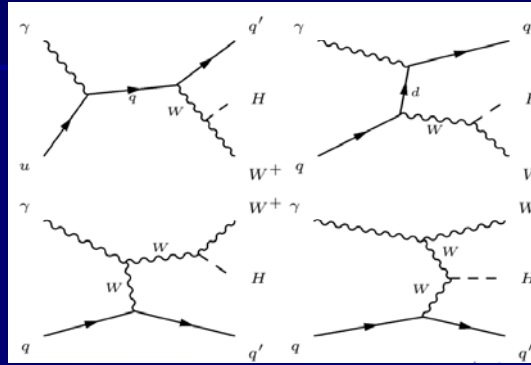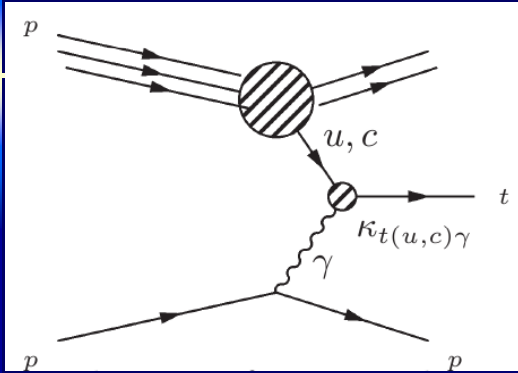
Photon-Photon Physics
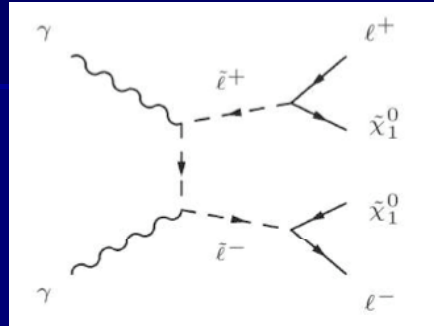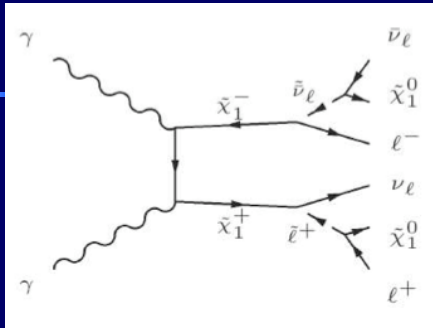
- **Extensive program of $\gamma\gamma$ –physics**
  - $\gamma\gamma\to \mu\mu,\ ee$ QED processes
  - $\gamma\gamma\to$ QCD (jets..)
  - $\gamma\gamma\to$ ZZ/WW anom. couplings
  - $\gamma\gamma\to$ top pairs
  - $\gamma\gamma\to$ Higgs
  - $\gamma\gamma\to$ Charginos....
- There is also an photoproduction 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→aa→ττττ

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
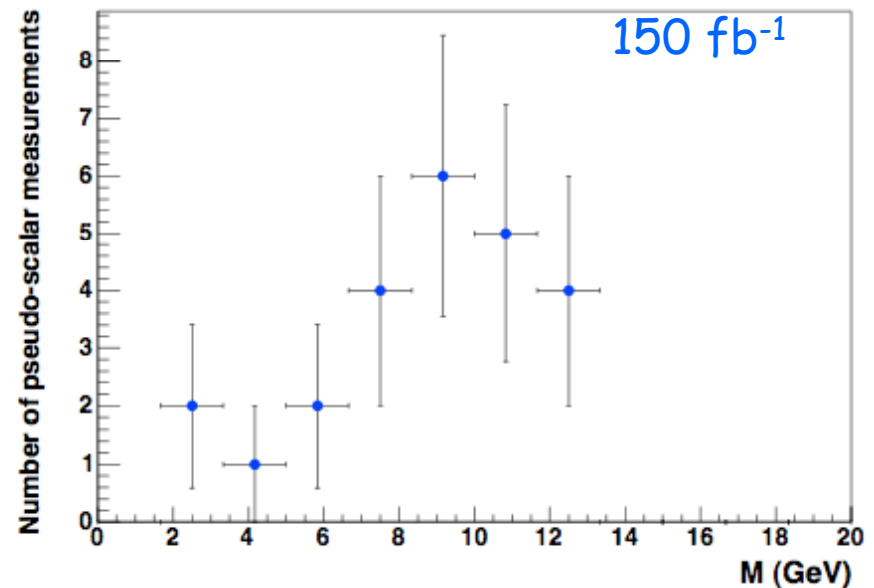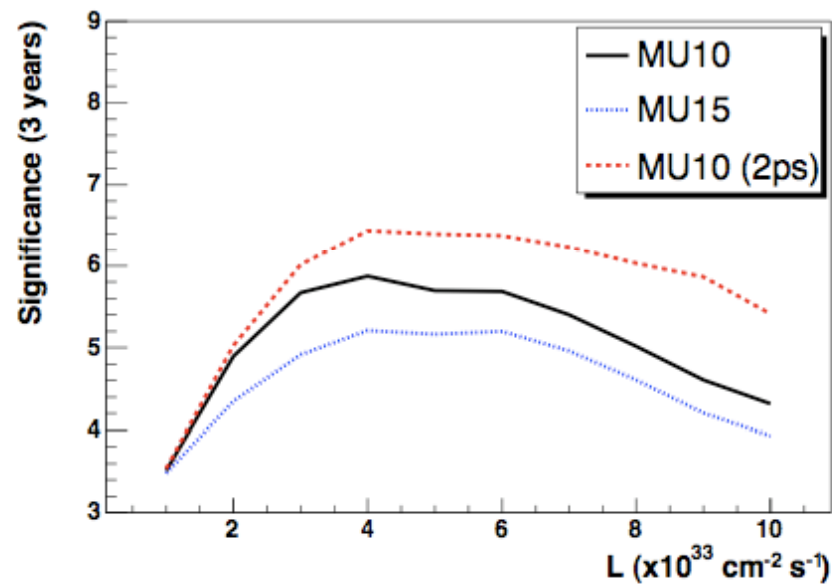
Exclusive Di-leptons – a Good Place to Search for the Odderon
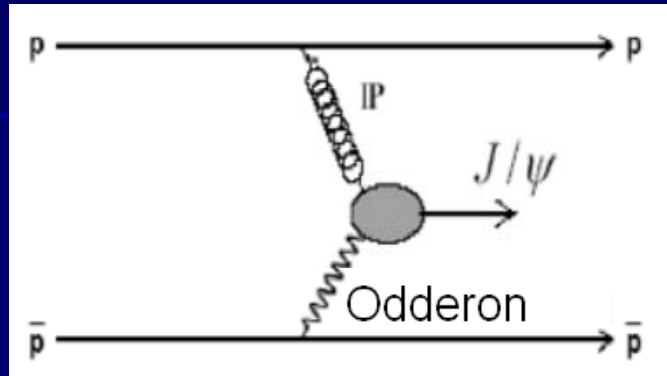
- *In perturbative QCD the lowest order prototype of the pomeron is the color neutral system of two gluons.*

- *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 hh-bar 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 $J/\Psi, \Psi', \Upsilon$ peaks unlike the χ_c background*

The Odderon
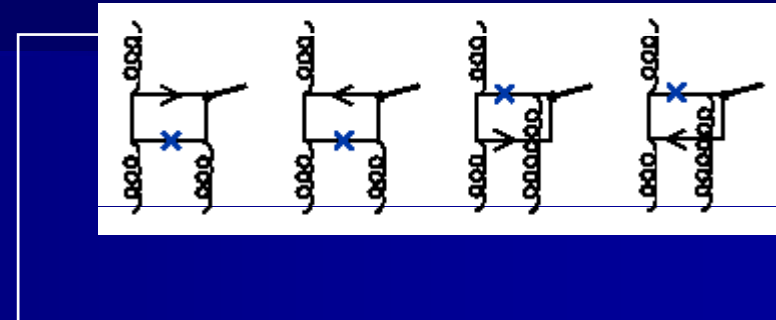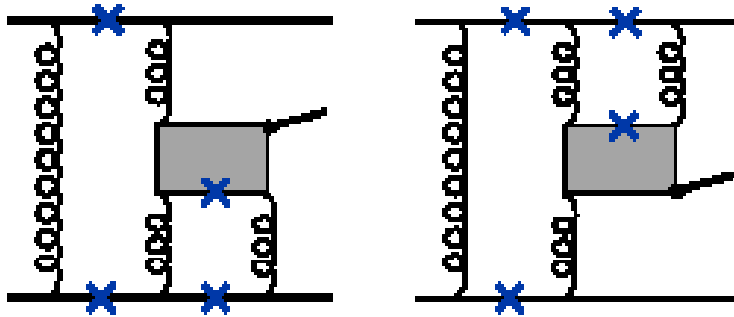
- *The color neutral gluon systems, exchanged at high energy scattering processes, can be classified wrt their C parity. The most important one is C-even system with quantum numbers of vacuum i.e. the pomeron.*

- *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
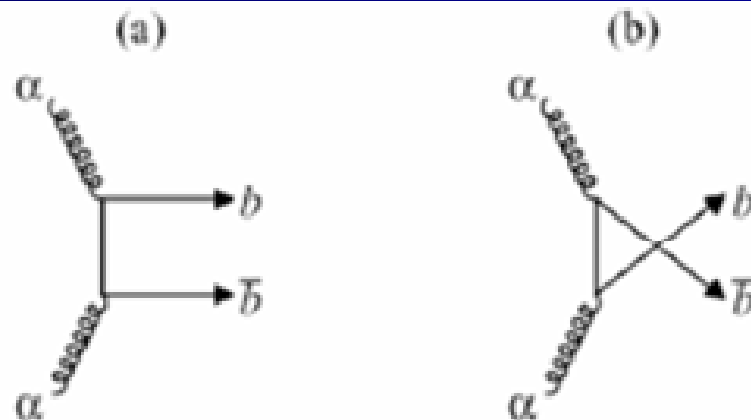
$J_z=0 \rightarrow$ for colour singlet bbar production, the born level contributions of a) and b) cancel in the limit $m_b \rightarrow 0$