Central Exclusive Production in $p\bar{p}$ Collisions at CDF II

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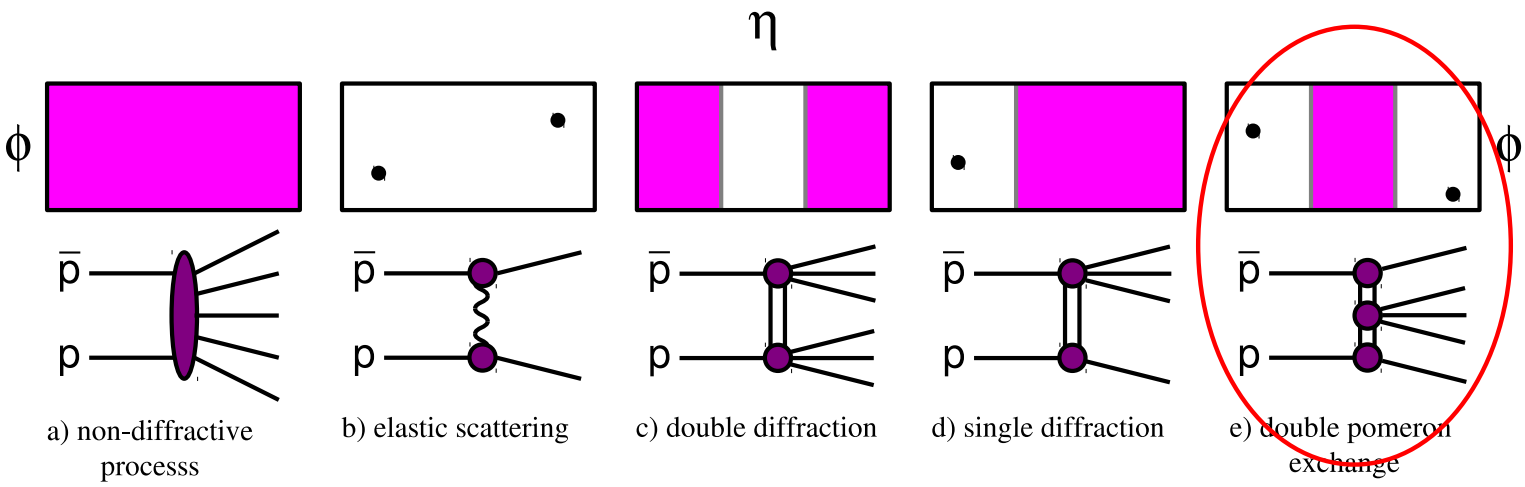
What is Central Exclusive Production?

- At hadron colliders reactions with vacuum quantum number (colorless) exchange are called diffractive.
- Characterized by rapidity gaps.



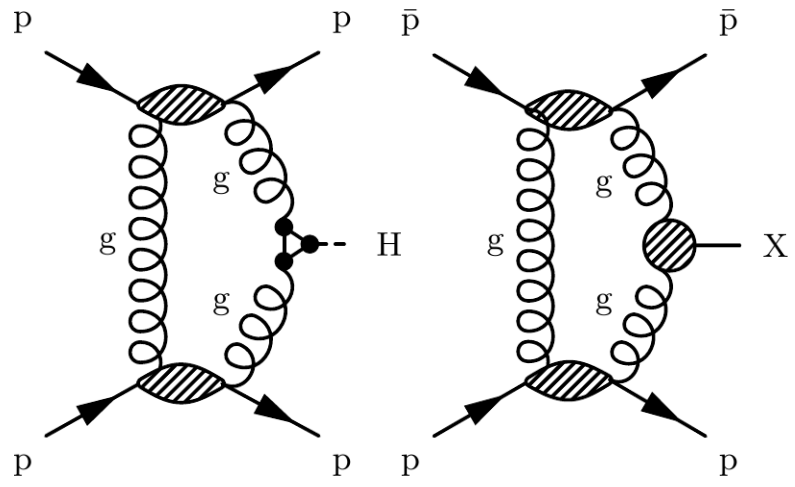
- Central produced system X with intact outgoing (anti-)proton.
- Large rapidity gaps on both sides.
- Can be exchange of strongly interactive objects or purely QED (Tevatron as photon collider) or a mixture of both.

Motivation

In case of QCD process:

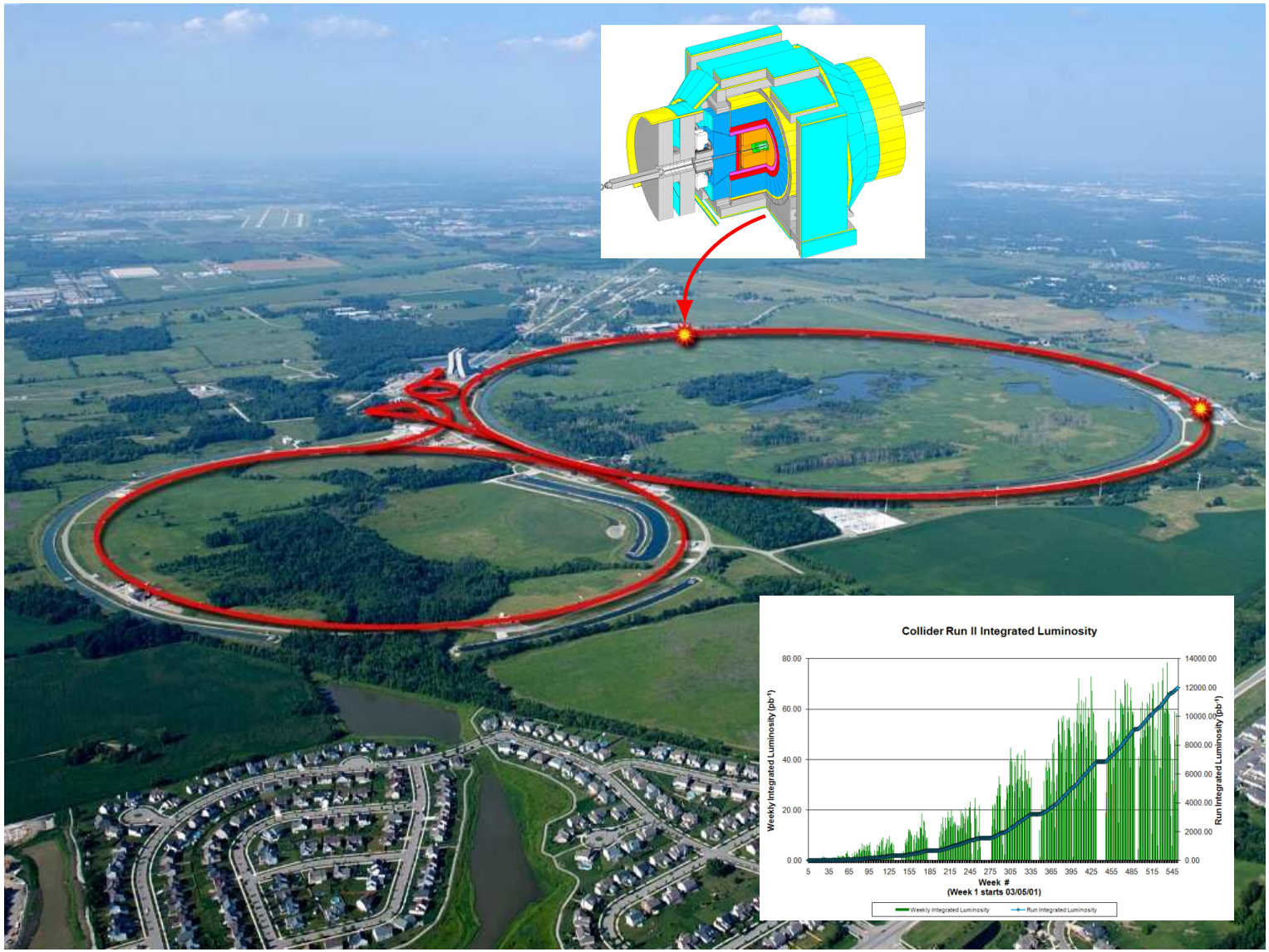
- $p\bar{p} \to p + X + \bar{p}$,
  $+$ denote large rapidity gap.
- QCD factorization.
- Hard process: gluon-gluon fusion.
- Soft part difficult to calculate.
- Large uncertainties; strong PDF dependency; Sudakov suppression; gap survival factor S^2.

✓ Motivation: Measuring CEP processes certainly constrains theoretical calculations.



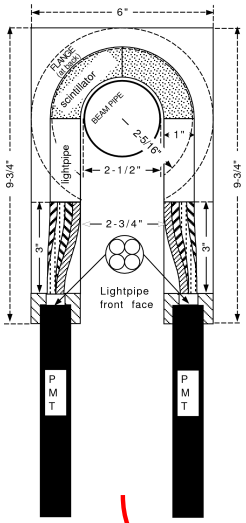
- Light exclusive standard model Higgs feasible at LHC.
- Many similar processes at Tevatron can test and calibrate predictions.

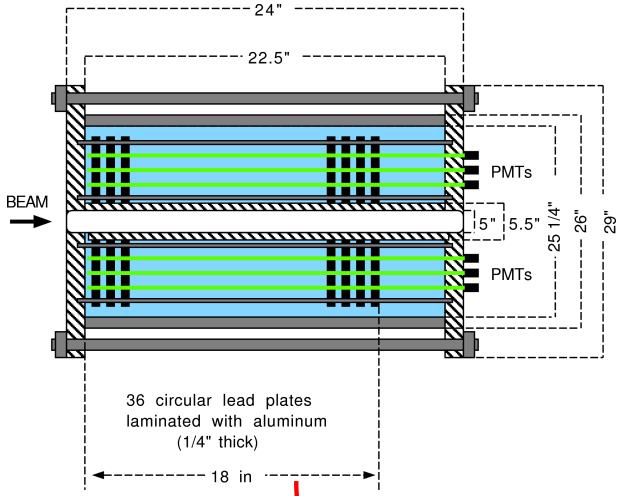
Fermilab, Tevatron and CDF

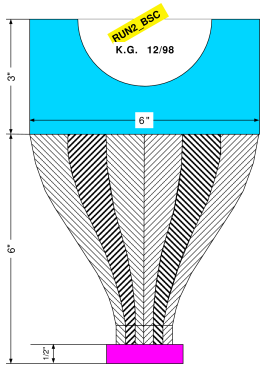


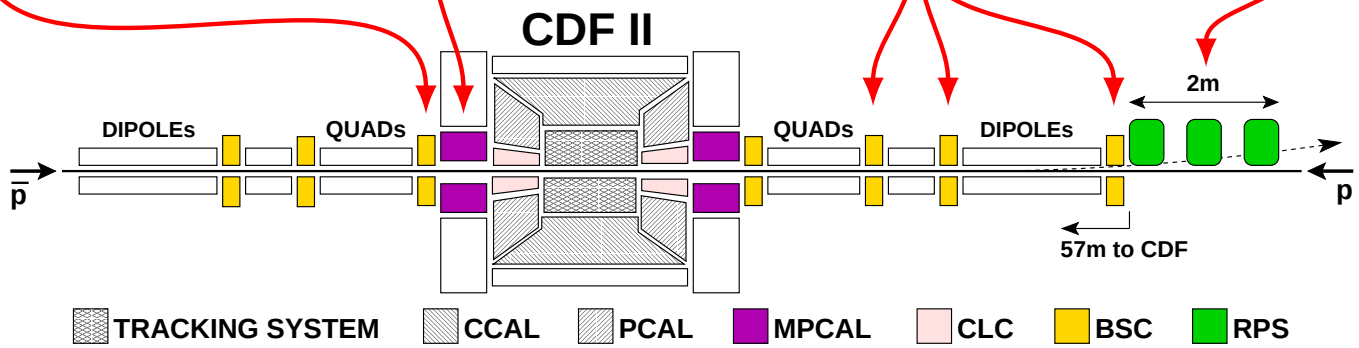
CDF Forward Coverage

BSC-1	Miniplug	BSC-2/3	RPS
$5.4 < \lvert\eta\rvert < 5.9$	$3.6 < \lvert\eta\rvert < 5.2$	$6.4 < \lvert\eta\rvert < 7.4(8.0)$	$0.02 < \xi < 0.1$









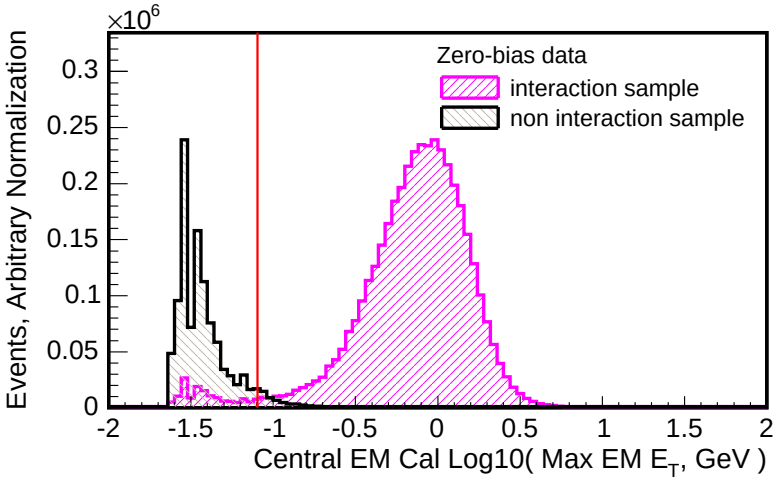
Key Method - Exclusivity (1)

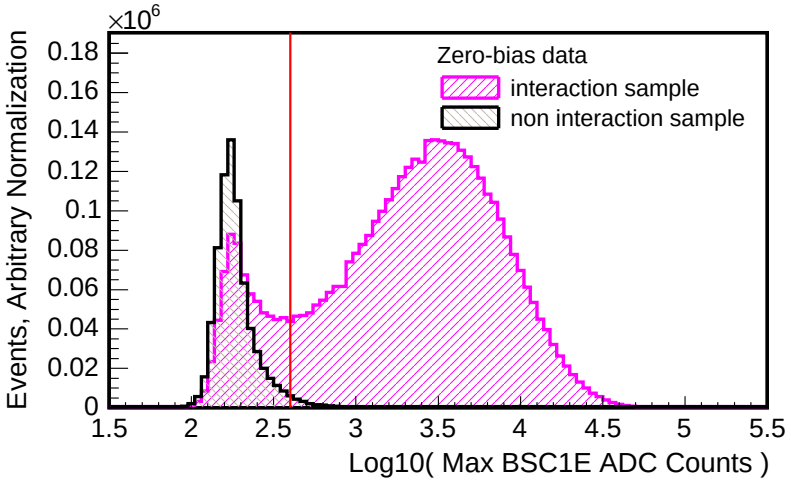
Selection of rapidity gap events (plots from excl. $\gamma\gamma$ study).

- Using Calorimetry + BSC's + CLC ($|\eta| < 7.4$).
- Calorimetry split into sections.

- Defining detector noise level using data triggered by bunch crossings (zero-bias).
- Reject events with signal above noise anywhere except signal showers.

Examples: Central EM CAL and BSC-1E (4 PMT's)

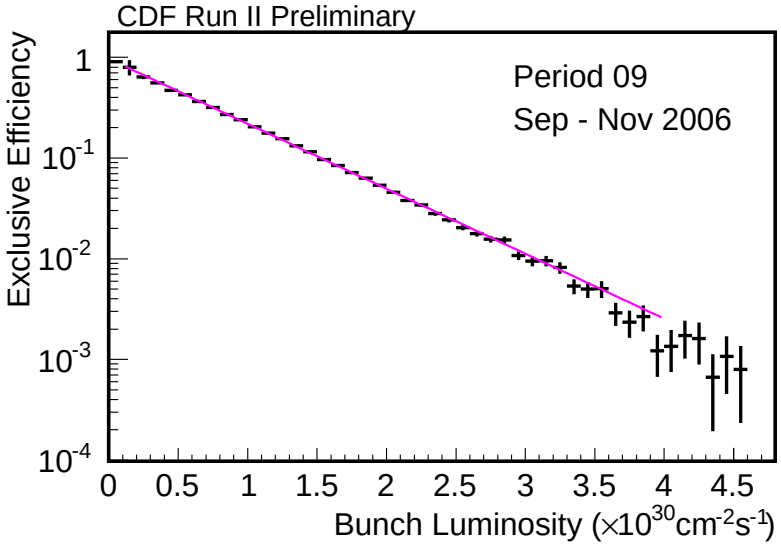


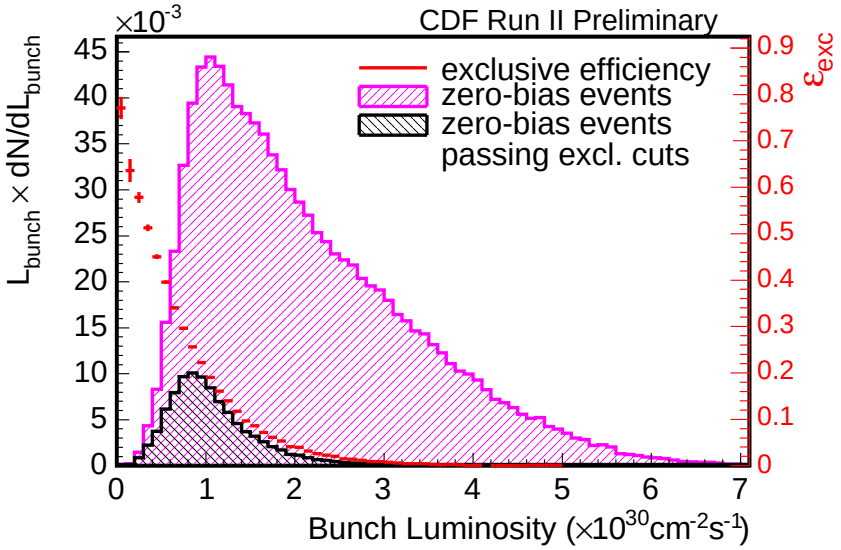


Note: non interaction sample: no tracks, no CLC hits, no muon stubs.

Key Method - Exclusivity (2)

- Efficiency estimation using zero-bias data as well.
- Efficiency: Fraction of zero-bias events passing all cuts.





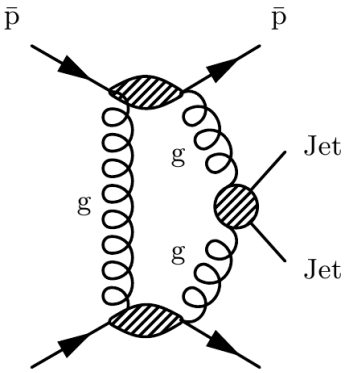
- Exponential fit: Intercept$= 0.98 \pm 0.2$, Abs. value of slope $\widehat{=} 67 \pm 6$ mb (consistent with σ_{inel})

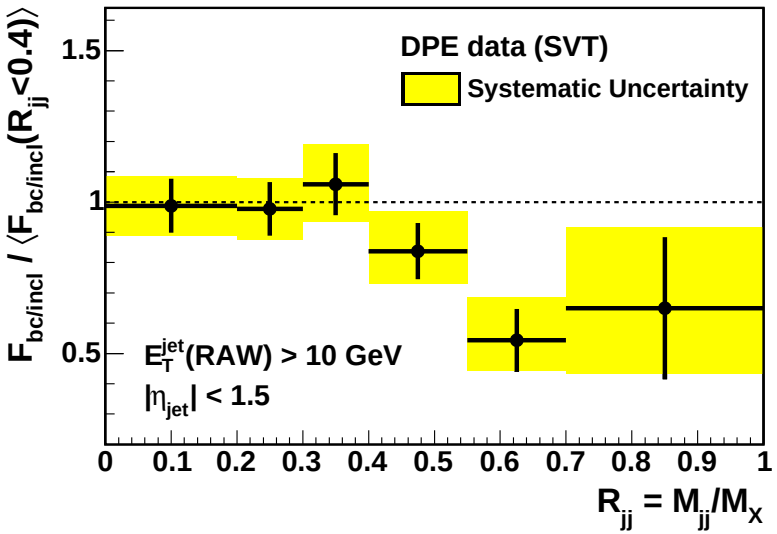
Overview of CEP Analyses done at CDF

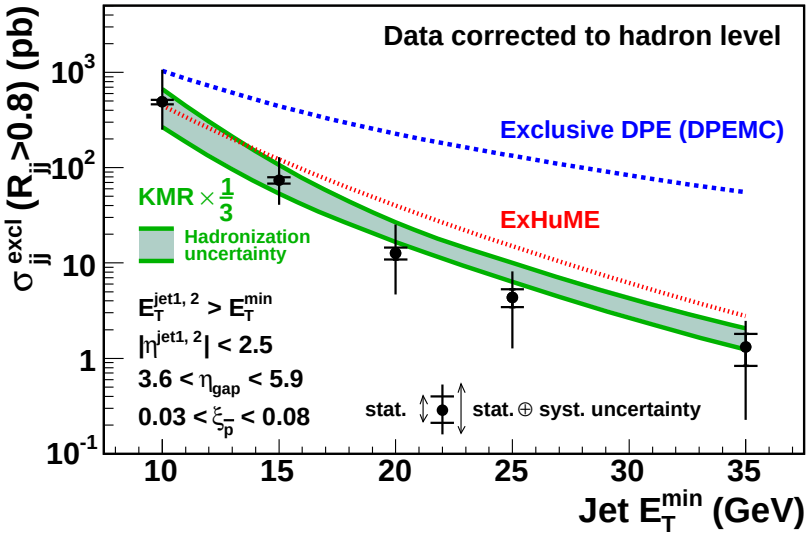
- **QED Production**
  - ★ Exclusive e^+e^- Production
  - ★ Exclusive $\mu^+\mu^-$ Production
- **Photoproduction**
  - ★ Exclusive J/Ψ Production
  - ★ Search for Exclusive Z Production
- **Double Pomeron Exchange**
  - ★ Exclusive Dijet Production
  - ★ Exclusive Charmonium and χ_c Production
  - ★ Exclusive $\gamma\gamma$ Production

Earlier: Exclusive Dijet Production

- Observation, PRD 77, 052004 (2008).
- $\bar{p} + p \to \mathbb{P} + \mathbb{P} \to \bar{p} + JJ + p$

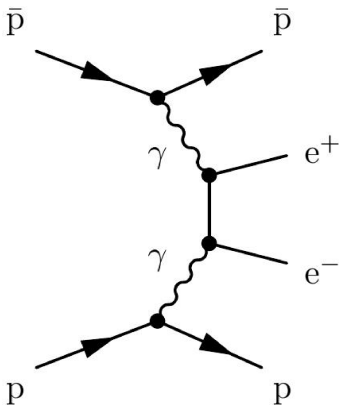


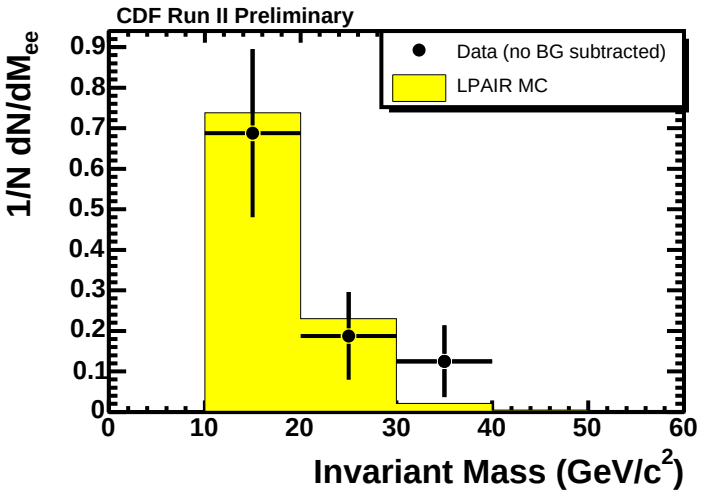


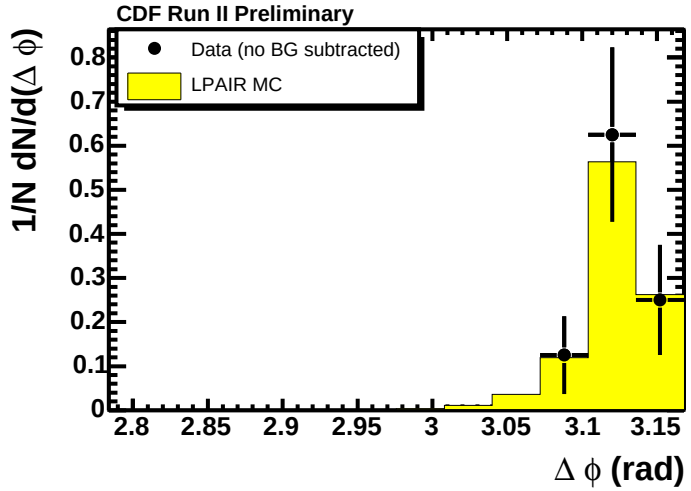


- $\mathcal{L}_{int} = 310\ \mathrm{pb}^{-1}$.
- $R_{JJ} = M_{JJ}/M_X \approx 1$.
- $J_Z = 0$ rule: jets should be gg, and qq suppressed.
- At high R_{JJ} heavy flavor jets suppressed relative to inclusive.
- Good agreement with KMR.

Earlier: Exclusive e^+e^- Production







- QED process observation, PRL 98, 112011 (2007).
- Electron and positron each with $|\eta| < 2$ and $E_T > 5$ GeV.
- 16 events in data of 532 pb^{-1}
- $\sigma = 1.6^{+0.5}_{-0.3}(\mathrm{stat}) \pm 0.3(\mathrm{syst})$ pb.
- In good agreement with theory: $\sigma = 1.71 \pm 0.01$ pb (Lpair MC)

Earlier: Exclusive Dimuon Production

- Observation, Phys. Rev. Lett. 102, 242001 (2009)
- Many processes in the $p + \bar{p} \to p + \mu^+\mu^- + \bar{p}$ study:

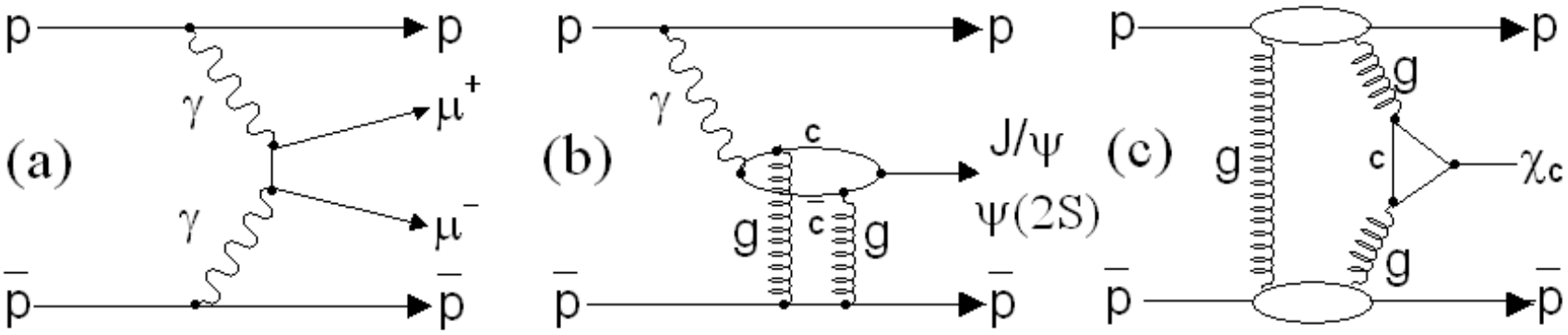


Figure: QED production of dimuon (left), photoproduction of J/Ψ (middle), and DPE production of χ_c (right).

- Note: Additional γ in charmonium production: $I\!P I\!P \to \chi_c \to J/\Psi + \gamma$
- $\mathcal{L}_{int} = 1.48$ fb^{-1}.

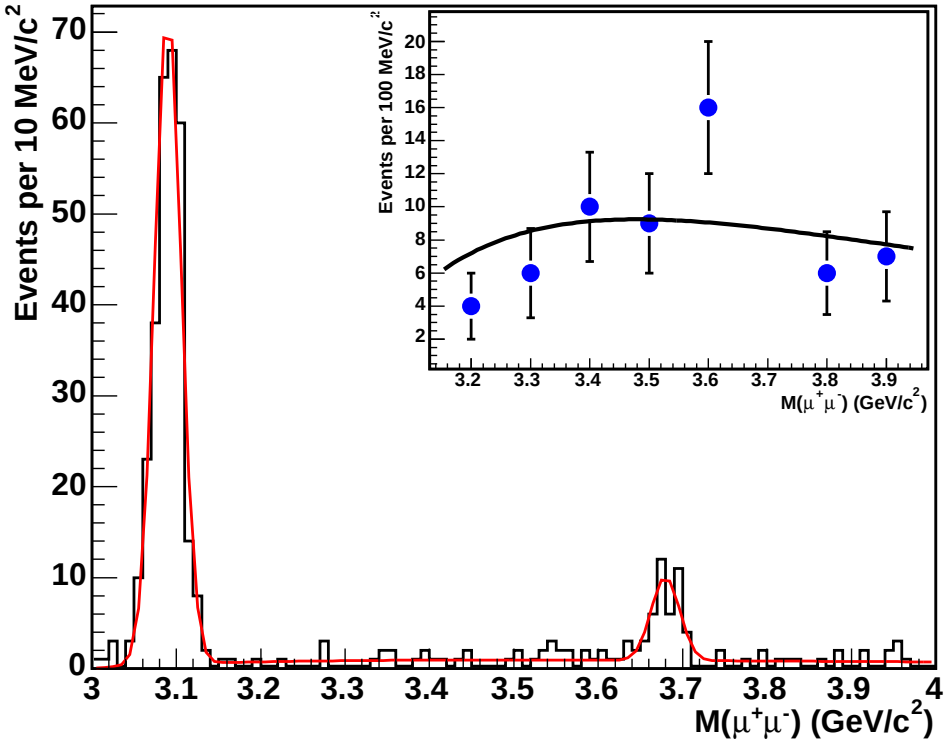
Exclusive J/Ψ and $\Psi(2s)$ Production

J/Ψ production: 243 ± 21 events.

- $d\sigma/dy|_{y=0} = 3.92 \pm 0.62$ nb.
- Theoretical Predictions:
  - 2.8 nb [Szczurek]
  - 2.7 nb [Klein & Nystrand]
  - 3.0 nb [Conclaves & Machado]
  - 3.4 nb [Motkya & Watt].

$\Psi(2s)$ production: 34 ± 7 events.

- $d\sigma/dy|_{y=0} = 0.54 \pm 0.15$ nb.
- $R = \frac{\Psi(2s)}{J/\Psi} = 0.14 \pm 0.05$
- HERA: $R = 0.166 \pm 0.012$ (similar kinematic region).



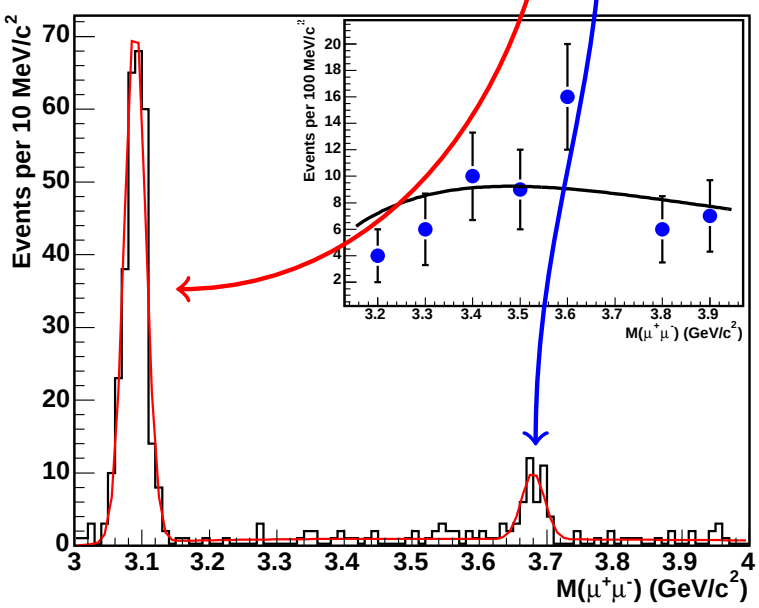
Exclusive χ_c Production

- In exclusive cuts we allow additional EM tower with $E_T > 80$ MeV.
- Significant increase of events in J/Ψ peak.
- Minor change in $\Psi(2s)$ peak.

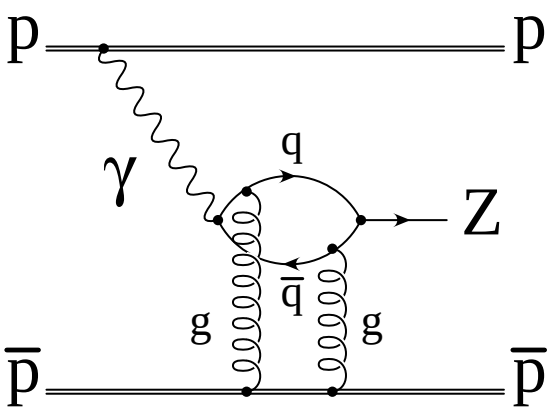
$\Rightarrow$ Evidence for $\chi_c \to J/\Psi + \gamma$ production.

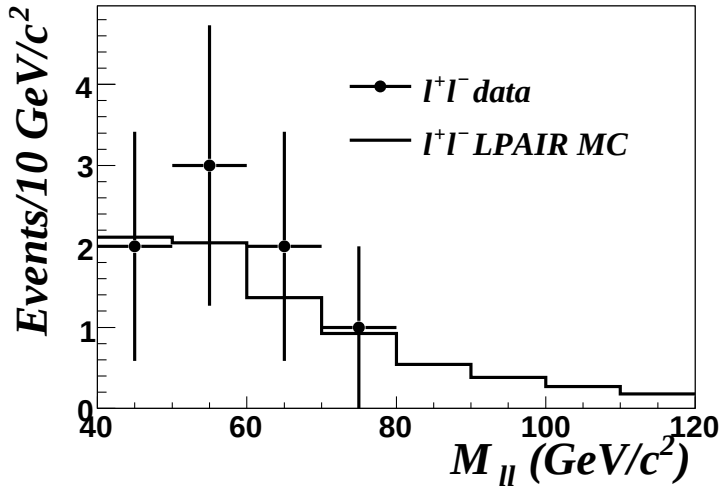
- $d\sigma/dy|_{y=0} = 75 \pm 14$ nb, compatible with theoretical predictions
  - 160 nb (Yuan 01)
  - 90 nb (KMR01)

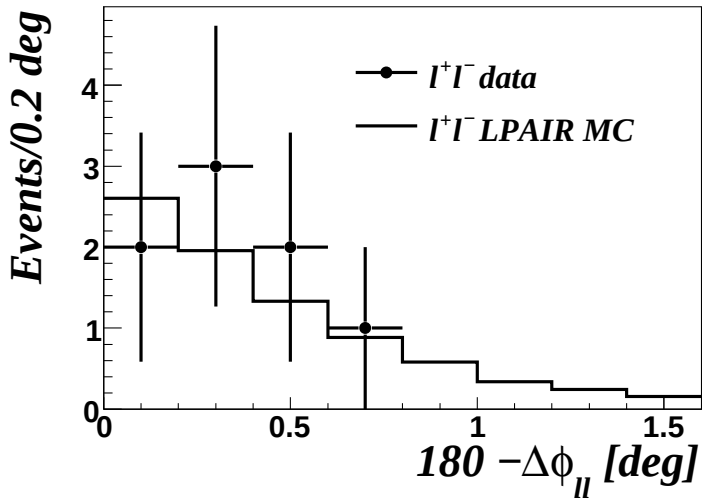
- J/Ψ production: $+66$ events.
- $\Psi(2s)$ production: $+1$ events.



Earlier: Search for Exclusive Z Production



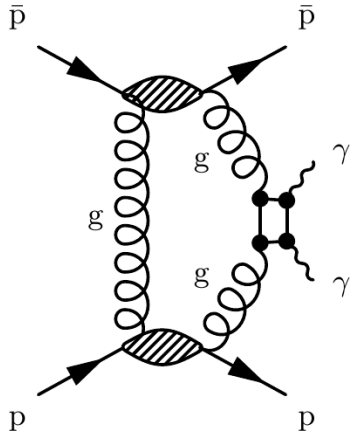




- PRL 102, 222002 (2009).
- $\mathcal{L}_{int} = 2$ fb^{-1}.
- 0 candidates $\rightarrow$ upper limit on cross section.
- But high mass dipletons observed and cross section meassured: $\sigma(\gamma\gamma \rightarrow l^+l^-,\ M_{l^+l^-} > 40\,\mathrm{GeV/c^2}) = 0.24^{+0.13}_{-0.10}$ pb.
- In good agreement with theory: $\sigma = 0.256$ pb.

New Exclusive $\gamma\gamma$: Trigger, Data and Selection

- Recorded data of 1.11fb^{-1} integrated luminosity, triggered on 2 EM showers $>$ 2 GeV and BSC-1 veto.
- Selection of EM object pairs plus nothing.
- EMO with $|\eta| < 1.0$ and $E_T > 2.5$ GeV.
- Filter for exclusivity (rapidity gap selection).
- Quality cuts and tracking cut.
- 2 samples:
  1. 2 EMO with good tracks $\Rightarrow$ 34 e^+e^- candidates.
  2. 2 EMO without any tracks $\Rightarrow$ 43 $\gamma\gamma$ candidates.



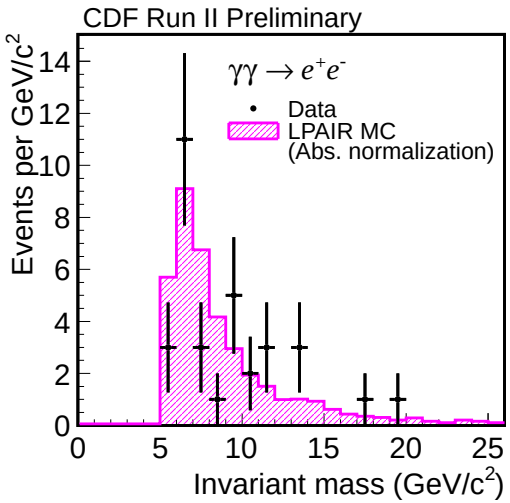
e^+e^- Revisited - Control Study

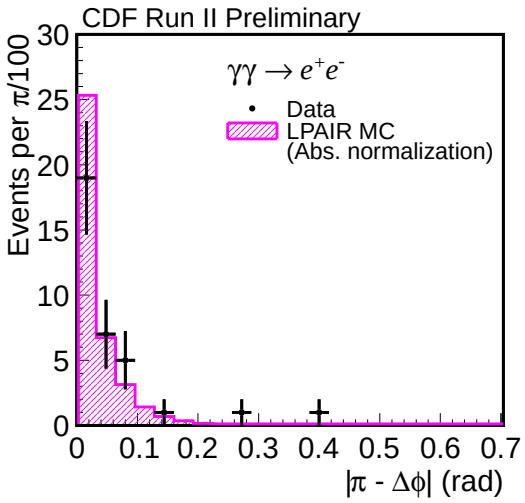
- 1 quality track per EMO ($p_T > 1$ GeV/c).
- No bremsstrahlung
- Good agreement with prediction (LPAIR MC, Nucl. Phys. **B229** 347 (1983))
- Good check for analysis.

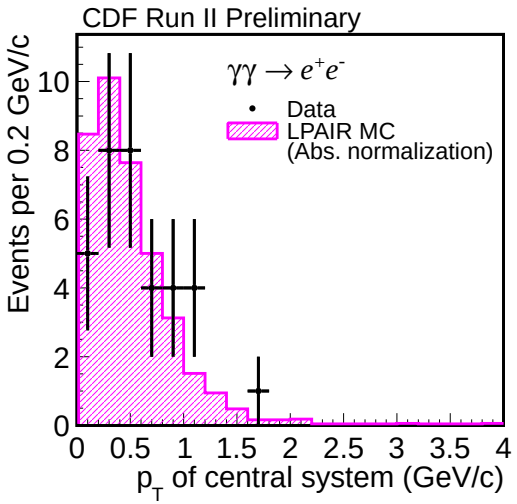
Exclusive e^+e^- (events)	34
$\mathcal{L}_{\text{int}}$	1.11 ± 0.07 fb^{-1}
Electron pair eff.	0.33±0.01(stat)±0.02 (syst)
Exclusive eff.	0.0680±0.004 (syst)
Radiative acceptance	0.42±0.08 (syst)
Dissoc. background (events)	3.8±0.4 (stat)±0.9 (syst)

$$\sigma^{|\eta(e)|<1, E_T(e)>2.5\text{GeV}}_{e^+e^-,\text{exclusive}} = 2.88\,^{+0.57}_{-0.48}(\text{stat}) \pm 0.63(\text{syst})\ \text{pb},$$

compared to 3.25±0.07 pb (QED).



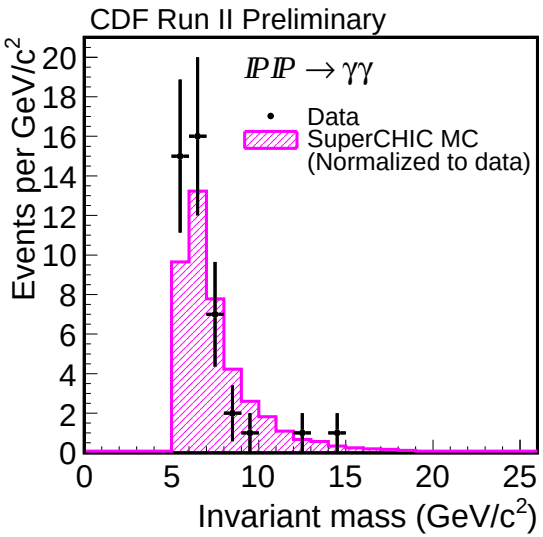


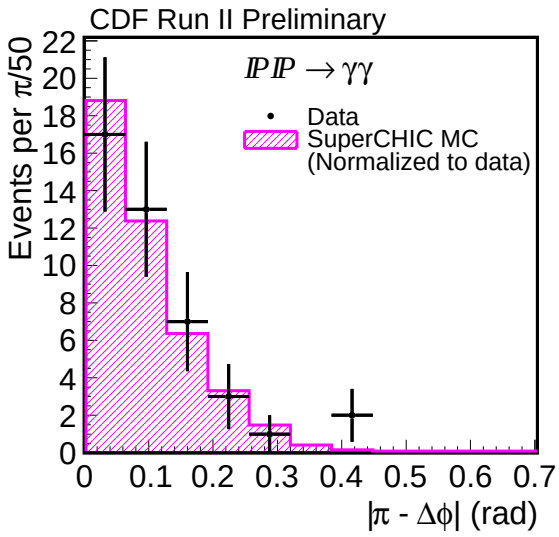


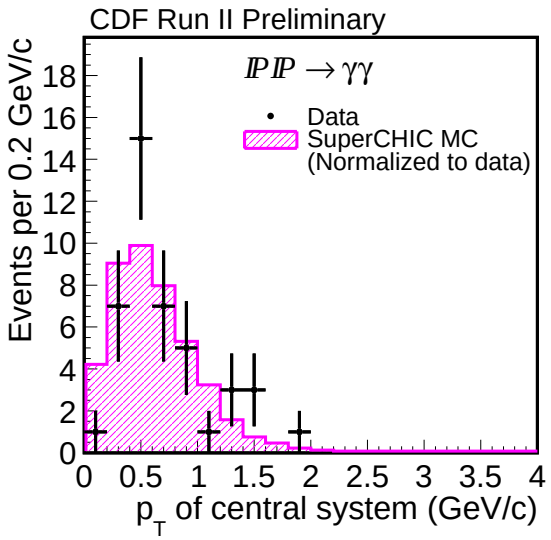
New Exclusive $\gamma\gamma$: Numbers and Kinematics

- No tracks in event.
- No conversion allowed.
- SuperCHIC signal MC (KMR, Harland-Lang, Eur.Phys.J. C69 (2010) 179).

Exclusive $\gamma\gamma$ (events)	43
$\mathcal{L}_{\text{int}}$	1.11 ± 0.07 fb^{-1}
Photon pair eff.	0.40 ± 0.02 (stat) ± 0.03 (syst)
Exclusive eff.	0.0680 ± 0.004 (syst)
Conversion acceptance	0.57 ± 0.06 (syst)
$\pi^0\pi^0$ background (events)	0.0, < 15 (95% C.L.)
Dissoc. backg. (events)	0.14 ± 0.14 (syst)





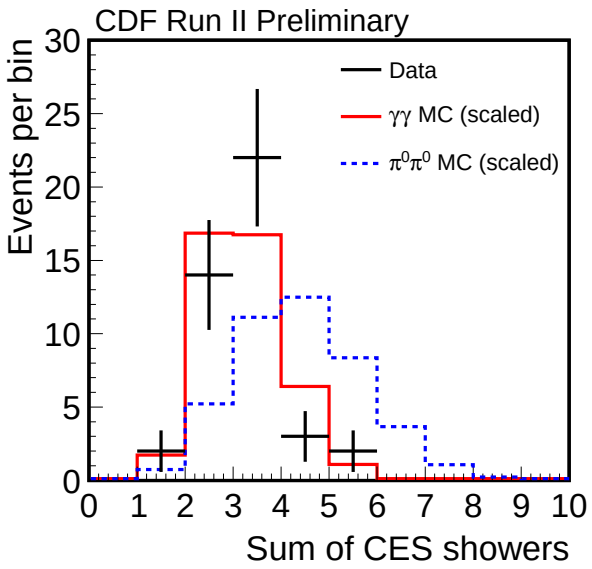


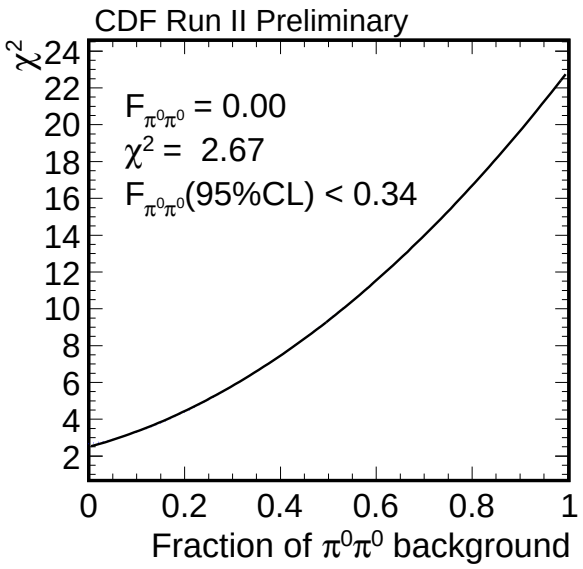
Note: Normalized to data. No overflow! Could be $\gamma\gamma$ or $\pi^0\pi^0$ ($\gamma\pi^0$ forbidden by C-parity).

New Exclusive $\gamma\gamma$: Background

Main background: inelastic $\gamma\gamma$ (p-dissociation) and possibly exclusive $\pi^0\pi^0$

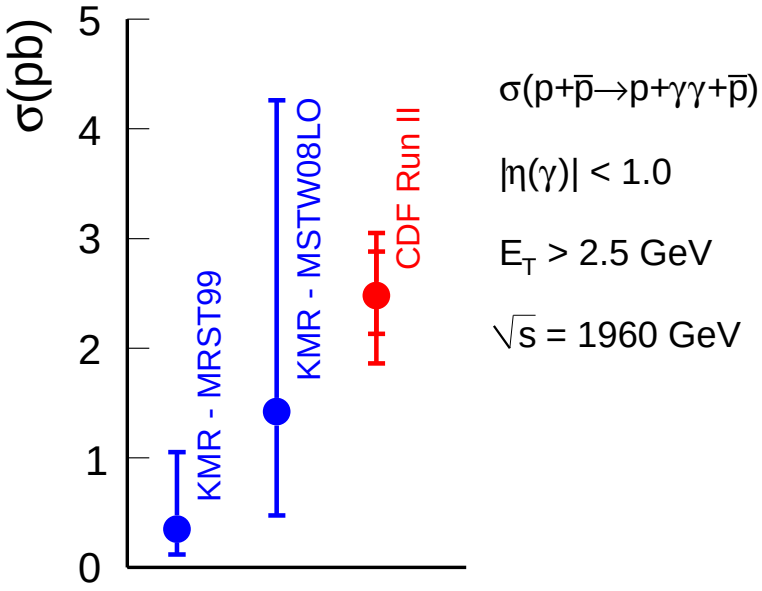
- $\pi^0 \to \gamma\gamma$; $\Delta\phi_{\text{min}} = 3.1^\circ$ for $p(\pi^0) = 5$ GeV
- Reconstructing of showers in wire chambers at shower max.
- Signal to hypothesis test with composition of signal and b/g MC.
- Scaled $\gamma\gamma$ and $\pi^0\pi^0$ MC.
- Using Pearson's χ^2 methods.
- Most likely b/g fraction $= 0$; <34% (95% CL) (15 events).
- Durham: $\pi^0\pi^0$ b/g $< 1\%$ ((KMR, Harland-Lang, arXiv:1105.1626 [hep-ph].)





New Exclusive $\gamma\gamma$: Conclusions

Exclusive Photon-Pair Production	
Theoretical	$\sigma_{\mathrm{SuperCHIC}}^{\lvert\eta\rvert<1,E_T>2.5\mathrm{GeV}} = 0.35^{\times 3}_{\div 3}\mathrm{pb}$ (MRST99)
	$\sigma_{\mathrm{SuperCHIC}}^{\lvert\eta\rvert<1,E_T>2.5\mathrm{GeV}} = 1.42^{\times 3}_{\div 3}\mathrm{pb}$ (MSTW08LO)
Measured	$\sigma_{\gamma\gamma\mathrm{excl.}}^{\lvert\eta\rvert<1,E_T>2.5\mathrm{GeV}} = 2.48\,^{+0.40}_{-0.35}(\mathrm{stat})\,^{+0.40}_{-0.51}(\mathrm{syst})\,\mathrm{pb}$



- First observation of exclusive $\gamma\gamma$ in hadron-hadron collissions.
- Measurement of the cross section of the exclusive production of two high-E_T photons in hadron hadron collisions.
- This corresponds to 1 in 25 billion inelastic collisions.
- Constraint on central exclusive Higgs if existing (produced by same mechanism).
- Paper recently published: Phys. Rev. Lett. 108, 081801 (2012).

Summary and What's Next?

CDF II results on CEP

- ✓ Observation of Exclusive Dijet events $\rightarrow$ PRD 77, 052004 (2008).
- ✓ Observation of Exclusive $e^+e^- \rightarrow$ PRL 98, 112011 (2007).
- ✓ Observation of Exclusive Charmonium and Dimuon $\rightarrow$ PRL 102, 242001 (2009).
- ✓ Search for Exclusive Z & High Mass Dilepton $\rightarrow$ PRL 102, 222002 (2009).
- ✓ New: Observation of Exclusive Diphoton $\rightarrow$ PRL 99, 242002 (2007) & PRL 108, 081801 (2012).

What next?

- Gap-X-Gap study: X being $\geqslant$ 2hadrons, and $\chi_c \rightarrow \pi^+\pi^-$, K^+K^-.
- More on exclusive $\gamma\gamma$ and $\pi^0\pi^0$ (limit?).
- Analysis of low s scan data (300 and 900 GeV).