Tevatron QCD for Cosmic-Rays

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on behalf of the DØ and CDF collaborations

Hadron-Hadron & Cosmic-Ray Interactions at multi-TeV Energies, Trento, 29.11 - 03.12 2010

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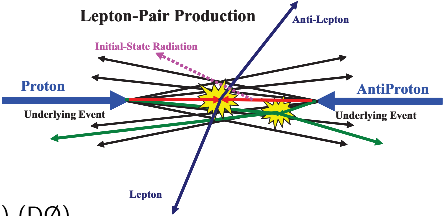
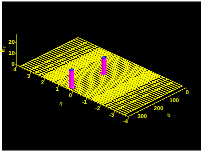
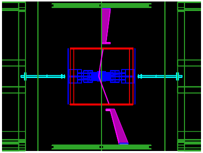
Outline

- Introduction:
  - Tevatron accelerator
  - DØ, CDF experiments
  - Tevatron kinematics/reach (wrt. cosmic rays)



- Diffractive and Exclusive production:
  - Elastic $p\bar{p}$ scattering (DØ)
  - Exclusive Z boson production (CDF)
  - Diffractive W/Z boson production (CDF)
  - Exclusive diffractive dijet production (high m_{jj}) (DØ)
  - Exclusive dijet production (CDF)
  - Diffractive dijet production (CDF)
  - Exclusive Charmonium production (CDF)
  - Exclusive $\gamma\gamma$ production (CDF)
  - Exclusive e^+e^- production (CDF)

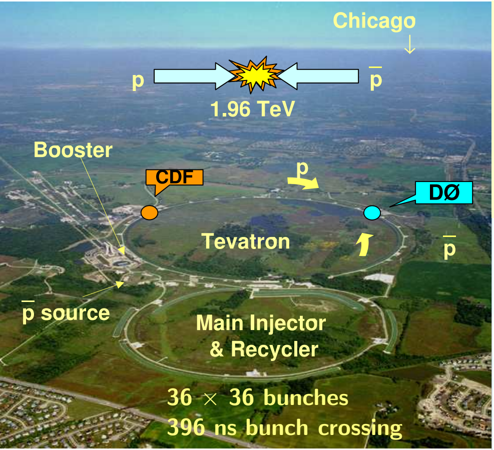




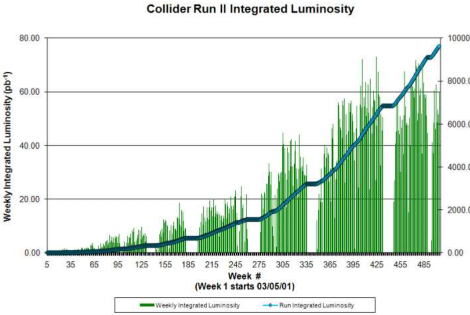
- Underlying event, DPS, MinBias:
  - MinBias $\Delta\phi$ (DØ)
  - MinBias Hyperons (CDF)
  - Double Parton Scattering (DØ)
  - UE in Drell-Yan production (CDF)
  - Thrust (CDF)
  - Jet particle k_T distributions (CDF)
- Conclusions

- Introduction

Fermilab Tevatron Run II



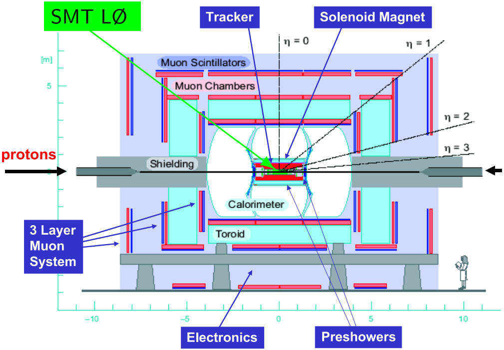
- Run II started in March 2001
- Peak Luminosity: $4 \cdot 10^{32}$ cm^{-2}s^{-1}
- Delivered: > 9.7 fb^{-1} (Run I: 0.16 fb^{-1})
- 12 fb^{-1} expected by end of FY 2011



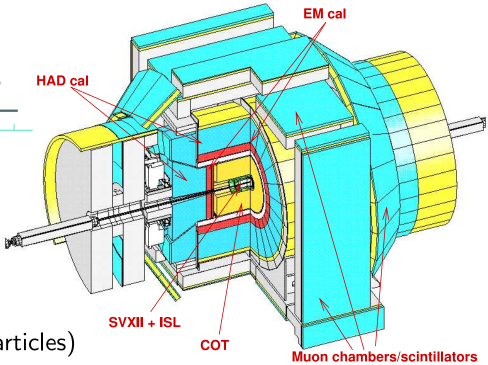
Thanks to all colleagues at the Tevatron for their contributions to this talk

The DØ and CDF detectors

- Data taking efficiency (DØ & CDF) $\simeq$ 90%

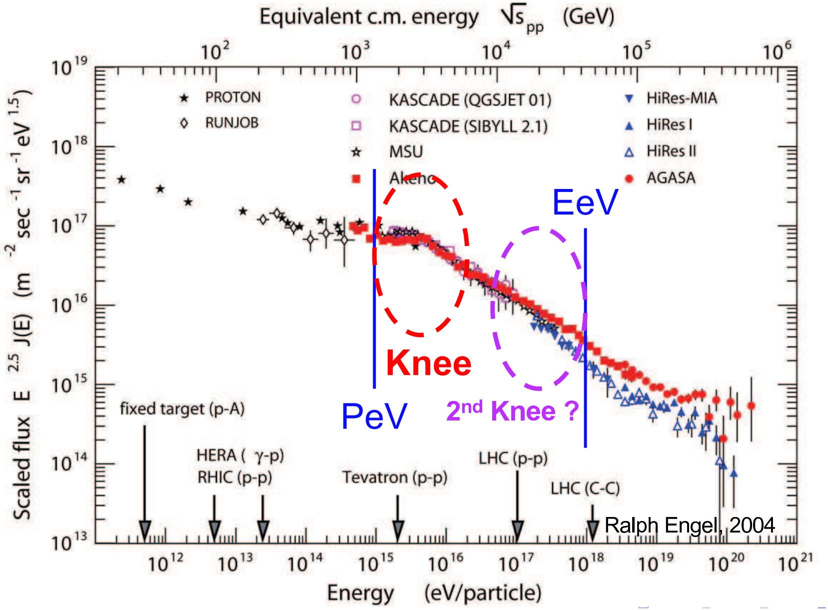


- Multi purpose detectors with broad particle ID capabilities
- Stable detectors and triggers

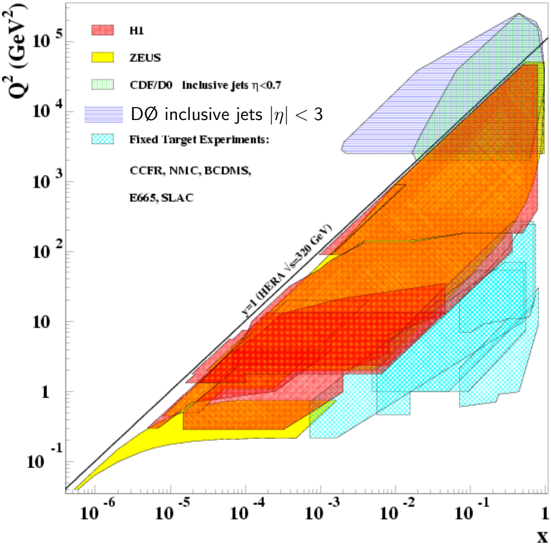


- Calorimeters ($\rightarrow$ jets, e, γ): Fine granularity and good energy resolution
  DØ: $\Delta\eta \times \Delta\phi \sim 0.1 \times 0.1$
  CDF: $\Delta\eta \times \Delta\phi \sim 0.1 \times 0.26$
- Central tracking systems ($\rightarrow$ charged particles)
- Muon spectrometers ($\rightarrow$ muons)

Cosmic ray and collider/Tevatron energies

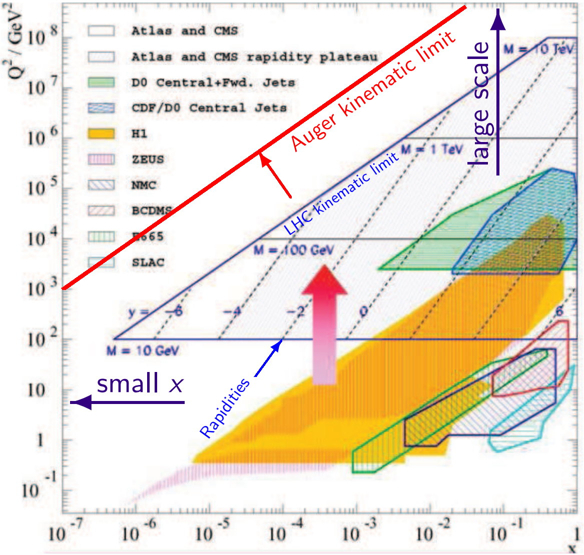


Kinematic plane: Q^2 vs. x



- Tevatron jet measurements cover a wide kinematic range
- Covers phase space regions beyond HERA (*ep* collisions) and fixed targets and has also overlap with HERA measurements
- DØ forward jets ($|\eta_{max}| = 3$) extends phase space to lower x considerably

The bigger picture



- LHC coverage included
  $Q = M$
  $x = (M/14\text{TeV})\exp(\pm y)$
- Wide range of rapidities and scales accessible
- Auger kinematic limit 100TeV c.m.s.
- Cosmic rays:
  Large region with small x (forward proton, diffractive physics)
  and large region with low scale (underlying event)

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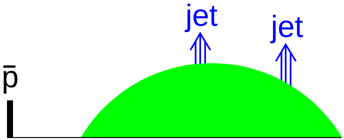
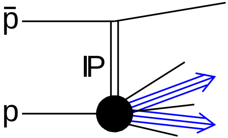
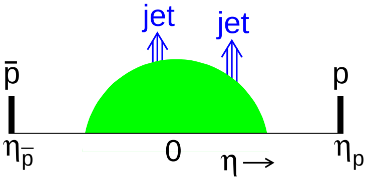
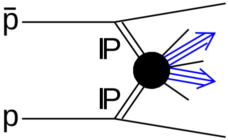
Diffractive jet production at the Tevatron



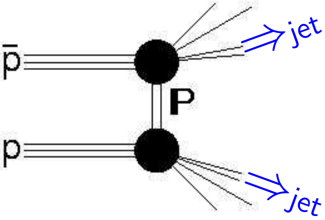


Single diffraction

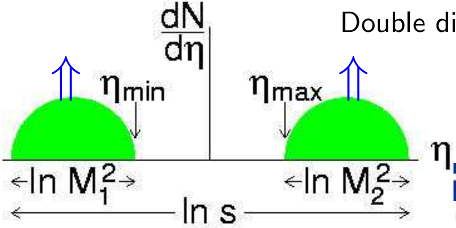




Double Pomeron exchange



Double diffraction



How measurements are done

- Data fully corrected for instrumental effects (acceptance, efficiency corrections)
  $\Rightarrow$ can be directly used for testing and improving existing event generators and any future calculations/models
- pQCD predictions are compared
  taking non-perturbative effects (hadronisation, UE) from simulation into account in the prediction
- Data and theory are compared at the particle level (hadronic final state)

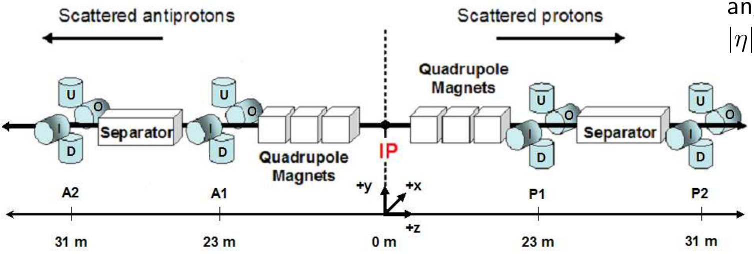
- Diffractive and Exclusive production

Differential cross section $d\sigma/d|t|$ in elastic $p\bar{p}$ scattering

DØ Collab., prelim. (2010), DØ Note 6056-Conf

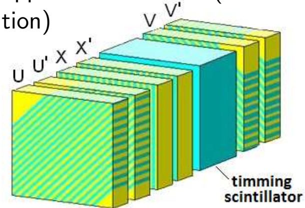
$\mathcal{L} = 30\ \text{nb}^{-1}$, $L = 0.5 \times 10^{30}\ \text{cm}^{-2}\text{s}^{-1}$

Forward Proton Detector (FPD)

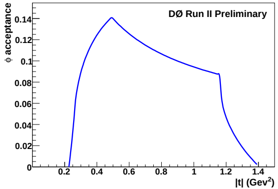


Elastic scattering angles: few mrad's, $|\eta| \simeq 8$

Trigger by coincidence of diametral opposite detectors (elastic combination)

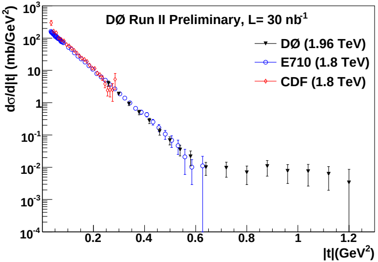


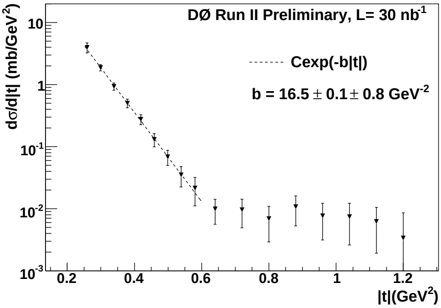
ϕ acceptance after fiducial cuts (closest detector position)

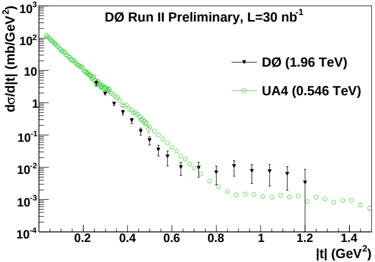


$$\frac{d\sigma}{d|t|} = \frac{1}{\mathcal{L}\times A\times\epsilon}\frac{dN}{d|t|}, \quad \text{fit} \sim C\exp(-b|t|)$$

- $b = 16.54 \pm 0.10(\text{stat}) \pm 0.80(syst)\ \text{GeV}^{-2}$
- First Tevatron measurement of first diffraction minimum of el. xsec. $d\sigma/d|t|$
- Position of first diffraction minimum moves to lower $|t|$ with higher energies





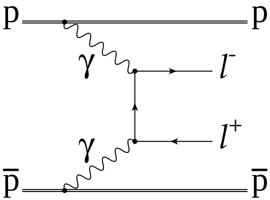


Search for exclusive Z boson production and Observation of high mass $p\bar{p} \to p\gamma\gamma\bar{p} \to p\ell^+\ell^-\bar{p}$ events

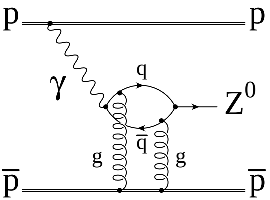
CDF Collab., Phys. Rev. Lett. **102**, 222002 (2009)

$\mathcal{L} = 2 - 2.2\ \text{fb}^{-1}$

Exclusive dilepton production



Exclusive Z boson production



$\ell^+\ell^-$ pairs:

- $M_{\ell\ell} > 40$ GeV
- $p_T^\ell > 25$ GeV

Z subsample:

- $82 < M_{\ell\ell} < 98$ GeV
- $p_T^\ell > 25$ GeV

- Miniplugs (lead-liquid scintillator calorimeters) $3.6 < |\eta| < 5.2$
- Beam Shower counters (scintillation counters) $5.4 < |\eta| < 7.4$
- Gas Čerenkov light counters (luminosity) $3.7 < |\eta| < 4.7$
- Tracking in Forward Proton Spectrometer (Roman Pot) $0.03 \lesssim \xi(\bar{p}) \lesssim 0.08$

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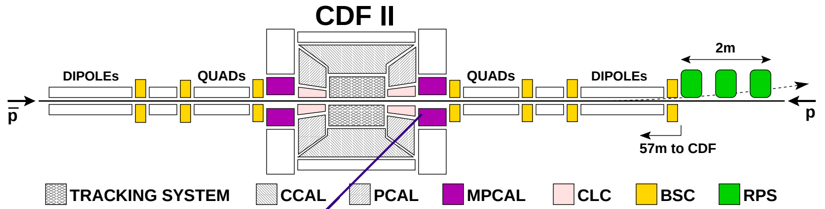
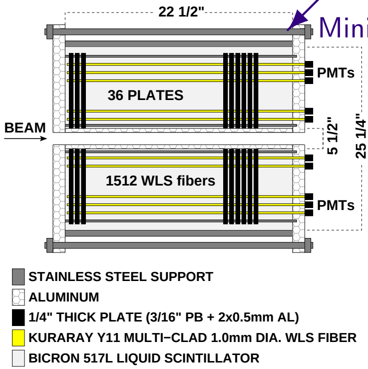
Search for exclusive Z boson production and Observation of high mass $p\bar{p} \to p\gamma\gamma\bar{p} \to p\ell^+\ell^-\bar{p}$ events



Mini Plug calorimeter

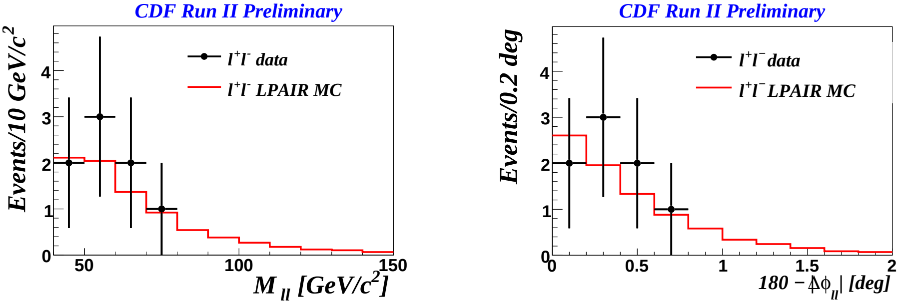


- Gas Čerenkov detectors $3.7 < |\eta| < 4.7$
- Mini Plug Calorimeters $3.6 < |\eta| < 5.2$
- Beam Shower Counters $5.4 < |\eta| < 7.4$
- Forward Proton Spectrometer $0.03 \lesssim \xi(\bar{p}) \lesssim 0.08$

Search for exclusive Z boson production and Observation of high mass $p\bar{p} \to p\gamma\gamma\bar{p} \to p\ell^+\ell^-\bar{p}$ events

Invariant $\ell\ell$ mass distribution

$\pi - \Delta\phi(\ell\ell)$ distribution



$$\sigma = \frac{N - N_{\text{bck}}}{\text{acc} \cdot \int \mathcal{L}_{\text{eff}}}$$

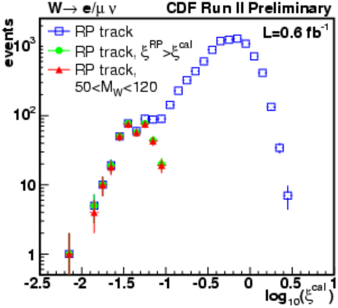
- $\sigma_{\text{excl}}(Z) < 0.96$ pb (@95% C.L.)
- $\sigma_{\text{excl}}(\ell\ell) = 0.24^{+0.13}_{-0.10}$ pb for $M_{\ell\ell} > 40$ GeV, $|\eta_\ell| < 4$ in agreement with SM prediction
- Exclusive dilepton events can be used at hadron colliders to calibrate Forward Proton Spectrometers

Diffractive W and Z boson production

CDF Collab., accepted by PRD (2010), arXiv:1007.5048

$\mathcal{L} = 0.6\ \text{fb}^{-1}$

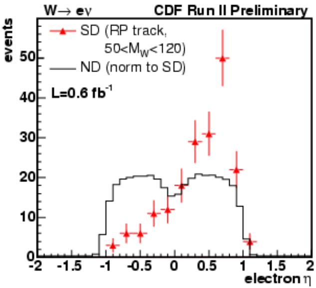
- Measure fraction of diffractive W, Z boson events to determine diffr. structure function
- Momentum fraction $0.03 < \xi < 0.10$ (of diffractive exchange), Momentum transfer (squared) $|t| < 1\ \text{GeV}^2$
- ξ determined from calorimeter energy deposits: $\xi^{\text{calo}} = \sum_{\text{towers}} \frac{E_T}{\sqrt{s}} e^{\eta}$
- In diff. W production determine ν kinematics from Roman Pot (RP) track: $\xi^{RP} - \xi^{\text{calo}} = \frac{\not{E}_T}{\sqrt{s}} e^{\eta_\nu}$

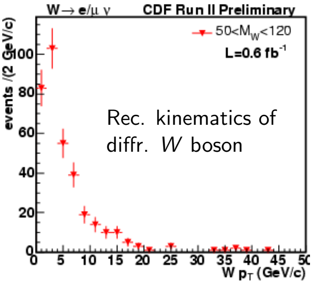


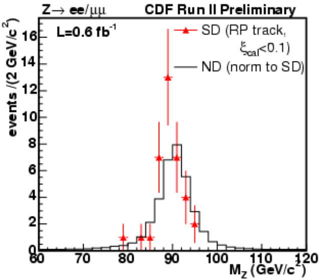
Kinematic selection

- central electron with $E_T > 25$ GeV or muon with $p_T > 25$ GeV
- Event z-vertex within 60 cm of nominal IP
- W boson:
  - $\not{E}_T > 25$ GeV
  - W transverse mass in range $40 - 120$ GeV
- Z boson:
  - 2. electron (central or plug) with $E_T > 25$ GeV or muon with $p_T > 25$ GeV
  - Reconstructed Z mass in range $66 - 116$ GeV

Diffractive W and Z boson production







Diffr. Z mass distribution seems to be (left) shifted KS probability of both distributions: 14%

$$R_W(SD/ND) = 0.97 \pm 0.05(\text{stat}) \pm 0.11(\text{syst})$$

$$R_Z(SD/ND) = 0.85 \pm 0.20(\text{stat}) \pm 0.11(\text{syst})$$

(for considered phase space: $0.03 < \xi < 0.10$ and $|t| < 1$ GeV^2)

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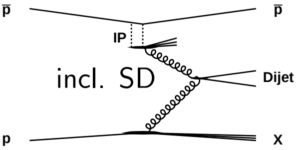
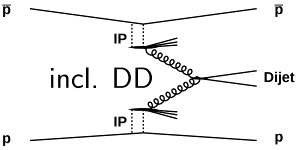
High mass exclusive diffractive dijet production

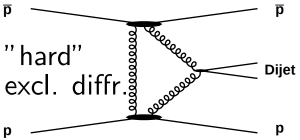
DØ Collab., prelim. (2010), DØ Note 6042-Conf, FERMILAB-PUB-10-361-E

$L = [5-100] \times 10^{30}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

$\Rightarrow$ other $p\bar{p}$ interactions $<$20%



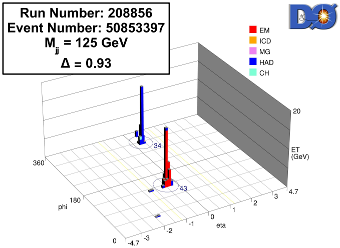




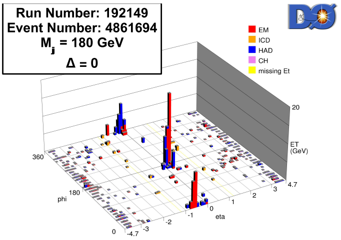
Event selection:

- $p_T^{1st\ j} > 60$ GeV
- $p_T^{2nd\ j} > 40$ GeV
- $m_{jj} > 100$ GeV
- $\Delta\phi > 3.1$
- $\not{E}_T < 0.7 p_T^{1st\ j}$

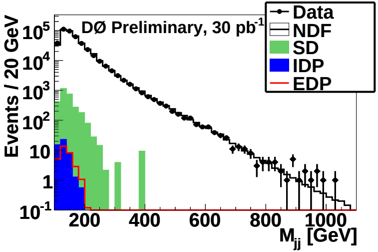
excl. diffr. signal event candidate

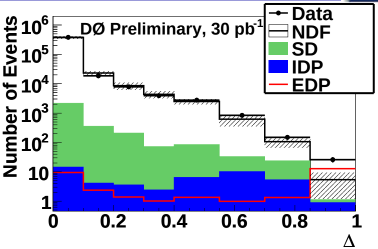


non diffr. background event candidate



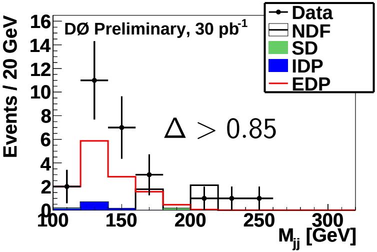
High mass exclusive diffractive dijet production





$$\Delta = \frac{1}{2}\exp(-\sum_{2<|\eta|<3} E_T) + \frac{1}{2}\exp(-\sum_{3<|\eta|<4.2} E_T)$$

- Leading systematics:
  - calorimeter cells calibration
  - JES
- Events with protons dissociating into low-mass states escaping detection $< 10\%$
- Probability of background fluctuation ($p = 2 \cdot 10^{-5}$) corresponds to 4.1σ

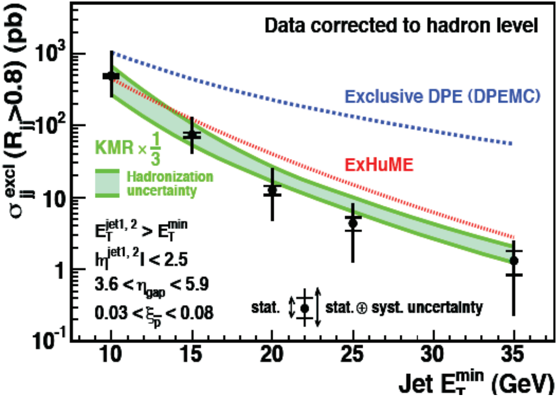


Observation of exclusive dijet production

CDF Collab., Phys. Rev. D **77**, 052004 (2008), `hep-ex/0712.0604` $\mathcal{L} = 310\ \text{pb}^{-1}$

$E_T^{\text{jet } 1,2} > 10$ GeV
$R_{jj} \equiv M_{jj}/M_x > 0.8$

Calculation by Khoze, Martin and Ryskin consistent within its factor of 3 uncertainty
Eur. Phys. J. C **14**, 525 (2000)



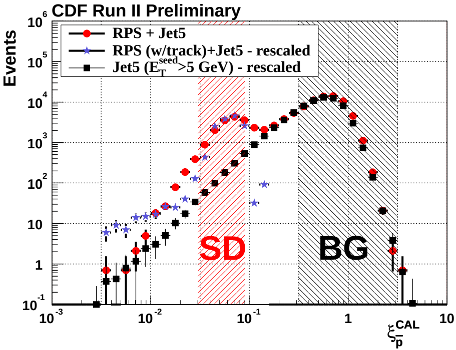
- Crucial to calibrate theoretical models
- Double pomeron exchange
  $\rightarrow$ possibility to study excl. Higgs production (@LHC)
  $\rightarrow$ predictions did vary by factor 1000 before this CDF measurement

Diffractive dijet production

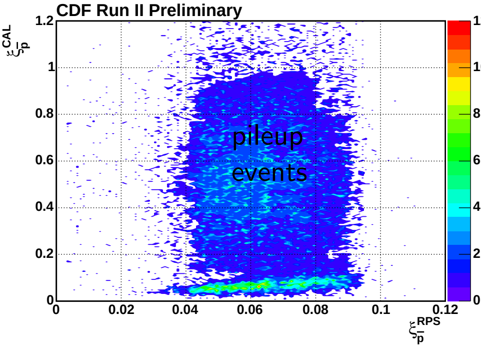
CDF Collab., prelim. (2006), `http://www-cdf.fnal.gov/physics/new/qcd/QCD.html`

$\mathcal{L} = 128\ \text{pb}^{-1}$

- Trigger: high E_T jet + recoil anti-proton in Roman Pot Spectrometer (RPS)
- Recoil anti-proton momentum loss $0.03 < \xi < 0.1$,
  Momentum transfer $|t| < 0.1\ \text{GeV}^2$
- Ratio SD/ND @ $10^{-3} < x_{Bj} < 10^{-1}$, $10^2 < Q^2 < 100^2\ \text{GeV}^2$



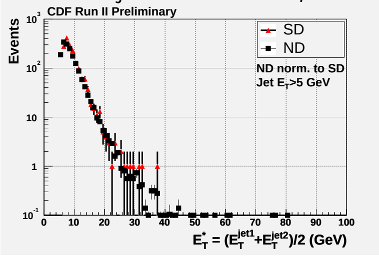
Events with reconstructed RPS track



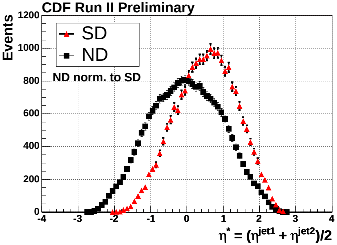
Diffractive dijet production

Kinematic distributions for SD dijet events

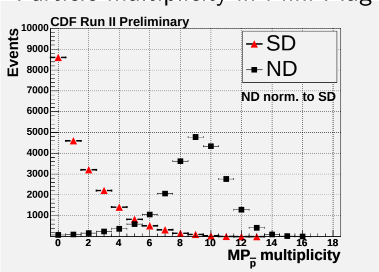
SD and ND dijets have similar E_T distributions



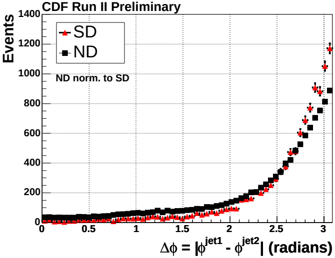
SD dijets are shifted to $+\eta$



Particle multiplicity in Mini Plug

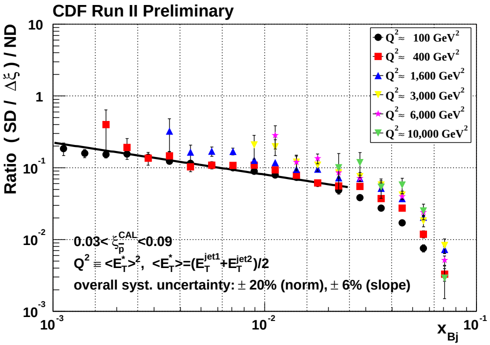


SD dijets are more back-to-back

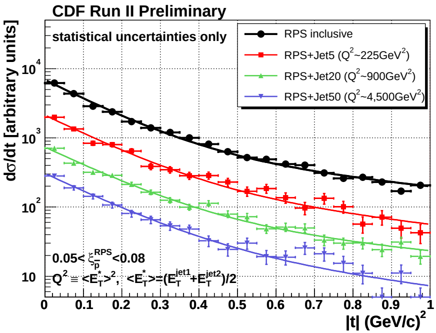


Diffractive dijet production

Ratio SD/ND: small Q^2 dependence



Diffr. $|t|$-distribution shape:
No observed Q^2 dependence



Consistent with Run I and composite Pomeron exchange

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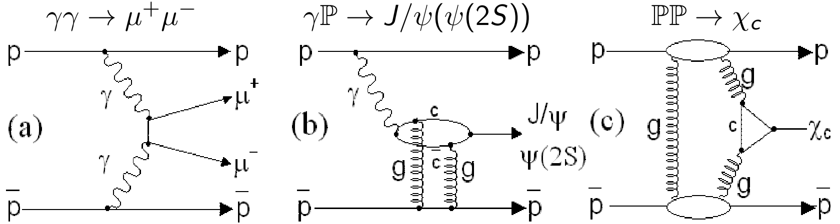
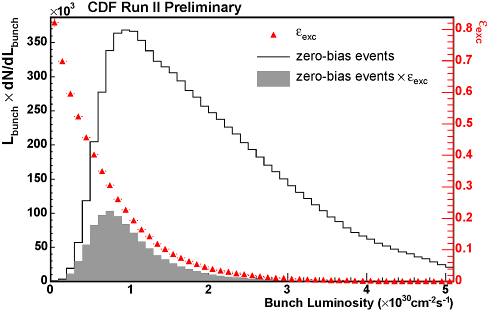
Exclusive Charmonium and $\gamma\gamma \to \mu^+\mu^-$ production

CDF Collab., Phys. Rev. Lett. 102, 242001 (2009), arXiv:0902.1271

$\mathcal{L} \simeq 1.5$ fb^{-1}



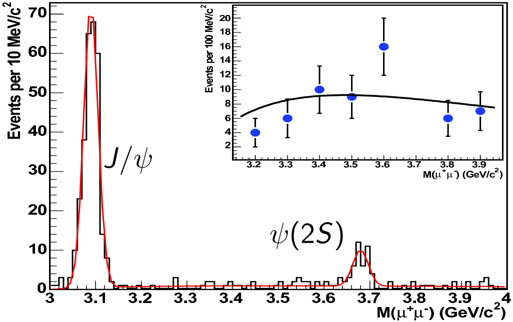
- 2 oppositely charged μ tracks
- $p_T(\mu) > 1.4$ GeV, $|\eta| < 0.6$
- No other particles in event
- ToF veto, $\Delta\theta_{3D} < 3.0$ rad, $3 < M_{\mu\mu} < 4$ GeV (cosmics)
- $\epsilon_{\text{excl}} = 0.093$ (No other inel. scat.)
- $\mathcal{L}_{\text{eff}} = \epsilon_{\text{excl}} \times \mathcal{L} = 139 \pm 8$ pb^{-1}



Exclusive Charmonium and $\gamma\gamma \to \mu^+\mu^-$ production

Backgrounds

- Proton fragmentation without products in forward detectors
- For J/ψ, χ_c additional γ with EM shower < 80 MeV
- Events with other particle(s) not detected



<u>Cross sections</u>

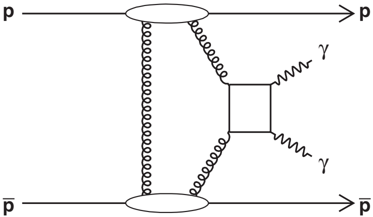
- $\gamma\gamma \to \mu^+\mu^-$ (QED)
  $\sigma(|\eta_\mu| < 0.6,\ 3 < M_{\mu\mu} < 4 \text{ GeV}) = 2.7 \pm 0.3(\text{stat}) \pm 0.4(\text{syst})$ pb
  In agreement with QED prediction: $\sigma = 2.18 \pm 0.01$ pb
- Cross sections $\left.\frac{d\sigma}{dy}\right|_{y=0}$:
  - for J/ψ: $3.92 \pm 0.25(\text{stat}) \pm 0.52(\text{syst})$ nb
  - for $\psi(2S)$: $0.53 \pm 0.09(\text{stat}) \pm 0.10(\text{syst})$ nb
  - for χ_{c0}: $76 \pm 10(\text{stat}) \pm 10(\text{syst})$ nb
- Odderon ($3g$, $C = -1$) limit $O\mathbb{P} \to J/\psi$: $d\sigma/dy|_{y=0} < 2.3$ nb

Search for exclusive $\gamma\gamma$ production

CDF Collaboration, Phys. Rev. Lett. **99**, 242002 (2007)

$\mathcal{L} \simeq 530$ pb^{-1}

Signal process: $p\bar{p} \rightarrow p\gamma\gamma\bar{p}$ with $gg \rightarrow \gamma\gamma$

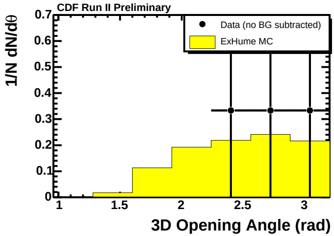


Contributions from

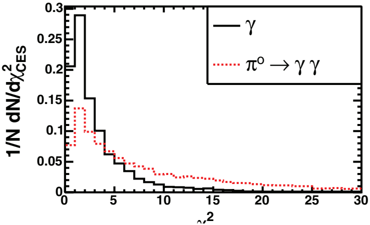
- $q\bar{q} \rightarrow \gamma\gamma$ ($< 5\%$)
- $\gamma\gamma \rightarrow \gamma\gamma$ ($< 1\%$)

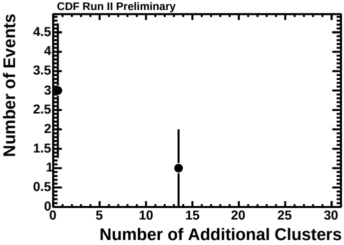
Dominant backgrounds ($< 25\%$)

- $\pi^0\pi^0$ production ($\pi^0 \rightarrow 2\gamma$)
- $\eta\eta$ production ($\eta \rightarrow 2\gamma$)



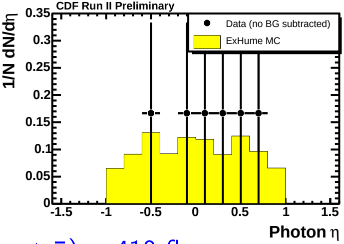
- EM showers $E_T > 5$ GeV, $|\eta| < 1$
- Ratio HAD/EM < 0.058
- No tracks or two adjacent tracks ($\gamma \rightarrow e^+e^-$)
- No additional particles in $|\eta| < 7.4$
- $p(\bar{p})$ energy deposit in BSC negligible for $p_T < 1.2$ GeV





Backgrounds

- Cosmic rays
- Misidentified excl. e^+e^- events
- Non-excl. evts. with missed particles
- Quasi-excl. (1 or 2 protons dissociation missed ($< 0.1\%$))
- Excl. $\pi^0\pi^0$, $\eta\eta$ production



Exclusion Limit @ 95% C.L.: $\sigma(p\bar{p} \to p + \gamma\gamma + \bar{p}) < 410$ fb

Prediction: 36^{+72}_{-24} fb

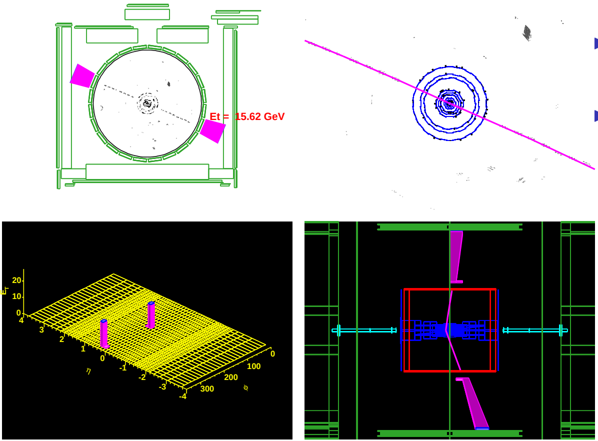
Exclusive e^+e^- production

CDF Collaboration, Phys. Rev. Lett. **98**, 112001 (2007)

$\mathcal{L} \simeq 530 \text{ pb}^{-1}$

Signal process: $p\bar{p} \to pe^+e^-\bar{p}$ with $\gamma\gamma \to e^+e^-$

Signal event candidate:



- Inv. mass of Central system additionally calculable by excl. processes
- Improving uncertainties on luminosity measurements
- Selection criteria:
  - 2 e candidates $E_T > 5$ GeV, $|\eta| < 2$
  - Matching track $p_T > 1$ GeV
  - Calorimeter timing (cosmics) $\epsilon_{\text{cosmic}} = 0.93$
  - $\epsilon_{\text{excl}} = 0.086$
  - $\epsilon_{\text{FSR}} = 0.79$

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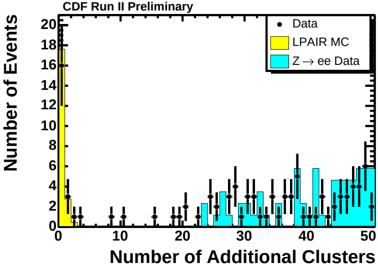
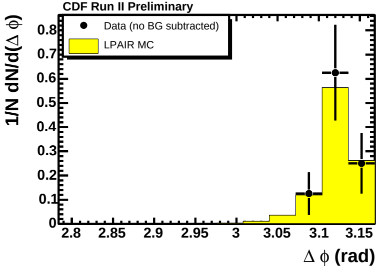
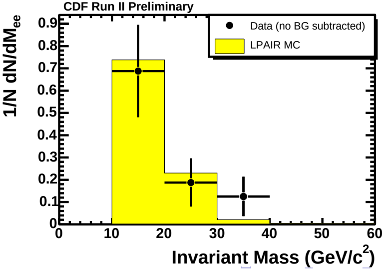
Exclusive e^+e^- production

$Z \rightarrow ee$ background estimated by fit



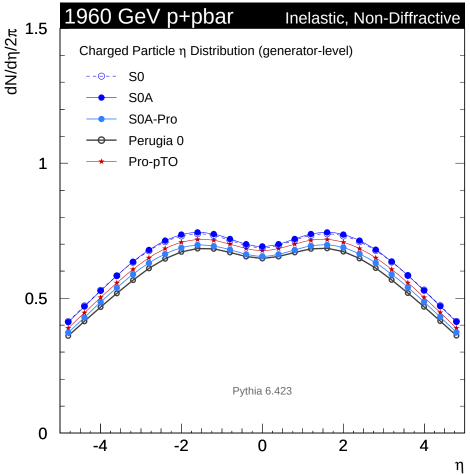
- $\sigma = \frac{N_{dat} - N_{bkg}}{\epsilon_{cosmic} \cdot \epsilon_{FSR} \cdot \epsilon_{ee} \cdot \epsilon_{excl} \cdot \mathcal{L}}$
- $\sigma(\text{excl.}) = 1.6^{+0.5}_{-0.3}(\text{stat}) \pm 0.3(\text{syst})$ pb
  In agreement with LPAIR MC prediction: $\sigma = 1.71 \pm 0.1$ pb
- $\sigma(\text{incl.}) = 1.8^{+0.5}_{-0.2}(\text{stat}) \pm 0.3(\text{syst})$ pb
  In agreement with LPAIR MC prediction: $\sigma = 1.9 \pm 0.4$ pb

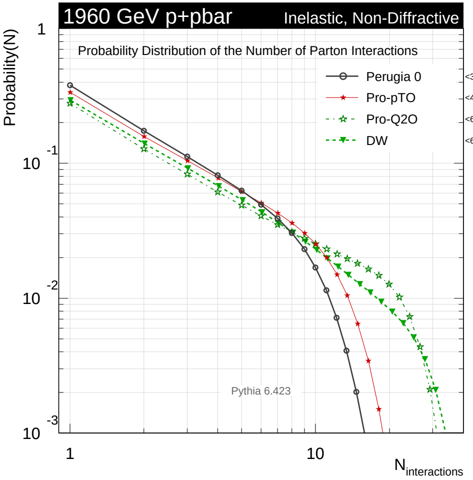




- Underlying event,
  Double Parton Scattering
  MinBias

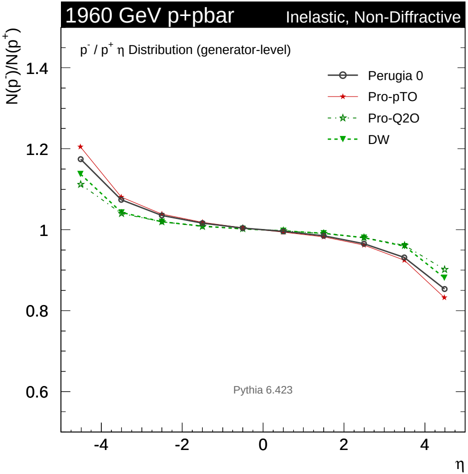
MinBias charged particle multiplicity/interactions at Tevatron

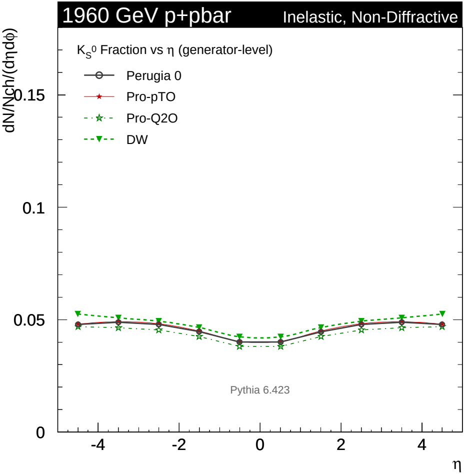




- PYTHIA 6.423, generator particle level with different tunes
- Plots from P. Skands
  (http://home.fnal.gov/∼skands/leshouches-plots)

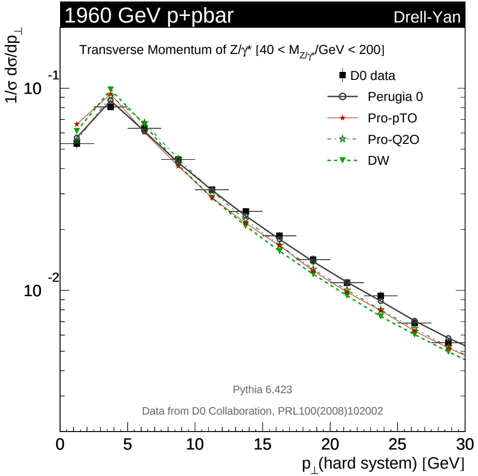
MinBias charged particle multiplicities at Tevatron

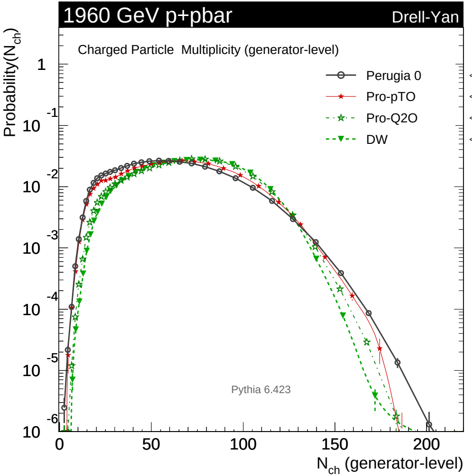




- PYTHIA 6.423, generator particle level with different tunes
- Plots from P. Skands (`http://home.fnal.gov/~skands/leshouches-plots`)

Drell-Yan transverse momentum and interactions at Tevatron





- PYTHIA 6.423, generator particle level with different tunes
- Plots from P. Skands
  (http://home.fnal.gov/~skands/leshouches-plots)

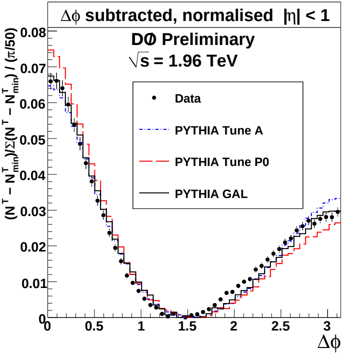
ϕ and η correlations in minimum bias events

DØ Collab., prelim. (2010), DØ Note 6054-Conf

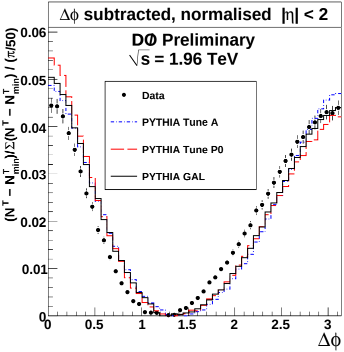
Data $\in [2002, 2006]$

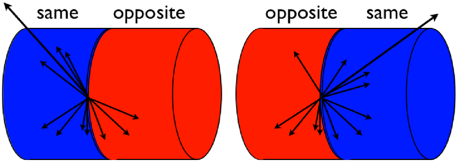
- $\Delta\phi$ between leading p_T track and other tracks
- One collision (PV) fires dimuon trigger ($p_T(\mu's) > 2$ GeV), others count as Min Bias PV ($p_T^{\text{track}} > 0.5$ GeV, $|\eta| < 2$, $\Delta z(VTX) < 20$ cm)
- $N_{\text{min}}^{\text{track}}$ subtracted (fake tracks, wrong assigned tracks flat in $\Delta\phi$)
- Normalised shape to unit area (after subtraction)

Existing Tunes for $|\eta| < 1$

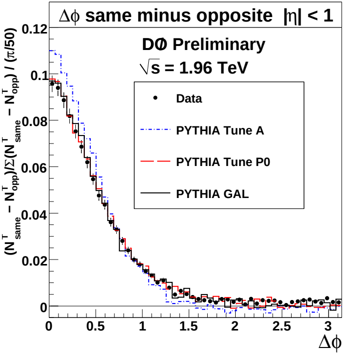


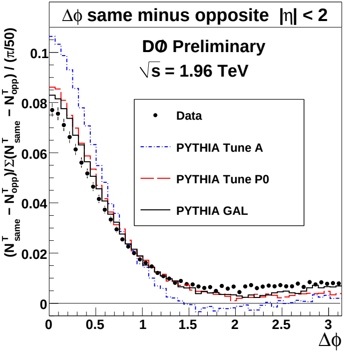
Maximised DØ acceptance: $|\eta| < 2$





- N^{track}(same side) − N^{track}(opposite side) wrt. leading p_T track
- Observables chosen for minimal systematic uncertainties (fake rates, efficiencies)
  $\Rightarrow$ ideal candidates for Tuning
- Large differences between tunes





Hyperon production in minimum bias events

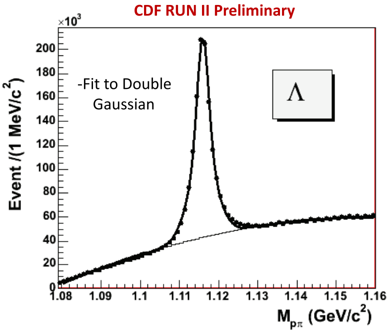
CDF Collab., prelim. (2010), CDF Note CDF/PUB/QCD/PUBLIC/10084

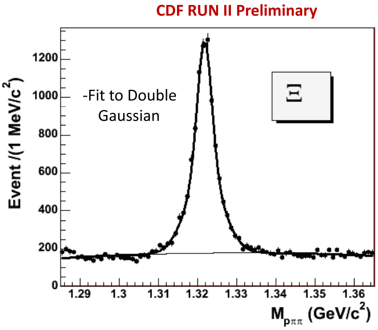
Data $\in [2002, 2008]$

- $\Lambda^0, \bar{\Lambda}^0 \to p\pi^-$
- Cascade decays:
  - $\Xi^- \to \Lambda\pi^- \to (p\pi^-)\pi^-$
  - $\Omega^- \to \Lambda^0 K^-, (\Xi^0\pi^-, \Xi^-\pi^0) \to p\pi^- K^-$
- Assigning p mass to high p_T track
- Reconstructing invariant Λ (Ξ, Ω) mass

Λ reconstruction:

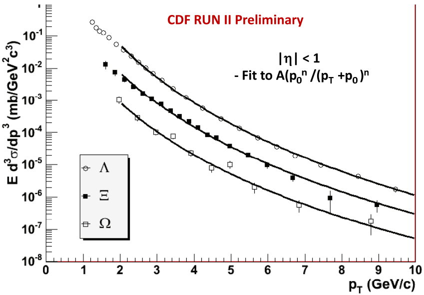
- Two oppositely charged tracks, $p_T > 0.325$ GeV, $|\eta| < 1$
- Secondary vertex $(\Delta Z_{1,2} < 1.5$ cm, $L_\Lambda > 2.5$ cm$)$

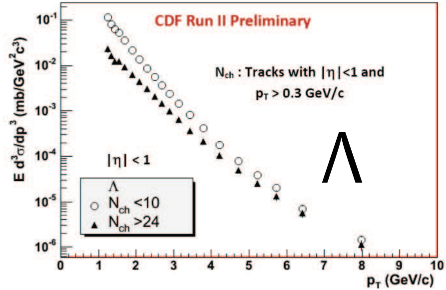


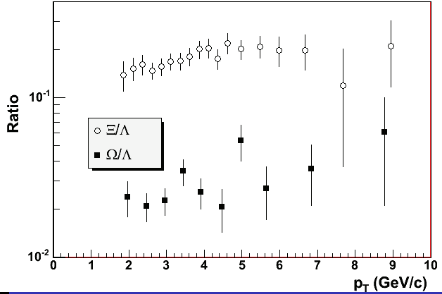


Hyperon production in minimum bias events

- Inclusive invariant p_T distribution for Λ, Ξ and Ω
- Acceptance corrected
- Fit to functional form $(A)(p_0)^n/(p_T + p_0)^n$ (power law)
- Two different track multiplicity regions: $N_{\text{ch}} < 10$, $N_{\text{ch}} > 24$
- Lower slope for lower multiplicity
- Production ratios constant over p_T





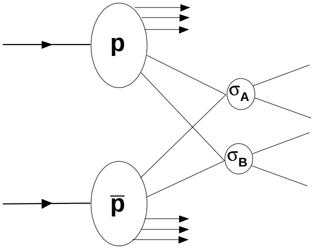


Double parton scattering in $\gamma + 3$ jet events

DØ Collab., PRD **81**, 052012 (2010)

$\mathcal{L} = 1.0\ \text{fb}^{-1}$

- Complementary information about proton structure: Spatial distribution of partons
  $\Rightarrow$ Possible parton-parton correlations. Impact on PDF's?
- Background in signal events (important for rare processes)

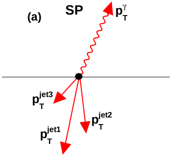


Event selection:

- $60 < p_T^{\gamma} < 80$ GeV
- Isolated
- $p_T^{\text{1st jet}} > 25$ GeV
- $p_T^{\text{2nd, 3rd jet}} > 15$ GeV

Main background:

Single parton scattering



$\sigma_{DP} = m \cdot \frac{\sigma_a \sigma_B}{2\sigma_{eff}}$ $(m = 2$ for $A \neq B)$

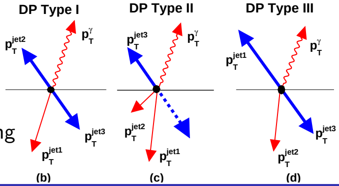
σ_A, σ_B: cross sections of processes A, B

σ_{eff}: $\sim$ size of effective interaction region

$\sigma_B / 2\sigma_{eff}$: prob. of 2^{nd} interaction, given 1^{st} one

Signal:

Double parton scattering



Double parton scattering in $\gamma + 3$ jet events

Discriminating variables

$$S_{p_T} = \frac{1}{\sqrt{2}}\sqrt{\left(\frac{|\vec{P_T}(\gamma,i)|}{\delta P_T(\gamma,i)}\right)^2 + \left(\frac{|\vec{P_T}(j,k)|}{\delta P_T(j,k)}\right)^2}$$

$$S_{p'_T} = \frac{1}{\sqrt{2}}\sqrt{\left(\frac{|\vec{P_T}(\gamma,i)|}{|\vec{P}_T^{\gamma}|+|\vec{P}_T^{i}|}\right)^2 + \left(\frac{|\vec{P_T}(j,k)|}{|\vec{P}_T^{j}|+|\vec{P}_T^{k}|}\right)^2}$$

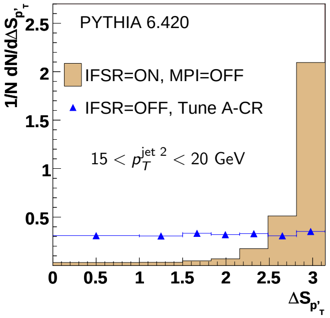
$$S_{\phi} = \frac{1}{\sqrt{2}}\sqrt{\left(\frac{\Delta\phi(\gamma,i)}{\delta\phi(\gamma,i)}\right)^2 + \left(\frac{\Delta\phi(j,k)}{\delta\phi(j,k)}\right)^2}$$

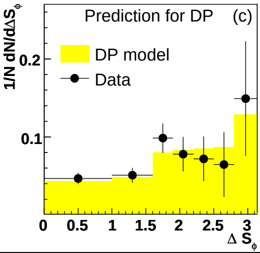
Computed for pair with minimum S

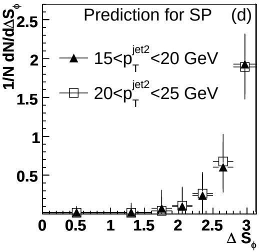
$$\Delta S = \Delta\phi(\vec{P}_T(\gamma,i), \vec{P}_T(j,k))$$

- Measurements in three bins of 2nd jet p_T: 15-20, 20-25 and 25-30 GeV
- Using data driven techniques (diff. p_T spectra)

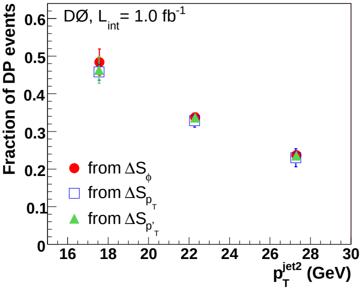
PYTHIA ΔS prediction

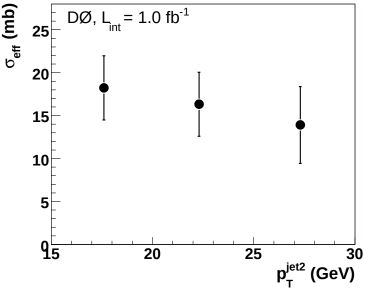






Double parton scattering in $\gamma + 3$ jet events





- DP fractions drop from 0.47 ($15 < p_T^{\text{2nd jet}} < 20$) to 0.23 ($25 < p_T^{\text{2nd jet}} < 30$)
- Average over three p_T bins: $< \sigma_{eff} >= 16.4 \pm 0.3(\text{stat}) \pm 2.3(\text{syst})$ mb
- Good agreement with previous CDF measurements in 4 jet and $\gamma + 3$ jet events

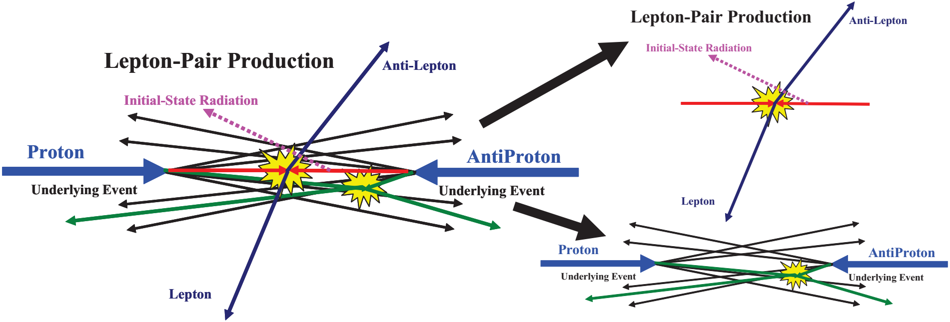
Spatial parton density models

Model	$\rho(r)$	σ_{eff}	R_{rms} (fm)
Solid sphere	const., $r < r_p$	$4\pi r_p^2/2.2$	0.41 ± 0.05
Gaussian	$e^{-r^2/2a^2}$	$8\pi a^2$	0.44 ± 0.05
Exponential	$e^{-r/b}$	$28\pi b^2$	0.47 ± 0.06

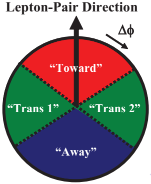
Underlying Event in Drell-Yan production

CDF Collab., Phys. Rev. **D82**, 034001 (2010), arXiv:1002.3146 $\mathcal{L} \simeq 2.7\ \mathrm{fb}^{-1}$

No final state gluon radiation in Drell-Yan production (compared to jet production)

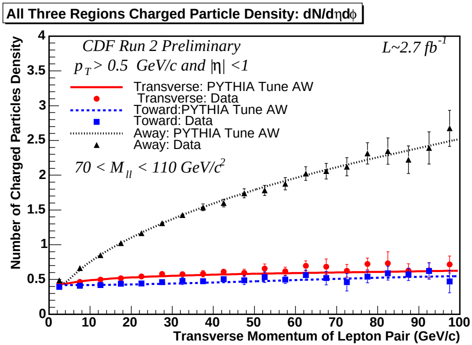


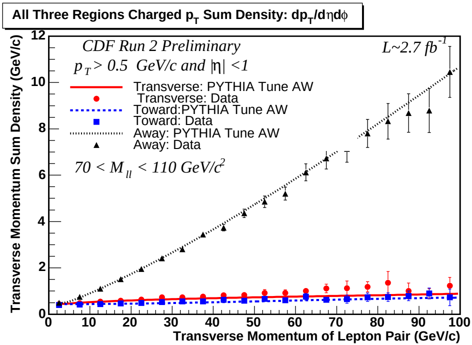
- Lepton pair $\ell^+\ell^-$ $p_T > 20$ GeV, $|\eta| < 1$, $70 < M_{\ell\ell} < 120$ GeV
- Charged tracks $0.5 < p_T < 150$ GeV
- Reconstructed objects corrected to particle level



- 3 regions: Toward $|\Delta\phi| < 60°$, Tranverse $60° < |\Delta\phi| < 120°$, Away $|\Delta\phi| > 120°$

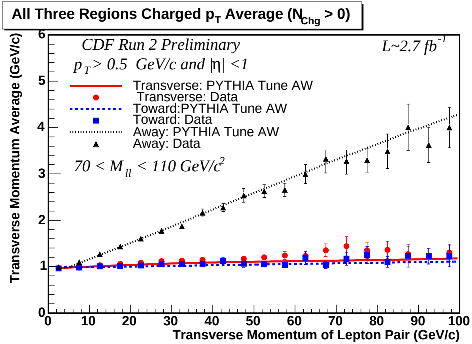
Underlying Event in Drell-Yan production

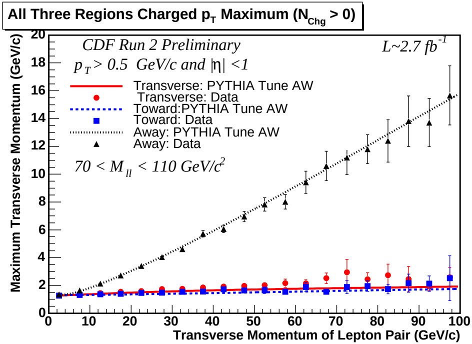




- Toward and transverse regions (excluding leptons) very sensitive to UE
- Pythia model with Tune AW parameter settings is able to describe data quite well. Though not perfect.

Underlying Event in Drell-Yan production





- Pythia model with Tune AW parameter settings is able to describe data quite well.
- Though not perfect.
- HERWIG + JIMMY (not shown) produces softer $< p_T >$ spectrum
- Drell-Yan underlying event behaves similar compared to high p_T leading jet events

Event shapes: Thrust and Minor Thrust

CDF Collab., prelim. (2010), `http://www-cdf.fnal.gov/physics/new/qcd/QCD.html`

$\mathcal{L} = 2.0\ \text{fb}^{-1}$

- Geometric properties of QCD final state energy flow (E [1st jet] > 200 GeV, $|\eta_{\text{jets}}| < 0.7$)
- Understanding dynamics of soft perturbative QCD

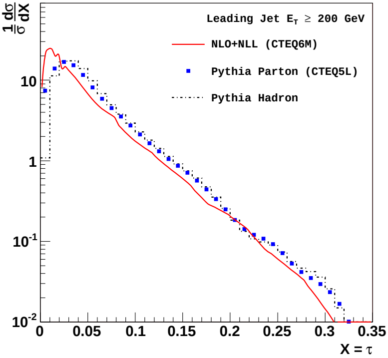
Thrust major: $T_M \equiv \max_{\vec{n} \cdot \vec{n}_T} \frac{\sum_i |\vec{p}_i \cdot \vec{n}|}{\sum_i |\vec{p}_i|}$

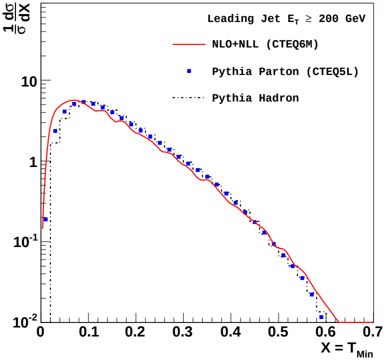
Thrust: $1 - \tau \equiv 1 - \max_{\vec{n}} \frac{\sum_i |\vec{p}_i \cdot \vec{n}|}{\sum_i |\vec{p}_i|}$

pencil vs. spheric like events

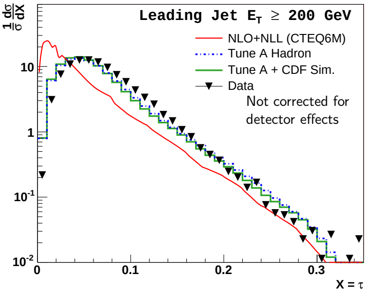
Thrust minor: $T_{\text{min}} \equiv \frac{\sum_i |p_{\perp,i}|}{\sum_i |\vec{p}_i|}$

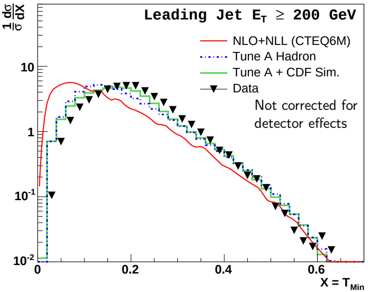
measures radiation out of τ , T_M plane



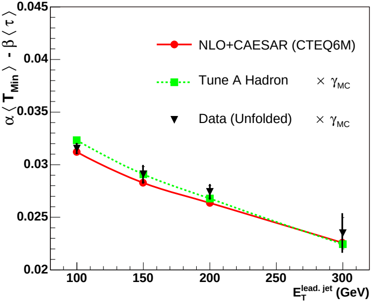


Event shapes: Thrust and Minor Thrust





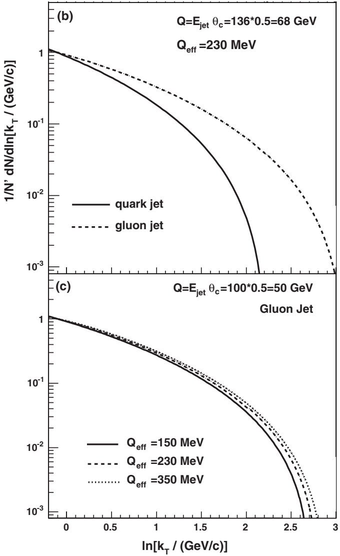
- Underlying event alters over-all shape
- Reconstruct linear combination observable $\mathcal{O}(<\tau>, <T_{\min}>)$
  $= \gamma_{MC}(\alpha < T_{\min} > - \beta < \tau >)$
  with $\alpha = 1 - 2/\pi$, $\beta = 2/\pi$,
  γ_{MC} = MC based normalisation factor
  $\Rightarrow$ Independant of UE



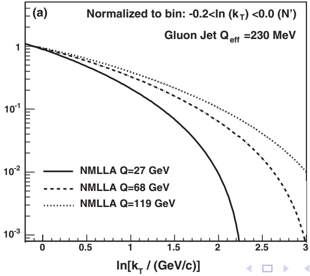
k_T distributions of particles in jets

CDF Collaboration, Phys. Rev. Lett. **102**, 232002 (2009)

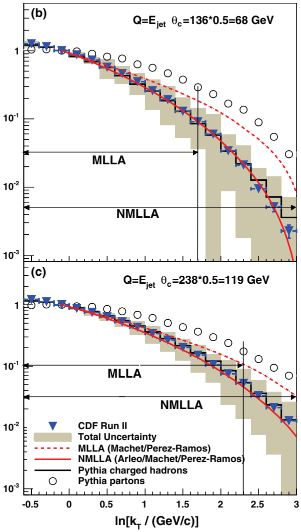
$\mathcal{L} \simeq 775\ \mathrm{pb}^{-1}$



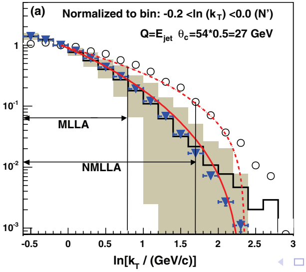
- Test pQCD to soft process of jet fragmentation
- Probing boundary between parton shower and hadronisation
- Checking Local Parton Hadron Duality (LPHD)
- Measure k_T of particles in cone $R = 0.5$ in jet (R=1.0)
- Jets balanced in E_T, $E_{T,\mathrm{min}}^{\mathrm{trig}} = 5$ GeV
- ≤ 2 extra jets $E_T^{\mathrm{extra}} < 5.5$ GeV $+0.065(E_T^1 + E_T^2)$



k_T distributions of particles in jets



- Shape comparison: theory normalised to data in bin $-0.2 < ln\,[k_T/\text{GeV}] < 0.0$
- Three Q (and corresponding dijet mass) bins:
  $Q = 27$ GeV, $95 < M_{jj} < 132$ GeV
  $Q = 68$ GeV, $243 < M_{jj} < 323$ GeV
  $Q = 119$ GeV, $428 < M_{jj} < 563$ GeV
- MLLA and NMLLA resummations describe data well in their region of validity
- Hadronisation effects are small $\Rightarrow$ further support for LPHD



- Conclusions

Conclusions

- Tevatron provides unique $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV with zero crossing angle ($\sqrt{s} = 1.8$ TeV in Run I)

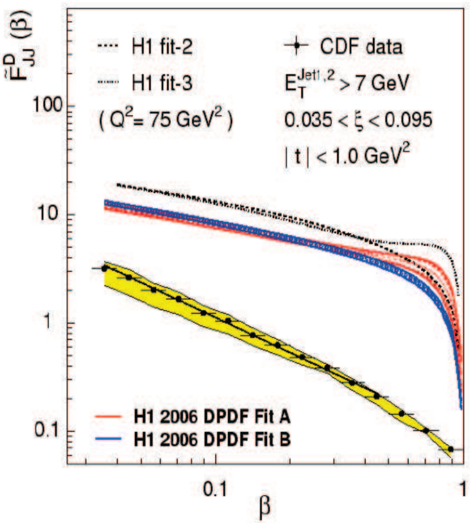
- Predictions agree in general with measurements

- Diffractive and Underlying Event
  - studies were in many cases pioneering
  - Methods established, widely used by LHC experiments today
  - Provided very important input to theorists, in particular for non-pQCD physics (theoretical models varying by quite a lot)

- In Run I ($\sqrt{s} = 1.8$ TeV) Tevatron/CDF provided already useful input for diffractive PDF's (breakdown of factorisation between HERA and Tevatron)

- Backup slides

Diffractive Structure Function



$\sqrt{s} = 1.8$ TeV

- Factorisation breakdown between HERA and Tevatron
- Production rate for Tevatron should be ∼8 times higher

β-momentum fraction of parton in pomeron