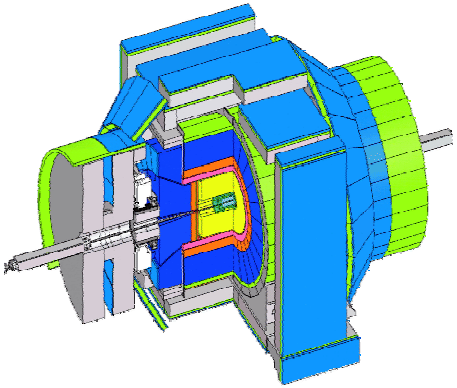
QCD at CDF



Régis Lefèvre

IFAE Barcelona

On behalf of the CDF Collaboration

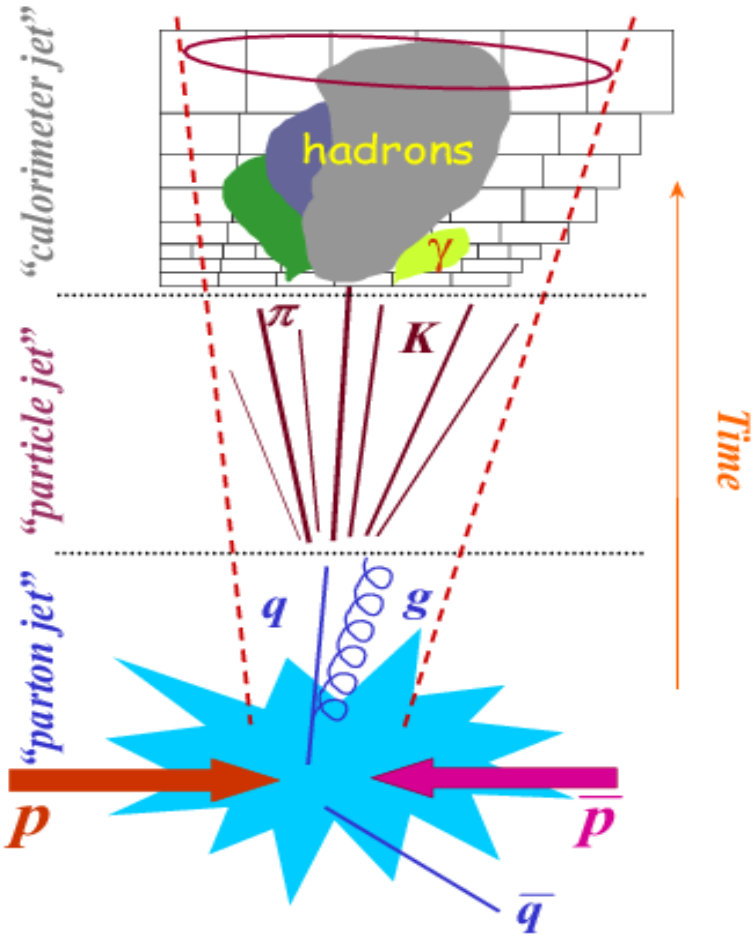
- Jet Inclusive Cross-Section
- Underlying event studies
- Jet Shapes
- Specific processes
  - W+Jets, $\gamma + \gamma$, γ + b/c, b-jet / $b\bar{b}$ jet
- Diffraction
  - Diffractive structure function, exclusive final states (dijets / χ_C)

Hadron Collider Physics 2004

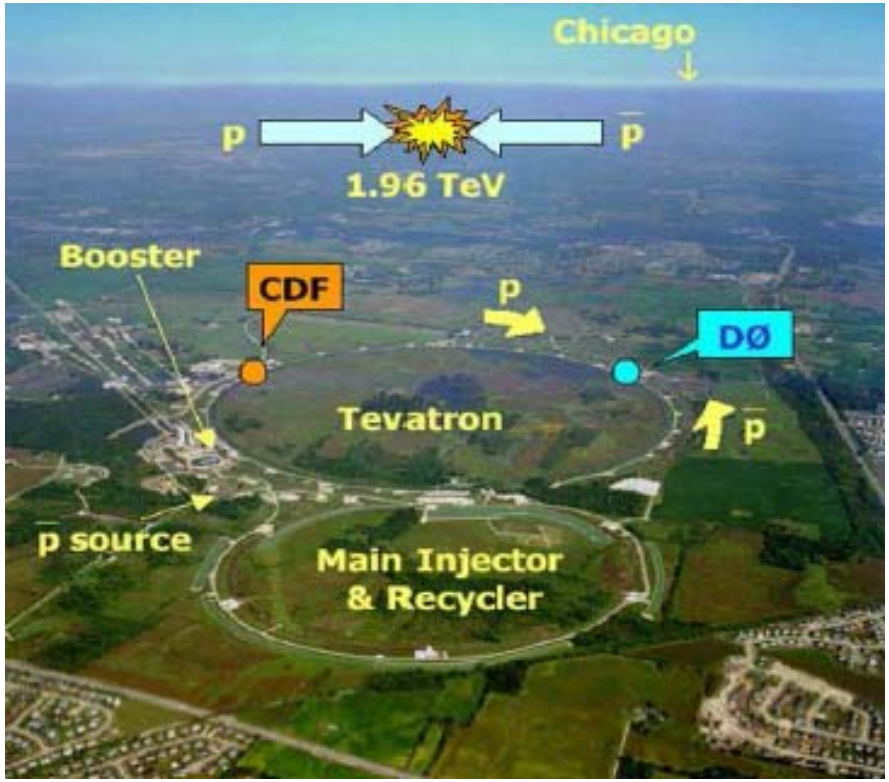
Michigan State University

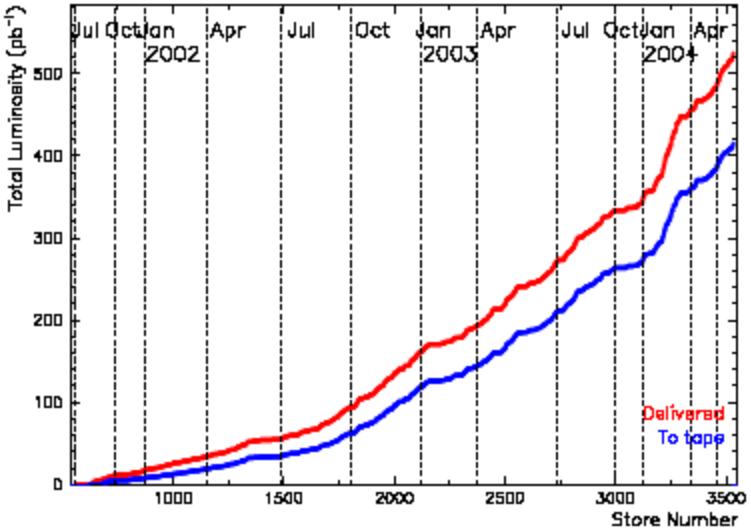
QCD at Tevatron

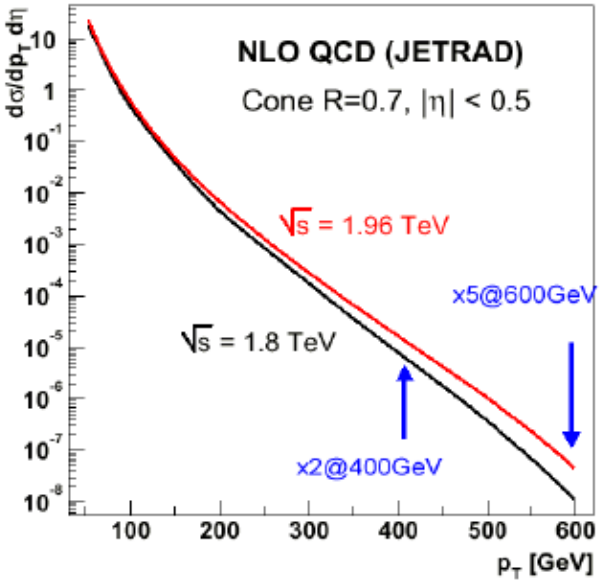
- Tevatron = Jet Factory
  - All production processes are QCD related
- Optimal understanding basic for all analyses
  - Fundamental parameters
    - High x gluon PDFs
  - Phenomenology of non-perturbative regime
    - Underlying Event modelling
  - Background for each process of interest
    - W+Jets for top and Higgs production
- Highest Q^2 probe: $\lambda \sim 10^{-19}$ m
  - Precise test of pQCD
  - Look for deviation → New Physics
- Other studies of interest
  - Heavy flavor, Diffraction…



About the Tevatron

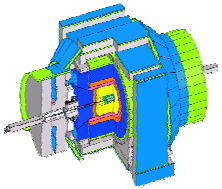




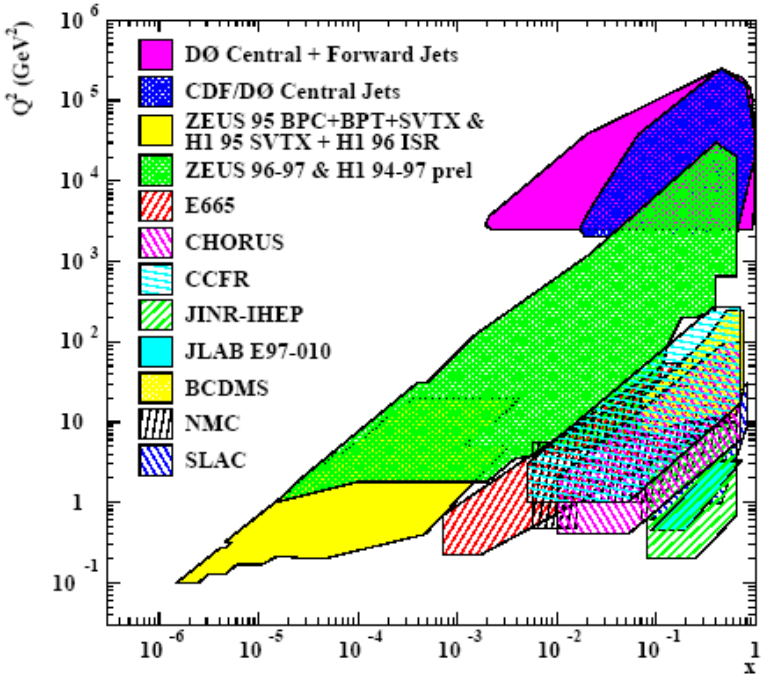


- Tevatron performing very well
  - Around 400 pb^{-1} on tape
- $\sqrt{s}$ enhancement appreciated
  - Increase kinematics range for jet production

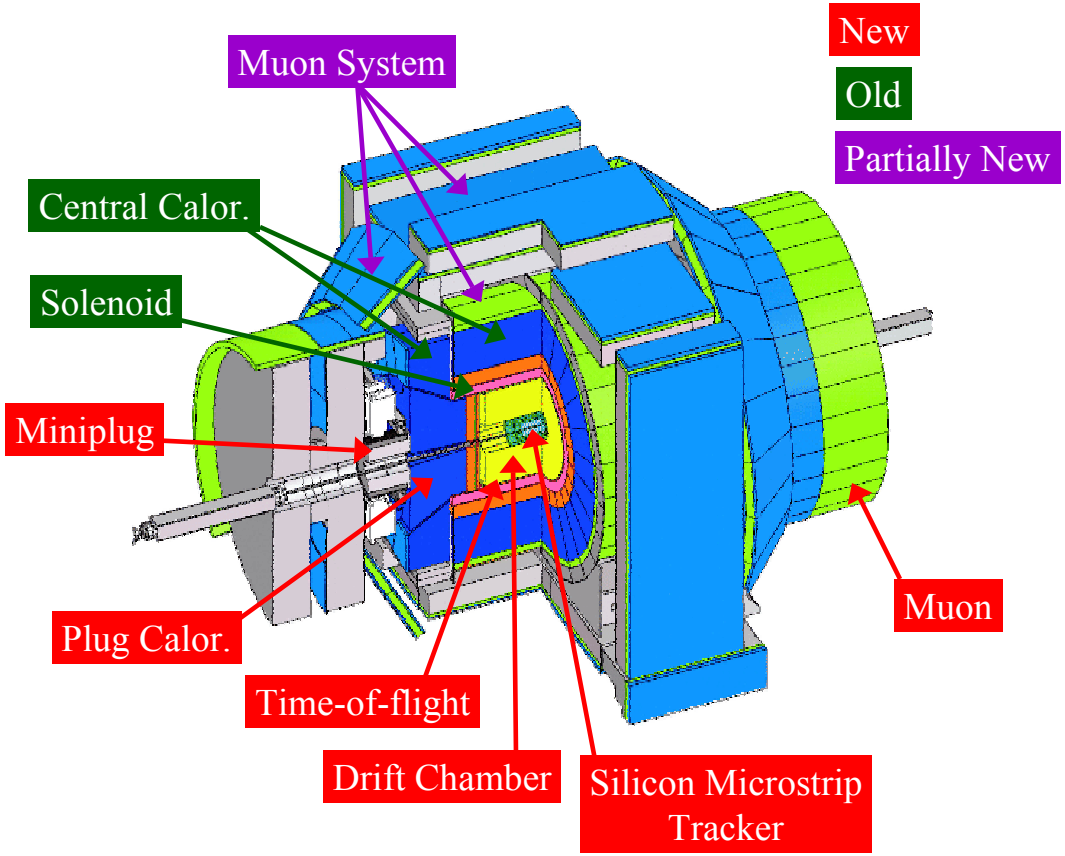
CDF Upgrades



- Si detector & Tracking
- Time of Flight detector
- Plug Calorimeters (up to $|\eta| = 3.6$)
  - Extend PDF measurement to lower x
- Forward detectors
  - Diffractive Physics
- Muon system
- DAQ electronics & Trigger

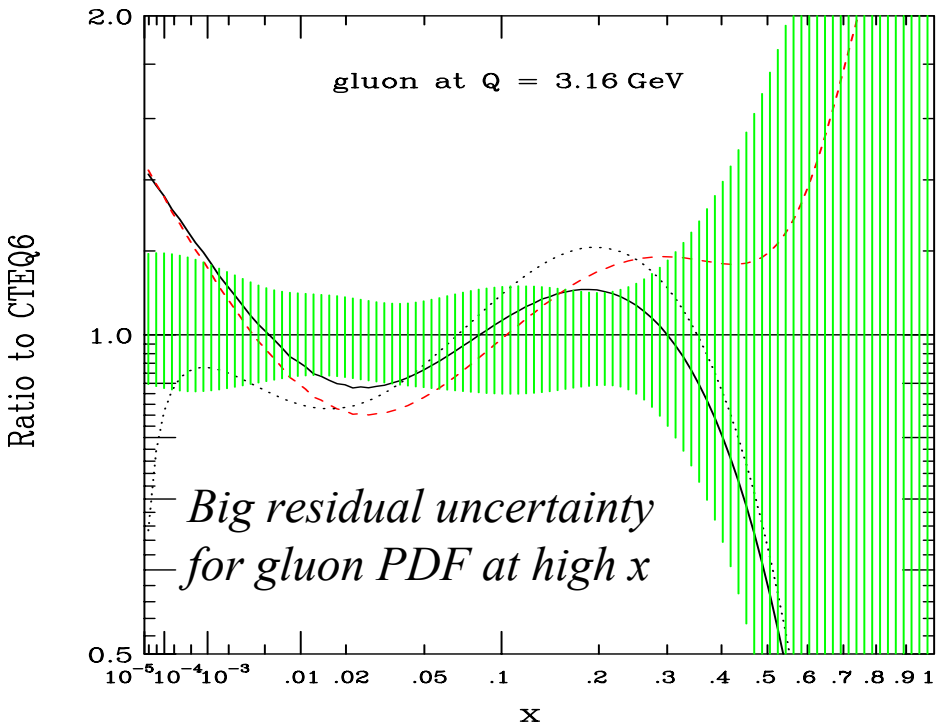


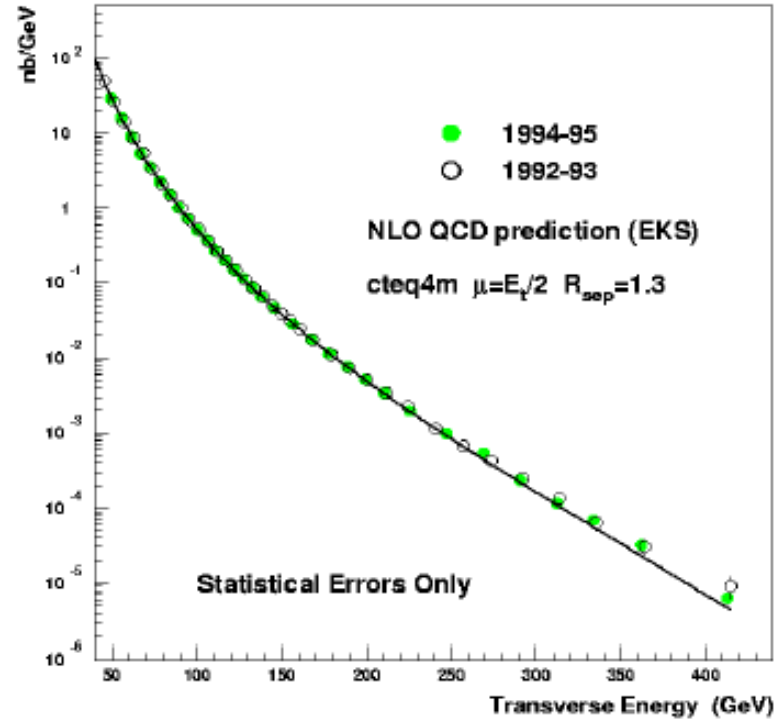
PDF measured region (CDF and D0: run I)



Inclusive Jet Cross Section

- Legacy from run I
  - Great interest about high E_T excess
  - SM explanation: increased high x contribution in gluon PDF
    - New PDFs from global fit including CDF/D0 high E_T data (CTEQ6, MRST2001)

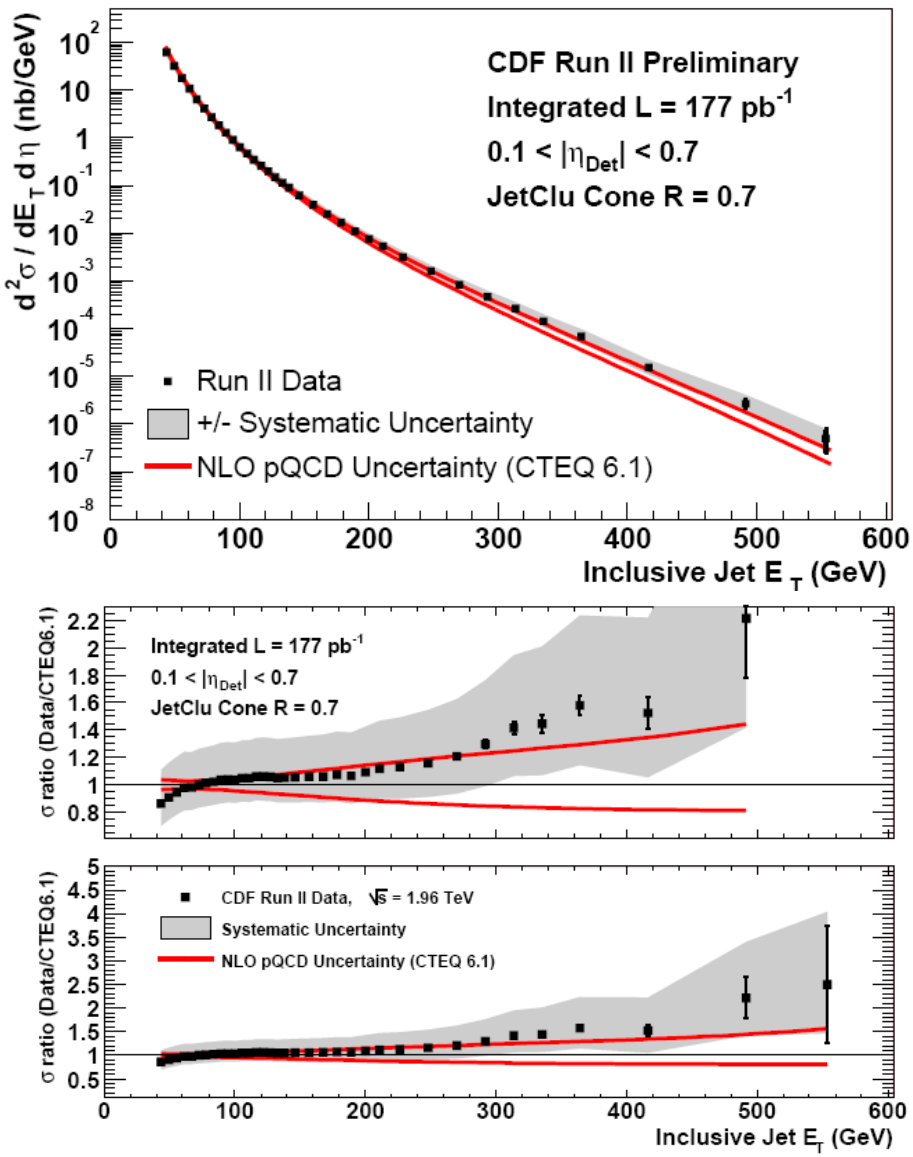




- Stringent test of pQCD
  - Over 8 order of magnitude
- Tail sensitive to new physics
  - Probing distance of 10^{-19} m
- Improve constraint on PDFs
  - Highest E_T reach / forward jets

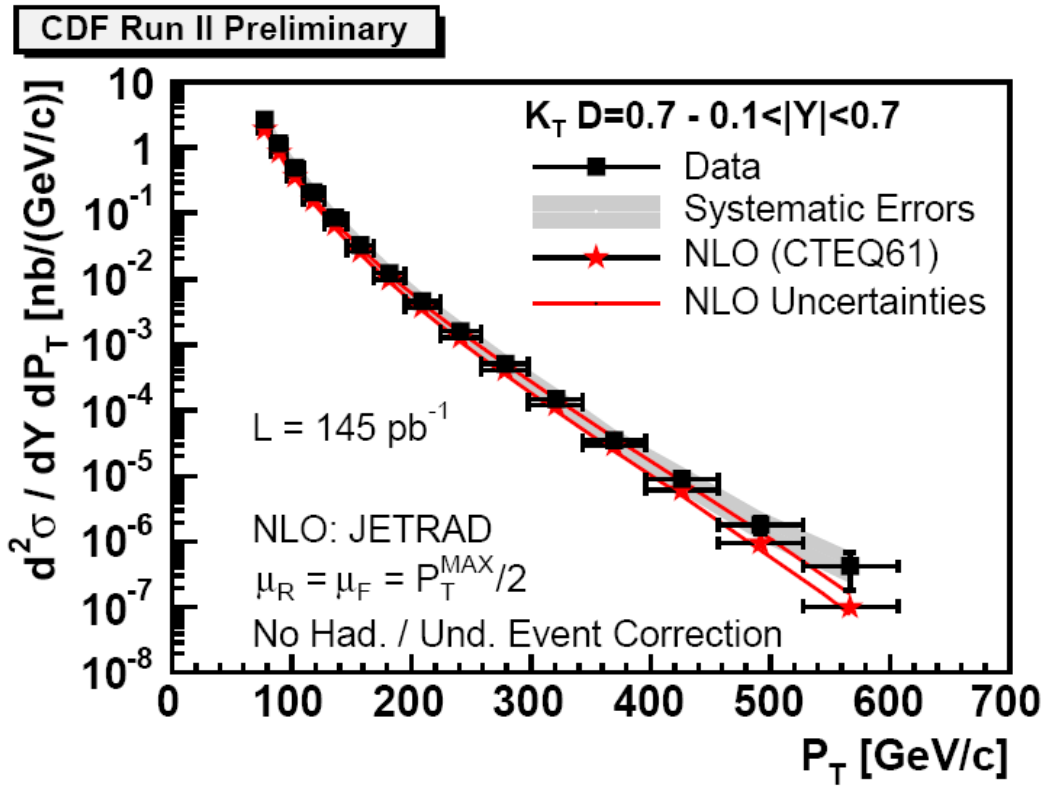
Jet Production with JetClu

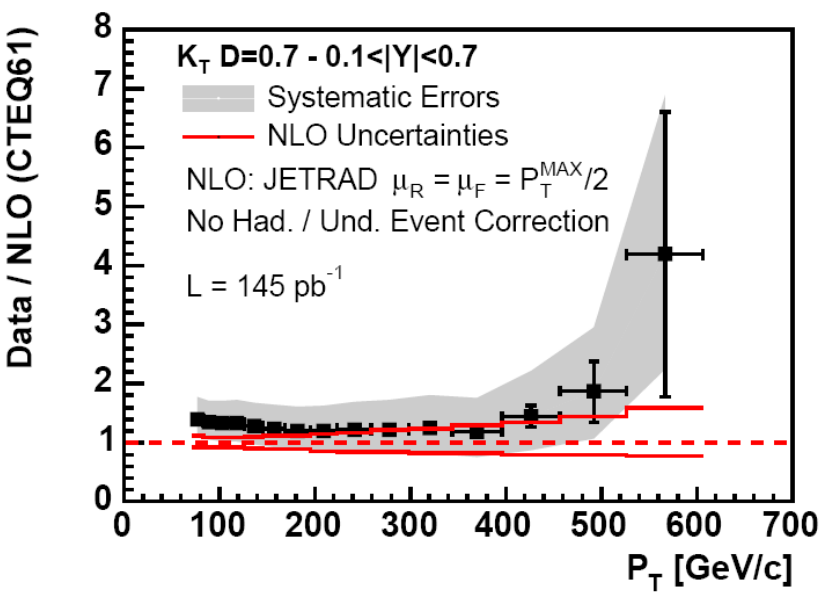
- NLO pQCD
  - EKS
    - $\mu = E_T/2$
    - $R_{SEP} = 1.3$
  - CTEQ6.1 PDFs
    - Include Run I results
- Run I reach extend by ~ 150 GeV
  - Reasonable data-theory agreement
    - Experimental uncertainty dominated by energy scale
    - Largest theoretical error from PDFs (high x gluon)
  - NLO not corrected for hadronisation
    - Particle level compared to parton level



Jet Production with K_T

- K_T preferred by theory
  - Infrared and collinear safe to all orders in pQCD
  - No merging / splitting
    - No R_{SEP} issue comparing to pQCD

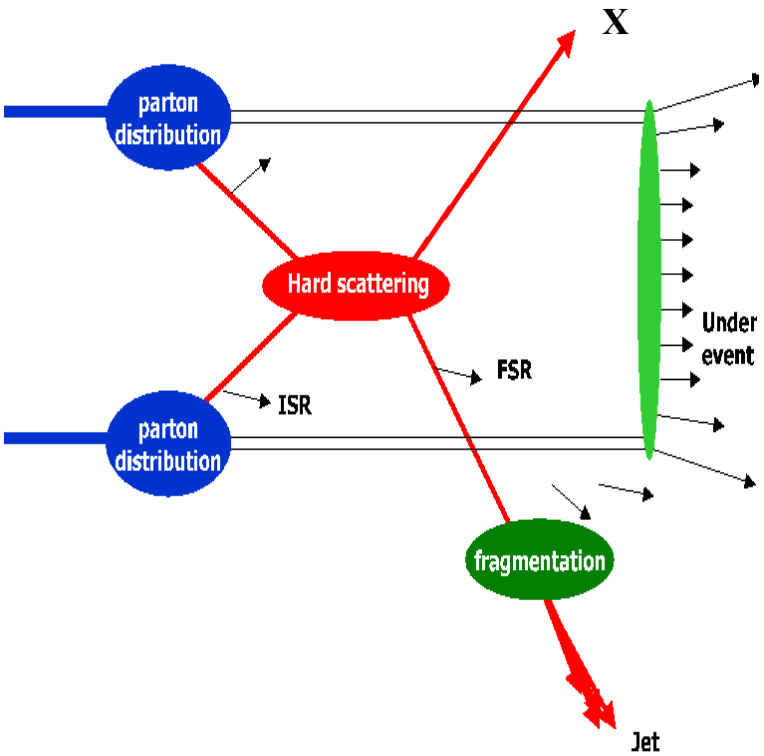


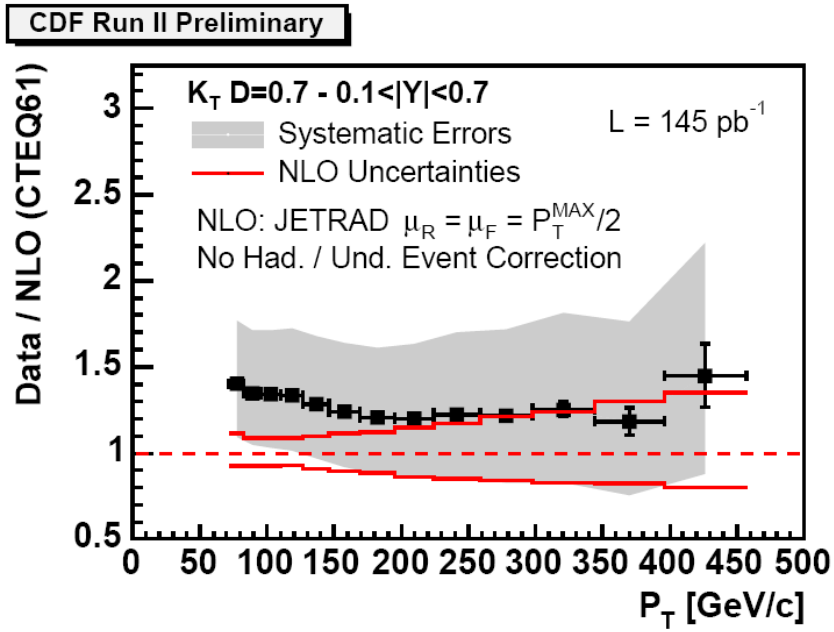


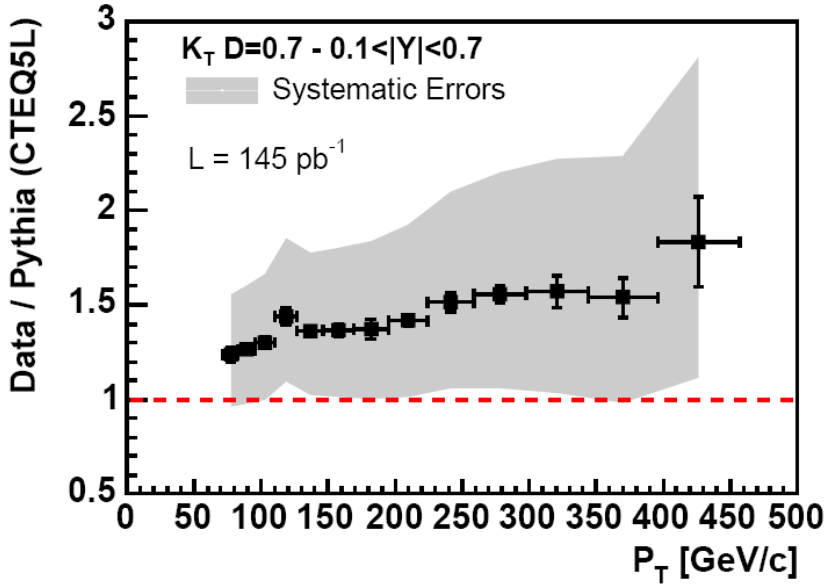
- Reasonable data-theory agreement
- NLO still need to be corrected for Hadronisation / Underlying Event

Jet Production: Ongoing Studies

- Hadronisation correction
- Reduction of systematic
- Midpoint
- Forward jets

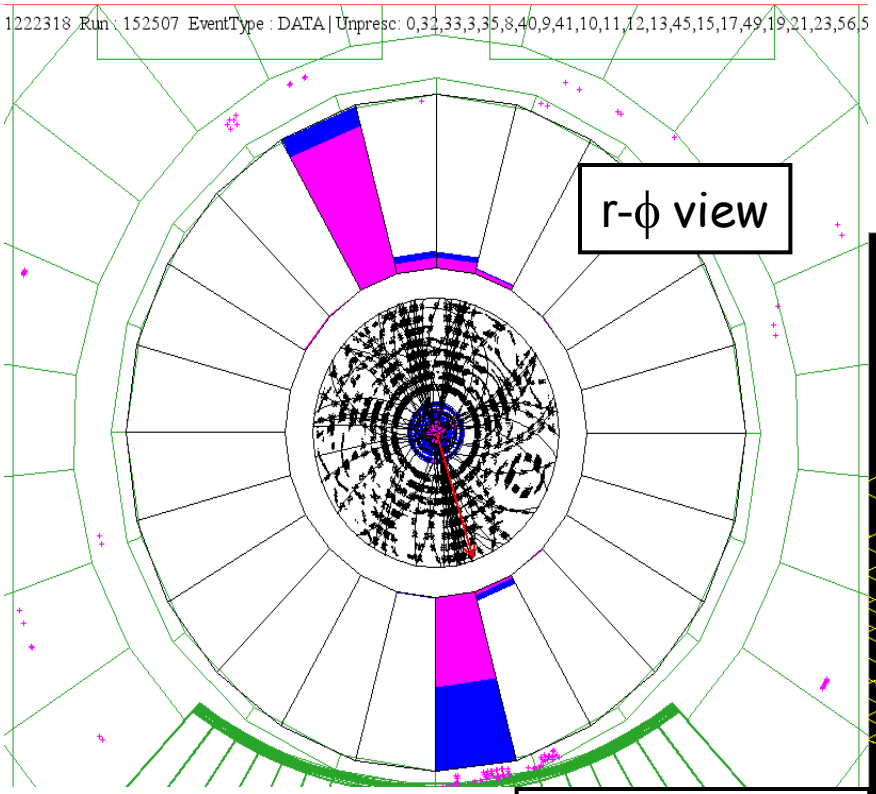




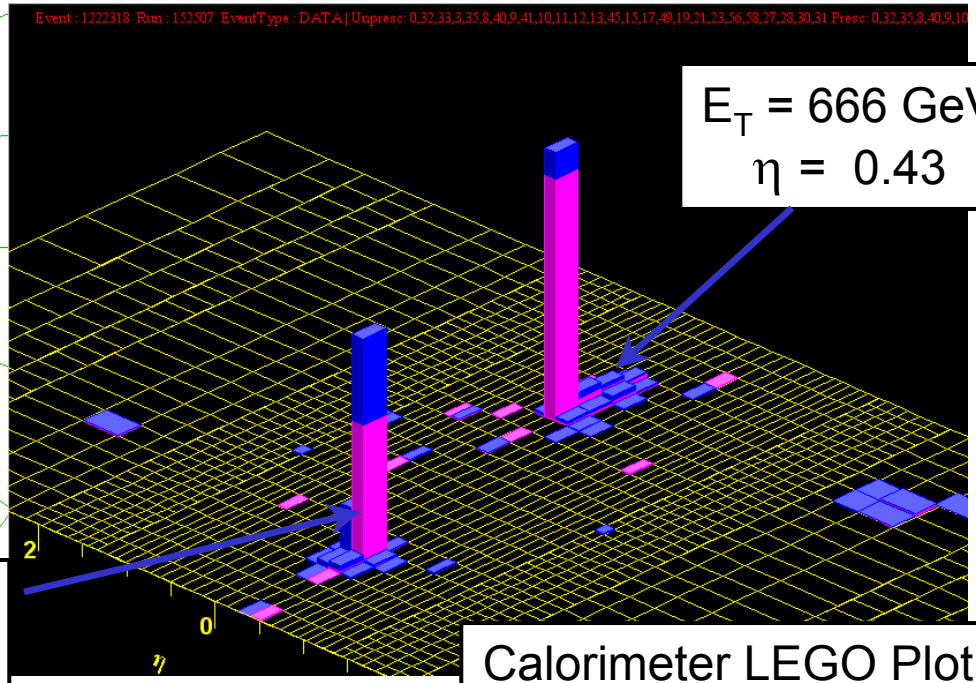


Highest Mass Dijet Event So Far

Mass = 1374 GeV/c^2



E_T = 633 GeV
η = -0.19



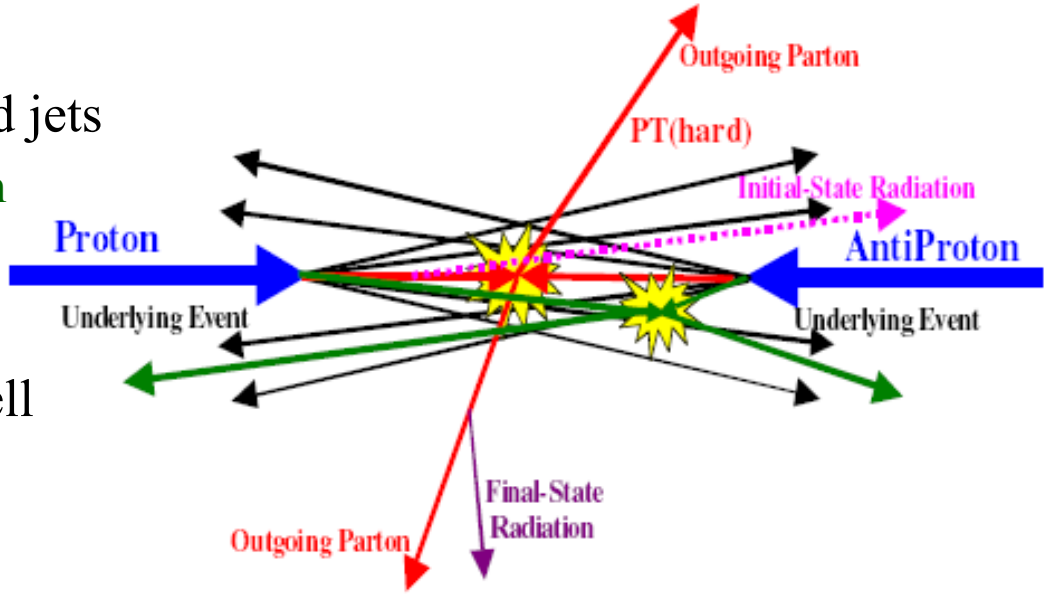
E_T = 666 GeV
η = 0.43

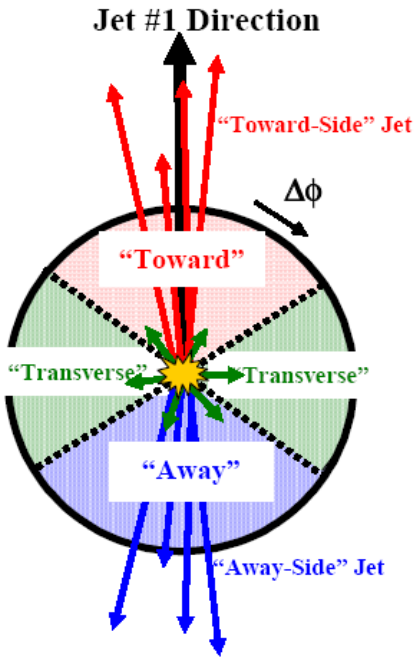
Calorimeter LEGO Plot

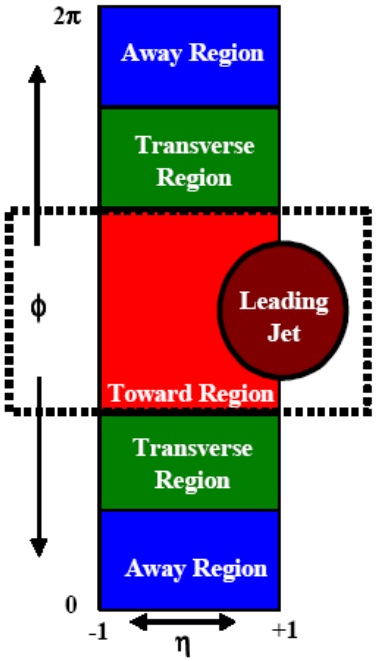
Underlying Event Studies

Underlying Event

- Everything but the 2 hard scattered jets
  - Hard initial and final state radiation
  - Beam-beam remnants
  - Multiple parton interaction
- Unavoidable background NOT well defined / modeled theoretically





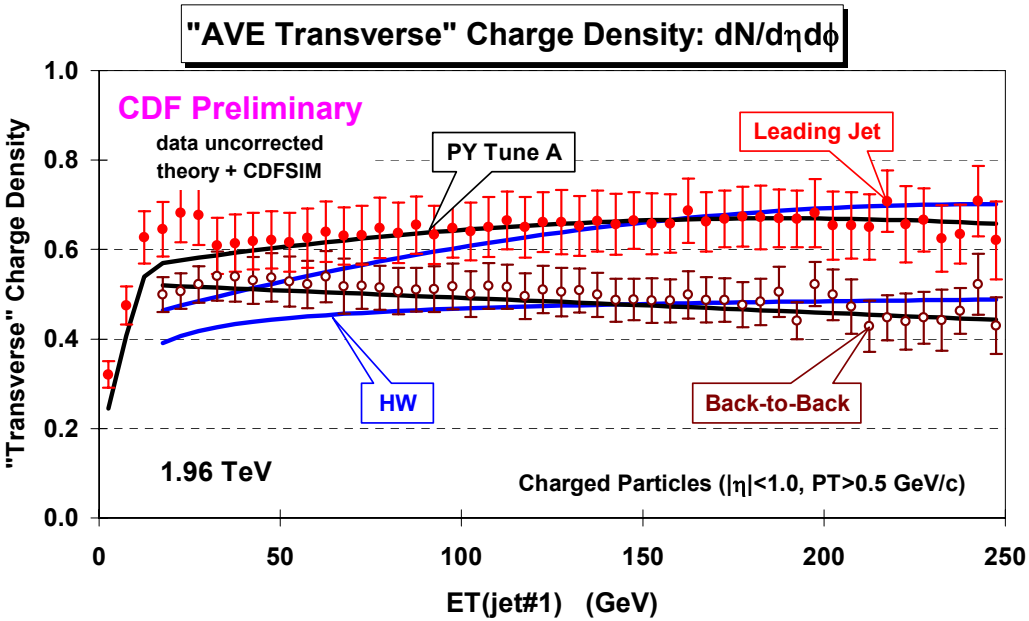


Phenomenological studies

- Leading calorimeter jet (JetClu R = 0.7, $|\eta| < 2$)
  - Define 3 regions of same size in η-ϕ space
    - "Transverse" region very sensitive to U.E.
- Charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$)
  - $\Delta\phi$ correlations with respect to leading jet

Underlying Event Studies

- Study "transverse" region for 2 topologies
  - Leading jet
    - No prescription on second jet
  - Back-to-back
    - 12 > 150, ETJ1 / ETJ2 > 0.8
      - Hard ISR and FSR suppressed

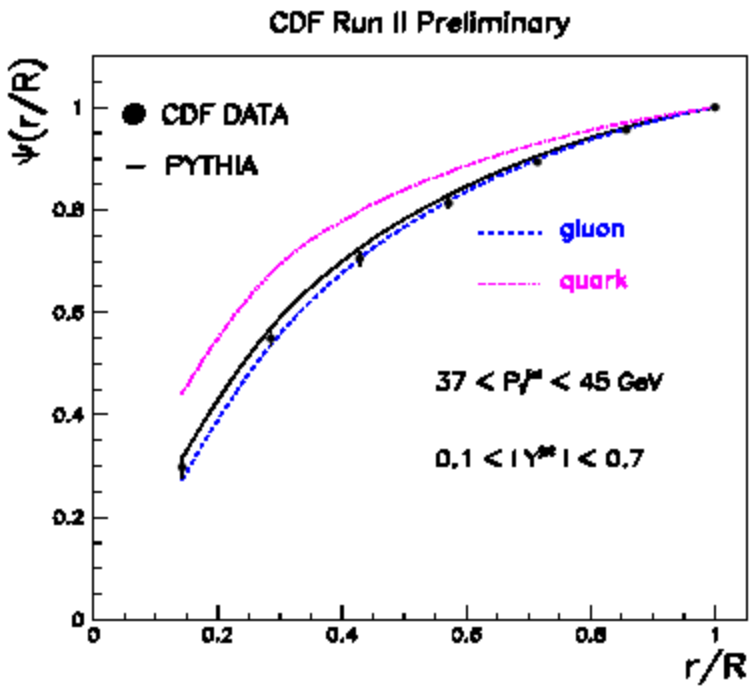


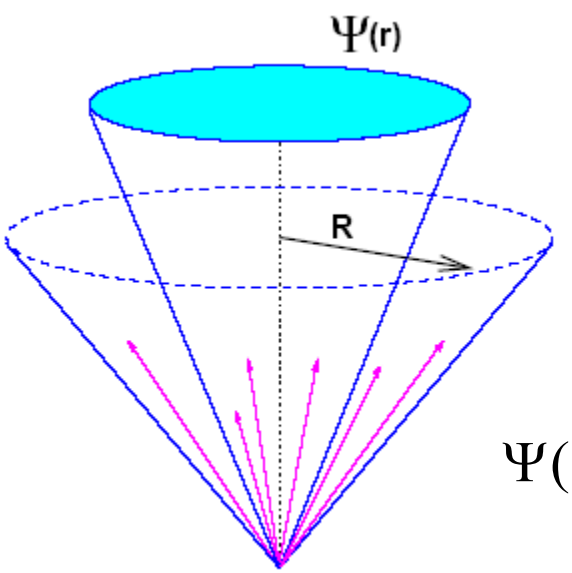
- Data not well reproduced by current MC with default settings
  - Pythia (6.026) tuned on Run I data with multiple parton interaction
    - Pythia Tune A
- Compare data with MC dijet events after detector simulation
  - Pythia Tune A in good agreement with Run II data
  - Herwig (no multiple parton interaction) works only at high ET

Energy Flow Inside Jets

Jet shapes governed by multi-gluon emission from primary parton

- Test of parton shower models
- Sensitive to underlying event structure
- Sensitive to quark and gluon mixture in the final state

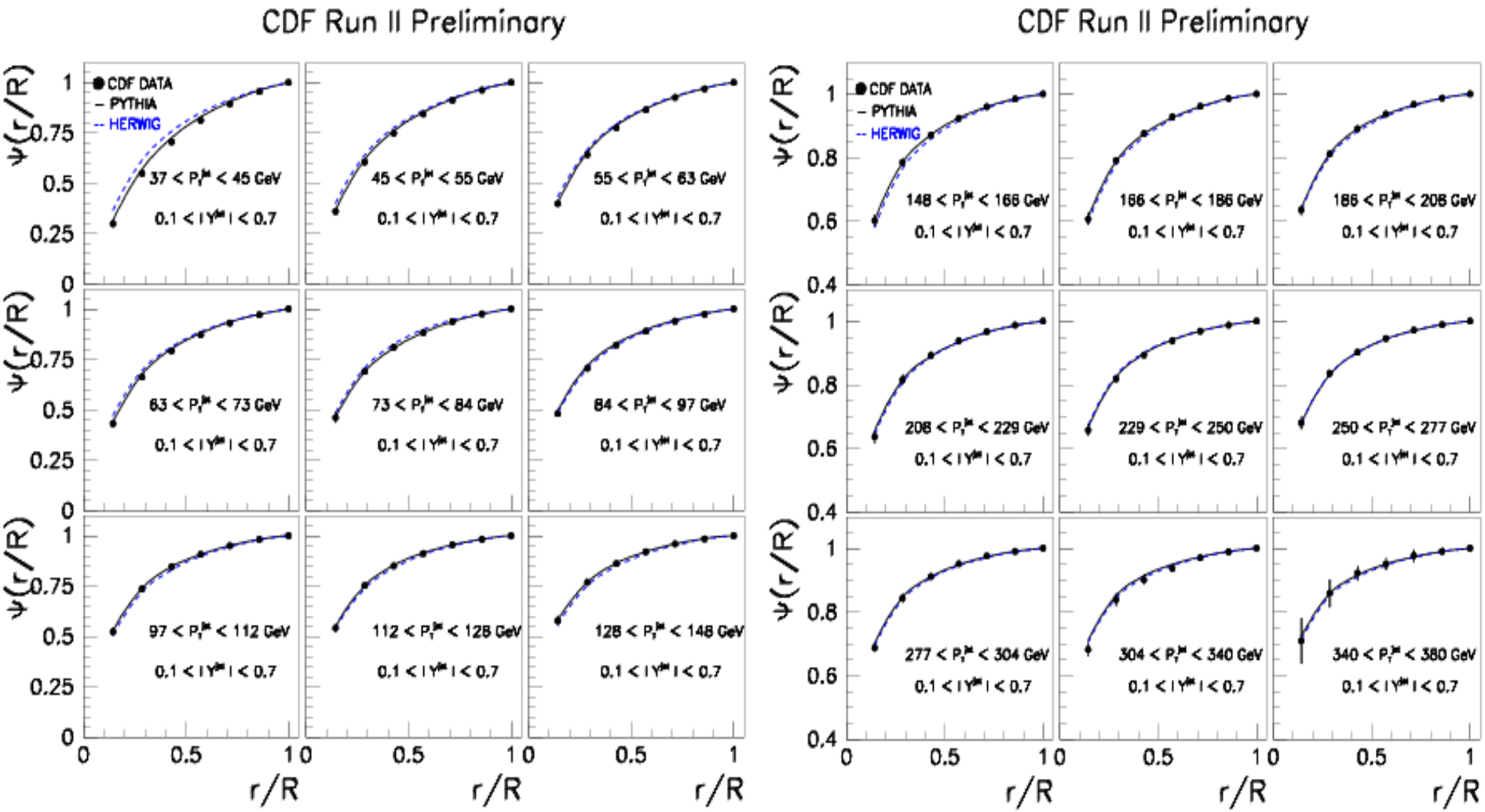




$$\Psi(r) = \frac{1}{N_{jets}} \sum_{jets} \frac{P_T(0,r)}{P_T(0,R)}$$

Midpoint: R = 0.7
- 0.1 < |Y| < 0.7
- 37 < P_T < 380 GeV/c

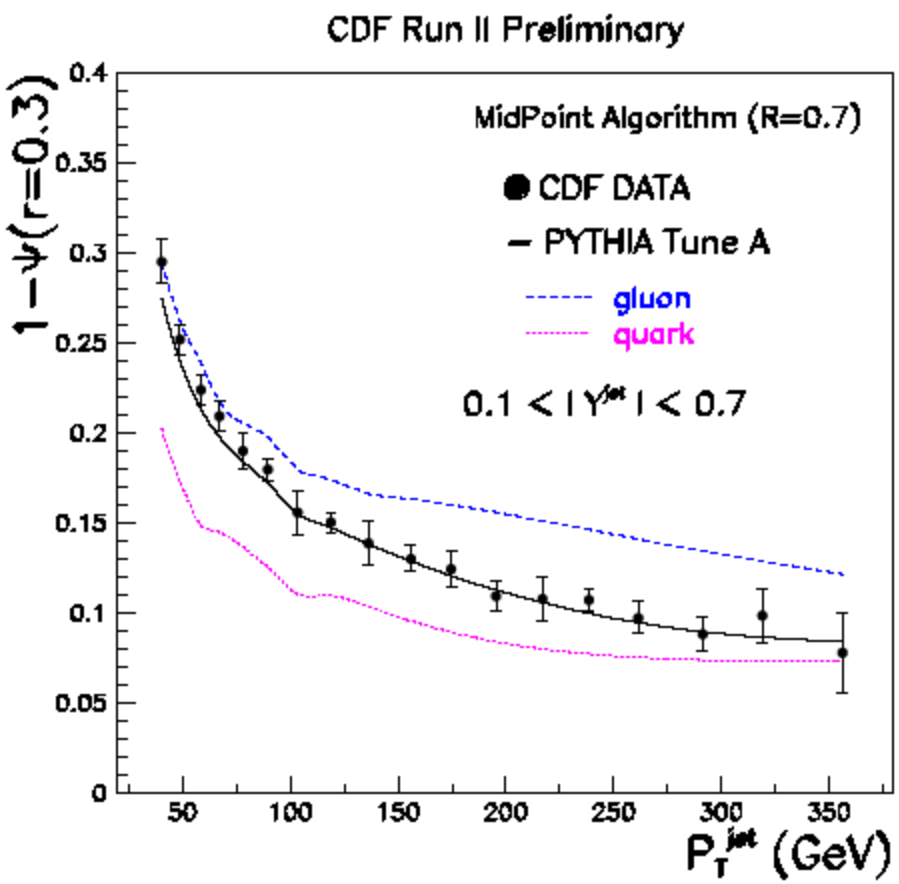
Jet Shape Measurements

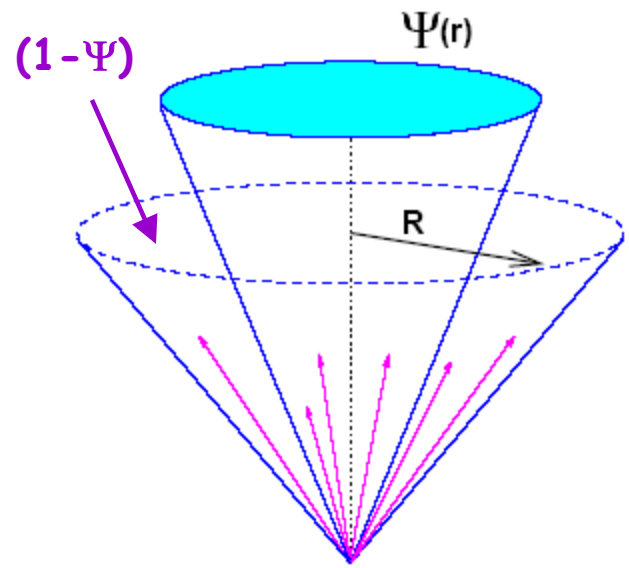


Select a fixed point $\psi(r/R = 0.3/0.7)$ and study P_T evolution…

Jet Shapes vs. P_T

Fraction of transverse momentum outside a fixed inner cone (r = 0.3 / R = 0.7)





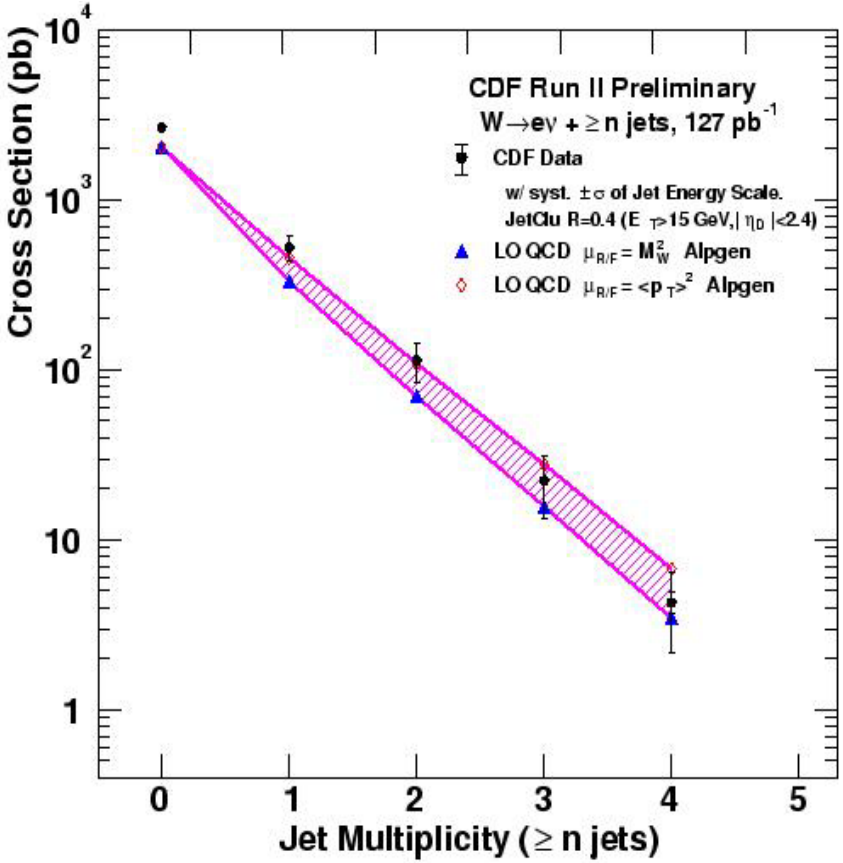
- Related to the running of α_S
- Able to study the evolution of the quark and gluon content
- Data very well described by Pythia Tune A

W+Jets Cross Section

- Test of pQCD at high Q^2 ($\geq M_W$)
- Fundamental channel for SM and new physics processes
  - top quark measurements
  - Higgs and Susy searches
- LO pQCD: ALPGEN
  - CTEQ5L
  - $\mu = M_W^2$ and $\mu = \langle P_T \rangle^2$

$\oplus$ Herwig $\oplus$ detector simulation

- Data-Theory agreement within errors
  - Experimental error dominated by jet energy uncertainty
  - Theoretical errors dominated by μ dependency

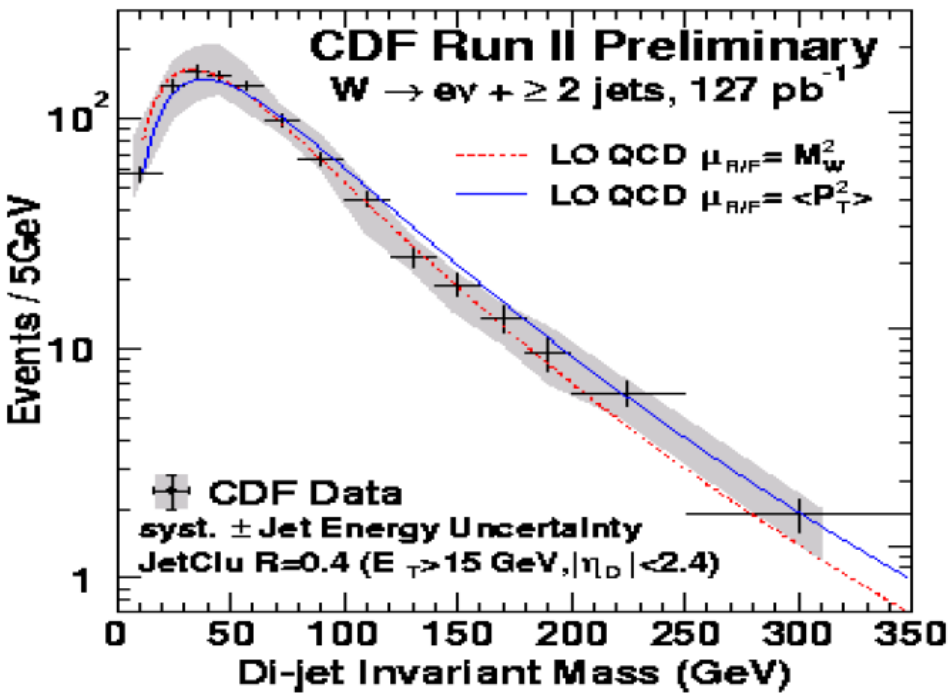


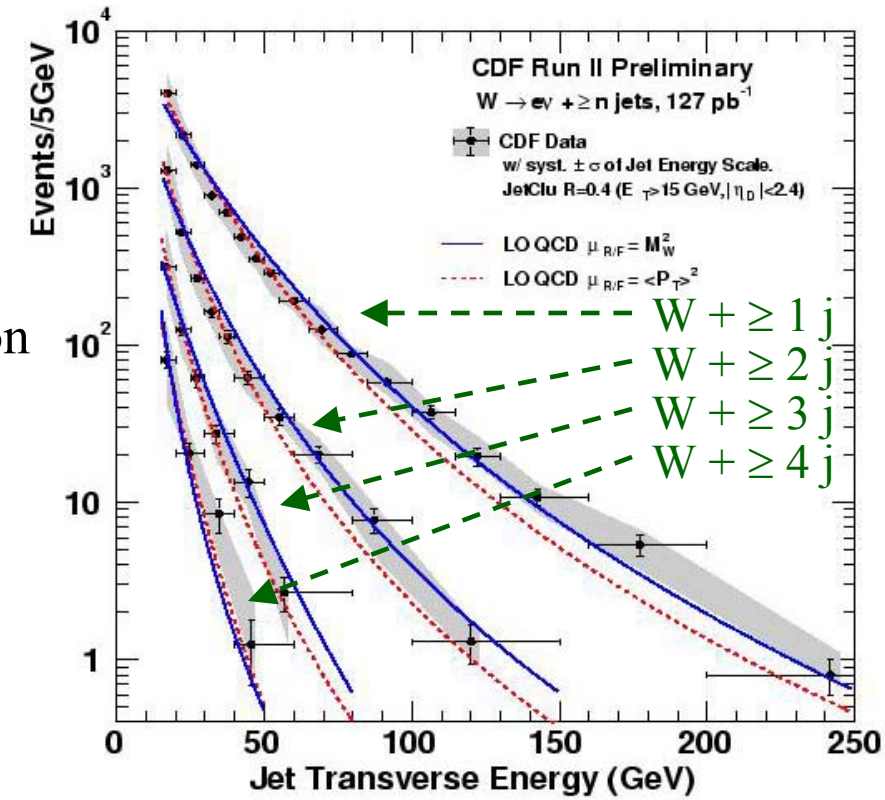
Systematic Uncertainty
~ 13 % for $\sigma_{\geq 1}$
~ 45 % for $\sigma_{\geq 4}$

W+Jets Cross Section

Kinematics distributions

- Differential cross section vs. E_T of the n-th highest E_T jet in W + ≥ n jets
  - Reduced dependence on μ
- Dijet invariant mass and angular separation
  - Sensitive to soft/collinear jet production

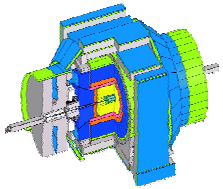


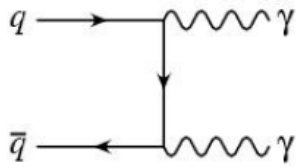


Fair data-theory agreement

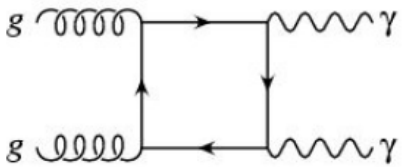
- Check of the implementation of Matrix Element ⊕ Parton Shower

$\gamma + \gamma$ Production



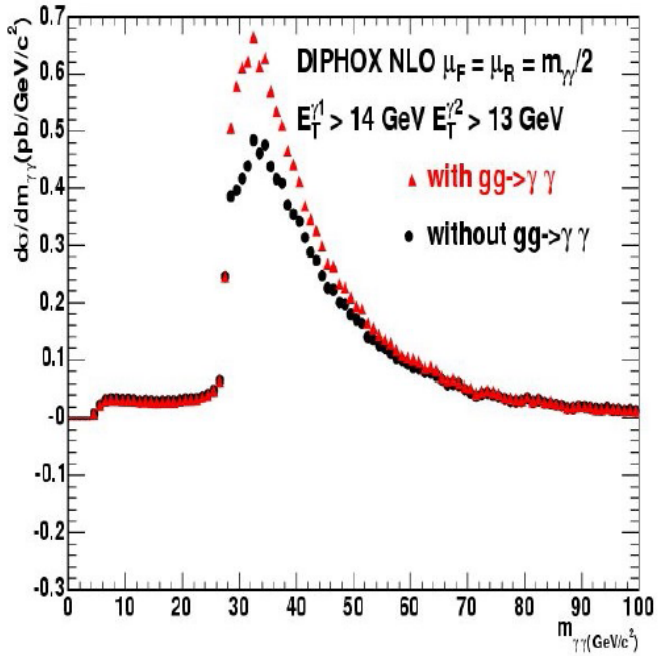


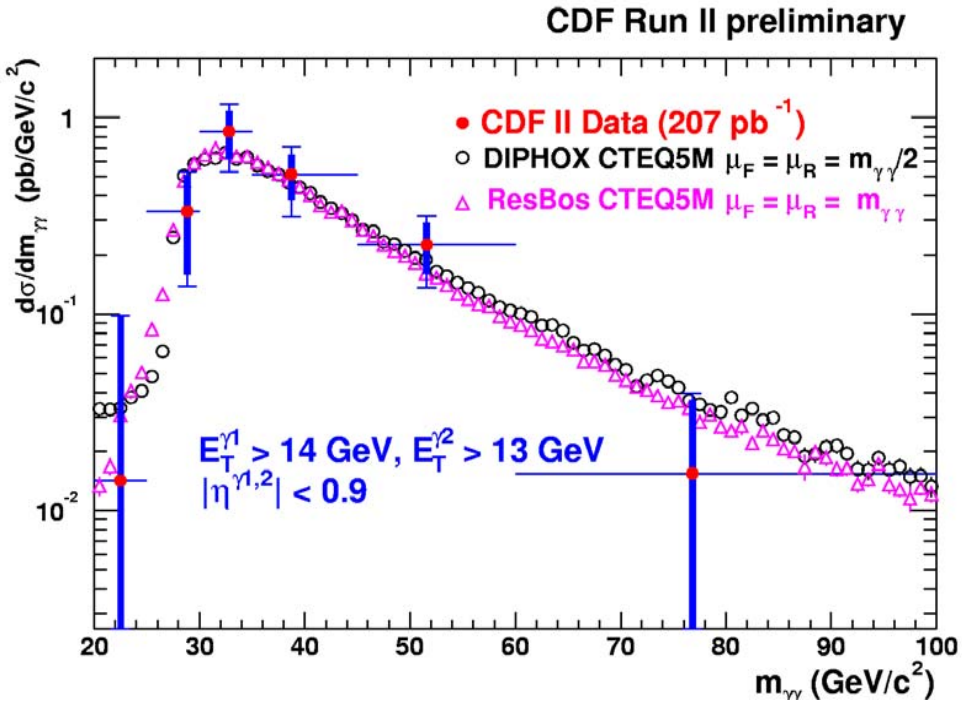
High $M_{\gamma\gamma}$



Low $M_{\gamma\gamma}$

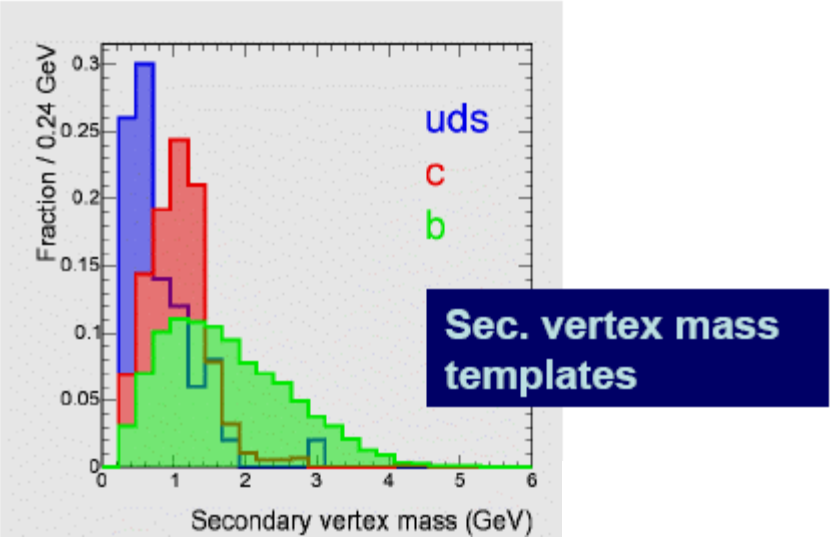
- Motivations
  - Test of QCD
  - Background to $H \rightarrow \gamma\gamma$
  - Possible signature on New Physics (Susy)
- Results consistent with NLO prediction
  - DIPHOX, Resbos
  - Poor agreement with LO (Pythia)

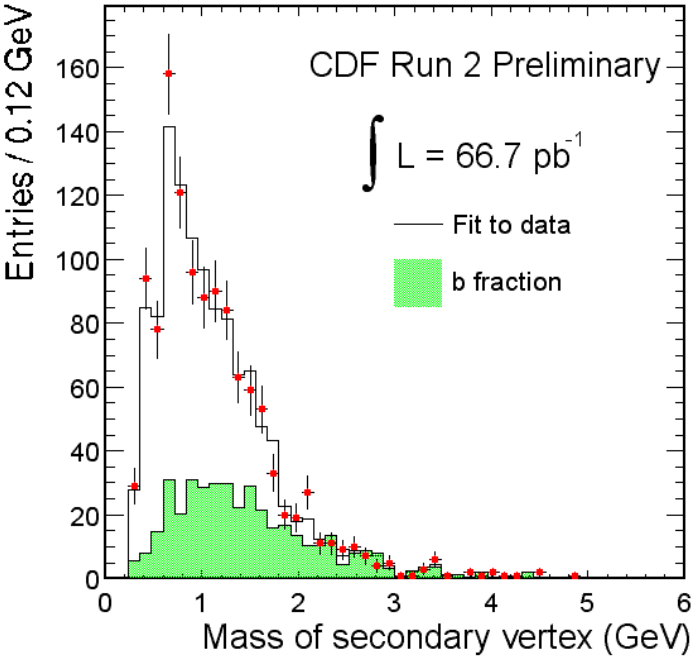




γ + b/c Cross Section

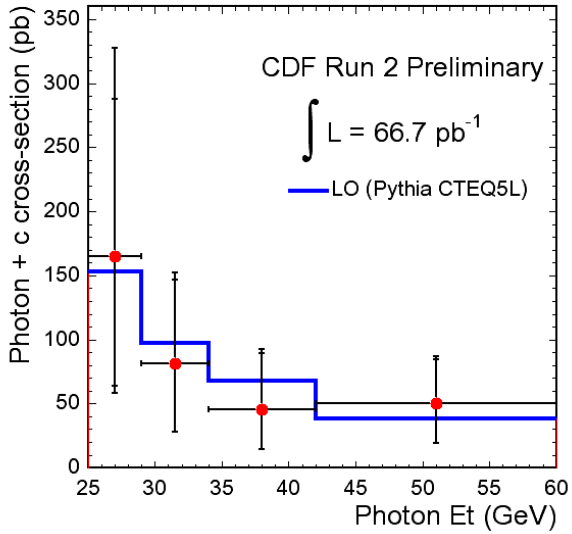
- Motivations
  - Test heavy flavor production in QCD
  - Probes heavy flavor content of the proton
  - Possible signature of New Physics (Susy)
- Basics requirements
  - One isolated γ
    - $E_T > 25$ GeV
    - $|\eta| < 1.0$
  - One jet with a secondary vertex
    - b/c "like" jet
- Number of events containing b, c and uds quarks in the data
  - Fit of the secondary vertex mass

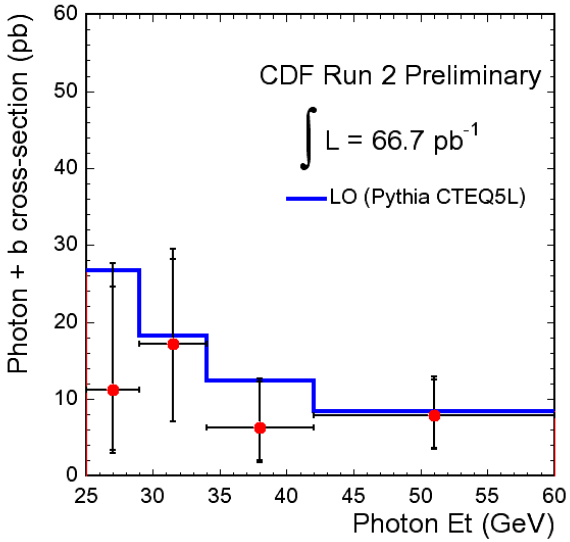




γ + b/c Cross Section

Cross section measurements agree with QCD prediction





$\sigma(b + \gamma)$ = 40.6 +/- 19.5 (stat.) + 7.4 -7.8 (sys.) pb
$\sigma(c + \gamma)$ = 486.2 +/- 152.9 (stat.) + 86.5 -90.9 (sys.) pb

Important check of the method

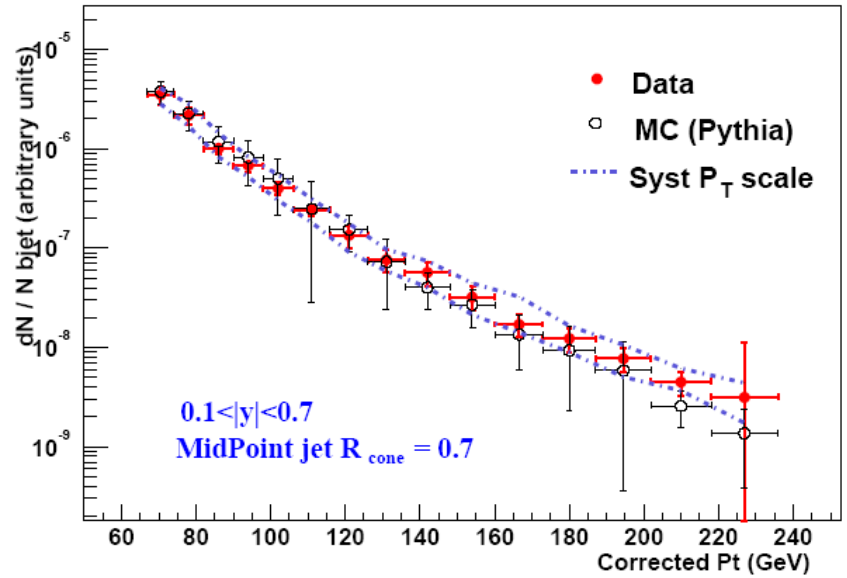
– Fitting the secondary vertex mass allow to extract the heavy flavor contributions

Future improvements

– More statistics
– Comparison to NLO
– Limits on Susy

b-jet / $b\bar{b}$ jet Production

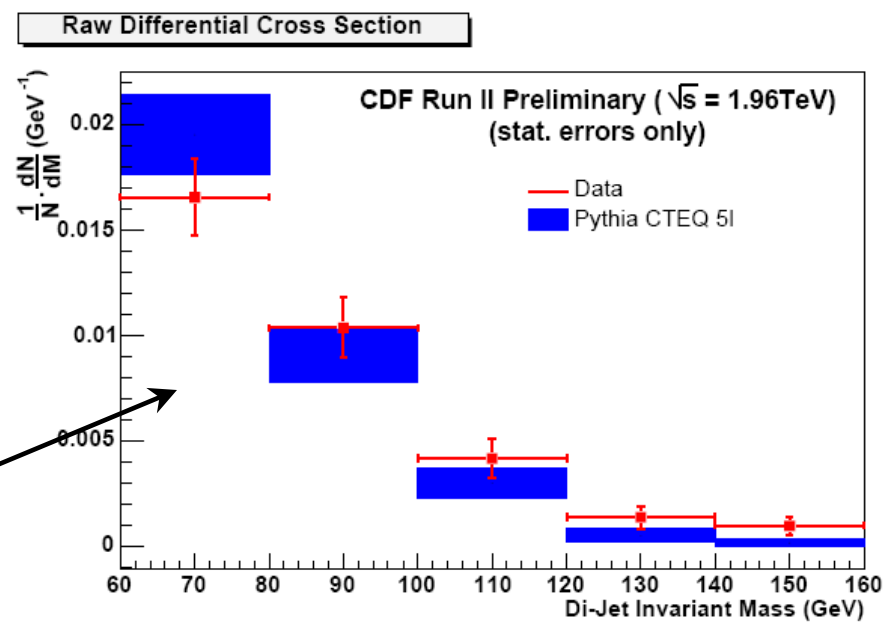
Here also: b contents from fit of secondary vertex mass



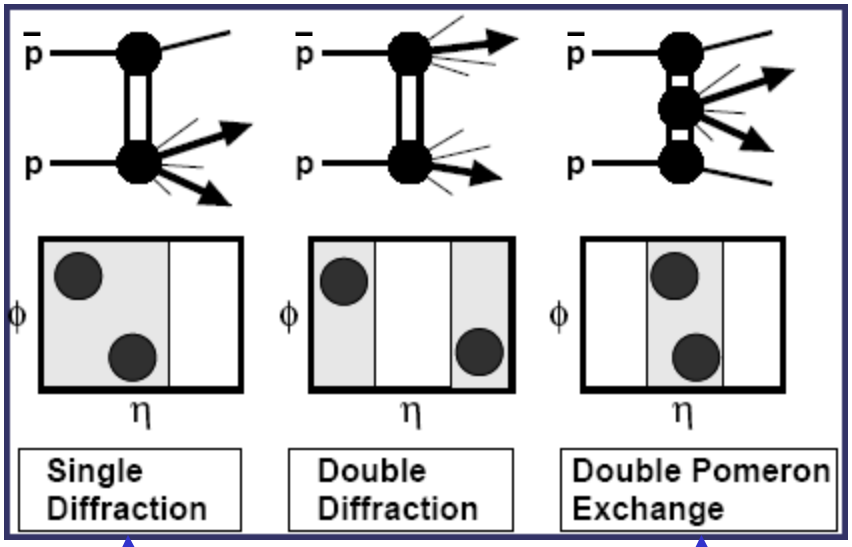
Ongoing analyses…

- Tagging efficiencies
- Systematic
- Comparison to NLO

JetClu: R = 0.7
- 2 tags jets within $|\eta| < 1.2$
- Leading jet: corrected $E_T > 30$ Gave
- Second jet: raw $E_T > 10$ Gave

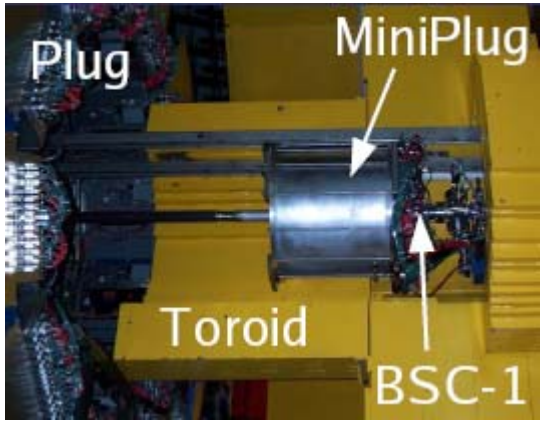


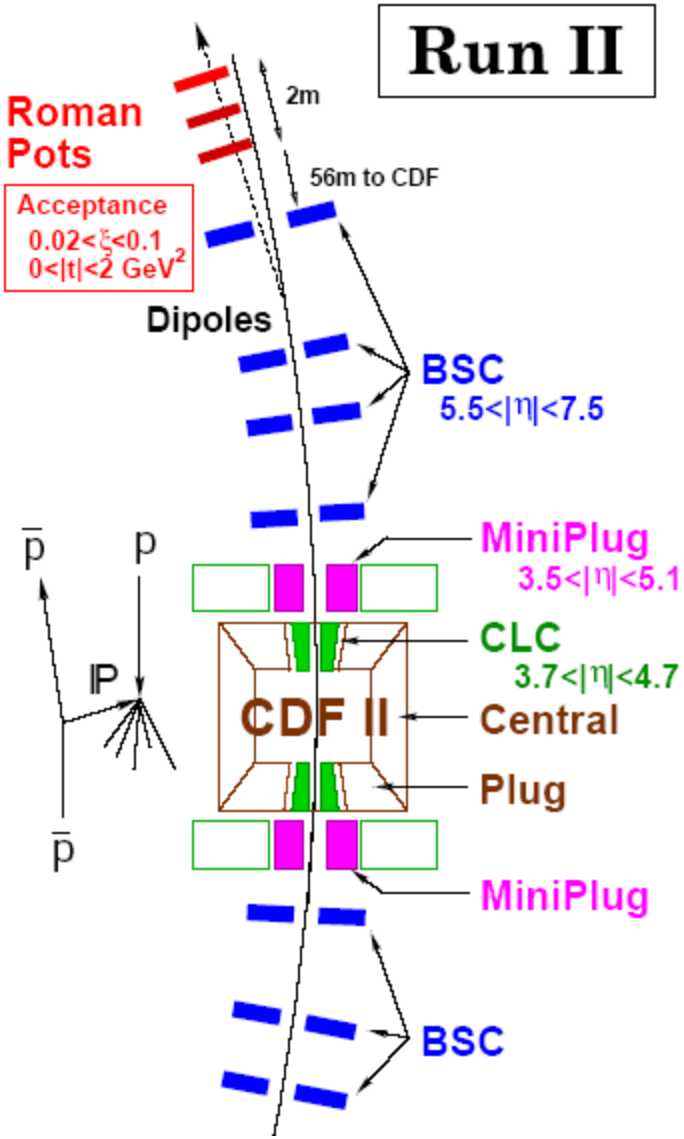
Diffractive Physics



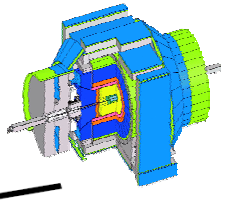
Diffractive structure function

Exclusive final states





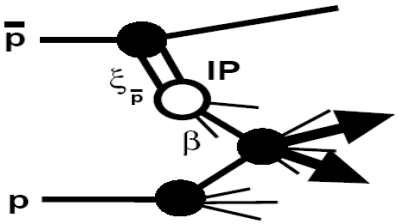
Diffractive Structure Function



Experimental measurement of F_{jj}^{D}

$$\frac{\sigma(SD_{jj})}{\sigma(ND_{jj})} = \frac{F_{jj}^{D}(x_{Bj})}{F_{jj}(x_{Bj})} \text{ (LO QCD)}$$

Measure — Known LO PDF

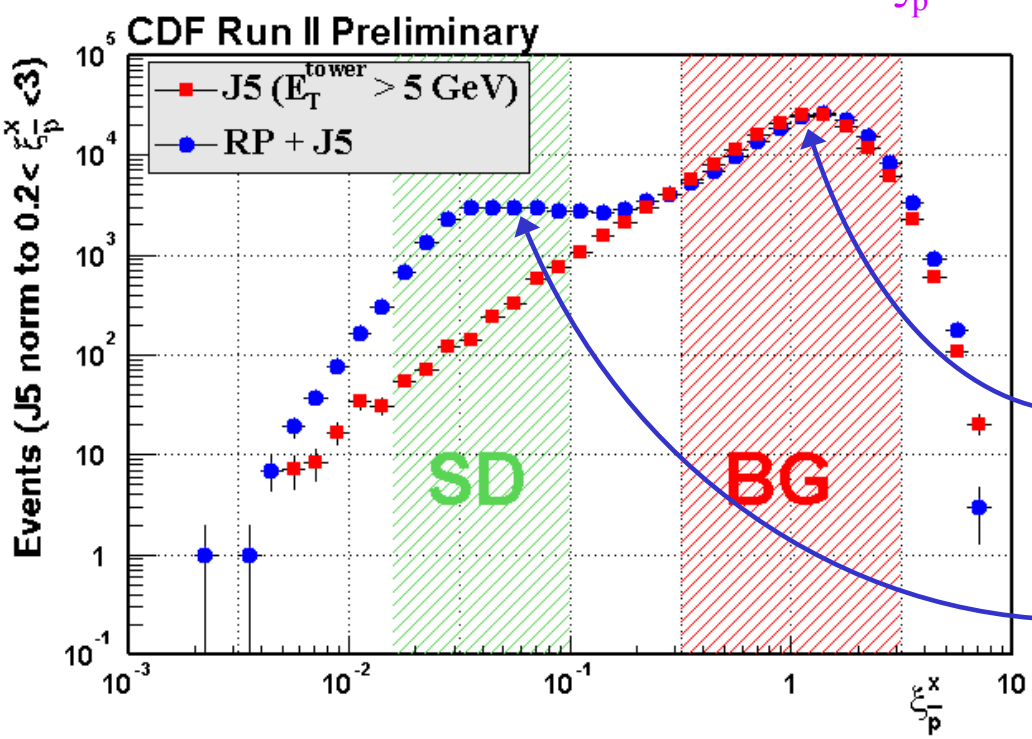


Parton $x_{Bj} = \beta\xi_{\bar{p}}$

- β = momentum fraction of parton in Pomeron
- $\xi_{\bar{p}}$ = momentum fraction of Pomeron in proton

$$\xi_{\bar{p}}^{X} = \frac{M_X^2}{s} \approx \frac{\sum_i E_T^i e^{-\eta_i}}{\sqrt{s}}$$

Sum over calorimeter towers (E_T > 100 MeV)

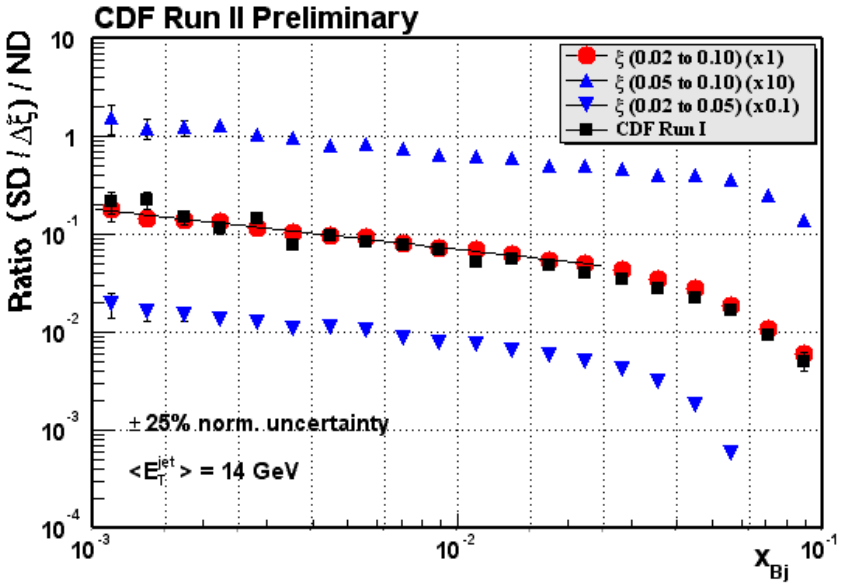


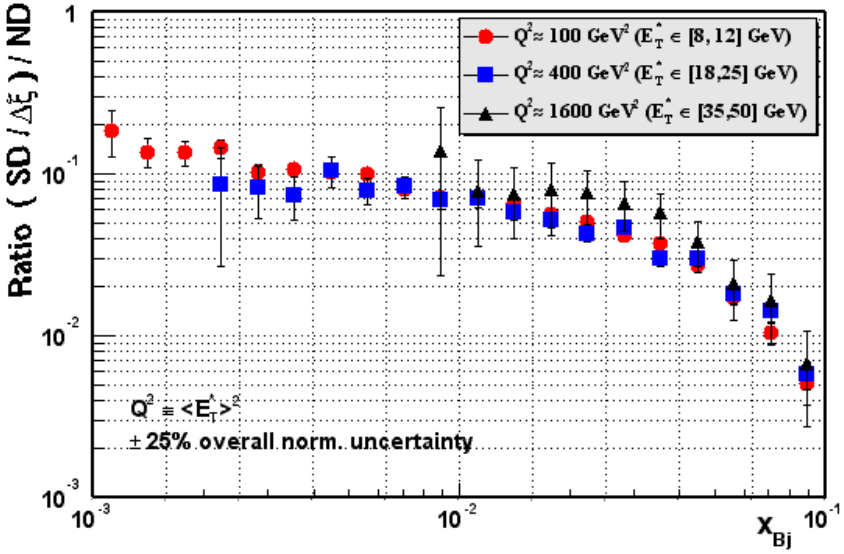
Offline cuts: at least 2 jets (cone R = 0.7)
E_T > 5 GeV, $|\eta|$ < 2.5; BSC gap in $\bar{p}$ side

Non diffractive single interactions ⊕ Multiple interactions: overlap of a non diffractive event and a diffractive one

$$\frac{d\sigma}{d\xi_{\bar{p}}} \propto \frac{1}{\xi_{\bar{p}}} \rightarrow \frac{d\sigma}{d(\log \xi_{\bar{p}})} = \text{Cte}$$

Diffractive Structure Function





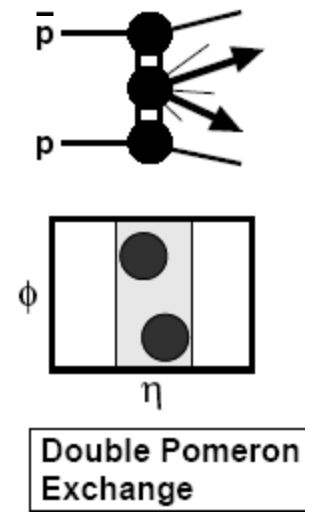
$$x_{Bj} = \frac{\sum_{JET} E_T^{JET} e^{-\eta_{JET}}}{\sqrt{s}}$$

Sum over 2 leading jets (+ 3rd jet when present)

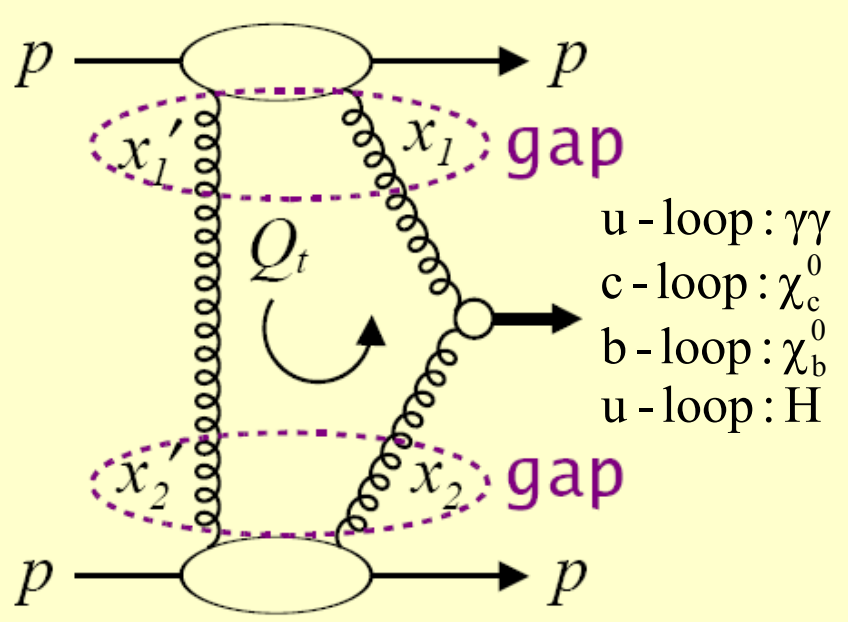
- Ratio of SD to ND dijet event rates as a function of x_{Bj}
  - No $\xi_{\bar{p}}$ dependence observed within $0.03 < \xi_{\bar{p}} < 0.1$
    - Confirm Run I results
  - No appreciable Q^2 dependence within $100 < Q^2 < 1600$ GeV^2
    - $Q^2 = < (E_T^1 + E_T^2) / 2 >^2$
    - New result
      - Pomeron evolve like proton?
- In progress
  - Possibility to explore lower $\xi_{\bar{p}}$ and higher Q^2

Diffractive Higgs Production in DPE

- Attractive Higgs discovery at LHC
  - Standard Model light Higgs: $M_H \sim 120\ \mathrm{GeV}/c^2$
  - "Exclusive" channel: $p + p \rightarrow p + H\,(\rightarrow b\bar{b}) + p$
    - $M_H = M_{miss} = \sqrt{s \cdot \xi_{p1} \cdot \xi_{p2}}$
      - Clean Signal: if $\Delta M_{miss} = 1\ \mathrm{GeV}/c^2$
        - » $\sigma_H^{excl} \sim 3$ fb , signal / background ~ 3 @ LHC
    - $\sigma \sim 40$ fb ?



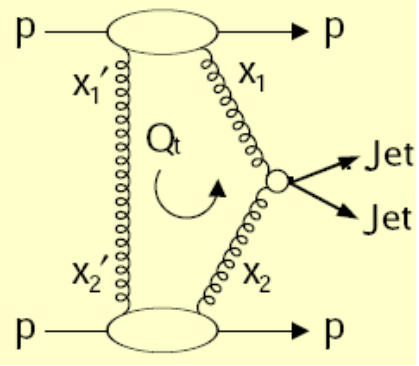
- Measurements of cross section or limits for inclusive processes very useful to calibrate / test the predictions
  - Exclusive dijets
    - Large cross section
  - Exclusive χ_c^0
    - Small cross section but clean signal

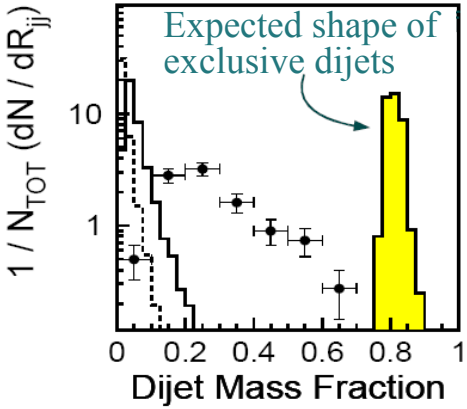


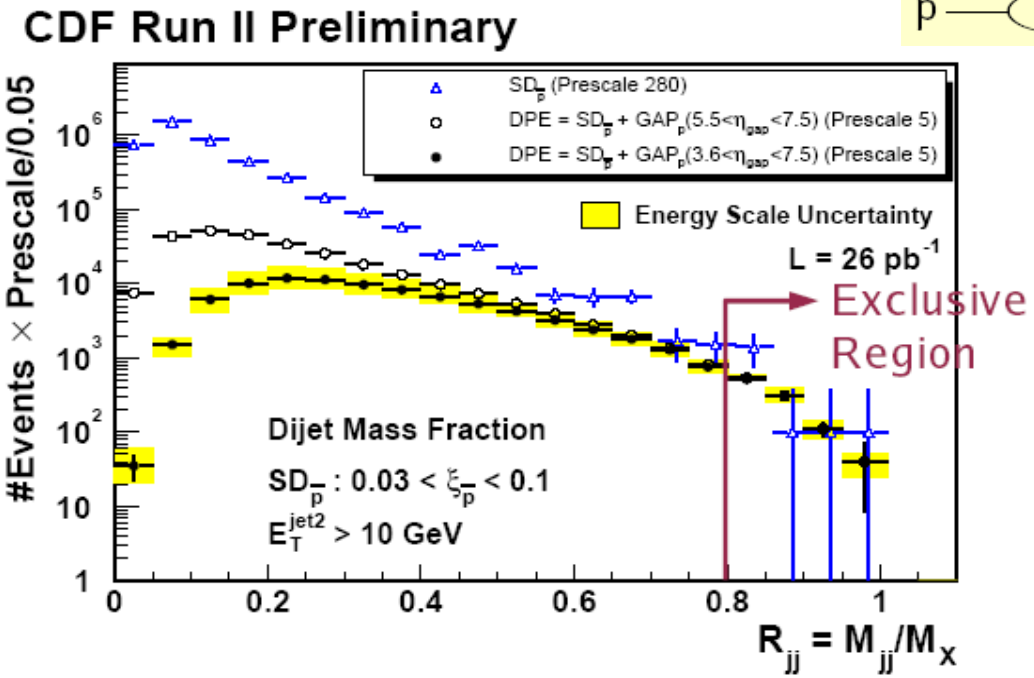
Exclusive Dijet Cross Section Limit

- Dedicated DPE trigger
  - RP + J5 + GAP_p^{BSC}
- Exclusive dijets expected at high dijet mass fraction
  - No significant excess

$$R_{jj} = \frac{M_{jj}}{M_X} = \frac{\sqrt{(E_{jet1}+E_{jet2})^2 - (\vec{P}_{jet1}+\vec{P}_{jet2})^2}}{\sqrt{s \cdot \xi_{\bar{p}}^X \cdot \xi_p^X}}$$







$$|\eta^{jet1,jet2}| < 2.5,\ R_{cone} = 0.7,$$
$$0.03 < \xi_{\bar{p}} < 0.1,\ 3.6 < \eta_{gap} < 7.5$$

$$\sigma_{DPE}(R_{jj} > 0.8, E_T^{jet1} > 10\ \text{GeV}) = 970 \pm 65(\text{sta}) \pm 270(\text{sys})\ \text{pb}$$

$$\sigma_{DPE}(R_{jj} > 0.8, E_T^{jet1} > 25\ \text{GeV}) = 34 \pm 5(\text{sta}) \pm 10(\text{sys})\ \text{pb}$$

KMR prediction: 60 pb (+/- factor 2) @ $25 < E_T^{jet} < 35$ GeV, $|\eta^{jet1} - \eta^{jet2}| < 2$

Exclusive χ_c^0 / Developments

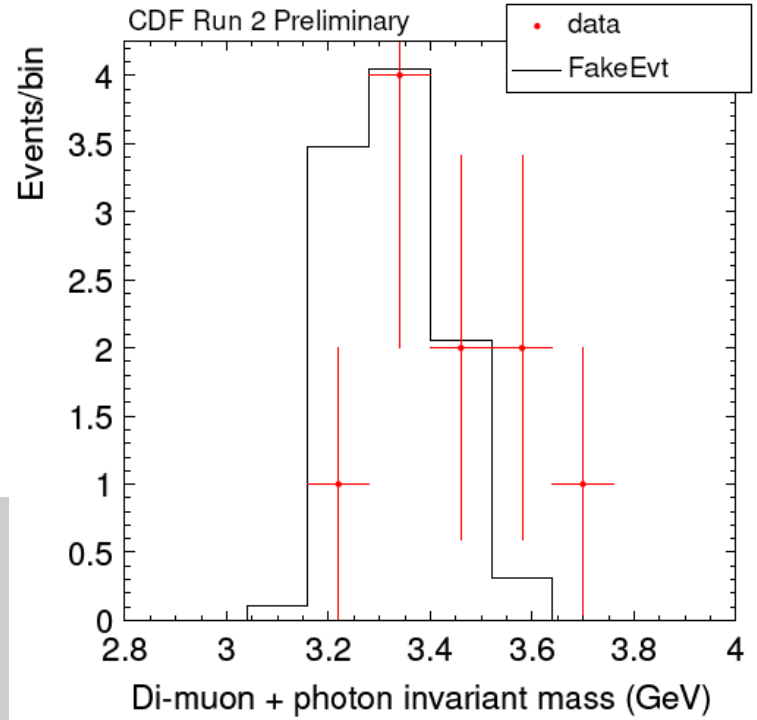
- $\bar{p} + p \rightarrow \bar{p} + \chi_c^0 \, (\rightarrow J/\psi + \gamma) + p$
  - Di-muon trigger data
    - Muons with $p_T > 1.5$ GeV/c, $|\eta| < 0.6$
  - Reject cosmic ray thanks to TOF
  - Select events in J/ψ mass window
  - Require large gaps on both p and $\bar{p}$ sides
  - 10 candidates: assuming all 10 are J/ψ + γ

➔ "Upper limit" on exclusive χ_c^0 production

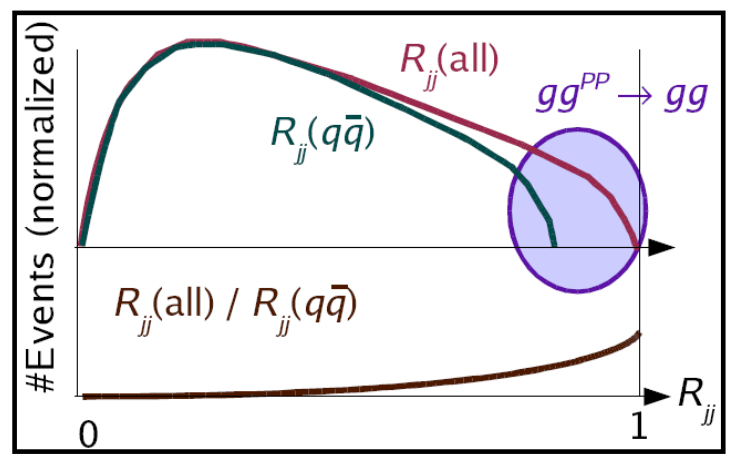
$$|Y^{J/\psi}| < 0.6, \;\; p_T^{J/\psi} < 2\,\mathrm{GeV/c}$$

$$\sigma(\bar{p}p \rightarrow \bar{p} + J/\psi + \gamma + p) = 49 \pm 18(\mathrm{sta}) \pm 39(\mathrm{sys})\ \mathrm{pb}$$

KMR prediction : $\sigma(\bar{p}p \rightarrow \bar{p} + \chi_c^0(\rightarrow J/\psi + \gamma) + p) \approx 70$ pb for $|Y^{J/\psi}| < 0.6$ ($\pm$ factor 2 – 5)



- Developments
  - Use $q\bar{q}$ suppression in exclusive dijets
    - HF quarks well identified: g miss tag @ O(1%)
      - DPE b-jet trigger under development
  - Triggers in DAQ soon: DPE-J/ψ, DPE-γγ



Conclusion

- CDF accumulating large samples of interesting events
  - Tevatron operating in a unique region of phase space
- Very exciting and important QCD Physics program at CDF
  - Jet inclusive cross section in reasonable agreement with NLO pQCD
    - Working on hadronisation correction and on better understanding of the jet energy scale
  - Both underlying event and jet shape well described by Pythia Tune A (tuned on Run I data)
    - Very important for precise jet measurements
  - Ongoing analyses of many important QCD processes
    - LO Matrix Element + Parton Shower give a reasonable description of W+Jets production (cross sections and kinematics)
    - NLO pQCD give good prediction of di-photon production (where LO failed)
    - Developed technique to extract heavy flavor contributions is working well
  - Thrilling Diffractive Physics program
    - Dedicated forward detectors / dedicated triggers
    - Big efforts on exclusive final state in DPE