QCD physics at the CDF experiment

Monica D ’ Onofrio

Universite’ de Geneve

on behalf of the CDF collaboration

IFAE, Torino April 15, 2004

Outline

- QCD physics program
- Tevatron and the CDF experiment
- Inclusive jet cross section
- Dijet mass and jet shape
- Inclusive b-jet cross section
- Gamma-b cross section
- Gamma-Gamma cross section
- Other analysis (W+jets, underline events..)

QCD physics program

Highest-energy accelerator currently operational ever developed

- All production processes are QCD related: optimal understanding basic for all analyses
  - Fundamental parameters (ex.: high x gluon PDFs)
  - background for each process of interest
    (e.g. bb or $\gamma\gamma$ production for *Higgs* channel studies)
  - Phenomenology on non-perturbative regime
    (e.g.: Underlying Event modeling)
- Highest Q^2 probed (distance scale ~ 10^{-17} cm)
  - Precise test of pQCD at NLO:
    check deviations $\rightarrow$ look for new physics

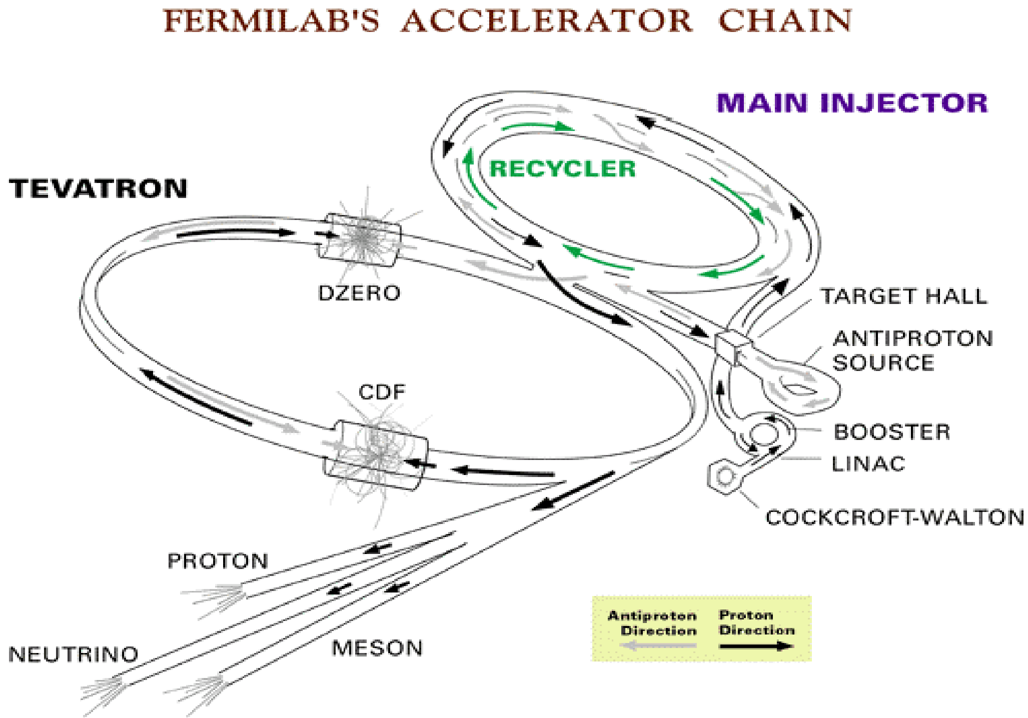
Tevatron

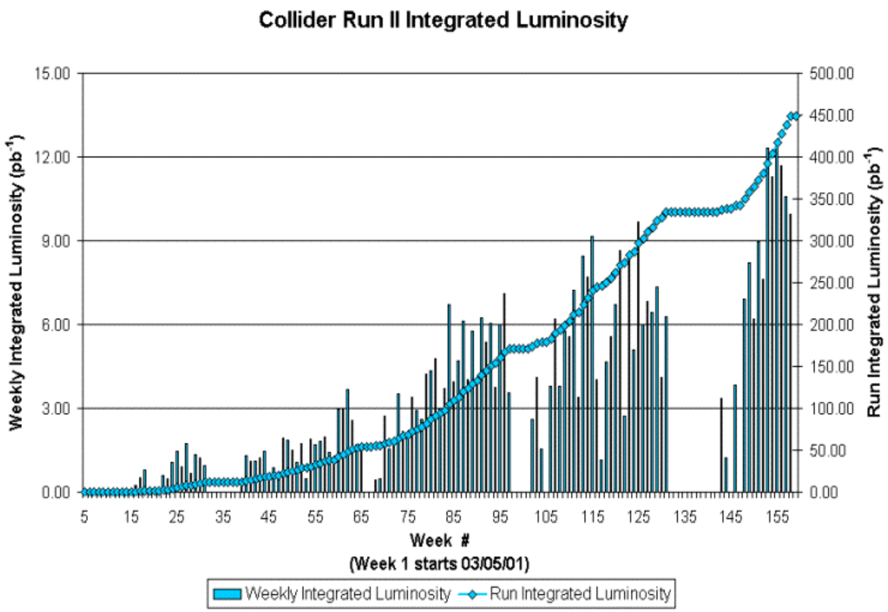
Performances (March 2004):

$L_{ins} \sim 6 \times 10^{31}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
$L_{int} \sim 400\ \mathrm{pb}^{-1}$ (delivered)

Long term goal (end 2009):

$L_{ins} \sim 2 \times 10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
$L_{int} \sim 4.4 - 8.5\ \mathrm{fb}^{-1}$





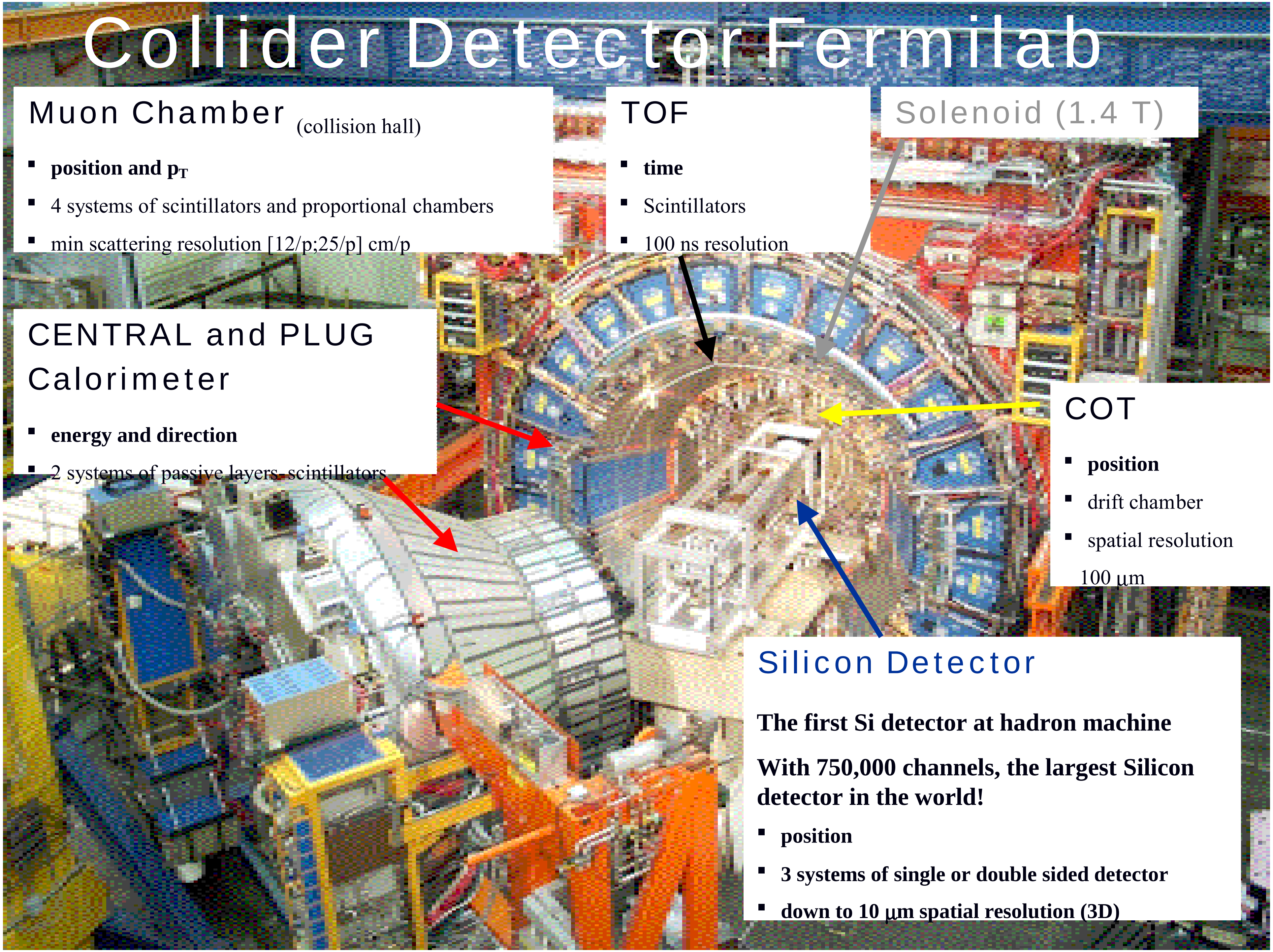
What's new in Run II:

Energy increase: $\sqrt{s} = 1.8$ TeV $\rightarrow$ 1.96 TeV
Bunch spacing decrease to 396 ns

Consequences:

Higher σ_{jet} (~ 5 times for $P_T \sim 600$ GeV)
Increased kinematic range for jet production

Collider Detector Fermilab



Muon Chamber (collision hall)

- **position and p_T**
- 4 systems of scintillators and proportional chambers
- min scattering resolution [12/p;25/p] cm/p

TOF

- **time**
- Scintillators
- 100 ns resolution

Solenoid (1.4 T)

CENTRAL and PLUG Calorimeter

- **energy and direction**
- 2 systems of passive layers-scintillators

COT

- **position**
- drift chamber
- spatial resolution 100 μm

Silicon Detector

The first Si detector at hadron machine

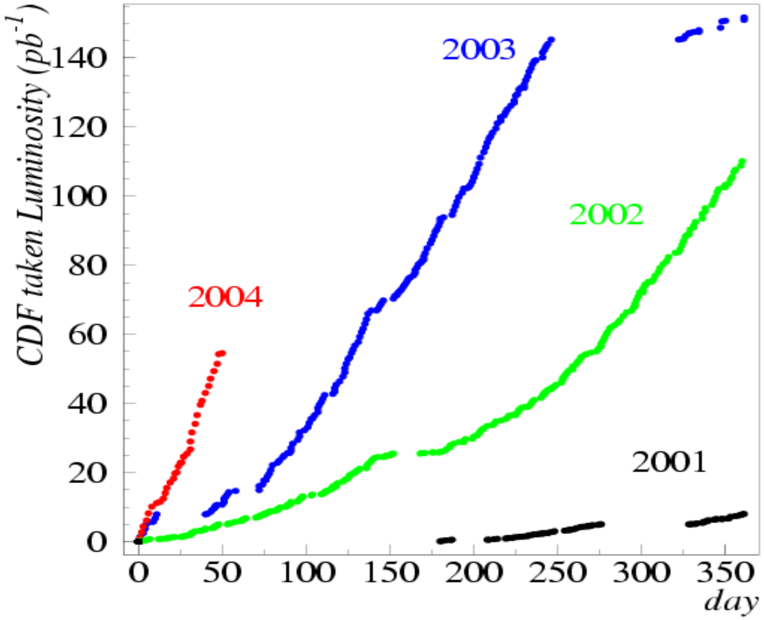
With 750,000 channels, the largest Silicon detector in the world!

- **position**
- **3 systems of single or double sided detector**
- **down to 10 μm spatial resolution (3D)**

CDF

Collider Detector at Fermilab

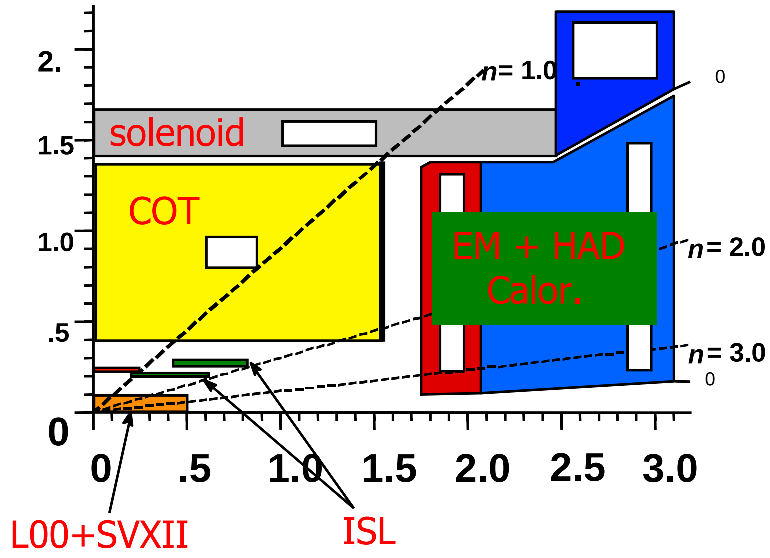
Record inst. luminosity:
5^{th} Febraury, 2004
6.18 $x10^{31}$ sec^{-1} cm^{-2}



New:

- tracking system:
  - silicon vertex (SVXII)
  - intermediate silicon layers (ISL)
  - central outer tracker (COT)
- scintillating tile end plug calorimeter
- intermediate muon detectors
- scintillator time of flight system
- front end electronics
- pipelined trigger system
- DAQ

Central muon detectors and calorimeters are unchanged.

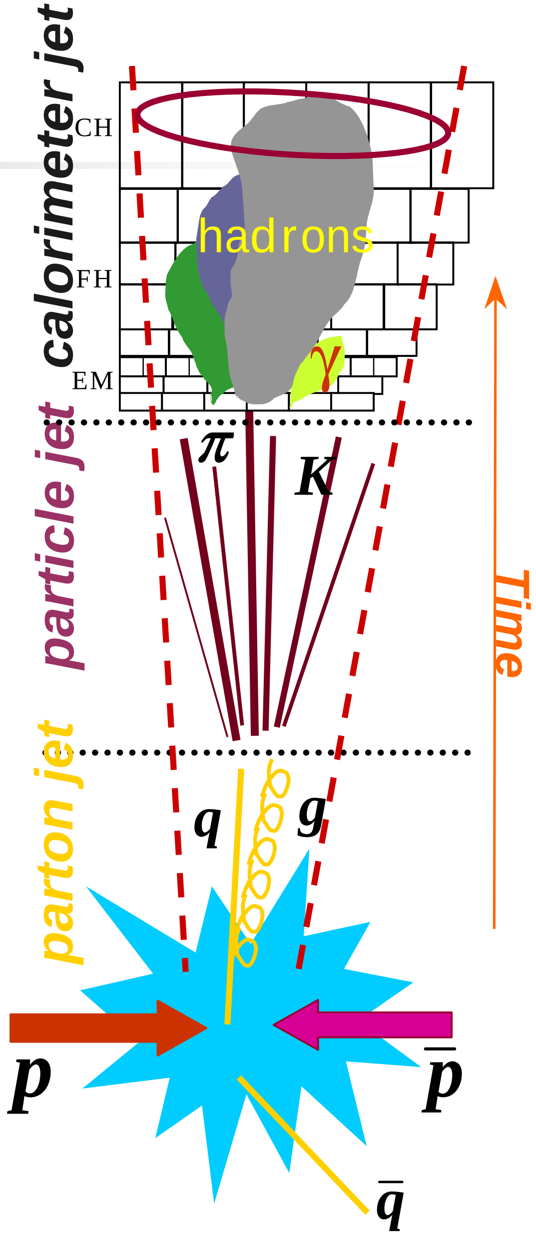


Jet reconstruction

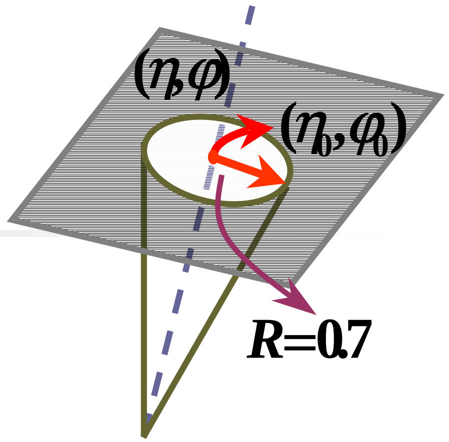
Algorithm:

- A method for grouping collimated particle paths in a calorimeter.
- Needed to provide a common, objective, and unambiguous definition for use by theorists and experimentalists.
- Ideally should be infrared- and collinear-safe: cross section should not change if parton radiates a soft parton or splits into two collinear ones.
- Jet direction should correspond with parent parton direction.

Used: JetClu, MidPoint and Kt



Cone algorithm



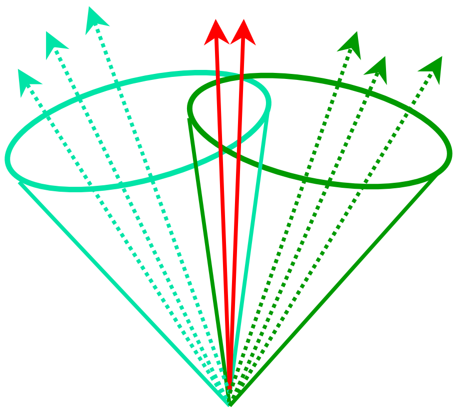
JETCLU

- List of seeds using CAL tower with Et > 1 GeV
- **Preclustering+ratcheting:** jet not free to move in (η, ϕ)
- draw a cone radius around each seed to form a "proto-jet" from towers inside (Snowmass convention)

$$E_T^{jet} = \sum_k E_T^K,$$

$$\eta^{jet} = \frac{\sum_k E_T^k \cdot \eta_k}{E_T^{jet}}, \quad \phi^{jet} = \frac{\sum_k E_T^k \cdot \phi_k}{E_T^{jet}}$$

- draw new cones around proto-jets and iterate until stabilized
- looking for overlaps (**merging**) and define final kinematics



Merging is basic problem of cone based jet algorithm

MIDPOINT

- **no precluster, no ratcheting**
- possible to have hadron and parton level algorithm, to factorize detector effect (difficult with JetCle because of pre-clustering and ratcheting)
- draw a cone of radius R around each seed and reconstructing proto-jet with Ejet and Pjet as sum of towers E and P
- Put seed in MidPoint $(\eta-\phi)$ for each pair of proto-jets
- separated by less than 2R and iterate for stable jets: this made the algorithm **infrared safe (good NNLO)**

Kt Algorithm

1) For each object i with E_{Ti}, define $d_{ii} = (E_{Ti})^2$

2) For each object pair i, j, define

- $(\Delta R_{ij})^2 = (\Delta\varphi_{ij})^2 + (\Delta\eta_{ij})^2$
- $d_{ij} = \min[(E_{Ti})^2,(E_{Tj})^2]\cdot(\Delta R_{ij})^2/D^2$

3) If the min of all d_{ii} and d_{ij} is a d_{ij}, i and j are combined; otherwise i is defined as a jet.

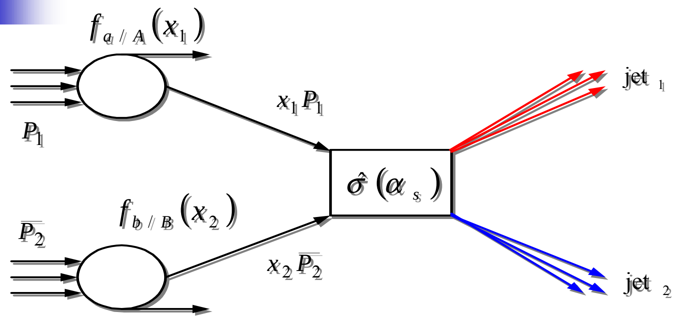
4) Continue until all objects are combined into jets.

The k_T algorithm differs from the cone algorithm because :

- Particles with overlapping calorimeter clusters are assigned to jets unambiguously (no problems of merging)
- Same jet definitions at parton and detector levels.
- NNLO predictions remain infrared safe.
- k_T jets can have more complicated boundaries than do the smooth cones; consequently less E_T near their boundaries.

First results on inclusive jet cross section measurement very promising

Inclusive jet cross section



Important test of Standard Model (SM) in terms of perturbative QCD

$$p\bar{p} \Rightarrow jet + X$$

$$\frac{1}{\Delta E_T \Delta\eta} \iint d\eta\, dE_T \frac{d^2\sigma}{dE_T\, d\eta} \longleftrightarrow \frac{N_{jet}}{\Delta E_T \Delta\eta\, \varepsilon \int L dt} \text{ vs. } E_T$$

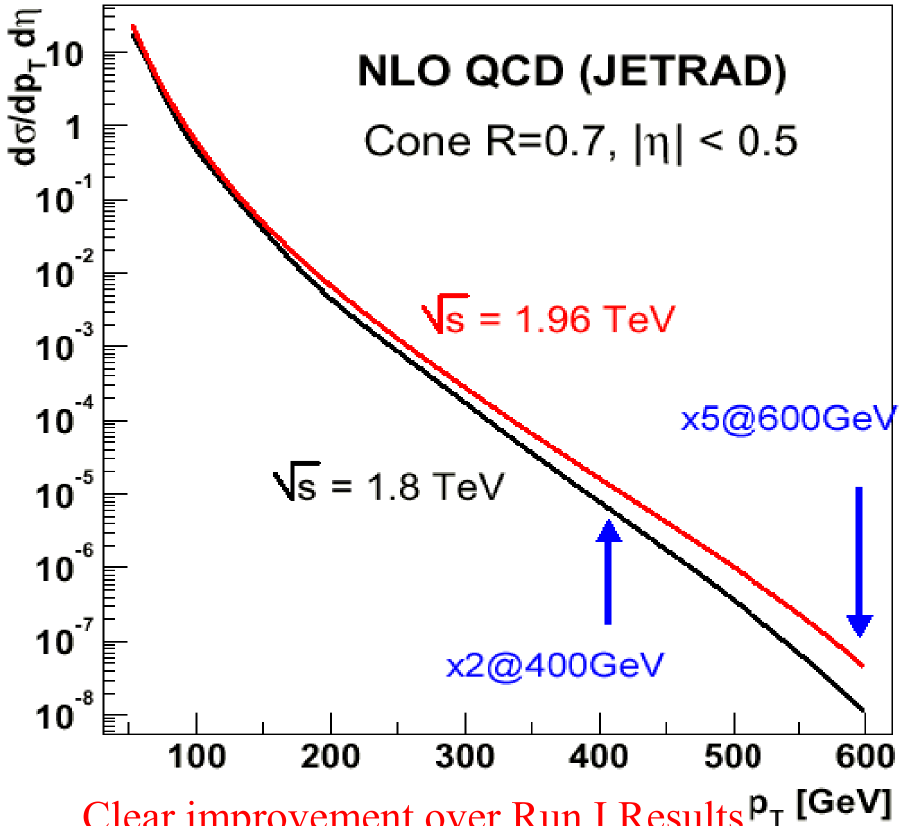
$\Delta E_T \rightarrow$ ***E_T bin size***

$\Delta\eta \rightarrow$ ***η bin size***

$N_{jet} \rightarrow$ ***# of jets in the bin***

$\varepsilon \rightarrow$ ***selection efficiency***

$L \rightarrow$ ***inst. Luminosity***



Clear improvement over Run I Results

Data samples

Inclusive calorimetric triggers:

- Level 1:

selection on Et of cal towers (EM+HAD)

- Level 2:

accept tower clusters with Et above a fixed threshold

- Level 3:

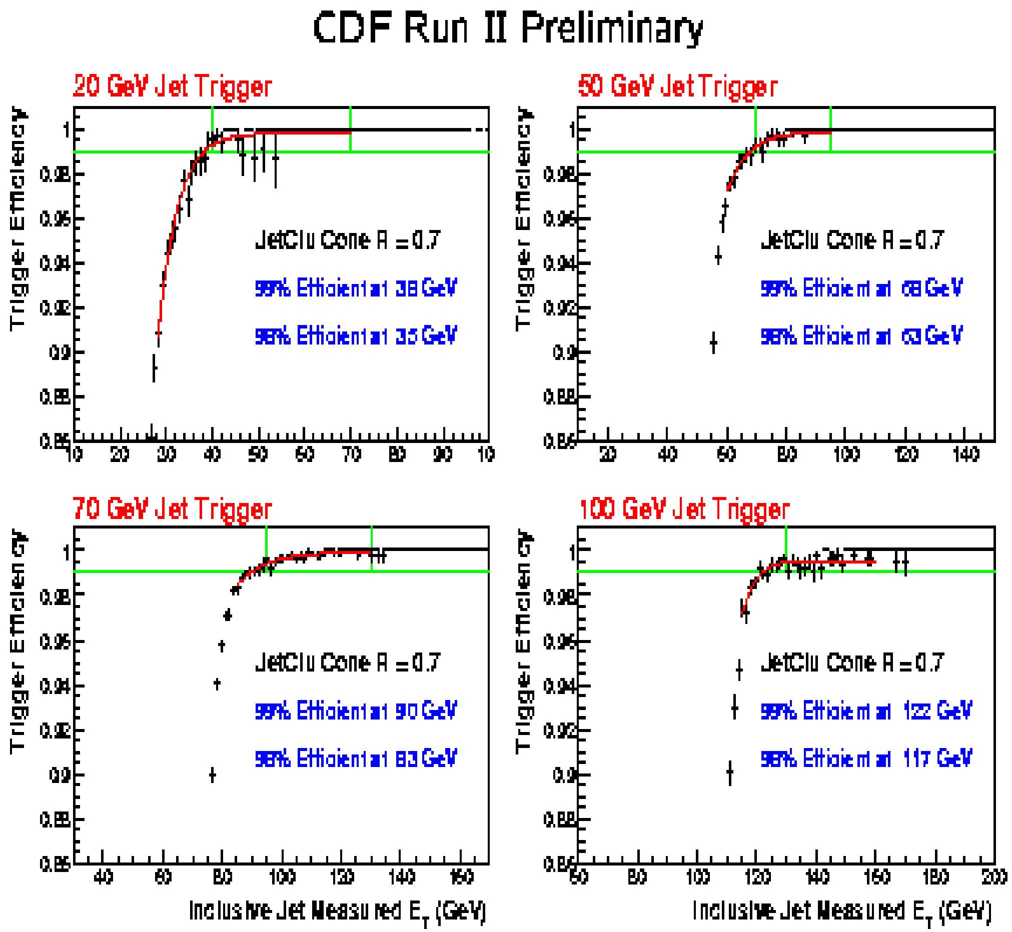
jets (R=0.7) are reconstructed assuming z vertex = 0; pass if Et>fixed threshold.

Datasets:

Jet20, Jet50, Jet70, Jet100

Jet Algorithm dependence:

MidPoint (used for $\sigma_{b\text{-}jet}$) and KT gives similar trigger performances

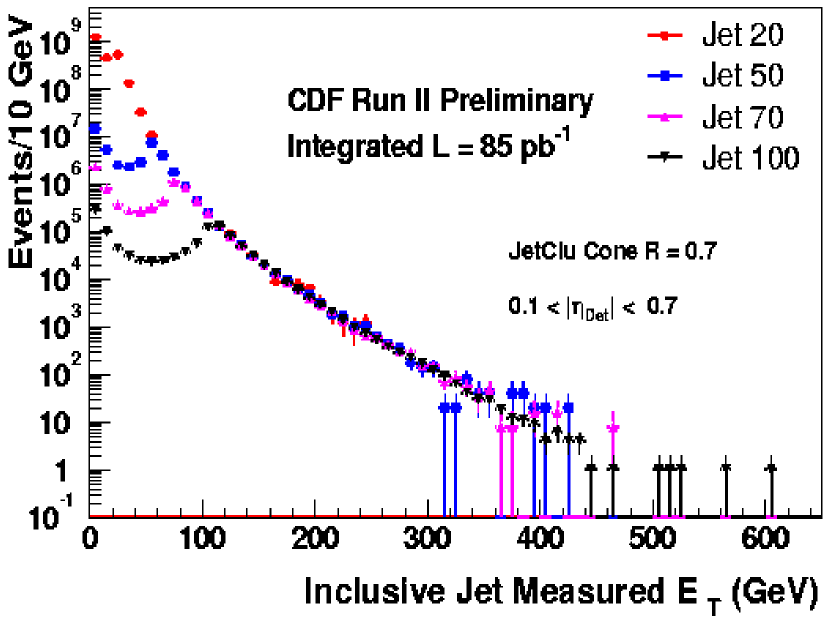


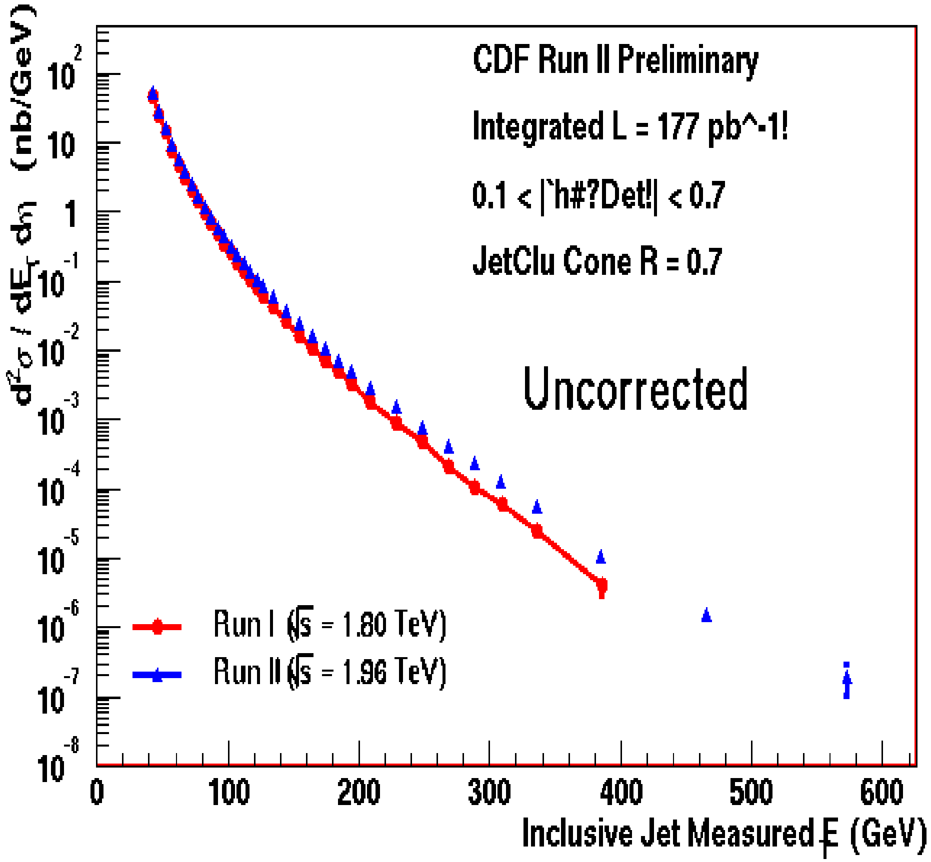
Each jet sample used in defined energy range where trigger efficiency is above 99%

Inclusive jet cross section

- Use JetClu cone algorithm (R cone = 0.7)
- Different E_T triggers
- Central jets considered

Jet E_T spectrum

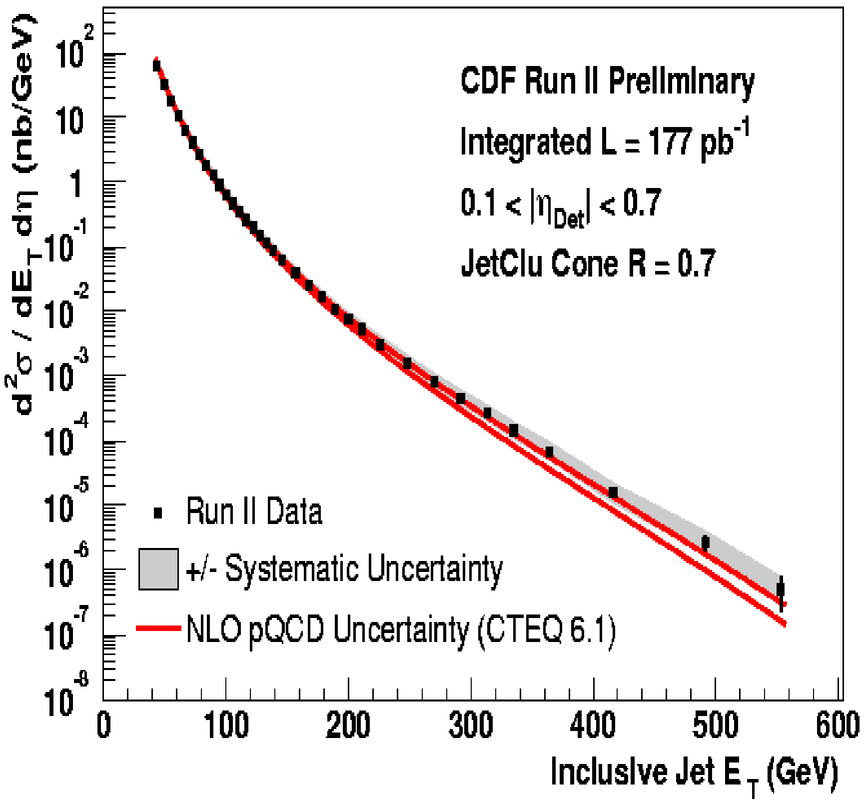


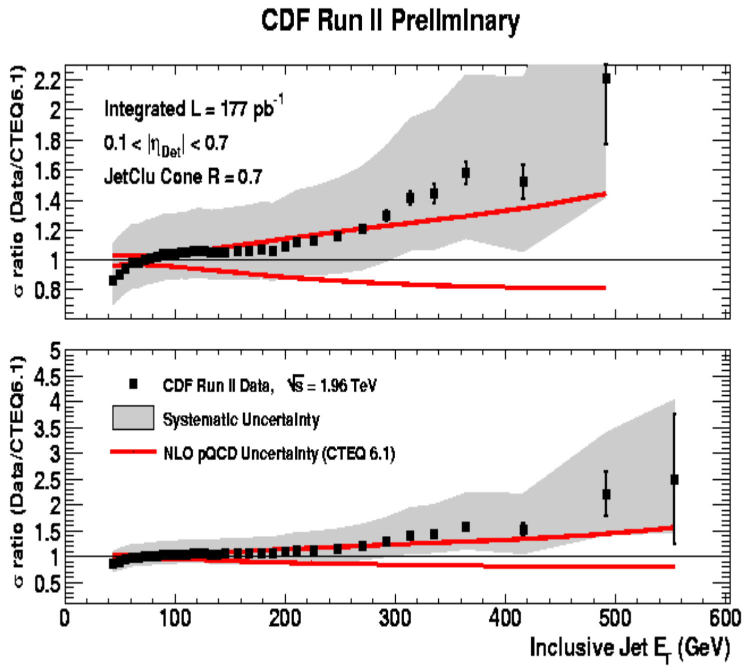


Run II data extends Run I by ~ 150 GeV

Inclusive jet cross section (2)

Reasonable data-theory agreement within errors (CTEQ6.1)

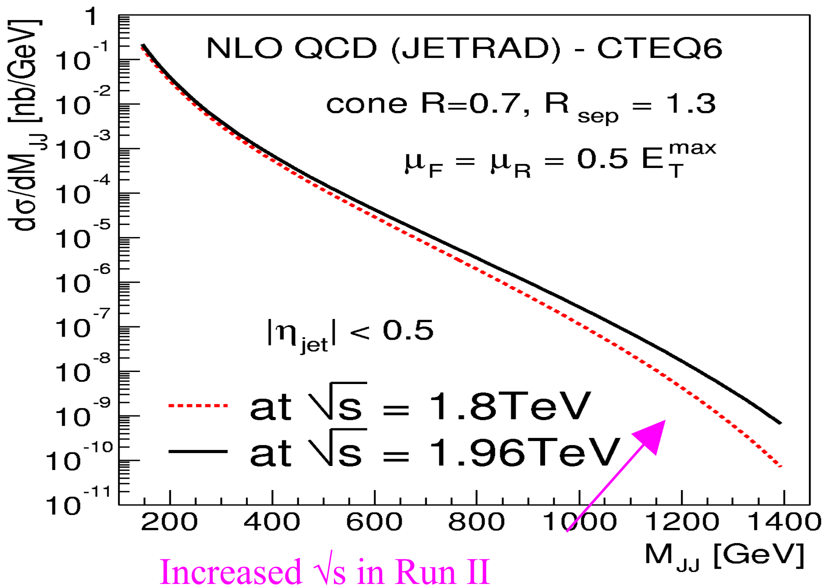




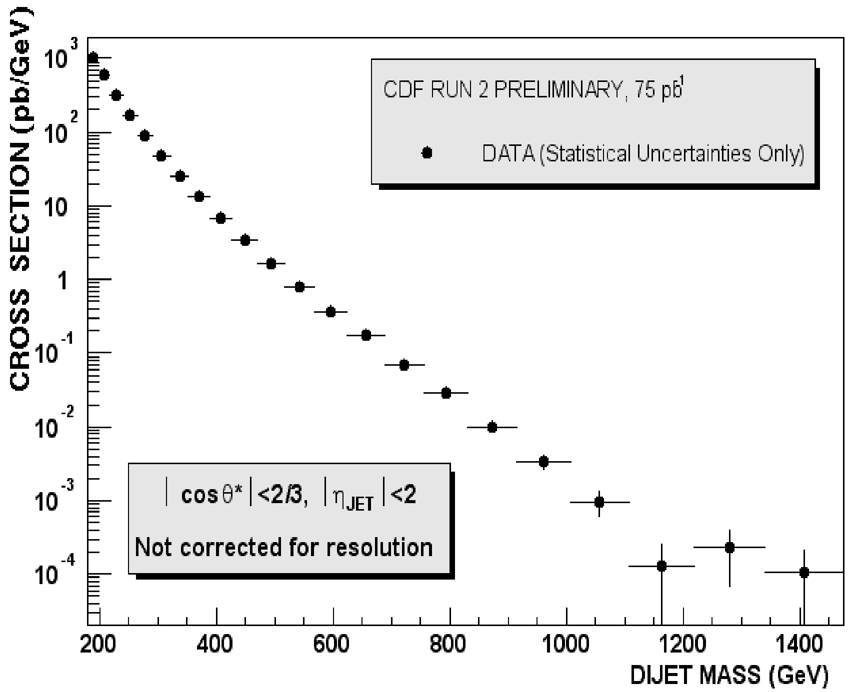
Ongoing: reduce systematics (largest uncertainty ~ 5% on E scale), use MidPoint and K_T algorithm

Dijet mass cross section

- Test of pQCD complementary to inclusive jet cross section analysis
- Great sensitivity to new physics
- Limits on theoretical parameters:
  e.g. M (new particles)



Increased √s in Run II extending Run I results

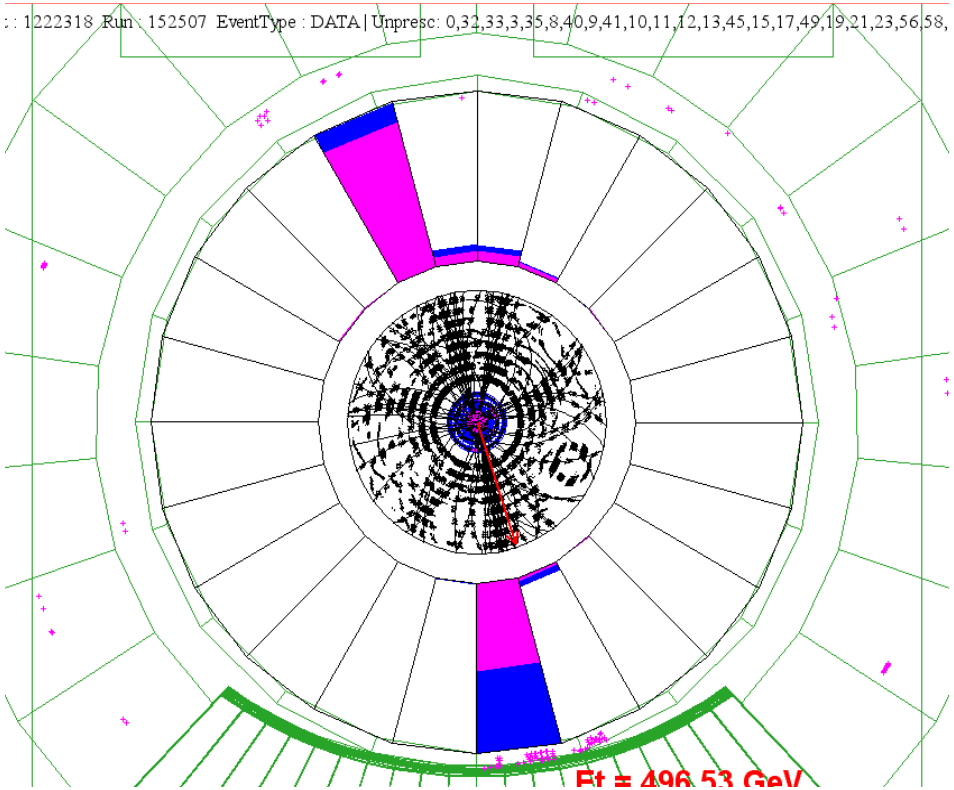


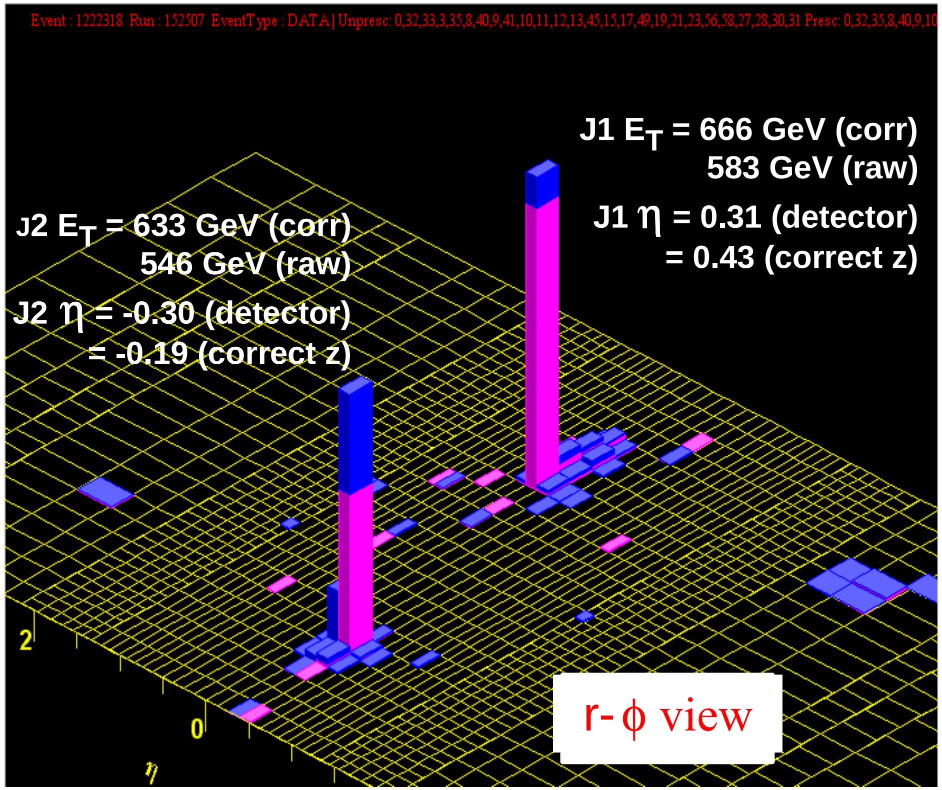
Preliminary measurements using similar analysis strategies as for σ_J:
comparing with Run I results
(JetClu $R = 0.7$, $|\eta| < 2.0$, jet corrected)

Dijet mass (2)

Highest Dijet mass event

Calorimeter “LEGO” Plot





Dijet Mass = 1364 GeV (corr)

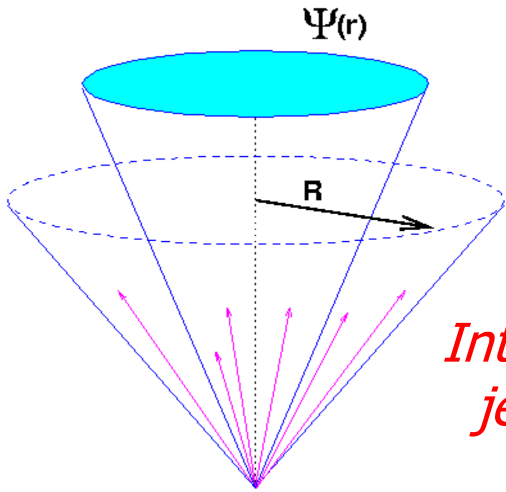
cos θ^* = 0.30

z vertex = -25 cm

Jet shapes

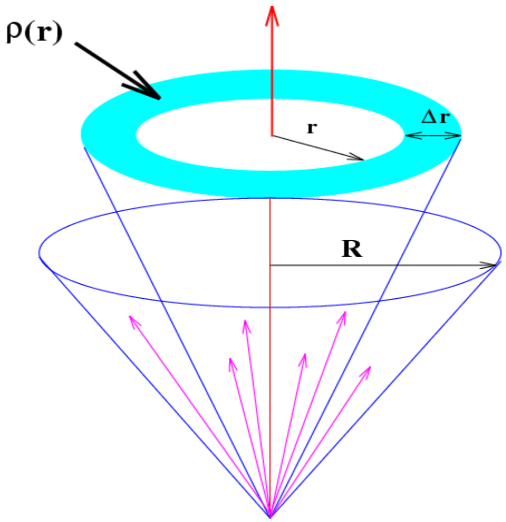
- Study of the internal structure of jets.
- Process dominated by multi-gluon emission, controlled by higher-order QCD.
- Tests models of parton cascades.
- Sensitive to:
  - Color structure of the hadronic final state + initial state radiation
  - Underlying event due to interactions between collision remnants

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



Integrated jet shape

Differential jet shape

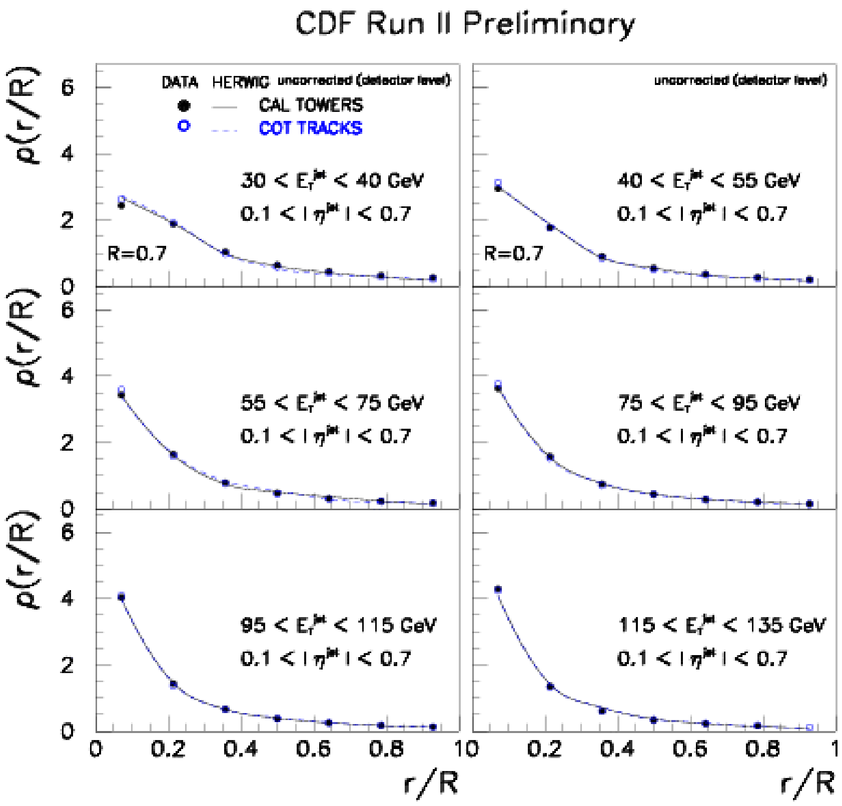


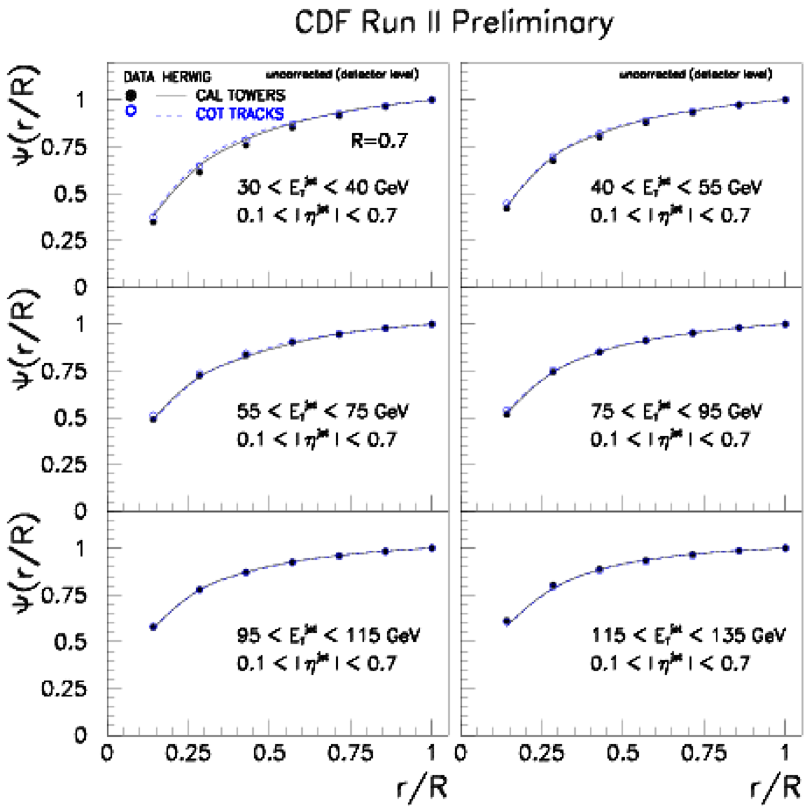
$$\rho(r) = \frac{1}{\Delta r} \frac{1}{N_{jet}} \sum_{jets} \frac{P_T(r \pm \Delta r/2)}{P_T(0,R)}$$

Jet shapes

Jet shapes determined using both calorimeter towers and tracks from the COT.

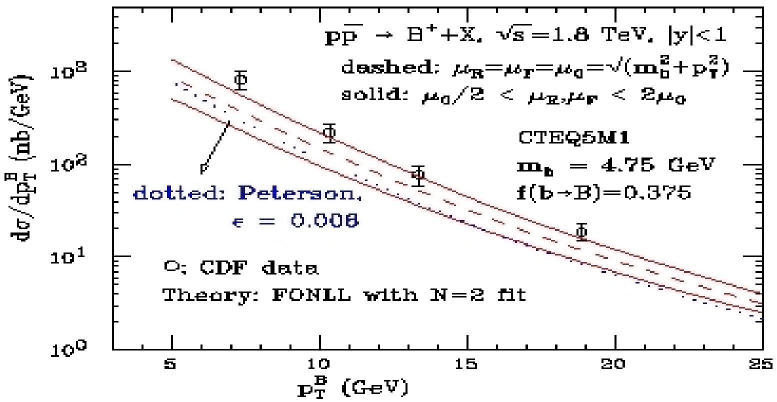
Good agreement with leading-order QCD Monte Carlo predictions

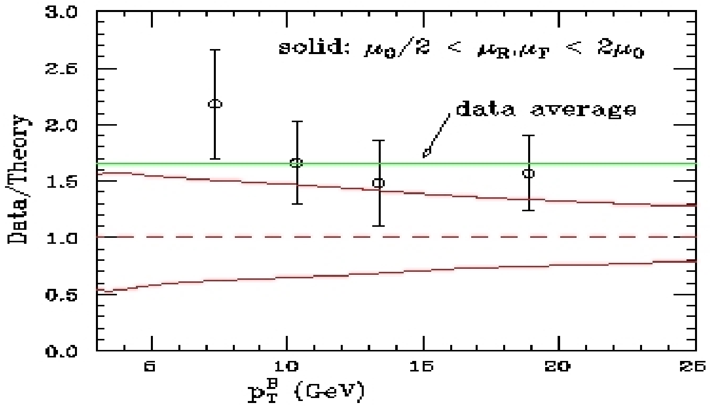




b production

- to understand and probe perturbative QCD
- can be a significant background to new physics





Make measurements where effects of fragmentation are reduced: jets

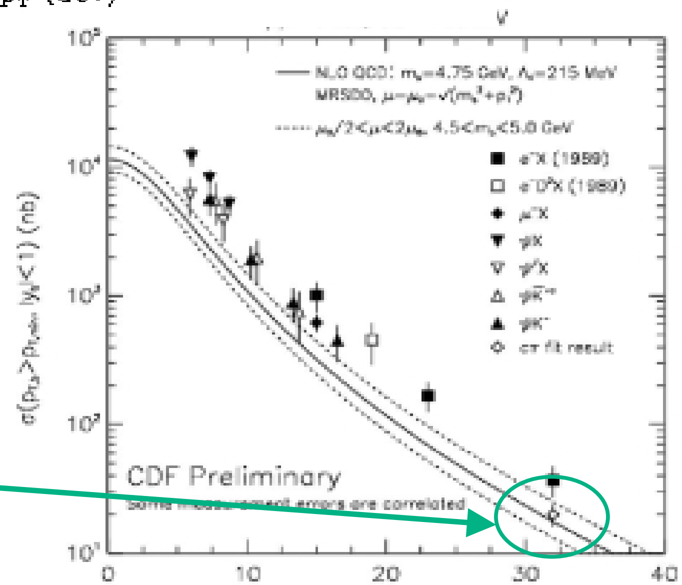
pp –> bjet + X (inclusive)

In RunI measure bottom and charm fraction

(P. Koehn,R. Hughes,R. Tipton CDF/ANAL/JET/CDFR/2894)

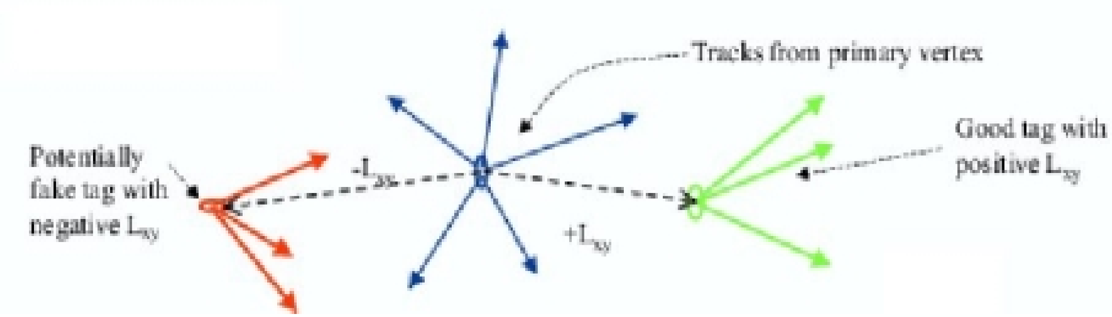
$\sigma = 19 \pm 2(\text{stat})^{+5}_{-6}$ (syst) nb

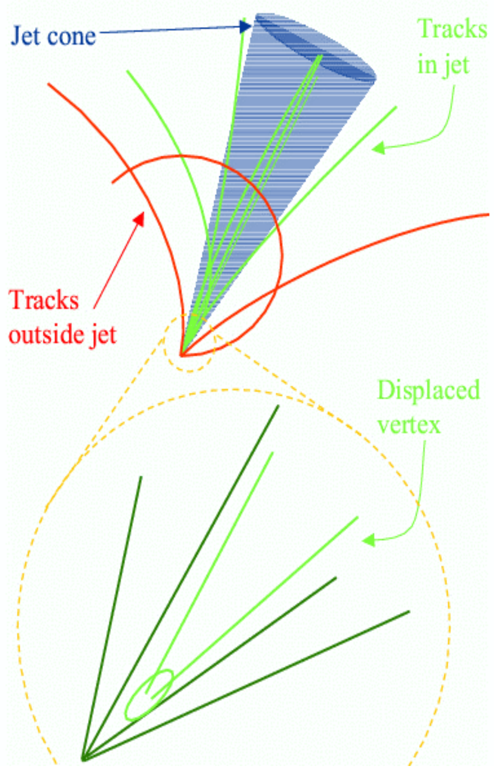
at $P_T > 35^{+3}_{-1}$ GeV/c for bottom



B tagging

- Looks for tracks associated with a jet (R=0.7) if within a sub-cone of 0.4 of jet axis
- A Primary vertex is defined for all tracks
- search for one (or more) secondary vertices inside the jets: the track selection is based on measurement of impact parameter (d0)
- Need ≥ two displaced tracks to reconstruct





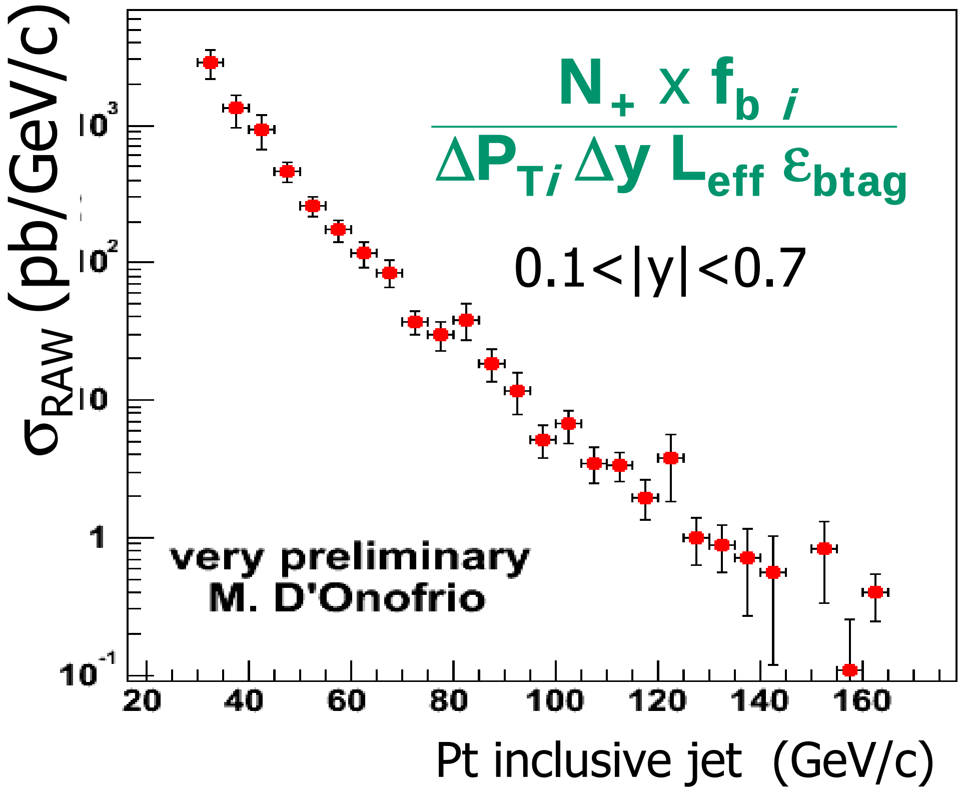
After secondary vertex reconstruction
→ additional cut madeon L_{xy}, distance primary to secondary vertex in rϕ space:
Jets sec vtx which passes L_{xy} cut: b-tagged

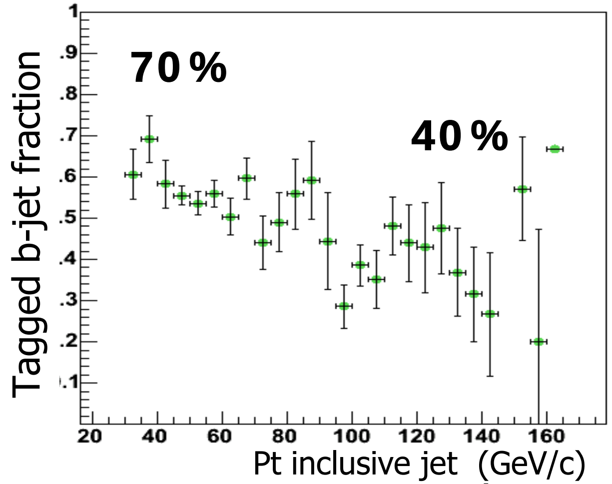
- Tags are positive ($+L_{xy}$) or negative ($- L_{xy}$)
- B-Tagging efficiency only uses positive tags.

Inclusive b-jet cross section

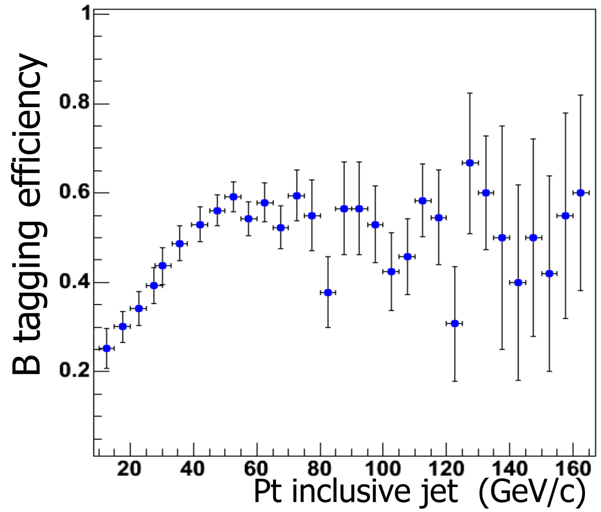
(not official results)

- Secondary vertex tagging
- MidPoint algorithm
- Use MC efficiency and b jet fraction





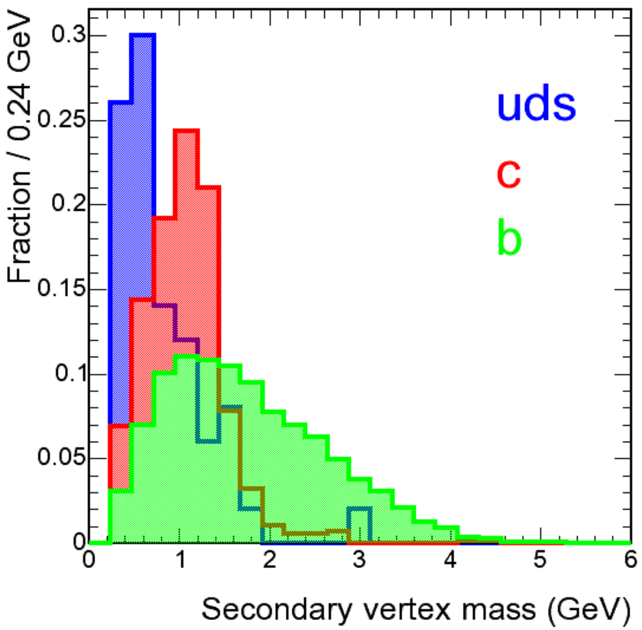
$$\varepsilon_{MC}\text{tag (per b-jet)} = \frac{\text{Njet (tag=+1)}}{\text{Ntaggable jet}}$$



γ+heavy flavour cross section

Cross-sections:

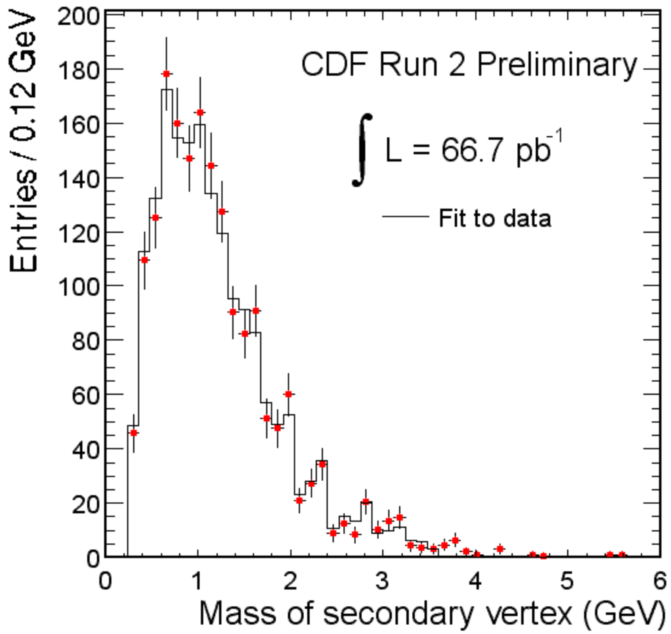
- as a function of photon Et: to test QCD predictions at different energy scales
- for all photons with an Et exceeding 25 GeV: to gain maximal statistical sensitivity to deviations that could signal new physics production.



Use of invariant mass of secondary vertex tracks in the jet to

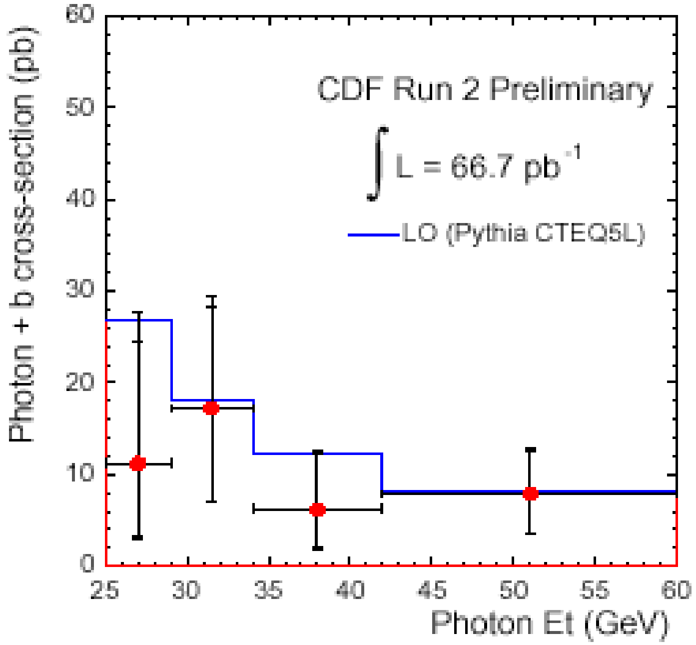
discriminate

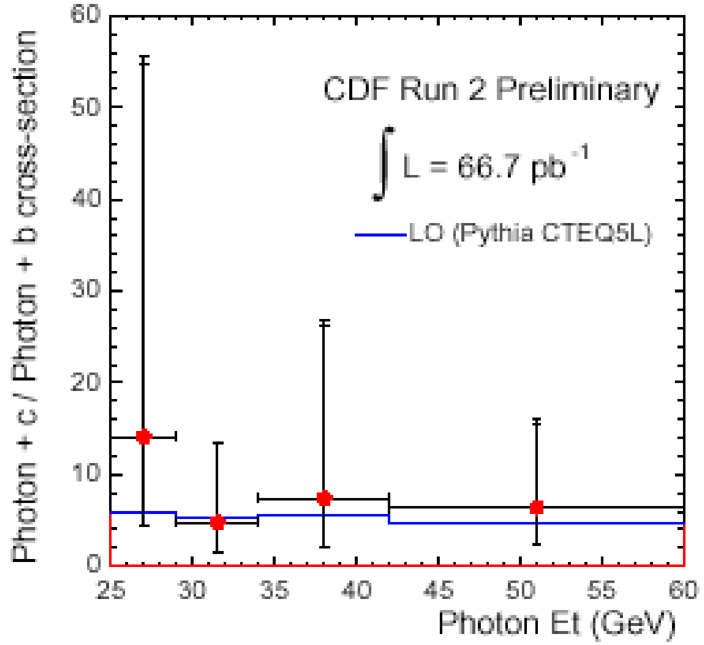
b/c/light quark



γ+heavy flavour cross section

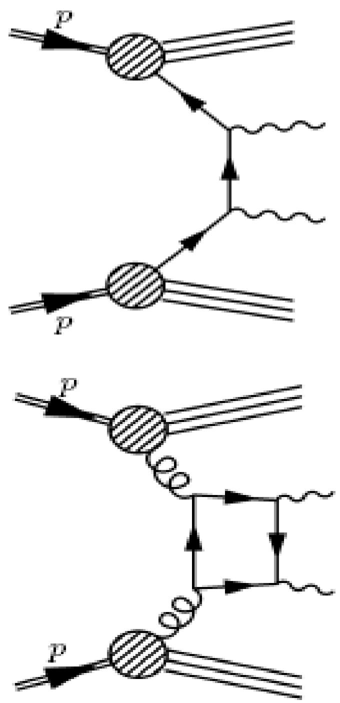
- Individual and ratio b/c cross section in agreement with NLO prediction
- Statistics limited: will improve with more luminosity
- Excess in γ+b,c, especially at high E_T, could be signal of new physics (light stop, …): no evidence found so far

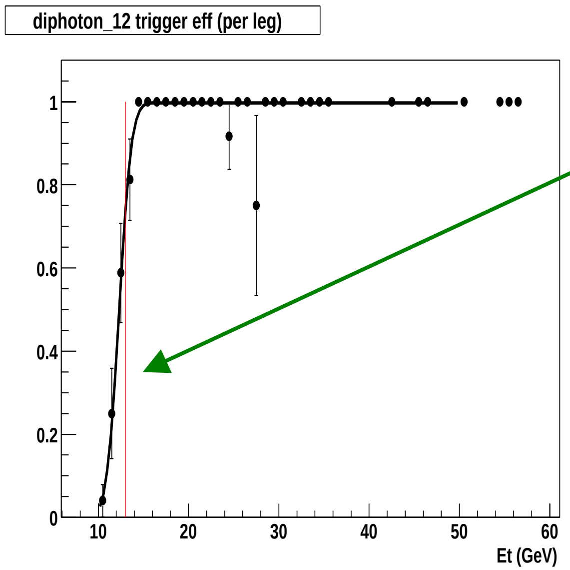




γγ cross section

- Final state momentum can be precisely measured → a good place to test the resummation formalisms or find new physics ...
- For Higgs searches at LHC, important to understand not only QCD production of diphotons, but also QCD production of the background to γγ.





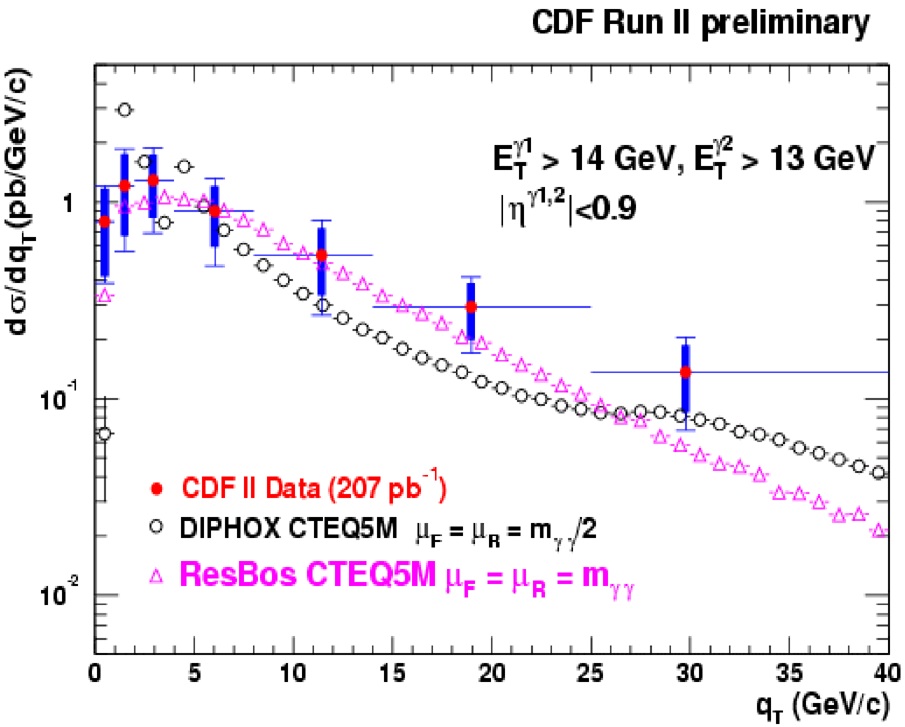
Use diphoton trigger
99% efficient at Et γ >13 GeV

Selections

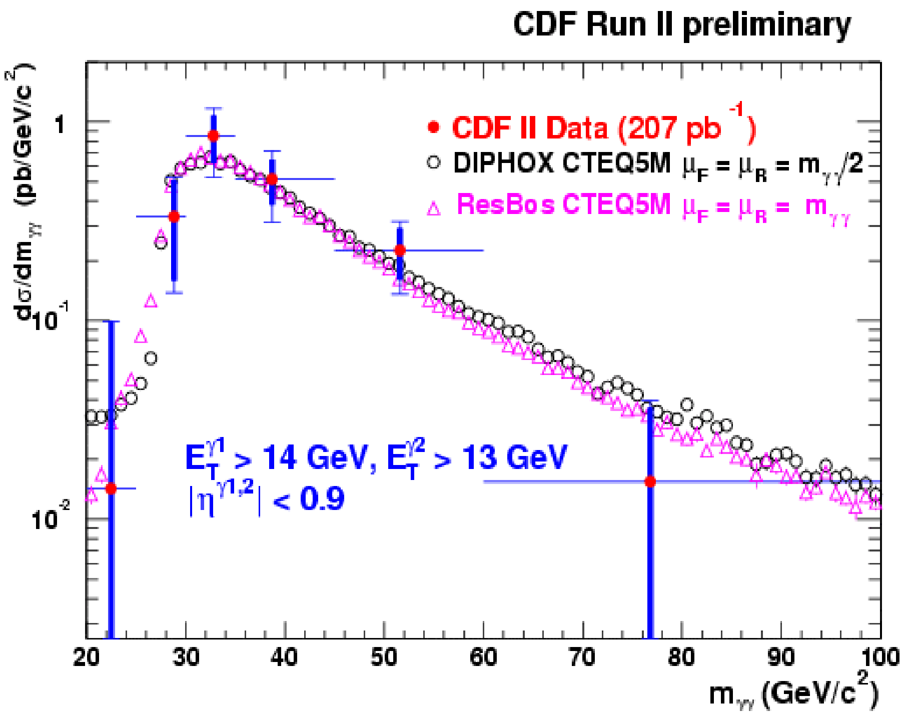
- Both photons at central, |η|<0.9
- Asymmetric cut on photons Et (14 and 13 GeV)
- Cal Isolation in 0.4 cone < 1GeV
- No tracks point at photon towers.

γγ cross section

- <u>Diphoton Qt :</u> soft gluon resummation important to describe the spectrum



Q_T: pt of the diphoton system sensitive to the magnitude of the effective transverse momentum vector of each of the two colliding partons



- Invariant mass: good agreement Data/Theory

(not sensitive to the soft gluon emissions)

More topics

Many other subjects are studied with very interesting results

- W + njets: comparison with LO pQCD, important background for top physics
- Underline events: Unavoidable background NOT well defined and modeled theorethically
- Diffractive physics program

Conclusion

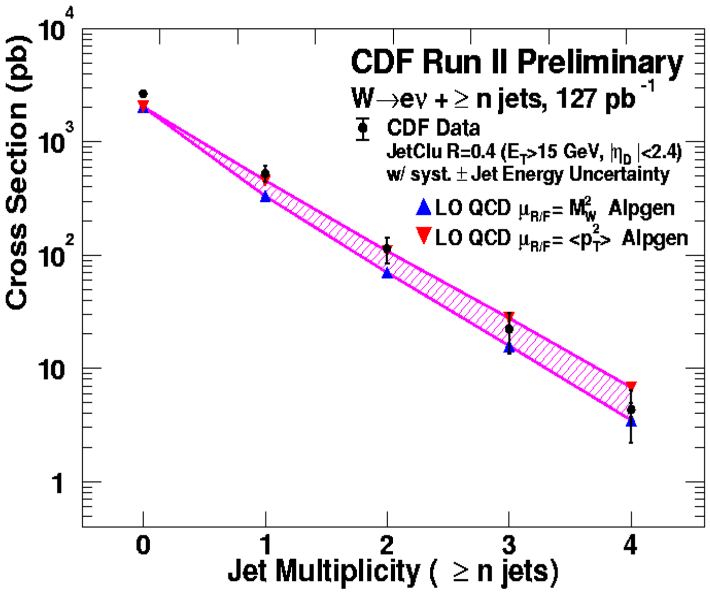
- A very exciting and important QCD physics program is ongoing at the Tevatron with the increased $\sqrt{s}$ and higher statistics of Run II extending measurements at high Q^2
- Careful study on general tools as jet algorithm is performed
- Some Preliminary results:
  - measured inclusive jet, dijet mass spectrum and jet shapes in reasonable agreement with NLO pQCD + CTEQ6.1/MRST01;
  - on going program to study b production
  - measurements on photon + heavy flavour cross section and diphoton cross section in agreement with SM predictions

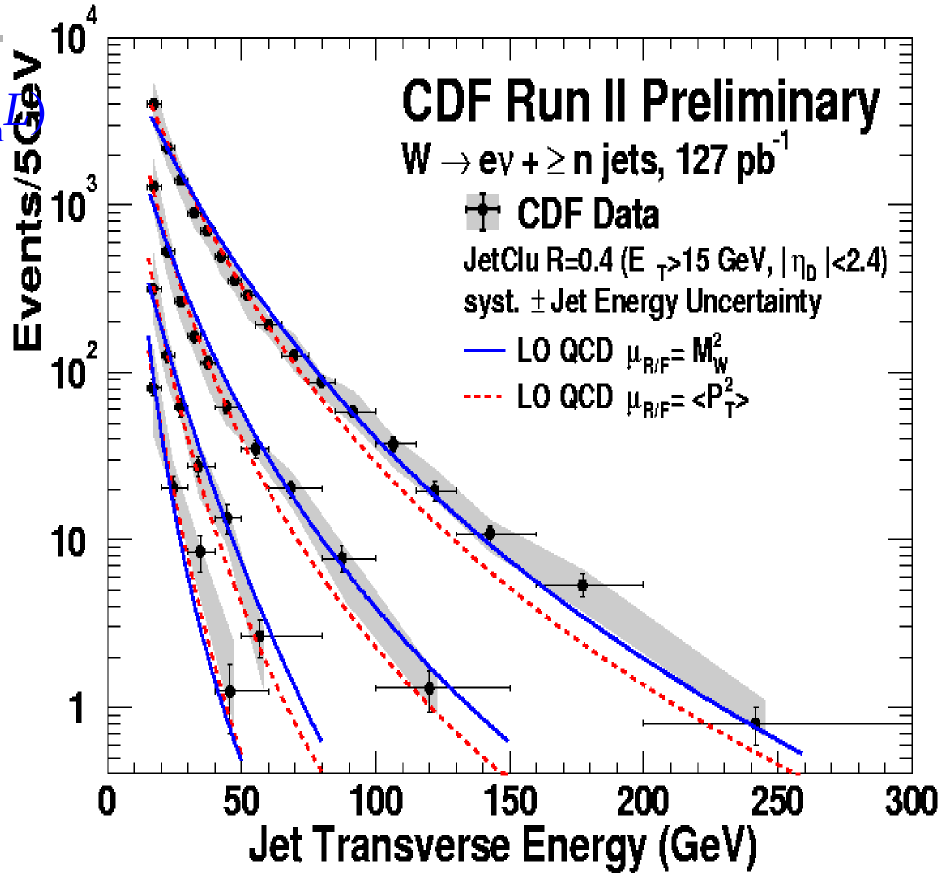
Back up slides

Other analysis: W+ njets

$\sigma_{n}(W) \times BR = (N_n - B_n)/(\mathfrak{M}_n L)$

- $\mathfrak{M}_n$: from data and MC studies
- LO pQCD: **ALPGEN** (CTEQ5L, ❍ = M_W^2, $< P_T^2 >$) + Herwig + detector simul.
- Theoretical errors dominated by dependence on ❍

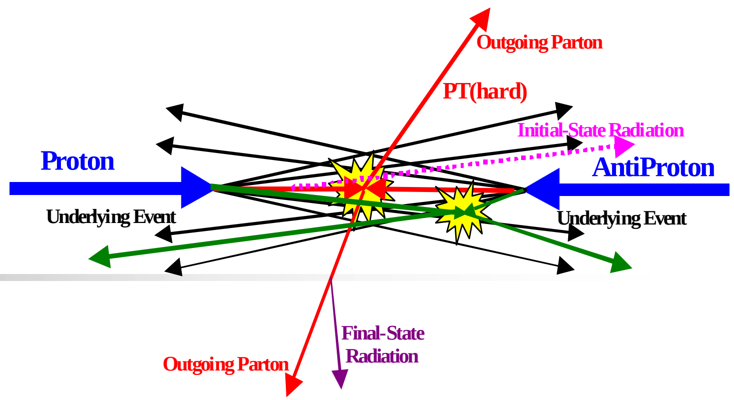




Diff. cross sec. vrs. E_T for *n* highest E_T jet:
reduced dependence on ❍

Fair data-theory agreement

Underlying events



Everything except the two outgoing hard scattered jets:

hard initial/final state radiation

beam-beam remnants

multiple parton interactions

Unavoidable background NOT well defined/modeled theoretically

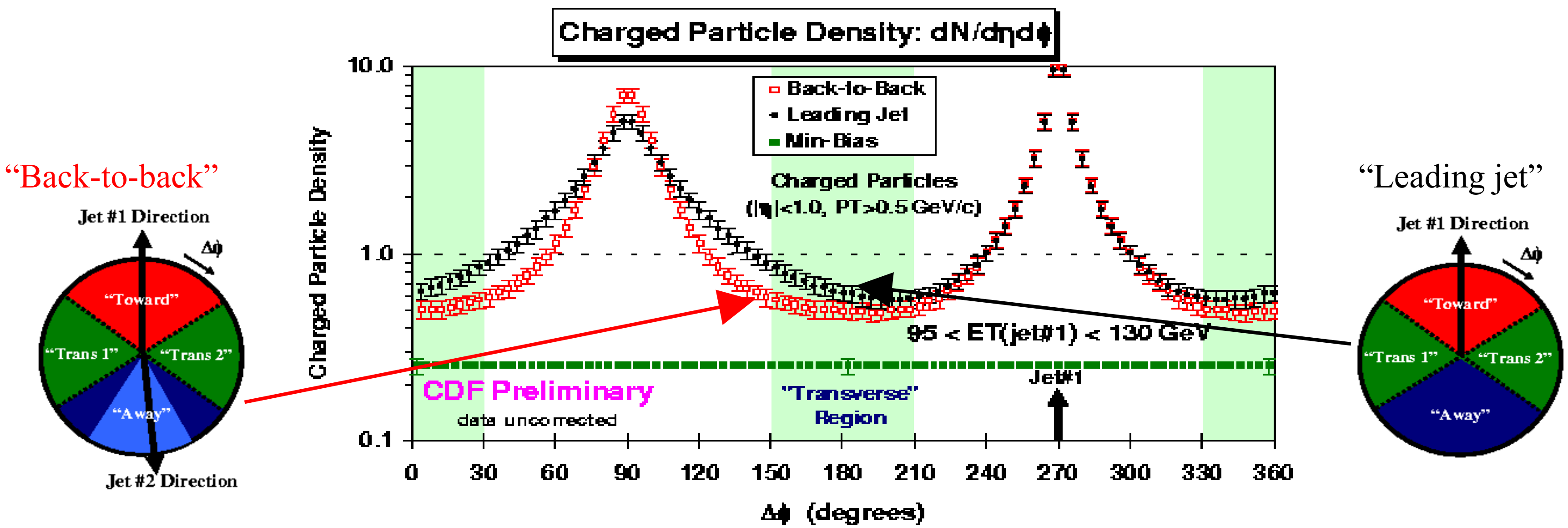
Phenomenological studies:

Leading calorimeter jet (JetClu $R = 0.7$, $|\eta| < 2$) defines 3 regions of same size in η-ϕ space

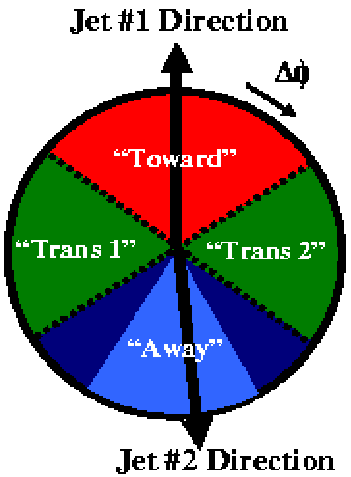
"Transverse" region very sensitive to U.E.

Charged particle ($p_T > 0.5$ GeV/c, $|\eta| < 1$) $\Delta\phi$ correlations with respect to jet #1

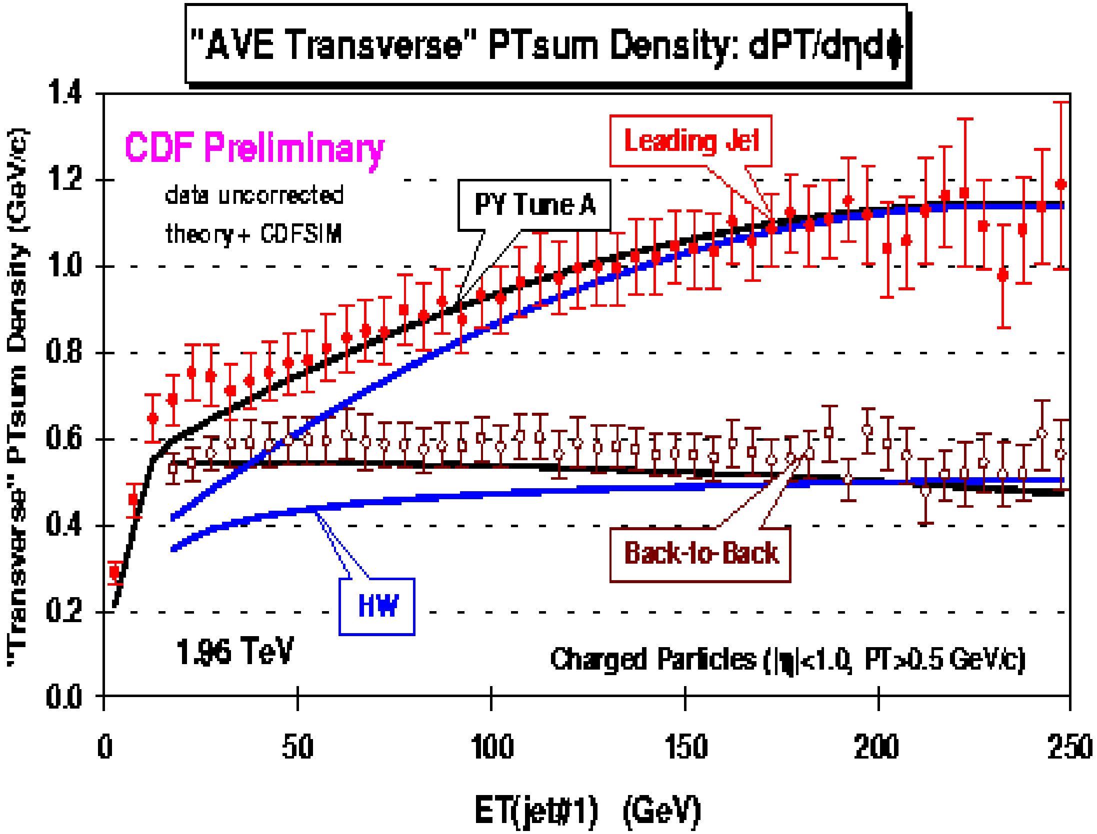
Min-bias & jet data vrs. Pythia and Herwig



Underlying events (2)



Comparing data with
MC Pythia & Herwig:

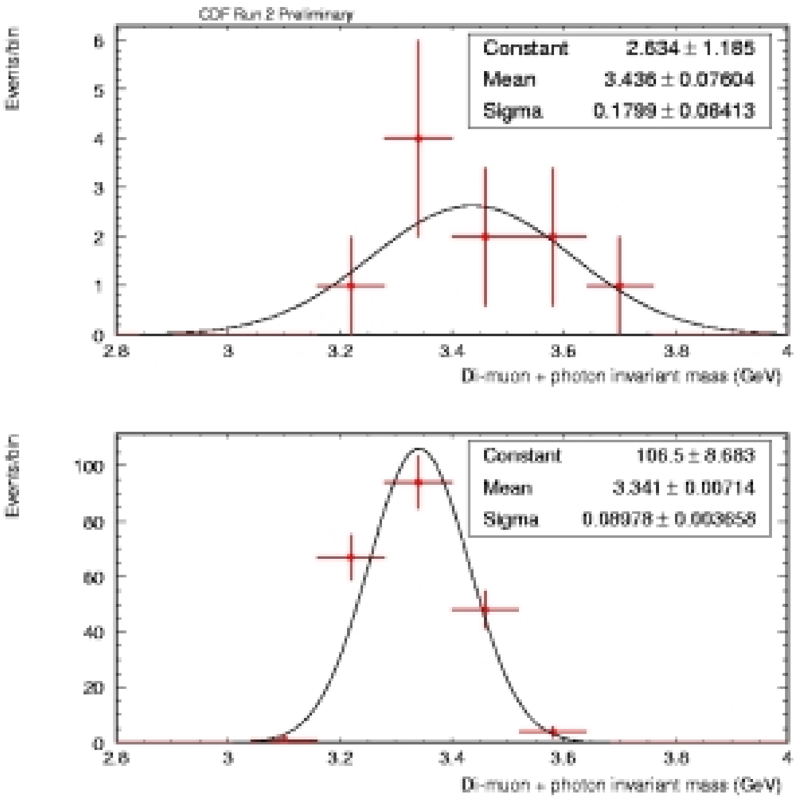


- Pythia (tuned on Run I)
in good agreement with Run II data
- Herwig (no multi-parton interaction)
works only at high E_t of jet 1

Diffractive physics

Very interesting and rich program

As example: *Exclusive J/psi+photon production*



Higgs boson produced by exclusive production:

$p + p \rightarrow p + H + p$

test prediction with a similar process:

$p + pbar \rightarrow p + \chi 0 + pbar$

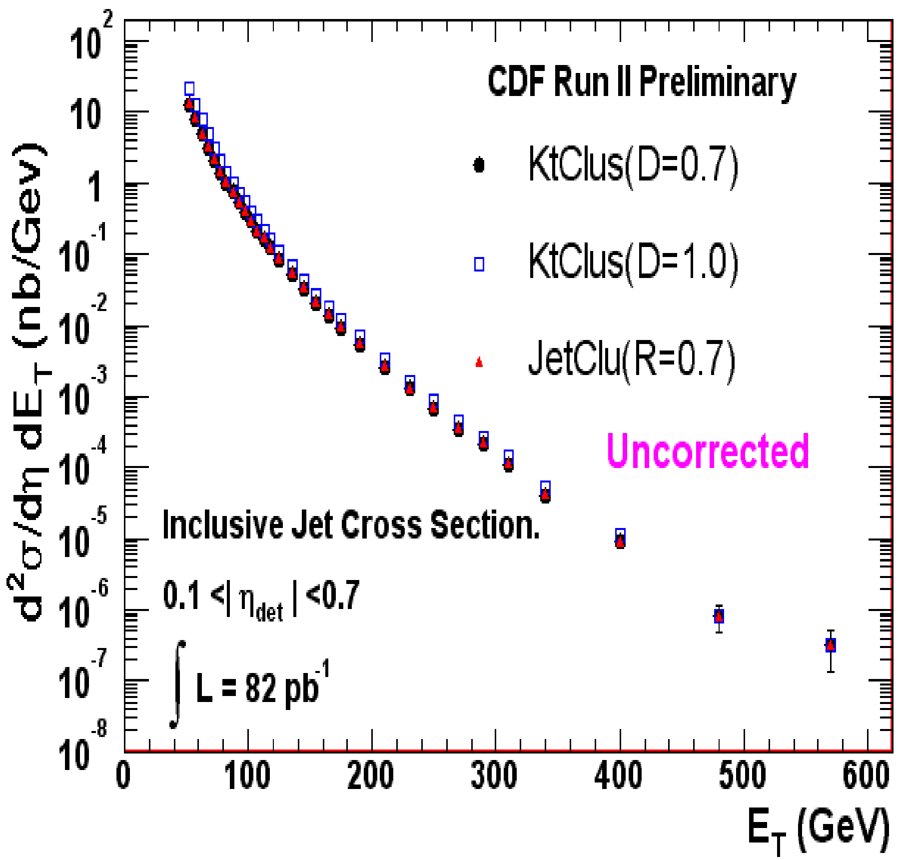
$\chi 0 \rightarrow J/psi + \gamma$, $J/psi \rightarrow \mu+\mu-$

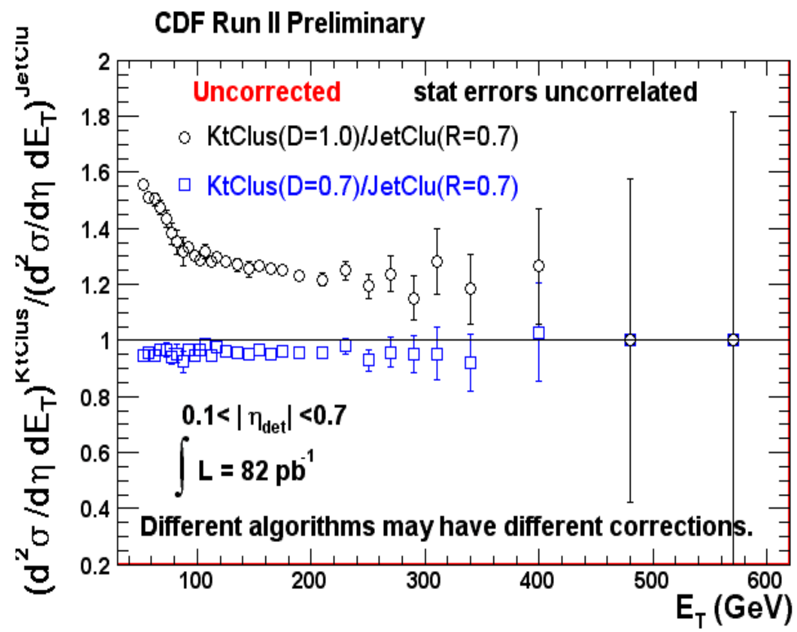
CDF Preliminary Results:
use the events to put an upper limit on the cross section for exclusive J/psi + γ production:

49 pb ± 18 (stat) ± 39 (syst), for $|\eta| < 0.6$.

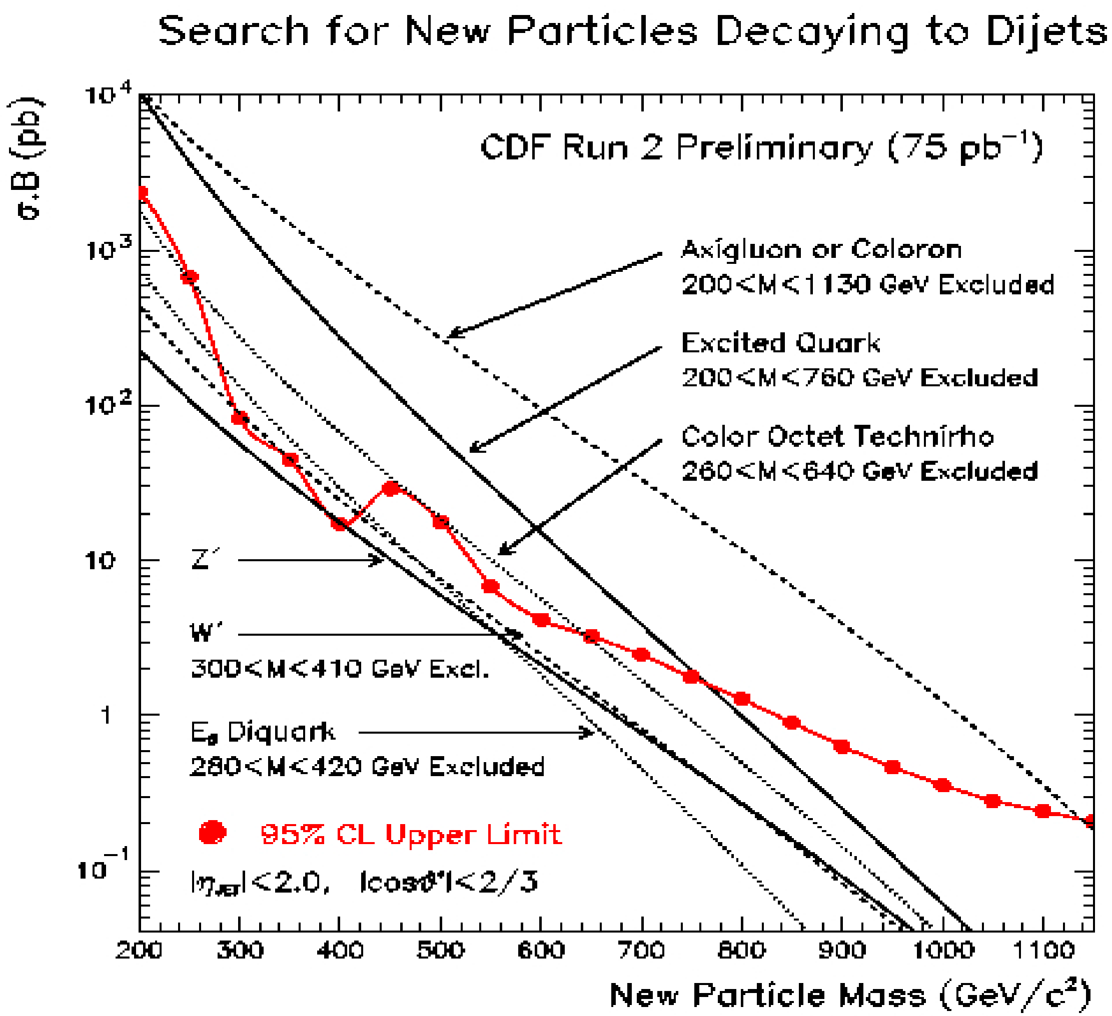
Inclusive jet cross section KT

KT algorithm





Dijet mass:
search for new particles



<u>do not exclude a Z'</u>
<u>in dijet decays in run 2</u>

there was no exclusion from run 1 either.