QCD Studies at CDF II

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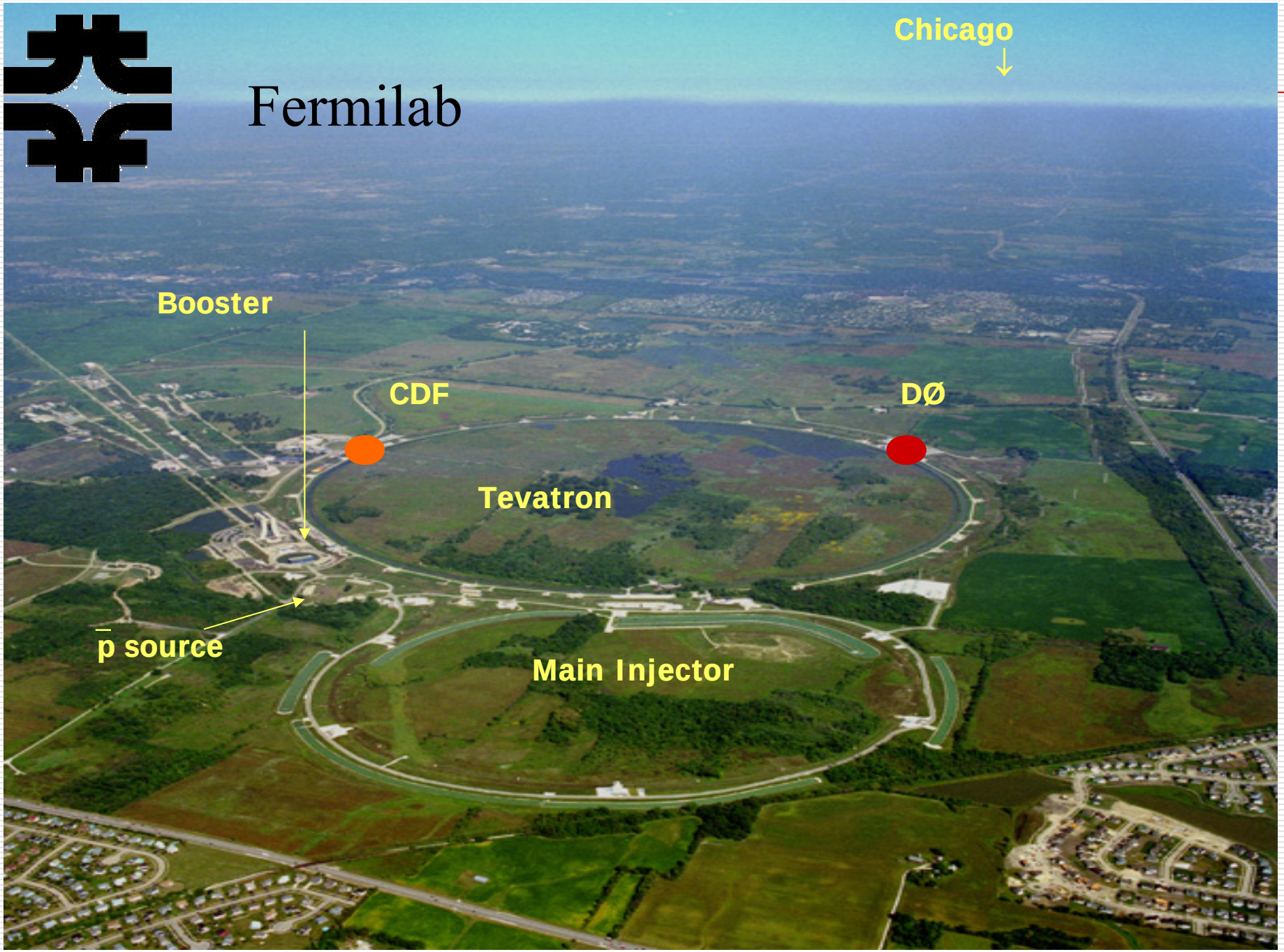
Outline

Introduction
Inclusive Jet Cross Section
b-jet cross section
Photon+heavy flavour production
DiPhoton Production
W+Jet Production
Conclusions

Fermilab



Tevatron

- Proton-Antiproton collisions

  $\sqrt{s} = 1.96\ \text{TeV}\ (\text{Run I} \rightarrow 1.8\ \text{TeV})$
- Main injector

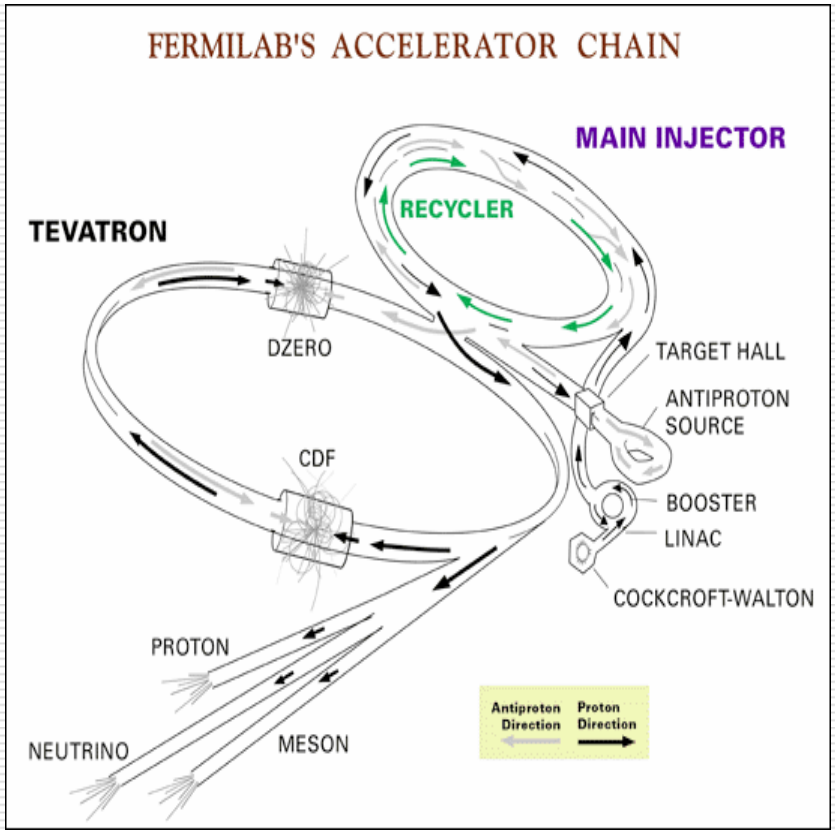
  (120 GeV proton storage ring)
- Antiproton recycler (commissioning)
  - Electron cooling this year
  - 40% increase in Luminosity

36 bunches (396 ns crossing time)

RUN IIa (2001~2005) ~1fb-1

(Celebrated 1 fb June 24,2005)

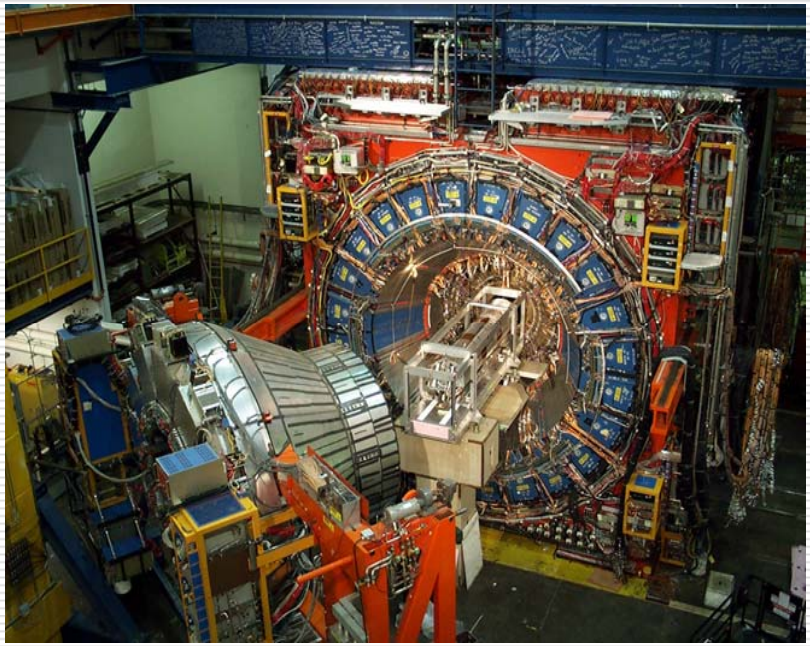
RUN I (1992-95) ~0.1fb-1



Long Term Luminosity Projection (by end FY2009)

Base Goal	4.4 fb-1
Design	8.5 fb-1

CDF Detector

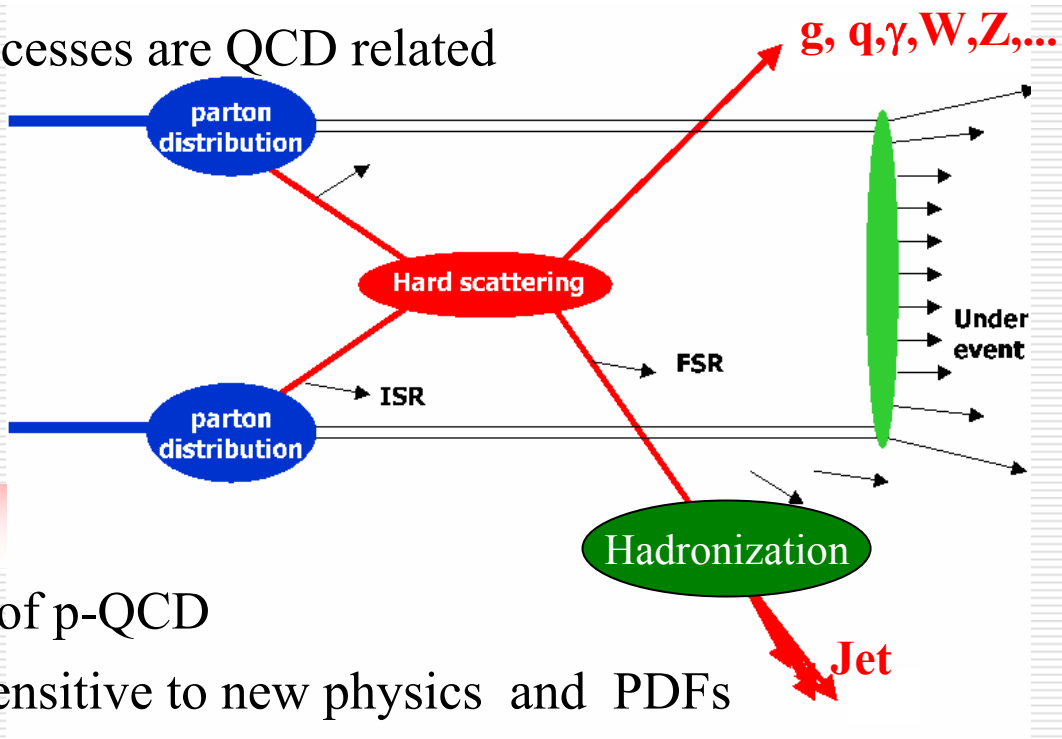


Upgrades

- ✓ Silicon detector & Tracking
- ✓ Time of Flight detector
- ★ Plug Calorimeters
- ✓ Forward detectors
- ✓ Muon System
- ✓ DAQ electronics and trigger

QCD at Tevatron

✓All production processes are QCD related



Jet Production

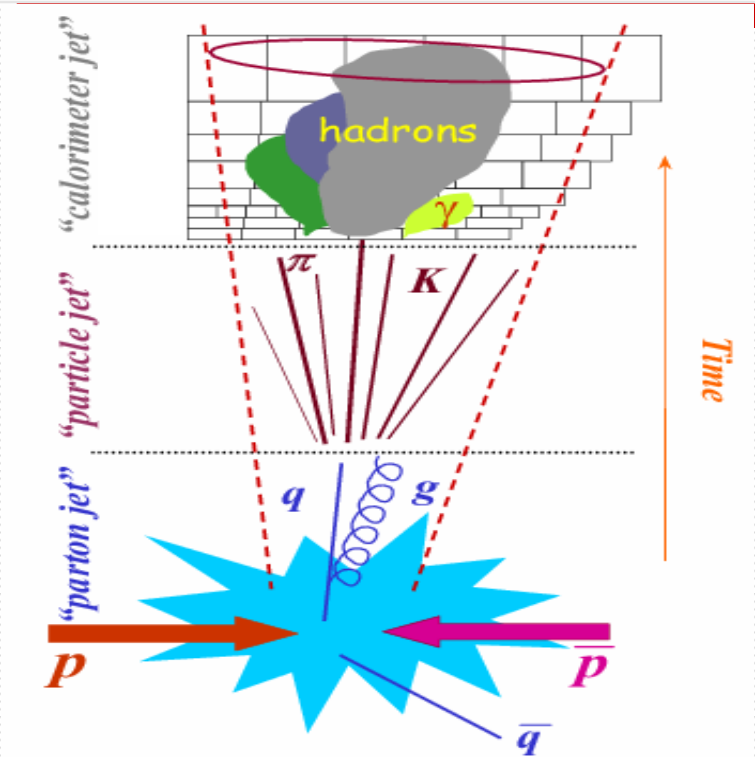
✓Stringent test of p-QCD

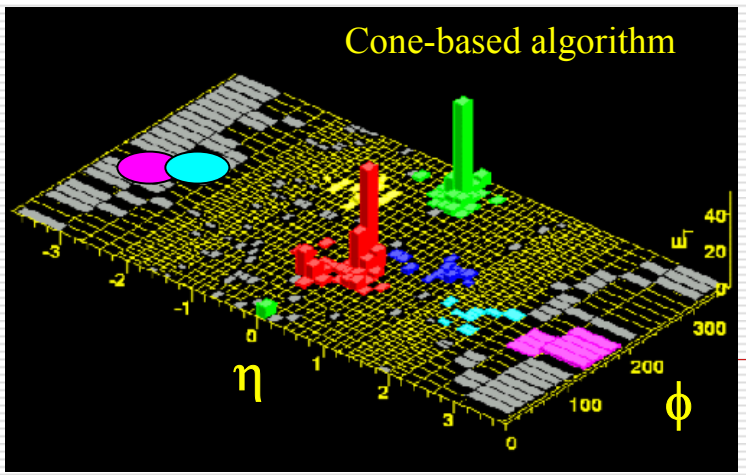
✓High-p_T tail sensitive to new physics and PDFs

Non-perturbative QCD contributions: Underlying event , Jet Hadronization

Other studies of interest: W+jets, diphoton, γ + heavy quark, inclusive b-jet production, hadron spectroscopy, diffraction

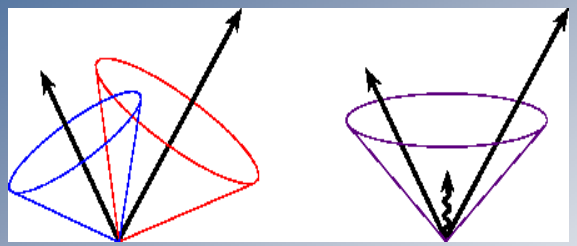
Jet Algorithms





Precise jet reconstruction algorithm necessary to compare with theory

Run I cone-based algorithm is not infrared and collinear safe to all orders in p-QCD



The jet multiplicity changed after emission of a soft parton

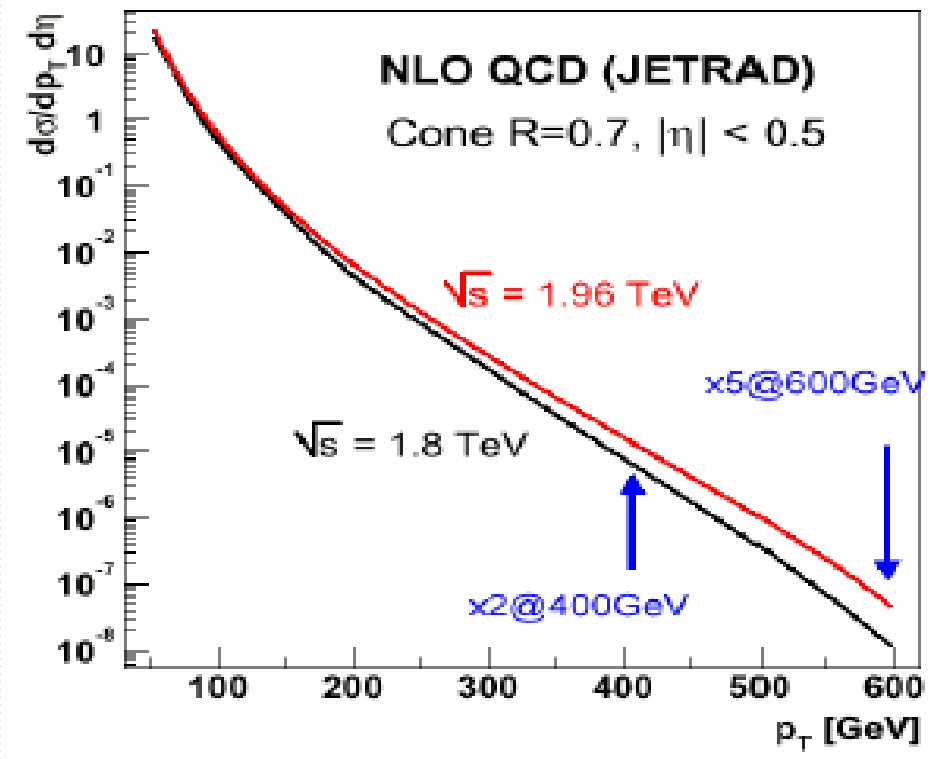
Run II ⇒ new cone-based algorithm: **MidPoint**

Cone-based jet algorithms include an "experimental" prescription to resolve situations with overlapping cones

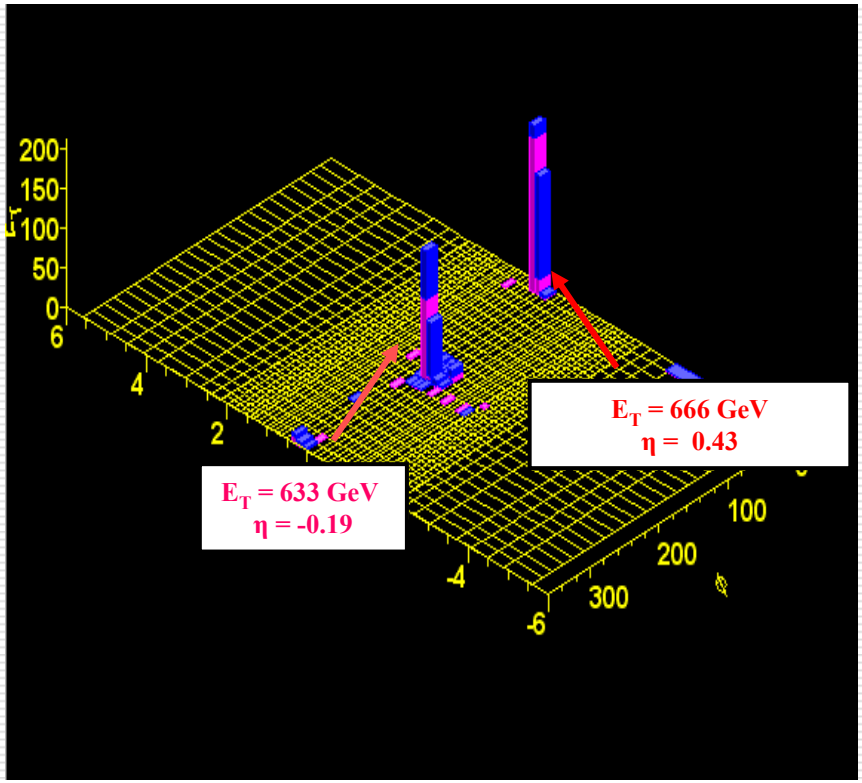
Theory prefer to separate jets according to their relative transverse momentum ⇒ **K_T algorithm**

Jet Physics at Tevatron

Inclusive Jet Cross Section



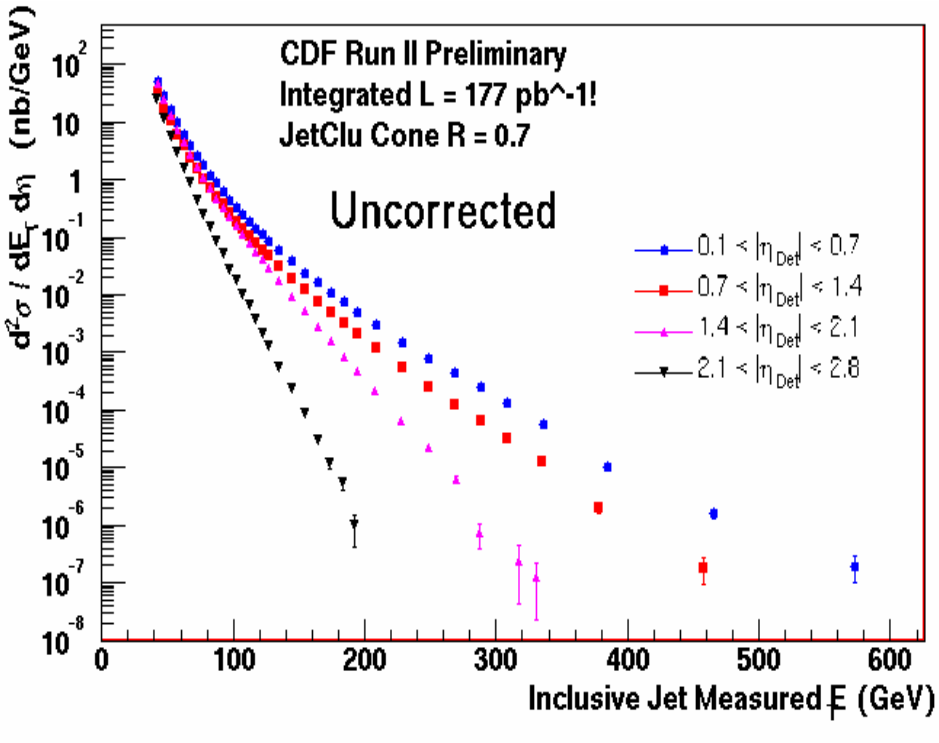
Highest dijet mass so far
Mass ≅1.3 TeV



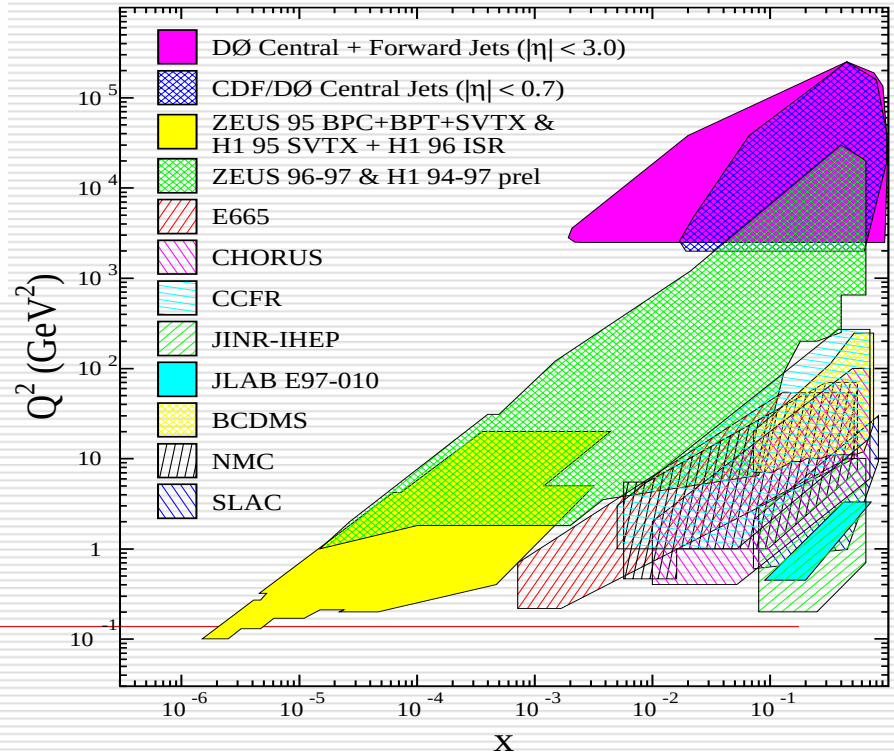
Higher σ_{jet} with respect to Run I

Increase p_T range for jet production

Parton Distributions



Measurements in different regions allow to further constrain the PDFs



MidPoint-Cone algorithm

Run I Cone algorithm is not infra-red safe. Add additional seed at middle two jets close by jets.

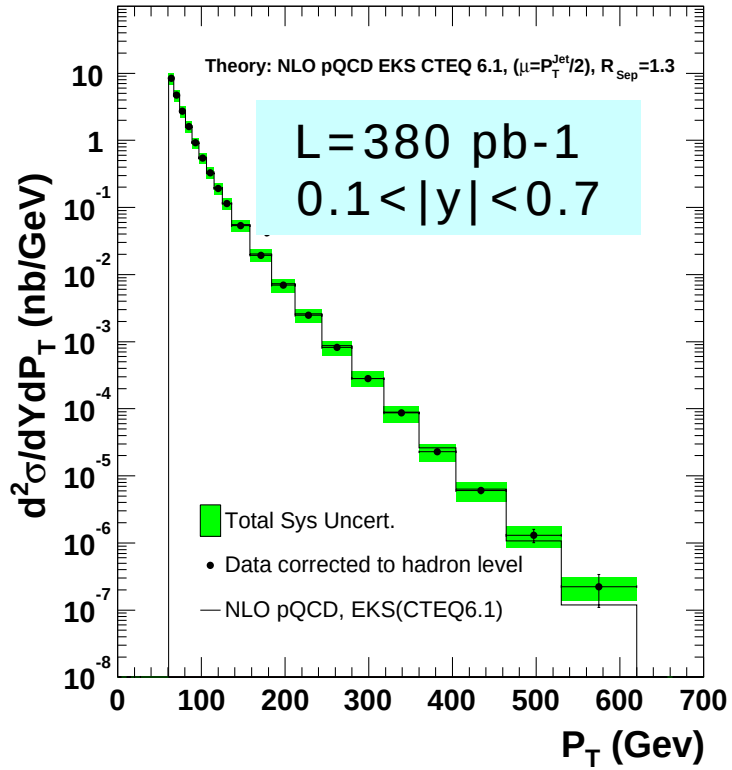
1. Define a E-ordered list of seeds using CAL towers with E > 1 GeV
2. Draw a cone of radius R around each seed and form "proto-jet"

$$E^{Jet} = \sum_k E^k \qquad \bar{P}^{Jet} = \sum_k \bar{P}^k$$

Massive jet use p_T^{Jet}, rapidity y^{Jet}

3. Draw new cones around "proto-jets" and iterate until stable cones
4. Put seed at Midpoint (η-ϕ) for each pair of proto-jets **separated by less than 2R** and iterate for stable jets
5. Merge two jets if overlap energy >75%.

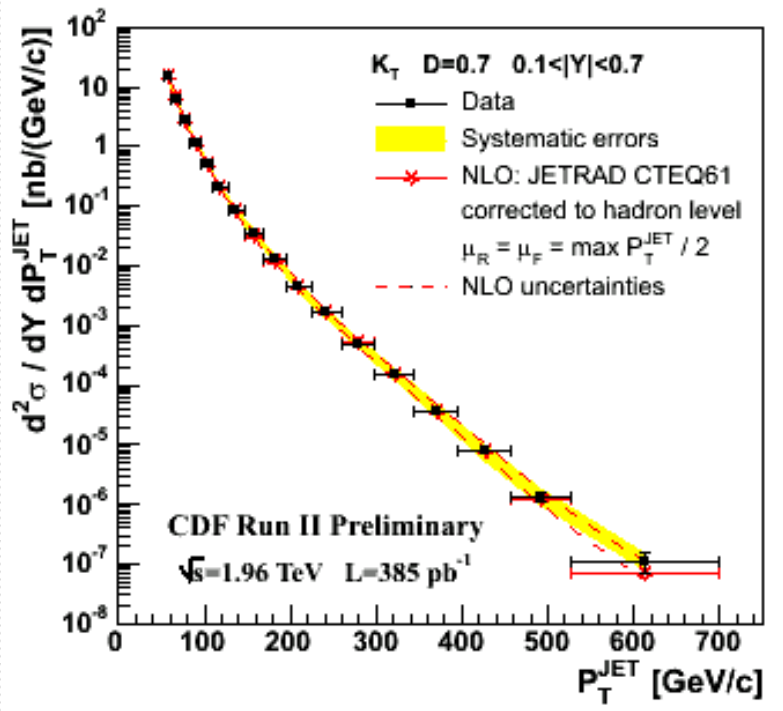
Experimental clustering still not modeled in NLO pQCD calculations. Use Rsep parameter.



Analysis using MidPoint Clustering using new jet energy scale ready for public release soon.

The data are in general agreement with NLO QCD (EKS,CTEQ6.1) predictions.

Inclusive Jet Cross Section with K_T



Data uncertanties dominated by energy scal
(5% energy scale systematic)

Data is not corrected for hadronization and Underlying Event energy.
NLO QCD prediction is modified for hadronization/UE effect.

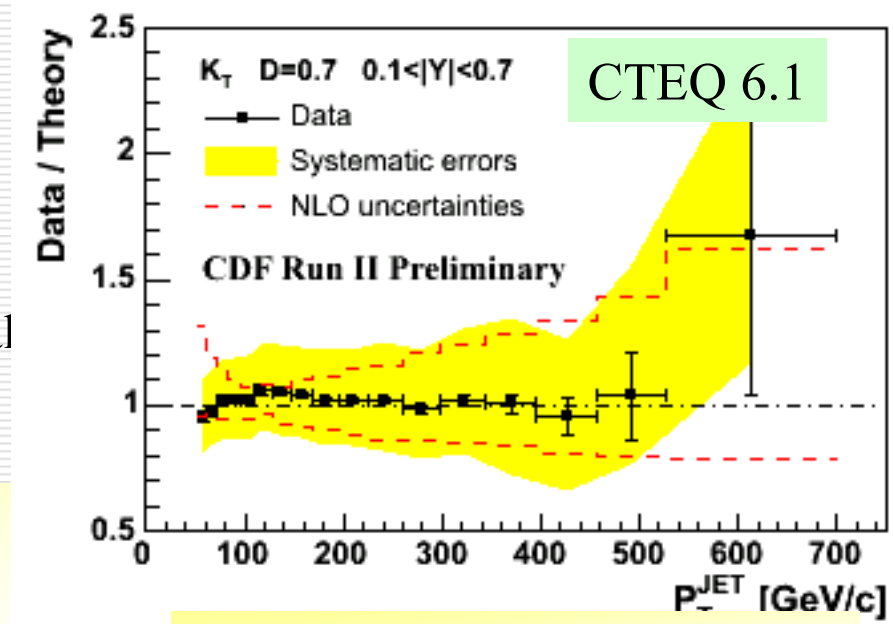
K_T Algorithm

$$d_{ij} = \min(P^2_{T,i}, P^2_{T,j}) \frac{\Delta R^2}{D^2}$$

$$d_i = (P_{T,i})^2$$

✓Infrared and collinear safe to all orders in p-QCD (relevant for NNLO)

✓No merging/splitting parameter



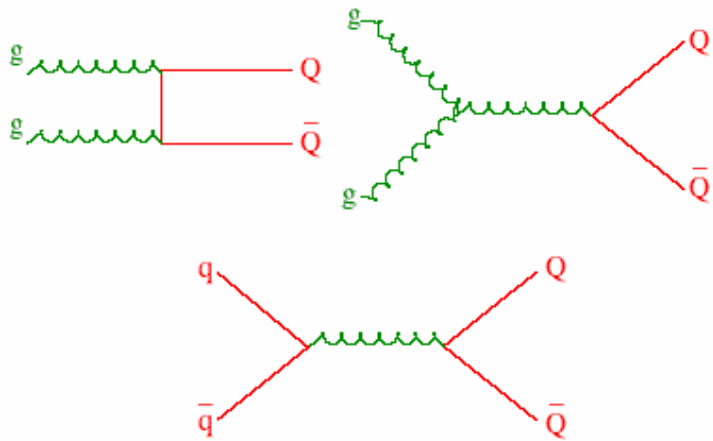
Good data-theory agreement

NLO error mainly from PDFs (high x gluon)

Beauty Production

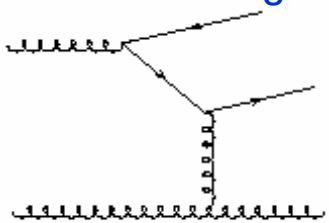
- To understand and probe perturbative QCD
- at E_{cm}=1.96 TeV $\sigma(b\bar{b})$ ~ 50 μb → few kHz event rate

Leading Order

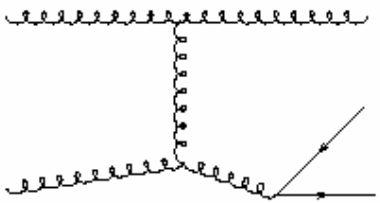


Flavor creation

Next to Leading Order



Flavor excitation



Gluon splitting

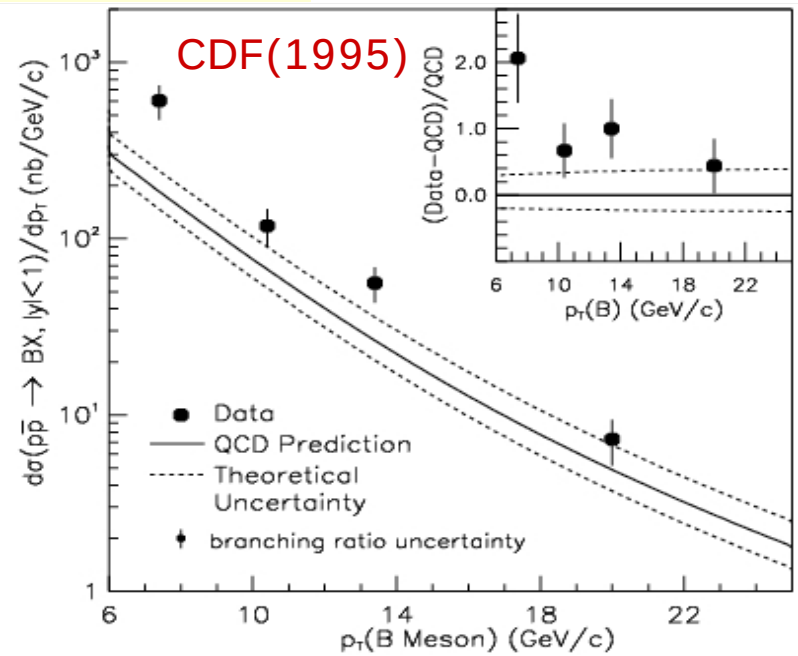
Full calculations have been done up to NLO and beyond ….

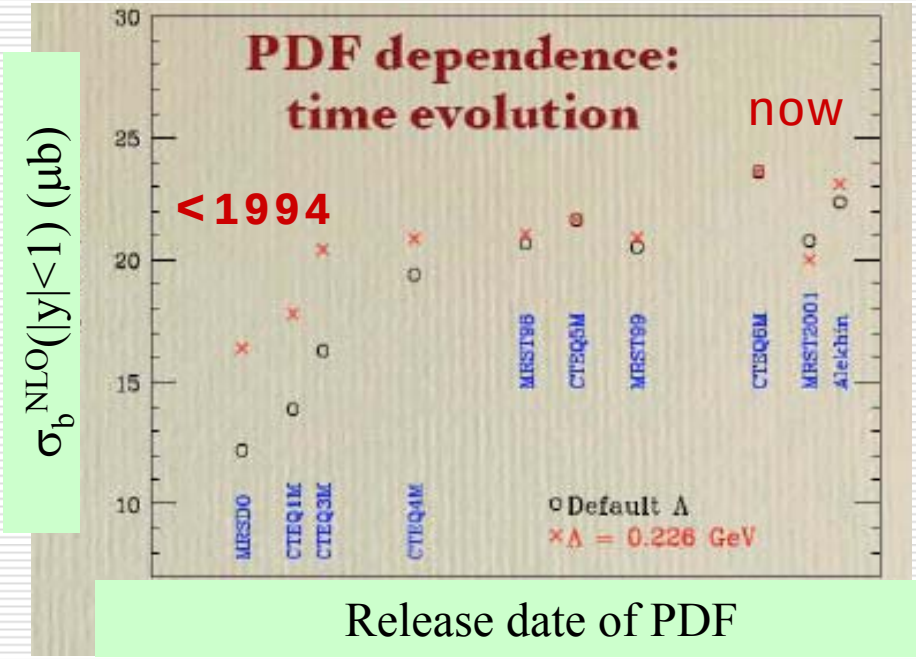
Many developments in the theoretical approach in the recent years

Recent developments

- Beyond NLO: resummation of $\log(p_T/m)$ terms → FONLL
- Substantial change in fragmentation function extraction (LEP data)
- new PDF functions

... the past





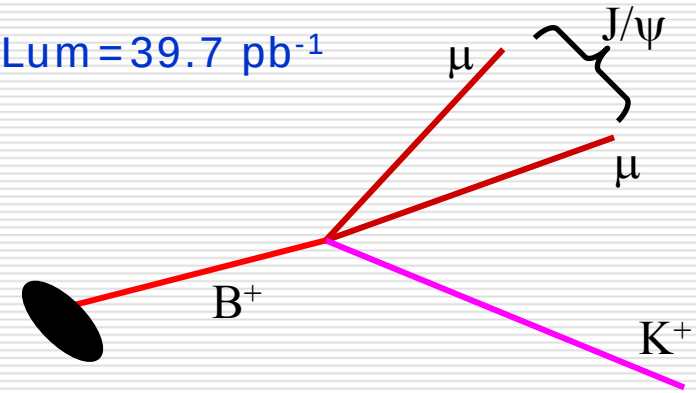
- Good data/theory agreement also due to improved treatment of experimental inputs (use b-jets and b-hadrons rather than b-quark)

... the present →

B hadron production using J/ψ

Subm. to PRD, FERMILAB-PUB-04-440-E

Lum=39.7 pb^{-1}

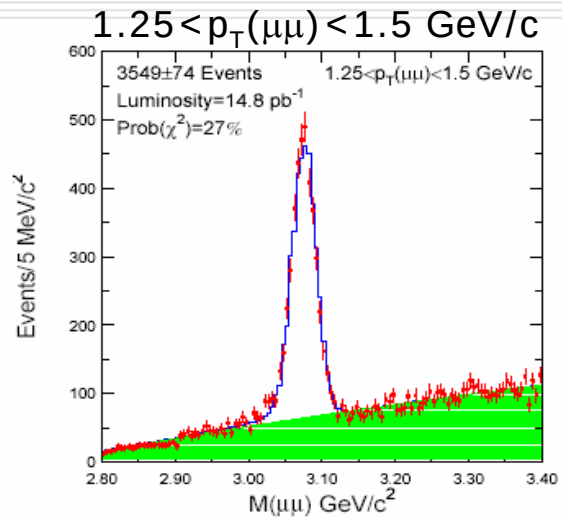


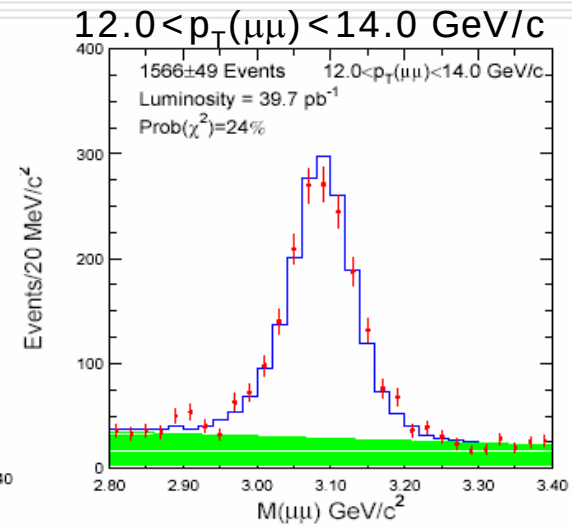
Exclusive decays of B-Hadrons used to measure the b production cross section

- Find J/ψ inclusive cross section
- Extract fraction of J/ψ from decay of long-lived b-hadrons
- Find b-hadrons cross section for $p_T(B)$ down to 0 considering $|y(J/\psi)|<0.6$

Counting J/ψ (p_T= 0 to 20 GeV/c)

- muon trigger: $\varepsilon=0.986\pm0.010$ for $p^{\mu}_{T}>1.5$ GeV/c ($|y|<0.6$)
- use detector simulation to model the shape as expected for J/ψ signal
- Mass resolution ~ 14-15 MeV





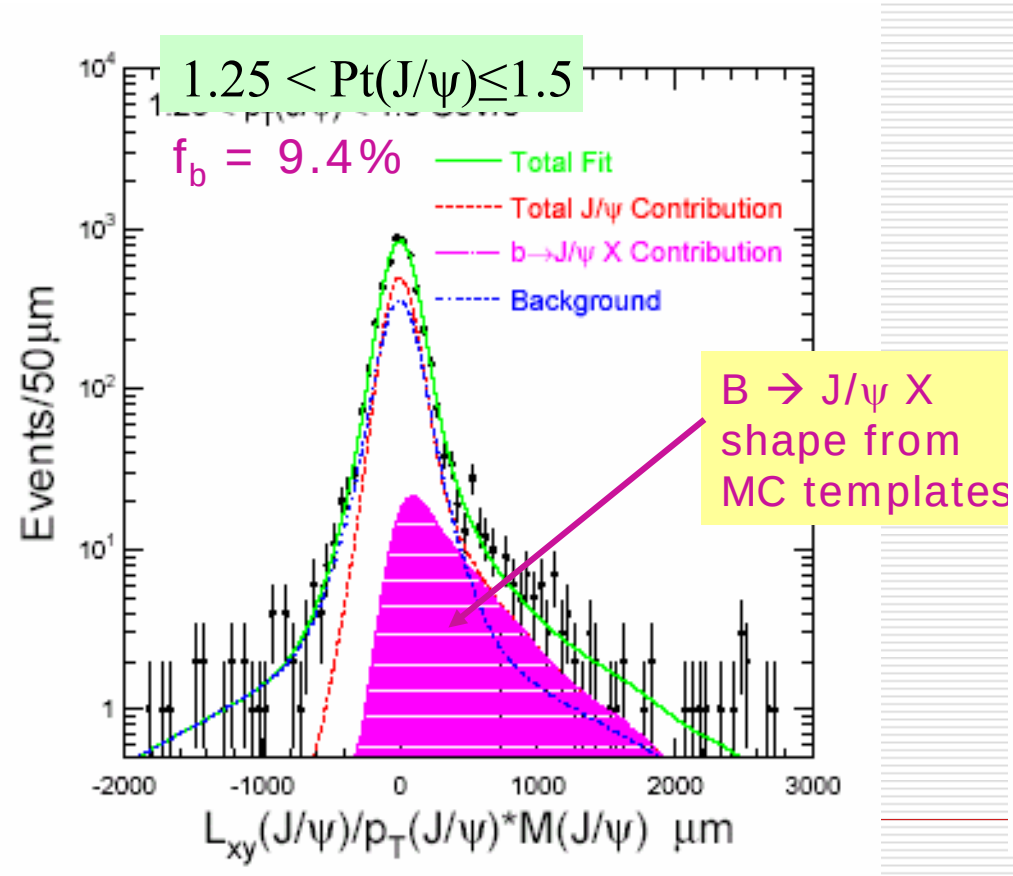
Extract b fraction

To reduce dependence on J/ψ p_T bin:

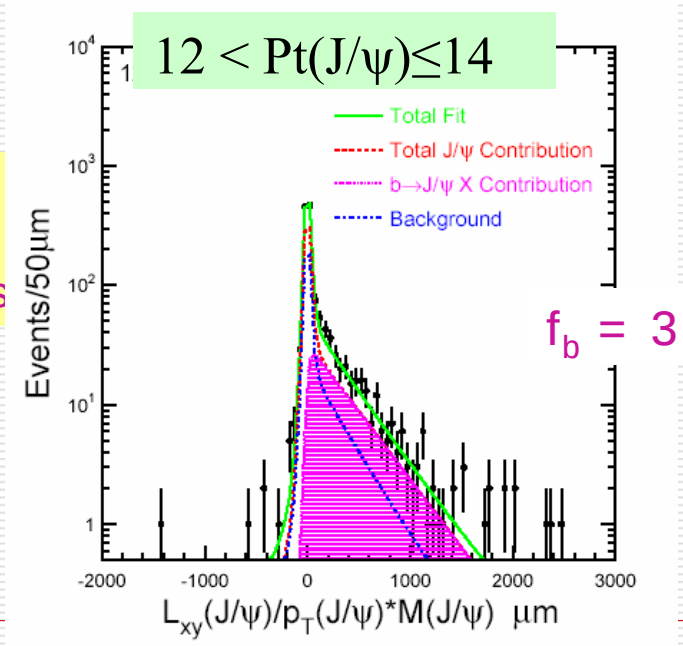
$x = L_{xy}(J/\psi) \cdot M(J/\psi) / p_T(J/\psi)$

= flight path of J/ψ in r-ϕ plane

Maximum likelihood fit to extract b fraction as function of $p_T(J/\psi)$



B → J/ψ X shape from MC templates

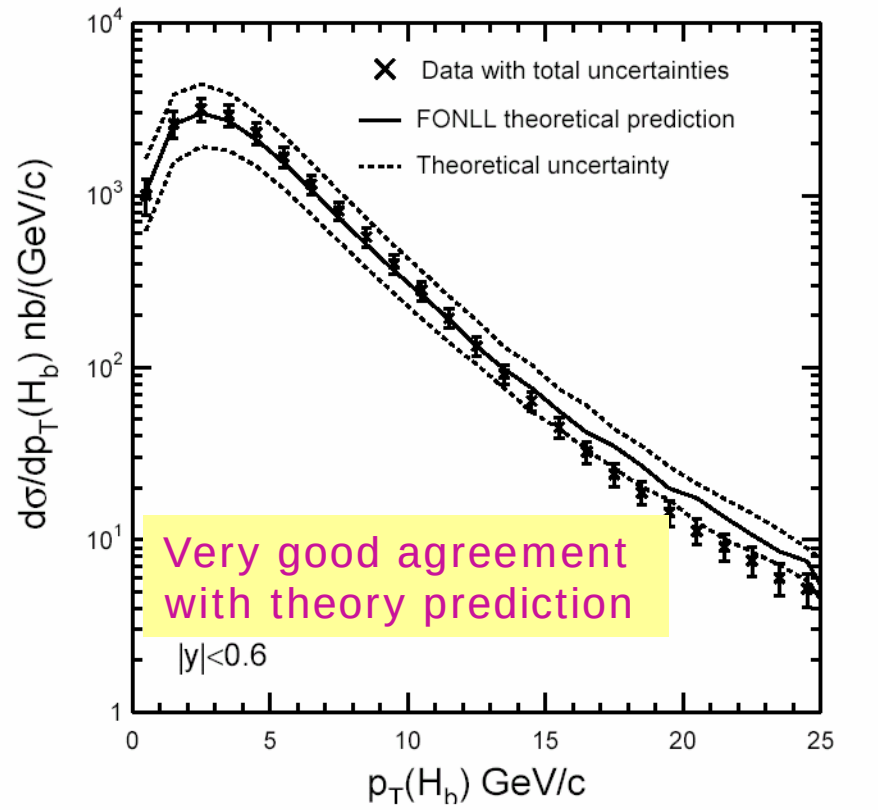


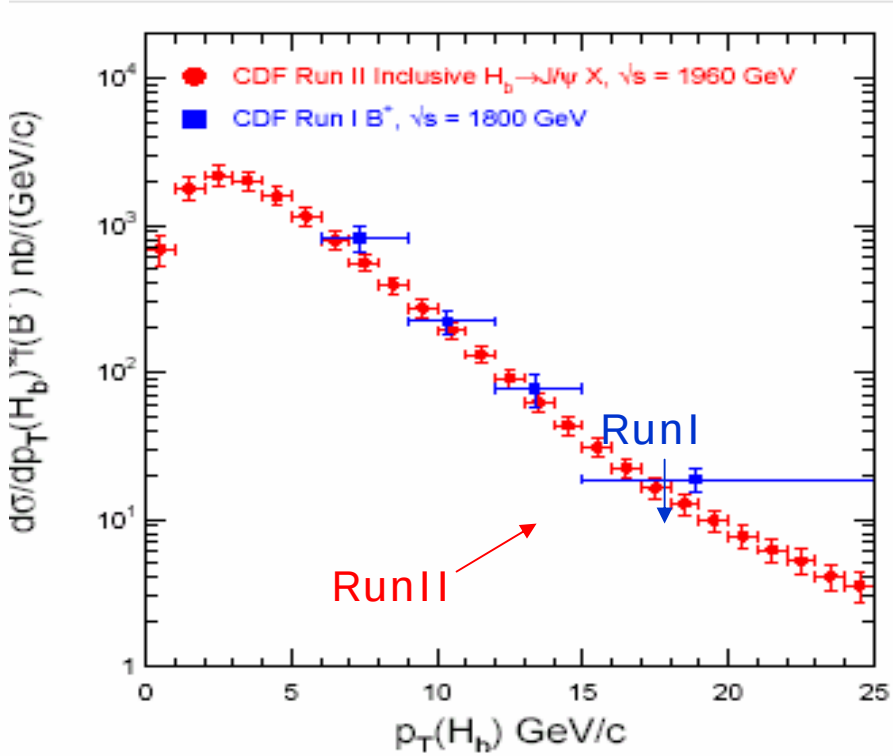
B hadron production cross section

Total inclusive single b-hadron (H_b) cross section

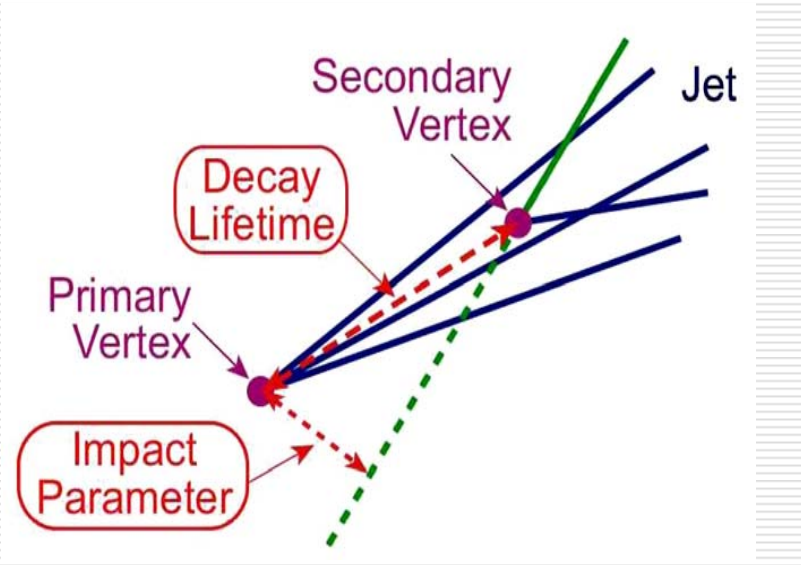
$$\sigma(p\bar{p} \to H_b X, |y| < 0.6) = 17.6 \pm 0.4(stat)^{+2.5}_{-2.3}(syst)\ \mu\mathrm{b}$$

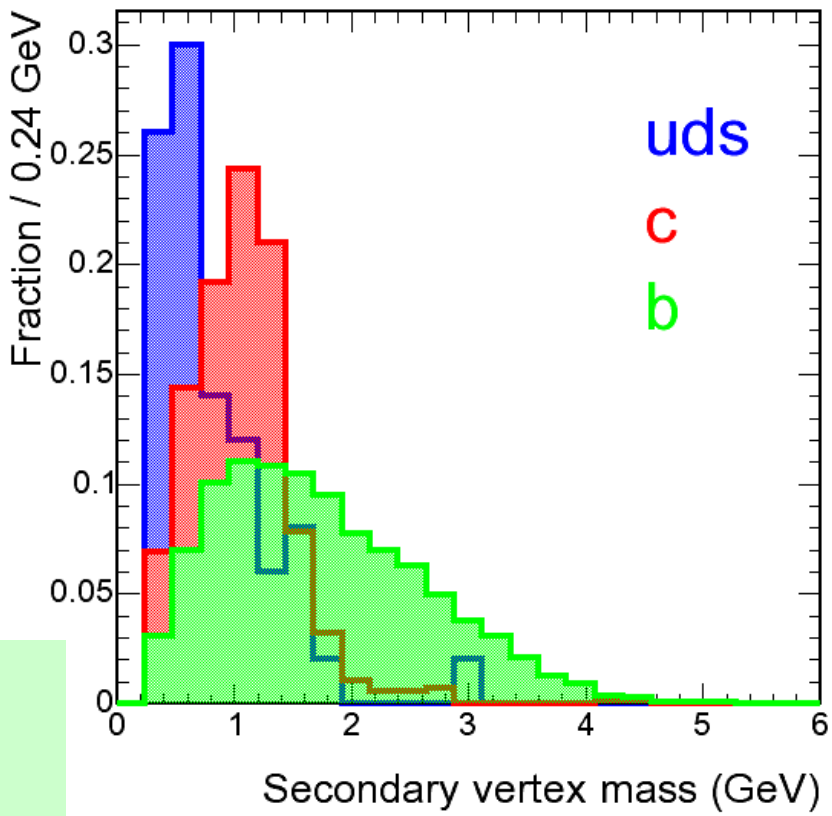
Using $Br(H_b \to J/\psi X)$ = 1.16±0.10% and $Br(J/\psi \to \mu\mu)$ = 5.88±0.10%





b-jet tagging

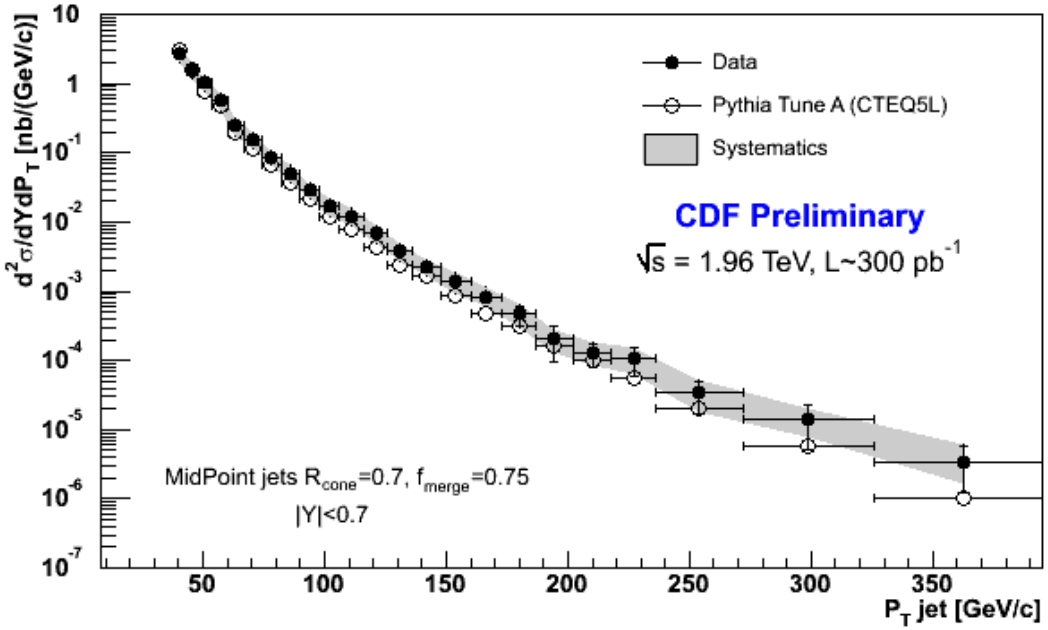


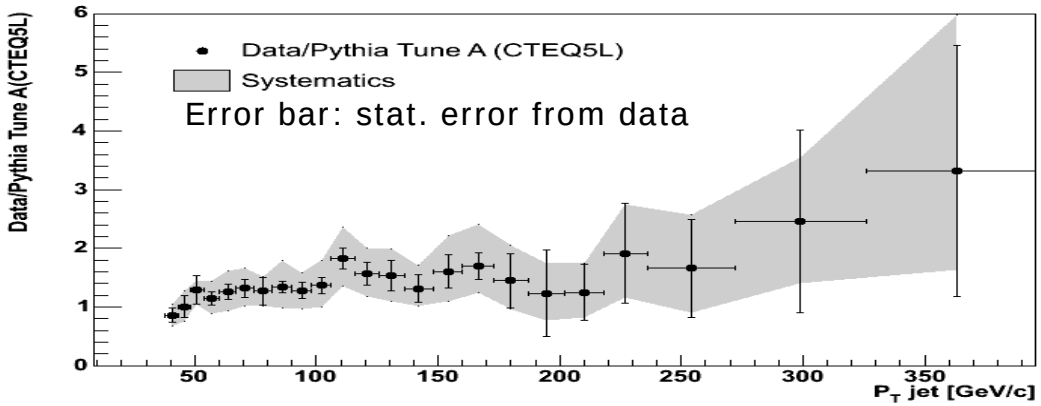


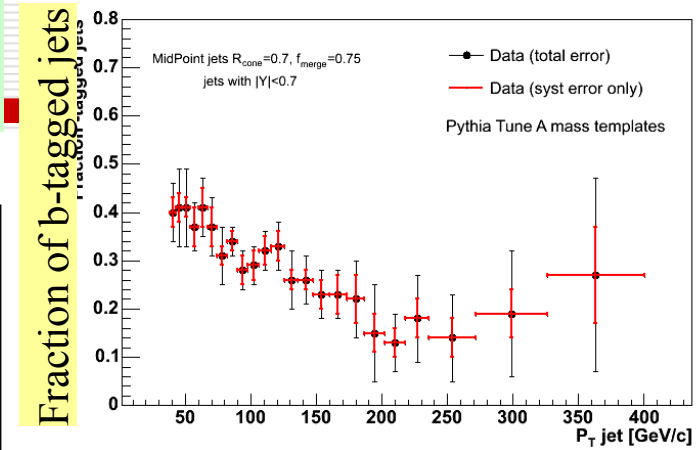
B-hadrons decay ~450 μm
Reconstruct secondary vertex using tracks in silicon tracker.
B-tagging efficiency (inclusive jet sample 50%(50 GeV)→25%(350 GeV)

Use secondary vertex mass to separate b-jets from c and light jets.

Inclusive b-jet cross section





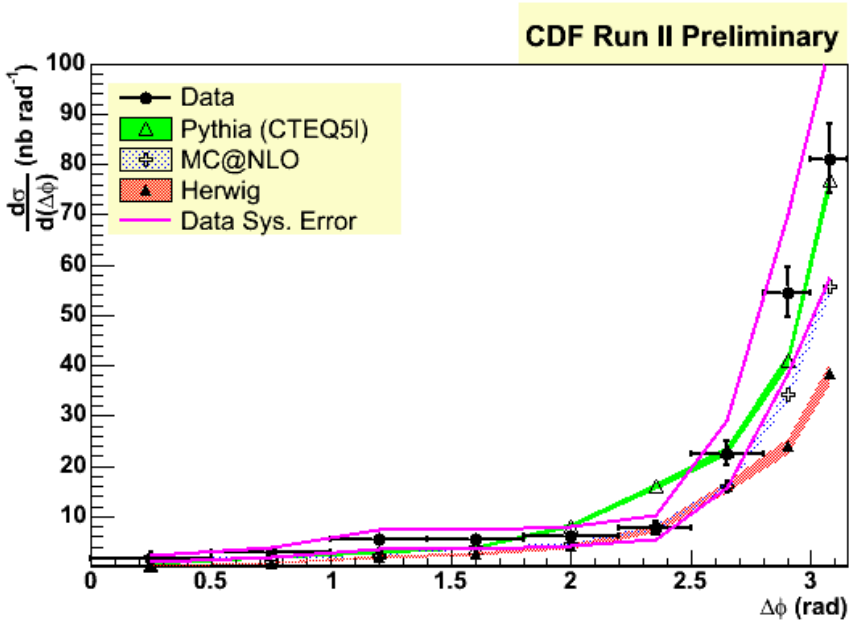


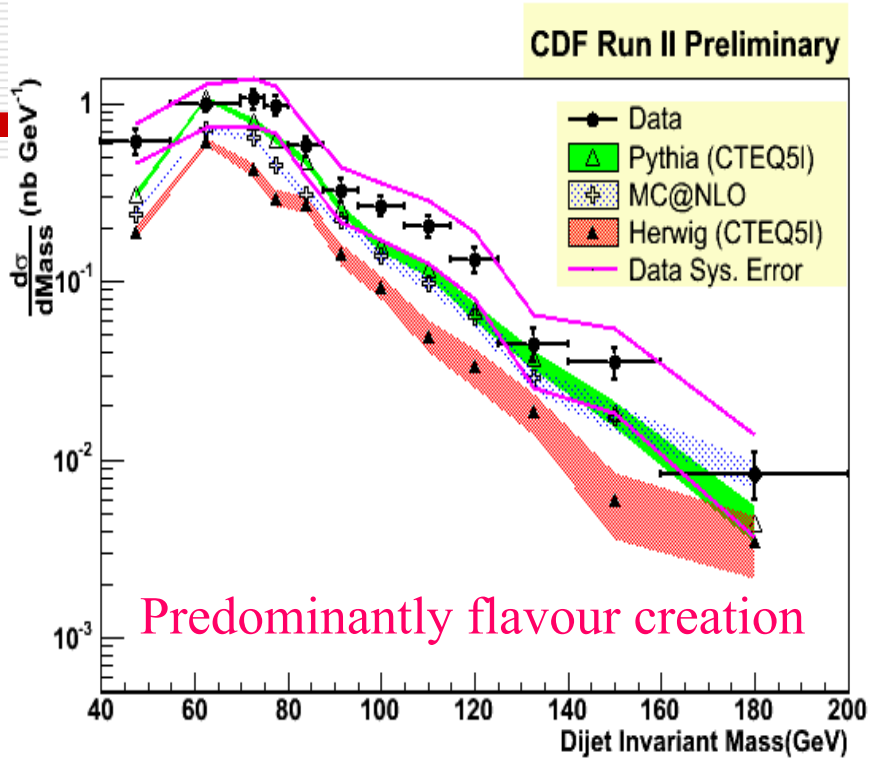
Fit each bin for b-jet fraction

Systematic Error	low P_T	high P_T
Luminosity	6%	6%
Absolute Energy Scale	15-20%	40%
Jet energy resolution	6%	6%
B-tagging efficiency	10%	15%
B-tagged jets fraction	10-15%	40%
Unfolding	8%	8%

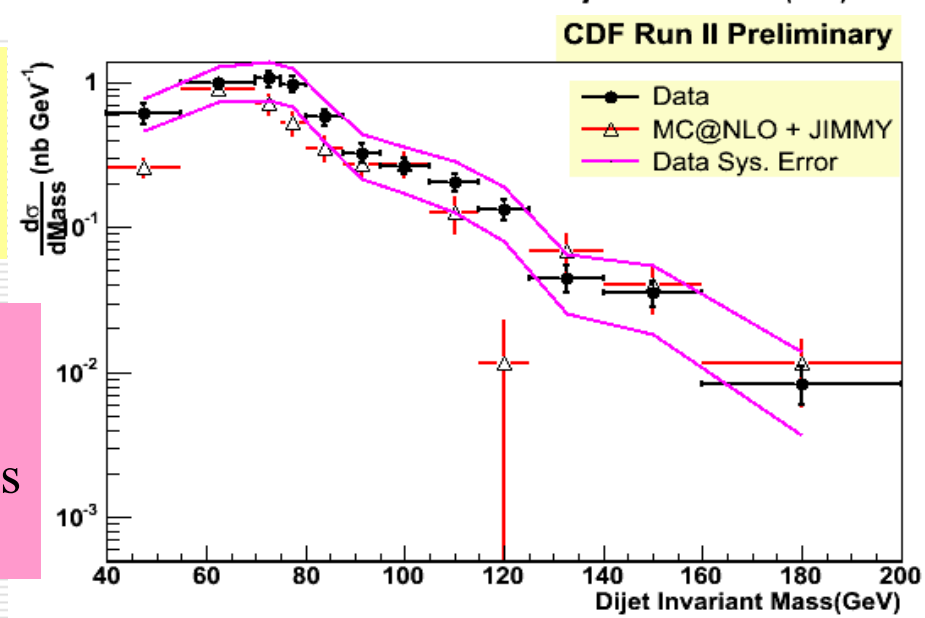
No comparaison with NLO yet.
Data/Pythia Tune A ~ 1.4
in agreement
with expectations

$b\bar{b}$ Production





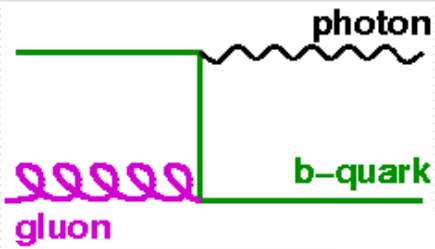
Pythia/MC@NLO describe Δφ dist.
Addition of Multiple Parton Interaction improves MC@NLO agreement.



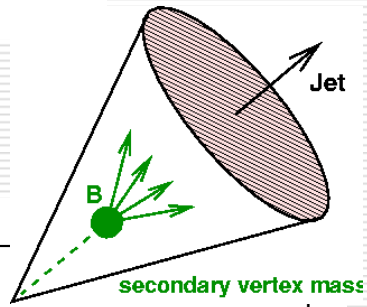
MC@NLO below data in cross section.

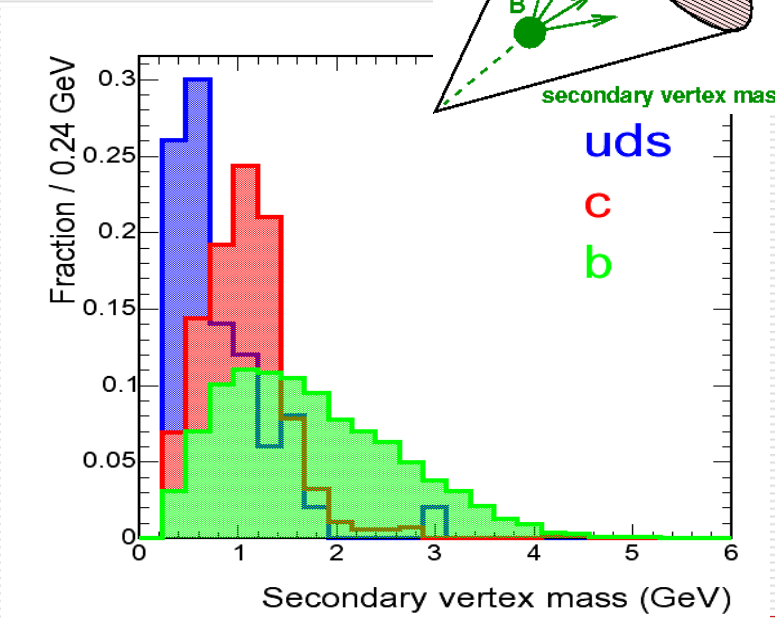
Addition of Multiple Parton Interactions improves the agreement.

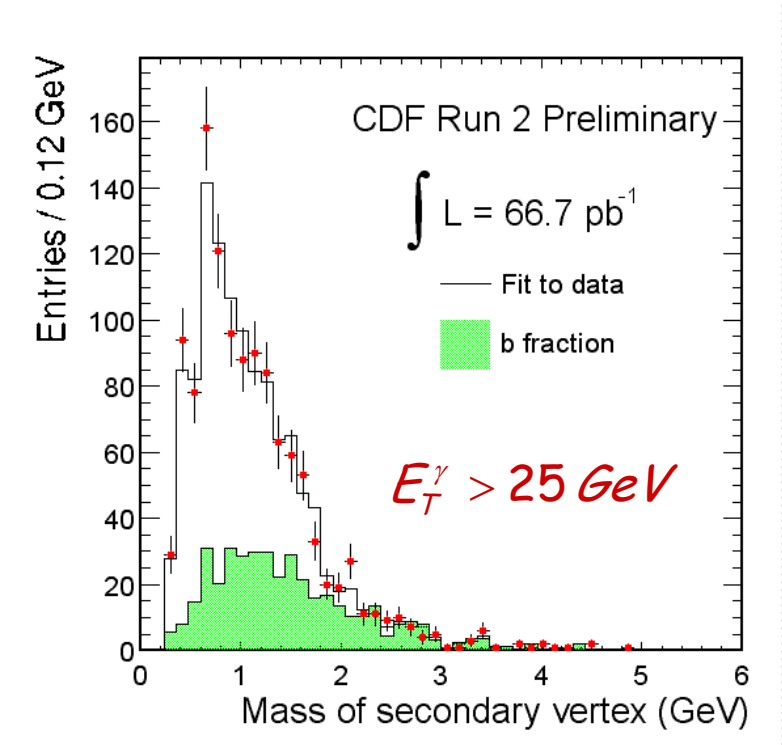
γ+heavy flavour production



- Probes heavy-quark PDFs
- b/c-quark tag based on displaced vertices
- Secondary vertex mass discriminates flavour





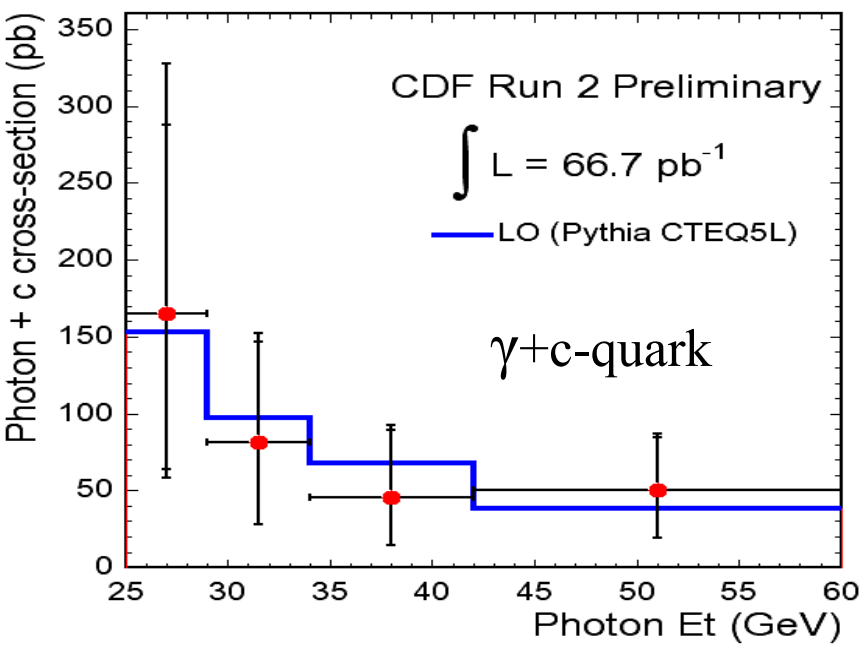


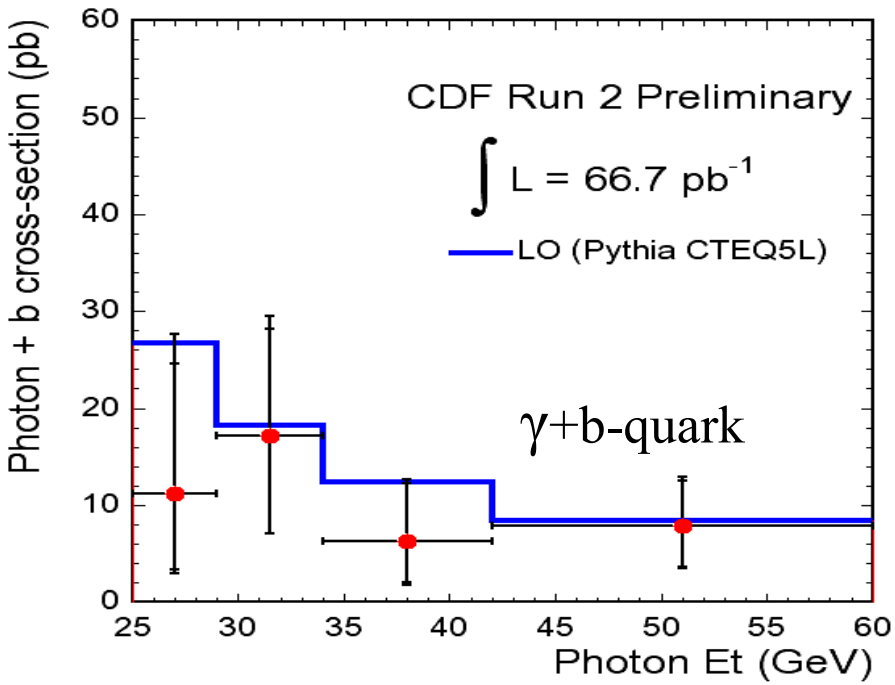
MC templates for b/c & (uds) used to extract b/c fraction in data

γ+heavy flavour production

Good agreement with LO pQCD within still very large stat. errors

Validates quark flavour separation using secondary vertex mass.



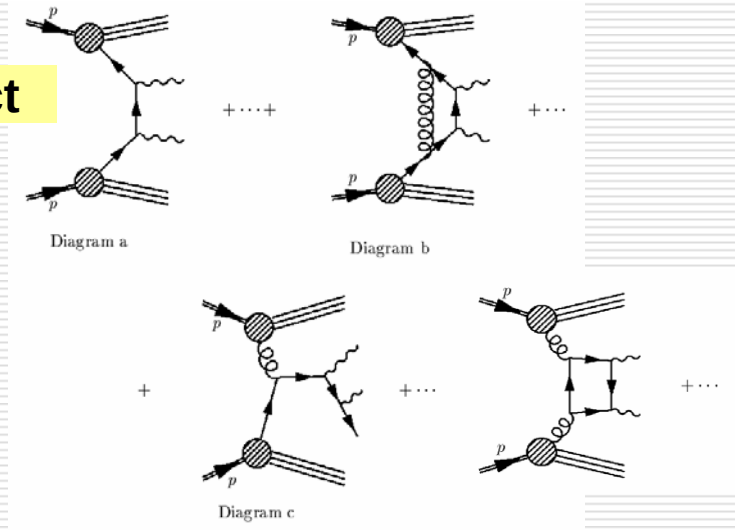


(pb)	25 – 29 GeV	29 – 34 GeV	34 – 42 GeV	42 – 60 GeV
σ(b + γ) (data)	11.2+16.4-8.2	17.2+12.3-10.1	6.2+6.4-4.4	7.9+5.0-4.1
σ(b + γ) (LO)	26.7	18.2	12.3	8.3
σ(c + γ) (data)	164.7+163.2-106.5	81.1+71.0-53.0	45.4+46.8-31.3	50.0+37.3-30.9
σ(c + γ) (LO)	153.5	97.1	68.1	38.4

b/c ratio in photon events, consistent with LO (Pythia) predictions

Diphoton Production Mechanisms

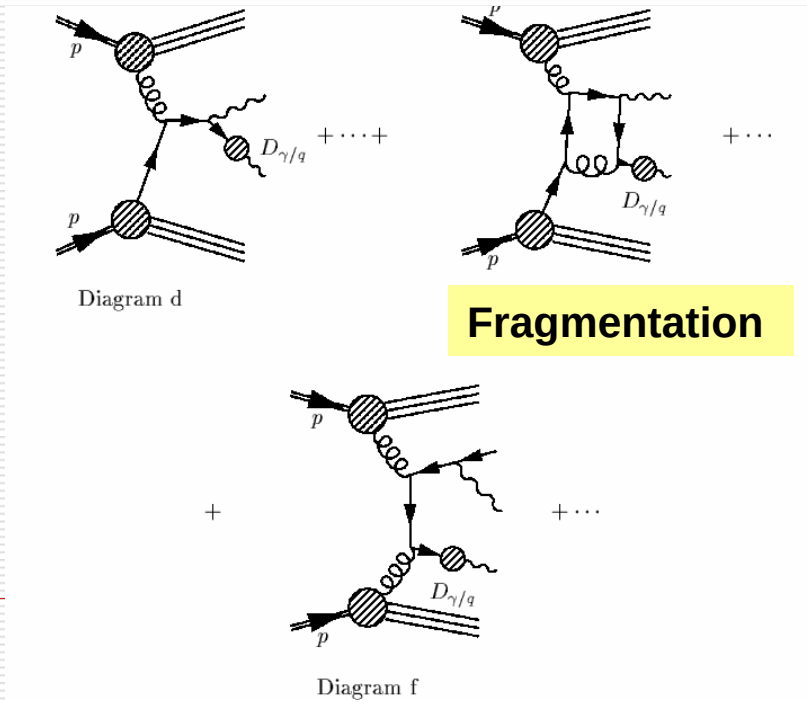
Direct



PYTHIA – T. Sjostrand, P. Eden, C. Friberg, L. Lonnblad, G. Miu, S. Mrenna and E. Norrbin (Computer Physics Commun. 135 (2001) 238

- Includes all processes at LO

Final state quark emits a photon



Fragmentation

DIPHOX – T.Binoth, J. Ph. Guillet, E. Pilon and M. Werlon (Eur. Phys. J. C 16, 311(2000)

- Includes all diagrams at NLO

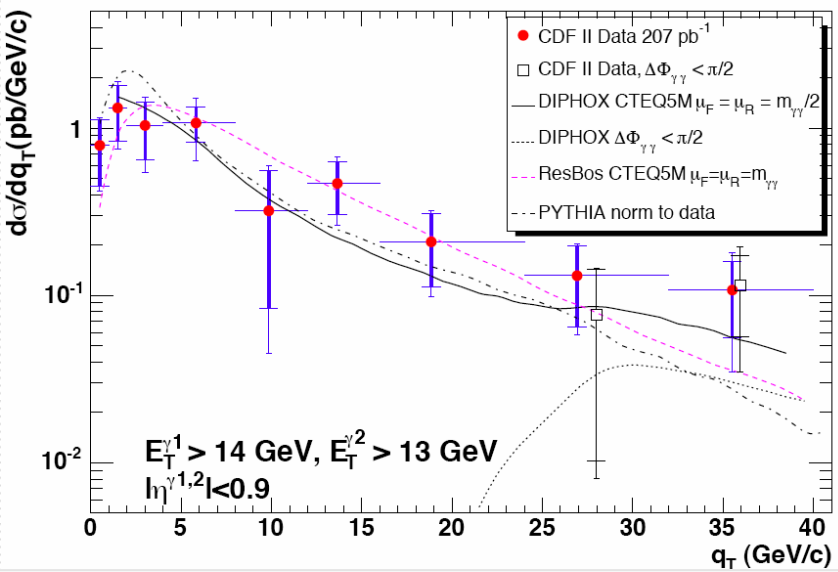
RESBOS – C. Balazs, E. L. Berger, S. Mrenna and C. –P. Yuan (Phys.Rev. D 57, 6934(1998))

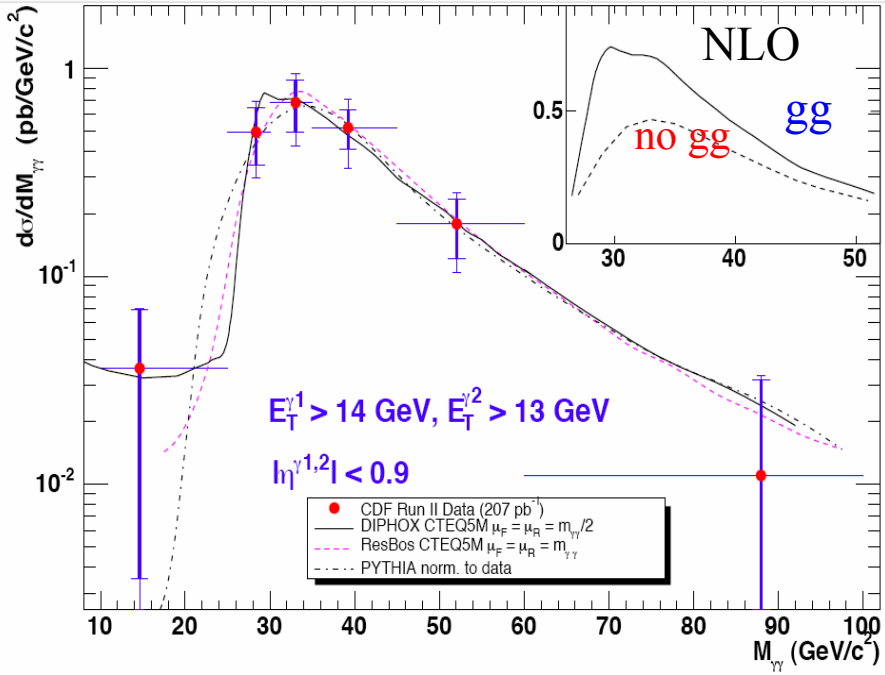
- Direct Processes at NLO,
- Fragmentation processes at LO
- Initial state soft gluon resummation

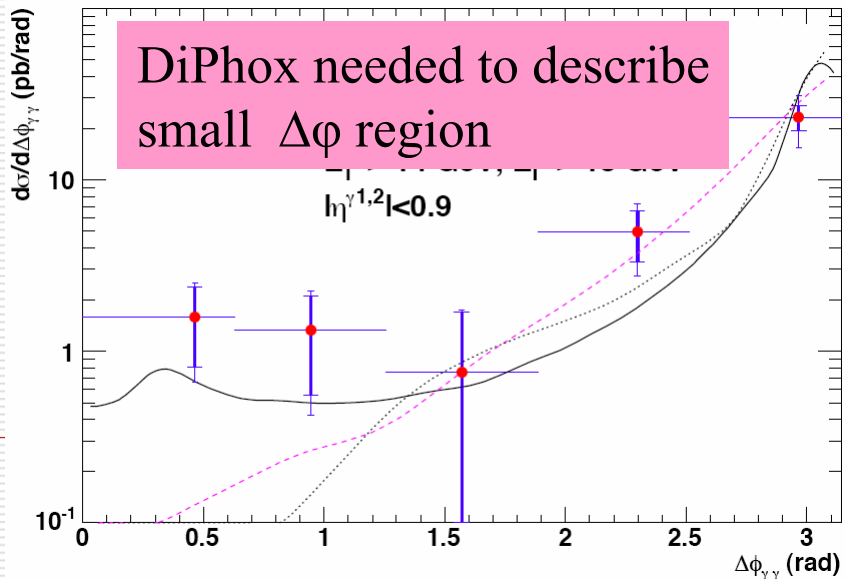
DiPhoton Production

- Testing NLO pQCD /resummation
- Signature of interesting physics
- Higgs discovery channels at LHC

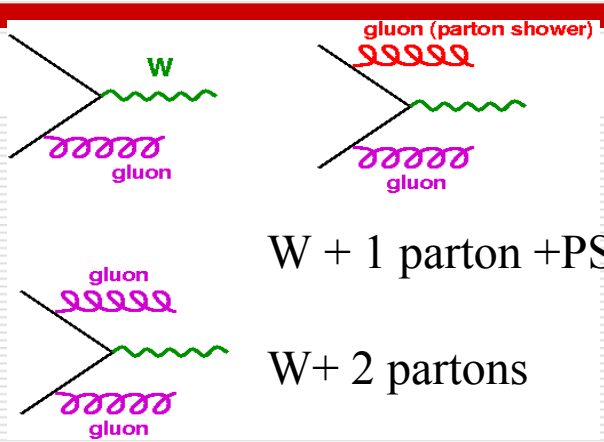
Small qT:
ResBos has better description.
Small Δφ :
NLO fragmentation important



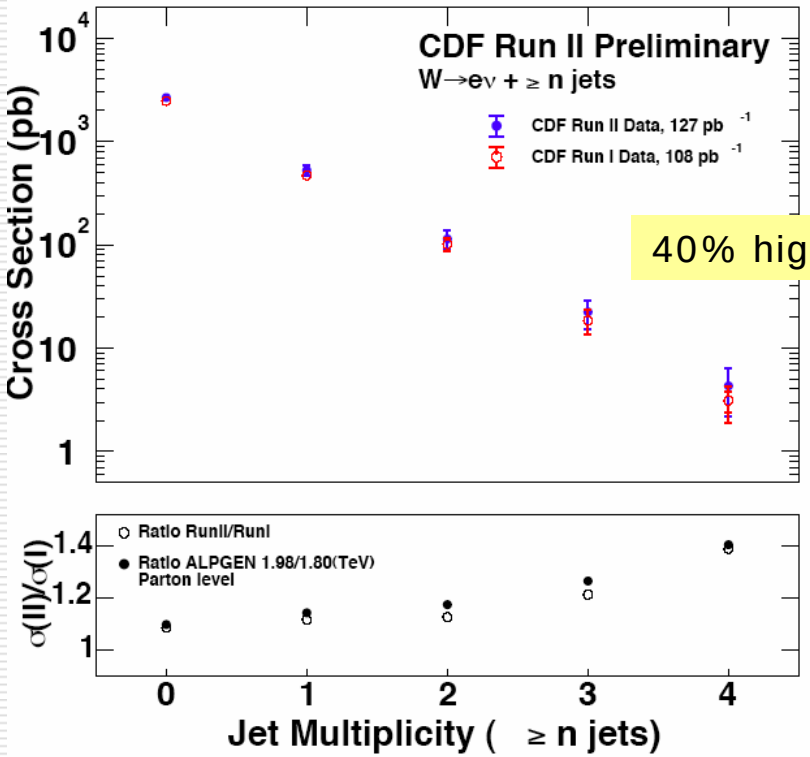




W+jet(s) Production (JetClu R=0.4)



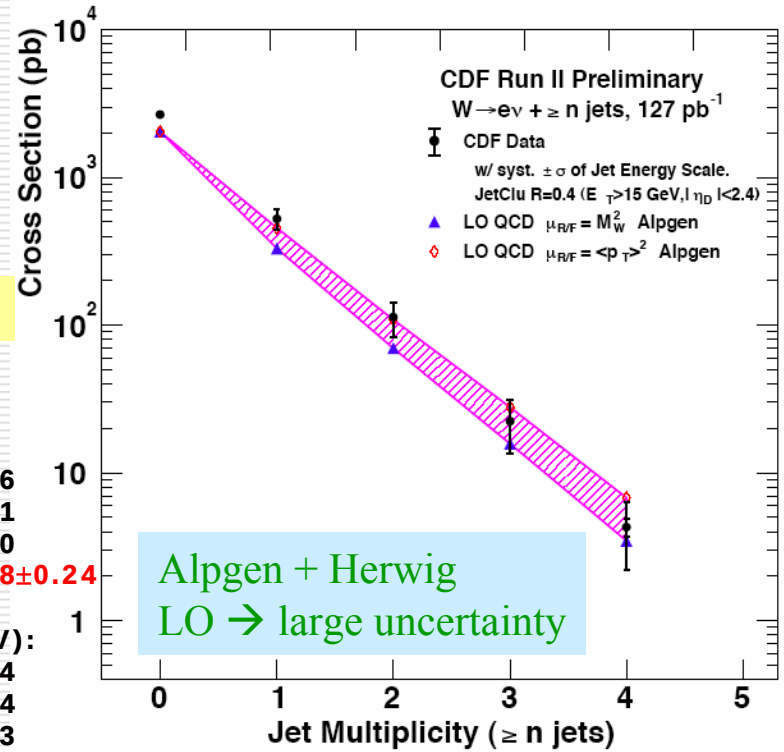
- Background to top and Higgs Physics
- Test Ground for ME+PS techniques (Special matching → MLM, CKKW to avoid double counting on ME+PS interface)



40% higher in Run II

Inclusive s (nb)

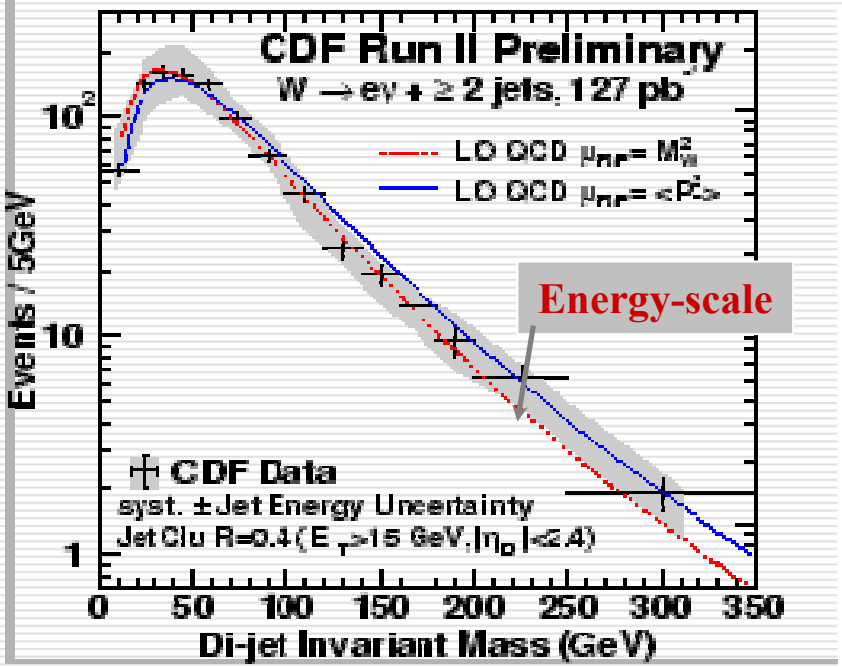
Run I (1.8 TeV):	
LO:	**1.76**
NLO:	**2.41**
NNLO:	**2.50**
CDF I:	**2.38±0.24**
Run II (1.96 TeV):	
LO:	**1.94**
NLO:	**2.64**
NNLO:	**2.73**
CDF II:	**2.64±0.18**



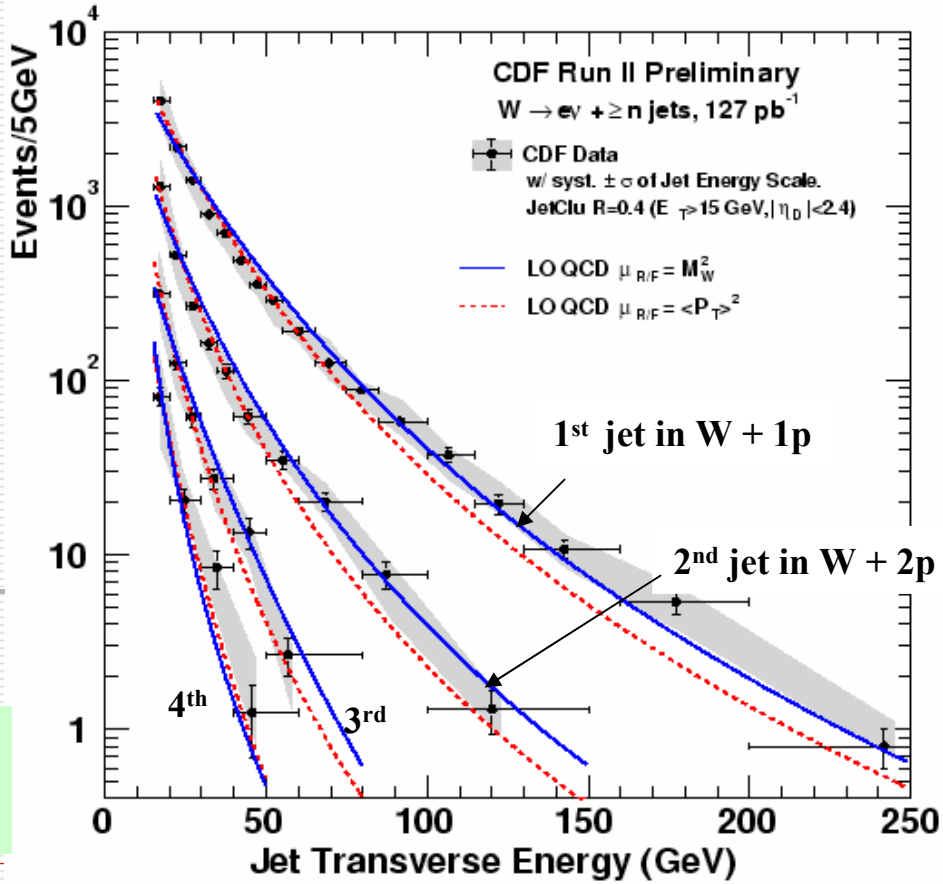
Alpgen + Herwig
LO → large uncertainty

W+ jet(s) Production (JetClu R=0.4)

Dijet Mass in W+2jets



ME+PS implementation tested using the Nth jet spectrum in $W+N^{jet}$ events.



Working to add more data to make it a stringer test of QCD predictions.

Summary and Conclusions

RunII at Tevatron will define a new level of precision for QCD studies in hadron-hadron collisions

CDF has a rich program: Inclusive jet cross section, W+jets, diphoton, γ + heavy quark, b-jet production, Underlying event studies.

Jet production studies with the MidPoint/K_T algorithm

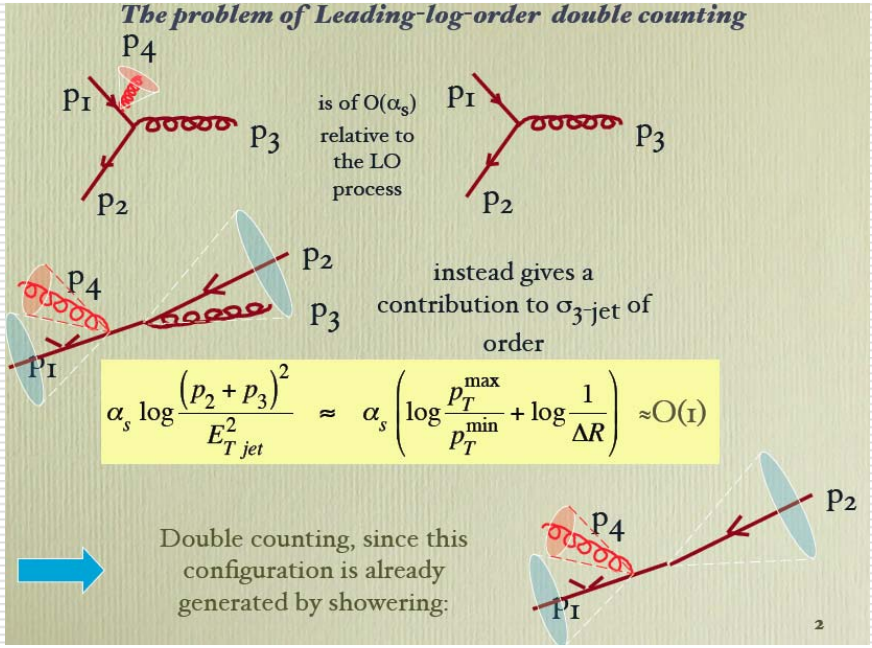
Good agreement with NLO QCD

B-Jet jet cross section measured upto 300 GeV, consistent with PYTHIA
B-jet through J/psi good agreement with theory.
B+heavy flavour agrees with LO Pythia predictions.

DiPhoton cross section, NLO fragmentations needed to describe $\Delta\varphi$ and qt distributions.
Gluon resummation at large qt

A lot of work to understand W+multi jet production.

1. W + jets comparisons at the Tevatron->predictions for the LHC
   - -NLO->MCFM
   - -CKKW
     - -Mrenna-Richardson
     - -Sherpa
2. parton shower/resummation
   - -predictions for tt, Higgs
   - -impact of new parton shower algorithms



- need to control size of unwelcome logs when interfacing ME and PS
- mlm and CKKW approaches for controlling logs both in use at Tevatron