QCD measurements at DØ

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NEW TRENDS IN HIGH ENERGY PHYSICS

Yalta, Crimea, Ukraine

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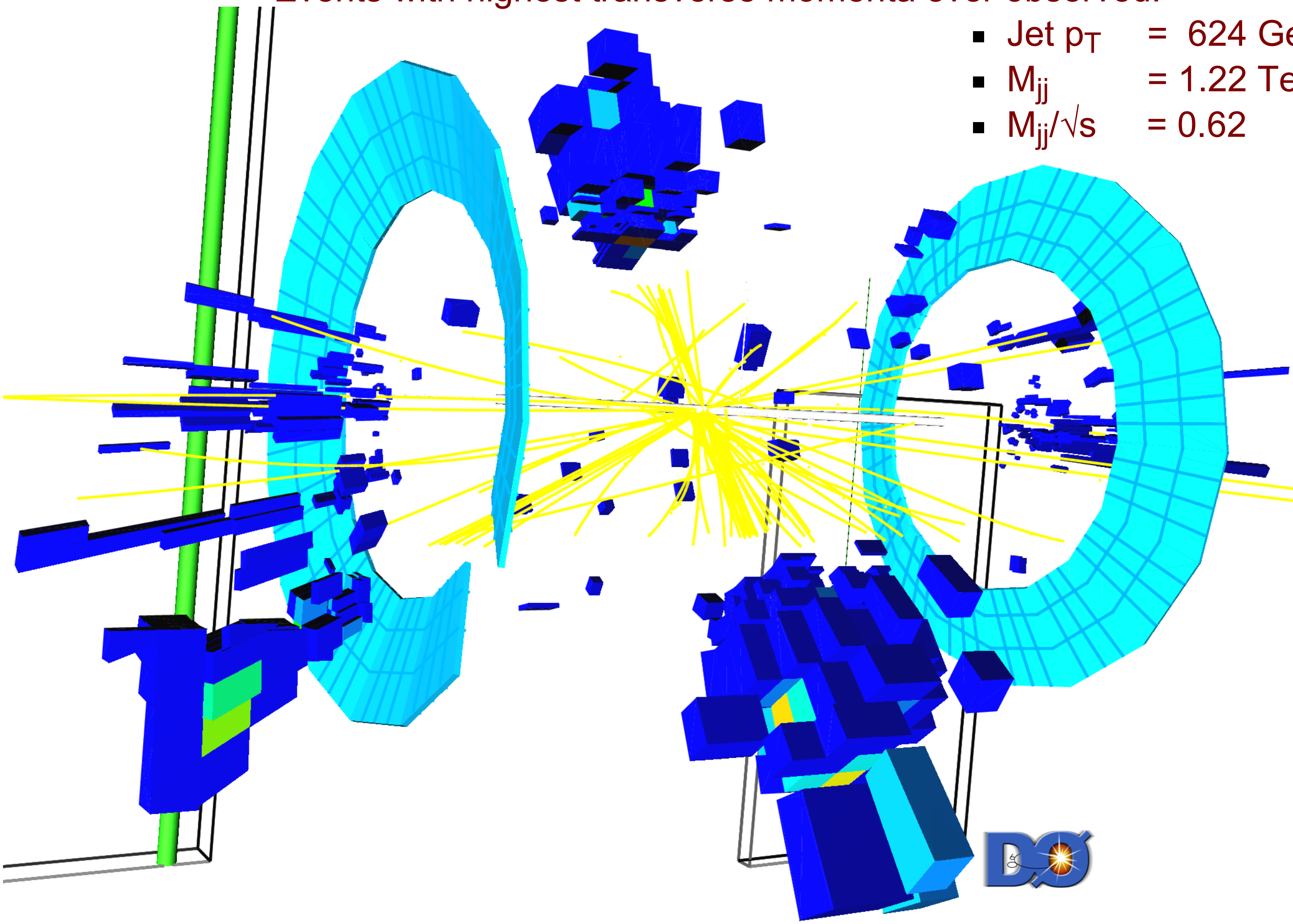
Setting the scene...

Events with highest transverse momenta ever observed!

- Jet p_T = 624 GeV
- M_{jj} = 1.22 TeV
- $M_{jj}/\sqrt{s}$ = 0.62

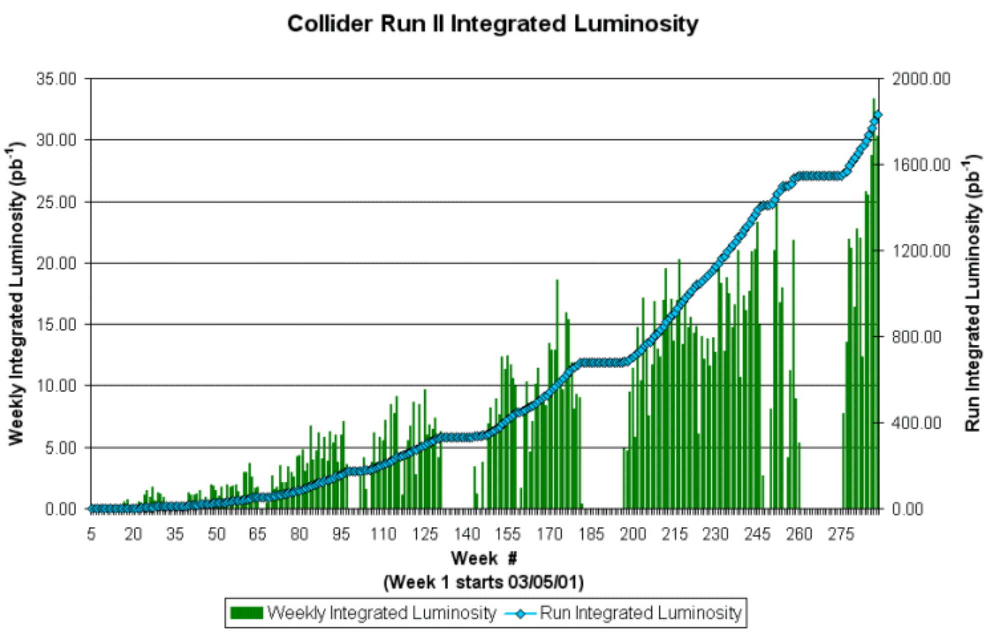


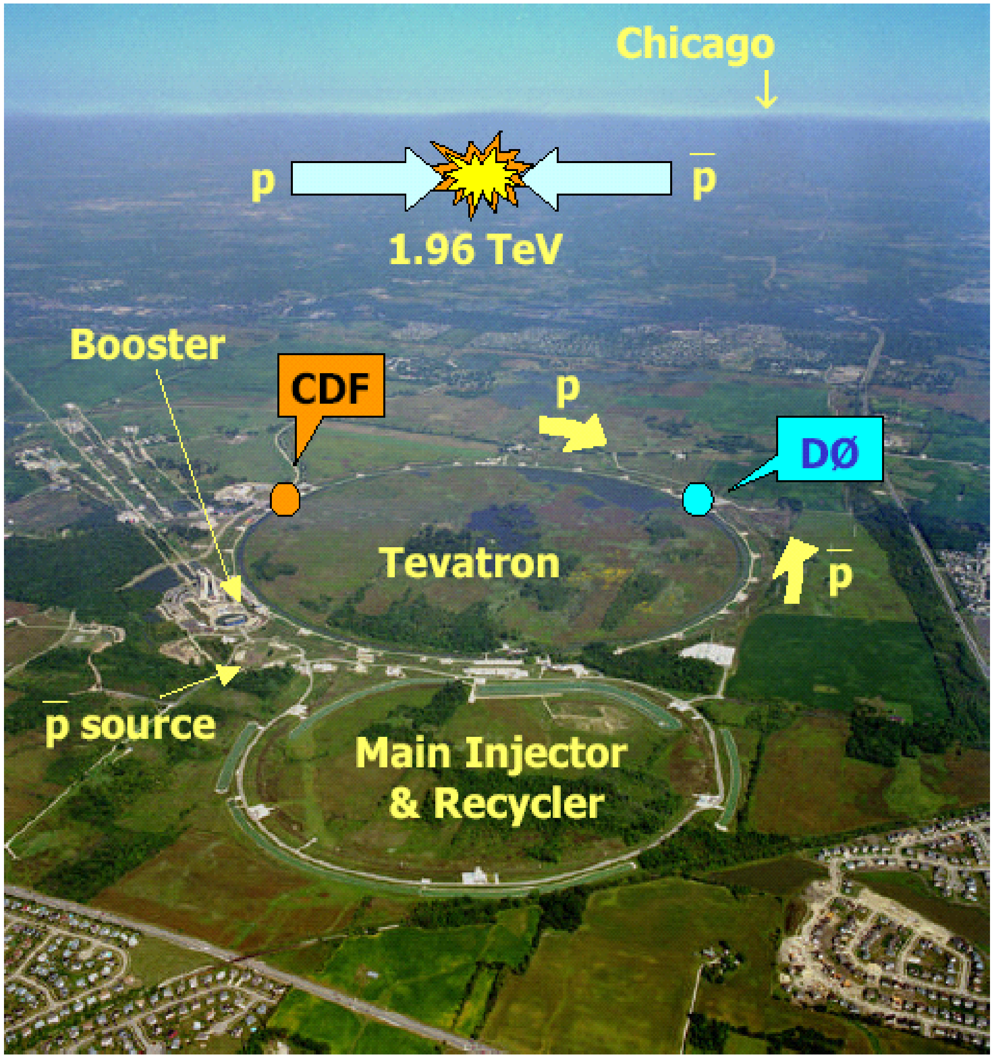
Outline

- Some fundamental concepts
- Inclusive jet cross section
- Inclusive isolated photon (γ) cross section
- Heavy flavor production
- Z + jets measurements
- Summary

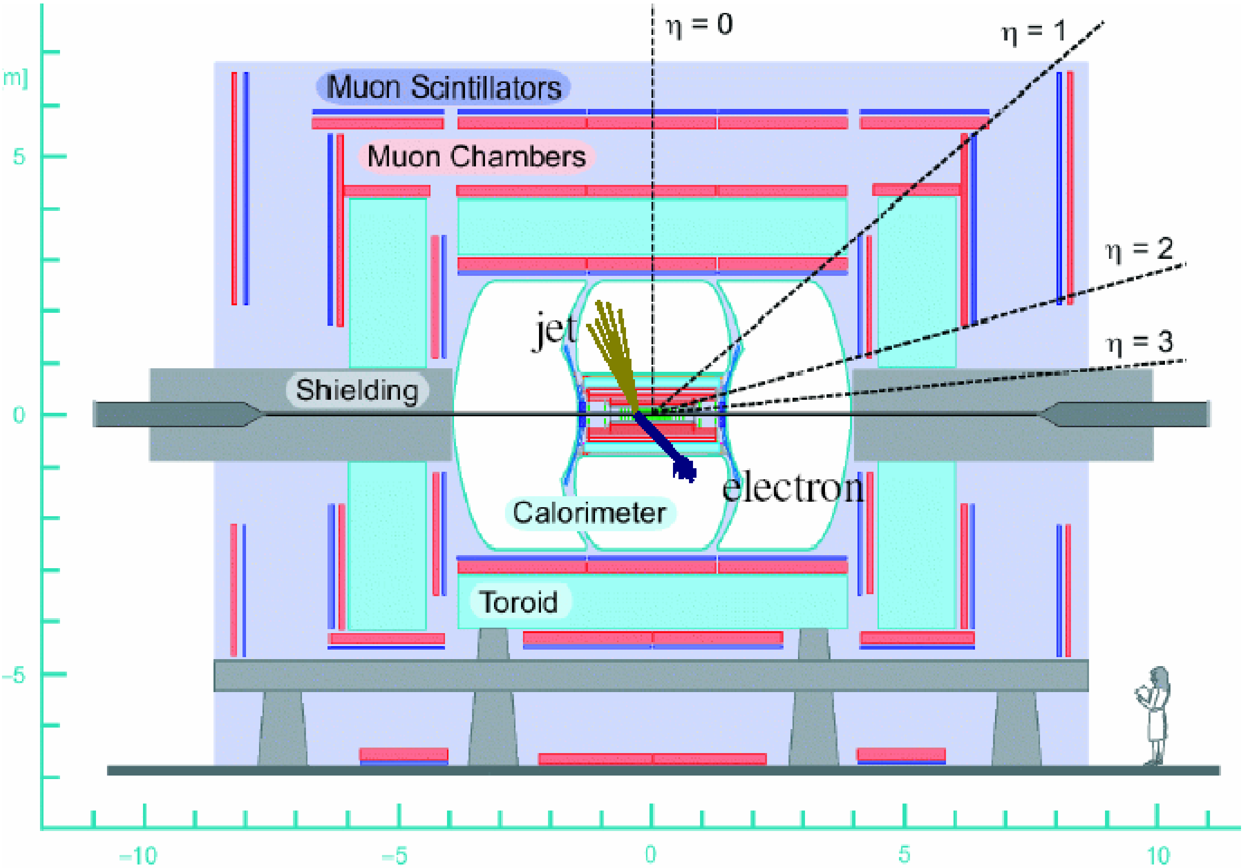
The Tevatron

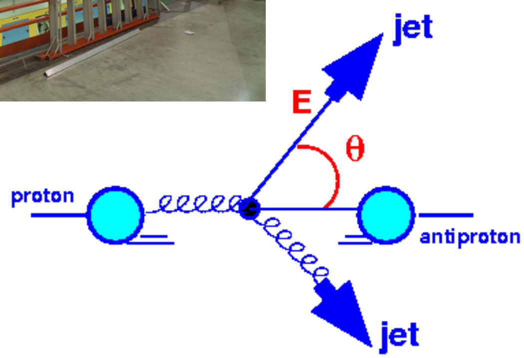
- Highest energy accelerator currently operational
- Proton antiproton collisions at 1.96 TeV (RunII)
- Experiments CDF and DØ
- Delivered well above 1 fb-1, goal for RunII is 4-9 fb-1





The DØ Detector





- Tracking
  - Silicon Tracker
  - Fiber Tracker
  - 2T magnetic field
  - Central and Forward Pre-shower detectors
- Calorimeter
  - Liquid Argon
  - 4 EM, 7 hadronic layers
- Muon Detector
  - 1.8T Toroid
  - $|\eta|<2$

Rapidity: $y = \frac{1}{2}\ln(\frac{E+p_z}{E-p_z})$

Distance:

$$\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta y)^2}$$

QCD at hadron colliders

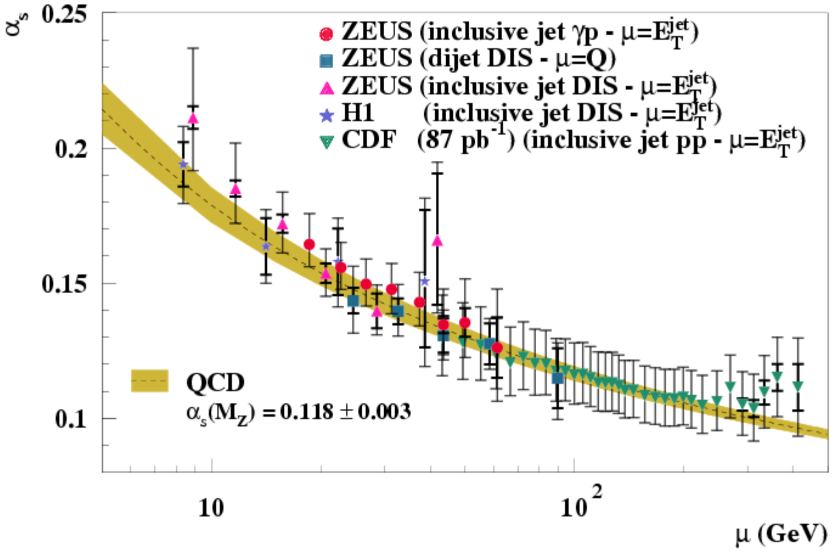
Quantum Chromo Dynamics describes the strong force mediated by gluons between quarks

Precision measurements allow for

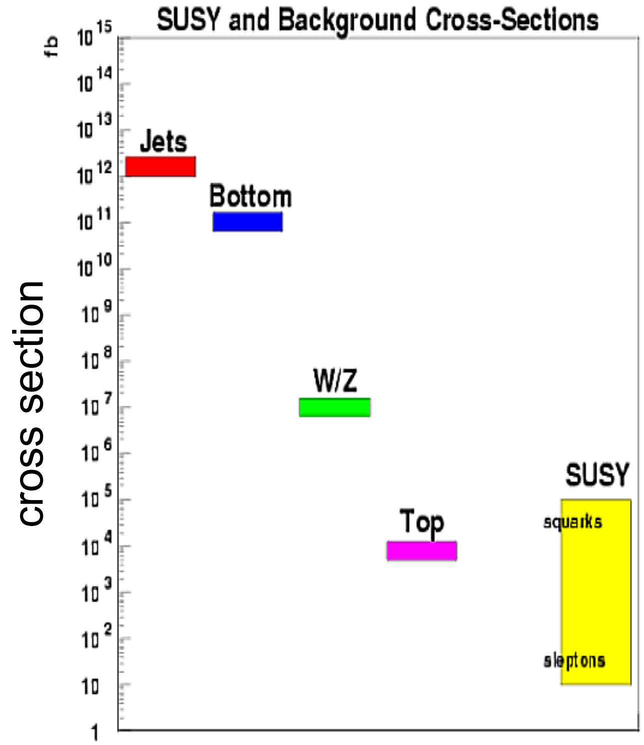
- extraction of Parton Density Functions (PDF)

and the testing of

- perturbative QCD calculations
- phenomenological models for fragmentation
- merging of higher order calculations with fragmentation models

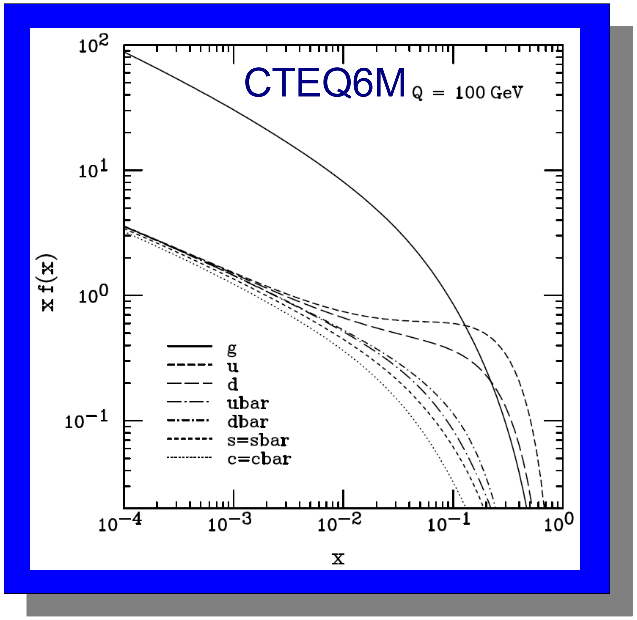


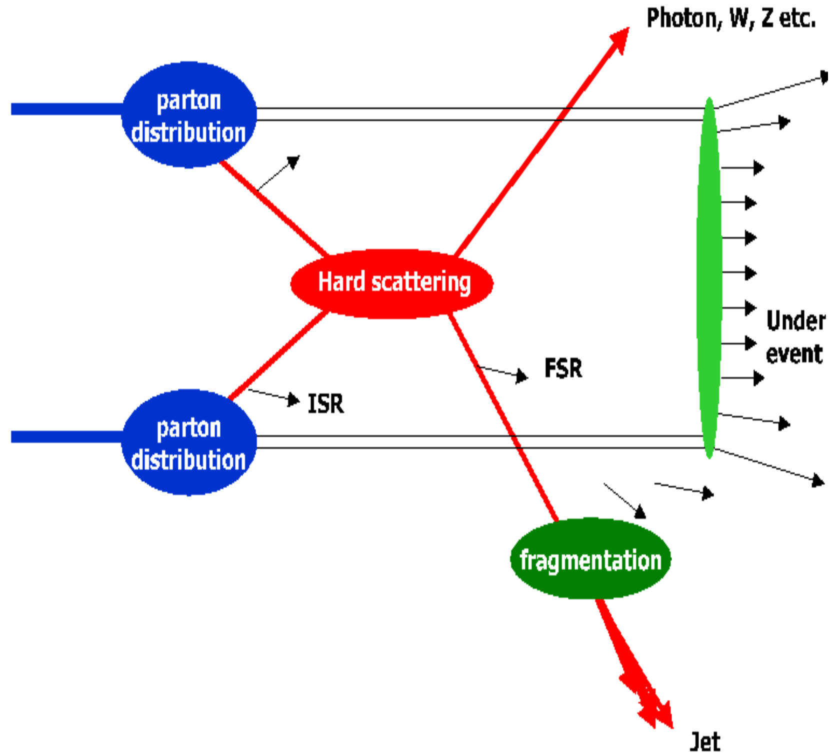
- QCD multijet production has a cross section several orders of magnitude larger than typical electroweak and new physics phenomena
- Understanding of this background is mandatory for most analysis performed at hadron colliders

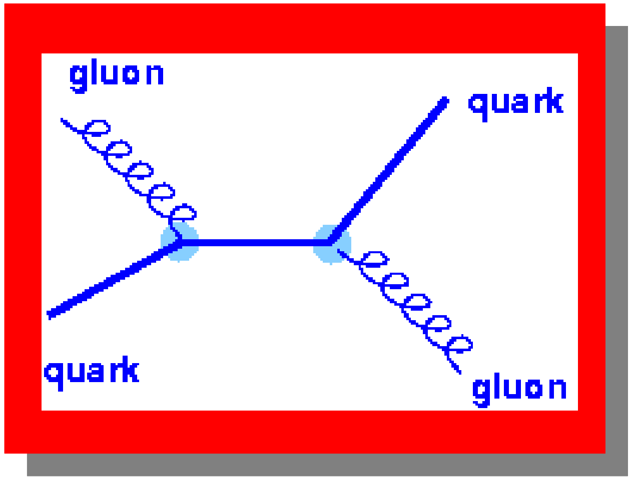


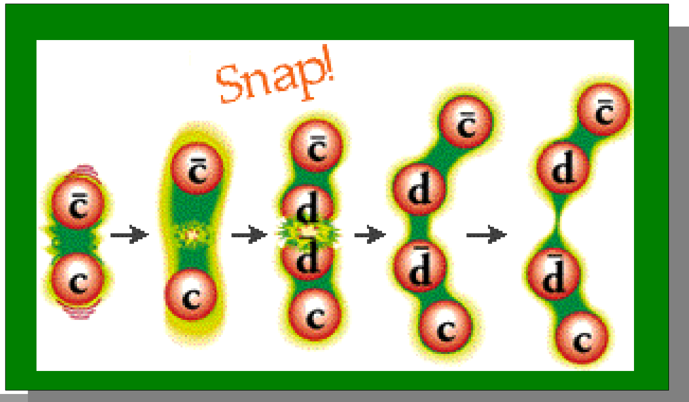
The Bits and Pieces

$$\sigma = \sum \int dx_1 dx_2 f_q(x_1, Q^2) f_g(x_2, Q^2) \hat{\sigma}_{qg \to qg}$$

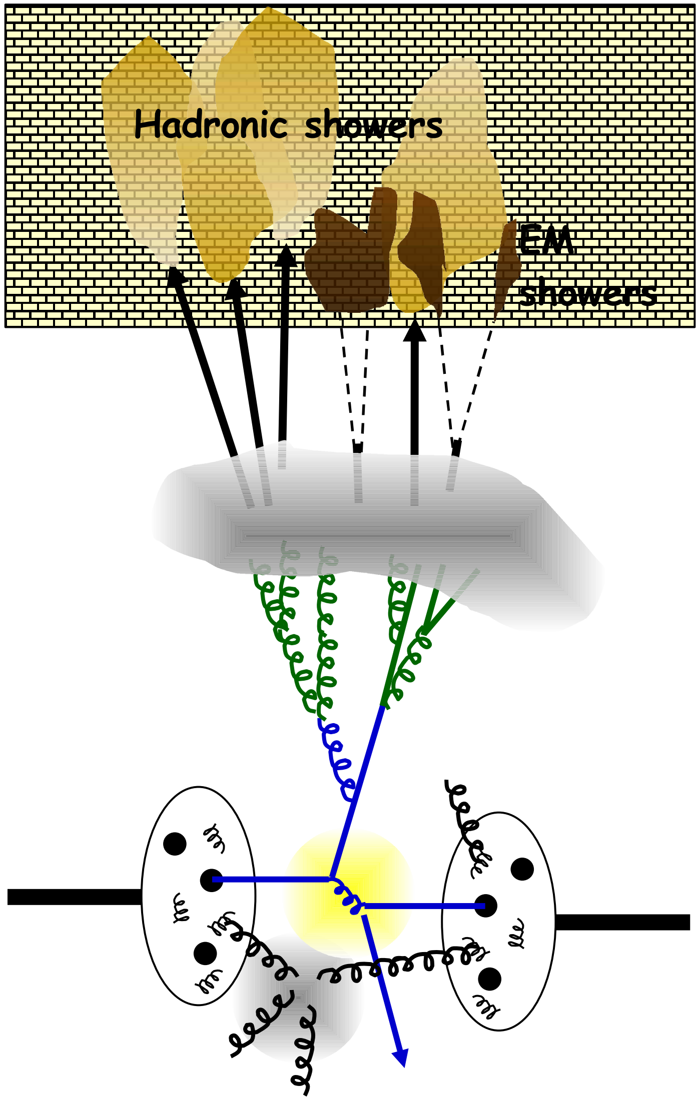








Comparing Data to Theory



Detector Level

- Cluster energy depositions in the calorimeter into jets, using a **Jet Algorithm**.
- Correct for detector resolution and efficiency
- Correct for additional energy depositions due to minimum bias interactions, pile-up, uranium noise,...

Hadron Level

- *Monte Carlo*: Cluster stable particles into jet, using jet finding algorithm
- *Data*: Correct for difference between MC particle jets and calorimeter jets

Parton Level

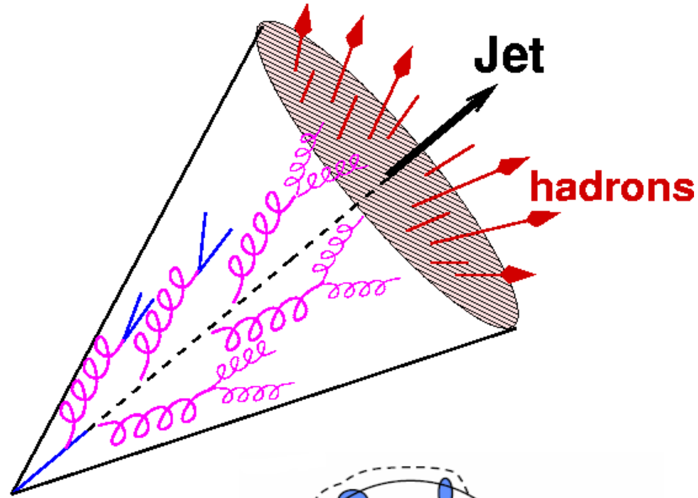
- apply fragmentation effects to particle level jets
- apply corrections for underlying event (soft initial and final state gluon radiation, beam remnant interactions)

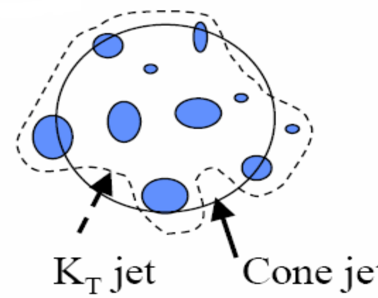
Measurement = PDF ⊕ ME ⊕ underlying event ⊕ hadronization ⊕ jet algorithm

Jet Algorithms

- Final state partons manifest themselves through collimated sprays of hadrons called **jets.**
- **Jet finding algorithms** define and identify jets.

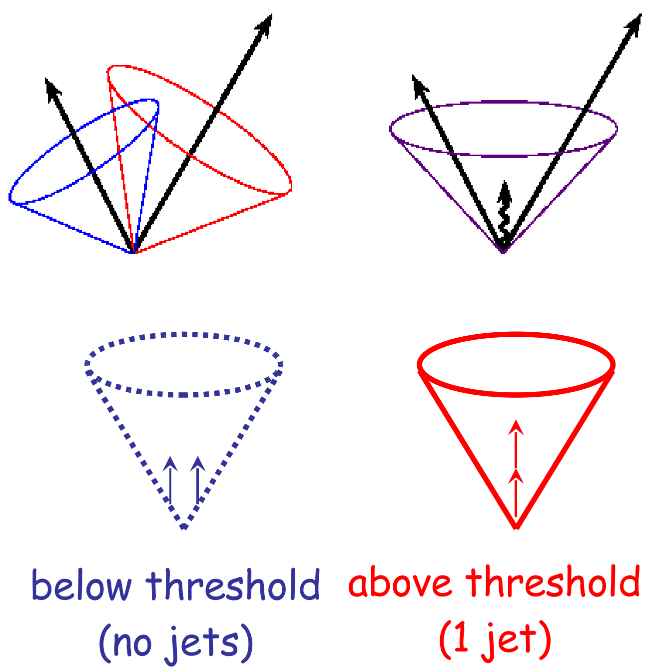
- Different jet algorithms correspond to different observables and give different results.
- Clustering based on MC particles or calorimeter towers
- Jets must be defined consistently when comparing theory with observation!





<u>D0: Run II Midpoint (Cone) Alg.</u>

- Cluster according to proximity in *y*-φ-plane
- Infrared safe ("*midpoint*")
- Merging/splitting of jets governed by parameter



<u>K_T Algorithm</u>

- Cluster according to relative p_T
- Infrared and collinear save
- No merging/splitting of jets

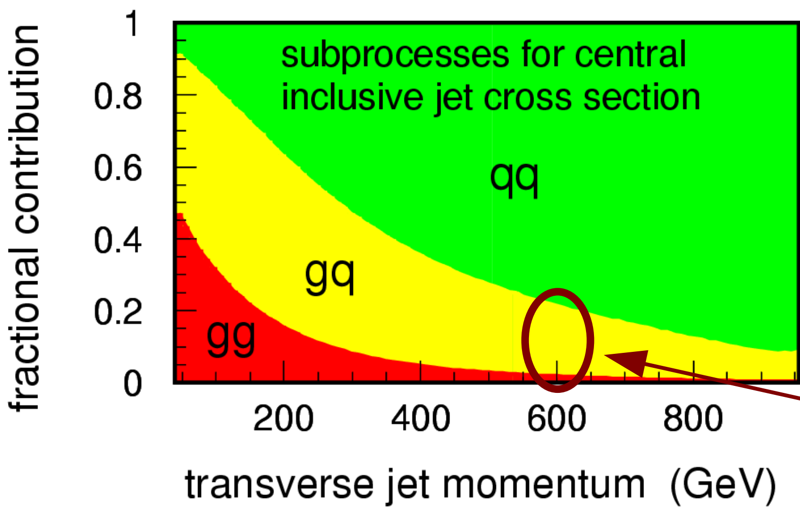
- Some fundamental concepts
- Inclusive jet cross section
- Inclusive isolated photon (γ) cross section
- Heavy flavor production
- Z + jets measurements
- Summary

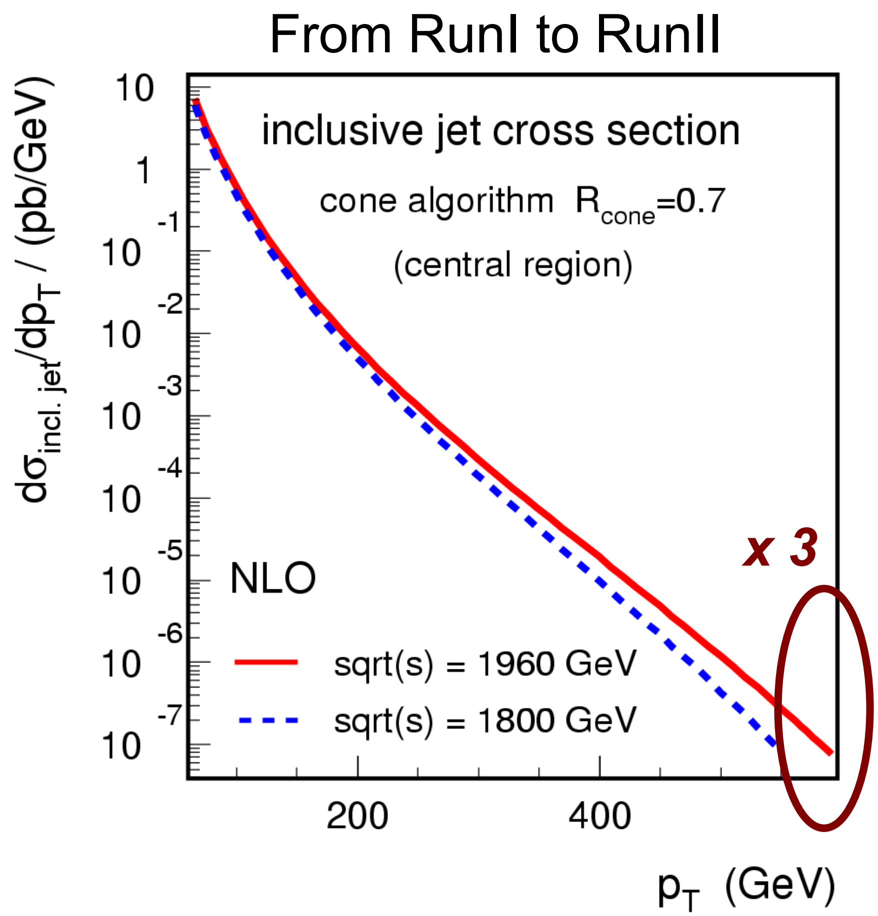
Inclusive Jet Production

- Inclusive jet cross section counts all jets:
  5 jets in event → 5 entries in cross section plot.

- High p_T cross section is expected to be dominated by quark-quark (*qq*) interactions. However, *qg*+*gg* fraction not negligible

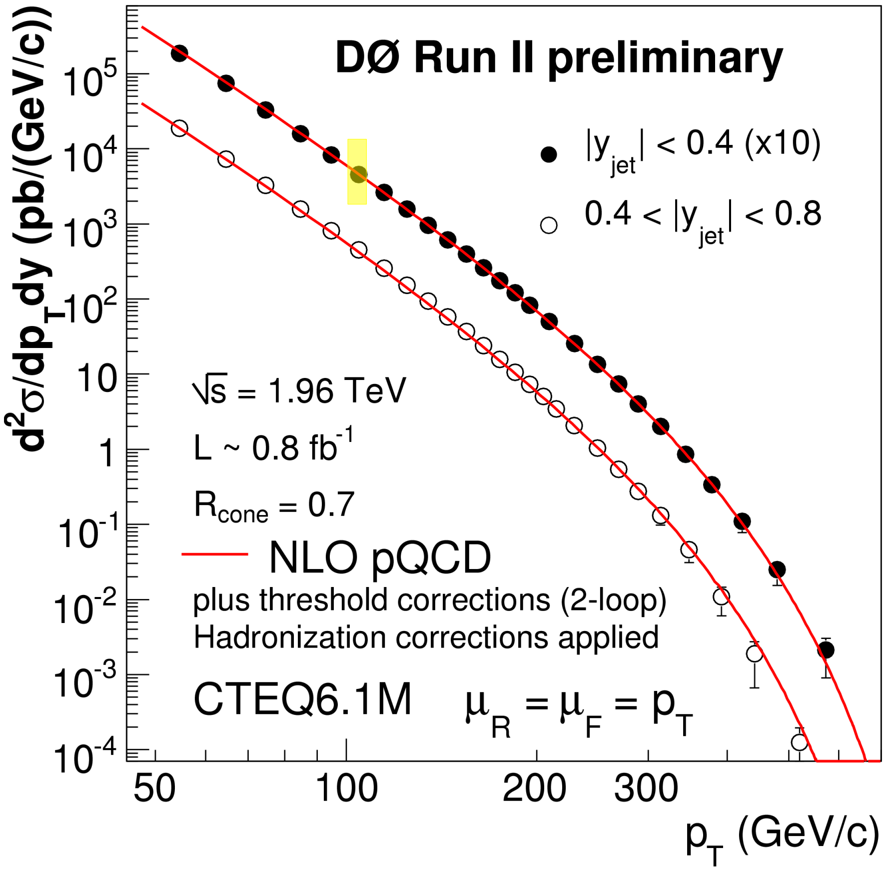
- Gluon Parton Density Function (PDF) not well known for large *x*. Increased Tevatron luminosity extends reach towards higher *x*





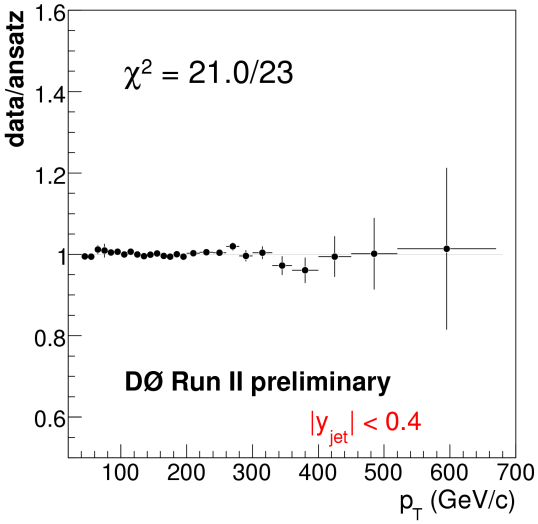
≈30% at 600 GeV

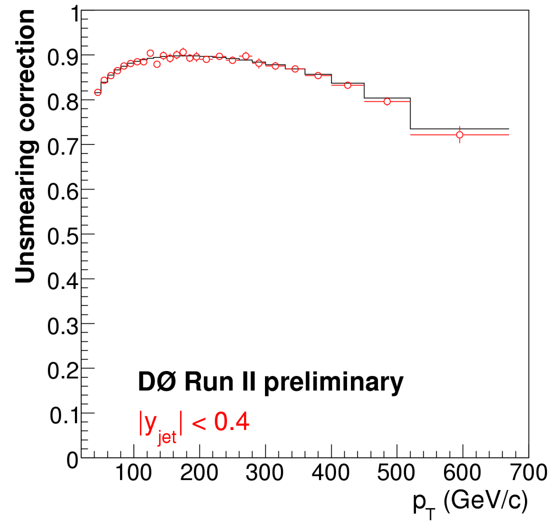
Inclusive Jet Cross Section



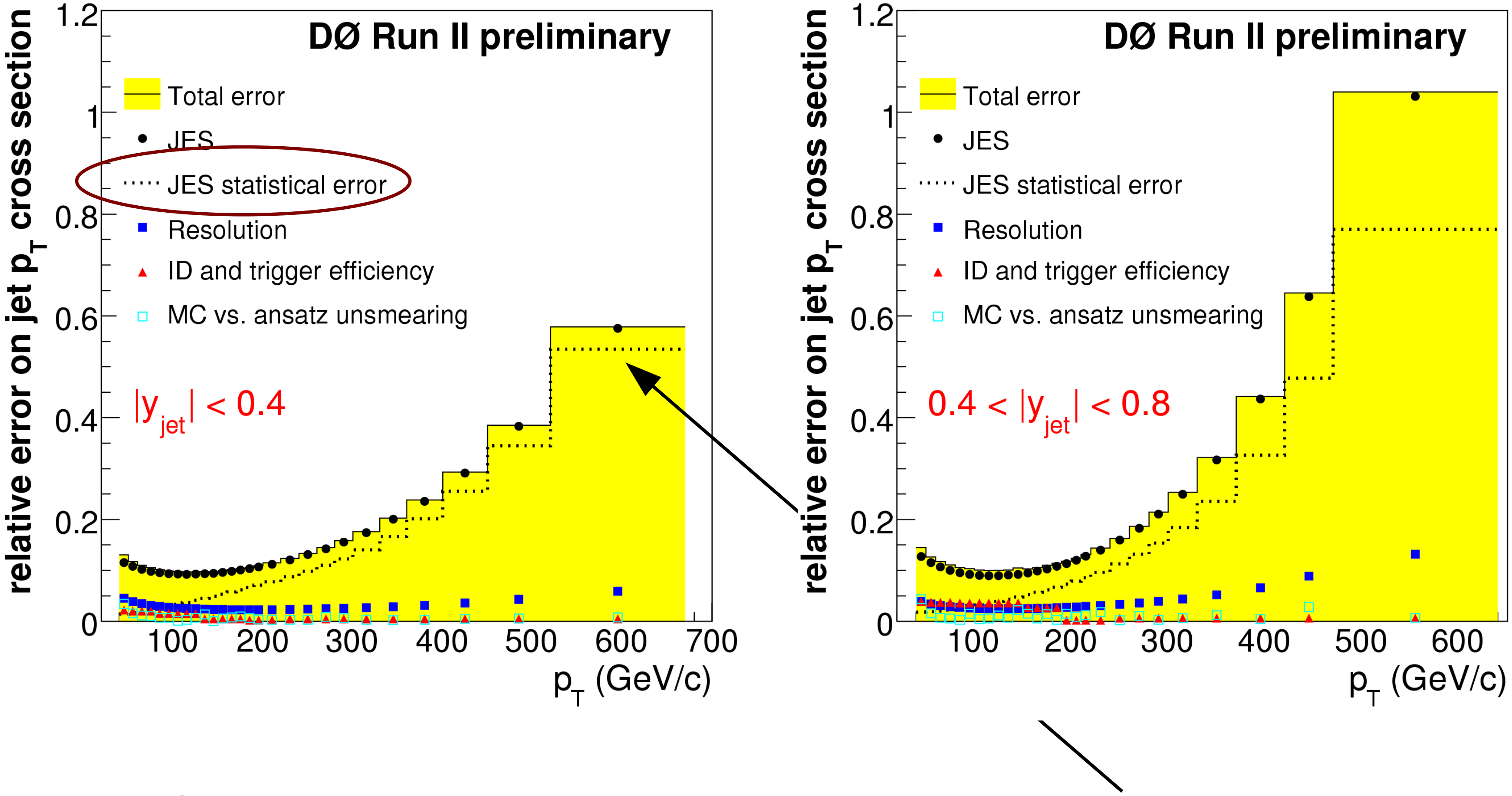
- RunII midpoint cone algorithm, *L=0.8 fb*$^{-1}$
- Measurement in two rapidity regions
- Data in good agreement with NLO pQCD calculation (incl. threshold 2-loop corrections)
- Data corrected back to hadron-level by *unsmearing correction* (fitting an ansatz function to the observed p_T spectrum)

- Shape comparison only! Theory normalized to *|y|<0.4* data at *100 GeV*
- DØ has not evaluated the luminosity of the data sample yet





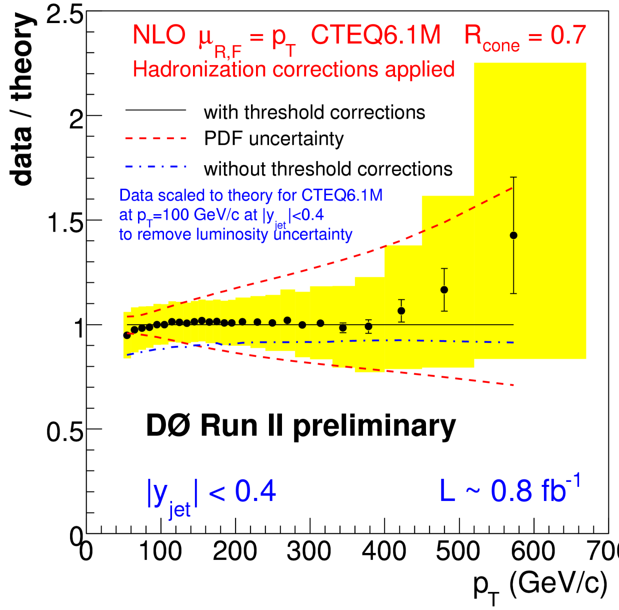
Systematic Uncertainties

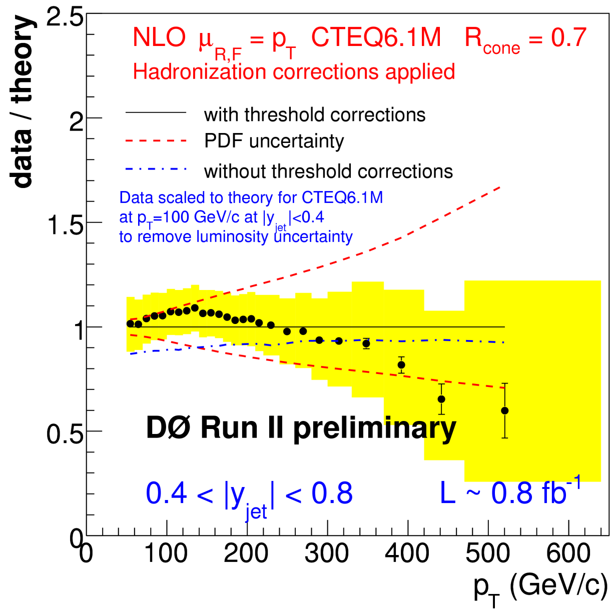


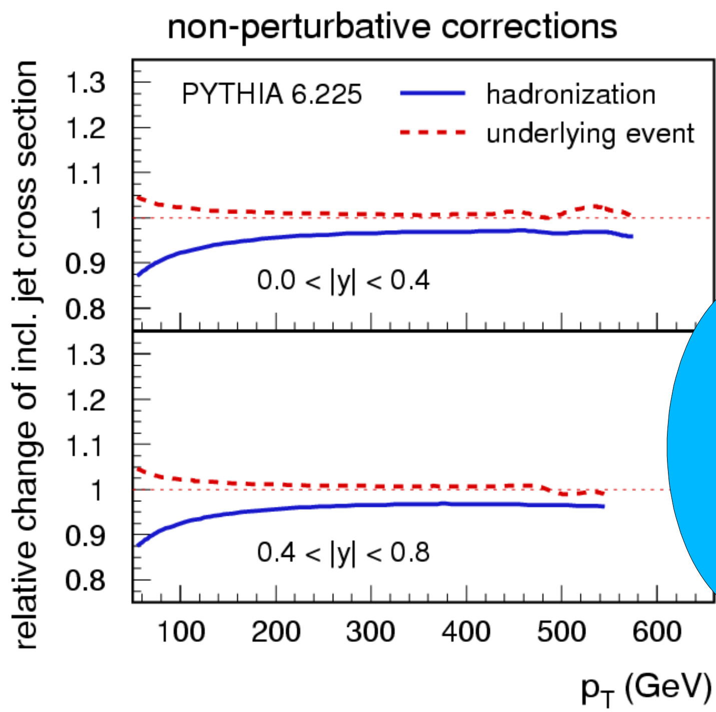
- Systematic uncertainty is dominated by the *statistical jet energy scale uncertainty*
- Used only 150 pb^{-1} of data to determine jet energy scale
- Once the jet energy scale is evaluated using the full 1 fb^{-1} data sample, the systematic uncertainty will improve significantly!

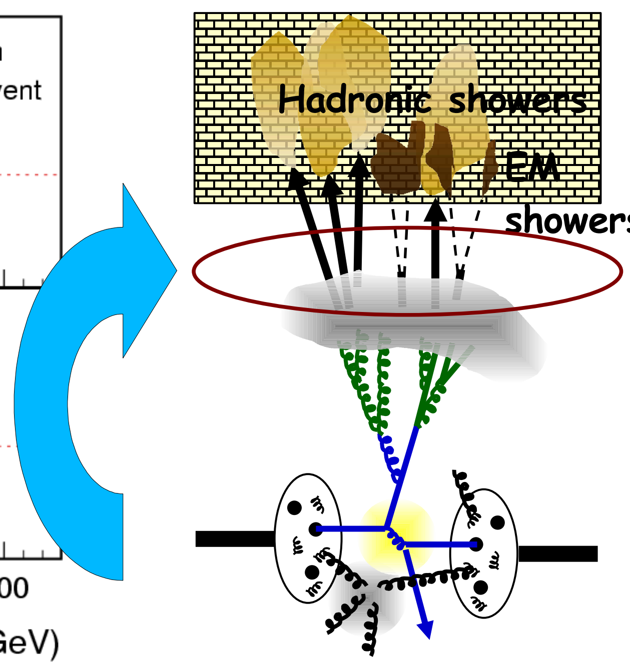
Data vs Theory

- Data is compared to theory at “hadron-level”, need to correct pQCD calculation for hadronization and underlying event effects.
- Phenomenological model of hadronization and underlying event needs to be tested in independent measurement (Pythia “Tune A”)

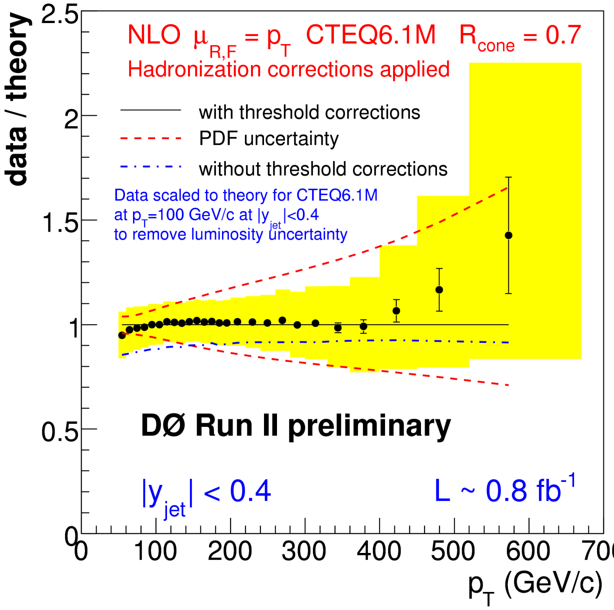


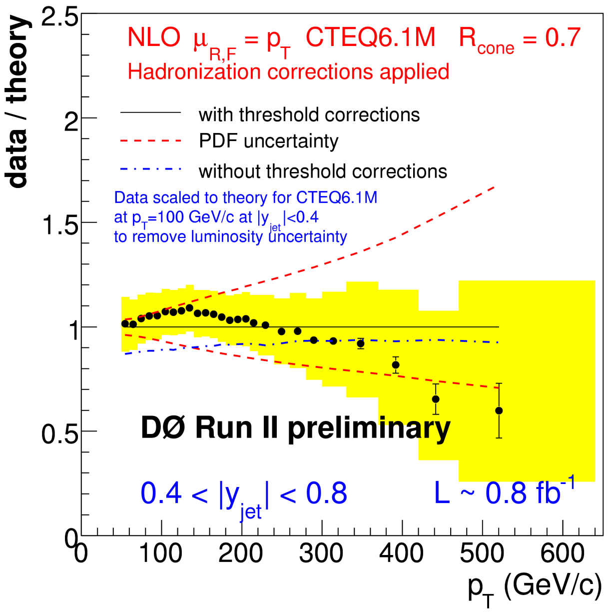




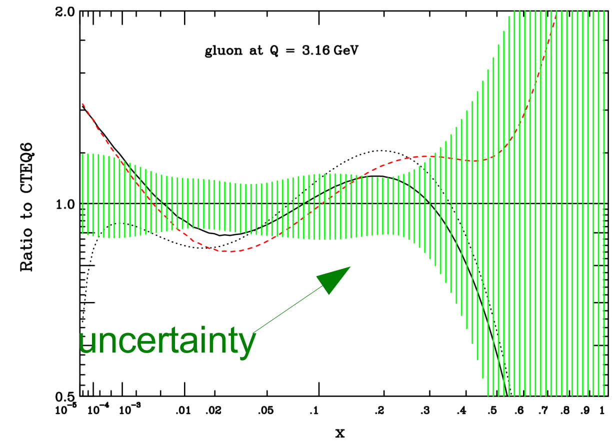


Constraining the gluon PDF

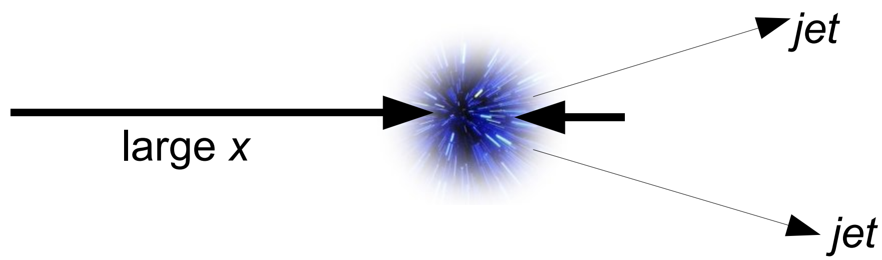




- New Physics expected in central region but not in *forward region*
- Possible discrepancy in forward region can be attributed to PDF



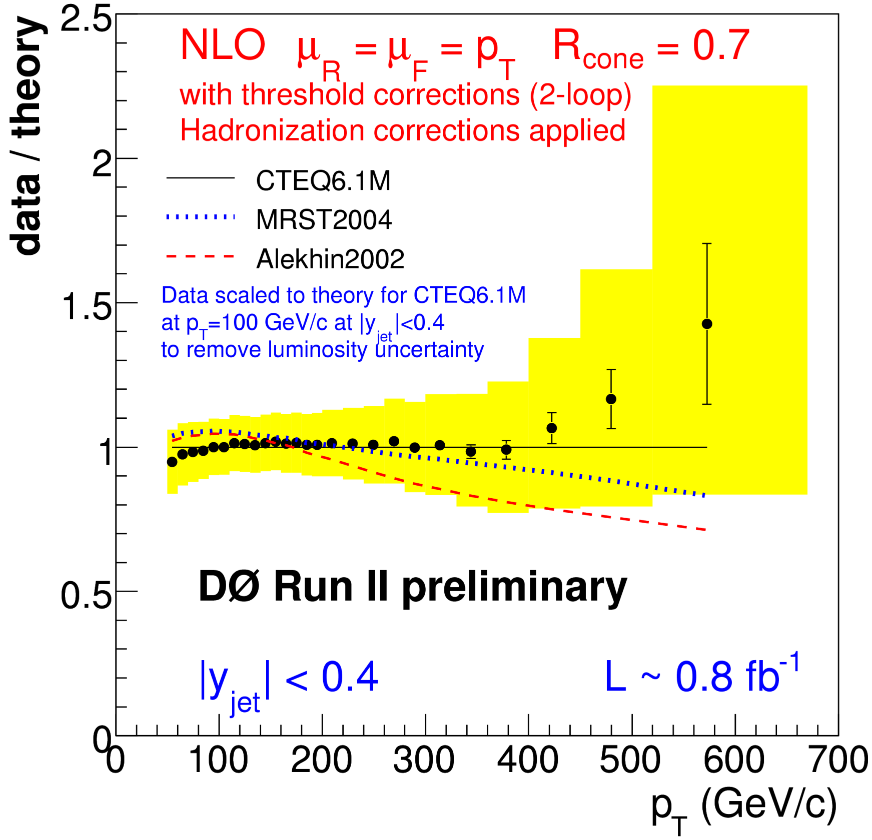
- Dominant PDF uncertainty comes from *gluon* part at large *x*, which is poorly known

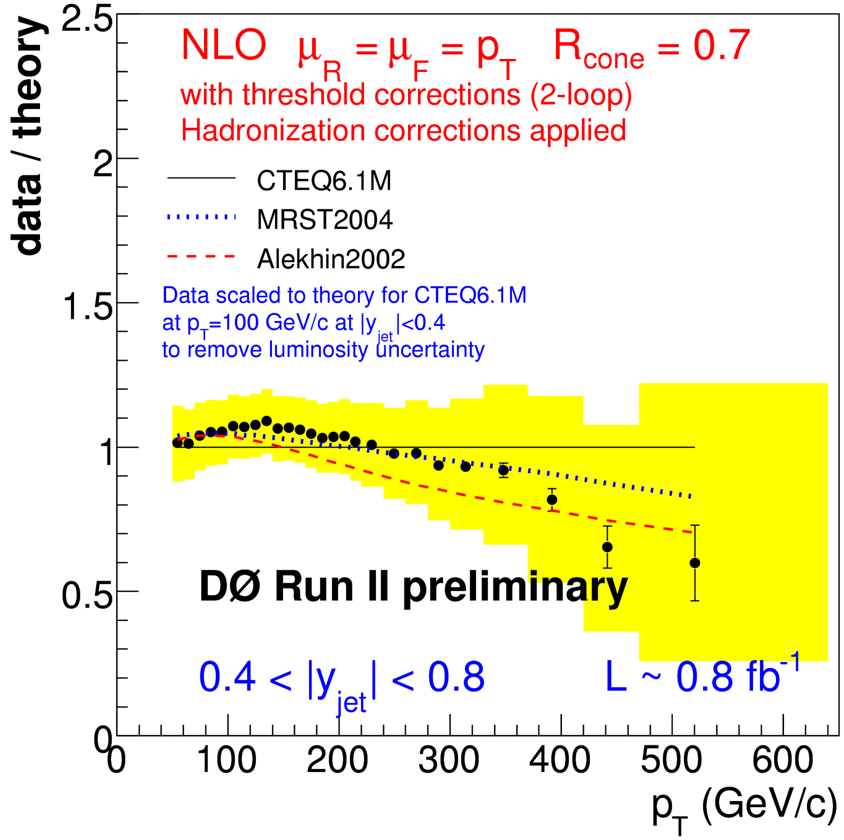


- Forward data is useful in constraining PDFs!

- Experimental uncertainties are comparable to PDF uncertainties.
- *Measurement with updated jet energy scale will place further constraint on PDF!*

Comparison of PDFs





- Not sensitive enough to decide on favorite PDF
- Trend at high p_T uncorrelated, dominated by statistical jet energy scale uncertainty!

- Some fundamental concepts
- Inclusive jet cross section
- **Inclusive isolated photon (γ) cross section**
- Heavy flavor production
- Z + jets measurements
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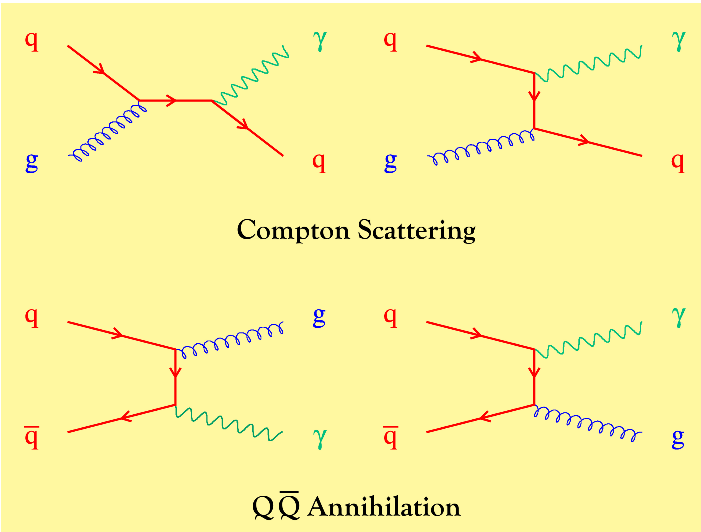
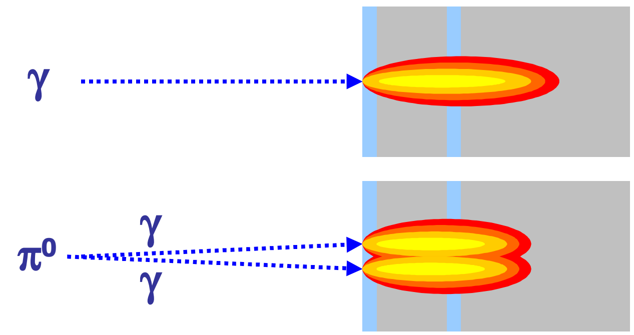
Inclusive γ cross section

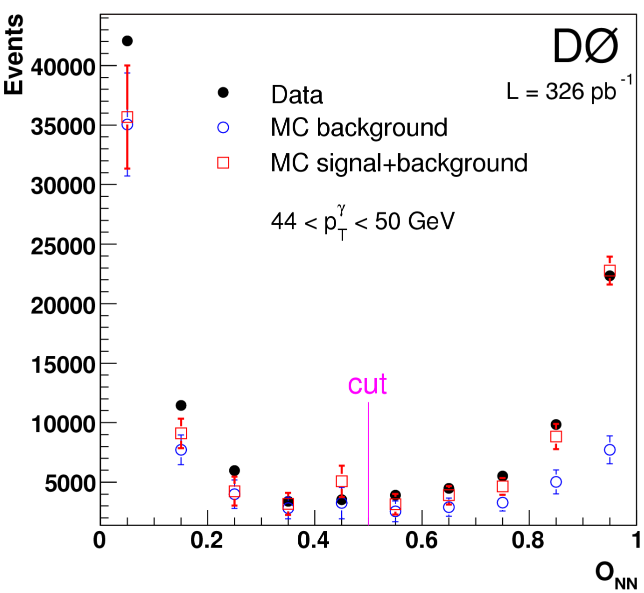


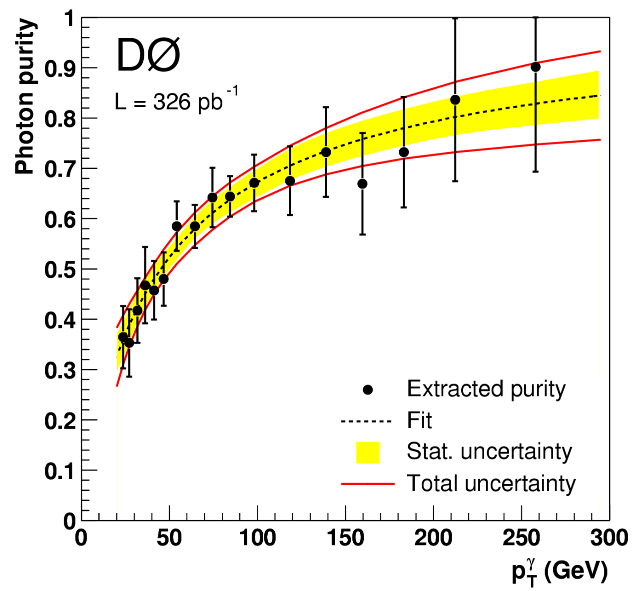
Leading Order Processes Yielding Direct Photons

- **Sensitive to PDF & hard scatter dynamics**
- **No need to define jets**

- Separating photons from jet background is challanging



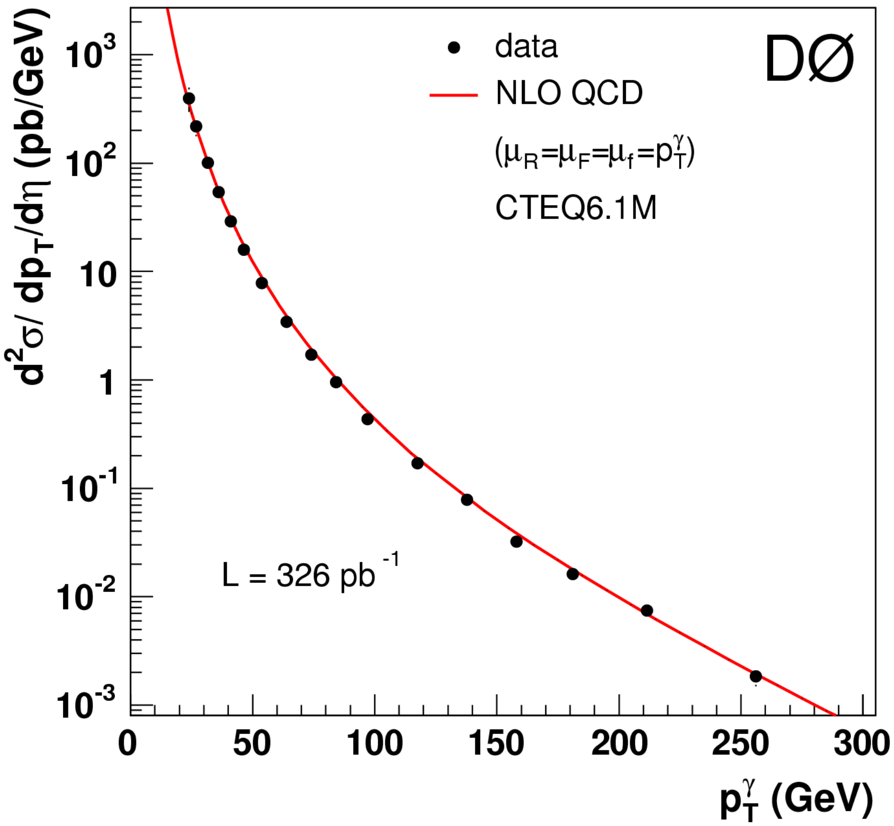




- Employ Artificial Neural Net to separate photons from jets and electrons
- Uses tracker and calorimeter isolation and showershape variables as input

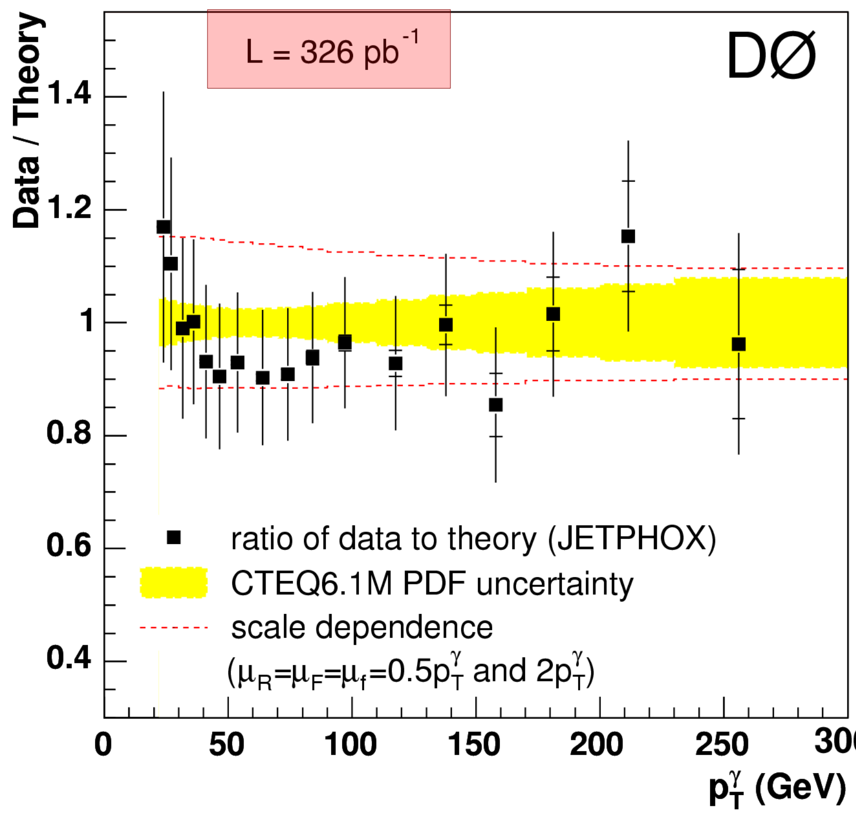
- No Jet Energy Scale error (EM scale well understood), purity uncertainty dominates

Inclusive γ cross section



- NLO pQCD calculation (JETPHOX) agrees well with data

- Errors are still of the order of 20%
- Promising to constrain the gluon PDF at high *x* with 1*fb*$^{-1}$



- Some fundamental concepts
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- **Heavy flavor production**
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b-jet Identification

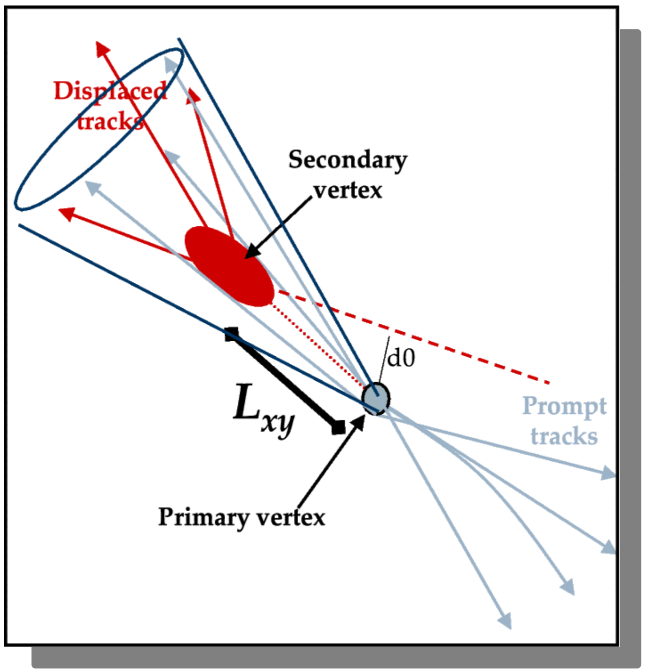
- QCD heavy flavor production is important background in many top-quark, Higgs and New Physics analyses

- *b*-jets are detected ("*tagged*") by identifying a *B*-hadron within the jet-cone

- Two main techniques to identify *B*-hadrons within a jet

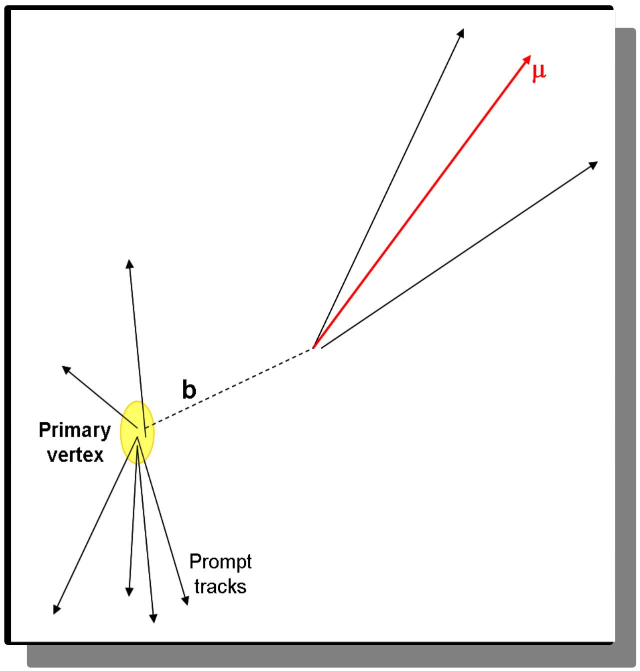
Lifetime tagging

- long *B*-hadron lifetime ($c\tau \approx 450\mu m$) results in secondary decay vertex



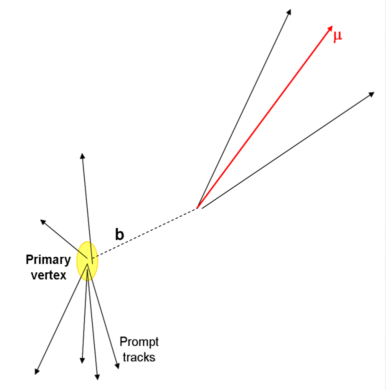
Soft lepton tagging

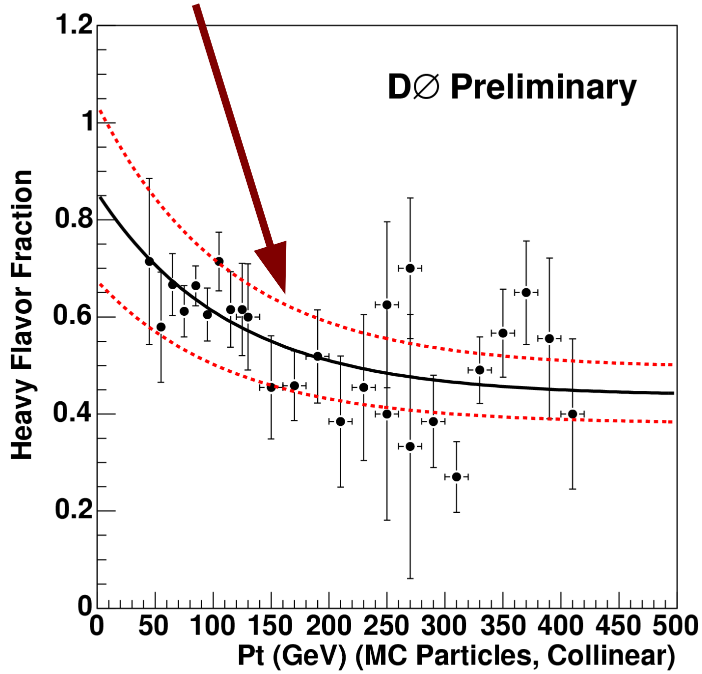
- heavy flavor hadrons decay to lighter hadrons
- use decay product for identification

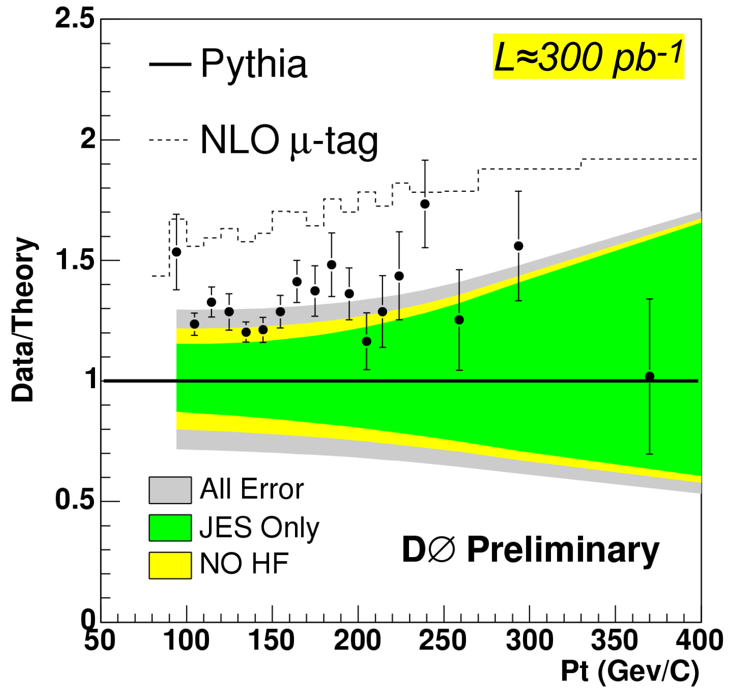


μ-tagged jet cross section

- $L \approx 300\ pb^{-1}$, $|Y|<0.5$, Run II Midpoint Cone ($R_{cone}=0.5$)
- Heavy flavor identification by *soft μ-tagging*
- Heavy flavor *(b/c)* fraction in *μ-tagged* jets estimated using simulated events, assign *20%* uncertainty to estimation







- Data lies between Pythia and NLO prediction
- "NLO *μ-tag*": NLOJET++ prediction times heavy flavor fraction determined using Pythia

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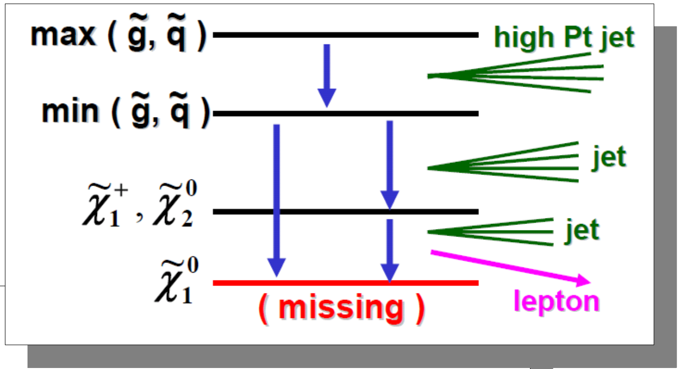
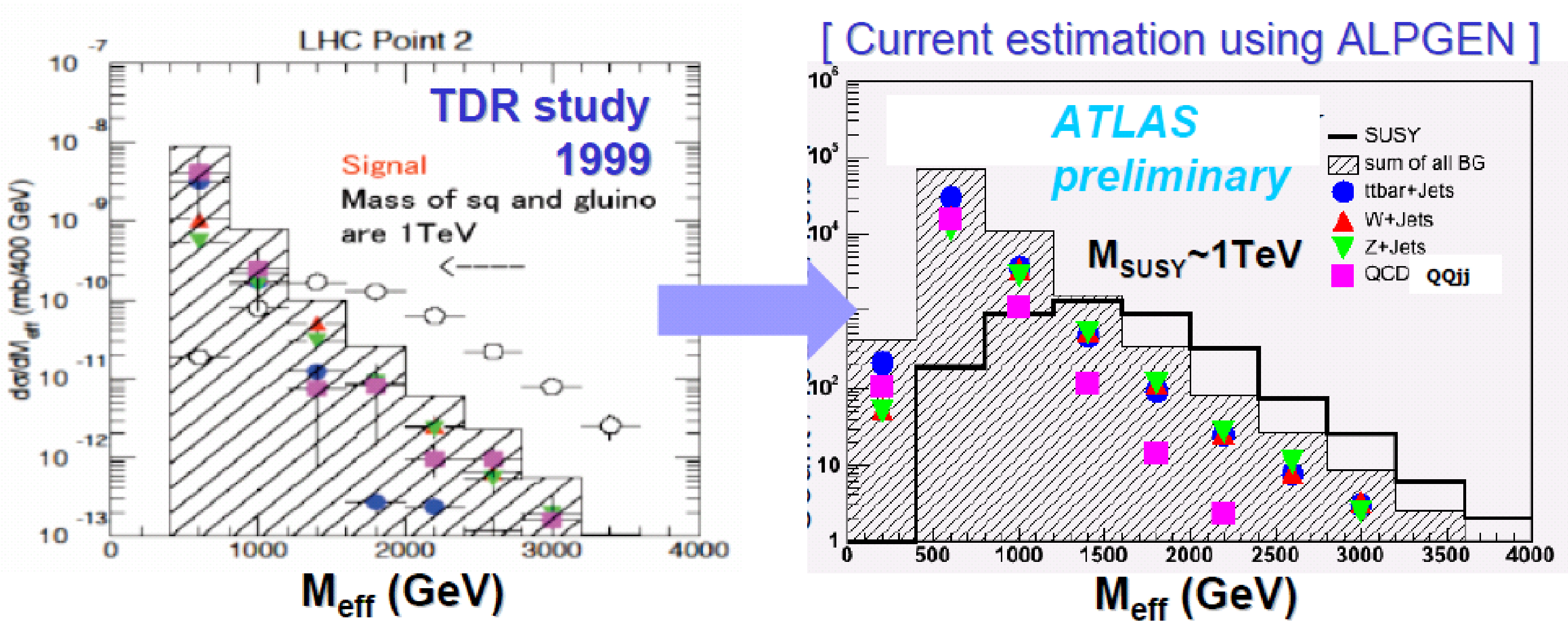
EW Boson + jets production

- Key sample to test LO and NLO ME+PS predictions
- Important background to top and new physics analyses

- Precise understanding important to estimate sensitivity, example SUSY discovery at ATLAS



Example from ATLAS



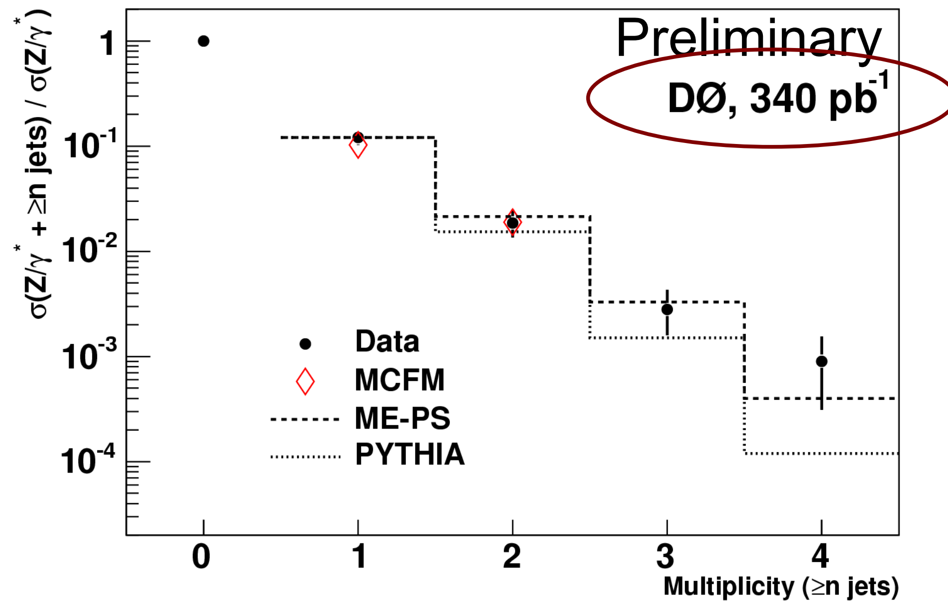
Background estimation increased by about 2-5 times

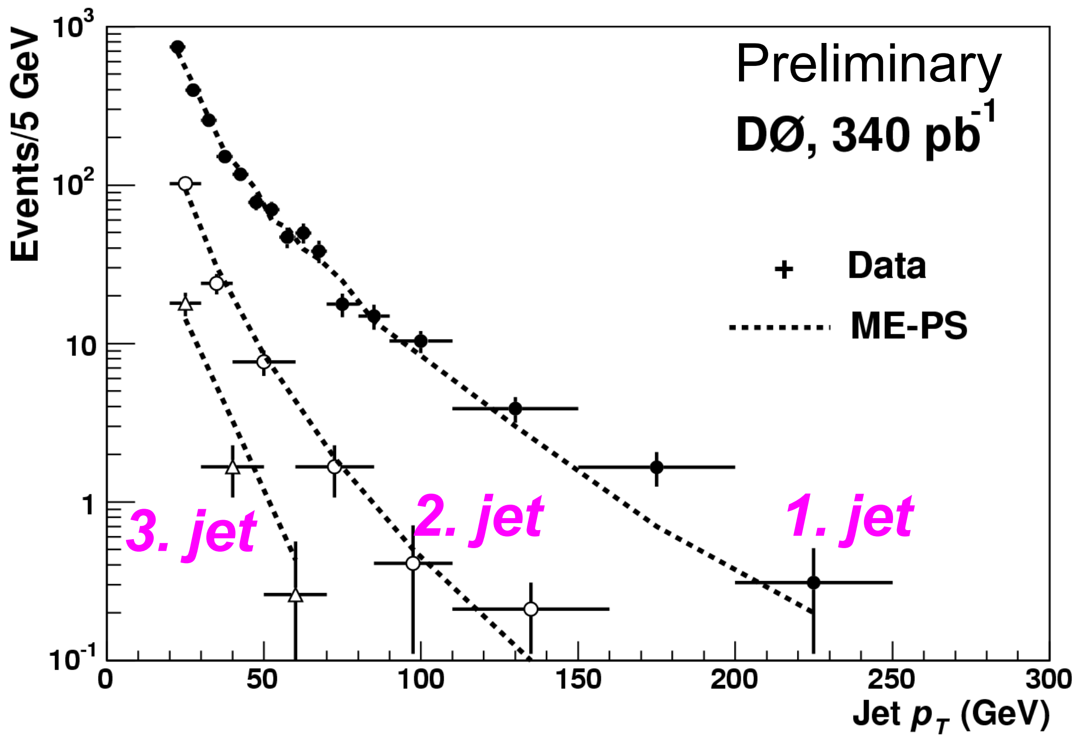
Z+jets production

$Z/\gamma^* \rightarrow e^+e^- + \text{jets}$

- $\sigma(Z+jets) \approx \sigma(W+jets) / 10$, but cleaner sample
- Mass constraint $75\ GeV < M_{ee} < 105\ GeV$

- Run II Midpoint Cone jet algorithm, $R=0.5$
- Jet requirements: $pT>20\ GeV$, $|\eta|<2.5$





- MCFM: NLO calculation for Z + up to 2 partons. *Good description of the measured cross sections.*

- ME-PS: MADGRAPH for tree level and PYTHIA for showering. *Shape of jet multiplicity and p_T distributions well reproduced.*

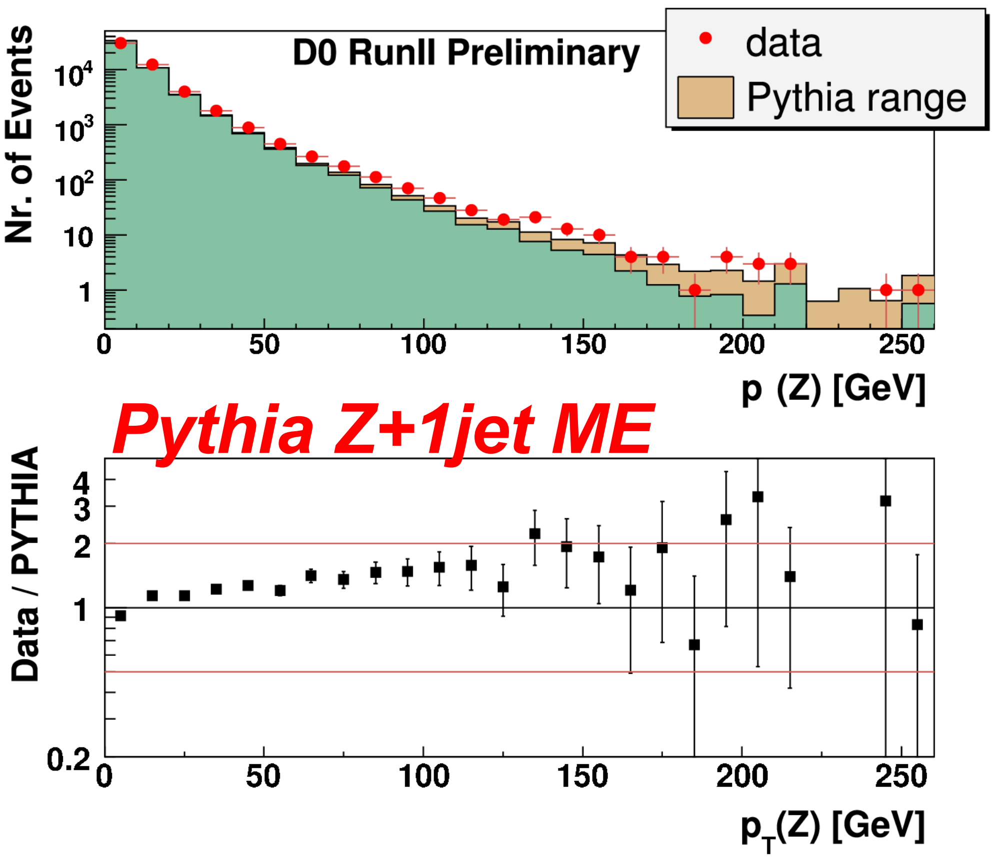
- PYTHIA: Too few events with high jet multiplicity.

SHERPA vs. PYTHIA

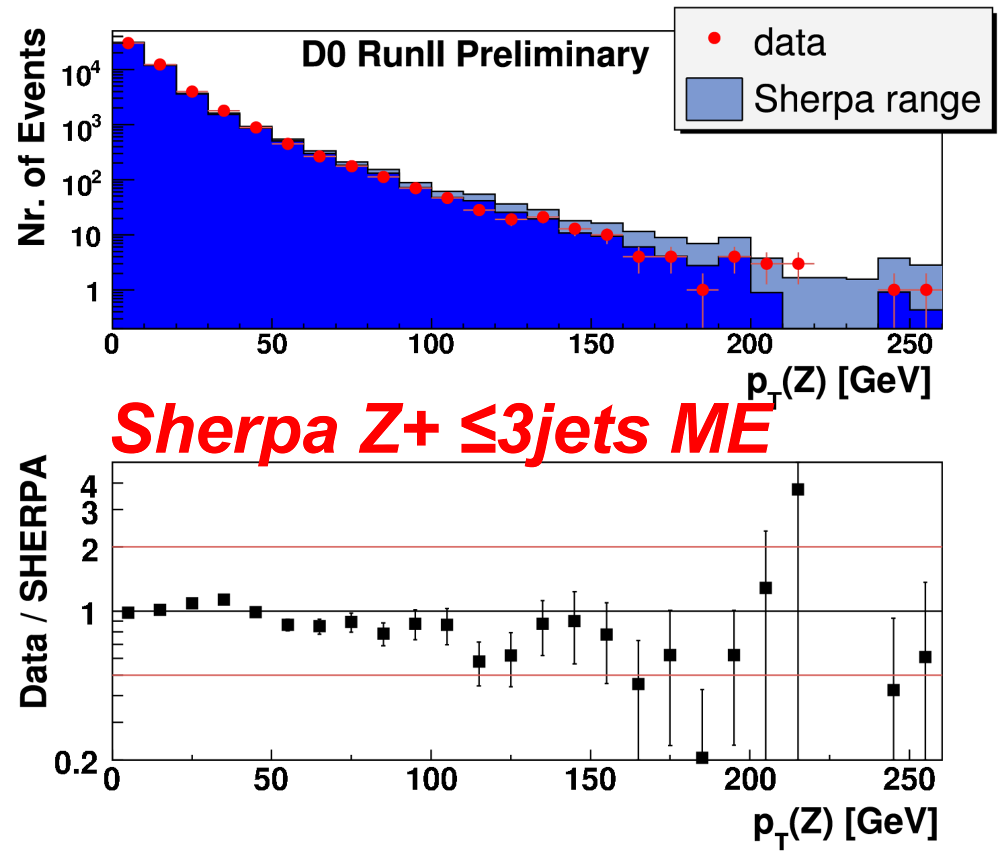
$Z/\gamma^* \rightarrow e^+e^- +$ jets

L=950 pb^{-1}

Pythia Z+1jet ME



Sherpa Z+ ≤3jets ME

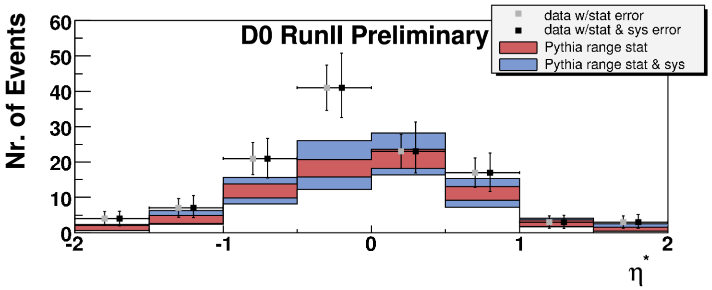


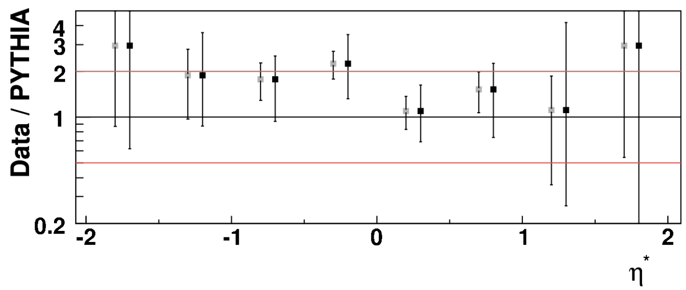
- Inclusive study of jets recoiling against the *Z* boson.
- Pythia tends to underestimate high p_T jets, especially at high jet multiplicities.
- Sherpa describes data well up to four jets.

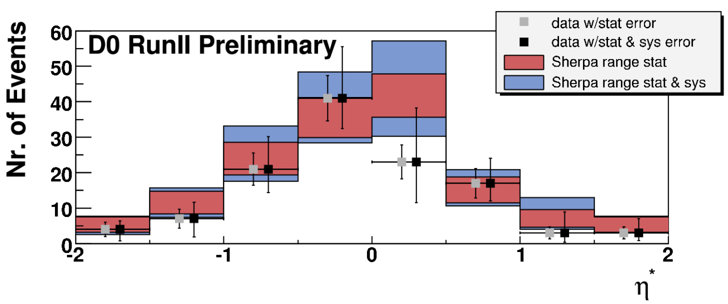
SHERPA vs. PYTHIA

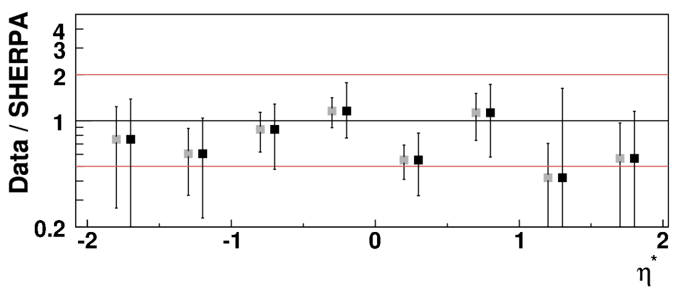
$Z/\gamma^* \rightarrow e^+e^- + \text{jets}$

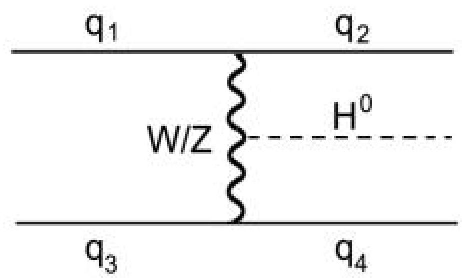
L=950 pb^{-1}

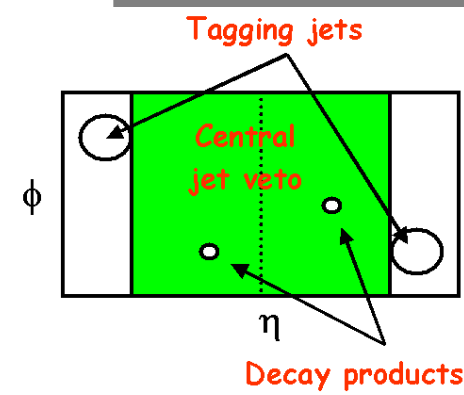




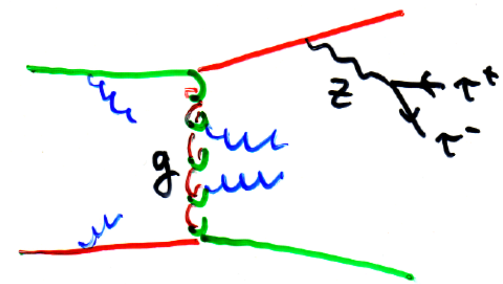








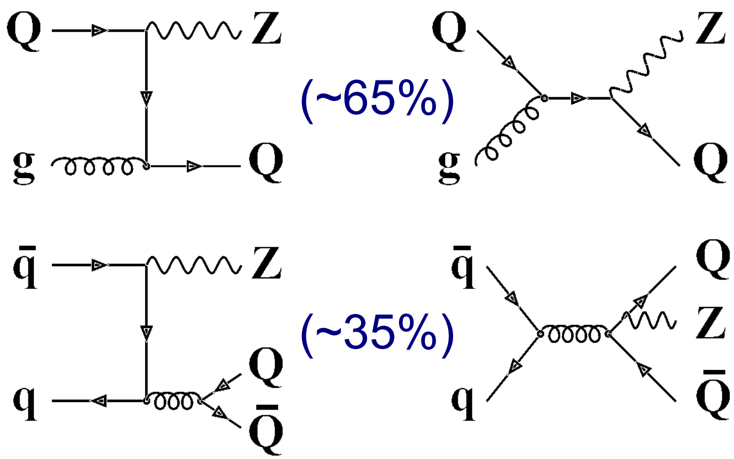
- Higgs Boson discovery potential at the LHC depends on understanding of “central jet veto” to suppress background.



- Can be studied at Tevatron, although cross section is small. Need more luminosity.

- SHERPA correctly predicts shape and rate of central jet.
- PYTHIA predicts a factor of ~1.7 less events than seen in data, shape OK within uncertainties.

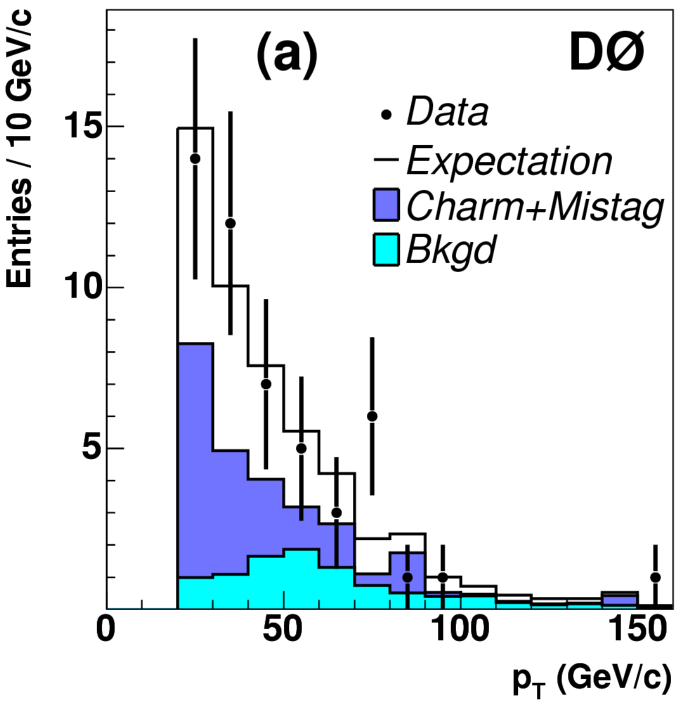
$Z + b$-jet production

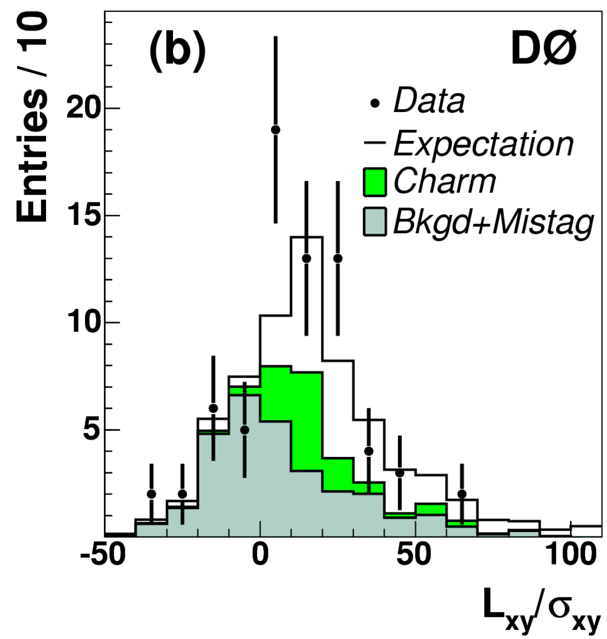


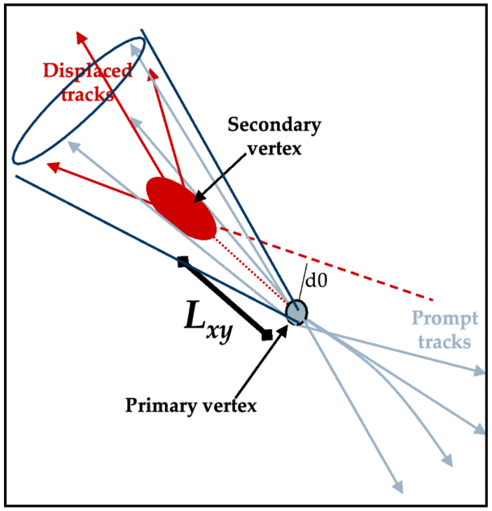
- Sensitive to *b*-quark PDF in the proton
- Important to predict production of particles coupling strongly to heavy flavor (i.e. Higgs, single top, ...)

- Important test of background to Standard Model Higgs production $ZH \rightarrow Zb\bar{b}$

- Select $Z \rightarrow e^+e^- / \mu^+\mu^-$ using mass constraint
- Cone jet algorithm, R=0.7, jet $E_T > 20$ GeV, $|\eta_{jet}| < 2.5$
- *b*-tagging using secondary vertex reconstruction







Z + *b*-jet production

- ***L = 180 pb^{-1}***
- Measuring the ratio of b to normal jets avoids the 6.5% luminosity uncertainty
- Assume theoretical value *$N_c = 1.96 N_b$*

$$\sigma(p\bar{p} \rightarrow Z + b\ \text{jet})/\sigma(p\bar{p} \rightarrow Z + \text{jet}) = 0.021 \pm 0.004(\text{stat})^{+0.002}_{-0.003}(\text{syst})$$

- ***L = 330 pb^{-1}***
- Use secondary vertex mass to estimate true b-fraction in sample

Cone0.7, $E_T^{\text{jet}} > 20$ GeV, $\lvert\eta^{\text{jet}}\rvert < 1.5$, $\sqrt{s} = 1.96$ TeV, $L \sim 335\ \text{pb}^{-1}$	CDF RUNII PreliminaryData	PYTHIA TuneA (CTEQ5L)	NLO J. Campbell	NLO with Had, UE
$\sigma(Z^0 + b\ \text{jet})$	$0.96 \pm 0.32 \pm 0.14$ pb	0.83 pb	0.48 pb	0.52 pb
$\sigma(Z^0 + b\ \text{jet})/\sigma(Z^0)$	$0.0038 \pm 0.0012 \pm 0.0005$	0.0034	0.0019	0.0021
$\sigma(Z^0 + b\ \text{jet})/\sigma(Z^0 + \text{jet})$	$0.0237 \pm 0.0078 \pm 0.0033$	0.0207	0.0185	0.0185

- Dominant systematic uncertainty for both analyzes is jet energy scale.
- Good agreement between the measurements and with theoretical prediction.

- Some fundamental concepts
- Inclusive jet cross section
- Inclusive isolated photon (γ) cross section
- Heavy flavor production
- Z + jets measurements
- **Summary**

Summary

QCD measurements are an active field at the Tevatron

Inclusive jet production is tested at the Tevatron to high precision

- Good agreement with pQCD predictions
- Covers 9 orders of magnitude in cross section
- Input to global PDF fits

Jets in association with vector boson

- Important background for many searches beyond the Standard Model
- Testing ground for Monte Carlo tools: NLO calculations, ME+PS matching, etc....
- Latest tools describe data well
- Important input to the LHC

Analyzes will improve with more luminosity, more to come from the Tevatron soon!