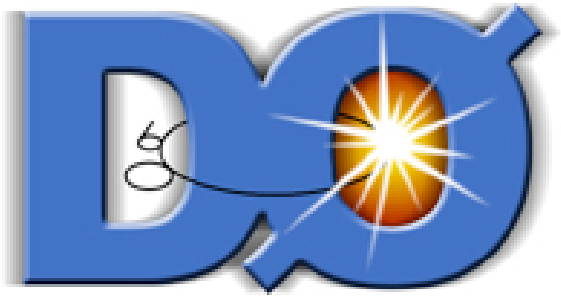
QCD Results and Monte Carlo issues

Avto Kharchilava

University of Notre Dame

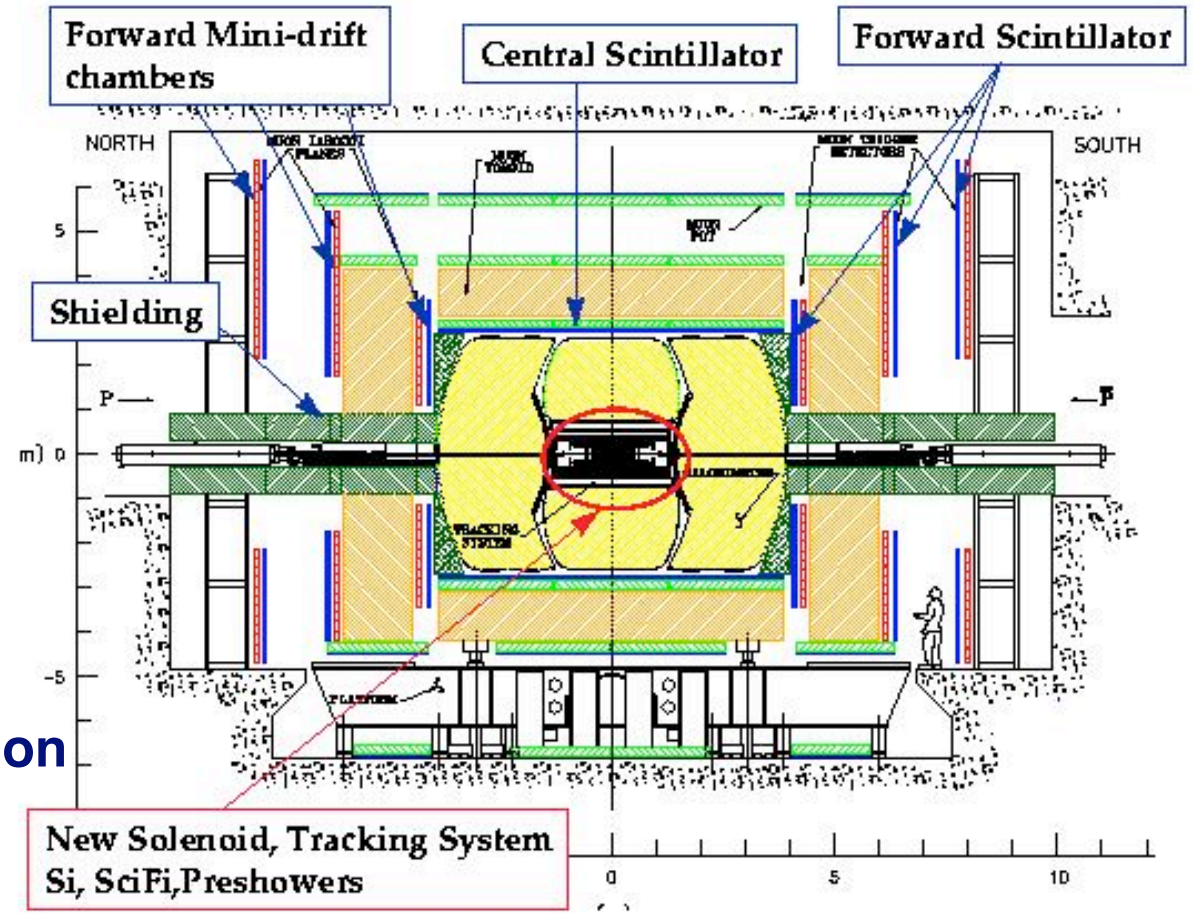
For the DØ Collaboration



Outline

- **Introduction**
  - **Monte Carlo tools**
  - **Jet algorithms**
- **Jets production**
  - **Inclusive cross section**
  - **Di-jet mass cross section**
  - **Angular correlations**
- **Vector boson plus jets**
  - **W + jets/bb**
  - **Z + jets/b**
    - **σ(Z+b)/σ(Z+j) ratio**
- **b(b)h associated production**
- **Summary**

Upgraded DØ detector in Run II of the Tevatron



Monte Carlo tools

- A snapshot of the DØ Monte Carlo event generators web site

DØ Run II Simulation

Parton Shower MC	Fixed Order Matrix Element MC	MC for Diffractive Physics
PYTHIA SM, SUSY, etc., general purpose event generator	**ALPGEN** LO ME event generator for multiparton final stat	**PHOJET** Event generator for h-h, etc., procs. based on Dual Parton Model
HERWIG SM, SUSY RPC and RPV event generato	**CompHep** LO SM and SUSY event generator, plus Feynman "diagramics" tool	**POMPYT** Pomeron event generator interfaced with PYTHIA
SUSYGEN SUSY RPC and especially RPV event generator	**OneTop** Top (single/pair production) and Wbb LO event generator	**POMWIG** Pomeron event generator interfaced with HERWIG
ISAJET SM, SUSY, ED, ... event generator	**TopRex** Top (single/pair production) and H/W/Z+jets LO event generator	**SCIPYT**
	VECBOS W+jets and Z+jets specialized LO event generator	**RapGap** Rapidity gaps specialized event generator
	CD MC Database Parton level MC events produced with exact M.Elements by theorists	
	MCFM W/Z/H+jets specialized LO and NLO event generator	

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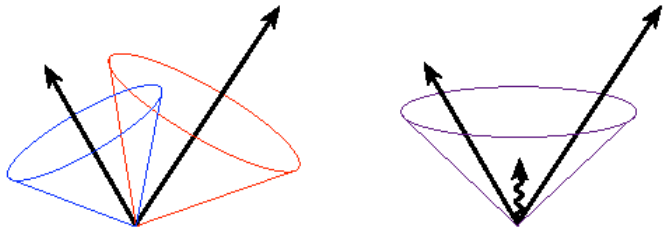
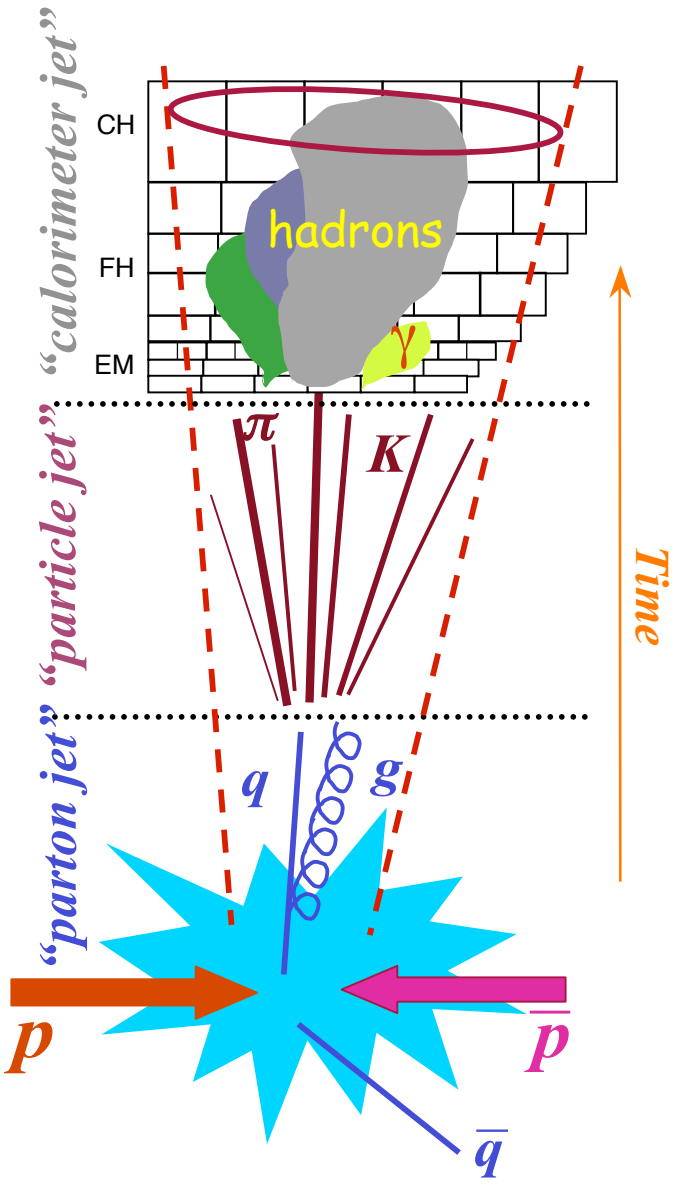
Jet definitions in Run II

- Run I cone algorithm
  - Add up towers around a "seed"
  - Iterate until stable
  - Jet quantities: E_T, η, ϕ

- Improvements for Run II
  - Use 4-vector scheme, p_T instead of E_T
  - Add midpoints of jets as additional starting seeds
  - Infrared safe

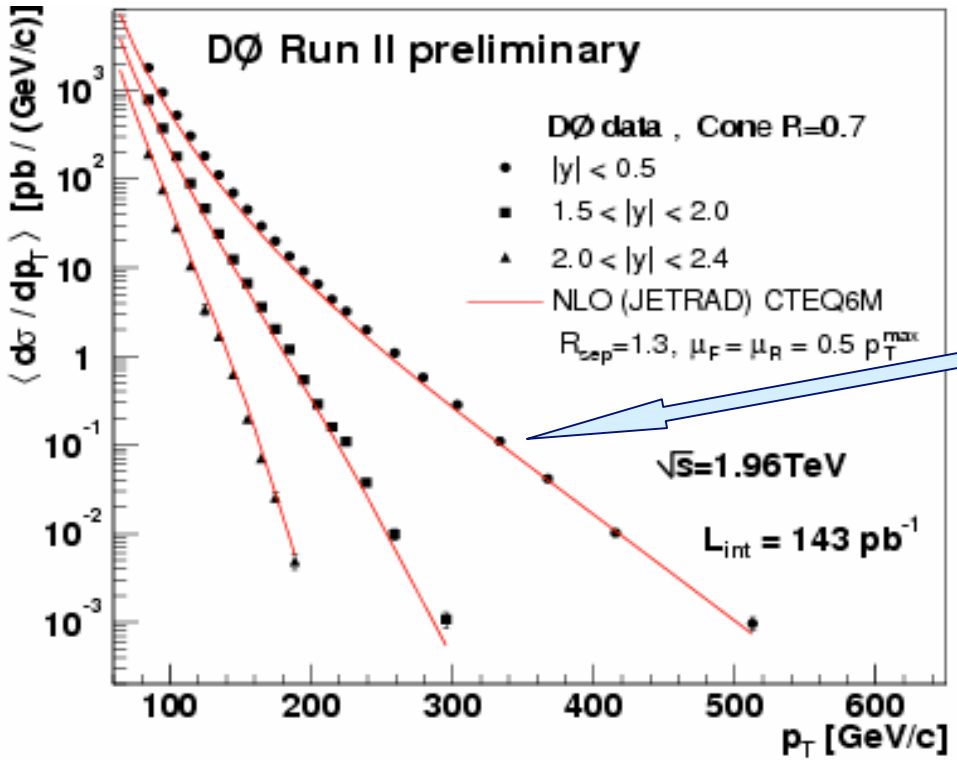


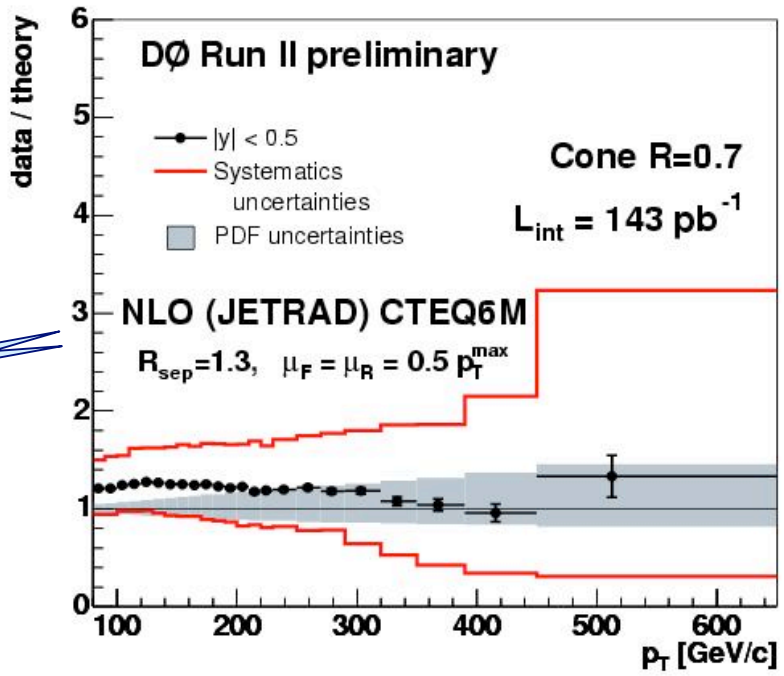
- Correct to particles
  - Underlying event, previous/extra interactions, energy loss out of cone due to showering in the calorimeter, detector response, resolution



Details in G.C.Blazey *et al.* "Run II Jet Physics", hep-ex/0005012

Inclusive jet cross section: Run II cone algorithm





- First Run II cross section for forward jets
  - Important PDF information in cross section vs. rapidity

- Agreement between data and theory
- Large uncertainties due to Jet Energy Scale (JES)
  - Updated, better JES measurements to be propagated into analysis soon

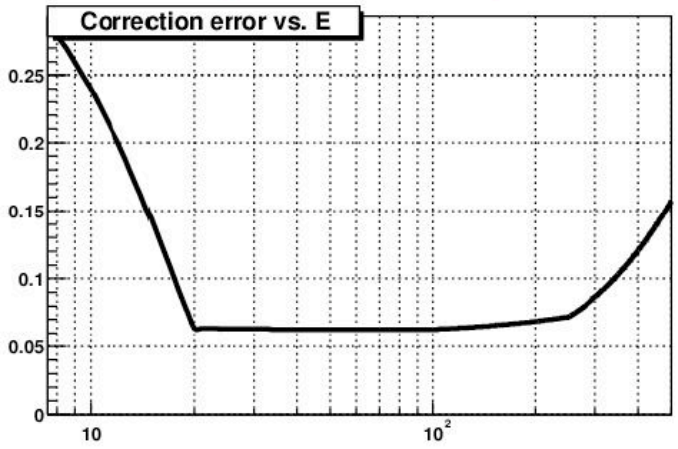
Next slide

Improvements on jet energy scale

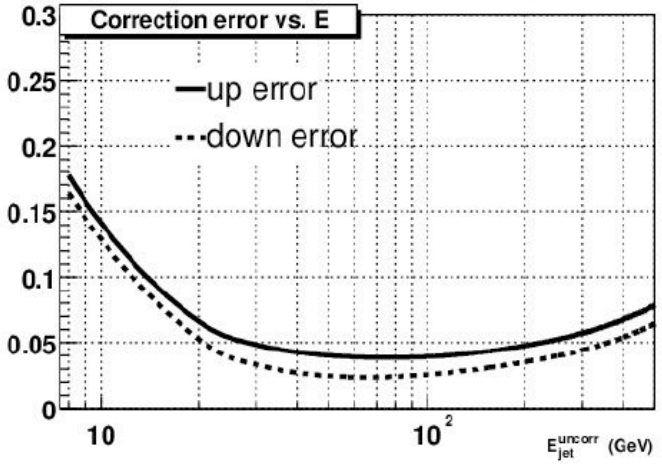
$$E_{jet}^{ptcl} = \frac{E_{jet}^{meas} - E_0(R,\eta,L)}{R_{jet}(E,\eta,L)\,R_{cone}(R,\eta,L)}$$

- E_0 is an energy offset (electronics and Uranium noise, energy pile-up from previous crossings, additional ppbar inetraction and underlying events.)
- R_{jet} is calorimeter response
- R_{cone} is the fraction of the jet calorimeter shower contained in the algorithm cone

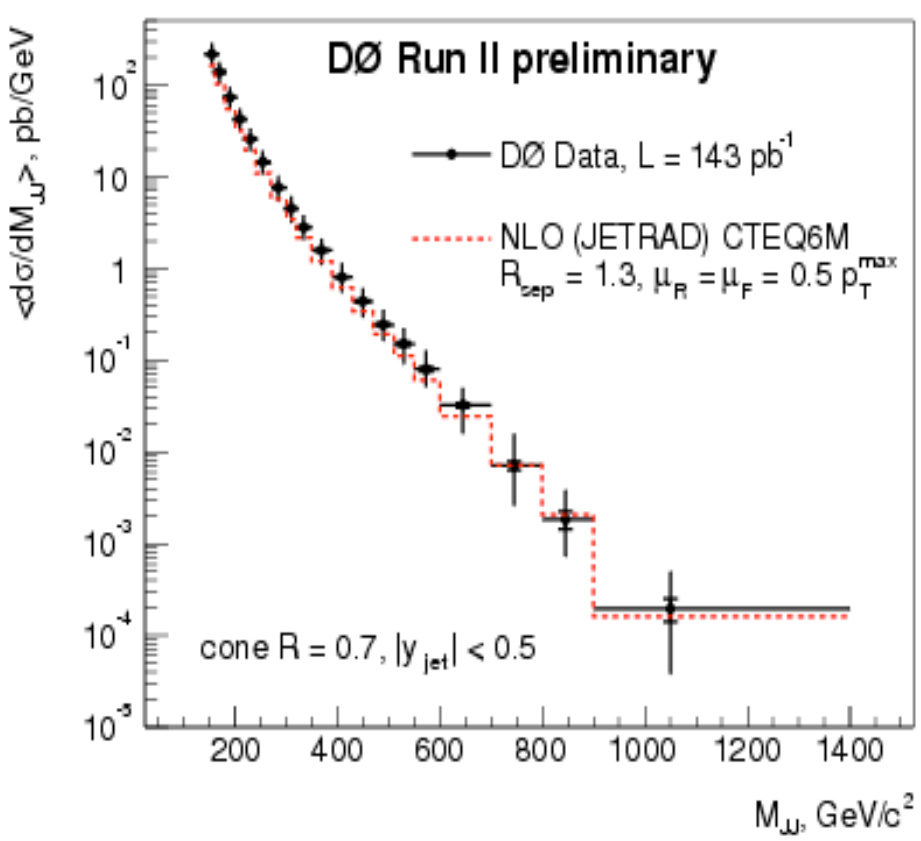
Old JES error

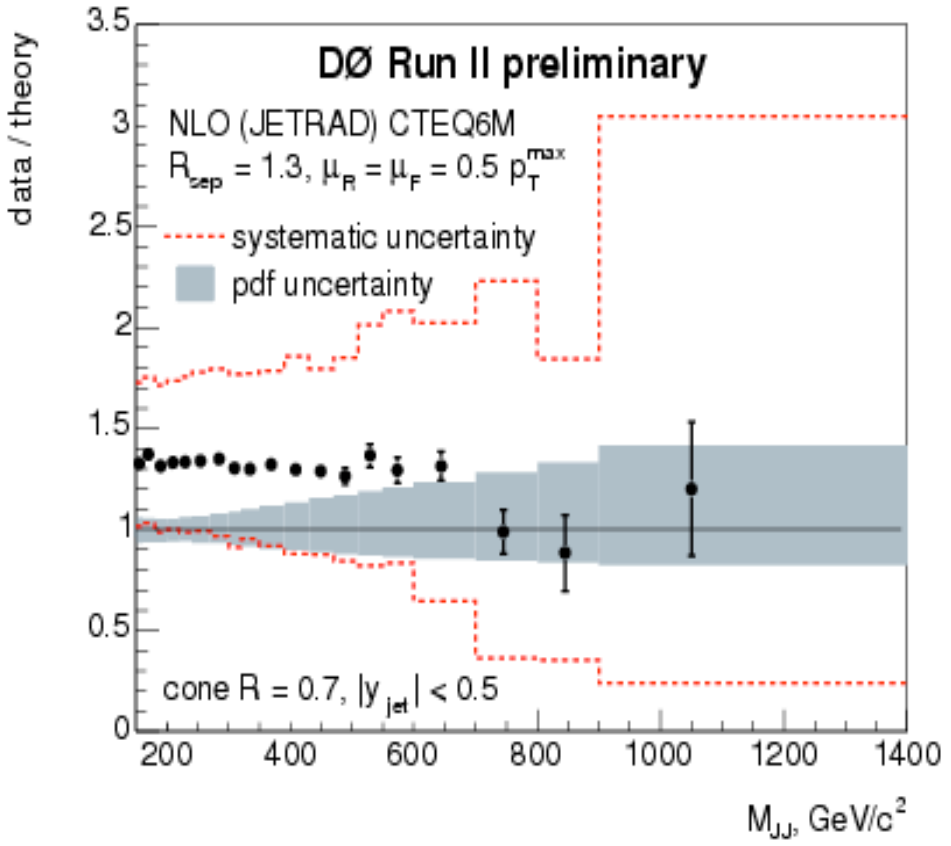


New JES error



Dijet production



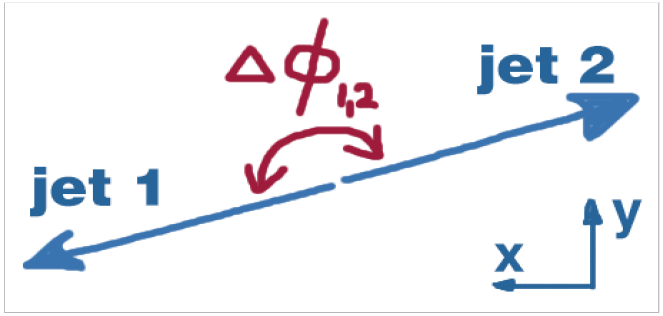


- Central region $|y_{jet}| < 0.5$, data sample ~143 pb^{-1}
- Agrees within uncertainties with NLO/CTEQ6M
- Jet Energy Scale – dominant error on the measurement
  - Again, expect significant improvements soon with the new JES

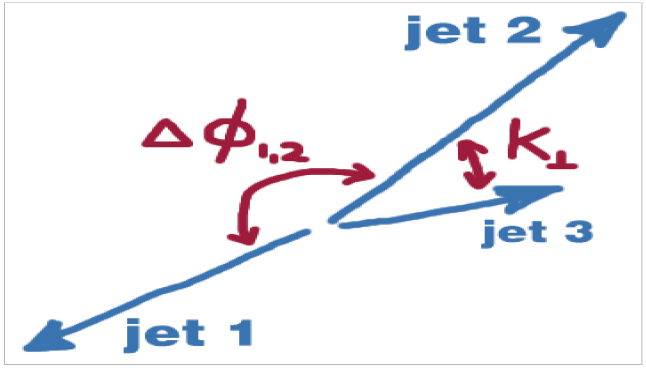
Azimuthal correlations between two leading jets

- In 2→2 scattering, partons emerge back-to-back
- Additional radiation introduces decorrelation in $\Delta\phi$ between the two leading partons/jets
  - Soft radiation: $\Delta\phi \sim \pi$
  - Hard radiation: $\Delta\phi < \pi$
- $\Delta\phi$ distribution is directly sensitive to higher order QCD processes
- Testing fixed order pQCD and parton-shower models across $\Delta\phi$
  - $\Delta\phi \sim \pi$:
    - Fixed-Order calculations unstable
    - Parton-shower Monte Carlo's applicable
  - $2\pi/3 < \Delta\phi < \pi$:
    - First non-trivial description by 2→3 tree-level ME
    - 2→3 NLO ME calculations became available recently (NLOJET++, Z. Nagy, Phys. Rev. D68, (2003) 094002)
  - $\Delta\phi < 2\pi/3$
    - 2→4 processes and higher

Di-jet production in lowest order pQCD



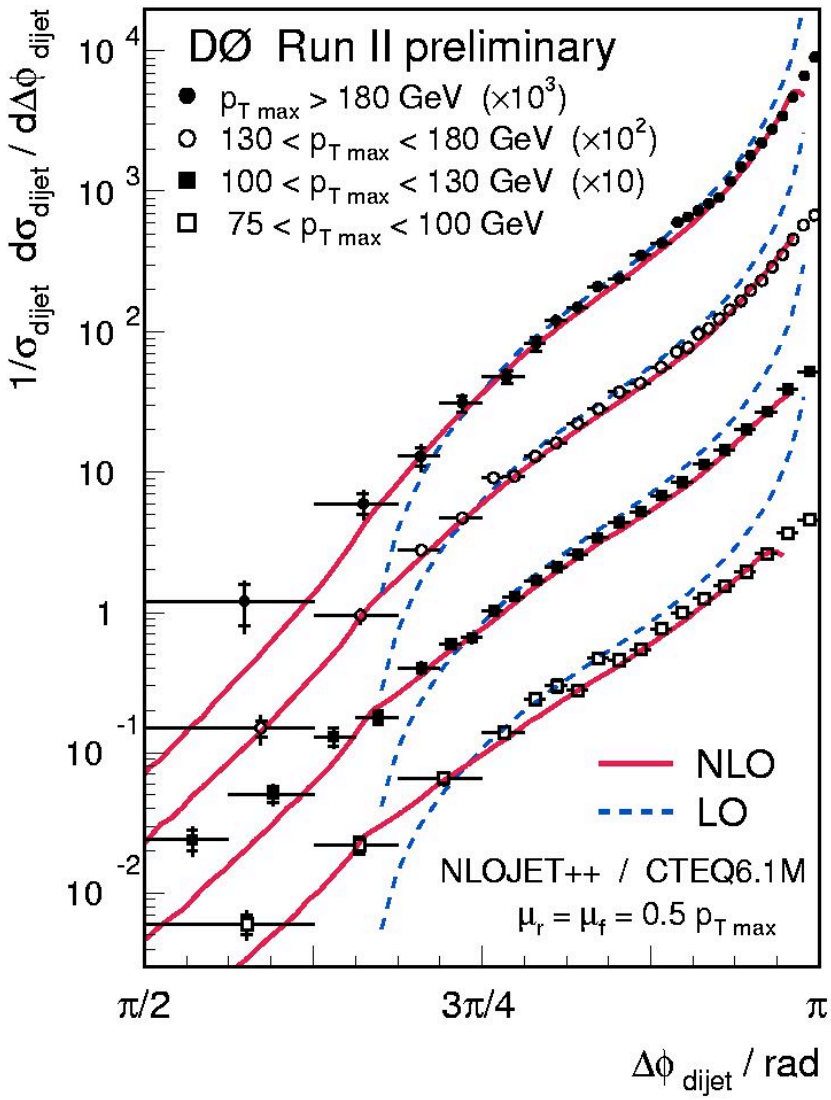
3-jet production in lowest order pQCD



Δφ: comparison to fixed order pQCD

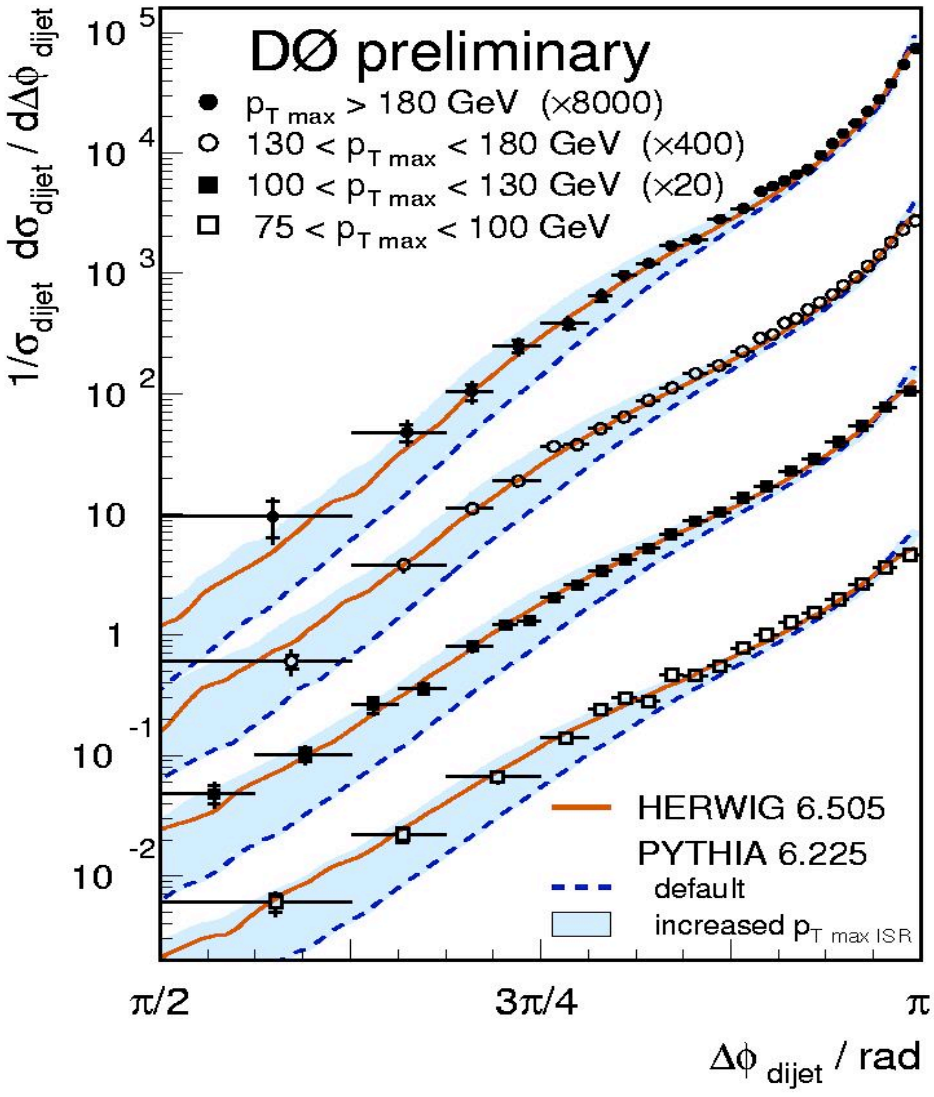
- Δφ between two leading jets
  - Sensitive to QCD radiation
  - No need to reconstruct any other jets
  - Reduced sensitivity to jet energy scale
- Data set corresponds to $L_{int} \sim 150\ pb^{-1}$
  - Central jets |y| < 0.5
  - Second leading jet with $p_T > 40$ GeV
- Towards larger p_T, Δφ spectra more strongly peaked at ~ π
  - Increased correlation in Δφ
- Distributions extend into the "4 final state parton regime", $\Delta\phi < 2\pi/3$
- Leading order (dashed blue curve)
  - Divergence at $\Delta\phi = \pi$
    - Need soft processes
  - No phase space at $\Delta\phi < 2\pi/3$
    - Only three partons
- Next-to-leading order (red curve)
  - Good description by NLOJET++ over the whole range, except in extreme Δφ regions

$$\frac{1}{\sigma_{dijet}} \cdot \frac{d\sigma_{dijet}}{d\Delta\Phi}$$



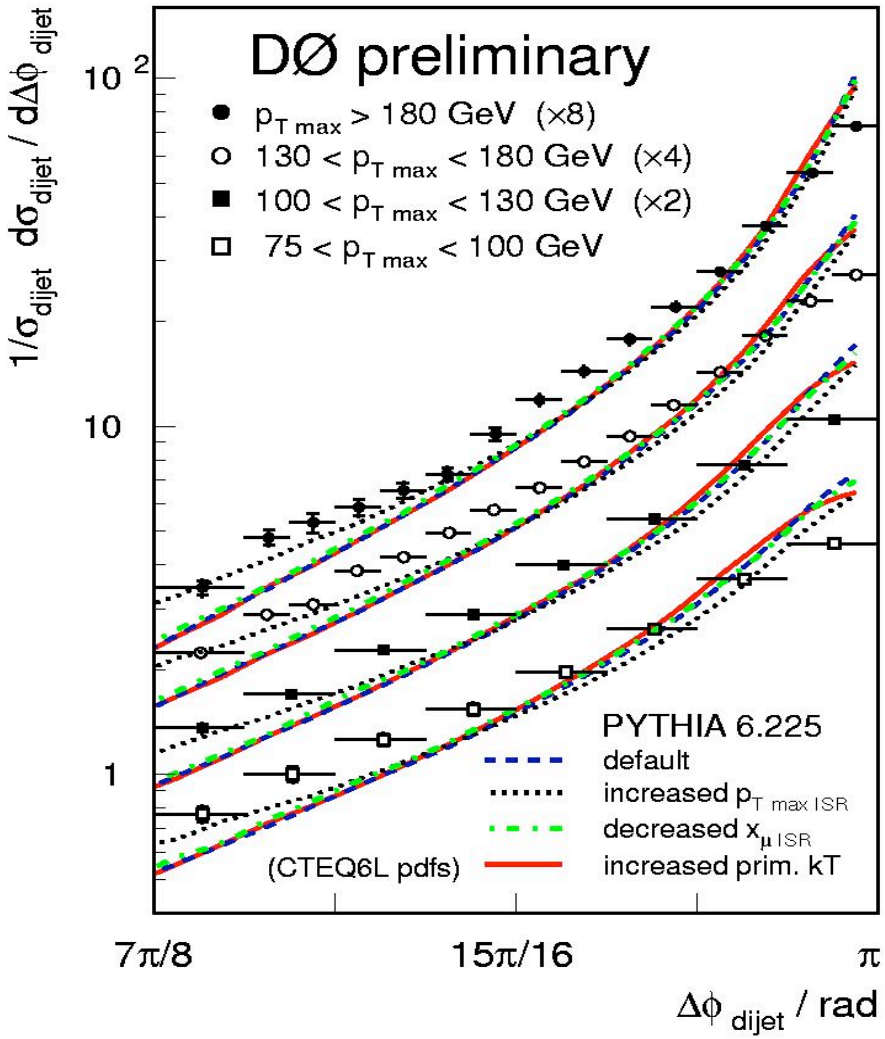
$\Delta\phi$: comparison to parton shower Monte Carlo's (1)

- Examine the radiation process
  - $3^{rd}/4^{th}$ jets generated by parton showers
- Herwig 6.505 (default settings)
  - Good overall description !
  - Slightly too high in mid-range
- Pythia 6.223 (default settings)
  - Very different shape
  - Too steep dependence
  - Underestimates low $\Delta\phi$
- $\Delta\phi$ distributions are sensitive to the amount of initial state radiation (ISR)
  - Plot shows variation of PARP(67) from 1.0 (current default) to 4.0 (previous default, "Tune A")
    - Controls the scale of parton showers
    - Allows for higher virtualities in ISR



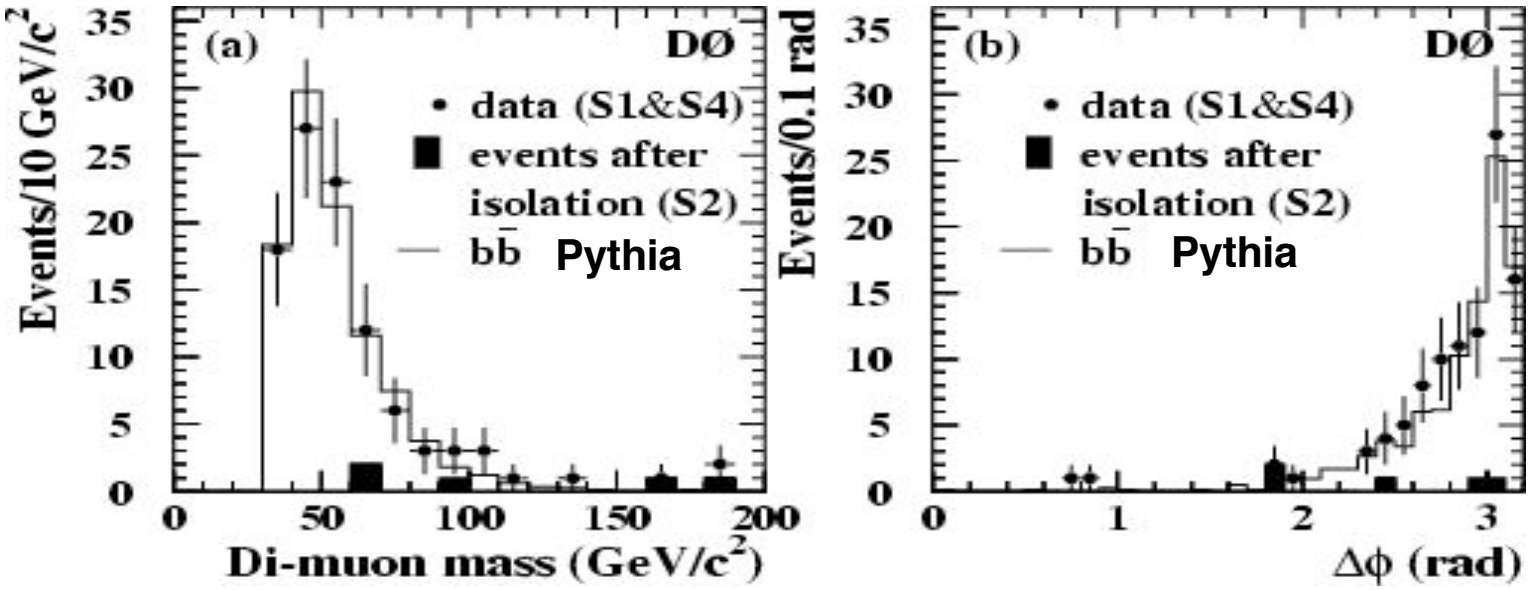
$\Delta\phi$: comparison to parton shower Monte Carlo's (2)

- More Pythia tunings
- Decrease Q^2 scale factor for α_s and PDF, PARP(64), from 1.0 to 0.5
  - Will increase ISR rate
  - No visible effect
- Increase primordial k_T in proton, PARP(91), from 1 GeV to 4 GeV simultaneously increasing the upper cut-off of Gaussian, PARP(93), from 5 GeV to 8 GeV
  - Suggested by other experiments
  - Observe an improvement in large $\Delta\phi$ region



b production (1)

- Emphasis is currently put on studies of B-hadron properties (see R. Jesik's talk)
  - No update is available for, e.g. bb production cross section measurement
- However, studies of bb→di-lepton kinematics/rate as a bkgd. to various searches are well under way
- Example: same sign, (non-)isolated muons with $p_T > 15$ GeV in $|\eta| < 2$

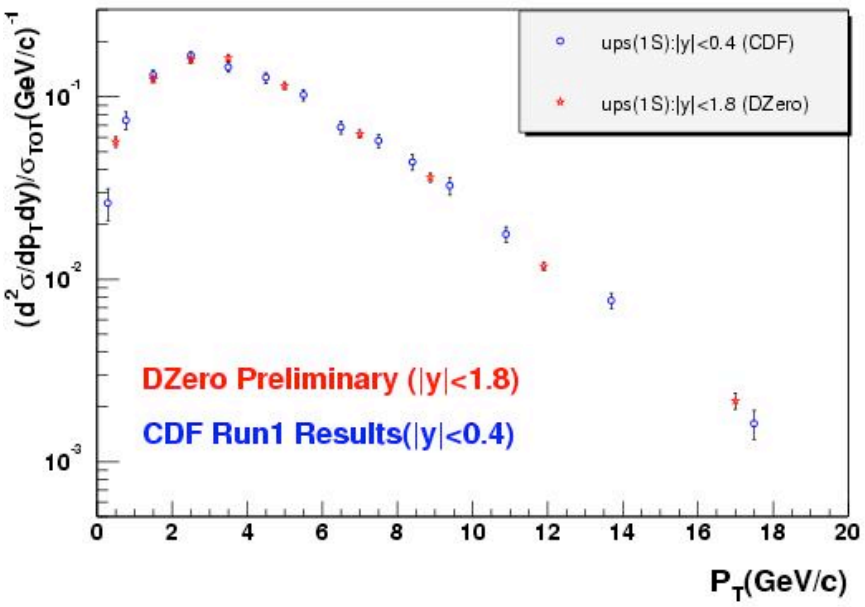


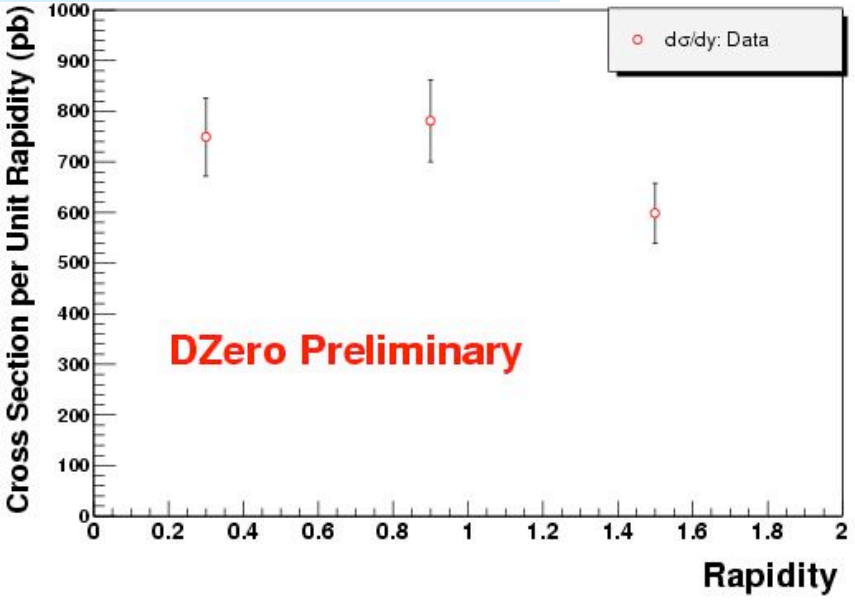
- Pythia reproduces $M_{\mu\mu}$ and $\Delta\phi$ shapes, and absolute rate (within ~20%)
  - "Tune A" w/ PARP(67) = 4.0 – increased from 1 to allow higher virtualities in ISR

b production (2)

- Help is needed from phenomenologists on
  - Common inputs/systematics, Monte Carlo settings (fragmentation and decay models), etc., to ease combination of results with CDF/other experiments
  - Lifetimes, mixings, limits on rare decays
  - Formalism for D**, B** interference
  - Modeling the X(3872) state production
  - Upsilon cross section: new theory predictions

Upsilon production cross section vs. p_T and rapidity

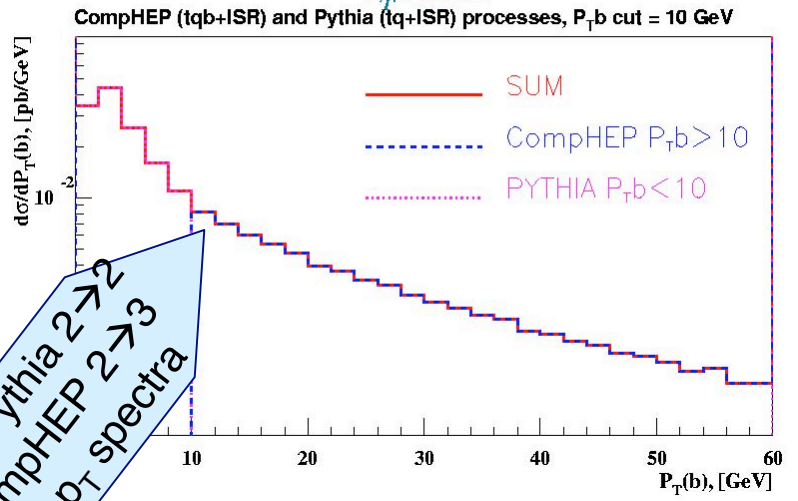




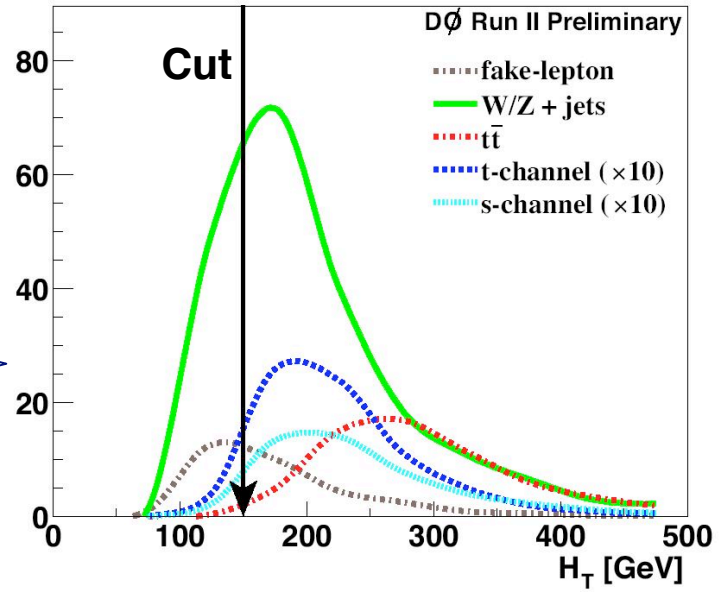
Top production

- Use LO ME event generators for ttbar processes
  - ALPGEN + Pythia showering (with full spin correlations included), or Pythia stand alone
- Single top production processes are more delicate to simulate
  - Details in Z. Sullivan's talk at the EW session
- Current DØ approach is based on a custom implementation of CompHEP ("Single Top")
  - Reproduces NLO kinematics, s-/t-channel production including decay angles
  - These parton configurations are processed through Pythia showering
    - Add underlying event, ISR, FSR, etc.

$\sigma_{\mathrm{PYTHIA}}(2\to 2) = \sigma_{\mathrm{NLO}} - \sigma_{\mathrm{CompHEP}}(2\to 3)\,|_{P_T^b > cut(P_T^b)}$,
where, $\sigma_{\mathrm{CompHEP}}(2\to 3)\,|_{P_T^b > 10\mathrm{GeV}} \approx 0.08$ pb



Matching Pythia 2→2 and CompHEP 2→3 b-quark p_T spectra



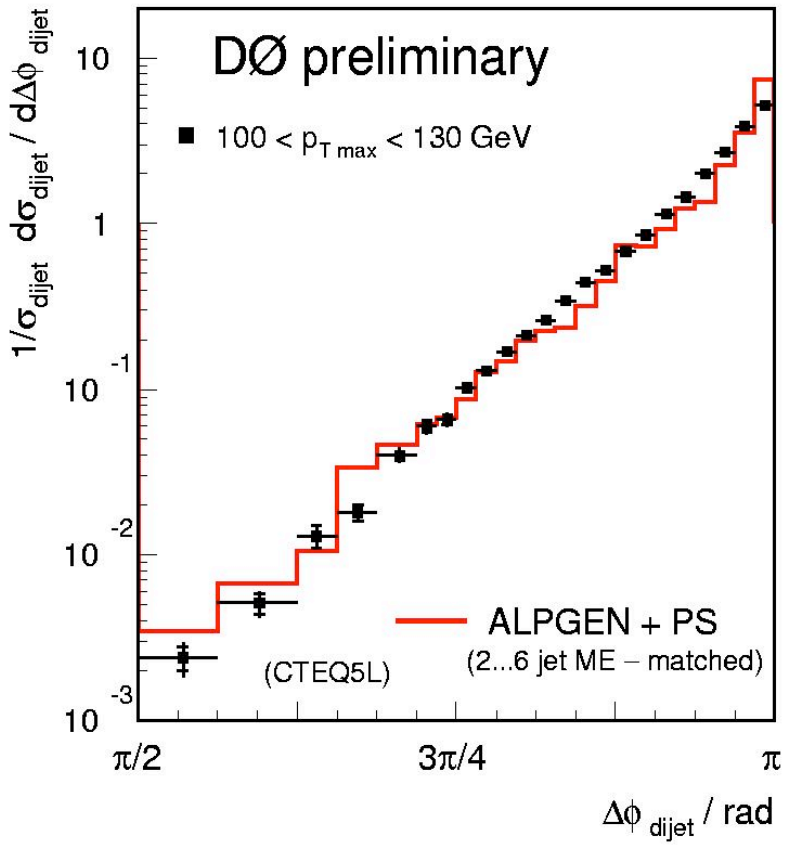
$H_T = p_T(\text{lepton}) + p_T(\text{2 leading jets}) + E_T(\text{missing})$ distribution after evt. preselection and b-tagging

- Important to do it right/reconcile approaches

Electro-Weak bosons + (b-)jets

- A laboratory to test QCD predictions
  - W/Z + n jets rate ~ α_s^n in lowest order
  - Perturbation theory should be reliable
    - Heavy boson _ large scale
  - NLO/MCFM calculations available up to 2 jets
    - What are the prospects for > 2 jets ?
    - Integrate/convert into event generator ?
- Important backgrounds for other physics
  - Top, Higgs, New phenomena
- Variety of multi-parton generators based on LO ME calculations are available
- How to combine them with parton-shower generators and avoid “double counting” ?
  - Various prescriptions, MLM, CKKW
- First attempt to test MLM matching prescription on high stat. QCD jets data sample using ALPGEN+Pythia MC
  - Generate n(=2-6) partons, pass them through Pythia, find parton jets, match them to original partons, apply event accept/reject condition

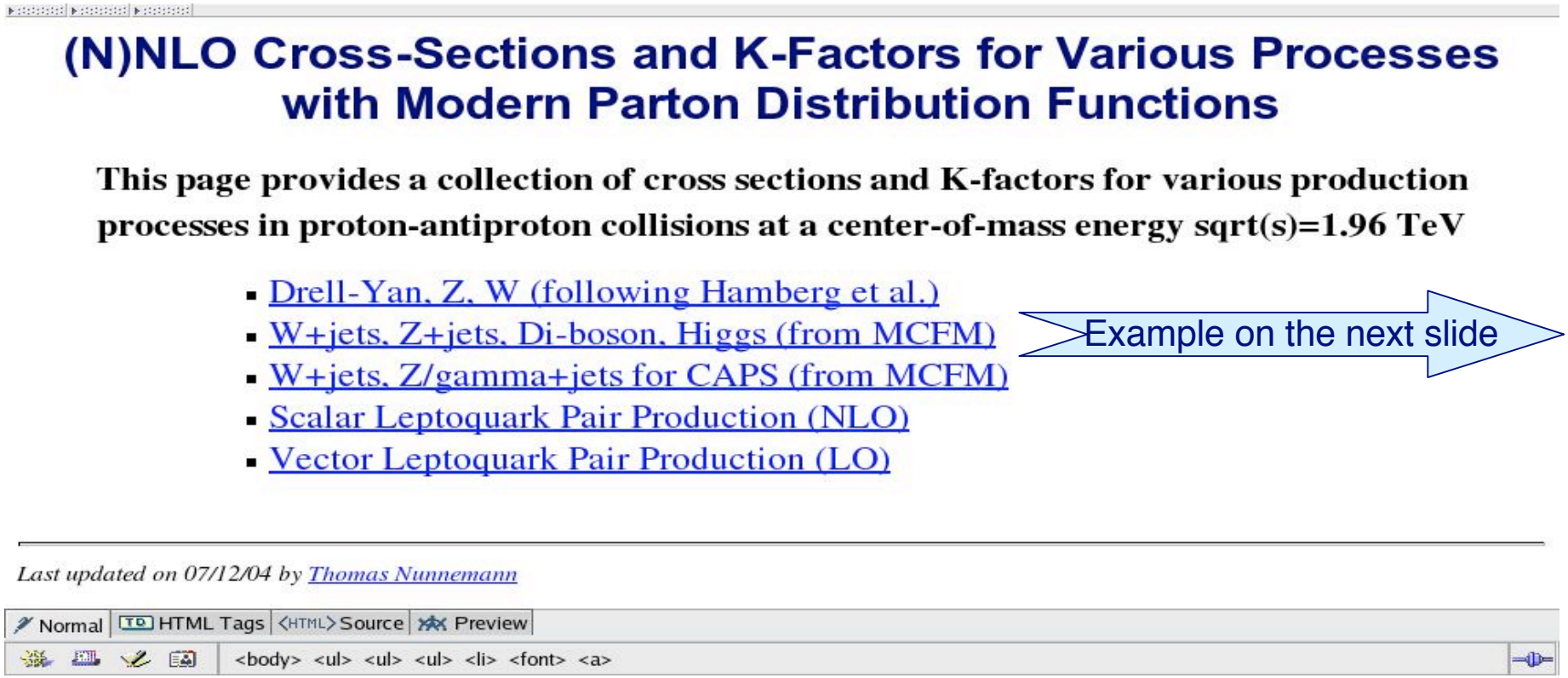
- Yet another look at $\Delta\phi$ correlations



- This work has just begun in DØ
  - Too early to make firm conclusions
  - Need more MC statistics (at least)
  - Approach/result is worth to discuss

Cross sections for reference processes (1)

- For students that are not comfortable with FORTRAN …
  - Have cross section calculations, NLO/LO K-factors, etc. documented on web:



(N)NLO Cross-Sections and K-Factors for Various Processes with Modern Parton Distribution Functions

This page provides a collection of cross sections and K-factors for various production processes in proton-antiproton collisions at a center-of-mass energy sqrt(s)=1.96 TeV

- Drell-Yan, Z, W (following Hamberg et al.)
- W+jets, Z+jets, Di-boson, Higgs (from MCFM)
- W+jets, Z/gamma+jets for CAPS (from MCFM)
- Scalar Leptoquark Pair Production (NLO)
- Vector Leptoquark Pair Production (LO)

Example on the next slide

Last updated on 07/12/04 by Thomas Nunnemann

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➔ Need help from theorists on signal and bkgd. calculations at higher orders
  - Cross sections, kinematics, uncertainties
  - Provide a standard on these for both experiments

Cross sections for reference processes (2)

MCFM Cross Sections

LO/NLO cross sections calculated using MCFM (v3.4.5) with CTEQ5L (for LO) and CTEQ5M (for NLO).
Drell-Yan processes with full fermion couplings and masses between 50 GeV -- 200 GeV.

Process	Scale	Cut	sigma(LO) [pb]	Error [pb]	sigma(NLO) [pb]	Error [pb]	K-factor	Error on K
W(e+nu)	sqrt(M_W^2+p_T(W)^2)	No	1020.955	0.323	1384.495	0.526	1.356	0.001
Wj (e+nu)	sqrt(M_W^2+p_T(W)^2)	1	346.968	0.271	413.043	0.644	1.190	0.002
Wjj (e+nu)	sqrt(M_W^2+p_T(W)^2)	1	90.168	0.126	135.180	0.844	1.499	0.005
Wbb (e+nu)	sqrt(M_W^2+p_T(W)^2)	1	0.883	0.003	1.925	0.010	2.179	0.004
Wbb (massive ME)	sqrt(M_W^2+p_T(W)^2)	1	0.743	0.002				
Z (e+e-)	sqrt(M_Z^2+p_T(Z)^2)	No	197.111	0.071	266.190	0.111	1.350	0.001
Zj (e+e-)		1	70.039	0.057	82.637	0.124	1.180	0.002
Zjj (e+e-)		1	18.276	0.025	26.543	0.399	1.452	0.011
Zbb (e+e-)		1	0.267	0.001	0.616	0.002	2.305	0.003
Zbb (massive ME)	sqrt(M_Z^2+p_T(Z)^2)	1	0.230	0.001				
W+W- (no BR)	2M_W	No	8.137	0.011	11.521	0.016	1.416	0.002

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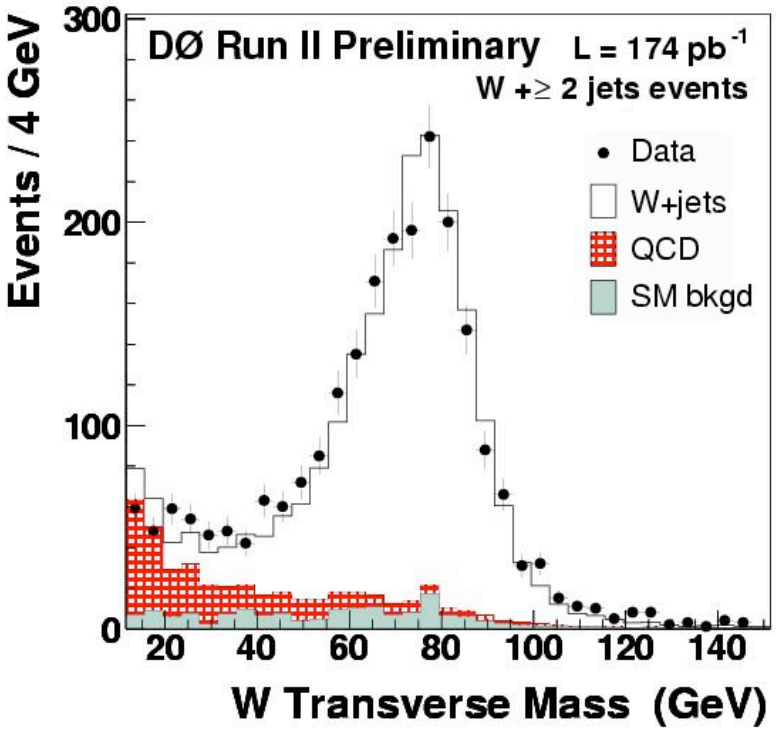
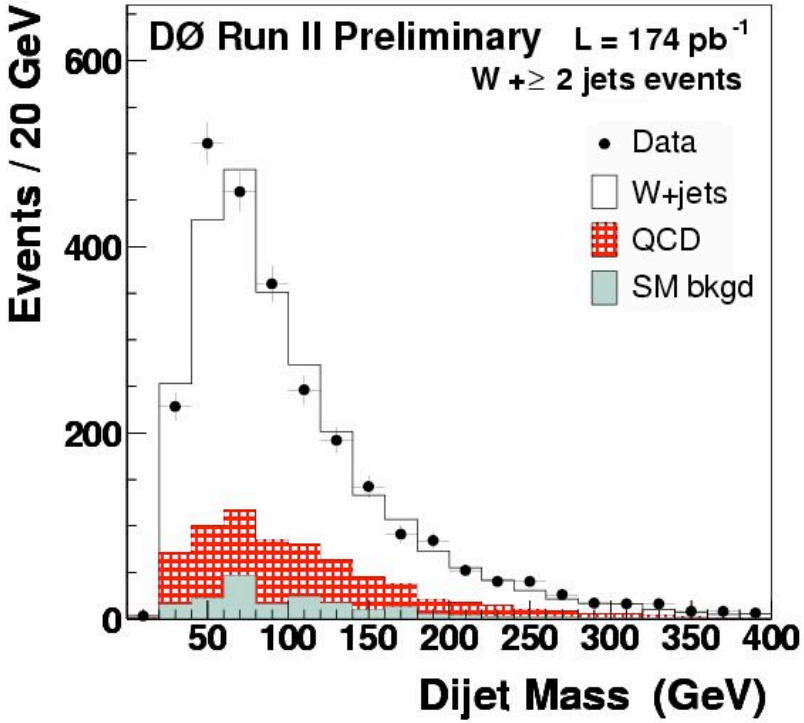
W(→eν)+jets associated production

- Event selection include
  - Central isolated e, $p_T > 20$ GeV
  - Missing $E_T > 25$ GeV
  - ≥ two jets: $E_T > 20$ GeV, $|\eta| < 2.5$

Details in K.Hanagaki's talk at Higgs session





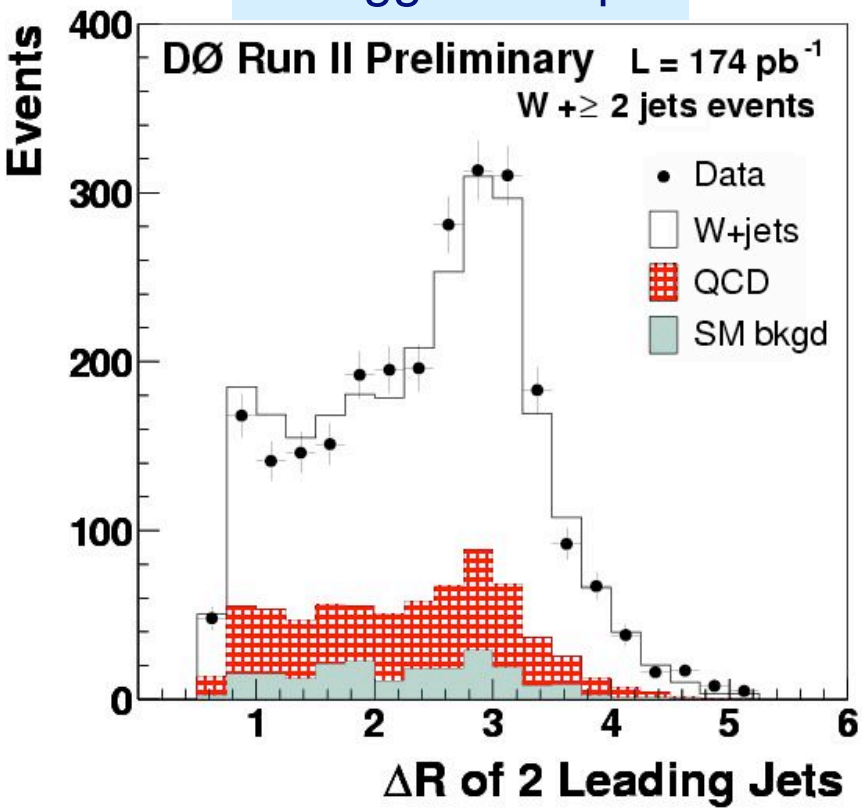
- Simulations with Alpgen plus Pythia through detailed detector response
- Cross sections normalized to MCFM NLO calculations

Good understanding of data

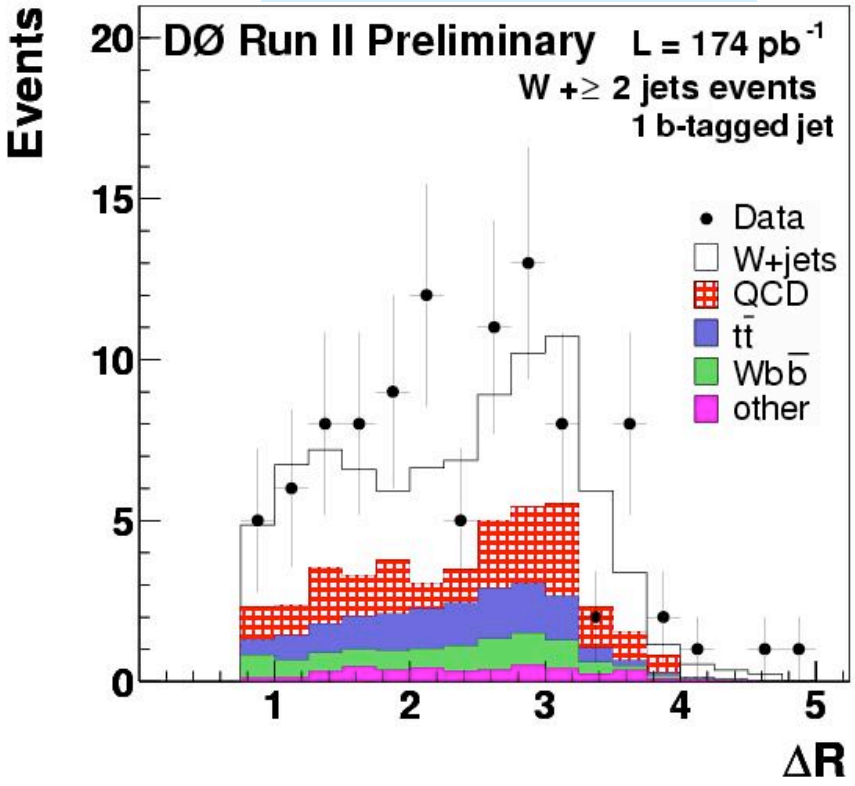
W(→eν)+jets/bb associated production

- Correlations between leading two jets in ΔR – a measure of distance in η–φ space
  - Sensitive to parton radiation processes
  - Reduced sensitivity to jet energy scale

Untagged sample



Sample with at least one b-tagged jet

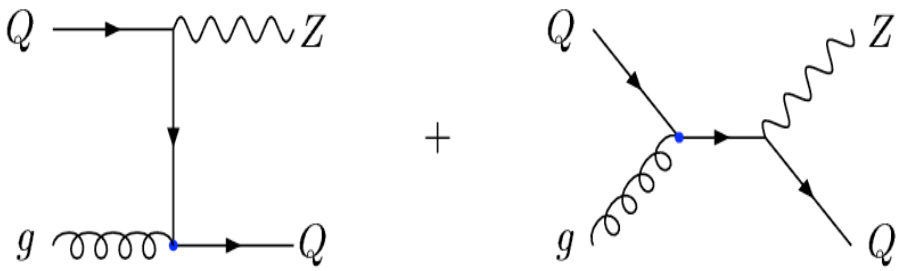


- Several processes "show up"

Again, good agreement between data and MC

Z(→ee/μμ)b associated production

- Motivation
  - Background to ZH production
  - Benchmark for SUSY Higgs boson production via gb→bh
  - Probes PDF of the b-quark
- Examples of ZQ (Zj) LO diagrams



- Measure cross section ratio
  - **σ(Z+b)/σ(Z+j)**
  - Many uncertainties cancel

- Data correspond to integrated lumi. of 184 (ee), 152 (μμ) pb^{-1}
- Event selection include
  - Isolated e/μ: p_T>15/20 GeV, |η|<2.5/2.0
  - Jet E_T > 20 GeV, |η| < 2.5
  - At least one b-tagged jet
- Simulations performed with Pythia or Alpgen plus Pythia passed
- Cross sections normalized to data
- Relative b- and c-quark content as given by MCFM NLO calculations
- Result: $0.024 \pm 0.005\ (\text{stat})\ ^{+\ 0.005}_{-\ 0.004}\ (\text{syst})$
- Prediction: ~ 0.02

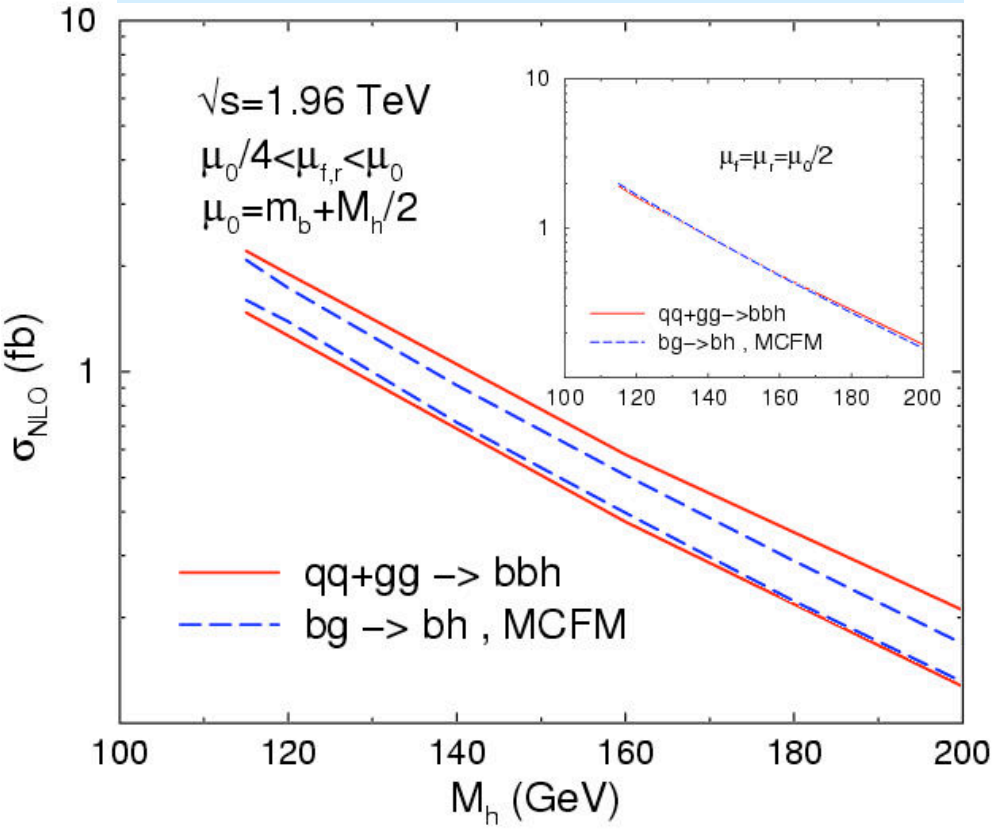
  J.Campbell, R.K.Ellis, F.Maltoni, S.Willenbrock, Phys.Rev.D69 (2004) 074021

Details of analysis in Higgs session

b(b)h production

- Have many commonalities with bZ production sub-processes
- Current theoretical uncertainty on bh production cross section at NLO is ~ 50% for M_h~120 GeV (from scale variation) plus uncertainty due to PDF
- In setting limits on SUSY Higgs production, this is by far the dominant contributing factor
  - Experimental systematics < 25%
- How useful are our Zb/Zj ratio measurement in reducing error on σ_{bh} ?
  - What is the accuracy needed to measure, e.g. Zb/Zj, to reduce the $\delta(\sigma_{bh})$ down to ~ 20% ?

b(b)h production cross section at NLO



From hep-ph/0408077 by S.Dawson, C.B.Jackson, L.Reina, D.Wackeroth

Summary

- QCD related issues arise in almost every analysis
- New results are obtained on di-jet angular correlations
- Zb/Zj cross section ratio – first of its kind measurement
- Several high priority issues have been raised to be considered by the community
- Steady progress overall in our understanding of data and various QCD phenomena