Hard QCD Results with Jets @ CDF

Christina Mesropian

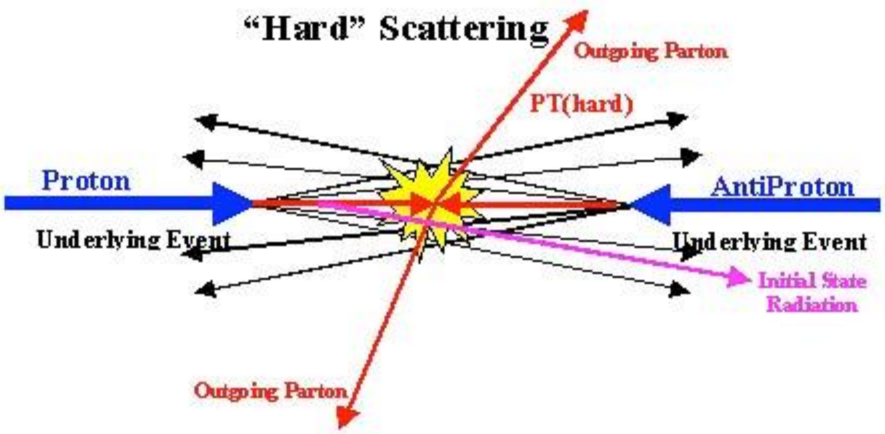
The Rockefeller University

Introduction

- **Mature QCD studies at the Tevatron benefit physics program at the LHC**
  - Challenging measurements, sensitive to (N)NLO effects as well as non-perturbative physics

- **Almost any new physics involves QCD**
  - Parton Distribution Functions (PDFs) for background and signal processes
  - QCD often a dominant background to new physics
  - e.g. diphotons for Higgs discovery, jet substructure for boosted Higgs, etc.

- **Better understanding of QCD means improved sensitivity to new physics**

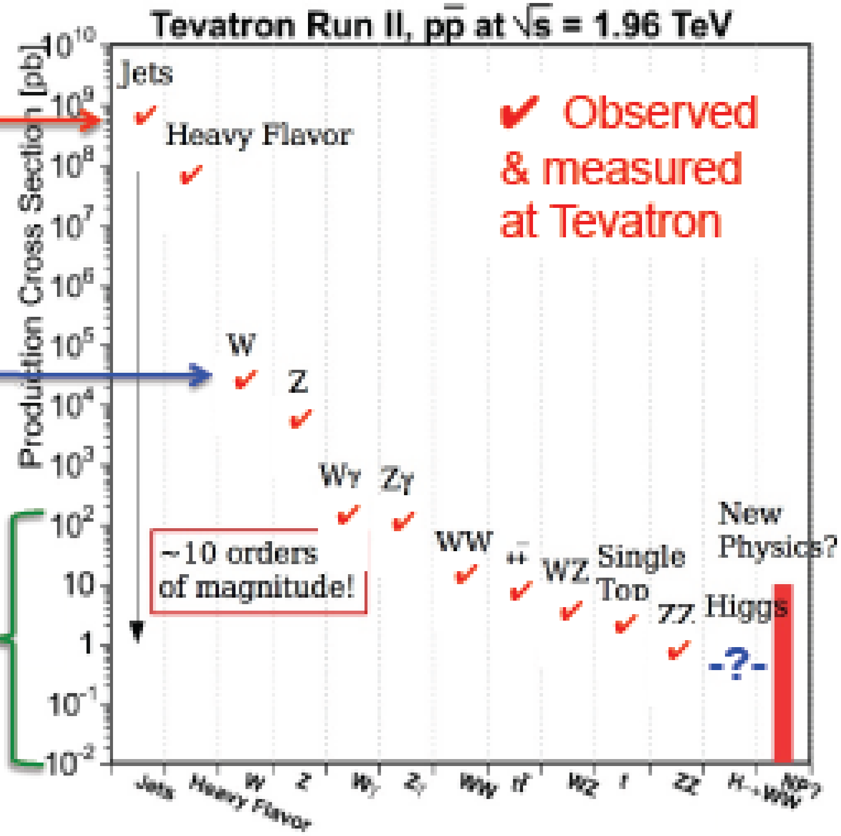


SM Processes at the Tevatron

QCD jets

Inclusive
W production:
10-15% is W+jets

Dibosons,
t-quark, Higgs,
New Physics?



Contents

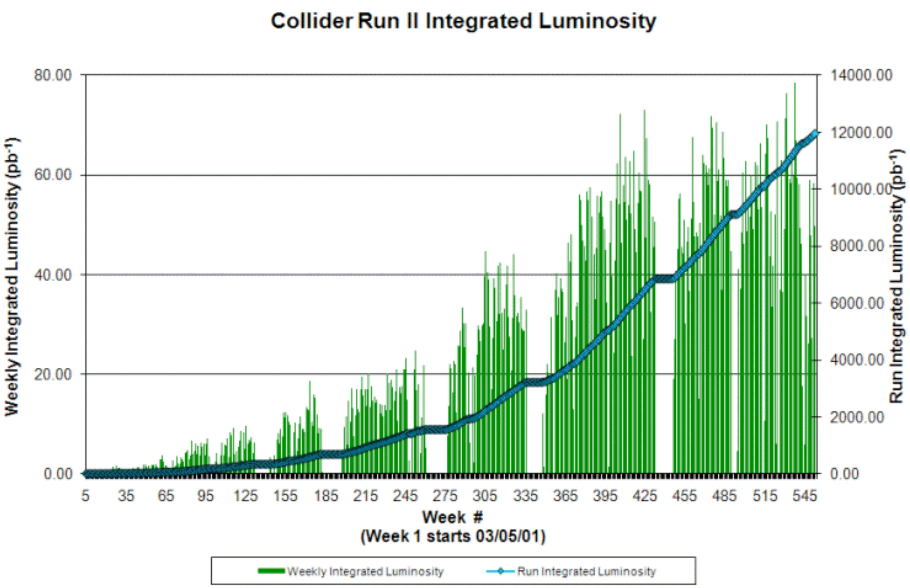
1. **Jets**
   - Incl.jets
   - Dijets
   - Jet substructure studies
2. **VB+jets**
   - W+jets
   - Z+jets
3. **VB+HF**
   - W+b
   - W+c
   - Z+b
4. **Diffraction**
   - *see talk by Dino Goulianos yesterday*

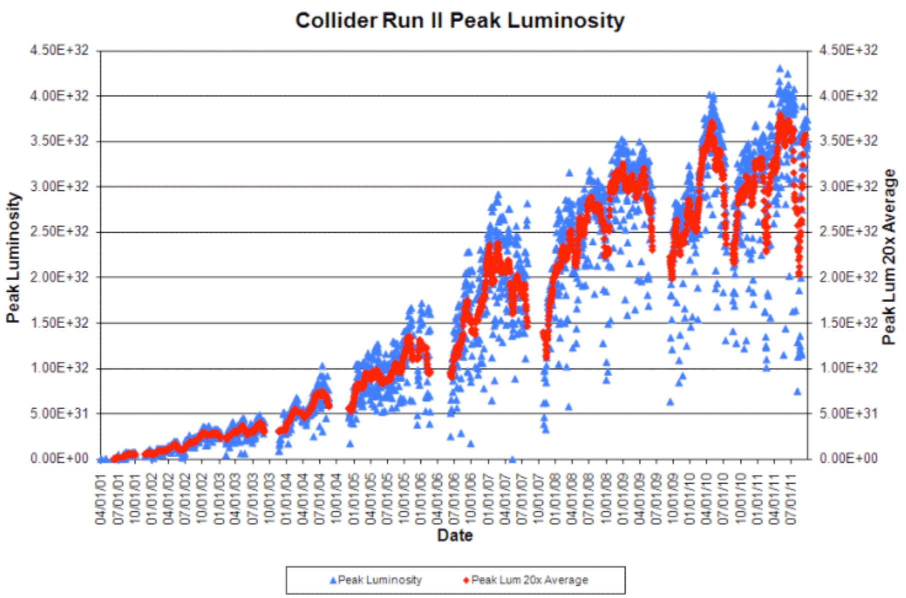
The Tevatron

p-pbar Collisions at $\sqrt{s}$=1.96 TeV

Tevatron Performance

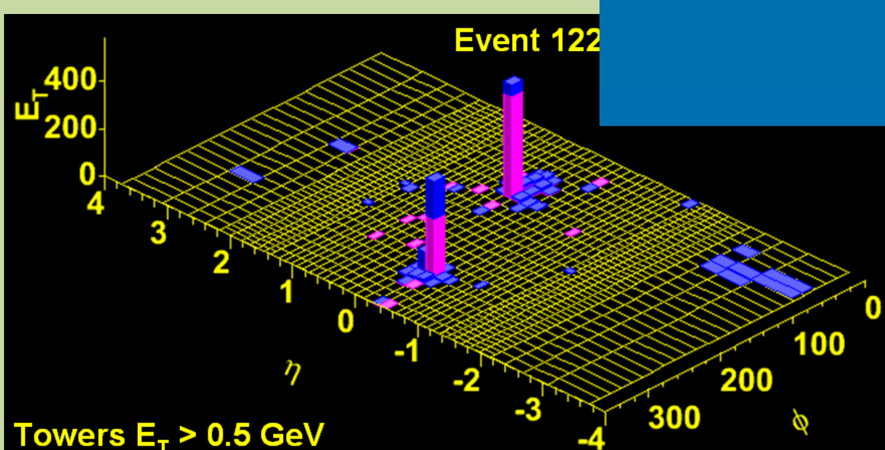
Run II ended September 30th, 2011

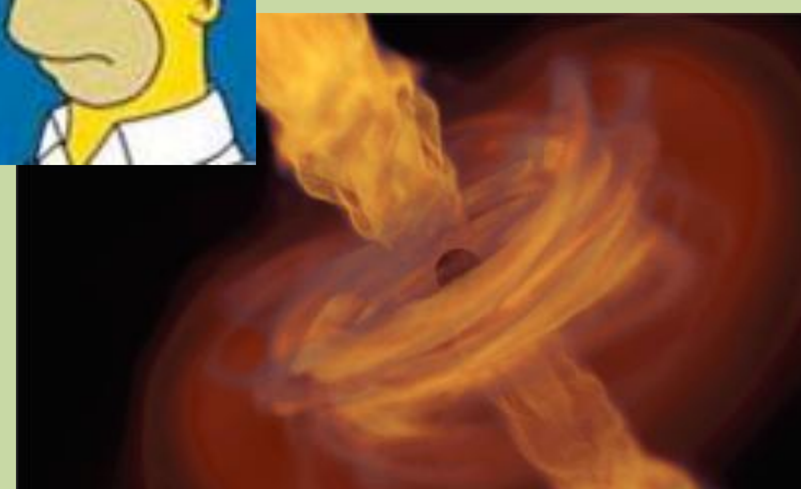




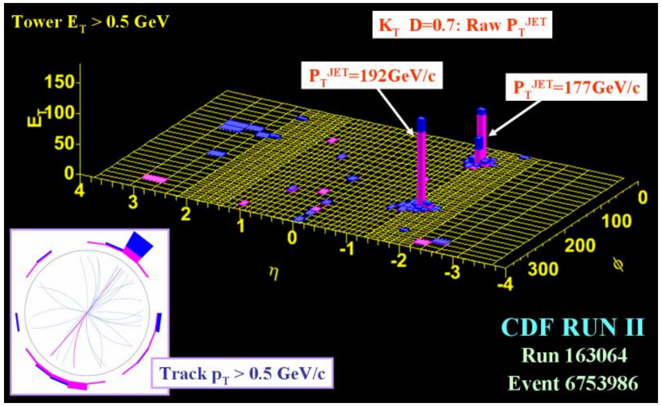
- Delivered 12 fb^{-1}
- Peak 4.3×10^{32} $cm^{-2}s^{-1}$
- By comparison, Run I delivered 120 pb^{-1}


Which one is a jet at the Tevatron?

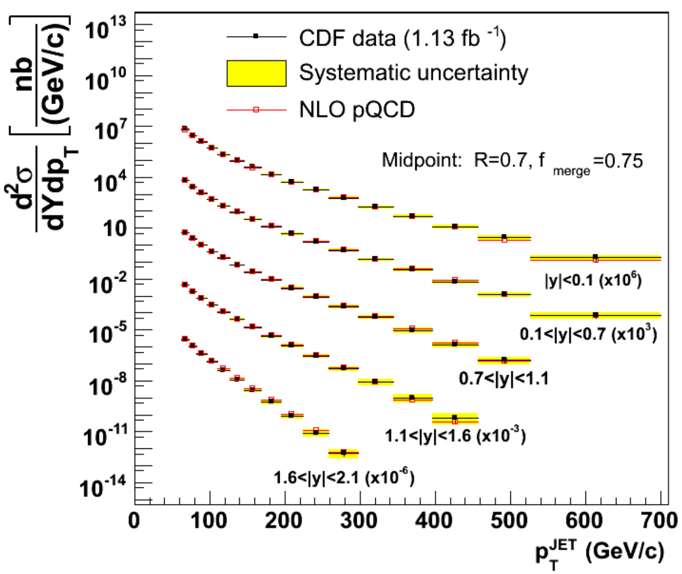

Event 122
E_T
400
200
0
4
3
2
1
0
-1
-2
-3
-4
η
0
100
200
300
ϕ
Towers E_T > 0.5 GeV

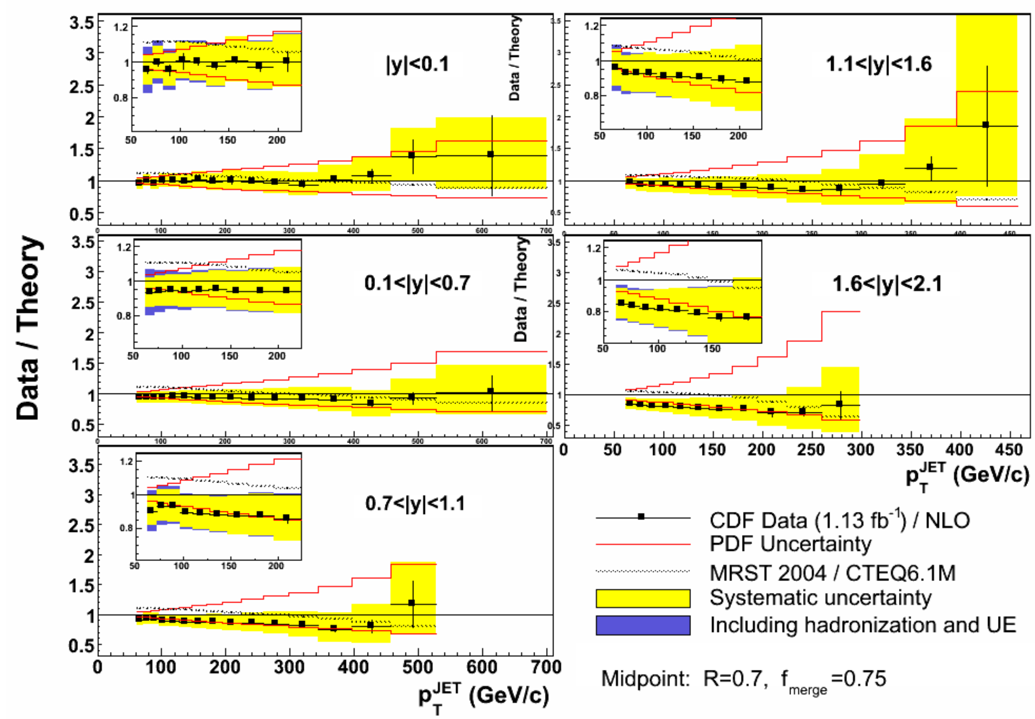


Inclusive Jet Cross Section



PRD 78, 052006 (2008)

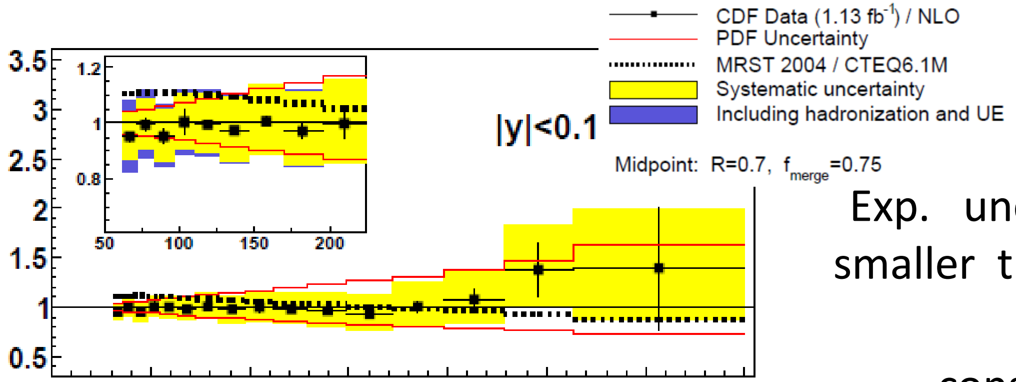




- Tests pQCD over 8 orders of magnitude
- highest p_T >600 GeV/c
- Measurements were done with 2 different clustering algorithms: Midpoint cone and k_T

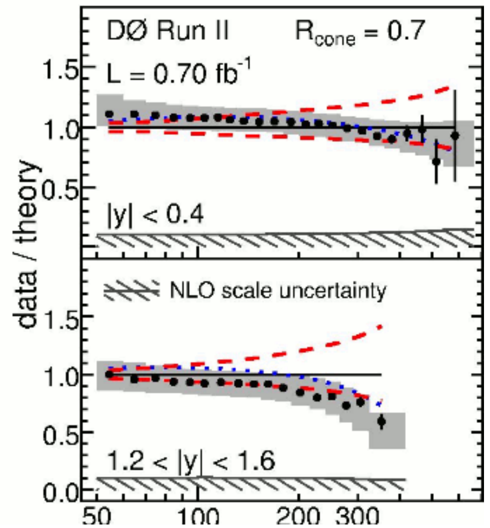
Jet production –Precision regime

PDF input

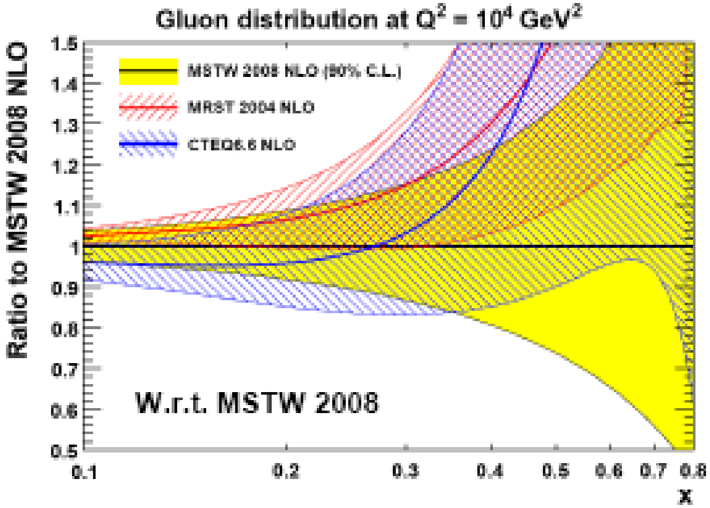


Exp. uncertainties are smaller than theoretical

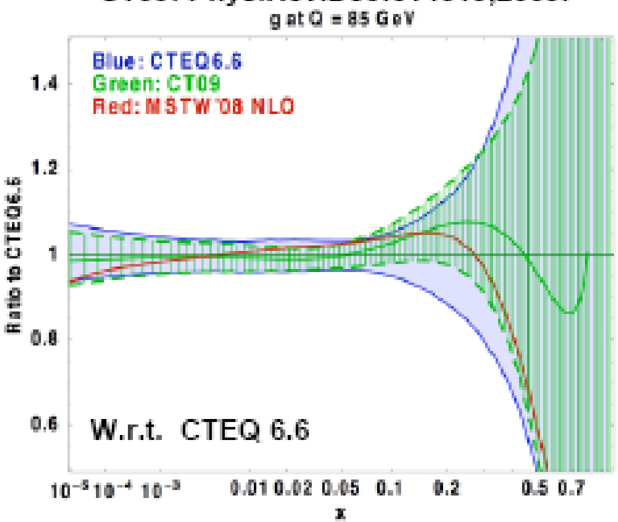
constrain PDF



MSTW08: arXiv:0901.0002, Euro. Phys. J. C

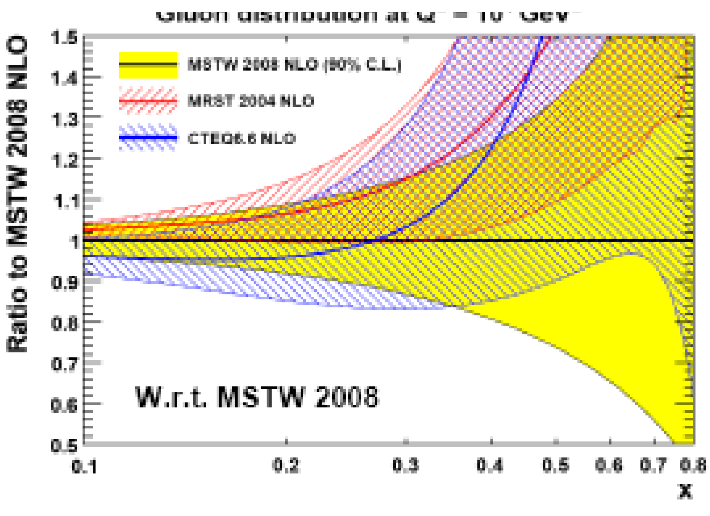


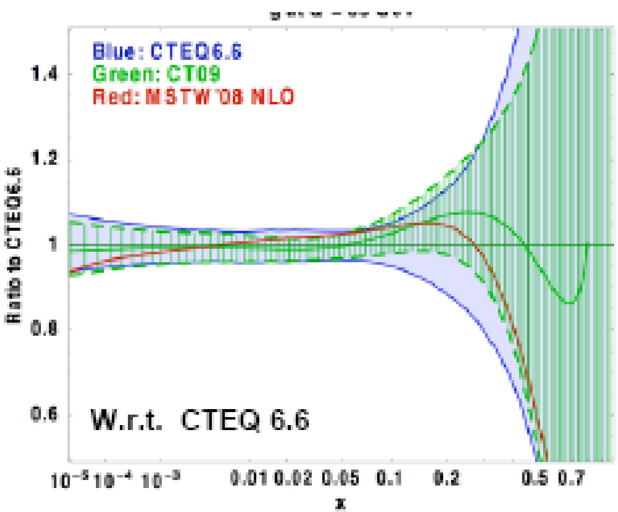
CT09: Phys.Rev.D80:014019,2009.



Jet production –Precision regime
PDF input

Conclusions from Les Houches QCD 2011:
“Tevatron jet data vital to pin down high-x gluon, giving smaller low-x gluon and therefore larger α_S in the global fit compared to a DIS-only fit.”



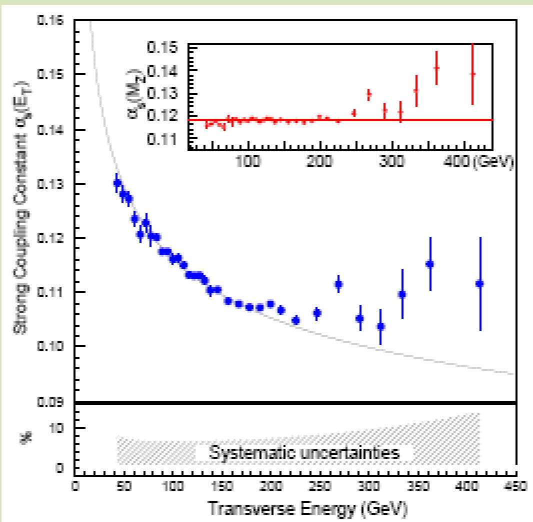


Jet production – Precision regime

α_s measurement

Historical note:

CDF Run I **Then** PRL 88:042001,2002

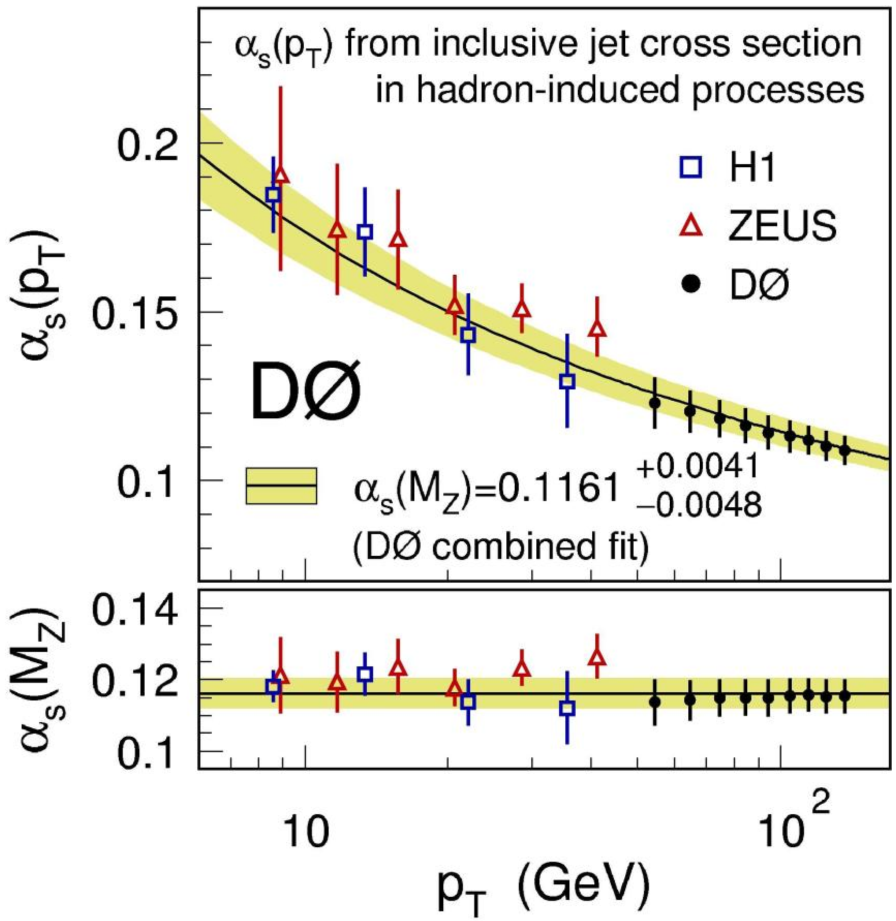


$\alpha_s(M_Z) = 0.1178 \pm 0.0001(\text{stat})^{+0.0081}_{-0.0095}(\text{syst})$

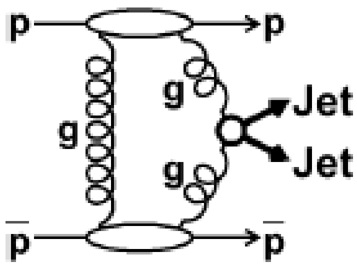
- Theory: NLO+2-loop threshold corrections
- Significantly improved precision
- Running tested to very high Q^2 values

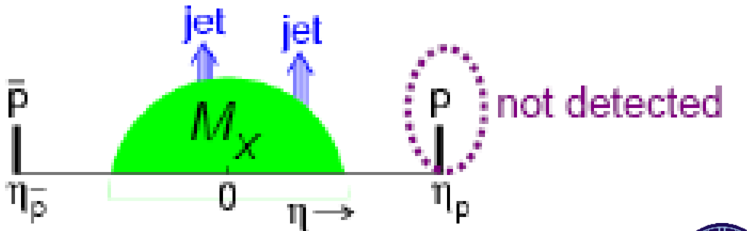
Now: $\alpha_s(M_Z) = 0.1173^{+0.0041}_{-0.0049}$

PRD 80, 111107 (2009)



Exclusive Dijet Production

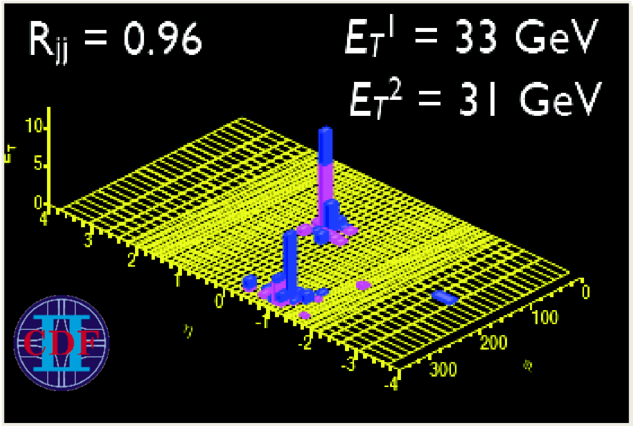


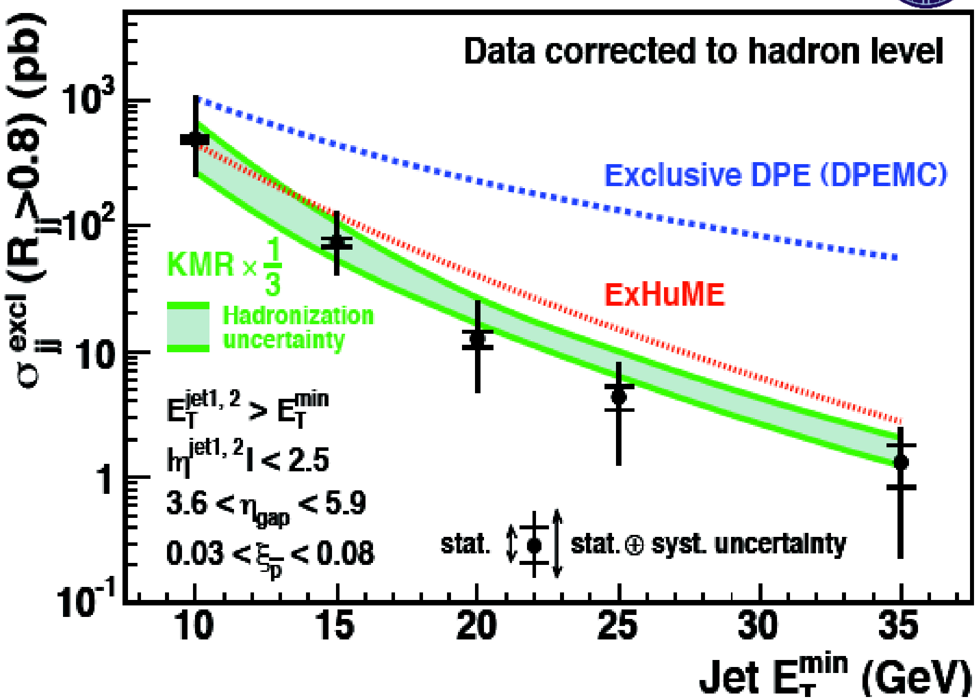


suppression at LO of the background sub-processes(J_z=0 selection rule)

"exclusive channel" →clean signal (no underlying event)

PRD 77, 052004 (2008)





Jet Substructure

MOTIVATION : **Mass of high-pT jets - important property, but only theor. studies:**

o High mass:

QCD NLO predictions for jet mass

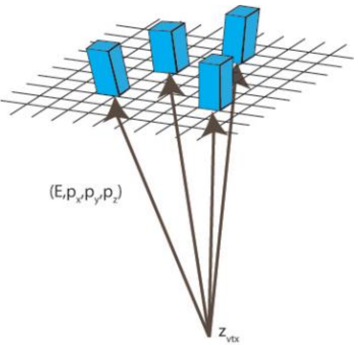
Ellis et al, 0712.2447

Alemeida, et al. 0810.0934

Such jets form significant background to new physics signals

Examples: high p_T tops, Higgs, neutralino …

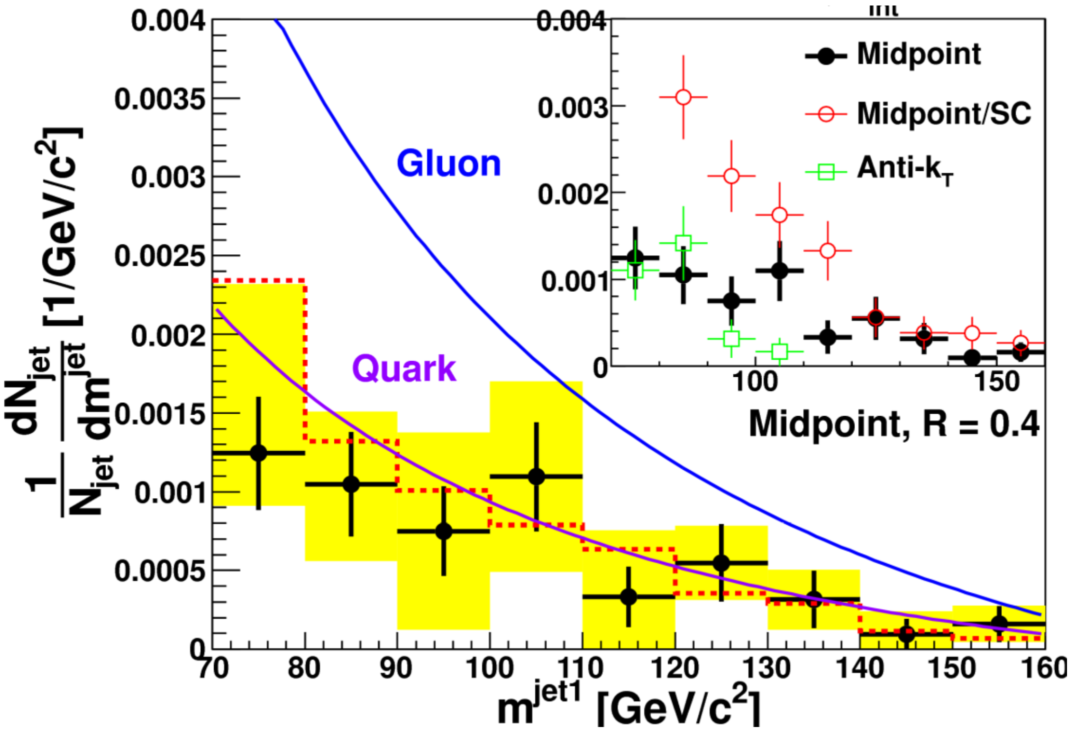
Use standard "e-scheme" for mass calculation



o 4-vector sum over towers in jet

o Each tower is a particle with m = 0

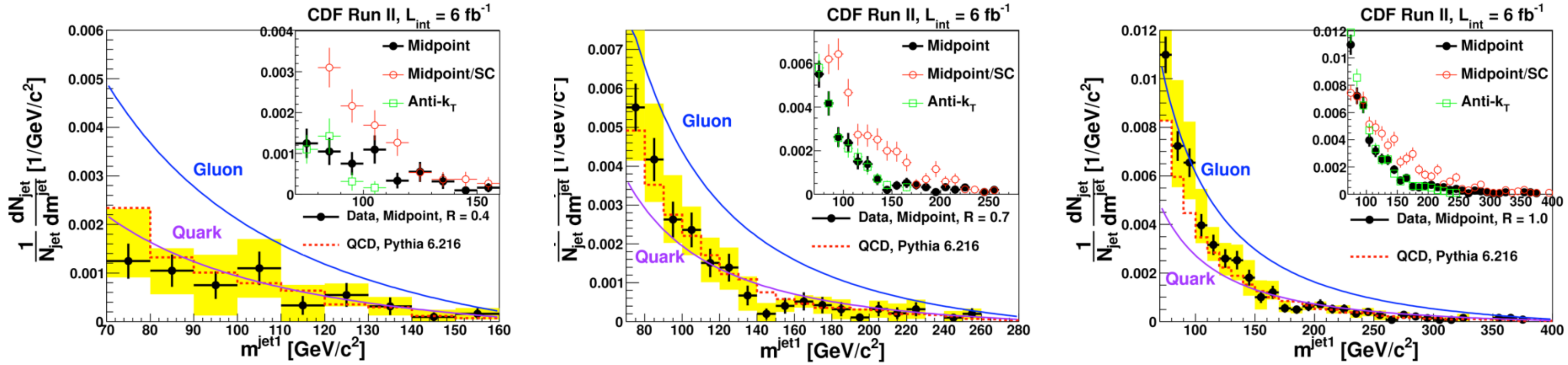
o Four vector sum gives (E,p_x,p_y,p_z)



Selection: > 1 jet
p_T>400 GeV/c
0.1<|η|<0.7

Jet Substructure
Jet Mass

- Compare differential jet cross section as a function of jet mass for different algorithms and cone sizes



- In leading-log approximation, a jet typically acquires a large mass due to a single hard gluon emission

Jet Substructure Studies: Angularity and Planar Flow

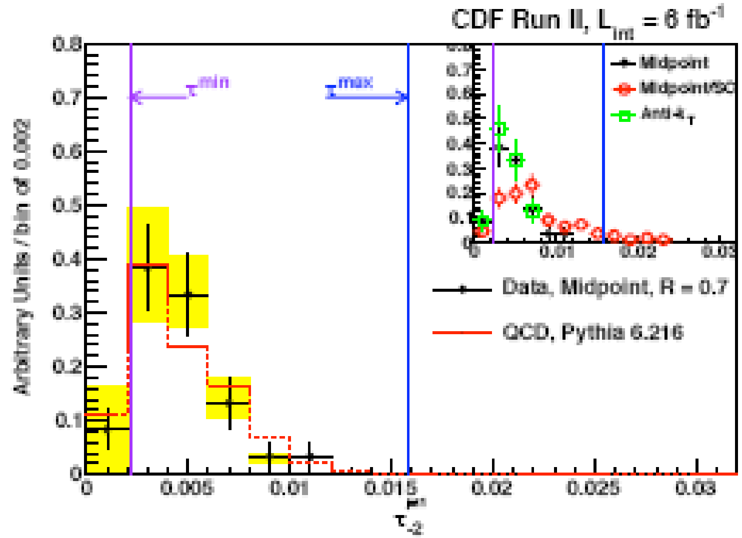
Jet substructure variables that are insensitive to soft radiation at high jet mass:

tower energy

Angularity :

$$\tau_a(R, p_T) = \frac{1}{m_J} \sum_{i \in jet} \omega_i \sin^a \vartheta_i [1 - \cos \vartheta_i]^{1-a}$$

- **Emphasizes cone-edge radiation**
- **For large m^{jet}, has analytic approximation**

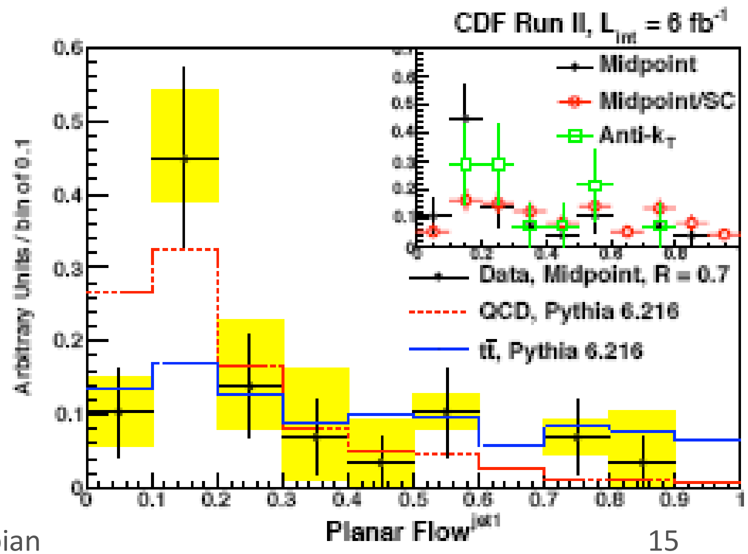


Planar flow:

- ***w_i - energy of particle I***
- **λ_1, λ_2 are eigenvalues**

$$I_w^{kl} = \frac{1}{m_{jet}} \sum_i \frac{p_{i,k}}{w_i} \frac{p_{i,l}}{w_i};$$

$$Pf \equiv \frac{4\lambda_1 \lambda_2}{(\lambda_1 + \lambda_2)^2}$$



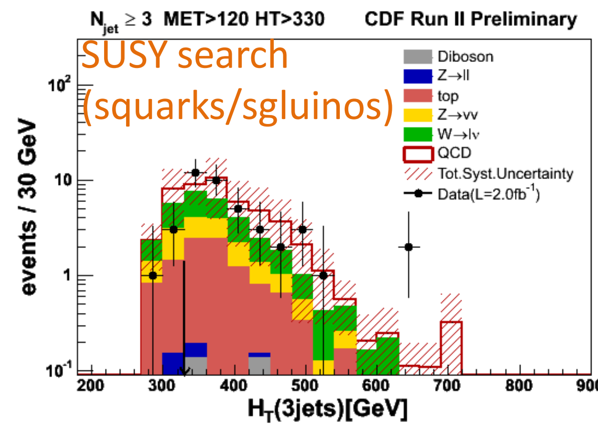
V + Jets Studies

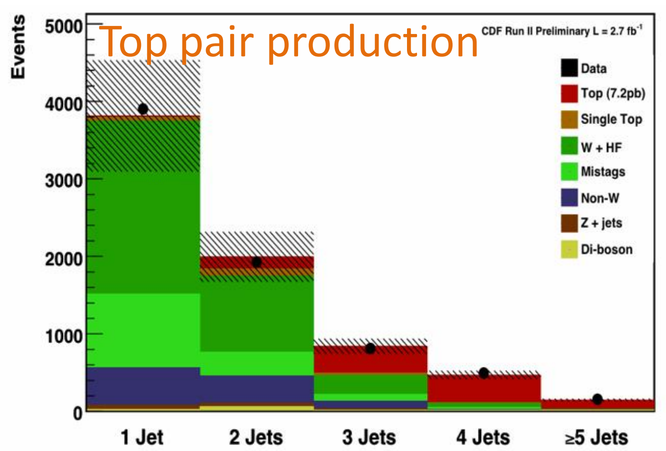
MOTIVATION:

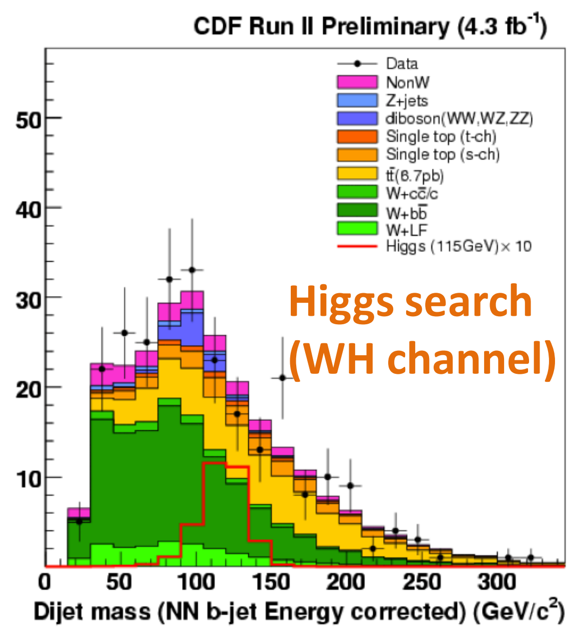
V + Jets Processes in many cases are in irreducible backgrounds in searches for new physics

- ❑ 30% - 40% uncertainty in some of the processes (boson + HF)

Need dedicated measurements on boson+jets

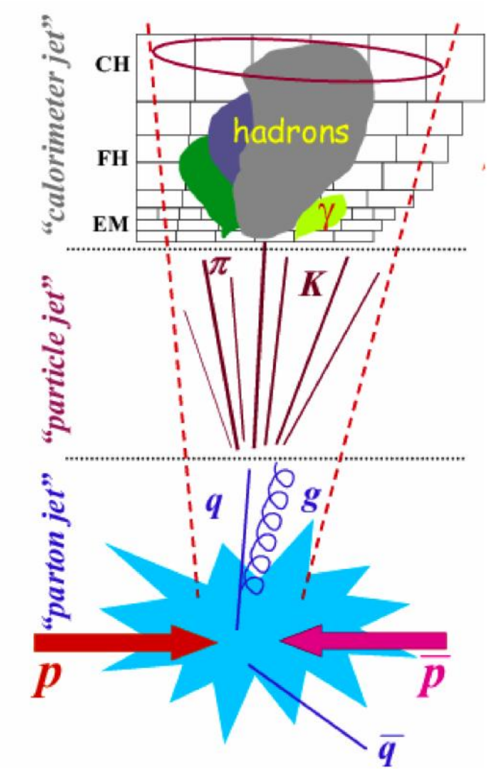






$Z/\gamma^* \rightarrow l^+l^-$ +jets

Measurement in the Z → e^+e^- channel published in PRL 100, 102001 (2008) with 1.7 fb^{-1}



- Combined $Z \rightarrow e^+ e^-$ and $Z \rightarrow \mu^+ \mu^-$ accounting for correlation between uncertainties
- **Results updated with $\mathcal{L}$ = 8 fb^{-1}**

Measurements are unfolded back to Hadron level

Differential distributions in Z + ≥3 jets final state

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

Data driven backgrounds

- QCD multi-jet
- W + jet

MC backgrounds

- Z + γ
- Top
- Diboson
- Z → ττ+ jets

Z Kinematic region

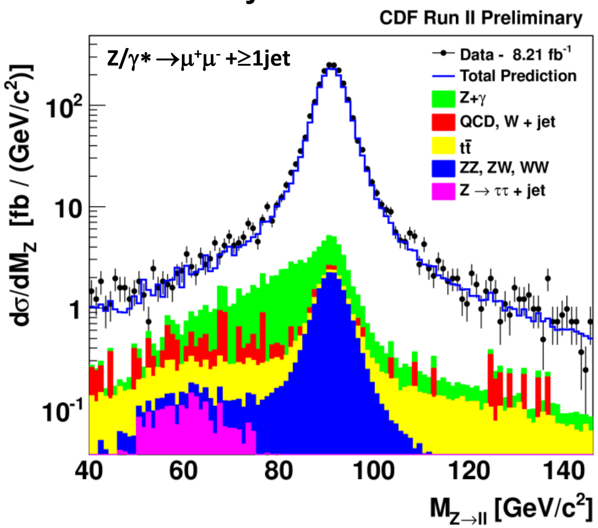
$66 < M_Z < 116$ GeV/c²

$E_T^l > 25$ GeV/c, $|\eta^l| < 1$

Jet selection

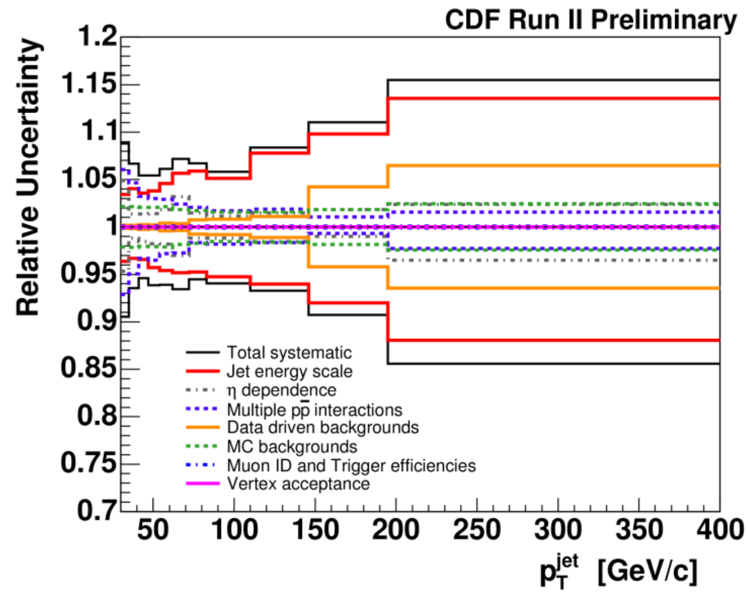
MIDPOINT R=0.7 jet

$p_T > 30$ GeV/c, $|Y| < 2.1$



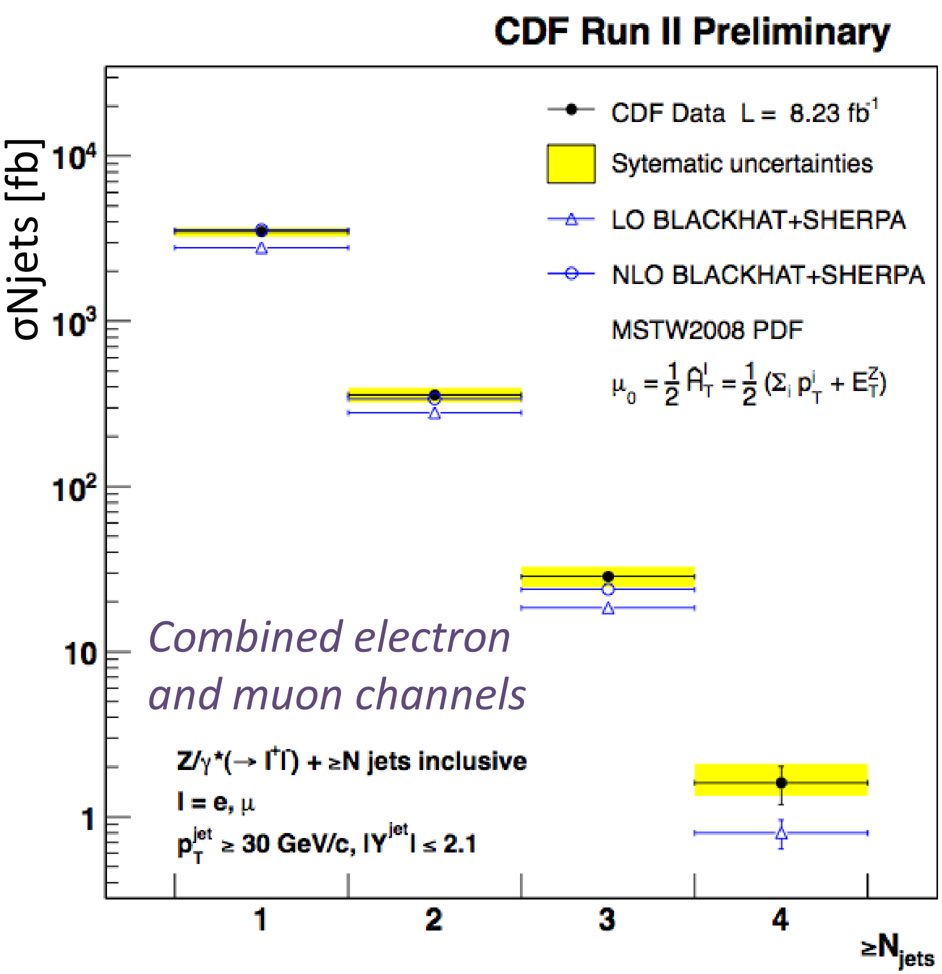
5% to 15% syst. uncertainties

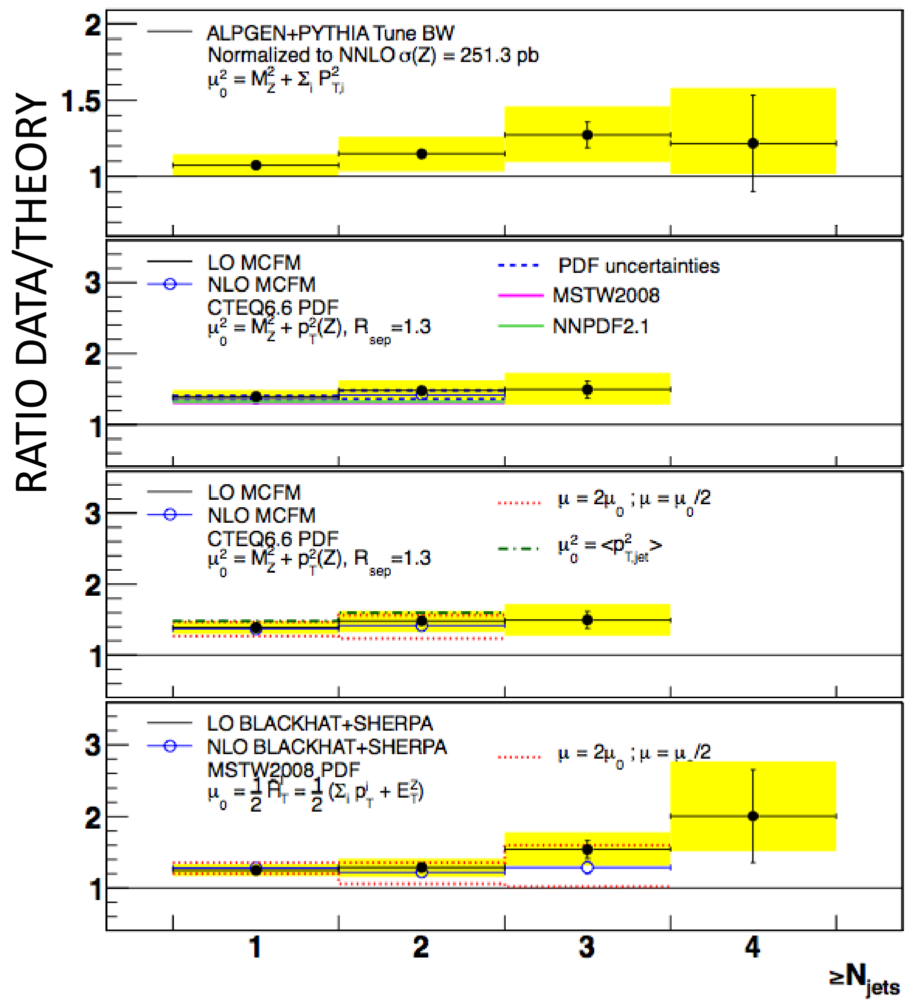
Jet Energy Scale is the dominant



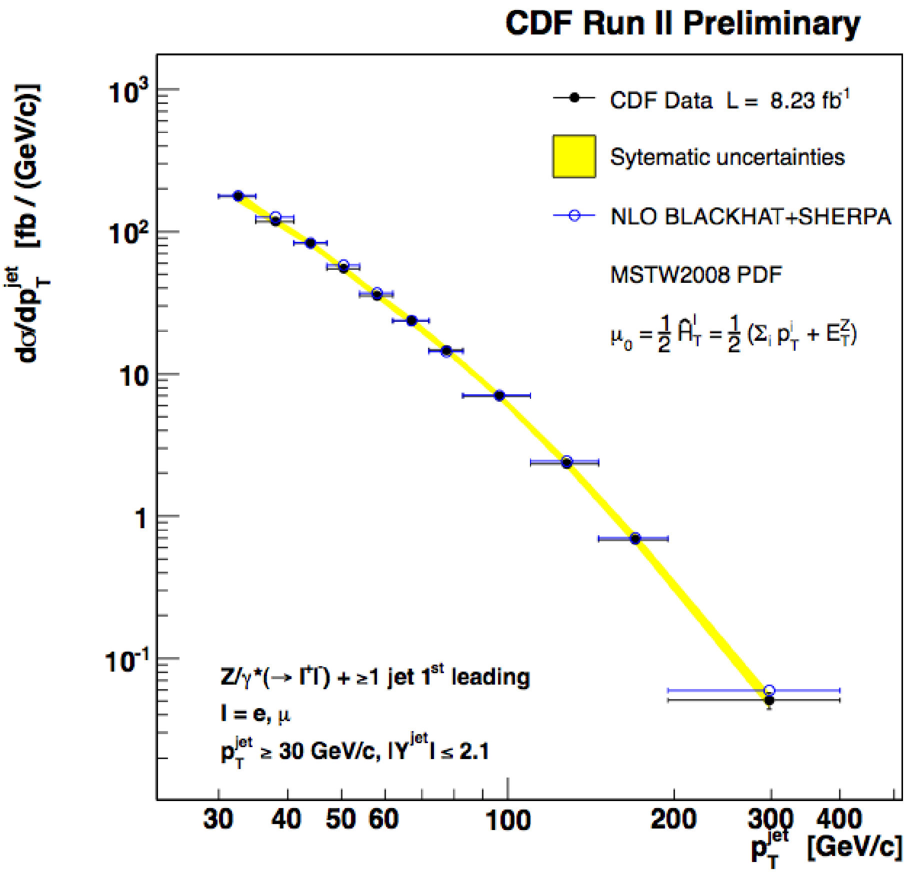
- **Total backgrounds between 5%-10%**
- **Main background is Z+γ**

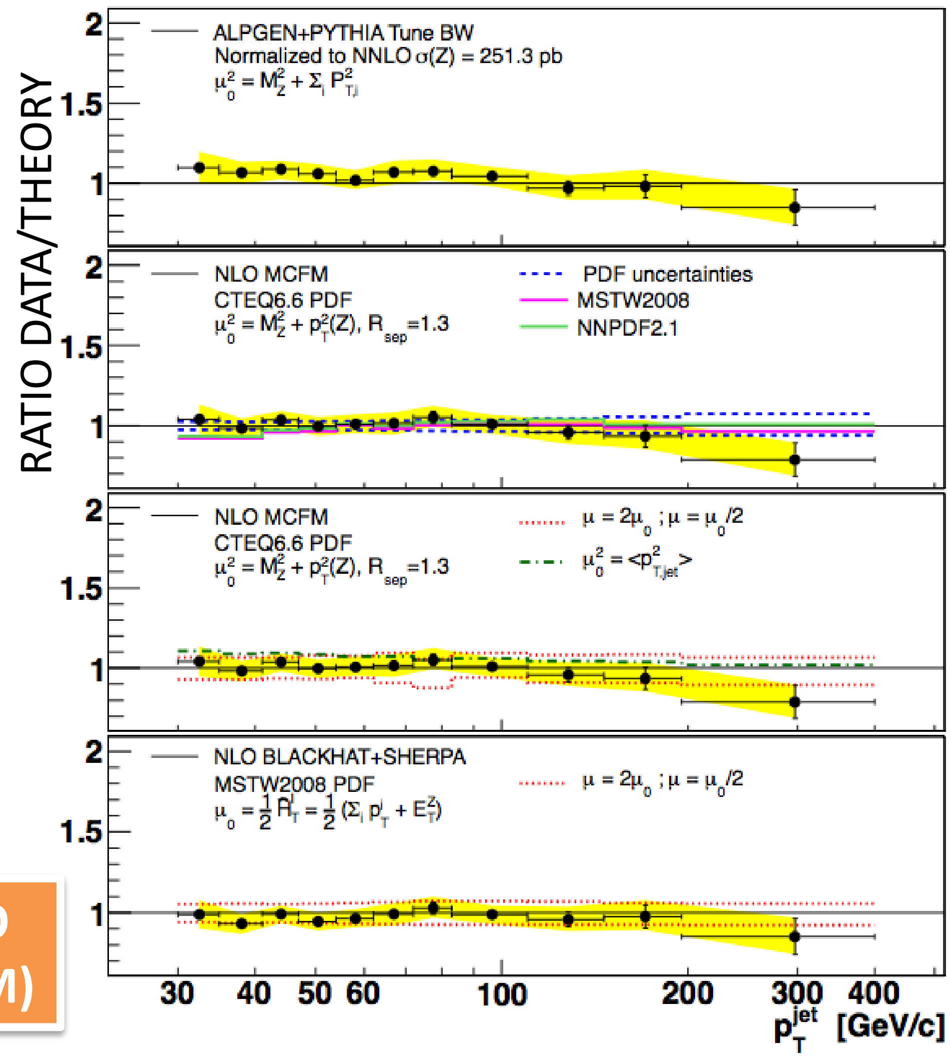
$Z/\gamma^* \rightarrow l^+l^-$ +jets





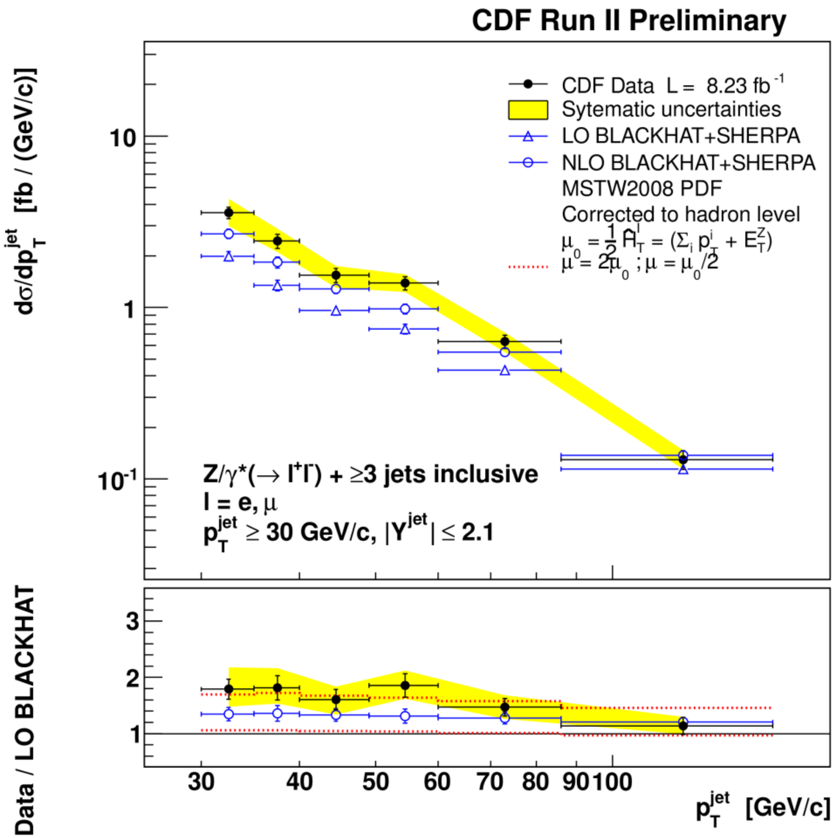
$Z/\gamma^{*} \rightarrow l^{+}l^{-}$ +jets

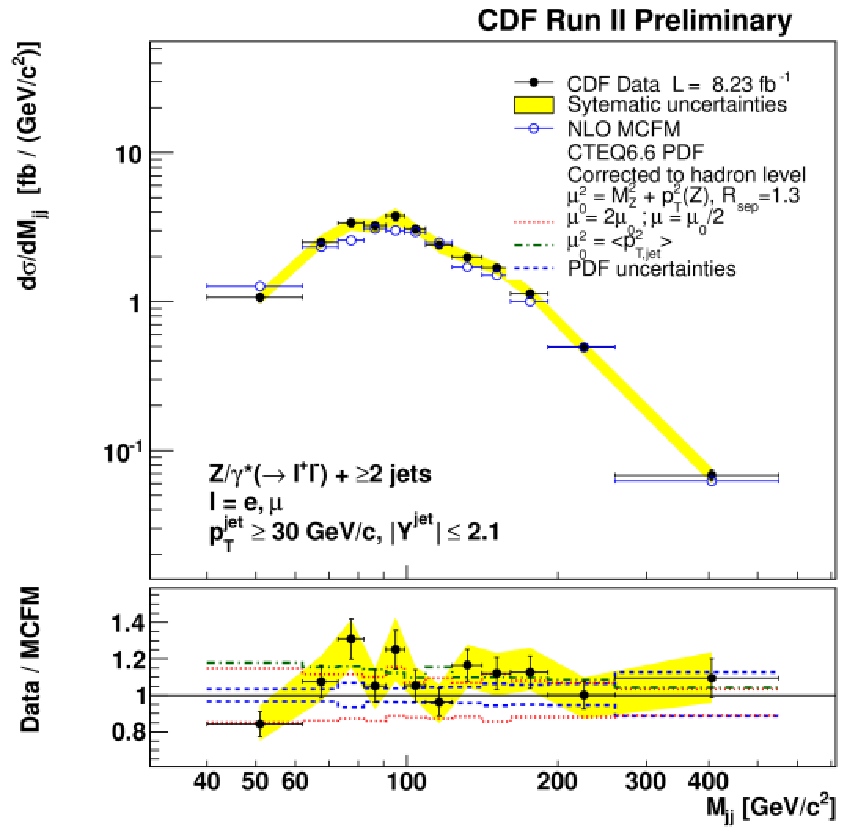




Good agreement between data and NLO pQCD predictions (BLACKHAT and MCFM)

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



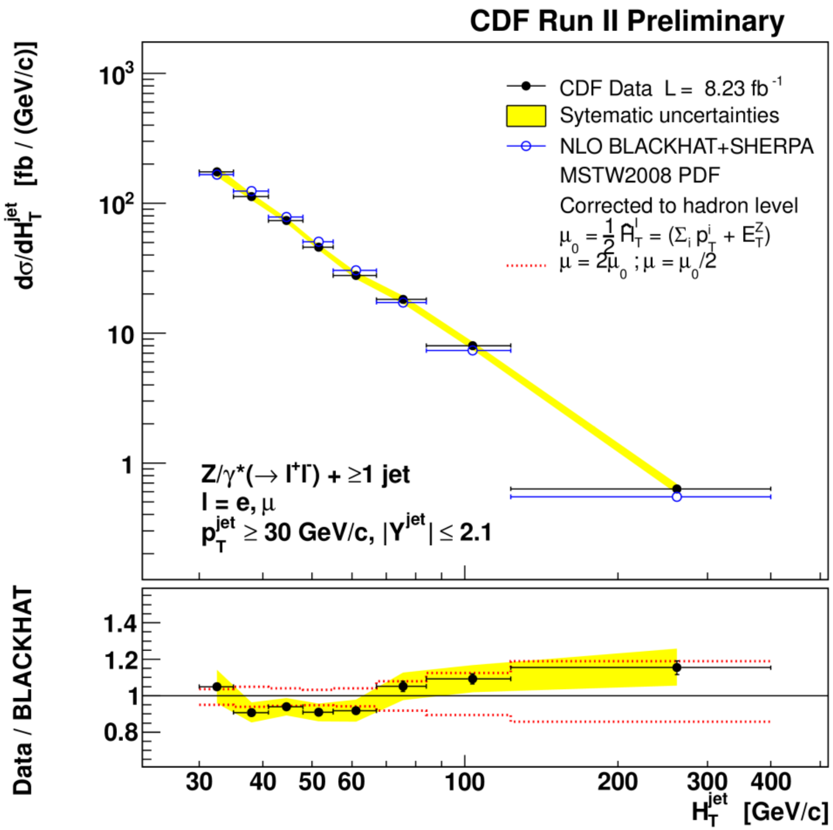


Z + ≥3 jets differential distributions compared to NLO pQCD prediction - BLACKHAT+SHERPA

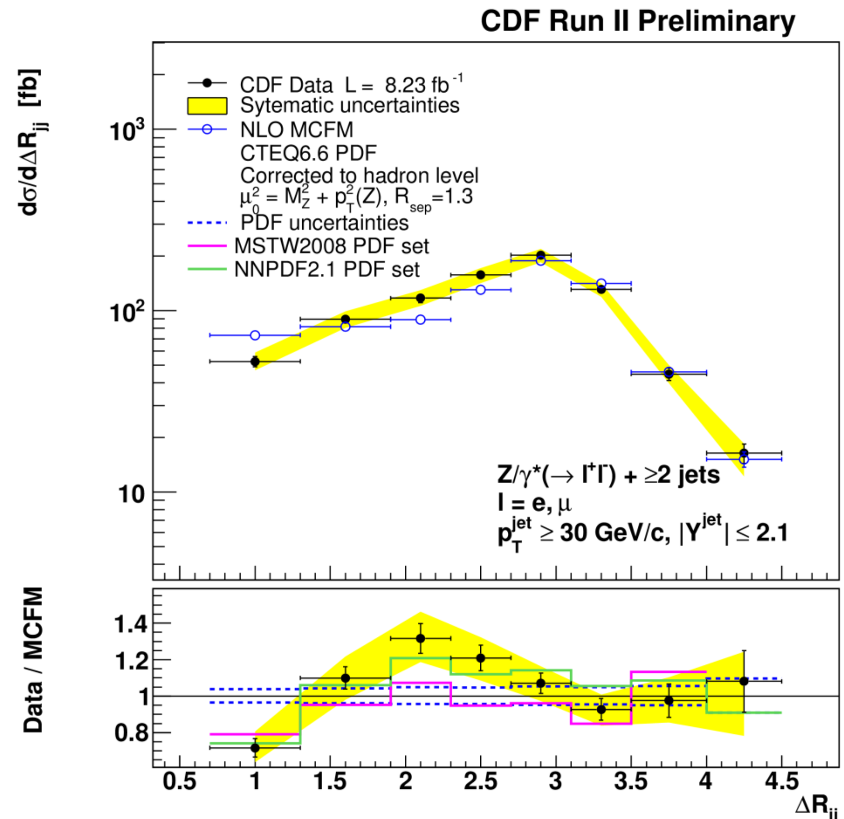
M_{jj} is sensitive to resonances production

Main uncertainty comes from fixed order calculation

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

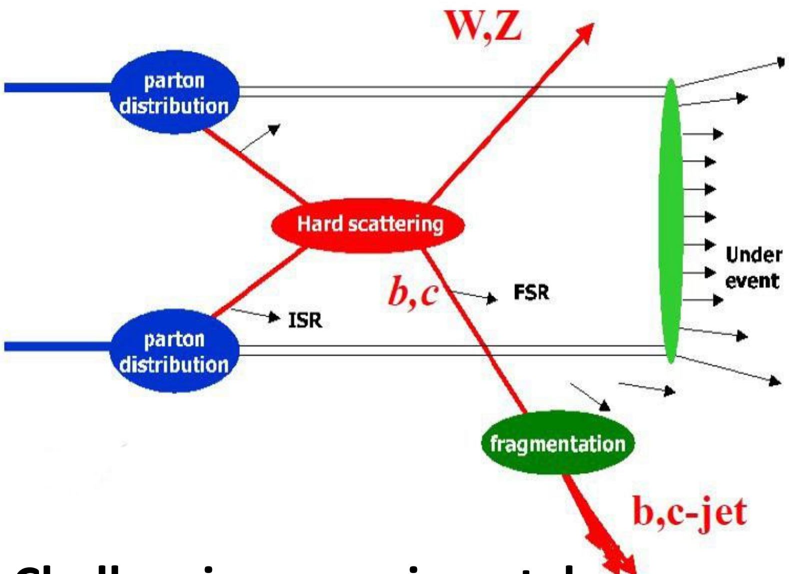


Some observables like HT(jet) are expected to have larger contribution from NNLO diagrams



Comparison with different PDF sets

W/Z + HF jets production

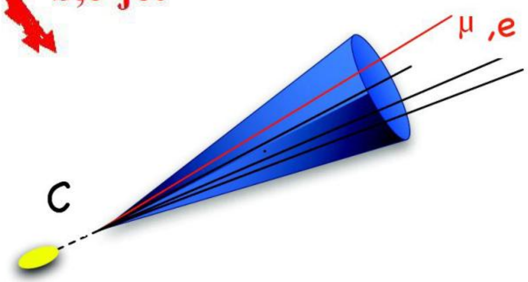


Challenging theory predictions

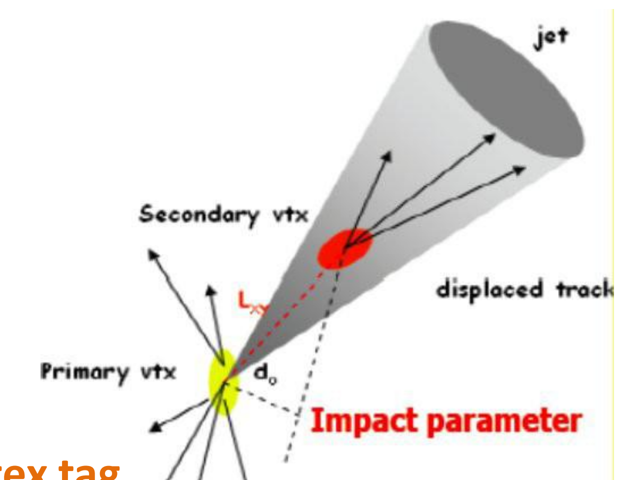
- Large variations wrt to scale choice
- PDF uncertainties at high momentum fraction x

Challenging experimental measurements

- b and c identification
- Low statistics



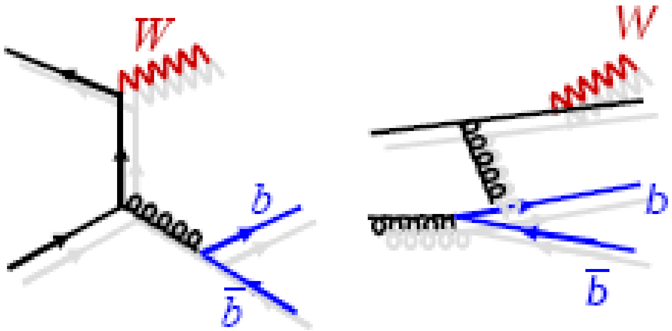
Soft Lepton tag
(20% Branching ratio)



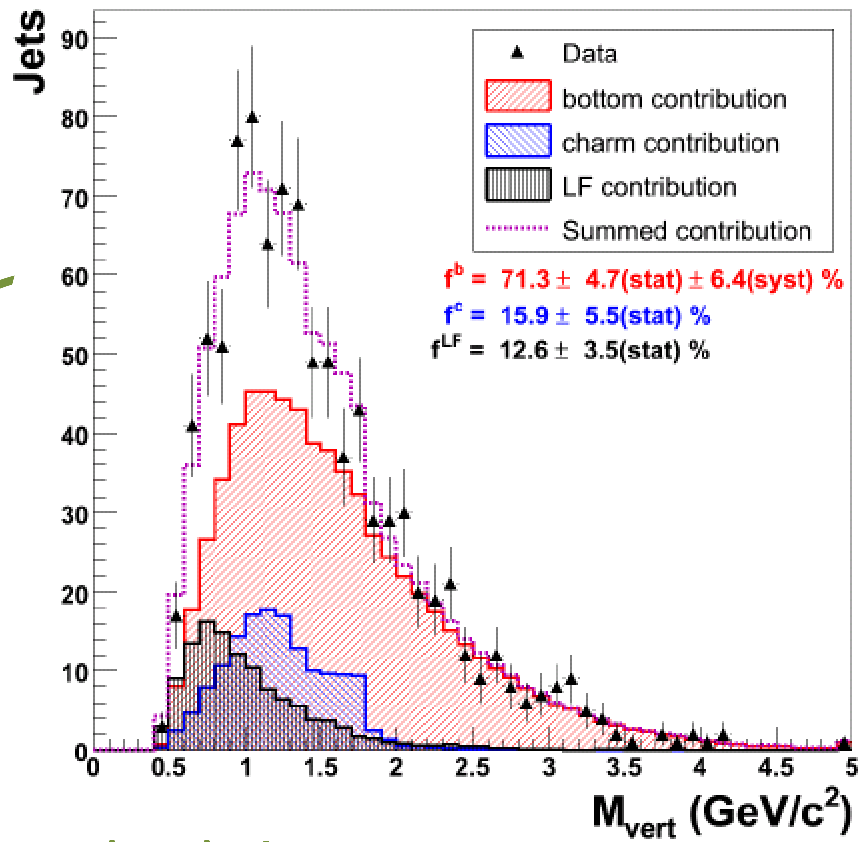
Secondary vertex tag
based on large B lifetime

W+b-Jet Production

Large background for many rare analysis



[Phys. Rev. Lett. 104, 131801 (2010)](#)



b-quark composition extracted from fit to secondary vertex mass

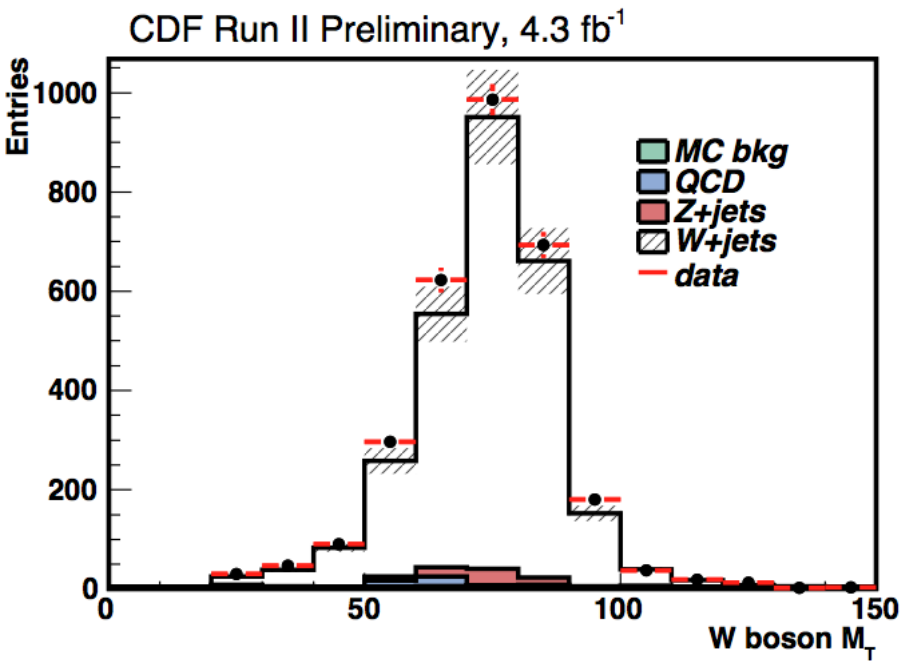
$\sigma_{(W+b\text{-}jets)} \cdot BR(W \rightarrow l\nu)$ = 2.74 ± 0.27 (stat) ± 0.42(syst) pb

NLO : 1.22±0.14 pb Alpgen: 0.78pb

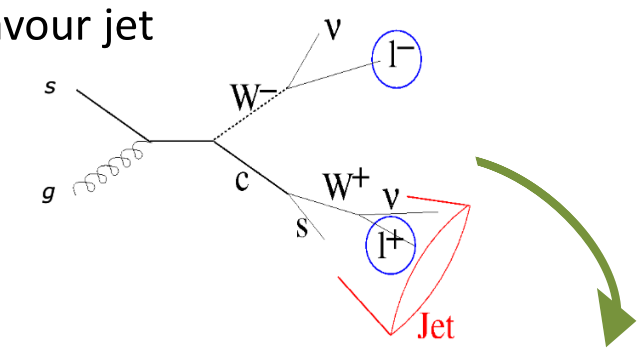
W+charm Production

Lepton	**Jet selection**
MET>25 GeV,	JETCLU R=0.4 jet
m_T(W)>20 GeV/c^2	p_T > 15 GeV/c, $\|\eta\| < 2.0$
p_T^l > 25 GeV/c, $\|\eta^l\| < 1$	

Measurement of W+c production: sensitive to s-quark PDF; background to single-top and associated WH production



Select events with semi-leptonic W + one jet
Use soft lepton tagging (SLT) to identify heavy-flavour jet



Exploit opposite charge correlation between W lepton and SLT lepton

$$\sigma_{Wc} \times \mathrm{BR}(W \to \ell\nu) = \frac{N_{\mathrm{tot}}^{OS-SS} - N_{\mathrm{bkg}}^{OS-SS}}{Acc \cdot \int L\, \mathrm{d}t}$$

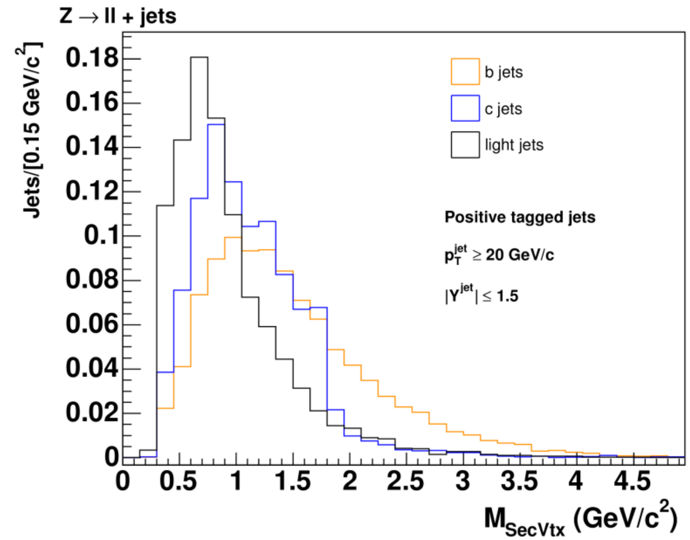
SLT_e = 13.4 ±2.3 (stat) ±2.4 (syst) ±1.1 (lumi) pb
SLT_μ = 14.2 ±6.5 (stat) ±3.4 (syst) ±1.2 (lumi) pb

Combination:= 13.3 +3.3- 2.9 (stat+syst) pb
NLO prediction = 11.3 ±2.2 pb

Z+b jets

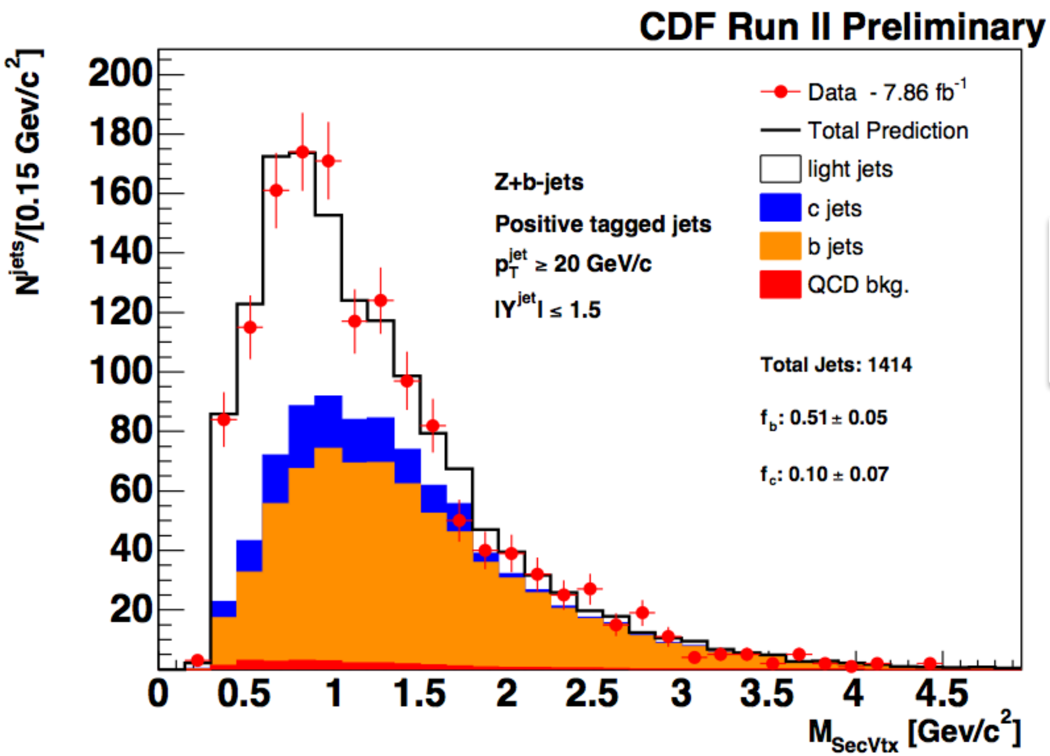
Test of pQCD calculations and b-quark fragmentation, b-quark PDF
Z+b important background to single-top, ZH, new phenomena

- Measure cross section ratio with respect to Z inclusive and Z+jet
- Z decays leptonically in muons or electrons
- Improved muon identification efficiency obtaining a 30% gain in Z acceptance



Z Kinematic region	Jet selection	B identification:
$66 < M_Z < 116$ GeV/c^2	MIDPOINT R=0.7 jet	Secondary Vertex Tagger
$E_T^l > 25$ GeV/c, $\lvert\eta^l\rvert < 1$	$p_T > 20$ GeV/c,	Extract b- jet composition
	$\lvert Y\rvert < 1.5$	from a fit to Secondary Vertex Mass

Z+b jets



$\sigma(Z+b)/\sigma(Z) = 0.284 \pm 0.029^{stat} \pm 0.029^{syst}$ %

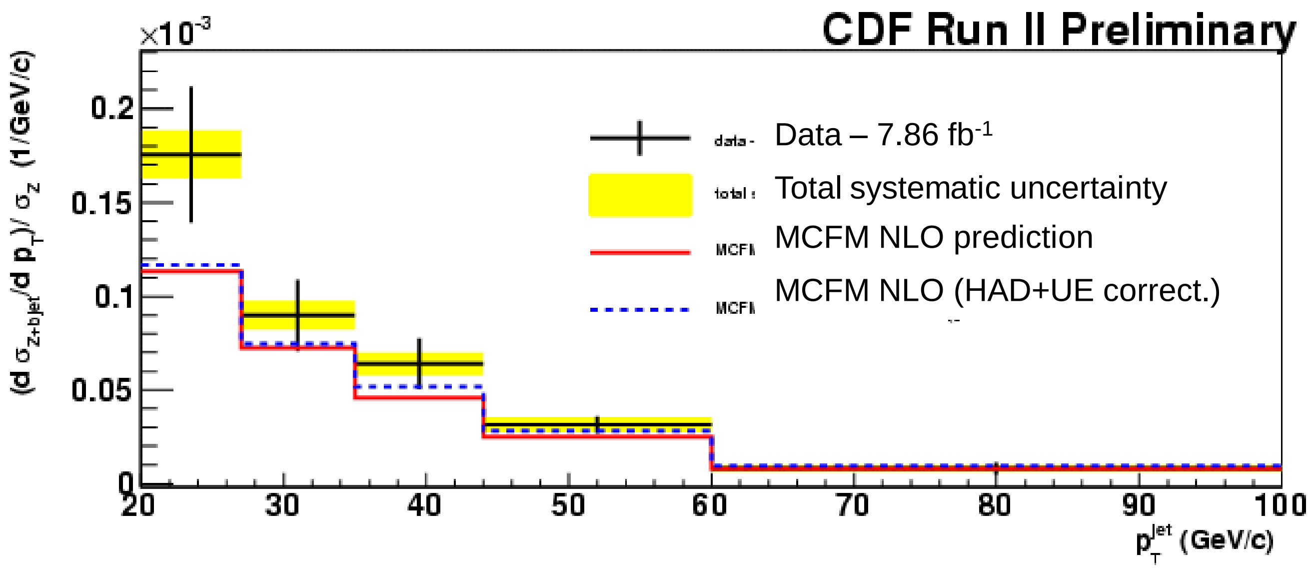
$\sigma(Z+b)/\sigma(Z+jet) = 2.24 \pm 0.24^{stat} \pm 0.27^{syst}$ %

NLO: (range from different scale choice)
$\sigma(Z+b)/\sigma(Z)$= 0.23—0.28%
$\sigma(Z+b)/\sigma(Z+jet)$= 1.8—2.2%

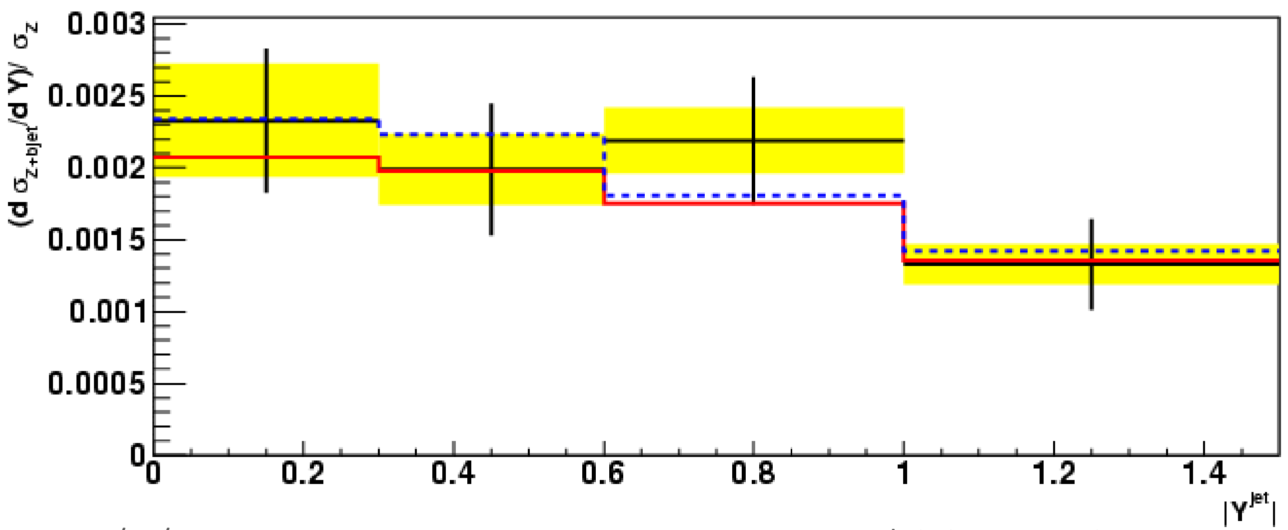
Good agreement with NLO MCFM

- **Main Systematic uncertainty due to vertex mass template modeling (9 %)**
- **Other systematics come from b-tag efficiency, JES, and backgrounds**

Z+b jets – Differential distributions



Dominated by stat. uncertainty



General agreement with theory

Low Energy scan of the Tevatron

Dates : Sept 8th– Sept 16th

Total data taking time :

10 h at 300 GeV

39 h at 900 GeV

Main goals of the program:

1. **Study of MB events**:
   charged particle multiplicities, $dN/d\eta$, etc…
2. **Study of UE events**
3. **Gap-X Gap events**

Special trigger table; 3 x 3 bunches, no low-β

Asked for ~ 1 interaction/crossing, to maximize singles (no-PU) rate.

Data summary

$\sqrt{s}$	0-bias	Minbias	Gap-X-Gap	Jets	e,μ,ν	Total # events
300	1.89 M	12.1 M	9.2 M	8.3 K	352	23.2 M
900	8.0 M	54.3 M	21.8 M	550 K	16 K	84.7 M

Low s Physics (I)

Peter Skands: "Energy Scaling of MinBias Tunes" arXiv:1103.3649,

Much support from event generator community.

Example of PYTHIA tunes, based on Tevatron 1960 data:

Note big uncertainty at √s = 300, even at 900 GeV.

|y| < 1, pT> 0.5 GeV

Factor 2 spread!

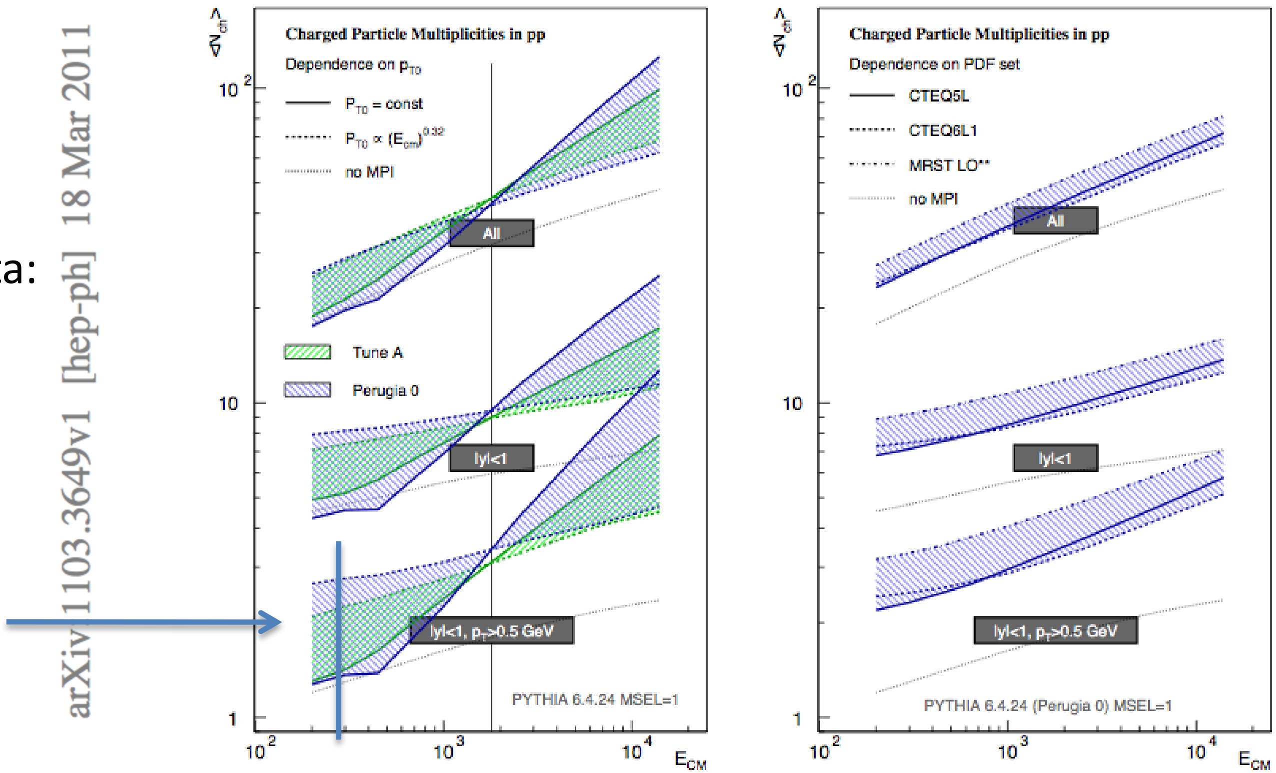


Figure 1: Energy scaling of charged-particle multiplicities in pp in three different phase space regions (top: inclusive, middle: central, bottom: central hard). *Left:* Dependence on the scaling of the $p_{\perp 0}$ parameter for two different PYTHIA models, represented by Tune A and Perugia 0, respectively. The solid vertical line represents the reference energy, 1800 GeV, at which PARP(82) is defined for both models. *Right:* Dependence on the PDF set, for the Perugia 0 model. For reference, Tune A without MPI is also shown (dotted lines).

Conclusions

- Understanding of jet identification, JES, and systematics leads (in many cases) to experimental systematic uncertainties smaller than theoretical uncertainties

- Next level of measurements
  - measurements of jet substructure variables
  - validating phenomenological models for diffraction

- Comprehensive Tevatron V+jets/HF results provide detailed information for testing latest pQCD calculations and tuning event generators

More to come from the QCD program at the Tevatron

http://www-cdf.fnal.gov/internal/physics/qcd/qcd.html