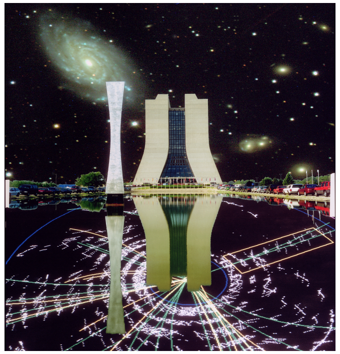
Studies on Boson+Jets in CDF



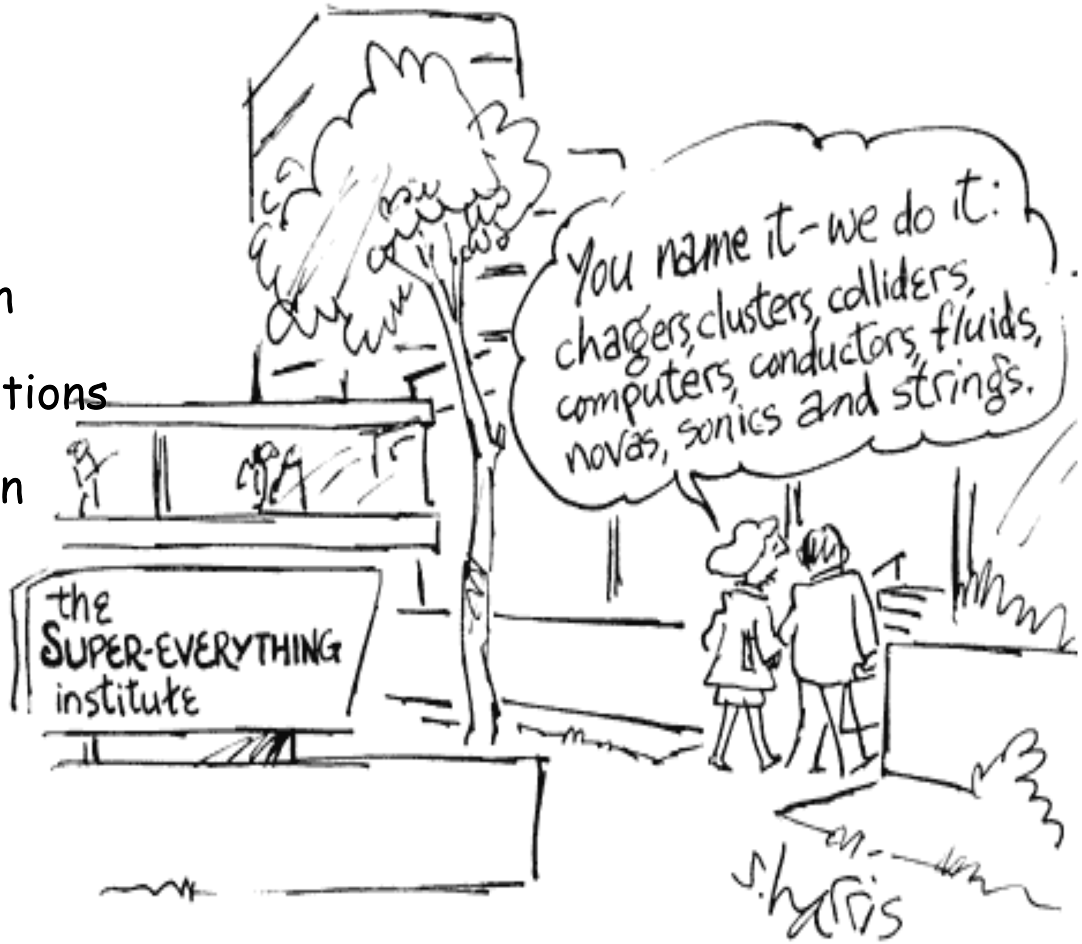
M. Martínez-Pérez

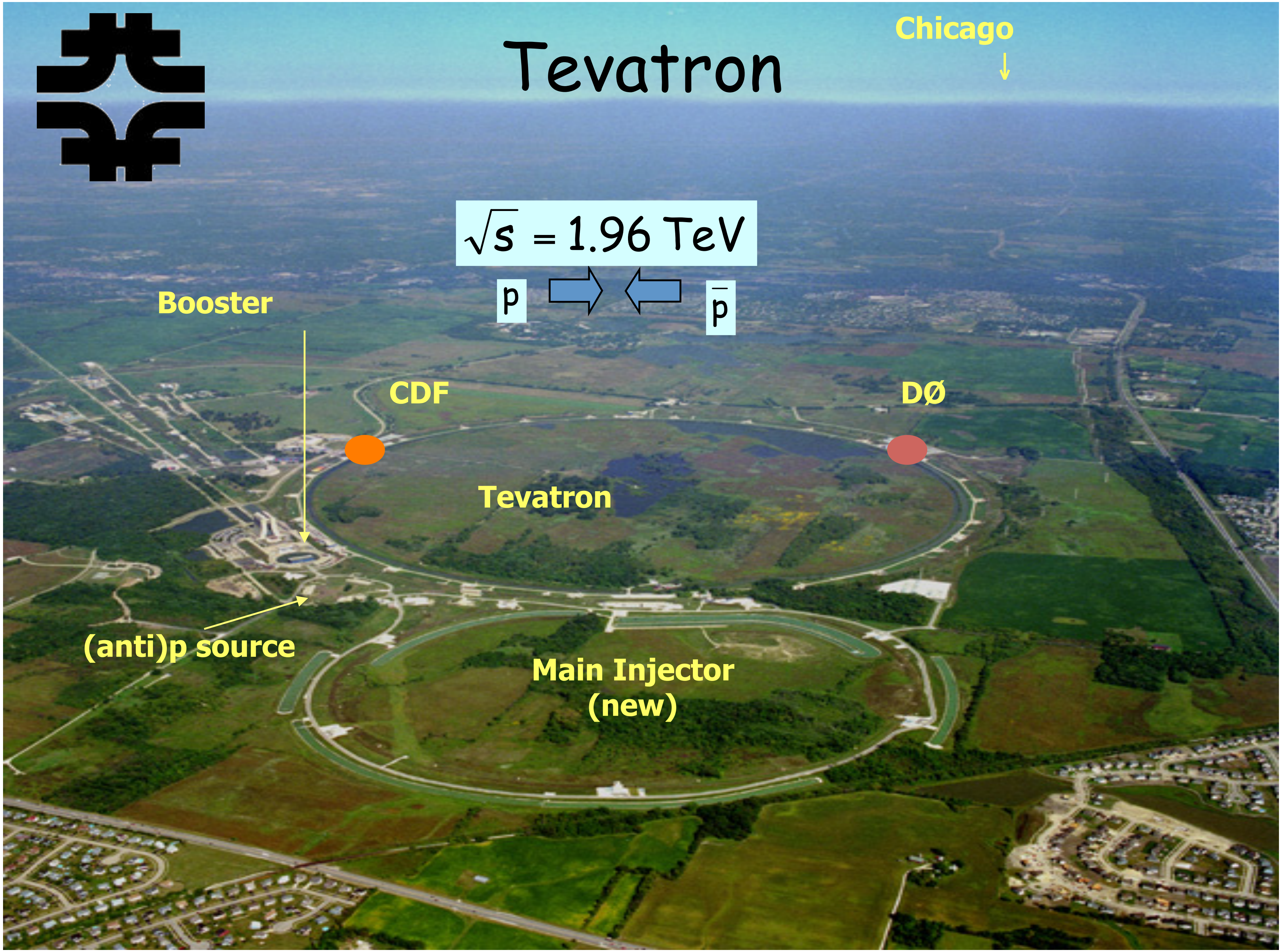
ICREA/IFAE-Barcelona

MC4LHC Workshop, 1st April 2010, CERN

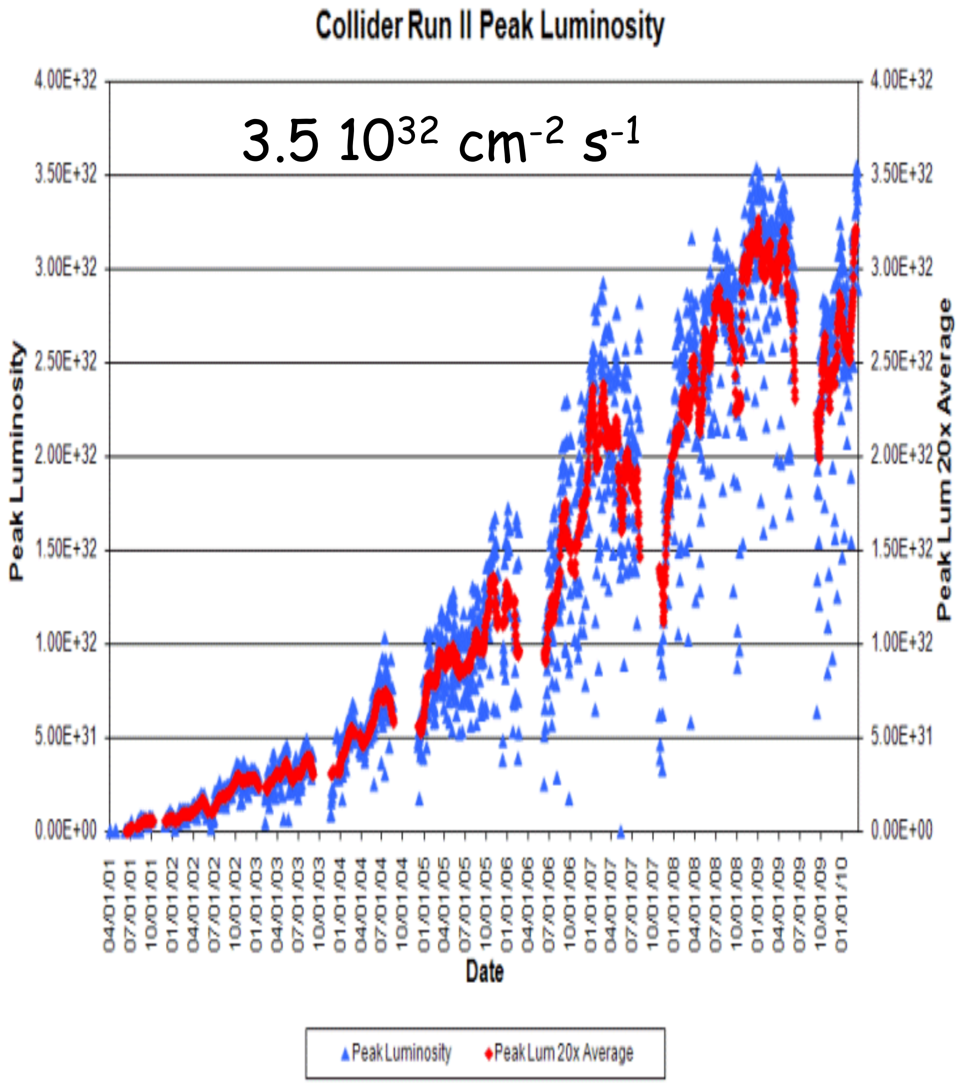
Outline

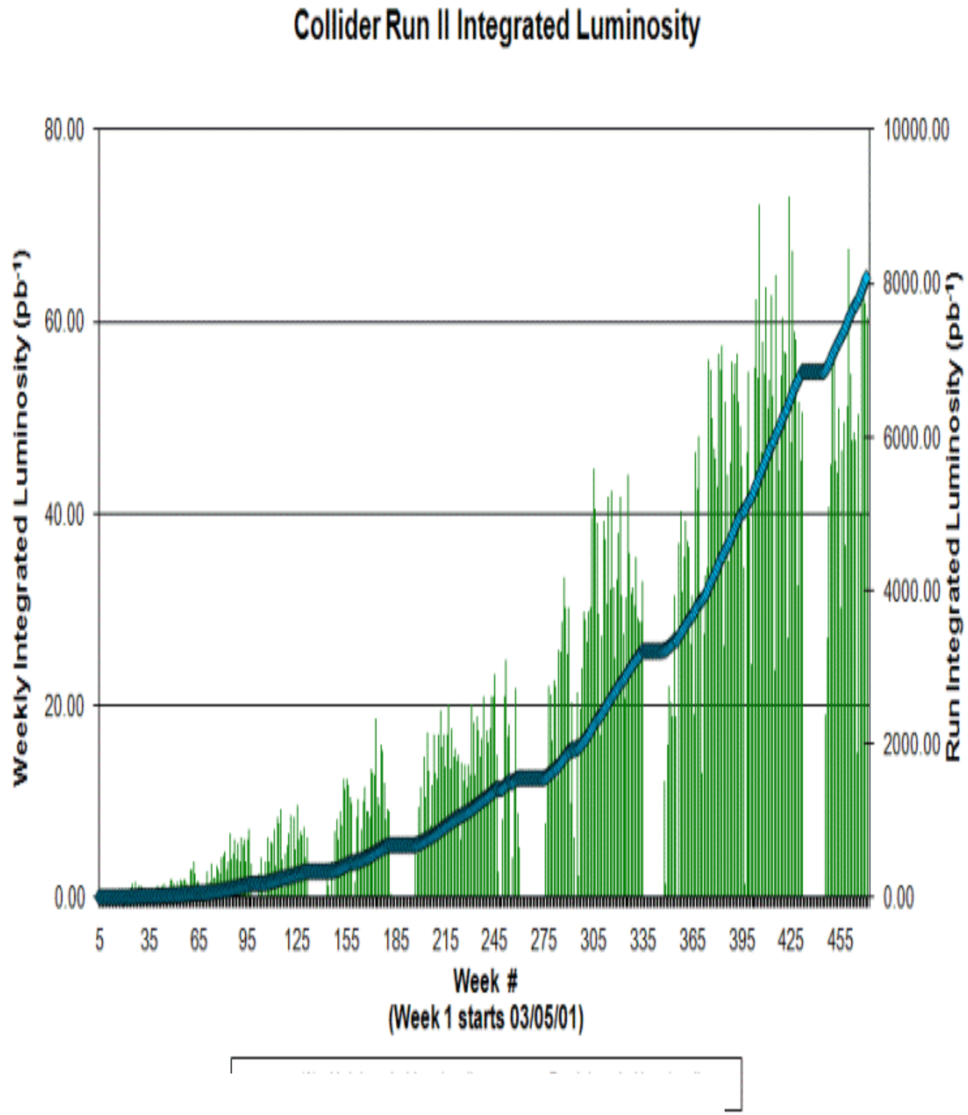
- Tevatron & CDF
- Motivation
- Inclusive DY production
- Jet Reconstruction and Calibration
- Importance of non-pQCD contributions
- Inclusive Prompt Photon Production
- W+jets Production
- Inclusive Z+jets Production
- W+b & W+c
- Photon+b
- Z+b
- Summary and Final Remarks




Tevatron
Chicago
$\sqrt{s} = 1.96$ TeV
p
$\bar{p}$
Booster
CDF
DØ
Tevatron
(anti)p source
Main Injector
(new)

Tevatron Performance

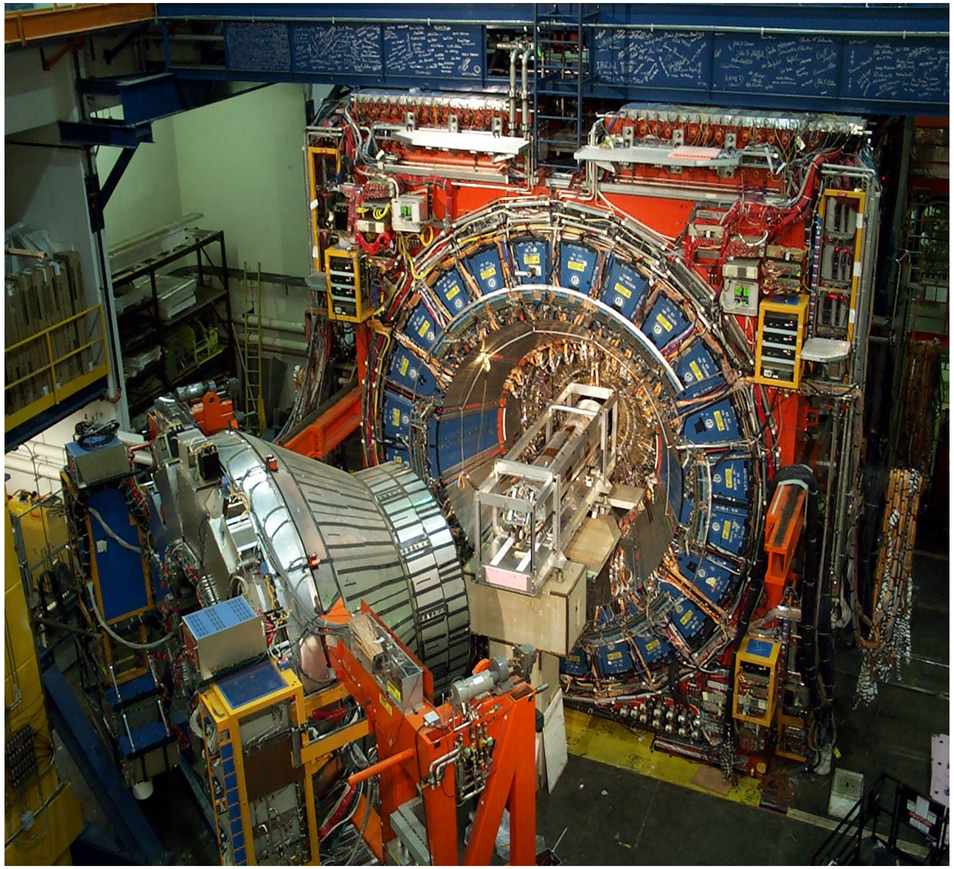


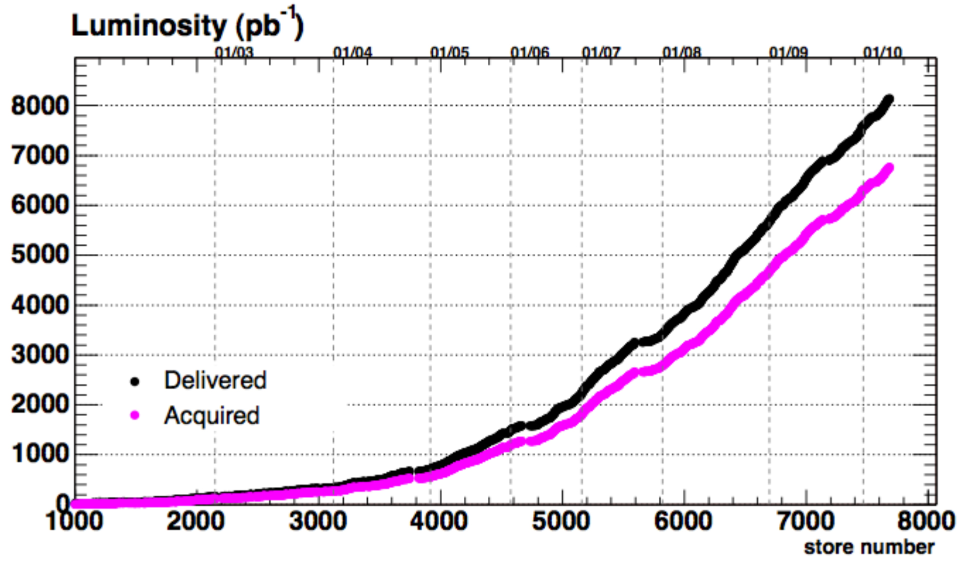


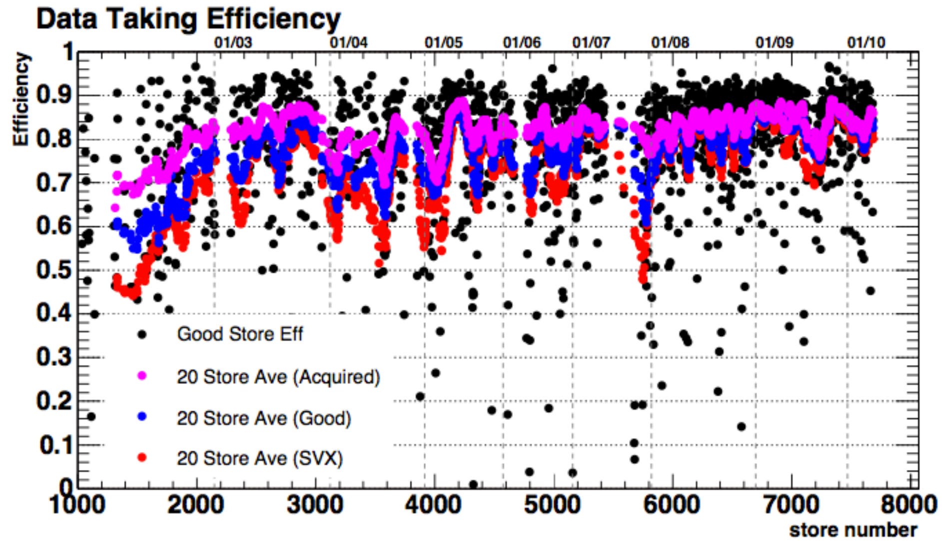
Tevatron delivered > 8 fb^{-1}

(> 10 fb^{-1} expected by end Run II) (Run I : 120 pb^{-1})

CDF in Run II



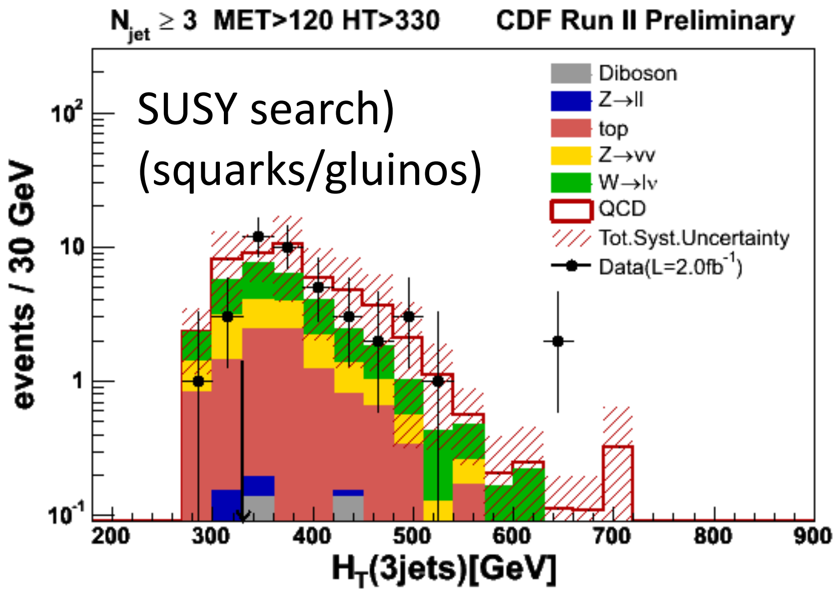


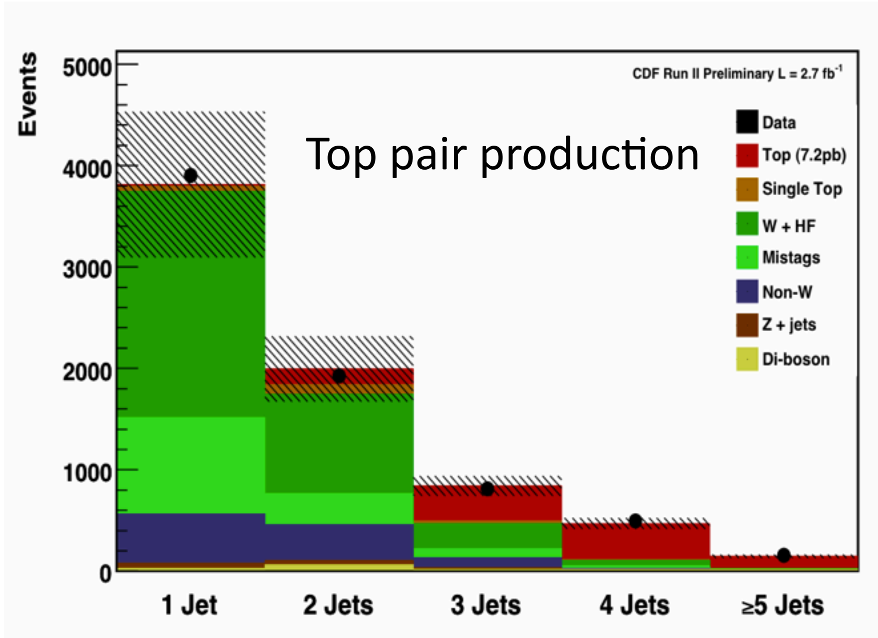


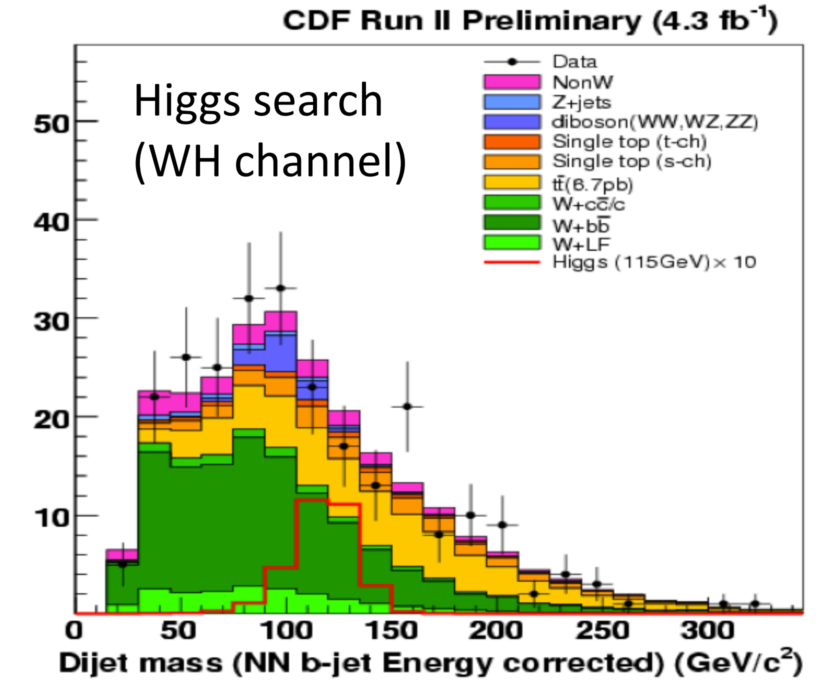
Experiment has already collected > 6 fb-1 on tape

CDF operating well and recording physics quality data with very high efficiency (~85%)

Motivation







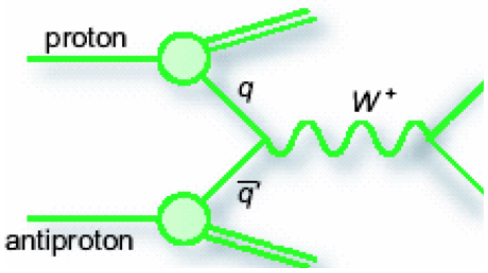
- Boson + Jet(s) Processes constitute in many cases irreducible backgrounds in searches for new physics

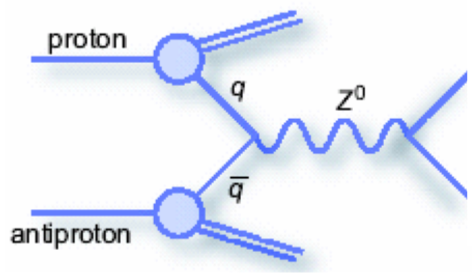
30% - 40% uncertainty in some of the processes (boson + HF)

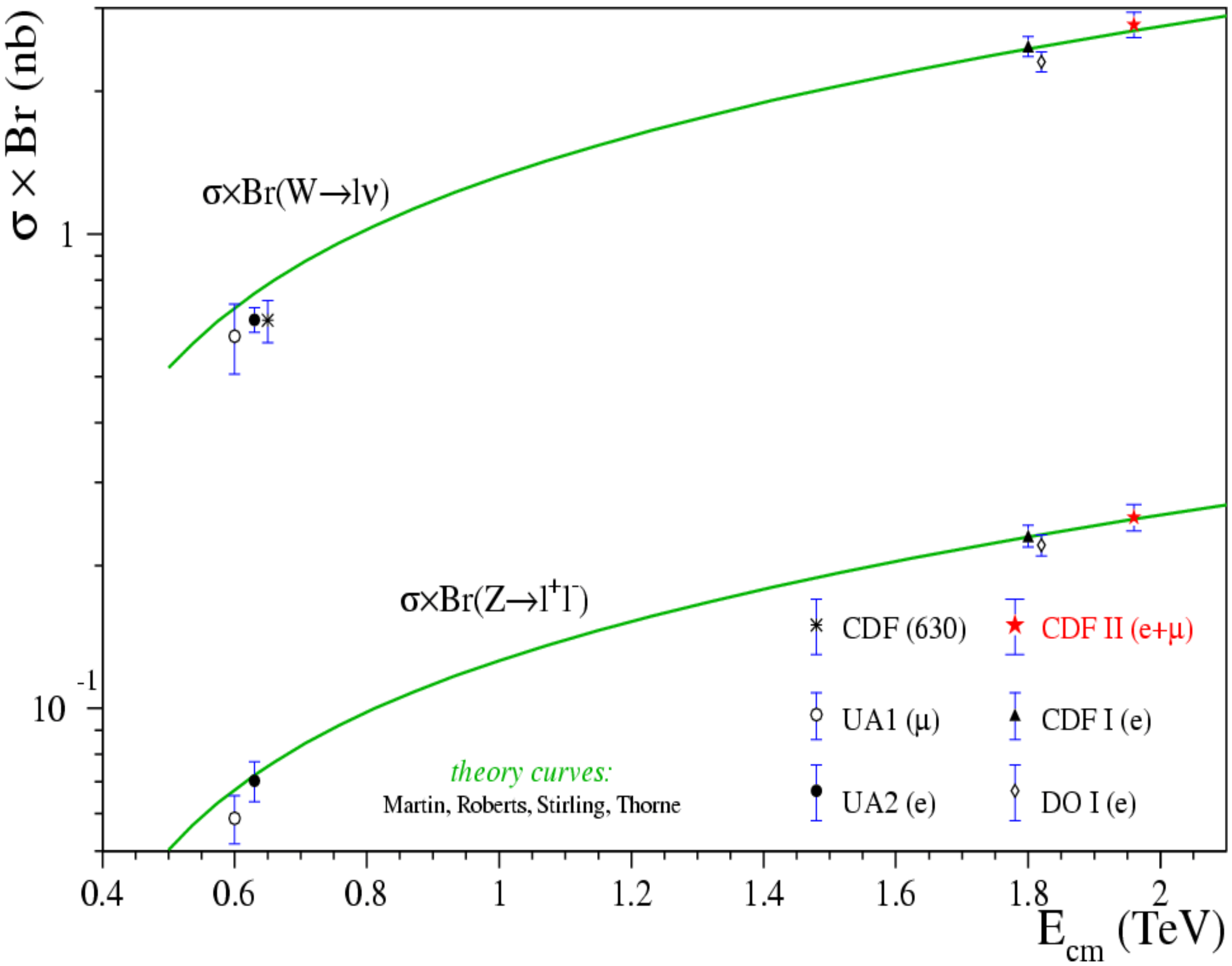
→Call for dedicate measurements on boson+jets

J. Phys. G: Nucl. Part. Phys. 34 (2007) 2457-2544

W & Z Production Cross Section







NNLO pQCD calculation describes the data very well

Jet Reconstruction

- In Run II at CDF jets are reconstructed with
  - Run I JETCLU algorithm
    - Cone 0.4 or 0.7 , merging/splitting fraction 0.75
    - E-scheme (algorithm runs based on Snowmass)
    - We know is not theoretically robust
      - This is very relevant for comparisons with fixed order calculations
      - Not so dramatic in case of comparisons with ME+PS MC predictions
  - Midpoint algorithm
    - Cone 0.7 mostly, merging splitting 0.75
    - E-scheme recombination
    - Theoretically better defined
  - Kt algorithm (only in inclusive jet production)
    - Different D parameters (0.5, 0.7, 1.0)… see later

    → Ongoing work with SISCone and Anti-KT

→ Measurements will be dominated by the accuracy in the reconstruction of the jets and HF (b/c quark) ID

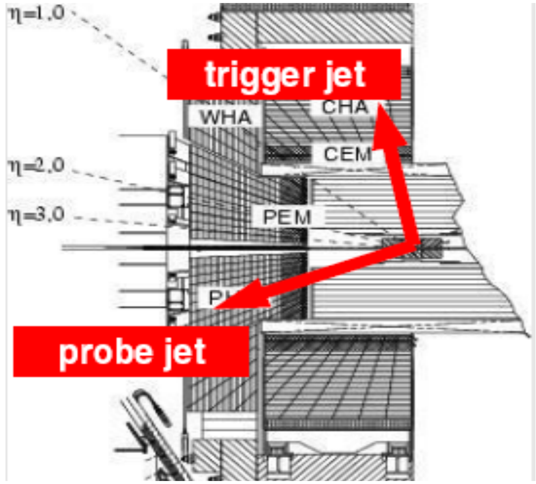
Jet Energy Corrections

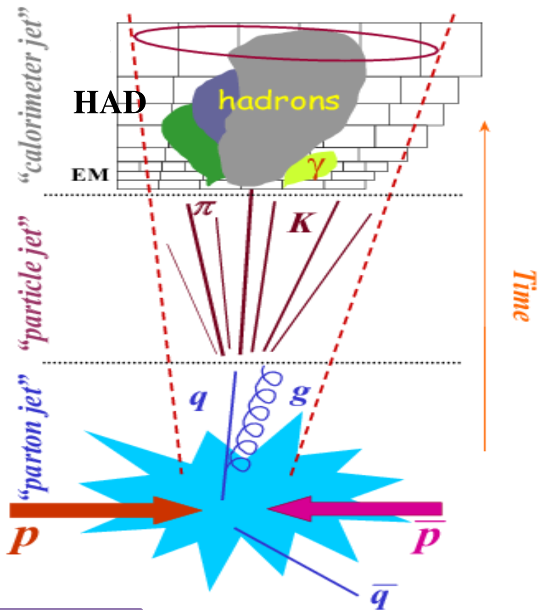
1. Relative Corrections
   - Jet response referred to central region
   - Imposing dijet balance in dijet events
   - Bias on dijet definition (veto on third jets)

2. Pileup
   - Due to multiple pp collisions at high Inst. Lumi
   - Remove a given amount of transverse energy for each additional primary vertex
   - Obtained using MB and random cones in $\eta-\phi$

3. Average correction to hadron level
   - Bring the jet energy back to the hadron level (correct for calorimeter response)
   - Extracted using Monte Carlo samples

4. Corrections "back to the parton level"
   - Physics and MC model dependent
   - Totally rely on Monte Carlo



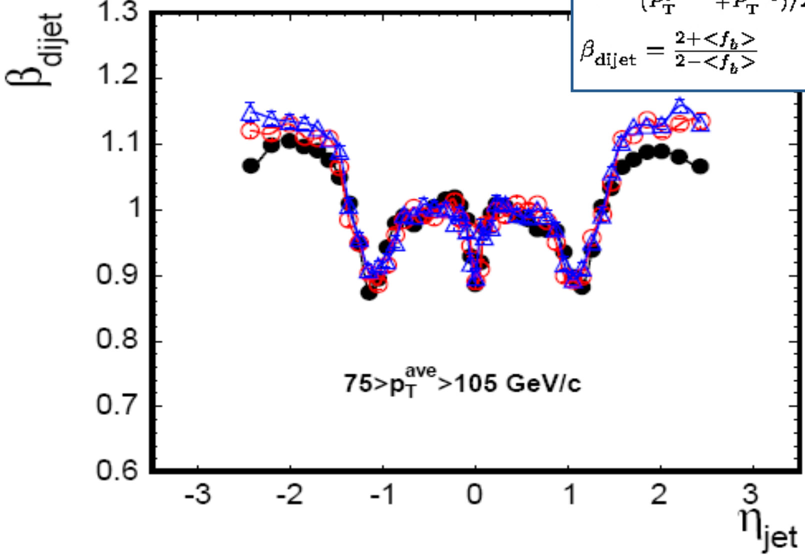


$$P_{T\,jet}(R) = [\,P_{T\,jet}^{raw}(R) \times f_{rel}(R) - MPI(R)] \times f_{abs}(R) \;\; - UE(R) + OC(R)$$

Nucl.Instrum.Meth.A566:375-412,2006

Jet Energy Corrections (cont.)

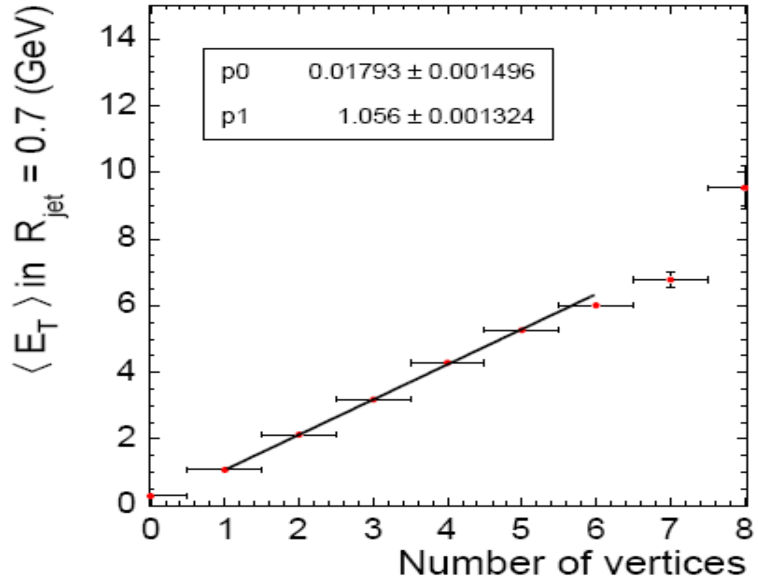
relative



$$f_b = \frac{P_T^{probe} - P_T^{trig}}{(P_T^{probe} + P_T^{trig})/2}$$

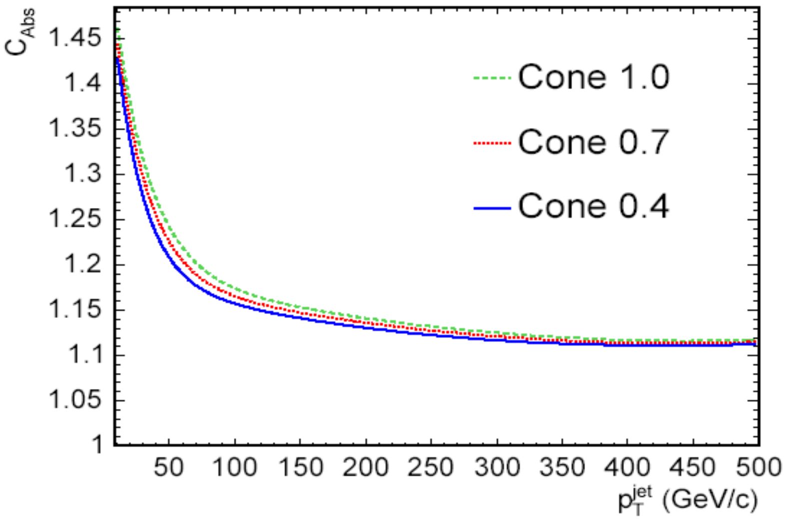
$$\beta_{dijet} = \frac{2+<f_b>}{2-<f_b>}$$

pileup

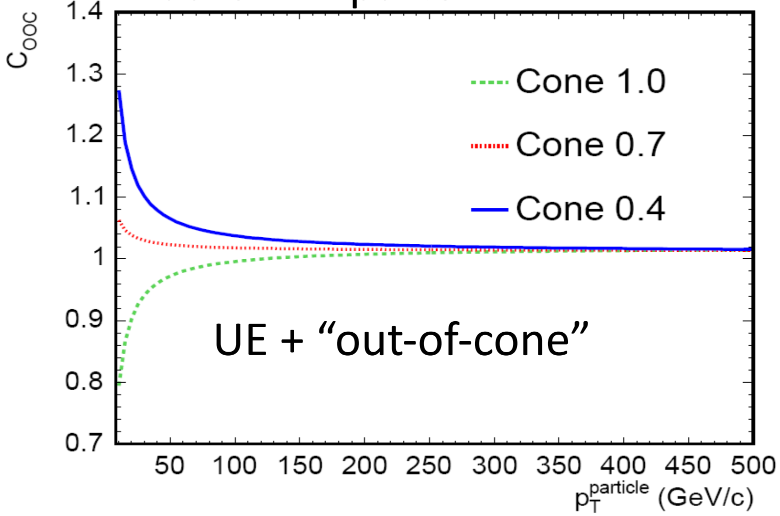


As they appear in CDF NIM publication (2005)

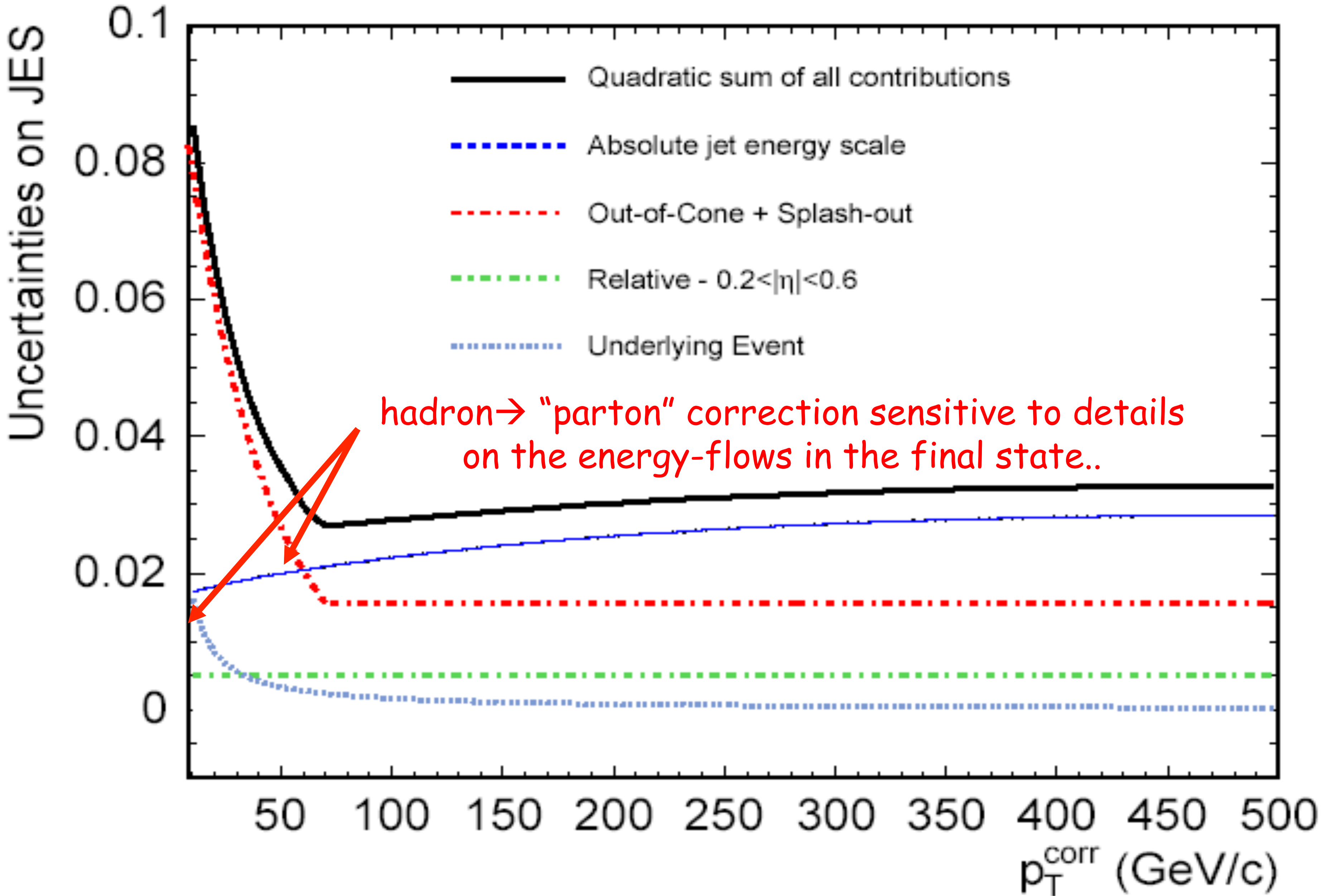
detector → hadron



hadron → parton

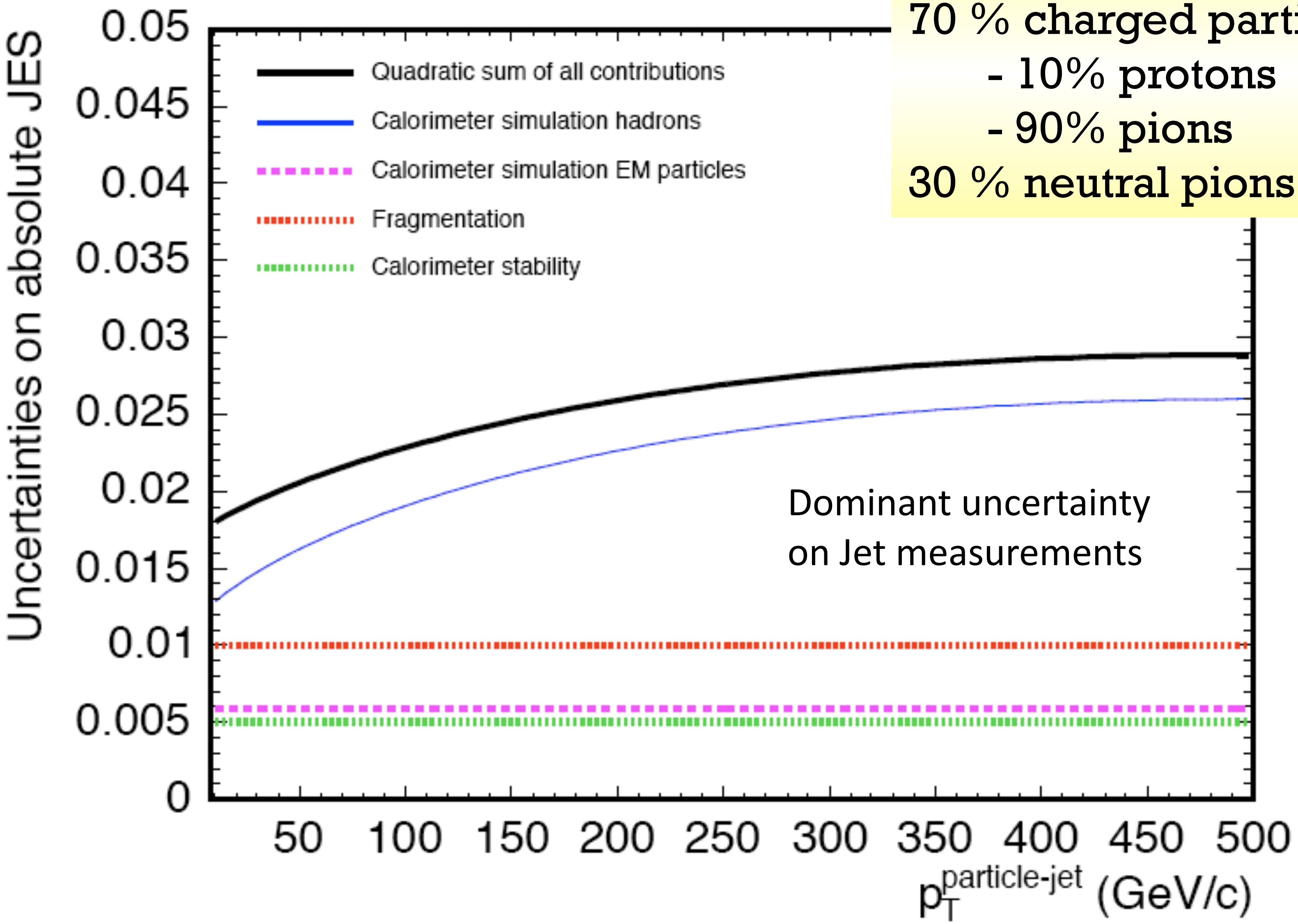


Uncertainties



→ Provide measured cross sections at the particle (hadron) level !!!!

Jet E-scale uncertainty: Summary



Jet composition:

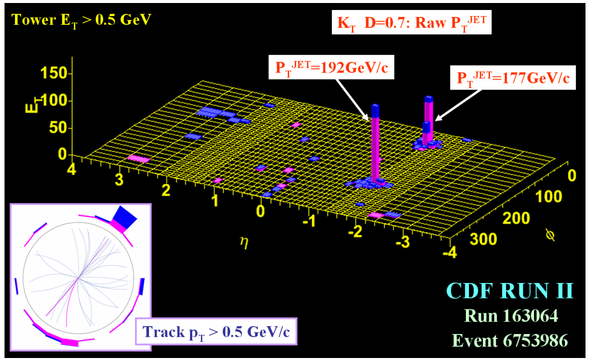
70 % charged particles

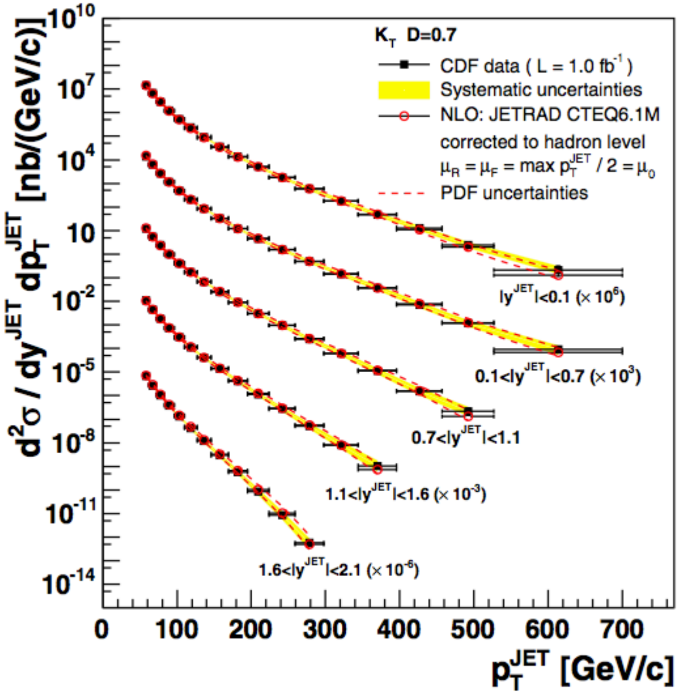
- 10% protons
- 90% pions

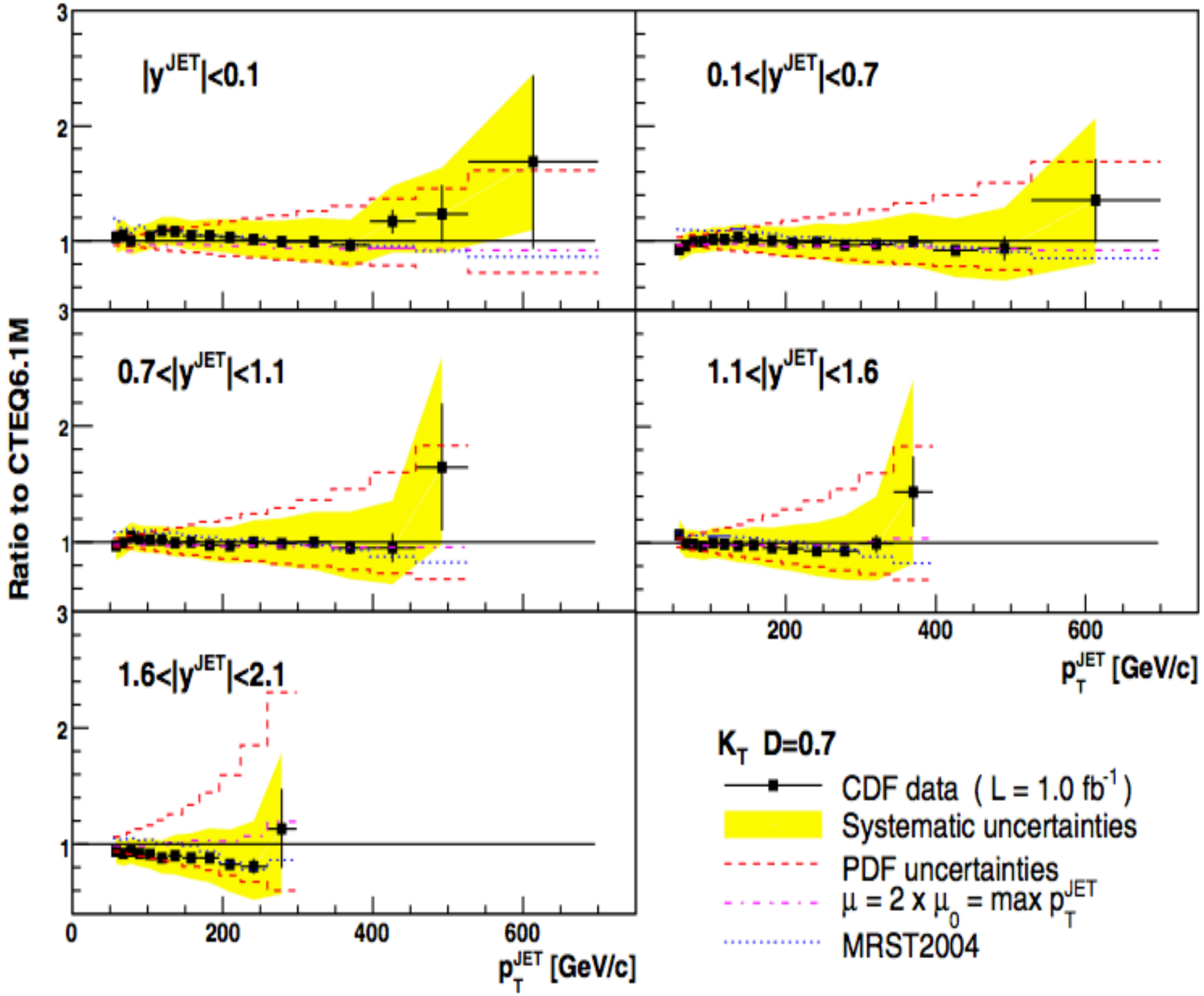
30 % neutral pions (→ γγ)

Phys. Rev. D 75, 092006 (2007)

Example: Inclusive Jet Production



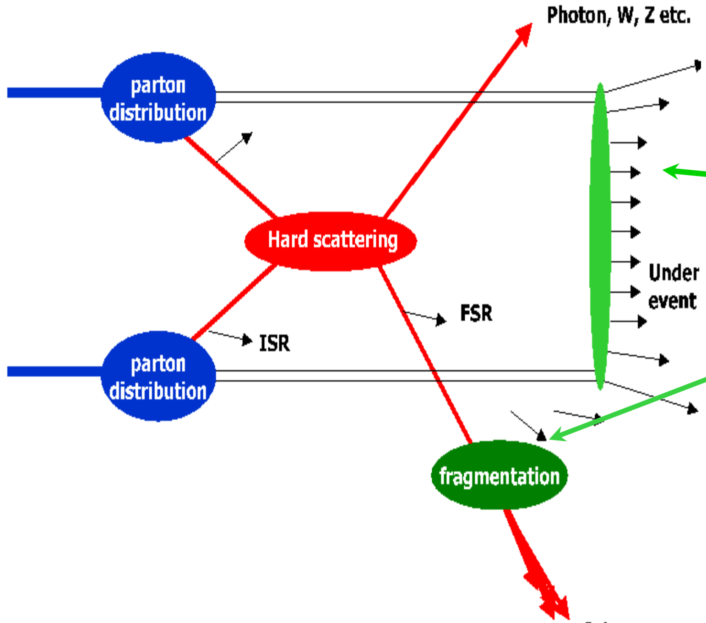




The observed agreement between data and NLO pQCD predictions at low P_T only obtained after including non-pQCD corrections in theoretical predictions…

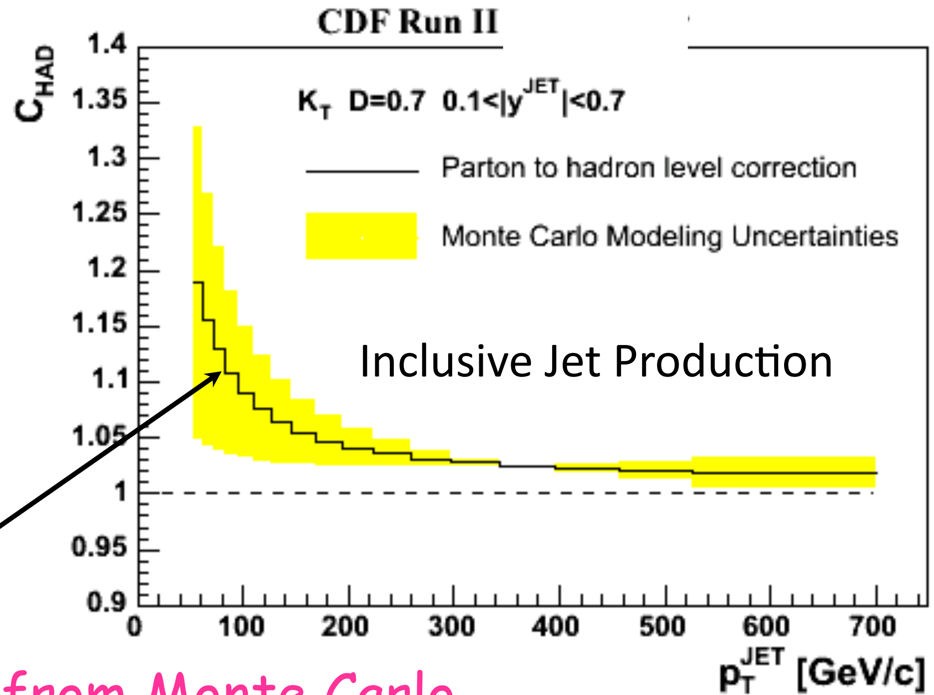
Non-pQCD contributions

(comparing data at hadron level with pQCD fixed order at parton level)



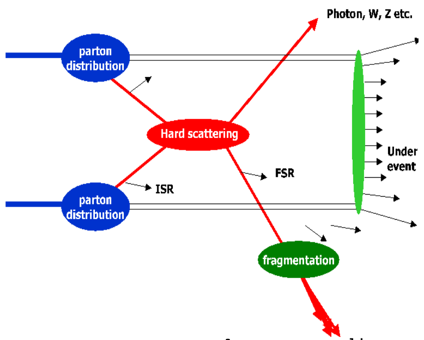
- Non-pQCD contributions
- Underlying Event (remnant-remnant interactions)
- Fragmentation into hadrons

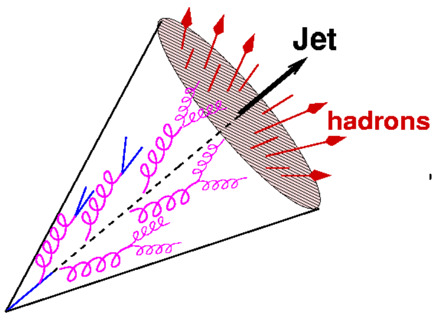
Underlying Event and Fragmentation contributions must be considered before comparing data to NLO QCD predictions (only way to perform a fair comparison)



Precise measurements at low Pt require good modeling of the non-pQCD terms

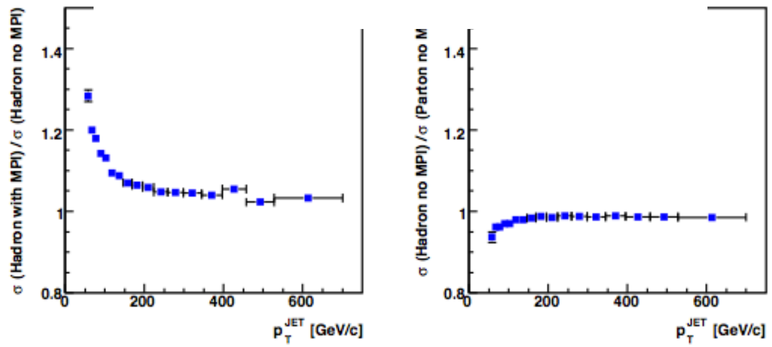
parton-to-hadron corrections taken from Monte Carlo and applied to NLO pQCD predictions (data untouched)





Underlying Event & hadronization Contribution

$$C_{HAD} = C_{MPI}^{Hadron\ Level} \times C_{Frag}^{No\ MPI}$$



- Estimated using MC PYTHIA

  (and Herwig for systematics)

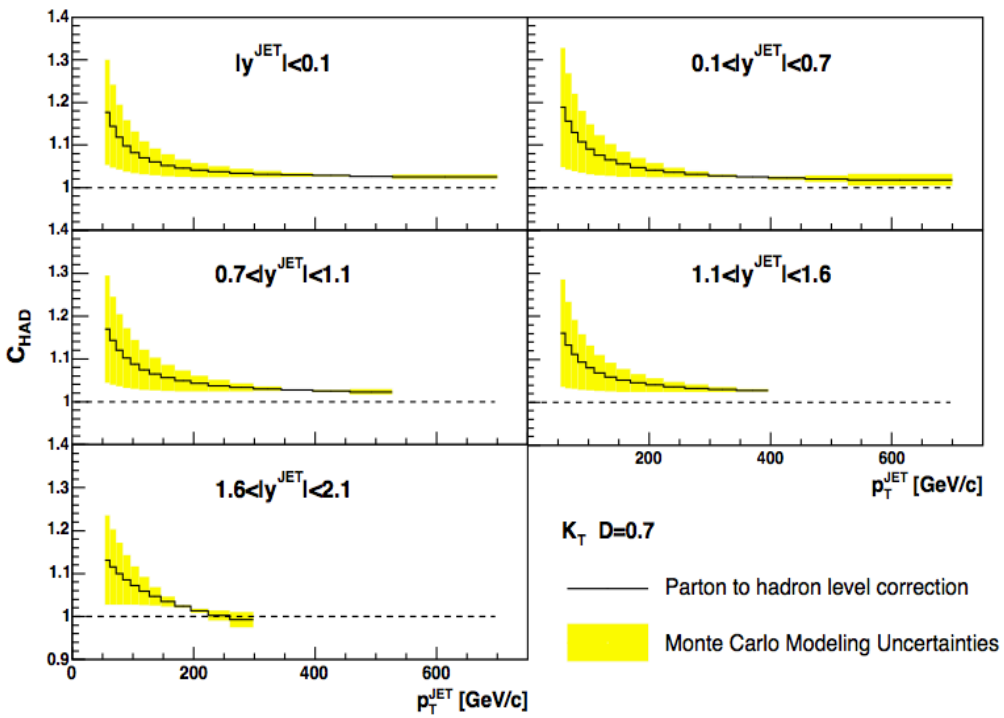
- Defined as the ratio of the generated distributions with/without UE and string fragmentation (Pythia)

$$C_{HAD}(p_T^{jet}, y^{jet}) = \frac{\sigma(\text{Hadron level with MPI})}{\sigma(\text{Parton level no MPI})}(p_T^{jet}, y^{jet})$$

- Applied to the parton-level fixed-order pQCD prediction

- The parton-to hadron factor comes with relatively large uncertainties due to dependence on the modeling

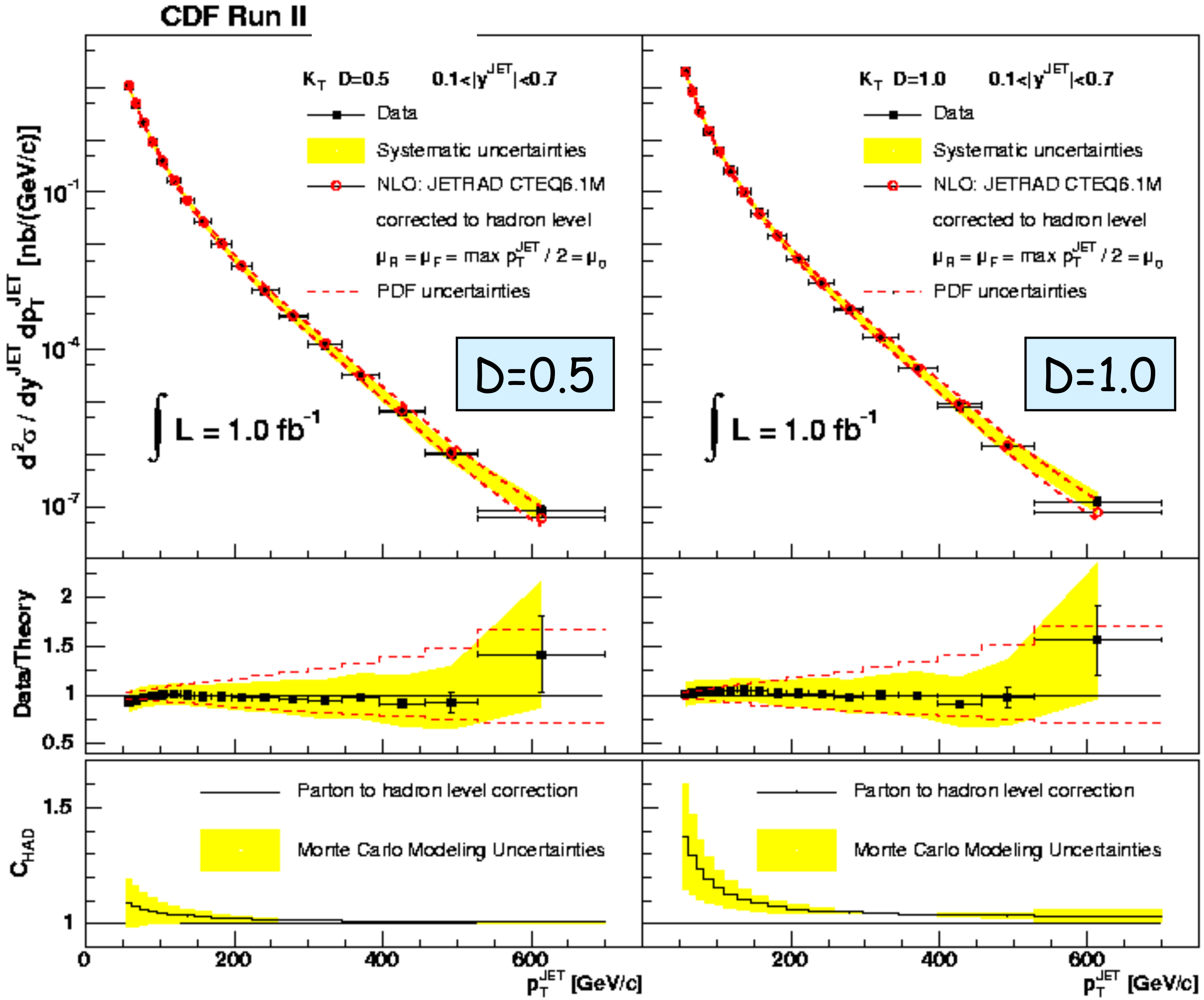
- Underlying Event dominates….



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

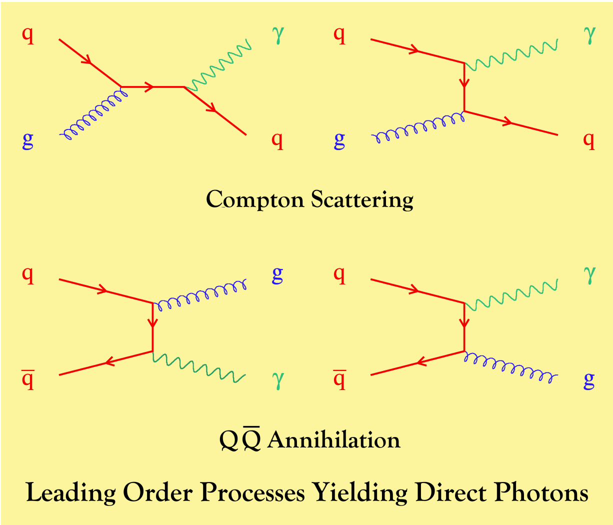
K_T Jets vs D

1 fb^{-1}

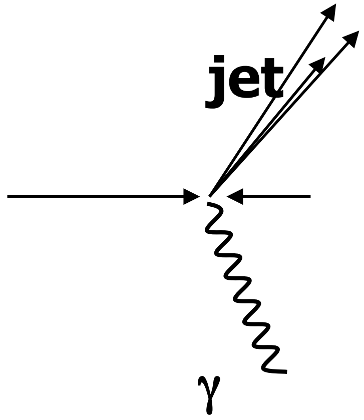


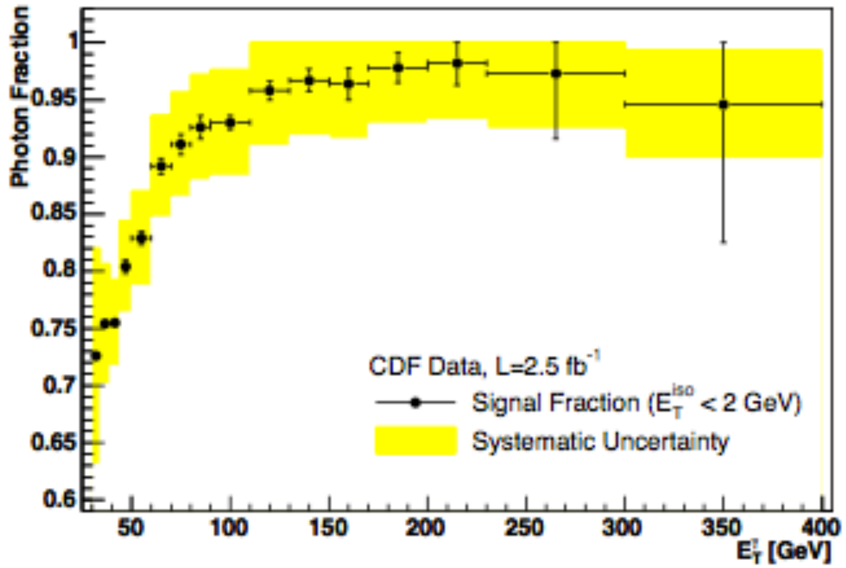
Fundamental to have separate measurements that validate the MC UE modeling...

Prompt Photon Production



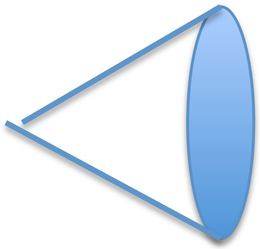
Leading Order Processes Yielding Direct Photons

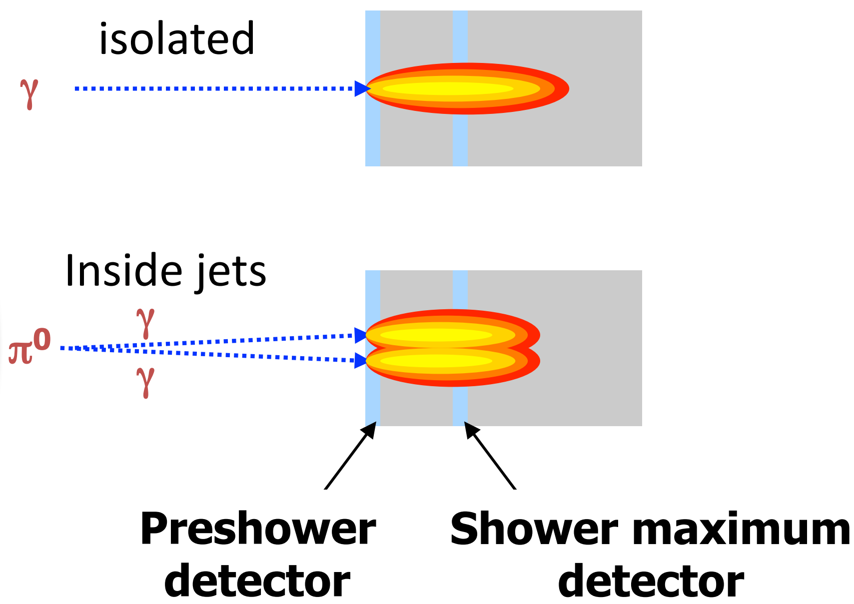




Using prompt photons one can precisely study QCD dynamics:

- Well known coupling to quarks
- Give access to lower Pt
- Clean: no need to define "jets"
- constrain of gluon PDF



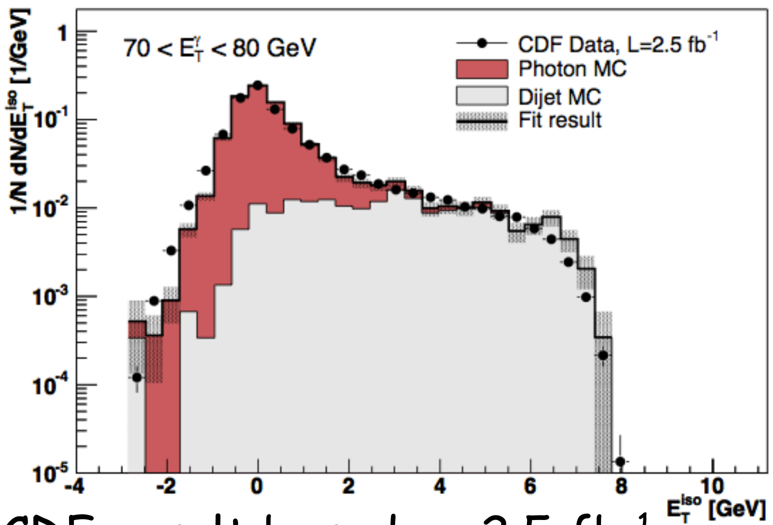


Experimentally difficult because of large background from π^0 decays

Phys. Rev. D80, 11106 (2009)

Inclusive Prompt Photon

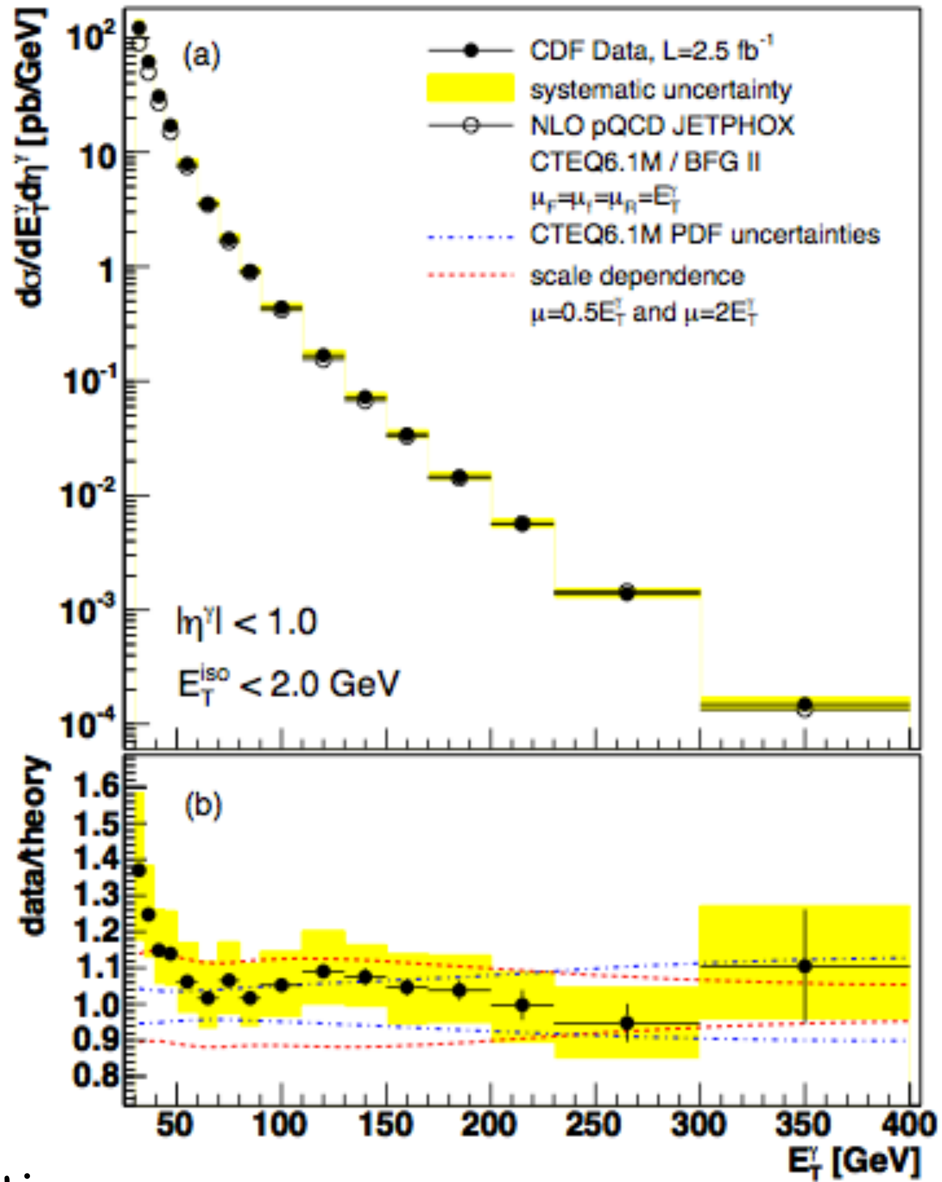
Isolated photons (E_T in R= 0.4 < 2 GeV)
P_t> 30 GeV/c, |η| < 1.0



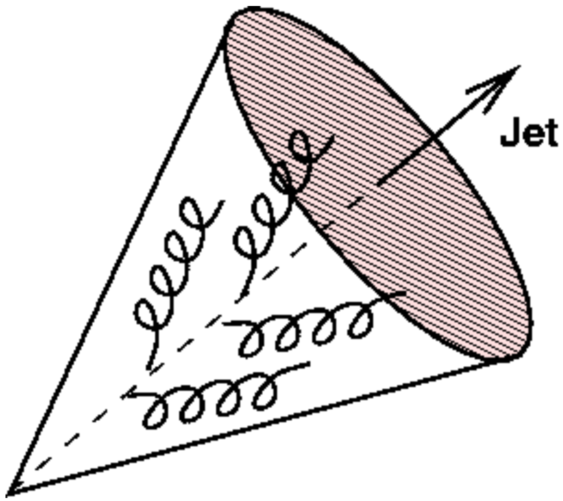
New CDF result based on 2.5 fb^{-1}

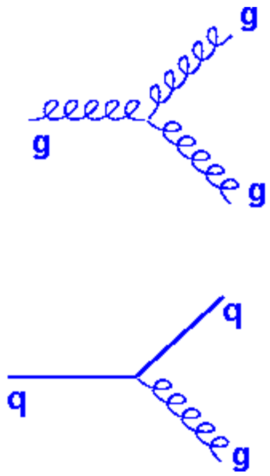
Agreement with NLO pQCD
(similar known shape at low P_t)

The NLO pQCD prediction is corrected for non-pQCD effects from the UE affecting the isolation …..
→ 10% reduction of theoretical cross section..



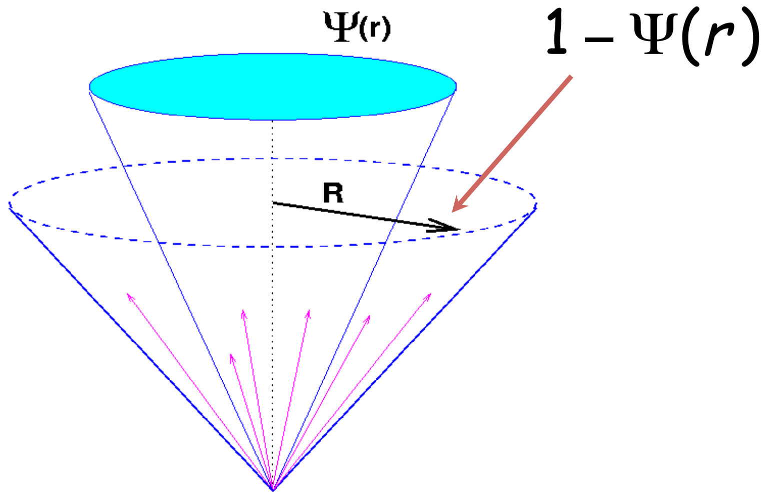
Jet Shapes





Gluons radiate
more than quarks
(QCD color charges)

Gluon jets Broader

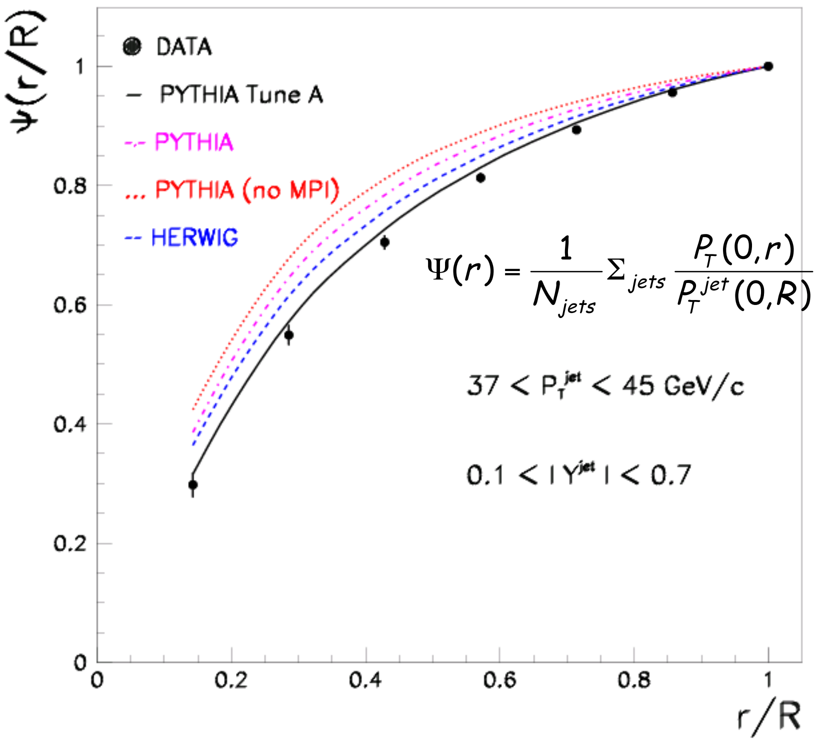


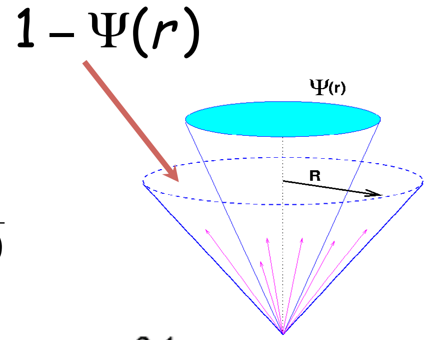
- Jet shape dictated by multi-gluon emission form primary parton
- Test of parton shower models and their implementations
- Sensitive to underlying event structure in the final state

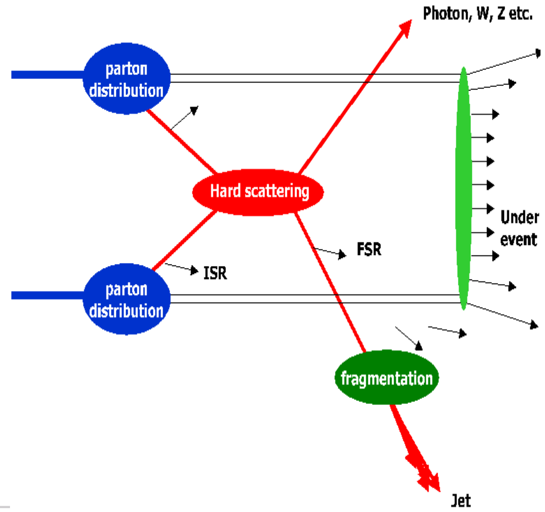
$$\Psi(r) = \frac{1}{N_{jets}} \Sigma_{jets} \frac{P_T(0,r)}{P_T^{jet}(0,R)}$$

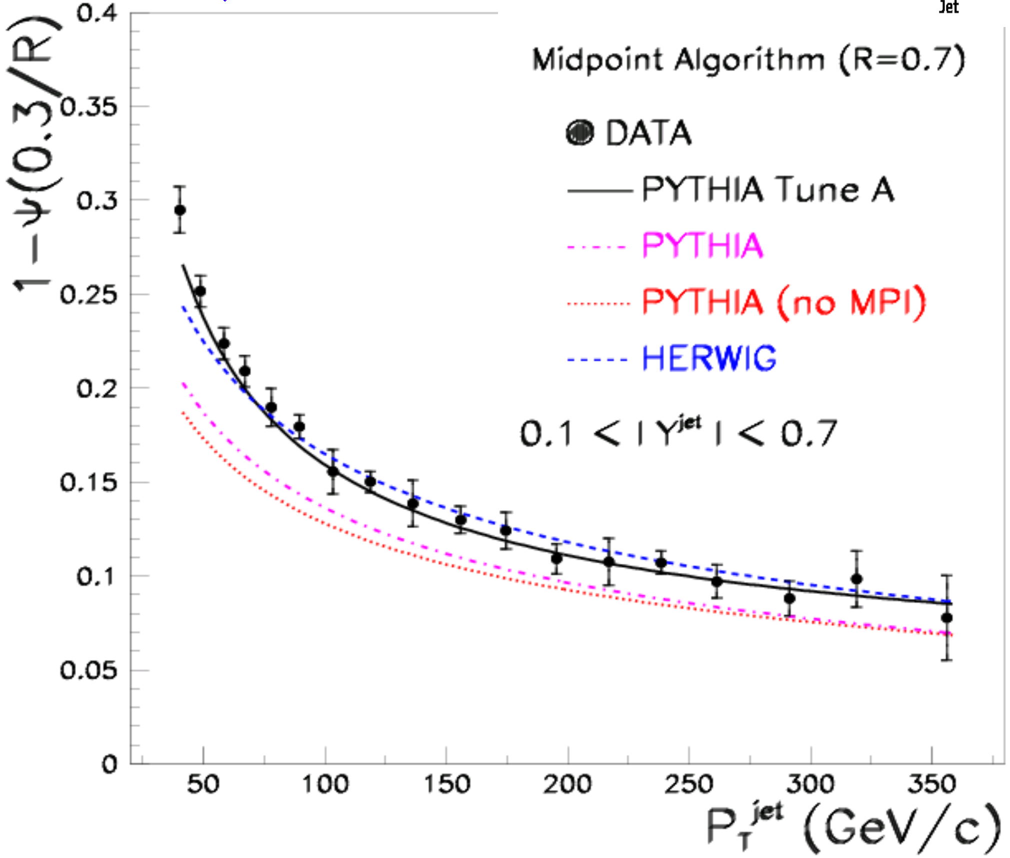
[Phys. Rev. D 71, 112002 (2005)]

Jet shapes





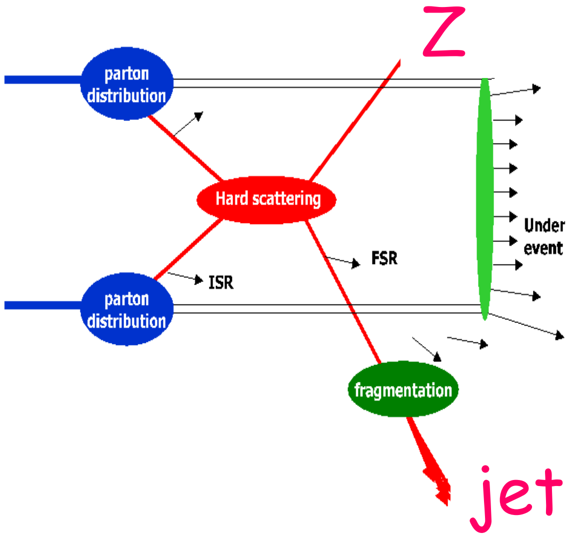


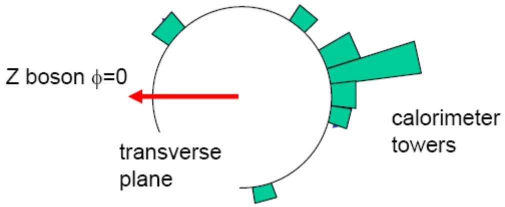


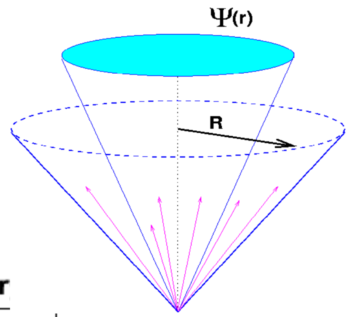
- PYTHIA 6.2 Tune A describes the data (enhanced ISR + MPI tuning)
- PYTHIA 6.2 default too narrow
- MPI are important at low Pt
- HERWIG 6.4 too narrow at low Pt

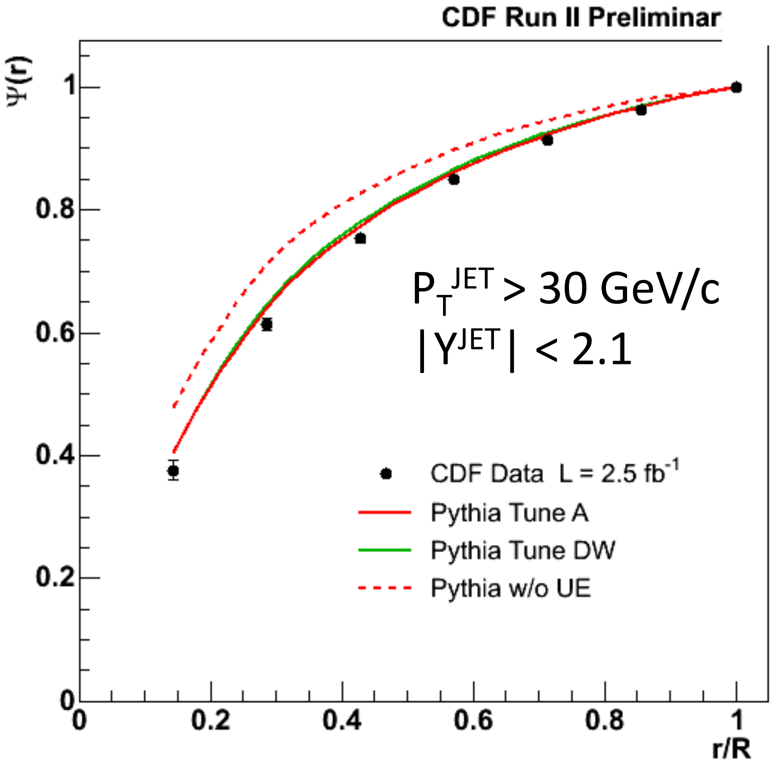
We know how to model the UE at 2 TeV for QCD jet processes

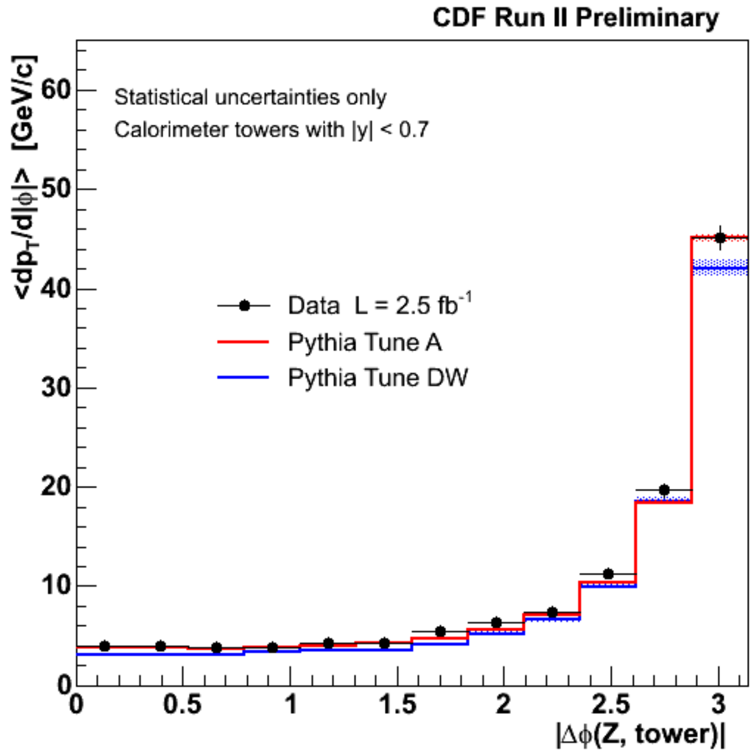
Soft radiation in Z+jet(s)









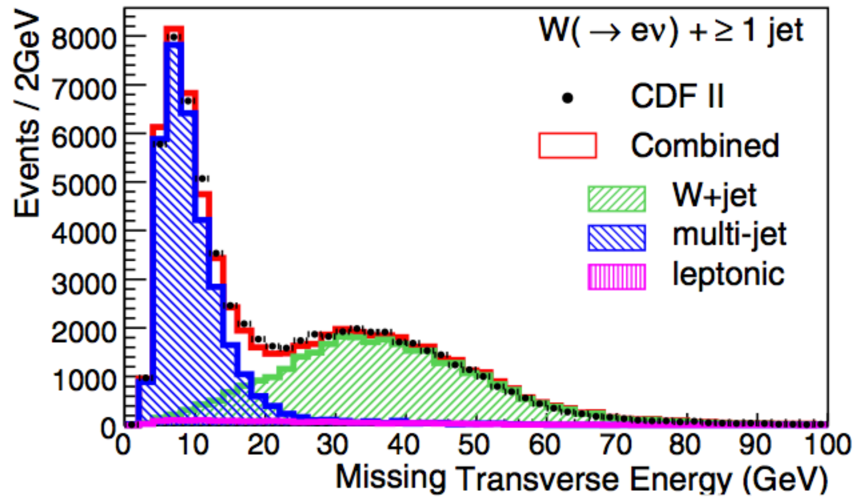


Pythia Tunes A/DW give a reasonable description of the jet shapes and energy flows in Z+jet(s) final states

W(-> en) +jet(s)

Phys. Rev. D ***77, 011108(R) (2008)***

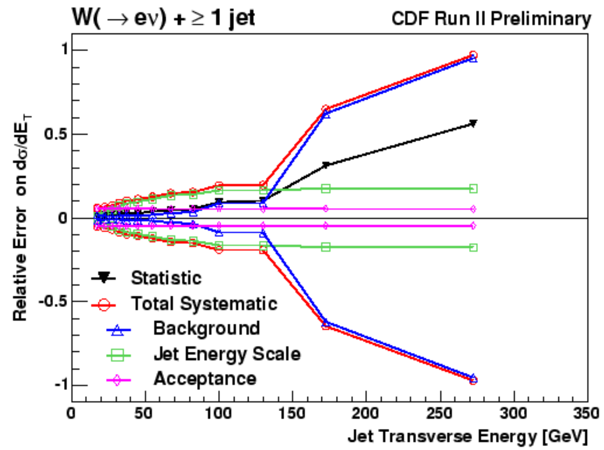
- CDF standard electron ID
  - E^e_T>20 GeV
  - $|\eta^e|$<1.1
  - MET > 30 GeV
  - M^W_T > 20 GeV



- At least one jet JetClu (R=0.4)
  - E_T^{jet} >20 GeV/c
  - $|\eta^{jet}|$ < 2.0
  - ΔR(e-jet) > 0.52

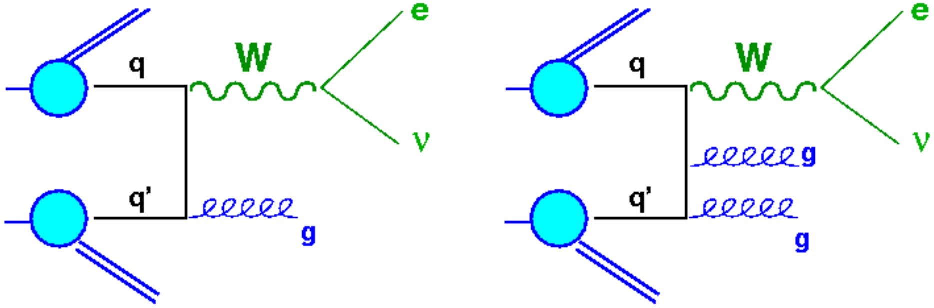
Background taken from fit to MET and lepton P_T distributions

- Measurement corrected for detector and defined in the given limited kinematic region (no extrapolation made)



(Background dominates de measurement at large E_T^{JET} due mainly to top contamination)

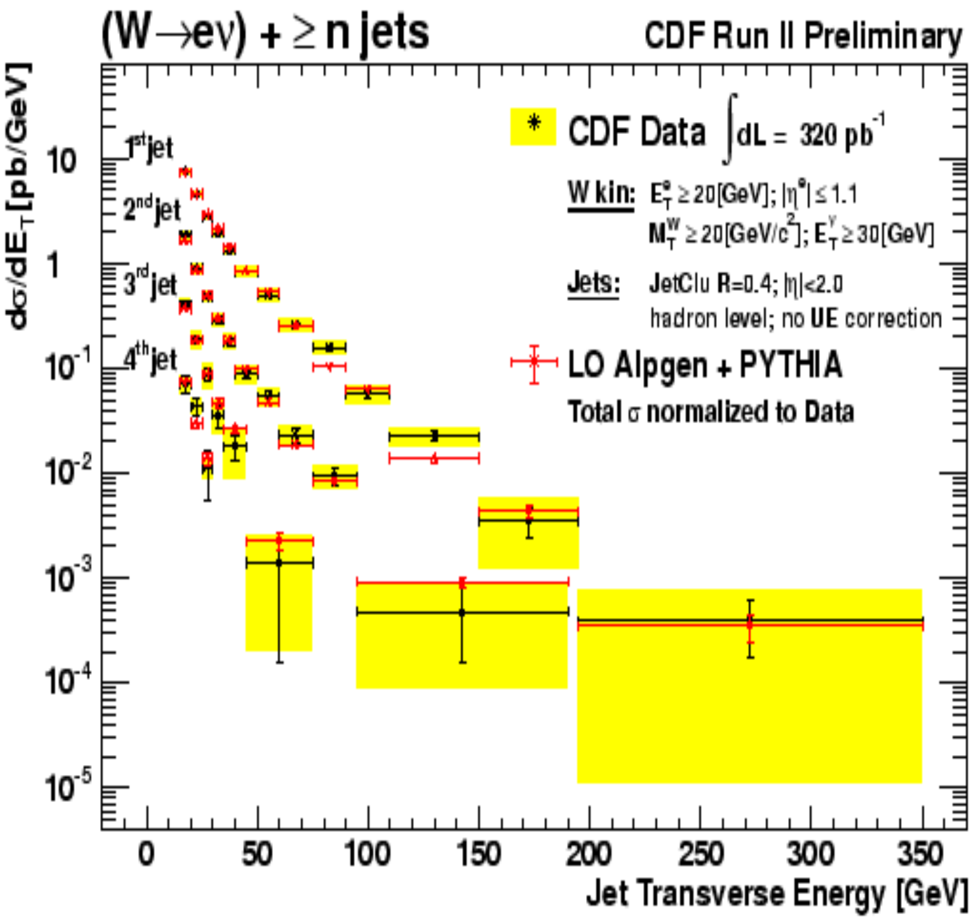
W+jet(s)

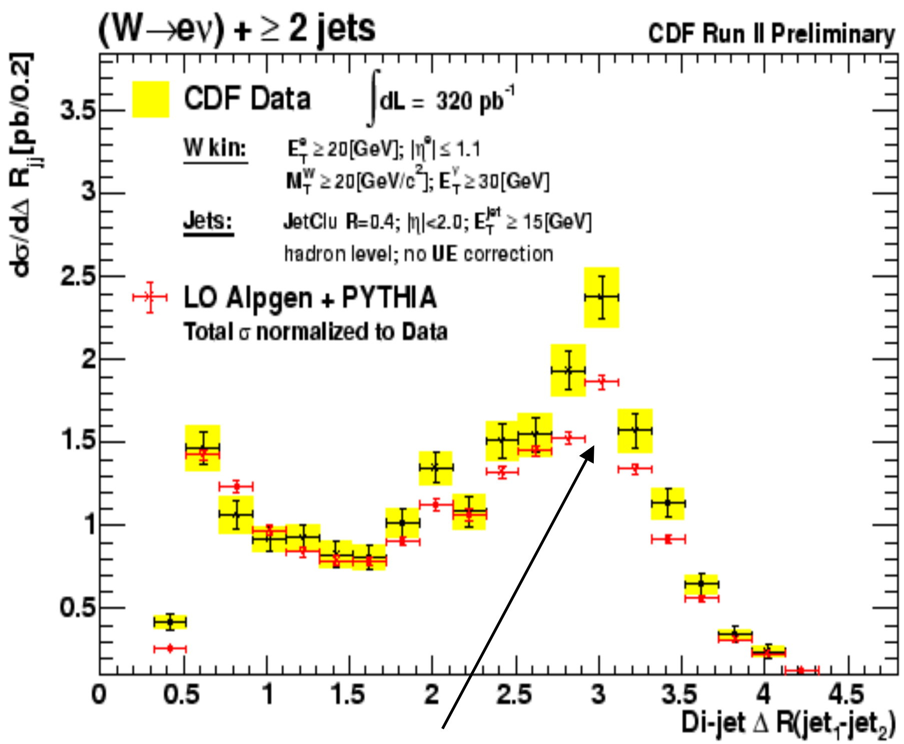


Comparison with ME+PS implementations for W+ N_{jet} production and different matching procedures

- MADGRAPH v4 + PYTHIA 6.3 (CKKW)
- ALPGENv2 + HERWIG 6.5 (MLM)

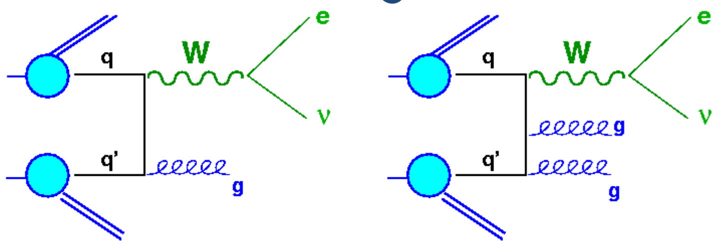
Comparison with NLO pQCD (MCFM)
CTEQ6.1M and $\mu^2 = M_W^2 + (P_T^W)^2$

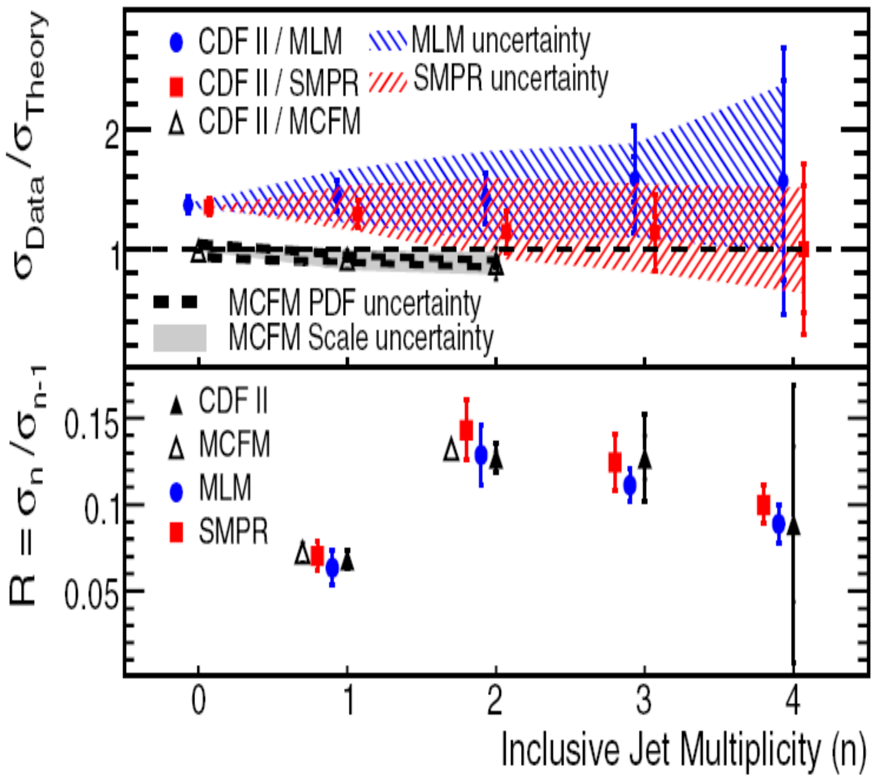


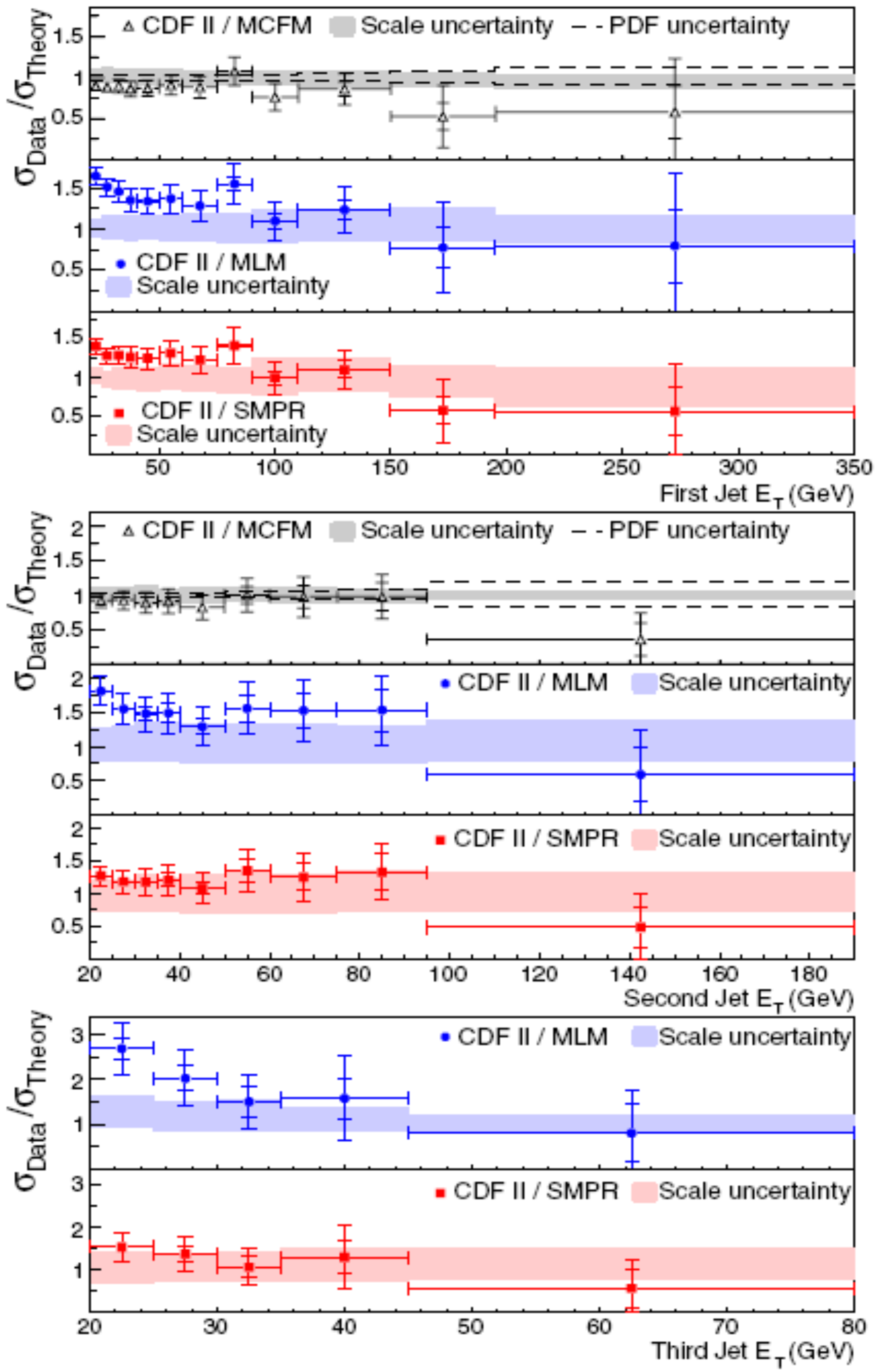


Affected by cutoff and soft radiation

W+jet(s)

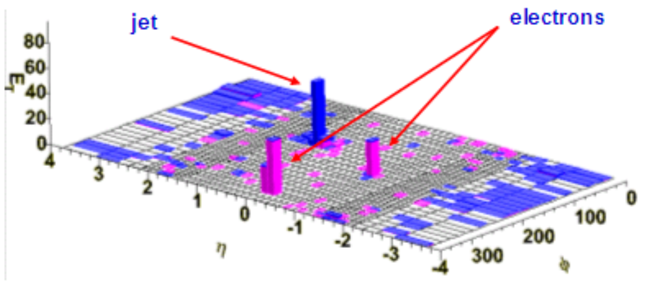






Good agreement with pQCD NLO calculation

ME+ PS needs UE contributions at low P_T and suffers scale uncertainties at large N_{jet} but describes the σ_N/σ_{N-1} ratios



$Z/\gamma^*(\to ee)$ +jet(s)

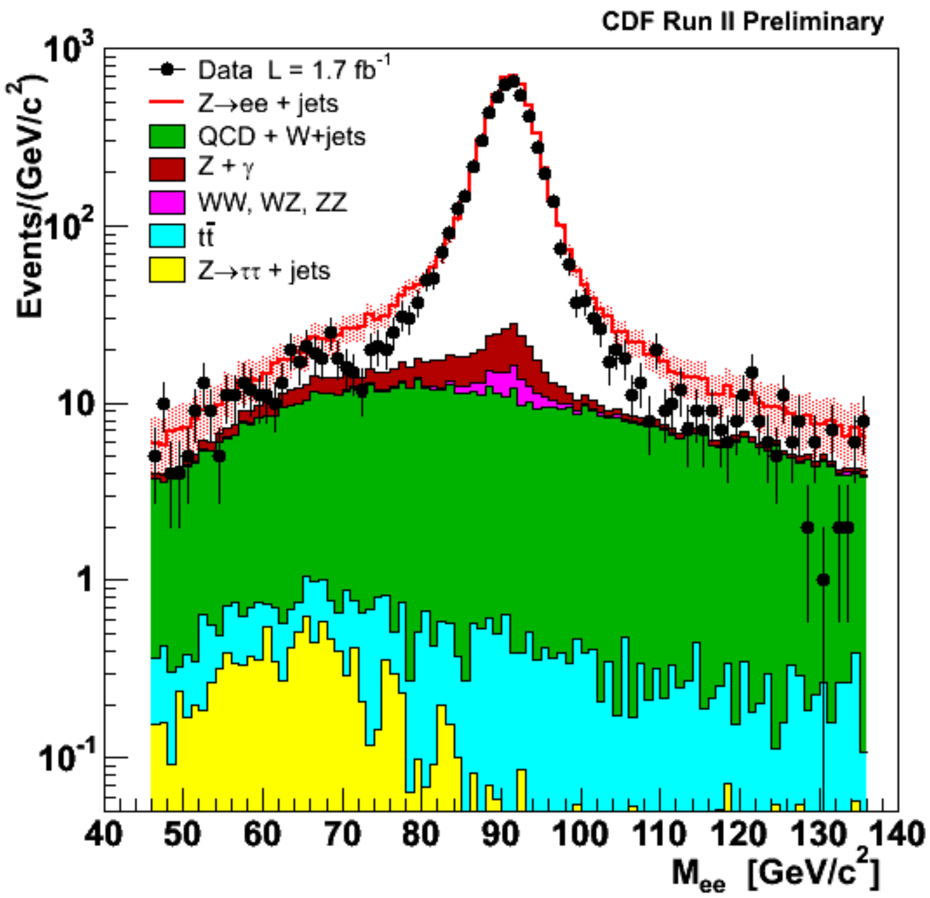
Results with 1.7 fb^{-1} → *Phys. Rev. Lett.* ***100, 102001 (2008)***

Updated results based on 2.5 fb^{-1}

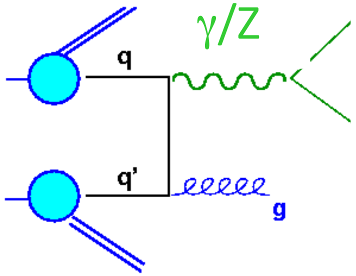
- CDF standard electron ID
  - At least one central electron
  - $E^e_T > 25$ GeV
  - $|\eta^{e1}|<1$, $|\eta^{e2}| <1$ or $1.2 < |\eta^{e2}|<2.8$
  - $66 < M_{ee} < 116$ GeV/c^2
  - No isolation requirements (avoids bias at very high P_T^{jet})

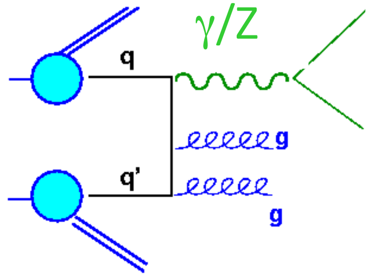
- At least one jet MidPoint (R=0.7)
  - Electrons removed before clustering
  - $P_T^{jet} > 30$ GeV/c
  - $|y^{jet}| < 2.1$
  - ΔR(e-jet) > 0.7

- Measurement corrected for detector effects back to the hadron level and defined in the given limited kinematic region (no extrapolation made)



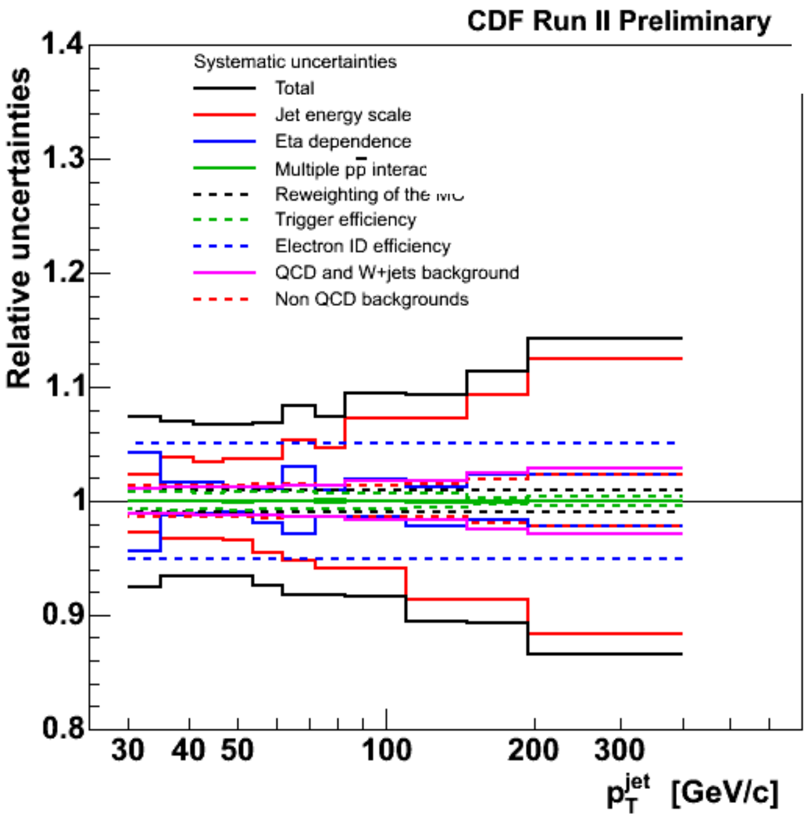
Background at the level of 12% - 17% (dominated by QCD and W+jets)

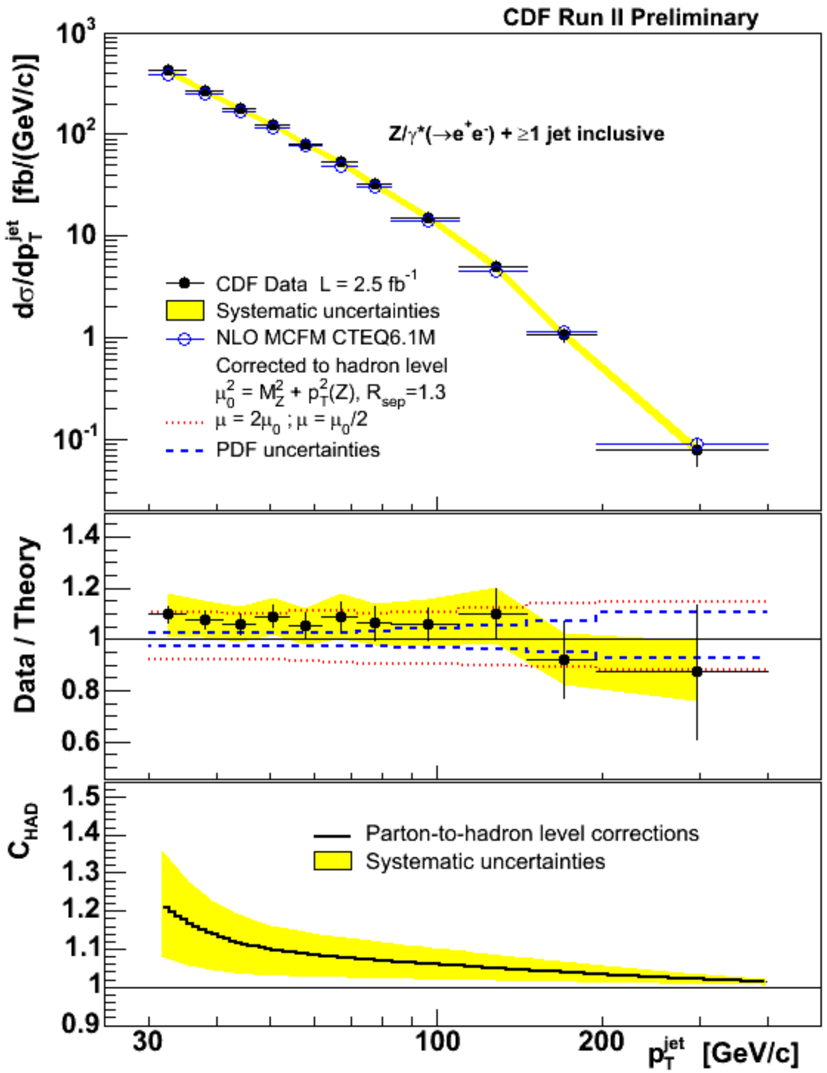




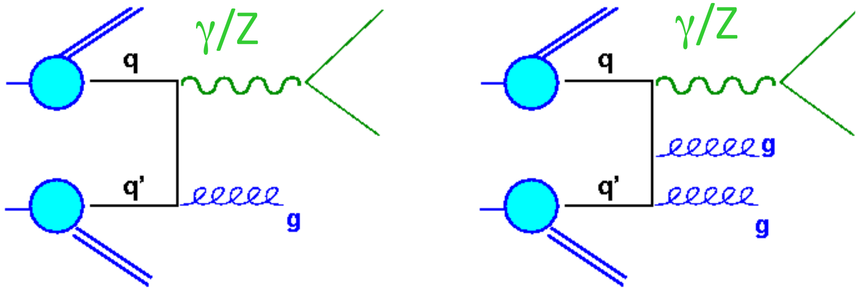
Inclusive Z/γ*(-> ee) + Jet

8% to 15% accuracy in the measurement
(dominant Jet Energy Scale uncertainty)



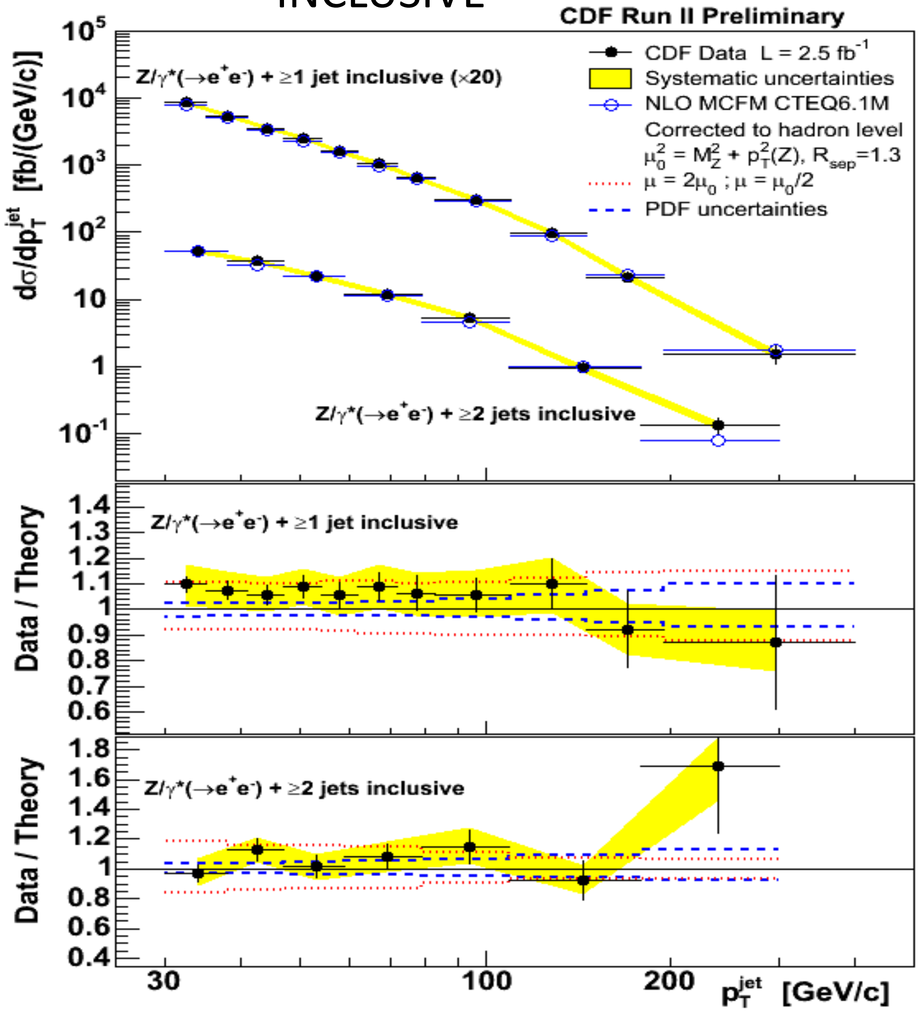


Good agreement with NLO pQCD (MCFM) predictions including non-pQCD corrections

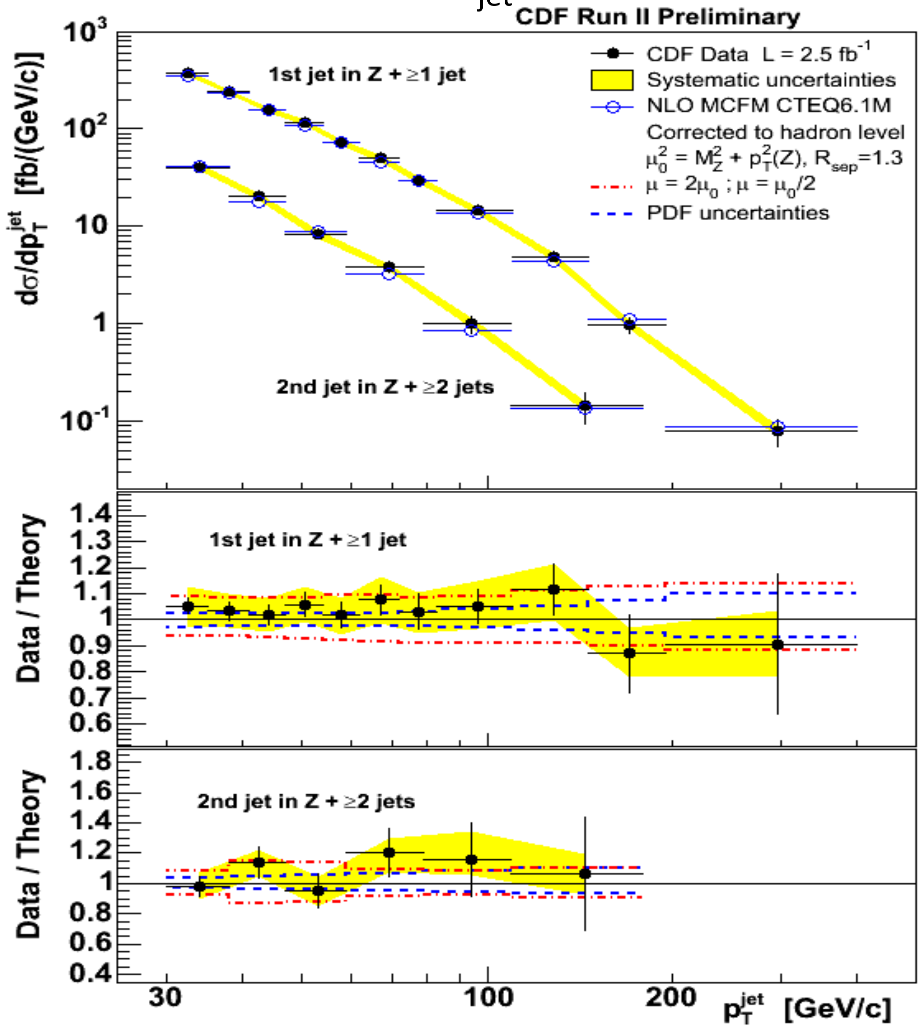


Z/γ*(-> ee) +jet(s)

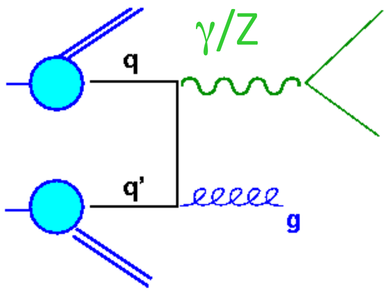
INCLUSIVE

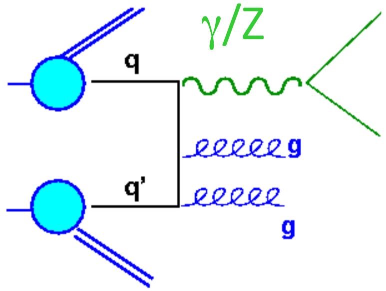


Nth Jet in incl. Z+ Njet

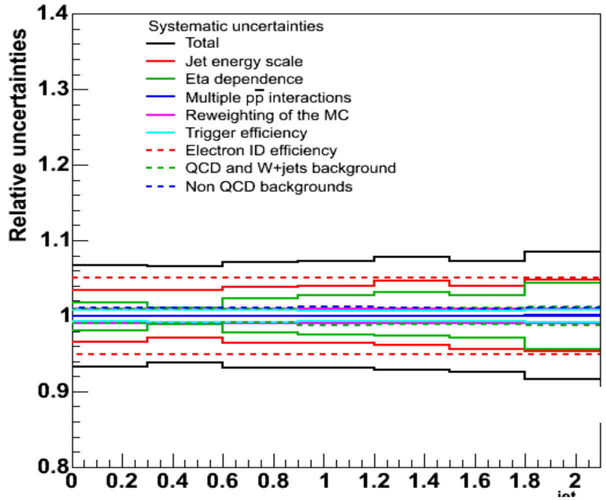


Good agreement with NLO pQCD predictions

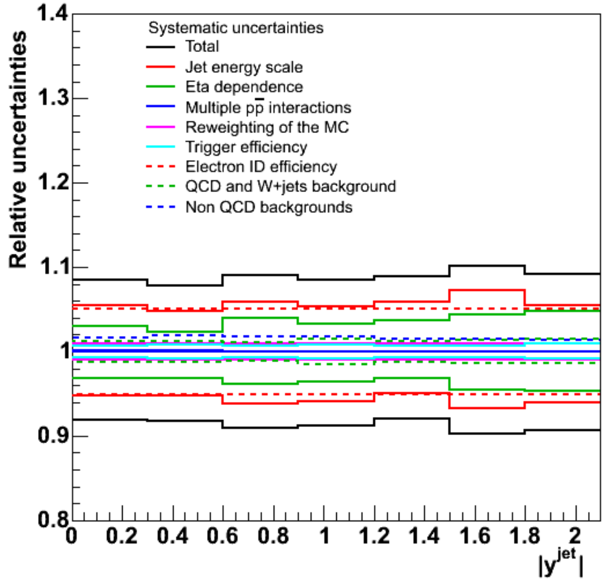


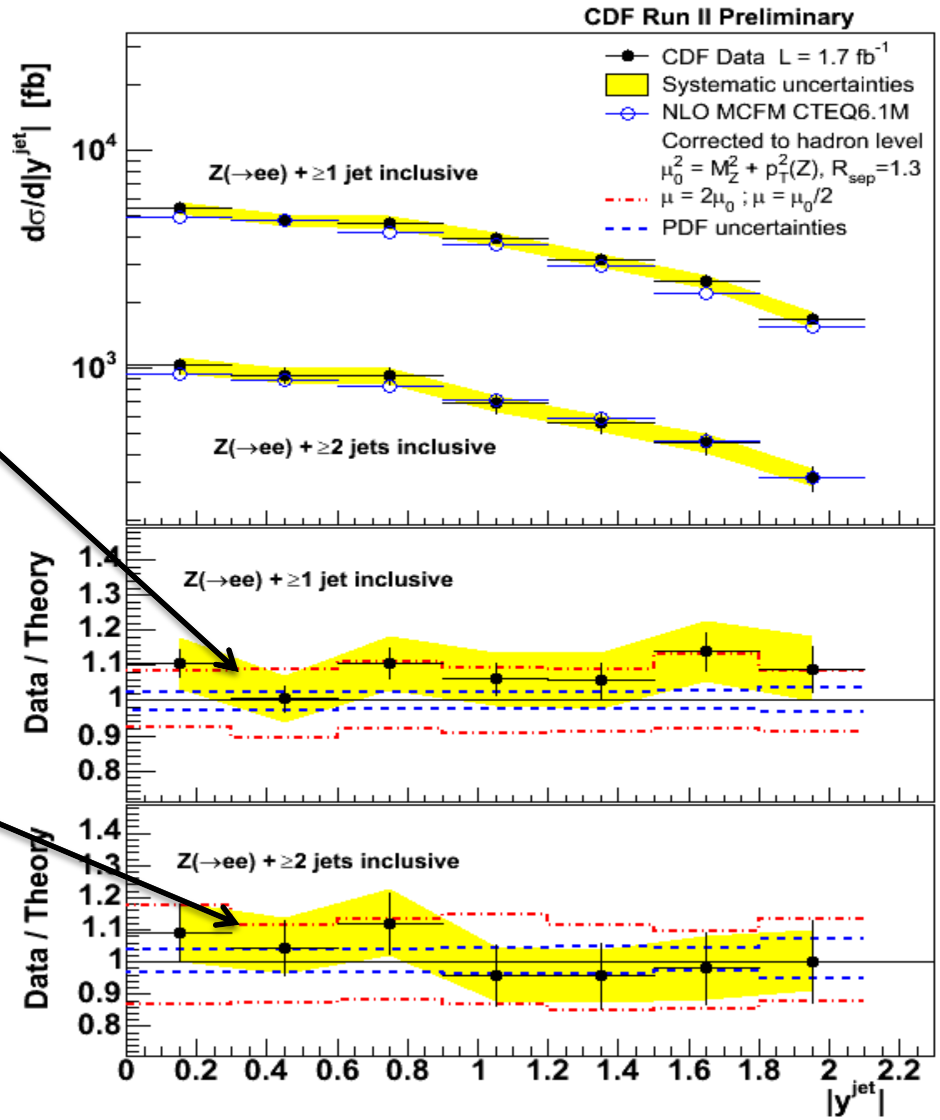


Cross Sections in $|y^{jet}|$



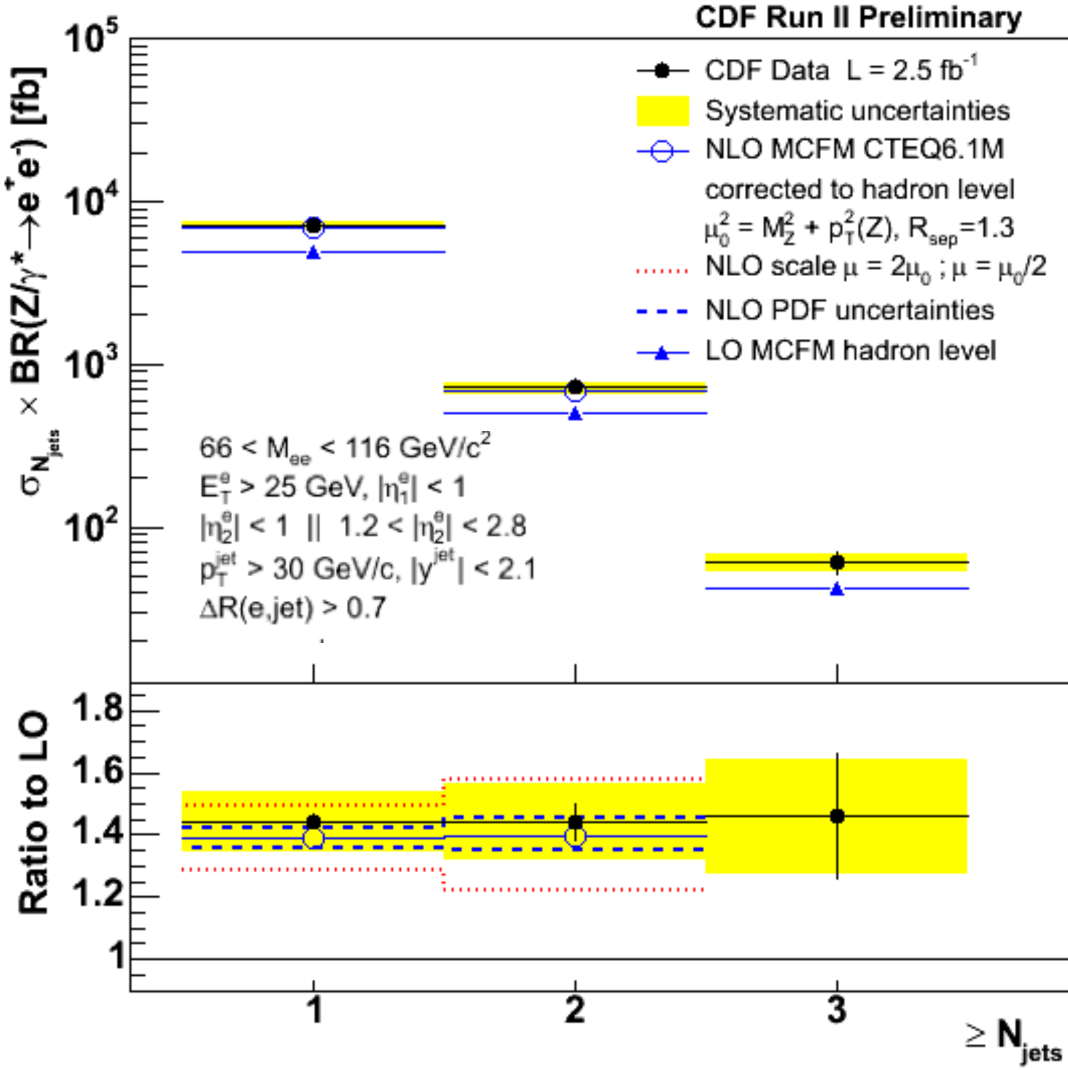
Systematics:
8 – 10 %

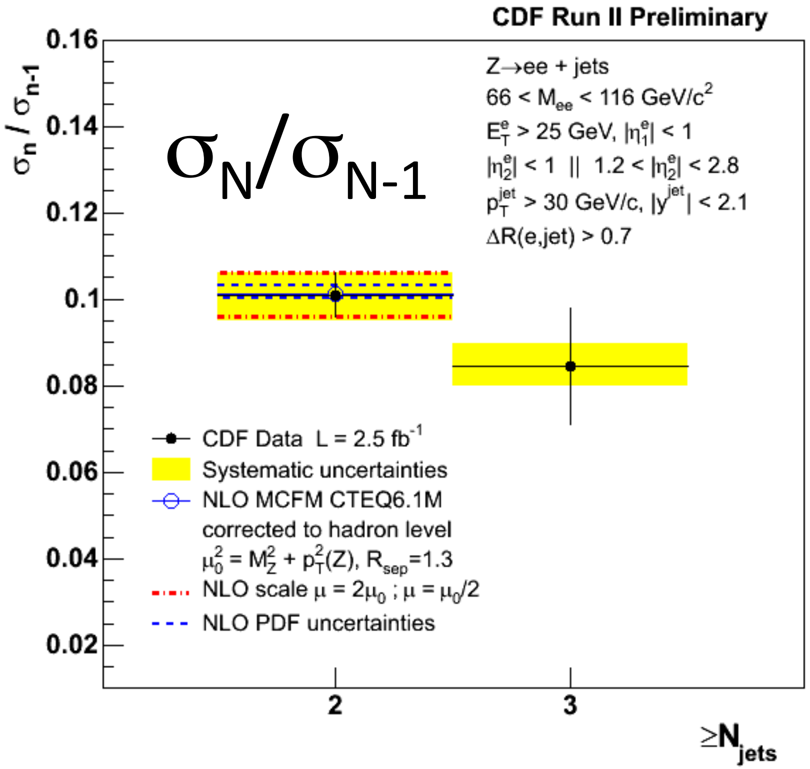


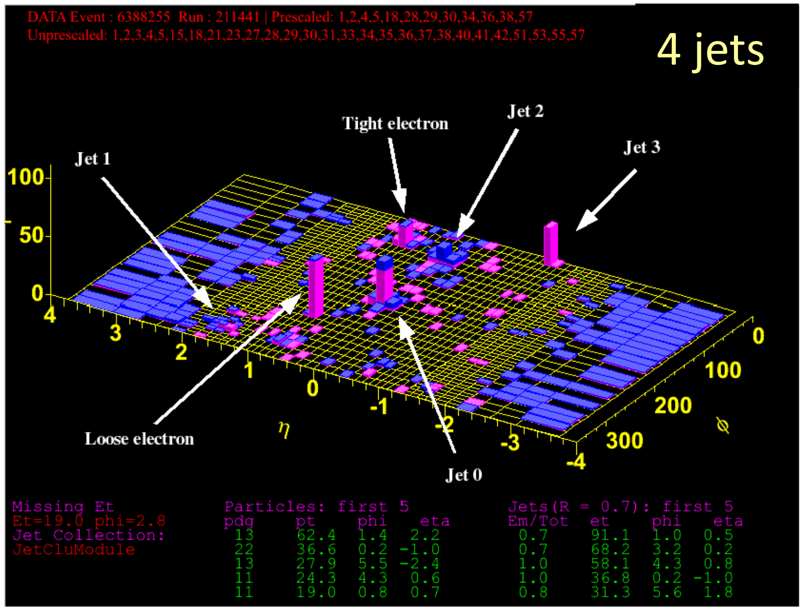


Good agreement with NLO pQCD predictions

Inclusive Jet Multiplicity





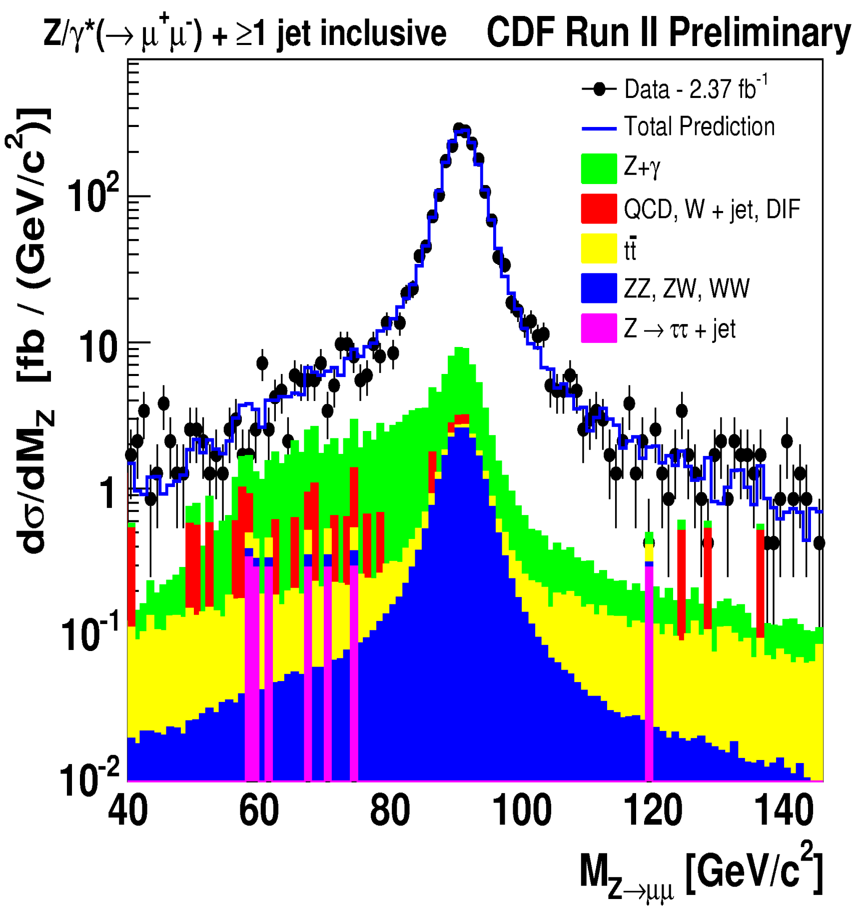


Data supports common LO-to-NLO K-factor
(note potential limitation due to ΔR(e,jet) > 0.7)

$Z/\gamma^*(\to \mu\mu)$ +jet(s)

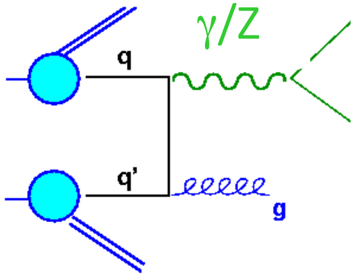
NEW results based on 2.4 fb^{-1}

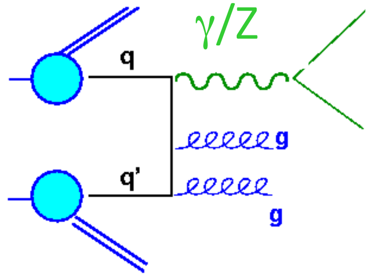
- CDF standard muon ID
  - $P_T > 25$ GeV
  - $|\eta^1|<1$, $|\eta^2|<1$
  - $66 < M_{\mu\mu} < 116$ GeV/c^2
- At least one jet MidPoint (R=0.7)
  - $P_T^{jet} > 30$ GeV/c
  - $|y^{jet}| < 2.1$
  - $\Delta R(\mu\text{-jet}) > 0.7$
- Follows the analysis in the electron channel with the aim for a future combination into a single result



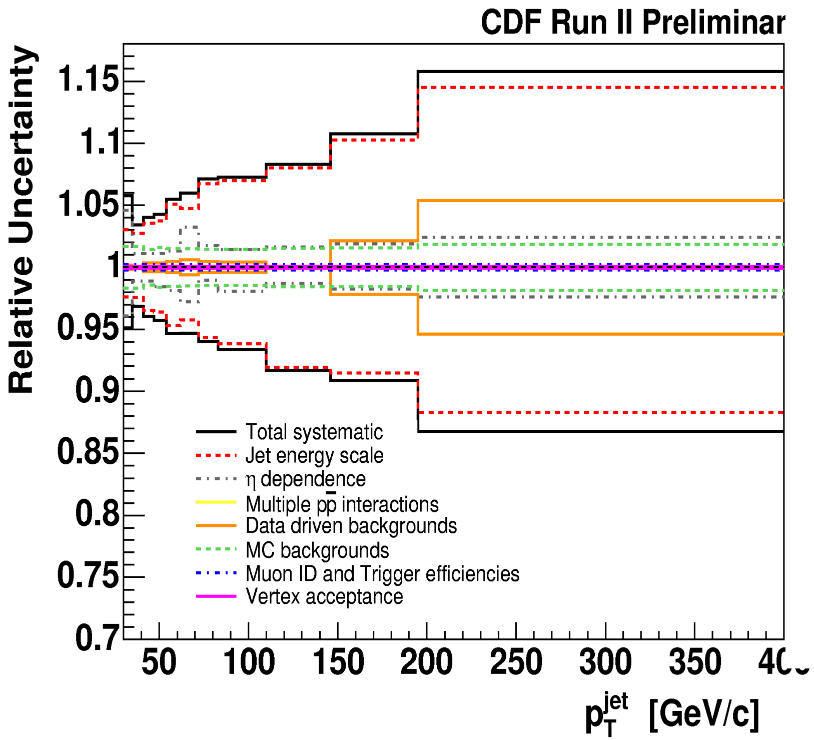
Background at the few % level

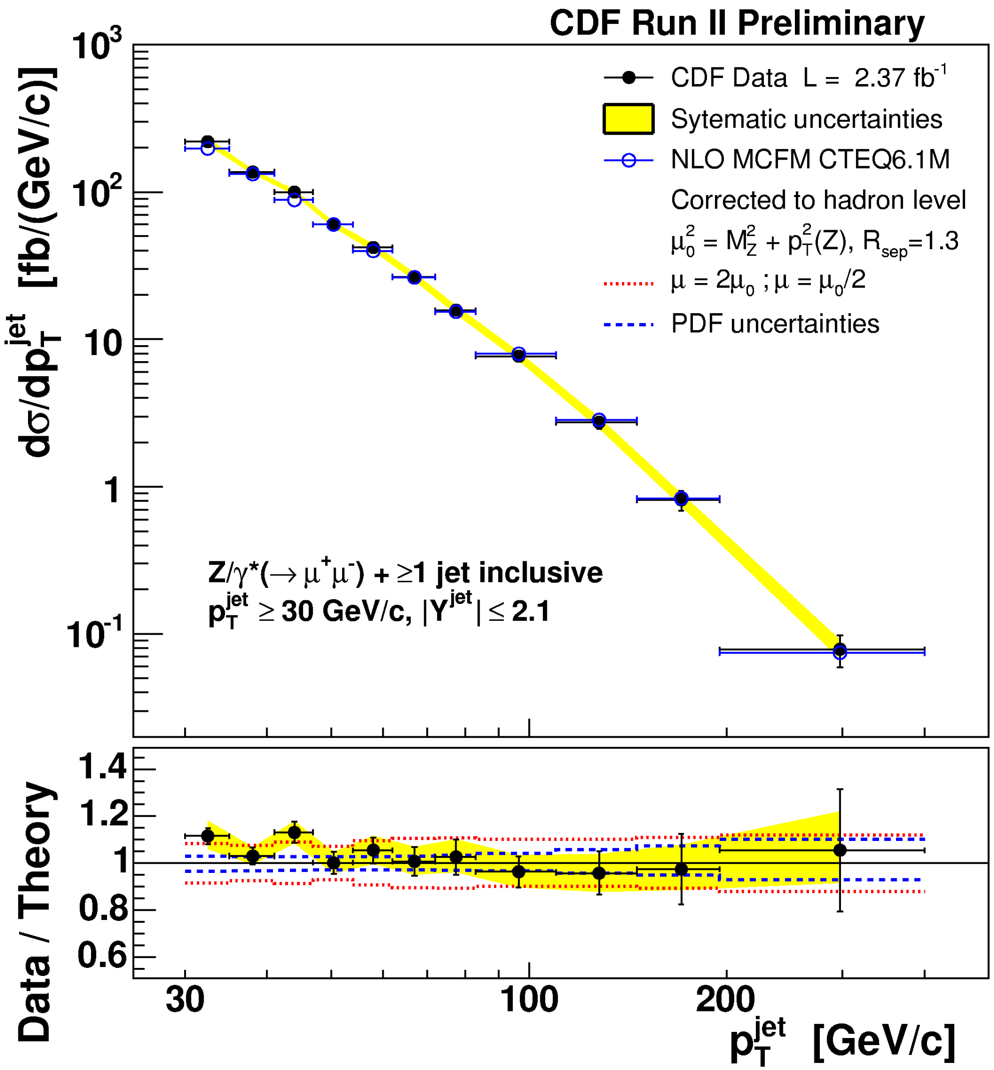
Inclusive $Z/\gamma^*(\rightarrow \mu\mu)$ + 1 Jet





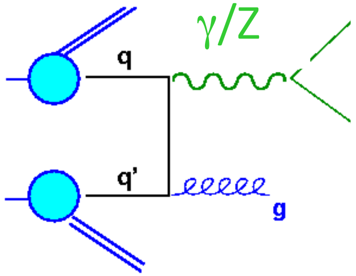
5% to 15% accuracy in the measurement
(dominant Jet Energy Scale uncertainty)

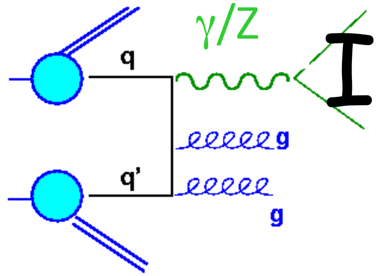




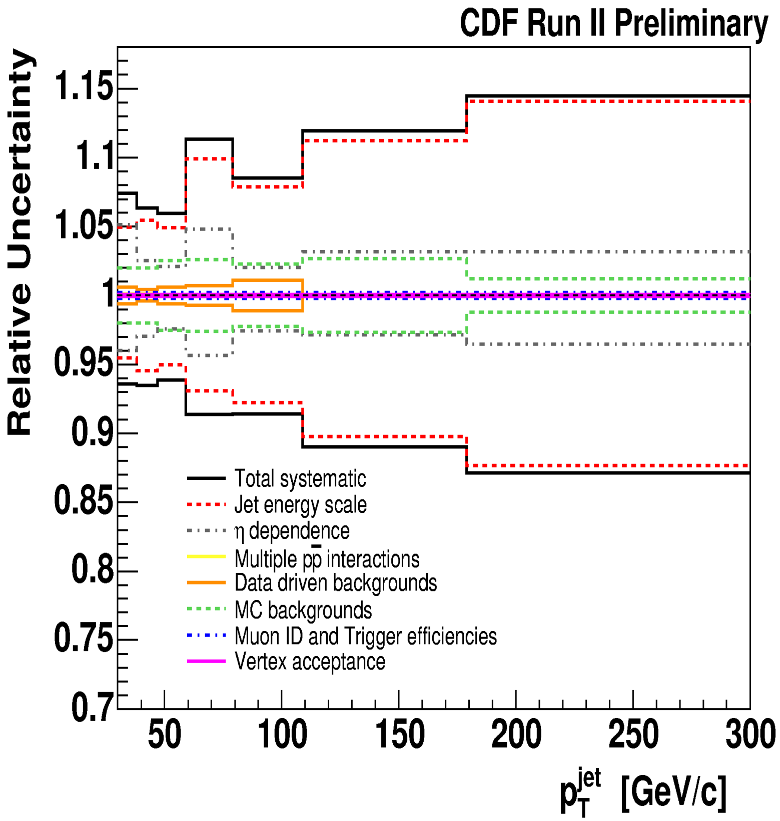
Good agreement with NLO pQCD (MCFM) predictions including non-pQCD corrections

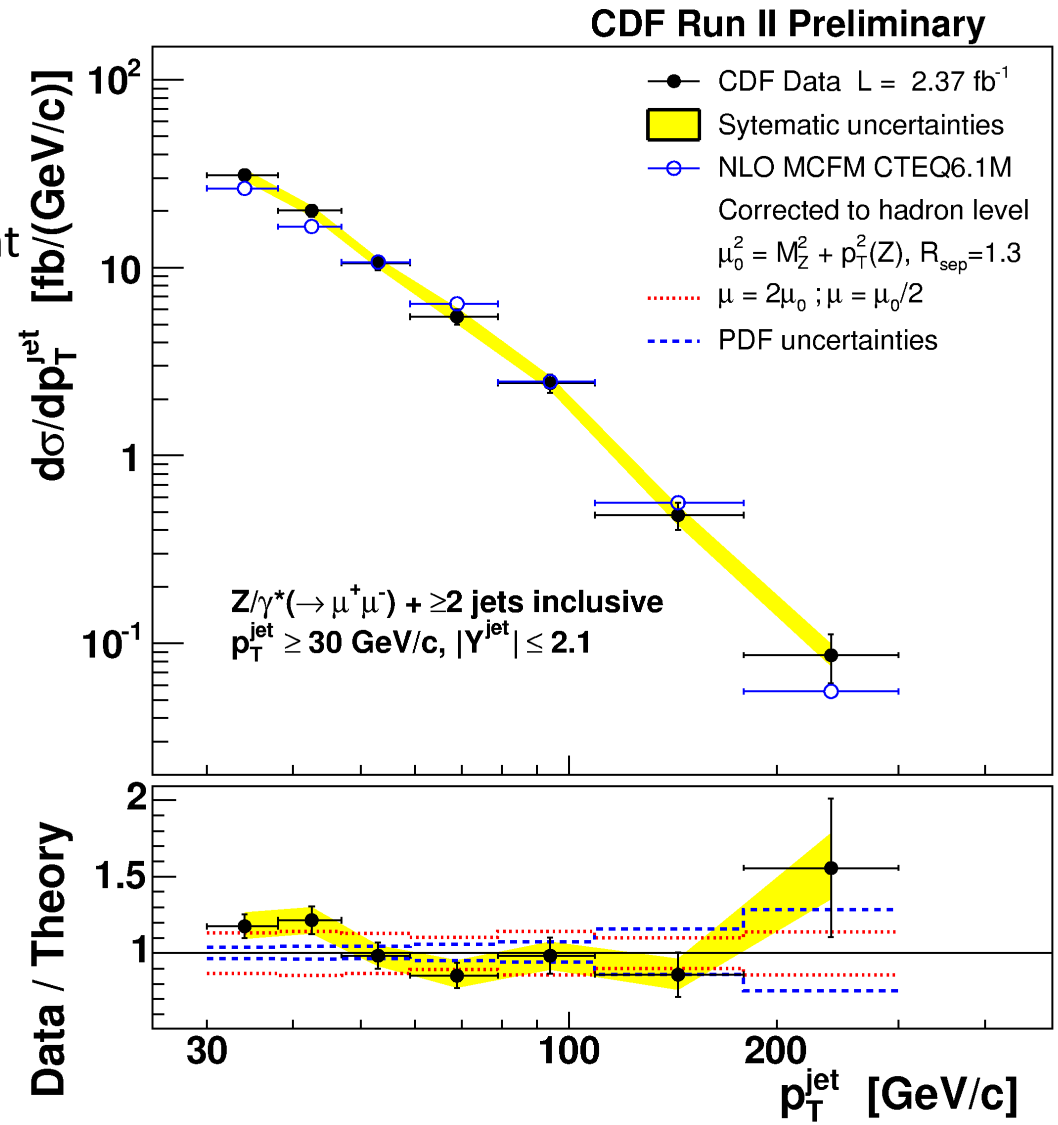
Inclusive Z/γ*(-> μμ) + 2 Jets



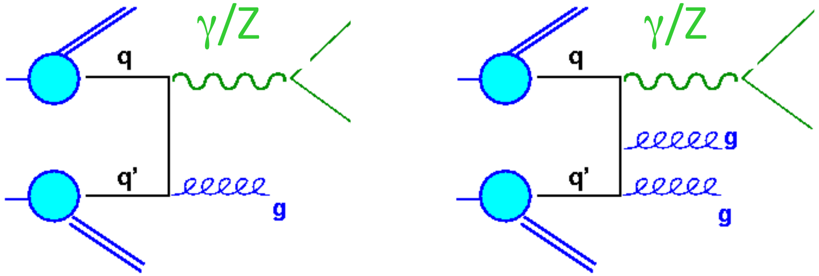


5% to 15% accuracy in the measurement
(dominant Jet Energy Scale uncertainty)

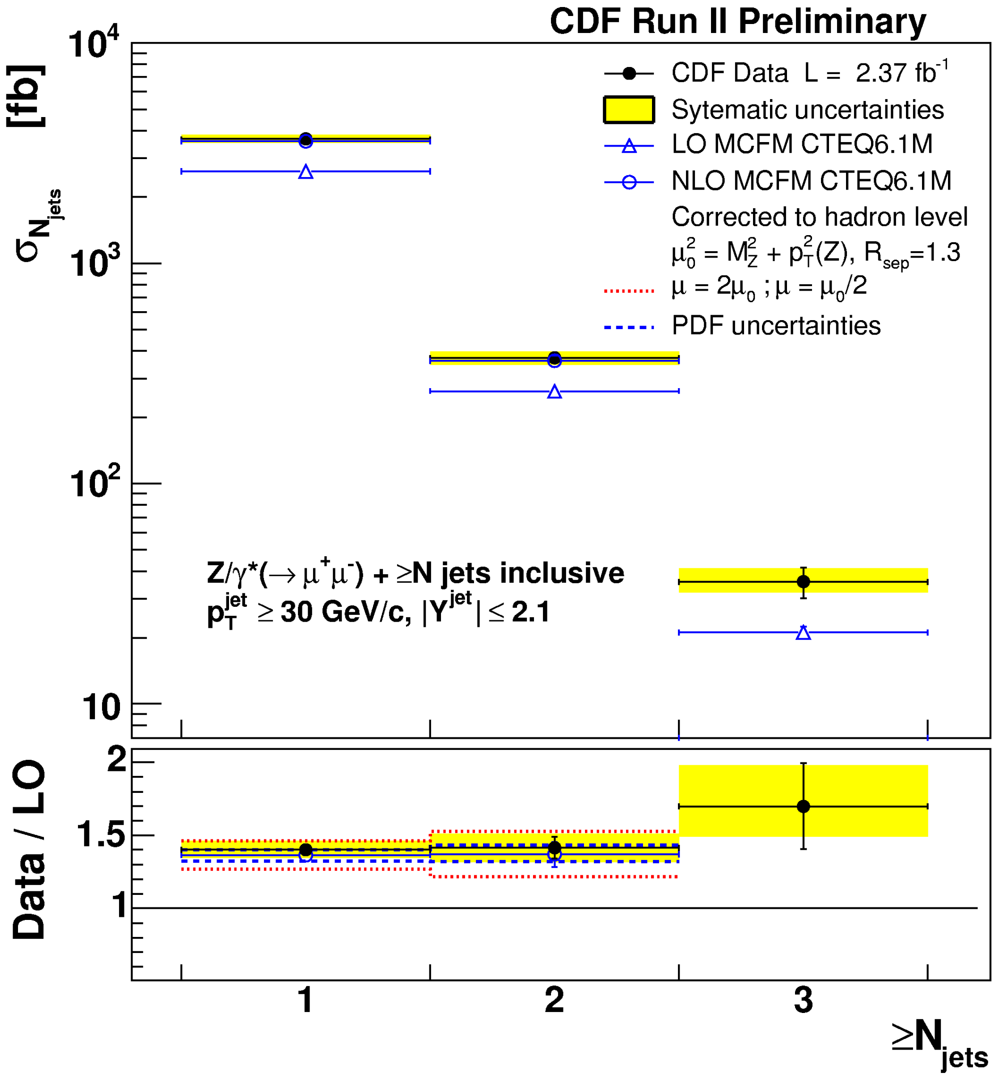




Good agreement with NLO pQCD (MCFM) predictions including non-pQCD corrections

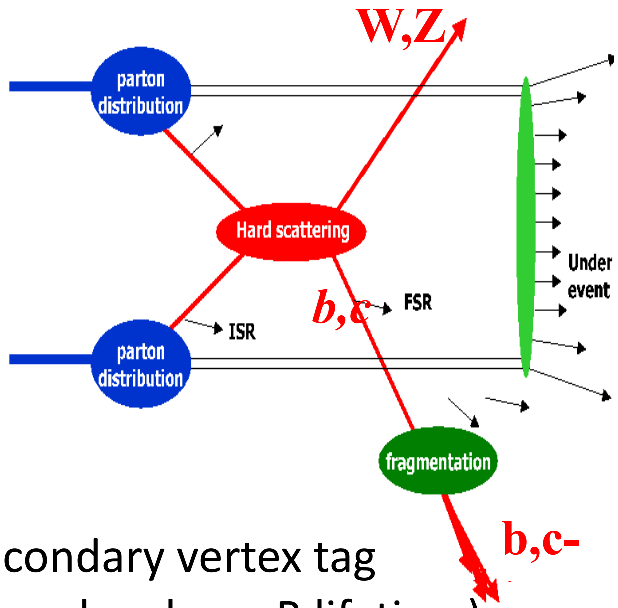


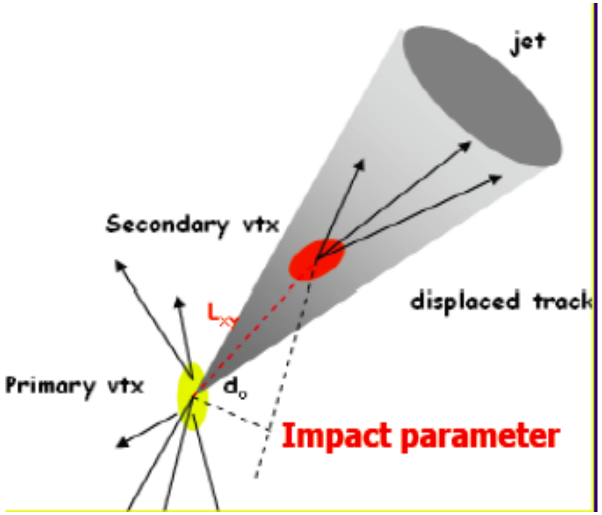
Inclusive Z/γ*(-> μμ) + Jet

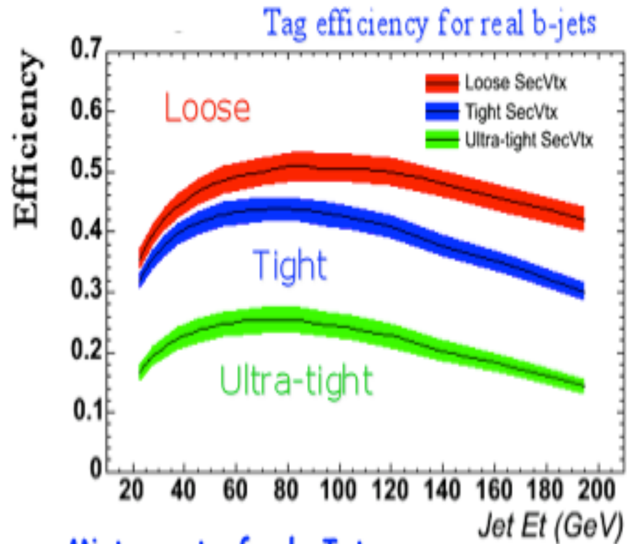


Plan to increase the data sample to ~5 fb-1 and combine electron and muon cross section measurements in a single result.

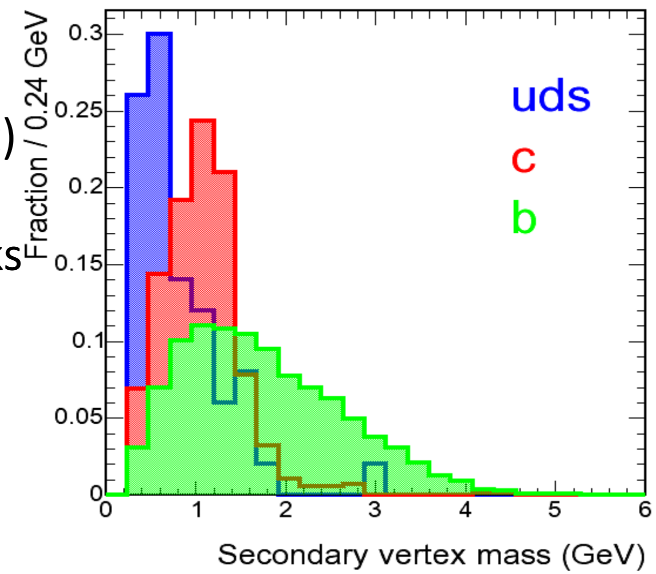
Boson + HF & B-tagging

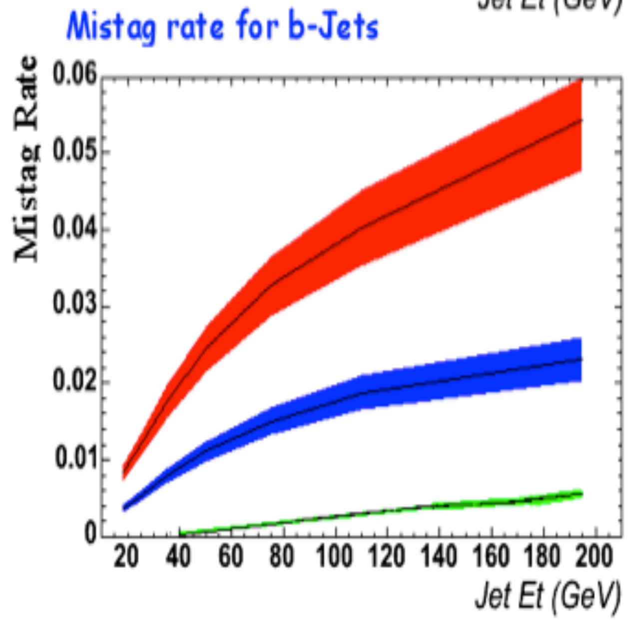




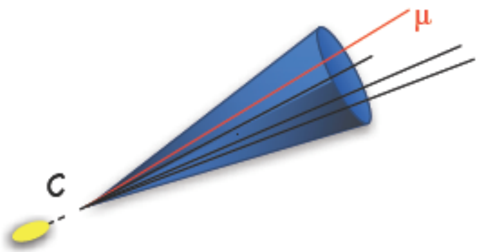


Secondary vertex tag
(based on large B lifetime)
- 3 operating points in efficiency and purity (loose/tight/ultra-tight)
- Secondary vertex mass used to separate light from c and b quarks



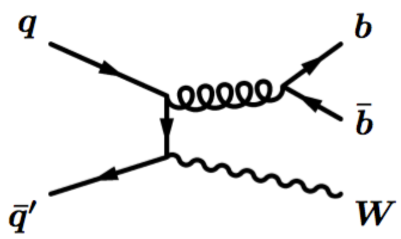


Soft Lepton Tag
(20% Branching ratio…)



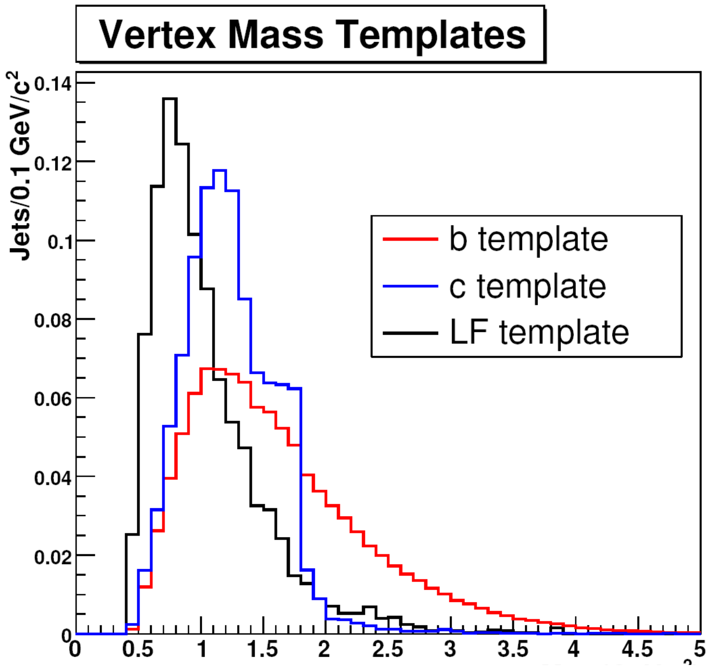
Main uncertainties from templates definition, b- tag efficiencies and mistag rates

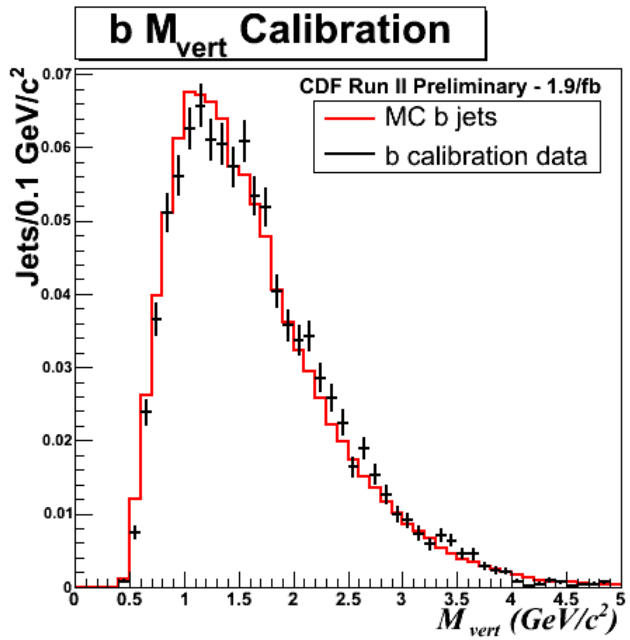
W +b-jet(s)



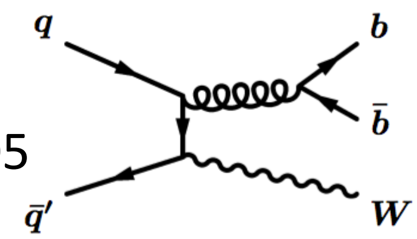
(submitted to PRL) arXiv:0909.1505v2

- Both electron and (muon) channels
  - P_T>20 GeV/c
  - $|\eta|$<1.1
  - MET > 25 GeV
- Exactly one or two jets JetClu (R=0.4)
  - E_T^{jet} >20 GeV/c
  - $|\eta^{jet}|$ < 2.0
- B-tagging looking for displaced vertices (ultra-tight)
  → 943 tags
- B-quark composition extracted
  from fit to secondary vertex mass
  - Templates for light, charm and bottom taken from MC
  - Validated in control samples in data
- Physics Processes that contribute:
  - W+b/c production (taken from ALPGEN)
  - Top and dibosons (taken from PYTHIA)
  - Single top production (taken from MADEVENT)
  - QCD multijets (from DATA)
- Comparison with theory in the restricted phase space
  (no extrapolation is made)





W+b-jet(s)



Fraction of b-jets : 0.71 +- 0.05

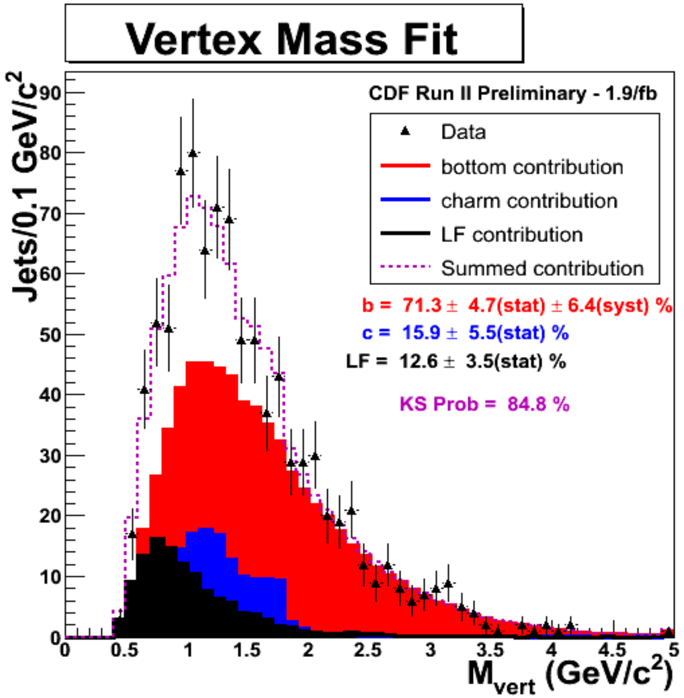
In 1.9 fb^{-1}
TOTAL : 670 +- 44 (stat.) b-tagged jets
BACKG.: 177 +- 22 (stat.) "

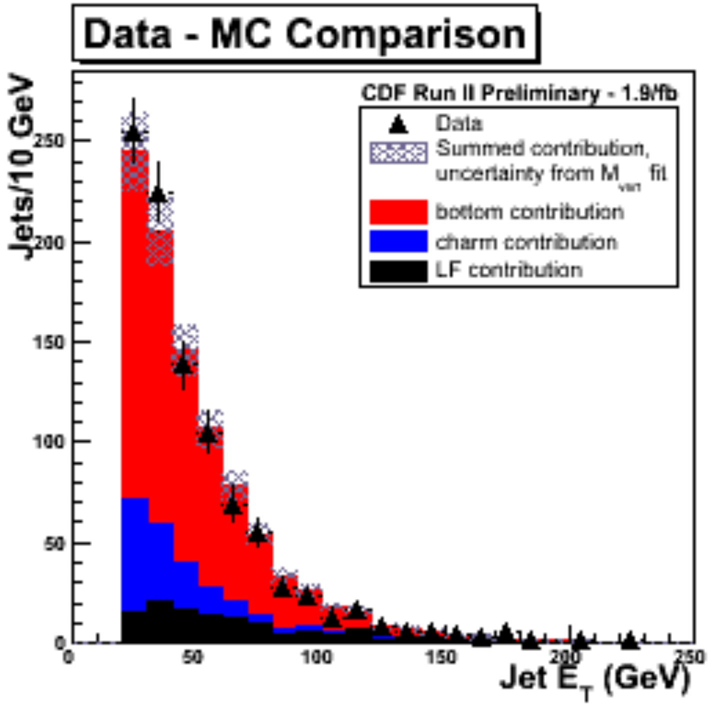
18% uncertainty on the measurement
vertex modeling (8%)
b-tag effi. (6%), lumi. (6%)

$$\sigma_{bjets}\ (W + b\ jets) \times BR(W \rightarrow l\nu)$$
$$= 2.74 \pm 0.27 \pm 0.42\ pb$$

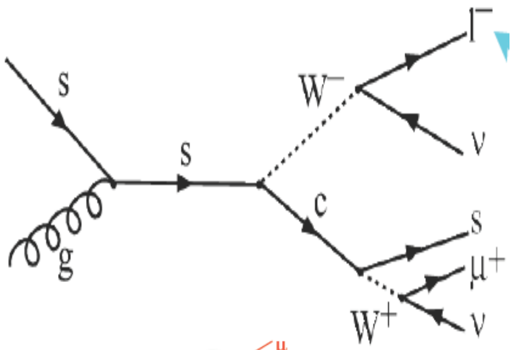
ALPGENv2 +PYTHIA 6.3 ($Q^2 = M_W^2 + P_{T,W}^2$) = 0.78 pb
NLO pQCD = 1.22 +- 0.14 pb

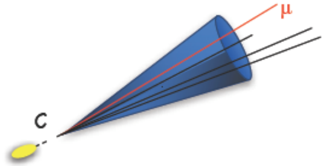
→ **More to come in terms of differential cross sections**

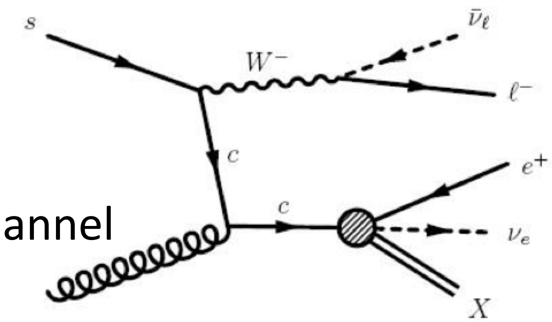




W+c







Muon channel | Electron channel

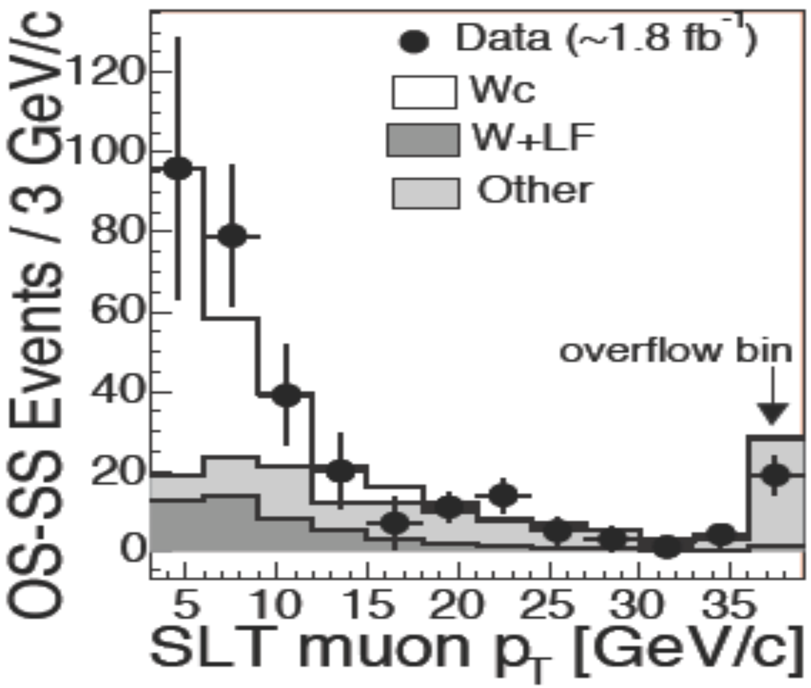
$$\sigma_{W+c} \times Br(W \to l\nu) = \frac{N^{OS-SS}_{measured} - N^{OS-SS}_{bkg}}{L \times A \times \varepsilon}$$

NEW (4.3 fb^{-1})

Muon channel

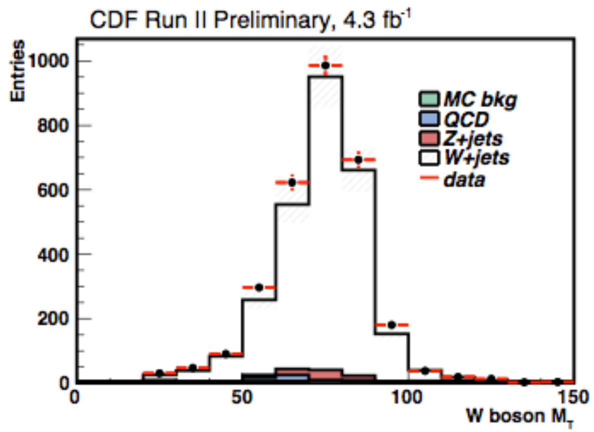
$\sigma_{Wc} x Br(W \to l\nu) = 9.8 \pm 3.2\, pb$

$NLO: 11.0^{+1.4}_{-3.0}\, pb\ (p_{Tc} > 20\ GeV/c,\ |\eta_c| < 1.5)$



Electron channel

E^e_T>20 GeV, $|\eta^e|$<1.1
MET > 30 GeV, M^W_T > 20 GeV



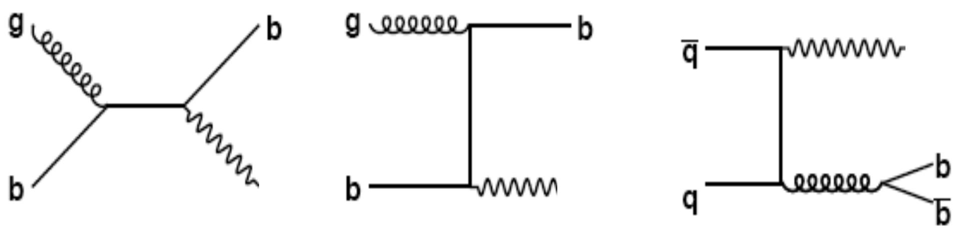
E_T^{jet} >20 GeV/c, $|\eta^{jet}|$ < 2.0 (R= 0.4)

$\sigma_{Wc} x Br(W \to l\nu) = 33.7 \pm 11.4(stat.) \pm 4.7(syst.)\, pb$

$ALPGEN: 16.5 \pm 4.7\, pb$

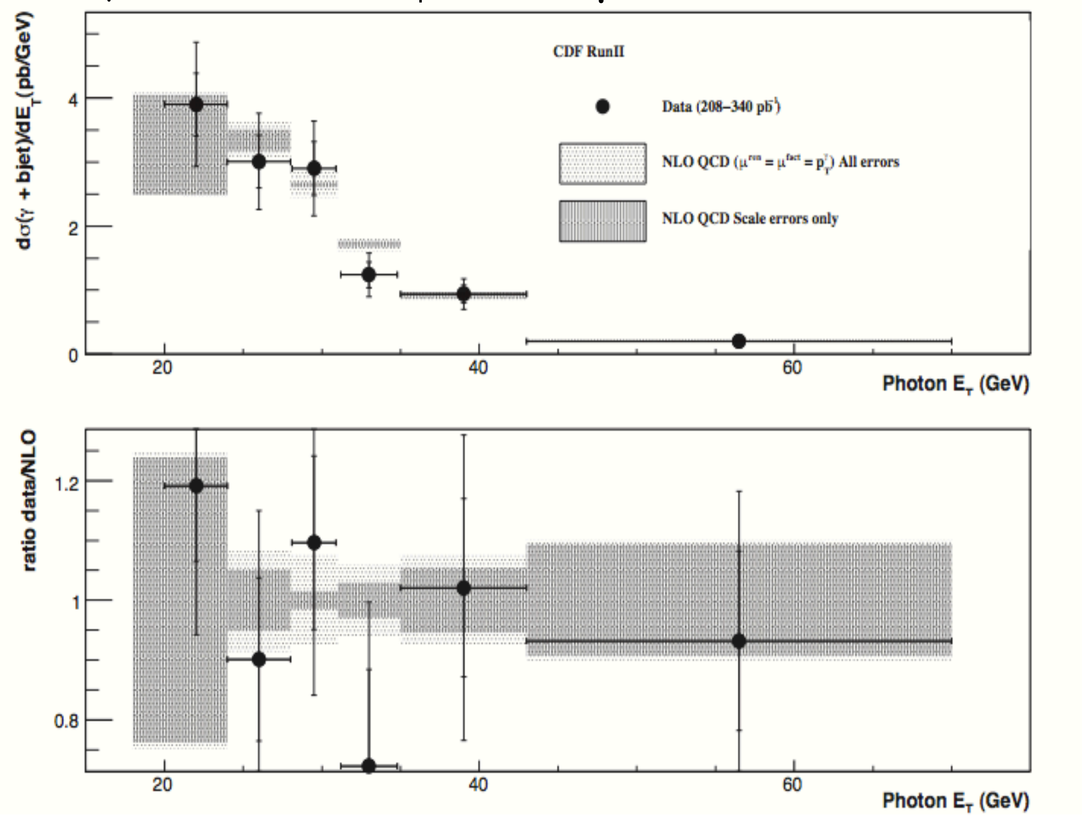
Phys. Rev. D81, 052006 (2010)

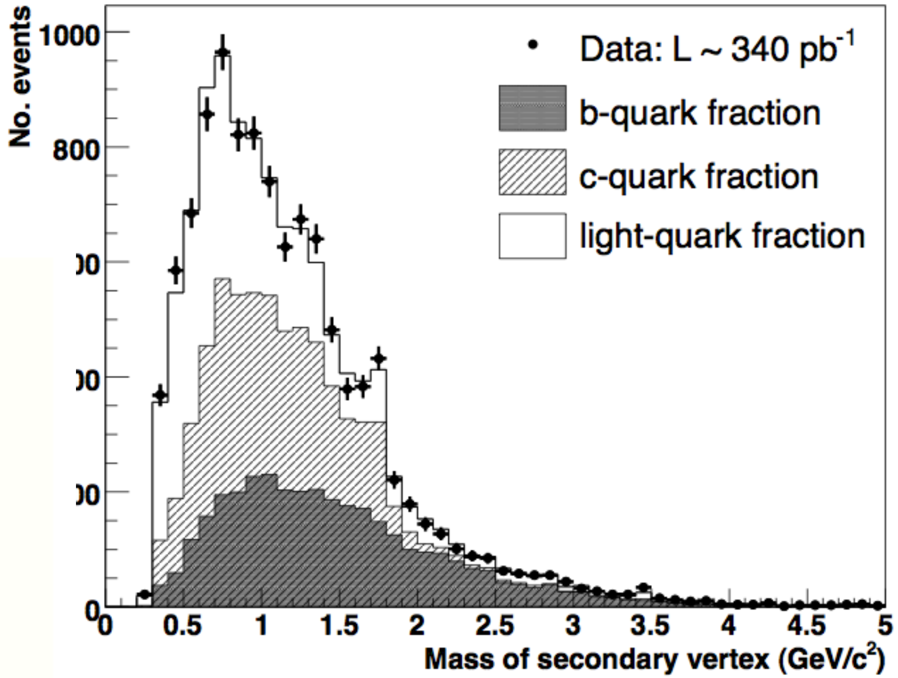
γ + b-quark



Isolated photons (E_T in R= 0.4 < 2 GeV)
E_T> 20 GeV/c, $|\eta|$ < 1.1

Jets with R=0.4 and R=0.7
E_T > 20 GeV, $|\eta|$ < 1.5 ("parton level")



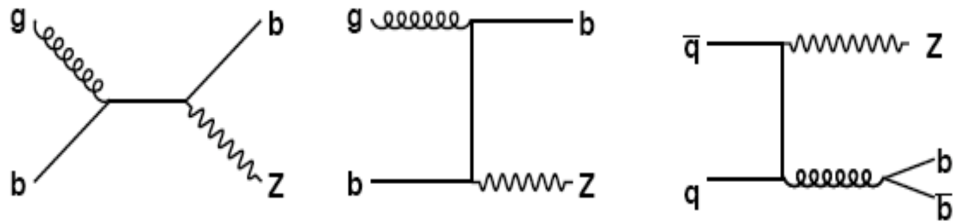


In agreement with NLO prediction
(no UE or fragmentation corrections
Included in this case…)

2 fb^{-1}

Phys.Rev.D79:052008,2009

Inclusive Z+b



$$\frac{\sigma^{\rm jet}(Z + b\,{\rm jet})}{\sigma(Z)} = \frac{N^{\rm jet}(Z + b\,{\rm jet})/N(Z)}{\epsilon^{\rm jet}(Z + b\,{\rm jet})/\epsilon(Z)}$$

Considering electron and muon channels

76 < M_{ll} < 106 GeV
(eff. 41% for Z→ ee, 23% for Z→ μμ)

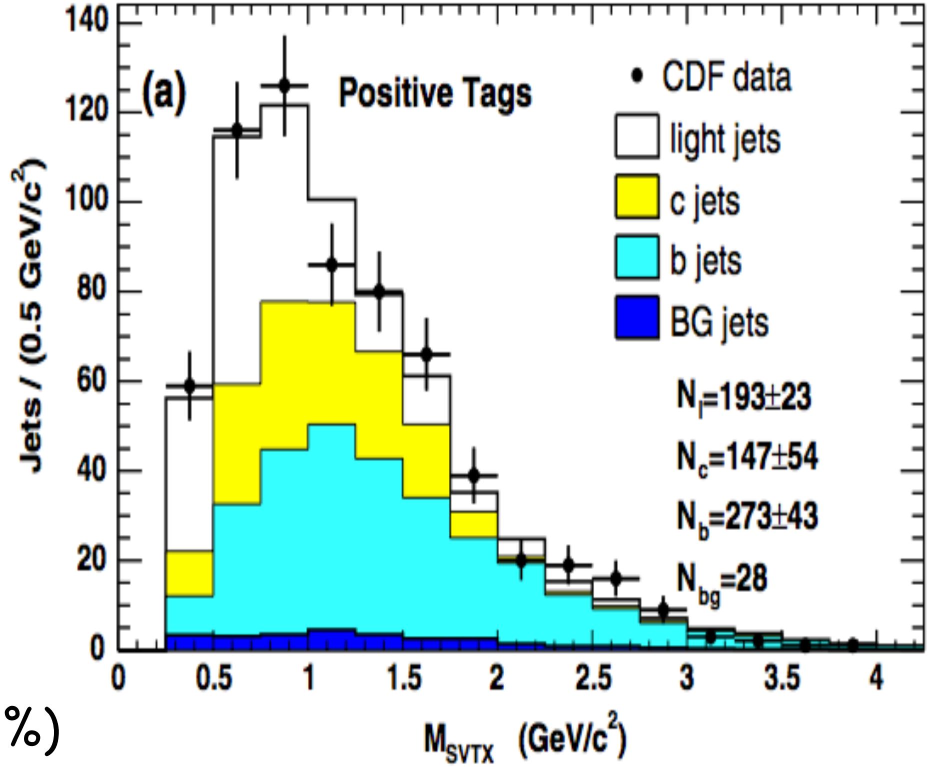
Jets with Et > 20 GeV and |η| < 1.5
(JETCLU R=0.7)

At least one jet b-tagged (eff. Z+b-jet : 9%)

(b-jet fraction from fit to vertex mass)

Background from other
physics processes taken from MC

non-pQCD corrections applied to MCFM : +8%

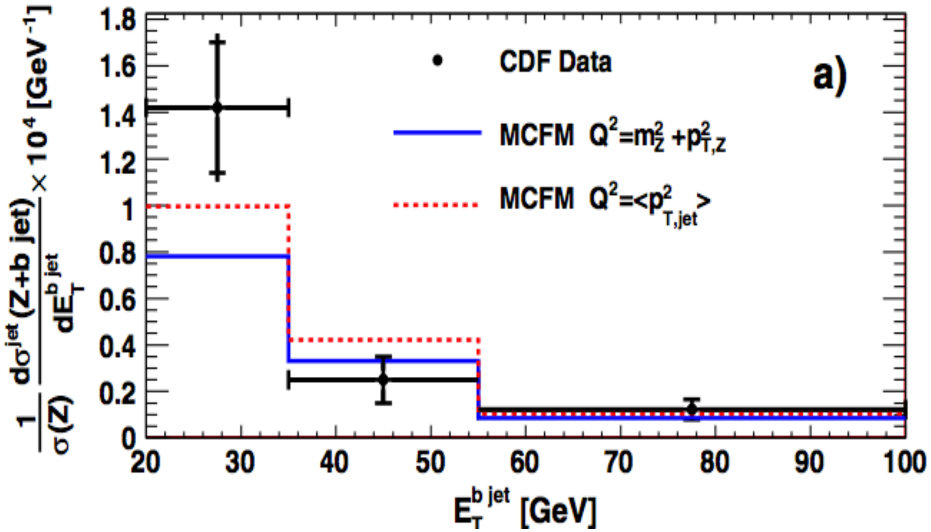


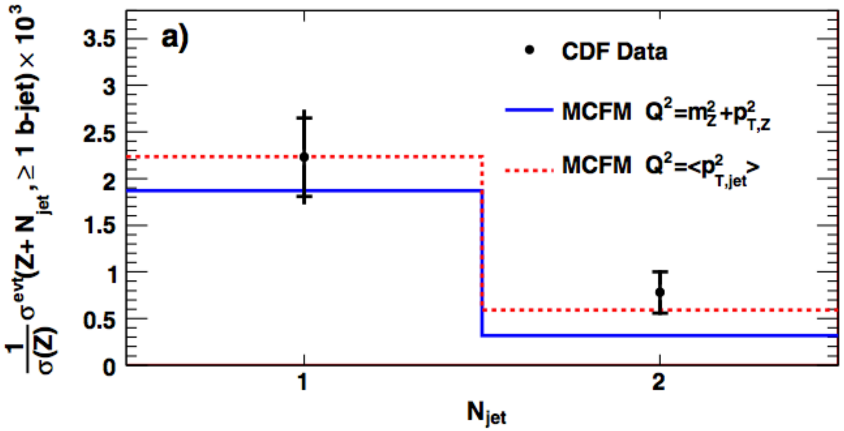
$$\frac{\sigma^{\rm jet}(Z + b\,{\rm jet})}{\sigma(Z)} = (3.32 \pm 0.53({\rm stat}) \pm 0.42({\rm syst})) \times 10^{-3}.$$

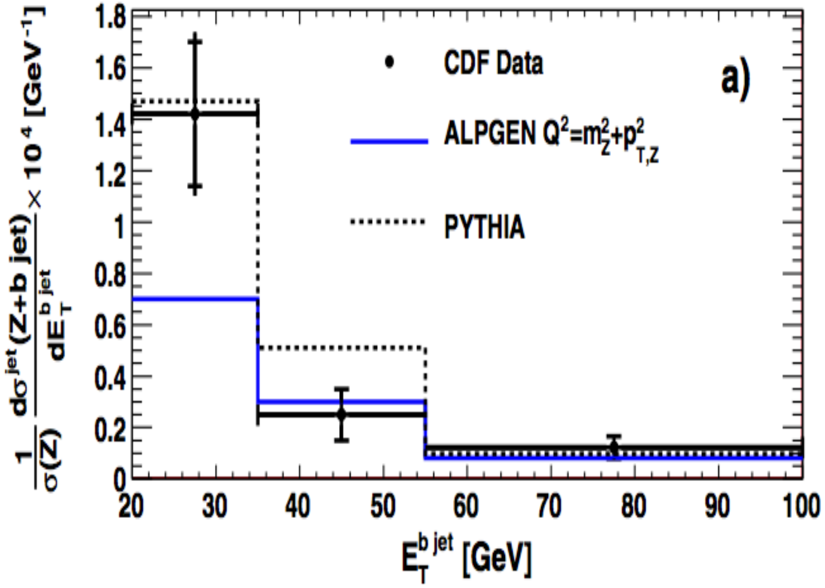
$$MCFM: 2.3 \times 10^{-3}\ (Q^2 = M_Z^2 + P_{T,Z}^2)$$

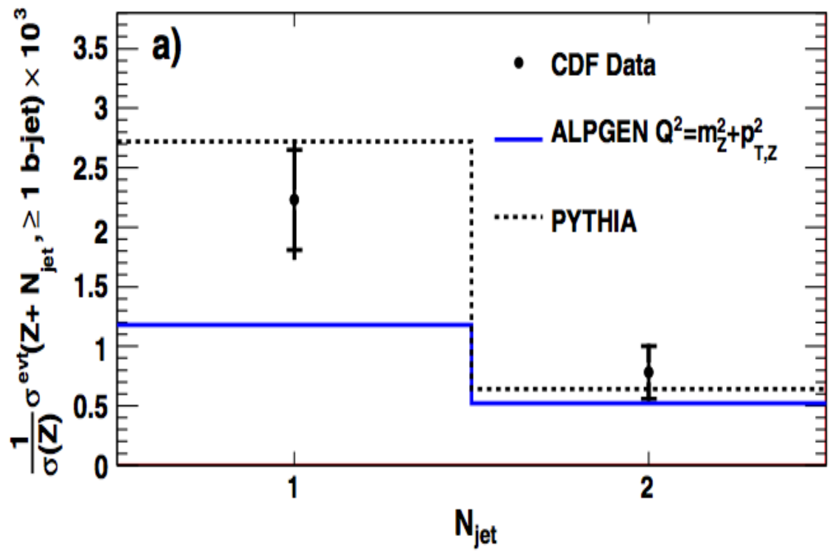
$$: 2.8\ \times 10^{-3}\ (Q^2 = \ < P_{T,Jet}^2 >)$$

Z+b









$$\frac{\sigma(Z+b)}{\sigma(Z+jets)} = 2.08 \pm 0.33 \pm 0.34(\%)$$

$$MCFM: 1.8\%\ (Q^2 = M_Z^2 + P_{T,Z}^2)\ ;\ 2.2\%\ (Q^2 = \ <P_{T,Jet}^2>)$$

Measurements in agreement with predictions
(large uncertainties in both data and theory)

Also large variations between PYTHIA and ALPGEN

MC4LHC and TeV4LHC

- **Z/W+jet(s) results test background estimations in searches for new physics**

- **New results on Z+jets and prospects for 5 fb-1 e/μ channels combination**

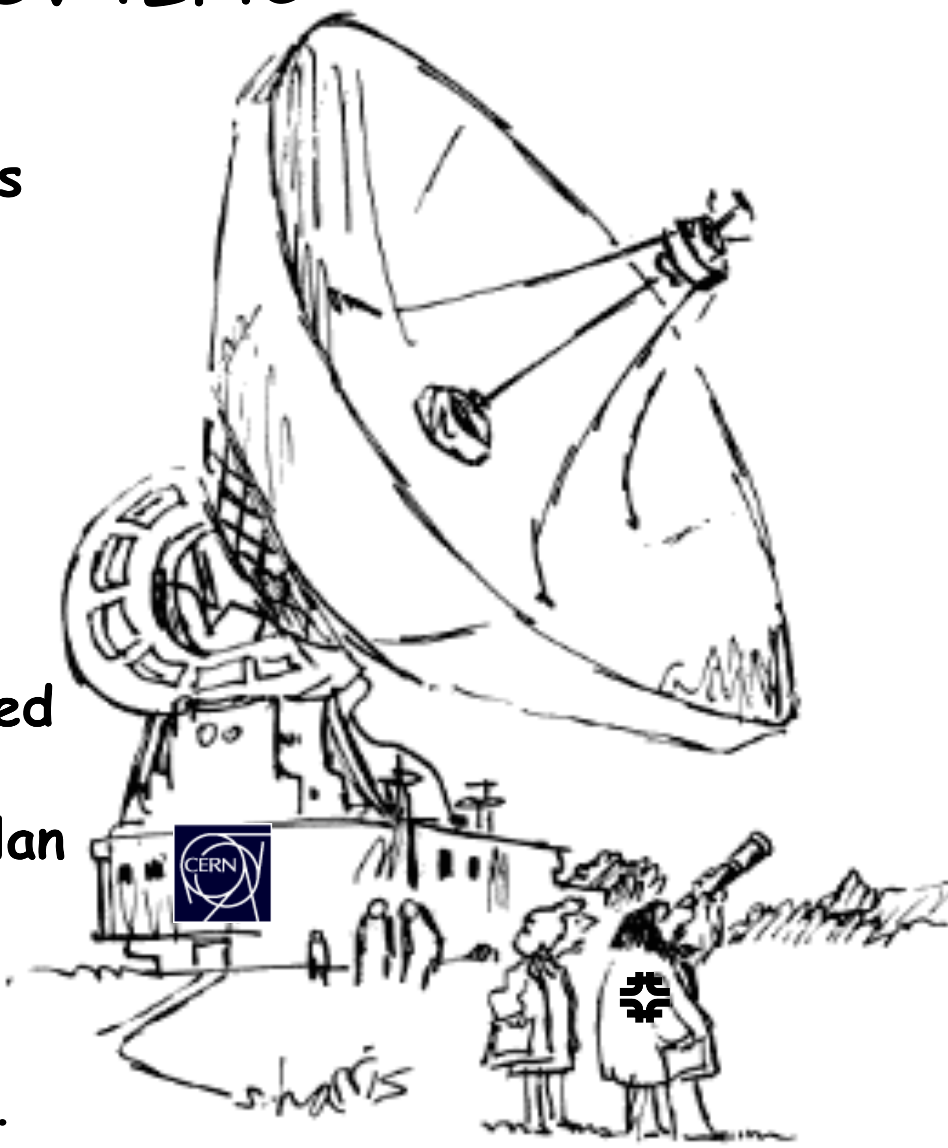
- **Z/W+HF measurements challenging large theoretical uncertainties**

→More data and better predictions needed

→Update on Z+b-jets and Z-bb in the plan

- **Tevatron: >10 fb^{-1} by end Run II**

- **First LHC physics results this summer….**



"Just checking."