Experimental Studies of W/Z + Jets and W/Z + Heavy Flavor Jets at the Tevatron

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on behalf of the
CDF and DØ Collaborations

HCP2008
19th Hadron Collider Physics Symposium 2008

27 May 2008
Galena, IL

Outline:

- **Importance of *W/Z* + jets**
- **Recent Tevatron progress**
- **Summary and future**

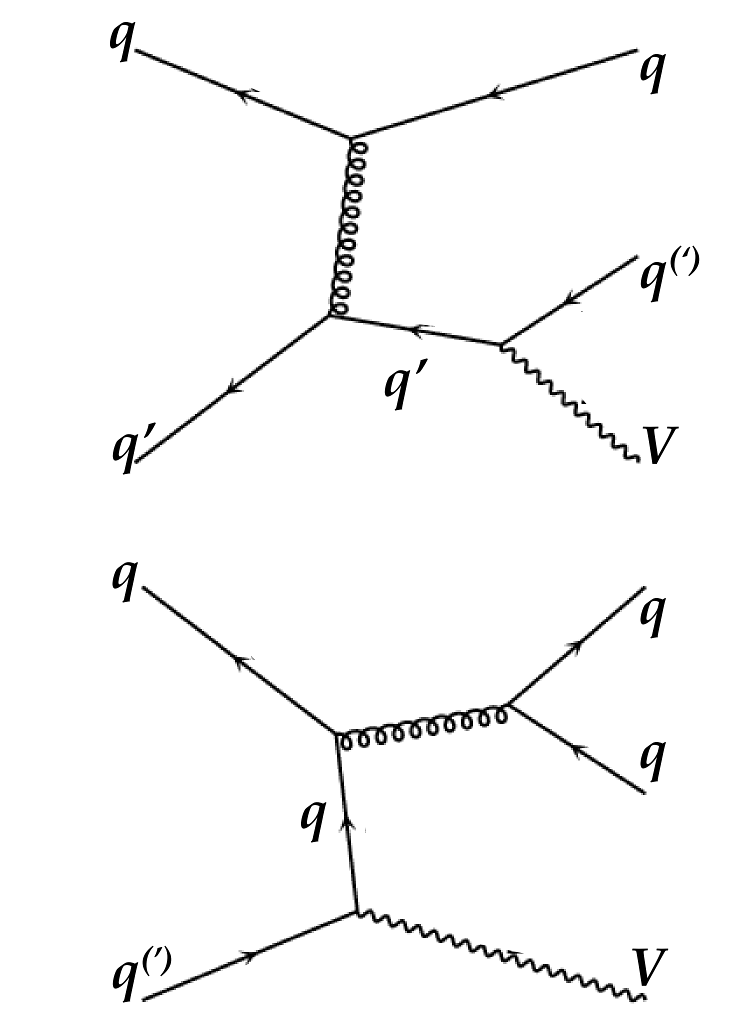
Importance of *W/Z* + Jet Physics

Why study W/Z +jet production?

- Important tests of Quantum Chromodynamics (QCD)
- Recent LO and NLO simulations need experimental verification
- Signature shared with top production, Higgs, other searches at Tevatron, LHC

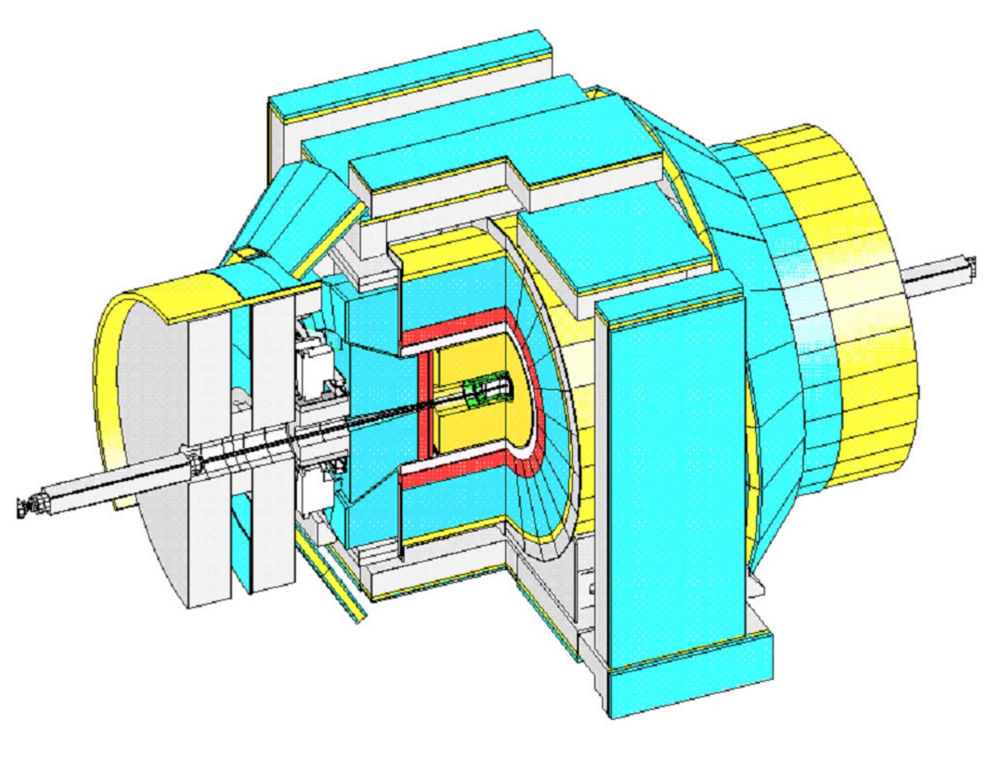
Result (1/fb)	DØ	CDF
W+jets	--	**0.320**
Z+jets	**0.950**	**1.700**
W+b-jets	0.382	**1.900**
Z+b-jets	0.152	**2.000**
W+c-jets	**1.000**	**1.800**
Z+c-jets	--	--

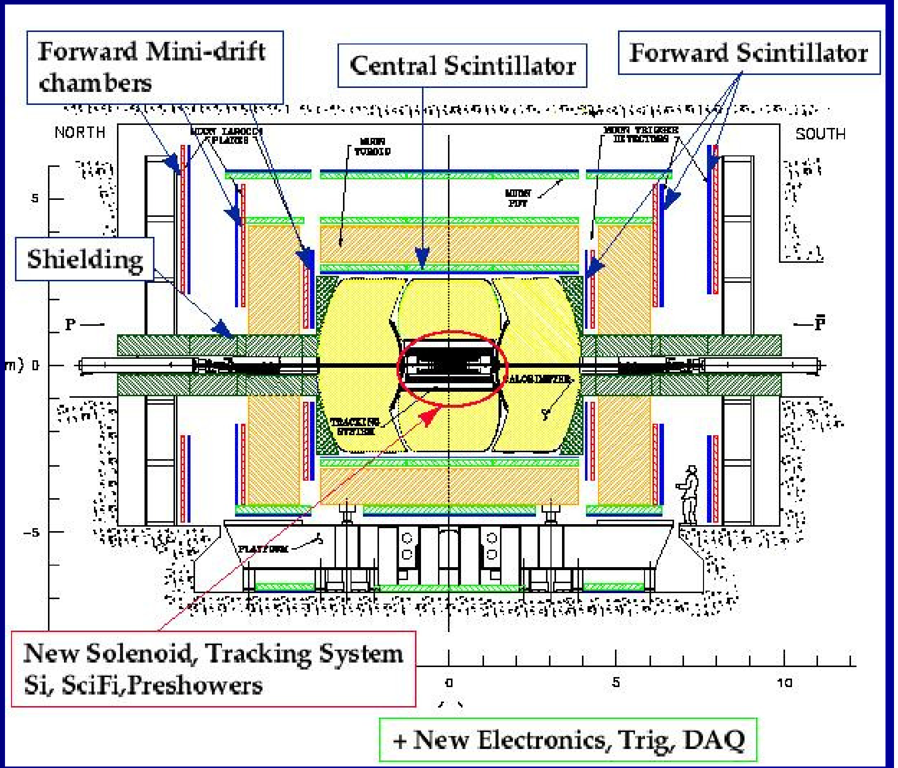
NB: New DØ results coming this summer!



V=W or *Z*

The CDF and DØ Experiments





Common features:

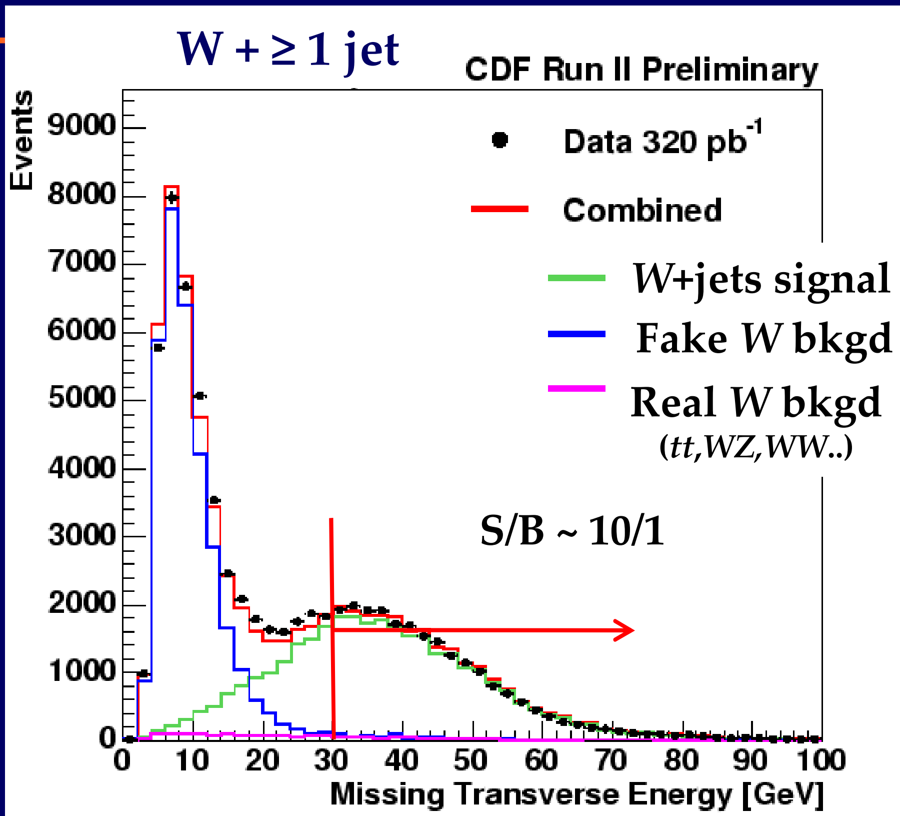
- Charged particle tracking in magnetic field
- Electromagnetic and hadronic calorimetry
- Muon detection
- Luminosity monitoring
- Three level event trigger

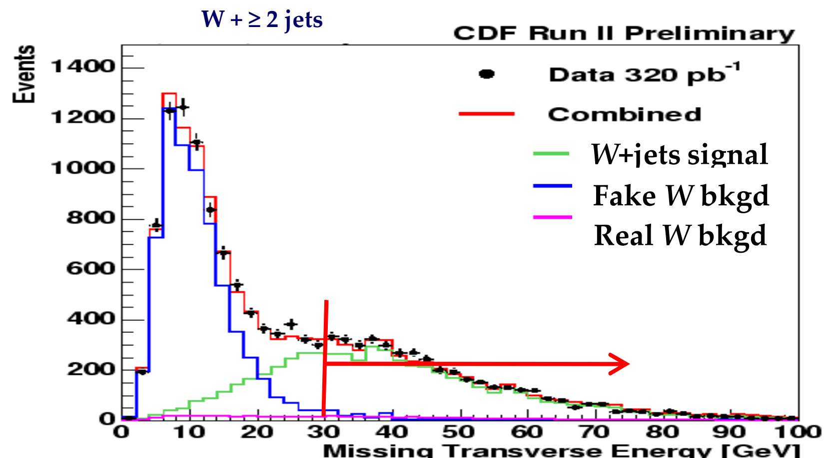
$\phi =$ azimuthal angle

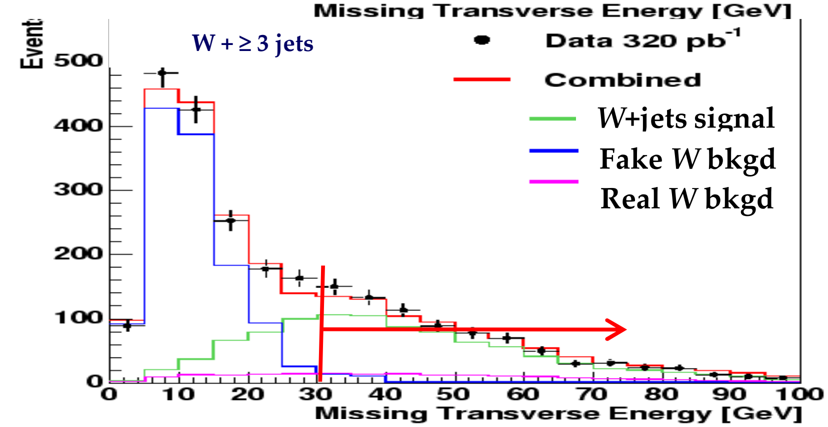
$$\eta = -\ln(\tan\frac{\theta}{2})$$

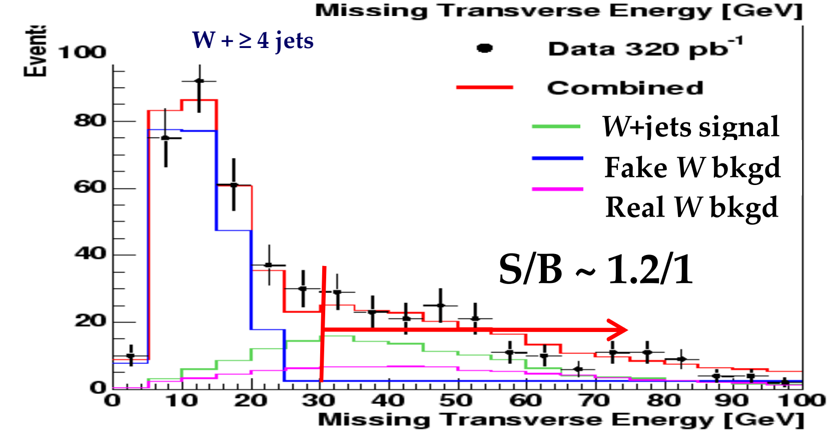
$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

W + Inclusive Jets









- ***W* selection:** seek $W \rightarrow e\ \nu$
  - *e*: $E_T > 20$ GeV, $|\eta| < 1.1$
  - ν: missing transverse energy MET > 30 GeV
  - $M_T(W) > 20$ GeV/c^2
- **Jet definition:** Cone algorithm, R= 0.4
  - Corrected $E_T > 20$ GeV, $|\eta| < 2.0$

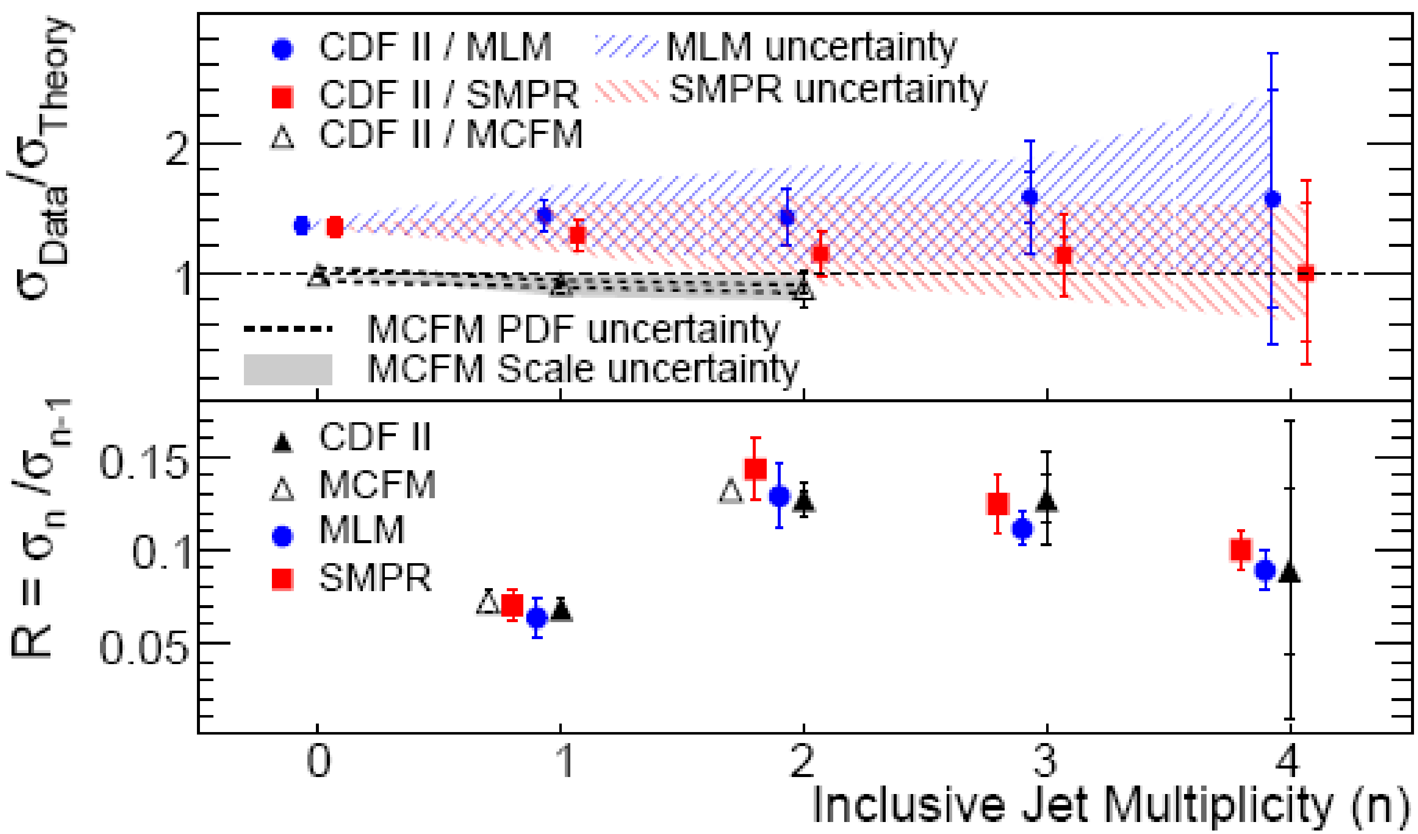
W + Inclusive Jets

"MCFM" :
MCFM (NLO) +
no shower

"MLM" :
ALPGEN (LO) +
Herwig (shower) +
MLM matching

"SMPR" :
MadGraph (LO) +
Pythia (shower) +
CKKW matching

PRD 77, 011108(R)



Total cross section for jet multiplicity, *n*:

$$\sigma_n = \sigma\left(W \to e\nu + \geq n - \text{jet}; E_T^n > 25\right)$$

Acronym key:

"MCFM":
Monte Carlo for Femtobarn Processes
"MLM":
M. Mangano
"SMPR":
S. Mrenna & P. Richardson
"CKKW" :
Catani, Krauss, Kuhn, Webber

NLO prediction more accurate than LO!

…and relative rates from bin-to-bin consistent with data.

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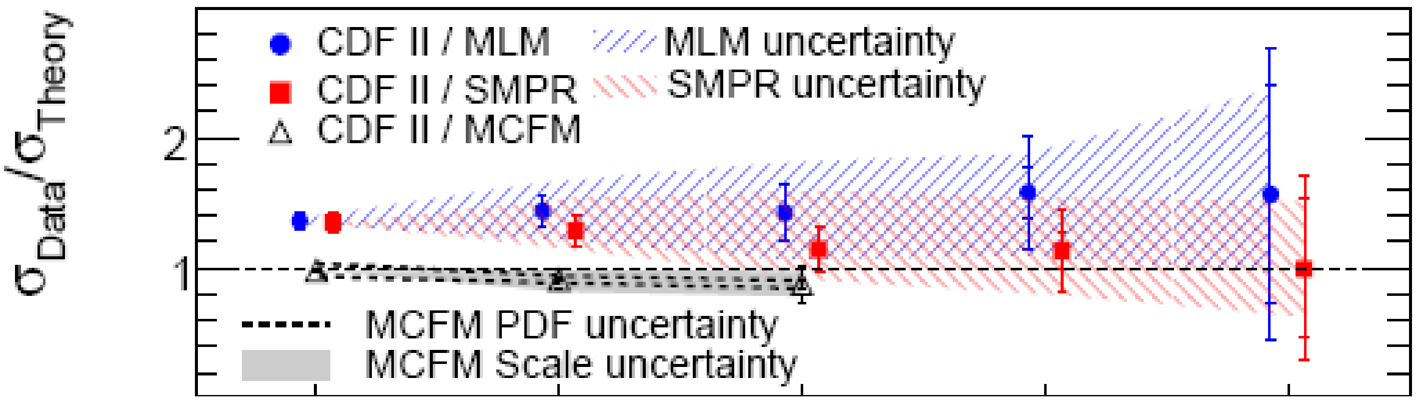

Can examine differential cross sections for nth jet within each multiplicity bin….

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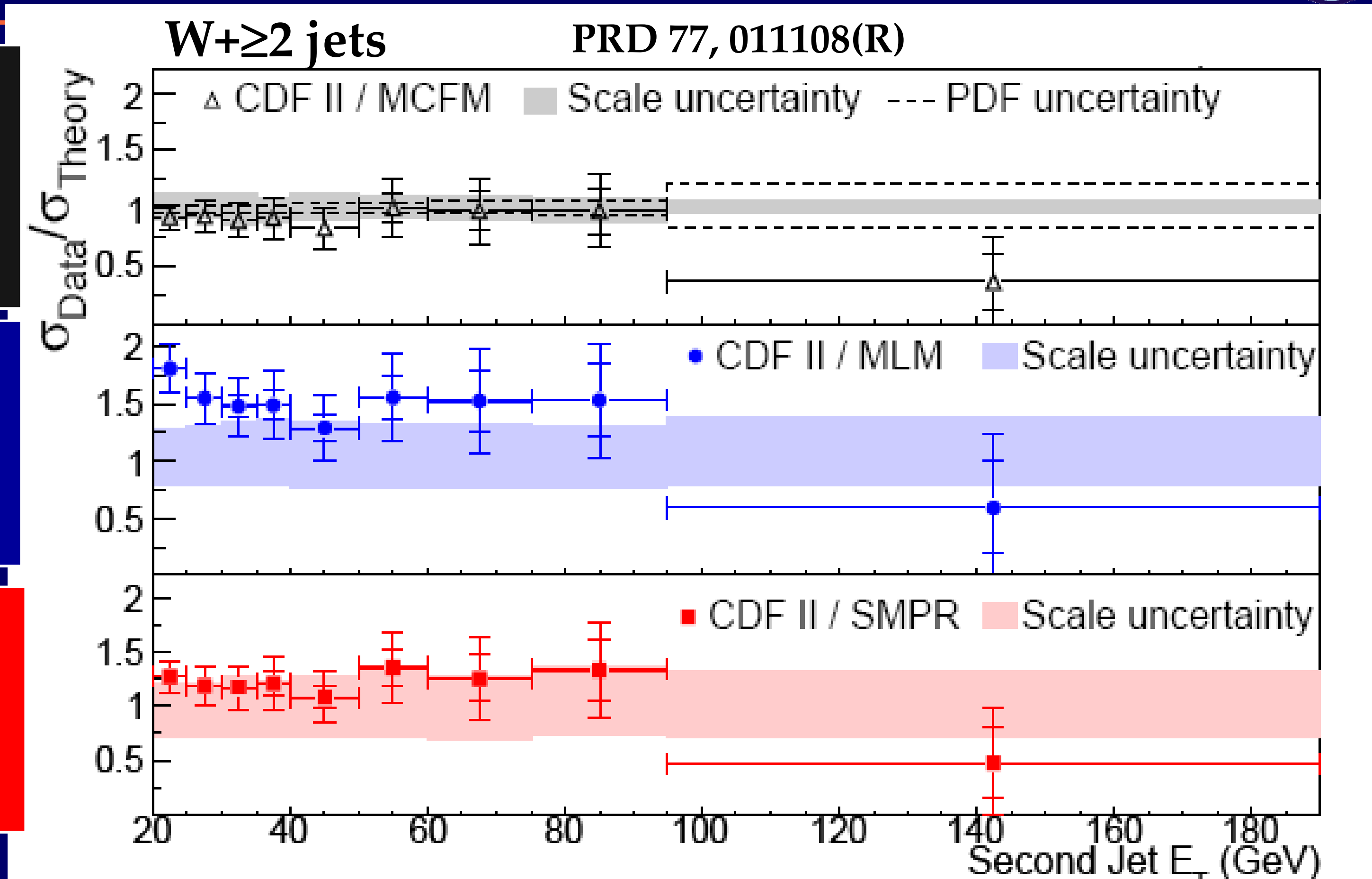

- LO calculation procedure: Generate $p\bar{p} \rightarrow W$+N partons at tree level, ignore loop corrections, employ parton shower
- Ambiguities arise:
  - Possibility for double counting if $N_{parton} \neq N_{jet}$
  - SMPR and MLM refer to algorithms for avoiding/removing overlaps

At LO, MadGraph+Pythia+CKKW provides better performance.

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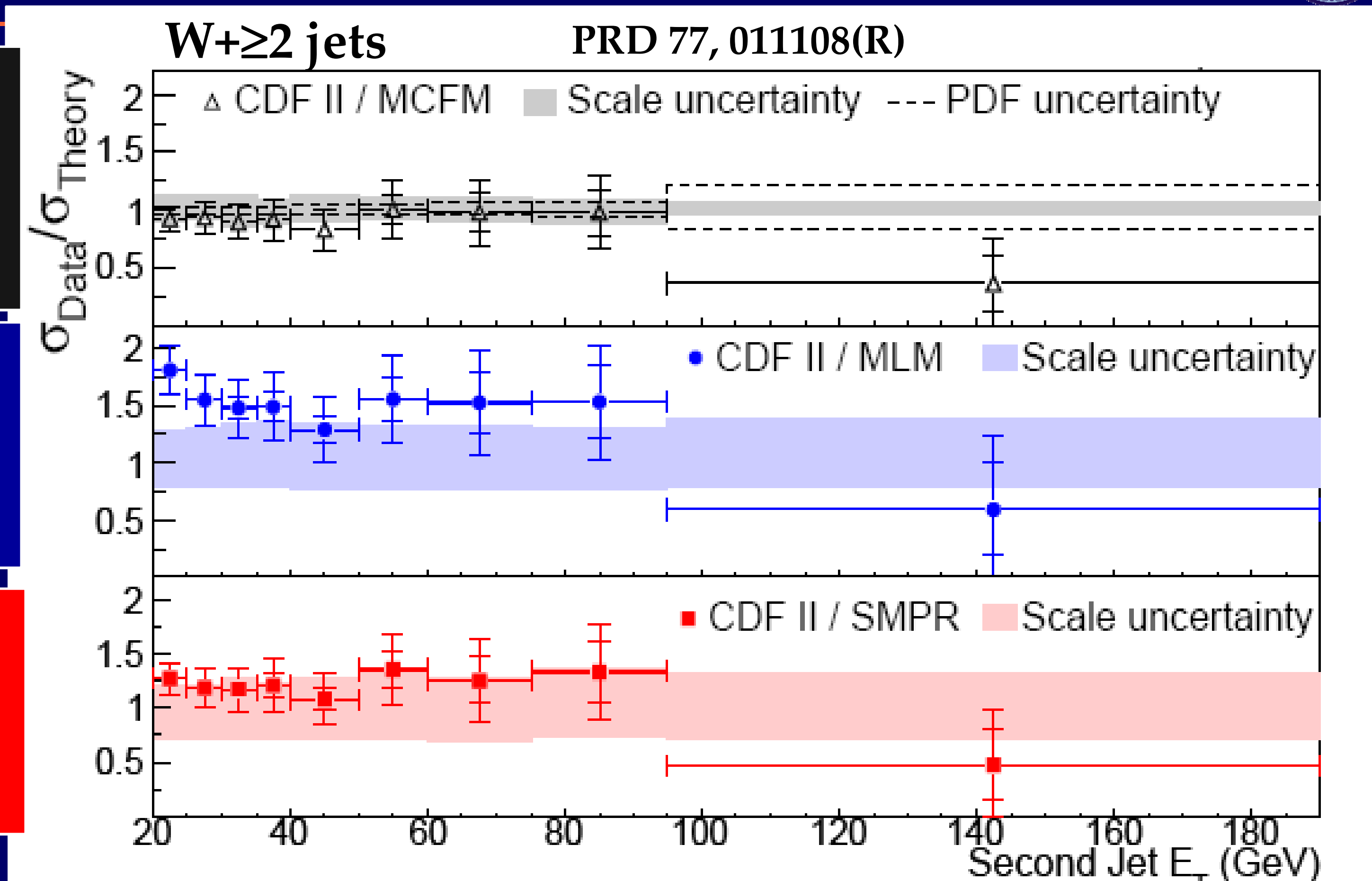
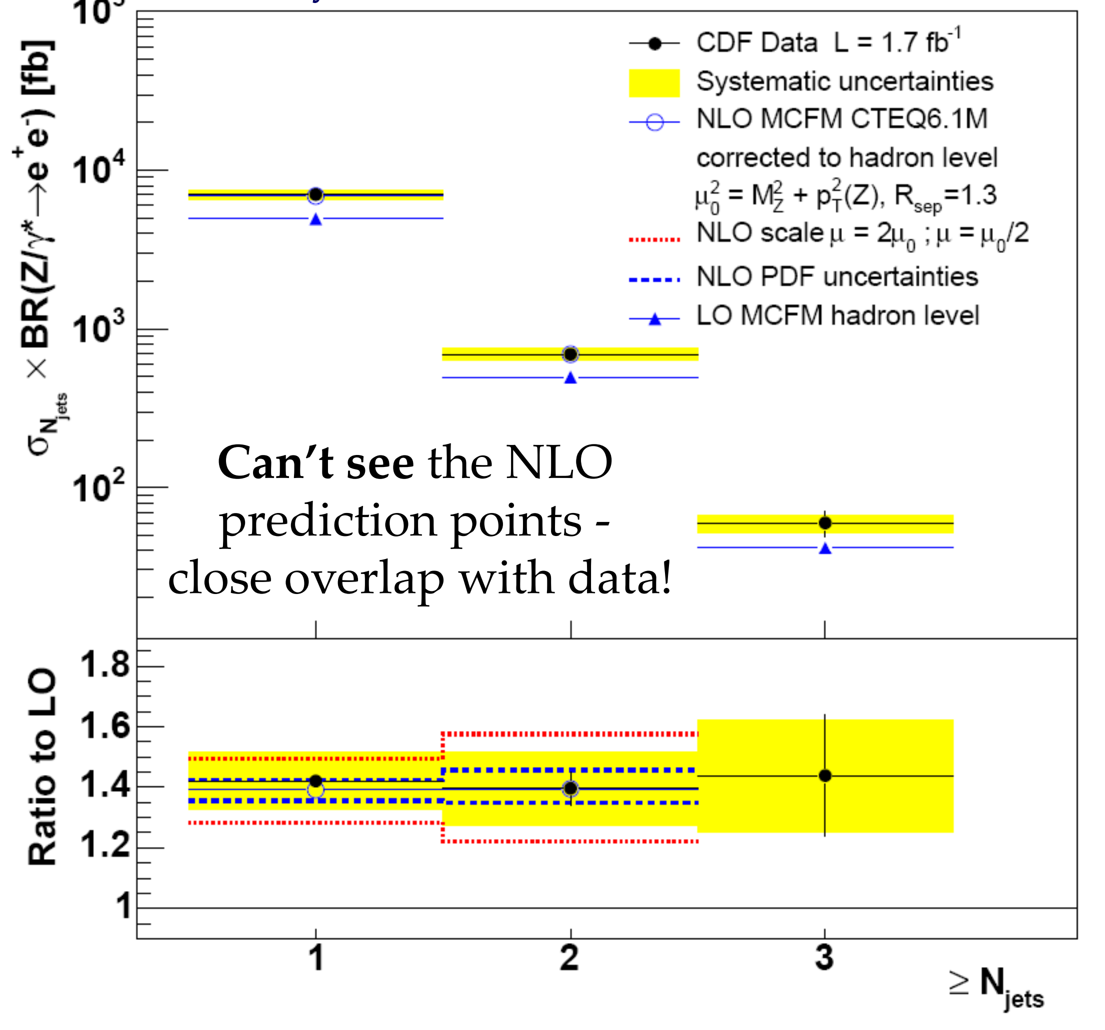


- LO calculation procedure: Generate $p\bar{p} \to W$+N partons at tree level… loop corrections, employ parton shower
- Ambiguities arise:
  - Possibility for double counting if N_{par}…
  - SMPR and MLM refer to algorithms fo… …ng/removing overlaps

But why? Is it the matrix element?
Shower? Matching?
Work is ongoing.

Z/γ^* + Inclusive Jets

Phys. Rev. Lett. 100, 102001 (2008)



NLO prediction once again more accurate than LO!

- **Validity of NLO predictions borne out in Z/γ^*+jets?**
- ***Z/γ^** selection**: seek $Z/\gamma^* \rightarrow e^+e^-$
  - Two $E_T > 25$ GeV electrons
  - $66 < M_{ee} < 116$ GeV/c^2
- **Jet definition:**
  - Corrected $p_T > 30$, $|y| < 2.1$
  - Cone algorithm , R=0.7

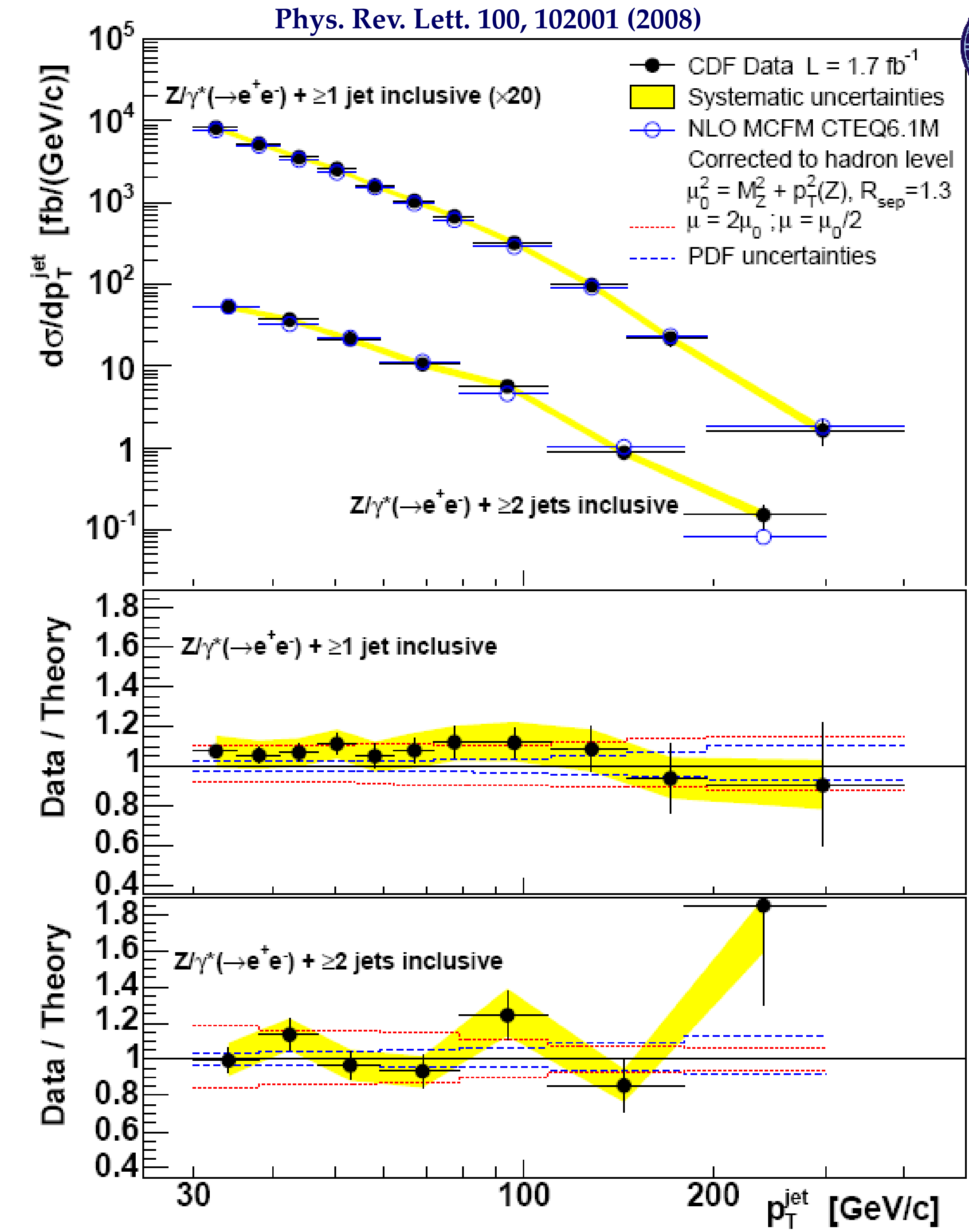
$$y = \frac{1}{2}\ln\left(\frac{E + p_z}{E - p_z}\right)$$

- **Major backgrounds: S/B ~ 7/1**
  - QCD multijets
  - *W* + jets
  - ttbar, diboson
  - $Z+\gamma$, $Z \rightarrow \tau\tau$

Z/γ^* + Inclusive Jets

- Differential cross section:
  - NLO was good in W+jets, true here too?

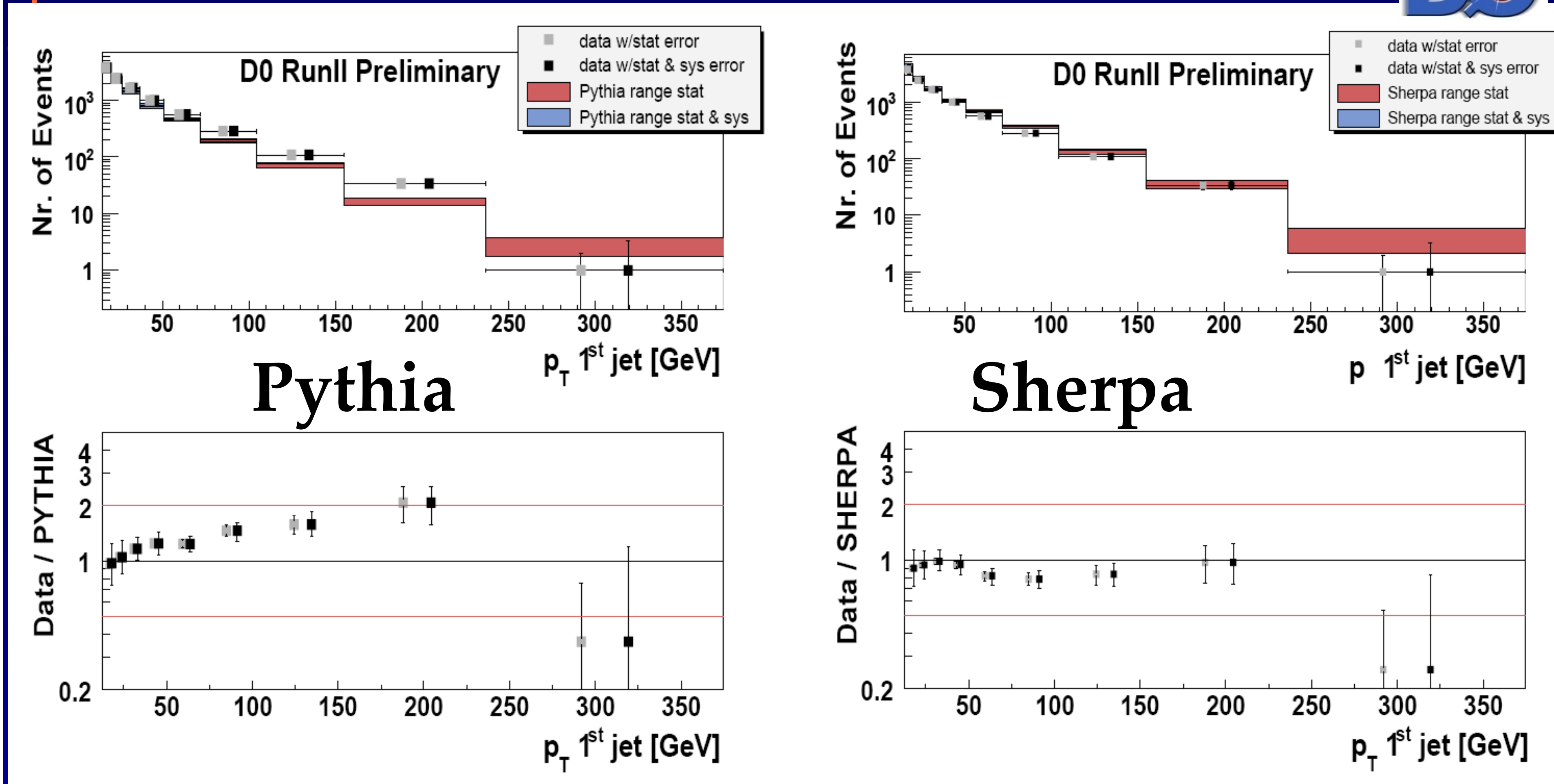
NLO prediction reliable – as in *W*+jets



- Analysis would benefit from increased statistics to further populate the Z+≥2-jets sample

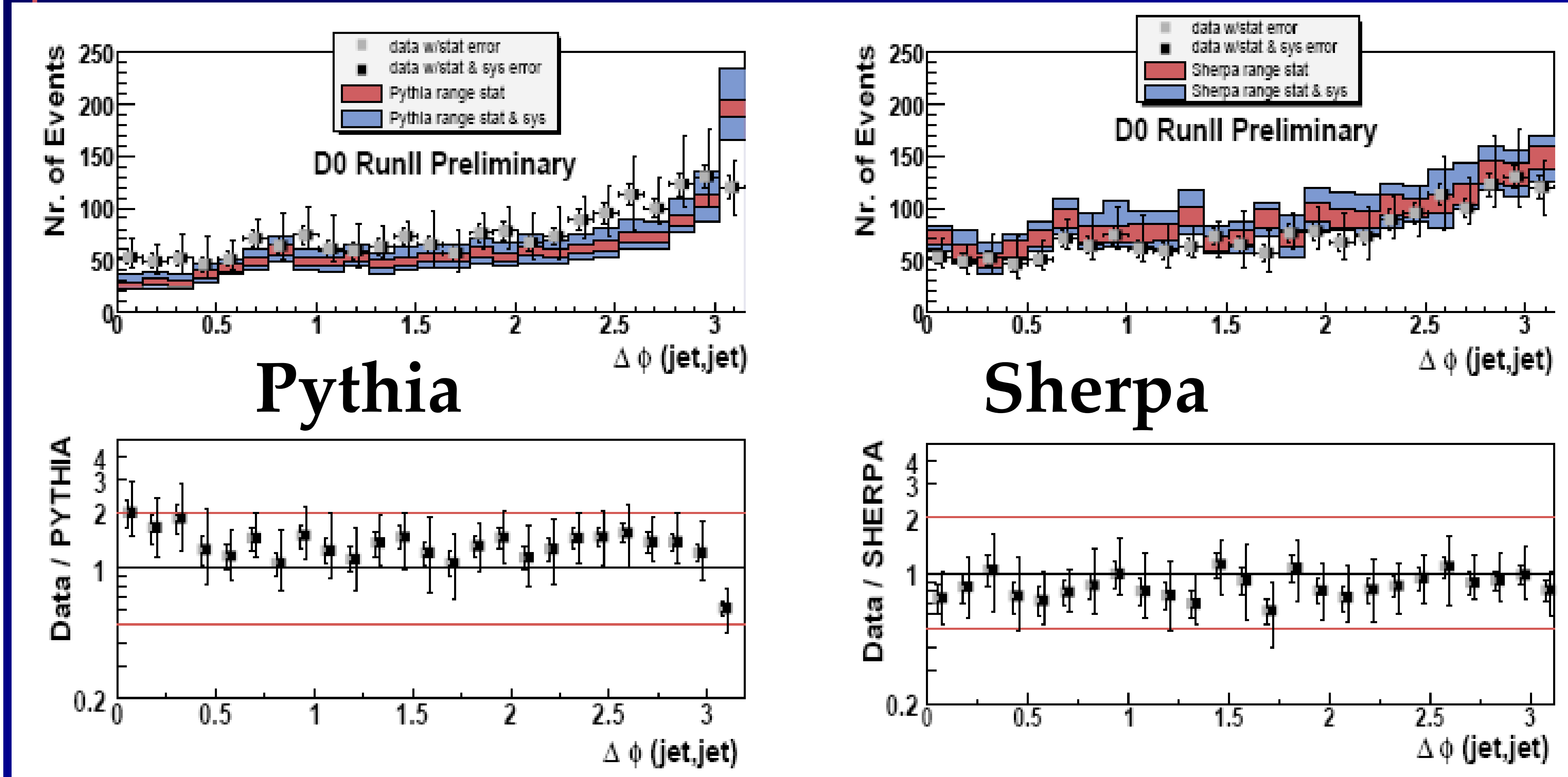
- NLO for Z+≥3-jets would be valuable as well.

Z / γ* + Inclusive Jets



- **DØ Z / γ*(→ee)+jets analysis:** 950/pb
- **Purpose here:** compare **Pythia** ($p\bar{p}$→W+1p+ internal PS) and **Sherpa** ($p\bar{p}$→W+Np + internal PS + CKKW matching) event generators
  - Test of different prediction techniques
  - Some confidence in CKKW from CDF *W*+jets LO studies…true here as well?

Z/γ^* + Inclusive Jets



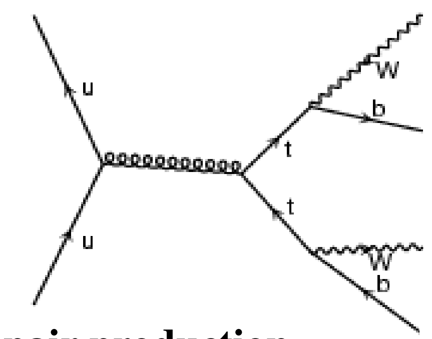
Sherpa + CKKW represents data better than Pythia

- p_T of jet 1,2,3
- Z p_T, Jet multiplicity
- $\Delta\eta$(jet, jet), $\Delta\varphi$(jet, jet)

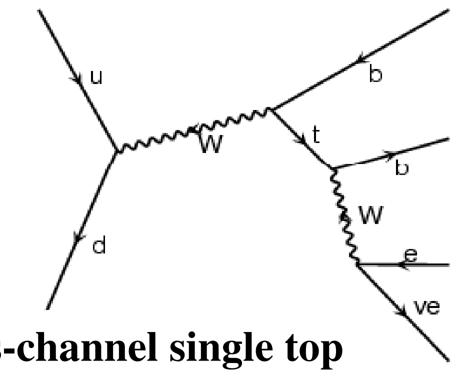
Not unexpected given the nature of Pythia's calculation.

Summary so far…

- *W/Z*+1,2 jet **NLO predictions** from MCFM **look reliable**
- NLO predictions **not yet in hand** for *W/Z*+≥3 jet
- Technique of calculating/generating *pp*→*W*+N+ **parton shower + matching** scheme (ala ALPGEN, MadGraph, Sherpa) **superior to Pythia+PS alone**
- **Differences among available tools still need to be understood**

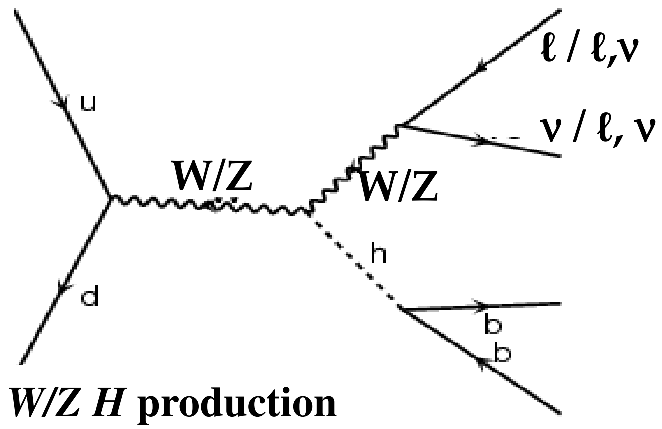


top pair production



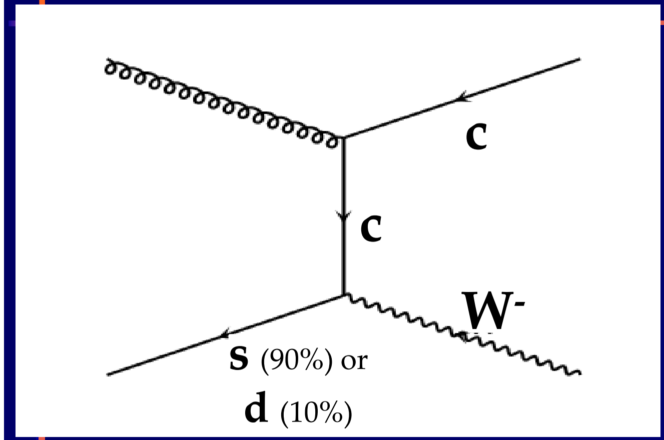
s-channel single top

- ***W/Z* + heavy flavor (*b*,*c*) jets also important**
  - background to top, Higgs, others
  - *W*+*c* production has unique features



***W/Z H* production**

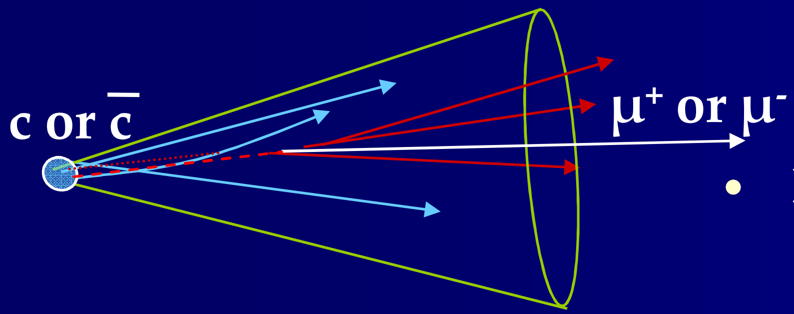
W + Single c Production



- **Importance of $W^{\pm}$ +single c:**
  - Insight on PDF for s at rather large Q^2
  - Insight on $|V_{cs}|$
  - Part of W+jets bkgd to top, Higgs searches
- **Event selection similar to W+jets:**
  - Here use $W \rightarrow e/\mu\ \nu$ for W selection
- **Exploit** $W^{\pm}$ +single c **feature:**
  - charm hadron semileptonic daughter and W have opposite charge

$$\sigma_{Wc} \times \mathrm{BR}(W \rightarrow \ell \nu) = \frac{N_{\mathrm{Tot}}^{\mathrm{OS-SS}} - N_{\mathrm{Bkg}}^{\mathrm{OS-SS}}}{A \cdot \mathcal{L}}$$

Soft Muon Identification



Parameterization for "mistags":
- decays in flight
- hadronic punch-through

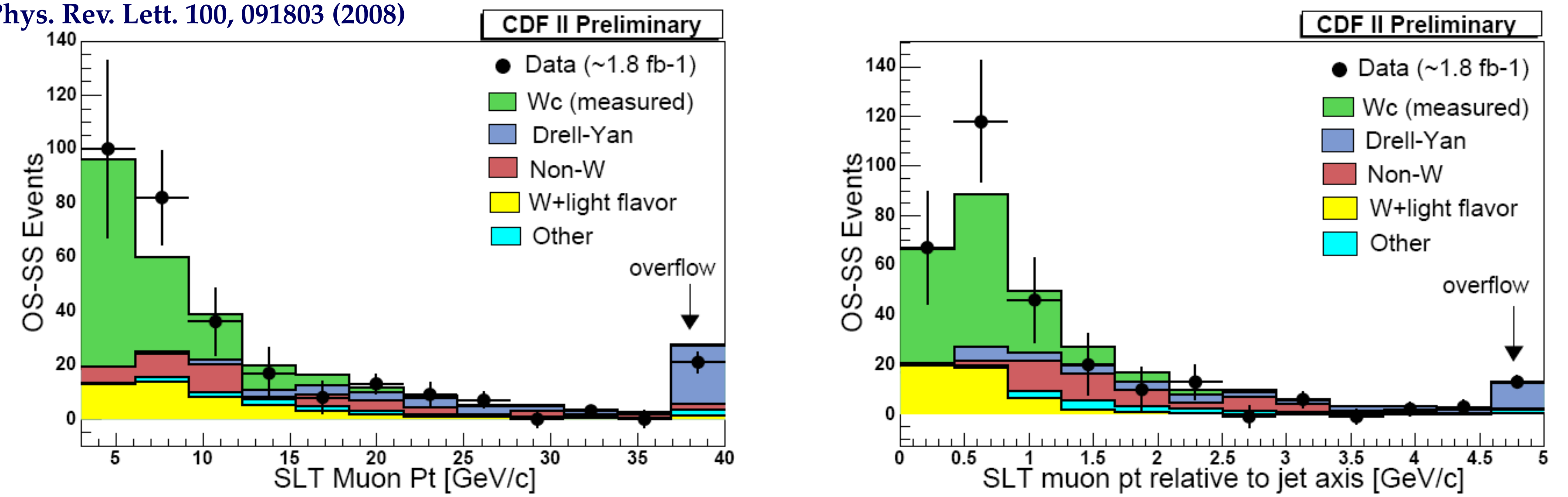
- Major opposite-sign (OS) backgrounds:
  - Drell Yan $\mu^+\mu^-$
  - Fake W
  - Wq
  - Insensitive to W+bb, W+cc, (OS/SS random)

W + Single c Production

- **Result:** for $p_T^c > 20$, $|\eta^c| < 1.5$
  $\sigma \mathrm{xBR} = 9.8 \pm 2.8\ (\mathrm{stat})\ ^{+1.4}_{-1.6} (\mathrm{syst}) \pm 0.6\ (\mathrm{lum})\ \mathrm{pb}$
- **Prediction: NLO from MCFM**
  $\sigma \mathrm{xBR} = 11.0\ ^{+1.4}_{-3.0}\ \mathrm{pb}$

Good agreement!

Phys. Rev. Lett. 100, 091803 (2008)



W + Single c Production

- Similar analysis completed at DØ: 1/fb
- Measures the ratio

$$\frac{\sigma(W + \text{single-}c)}{\sigma(W + jets)}$$

which allows for cancellation of many systematic errors

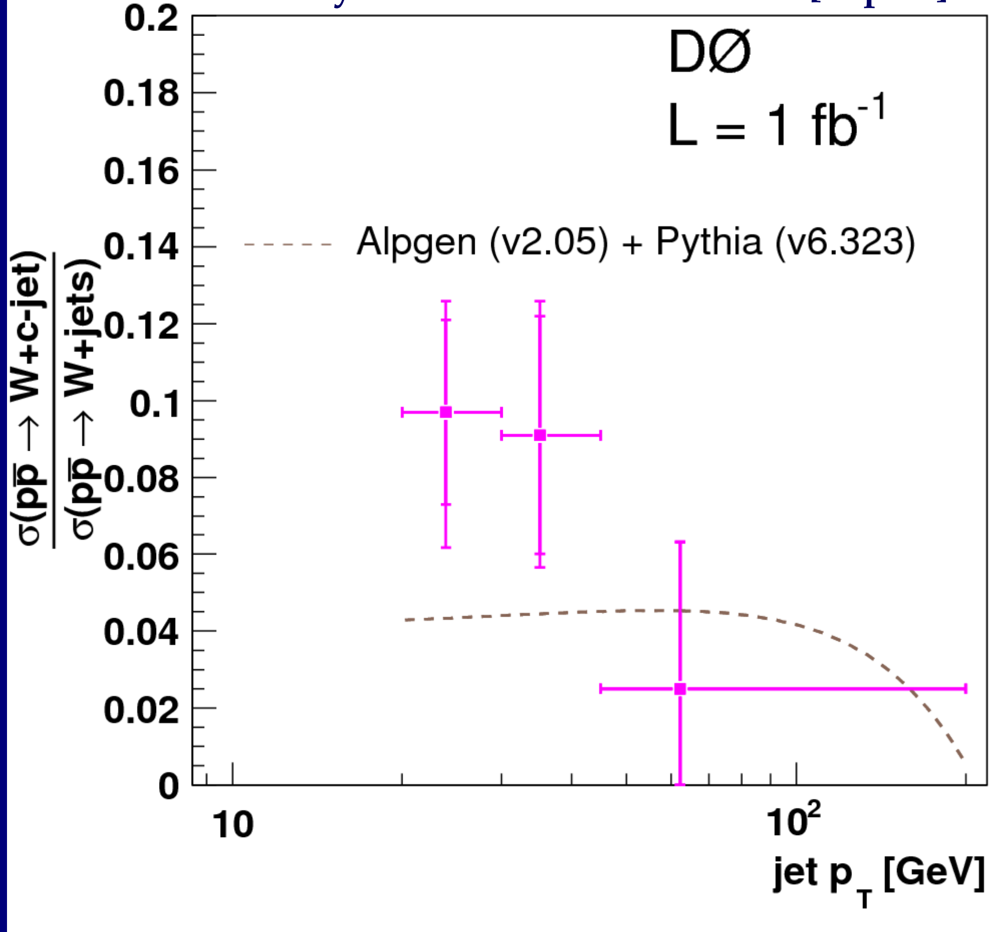
- Result:

$$\frac{\sigma(W + \text{single-}c)}{\sigma(W + jets)} = 0.071 \pm 0.017$$

which can be compared to the LO prediction: 0.040 ± 0.003 (PDF)

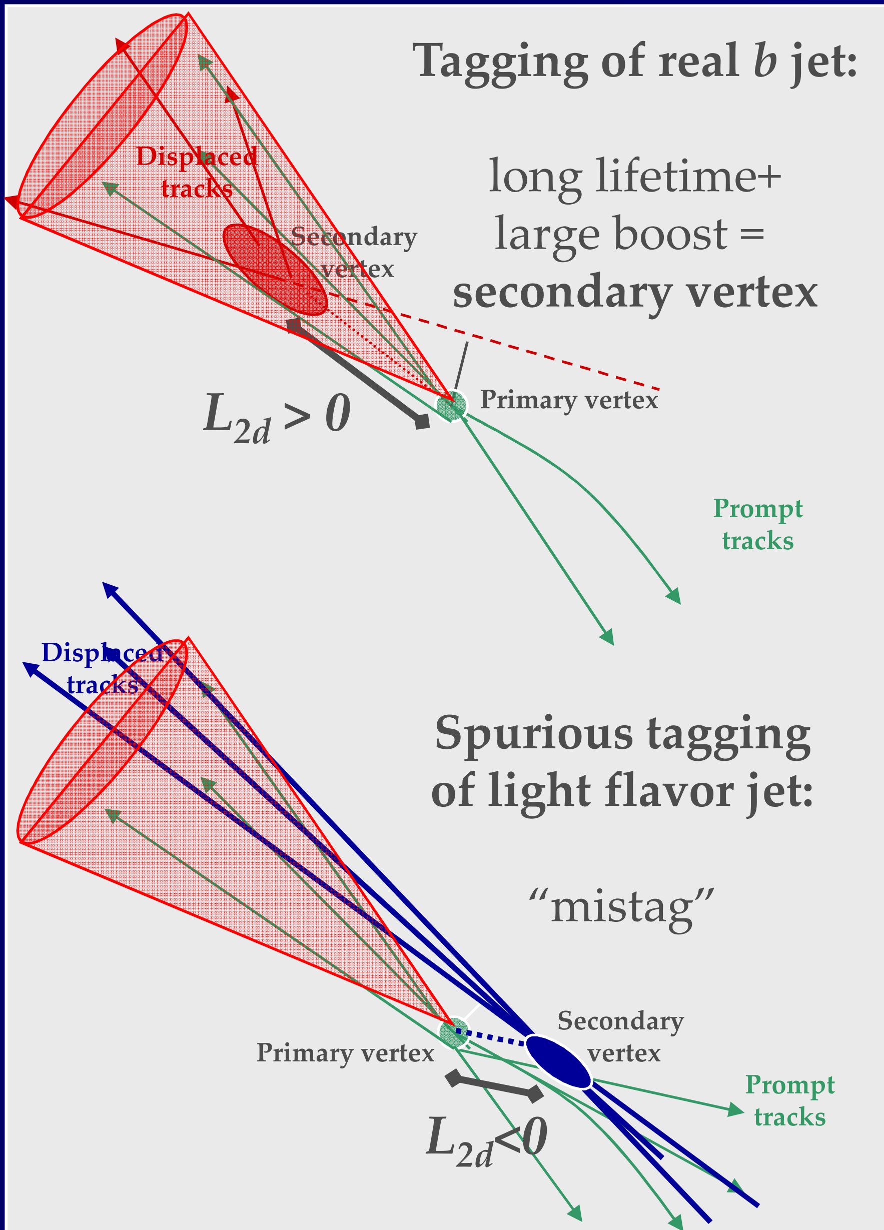
LO prediction reasonably good.

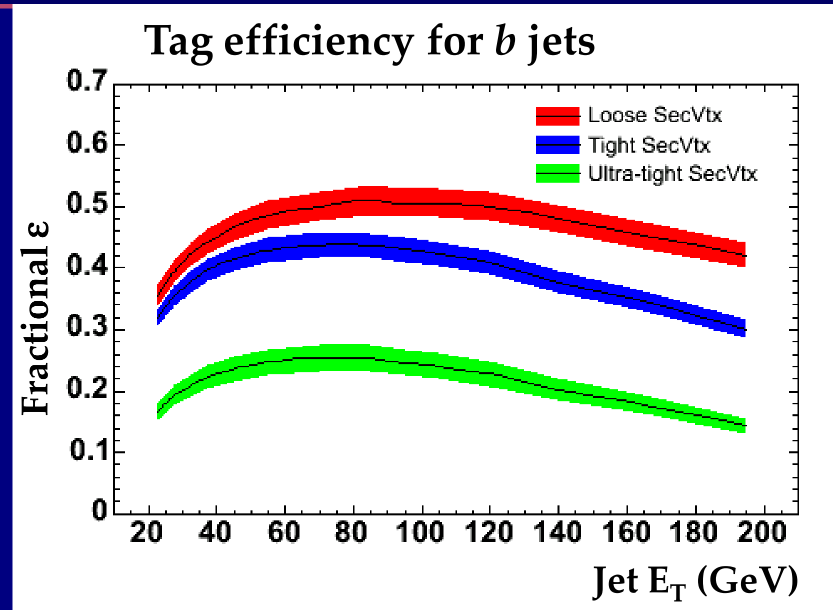
Submitted to Phys. Lett. B - arXiv:/0803.2259 [hep-ex]

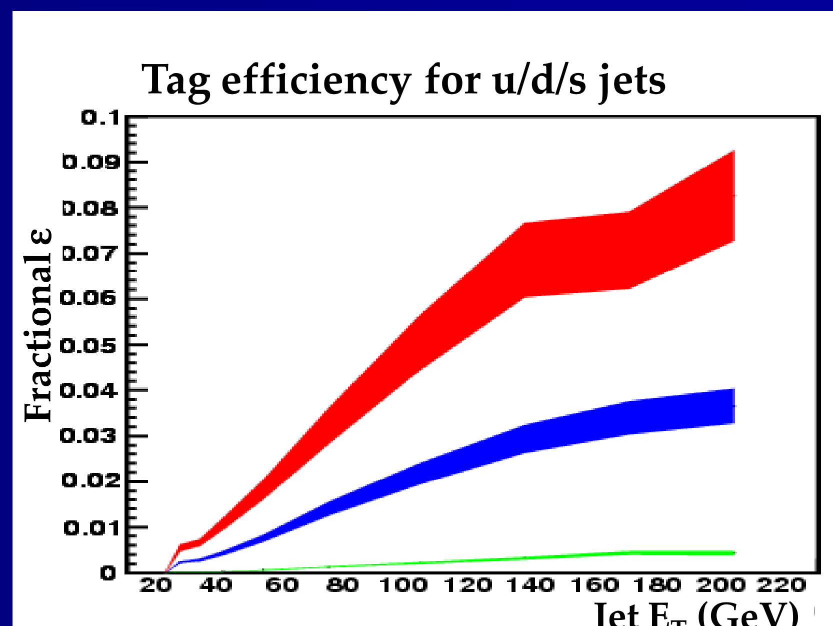


Statistics limited measurement
Systematics dominated by JES.

Vertex Tagging: *b*'s and Non-*b*'s

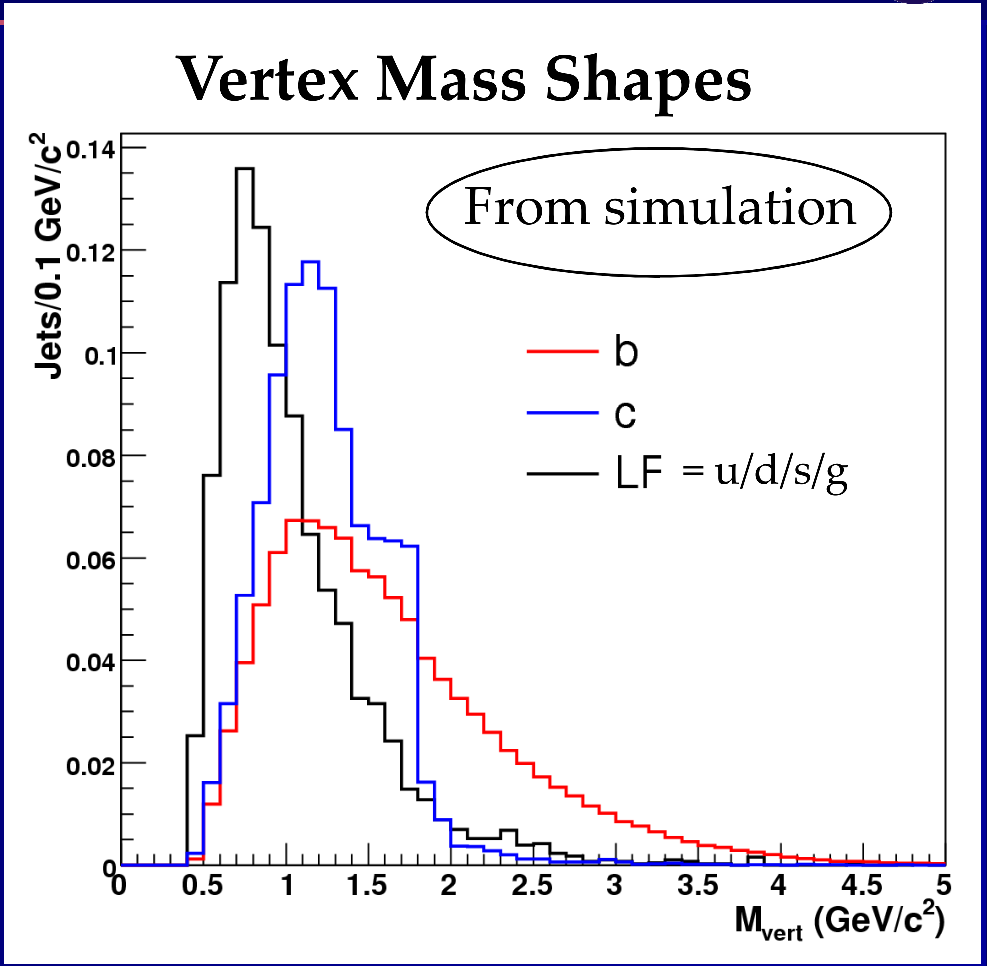






$W + b$-Jets

- **Goals:**
  - Measure W+b-jet production cross section
  - Use measurement to improve background estimate for Higgs search
- W and jets selection here similar to W + inclusive jets analysis
  - key difference: 1 or 2 jets only
- Here we need to identify jets that are **likely** b's (via **high purity tagging**) and determine how many are **really** b's via **vertex mass:**
  - invariant mass of charged particle tracks in secondary vertex



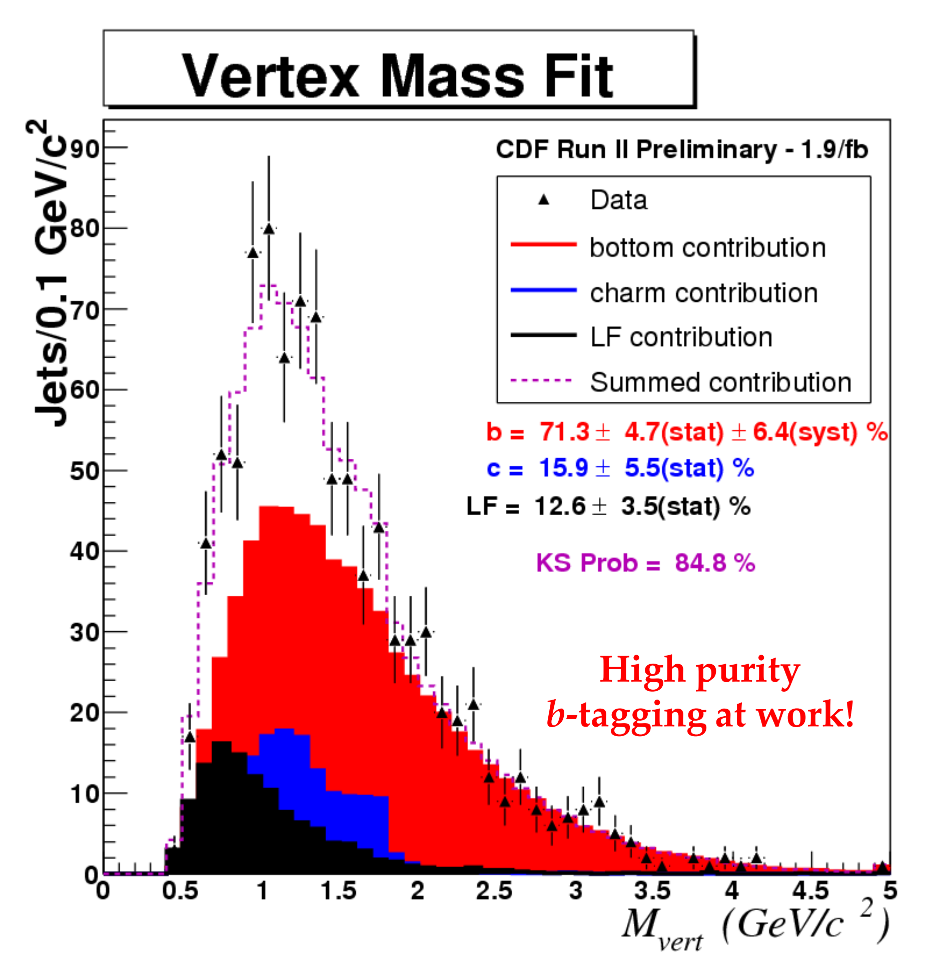
Generally,

$$M_{B\text{-hadrons}} \gtrsim M_{C\text{-hadrons}} \gtrsim M_{LF\text{-hadrons}}$$

so

$$M^{b}_{vert} \gtrsim M^{c}_{vert} \gtrsim M^{LF}_{vert}$$

$W + b$-Jets



~1000 tagged jets
among which ~700 are
consistent with coming from a *b* quark

- **Largest backgrounds:** S/B ~ 3/1
  - ttbar (40% of total bkgd)
  - single top (30%)
  - Fake *W* (15%)
  - *WZ* (5%)
  - *Total contribution:* ~180 tagged *b* jets

- **Result:** measure $\sigma_{b\text{-jets}}(W+b\text{-jets}) \times BR(W\rightarrow l\nu)$

$$\boxed{\sigma \times BR = 2.74 \pm 0.27\ (\text{stat}) \pm 0.42\ (\text{syst})\ \text{pb}}$$

- **Prediction:**

  $\sigma \times BR = 0.78$ pb

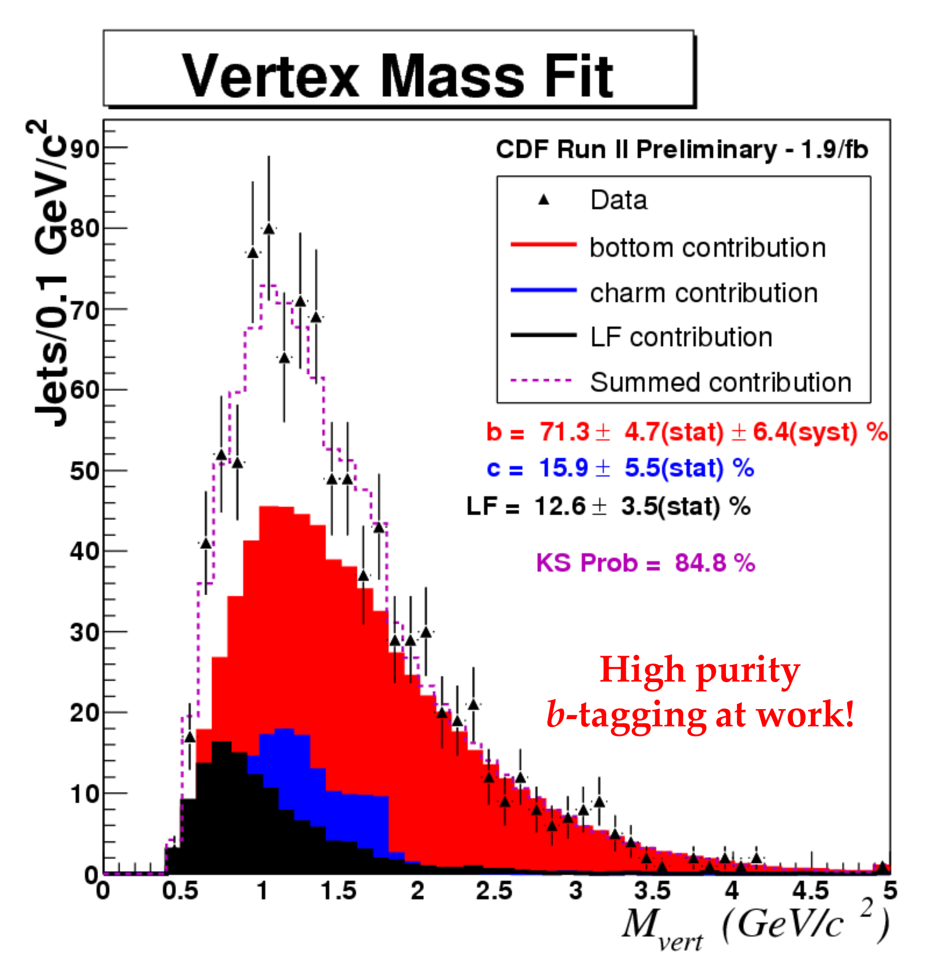
  (default ALPGEN)

New result - x3.5 mismatch

NB: This cross section is for *b* jets from *W*+*b*-jet production in events with a high p_T central lepton, high p_T neutrino and 1 or 2 total jets.

Publication in preparation.

$W + b$-Jets



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Other predictions?
Work is ongoing.

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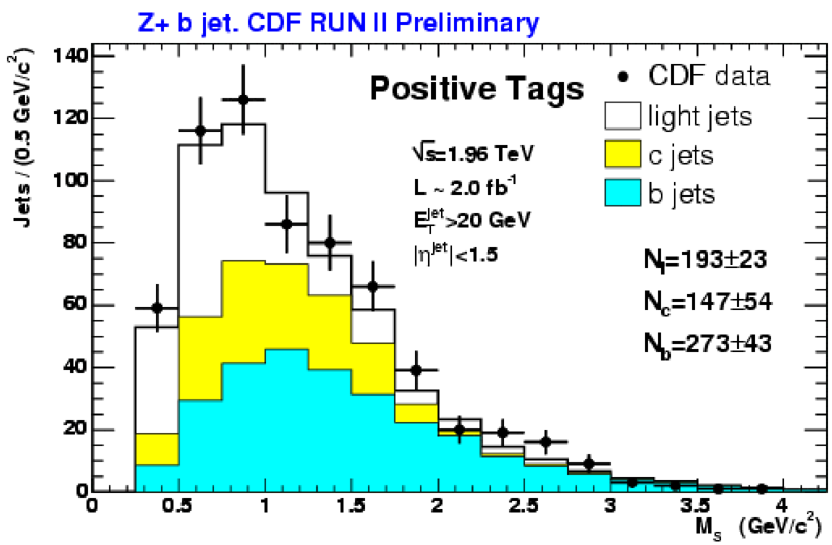
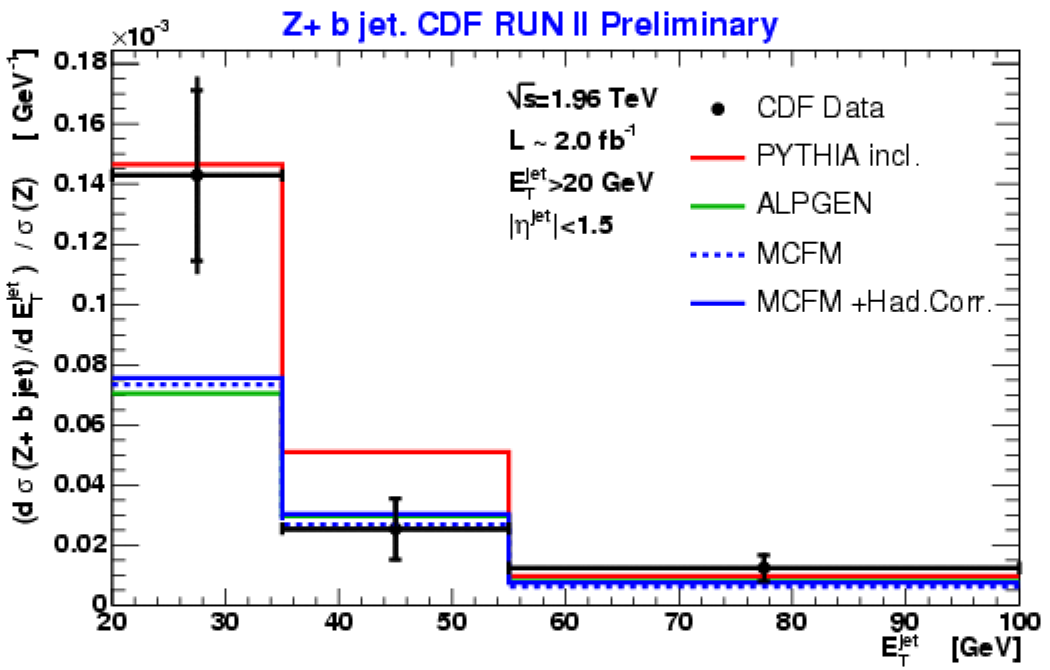
$Z + b$-Jets

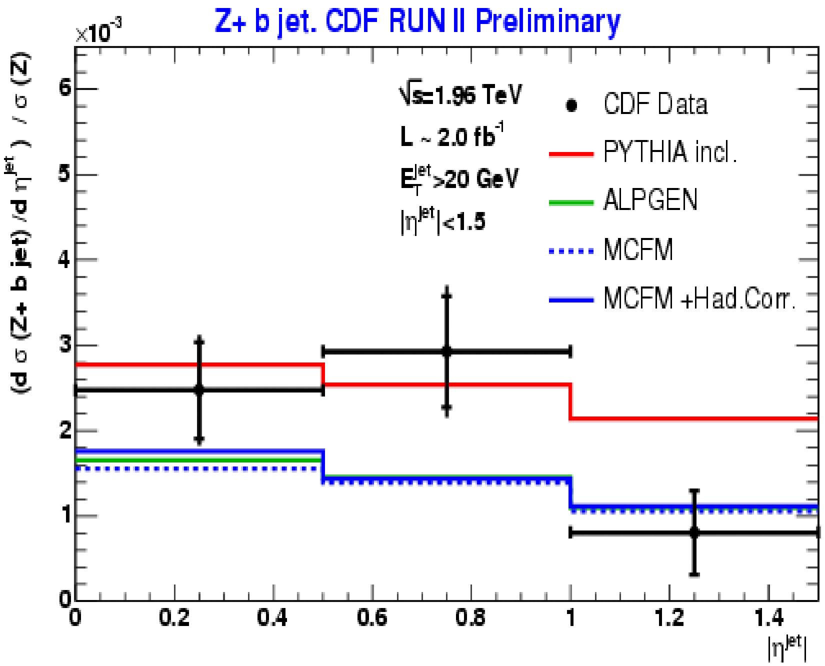


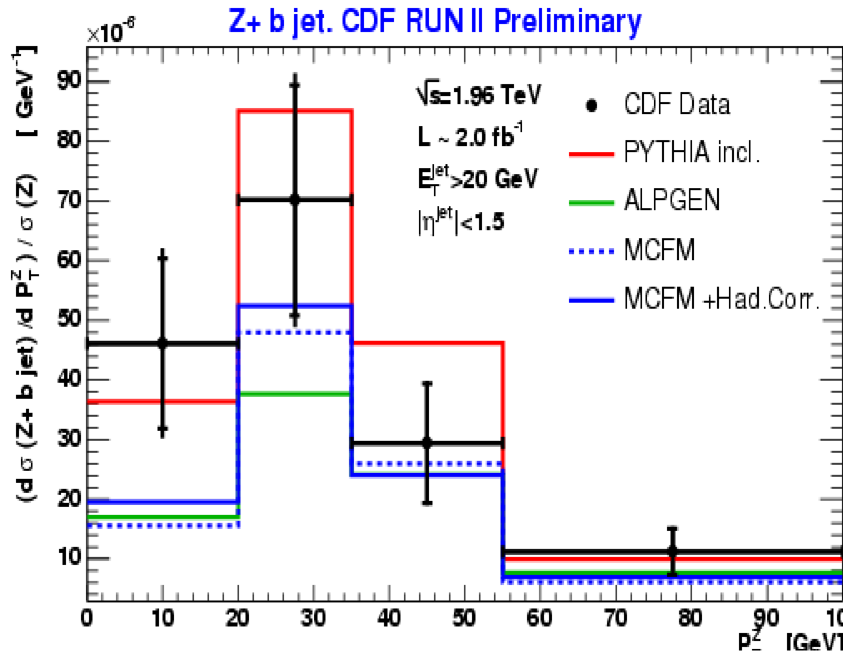
- Similar CDF analysis for *Z+b*-jets: 2/fb
- Utilize $Z \rightarrow ee$ and $\mu\mu$
- Similar jet definition
  - Corrected $E_T > 20$ GeV, $|\eta| < 1.5$
  - Cone algorithm with R=0.7
  - Secondary vertex tags

- Differential cross sections with comparisons to LO, NLO predictions
- Dividing by σ(Z) puts LO, NLO on equal footing
- Pythia does a good job at low jet E_T



$Z + b$-Jets

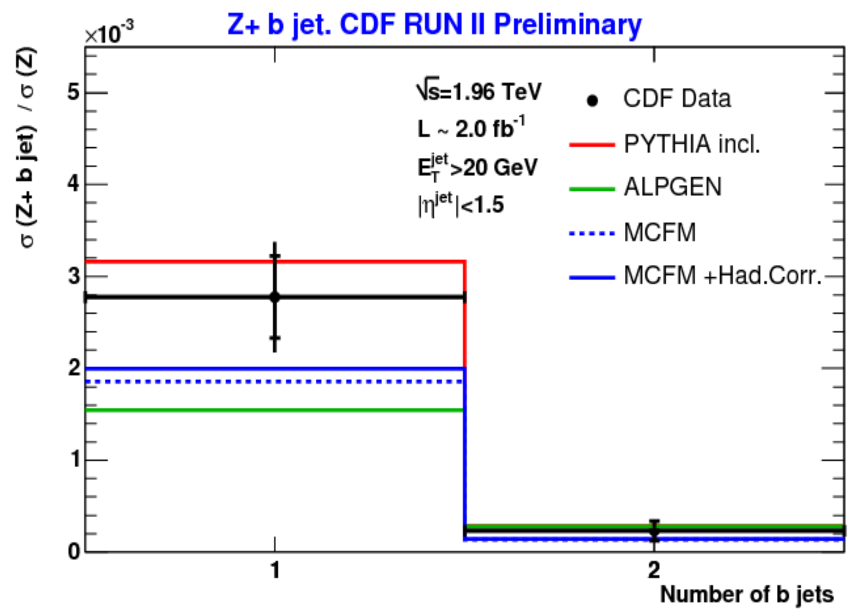




- ALPGEN (LO) and MCFM (NLO) undershoot data in several bins

- Pythia on target in some regimes – despite LO predictions being low in other analyses (eg, Z+jets).

Publication in preparation.



W/*Z* + *b*-Jets: Summary

	CDF Data	Pythia	ALPGEN	Herwig	NLO	NLO(corr'd)
σ(Z+b jet) (pb)	0.9 ± 0.1 ± 0.1	-	-	-	0.51	0.53
σ(Z+b jet)/σ(Z) (%)	0.34 ± 0.05 ± 0.04	0.35	0.21	0.21	0.21	0.23
σ(Z+b jet)/σ(Z+jet) (%)	2.11 ± 0.33 ± 0.34	2.18	1.45	1.24	1.88	1.77
σ(W+b jet) (pb)	2.7 ± 0.3 ± 0.4	-	0.8	-	-	-

Raw NLO predictions corrected for underlying event and hadronization effects.

- More studies for *W*+*b*-jets are forthcoming
- Need to understand NLO predictions
  - In *Z*+*b*-jets it is strange that the NLO prediction undershoots data
  - Borne out in *W*+*b*-jets?

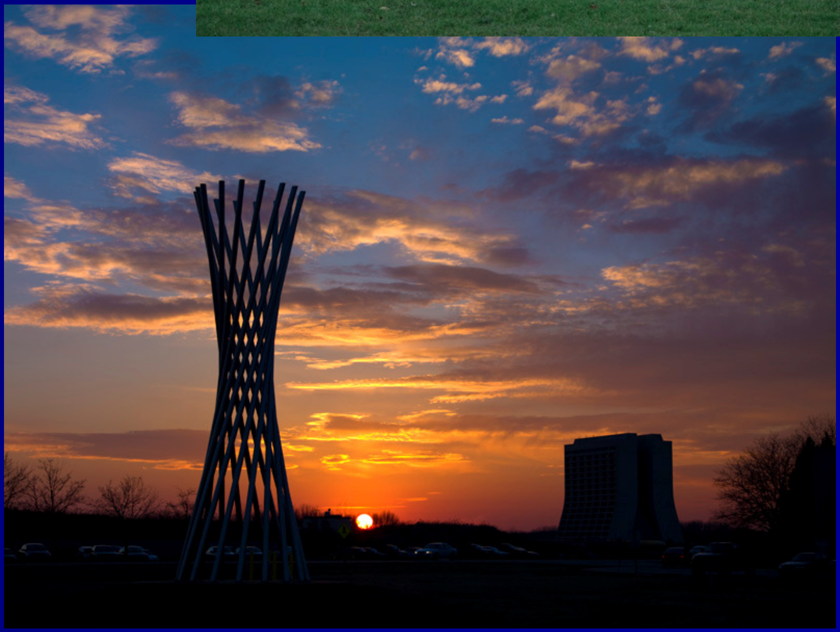
Conclusions

- W/Z + jets physics plays an **important role** in current collider physics programs

- Current NLO predictions for W/Z + look to be **accurate**, higher multiplicities desirable

- ***W/Z+b-jets*** studies have indicated deficiencies in both LO and NLO predictions; **more study and more data is needed**

- *W*+single *c* studies indicate **reasonable agreement** with NLO, LO predictions



Backup Slides

W + Inclusive Jets

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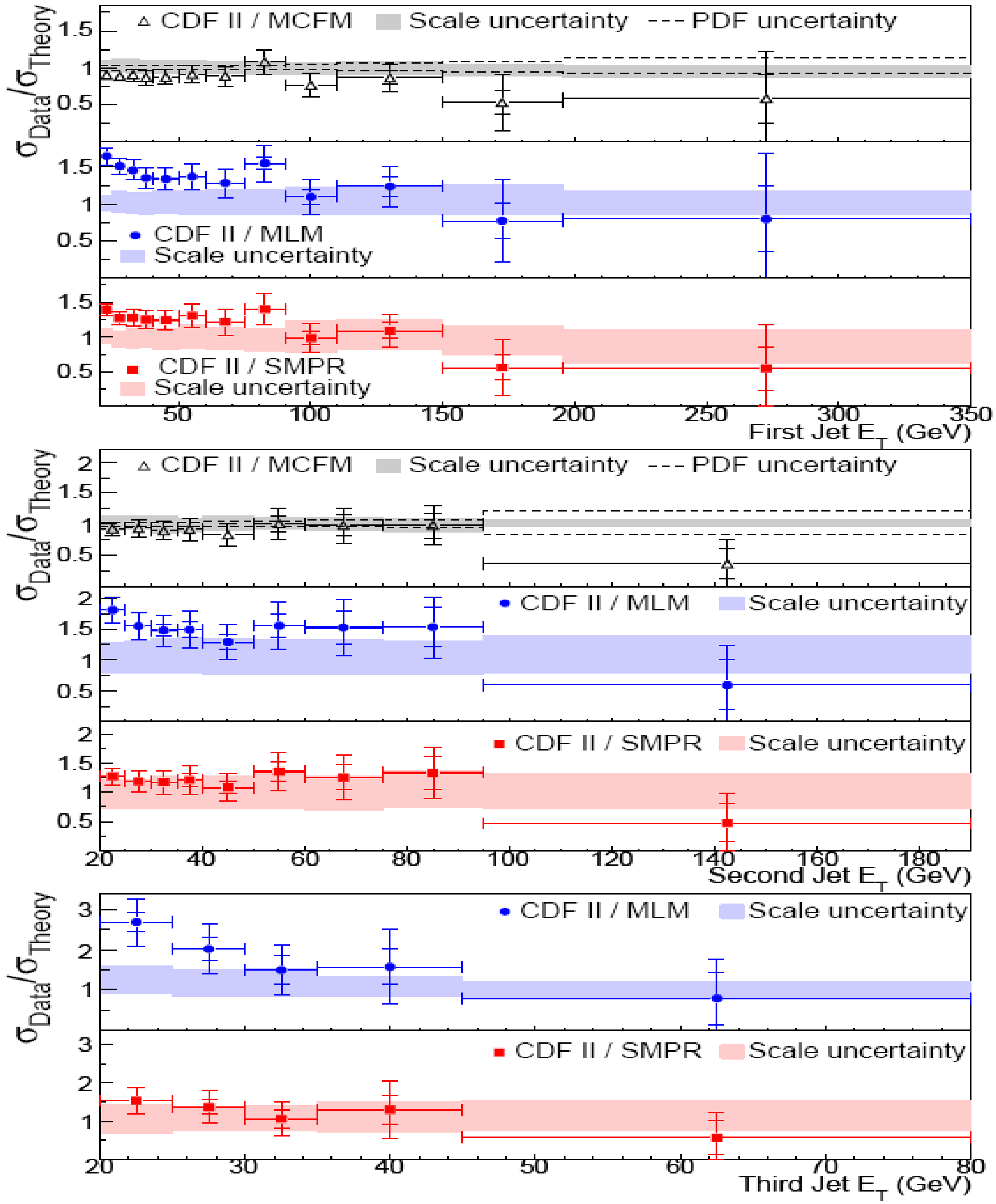

W + Inclusive Jets: Definition of Terms

MCFM :
MCFM (NLO)

MLM :
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MLM matching

SMPR :
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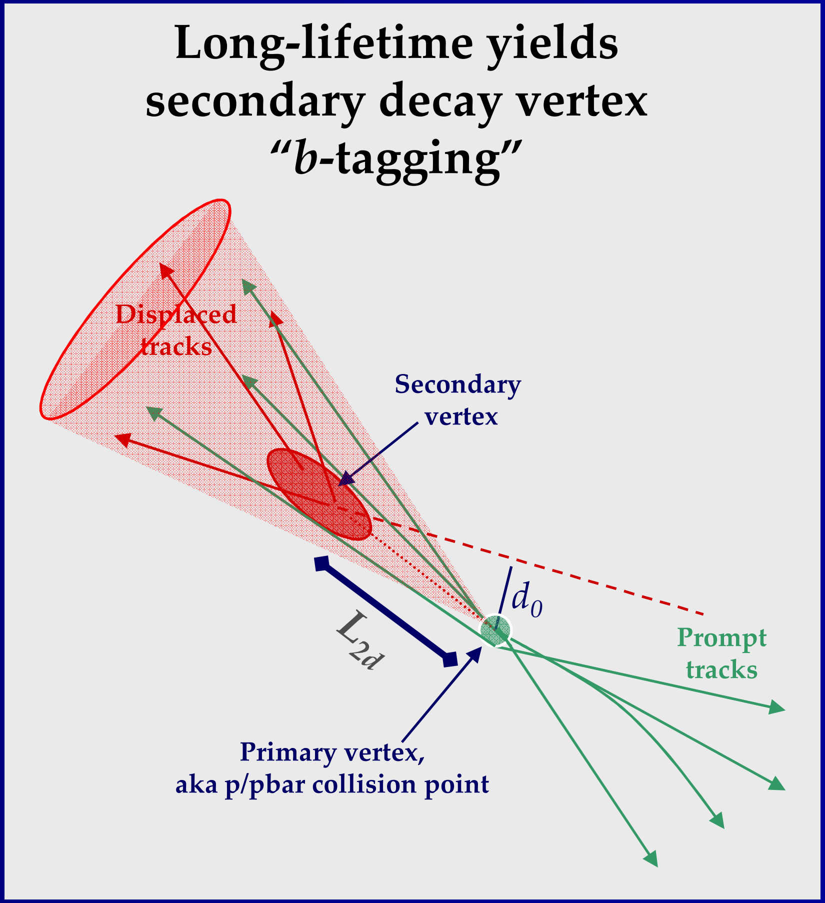
CKKW matching

- **MCFM**: Monte Carlo for Femtobarn Processes
  - NLO predictions for cross sections and kinematics
- **MLM**: Michelangelo Mangano, author of ALPGEN
- **ALPGEN, MadGraph**: matrix element generators
  - Generate fixed order processes (eg., W+0,1,2,3 partons for W+jets)
  - Shower the N-parton final state to get N-jets (eg. Pythia or Herwig)
  - Gather all the fixed order samples (eg., W+N-p for W+jets)
  - Remove double-counting via *matching algorithm*
- MLM matching:
  - Allow event iff $N_{jets} = N_{partons}$ (exclusive) or $N_{jets} \geq N_{partons}$ (inclusive)
- CKKW matching:
  - Assign each event weights from α_s nodes, legs
  - Veto event if event weight is below some cut
  - Use shower to add legs only up to some cutoff
- SMPR: variant of CKKW, named after S Mrenna and P Richardson

Identifying *b* Jets

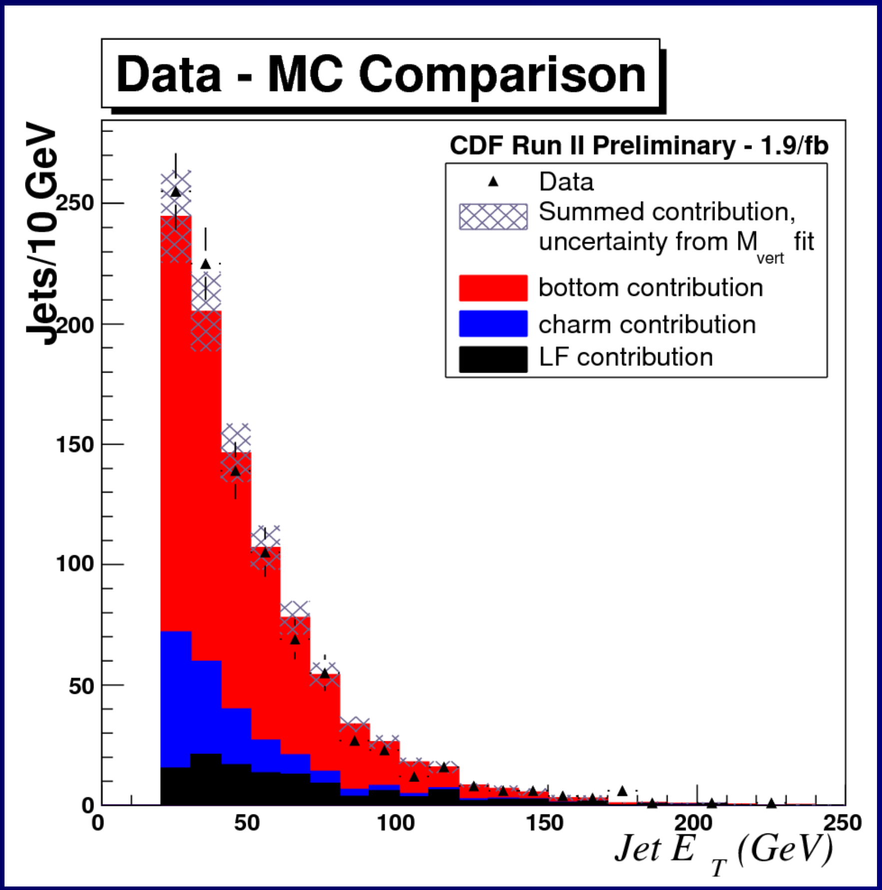
- ***B* hadron lifetime**: ~1.5 ps
  - Large boost (v ~ 0.95*c*) means the *B* lifetime is long in the lab frame
  - *B* travels macroscopic distance before decaying which we can detect



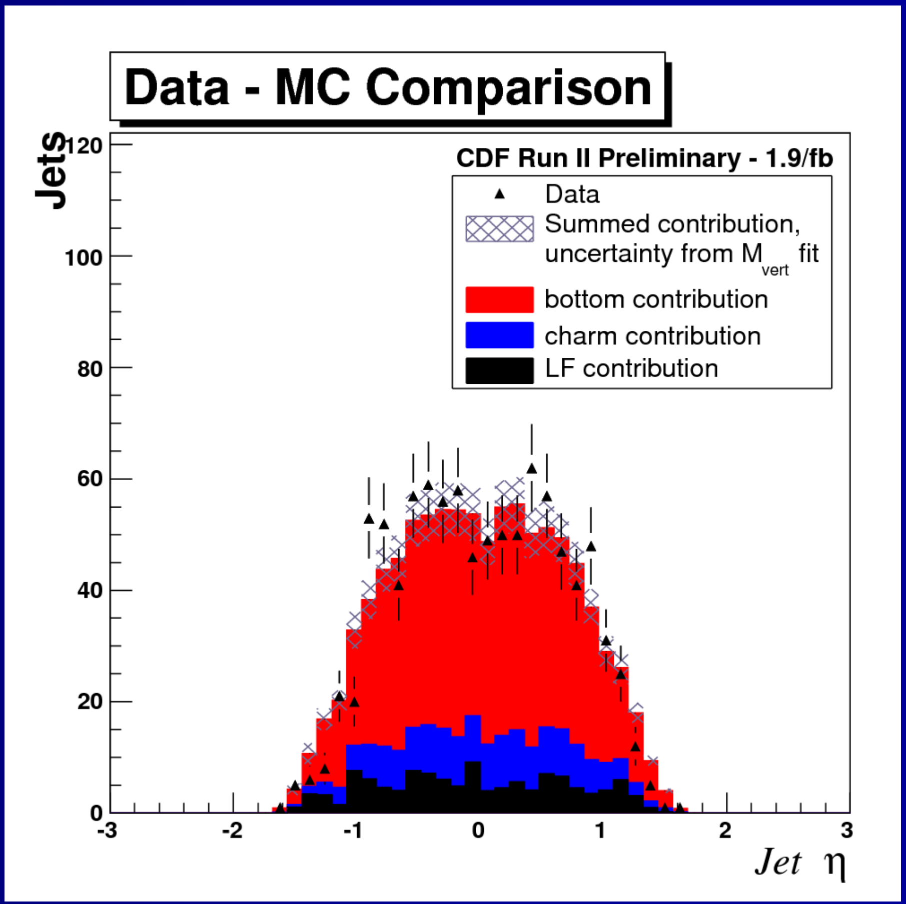
- **Exploit the long lifetime -**
  - Reconstruct charged particle tracks
  - See if they intersect at a common point
  - Require the common point be significantly displaced from the primary p-p collision point

	Meaning	Typical	Resolution
d_0	Track impact parameter	150um	40um
L_{2d}	Vertex displacement	2-3mm	100um

$W + b$-Jets

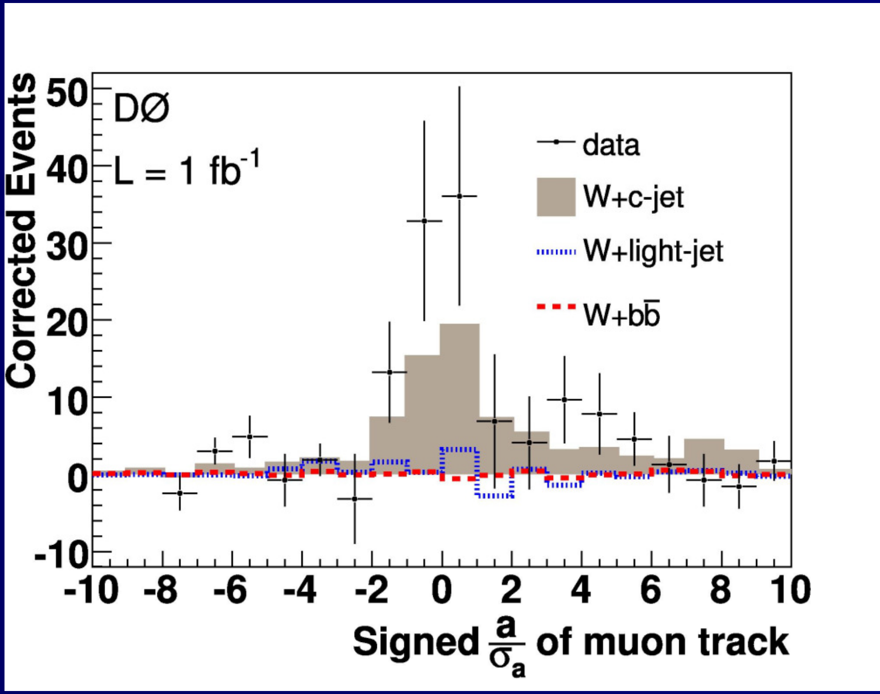


Data - MC Comparison
CDF Run II Preliminary - 1.9/fb
Data
Summed contribution, uncertainty from M vert fit
bottom contribution
charm contribution
LF contribution
Jets/10 GeV
0
50
100
150
200
250
Jet E T (GeV)



Data - MC Comparison
CDF Run II Preliminary - 1.9/fb
Data
Summed contribution, uncertainty from M vert fit
bottom contribution
charm contribution
LF contribution
Jets
0
20
40
60
80
100
120
-3
-2
-1
0
1
2
3
Jet η

W + Single c Production



Signed μ track impact parameter significance.

μ p_T relative to jet axis