Vector Boson + Heavy Flavor Jets Production at the Tevatron

Kenichi Hatakeyama
The Rockefeller University

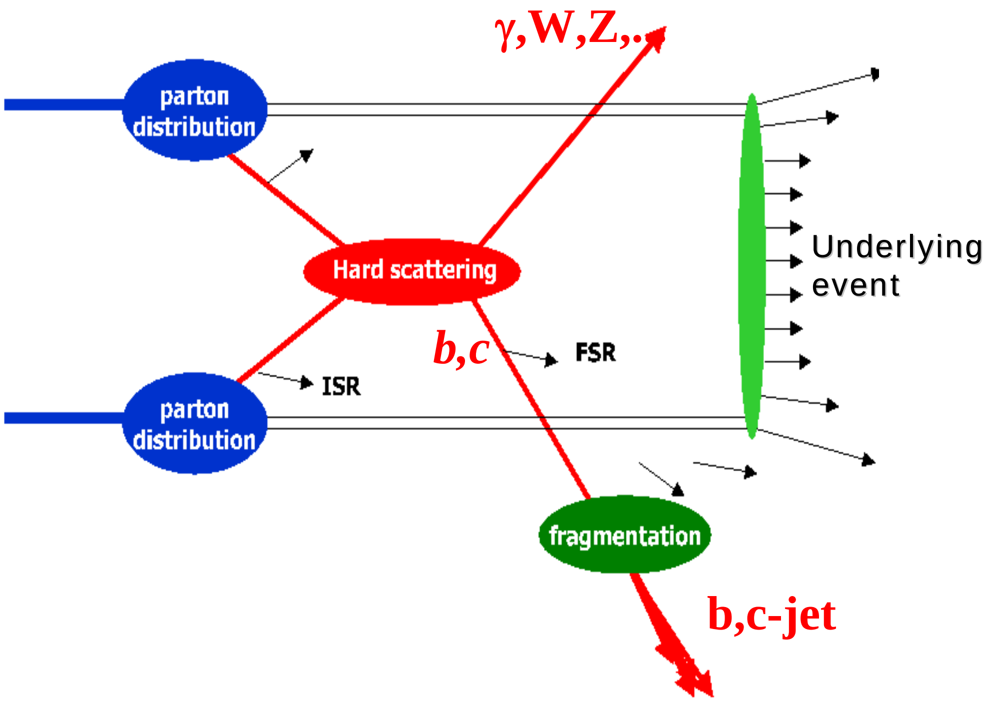
on behalf of the CDF and D0 Collaborations

34th International Conference on High Energy Physics,
Philadelphia, PA.
July 29 – August 5, 2008

Introduction

Vector boson + heavy flavor (HF) jets production is important for physics program at Tevatron

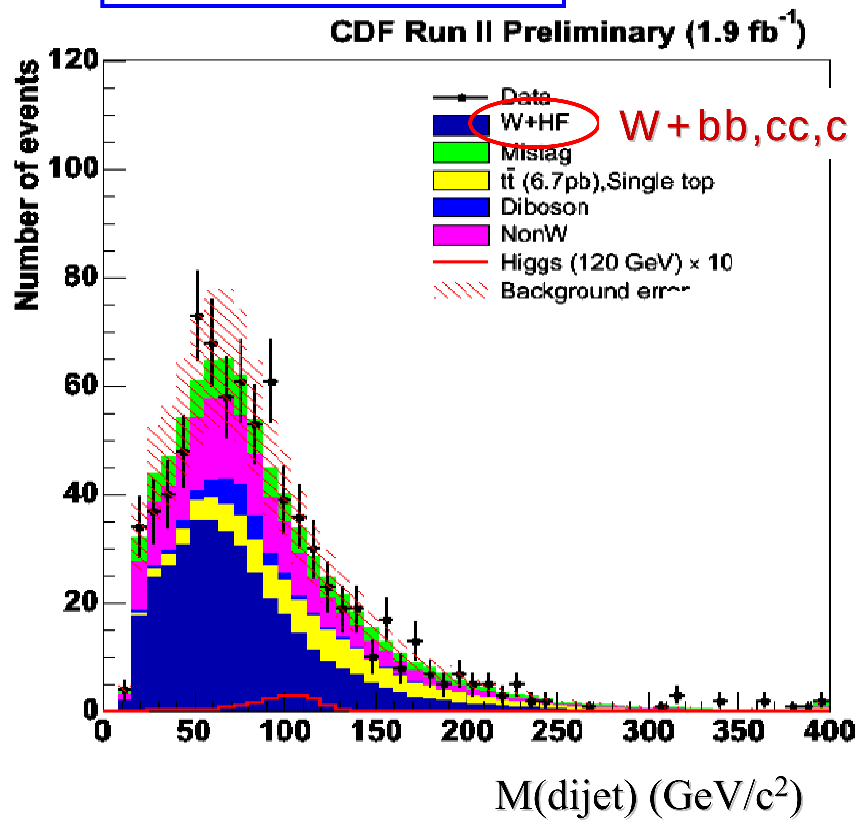
- For QCD
  - γ/W/Z provides direct probe of hard scattering dynamics
  - W/Z ensures high Q^2 ($\sim M_{W/Z}$) interactions, perturbative theory
  - Sensitive to HF content of proton PDF derived from gluon densities



Introduction

Vector boson + heavy flavor (HF) jets production is important for physics program at Tevatron

WH→lνbb search

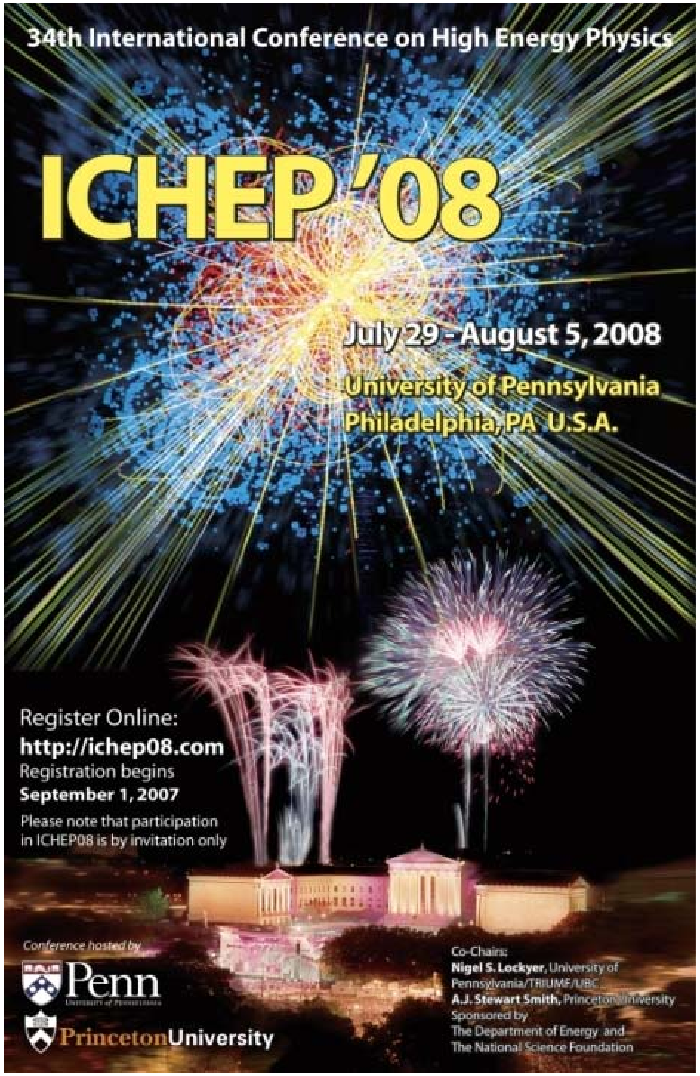


- Bkgd for many physics analyses
  - W/Z+HF-jet production is BG for studies of ttbar, single top, and searches for low mass Higgs, SUSY, Technicolor…
  - Photon+HF is also BG for broad range of analyses, e.g. SUSY, Technicolor, new generation, quark compositeness, …

Good understanding of these processes will enhance the physics potential

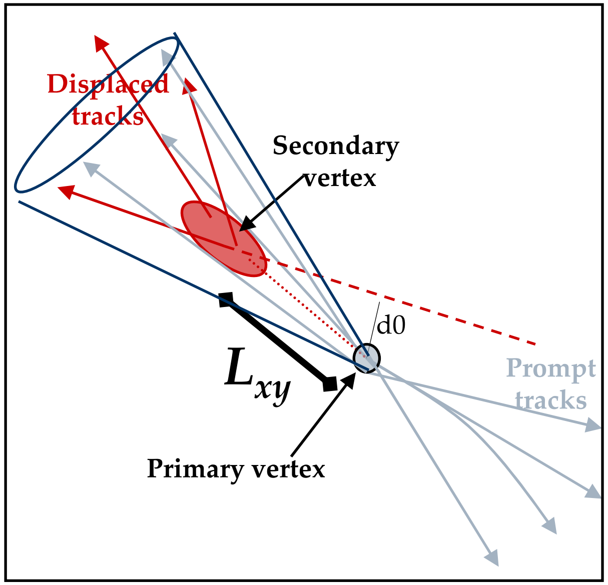
Outline

- Experimental techniques
  - B-jet identification
- W+*b*-jet production
- Z+*b*-jet production
- Photon+*b/c*-jet production
- W+single *c*-jet production
- Conclude



b-jet identification

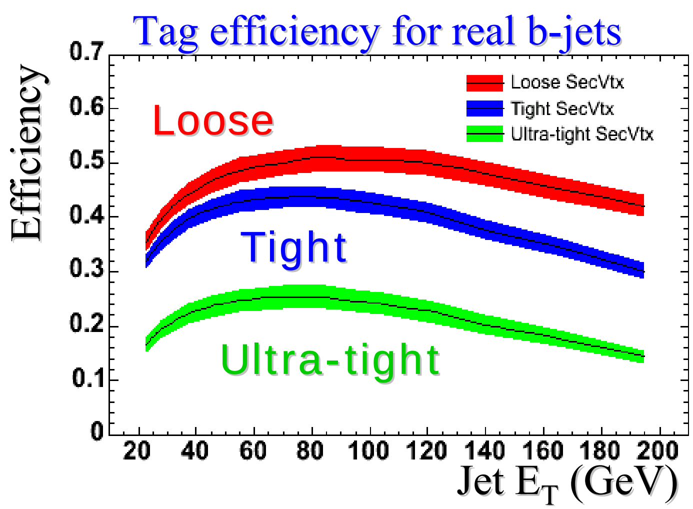
- The most commonly used "tagging" technique identifies *b*-jets with a displaced secondary vertex (long B hadron lifetime, $c\tau \sim 0.5$ mm)
  - Consider tracks in η-φ cone of 0.4 around jet axis
  - Reconstruct secondary vertex from displaced tracks
  - If the vertex has large transverse displacement (Lxy), the jet is "*b*-tagged".



- Evaluate *b*-tagging performance:
  - Tag efficiency for *b*-jets
  - *b*-fraction: fraction of *b's* in the tagged sample

b-jet identification cont'd

Tagging efficiency:

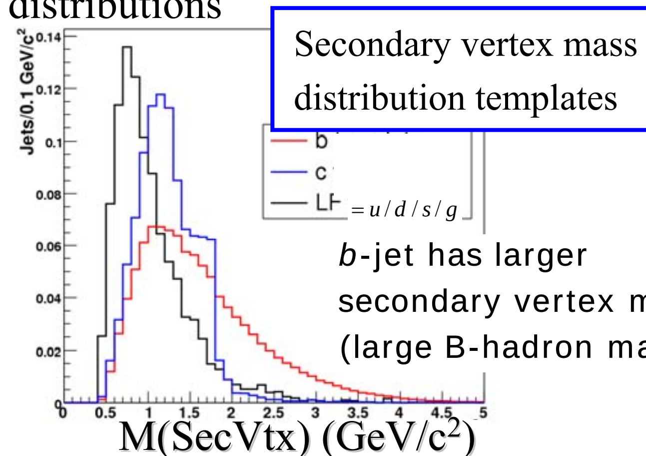


- Different requirements on displaced tracks & # of tracks in secondary vertex define different *operating points* of tagging algorithm:

  Loose, Tight, Ultra-tight.
- When the tag efficiency for b-jets is increased, the mis-tag probability of non-b jets also increases.

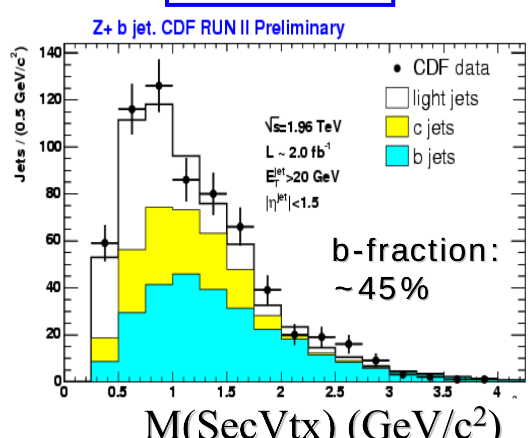
b-fraction in tagged sample (purity):

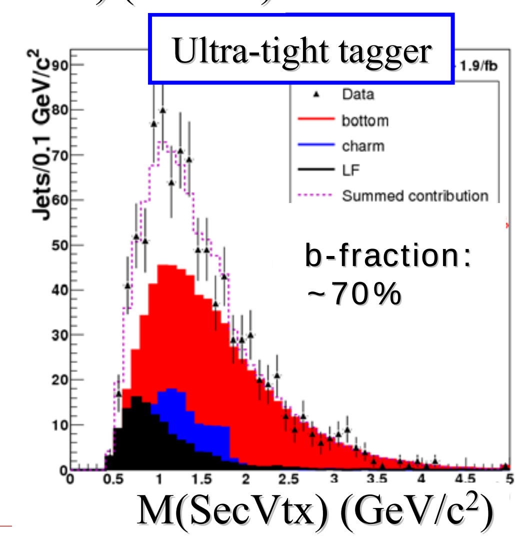
Make template fits to the secondary vertex mass distributions



b-jet has larger secondary vertex mass (large B-hadron mass)

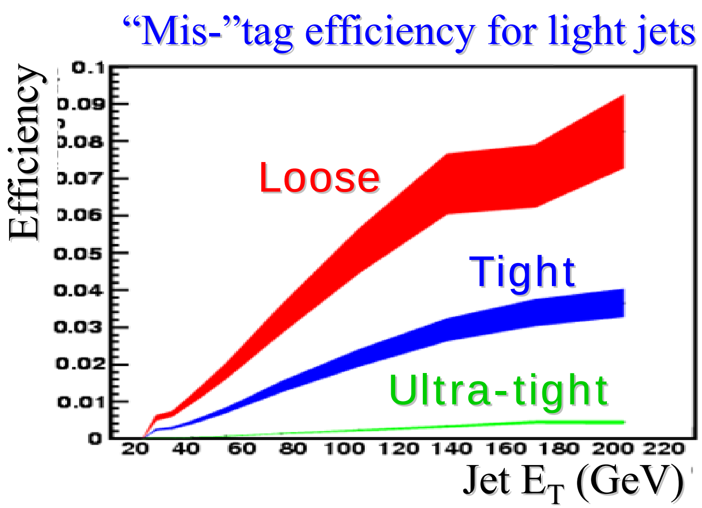
Tight tagger





b-jet identification cont'd

Tagging efficiency:

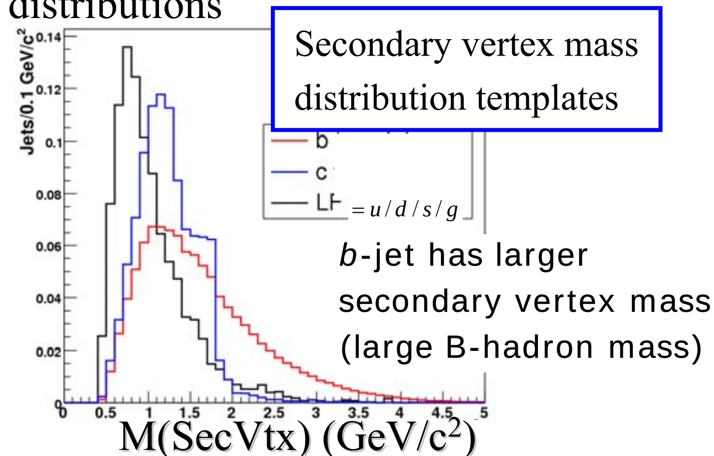


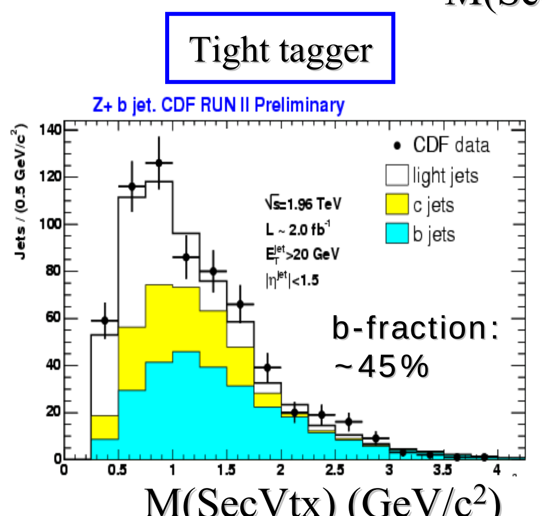
- Different requirements on displaced tracks & # of tracks in secondary vertex define different *operating points* of tagging algorithm:

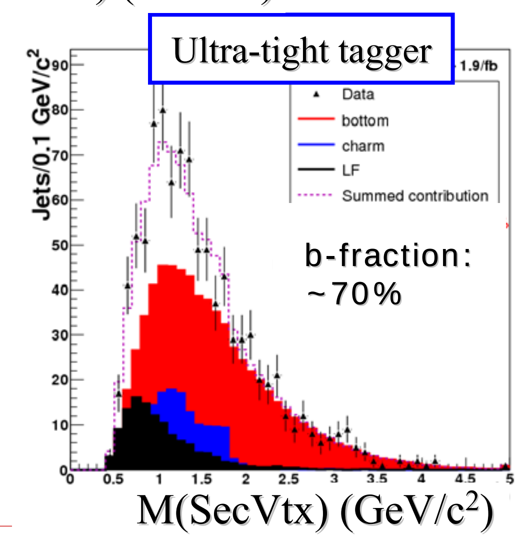
  Loose, Tight, Ultra-tight.
- When the tag efficiency for b-jets is increased, the mis-tag efficiency of non-b jets also increases.

b-fraction in tagged sample (purity):

Make template fits to the secondary vertex mass distributions

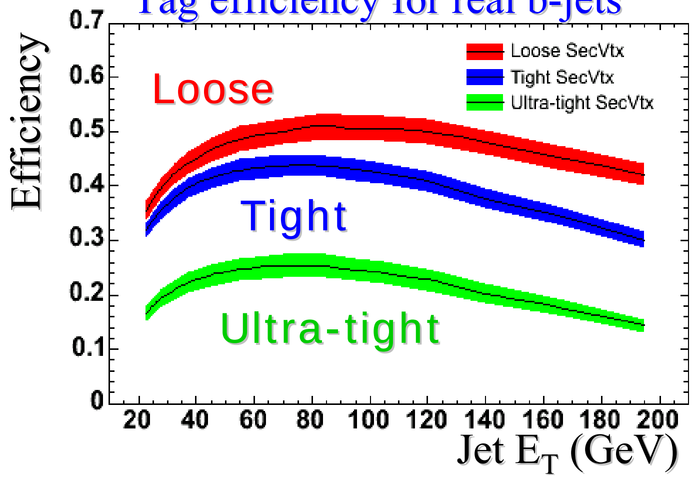






b-jet identification cont'd

Tagging efficiency:



- Different requirements on displaced tracks & # of tracks in secondary vertex define different *operating points* of tagging algorithm:

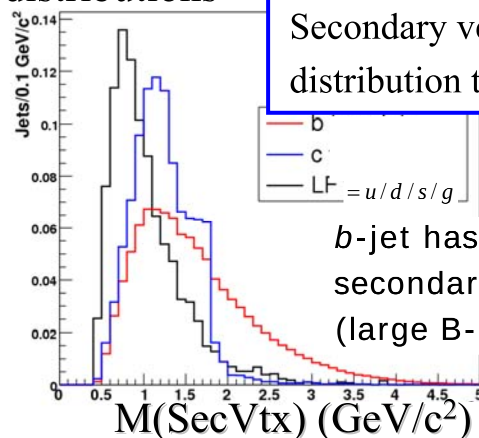
  Loose, Tight, Ultra-tight.

- When the tag efficiency for b-jets is increased, the mis-tag efficiency of non-b jets also increases.

b-fraction in tagged sample (purity):

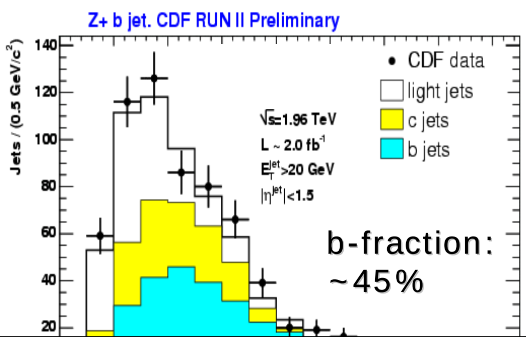
Make template fits to the secondary vertex mass distributions

Secondary vertex mass distribution templates



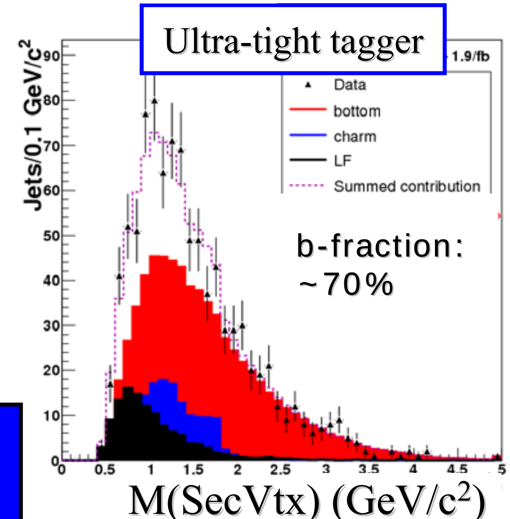
b-jet has larger secondary vertex mass (large B-hadron mass)

Tight tagger



b-fraction: ~45%

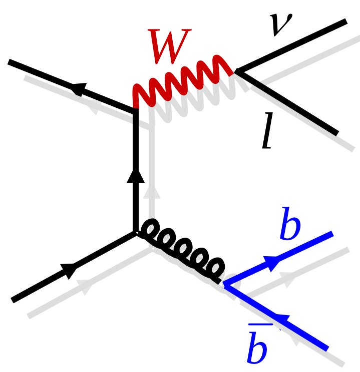
Ultra-tight tagger



b-fraction: ~70%

Choose operating point depending on the analysis needs!

W+*b*-jets production



Large background for many analyses

- SM Higgs (WH) production
- Single top quark production
- $t\bar{t}$ production

Hope is to use this measurement to improve background estimate for these studies.

Analysis

- **$W \to l\ \nu\,(l=e,\mu)$ selection:**
  - e: $E_T > 20$ GeV, $|\eta| < 1.1$
  - μ: $p_T > 20$ GeV/c, $|\eta| < 1.0$
  - ν: Missing E_T, MET > 25 GeV
- **b-Jet selection:**
  - Cone algorithm, R= 0.4
  - $E_T > 20$ GeV, $|\eta| < 2.0$
  - b-identification: "ultratight" secondary vertex tagging
- **W+b-jets cross section:**

$$\sigma_{W+bjets} \cdot Br = \frac{N_{b-tags} \cdot f^{bjets} - N_{bkg}^{bjets}}{L \times A \times \varepsilon}$$

N_{b-tags} : number of b – tags

f^{bjets} : b – jet purity in b - tag sample

N_{bkg}^{bjets} : number of tagged b – jets not from $W + b\bar{b}$

W+*b*-jets production

$$\sigma_{W+bjets} \cdot Br = \frac{N_{b-tags} \cdot f^{bjets} - N^{bjets}_{bkg}}{L \times A \times \varepsilon}$$

- **Major b-jets bkgd. (S/B ~ 3/1):**
  - ttbar (40% of total bkgd)
  - single top (30%)
  - Fake *W* (15%)
  - *WZ* (5%)

  Total contribution: ~180 tagged b jets

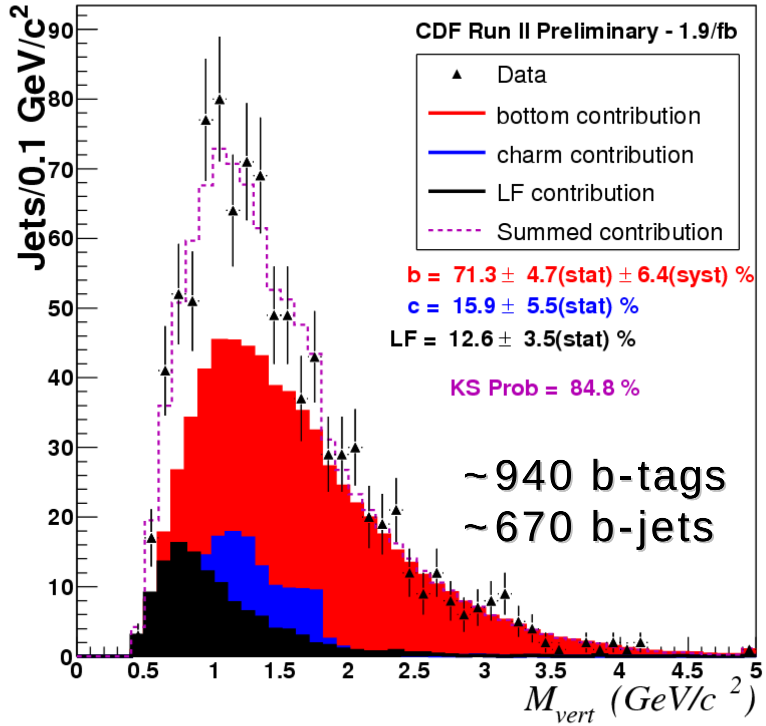
- **Measurement:**

  $\sigma \cdot BR$ =2.74 ± 0.27(stat) ± 0.42(syst) pb

  ($p_T^{e\mu}$>20 GeV/c, $|\eta^{e\mu}|$<1.1, p_T^{ν}>25 GeV, E_T^{bjet}>20 GeV, $|\eta^{bjet}|$<2.0)

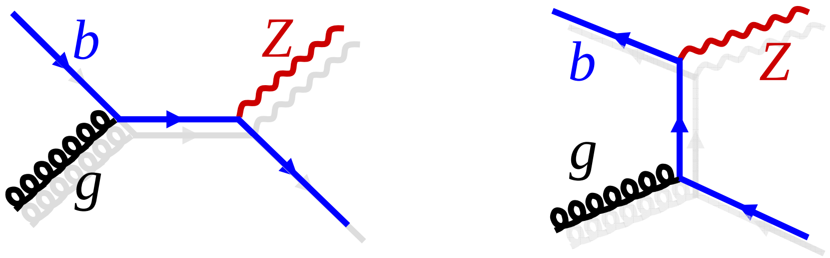
- **Alpgen (LO) prediction:**

  $\sigma \cdot BR$ = 0.78 pb



The measurement x3.5 larger than the Alpgen prediction. Waiting for other theoretical predictions (MCFM NLO etc.)

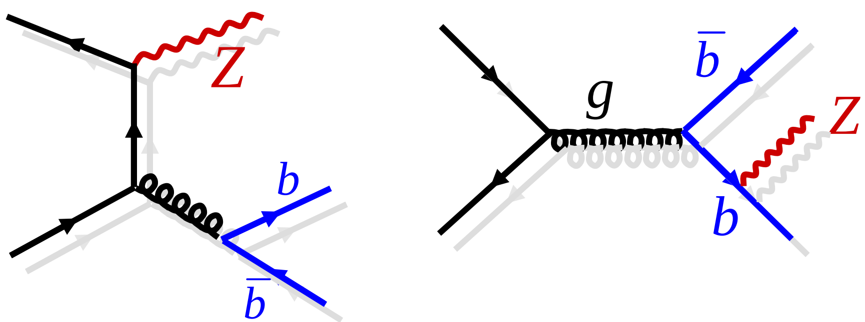
Z + *b*-jets production



Probe the less-well-known heavy flavor content of the proton.

The knowledge of the *b*-density in the proton influences:

- Single top-quark production $qb \to q't$ and $gb \to Wt$
- Supersymmetric higgs boson production, $gb \to hb, bb \to h$



Major background for SM higgs searches (ZH, H $\to$ $b\bar{b}$)

Z + *b*-jets production

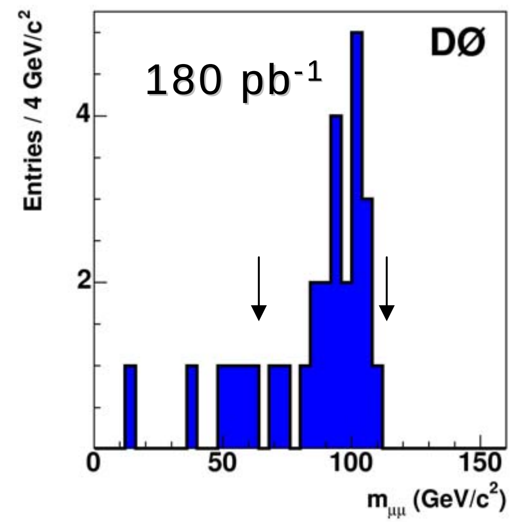
- Z events selected with ee/μμ
- *b*-jet identification by secondary vertex
- Measured σ(Z+b jets)/σ(Z+jets) allowing the cancellation of many systematic uncertainties

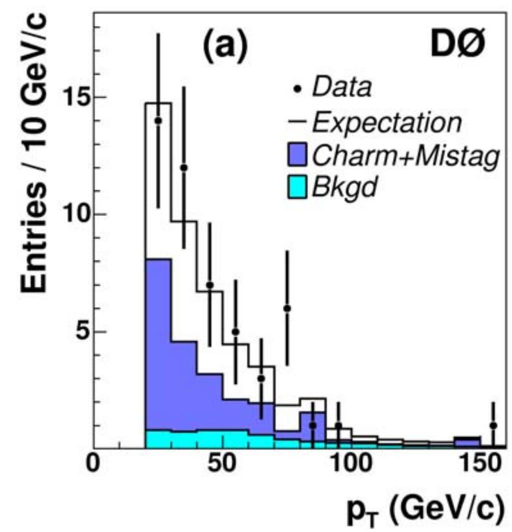
- Measurement: $(p_T^{jet} > 20\,\mathrm{GeV/c}\ \text{and}\ |\eta^{jet}| < 2.5)$

$$2.1 \pm 0.4(\mathrm{stat})^{+0.2}_{-0.3}(\mathrm{syst})\%$$

- In agreement with the NLO prediction: 1.8 ± 0.4 % based on CTEQ6 PDF.
  Phys. Rev. Lett. 94, 161801.

- CDF made similar measurement with 340 pb^{-1}
  Phys. Rev. D 74, 032008.

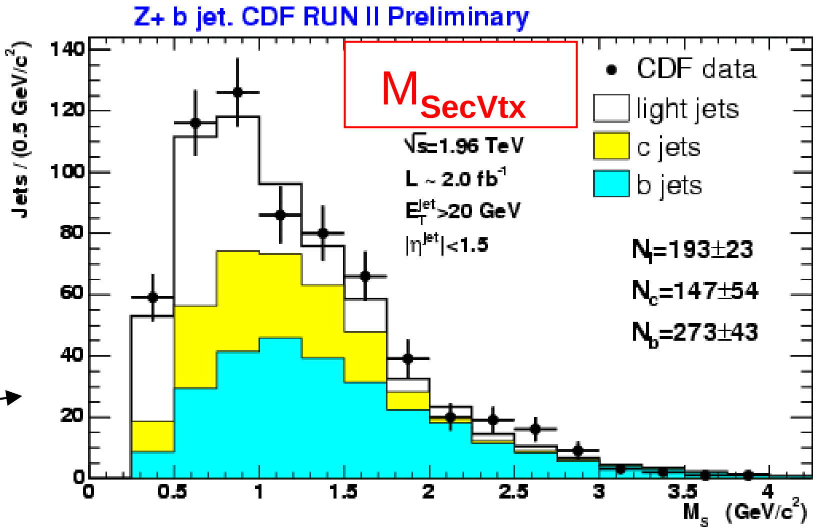




Z+*b* jets Production

- L = 2.0 fb^{-1}
- Z events selected with ee/μμ
- *b*-jet identification: Tight secondary vertex tagging

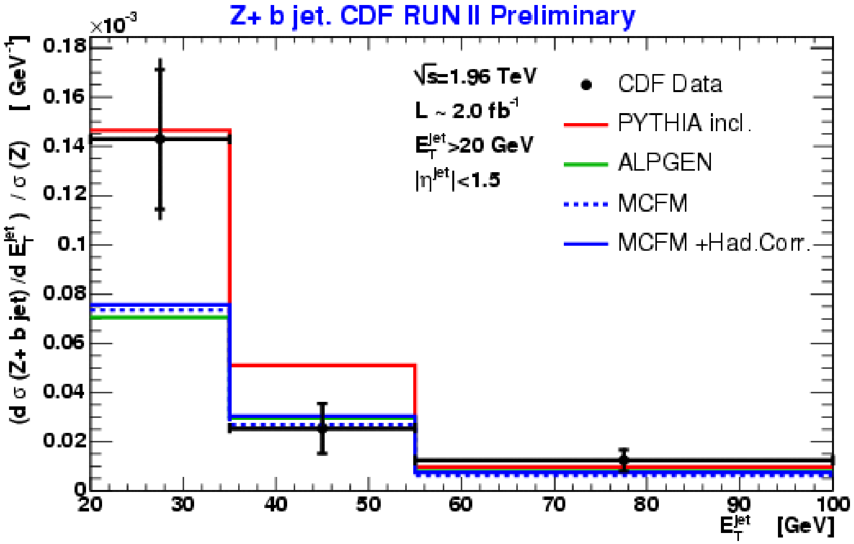
b, c and light fractions determined from the template fit of the secondary vertex mass distributions →

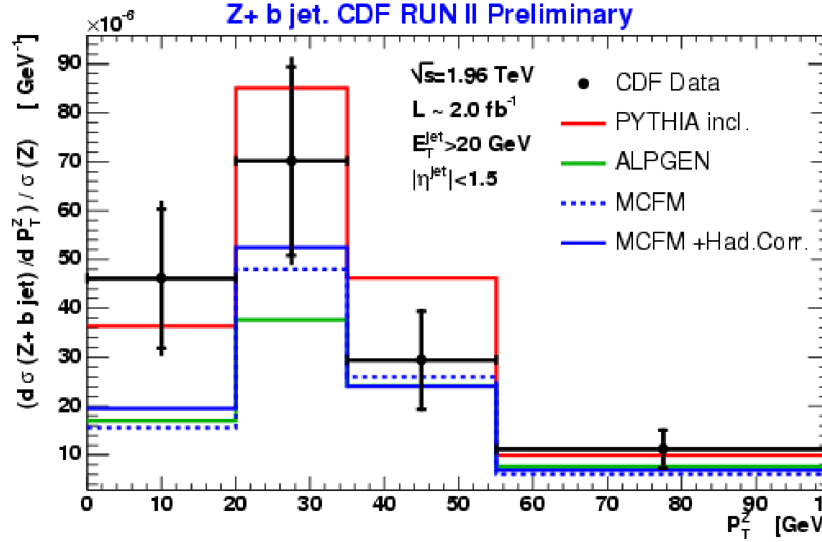


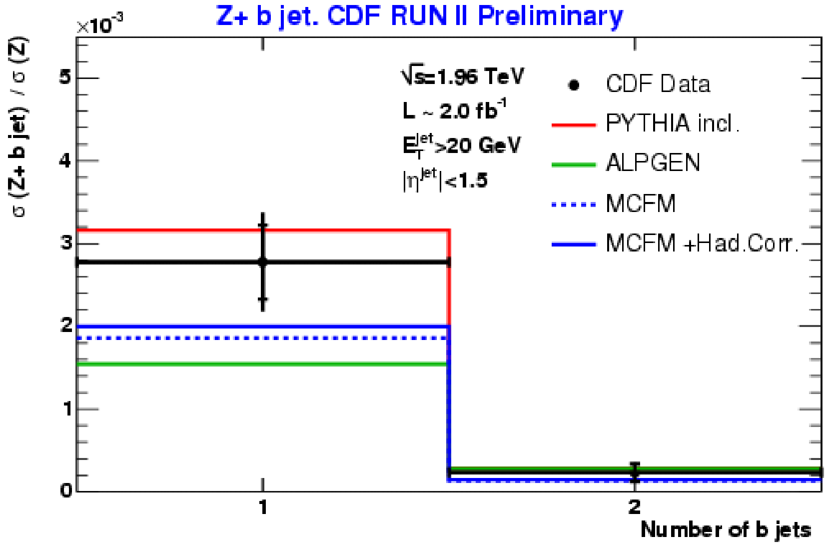
E_T^{jet}>20 GeV, $\|\eta^{jet}\|$<1.5 R_{jet}=0.7	Measurement	PYTHIA	Alpgen	NLO	NLO + UE + hadr.
σ(Z+*b*-jet)	0.86 ± 0.14 ± 0.12 (pb)			0.51 pb	0.53(pb)
σ(Z+*b*-jet)/ σ(Z)	0. 336 ± 0.053 ± 0.041 %	0.35 %	0.21%	0.21 %	0.23 %
σ(Z+*b*-jet)/ σ(Z+jet)	2.11 ± 0.33 ± 0.34 %	2.18 %	1.45%	1.88 %	1.77 %

Data somewhat higher than NLO predictions. NLO vs PYTHIA differences not well understood yet. In touch with theorists.

Z+*b* jets Production





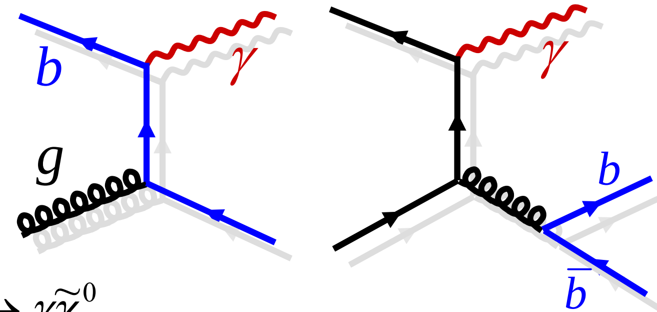


- First measurement of differential distributions.
- Alpgen (LO) and NLO pQCD predictions too low at low E_T
- Interestingly, Pythia (LO) predictions reasonable in some kinematic regions.

Photon+*b* jets production

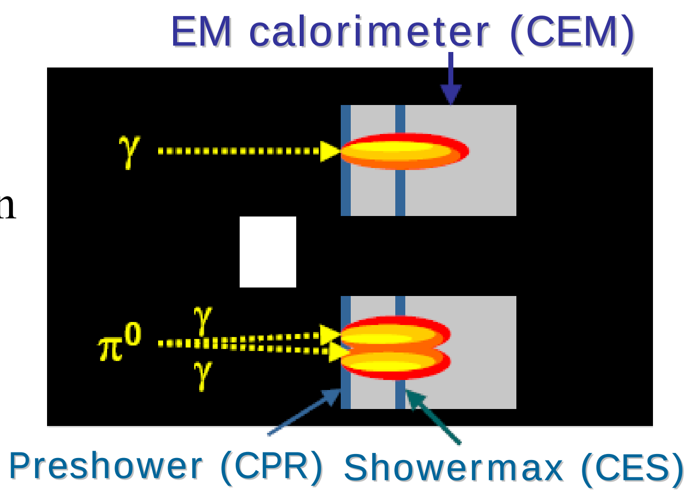
Motivation:

- Sensitive to b-content of proton PDF
- Many new physics models lead to photon+*b* final state:
  - Technicolor: $\omega_{TC} \to \gamma\pi_{TC} \to \gamma b\bar{b}$
  - SUSY: $e.g.\ \tilde{\chi}_i^+\tilde{\chi}_2^0, \tilde{\chi}_i^\pm \to \tilde{t}\,b \to bc\tilde{\chi}_1^0, \tilde{\chi}_2^0 \to \gamma\tilde{\chi}_1^0$
  - 4^{th} generation, excited *b*-quark
  - …

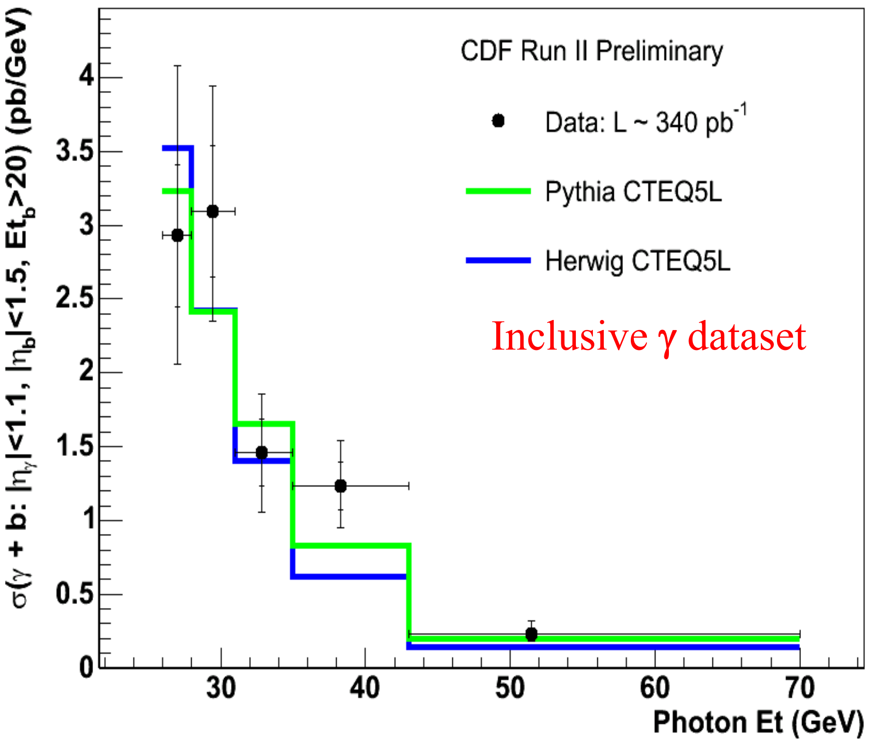


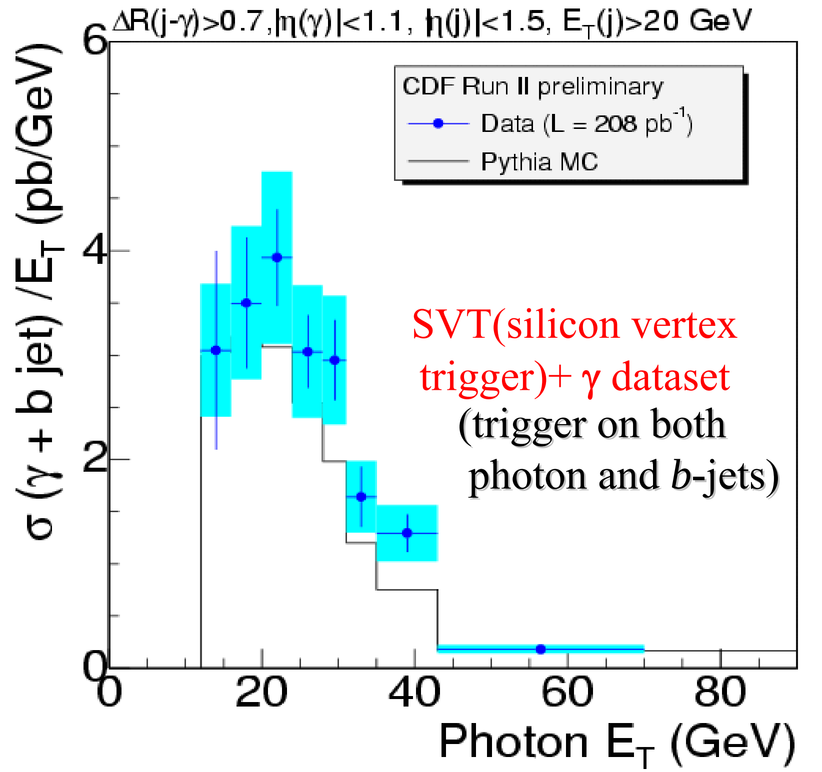
Strategy:

- Photon identification
  - Statistical separation from π^0 based on measured shower shape
  - Purity ~ 60% at p_T^{γ}=26 GeV/c (CDF)
- b-jet identification
  - Tight secondary vertex tagging



Photon + *b* Jet Production

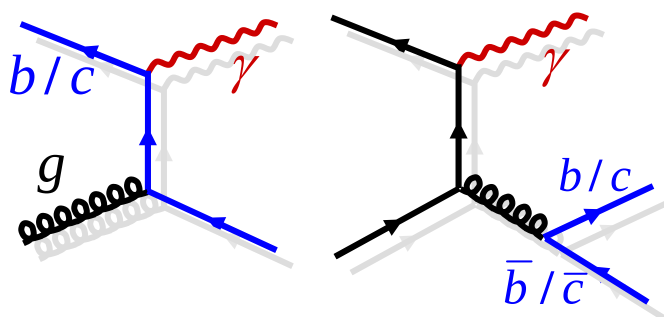




E_T^{γ} down to 12 GeV

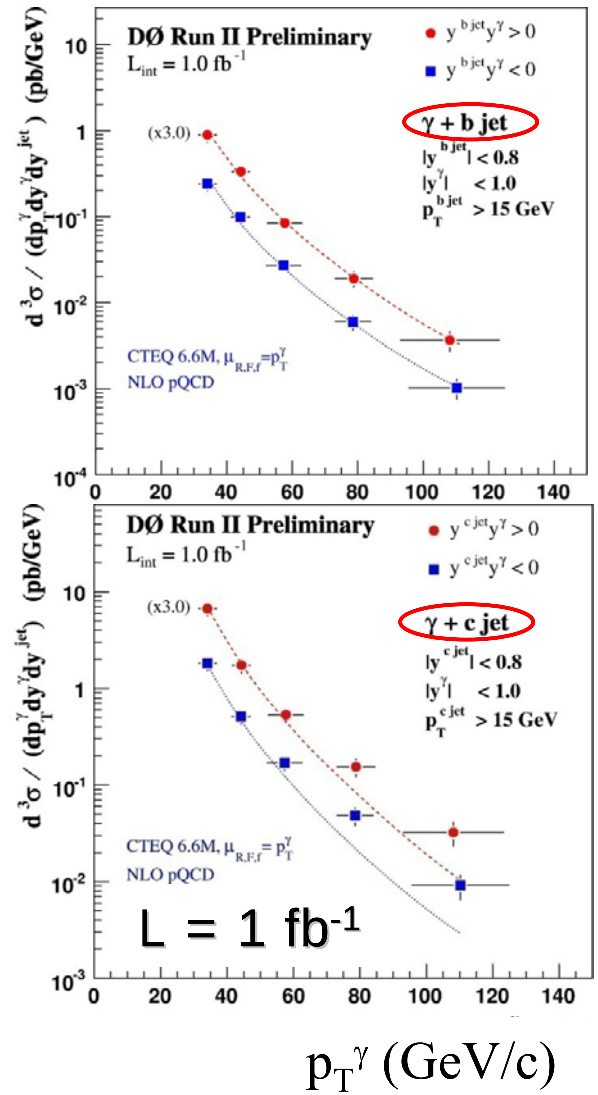
In reasonable agreement with Pythia (LO) predictions. Waiting for NLO pQCD calculations for this process.

Photon + HF Jet Production



- Photon p_T: 30 – 150 GeV/c
- Rapidities: $|y^{\gamma}|<1.0$, $|y^{jet}|<0.8$
  - $y^{\gamma}\cdot y^{jet} > 0$: $0.01<x_1<0.03$, $0.03<x_2<0.09$
  - $y^{\gamma}\cdot y^{jet} < 0$: $0.02<x_1,x_2<0.06$
- Measure triple differential cross sections.

$$d^3\sigma/(dp_T^{\gamma}dy^{\gamma}dy^{jet})$$

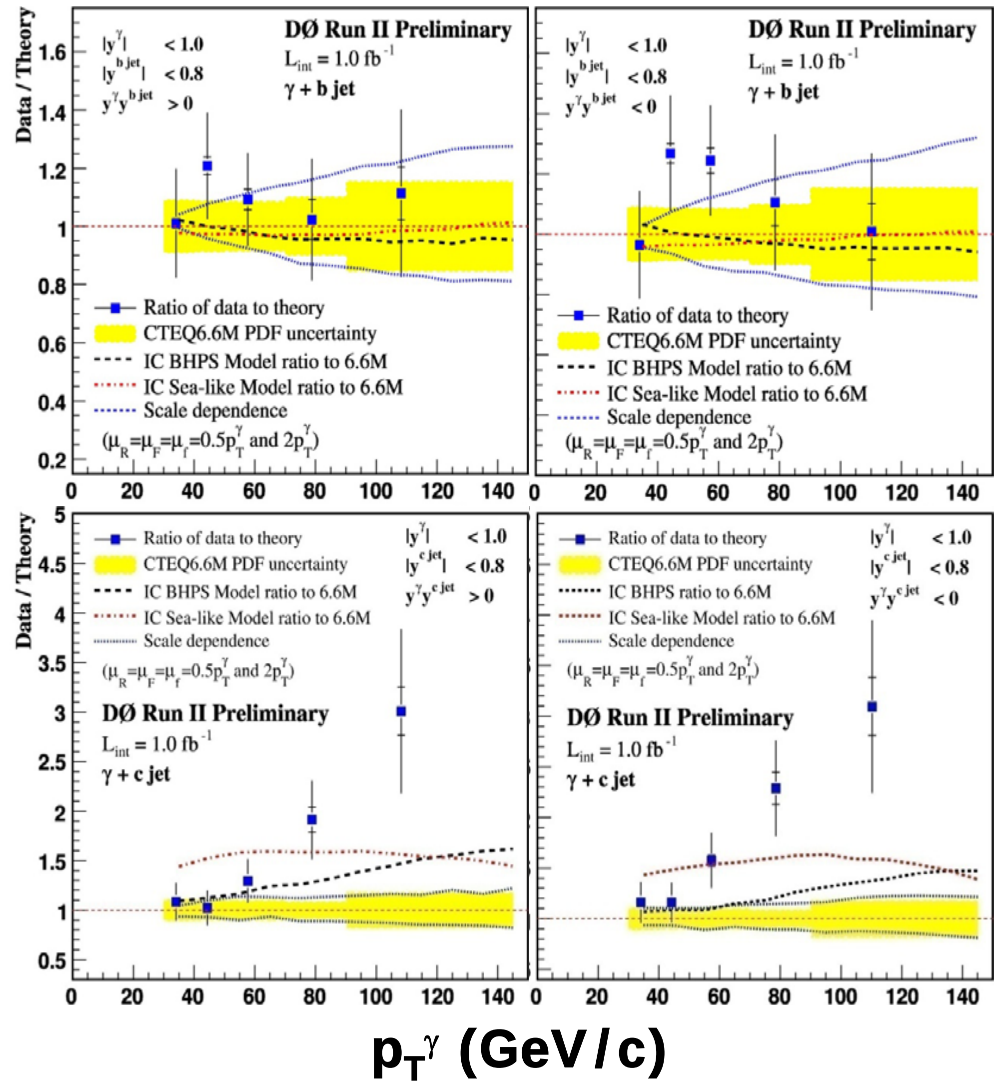


Photon + HF Jet Production

- Photon+*b*:

  Agreement over full p_T^γ range: 30 – 150 GeV/c

- Photon+*c*:
  - Agree only at p_T^γ<50 GeV/c
  - Disagreement increases with photon p_T^γ.
  - Using PDF including the intrinsic charm (IC) improves the p_T^γ dependence



W + Single *c* Production

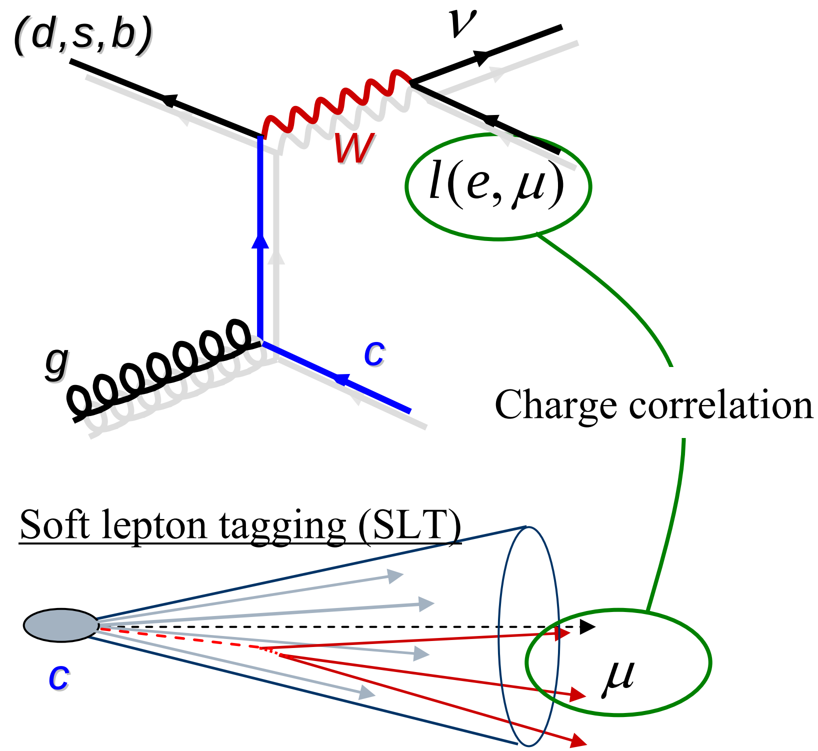
Motivation:

- Probe *s*-content of proton at high Q^2
  - $g{+}s \sim 0.9,\ g{+}d \sim 0.1.$
- Important BG for top quark studies, searches for Higgs, stop…

Strategy:

- $W \rightarrow l{+}\nu$ selected by high p_T e,μ + MET
- Charm-jet identified by the soft lepton (muon) tagging (SLT) algorithm.
- Utilize charge correlation between W lepton and SLT muon.
  - In W+c production, opposite sign (OS) > same sign (SS).
  - In W+bb(cc), same sign (SS) ~ OS.

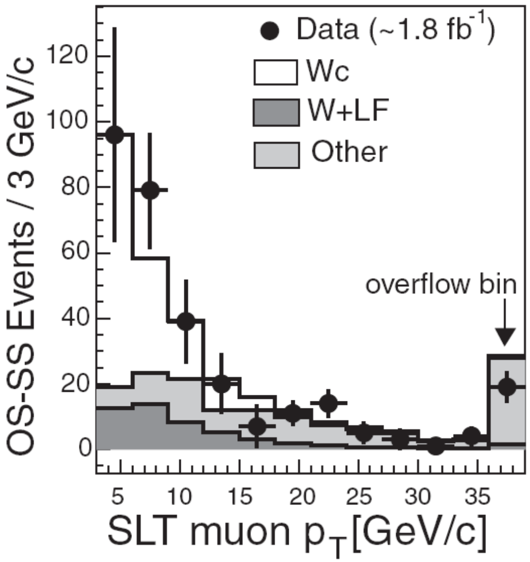
$$\sigma_{W+c} \times Br(W \rightarrow l\nu) = \frac{N^{OS-SS}_{measured} - N^{OS-SS}_{bkg}}{L \times A \times \varepsilon}$$

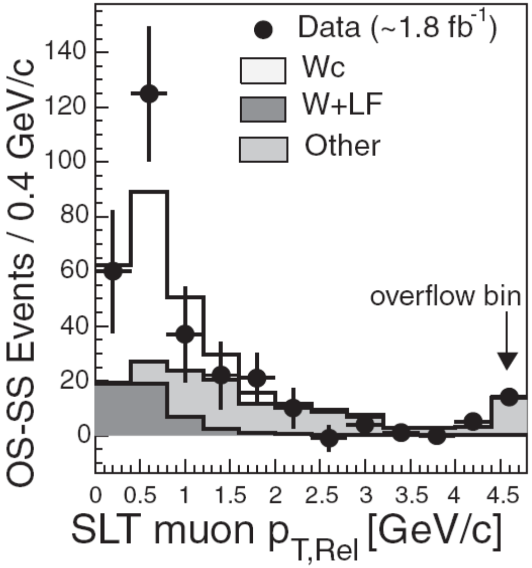


Main OS-SS backgrounds

- Fake W
- W+light jets
- Drell-Yan

W + Single *c* Production





Total: 298 events, W+c = 149 ± 42 ± 15 events.

Measurement ($p_T^c > 20$ GeV , $|\eta_c| < 1.5$) **:**

$\sigma_{W+c} \cdot BR(W \rightarrow l\nu) = 9.8 \pm 2.8\ (\text{stat})\ ^{+1.4}_{-1.6}\ (\text{syst}) \pm 0.6\ (\text{lum})\ \text{pb}$

NLO pQCD prediction:

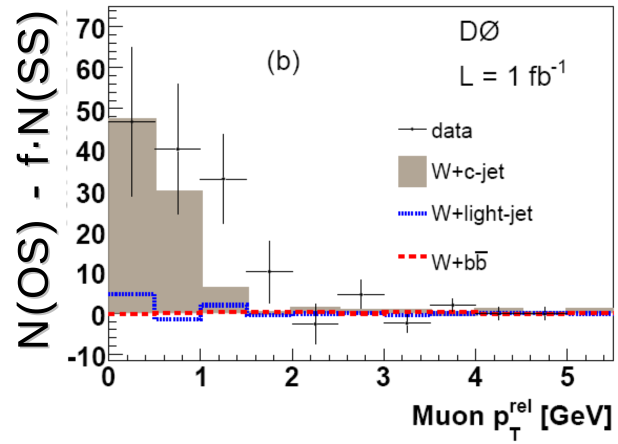
$11.0\ ^{+1.4}_{-3.0}$ pb

In good agreement

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

W + Single *c* Production

- Measure the ratio $\sigma_{W+c}/\sigma_{W+jets}$. Many systematic uncertainties cancel.
- Measurement made as function of jet p_T.



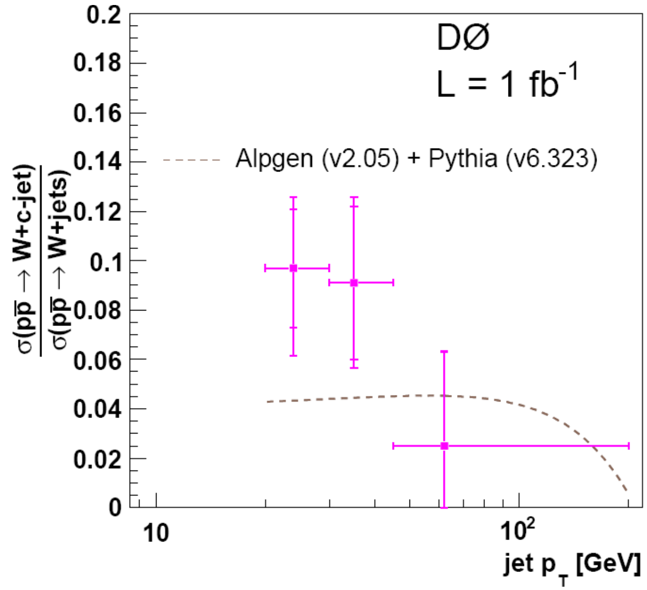
- **Measurement** (p_T^{jet}>20 GeV/c, $|\eta_{jet}|$<2.5) :

$$\frac{\sigma_{W+c}}{\sigma_{W+jets}} = 0.074 \pm 0.019(stat.)^{+0.012}_{-0.014}(syst.)$$

Alpgen+Pythia prediction:

0.040 ± 0.003 (PDF)

In reasonable agreement



arXiv:0803.2259 [hep-ex]

Conclusions

- Good understanding of vector boson + heavy flavor jets production is critical for physics analyses at the Tevatron and at the upcoming LHC

- W+single c and γ+b measurements well described by the state-of-the-art recent theoretical calculations

- However, W/Z+b-jets and γ+*c*-jets measurements are not well described by current theory predictions.

  More development in theoretical calculations and more accurate experimental measurements are critical!