Hadronic final states in high-p_T QCD at CDF

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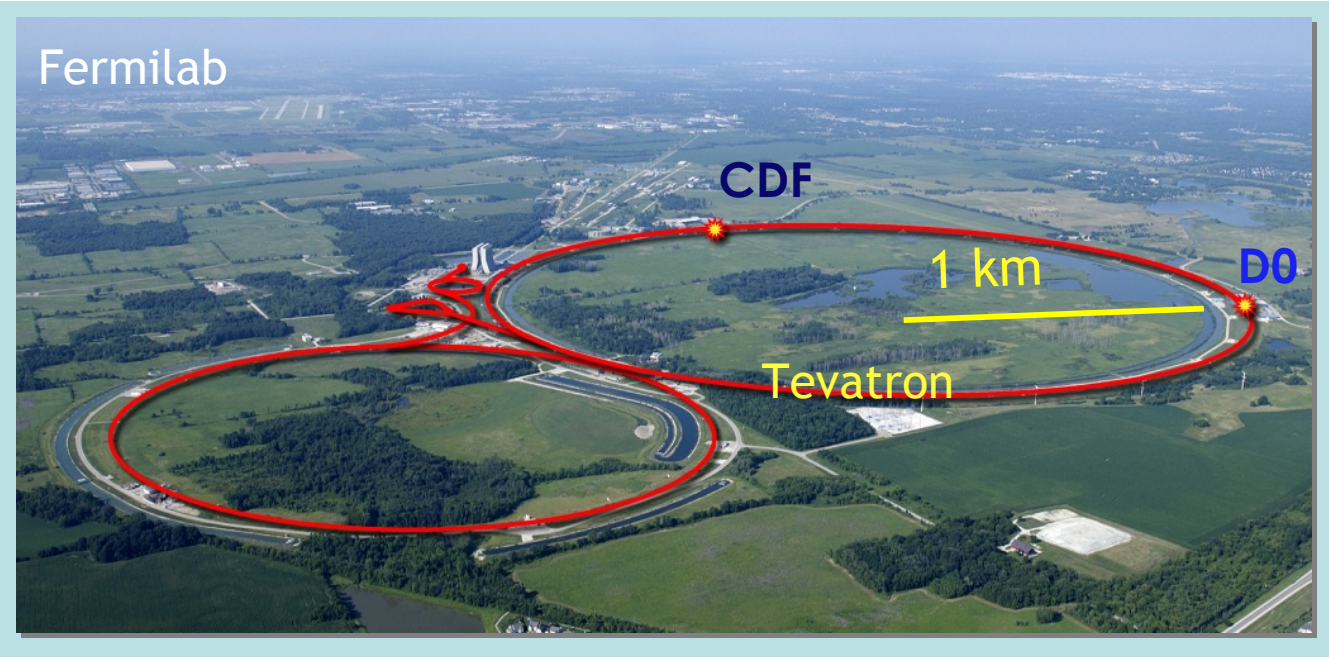
Agenda

- Tevatron / CDF
  - A brief refresher
- Prompt γ plus heavy flavor production
  - Is a clean probe to test QCD predictions
  - Describes background for searches with final state γ+*b/c*
- W/Z plus heavy flavor
  - Probes the quark content of the proton
  - Tests models of QCD fragmentation
- Will present:
  - Recent results from CDF, comparison with predictions, and interpretations

Tevatron

- Collided $p\bar{p}$ bunches at $\sqrt{s}$=1.96 GeV through 30/09/2011

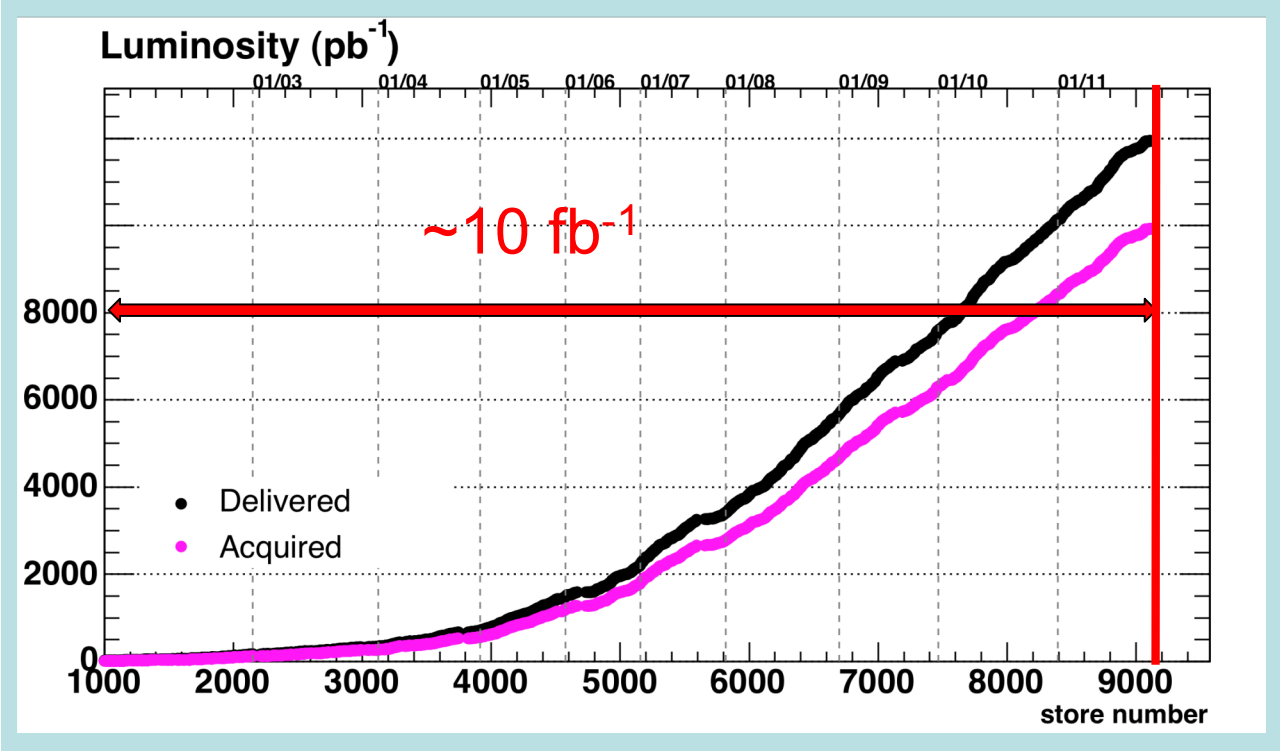


(Also ran at $\sqrt{s}$=300, 900 MeV near end of operation: talks later this week!)

- Peak luminosity ~3-4 x 10^{32} cm^{-2} s^{-1}
- ~5M $p\bar{p}$ collisions per second!

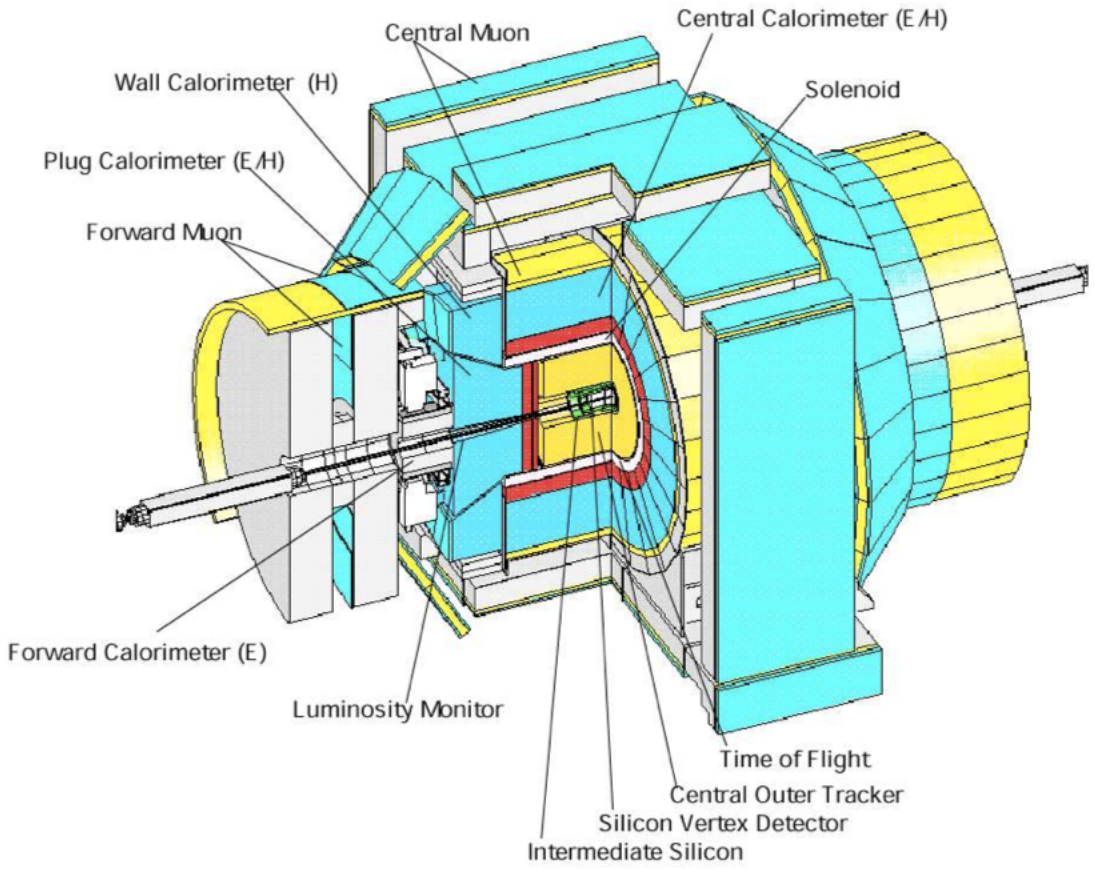
The Tevatron delivered ~12 fb^{-1}

- Up to ~10 fb^{-1} recorded by each experiment



- Lots of data for exploring hadron interactions and QCD physics (among other physics!)

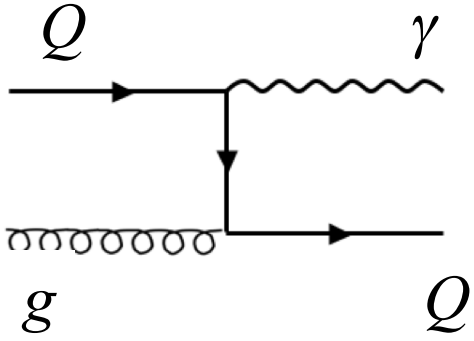
CDF is a multi-purpose detector



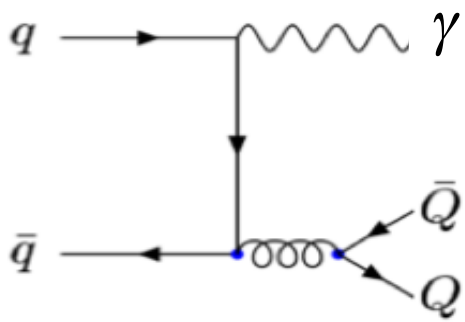
- Excellent tracking enables heavy flavor identification
- Calorimeters used to identify photons, charged leptons
- Muon drift chambers used to identify highly-penetrating particles

Prompt γ plus heavy flavor production probes QCD processes

- For $p_T(\gamma) < 70$ GeV, these events are produced in QCD primarily as $g+Q \rightarrow \gamma+Q$, $(q=b,c)$. At high $p_T(\gamma)$, primarily as $q+\bar{q} \rightarrow \gamma+g(\rightarrow Q\bar{Q})$.



Dominates for $p_T(\gamma) < 70$ GeV

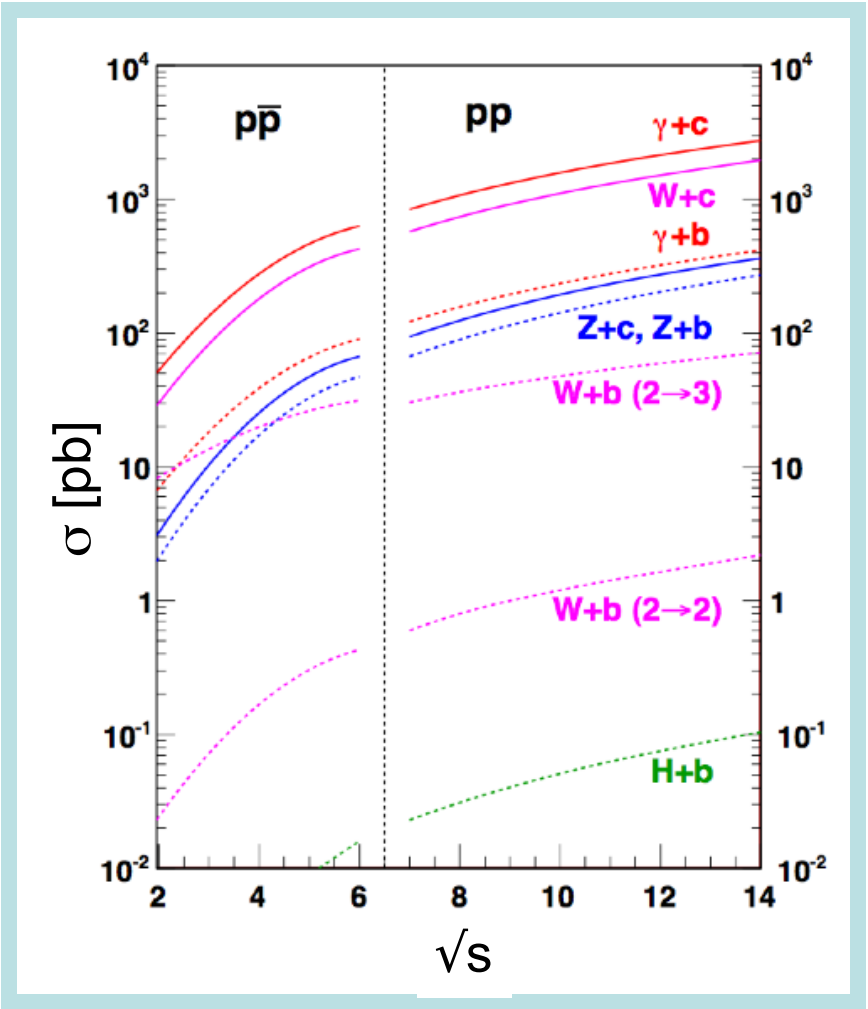


Dominates for high $p_T(\gamma)$

- These events act as a direct test of γ+b/c production. They also probe parton fractions and momentum transfer scales in hard-scattering QCD sub-processes.

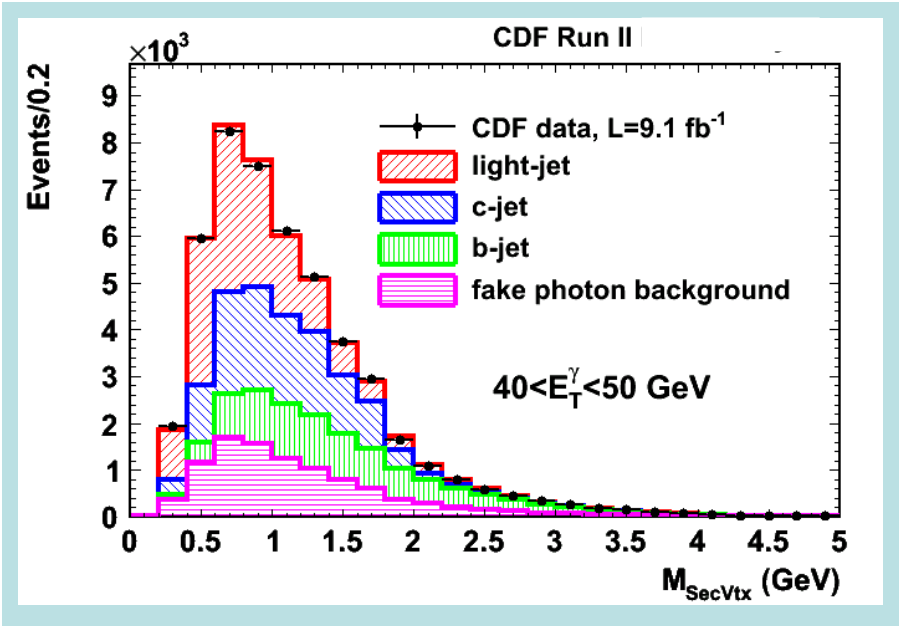
Cross sections for γ + *h.f.* (and *W/Z* + *h.f.*) are small

- This makes these measurements challenging
- It also means that understanding these processes is necessary for for high-precision tests of EWK and QCD theory



CDF identifies prompt γ plus h.f. with a three-part procedure [PRL 111.042003 (2013)]

- Photons reconstructed in calorimeter
  - Separated from jets with isolation cuts and a neural network (isolation, shower shape and HAD/EM fractions)

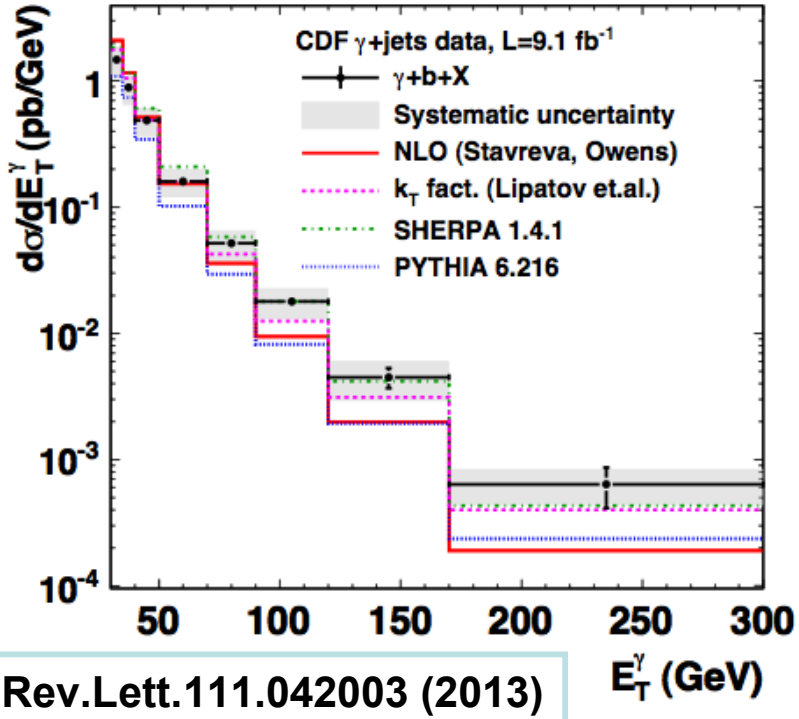


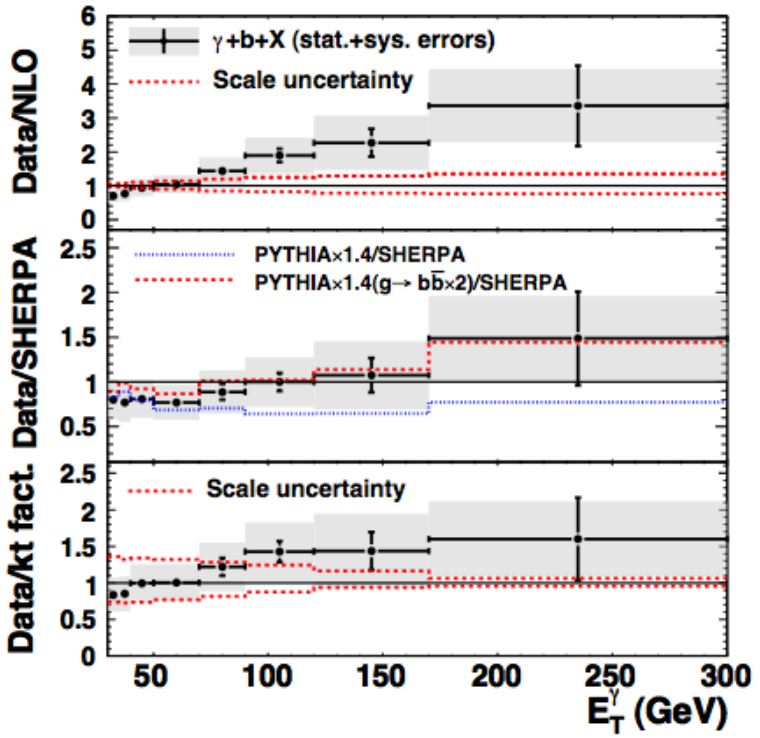
- Jets are identified
  - Jet acceptance requires cuts on E_T, $|\eta|$
  - Light jets suppressed with b-tagger (looks at impact parameters, Lxy, & secondary vertex properties)

- The invariant mass of the jet's secondary vertex, M_{SecVtx}, is fit with templates to determine relative fractions of b, c and light jets

The analysis makes differential cross-section measurement $d\sigma(\gamma+b)/dp_T(\gamma)$

- Measured cross-sections are in agreement with NLO QCD predictions up to $p_T \approx 70$ GeV, but disagree for large p_T



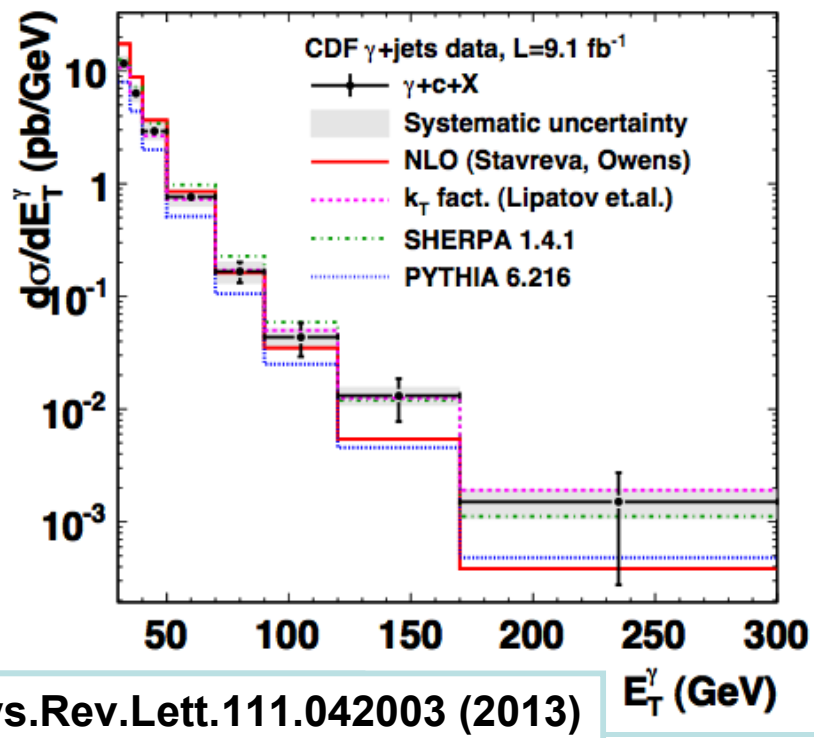


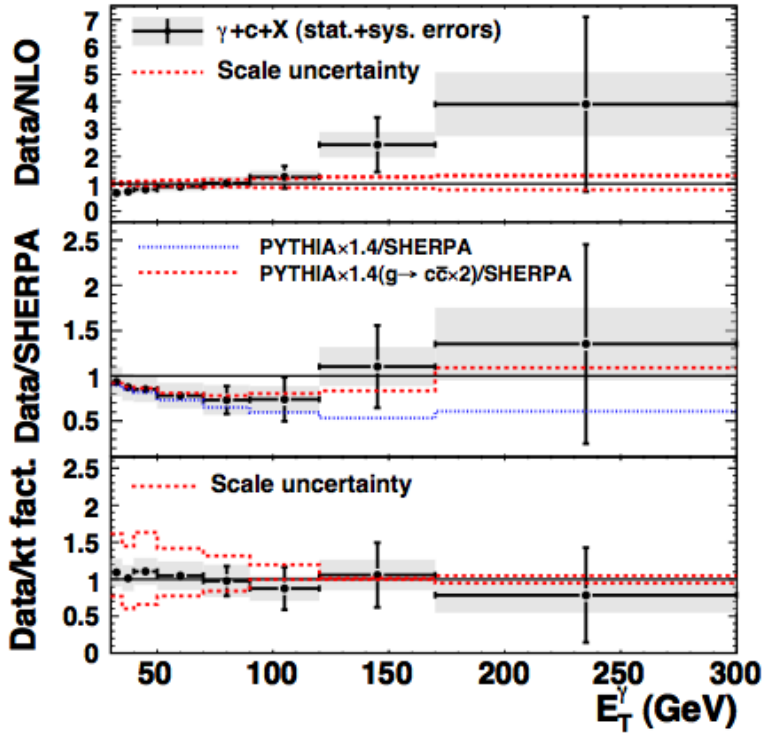
Phys.Rev.Lett.111.042003 (2013)

- k_T-factorization and SHERPA agree reasonably well with data

Finds the same trends in differential cross-section $d\sigma(\gamma+c)/dp_T(\gamma)$

- Pythia with doubled $g \rightarrow (cc/bb)$ rate better describes these shapes



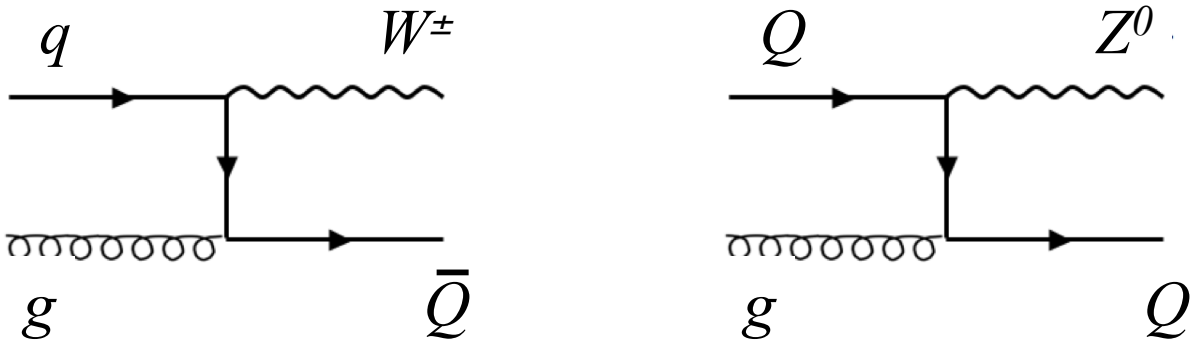


Phys.Rev.Lett.111.042003 (2013)

- Suggests that higher-order perturbative QCD corrections are needed in the high-p_T region (dominated, recall, by $q+q \rightarrow \gamma+g(\rightarrow bb)$)

W/Z plus heavy flavor production is also a good probe of QCD…

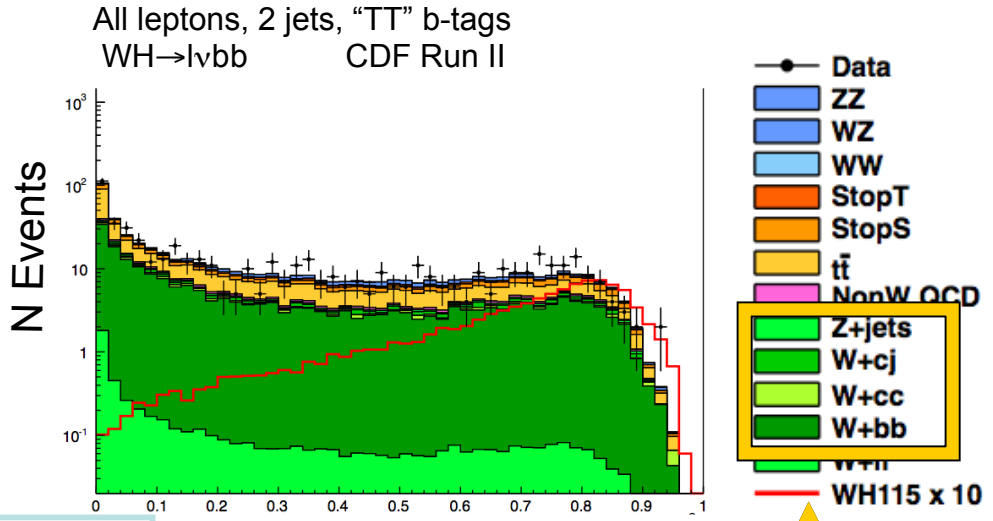
- First-order production is sensitive to HF content of the proton



- Provides stringent test of perturbative QCD calculations

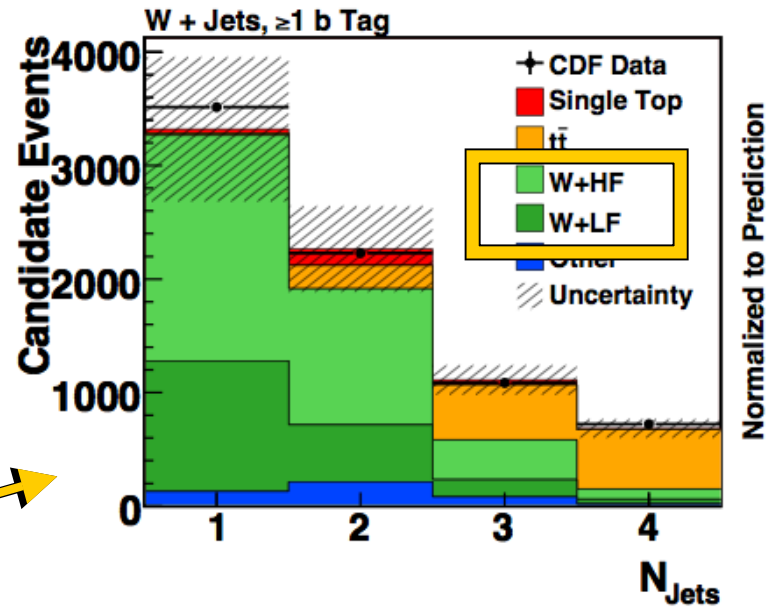
… and is an important model for background in other searches

e.g. for Higgs…
[PRL 109, 071804 (2012)]



Note the log scale

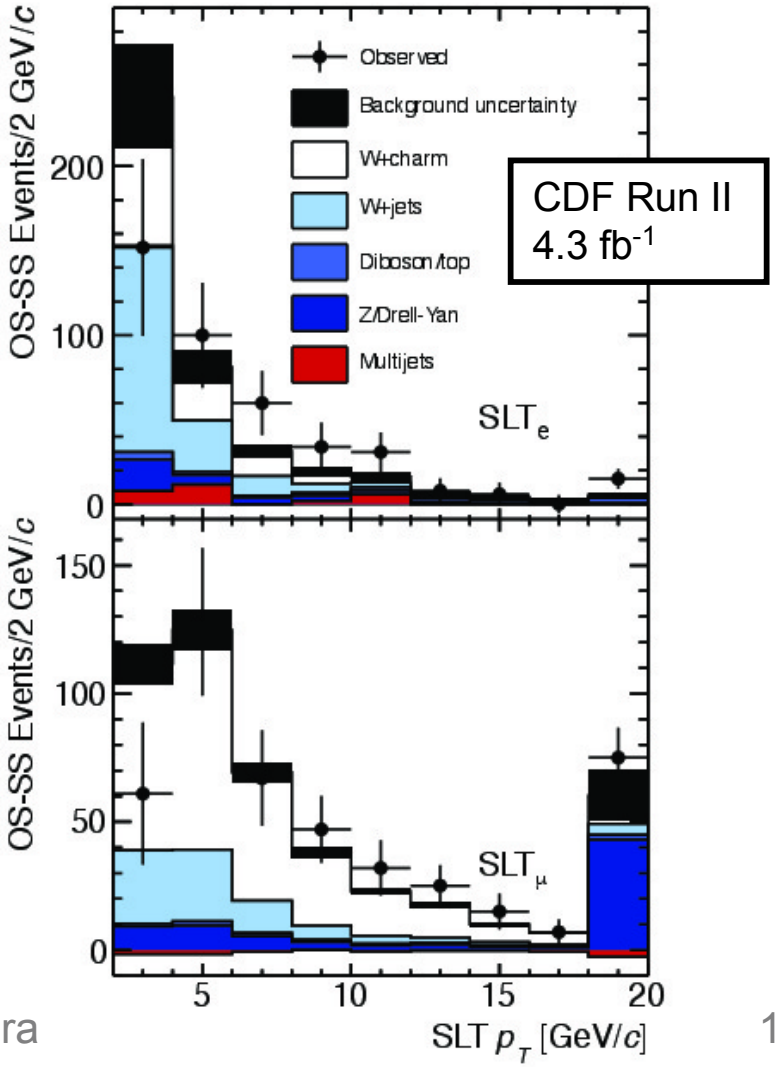
… and single top
[PRD 82, 112005 (2010)]



W/Z+h.f. makes substantial contributions to these backgrounds!

CDF made a recent observation of $p\bar{p} \rightarrow W+c$ production **[PRL 110, 071801]**

- First, identify W/Z events
  - High-E_T charged lepton
  - Missing energy
- Then, tag charm jets
  - Require an electron or muon from charm-hadron semi-leptonic decay within the jet (soft lepton tagging)
  - Count events with W lepton and soft lepton same sign (N_{SS}), and opposite sign (N_{OS})
  - Subtract N_{OS}-N_{SS} to suppress background and measure $p\bar{p} \rightarrow W+c$



Results of this work are in agreement with theory

- Measure cross-section times branching fraction

$$\sigma(p\bar{p} \rightarrow W + c) \times \mathrm{Br}(W \rightarrow \ell\nu) = 13.3^{+3.3}_{-2.9}\ \mathrm{pb}\ (\mathrm{stat} + \mathrm{syst})$$

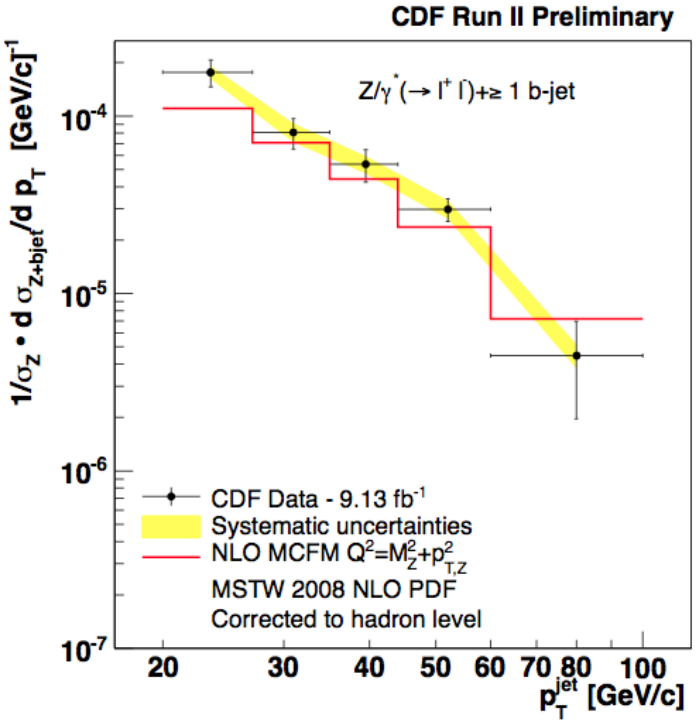
- Compatible with theoretical NLO prediction

$$\sigma_{NLO}(p\bar{p} \rightarrow W + c) \times \mathrm{Br}(W \rightarrow \ell\nu) = 11.3 \pm 2.2\ \mathrm{pb}$$

- This work is notable as being the first Tevatron measurement of specific charm process $p\bar{p} \rightarrow W+c$

There is an updated measurement of $Z+b$ in 9.1 fb^{-1} [CDF Public note 10594]

- Measures differential cross-section $d\sigma(Z+b\ jet)/dp_T(jet)$



Integrated cross-sections:

$$\frac{\sigma_{Z\_bjet}}{\sigma_Z} = 0.261 \pm 0.023^{stat} \pm 0.029^{syst}\%$$

$$\frac{\sigma_{Z\_bjet}}{\sigma_{Zjet}} = 2.08 \pm 0.18^{stat} \pm 0.27^{syst}\%$$

To compare with NLO prediction with MCFM:

	$Q^2 = m_Z^2 + p_{T,Z}^2$	$Q^2 = < p_{T,jet}^2 >$
$\frac{\sigma_{Z\_bjet}}{\sigma_Z}$	0.23 %	0.29 %
$\frac{\sigma_{Z\_bjet}}{\sigma_{Zjet}}$	1.8 %	2.2%

- Differential cross-section is higher than predicted at low p_T, but cross-section overall shows good agreement with theory.

CDF is also exploring a new approach to *W/Z+h.f.* analysis

- This approach explores a different kinematic regime, making it complementary to previous studies

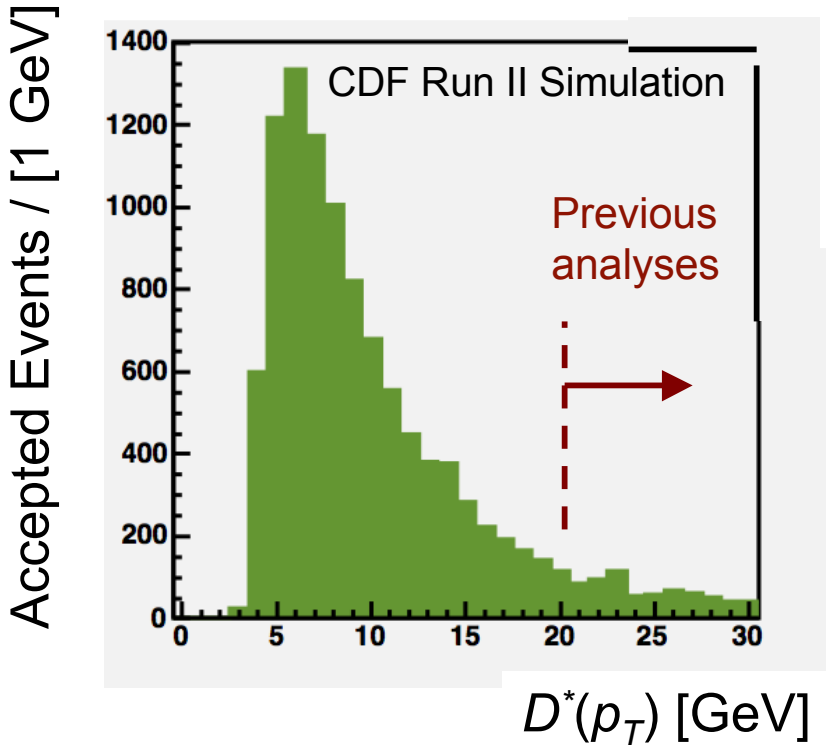
- It involves fully reconstructing the charmed meson in $W/Z+c(\rightarrow D^{*})$ events
  - Begin with standard selection of *W/Z* events
  - Use vertex fitting to reconstruct decay $D^{*+}\rightarrow D^{0}(K^{-}\pi^{+})\pi^{+}$
  - Cut on track kinematics and reconstructed D^{0} mass
  - Bin $\Delta m=m(K\pi\pi)-m(K\pi)$ of remaining candidates
  - Fit Δm distribution to hypothesis of signal plus background

- ATLAS and CMS have used this charm-tagging procedure in high-E_T jet events, but this is its first application to *W/Z+c* studies at Tevatron!

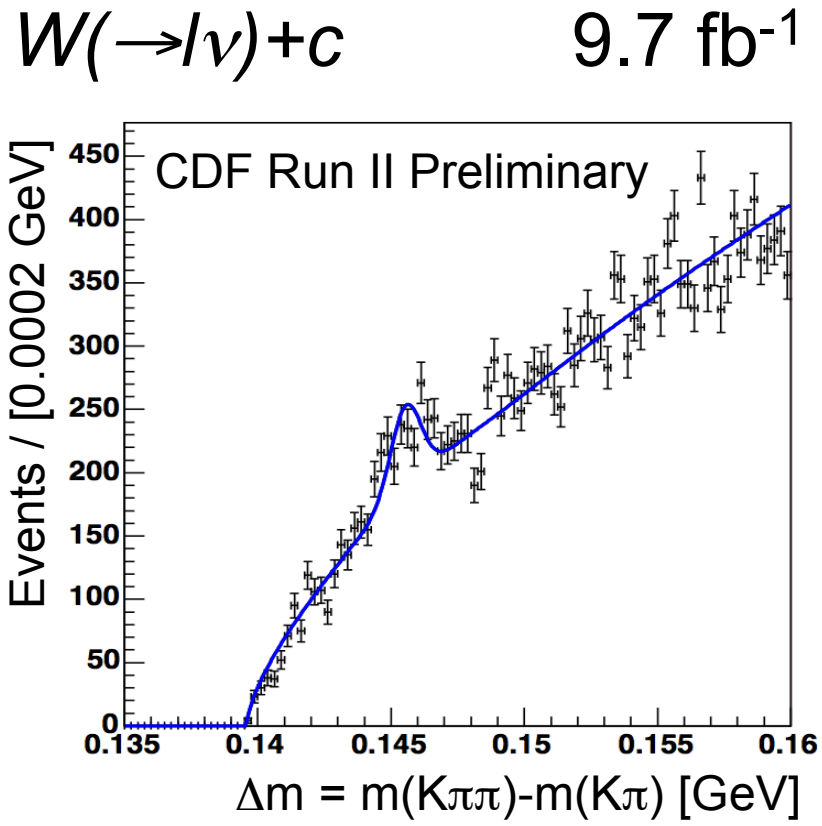
This technique probes a lower $p_T(c)$ regime than do jet-based analyses

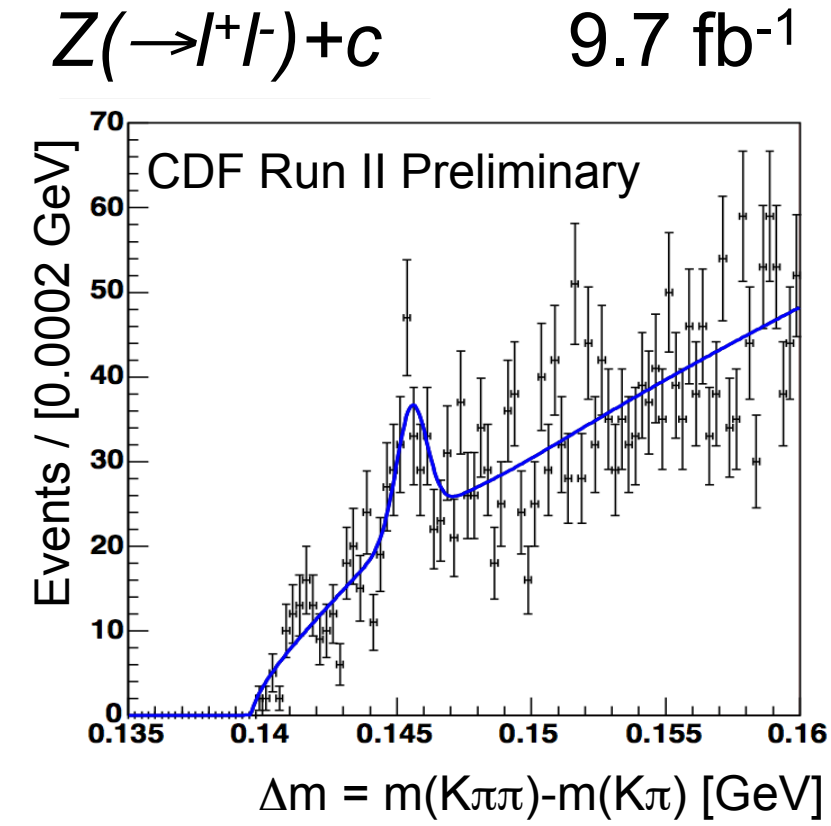
- Running over PYTHIA $p\bar{p} \rightarrow W+c$ events shows that the p_T spectrum of tagged events strongly favors the < 20 GeV regime

- This provides a probe of unexplored territory in QCD!
- Is complementary to jet-based $W+c$ analyses
- This technique also selects D^* from $W+b$, where $b \rightarrow B \rightarrow D^*+X$. Can use lifetime information to separate prompt D^* from secondary D^*.



It's been used to identify $W(\rightarrow l\nu)+D^*$ and $Z(\rightarrow l^+l^-)+D^*$ events in 9.7 fb^{-1}





- This work is ongoing. Aim to finalize results and compare to theory soon.

Summary

- Exciting time for EWK gauge boson plus h.f. physics
- Results suggest that *c,b* fractions in γ+*jets* may be higher than NLO predictions; supports higher $g \rightarrow c\bar{c}/b\bar{b}$ fractions
- CDF is probing new h.f. regimes: low $p_T(c)$ in *W/Z* events
- Higher statistics at LHC will extend these measurements in complementary kinematic regions
- Improved *W*/*Z*/γ+heavy flavor models will benefit future analyses, especially as a model of background

Further Reading

- All results discussed in this talk are available on the CDF Public Results page:

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