QCD Results from CDF

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LOW X WORKSHOP
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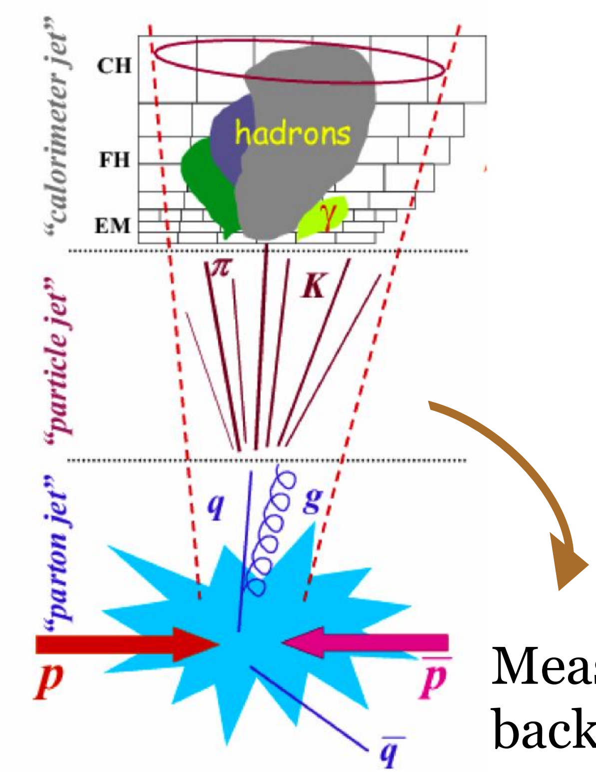
Outline

1JET RESULTS
Z+JETS
Z+B JETS
W+SINGLE CHARM.
2.PHOTONS
PHOTON+HF
DIPHOTONS
3.NEW ENERGY SCAN RESULTS
CENTRAL EXCLUSIVE PRODUCTION
UE STUDIES

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

- Combined $Z \to e^+ e^-$ and $Z \to \mu^+ \mu^-$ accounting for correlation between uncertainties
- **Results with full data set**

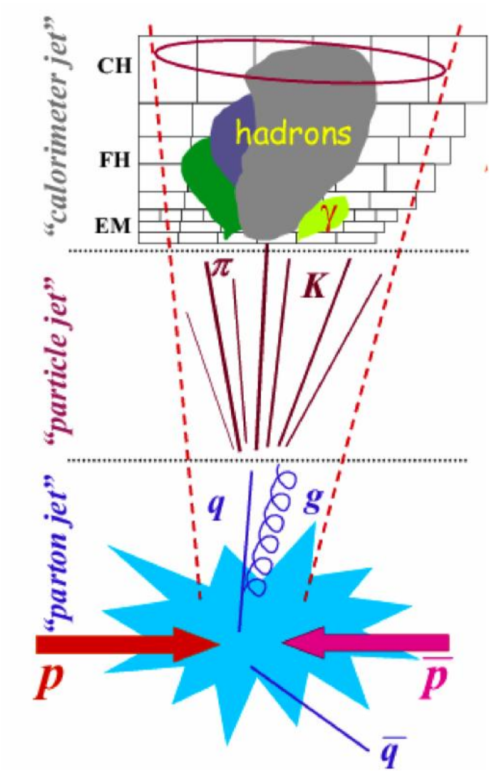
  $\mathcal{L} = 9.4\ fb^{-1}$



Measurements are unfolded back to Hadron level

Differential distributions in Z + ≥3 jets final state

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



Differential distributions in Z + ≥3 jets final state

- **Results with full data set** $\mathcal{L} = 9.4\,fb^{-1}$

Theoretical predictions :

- approximate nNLO LOOPSIM+MCFM
- LO and NLO MCFM
- LO and NLO BLACKHAT+SHERPA
- ME+PS ALPGEN+PYTHIA
- NLO+PS POWHEG+PYTHIA
- NLO QCD ⊗ NLO EW

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

Data driven backgrounds
- QCD multi-jet
- W + jet

MC backgrounds
- $Z + \gamma$
- Top
- Diboson
- $Z \rightarrow \tau\tau$+ jets

Z Kinematic region

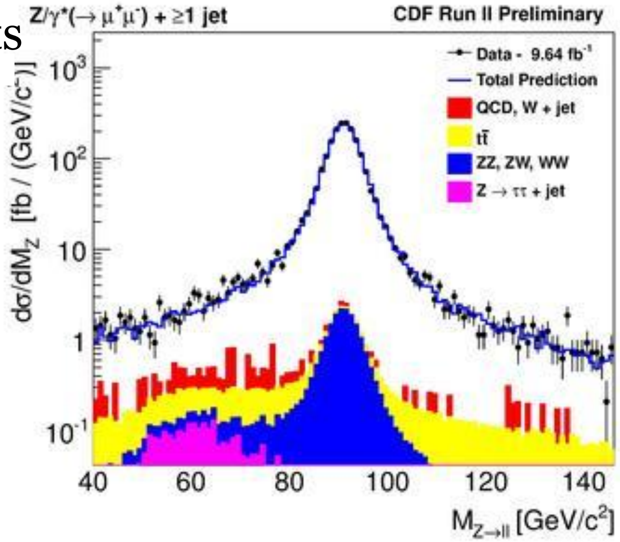
$66 < M_Z < 116$ GeV/c²

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

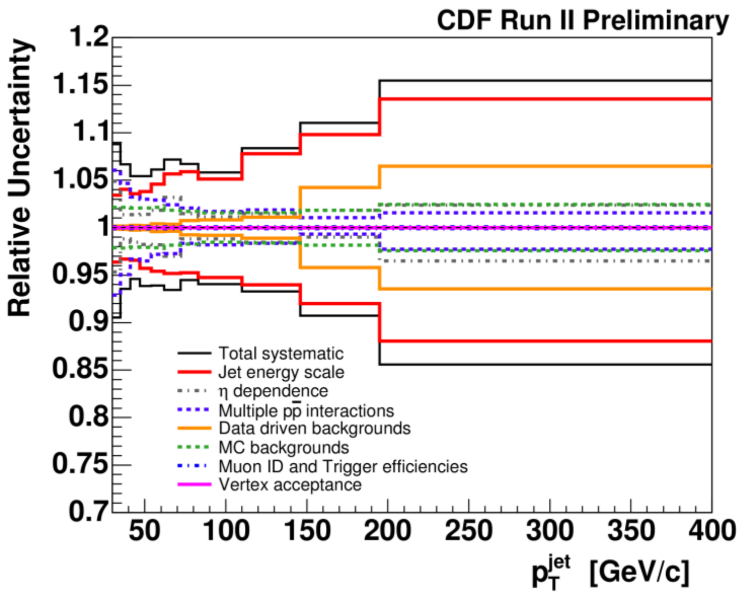
Jet selection

MIDPOINT R=0.7 jet

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



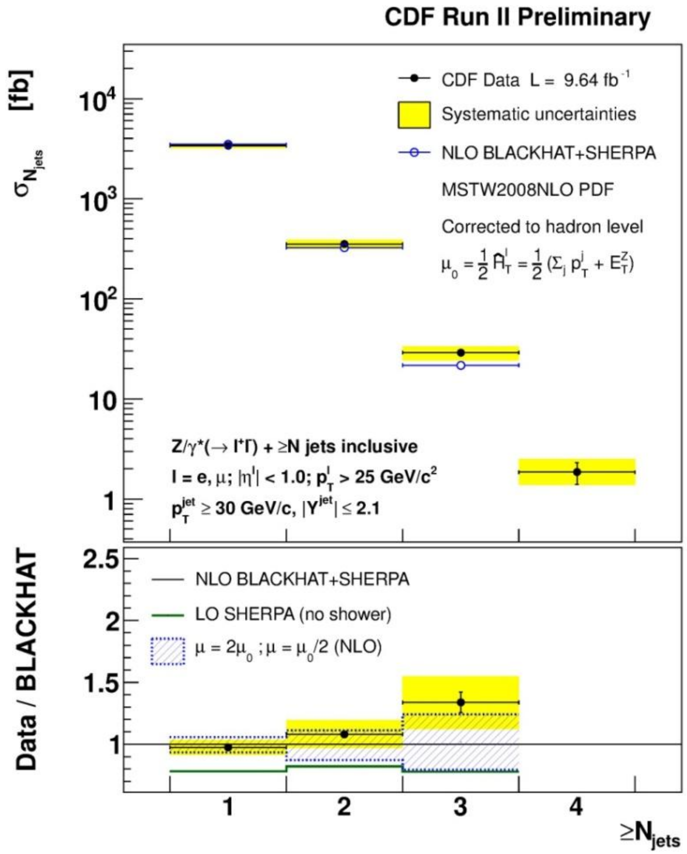
5% to 15% syst. uncertainties
Jet Energy Scale is the dominant

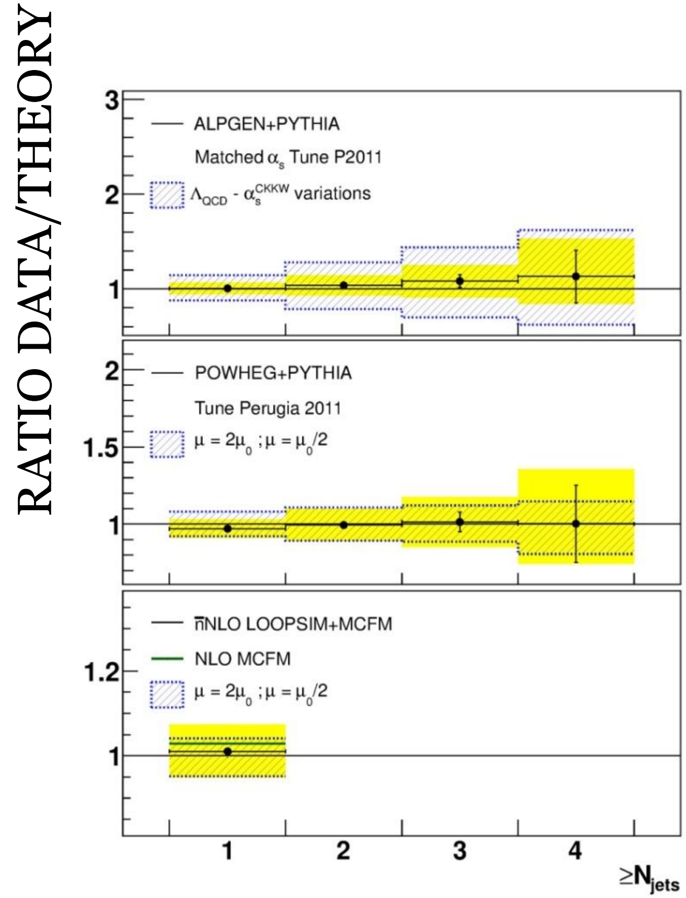


- **Total backgrounds between 5%-10%**
- **Main background is $Z+\gamma$**

Z/γ*→l⁺l⁻ +jets

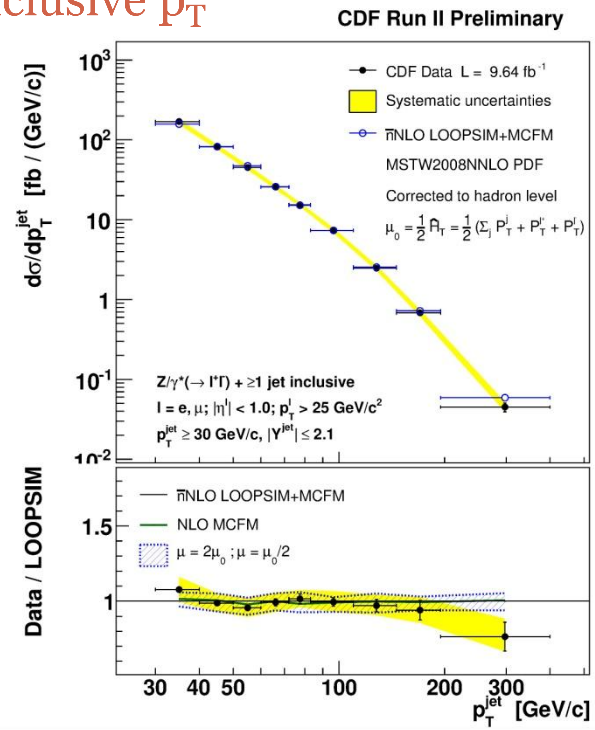
Cross Sections as a function of inclusive jet multiplicity N_{jet}

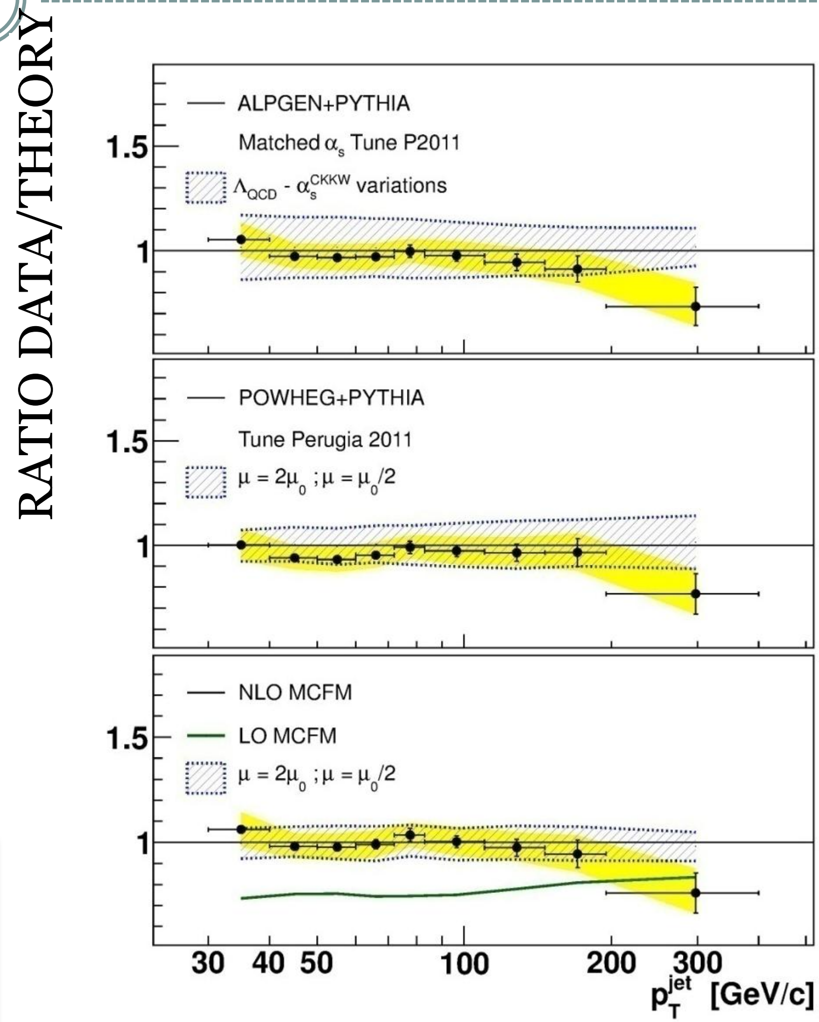




Z/γ*→l⁺l⁻ +jets

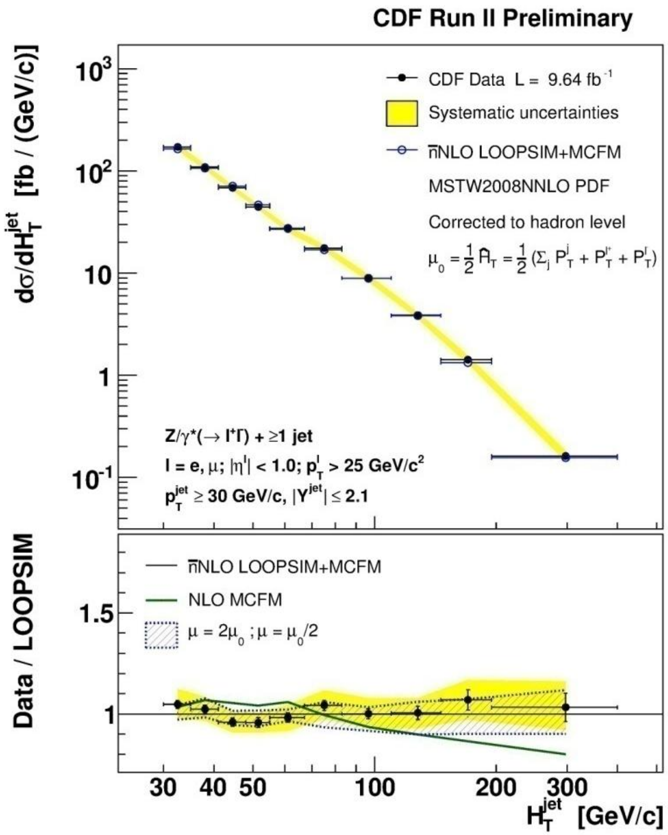
Cross Sections as a function of inclusive p_T^{jet}

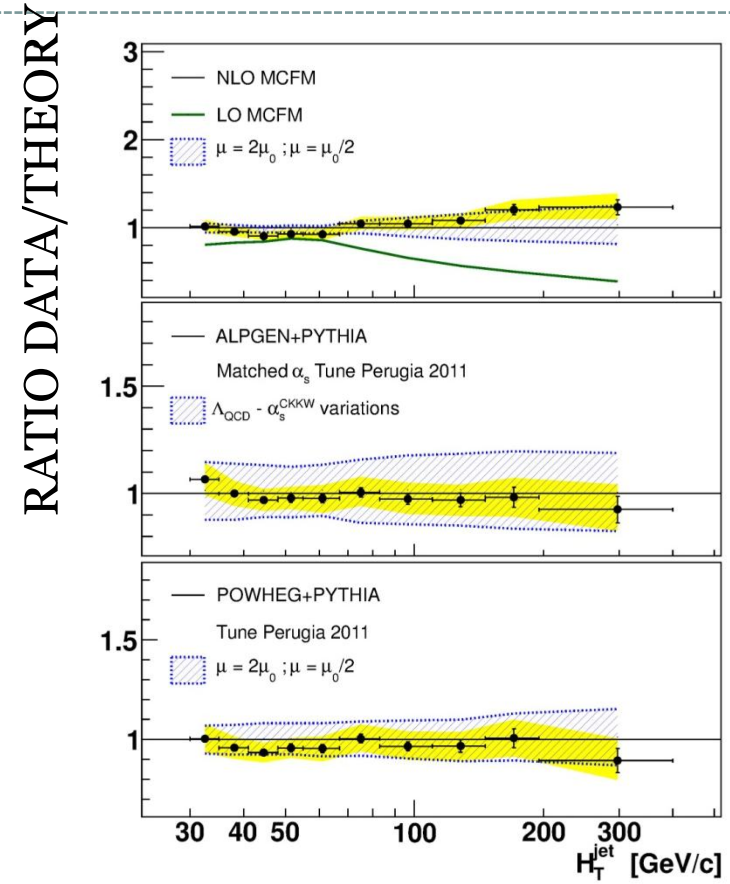




Good agreement between data and NLO pQCD predictions (BLACKHAT and MCFM)

Z/γ*→l⁺l⁻ +jets

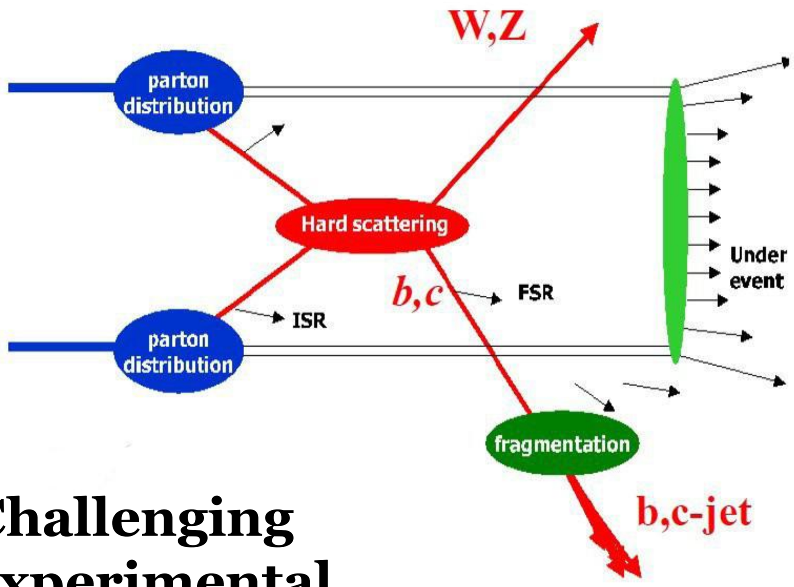




Some observables like H_T(jet) are expected to have larger contribution from NNLO diagrams

Comparison with different PDF sets

W/Z + HF jets production

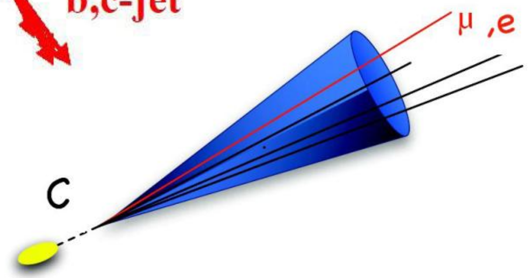


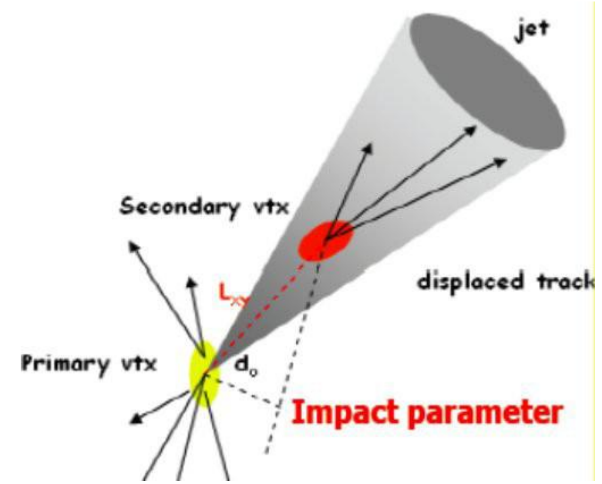
Challenging theory predictions

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

Challenging experimental measurements

- b and c identification
- Low statistics





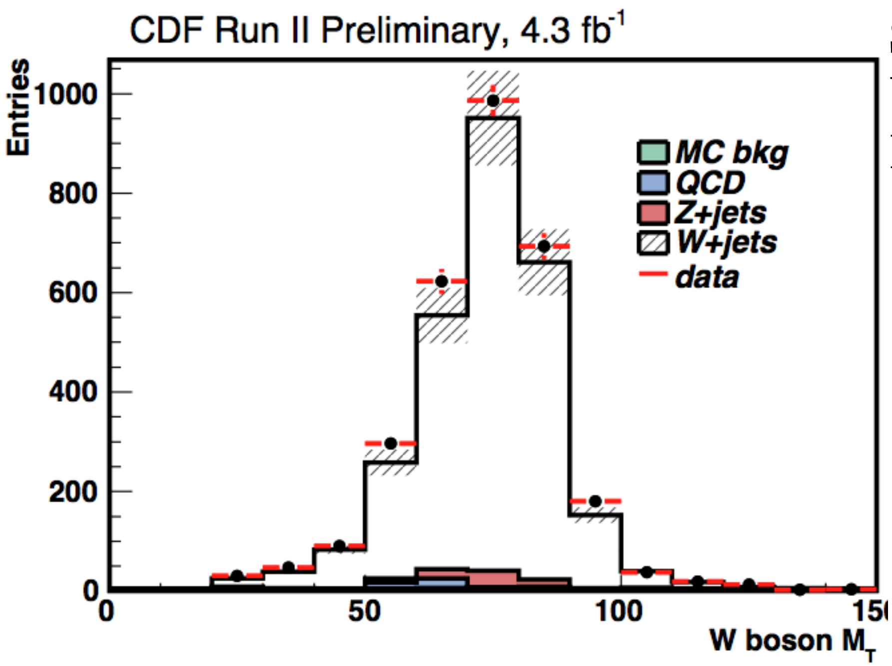
Soft Lepton tag (20% Branching ratio)

Secondary vertex tag based on large B lifetime

W+charm Production

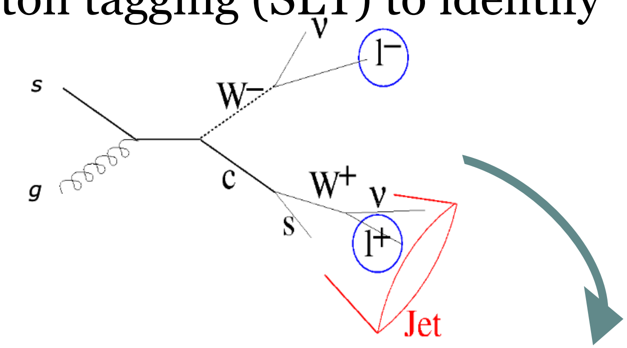
Lepton	Jet selection
MET>25 GeV,	JETCLU R=0.4 jet
m_T (W)>20 GeV/c²	p_T > 15 GeV/c,
p_T^l > 25 GeV/c, $\|\eta^l\|$ < 1	$\|\eta\|$ < 2.0

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 HF jet



Exploit opposite charge correlation between W lepton and SLT lepton

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

SLT_e = 13.4 ±2.3 (stat) ±2.4 (syst) ±1.1 (lumi) pb

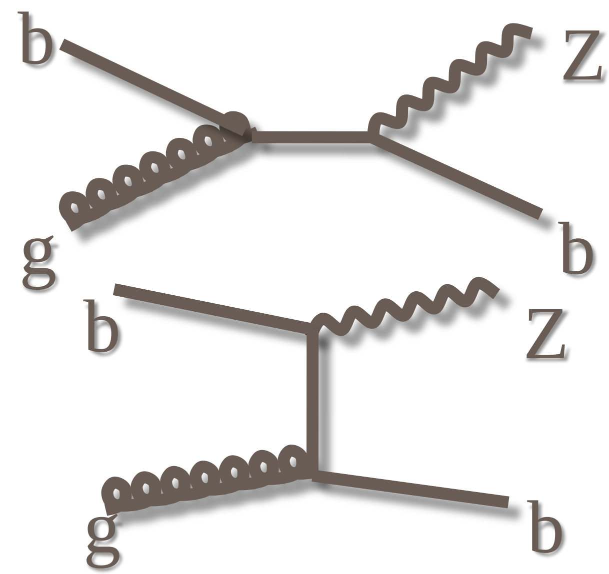
SLT_μ = 14.2 ±6.5 (stat) ±3.4 (syst) ±1.2 (lumi) pb

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

$66 < M_Z < 116$ GeV/c²
$E_T^l > 25$ GeV/c, $|\eta^l| < 1$

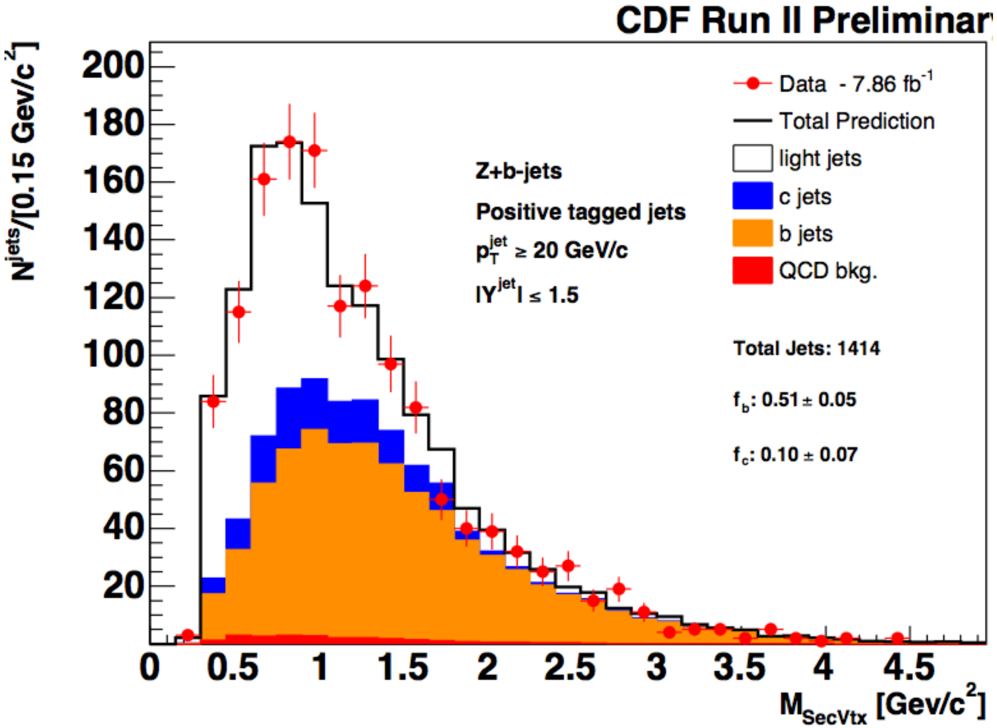
Jet selection

MIDPOINT R=0.7 jet
$p_T > 20$ GeV/c,
$|Y| < 1.5$

B identification:

Secondary Vertex Tagger
Extract b- jet composition 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 diff. μ choice)

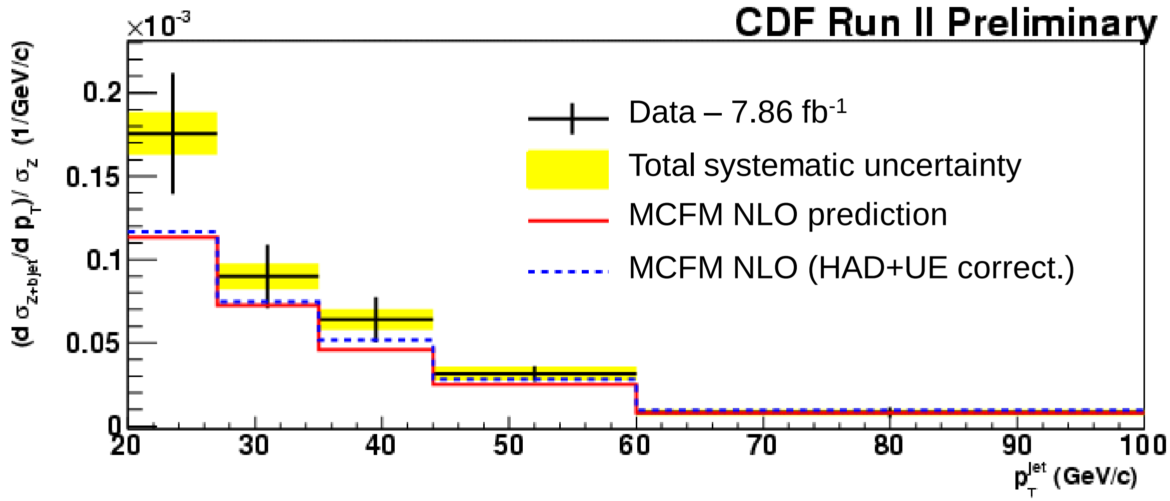
$\sigma(Z+b)/\sigma(Z)$= 0.23—0.28%

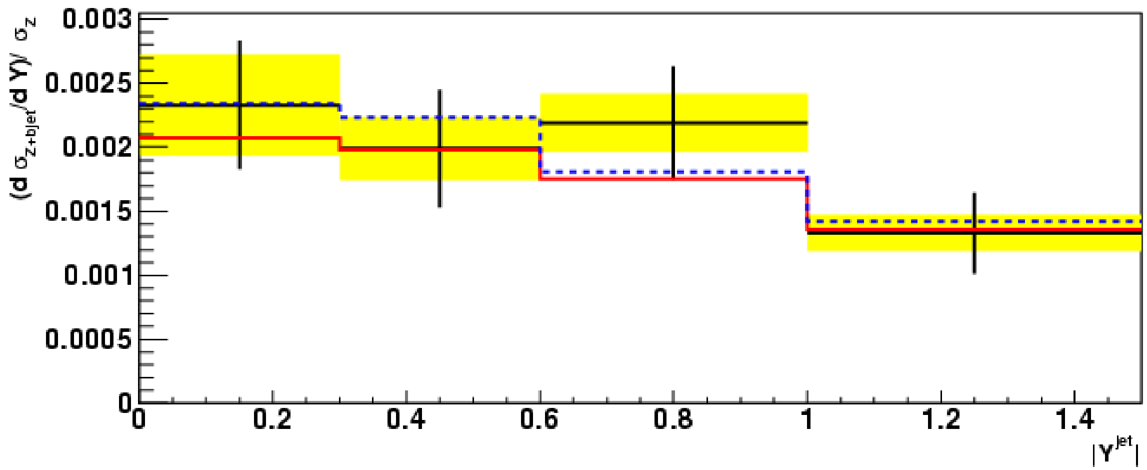
$\sigma(Z+b)/\sigma(Z+jet)$= 1.8—2.2%

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





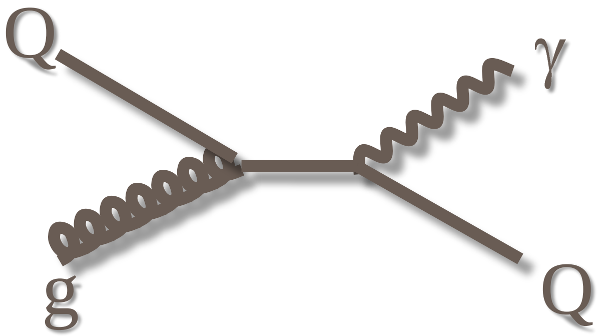
Dominated by stat. uncertainty

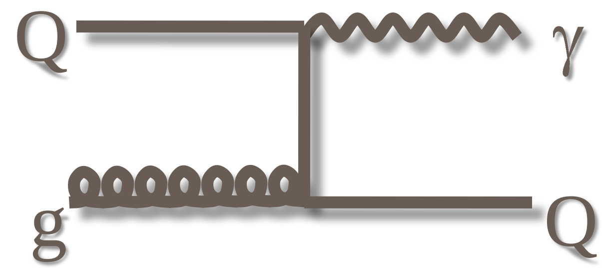
General agreement with theory

γ+b/c Production

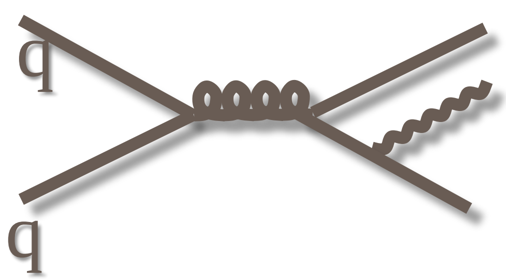
Probes heavy flavor content in hadrons

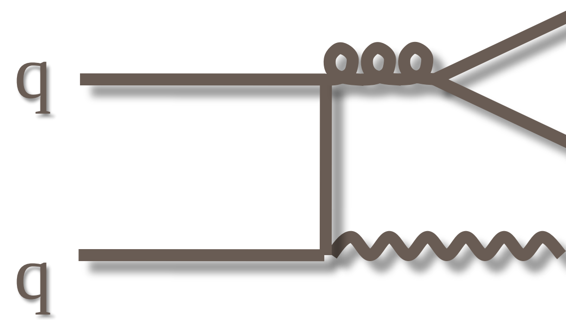
LO - Compton scattering - relevant for $E_T^{\gamma} < 70$ GeV $\sim \alpha\alpha_S$



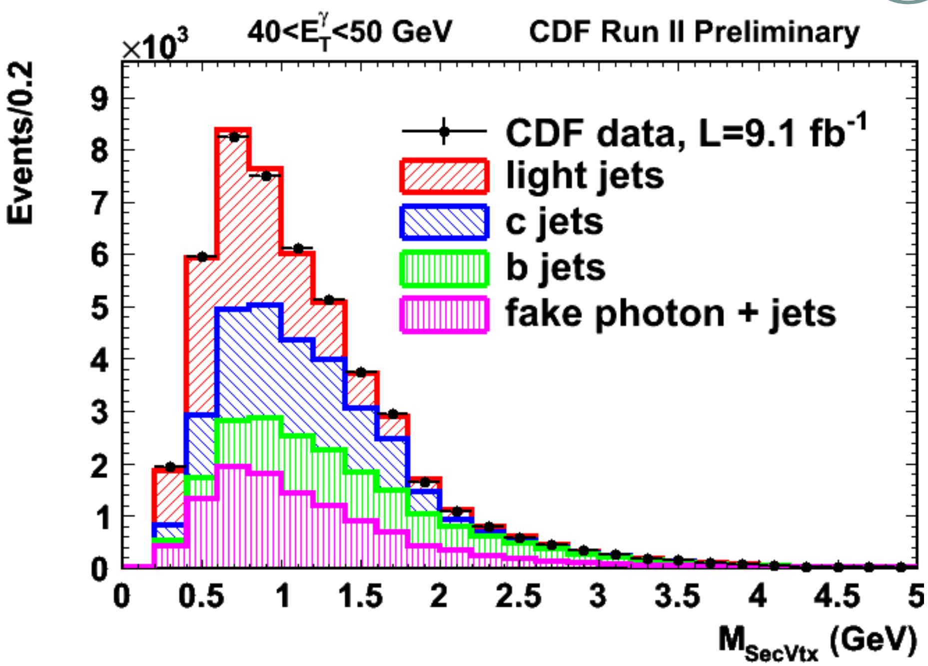


NLO - annihilation + brems. relevant for $E_T^{\gamma} \geq 70$ GeV $\sim \alpha\alpha_S^2$





γ+b/c Production



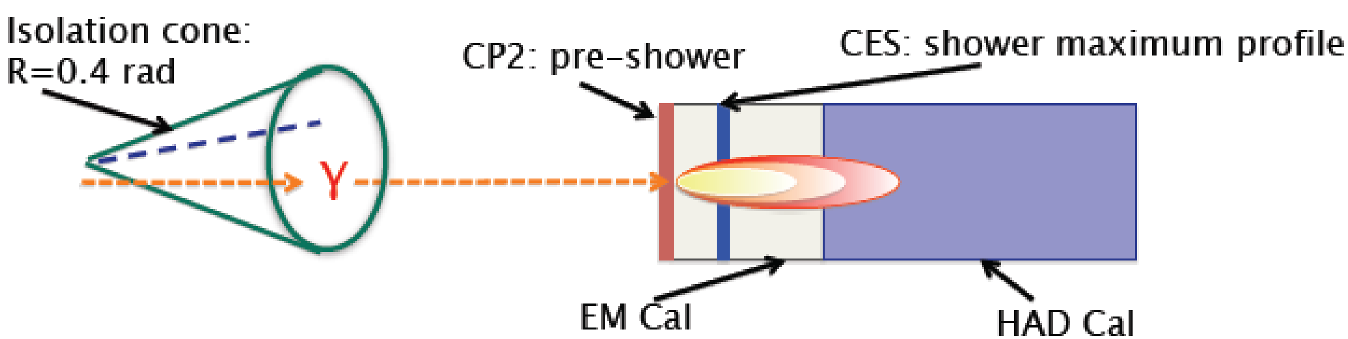
Measure jet fractions via template method in 8 bins of E_T^γ

Calculate cross sections covering

photons- 30< E_T^γ < 300 GeV, y^γ<1.0

isolation cuts:
E_T(iso)<2 GeV in the cone of 0.4 around the photon

jets - E_T^{jet} < 20 GeV, y^{jet}<1.5



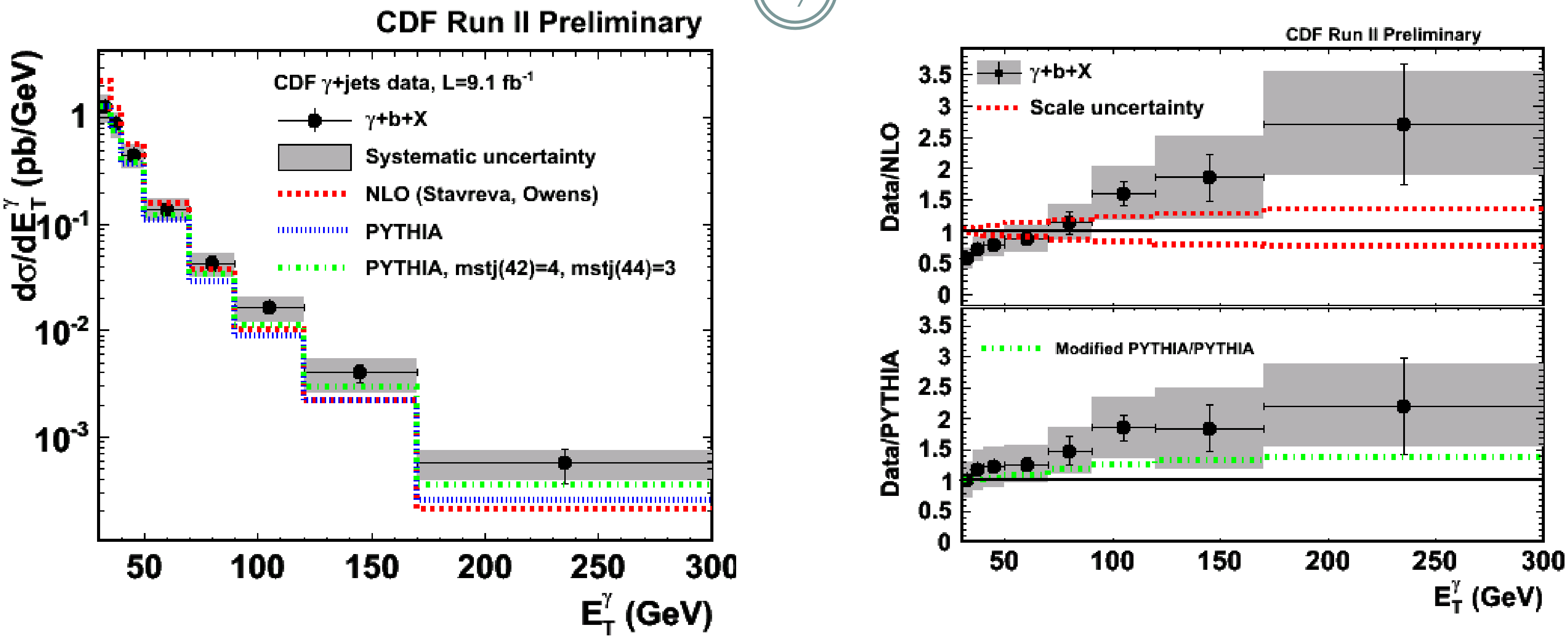
Photon + HF: theoretical predictions

- **NLO** Pointlike photon subprocesses through $O(\alpha\alpha s2)$ and fragmentation subprocesses through $O(\alpha s\ 3)$ are included
  PDF: CTEQ6.6M
  Stavreva and Owens, 0901.3791v1

- **PYTHIA** LO parton-shower calculation ,Prompt photon production
  PDF: CTEQ5L
  version 6.2.26

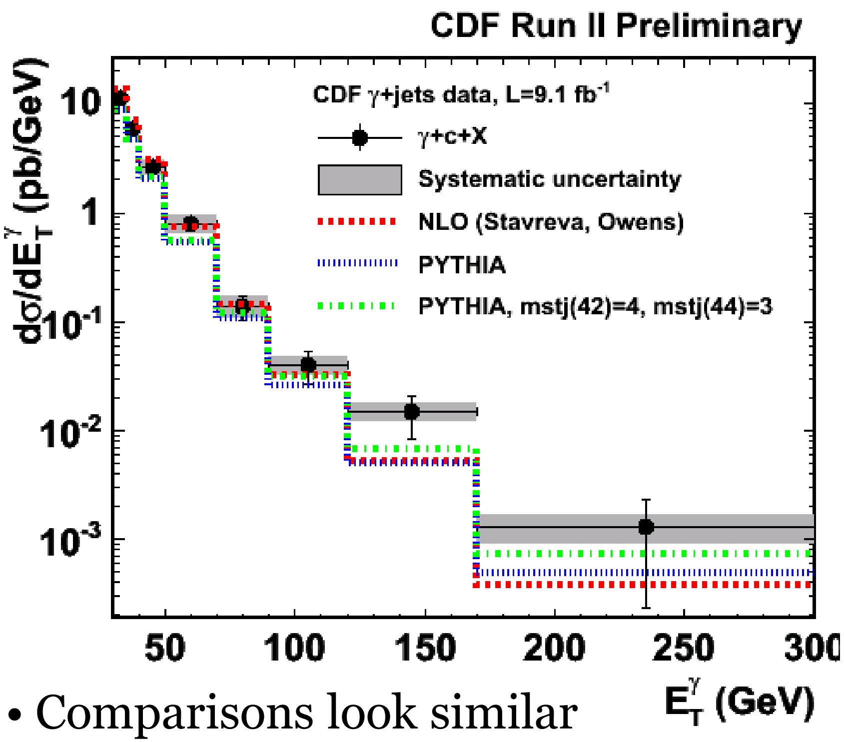
	Total γ+b cross section (pb)	Total γ+c cross section (pb)
Data	19.7±0.7 stat. ±5.0 syst	132.2±4.6 stat. ±19.2 syst
PYTHIA	17.0	101.3
NLO	27.3-1.5/+2.0	152.6-9.6/+12.2

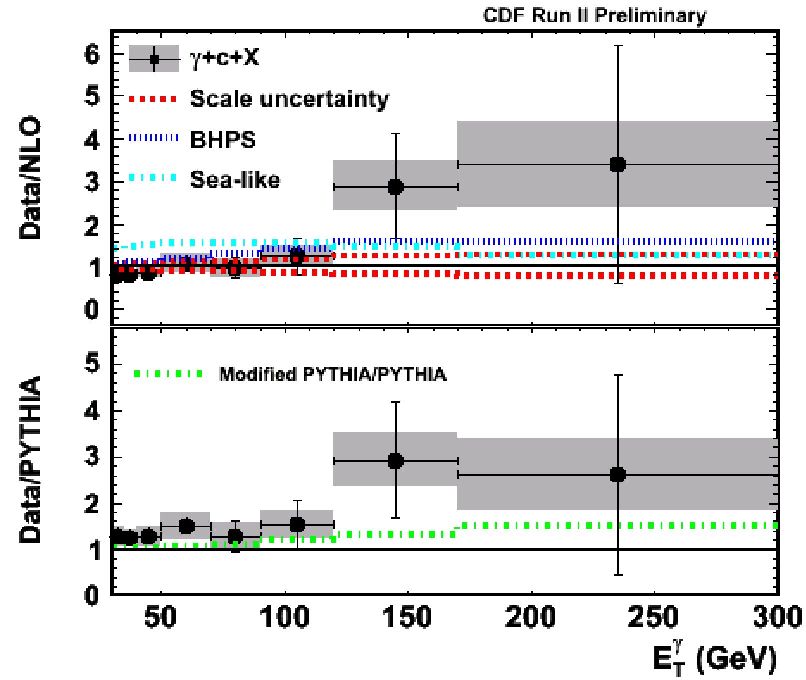
Photon+b:



- **Pythia** prediction is lower than NLO at low p_T: loop/HO corrections, resummation?
- **Pythia** prediction agrees with NLO at high p_T
- A factor of 2-3 difference between data and theories at high p_T
- **NLO** has larger scale uncertainty at high p_T
- **Pythia** with increased gluon splitting to heavy quarks agrees better with data

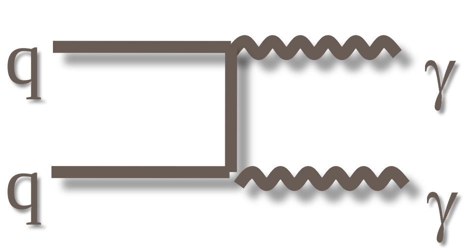
Photon+c



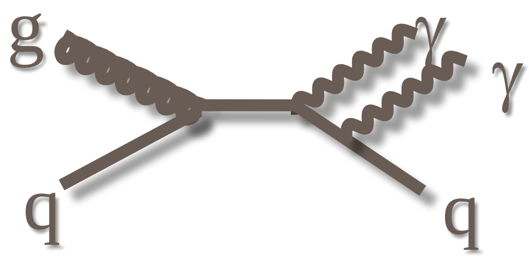


- Comparisons look similar
- **NLO** predictions with two intrinsic c-quark models:
  - **BHPS:** increase the cross section by 40% over the entire p_T range
  - **Sea- like**: keep low-p_T cross section unchanged but increase high-p_T cross section by ≤ 60%
- No intrinsic b-quark model is available at this moment

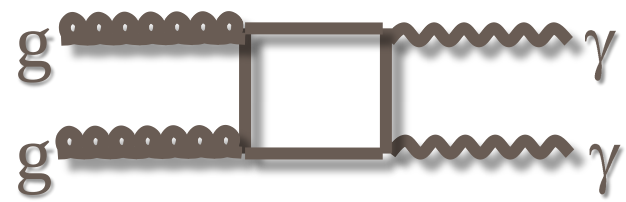
Prompt Diphoton Production



Born: Dominant at the Tevatron



Brems: Suppressed by the isolation requirement



"Box": Dominant at the LHC

Prompt photon pairs represent large irreducible background to low mass $H\rightarrow\gamma\gamma$, searches for heavy resonances, extra spatial dimensions, etc.

Tool to check pQCD soft gluon resummation techniques

Particularly effective because prompt photons do not interact with other FS particles, and are well-measured by EM calorimeters

Diphotons- Theoretical Predictions

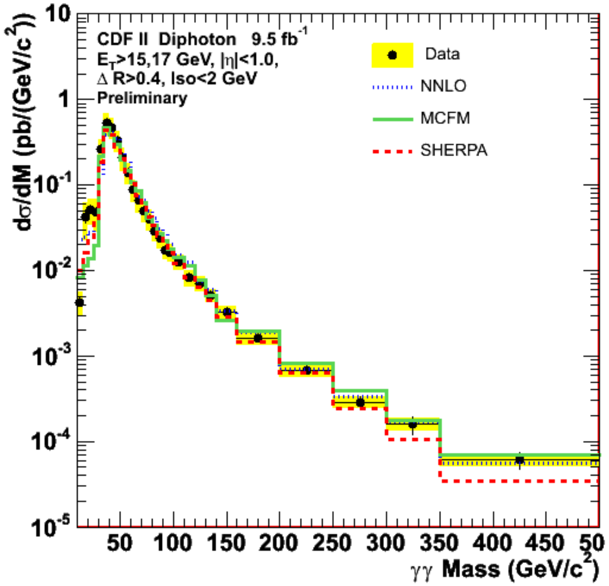
- **PYTHIA:** LO parton-shower calculation
  T. Sjöstrand et al., Comp. Phys. Comm. 135, 238 (2001)
- **SHERPA:** LO parton-shower calculation with improved matching between hard and soft physics
  T. Gleisberg et al., JHEP 02, 007 (2009)
- **MCFM:** Fixed-order NLO calculation including non-perturbative fragmentation at LO
  J. M. Campbell et al., Phys. Rev. D 60,113006 (1999)
- **DIPHOX:** Fixed-order NLO calculation including non-perturbative fragmentation at NLO
  T. Binoth et al., Phys. Rev. D 63,114016 (2001)
- **RESBOS:** Low-PT analytically resummed calculation matched to high-P_T NLO
  T. Balazs et al., Phys. Rev. D 76, 013008 (2007)
- **NNLO** calculation with q_T subtraction
  L. Cieri et al., http://arxiv.org/abs/1110.2375(2011)

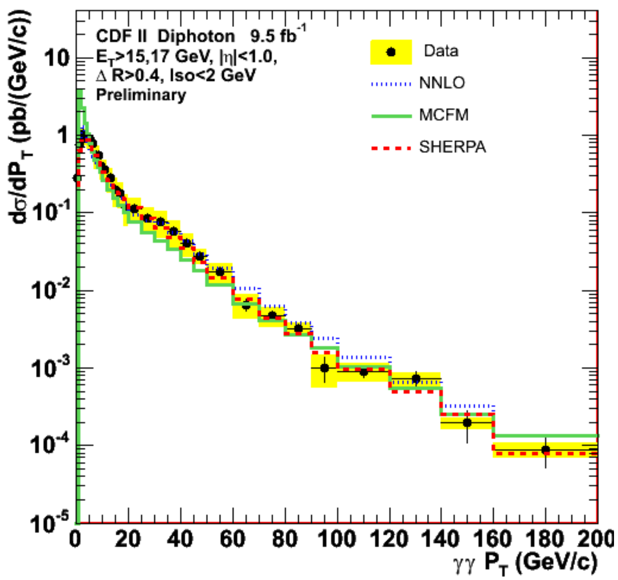
Diphotons – Cross Sections

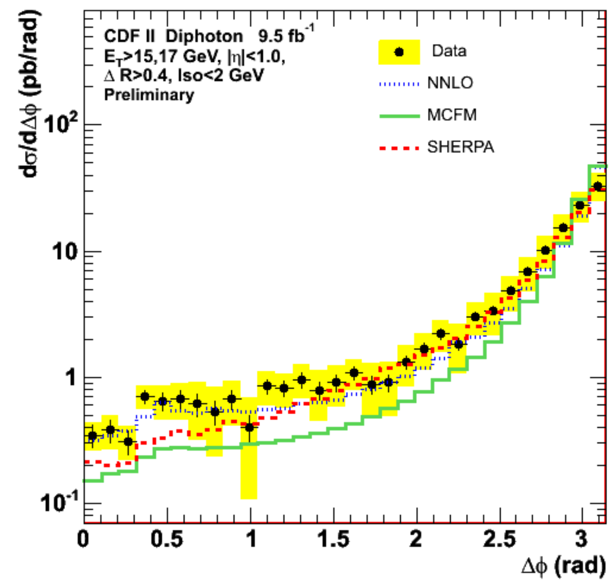
- **PYTHIA:**
- **SHERPA:**
- **MCFM:**
- **DIPHOX:**
- **RESBOS:**
- **NNLO**

	Total Cross Section (pb)
Data	**12.3±0.2(stat) ±3.5(syst)**
RESBOS	**11.3±2.4**
DIPHOX	**10.6±0.6**
MCFM	**11.6±0.3**
SHERPA	**10.9**
PYTHIA+γγ+γj	**9.2**
PYTHIA+γγ	**5.0**
NNLO	**11.8+1.7/-0.6**

Diphotons – Differential Cross Sections





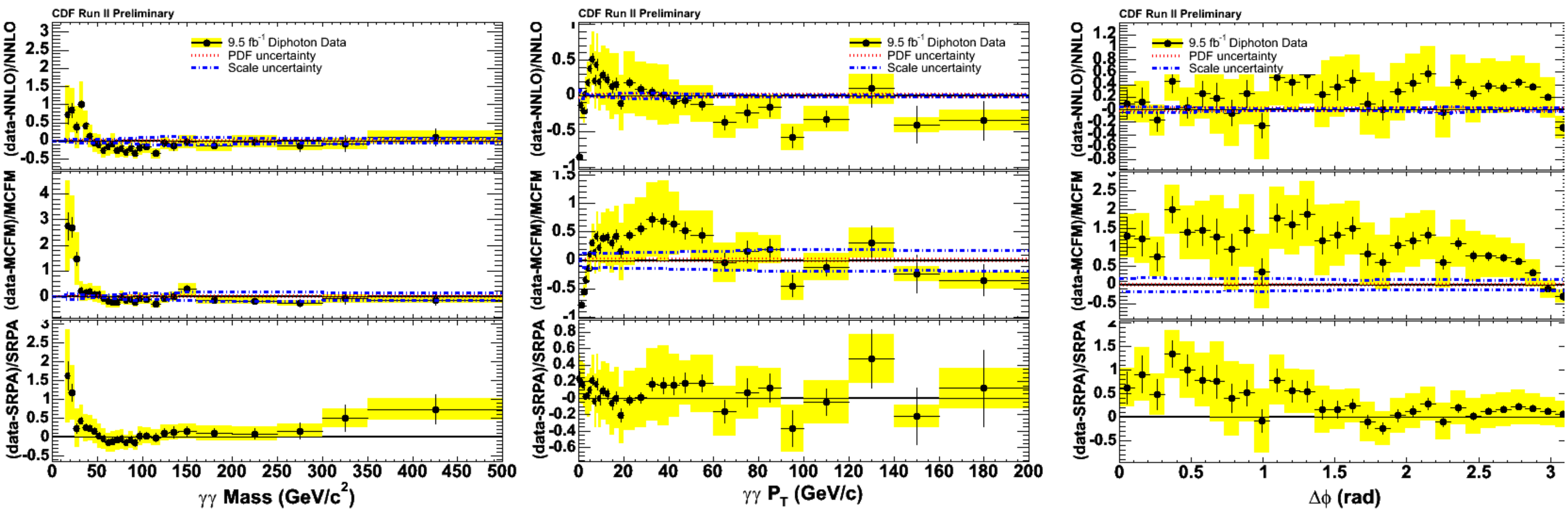


Good agreement between data and theory for $M_{\gamma\gamma}$>30 GeV/c²

- Resummation important for $P_T(\gamma\gamma)$>20GeV/c
- Fragmentation causes excess of data over theory for $P_T(\gamma\gamma)$=20–50GeV/c (the "Guillet shoulder")

- Resummation important for $\Delta\varphi_{\gamma\gamma}$>2.2rad
- Data spectrum harder than predicted

Diphotons – Differential Cross Sections



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Low Energy Scan of the Tevatron

Total data taking time :

10 h at 300 GeV

39 h at 900 GeV

Main goals of the program:

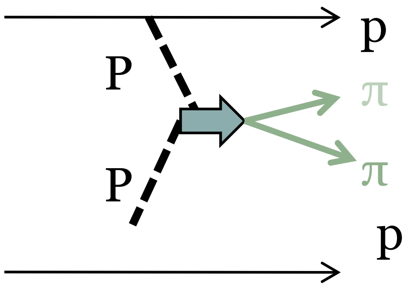
1. **Study of MB events:**
   charged particle multiplicities, $dN/d\eta$, etc…
2. **Study of UE events**
3. **Gap-X Gap events**

Special trigger table; 3 x 3 bunches, no low-β
Asked for ~ 1 interaction/crossing, to maximize singles (no-PU) rate.

<u>Data summary</u>

√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

Central Exclusive Production studies



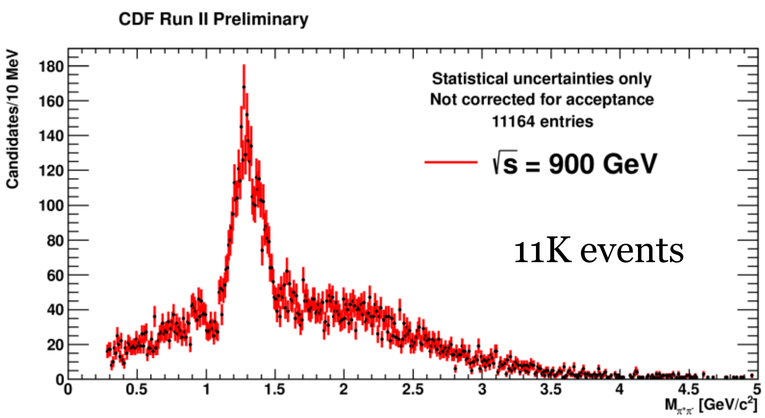
Interest:

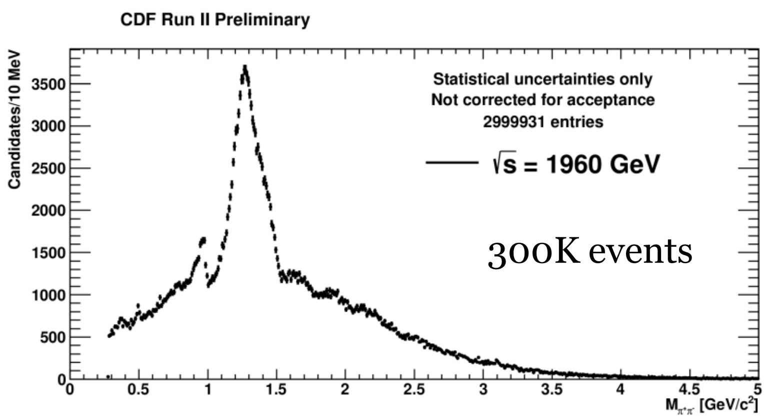
Meson spectroscopy: $I^G J^{PC} = 0^+0/2^{++}$ & glue-rich

Understanding nature of pomeron P (~ gg)

2-track mass spectra between rapidity gaps from |η|=1.32 to 5.9 at √s = 1960 & 900 GeV. 1.16/pb at 1960 GeV

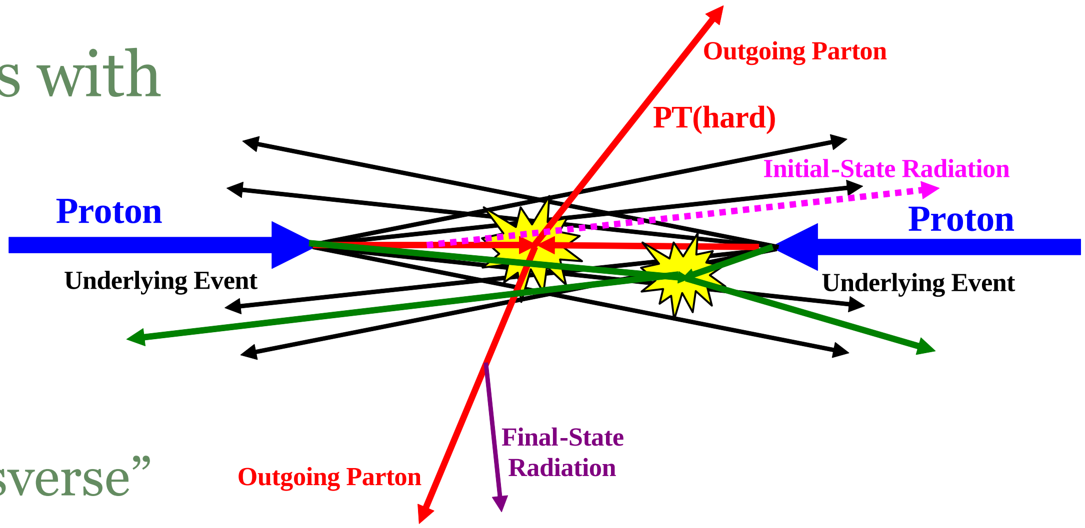
All CDF detectors at noise level except two tracks (Q=0)



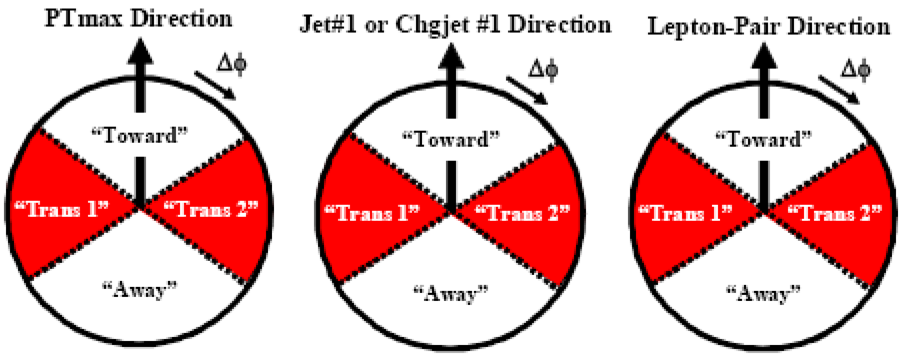


Underlying Event Studies

UE are studied in events with hard scattering



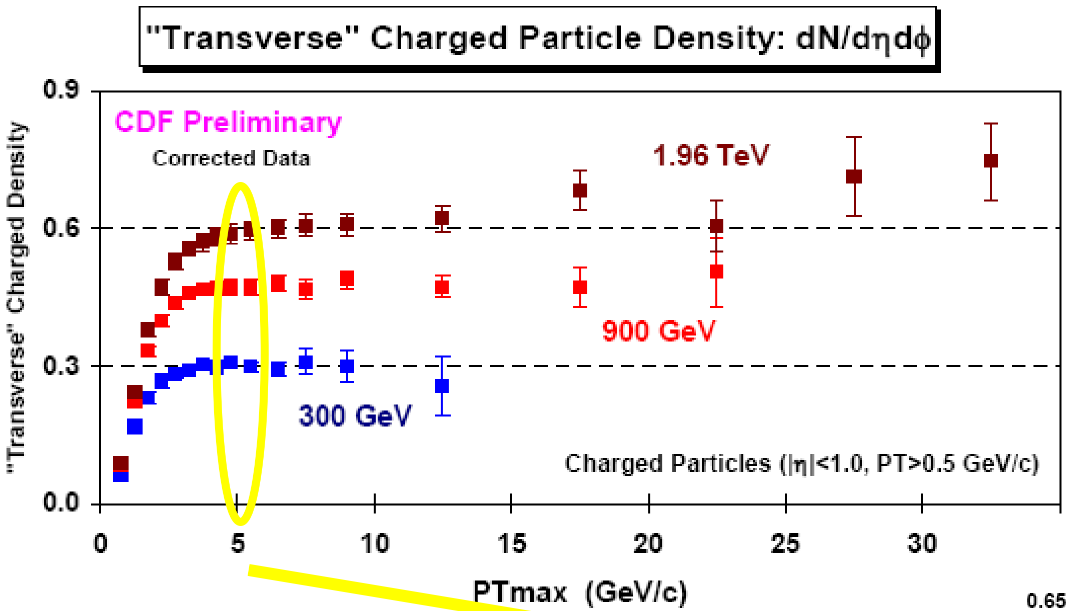
on the event by event basis choose leading object and define 3 regions: "toward", "away", and "transverse"



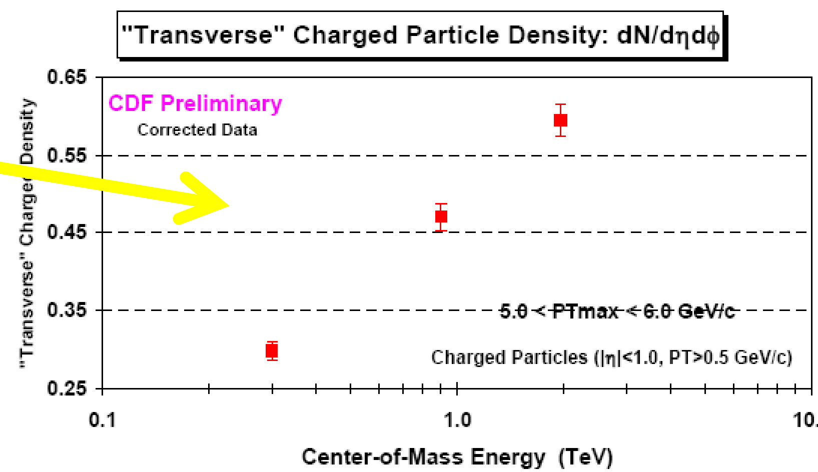
many measurements from CDF:

as a *"leading object"*
Run I – charged particle jet
Run II - leading calorimeter jet
Z boson

Underlying Event Studies



For these studies using
leading charged particle p_{Tmax}
Require:
$p_T > 0.5$ GeV/c
$|\eta| < 1.0$
Data corrected to the particle level
pile-up corrections



many more variables are coming:
$dN/d\eta d\phi$; $dp_T/d\eta d\phi$; $<p_T>$

Summary

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

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

- New set of data from the Tevatron energy scan results on exclusive production, and UE studies

More to come from the QCD program at the Tevatron