Probing QCD with photons at the Tevatron

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on behalf of CDF & D0 Collaborations

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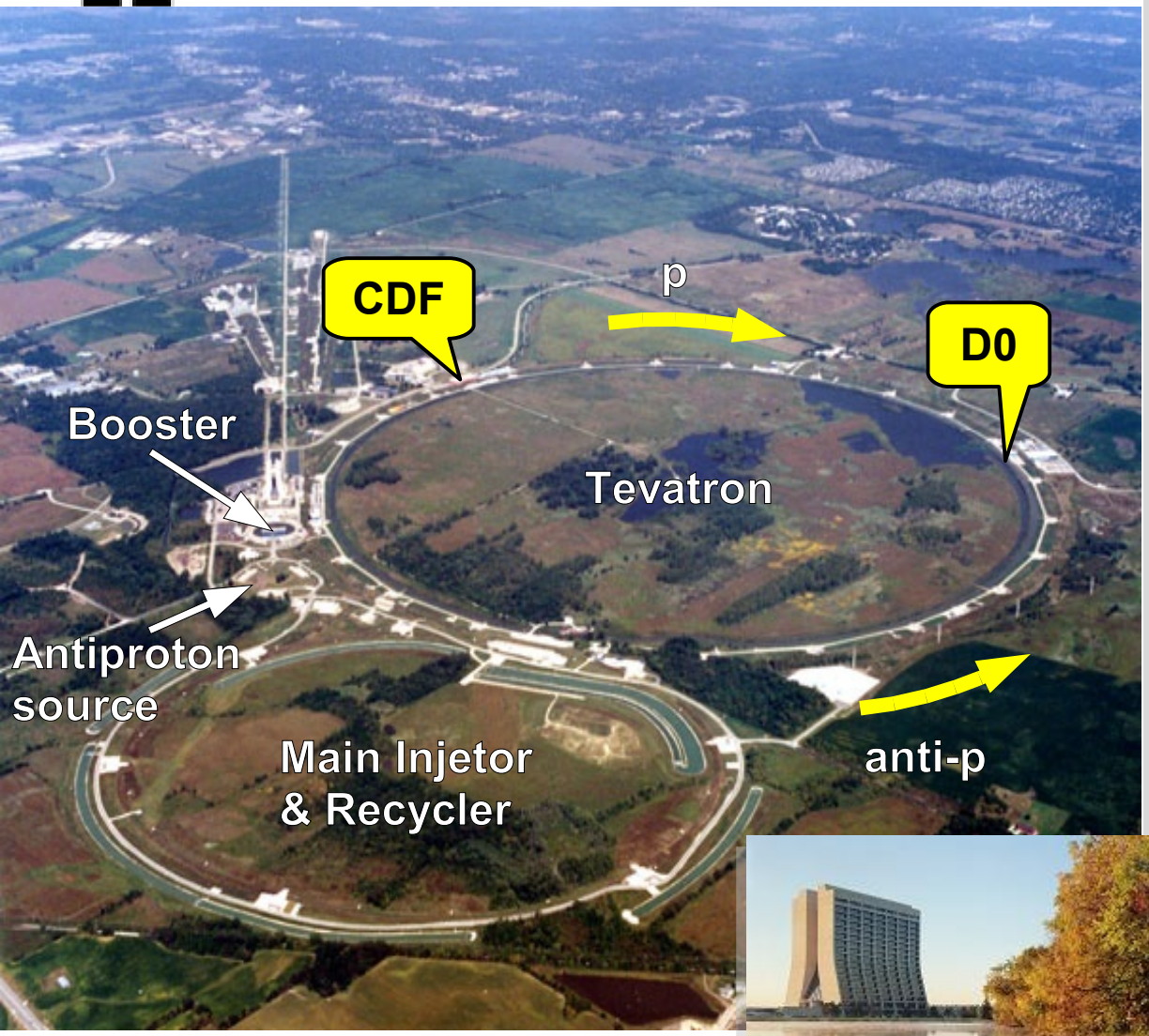
Outline

1. Introduction to: Tevatron, CDF & D0 in Run II.
2. Motivation for studying prompt photons.
3. Isolated photon + jet.
4. Photon + b/c jets.
5. Di-photons.
6. Conclusions and outlooks.

Tevatron at Fermilab

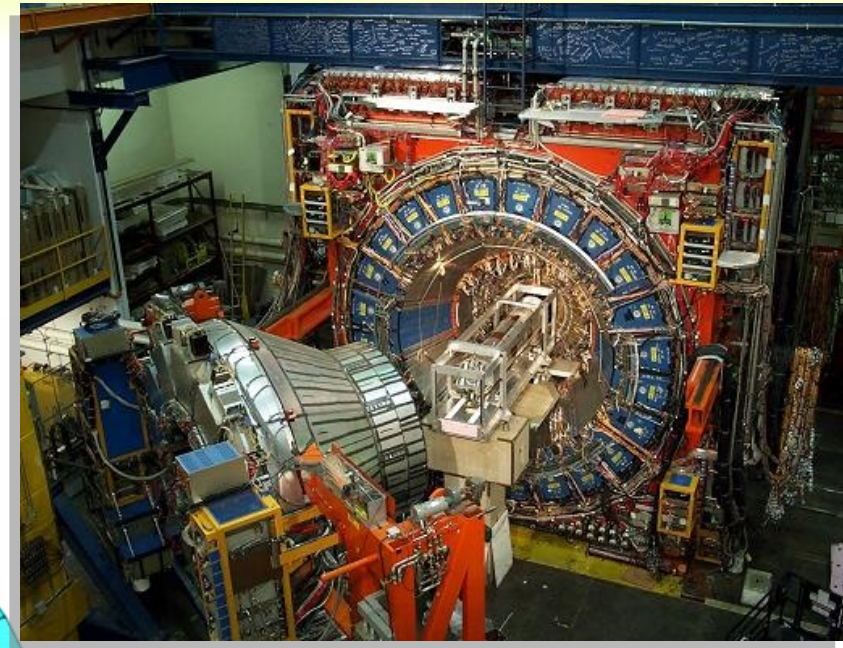


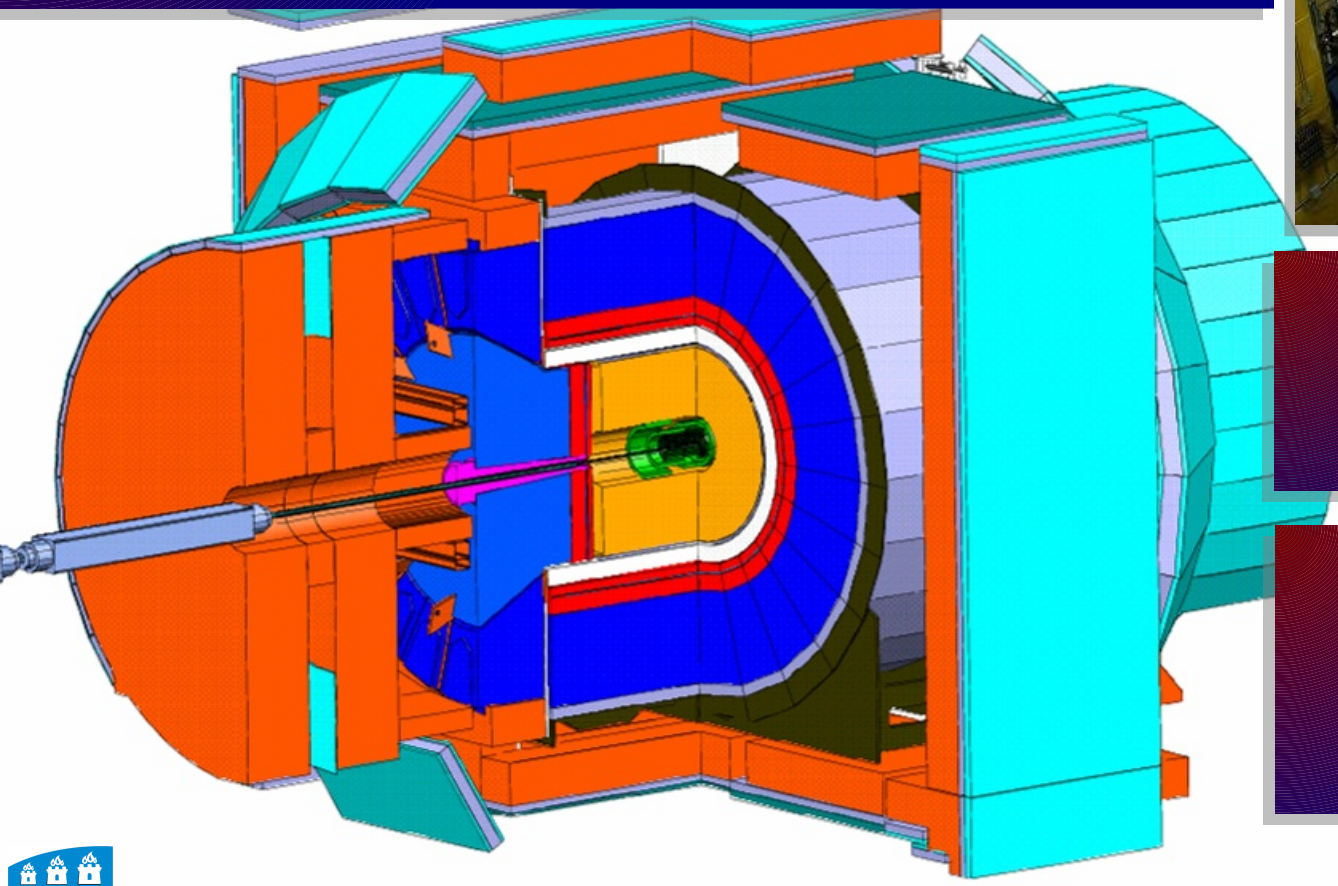
- **$\sqrt{s}$=1.96 TeV in Run II**
  (1.8 TeV in Run I)
- Bunches collide every 396 ns
  (3500 ns in Run I)
- 36x36 bunches
  (6x6 in Run I)
- 2-3 interactions per crossing
- **Peak luminosity: 205×10^{30} cm^{-2}s^{-1}**
- Peak efficiency: 30 pb^{-1} / week
- Delivered: ~1.7 fb^{-1} / experiment:
  Run IIa : Mar 2001 – Feb 2006
  Run IIb: started in June 2006
  (~0.26 fb^{-1} in Run I)
- Recorded: ~1.5 fb^{-1} / experiment
  (CDF & D0)
- **8 fb^{-1} anticipated by 2009**

CDF detector in Run II

- **Tracker**
  (Silicon Microstrips + Wire Chamber):

6 layers of inner Silicon Vertex Det: $|\eta| < 2$
Intermediate Silicon Layer: $1 < |\eta| < 2$
Central Outer Tracker: $|\eta| < 1$
1.5 T superconducting solenoid



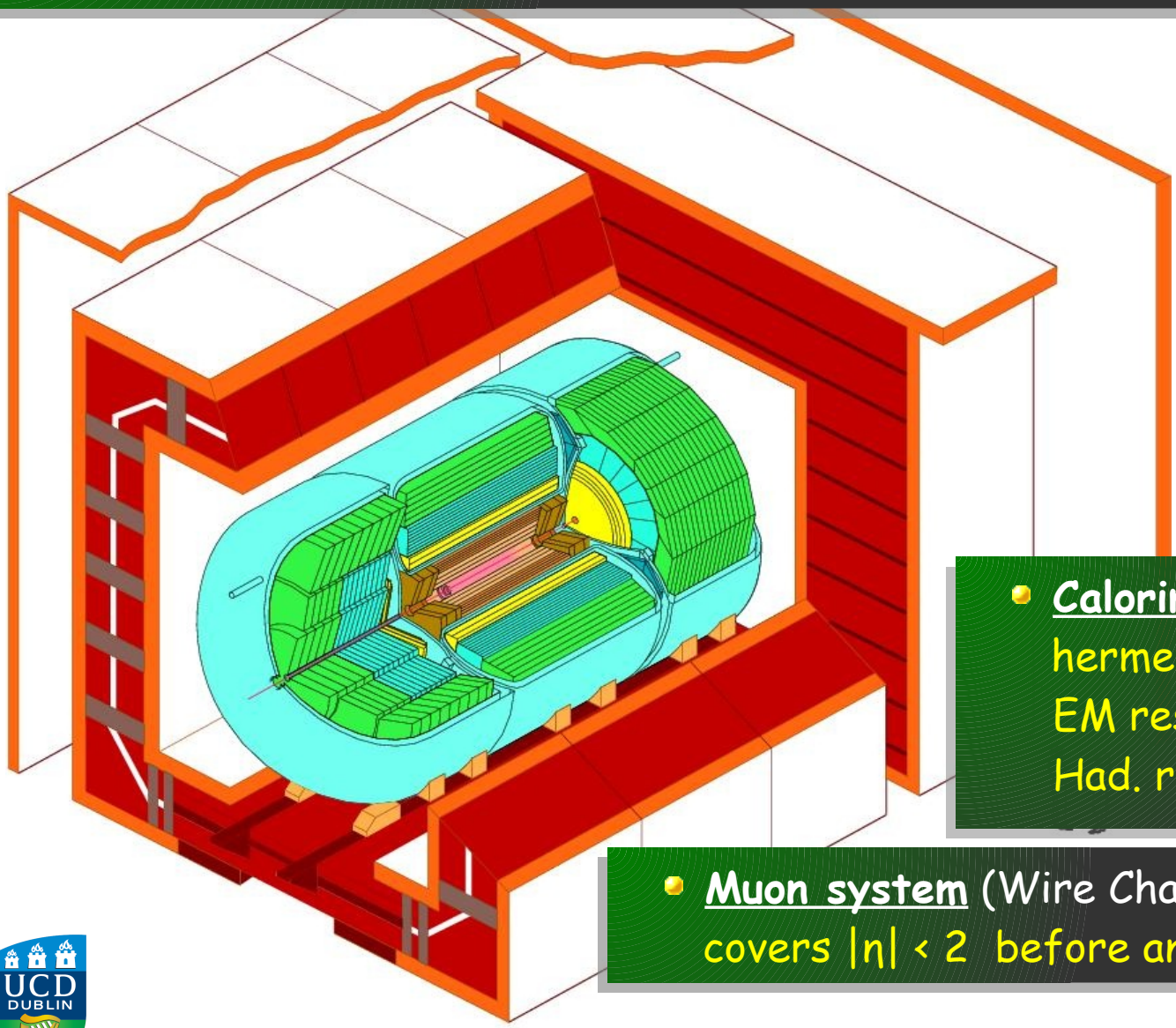


- **Calorimeter** (sampling Pb,Fe/ Scintillator,Wire Chambers):
  covers $|\eta| < 3.6$

- **Muon System** (Scintillators + Proportional Wire Chambers):
  behind steel shielding
  covers $|\eta| < 1.5$

DZero detector in Run II

- **Tracker** (Silicon Microstrips + Scintillating Fibers): covers $|\eta| < 2.5$ inside 2 T superconducting solenoid



- **Calorimeter** (Sampling U/Liquid Ar):
  hermetic coverage: $|\eta| < 4.2$
  EM resolution: 13-15%/$\sqrt{E[GeV]}$
  Had. resolution: 50-80%/$\sqrt{E[GeV]}$

- **Muon system** (Wire Chambers + Scintillators): covers $|\eta| < 2$ before and after toroid

Motivation

Direct photons emerge unaltered from hard interaction

- direct probing of the hard scattering dynamics
- not affected by uncertainties due to fragmentation and jet measurement

PDF sensitivity:

- production cross section sensitive to proton's gluon density (gluon involved at LO)
- probing PDFs at a region of $0.005 < x < 0.3$
- can be used as an additional source for constraining PDFs

Testing QCD predictions:

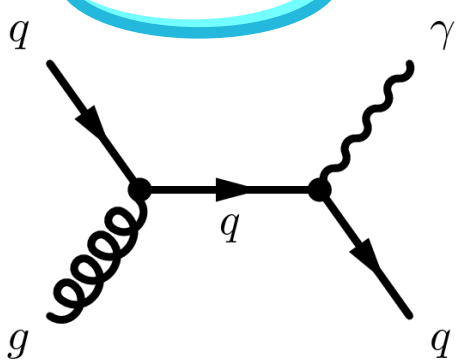
- NLO perturbative QCD
- soft gluon resummation
- gluon radiation models

Source of background for new discoveries:

- understanding production of QCD photons is essential for searches such as: GMSB SUSY, Large Extra Dimensions, $H \rightarrow \gamma\gamma$

Prompt photon production

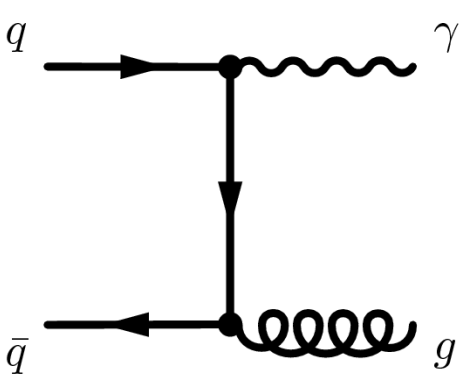
Compton



For centrally produced photons Compton scattering dominates at $\mathbf{p_T^{\gamma} < 120}$ **GeV**

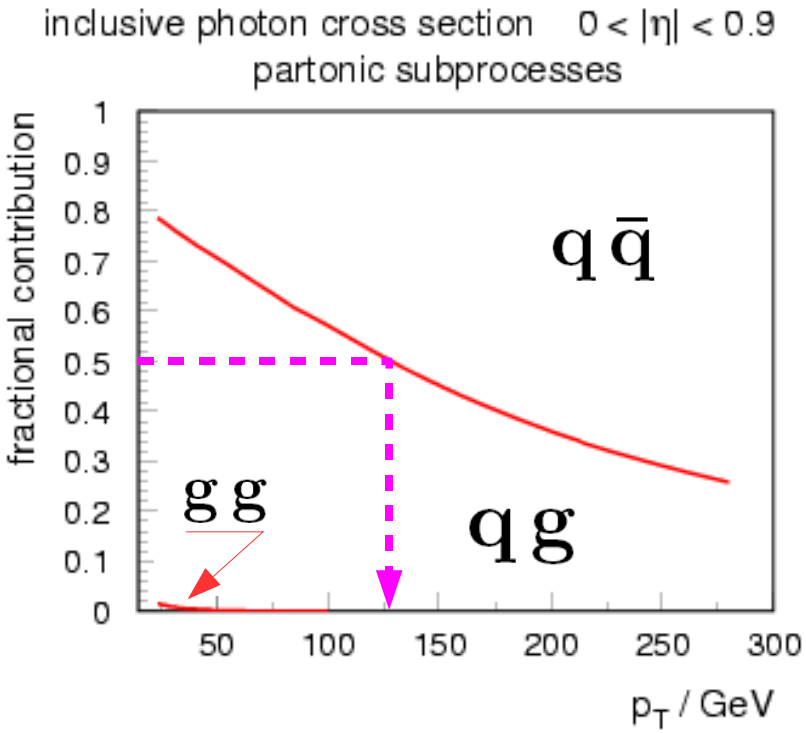
Cross section sensitive to $G(x_T,Q^2)$ at large Q^2 and wide x_T range: $0.02<x_T<0.25$

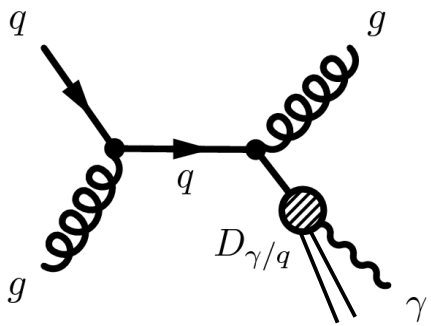
Annihilation



Challenging experimental measurement since $\sigma(\text{jets})/\sigma(\gamma) \approx 10^3$

Severe background from parton fragmenting into a leading π^0 or η at small $\mathbf{p_T^{\gamma}}$





Isolated photon + jet

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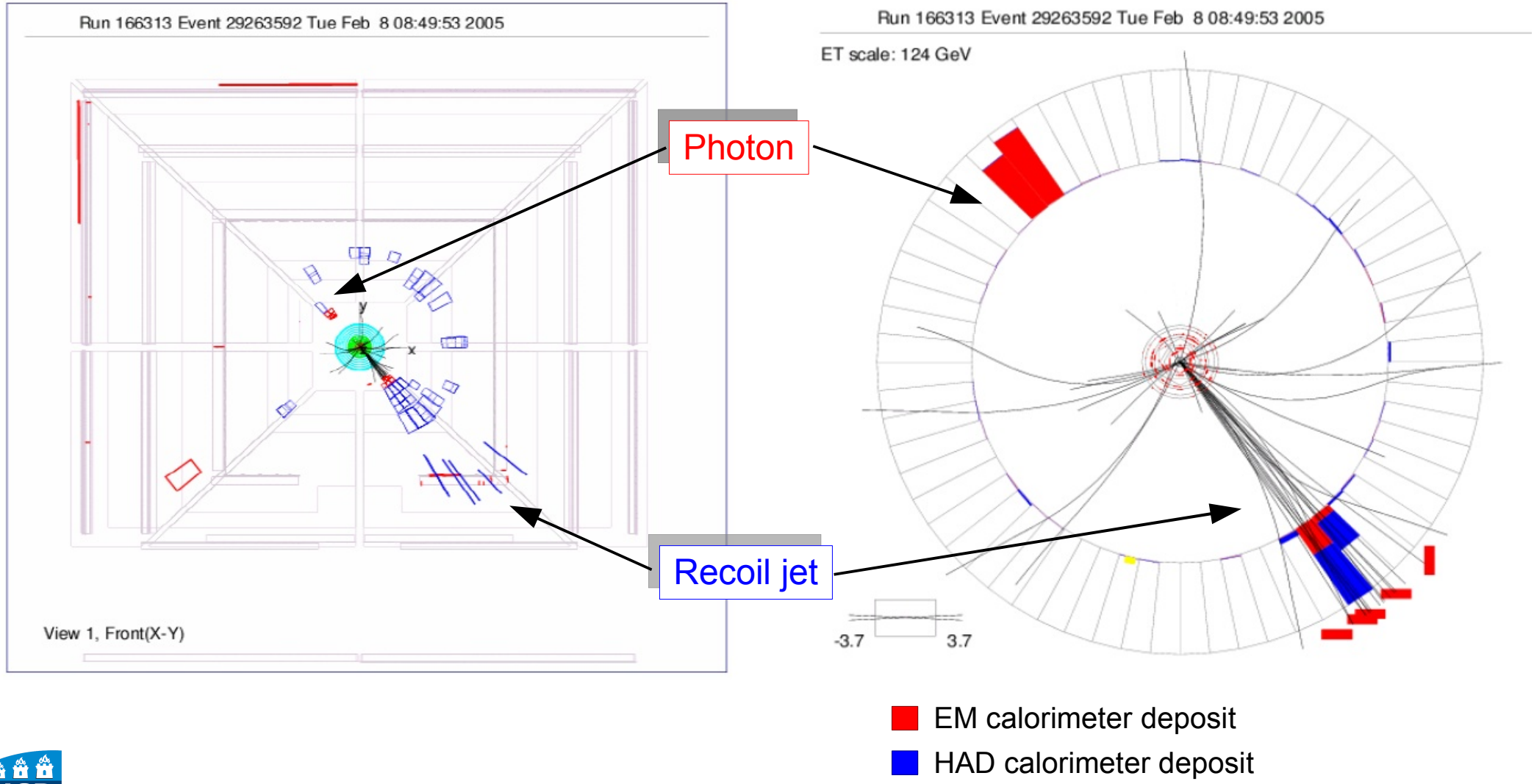
A good γ + 1 jet candidate event as seen by D0 detector (transverse plane view)



Isolated photon + jet

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Isolated shower in EM calorimeter:

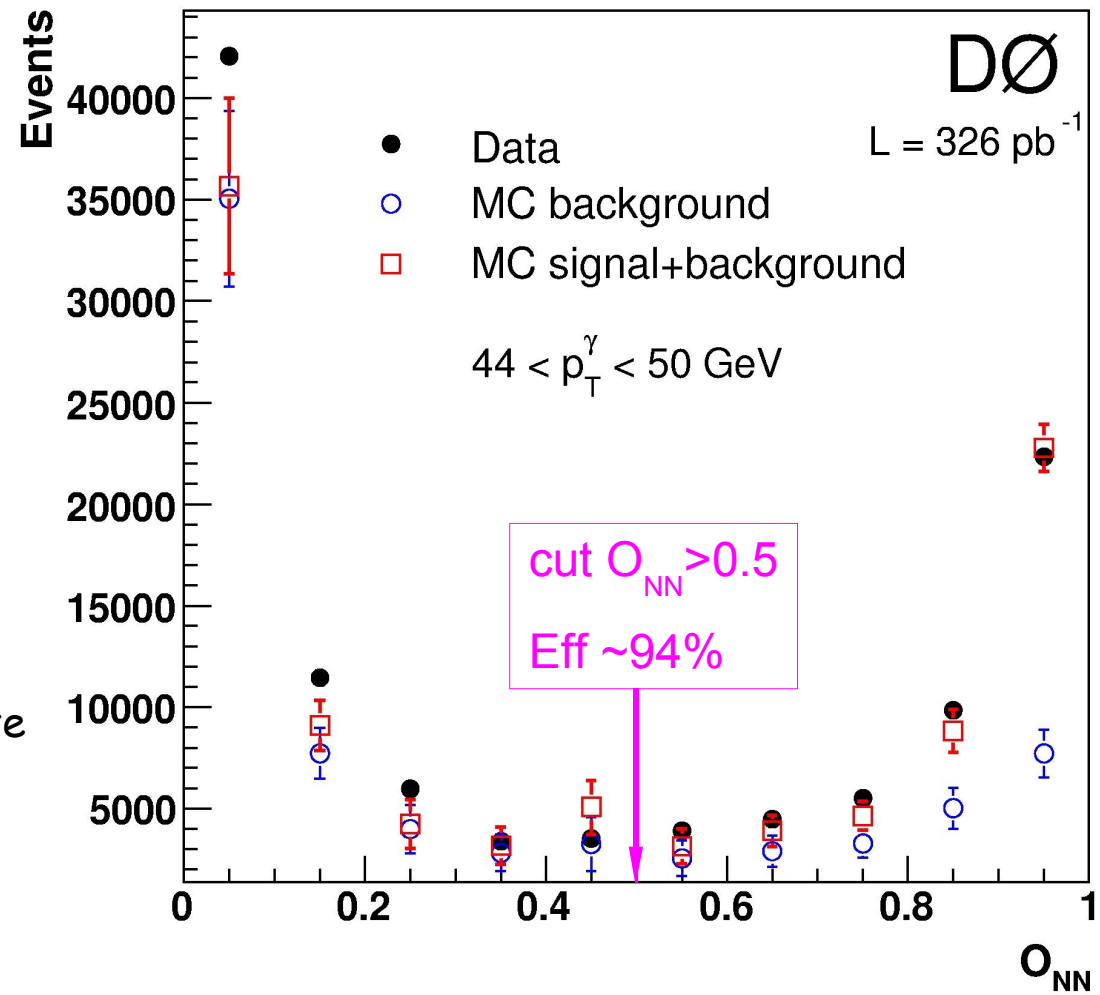
- $|\eta^\gamma| < 0.9$
- $p_T^\gamma > 23$ GeV
- no associated track

Small background from cosmics and electrons from $W \to e\,\nu$:

- apply cut: (Missing E_T)/p_T^γ < 0.7

Main background from jets with large EM fraction due to energetic: π^0, η, K^0_s and ω can be reduced but not eliminated:

- use **Neural Network** trained to discriminate between direct photons and EM jets
- NN uses 4 discriminant variables
- NN tested on $Z \to ee$ MC and data events



Isolated photon + jet

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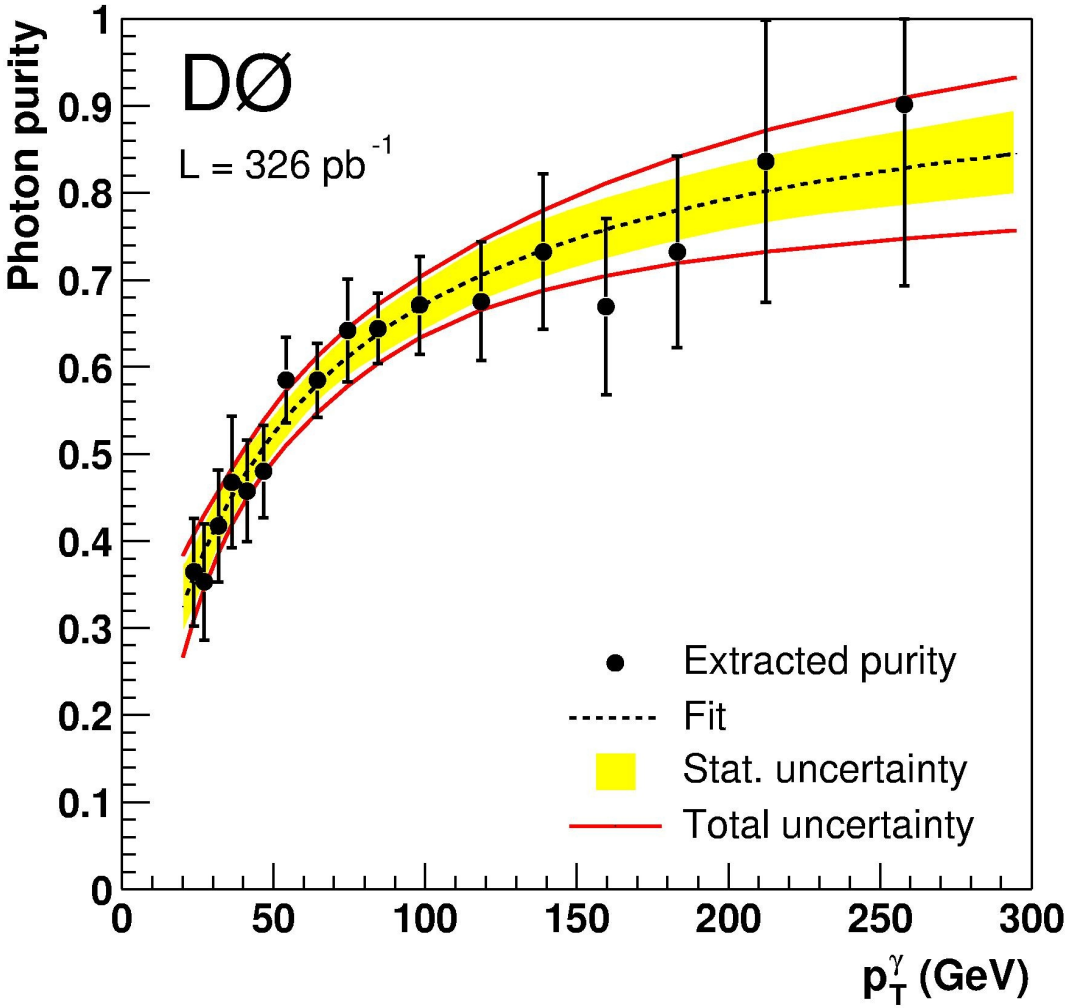

326 pb^{-1} data sample:

2.7×10^6 photon candidates after NN selection

17 photon p_T bins:

$23 < p_T^\gamma < 300$ GeV

Photon purity:

- For each p_T^γ bin NN output in data was fitted to NN output prediction for signal and background
- stat. uncertainties: MC statistics for EM jets (low p_T^γ), data (high p_T^γ)
- syst. uncertainties: fit, fragmentation model in PYTHIA

- electron-based EM calorimeter calibration corrected for photons
- p_T^γ spectrum unsmeared to correct for a finite calorimeter resolution

Isolated photon + jet

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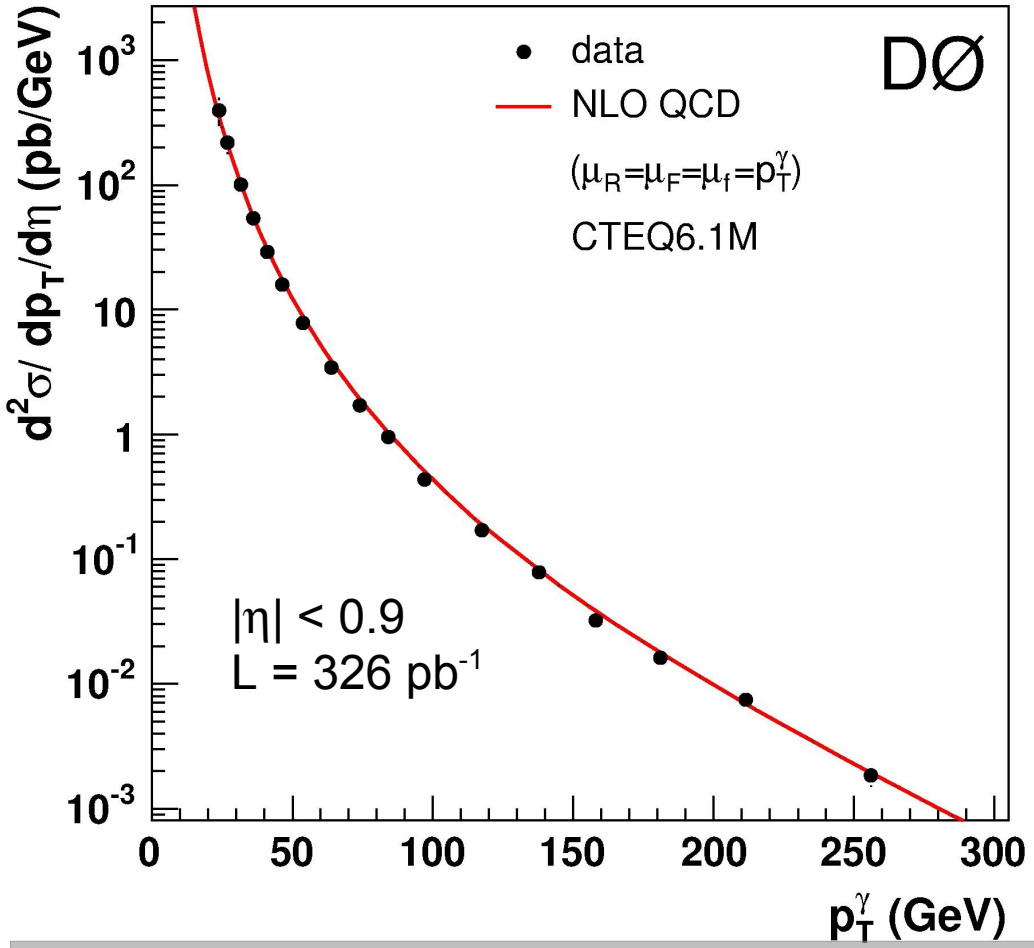
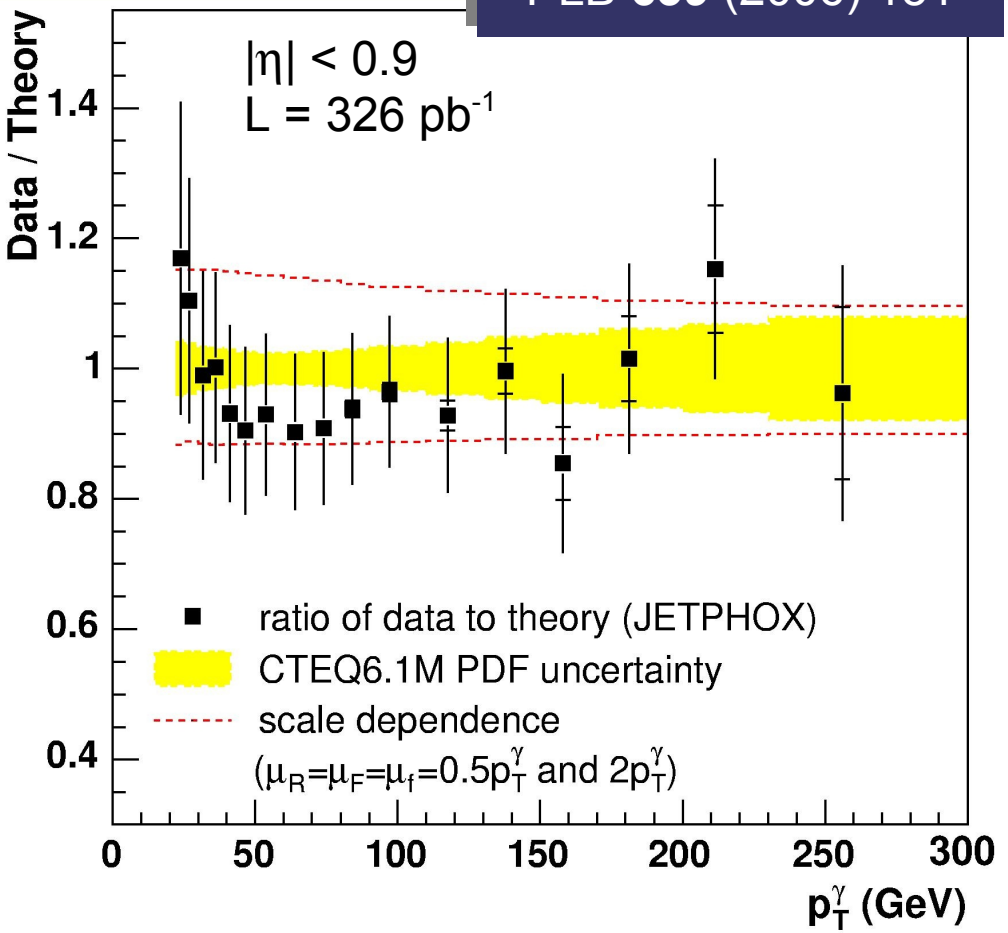




Data agree with NLO pQCD theory prediction by **JETPOX** (using CTEQ6.1M PDFs and BFG FFs)
[MRST 2004 or Alekhin 2004 PDFs ⇒ agree within 7%]

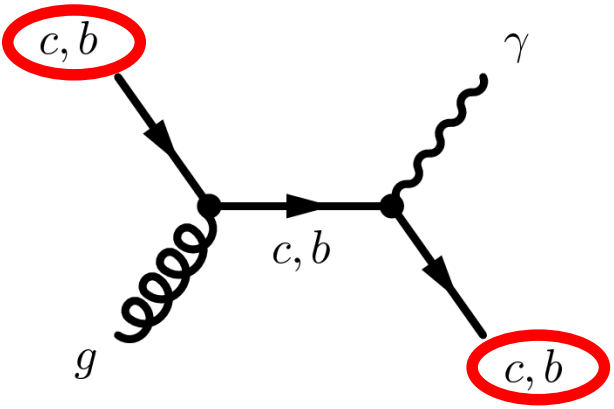
Another NLO pQCD prediction by **Gordon & Vogelsang** (small cone approximations, GRV FFs) ⇒ agrees within **5%**

PDF sensitivity requires:

- Reduction of exp. uncertainties (higher statistics, better purity)
- Improved theory (NNLO / resummation)

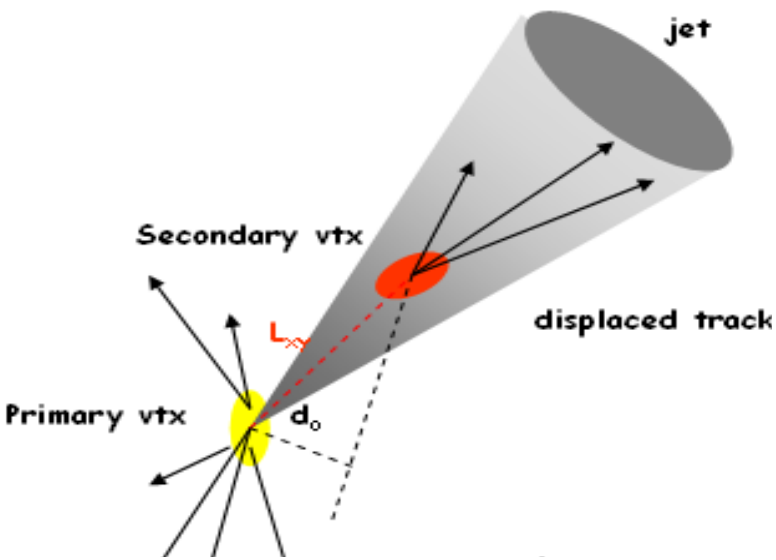
Photon + b/c jet

CDF note 8377



Heavy Flavour jet:

- 3D reconstruction of displaced secondary vertices to identify HF jets using SVT/SVX trackers ($c\tau$ ~3mm for B hadrons)
- $|\eta^{jet}| < 1.5$
- $E_T^{jet} > 20$ GeV



Central isolated photon:

- $E_T^{\gamma} > 26$ GeV
- $|\eta^{\gamma}| < 1.1$
- $\Delta R(\text{jet},\gamma) > 0.7$

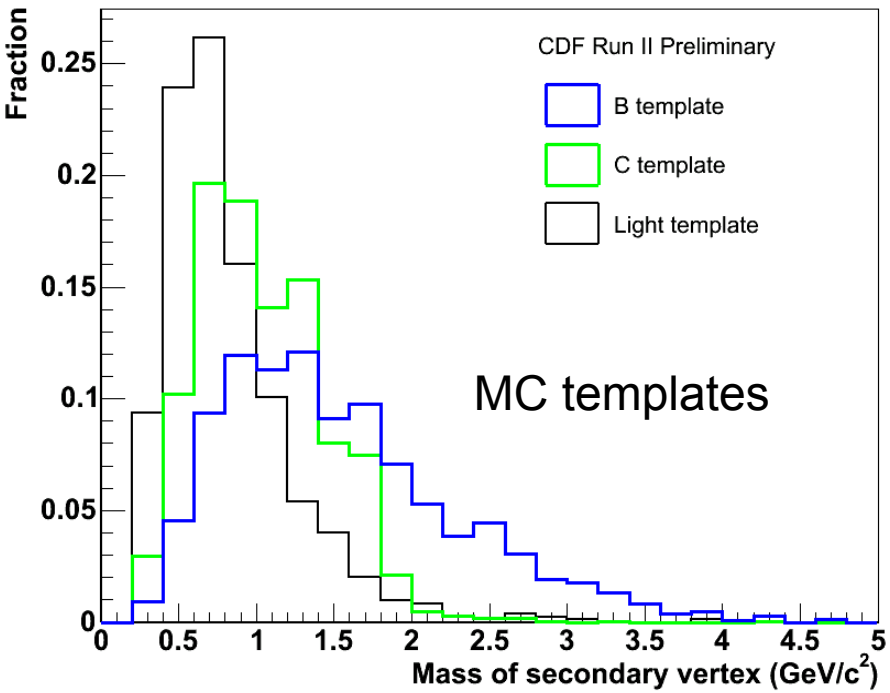
Signal fraction:

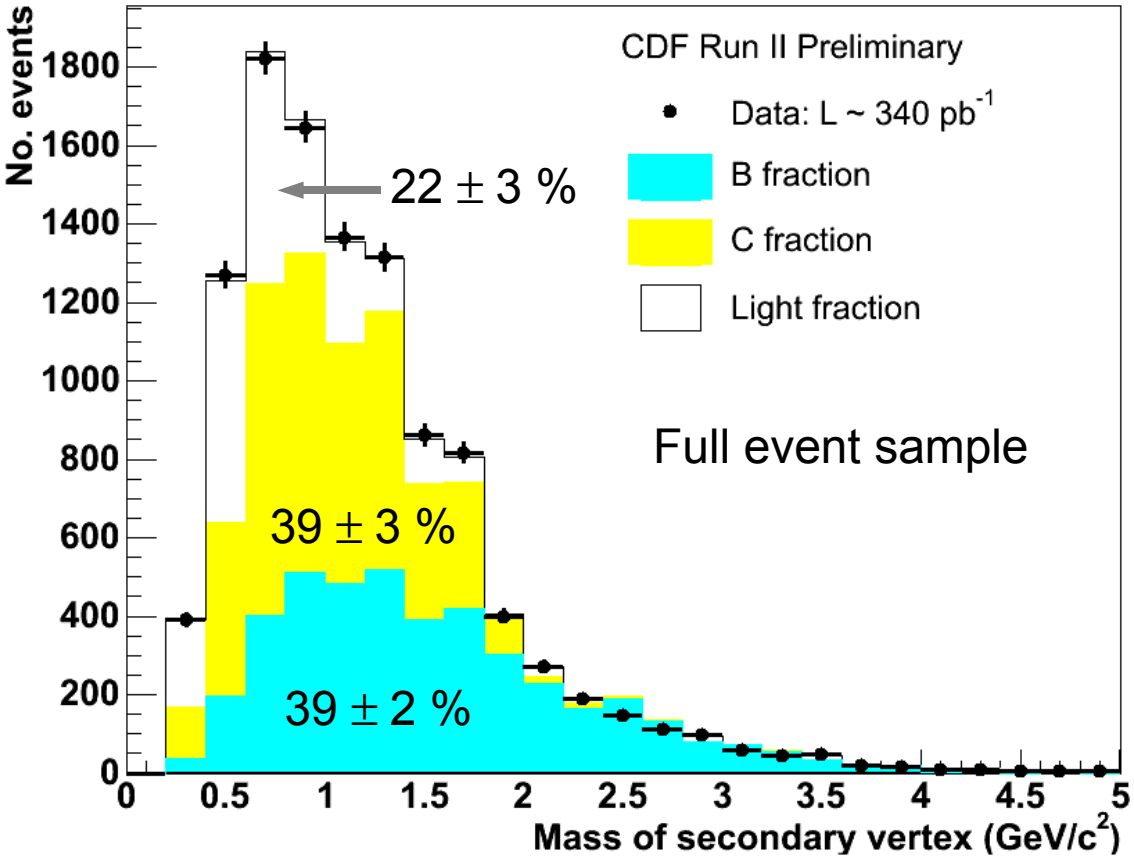
preshower detector (CPR) used to distinguish between single photons and background particles decaying into 2 photons

Photon + b/c jet

Fit secondary vertex mass distribution in data to MC templates for **b, c, light quarks**

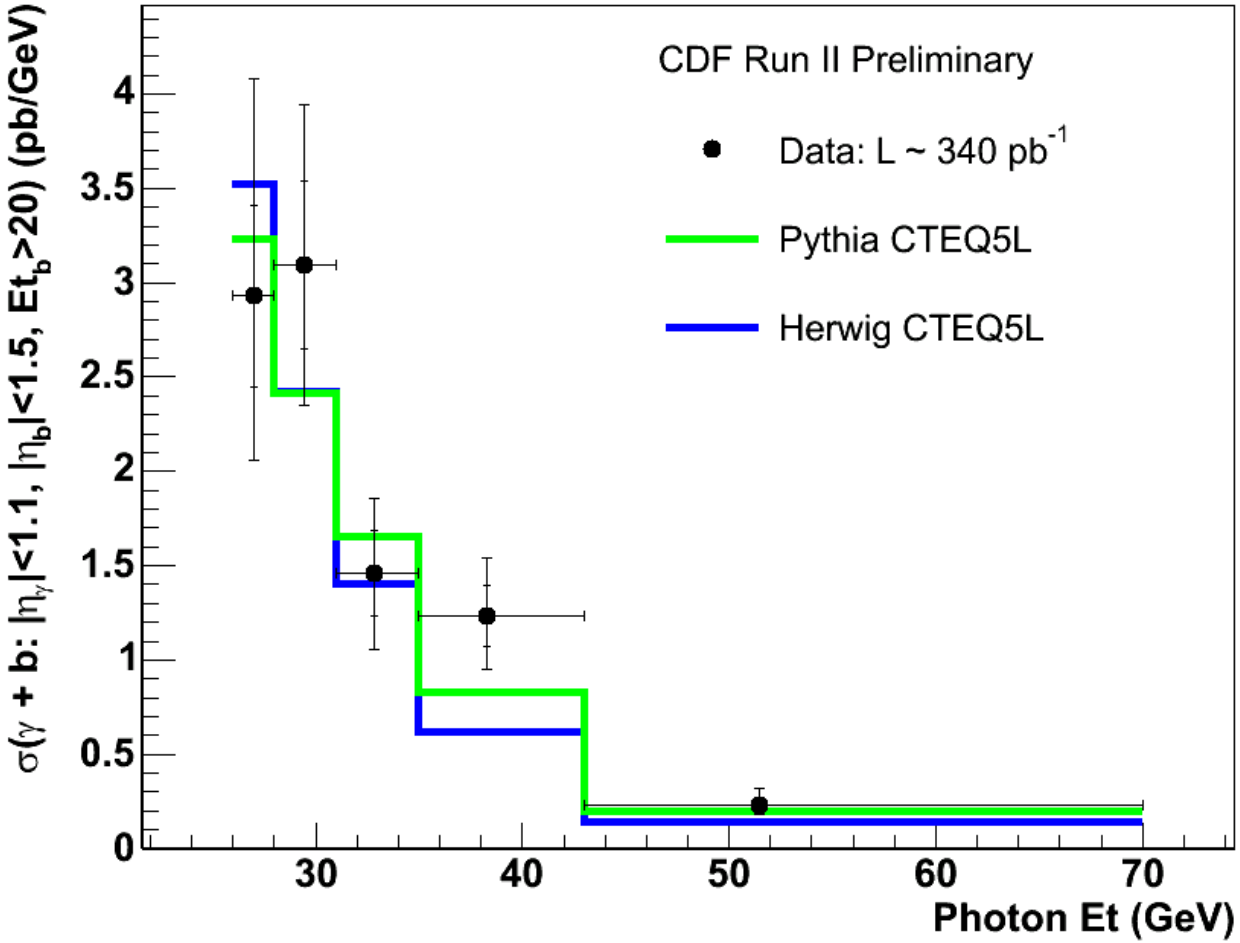
Fits were done for **5 photon E_T bins** between 26 and 70 GeV





CDF note 8377

Photon + b/c jet



340 pb^{-1} data sample

Differential γ+b cross section measured for 5 photon E_T bins between 26 and 70 GeV

Integrated γ+b cross section for E_T^γ > 26 GeV (and after all cuts) is: **$42.0 \pm 3.8\ ^{+8.8}_{-7.0}$ pb**

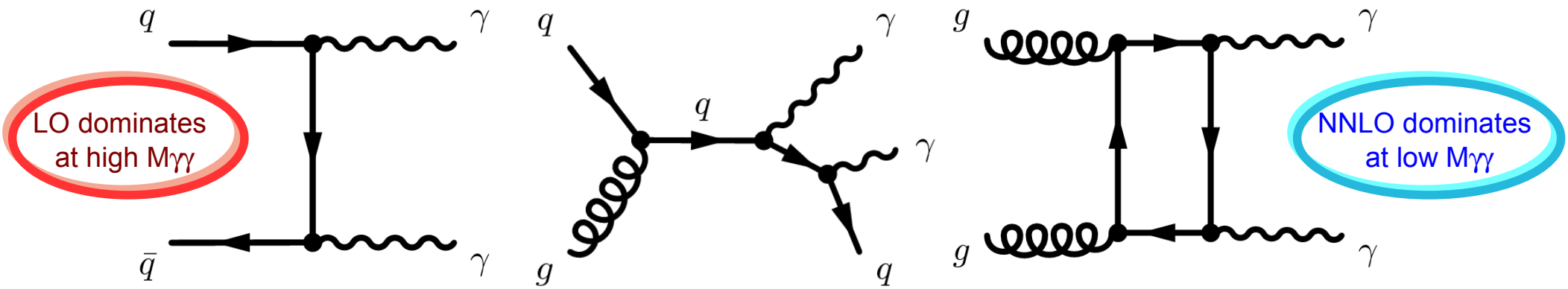
Data consistent with LO QCD theory prediction by by **PYTHIA** and **HERWIG** using CTEQ5L

CDF note 8377

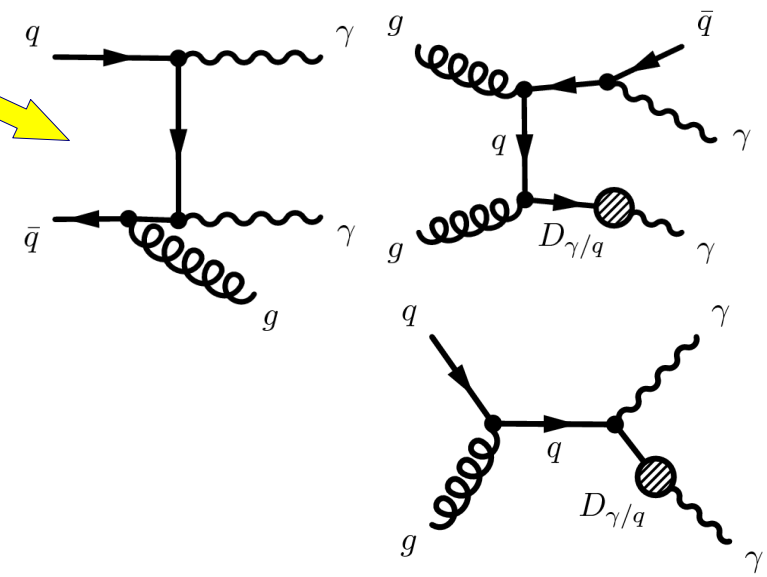
Di-photon production

PRL **95** (2005) 022003

Direct di-photon production diagrams (LO/NLO/NNLO):



Contributions from **gluon ISR** and **fragmentation:**



Require **2 isolated EM showers** in EM calorimeter:

- $E_T^{\gamma 1} > 14$ GeV
- $E_T^{\gamma 2} > 13$ GeV
- $|\eta^{\gamma 1}|, |\eta^{\gamma 2}| < 0.9$

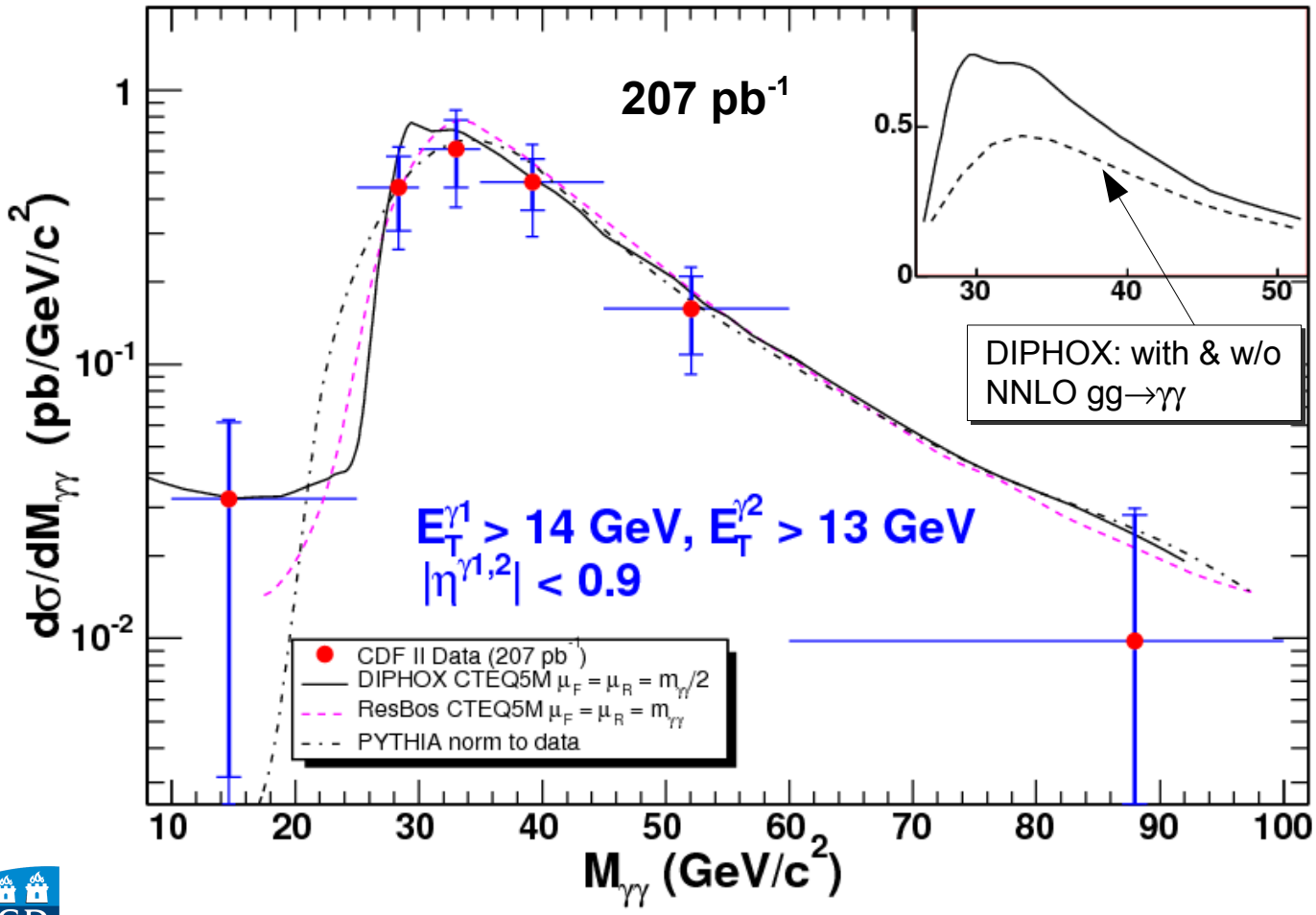
Total selection efficiency: 15.2%, sample purity: ~50%

889 γγ candidate events from **207 pb^{-1}** data sample

Di-photon production

PRL **95** (2005) 022003

Differential cross section measured as a function of: invariant mass ($M_{\gamma\gamma}$), azimuthal angle ($\Delta\phi_{\gamma\gamma}$) and total transverse momentum (q_T) of the photon pair



Comparison with theory:

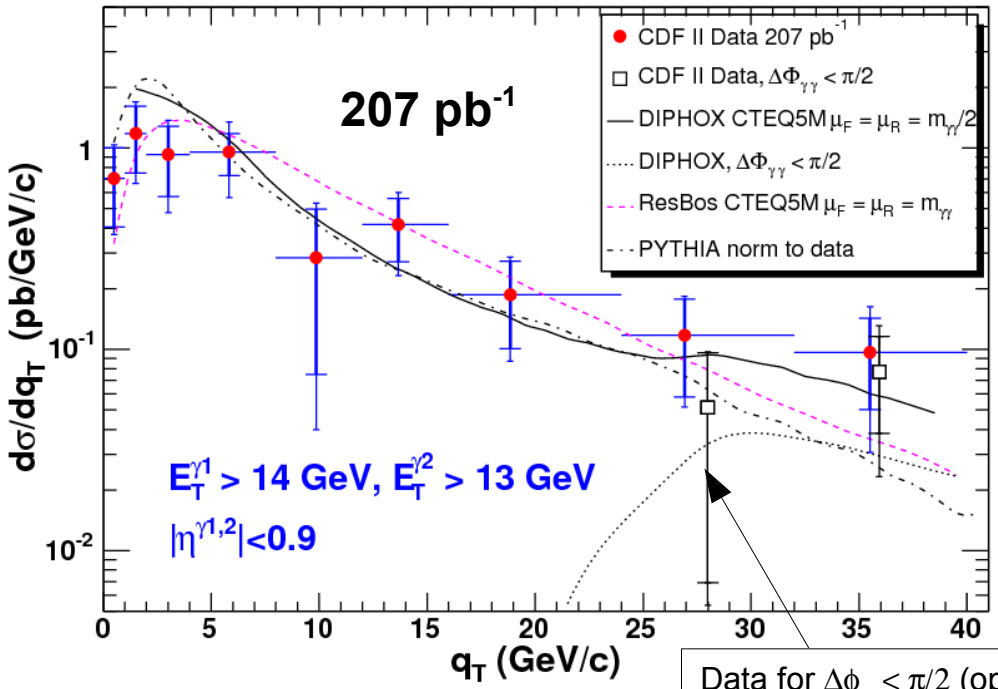
DIPHOX:
NLO propmt di-photons
NLO fragmentation (1 or 2 γ)
NNLO gg→γγ

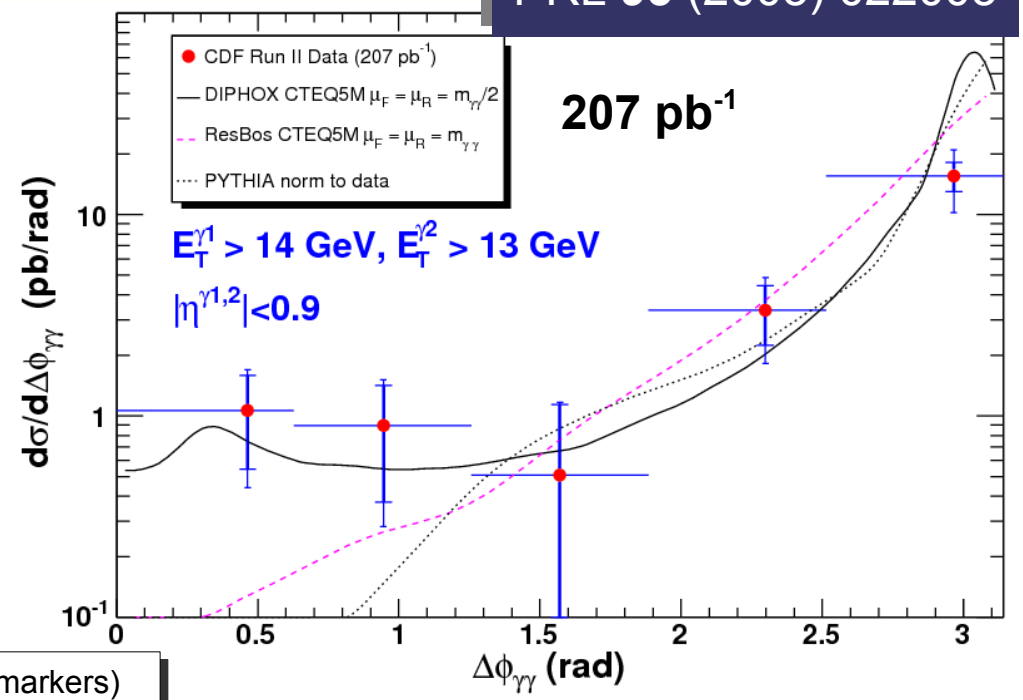
ResBos:
NLO propmt di-photons
LO fragmentation
resummed gluon ISR

PYTHIA:
had to be multiplied by a factor of 2 to normalize to the data

Di-photon production

PRL **95** (2005) 022003





Data for $\Delta\phi_{\gamma\gamma} < \pi/2$ (open markers) compared with DIPHOX

- NLO fragmentation contribution important at: high q_T, low $\Delta\phi$, low mass ($\Rightarrow$ DIPHOX)
- Resummed gluon ISR important at: low q_T, high $\Delta\phi$ ($\Rightarrow$ ResBos)
- NNLO $gg\rightarrow\gamma\gamma$ graph important at low mass ($\Rightarrow$ DIPHOX)

NLO pQCD gives a reasonable overall description of the data

No single model describes data accurately in the entire phase space studied ($M_{\gamma\gamma}$, $\Delta\phi_{\gamma\gamma}$, q_T)

$\Rightarrow$ need a combined calculation with: NLO direct production and fragmentation, NNLO $gg\rightarrow\gamma\gamma$, resummed initial-state gluon radiation.

Conclusions

Single photons:

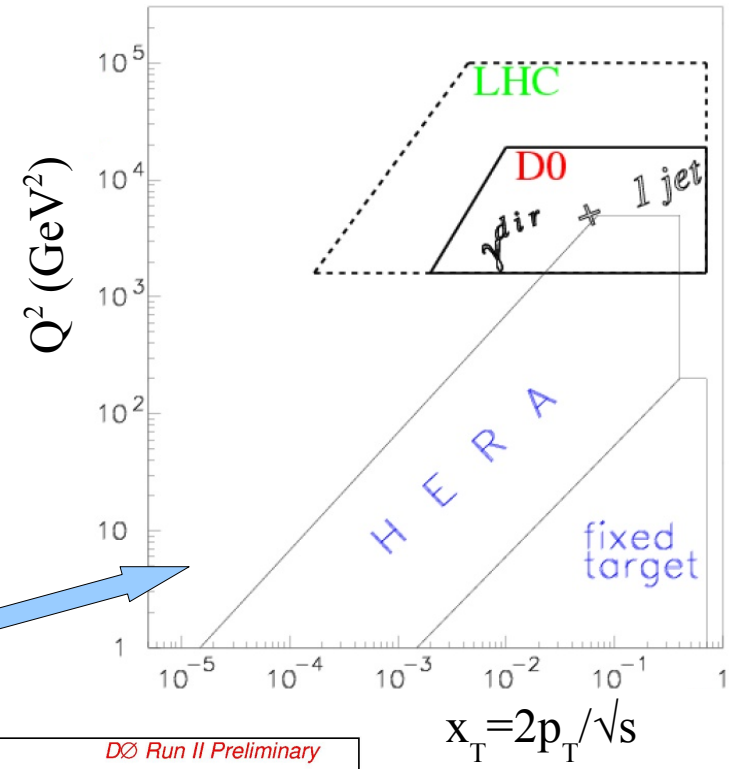
1. **Isolated photon differential cross section is well described by NLO pQCD prediction (JETPOX with CTEQ6.1M)**
   Sensitivity to gluon PDF requires smaller experimental uncertainties and improved theory (NNLO/resummation).
2. **Differential photon + b jet cross section agrees with LO pQCD predictions by HERWIG and PYTHIA using CTEQ5M PDFs within (large) experimental errors.**

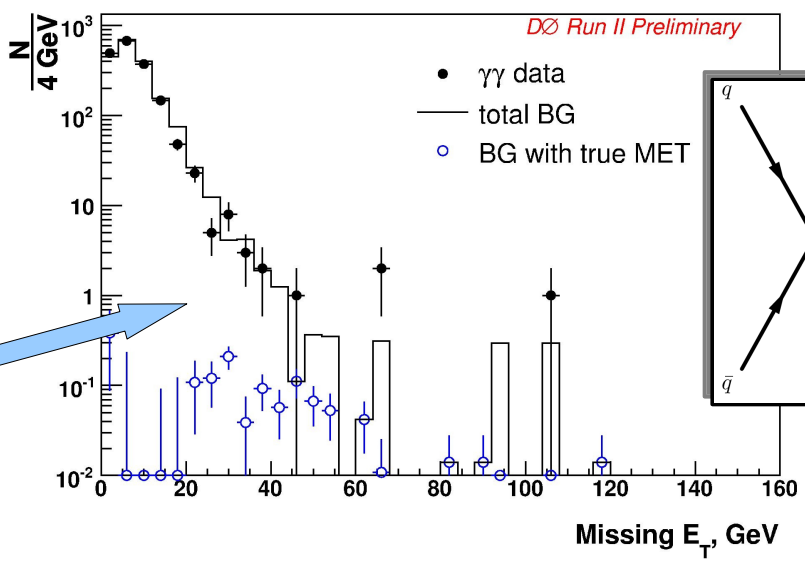
Di-photons:

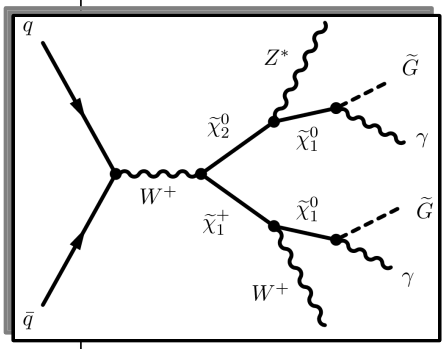
3. **In general good agreement between data and NLO pQCD models (DIPHOX, ResBos).**
   However, the observed data can't be described accurately by a single model in all critical regions of the phase space studied.
4. Would be useful to have a combined calculation with: direct di-photon production up to NNLO, NLO fragmentation contribution and gluon ISR resummation.

Outlooks

1. **Results presented in this talk use only a fraction of statistics available from Tevatron's Run II.**
2. **CDF & D0 collaborations anticipate to collect data samples corresponding to 8 fb^{-1} by 2009.**
3. **Improved and new analyzes using ~1 fb^{-1} are under way.** For instance, in D0:
   - Improved inclusive photon cross section analysis aimed to constrain gluon PDFs. There is an overlap between x-Q^2 regions covered by: LHC, Tevatron and HERA.
   - Diphoton cross section measurement is in progress
   - Search for GMSB in diphoton final states with large missing E_T







lightest neutralino
$m_{\tilde{\chi}_1^0} > 120$ GeV

BACKUP slides

Isolated photon + jet

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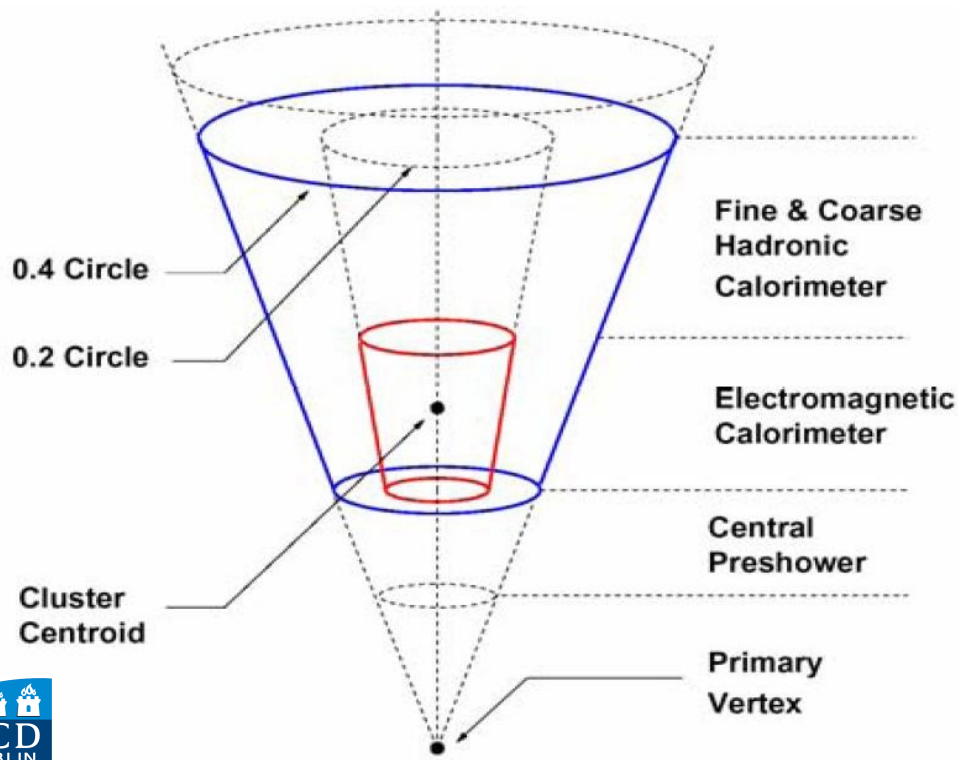
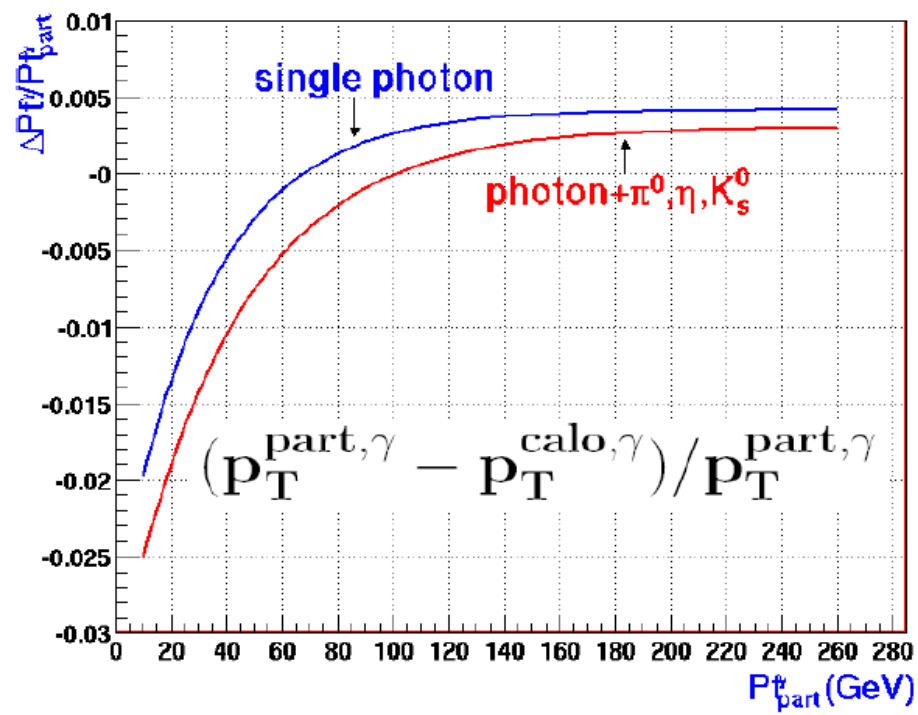
Photon Isolation:

- reconstruct EM objects from energy of the clusters found by a cone algorithm (R=0.4)
- > 95% of energy in EM layers
- $\{ E_T^{TOT}(R=0.4)-E_T^{EM}(R=0.2) \} / E_T^{EM}(R=0.2) < 10\%$
- veto any tracks around EM cluster
- shower profile combatible with photon

Photon Energy Scale correction:

- calorimeter calibration factors used to reconstruct true energy of EM particles are based on electron events
- photons lose less energy in material upstream of the calorimeter than electrons
- additional shift due to π^0, η, K^0_S decaying into photons of smaller energy





Isolated photon + jet

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Systematic uncertainties [%]:

Luminosity	6.5	
Vertex determination	$3.6 \rightarrow 5.0$	*(low* $\rightarrow$ *high* p_T^{γ}*)*
Energy calibration	$9.6 \rightarrow 5.5$	
Fragmentaion model	$1.0 \rightarrow 7.3$	
Photon conversions	3	
Photon purity fit	$6 \rightarrow 13$	
Geometric acceptance	1.5	
Trigger efficiency	$11 \rightarrow 1$	
Selection efficiency	$5.4 \rightarrow 3.8$	
Unsmearing	1.5	

Photon + b/c jet analysis

CDF note 8377

Statistical uncertainties:

Photon E_T /GeV	26-28	28-31	31-35	35-43	43-70	> 26
Fake photon	±0.32	±0.28	±0.15	±0.10	±0.02	±1.7
B purity	±0.27	±0.25	±0.13	±0.09	±0.02	±2.3
B background	±0.07	±0.08	±0.04	±0.03	±0.01	±1.1
Photon efficiency	±0.02	±0.02	±0.01	±0.01	±0.01	±0.3
b jet efficiency	±0.17	±0.16	±0.08	±0.06	±0.01	±1.0
b tag efficiency	±0.15	±0.15	±0.07	±0.06	±0.01	±2.1
Total stat. error (pb/GeV)	±0.48	±0.44	±0.23	±0.17	±0.03	±3.8 pb

Systematic uncertainties:

Photon E_T /GeV	26-28	28-31	31-35	35-43	43-70	> 26
Luminosity	±0.18	±0.19	±0.09	±0.07	±0.01	±2.5
Fake photon estimate	$^{+0.18}_{-0.20}$	$^{+0.15}_{-0.17}$	$^{+0.09}_{-0.13}$	$^{+0.05}_{-0.07}$	$^{+0.01}_{-0.02}$	$^{+1.8}_{-2.7}$
Jet energy scale	$^{+0.14}_{-0.15}$	$^{+0.11}_{-0.06}$	$^{+0.02}_{-0.04}$	±0.02	±0.01	±1.0
Photon efficiency	±0.04	±0.05	±0.02	±0.02	±0.01	±0.6
Template shapes	$^{+0.89}_{-0.39}$	$^{+0.51}_{-0.36}$	$^{+0.25}_{-0.20}$	$^{+0.20}_{-0.14}$	$^{+0.07}_{-0.03}$	$^{+7.4}_{-4.0}$
Background composition	±0.04	±0.03	±0.03	±0.01	±0.01	±0.4
b tagging efficiency	$^{+0.45}_{-0.18}$	$^{+0.43}_{-0.19}$	$^{+0.16}_{-0.09}$	$^{+0.11}_{-0.07}$	$^{+0.02}_{-0.01}$	$^{+3.4}_{-2.6}$
Jet E_T modelling	-0.50	-0.35	-0.18	-0.13	-0.01	-3.5
Total sys. error (pb/GeV)	$^{+1.04}_{-0.73}$	$^{+0.72}_{-0.60}$	±0.33	$^{+0.26}_{-0.23}$	$^{+0.08}_{-0.04}$	$^{+8.8}_{-7.0}$ pb

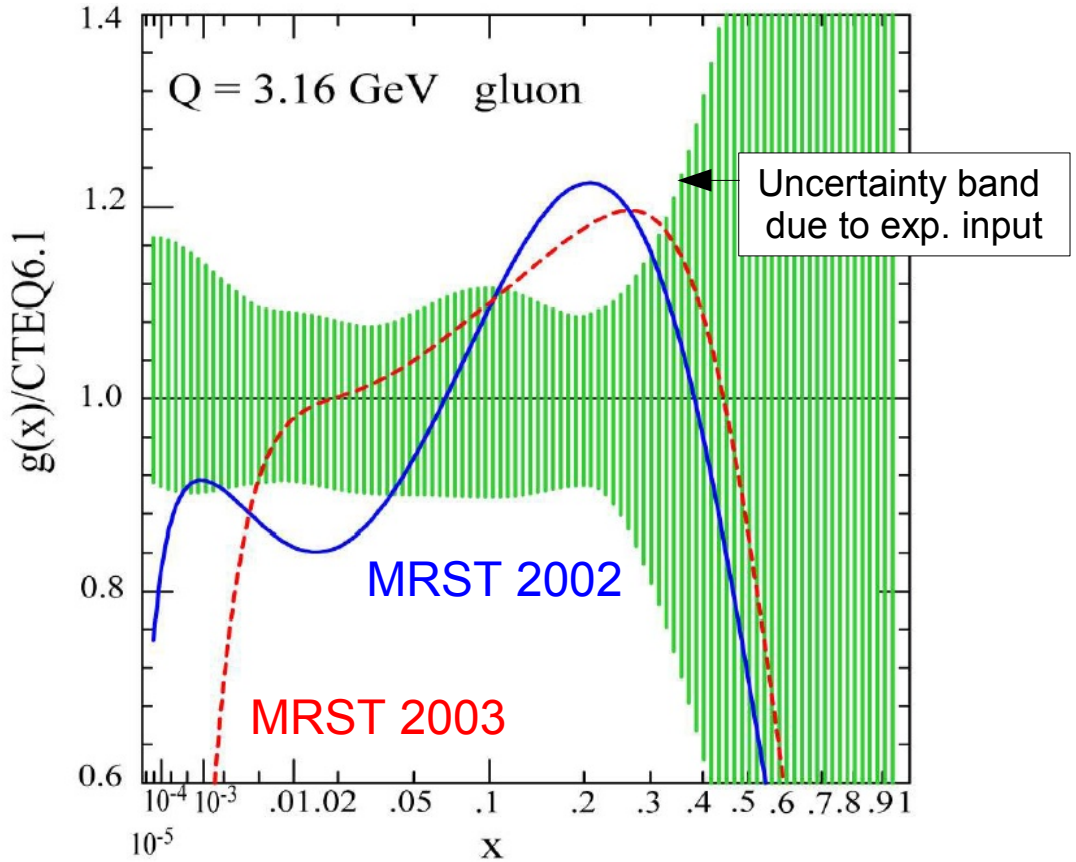
Di-photon production

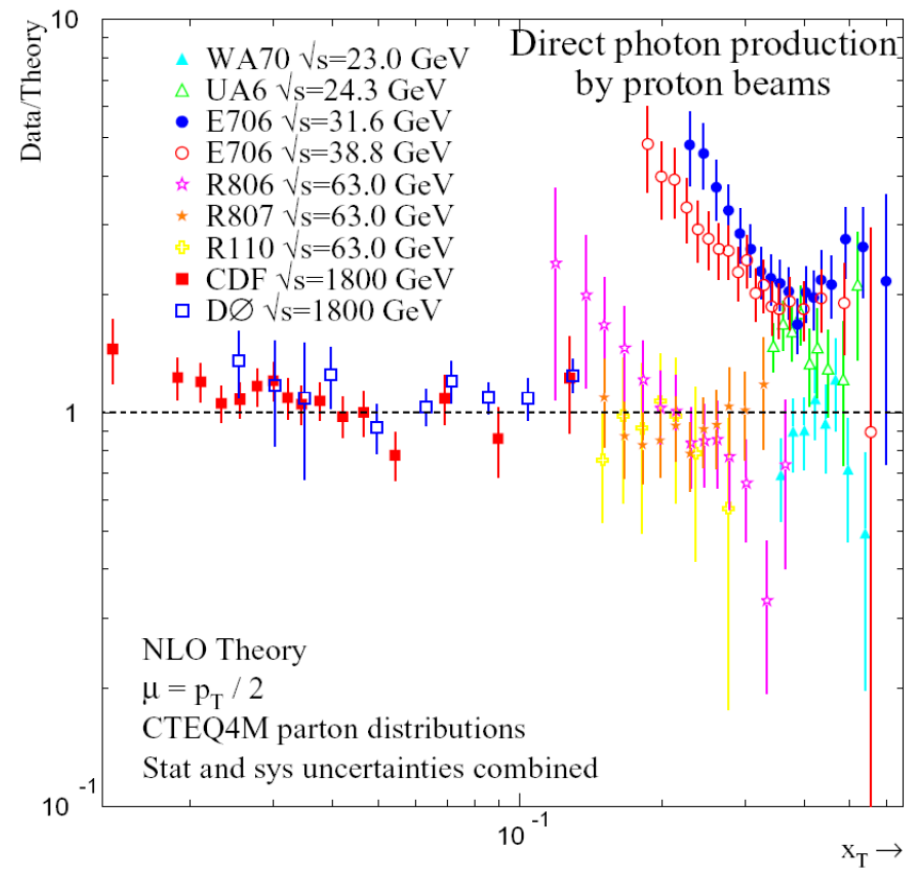
PRL **95** (2005) 022003

Systematic uncertainties [%]:

Luminosity	6
Selection efficiencies	11
Background subtraction	20-30

Constraining gluon PDF





$G(x,Q^2)$ is the most uncertain of the PDFs. Uncertainties due to experimental input only (green band) are ~15% for x < 0.25 and increase at larger x. Theoretical uncertainties increase at small x widening the error band.

Direct photon data is not used in the global PDF fit anymore because of the large theoretical uncertainties coupled with the poor agreement with most of the world's photon data.

Direct photon cross section [hep-ex/0304010, Eur.Phys.J. ***C37***, 185 (2004)] and/or photon+jet asymmetries [PRD **59**, 014016 (1999)] can be used to determine $G(x,Q^2)$.