CT10 NNLO update and QED effects in PDFs

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On behalf of CTEQ-TEA group

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Outline

1) CT10 NLO/NNLO PDFs review and update Gao et al, PRD **89**, 033009 (2014)

2) Benchmark Studies Ball et al, JHEP 1304 (2013) 125
and MetaPDFs Gao and Nadolsky, arXiv:1401.001[hep-ph]

3) QED effects in parton evolution and Photon PDFs (in preparation)

Also –

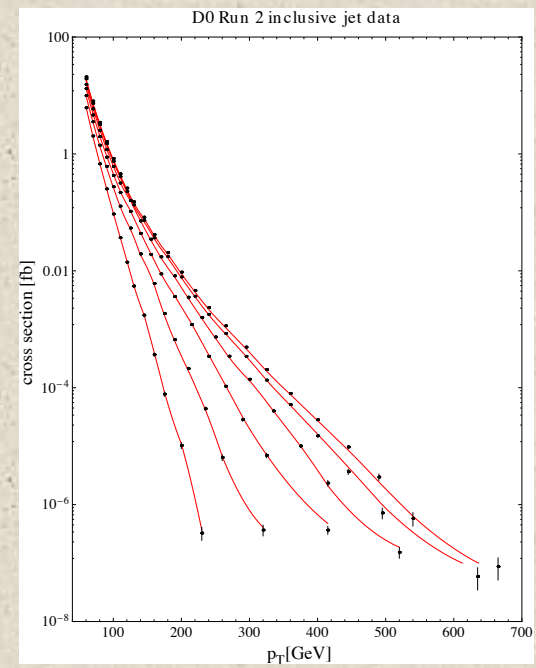
Intrinsic Charm Dulat et al, PRD **89**, 073004 (2014)

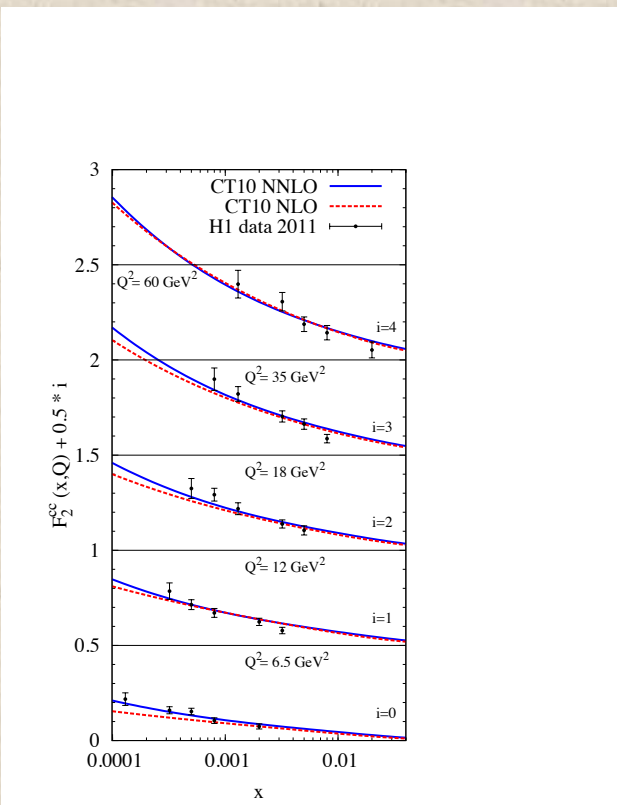
Uncertainty Analysis on $gg \to H$ and $gg \to ttbar$

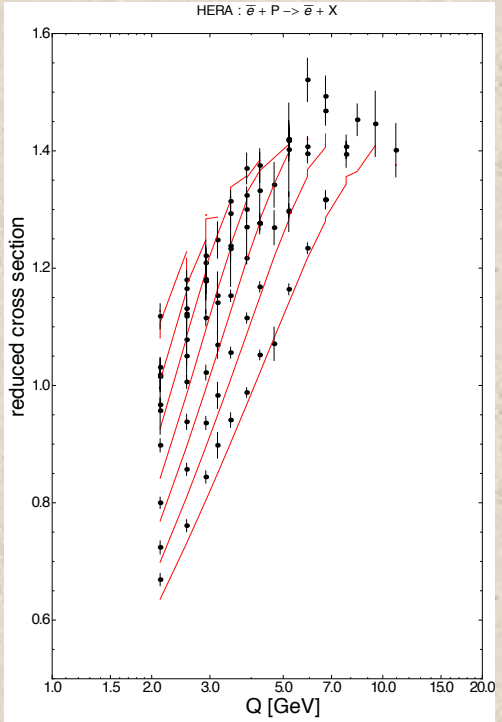
Dulat et al, arXiv:1309.0025[hep-ph]

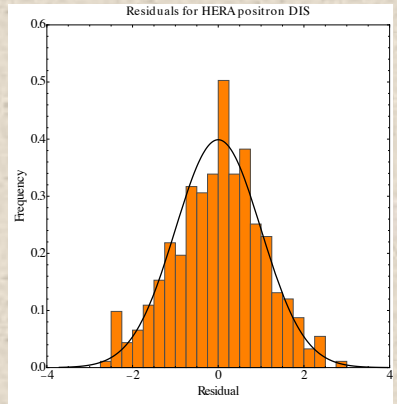
(See talk 15:36 in WG3+WG5 joint session)

CT10NNLO vs. fitted data



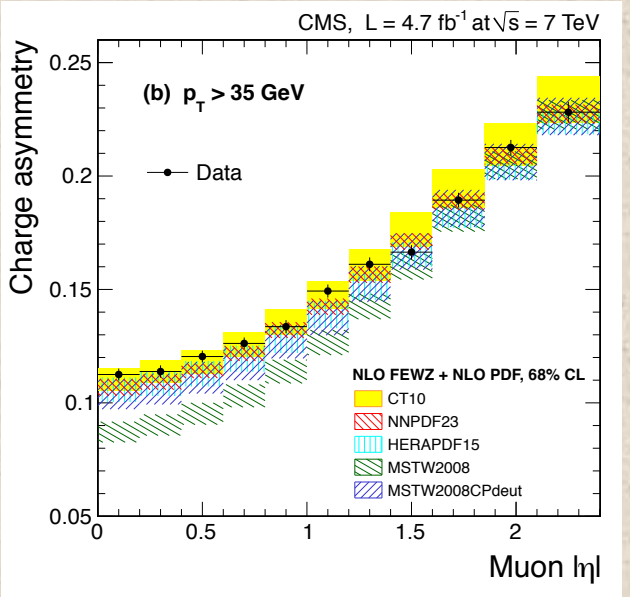


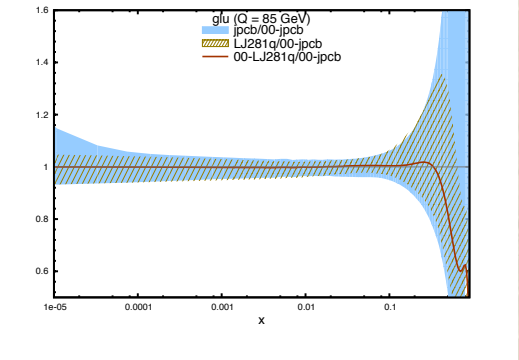


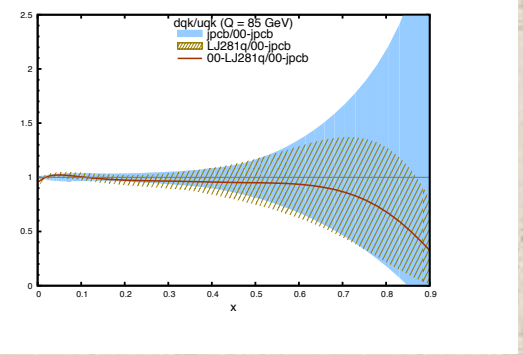


Fits well: $\chi^2/N_{pt} = 2950/2641 = 1.11$

CT10, CT1X, and LHC data



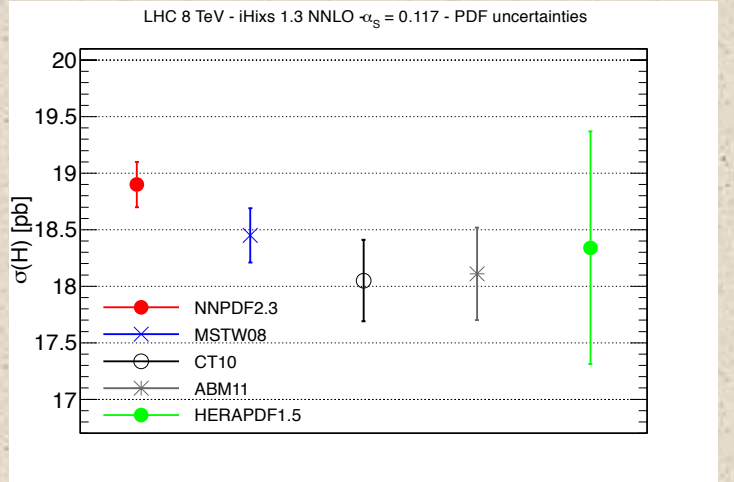




Sample new parametrizations

- We have since included early (7 TeV) LHC data: Atlas W/Z production and asymmetry at 7 TeV, Atlas single jet inclusive, CMS W asymmetry, HERA F_L and F_2^c
- More flexible parametrization – gluon, d/u at large x and both, d/u and dbar/ubar at small x, strangeness, and s - sbar.
- Improvements modest so far, but expectation from ttbar, W/Z, Higgs, etc.

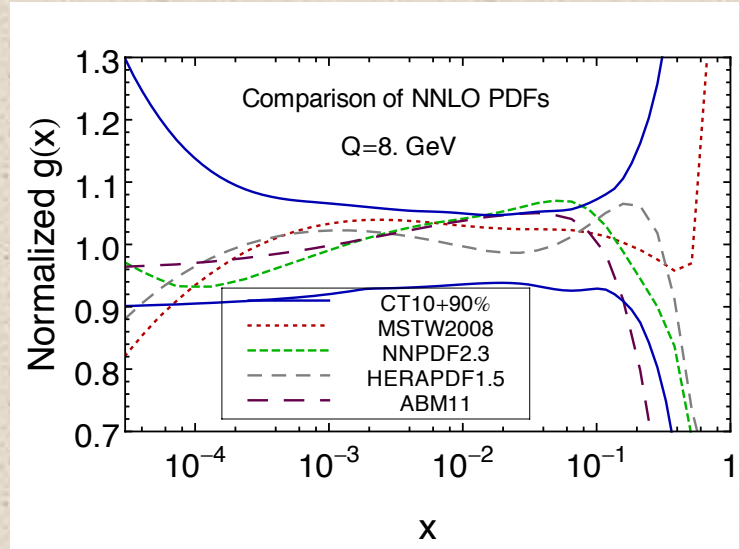
PDF Benchmarking and MetaPDFs



Benchmarking-

Ongoing study to compare and understand differences in PDF predictions at LHC

Ball et al, JHEP 1304 (2013) 125



MetaPDFs-

Combine different PDF groups in a Meta-PDF set, to compare systematic uncertainties

Gao and Nadolsky, arXiv:1401.0013[hep-ph]

Photon PDFs

1) Previous studies
   a) MRST Martin et al., EPJC 39 (2005) 155
      - Radiation off "primordial current quark" distributions
   b) NNPDF Ball et al., Nuc. Phys. B 877 (2013) 290
      - parametrized fit, predominantly constrained by W,Z,γ^* Drell-Yan
   c) Sadykov arXiv:1401.1133
      - photon evolution in QCDNum

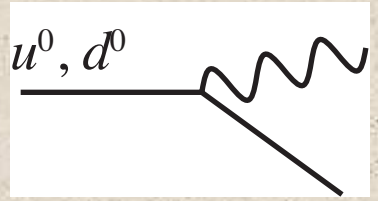
2) Photon evolution at LO in α and NLO in α_S currently implemented in CTEQ-TEA global analysis package
   a) Alternative parametrization approach
   b) Constrain with DIS + photon data

Photon PDF Parametrization

"Radiative ansatz" for initial Photon PDFs (generalization of MRST choice)

$$\gamma^p = \frac{\alpha}{2\pi}\left(A_u e_u^2 \tilde{P}_{\gamma q} \circ u^0 + A_d e_d^2 \tilde{P}_{\gamma q} \circ d^0\right)$$

$$\gamma^n = \frac{\alpha}{2\pi}\left(A_u e_u^2 \tilde{P}_{\gamma q} \circ d^0 + A_d e_d^2 \tilde{P}_{\gamma q} \circ u^0\right)$$



where u^0 and d^0 are "primordial" valence-type distributions of the proton.
Assumed approximate isospin symmetry for neutron.
Here, we take A_u and A_d as unknown fit parameters.

MRST choice: $A_q = \ln\left(Q_0^2 / m_q^2\right)$ "Radiation from **C**urrent **M**ass" – **CM**

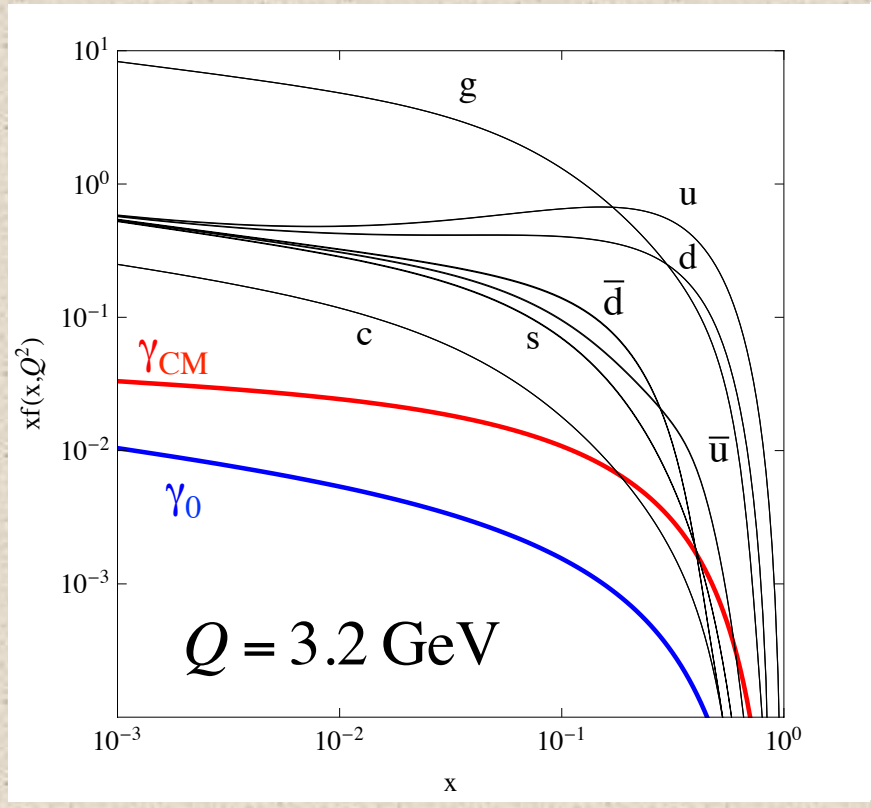
We use $u^0 = u^p \equiv u^p(x, Q_0), \quad d^0 = d^p \equiv d^p(x, Q_0)$
and reduce the number of parameters further (for initial study) by setting

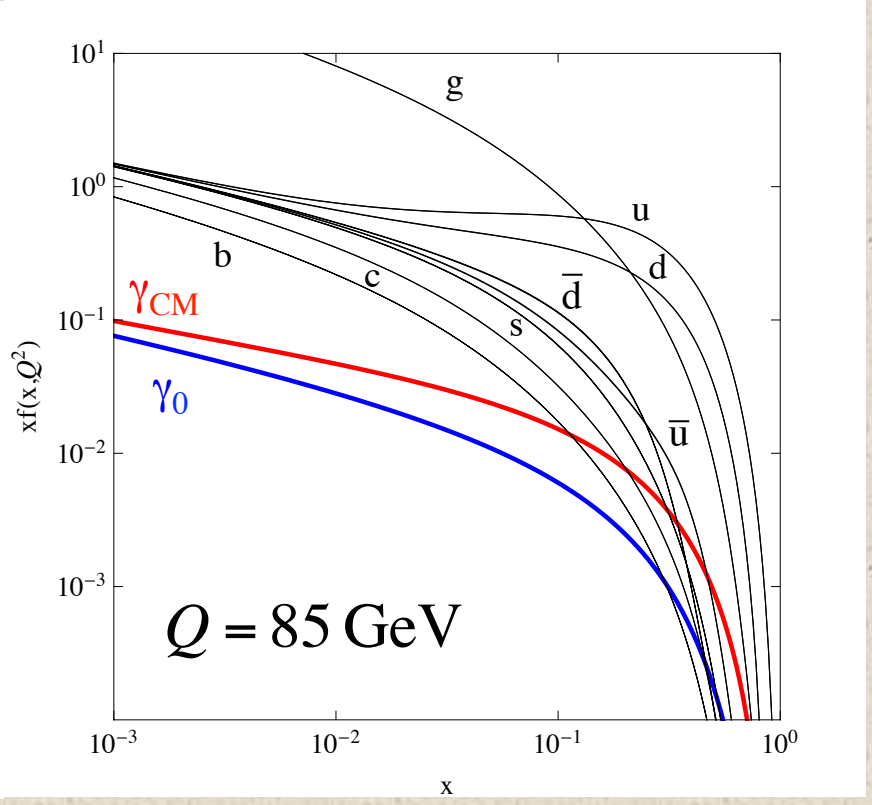
$$A_u = A_d = A_0$$

Now everything effectively specified by one unknown parameter:

$$A_0 \Leftrightarrow p_0^\gamma \equiv p^{\gamma/P}(Q_0)$$ (Initial Photon momentum fraction)

Photon PDFs (in proton)





γ momentum fraction:

$p^{\gamma}(Q)$	$\gamma(x,Q_0)=0$	$\gamma(x,Q_0)_{CM}$
$Q = 3.2$ GeV	0.05%	0.34%
$Q = 85$ GeV	0.22%	0.51%

Photon PDF can be larger than sea quarks at large x!

← Initial Photon PDF still significant at large Q.

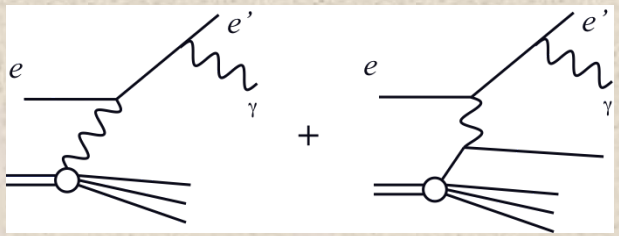
Constraining Photon PDFs

1) Global fitting
   - Isospin violation, momentum sum rule lead to constraints in fit
   - We find p_0^γ can be as large as ~ 5% at 90%CL, much more than **CM** choice

2) Direct photon PDF probe
   - DIS with observed photon, $ep \to e\gamma + X$
   - Photon-initiated subprocess contributes at LO, and no larger background with which to compete
   - But must include quark-initiated contributions consistently
   - Treat as NLO in α, but discard small corrections, suppressed by $\alpha\,\gamma(x)$.

$ep \rightarrow e\gamma + X$

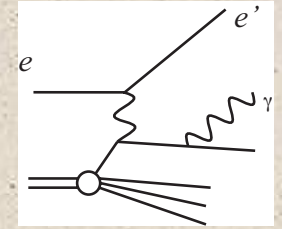
Subprocess contributions:



LL Emission off Lepton line

Both quark-initiated and photon-initiated contributions are $\sim \alpha^3$ if $\gamma(x) \sim \alpha$

Collinear divergence cancels (in d=4-2ε) by treating as NLO in α with $\gamma^{\text{bare}}(x) = \gamma(x) + \frac{(4\pi)^{\varepsilon}}{\varepsilon}\Gamma(1+\varepsilon)\frac{\alpha}{2\pi}\left(P_{\gamma q} \circ q\right)(x)$ (MSbar)



QQ Emission off Quark line

Has final-state quark-photon collinear singularity

QL Interference term

Negligible < about 1% (but still included)

Previous calculations:

quark-initiated only – (GGP) Gehrmann-De Ridder, Gehrmann, Poulson, PRL 96, 132002 (2006)

photon initiated only – (MRST), Martin, Roberts, Stirling, Thorne, Eur. Phys. J. C 39, 155 (2005)

Zeus Experimental Cuts

Photon Cuts

$4\ \text{GeV} < E_T^\gamma < 15\ \text{GeV}$

$-0.7 < \eta^\gamma < 0.9$

Lepton Cuts

$E_{\ell'} > 10\ \text{GeV}$

$139.8° < \theta_{\ell'} < 171.8°$

$10\ \text{GeV}^2 < Q^2 < 350\ \text{GeV}^2$

Photon Isolation Cut

Photon must contain 90% of energy in jet to which it belongs.

Also require N ≥ 1 forward jet

Two theoretical approximations to photon isolation implemented:

1) Smooth isolation (Frixione): $E_{q'} < \frac{1}{9} E_\gamma \left(\frac{1-\cos r}{1-\cos R} \right)$ for $r = \sqrt{\Delta\eta_{q'\gamma}^2 + \Delta\varphi_{q'\gamma}^2} < R = 1$

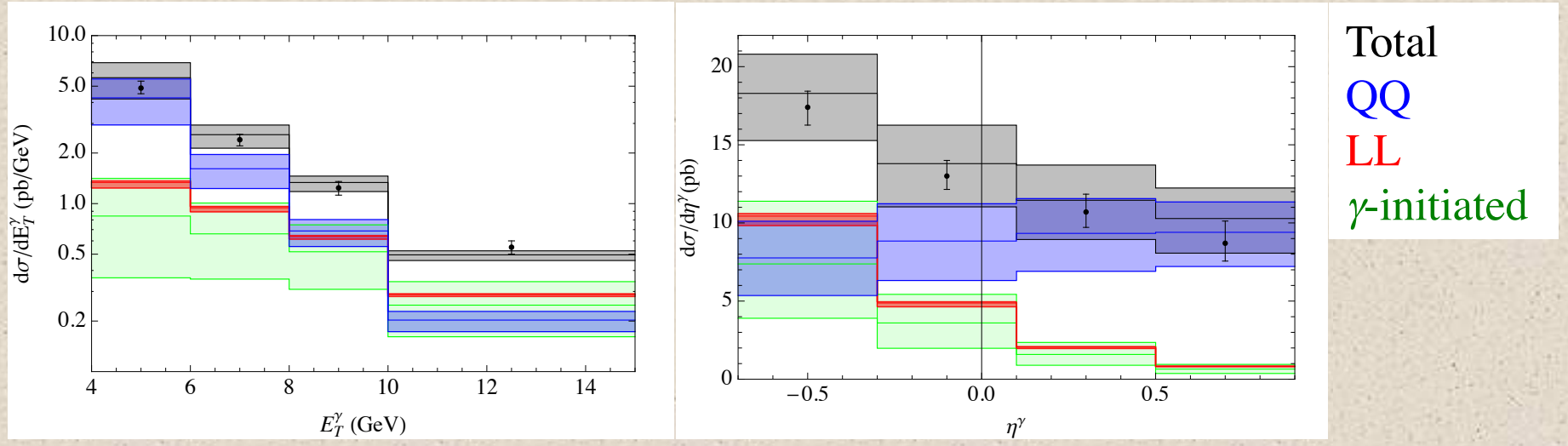
   - Removes fragmentation contribution

2) Sharp isolation: $E_{q'} < \frac{1}{9} E_\gamma$ for $r < R = 1$

   - Requires fragmentation contribution
     (Use Aleph LO parametrization)

Theoretical Uncertainties

1) Factorization Scale

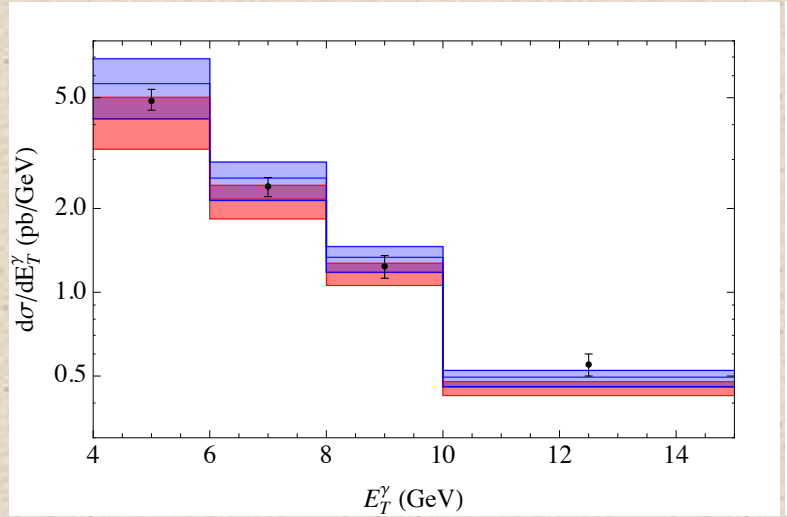


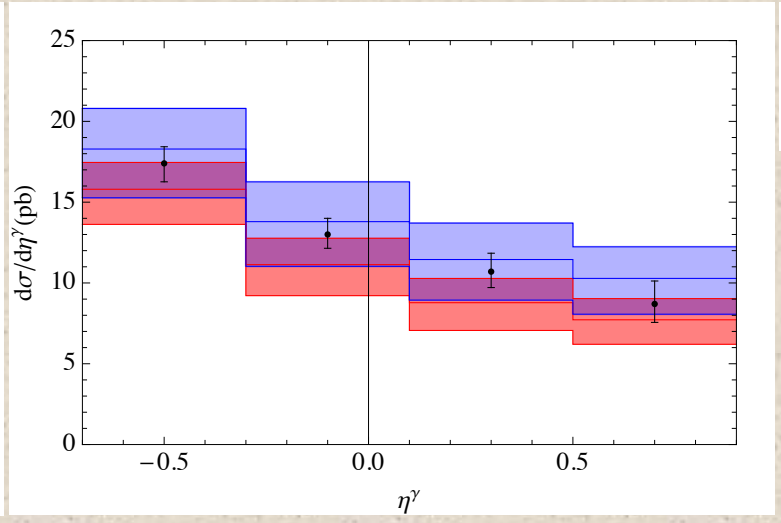
($p_0^\gamma = 0$, Smooth Isolation, $0.5E_T^\gamma < \mu_F < 2E_T^\gamma$)

- Scale dependence of LL contribution reduced drastically compared to photon-initiated alone
- QQ and LL have different-shaped distributions. LL dominates at large E_T^γ and small η^γ . Can be used to extract photon PDF
- Scale dependence of QQ and total is still large (LO in α_S)

Theoretical Uncertainties

2) Isolation Prescription





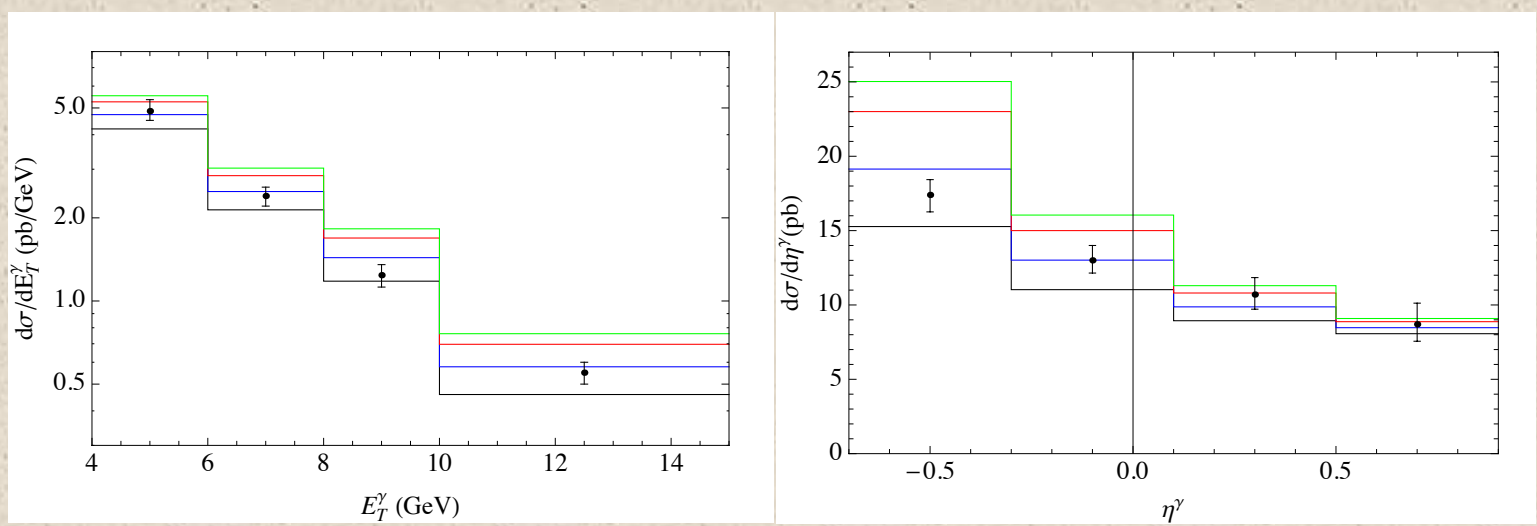
Smooth
Sharp

$$(p_0^\gamma = 0 , \ 0.5 E_{T\gamma} < \mu_F < 2 E_{T\gamma})$$

- Difference between two isolation prescriptions is about same size as scale uncertainty
- Smooth prescription gives larger predictions. In principle, should give smaller.
- Uncertainty in fragmentation function, and higher order effects in both prescriptions are major sources of difference.
- Use both prescriptions as measure of uncertainty in prediction.

Distributions

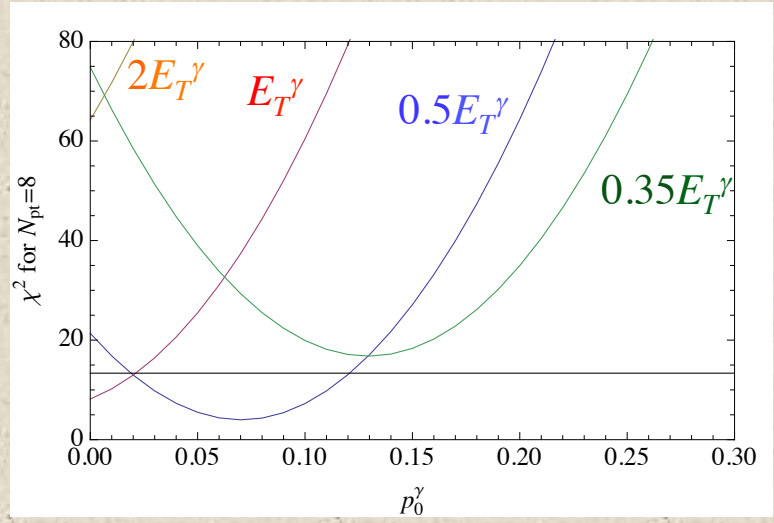
1) Photon Variables E_T^γ and η^γ



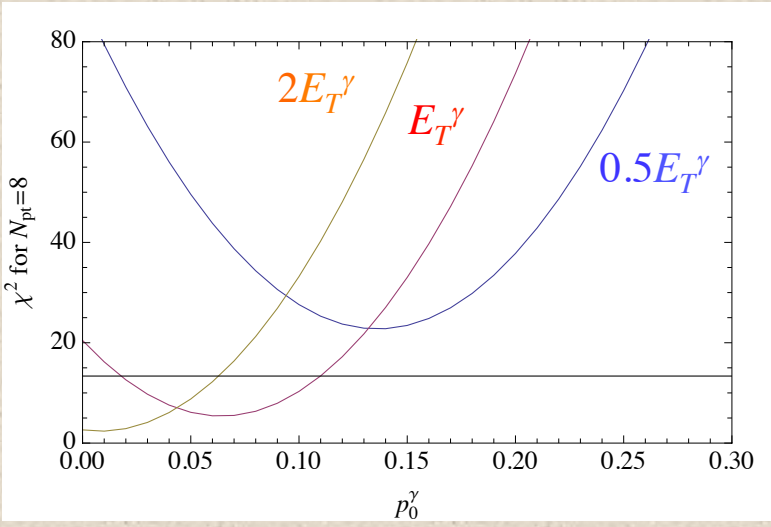
(Smooth Isolation, $\mu_F = 0.5 E_T^\gamma$)

- Best fit for p_0^γ is correlated with choice of isolation and factorization scale μ_F.
- Can obtain excellent fit to shape of distributions for reasonable scale choices.
- "Current Mass" ansatz cannot fit shape (prediction too large at large E_T^γ and small η^γ where LL dominates), regardless of scale choice.

Limits on Photon PDF



Smooth Isolation



Sharp Isolation

- Different χ^2 curves for choice of isolation and scale μ_F
- 90% C.L. for $N_{pt} = 8$ corresponds to $\chi^2 = 13.36$
- Obtain $p_0^\gamma \leq 0.14\%$ at 90 % C.L. independent of isolation prescription

  (More generally, constrains $\gamma(x)$ for $10^{-3} < x < 2\times10^{-2}$.)
- "Current Mass" ansatz has $\chi^2 > 45$ for any choice of isolation and scale

Conclusions

- CT1X update in progress
  - New LHC data, New parametrizations, …

- Other CTEQ-TEA activities
  - Benchmarking, MetaPDFs
  - Intrinsic Charm, Lagrange Multiplier uncertainties in Higgs, ttbar (this afternoon)

- Photon PDF
  - Strong constraint from $ep \to e\gamma + X$
  - $p_0^\gamma \leq 0.14\%$ at 90 % C.L. for radiative photon ansatz.

  - Consistent with NNPDF Drell-Yan analysis:

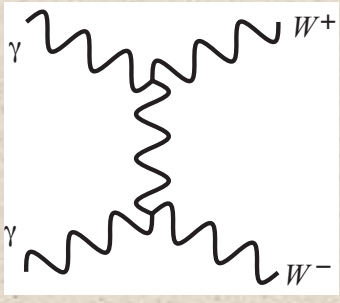
    Photon PDF smaller than expected?

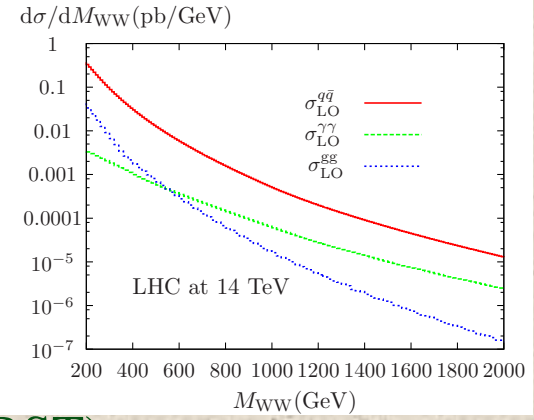
Backup Slides

Motivation

1) Sensitivity to NNLO QCD is at few % level.
   - QED and Electroweak corrections are now significant.
   - E.g, QED corrections to $pp \to W + X$ require order α effects in parton evolution
2) Photon induced processes can be kinematically enhanced.

$$\gamma\gamma \to W^+W^- \quad \text{asymptotically} \quad \hat{\sigma}_{\gamma\gamma} \approx 8\pi\alpha^2 / M_W^2$$





Bierweiler et al., JHEP 1211 (2012) 093

3) Last considered in 2004 (MRST) Martin et al., EPJC 39 (2005) 155.
   - Time for more detailed study.

This talk is an update of CTEQ-TEA activities on this topic.

Inclusion of Photon PDFs

LO QED + (NLO or NNLO) QCD evolution:

$$\frac{dq}{dt} = \frac{\alpha_s}{2\pi}\left(P_{qq} \circ q + P_{qg} \circ g\right) + \frac{\alpha}{2\pi}\left(e_q^2 \tilde{P}_{qq} \circ q + e_q^2 \tilde{P}_{q\gamma} \circ \gamma\right)$$

$$\frac{dg}{dt} = \frac{\alpha_s}{2\pi}\left(P_{gg} \circ g + P_{gq} \circ \sum (q + \bar{q})\right) \qquad t = \ln Q^2$$

$$\frac{d\gamma}{dt} = \frac{\alpha}{2\pi}\left(\tilde{P}_{\gamma\gamma} \circ \gamma + \tilde{P}_{\gamma q} \circ \sum e_q^2 (q + \bar{q})\right)$$

"Radiative ansatz" for initial Photon PDFs (generalization of MRST choice)

$$\gamma^p = \frac{\alpha}{2\pi}\left(A_u e_u^2 \tilde{P}_{\gamma q} \circ u^0 + A_d e_d^2 \tilde{P}_{\gamma q} \circ d^0\right)$$

$$\gamma^n = \frac{\alpha}{2\pi}\left(A_u e_u^2 \tilde{P}_{\gamma q} \circ d^0 + A_d e_d^2 \tilde{P}_{\gamma q} \circ u^0\right)$$

where u^0 and d^0 are "primordial" valence-type distributions of the proton.
Assumed approximate isospin symmetry for neutron.
Here, we take A_u and A_d as unknown fit parameters.

MRST choice: $A_q = \ln\left(Q_0^2 / m_q^2\right)$ "Radiation from **C**urrent **M**ass" - **CM**

Inclusion of Photon PDFs (2)

Isospin violation occurs radiatively in u and d. To this order in α:

$$u^n = d^p + \frac{\alpha}{2\pi}\left(A_u e_u^2 - A_d e_d^2\right)\tilde{P}_{qq} \circ d^0 \quad , \quad d^n = u^p + \frac{\alpha}{2\pi}\left(A_d e_d^2 - A_u e_u^2\right)\tilde{P}_{qq} \circ u^0$$

Isospin violation in initial sea and gluon assumed negligible. $\left(\bar{q}^n = \bar{q}^p, g^n = g^p\right)$

With this ansatz, number and momentum sum rules automatically satisfied for neutron, <u>for any choice of</u> u^0 and d^0 .

i.e., $\sum p^{i/P} = 1 \quad \Rightarrow \quad \sum p^{i/N} = 1$, where $p^{i/h} = \int_0^1 x\, f_{i/h}(x)\, dx$

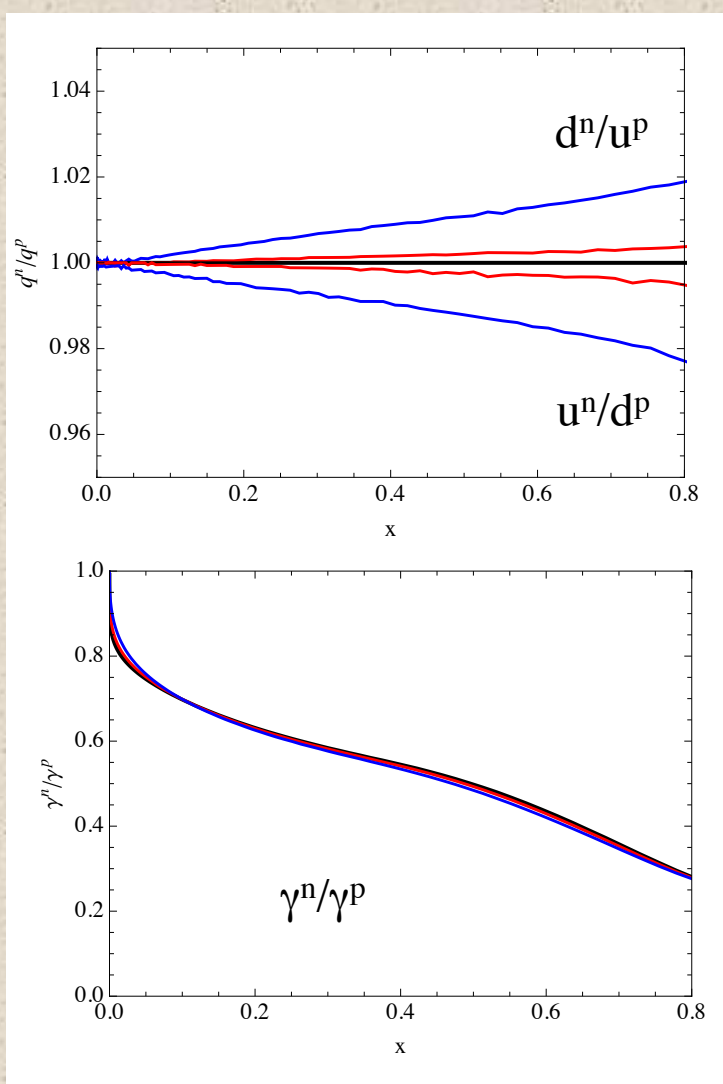
Here, assume $u^0 = u^p \equiv u^p(x, Q_0), \quad d^0 = d^p \equiv d^p(x, Q_0)$

Also, let $A_u = A_0\left(1+\delta\right), \quad A_d = A_0\left(1-\delta\right)$
Expect δ to be small.

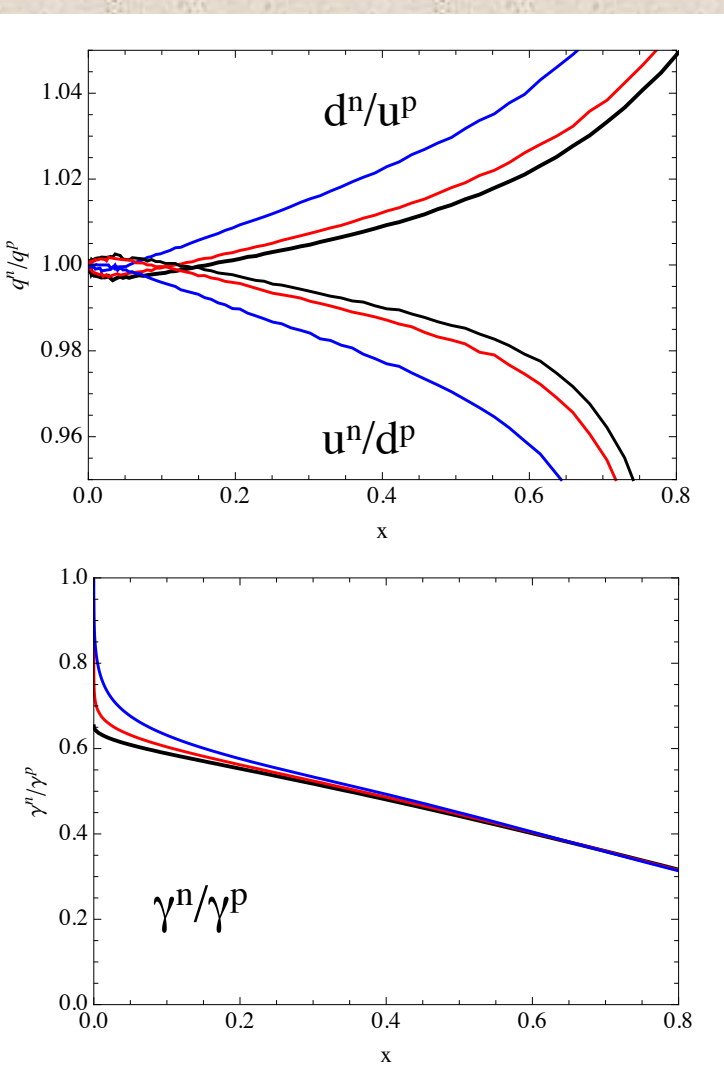
Now everything effectively specified by one unknown parameter:

$$A_0 \Leftrightarrow p_0^\gamma \equiv p^{\gamma/P}(Q_0)$$ (Initial Photon momentum fraction)

Isospin violation



$\gamma\left(x,Q_0^2\right)=0$



$\gamma\left(x,Q_0^2\right)_{\mathrm{CM}}$

$Q=Q_0=1.3$ GeV
Q=3.2 GeV
Q=85 GeV

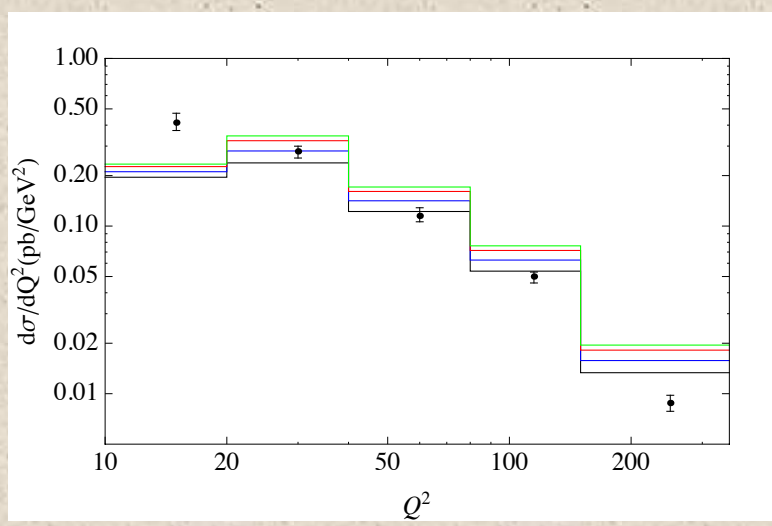
Constraints on Photon PDFs

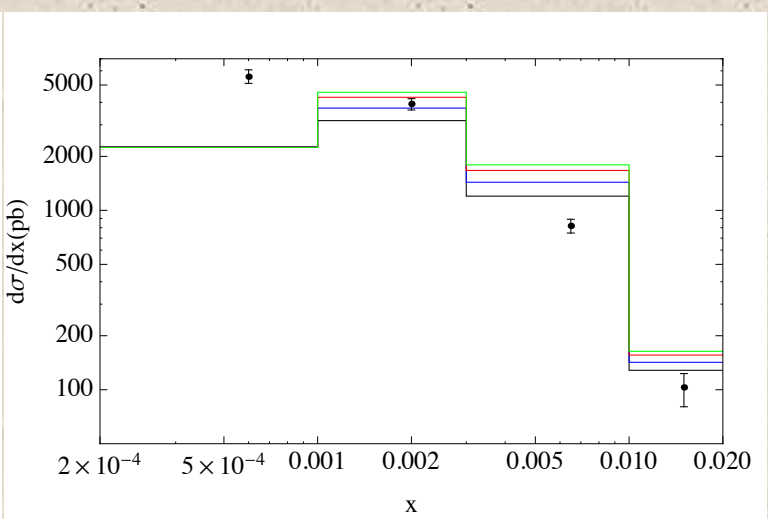
1) Global fitting
   a. Isospin violation effects
      - come from scattering off nuclei
      - perturbativity cuts on W^2 generally require $x < .2$-$.4$
      - constraints likely to be small (MRST)
   b. Momentum sum rule
      - momentum carried by photon leaves less for other partons
      - constrains momentum fraction of photon (upper bound)
   c. Otherwise, $O(\alpha)$ corrections to hadronic processes are small
   d. Global fit finds p_0^γ can be as large as $\sim 5\%$, much more than **CM** choice

2) Direct photon PDF probe
   - DIS with observed photon, $ep \to e\gamma + X$
   - Photon-initated subprocess contributes at LO !

Distributions

2) Lepton Variables Q^2 and x





$p_0^\gamma = p_0^\gamma$ (cm) $= 0.29$ %

$p_0^\gamma = 0.2$ %

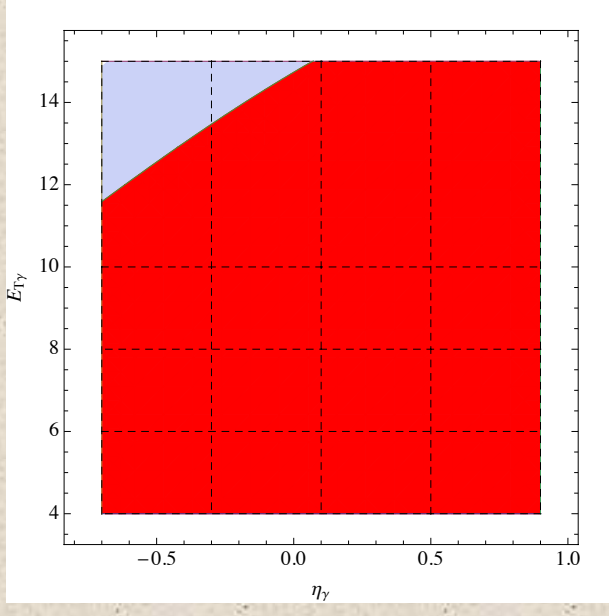
$p_0^\gamma = 0.1$ %

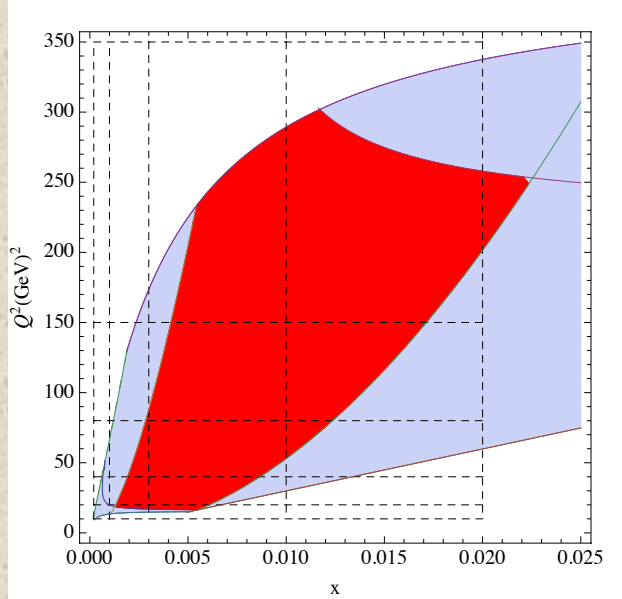
$p_0^\gamma = 0.0$ %

(Smooth Isolation, $\mu_F = 0.5 E_T^\gamma$)

- Cannot fit shape for any choice of isolation, scale, or p_0^γ.
- Q^2 and x distributions more sensitive to higher order corrections.
  (Small Q^2 and x, in particular will receive contributions from more radiation.)
- Additional cuts on E_T^γ and η^γ make Q^2 and x distributions less inclusive.

Kinematic Phase Space





Photon Cuts

$4\ \text{GeV} < E_T^\gamma < 15\ \text{GeV}$

$-0.7 < \eta^\gamma < 0.9$

Lepton Cuts

$E_{\ell'} > 10\ \text{GeV}$

$139.8° < \theta_{\ell'} < 171.8°$

$10\ \text{GeV}^2 < Q^2 < 350\ \text{GeV}^2$

- Dashed lines show kinematic bins
- Red region allowed for "photon + lepton + 0 additional partons"
  (LO photon-initiated kinematics)
- Red plus Blue region allowed for "photon + lepton + anything"
- Q^2 and x distributions more affected by additional photon cuts.
- Smallest x bin requires ≥1 extra parton to satisfy cuts.

Use only E_t^γ and η^γ distributions to constrain photon PDF