CT10 NNLO update and QED effects in PDFs

Carl Schmidt
Michigan State University

On behalf of CTEQ-TEA group

April 29, 2014
DIS2014, Warsaw, Poland
Outline

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

2) Benchmark Studies
   and MetaPDFs  
   Ball et al, JHEP 1304 (2013) 125

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

Also –

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

Uncertainty Analysis on $gg \rightarrow H$ and $gg \rightarrow t\bar{t}b$
   (See talk 15:36 in WG3+WG5 joint session)
Fits well: $\chi^2 / N_{pt} = 2950 / 2641 = 1.11$
**CT10, CT1X, and LHC data**

- 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.

Sample new parametrizations
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

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 $W, Z, \gamma^* \text{Drell-Yan}$
   c) Sadykov  arXiv:1401.1133
      - photon evolution in QCDNum

2) Photon evolution at LO in $\alpha$ and NLO in $\alpha_s$ 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: \( A_q = \ln \left( \frac{Q_0^2}{m_q^2} \right) \) “Radiation from Current Mass” – CM

We use \( u^0 = u^p \equiv u^p(x,Q_0) \), \( d^0 = d^p \equiv d^p(x,Q_0) \) 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:

\[
A_0 \Leftrightarrow p_0^\gamma \equiv p^{\gamma/p}(Q_0) \quad \text{(Initial Photon momentum fraction)}
\]
Photon PDFs (in proton)

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

Initial Photon PDF still significant at large $Q$.

<table>
<thead>
<tr>
<th>$p^\gamma(Q)$</th>
<th>$\gamma(x,Q_0) = 0$</th>
<th>$\gamma(x,Q_0)_{CM}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q = 3.2 \text{ GeV}$</td>
<td>0.05%</td>
<td>0.34%</td>
</tr>
<tr>
<td>$Q = 85 \text{ GeV}$</td>
<td>0.22%</td>
<td>0.51%</td>
</tr>
</tbody>
</table>
Constraining Photon PDFs

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

2) Direct photon PDF probe
   - DIS with observed photon, $ep \rightarrow e\gamma + X$
   - 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 $\alpha$, but discard small corrections, suppressed by $\alpha \gamma(x)$. 
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 \( d=4-2\epsilon \)) by treating as NLO in \( \alpha \) with
\[
\gamma^{\text{bare}}(x) = \gamma(x) + \left( \frac{4\pi}{\epsilon} \Gamma(1+\epsilon) \right) \frac{\alpha}{2\pi} \left( P_{\gamma q} \circ q \right)(x)
\] (MSbar)

**QQ** Emission off Quark line
Has final-state quark-photon collinear singularity

**QL** Interference term
Negligible < about 1% (but still included)

Previous calculations:
**Zeus Experimental Cuts**

<table>
<thead>
<tr>
<th>Photon Cuts</th>
<th>Lepton Cuts</th>
<th>Photon Isolation Cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>$4 \text{ GeV} &lt; E_T^\gamma &lt; 15 \text{ GeV}$</td>
<td>$E_\ell &gt; 10 \text{ GeV}$</td>
<td>Photon must contain 90% of energy in jet to which it belongs.</td>
</tr>
<tr>
<td>$-0.7 &lt; \eta^\gamma &lt; 0.9$</td>
<td>$139.8^\circ &lt; \theta_\ell &lt; 171.8^\circ$</td>
<td></td>
</tr>
<tr>
<td>$10 \text{ GeV}^2 &lt; Q^2 &lt; 350 \text{ GeV}^2$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Also require $N \geq 1$ forward jet

Two theoretical approximations to photon isolation implemented:

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

   - Removes fragmentation contribution

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

   - Requires fragmentation contribution

(Use Aleph LO parametrization)
Theoretical Uncertainties

1) Factorization Scale

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

$\left( p_0^\gamma = 0, \text{ Smooth Isolation, } 0.5E_T^\gamma < \mu_F < 2E_T^\gamma \right)$
Theoretical Uncertainties

2) Isolation Prescription

- 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.

\[
(p_0^\gamma = 0, \ 0.5E_T^\gamma < \mu_F < 2E_T^\gamma)
\]
Distributions

1) Photon Variables $E_T^\gamma$ and $\eta^\gamma$

- Best fit for $p_0^\gamma$ is correlated with choice of isolation and factorization scale $\mu_F$.
- Can obtain excellent fit to shape of distributions for reasonable scale choices.
- “Current Mass” ansatz cannot fit shape (prediction too large at large $E_T^\gamma$ and small $\eta^\gamma$ where LL dominates), regardless of scale choice.

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

\[
p_0^\gamma = p_0^\gamma \text{ (cm)} = 0.29 \%
\]
\[
p_0^\gamma = 0.2 \%
\]
\[
p_0^\gamma = 0.1 \%
\]
\[
p_0^\gamma = 0.0 \%
\]
Limits on Photon PDF

- Different $\chi^2$ curves for choice of isolation and scale $\mu_F$
- 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 $10^{-3} < x < 2 \times 10^{-2}$.)

- “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 $ep \rightarrow e\gamma + X$
  - $p_0^{\gamma} \leq 0.14\%$ 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 $pp \rightarrow W + X$ require order $\alpha$ effects in parton evolution

2) Photon induced processes can be kinematically enhanced.
   \[ \gamma\gamma \rightarrow W^+W^- \] asymptotically \[ \hat{\sigma}_{\gamma\gamma} \approx \frac{8\pi\alpha^2}{M_W^2} \]

   - 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:

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

\[
\frac{dg}{dt} = \frac{\alpha_s}{2\pi} \left( P_{gg} \circ g + P_{qg} \circ \sum(q + \bar{q}) \right)
\]

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

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

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

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

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 Current Mass” - CM
Inclusion of Photon PDFs (2)

Isospin violation occurs radiatively in u and d. To this order in $\alpha$:

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

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

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

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

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

Also, let \( A_u = A_0 (1 + \delta) , \quad A_d = A_0 (1 - \delta) \)

Expect $\delta$ to be small.

Now everything effectively specified by one unknown parameter:

\[ A_0 \iff p^\gamma_0 \equiv p^{\gamma/p}(Q_0) \quad \text{(Initial Photon momentum fraction)} \]
Isospin violation

\[ \gamma(x, Q_0^2) = 0 \]

\[ Q = Q_0 = 1.3 \text{ GeV} \]

\[ Q = 3.2 \text{ GeV} \]

\[ Q = 85 \text{ GeV} \]
**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 $p_0^\gamma$ can be as large as $\sim 5\%$, much more than CM choice

2) Direct photon PDF probe
   - DIS with observed photon, $ep \rightarrow e\gamma + X$
   - Photon-initiated subprocess contributes at LO!
2) Lepton Variables $Q^2$ and $x$

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

- Cannot fit shape for any choice of isolation, scale, or $p_0^\gamma$.
- $Q^2$ 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 $E_T^\gamma$ and $\eta^\gamma$ make $Q^2$ and $x$ distributions less inclusive.
Kinematic Phase Space

- 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 $\geq 1$ extra parton to satisfy cuts.

Use only $E_T^\gamma$ and $\eta^\gamma$ distributions to constrain photon PDF

Photon Cuts
4 GeV $< E_T^\gamma < 15$ GeV
-0.7 $< \eta^\gamma < 0.9$

Lepton Cuts
$E_\ell^\gamma > 10$ GeV
139.8° $< \theta_\ell^\gamma < 171.8°$
10 GeV$^2 < Q^2 < 350$ GeV$^2$