Beyond CT14: Hera II data and new interpretation of CT14QED photon

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On behalf of the CTEQ-TEA group

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CTEQ-TEA group

- CTEQ – Tung et al. (TEA)

  in memory of Prof. Wu-Ki Tung,
  who established CTEQ Collaboration in early 90's

- Current members of CTEQ-TEA group:

  Sayipjamal Dulat (Xinjiang U.),
  Tie-Jiun Hou, Pavel Nadolsky (Southern Methodist U.),
  Jun Gao (Argonne Nat. Lab.),
  Marco Guzzi (U. of Manchester),
  Joey Huston, Jon Pumplin, Dan Stump, CS, C.-P.Yuan (Michigan State U.)

Outline

- Brief overview of CT14 global analysis

  Dulat et al, ArXiv:1506.07433[hep-ph]

- Impact of HERA I + II data on CT PDF analysis:

  CT14HERA2

- New interpretation of CT14QED photon PDFs and CMS data:

  CT14QED (CS et al, arXiv:1509.02905[hep-ph])

- Conclusions

Overview of CT14 analysis

- CT10 includes only pre-LHC data
- CT14 is the first CT analysis including LHC Run 1 data
- CT14 also includes the new Tevatron D0 Run 2 data on W-electron charge asymmetry
- CT14 uses a more flexible parametrization in the non-perturbative PDFs.
- We have published its results at NNLO, NLO and LO.

Produce 90% C.L. error PDF sets from Hessian method, scaled by 1/1.645 to obtain 68% C.L. eigenvector sets.
For NNLO, Chi^2/d.o.f is about 1.1 for about 3000 data points included in the fits.

Experimental Data for CT14

- Based on CT10 data set, but updated with new HERA F_L and F_2^c, and dropped Tevatron Run 1 CDF and D0 inclusive jet
- Included some LHC Run 1 (at 7 TeV) data:
  ATLAS and LHCb W/Z production,
  ATLAS, CMS and LHCb W-lepton charge asymmetry,
  ATLAS and CMS inclusive jet
- Replace old by new D0 (9.7 1/fb) W-electron rapidity asymmetry data

Theory Analysis in CT14

- CT14 has 26 shape parameters, plus four extreme sets for describing s- and g-PDFs in small-x region. In comparison, CT10 has 24 shape parameters, plus two extreme sets for describing g-PDFs in small-x region.

- More flexible parametrization – gluon, d/u at large x, and both d/u and dbar/ubar at small x, strangeness (assuming sbar = s)

- Non-perturbative parametrization form:

$$x\, f_a(x) = x^{a_1}\,(1-x)^{a_2}\,P_a(x)$$

where $P_a(x)$ is expressed as a linear combination of Bernstein polynomials to reduce the correlation among its coefficients.

Theory Analysis in CT14

- Choose experimental data with $Q^2 > 4$ GeV^2 and $W^2 > 12.5$ GeV^2 to minimize higher-twist, nuclear correction, etc., and focus on perturbative QCD predictions.
- PDFs are parametrized at Q=1.3 GeV.
- Take $\alpha_s(Mz) = 0.118$, but also provide α_s-series PDFs.
- Use s-ACOT-χ prescription for heavy quark partons, and take pole mass M_c =1.3 GeV and M_b=4.75 GeV
- NNLO calculations for DIS, DY, W, Z, except jet (at NLO).
- Correlated systematic errors are taken into account.
- Check Hessian method results by Lagrangian Multiplier method which does not assume quadratic approximation in chi-square.

Impact of HERA I + II data on CT PDF analysis:

CT14HERA2

PDF parametrization in CT14HERA2

- Use the CT14 PDF functional forms at initial scale Q_0.

$$x\, f_a(x, Q_0) = x^{a_1} (1-x)^{a_2} P_a(x)$$

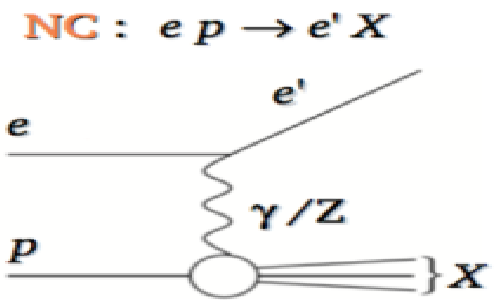
Except:

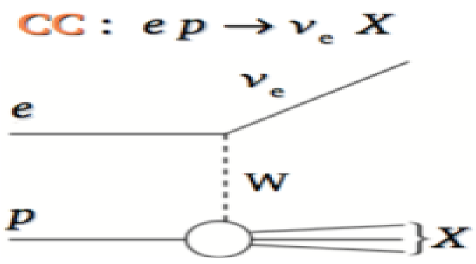
- CT14HERA2 has 27 shape parameters, plus two extreme sets for describing g-PDF in small-x region. In comparison, CT14 has 26 shape parameters, plus four extreme sets for describing s- and g-PDFs in small-x region.

- Add one more shape parameter (in total 3) for describing s-PDF. ($a_1(s)=a_1(\bar{s})$ no longer tied to $a_1(\bar{u}) = a_1(\bar{d})$.)

HERA I+II data

- H1 and ZEUS experiments at HERA for neutral current and charged current e^+p, e^-p scattering collected ~1/fb of data.
- E_p = 920, 820, 575 and 460 GeV and E_e = 27.5 GeV.





arXiv:1506.06042

Cross sections for NC interactions have been published for

$0.045 < Q^2 < 50000$ GeV^2 $\quad 6.\,10^{-7} < x_{Bj} < 0.65$

Cross sections for CC interactions have been published for

$$200 \leq Q^2 \leq 50000\,\mathrm{GeV}^2 \text{ and } 1.3 \cdot 10^{-2} \leq x_{\mathrm{Bj}} \leq 0.40$$

- HERAI+II data has 1120 data points with
  - $Q^2 > 4\ GeV^2$ and $W^2 > 12.5\ GeV^2$,
  - 162 correlated systematic errors,
  - 7 procedural uncertainties;
  - separated into four sets, depending on whether e+ or e- beam, neutral or charged current, at various collider energies.

- HERA-1 data has 579 data points with
  - $Q^2 > 4\ GeV^2$ and $W^2 > 12.5\ GeV^2$,
  - 110 correlated systematic errors,
  - 4 procedural uncertainties.

- CT14 with HERA1 has about 3000 data points.

  After replacing the HERA I with HERA I+II data, there are about 3300 data points in total, in which we have removed NMC muon-proton data (ID=106, with 201 data points). Its chi^2/npt is about 1.85 in CT14 fit.

Impact of the HERAI +II data on the fit

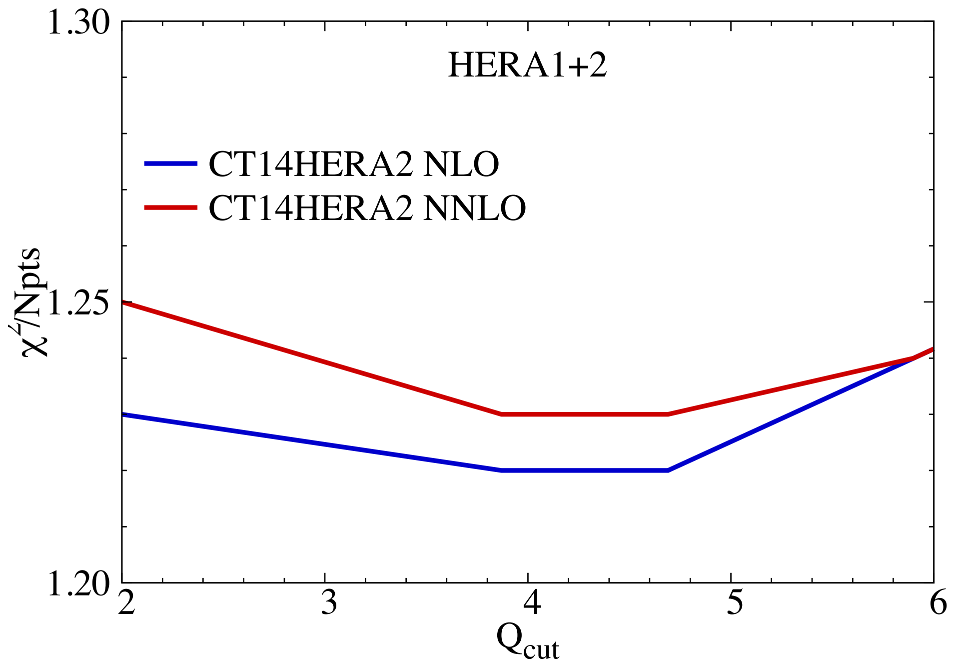
Summary of the chi2 values for the HERA run I and HERA1+2 measurements in both CT14 and CT14HERA1+2 fits

	$\chi^2_{\mathrm{HERA\ I}}$; N_{pts} : 579	$\chi^2_{\mathrm{HERA1+2}}$; N_{pts} : 1120
CT14NLO	590 (1.02)	1402
CT14NNLO	591 (1.02)	1471
CT14HERA1+2(NLO)	597	1374 (1.23)
CT14HERA1+2((NNLO)	610	1403 (1.25)

NNLO vs. NLO fits and impact of Q cut

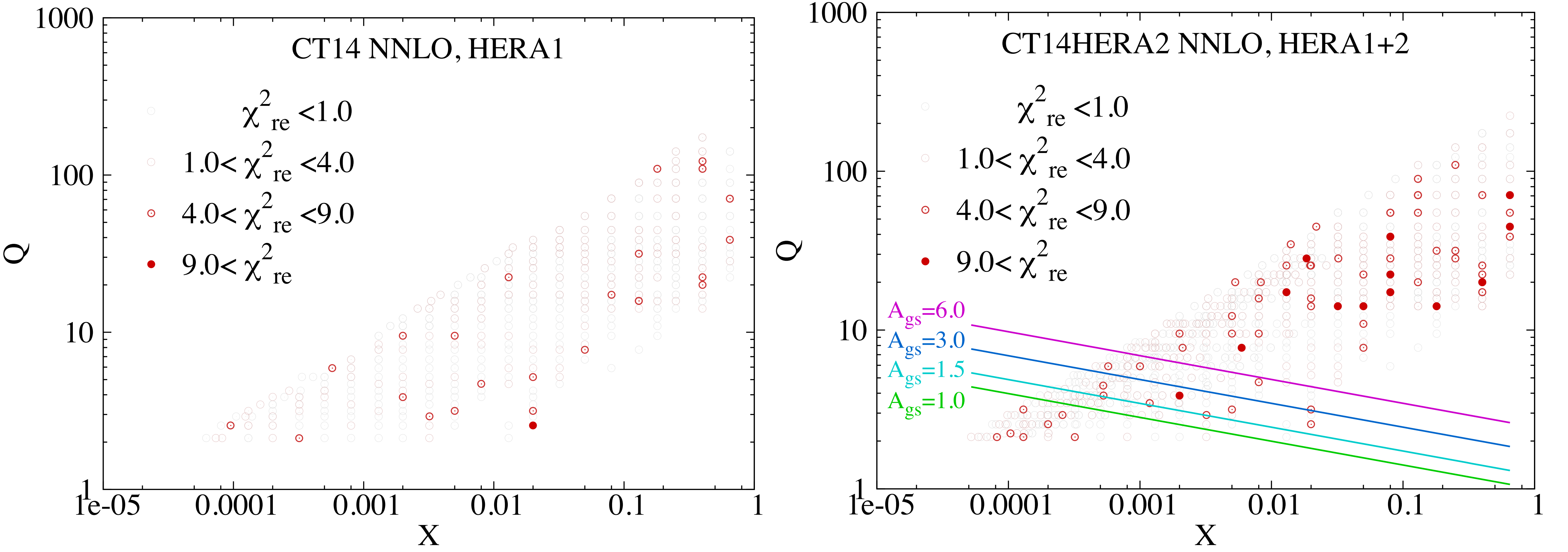
1.25 for NNLO fit

1.23 for NLO fit



- Our nominal Q cut is 2 GeV.
- Chi^2/Npts increases above Qcut=5 GeV and below 2 GeV.
- NNLO fit is slightly worse than NLO fit

The distribution of the χ^2-residuals of HERA I and HERA2 ensembles in the (x, Q) plane for the CT14Hera2 fit.

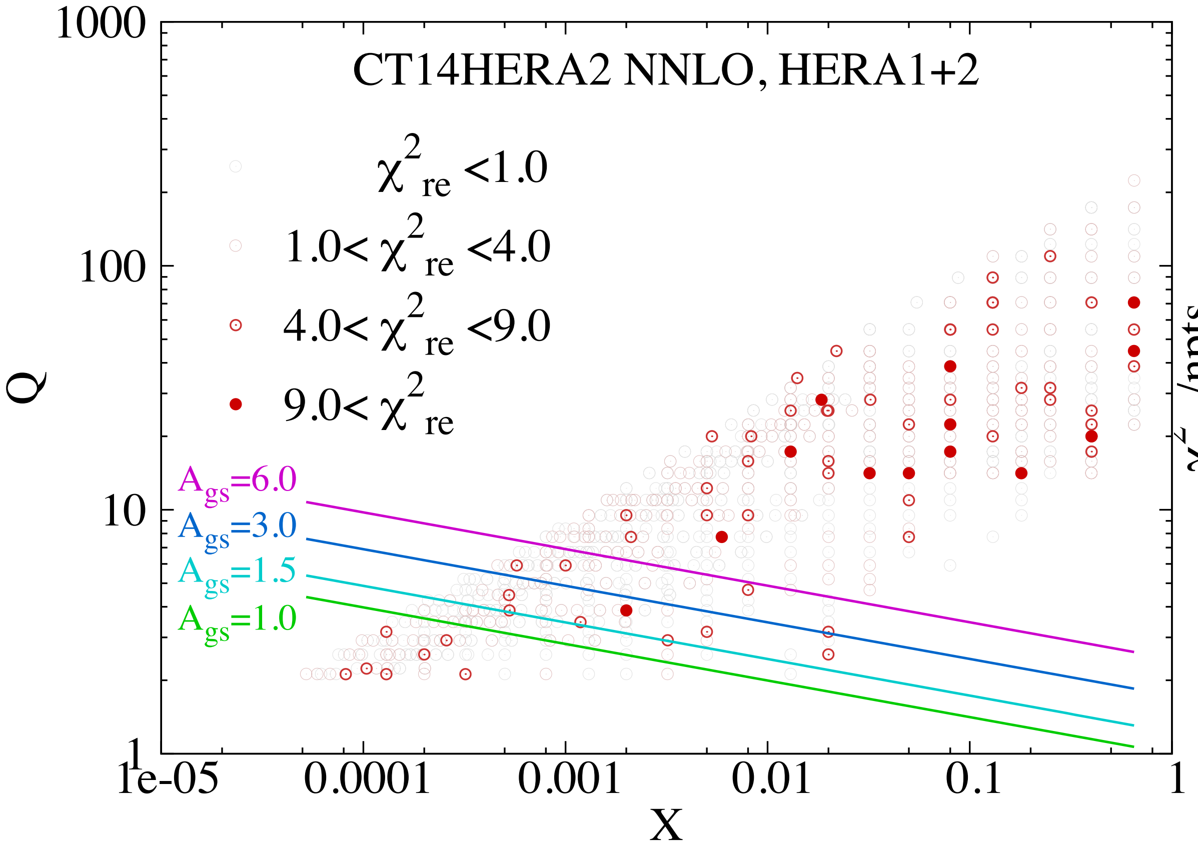


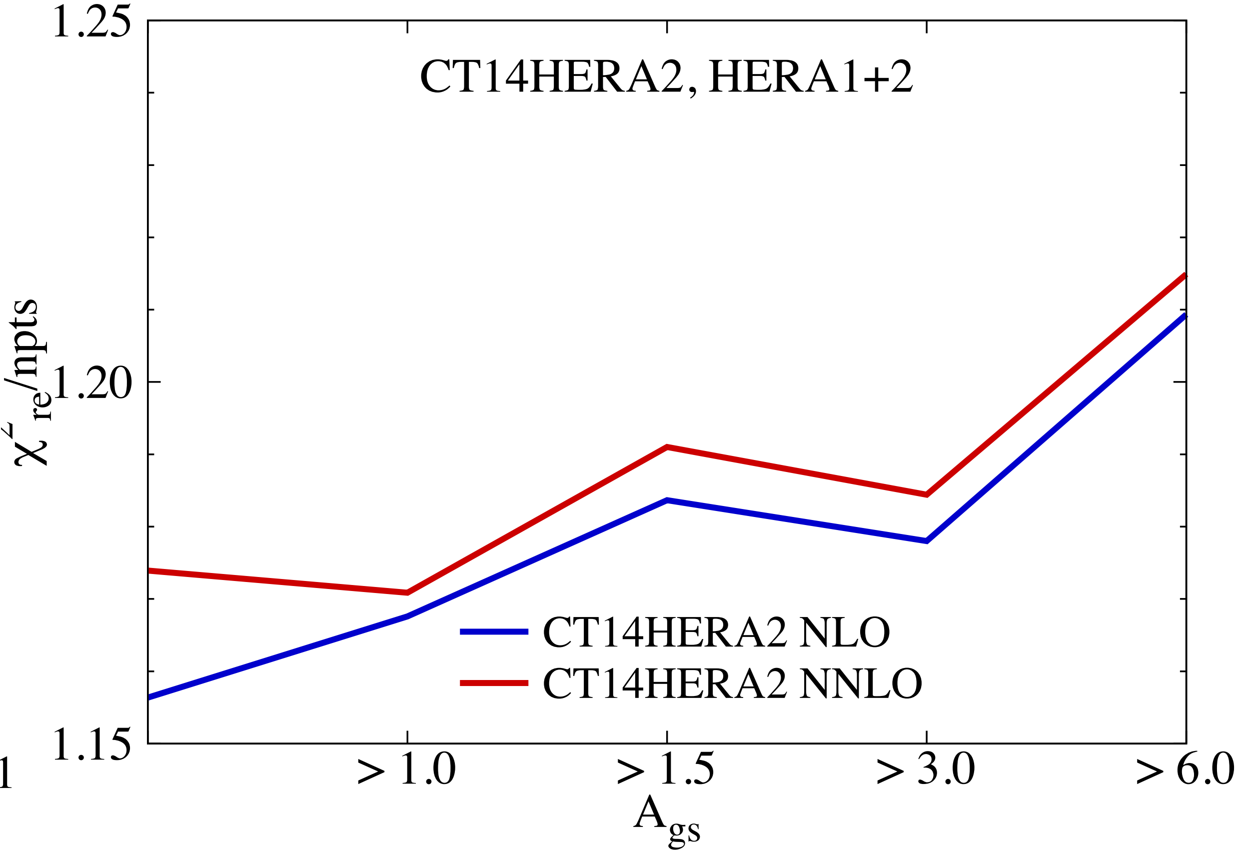
HERA I

NNLO fits

HERA I+II

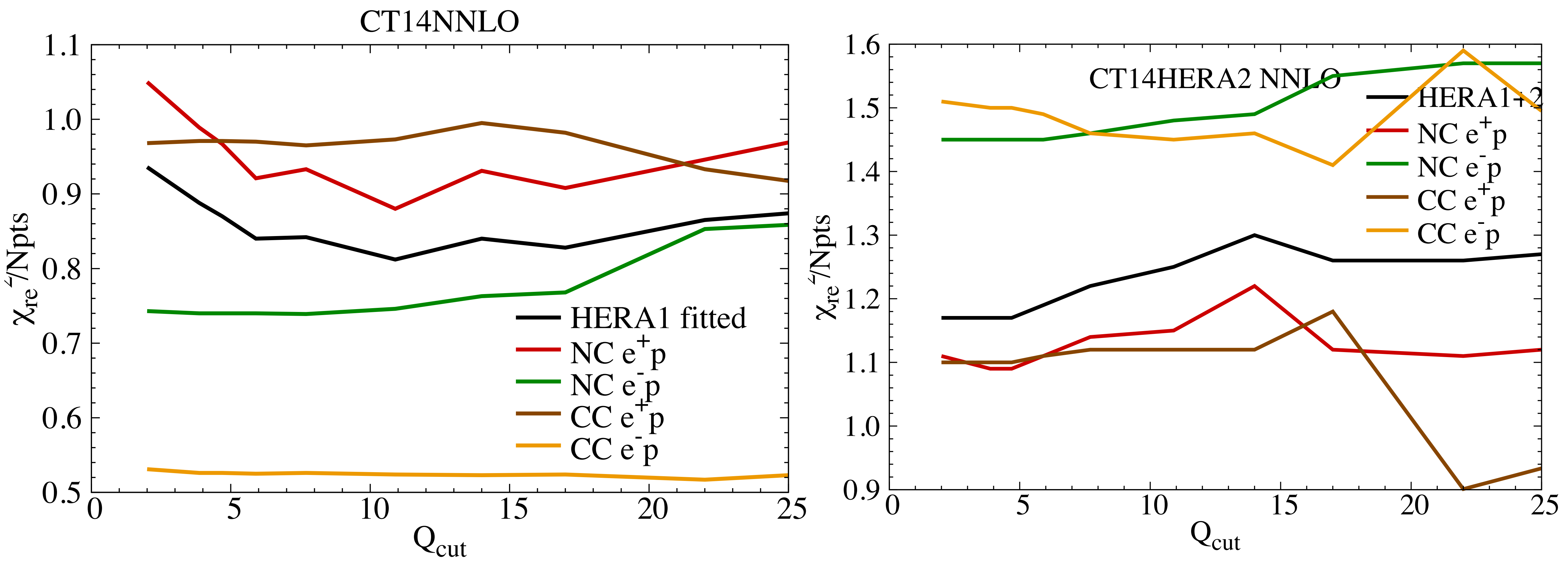
Cuts on x-Q plane





Geometric Scaling variable: $A_{gs} = Q^2\, x^{0.3}$

Goodness of fit to data subsets



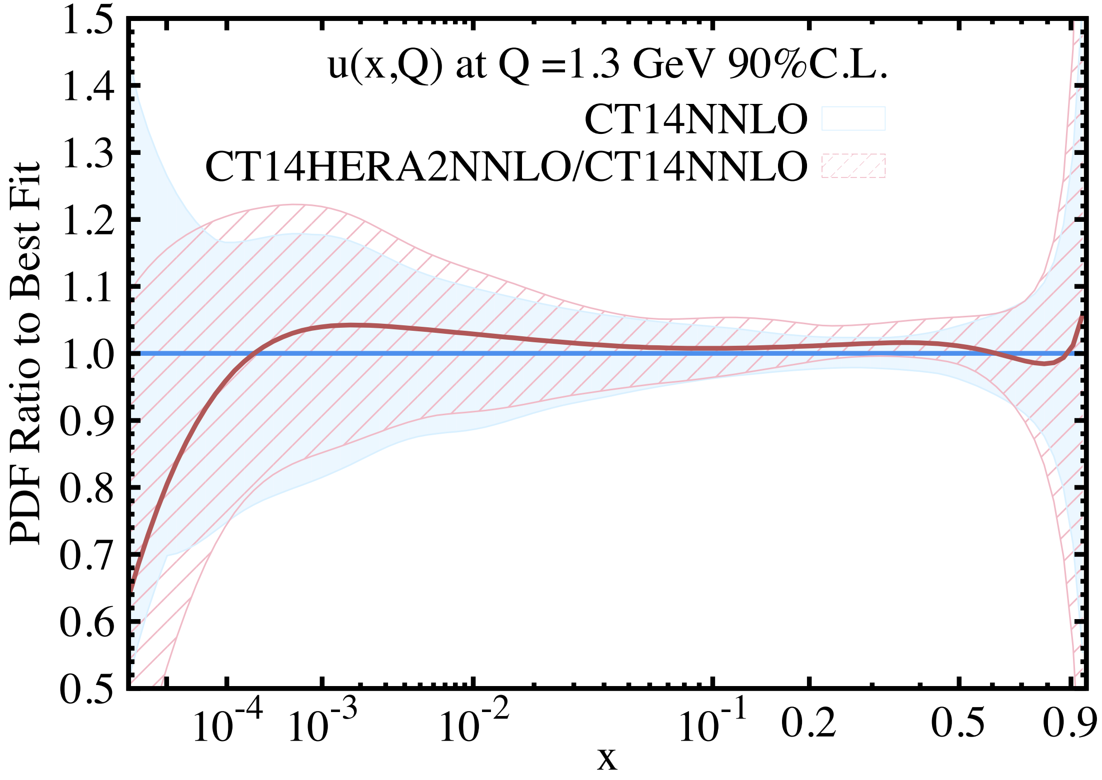
HERA I

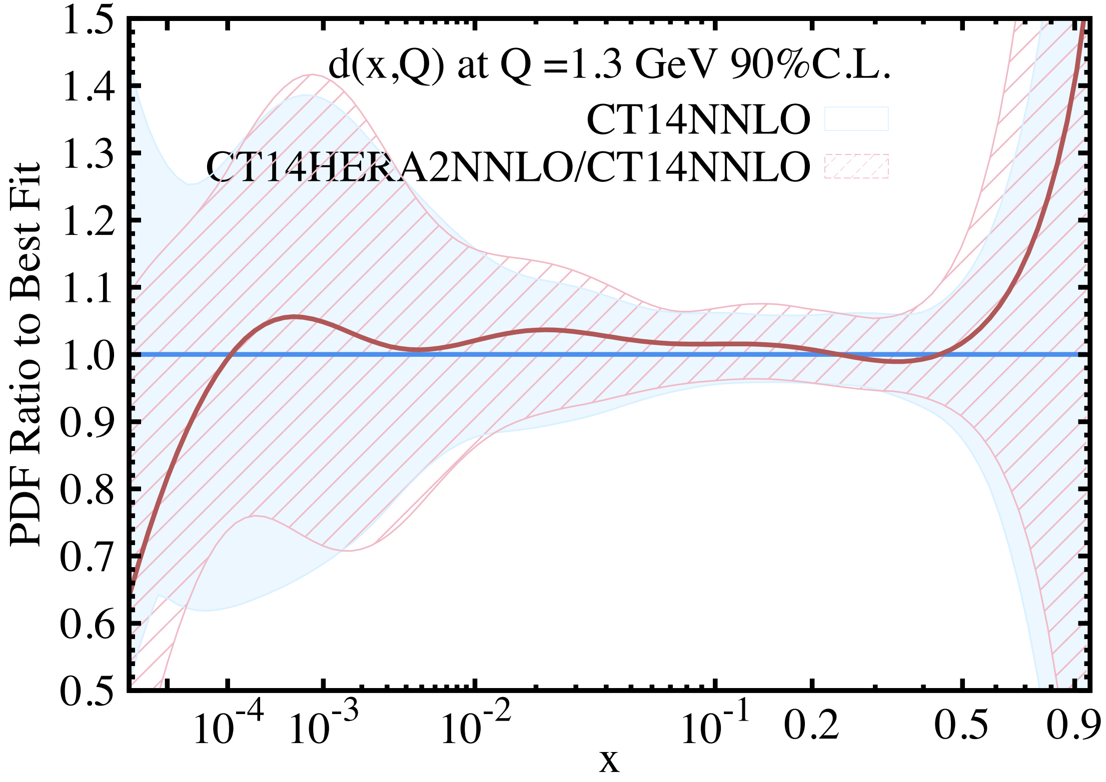
NNLO fits

HERA I+II

CT14HERA2 vs. CT14

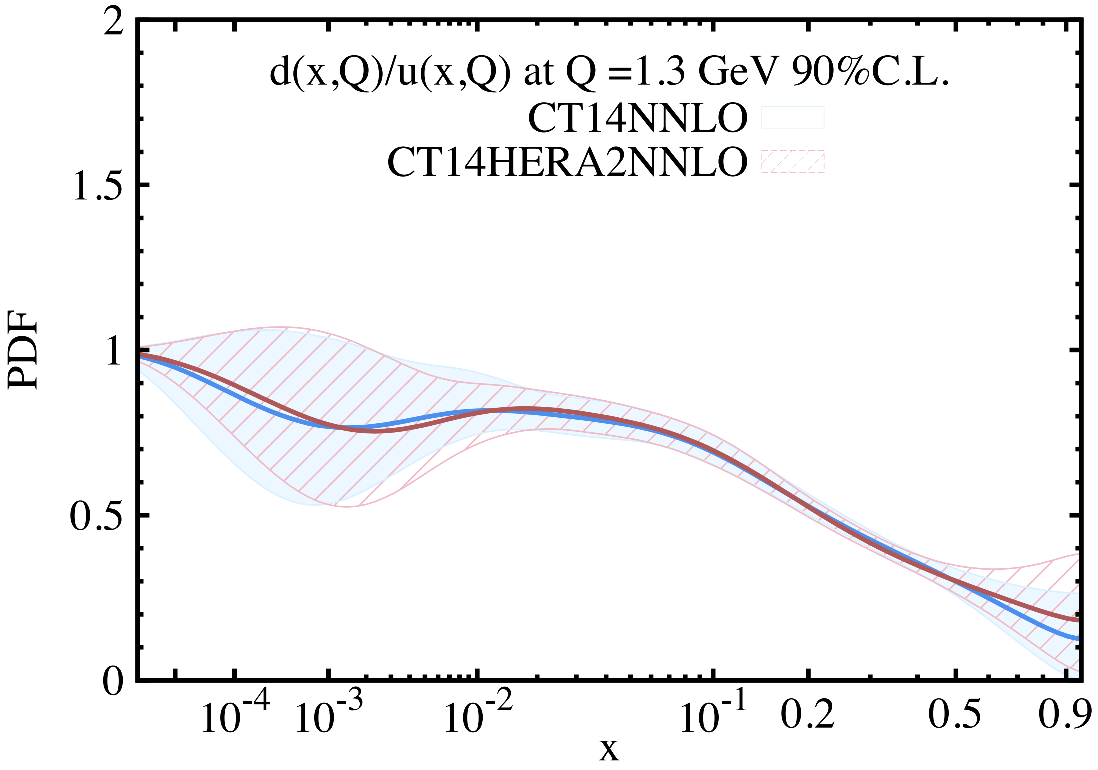
u and d PDFs

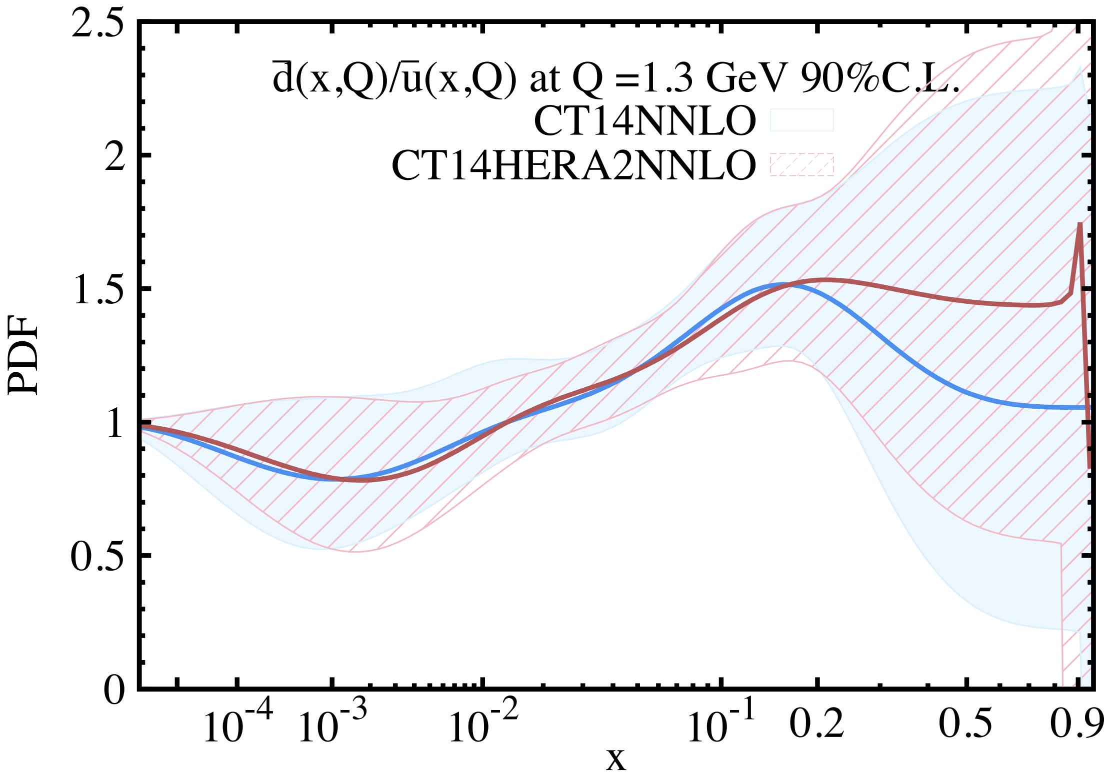




HERAI+II data prefers slightly larger u and d at moderate x
Largest effect is u near x~0.3, where new fit is near edge of old uncertainty.

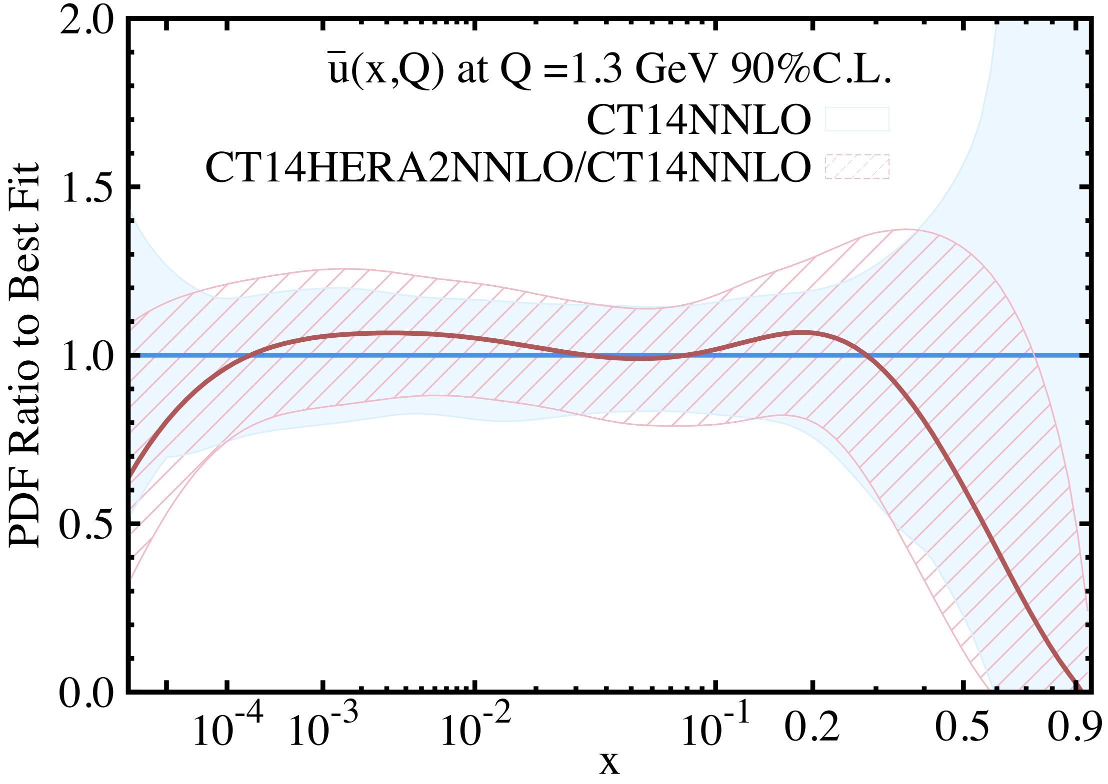
d/u and dbar/ubar PDFs

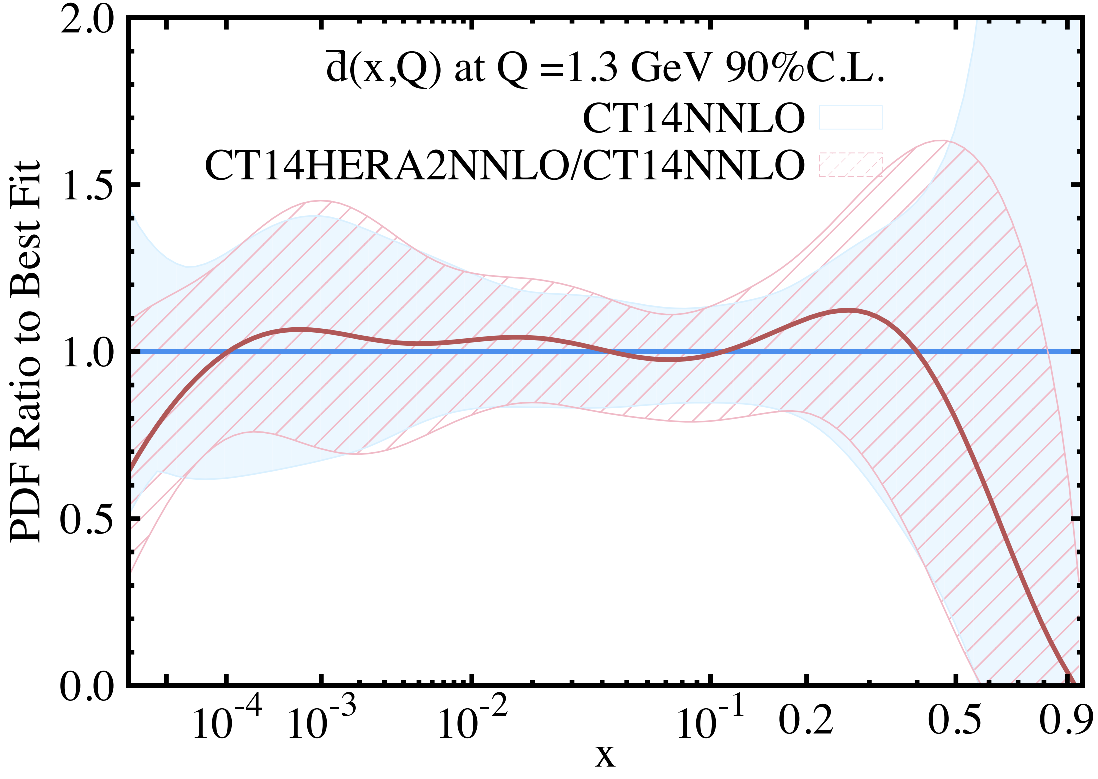




Changes are minimal, well within uncertainty bands.
HERAI+II data prefers slightly smaller dbar/ubar around $x \sim 10^{-1}$.

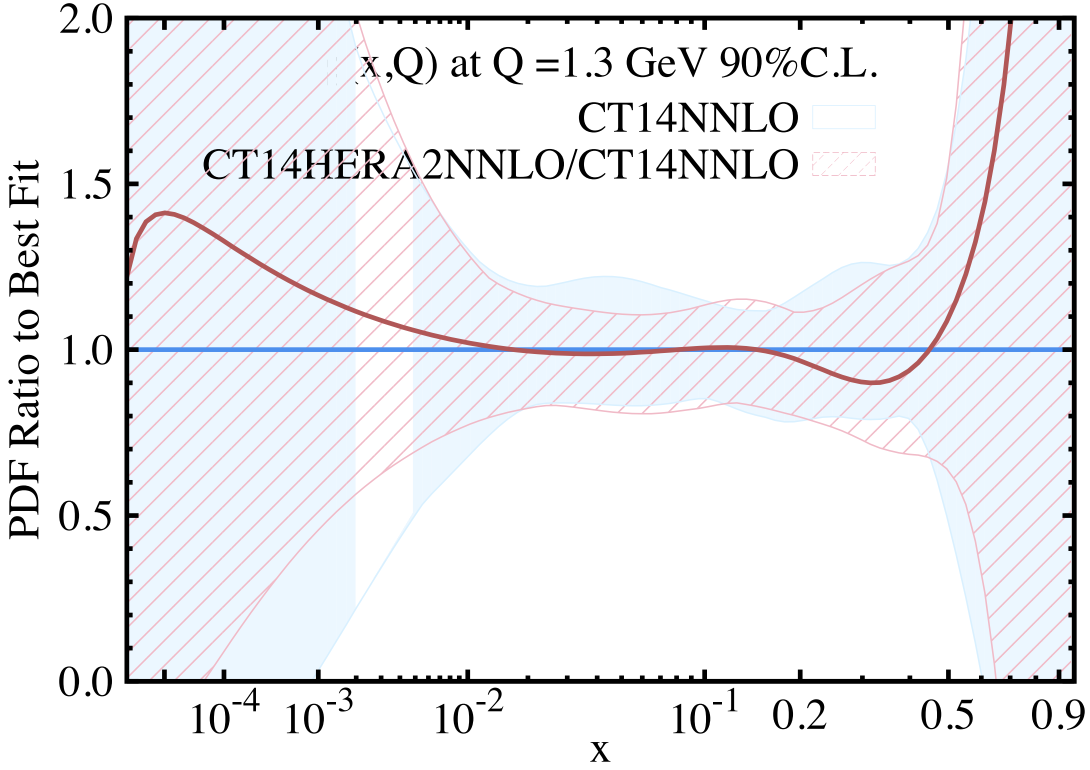
ubar and dbar PDFs

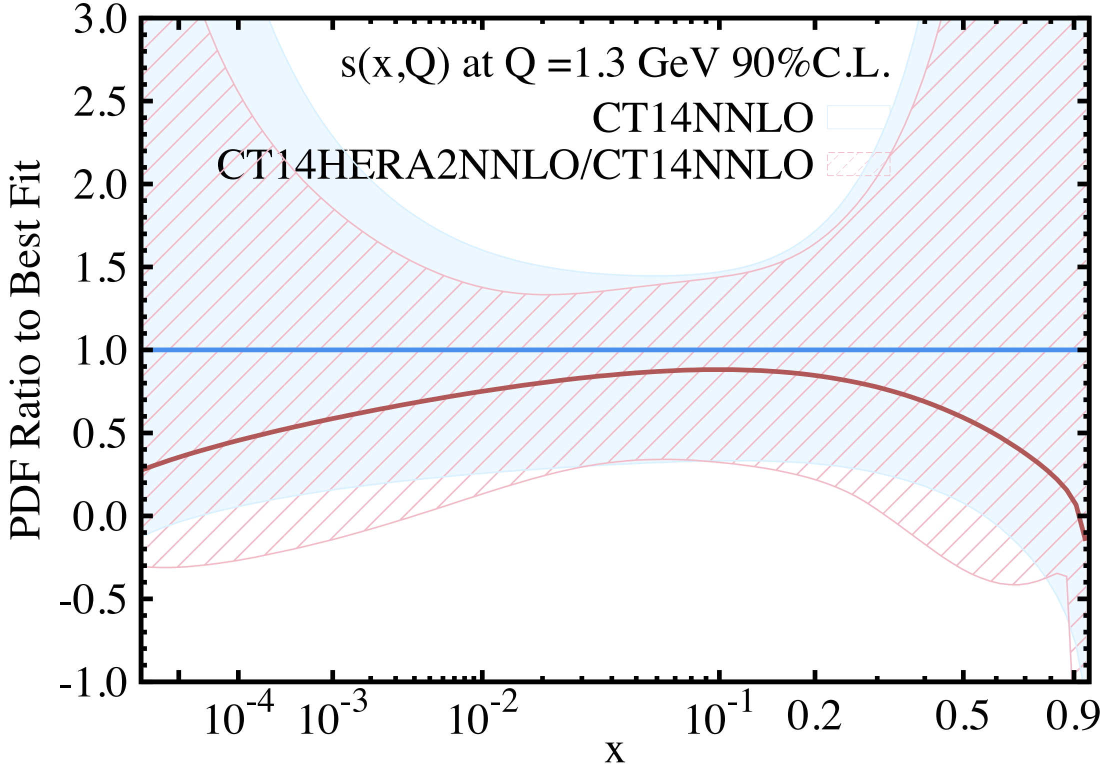




Again changes are mimimal, well within uncertainties.

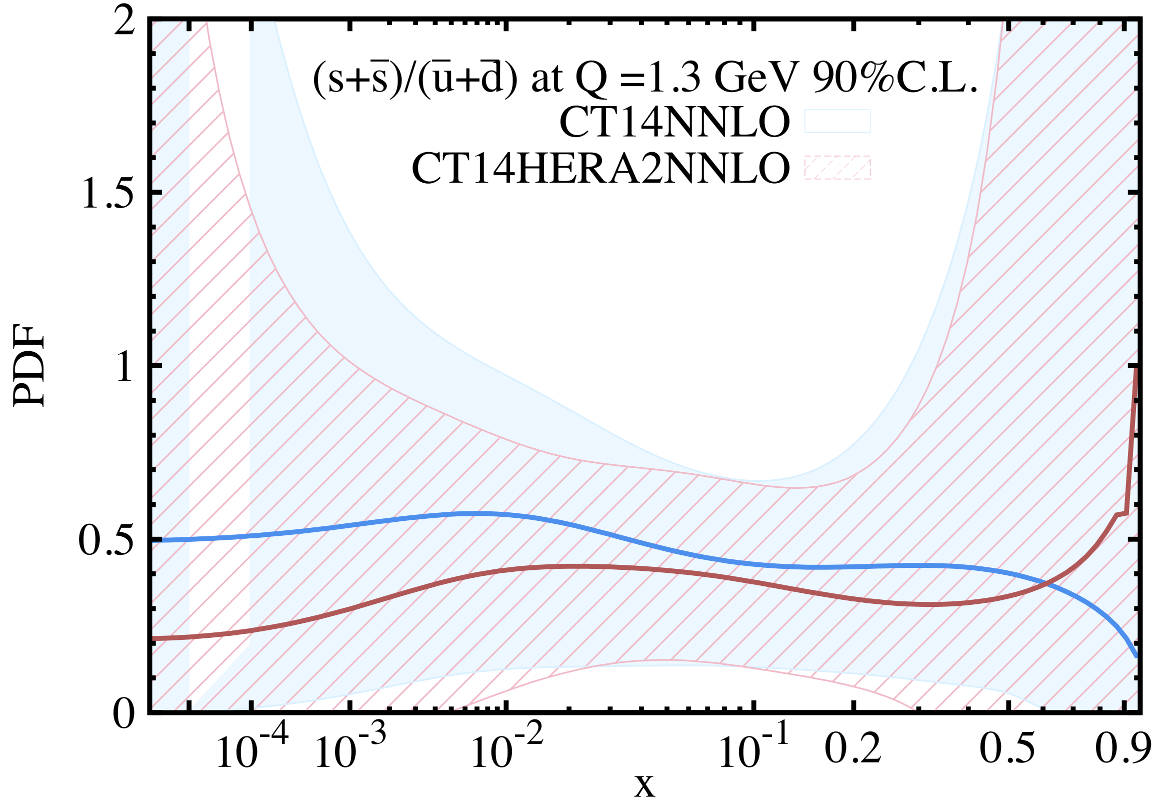
g and s PDFs





HERAI+II data prefers smaller gluon around x~0.2-0.5.
Change in strange PDF mostly due to more flexible parametrization.

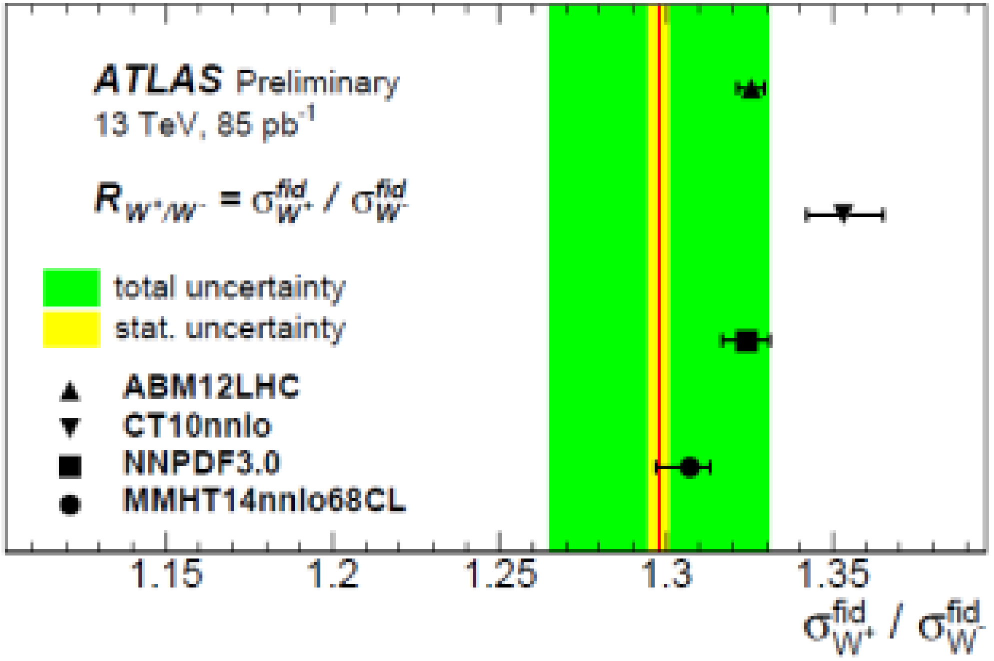
(s+sbar)/(ubar+dbar) PDFs

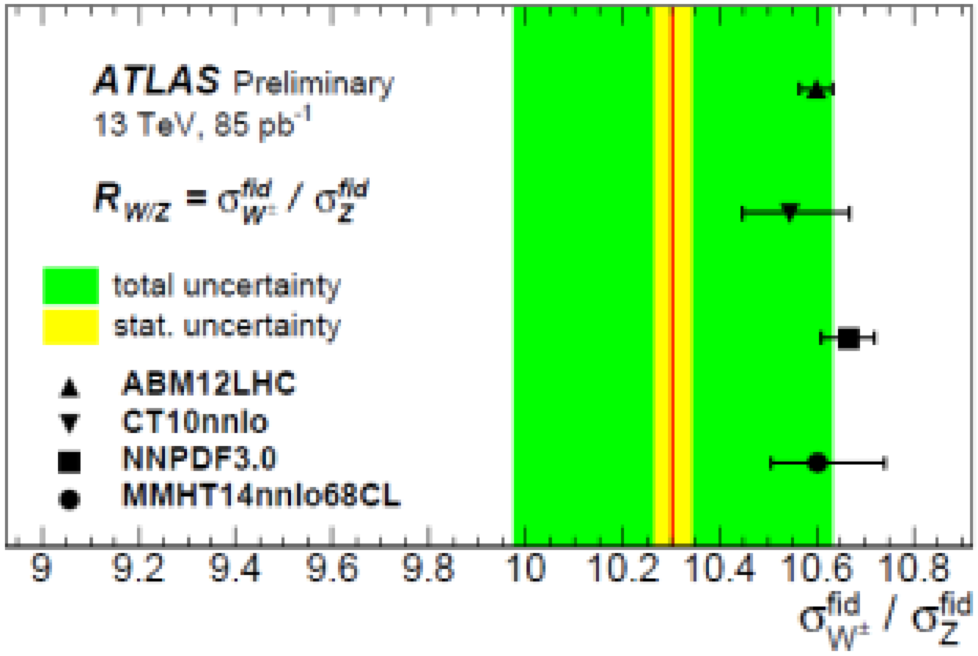


More-flexible strange PDF prefers smaller value,
but still with large uncertainty.

The cross section ratios: W^+/W^- and $(W^++W^-)/Z$

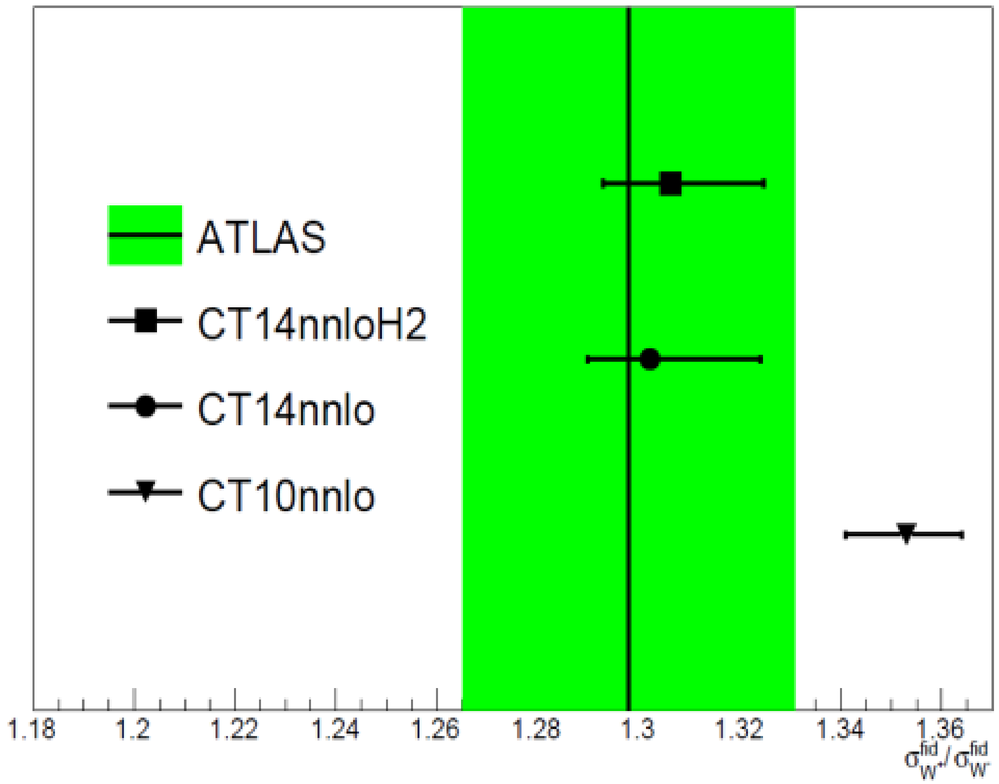
- Measured by the ATLAS and CMS collaboration and proved to be powerful tools to constrain PDFs
- The ratio **W^+/W^-** is mostly sensitive to the difference of u valence and d valence quark distributions.
- The ratio of $(W^++W^-)/Z$ constrains the strange-quark distribution.

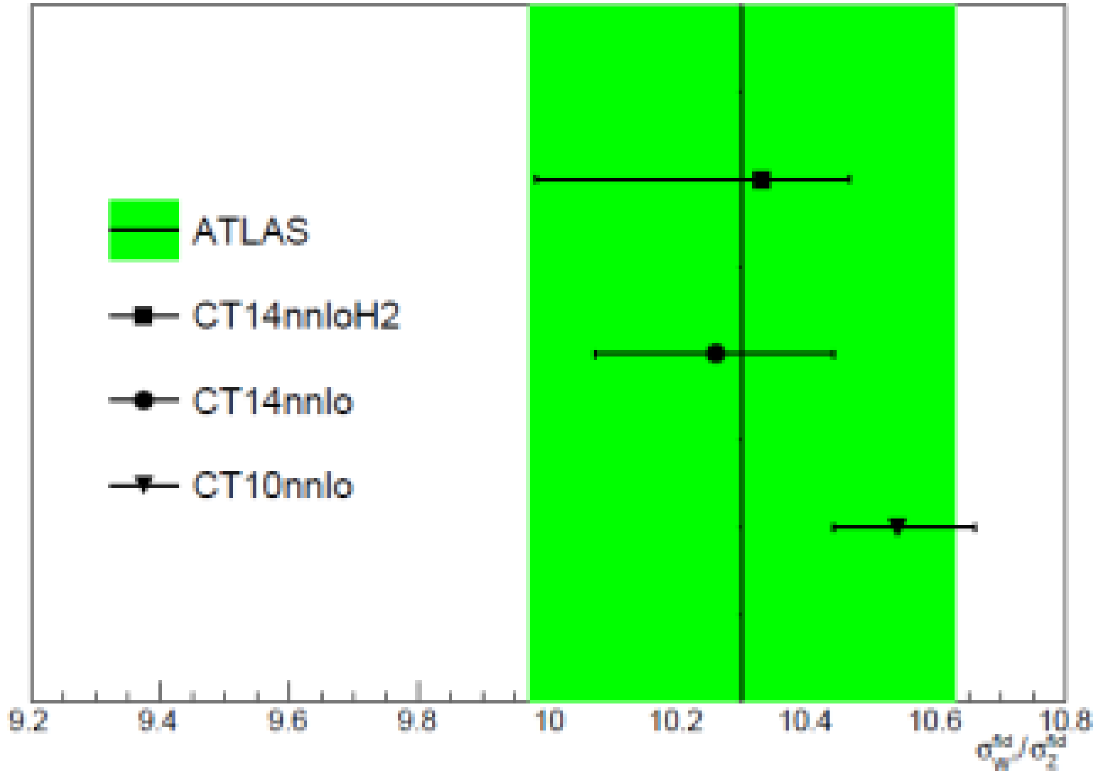




The cross section ratios: W^+/W^- and $(W^+ + W^-)/Z$

CT14HERA2 vs. CT14





$p_T^l > 25\ GeV\ , \quad |\eta_l| < 2.5\ , \quad 66 < m_{ll} < 116\ GeV$

$p_T^l > 25\ GeV\ , \quad p_T^\nu > 25\ GeV\ , \quad |\eta_l| < 2.5\ , \quad m_T > 50\ GeV$

New interpretation of CT14QED Photon PDFs and CMS data

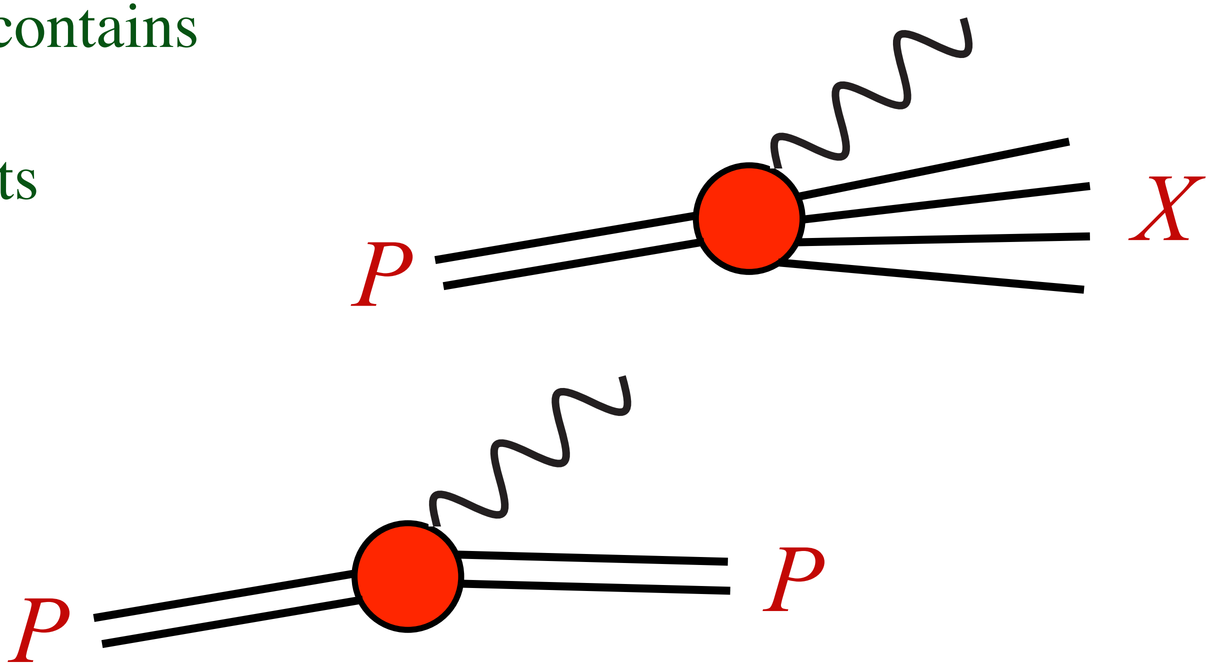
CT14QED

“Inclusive” Photon PDFs

- “Inclusive” Photon PDF contains
  - “inelastic” components

    and

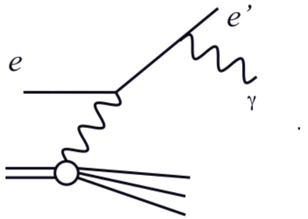
  - “elastic” components



- Martin and Ryskin: (arXiv:0909.4223v2)
  - Dominant contribution at scale Q_0 is “elastic” and calculable
  - Equivalent Photon Approximation: determined from photon form factors
  - “Elastic” photon at Q_0=1.3 GeV carries momentum fraction 0.15%.

CT14QED Photon PDFs

- CT14QED Photon PDF constrained by ZEUS DIS + isolated photon data:
  - $p_0^{\gamma} \leq 0.14\%$ at 90 % C.L.



  - CT14QED Photon PDF should be interpreted as “Inelastic” component.

- ZEUS: “At least one reconstructed track, well separated from the electron, was required, ensuring some hadronic activity which suppressed deeply virtual Compton scattering (DVCS) to a negligible level.”
  - This requirement also removes “elastic” component of photon PDF.

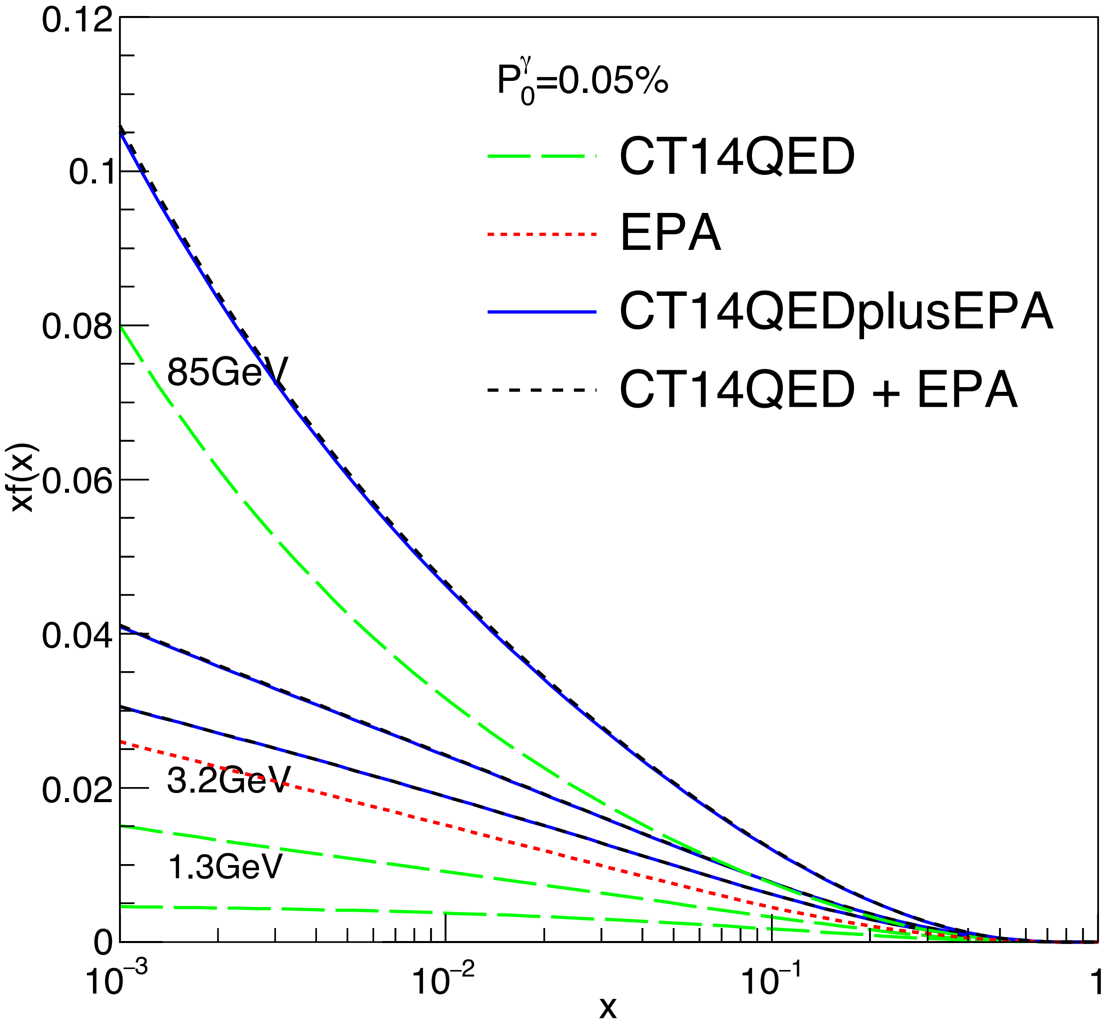
CT14QED Photon PDFs

- Important point:

$$\left(f_{\text{EPA}} + f_{\text{inelastic}}\right)(x,Q) \approx f_{\text{EPA}}(x,Q) + f_{\text{inelastic}}(x,Q)$$

- $f_{\text{EPA}}(x,Q)$ changes little from Q_0 to Q because of falloff from form factor
- Up to corrections of order α, the photon PDF evolves additively:

$$f(x,Q) \approx f(x,Q_0) + \int_{Q_0^2}^{Q^2} \frac{dQ^2}{Q^2} \frac{\alpha}{2\pi} P_{\gamma q} \circ \sum e_q^2 f_q(x,Q)$$



CMS A A -> W^+ W^- Analysis

CERN-PH-EP/2013-084
2013/08/22

CMS-FSQ-12-010

Study of exclusive two-photon production of W^+W^- in pp collisions at $\sqrt{s} = 7$ TeV and constraints on anomalous quartic gauge couplings

The CMS Collaboration*

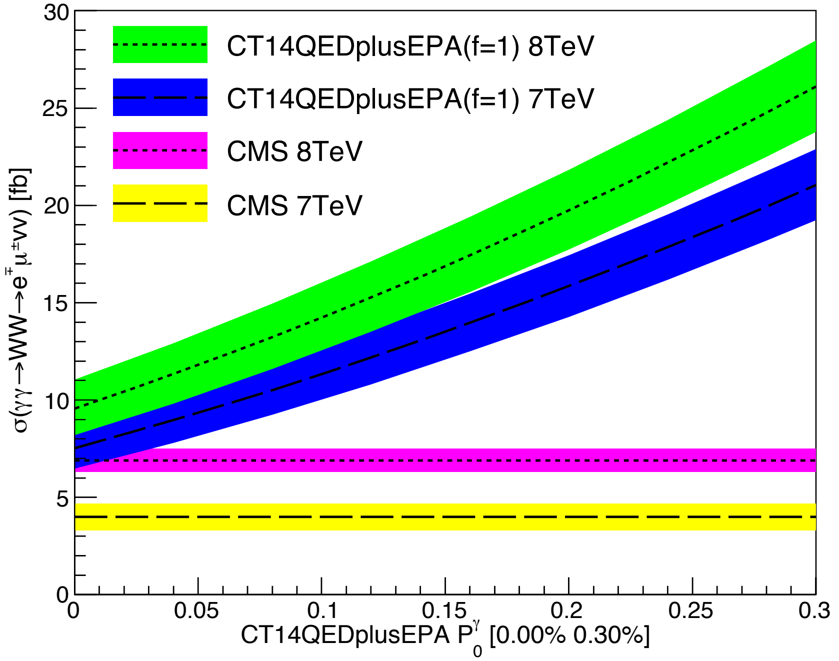
(Also newer analysis at 8 TeV, 2015/06/16)

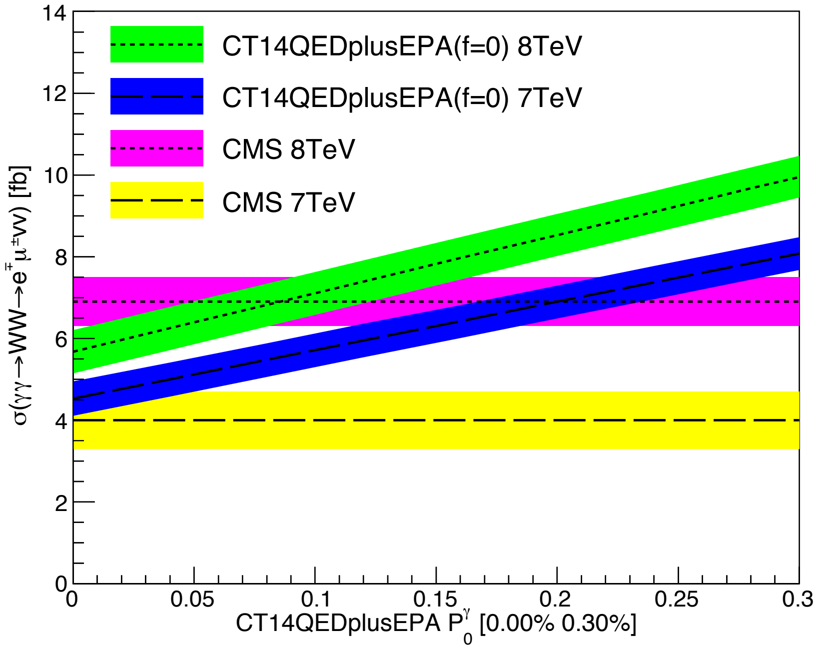
CMS A A -> W^+ W^- Analysis

- Using off-Z-peak $\mu^+\mu^-$ data they obtained an "effective photon luminosity" used to calculate the W^+W^- cross section
- We can compare this to our calculation using photon PDFs
- But:
  - They require zero charged tracks to isolate photon-photon production.
  - This removes some, but not all, inelastic contribution
  - Events can be divided into: elastic-elastic, elastic-inelastic, inelastic-inelastic, depending on whether 0, 1, or both protons dissociate.
- Crude approximation:
  - Assume all elastic-elastic and elastic-inelastic events pass the cut, while inelastic-inelastic are reduced by a fraction f, with $0<f<1$.
  - (Double-dissociative are most affected by re-scattering.)

Comparison with CMS predictions

f=1





f=0

- Experimental error bands are 68% CL, Theory error bands are scale variation.
- Theory bands plotted as function of initial "inelastic" photon momentum
- f=1 is strongly disfavored, especially for the 7 TeV analysis
- Even if no double-dissociative events pass the zero-track cut, there are constraints on the initial photon momentum: $p_0^\gamma \leq 0.05\%$ (7 TeV), $p_0^\gamma \leq 0.16\%$ (8 TeV)
- Consistent with DIS + Isolated photon analysis

Photon-Photon Luminosity

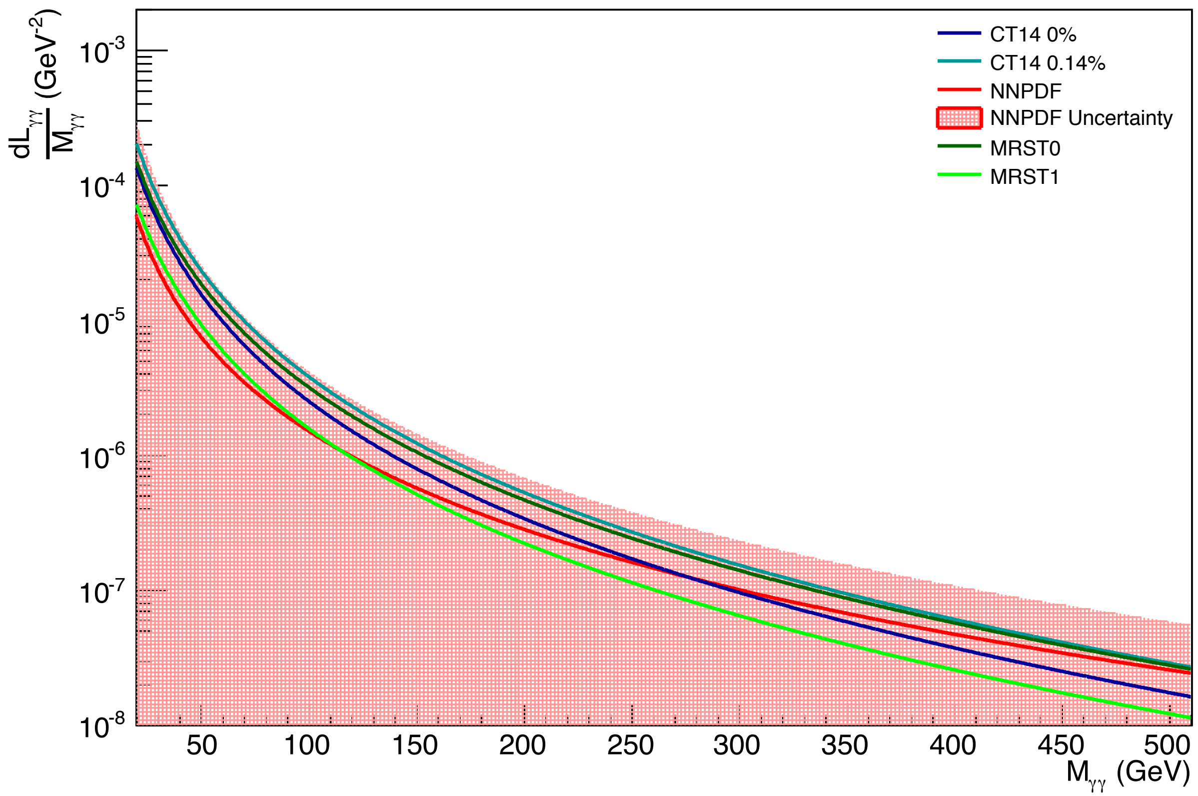


FIG. 4: Photon-photon luminosity for an invariant mass of 20 GeV to 500 GeV for 13 TeV collider energy

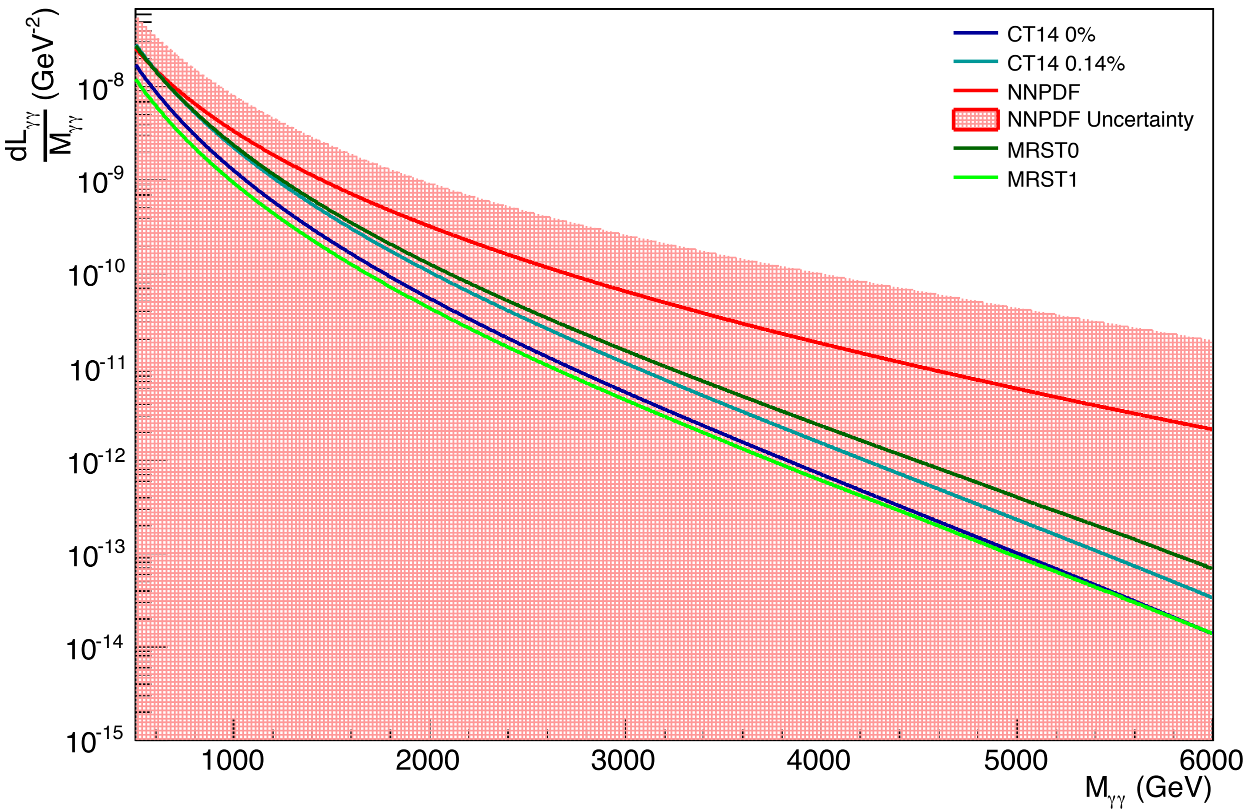
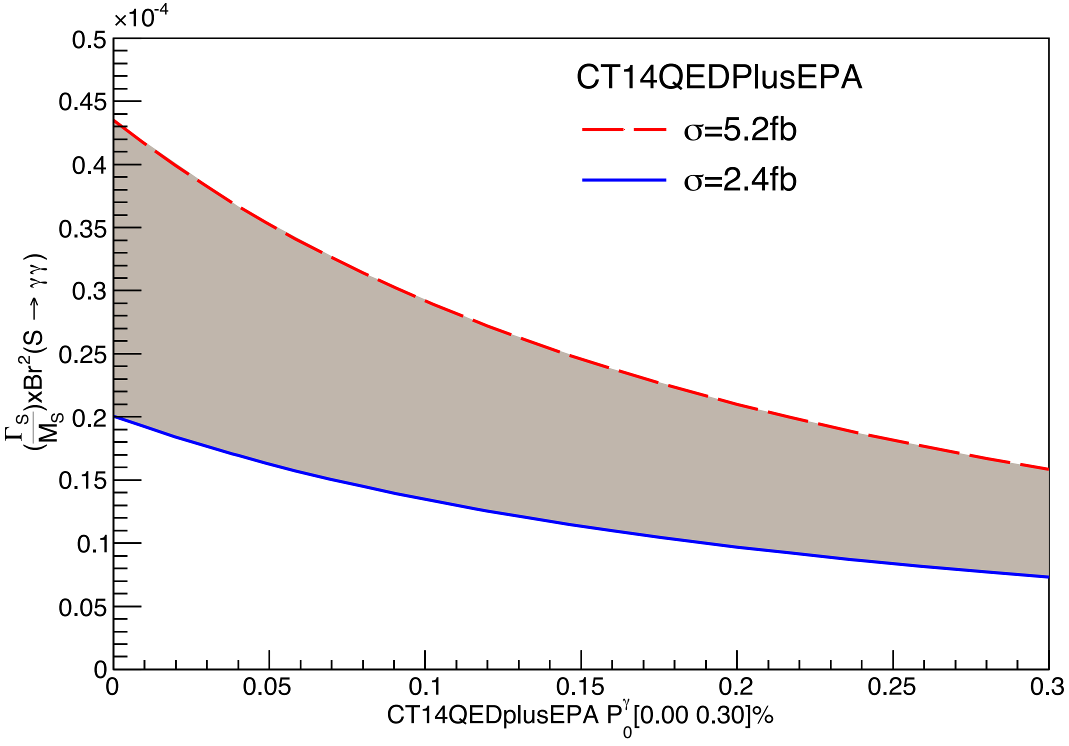


FIG. 5: Photon-photon luminosity for and invariant mass of 500 GeV to 6000 GeV for 13 TeV collider energy

- Central NNPDF photon harder at large x.

Constraints on CMS 750 GeV excess



- If CMS 750 excess is due to resonant production in gamma-gamma channel:
  - Constraints on cross section (John Paul Chou, talk at Moriond, March 20,2016)
- From calculated photon-photon luminosities, obtain constraints on *Γ/M*
- Assuming Br~1, this model requires small *Γ/M*~10^{-4} to fit the data.

Conclusions

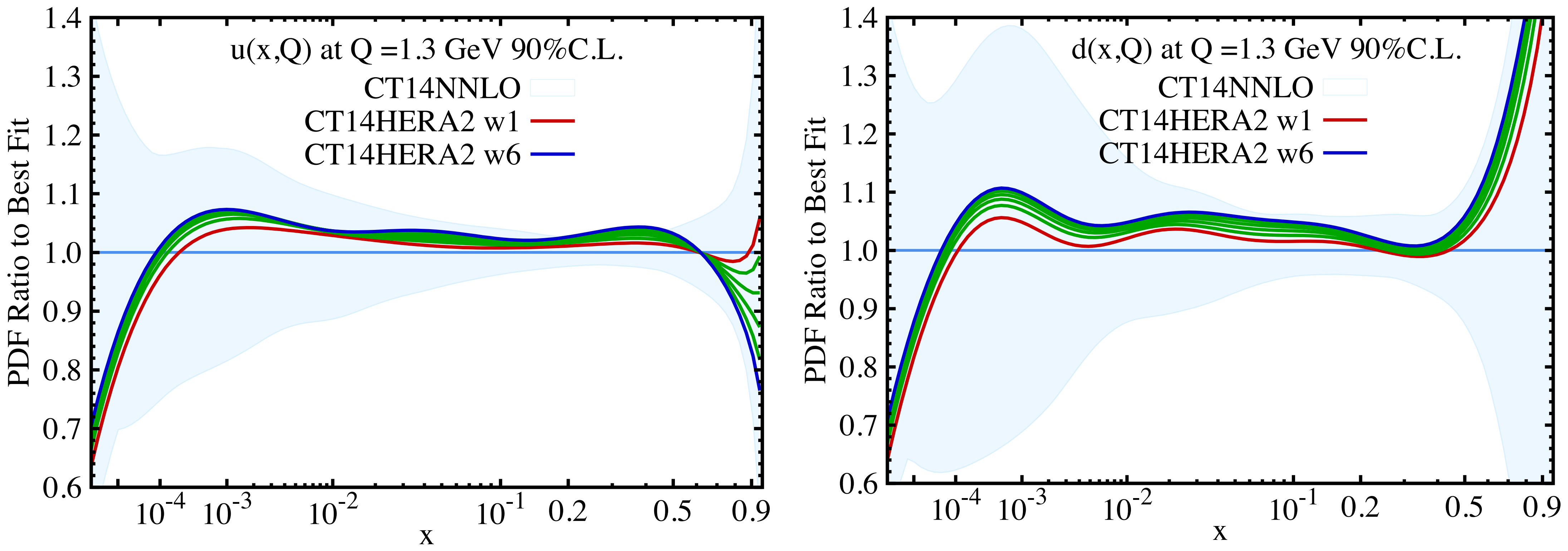
- Impact of HERA I + II data on CT PDF analysis: **(CT14HERA2)**
  - Worse fit than HERA I, especially in $e^{-}p$ NC and CC channels
  - But changes to PDFs generally small
- New interpretation of CT14QED photon PDFs and CMS data:
  - **CT14QEDplusEPA**
  - CMS analysis consistent with constraints from ZEUS on inelastic contribution
  - Better understanding of Photon PDFs important for new physics analyses

- We are including more LHC data into the global analysis.

Backup Slides

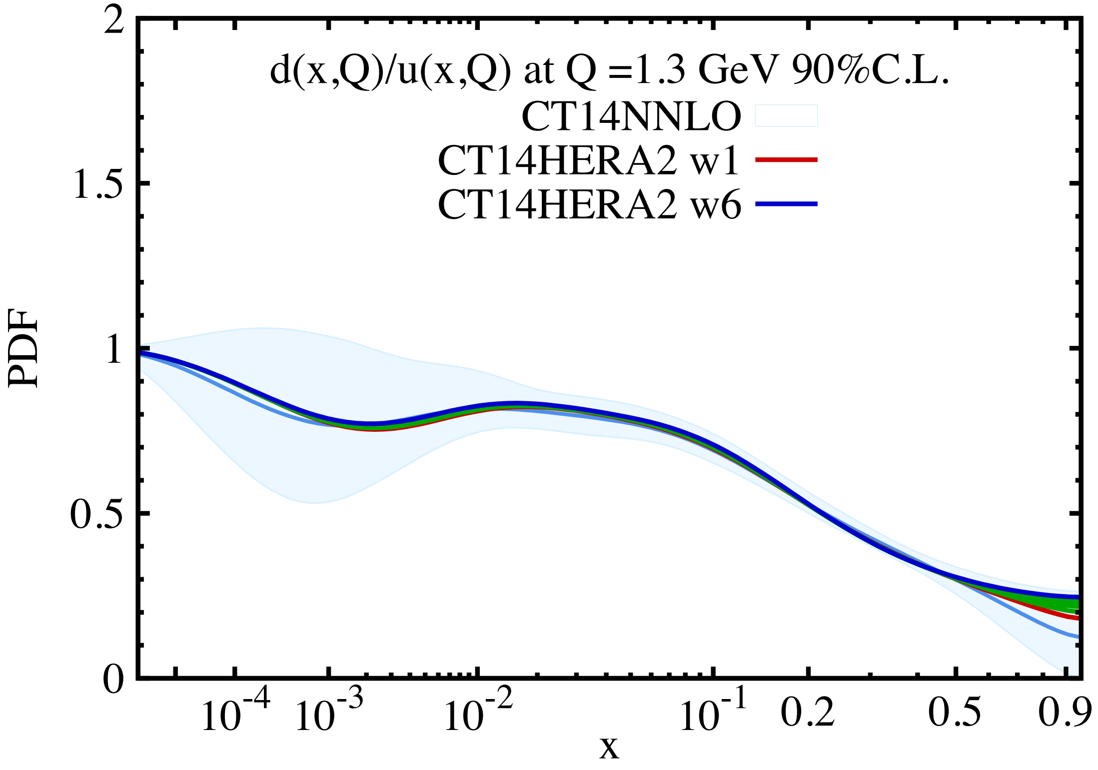
CT14HERA2 vs. CT14

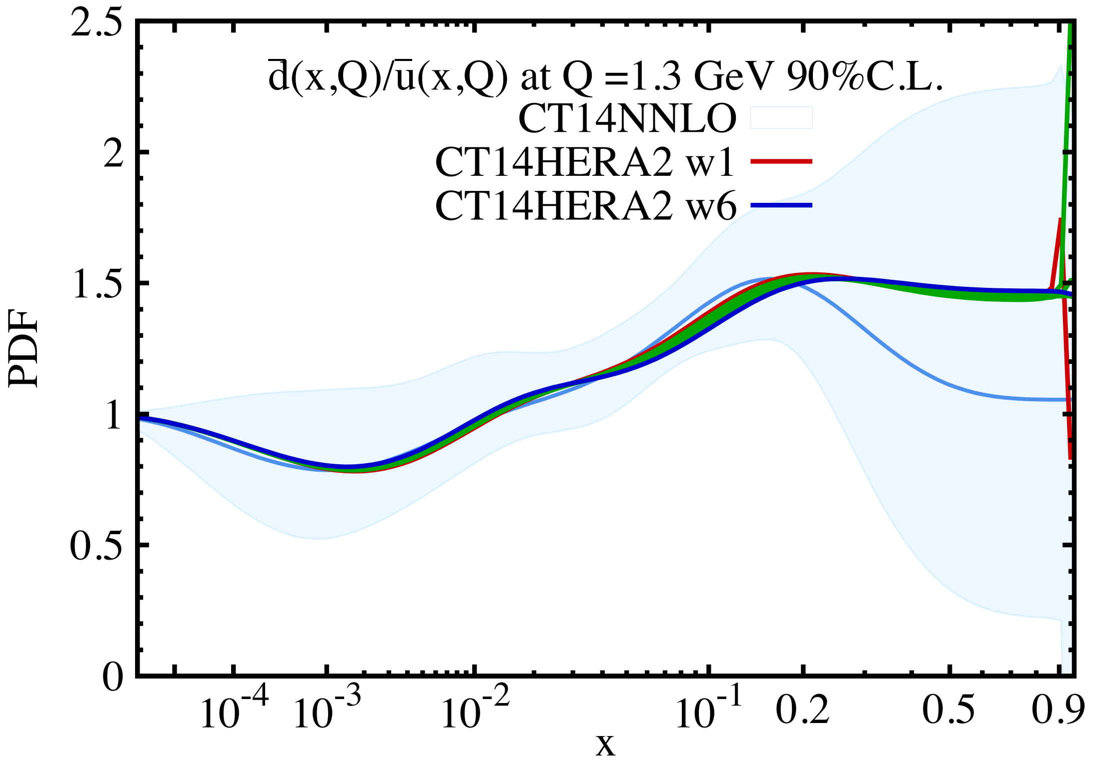
u and d PDFs



HERAI+II data prefers slightly larger u and d at moderate x
Largest effect is u near x~0.3, where new fit is near edge of old uncertainty.

d/u and dbar/ubar PDFs

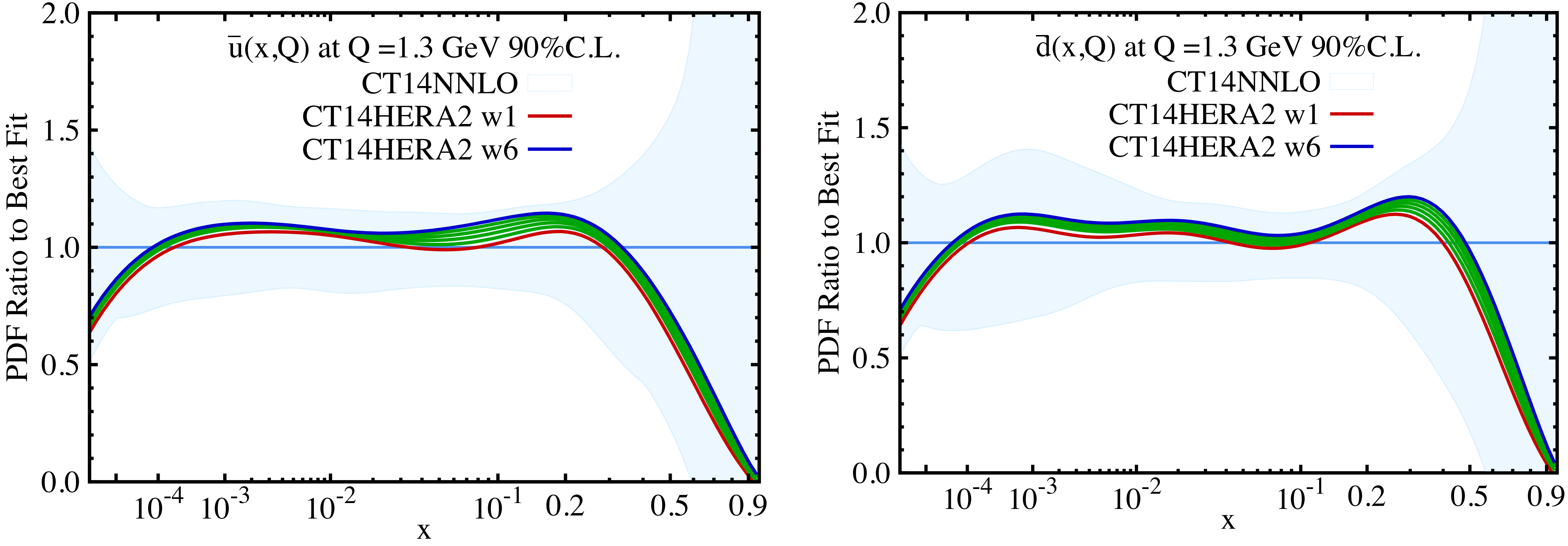




Changes are minimal, well within uncertainty bands.

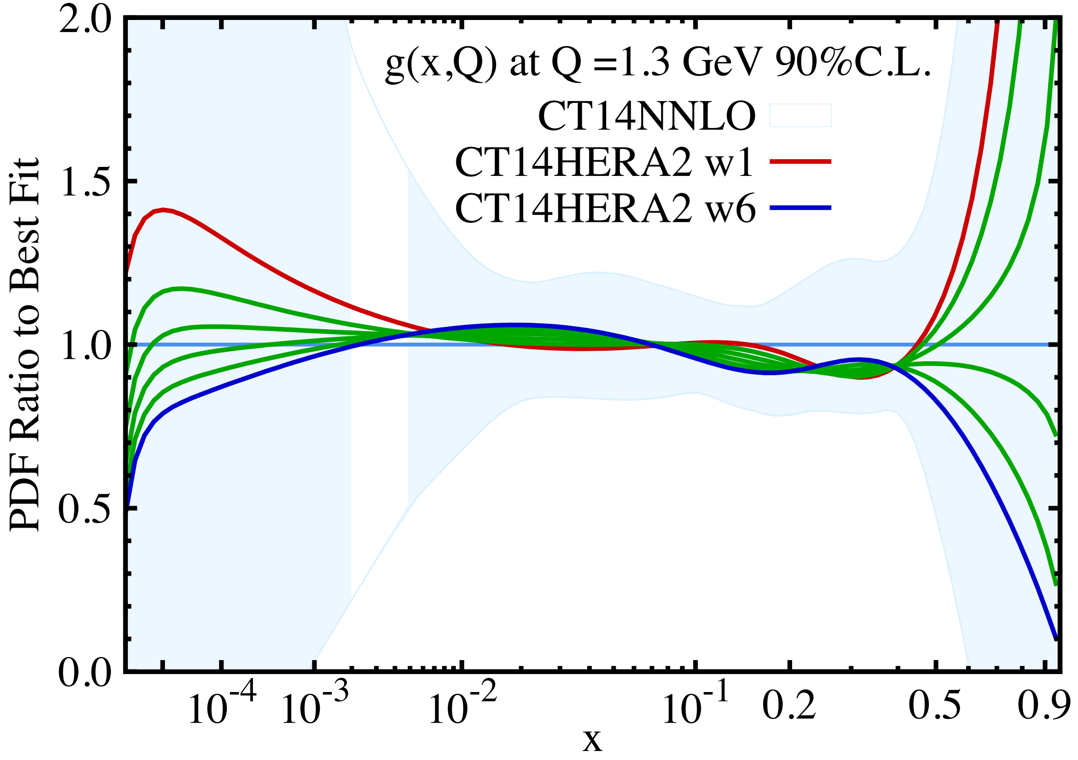
HERAI+II data prefers slightly smaller dbar/ubar around $x \sim 10^{-1}$.

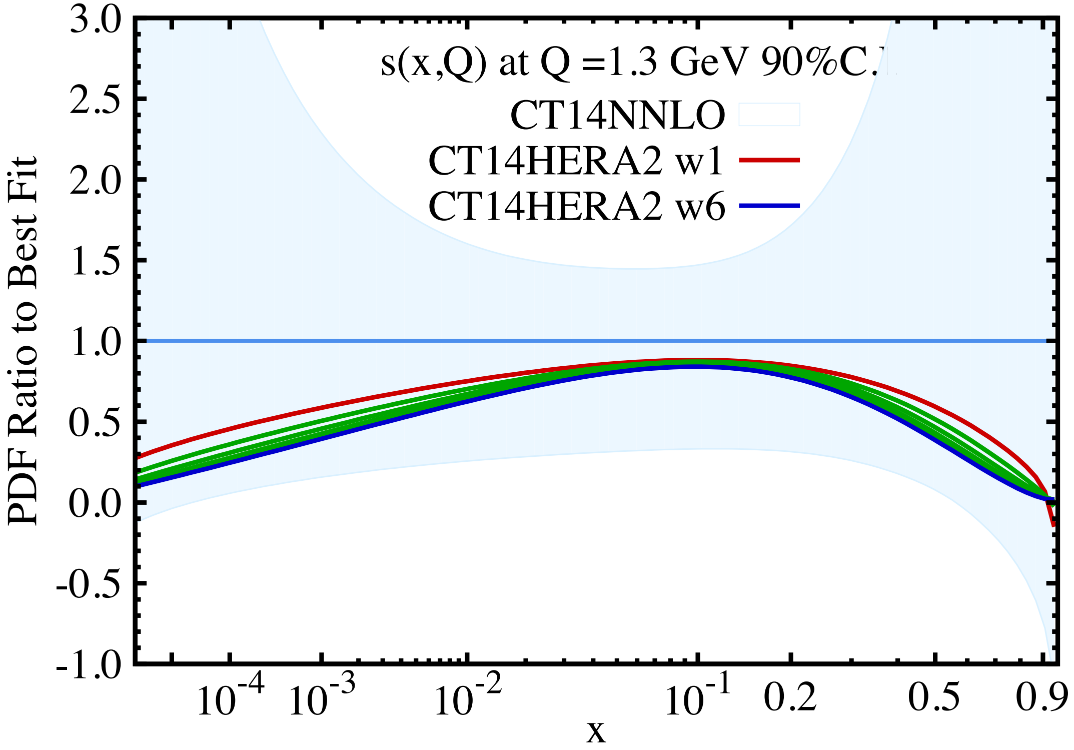
ubar and dbar PDFs



Again changes are mimimal, well within uncertainties.

g and s PDFs

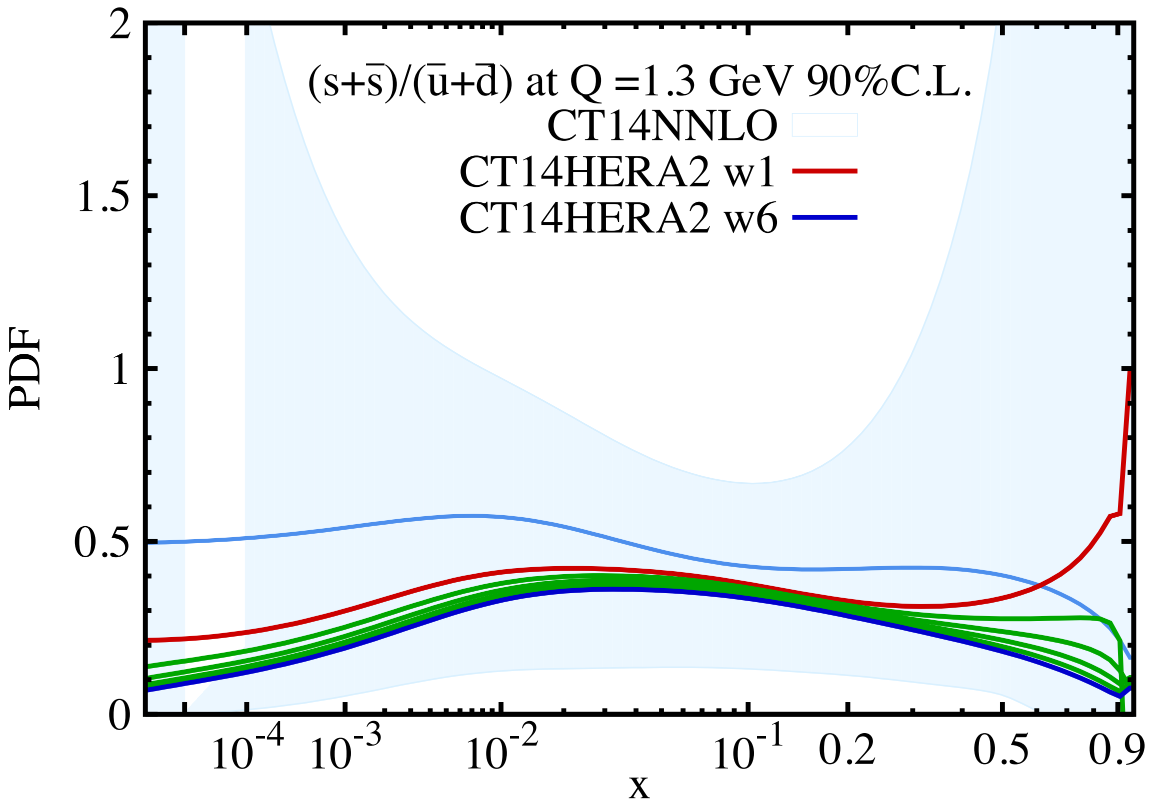




HERAI+II data prefers smaller gluon around x~0.2-0.5.

Change in strange PDF mostly due to more flexible parametrization.

(s+sbar)/(ubar+dbar) PDFs



More-flexible strange PDF prefers smaller value,
but still with large uncertainty.

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

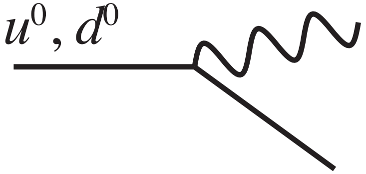
2) Photon evolution at LO in α and NLO in α_S currently implemented in CTEQ-TEA global analysis package
   a) Alternative parametrization approach
   b) Constrain with DIS + photon data

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**

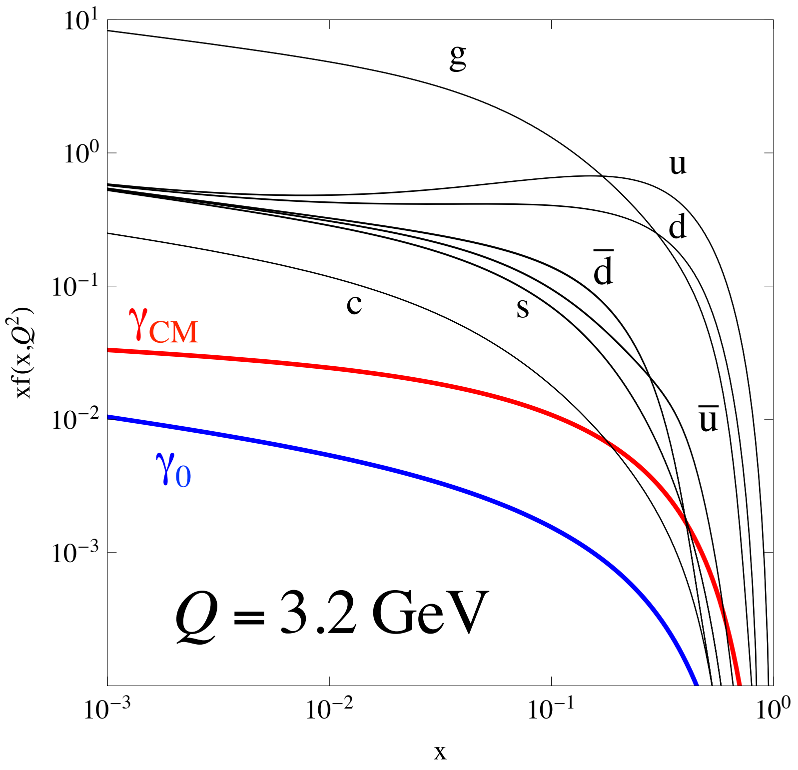
We use $u^0 = u^p \equiv u^p(x, Q_0), \quad d^0 = d^p \equiv d^p(x, Q_0)$
and reduce the number of parameters further (for initial study) by setting

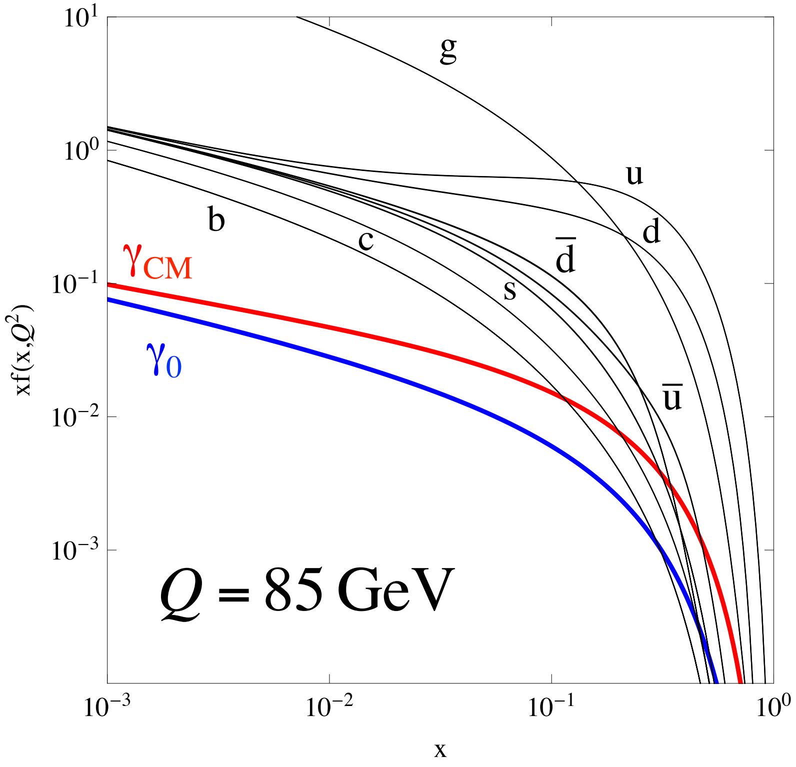
$$A_u = A_d = A_0$$

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.

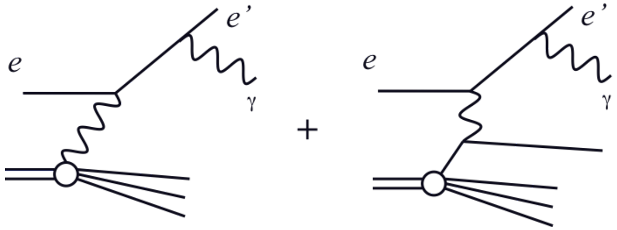
Constraining Photon PDFs

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

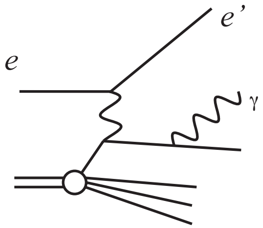
2) Direct photon PDF probe
   - DIS with observed photon, $ep \rightarrow e\gamma + X$
   - Photon-initiated subprocess contributes at LO, and no larger background with which to compete
   - But must include quark-initiated contributions consistently
   - Treat as NLO in α, but discard small corrections,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

$ep \to e\gamma + X$

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)

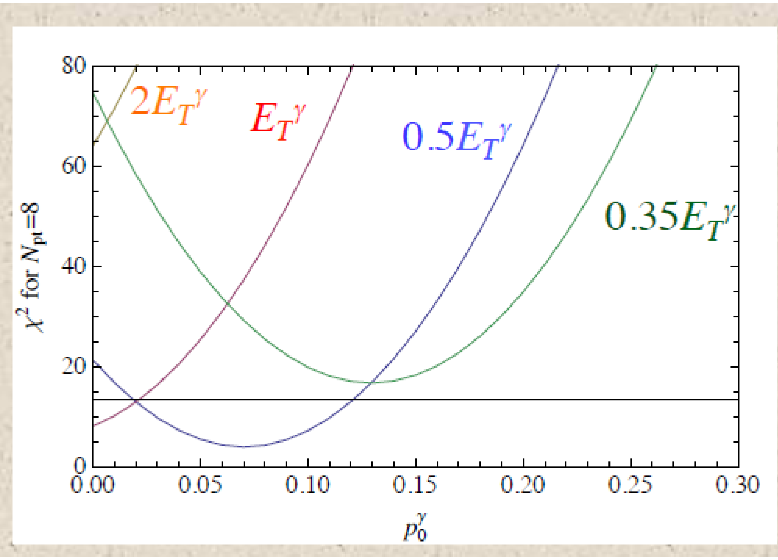


QQ Emission off Quark line
Has final-state quark-photon collinear singularity

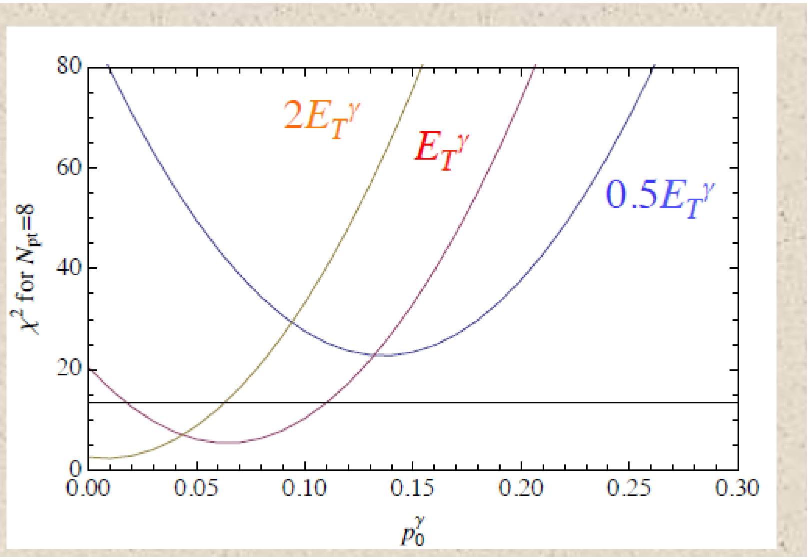
QL Interference term
Negligible < about 1% (but still included)

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)

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 $10^{-3} < x < 2\text{x}10^{-2}$.)

- "Current Mass" ansatz has $\chi^2 > 45$ for any choice of isolation and scale