CT14 Global Analysis and CT14QED

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On behalf of the CTEQ-TEA group

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INT-15-3 Program

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

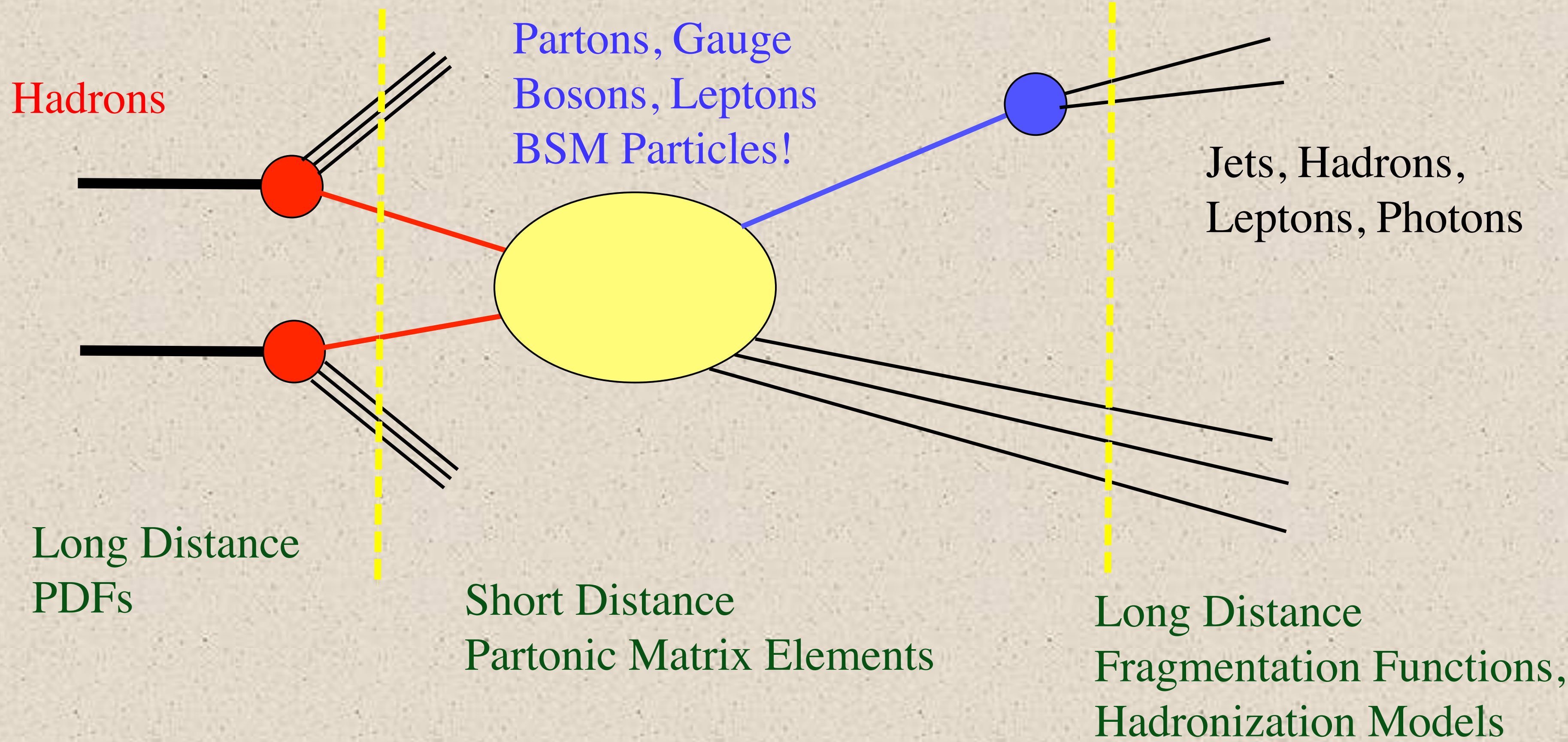
1) CT14 Global Analysis of Quantum Chromodynamics

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

2) CT14QED PDFs from Isolated Photon Production in DIS

    CS, J. Pumplin, D. Stump, C.-P, Yuan, arXiv:1509.02905[hep-ph]

Hadron Collider Physics



$$\sigma(p_1 p_2 \to H + X) = \sum_{a,b} \int dx_1 \int dx_2 \, f_{a/p_1}(x_1,\mu) f_{b/p_2}(x_2,\mu) \hat{\sigma}^{ab}(x_1 x_2 s, \mu) + O\left(\frac{\Lambda^2}{Q^2}\right)$$

Parton Density Functions

- PDFs difficult to calculate theoretically from first principles (although work in that direction being done)
- Therefore, extract from experimental data
- PDFs are universal
  - DIS in lepton-hadron colliders
  - Drell-Yan, Vector Boson Production in hadron-hadron colliders
  - Jet production in hadron-hadron colliders
- Global analysis to extract PDFs from multiple data inputs
  - Different data probes unique combinations of partonic PDFs

Importance of PDFs

- Higher order (NLO, NNLO, etc) in QCD requires comparable precision
  - gg=>Higgs at NNNLO!, errors from PDFs comparable or larger than renormalization/factorization uncertainties
- Are discrepancies from SM signs of new physics?
  - Counting experiments (single top, SUSY, …) require well-understood signal and background => PDFs
  - Precision Higgs and top measurements
  - Gauge Boson, Jet cross section predictions
    - influenced by PDF assumptions?
- EW corrections => photon PDFs, may have important contributions (WW at high root-s?)

CT14 Global Analysis - Data

Minimize $\chi^2 = \sum_{\alpha=1}^{N} \chi^2_\alpha$ with $\chi^2_\alpha = \sum_{i=1}^{N_\alpha} \left(\frac{\text{data}_i - \text{theory}_i}{\text{error}_i} \right)^2$

$N = 33$ Experiments, $N \bullet N_\alpha = 2947$ data points
Careful treatment of Correlated systematic errors

ID#	Experimental data set		$N_{pt,n}$	χ^2_n	$\chi^2_n/N_{pt,n}$	S_n
101	BCDMS F_2^p	[24]	337	384	1.14	1.74
102	BCDMS F_2^d	[25]	250	294	1.18	1.89
104	NMC F_2^d/F_2^p	[26]	123	133	1.08	0.68
106	NMC σ^p_{red}	[26]	201	372	1.85	6.89
108	CDHSW F_2^p	[27]	85	72	0.85	-0.99
109	CDHSW F_3^p	[27]	96	80	0.83	-1.18
110	CCFR F_2^p	[28]	69	70	1.02	0.15
111	CCFR xF_3^p	[29]	86	31	0.36	-5.73
124	NuTeV $\nu\mu\mu$ SIDIS	[30]	38	24	0.62	-1.83
125	NuTeV $\bar{\nu}\mu\mu$ SIDIS	[30]	33	39	1.18	0.78
126	CCFR $\nu\mu\mu$ SIDIS	[31]	40	29	0.72	-1.32
127	CCFR $\bar{\nu}\mu\mu$ SIDIS	[31]	38	20	0.53	-2.46
145	H1 σ_r^b	[32]	10	6.8	0.68	-0.67
147	Combined HERA charm production	[33]	47	59	1.26	1.22
159	HERA1 Combined NC and CC DIS	[34]	579	591	1.02	0.37
169	H1 F_L	[35]	9	17	1.92	1.7

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201	E605 Drell-Yan process	[37]	119	116	0.98	-0.15
203	E866 Drell-Yan process, $\sigma_{pd}/(2\sigma_{pp})$	[38]	15	13	0.87	-0.25
204	E866 Drell-Yan process, $Q^3 d^2\sigma_{pp}/(dQdx_F)$	[39]	184	252	1.37	3.19
225	CDF Run-1 electron A_{ch}, $p_{T\ell} > 25$ GeV	[40]	11	8.9	0.81	-0.32
227	CDF Run-2 electron A_{ch}, $p_{T\ell} > 25$ GeV	[41]	11	14	1.24	0.67
234	DØ Run-2 muon A_{ch}, $p_{T\ell} > 20$ GeV	[42]	9	8.3	0.92	-0.02
240	LHCb 7 TeV 35 pb^{-1} W/Z $d\sigma/dy_\ell$	[43]	14	9.9	0.71	-0.73
241	LHCb 7 TeV 35 pb^{-1} A_{ch}, $p_{T\ell} > 20$ GeV	[43]	5	5.3	1.06	0.30
260	DØ Run-2 Z rapidity	[44]	28	17	0.59	-1.71
261	CDF Run-2 Z rapidity	[45]	29	48	1.64	2.13
266	CMS 7 TeV 4.7 fb^{-1}, muon A_{ch}, $p_{T\ell} > 35$ GeV	[46]	11	12.1	1.10	0.37
267	CMS 7 TeV 840 pb^{-1}, electron A_{ch}, $p_{T\ell} > 35$ GeV	[47]	11	10.1	0.92	-0.06
268	ATLAS 7 TeV 35 pb^{-1} W/Z cross sec., A_{ch}	[48]	41	51	1.25	1.11
281	DØ Run-2 9.7 fb^{-1} electron A_{ch}, $p_{T\ell} > 25$ GeV	[14]	13	35	2.67	3.11
504	CDF Run-2 inclusive jet production	[49]	72	105	1.45	2.45
514	DØ Run-2 inclusive jet production	[50]	110	120	1.09	0.67
535	ATLAS 7 TeV 35 pb^{-1} incl. jet production	[51]	90	50	0.55	-3.59
538	CMS 7 TeV 5 fb^{-1} incl. jet production	[52]	133	177	1.33	2.51

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New for CT14

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CT14 Global Analysis -Theory

Theory Input:

- Parametrize PDFs at Q_0=1.295 GeV

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

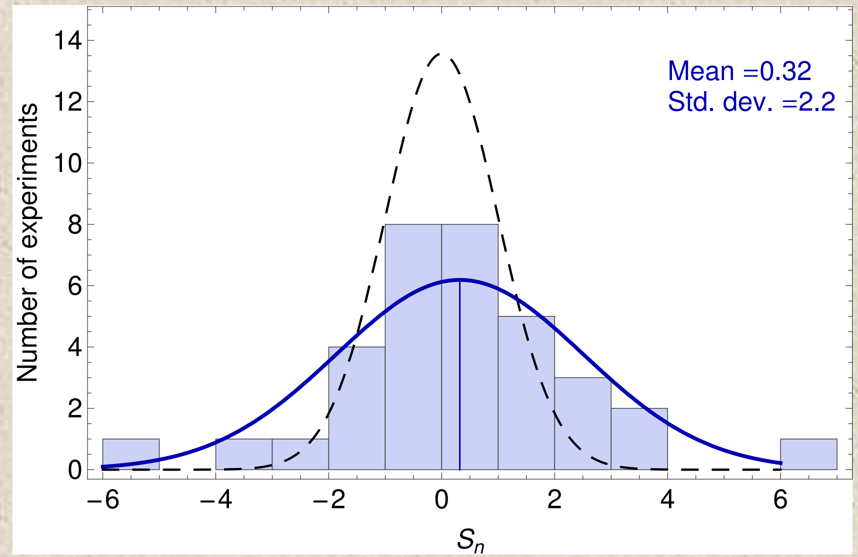
- $P_a(x)$ are Bernstein Polynomials
  - Less correlations between parameters, better control at $x \rightarrow 0,1$
- Increase number of parameters in CT14 for more flexibility
  - 28 parameters for CT14 vs 25 for CT10
  - Most visible in gluon, d/u at large x, both d/u, dbar/ubar at small x and s quarks (assume s=sbar)
- Use S-ACOT-χ for heavy quarks (m_c=1.3 GeV, m_b=4.75 GeV pole mass)
- For NNLO PDFs use NNLO calculations for all except jet production and DIS CC (use NLO for NNLO PDFs)
- Only use data with Q^2>4 GeV^2 and W^2>12.6 GeV^2 to minimize nonperturbative effects

CT14 PDF Error Estimation

First consider consistency of data:

Map χ^2 distribution $(\chi_n^2, N_n) \rightarrow S_n$ "Effective Gaussian Variable" for each experiment

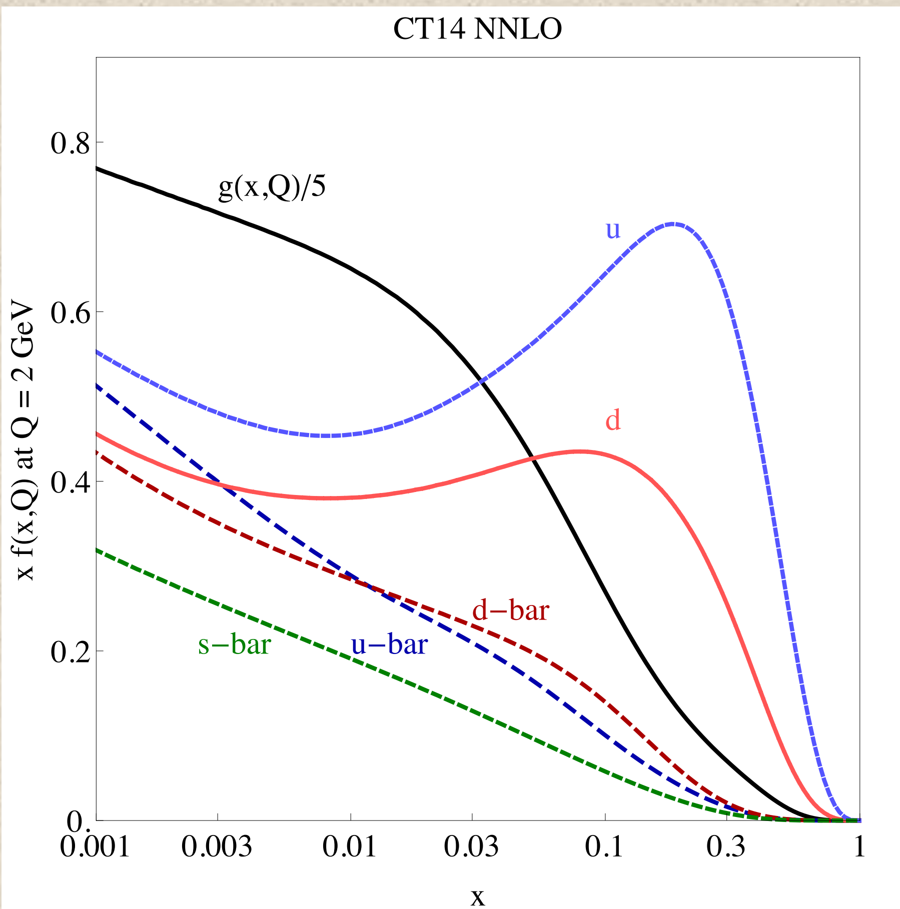
- $-1<S_n<1$ is good fit
- $S_n>2$ is bad fit
- $S_n<-2$ is anomalously good fit
- Ideal distribution would have Std. dev.=1



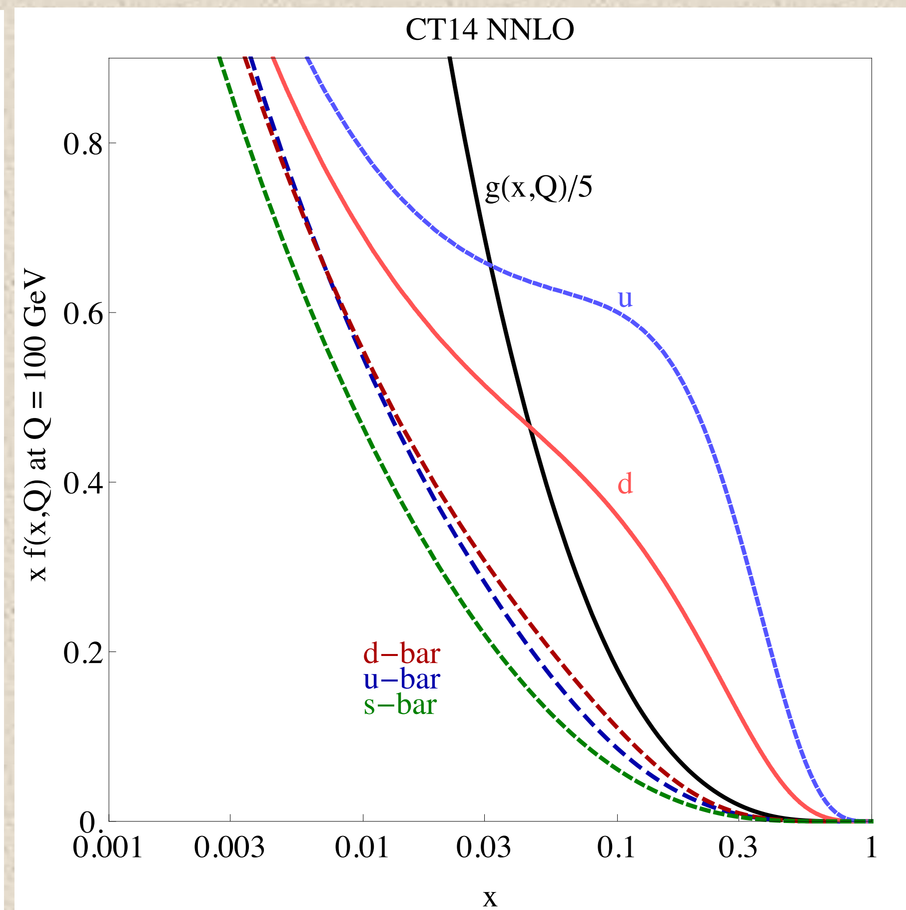
Hessian Method

- 56 Eigenvector sets, to estimate errors for observables
- 90% CL tolerance $\Delta\chi^2 < T^2=100$ (68% CL=> T/1.645)
- Also require no particular experiment is fit too badly, using S_n. (Tier 2 penalty)
- Assumes quadratic dependence of χ^2 and linear dependence of observables on PDF parameters around minimum
- Lagrange Multiplier Method used to confirm Hessian results

The CT14 PDFs

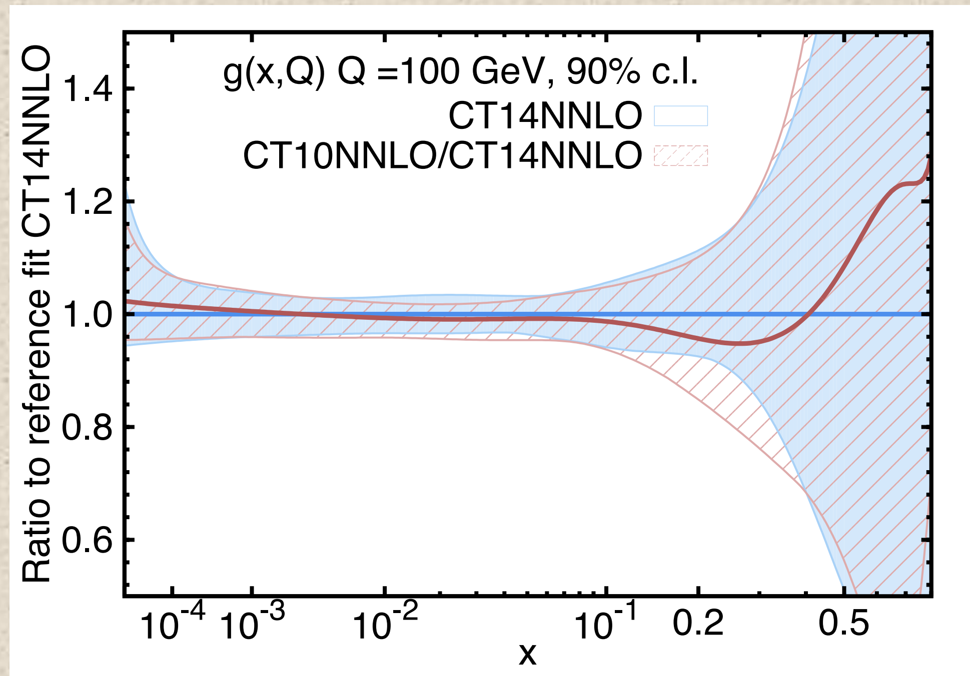


Q=2 GeV



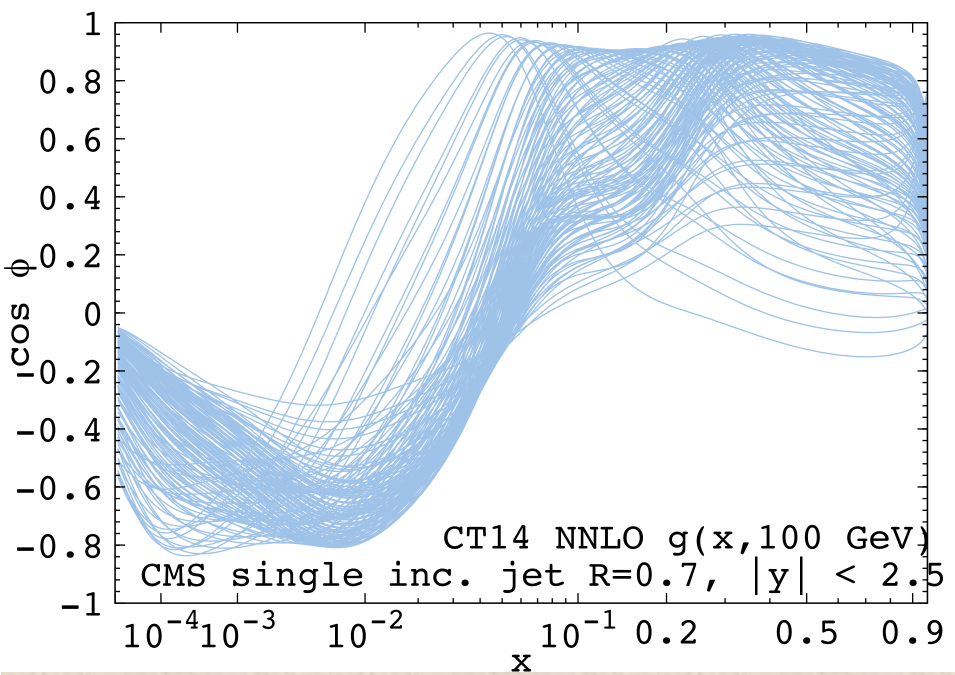
Q=100 GeV

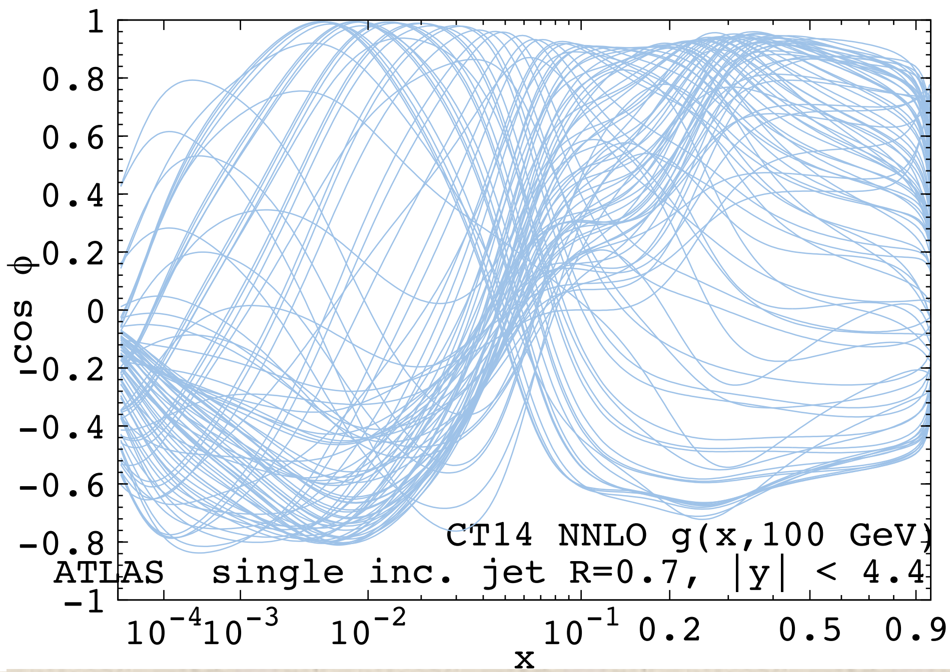
CT14 gluon PDF



- Gluon has increased 1-2% over CT10 for most of the range
- But still within CT10 errors
- Due partially to CMS data

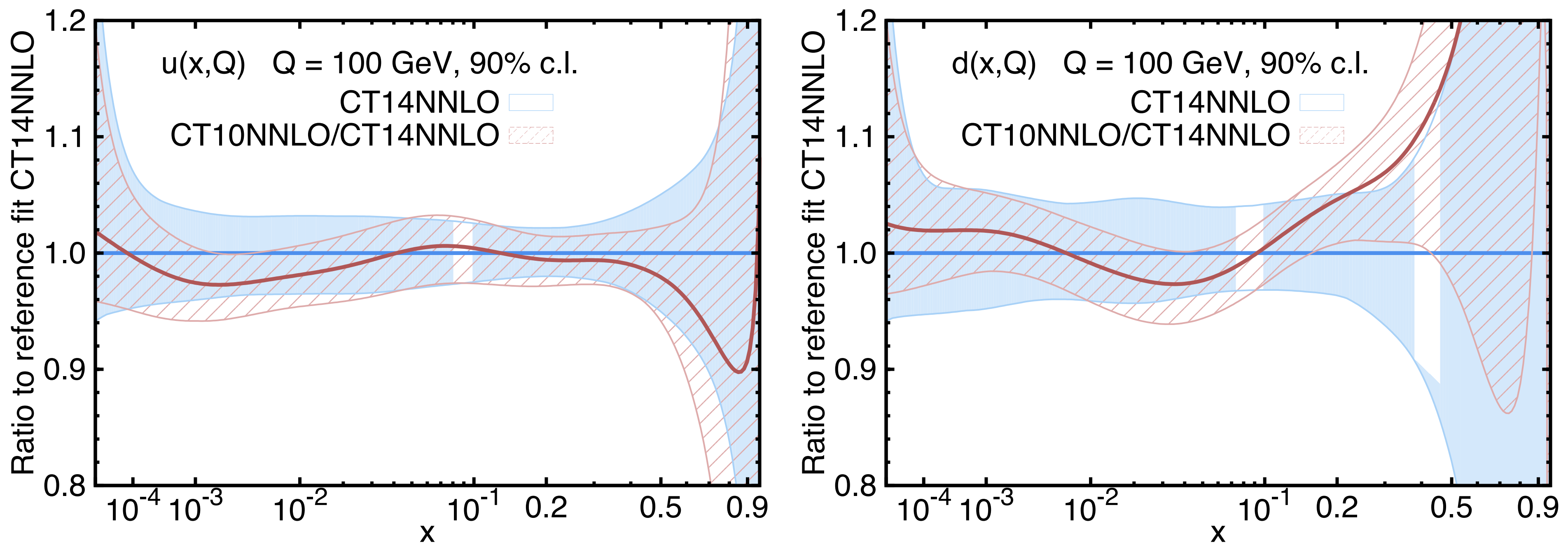
CT14 gluon PDF





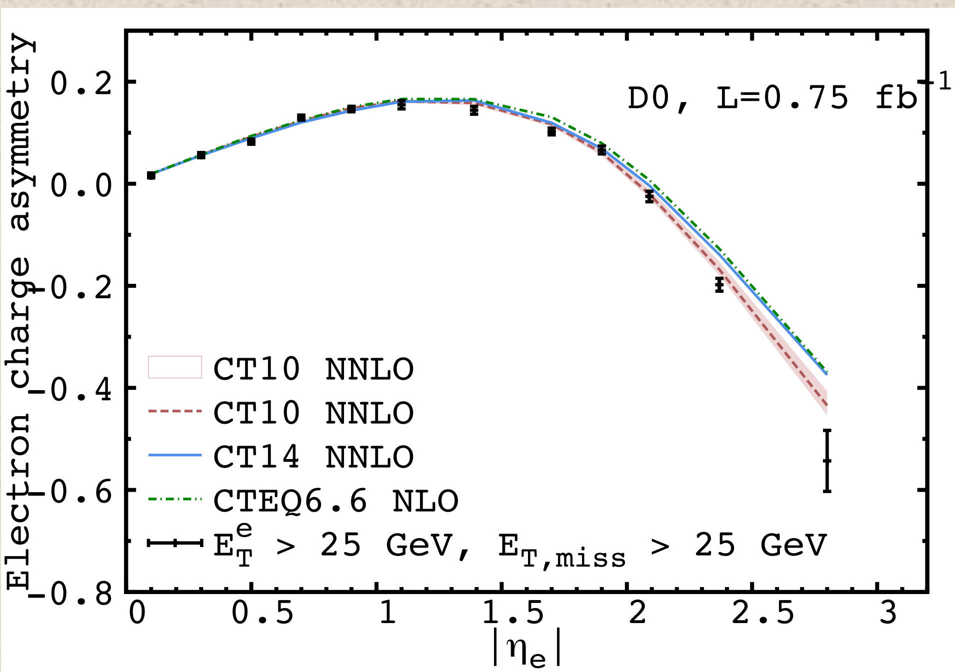
- Correlation Cosine between Data points and $f_g(x)$
- 1=Strong correlation, -1=Strong Anticorrelation
- CMS and ATLAS correlated over larger range of x than CDF/D0
- (Especially ATLAS, because of large rapidity range)
- However, ATLAS errors still large

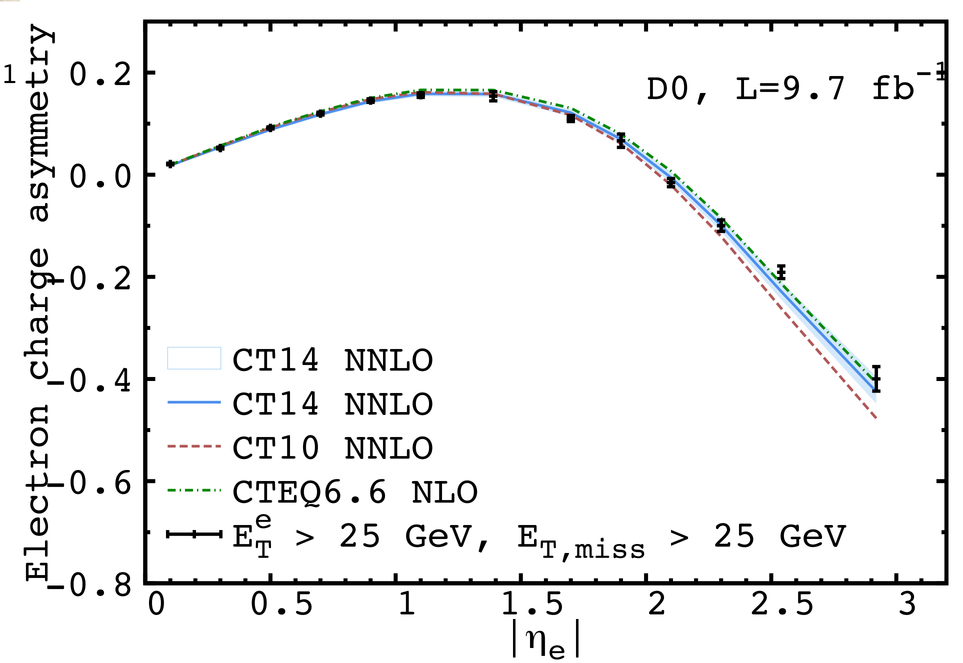
CT14 valence quark PDFs



- Increase in u and decrease in d at small $x \sim 10^{-3}$ due to increased flexibility of parametrization
- Increase in d at x~0.05 due to ATLAS/CMS/LHCb W/Z data
- Increase in u, decrease in d at large x, due to updated D0 charge asymmetry (also parametrization)

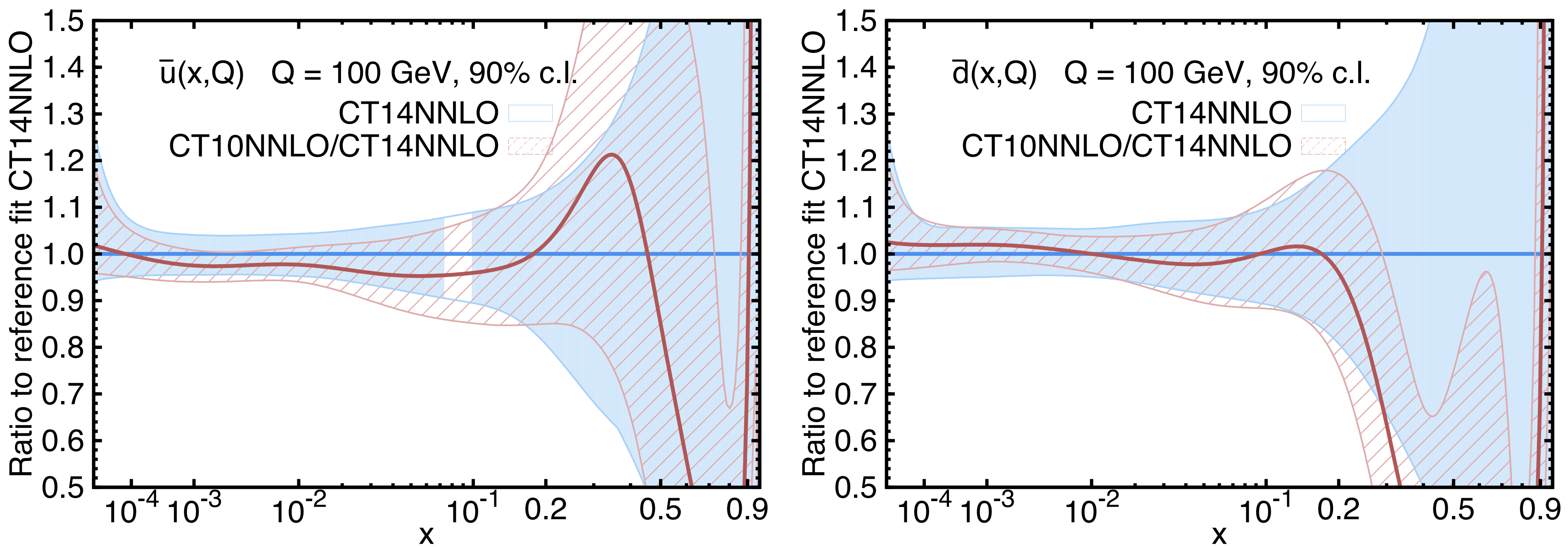
CT14 valence quark PDFs





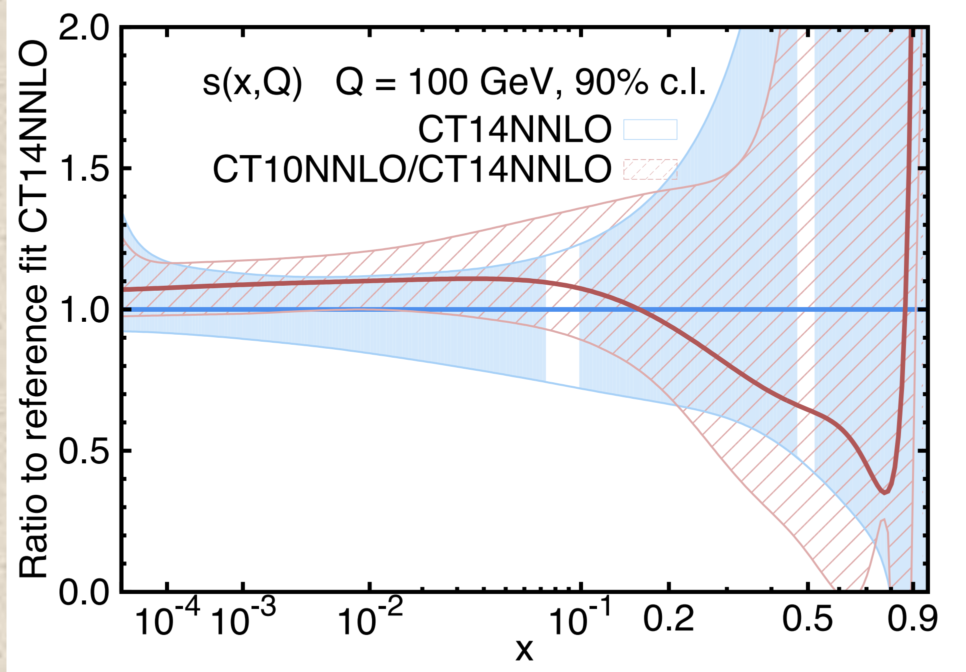
- Replacing old (L=0.75 fb^{-1}) D0 data with new (L=9.7 fb^{-1}) moves CT14 closer to earlier CTEQ6.6 than CT10.
- Reduces d/u for x>0.1

CT14 sea quark PDFs



- Change in behavior of dbar/ubar at $x<10^{-3}$ and x>0.2 due to parametrization, but data constraints are weak in that range
- In middle range of x, both ubar and dbar have increased over CT10

CT14 strange quark PDF



- Assumed s=sbar
- In region constrained by data, s has decreased sizably, but still within uncertainty limits of CT10
- Due to multiple factors
- LHC measurements of W+c may provide information on s-sbar

CT14 strange quark PDF

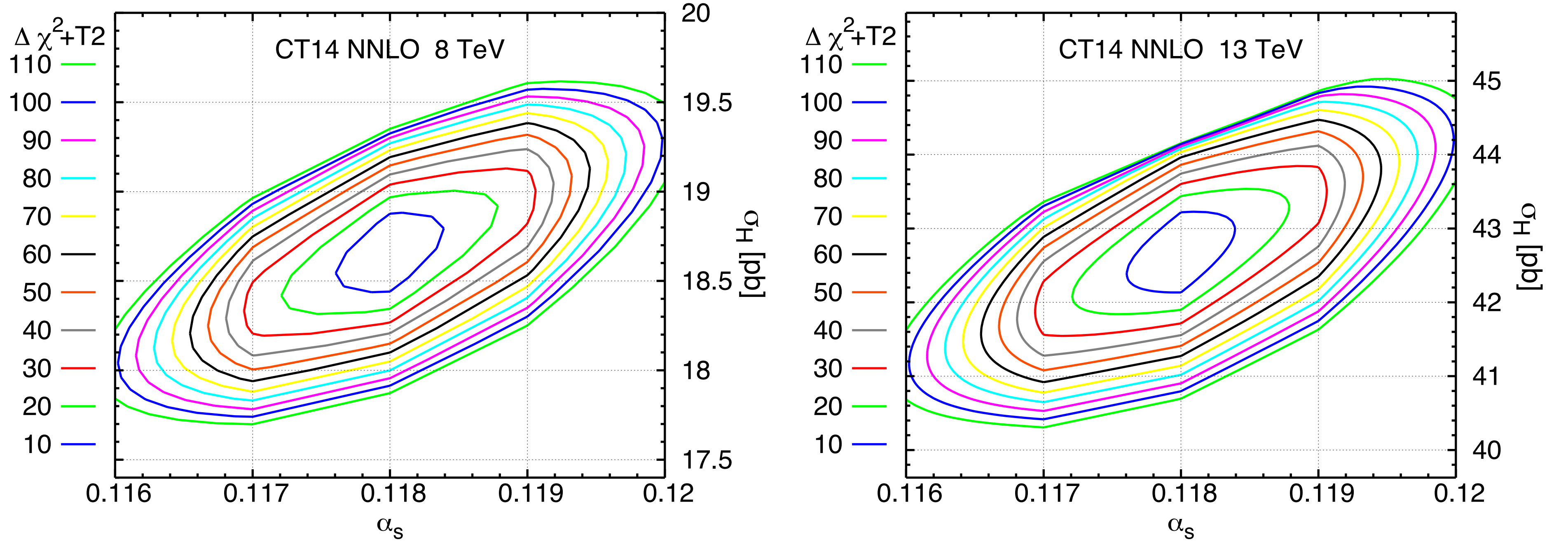
- Conflicting results from experiments:
- ATLAS $r^s = \frac{\bar{s}(x,Q)}{\bar{d}(x,Q)} = 0.96^{+0.26}_{-0.30}$ at $x = 0.023, \quad Q = 1.4$ GeV

$$r^s_{\text{CT14NNLO}} = 0.53 \pm 0.20$$
$$r^s_{\text{CT10NNLO}} = 0.76 \pm 0.17$$

- CMS $\kappa^s = \frac{\int_0^1 x\left[s(x,Q) + \bar{s}(x,Q)\right]dx}{\int_0^1 x\left[\bar{u}(x,Q) + \bar{d}(x,Q)\right]dx} = 0.52^{+0.18}_{-0.15}$ at $Q^2 = 20$ GeV^2
- NOMAD $\kappa^s = 0.591 \pm 0.019$

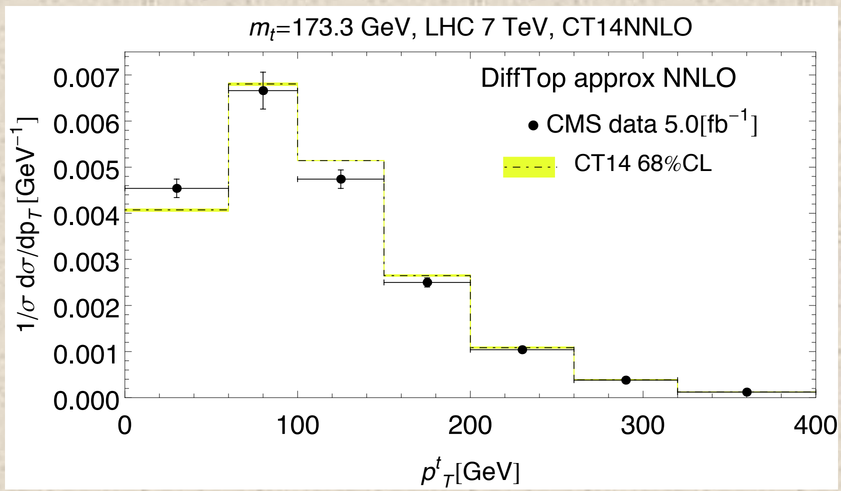
$$\kappa^s_{\text{CT14NNLO}} = 0.62 \pm 0.14$$
$$\kappa^s_{\text{CT10NNLO}} = 0.73 \pm 0.11$$

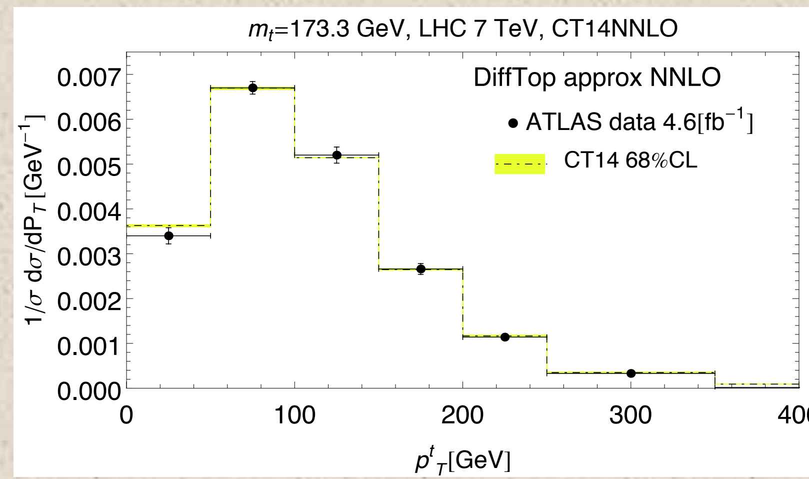
PDF uncertainties on gg->H

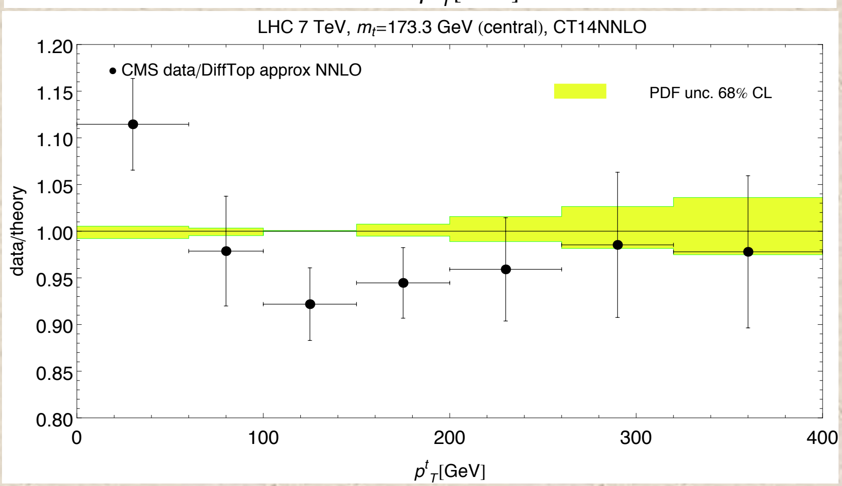


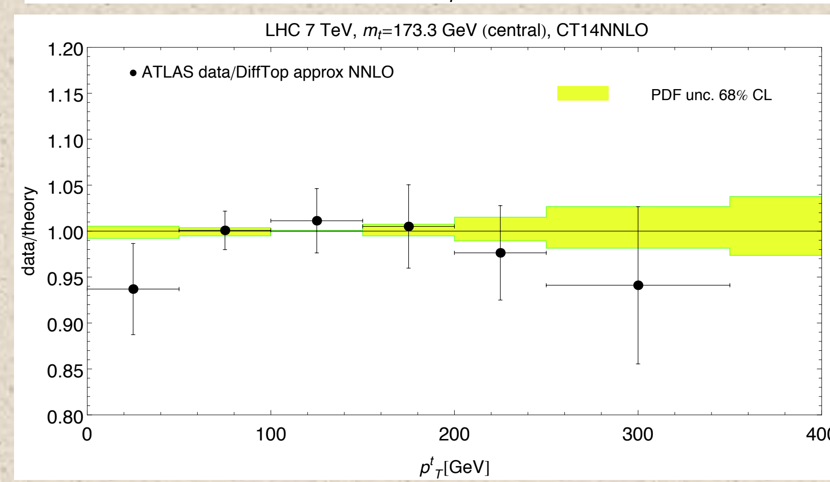
- Error ellipse computed using with iHixs, using Lagrange Multiplier method
- Strong correlation between α_s and cross section
- Central value prediction agrees perfectly with MMHT2014 and NNPDF3.0

PDFs and ttbar production









- Computed with DiffTop (Guzzi, Lipka, Moch JHEP 2014)
- CT14 PDF errors are smaller than experimental errors

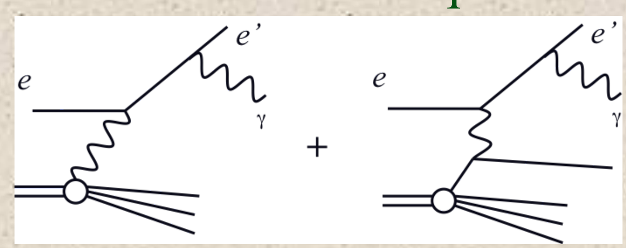
Other PDF Sets

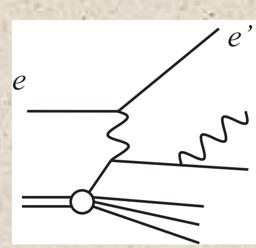
- CT14NLO, including Hessian error sets
- CT14LO, with 1-loop or 2-loop running of α_s
- Series of (N)NLO with $\alpha_s(M_Z)$=0.111 – 0.123
- Sets with Heavy Quark schemes with up to 3, 4, and 6 active flavors
- Sets with nonperturbative charm
- Sets which include QED evolution at order α

CT14QED 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

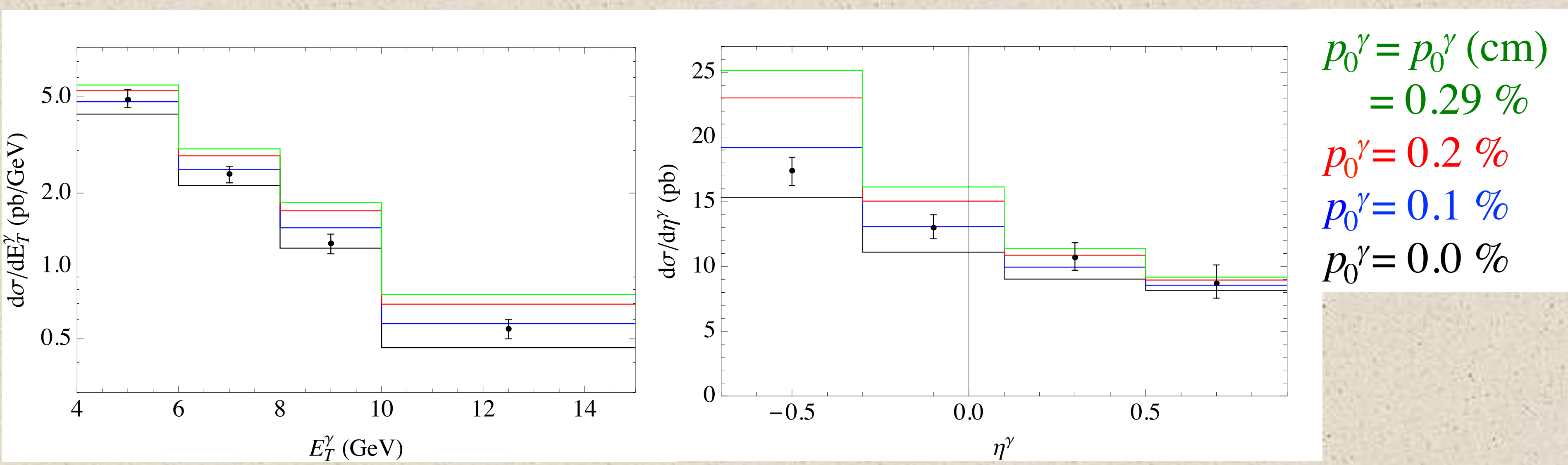
2) First CT QED PDF set
   - Evolve α at LO and α_s at NLO
   - Photon PDF is one-parameter generalization of radiative ansatz off CT14NLO, specified by initial photon momentum fraction p_0^γ at Q_0=1.295 GeV
   - Constrained by ZEUS DIS + isolated photon data $ep \rightarrow e\gamma + X$
   - Required new calculation, consistently combining photon-initiated contributions and quark initiated contributions





Distributions

1) Photon Variables E_T^γ and η^γ

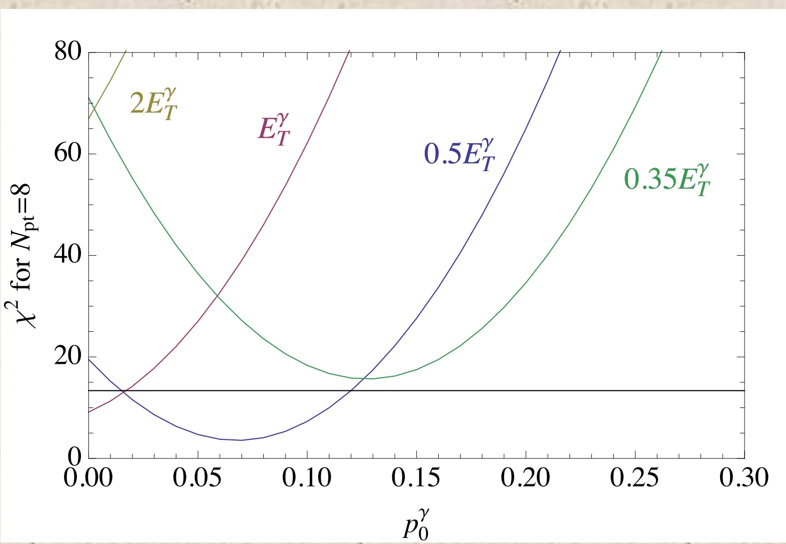


(Smooth Isolation, $\mu_F = 0.5 E_T^\gamma$)

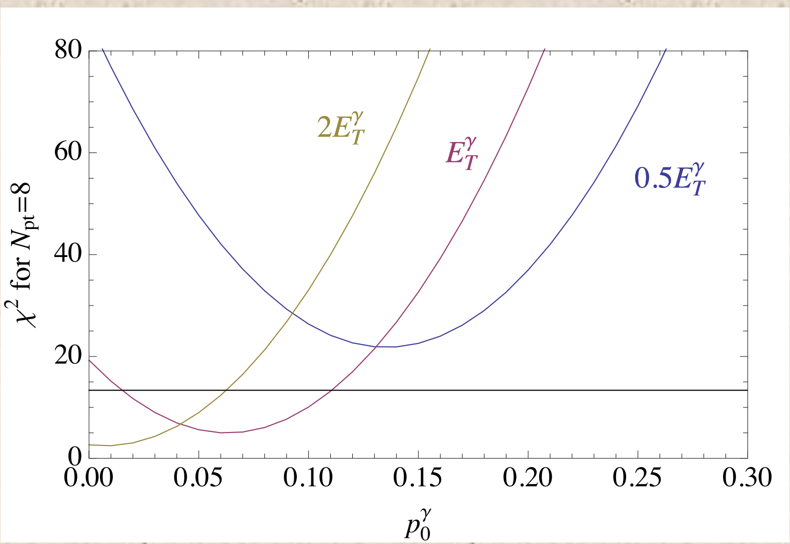
- Theoretical uncertainties due to factorization scale, and isolation prescription
- We used two isolation models:
  - Frixione smooth isolation $E_{q'} < \frac{1}{9} E_\gamma \left(\frac{1-\cos r}{1-\cos R} \right)$ for $r = \sqrt{\Delta\eta_{q'\gamma}^2 + \Delta\varphi_{q'\gamma}^2} < R = 1$
  - Sharp isolation with photon fragmentation function

    $E_{q'} < \frac{1}{9} E_\gamma$ for $r < R = 1$ (Use Aleph LO fragmentation)

Limits on Photon PDF



Smooth Isolation



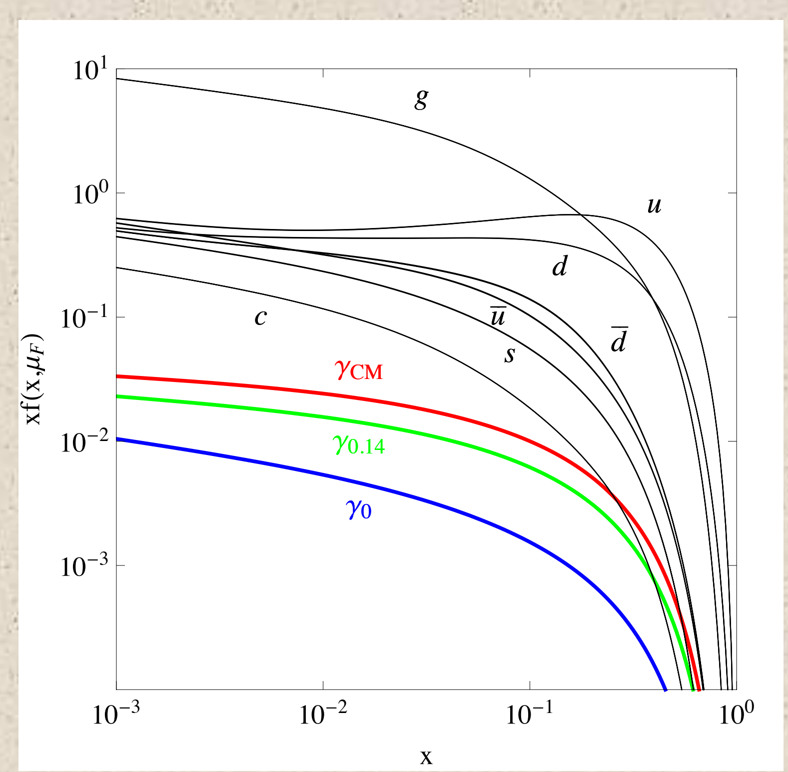
Sharp Isolation

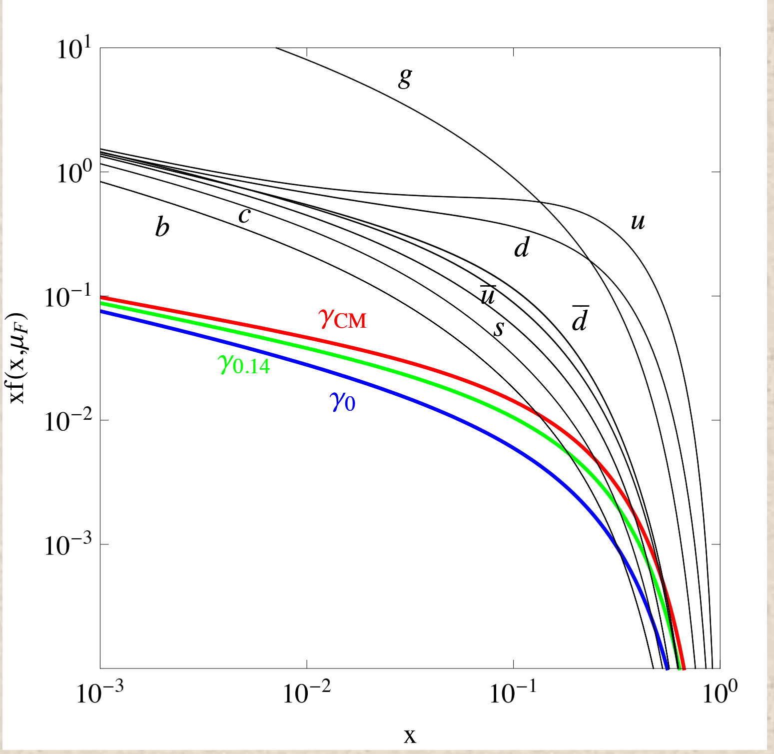
- Different χ^2 curves for choice of isolation and scale μ_F
- 90% C.L. for $N_{pt} = 8$ corresponds to $\chi^2 = 13.36$
- Obtain $p_0^\gamma \leq 0.14\%$ at 90 % C.L. independent of isolation prescription

  (More generally, constrains $\gamma(x)$ for $10^{-3} < x < 2x10^{-2}$.)

- "Current Mass" ansatz has $\chi^2 > 46$ for any choice of isolation and scale

Photon PDFs (in proton)





γ momentum fraction:

$p^{\gamma}(Q)$	$\gamma(x,Q_0)=0$	$\gamma(x,Q_0)=0.14\%$
$Q = 3.2$ GeV	0.05%	0.19%
$Q = 85$ GeV	0.22%	0.35%

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

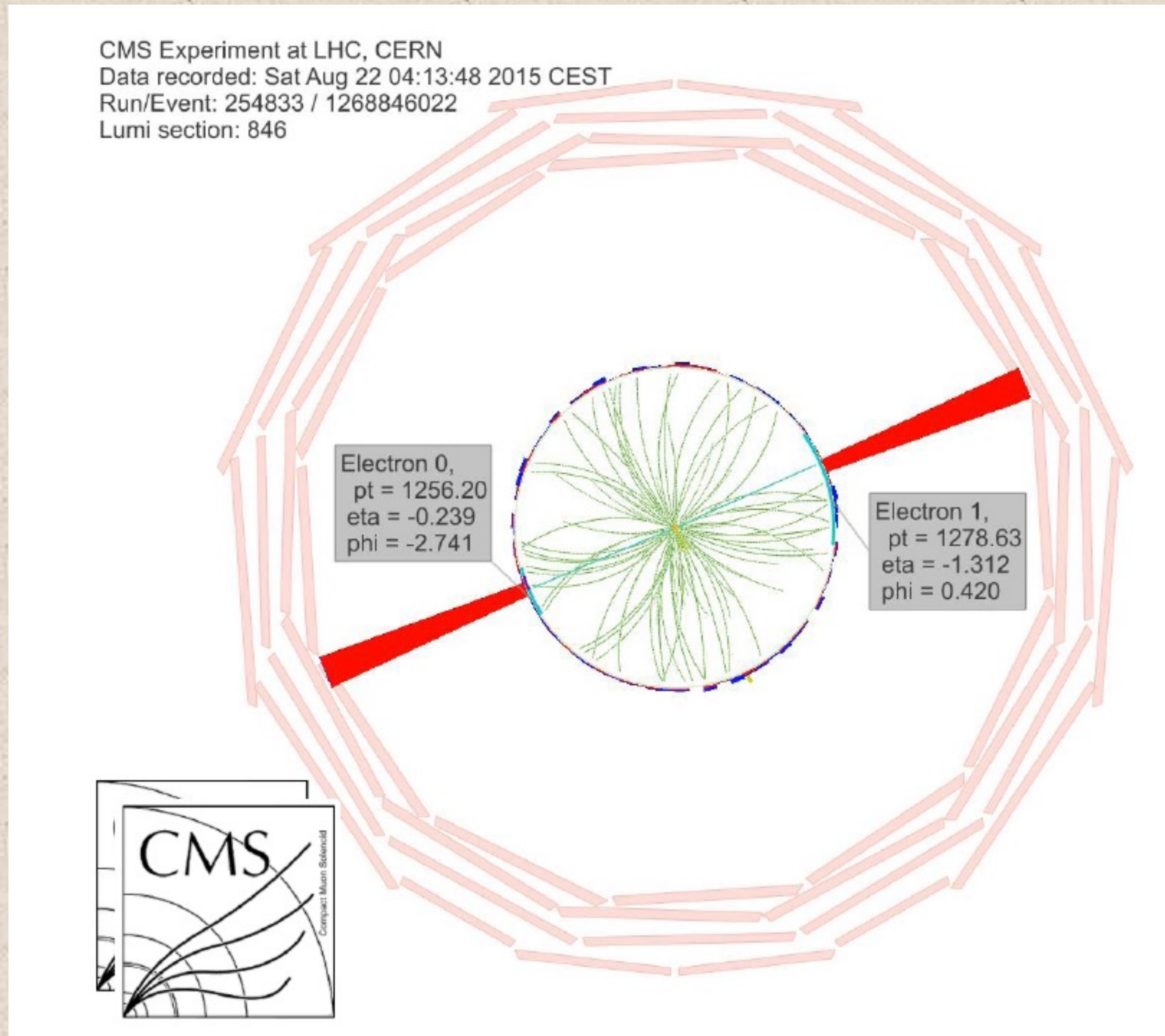
Initial Photon PDF still ← significant at large Q.

Conclusions

- The CTEQ-TEA group has been very busy.
- CT14 PDFs are first CT PDFs to include LHC data.
- CT14QED PDFs are first CT PDFs to include QED evolution, necessary for consistent EW corrections
- Data from current LHC run will further constrain PDFs
- Necessary for precision SM and BSM predictions at high energy colliders

CMS-DP-2015-039 ; CERN-CMS-DP-2015-039

Event Display of a Candidate Electron-Positron Pair with an Invariant Mass of 2.9 TeV


CMS Experiment at LHC, CERN
Data recorded: Sat Aug 22 04:13:48 2015 CEST
Run/Event: 254833 / 1268846022
Lumi section: 846
Electron 0,
pt = 1256.20
eta = -0.239
phi = -2.741
Electron 1,
pt = 1278.63
eta = -1.312
phi = 0.420
CMS
Compact Muon Solenoid

SM rate is small

SM Background Expectations

mass range	SM Bkg Expection
>1 TeV	0.21
> 2 TeV	0.007
> 2.5 TeV	0.002

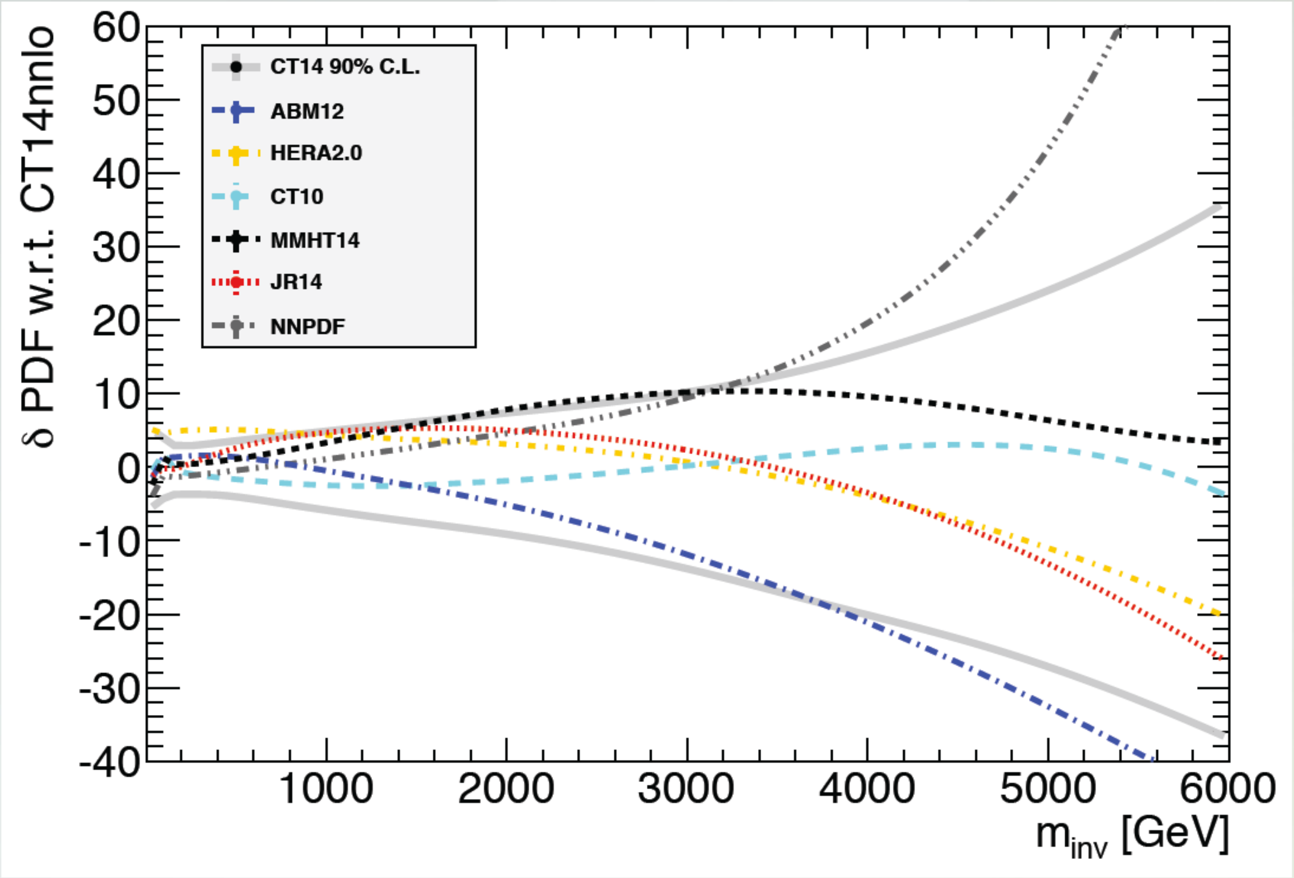
electrons are required to satisfy:
E_T > 35 GeV
$|\eta| < 1.4442$ or $1.566 < |\eta| < 2.5$
pass high energy ele selection

in addition one electron must have
$|\eta| < 1.4442$

- the values of this table have been obtained from the mass spectrum distribution in CERN-CMS-PD-2015-037 and scaled to the luminosity of 65pb^{-1}, which is the luminosity of full 50ns dataset

SM cross section is 7.7E-3 fb for 2.8 < M_{ee} < 3.0 TeV.

NC DY - CT14nnlo PDF Variation, and Choice.



CT14 PDF uncertainty is about +10% -14% around 2.9 TeV, at the 68% CL.

Daniel Hayden

Backup Slides

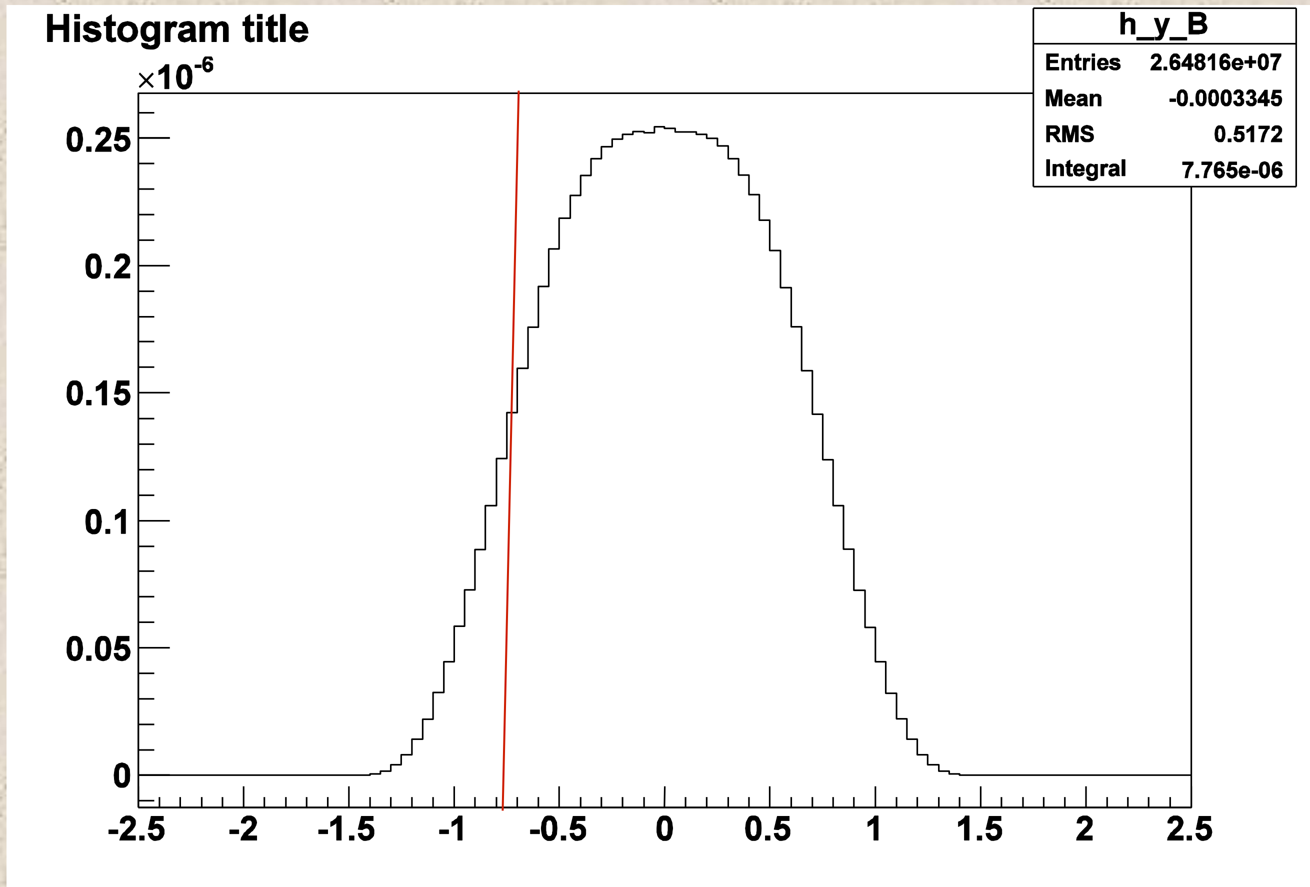
CMS @ 13 TeV LHC with 65 1/pb

Event Kinematic Details

	electron 0	electron 1
E_T	1260 GeV	1280 GeV
η	-0.24	-1.31
ϕ	-2.74 rad	0.42 rad
charge	-1	+1
mass	2.91 TeV	
$\cos\theta^*_{CS}$	-0.49	
y	-0.78	

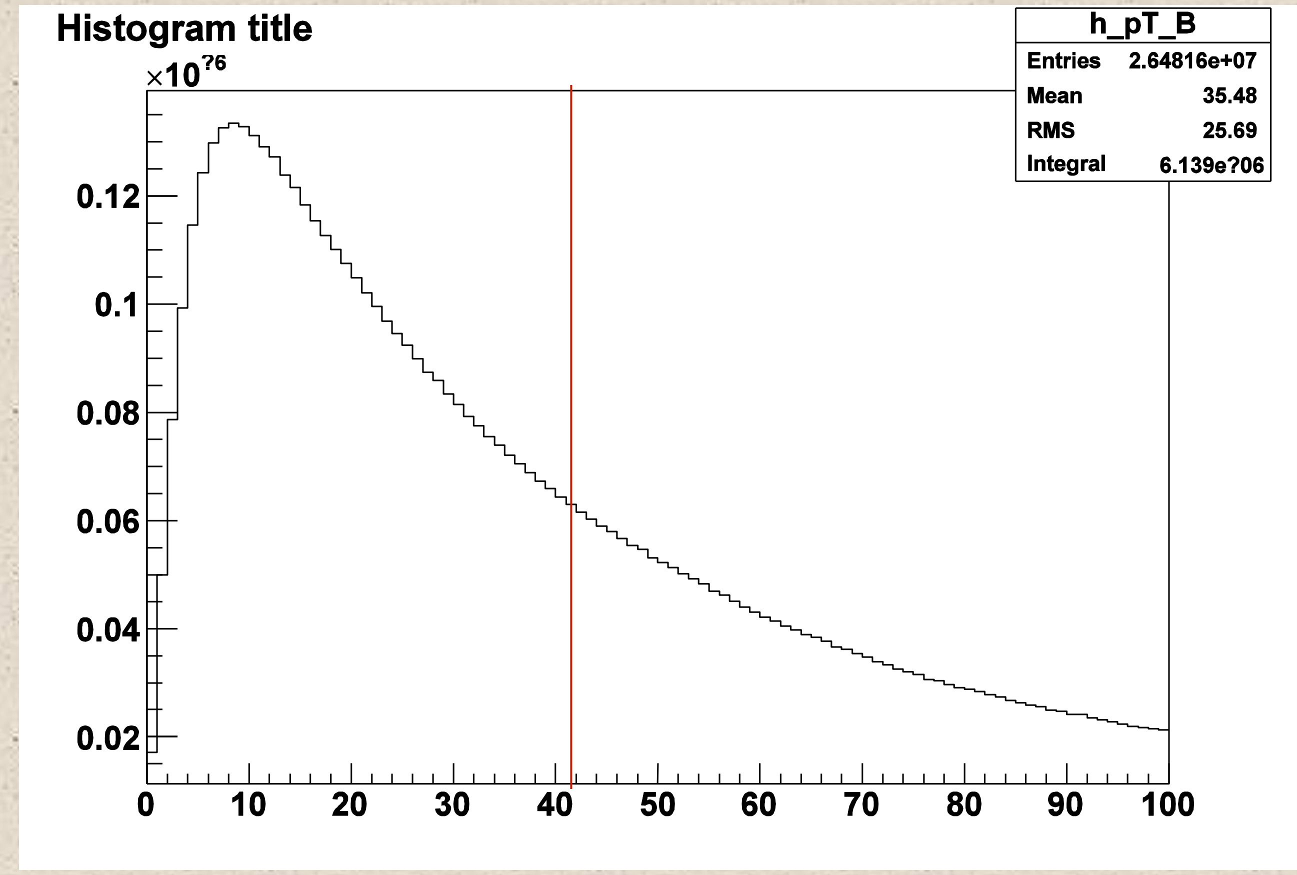
pT of this Drell-Yan pair is 41.6 GeV, and its p_Z < 0

Rapidity distribution of a 2.9 TeV Drell-Yan pair



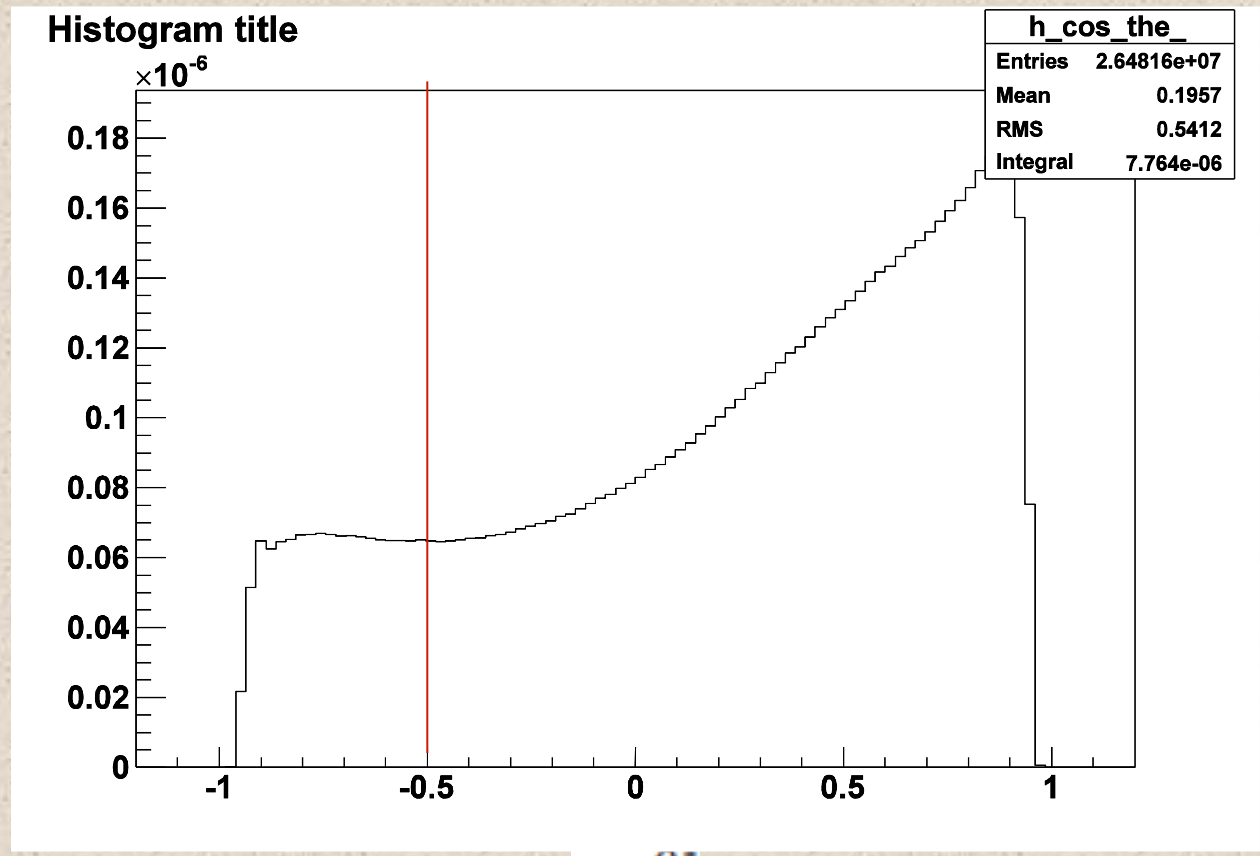
y= -0.78

pT distribution of a 2.9 TeV Drell-Yan pair



pT = 41.6 GeV

$\cos\theta^*$ distribution for a 2.9±0.1 TeV Drell-Yan pair



$\cos\theta^*$

$\cos(\theta^*) = -0.49$ and $P\_Z < 0$

“Modified” Collins-Soper angle

The angle θ^* is then taken as the angle between this z-axis and the outgoing negatively charged lepton, using the formula

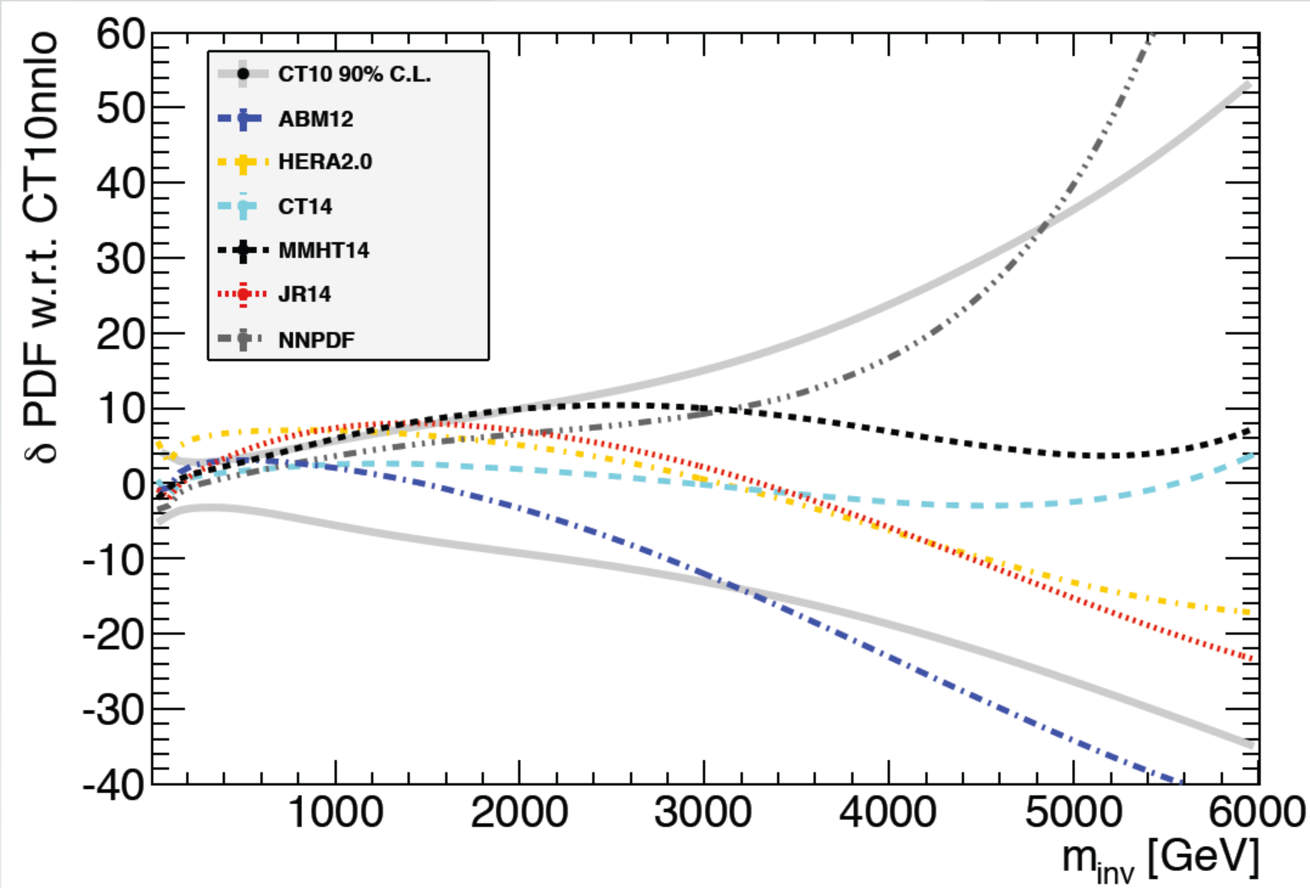
$$\cos\theta^* = \frac{p_z(\ell^+\ell^-)}{|p_z(\ell^+\ell^-)|} \frac{2(p_1^+ p_2^- - p_1^- p_2^+)}{m(\ell^+\ell^-)\sqrt{m(\ell^+\ell^-)^2 + p_T(\ell^+\ell^-)^2}} ,$$

where $p_n^{\pm}$ denotes $\frac{1}{\sqrt{2}}(E \pm p_z)$ and $n = 1$ or 2 corresponds to the negatively charged or positively charged leptons, respectively. From this angle, a forward-backward asymmetry, which is sensitive to the chiral structure of the interaction, is defined as follows:

$$A_{\mathrm{FB}} = \frac{N_{\mathrm{F}} - N_{\mathrm{B}}}{N_{\mathrm{F}} + N_{\mathrm{B}}} ,$$

where N_{F} (N_{B}) is the number of events with $\cos\theta^*$ greater (smaller) than zero.

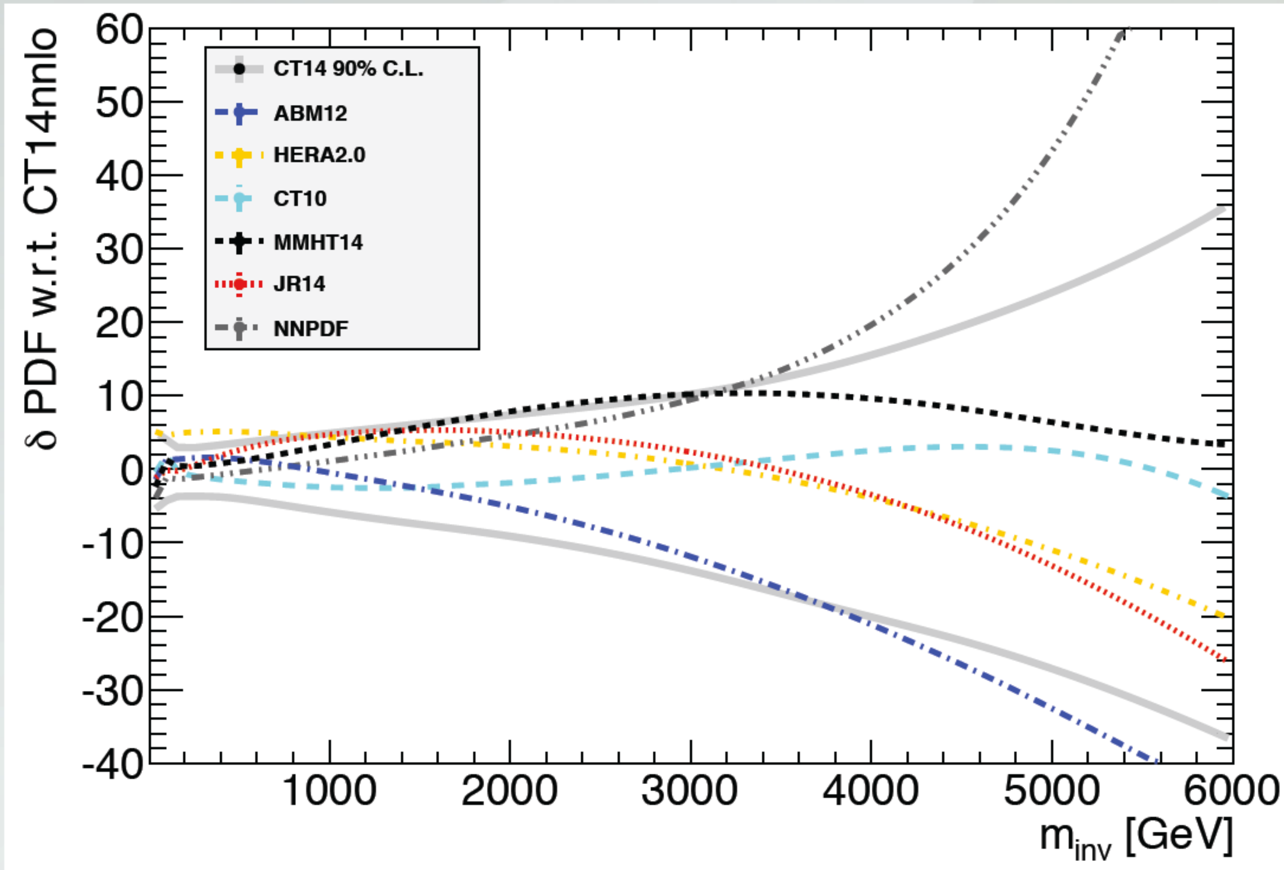
NC DY - CT10nnlo PDF Variation, and Choice.



CT10 PDF uncertainty is about ±14% around 2.9 TeV, at the 68% CL.

Daniel Haydenv

NC DY - CT14nnlo PDF Variation, and Choice.



CT14 PDF uncertainty is about +10% -14% around 2.9 TeV, at the 68% CL.

Daniel Haydenvv

Constraining Photon PDFs

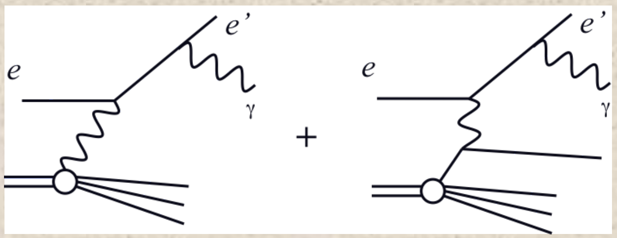
1) Global fitting
   - Isospin violation, momentum sum rule lead to constraints in fit
   - We find p_0^γ can be as large as ~ 5% at 90%CL, much more than **CM** choice

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 $\alpha\,\gamma(x)$.

$ep \to e\gamma + X$

Subprocess contributions:

LL Emission off Lepton line

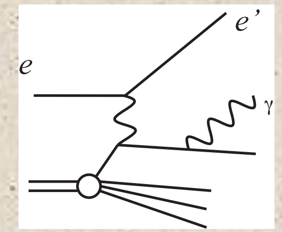


Both quark-initiated and photon-initiated contributions are $\sim \alpha^3$ if $\gamma(x) \sim \alpha$

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)

Zeus Experimental Cuts

Photon Cuts

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

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

Lepton Cuts

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

$139.8° < \theta_{\ell'} < 171.8°$

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

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 $r = \sqrt{\Delta\eta_{q'\gamma}^2 + \Delta\varphi_{q'\gamma}^2} < R = 1$

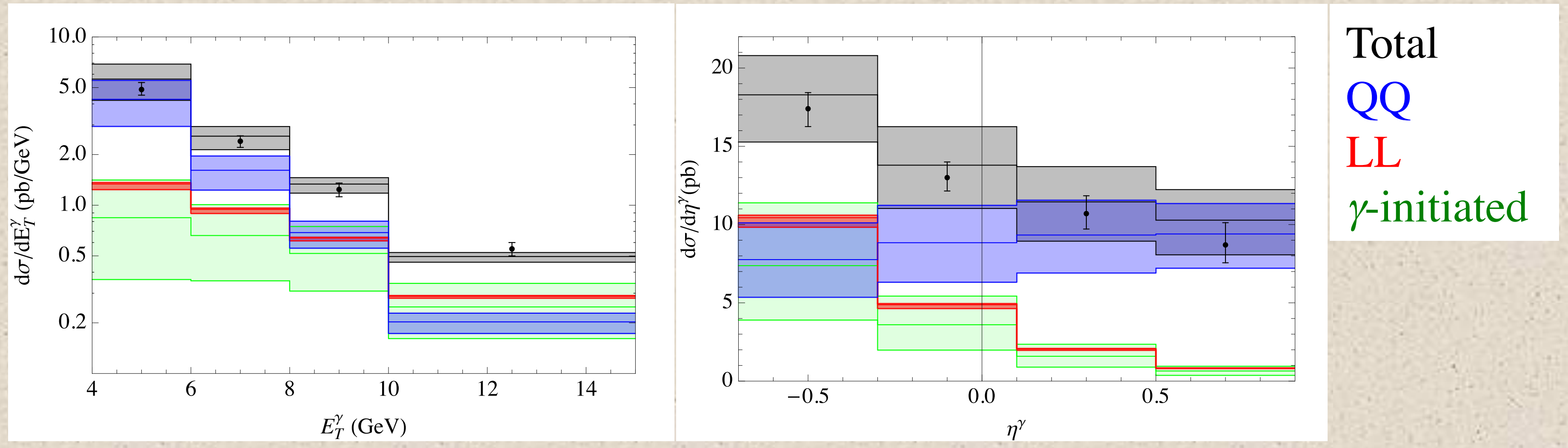
- Removes fragmentation contribution

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

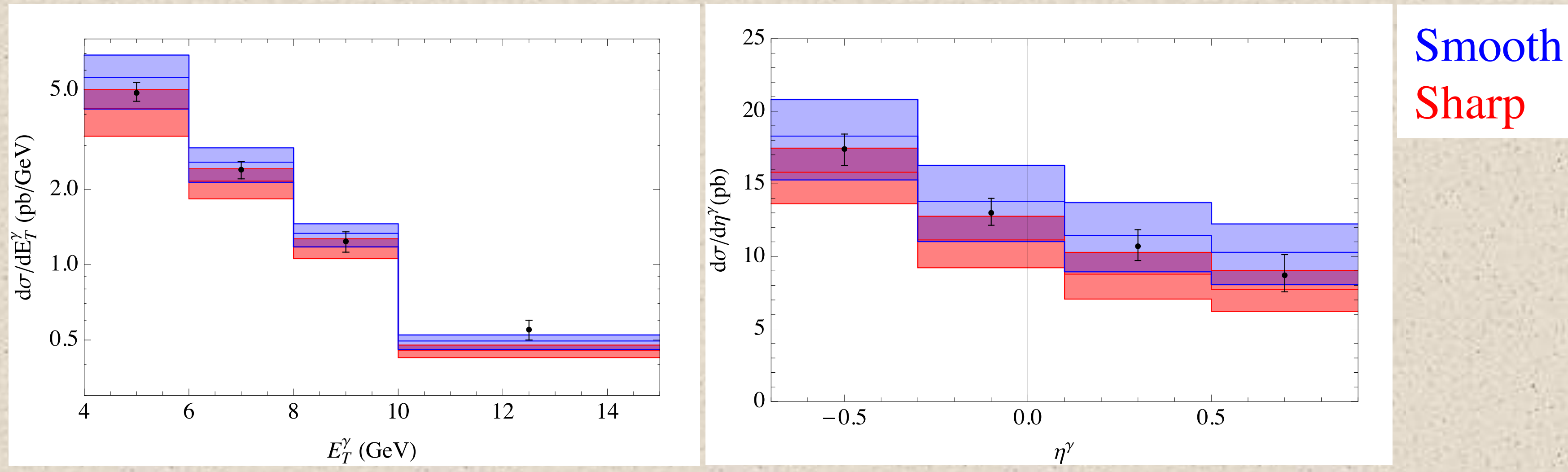


$(p_0^\gamma = 0,$ Smooth Isolation, $0.5E_T^\gamma < \mu_F < 2E_T^\gamma)$

- 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

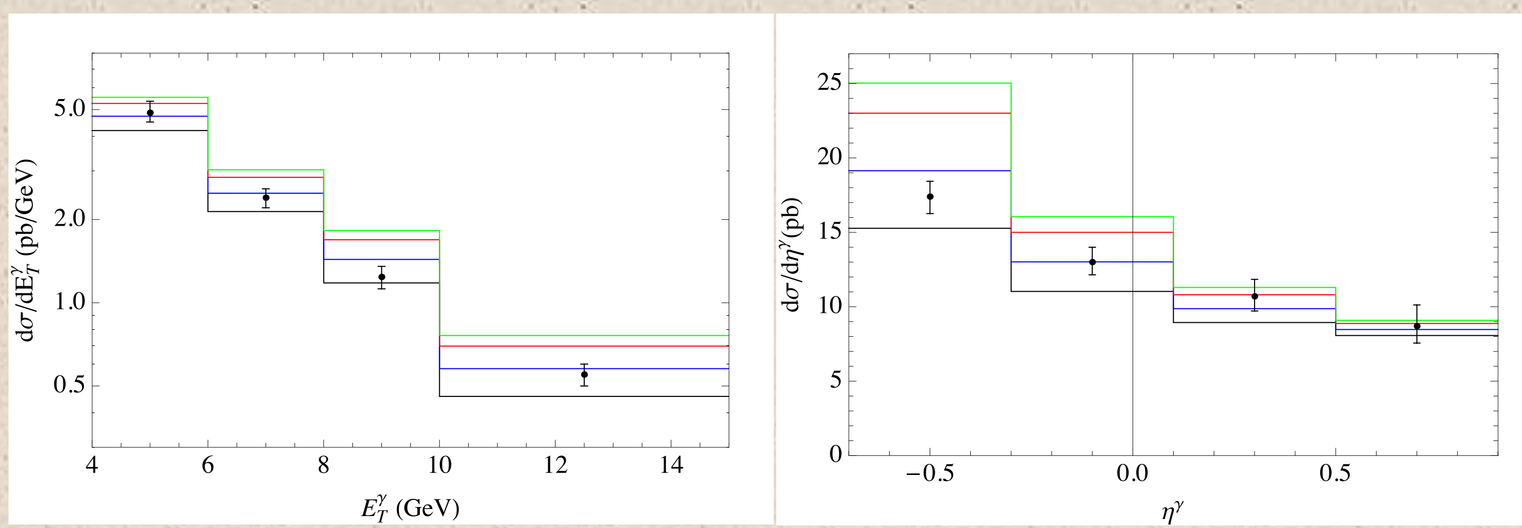


$$(p_0^\gamma = 0, \; 0.5E_{T\gamma} < \mu_F < 2E_{T\gamma})$$

- 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



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

$p_0^\gamma = 0.2$ %

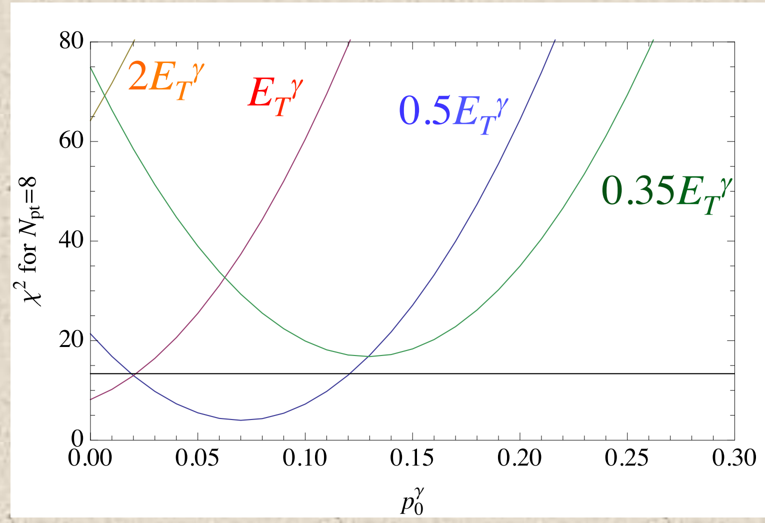
$p_0^\gamma = 0.1$ %

$p_0^\gamma = 0.0$ %

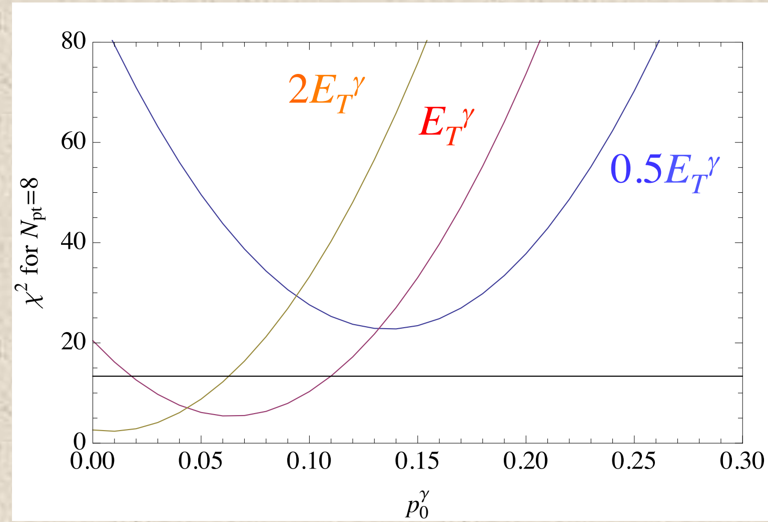
(Smooth Isolation, $\mu_F = 0.5 E_T^\gamma$)

- 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

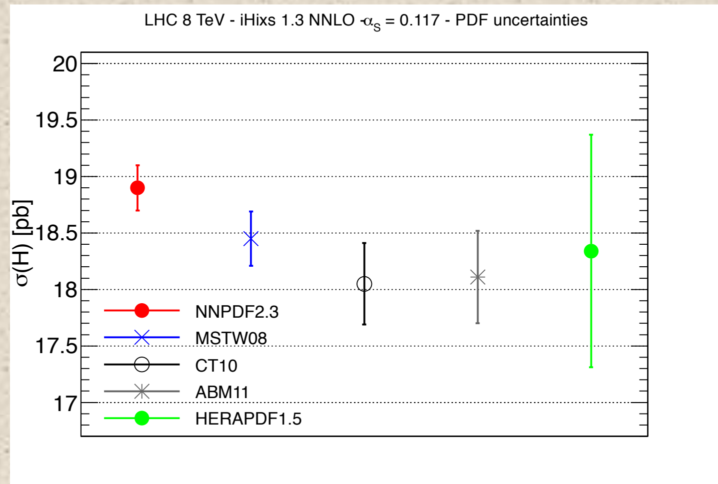
(More generally, constrains $\gamma(x)$ for $10^{-3} < x < 2x10^{-2}$.)

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

Conclusions

- CT1X update in progress
  - New LHC data, New parametrizations, …
- CT10 IC sets available
- CT10 H extreme sets for Higgs studies available
  - LM analysis confirms standard Hessian for this process
- 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 predicted by current mass ansatz

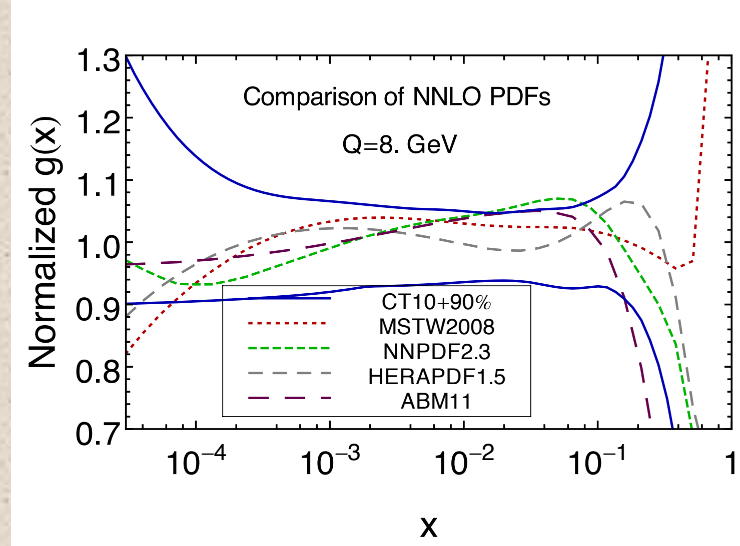
PDF Benchmarking and MetaPDFs



Benchmarking-

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

Ball et al, JHEP 1304 (2013) 125



MetaPDFs-

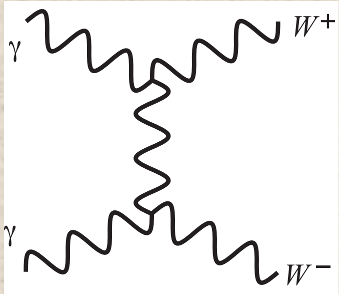
Combine different PDF groups in a Meta-PDF set, to compare systematic uncertainties

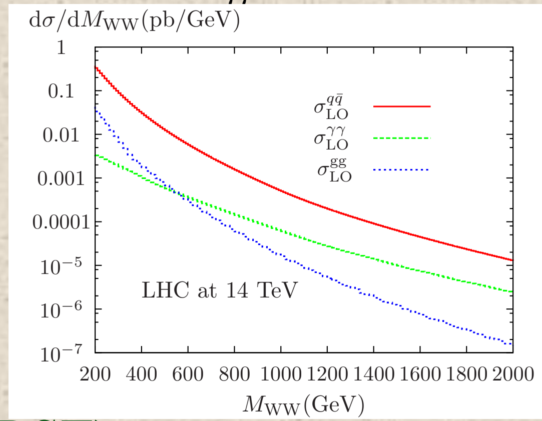
Gao and Nadolsky, arXiv:1401.0013[hep-ph]

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 α effects in parton evolution
2) Photon induced processes can be kinematically enhanced.

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





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:

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

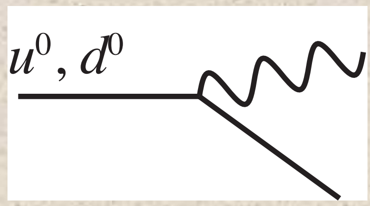
$$\frac{dg}{dt} = \frac{\alpha_s}{2\pi}\left(P_{gg} \circ g + P_{gq} \circ \sum (q + \bar{q})\right) \qquad t = \ln Q^2$$

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

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

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

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

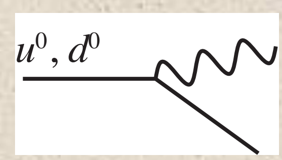


where u^0 and d^0 are "primordial" valence-type distributions of the proton.
Assumed approximate isospin symmetry for neutron.
Here, we take A_u and A_d as unknown fit parameters.

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. $\left(\overline{q}^n = \overline{q}^p \,, g^n = g^p\right)$

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

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

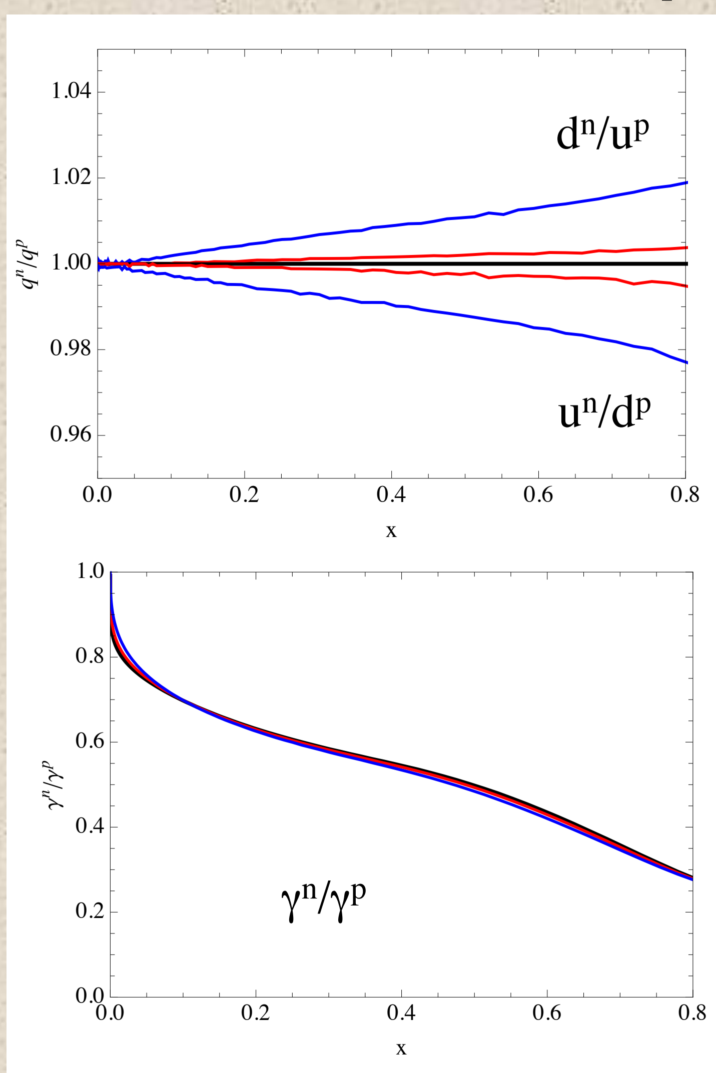
Here, assume $u^0 = u^p \equiv u^p(x,Q_0), \quad d^0 = d^p \equiv d^p(x,Q_0)$

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

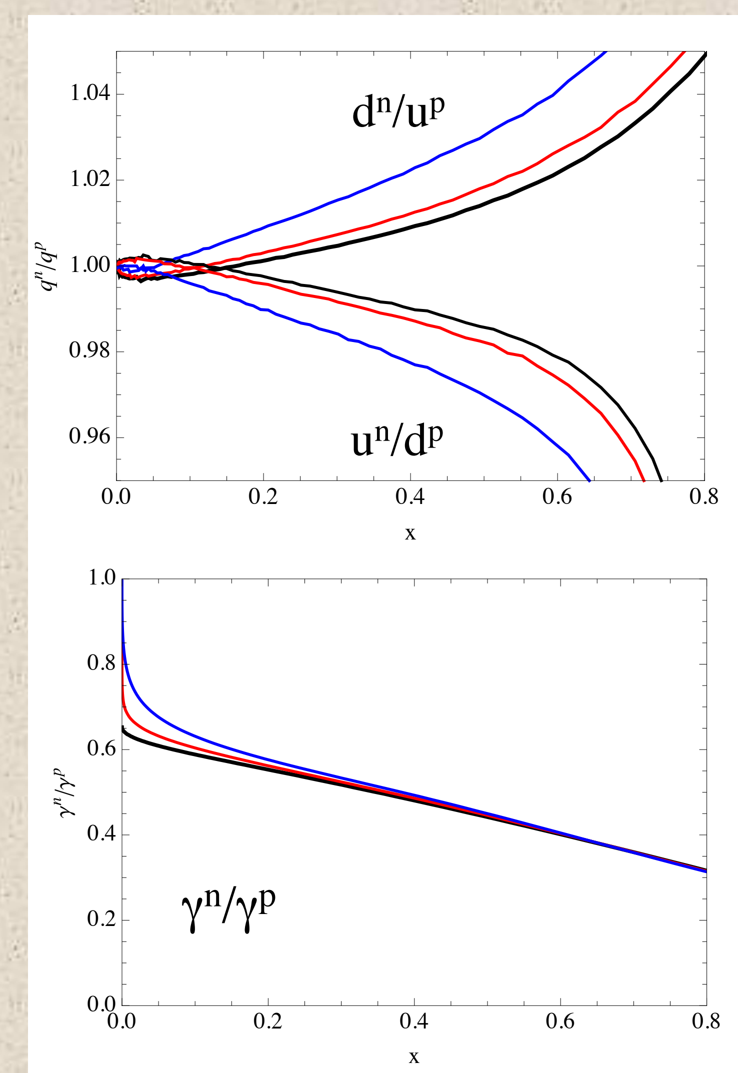
Now everything effectively specified by one unknown parameter:

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

Isospin violation



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



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

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

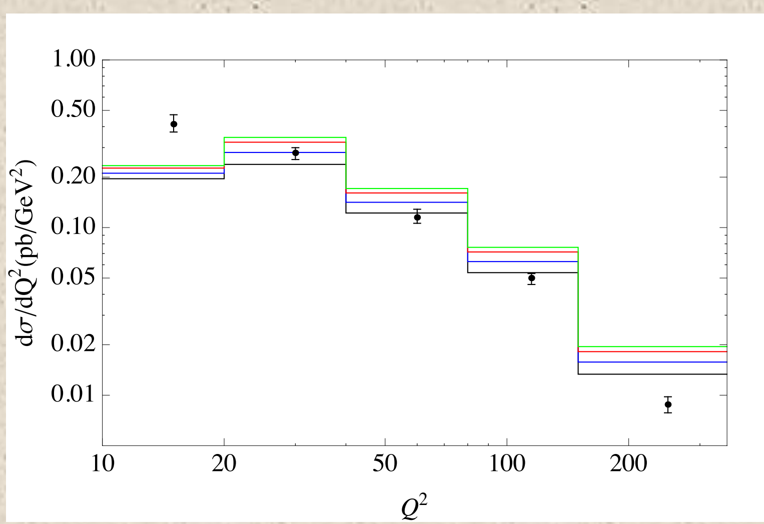
Constraints on Photon PDFs

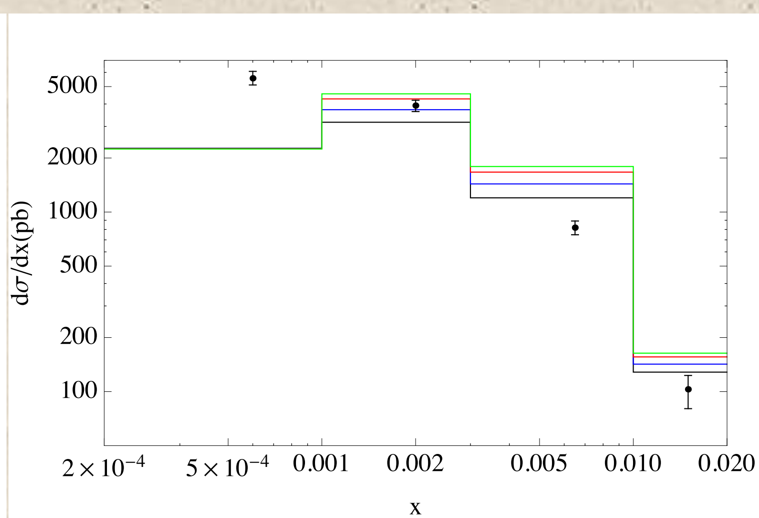
1) Global fitting
   a. Isospin violation effects
      - come from scattering off nuclei
      - perturbativity cuts on W^2 generally require x < .2-.4
      - constraints likely to be small (MRST)
   b. Momentum sum rule
      - momentum carried by photon leaves less for other partons
      - constrains 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 ~ 5%, much more than **CM** choice

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

Distributions

2) Lepton Variables Q^2 and x





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

$p_0^\gamma = 0.2$ %

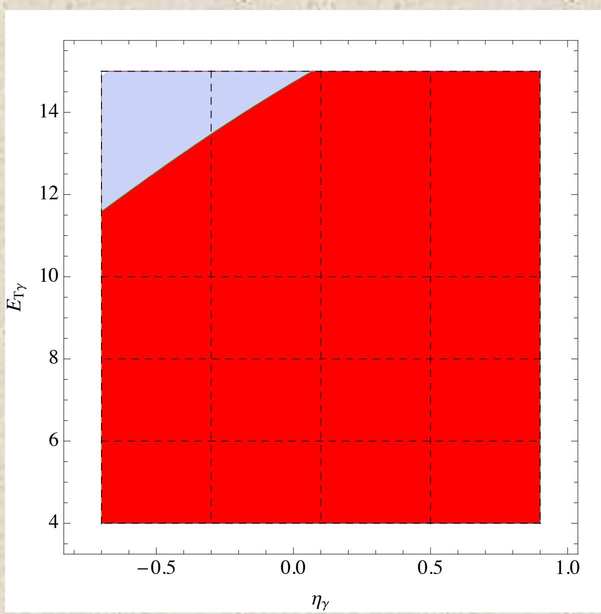
$p_0^\gamma = 0.1$ %

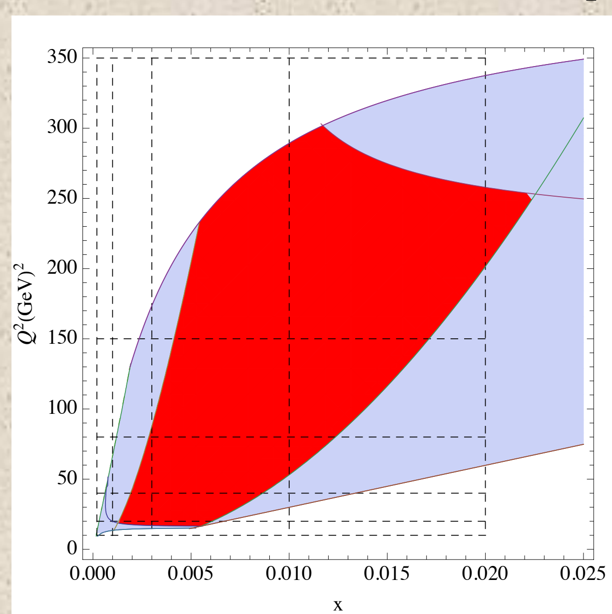
$p_0^\gamma = 0.0$ %

(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