Parton Distributions at High Energy Colliders

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In collaboration with
CTEQ-TEA

HEP seminar@PKU
June 6, 2014

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:

Sayipjamal Dulat (Xinjiang Univ.)

Tie-Jiun Hou (Academia Sinica, Taipei)

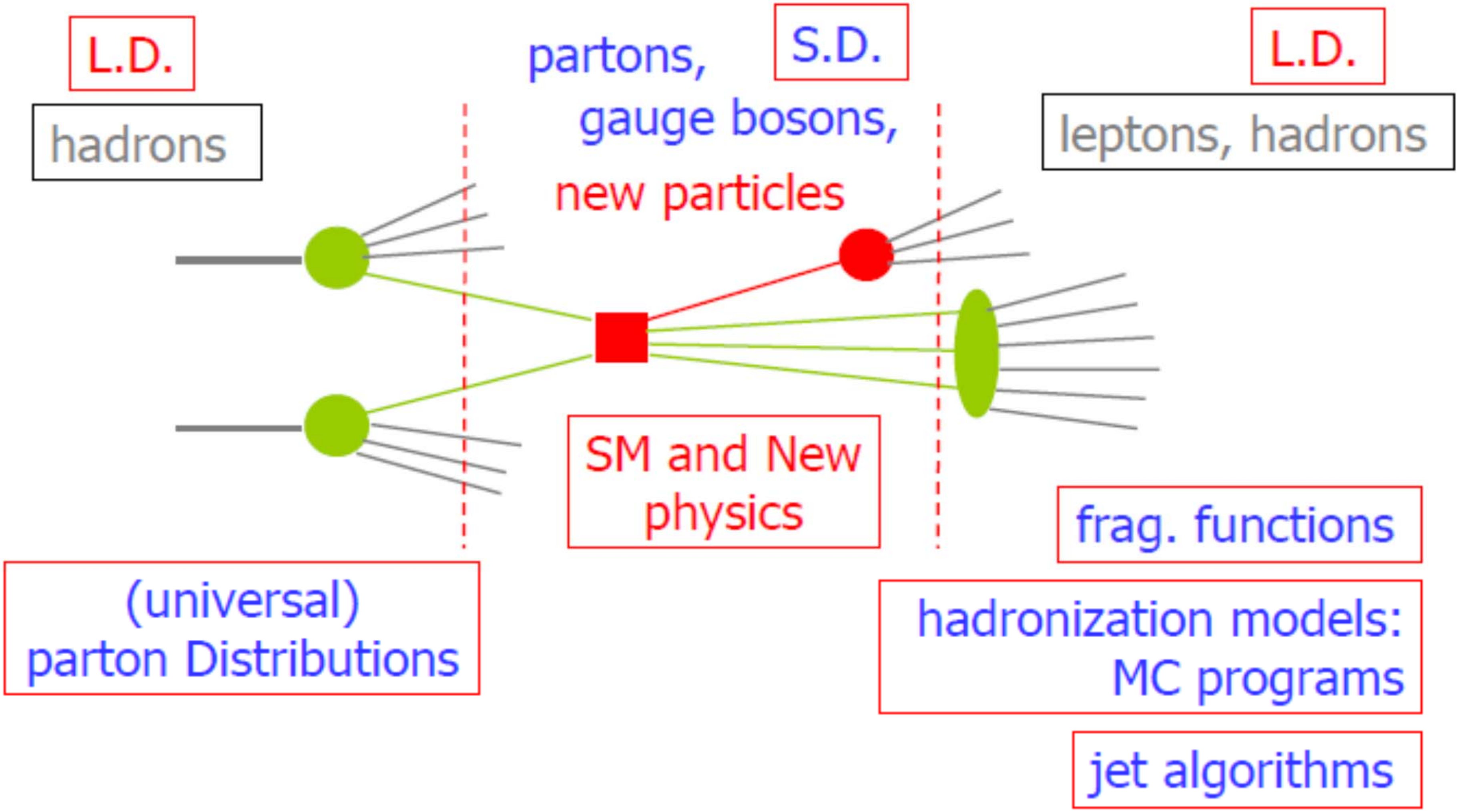
Southern Methodist Univ. -- Pavel Nadolsky, Jun Gao, Marco Guzzi

Michigan State Univ. -- Jon Pumplin, Dan Stump, Carl Schmidt, CPY

Parton Distribution Functions

Needed for making theoretical calculations to compare with experimental data

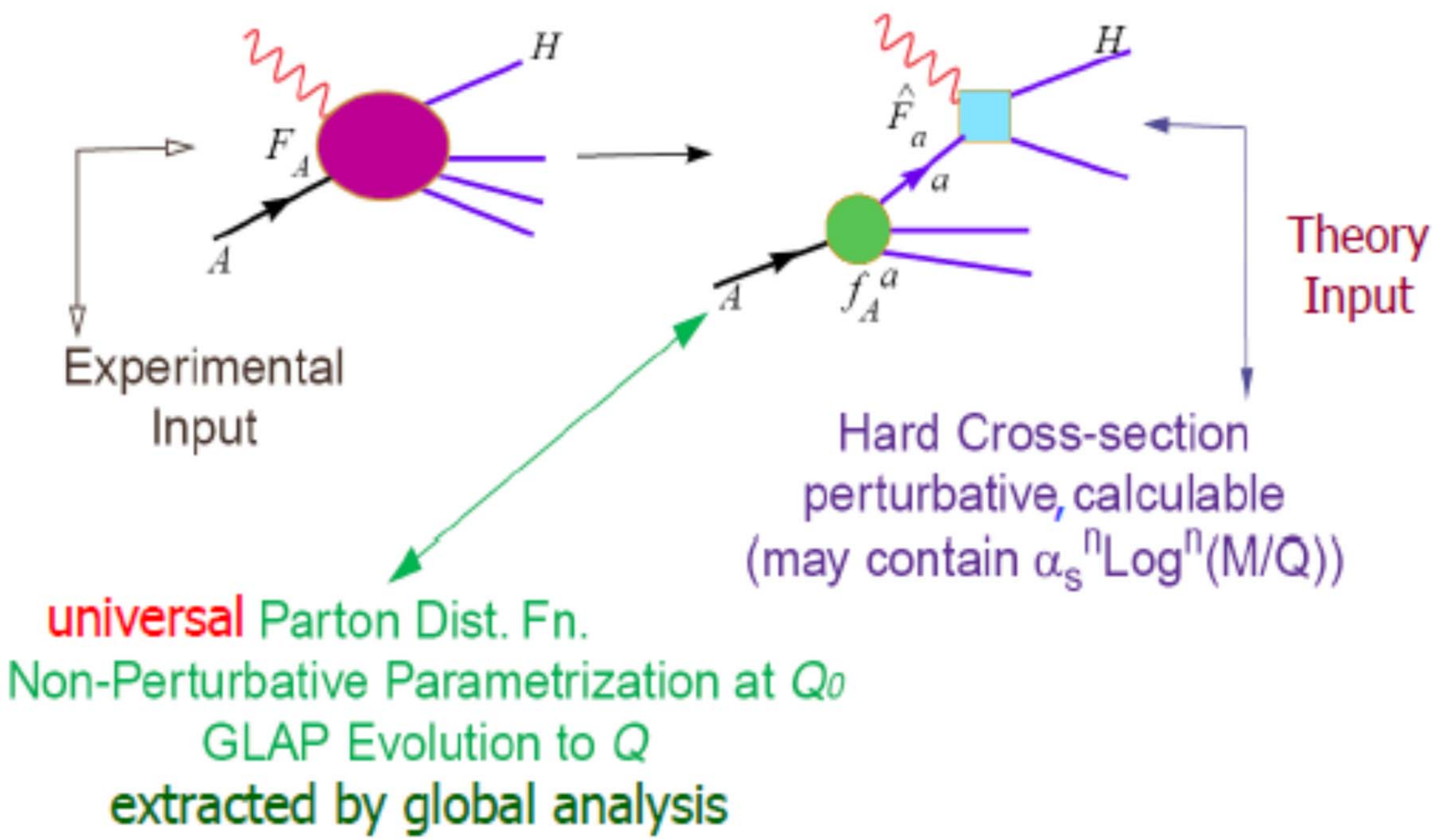
Hadron Collider Physics



Deep Inelastic Scattering process

Master Equation for QCD Parton Model
– the Factorization Theorem

$$F_A^{\lambda}(x,\frac{m}{Q},\frac{M}{Q}) = \sum_a f_A^a(x,\frac{m}{\mu}) \otimes \hat{F}_a^{\lambda}(x,\frac{Q}{\mu},\frac{M}{Q}) + \mathcal{O}((\frac{\Lambda}{Q})^2)$$

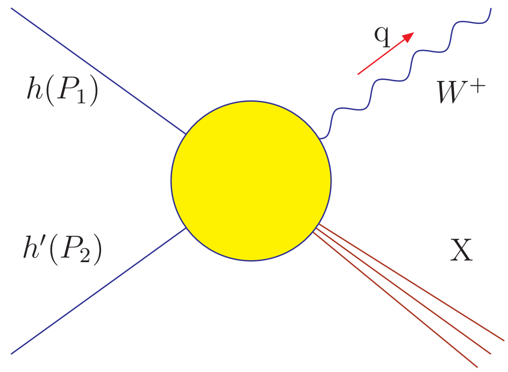


Drell-Yan Process

- Naïve parton model
- QCD improved parton model
- Factorization Theorem

Parton Model

$\sigma_{hh' \to W^+ X} =$



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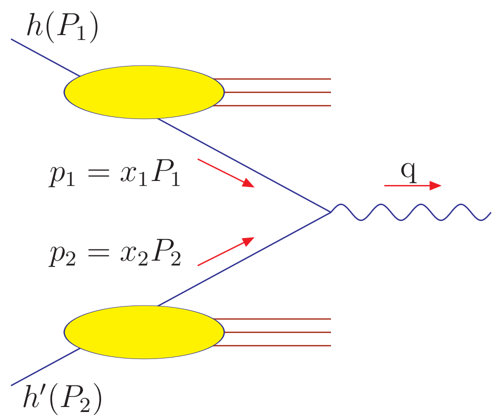


$$\sigma_{hh' \to W^+ X} = \sum_{f, f' = q, \bar{q}} \int_0^1 dx_1 dx_2 \left\{ \phi_{f/h}(x_1)\, \hat{\sigma}_{f f'} \phi_{\bar{f}'/h'}(x_2) + (x_1 \leftrightarrow x_2) \right\}$$

Partonic "Born" Cross Section of $f\overline{f}' \to W^+$

The probablility of finding a "parton" f with fraction x_1 of the hadron h momentum

Factorization Theorem

$$\sigma_{hh'} = \sum_{i,j} \int_0^1 dx_1 dx_2\, \phi_{i/h}\left(x, Q^2\right) H_{ij}\left(\frac{Q^2}{x_1 x_2 S}\right) \phi_{j/h'}\left(x_2, Q^2\right)$$

Nonperturbative, but universal, hence, measurable

IRS, Calculable in pQCD

Procedure:

(1) Compute σ_{kl} in pQCD with k, l partons

(not h, h' hadron)

$$\sigma_{kl} = \sum_{i,j} \int_0^1 dx_1 dx_2\, \phi_{i/k}\left(x_1, Q^2\right) H_{ij}\left(\frac{Q^2}{x_1 x_2 S}\right) \phi_{j/l}\left(x_2, Q^2\right)$$

(2) Compute $\phi_{i/k}, \phi_{j/l}$ in pQCD

(3) Extract H_{ij} in pQCD

H_{ij} IRS $\Rightarrow$ H_{ij} indepent of k, l

$\Rightarrow$ same H_{ij} with $(k \to h, l \to h')$

(4) Use H_{ij} in the above equation with $\phi_{i/h}, \phi_{j/h'}$

Extracting H_{ij} in pQCD

- Expansions in α_s:

$$\sigma_{kl} = \sum_{n=0}^{\infty} \left(\frac{\alpha_s}{\pi}\right)^n \sigma_{kl}^{(n)} \qquad \alpha_s = \frac{g^2}{4\pi}$$

$$H_{ij} = \sum_{n=0}^{\infty} \left(\frac{\alpha_s}{\pi}\right)^n H_{ij}^{(n)}$$

$$\phi_{i/k}(x) = \delta_{ik}\delta(1-x) + \sum_{n=1}^{\infty} \left(\frac{\alpha_s}{\pi}\right)^n \phi_{i/k}^{(n)}$$

↑

$\phi_{i/k}^{(0)}$ ($\alpha_s = 0 \Rightarrow$ Parton k " stays itself ")

- Consequences:

$$H_{ij}^{(0)} = \sigma_{ij}^{(0)} = \text{“Born”}$$

suppress "^" from now on

$$H_{ij}^{(1)} = \sigma_{ij}^{(1)} - \left[\ \sigma_{il}^{(0)} \phi_{l/j}^{(1)} + \phi_{k/i}^{(1)} \sigma_{kj}^{(0)}\ \right]$$

Computed from Feynman diagrams (process dependent) — for $\sigma_{ij}^{(1)}$ and $\sigma_{il}^{(0)}$

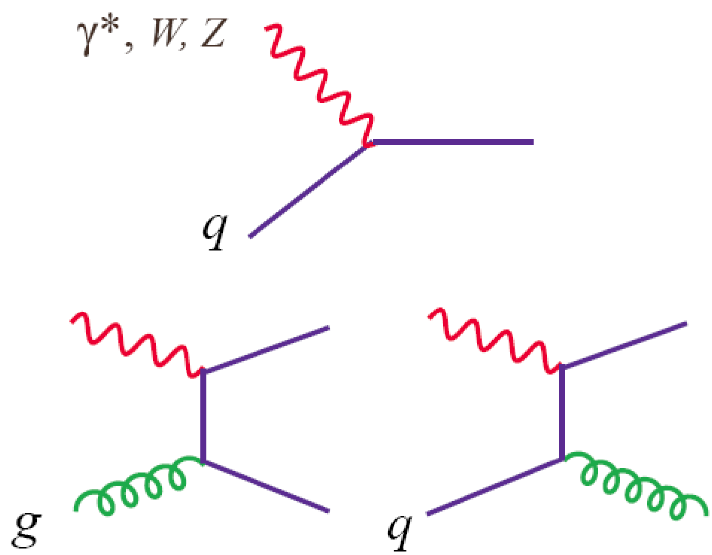
Computed from the definition of perturbative parton distribution function (process independent, scheme dependent) — for $\phi_{l/j}^{(1)}$ and $\phi_{k/i}^{(1)}$

Experimental Input:
Phyical Processes & Experiments

DIS

e N

μ N



ν N

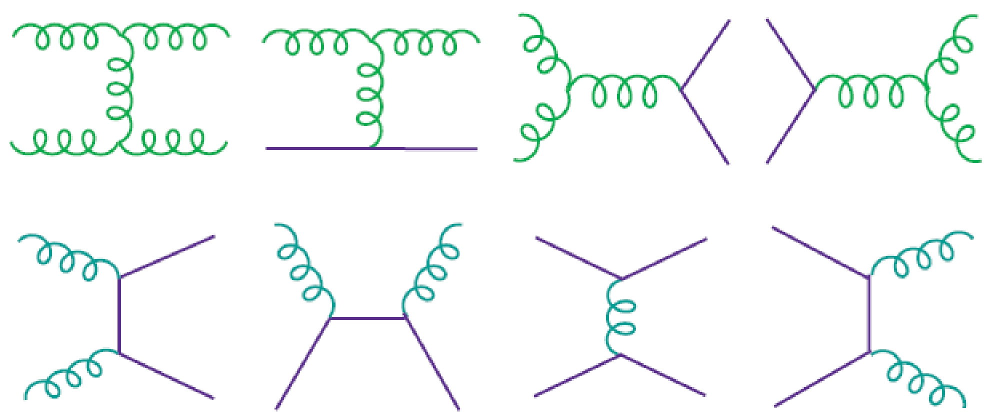
$\bar{\nu}$ N

SLAC
BCDMS
NMC, E665
H1, ZEUS

CDHS, CHARM
CCFR
CHORUS
NuTev

Jet Inc.

$\bar{p}$ p

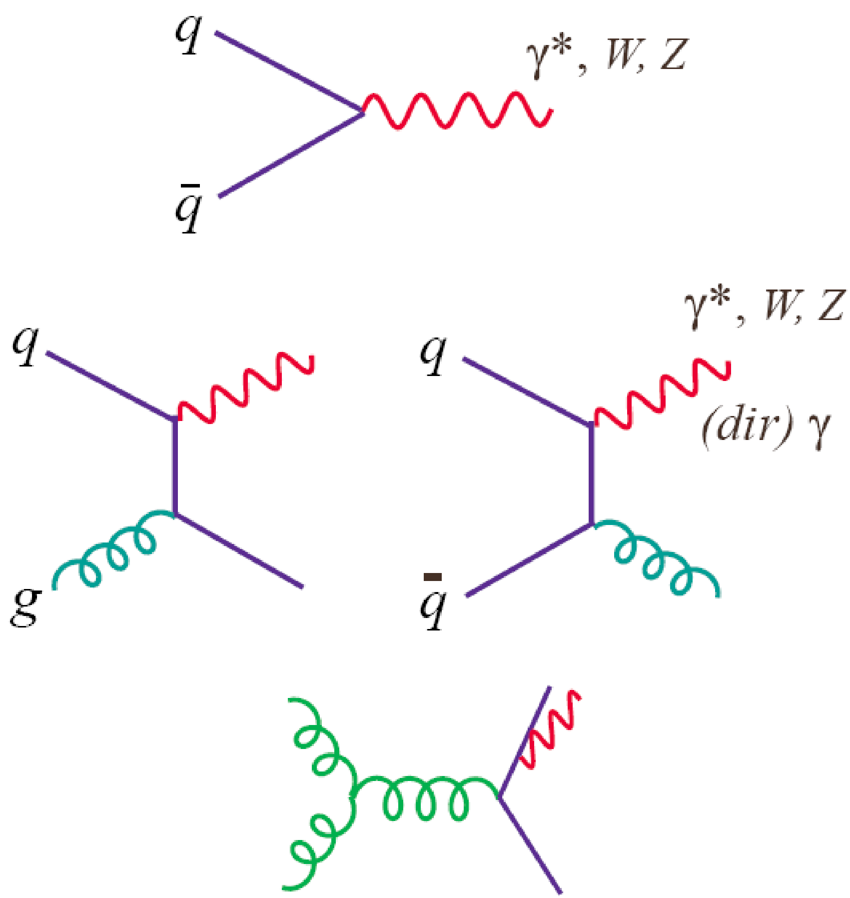


CDF, D0

Experimental input (continued)

DY

$p\,N$
$\pi\,N$
$k\,N$
$\bar{p}\,N$



E605, E772
NA51
E866

CDF, D0

(*Dir.Ph.*)

$p\,N$
$\pi\,N$
$k\,N$
$\bar{p}\,N$

WA70, UA6
E706

CDF, D0

(DIS jets, heavy quark prod. ...)

Some basics about PDFs

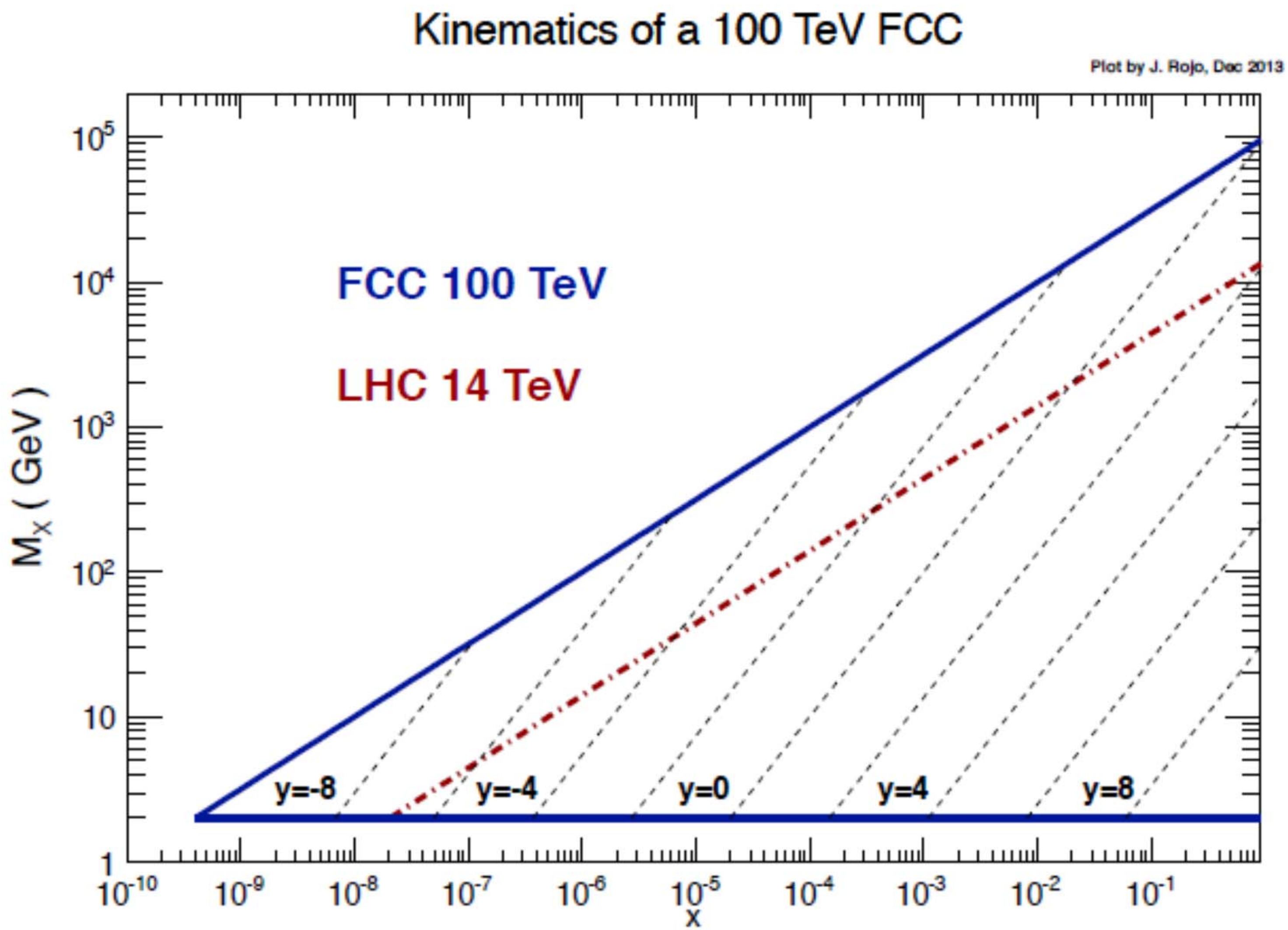
- Parton Distribution Function $f(x, \mathrm{Q})$
- Given a heavy resonance with mass Q produced at hadron collider with c.m. energy $\sqrt{S}$
- What's the typical x value?

$$< x >= \frac{Q}{\sqrt{S}}$$ at central rapidity (y=0)

- Generally, $x_1 = \frac{Q}{\sqrt{S}} e^{y} \quad and \quad x_2 = \frac{Q}{\sqrt{S}} e^{-y}$

$$x_1 + x_2 = 2\frac{Q}{\sqrt{S}}\cosh(\mathrm{y}) \Longrightarrow y_{\max} : \; x_1 + x_2 = 1$$

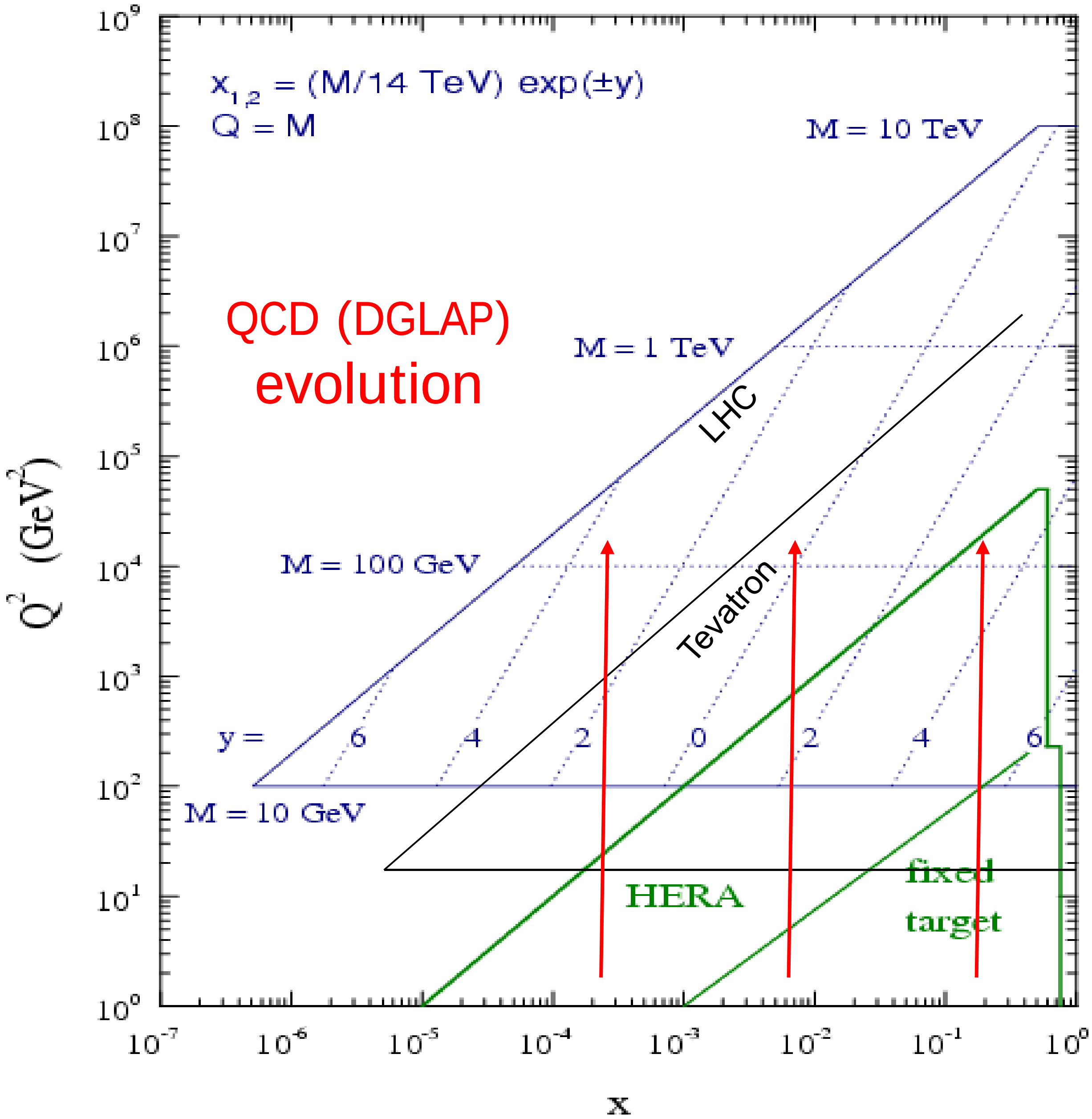
Kinematics of a 100 TeV SppC



- J. Rojo: kickoff meeting for FCC at CERN, Feb. 2014

Kinematics of Parton variables

Predictive power of global analysis of PDFs is based on the renormalization group properties of the universal Parton Distributions f(x,Q).



On to a 100 TeV SppC

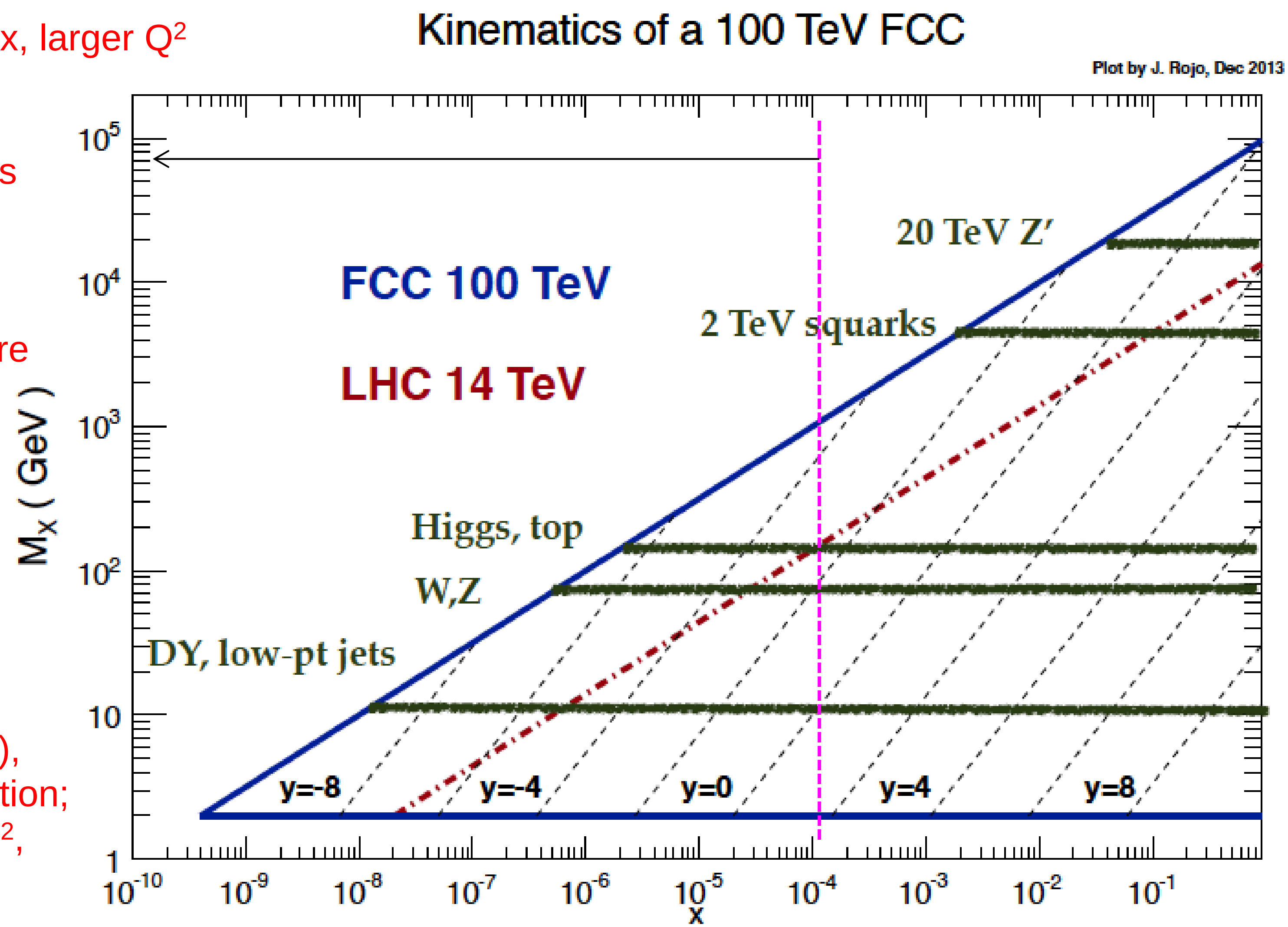
will access smaller x, larger Q^2

currently have no constraints on PDFs for x values below 1E-4

we don't know where at low x, BFKL effects start to become important

poor constraints (still) as well for high x PDFs

at high masses (Q^2), rely on DLAP evolution; we know at large Q^2, EW effects also become important



CT10 PDFs

- NLO
- NNLO

CT10 PDF sets: the naming conventions

- **Two NLO PDF sets**, without/with Tevatron Run-2 data on W charge asymmetry A_ℓ

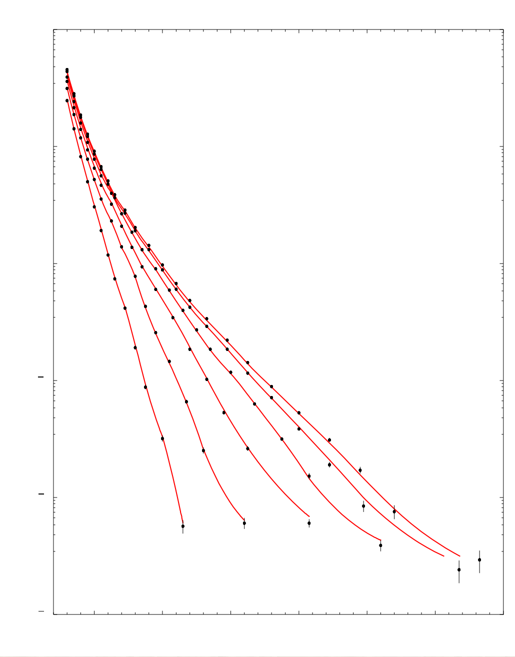
  CT10 NLO does not include
  CT10W NLO includes
  4 $p_{T\ell}$ bins of D0 Run-2 A_ℓ data

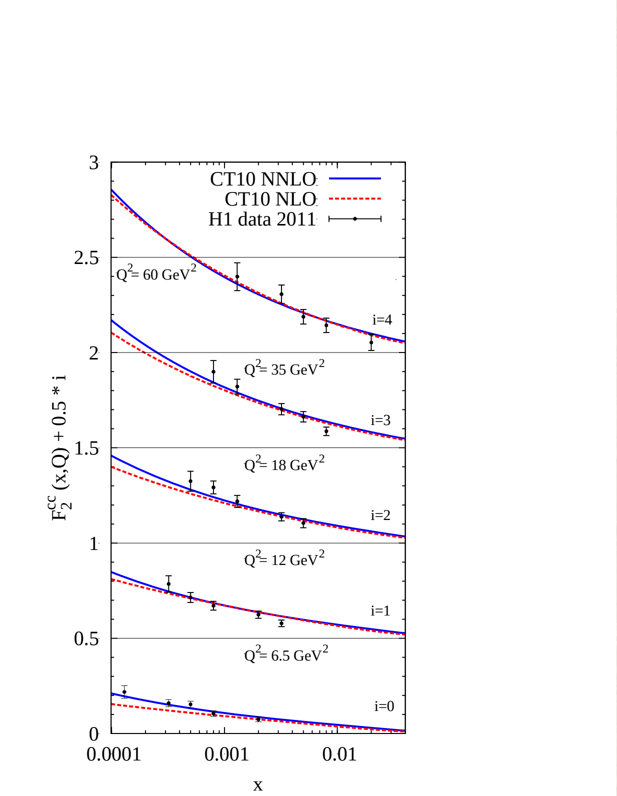
$\Rightarrow$ CT10 and CT10W sets differ mainly in the behavior of $d(x,Q)/u(x,Q)$ at $x > 0.1$

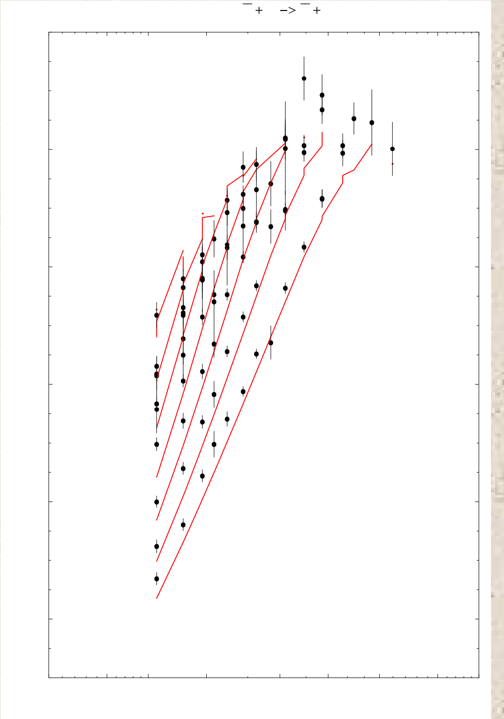
- **One NNLO PDF set:** only inclusive $p_{T\ell}$ bins of D0 Run-2 A_ℓ (e and μ) data are included that have smallest theory uncertainties

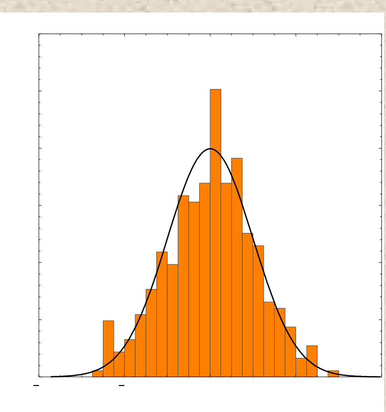
- **The NNLO set is a counterpart of both CT10 NLO and CT10W NLO. It uses only a part of the A_ℓ data sample that distinguishes between CT10 NLO and CT10W NLO.**

CT10NNLO vs. fitted data



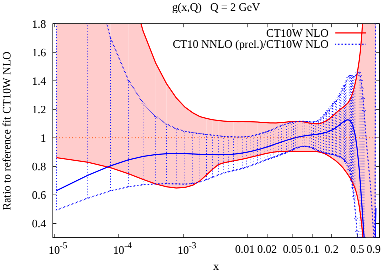


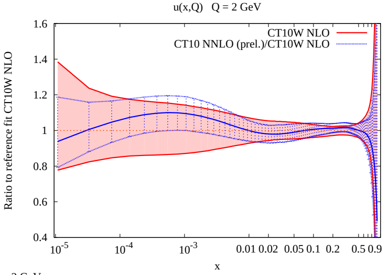


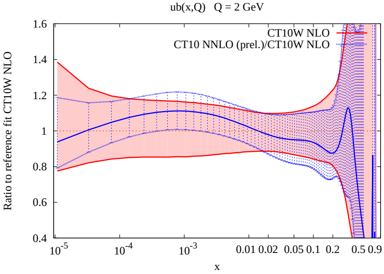


Fits well: $\chi^2 / N_{pt} = 2950/2641 = 1.11$

CT10 NNLO error PDFs (compared to CT10W NLO)



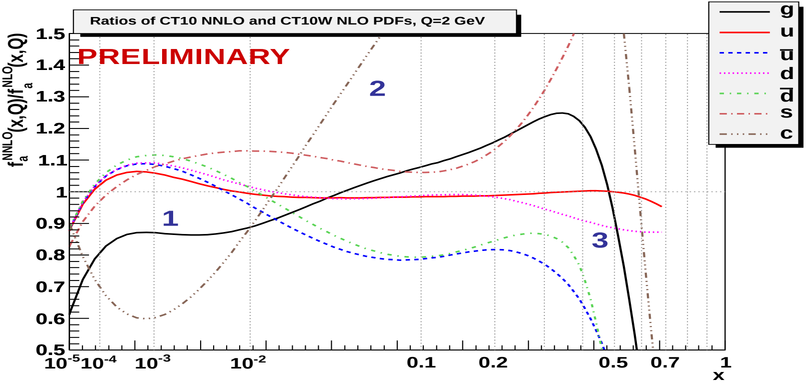




Striving for NNLO accuracy in the PDFs

- So far, only "partial NNLO" global fits exist. For some fitted processes (inclusive jet production, CC DIS with $m_q \neq 0$), QCD contributions are known only to NLO. (NLO EW contributions, power corrections, other systematic errors may be comparable to NNLO QCD effects.)
- CT10 "NNLO" PDFs underwent validation studies for about one year. We identified several types of uncertainties that compete with NNLO QCD contributions.
- CT10 NNLO and NLO PDFs produce about the same $\chi^2/N_{pt} \approx 1.05 - 1.10$ for $N_{pt} \simeq 2700$ data points
- Shapes of the NNLO PDFs have noticeably evolved compared to NLO as a result of $\mathcal{O}(\alpha_s^2)$ contributions, updated electroweak contributions, revised statistical procedures

CT10 NNLO central PDFs, as ratios to NLO, Q=2 GeV



1. At $x < 10^{-2}$, $\mathcal{O}(\alpha_s^2)$ evolution suppresses $g(x,Q)$, increases $q(x,Q)$
2. $c(x,Q)$ and $b(x,Q)$ change as a result of the $\mathcal{O}(\alpha_s^2)$ GM VFN scheme
3. In large x region, $g(x,Q)$ and $d(x,Q)$ are reduced by not including Run-1 inclusive jet data, revised EW couplings, alternative treatment of correlated systematic errors, scale choices.

CT10 NNLO PDFs

- PDF error bands
  - u and d PDFs are best known
  - currently no constraint for x below 1E-4
  - large error for x above 0.3
  - larger sea (e.g., ubar and dbar) quark uncertainties in large x region
  - with non-perturbative parametrization form dependence in small and large x regions
- PDF eigensets
  - useful for calculating PDF induced uncertainty
  - sensitive to some special (combination of) parton flavor(s).

  (e.g., eigenset 7 is sensitive to d/u or dbar/ubar; hence, W asymmetry data at Tevatron and LHC.)

CT10 NNLO PDFs

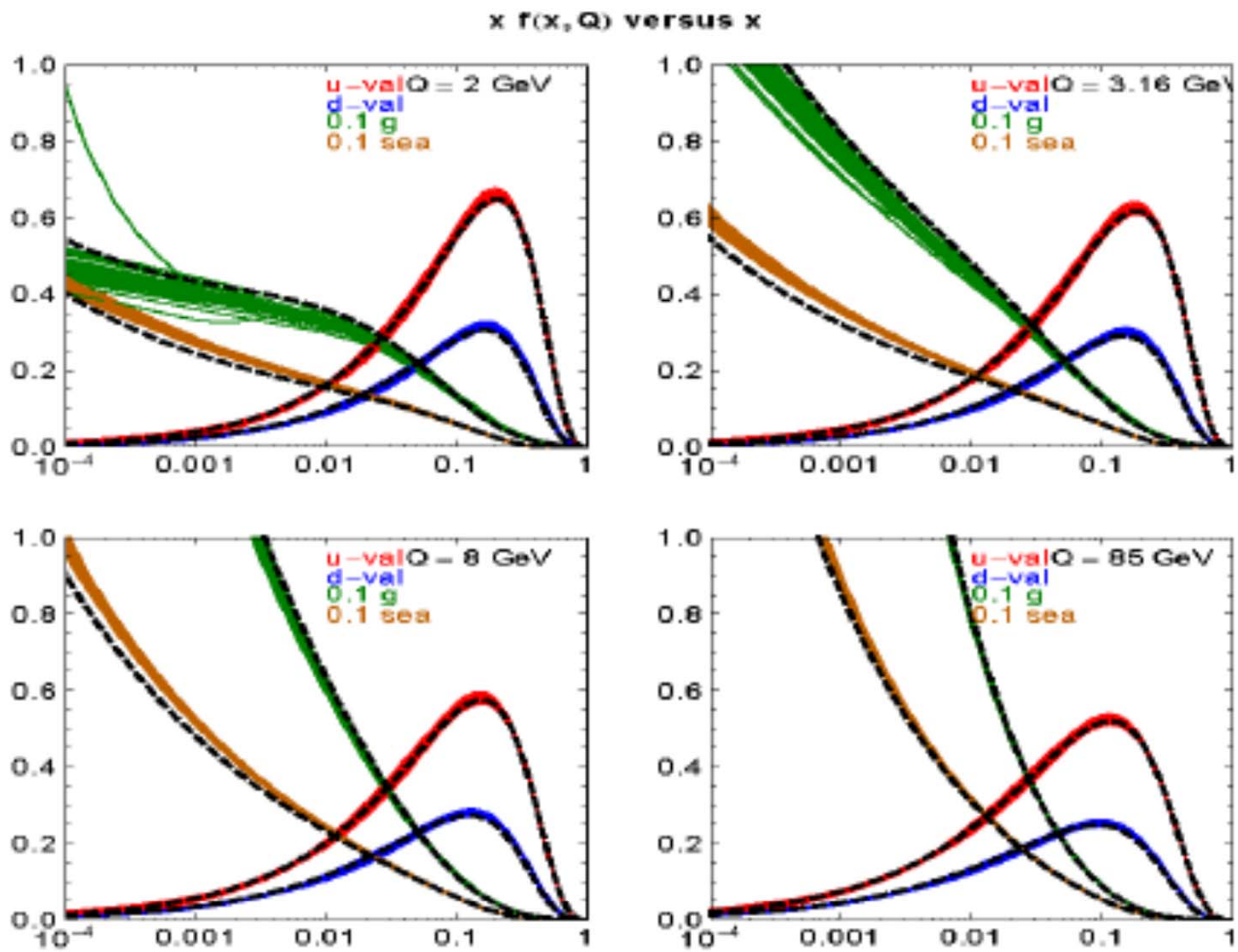
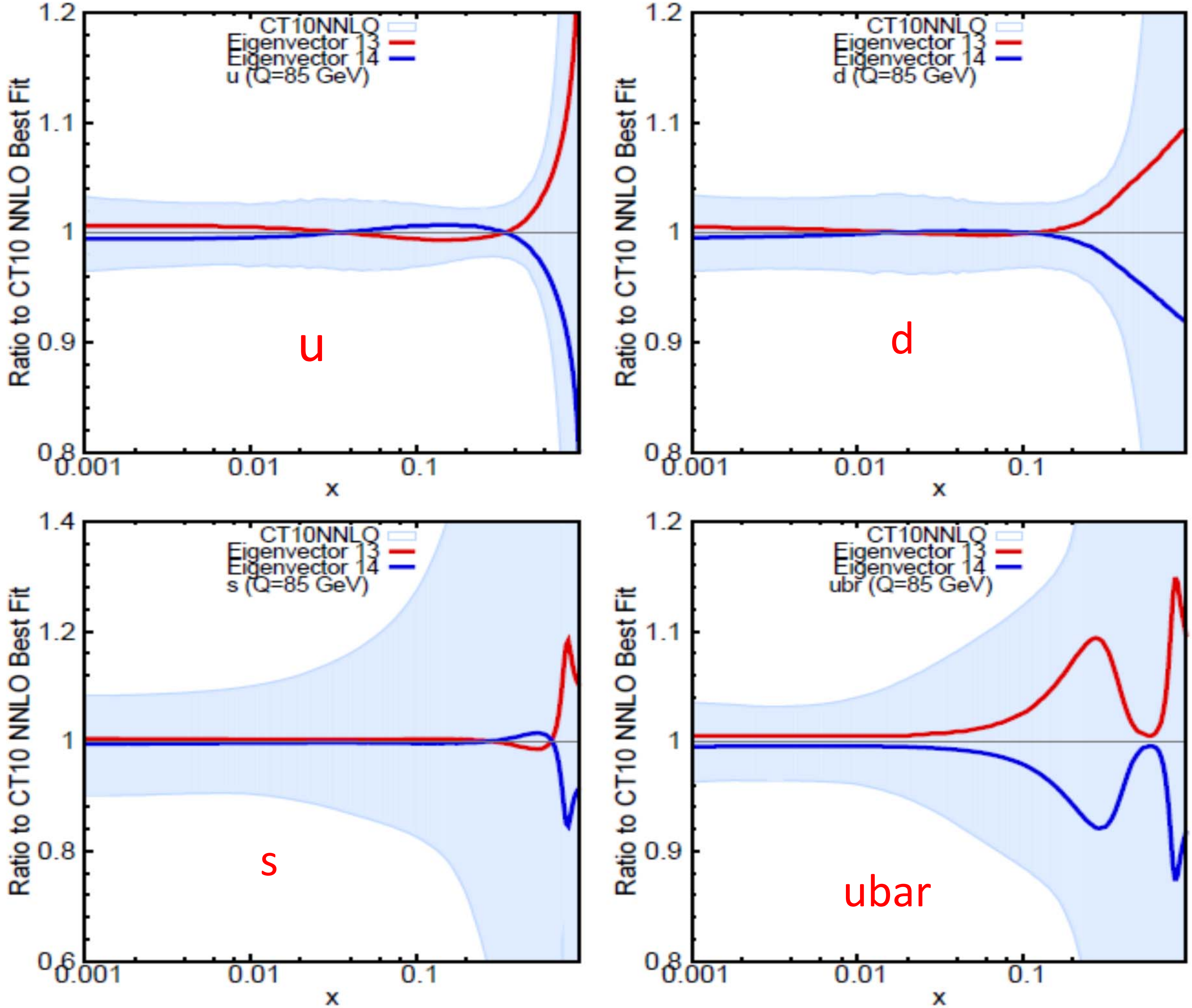
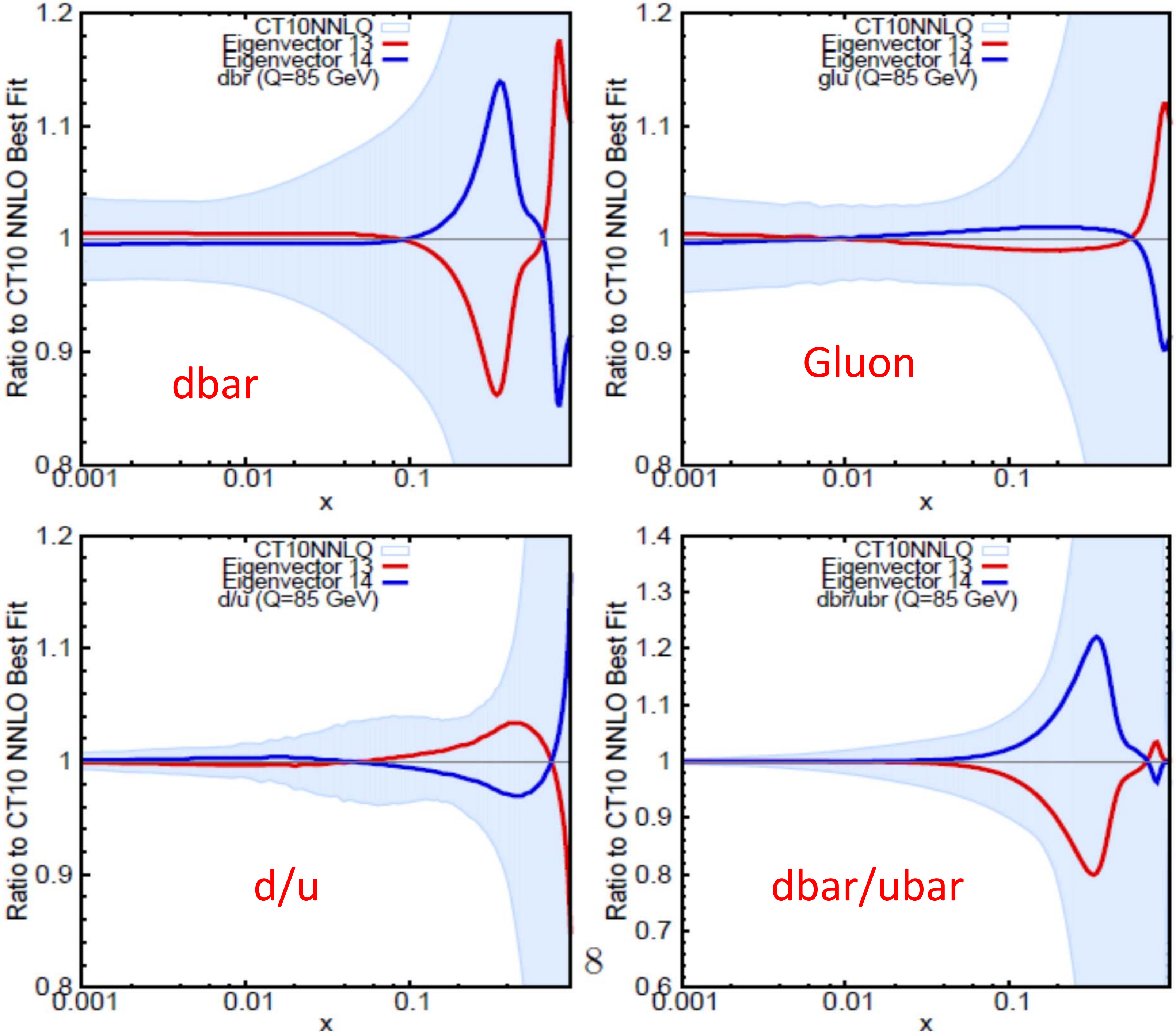


Figure 3: CT10-NNLO parton distribution functions. These figures show the *alternate fits* for the CT10-NNLO analysis. Each graph shows $x\,u_{\text{valence}} = x(u - \overline{u}), x\,d_{\text{valence}} = x(d - \overline{d}), 0.10\,x\,g$ and $0.10\,x\,\overline{q}$sea as functions of x for a fixed value of Q. The values of Q are $2, 3.16, 8, 85$ GeV. Sea $= 2(\overline{d} + \overline{u} + \overline{s})$. The dashed curves are the central NLO fit, CT10.

7th CT10 Eigenset

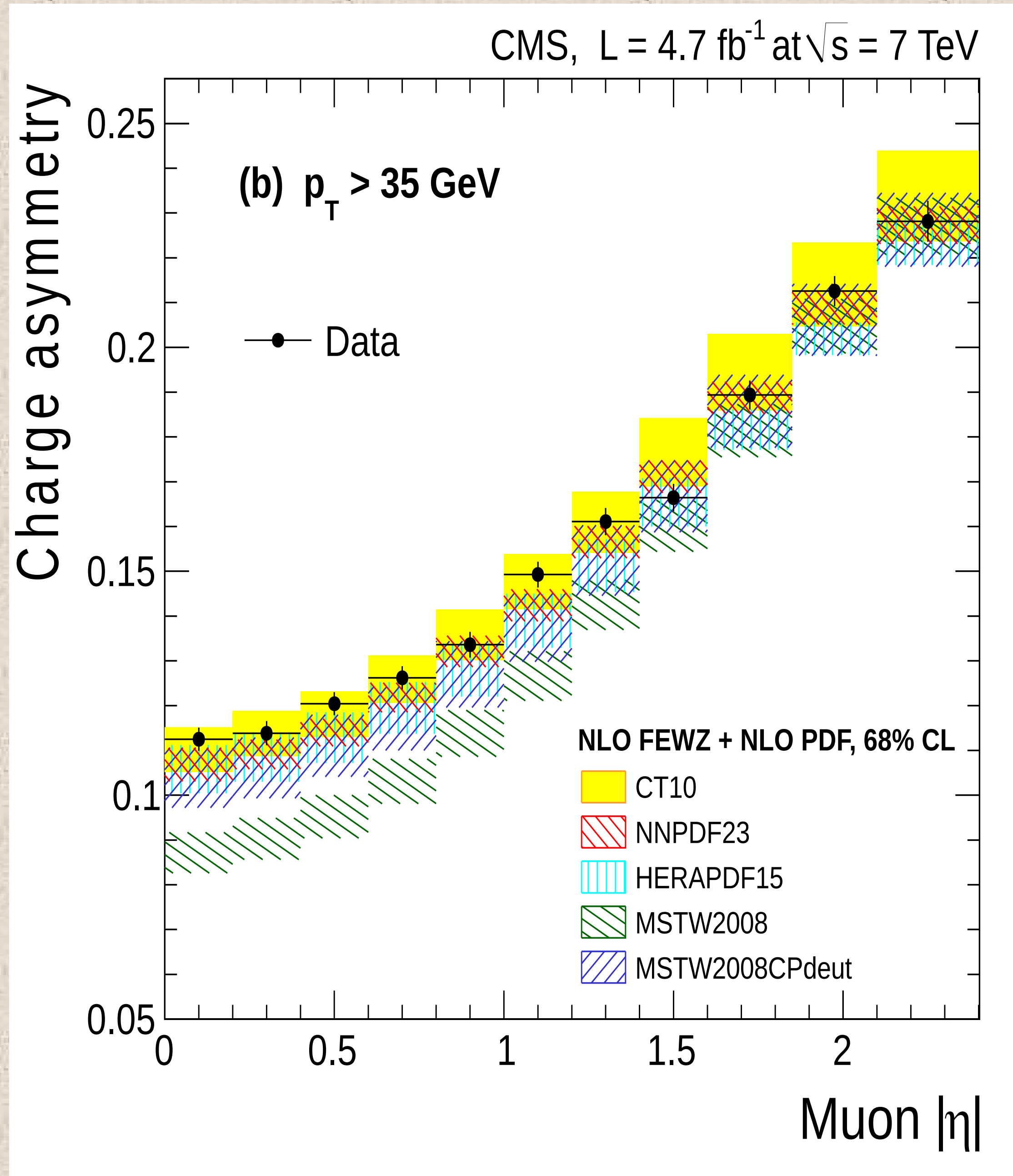


7th CT10 Eigenset



CT10, CT14, 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.



Data is already more precise than current PDF uncertainty.

Will help to determine PDFs in small x region.

Most useful for determining dbar/ubar.

Uncertainties on H and ttbar Predictions at the LHC
(and update on Intrinsic Charm)

Carl Schmidt

Michigan State University

On behalf of CTEQ-TEA group

April 29, 2014

DIS2014, Warsaw, Poland

Outline

1) Update of CTEQ-TEA activities discussed this morning
   CT10 update, MetaPDFs, photon PDF, etc.

2) Update of Intrinsic Charm Analysis
   Dulat et al, PRD **89**, 073004 (2014)

3) Lagrange Multiplier (LM) Uncertainty Analysis on gg->H
   Dulat et al, arXiv:1309.0025[hep-ph]

4) Uncertainty Analysis on gg->ttbar

Intrinsic Charm and CT10IC

1) Update of CTEQ6.5 IC study from 2007 to CT10NNLO
   - includes combined H1 and ZEUS data, HERA inclusive charm

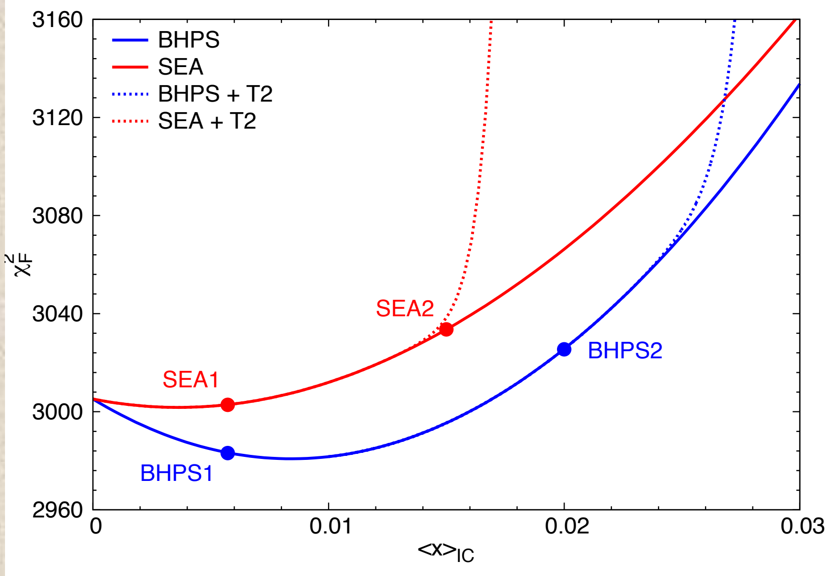
2) Recent CT10 global analysis study of charm quark mass:
   $m_c(m_c) = 1.15^{+0.18}_{-0.12}$ GeV   Gao et al, Eur.Phys.J. C73 (2013) 2541
   Use m_c(pole)=1.3 GeV for this study
   - some correlation between m_c and IC
3) Two model Intrinsic Charm distributions at Q_c=1.3 GeV
   - BHPS valence-like model (Brodsky et al, Phys. Lett. **93B**, 451 (1980))
   - SEA-like model

$$\langle x \rangle_{\mathrm{IC}} = \int_0^1 x\left[c(x,Q_c) + \bar{c}(x,Q_c)\right]dx$$

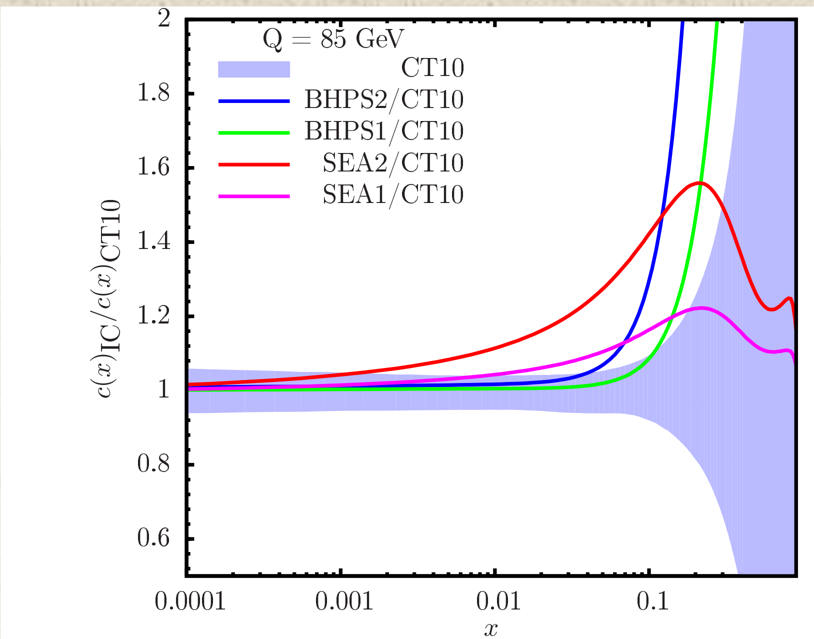
4) 90% CL limits:

$$\langle x \rangle_{\mathrm{IC}} \le 0.025 \quad \text{BHPS}$$

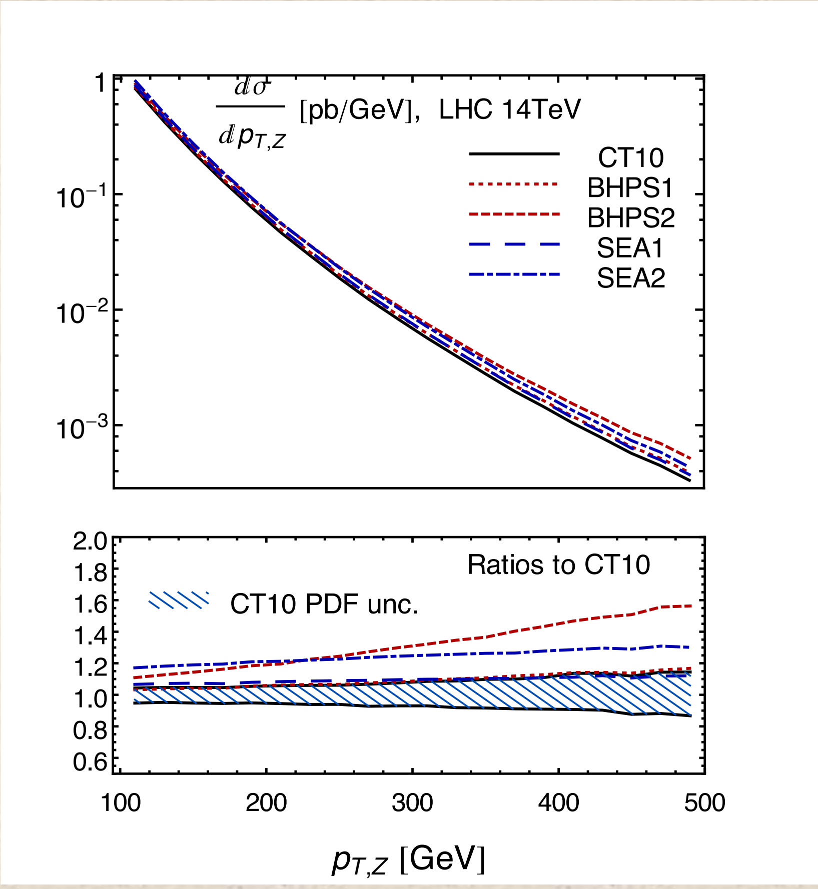
$$\langle x \rangle_{\mathrm{IC}} \le 0.015 \quad \text{SEA}$$



Intrinsic Charm at LHC



IC vs CT10 charm PDF



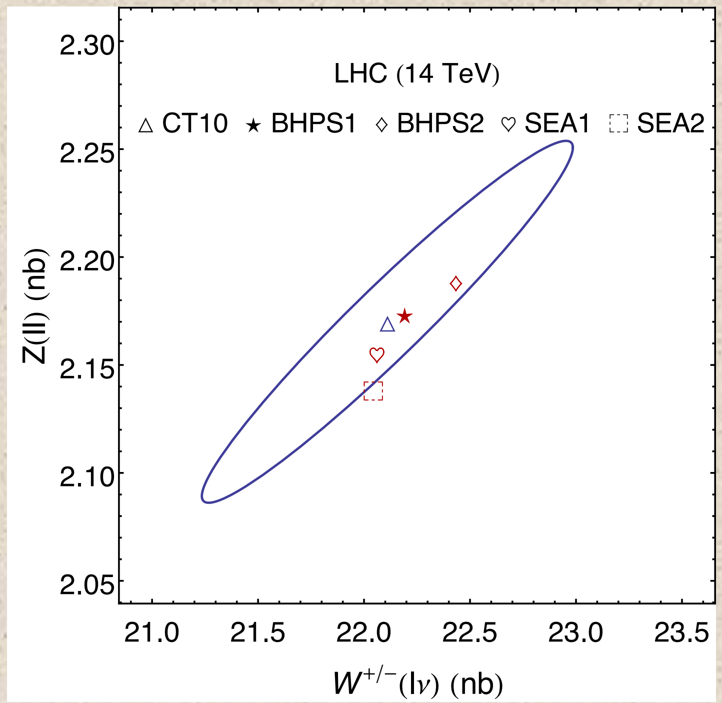
SEA1/BHPS1: $\langle x \rangle_{\rm IC} = 0.57\%$

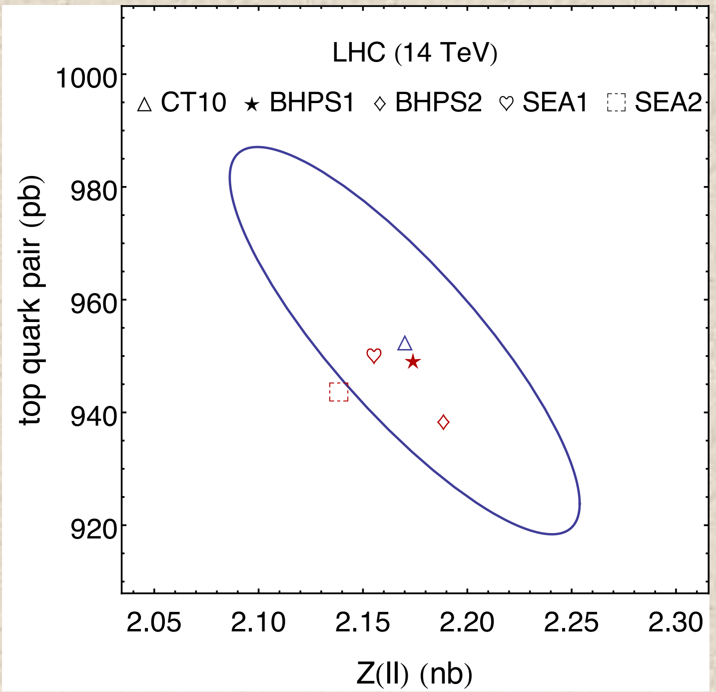
SEA2: $\langle x \rangle_{\rm IC} = 1.5\%$

BHPS2: $\langle x \rangle_{\rm IC} = 2.0\%$

$pp \to Zc$ at LHC may further constrain valence-like model

CT10 IC at LHC





W, *Z* and top production at LHC

CT10 IC distributions publicly available

PDF uncertainties in $gg \to H$

1) Most analyses use Hessian Method (n error PDF sets)

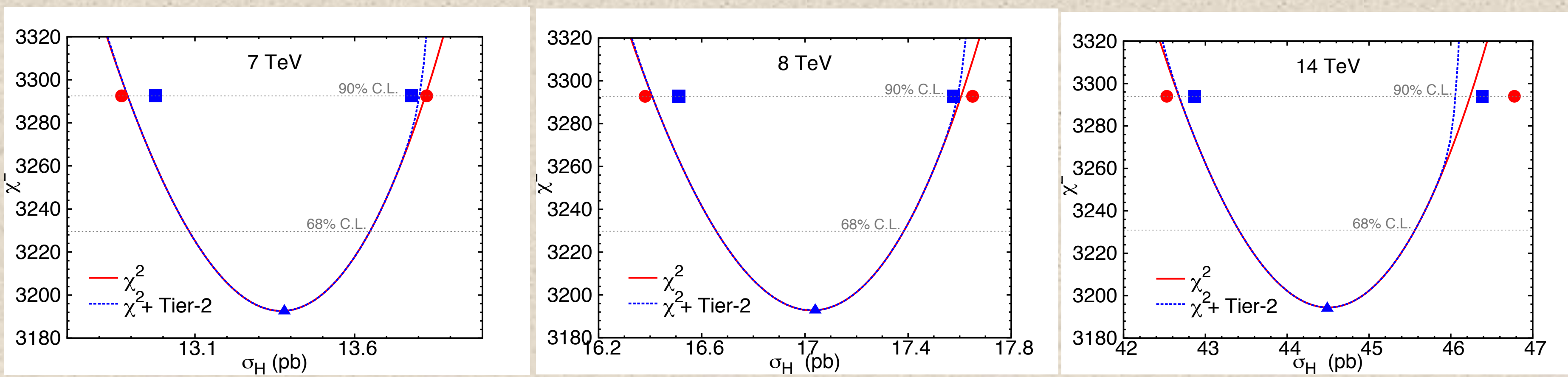
$$\left(\delta X\right)^2 = \frac{1}{4}\sum_{k=1}^{n}\left(X(a_k^+) - X(a_k^-)\right)^2$$

- Error sets can be used by anyone for any observable
- Assume quadratic and linear dependence of χ^2, X on a_k

2) Lagrange Multiplier (LM) method is more robust

- Find best fit for each constrained value of observable X
- No assumptions on dependence of χ^2, X on a_k
- Can validate Hessian method
- Can display correlations between PDFs and Observable
- Must calculate separately for each observable

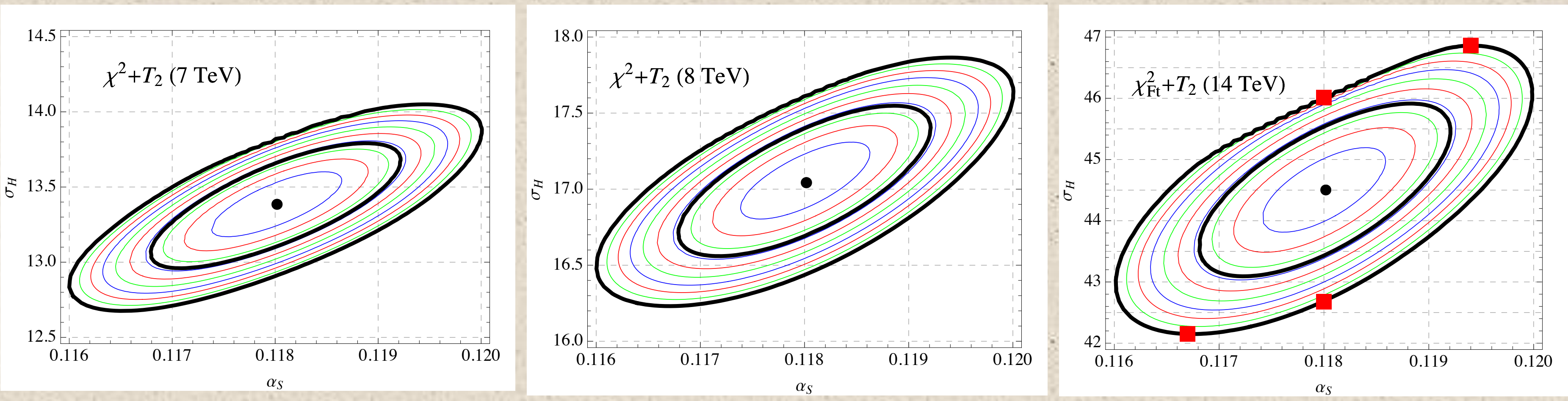
Uncertainties in $gg \rightarrow H$



- Curves are LM, circles/squares are Hessian
- Red use χ^2
- Blue add Tier-2 penalty to ensure no specific experiment is too badly fit
- Allowed Tolerance is 100 at 90% CL

- Small differences in asymmetries, but in general the two methods agree well for this observable

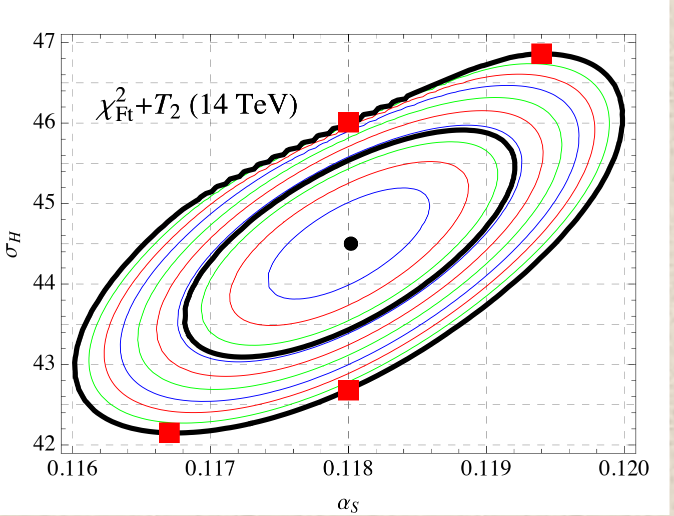
Combined PDF+α_S Uncertainties



- Can include α_S uncertainty as contribution to total χ^2 in LM method
- Use PDF4LHC choice of α_S=0.118±0.002 at 90% CL
- Black curves are 68% and 90% CL contours

- Hessian method adds α_S and PDF uncertainties in quadrature
- Hessian and LM agree well for Higgs cross section (despite non-quadratic behavior, especially obvious at 14 TeV)
- For instance 90% CL uncertainties at 14 TeV (% of central value):
  - LM: +5.2/-5.2 Hessian: +5.4/-5.0

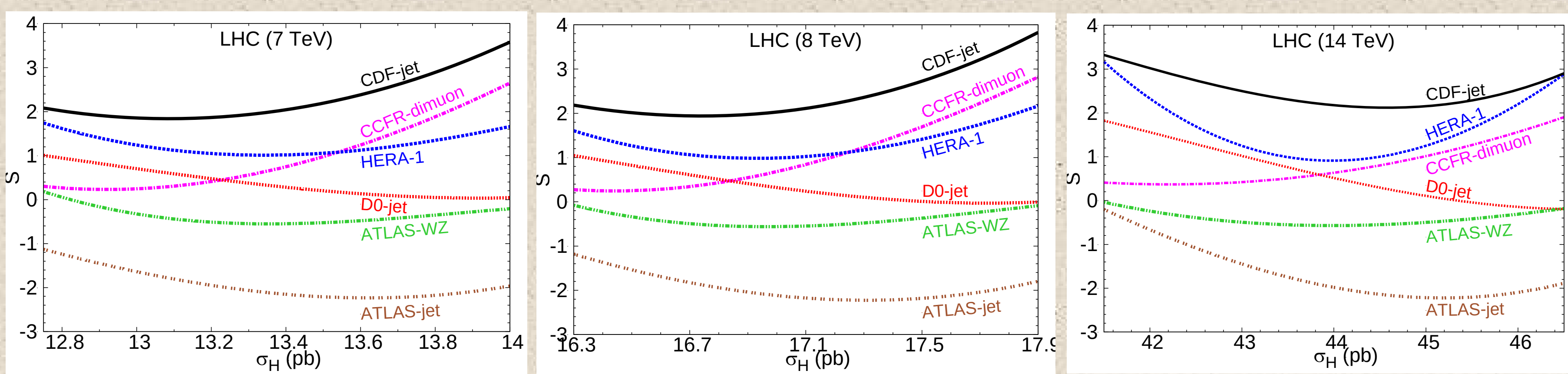
CT10H Extreme Sets



- PDF sets that give extreme values of Higgs cross section at 90% CL are publically available as CT10H sets
- Shown on contour plot as Red squares
- PDF uncertainly only or PDF+α_S uncertainty

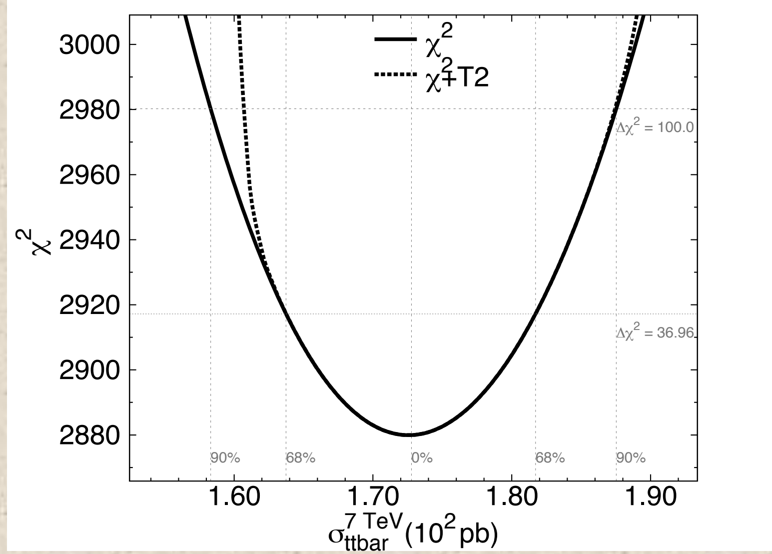
- Useful for efficient $gg \to H$ analyses

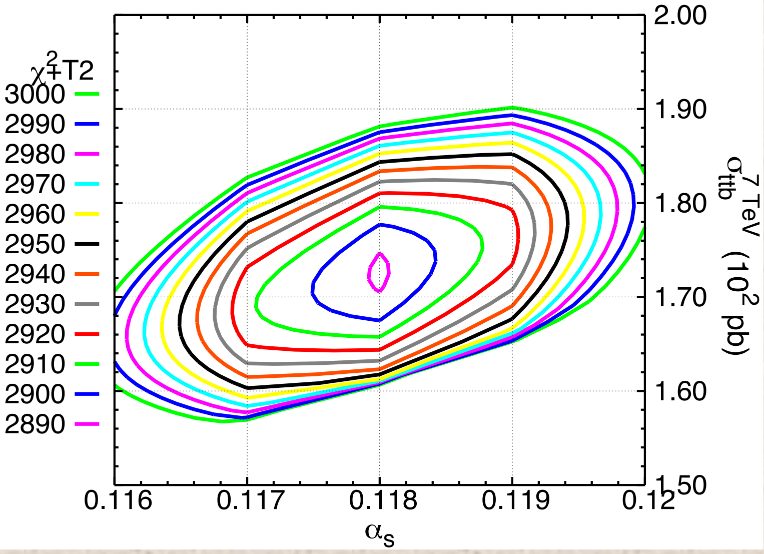
Sensitivity to Data Sets

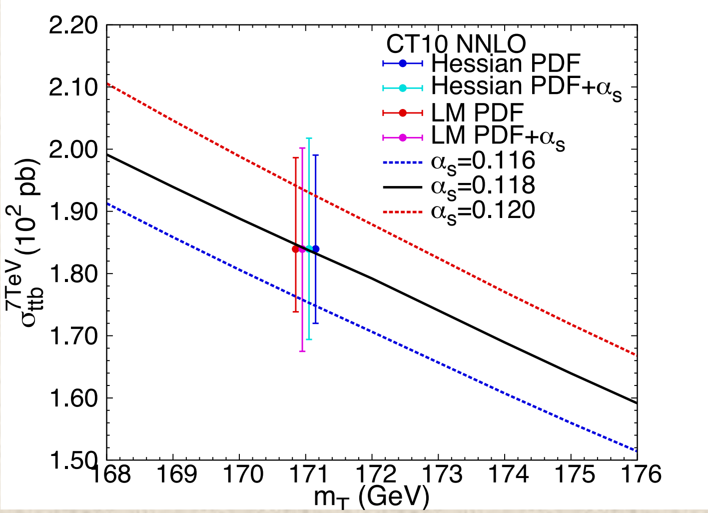


- How sensitive are included data sets to value of σ_H ?
- "Effective Gaussian Variable" S maps cumulative χ^2 distribution for N_{pt} onto cumulative Gaussian distribution
  - +1,+2,+3,… equivalent to that many sigma deviations
  - Negative values correspond to anomalously well-fit data
- Most strongly correlated data: high p_T jet, inclusive HERA, CCFR-dimuon
  - HERA more strongly correlated with 14 TeV—smaller x
  - CCFR dimuon correlation due to gluon-strange interdependence

Uncertainties in gg→ttbar

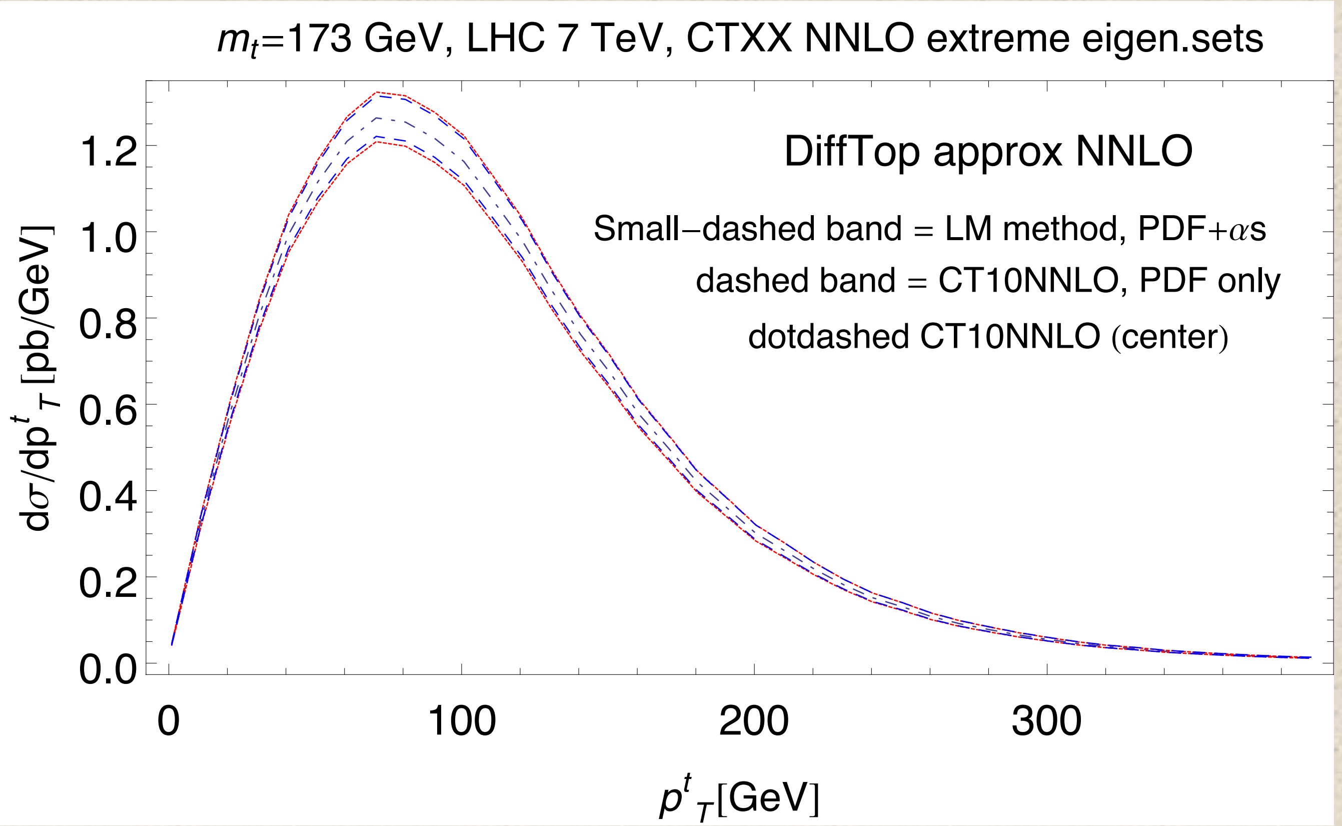






- Same analyses applied to *gg*→ttbar
- HERA combined data (T2) constrains low values of cross section
- But T2 less important for combined PDF+α_S
- Hessian and LM consistent

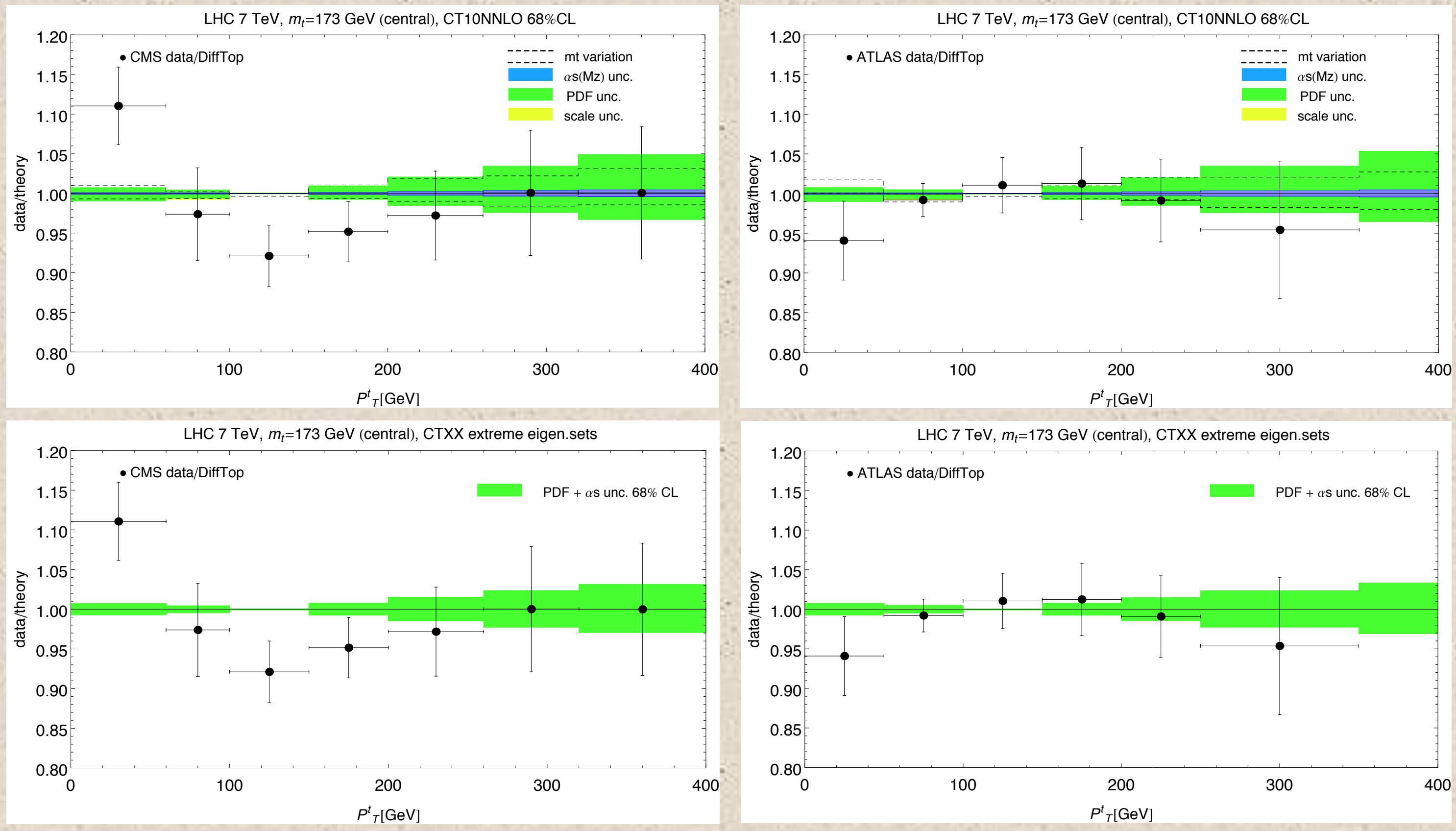
CT10tt extreme sets



- Pairs of CT10tt extreme sets (PDF, PDF+α_S) to be released
  - for focused ttbar analyses

Results provided by DiffTop group (M. Guzzi, K. Lipka, S. Moch)

CT10tt extreme sets



- Comparison with CMS (left) and ATLAS (right) data
- Hessian top, LM extreme sets bottom
- Extreme sets useful if highly correlated with inclusive ttbar (note high p_T)

Results provided by DiffTop group (M. Guzzi, K. Lipka, S. Moch)

Conclusions

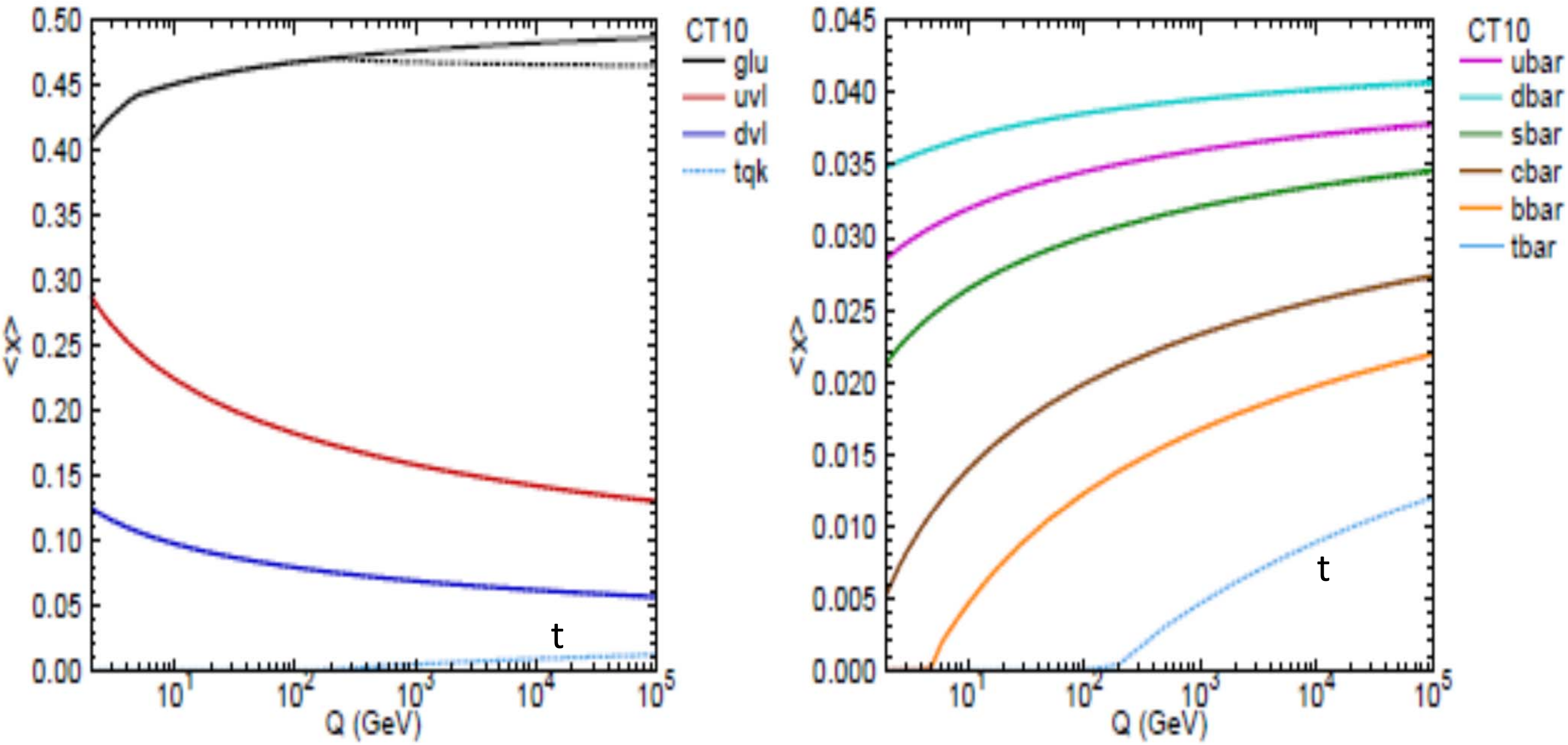
- Intrinsic Charm
  - Limits on valence-like and sea-like IC
  - CT10IC PDFs available for further study
  - LHC will probe further
- Lagrange Multiplier Uncertainty analysis
  - Less dependent on assumptions than Hessian analysis
  - Allows study of data correlations with particular observable
  - Test of Hessian results
    - Consistent with Hessian results for both Higgs and ttbar
  - CT10H extreme sets available for focussed studies

    (CT10tt extreme sets to come)

Top quark as a parton

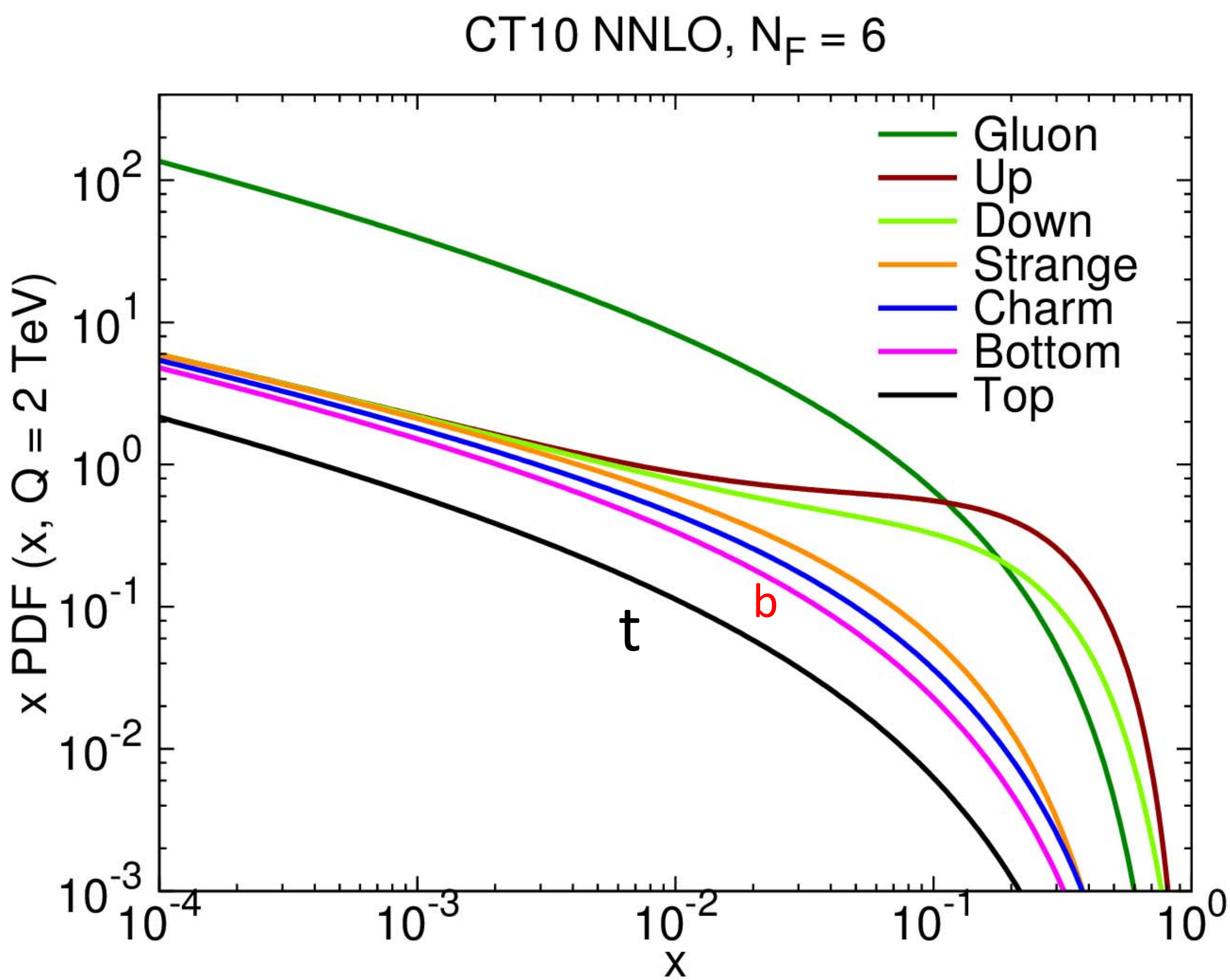
- For a 100 TeV SppC, top mass (172 GeV) can be ignored; top quark, just like bottom quark, can be a parton of proton.
- Top parton will take away some of the momentum of proton, mostly, from gluon (at NLO).
- Need to use s-ACOT scheme to calculate hard part matrix elements, to be consistent with CT10 PDFs.

Momentum fraction inside proton



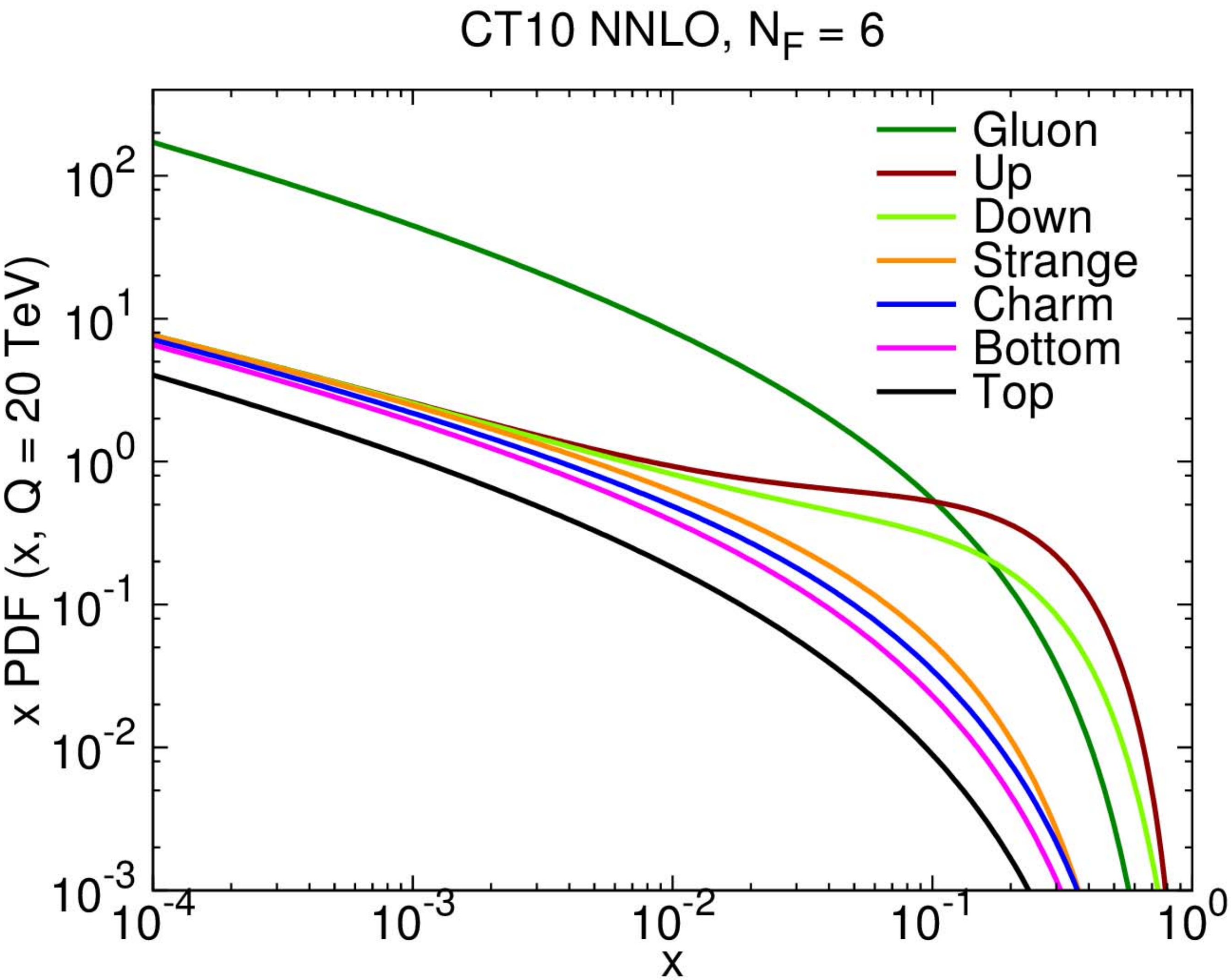
Solid curves: CT10 NNLO
Dashed curves: CT10Top NNLO

CT10Top PDFs (Q=2 TeV)

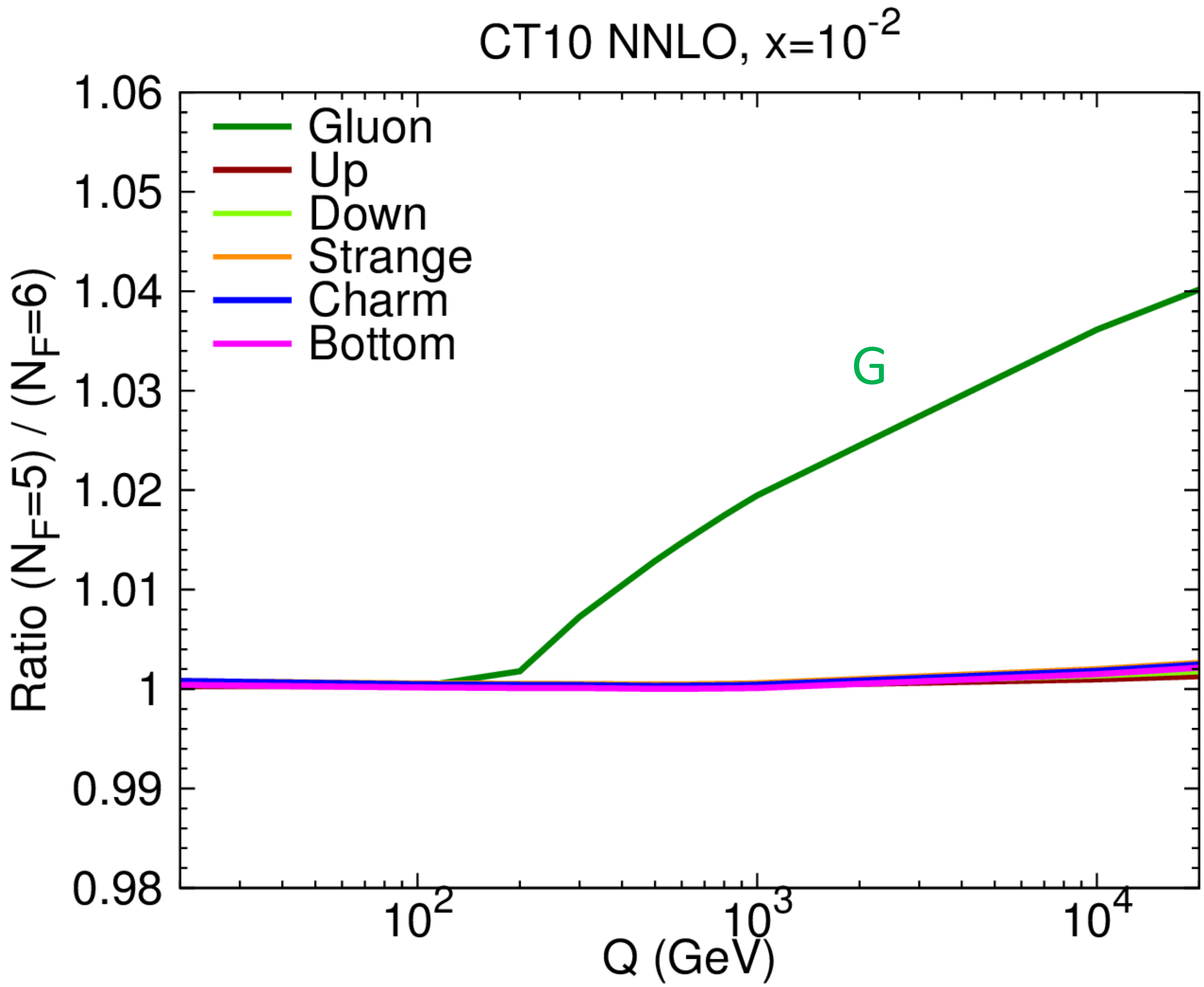


Top PDF is only a factor of 2 smaller than b PDF

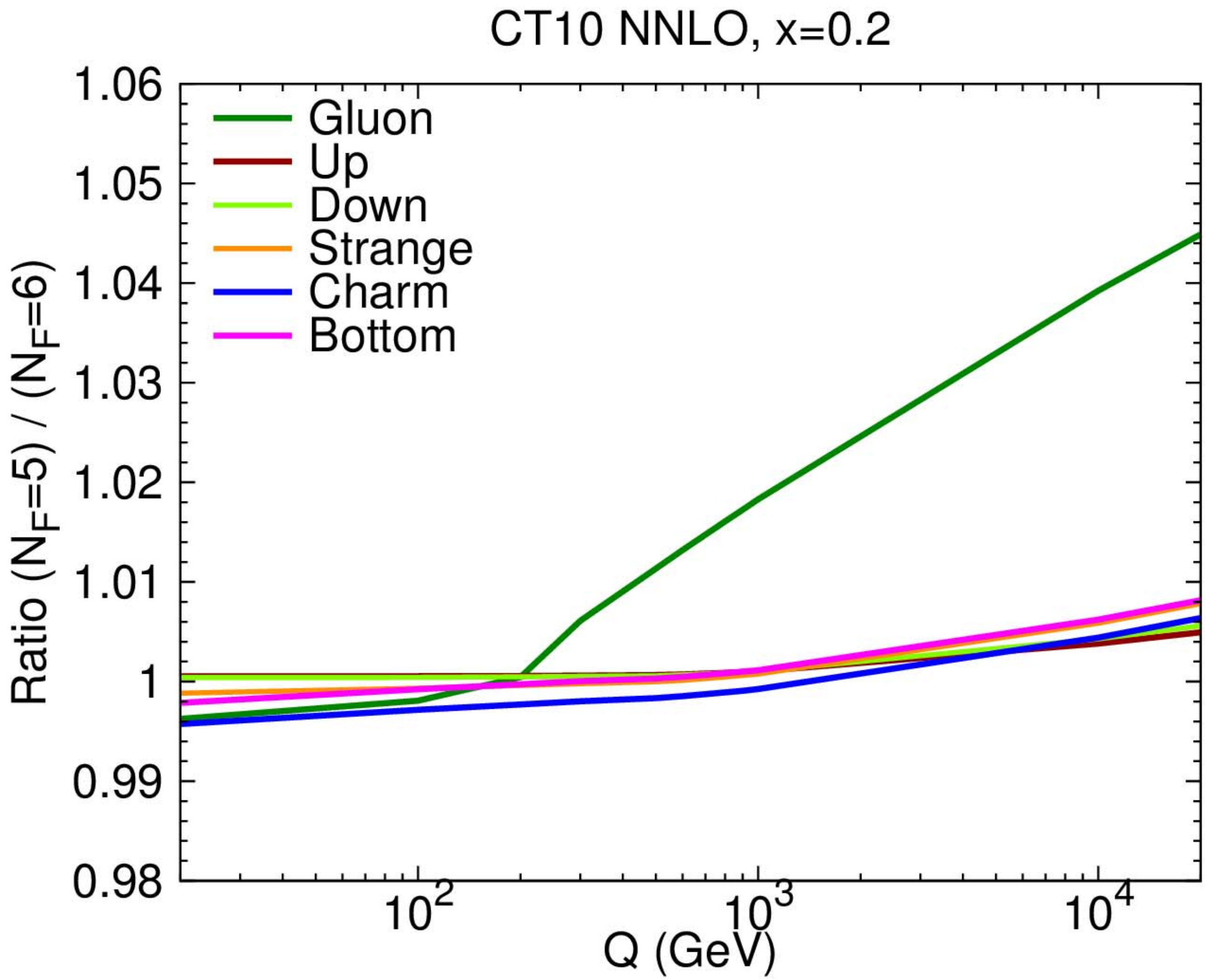
CT10Top PDFs
(Q=20 TeV)



CT10Top PDFs



CT10Top PDFs



PDF luminosities

$$\sigma = \int dx_1 dx_2 \; g(x_1, M) g(x_2, M) \hat{\sigma}(M)$$

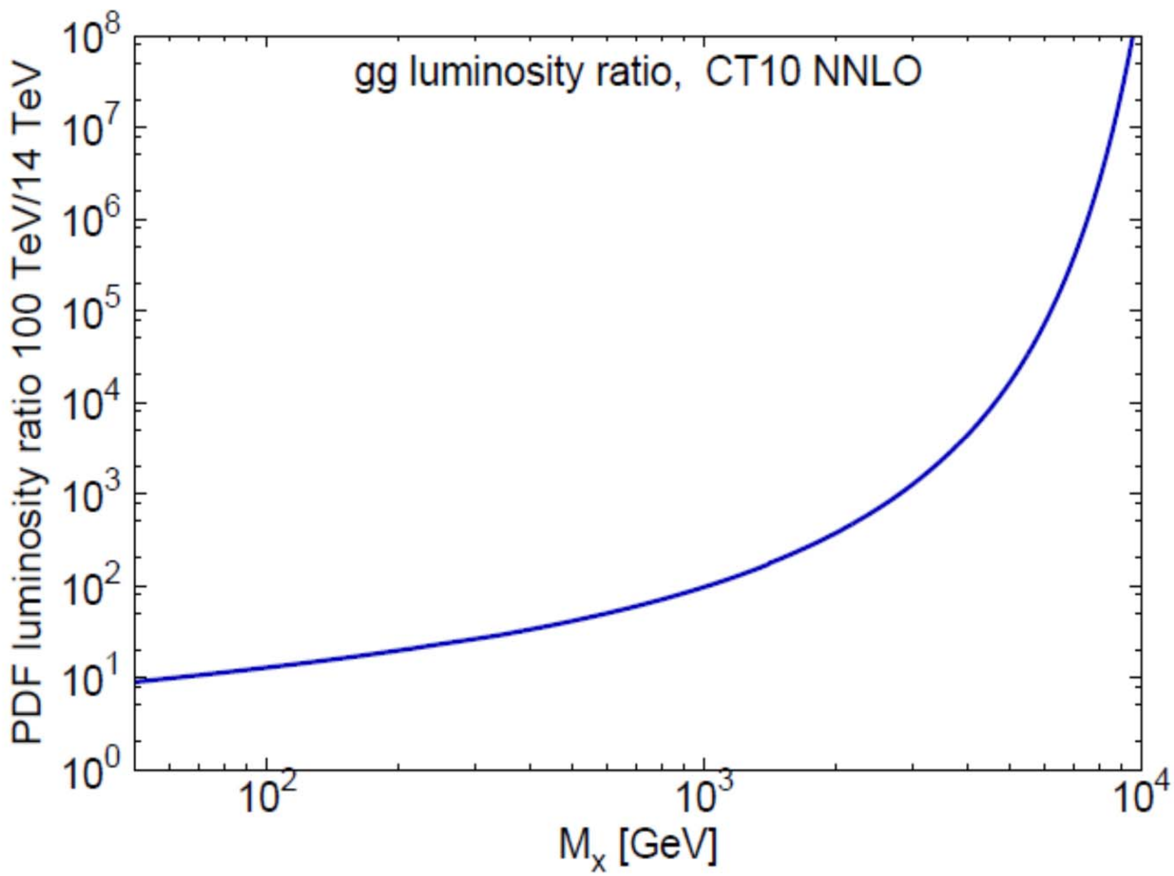
$$= \int d\tau dy \; g(x_1, M) g(x_2, M) \hat{\sigma}(M)$$

$$\equiv \int dM^2 \frac{dL}{dM^2} \hat{\sigma}(M)$$

PDF Luminosity

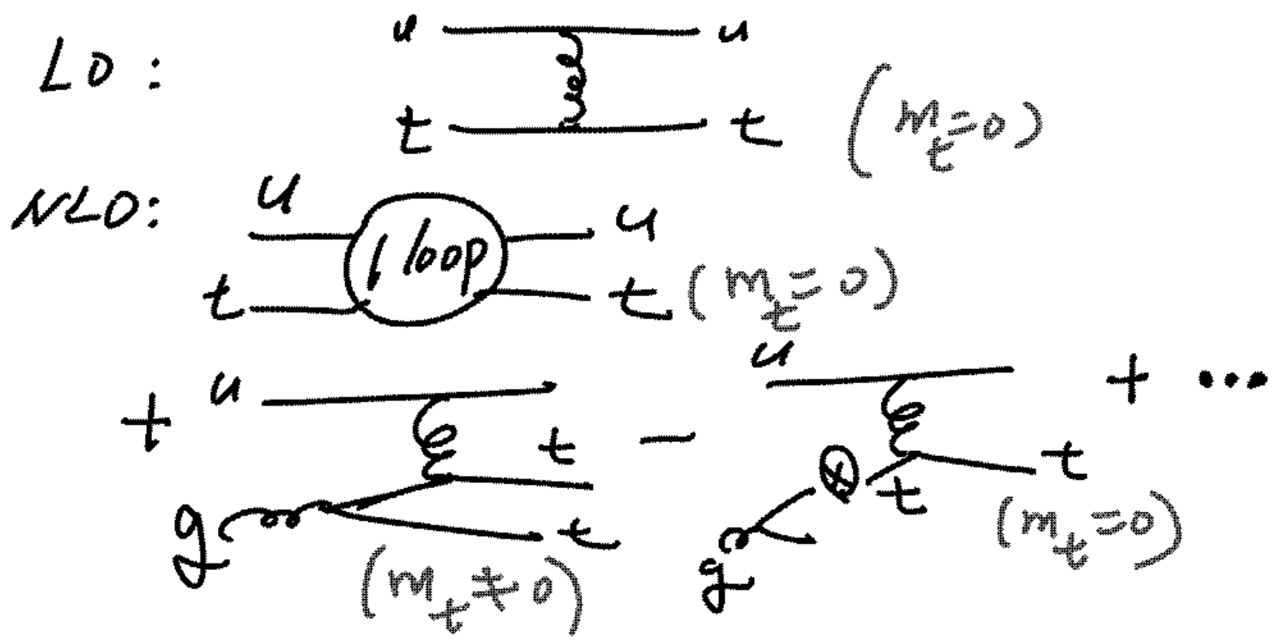
$$\tau = x_1 x_2$$

$$y = \frac{1}{2} \ln\left(\frac{x_1}{x_2}\right)$$



Hard part calculation

- S-ACOT scheme
- Example: single-top production



CT10 NNLO update and QED effects in PDFs

Carl Schmidt

Michigan State University

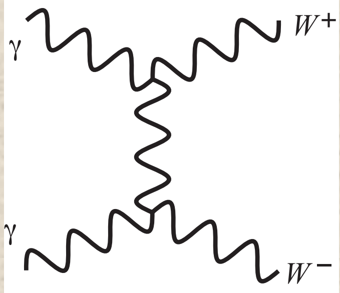
On behalf of CTEQ-TEA group

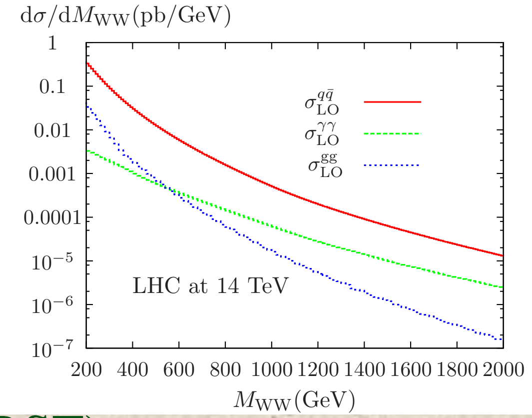
April 29, 2014

DIS2014, Warsaw, Poland

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



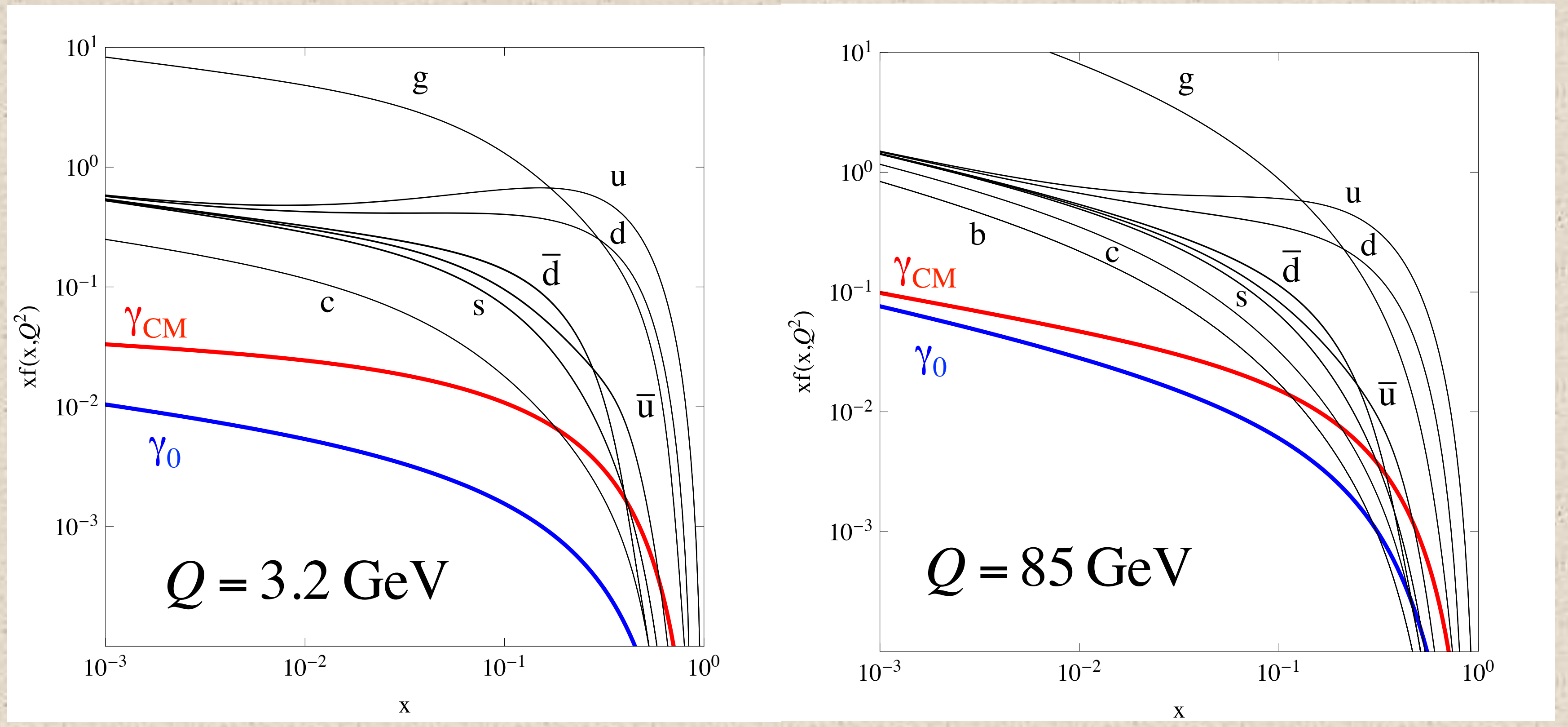


Bierweiler et al., JHEP 1211 (2012) 093

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.

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!

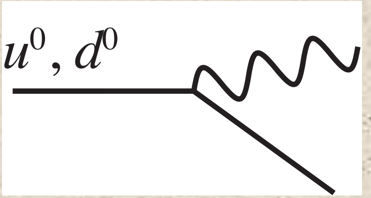
Initial Photon PDF still ← significant at large Q.

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)

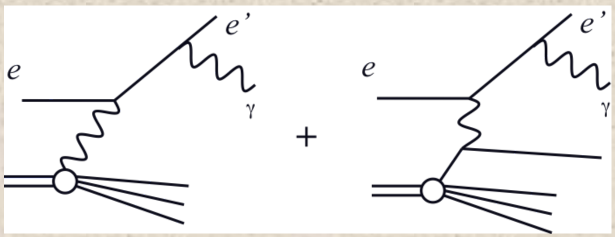
Constraining Photon PDFs

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

$ep \to e\gamma + X$

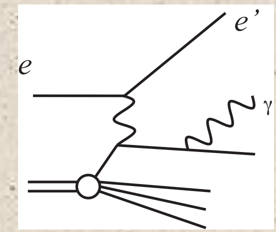
Subprocess contributions:



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)

Zeus Experimental Cuts

Photon Cuts

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

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

Lepton Cuts

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

$139.8^\circ < \theta_{\ell'} < 171.8^\circ$

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

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

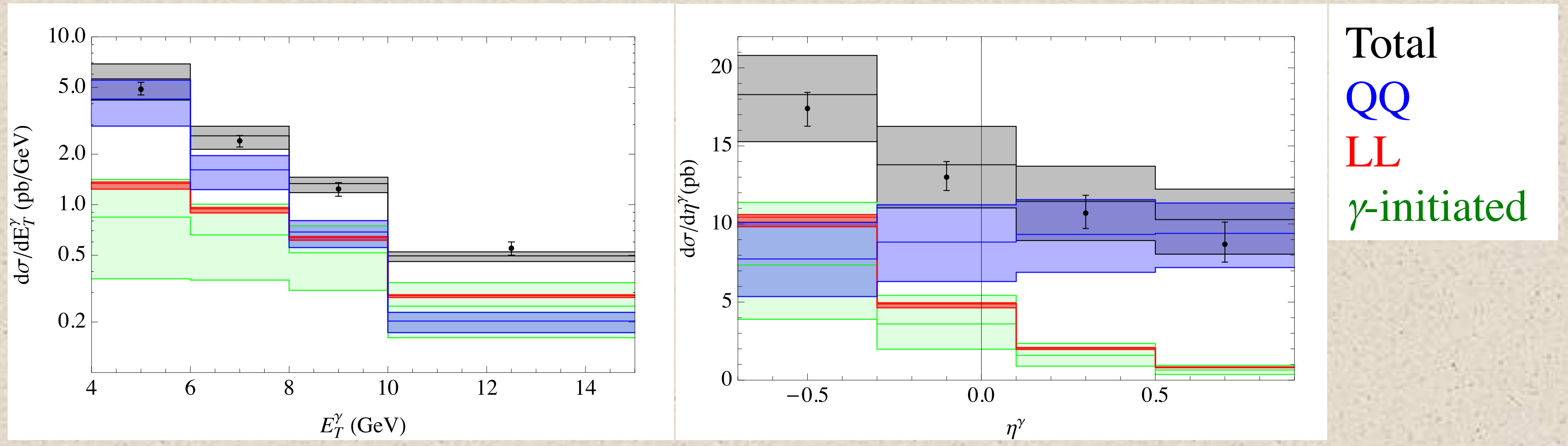
- Removes fragmentation contribution

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

- Requires fragmentation contribution
  (Use Aleph LO parametrization)

Theoretical Uncertainties

1) Factorization Scale

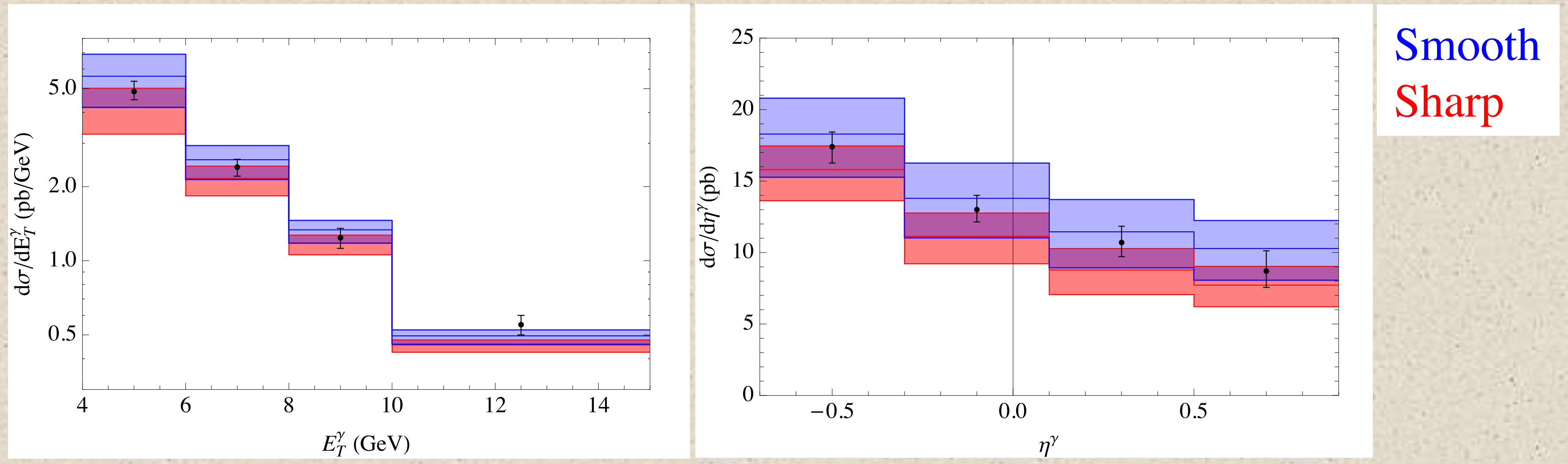


($p_0^\gamma = 0$, Smooth Isolation, $0.5E_T^\gamma < \mu_F < 2E_T^\gamma$)

- 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

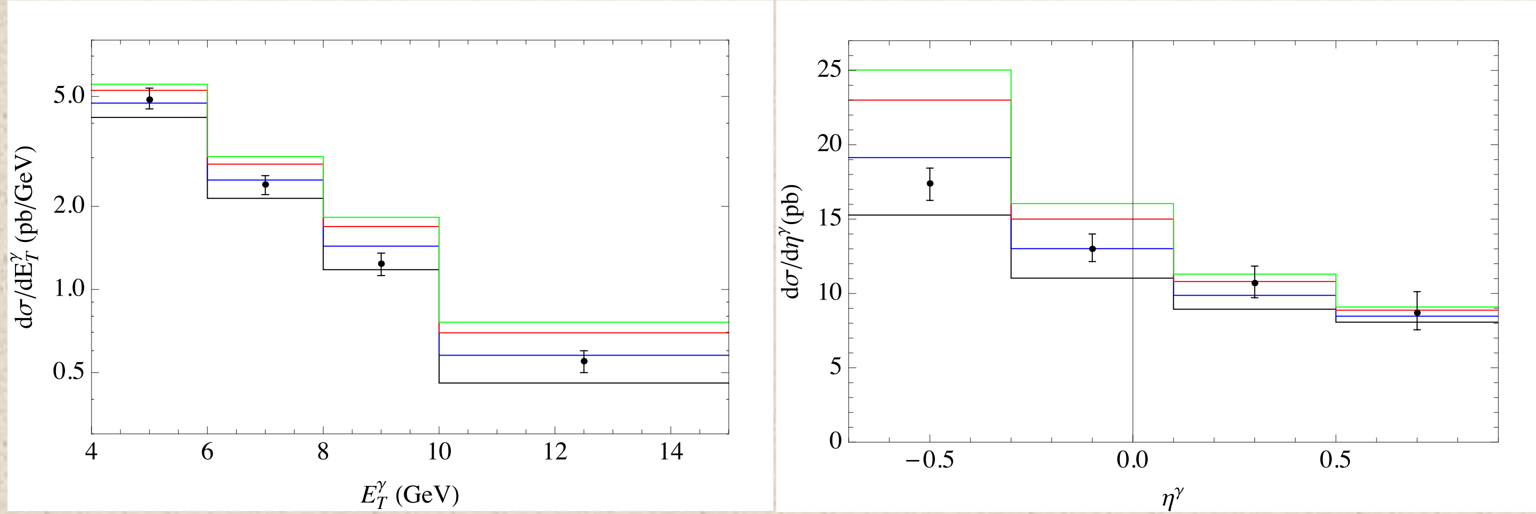


$$(p_0^\gamma = 0 ,\ 0.5 E_{T\gamma} < \mu_F < 2 E_{T\gamma})$$

- 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



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

$p_0^\gamma = 0.2$ %

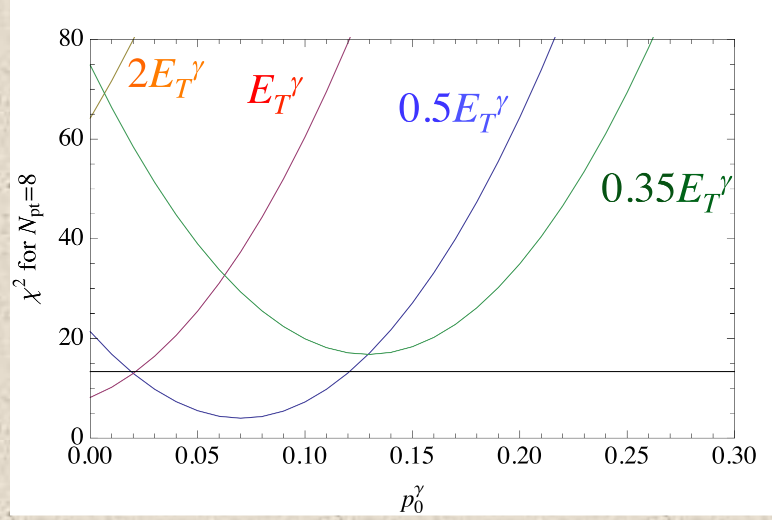
$p_0^\gamma = 0.1$ %

$p_0^\gamma = 0.0$ %

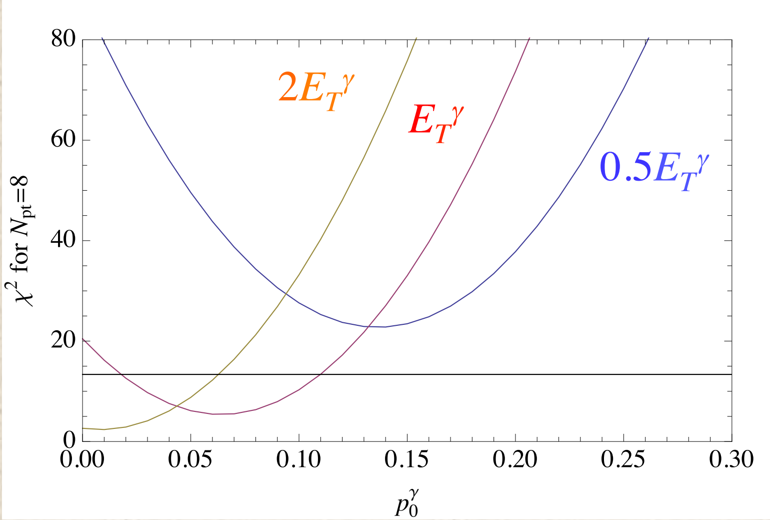
(Smooth Isolation, $\mu_F = 0.5 E_T^\gamma$)

- 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

Summary

- PDFs have larger uncertainties in both small x and large x regions.
- PDFs will be further determined by LHC data.
- Photon can be treated as a parton inside proton.
- In a 100TeV SppC, top quark can be a parton of proton, consistent hard part calculations are needed.

Backup Slides

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)

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

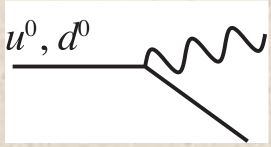
$$\gamma^n = \frac{\alpha}{2\pi}\left(A_u e_u^2 \tilde{P}_{\gamma q} \circ d^0 + A_d e_d^2 \tilde{P}_{\gamma q} \circ u^0\right)$$

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 .

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

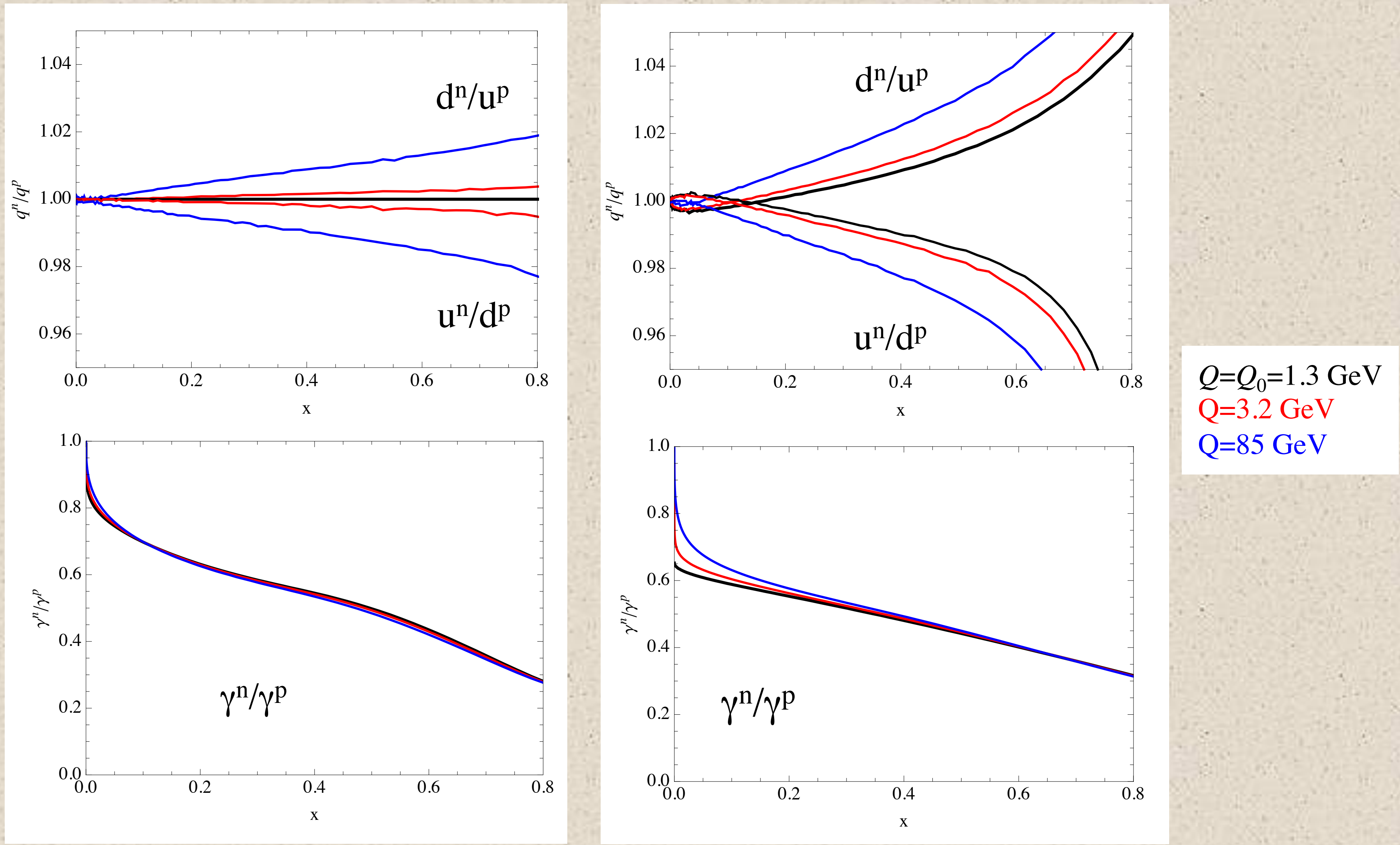
Here, assume $u^0 = u^p \equiv u^p(x,Q_0), \quad d^0 = d^p \equiv d^p(x,Q_0)$

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:

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

Isospin violation



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

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

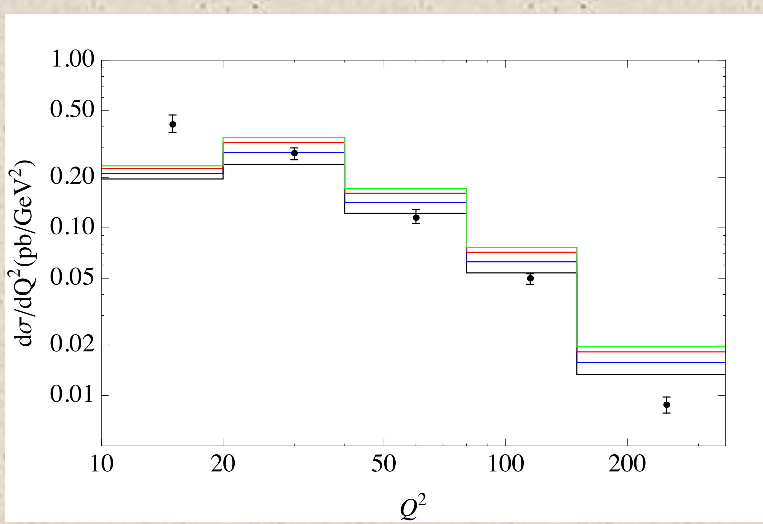
Constraints on Photon PDFs

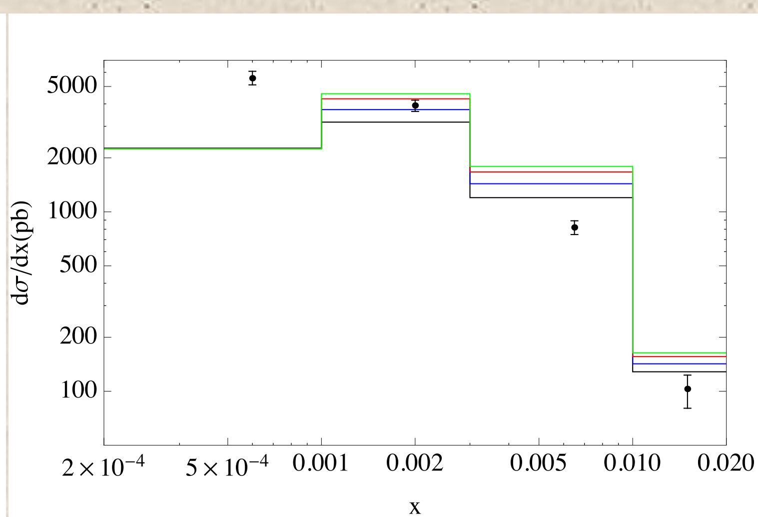
1) Global fitting
   a. Isospin violation effects
      - come from scattering off nuclei
      - perturbativity cuts on W^2 generally require $x < .2-.4$
      - constraints likely to be small (MRST)
   b. Momentum sum rule
      - momentum carried by photon leaves less for other partons
      - constrains 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) $= 0.29$ %

$p_0^\gamma = 0.2$ %

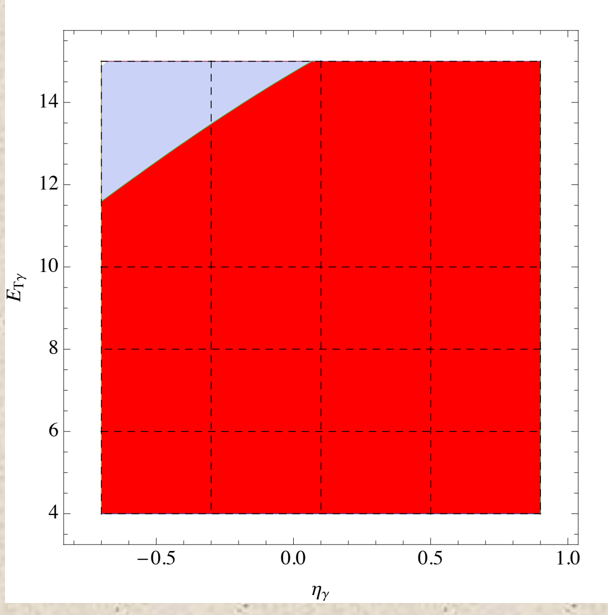
$p_0^\gamma = 0.1$ %

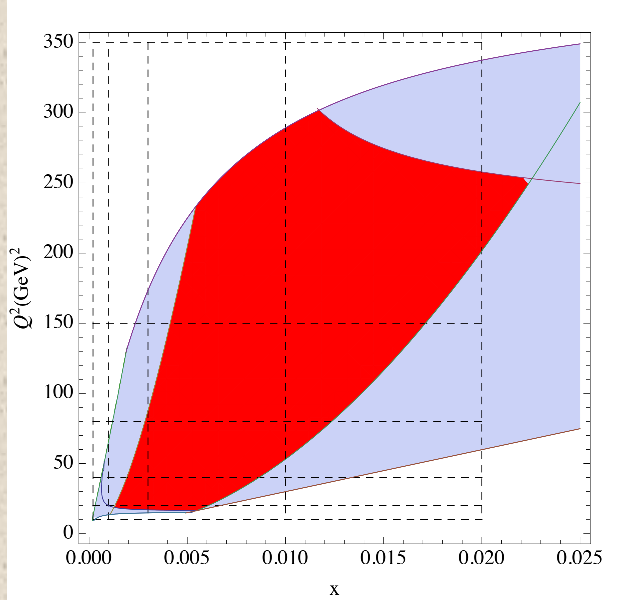
$p_0^\gamma = 0.0$ %

(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

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?