Impact of direct photon production at NLO+NLL on gluon distribution at large x

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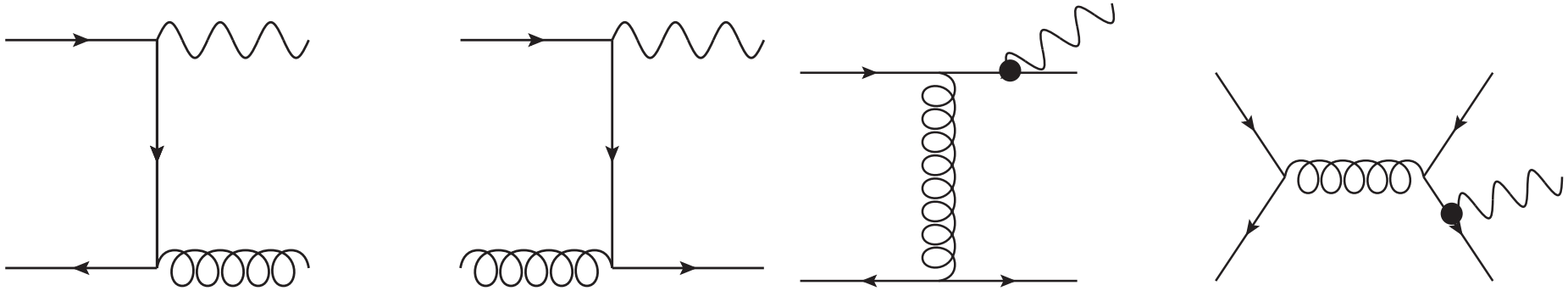
EXPLORING THE NATURE OF MATTER

Motivations:

- The data of direct photon production has the potential to constrain large x gluons.
- Currently, direct photon data are largely excluded from global fits due to inconsistencies among the data and the theory at NLO in pQCD.
- Threshold resummation at NLO+NLL seems to alleviate the disagreement (Catani *et al*, de Florian,Vogelsang).

Direct photon production.

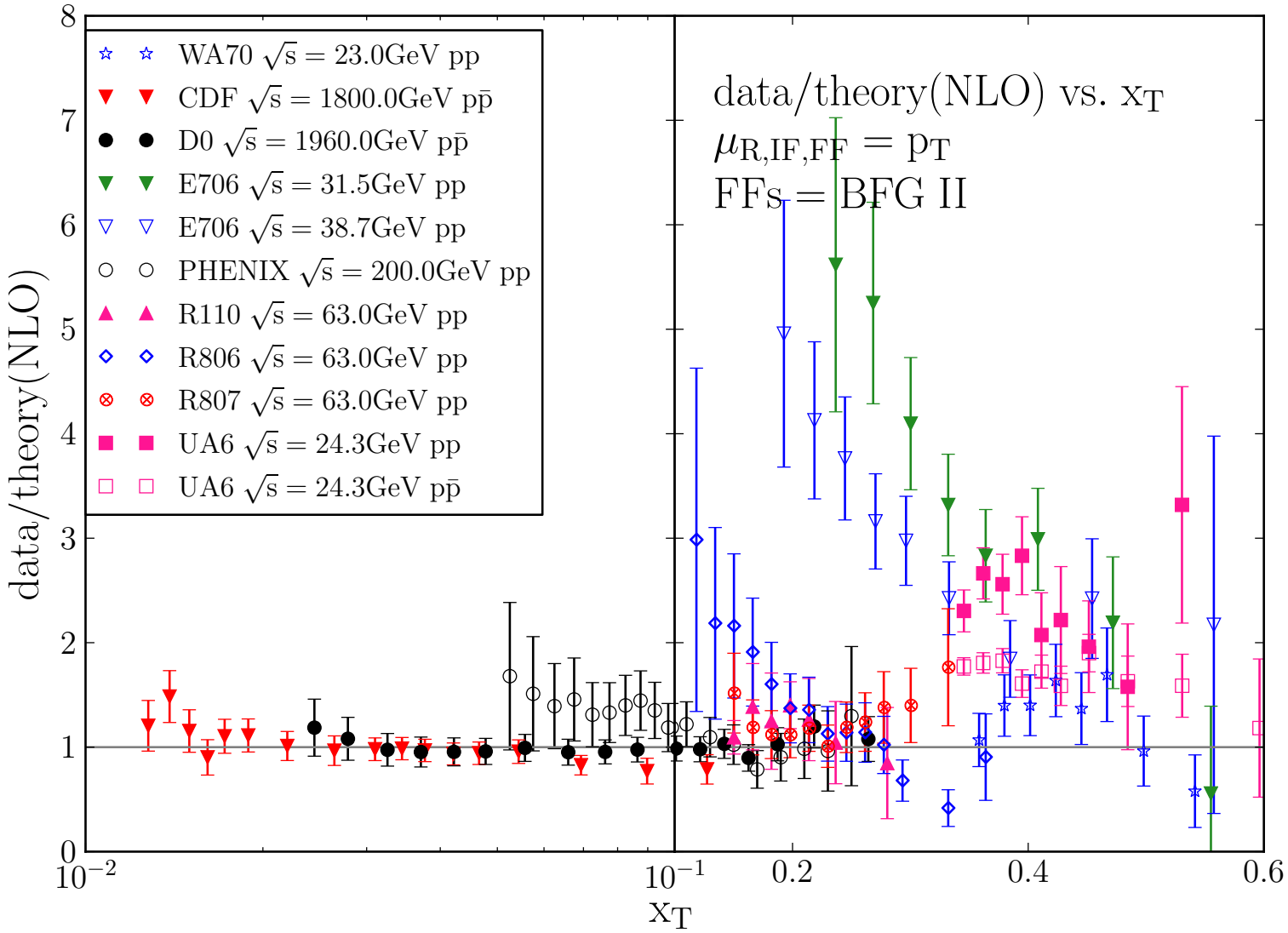
The *leading-order* (LO)



- In proton-proton collisions direct photon productions is dominated by qg scattering.

Do we understand direct photons?

Direct photon production.



Can we improve the theory predictions?

Direct photon production.

Rapidity integrated cross section

$$p_T^3 \frac{d\sigma}{dp_T}(x_T^2) = \sum_{a,b,c} \int_{x_T^2}^1 dx_a f_{a/A}(x_a, \mu_{IF}) \int_{x_T^2/x_a}^1 dx_b f_{b/B}(x_b, \mu_{IF})$$
$$\times \int_{x_T/\sqrt{x_a x_b}}^1 dz z^2 D_{\gamma/c}(z, \mu_{FF}) \frac{\hat{x}_T^4 \hat{s}}{2} \frac{d\sigma_{a,b}^{(0)}}{d\hat{x}_T^2}(\hat{x}_T^2, \mu_R)$$
$$\times \left[1 + \alpha_s(\mu_R)\{A' \ln^2(1 - \hat{x}_T^2) + B' \ln(1 - \hat{x}_T^2) + C' + ...\}\right]$$

- $x_T = 2p_T/\sqrt{S}$
- $\hat{x}_T = 2p_T/z\sqrt{x_a x_b S}$
- At large x_T the role of logs are more relevant.

Direct photon production.

$$p_T^3 \frac{d\sigma(x_T)}{dp_T} = \sum_{a,b,c} f_{a/A}(x_a, \mu_{IF}) * f_{b/B}(x_b, \mu_{IF}) * D_{\gamma/c}(z, \mu_{FF}) * \hat{\Sigma}(\hat{x}_T, ...)$$

$\hat{\Sigma}(\hat{x}_T, ...) \supset$

1				LO
$\alpha_s L^2$	$\alpha_s L$	α_s		NLO
$\alpha_s^2 L^4$	$\alpha_s^2 L^3$	$\alpha_s^2 L^2$	$\alpha_s^2 L$	NNLO
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
$\alpha_s^n L^{2n}$	$\alpha_s^n L^{2n-1}$	$\alpha_s^n L^{2n-2}$	...	N^{n}LO
LL	NLL	NNLL	...	

- It is possible to include "towers" of logs into the cross section$\rightarrow$ Threshold Resummation

Direct photon production.

- Resummation is performed in "mellin space":

$$f_N = \int_0^1 dx x^{N-1} f(x) \qquad f(x) = \frac{1}{2\pi i}\int_{c-i\infty}^{c+i\infty} dN x^{-N} F_N$$

- The invariant cross section in N-space:

$$p_T^3 \frac{d\sigma(N)}{dp_T} = \sum_{a,b,f} f_{a/A}(N+1) f_{b/B}(N+1) D_{\gamma/c}(2N+3)\hat{\Sigma}(N)$$

- The partonic cross section at NLO:

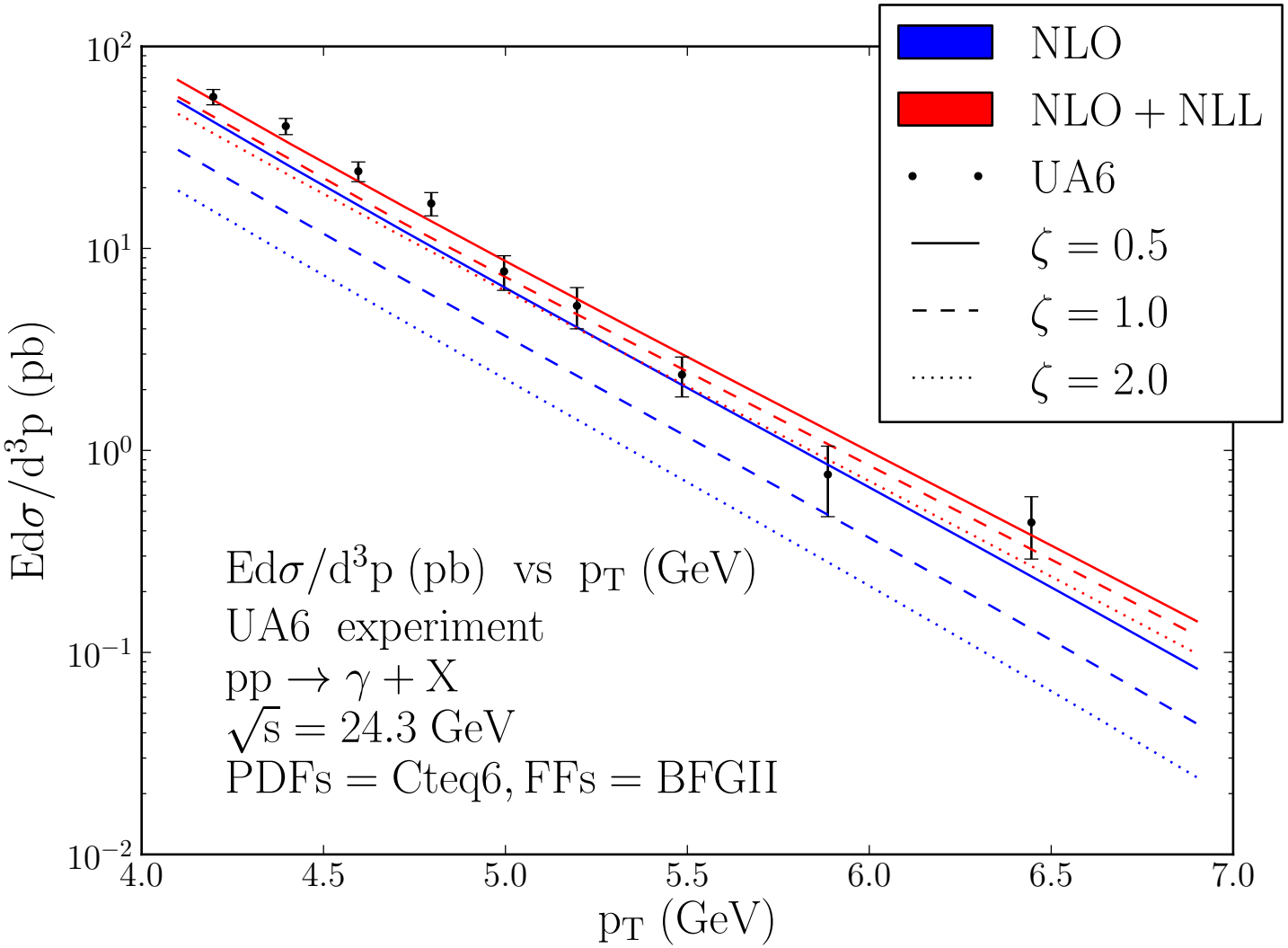
$$\hat{\Sigma}^{\mathsf{NLO}}(\hat{x}_T) = \hat{\Sigma}^{\mathsf{Born}}\left[1 + \alpha_s \ln(1-\hat{x}_T^2)^2 + ...\right]$$
$$\hat{\Sigma}^{\mathsf{NLO}}(N) = \hat{\Sigma}^{\mathsf{Born}}\left[1 + \alpha_s \ln(1+N)^2 + ...\right]$$

- The resummed partonic cross section in N-space is given by:

$$\hat{\Sigma}^{\mathsf{NLL}}(N) = C\left(\Delta_N^a \Delta_N^b \Delta_N^c J_N^d \sum_i G_i \Delta_{i,N}^{(\mathsf{int})}\right)\hat{\Sigma}^{\mathsf{Born}}(N)$$

Global analysis

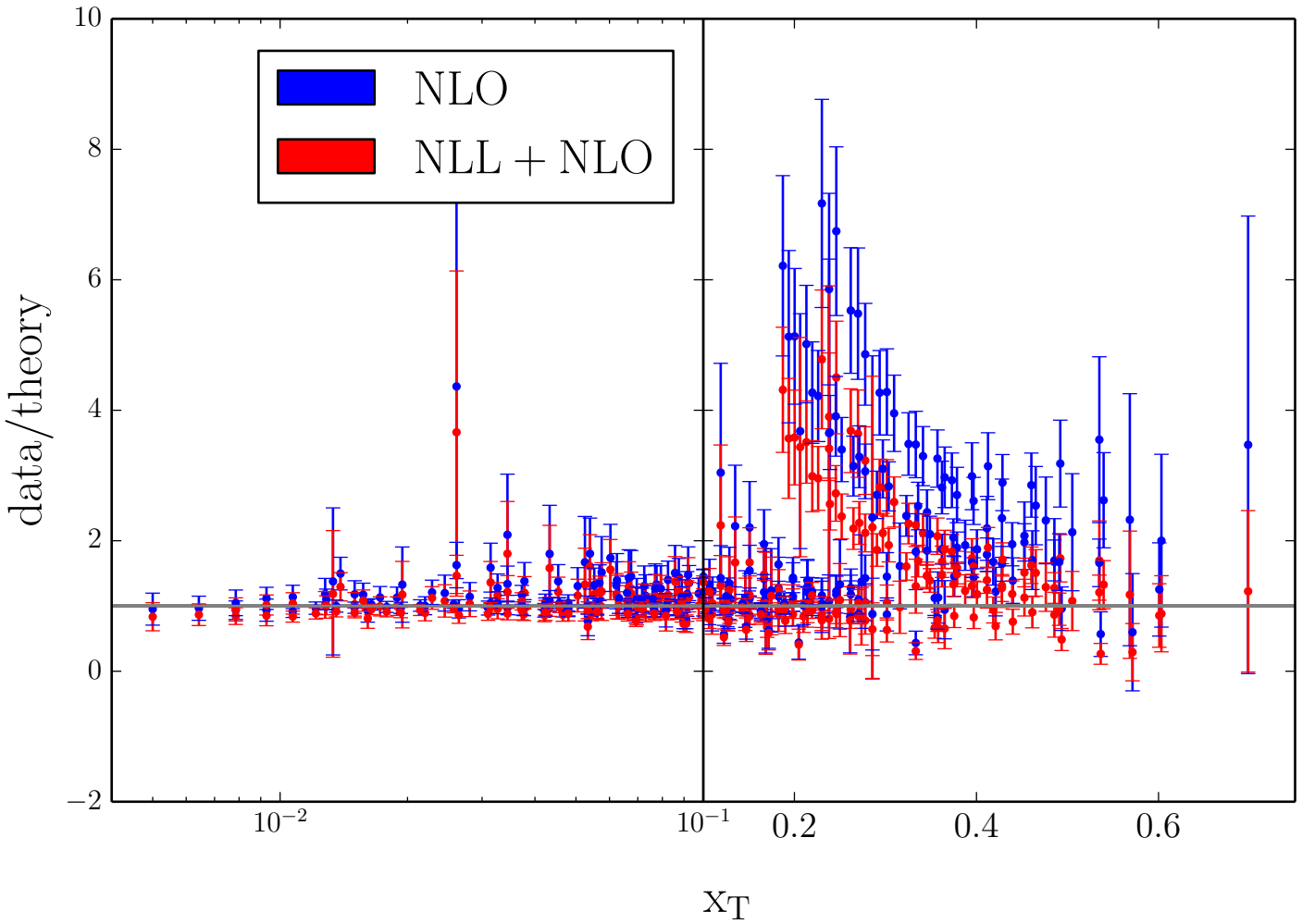
Example: UA6 experiment ($\sqrt{s} = 24.3$ GeV)



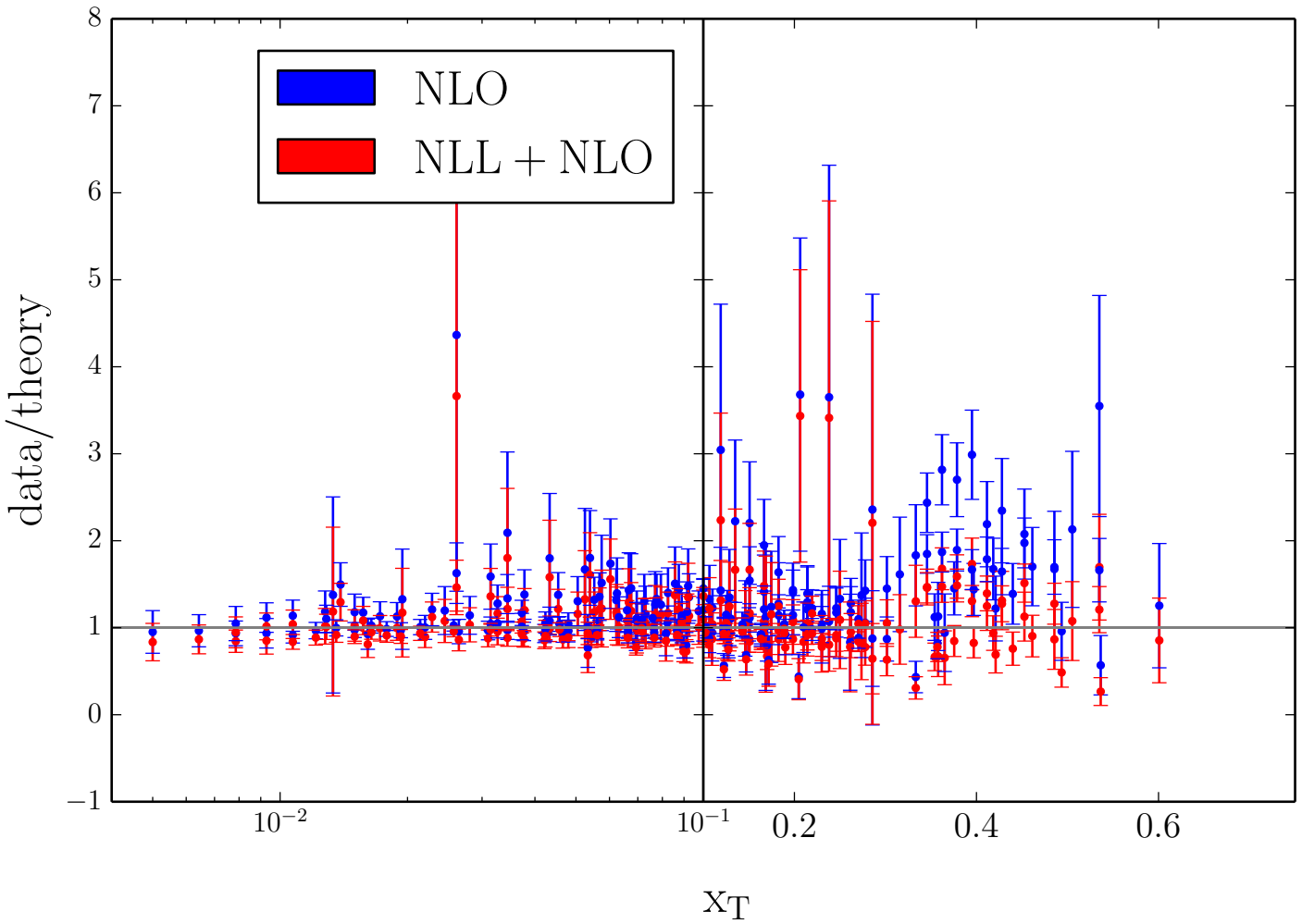
Global Data

exp/col	date	reaction	$\sqrt{s}$ (GeV)	# pts	p_T (GeV) range	x_T range	norm
WA70	1988	pp	23.30	8	[4.0,6.5]	[3.43e-01,5.58e-01]	10.0
NA24	1987	pp	23.75	5	[3.0,6.5]	[2.53e-01,5.47e-01]	7.0
UA6	1998	pp	24.30	9	[4.1,6.9]	[3.37e-01,5.68e-01]	11.0
UA6	1998	$p\bar{p}$	24.30	10	[4.1,7.7]	[3.37e-01,6.34e-01]	11.0
E706	2004	pBe	31.50	17	[3.5,12.0]	[2.22e-01,7.62e-01]	8.0
E706	2004	pp	31.50	8	[3.5,10.0]	[2.22e-01,6.35e-01]	8.0
E706	2004	pBe	38.70	16	[3.5,10.0]	[1.81e-01,5.17e-01]	8.0
E706	2004	pp	38.70	9	[3.5,12.0]	[1.81e-01,6.20e-01]	8.0
R110	1989	pp	63.00	7	[4.5,10.0]	[1.43e-01,3.17e-01]	5.0
R806	1982	pp	63.00	14	[3.5,12.0]	[1.11e-01,3.81e-01]	-
R807	1990	pp	63.00	11	[4.5,11.0]	[1.43e-01,3.49e-01]	-
PHENIX	2012	pp	200.00	18	[5.2,25.0]	[5.25e-02,2.50e-01]	15.29
UA1	1988	$p\bar{p}$	546.00	6	[17.0,46.0]	[6.23e-02,1.68e-01]	23.0
UA1	1988	$p\bar{p}$	630.00	16	[17.0,90.0]	[5.40e-02,2.86e-01]	23.0
UA2	1992	$p\bar{p}$	630.00	13	[15.9,82.3]	[5.05e-02,2.61e-01]	9.0
CDF	2002	$p\bar{p}$	630.00	7	[9.9,33.6]	[3.14e-02,1.07e-01]	12.0
CDF	2002	$p\bar{p}$	1800.00	17	[11.5,114.7]	[1.28e-02,1.27e-01]	12.0
CDF	2009	$p\bar{p}$	1960.00	16	[30.0,400.0]	[3.06e-02,4.08e-01]	6.0
D0	2001	$p\bar{p}$	630.00	7	[7.3,49.0]	[2.33e-02,1.56e-01]	-
D0	2000	$p\bar{p}$	1800.00	9	[10.0,140.0]	[1.11e-02,1.56e-01]	-
D0	2006	$p\bar{p}$	1960.00	17	[23.0,300.0]	[2.35e-02,3.06e-01]	-
CMS	2011	pp	7000.00	15	[25.0,400.0]	[7.14e-03,1.14e-01]	-
ATLAS	2011	pp	7000.00	8	[15.0,100.0]	[4.29e-03,2.86e-02]	-

All the data sets



All the data sets without E706



Constraints on Gluon PDF

Bayesian Approach

$$\mathcal{P}(\vec{a}|D) = \frac{\mathcal{P}(D|\vec{a})}{\mathcal{P}(D)} \times \mathcal{P}(\vec{a})$$

The Bayesian approach in practice

- The expectation value

$$\begin{aligned}\mathsf{E}[\mathcal{O}] &= \int d^n\alpha \mathcal{P}(\vec{\alpha}|D)\mathcal{O}(\vec{\alpha}) \\ &= \int d^n\alpha \frac{\mathcal{P}(D|\vec{\alpha})}{\mathcal{P}(D)}\mathcal{P}(\vec{\alpha})\mathcal{O}(\vec{\alpha}) \\ &= \frac{1}{N}\sum_k w_k \mathcal{O}(\vec{\alpha}_k)\end{aligned}$$

- The variance

$$\mathsf{Var}[\mathcal{O}] = \frac{1}{N}\sum_k w_k(\mathcal{O}(\vec{\alpha}_k) - \mathsf{E}[\mathcal{O}])^2$$

The Bayesian approach in practice

- Construct replica PDFs (Monte Carlo sampling) from the uncertainty band of a gives PDF set
- Compute replica cross sections.
- Assign a weight to each replica PDF:

$$w_k \propto \exp\left(-\frac{1}{2}\sum_e \chi_e^2(k)\right)$$

The Bayesian approach in practice

- Get reweighted theoretical cross sections

$$\mathsf{E}[\sigma] = \sum_k w_k \sigma_k$$

$$\mathsf{VAR}[\sigma] = \sum_k w_k (\sigma_k - \mathsf{E}[\sigma])^2$$

- Get reweighted PDFs

$$\mathsf{E}[f] = \sum_k w_k f_k$$

$$\mathsf{VAR}[f] = \sum_k w_k (f_k - \mathsf{E}[f])^2$$

A trick for the MC sampling

- MC sampling in PDF space

$$f_k(x) = f^0(x) + \frac{1}{2}\sum_i R_i^k (f_i^+(x) - f_i^-(x))$$
$$\equiv f^0(x) + \frac{1}{2}\sum_i R_i^k \Delta f_i(x)$$

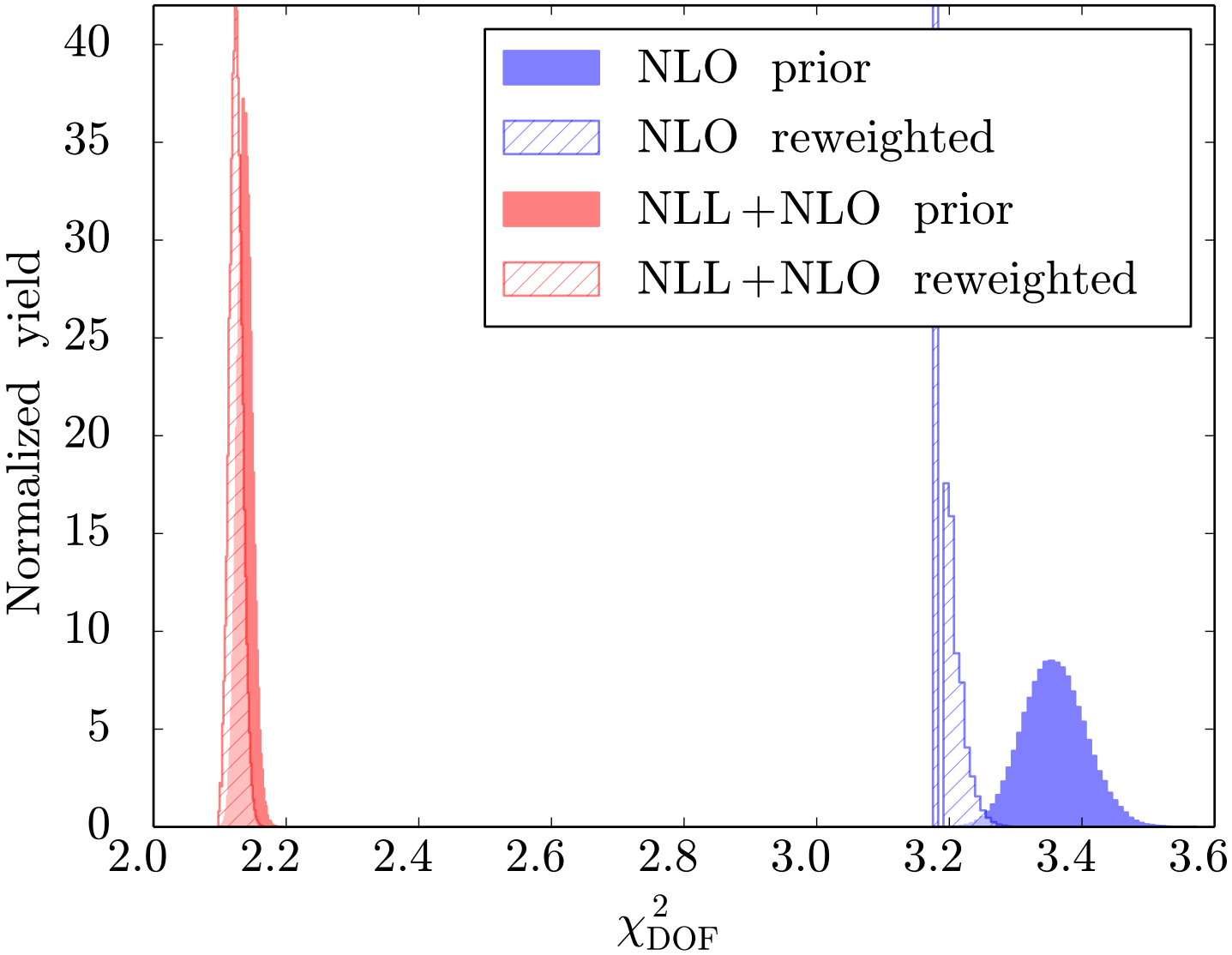
- MC cross sections

$$\sigma_k(x_T) = \sigma_{00}(x_T) + \frac{1}{2}\sum_i R_i^k \left[\sigma_{0i}(x_T) + \sigma_{i0}(x_T)\right]$$

Results

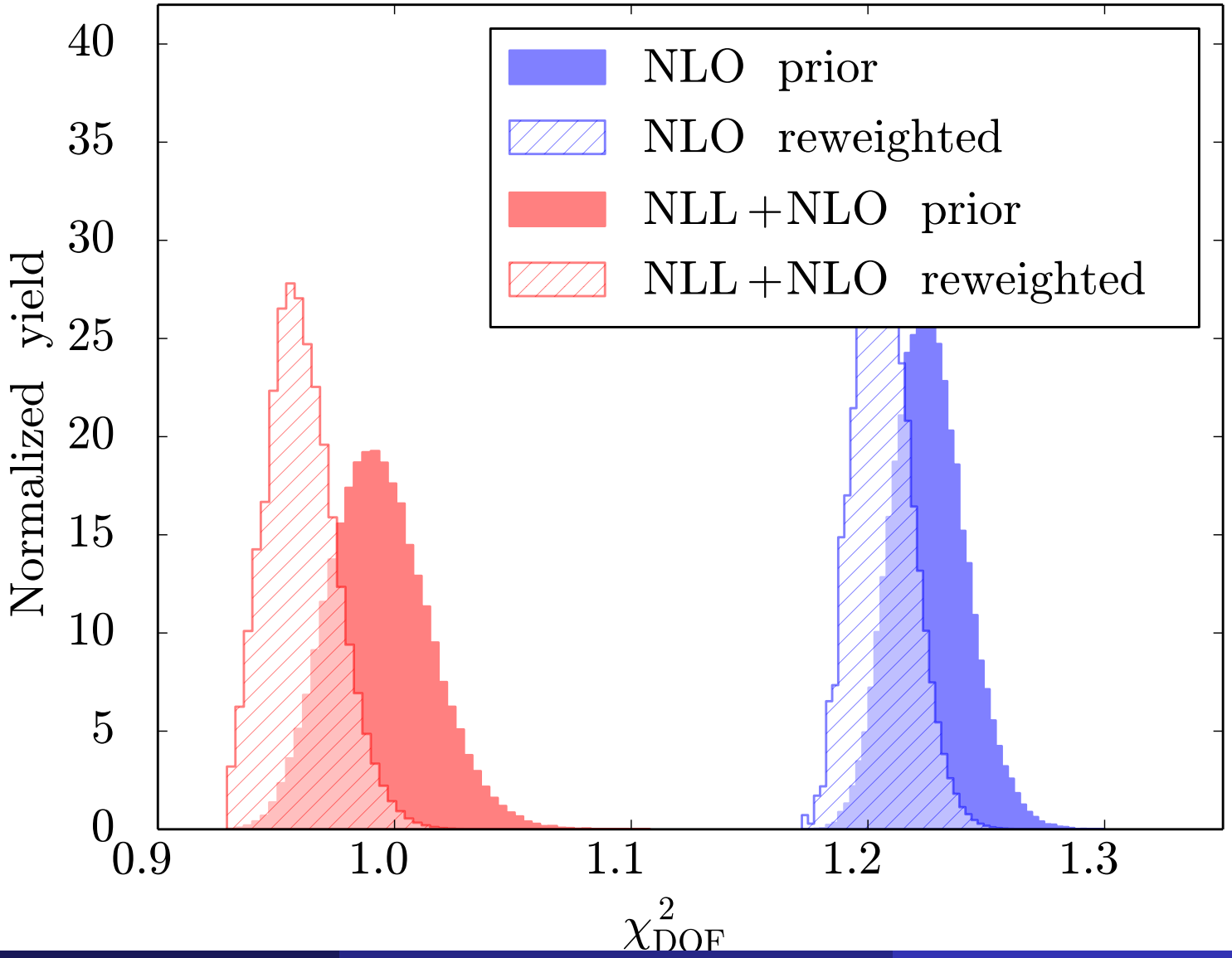
Reweighting PDFs

All the data sets

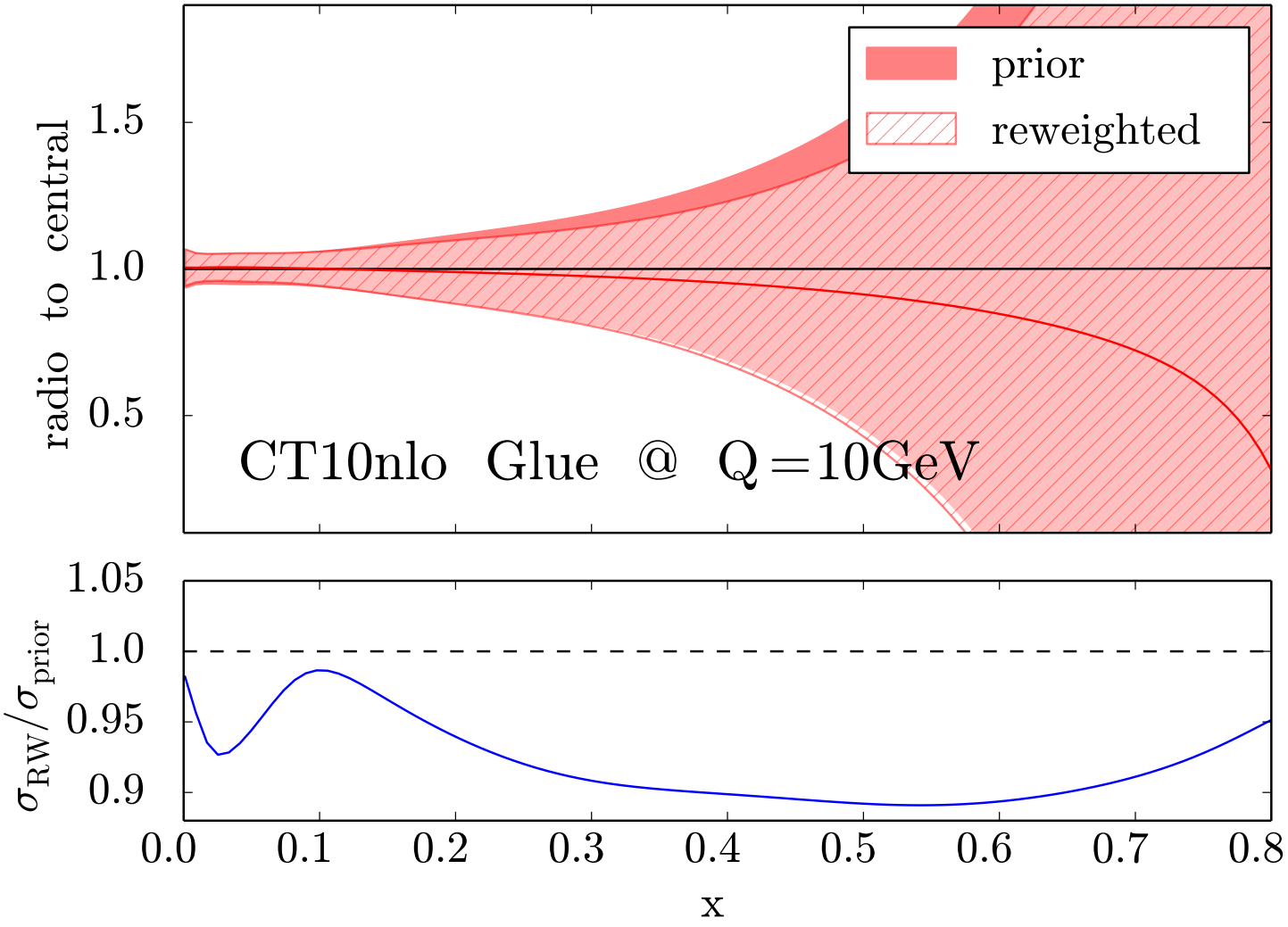


Reweighting PDFs

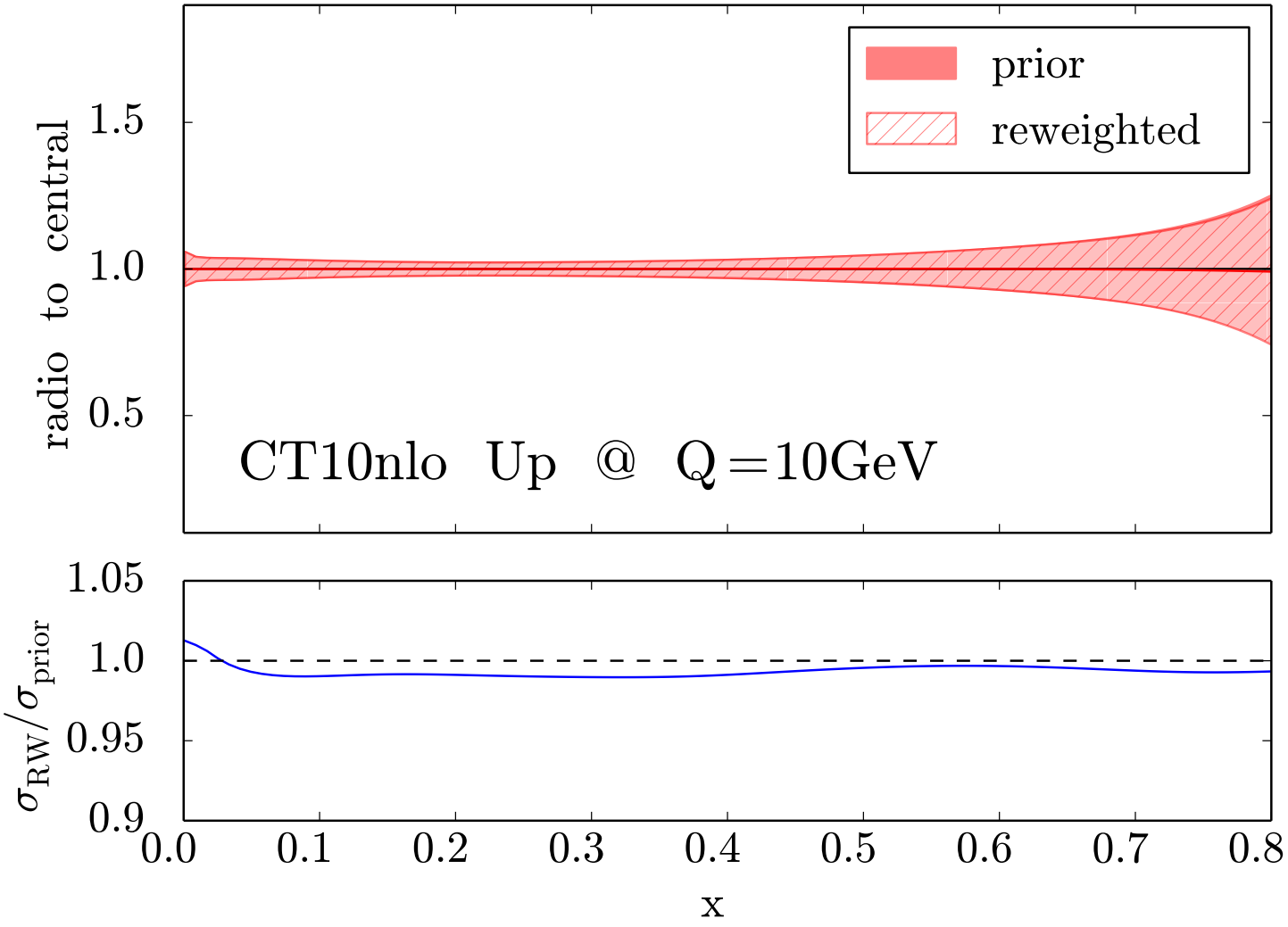
All the data sets excluding E706



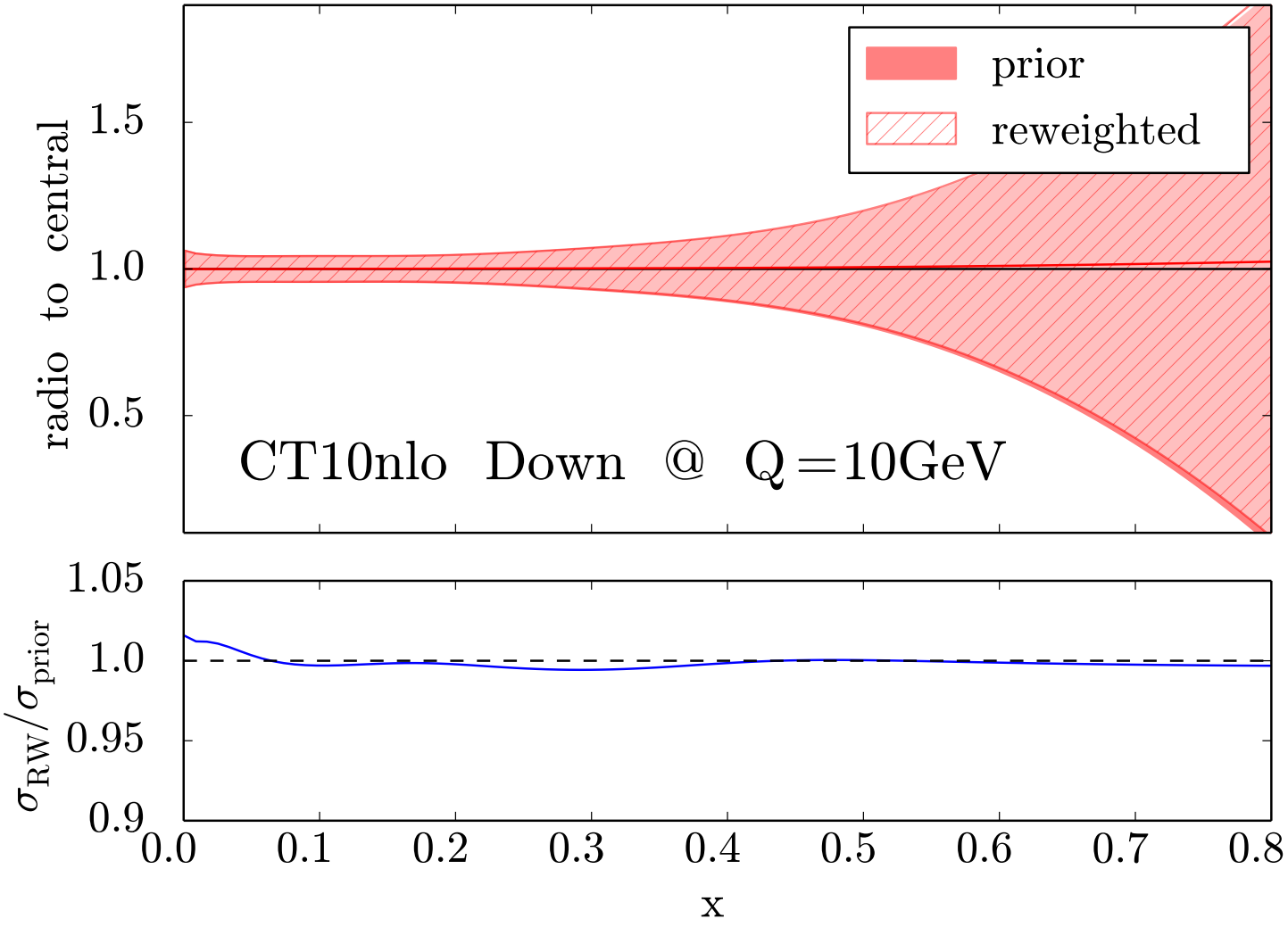
Reweighting PDFs



Reweighting PDFs



Reweighting PDFs



Summary

- Threshold resummation can provide a consistent picture of direct photon phenomenology from $\sqrt{s} = 23$ GeV to 7 TeV. (except for E706 data)

- The uncertainties of the gluon can be decreased by $\sim 10\%$ in the range of $x \simeq 0.4 - 0.6$ using direct photon data (w/o E706).

END