Impact of electroweak and forward measurements on **P**arton **D**istribution **F**unctions (**PDF**s)

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479. WE-Heraeus-Seminar on "Physics at LHCb"
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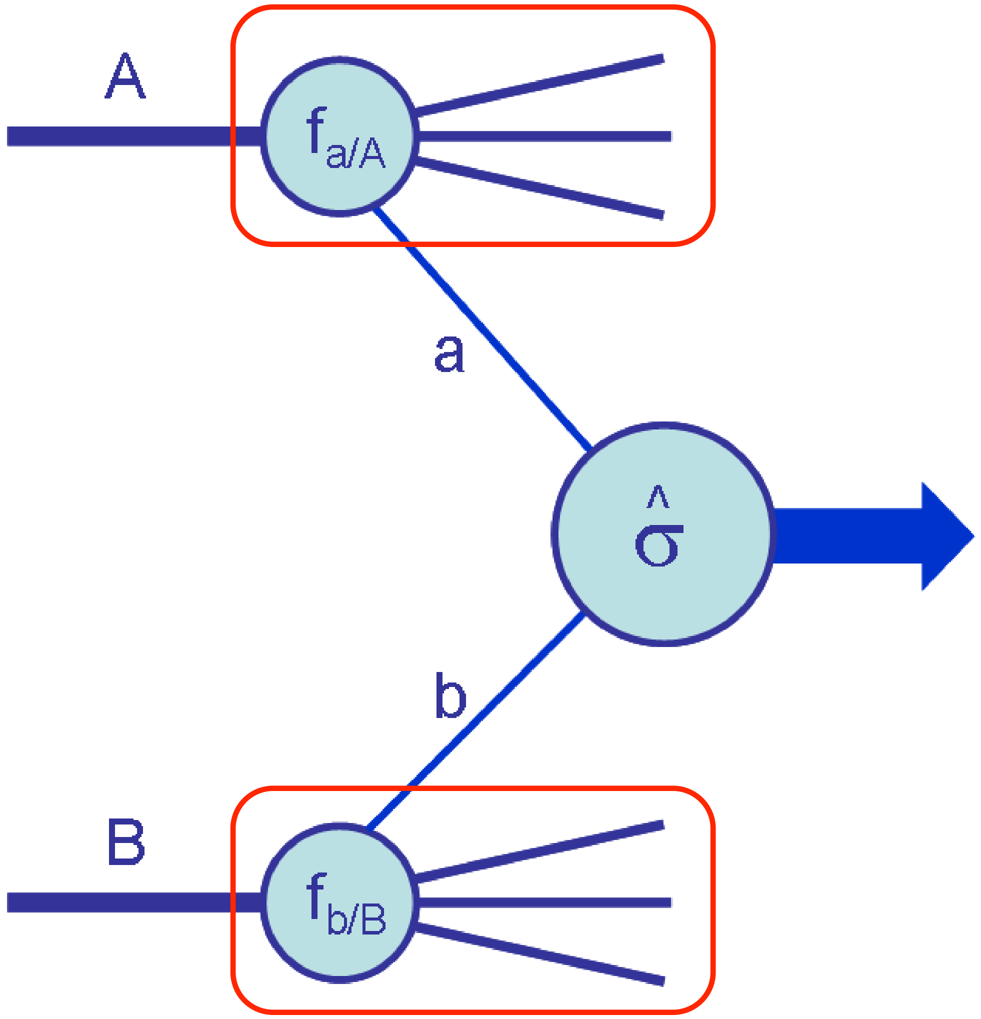
Reference (slightly old, but still relevant):
R. S. Thorne, A. D. Martin, W. J. Stirling and G. Watt,
"Parton Distributions and QCD at LHCb",
in the proceedings of DIS 2008 [arXiv:0808.1847].

Outline of talk

- Introduction to proton PDFs and global fits.
- Rôle of LHCb electroweak data:
    - W^+, W^-, Z cross sections (and their ratios).
    - $W^\pm \to l^\pm \nu$ charge asymmetry.
    - Z rapidity distribution.
- Forward low-mass Drell-Yan production and the theoretical motivation for such a measurement.

Event rate = Cross section (σ) × Luminosity (L)



Phenomenology

Theory ⟷ Cross sections ⟷ Experiment

- Theoretical calculations: Feynman diagrams have initial quarks and gluons.
- **Problem:** the LHC collides protons. Need to know density of quarks and gluons (partons) inside the proton.

Parton **D**istribution **F**unctions (**PDFs**)

$$\sigma = f_{a/A} \otimes f_{b/B} \otimes \hat{\sigma}_{ab}$$

No predictions for signal or background cross sections without knowledge of PDFs!

QCD factorisation

QCD = Quantum ChromoDynamics

(describes interactions between quarks and gluons)

- $f_{a/A}(x, Q^2)$ gives *number density* of partons a in hadron A with momentum fraction x at a hard scale $Q^2 \gg \Lambda^2_{\rm QCD}$.

$$\sigma_{AB} = \sum_{a,b=q,g} \int_0^1 \mathrm{d}x_a \int_0^1 \mathrm{d}x_b \, f_{a/A}(x_a, Q^2) \, f_{b/B}(x_b, Q^2) \, \hat{\sigma}_{ab}$$

Perturbative expansion: $\hat{\sigma}_{ab} = \hat{\sigma}_{ab}^{\rm LO} + \alpha_S \, \hat{\sigma}_{ab}^{\rm NLO} + \alpha_S^2 \, \hat{\sigma}_{ab}^{\rm NNLO} + \ldots$

PDF evolution:
(DGLAP equation)

$$\frac{\partial f_{a/A}}{\partial \ln Q^2} = \frac{\alpha_S}{2\pi} \sum_{a'=q,g} \left[P_{aa'}^{\rm LO} + \alpha_S P_{aa'}^{\rm NLO} + \ldots \right] \otimes f_{a'/A}$$

α_S evolution:

$$\frac{\partial \alpha_S}{\partial \ln Q^2} = -\beta^{\rm LO} \alpha_S^2 - \beta^{\rm NLO} \alpha_S^3 - \ldots$$

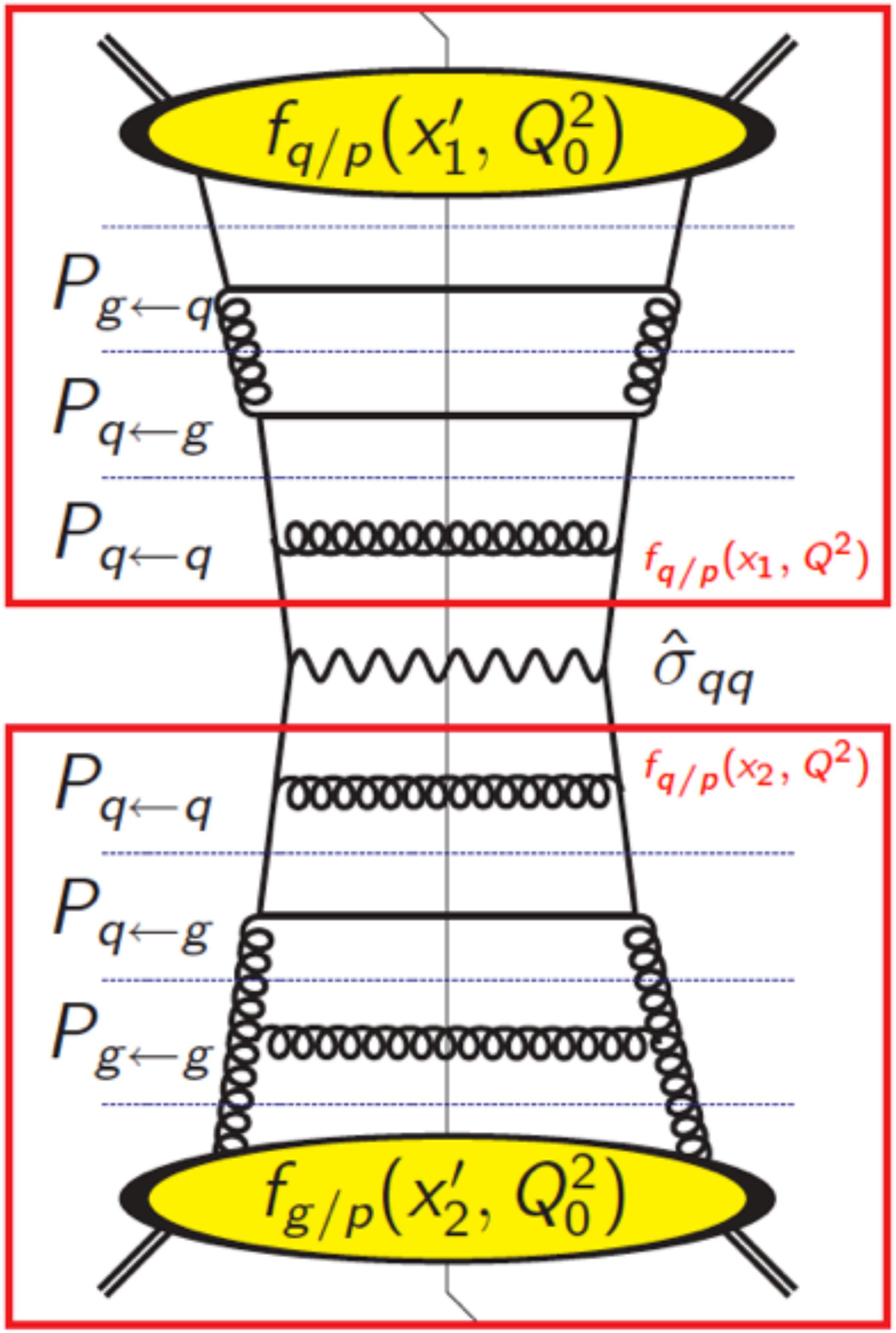
- Need to extract input values $f_{a/A}(x, Q_0^2)$ and $\alpha_S(M_Z^2)$ from data.

NLO is standard.

NNLO $P_{aa'}$ (2004) and $2 \rightarrow 1$.

Lattice QCD?

Diagrammatic interpretation



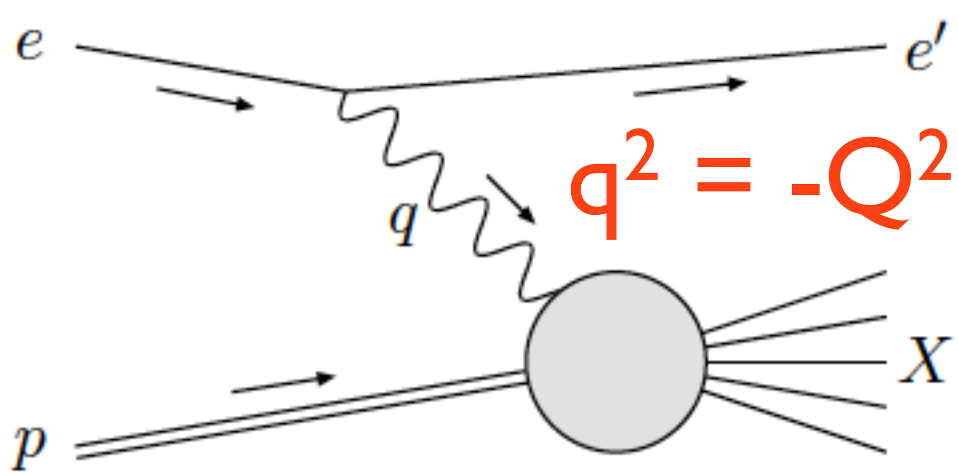
- Drell–Yan production at LO: $q\bar{q} \rightarrow V = W/Z/\gamma^*$
- Cut diagram: $|\mathcal{M}|^2 = \mathcal{M}\mathcal{M}^*$
- Large logarithm from collinear gluon emission: $\int_{k_0^2}^{Q^2} (\mathrm{d}k_T^2/k_T^2)\, \frac{\alpha_s}{2\pi}\, P_{q\leftarrow q}(z)$
- Similar collinear logs from other parton splittings.
- DGLAP evolution equation:

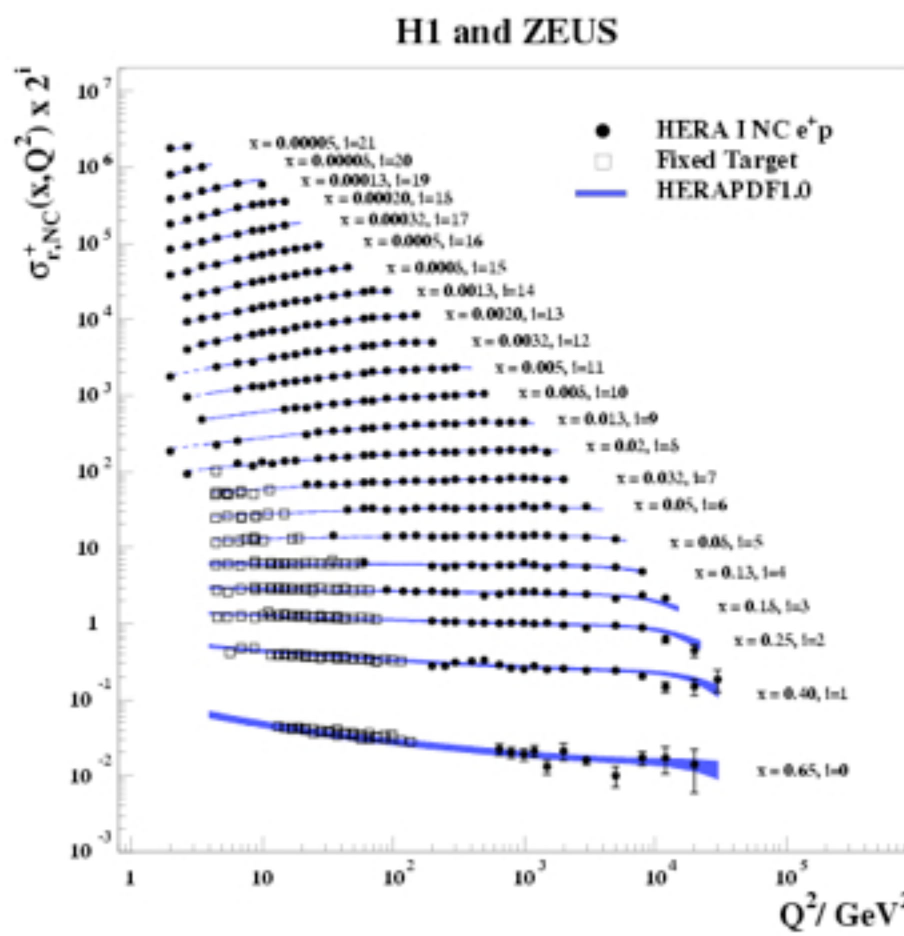
$$\frac{\partial f_{a/p}}{\partial \ln Q^2} = \frac{\alpha_S}{2\pi} \sum_{a'=q,g} P_{a\leftarrow a'} \otimes f_{a'/p}$$

- $f_{a/p}(x, Q_0^2) \Rightarrow f_{a/p}(x, Q^2)$

Deep-inelastic scattering (DIS)

$$F_i\left(x, Q^2\right) = \sum_{a=q,g} C_{i,a} \otimes f_{a/A}, \quad C_{i,a} = C_{i,a}^{\mathrm{LO}} + \alpha_S C_{i,a}^{\mathrm{NLO}} + \ldots$$

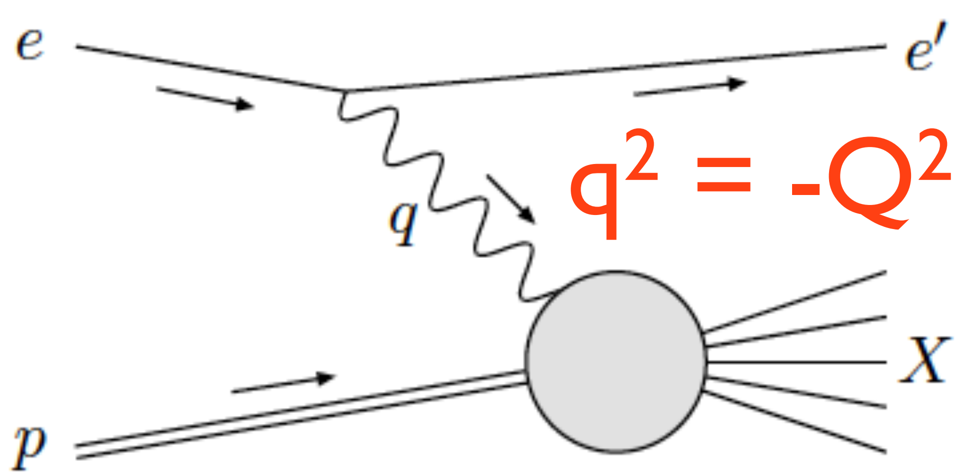


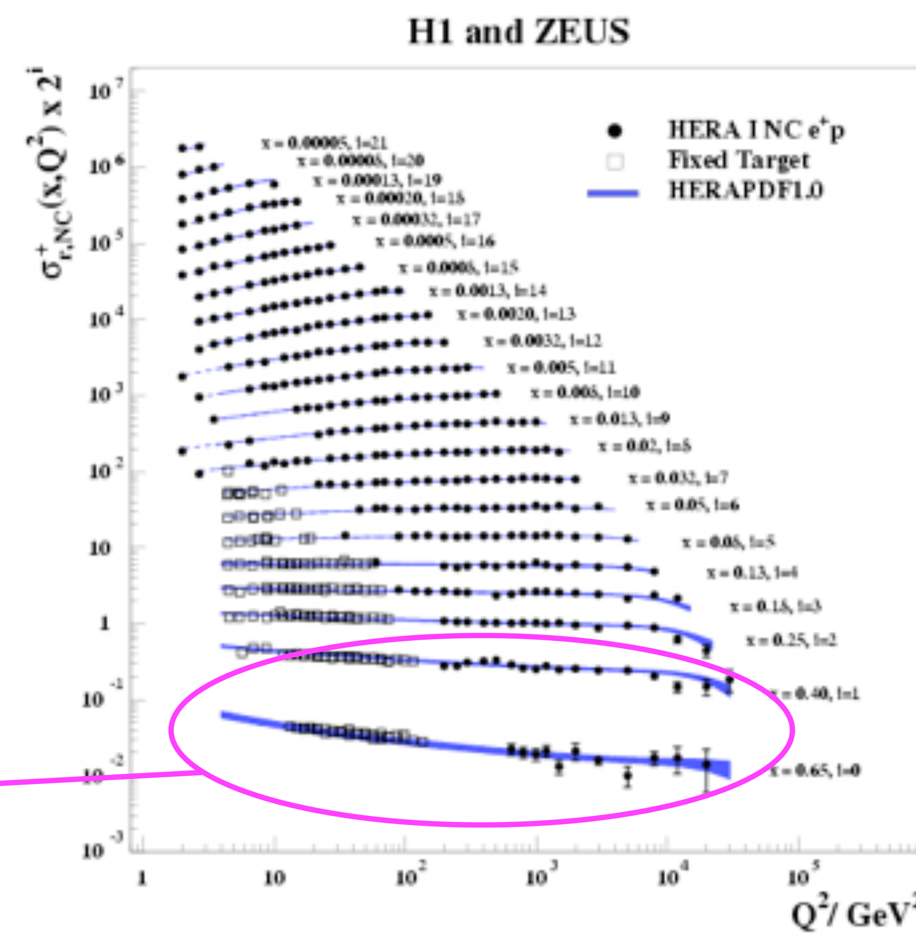


$$F_2^{\mathrm{LO}}(x, Q^2) = \sum_q e_q^2 \, x f_{q/p}$$

Deep-inelastic scattering (DIS)

$$F_i\left(x, Q^2\right) = \sum_{a=q,g} C_{i,a} \otimes f_{a/A}, \quad C_{i,a} = C_{i,a}^{\mathrm{LO}} + \alpha_S C_{i,a}^{\mathrm{NLO}} + \ldots$$





$$F_2^{\mathrm{LO}}(x, Q^2) = \sum_q e_q^2 \, x f_{q/p}$$

At large x,
F_2 falls with Q^2

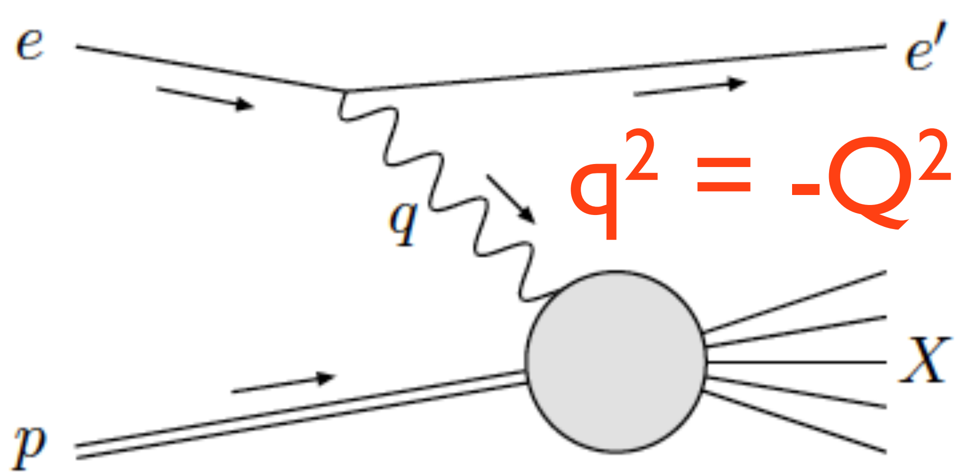
QCD scaling violations

DGLAP

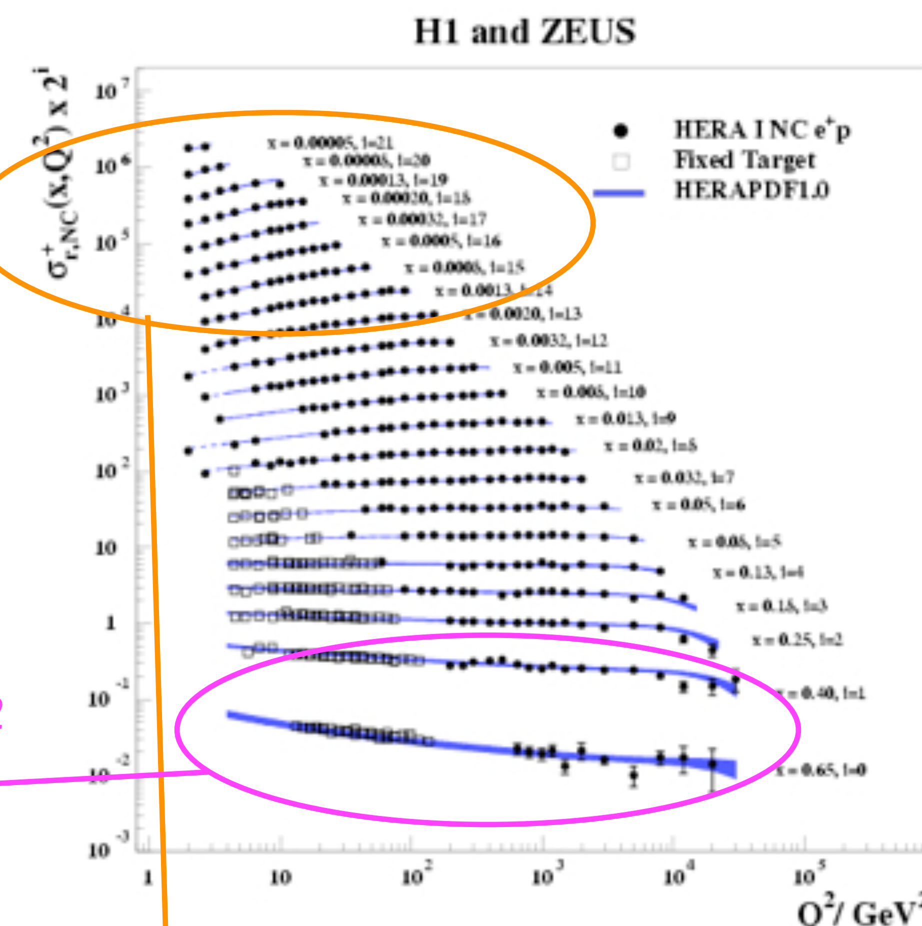
$$\frac{\partial F_2^{\mathrm{LO}}(x, Q^2)}{\partial \ln Q^2} = \frac{\alpha_S}{2\pi} \left[P_{q\leftarrow q}^{\mathrm{LO}} \otimes F_2^{\mathrm{LO}} + \sum_q e_q^2 \, P_{q\leftarrow g}^{\mathrm{LO}} \otimes f_{g/p} \right]$$

Deep-inelastic scattering (DIS)

$$F_i\left(x,Q^2\right) = \sum_{a=q,g} C_{i,a} \otimes f_{a/A}, \quad C_{i,a} = C_{i,a}^{\rm LO} + \alpha_S C_{i,a}^{\rm NLO} + \ldots$$



$$F_2^{\rm LO}(x,Q^2) = \sum_q e_q^2\, x f_{q/p}$$



↓ At large x, F_2 falls with Q^2

QCD scaling violations

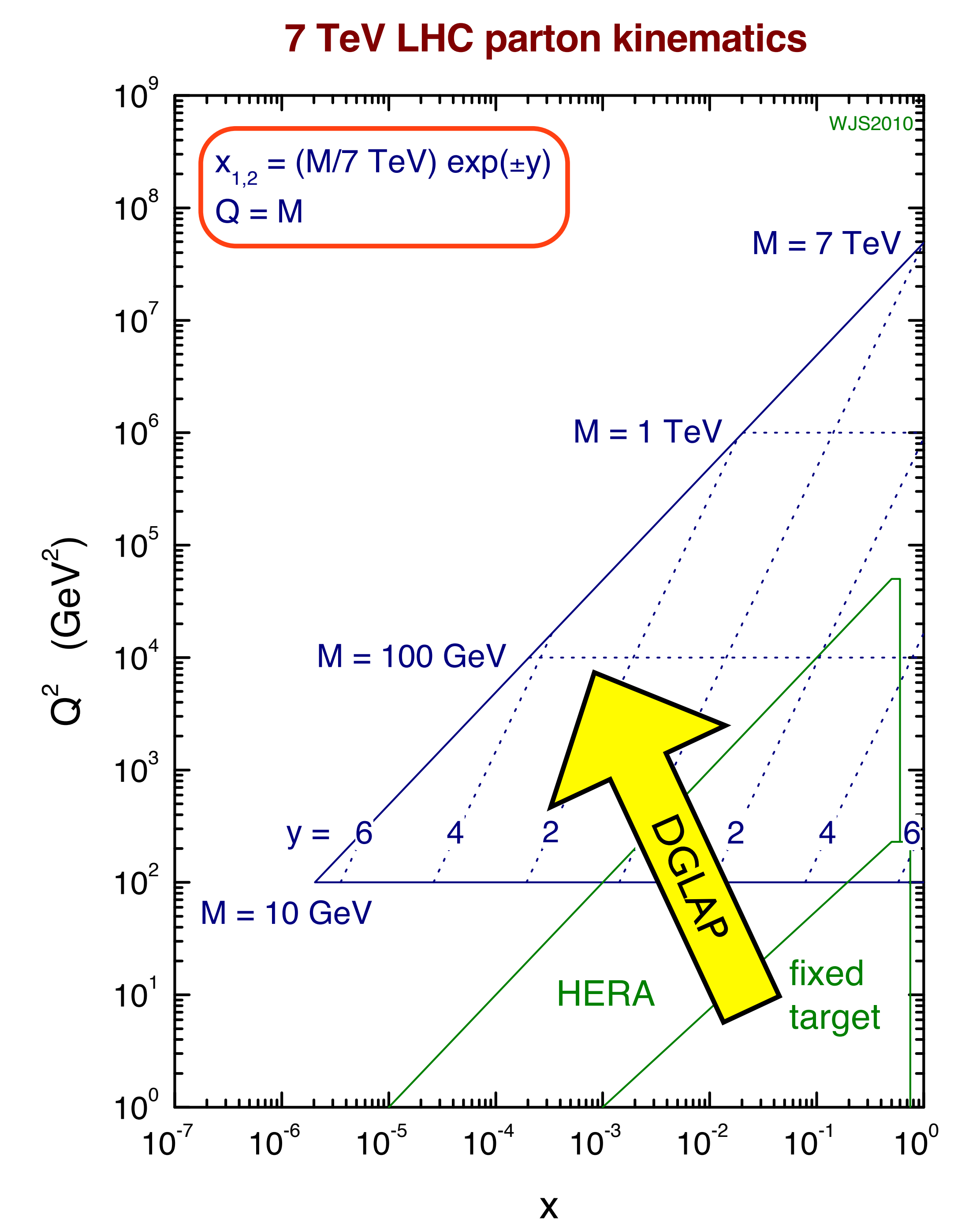
DGLAP

$$\frac{\partial F_2^{\rm LO}(x,Q^2)}{\partial \ln Q^2} = \frac{\alpha_S}{2\pi}\left[P_{q\leftarrow q}^{\rm LO} \otimes F_2^{\rm LO} + \sum_q e_q^2\, P_{q\leftarrow g}^{\rm LO} \otimes f_{g/p}\right]$$

↑ At small x, F_2 rises with Q^2

LHC kinematic plane

Produce a final state of mass $M = \sqrt{(x_1\ x_2\ s)}$ and rapidity $y = 0.5 \log(x_1/x_2)$ at LHC ($\sqrt{s}$ = 7 TeV) from two partons with momentum fractions x_1 and x_2.



- PDFs are **universal**.
- Fit existing data from HERA and fixed-target experiments, together with Tevatron data.
- HERA *ep* (H1, ZEUS).
- Fixed-target experiments:
  ℓp, ℓd (BCDMS, NMC, E665, SLAC),
  νN (CCFR, NuTeV, CHORUS),
  pp, *pd* (E866/NuSea).
- Tevatron $p\bar{p}$ (CDF, DØ).
- DGLAP evolution gives PDFs at higher Q^2 for LHC.

Which processes constrain different PDFs?

Processes included in MSTW08 global analysis [arXiv:0901.0002]:

	Process	Subprocess	Partons	x range
Fixed target	$\ell^{\pm}\{p,n\} \to \ell^{\pm} X$	$\gamma^* q \to q$	$q, \bar{q}, g$	$x \gtrsim 0.01$
	$\ell^{\pm} n/p \to \ell^{\pm} X$	$\gamma^* d/u \to d/u$	d/u	$x \gtrsim 0.01$
	$pp \to \mu^+\mu^- X$	$u\bar{u}, d\bar{d} \to \gamma^*$	$\bar{q}$	$0.015 \lesssim x \lesssim 0.35$
	$pn/pp \to \mu^+\mu^- X$	$(u\bar{d})/(u\bar{u}) \to \gamma^*$	$\bar{d}/\bar{u}$	$0.015 \lesssim x \lesssim 0.35$
	$\nu(\bar{\nu}) N \to \mu^-(\mu^+) X$	$W^* q \to q'$	$q, \bar{q}$	$0.01 \lesssim x \lesssim 0.5$
	$\nu N \to \mu^-\mu^+ X$	$W^* s \to c$	s	$0.01 \lesssim x \lesssim 0.2$
	$\bar{\nu} N \to \mu^+\mu^- X$	$W^* \bar{s} \to \bar{c}$	$\bar{s}$	$0.01 \lesssim x \lesssim 0.2$
HERA	$e^{\pm} p \to e^{\pm} X$	$\gamma^* q \to q$	$g, q, \bar{q}$	$0.0001 \lesssim x \lesssim 0.1$
	$e^+ p \to \bar{\nu} X$	$W^+\{d,s\} \to \{u,c\}$	d, s	$x \gtrsim 0.01$
	$e^{\pm} p \to e^{\pm} c\bar{c} X$	$\gamma^* c \to c,\ \gamma^* g \to c\bar{c}$	c, g	$0.0001 \lesssim x \lesssim 0.01$
	$e^{\pm} p \to \text{jet} + X$	$\gamma^* g \to q\bar{q}$	g	$0.01 \lesssim x \lesssim 0.1$
Tevatron	$p\bar{p} \to \text{jet} + X$	$gg, qg, qq \to 2j$	g, q	$0.01 \lesssim x \lesssim 0.5$
	$p\bar{p} \to (W^{\pm} \to \ell^{\pm}\nu) X$	$ud \to W, \bar{u}\bar{d} \to W$	$u, d, \bar{u}, \bar{d}$	$x \gtrsim 0.05$
	$p\bar{p} \to (Z \to \ell^+\ell^-) X$	$uu, dd \to Z$	d	$x \gtrsim 0.05$

Need many processes from different experiments
$\Rightarrow$ **global** analysis needed for flavour separation.

Paradigm for PDF determination

1. **Parameterise** the x dependence for each flavour $a = q, g$ at the input scale $Q_0^2 \sim 1\ \text{GeV}^2$ in some flexible form, e.g.

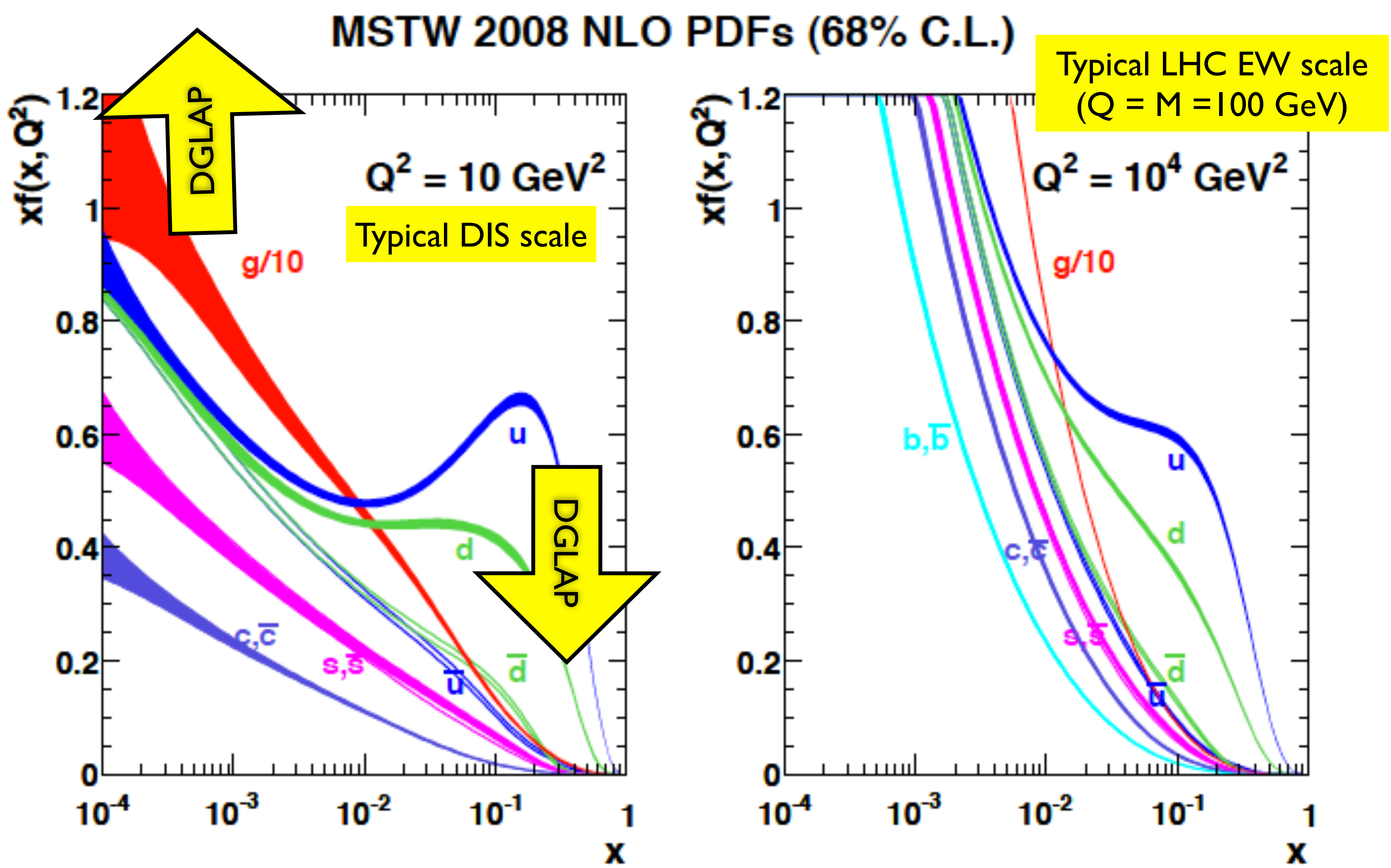
$$xf_{a/p}(x, Q_0^2) = A_a\, x^{\Delta_a}\, (1-x)^{\eta_a}\, (1 + \epsilon_a \sqrt{x} + \gamma_a\, x),$$

   subject to number- and momentum-sum rule constraints.
2. **Evolve** the PDFs to higher scales $Q^2 > Q_0^2$ using the DGLAP (Dokshitzer–Gribov–Lipatov–Altarelli–Parisi) evolution equations.
3. **Convolute** the evolved PDFs with $C_{i,a}$ and $\hat{\sigma}_{ab}$ to calculate theory predictions corresponding to a wide variety of data.
4. **Vary** the input parameters $\{A_a, \Delta_a, \eta_a, \epsilon_a, \gamma_a, \ldots\}$ to minimise

$$\chi^2 = \sum_{i=1}^{N_{\text{pts.}}} \left(\frac{\text{Data}_i - \text{Theory}_i}{\text{Error}_i} \right)^2$$

   or generalisations to account for *correlated* systematic errors.

Example of PDFs from global analysis



- **Error bands** shown are obtained from propagation of experimental uncertainties on the fitted data points.

$$\int_0^1 \mathrm{d}x \; [f_{q/p}(x,Q^2) - f_{\bar{q}/p}(x,Q^2)] = n_q \qquad (n_u = 2, n_d = 1, n_s = 0),$$

Number sum rules

$$\sum_{a=q,\bar{q},g} \int_0^1 \mathrm{d}x \; x f_{a/p}(x,Q^2) = 1$$

Momentum sum rule

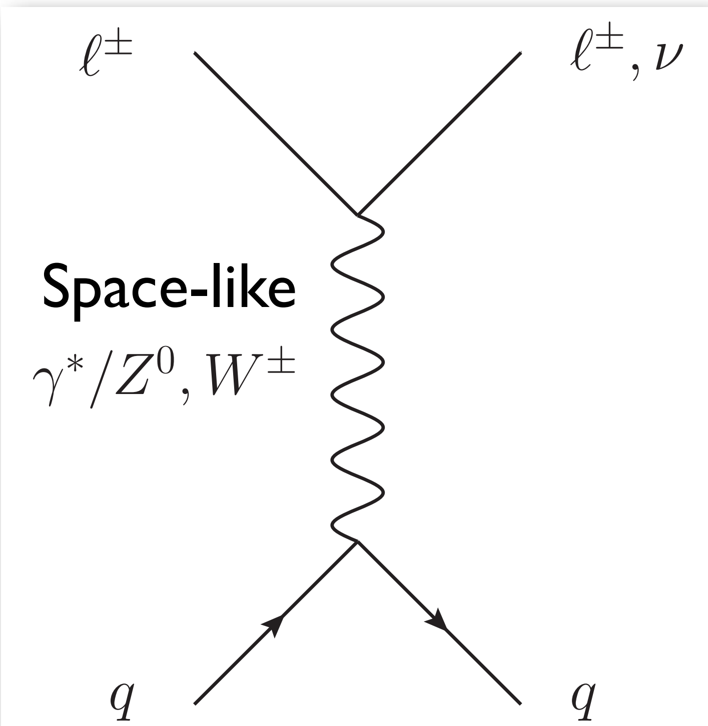
Most recent public PDF fits

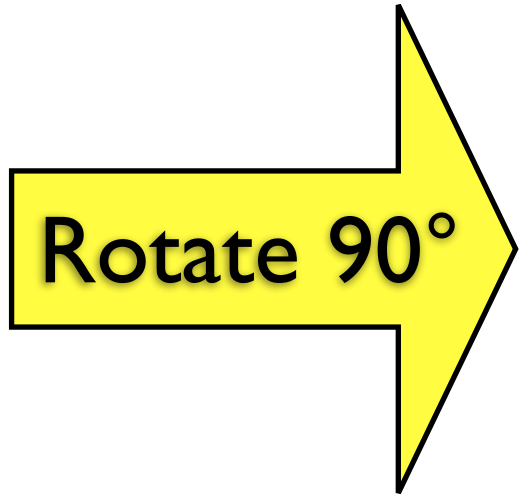
Name of fit	Who?	Global?	NNLO?
MSTW08	A. D. **M**artin, W. J. **S**tirling, R. S. **T**horne, G. **W**att	✔	✔
CT10	CTEQ Collaboration: H.-L. Lai, M. Guzzi, J. Huston, Z. Li, P. Nadolsky, J. Pumplin, C.-P. Yuan	✔	✘
NNPDF2.1	R. Ball, V. Bertone, F. Cerruti, L. Del Debbio, S. Forte, A. Guffanti, J. Latorre, J. Rojo, M. Ubiali	✔	✘
HERAPDF1.0	H1 and ZEUS Collaborations	✘	✔
ABKM09	S. **A**lekhin, J. **B**lümlein, S. **K**lein, S. **M**och	✘	✔
GJR08/JR09	M. **G**lück, P. **J**imenez-Delgado, E. **R**eya	✘	✔

- "Global" ≡ DIS + fixed-target Drell-Yan + Tevatron W, Z, jets.
- **NN**PDF: parameterise input PDFs by a **N**eural **N**etwork.
- GRV/GJR: more restrictive "dynamical" parameterisation.
- *Three* groups with **NLO** global fits, but only *one* at **NNLO**.

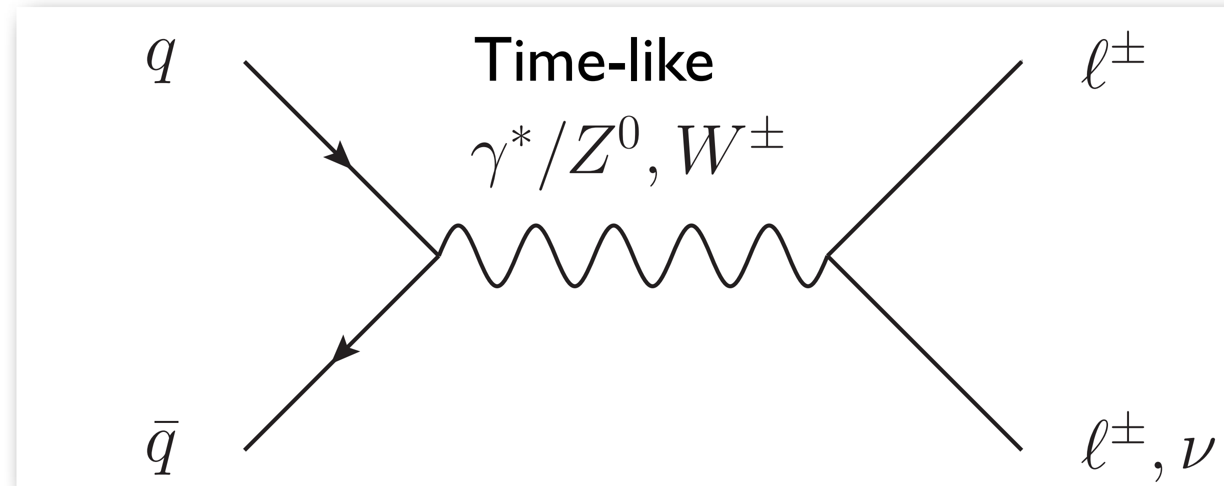
Drell-Yan production at LHC

DIS





Drell-Yan

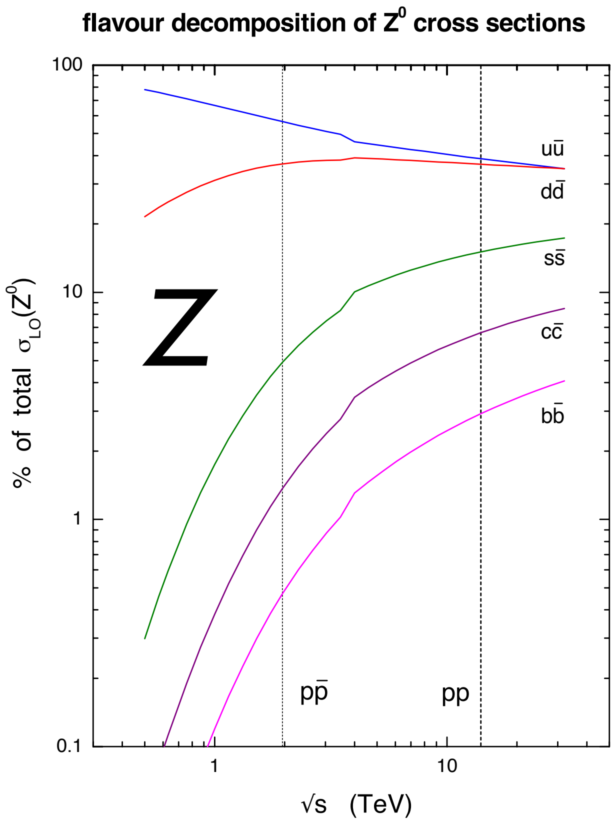


- Analogous process to DIS at a hadron collider.

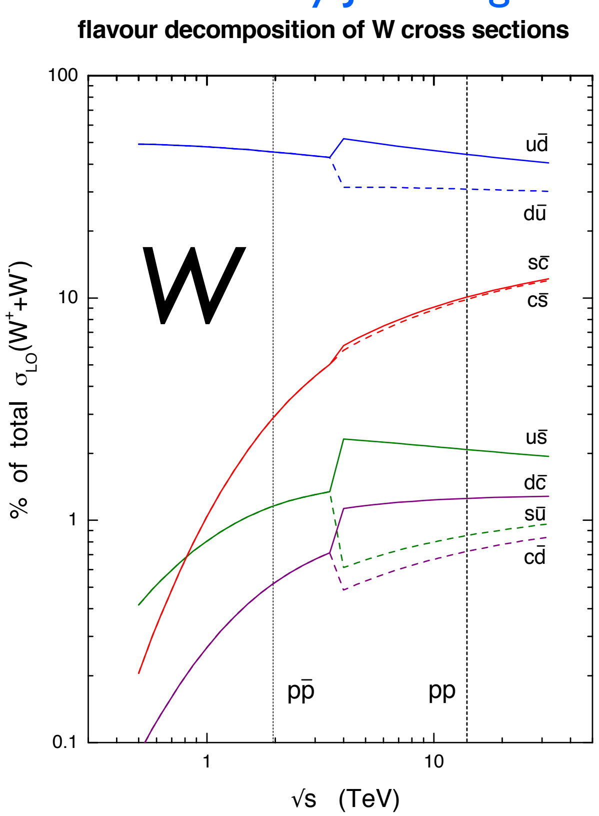
- Fixed-order calculations known to NNLO:
  - Total cross section [Hamberg, van Neerven, Matsuura, 1991 (Erratum, 2002)].
  - Vector boson rapidity distributions: Anastasiou, Dixon, Melnikov, Petriello, hep-ph/0312266, Vrap code.
  - "Fully exclusive" allowing cuts on leptonic decay products: Melnikov, Petriello, hep-ph/0609070, FEWZ code; Catani, Cieri, Ferrera, de Florian, Grazzini, arXiv:0903.2120, DYNNLO code.

Boson p_T distributions not described by fixed-order theory.

DY flavour decomposition



Plots by J. Stirling



$$\sigma_{W^+} \sim u(x_1)\bar{d}(x_2)$$

$$\sigma_{W^-} \sim d(x_1)\bar{u}(x_2)$$

$$\sigma_{Z^0} \sim 0.29\, u(x_1)\bar{u}(x_2) + 0.37\, d(x_1)\bar{d}(x_2)$$

$$\sigma_{\gamma^*} \sim 0.44\, u(x_1)\bar{u}(x_2) + 0.11\, d(x_1)\bar{d}(x_2)$$

$$\frac{\sigma_{W^+} + \sigma_{W^-}}{\sigma_{Z^0}} \sim \frac{u(x_1) + d(x_1)}{0.29\, u(\tilde{x}_1) + 0.37\, d(\tilde{x}_1)}$$

Almost insensitive to PDFs.

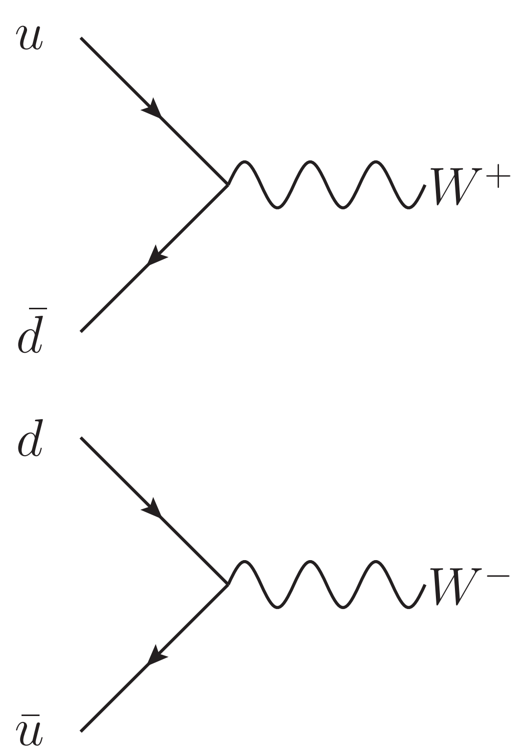
$$\frac{\sigma_{W^+}}{\sigma_{W^-}} \sim \frac{u(x_1)}{d(x_1)}$$

Sensitive to u/d ratio.

Scale $Q = M_W$.

$$x_1 = (M_V/\sqrt{s}) \exp(+y_V)$$

$$x_2 = (M_V/\sqrt{s}) \exp(-y_V)$$



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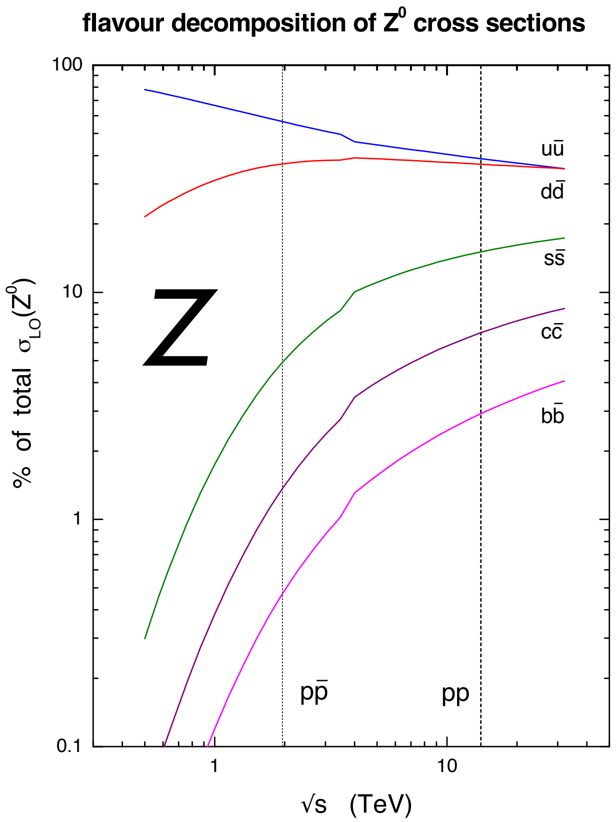

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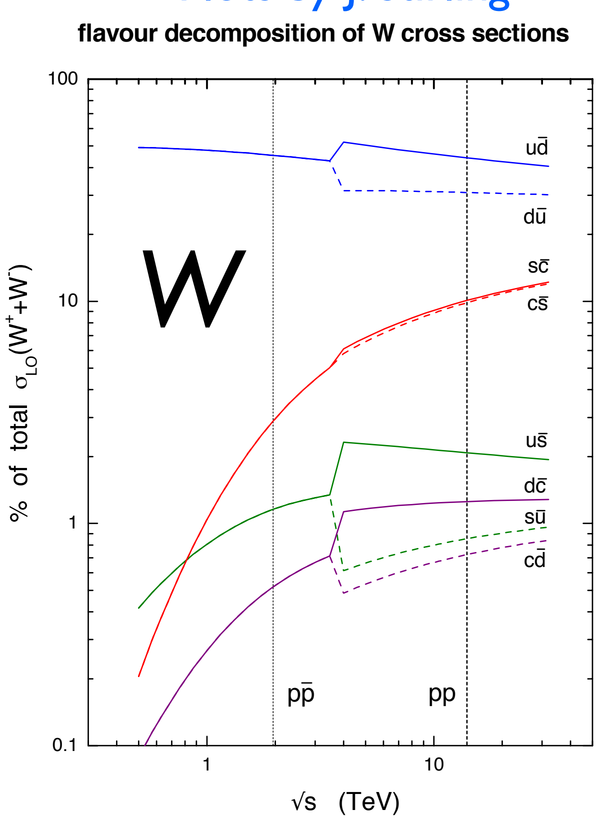

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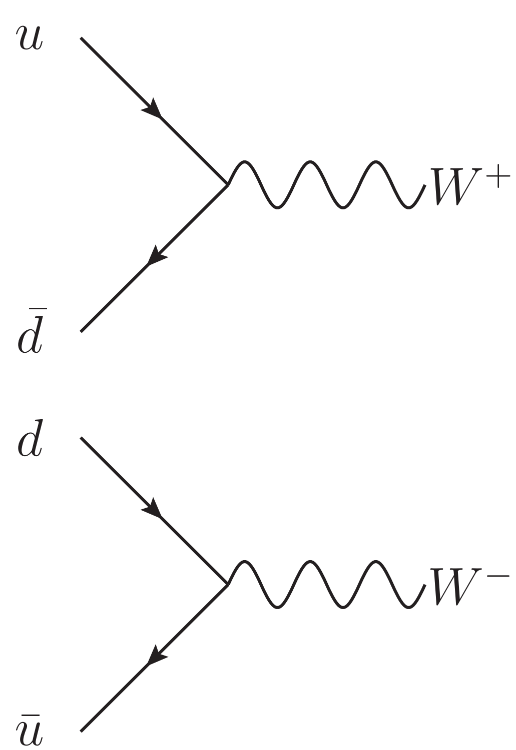


$$x_1 = (M_V/\sqrt{s})\exp(+y_V)$$
$$x_2 = (M_V/\sqrt{s})\exp(-y_V)$$

Structure functions need nuclear corrections.

Neutral-current DIS in charged-lepton–nucleon scattering

$$F_2^{\ell^\pm p} = x\left[\frac{4}{9}(u + \bar{u} + \ldots) + \frac{1}{9}(d + \bar{d} + \ldots)\right]$$

$$F_2^{\ell^\pm d} = (F_2^{\ell^\pm p} + F_2^{\ell^\pm n})/2 = \frac{5}{18}x\,(u + \bar{u} + d + \bar{d}) + \ldots$$

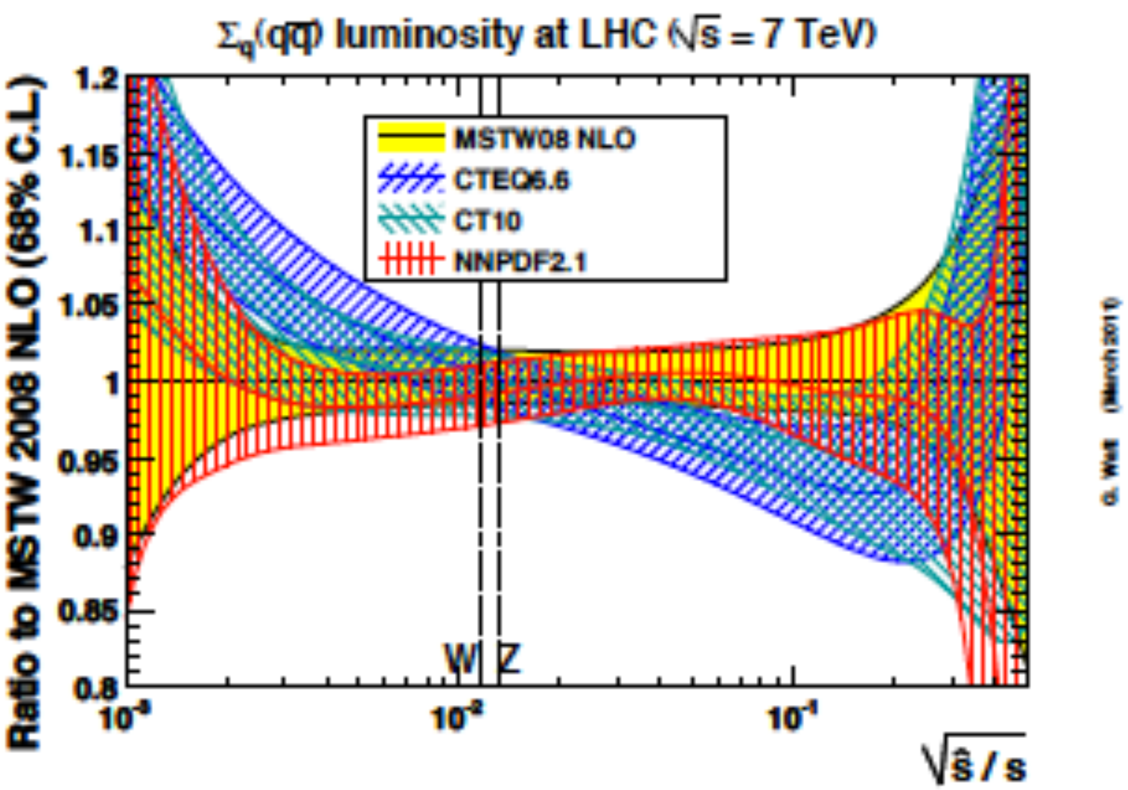
Charged-current DIS in neutrino–nucleus scattering

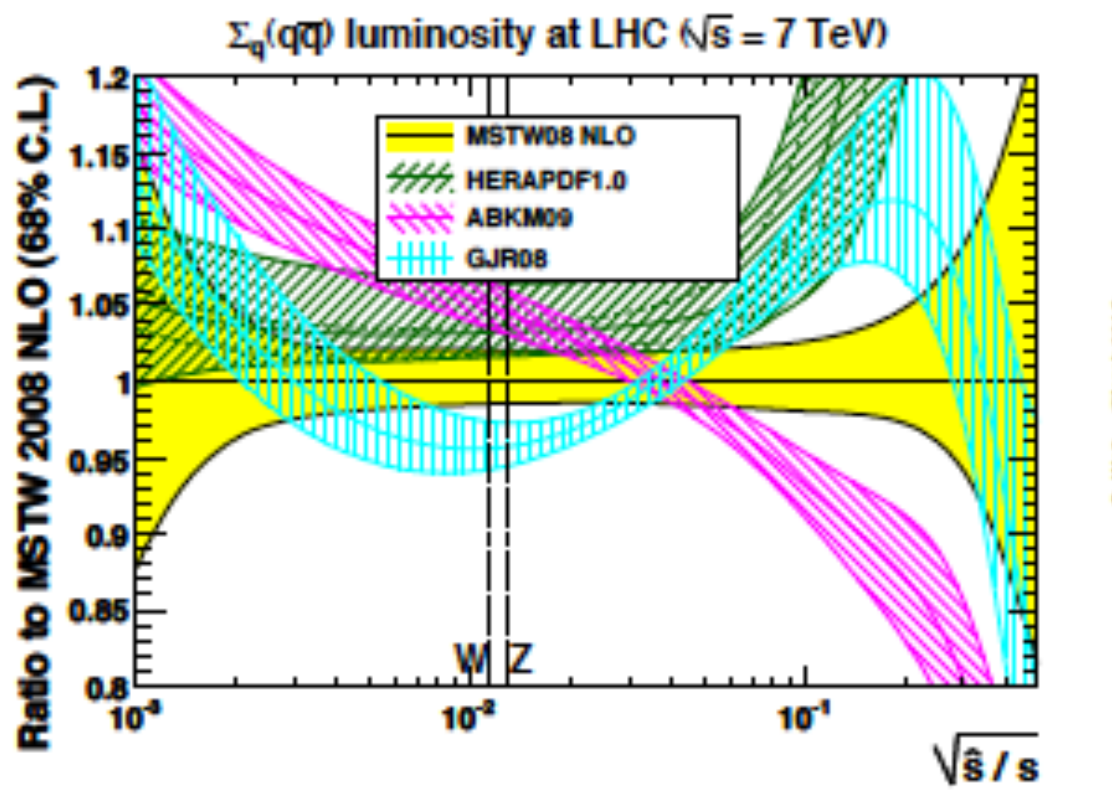
$$F_2 \equiv (F_2^{\nu N} + F_2^{\bar{\nu} N})/2 = x\,(u + \bar{u} + d + \bar{d} + \ldots)$$
$$xF_3 \equiv (xF_3^{\nu N} + xF_3^{\bar{\nu} N})/2 = x\,(u - \bar{u} + d - \bar{d} + \ldots)$$

NLO partonic luminosities

$$\frac{\partial \mathcal{L}_{\Sigma_q(q\bar{q})}}{\partial \tau} = \int_0^{y_{\max}} \mathrm{d}y \sum_{q=d,u,s,c,b} [f_q(x_1,\hat{s}) f_{\bar{q}}(x_2,\hat{s}) + (q \leftrightarrow \bar{q})]$$

$$\tau \equiv \sqrt{\hat{s}/s} \qquad y_{\max} = \ln(1/\sqrt{\tau}) \qquad x_1 = \sqrt{\tau}\, \mathrm{e}^{y} \qquad x_2 = \sqrt{\tau}\, \mathrm{e}^{-y}$$



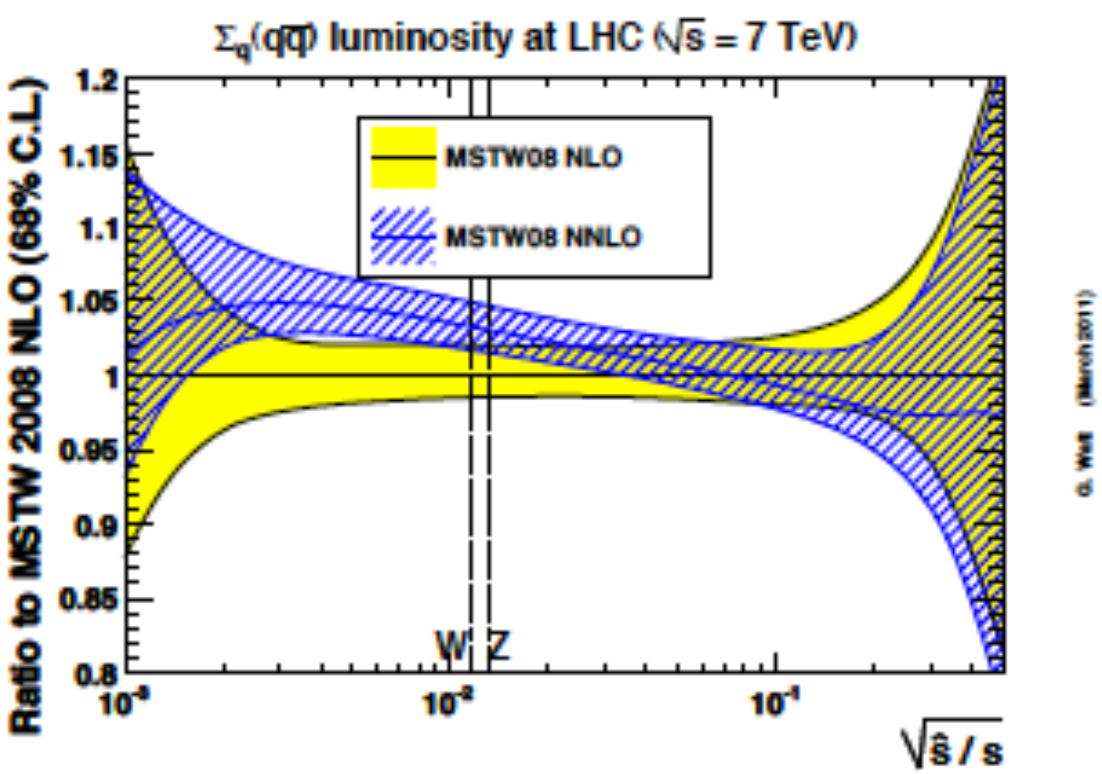


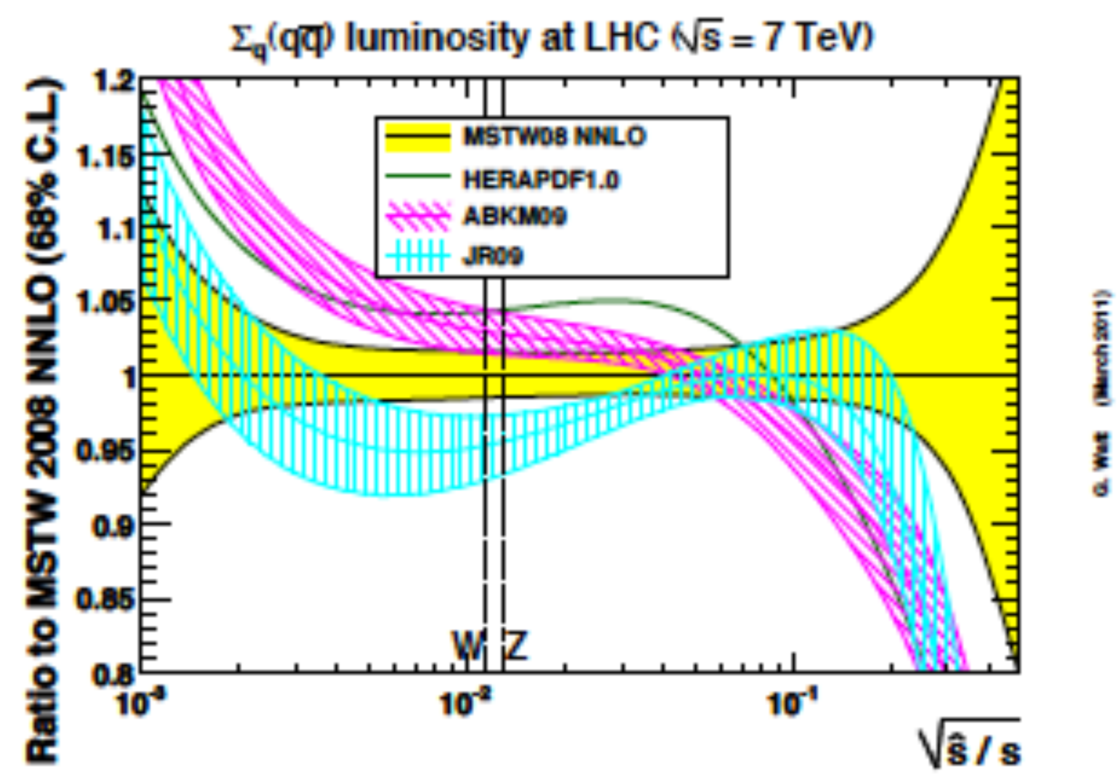
- Relevant values of $\sqrt{\hat{s}} = M_{W,Z}$ are indicated: good agreement for global fits (*left*), but more variation for other sets (*right*).

NNLO partonic luminosities

$$\frac{\partial \mathcal{L}_{\Sigma_q(q\bar{q})}}{\partial \tau} = \int_0^{y_{\max}} \mathrm{d}y \sum_{q=d,u,s,c,b} \left[f_q(x_1,\hat{s}) f_{\bar{q}}(x_2,\hat{s}) + (q \leftrightarrow \bar{q}) \right]$$

$\tau \equiv \sqrt{\hat{s}/s}$ $\quad$ $y_{\max} = \ln(1/\sqrt{\tau})$ $\quad$ $x_1 = \sqrt{\tau}\,\mathrm{e}^{y}$ $\quad$ $x_2 = \sqrt{\tau}\,\mathrm{e}^{-y}$

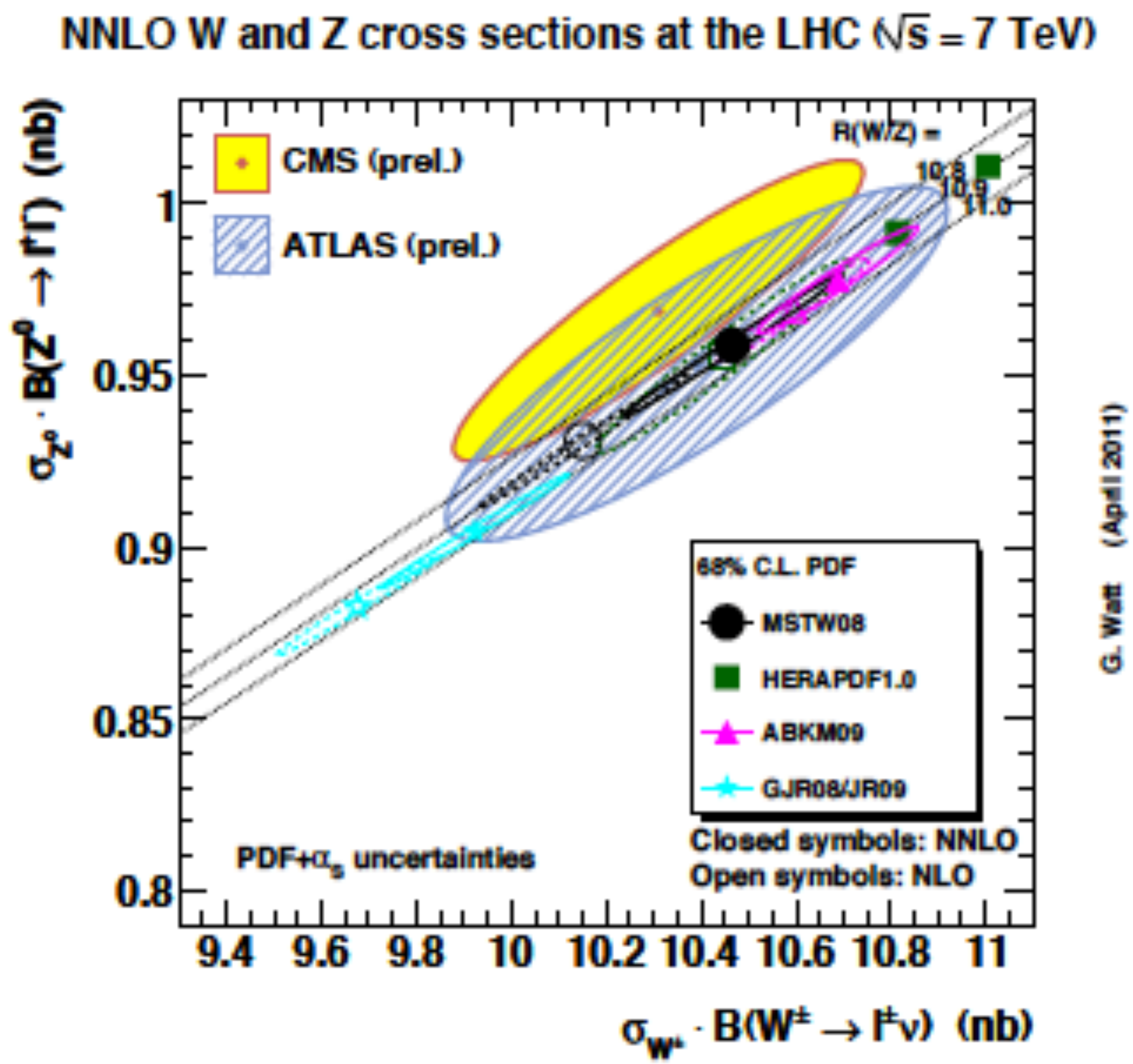


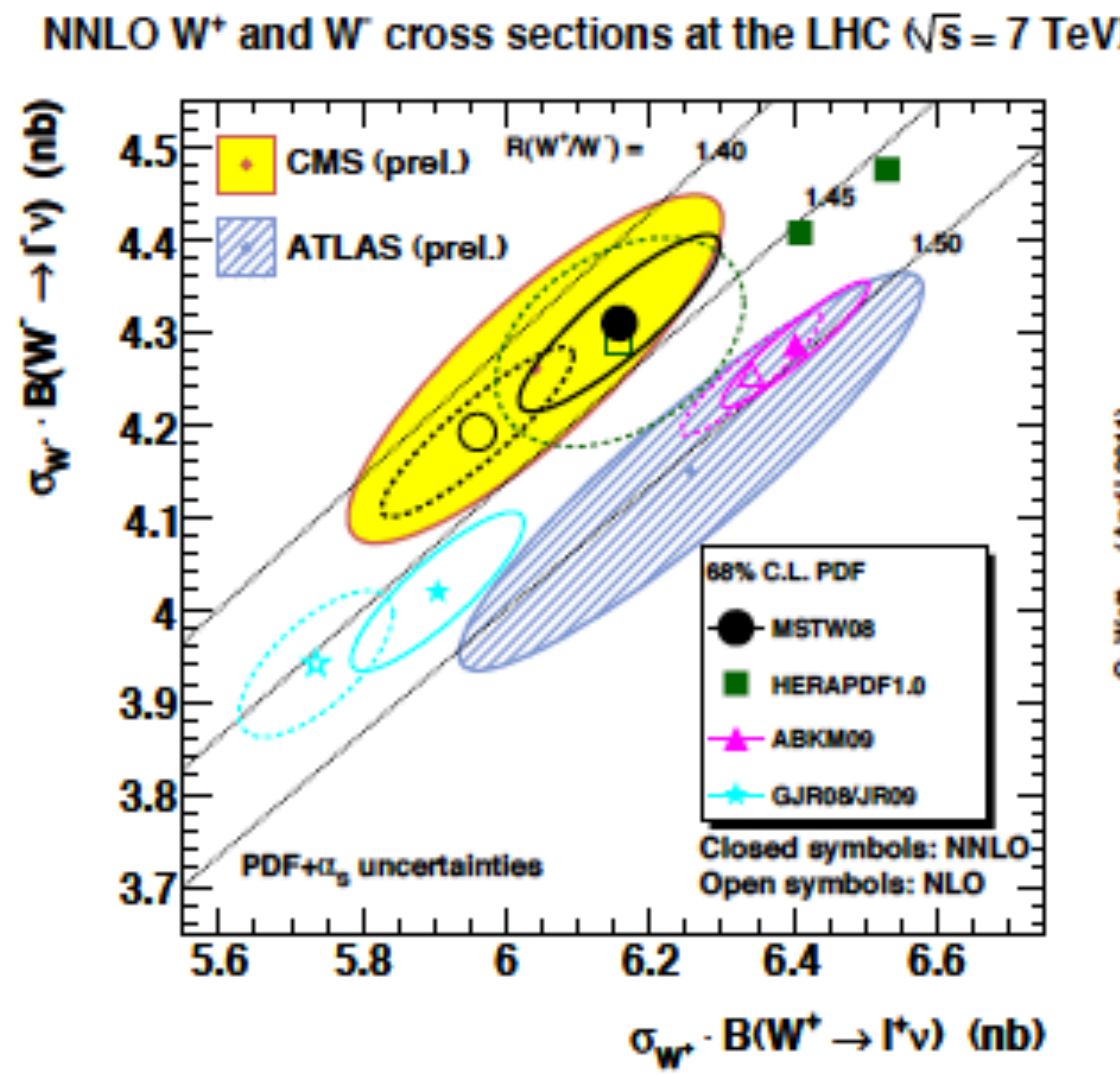


- **Left plot:** compare MSTW NLO and NNLO luminosities.
- **Right plot:** NNLO trend between groups similar to NLO.

NNLO total cross sections

- Correlation of ellipse ⇔ uncertainty in ratio of cross sections.





- Apparent discrepancy between CMS and ATLAS for W^+/W^-. CMS ratio favours **MSTW08**, ATLAS favours ABKM09 (?).

Acceptance: a cautionary tale

- Only about half total cross sections inside ATLAS/CMS acceptance.

- CMS [arXiv:1012.2466, CMS PAS EWK-10-005] use POWHEG (with CTEQ6.6/CT10, MSTW08NLO, NNPDF2.0), check with FEWZ.

$$\Rightarrow \frac{\sigma^{\rm tot}_{W+}}{\sigma^{\rm tot}_{W-}} = \begin{cases} 1.418 \pm 0.008({\rm stat.}) \pm 0.022({\rm syst.}) \pm 0.029({\rm th.}) & (e) \\ 1.423 \pm 0.008({\rm stat.}) \pm 0.019({\rm syst.}) \pm 0.031({\rm th.}) & (\mu) \\ 1.421 \pm 0.006({\rm stat.}) \pm 0.014({\rm syst.}) \pm 0.030({\rm th.}) & (e+\mu) \end{cases}$$

- ATLAS [arXiv:1010.2130, ATLAS-CONF-2011-041] use PYTHIA (with MRSTLO*) $\Rightarrow \sigma^{\rm tot}_{W+}/\sigma^{\rm tot}_{W-} = 1.51 \pm 0.03$ $(e+\mu)$ [from ATLAS ellipse].

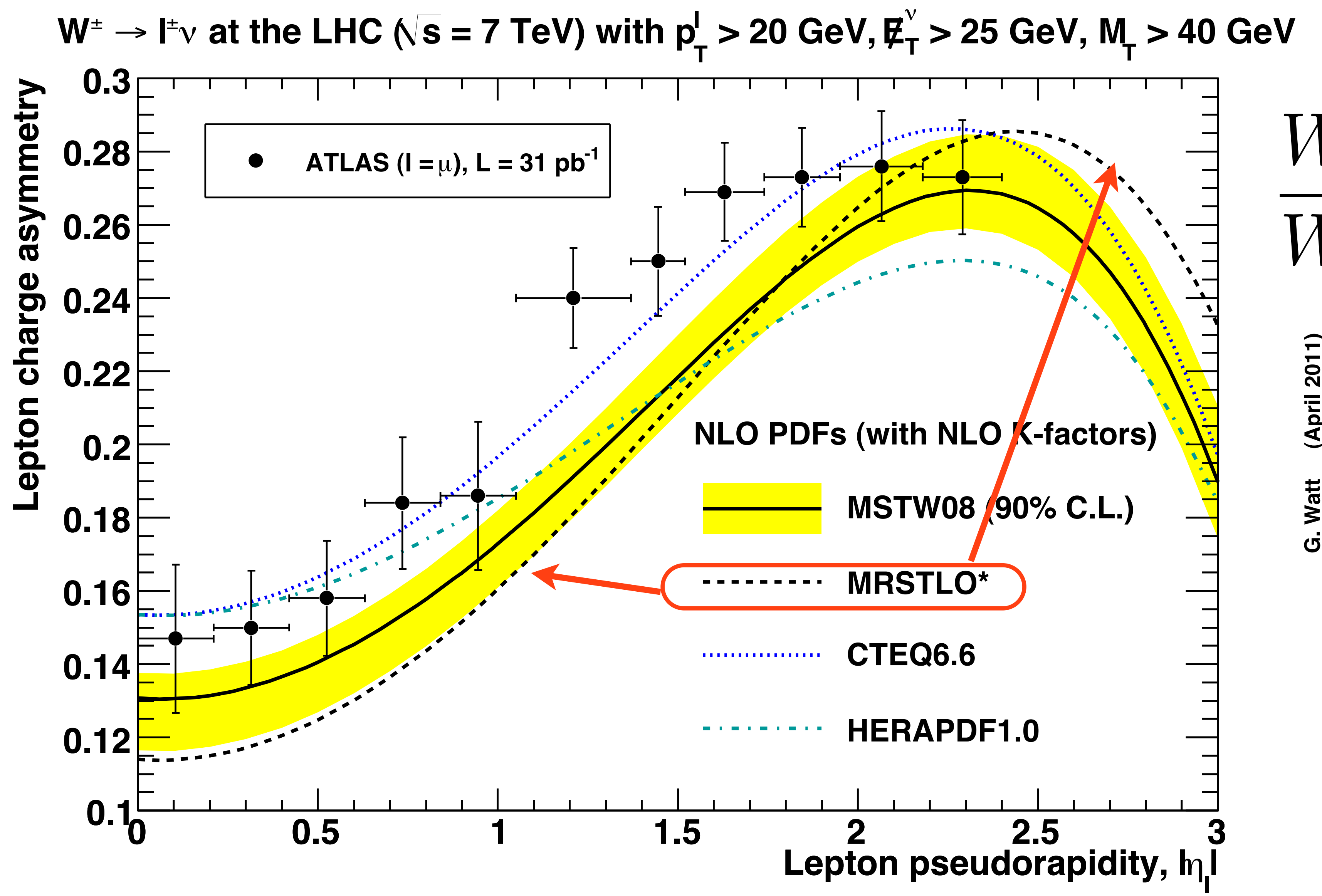
MC+PDF	A_{W+}/A_{W-} e	A_{W+}/A_{W-} μ	$\sigma^{\rm tot}_{W+}/\sigma^{\rm tot}_{W-}$ e	$\sigma^{\rm tot}_{W+}/\sigma^{\rm tot}_{W-}$ μ
PYTHIA+MRSTLO*	1.02	1.02	1.50	1.51
PYTHIA+CTEQ6.6	1.05	1.05	1.46	1.47
PYTHIA+HERAPDF1.0	1.03	1.04	1.48	1.49
MC@NLO+HERAPDF1.0	1.05	1.05	1.46	1.47
MC@NLO+CTEQ6.6	1.06	1.06	1.45	1.46

$$\frac{\sigma^{\rm tot}_{W+}}{\sigma^{\rm tot}_{W-}} = \frac{\sigma^{\rm fid}_{W+}}{\sigma^{\rm fid}_{W-}} \cdot \frac{A_{W-}}{A_{W+}}$$

Alternative acceptance calculations move ATLAS $\sigma^{\rm tot}_{W+}/\sigma^{\rm tot}_{W-}$ much closer to CMS.

Preliminary ATLAS ellipse [ATLAS-CONF-2011-041] neglected correlations between A_{W+} and A_{W-}.

Acceptance for ATLAS

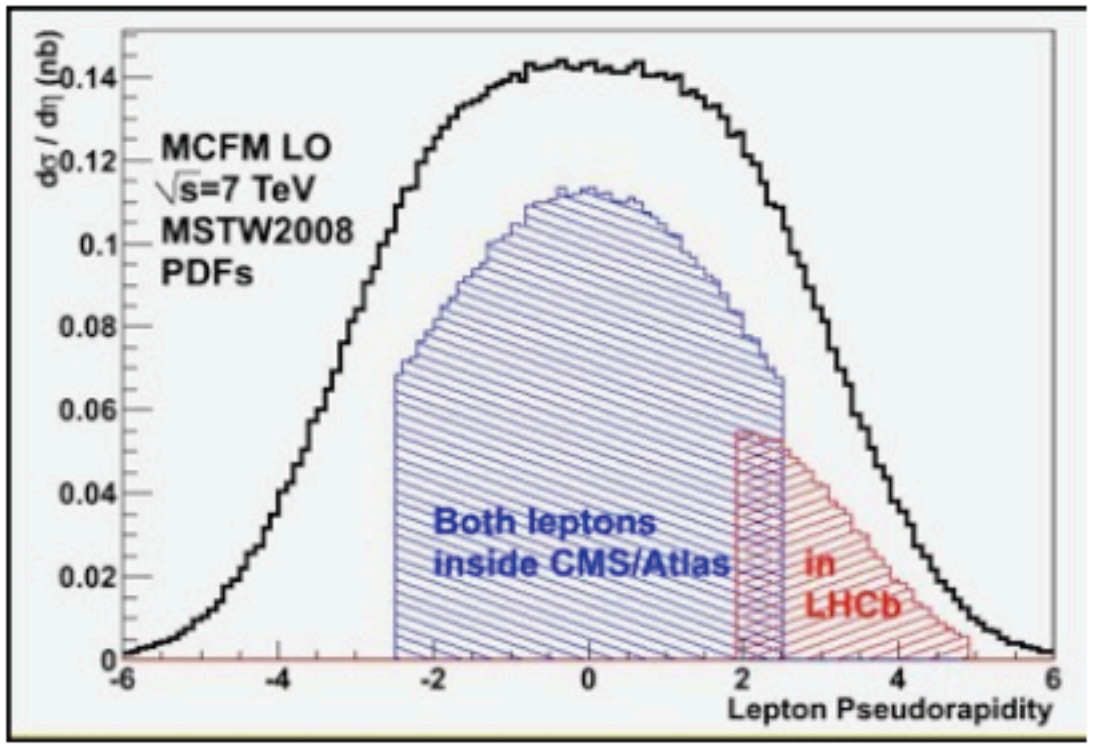


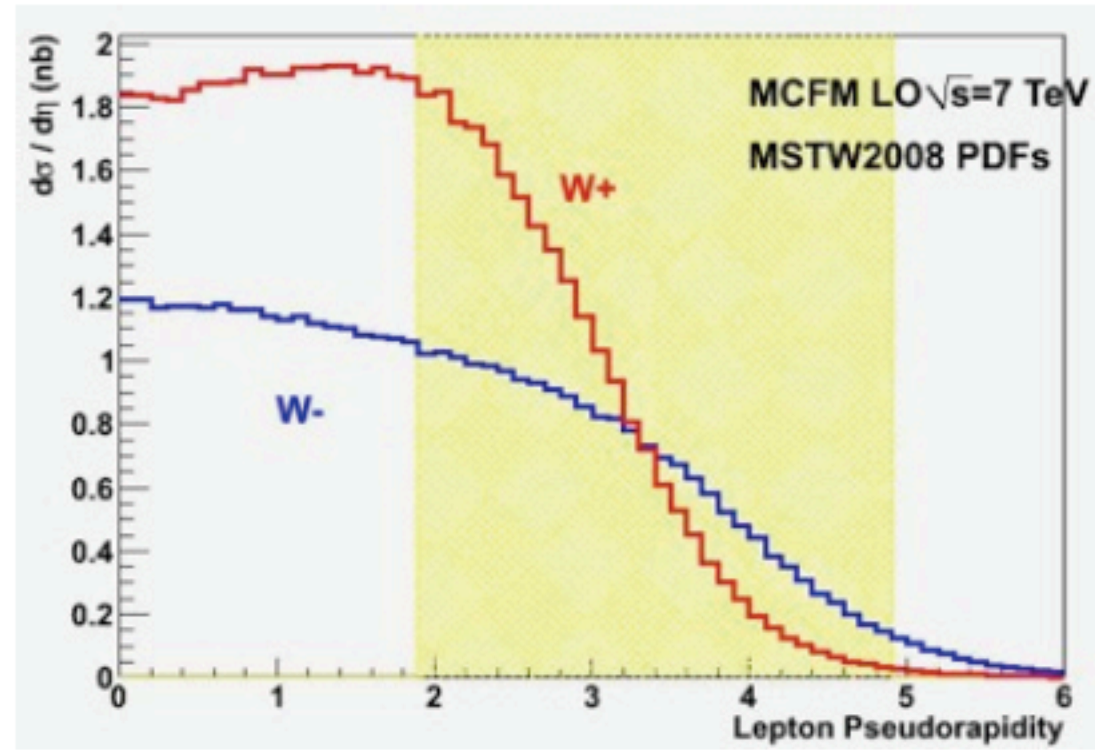
$$\frac{W^+/W^- - 1}{W^+/W^- + 1}$$

Acceptance = inside/(inside+outside)

- MRSTLO* lies well *below* almost all ATLAS data points, then is *above* other theory predictions at larger η_l.
  ⇒ Close to worst possible PDF choice for acceptance.

Acceptance for LHCb



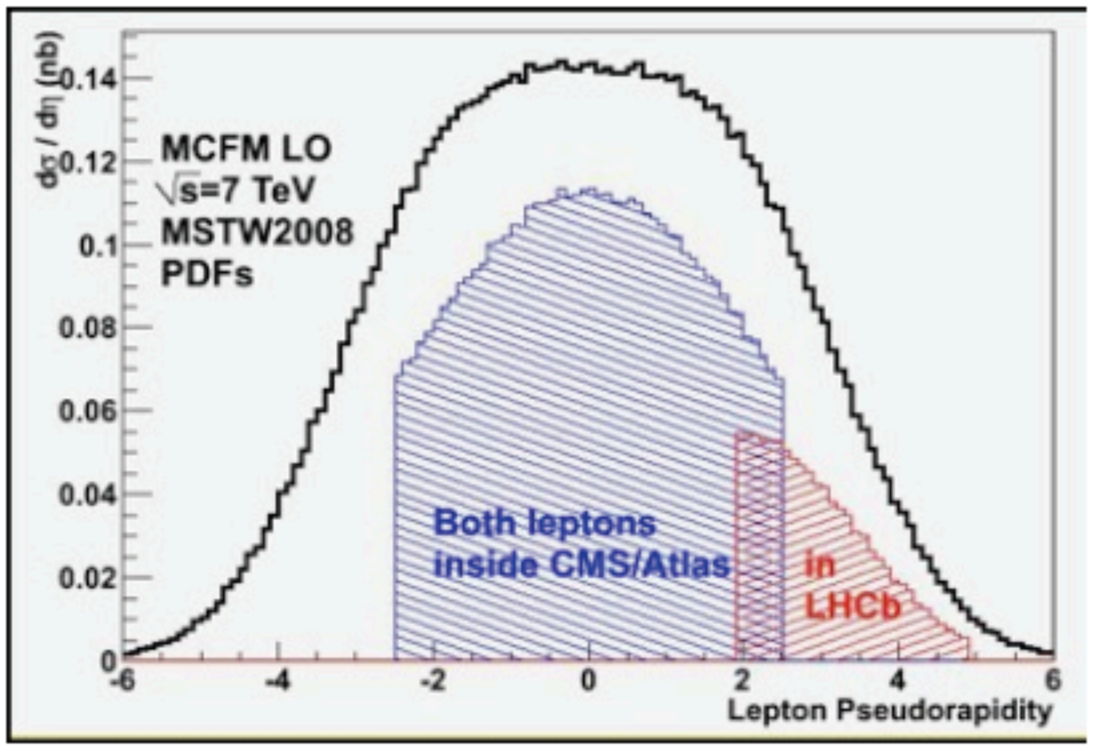


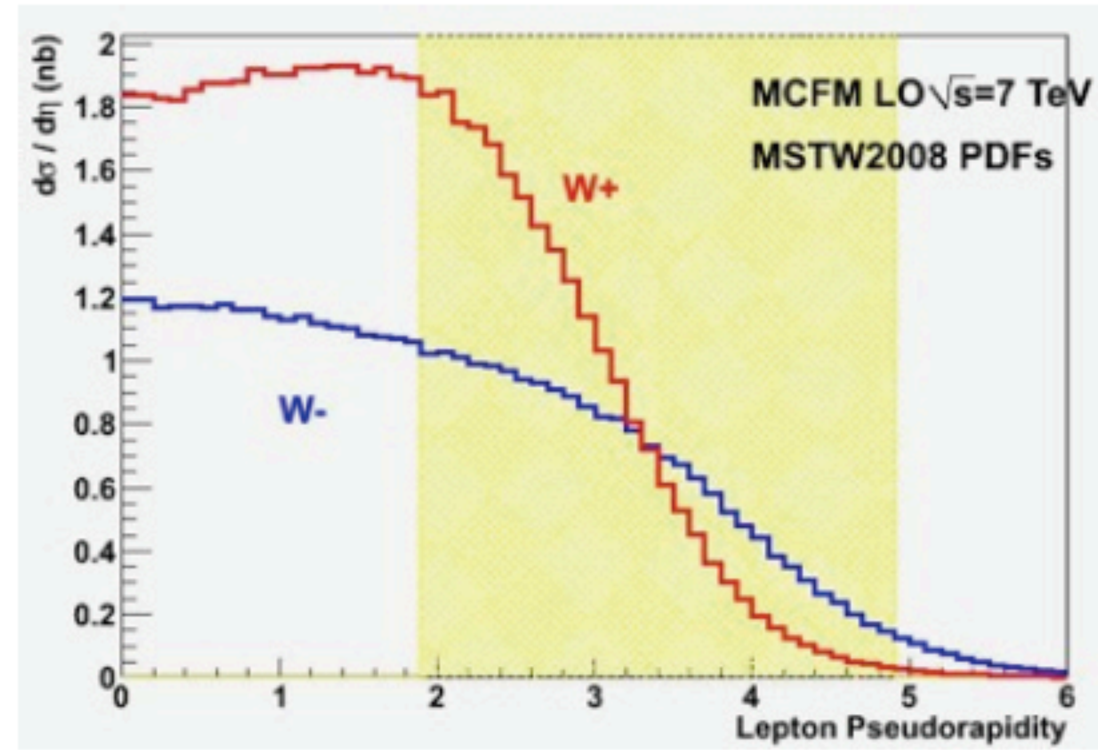
8% of Z within LHCb acceptance

17% (16%) of W^+ (W^-) within LHCb acceptance

- Q. Should LHCb "measure" a total cross section by extrapolating over all pseudorapidity?

Acceptance for LHCb



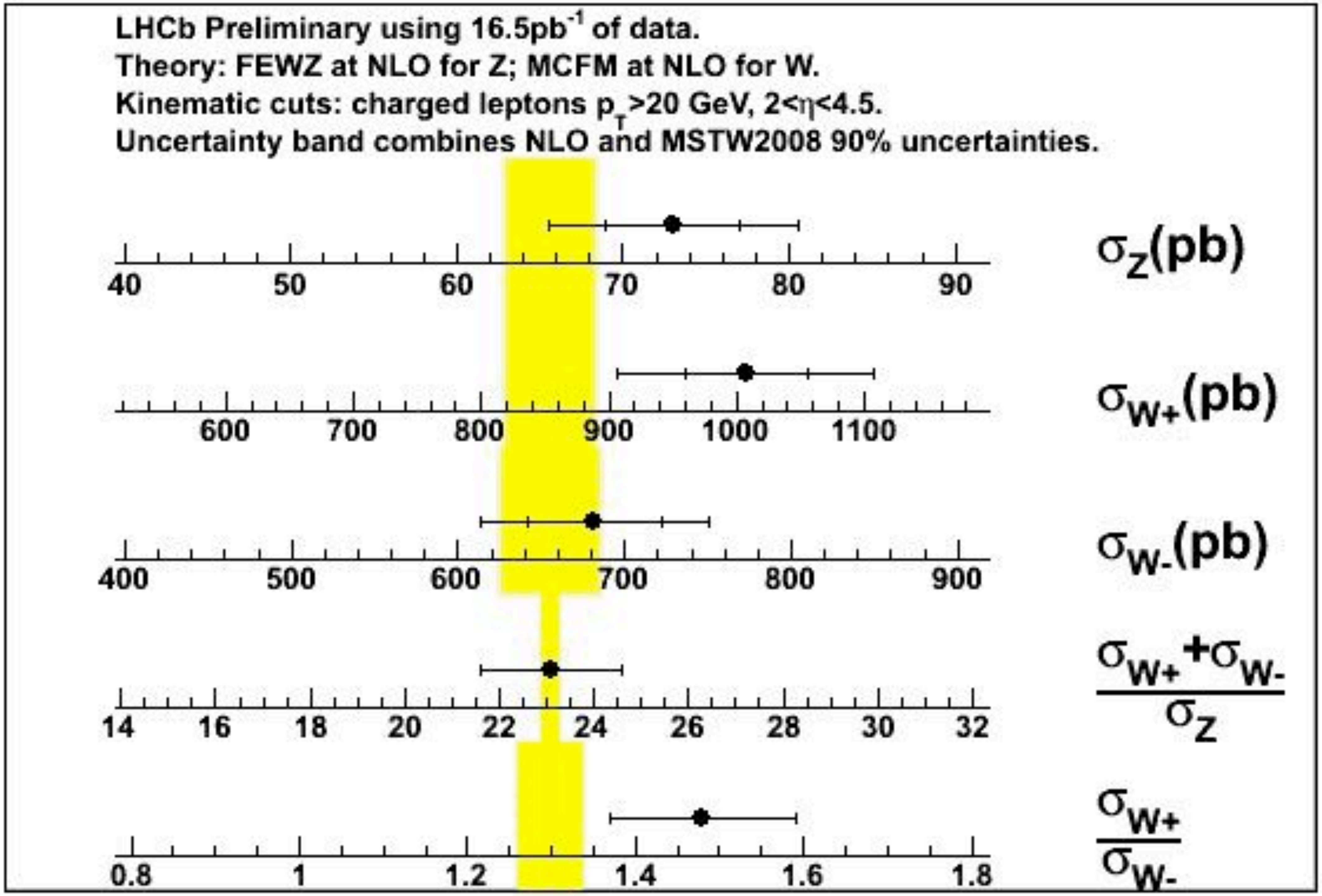


8% of Z within LHCb acceptance

17% (16%) of W^+ (W^-) within LHCb acceptance

- Q. Should LHCb "measure" a total cross section by extrapolating over all pseudorapidity?
- A. Don't even think about it!

LHCb Preliminary results



- Compare to theory only inside kinematic cuts. ✔

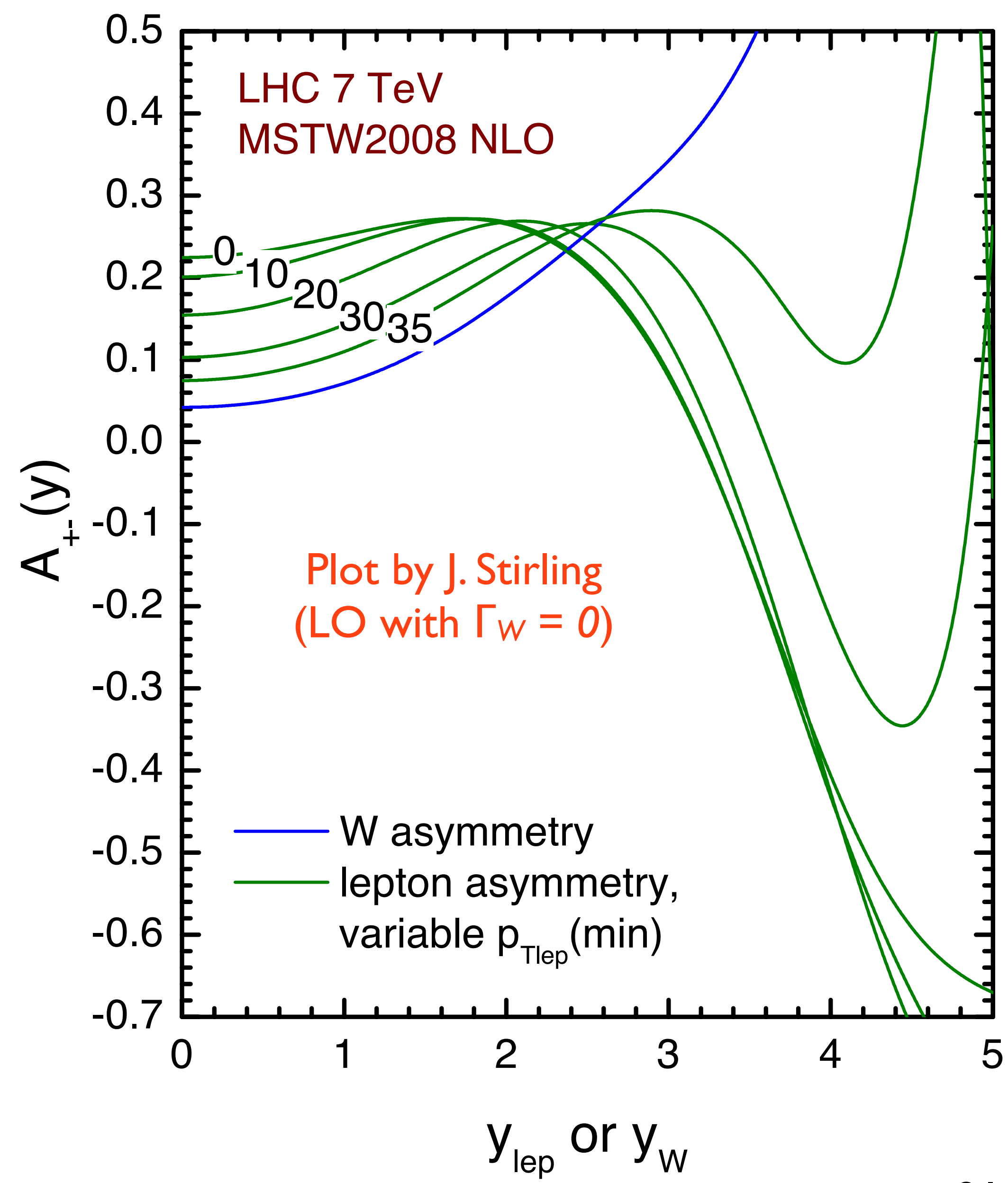
$W^{\pm} \rightarrow l^{\pm}\nu$ charge asymmetry

$$A_W(y_W) = \frac{\mathrm{d}\sigma(W^+)/\mathrm{d}y_W - \mathrm{d}\sigma(W^-)/\mathrm{d}y_W}{\mathrm{d}\sigma(W^+)/\mathrm{d}y_W + \mathrm{d}\sigma(W^-)/\mathrm{d}y_W} \approx \frac{u_v(x_1) - d_v(x_1)}{u(x_1) + d(x_1)}$$

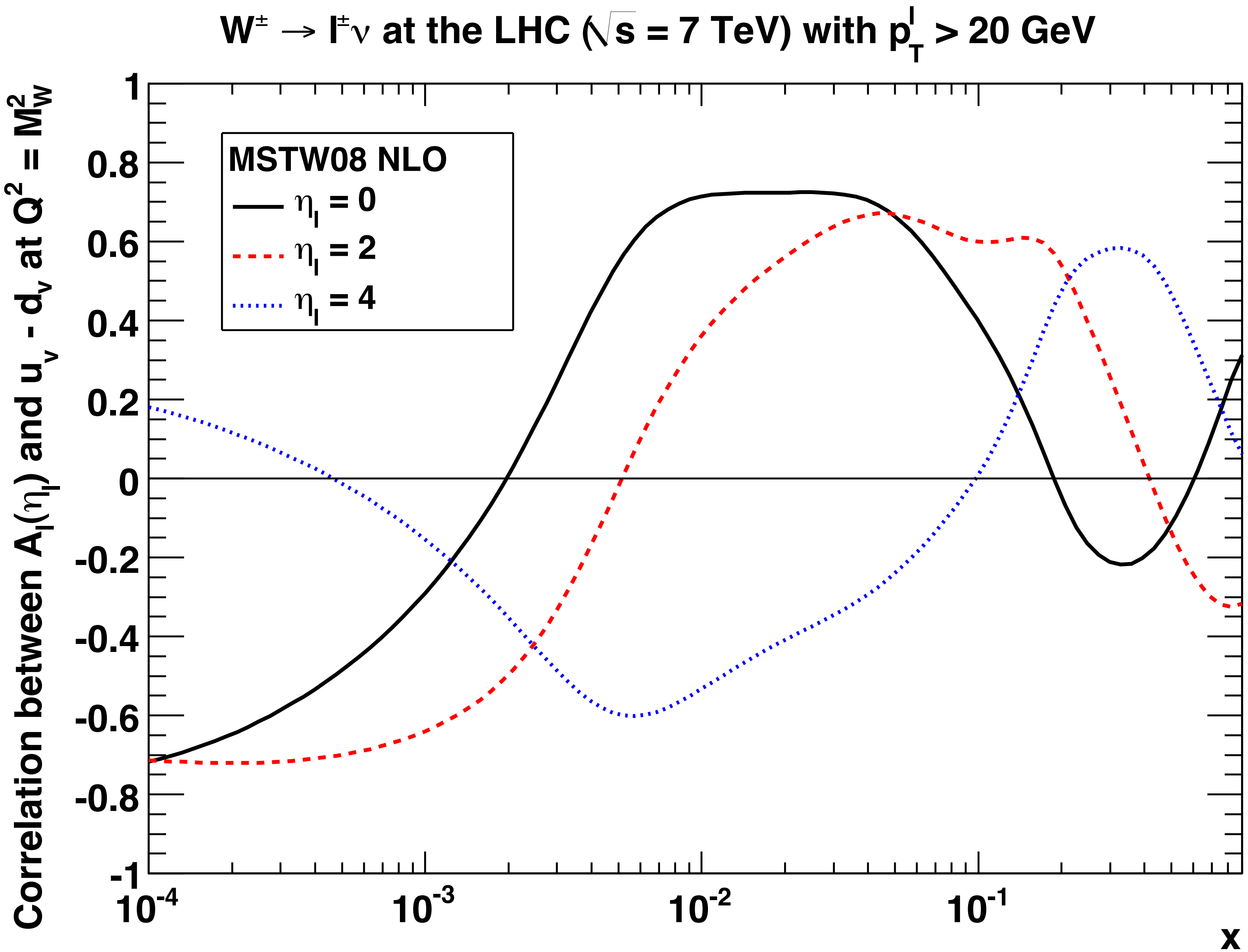
- But can't measure longitudinal momentum of neutrino. ☹
- Lepton charge asymmetry:

$$A_\ell(\eta_\ell) = \frac{\mathrm{d}\sigma(\ell^+)/\mathrm{d}\eta_\ell - \mathrm{d}\sigma(\ell^-)/\mathrm{d}\eta_\ell}{\mathrm{d}\sigma(\ell^+)/\mathrm{d}\eta_\ell + \mathrm{d}\sigma(\ell^-)/\mathrm{d}\eta_\ell}$$
$$= A_W(y_W) \otimes (W^{\pm} \rightarrow \ell^{\pm}\nu)$$

- Complex interplay of PDF and *V-A* effects from $W^{\pm} \rightarrow l^{\pm}\nu$ decay.

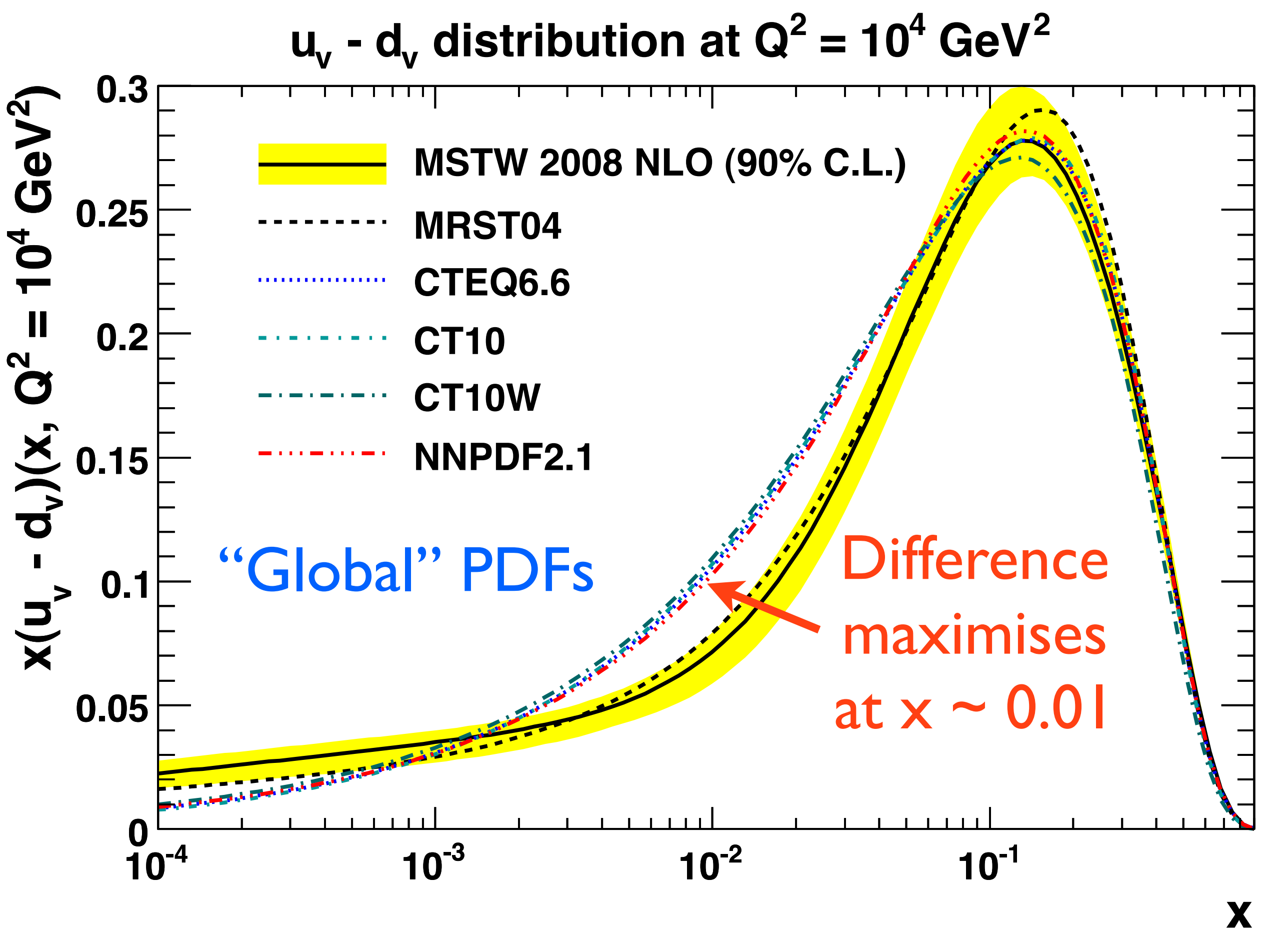


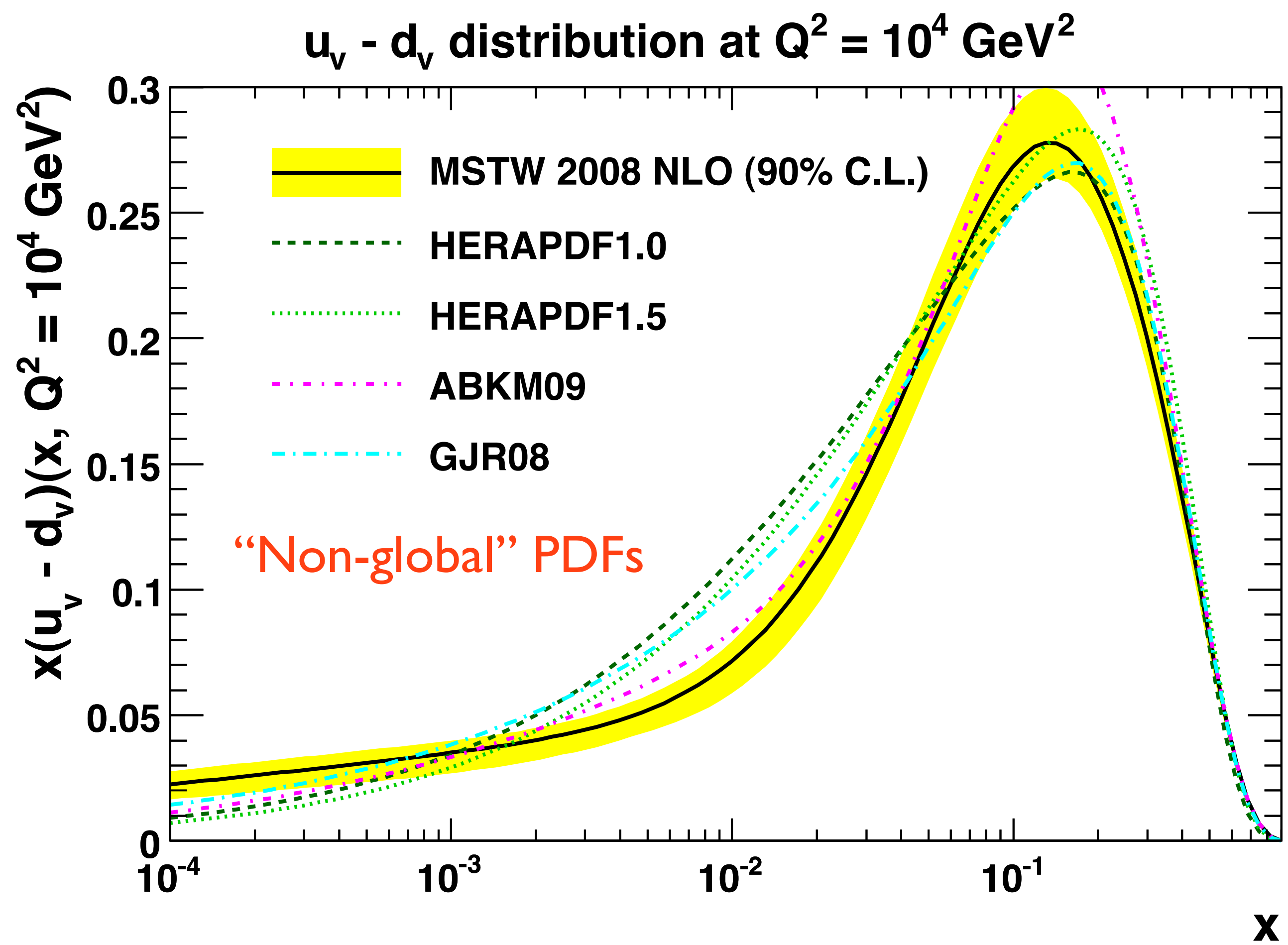
PDF correlation between asymmetry and u_v-d_v versus x



- Indirect (anti)correlation at small x from sum rule: $\int_0^1 \mathrm{d}x\ (u_v - d_v) = 1$

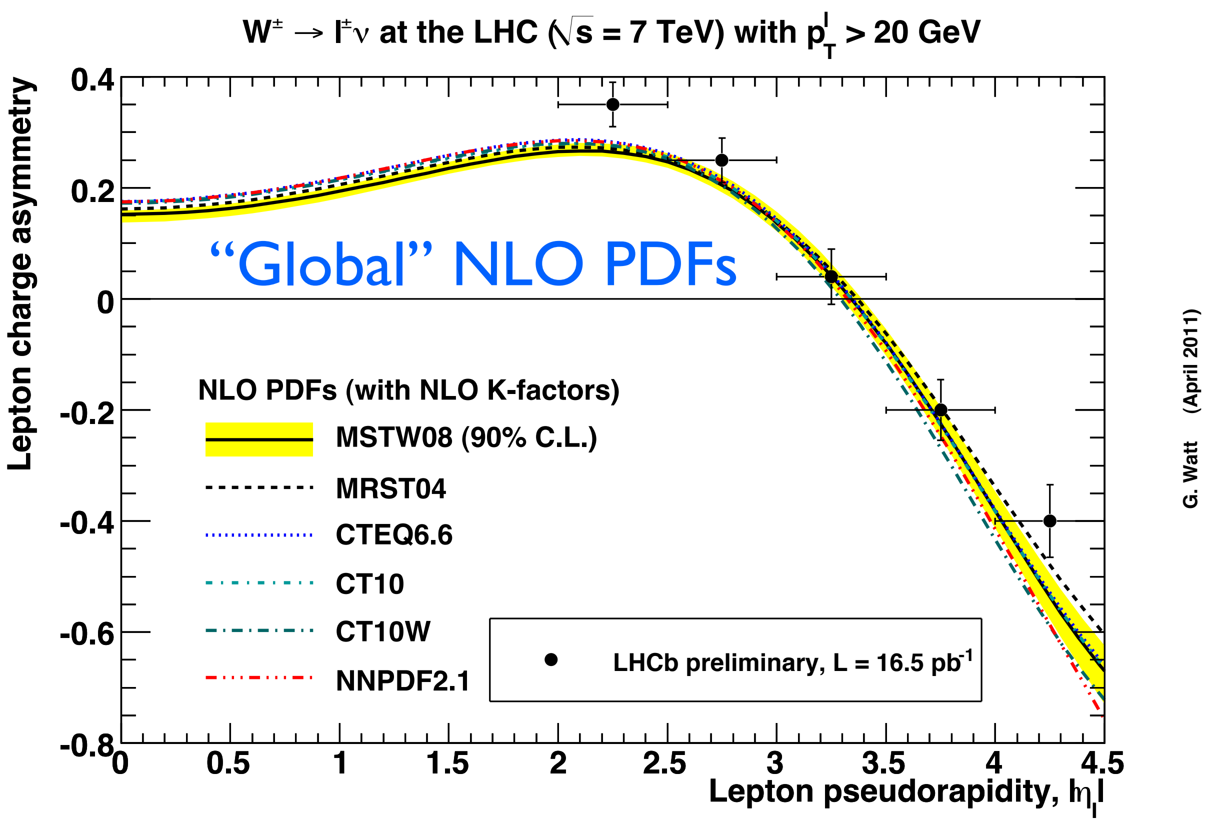
u_v-d_v for different NLO PDFs

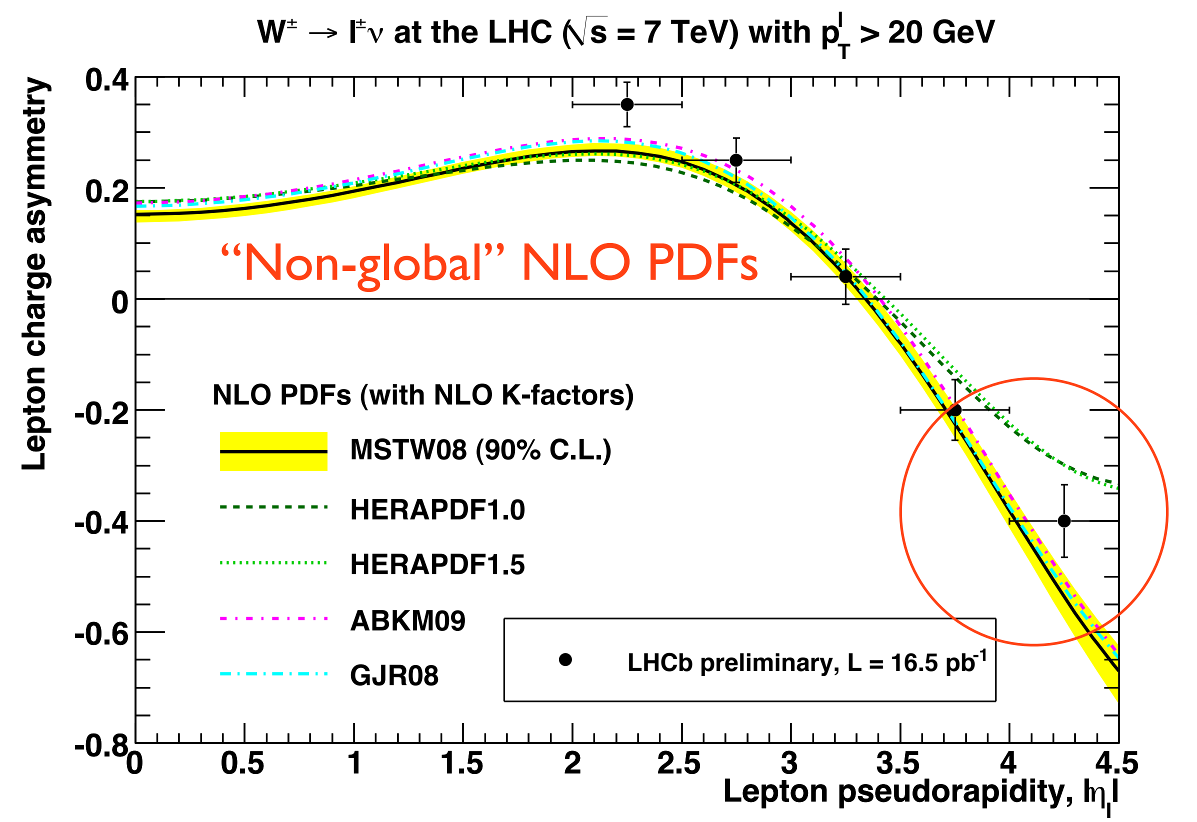




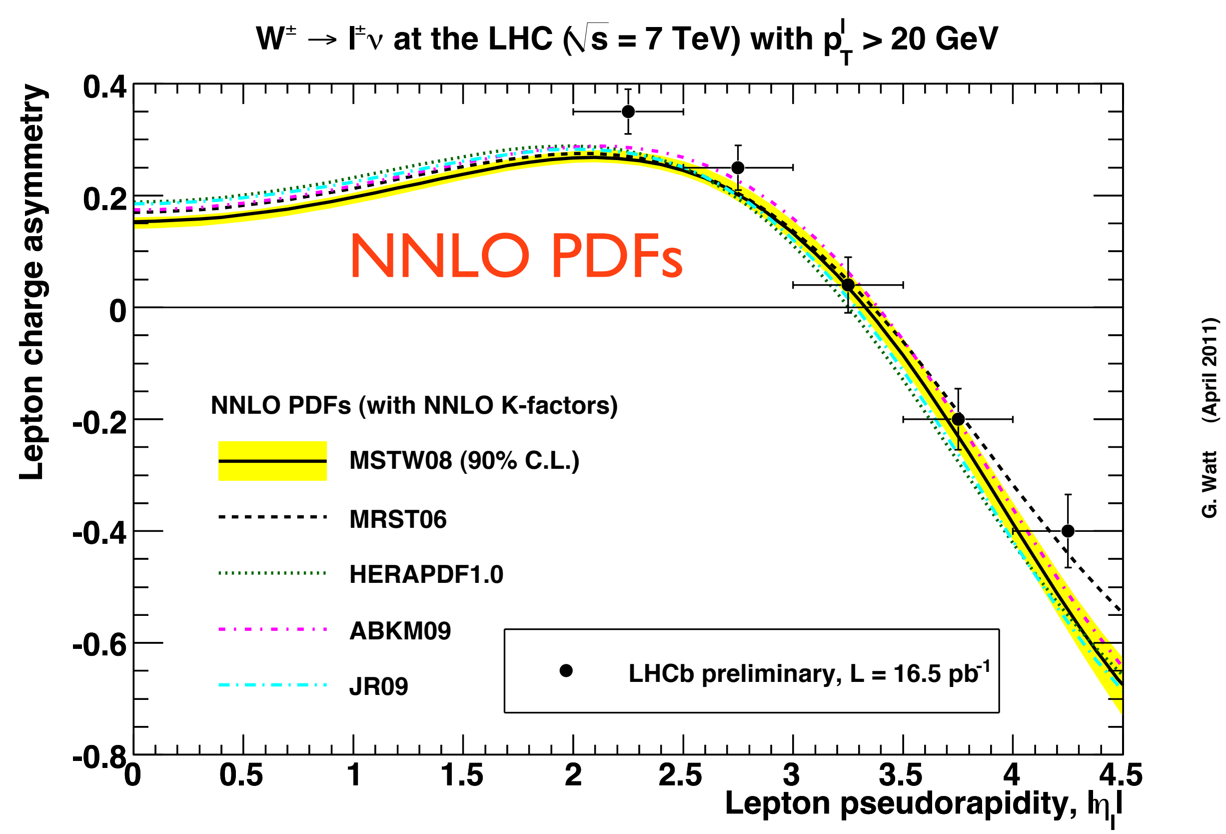
- **MSTW08** has input $xu_v \propto x^{0.29\pm0.02}$ and $xd_v \propto x^{0.97\pm0.11}$.
  Many other groups **assume** equal powers $\Rightarrow$ parameterisation bias.
  (NNPDF: restricted range of small-x preprocessing exponents.)

Description of LHCb data

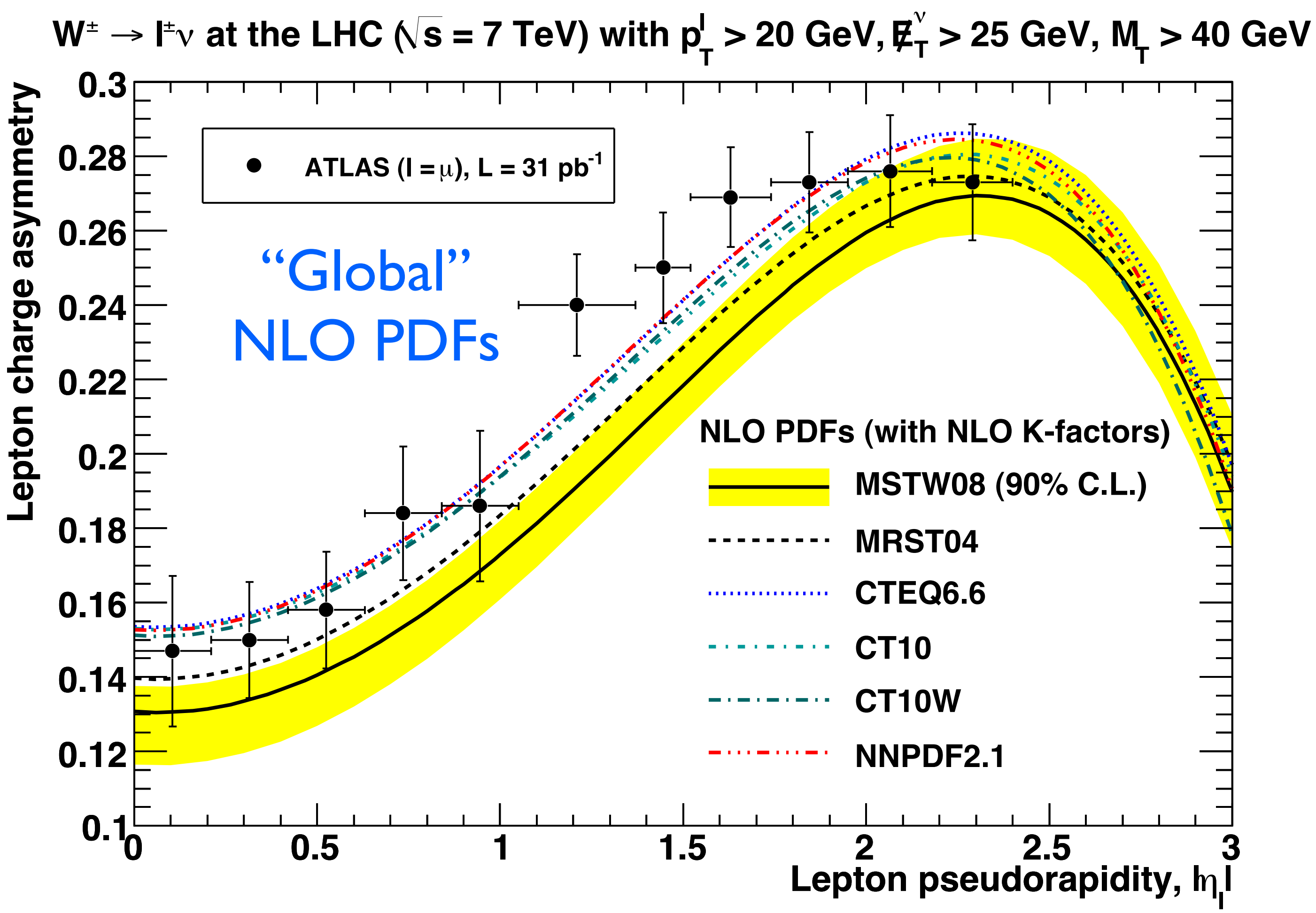


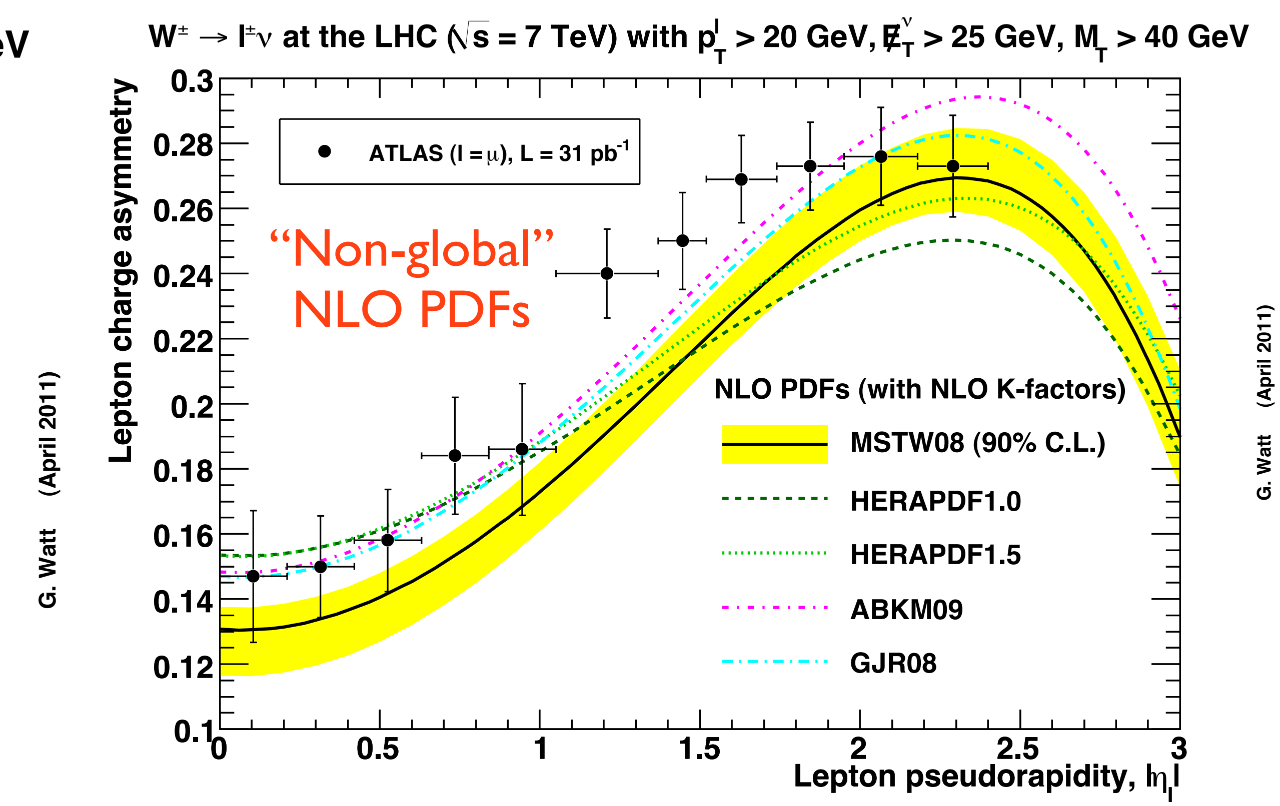


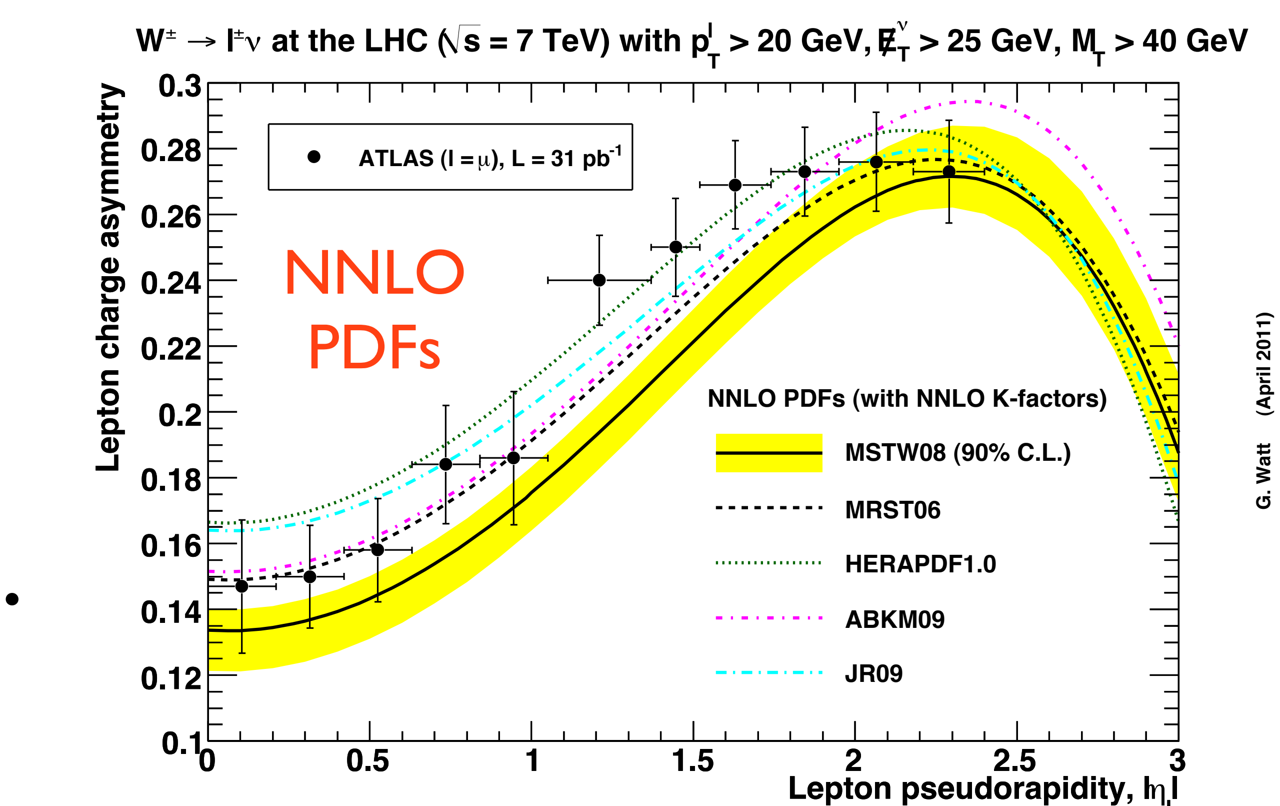
- All PDFs give good description.
- First LHCb data point higher than theory (and ATLAS/CMS).
- HERAPDF different at high η.
- Preliminary LHCb data not corrected for QED FSR.



Description of ATLAS data

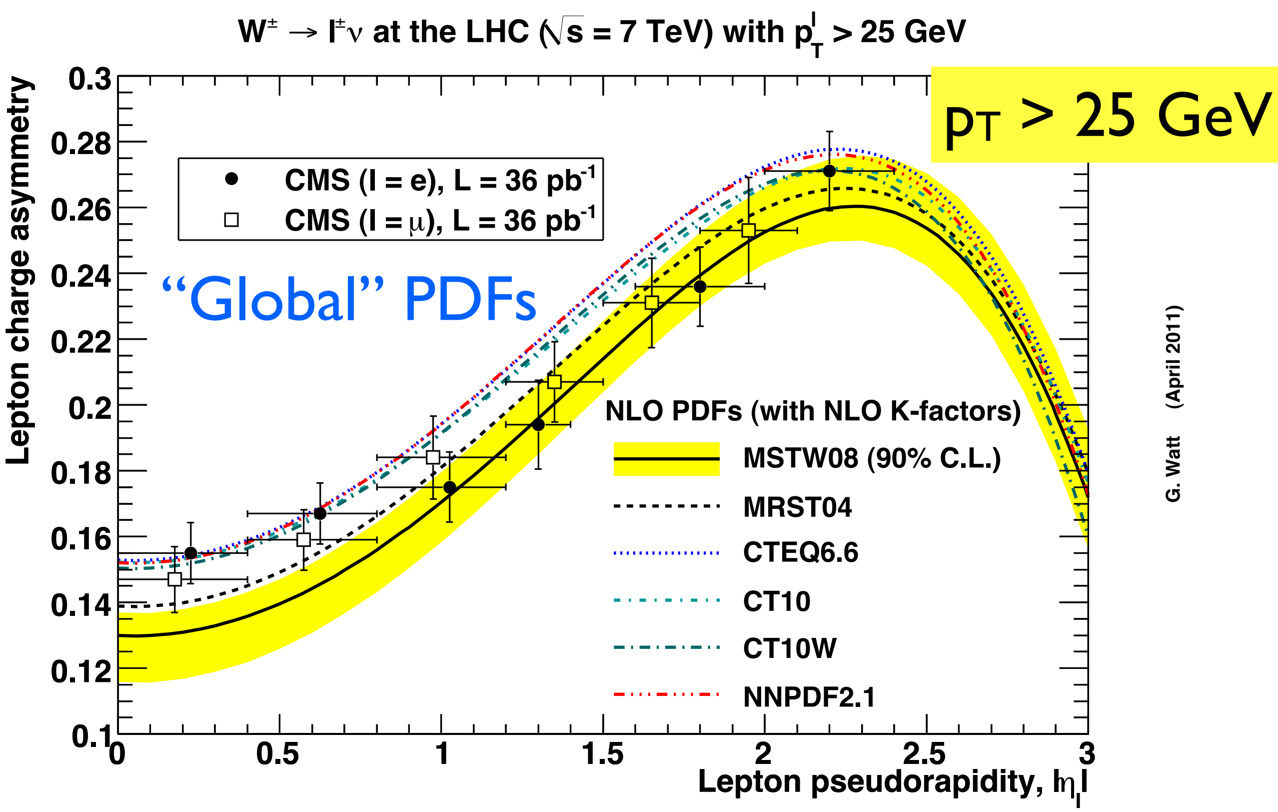


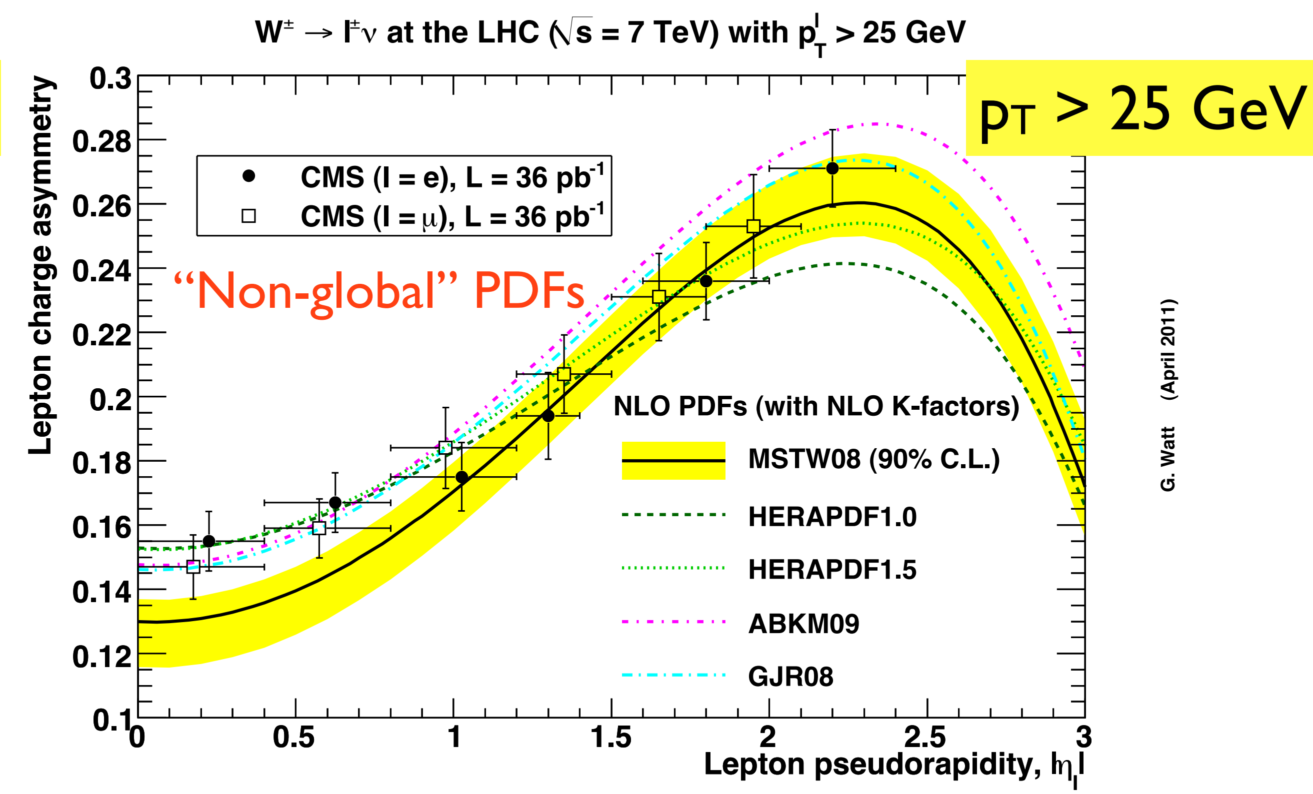


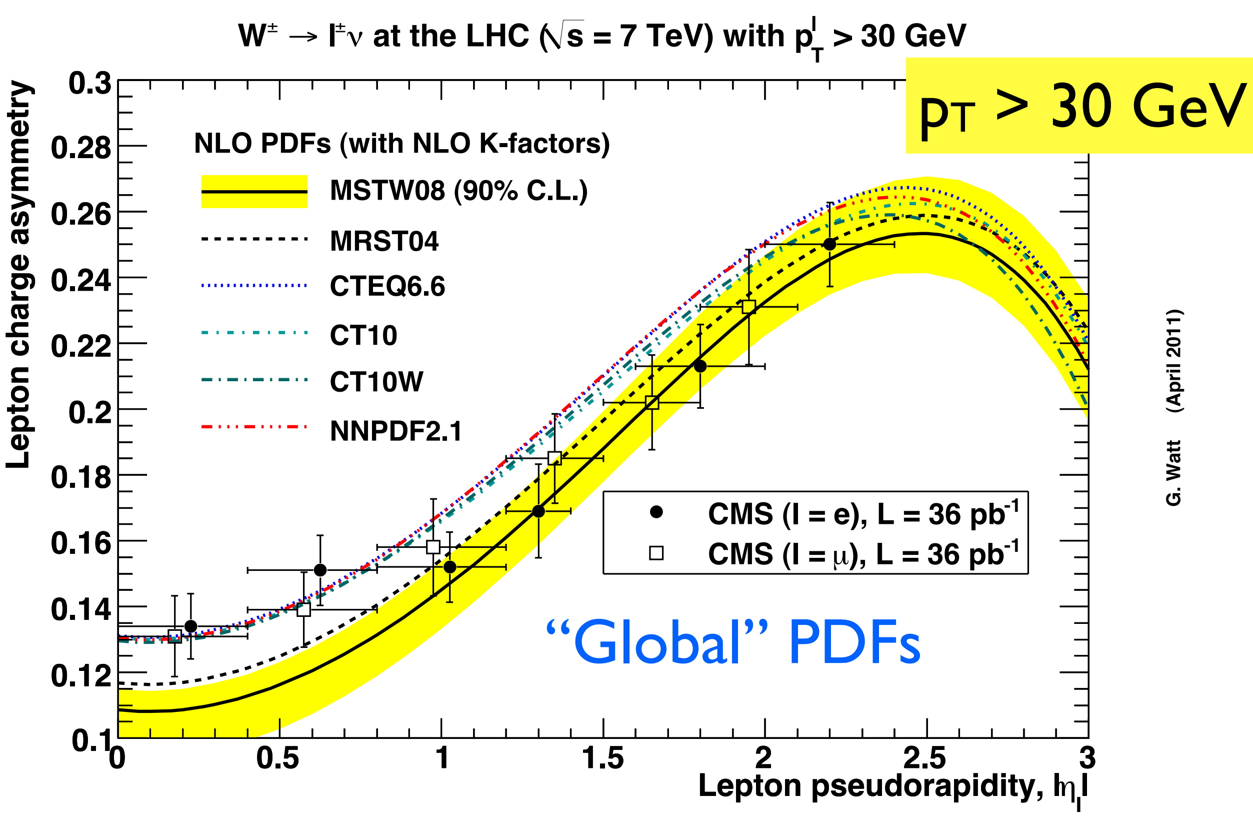


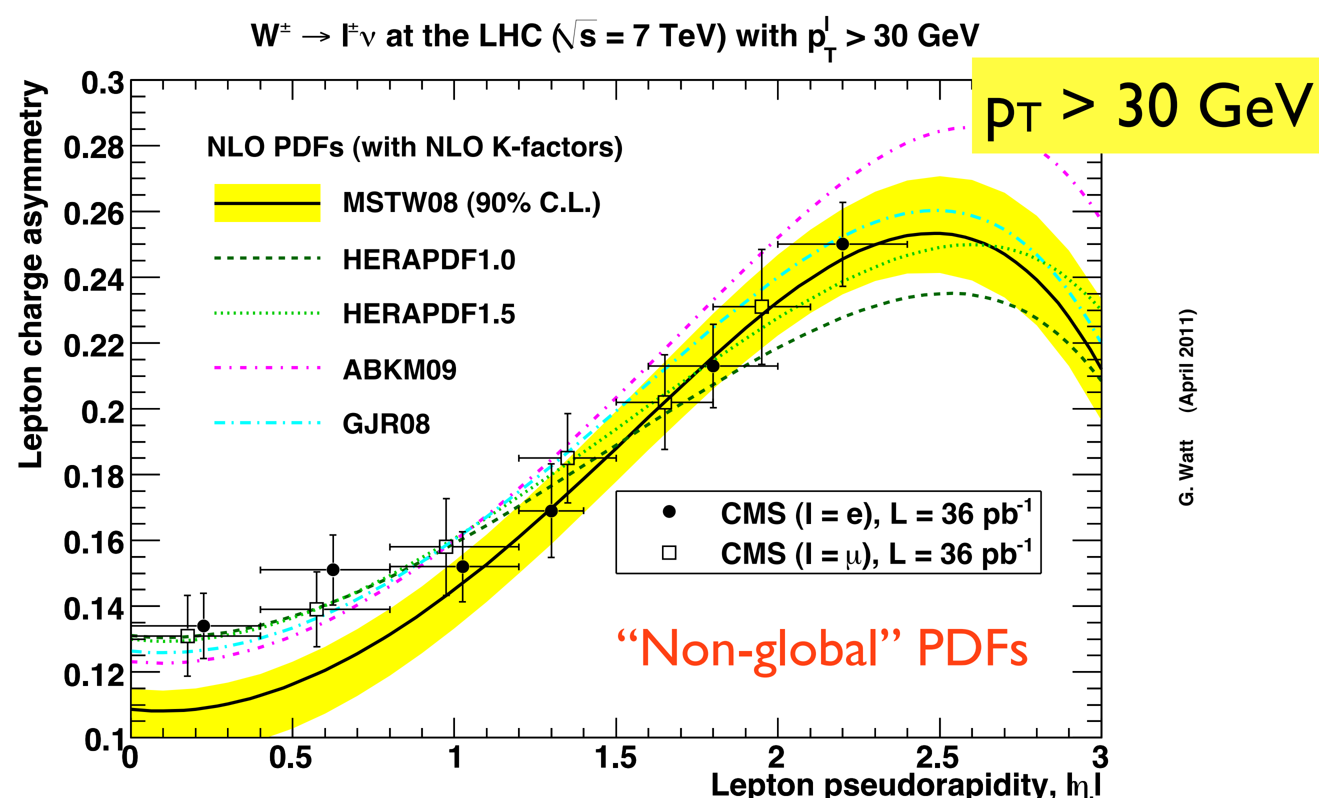
- Wide spread in predictions using different PDF sets ⇒ input to future global fits.

Description of CMS data

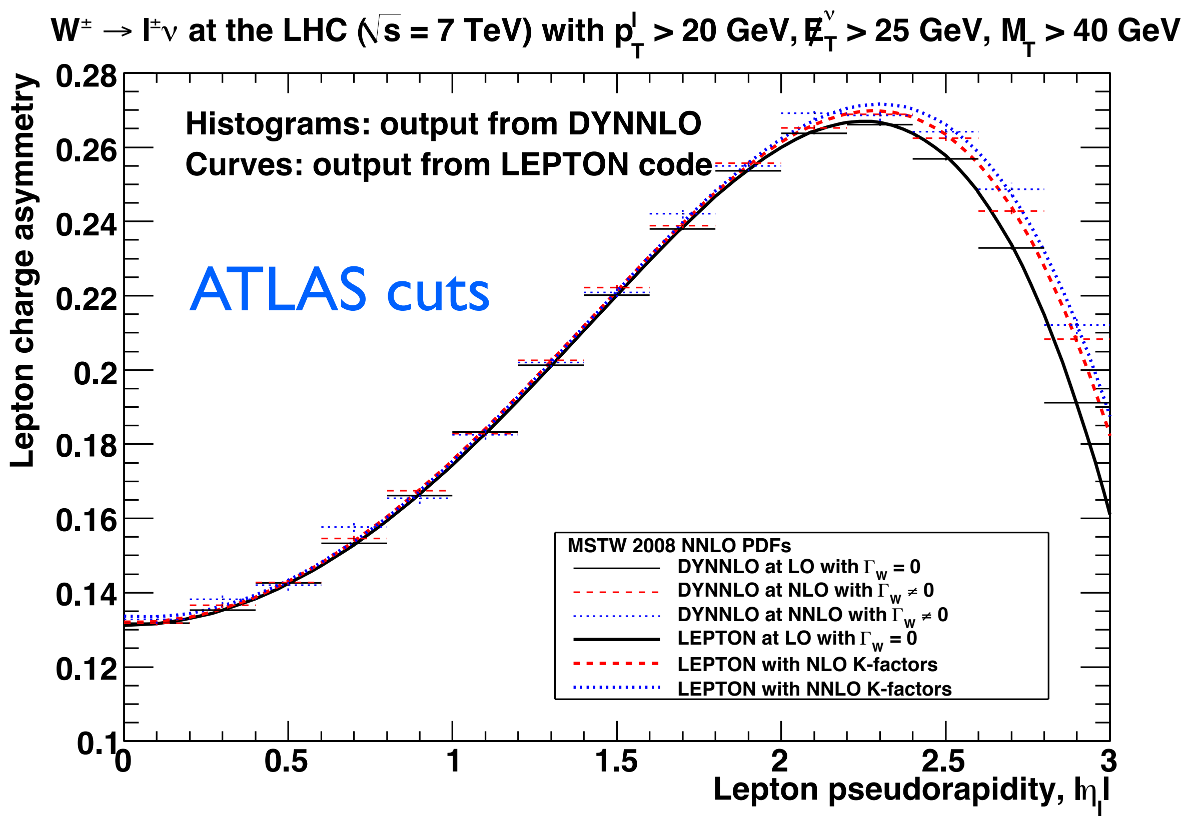


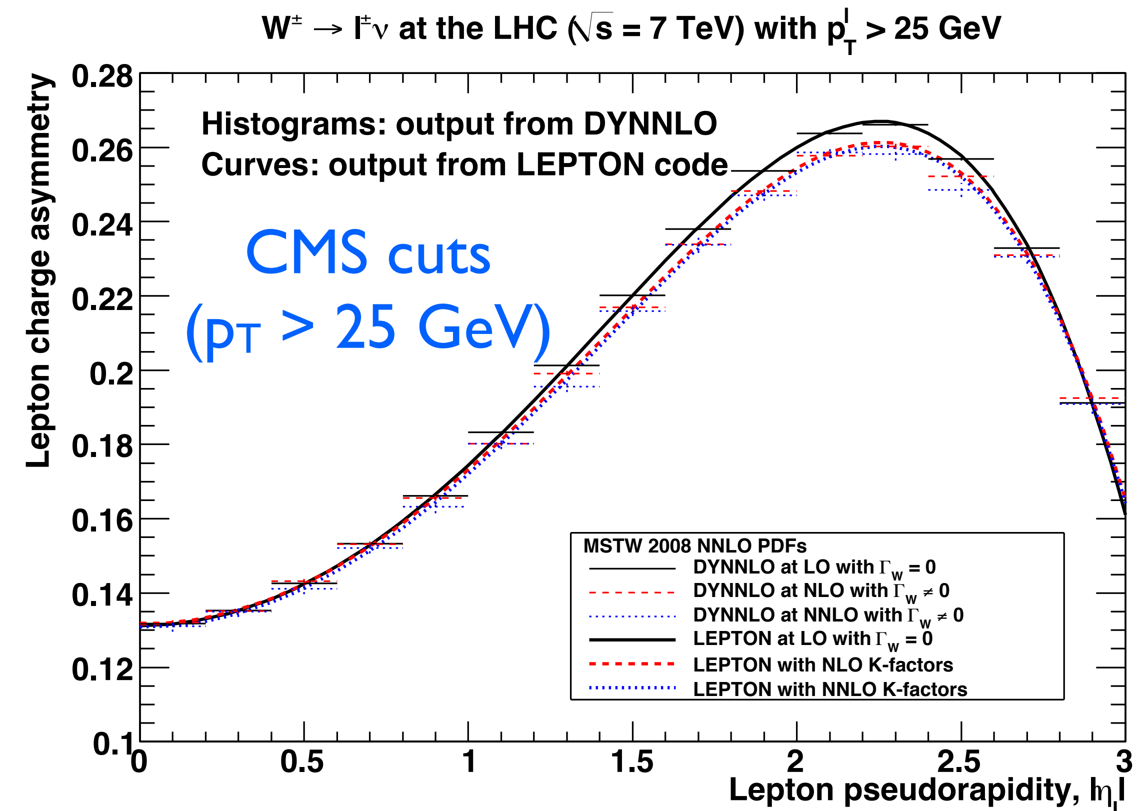


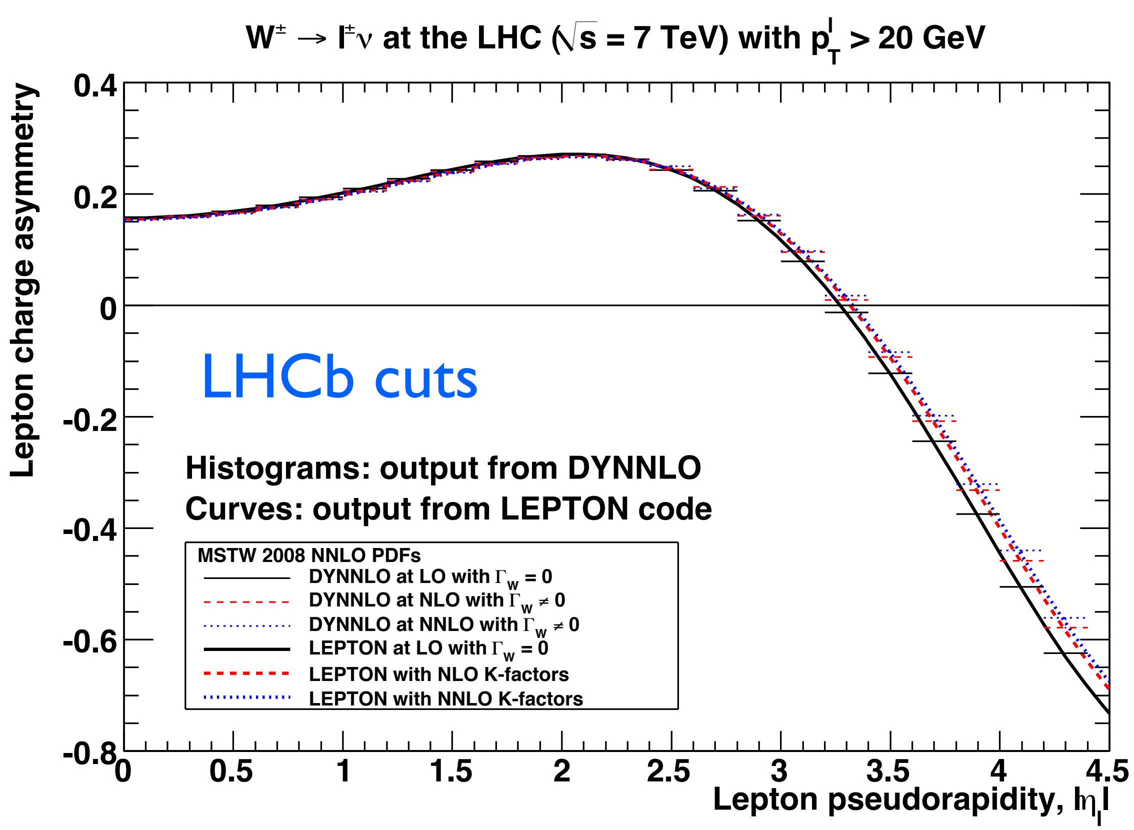


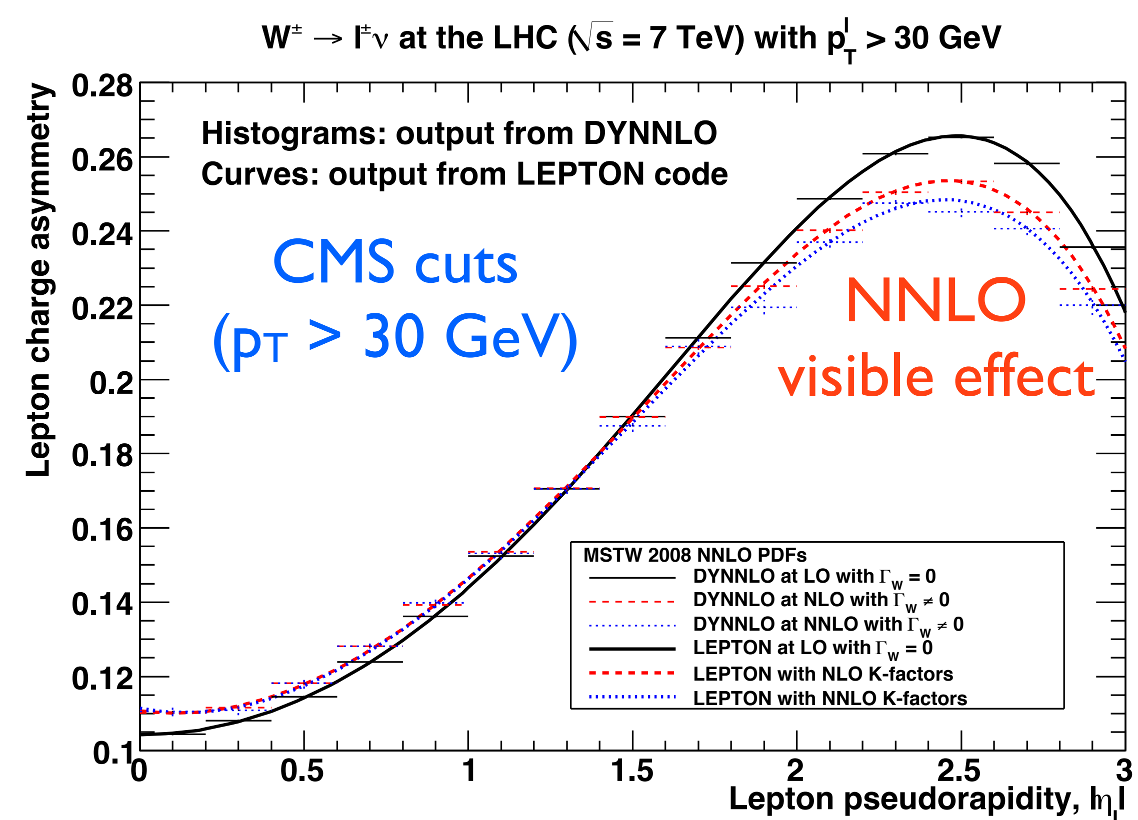


Size of NLO/NNLO corrections

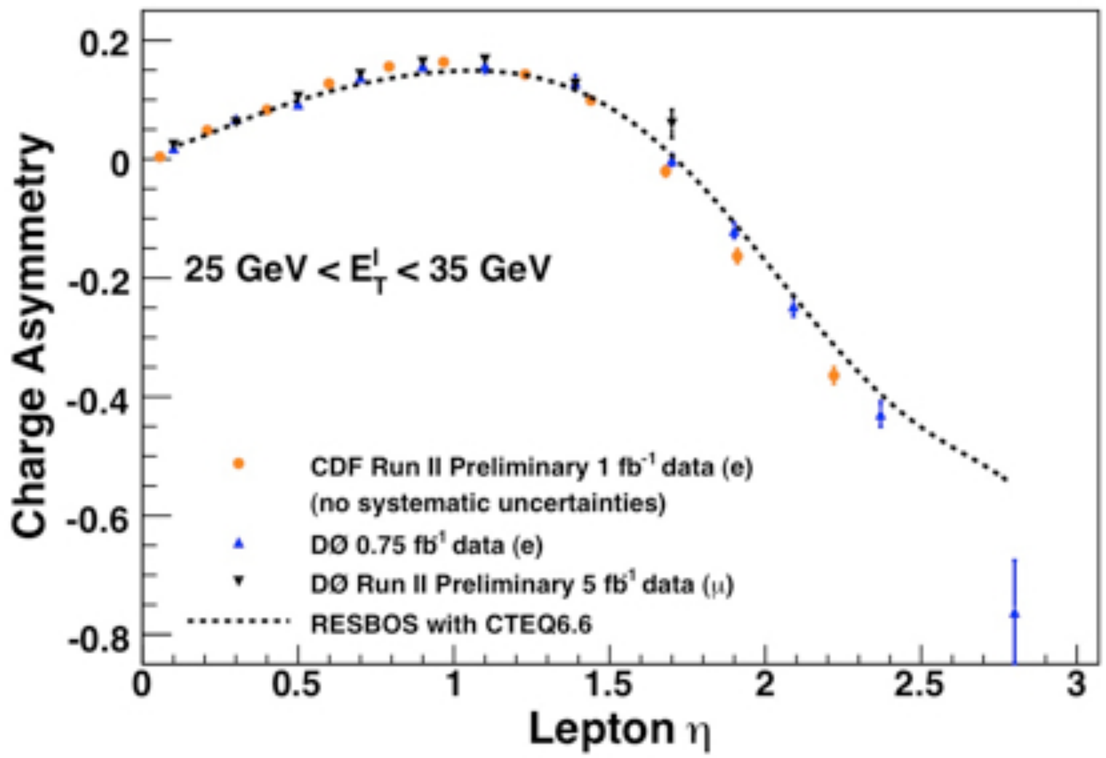


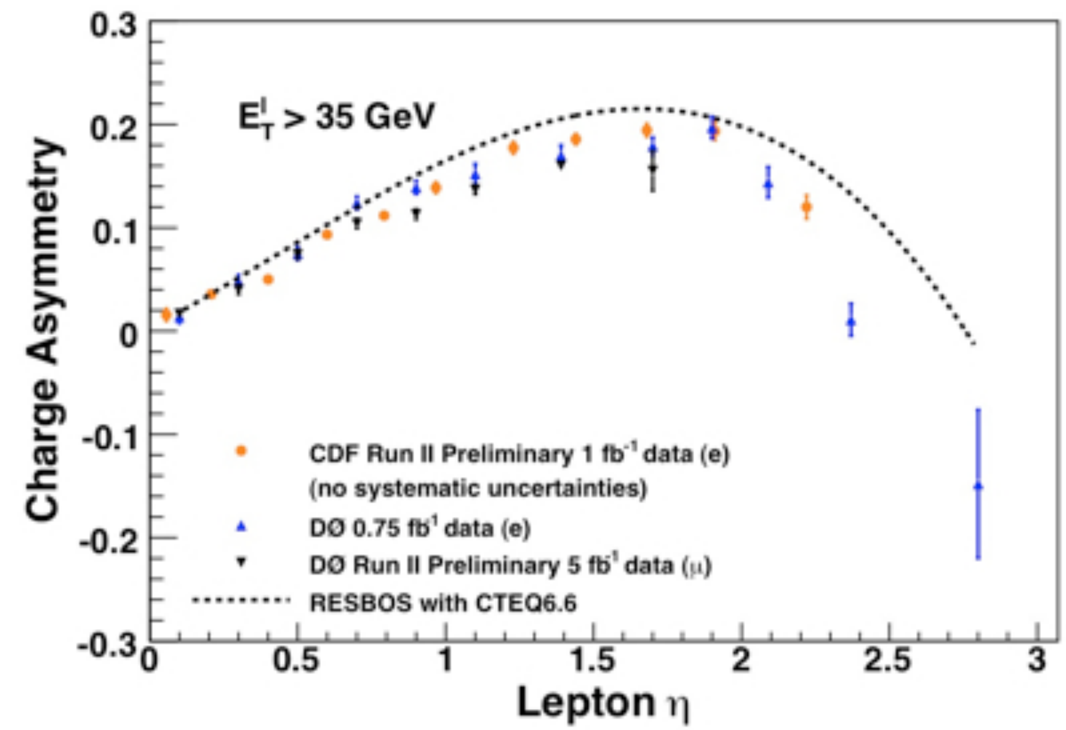






Tevatron $W^{\pm} \rightarrow l^{\pm} \nu$ asymmetry

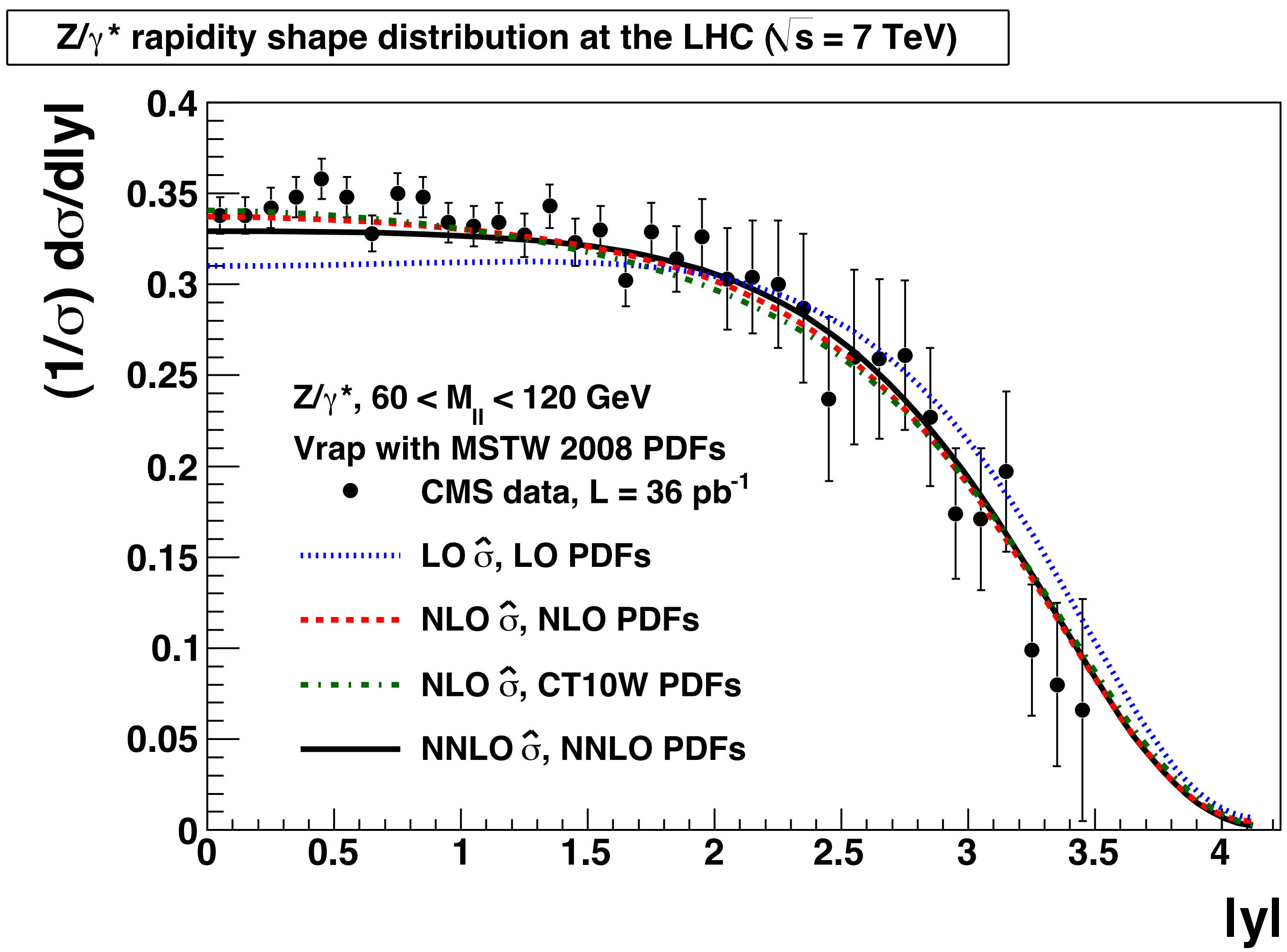


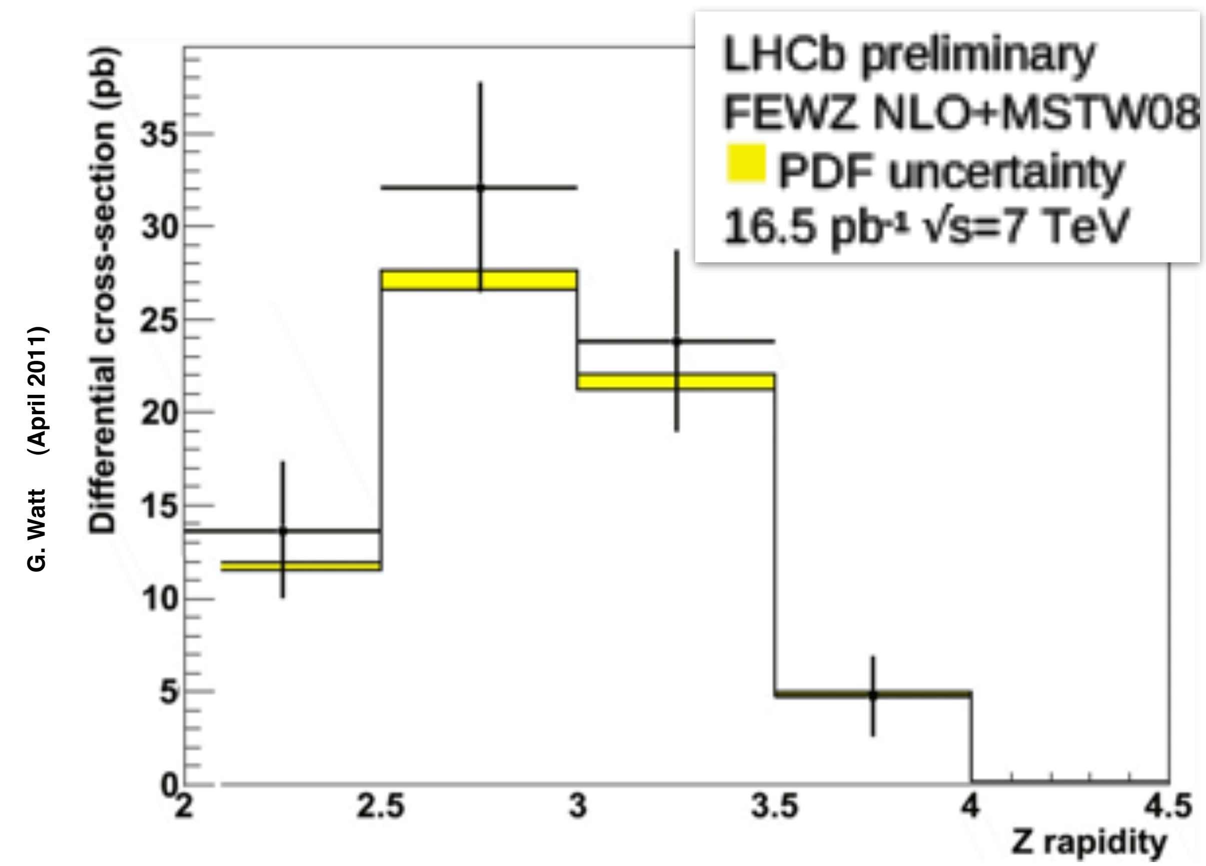


- Unresolved issues with Tevatron data split into E_T bins, especially for E_T > 35 GeV.
- See MSTW write-up [arXiv:1006.2753].
- Precise LHC measurements in lepton p_T bins might help, otherwise more inclusive generally provides a safer PDF constraint.

Z/γ* rapidity from CMS/LHCb

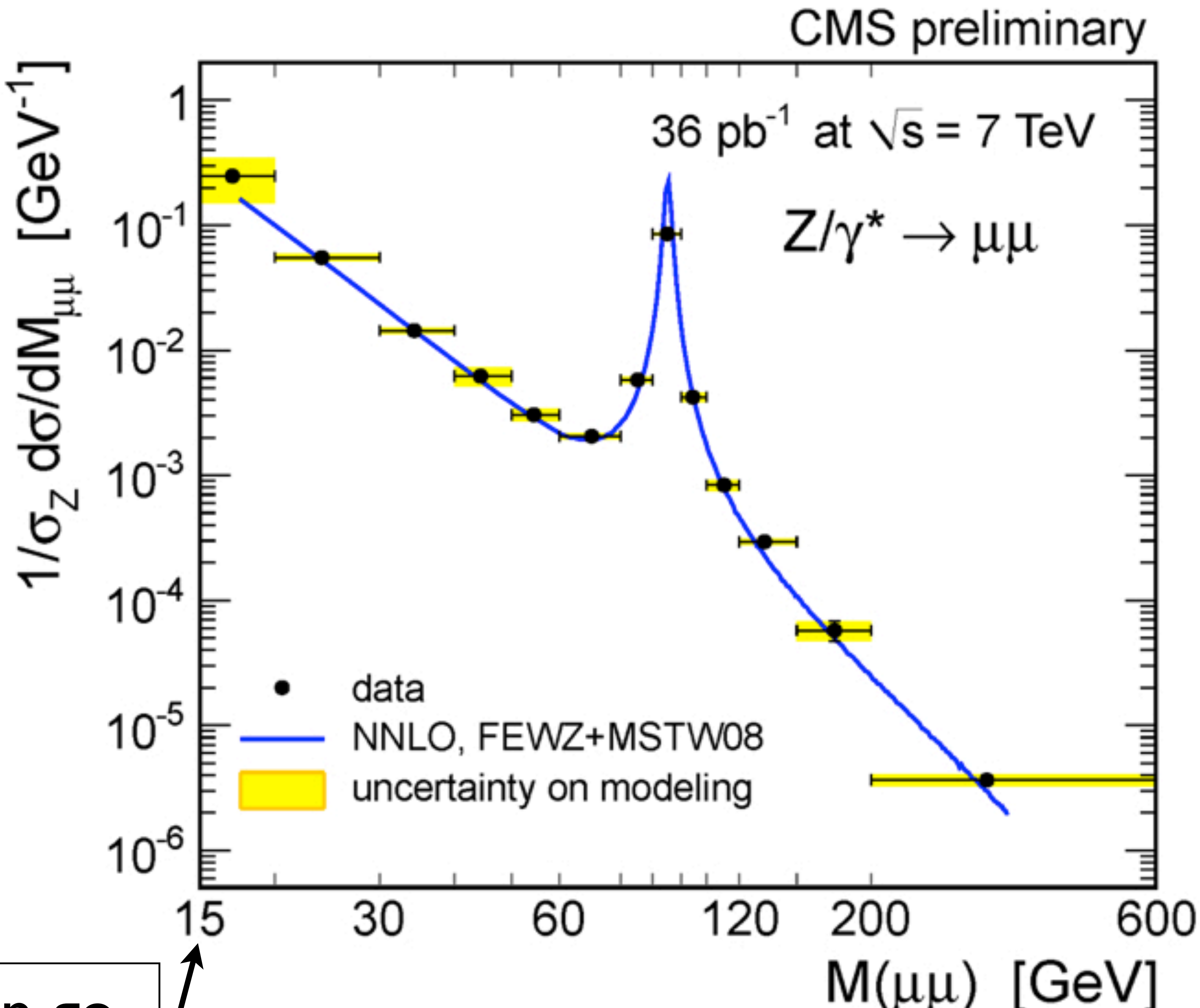
$$\frac{d\sigma_Z}{dy} \sim 0.29\, u(x_1)\bar{u}(x_2) + 0.37\, d(x_1)\bar{d}(x_2), \quad x_{1,2} = \frac{M_Z}{\sqrt{s}} \exp(\pm y)$$





- Preliminary CMS data [CMS PAS EWK-10-010].
- CMS: NLO/NNLO PDFs favoured over LO.
- LHCb: both muons with $2 < \eta_\mu < 4.5$.

DY away from the Z peak

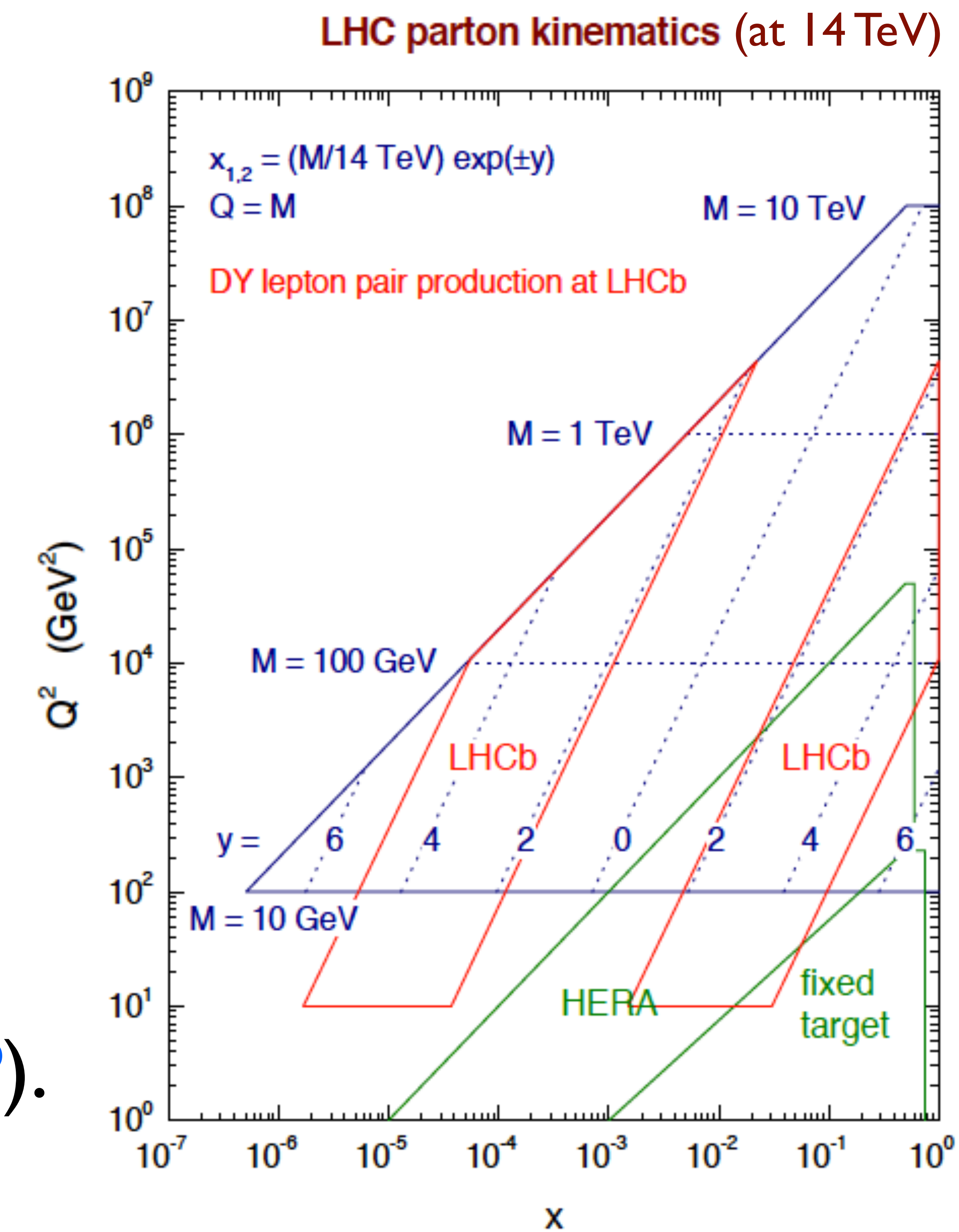


LHCb can go to lower $M_{\mu\mu}$!

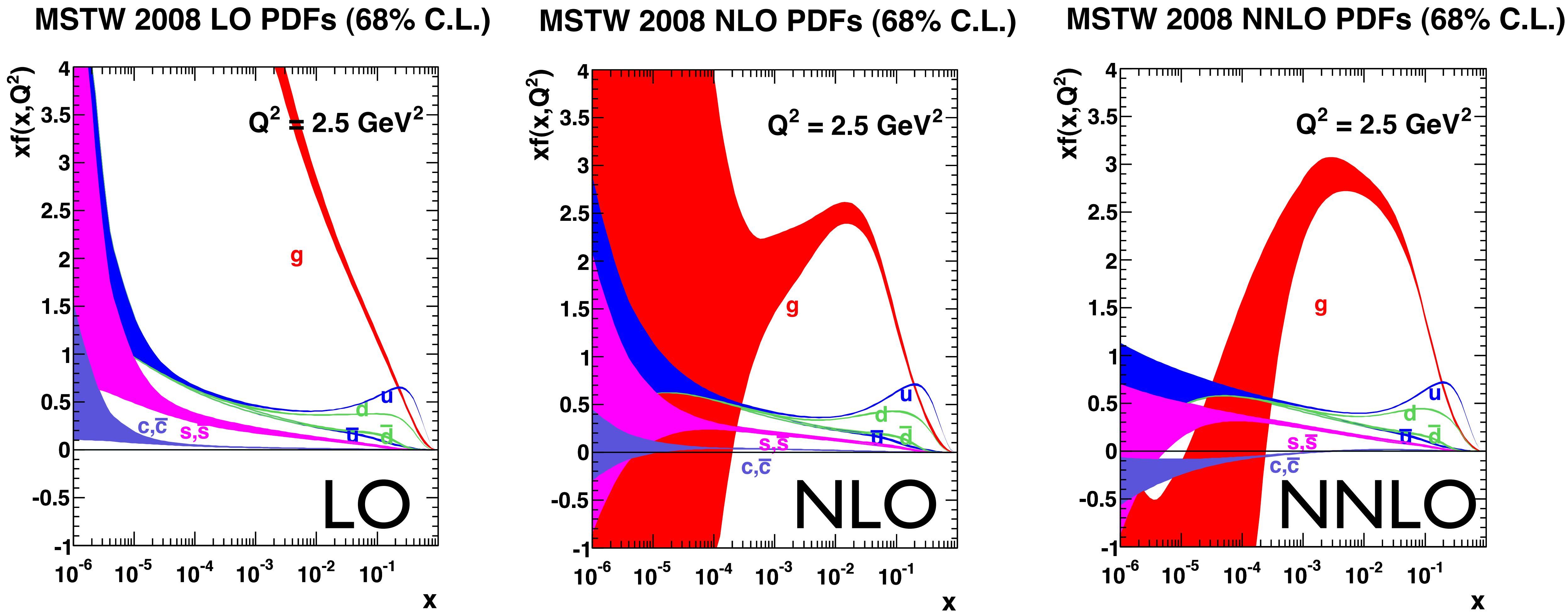
[CMS PAS EWK-10-007]

Low-mass Drell-Yan at LHCb

- Measure low-mass ($M_{\mu\mu} > 2.5$ GeV) Drell-Yan at forward rapidities to access small-x PDFs beyond the reach of HERA.
- Expect need to resum $\alpha_S \log(1/x)$ terms (BFKL) in addition to usual $\alpha_S \log(Q^2)$ terms (DGLAP).



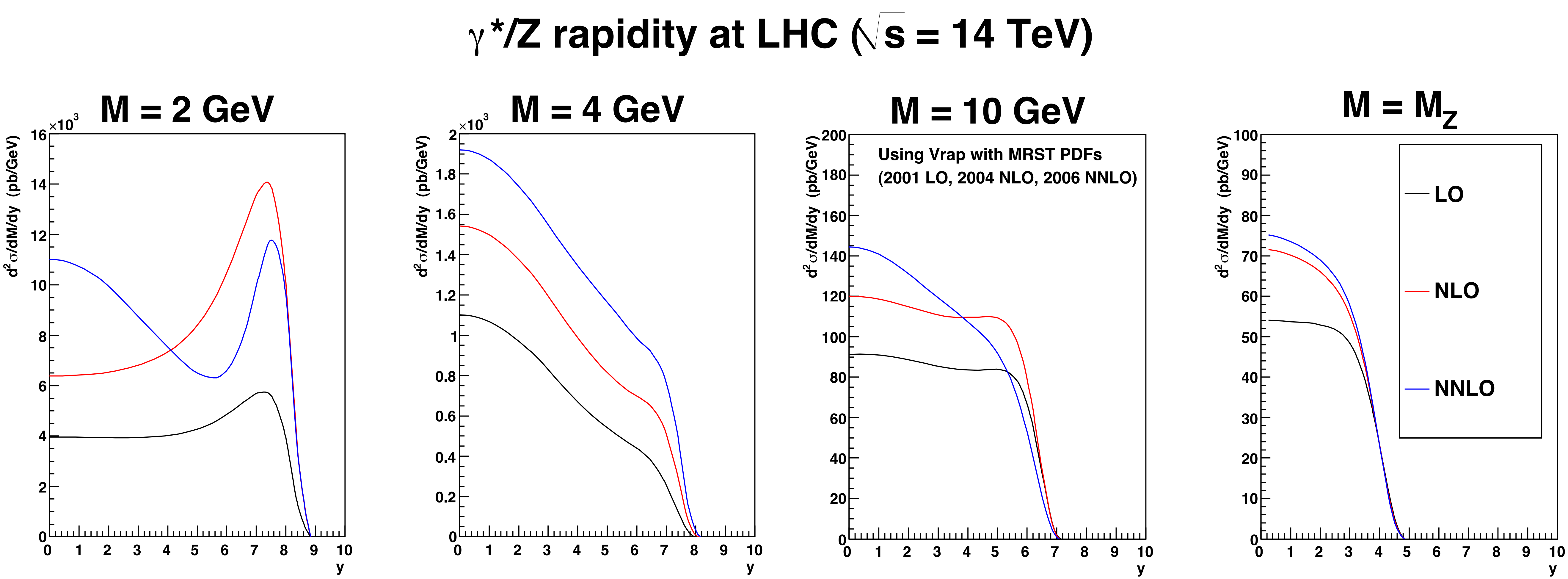
PDFs at low x and Q^2



- Little or no data constraint for $x < 10^{-4}$.
- Large differences in small-*x* PDFs at different perturbative orders, particularly for the gluon.

Drell-Yan rapidity distributions

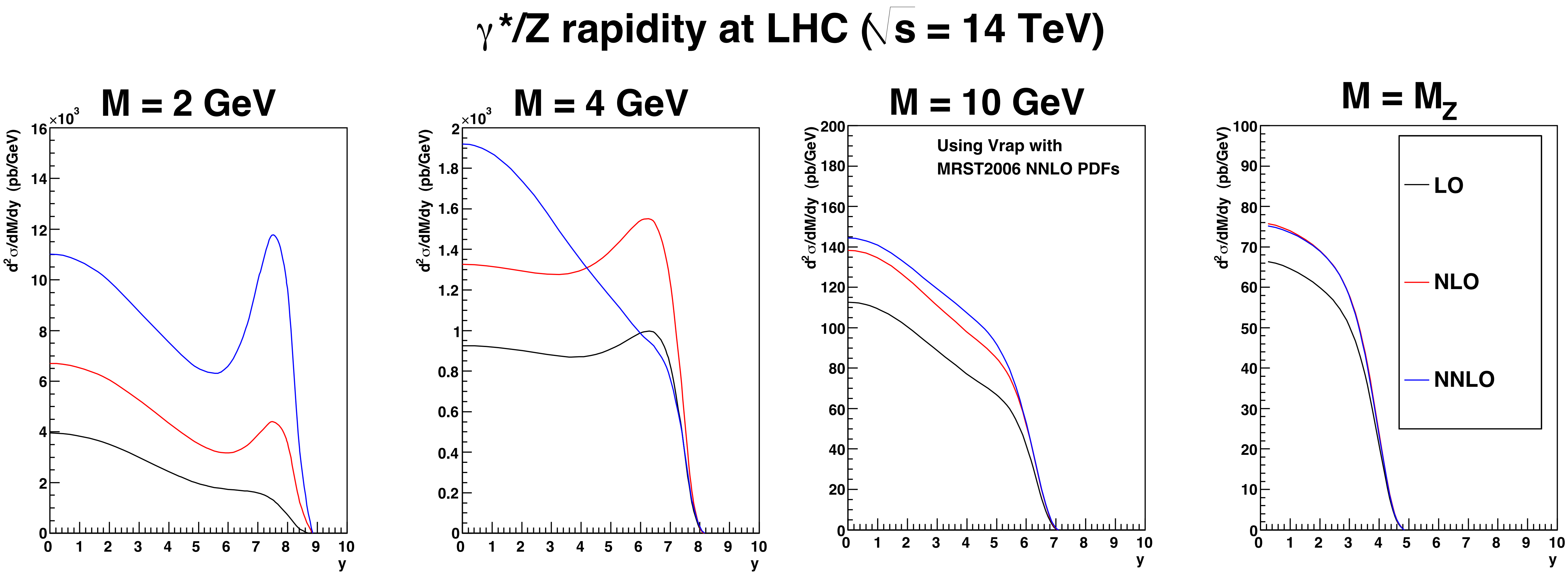
- Look at LO→NLO→NNLO behaviour.
- Match order of PDF to order of calculation.



- Rapidity distributions unstable for $M^2 \ll s$.

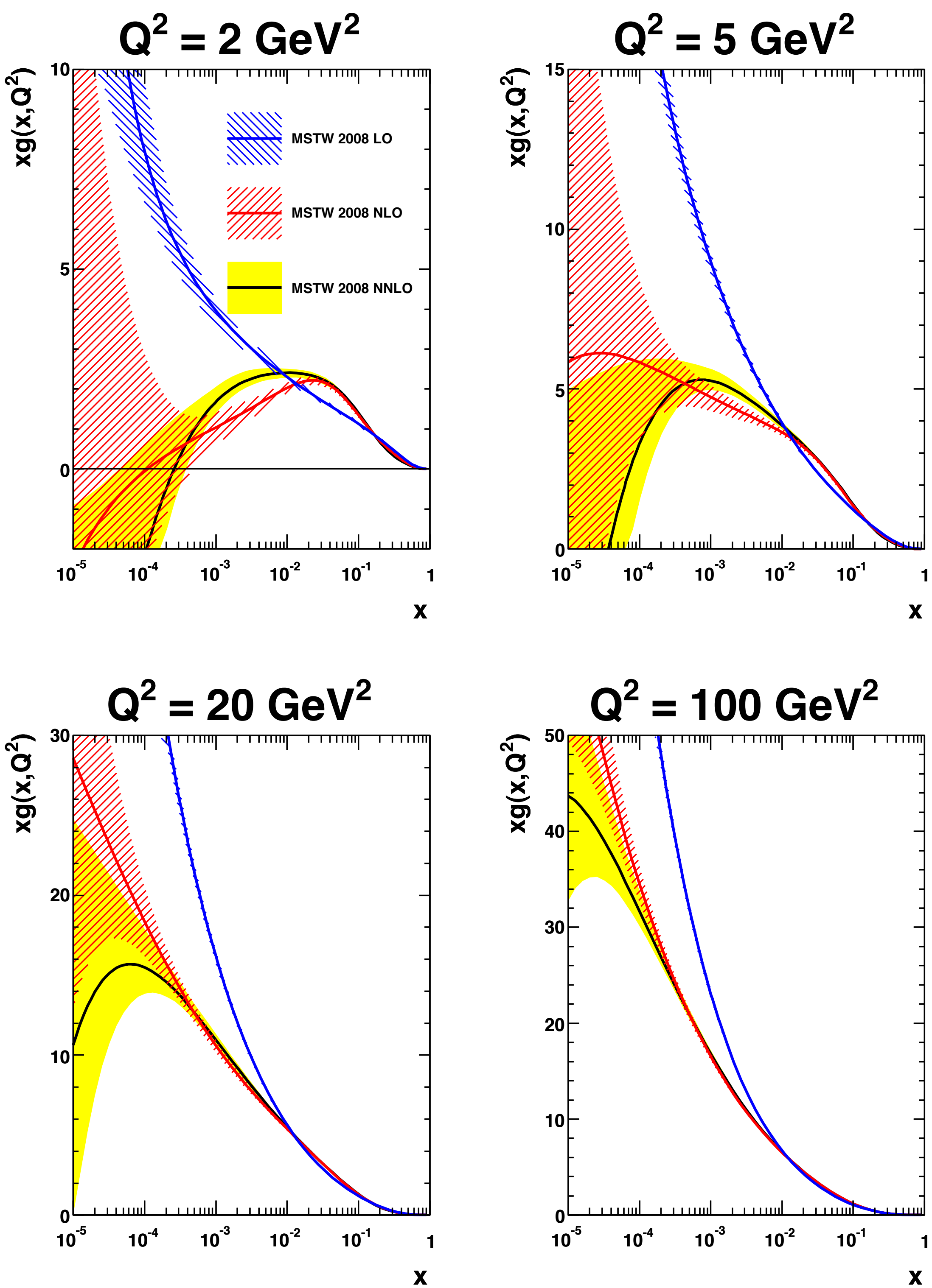
Drell-Yan rapidity distributions

- Same NNLO PDF at each perturbative order.
  ⇒ Isolate differences from partonic cross section.

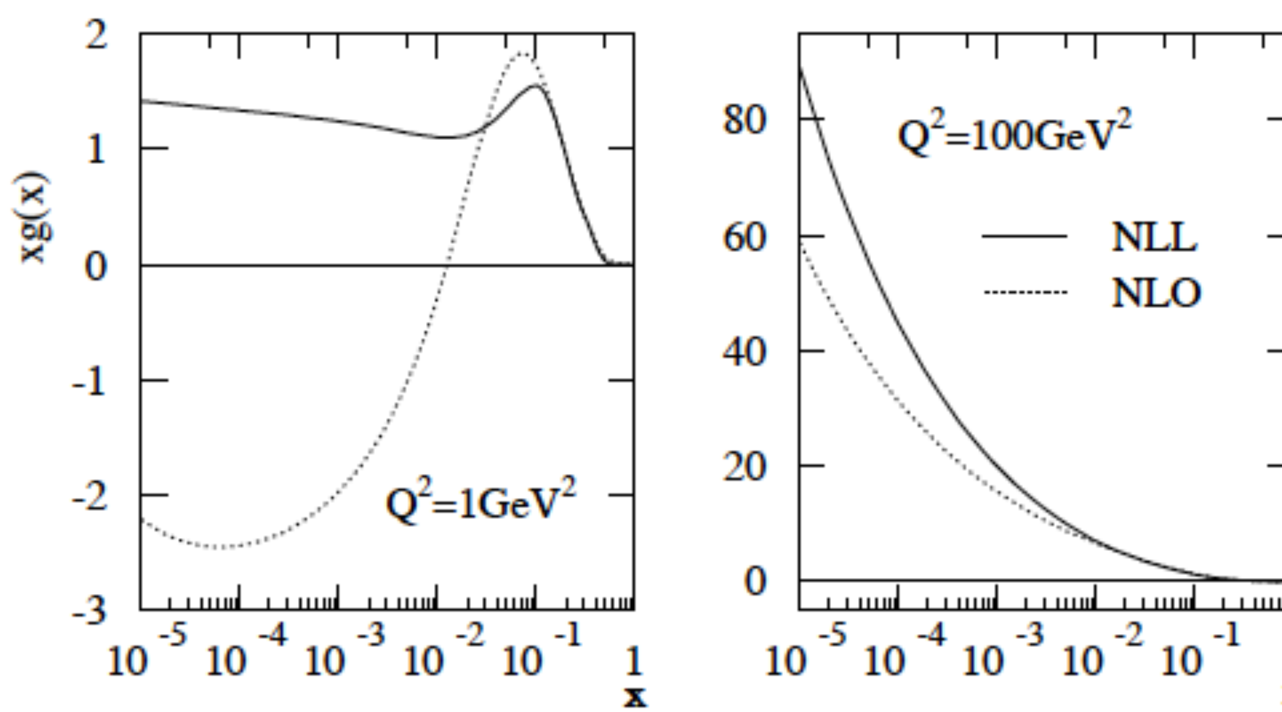


- DY coefficient functions unstable for $M^2 \ll s$.

Small-x gluon distribution



- Gluon perturbatively unstable as the scale Q^2 is lowered.
- Behaviour improved by small-*x* resummation: C. D. White and R. S. Thorne [hep-ph/0611204].

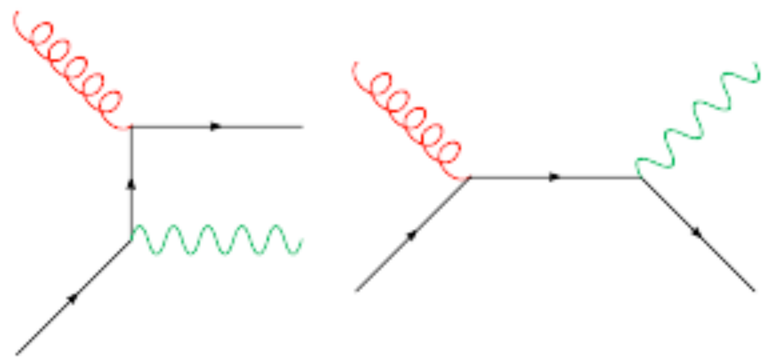


Small-x resummation for Drell-Yan at LHC

S. Marzani and R. D. Ball [arXiv:0812.3602, arXiv:0906.4729, arXiv:1006.2314]

Resummed coefficient functions

$$g^* q \to \gamma^* q$$

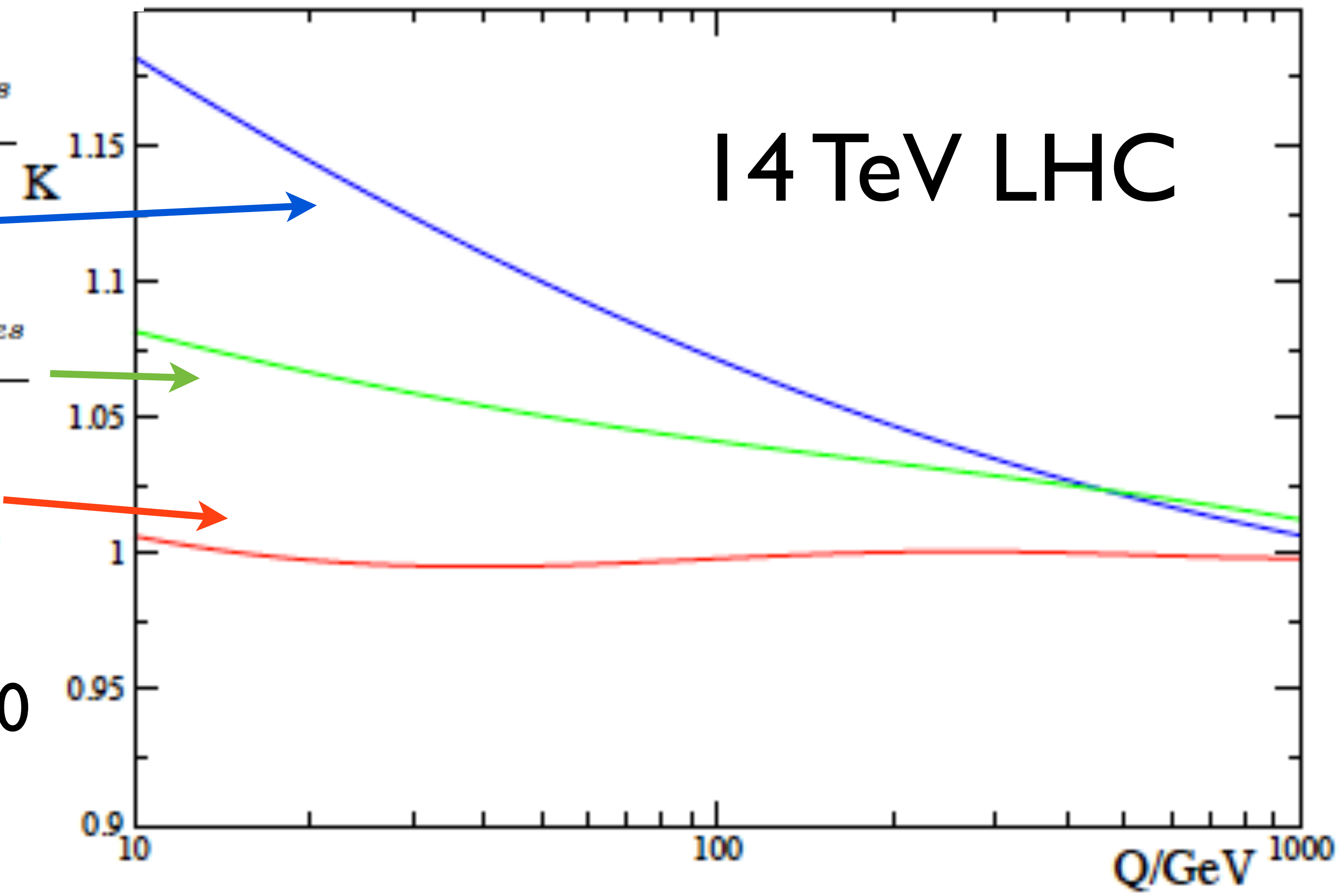


Resummed evolution kernels:
Altarelli, Ball, Forte [arXiv:0802.0032]

$$K^{NLO} = \frac{D_{ij}^{\mathrm{NLOres}} \otimes f_i^{\mathrm{NLOres}} \otimes f_j^{\mathrm{NLOres}}}{D_{ij}^{\mathrm{NLO}} \otimes f_i^{\mathrm{NLO}} \otimes f_j^{\mathrm{NLO}}}$$

$$K_1^{NNLO} = \frac{D_{ij}^{\mathrm{NNLOres}} \otimes f_i^{\mathrm{NLOres}} \otimes f_j^{\mathrm{NLOres}}}{D_{ij}^{\mathrm{NNLO}} \otimes f_i^{\mathrm{NLO}} \otimes f_j^{\mathrm{NLO}}}$$

$$K_2^{NNLO} = \frac{D_{ij}^{\mathrm{NNLOres}} \otimes f_i^{\mathrm{NNLO}} \otimes f_j^{\mathrm{NNLO}}}{D_{ij}^{\mathrm{NNLO}} \otimes f_i^{\mathrm{NNLO}} \otimes f_j^{\mathrm{NNLO}}}.$$

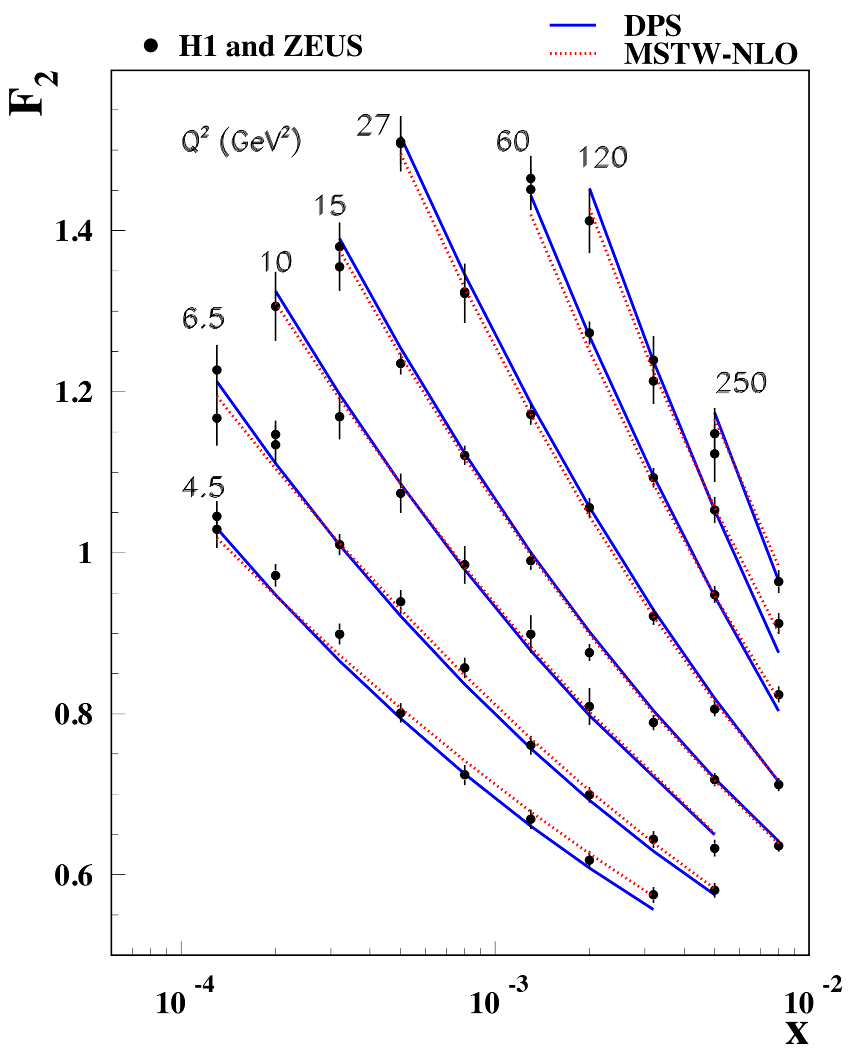


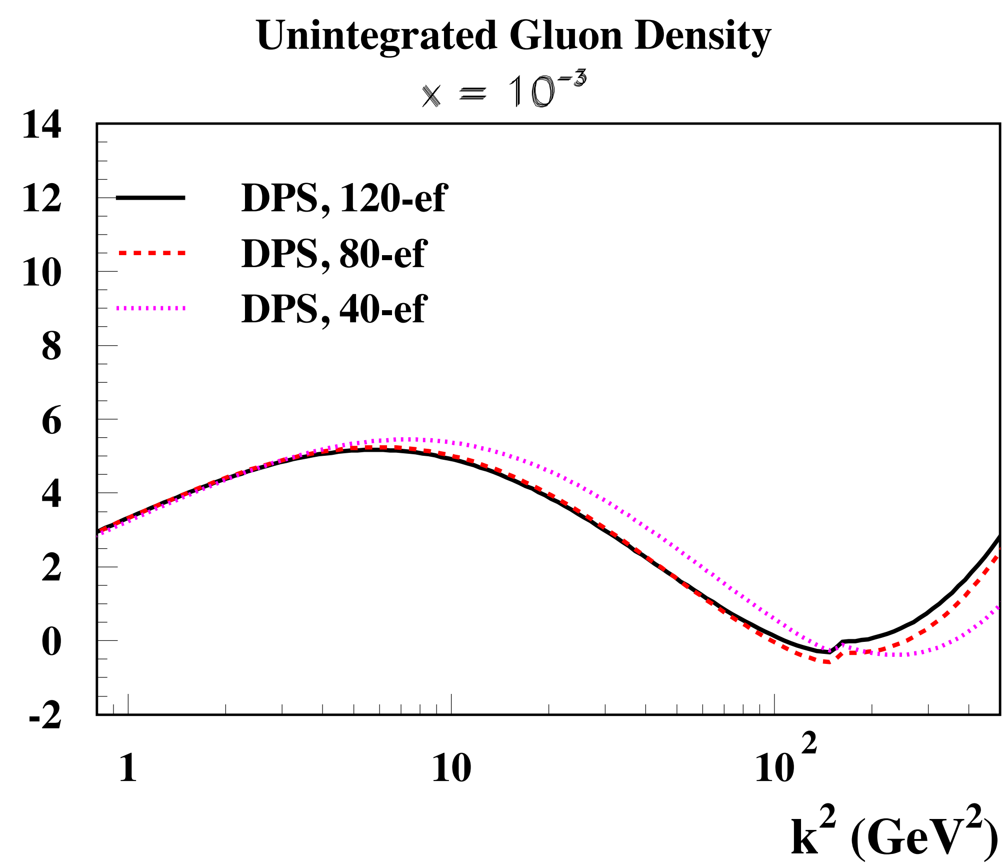
- Input PDFs from NNPDF1.0 at Q_0 = 3 GeV (no refit).

- Larger effects expected for DY rapidity distributions (in progress). Method applied to $gg \to H$ by Caola, Forte, Marzani [arXiv:1010.2743].

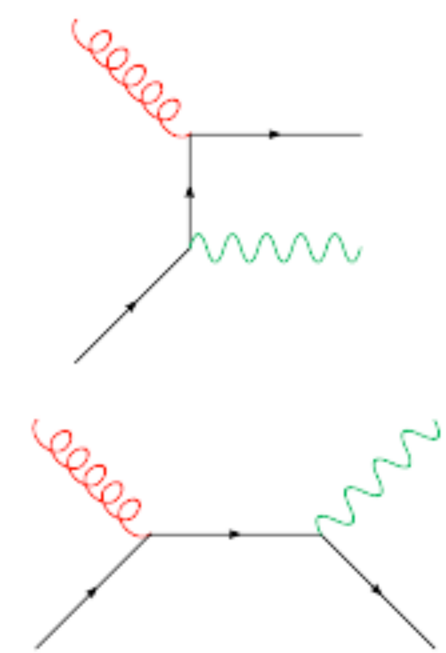
Discrete Pomeron Solution to BFKL equation

H. Kowalski, L. N. Lipatov, D.A. Ross, G.Watt [arXiv:1005.0355]



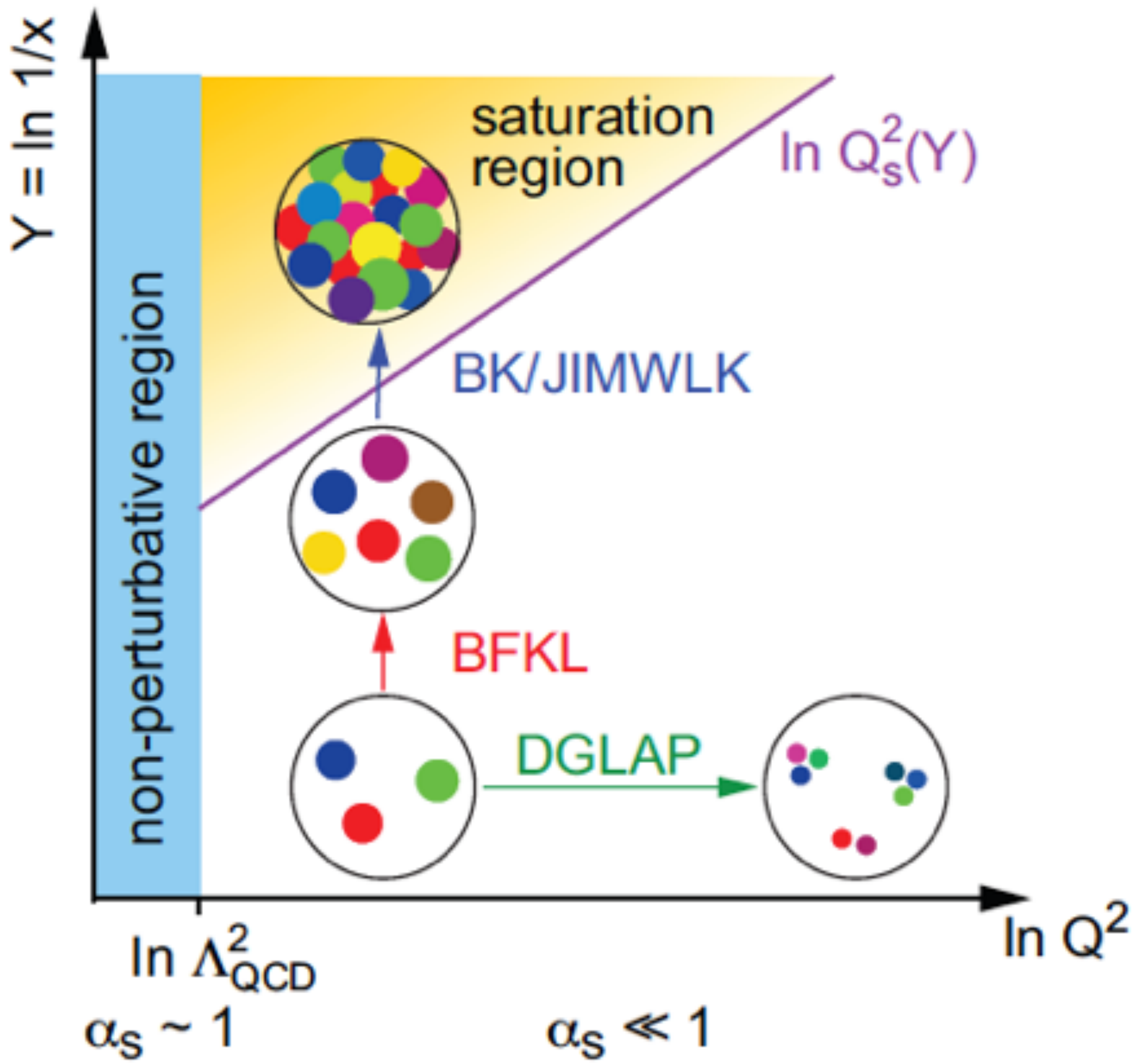


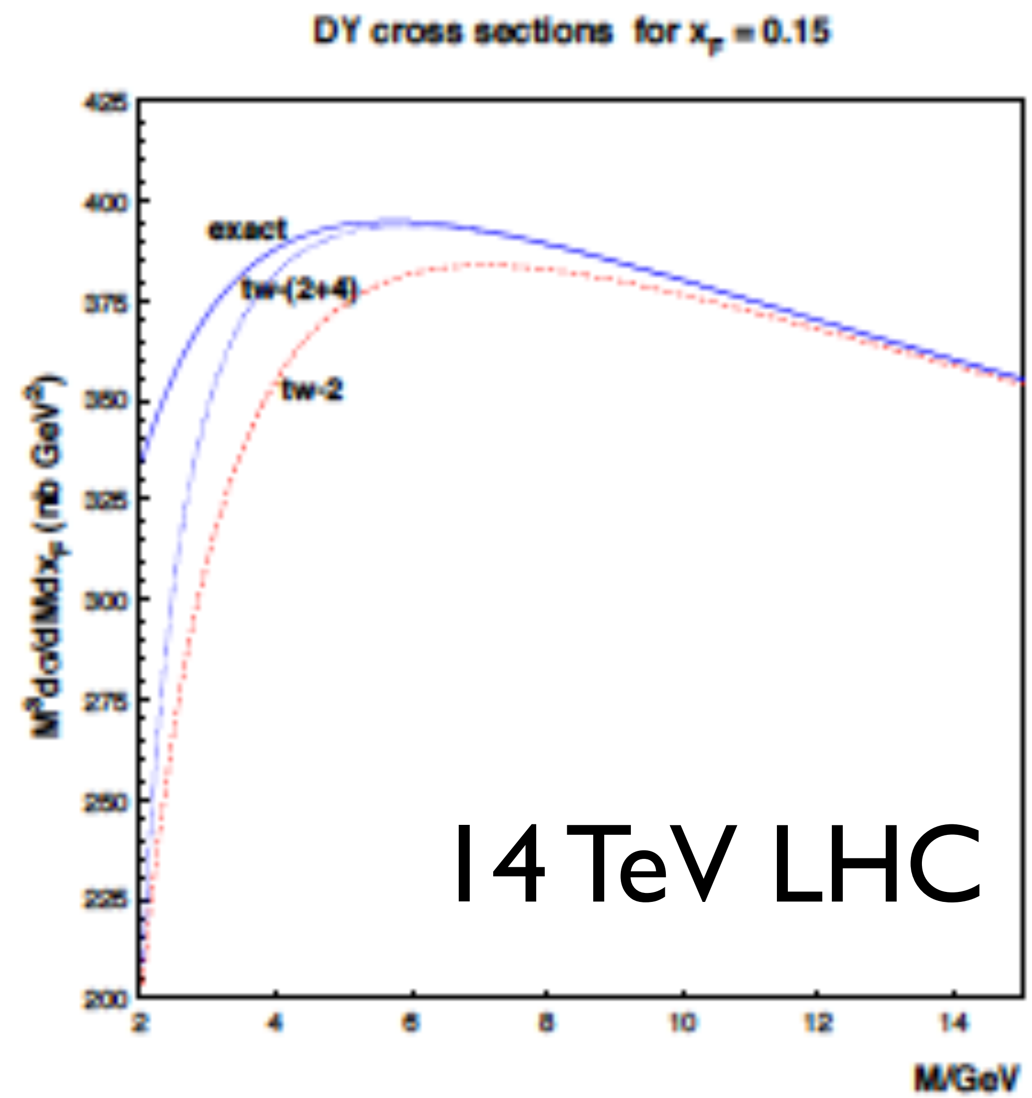
$$g^*q \to \gamma^*q$$



- Successful BFKL description of HERA data.
- Could use "unintegrated" gluon density with $g^*q \to \gamma^*q$ subprocess to calculate forward Drell-Yan at LHC.

Parton saturation effects

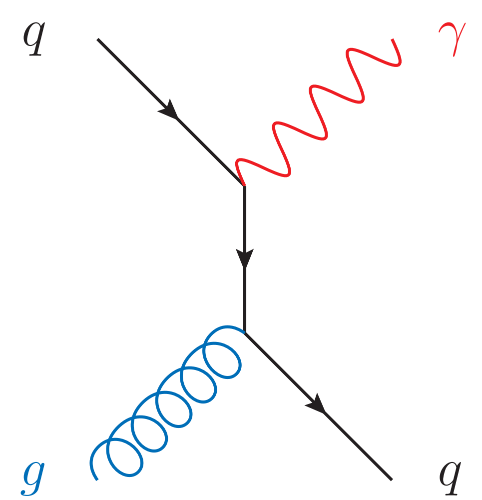




Golec-Biernat, Lewandowska, Staśto [arXiv:1008.2652]

- *Twist* expansion in powers of (Q_s^2 / M^2).
- Leading-twist sufficient for *M* larger than ~6 GeV. Twist expansion divergent for *M* < 4 GeV.

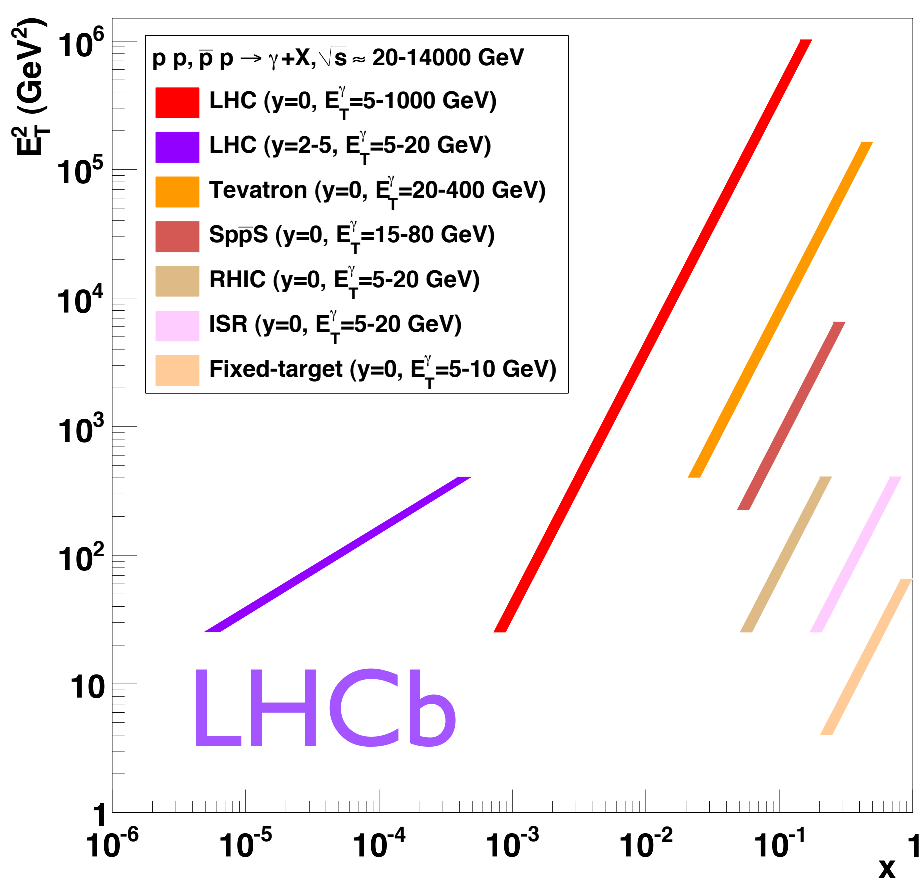
Isolated photon production



- Early PDF fits used fixed-target data on prompt photon production to provide a gluon constraint, but later omitted due to problems with both data and theory.
- Situation at LHC looks more promising.
  - LHCb measurement of isolated photons could constrain gluon.

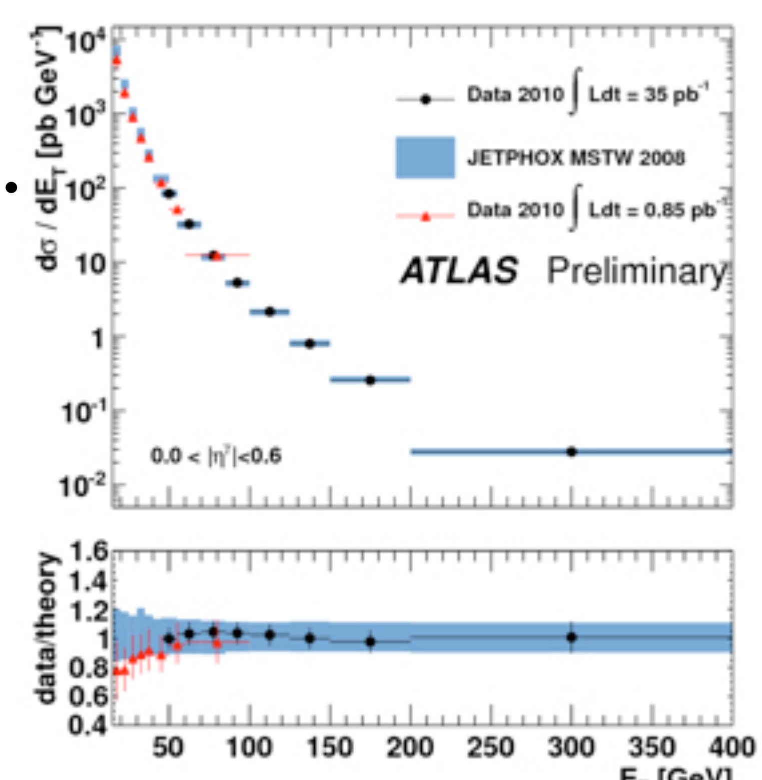
$$x \sim x_T = \frac{2E_T^\gamma}{\sqrt{s}}$$

  - Variations: $gs \to Wc$, $gc \to \gamma c$, $gb \to \gamma b$, $gc \to Zc$, $gb \to Zb$.
- Also jets, heavy flavour production.



R. Ichou and D. d'Enterria [arXiv:1005.4529]

[ATLAS-CONF-2011-058]



Summary

- **P**arton **D**istribution **F**unctions (**PDF**s) are a non-negotiable input to almost all theory predictions at the LHC.
- LHCb electroweak physics programme can provide significant PDF constraints complementary to ATLAS and CMS:
  - W^+, W^-, Z cross sections (and their ratios).
  - $W^\pm \rightarrow l^\pm \nu$ charge asymmetry in forward region.
  - Z/γ^* rapidity distribution in Z mass window.
- LHCb can uniquely measure forward low-mass Drell-Yan to probe small-x PDFs where resummation/saturation needed.
- Other PDF constraints: isolated photons, jets, heavy flavours.