Scaling properties of inclusive W production

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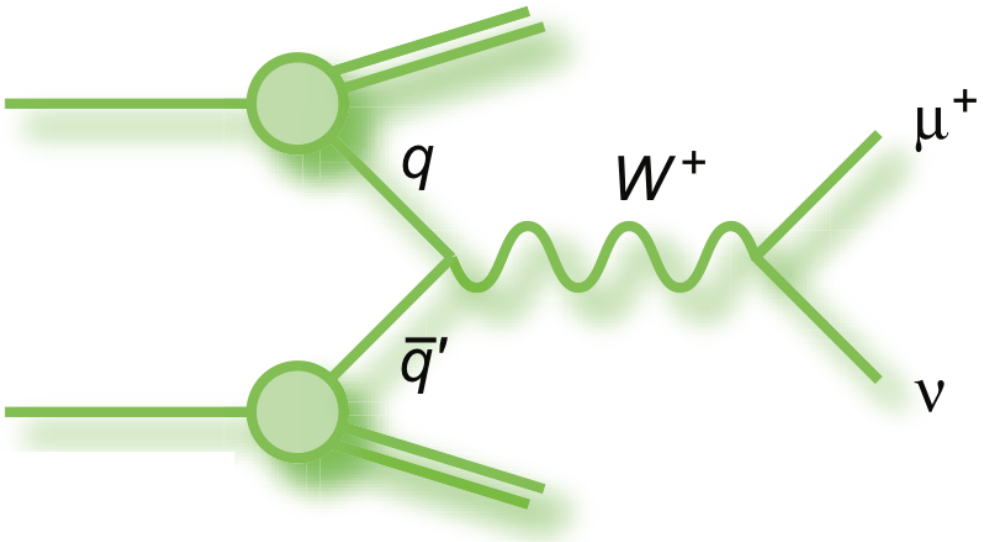
Introduction

- We consider a well understood processes of $W^{\pm}$ production:

$$\mathrm{H}_1 + \mathrm{H}_2 \to \mathrm{W}^- + \mathrm{X} \to \ell^- + \bar{\nu} + \mathrm{X},$$

$$\mathrm{H}_1 + \mathrm{H}_2 \to \mathrm{W}^+ + \mathrm{X} \to \ell^+ + \nu + \mathrm{X}.$$



Here, our focus will be at $|\eta^{\ell^{\pm}}| \gg 0$.

Leading-order considerations

- In leading-order and narrow-width approximation ($\Gamma_{\rm W} \ll M_{\rm W}$)

$$\frac{d^2\sigma^{\ell^\pm}(s)}{dydp_{\rm T}} \approx \frac{\pi^2}{24s}\left(\frac{\alpha_{\rm em}}{\sin^2\theta_{\rm W}}\right)^2 \frac{1}{M_{\rm W}\Gamma_{\rm W}} \frac{p_T}{\sqrt{1-4p_T^2/M_{\rm W}^2}} \sum_{i,j} |V_{ij}|^2\, \delta_{e_{q_i}+e_{\overline{q}_j},\pm 1}$$

$$\left\{ \left[1 \mp \sqrt{1-4p_T^2/M_{\rm W}^2}\right]^2 q_i^{\rm H_1}(\mathbf{x_1^+})\overline{q}_j^{\rm H_2}(\mathbf{x_2^+}) + \left[1 \pm \sqrt{1-4p_T^2/M_{\rm W}^2}\right]^2 q_i^{\rm H_1}(\mathbf{x_1^-})\overline{q}_j^{\rm H_2}(\mathbf{x_2^-}) + \right.$$

$$\left. \left[1 \pm \sqrt{1-4p_T^2/M_{\rm W}^2}\right]^2 \overline{q}_j^{\rm H_1}(\mathbf{x_1^+})q_i^{\rm H_2}(\mathbf{x_2^+}) + \left[1 \mp \sqrt{1-4p_T^2/M_{\rm W}^2}\right]^2 \overline{q}_j^{\rm H_1}(\mathbf{x_1^-})q_i^{\rm H_2}(\mathbf{x_2^-}) \right\},$$

where the momentum arguments of the PDFs are

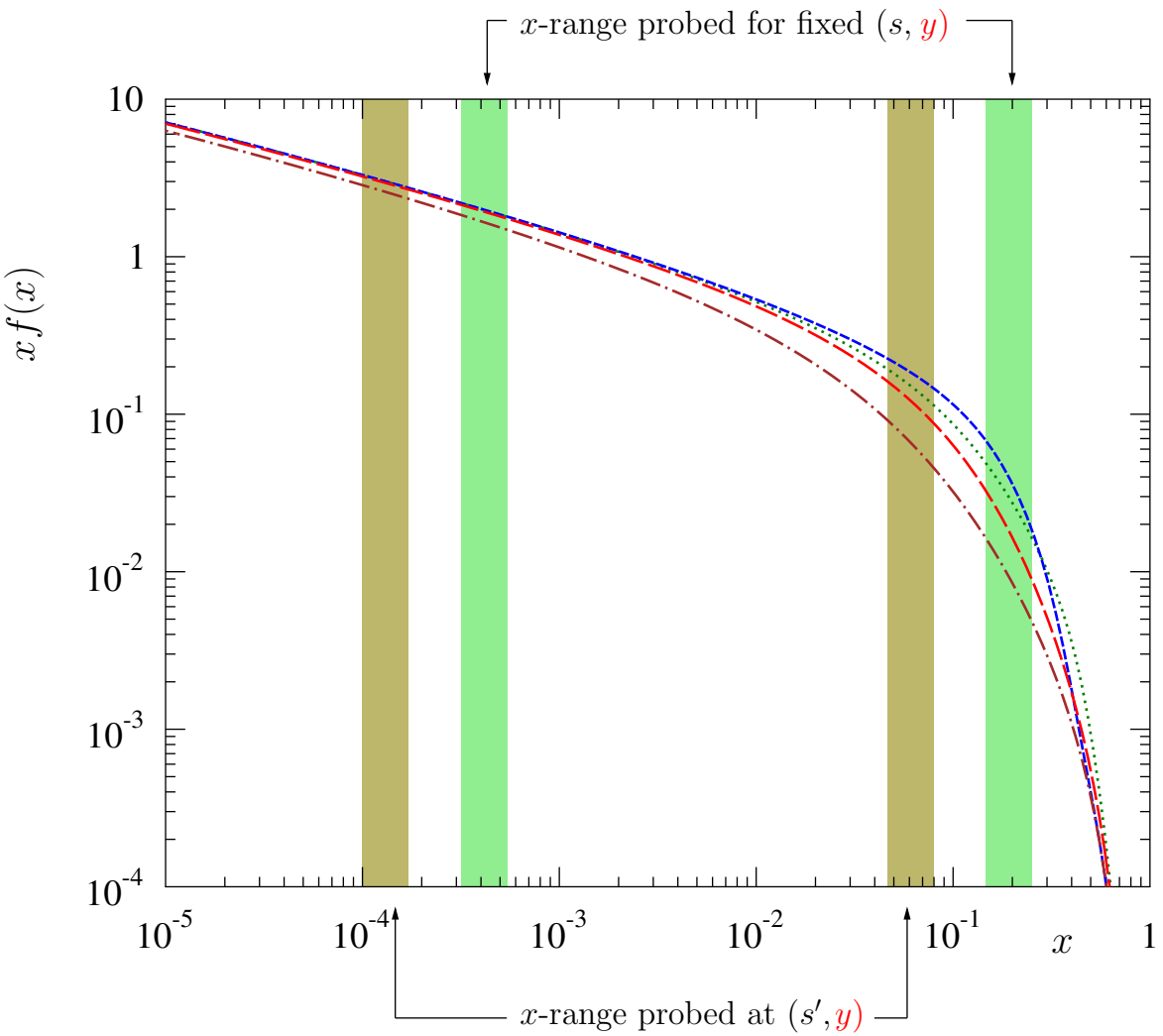
$$x_1^\pm \equiv \frac{M_{\rm W}^2 e^y}{2p_T\sqrt{s}}\left[1 \mp \sqrt{1-4p_T^2/M_{\rm W}^2}\right], \qquad x_2^\pm \equiv \frac{M_{\rm W}^2 e^{-y}}{2p_T\sqrt{s}}\left[1 \pm \sqrt{1-4p_T^2/M_{\rm W}^2}\right]$$

- Define a scaling variable ξ_1,

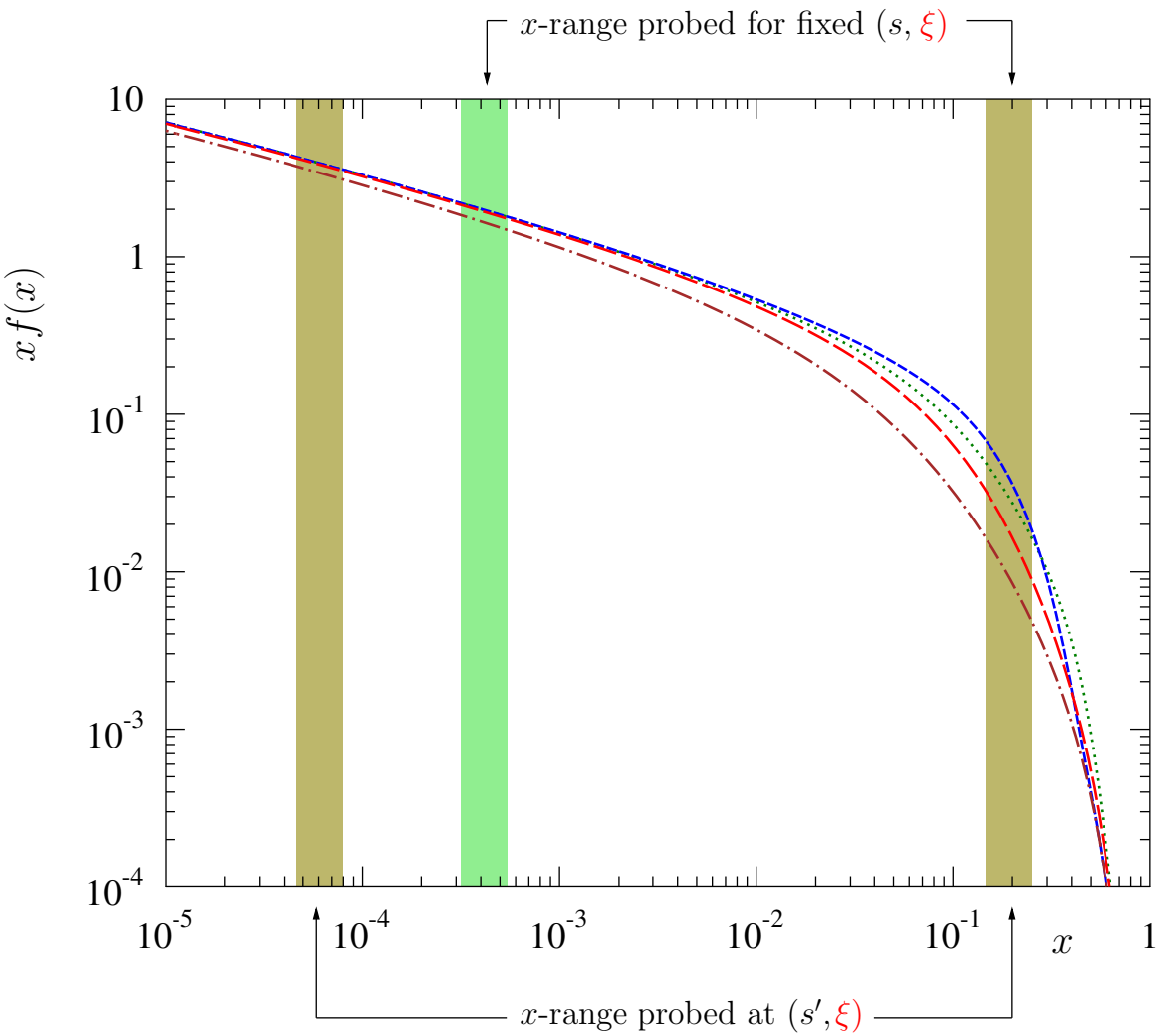
$$\xi_1 \equiv \frac{M_{\rm W}}{\sqrt{s}} e^y \implies x_1^\pm \to \frac{M_{\rm W}}{2p_T}\xi_1 \left[1 \mp \sqrt{1-4p_T^2/M_{\rm W}^2}\right]$$

$\implies$ Cross-sections at fixed ξ_1 are sensitive to PDFs of H_1 at particular values of x independently of $\sqrt{s}$.

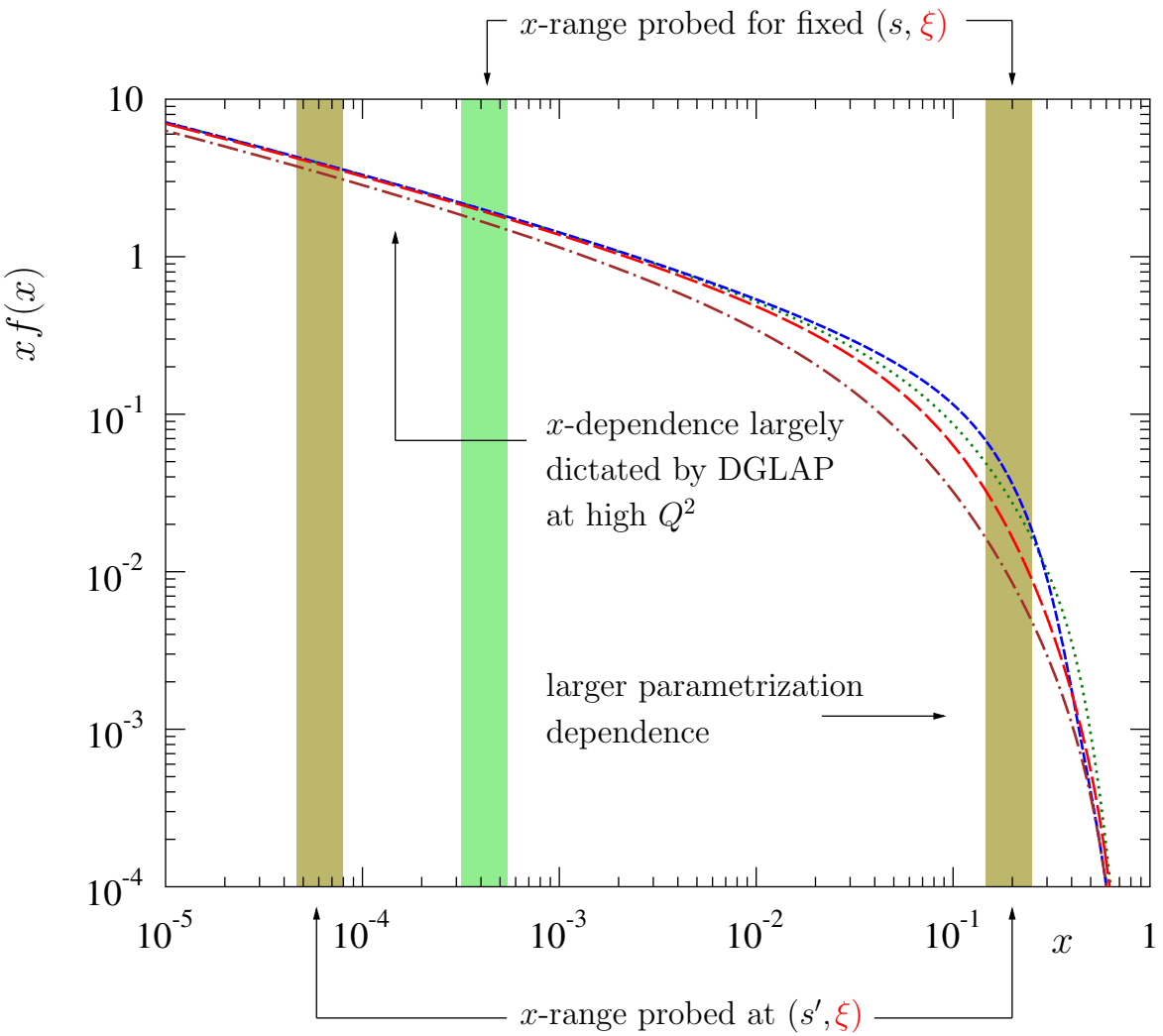
Fixed $y \gg 0$


x-range probed for fixed (s, y)
$x\,f(x)$
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
x
1
x-range probed at (s', y)

Fixed ξ ($y \gg 0$)



Fixed ξ ($y \gg 0$)



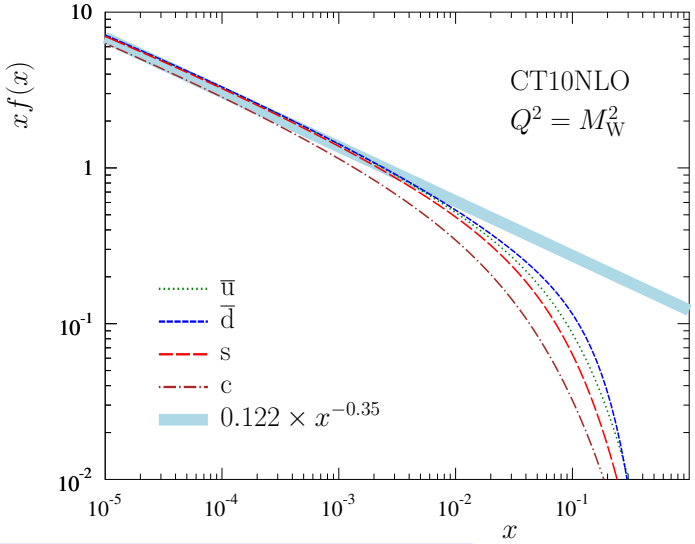
Leading-order considerations

- Approximating the small-x PDFs by a power law

$$x\overline{q}_i(x, Q^2) \approx xq_i(x, Q^2) \approx N_i \; x^{-\beta(Q^2)},$$

$$x \ll 1, \quad \beta(Q^2) > 0,$$

$[\beta \equiv \beta(Q^2 = M_{\rm W}^2) \approx 0.35]$ it follows that



$$\frac{d\sigma^{\ell^\pm}(\sqrt{s},\xi_1)}{d\xi_1} \approx \left(\sqrt{s}\right)^{2\beta} \times F^\pm(\xi_1, \mathrm{H}_1, \mathrm{H}_2), \quad y \gg 0,$$

where $F^\pm(\xi, \mathrm{H}_1, \mathrm{H}_2)$ is a function that does not depend explicitly on $\sqrt{s}$ or y.

$\Longrightarrow$ A simple approximate prediction for the $\sqrt{s}$ dependence of xsecs at $y \gg 0$.

Leading-order considerations

- For the W charge asymmetry, the $\sqrt{s}$ dependence cancels:

$$\mathcal{A}(\xi_1, \sqrt{s}, H_1, H_2) = \frac{d\sigma^{\ell^+}/d\xi_1 - d\sigma^{\ell^-}/d\xi_1}{d\sigma^{\ell^+}/d\xi_1 + d\sigma^{\ell^-}/d\xi_1} \approx \frac{F^+(\xi_1,\mathrm{H}_1,\mathrm{H}_2) - F^-(\xi_1,\mathrm{H}_1,\mathrm{H}_2)}{F^+(\xi_1,\mathrm{H}_1,\mathrm{H}_2) + F^-(\xi_1,\mathrm{H}_1,\mathrm{H}_2)}$$

even if the β was x dependent (as it of course is).

- Making a further approximation that the behaviour of small-x PDFs is flavor independent

$$x\overline{q}_i(x, Q^2) \approx xq_i(x, Q^2) \approx N\, x^{-\beta(Q^2)}, \quad x \ll 1, \quad \beta(Q^2) > 0,$$

it follows that

$$\mathcal{A}(\xi_1, \sqrt{s}, \mathrm{H}_1, \mathrm{H}_2) \approx F(\xi_1, \mathrm{H}_1), \qquad y^{\ell^\pm} \gg 0$$

- The W charge asymmetry depends effectively only on ξ_1 and the species (proton, nucleus) probed at large x.

$\Longrightarrow$ Can directly compare W charge asymmetry e.g. p-p and p-Pb at $y^{\ell^\pm} \gg 0$.

Leading-order considerations

- We can plot the data directly as a function of $\xi_1 = (M_{\mathrm{W}}/\sqrt{s})e^y$ or alternatively as a function of shifted rapidity

$$y_{\mathrm{ref}} \equiv y + \log\left(\frac{\sqrt{s_{\mathrm{ref}}}}{\sqrt{s}}\right),$$

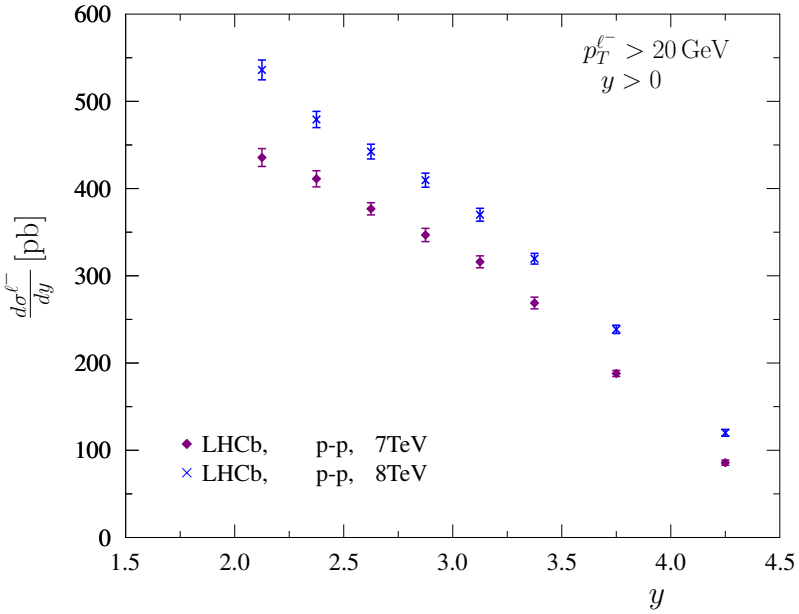
- For example, if we take $\sqrt{s_{\mathrm{ref}}} = 7\,\mathrm{TeV}$ the rapidity at 8TeV is shifted by

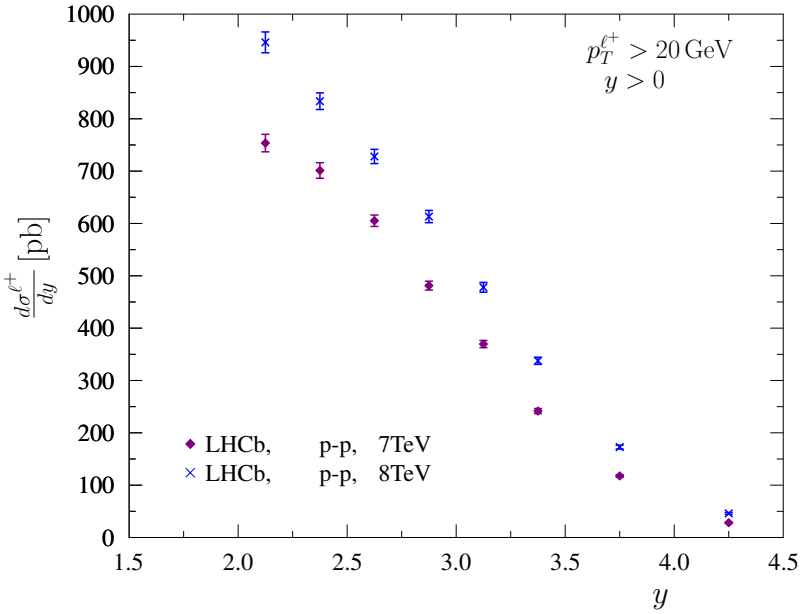
$$y \to y + \log(7\mathrm{TeV}/8\mathrm{TeV}) \approx y - 0.134$$

- Similar rapidity shift recently discussed also in the context of heavy-flavor production [Gauld, arXiv:1703.03636].

Absolute spectra at LHCb: 7TeV vs. 8TeV

- The LHCb data as a function of usual rapidity

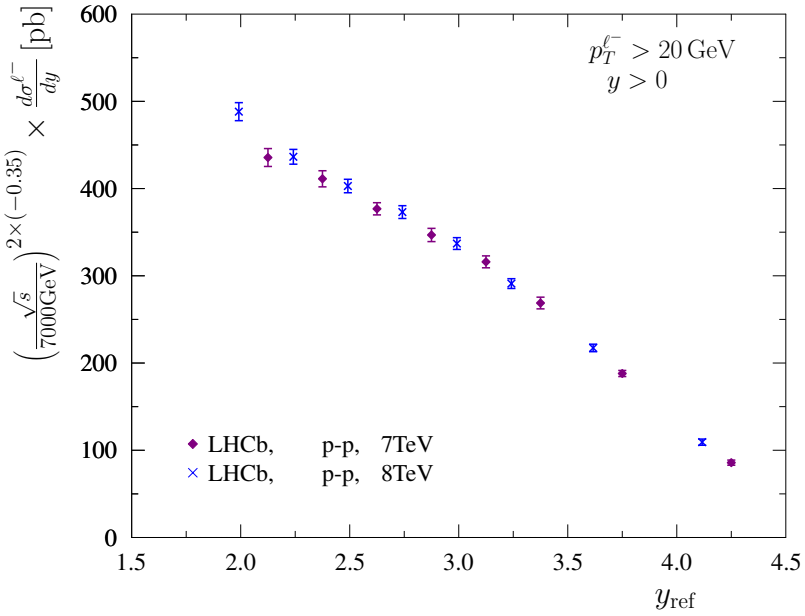


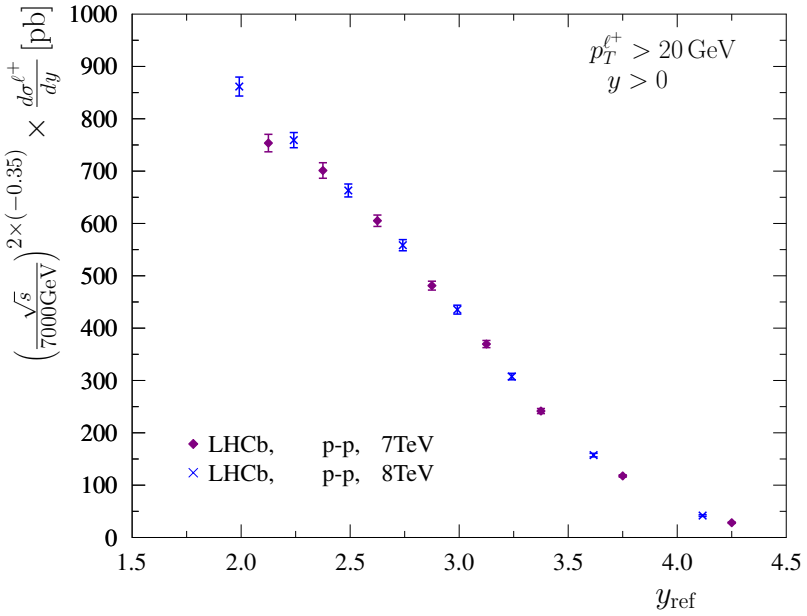


$$\frac{d\sigma^{\ell^\pm}(\sqrt{s},\xi_1)}{d\xi} \approx \left(\sqrt{s}\right)^{2\beta} \times F^{\pm}(\xi_1, \mathrm{H}_1, \mathrm{H}_2), \quad y \gg 0,$$

Absolute spectra at LHCb: 7TeV vs. 8TeV

- Shift the 8TeV data by $y \to y - \log(8\mathrm{TeV}/7\mathrm{TeV})$ and multiply by $(8\mathrm{TeV}/7\mathrm{TeV})^{-2\beta}$, $\beta = 0.35$.

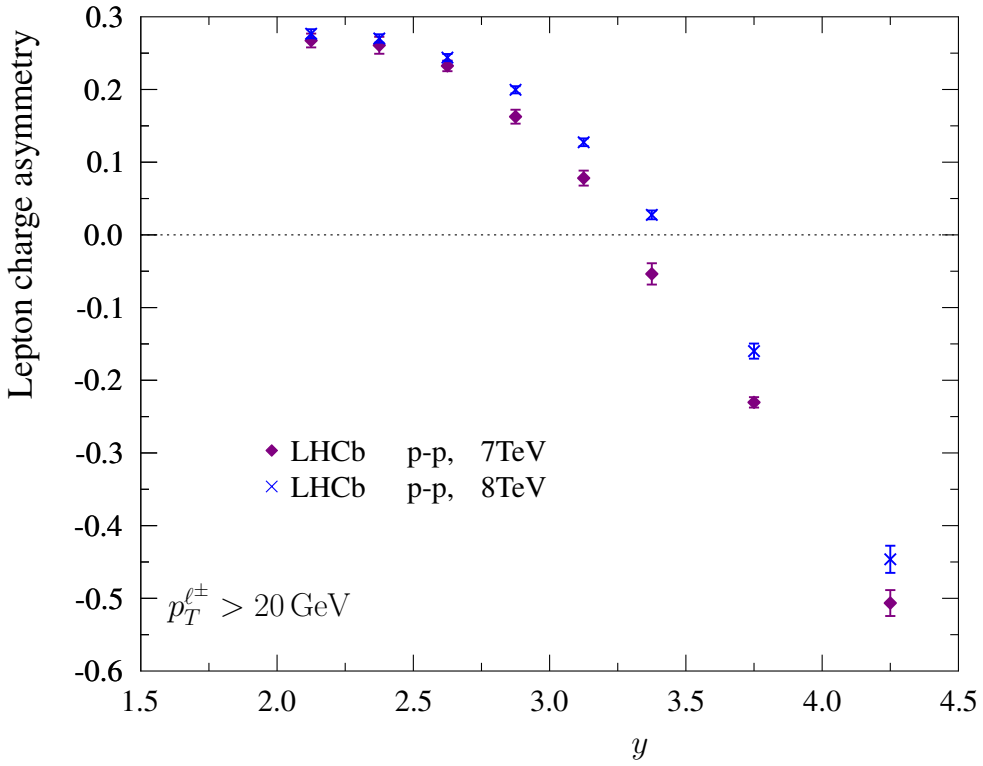




$$\frac{d\sigma^{\ell^\pm}(\sqrt{s},\xi_1)}{d\xi} \approx \left(\sqrt{s}\right)^{2\beta} \times F^{\pm}(\xi_1, \mathrm{H}_1, \mathrm{H}_2), \quad y \gg 0,$$

Charge asymmetry at LHCb: 7TeV vs. 8TeV

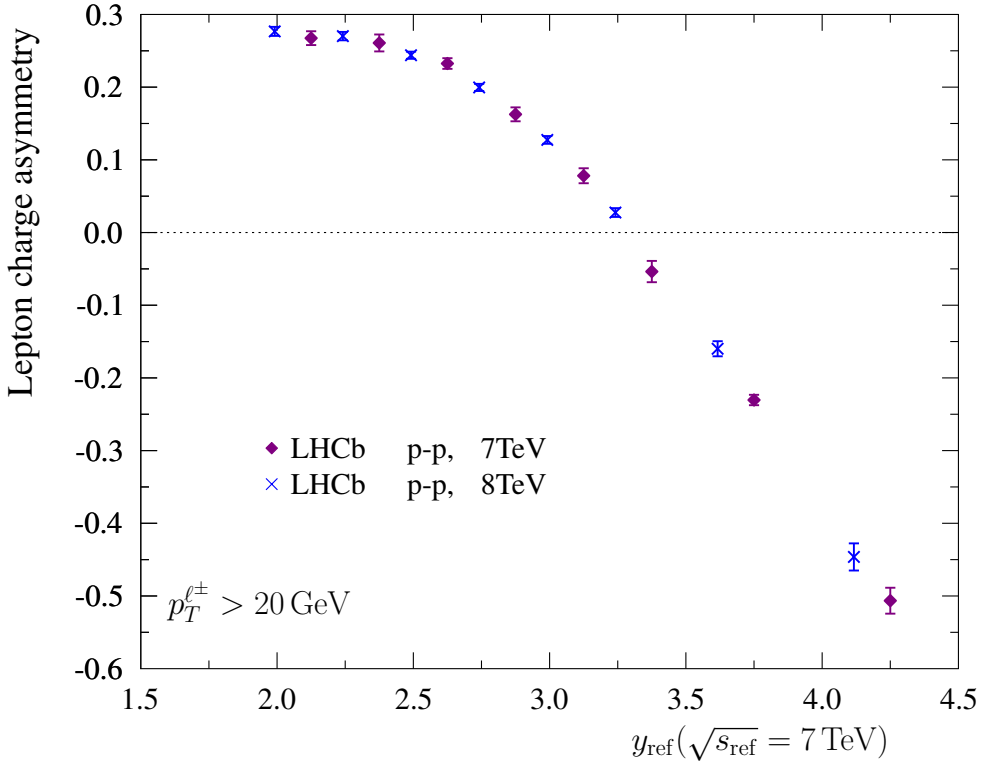
- The LHCb data as a function of usual rapidity



$$\mathcal{A}(\xi_1, \sqrt{s}, H_1, H_2) \approx \frac{F^+(\xi_1,\mathrm{H}_1,\mathrm{H}_2) - F^-(\xi_1,\mathrm{H}_1,\mathrm{H}_2)}{F^+(\xi_1,\mathrm{H}_1,\mathrm{H}_2) + F^-(\xi_1,\mathrm{H}_1,\mathrm{H}_2)}$$

Charge asymmetry at LHCb: 7TeV vs. 8TeV

- Shift the 8TeV data by $y \to y - \log(8\mathrm{TeV}/7\mathrm{TeV})$

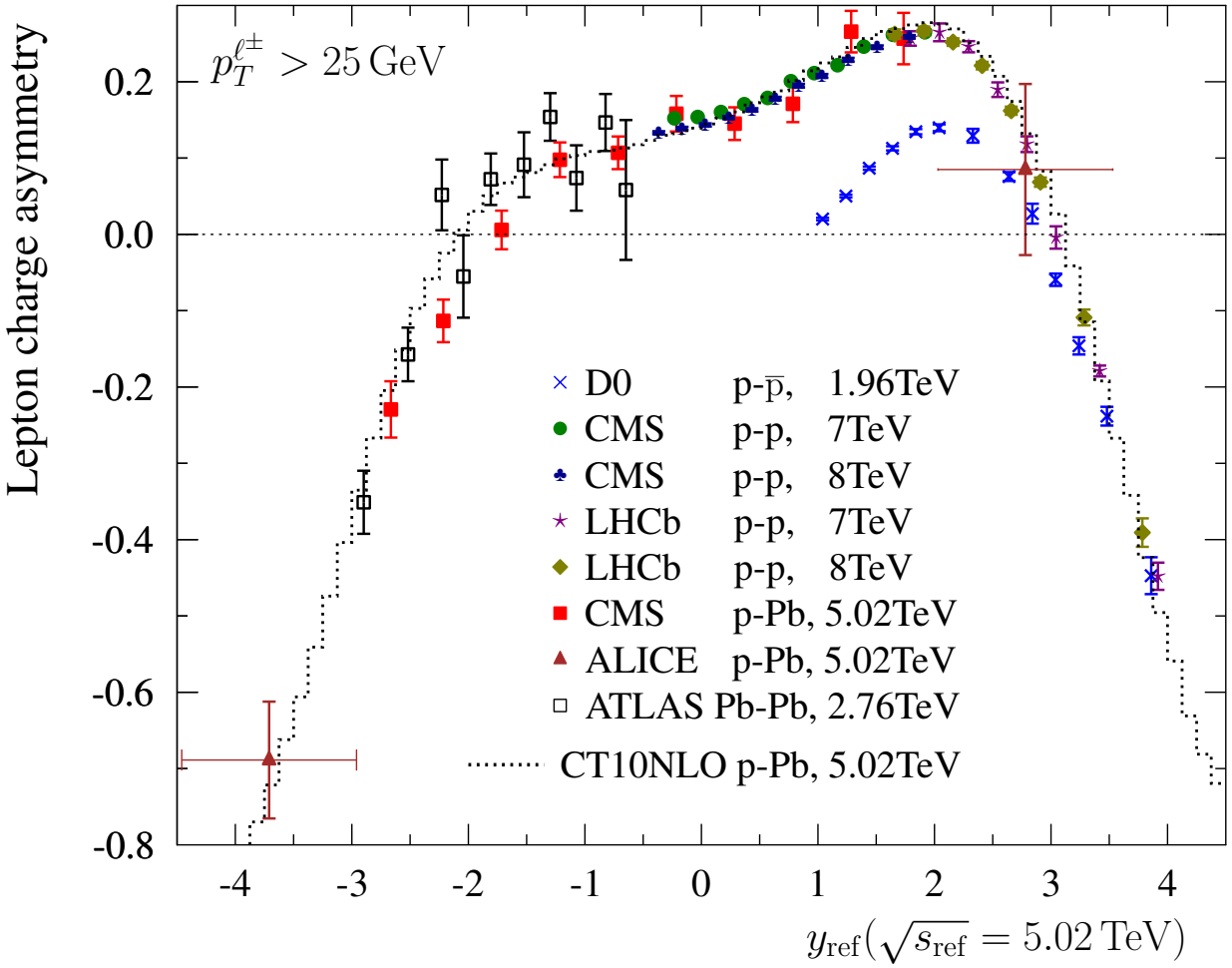


$$\mathcal{A}(\xi_1, \sqrt{s}, H_1, H_2) \approx \frac{F^+(\xi_1,\mathrm{H}_1,\mathrm{H}_2) - F^-(\xi_1,\mathrm{H}_1,\mathrm{H}_2)}{F^+(\xi_1,\mathrm{H}_1,\mathrm{H}_2) + F^-(\xi_1,\mathrm{H}_1,\mathrm{H}_2)}$$

Charge asymmetry, world data

- Charge asymmetry across different collision systems

$$y \gg 0 \quad : \quad CA(\mathrm{p\bar{p}}) \approx CA(\mathrm{pp}) \approx C(\mathrm{pPb}) \quad \text{(probe p at large } x\text{)}$$
$$y \ll 0 \quad : \quad CA(\mathrm{pPb}) \approx C(\mathrm{PbPb}) \quad \text{(probe Pb at large } x\text{)}$$

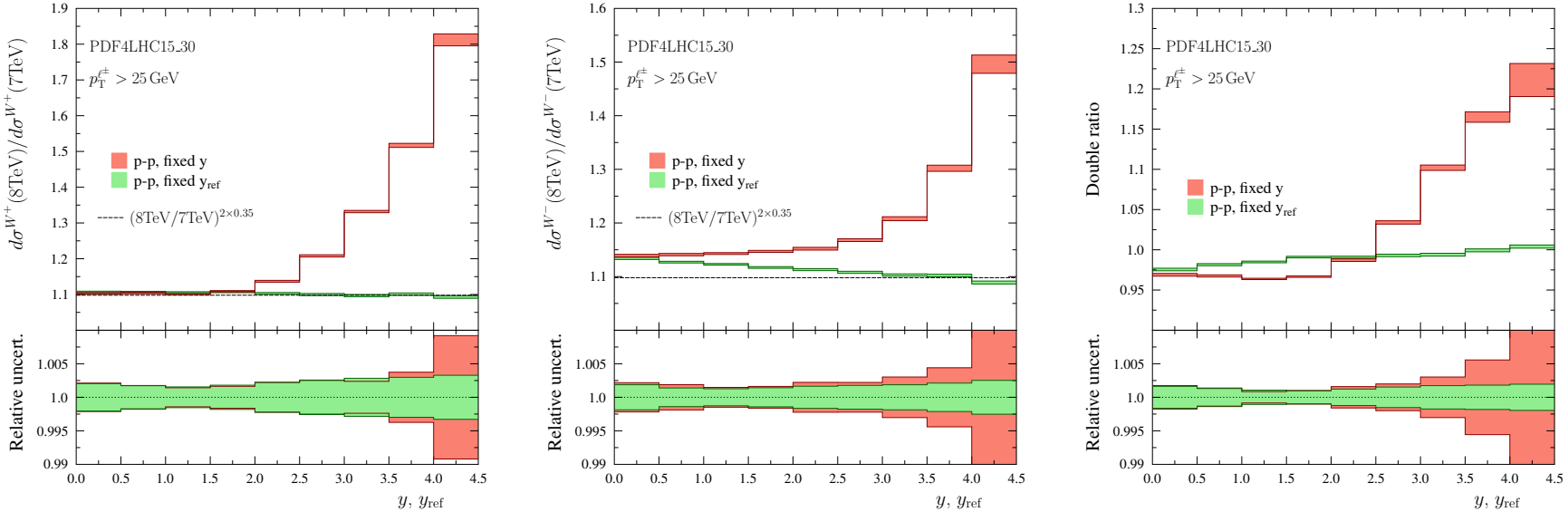


Cross-section ratios (fixed y vs. fixed $y_{\rm ref}$): 8TeV/7TeV

- Cross-section ratios between different c.m. energies

$$R^{+}_{8/7} = \frac{d\sigma^{\rm W^+}(\sqrt{s} = 8\,{\rm TeV})}{d\sigma^{\rm W^+}(\sqrt{s} = 7\,{\rm TeV})}, R^{-}_{8/7} = \frac{d\sigma^{\rm W^-}(\sqrt{s} = 8\,{\rm TeV})}{d\sigma^{\rm W^-}(\sqrt{s} = 7\,{\rm TeV})},$$

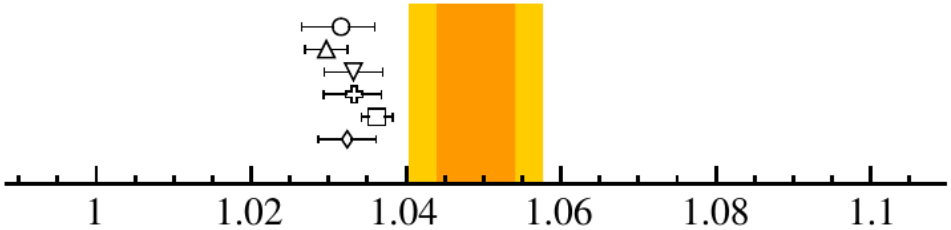
and the double ratio $\mathcal{D}_{8/7} = (R^{+}_{8/7})/(R^{-}_{8/7})$:



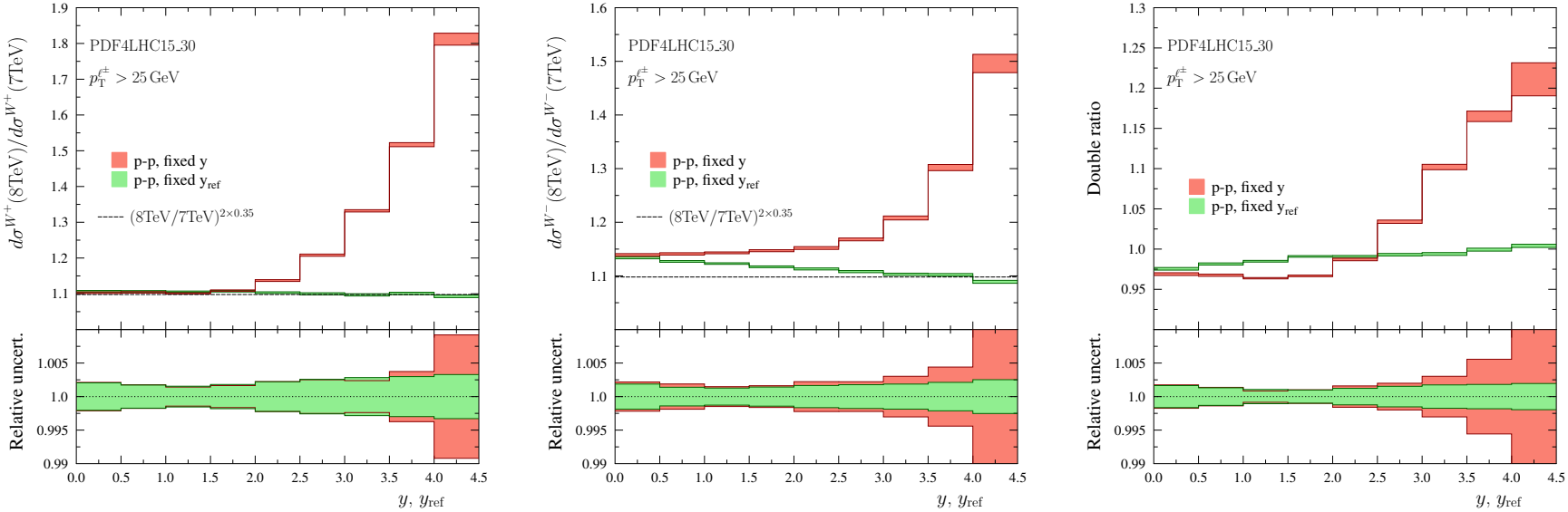
$\Longrightarrow$ The PDF uncertainties partly suppressed when the ratios are formed at fixed $y_{\rm ref}$.

Cross-section ratios (fixed y vs. fixed y_{ref}): 8TeV/7TeV

LHCb plot [JHEP 1601 (2016) 155], data vs. PDF predictions



$$\frac{\sigma^{8\mathrm{TeV}}_{W^+\to\mu^+\nu}}{\sigma^{7\mathrm{TeV}}_{W^+\to\mu^+\nu}} \quad \frac{\sigma^{7\mathrm{TeV}}_{W^-\to\mu^-\bar{\nu}}}{\sigma^{8\mathrm{TeV}}_{W^-\to\mu^-\bar{\nu}}}$$



$\Longrightarrow$ Binning in y_{ref} could help in understanding the deviations observed by LHCb (PDF related or not?)

Summary

• The $\sqrt{s}$ dependence of inclusive W cross sections at the LHC are well approximated by a power law $[\xi_1 = (M_{\mathrm{W}}/\sqrt{s})e^y]$

$$\frac{d\sigma^{\ell^\pm}(\sqrt{s},\xi_1)}{d\xi} \approx \left(\sqrt{s}\right)^{2\beta} \times F^\pm(\xi_1, \mathrm{H}_1, \mathrm{H}_2), \quad y \gg 0,$$

where $\beta \approx 0.35$ reflects the small-x slope of the quark PDFs.

• The W charge asymmetry is approximately independent $\sqrt{s}$ and the hadron probed at small x

$$\mathcal{A}(\xi_1, \sqrt{s}, \mathrm{H}_1, \mathrm{H}_2) \approx F(\xi_1, \mathrm{H}_1), \qquad y^{\ell^\pm} \gg 0$$

$\Longrightarrow$ Simple ways to approximate the energy evolution of W xsecs and compare charge asymmetry across various systems ($\mathrm{p\overline{p}}$, pp, pPb, PbPb)

• In xsec ratios at fixed ξ_1 (or equivalently $y_{\mathrm{ref}} \equiv y + \log \frac{\sqrt{s_{\mathrm{ref}}}}{\sqrt{s}}$) partial cancellation of large-x PDF uncertainties towards $y \gg 0$.

$\Longrightarrow$ Gain a better sensitivity for physics