Advancing precision predictions for the LHC

Sven-Olaf Moch

Universität Hamburg

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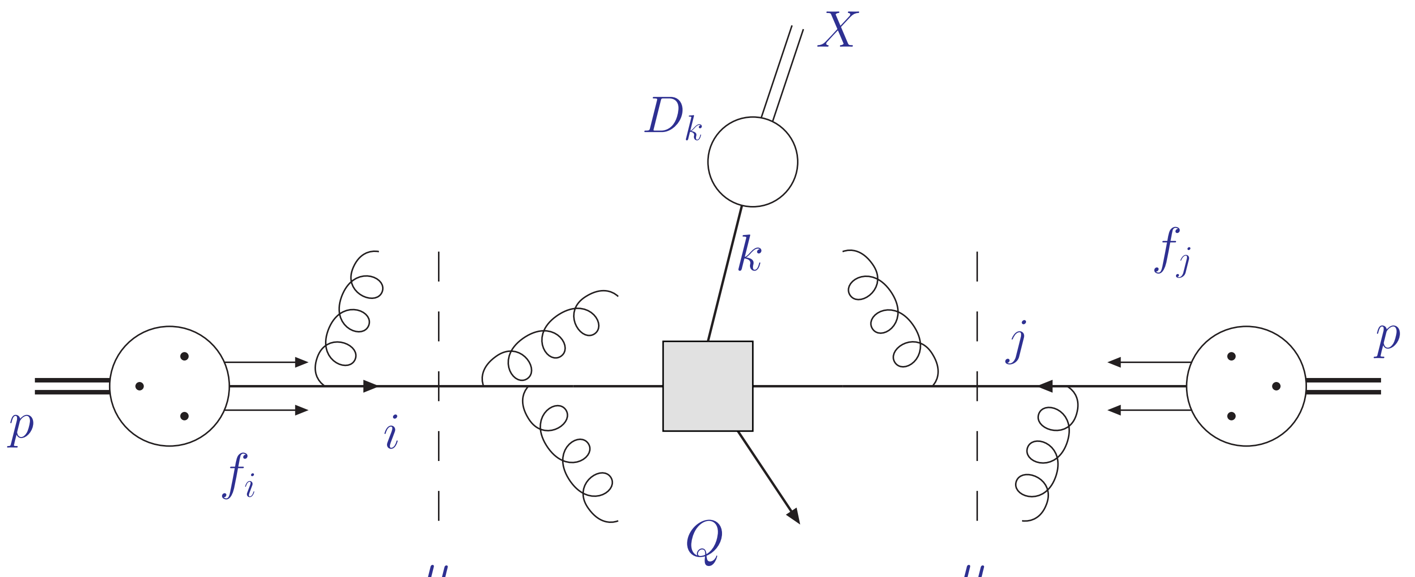
Plan

- $W\pm$- and Z-boson production at the LHC
- Hadro-production of jets
- Heavy-quark pair production (b- and c-quark production at the LHC)

QCD factorization



$$\sigma_{pp\to X} = \sum_{ij} f_i(\mu^2) \otimes f_j(\mu^2) \otimes \hat{\sigma}_{ij\to X}\left(\alpha_s(\mu^2), Q^2, \mu^2, m_X^2\right)$$

- Factorization at scale μ
  - separation of sensitivity to dynamics from long and short distances
- Hard parton cross section $\hat{\sigma}_{ij\to X}$ calculable in perturbation theory
  - cross section $\hat{\sigma}_{ij\to k}$ for parton types i, j and hadronic final state X
- Parton distribution functions f_i, strong coupling α_s, particle masses m_X
  - known from global fits to exp. data, lattice computations, ...

Parton luminosity

- Long distance dynamics due to proton structure

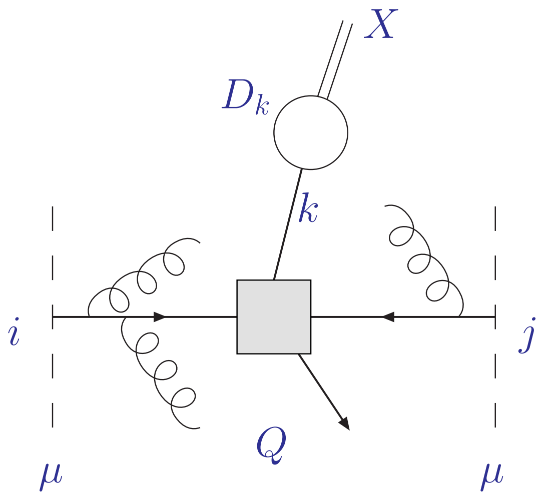
- Cross section depends on parton distributions f_i

$$\sigma_{pp \to X} = \sum_{ij} f_i(\mu^2) \otimes f_j(\mu^2) \otimes \Big[\ldots\Big]$$

- Parton distributions known from global fits to exp. data
  - available fits accurate to NNLO
  - information on proton structure depends on kinematic coverage

Hard scattering cross section

- Parton cross section $\hat{\sigma}_{ij\to k}$ calculable pertubatively in powers of α_s
  - known to NLO, NNLO, . . . ($\mathcal{O}(\text{few}\%)$ theory uncertainty)

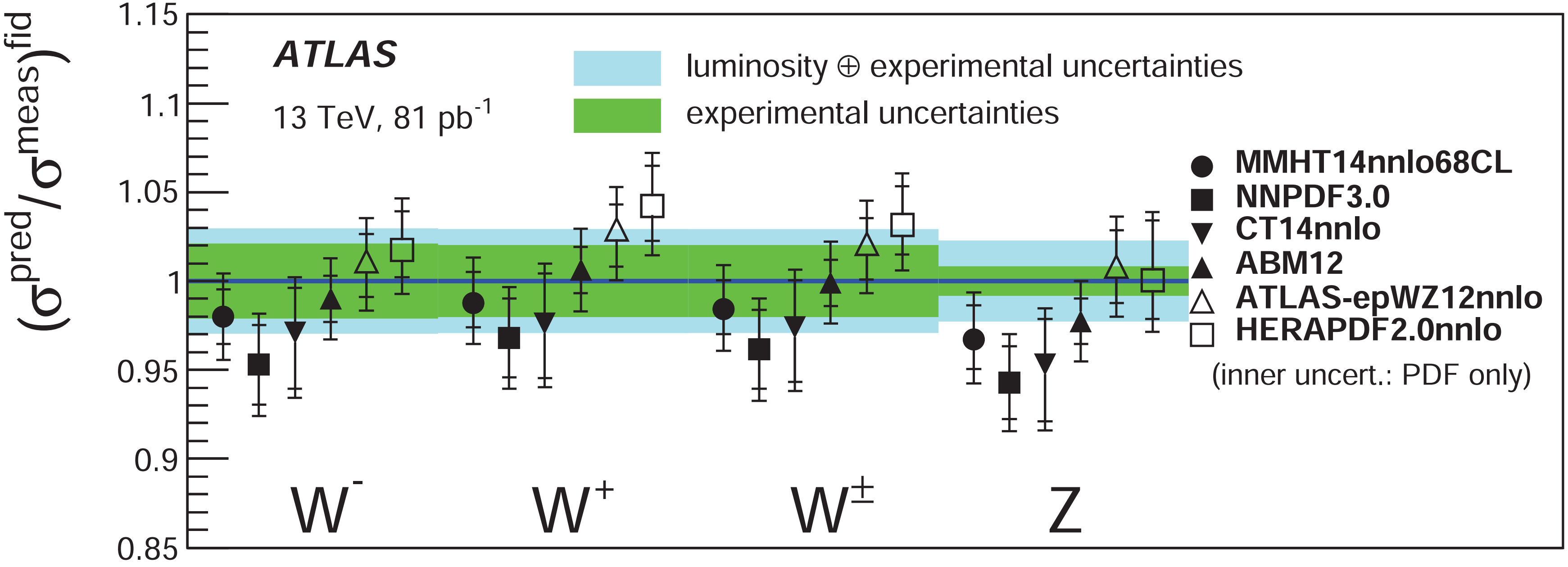


- Accuracy of perturbative predictions
  - LO (leading order) ($\mathcal{O}(50 - 100\%)$ unc.)
  - NLO (next-to-leading order) ($\mathcal{O}(10 - 30\%)$ unc.)
  - NNLO (next-to-next-to-leading order) ($\lesssim$ $\mathcal{O}(10\%)$ unc.)
  - N^3LO (next-to-next-to-next-to-leading order)
  - . . .

$W^{\pm}$- and Z-boson production at the LHC

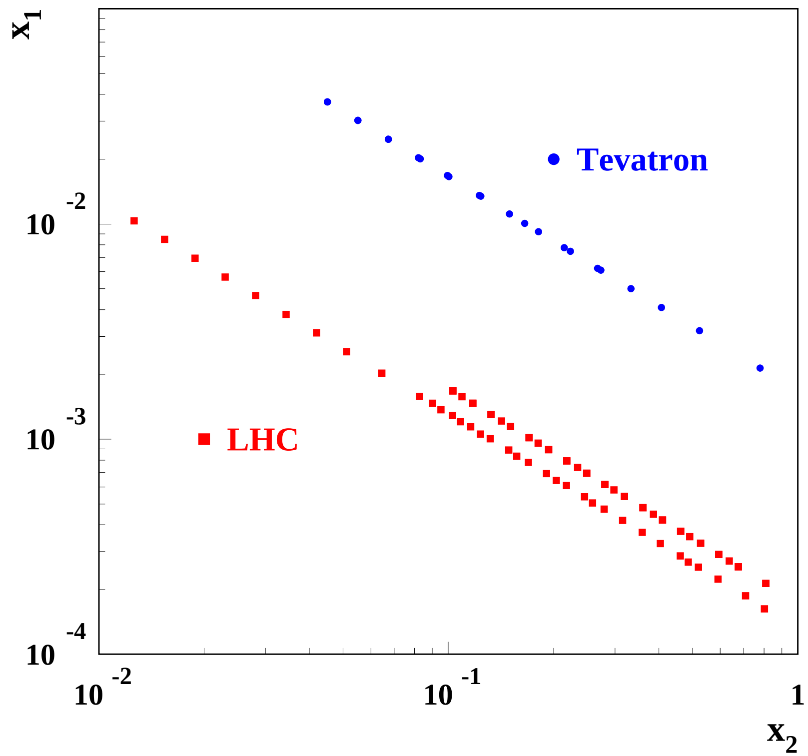
W- and Z-boson cross sections

- High precision data from LHC ATLAS, CMS, LHCb and Tevatron D0
  - differential distributions extend to forward region
  - sensitivity to light quark flavors at $x \simeq 10^{-4}$
  - statistically significant: $NDP = 172$ in ABMP16
- ATLAS measurement at $\sqrt{s} = 13$ TeV from arXiv:1603.09222



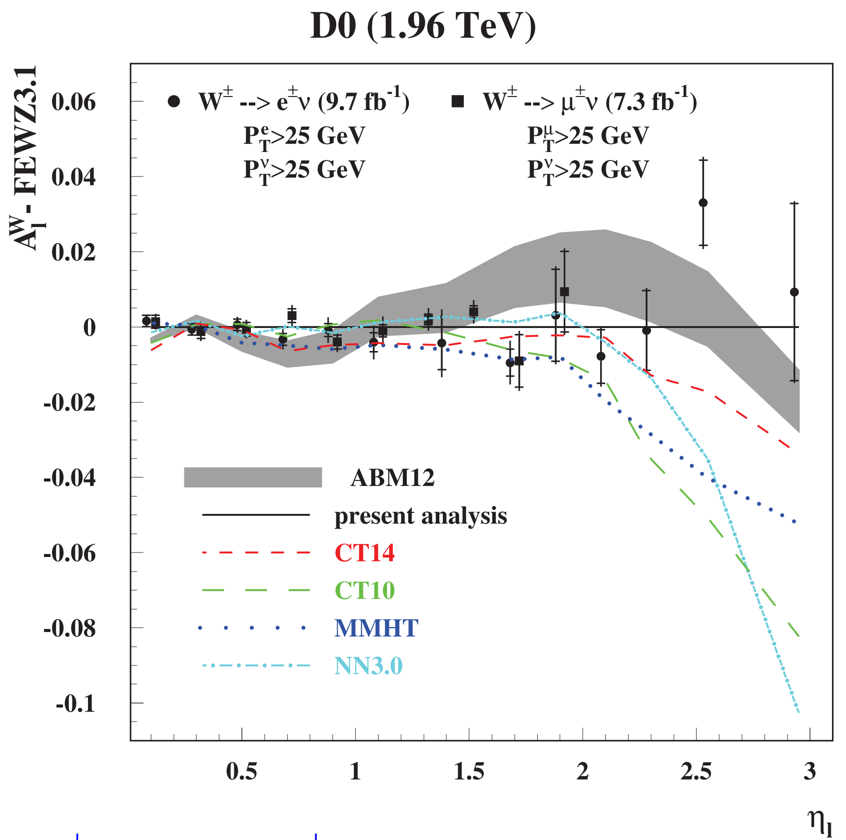
- Spread in predictions from different PDFs significantly larger than experimental precision

$W^{\pm}$- and Z-boson production



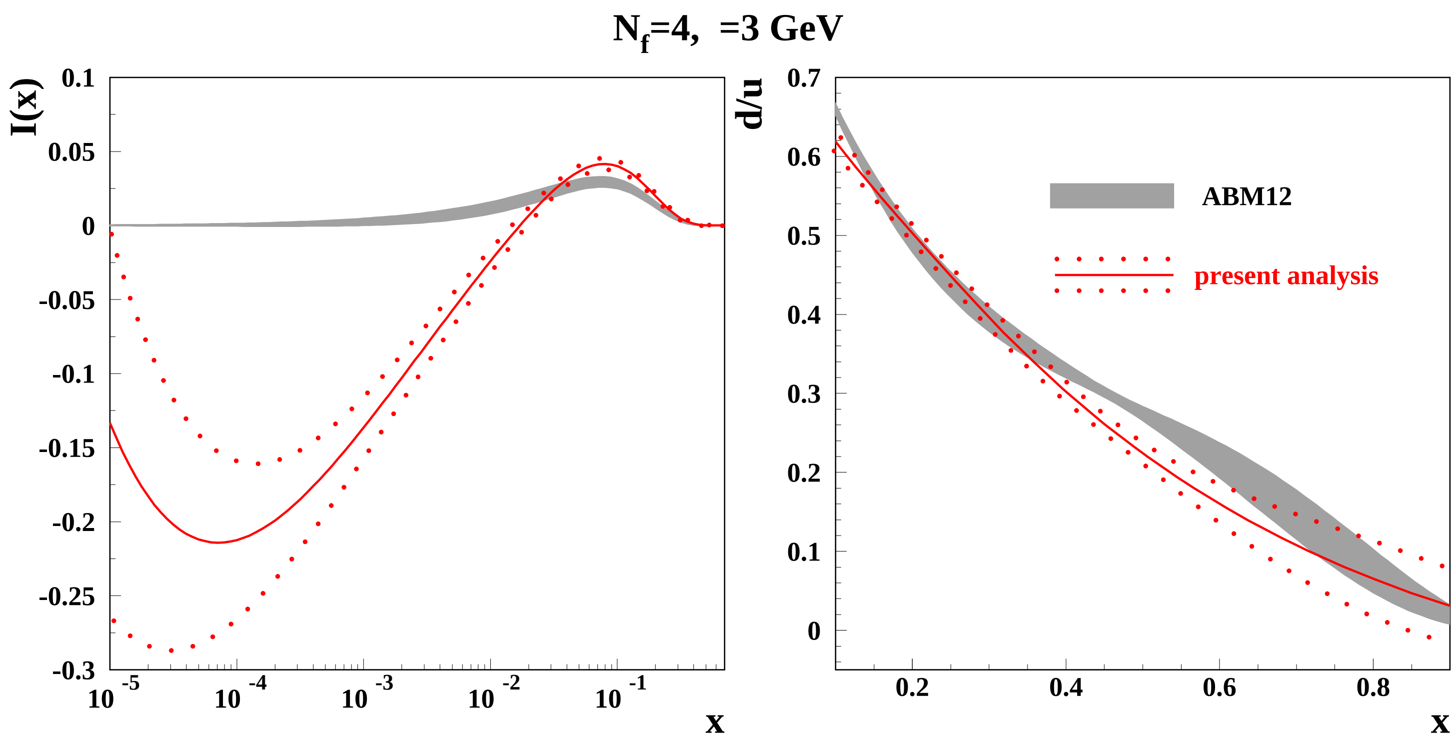
- High precision data from LHC ATLAS, CMS, LHCb and Tevatron D0
  - statistically significant $NDP = 172$
- Differential distributions extend to forward region
  - sensitivity to light quark flavors at $x \simeq 10^{-4}$
  - leading order kinematics with $\sigma(W^+) \simeq u(x_2)\bar{d}(x_1)$ and $\sigma(W^-) \simeq d(x_2)\bar{u}(x_1)$ and $\sigma(Z) \simeq Q_u^2 u(x_2)\bar{u}(x_1) + Q_d^2 d(x_2)\bar{d}(x_1)$
  - cf. DIS: $\sigma(\mathrm{DIS}) \simeq q_u^2 u(x) + q_d^2 d(x)$

Tevatron charged lepton asymmetry



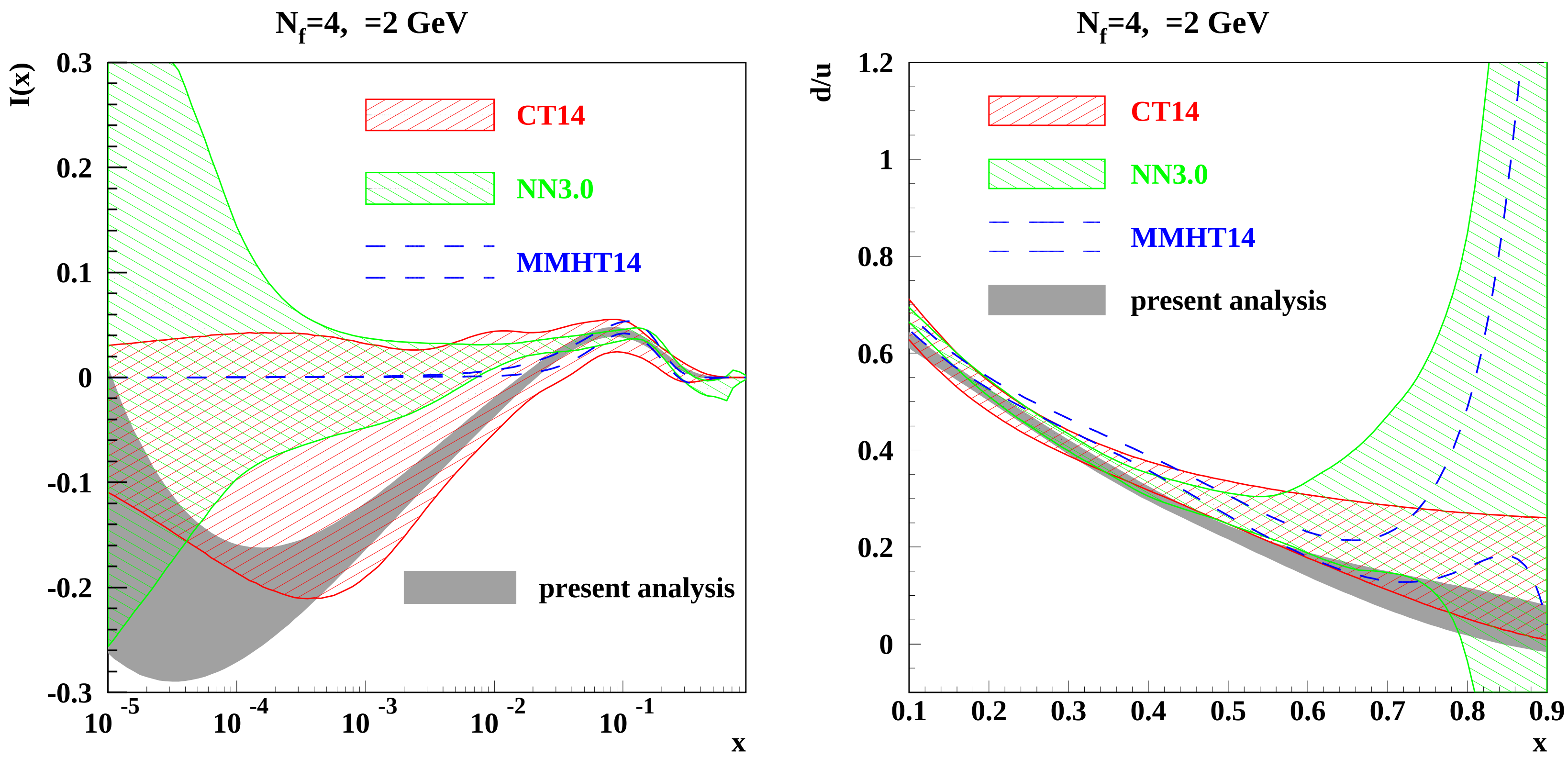
- D0 data for $p\bar{p} \to W^\pm + X \to l^\pm\nu$ (electrons and muons) at $\sqrt{s} = 1.96$ TeV
- Charged lepton asymmetry as function of pseudo-lepton rapidity η_l
- NNLO QCD predictions with FEWZ (version 3.1)
- Comparison with ABM12 (including combined PDF+α_s uncertainty), CT10, CT14, MMHT, and NN3.0

Light flavor PDFs



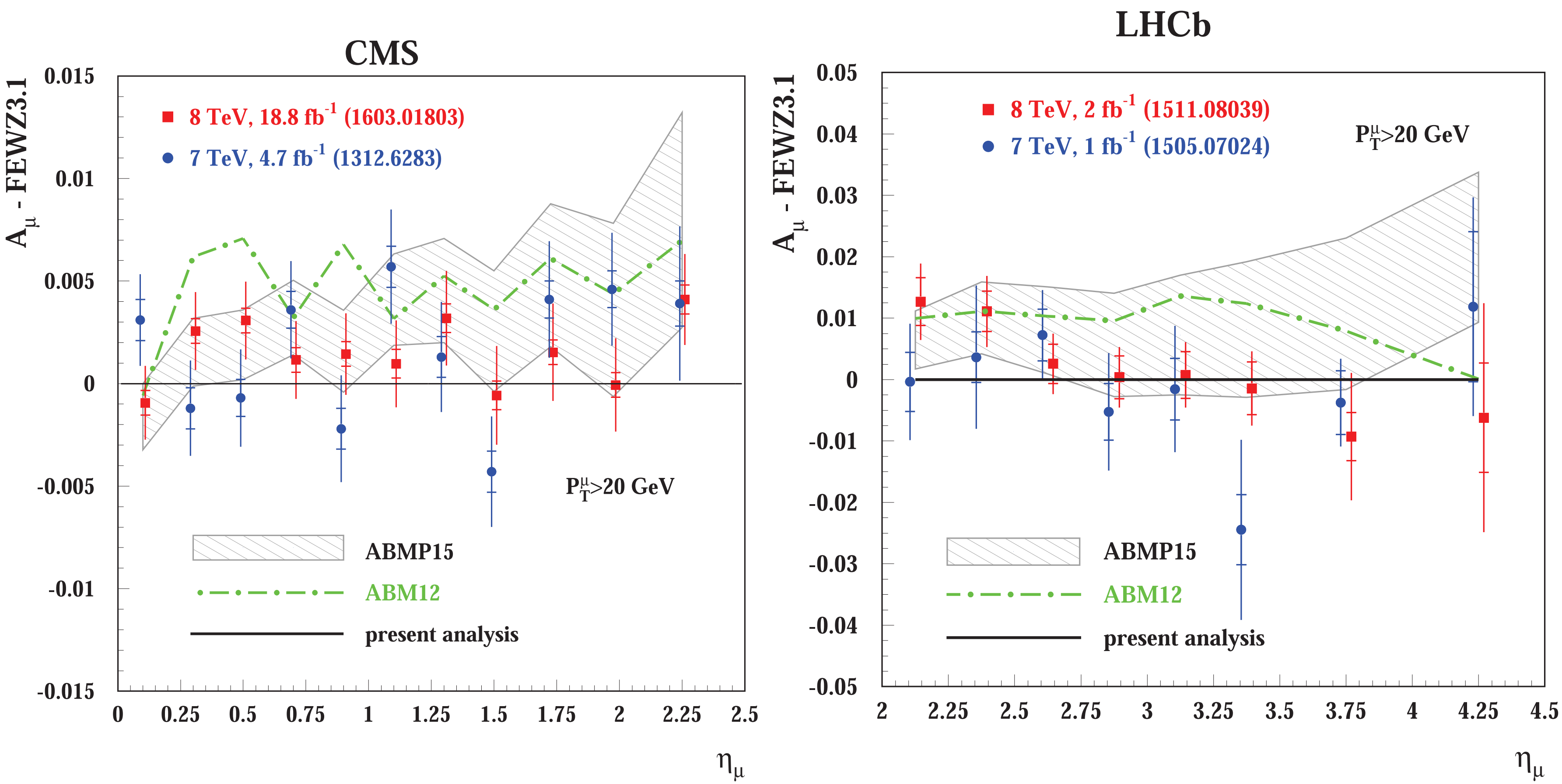
- Light flavor decomposition not well constrained in DIS data
  - ratio d/u at large x from fixed target Drell-Yan data E-605, E-866 at the price of modelling nuclear corrections
- Iso-spin asymmetry of sea $I(x) = \bar{d} - \bar{u}$
  - Regge theory arguments for small x predict $I(x) \simeq 0$
  - $I(x)$ at small x constrained by new Tevatron and LHC data
- Upshot: non-vanishing $I(x)$ at small $x \simeq 10^{-4}$

Comparision with other PDFs



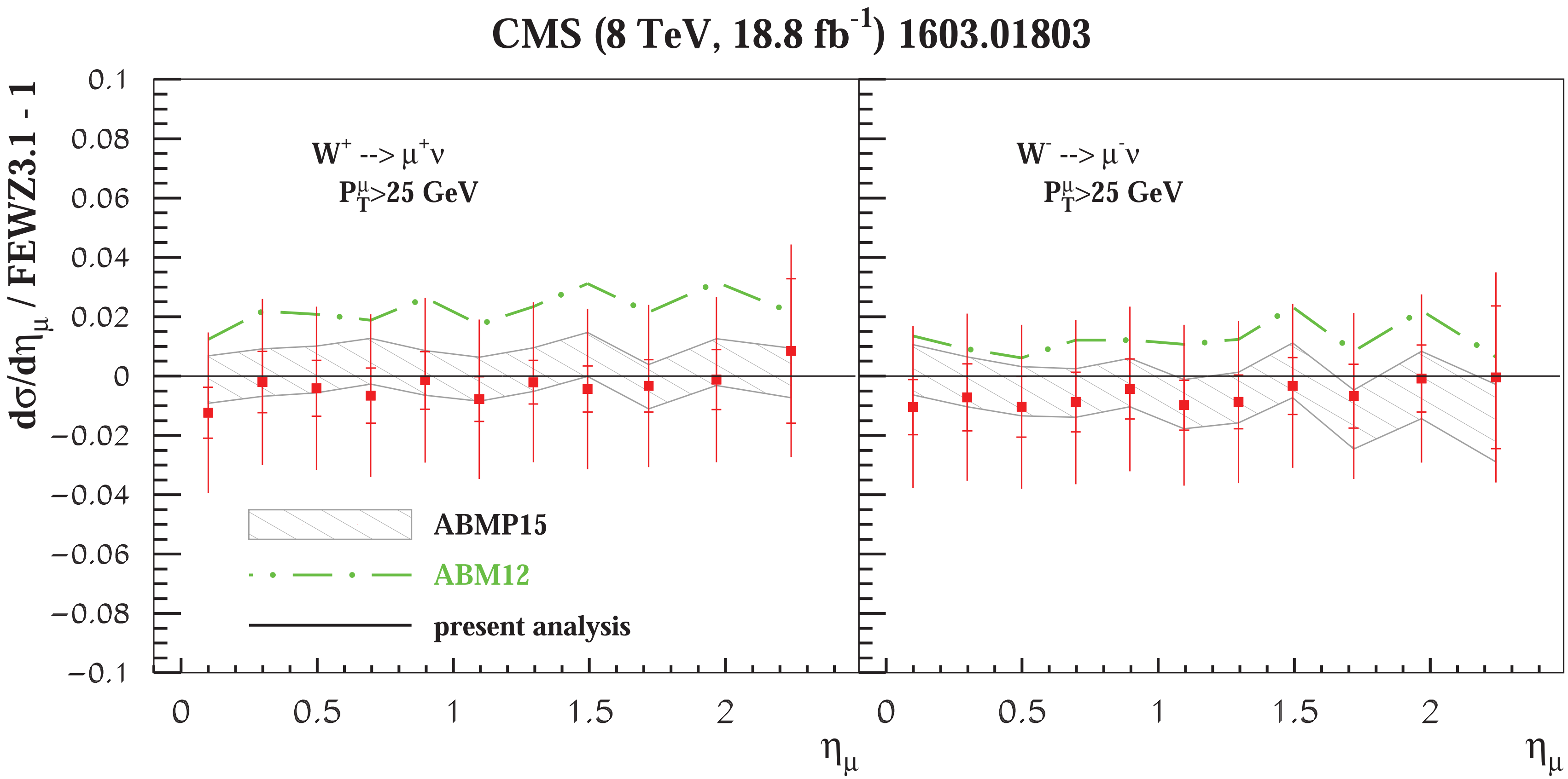
- Iso-spin asymmetry of sea $I(x)$ at small x and ratio d/u at large x with 1σ uncertainty band
- Comparison with CT14, MMHT14, NN3.0
  - CT14 finds non-vanishing $I(x)$ from fit to Tevatron charged lepton asymmetry (D0 data), but with large uncertainties

Muon charge asymmetry from LHC



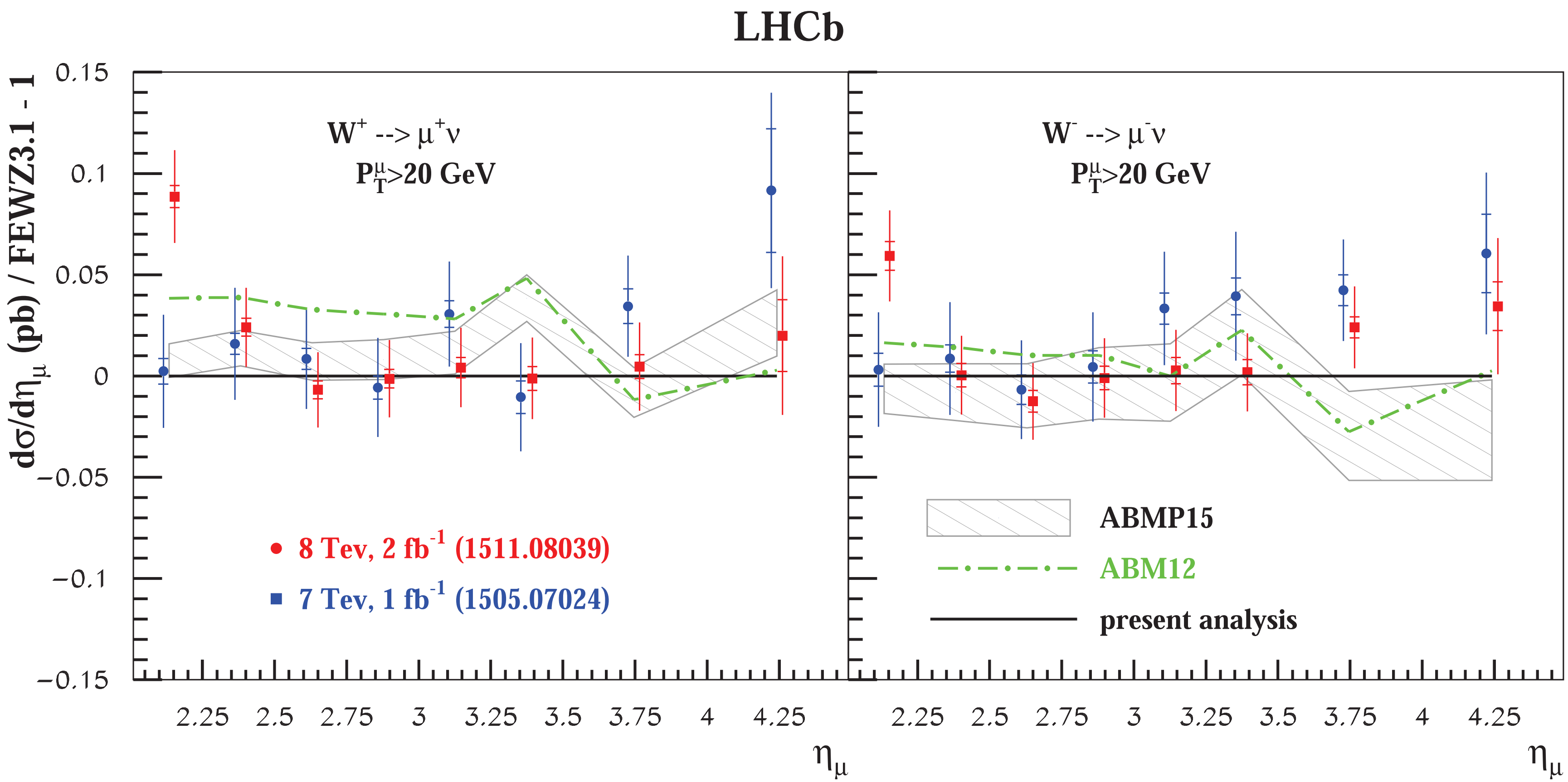
- CMS and LHCb data for $pp \to W^\pm + X \to \mu^\pm \nu + X$ at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV
  - comparison of ABM12, ABMP15 and ABMP16 fits
- Problematic data point at $\eta_\mu = 3.375$ for $\sqrt{s} = 7$ TeV in LHCb data are omitted in fit

$W^{\pm}$-boson production from LHC (I)



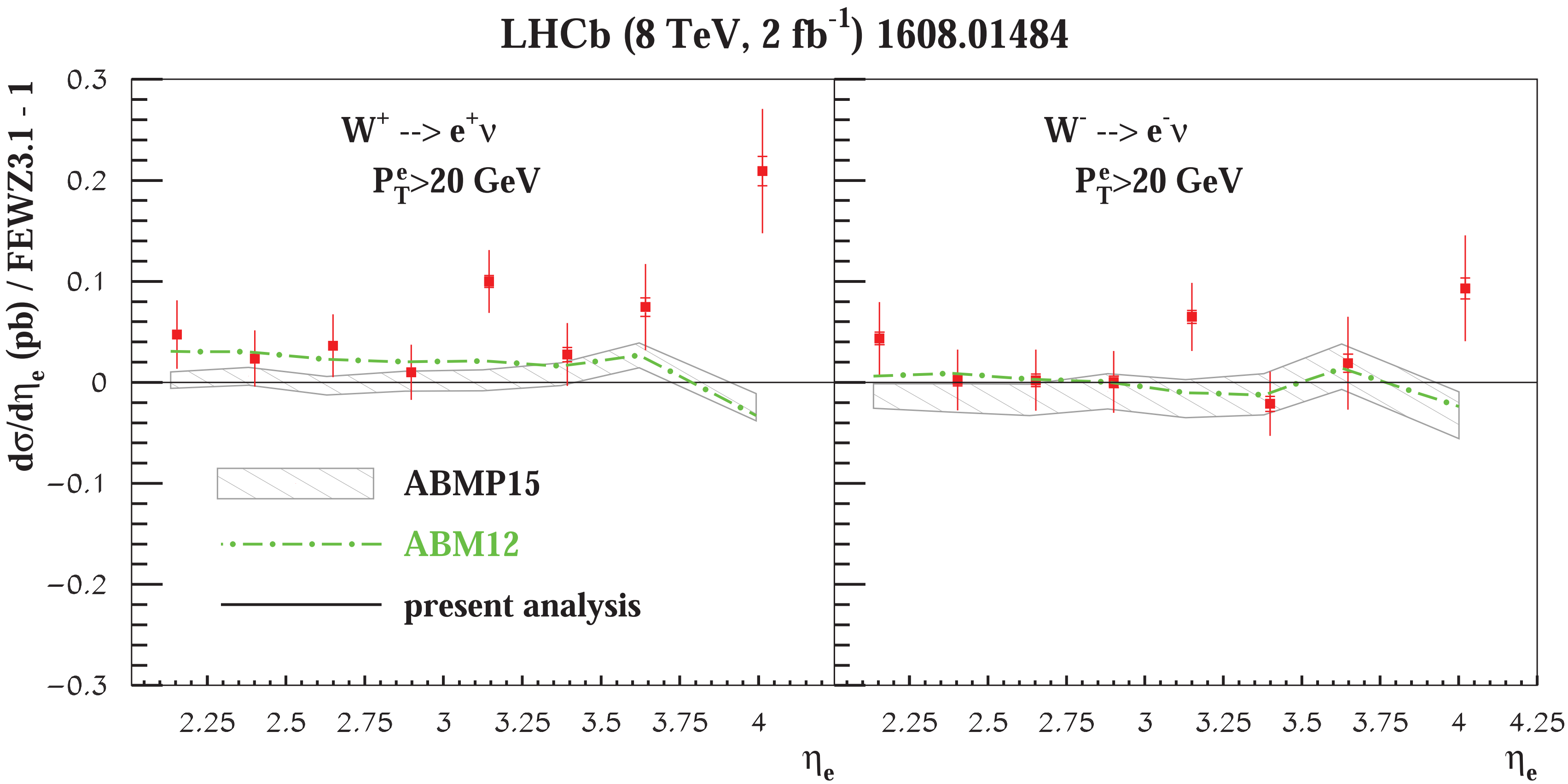
- CMS data on cross section of inclusive $W^{\pm}$-boson production at $\sqrt{s} = 8$ TeV
  - channel $W^{\pm} \to \mu^{\pm}\nu$

$W^{\pm}$-boson production from LHC (II)



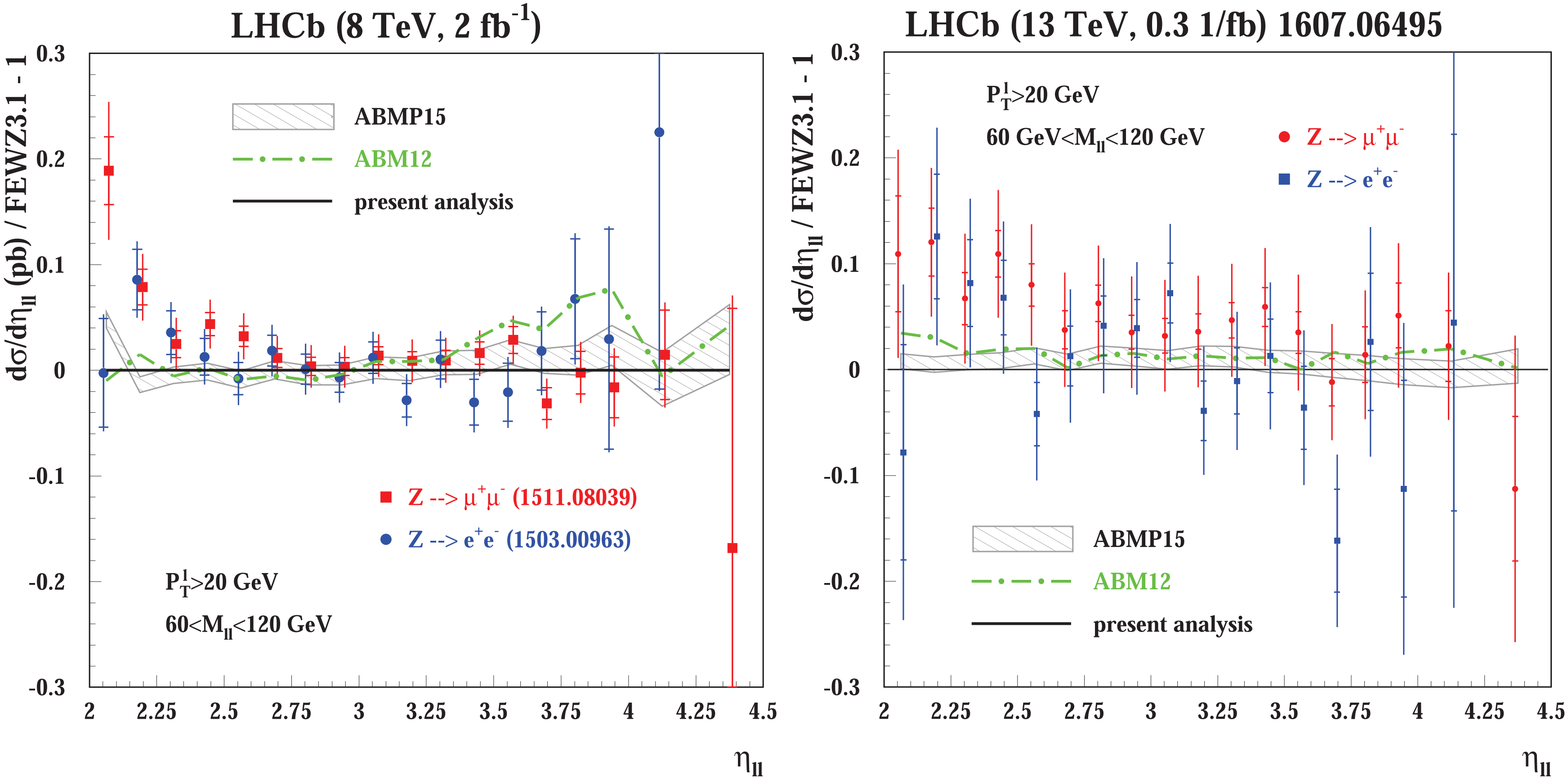
- LHCb data on cross section of inclusive $W^{\pm}$-boson production at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV
  - channel $W^{\pm} \to \mu^{\pm}\nu$
- Points at $\eta_{\mu} = 2.125$ for $\sqrt{s} = 8$ TeV are not used in fit

$W^{\pm}$-boson production from LHC (III)



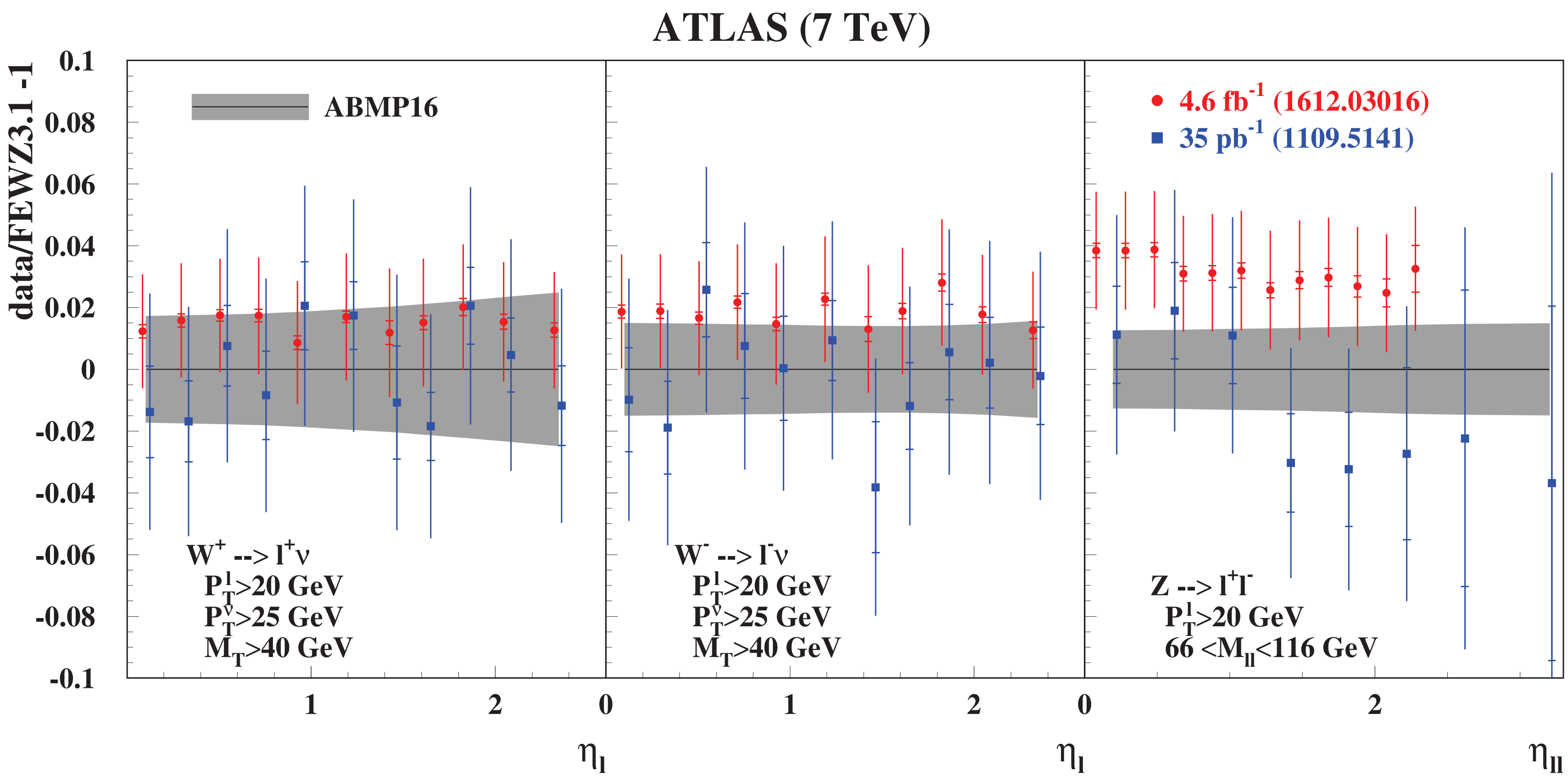
- LHCb data on cross section of inclusive $W^{\pm}$-boson production at $\sqrt{s} = 8$ TeV
  - channel $W^{\pm} \to e^{\pm}\nu$

Z-boson production from LHC



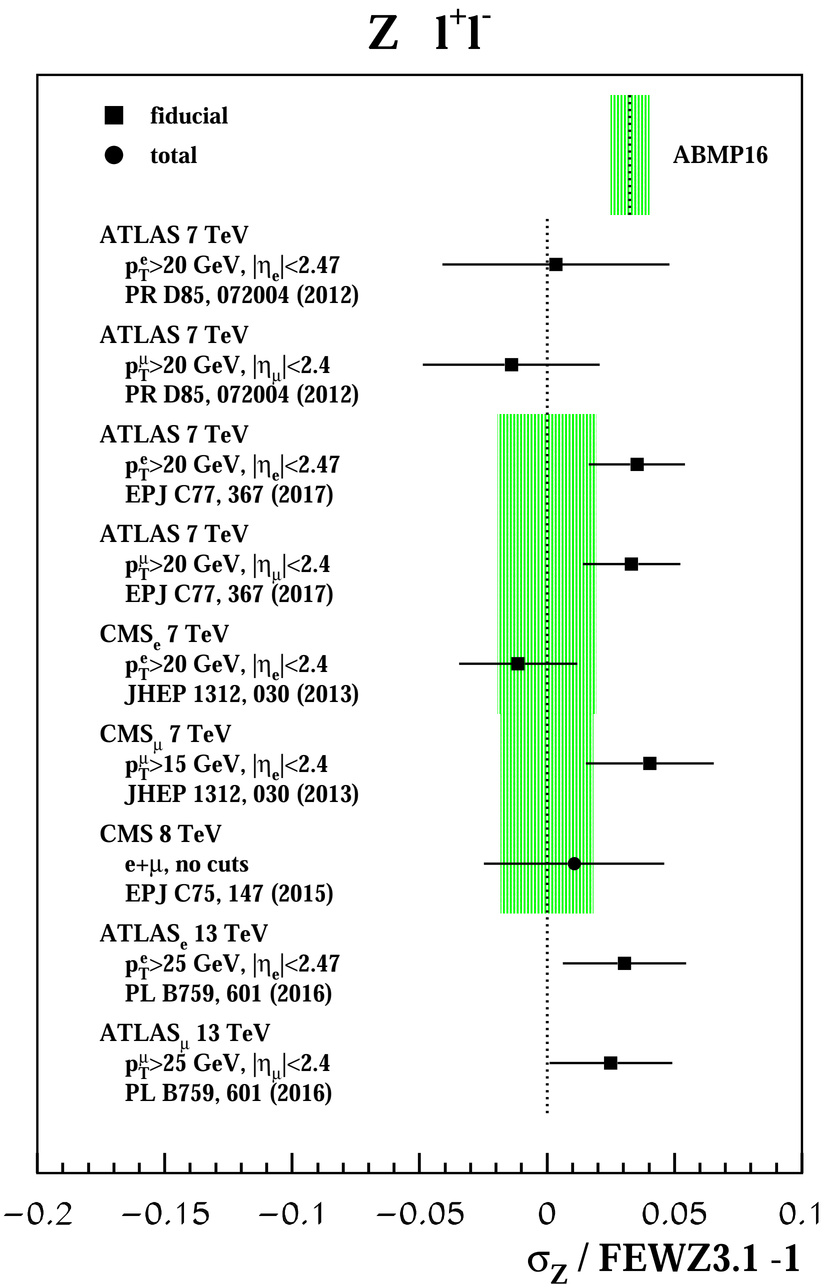
- LHCb data for $pp \to Z + X \to l\bar{l}$ at $\sqrt{s} = 8$ TeV and $\sqrt{s} = 13$ TeV
  - channels $Z \to e^+e^-$ and $Z \to \mu^+\mu^-$

New $W^{\pm}$- and Z-boson production from LHC



- Pulls for ATLAS data for $pp \to W^{\pm} + X \to \mu^{\pm}\nu + X$ and $pp \to Z + X \to l\bar{l}$ at $\sqrt{s} = 7$ TeV compared to ABMP16
  - collected at luminosity of 35 pb^{-1} (2011) (blue squares)
  - collected at luminosity of 4.6 fb^{-1} (2016) (red circles)

Pulls of Z-boson production from LHC

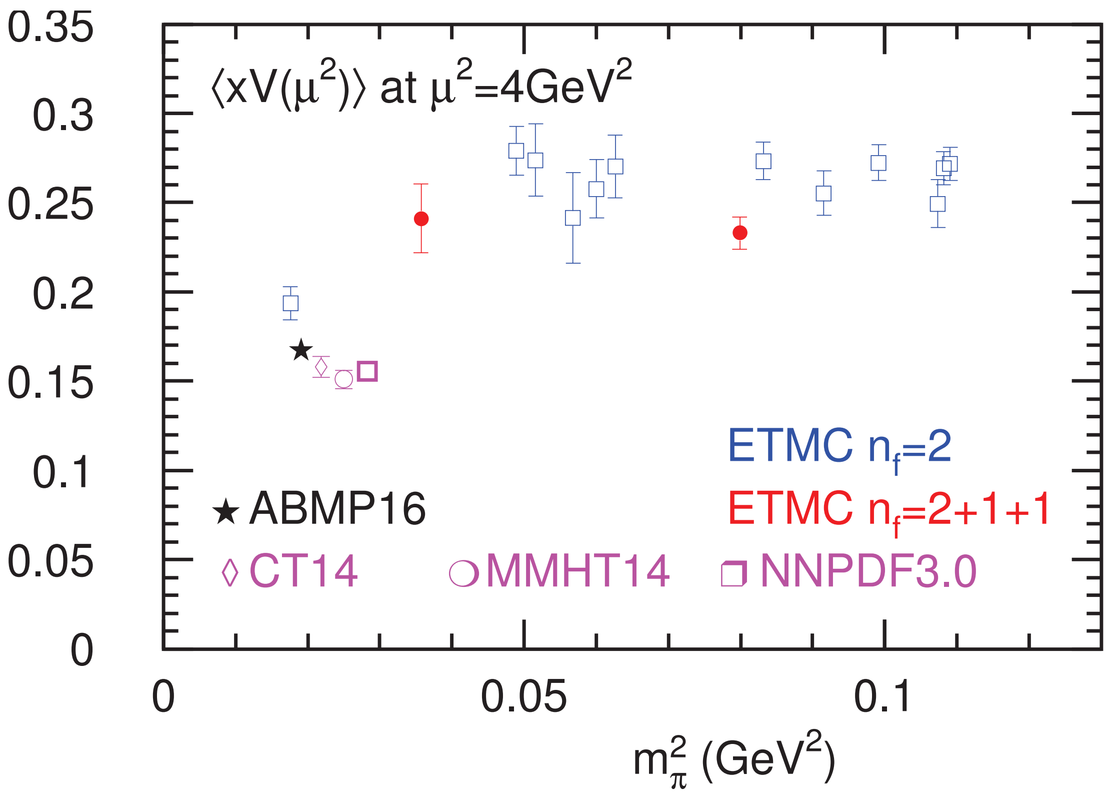


- Integrated cross sections of Z-boson production in proton-proton collisions in central-region measured by ATLAS and CMS in e- and μ-decay channels at different center-of-mass energies

Lattice results

- Moments of valence quark densities at NNLO at scale $Q^2 = 4\ \mathrm{GeV}^2$

$$\langle x \rangle_{u-d}(Q^2) \quad = \quad \int_0^1 dx\, x \left\{ \left[u(x,Q^2) + \bar{u}_s(x,Q^2) \right] - \left[d(x,Q^2) + \bar{d}_s(x,Q^2) \right] \right\}$$



Alekhin, Blümlein, S.M. ‘17

- Lattice QCD for $n_f = 2$ now down to nearly physical quark masses

Lattice results

- Moments of valence quark densities at NNLO at scale $Q^2 = 4\ \mathrm{GeV}^2$

$$\langle x \rangle_{u-d}(Q^2) \quad = \quad \int\limits_0^1 dx\, x \left\{ \left[u(x,Q^2) + \bar{u}_s(x,Q^2) \right] - \left[d(x,Q^2) + \bar{d}_s(x,Q^2) \right] \right\}$$

	$\langle x u_v(x) \rangle$	$\langle x d_v(x) \rangle$	$\langle x[u_v - d_v](x) \rangle$	$\langle x V(x) \rangle$
ABM11 Alekhin, Blümlein, S.M. '12	0.2966 ± 0.0039	0.1172 ± 0.0050	0.1794 ± 0.0041	0.1652 ± 0.0039
ABM12 Alekhin, Blümlein, S.M. '13	0.2950 ± 0.0029	0.1212 ± 0.0016	0.1738 ± 0.0025	0.1617 ± 0.0031
ABMP16 Alekhin, Blümlein, S.M., Placakyte '17	0.2911 ± 0.0024	0.1100 ± 0.0031	0.1811 ± 0.0032	0.1674 ± 0.0037
CT14 Dulat et al. '15	$0.2887\ ^{+\,0.0074}_{-\,0.0073}$	$0.1180\ ^{+\,0.0053}_{-\,0.0041}$	$0.1707\ ^{+\,0.0078}_{-\,0.0092}$	$0.1579\ ^{+\,0.0095}_{-\,0.0117}$
MMHT14 Martin, Motylinski, Harland-Lang, Thorne '14	$0.2852\ ^{+\,0.0052}_{-\,0.0034}$	$0.1202\ ^{+\,0.0030}_{-\,0.0031}$	$0.1650\ ^{+\,0.0047}_{-\,0.0034}$	$0.1509\ ^{+\,0.0053}_{-\,0.0039}$
NNPDF3.0 Ball et al. '14	0.2833 ± 0.0042	0.1183 ± 0.0049	0.1650 ± 0.0054	0.1553 ± 0.0037
NNPDF3.1 Ball et al. '17	0.2888 ± 0.0042	0.1139 ± 0.0048	0.1749 ± 0.0047	0.1533 ± 0.0030

- Differences, even for low pion masses, between lattice measurements and experimental determination $\langle x \rangle_{u-d} = 0.1811$ ABM16

Status (Wrap-up)

Data

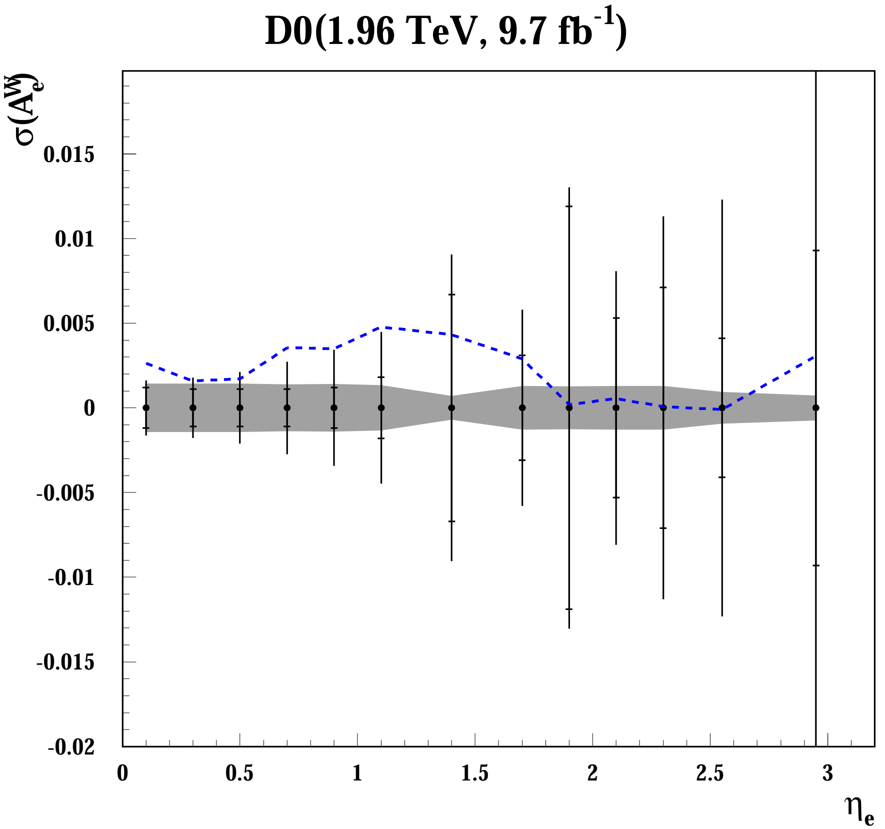
- High precision experimental data, e.g. rapidity distributions with uncertainties less than 1% for central rapidities
  - $W^{\pm}$- and Z-boson production from Tevatron and LHC
  - $Z+$jet production

Theory

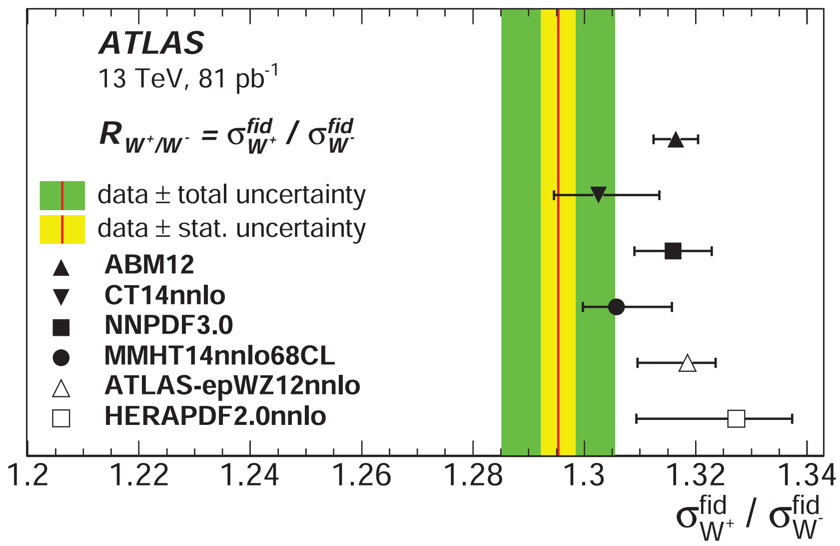
- Complete NNLO QCD corrections with fully differential kinematics to match experimental precision
- Public codes at NNLO
  - FEWZ (v3.1) (sector decomp.) — Gavin, Li, Petriello, Quackenbush '12
  - DYNNLO (v1.5) (q_T slicing) — Catani, Grazzini '07
  - SHERPA-NNLO-FO (q_T slicing) — Höche, Li, Prestel '14
  - MCFM at NNLO (N-jettiness slicing) — Boughezal, Campbell, Ellis, Focke, Giele, Liu, Petriello, Williams '16

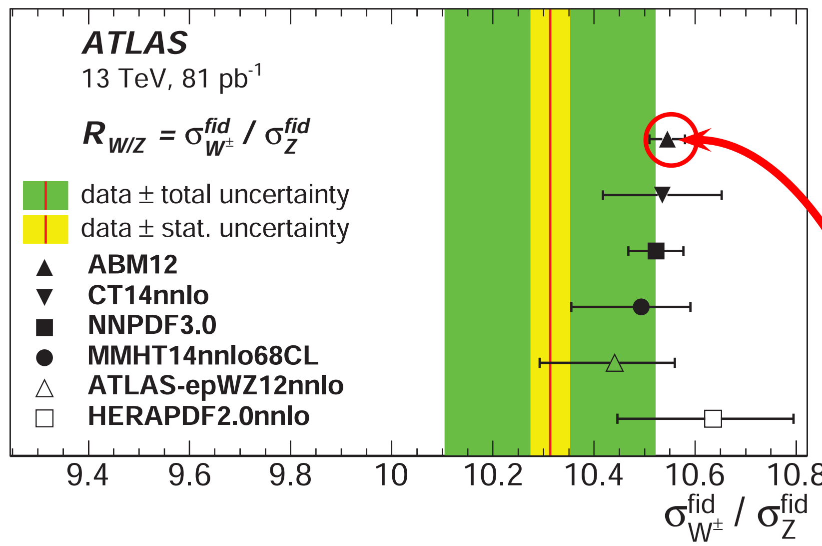
Theory issues

- Data on electron asymmetry with high precision at central rapidities D0
- NNLO corrections in coefficient functions not uniform in η_e (dashed curve)
- Numerical accuracy at NNLO (shaded area) obtained with FEWZ (v3.1)
- Accuracy of $\mathcal{O}(1 \text{ ppm})$ to meet uncertainties in experimental data requires $\mathcal{O}(10^4 \text{h})$ of running FEWZ (v3.1) at NNLO



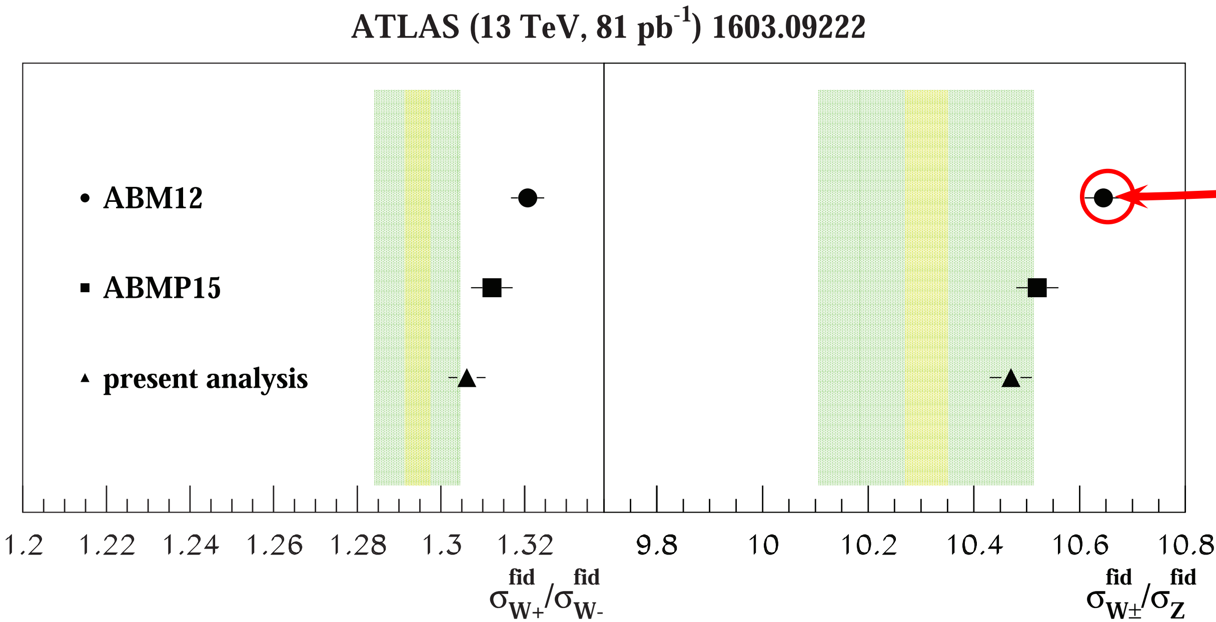
W- and *Z*-boson cross sections





DYNNLO (v1.5)

Catani, Grazzini '07

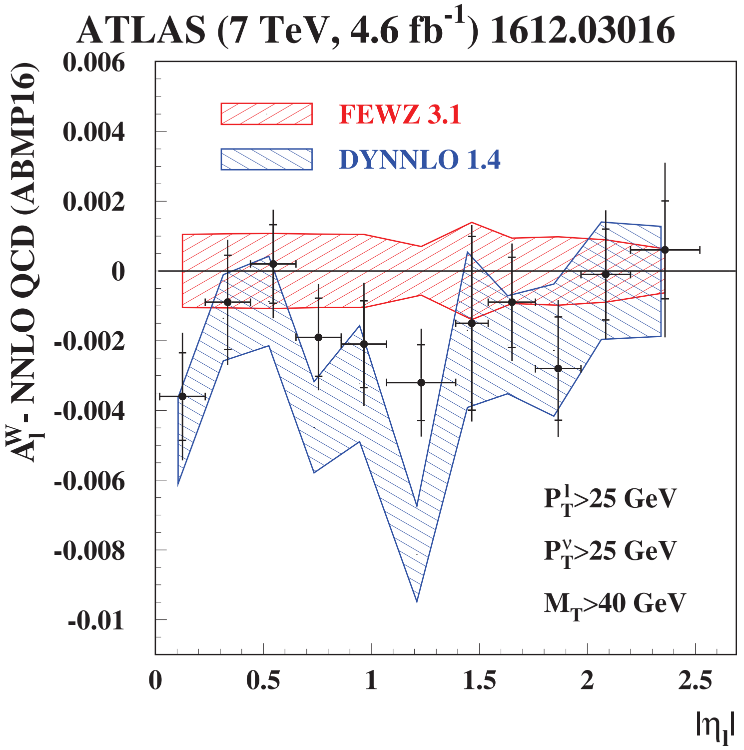


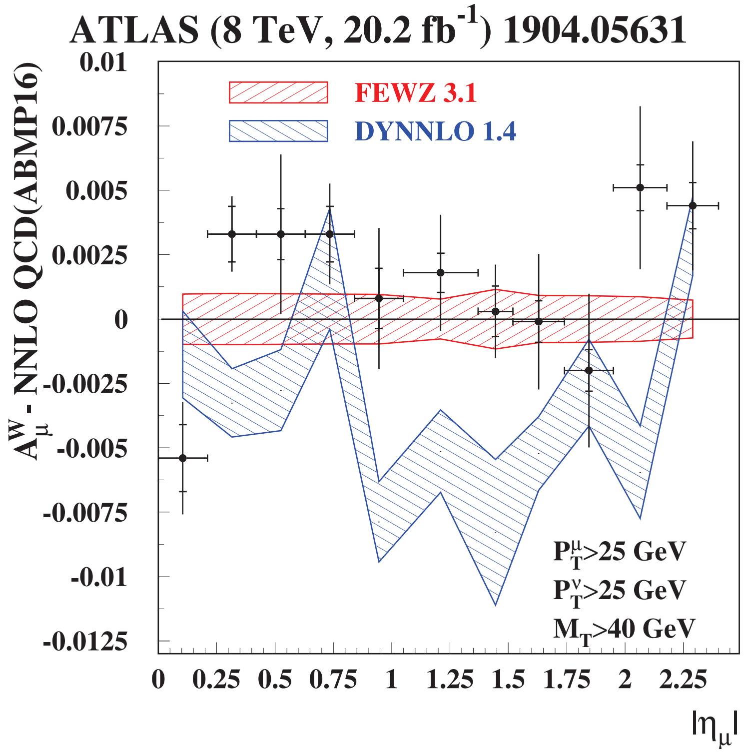
FEWZ (v3.1)

Gavin, Li, Petriello, Quackenbush '12

- Differences at NNLO between DYNNLO and FEWZ up to $\mathcal{O}(1\%)$ or more

W- and Z-boson cross sections



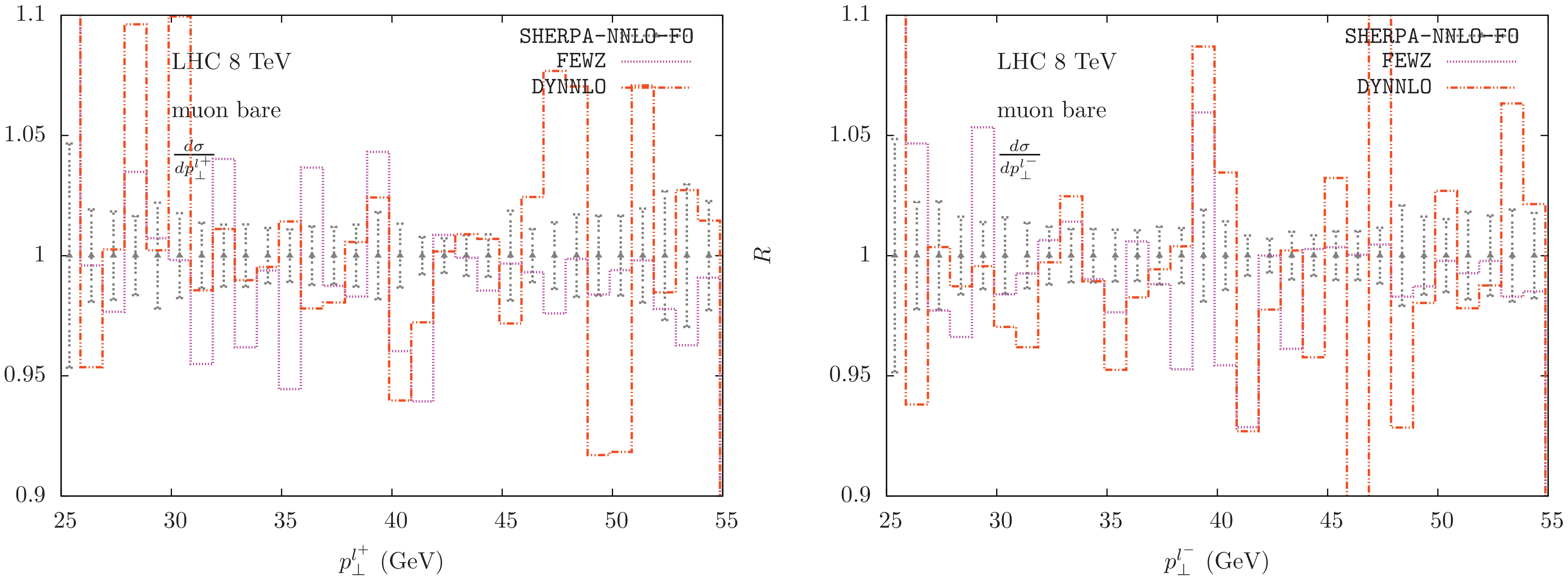


- Recent comparision of data on lepton asymmetry A_l measured by ATLAS at $\sqrt{s} = 7$ TeV (arXiv:1612.03016) and $\sqrt{s} = 8$ TeV (arXiv:1904.05631)
- Use of various NNLO tools
  - FEWZ (v3.1) Gavin, Li, Petriello, Quackenbush '12
  - DYNNLO (v1.4) Catani, Grazzini '07
- Results obtained with $\mathcal{O}(\mathrm{months})$ of computer wall time

Benchmark of NNLO predictions

Benchmark

- LPCC *Electroweak Precision Measurements at the LHC WG1* summary of activity dedicated to systematic comparison of public Monte Carlo codes (arXiv:1606.02330)
  - ratio of FEWZ (v3.1) and DYNNLO (v1.5) to SHERPA-NNLO-FO with uncertainties from numerical integration
  - focus on distributions related to W-mass measurements



Cuts on final state momenta

Problem of symmetric cuts

- Symmetric cuts on the transverse momentum of lepton and missing energy display pathological behavior Frixione, Ridolfi '97
  - assume staggered cuts with minimum transverse momentum Δ, $p_{T,l} \geq E_T^{\rm cut}$ and $E_{T,miss} \geq E_T^{\rm cut} + \Delta$
  - leading collinear singularity of in NLO real-emission contribution with collinear cutoff δ (slicing)

$$\sigma^{(r)} = \int d^2p_{1T}\, \theta(E_{1T} - E_T^{\rm cut}) \int d^2p_{2T}\, \theta(E_{2T} - E_T^{\rm cut} - \Delta)\, \frac{1}{|\vec{p}_{1T} + \vec{p}_{2T}|^2 + \delta}$$

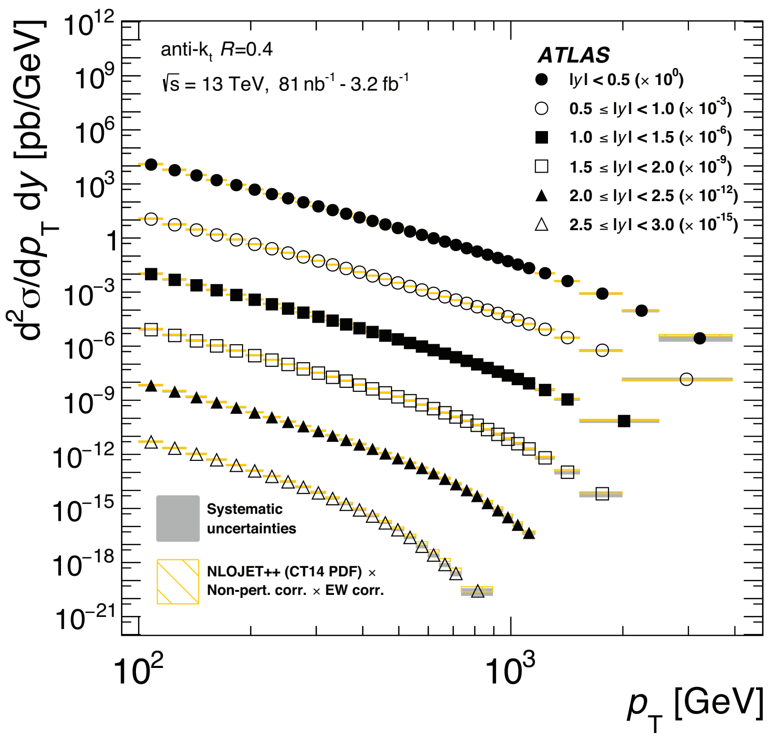
- Real-emission contribution to integrated NLO cross section

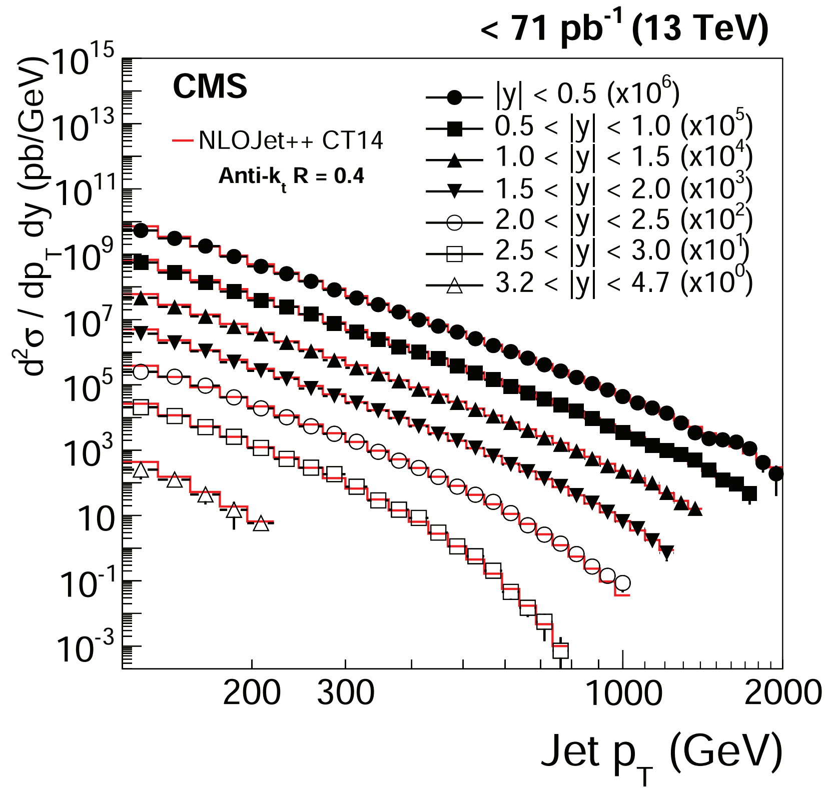
$$\sigma^{(r)} = A(\Delta, \delta) + B \log \delta - C(\Delta + \delta) \log(\Delta + \delta)$$

  - $A(\Delta, \delta)$ and first derivative $\frac{\partial}{\partial \Delta} A(\Delta, \delta)$ regular in $\Delta = 0$ for any δ
  - B identifies collinear singularity
  - $-C(\Delta + \delta) \log(\Delta + \delta)$ regular for finite Δ and δ, but becomes $\propto \delta \log \delta$ but for symmetric cuts Δ
- Upshot: residual uncertainty in subtraction schemes with q_T slicing

Hadro-production of jets

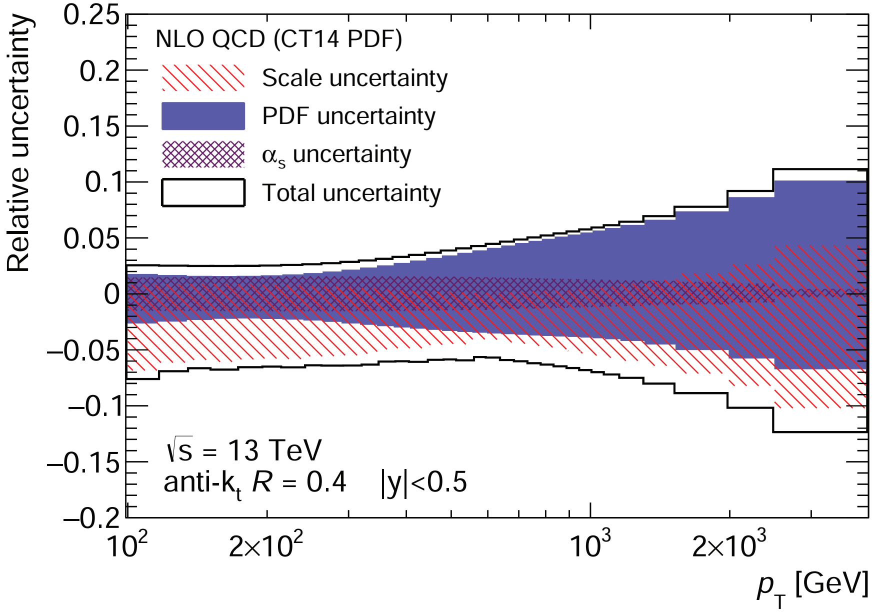
Single-inclusive jet production

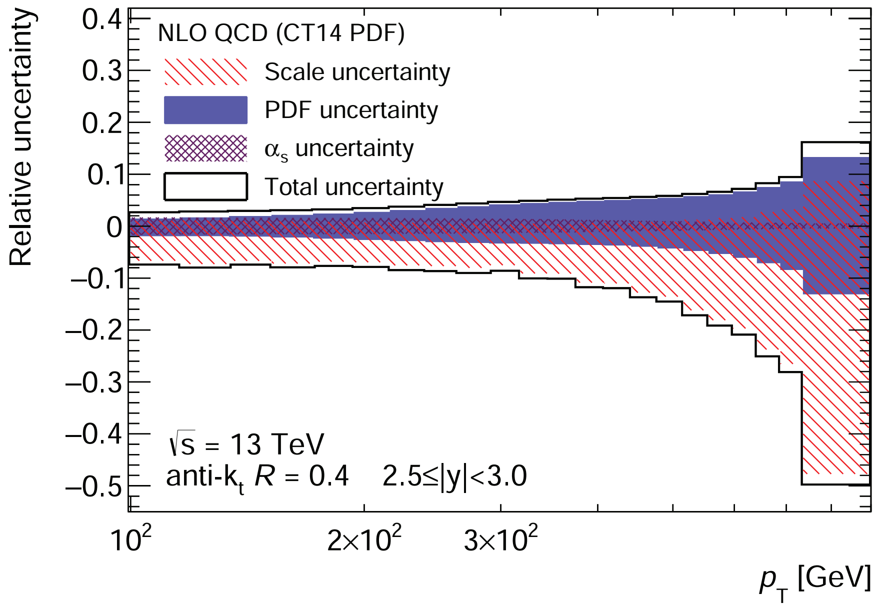




- Double differential cross section for $pp \to \text{jet} + X$ at $\sqrt{s} = 13$ TeV
  - transverse momentum p_T and rapidity y of signal-jet
  - ATLAS arXiv:1711.02692 (left), CMS arXiv:1605.04436 (right)
- Comparison with NLO perturbative QCD predictions (NLOJET++ Nagy)
  - impressive agreement over several orders of magnitude

Uncertainties

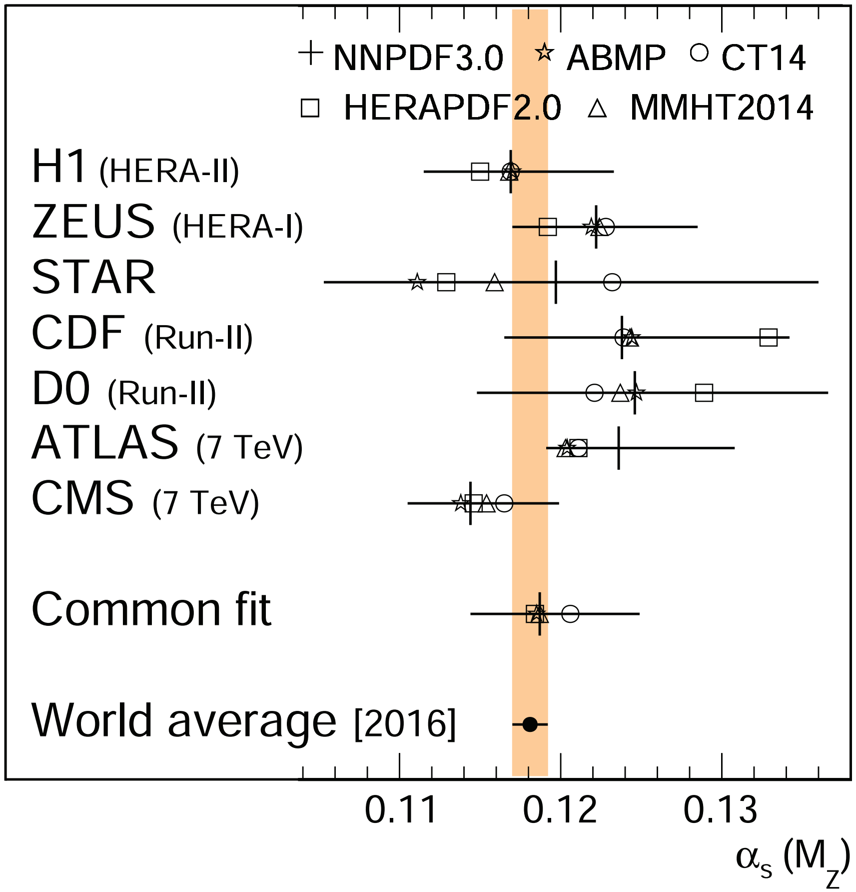




- Relative QCD uncertainties in single-inclusive jet cross-sections at NLO
  - first and last $|y|$ bins for inclusive jet measurement
  - uncertainties due to renormalization and factorization scales, μ_R, μ_F, the strong coupling α_s with $\Delta\alpha_s = 0.0015$ and PDFs CT14
- Sizable uncertainties
  - $\mathcal{O}(10\%)$ for central rapidities $|y| < 0.5$
  - $\mathcal{O}(30 - 40\%)$ forward $2.5 \leq |y| < 3.0$ at large p_T

Uses of inclusive jet data

- Dermination of $\alpha_s(M_Z)$ and PDFs (gluon at medium to large x)
  - partonic cross sections $\hat{\sigma}_{ij\to\mathrm{jet}} \propto \alpha_s^2(\mu)$
  - jet cross section $d\sigma_{pp\to\mathrm{jet}} = \alpha_s^2(\mu)\sum_{ij} f_i(\mu)\otimes f_j(\mu)\otimes[\dots]$



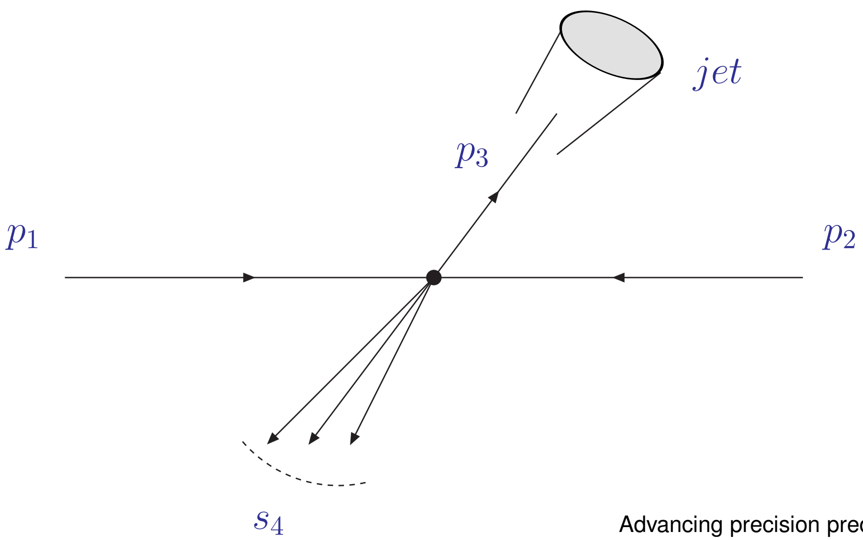
- $\alpha_s(M_Z)$ at NLO in QCD from inclusive jet cross section data
  Britzger, Rabbertz, Savoiu, Sieber '17
- correlations between PDFs and $\alpha_s(M_Z)$ are important

QCD factorization

- Double differential cross section for $pp \to \text{jet} + X$
  - transverse momentum p_T and rapidity η of signal-jet

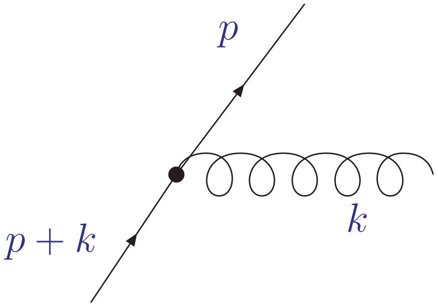
$$\frac{p_T^2 \mathrm{d}^2\sigma}{\mathrm{d}p_T^2 \mathrm{d}\eta} = \sum_{i_1 i_2} \int_0^{V(1-W)} \mathrm{d}z \int_{\frac{VW}{1-z}}^{1-\frac{1-V}{1-z}} \mathrm{d}v \, x_1^2 \, f_{i_1}(x_1) \, x_2^2 \, f_{i_2}(x_2) \, \frac{\mathrm{d}^2 \hat{\sigma}_{i_1 i_2}}{\mathrm{d}v \, \mathrm{d}z}(v, z, p_T, R)$$

- PDFs f_i and variables $V = 1 - p_T e^{-\eta}/\sqrt{S}$, $VW = p_T e^{\eta}/\sqrt{S}$
- Partonic cross sections $\hat{\sigma}_{i_1 i_2}$ dependent on partonic kinematic variables on $s = x_1 x_2 S$, $v = u/(u+t)$ and partonic threshold $z = s_4/s \to 0$
- Mandelstam variables $s = (p_1 + p_2)^2$, $t = (p_1 - p_3)^2$ and $u = (p_2 - p_3)^2$ with kinematics constraint $s + t + u = s_4$



Threshold logarithms

- Soft and collinear regions of phase space
  - double logarithms from singular regions in Feynman diagrams
  - propagator vanishes for: $E_g = 0$, soft $\theta_{qg} = 0$ collinear



$$\frac{1}{(p+k)^2} = \frac{1}{2p\cdot k} = \frac{1}{2E_q E_g (1-\cos\theta_{qg})}$$

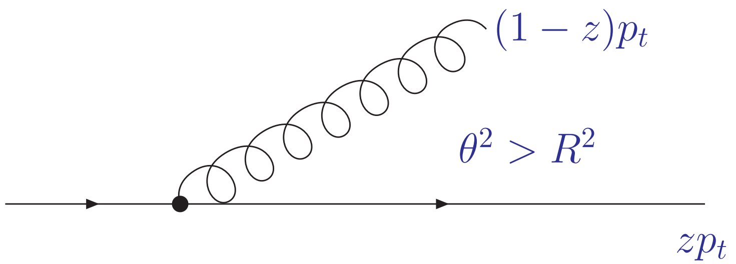
$$\alpha_s \int d^4k \frac{1}{(p+k)^2} \longrightarrow \alpha_s \int dE_g \, d\sin\theta_{qg} \, \frac{1}{2E_q E_g (1-\cos\theta_{qg})}$$

$$\longrightarrow \alpha_s \ln^2(\dots)$$

- Large double-logarithmic corrections $\ln(\dots) \gg 1$ near threshold
- Single-inclusive jet production with threshold logarithms $\alpha_s^n (\ln^{2n-1}(z)/z)_+$ for $z = s_4/s \to 0$
  - *positive* corrections enhance partonic cross sections $\hat{\sigma}_{i_1 i_2}$
  - long history of resummation Sterman '87; Catani, Trentadue '88; ...
- Same for weak radiative corrections: positive correction for large $p_t \gg M_W$ Dittmaier, Huss, Speckner '12

Jet radius logarithms (I)

- Collinear singularity when the jet becomes very narrow
  - partons radiated outside of jet (not recombined with jet by chosen jet algorithm) become more and more collinear to emitter
- Example
  - loss of transverse momentum for leading jet
  - quasi-collinear branching of quark with transverse momentum p_t



$$\delta p_t = (1-z)p_t - p_t = -zp_t \text{ for } (1-z) > z$$
$$\delta p_t = (1-z)p_t - p_t = -zp_t \text{ for } z > (1-z)$$

- Perturbative radiation loss for average $\langle \delta p_t \rangle_{\mathrm{q}}$

$$\langle \delta p_t \rangle_{\mathrm{q}} = p_t \frac{\alpha_s}{2\pi} \int_{R^2}^{1} \frac{d\theta^2}{\theta^2} \int dz \big(\max[z, 1-z] - 1 \big) P_{qq}(z)$$

Jet radius logarithms (II)

- Leading order result for quark and gluon jets Dasgupta, Magnea, Salam '07

$$\langle \delta p_t \rangle_{\rm q} = C_F \frac{\alpha_s}{\pi} p_t \ln(R) \left(2\ln 2 - \frac{3}{8} \right) = 0.43\, \alpha_s \ln(R)$$

$$\langle \delta p_t \rangle_{\rm g} = \frac{\alpha_s}{\pi} p_t \ln(R) \left[C_A \left(2\ln 2 - \frac{43}{96} \right) + T_f\, n_f \frac{7}{48} \right] = 1.02\, \alpha_s \ln(R)$$

- Large single-logarithmic corrections $\ln(1/R) \gg 1$ for small R
  - *negative* corrections decrease partonic cross sections $\hat{\sigma}_{i_1 i_2}$
  - resummation …

Joint resummation

SCET factorization

- Factorization in small-R and $z \to 0$ threshold limit
  - assume anti-k_t jet algorithm, $z \sim R$, and small finite mass of jet

$$
\begin{aligned}
\frac{\mathrm{d}^2\hat{\sigma}_{i_1 i_2}}{\mathrm{d}v\,\mathrm{d}z} \;=\;& s \int \mathrm{d}s_X\,\mathrm{d}s_c \mathrm{d}s_G\, \delta(zs - s_X - s_G - s_c) \\
&\times \mathrm{Tr}\left[\mathbf{H}_{i_1 i_2}(v, p_T\,, \mu_h\,, \mu)\, \mathbf{S}_G(s_G\,, \mu_{sG}\,, \mu)\right]\; J_X(s_X\,, \mu_X\,, \mu) \\
&\times \sum_m \mathrm{Tr}\left[J_m(p_T R\,, \mu_J\,, \mu) \otimes_\Omega S_{c,m}(s_c R\,, \mu_{sc}\,, \mu)\right]
\end{aligned}
$$

- Specific functions for individual kinemtic regions
  - hard functions for $2 \to 2$ scattering $\mathbf{H}_{i_1 i_2}$ (known to 2-loops Broggio, Ferroglia, Pecjak, Zhang '14)
  - inclusive jet function $J_X(s_X)$ dependent on invariant mass s_X of the recoiling collimated radiation (known to order α_s^2 Becher, Neubert '06, Becher, Bell '10)
  - global soft function $\mathbf{S}_G$ accounts for wide-angle soft radiation which cannot resolve the small radius R (known to NLO Liu, S.M., Ringer '17)

Joint resummation

SCET factorization

- Factorization in small-R and $z \to 0$ threshold limit
  - assume anti-k_t jet algorithm, $z \sim R$, and small finite mass of jet

$$
\begin{aligned}
\frac{\mathrm{d}^2\hat{\sigma}_{i_1 i_2}}{\mathrm{d}v\,\mathrm{d}z} \quad = \quad & s \int \mathrm{d}s_X\,\mathrm{d}s_c\mathrm{d}s_G\,\delta(zs - s_X - s_G - s_c) \\
& \times \mathrm{Tr}\,[\mathbf{H}_{i_1 i_2}(v, p_T\,, \mu_h\,, \mu)\,\mathbf{S}_G(s_G\,, \mu_{sG}\,, \mu)]\;\; J_X(s_X\,, \mu_X\,, \mu) \\
& \times \sum_m \mathrm{Tr}\,[J_m(p_T R\,, \mu_J\,, \mu) \otimes_\Omega S_{c,m}(s_c R\,, \mu_{sc}\,, \mu)]
\end{aligned}
$$

- Specific functions for individual kinemtic regions
  - signal-jet function $J(p_T\,R)$ accounts for energetic radiation inside jet Becher, Neubert, Rothen, Shao ‘15
  - soft-collinear (“coft”) function $S_c(s_c R)$ captures soft radiation near jet boundary Becher, Neubert, Rothen, Shao ‘15, Chien, Hornig, Lee ‘15
- Sum runs over all collinear splittings and traces taken in color space
- ‘$\otimes_\Omega$’ denotes associated angular integrals Becher, Neubert, Rothen, Shao ‘15

Phenomenology

- Evaluation of cross section in SCET (resummation) with renormalization group equations
  - evolution of all functions from their natural scales μ_i to common hard scale $\mu = p_T^{\max}$
- Matching of NLL resummed results with full NLO calculation (need to avoid double counting)

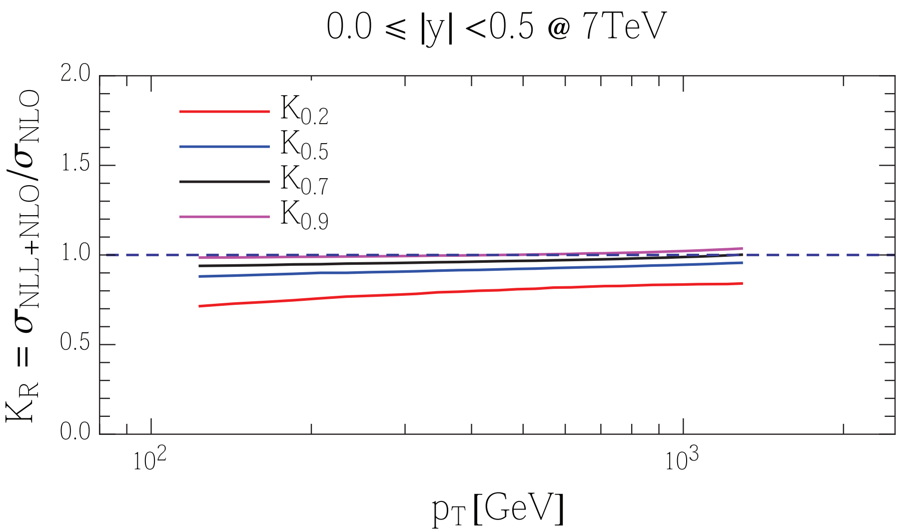
$$\mathrm{d}\sigma = \mathrm{d}\sigma_{\mathrm{NLL}} - \mathrm{d}\sigma_{\mathrm{NLO}_{\mathrm{sin}}} + \mathrm{d}\sigma_{\mathrm{NLO}}$$

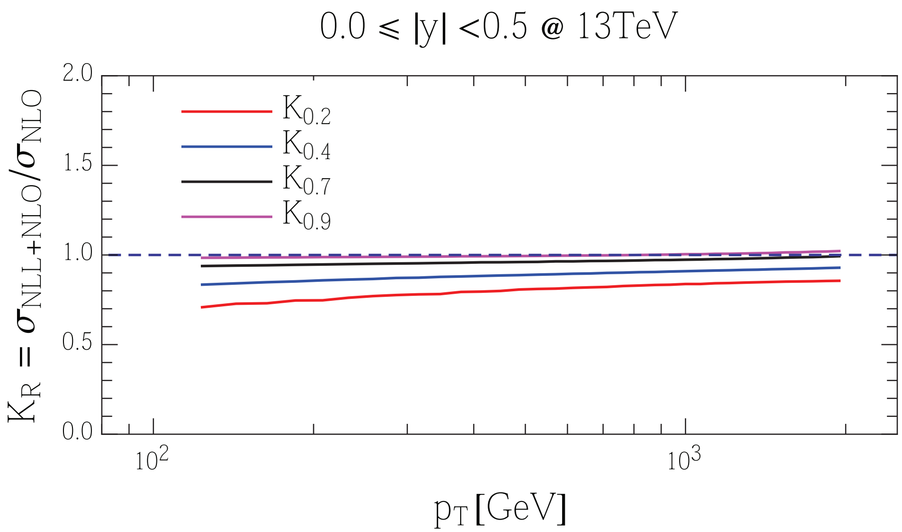
  - resummed cross section $\mathrm{d}\sigma_{\mathrm{NLL}}$
  - fixed order NLO result in singular limit $\mathrm{d}\sigma_{\mathrm{NLO}_{\mathrm{sin}}}$
  - complete fixed order NLO result $\mathrm{d}\sigma_{\mathrm{NLO}}$

Jet radius dependence (I)

Resummation for various R

- Ratio K_R of NLO + NLL and NLO cross sections for different jet radii
  $$K_R = \frac{\sigma_{\mathrm{NLL+NLO}}(R)}{\sigma_{\mathrm{NLO}}(R)}$$
- LHC at $\sqrt{S} = 7$ TeV (left) and 13 TeV (right) with NLO PDF set of MMHT



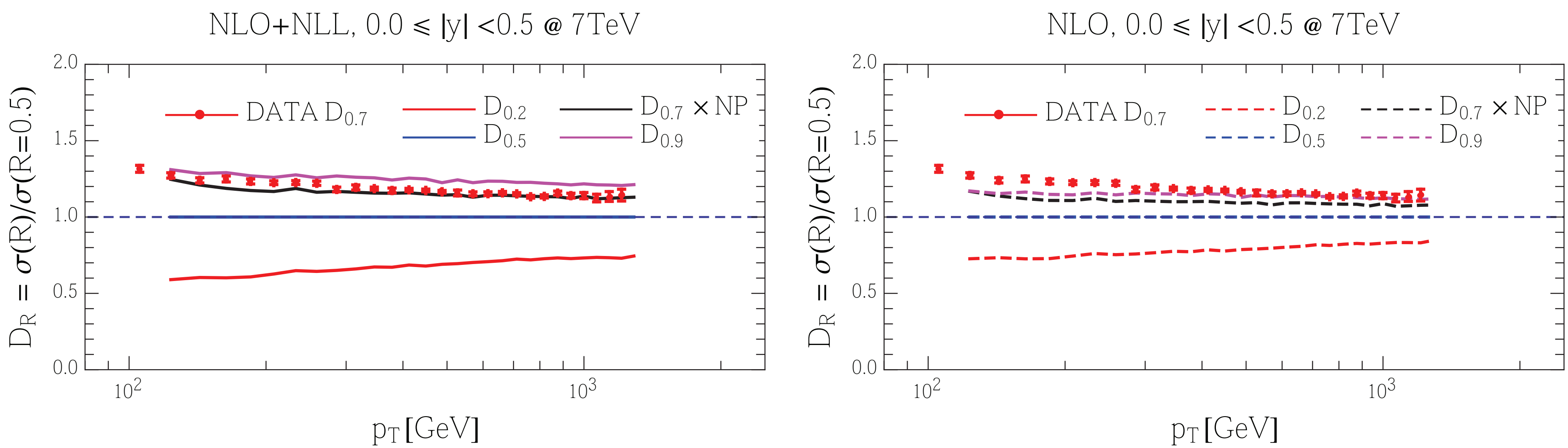


- Significant effect for small jet radii; reduction of $\mathcal{O}(20\%)$ for $R = 0.2$ in entire range of p_t

Jet radius dependence (II)

Impact of joint resummation

- Cross section ratio $D_R = \dfrac{\sigma(R)}{\sigma(R_{\text{fixed}})}$
- D_R for NLO + NLL (left) and NLO (right) cross sections for $R_{\text{fixed}} = 0.5$ at $\sqrt{S} = 7$ TeV with NLO PDF set of MMHT14
- Single-inclusive jet data from collected at $\sqrt{S} = 7$ TeV with $R = 0.7$ by CMS `arXiv:1406.0324` (with NP correction factors)

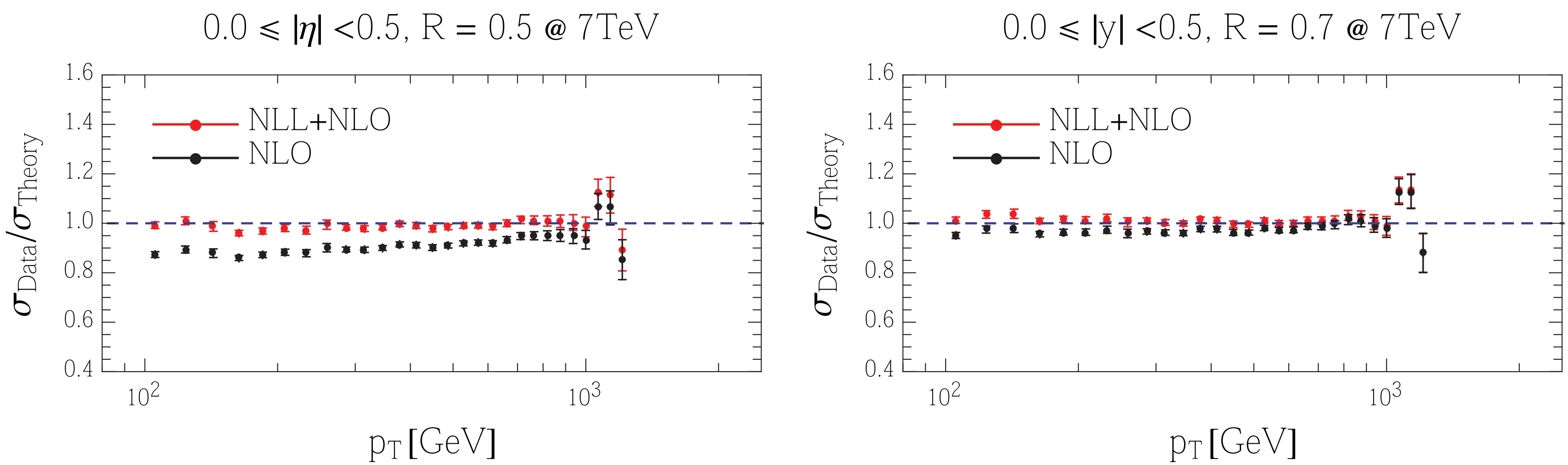


- NLO result overshoots; joint resummation agrees with data for $D_{R=0.7}$

Data vs. theory (I)

LHC data at $\sqrt{S} = 7$ TeV

- Ratio $\sigma_{\rm Data}/\sigma_{\rm Theory}$ with $R = 0.5$ (left) and $R = 0.7$ (right) to theoretical results at NLO (black dots) and at NLO + NLL (red dots) accuracy
  - NLO PDF set of MMHT14
  - data at $\sqrt{S} = 7$ TeV by CMS arXiv:1406.0324

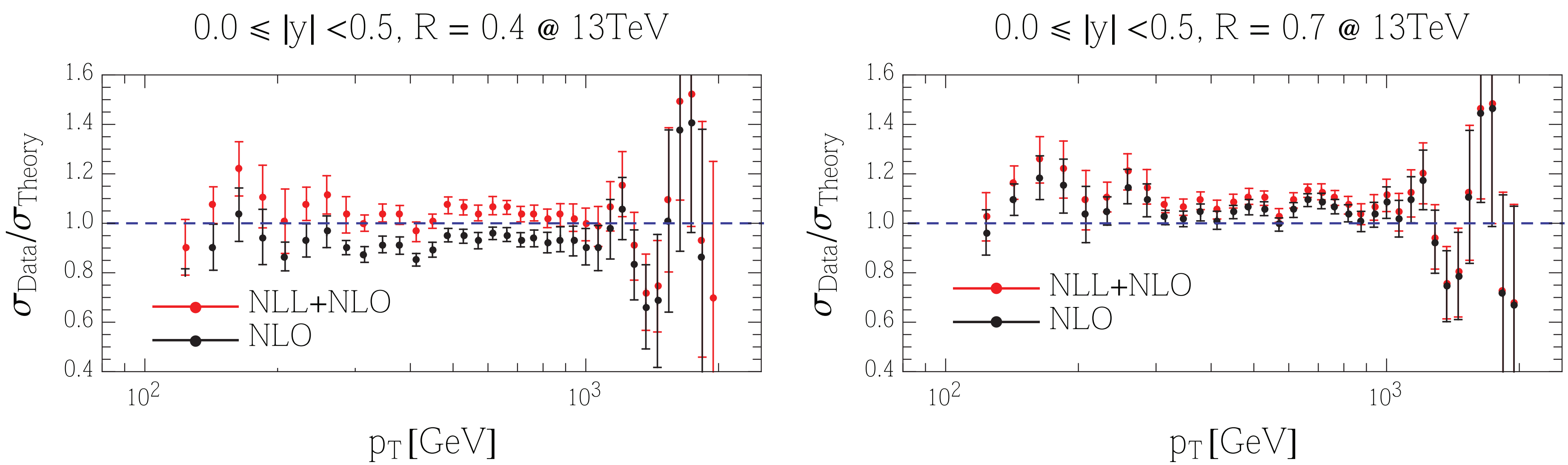


- Joint resummation agrees well with data; ratio with NLO predictions undershoots

Data vs. theory (II)

LHC data at $\sqrt{S} = 13$ TeV

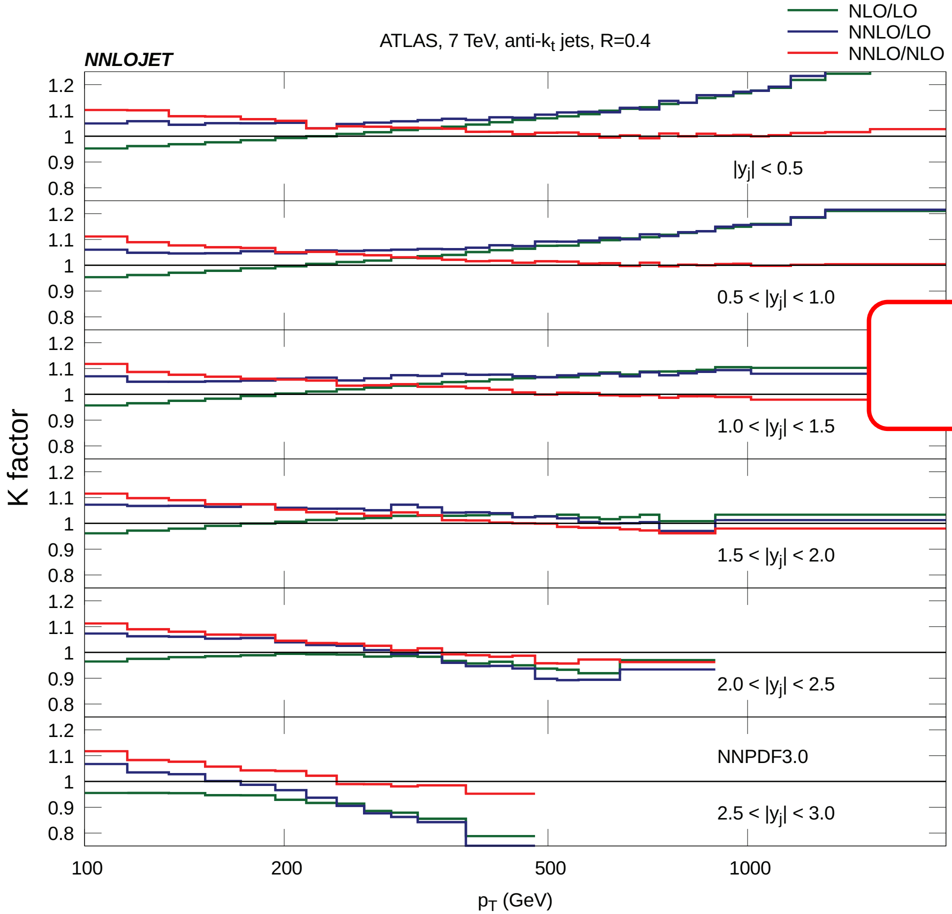
- Ratio $\sigma_{\text{Data}}/\sigma_{\text{Theory}}$ with $R = 0.4$ (left) and $R = 0.7$ (right) to theoretical results at NLO (black dots) and at NLO + NLL (red dots) accuracy
  - NLO PDF set of MMHT14
  - data at $\sqrt{S} = 13$ TeV by CMS `arXiv:1605.04436`



- Same trend as for data at $\sqrt{S} = 7$ TeV, but still large experimental uncertainties

Hadronic jets at NNLO

- Hadroproduction of jets at NNLO with all partonic channels
  - leading color contributions Gehrmann-De Ridder, Gehrmann, Glover, Pires ‘13; Currie, Glover, Pires ‘16
- Production run with fixed $\sqrt{s}$, fixed $\sqrt{R}$, fixed PDF, three scales

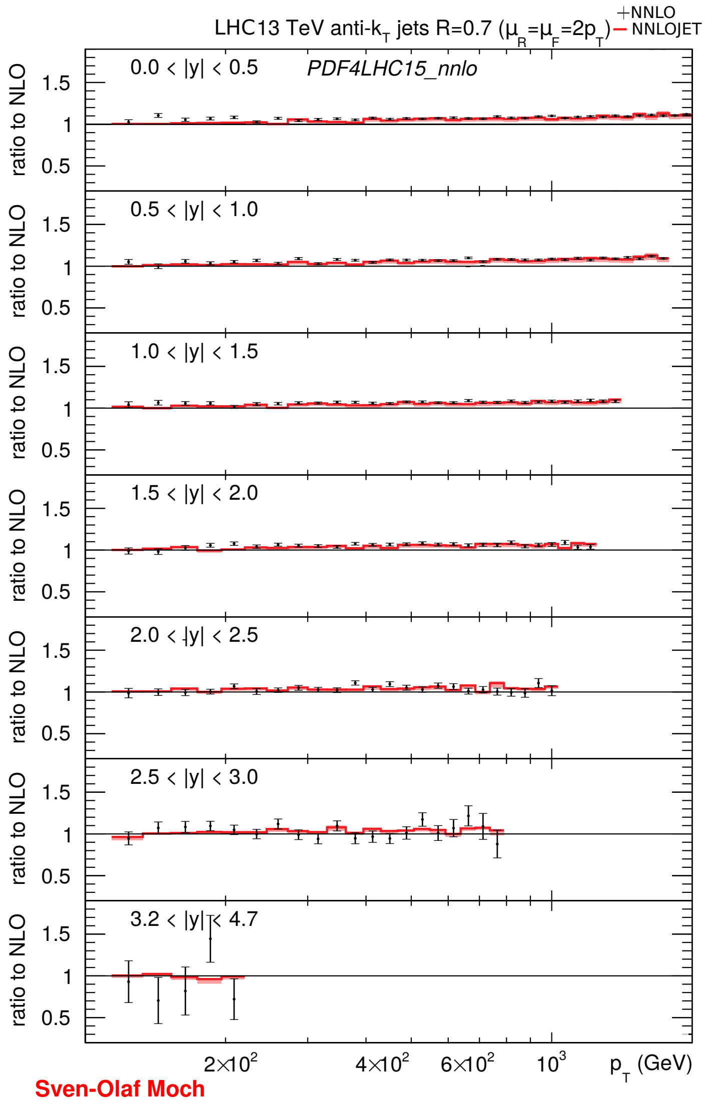


CPU cost
353850 h

Hadronic jets at NNLO

- Hadroproduction of jets at NNLO with all partonic channels
  - full color contributions

Czakon, van Hameren, Mitov, Poncelet '19



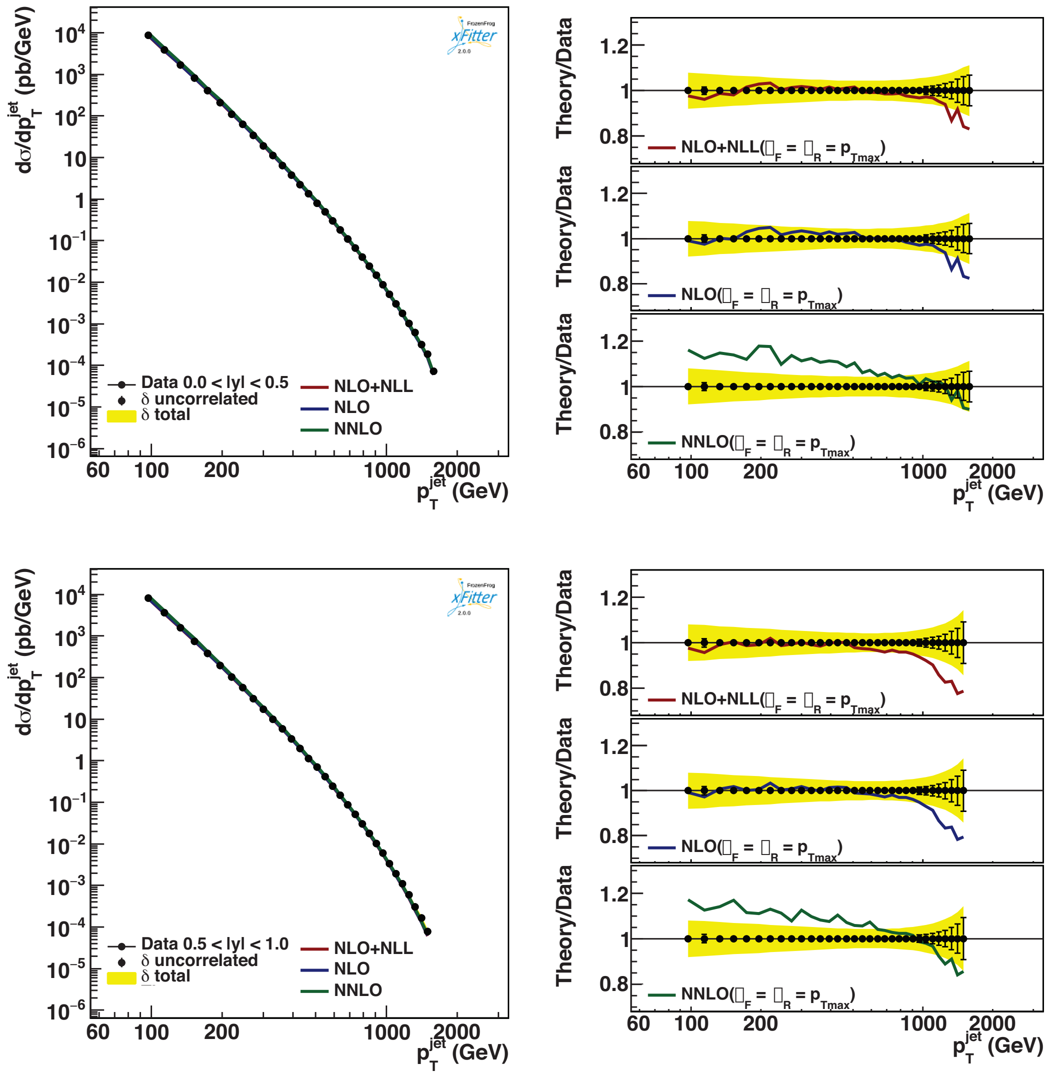
CPU cost

$\sim$ 350000 h

Data vs. theory (III)

LHC data at $\sqrt{S} = 8$ TeV

- Ratio $\sigma_{\text{Theory}}/\sigma_{\text{Data}}$ for NLO+NLL, NLO, and NNLO
  S.M., Eren, Lipka, Liu, Ringer '18
  - NNLO PDF set of CT14
  - $R = 0.7$
  - scale $\mu = p_T^{\max}$
- Joint resummation agrees well with data
- NNLO predictions overshoot data
- Rapidity ranges $y = [0, 0.5]$ and $[0.5, 1]$



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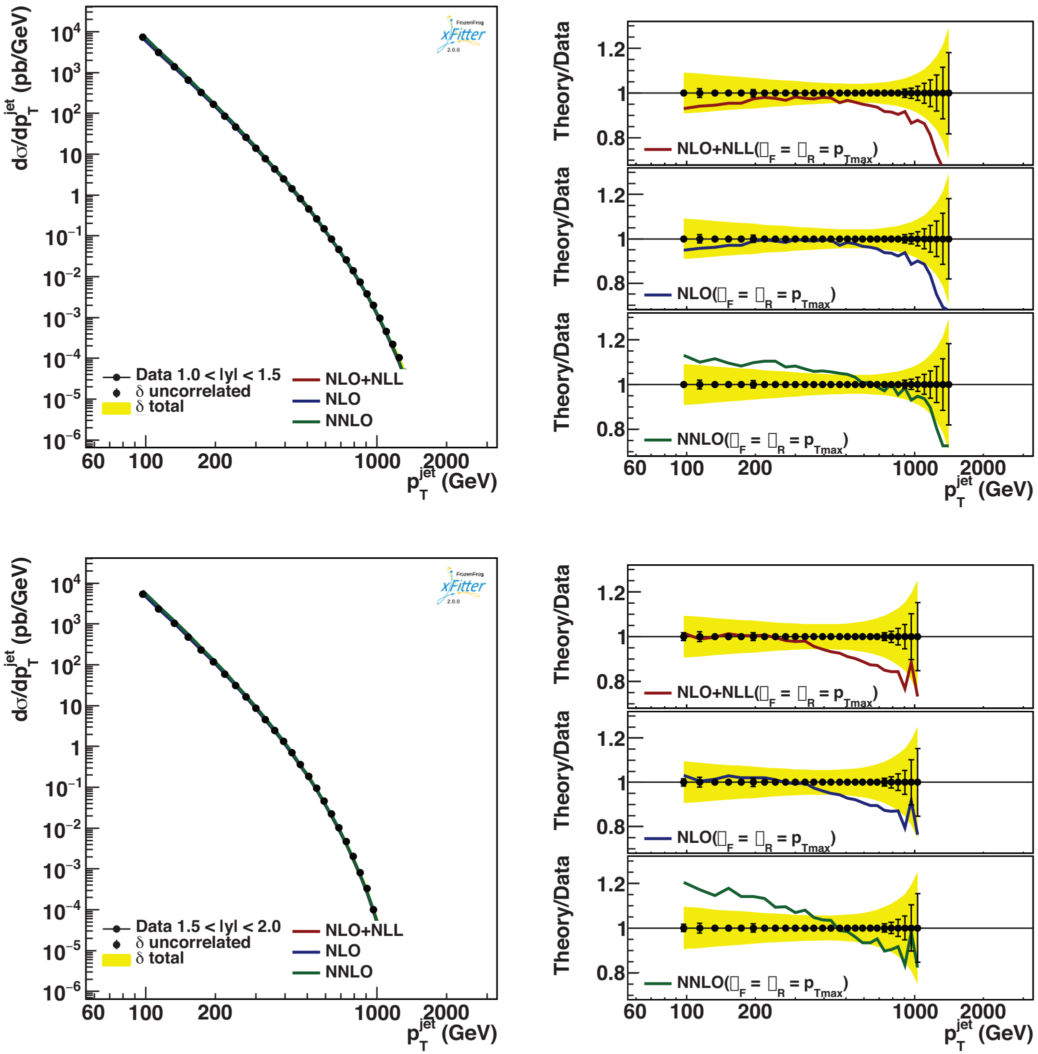
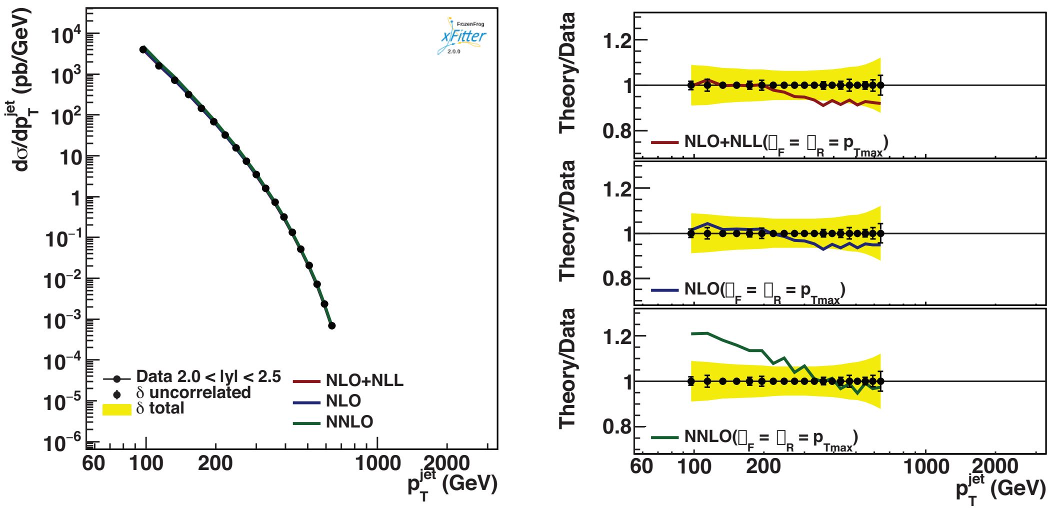
  - NNLO PDF set of CT14
  - $R = 0.7$
  - scale $\mu = p_T^{\rm max}$
- Joint resummation agrees well with data
- NNLO predictions overshoot data
- Rapidity ranges $y = [1,\ 1.5]$ and $[1.5,\ 2]$

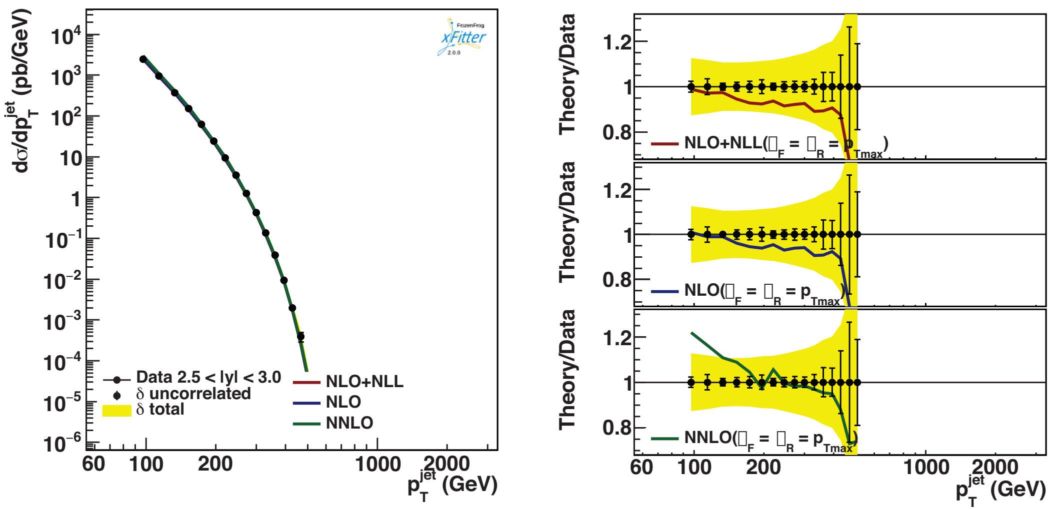


Data vs. theory (III)

LHC data at $\sqrt{S} = 8$ TeV

- Ratio $\sigma_{\rm Theory}/\sigma_{\rm Data}$ for NLO+NLL, NLO, and NNLO
  S.M., Eren, Lipka, Liu, Ringer '18
  - NNLO PDF set of CT14
  - $R = 0.7$
  - scale $\mu = p_T^{\rm max}$
- Joint resummation agrees well with data
- NNLO predictions overshoot data
- Rapidity ranges $y = [2,\, 2.5]$ and $[2.5,\, 3]$





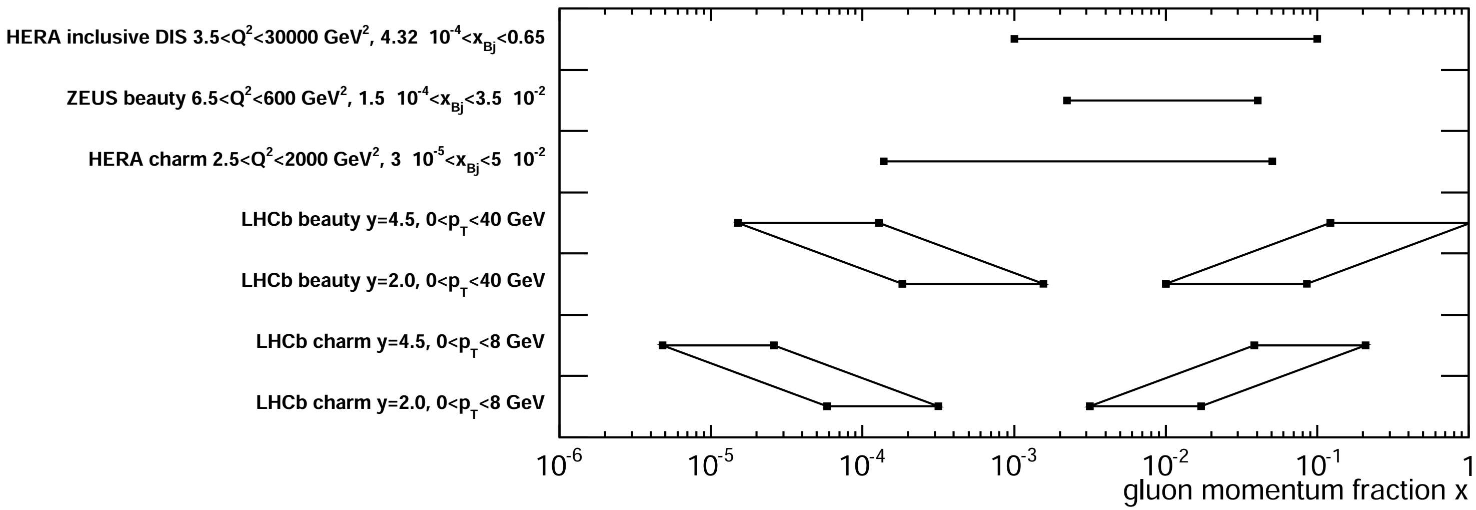
Heavy-quark pair production

- b- and c-quark production at the LHC

Uses of D- and B-meson measurements

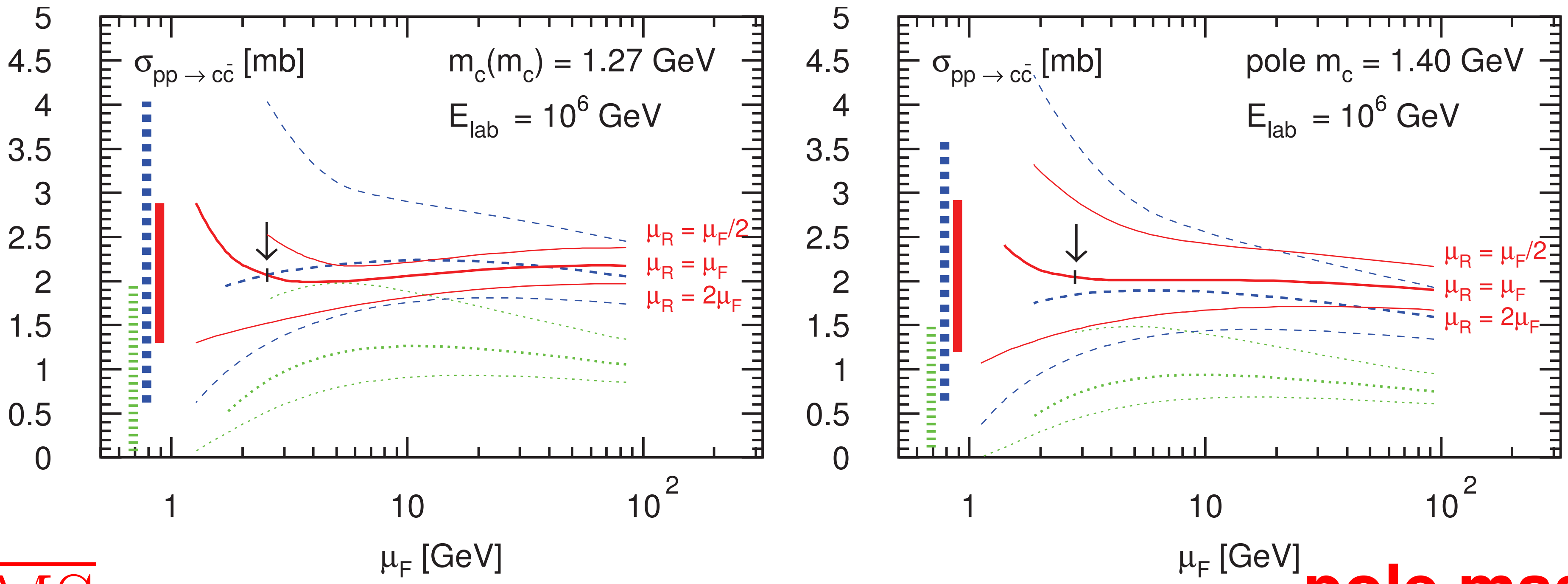
Heavy-quark pair production

- Production process at LHC sensitive to values of
  - heavy-quark mass m_Q
  - strong coupling $\alpha_S(M_Z)$
  - gluon distribution $g(x)$
- Correlation $\sigma_{Q\bar{Q}} \sim \alpha_s^2 \, m_Q^2 \, g(x) \otimes g(x)$
- Effective parton kinematics with $x_{1,2} = 2m_Q/\sqrt{S}\mathrm{e}^{\pm y}$



Charm quark hadro-production (I)

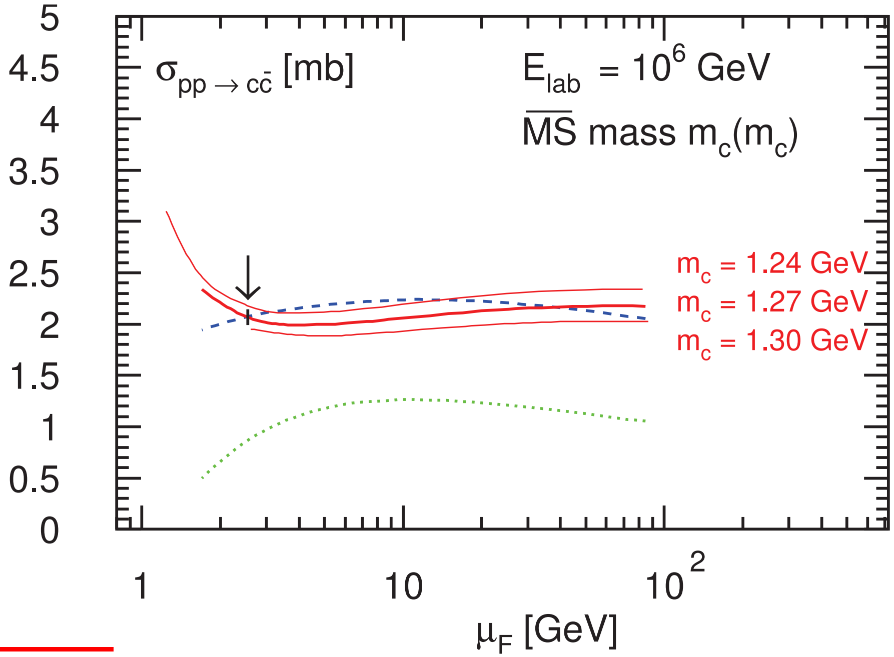
- Theory predictions for charm hadro-production
- NNLO cross section with running charm mass $m_c(m_c)$ significantly improved
  - good apparent convergence of perturbative expansion
  - small theoretical uncertainity from scale variation

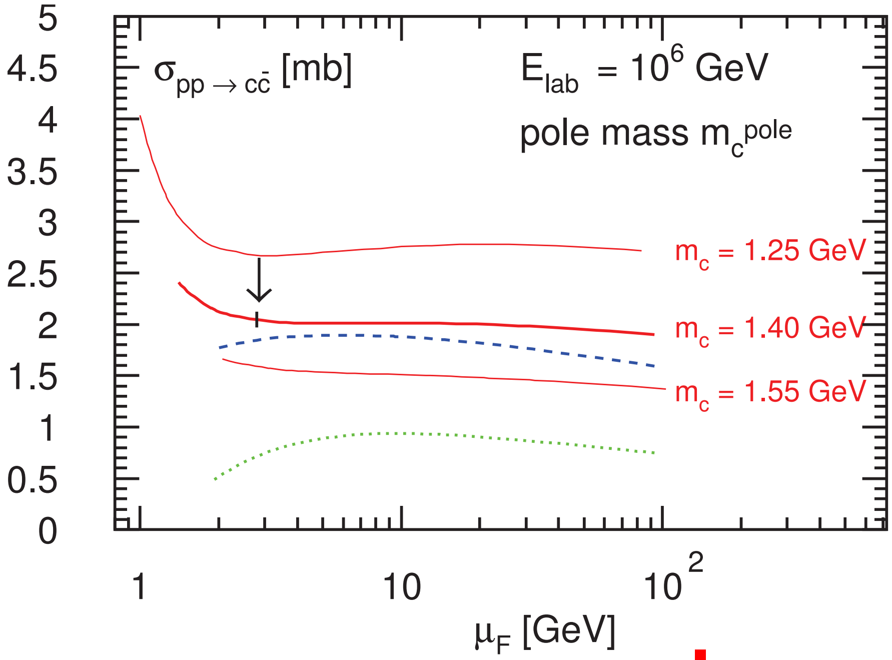


$\overline{\text{MS}}$ mass **pole mass**

Charm quark hadro-production (II)

- Scale choice by comparison of NLO and NNLO cross sections
  - minimal sensitivity at renormalization and factorization scale
    $\mu_R, \mu_F = 2m_c(m_c)$



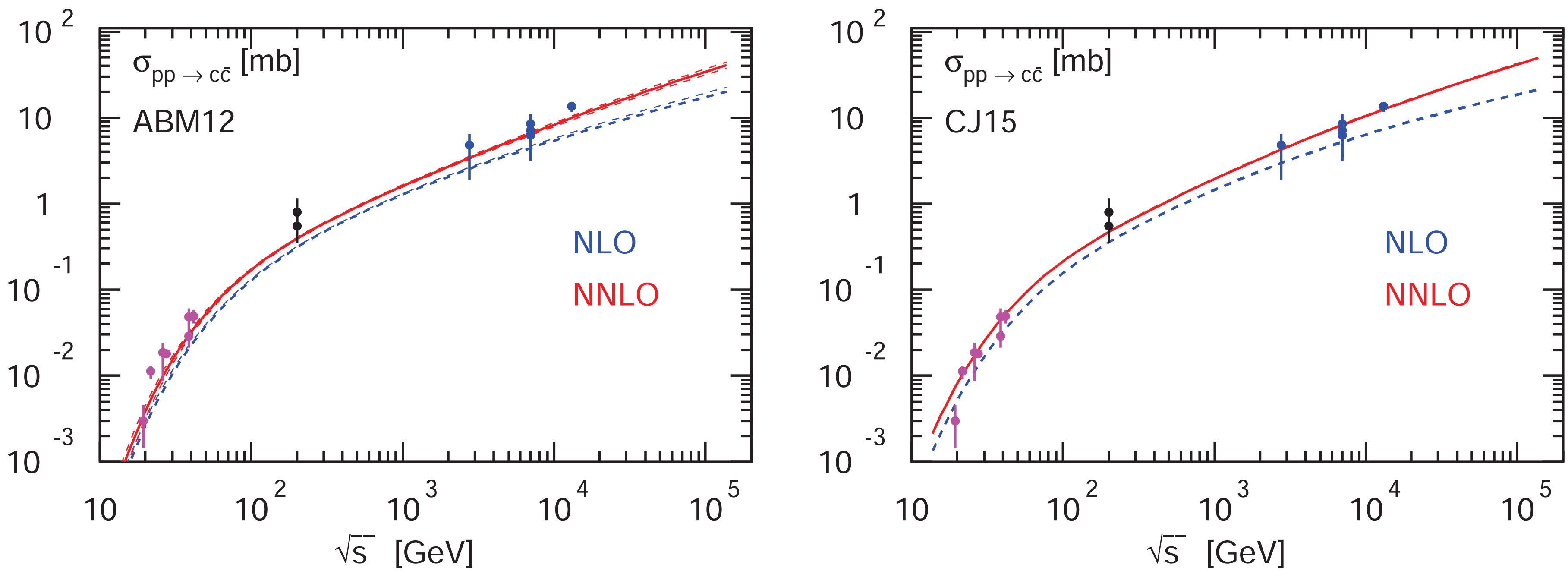


$\overline{\mathrm{MS}}$ mass

pole mass

Parton distribution functions (I)

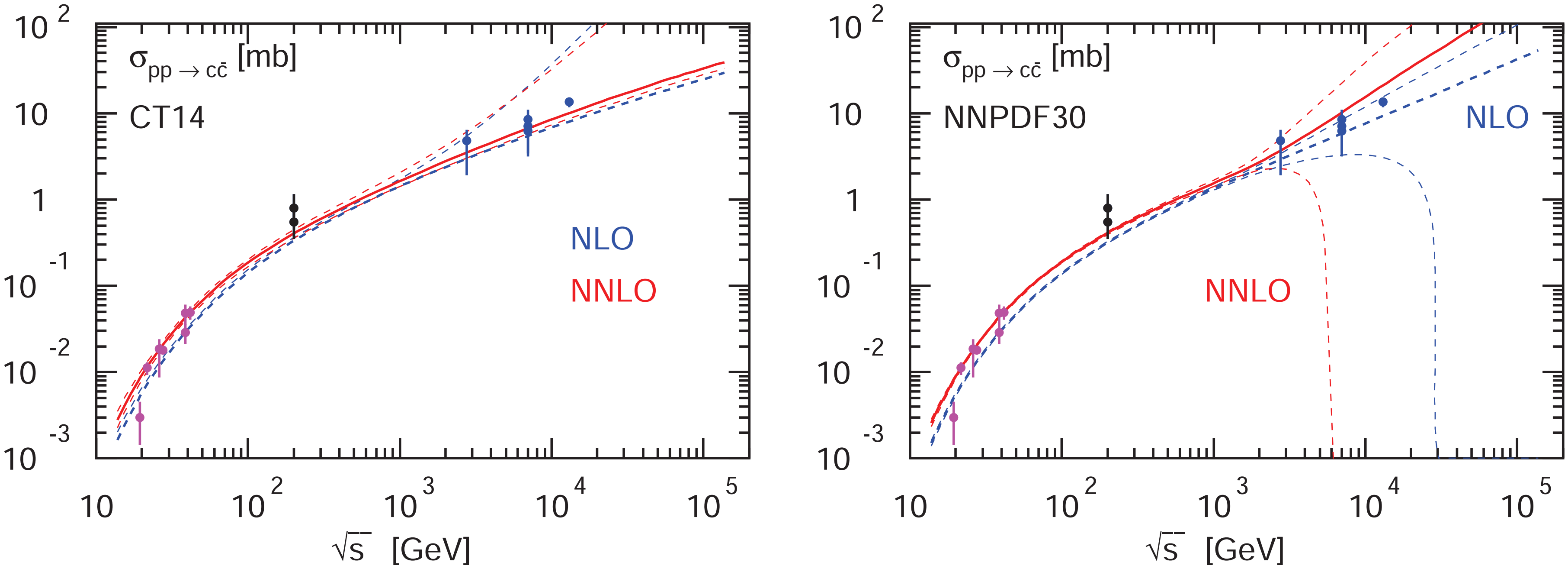
- Charm-quark hadro-production at high energies
  - quark-gluon parton luminosity dominates
- Gluon PDF at small-x
  - fits yield $xg(x) \simeq x^a$; e.g. $a \simeq -0.2$ in ABM12
  - kinematic coverage of data down to $x \simeq 10^{-5}$ (DIS structure function F_L)
- Predictions compatible with LHC measurements (Alice, ATLAS, LHCb)



Parton distribution functions (II)

Issues

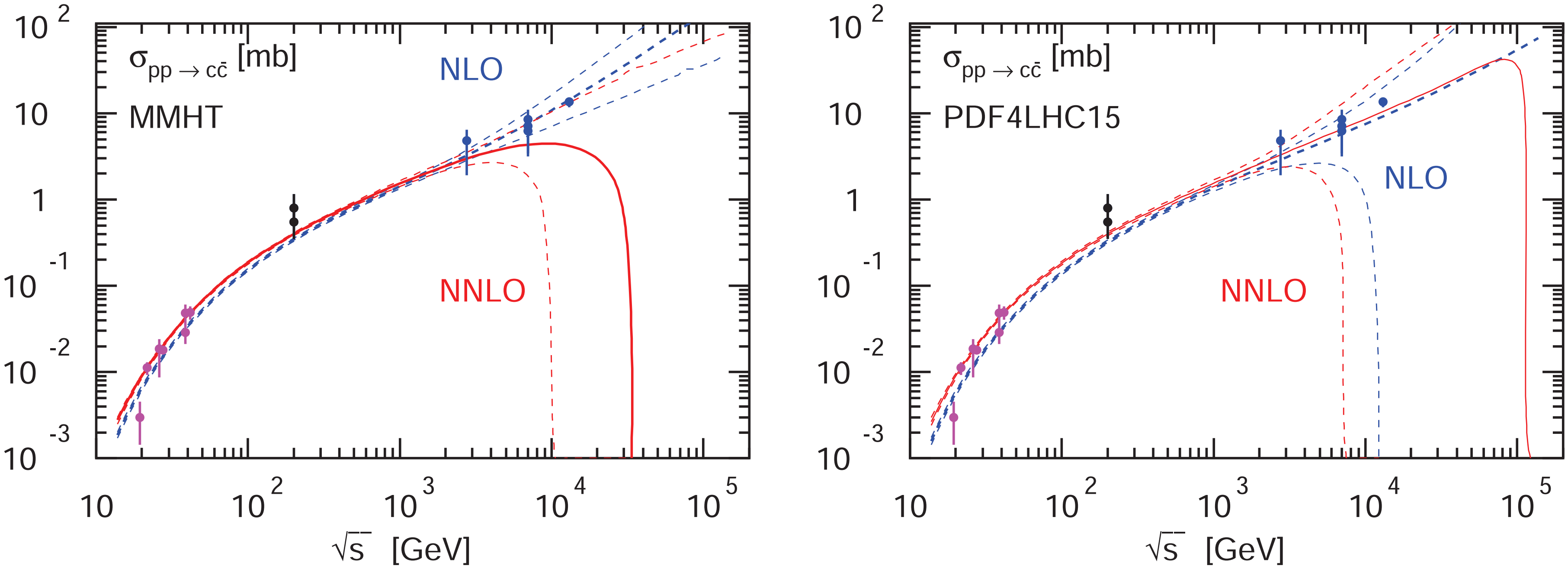
- Extrapolation of gluon PDF towards smaller x
  - some PDFs feature large uncertainities for extrapolation to unmeasured regions $\longrightarrow$ this invalidates predictive potential



Parton distribution functions (III)

More issues

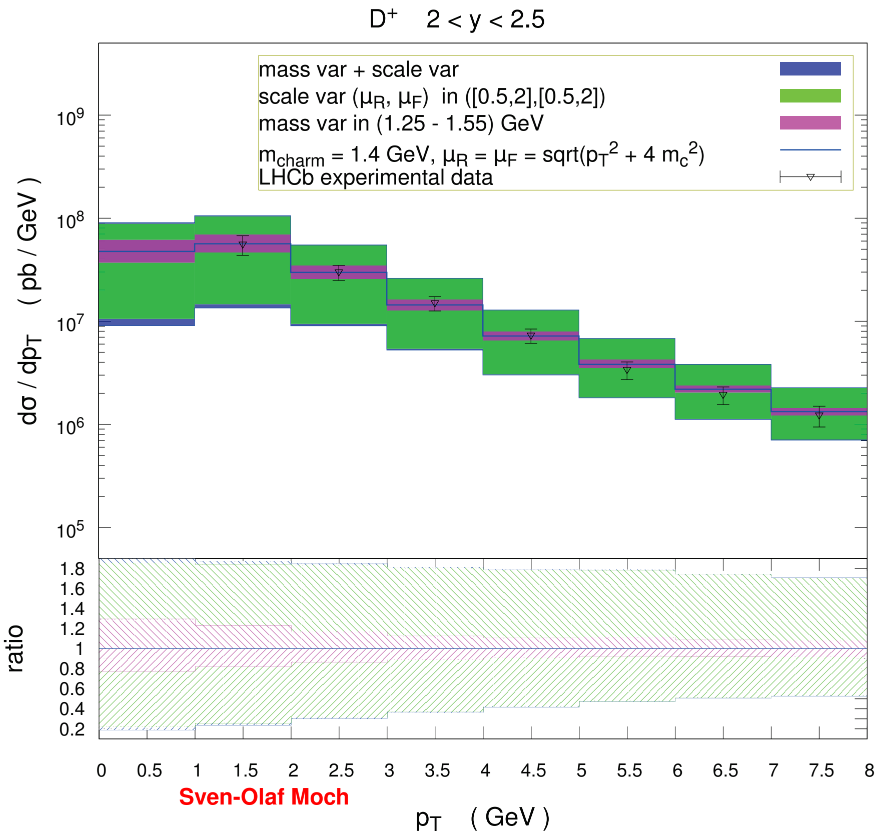
- Some PDFs predict negative gluon PDF at small-x and low scales $\mu_F \simeq 2m_c$
  - negative cross section is unphysical; consequence of modelling in variable flavor number schemes applied and description of structure function F_L at NNLO
  - large differences between gluon PDFs fitted at NLO and NNLO

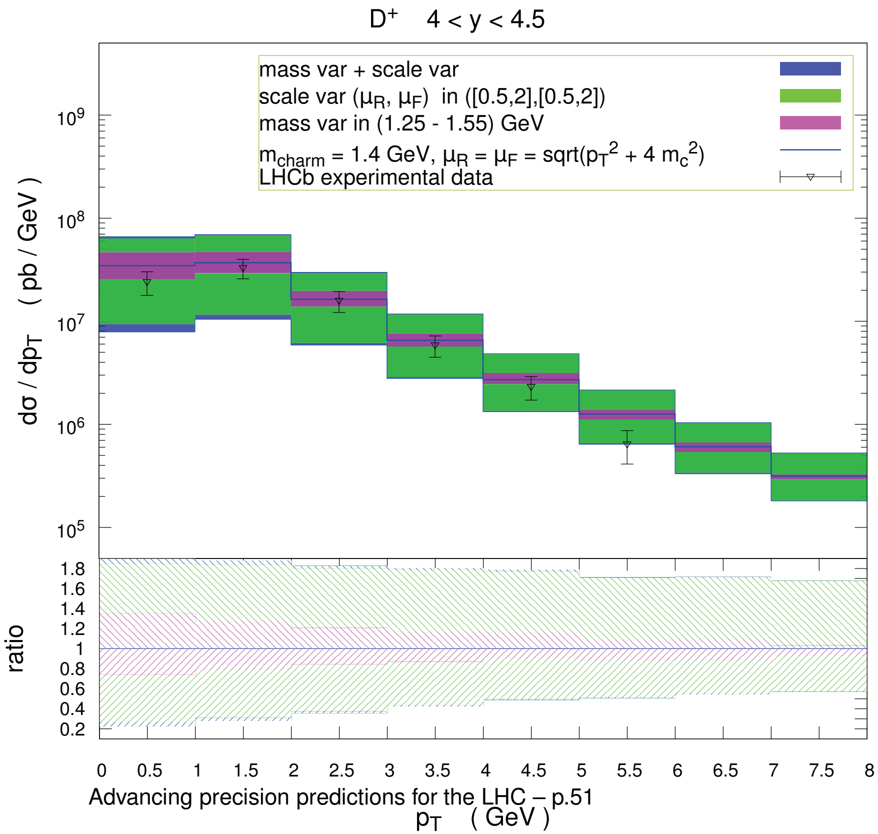


LHCb data on charmed mesons (I)

Comparison of theory predictions with LHCb data

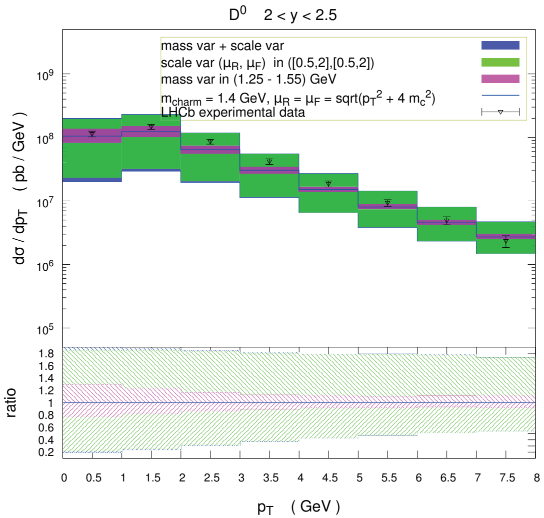
- Charmed meson production $pp \to D^+ + X$ at $\sqrt{s} = 7$ TeV
  - theory predictions to NLO with PowHeg + Pythia and ABM PDFs
  - data within theory uncertainties due to scale and mass variation both for central and for more peripheral collisions
  - theory improvement needed to match accuracy of experimental data

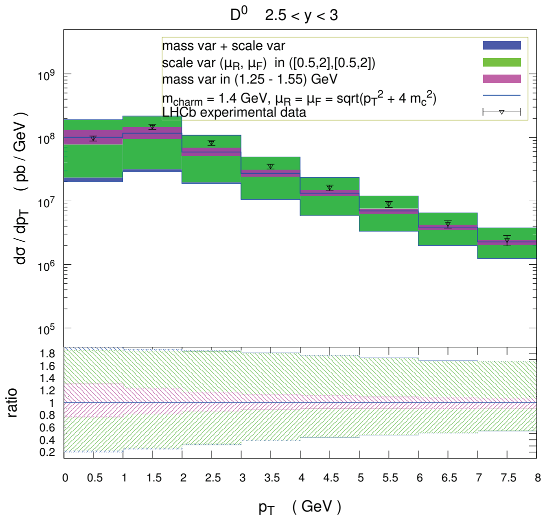


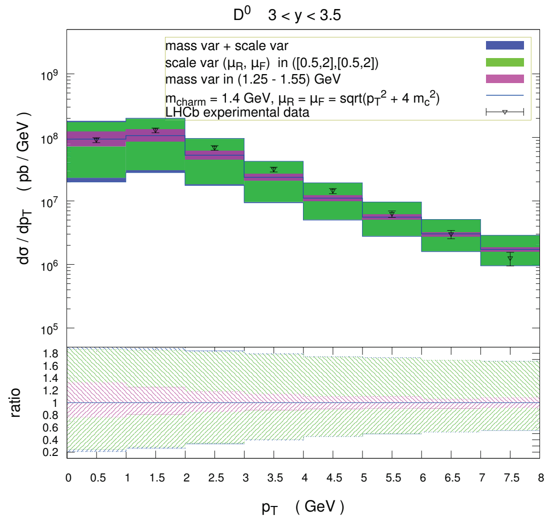


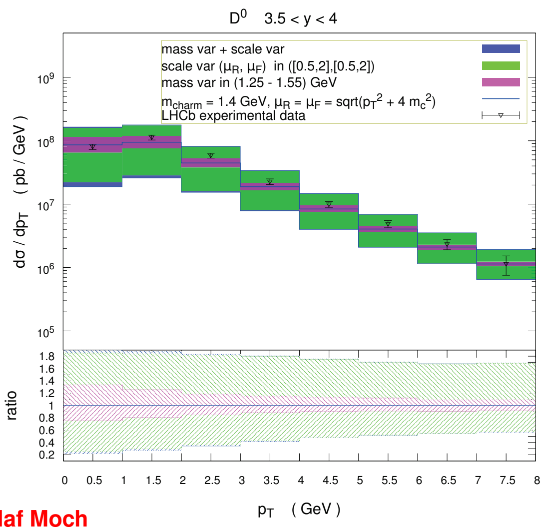
LHCb data on charmed mesons (II)

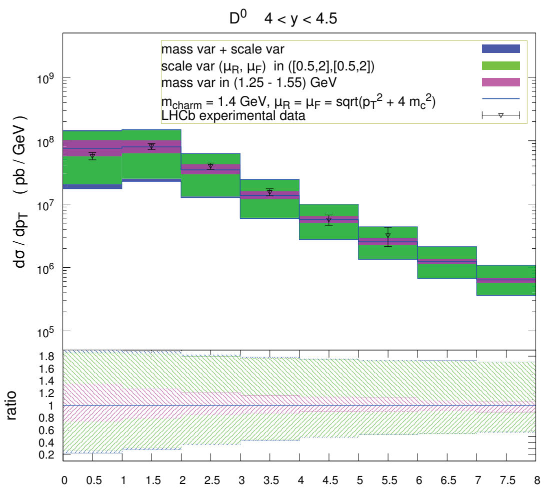
- Charmed meson production $pp \to D^0 + X$
  - data compatible with theory predictions within uncertainties in all measured rapidity bins





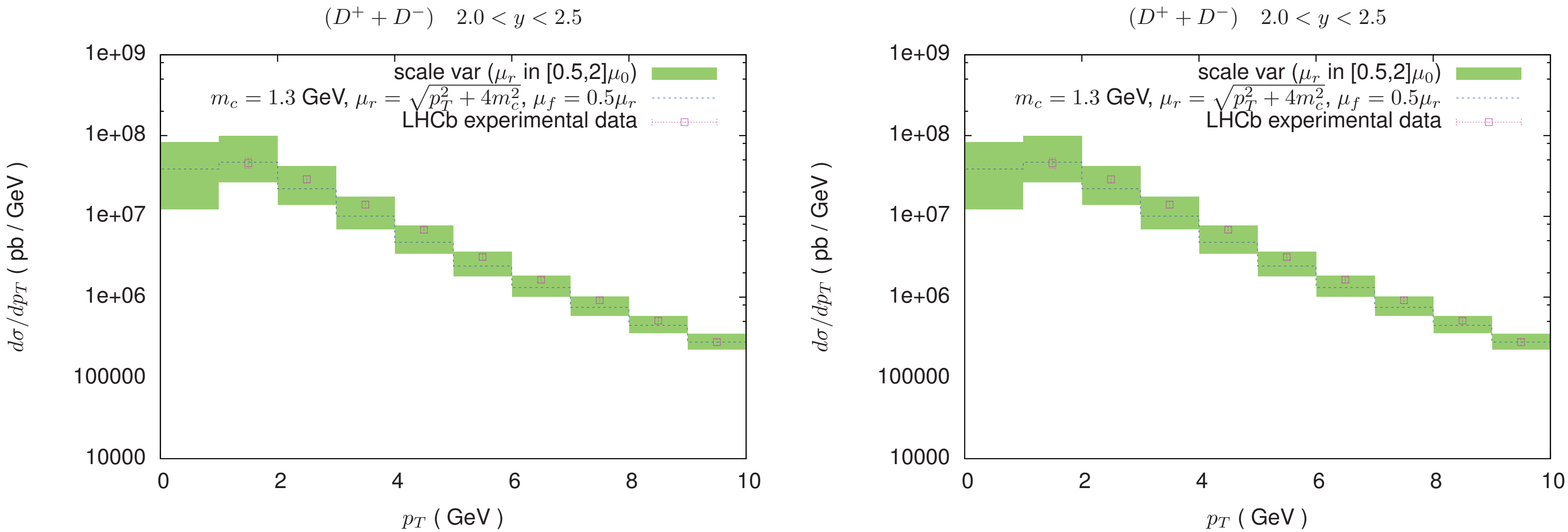






Current status

- Theory predictions at NLO (fully differential) available since long
- Improvements with resummation of logarithms $\ln(m_Q/p_T)$ at NLL
  Benzke, Garzelli, Kniehl, Kramer, Moch, Sigl '17
- NLO QCD predictions for (D^+ + D^-) transverse-momentum distributions at $\sqrt{s}$=5 TeV and LHCb experimental data (arXiv:1610.02230)
  - large uncertainties in NLO predictions due to scale variations



- Experimantal uncertainties are challenging theory predictions
  - large amount of data on D- and B-production from LHC

Summary

$W\pm$- and Z-boson production at the LHC

- Need for fast and precise public code for differential distribution at NNLO (per mil level accuracy)
- Chances for precision comparisons of local and non-local subtraction schemes (q_T slicing, N jettiness)

Hadro-production of jets

- Improved predictions for single-inclusive jet production with joint resummation at NNLL
- Need for fast and precise public code for differential distribution at NNLO (per mil level accuracy)

Heavy-quark pair production

- Single-differential distributions for b- and c-quark production at NNLO