Charm final states at HERA[1]
Impact of LHCb heavy flavour data on PDFs[2]

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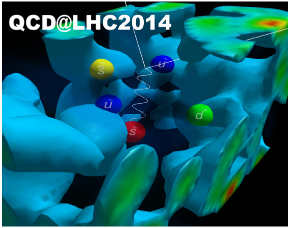
(DESY)

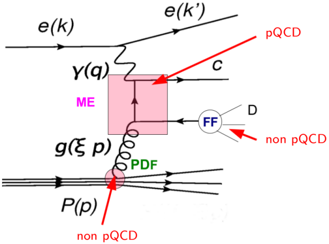


[1] on behalf of the H1 and ZEUS collaborations
[2] on behalf of the PROSA collaboration

QCD@LHC, Suzdal, 26.08.2014

Charm final states at HERA

$$\sigma = \mathbf{PDF} \otimes \mathbf{ME} \otimes \mathbf{FF}$$



- Test of pQCD (multiple hard scales: Q^2, p_T, m_c)
- Heavy quarks are predominantly produced via Boson-Gluon Fusion (BGF) process: sensitive to g density in proton and to m_c

Recent results from HERA:

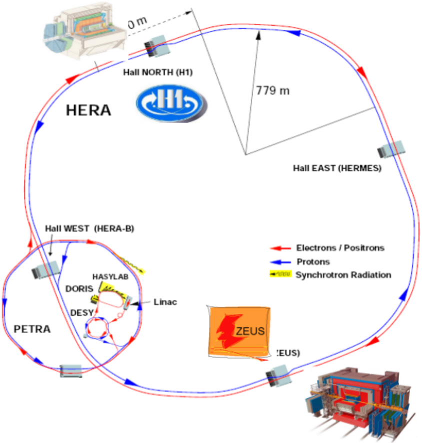
- Measurement of charm production in Deep Inelastic Scatterring (DIS) using secondary vertices [arXiv:1405.6915] (recent measurement from 2014)
- Charm measurements in DIS using $D^{\pm}$ [JHEP05 (2013) 023], D^* [JHEP 05 (2013) 097] and secondary vertices: *summary comparison to HERA charm combination* [EPJ C73 (2013) 231 1]
- Combination of D^* visible cross sections (HERA preliminary)
- Measurement of D^* in Photoproduction (PHP) at different centre-of-mass energies [arXiv:1405.5068] (recent measurement from 2014)
- Measurement of charm fragmentation fractions in PHP [JHEP09 (2013) 058]

HERA Collider

- ep interactions
- $\sqrt{s} = 300...318$ GeV

H1 and ZEUS:

- 4π multipurpose detectors
- $\mathcal{L} \sim 500$ pb^{-1} per each experiment



$E_p = 920\,GeV$ $\quad E_e = 27.5\,GeV$

$\sqrt{s} = 318\,GeV$

Charm final states at HERA. Kinematics

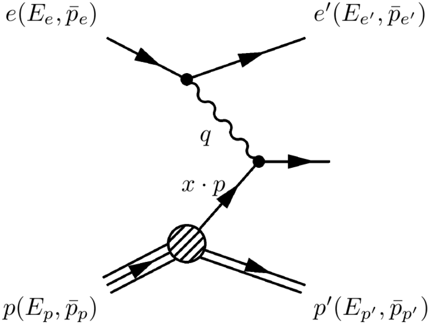
$$Q^2 = -q^2 = -(e - e')^2$$

$$x = \frac{Q^2}{2q \cdot p}$$

$$y = \frac{q \cdot p}{q \cdot e}$$

$$s = (e + p)^2$$

$$Q^2 = sxy$$

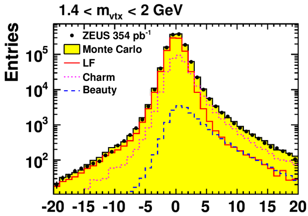


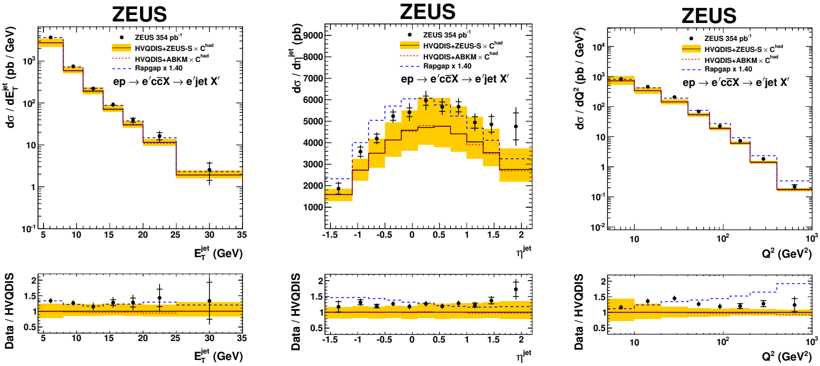
Any two of the variables (Q^2, x, y) define kinematics

$Q^2 > 1\ GeV^2$ — deep inelastic scattering (DIS)
$Q^2 < 1\ GeV^2$ — photoproduction processes (PHP)

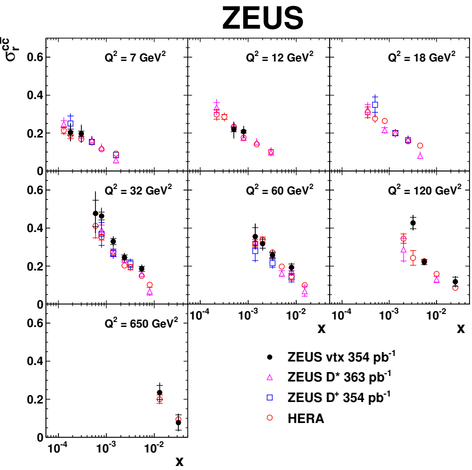
Charm final states at HERA. Measurement of charm production in DIS using secondary vertices [arXiv:1405.6915]

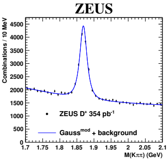
- Charm and beauty production with at least one jet measured using decay-length significance S of associated to jet secondary vertex
- Differential cross sections as a function of Q^2, x, E_T^{jet}, η^{jet}
- Well described by NLO QCD predictions

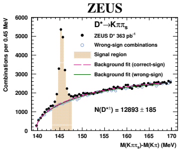


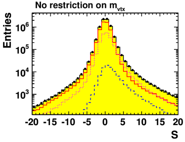


Charm final states at HERA. Charm measurements in DIS using $D^{\pm}$, D^{*} and secondary vertices: summary comparison









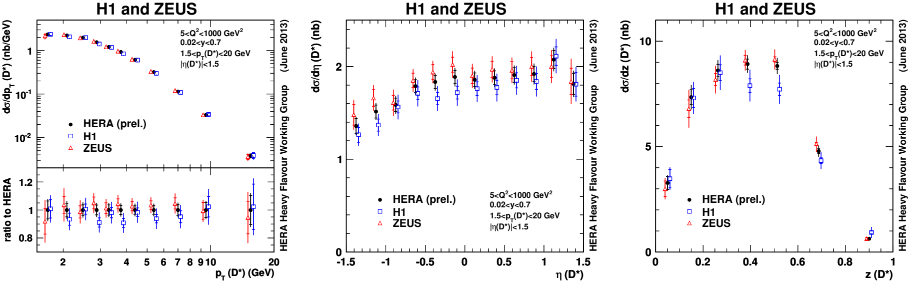
New measurements are consistent with the HERA charm combination and have competitive precision

⇒ can improve the combination!

Charm final states at HERA. Combination of D^* visible cross sections

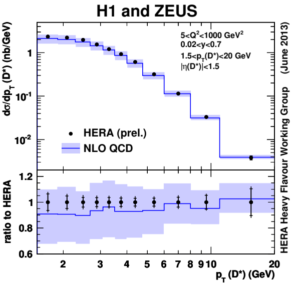
Advantages of the D^* visible cross sections combination:

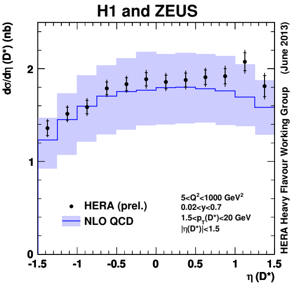
- Directly measured quantities in very similar phase space and bins $\Rightarrow$ neglibly small extrapolation uncertainties
- New observables are available: $p_T(D^*)$, $\eta(D^*)$, $z(D^*) = \frac{E(D^*)-p_Z(D^*)}{2E_e y}$

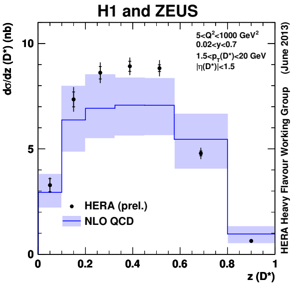


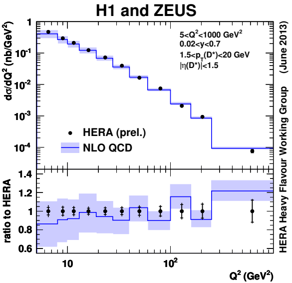
- Good agreement between H1 and ZEUS
- Improvement in precision $\sim \sqrt{2}$

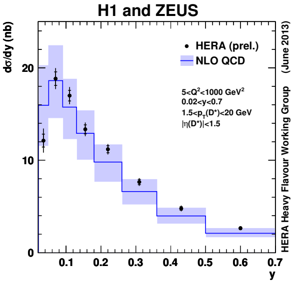
Charm final states at HERA. Combination of D^* visible cross sections





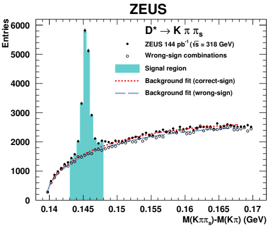


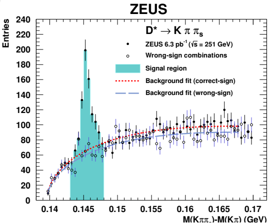


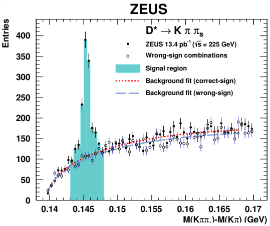


- Well described by FFNS NLO convoluted with FF measured by H1 and ZEUS
- Data are more precise than theory
- $\Rightarrow$ NNLO and improved fragmentation are wanted!

Charm final states at HERA. Measurement of D^* in PHP at different centre-of-mass energies [arXiv:1405.5068]





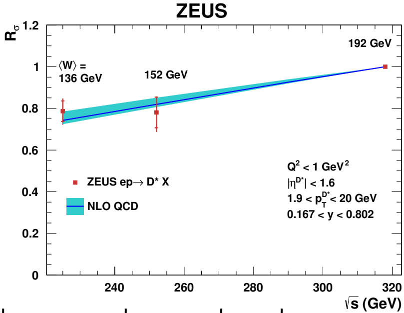


- ZEUS, 2006 / 2007 years;
- Photoproduction ($Q^2 < 1$ GeV^2)
- Phase Space: $(W^2 = (q+p)^2)$

$130 < W_{HER} < 285$ GeV
$103 < W_{MER} < 225$ GeV
$92 < W_{LER} < 201$ GeV
} $0.167 < y < 0.802$

$1.9 < p_T(D^*) < 20$ GeV

$|\eta(D^*)| < 1.6$

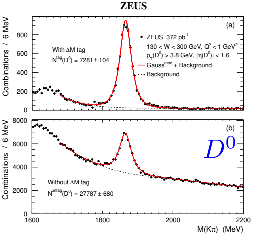


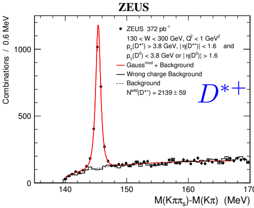
NLO QCD predictions (FMNR) well describe measured energy dependence

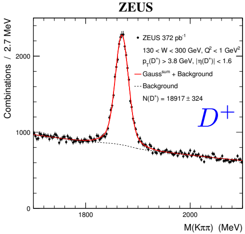
⇒ theory is reliable for extrapolation to future ep colliders

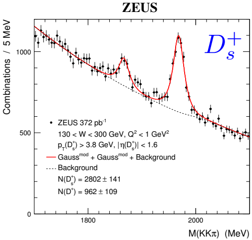
Charm final states at HERA. Measurement of charm fragmentation fractions in γp [JHEP09 (2013) 058]

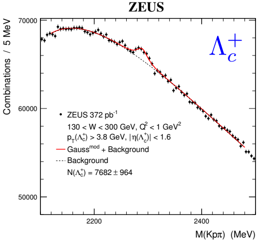
$f(c \to H_c)$: probability of c-quark to hadronize into particular hadron.









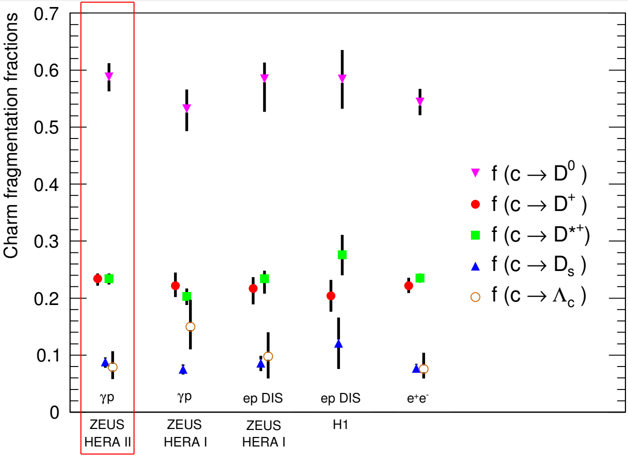


Analyzed channels:

- $D^0 \to K^-\pi^+$
- $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$
- $D^+ \to K^-\pi^+\pi^+$
- $D_s^+ \to K^+K^-\pi^+$
- $\Lambda_c^+ \to pK^-\pi^+$

Is the charm fragmentation fractions $f(c \to H_c)$ universal?

Charm final states at HERA. Measurement of charm fragmentation fractions in γp [JHEP09 (2013) 058]



- Consistent with all other measurements:
  $\Rightarrow$ confirms frgamentation universality
- Precision competitive to e^+e^-

Summary

- New precise charm measurement in DIS using secondary vertices
- Together with recent $D^{\pm}$ and D^{*}:
  - *potential improvement of HERA charm combination*
- New HERA combination of D^{*} visible cross section:
  - *more precise than available QCD calculations*
- New measurement of D^{*} in PHP in different centre-of-mass energy:
  - *well described by NLO QCD*
- Measurement of charm fragmentation fractions in PHP:
  - *confirms fragmentation universlity*
  - *potential to improve world average fragmentation fractions*

After 7 years of HERA shutdown
H1 and ZEUS are still very active in charm studies!

Impact of LHCb heavy flavour data on PDFs

Overview:

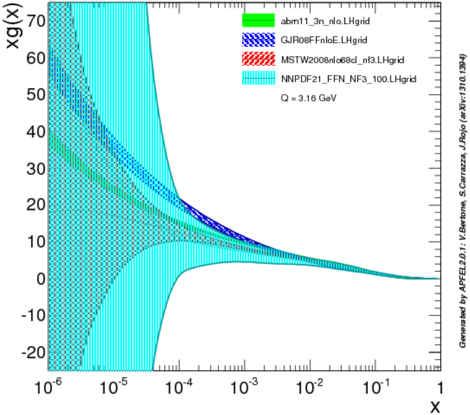
- Introduction to PROSA Collaboration
- Motivation: gluon PDF at low x and low Q^2
- Framework:
  - HERAFitter: PDF fitting package
  - input data: HERA + LHCb
  - theoretical calculations: FFNS NLO QCD
- PDF fits with LHCb heavy flavour data at threshold:
  - fitting absolute LHCb cross sections
  - fitting normalised LHCb cross sections
- Discussion of results

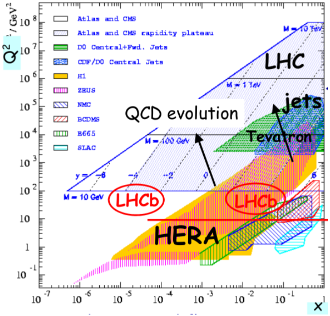
PROton Structure Analyses in hadronic collisions (PROSA)

- PROSA is a novel collaborative effort between high-energy physicists in experiment and theory, from DESY, German universities, and international partners, in order to advance the interpretation of proton collision data from the CERN Large Hadron Collider (LHC) and elsewhere.
- Our goal is significant improvement in the precision of parameters of the Standard Model and thus in its predictive power in order to facilitate the advanced interpretation of LHC results
- Working Packages:
    - WP1 Experimental Analyses
    - WP2 Theoretical Predictions
    - WP3 Tool Development
    - WP4 Integrated Physics Analysis
- See more at https://prosa.desy.de

Impact of LHCb heavy flavour data on PDFs. Motivation

Benchmark of gluon PDF at $Q^2 = 10\ \text{GeV}^2$,
Fixed-Flavour-Number Scheme (FFNS), n_f=3





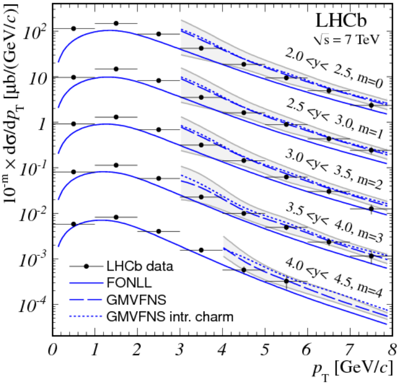
LHCb heavy flavour data uniquely cover the low x low Q^2 region

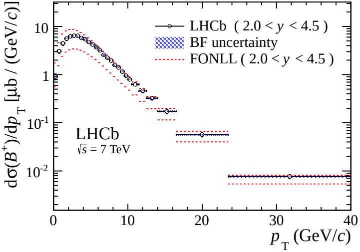
- Large spread due to lack of data in the low x low Q^2 region in fits
- LHCb heavy flavour data have a potential to constrain gluons there

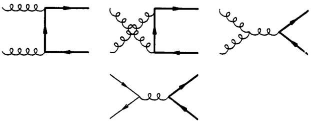
Impact of LHCb heavy flavour data on PDFs. LHCb data

LHCb has recently measured charm and beauty production in the forward region $2.0 < y < 4.5$:

- charm, $0 < p_T < 8\ GeV$ [NPB871 (2013) 1]
- beauty, $0 < p_T < 40\ GeV$ [JHEP08 (2013) 117]







- Theory describes data well within large theoretical uncertainties
- Dominant theoretical uncertainties (~ 2) from scales μ_f, μ_r variations

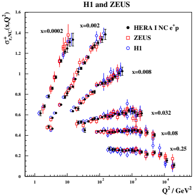
Impact of LHCb heavy flavour data on PDFs. Framework

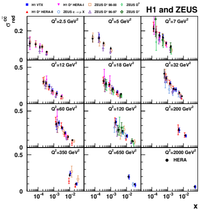
Closely followed HERAPDF fit:

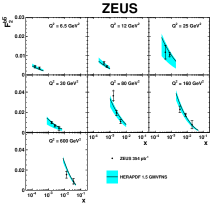
- Platform: HERAFitter [www.herafitter.org]
- Input data:
  - HERA-I $e^{\pm}p$ inclusive data ($\sim$ %) [JHEP01 (2010) 109]
  - Combined HERA charm data ($\sim$ 5-10%) [EPJ C73 (2013) 2311]
  - ZEUS beauty vertex data ($\sim$ 10-25%) [arXiv:1405.6915]
  - LHCb charm data ($\sim$ 5-20%) [NPB871 (2013) 1]
  - LHCb beauty data ($\sim$ 5-35%) [JHEP08 (2013) 117]

- Theoretical predictions (FFNS scheme)
  - NLO QCD predictions for $pp \rightarrow$ HQ by M. Mangano, P. Nason and G. Ridolfi [MNR] [NPB327 (1989) 49]
  - HQ frag. functions: c as meas. at HERA [EPJ C59 (2009) 589, JHEP04 (2009) 082], b as meas. at LEP [NPB565 (2000) 245]
  - HQ frag. fractions: comb. of LEP and HERA meas. [arXiv:1112.3757]
  - NLO QCD predictions for HERA data: FFNS ABM scheme
  - pole HQ masses m_c, m_b left free in the fit
  - $\alpha_s^{n_f=3}(M_Z) = 0.1059 \pm 0.0005$ (equivalent to PDG $\alpha_s^{n_f=5}(M_Z) = 0.1185 \pm 0.0006$)
  - DGLAP NLO PDF evolution

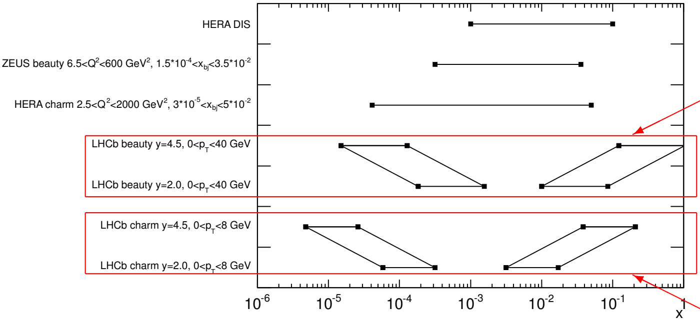
- PDF parametrisation: 13p HERAPDF style, $Q_0^2 = 1.4\ GeV^2$ (more information in BACKUP)

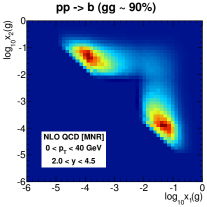




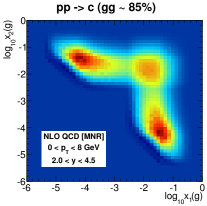


Impact of LHCb heavy flavour data on PDFs. Kinematics: gluon x ranges





$(Q^2 \sim 2..100\ GeV^2)$



$(Q^2 \sim 20..2000\ GeV^2)$

- LHCb data cover $x \sim 10^{-5}..10^{-3}$ (*small* x) and $x \sim 10^{-3}..10^{-1}$ (*medium* x)
- *Medium* x covered by HERA data $\Rightarrow$ expect improvement at *small* x

Impact of LHCb heavy flavour data on PDFs. PDF uncertainties

Followed HERAPDF fit:

Fit unc.:

- $\chi^2 = \chi_0^2 + 1$

Model unc.:

- $f_s = 0.31^{+0.07}_{-0.08}$
- m_c,m_b —free parameters, unc. included in the $\chi^2 = \chi^2 \pm 1$
- $Q^2_{min} = 3.5^{+1.5}_{-1.0}\ GeV^2$
- $\alpha_s(M_Z) = 0.1059 \pm 0.0005$
- μ_f, μ_r for HQ in ep varied simult. by a factor 2

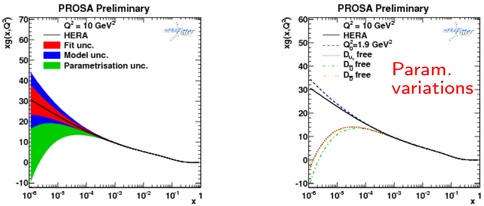
Parametrisation unc.:

- Different parametrisations
- $Q_0^2 = 1.9\ GeV^2$

(take the largest deviation)

Fit with HERA data only

$(\chi^2/NDoF = 647/646)$



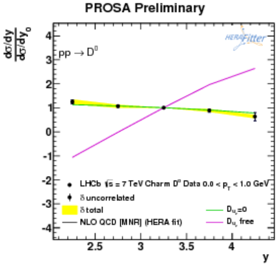
At low x, low Q^2:

- no data in this region, "fitted" only with parametrisation and sum rules

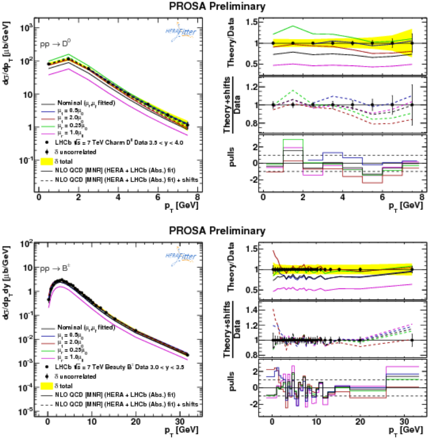
  $\Rightarrow$ dominant uncertainties are parametrisation ones

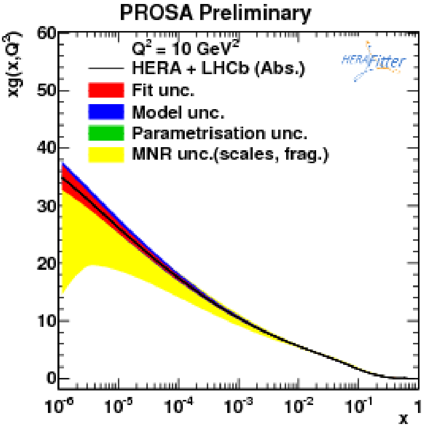
Impact of LHCb heavy flavour data on PDFs. Two approaches to fit LHCb data

- Fit the absolute cross sections $\frac{d\sigma}{dp_T dy}$
  - using all available information, but
  - suffer from large scale uncertainties $\sim$ factor 2
  - $\Rightarrow$ scales μ_f, μ_r parametrised as
    $\mu_f^c = A_f^c\sqrt{p_T^2 + m_c^2}, \quad \mu_r^c = A_r^c\sqrt{p_T^2 + m_c^2}, \quad \mu_f^b = A_f^b\sqrt{p_T^2 + m_b^2}, \quad \mu_r^b = A_r^b\sqrt{p_T^2 + m_b^2}$
    (A_f^c, A_r^c, A_f^b, A_r^b left free in the fit)
  - μ_f, μ_r varied in the ranges
    $$A_f^c = A_f^b = 0.50, \quad A_f^c = A_f^c = 2.00, \quad A_r^c = A_r^b = 0.25, \quad A_r^c = A_r^b = 1.00$$
    (other scales refitted)
  - data dependent theory concept, but each scale varied by factor 2
- Fit the normalised in y cross sections $\frac{d\sigma}{dy} / \frac{d\sigma}{dy_0}$
  (y_0 in the central LHCb bin $3.0 < y < 3.5$):
  - y is directly related to parton x
  - scale uncertainties reduced to $\sim 10\%$
  - $\Rightarrow$ scales μ_f, μ_r set to:
    $$\mu_f^c = \mu_r^c = \mu_f^b = \mu_r^b = \sqrt{p_T^2 + m_Q^2}$$
  - μ_f, μ_r varied independently in the range [0.5;2.0]
  - fully data independent theory concept



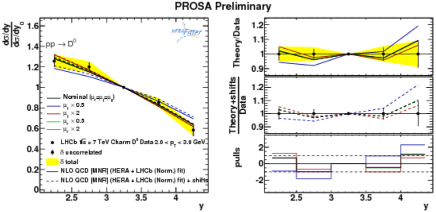
Impact of LHCb heavy flavour data on PDFs. Fit with absolute LHCb data

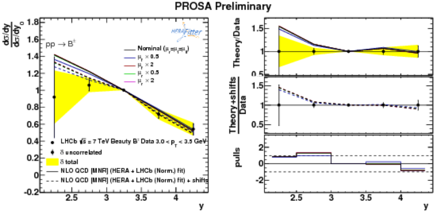


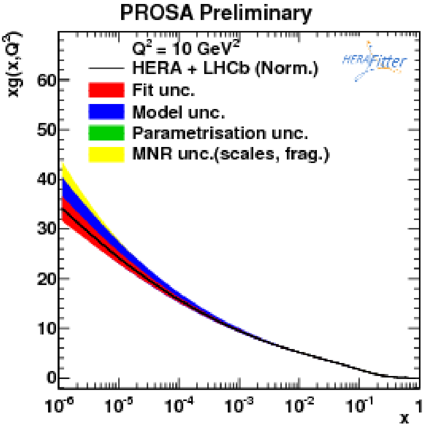


- $\chi^2/NDoF = 1073/1087$
- drastical reduction of par. unc. at low x
- but instead large new MNR unc.
- $\Rightarrow$ still significant improvement of total unc. at low x

Impact of LHCb heavy flavour data on PDFs. Fit with normalised LHCb data

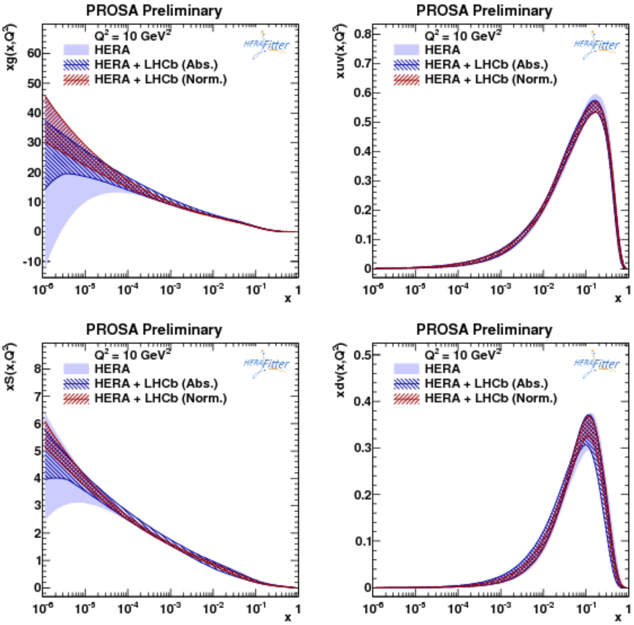






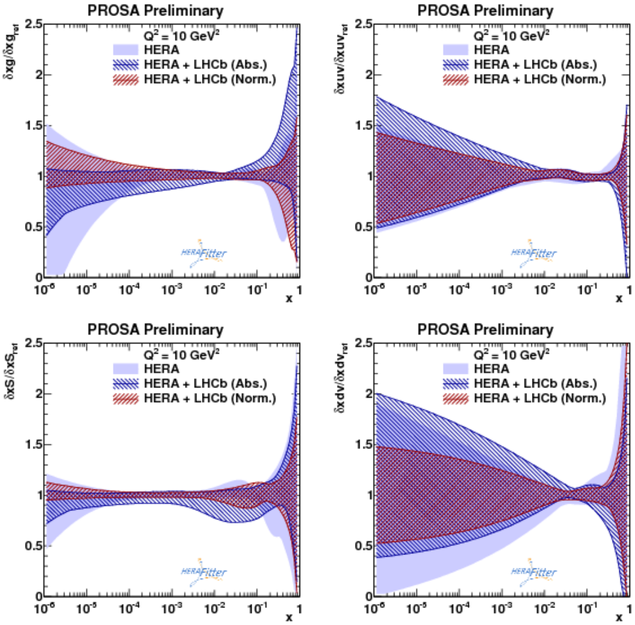
- $\chi^2/NDoF = 960/996$
- drastical reduction of par. unc. at low x
- moderate new MNR unc.
- $\Rightarrow$ significant improvement of total unc. at low x

Impact of LHCb heavy flavour data on PDFs. PDF shape



- "HERA + LHCb" densities are within "HERA"
- significant improvement for g and sea quarks densities at low x with both approaches
- both approaches give consistent results
- smaller total uncertainties with the normalised approach

Impact of LHCb heavy flavour data on PDFs. Uncertainties



- "HERA + LHCb" densities are within "HERA"
- significant improvement for g and sea quarks densities at low x with both approaches

- both approaches give consistent results
- smaller total uncertainties with the normalised approach

Summary

- Two approaches to include the forward LHCb heavy flavour data in the PDF fit: fit the absolute or normalised in y cross sections.
- With both approaches a strong impact of the new data on the low x low Q^2 gluons and sea quarks is observed.
- While in the first approach all information from the measured data is used, results suffer from large theory uncertainties.
- In the second approach theory dependence is much reduced; although only the y shape of the cross sections is used, resulting uncertainties for the PDFs are smaller.
- Improvements in theory (NNLO and fragmentation) are very desirable

Despite the large uncertainties of the current QCD calculations the LHCb heavy flavour data can be used in PDF fits to constrain gluons at low x.

BACKUP. Charm final states at HERA. pQCD approximation of heavy flavour production

Fixed Flavour Number Scheme (FFNS)

- c,b-quarks are massive $\Rightarrow$ not a part of the proton, produced perturbatively in hard scattering
- valid for $Q^2 \sim m_{c,b}^2$

Zero Mass Variable Flavour Number Scheme (ZMVFNS)

- c,b-quarks are massless $\Rightarrow$ a part of the proton
- valid for $Q^2 >> m_{c,b}^2$

General Mass Variable Flavour Number Scheme (GMVFNS)

- equivalent to FFNS at low Q^2
- equivalent to ZMVFNS at high Q^2
- not unique (RT, ACOT, ...)

BACKUP. Impact of LHCb heavy flavour data on PDFs. Parametrisation

PDF parametrisation: 13p HERAPDF style:

$$xg(x) = A_g x^{B_g} (1-x)^{C_g} - A'_g x^{B'_g} (1-x)^{C'_g}$$
$$xu_v(x) = A_{u_v} x^{B_{u_v}} (1-x)^{C_{u_v}} (1 + E_{u_v} x^2)$$
$$xd_v(x) = A_{d_v} x^{B_{d_v}} (1-x)^{C_{d_v}}$$
$$x\bar{U}(x) = A_{\bar{U}} x^{B_{\bar{U}}} (1-x)^{C_{\bar{U}}},\ x\bar{D}(x) = A_{\bar{D}} x^{B_{\bar{D}}} (1-x)^{C_{\bar{D}}}$$

(parametrised at starting scale $Q_0^2 = 1.4\ GeV^2$)

Additional constrains:

$$A_{\bar{U}} = A_{\bar{D}}(1 - f_s)$$
$$B_{\bar{U}} = B_{\bar{D}}$$
$$C'_g = 25$$
$$\int_0^1 [\sum_i (q_i(x) + \bar{q}_i(x)) + g(x)] x dx = 1$$
$$\int_0^1 [u(x) - \bar{u}(x)] dx = 2$$
$$\int_0^1 [d(x) - \bar{d}(x)] dx = 1$$

BACKUP. Impact of LHCb heavy flavour data on PDFs. Partial χ^2

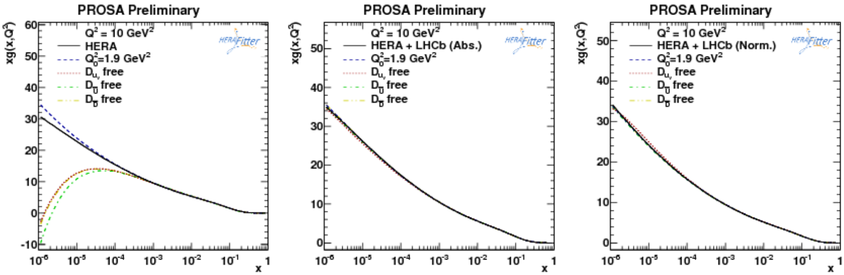
HERA + LHCb Abs.

Dataset	nominal
NC cross section HERA-I H1-ZEUS combined e-p.	108 / 145
NC cross section HERA-I H1-ZEUS combined e+p.	419 / 379
CC cross section HERA-I H1-ZEUS combined e-p.	26 / 34
CC cross section HERA-I H1-ZEUS combined e+p.	39 / 34
Charm cross section H1-ZEUS combined	78 / 52
Beauty cross section ZEUS Vertex (no shift)	16 / 17
LHCb Dzero pT-y cross section	68 / 38
LHCb Dch pT-y cross section	53 / 37
LHCb Dstar pT-y cross section	50 / 31
LHCb Ds pT-y cross section	24 / 28
LHCb Lambdac pT cross section	5.3 / 6
LHCb Bch pT-y cross section	99 / 135
LHCb Bzero pT-y cross section	66 / 95
LHCb Bs pT-y cross section	78 / 75
Total χ^2 / dof	1073 / 1087
χ^2 p-value	0.61

HERA + LHCb Norm.

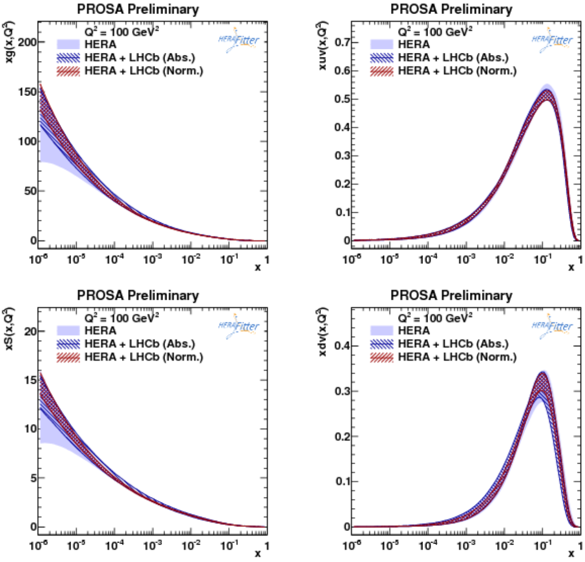
Dataset	nominal
NC cross section HERA-I H1-ZEUS combined e-p.	108 / 145
NC cross section HERA-I H1-ZEUS combined e+p.	419 / 379
CC cross section HERA-I H1-ZEUS combined e-p.	26 / 34
CC cross section HERA-I H1-ZEUS combined e+p.	41 / 34
Charm cross section H1-ZEUS combined	47 / 52
Beauty cross section ZEUS Vertex (no shift)	12 / 17
LHCb Dzero pT-y cross section	17 / 30
LHCb Dch pT-y cross section	18 / 29
LHCb Dstar pT-y cross section	19 / 22
LHCb Ds pT-y cross section	11 / 20
LHCb Lambdac y cross section	4.9 / 3
LHCb Bch pT-y cross section	81 / 108
LHCb Bzero pT-y cross section	35 / 76
LHCb Bs pT-y cross section	23 / 60
Total χ^2 / dof	958 / 994
χ^2 p-value	0.79

BACKUP. Impact of LHCb heavy flavour data on PDFs. Parametrisation uncertinties



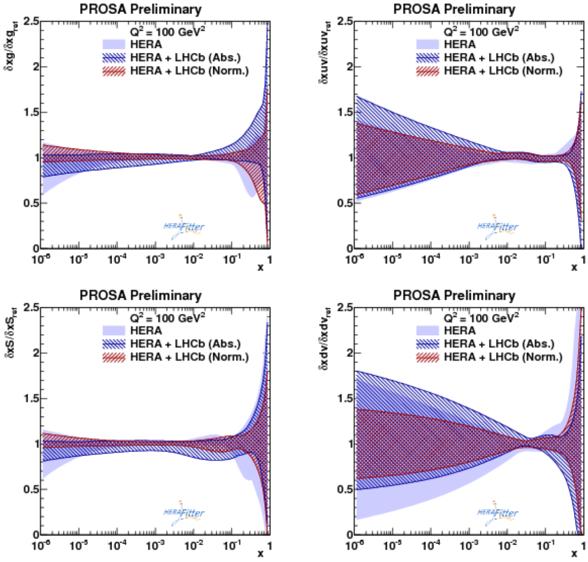
Drastical reduction of the parametrisation uncertinties at low x when the LHCb heavy flavour data are included in the fit

BACKUP. Impact of LHCb heavy flavour data on PDFs. Discussion, $Q^2 = 100\ GeV^2$



- significant improvement for g and sea quarks densities at low x with both approaches
- both approaches give consistent results

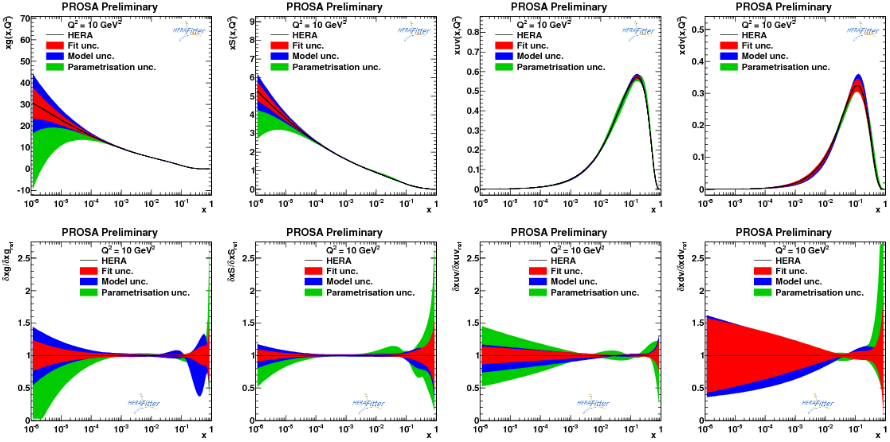
BACKUP. Impact of LHCb heavy flavour data on PDFs. Discussion, $Q^2 = 100\ GeV^2$



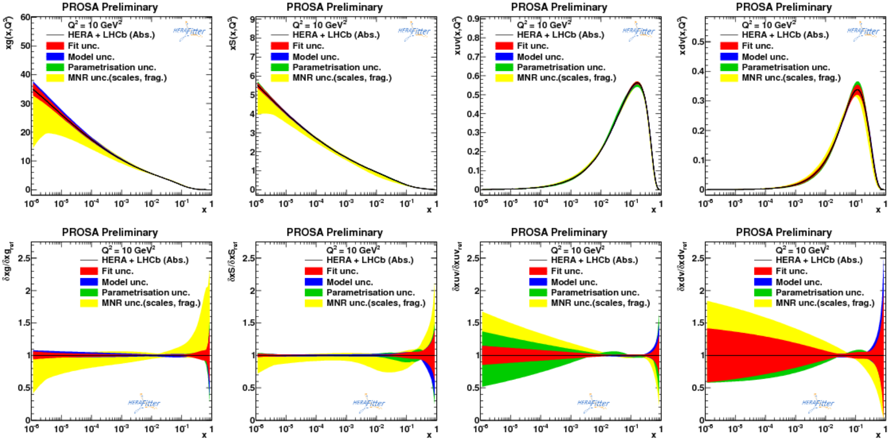
Relative PDF uncertainties:

- smaller total uncertainties with the normalised approach

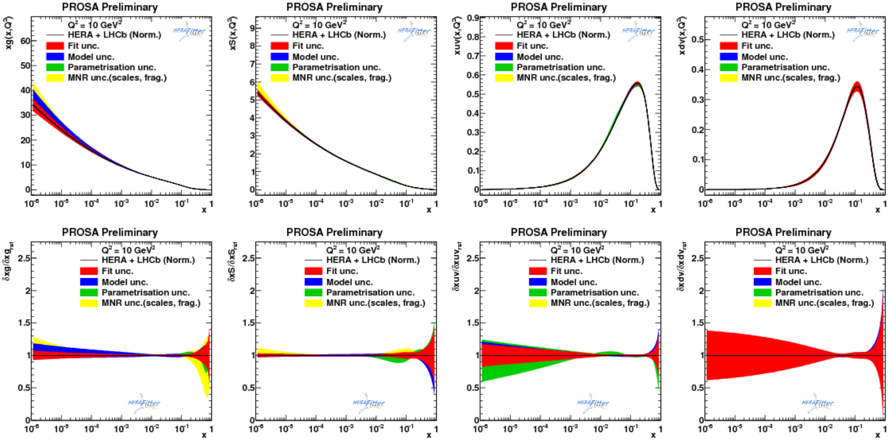
BACKUP. Impact of LHCb heavy flavour data on PDFs. Individual PDF uncertainties, $Q^2 = 10\ GeV^2$



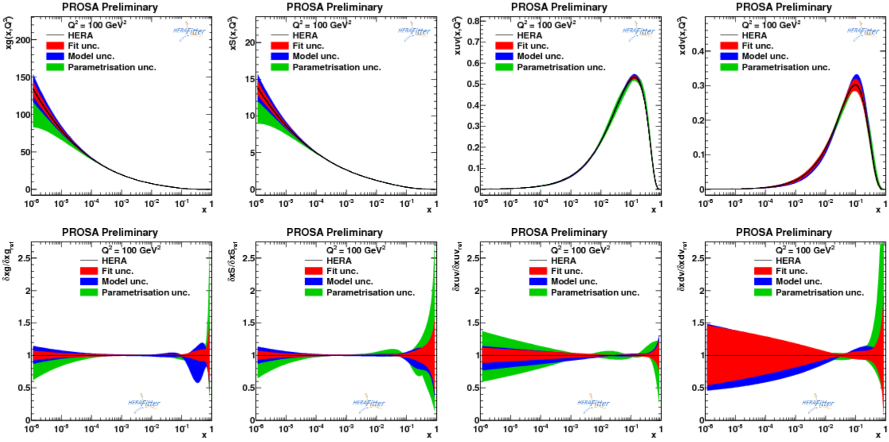
BACKUP. Impact of LHCb heavy flavour data on PDFs. Individual PDF uncertainties, $Q^2 = 10\ GeV^2$



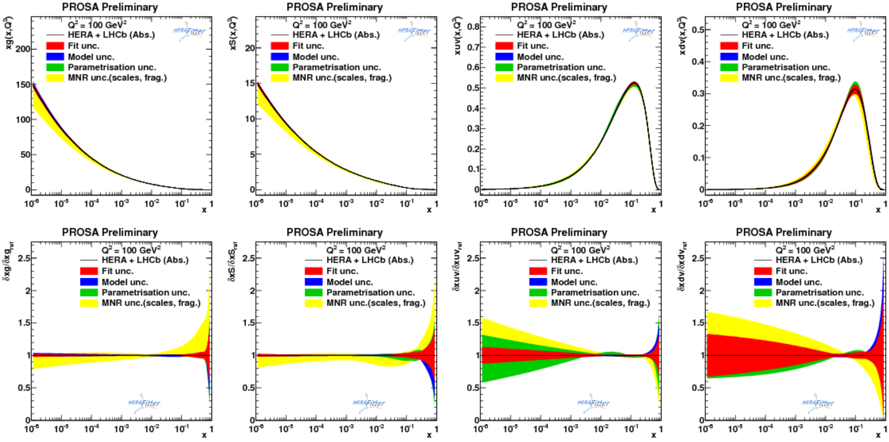
BACKUP. Impact of LHCb heavy flavour data on PDFs. Individual PDF uncertainties, $Q^2 = 10\ GeV^2$



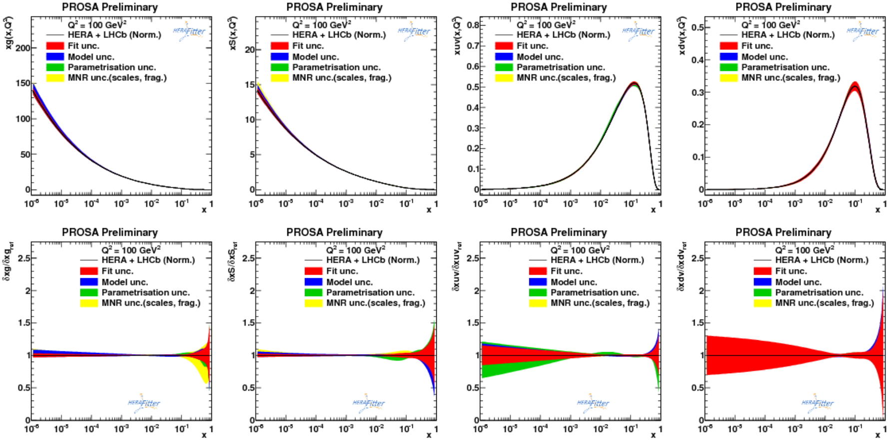
BACKUP. Impact of LHCb heavy flavour data on PDFs. Individual PDF uncertainties, $Q^2 = 100\ GeV^2$



BACKUP. Impact of LHCb heavy flavour data on PDFs. Individual PDF uncertainties, $Q^2 = 100\ GeV^2$

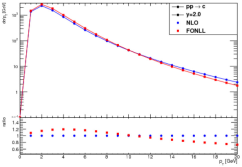


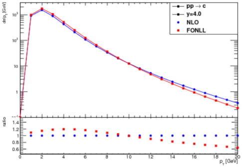
BACKUP. Impact of LHCb heavy flavour data on PDFs. Individual PDF uncertainties, $Q^2 = 100\ GeV^2$



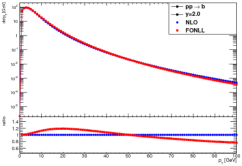
BACKUP. Impact of LHCb heavy flavour data on PDFs. NLO vs. FONLL

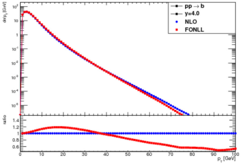
Charm:



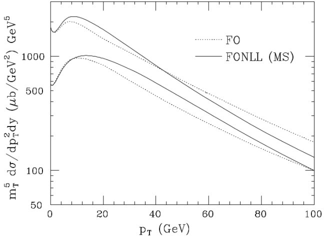


Beauty:





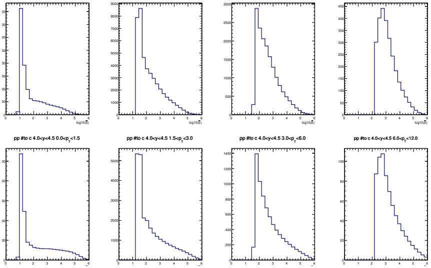
In our kinematic region difference $<20\%$ ⇒ very well within scales uncertainties (NLL correction is small)



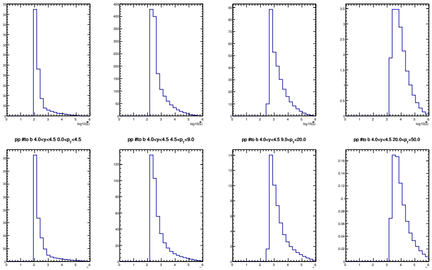
Cacciari et all., JHEP05 1998 007: "...In summary, we observed that our resummation procedure indicates the presence of a small enhancement in the intermediate p_T region, followed by a reduction of the cross section (and of the uncertainty band) at larger p_T..."

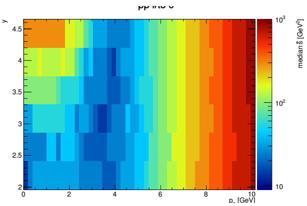
BACKUP. Impact of LHCb heavy flavour data on PDFs. Kinematics: low p_T region

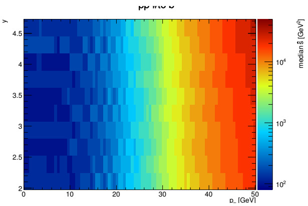
Charm:



Beauty:







For low p_T charm $(0.0 \leq p_T \leq 2.5)$ significant contribution $(\sim 50\%)$ comes from $\hat{s}$ $10^2..10^5\ GeV^2$: not dominated by low x g. Effect increases with increasing y. No such trend for beauty.