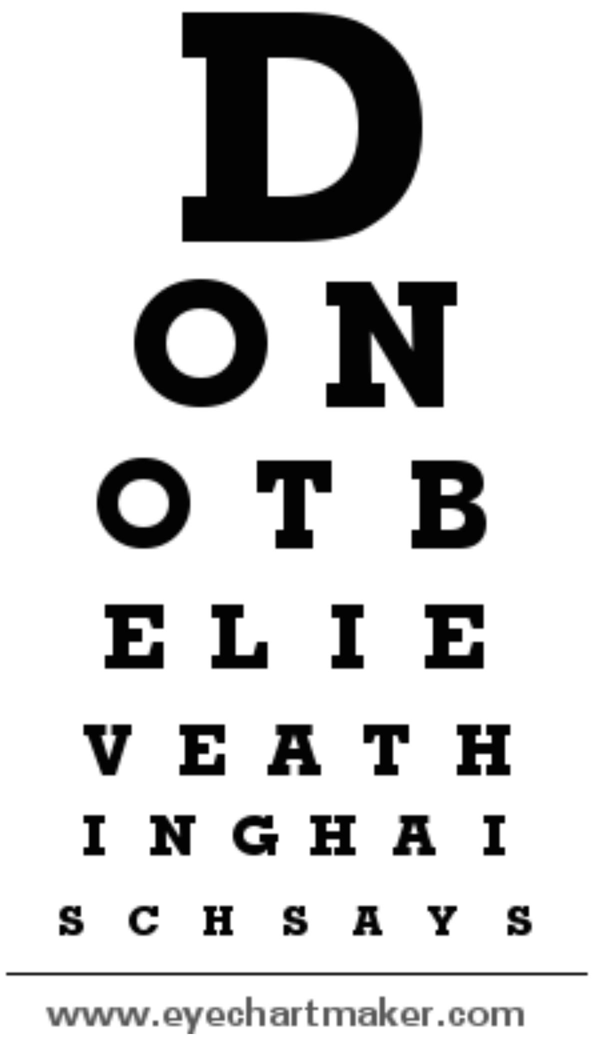
The lows and highs of (n)PDFs

Rhorry Gauld

Exotica and EW session
LHCb Implications Workshop 2015

General Introduction and Motivation



Proton-Proton

- low-x (D production)
- high-x (top production, W+jets)

Proton-Lead (if time permits)

- constraining Cold Nuclear Matter effects

Outlook

- PDF `wish-list’

The Problem

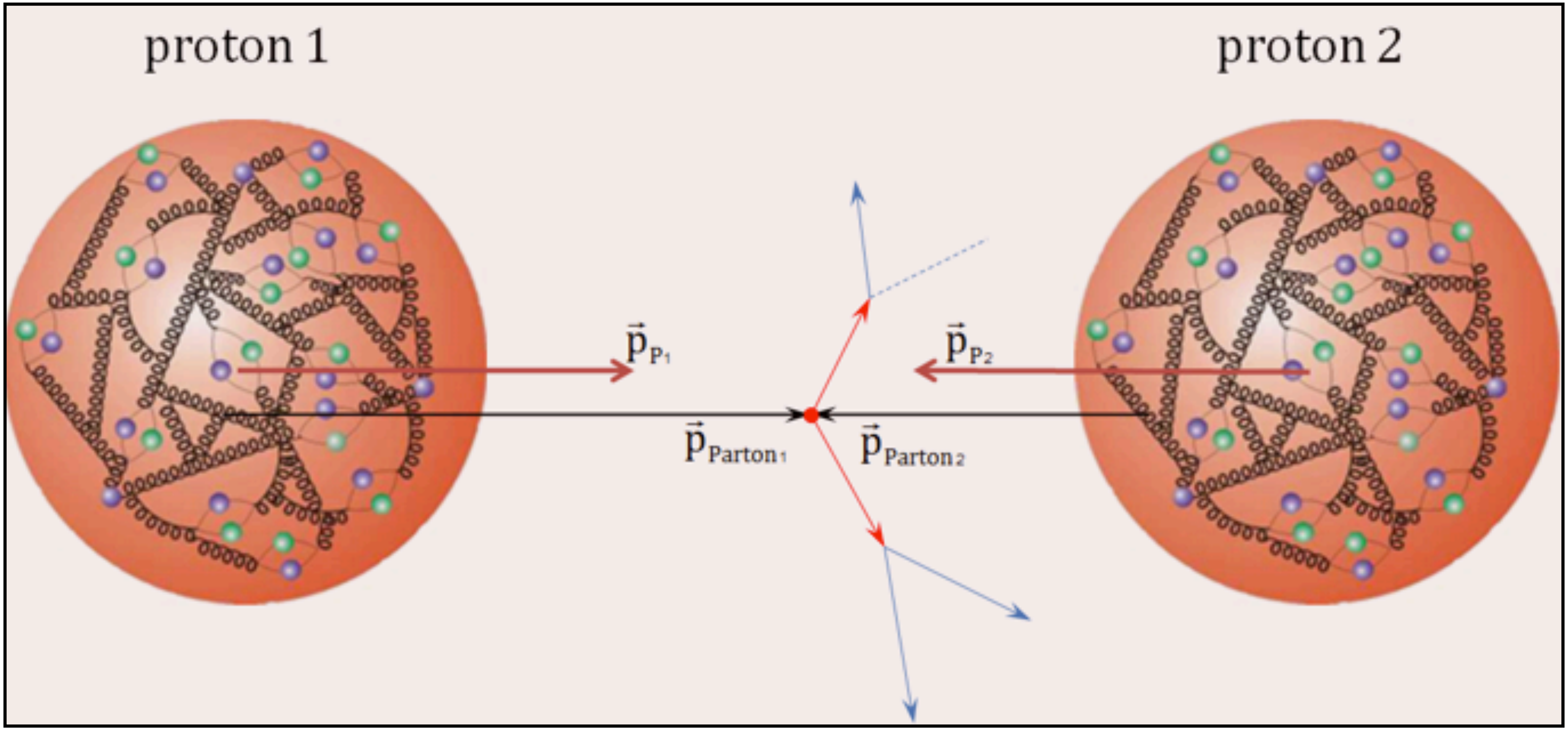
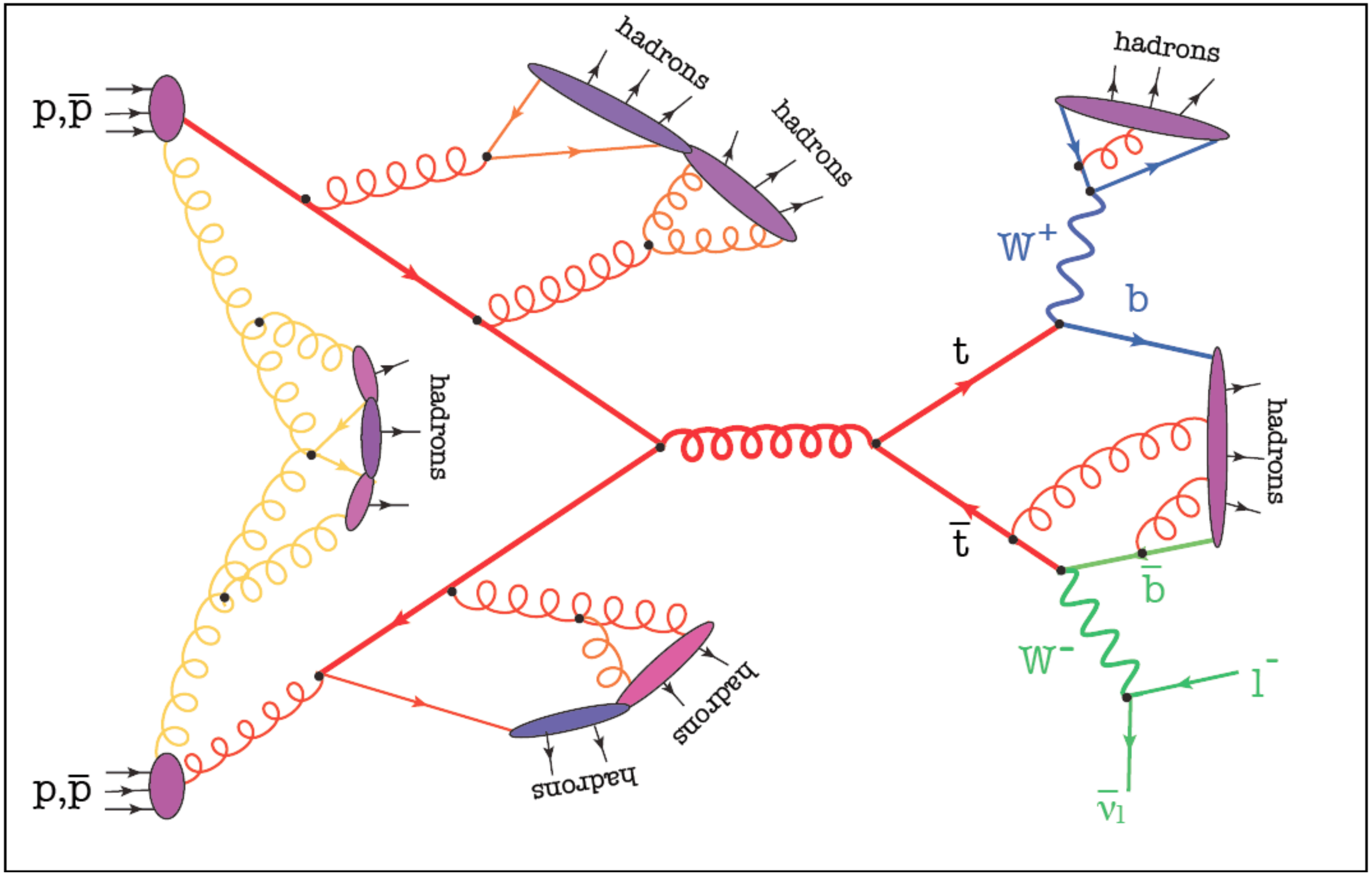


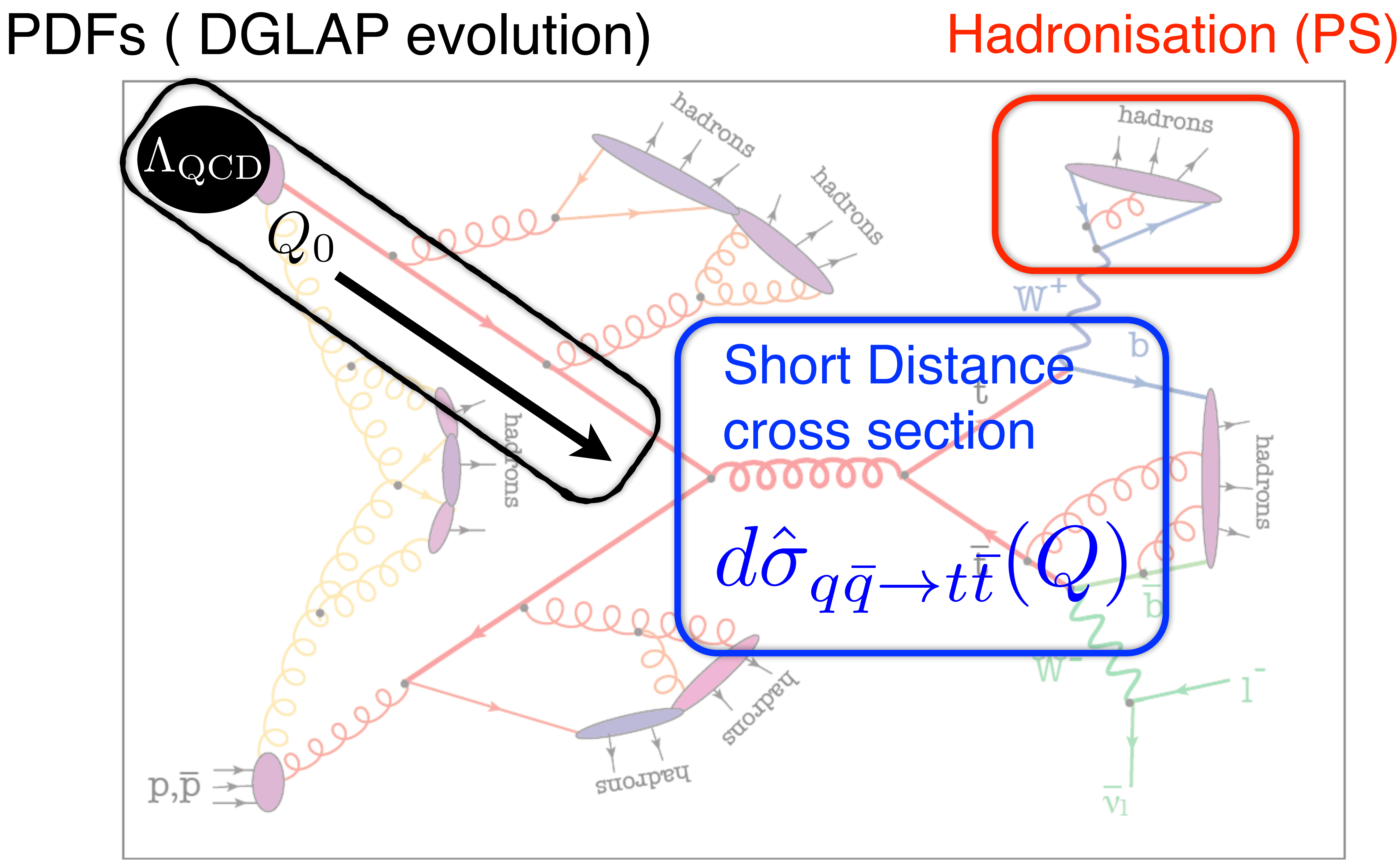
Image from Juan Rojo

The Approach



Drawing by Keith Hamilton

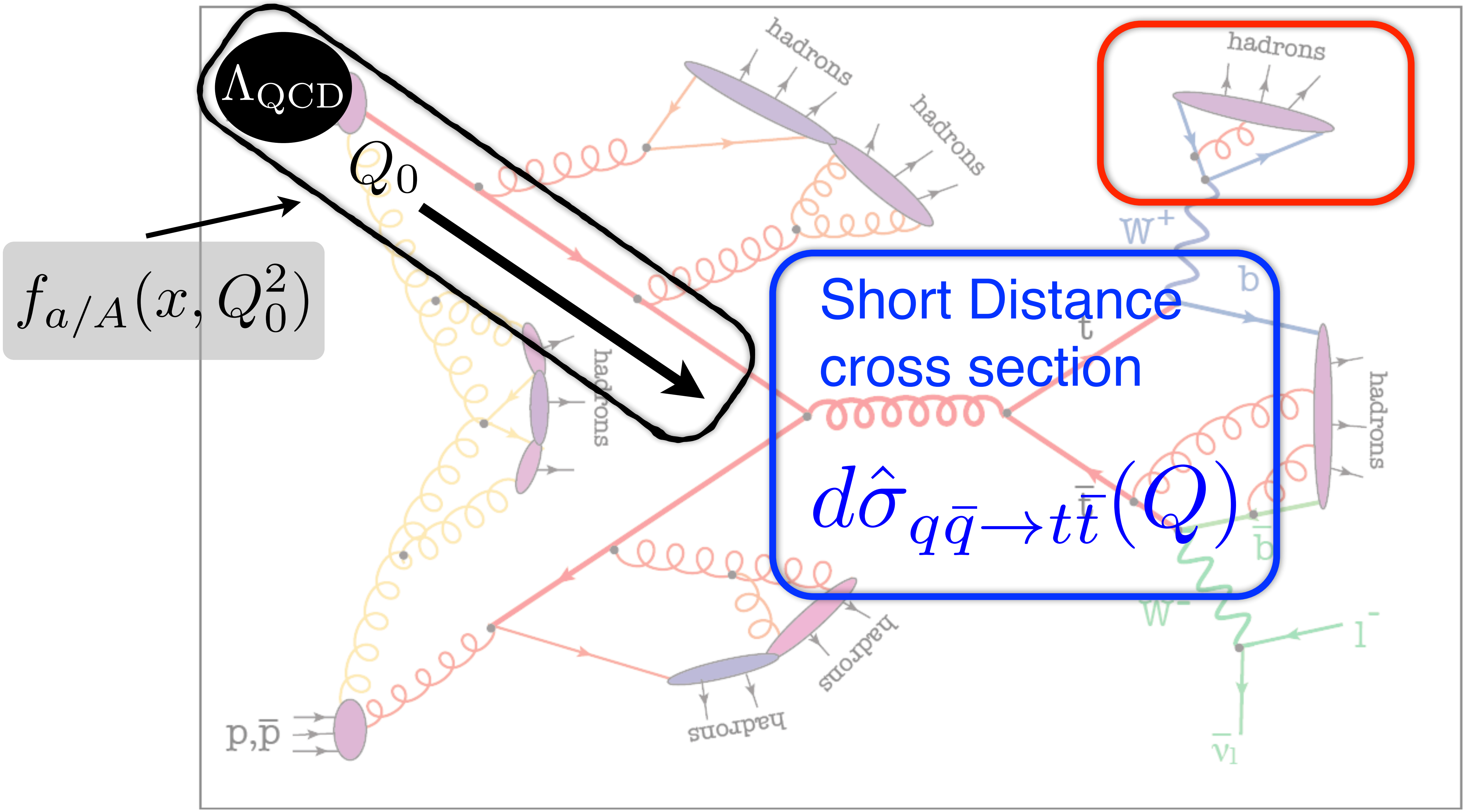
The Approach



Drawing by Keith Hamilton

The Approach

PDFs (DGLAP evolution) Hadronisation (PS)



Drawing by Keith Hamilton

Constrain PDFs by measuring many process dependent cross sections

Modern PDFs and recommendations

ABM12	arXiv:1310.3059	Global analysis
CT14	arXiv:1506.07443	Global analysis
CJ12	arXiv:1212.1702	High-x
HERA2.0	arXiv:1506.06042	HERA only
JR14	arXiv:1403.1852	Global analysis
MMHT14	arXiv:1412.3989	Global analysis
NNPDF3.0	arXiv:1410.8849	Global analysis (MC errors)

Modern PDFs and recommendations

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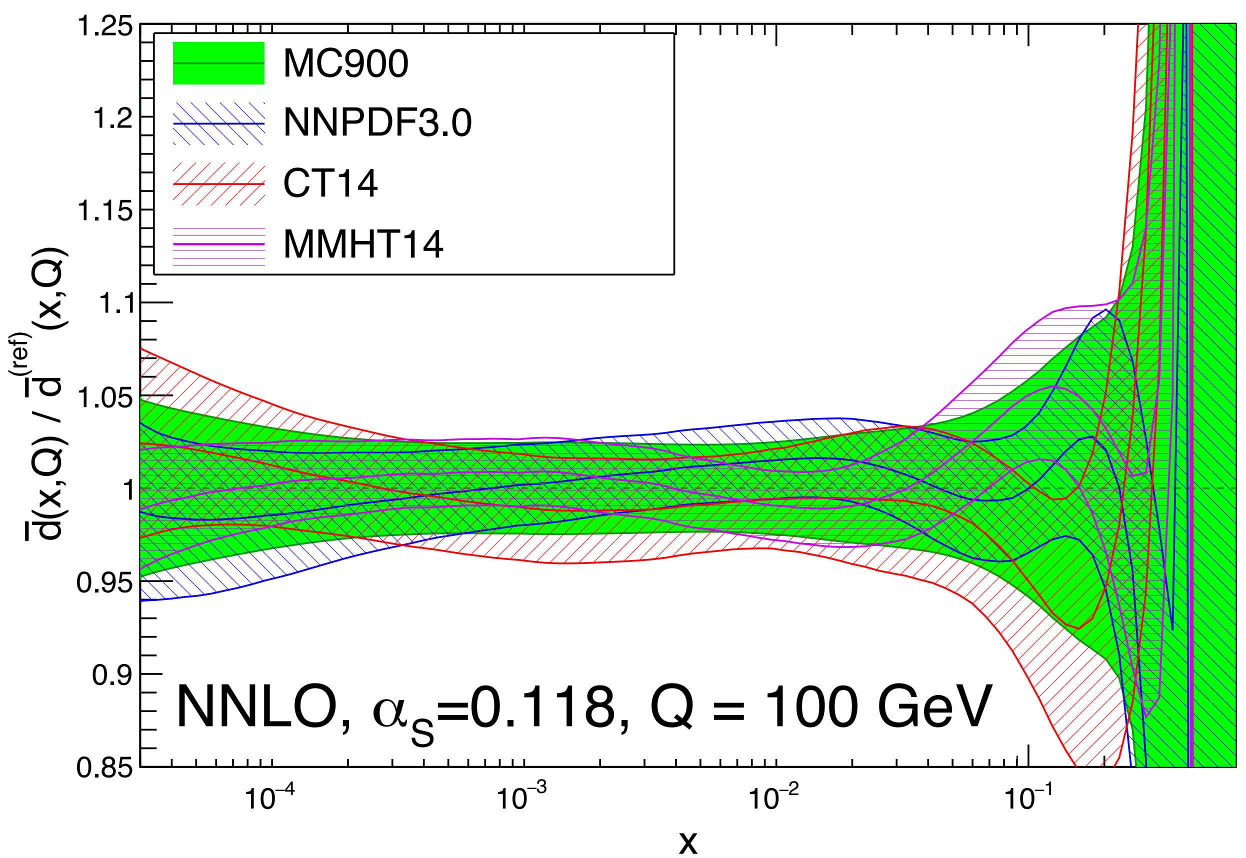
Contains LHCb Electroweak data from Run I - see Ronans talk

Accessible via the LHAPDF6 Interface, see arXiv:1412.7420

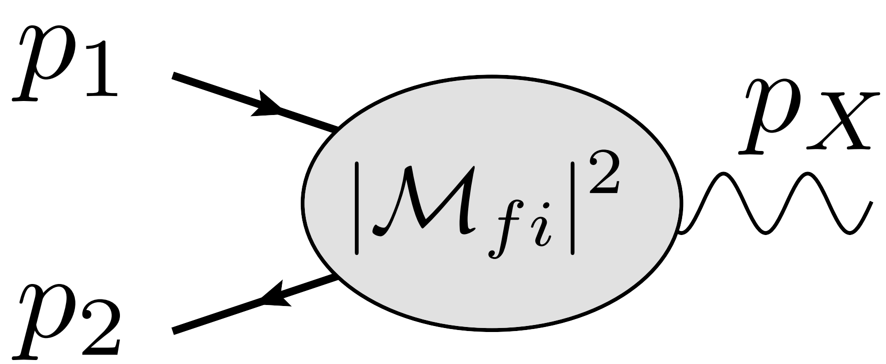


PDF4LHC Recommendation (arXiv:1510.03865)

MonteCarlo combination of:

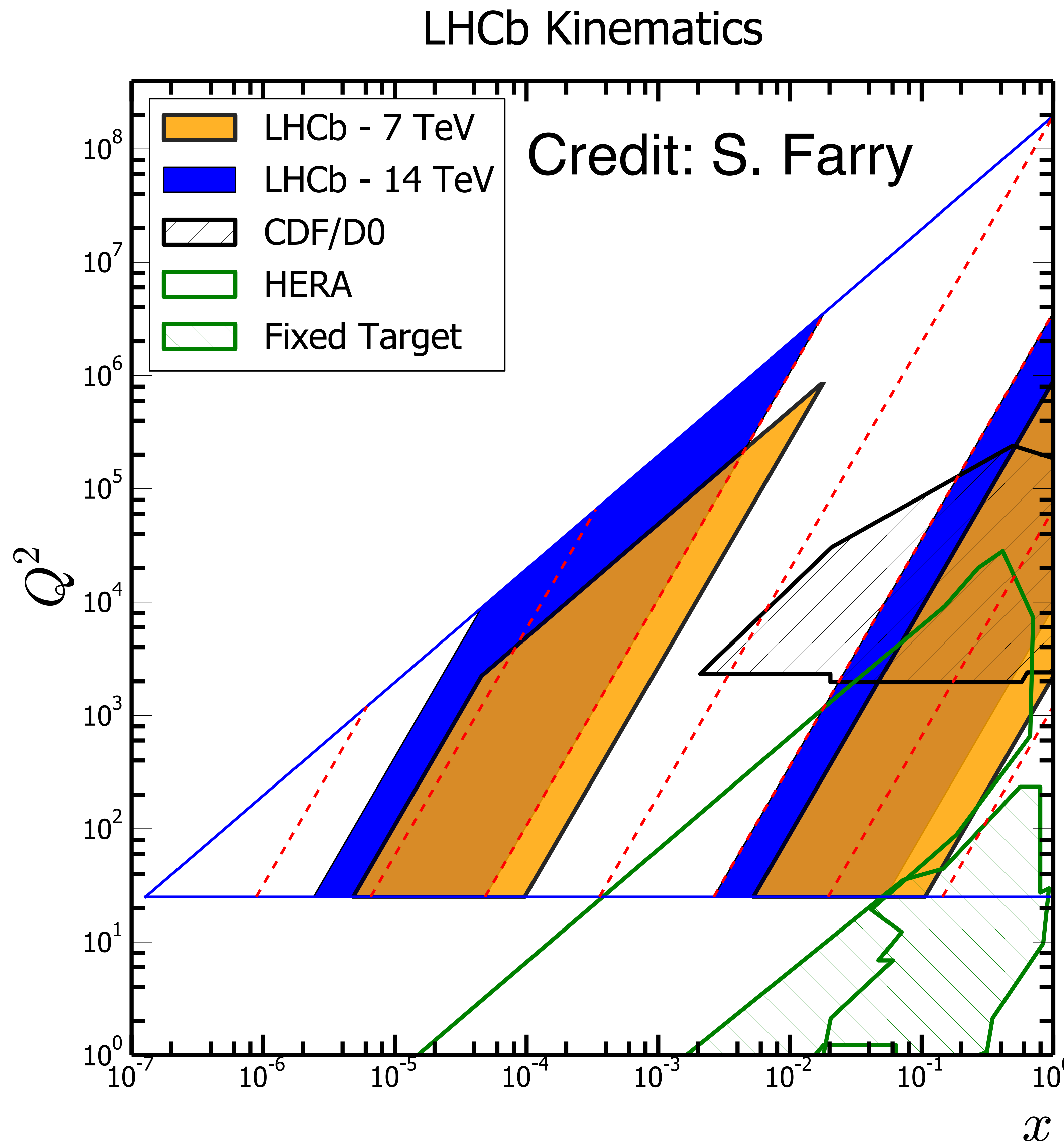
NNPDF3.0
CT14
MMHT14

LHCb Kinematics

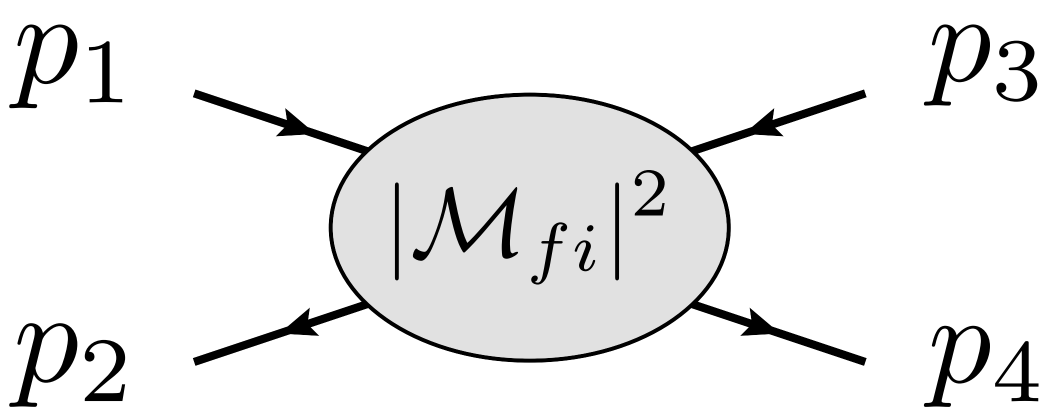


$$x_{1,(2)} = \frac{M_X}{\sqrt{s}} e^{(-)y_X}$$

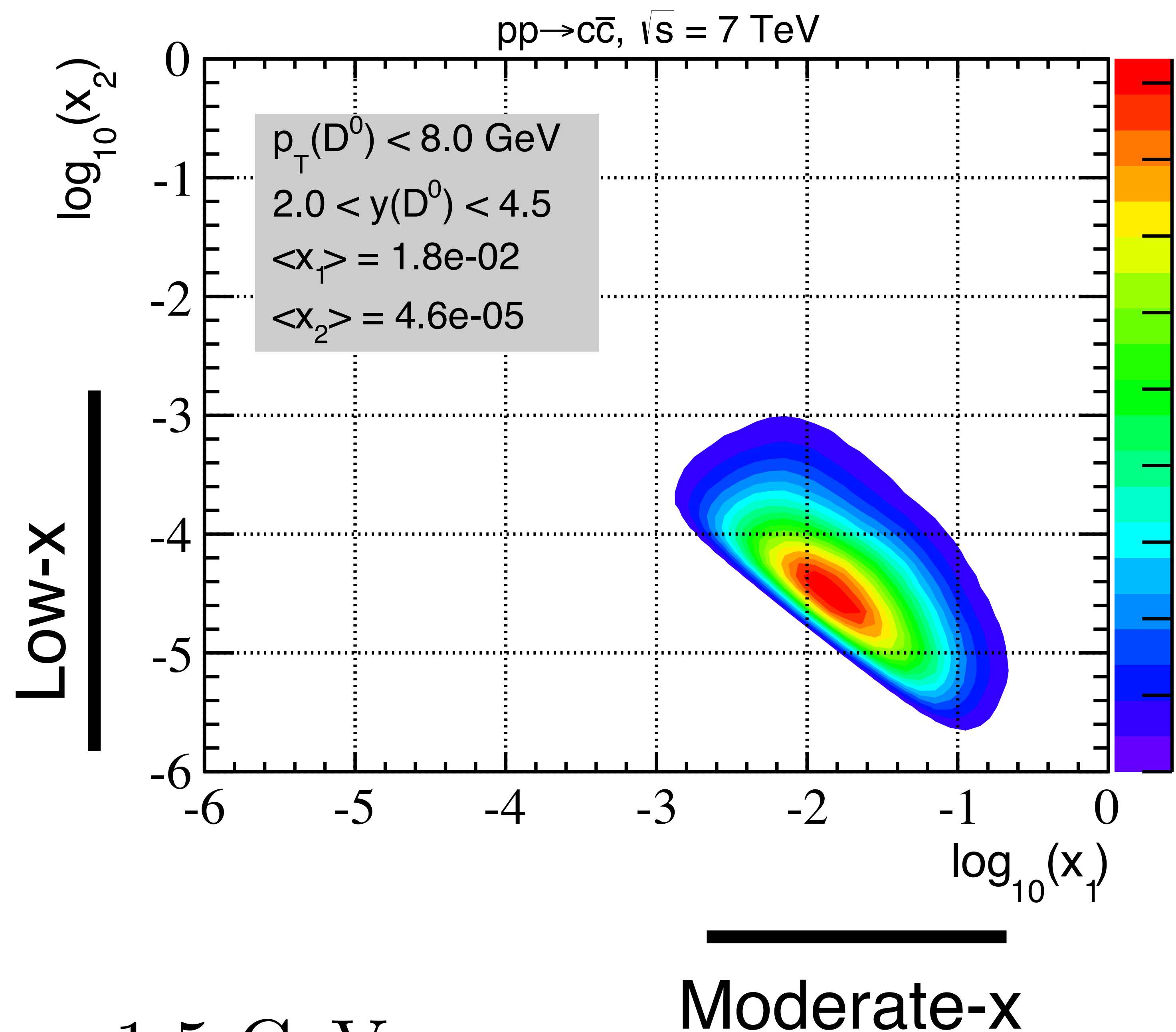
x_i : fraction of momentum
y_j : rapidity
$\sqrt{\hat{s}}$: partonic COM
M_X : particle X mass



$pp \to c\bar{c}$



$$x_{1,(2)} = \frac{m_T}{\sqrt{\hat{s}}}(e^{(-)y_3} + e^{(-)y_4})$$

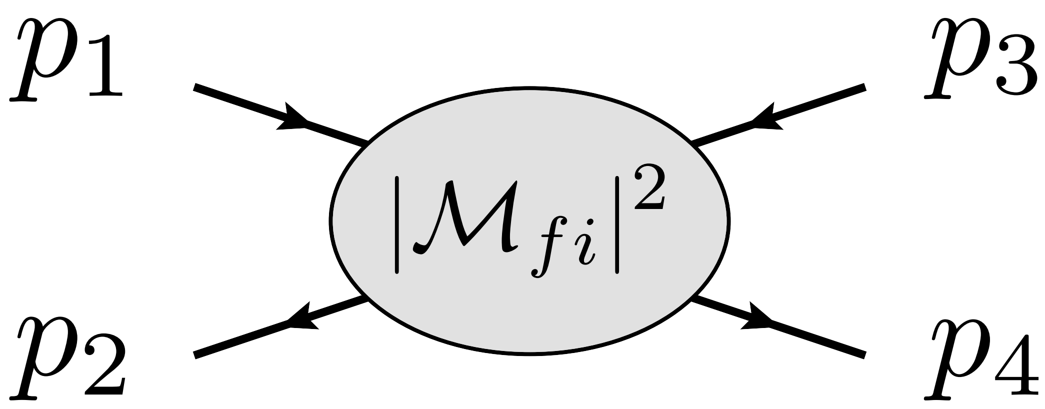


x_i : fraction of momentum
y_j : rapidity
$\sqrt{\hat{s}}$: partonic COM
m_T: transverse mass

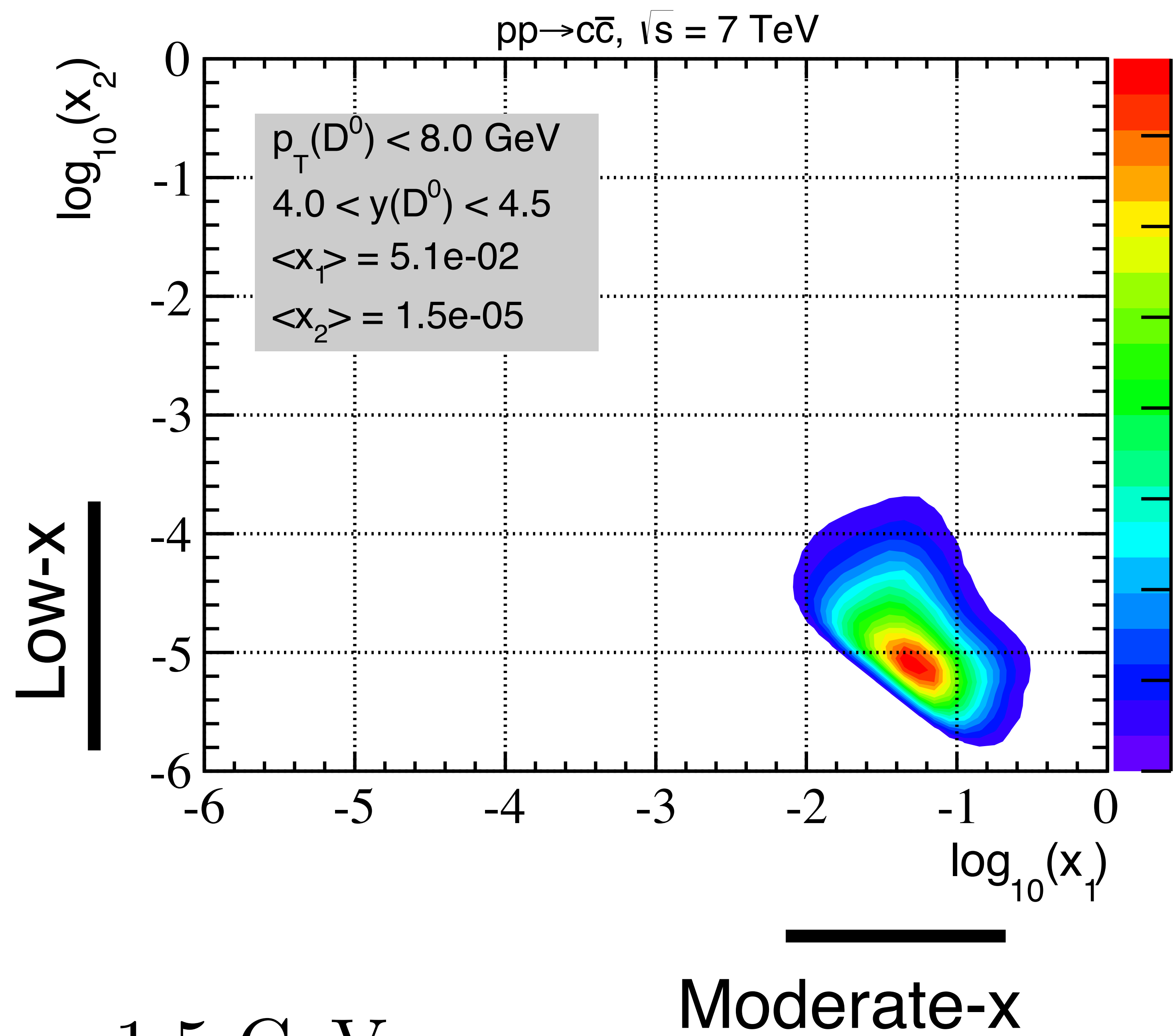
$m_c \simeq 1.5$ GeV

LHCb acceptance, $2.0 < y(D^0) < 4.5$

$pp \to c\bar{c}$



$$x_{1,(2)} = \frac{m_T}{\sqrt{\hat{s}}}\left(e^{(-)y_3} + e^{(-)y_4}\right)$$

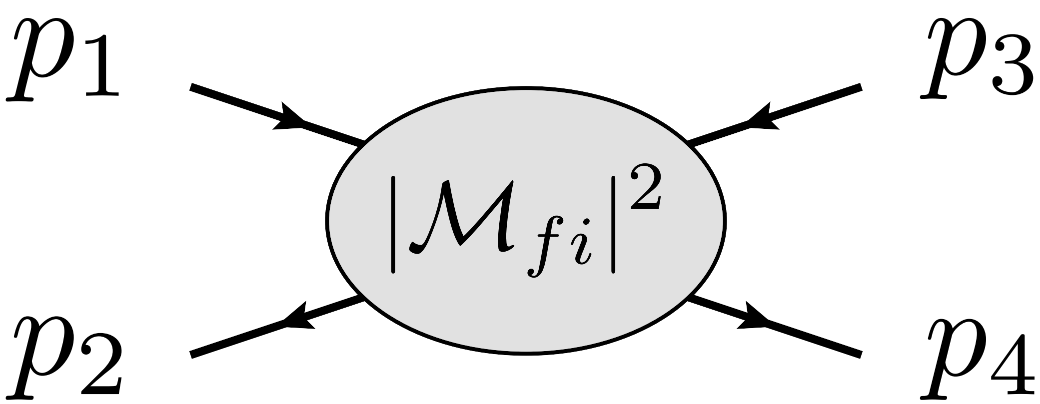


x_i : fraction of momentum
y_j : rapidity
$\sqrt{\hat{s}}$: partonic COM
m_T: transverse mass

$m_c \simeq 1.5$ GeV

\`Forward' LHCb acceptance, $4.0 < y(D^0) < 4.5$

$pp \to t\bar{t}$



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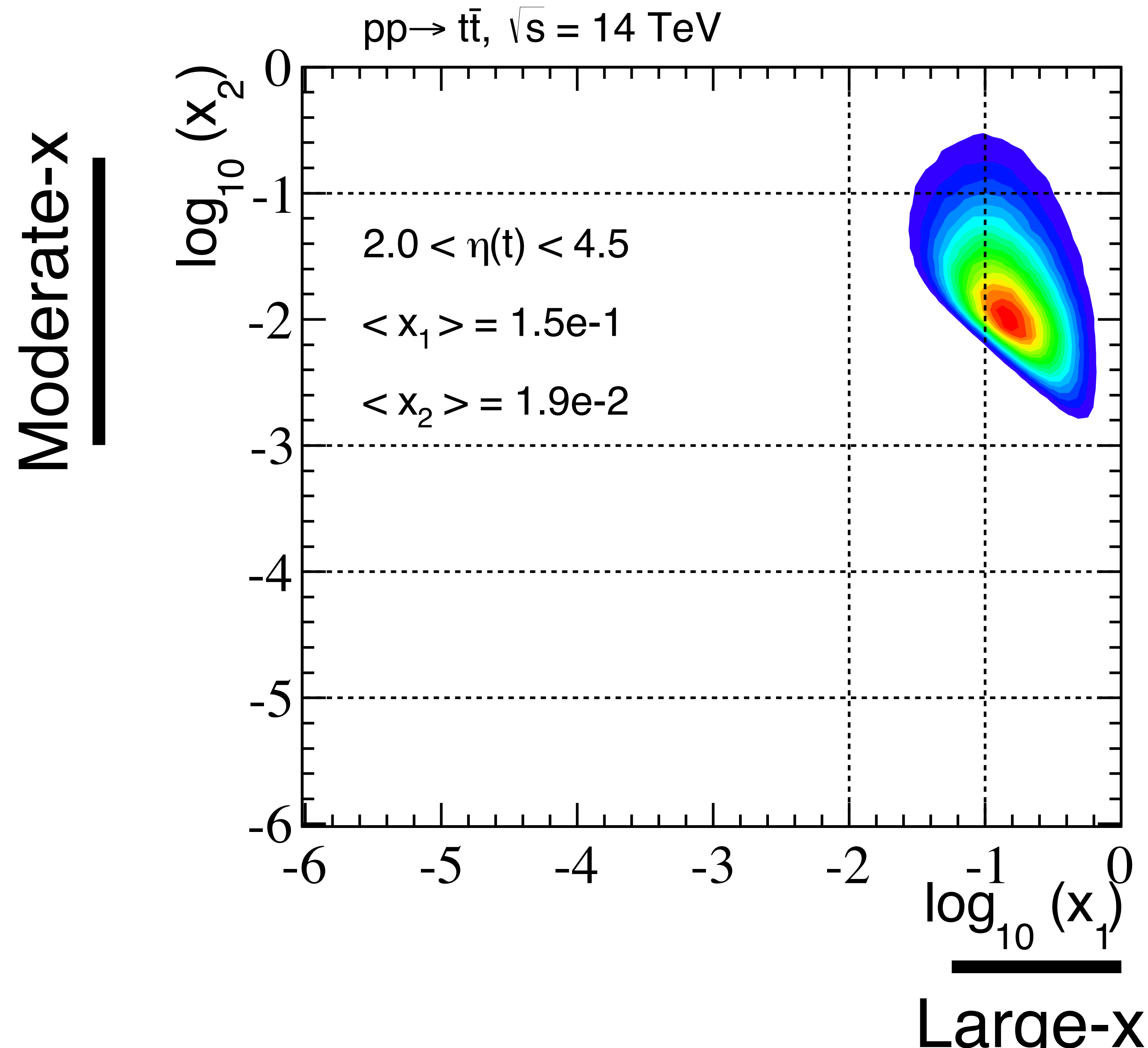


x_i : fraction of momentum

y_j : rapidity

$\sqrt{\hat{s}}$: partonic COM

m_T: transverse mass

$$m_t \simeq 173.25\ GeV$$

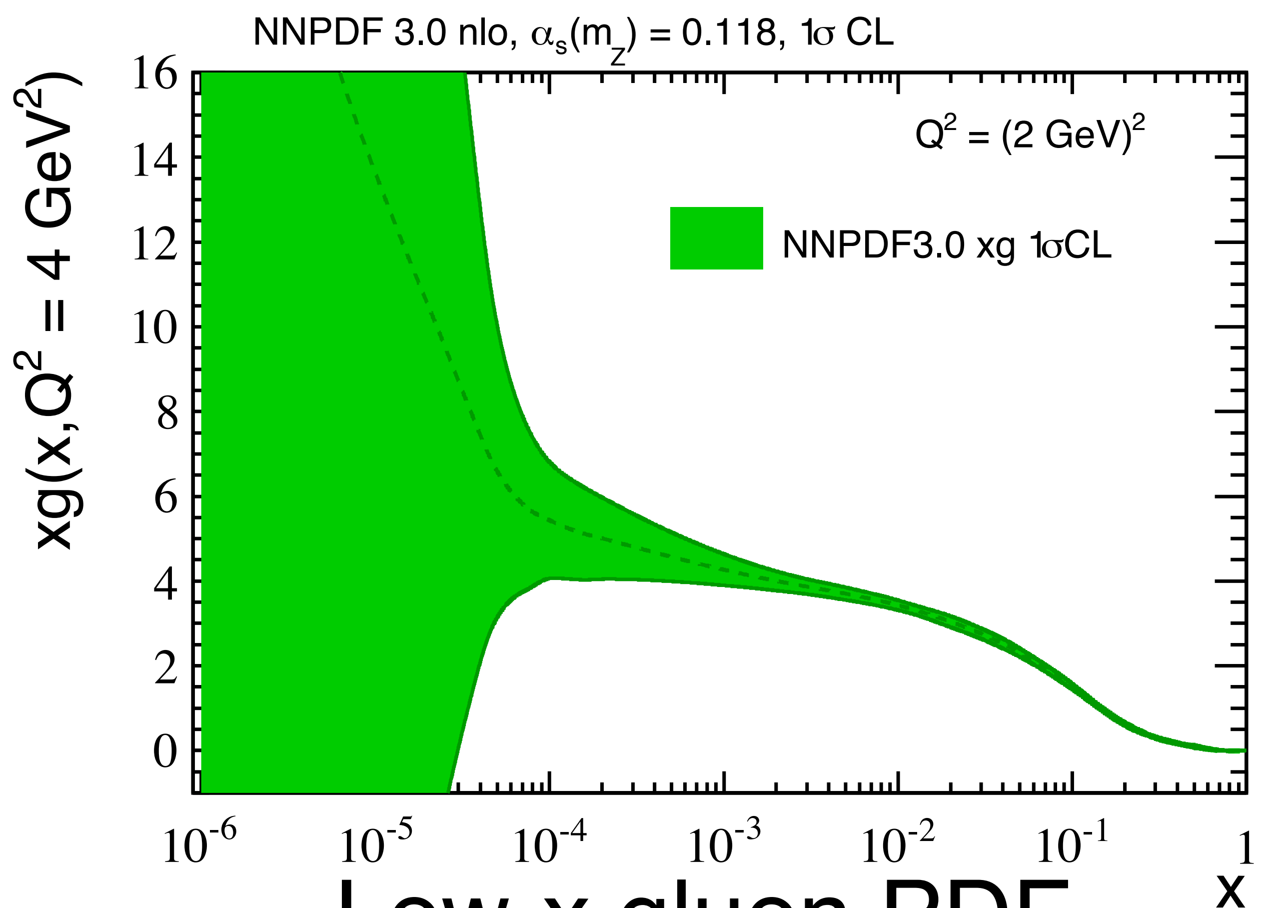
\`Forward' LHCb acceptance, $2.5 < \eta(t) < 4.5$

Summary of introduction

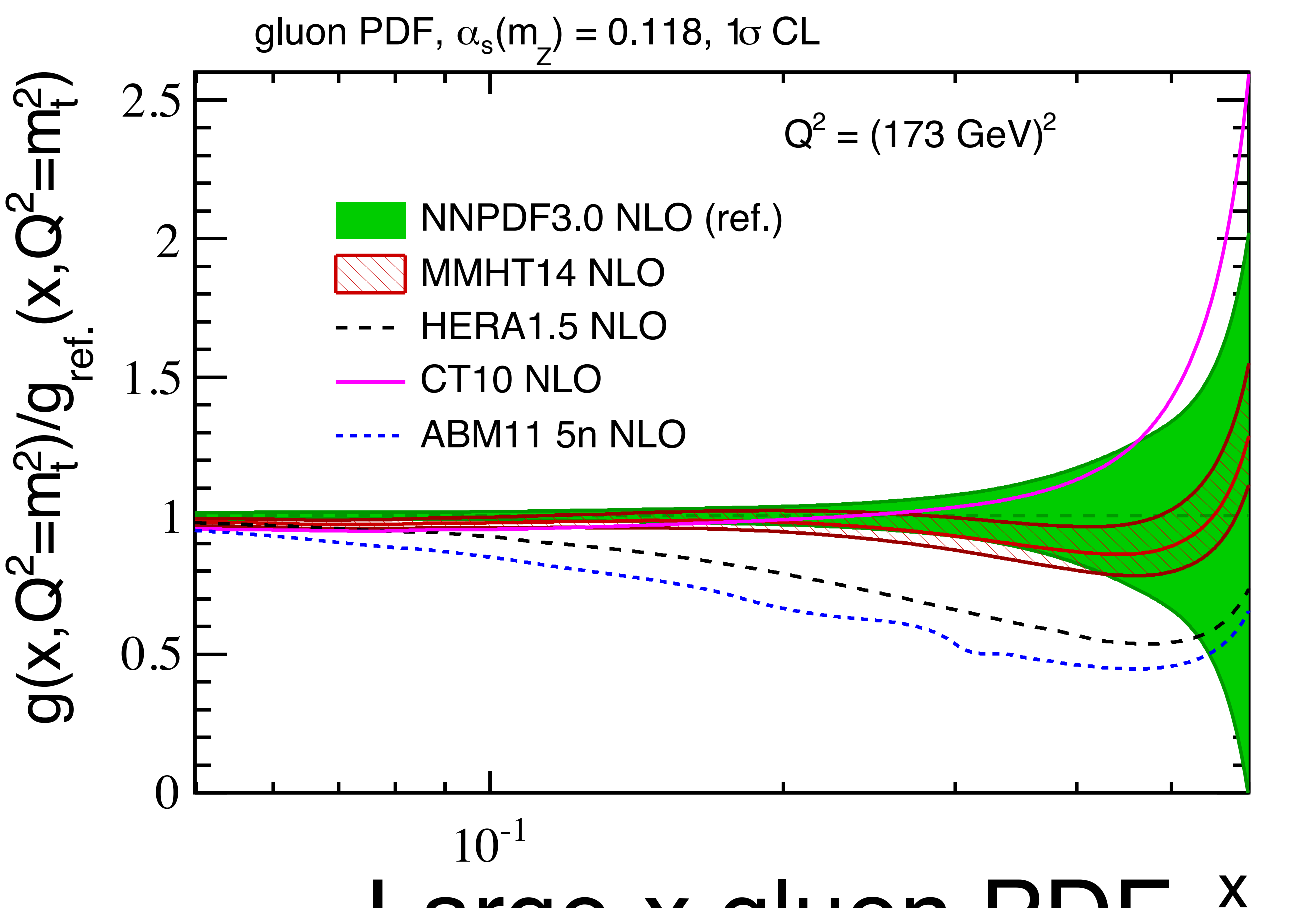
LHCb simultaneously sensitive to **low-** and **high-x**

Large-x constraints:
- q/g distributions important for NP searches
- interplay with nuclear physics

Low-x constraints:
- study DGLAP/saturation at low-x
- input for atmospheric neutrino flux



Low-x gluon PDF



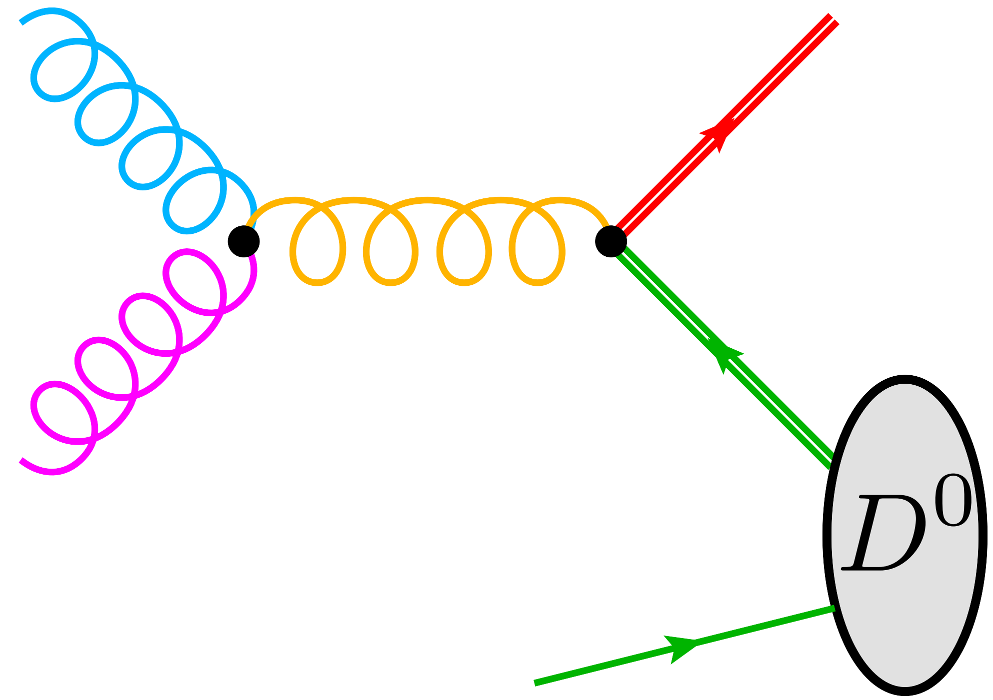
Large-x gluon PDF

Proton-Proton

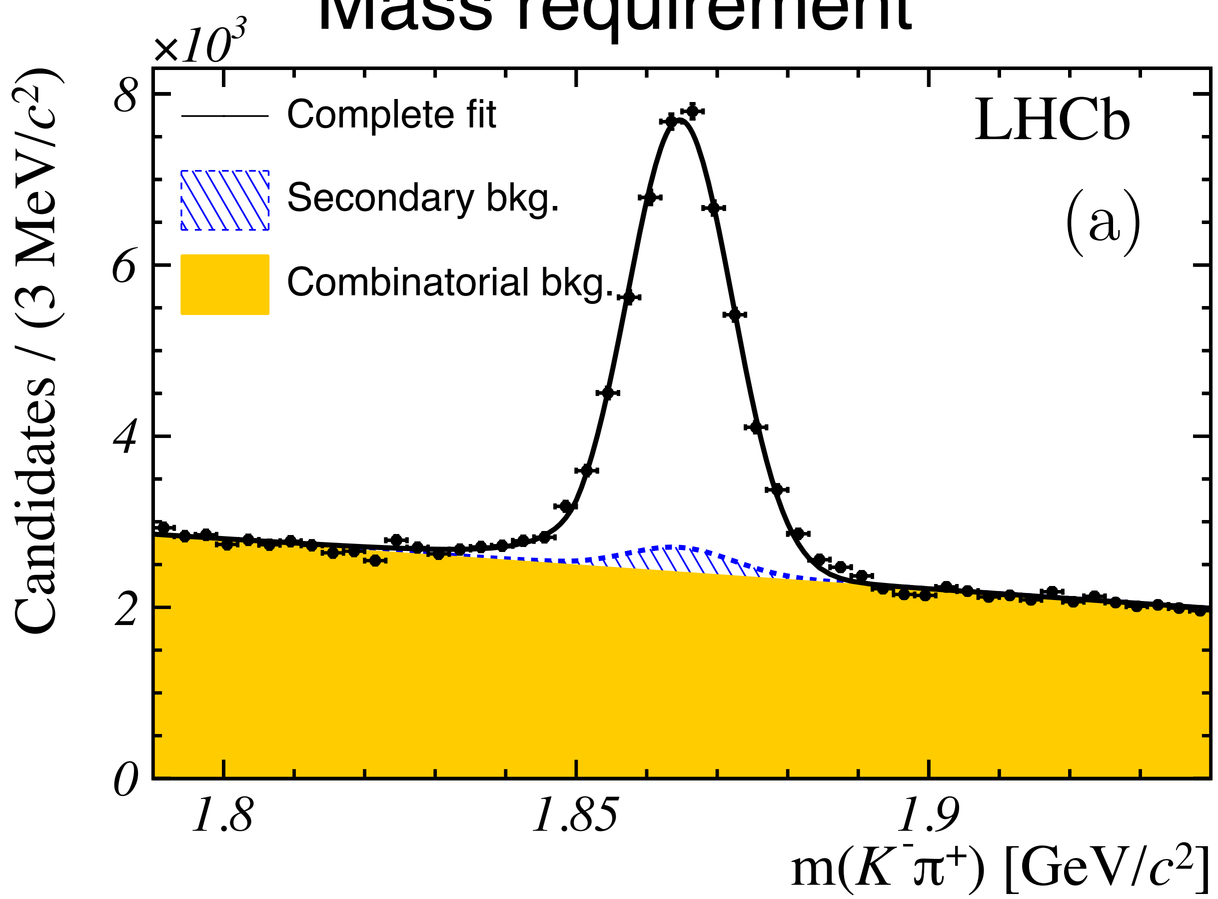
D production in pp

7 TeV measurement - arXiv: 1302.2864

$$pp \to D + X$$
$$2.0 < y_D < 4.5$$
$$D p_T < 8.0 GeV$$



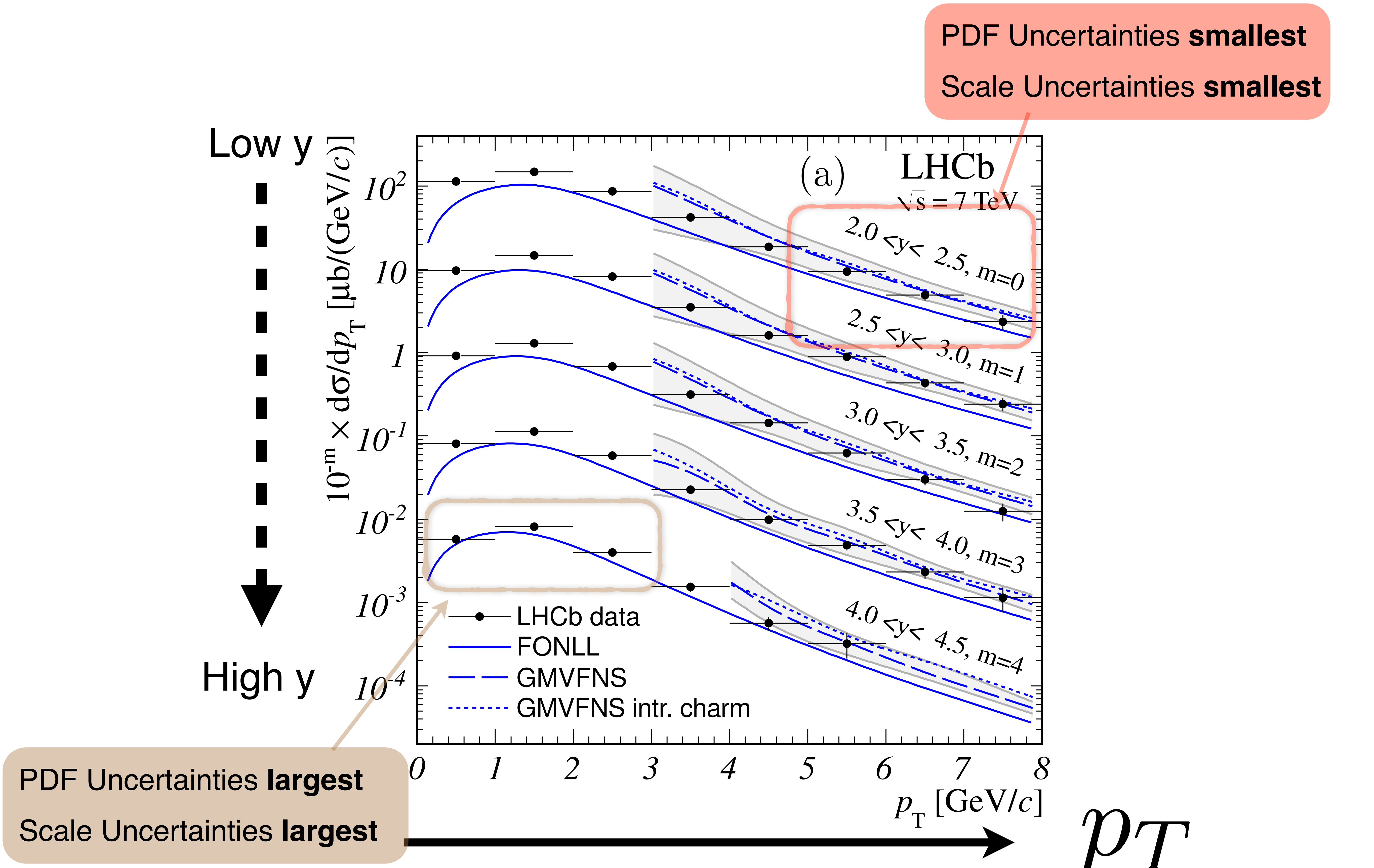
Mass requirement



$$\frac{d^2\sigma^D(p_T, y)}{dp_T\, dy}$$

Measurement performed double differentially in: p_T, y

D production in pp



D production in pp

$$\frac{d^2\sigma}{dy\,dp_T} \Big/ \frac{d^2\sigma}{dy\,dp_T}\Big|_{p_T=max,y=min}$$

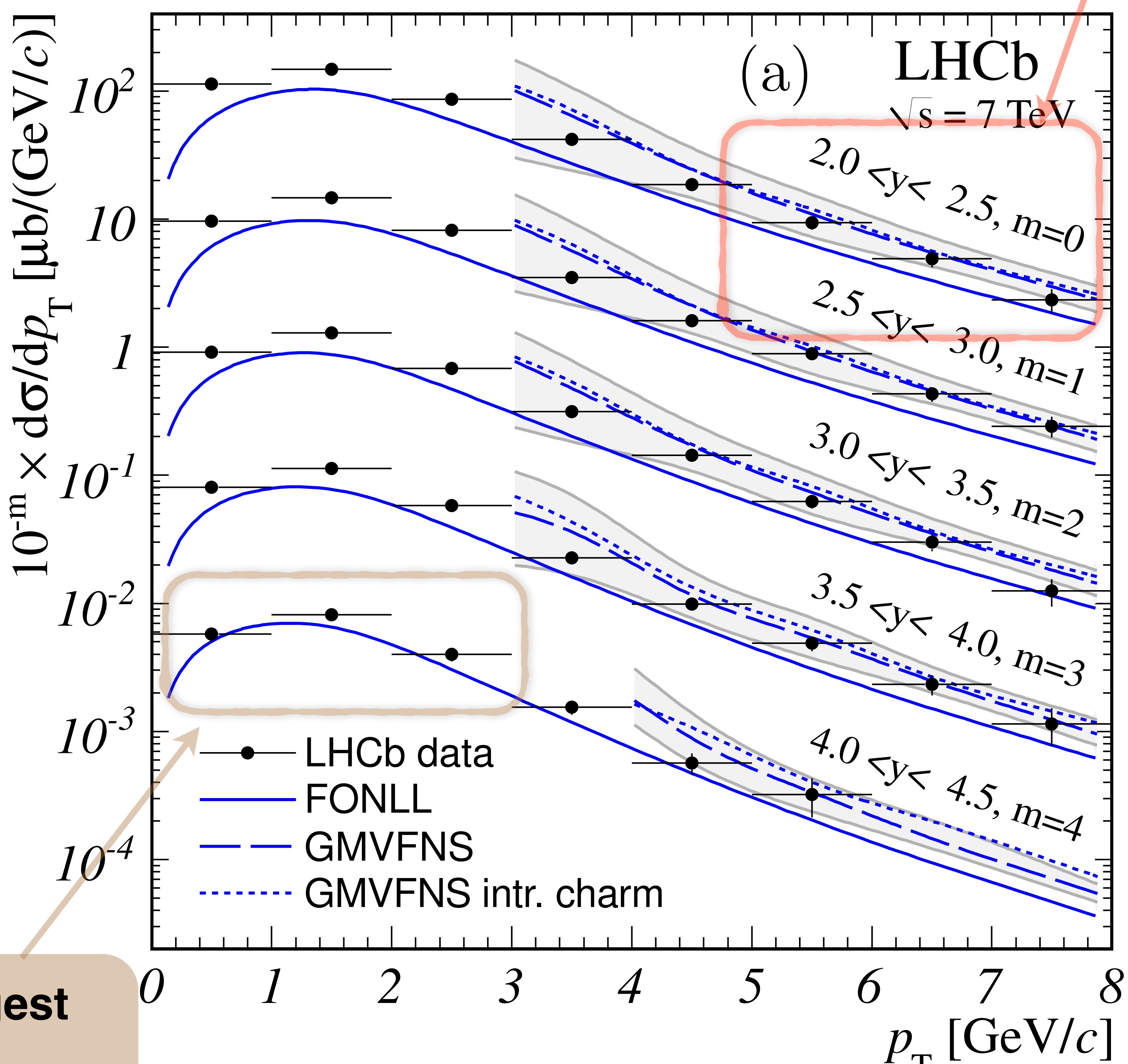
Normalised Differential Cross-section

PDF Uncertainties **smallest**

Scale Uncertainties **smallest**

Low y

High y

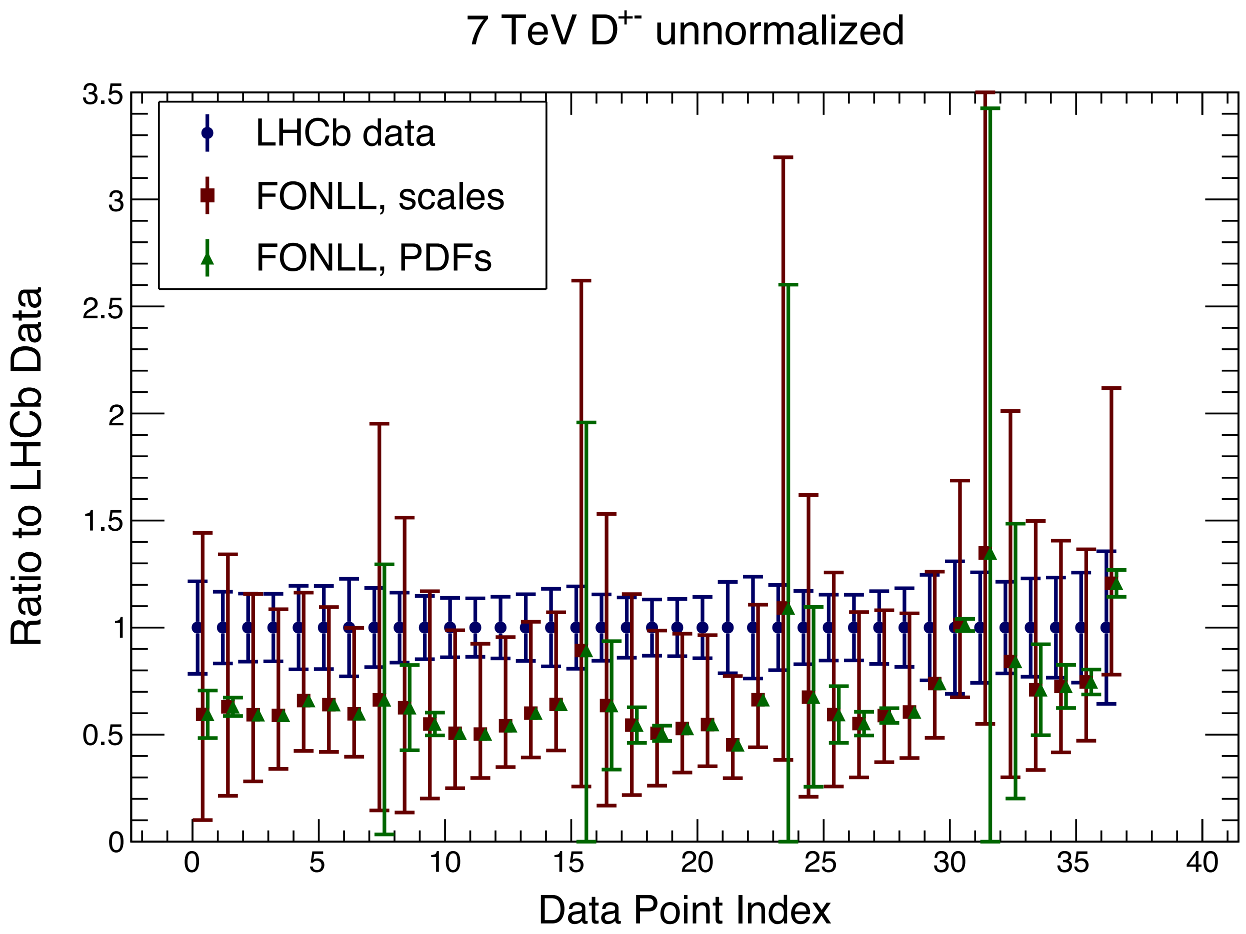


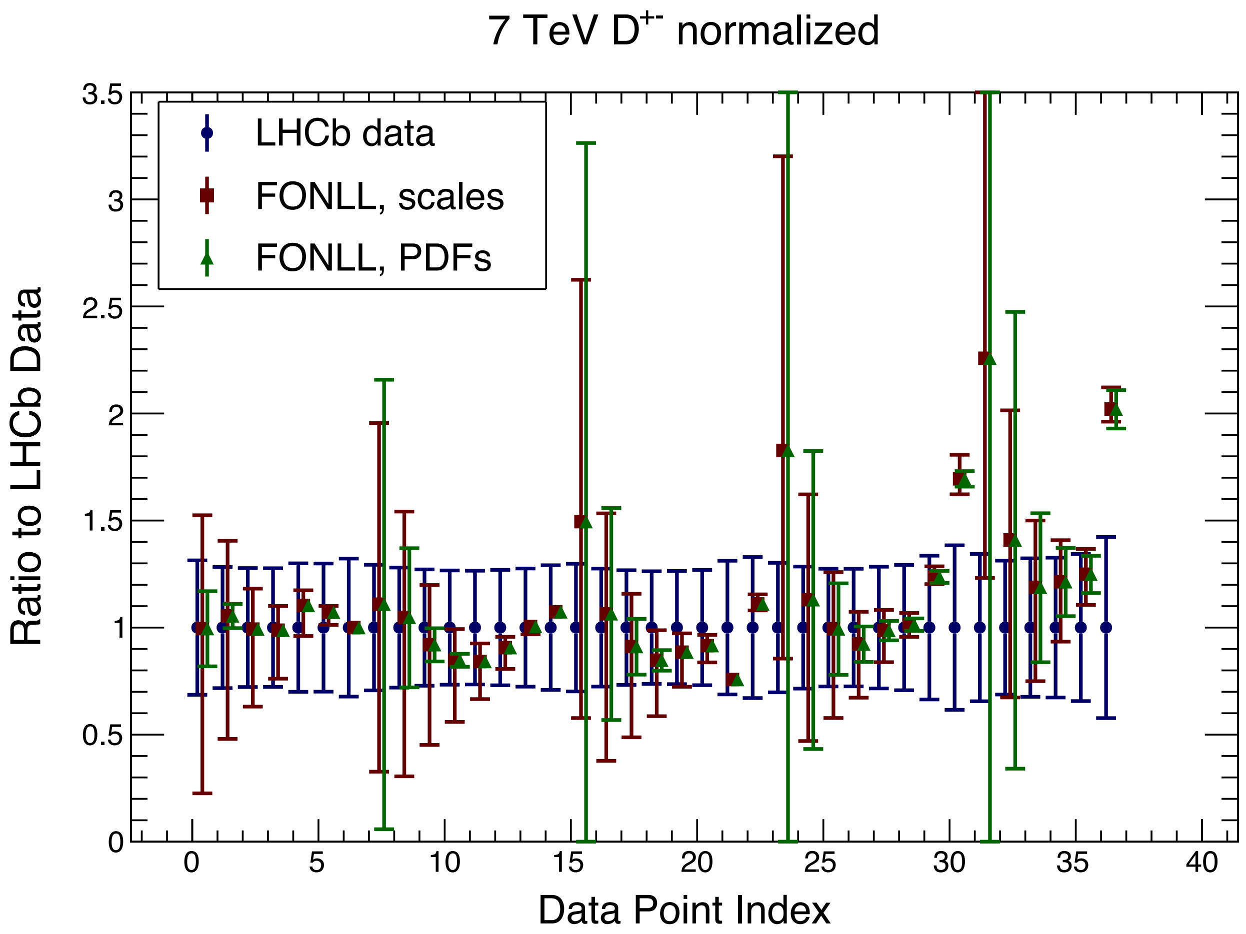
PDF Uncertainties **largest**

Scale Uncertainties **largest**

p_T

Normalising 7 TeV data





Not-normalised,
data on the high side

$$\frac{d^2\sigma_i}{dydp_T}$$

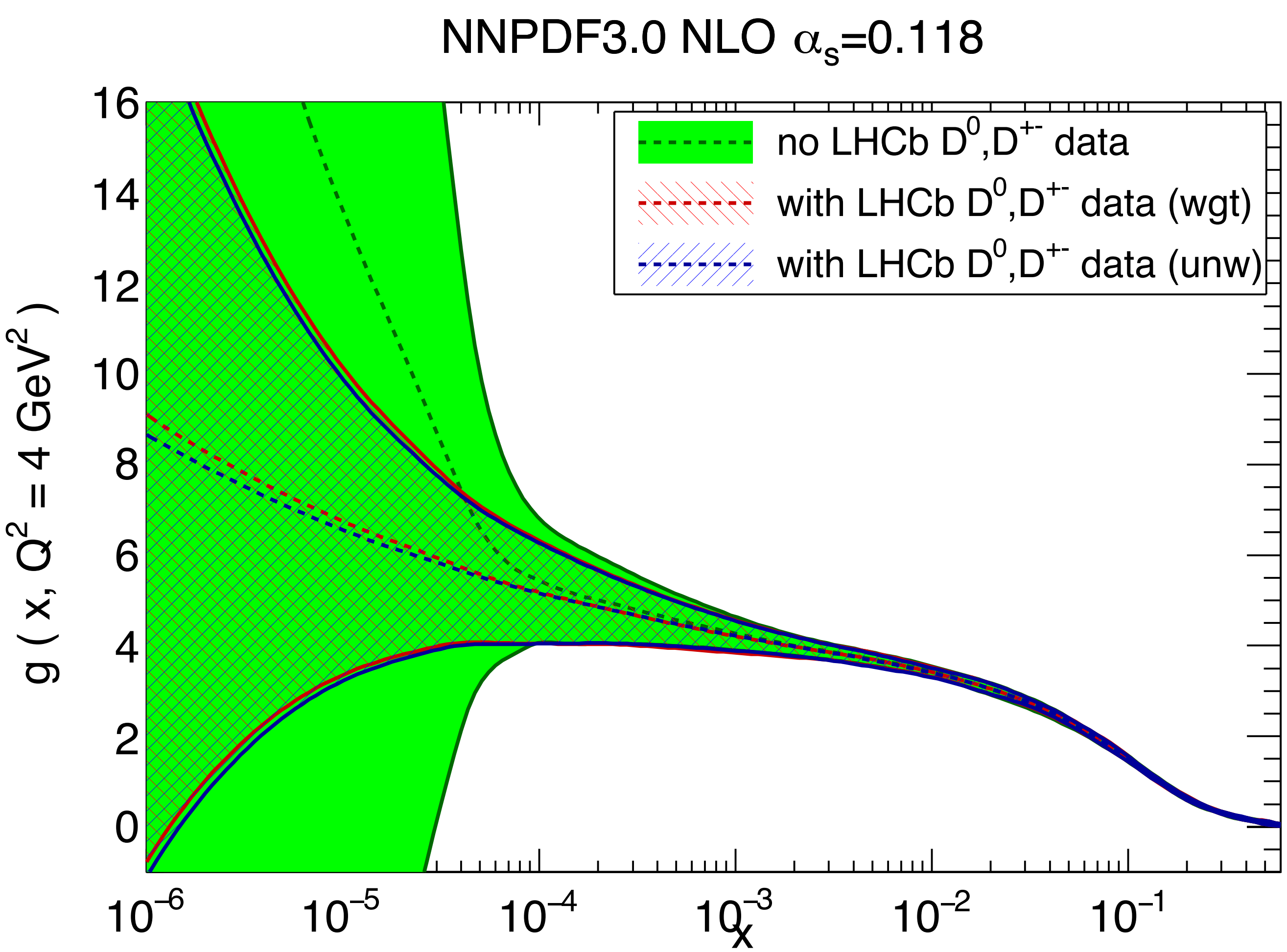
Normalised,
generally good agreement
….few outliers

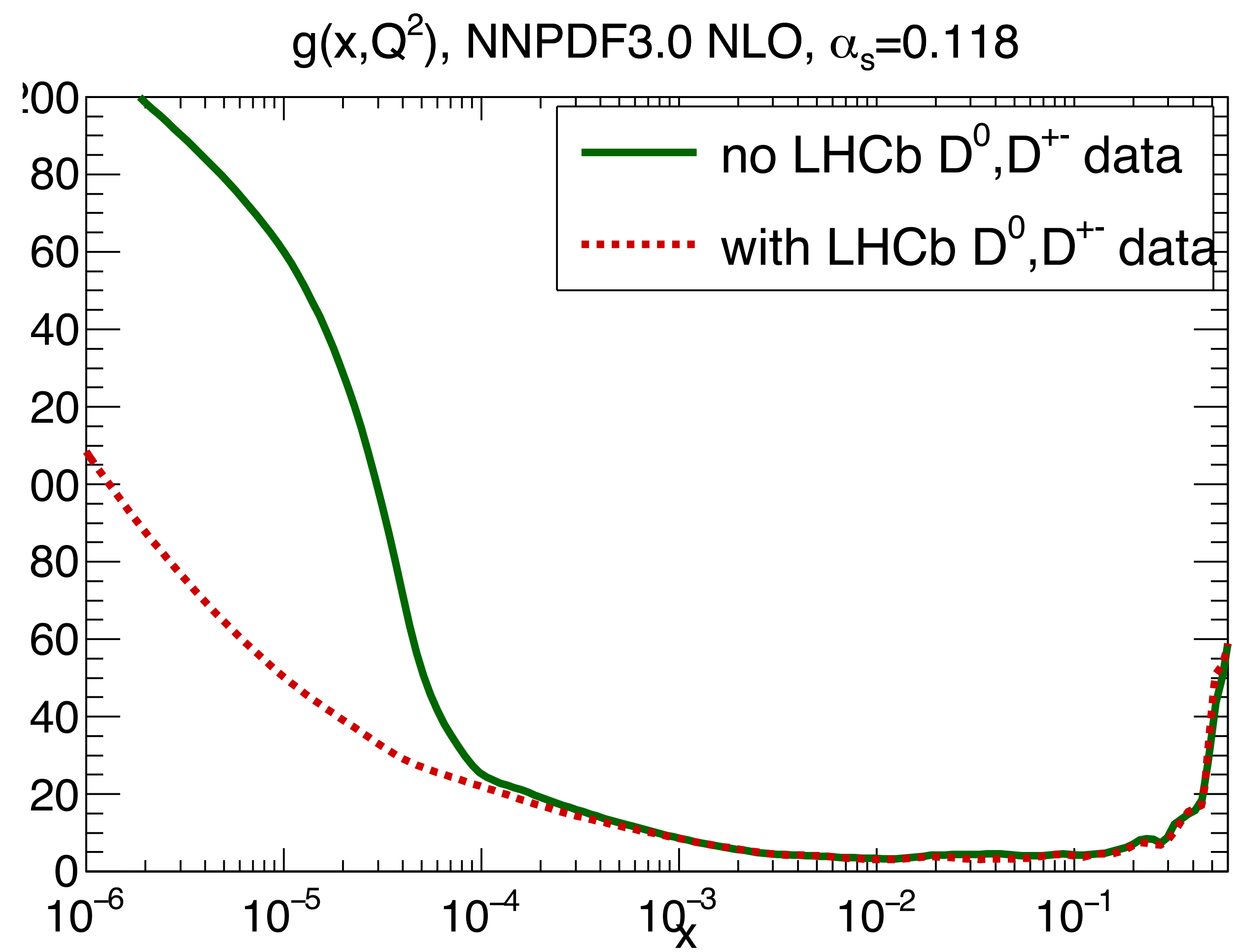
$$\frac{d^2\sigma_i}{dydp_T} \Bigg/ \frac{d^2\sigma_{ref}}{dydp_T}$$

Results of including data

RG, J. Rojo, L. Rottoli, J. Talbert - arXiv:1506.08025

1) Normalise LHCb differential charm data to **high-pt**, **low-y** bin
2) Reweight the 100 replicas based on compatibility with LHCb data (here we use the FONLL predictions obtained from public web interface)





Comparison of HERA+LHCb data

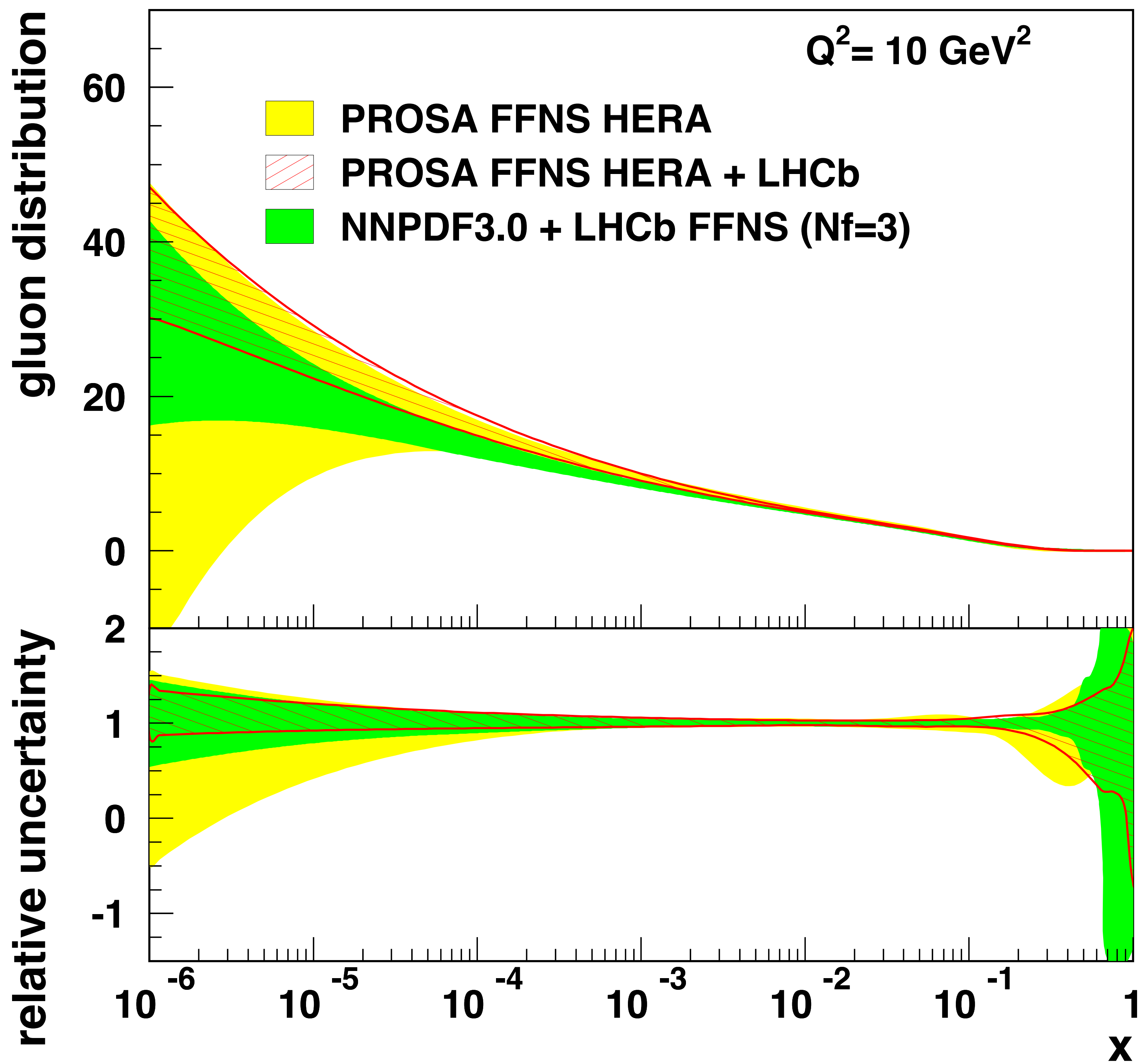
PROSA Collaboration analysis - arXiv:1503.04581

Similar analysis, earlier performed by PROSA.

Differs in approach:

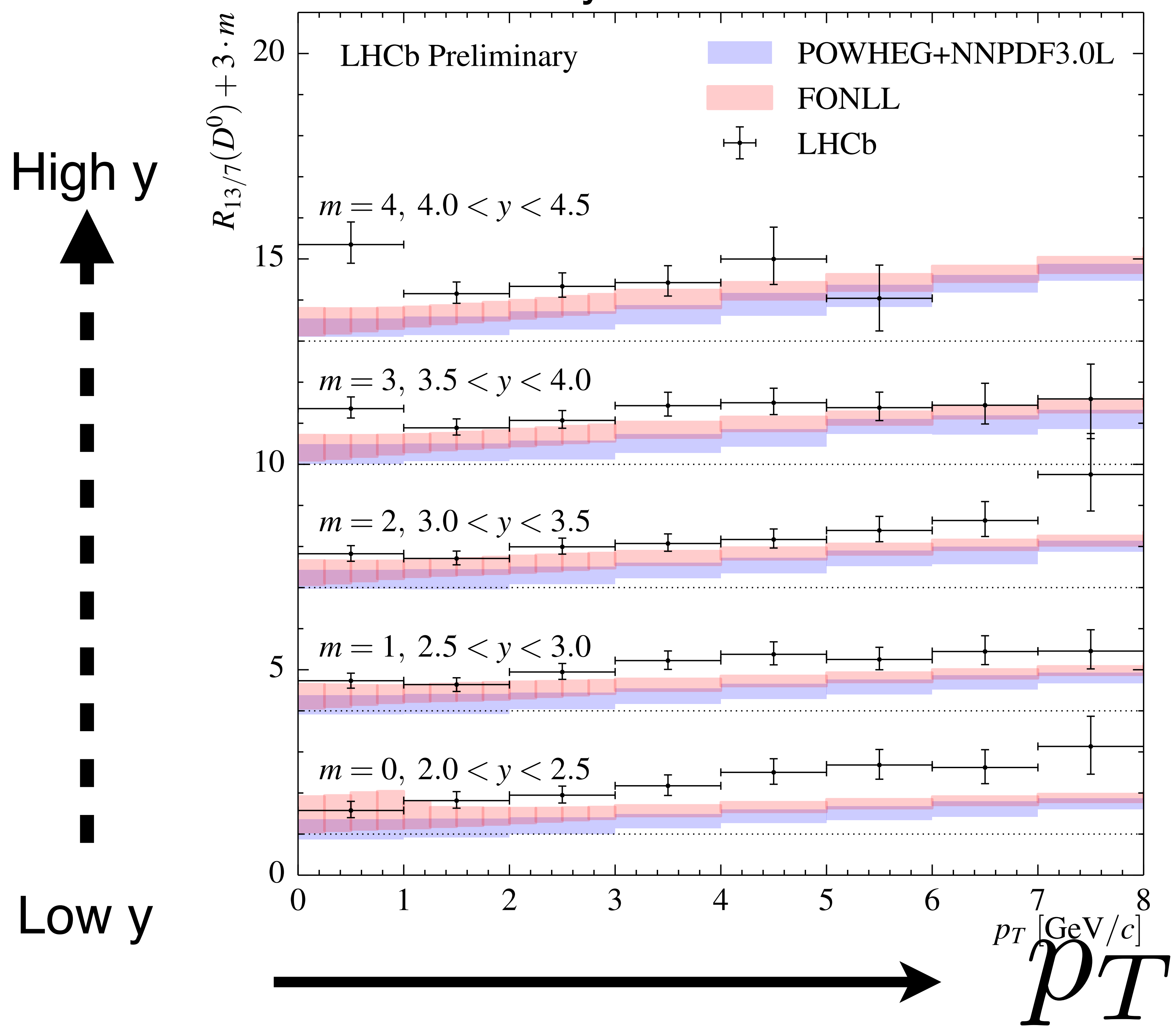
- HERA+LHCb Data PDF fit
- FFS, NF=3
- Normalise to 'middle' rapidity bin for each pT bin
- HERAfitter framework

Consistent Results!



New 13 TeV LHCb data already

LHCb 13 TeV analysis - arXiv:1510.01707



FONLL: Cacciari, Mangano, Nason - arXiv:1507.06197

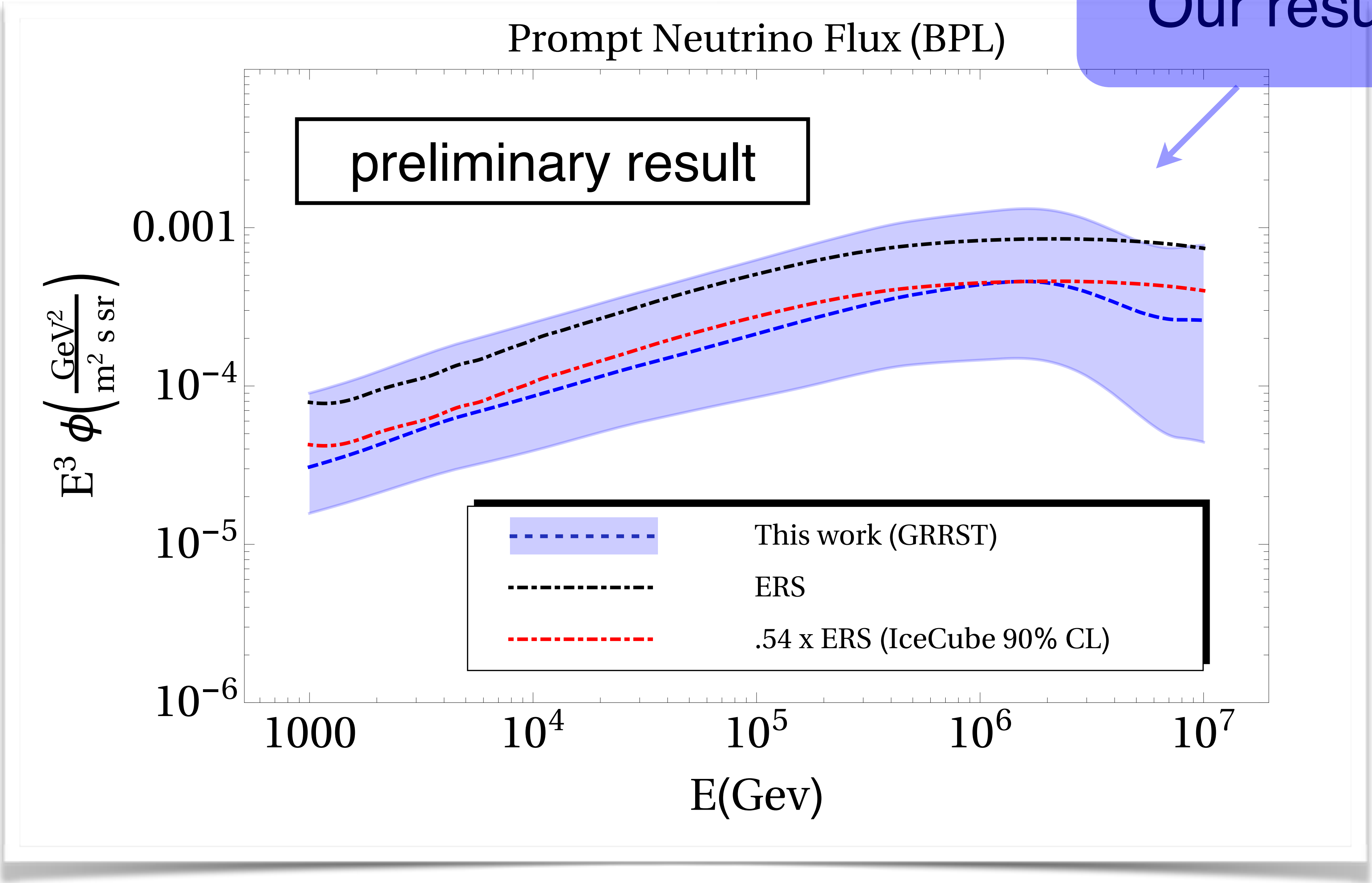
Using the PDF with LHCb data for astrophysics

In progress RG, J. Rojo, L. Rottoli, S. Sarkar, J. Talbert - arXiv:1511.XXX

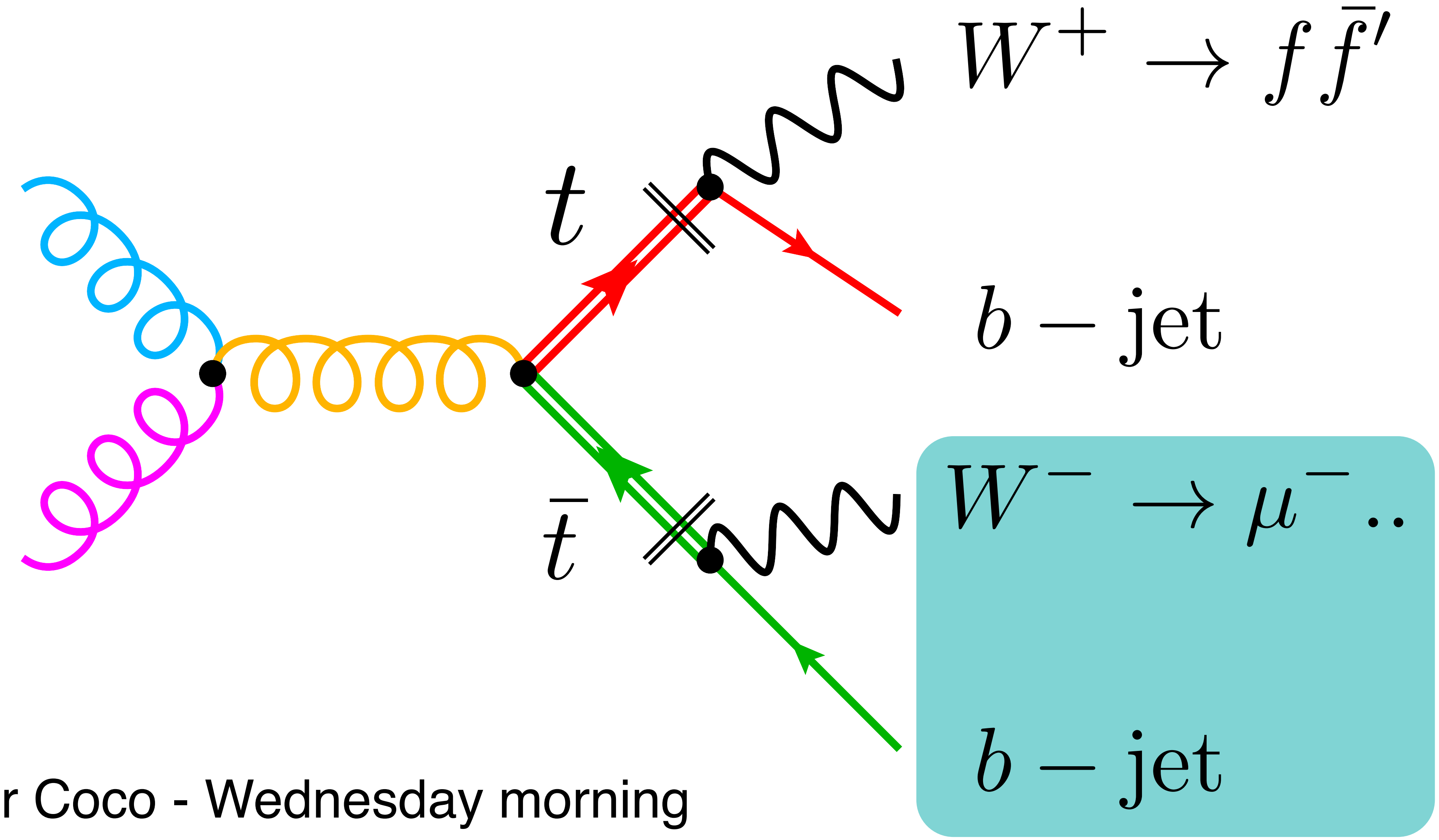
prompt neutrino flux background to extraterrestrial neutrinos

$$nA \to (D \to \nu_l X) + Y$$

Our result blue!



Top at LHCb



See talk of Victor Coco - Wednesday morning

Top measurements proposed - Kagan, Kamenik, Perez, Stone arXiv:1103.3747

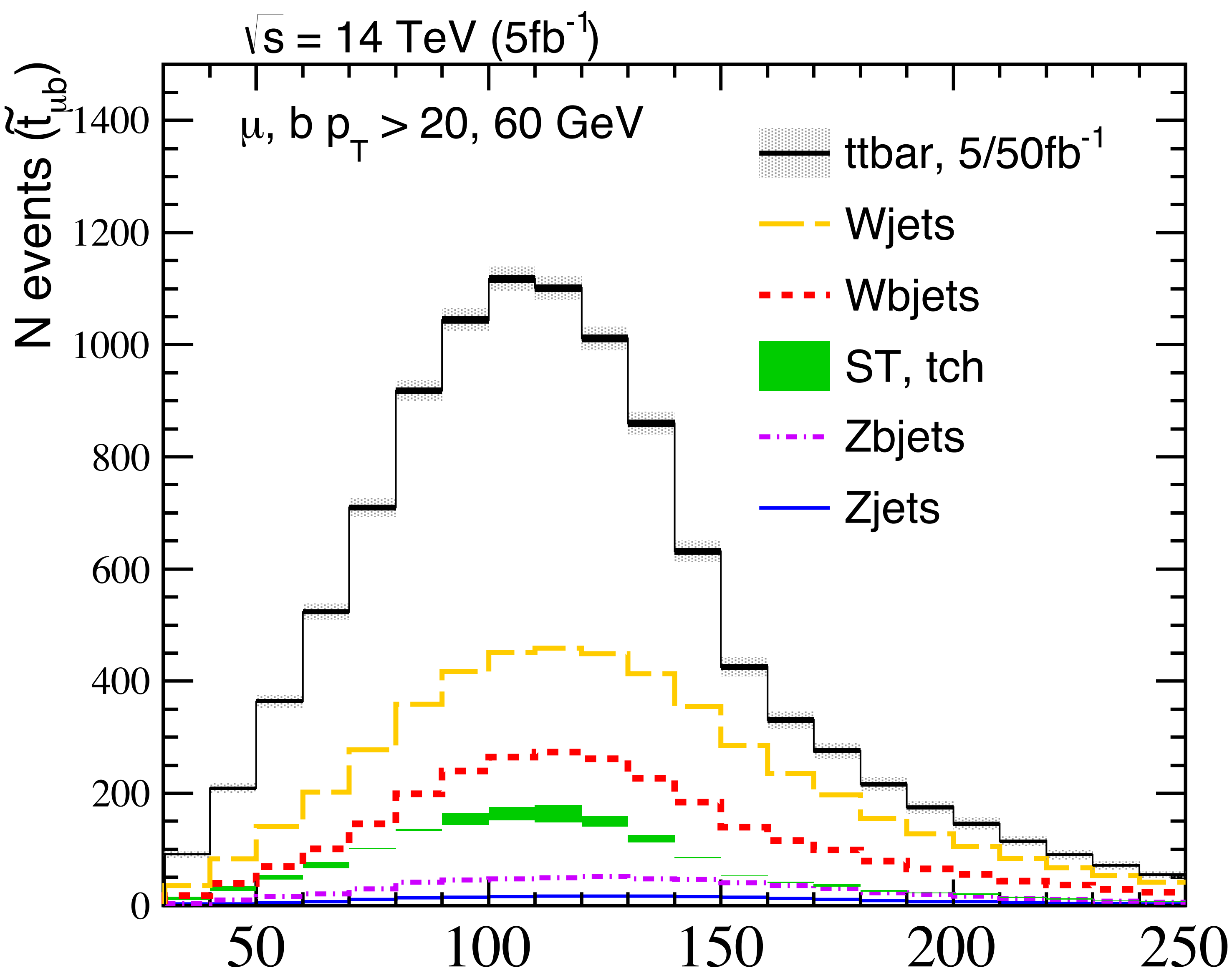
PDF Constraints and SM asymmetry predictions - RG arXiv: 1311.1810, 1409.8631

Observation of forward top quark production - LHCb arXiv: 1506.00903

Approach same as D - reconstruct `one' of the heavy quarks

Top at LHCb: Potential at 14 TeV

POWHEG+Pythia8 (NLO+PS), Signal+Background stacked
b-tagging : 1% mis-tag, 70% efficiency   muon: 75% efficiency



RG arXiv: 1311.1810

$$t\bar{t} \to l^{\pm} b X$$

14 TeV

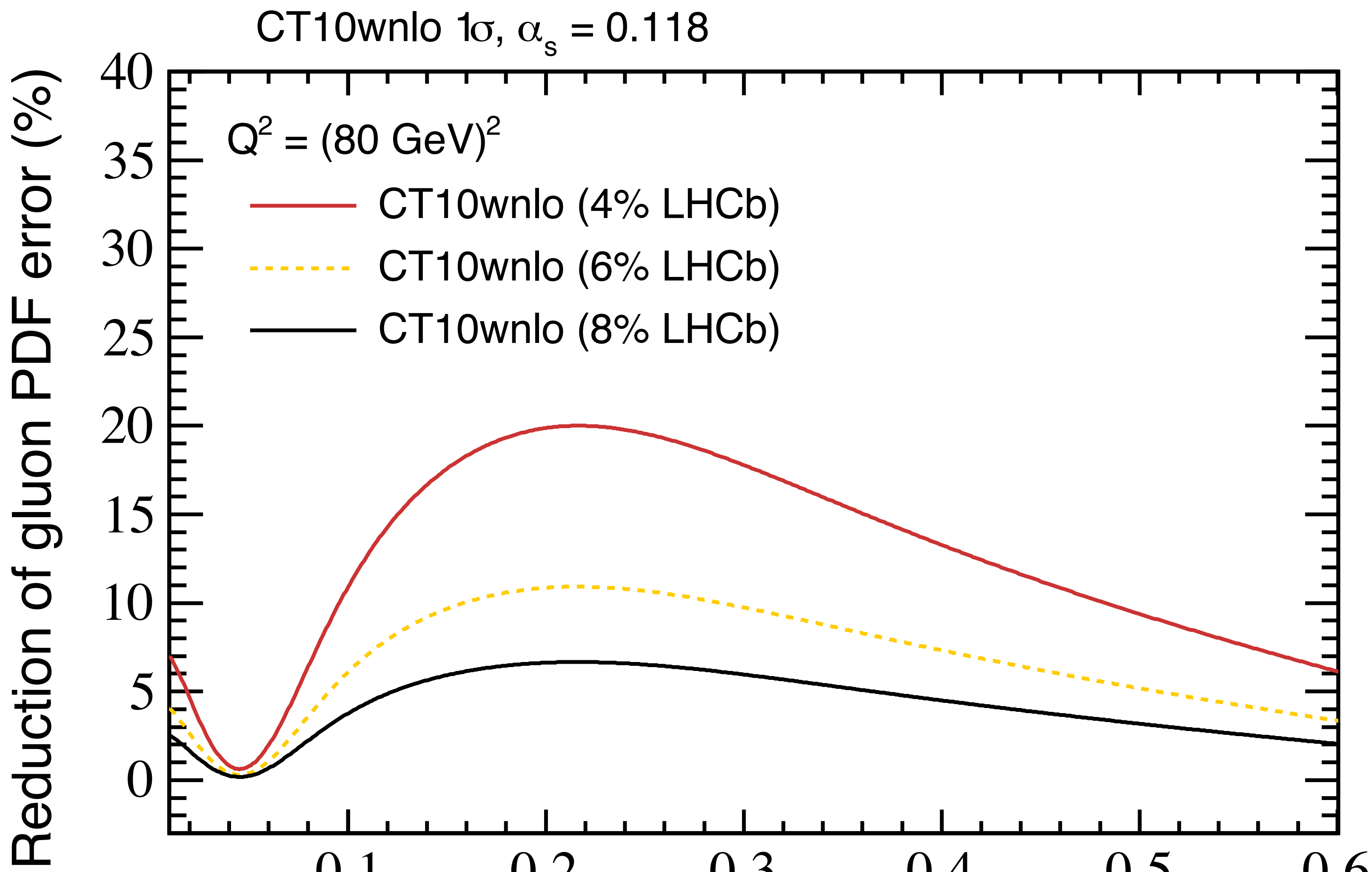
$$2.0 < \eta(l,b) < 4.5$$
$$p_T(l/b) > 20/60 \text{ GeV}$$
$$\Delta R(l^{\pm}, \text{jet}) \geq 0.5$$

Cuts slightly different to Run I measurement

High statistical precision expected within 1-2 year of data taking

Top at LHCb: Potential at 14 TeV

Consider impact of a fiducial cross section measurement on gluon PDF

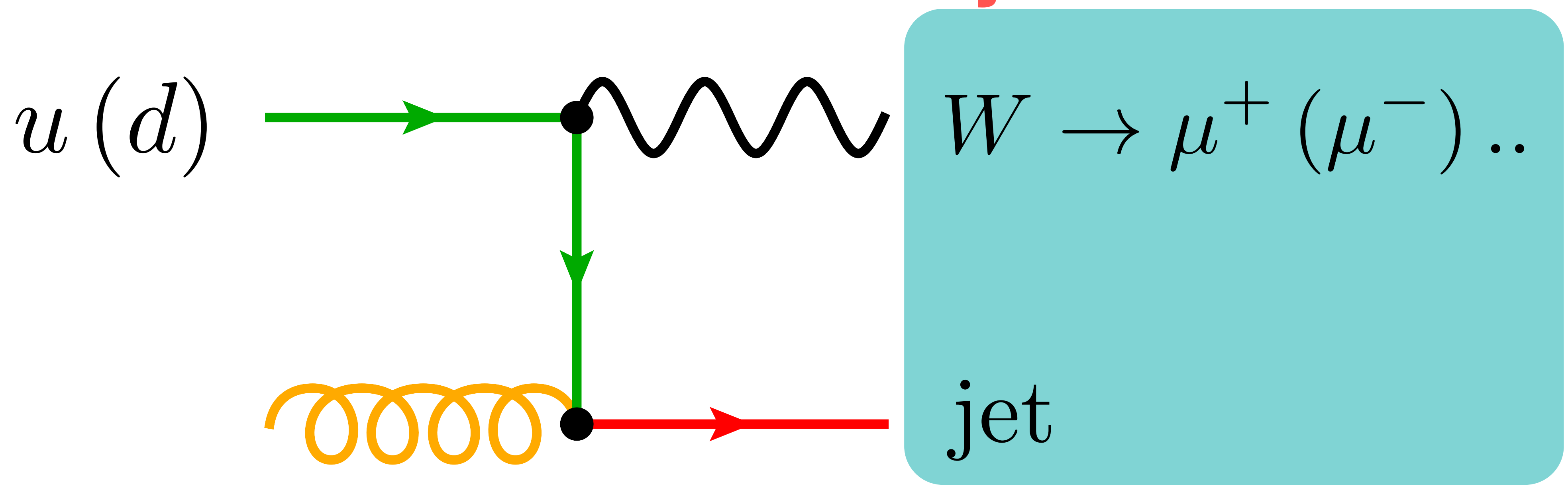


RG arXiv: 1311.1810

Only parton-level. So actual measurement more constraining…

Actual fit would need to be performed at lepton+jets level

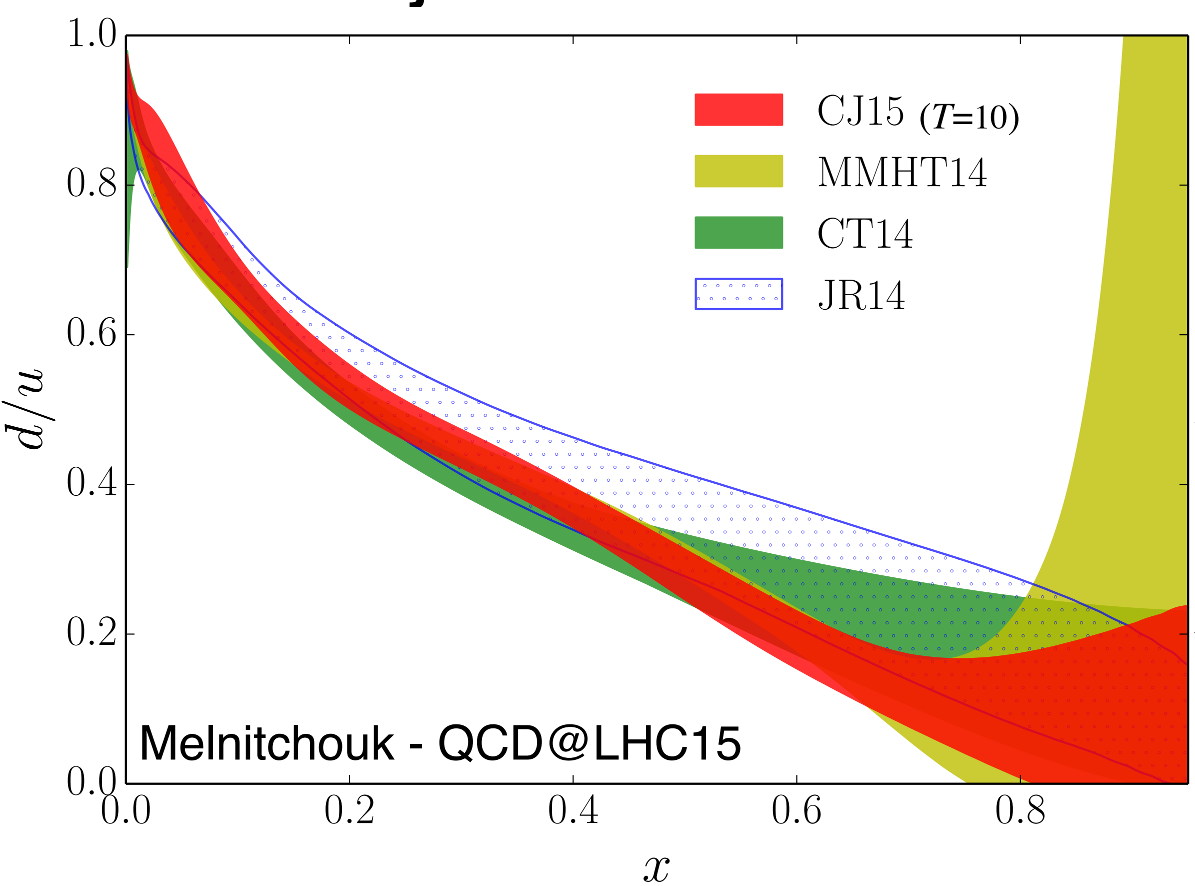
Electroweak+jets



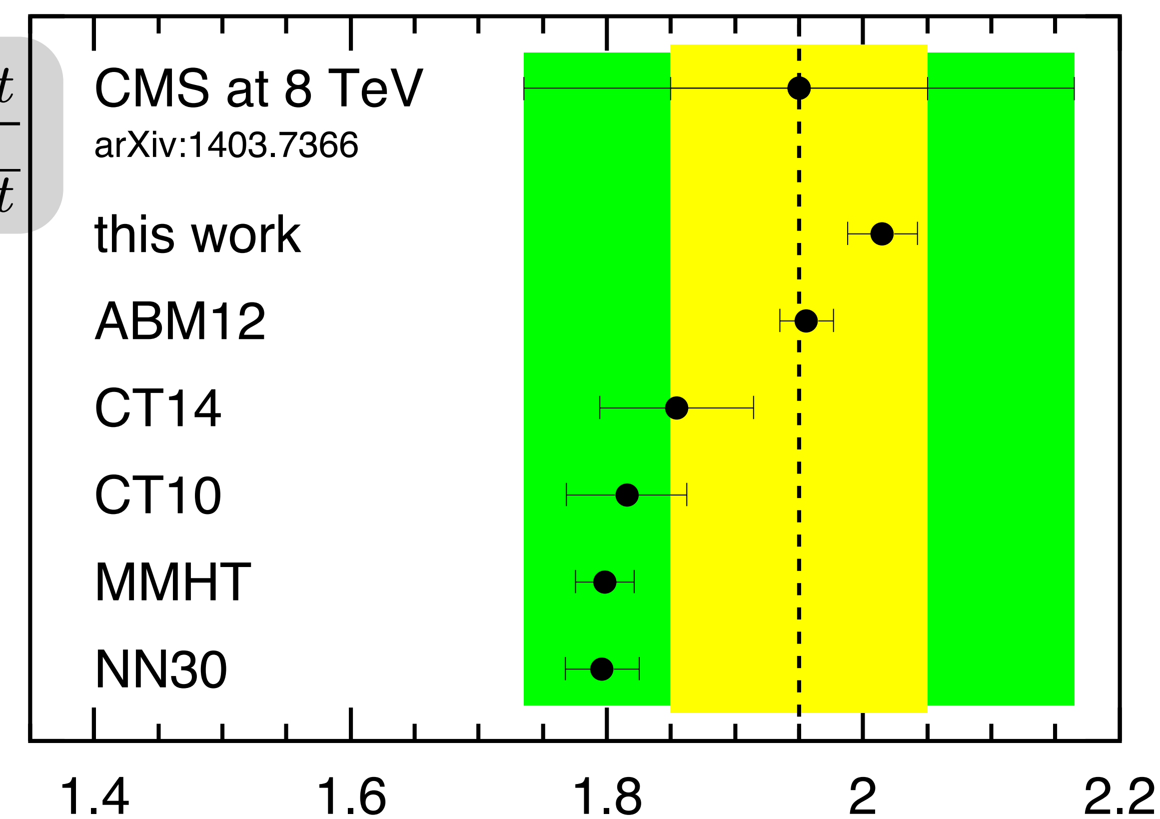
Motivation:
probe the large-x u/d content

$$A^l = \frac{d\sigma^{\mu^+ j}/d\eta_\mu - d\sigma^{\mu^- j}/d\eta_\mu}{d\sigma^{\mu^+ j}/d\eta_\mu + d\sigma^{\mu^- j}/d\eta_\mu}$$

Cuts on jet increase Q^2, x_1, x_2



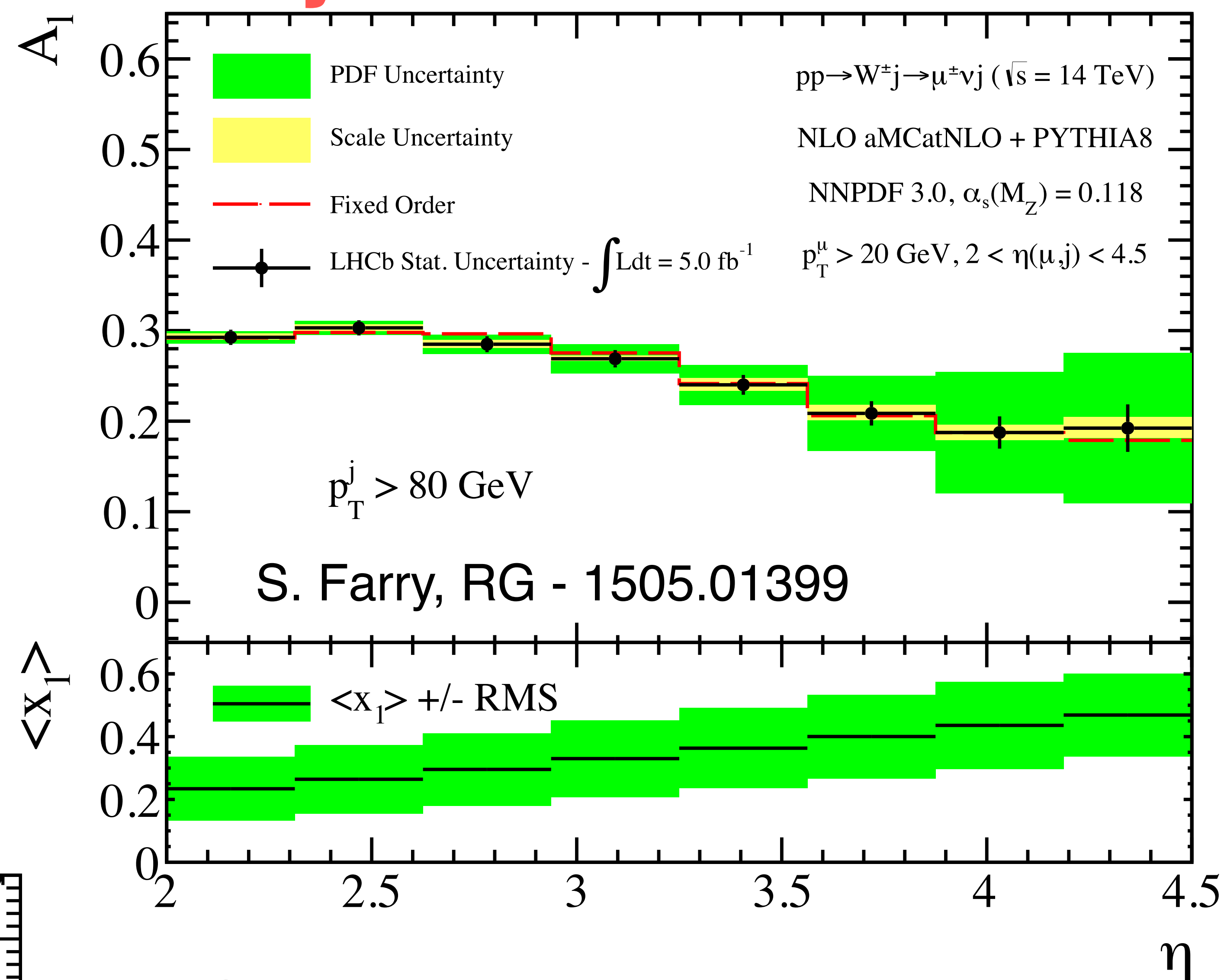
$$R = \frac{\sigma_t}{\sigma_{\bar{t}}}$$



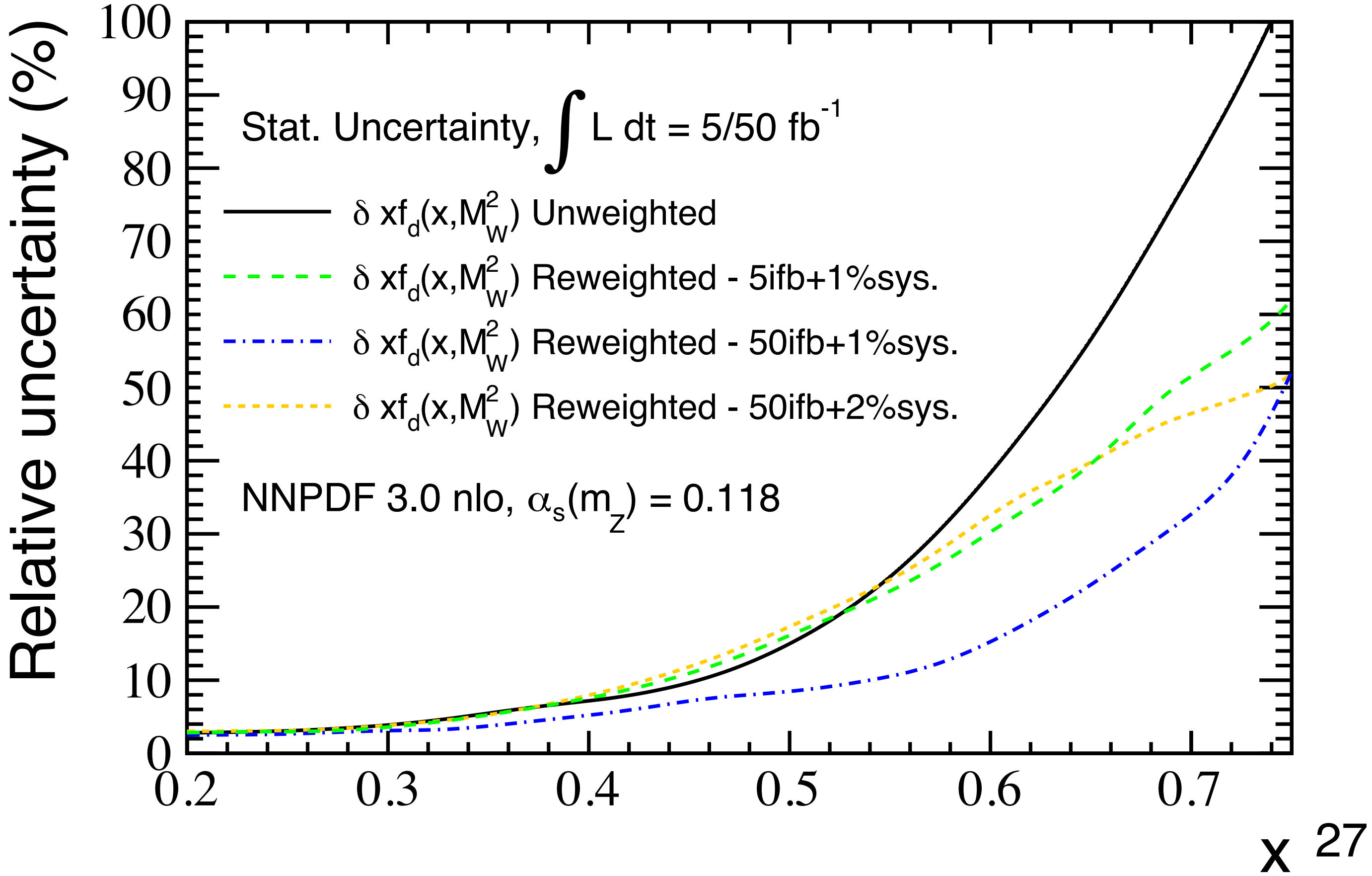
Alekhin, Blumlein, Moch, Placakyte - 1508.07923

Electroweak+jets

$$2.0 < \eta(l,j) < 4.5$$
$$p_T(l/j) > 20/80 \text{ GeV}$$
$$\Delta R(l^{\pm}, \text{jet}) \geq 0.5$$



- PDF uncertainty
- Scale Uncertainty
- Fixed-Order
- LHCb `stat uncertainty'



Study the impact on NNPDF3.0

Relative improvement in d PDF

Different stat./sys. assumptions

$$\frac{\delta f_d^{\text{Now}}(x=0.7, m_W^2)}{\delta f_d^{50ib}(x=0.7, m_W^2)} \simeq 3$$

Sensitivity to high-x nuclear corrections

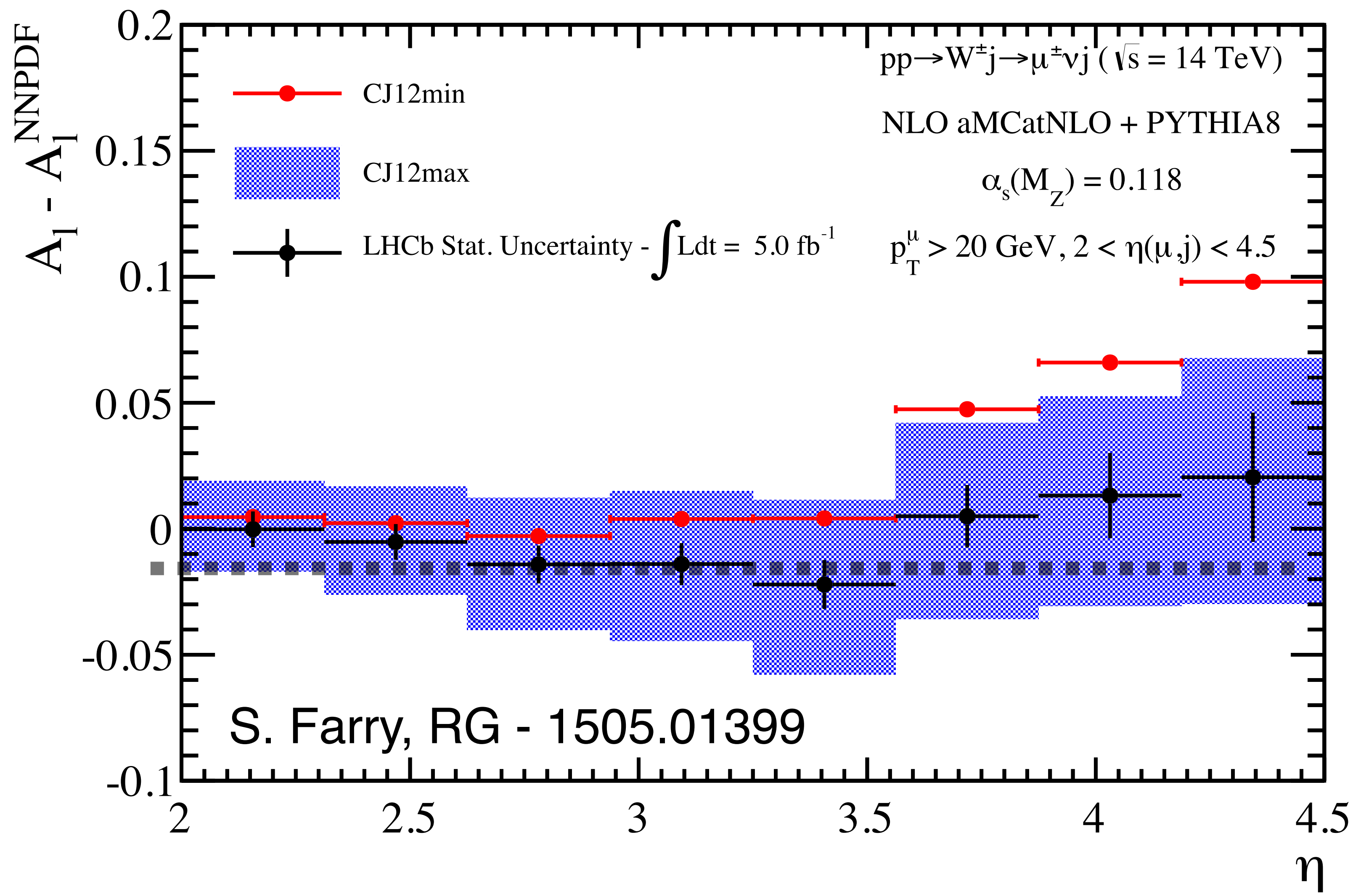
Approach of CT-JLAB (1212.1702), fit proton + deutron DIS

neutron DIS: more data at high-x + higher-twist corrections

Plot of A(CJ12)- A(NNPDF)

Note, Red vs. **Black** points (nuclear corrections)

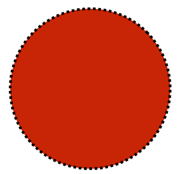
At high η, can distinguish between CJ12min/max

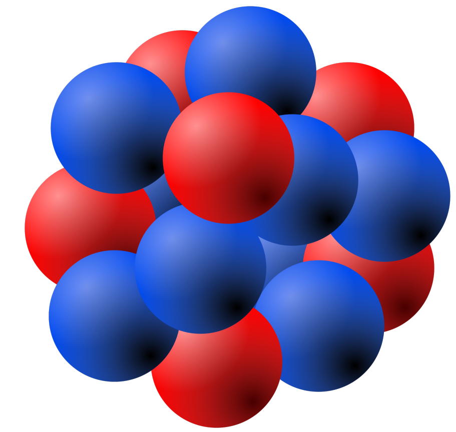


Modelling the binding in Deuteron
Min : WJC1 - see arXiv:0802.1552 [nucl-th]
Max : CD-Bonn - see arXiv:0006014 [nucl-th]
(extracted from N-N scattering < 350 MeV)

p-Pb collisions

p-Pb collisions



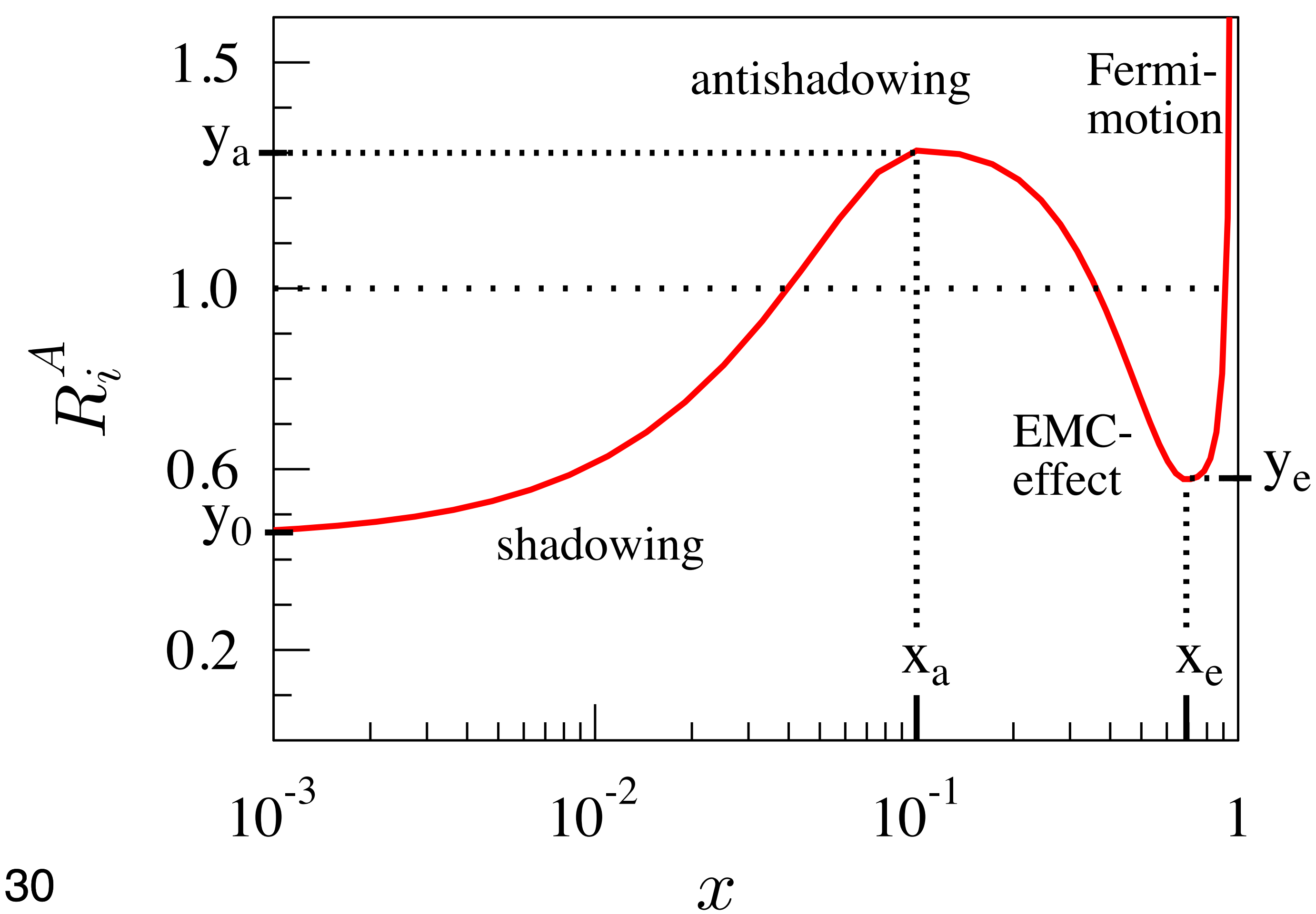


Is the distribution of partons the same in bound and free nuclei?

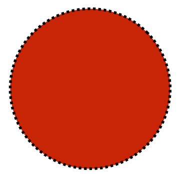
$$f_i^A(x, \mu_F^2) = R_i^A(x, \mu_F^2) \otimes f_i^{\text{free}}(x, \mu_F^2)$$

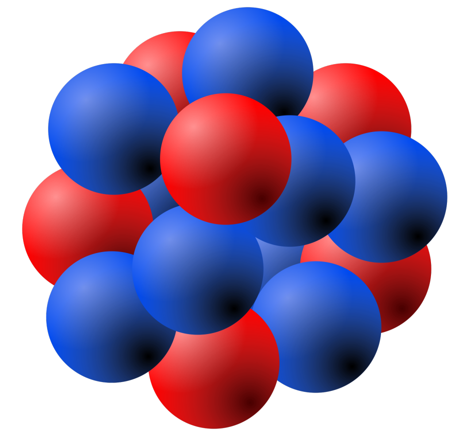
Nuclear modification of PDFs, extracted from data! e.g.:

nCTEQ15 - arXiv 1509.00792
EPS09 - arXiv 0902.4154
DSSZ - arXiv 1112.6324
HKN07 - arXiv 0709.3038



p-Pb collisions





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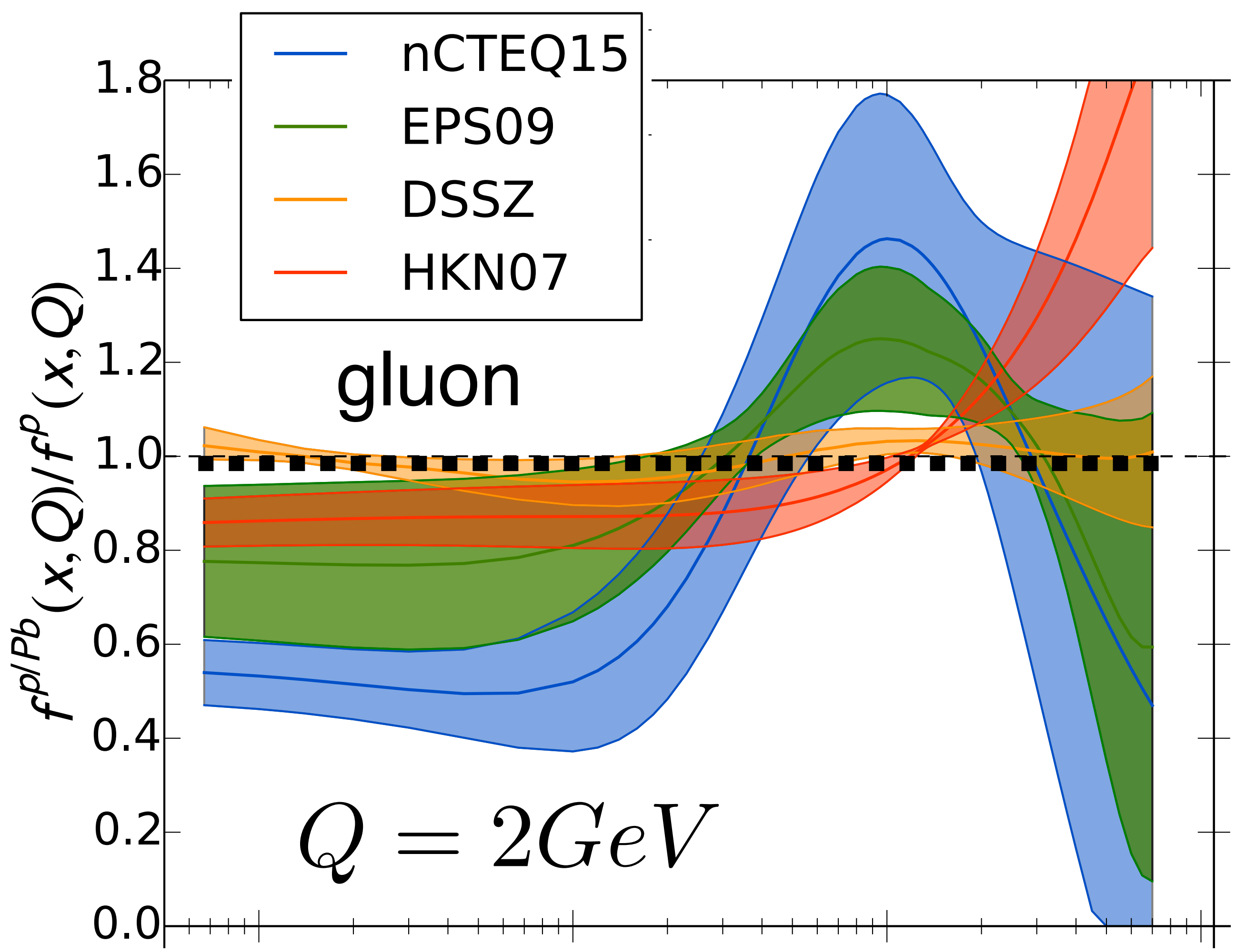


D-hadron predictions for LHCb

$$\sigma_{pA\to Q\bar{Q}} = A \sum_{i,j} \int dx_{i,j} f_{i/p}(x_i,\mu_F^2) R^{\text{nuc}}_{j/A} \otimes f_{j/N}(x_j,\mu_F^2)$$

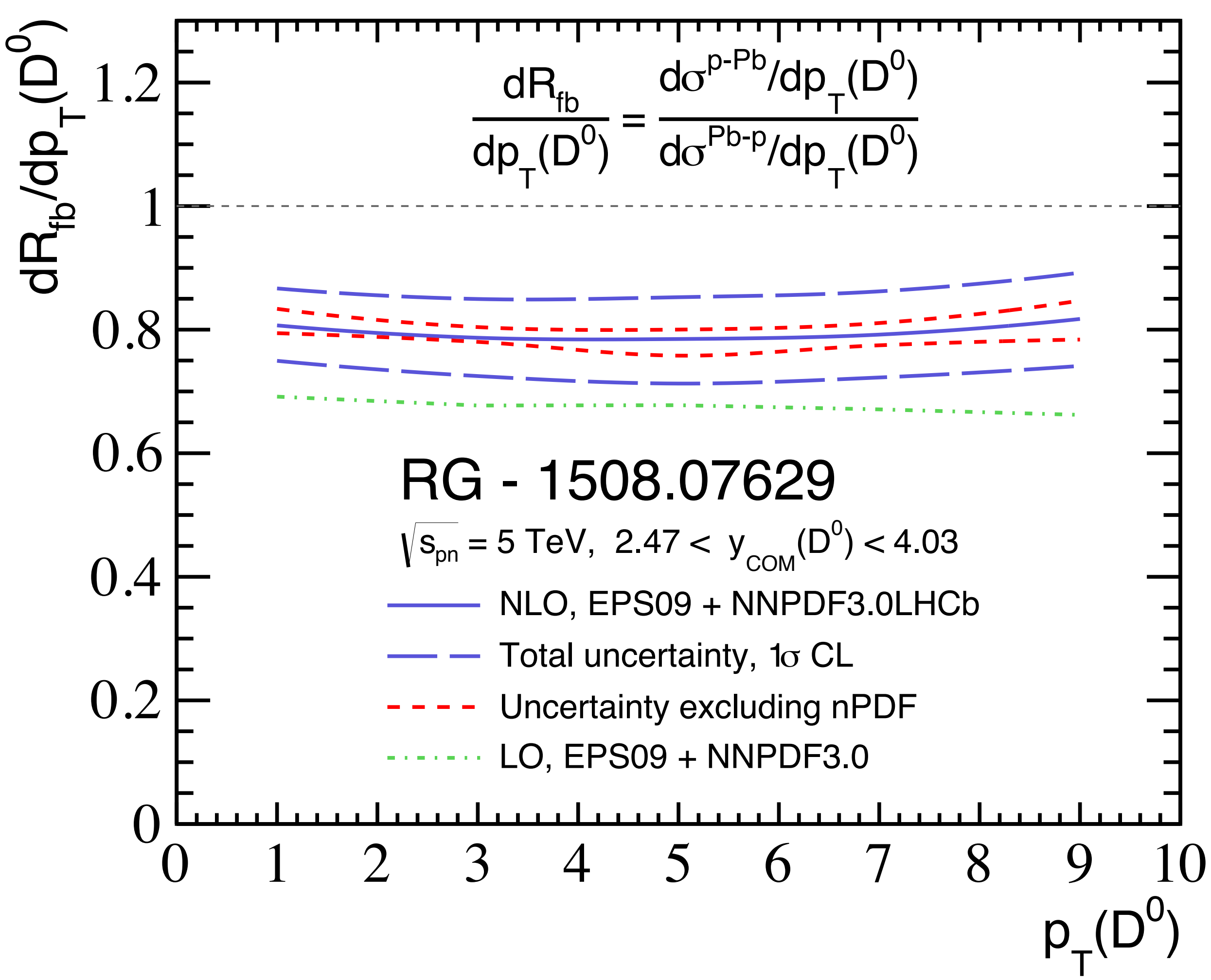
$$d\hat{\sigma}_{ij\to Q\bar{Q}X}\left(\hat{s},\mu_F^2,\mu_R^2,\alpha_s(\mu_R^2),m_Q\right) + \ldots$$

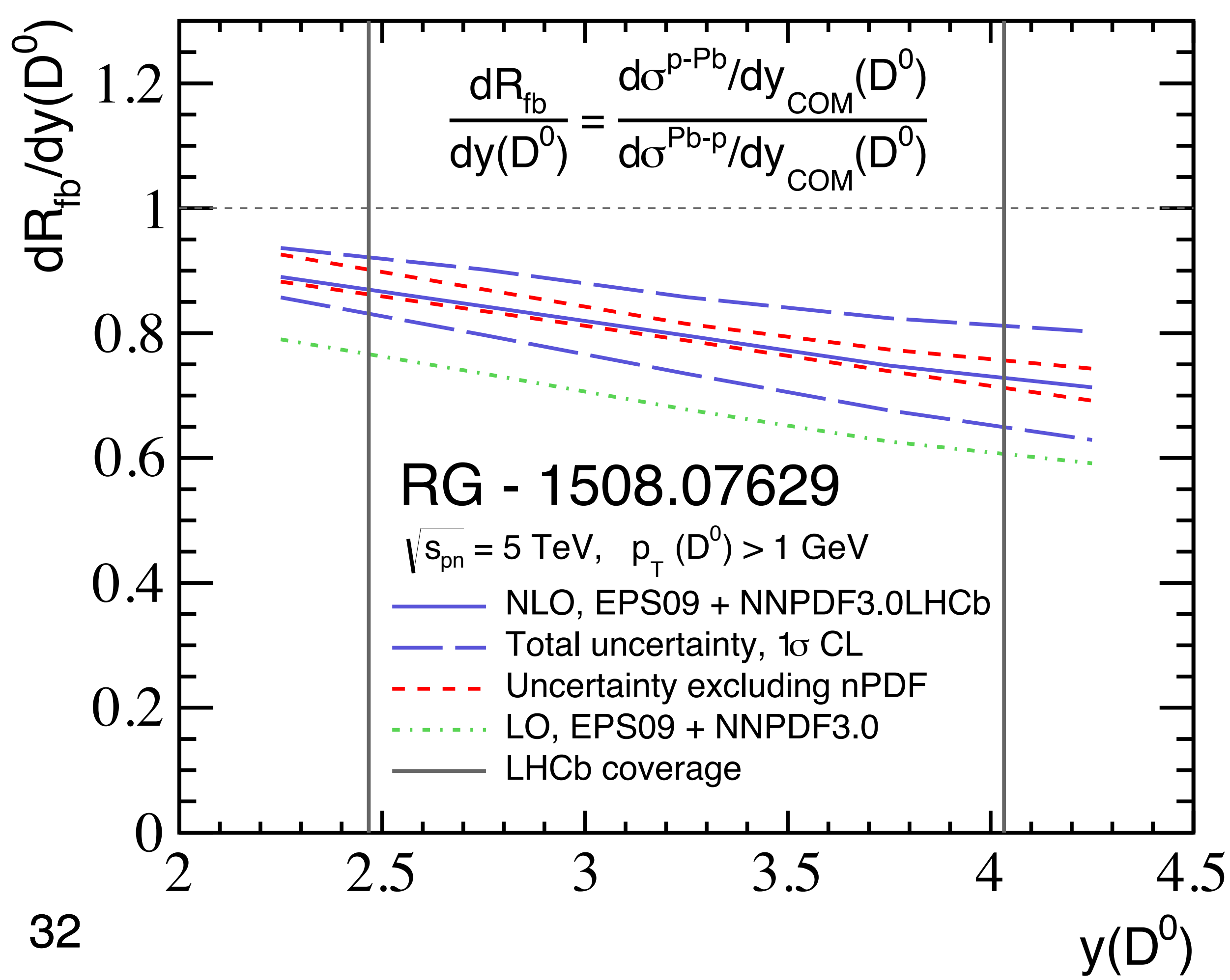
Double differential within LHCb acceptance - RG arXiv: 1508.07629

$$\frac{dR_{fb}}{dx} \equiv \frac{d\sigma^{pPb}(x)}{dx} \Bigg/ \frac{d\sigma^{Pbp}(x)}{dx}$$

pPb $\quad \int Ldt = 1.1nb^{-1}$

Pbp $\quad \int Ldt = 0.5nb^{-1}$





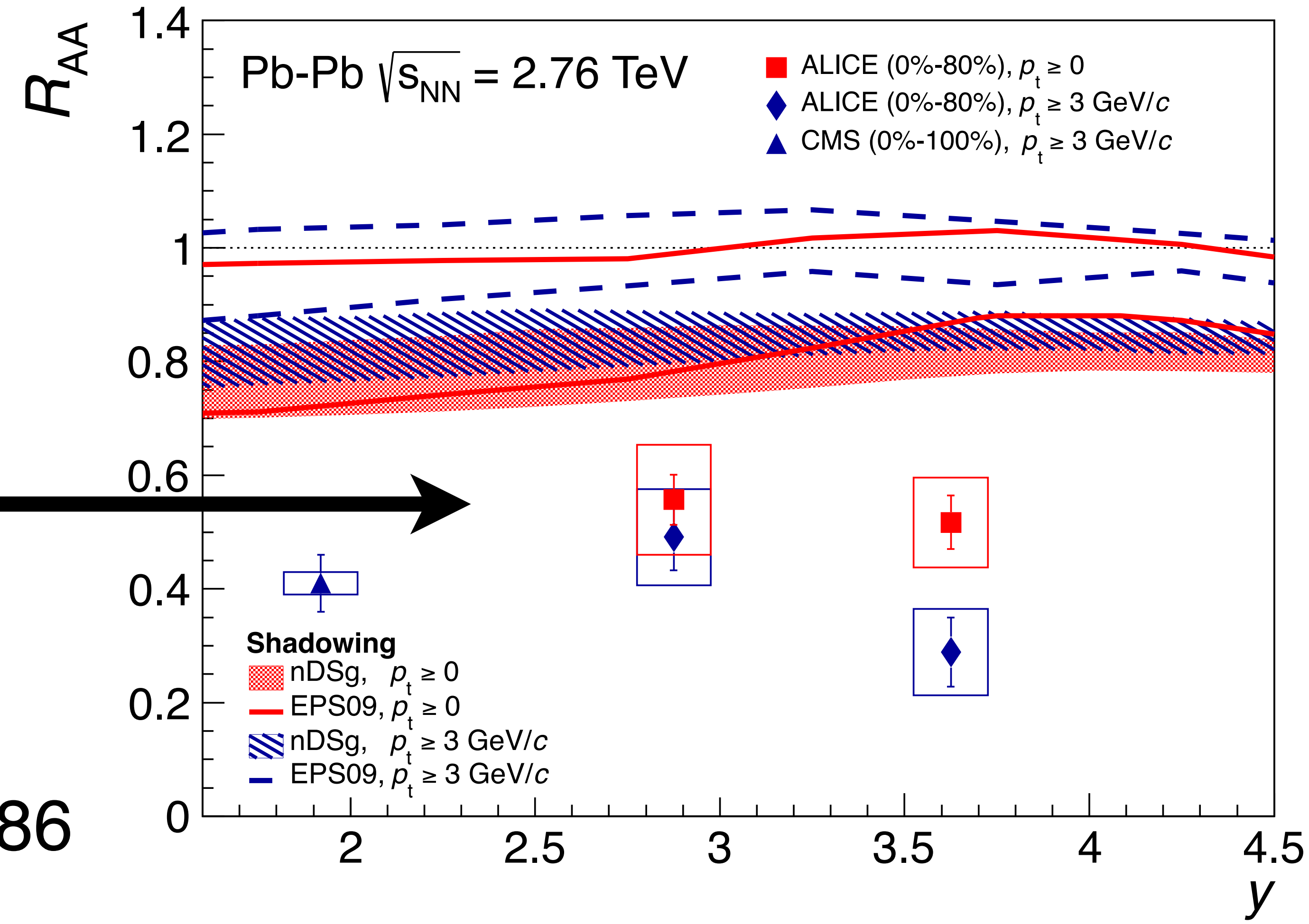
Importance of constraining CNM effects

Measurements of J/ψ suppression in Pb-Pb vs. reference pp collisions

ALICE arXiv:1202.1383

A suppression beyond nuclear shadowing observed

Interpreted otherwise as QGP
Matsui, Satz Phys. Lett., B178(416),1986



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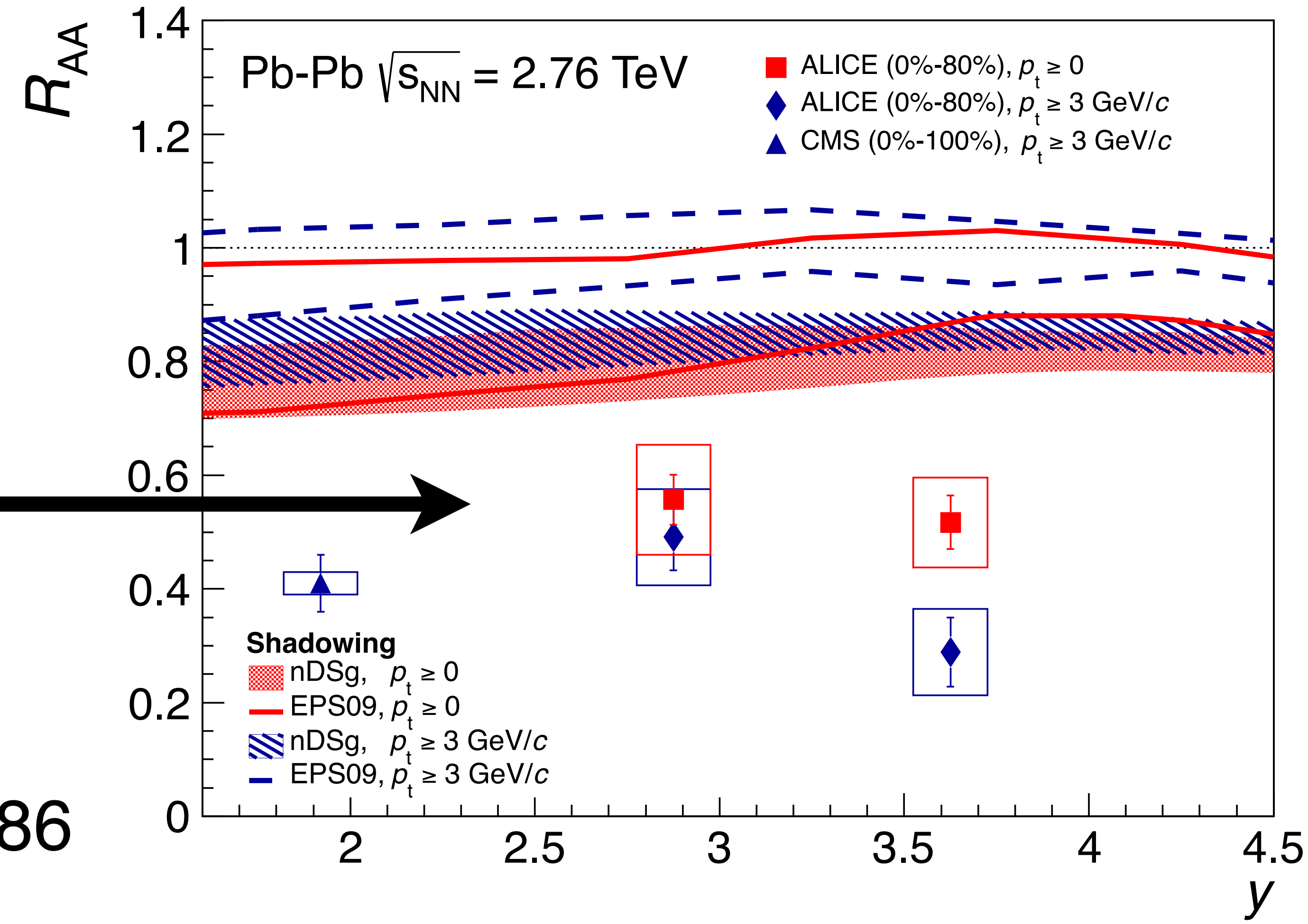

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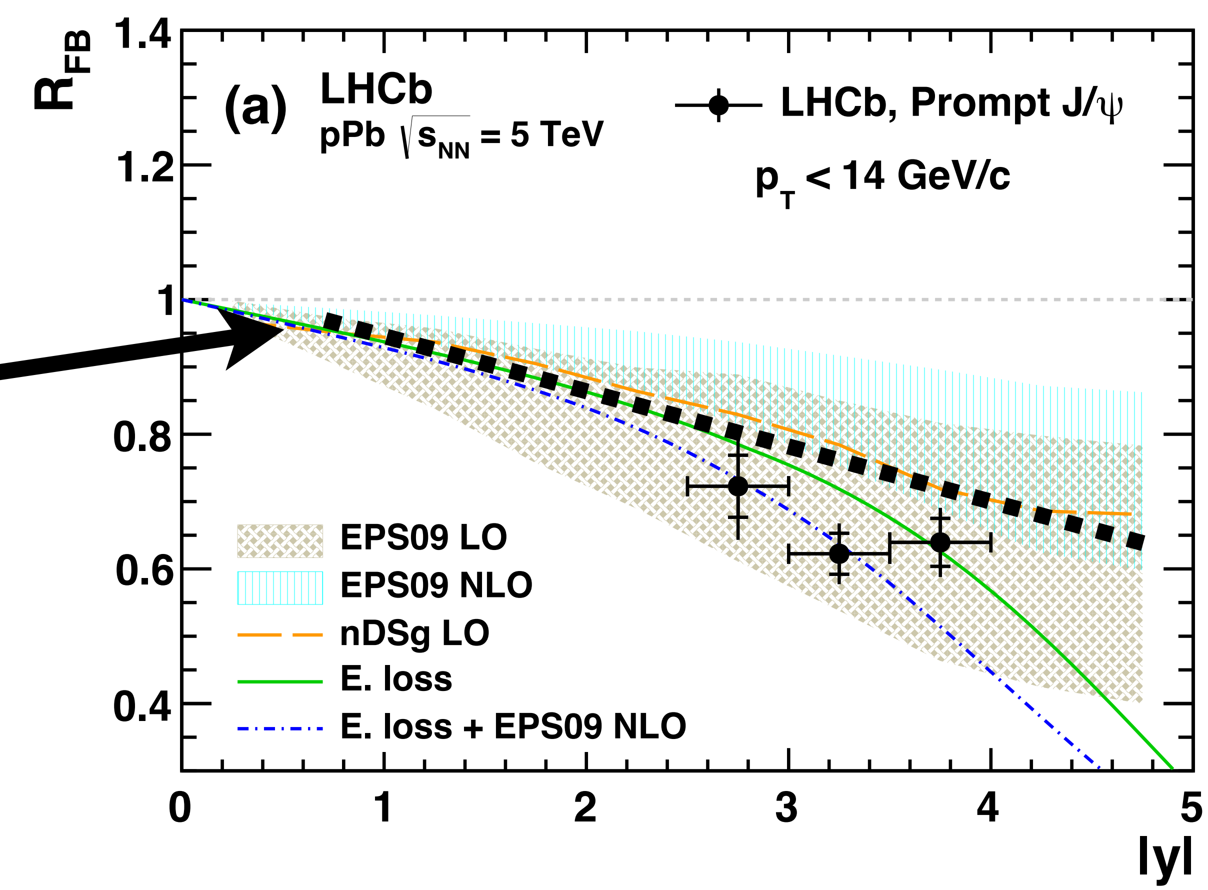
LHCb forward J/ψ measurement Pb-p



Indicate NLO EPS09 nPDFs alone underestimate the suppression

Need more data to constrain the nPDFs

Outlook

PDF wishlist

process	measurement type	x_1	x_2	sensitivity
pp **collisions**				
$W^\pm$-jets	Lepton asymmetry / cross-section	**large**	moderate	u/d
$W^\pm c$-jets	Lepton asymmetry / cross-section	**large**	moderate	$s/\bar{s}$
$t\bar{t}$	cross-section	**large**	moderate	g
$t/\bar{t}$	Asymmetry	**large**	moderate	u/d
dijets	cross-section	**large**	moderate	g
$Q\bar{Q}$	cross-section (large m_{QQ})	**large**	moderate	g
D/B	Ratio (13/7) / cross-section	moderate	**low**	g
Drell-Yan (low m_{ll})	cross-section	moderate	**low**	$q/\bar{q}$
pPb **collisions**				
D/B	R_{FB} / cross-section	**moderate**	**low**	R_g^{Pb}
Drell-Yan (low m_{ll})	R_{FB} /cross-section	**moderate**	**low**	$R_{q/\bar{q}}^{Pb}$

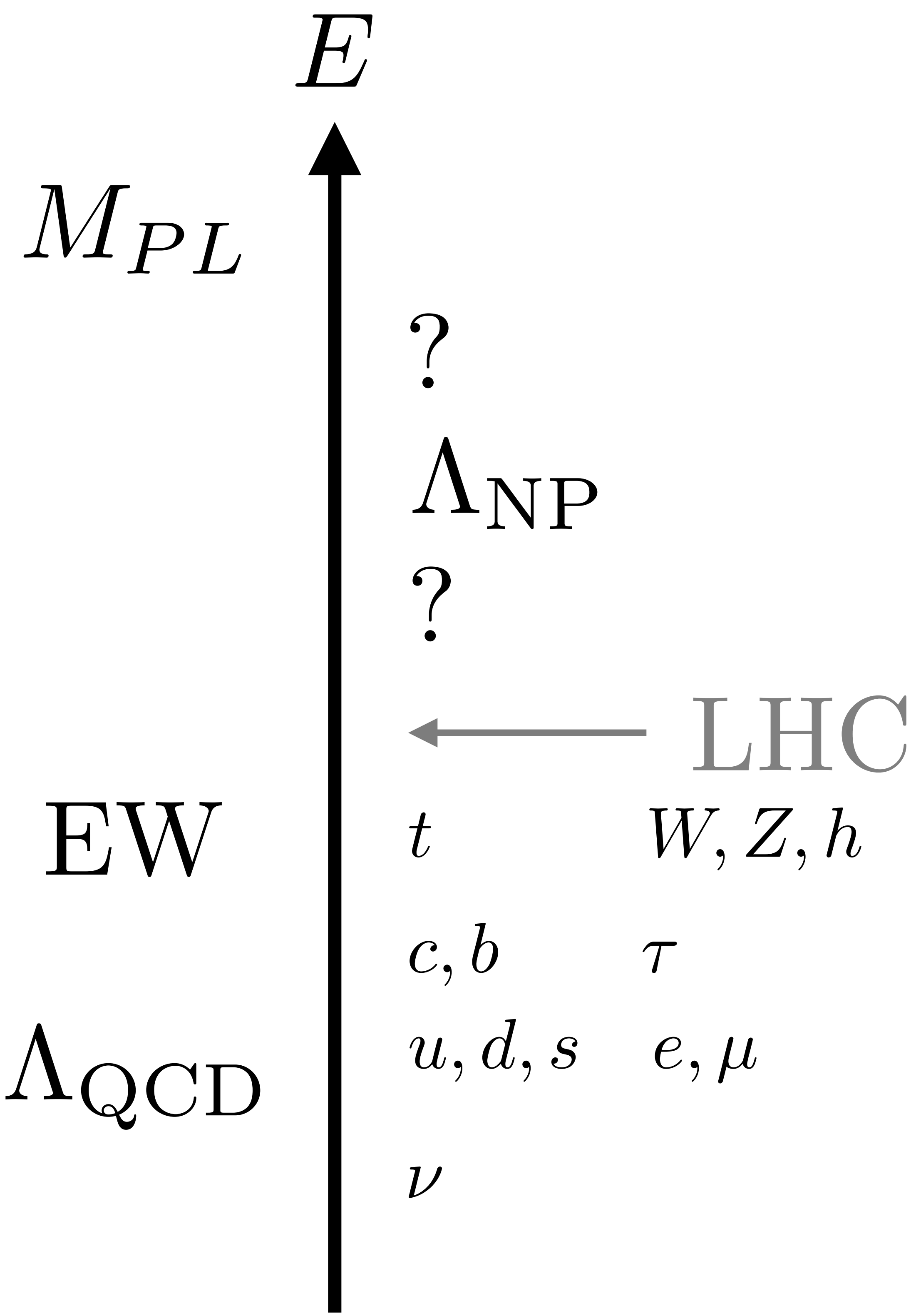
Have not considered Onia+CEP production... someone better qualified should comment on this.

Thanks for your attention!

Bonus slides

Fitting era of the LHC

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}^{(6)}\,; \qquad \mathcal{L}^{(6)} = \sum_i C_i Q_i$$



$1: X^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$Q_{\widetilde W}$	$\epsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

$2: H^6$	
Q_H	$(H^\dagger H)^3$

$3: H^4 D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$

$5: \psi^2 H^3 + \text{h.c.}$	
Q_{eH}	$(H^\dagger H)(\bar l_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar q_p u_r \widetilde H)$
Q_{dH}	$(H^\dagger H)(\bar q_p d_r H)$

$4: X^2 H^2$	
Q_{HG}	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$
$Q_{H\widetilde G}$	$H^\dagger H\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$
$Q_{H\widetilde W}$	$H^\dagger H\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde B}$	$H^\dagger H\, \widetilde B_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde W B}$	$H^\dagger \tau^I H\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$

$6: \psi^2 X H + \text{h.c.}$	
Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r) \tau^I H W^I_{\mu\nu}$
Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r) \widetilde H\, G^A_{\mu\nu}$
Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r) \tau^I \widetilde H\, W^I_{\mu\nu}$
Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r) \widetilde H\, B_{\mu\nu}$
Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r) H\, G^A_{\mu\nu}$
Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r) \tau^I H\, W^I_{\mu\nu}$
Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

$7: \psi^2 H^2 D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar l_p \gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar l_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar e_p \gamma^\mu e_r)$
$Q_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar q_p \gamma^\mu q_r)$
$Q_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar q_p \tau^I \gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar u_p \gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar d_p \gamma^\mu d_r)$
Q_{Hud} + h.c.	$i(\widetilde H^\dagger D_\mu H)(\bar u_p \gamma^\mu d_r)$

$8: (\bar L L)(\bar L L)$	
Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$
$Q_{lq}^{(1)}$	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$

$8: (\bar R R)(\bar R R)$	
Q_{ee}	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$
Q_{uu}	$(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$
Q_{dd}	$(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$
Q_{eu}	$(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$
Q_{ed}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$
$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$

$8: (\bar L L)(\bar R R)$	
Q_{le}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
Q_{lu}	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
Q_{ld}	$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$
Q_{qe}	$(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
$Q_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
$Q_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$

$8: (\bar L R)(\bar R L) + \text{h.c.}$	
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_{tj})$

$8: (\bar L R)(\bar L R) + \text{h.c.}$	
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\epsilon_{jk}(\bar q_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\epsilon_{jk}(\bar q_s^k T^A d_t)$
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\epsilon_{jk}(\bar q_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$

Fitting era of the LHC

Taking a bottom-up approach…

Motivation: interpret Higgs couplings measurements in a robust framework
see - Progress in Higgs Effective Field Theories (Higgs Couplings 2015), M. Trott

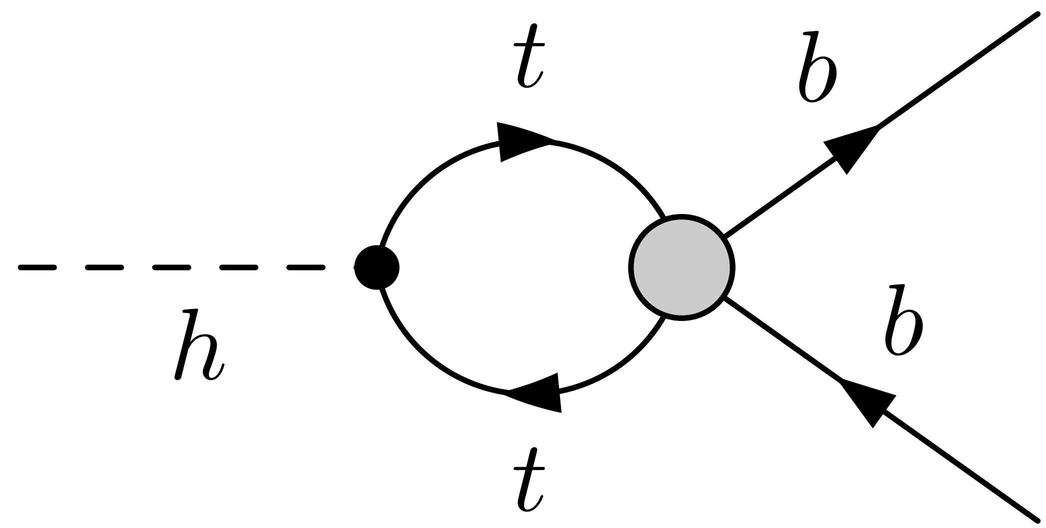
Take for example,

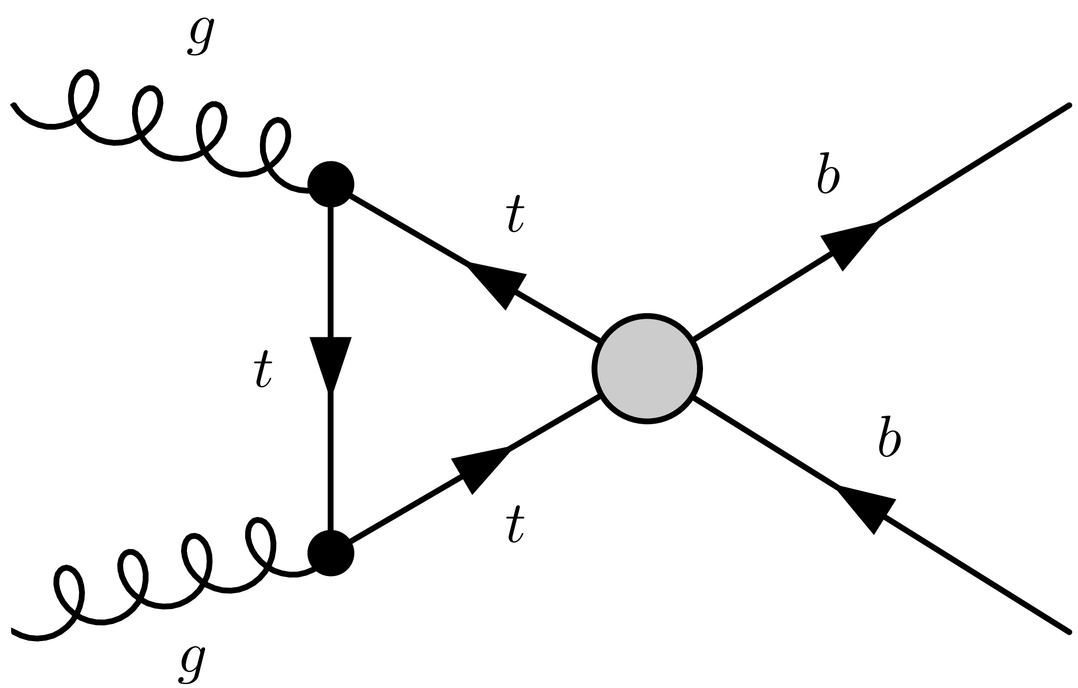
$$h \to b\bar{b}$$

at one-loop in the SMEFT

Receives $\mathcal{O}(m_t^3)$ corrections from

$$Q_{qtqb}^{(1,8)} = (\bar{q}^j T^{1,A} t)\epsilon_{jk}(\bar{q}^k T^{1,A} b)$$





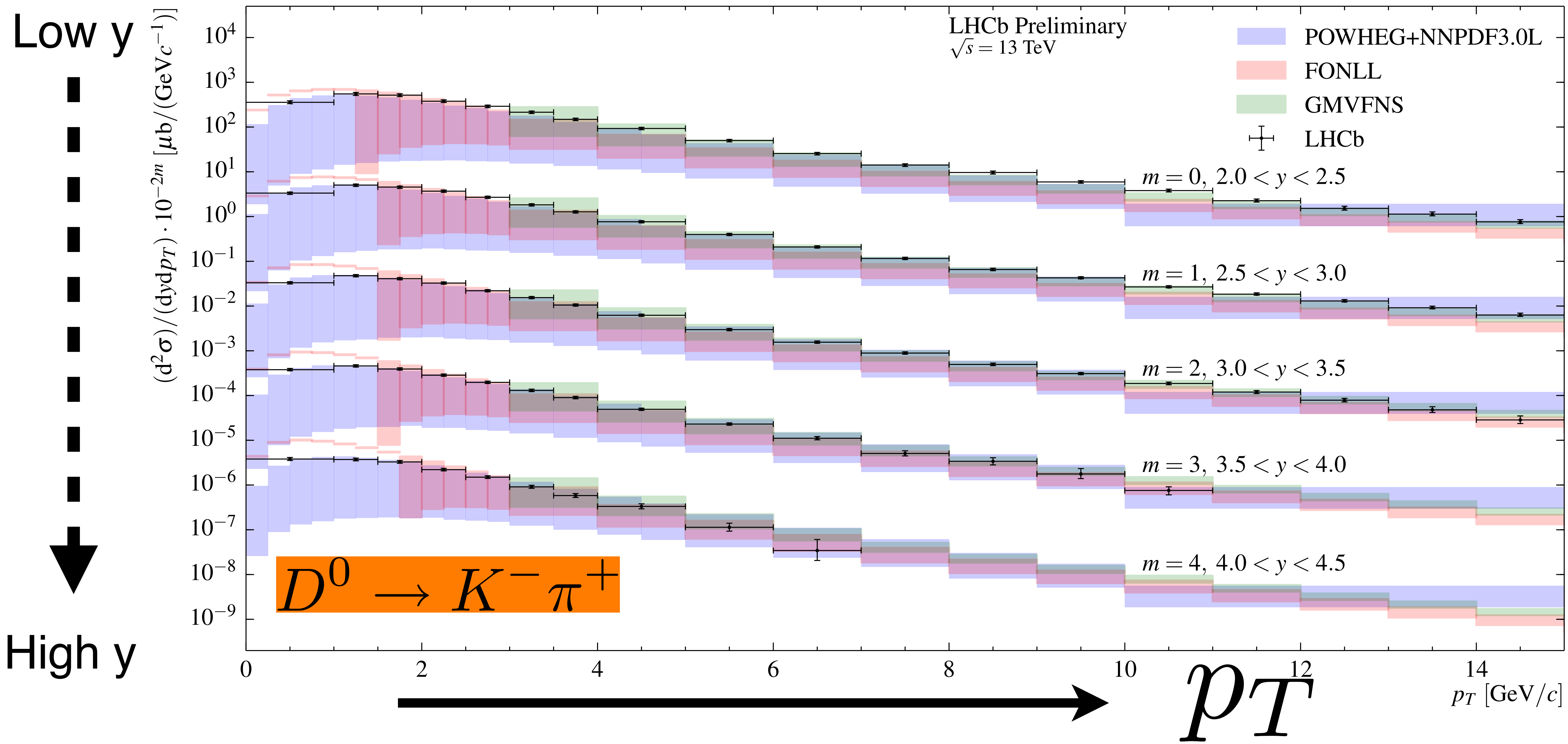
LHCb already `measured' the differential b-quark pair cross-section

$$\frac{dA_{FB}}{dM_{b\bar{b}}} = \frac{d\sigma^{asym.}/dM_{b\bar{b}}}{d\sigma^{sym.}/dM_{b\bar{b}}}$$

LHCb data arXiv:1406.4789

13 TeV D data from LHCb

See talk from M. Needham - Heavy Flavour parallel QCD@LHC 2015



1) POWHEG+NNPDF3.0 reweighted with LHCb 7 TeV data (NLO+LLcoll.) 1506.08025
2) FONLL+NNPDF3.0 (without reweighting), Cacciarai, Mangano, Nason 1507.06197
3) GMVFNS - Kniehl et al. EPJC 72 (2012) 2082

LHCb kinematics: Pb-p

p-Pb probe shadowing (low-x)

Pb-p probe anti-shadowing (x~0.05)

Rfb simultaneously sensitive to these effects

Increasing D pT gains sensitivity to anti-shadowing regime!