High-x opportunities at A Fixed Target ExpeRiment using the LHC beams (AFTER@LHC)

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Outline

- **Part I: AFTER@LHC**
  - What is AFTER@LHC?
  - Possible technical implementations
  - Main kinematical features
  - Physics motivations
- **Part II: A selection of projected high-x performances**
  - Drell Yan lepton pair production
  - W production
  - The large-x gluon
  - Intrinsic charm
- **Conclusions**

Part I:

AFTER@LHC

What is AFTER@LHC?

AFTER@LHC is a proposal for a multi-purpose **fixed target experiment using the LHC proton or heavy ion beams**, with three main physics objectives:

- Advance our understanding of the **large-x parton content in nucleons/nuclei**
- Advance our understanding of the **dynamics and spin of gluons inside (un)polarised nucleons/nuclei**
- Study **heavy-ion collisions** between RHIC and SPS energies towards large rapidities

Several advantages of the fixed-target mode wrt the collider mode:

- Accessing **high-x frontier** (ycm<0 and parton momentum fraction x>0.5)
- Achieving **high luminosity** thanks to the high density of the targets
- **Large number of target species** with varying atomic mass number
- **Polarizing the target**

- This can be realized at LHC in parasitic mode
- Fixed-target mode started at LHCb with a low-density gas target (SMOG)

Possible implementations

- Internal gas target
  - can be installed in one of the existing LHC caverns, and coupled to existing experiments
  - currently validated validated by the LHCb collaboration via a luminosity monitor (SMOG)
  - uses the high LHC particle current: p flux = $3.4 \times 10^{18}\ s^{-1}$ & Pb flux = $3.6 \times 10^{14}\ s^{-1}$

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- Beam line extracted by a bent cristal
  - crystals successfully tested at the LHC for proton and lead beam collimation
  - provides a new facility with 7 TeV proton beam but requires civil engineering
  - the LHC beam halo is recycled on a dense target
    - proton flux = $5 \times 10^{8}\ s^{-1}$ & lead flux = $2 \times 10^{5}\ s^{-1}$

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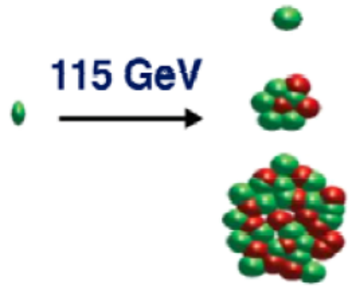
- The internal solid target & beam split option: similar possibilities; the latter is cleaner
- The gas target is the best for polarized target and satisfactory for heavy ion studies

Main kinematic features of AFTER@LHC

Energy range

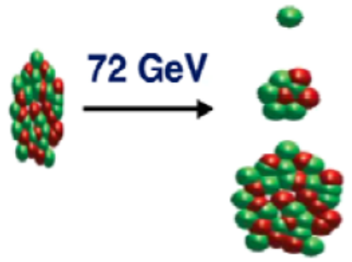
7 TeV proton beam on a fixed target

c.m.s. energy:	$\sqrt{s}=\sqrt{2m_N E_p}\approx 115\,\mathrm{GeV}$	**Rapidity shift:** $y_{c.m.s.}=0\rightarrow y_{lab}=4.8$
Boost:	$\gamma=\sqrt{s}/(2m_N)\approx 60$	

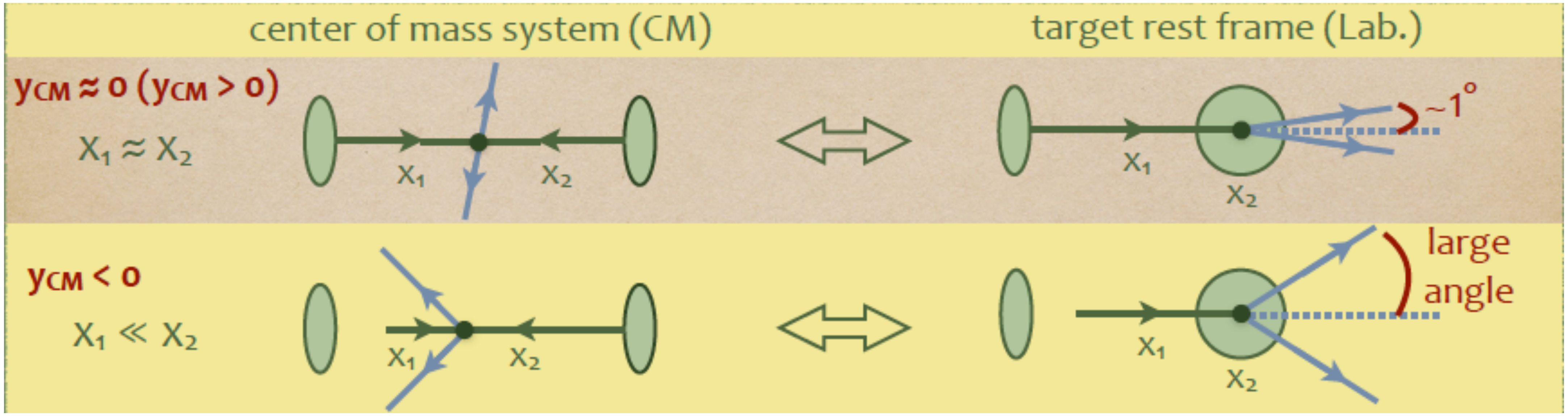


2.76 TeV Pb beam on a fixed target

c.m.s. energy:	$\sqrt{s_{NN}}=\sqrt{2m_N E_{\mathrm{Pb}}}\approx 72\,\mathrm{GeV}$	**Rapidity shift:** $y_{c.m.s.}=0\rightarrow y_{lab}=4.3$
Boost:	$\gamma\approx 40$	

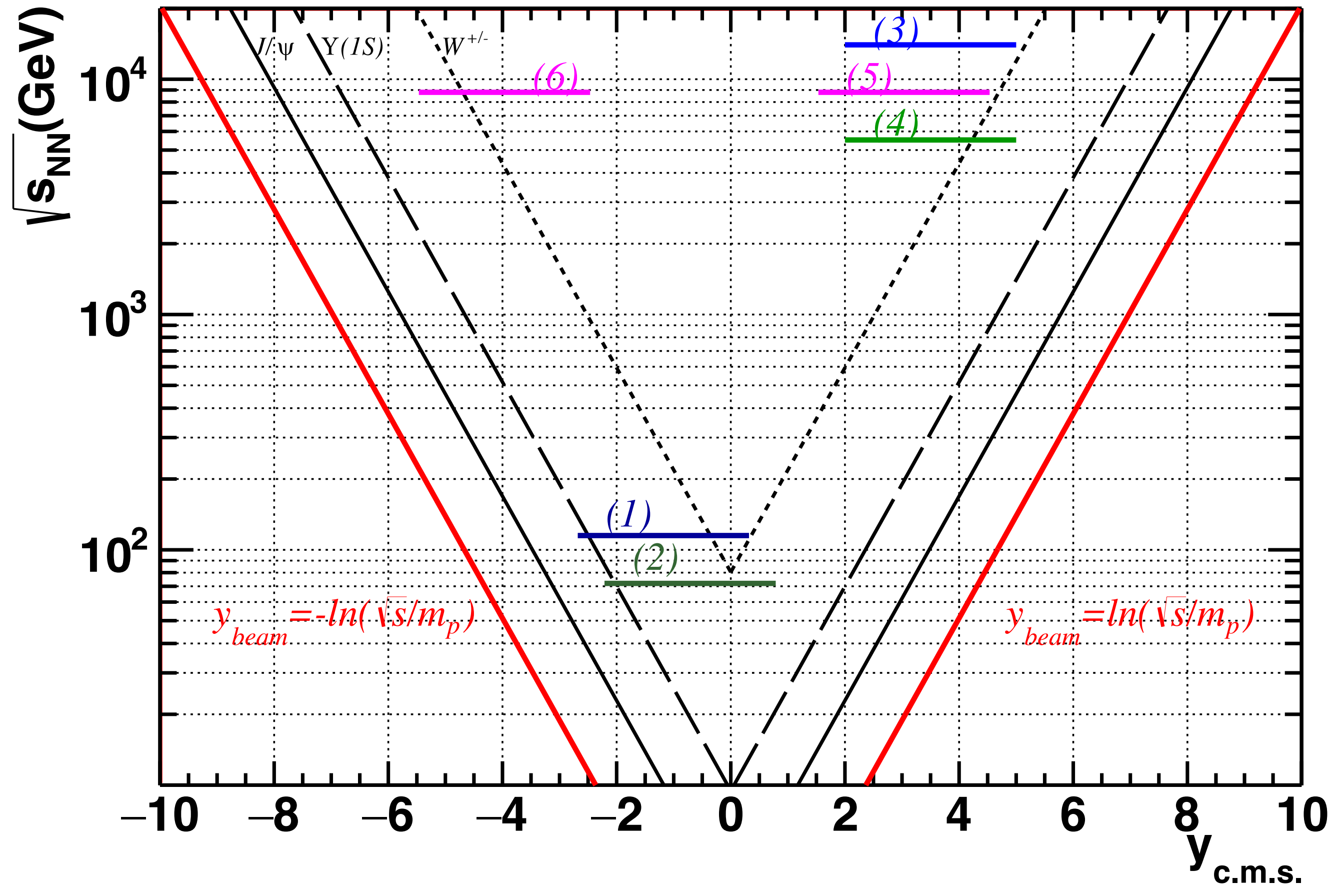


Rapidity range



- Entire center-of-mass forward hemisphere ($y_{cm}>0$) within 1 degree
- Easy access to (very) large backward rapidity range ($y_{cm}<0$) and large parton momentum fraction in the target (x_2)

Main kinematic features of AFTER@LHC



Example of acceptance for an LHCb like detector: $2 < \eta_{lab} < 5$

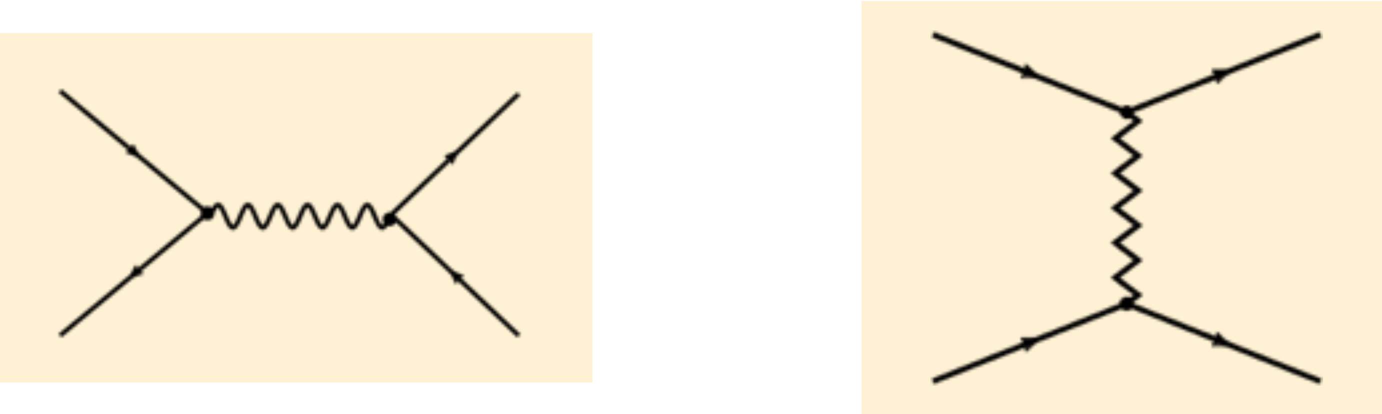
(1) pA collisions in fixed target mode, $\sqrt{s_{NN}}$ = 115 GeV
(2) PbA collisions in fixed target mode, $\sqrt{s_{NN}}$ = 72 GeV

(3) pp collisions in collider mode, $\sqrt{s}$ = 14 TeV
(4) PbPb collisions in collider mode, $\sqrt{s_{NN}}$ = 5.5 TeV
(5) pPb collisions in collider mode, $\sqrt{s_{NN}}$ = 8.8 TeV
(6) Pbp collisions in collider mode, $\sqrt{s_{NN}}$ = 8.8 TeV

Fixed target mode (1):
Negative y_{cms}: $x_1 < x_2$: $x_F = x_1 - x_2 < 0$
Quite special!

General Physics Motivations

- Due to its unique features (kinematics, high luminosity, targets, polarization) **AFTER@LHC** can address **key challenges in QCD & Hadron physics**
  - Understanding the partonic structure of nucleons and nuclei from QCD
  - Understanding the spin structure of nucleons and nuclei
  - Understanding confinement & hadronization from QCD
- AFTER@LHC complementary to an Electron-Ion Collider
  - **Drell-Yan process** vs. **Deep Inelastic Scattering**



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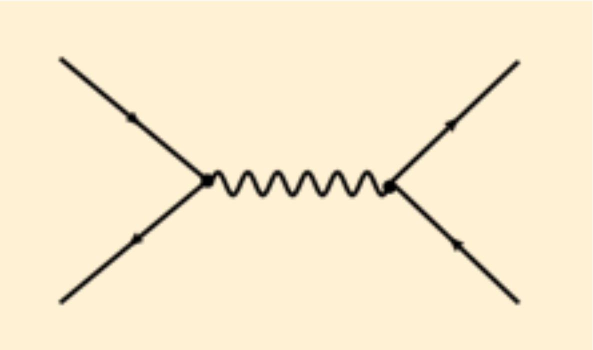
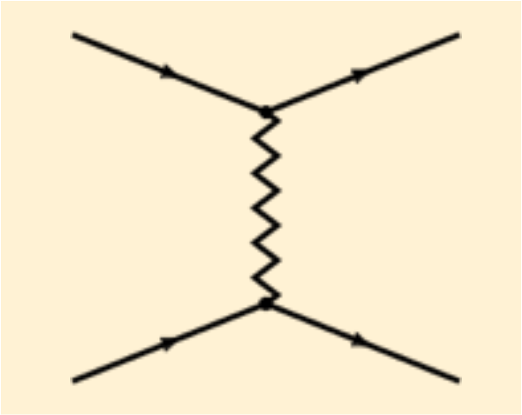




Light parton structure at high-x

Partonic structure at high-x

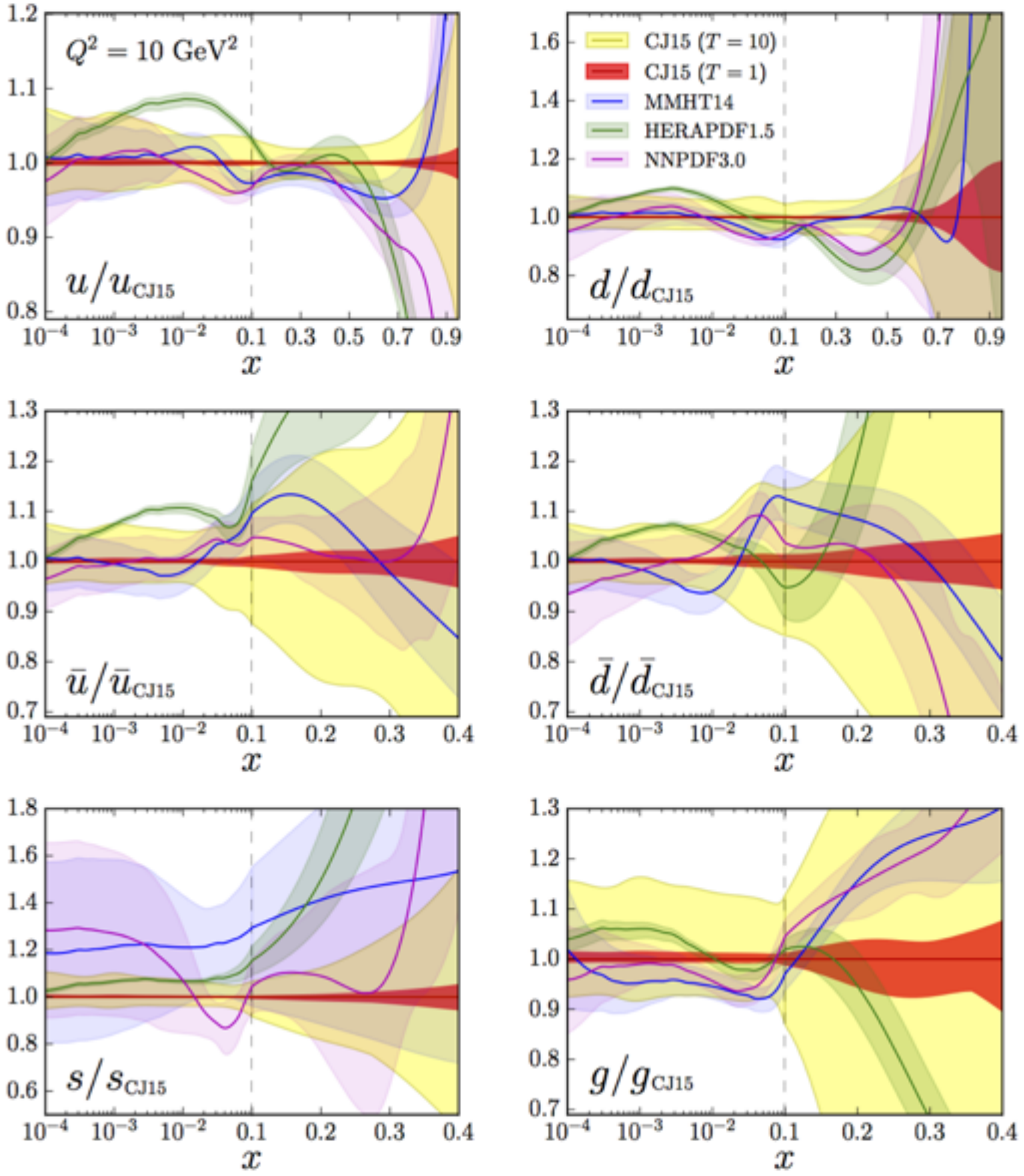
- Partonic structure of nucleons/nuclei at high-x (x>0.5) poorly known:
    - >50% uncertainty on d(x) at x>0.6
    - >50% uncertainty on g(x) at x>0.2
    - very large uncertainties on quark sea

- Better understanding provides tests of models of hadron structure
    - d/u→1/2 : SU(6) Spin-Flavor symmetry
    - d/u→0 : Scalar diquark dominance
    - d/u→1/5 : pQCD power counting
    - Local quark hadron duality:

$$\mathbf{d/u} \to \frac{4\mu_n^2/\mu_p^2 - 1}{4 - \mu_n^2/\mu_p^2} \simeq 0.42$$

- Better understanding important for BSM searches of new heavy states

CJ15 global fit, PRD93(2016)114017



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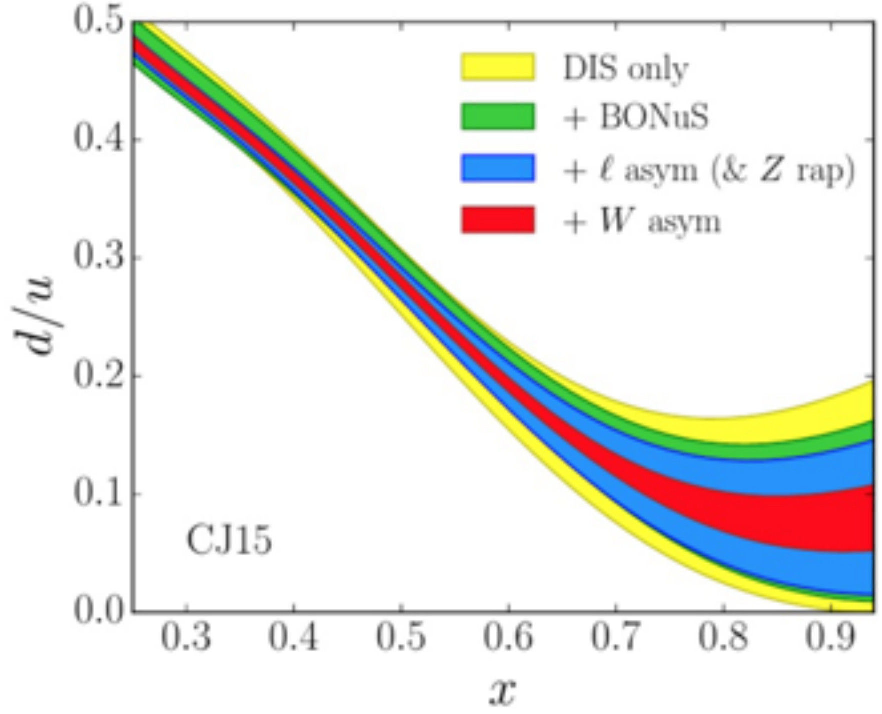

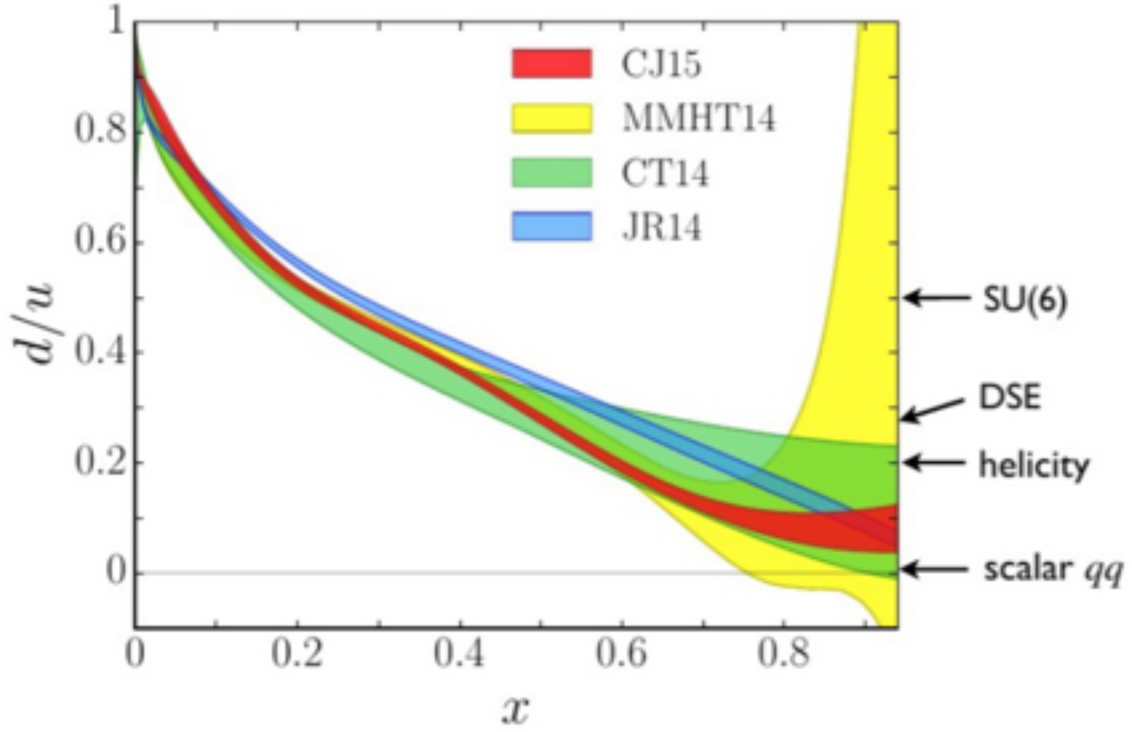

Partonic structure at high-x

- Large-x behaviour: $x\ f_i(x,Q_0) \sim (1-x)$^b_i
- Counting rule expectations: $b\_u_v = b\_d_v = 3$
- Currently only b_u_v relatively well constrained

  $2.6 < b\_u_v < 3.4$

  Ball, Nocera, Rojo, arXiv:1604.00024
- Down valence quark less well known

  $1.4 < b\_d_v < 4.6$
- Exponents for the sea quarks and the gluon very poorly known

A simple ratio in the limit $x_F \to -1$

- For example:

  $x_F = -0.8$, M = 10 GeV gives $x_2 = 0.8$, $x_1 = 0.01$
  $x_F = -0.8$, M = 15 GeV gives $x_2 = 0.8$, $x_1 = 0.02$

- In this limit with $r_v = d(x_2)/u(x_2)$

$$R = \frac{\sigma^{\mathrm{DY}}(pn)}{\sigma^{\mathrm{DY}}(pp)} \simeq \frac{4\bar{u}(x_1)d(x_2) + \bar{d}(x_1)u(x_2)}{4\bar{u}(x_1)u(x_2) + \bar{d}(x_1)d(x_2)} \simeq \frac{4d(x_2) + u(x_2)}{4u(x_2) + d(x_2)} = \frac{1 + 4r_v}{4 + r_v}$$

- Amusing to note: $1/4 < R < 4$

  similar to the famous Nachtmann ratio for DIS structure functions $1/4 < F_2^n / F_2^p < 4$

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- In this limit with $r_v = d(x_2)/u(x_2)$

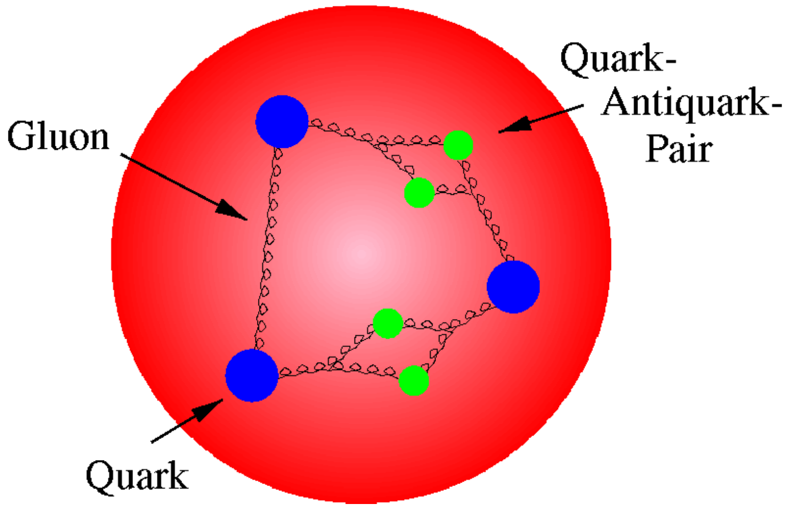
$$R_{d/p}(x_2) = \frac{\sigma^{\mathrm{DY}}(pd)}{\sigma^{\mathrm{DY}}(pp)} = 1 + \frac{\sigma^{\mathrm{DY}}(pn)}{\sigma^{\mathrm{DY}}(pp)} \simeq 5\,\frac{1 + r_v(x_2)}{4 + r_v(x_2)} \,.$$

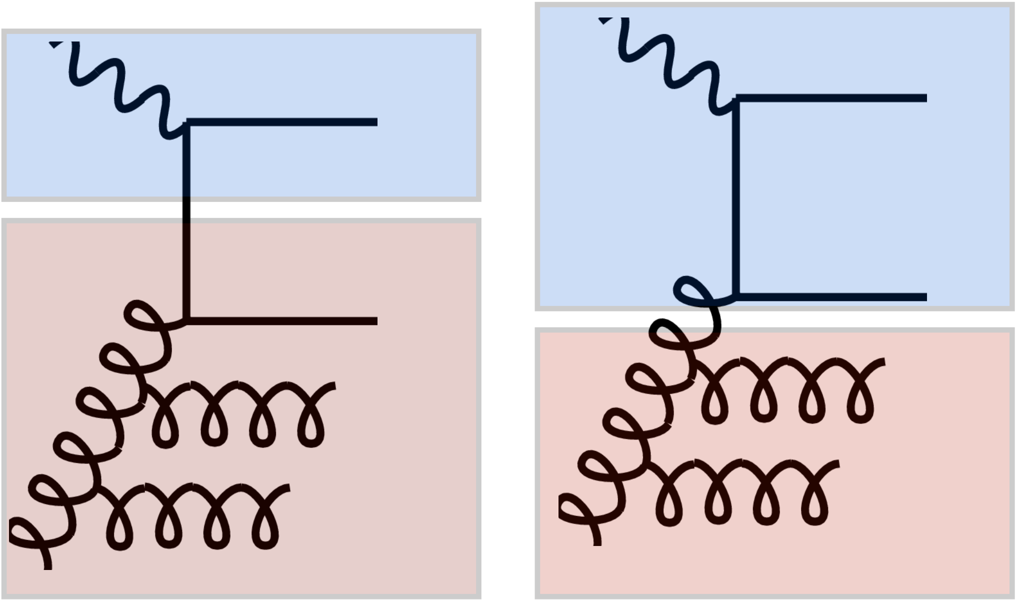
$$R_{d/p} \to \begin{cases} 2 & ; \quad r_v = 1 \\ 2.5 & ; \quad r_v = 0 \\ 5 & ; \quad r_v \to \infty \end{cases}$$

Charm parton content at high-x

Is there charm in the nucleon?

- Standard approach: Charm entirely perturbative
- Heavy Flavour Schemes
  - FFNS: charm not in the proton
keep logs(Q/m) in fixed order
  - VFNS: charm PDF in the proton
resum logs(Q/m)
- Different Heavy Flavour Schemes = different ways to organize the perturbation series
- What is structure? What is interaction?
Freedom to choose the factorization scale
- However, charm not so much heavier than Λ_{QCD}
- There could be a non-perturbative intrinsic charm component (added to the VFNS or even FFNS)
- Important to test the charm PDF experimentally





Charm PDFs

- Large majority of global analyses:

  Charm PDF is **calculated**,
  there is no fit parameter!

- Boundary condition for DGLAP evolution calculated perturbatively:

  (matching condition when switching from $n_f=3$ to $n_f=4$ flavours)

  $c(x,Q=m_c) = 0$ @NLO, MSbar

Models for intrinsic charm

- For a recent review see arXiv:1504.06287
- Most models are concentrated at large x and have a precise x-shape but do not predict the scale (BHPS, Meson cloud models)
- In some models c(x)=cbar(x) in others not
- In global analyses also phenomenological models with a sea-like charm (broad range in x) are analyzed

BHPS model

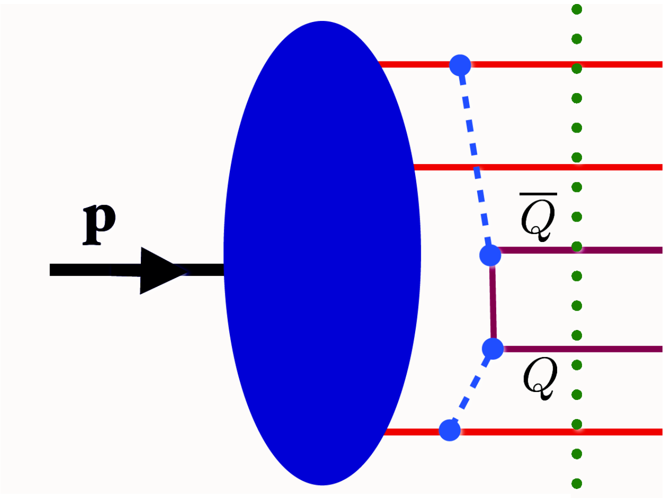


Figure 1: Five-quark Fock state $|uudQ\overline{Q}\rangle$ of the proton and the origin of the intrinsic sea.

- Light cone Fock space picture
- |uudQQbar> state with heavy quarks connected to valence quarks, fundamental property of wave function
- Intrinsic contribution dominant at large x and on the order $O(\Lambda^2/m_Q^2)$
- A finite IC contribution has been extracted from the lattice: Probability for the <N|c cbar|N> ME of 5 to 6% [MILC collab., arXiv:1204.3866]

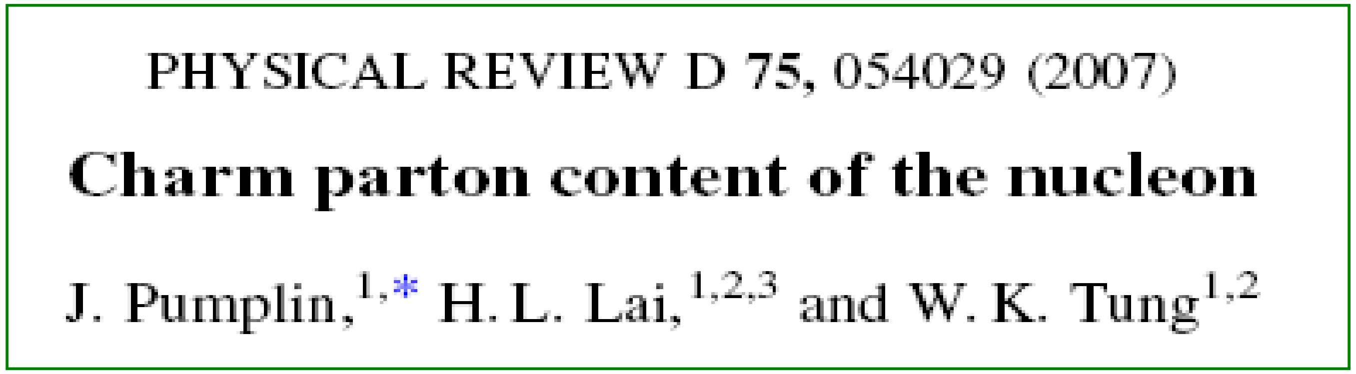
The x-dependence predicted by the BHPS model, unknown at which scale:

$$c_1(x) = \bar{c}_1(x) \propto x^2[6x(1+x)\ln x + (1-x)(1+10x+x^2)]$$

Typical moments;

	$\int_0^1 dx\ c(x)$	$\int_0^1 dx\ x\,[c(x)+\bar{c}(x)] \equiv < x >_{c+\bar{c}}$
CTEQ6.6	0	0
CTEQ6.6c0	0.01	0.0057
CTEQ6.6c1	0.035	0.0200

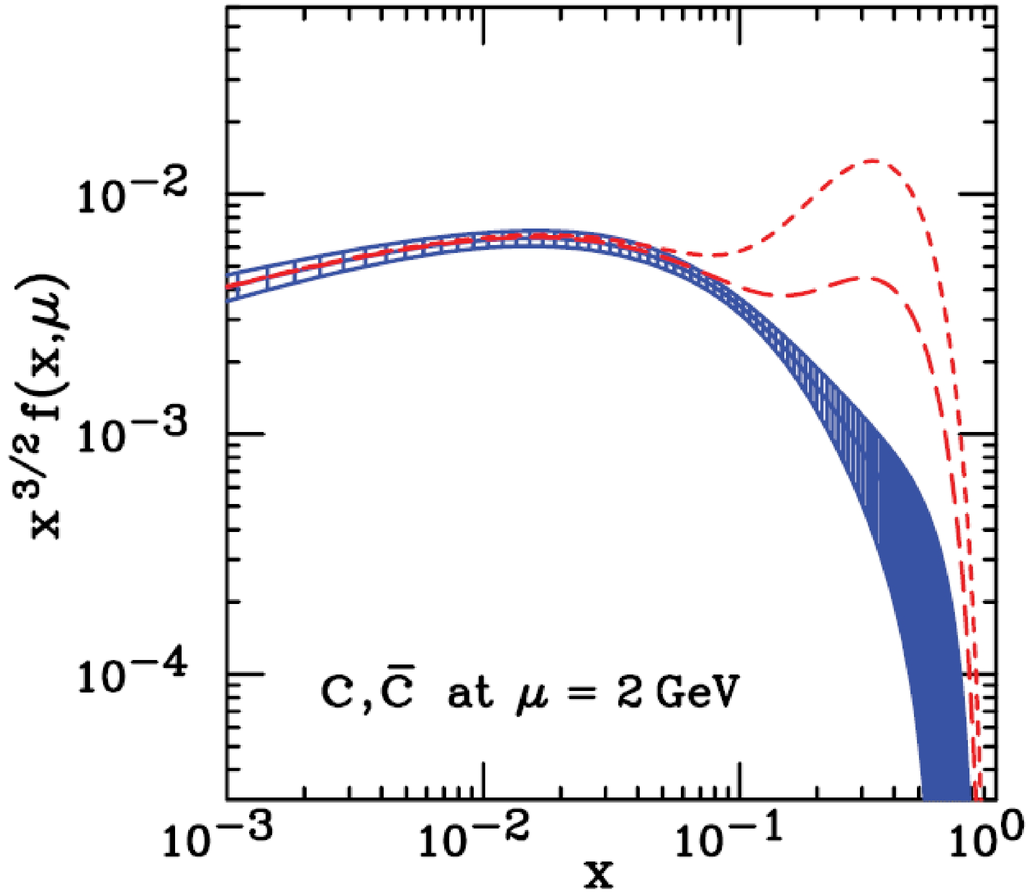
A global fit by CTEQ to extract IC



PHYSICAL REVIEW D 75, 054029 (2007)

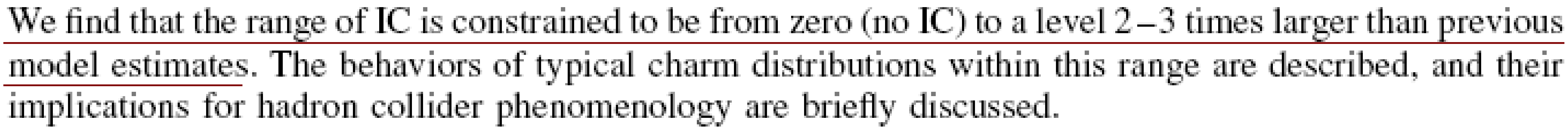
Charm parton content of the nucleon

J. Pumplin,[1,*] H. L. Lai,[1,2,3] and W. K. Tung[1,2]



Blue band corresponds to CTEQ6 best fit, including uncertainty

Red curves include intrinsic charm of 1% and 3% (χ^2 changes only slightly)



We find that the range of IC is constrained to be from zero (no IC) to a level 2–3 times larger than previous model estimates. The behaviors of typical charm distributions within this range are described, and their implications for hadron collider phenomenology are briefly discussed.

No conclusive evidence for intrinsic-charm

Parton-Parton Luminosities: Charm

arXiv:1504.05156

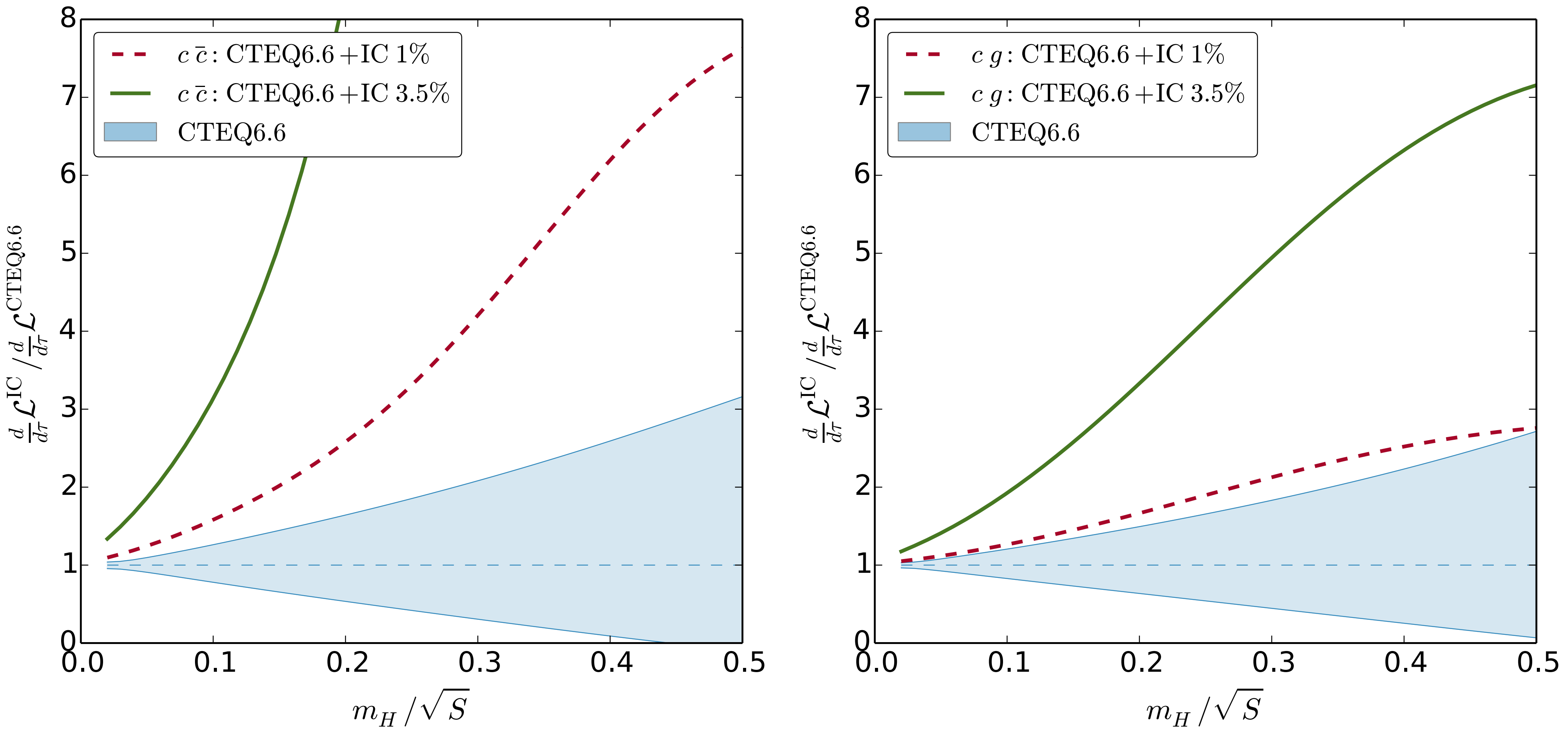
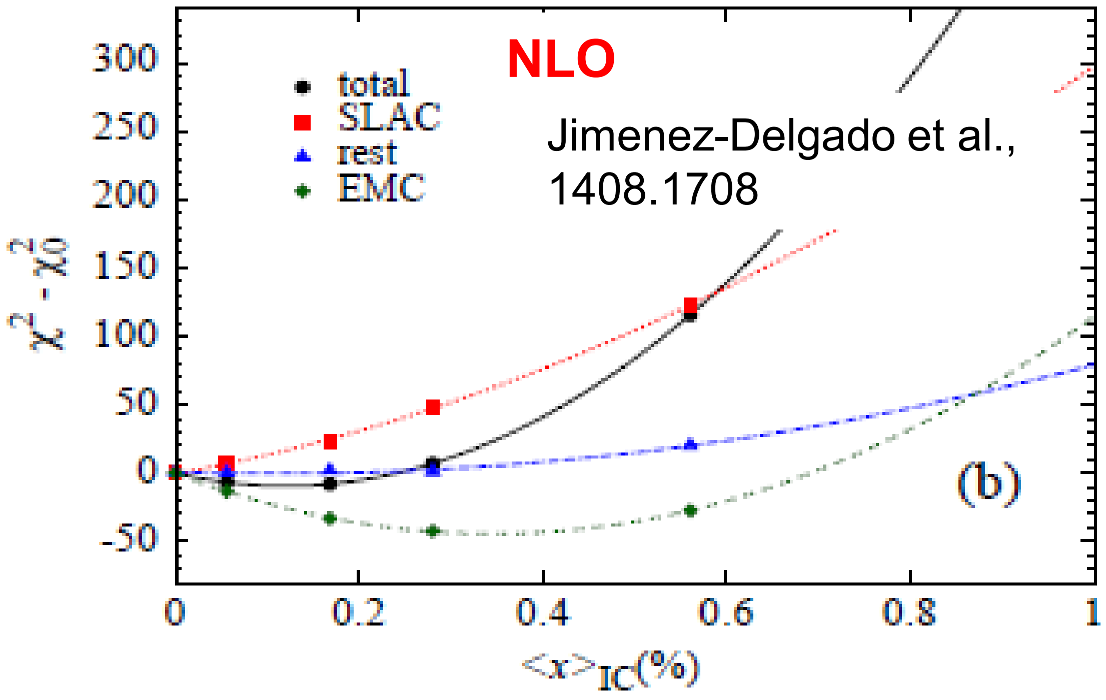


Figure 10. Ratio of $c\bar{c}$ luminosities (left) and cg luminosities (right) at the LHC14 for charm-quark PDF sets with and without an intrinsic component as a function of $\sqrt{\tau} = m_H/\sqrt{S}$. The ratio for the $c\bar{c}$ luminosity (solid, green line) in the left figure reaches values of 50 at $\sqrt{\tau} = 0.5$. In addition to the curves with 1% normalization (red, dashed lines) we include the results for the 3.5% normalization (green, solid lines) which was found to be still compatible with the current data [25].

Recent PDFs with fitted charm

Several studies conclude that IC may carry no more than 1% of the proton's momentum

Constraints depend on data selection (e.g., on whether the EMC F_2^c data are included) and methodology (CTEQ vs. NNPDF)



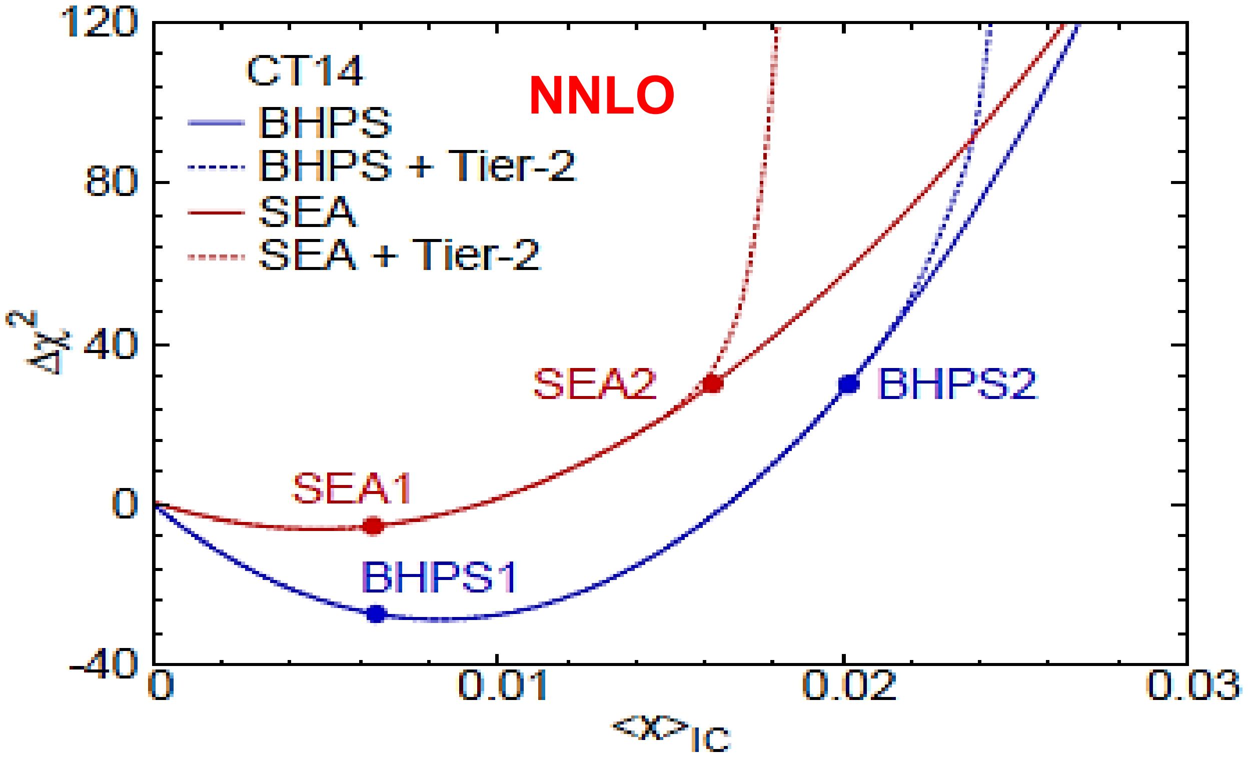
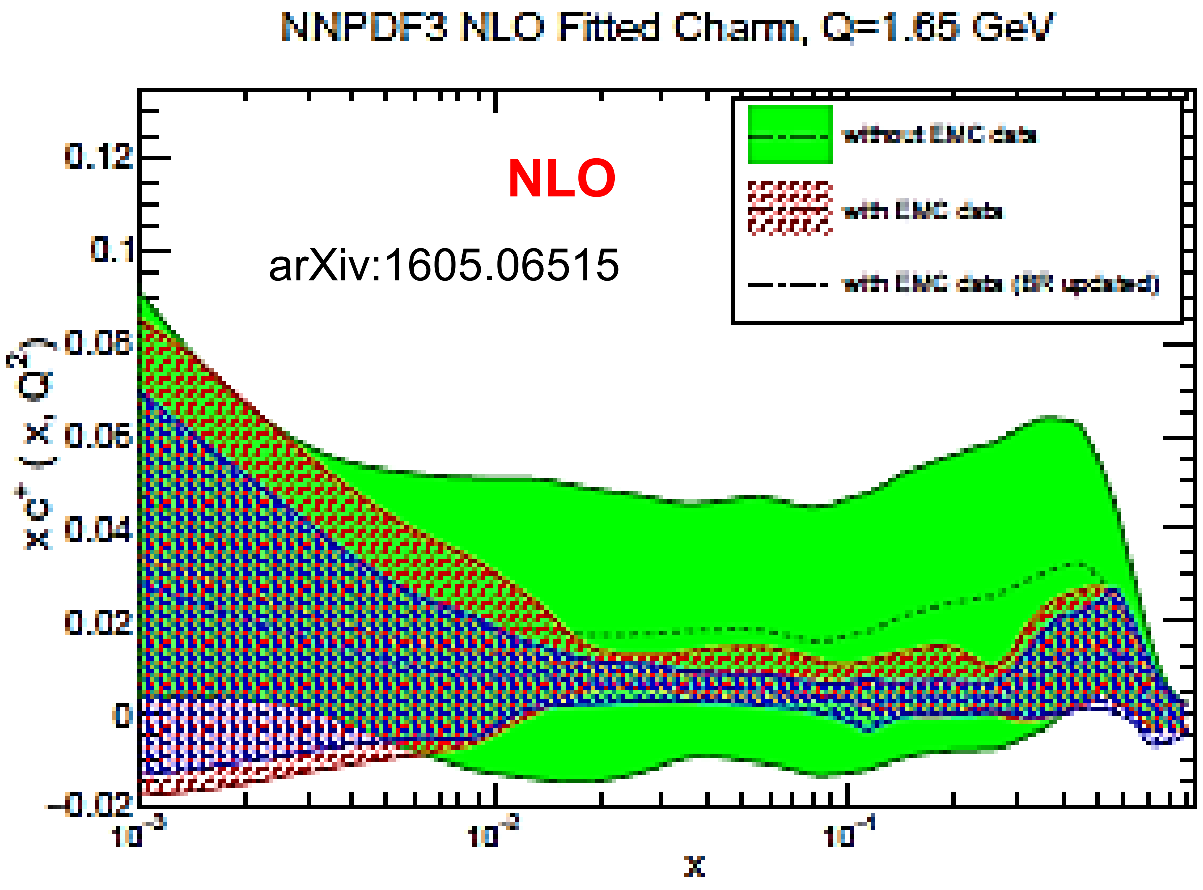


Figure 1: The $\Delta\chi^2$ versus the momentum fraction of charm $\langle x \rangle_{IC}$. **PoS DIS2015 (2015) 166**



How to probe the high-x charm?

- F_2^c at EIC:

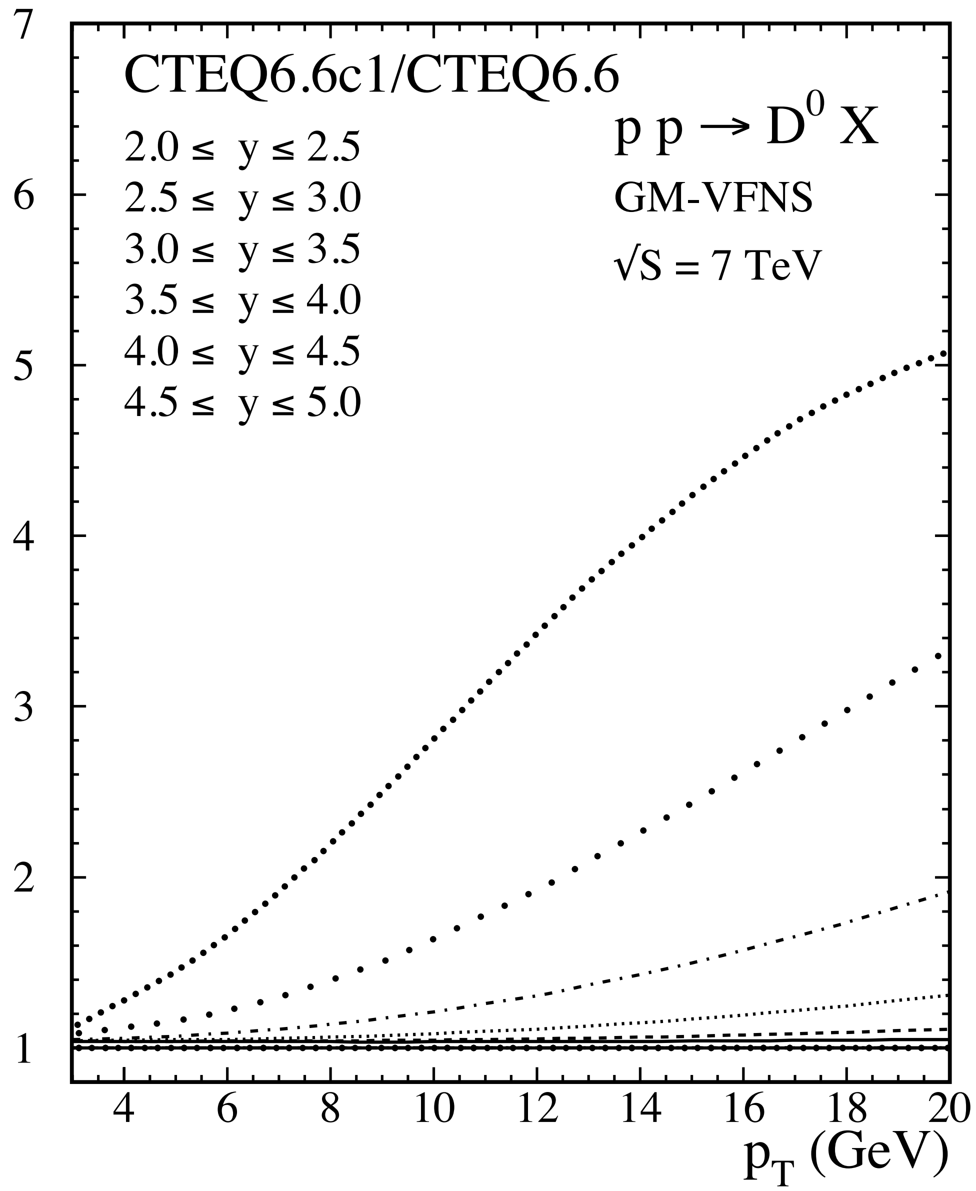
  probing larger x-values (x~0.3)

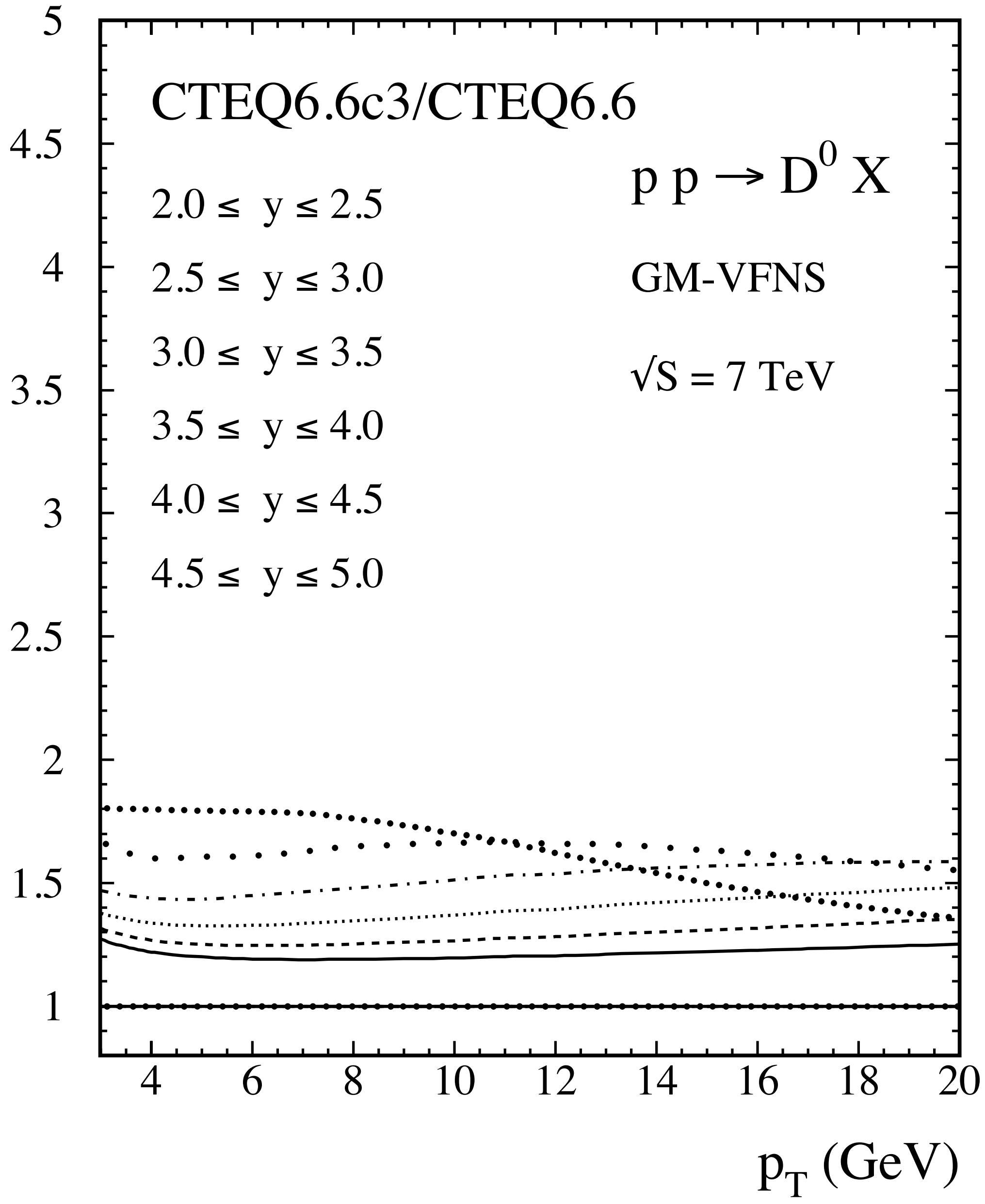
- Fixed target experiments using the LHC beam (AFTER@LHC): $\sqrt{S}$=115 GeV

  would be ideal to probe large-x IC in hadronic collisions

Inclusive D meson production at LHCb

arXiv:1202.0439,arXiv:0901.4130





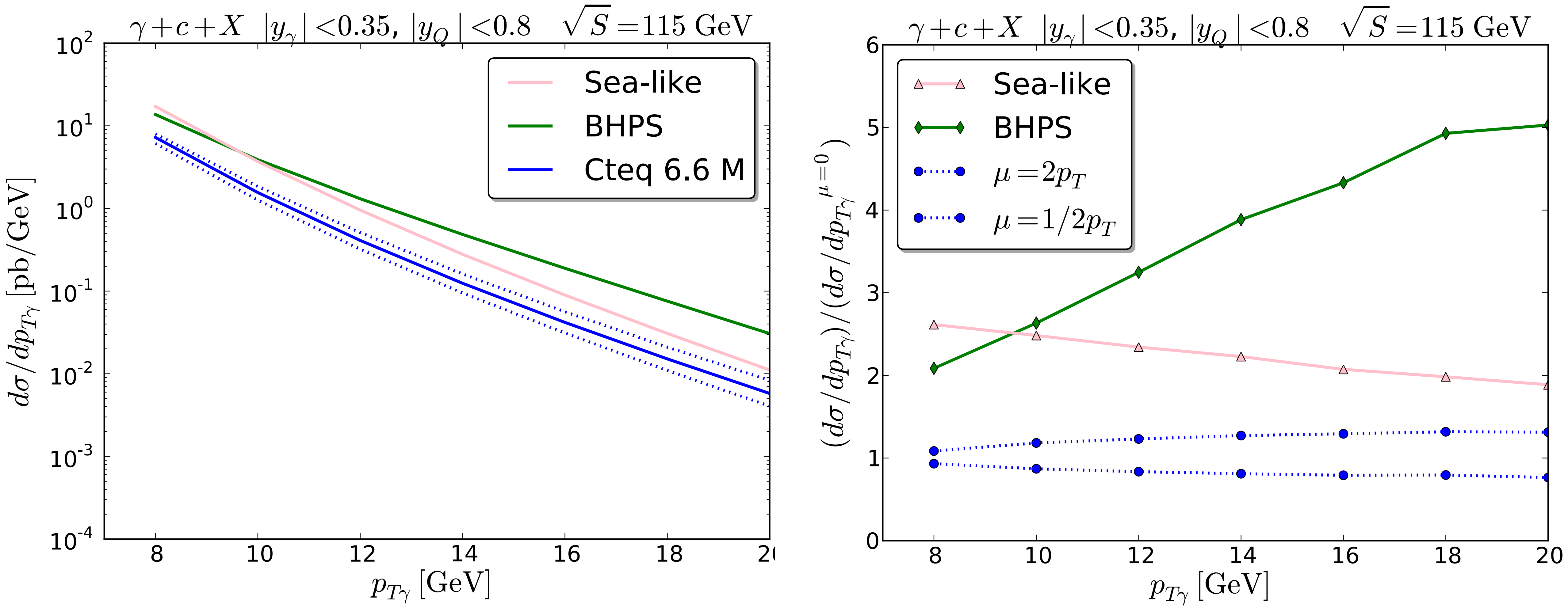
CTEQ6.6 updated:

BHPS, 3.5 % $(c + \bar{c})$ at $\mu = 1.3$ GeV

high-strength sea-like charm

➜ large effects expected at large rapidities

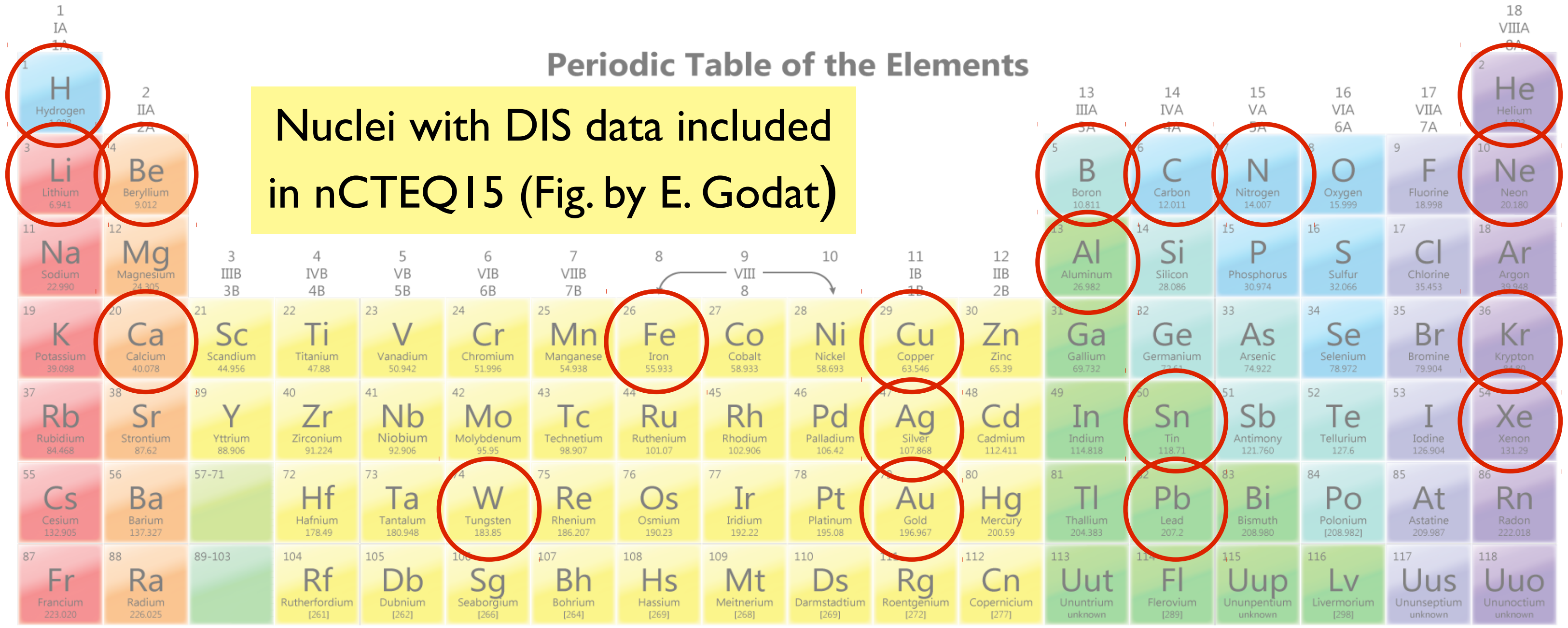
Probing IC with γ+Q at AFTER



Problems: Photon efficiency and photon isolation

A-dependence of parton structure

A-dependence of the partonic structure

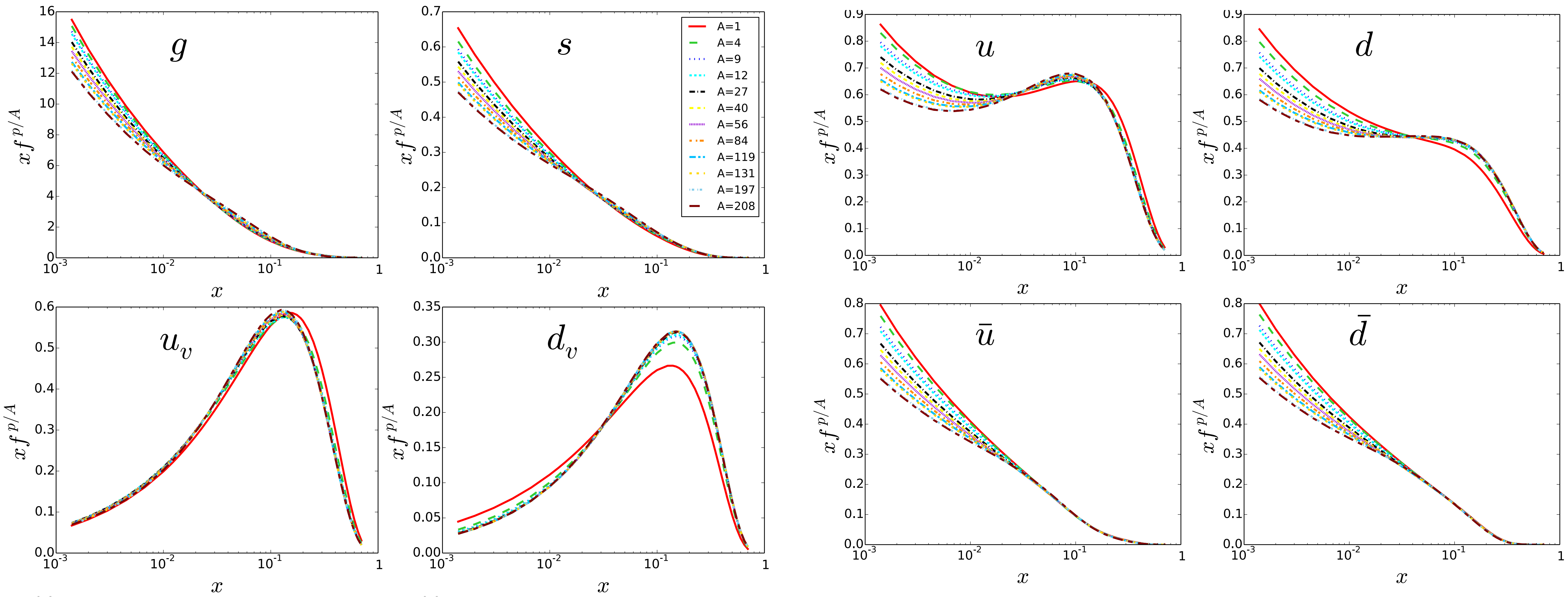


Nuclei with DIS data included in nCTEQ15 (Fig. by E. Godat)

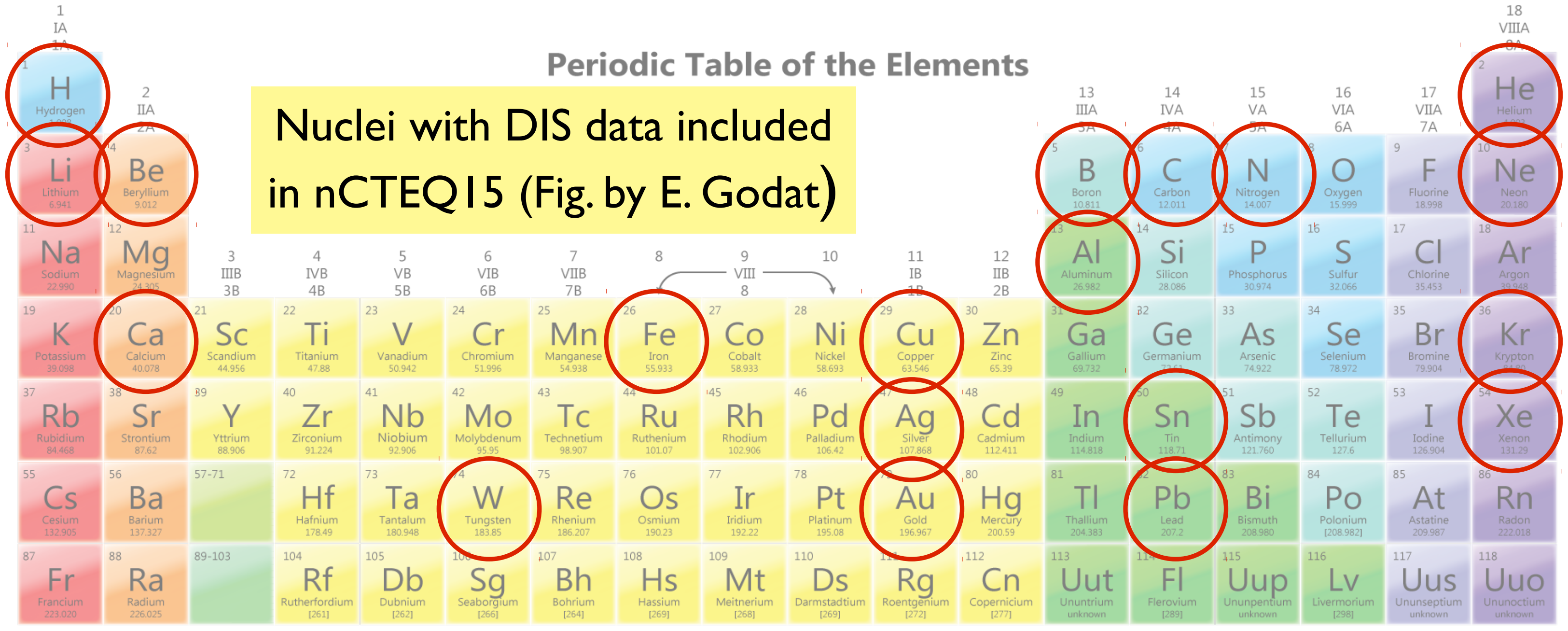
- Fundamental quest
- New data from LHC, AFTER@LHC, EIC will allow a refined parametrization; zoom in on high-x region
- Ultimately, fits to lead only (or other targets); no need to combine different A in one analysis

nCTEQ15, arXiv:1509.00792

$$xf_i^{p/A}(x,Q_0) = x^{c_1}(1-x)^{c_2}e^{c_3 x}(1+e^{c_4}x)^{c_5} \qquad c_k(A) = c_{k,0} + c_{k,1}(1 - A^{-c_{k,2}})$$



A-dependence of the partonic structure



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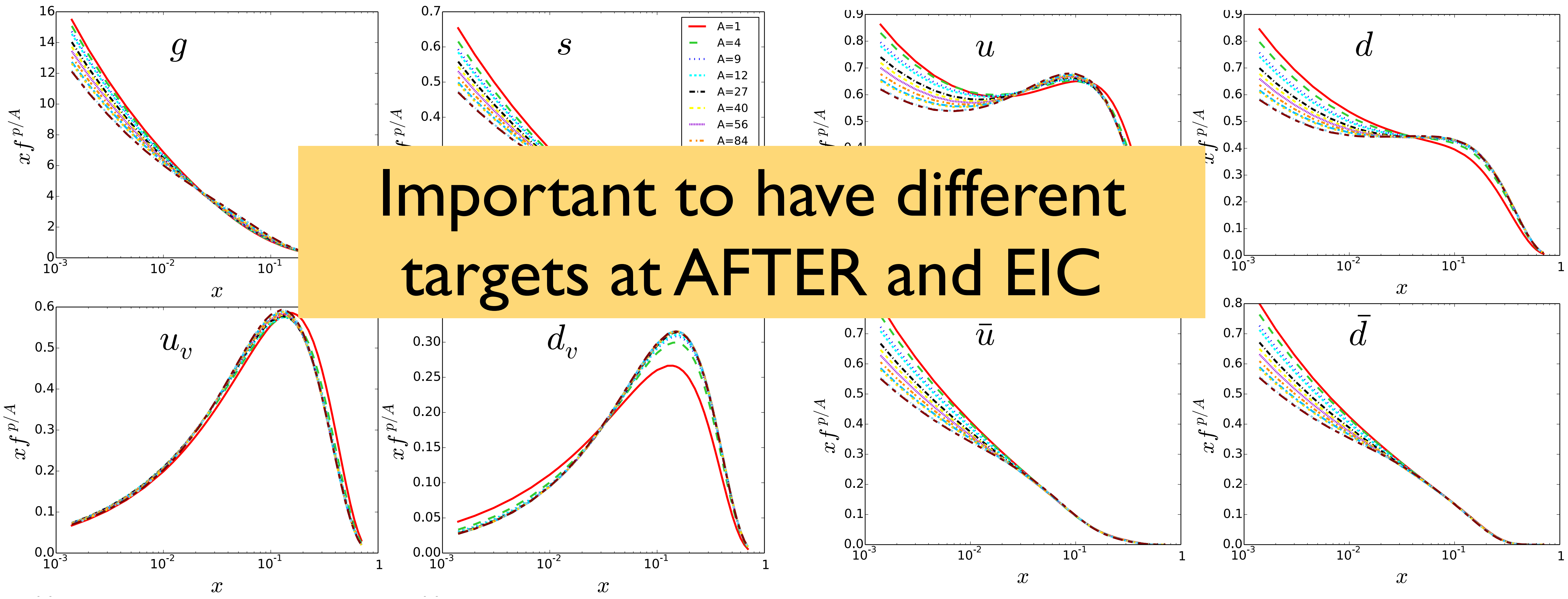
nCTEQ15, arXiv:1509.00792

$$x f_i^{p/A}(x, Q_0) = x^{c_1}(1-x)^{c_2} e^{c_3 x}(1+e^{c_4} x)^{c_5}$$

$$c_k(A) = c_{k,0} + c_{k,1}\left(1 - A^{-c_{k,2}}\right)$$

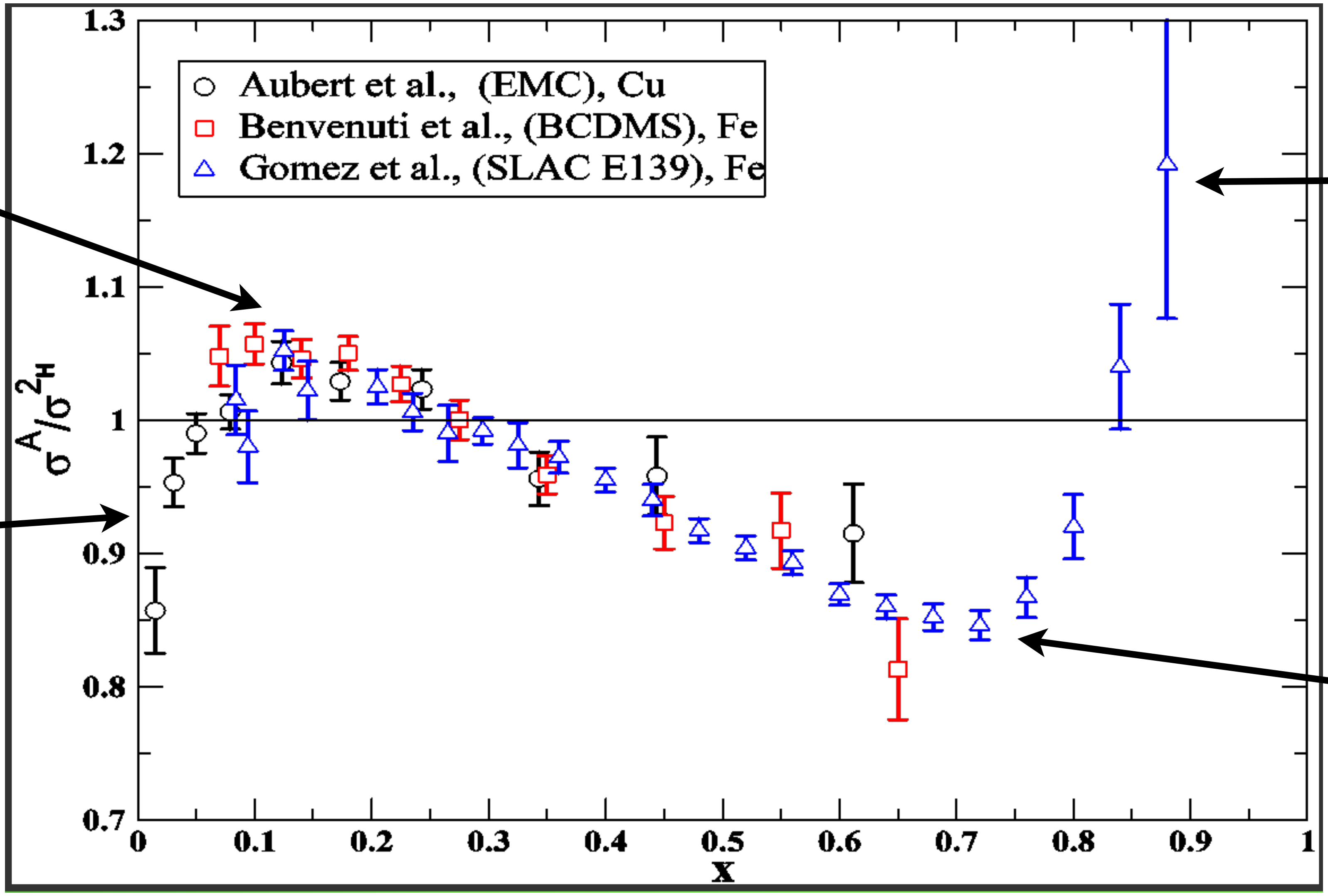


Important to have different targets at AFTER and EIC

EMC effect in DY?

Nuclear modifications of DIS structure functions

$$F_2^A(x) \neq ZF_2^p(x) + NF_2^n(x)$$



Anti-shadowing enhancement

Rise due to Fermi motion

Shadowing suppression at small x

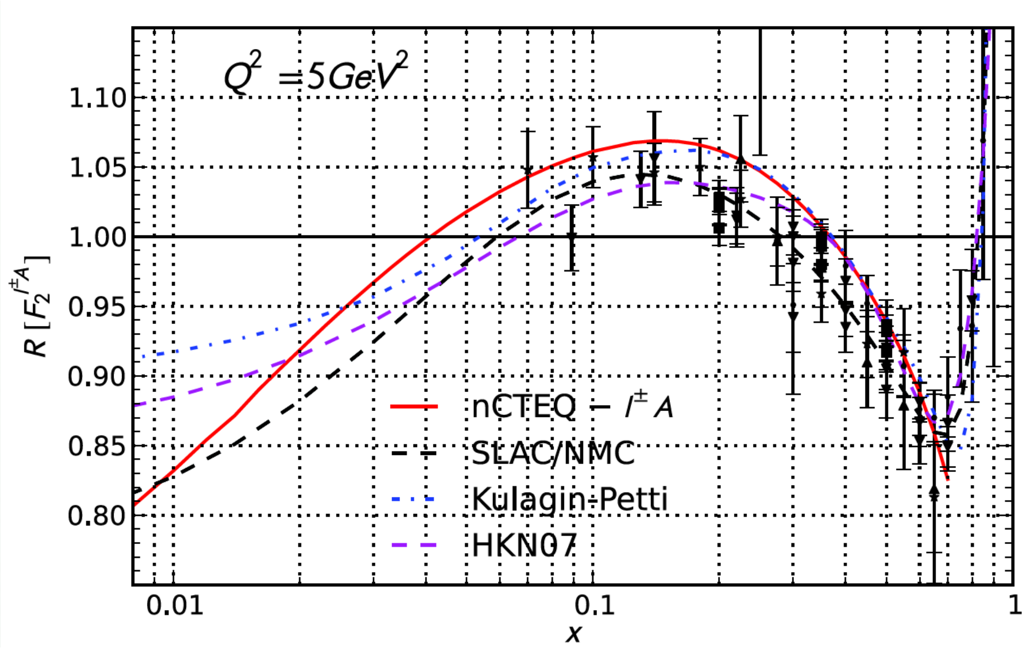
EMC effect

Can we translate these modifications into universal nuclear PDFs?

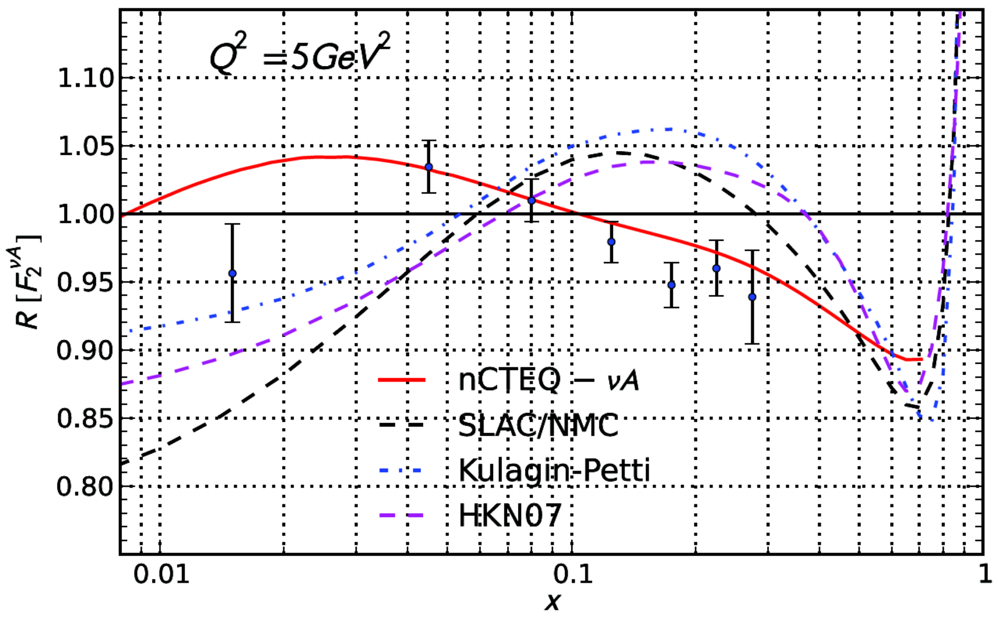
Nuclear modifications: l-A DIS vs nu-A DIS vs DY

nCTEQ, arXiv:1012.0285,
arXiv:0907.2357

Fit to $l^{\pm}A$ DIS and DY data
$\chi^2/\mathrm{dof} = 0.89$

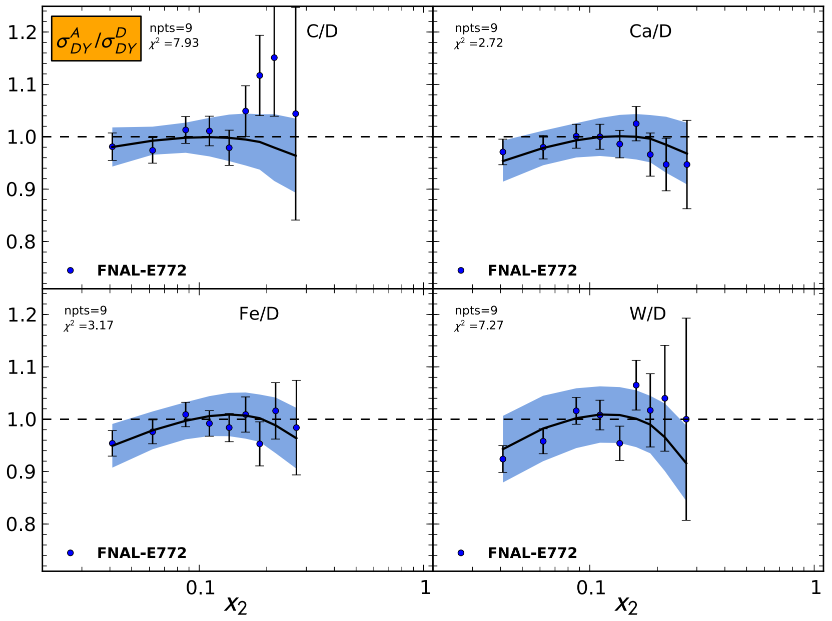


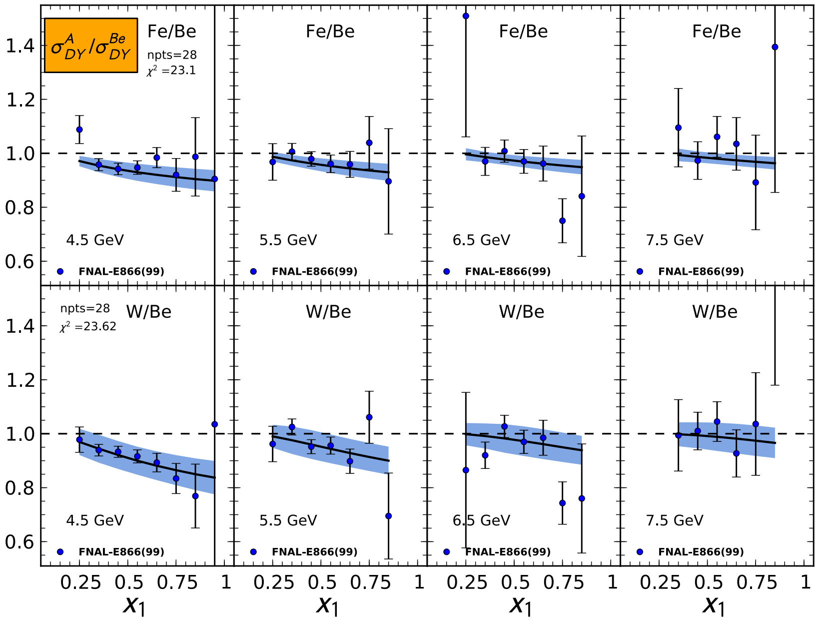
Fit to νA DIS data only
$\chi^2/\mathrm{dof} = 1.33$



EMC effect in DY?
Less obvious

nCTEQ15, arXiv:1509.00792



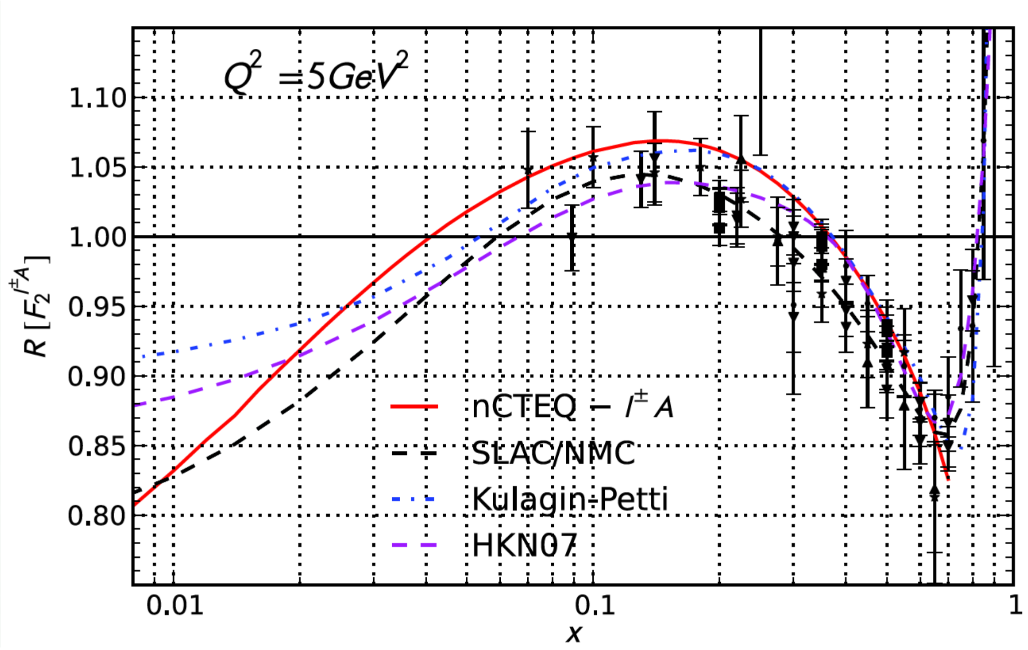


$\sigma^{\mathrm{pA}}_{\mathrm{DY}}/\sigma^{\mathrm{pA'}}_{\mathrm{DY}}$: Observable	Experiment	ID	Ref.	# data	# data after cuts	χ^2
C/H2	FNAL-E772-90	5203	[65]	9	9	7.92
Ca/H2	FNAL-E772-90	5204	[65]	9	9	2.73
Fe/H2	FNAL-E772-90	5205	[65]	9	9	3.17
W/H2	FNAL-E772-90	5206	[65]	9	9	7.28
Fe/Be	FNAL-E886-99	5201	[66]	28	28	23.09
W/Be	FNAL-E886-99	5202	[66]	28	28	23.62
Total:				92	92	67.81

Nuclear modifications: l-A DIS vs nu-A DIS vs DY

nCTEQ, arXiv:1012.0285,
arXiv:0907.2357

Fit to $l^{\pm}A$ DIS and DY data
$\chi^2/\mathrm{dof} = 0.89$



Fit to νA DIS data only
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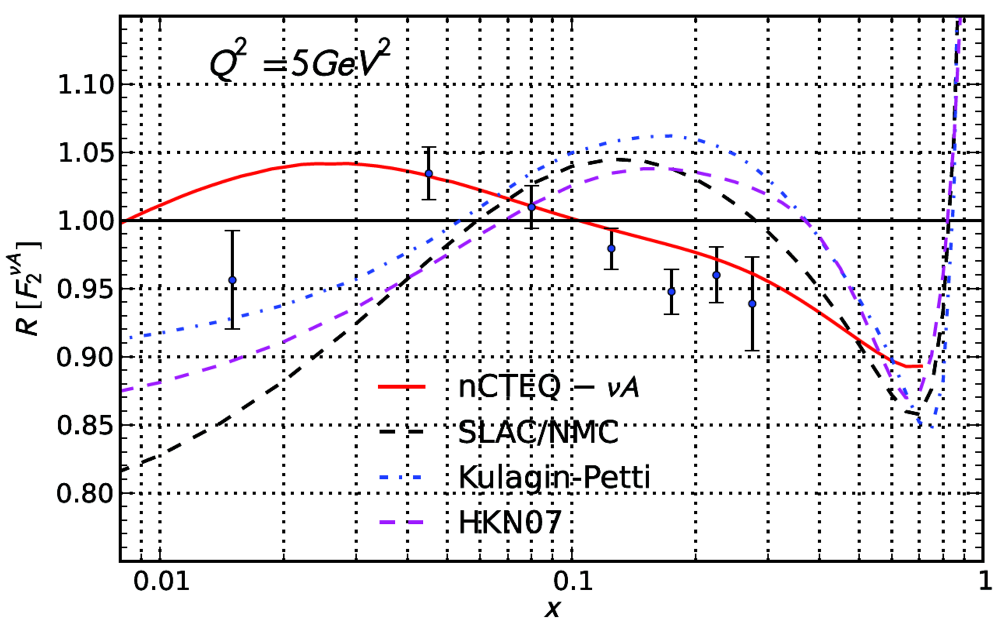
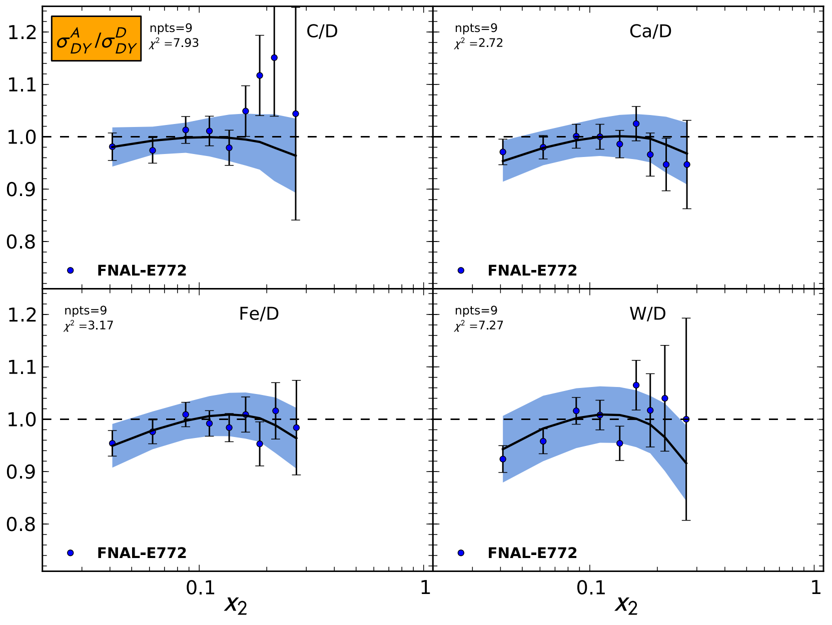
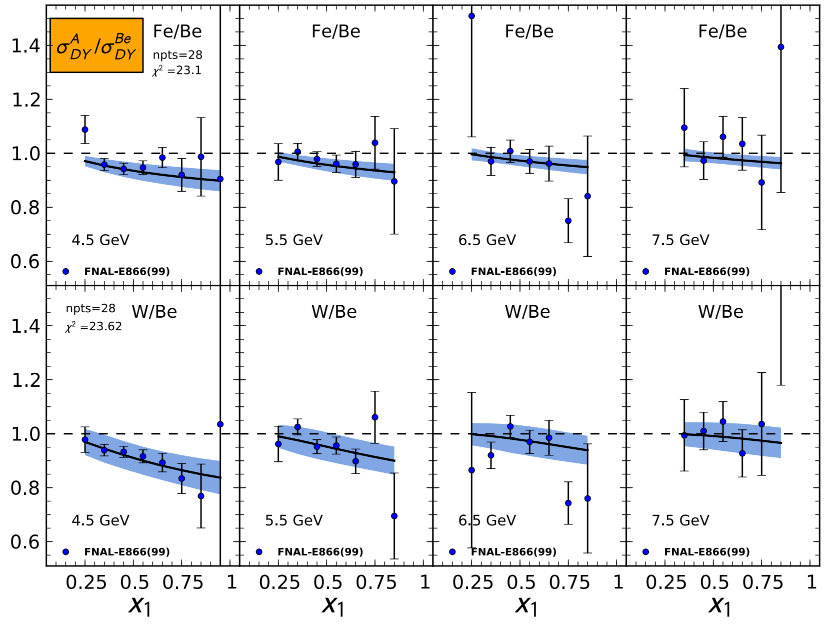


EMC effect in DY?
Less obvious

nCTEQ15, arXiv:1509.00792





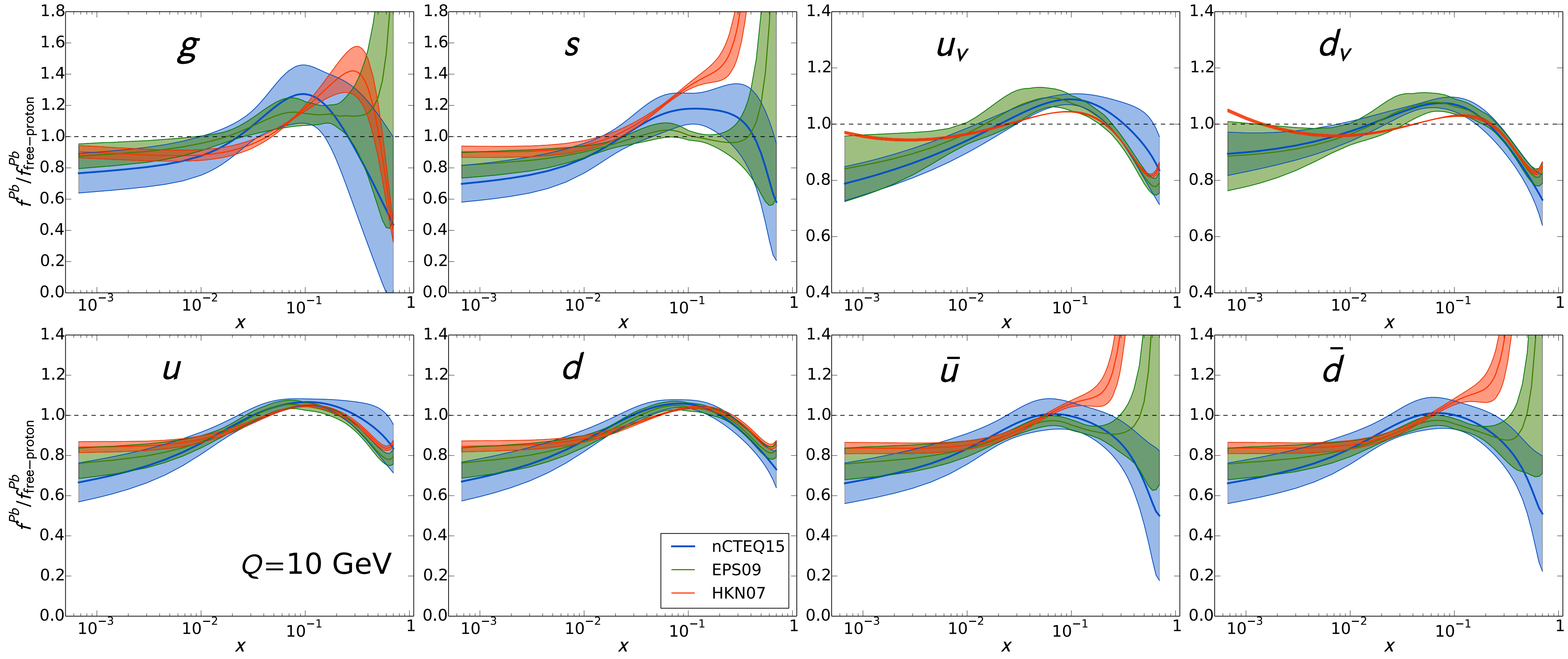
$\sigma^{\rm pA}_{\rm DY}/\sigma^{\rm p}$ Observa	χ^2
C/H2	7.92
Ca/H2	2.73
Fe/H2	3.17
W/H2	7.28
Fe/Be	23.09
W/Be	23.62
Total:	67.81

- Only 92 DY data points in global analysis
- Need more precise DY data at high-x. Important for flavor separation of EMC effect
- AFTER@LHC can greatly contribute with different targets

Flavor separation of EMC effect?

f^{Pb}/f^{Pb0}

nCTEQ15, arXiv:1509.00792



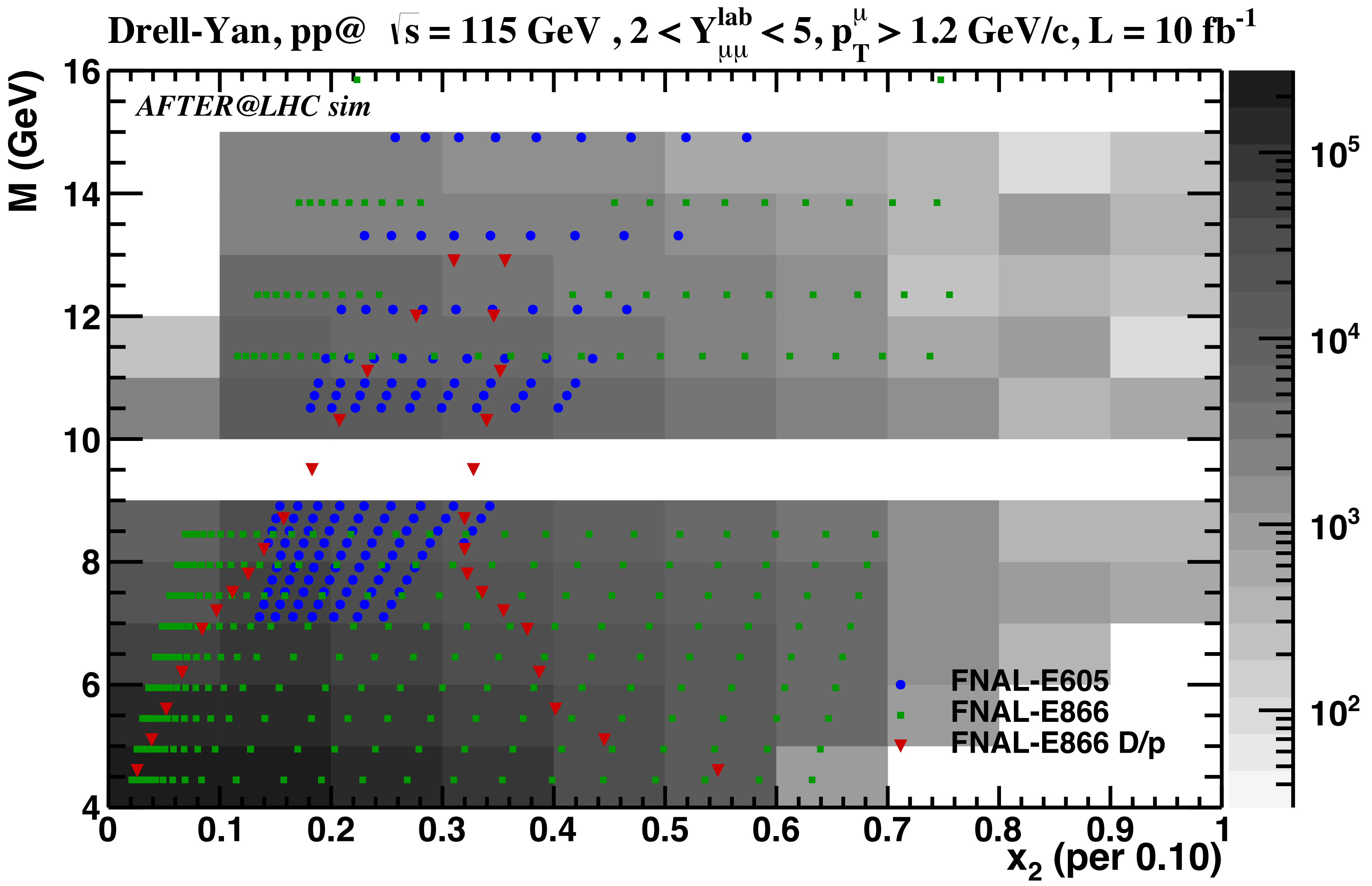
- $F_2 \sim 4\,u + d$ at high-x : with $u^{Pb} = (82\,u^{p/Pb} + 125\,d^{p/Pb})/207$, $d^{Pb} = (82\,d^{p/Pb} + 125\,u^{p/Pb})/207$
  Note: separation into $u^{p/Pb}$, $d^{p/Pb}$ tricky! The real thing are the full nPDFs for lead
- For flavor separation (at high-x) need **more observables**!
  DIS with weak currents (neutrino DIS, charged current electron DIS),
  non-isoscalar targets, F_L (gluon), DY (sea quarks) ...
- gluon, sea quarks have huge uncertainties at high-x (where these PDF flavors get ver small)

Part II:

A selection of projected high-x performances

Drell-Yan lepton pair production in pp

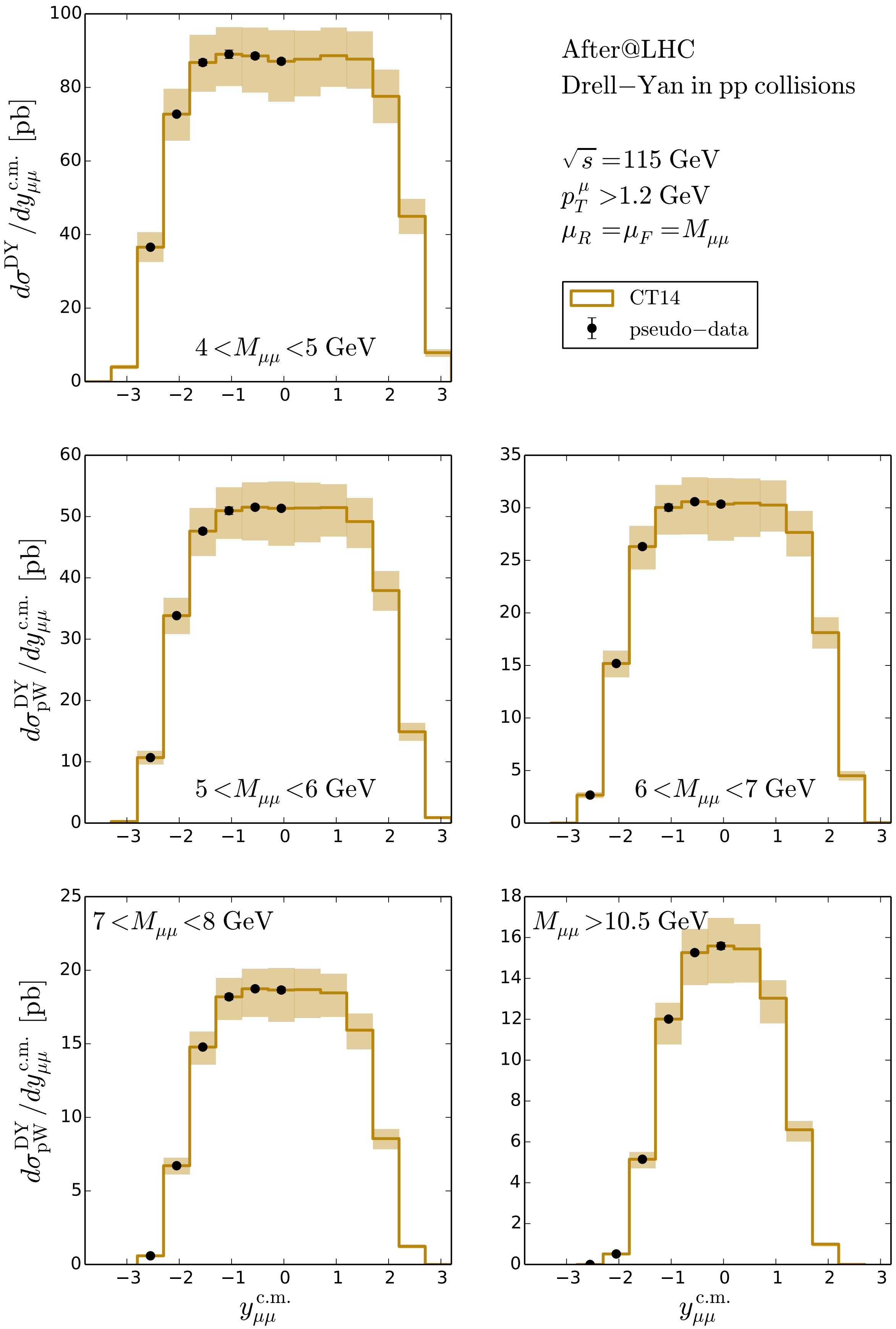
Kinematical plane of DY at AFTER



AFTER:

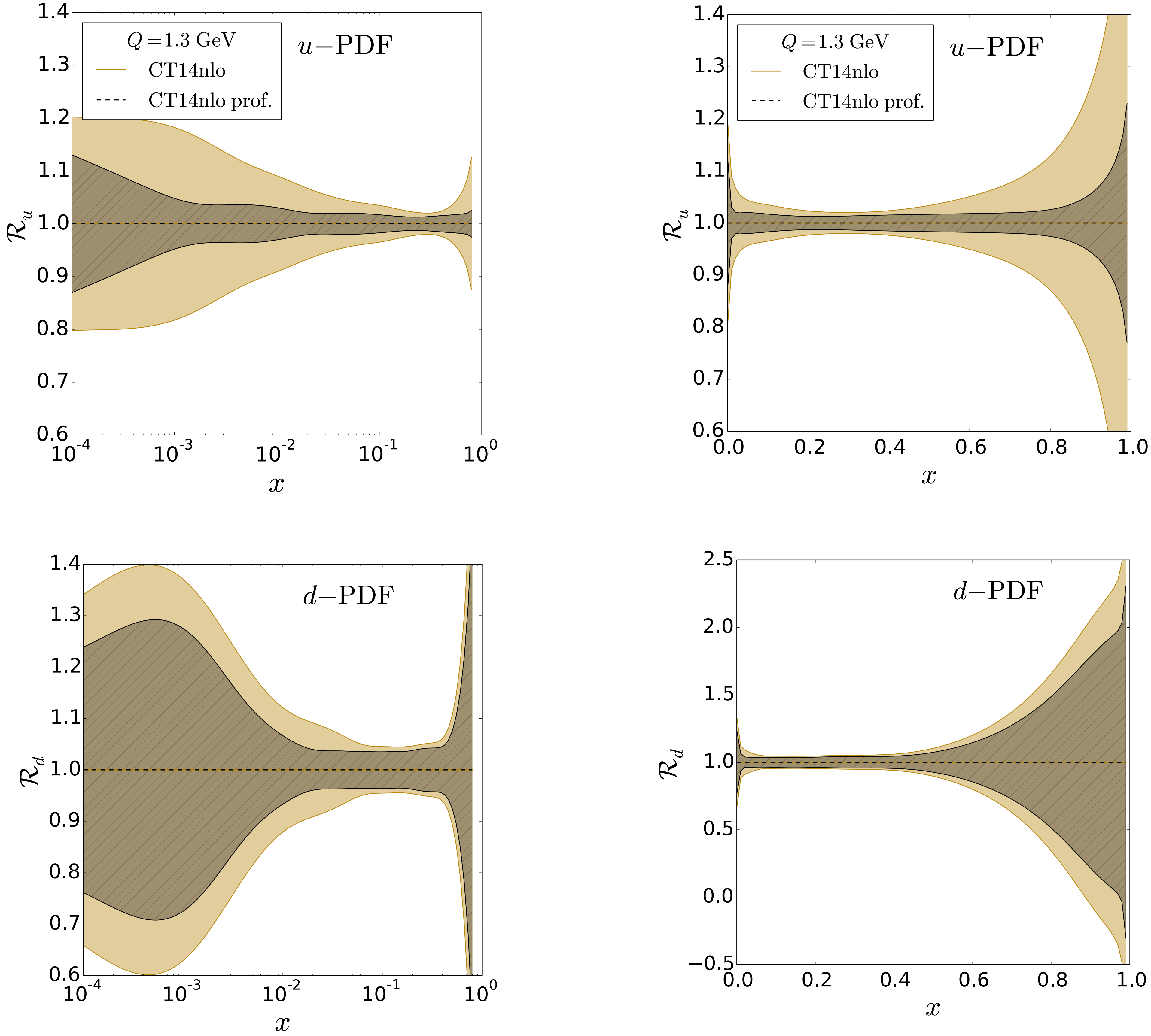
- Extend kinematic plane to very large x (and smaller x, M > 10 GeV)
- Much higher statistics in the region covered by NuSea (E866)
- Data points used in global analysis of NNPDF

DY pseudo data compared to NLO theory

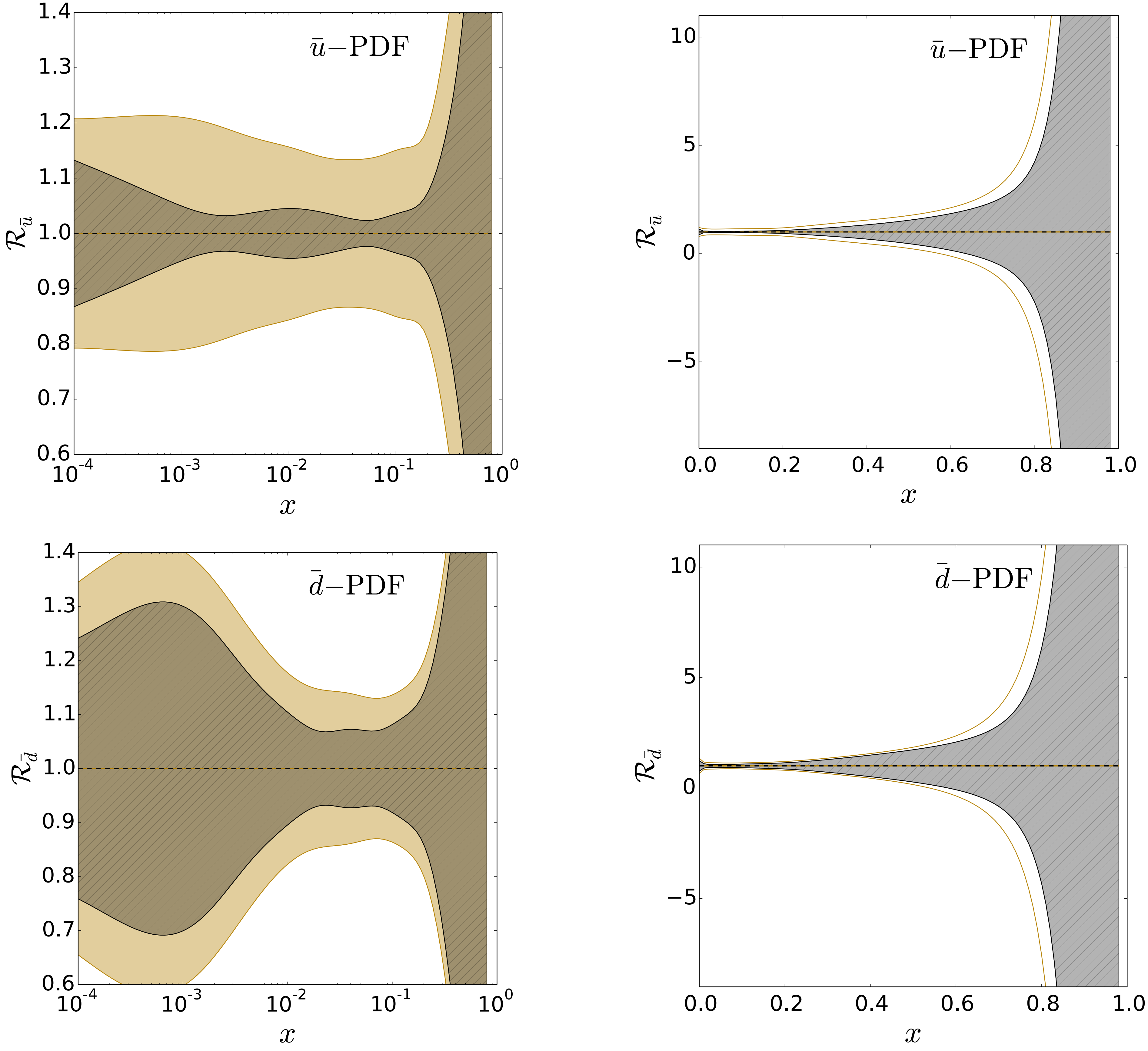


- Pseudo-data for the rapidity distributions using MCFM and projected experimental uncertainties
- Performed reweighting analysis using the XFitter package

Impact of DY pseudo data on proton PDFs

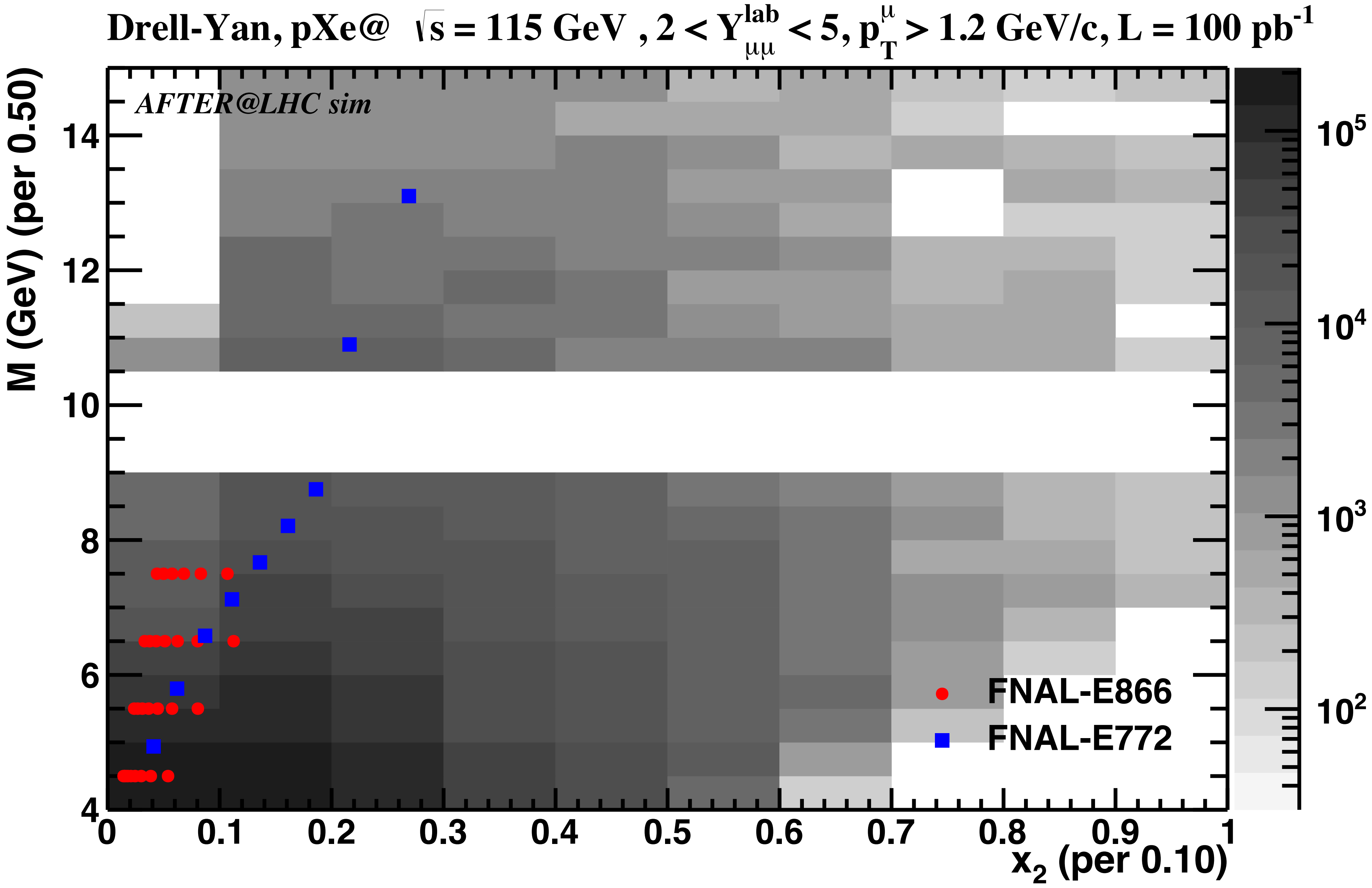


Impact of DY pseudo data on proton PDFs



Drell-Yan lepton pair production in pA

Kinematical plan of DY in p-Xe

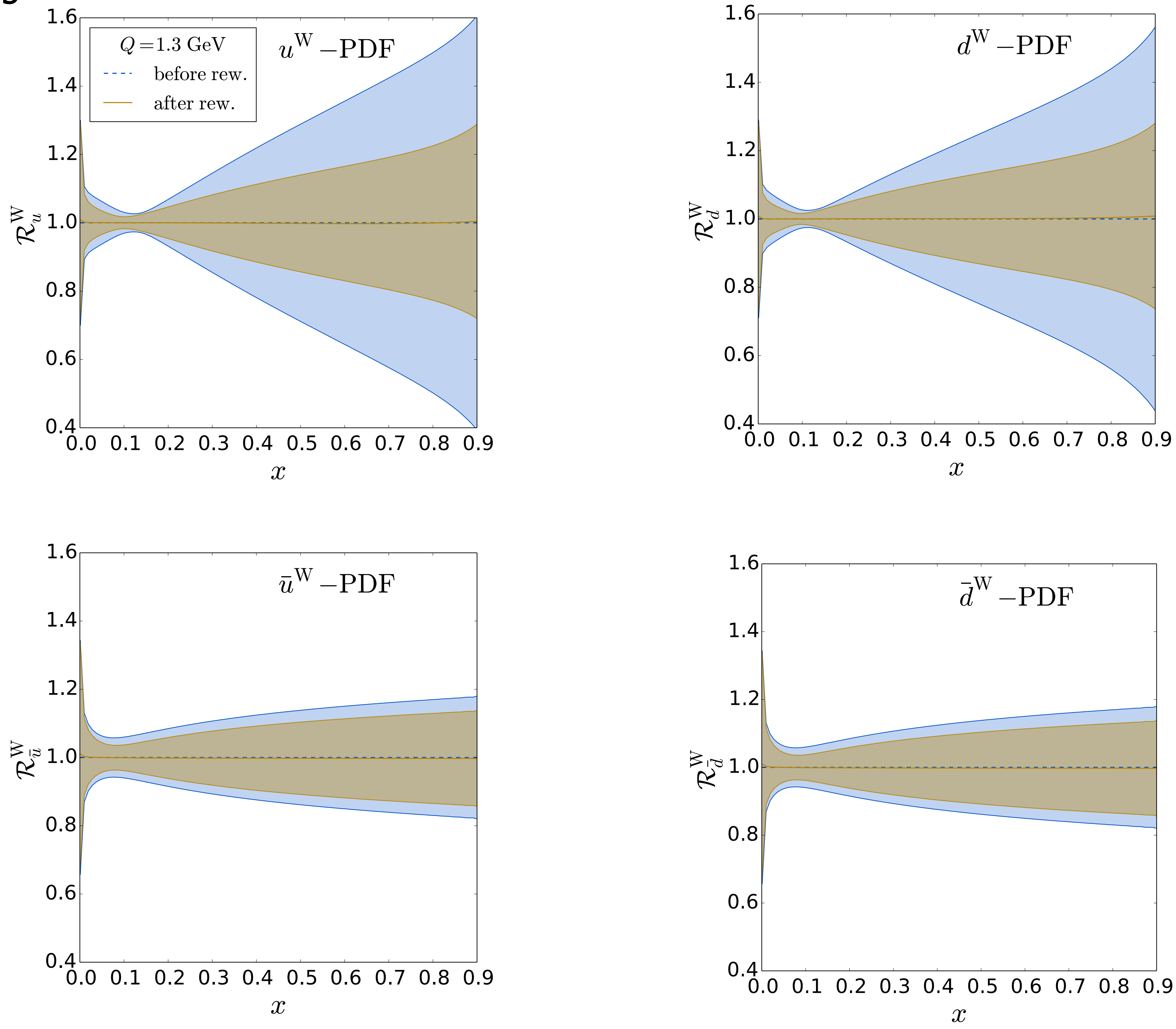


AFTER:

- Unique acceptance compared to existing DY pA data used in global analyses of nuclear PDFs (E866 & E772 @Fermilab)
- Extremly large yields up to $x_2 \rightarrow 1$ [plot made for p-Xe with a HERMES like target]

Impact of DY pA pseudo data on nCTEQ15 NPDFs

L=150/pb



W boson production

Motivation

- W production close to threshold never been measured

  Proxy for heavy resonance searches at the LHC

- Potential to provides constraints on light quark sea and the valence quarks
  (flavor separation)

A simple ratio in the limit of large x_1, x_2

- W-production at AFTER is close to the threshold
(In fact, it's dominated by off-shell W bosons)

- Both, x_1 and x_2 are large. In this limit:

$$R^W = \frac{\frac{d\sigma}{dy}(pn \to W^+ + W^-) - \frac{d\sigma}{dy}(pp \to W^+ + W^-)}{\frac{d\sigma}{dy}(pn \to W^+ + W^-) + \frac{d\sigma}{dy}(pp \to W^+ + W^-)} = 1 - 2\frac{\frac{d\sigma}{dy}(pp \to W^+ + W^-)}{\frac{d\sigma}{dy}(pd \to W^+ + W^-)}$$

$$= \frac{[u(x_1) - d(x_1)][\bar{u}(x_2) - \bar{d}(x_2)] + [\bar{u}(x_1) - \bar{d}(x_1)][u(x_2) - d(x_2)]}{[u(x_1) + d(x_1)][\bar{u}(x_2) + \bar{d}(x_2)] + [\bar{u}(x_1) + \bar{d}(x_1)][u(x_2) + d(x_2)]} .$$

- At $y^*=0$, $x_1=x_2$ on has access to r_s= dbar(x)/ubar(x)

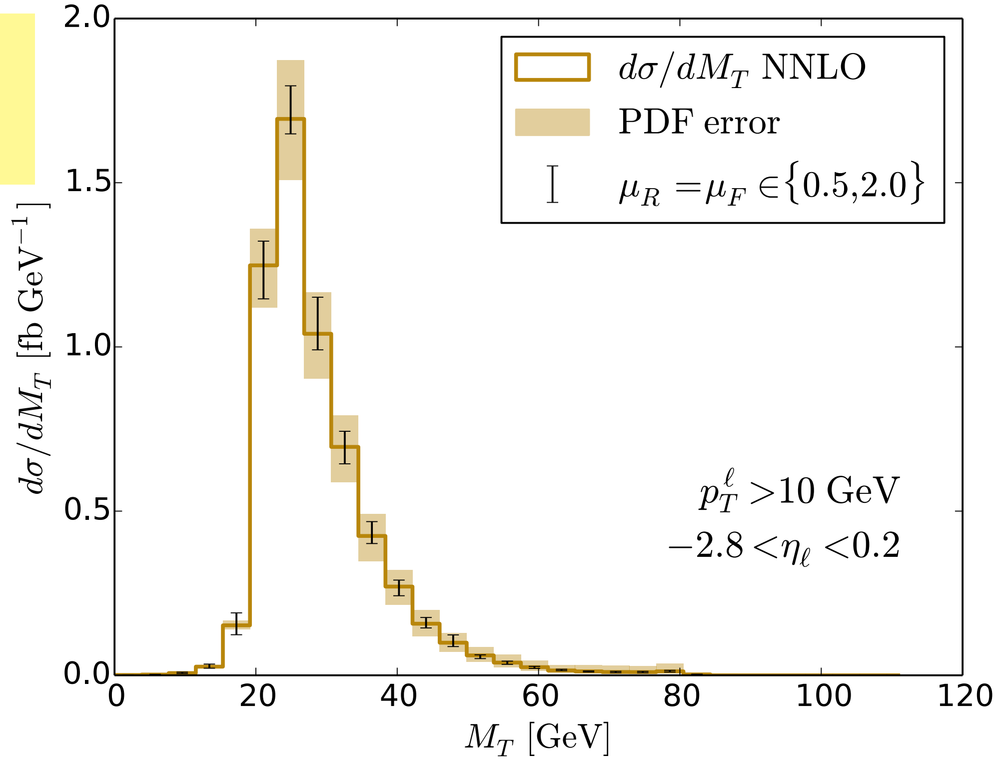
$$R^W(y = 0) = \frac{(1 - r_v)(1 - r_s)}{(1 + r_v)(1 + r_s)}$$

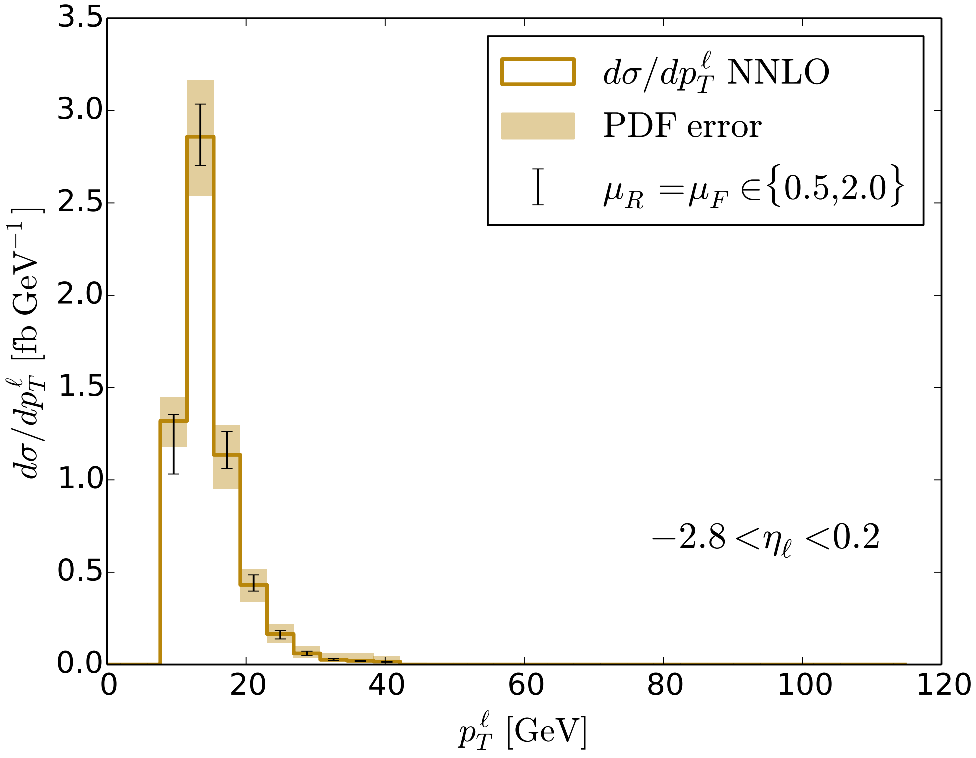
Predictions for W-boson production at AFTER

pp	W^+			W^-		
	NLO	NNLO	Counts/year	NLO	NNLO	Counts/year
$p_T^l > 10$ GeV	$22.5^{+4.8}_{-4.3}$	$25.9^{+4.8}_{-5.0}$	259 ± 49	$5.5^{+1.3}_{-1.3}$	$6.2^{+1.1}_{-1.4}$	62 ± 13
$p_T^l > 20$ GeV	$1.9^{+1.2}_{-0.7}$	$2.3^{+1.3}_{-1.1}$	23 ± 12	$0.38^{+0.29}_{-0.20}$	$0.50^{+0.25}_{-0.25}$	5 ± 2.5
$p_T^l > 30$ GeV	$0.28^{+0.91}_{-0.27}$	$0.27^{+0.72}_{-0.24}$	2.7 ± 4.8	$0.035^{+0.091}_{-0.039}$	$0.04^{+0.09}_{-0.04}$	0.4 ± 0.7

TABLE I Cross section at NLO and NNLO integrated over the rapidity range $2 < \eta_\mu < 5$ and imposing a cut $p_T^\mu > 10$ GeV in [fb]. The results have been obtained for pp collisions at $\sqrt{s} = 115$ GeV with FEWZ [98] using the CT14 PDFs [99]. The asymmetric uncertainties have been calculated using the error PDFs. The expected number of events has been obtained with a yearly luminosity of 10 fb^{-1}.

Note: the production is mostly off-shell!

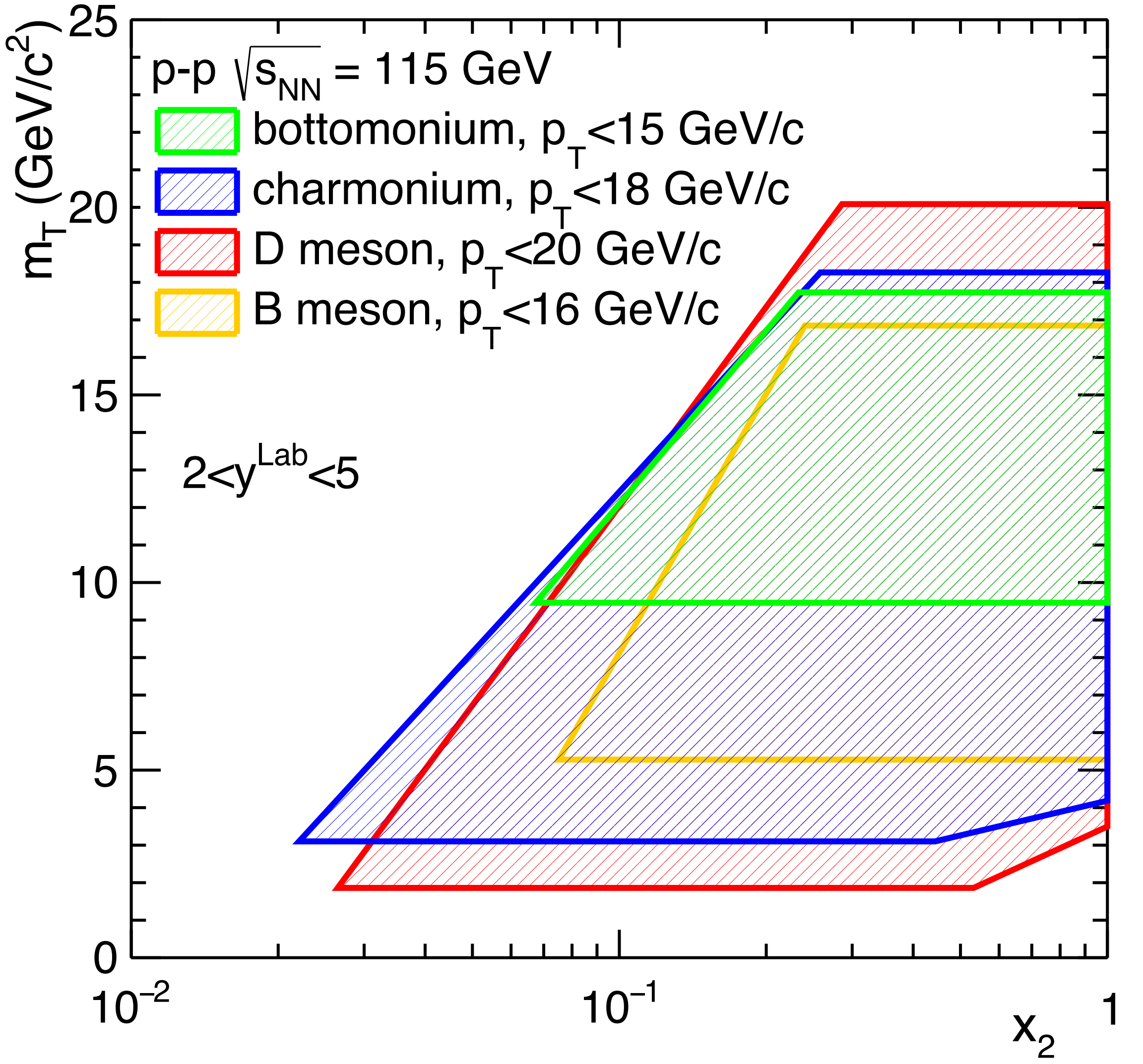


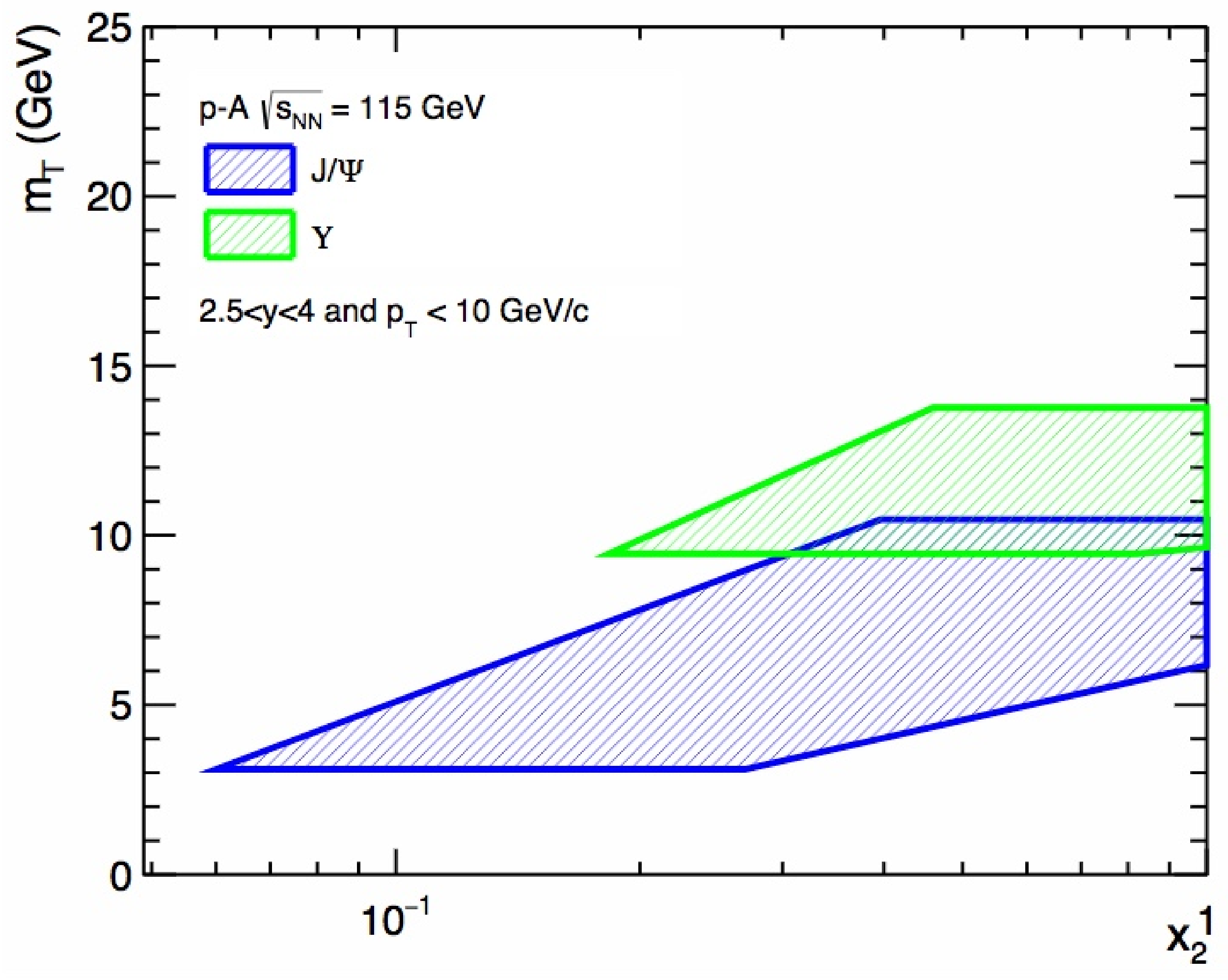


work in progress

Heavy flavour studies

Heavy-flavour studies: kinematical ranges





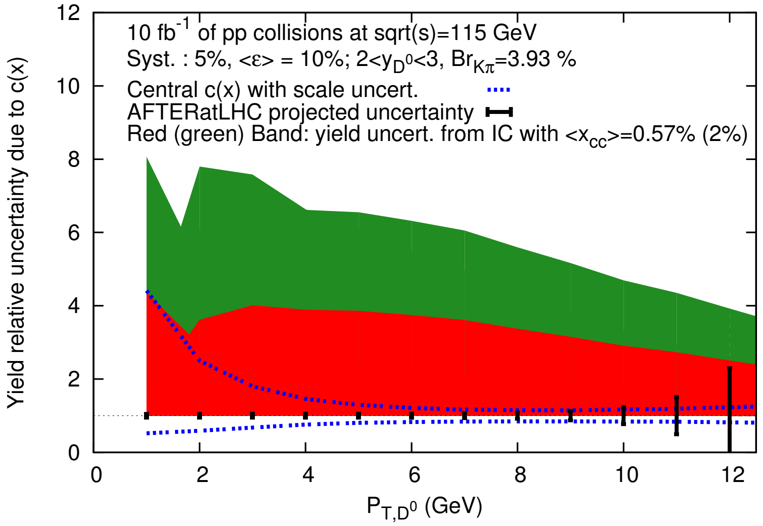
- Left: for LHCb based on 10 fb^{-1} of data
- Right : for ALICE based on a P_T cut (to be improved with 0.25 fb^{-1} of data)

Open charm projections

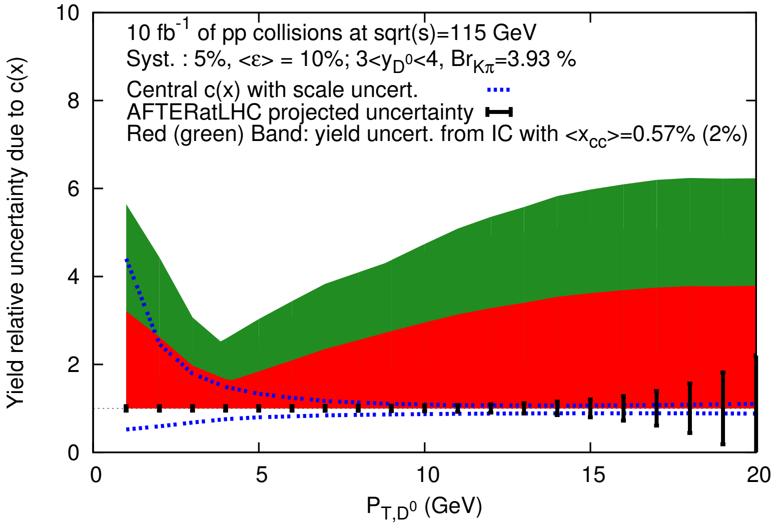
- Huge data sample over a wide kinematical range gives a unique handle on the charm content in the proton at high x

- Longstanding debate in the QCD community: perturbative vs. non-perturbative origin

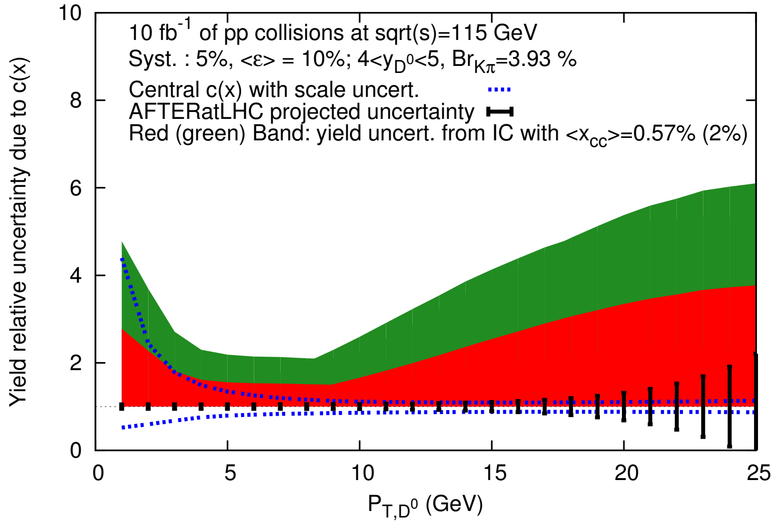
- Relevant for cosmic neutrinos [not well constrained by lack of inputs]



(a) $2 < y_{\mathrm{Lab}} < 3$



(b) $3 < y_{\mathrm{Lab}} < 4$



(c) $4 < y_{\mathrm{Lab}} < 5$

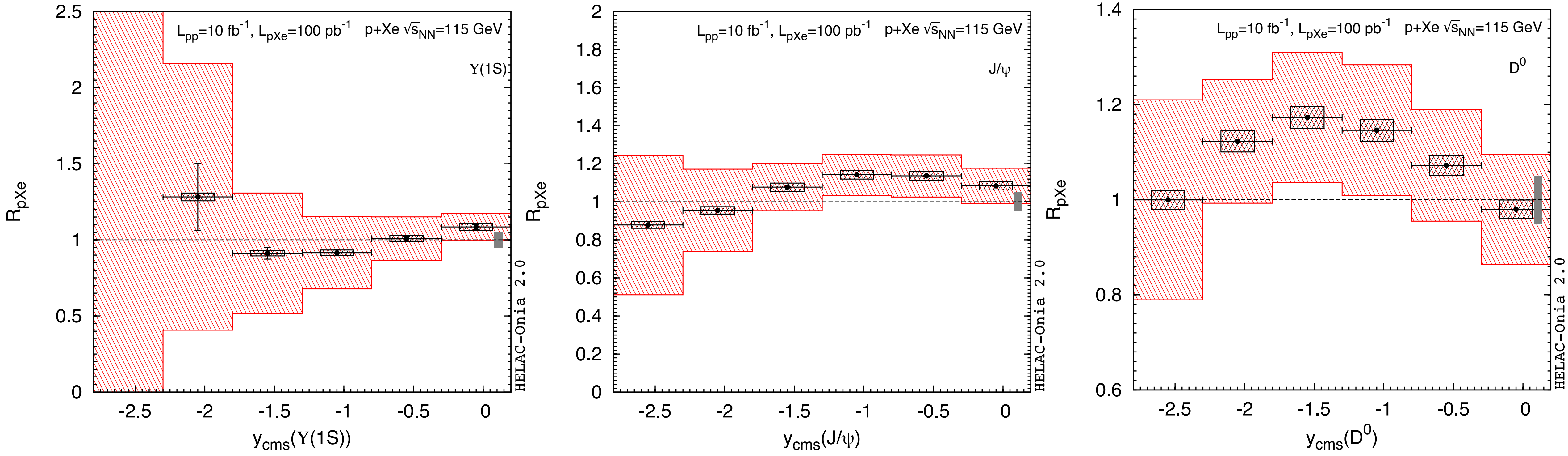
- Systematic uncertainties of 5% are included and the statistical uncertainty for the background subtraction is assumed to be negligible
- Even for pT<15 GeV the expected precision of the measurement will allow to constrain the IC model by up to an order of magnitude

Probing gluons at high-x in nuclei

The extraction of gluons nPDF necessitates :

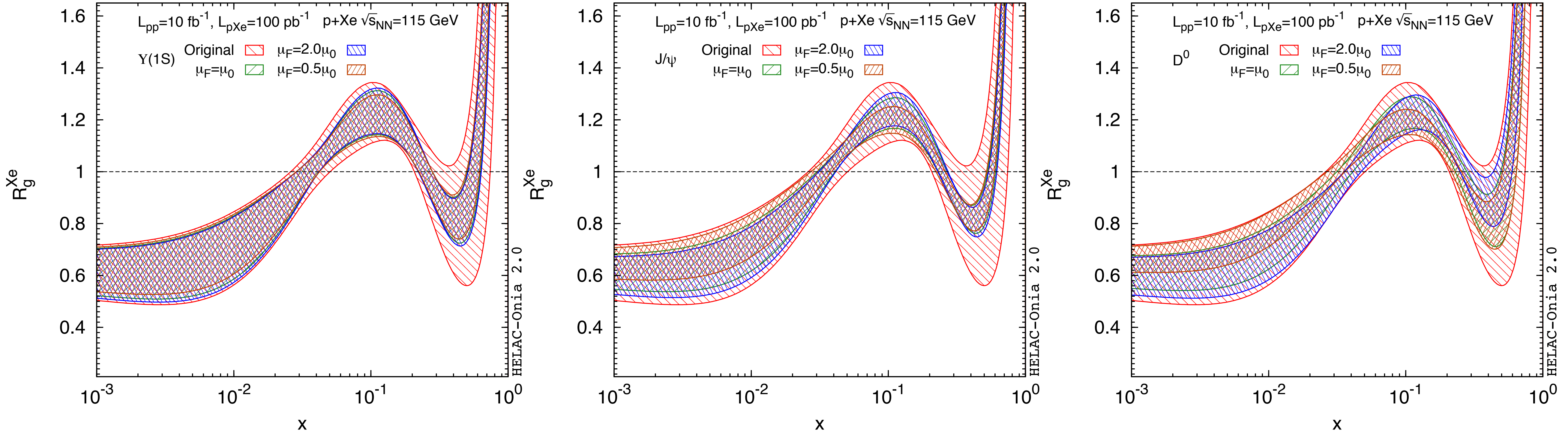
- Multiple gluon-sensitive probes to disentangle the nPDF from other effects
- A good *pp* reference [challenging for SMOG]
- Multiple colliding systems to probe the *A* dependence
- All this is available with the fixed-target mode

nCTEQ uncertainties vs. projected statistical uncertainties



Reweighting analysis

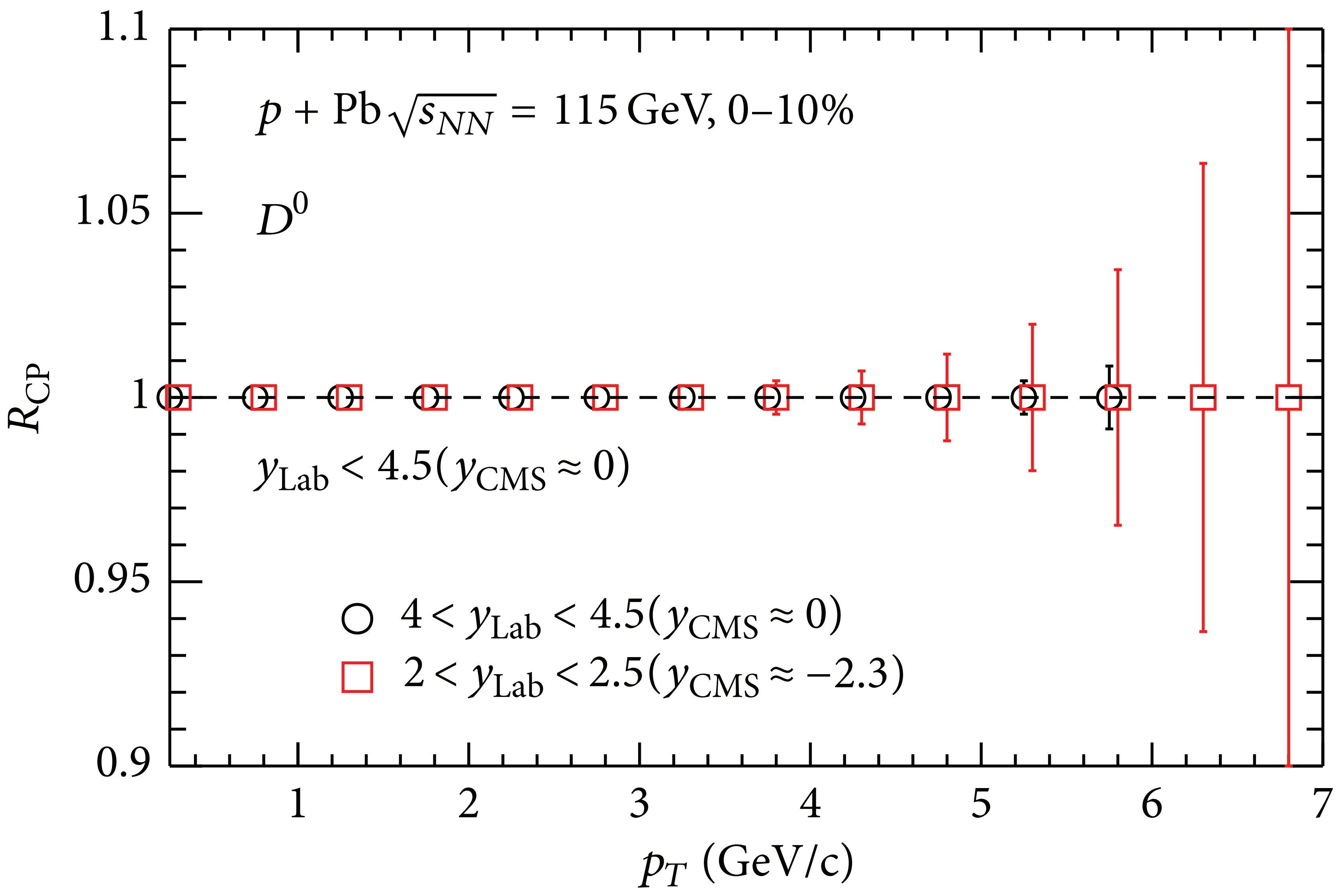
nCTEQ reweighting uncertainties: main uncertainties is the scale



Clear decrease of the nPDF uncertainty in the EMC region: uncharted for gluons!

R_{CP} for D^0 production in p-Pb

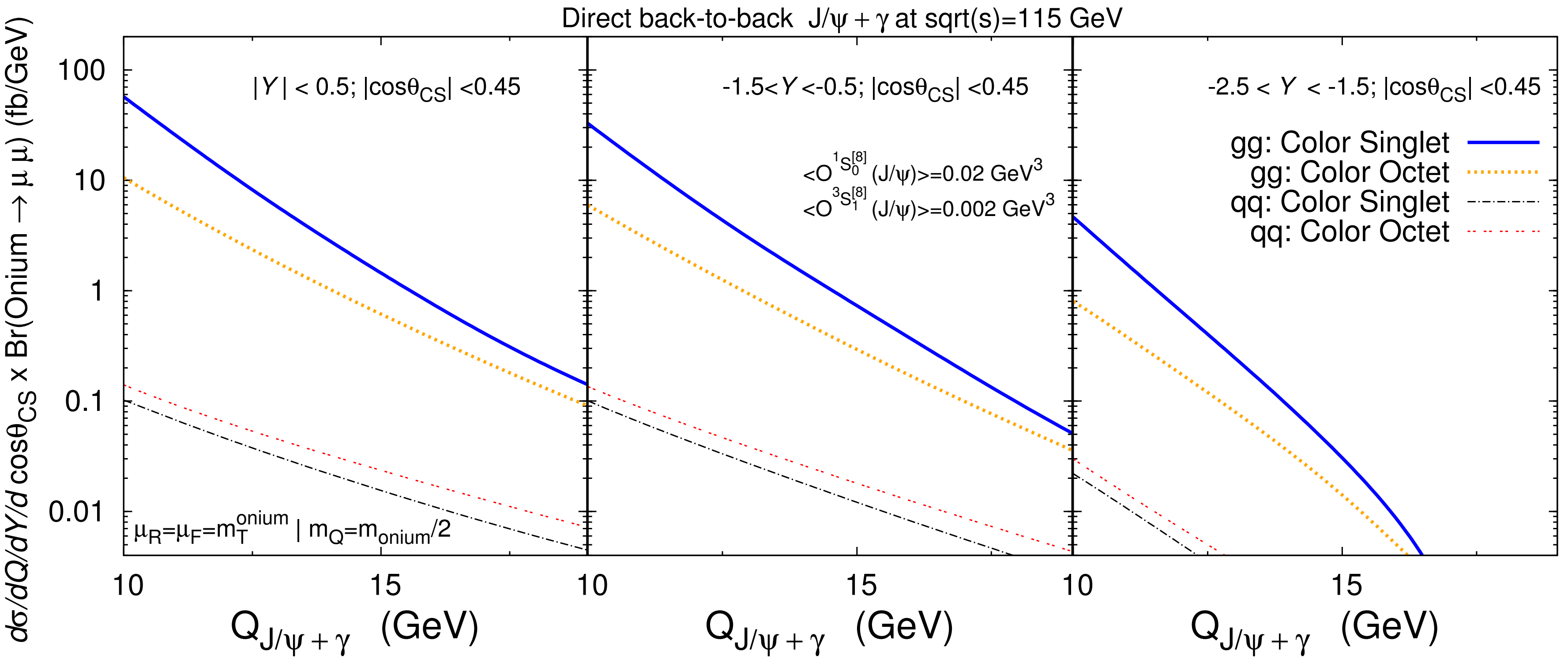
Projection of the statistical uncertainty for the central to peripheral nuclear modification factor for D^0 production in pPb



Heavy flavour + Gamma

Associated production of J/Psi + gamma

Dominated by gg fusion



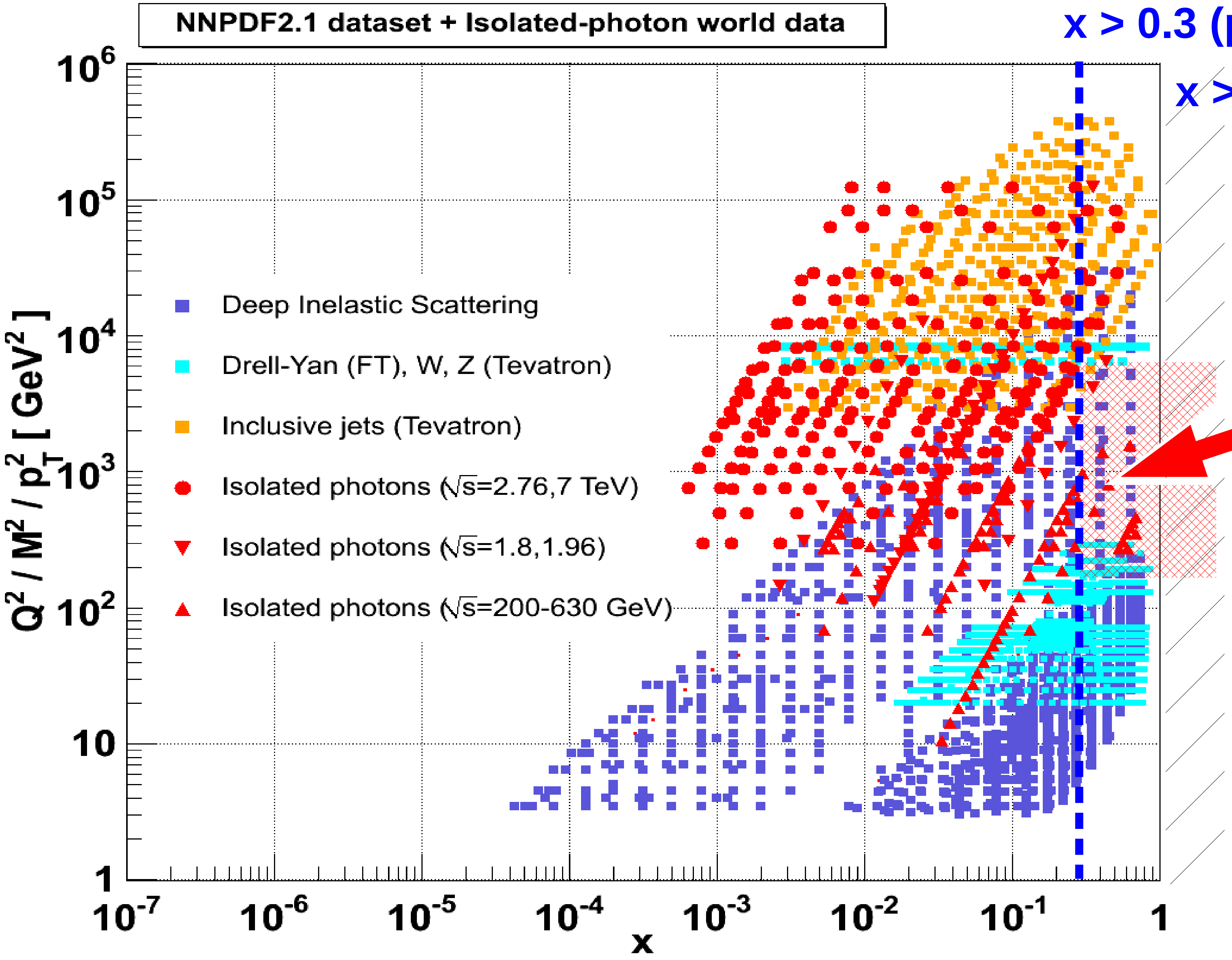
Isolated $J/\psi + \gamma$	$\langle x_2 \rangle \sim \frac{Q_{\psi\gamma}}{\sqrt{s}} e^{-Y}$	σ_{gg} [fb]	$\sigma_{q\bar{q}}$ [fb]	Counts/year
$\lvert Y_{\psi\gamma}\rvert < 0.5$	0.1	93	0.23	930
$-1.5 < \lvert Y_{\psi\gamma}\rvert < -0.5$	0.25	52	0.23	520
$-2.5 < \lvert Y_{\psi\gamma}\rvert < -1.5$	0.6	7	0.04	70

(x,Q^2) map of AFTER isolated-γ

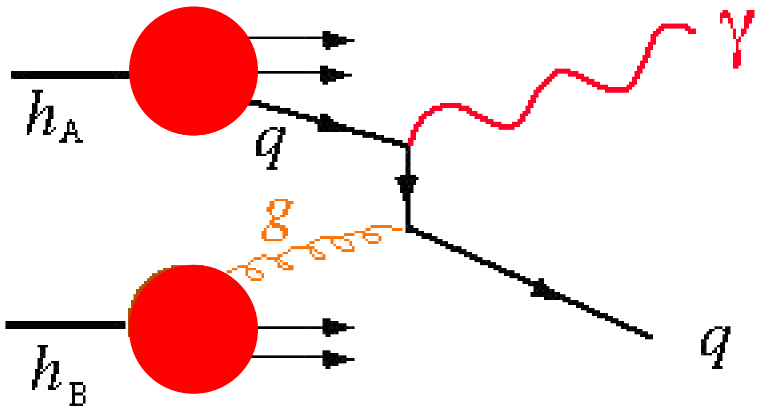
[D.d'E & J.Rojo, NPB 860 (2012) 311]

- p-p kinematics at fixed-target LHC:

To access x > 0.3 one needs isolated-γ with: $p_T = x_T\sqrt{s}/2$ > 10-20 GeV/c



AFTER region: pp → γ *X*



Isolated-γ in p(7 TeV)-p(rest): √s ~ 115 GeV

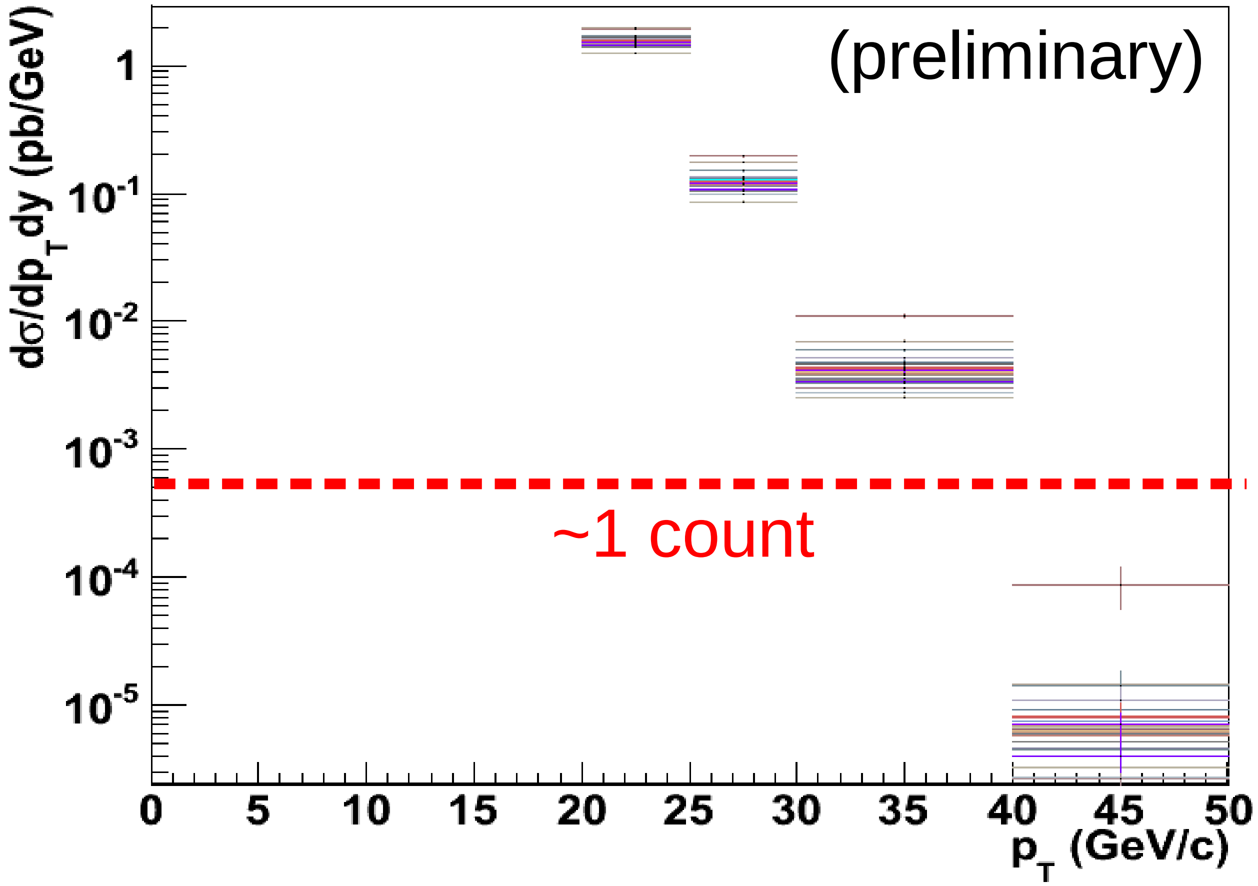
- p-p photon kinematics at fixed-target LHC (backwards rapidities):
  To access $x > 0.3$ one needs isolated-γ at: $p_T = x_T\sqrt{s}/2e^{-y} > 10$ GeV/c
- JETPHOX NLO pQCD calculations:

  p-p at $\sqrt{s}$=115 GeV

  $0<y<-3.$, p_T>20 GeV/c

  Isolation: R=0.4, E_T^{had}<5 GeV

  $\mathcal{L}$(10 cm H_2-target) ~ $2\bullet10^3$ pb^{-1}/year



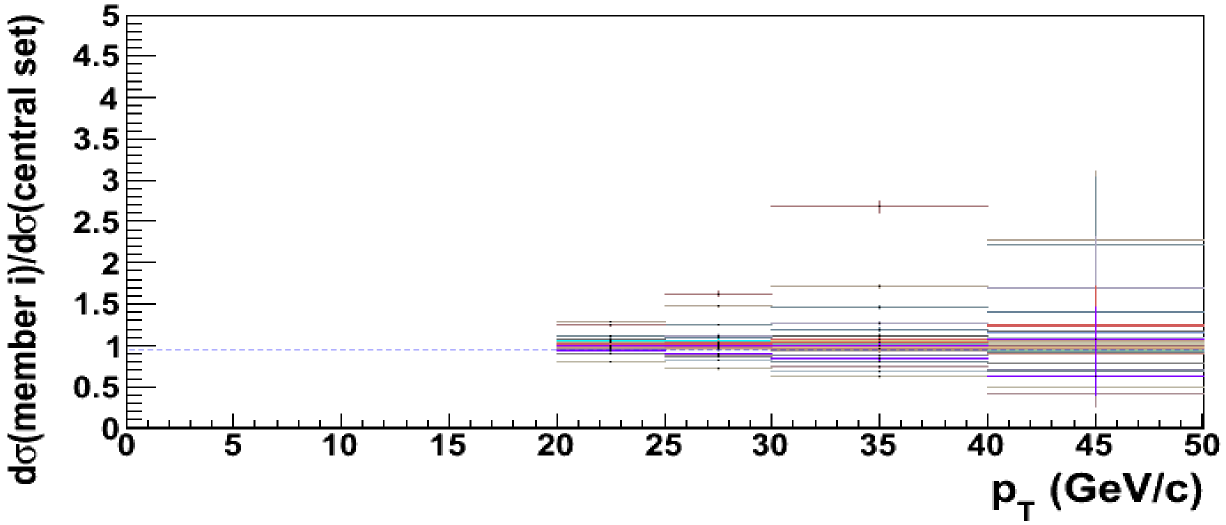
PDF: CT10 52 eigenval. (90% CL)

Scales: $\mu_i = p_T$

FF = BFG-II

x-section uncertainties$^{(*)}$ of ±170%

$^{(*)}$ (68%CL)/(90% CL) ~ 1.65



Part III:

Conclusions

Conclusions

- **Three main themes motivate a fixed target program at the LHC which will be complementary to an EIC in many respects**
    - The high-x frontier
    - The nucleon spin and the transverse dynamics of the partons
    - The approach to the deconfinement phase transition
- **2 ways towards fixed-target collisions with the LHC beams**
    - A slow extraction with a bent crystal
    - An internal gas target inspired from SMOG@LHCb/HERMES,...
    - Based on fast simulations, the AFTER@LHC study group has made FoMs for LHCb and ALICE in the FT mode which clearly support a full physics program
    - In synergy with & under the advice of the Physics Beyond Colliders (PBC) study group at CERN we now prepare a document on the fixed-target physics at the LHC

Conclusions

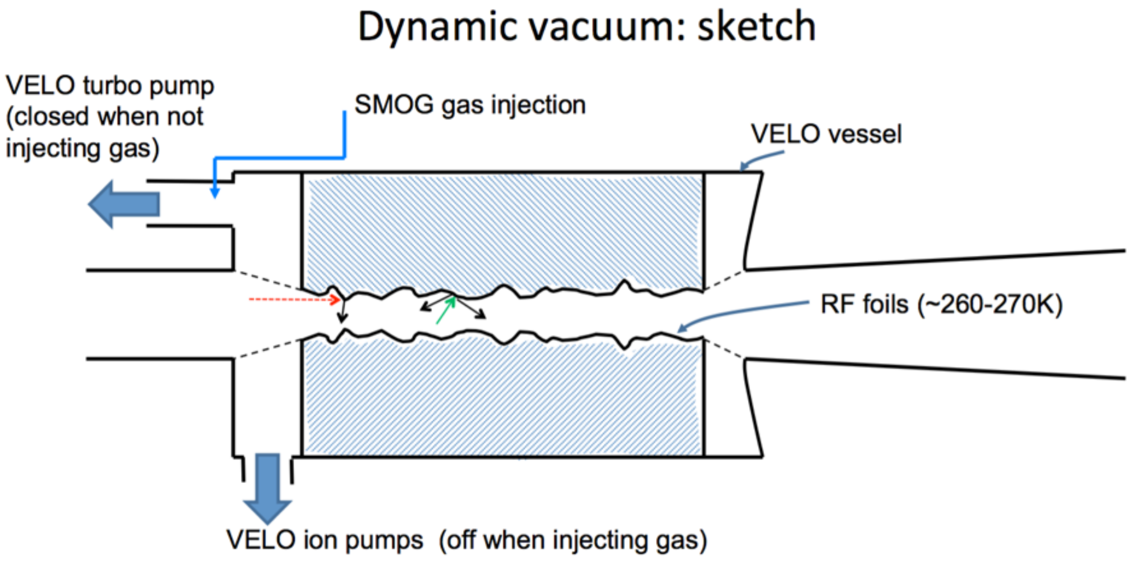
- **This talk: focus on the (unpolarized) partonic structure at high-x**
- **Many interesting observables in pp and pA collisions providing novel information on the partonic structure of nucleons/nuclei at high-x**
  - Drell Yan lepton pair production
  - W production
  - Heavy Flavour Studies

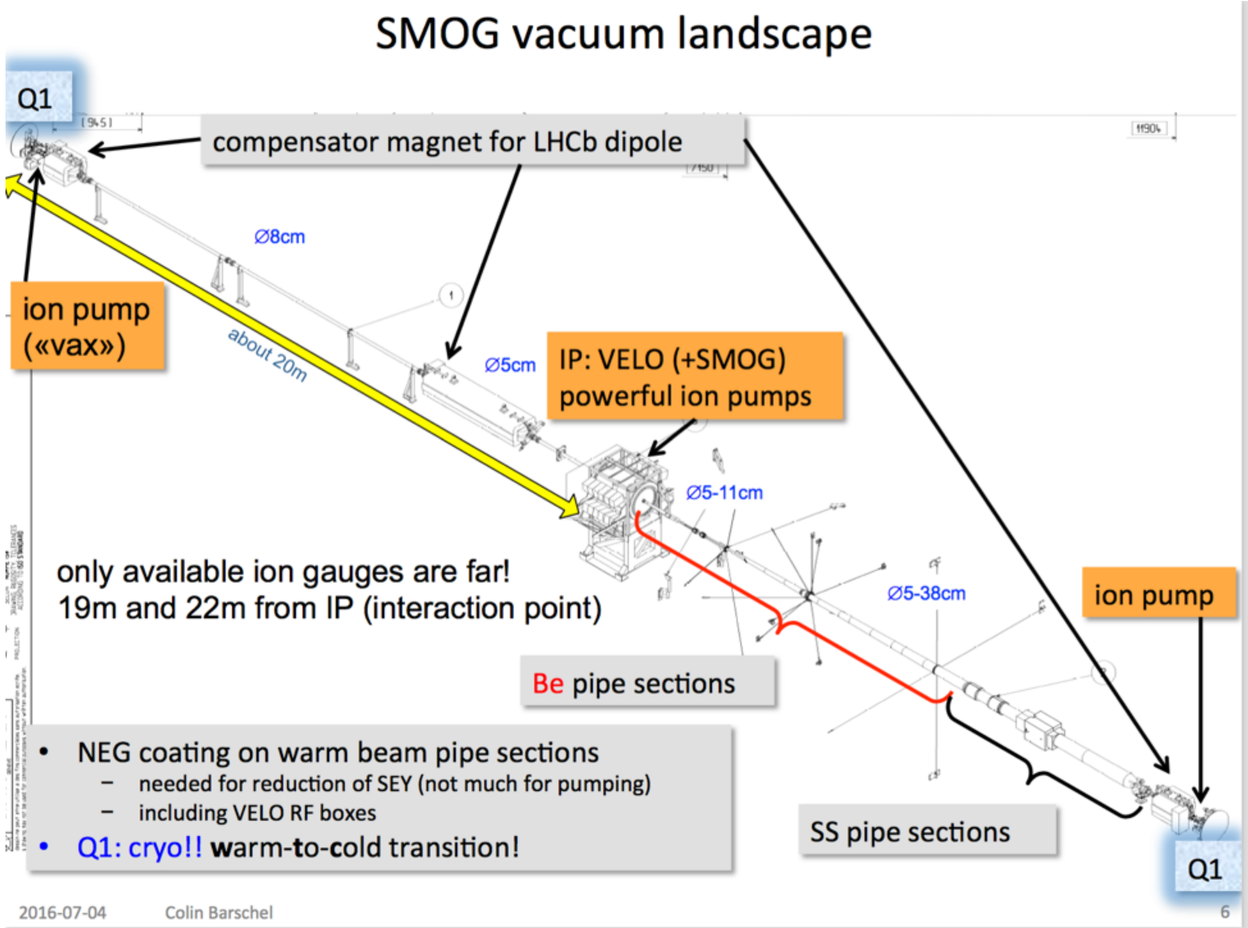
Backup

Internal gas target: SMOG in LHCb

System for Measuring the Overlap with Gas (SMOG): high precision lumi measurement

VELO (+SMOG)





SMOG vacuum landscape

only available ion gauges are far! 19m and 22m from IP (interaction point)

- NEG coating on warm beam pipe sections
  - needed for reduction of SEY (not much for pumping)
  - including VELO RF boxes
- Q1: cryo!! warm-to-cold transition!

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SMOG/LHCb (System for Measuring the Overlap with Gas)

- Gas injecting into Vertex Locator (VELO) vacuum chamber: P ~1.5 10^{-7} mbar
- LHC vacuum ion pump stations located ±20m on both sides
- Noble gas already injected: He, Ne, Ar
- Use full intensity of the LHC proton and lead beam without decrease of the beam lifetime
- Limited running time: so far, at most 1 week
- Typical integrated luminosities: pAr, 17h of data-taking: L_{int} ~ 3.75/nb

Internal gas target: gas-jet

Polarised H-jet polarimeter at RHIC-BNL *Zelenski et al. NIM A 536 (2005) 248*

- Used to measure the proton beam polarisation at RHIC
- 9 vacuum chambers: 9 stages of differential pumping
- Polarised gas: free atomic beam source (ABS) crossing the RHIC beam: H, D and $_3$He possible
- Holding field in the target vacuum chamber
- Diagnostic system: Breit-Rabi polarimeter

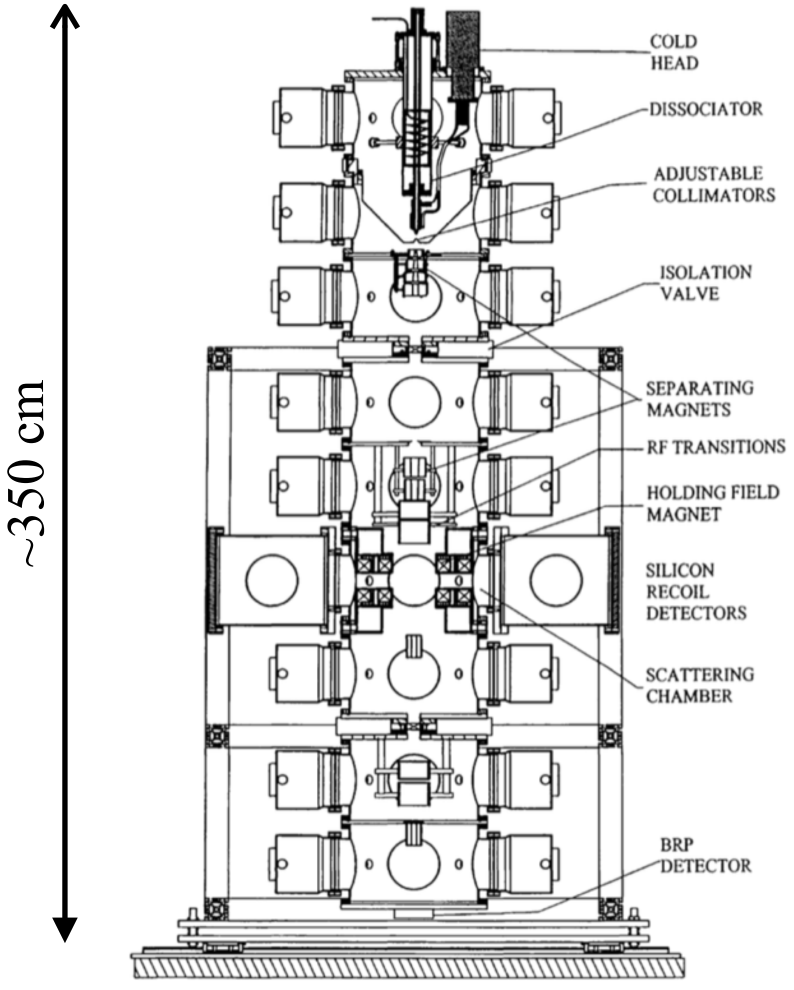


Fig. 1. H-jet polarimeter general layout.

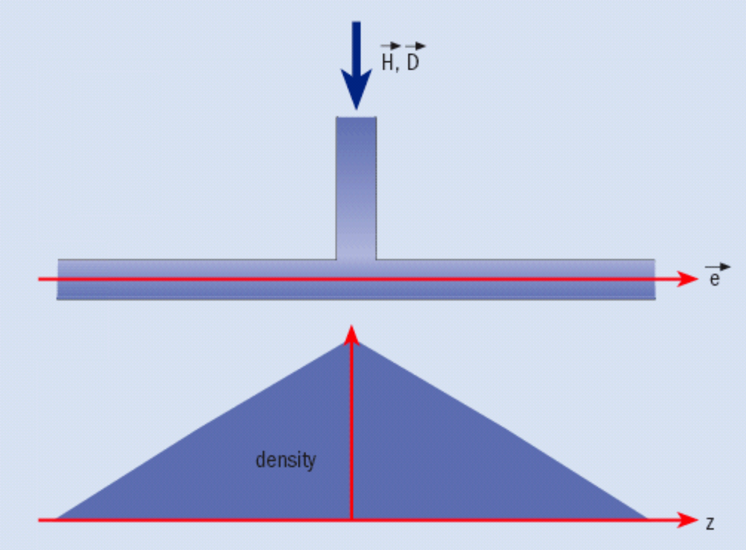
Density

- Polarised inlet $H_{\uparrow}$ flux: $1.3\ 10^{17}$ H/s
- Areal density $\vartheta_{H\uparrow} = 1.2\ 10^{12}$ atoms/cm^2 (7-15 × SMOG)
- Higher flux can be obtained for $^3He_{\uparrow}$ (x100) and H_2 (x1000)
- Gas target profile at interaction point: gaussian with a full width of ~6 mm

Luminosity

- Using nominal LHC bunch number [2808 bunches for proton and 592 for lead] and for 1 LHC year [10^7s proton beam and 10^6s lead beam]
- $\mathcal{L}_{p\text{-}H\uparrow} = 4.5\ 10^{30}$ cm^{-2}s^{-1} [$t = 10^7$s: $\mathcal{L}_{p\text{-}H\uparrow} = 45$/pb]
- $\mathcal{L}_{p\text{-}H2} = 10^{33}$-$10^{34}$ cm^{-2}s^{-1} [$t = 10^7$: $\mathcal{L}_{p\text{-}H2} = 10$-$100$/fb]

Internal gas target: storage cell



HERMES/DESY T-shape internal storage cell target:

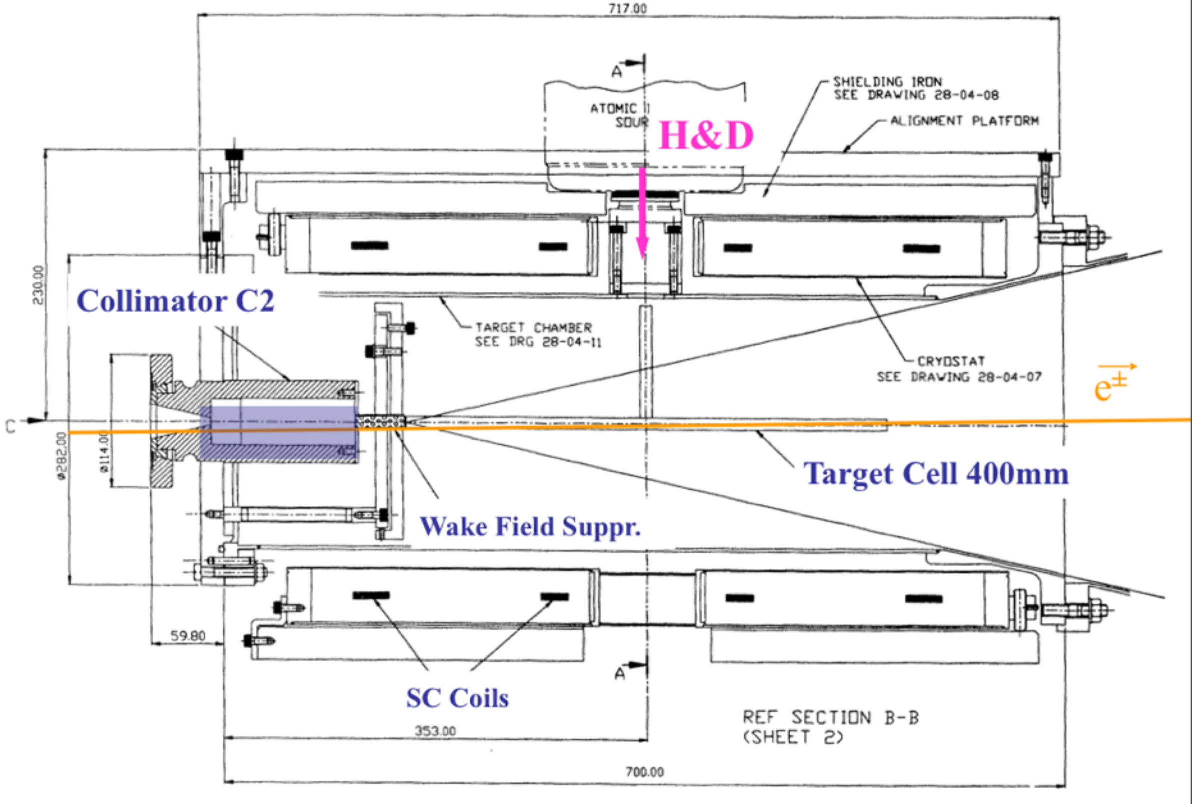
- Vacuum chamber target ~ 72 cm x 50 cm and pumping system
- Polarised gas: atomic beam source
- Holding field in the target chamber
- Diagnostic systems: target gas analyzer and polarimeter
- Unpolarized gas via capillary
- Proposal for LHC using an openable storage cell of 1m long and 2.8 cm wide: ***C. Barschel et al. Adv.High Energy Phys. 2015 (2015) 463141***

Density

- Polarised inlet $H_{\uparrow}$ flux: 6.5 10^{16} $H_{\uparrow}/s$
- Areal density $\vartheta_{H\uparrow} = 2.5\ 10^{14}$ atoms/cm^2 (~100 × gas jet)
- Unpolarised gas pressure limited by beam lifetime

Luminosity

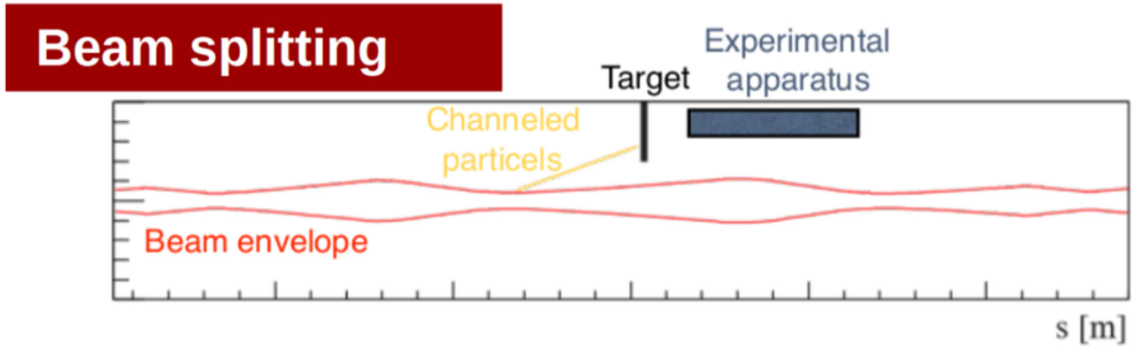
- $\mathscr{L}_{p\text{-}H\uparrow} = 0.9\ 10^{33}\ cm^{-2}s^{-1}$ [$t = 10^7 s$: $\mathscr{L}_{p\text{-}H\uparrow} = 9/fb$]
- $\mathscr{L}_{p\text{-}H2} = 5.8\ 10^{33}\ cm^{-2}s^{-1}$ [$t = 10^7 s$: $\mathscr{L}_{p\text{-}H2} = 58/fb$]
- $\mathscr{L}_{Pb\text{-}Xe} = 3\ 10^{28}\ cm^{-2}s^{-1}$ [$t = 10^6 s$: $\mathscr{L}_{Pb\text{-}Xe} = 30/nb$]

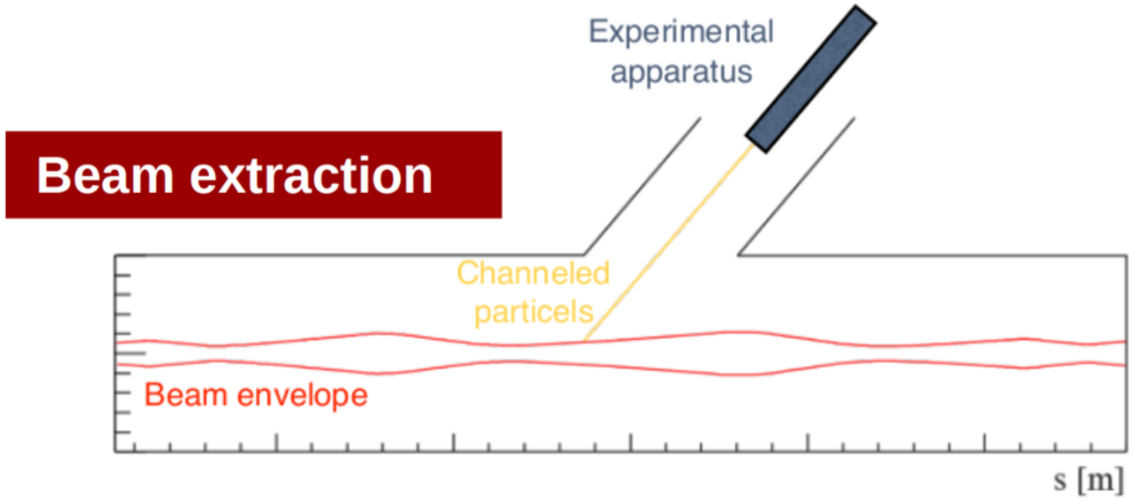


HERMES EXPERIMENT - SECTION THROUGH TARGET CHAMBER

Slow beam extraction using bent crystal

S.Redaelli, *Physics Beyond Collider Kickoff workshop*, CERN, Sept. 2016


Beam splitting


Beam extraction

Bent crystals studied by UA9

- For collimation purpose at the LHC
- Beam extraction: new beam line possible (long-term projet)
- Beam splitting
    - Crystal located ~100 m downstream the target
    - Solid target internal to the beam pipe close to an existing experimental apparatus
    - Absorber ~100 m upstream the detector

Extracted proton and lead flux

- Proton flux ~5 x 10^8 p/s (LHC beam loss: ~10^9 p/s)
- Lead flux ~2 x 10^5 Pb/s

Luminosity

- Assuming 5 mm target length
- $\mathscr{L}_{\text{p-H}} = 1.3\ 10^{31}\ \text{cm}^{-2}\text{s}^{-1}$ [$t = 10^7$s: $\mathscr{L}_{\text{p-H}} = 0.1$/fb]
- $\mathscr{L}_{\text{Pb-W}} = 3\ 10^{27}\ \text{cm}^{-2}\text{s}^{-1}$ [$t = 10^6$s: $\mathscr{L}_{\text{Pb-Xe}} = 3$/nb]
- Similar luminosities as the internal storage cell if larger target thickness

Luminosity if slow beam extraction is coupled with polarised target e.g. COMPASS NH_3

- $\mathscr{L}_{\text{p-NH3}\uparrow} = 10^{33}\ \text{cm}^{-2}\text{s}^{-1}$ [$t = 10^7$s: $\mathscr{L}_{\text{p-H}} = 1$/fb]

Nuclear modifications: l-A DIS

nCTEQ15, arXiv:1509.00792

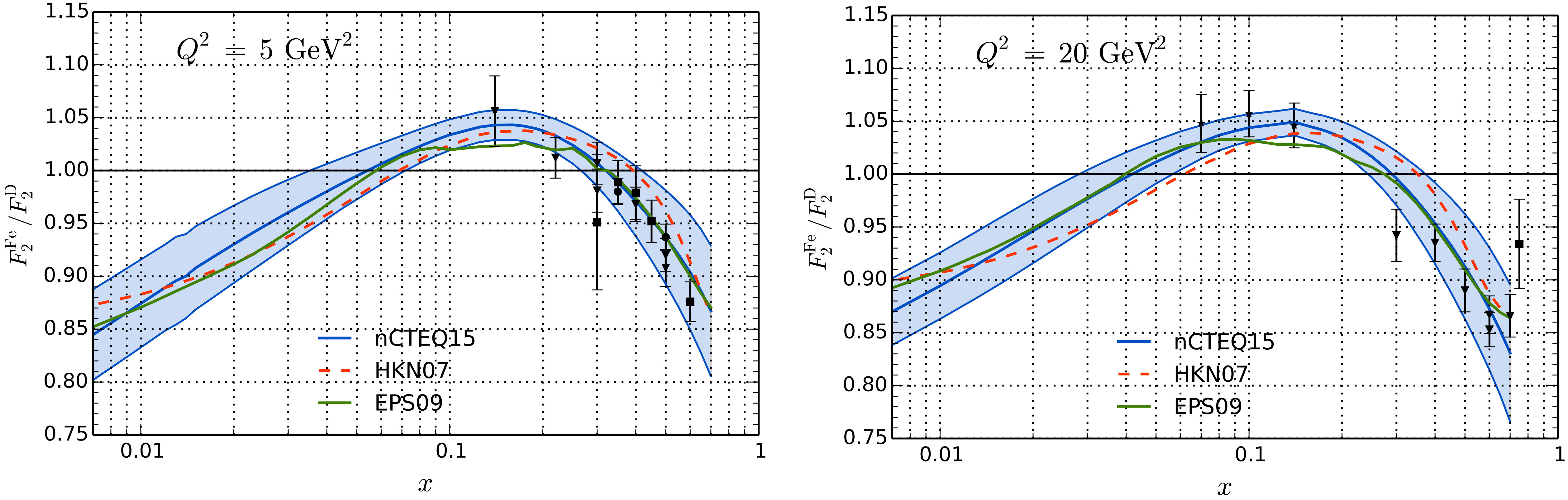
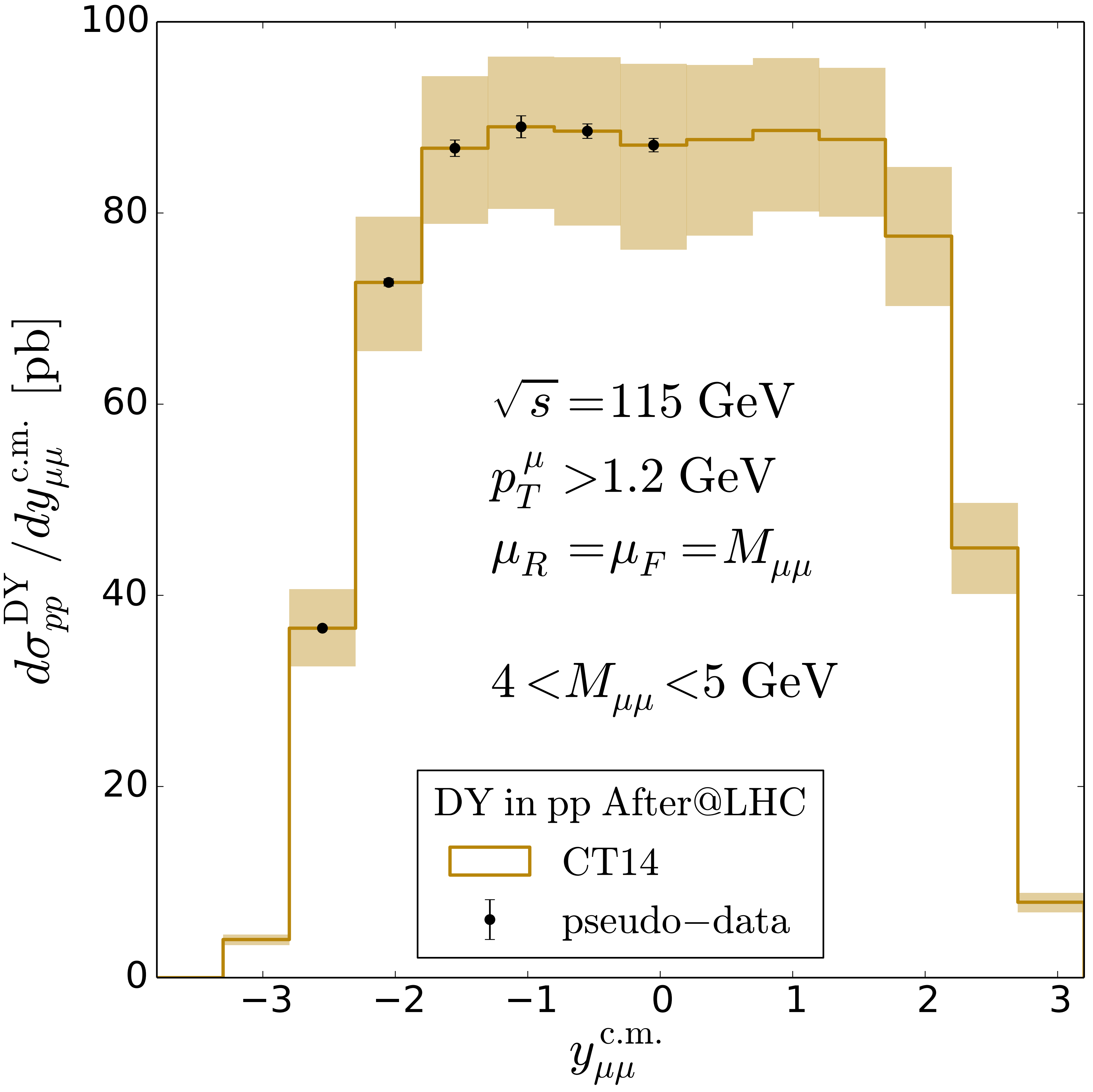
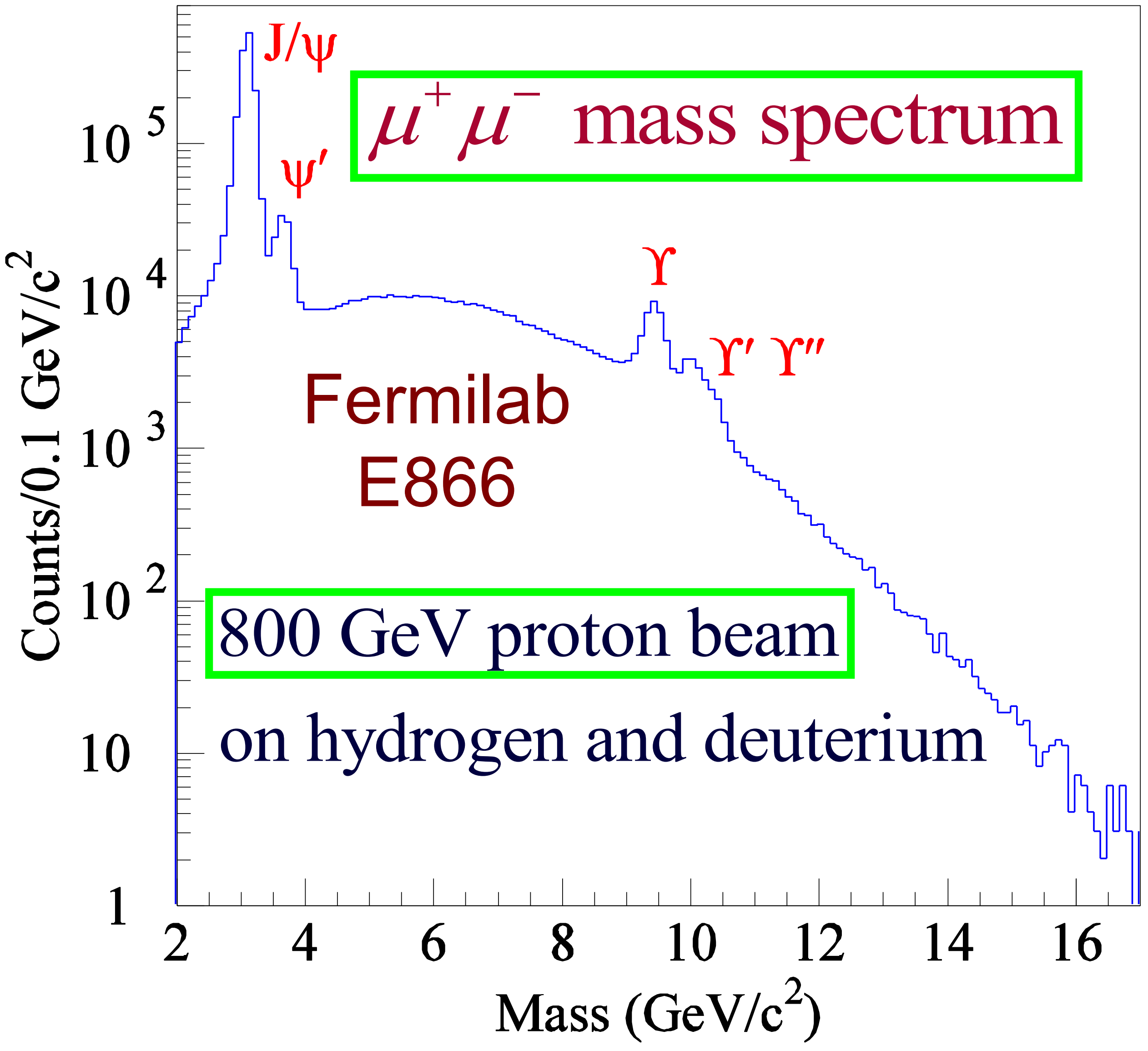


Figure 13: Ratio of the F_2 structure functions for iron and deuteron calculated with the `nCTEQ15` fit at (a) $Q^2 = 5$ GeV^2 and (b) $Q^2 = 20$ GeV^2. This is compared with the fitted data from SLAC-E049 [57] SLAC-E139 [51] SLAC-E140 [59] BCDMS-85 [56] BCDMS-87 [60] experiments and results from EPS09 and HKN07. (The data points shown are within 50% of the nominal Q^2 value.)


100
80
60
40
20
0
−3
−2
−1
0
1
2
3
$d\sigma^{\mathrm{DY}}_{pp}/dy^{\mathrm{c.m.}}_{\mu\mu}$ [pb]
$y^{\mathrm{c.m.}}_{\mu\mu}$
$\sqrt{s}$ =115 GeV
p_T^{μ} >1.2 GeV
$\mu_R = \mu_F = M_{\mu\mu}$
$4 < M_{\mu\mu} < 5$ GeV
DY in pp After@LHC
CT14
pseudo−data

$\bar{d}/\bar{u}$ flavor asymmetry from Drell-Yan

$$\left(\frac{d^2\sigma}{dx_1 dx_2}\right)_{D.Y.} = \frac{4\pi\alpha^2}{9sx_1x_2}\sum_a e_a^2\left[q_a(x_1)\bar{q}_a(x_2)+\bar{q}_a(x_1)q_a(x_2)\right]$$

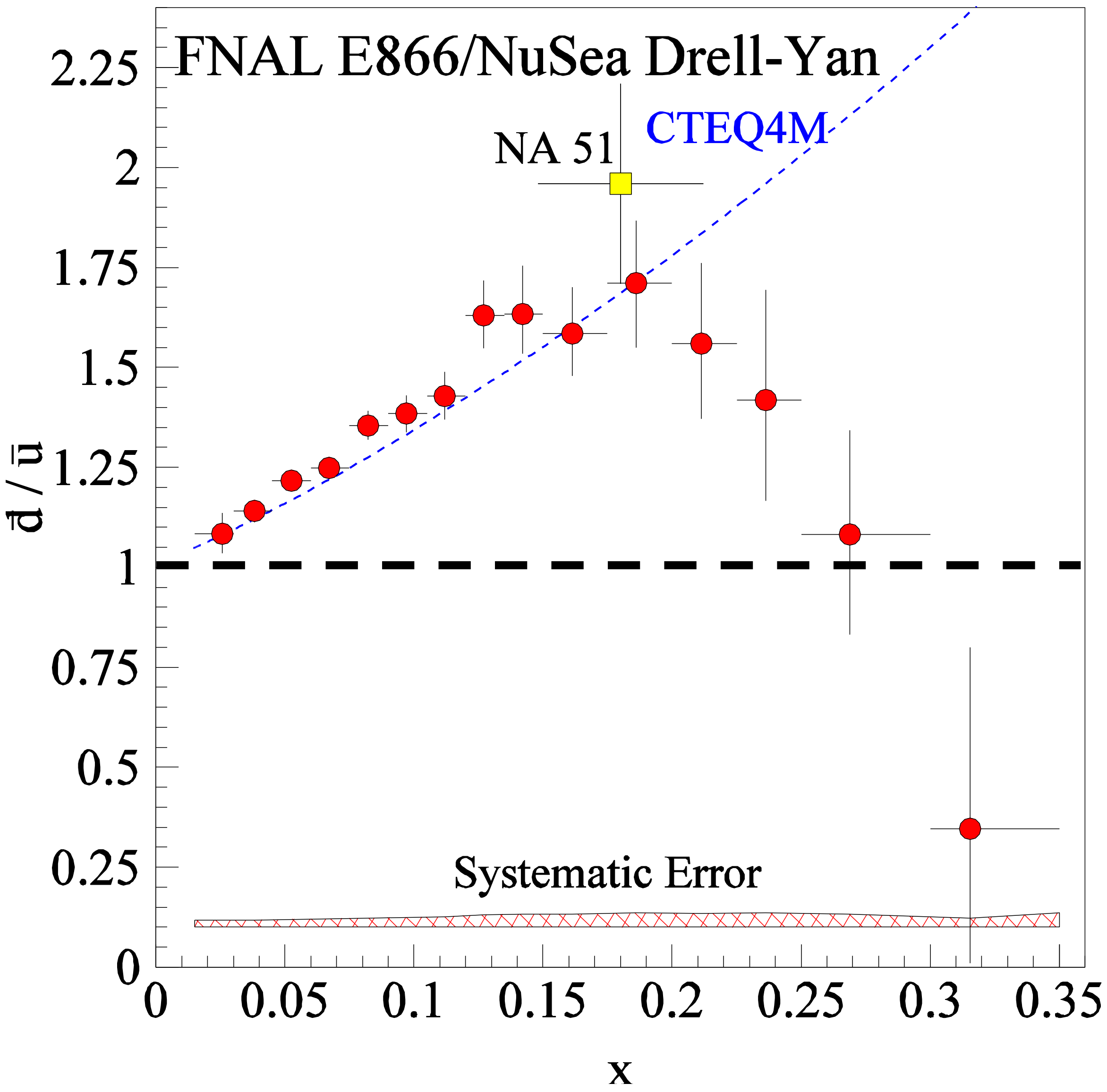


$\mu^+\mu^-$ mass spectrum

Fermilab
E866

800 GeV proton beam

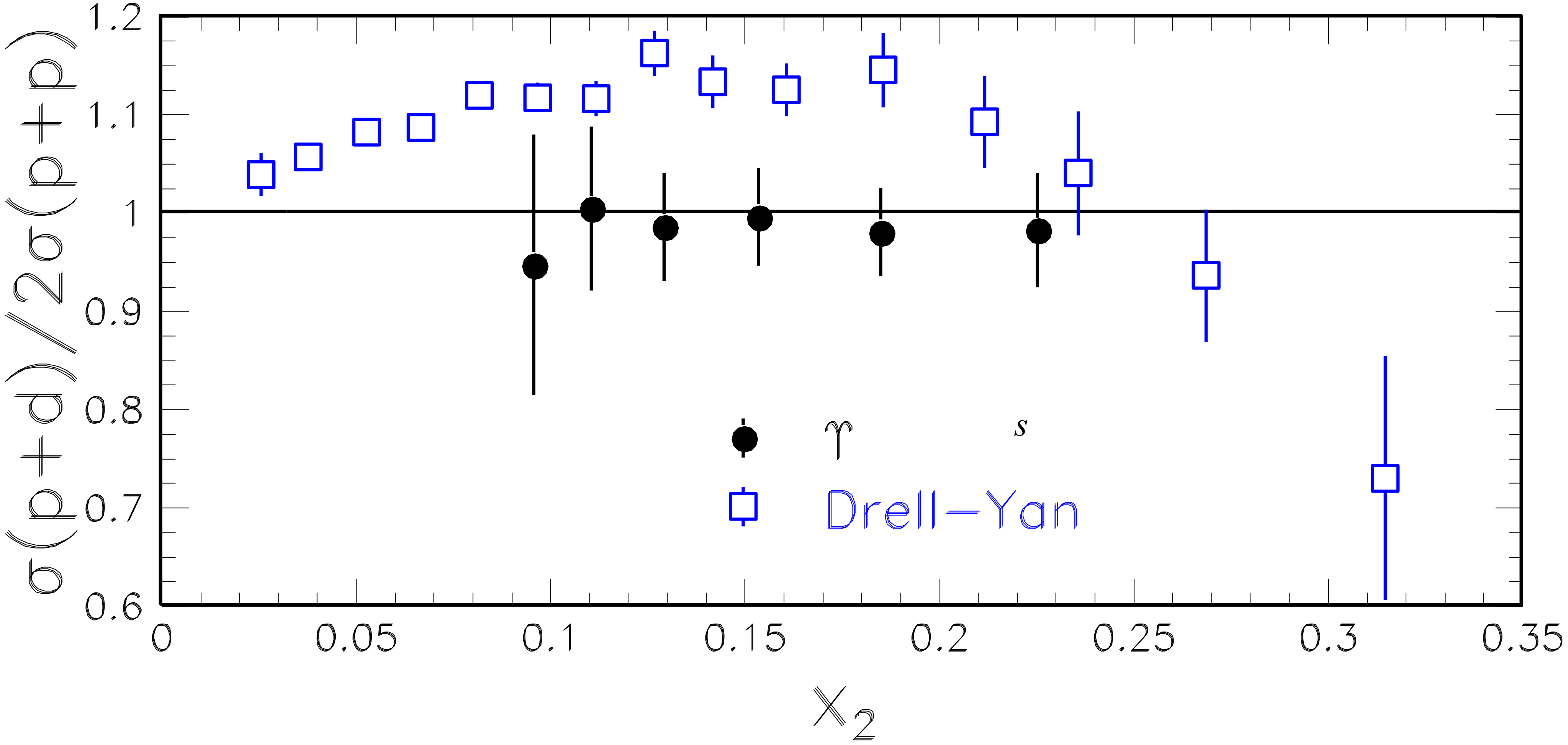
on hydrogen and deuterium



$at\ x_1 > x_2$: Drell-Yan: $\boxed{\sigma^{pd}/2\sigma^{pp} \sim \frac{1}{2}\left(1+\bar{d}(x_2)/\bar{u}(x_2)\right)}$

Gluon distributions in proton versus neutron?

$$\text{E866 data}: \sigma(p+d \rightarrow \Upsilon X)/2\sigma(p+p \rightarrow \Upsilon X)$$



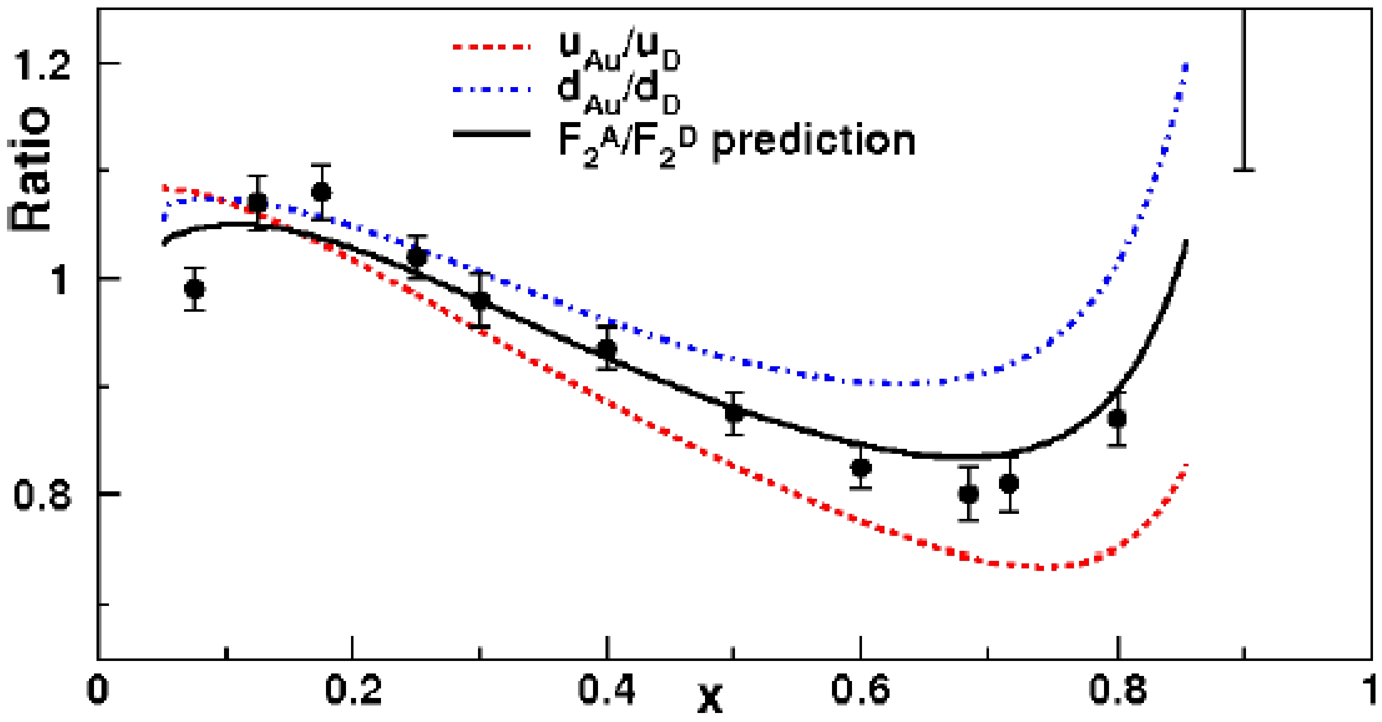
Lingyan Zhu et al., PRL, 100 (2008) 062301 (arXiv: 0710.2344)

$$\mathit{Drell-Yan}: \quad \sigma^{pd}/2\sigma^{pp} \simeq [1+\bar{d}(x)/\bar{u}(x)]/2$$

$$J/\Psi, \Upsilon: \quad \sigma^{pd}/2\sigma^{pp} \simeq [1+g_n(x)/g_p(x)]/2$$

If gluon distributions in proton and neutron are different, then charge-symmetry is violated at the partonic level

Flavor dependence of the EMC effects ?



Isovector mean-field generated in Z≠N nuclei can modify nucleon's *u* and *d* PDFs in nuclei

Cloet, Bentz, and Thomas, arXiv:0901.355
(see also Kumano et al.)

How can one check this prediction?

- SIDIS (Semi-inlusive DIS) and PVDIS (Parity-violating DIS)
- Pion-induced Drell-Yan