Constraints on Gluon Distribution Functions in the Nucleon and Nucleus from Open Charm Hadron Production

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In collaboration with Reynier Cruz-Torres, Xin Dong, Yuanjing Ji, Sooraj Radhakrishnan, Ernst Sichtermann; arXiv:2107.05632

Outline

1) **Introduction**

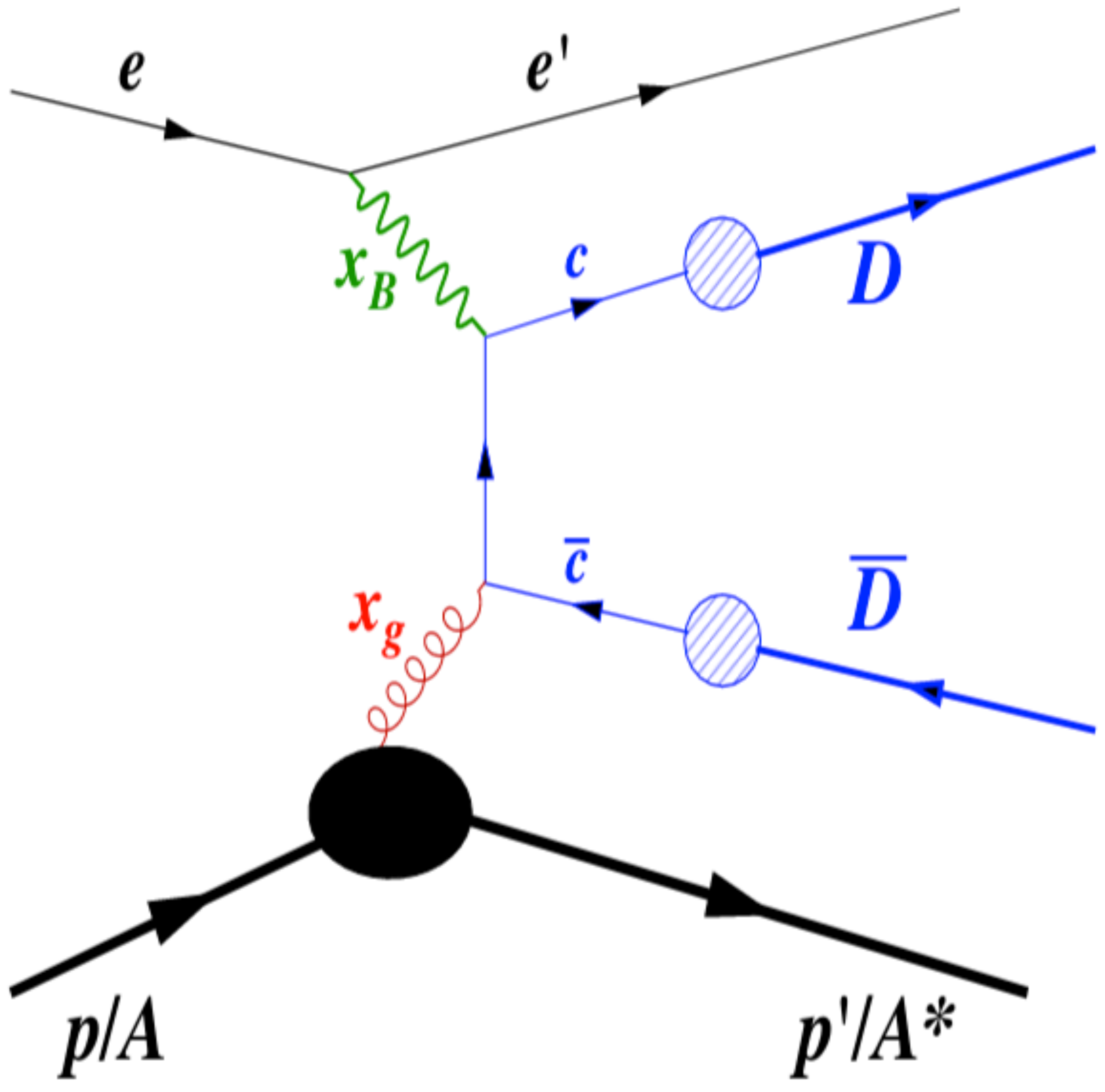
2) **Simulation setup and baseline charm projections**

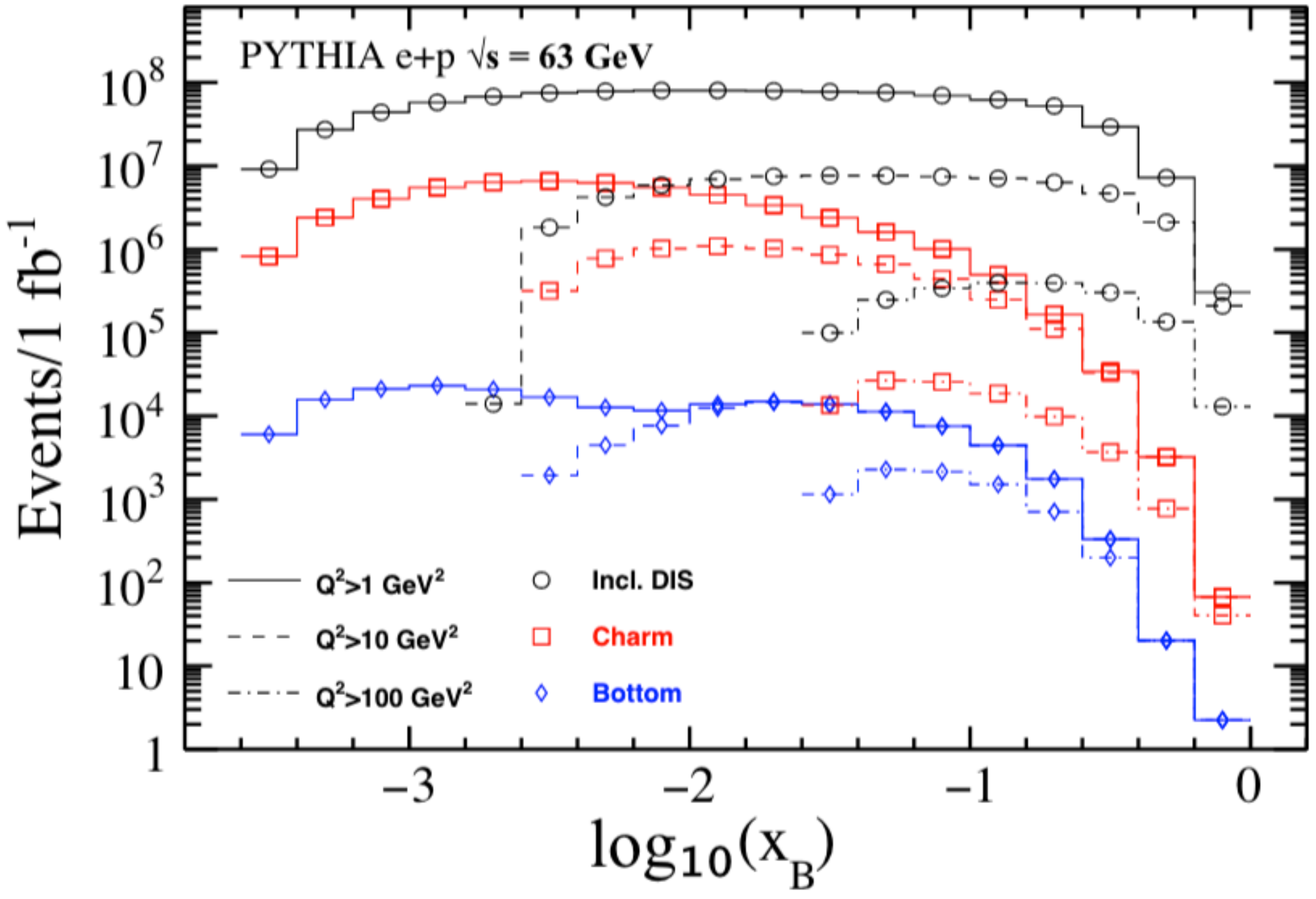
3) **Effects of intrinsic charm on projected data**

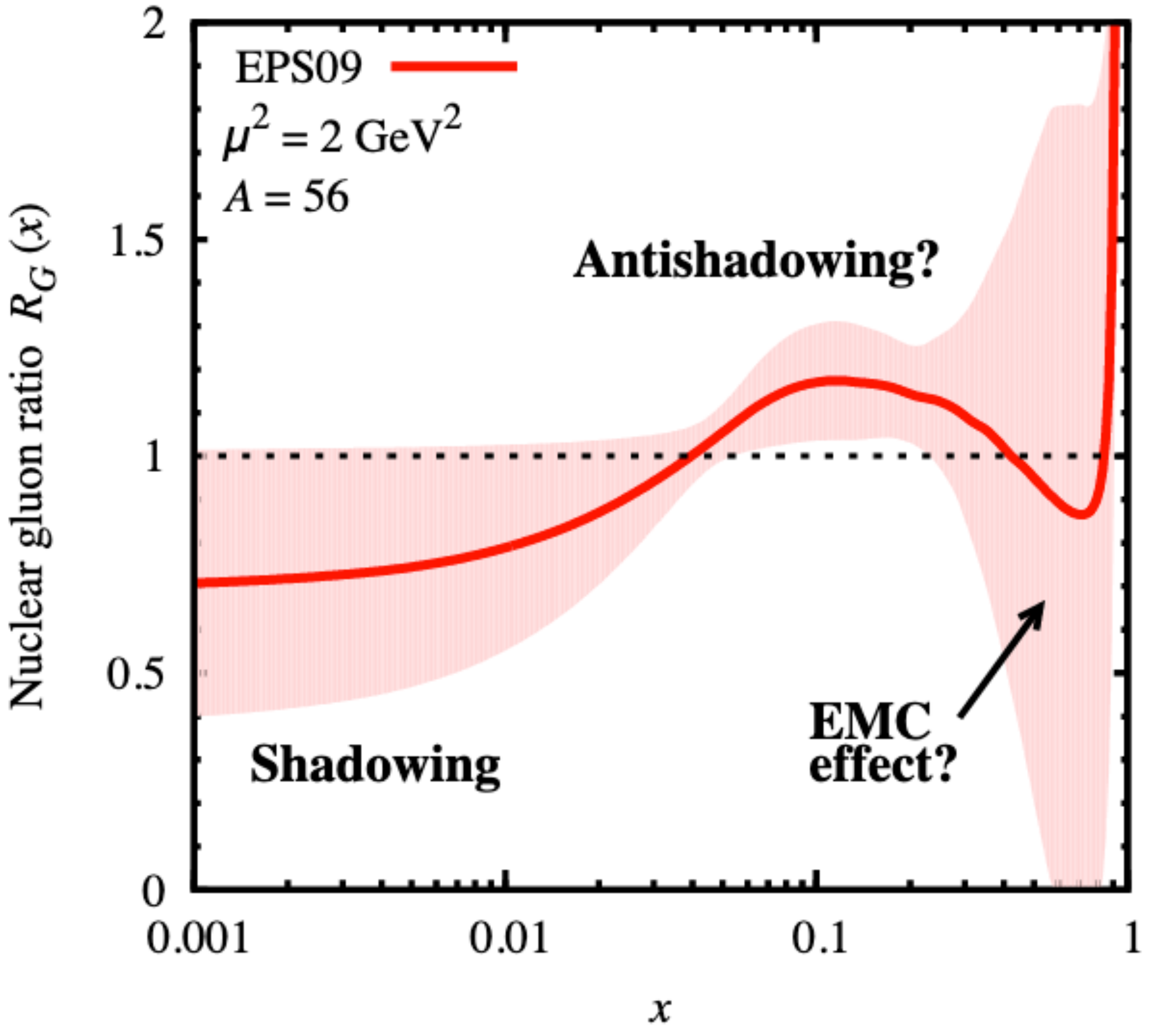
4) **Constraints to nuclear gluon PDFs from e+Au**

Introduction

E. Chudakov et al. Phys. Conf. Ser.770, 012042 (2016)







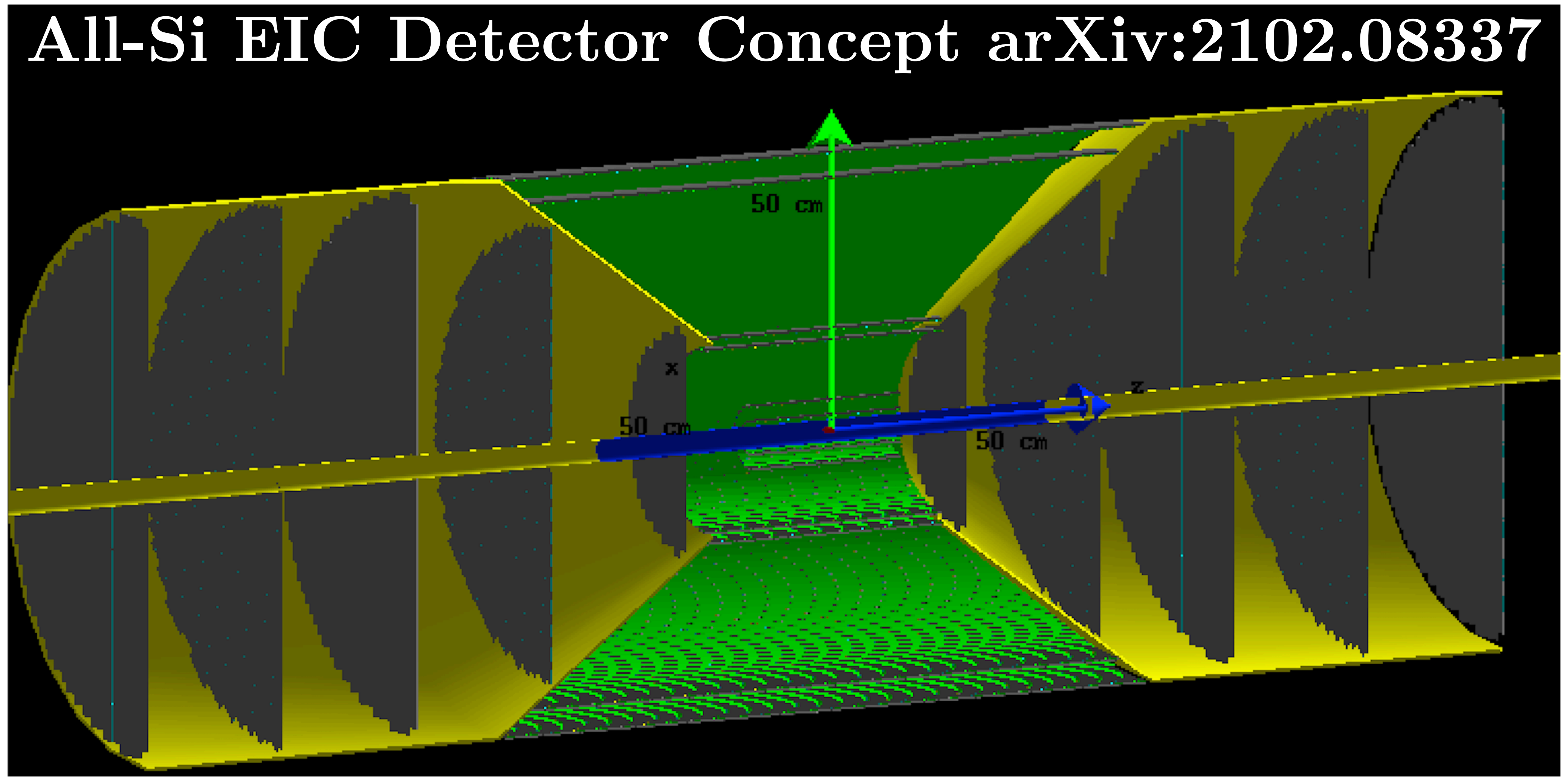
Charm quarks are produced via photon-gluon fusion at leading-order in deep inelastic scatterings (DIS)

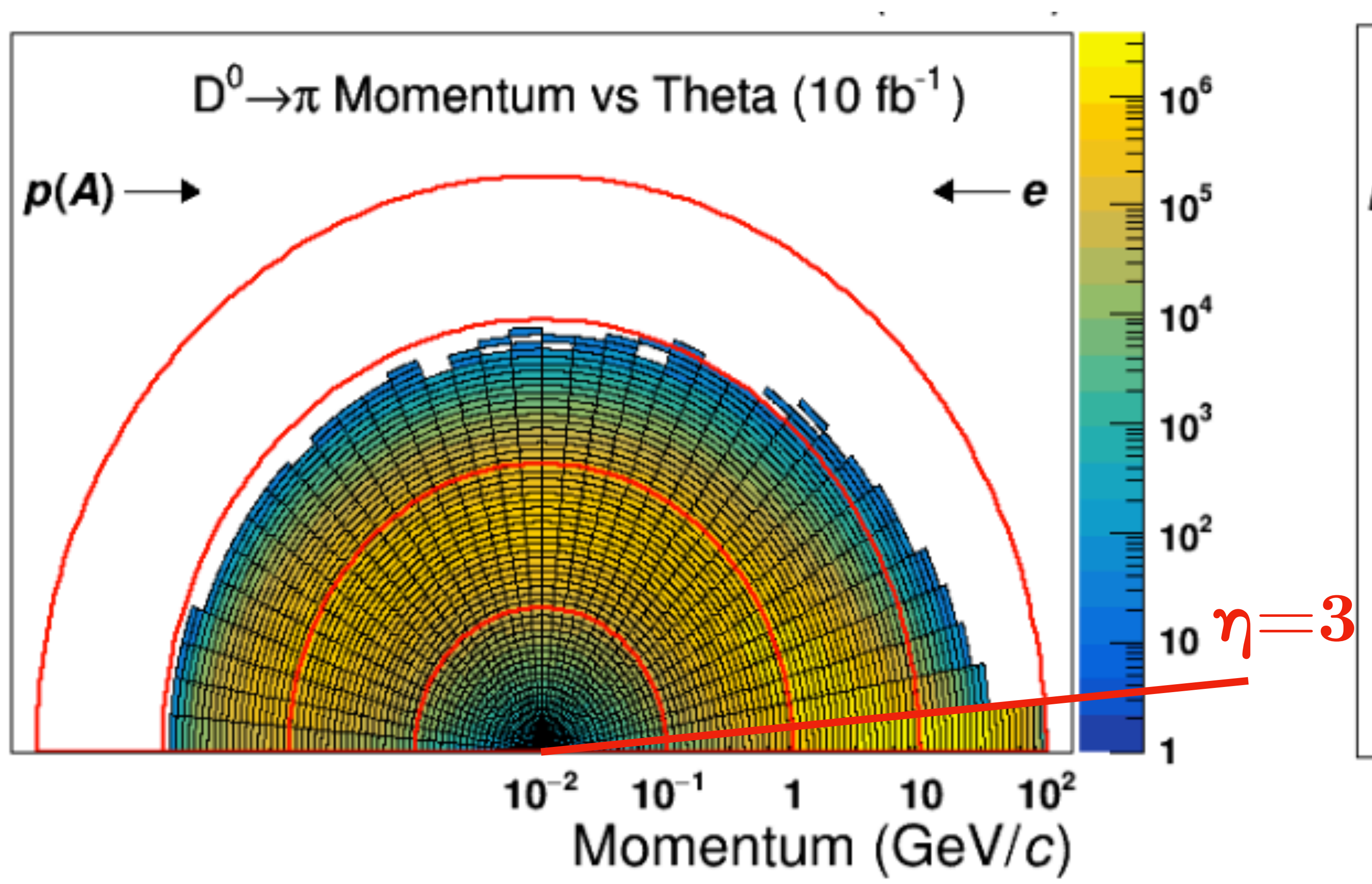
- Direct and clean access to gluonic structure in the nucleon/nuclei

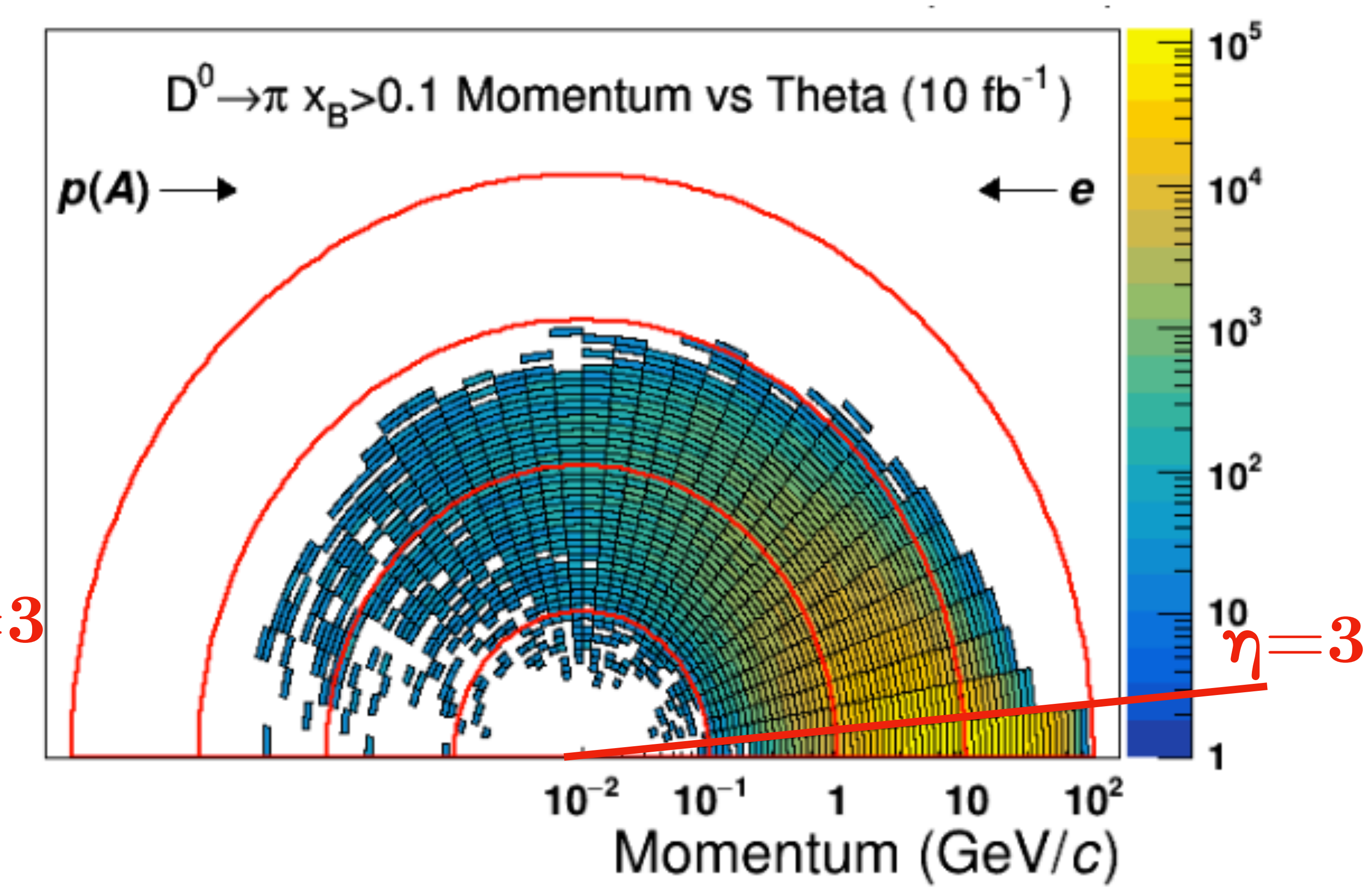
Future EIC experiments will probe both low and high partonic longitudinal momentum fraction x

- Nuclear gluon PDFs, Intrinsic charm PDFs, Gluon TMDs, ...

Simulation for Charm Studies





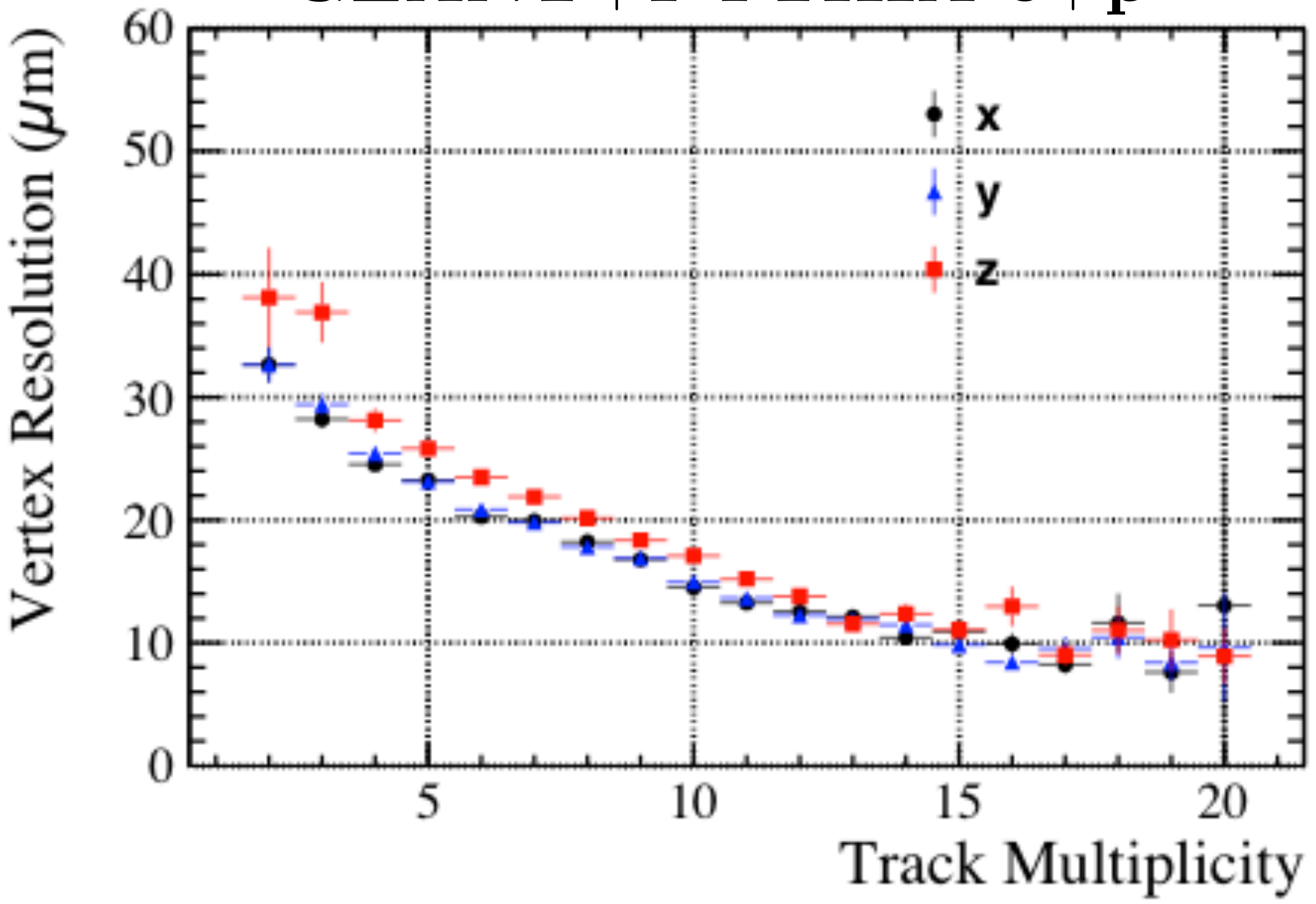


Events generated with PYTHIA 6 fast simulations

- High statistics needed for large $\mathscr{L}$ projections; $\sqrt{s}$ = 63, 29 GeV
- Guided by studies of a compact all-Si detector
- Parametrized detector response (momentum/ pointing res.+PID, $|\eta|<3$)

η	$\sigma(\mathrm{DCA}_{r\phi})$ (μm)
(-3.0,-2.5)	$60/p_T \oplus 15$
(-2.5,-2.0)	$60/p_T \oplus 15$
(-2.0,-1.0)	$40/p_T \oplus 10$
(-1.0,1.0)	$30/p_T \oplus 5$
(1.0,2.0)	$40/p_T \oplus 10$
(2.0,2.5)	$60/p_T \oplus 15$
(2.5,3.0)	$60/p_T \oplus 15$

Geant4-based simulation for primary vertex resolution study



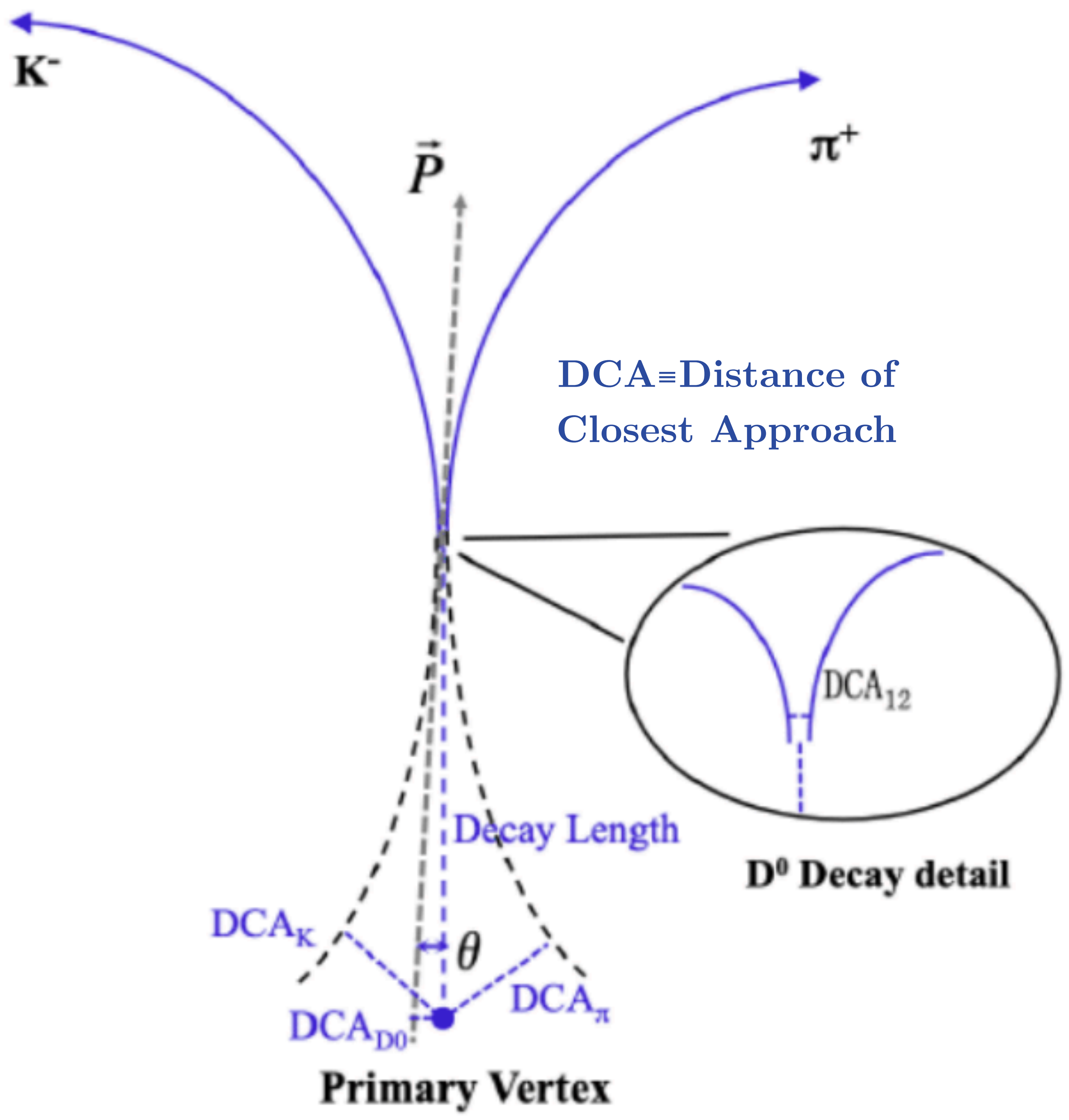
Charm Reconstruction

Projected cross sections calculated with $D^0 \rightarrow K^-\pi^+$ (+C.C) exclusive hadronic channel

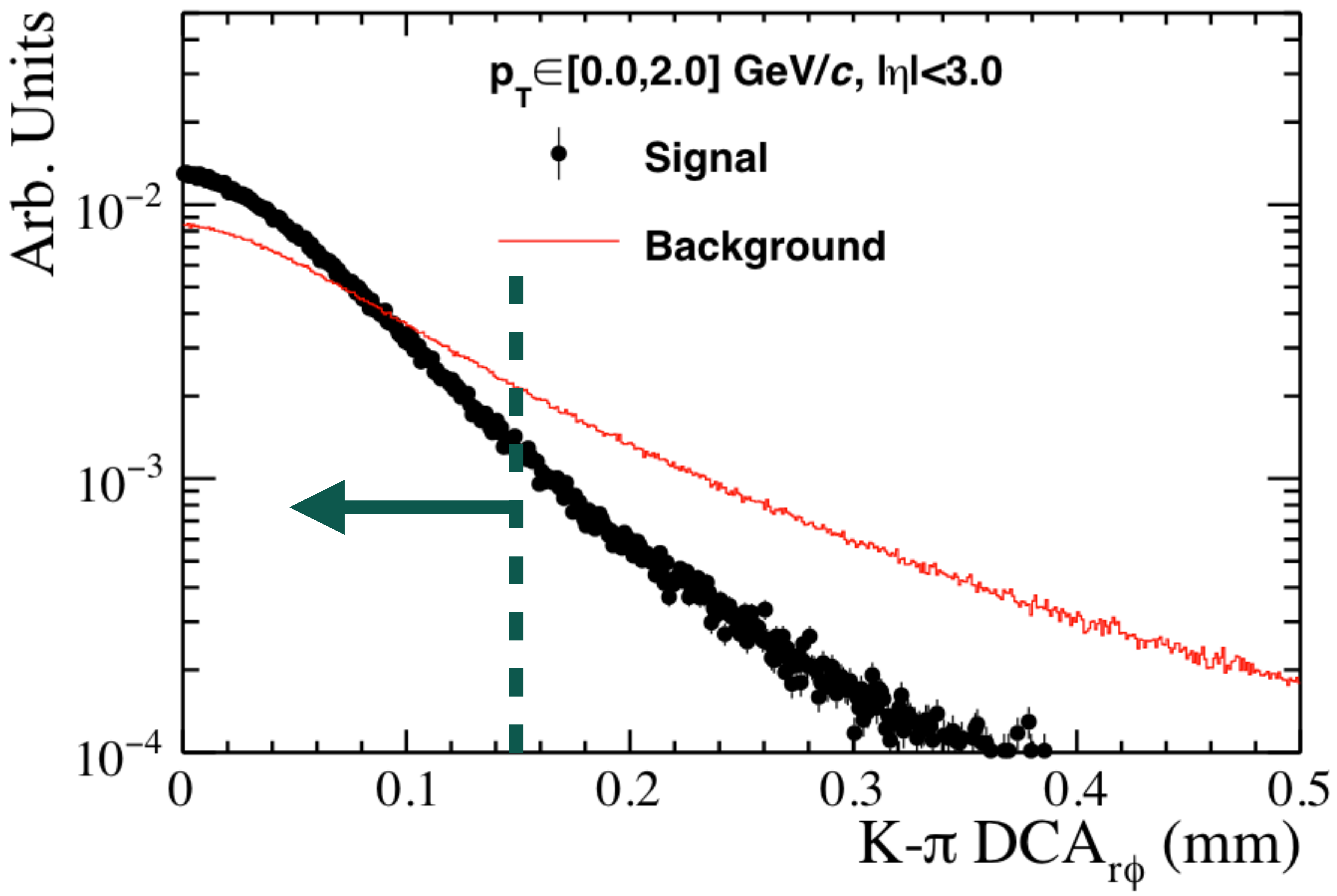
- D^0 cτ∼120 μm; $\mathscr{B}(D^0 \rightarrow K^-\pi^+) = 3.954\%$

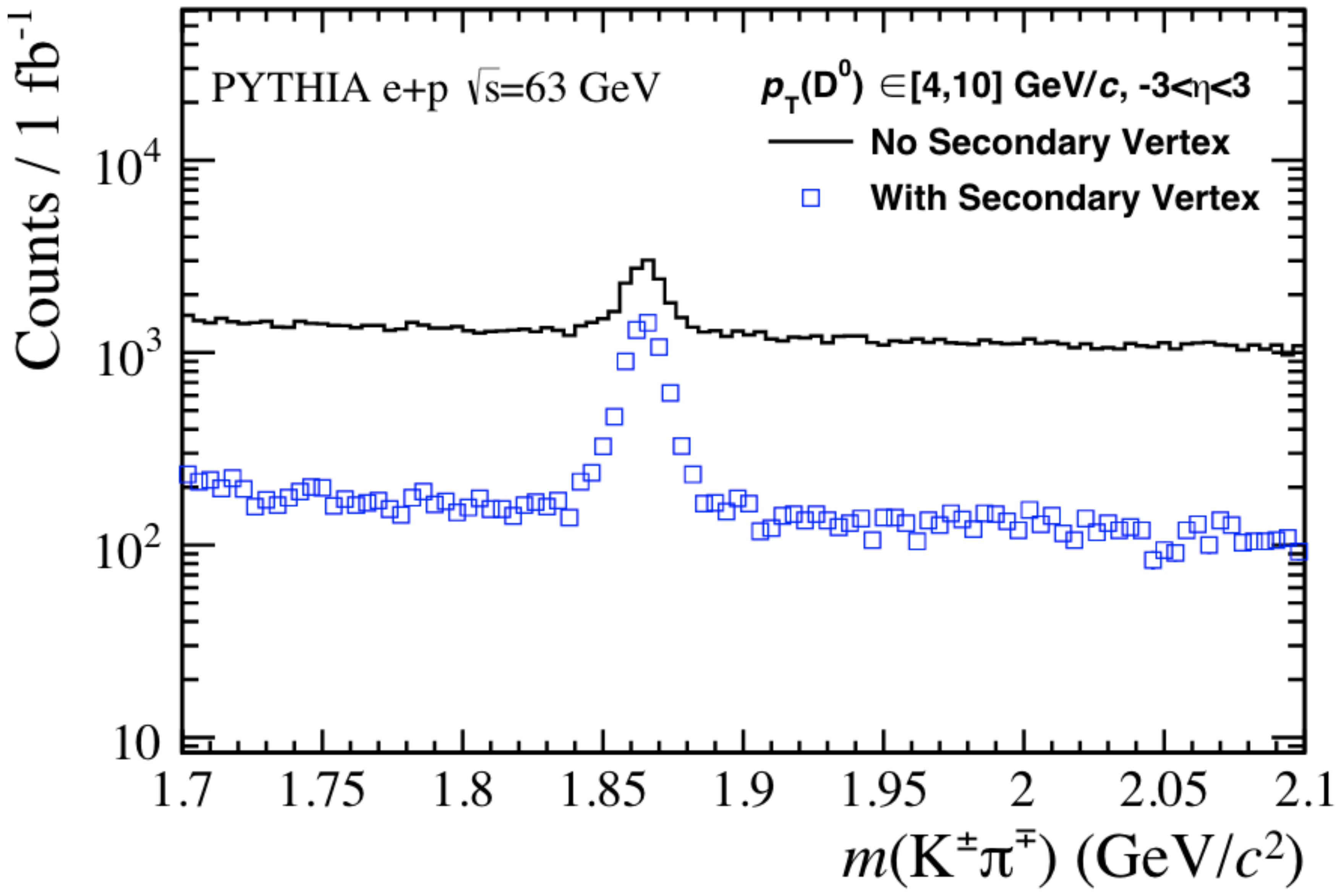
Improved S/B by identification of charm hadron decay vertex; Topological selection

- Performance driven by pointing+PV resolution



Example Topo. Distribution

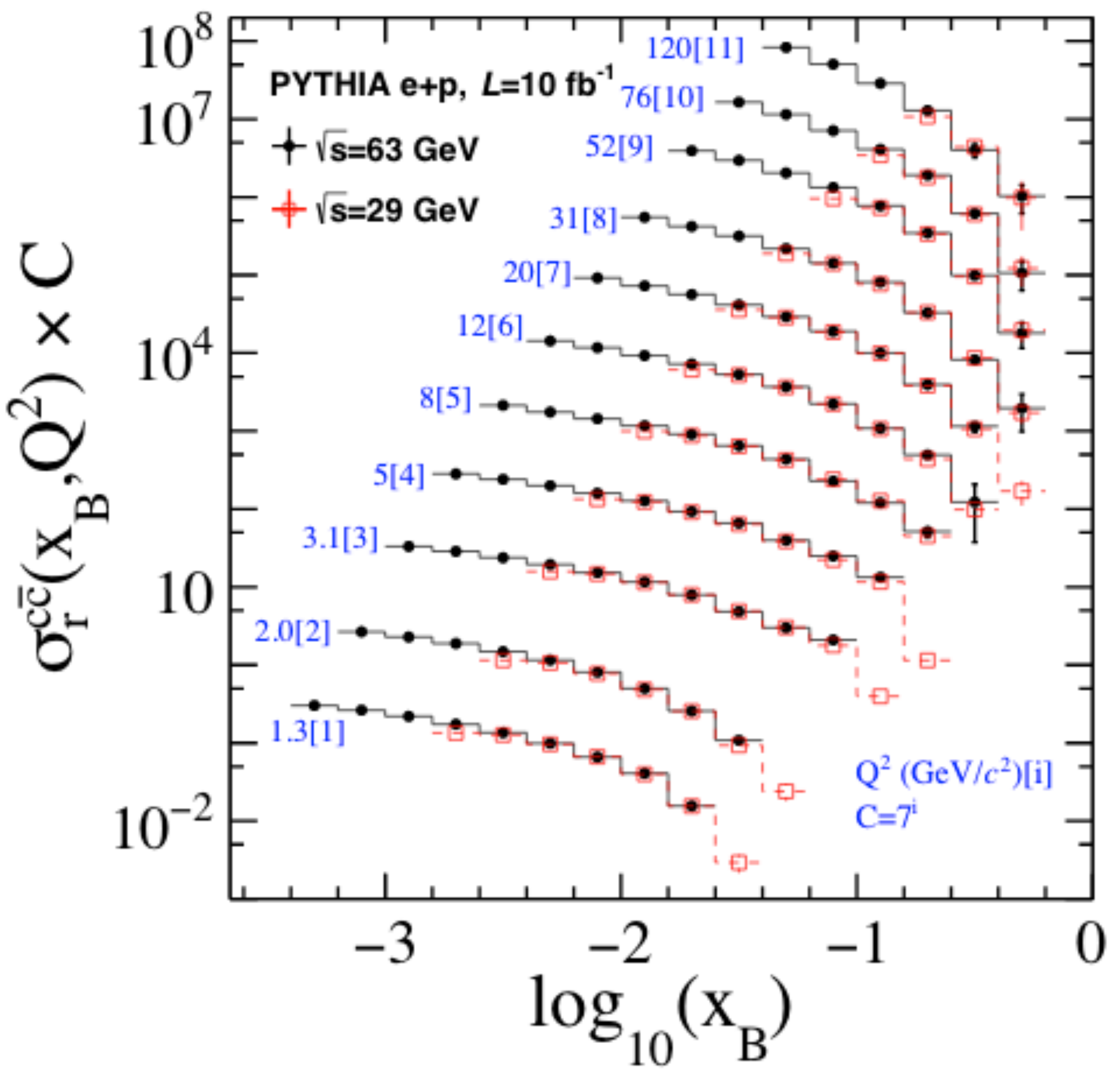


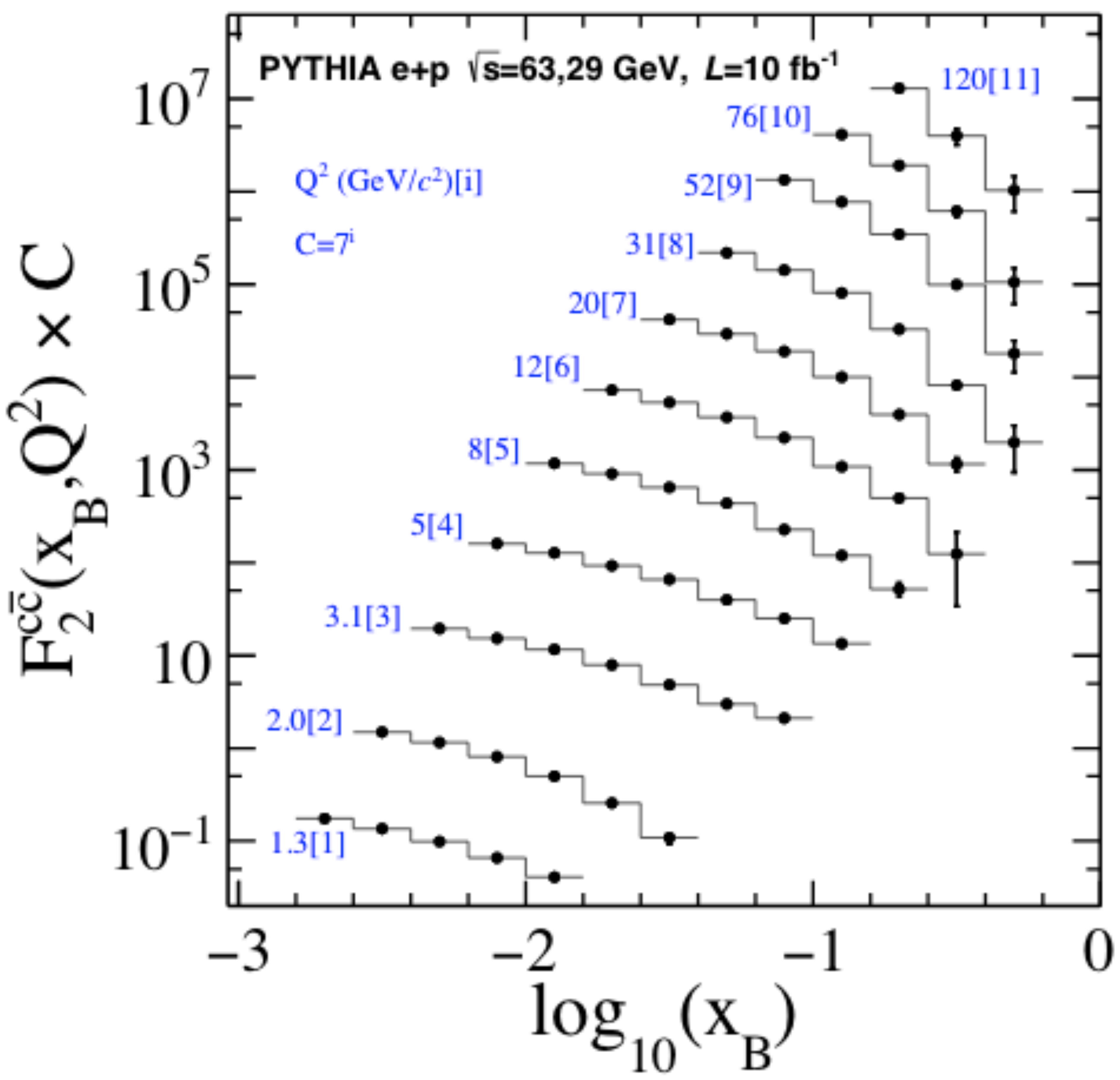


Charm Production Projections for the EIC

$$\sigma_r^{c\bar{c}}(x_B, Q^2) = \frac{dN(D^0 + \overline{D}^0)/2}{\mathcal{L}\cdot\varepsilon\cdot\mathcal{B}(D^0\to K\pi)\cdot f(c\to D^0)\cdot \mathrm{d}x_B \mathrm{d}Q^2} \times \frac{x_B Q^4}{2\pi\alpha^2[1+(1-y)^2]}$$

$$\sigma_r^{c\bar{c}}(x_B, Q^2) = F_2^{c\bar{c}}(x_B, Q^2) - \frac{y^2}{Y+} F_L^{c\bar{c}}(x_B, Q^2)$$





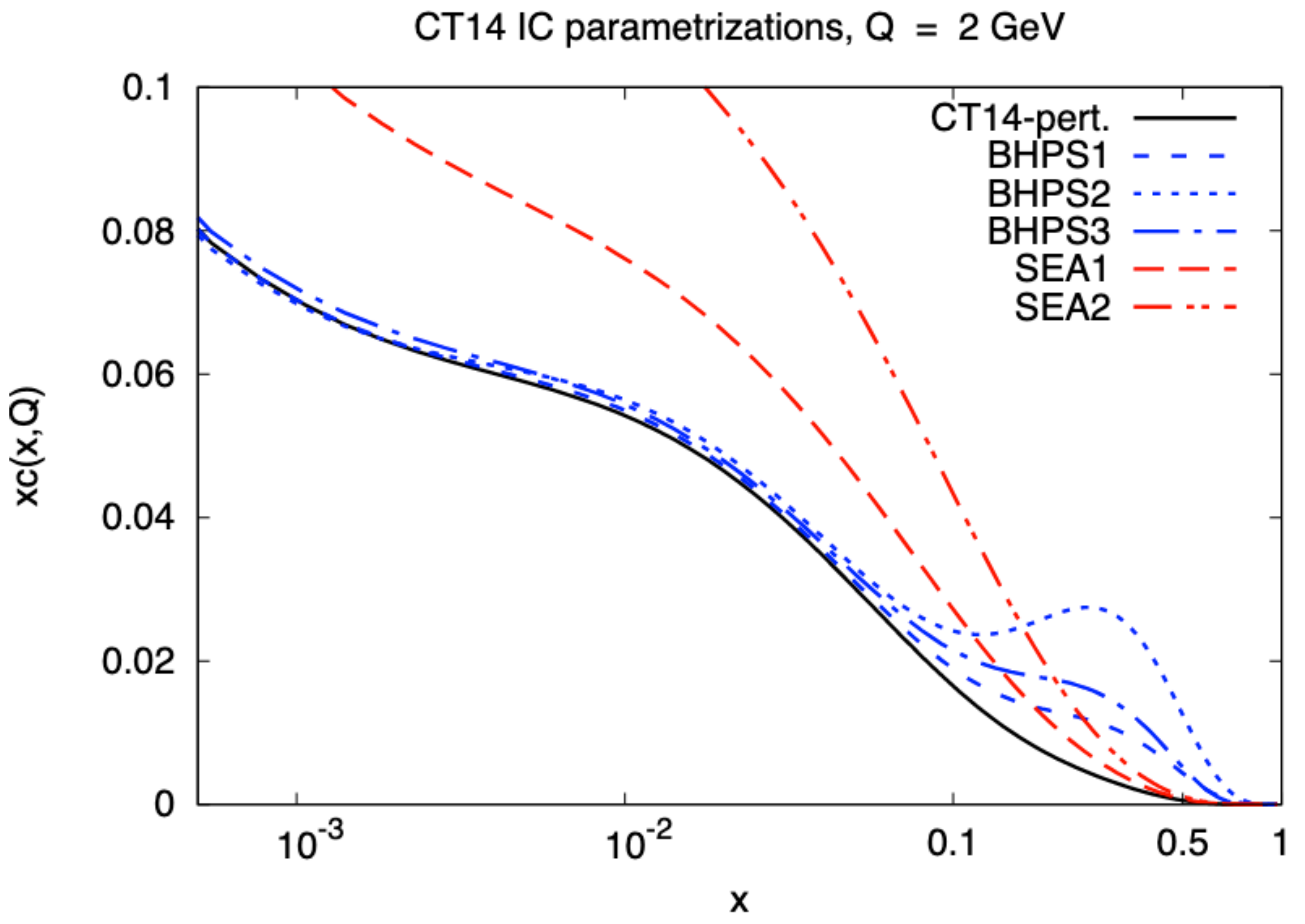
Broad and precise coverage at nominal $\mathscr{L} = 10$ fb^{-1}/energy

Effects of Intrinsic Charm PDFs

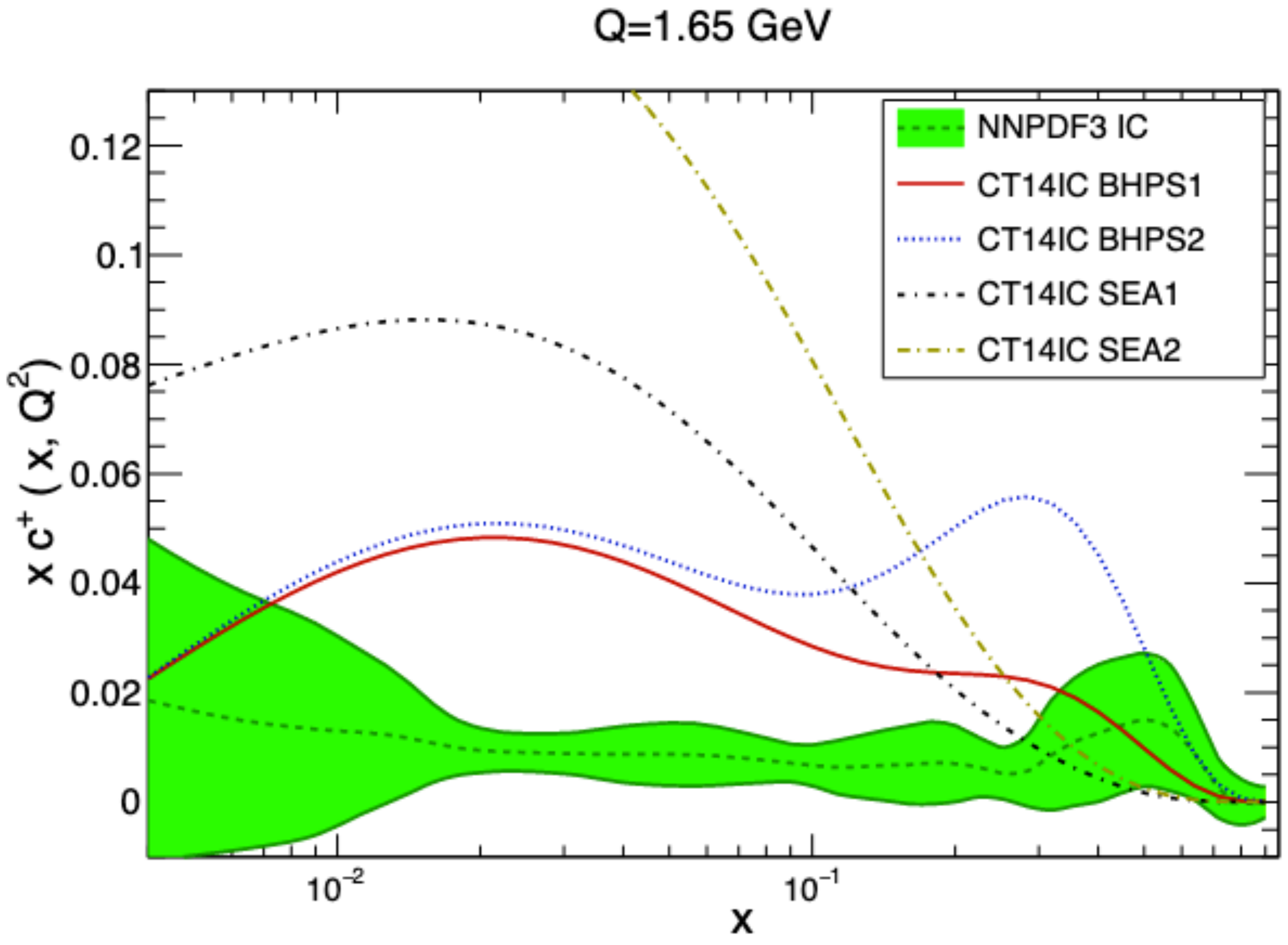
Existence of intrinsic charm (IC) quarks still an open question

- Non-perturbative $|uudc\bar{c}\rangle$ Fock state of the proton wave function

Several models on the market; Most analyses find a IC at high parton-x region due to charm quark mass



T. Hou et al. JHEP 2018, 59 (2018)

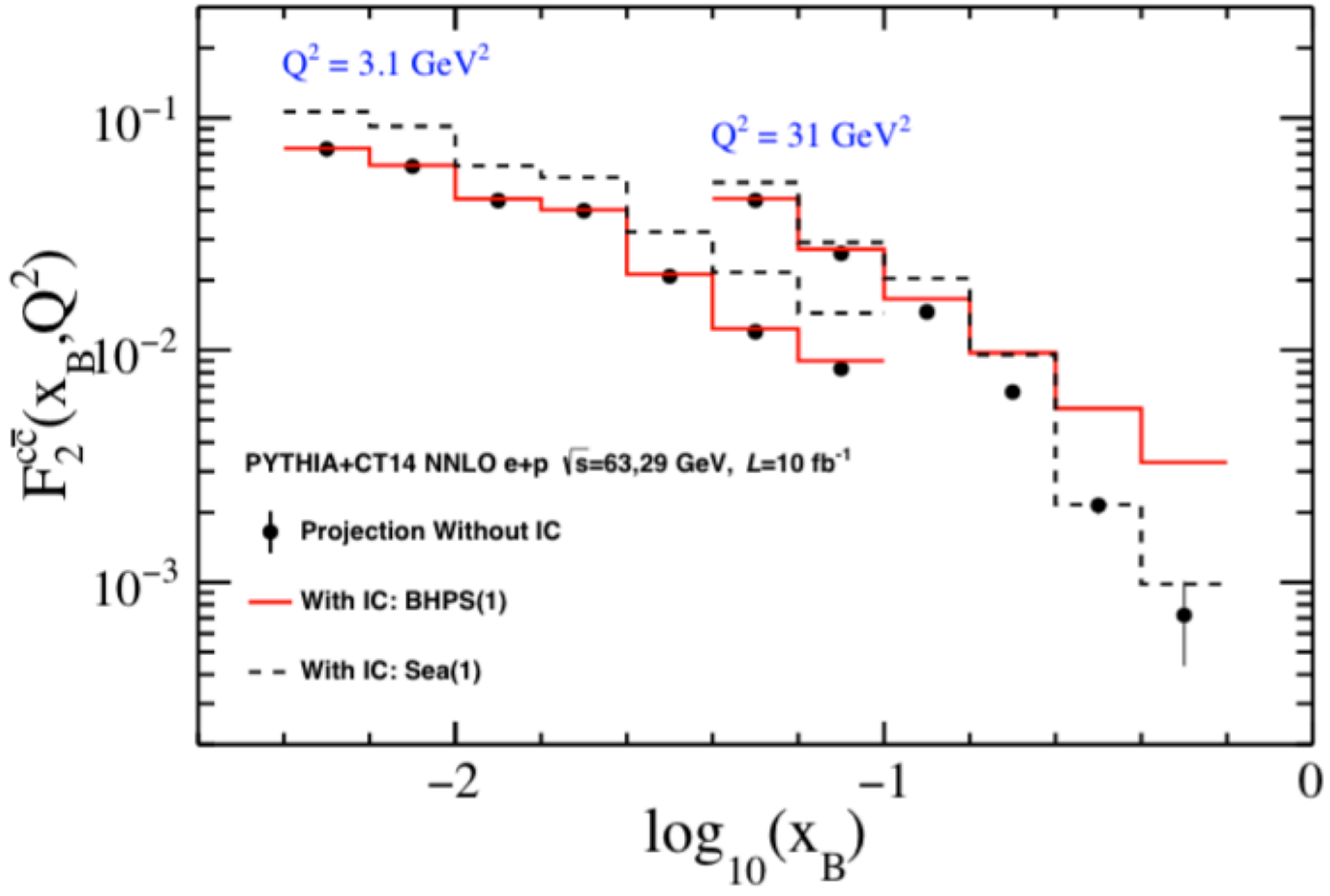


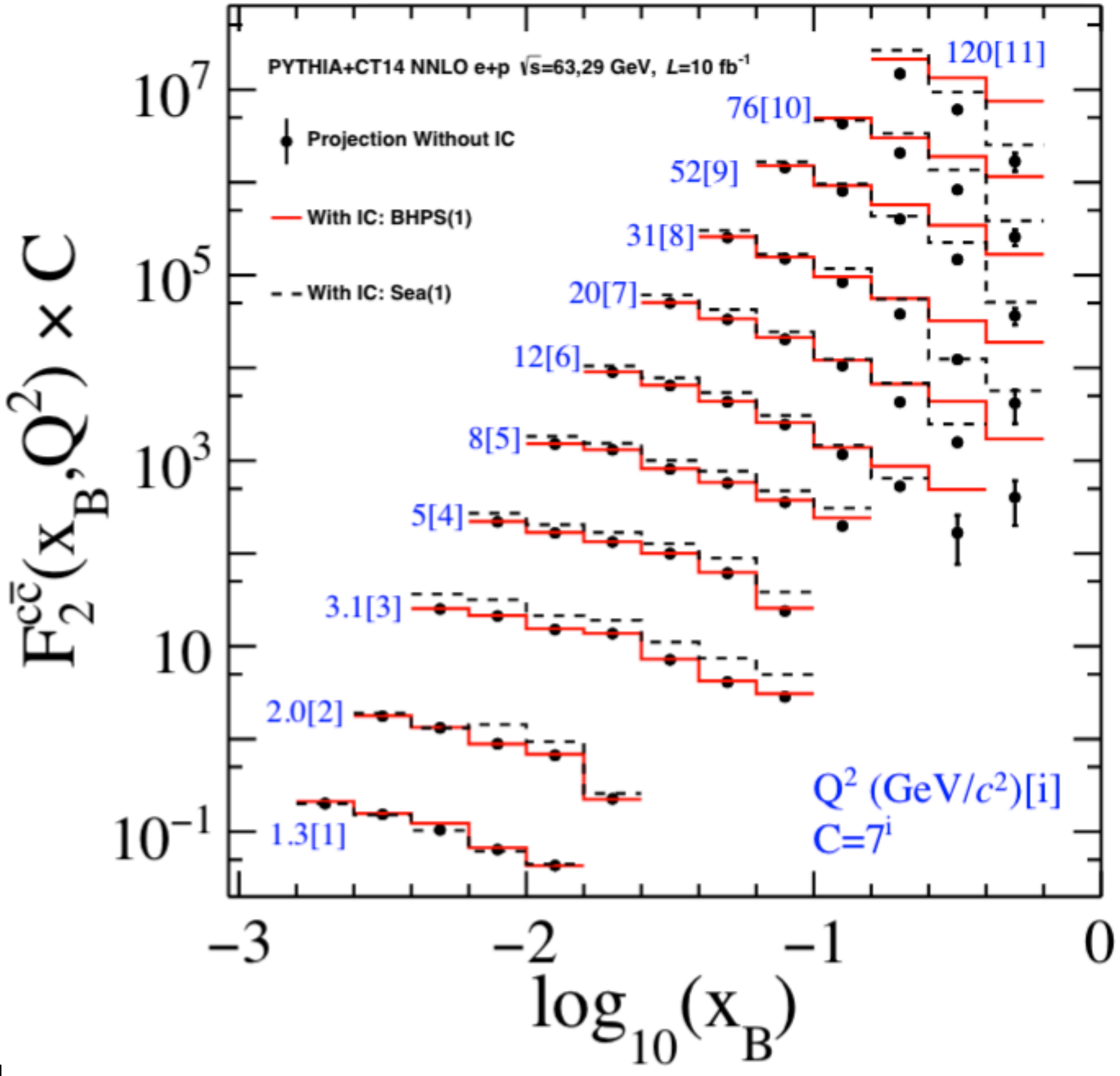
NNPDF collaboration *Eur. Phys. J.C* 76 (2016) 11, 647
Fitted Charm Method

Effects of Intrinsic Charm PDFs

Significant difference between projected data using CT14 PDFs with and without IC*

Precise EIC data will distinguish models

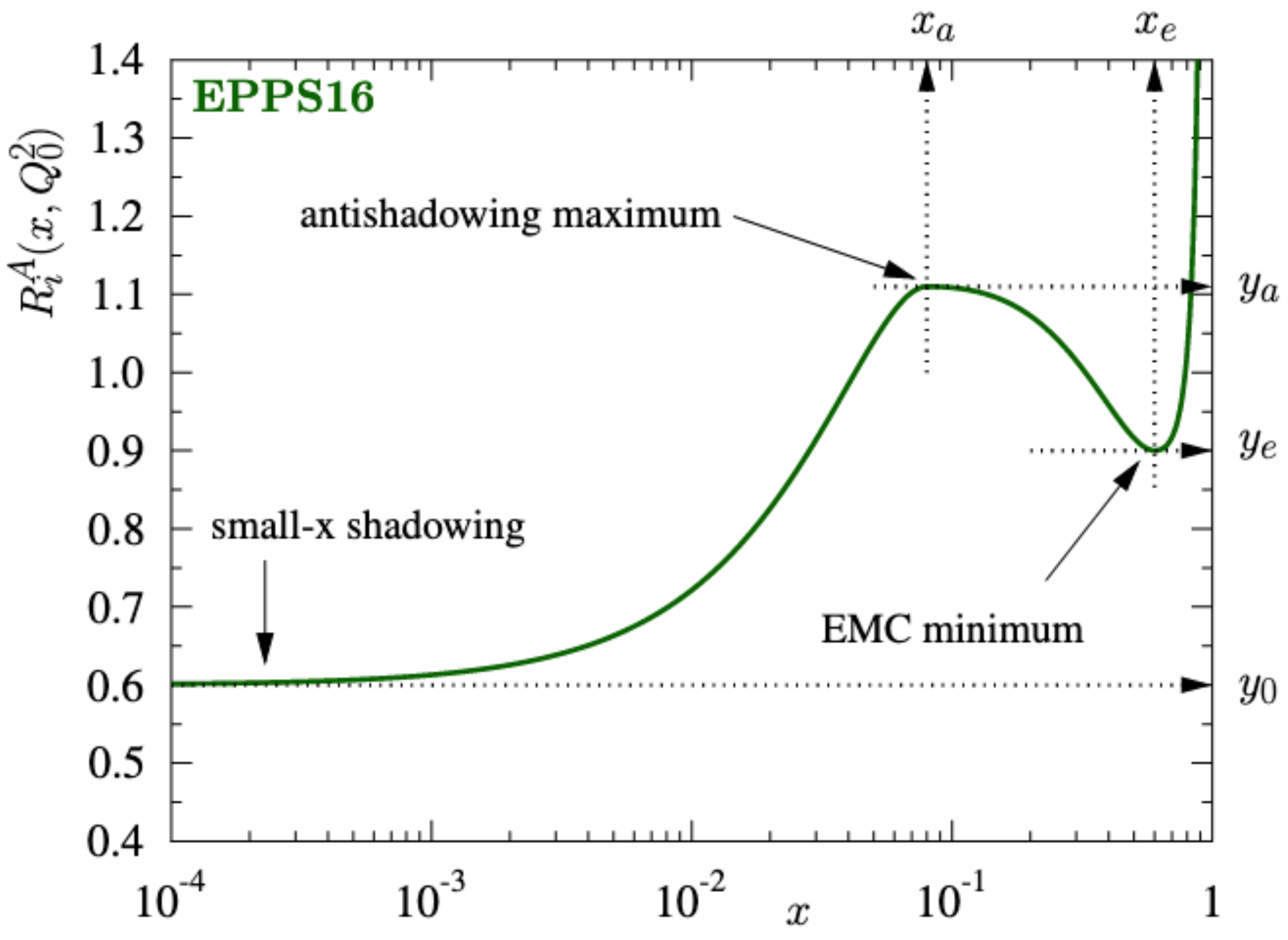


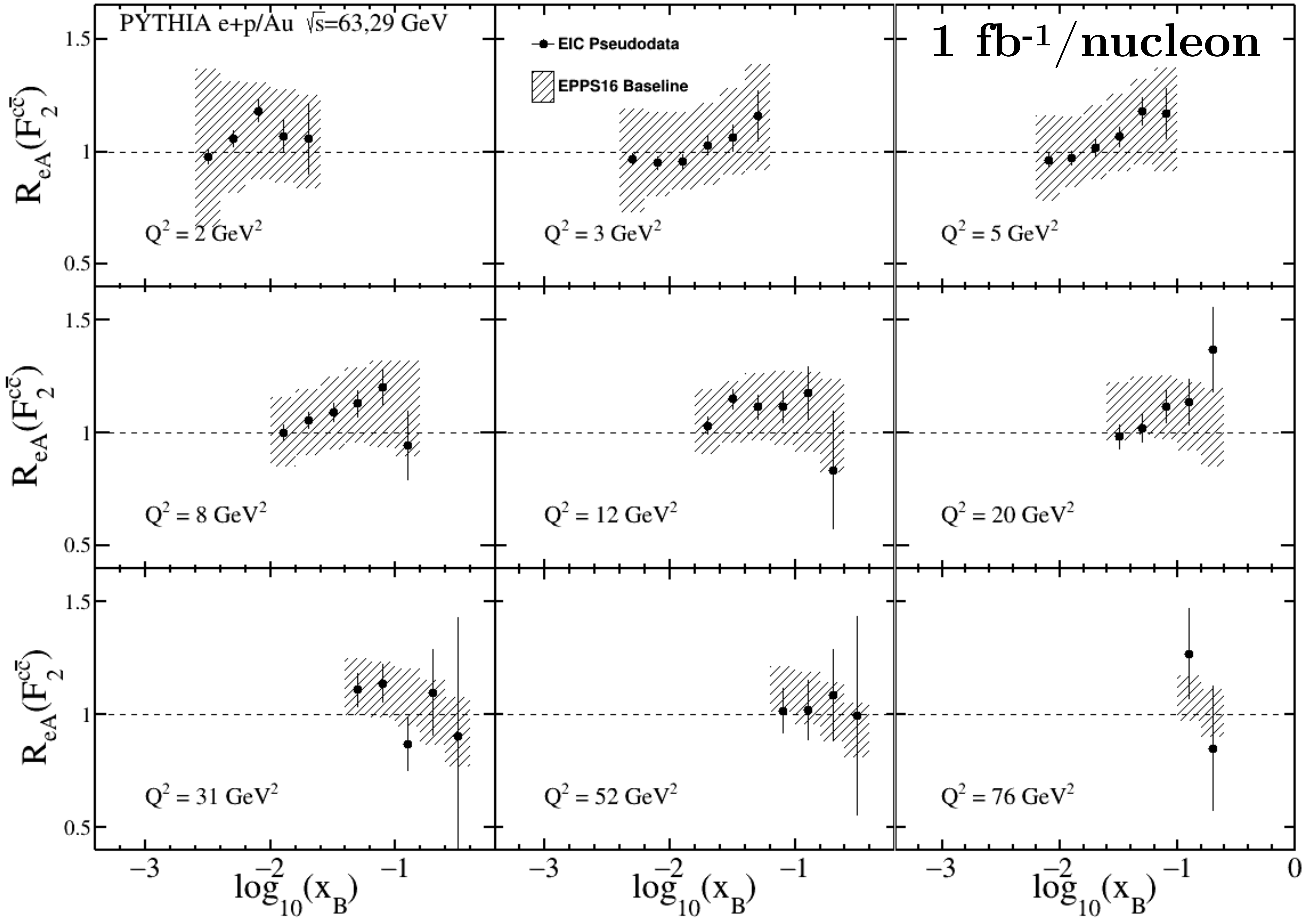


*NNPDF3 IC PDF produces qualitatively similar projections as BHPS1

Nuclear Gluon PDFs

K.J. Eskola et al. Eur. Phys. J. C 77, 163 (2017)





Nuclear modification in PYTHIA analysis via nuclear PDFs for Au nuclei*

Pseudo-data ($F_2^{c\bar{c}}$ ratios) generated by displacing projections randomly by statistical errors

*EPPS16 (Eur. Phys. J. C 77, 163 (2017)), nCTEQ15 (PRD 93, 085037), and nNNPDF2.0 (JHEP 2020, 183 (2020))nPDFs

Bayesian PDF Re-weighting

Impact on gluon nPDF studied with a Bayesian PDF re-weighting procedure*

- Bayes theorem: $\mathcal{P}_{\text{new}}(f) \propto \mathcal{P}(\vec{y}|f)\,\mathcal{P}_{\text{old}}(f)$

Generate a large sample of nPDF replicas**

$$f_k = f_0 + \sum_i \left(\frac{f_{i,+} + f_{i,-}}{2}\right) r_{k,i}$$

Calculate weights w_k of each replica according to χ^2 with respect to pseudo-data

→ Re-weight eigen PDFs

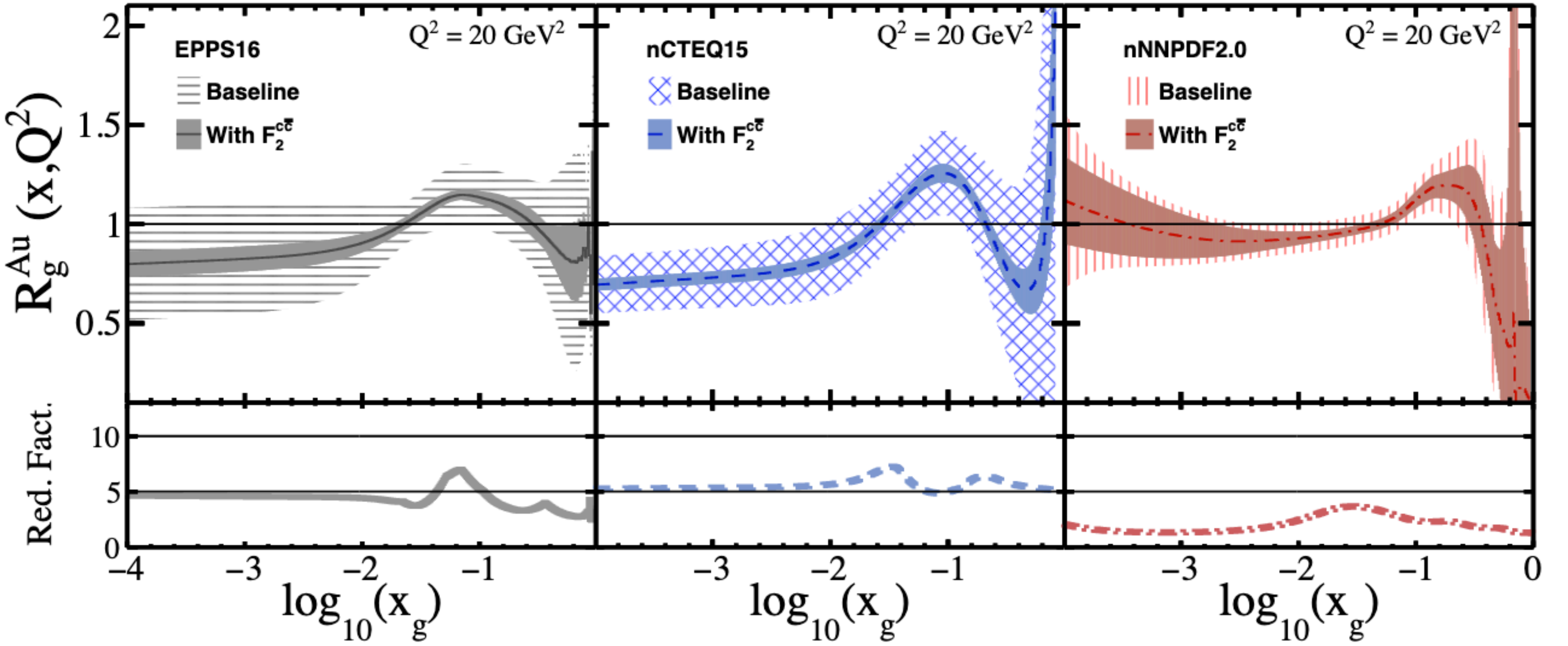
$$w_k = \frac{exp[-\chi_k^2/2]}{\frac{1}{N_{rep}}\sum_k exp[-\chi_k^2/2]} \qquad f_{new} = f_0 + \sum_i \left(\frac{f_{i,+} + f_{i,-}}{2}\right)\left[\frac{1}{N_{rep}}\sum_k w_k r_{k,i}\right]$$

*H. Paukkunen and P. Zurita JHEP 2014, 100 (2014)

**This is done for the Hessian PDFs; For NNPDF we use provided MC replicas and "chi2" weights

Impact on Gluon nPDF

Similar trends across all scales



Significant reduction to input gluon nPDF uncertainties

- Particularly at high-x (>0.1) where inclusive measurements provide less constraint
- Qualitatively similar across various input nPDFs used

Qualitatively similar impact as in previous EIC studies*, but with full detector effects implemented

*E. C. Aschenauer et al. Phys. Rev. D 96, 114005

Conclusions

Precise measurements of charm hadrons via exclusive decay channels will be possible with an all-Si vertex detector at future EIC experiments

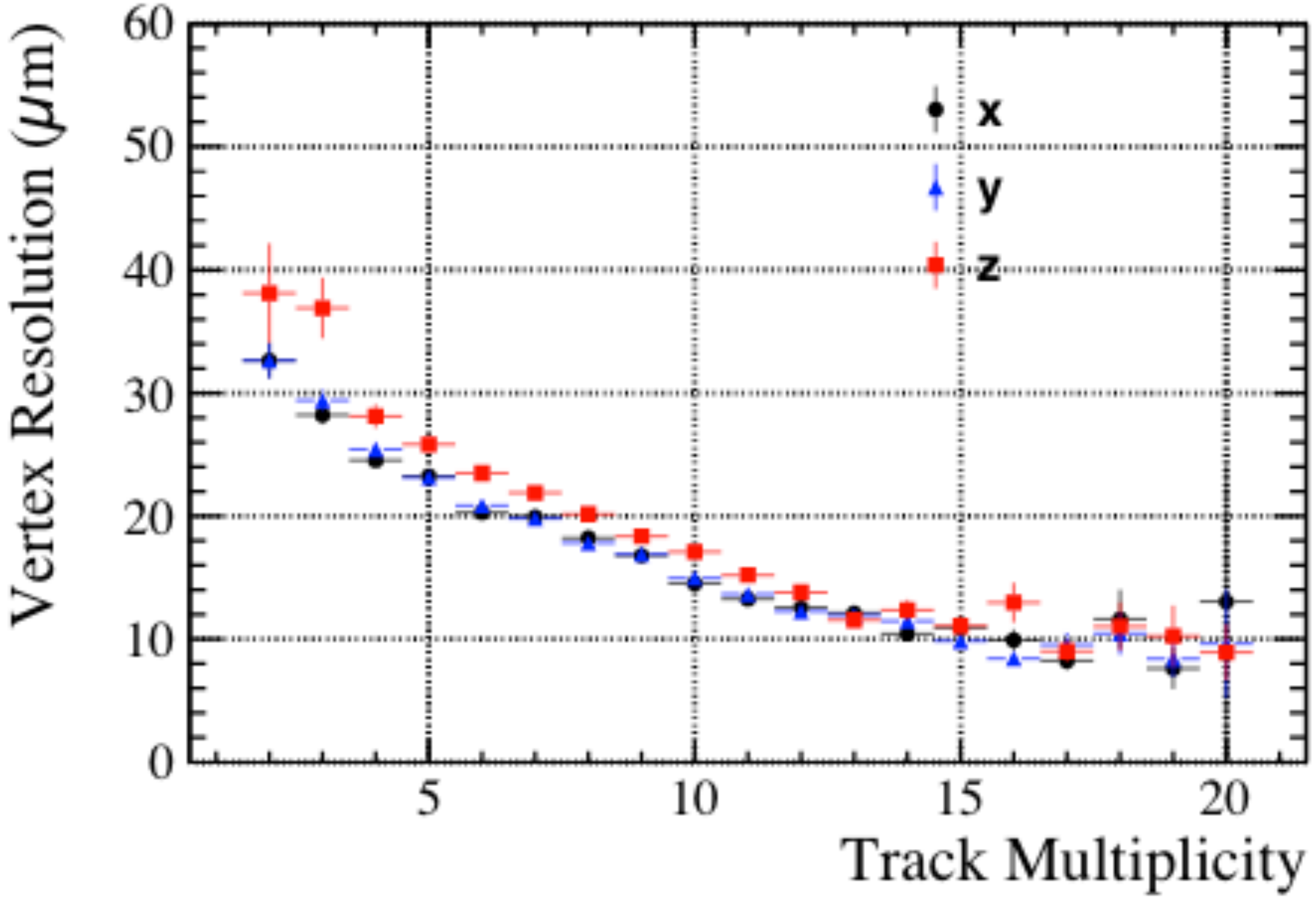
The projected charm structure functions $F_2^{c\bar{c}}$ in e+p/Au collisions will span a broad kinematic reach in Q^2 and x

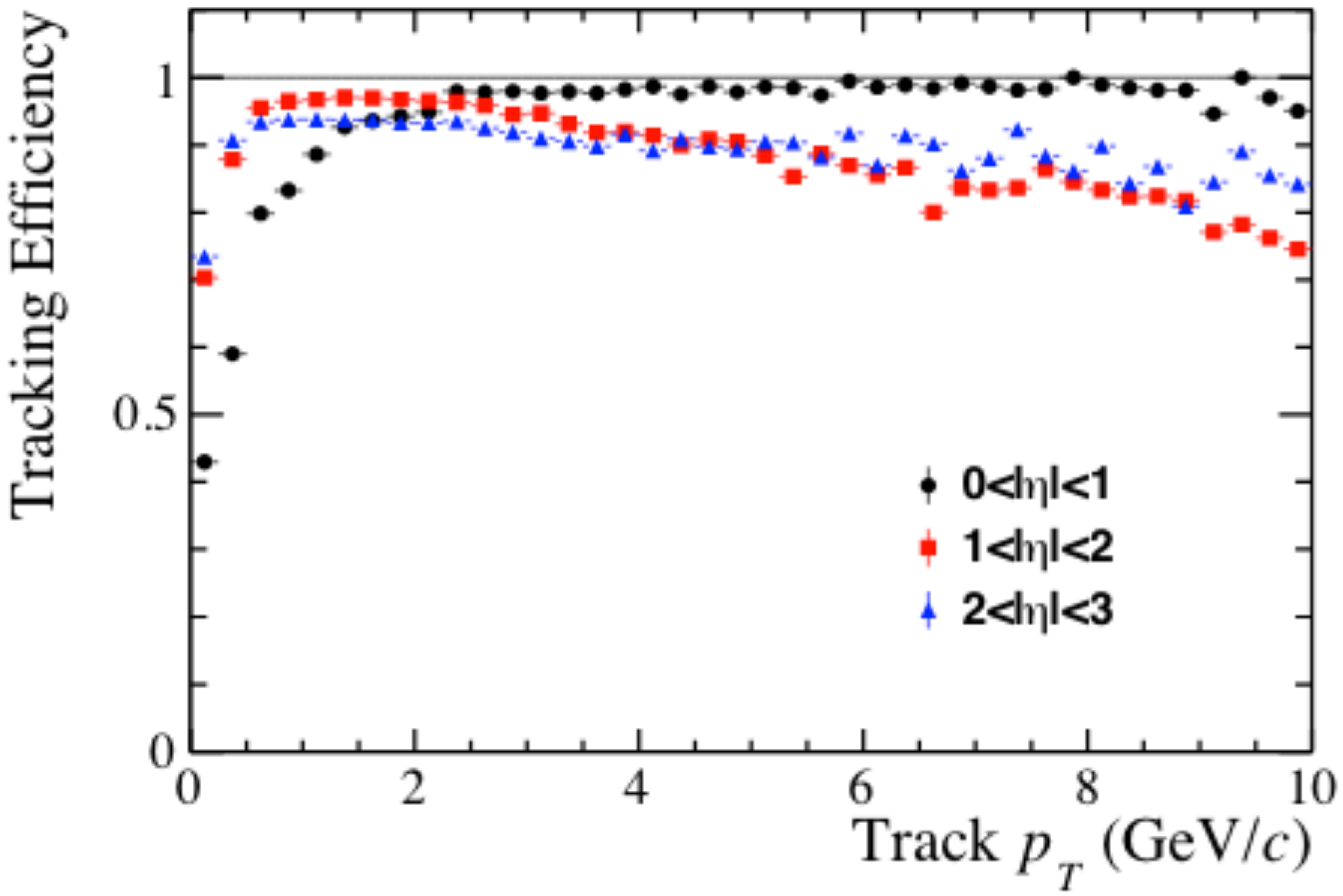
→Data will be extremely sensitive to IC and can distinguish various models

→Will provide significant constraint to the gluon nPDFs

BACKUP SLIDES FOLLOW

GEANT4-Based Simulations

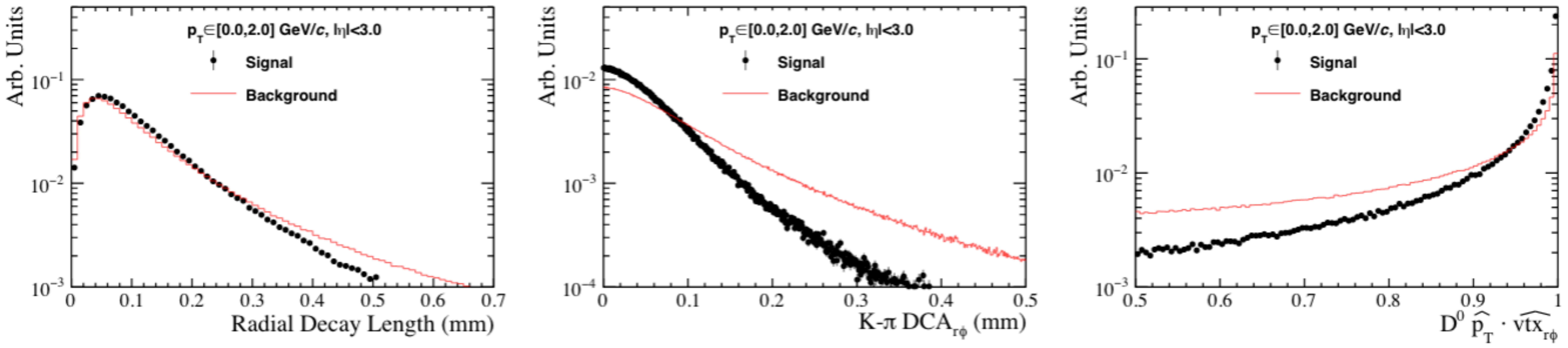




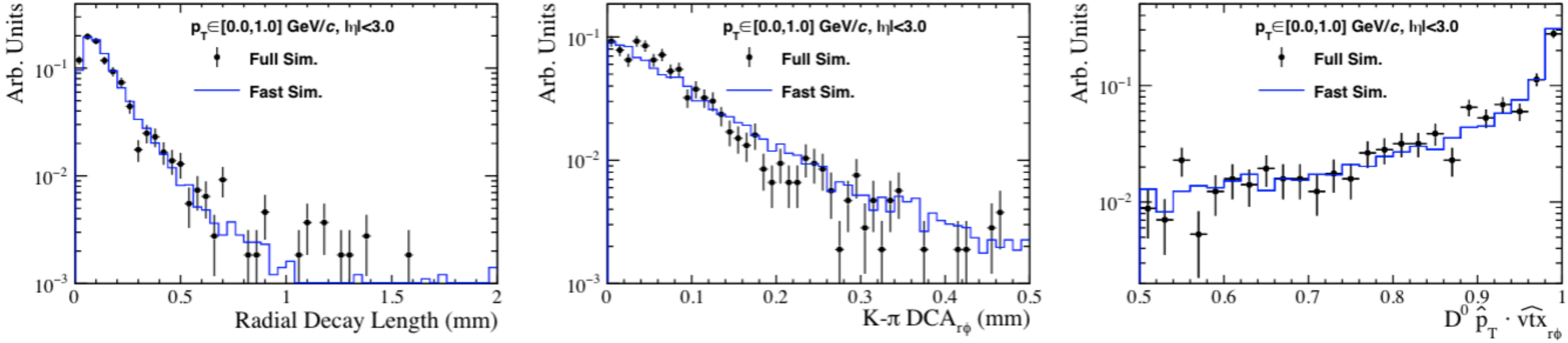
Fast Simulation Parameters

η	σ_p/p - 3.0 T (%)	(%)	$\sigma(\mathrm{DCA}_{r\phi})$ (μm)	$p_{\mathrm{max}}^{\mathrm{PID}}$ (GeV/c)
(-3.0,-2.5)	$0.1 \cdot p \oplus 2.0$		$60/p_T \oplus 15$	10
(-2.5,-2.0)	$0.02 \cdot p \oplus 1.0$		$60/p_T \oplus 15$	10
(-2.0,-1.0)	$0.02 \cdot p \oplus 1.0$		$40/p_T \oplus 10$	10
(-1.0,1.0)	$0.02 \cdot p \oplus 0.5$		$30/p_T \oplus 5$	6
(1.0,2.0)	$0.02 \cdot p \oplus 1.0$		$40/p_T \oplus 10$	50
(2.0,2.5)	$0.02 \cdot p \oplus 1.0$		$60/p_T \oplus 15$	50
(2.5,3.0)	$0.1 \cdot p \oplus 2.0$		$60/p_T \oplus 15$	50

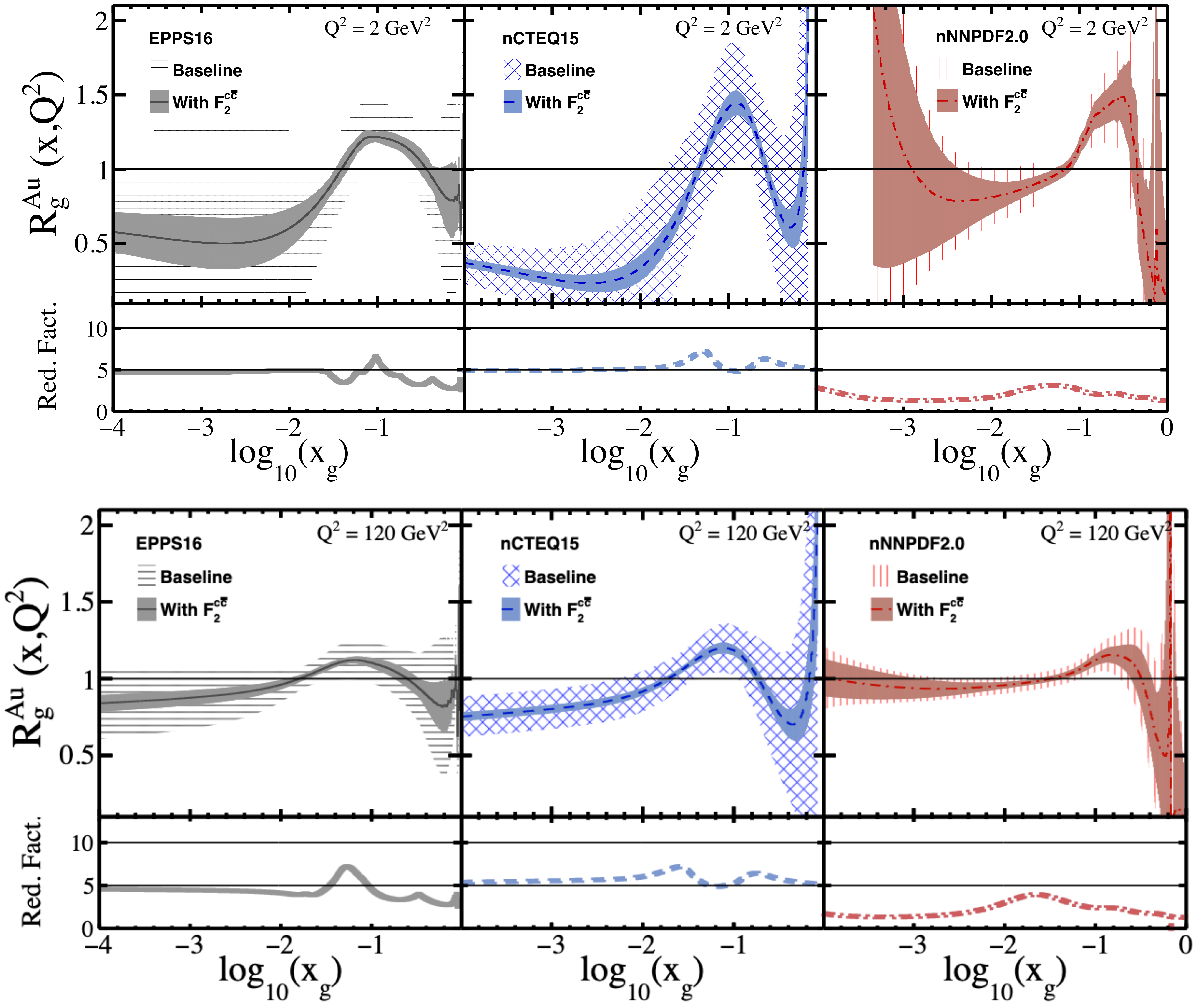
$D^0 \rightarrow K\pi$ Topological Variables



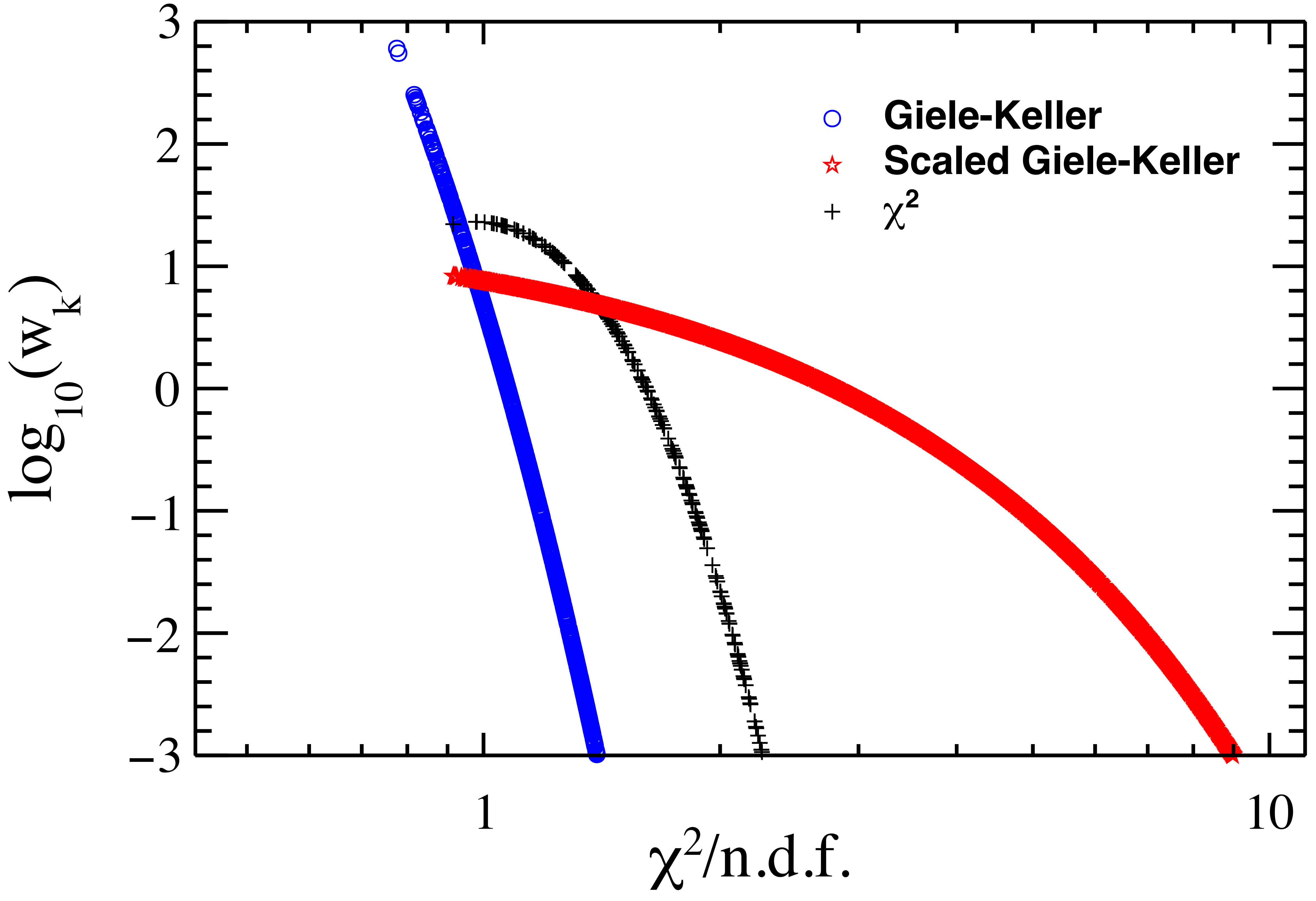
Fast Simulation Validation

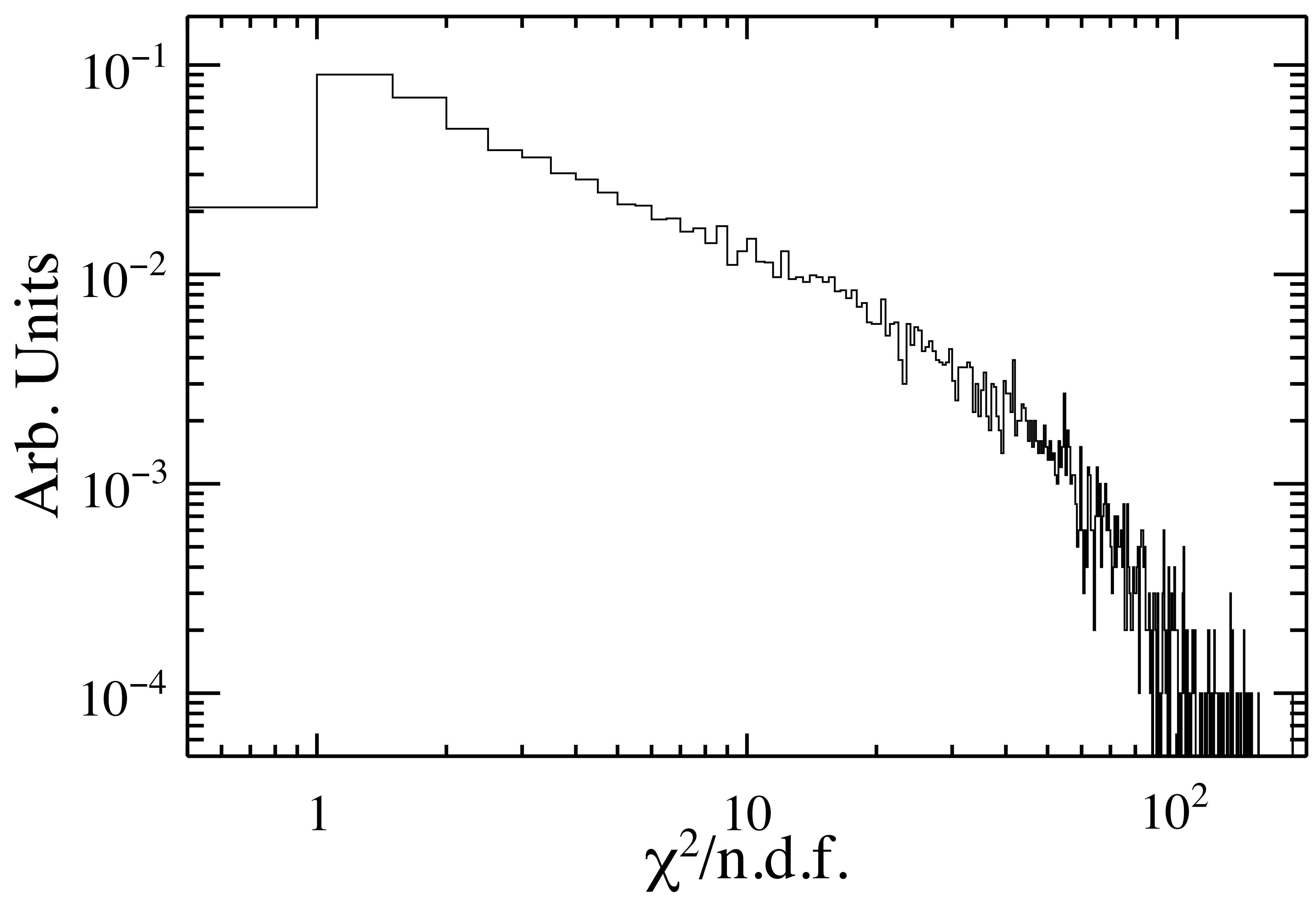


Impact on Gluon nPDF



EPPS16 Replica Distributions





Impact on Gluon nPDF