Overview of the QCD landscape

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PBC Annual Workshop
CERN, 21-22 November 2017

Goals of this talk

- Preparation of the QCD context document for the PBC deliverables
  - ★ sketch the envisaged structure and types of performance plots/measures

  this is a proposal, please give us feedback

- Sketch the different proposals in this context
  → details in the talks to come

- Point out critical issues, as we see them now
  please consider us as friendly critics/critical friends

Aim: make proposals as attractive as possible

QCD context document: general structure

- introduction: present physics areas and experimental proposals
- individual sections on the physics topics
  - ★ physics motivation/theory background
  - ★ worldwide context: existing and possible future experiments
  - ★ experimental proposal(s) within PBC study
    - ✦ brief presentation, unique features
    - ✦ key requirements for detector, beam
      necessary construction, beam time, timeline
  - ★ critical issue: expected physics gain vs required resources
    - ✦ performance plots, comparison with worldwide competition
    - ✦ open questions, planned feasibility studies
- overall summary

rest of this talk follows the overall structure just outlined

with open questions instead of final results
rough instead of polished
order of individual sections may change

note on the physics topics:

we aim to focus on the main issues
please let us know if we forgot any

Introduction: physics and proposals

	ALICE	LHCb	AFTER	COMPASS	MUonE	DIRAC++	NA60++	NA61++	crystals
unpolarised proton structure	x	x	x						
structure of nuclei	x	x	x						
polarised proton structure	x	x	x	x					
meson structure (K and π)				x					
heavy ion physics	x	x	x				x	x	
elastic μe or μp scattering				x	x				
spectroscopy, magn. moments				x					x
chiral dynamics				x		x			
measurements for cosmic rays		x		x				x	

"**x**" means "under study", feasibility to be confirmed

please let us know if we forgot anything

Structure of hadrons and nuclei

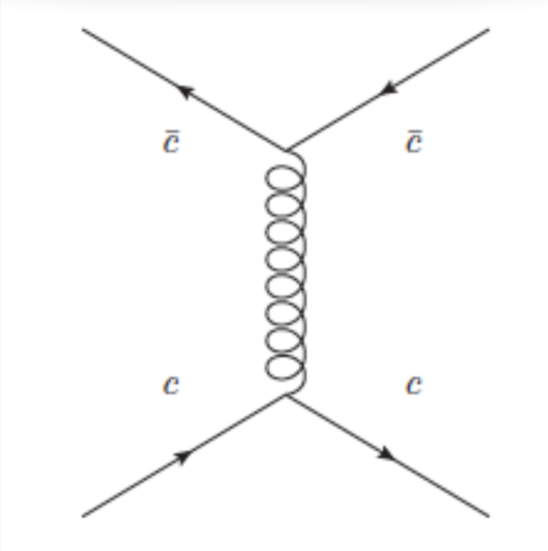
unpolarised proton structure (1)

- LHC fixed target studies: ALICE, LHCb, AFTER
- main topic: parton densities (PDFs) at large x, especially gluon and charm distributions
  - ★ very important for LHC programme: parton luminosities for producing very heavy particles
  - ★ of interest on its own, intrinsic charm
  - ★ crosslinks to cosmic-ray physics (atmospheric neutrino flux)
- main competition: LHC collider measurements; JLab (11 GeV on fixed target) can reach large x but at much lower Q^2: complementary
- main processes at LHC fixed target: charm production, Drell-Yan
- typical comparison and performance plots: PDFs with uncertainty bands (current and projected); plots of Xsections with uncertainties; kinematic x-Q^2 plane coverage (need a way to also fold in info on rates)

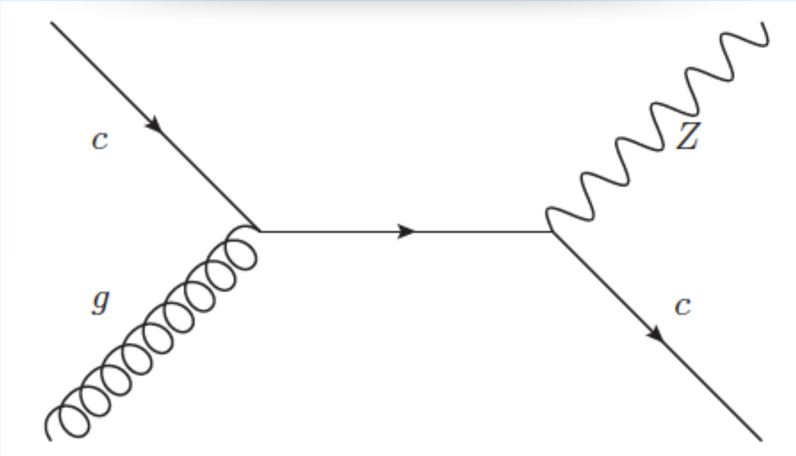
The charm PDF: implications for the LHC

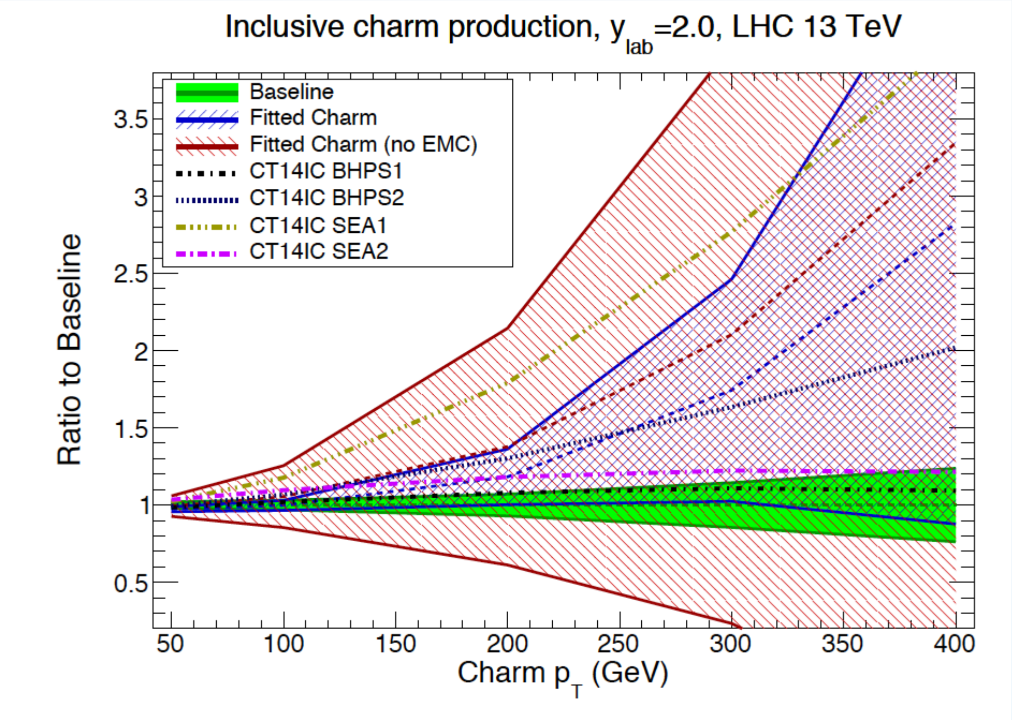
- A number of LHC processes are sensitive to the **charm content of the proton**
- Typically to probe **large-x charm** we need either **large pT** or **forward rapidities** production
- Within the **reach of the LHC** at Run II

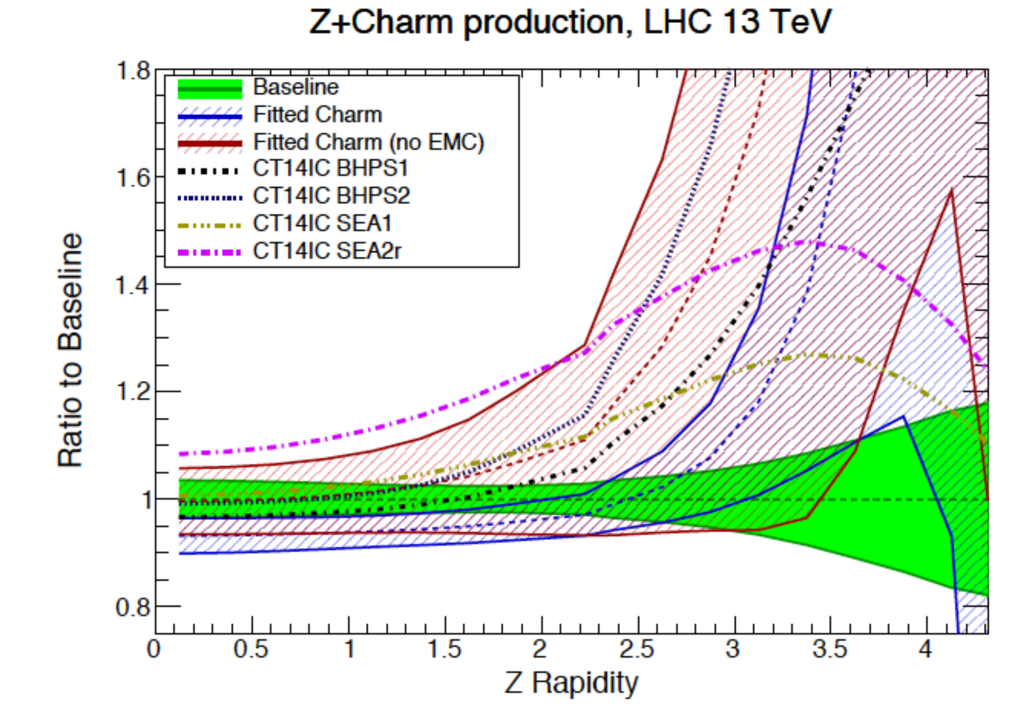
D meson production



Z+charm production



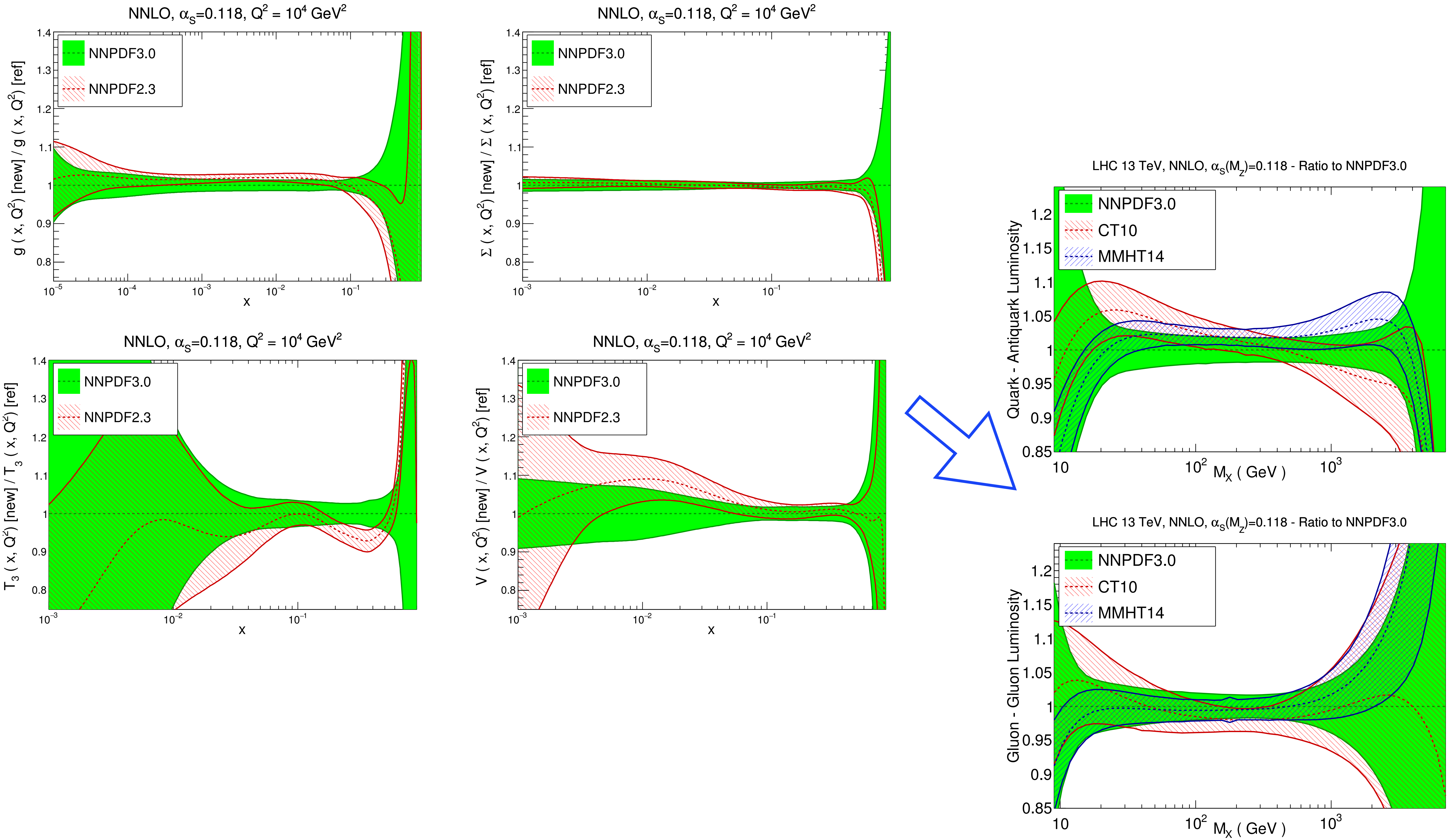




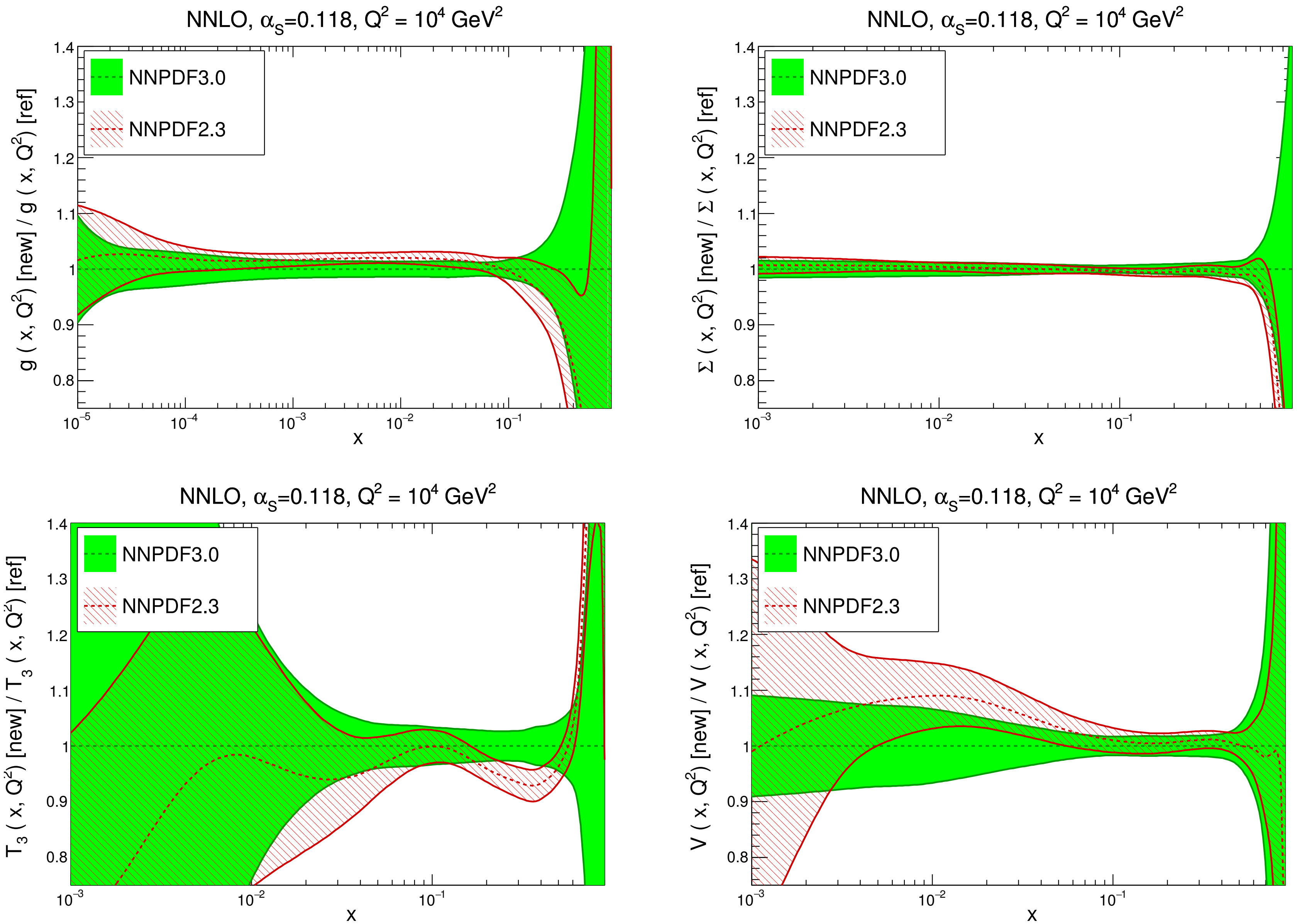
J. Rojo @ QCD-N'16

Juan Rojo

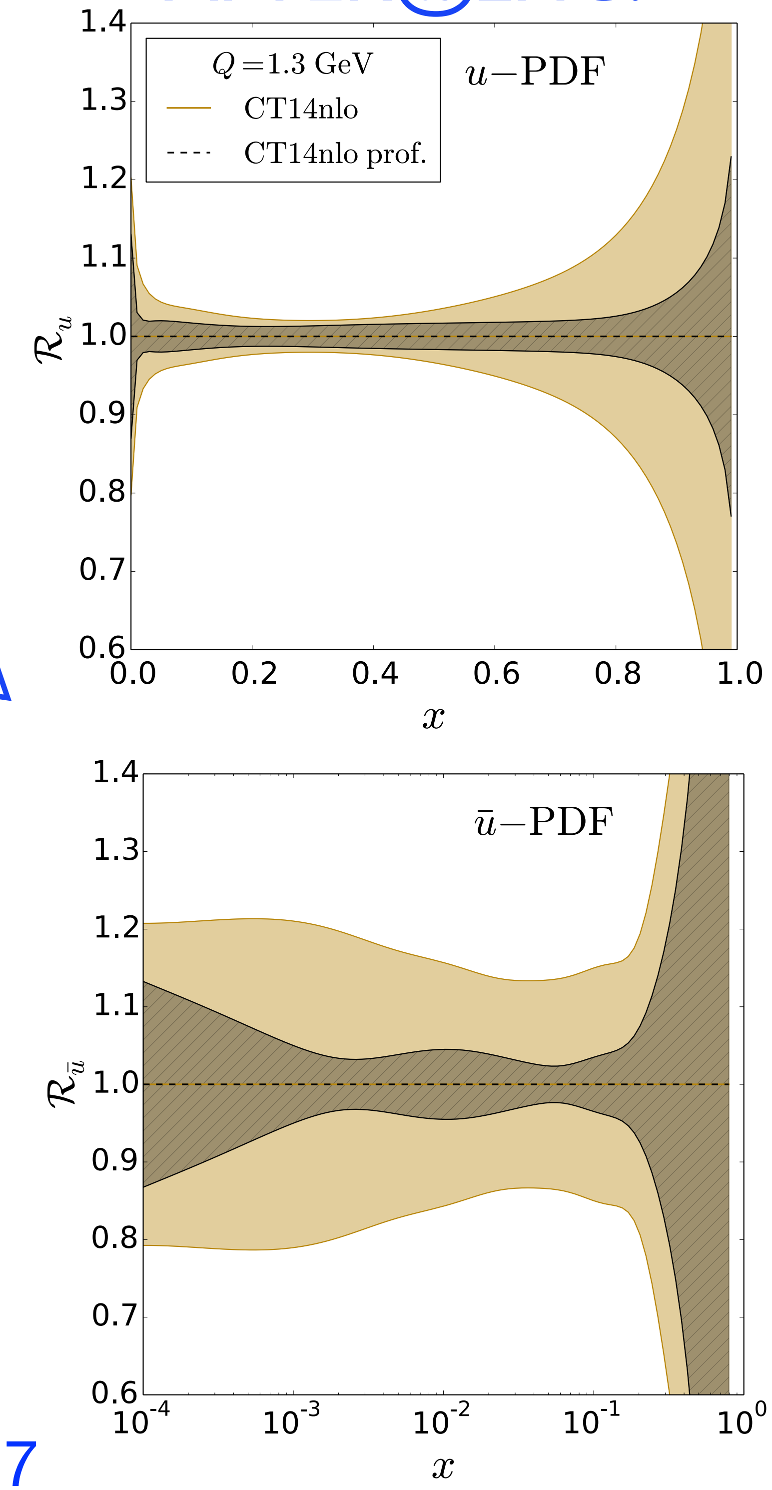
PDF & resulting parton luminosity uncertainties



PDF & resulting parton luminosity uncertainties



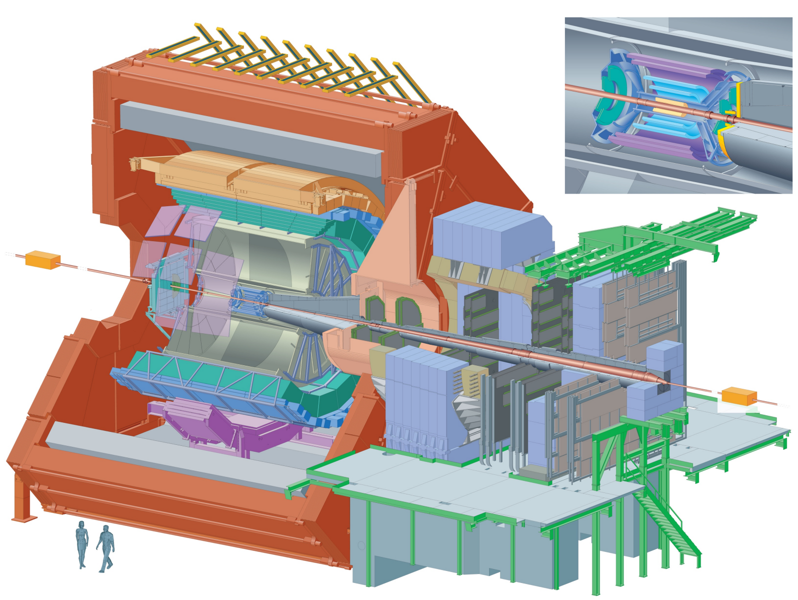
AFTER@LHC:

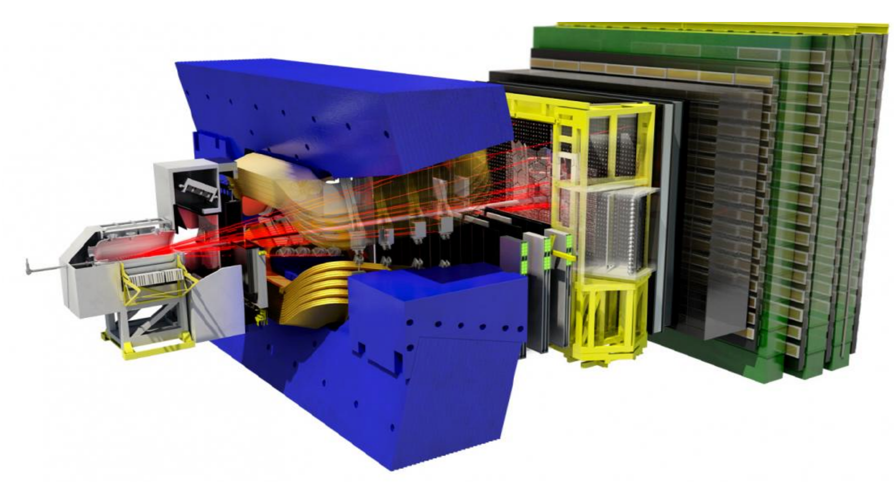


Structure of hadrons and nuclei

unpolarised proton structure (2)

- experimental aspects and ongoing studies
  - ★ fixed target options: luminosity, impact on LHC beams and on detectors (parasitic vs dedicated running)
  - ★ acceptance of ALICE and LHCb detectors
    LHCb forward, ALICE more central (depending on location of target)
  - ★ explore complementarity of ALICE & LHCb

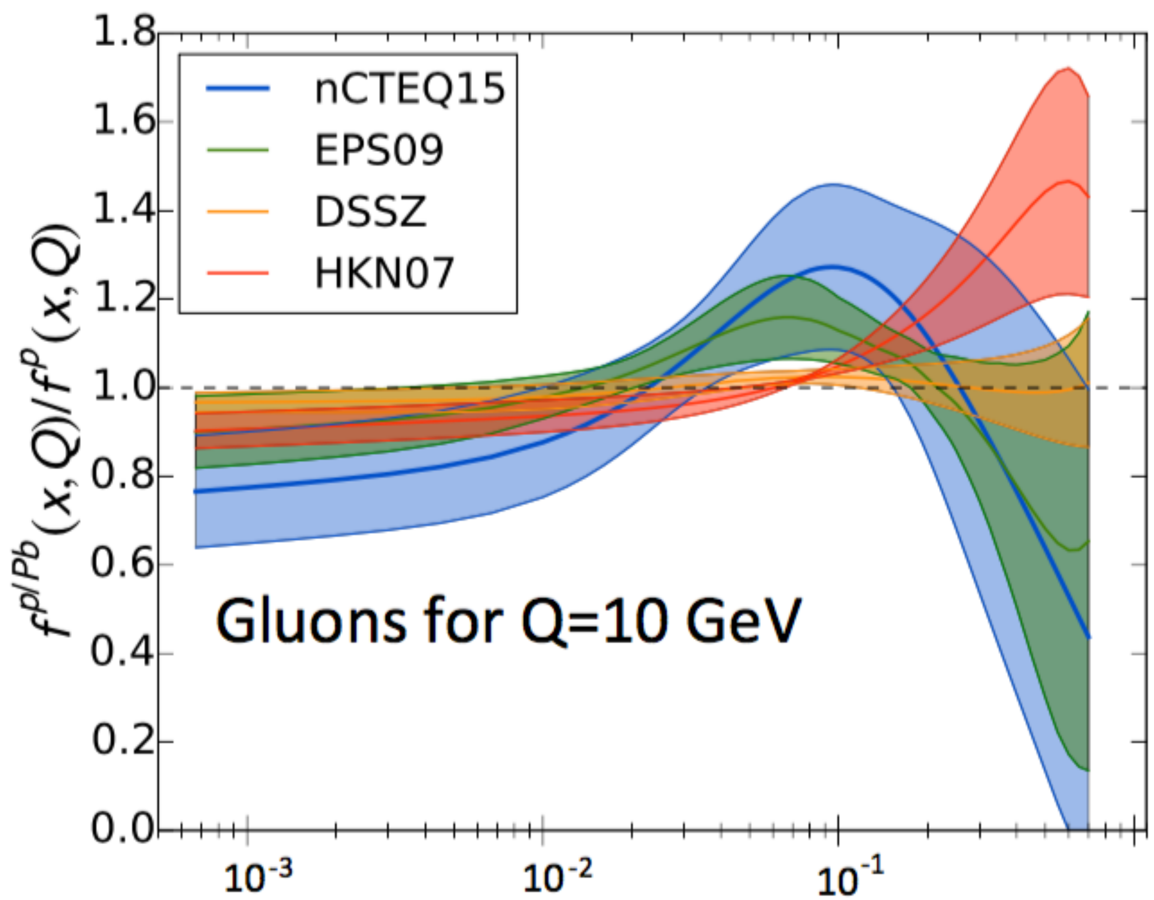




Structure of hadrons and nuclei

structure of nuclei (1)

- LHC fixed target studies: ALICE, LHCb, AFTER
  now with nuclear targets or beams
- main topics:
  - ★ nuclear PDFs at large x (also at small x?)
  - ★ propagation of hadrons in cold nuclear medium (?)
- example for gluon density in Pb:



Structure of hadrons and nuclei

structure of nuclei (2)

- physics motivation:
  - ★ input for heavy-ion physics (baseline measurements for A+A)
  - ★ intrinsic interest: how does nuclear medium modify nucleon?
- main competition: LHC collider, RHIC, EIC
  → point out different kinematic regimes / complementary
- experimental realization: similar questions as for unpolarized proton case
- typical performance and comparison plots:
  - similar to unpolarised proton structure (previous slides);
  - additional plots for propagation in medium (if applicable)

Structure of hadrons and nuclei

polarised proton structure (1)

- COMPASS (antiproton beam); LHC fixed target
- main physics topics:
  - ★ single-spin asymmetries and associated distributions (Sivers, Boer-Mulders functions): generated by soft-gluon effects
    - ✦ fundamental aspect of factorisation between hadron structure and short-distance scattering (also relevant to unpolarised physics)
    - ✦ paradigm of controlled process dependence: hadron-hadron vs. lepton-hadron scattering
  - ★ transverse quark polarisation (transversity), related to **nucleon tensor charge** by a sum rule
  - ★ linear gluon polarisation
  - ★ significant worldwide activity, a cornerstone of programs at JLab12 and the proposed EIC (Electron-Ion-Collider in the US), strong community

Structure of hadrons and nuclei

polarised proton structure (2)

- main processes: Drell-Yan; charm production (?)
  competition: several proposed DY experiments **worldwide**, point out different kinematic regimes and achievable rates, e.g.

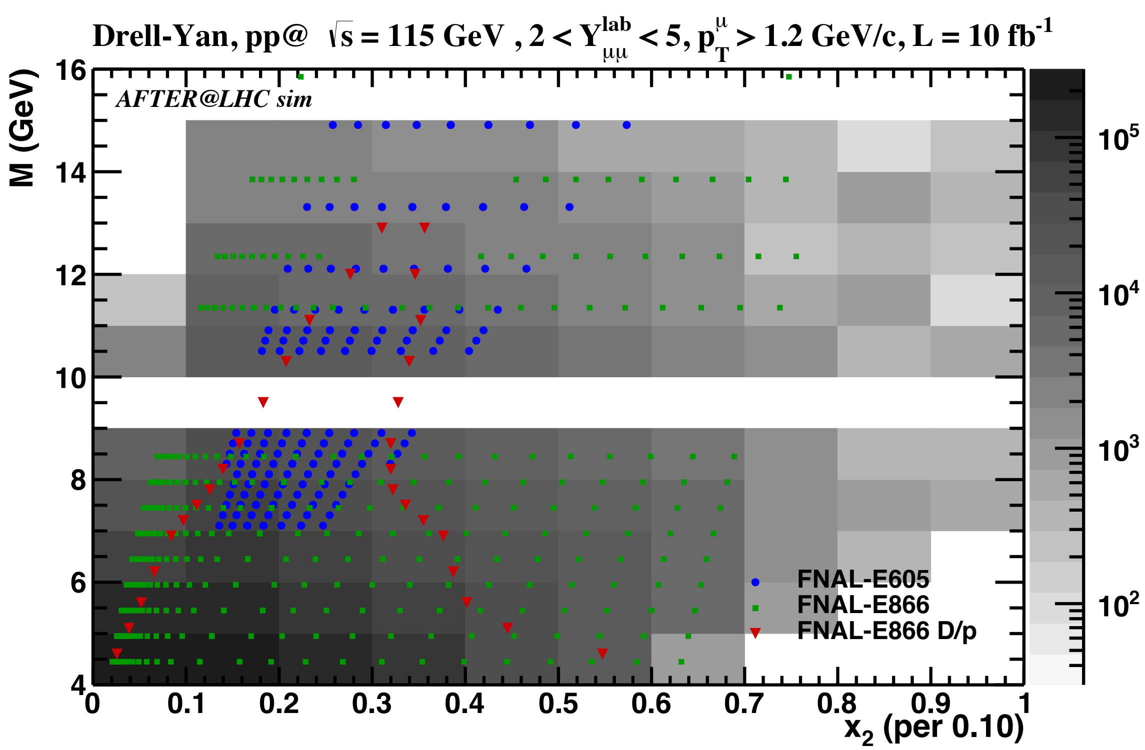
Experiment	particles	beam energy (GeV)	$\sqrt{s}$ (GeV)	$x^{\uparrow}$	$\mathcal{L}$ (cm^{-2}s^{-1})	$\mathcal{P}_{\text{eff}}$	$\mathcal{F}$ (cm^{-2}s^{-1})
AFTER@LHCb	$p + p^{\uparrow}$	7000	115	$0.05 \div 0.95$	$1 \cdot 10^{33}$	80%	$6.4 \cdot 10^{32}$
AFTER@LHCb	$p + {}^{3}\text{He}^{\uparrow}$	7000	115	$0.05 \div 0.95$	$2.5 \cdot 10^{32}$	23%	$1.4 \cdot 10^{31}$
AFTER@ALICE$_{\mu}$	$p + p^{\uparrow}$	7000	115	$0.1 \div 0.3$	$2.5 \cdot 10^{31}$	80%	$1.6 \cdot 10^{31}$
COMPASS (CERN)	$\pi^{\pm} + p^{\uparrow}$	190	19	**0.1** ~~0.2~~ $\div 0.3$	$2 \cdot 10^{33}$	18%	$6.5 \cdot 10^{31}$
PHENIX/STAR (RHIC)	$p^{\uparrow} + p^{\uparrow}$	collider	510	$0.05 \div 0.1$	$2 \cdot 10^{32}$	50%	$5.0 \cdot 10^{31}$
E1039 (FNAL)	$p + p^{\uparrow}$	120	15	$0.1 \div 0.45$	$4 \cdot 10^{35}$	15%	$9.0 \cdot 10^{33}$
E1027 (FNAL)	$p^{\uparrow} + p$	120	15	$0.35 \div 0.9$	$2 \cdot 10^{35}$	60%	$7.2 \cdot 10^{34}$
NICA (JINR)	$p^{\uparrow} + p$	collider	26	$0.1 \div 0.8$	$1 \cdot 10^{32}$	70%	$4.9 \cdot 10^{31}$
fsPHENIX (RHIC)	$p^{\uparrow} + p^{\uparrow}$	collider	200	$0.1 \div 0.5$	$8 \cdot 10^{31}$	60%	$2.9 \cdot 10^{31}$
fsPHENIX (RHIC)	$p^{\uparrow} + p^{\uparrow}$	collider	510	$0.05 \div 0.6$	$6 \cdot 10^{32}$	50%	$1.5 \cdot 10^{32}$
PANDA (GSI)	$\bar{p} + p^{\uparrow}$	15	5.5	$0.2 \div 0.4$	$2 \cdot 10^{32}$	20%	$8.0 \cdot 10^{30}$

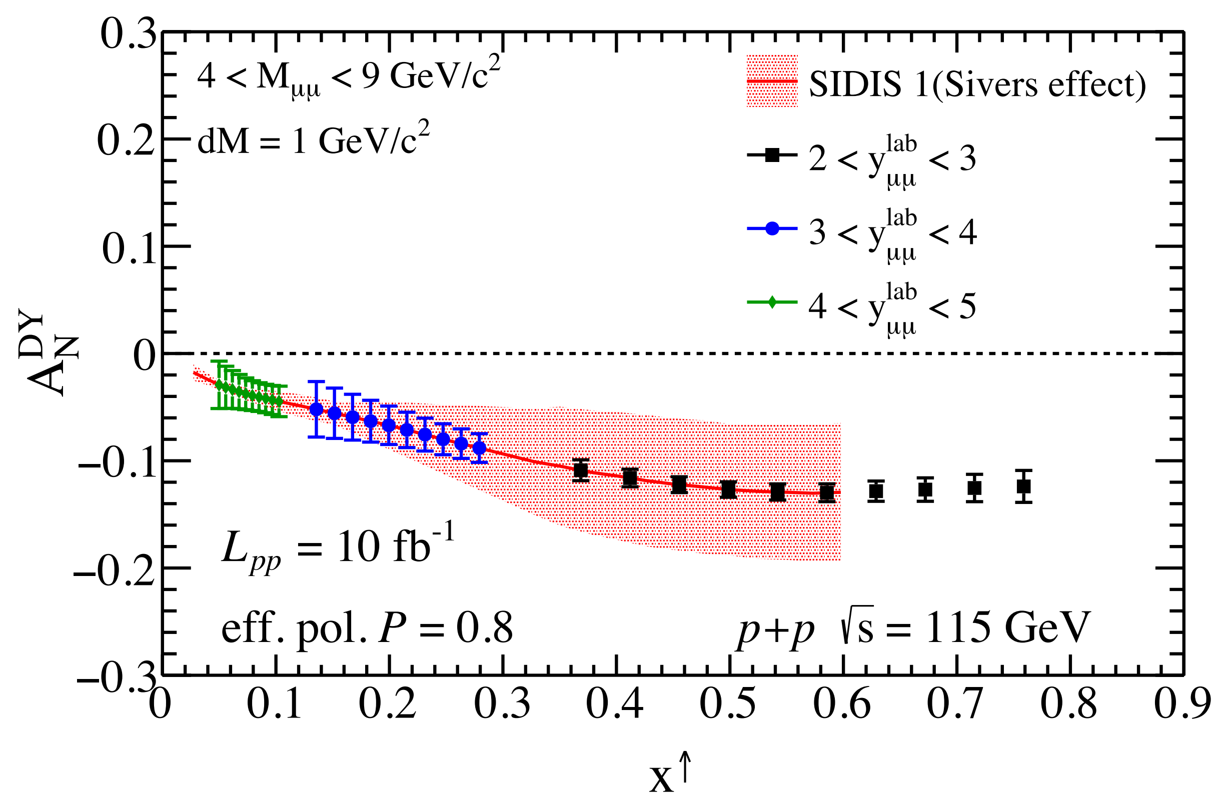
arXiv:1702.01546

Structure of hadrons and nuclei

polarised proton structure (3)

- typical performance plots and comparison: table of DY measurements (past and future); projected asymmetries; kinematic plane (x vs Q^2), e.g. (AFTER@LHC): ideally also: uncertainty bands (present and projected) for polarised distributions





- experimental realisation: similar as for unpolarized case (requirements; impact on LHC), polarization / figure of merit, …

Structure of hadrons and nuclei

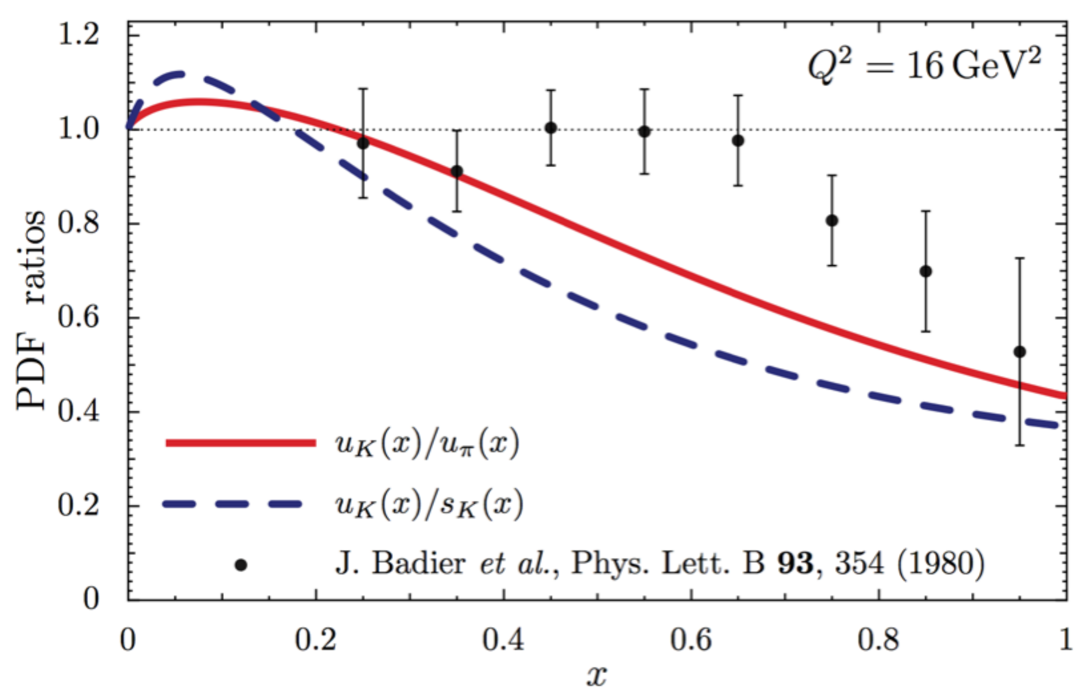
kaon vs pion structure

- COMPASS with RF separated kaon beams
  main processes: prompt photon production (and DY?)

- physics: extract kaon PDFs, compare with those of pion

  ★ effects of flavour SU(3) breaking (s vs u, d masses)
  special role of π and K in QCD (pseudo Goldstone bosons)

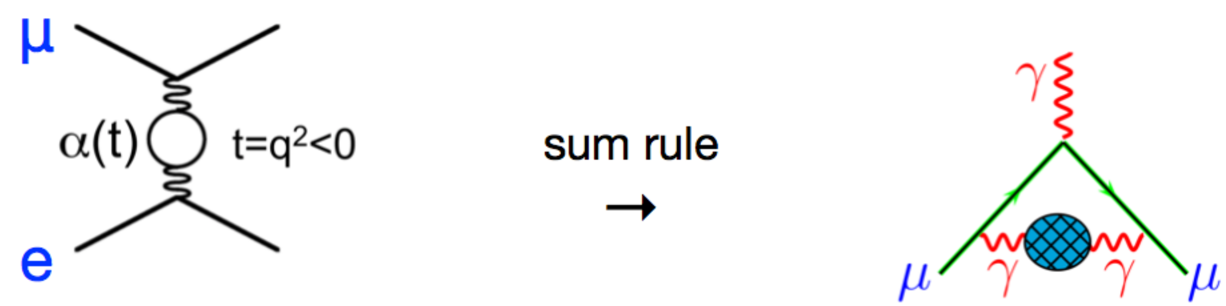
  ★ theoretical studies in quark models, lattice QCD …, e.g., NJL model, arXiv:1604.02853:



- experimental realisation: beam requirements, rates (beam time), detector upgrades?

Elastic scattering: μe

- MUonE proposal



- physics motivation: $(g\text{-}2)_\mu$ discrepancy; precision of future experiments requires improved estimate of hadronic contribution

- no direct experimental competition, point out advantage of CERN energy range

- target precision set by $(g\text{-}2)_\mu$ discrepancy and alternative methods (e^+e^- → hadrons, lattice)

  ➡ crucial to show how can be achieved experimentally
  in addition to quantifying theoretical uncertainty in sum rule

Elastic scattering: μp (1)

- COMPASS proposal (submitted as CERN-SPSC-2017-034)
- extract proton radius r_p from elastic scattering close to Q=0
- motivation: discrepancies between r_p determinations from
  - ★ Lamb shift in muonic vs ordinary hydrogen
    recent proposal to solve by adjusting Rydberg constant, remains to be settled in atomic physics community
  - ★ ep elastic scattering (current/recent exp's at MAMI, JLab)
    - ✦ must extract slope at Q=0 from data at finite Q: existing analyses get close to either of the two Lamb shift results depending on fitting procedure

Elastic scattering: μp (2)

Proton radius measurements

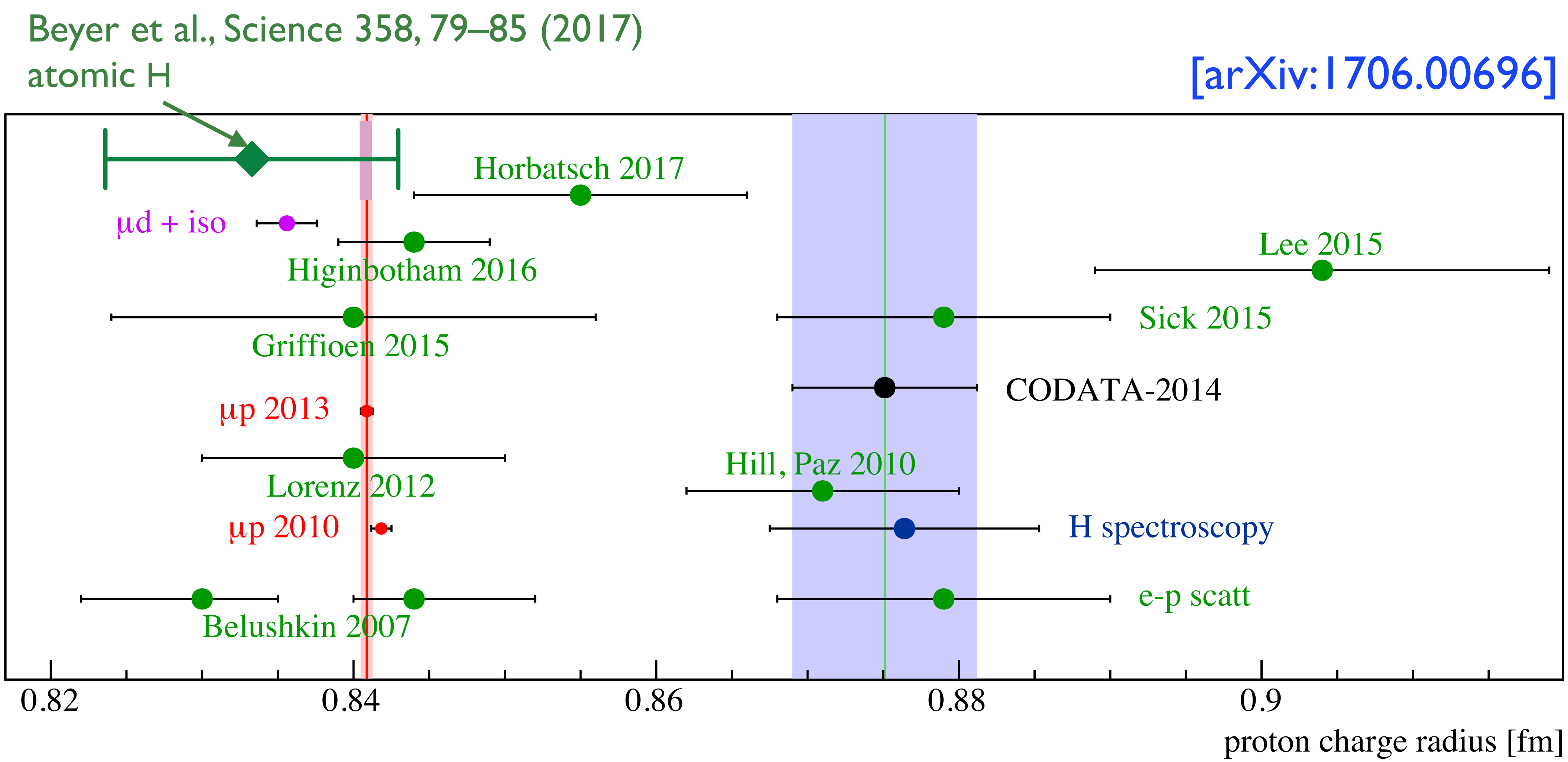


Figure 3 – Proton radius from muonic hydrogen (red), hydrogen spectroscopy (blue) and electron-proton scattering (green). The CODATA value does not account for the muonic results.

Elastic scattering: μp (3)

- must show advantages of proposal over ep and low-energy μp (proposed at PSI)
  - ★ smaller QED and multiple scattering corrections (but not their size matters, but their uncertainties and contribution to overall error on r_p)
  - ★ range of and binning in Q: can proposed measurement overcome present uncertainty from fitting procedure?
    - ➡ answer by applying different present fitting procedures to simulated data
- experimental realisation: beam requirements, rates (beam time), detector upgrades, …

Heavy ion physics

physics case

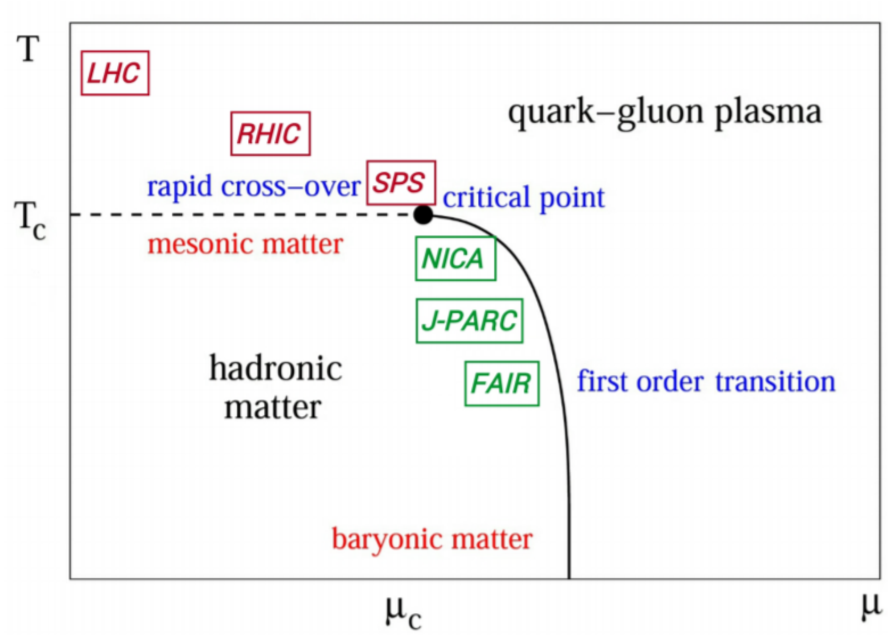
- ALICE, LHCb, AFTER, N60+, NA61+
- main physics topics:
  - ★ deconfinement at large densities
    - ✦ open charm and J/ψ production mechanism, and signal for deconfinement (NA61+)
    - ✦ dimuon mass $\mathrm{m}_{\mu\mu}$ and p_{T} spectrum (NA60+)
    - ✦ quarkonia between SPS and RHIC, v_{n} at large rapidities for constraining η/s (AFTER)
  - ★ search for critical endpoint
    - ✦ caloric curve (NA60+)
- main competitors/complementary: BES, CBM FAIR, NICA

Heavy ion physics

Uniqueness & complementarity

Uniqueness of NA61 open charm program

Landscape of present and future heavy ion experiments



Only NA61/SHINE is able to measure open charm production in heavy ion collisions in full phase space in the near future

- **LHC and RHIC at high energies**: measurements in small phase space due to collider geometry
- **RHIC BES collider**: measurement not possible due to collider topology
- **RHIC BES fixed-target**: measurement require dedicated setup, not under consideration
- **NICA (< 80*A* GeV/*c*)**: measurement during stage 2 under consideration
- **J-PARC (< 20*A* GeV/*c*)**: maybe possible after 2025
- **FAIR (< 10*A* GeV/*c*)**: not possible

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Marek Gazdzicki
for NA61/SHINE

Heavy ion physics

Uniqueness & complementarity

- ALICE, LHCb, AFTER, N60+, NA61+
- Embedding in the rich landscape of heavy ion experiments
  - ★ Uniqueness: comparison to all other (seeming) competitors
    - e.g. interaction rate
    - e.g. energy range
    - e.g. specific measurement
  - ★ complementarity: comparison with all other (seeming) competitors
    - e.g. importance of results for other experiments
    - e.g. coverage of whole energy range ➡ detection potential
    - e.g. different features at different energies

we already have a lot….but we need more!!

Low-energy hadron structure: spectroscopy

- COMPASS with RF separated kaon/antiproton beams
- spectroscopy of mesons in high mass range (states, masses, widths)
  - ★ excited kaon states, SU(3) multiplets
  - ★ exotic (non-qqbar) mesons
- no detailed studies yet
- must clarify competition, e.g. PANDA for antiprotons (much higher luminosity), proposed kaon beam program at JLab Hall D, JPARC, and advantage of COMPASS proposal

Low-energy hadron structure: magnetic moments

- proposed measurement with crystals at LHC
- magnetic moments of short-lived baryons:
  - ★ so far studies concentrate on Λ_c^+
  - ★ possible extension to Ξ_c^+, heavier states, ultimately to τ lepton
- possibility to measure EDM (CP violating) being considered
  → talk in session on new ideas tomorrow
- physics motivation: QCD for heavy-light systems
  modern predictive tools such as heavy-quark effective theory
- estimated target precision ~0.1 for g factor of Λ_c
  present theory predictions have g = 1.80 .. 2.05
- to get constraints/information on (g-2) of charm quark (BSM)
  would require detailed analysis of QCD uncertainties

Chiral dynamics: πK scattering lengths

- DIRAC: pioneering experiment at CERN PS producing π π and π K atoms and measuring their lifetimes
  → compute π π and π K scattering lengths
- physics: chiral symmetry breaking in QCD
  → low-energy interactions between π's and K's predicted
  → chiral perturbation theory (ChPT)

★ kaon: chiral dynamics in strange sector, SU(3) breaking

- DIRAC++ at SPS: would have significantly higher yield for π K atoms
  → measure $|a_{1/2} - a_{3/2}|$ with accuracy below 5%

★ quantity computed using ChPT/lattice techniques

Chiral dynamics: kaon polarisabilities

- COMPASS with RF separated kaon beam:
  Primakoff process $K\,p \rightarrow K\,\gamma\,p$
    - ★ was done for π in completed COMPASS programme
- polarisabilities quantify charge deformation in static e.m. field
    - ★ calculable in chiral perturbation theory (ChPT)
      → see previous slide
- present error estimate: $0.25 \times 10^{-4}\ \mathrm{fm}^3$ in 1 year
  based on pion analysis
- theory prediction = $0.6 \times 10^{-4}\ \mathrm{fm}^3$ from ChPT

Measurements for cosmic ray physics

- LHC fixed target, COMPASS, NA61

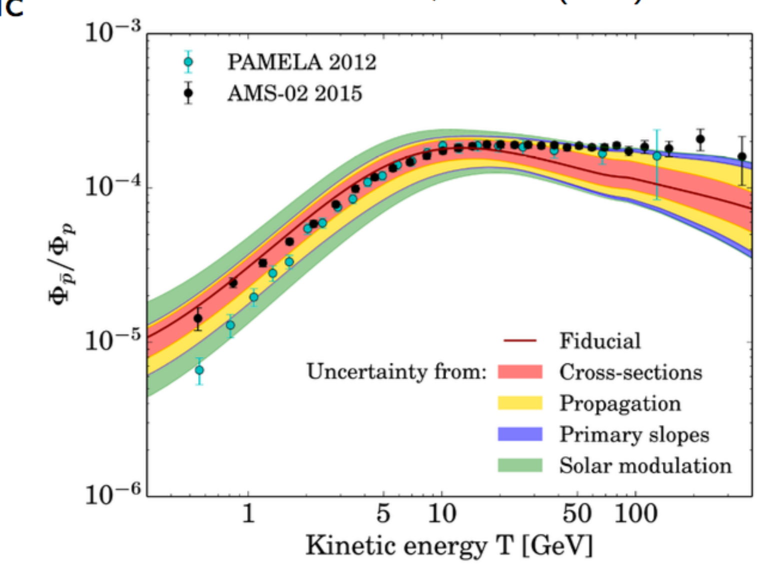
Fixed target data at 100 GeV provides inputs to MC models describing underlying event:
Important for modeling cosmic ray showers in the atmosphere

AMS02 measurement of $\overline{p}/p$ ratio in cosmic rays shows hints of excess at high energies

$\overline{p}/p$ predictions from spallation of primary cosmic rays on interstellar medium (H or He):

- Limitation from uncertainties on $\overline{p}$ production cross-sections
- No previous measurement in pHe
- Predictions from soft QCD models vary within a factor 2

PRL 117, 091103 (2016)



LHCb in fixed-target mode is well suited to measure $\overline{p}$ production cross section in pHe

4/17

E. Maurice (LAL, LLR) Fixed-target physics at LHCb LHCP 2017

- existing measurements: LHCb-CONF-2017-002
NA61/SHINE EPJC 77 (2017) 671
- future possibilities: compare experiments (kinematics, rates), quantify impact on cosmic ray physics

Conclusions

- PBC proposals cover a wide range of important topics in QCD
- some are quite unique, others in tight competition worldwide
- for PBC document, work of next months will be crucial:
  - ★ quantify expected reach/performance for physics output
  - ★ estimate required experimental effort/timeline/cost
  - ★ quantitative comparison with competition
    - ➡ what are the physics advantages of your proposal?

backup

nPDF landscape

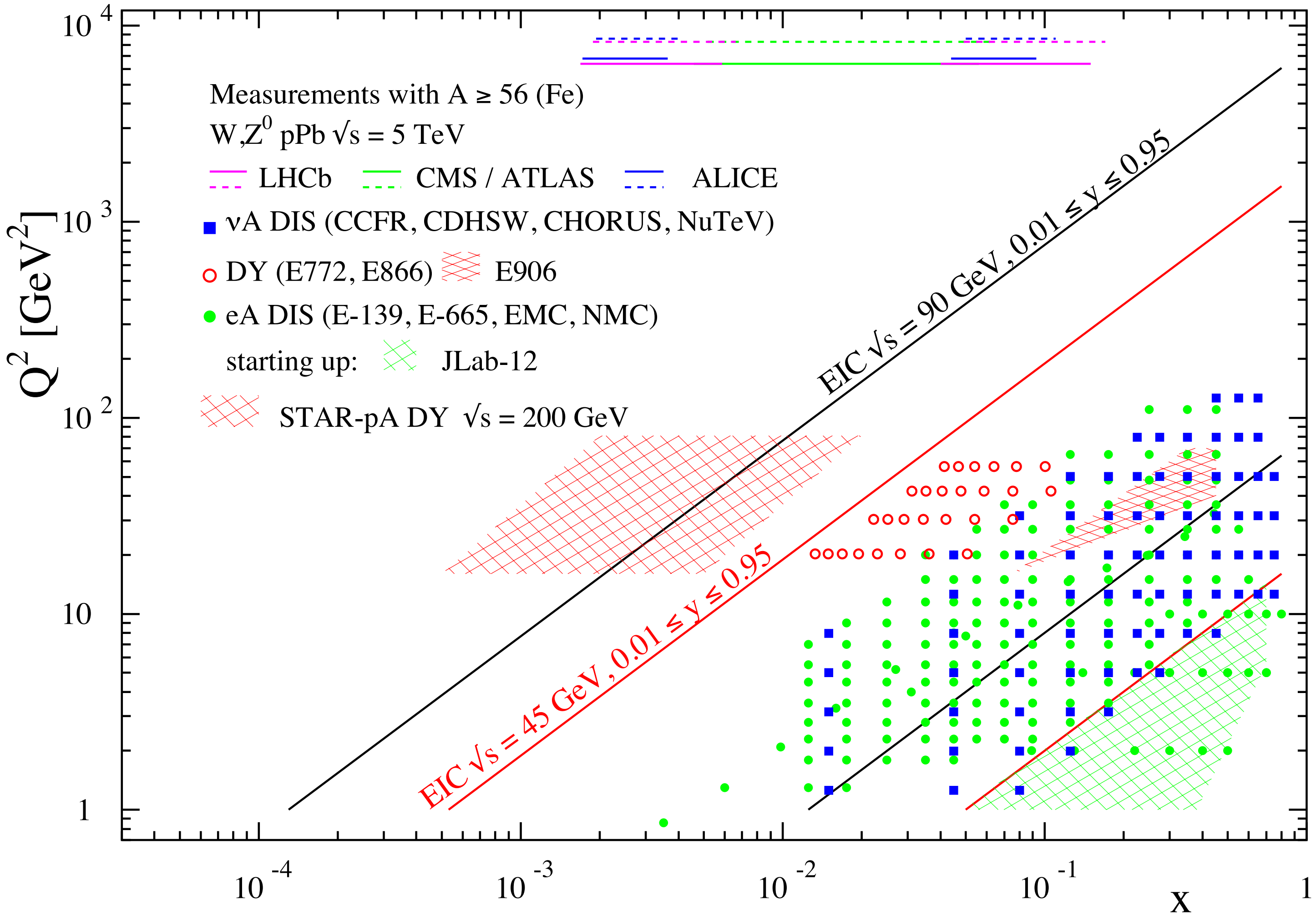


Figure 4-5: The kinematic coverage in x–Q^2 of past, present and future experiments constraining nPDFs with access to the exact parton kinematics event-by-event and no fragmentation in the final state.

projected precision using EIC data