A new QCD facility at the M2 beam line of the CERN SPS

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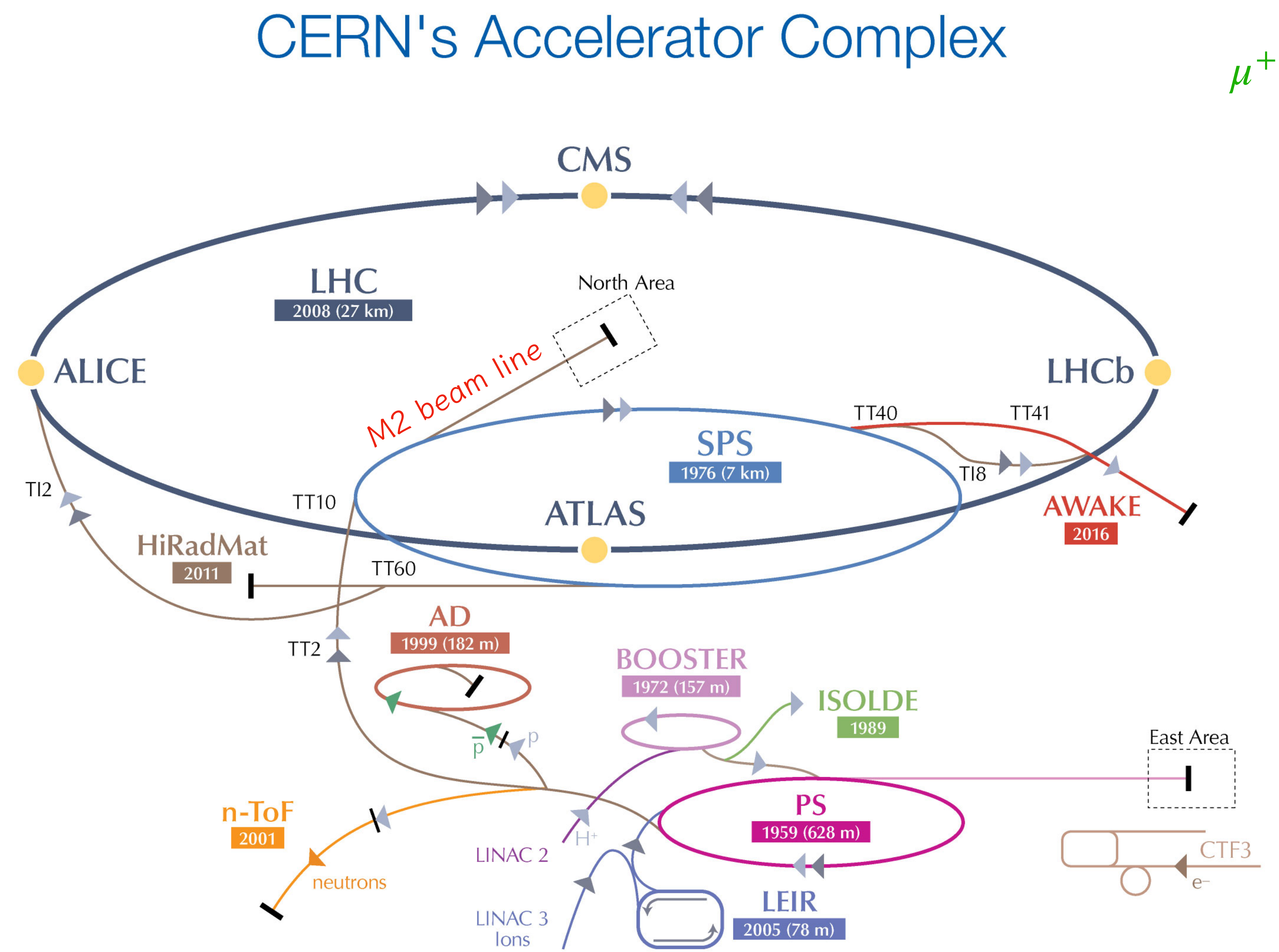
Workshop on Progress on Hadron structure functions in 2018

19th November 2018

CERN M2 beam line



μ^+, μ^- $\pi^+, \pi^-, p, \bar{p}, K^+, K^-$

muon and hadron beams from the same beam line

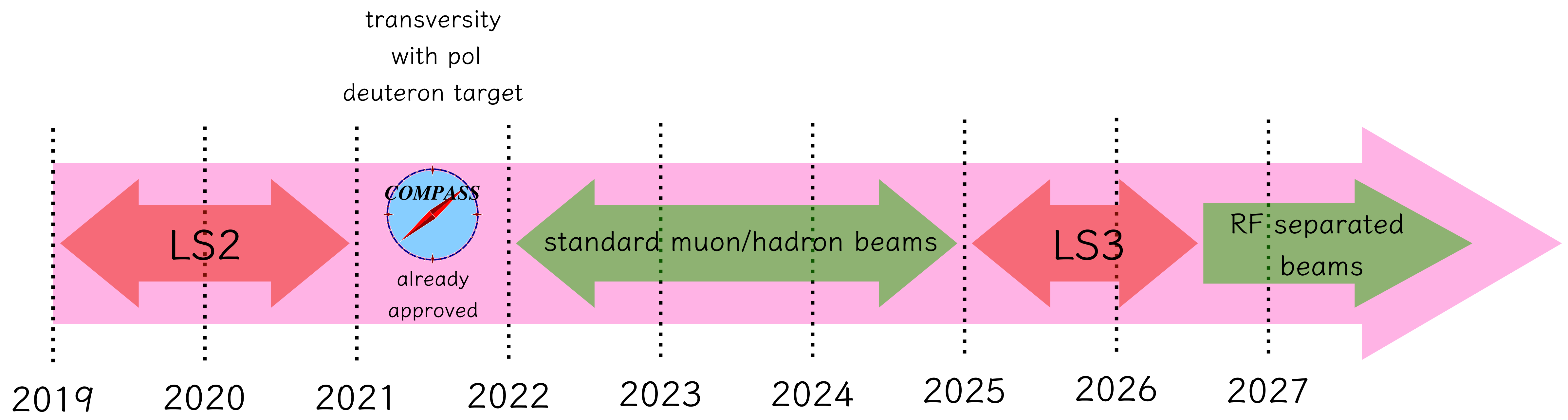
unique feature of M2 beam line at CERN

Letter of Intent for a new QCD facility

Submitted in August 2018

arXiv:1808.00848

1. Hadron physics with standard muon beams
2. Hadron physics with standard hadron beams
3. Hadron physics with RF-separated beams

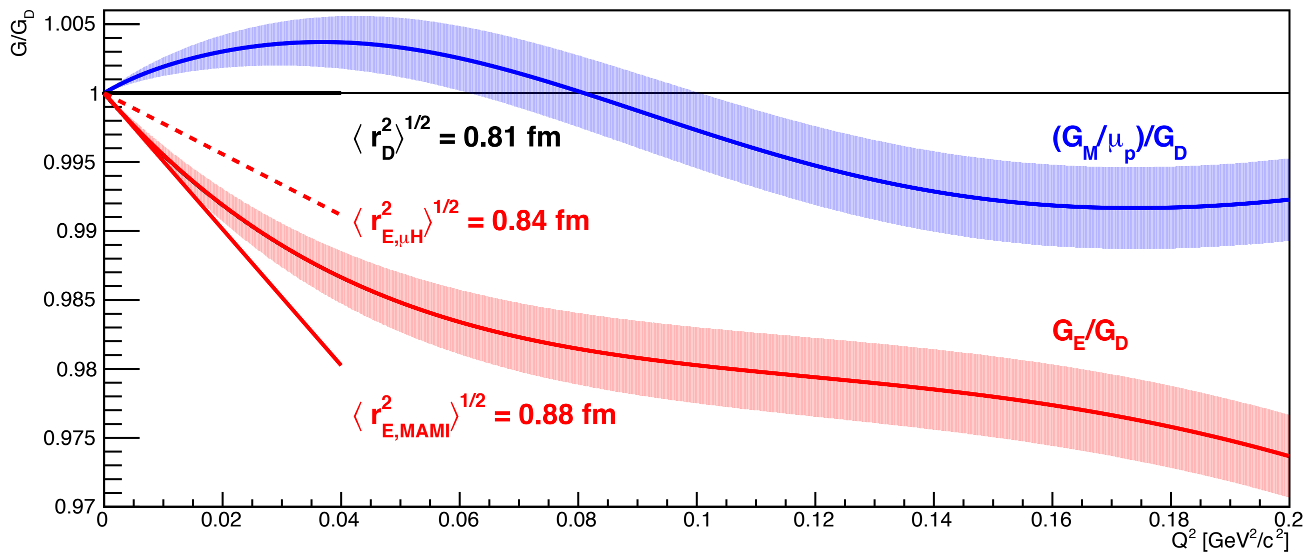


Proton radius measurement using μ-p elastic scattering

Proton radius measurement using μ-p elastic scattering

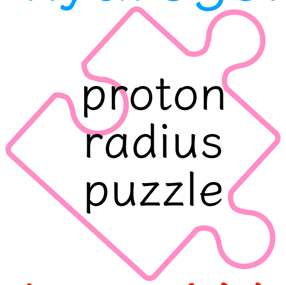
$$\langle r_E^2 \rangle = -6\hbar^2 \frac{dG_E(Q^2)}{dQ^2}\Bigg|_{Q^2\to 0} \overset{\text{dipole}}{=} \frac{12\hbar^2}{a^2} \approx (0.81\ fm)^2 \equiv \langle r_D^2 \rangle$$

Different ways to measure the proton radius



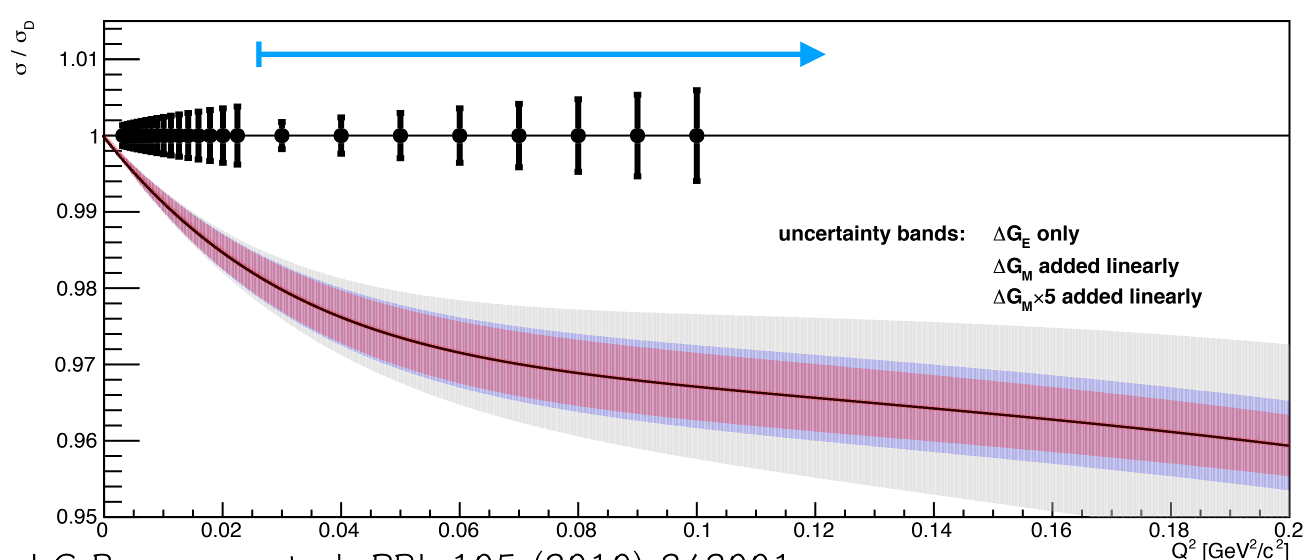
laser spectroscopy of muonic hydrogen

striking discrepancy ~3σ



elastic electron-proton scattering - MAMI

the non-linearity of the Q^2 dependence becomes the predominante source of uncertainty



new experiment contribution

elastic muon-proton scattering

good precision in the range

$$0.001 < Q^2/(GeV^2/c^2) < 0.02$$

constrains the p radius to an accuracy better than 0.01 fm

J.C.Bernauer et al, PRL 105 (2010) 242001

R. Pohl et al, Nature 466 (2010) 213-216

New measurement at CERN

proton
radius
puzzle

to reach the precision required (<0.01fm)

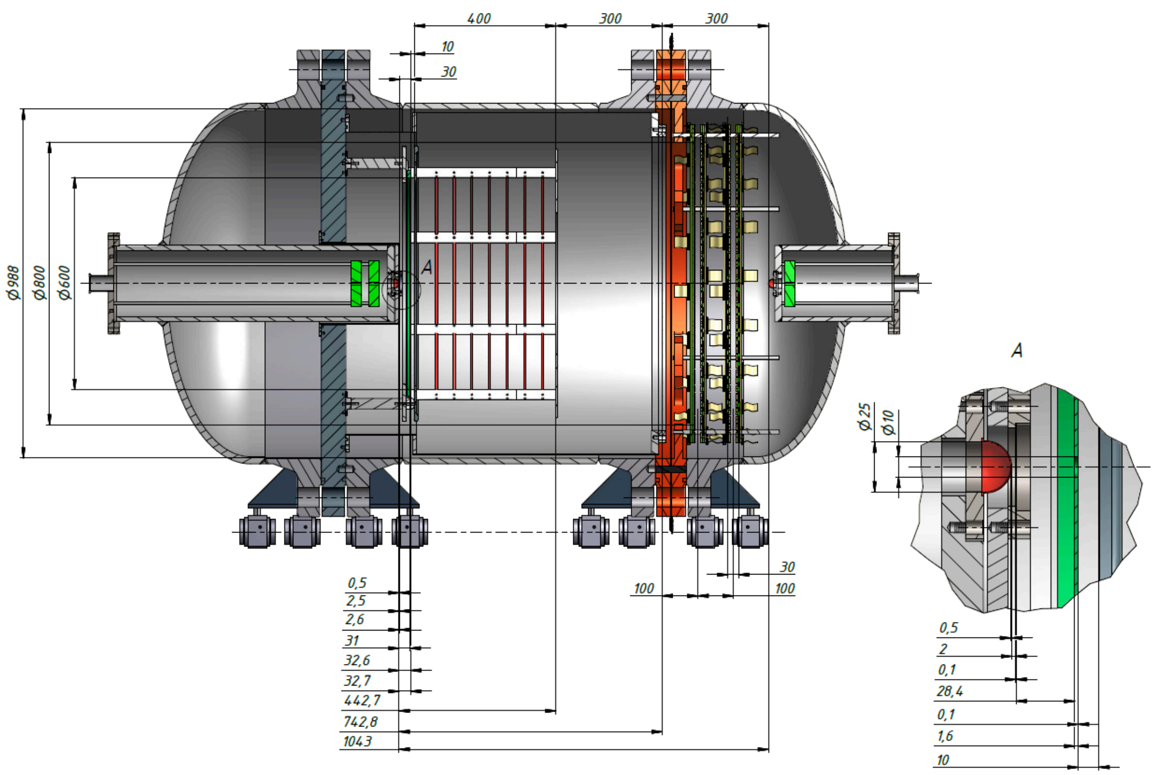
↓

detect the small energy recoil p

↓

target should work also as a detector

Time Projection Chamber (TPC)



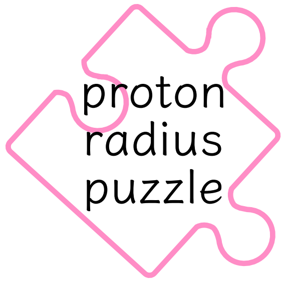
sketch of a TPC used at MAMI

100 GeV/c μ beam

pressurized hydrogen gas target

requirement of a new trigger to select muons with a scattering angle larger than 100 μrad

Competition & complementarity



elastic electron-proton scattering vs elastic muon-proton scattering

like at MAMI

requires QED radiative corrections

much smaller radiative corrections

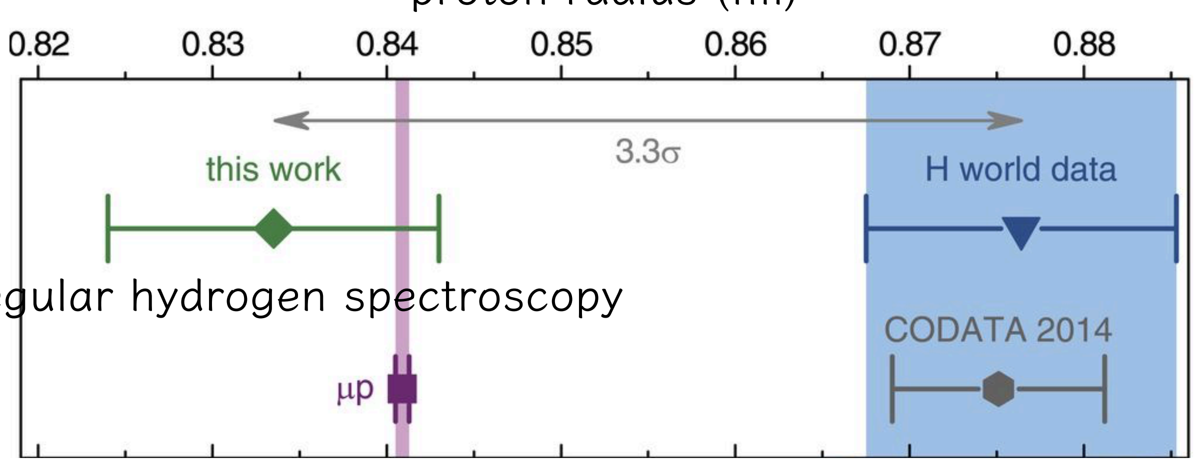
important to test systematic effects related to radiative corrections

if at low beam energies like at MUSE @ PSI

there is a substancial correction from Coulomb distortion of the low-velocity muon wave function

spectroscopy of further muonic atoms

proton radius (fm)



regular hydrogen spectroscopy

muonic hydrogen spectroscopy

A. Beyer et al., Science 358 (2017) 79

regular hydrogen spectroscopy

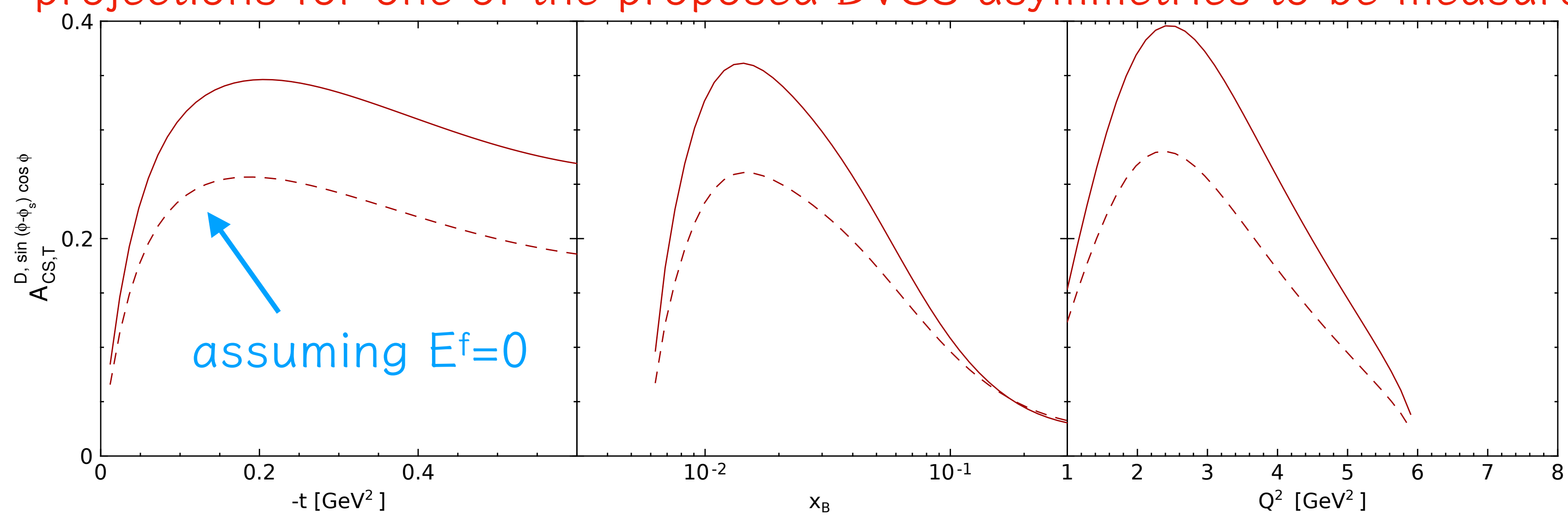
regular hydrogen spectroscopy + deuterium spectroscopy + elastic electron scattering

Exclusive reactions with muon beams and transversely polarised target

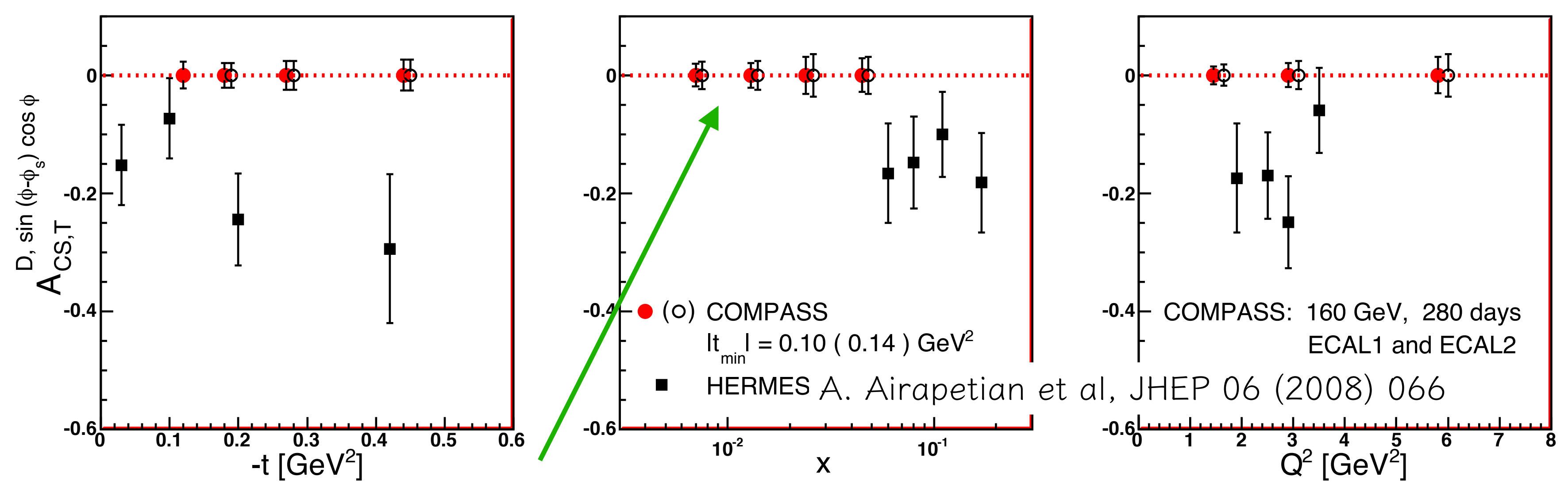
Exclusive reactions with μ beams and transversely polarised target

GPDs E^f can be accessed using both polarised beam and target → Deeply Virtual Compton Scattering (DVCS) / Deeply Virtual Meson Production (DVMP)

projections for one of the proposed DVCS asymmetries to be measured



statistical projection for 280 day with transversely polarised NH3 target



most challenging

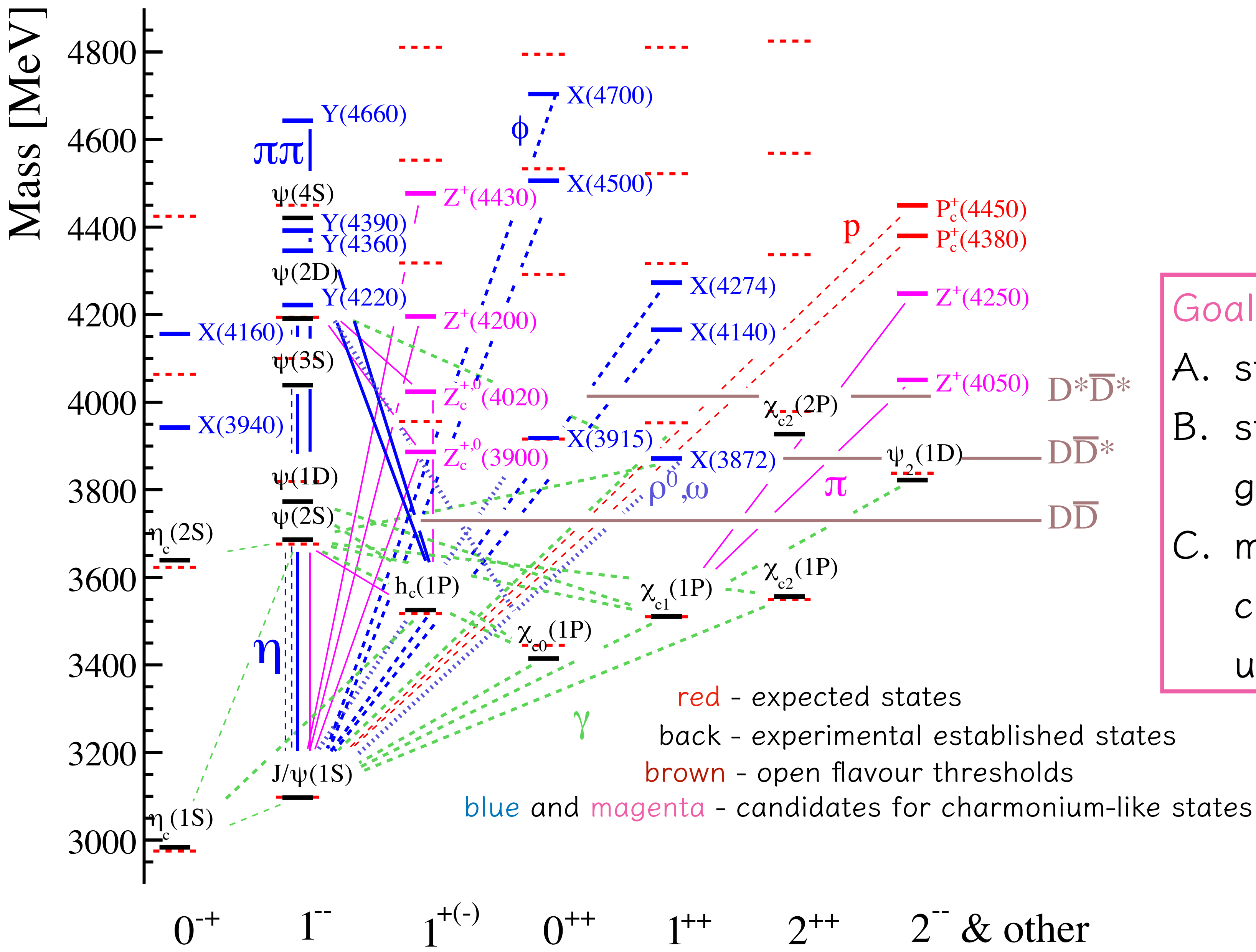
to detect the recoil particles with polarised-solid state targets

good accuracy +-3% in a complementary region to HERMES and JLab, unique before any collider is built

Spectroscopy with low-energy antiprotons

Spectroscopy with low energy antiprotons

charmonium-like spectrum



S.L.Olsen et al, Rev. Mod. Phys. 90 (1) (2018) 015003

pbar at 12 and 20 GeV/c

↓

would require some minor improvements/changes in the beam line

good beam PID - Cedars

Goals:

A. study the charmonium-like spectrum
B. study exotic states (multi-quarks, hybrids, glueballs)
C. measurement of the ppbar production cross-sections for XYZ states (major uncertainty source for PANDA projections)

past experiments with ppbar:

Crystal Barrel at LEAR

E760 and E835 at FermiLab

future experiments with ppbar:

PANDA at FAIR (>2025)

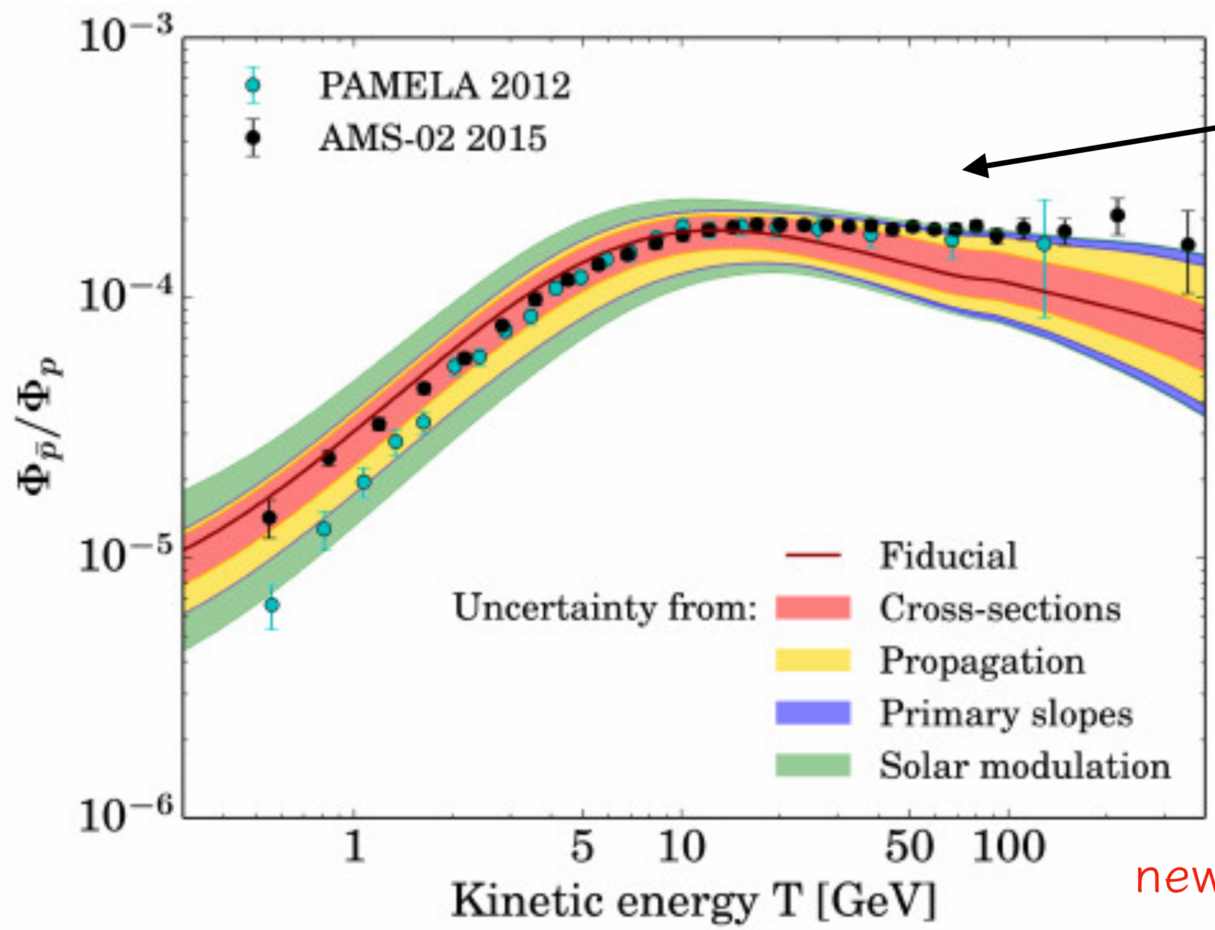
Measurement of antimatter production cross sections for Dark Matter Search

Measurement of the antimatter production cross sections for Dark Matter Search

$\chi + \chi \rightarrow q\bar{q}, W^+W^-, \ldots \rightarrow \bar{p}, \bar{D}, e^+, \gamma, \nu$ search of the Dark Matter annihilation products

AMS-02 experiment on the International Space Station

important to well know cross-section of antiprotons and antideuterons



O. Adriani et al, JETP Letters 96 (10) (2013) 621-627

M.A. et al, PRL 117 (2016) 091103

above ~60GeV the ratio pbar/p becomes independent of the energy

dominant reaction on the production of secondary antiprotons

$p - p, p - He, He - p, He - He$

several datasets available

1st dataset end of 2016 LHCb at 4 and 7 TeV

new experiment contribution from a few 10 to 250 GeV/c is complementary to higher energy p measurements

a required percent statistical accuracy would be achieved after few hours of data taking

1 to 2 months of data taking

Drell-Yan and charmonium production with conventional hadron beams

Drell-Yan and charmonium production with conventional hadron beams

The current hadron beam at CERN M2 beam line is dominated by pions in the case of negative hadrons and has a good fraction of them in the case of positive hadrons

Detailed picture of the pion structure

Physics goals foreseen:

1. determination of the valence and sea quark pion distributions
2. study of charmonium production mechanism in order to extract the gluon distribution in the pion
3. investigate flavour-dependent effects in nuclear targets

nuclear PDFs in high x

Motivation for the study of the pion structure

How to explain the origin of the mass of composite hadrons?

How is their structure?

DIS, jet, hadron
and DY cross-sections from
pp and ppbar

proton

many data

~1 GeV/c^2

precise knowledge of
quark and gluon
dist. functions

light mesons
(pion, kaon)

few data

~0 GeV/c^2

pion induced DY,
indirect measurement from
neutron tagged DIS

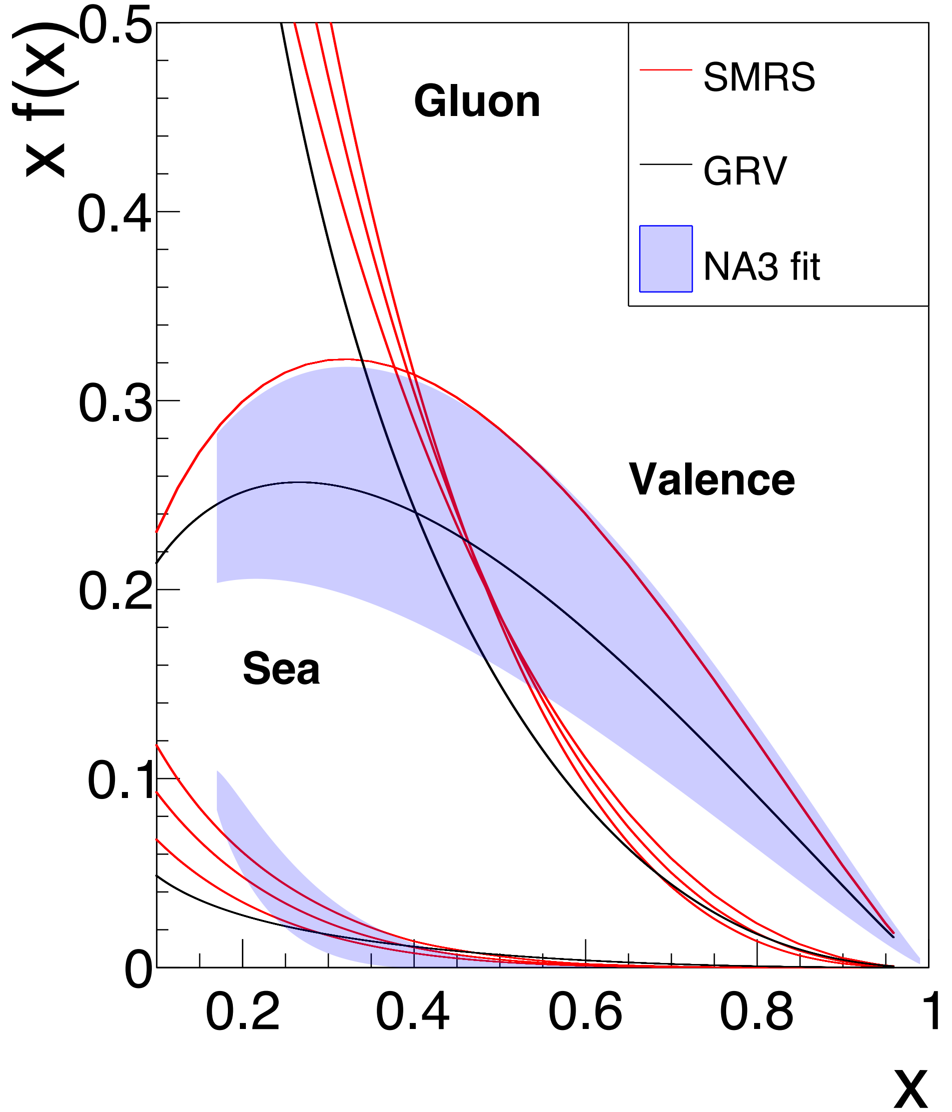
quark and gluon
meson structure
is poorly constrained for pions
and
completely unconstrained for kaons

binding energy + val. quarks

There are several models to describe the parton structure of the mesons

Separation of the valence and sea contributions in the pion

sea is the most unknown contribution



SMRS: P. J. Sutton et al, Phys.Rev.D 45 (1992) 2349-2359

GRV: M. Gluck et al, Z.Phys.C 53 (1992) 651–656

NA3: J. Badier, et al., Z.Phys.C 18 (1983) 281

two diff global analyses (SMRS and GRV)
using pi- DY data from NA10 and E615,
do not include uncertainties

SMRS analysis:

sea content - three different scenarios (10%, 15% or 20%)

GRV analysis:

sea content - derived from momentum conservation

glue content - constrained by the direct photon measurements from WA70 and NA24

NA3 fit:

using the published fit coefficients and correlation matrix

Contribution from the new experiment at CERN

$$\sum_{val}^{\pi C} = -\sigma^{\pi^+ C} + \sigma^{\pi^- C}$$

only valence-valence terms

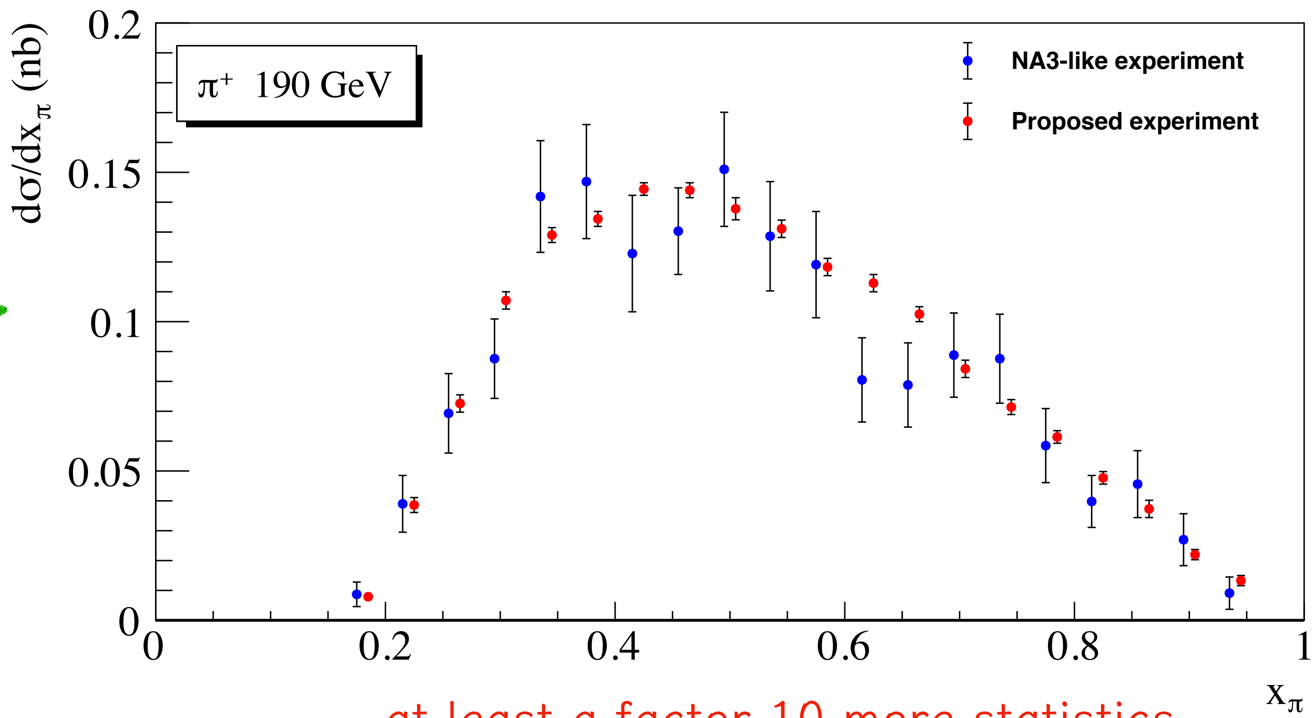
$$\sum_{sea}^{\pi C} = 4\sigma^{\pi^+ C} - \sigma^{\pi^- C}$$

valence-sea and sea-valence terms

light isoscalar carbon target
to reduce nuclear effects
(past experiments used non-isoscaler targets like platinum and tungsten)

Goal: precise cross-section measurements, with a level of 3% systematic uncertainty

LO DY from PYTHIA, k-factor=2 , 255 days,
4 C targets 25 cm each, 7*10^7 beams/s
4.8s spill, 2 spills per 52s,
90% cedar eff, 13% eff.*acc*life-time

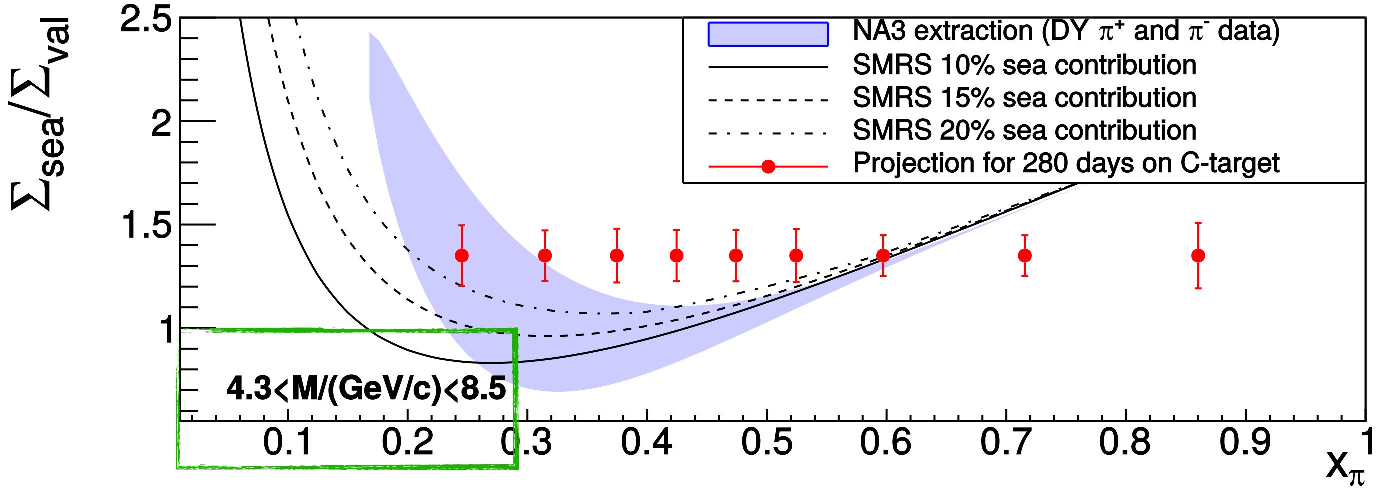


at least a factor 10 more statistics

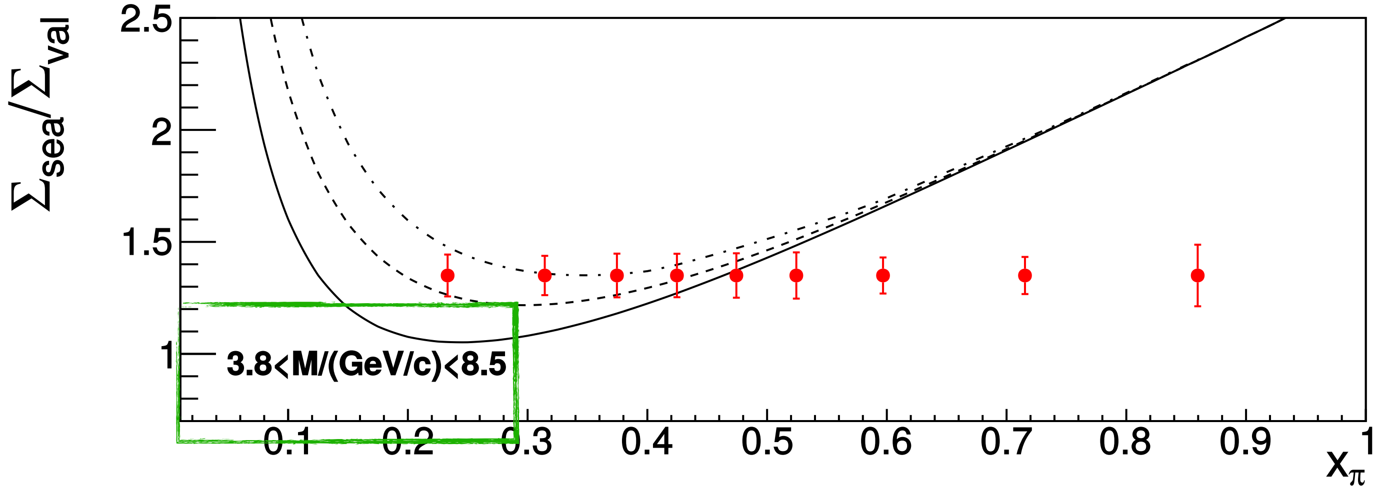
+25 days of pi-

ratio 10:1 between pi+ and pi- due to the cross-section diff.
and the hadron beam composition at cern M2 beam line

Sea quark contribution



background free DY mass range



if machine learning techniques succeed to isolate DY from background

hot topic currently ongoing

cross-check of the relative normalisation - using J/psi since its cross-section does not depend on the pion charge when using isoscaler target

J/psi production mechanism and the gluon dist. in the pion

There will be a large sample of J/psi available for free ⟼ may give access to gluon dist. in pion

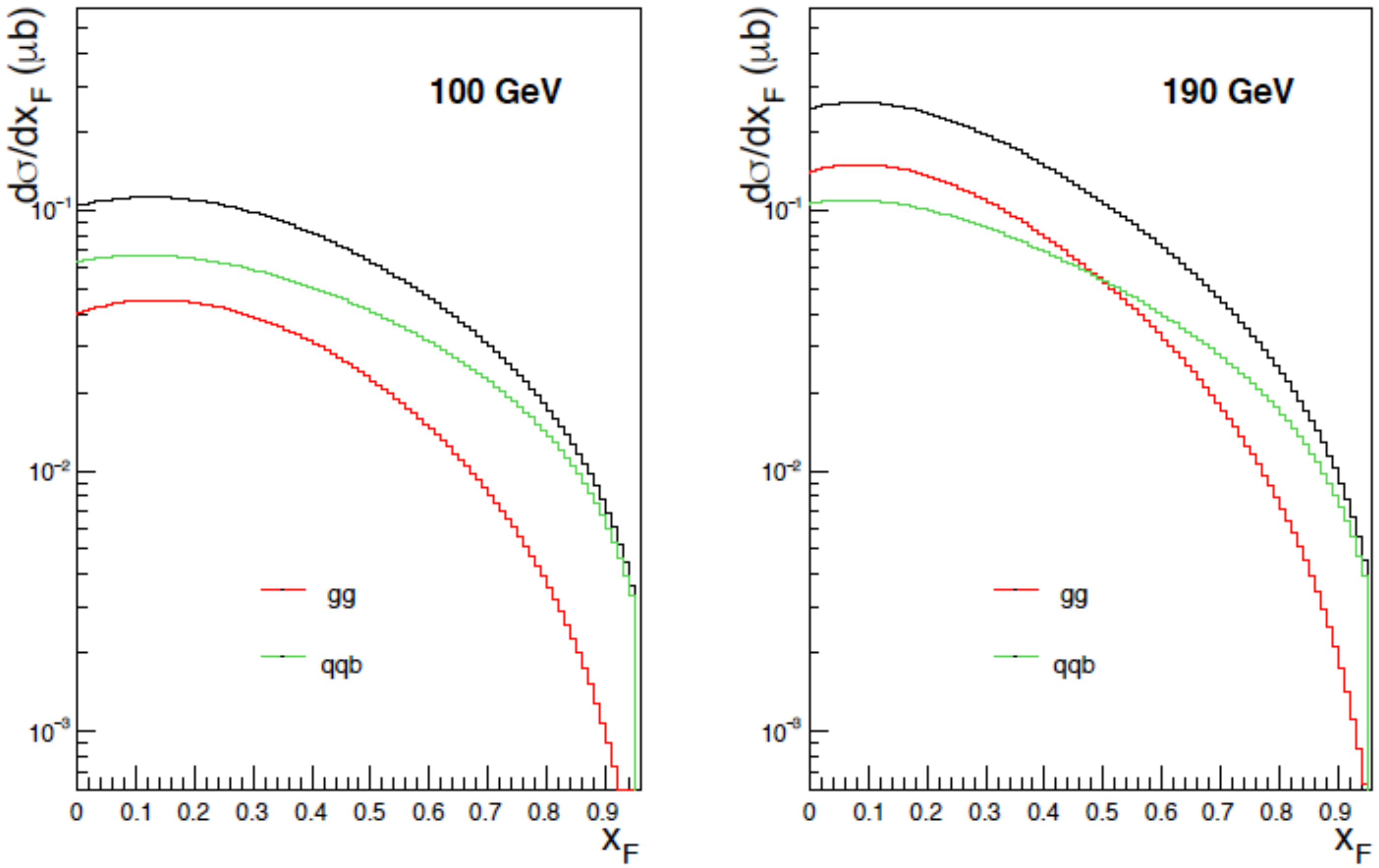
at the fixed target experiments energy

$$gg \to J/\psi$$

$$q\bar{q} \to J/\psi$$

the different quark and gluon densities lead to different xF dependences

the separation of the two contributions allows to access the parton dist. of the pion

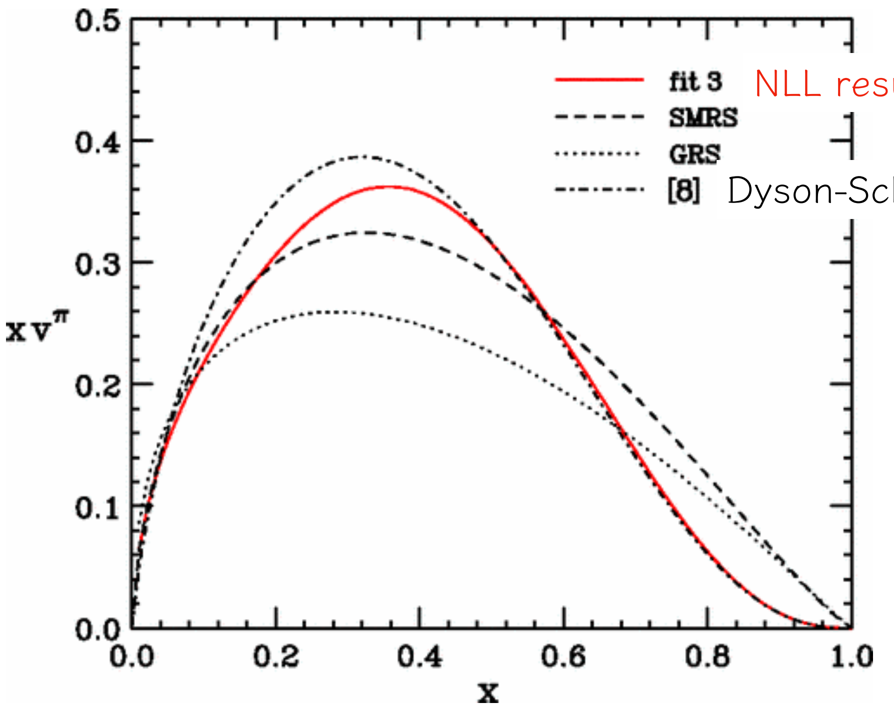


LO CEM model

at 190 GeV/c - gg dominates at low xF, and qq term becomes important at large xF

Recent studies on pion

Pion valence distribution

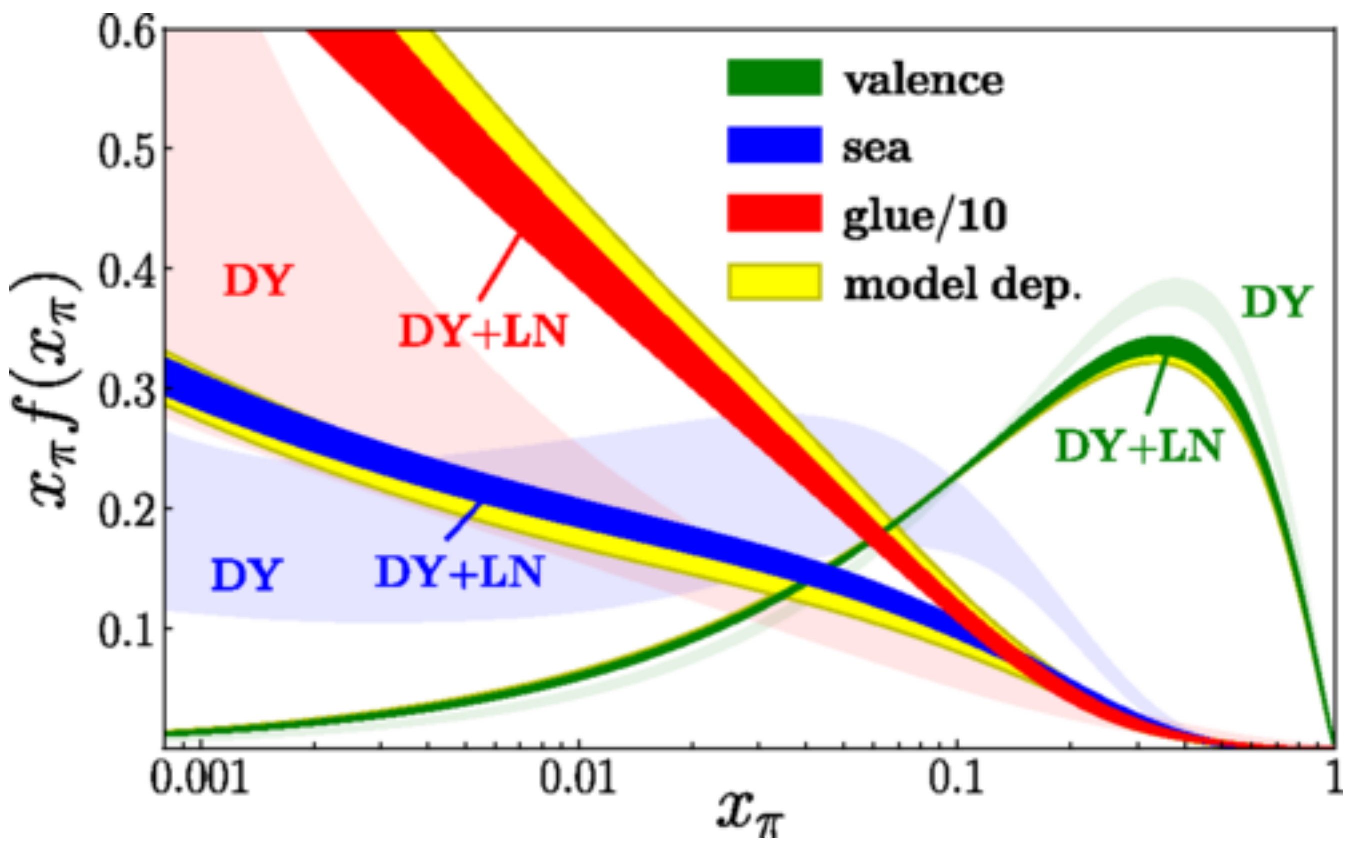


M. Aicher et al, PRL 105, 252003 (2010)

only DY data was used

impact of leading neutron (LN) data from HERA

First MC global QCD analysis



P.C.Barry et al, PRL 121, 152001 (2018)

huge impact of LN data

pion cloud model dependent

the new experiment aim to contribute significantly for this analysis

Nuclear dependance studies:
Flavour-dependent valence modifications

More than 30 years ago - the EMC effect

the parton distributions in a bound nucleon differ from those in a free nucleon

Recently after the E03-103 experiment at JLab Hall-C

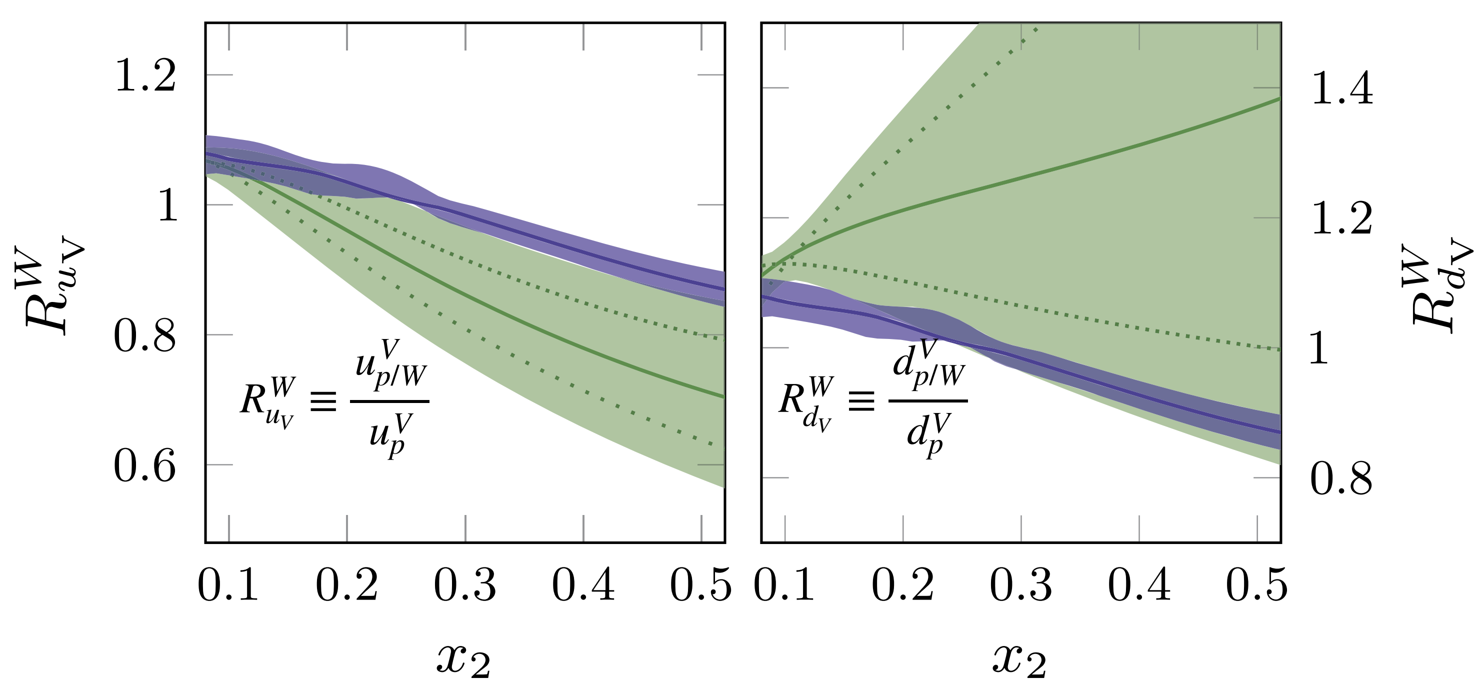
the nuclear dependence is not always a function of the atomic number or the mean nuclear density

J. Seely et al, PRL 103 (2009) 202301

Contrary to DIS, DY may probe the quark flavour involved and see if if the nuclear effects depend on it

this may have a strong effect on global fits of nuclear PDFs

nuclear modification factors



P. Paakkinen et al, PLB 768 (2017) 7-11

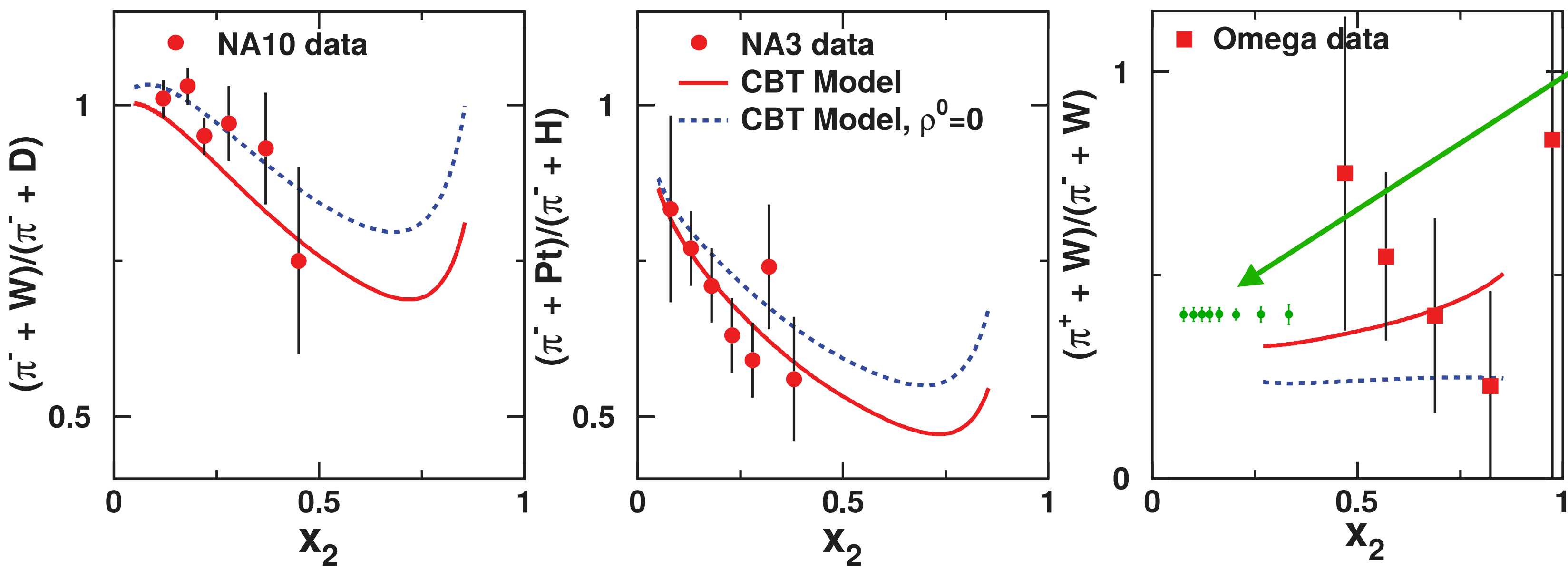
nCTEQ15 global fit with no quark flavour constrains

EPS09 global fit imposes the same nuclear modifications for u and d

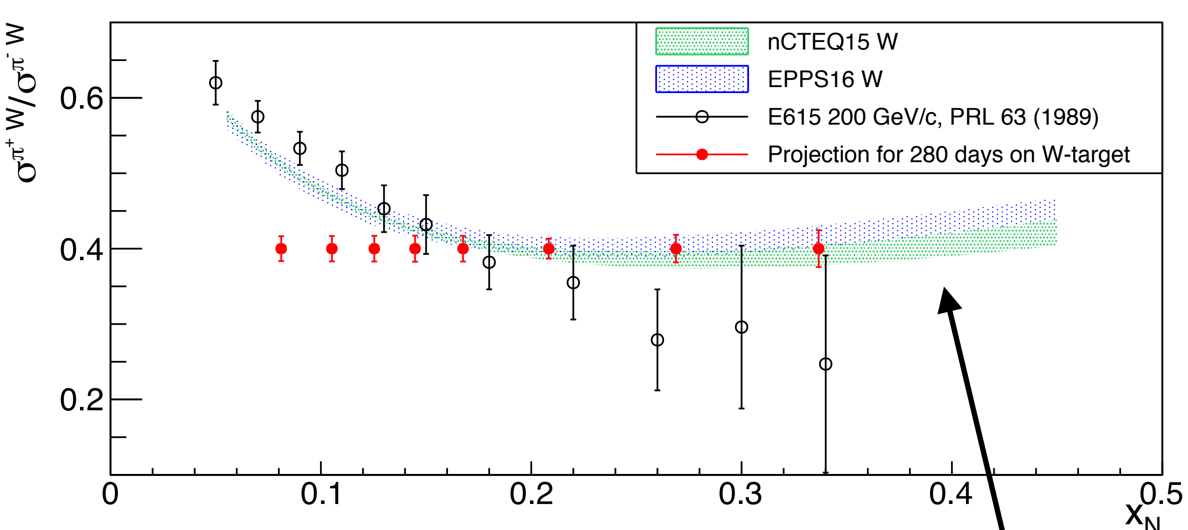
Nuclear dependance studies: New experiment contribution

W target 40 cm downstream from C targets

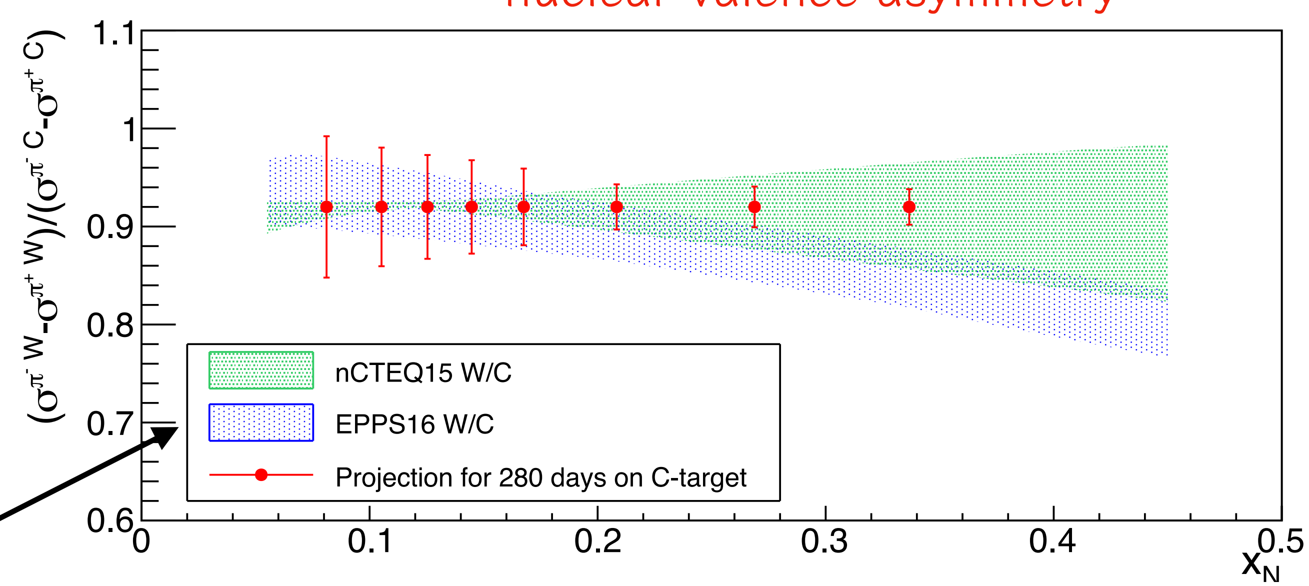
D. Dutta et al, Phys. Rev. C 83 (2011) 042201



statistical projection from the planned measurement at CERN



observable more sensitive to the nuclear valence asymmetry



two recent nuclear PDFs

Run plan - improvements

improved radiation shielding

↓

increase the beam intensity

↓

reach the same statistical uncertainties in 1 year

new analysis tools

↓

machine learning techniques

↓

extend the DY sample for masses lower than 4.3 GeV/c^2

New and improved instrumentations:

1. Cedars or equivalent detectors: requirement of a beam PID efficiency higher than 90%
2. Dedicated luminosity detectors, counters before each target: precise luminosity measurement, ~3%
3. Beam trackers: precise beam reconstruction
4. Vertex detector: improvement on vertex resolution
5. Dimuon trigger: high purity and precision and with target pointing capability

Worldwide competition

high energy pion beams are exclusively available at CERN

pion parton distributions

measurements through leading-neutron DIS electron-production

using tagging techniques

relies on the validity of the pion-cloud model

unknown normalisation of the pion flux

measurements at HERA - cover the x region below 0.01

new experiment at JLab in larger x and EIC in low x

need precise DY data to fix the normalisation at high x

pion induced charmonium production

no competition

quark distribution for different nuclei

SeaQuest experiment probe the sea quarks (p-p)

complementary to this experiment, when combined with the data for the valence quarks (π-p)

flavour dependent nuclear modifications

JLab EMC PVDIS propose to investigate it as well

Summary

3 years available from 2022 to 2025 with the possibility to use the already existing beams at M2 beam line

Hadron physics with standard muon beams

1. Proton radius measurement using mu-p elastic scattering 1st priority
2. Exclusive reactions with muon beams and transversely polarised target 2nd priority

Hadron physics with standard hadron beams

1. Drell-Yan and charmonium production with conventional hadron beams 1st priority
2. Spectroscopy with low-energy antiprotons 2nd priority
3. Measurement of antimatter production cross sections for Dark Matter Search "for free"

as currently stated in the LoI

Year	Activity	Duration	Beam
2019 2020	LS2	2 years	-
2021	COMPASS transversity with polarised deuteron target	1 year	muon
2022	proton radius	1 year	muon
2023 2024	Drell-Yan for π and K PDFs and charmonium production mechanism	$\lesssim 2$ years	p, K^+, π^+ $\bar{p}, K^-, \pi^-$
	Antiproton cross section for Dark Matter Search	2 month	p
2025	LS3 (for SPS)		

Table 1: Tentative schedule of the CERN M2 beam line

end of COMPASS (2019–2021)

new QCD facility (2022–2025)

Deadlines and New collaborators

The LoI is open for new ideas and authors

To be submitted to CERN committee (SPSC) by the end of 2018
with the final author list

After the submission the efforts will be focus on the preparation of the proposal

To be submitted by the end of 2019

More info on the webpage https://nqf-m2.web.cern.ch/

Everybody is welcome to join