Dimuon experiments (DY and J/ψ production) at the new COMPASS++/AMBER facility at CERN

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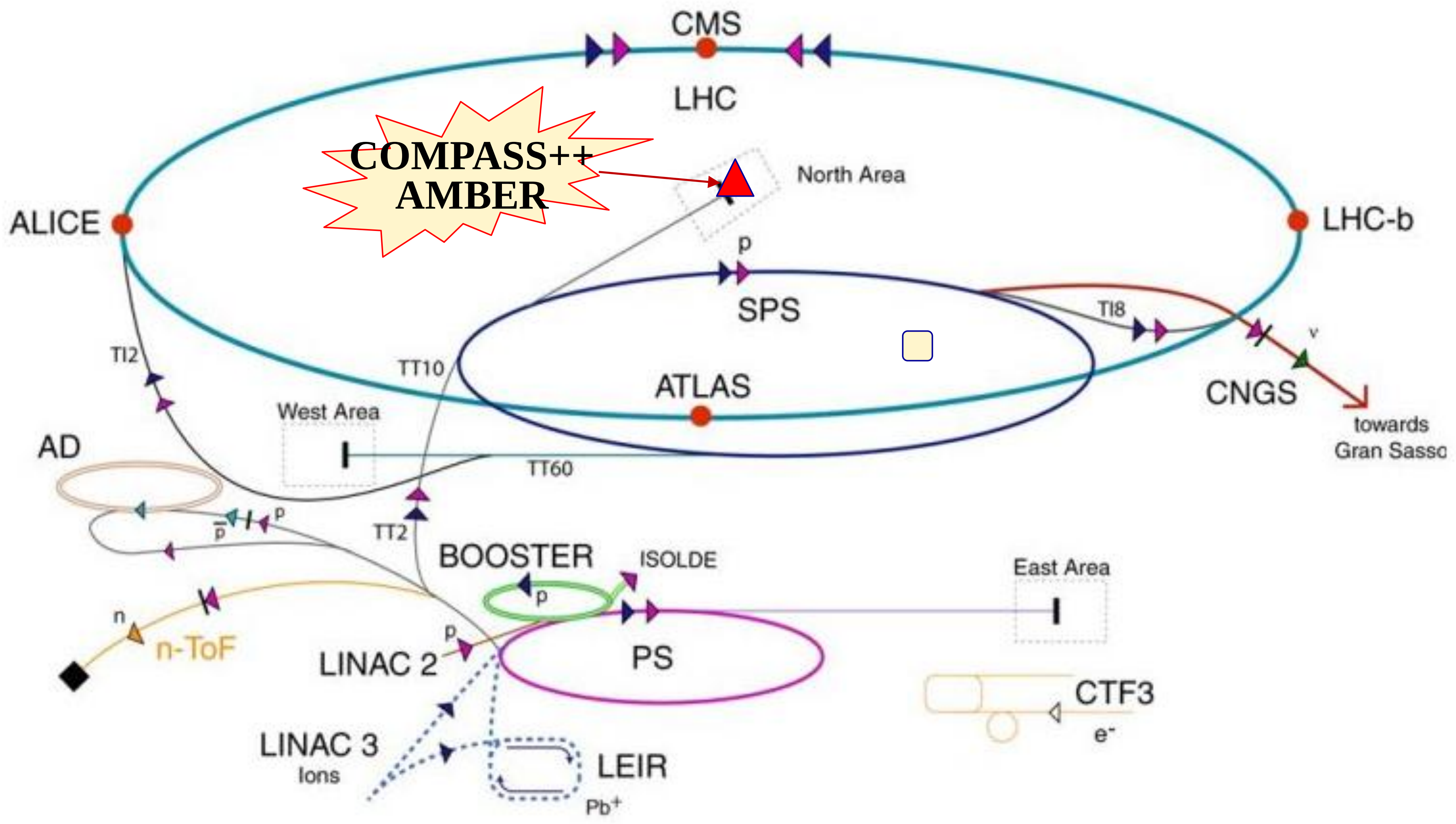
QCD on the light cone

Ecole Polytechnique, Palaiseau, France, 16 – 20 September 2019

COMPASS++/AMBER@CERN accelerator complex



COMPASS++/AMBER Collaboration

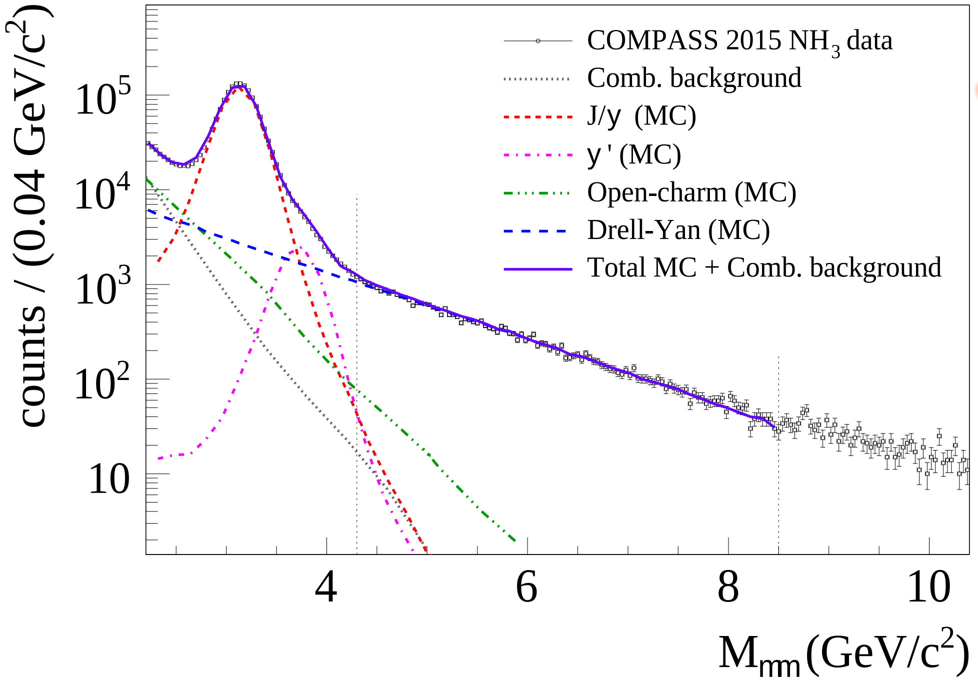
- Experiments planned for CERN RUN3 (2022-2024) :
  proposal submitted to SPSC, second version to be released end of September
  - Proton radius measurement using μ-p elastic scattering
  - Antiproton production cross section for dark matter search
  - **Drell-Yan and charmonium production with pion beams : present talk**

- Experiments also planned for CERN RUN4 (2026++) : described in a Letter of Intent
  - Drell-Yan and charmonium production with kaon and antiproton beams:
  - Study of the kaon PDFs, J/psi production mechanism, prompt photon production with K and π beams, etc….

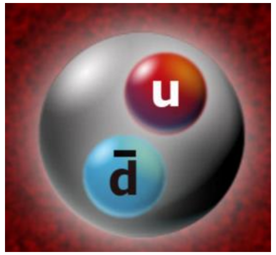
Dedicated web page: **https://nqf-m2.web.cern.ch/**

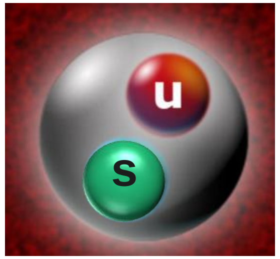
Main motivations of the (dimuon section) of the proposal

- Structure of the pion
  - Separate pion valence and pion sea PDFs, using positive and negative pion beams
- Flavor-dependent effects in nuclear targets
  - Make use of two pion beam charges in combination with light and heavy targets.
- Charmonium production mechanism at fixed-target energies
  - Measure pion and proton-induced J/ψ cross sections simultaneously



1) Hadron structure: why study the light mesons





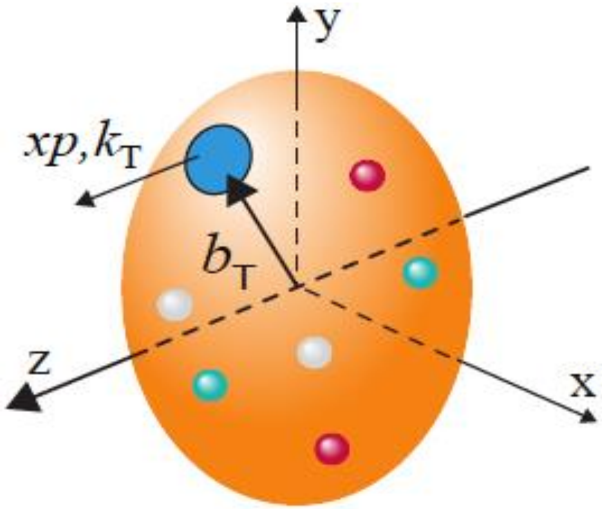
- Meson structure
  - What is the behavior of the kaon and pion PDFs vs the nucleon?
  - Are kaon and pion gluon distributions identical?
  - The *s* quark in the kaon is heavier: how is the total momentum shared?
- Double nature
  - The lightest quark-antiquark pairs
  - Massless Nambu-Goldstone bosons that acquires mass through DCSB
- Recently : significant progress of non-pQCD calculations: lattice-QCD, DSE, etc..
  - Aim at describing hadron properties

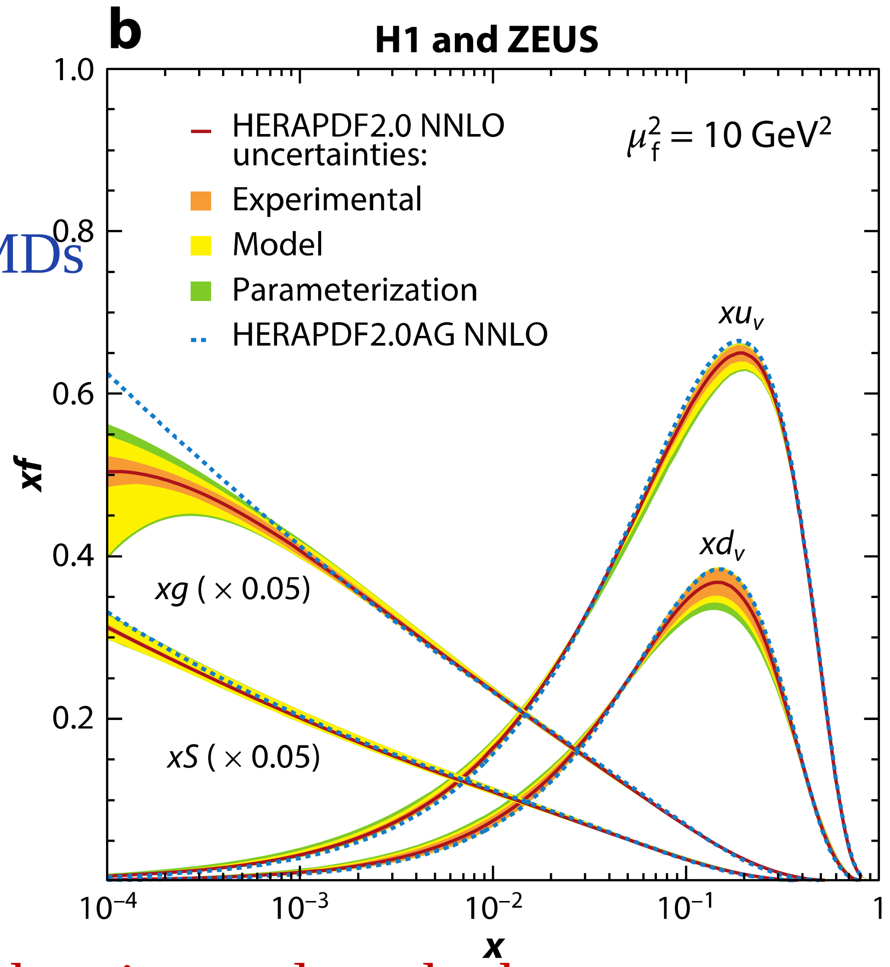
  Craig Roberts (2016): *"Thus, enigmatically, the properties of the massless pion are the cleanest expression of the mechanism that is responsible for almost all the visible mass in the universe."*

  Needed is: experimental information on meson's valence, sea and gluon PDFs

Digression: nucleon structure

- Main laboratory for QCD studies
  - More than 4 decades of extensive investigations
  - Parton distributions well known in a large *x* domain
  - Today: aim at a full multidimensional picture : GPDs, TMDs





Sharp contrast with the present knowledge on the pion and on the kaon
Almost no new meson data since more than three decades!

Pion valence PDF – present status

- Drell-Yan pion data available today are three decades old !
  - ~Fermilab and CERN : E331(1979), NA3(1983), NA10(1985), E537(1988), E615(1989)

Badier et al., Z.Phys. C18, 281 (1983).

Anassontzis et al., PRD38, 1377 (1988).

Conway et al., PRD 39, 92 (1989).

E = 200 GeV

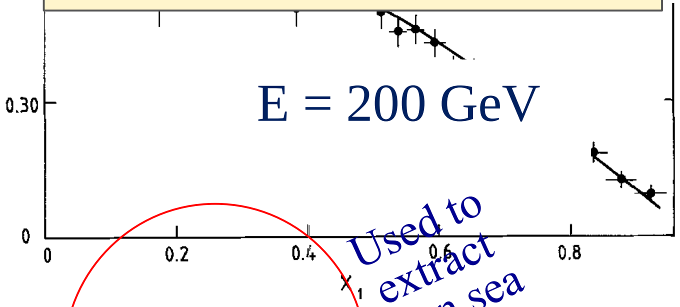


Fig. 1. a π^- 200 GeV data. The data points represent $F_\pi(x_1)$ as defined b curve represents the valence structure function of the pion obtained from function as defined by (2). **b** The data points represent $F_\pi(x_2)$ as defined structure function $1.6u(x_2)+2.4d(x_2)$ for π^-. Solid curve represent the (v curves have been scaled up by a factor $K=2.3$

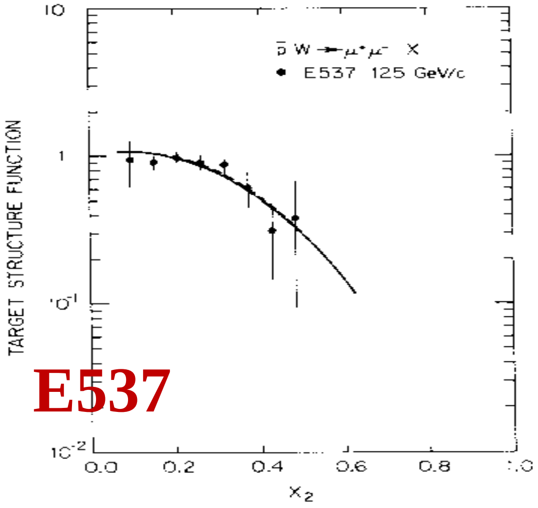
Table 4. Result of the fit of the pion valence structure function with the data at $\langle M^2_{\mu\mu}\rangle = 25$ GeV^2. The π sea and nucleon valence and sea structur

NA3

	σ	Correlation coefficients	Systema
			pion sea
π^- 150 GeV/c	$\alpha^\pi=0.41$	0.05	∓0.03

E = 125 GeV

398



E615

E. AN

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NA3

eral $m_{\mu\mu}$ intervals. The solid line is the cross sec ected from the structure-function determination.

3. *Pion structure*

NA10

he results for the pion structure function are sh ig. 12(a). The parameters corresponding to the cu given in Table I, column 1 and the projected va the pion structure function in Table II. The para ation makes no allowance for scale-breaking eff ause these are very small as shown below.

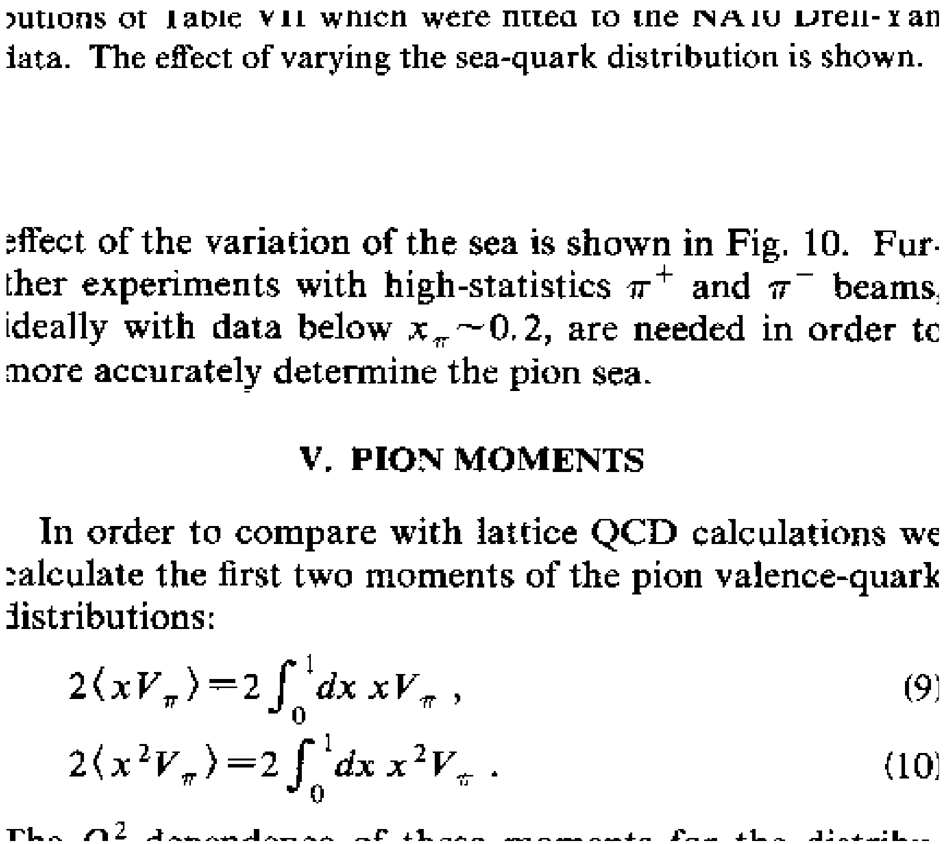
E615

The data determine only the pion valence ($x > 0.2$) PDF …

Pion valence PDF: Main "global" fits available

SMRS (NLO) 1992

Sutton, Martin, Roberts and Stirling, PRD 45, 2349 (1992).


ɔutions of Table VII which were fitted to the NA10 Drell-Yan
lata. The effect of varying the sea-quark distribution is shown.

effect of the variation of the sea is shown in Fig. 10. Further experiments with high-statistics π^+ and π^- beams, ideally with data below $x_\pi \sim 0.2$, are needed in order to more accurately determine the pion sea.

V. PION MOMENTS

In order to compare with lattice QCD calculations we calculate the first two moments of the pion valence-quark distributions:

$$2\langle xV_\pi\rangle = 2\int_0^1 dx\, xV_\pi\ , \quad (9)$$

$$2\langle x^2V_\pi\rangle = 2\int_0^1 dx\, x^2V_\pi\ . \quad (10)$$

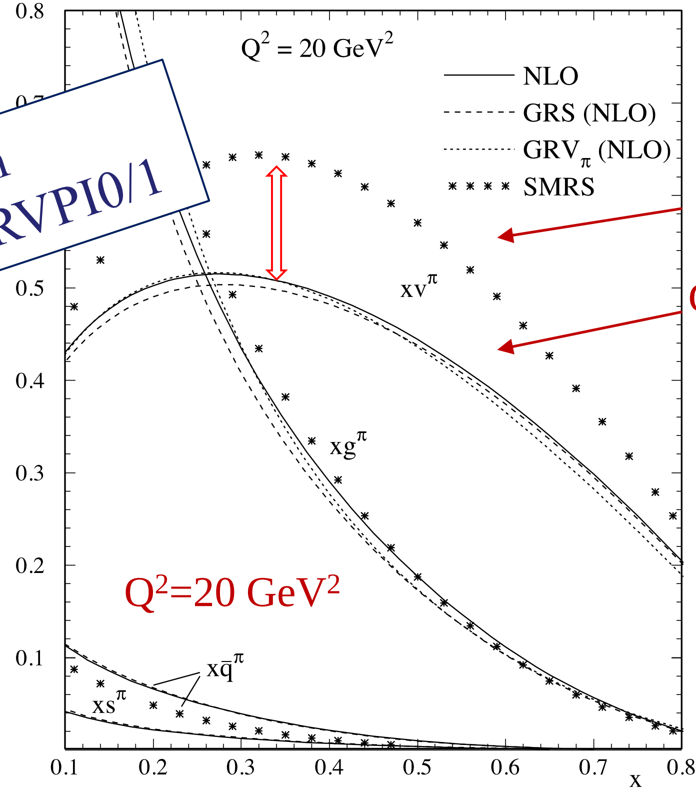
The Q^2 dependence of these moments for the distribu-

GRV/S (NLO) 1992,1999

GRV: Z Phys C53, 651 (1992).

GRSh: Eur Phys J C10, 313 (1999).

Mostly used in LHAPDF: GRVPI0/1



Q^2=20 GeV^2

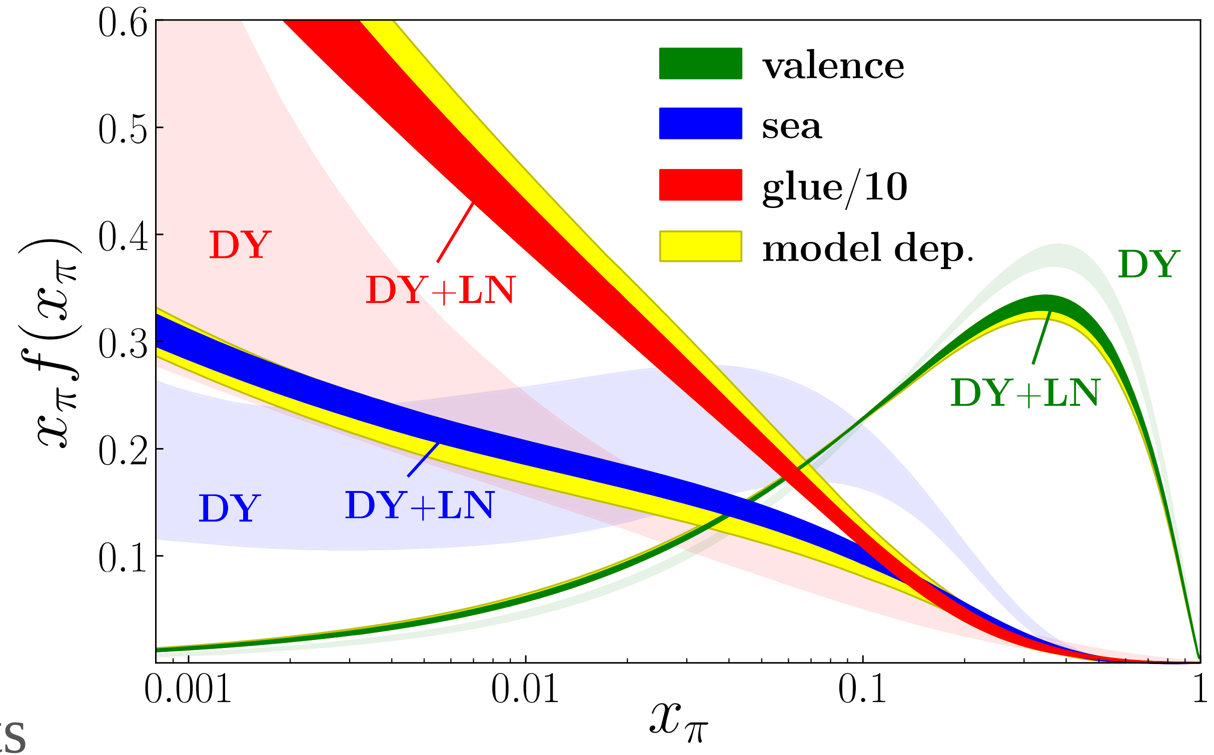
SMRS

GRV/S

Global fits produce non-consistent results : 20% difference at x = 0.5 !

2018: new, MC-type, global fit of pion PDFs

Barry et al., PRL 121, 2018



- Results
  - Uncertainties are reduced using DY+LN, as compared to DY alone
  - Large-x behavior: ~ $(1\text{-}x)^1$, instead of $(1\text{-}x)^2$ as expected by QCD or DSE.
  - Momentum fractions closer to SMRS-3: valence 48%, sea 17%, glue 35%.

AMBER goal: improve valence PDF and extract sea PDF

- Write cross sections for π^+ and π^- beams

$$\sigma(\pi^+ p) \propto \frac{4}{9}\left[u_v^p(x)\cdot \bar{u}_s^p(x)\right] + \frac{4}{9}\left[\bar{u}_s^p(x)\cdot u_v^p(x)\right] + \frac{1}{9}\left[\bar{d}_v^p(x)\cdot d_v^p(x)\right] + \frac{1}{9}\left[d_s^p(x)\cdot \bar{d}_s^p(x)\right]$$

$$\sigma(\pi^- p) \propto \frac{4}{9}\left[\bar{u}_v^p(x)\cdot u_v^p(x)\right] + \frac{4}{9}\left[u_s^p(x)\cdot \bar{u}_s^p(x)\right] + \frac{1}{9}\left[\bar{d}_s^p(x)\cdot d_v^p(x)\right] + \frac{1}{9}\left[d_v^p(x)\cdot \bar{d}_s^p(x)\right]$$

- Apply charge and isospin invariance and form two combinations:

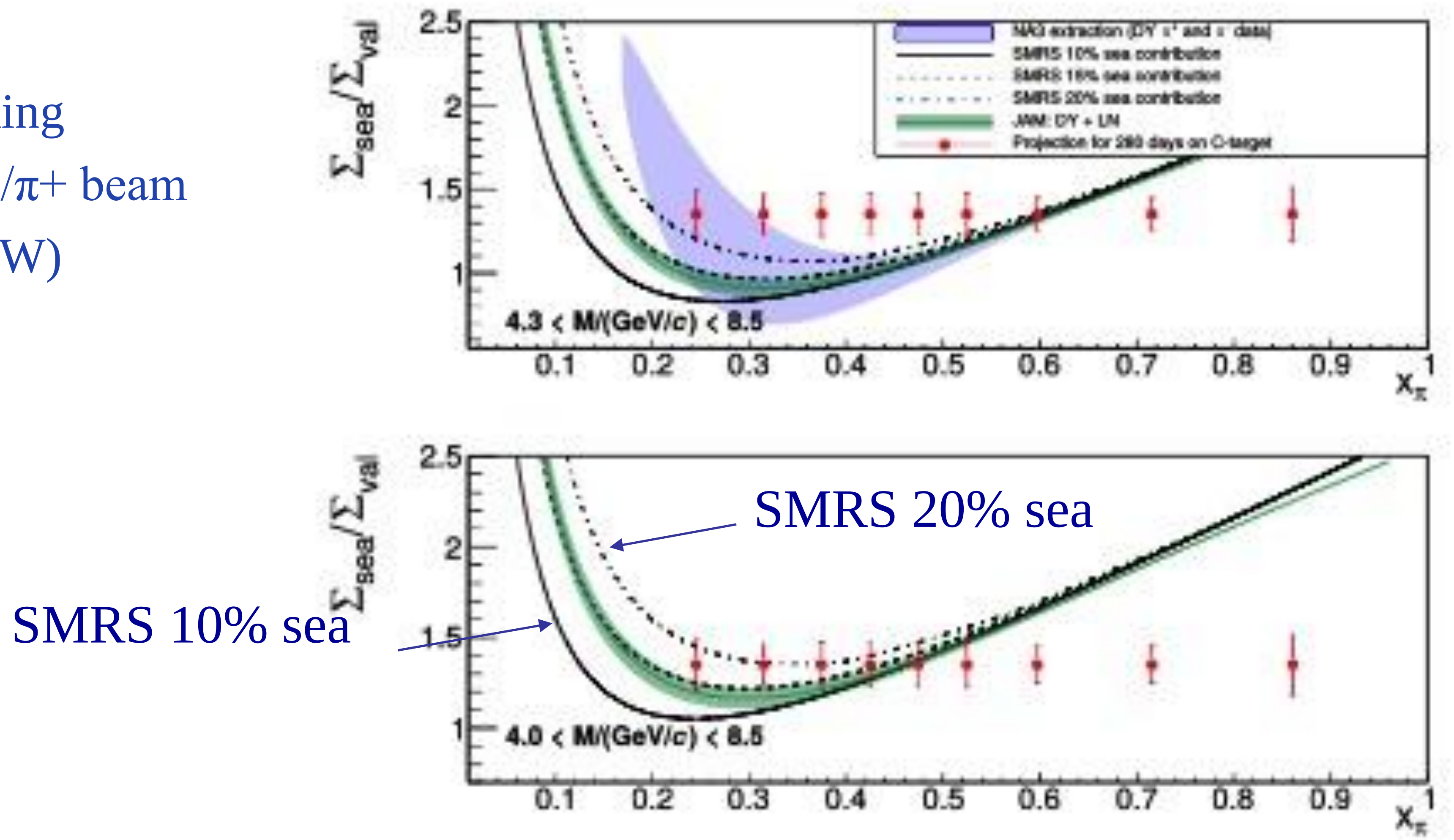
$$\Sigma_{sea}^{pD} = 4\sigma^{\pi^+ D} - \sigma^{\pi^- D}$$ No valence-valence terms

$$\Sigma_{val}^{pD} = -\sigma^{\pi^+ D} + \sigma^{\pi^- D}$$ Only valence-valence terms

- Expected statistics in 4.0 – 8.5 GeV on 12C: ~30 000 π+ and ~30 000 π−

Valence-sea separation in π: projected results

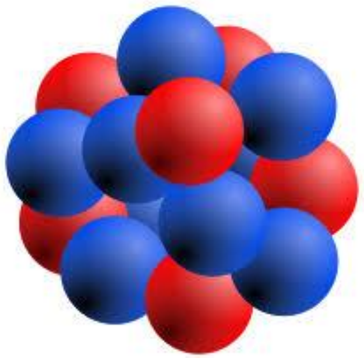
- Assumptions
  - 280 days of data taking
  - 1/8 separation of π−/π+ beam
  - ^{12}C target (and also W)



Clean separation between valence and sea for $x_\pi < 0.40$

2) Nuclear effects – studies using π-induced dimuon production

- Separate valence and sea nuclear effects with DY (DIS doesn't separate them)
  - Pion beams : probe mainly valence quarks of the target
  - Proton beams probe mainly sea quarks
    - Complementary experiments !

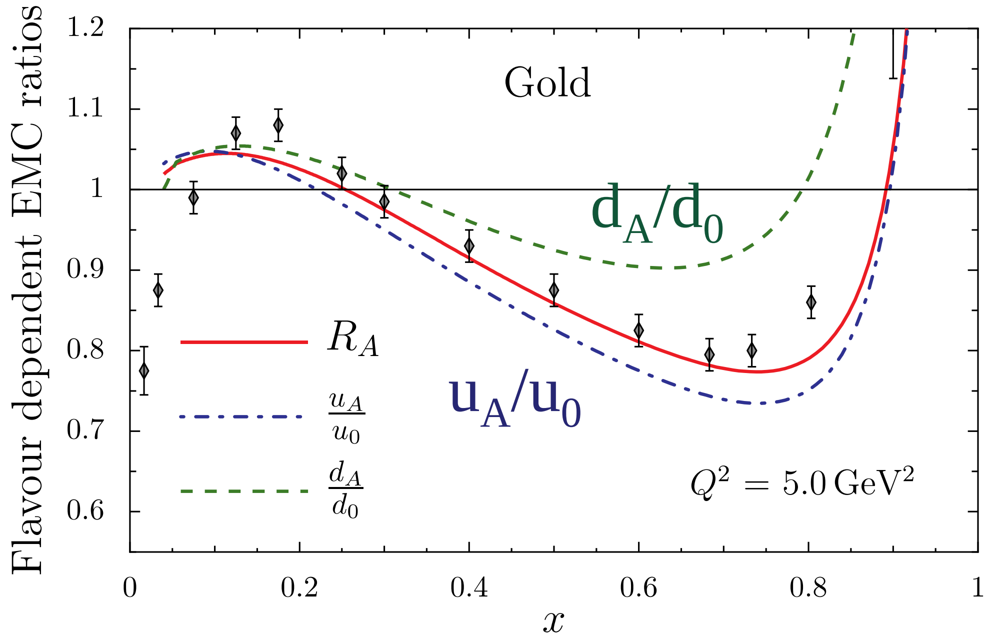


- Separate different flavors (DIS is not sensitive to the individual flavors)
  - Pion (π^-) beam : probes (preferentially) valence u quarks
  - Pion (π^+) beam : probes (preferentially) valence d quarks
  - Can probe the flavor dependence of the nuclear mean field
- Study the partonic energy loss effects
  - Comparison between DY and J/psi

Flavour dependence of the EMC effect

Cloët, Bentz and Thomas, PRL 102, 252301 (2009)

- Cloët, Benz and Thomas (2009):
  - use nuclear matter within a covariant Nambu–Jona-Lasinio model
  - look for flavour-dependence of the nuclear PDFs
    - *"…for N≠Z nuclei, the u and d quarks have distinct nuclear modifications."*



Free nucleon PDFs: u0, d0
Medium modified PDFs: uA, dA

DIS data are not sensitive to the flavour-dependence. Pion-induced DY data are.

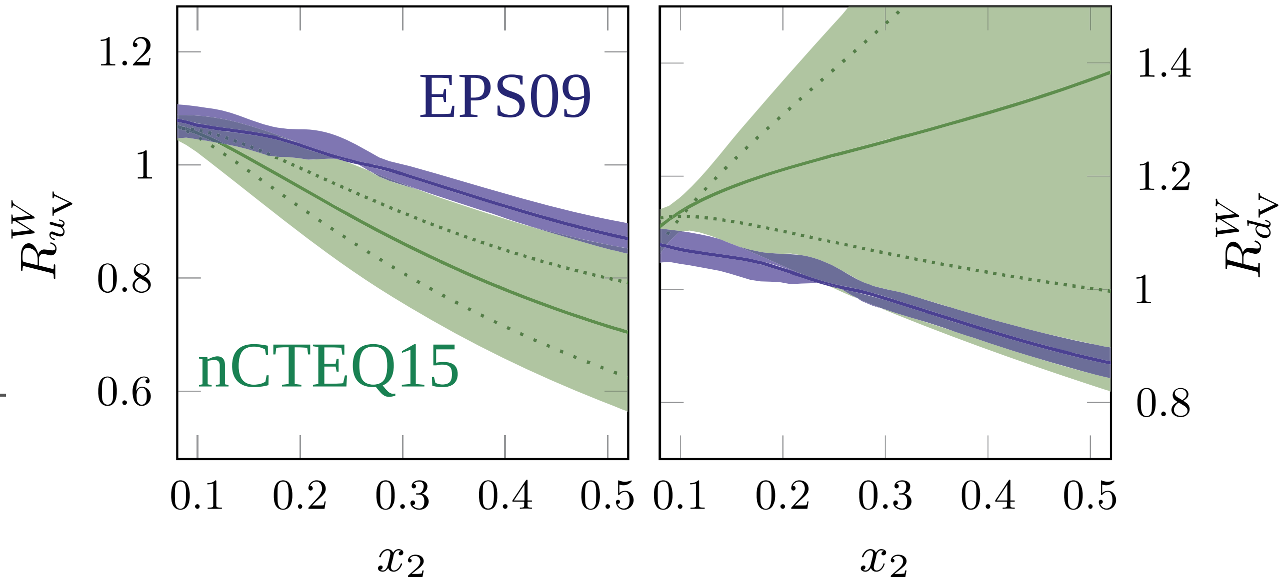
Flavour dependence of EMC effect

- When taking into account the possible flavor- dependence, the uncertainties of the nPDFs become much larger

- Pion-induced Drell-Yan with π+ and π−
  - $\pi^+(\bar{d}u)$: sensitive to the down quarks
  - $\pi^-(\bar{u}d)$: sensitive to the up quarks

$$R_{\pm} = \frac{\sigma^{DY}(\pi^+ + A)}{\sigma^{DY}(\pi^- + A)} \approx \frac{d_A(x)}{4\,u_A(x)}$$

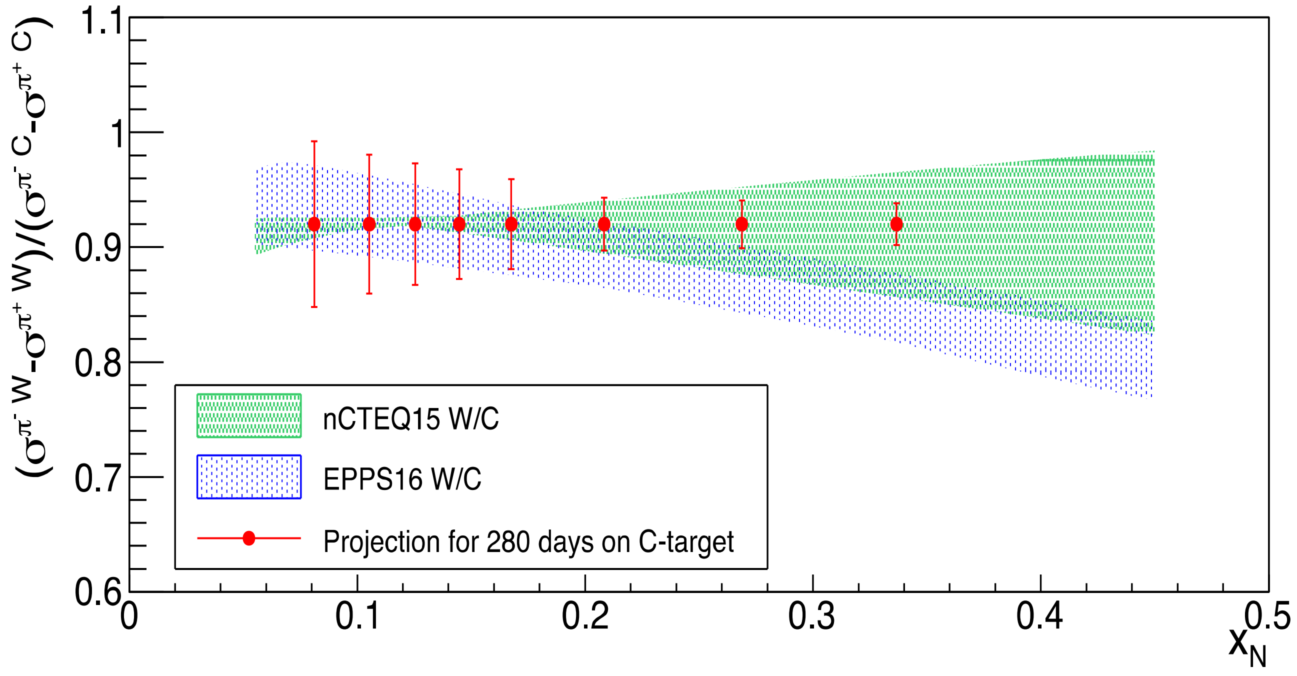
Paakkinen et al., Phys. Lett. B 768 (2017) 7



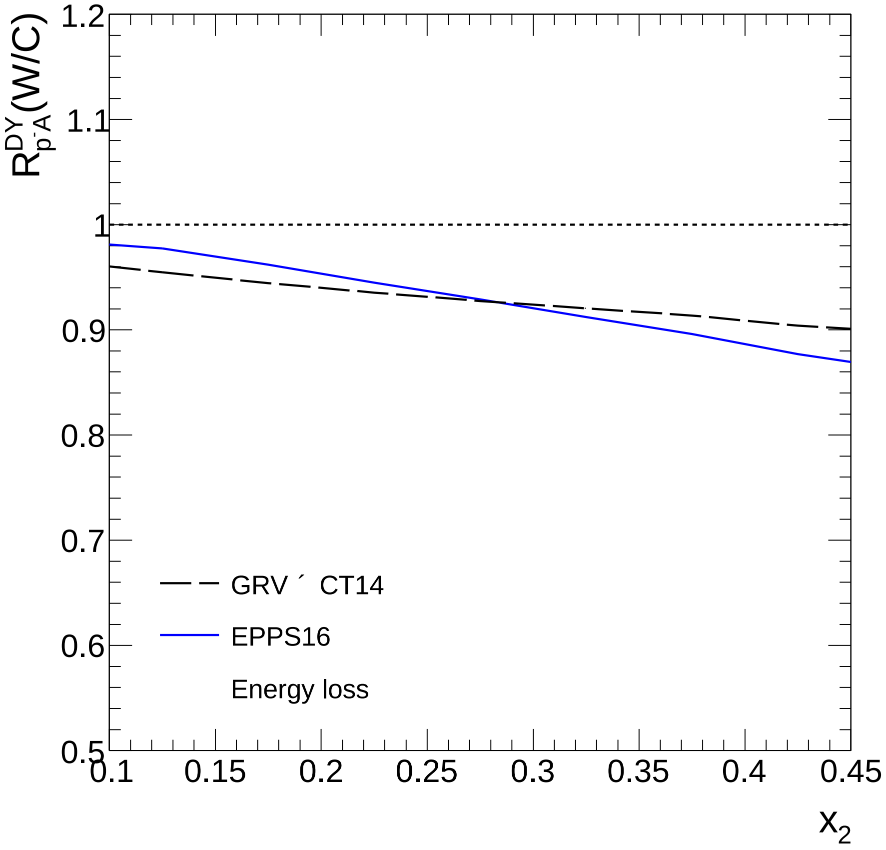
$u_V(x)$ $d_V(x)$

nCTEQ15 allows for different u and v nuclear dependences

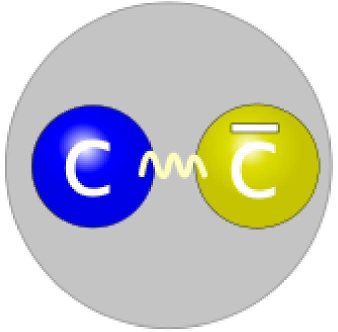
Cold nuclear effects: nPDFs and partonic energy loss



Arleo et al., JHEP 01 (2019) 129



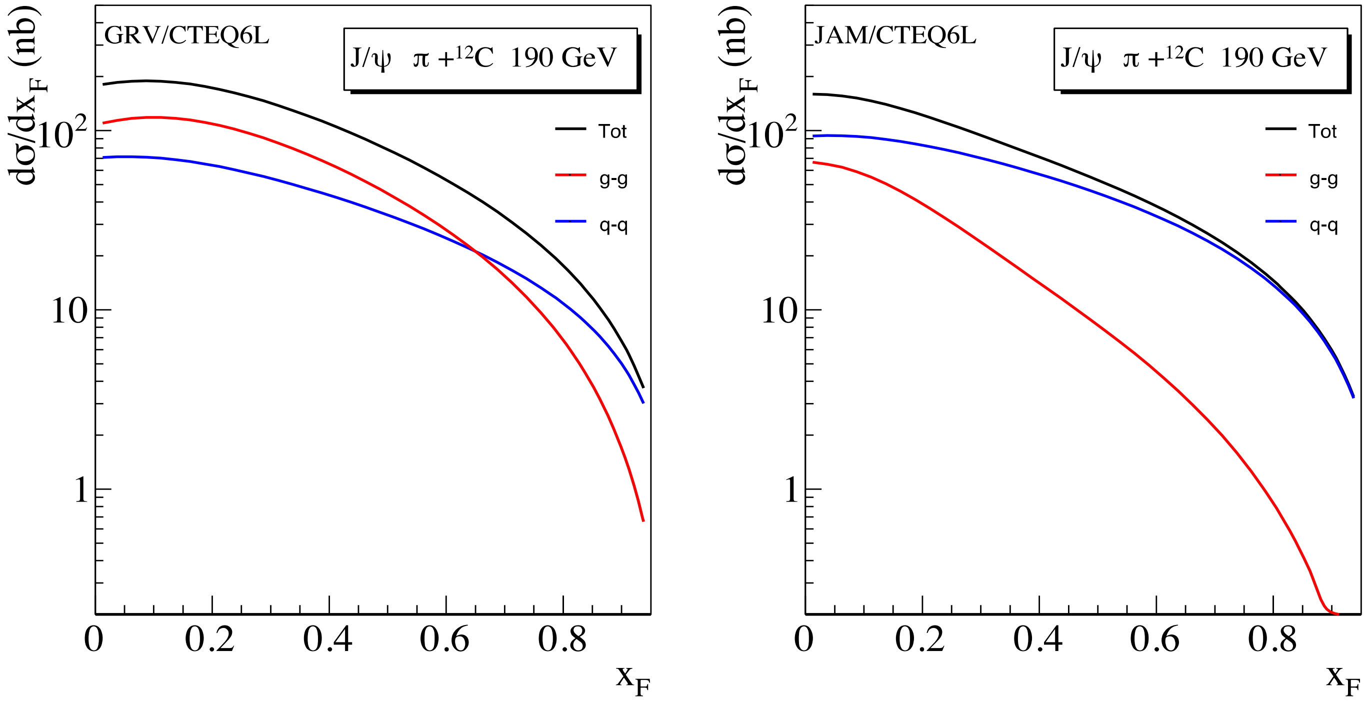
3) Charmonium production mechanism at FT energies



- Accumulate very large statistics: more than 10^6 events with:
  - positive pions, protons (collected simultaneously), negative pions
- Measure x_F distribution, p_T distribution, polarisation
  - Try to disentangle $q\bar{q}$ and gg contributions to the cross section
- Explore sensitivity of the data to the pion valence and gluon PDFs
- Access simultaneously ψ'
  - Compare J/ψ and ψ' observables

Pion-induced J/ψ cross section: model dependence

- J/ψ cross section for two different pion PDFs (CEM-LO)

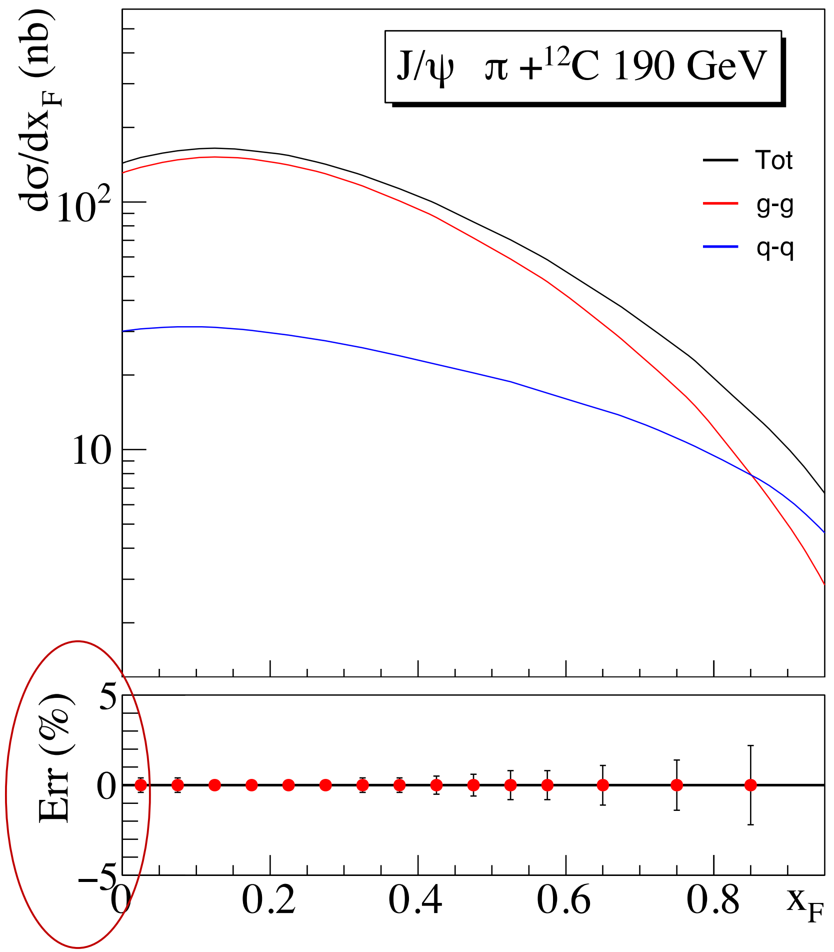


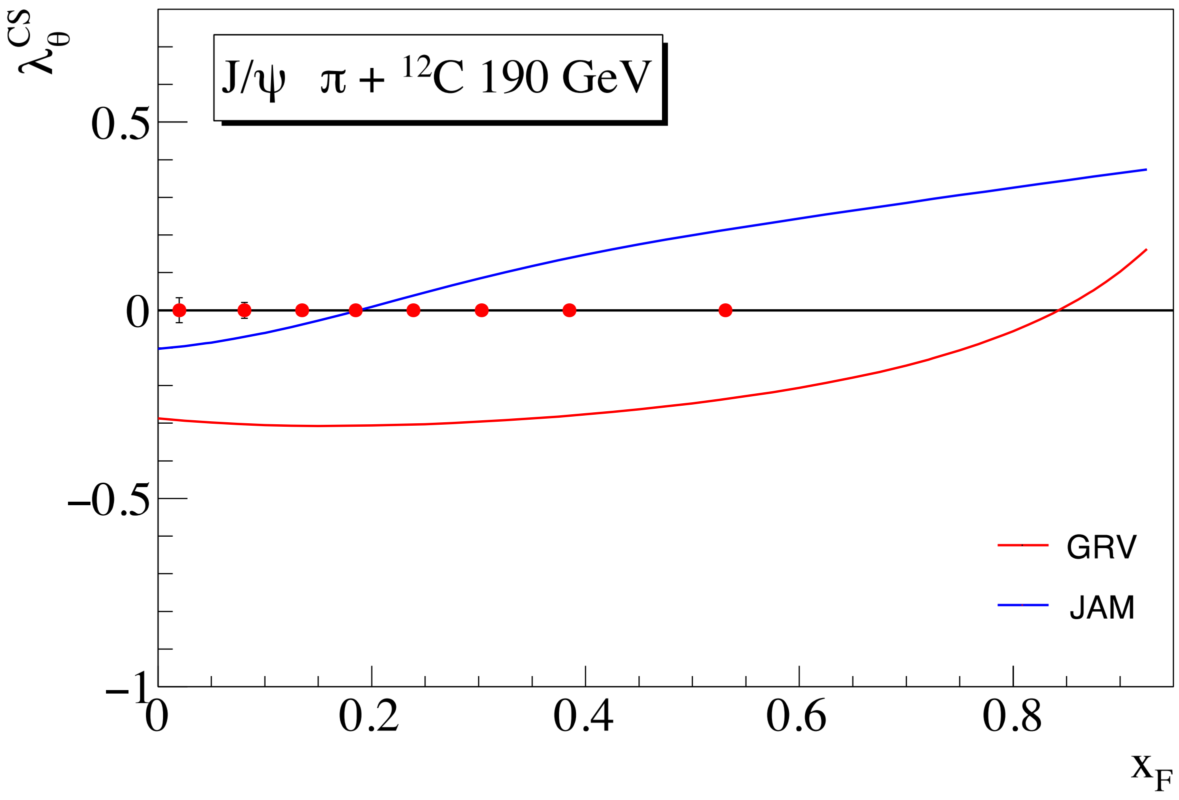
- J/psi proton-induced cross sections will be collected simultaneously with the pion ones
- A very large statistics foreseen

J/ψ production: expected statistics (ICEM model, NLO)

- Cross section as a function of xF

Polarisation

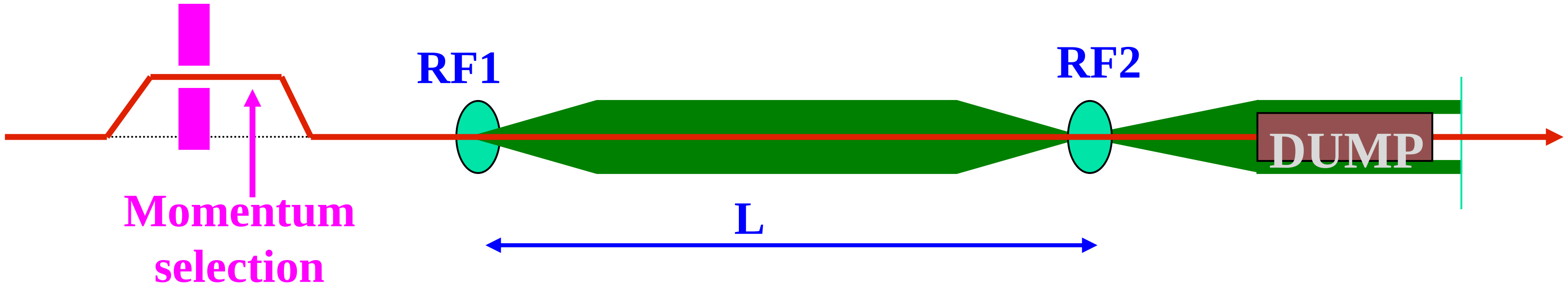




Cheung and Vogt, Phys. Rev. D98 (2018) 114029 and priv.comm.

Future: RF separated beams – high-intensity antiprotons and kaons

- Studies underway at CERN for RUN4 (2026++)
- Some assumptions:
  - L = 450 m, f = 3.9 GHz, beam spot within 1.5 mm
  - Reasonable primary target efficiency, 80% wanted particles pass dump
  - Number of primary protons: 100 - 400x10^{11} ppp on the production target



  - Energy limitation : 120 GeV

Large improvement in kaon and antiproton intensities (> x 20 !)

Outlook: why do dimuon experiments at AMBER@CERN

- CERN: only place in the world with
  - 1) mesons beams (pions, kaons) ; also proton and antiproton beams
  - 2) positive or negative beam charge
  - 3) large and uniform acceptance spectrometer (and planned improvements...)
  - 4) R&D for a new RF-separated beam line with unprecedented kaon/antiproton intensities

Unique features

- Proposed dimuon studies:
  - Valence and sea structure of the pion, kaon in the future
  - Flavor-dependent effects in nuclear targets
  - Charmonium production mechanism at fixed-target energies

Thank you