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

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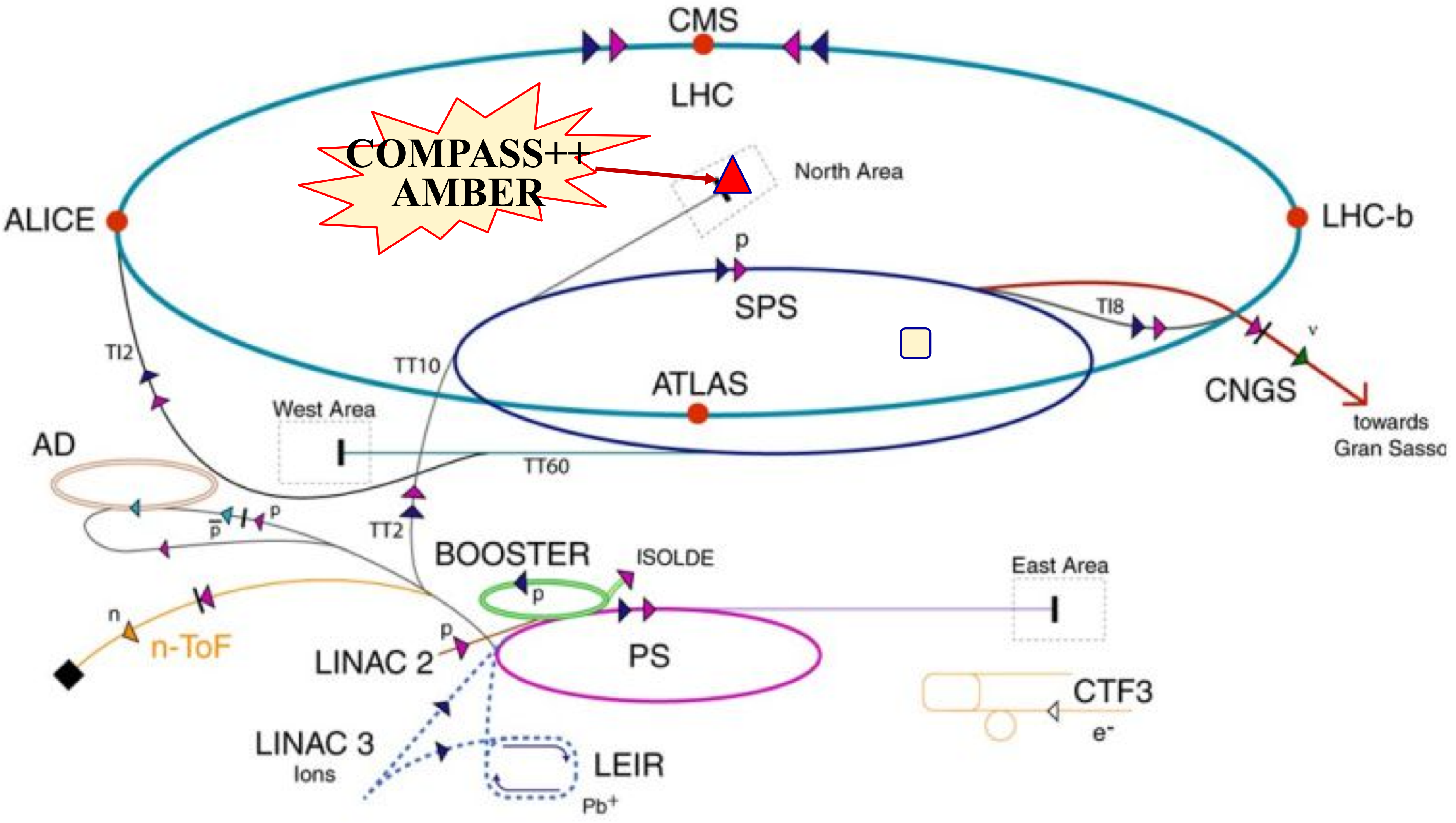
QCD on the light cone

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

COMPASS++/AMBER@CERN accelerator complex



COMPASS++/AMBER Collaboration

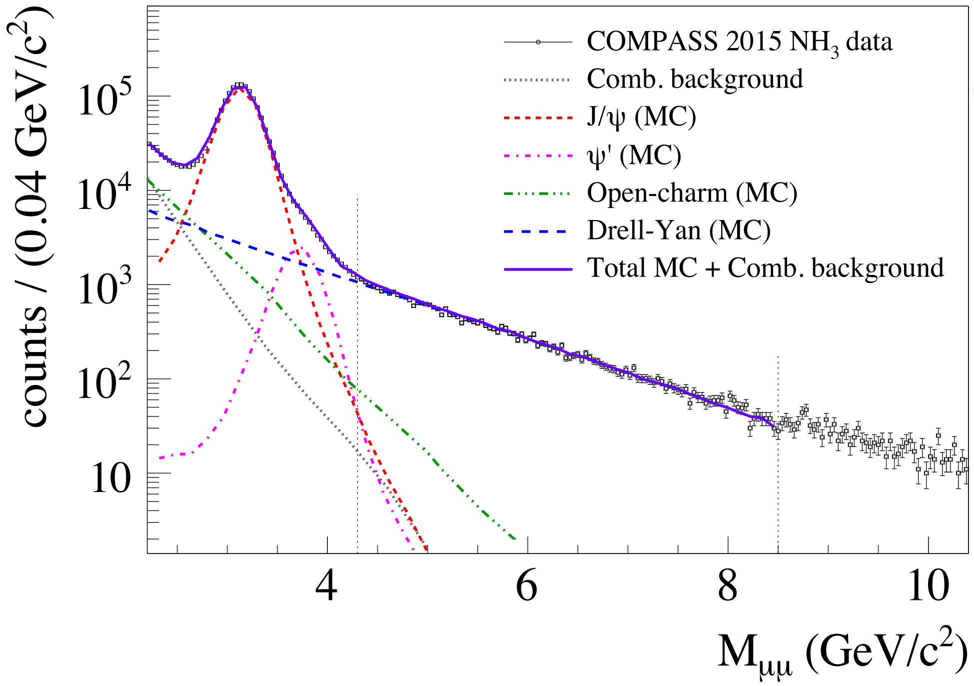
- Experiments planned for CERN RUN3 (2022-2024) :
  proposal submitted to SPSC, second version to be released end of September
  - Proton radius measurement using μ-p elastic scattering
  - Antiproton production cross section for dark matter search
  - **Drell-Yan and charmonium production with pion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

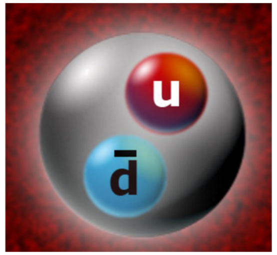
Dedicated web page: **https://nqf-m2.web.cern.ch/**

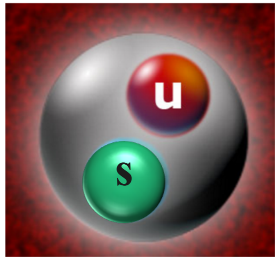
Main motivations of the (dimuon section) of the proposal

- 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





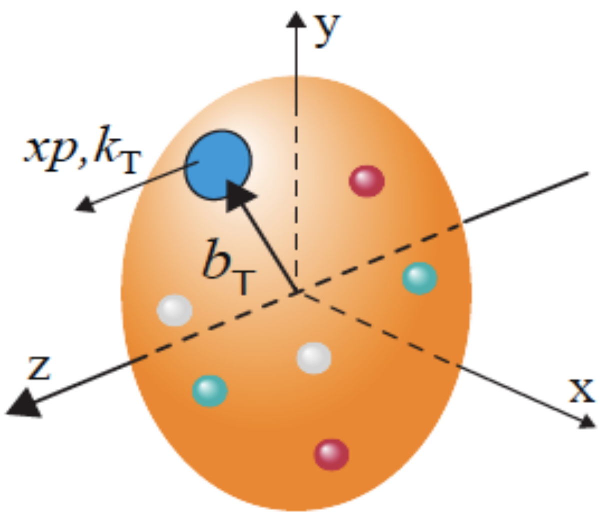
- Meson structure
  - What is the behavior of the kaon and pion PDFs vs the nucleon?
  - Are kaon and pion gluon distributions identical?
  - The *s* quark in the kaon is heavier: how is the total momentum shared?
- Double nature
  - The lightest quark-antiquark pairs
  - Massless Nambu-Goldstone bosons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

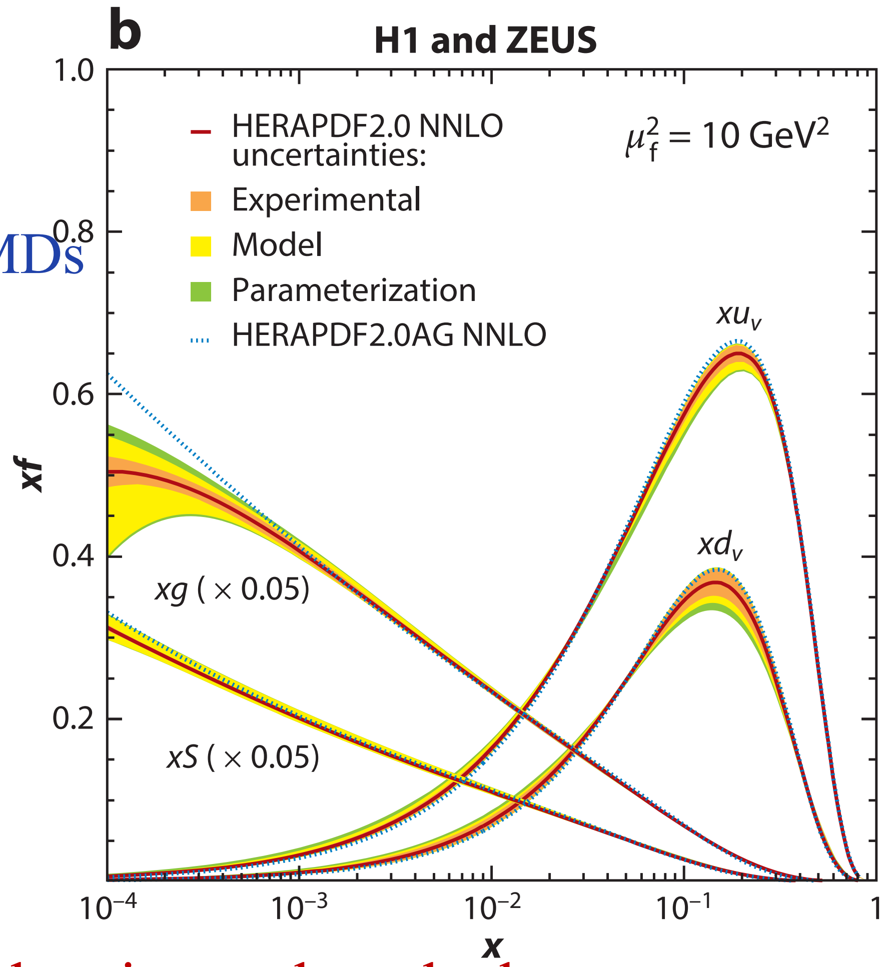
    Craig Roberts (2016): *"Thus, enigmatically, the properties of the massless pion are the cleanest expression of the mechanism that is responsible for almost all the visible mass in the universe."*

    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



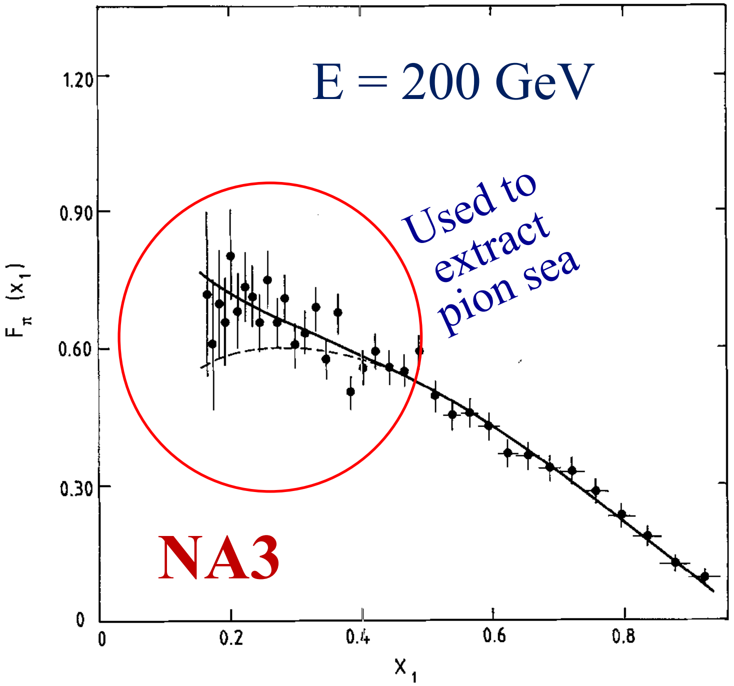


Sharp contrast with the present knowledge on the pion and on the kaon
Almost no new meson data since more than three decades!

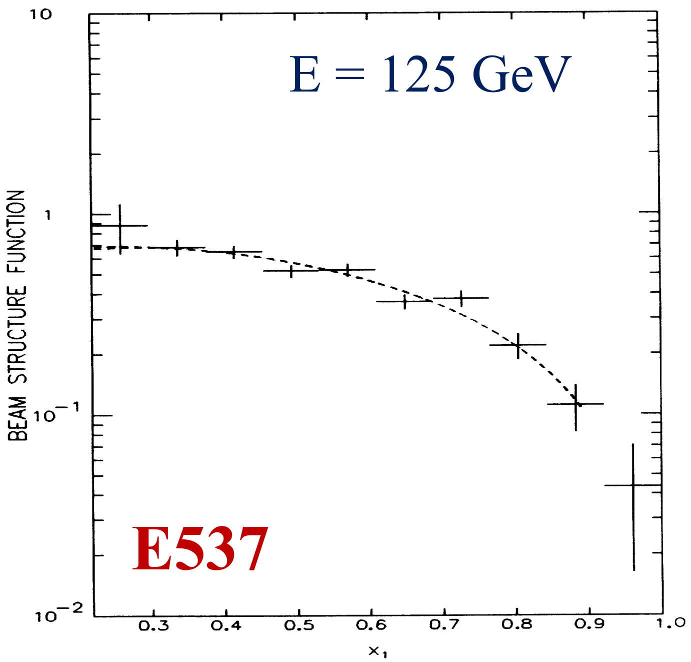
Pion valence PDF – present status

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

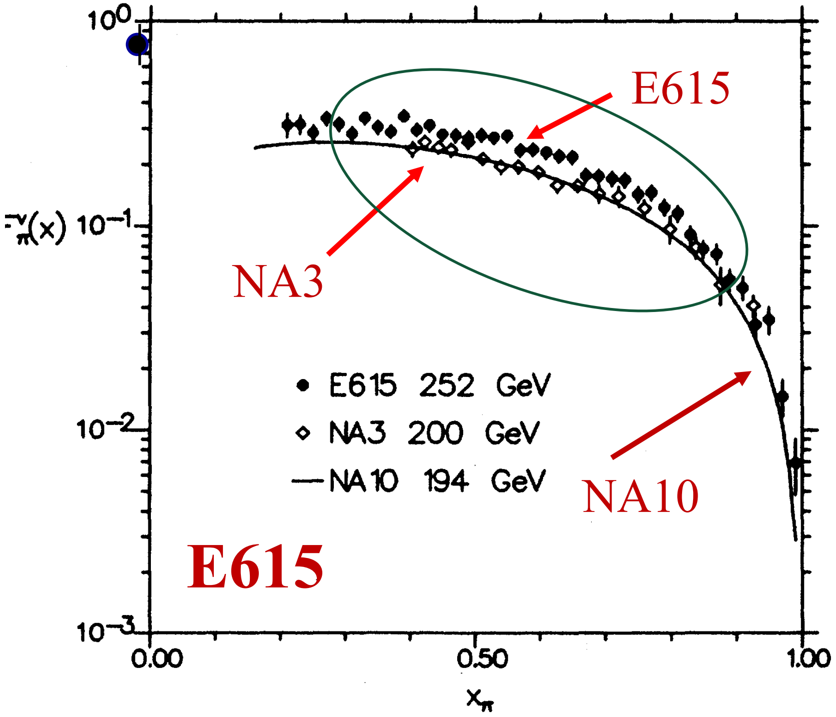
Badier et al., Z.Phys. C18, 281 (1983).



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



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

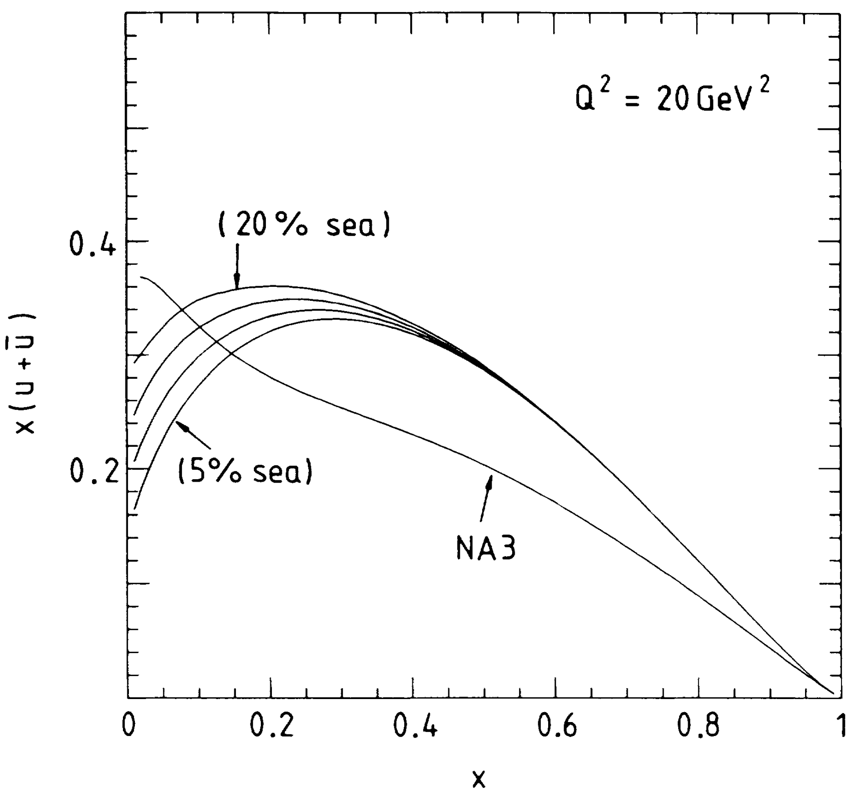


The data determine only the pion valence ($x > 0.2$) PDF …

Pion valence PDF: Main "global" fits available

SMRS (NLO) 1992

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

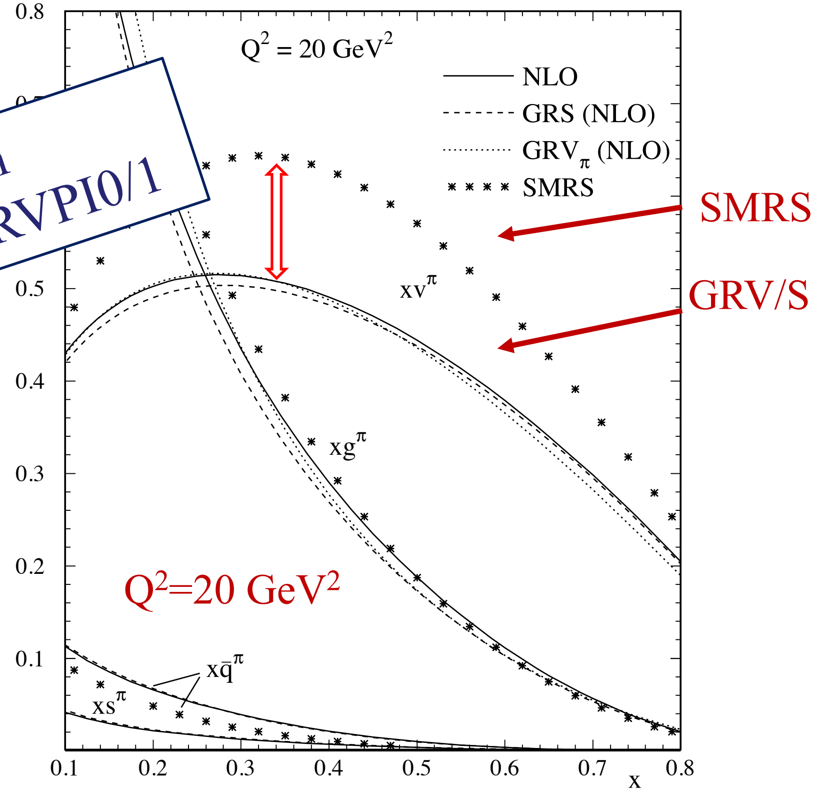


GRV/S (NLO) 1992,1999

GRV: Z Phys C53, 651 (1992).

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

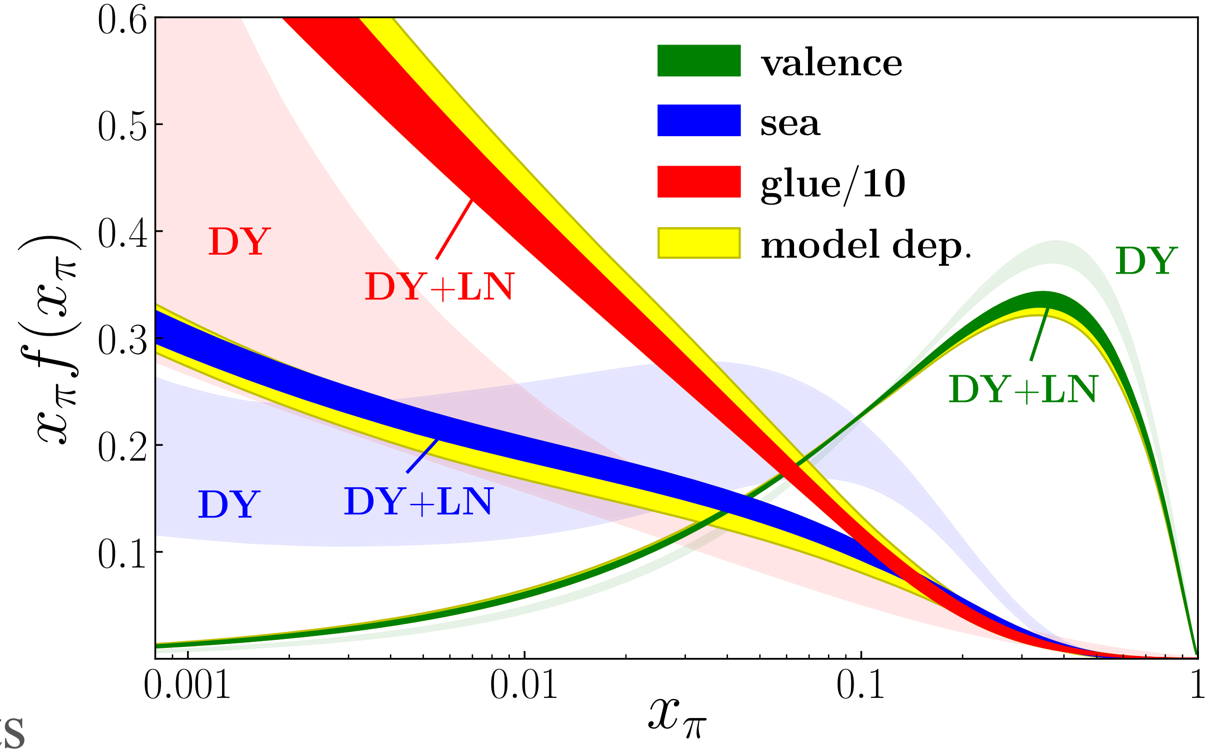
Mostly used in LHAPDF: GRVPI0/1



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

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

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

- Apply charge and isospin invariance and form two combinations:

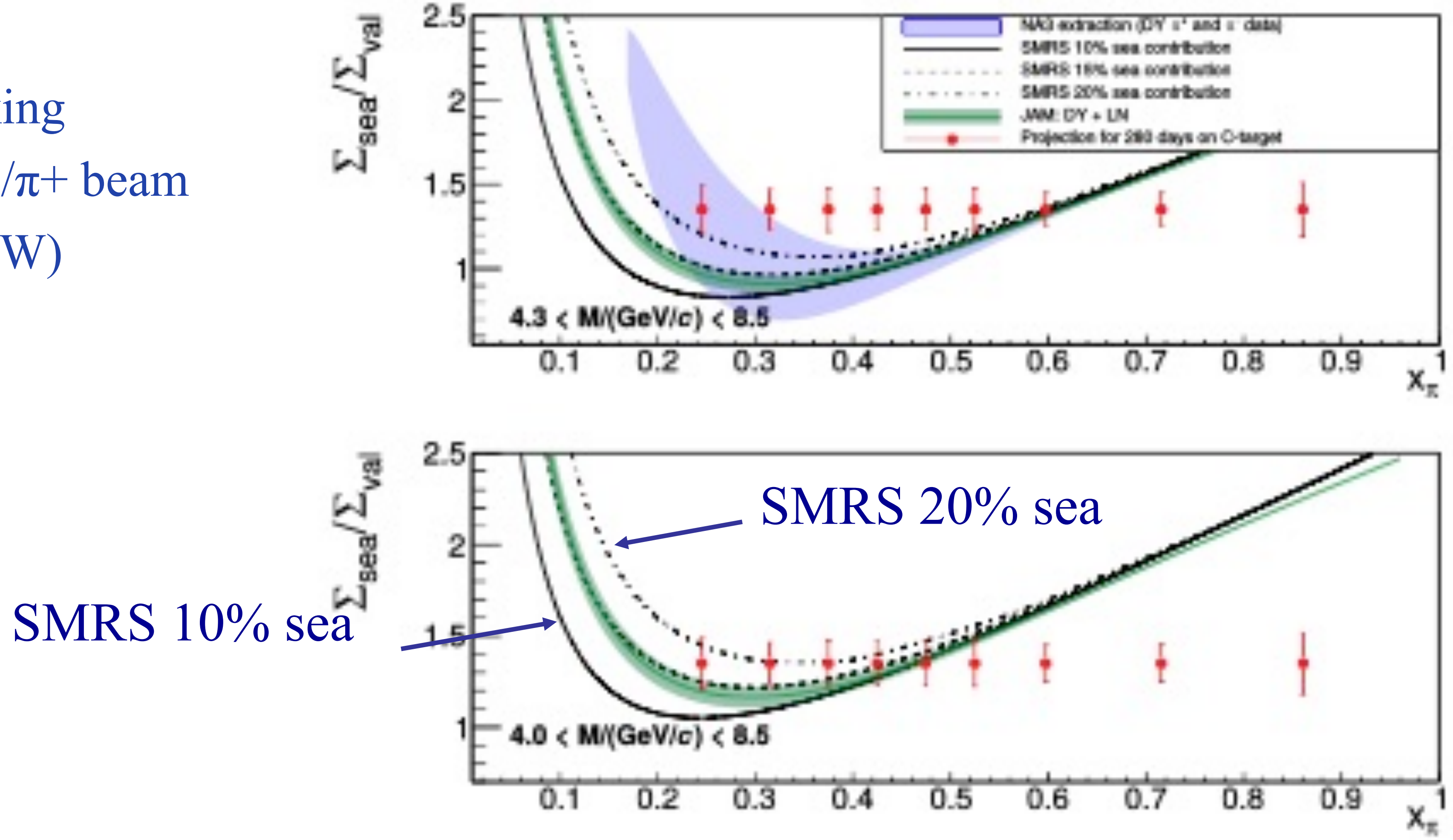
$$\Sigma_{sea}^{\pi D} = 4\sigma^{\pi^+ D} - \sigma^{\pi^- D}$$ No valence-valence terms

$$\Sigma_{val}^{\pi D} = -\sigma^{\pi^+ D} + \sigma^{\pi^- D}$$ 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

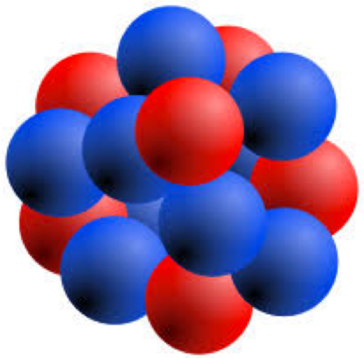
- Assumptions
  - 280 days of data taking
  - 1/8 separation of π^-/π^+ beam
  - ^{12}C target (and also W)



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 !

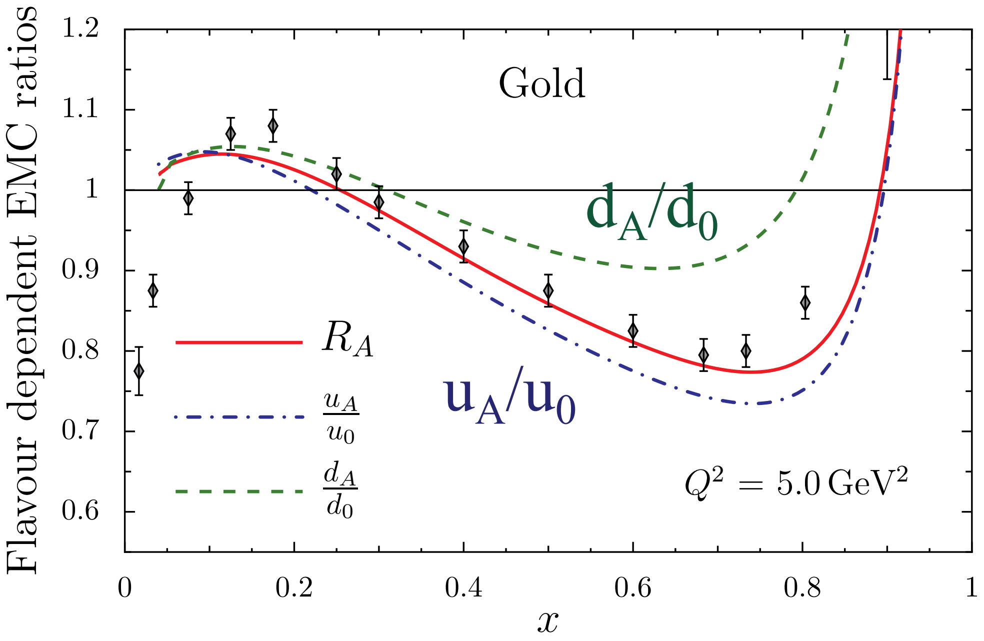


- Separate different flavors (DIS is not sensitive to the individual flavors)
  - Pion (π^-) beam : probes (preferentially) valence u quarks
  - Pion (π^+) beam : probes (preferentially) valence d quarks
  - Can probe the flavor dependence of the nuclear mean field
- Study the partonic energy loss effects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

Flavour dependence of the EMC effect

- Cloët, 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."*

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



Free nucleon PDFs: u0, d0

Medium modified PDFs: uA, dA

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

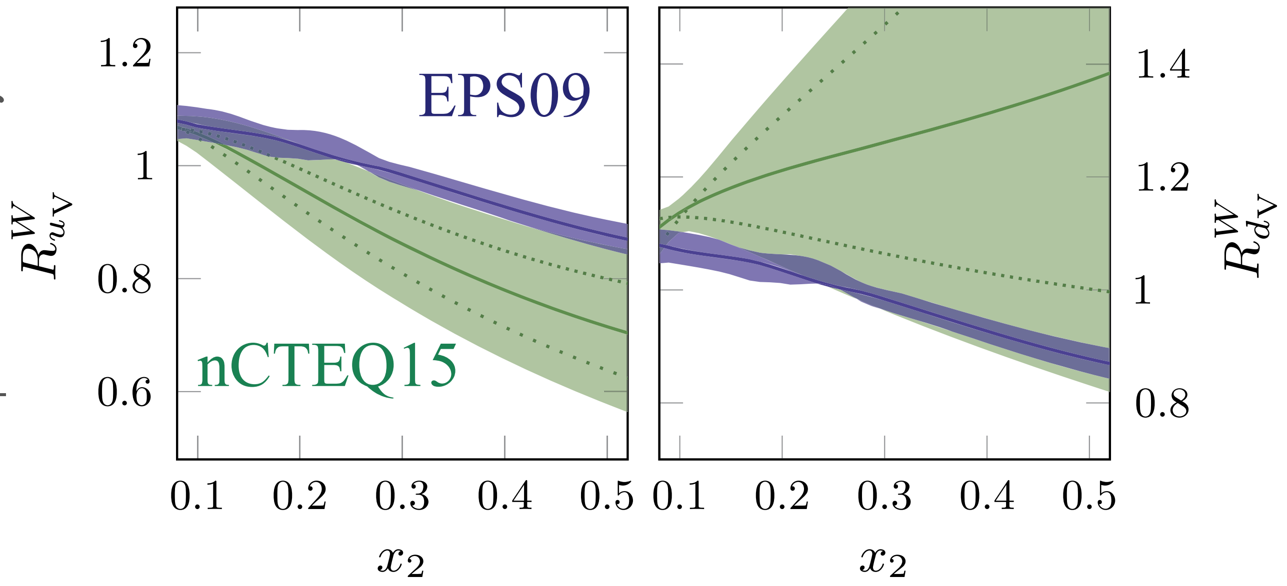
Flavour dependence of EMC effect

- 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

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

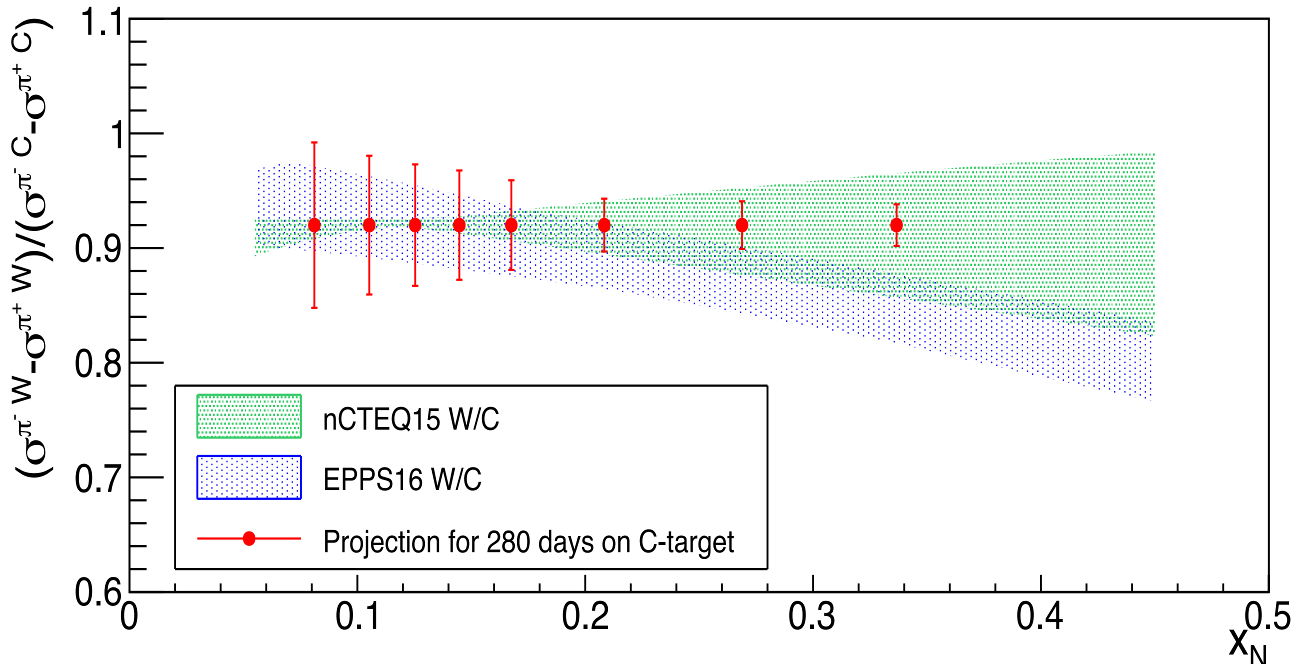
Paakkinen et al., Phys. Lett. B 768 (2017) 7



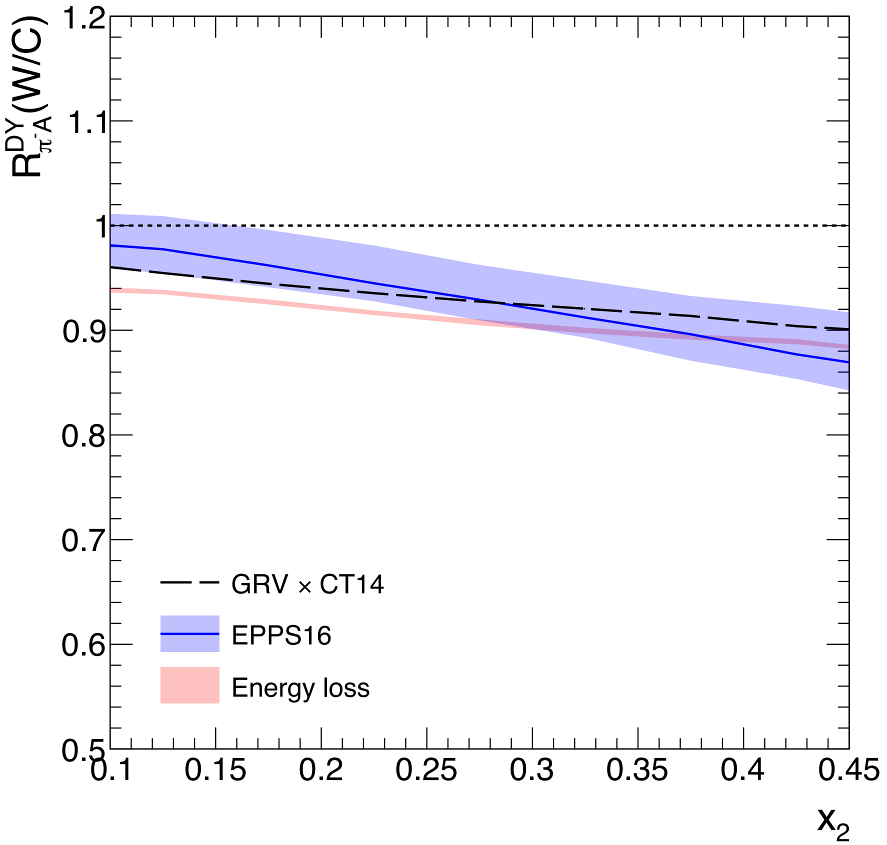
$u_V(x)$ $d_V(x)$

nCTEQ15 allows for different u and v nuclear dependences

Cold nuclear effects: nPDFs and partonic energy loss

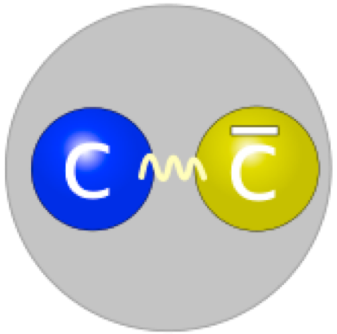


Arleo et al., JHEP 01 (2019) 129



3) Charmonium production mechanism at FT energies

- Accumulate very large statistics: more than 10^6 events with:
  - positive pions, protons (collected simultaneously), negative pions



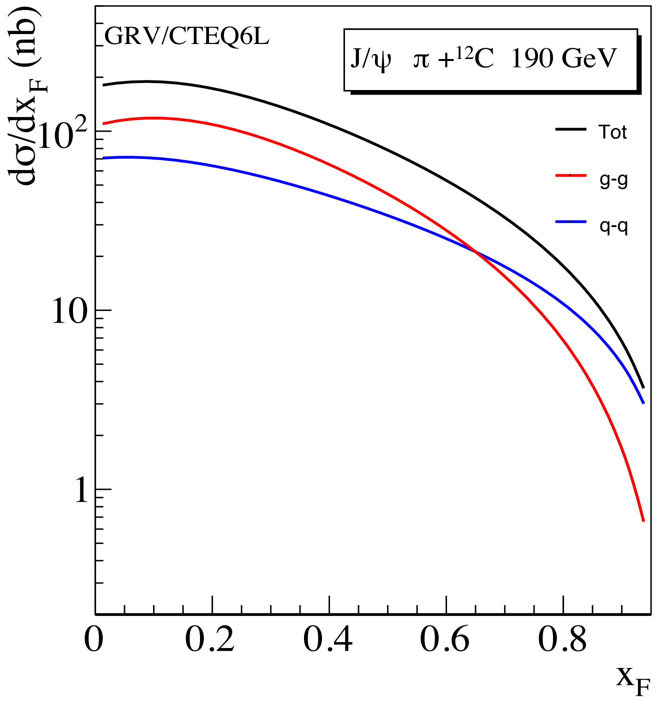
- Measure x_F distribution, p_T distribution, polarisation
  - Try to disentangle $q\bar{q}$ and gg contributions to the cross section

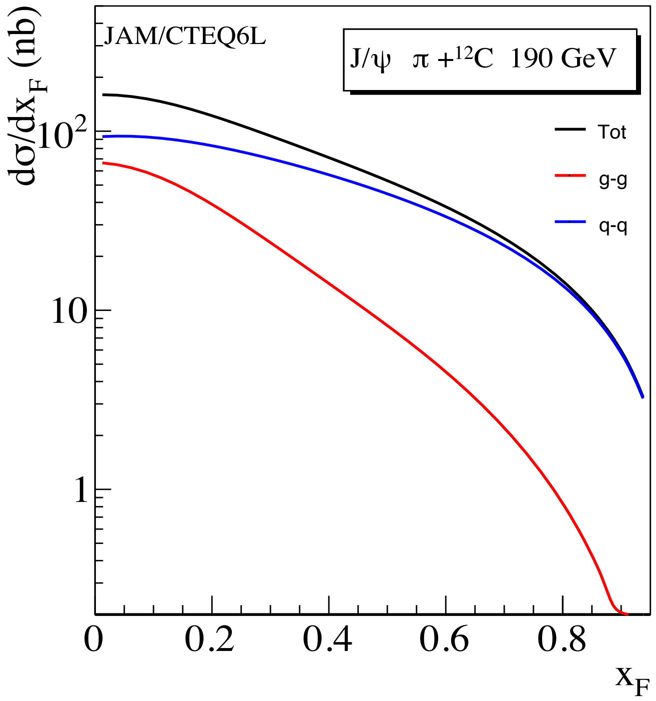
- Explore sensitivity of the data to the pion valence and gluon PDFs

- 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)

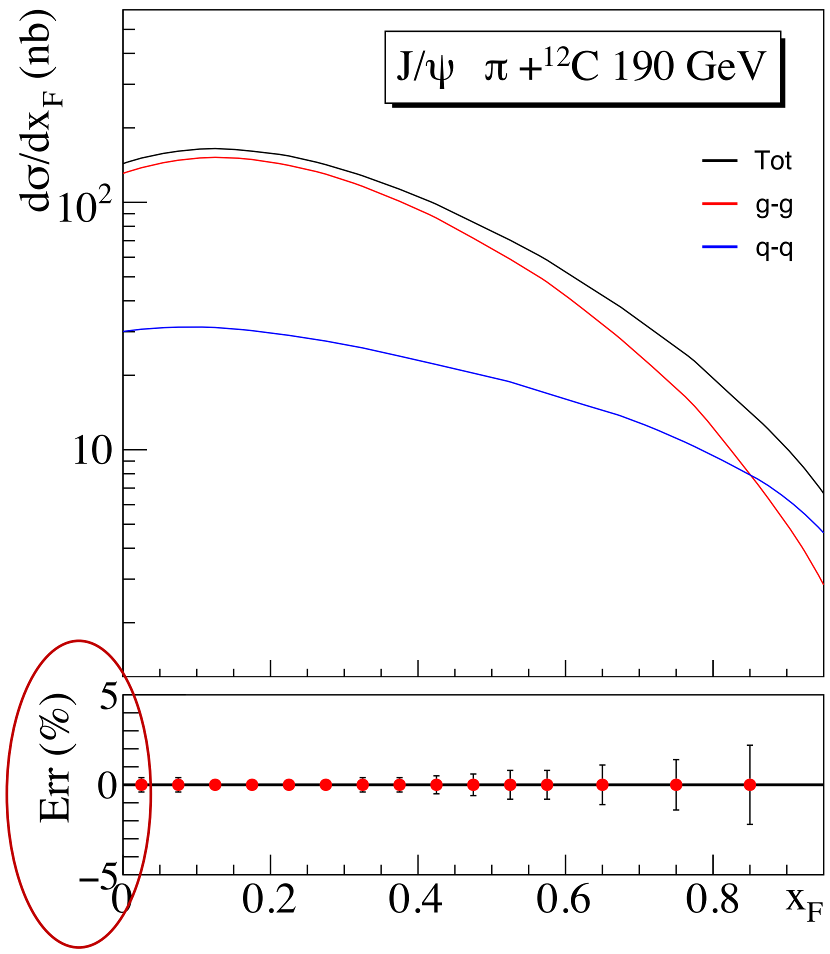




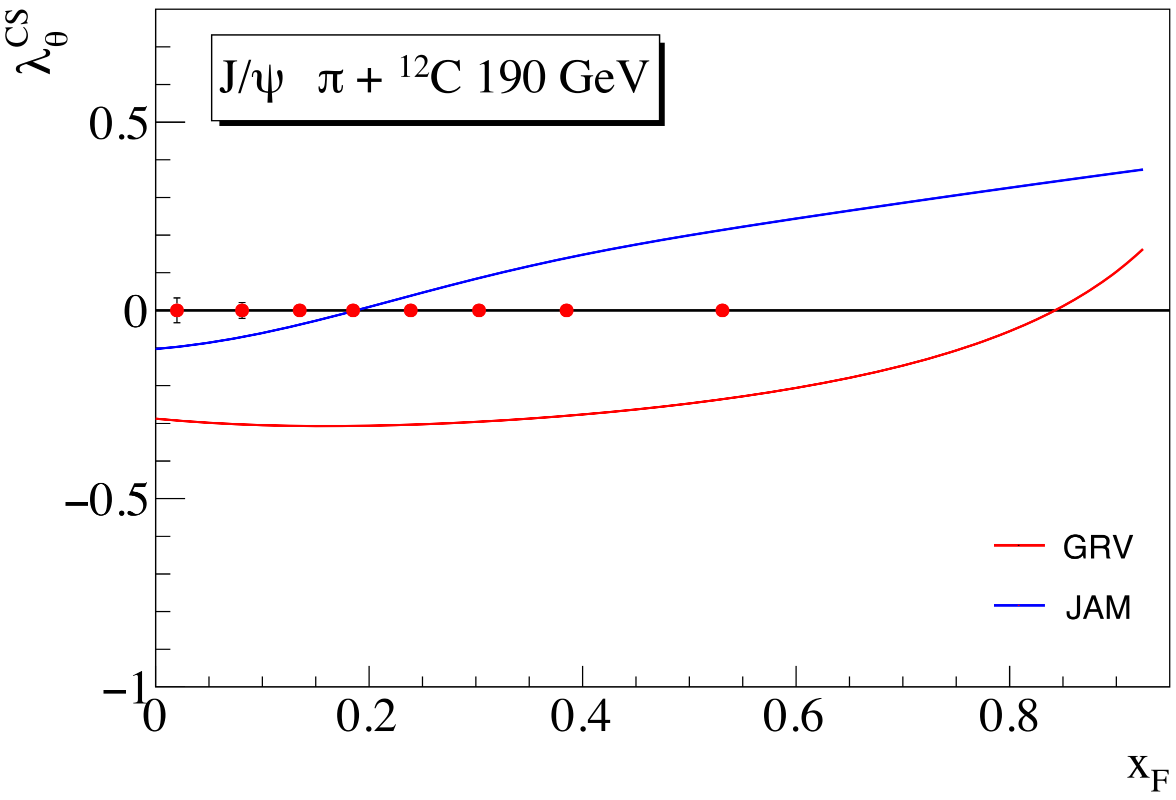
- J/psi proton-induced cross sections will be collected simultaneously with the pion ones
- A very large statistics foreseen

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

- Cross section as a function of xF



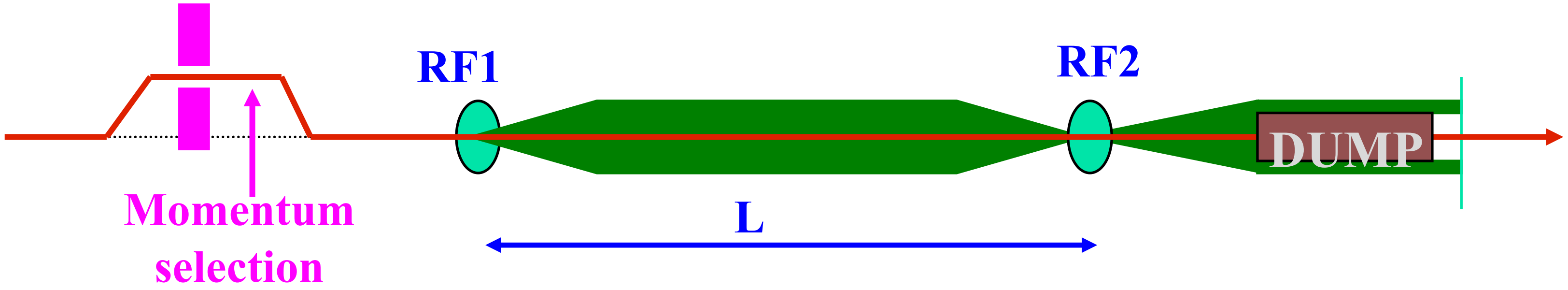
Polarisation



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