Stephane Platchkov

Paris-Saclay University, CEA/IRFU, France

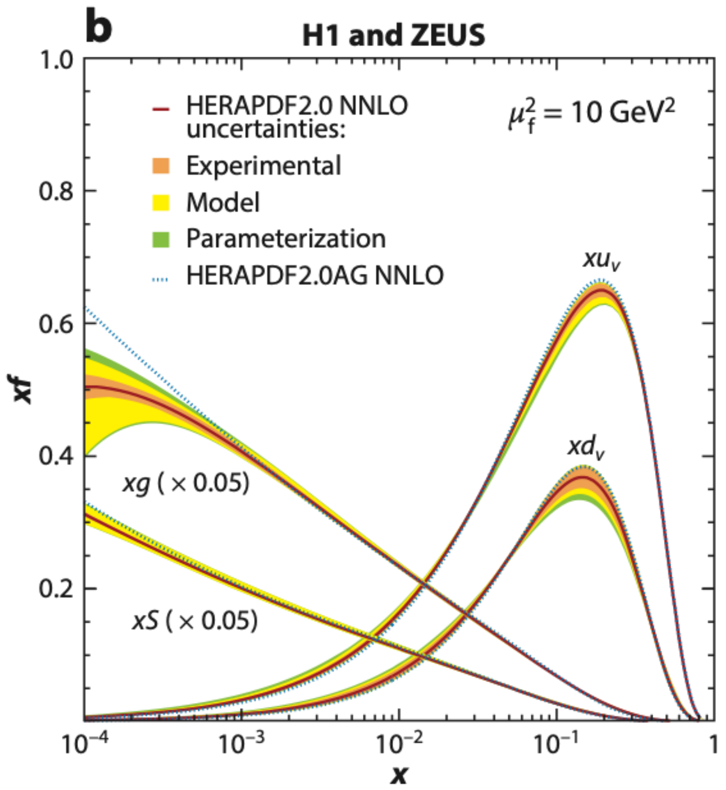
International Workshop on Hadron Structure and Spectroscopy
Aug 29 – 31, 2022, CERN

Pion and Kaon Structure Studies with AMBER

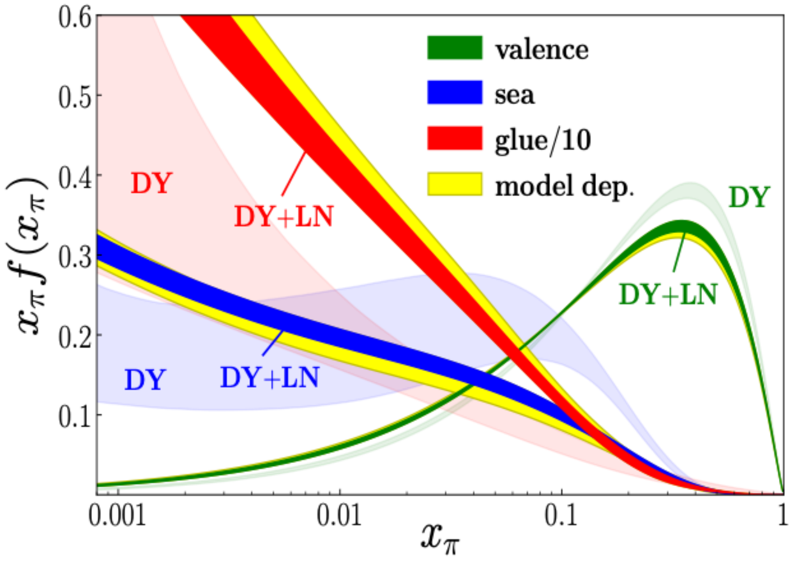
Apparatus for Meson and Baryon Experimental Research

PDFs of p, π, K: present experimental knowledge

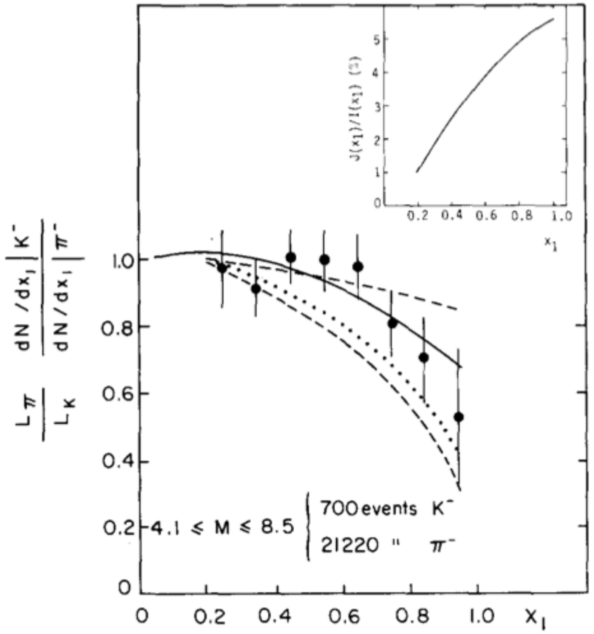
Proton	Pion	Kaon
Hundreds of data sets	Less than 10 data sets	A single data set



JAM



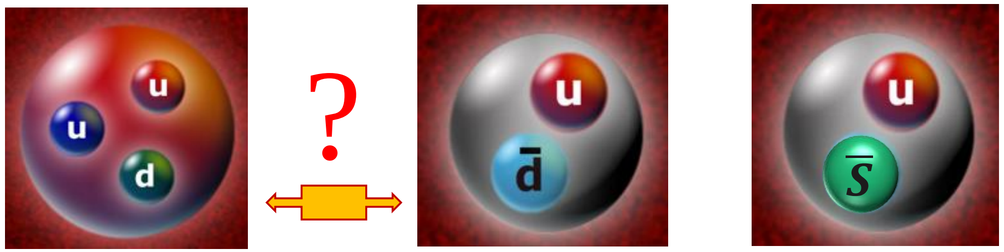
NA3



The parton structure of the two lightest mesons is nearly unknown

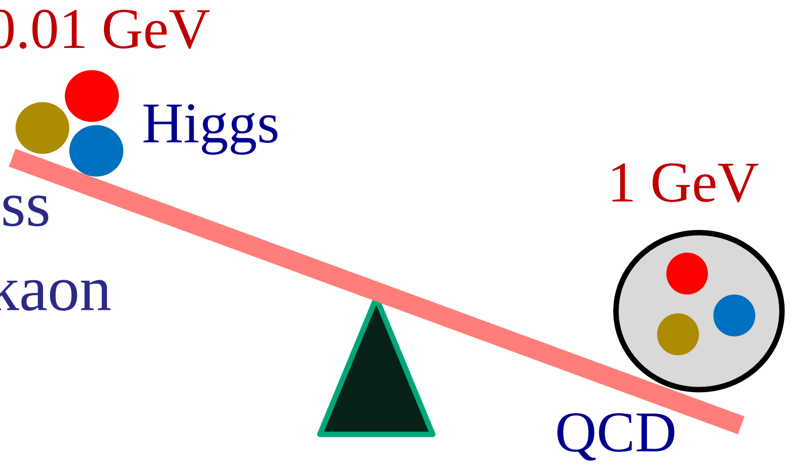
Properties of the the pion and the kaon: why?

- Light meson properties
  - How the (simplest) light mesons compare to the nucleon?



Mass (MeV):	938	135	493
Radius (fm):	0.841(2)	0.659(4)	0.560(31)

- Emergence of the hadron masses
  - Higgs mechanism explain only 1% of the nucleon mass
  - EHM: must explain BOTH the nucleon and the pion/kaon
    - Meson PDFs: input for π and K needed!

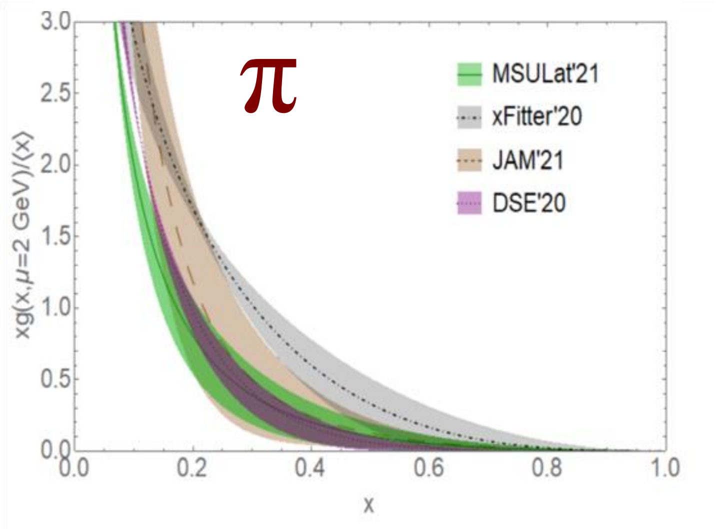


Craig Roberts : *"Thus, enigmatically, the properties of the massless pion are the cleanest expression of the mechanism that is responsible for almost all the visible mass in the universe."*

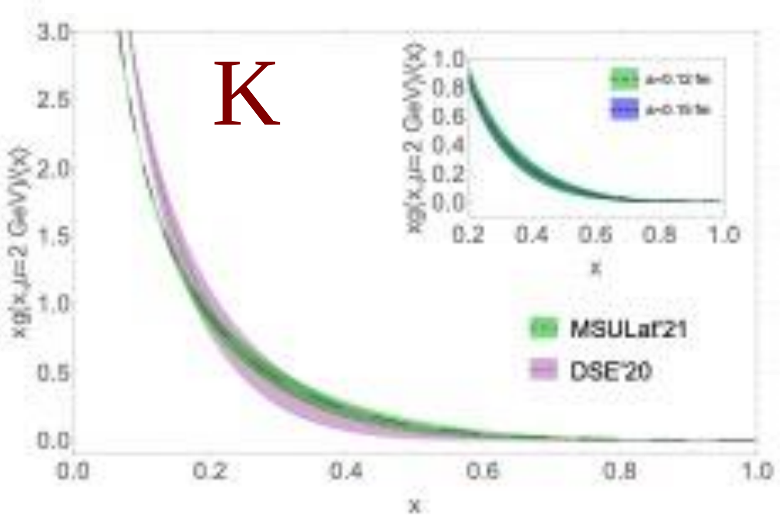
Pion PDFs: recent theoretical progress on $g_\pi(x)$

- *Tremendous theoretical effort in the last few years….*
- *"Breaking news for glue in π… and in K "* (Craig Roberts, EHM, May 2022)

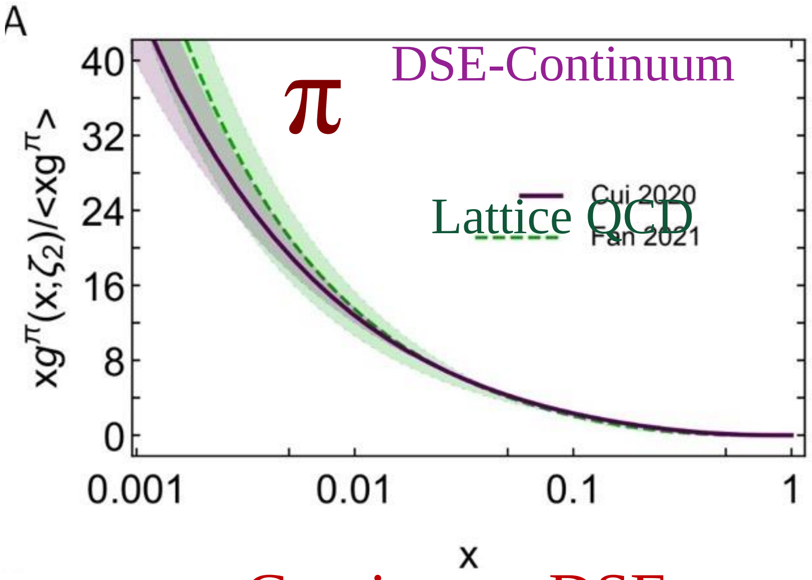
Z. Fan and H-W. Lin,
Phys. Lett. B 823 (2021)136778



A. Salas-Chavira, Z. Fan and H-W. Lin,
arXiv212.03112



L. Chang and C. Roberts,
Chin. Phys. Lett. 38 (2021)081101



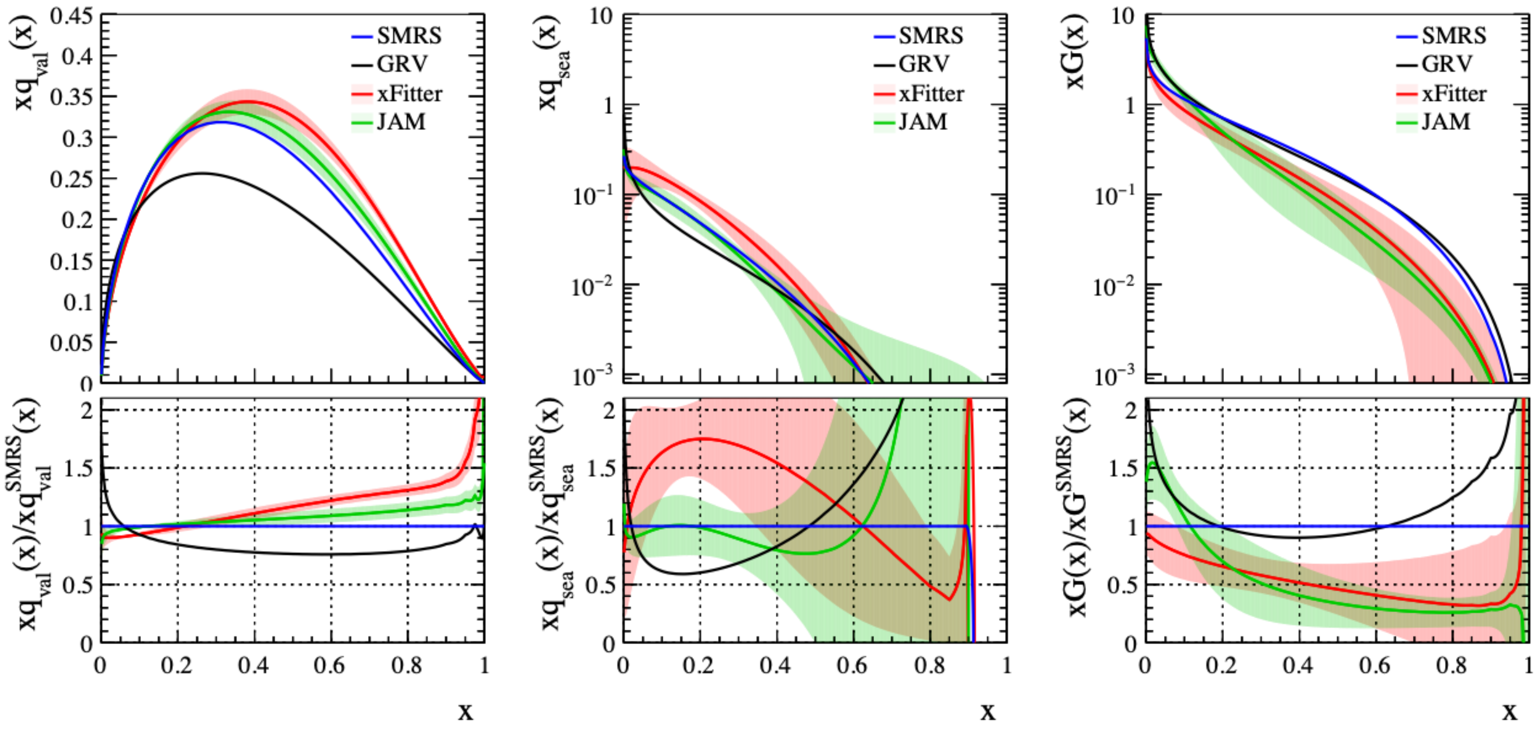
Lattice QCD calculation

Continuum DSE

Pion PDFs from experiment: JAM, xFitter, SMRS, GRV fits

Chang, Peng, SP, Sawada.
in preparation…

valence sea gluons



$Q^2 = 9.6\ GeV^2$

Four different global fits, all use the same DY data !

Valence PDF: must be improved. Sea and gluons: nearly unknown

Physics potential of AMBER – Phase 1 (“conventional” beam)

- Three important advantages of CERN + AMBER (dimuon experiments’ part) :
  - 1) availability of meson beams
  - 2) both positive and negative beams – very important!
  - 3) Large and uniform acceptance spectrometer

Unique place in the world!

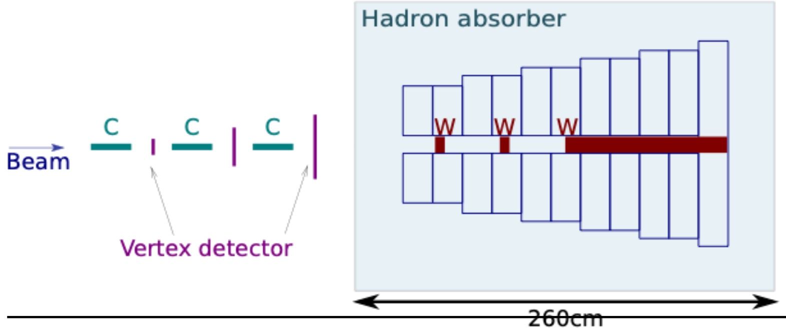
- Four main physics goals of AMBER phase-1:
  - 1) Separate valence and sea pion PDFs using DY
  - 2) Access gluon distribution in the pion using J/ψ and ψ’ production
  - 3) Access valence/glue in the Kaon using J/ψ production
  - 4) + Study flavor dependence of the EMC effect

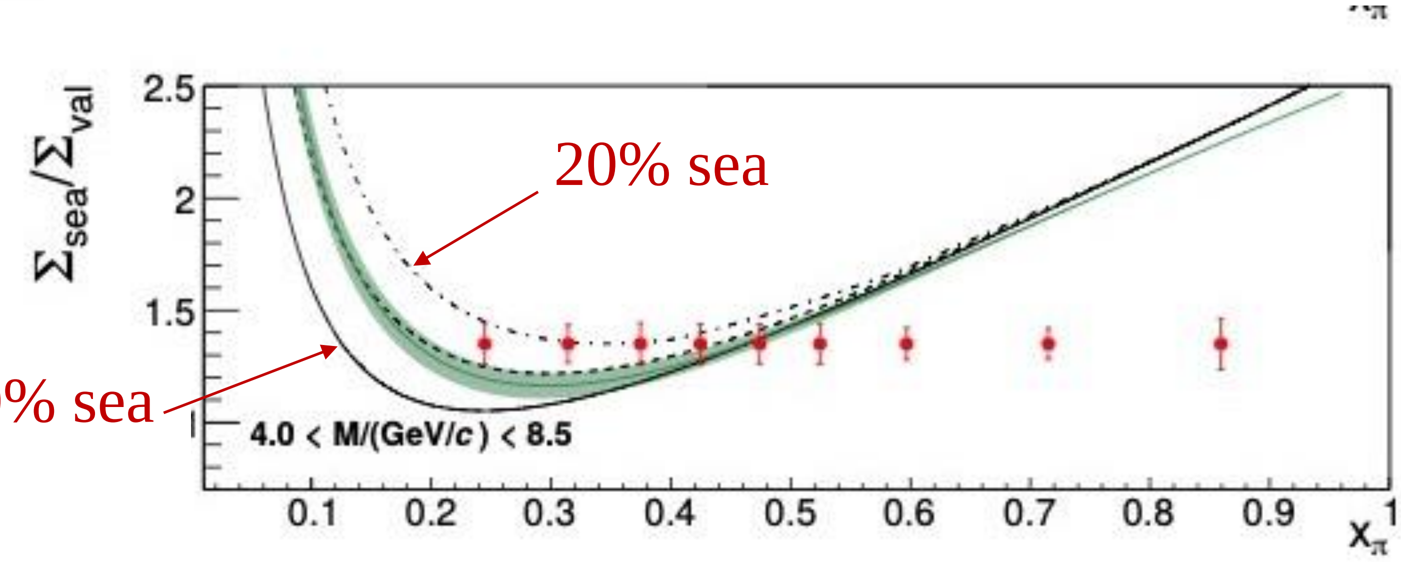
Fall 2020: official approval by SPSC!

Goal 1: valence/sea separation in the pion (π+ and π− beams)

$$S_{sea}^{pD} = 4s^{p^+D} - s^{p^-D}$$ no valence

$$S_{val}^{pD} = -s^{p^+D} + s^{p^-D}$$ only valence





Statistics vs available

This exp	75 cm C	190	π^+	1.7×10^7	4.3 – 8.5 4.0 – 8.5	26000 37000
		190	π^-	6.8×10^7	4.3 – 8.5 4.0 – 8.5	25000 34000
	12 cm W	190	π^+	0.2×10^7	4.3 – 8.5 4.0 – 8.5	10000 14000
		190	π^-	1.0×10^7	4.3 – 8.5 4.0 – 8.5	9000 12000

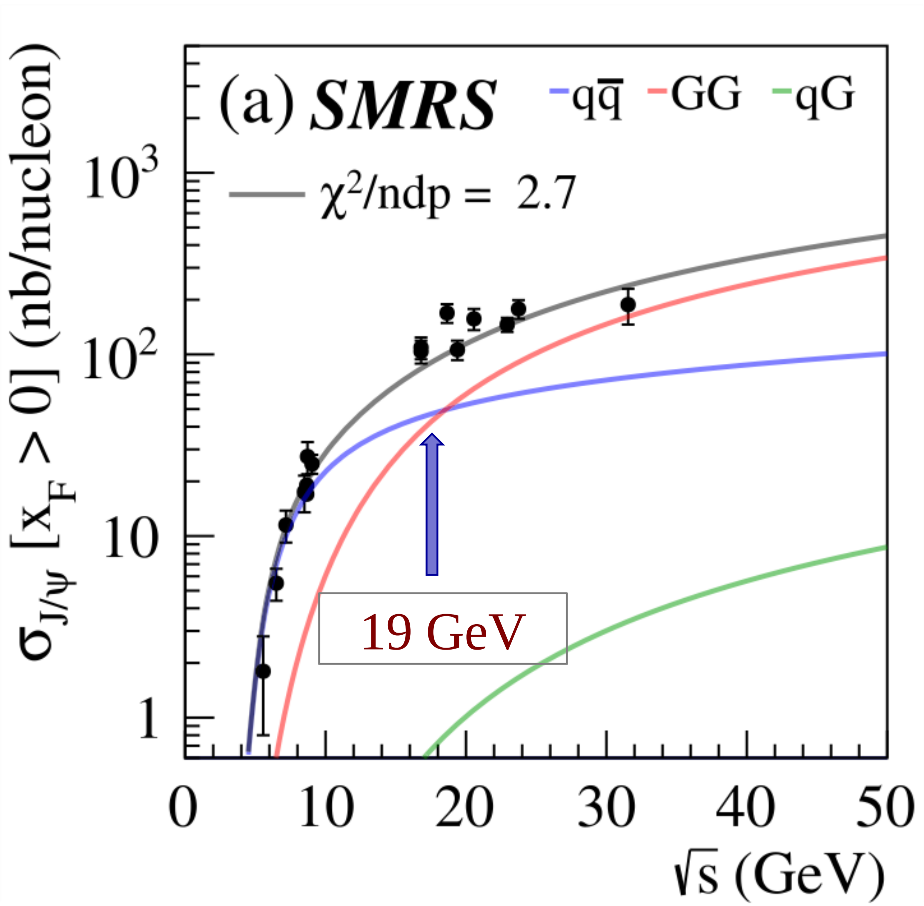
x20 !

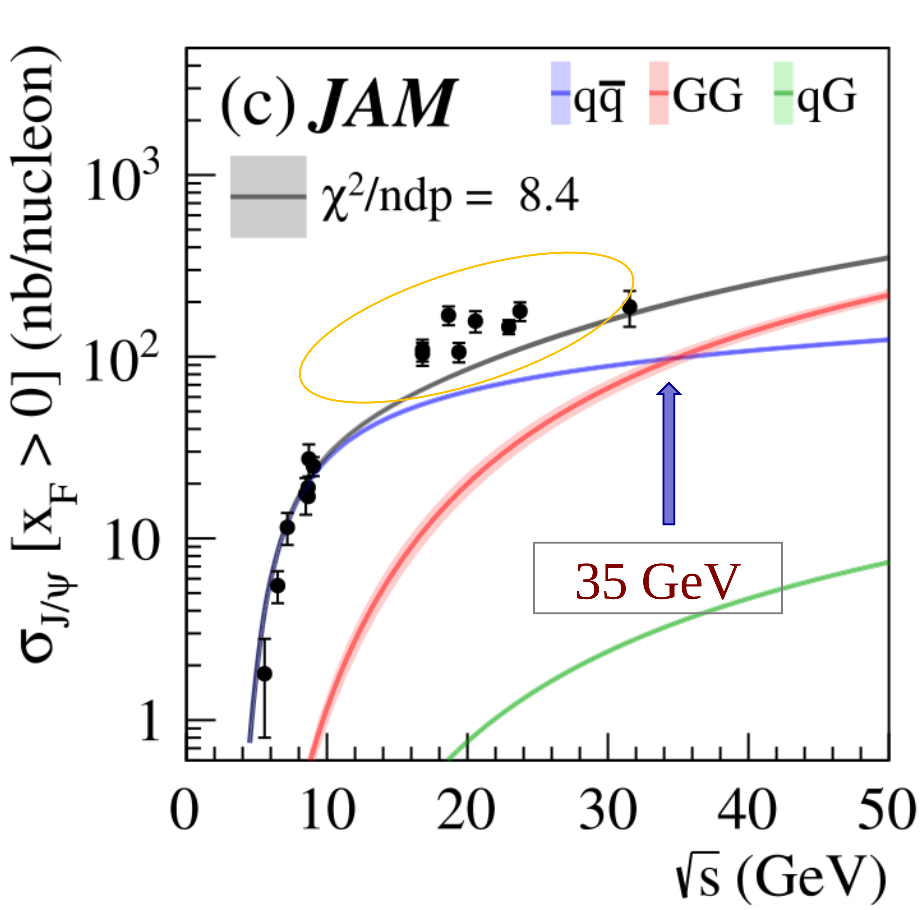
x8 !

Goal 2: gluon distribution in the pion through J/ψ production

Model dependence of the J/ψ production cross section

Chang, Peng, SP, Sawada, in preparation…

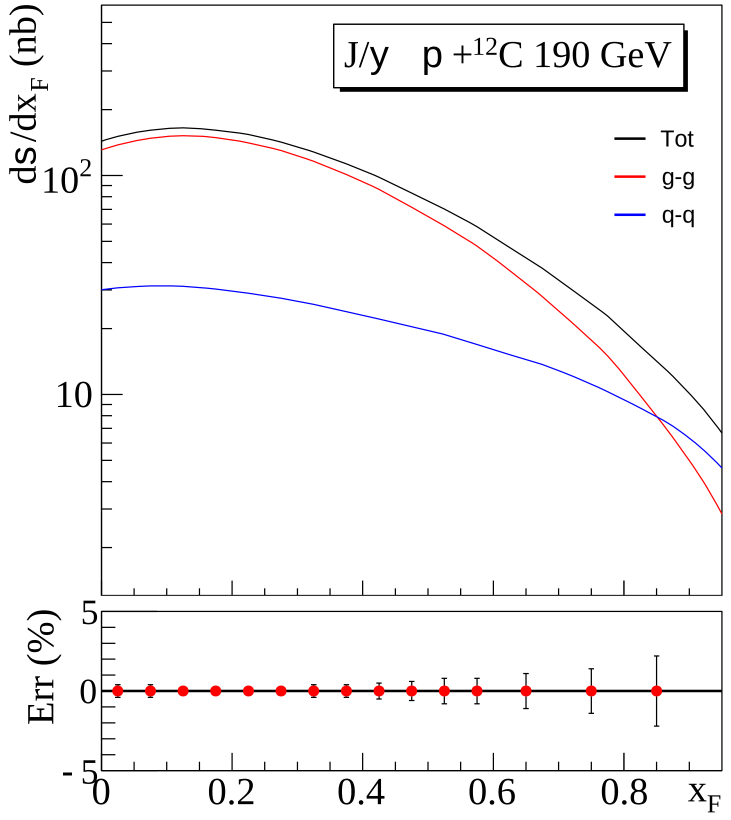




SMRS vs JAM fits: strong dependence on the PDFs

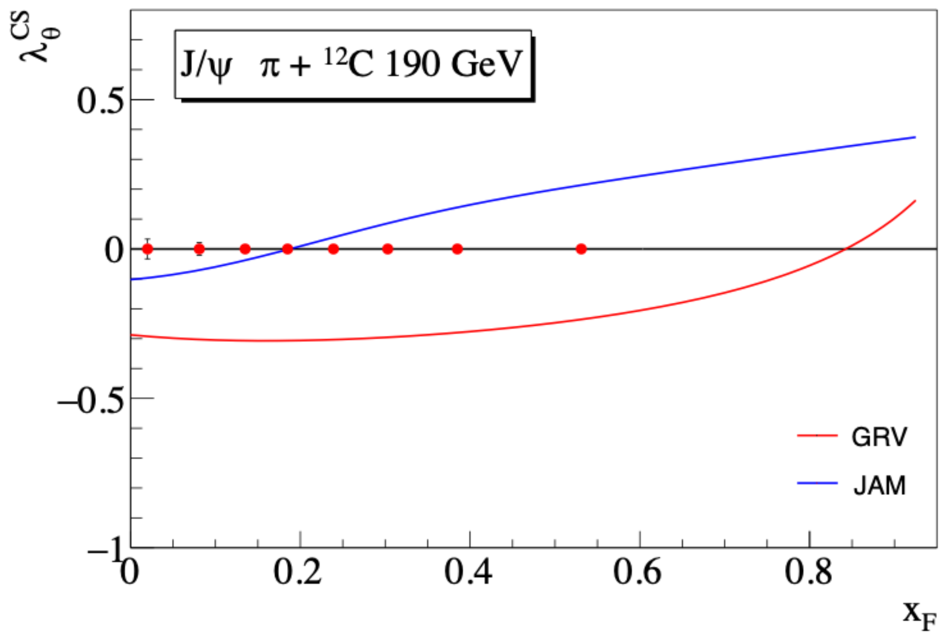
Goal 2: gluon distribution in the pion through J/ψ production

Cross section (ICEM)



Polarization (ICEM)

CHEUNG AND VOGT, PRIV. COMM., 2020



Both x_F-distribution and polarization depend on the relative amount of valence and glue

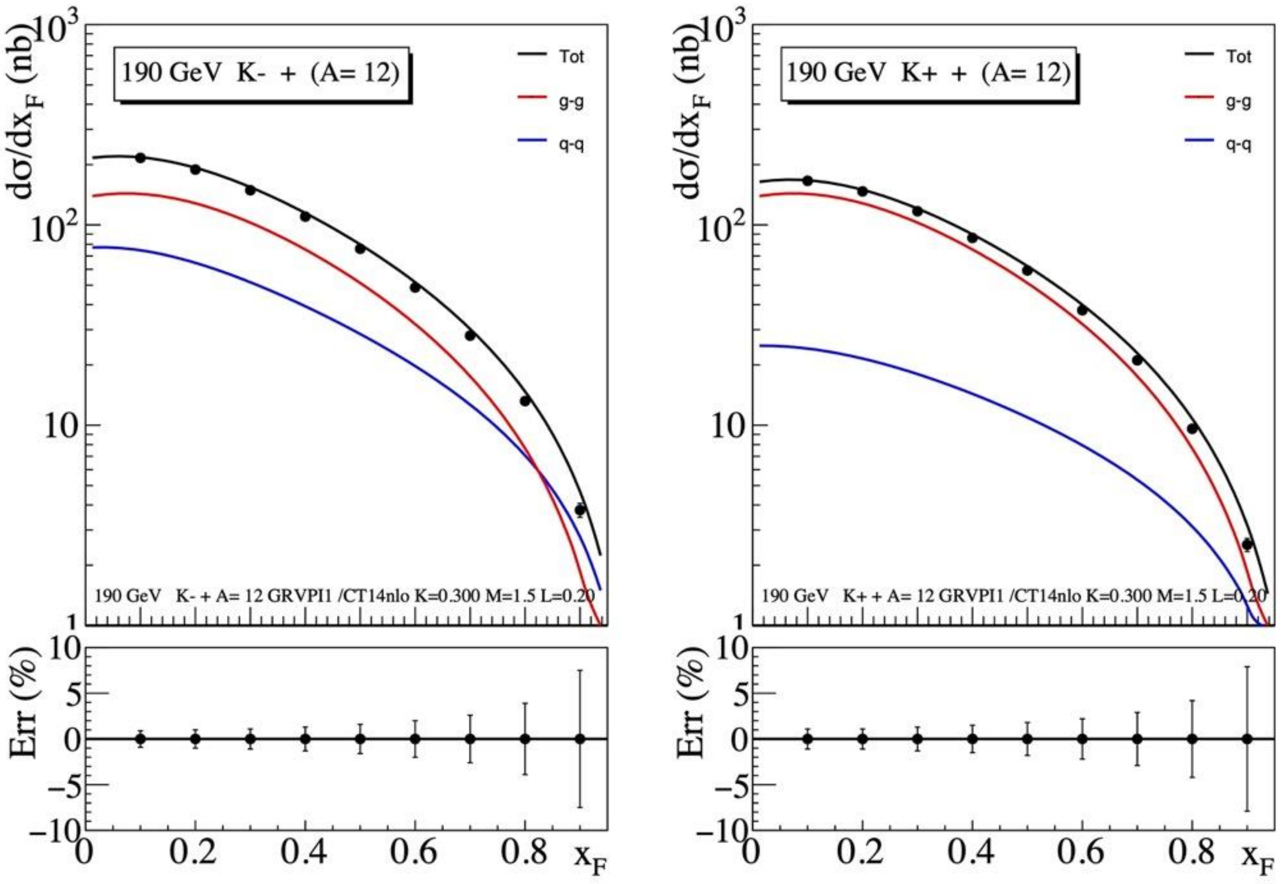
Huge statistics: $\pi+$, $\pi-$, p : 1.2 – 1.8 M J/ψ and 20 – 30 k ψ'

Goal-3: Valence/gluon PDFs in the Kaon

- Identify the kaon component with the CEDARs
  - positive beam (K = 1.5%)
  - negative beam (K = 2.4%)

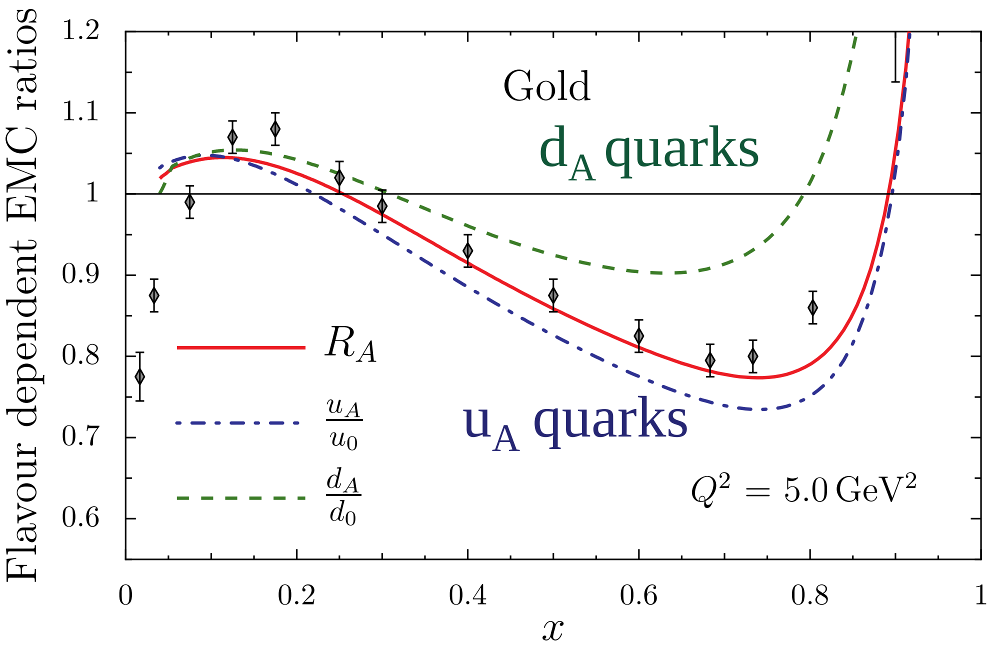
  - Expected statistics
    - 210 days of positive beam (K+)
    - 70 days of negative beam (K−)
    - CEDARs efficiency: 60%

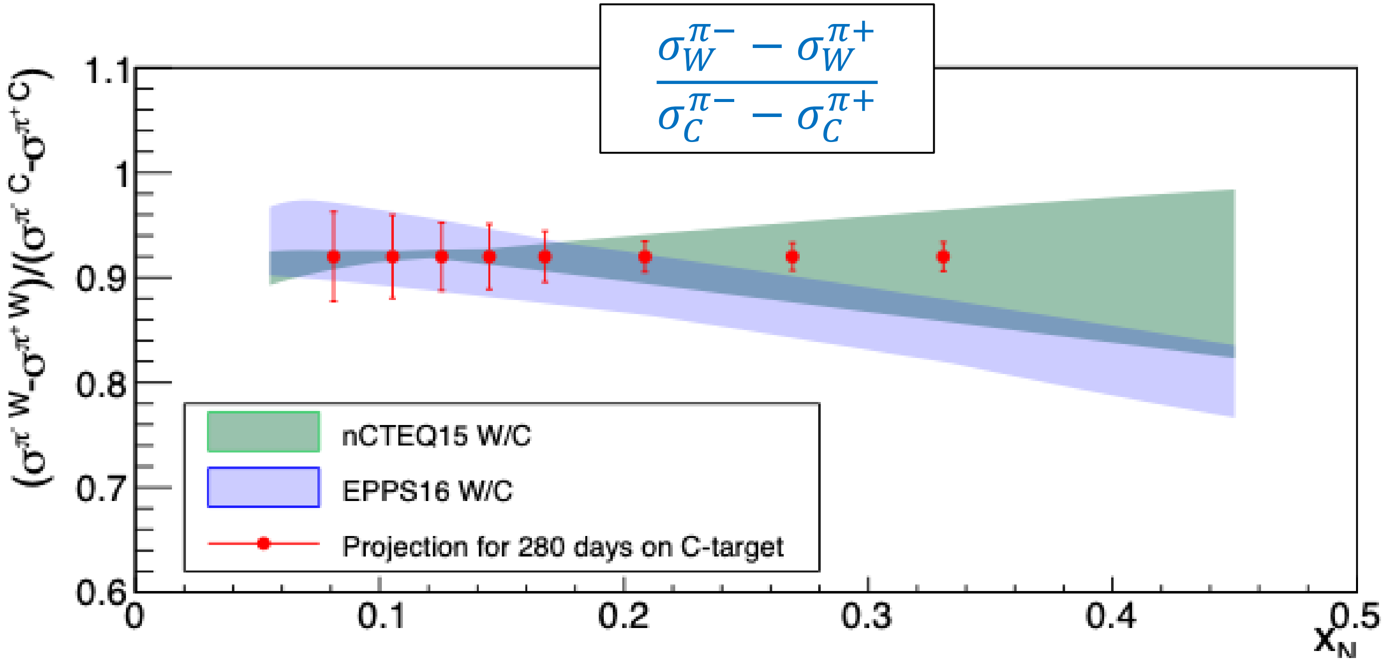
Nb of events: 25 000 K^- 32 000 K^+



Goal-4: Flavor dependence of the EMC effect

- Prediction: Cloët, Benz and Thomas (2009):
  - *"…for N≠Z nuclei, the u and d quarks have distinct nuclear modifications."*





Can be accessed ONLY through parity-violating DIS (JLAB) or with AMBER@CERN

Summary AMBER Phase I (SPSC approved)

- Map out the pion parton structure at large x, x > 0.1
  - 1) DY data : separate valence and sea distributions in the pion
  - 2) J/ψ and ψ' data : study pion-induced production – infer π valence and glue
- Glimpse on the kaon valence and gluon distribution
  - 3) J/ψ data from Kaons – compare K^+ and K^- production

  ▸ AMBER@CERN is unique for these meson PDFs measurements

- Nuclear dependence at large x
  - 4) EMC effect – first look at the flavor dependence of the nuclear mean field

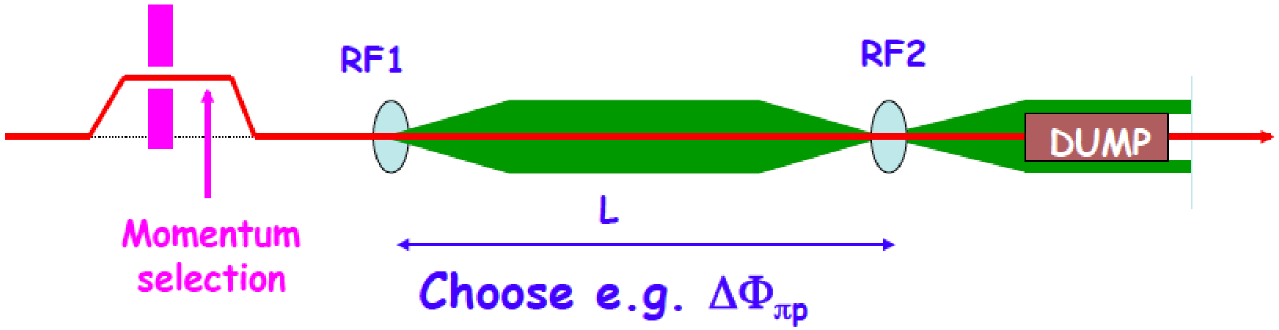
  ▸ AMBER@CERN is unique for this nuclear stricture measurement

Four fundamental measurements with this unique data set !!

AMBER Phase II

(topics in the LoI)

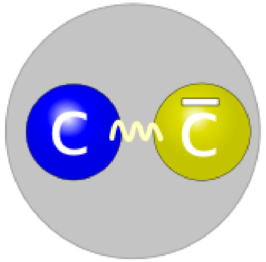
(Proposal to be written)



AMBER Phase-2: RF-separated beam parameters

- RF kaons: expected parameters…
  - Energy: up to 80 GeV
  - Flux: ~5x10^5 kaons/s (instead of ~10^7, optimistically hoped)
  - Purity of the beam: > 50%

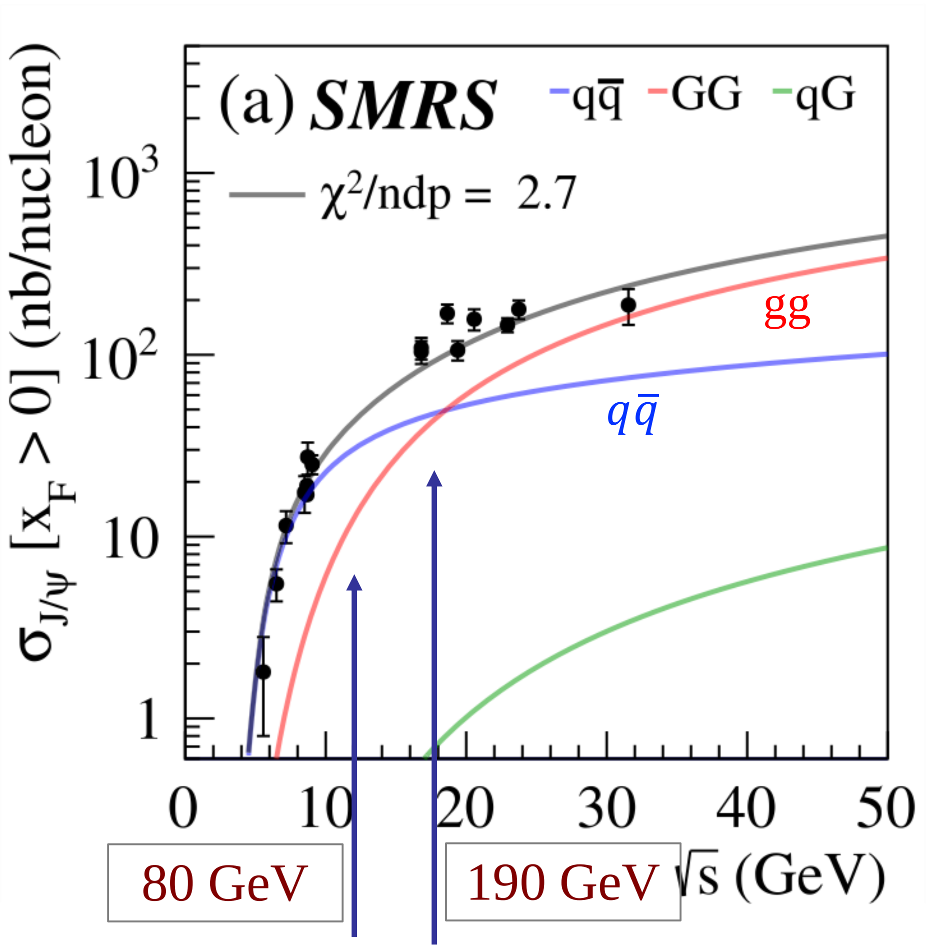
- Corollary
  - Drell-Yan measurements: no improvement vs available data
  - Charmonium measurements: much larger cross sections => yes, possible



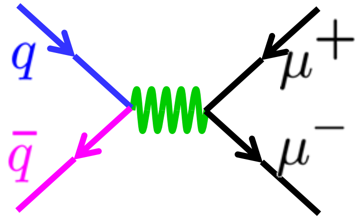
- Advantages …
  - Low intensity allows for an open spectrometer => better mass resolution
  - At lower energies the $q\bar{q}$ term (in J/ψ prod.) becomes dominant (vs gg)

Energy dependence of the J/ψ production cross section

Processes contributing to the cross section

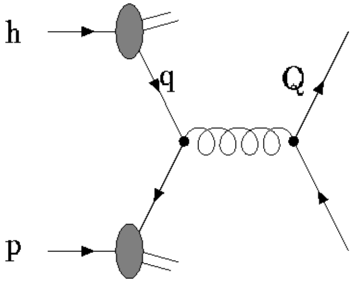


Drell-Yan (LO)

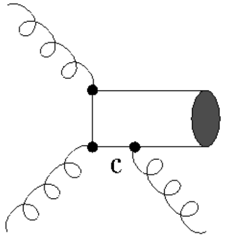


$q\bar{q}$ annihilation

J/ψ production (LO)



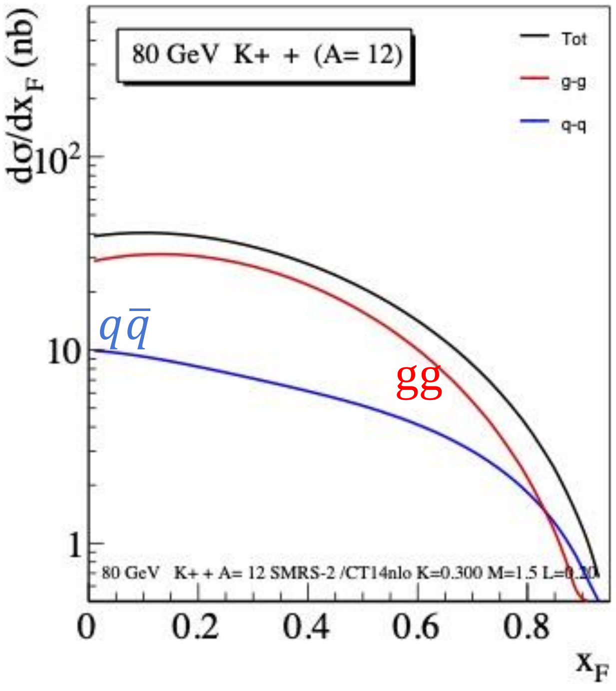
$q\bar{q}$ annihilation



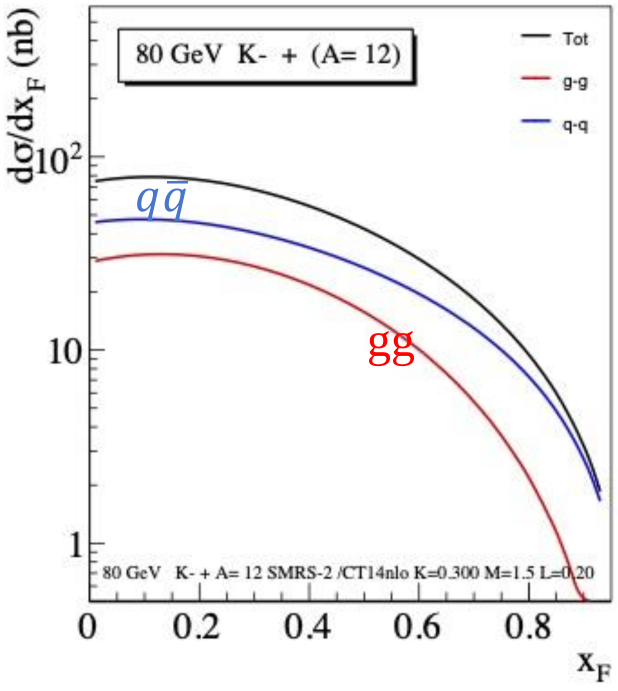
gg fusion

Beam charge dependence: K^+ vs K^- 80 GeV

K^+ beam



K^- beam



identical gg contributions

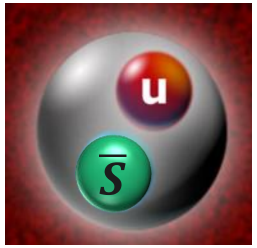
u-valence term dominates for K^-; absent for K^+

The K^+ cross section is smaller than the K^- one
But the *gg* contributions are equal

J/ψ – access to the kaon valence PDF

- Quark content in the kaon:

$$K^{+}(u\bar{s});\quad K(\bar{u}s)$$



- Production cross section for K$^+$ and K$^-$

$$K^{-}(\bar{u}s)+p(uud)\propto gg+\left[\bar{u}_v^K u_v^p\right]+\left[\bar{u}_v^K u_s^p+s_v^K s_s^p\right]+\left[\bar{u}_s^K u_v^p\right]+\left[\bar{u}_s^K u_s^p+u_s^K\bar{u}_s^p+s_s^K\bar{s}_s^p+\bar{s}_s^K s_s^p\right]$$

$$K^{+}(u\bar{s})+p(uud)\propto gg+\left[---\right]+\left[u_v^K\bar{u}_s^p+\bar{s}_v^K s_s^p\right]+\left[\bar{u}_s^K u_v^p\right]+\left[\bar{u}_s^K u_s^p+u_s^K\bar{u}_s^p+s_s^K\bar{s}_s^p+\bar{s}_s^K s_s^p\right]$$

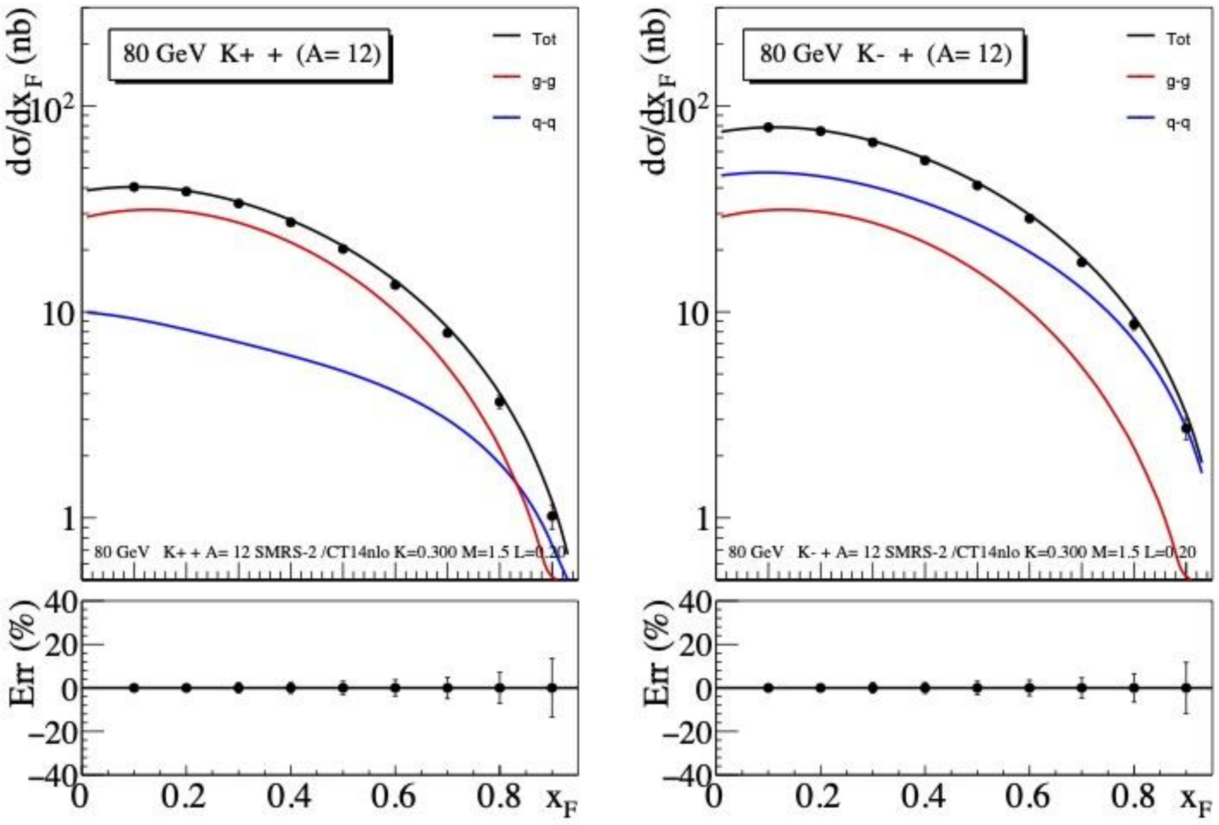
val-val | val-sea | sea-val | sea-sea

- The cross section difference isolates the val-val term: $\sigma(K^{-})-\sigma(K^{+})\propto\bar{u}_v^K u_v^p$

Error estimates: K^- and K^+ -induced J/ψ cross sections

- Assumptions
  - Flux: 5.10^5/s
  - ~10 000 events for each beam (conservative number)
  - Beam sharing: ~70 d of K− and ~210 d of K+
  - 3 carbon targets, length of 25cm each
  - x_F coverage: 0.10 – 0.95
- Lower panel: statistical errors in %

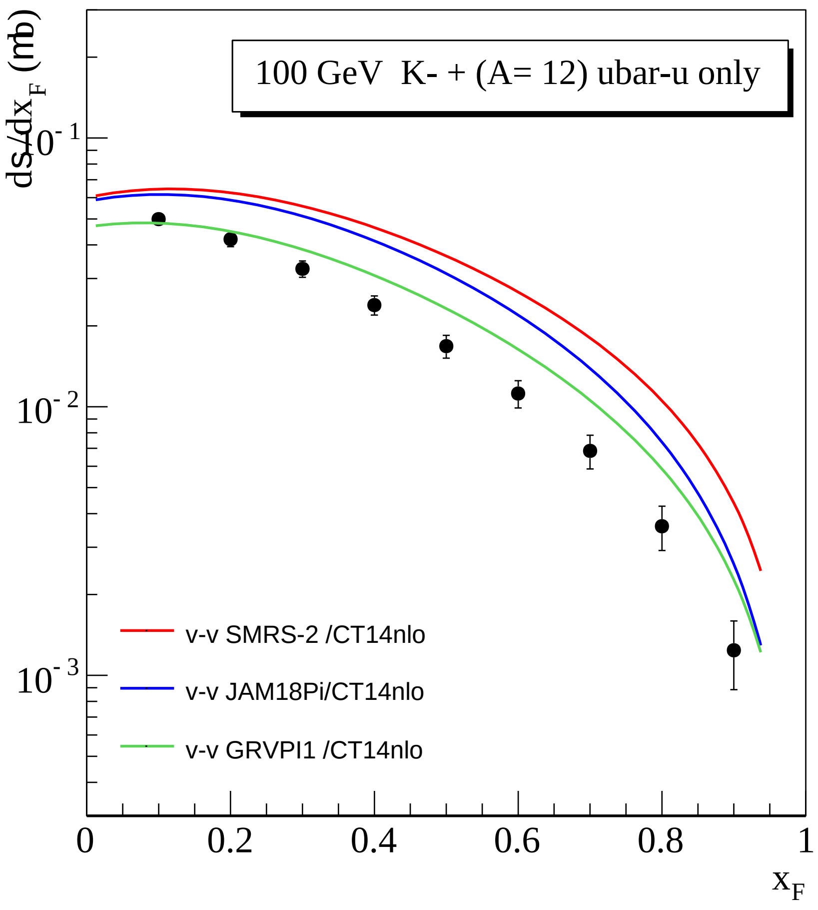
K^+ beam | K^- beam



Difference between K⁻ and K⁺ -induced J/ψ production

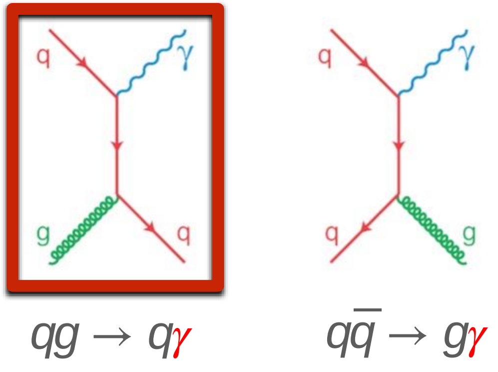
- Assumptions
  - Both K charges measured with ~10^4 events
- Plotted quantity
  - The valence-valence part ($\bar{u}u$) of the J/ψ production cross section for K⁻
  - 3 different models for the pion PDF-u
  - The errors include both statistical and systematic (4%) uncertainties

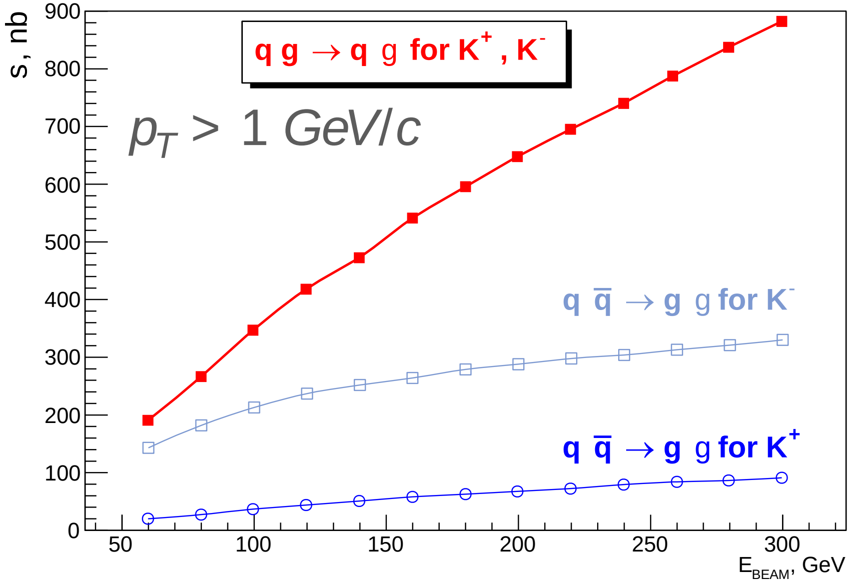
valence-valence term of K-



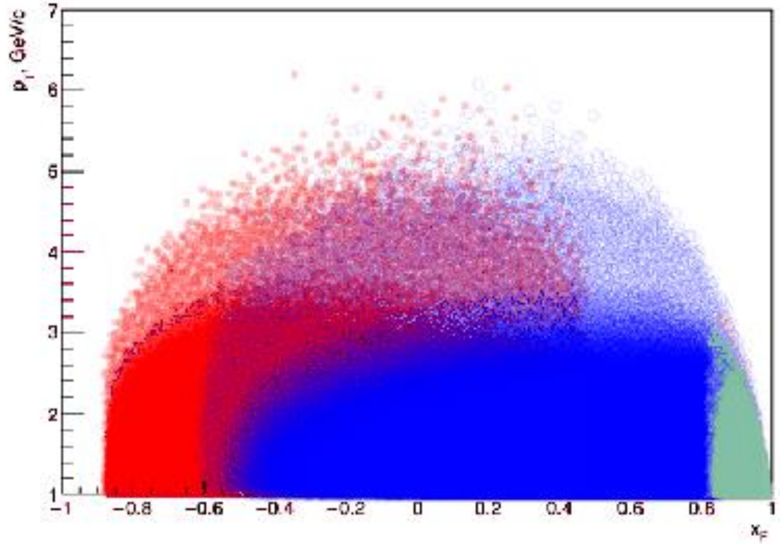
Gluon distribution in K via direct-photon production

- Only feasible without absorber: need EM calorimeters
- Process used: gluon Compton scatt: $qg \to q\gamma$
  - Competition with $q\bar{q} \to g\gamma$
  - Main difficulty: large background





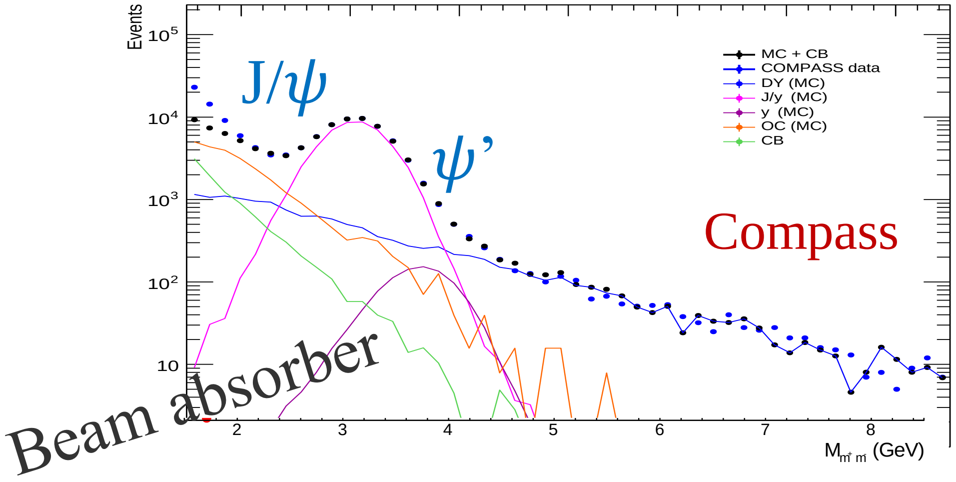
100 GeV kaon beam



Advantage: large x_F coverage

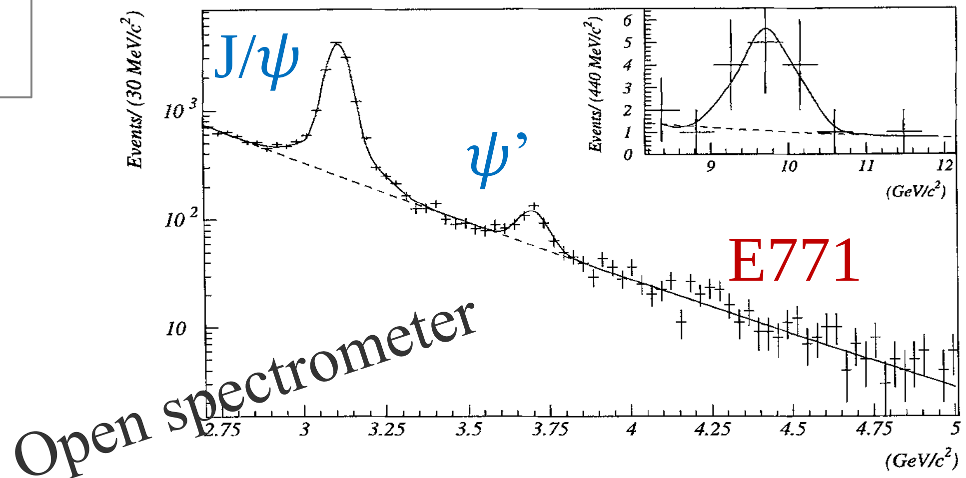
Higher charmonium states – need mass resolution

- Kaon-induced ψ' production
  - Unknown: can be measured for both kaon charges
  - Expected statistics: 200 ev./ beam charge



Advantages of ψ' cross sections:
- Cleaner than J/psi, no feeddown
- More sensitive to the quark content than J/ψ

E771 Collaboration / Physics Letters B 374 (1996) 271–276



- χ_c production and decay to J/ψ
  - detect photons in coincidence
  - not known for kaon beams

Physics opportunities with a RF separated beam

- Drell-Yan data: very limited statistics
  - Only marginal improvement of the available data

- Charmonium production => excellent J/ψ and ψ' separation
  - J/ψ production: determine the kaon valence PDF, infer gluon PDF
  - ψ' production: kaon valence PDF, charmonium production mechanism
  - χ_c production: never measured for kaons; detect photons in coincidence.

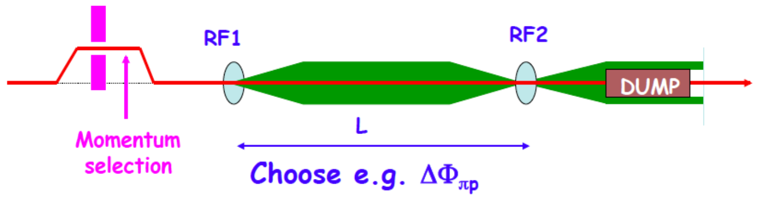
- Direct photon production
  - Separate valence and gluon PDFs.

- Other options: π and K radii….

Only place in the world for extensive π/K structure studies

AMBER roadmap (slide from Oleg D.)

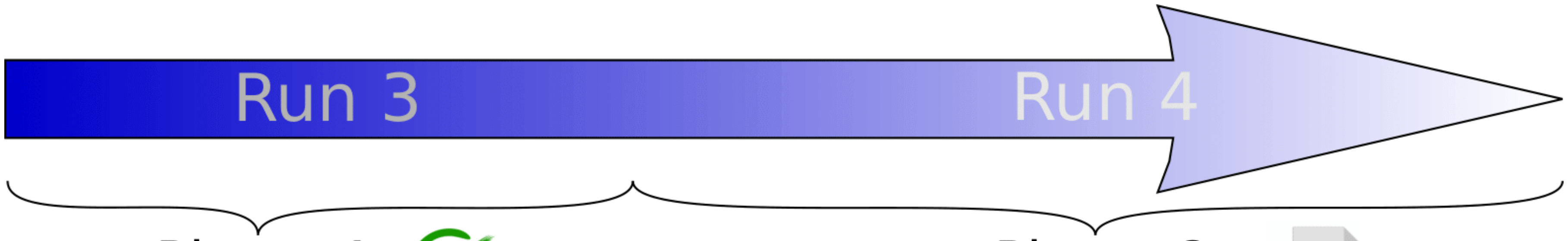
AMBER: > 200 physicists, 41 participating institutes, 14 countries.



$\Delta\Phi = 2\pi\,(L\,f\,/\,c)\,(\beta_1^{-1} - \beta_2^{-1})$ with $\beta_1^{-1} - \beta_2^{-1} = (m_1^2 - m_2^2)/2p^2$

Conventional muon/hadron M2 beams

RF "pure" beams



Phase-1

Phase-2

Proton Radius Measurement
Antimatter production cross section
Pion structure (PDFs) via DY and charmonia
Flavour-dependence of the EMC effect

Kaon and pion structure (PDFs and PDAs)
High precision strange-meson spectrum
Kaon and pion charge radius
Kaon induced Primakoff reaction

Thank you