Gluon content of pion and kaon with the COMPASS++/AMBER setup at CERN

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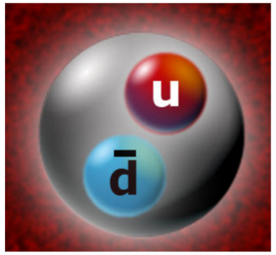
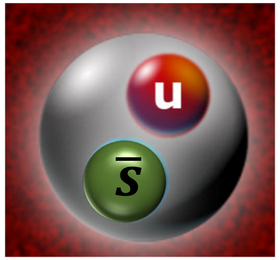
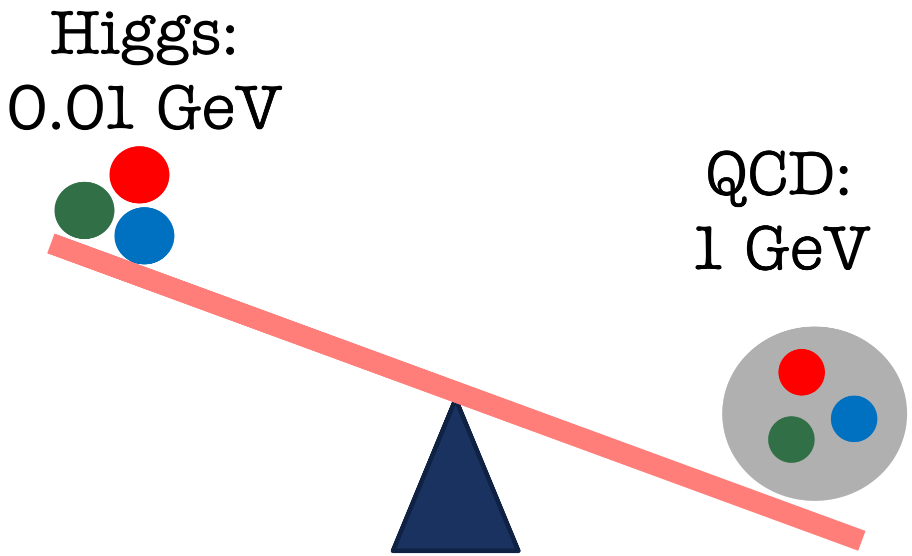
(On behalf of Compass++/AMBER collaboration)
input from W.-C. Chang, J.-C. Peng, T. Sawada, and P. Faccioli

Interest in meson structure

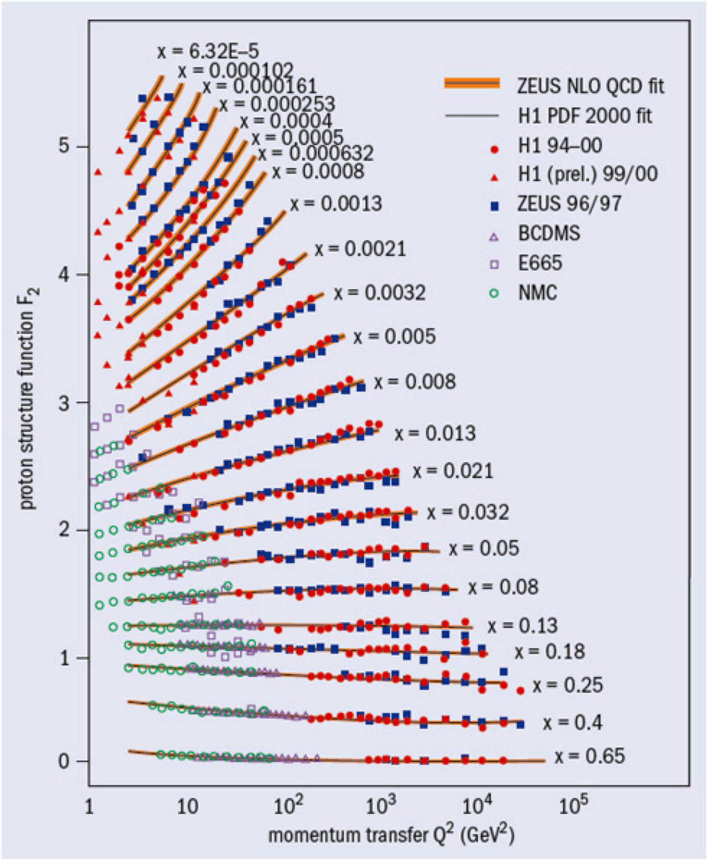
- Fundamental QCD quantities
  - What is the behavior of the kaon and pion PDFs vs the PDFs in the nucleon?
  - Are kaon and pion gluon PDFs identical?
- Double nature
  - The lightest quark-antiquark pairs
  - Massless Nambu-Goldstone bosons
- Help understanding the hadron mass budget
  - Higgs mechanism can't explain hadron masses
  - Meson PDFs: Important input



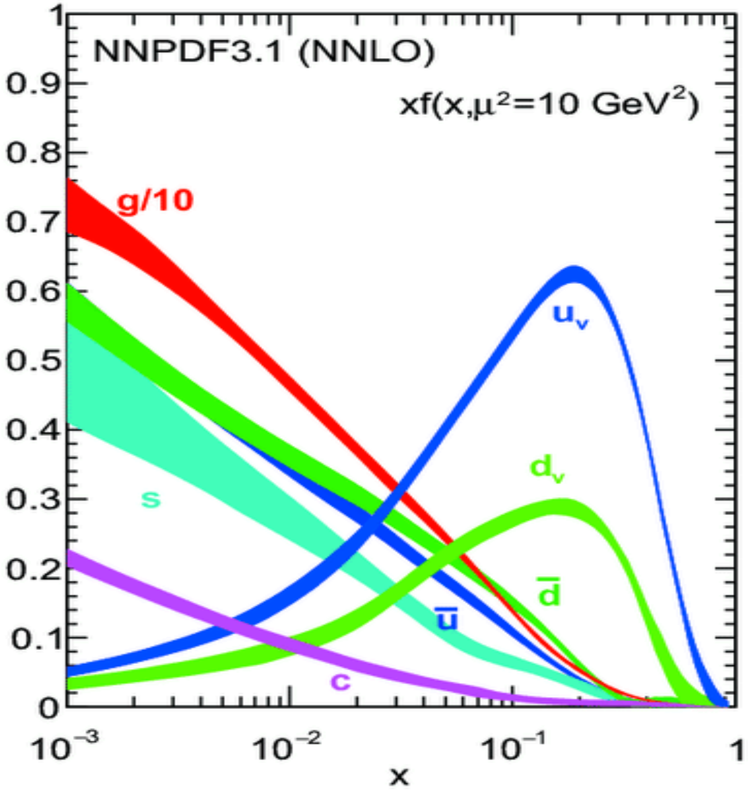




Nucleon PDFs, as determined by NNPDF

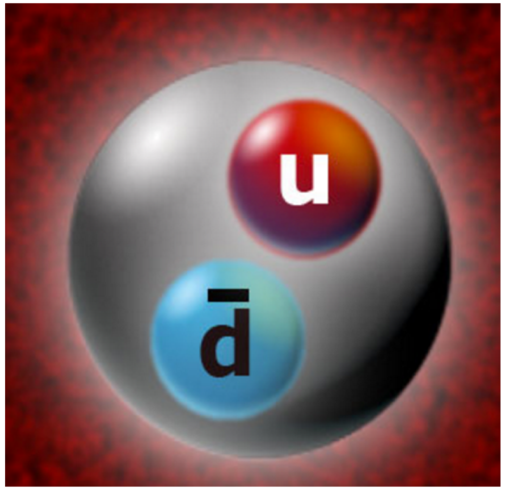


Del Debbio, EPJ Web of Conferences 175, 01006 (2018)



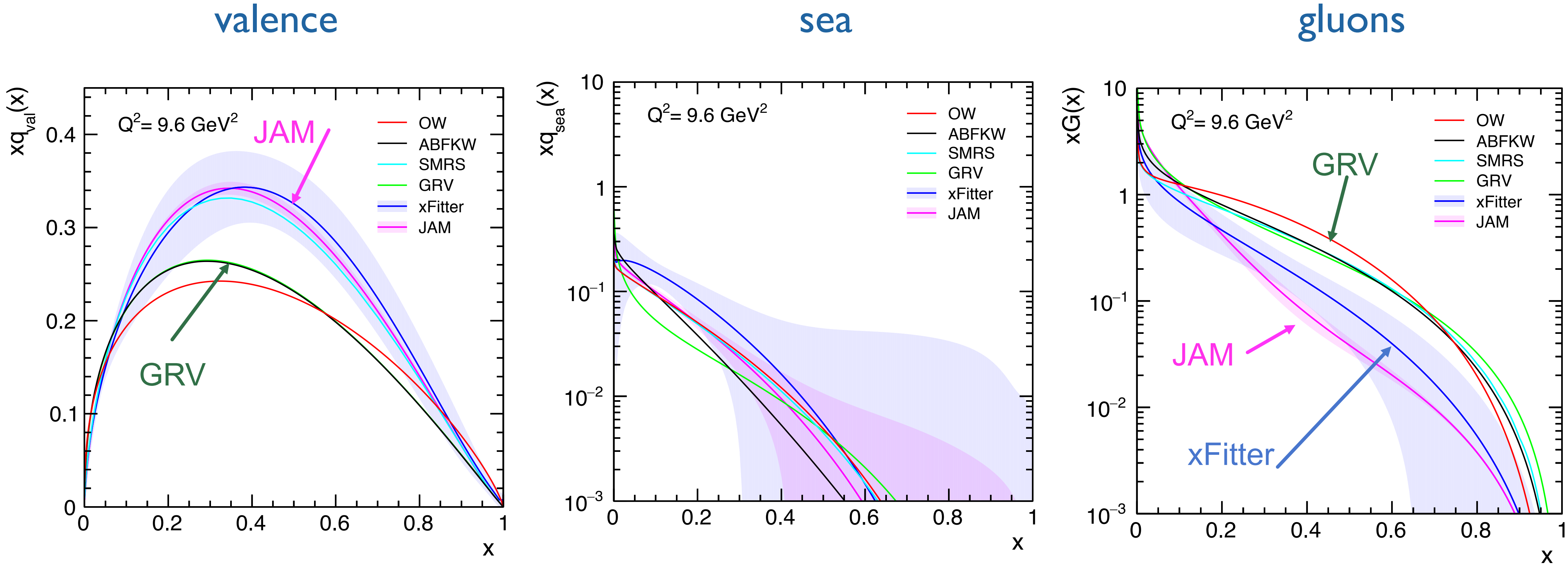
Nucleon PDFs are quite well known – thanks to numerous measurements made over more than 4 decades

I. The pion.



Comparison of the pion PDFs from available "global fits"

From Chang, Peng, SP, Sawada, PRD102.054024



There are large differences between the available parametrizations

Comparison of the global fit PDFs – first moments

From Chang, Peng, SP, Sawada, PRD102.054024

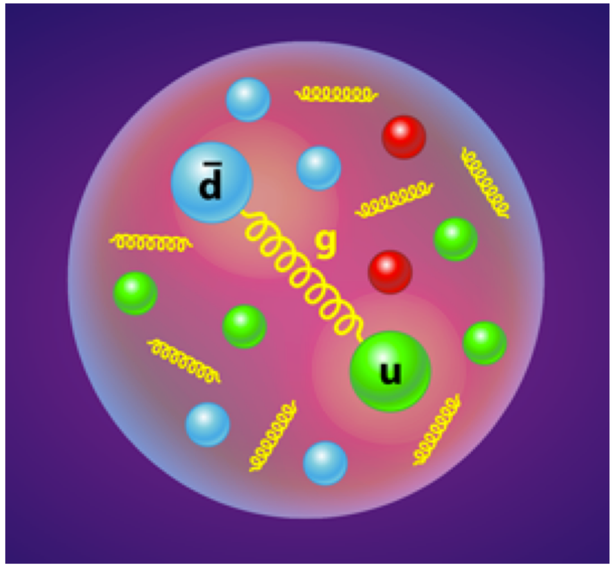
Scale= 9.6 GeV^2

Year	PDF	$\int_0^1 x\bar{u}_{val}(x)dx$	$\int_0^1 x\bar{u}_{sea}(x)dx$	$\int_0^1 xG(x)dx$
		valence	sea	gluons
1992	SMRS	0.245	0.026	0.394
1992	GRV	0.199	0.020	0.513
2018	JAM$^{(a)}$	0.225 ± 0.003	0.028 ± 0.002	0.365 ± 0.016
2020	xFitter$^{(a)}$	0.228 ± 0.009	0.040 ± 0.020	0.291 ± 0.119

Large differences in the gluon first moments

How to access the pion gluon PDF?

- Direct-photon production using pion beams:
  - $gq \to q\gamma$ and $q\bar{q} \to q\gamma$.
  - Two CERN experiments: NA24, WA70 (1987).
- J/ψ production
  - A number of pion-induced experiments (1980-2000)
  - H to ^{195}Pt targets
- Sullivan process at the energies of HERA/EIC
  - Sullivan process – scattering from nucleon-meson fluctuations



from PRL, Barry et al., 2018

Comparison with π-induced J/ψ data – differential cross sections

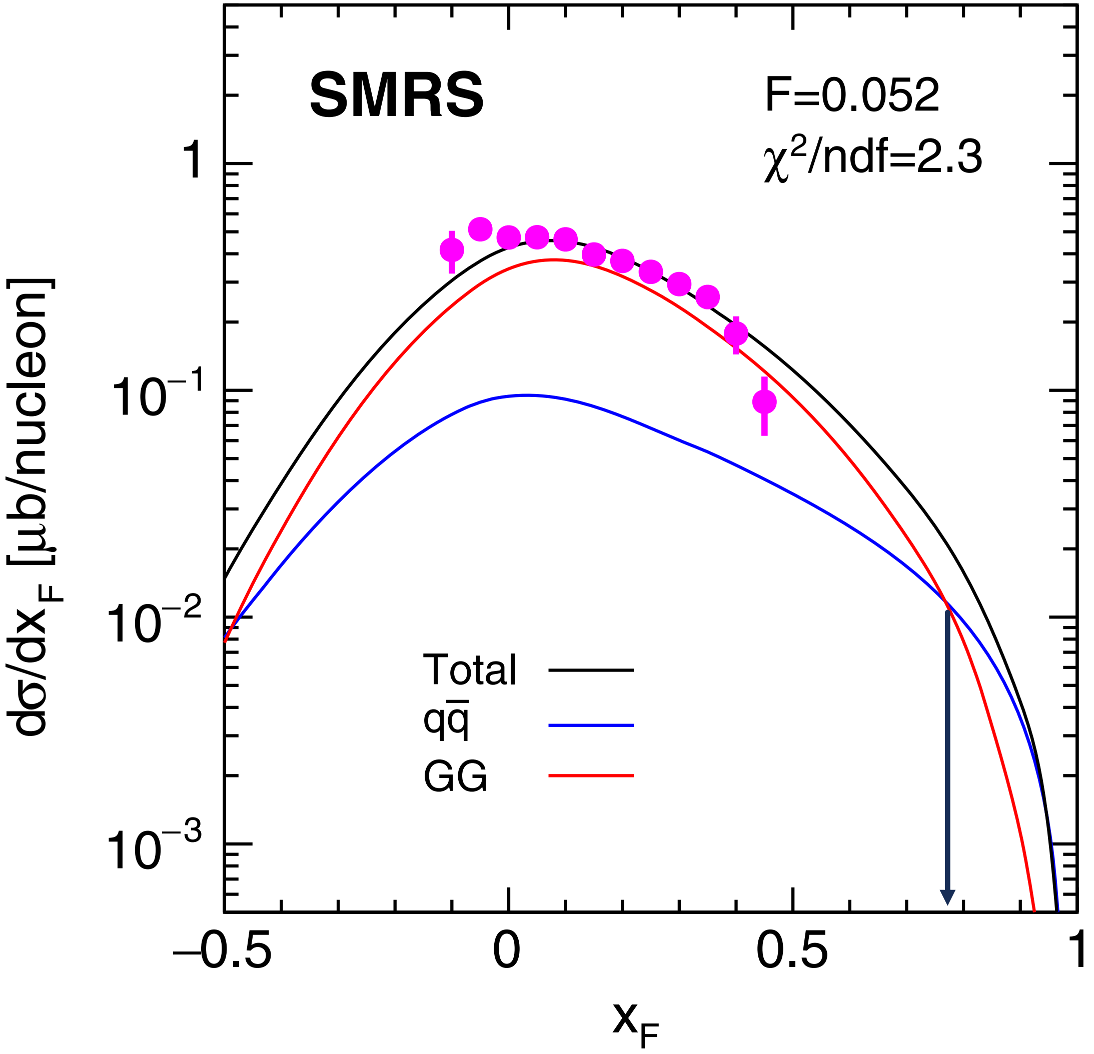
Year	Experiment	P_{beam} (GeV/c)	Target	Normalization[a]	References
1996	FNAL E672, E706	515	Be	12.0	[68]
1992	FNAL E705	300	Li	9.5	[69]
1983	CERN NA3[b]	280	p	13.0	[70]
1983	CERN NA3[b]	200	p	13.0	[70]
1983	CERN WA11[b]	190	Be	c	[72]
1983	CERN NA3[b]	150	p	13.0	[70]
1993	FNAL E537	125	Be	6.0	[73]
1980	CERN WA39[b]	39.5	p	15.0	[74]

Only data on hydrogen, Li, Be – to avoid heavy-target nuclear effects

How sensitive are these data to the gluon (and valence) PDF of the pion?

CEM calculation @ NLO, data from E705

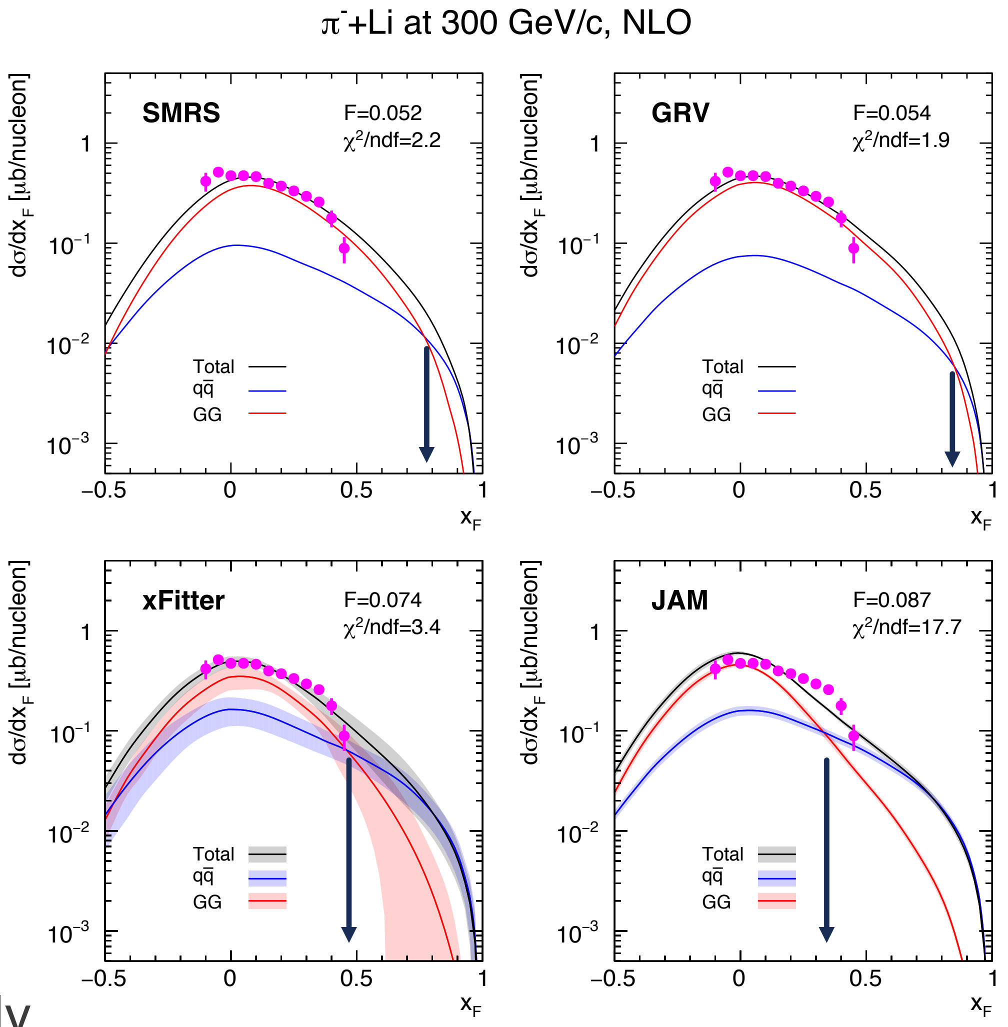
- Experiment: E705 (Fermilab, 1992)
- 300 GeV pions on ^{6}Li
- Nucleon PDF: CT14nlo
- Pion PDF: SMRS



gg fusion is dominant up to $x_F \simeq 0.8$; $q\bar{q}$ is dominant for $x_F > 0.8$

CEM calculation: NLO at E = 300 GeV (E705), ^{6}Li target

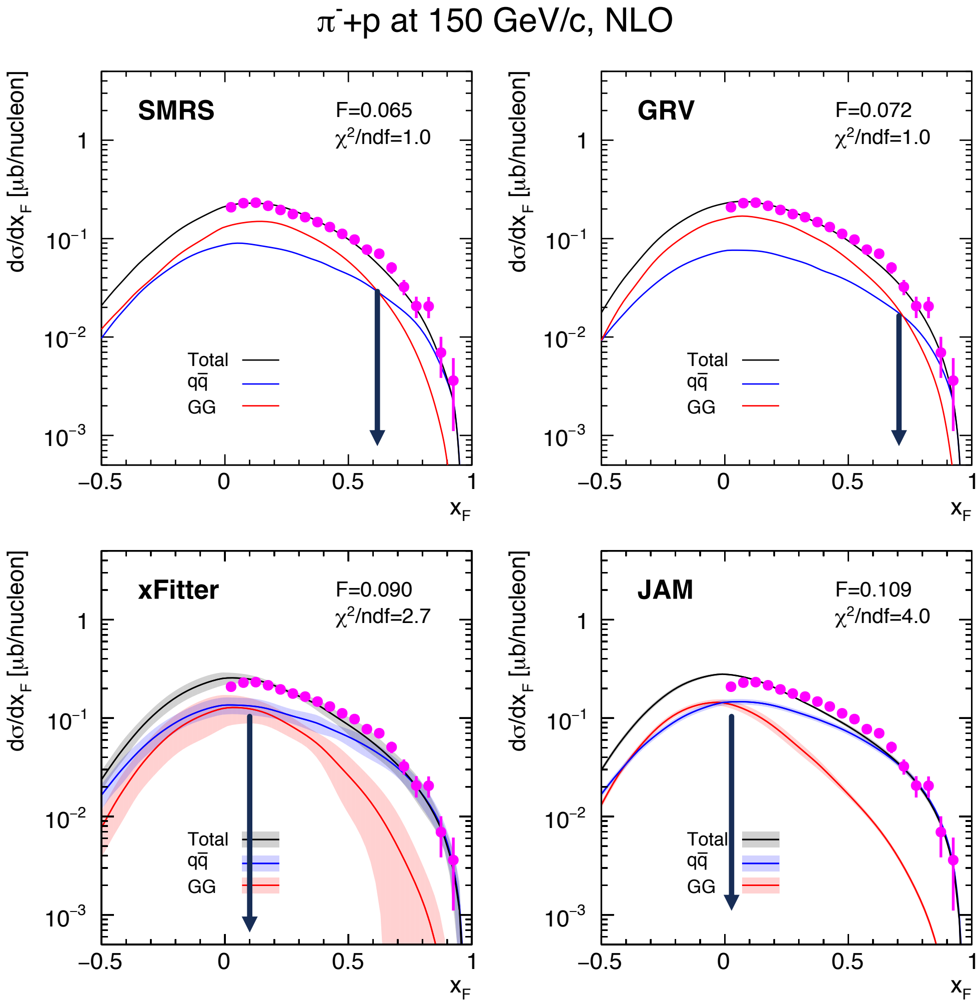
- The different PDF sets have different $q\bar{q}$ and gg contributions
- At E = 300 GeV, gg is dominant up to:
  - SMRS: 0.78
  - GRV: 0.82
  - xFitter: 0.48
  - JAM: 0.35
- Chi2 values: from 1.9 to 17.7



The shape of the J/psi cross section strongly depends on the shape of the pion PDFs

CEM calculation: NLO at E = 150 GeV (NA3), H_2 target

- Nice data, unfortunately, no published cross sections
- Similar trend as before: different $q\bar{q}$ and gg contributions.
- At E = 150 GeV, gg is dominant up to:
  - SMRS: 0.62
  - GRV: 0.70
  - xFitter: 0.12
  - JAM: 0.05
- Chi2 from 1.0 to 4.0

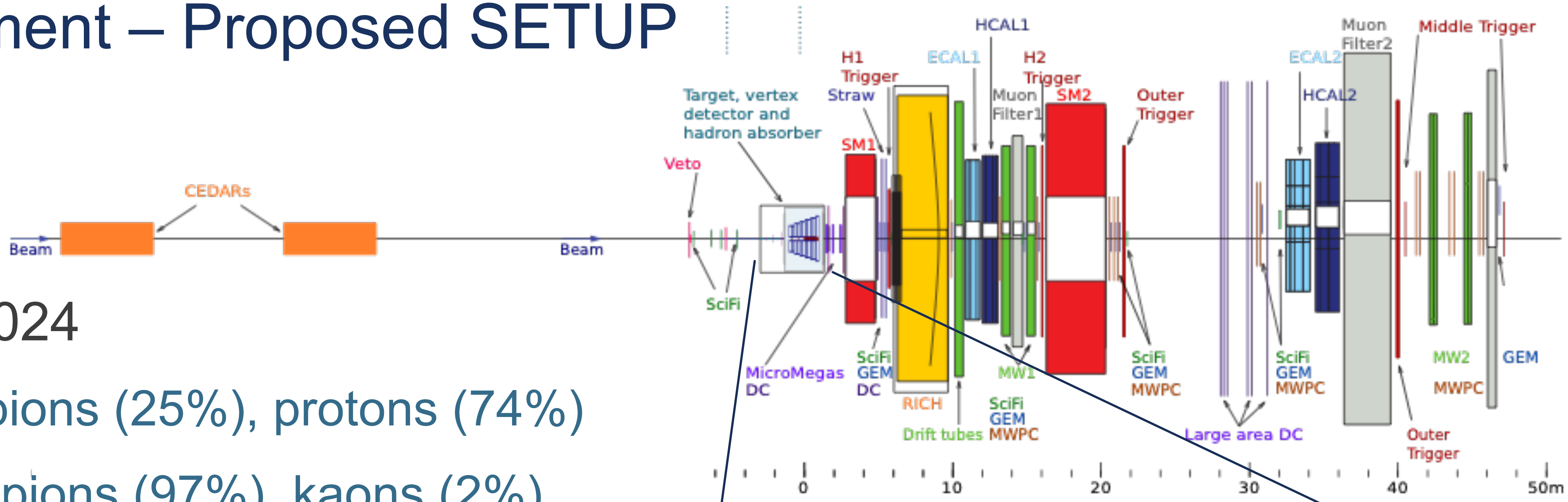


The shape of the J/psi cross section strongly depends on the shape of the pion PDFs…

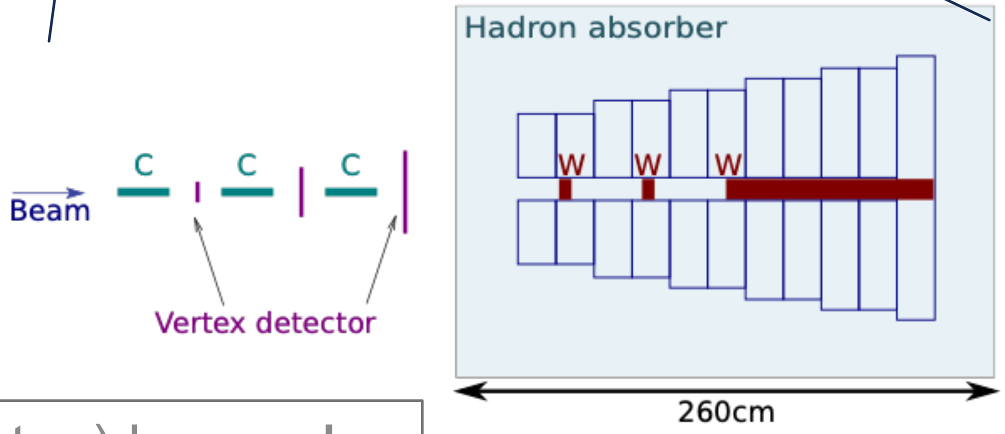
…and on the incident pion momentum

What AMBER can do for the pion?

AMBER experiment – Proposed SETUP



- Run 3: 2022 – 2024
  - ➢ positive beam: pions (25%), protons (74%)
  - ➢ negative beam: pions (97%), kaons (2%)
- Run 4 (with RF): > 2026
  - ➢ negative kaons (~50%), pions (~50%)
  - ➢ positive kaons
  - ➢ antiprotons



Only place in the world with pion and (kaon, antiproton) beams !

Charmonium studies WITH AMBER

- Advantages of (our) FT energies: 100 – 200 GeV
  - J/ψ has large cross sections – factor of 30-40 larger than Drell-Yan at 190 GeV
  - Fixed-target energies: production is dominated by 2 -> 1 processes
  - Can measure x_F, p_T, λ distributions with unprecedented statistics (> 1 M events)
  - Collect also ψ' data, together with J/ψ

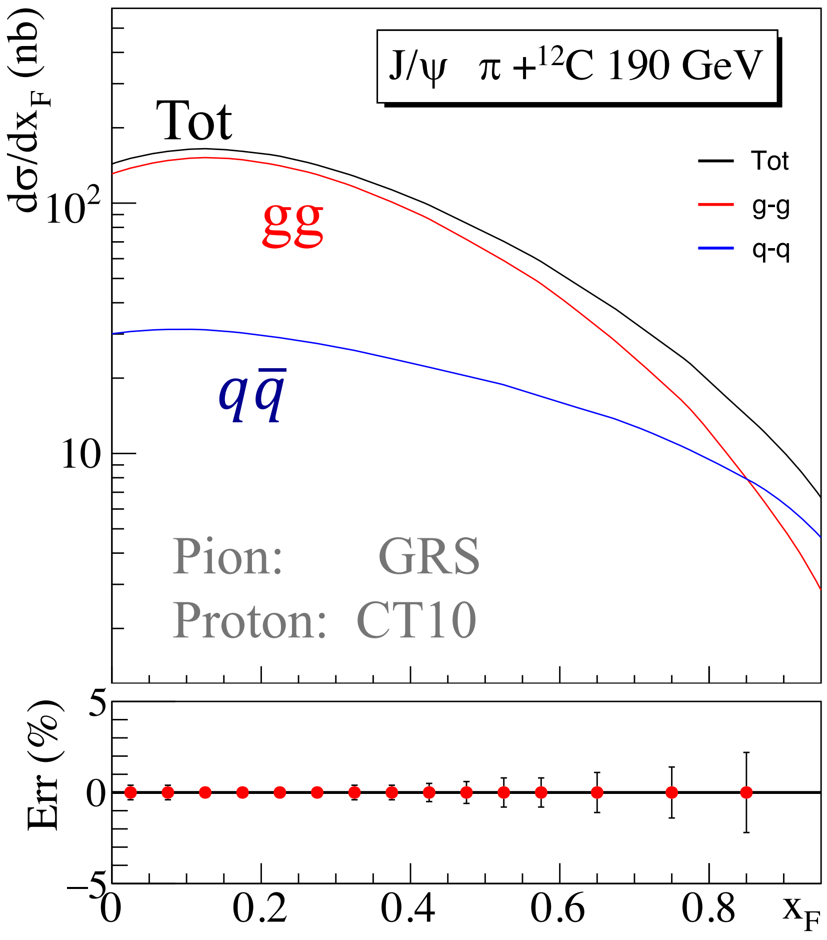
- Present status of FT measurements
  - Meson FT data come from CERN and Fermilab experiments: mostly 80's, 90's
  - No new FT data since nearly two decades – contrary to charmonium collider data

DIMUON (DY and charmonium) studies IN COMPASS++/AMBER

- Run 3: 2022 – 2024
  - E = 190 GeV, positive and negative hadron beams
  - light (^{12}C) and heavy (^{184}W) targets
  - Simultaneous measurements: π^+ and p, and also π^-
- Run 4:
  - strongly relies on RF separated beams
  - E < 100 GeV, positive and negative beams
  - New, highest-ever statistics measurements with K^+, K^-, antiprotons …

Note that: Drell-Yan and charmonium data are collected in parallel

ICEM predictions – x_F dependence



ICEM: Cheung and Vogt, PRD98,114029 (2018) and priv. comm.

Relative statistical errors (%!)

Polarization

- J/ψ is a 1^{--} particle; its third component is $J_z = 0, +1, -1$.
  - $\alpha = +1$: 100% transverse polarization ($J_z = \pm 1$)
  - $\alpha = 0$: unpolarized
  - $\alpha = -1$: 100% longitudinal polarization ($J_z = 0$)

$$\frac{d\sigma}{d(\cos\theta)} \propto 1 + \alpha\cos^2\theta,$$

On polarization : see talk by P. Faccioli

- Polarization is a fundamental observable
  - angular momentum, chirality, parity conservations preserve the properties of the J/ψ: from production to the 2μ decay
  - Nature wants to help us, for $q\bar{q}$: $\alpha \simeq +1$, but for gg: $\alpha \simeq -1$
  - Key variable for understanding the bound state formation

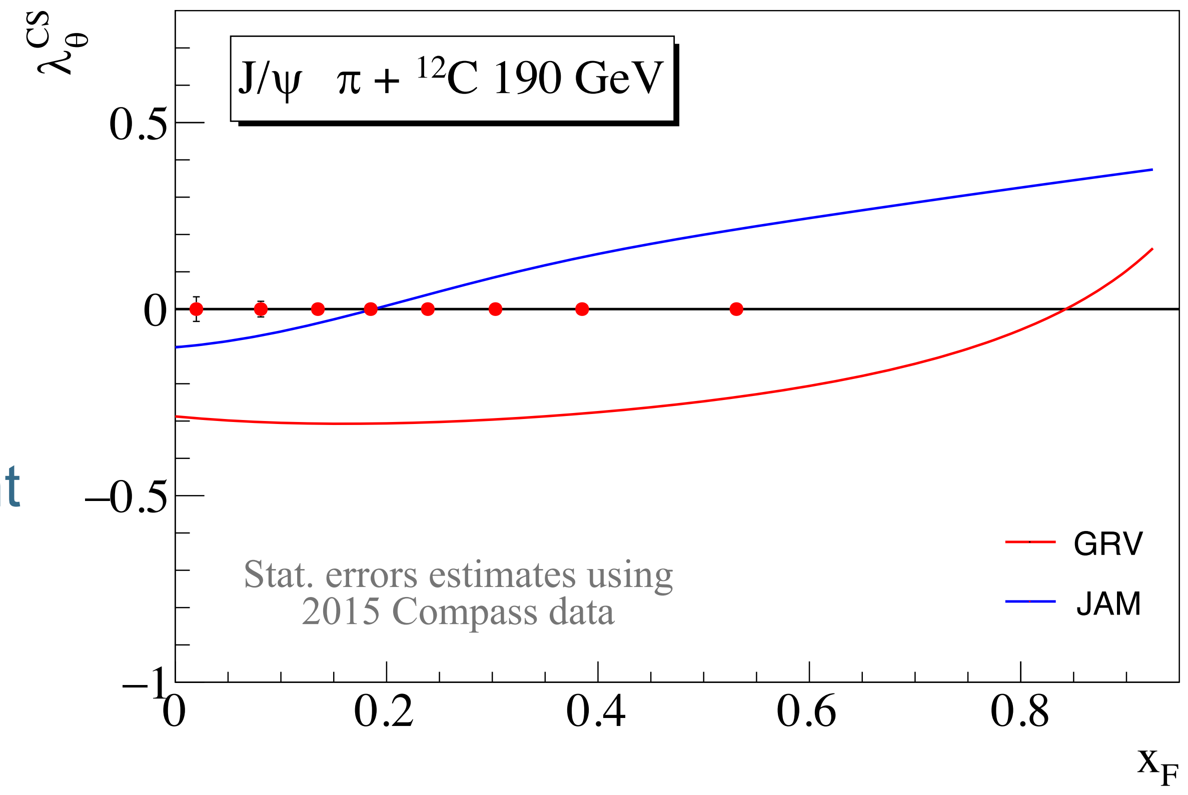
Polarization: expected results (Cheung and Vogt, priv. comm.)

- ICEM xF-dependent predictions
  - with minimal model-dependence

$$\lambda_\vartheta^{CS} \approx +0.4 \text{ for } q\bar{q}$$

$$\lambda_\vartheta^{CS} \approx -0.6 \text{ for } gg$$

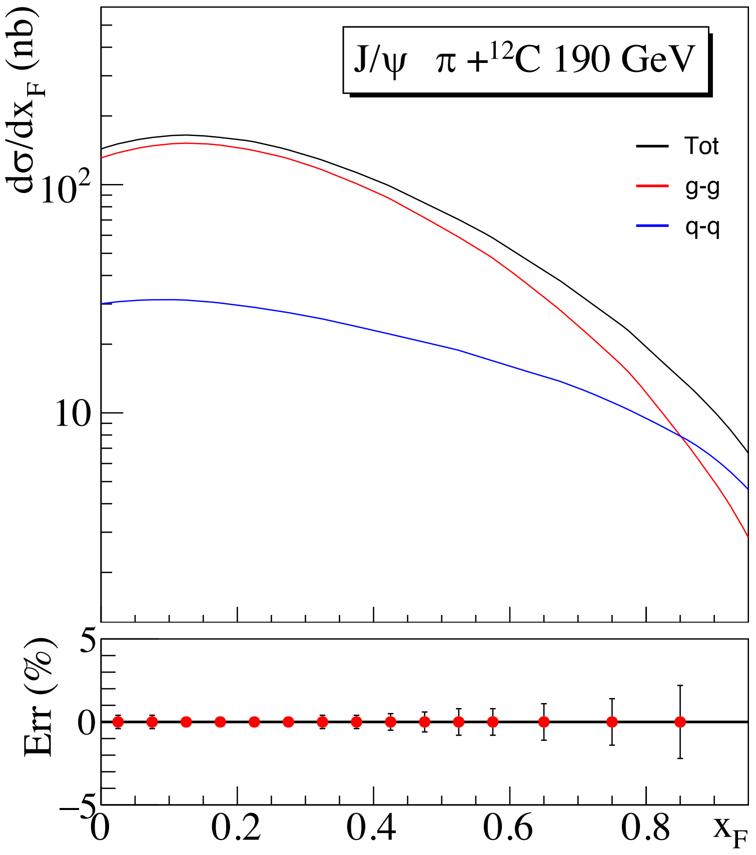
  - The difference between the two predictions results from the different amount of $q\bar{q}$ and gg contributions as a function of x_F.



The polarization value as a function of x_F is sensitive to the shape differences between gg and $q\bar{q}$ contributions to the cross section

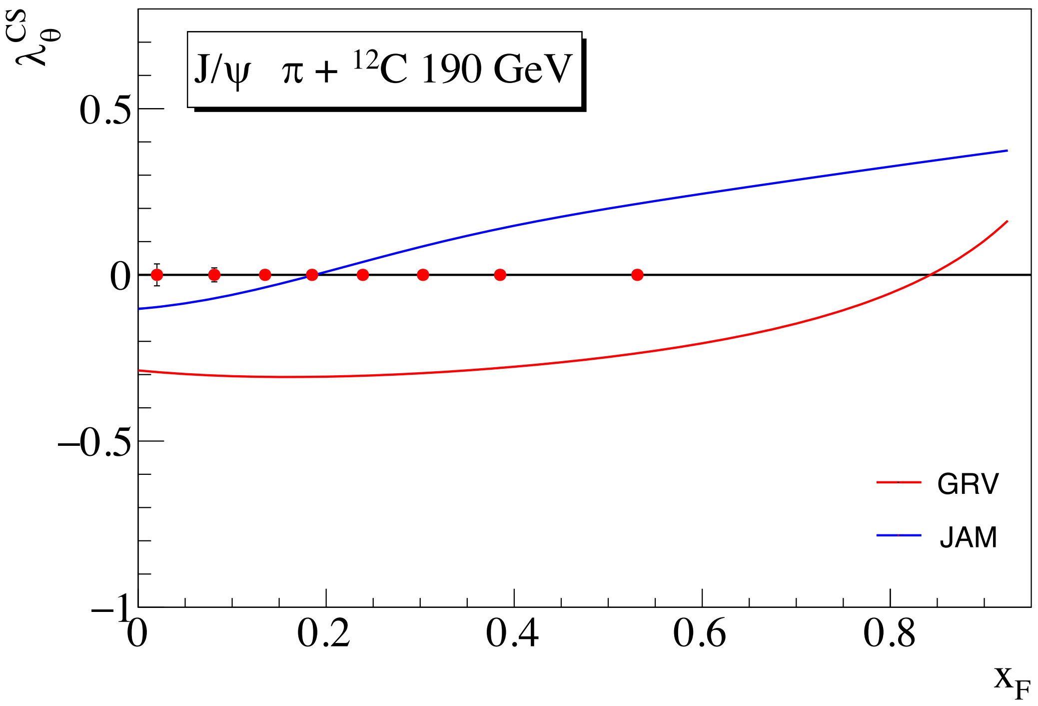
J/ψ measurements at COMPASS++/AMBER

Cross section (ICEM)



Polarization (ICEM)

ICEM: CHEUNG AND VOGT, PRIV. COMM.



Multidimensional analysis of both cross section and dilepton decay angles should provide constraint on the gg and $q\bar{q}$ fractions

ψ' production

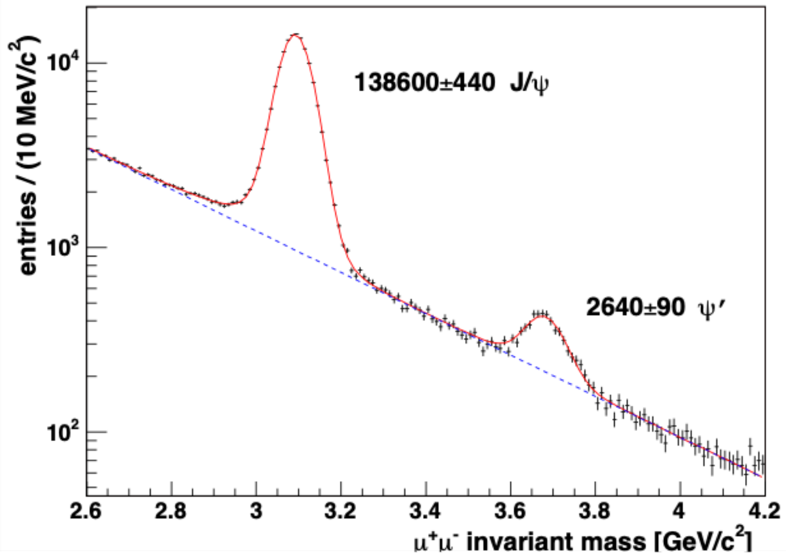
- Advantages
  - No feed-down contributions. Consequences:
    - straightforward test of production models, no dilution.
    - $q\bar{q}$ and gg contributions could reach their maximum polarization values
  - x_F and p_T dependences could be measured altogether with the polarization
  - AMBER could provide the largest ψ' data set ever.
- Requirements
  - Good mass resolution (≤ 100 MeV) to separate J/ψ and ψ' – vertex detectors
  - Alternative: dedicated run for charmonium studies without absorber – much improved resolution, but significantly lower statistics.

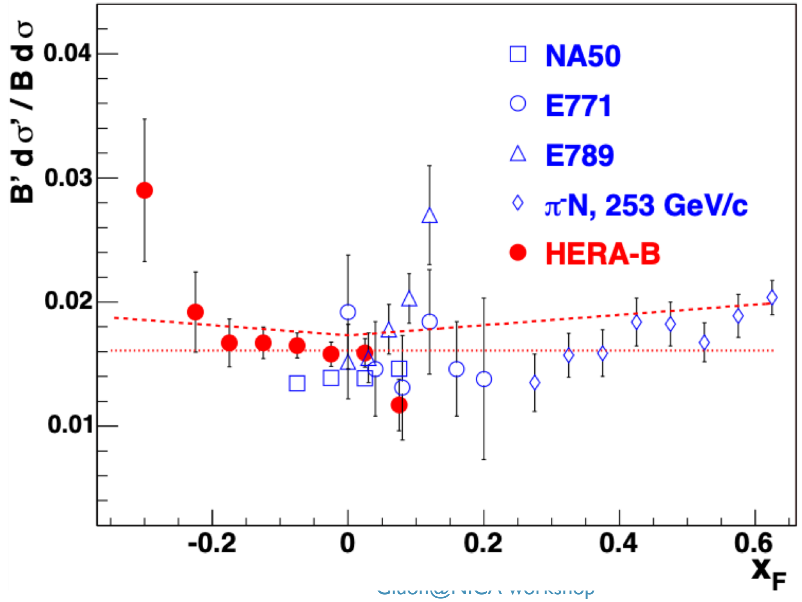
ψ' production – expected statistics

- From previous measurements (e.g. HERA-B, 2007)
  - R (ψ'/J/ψ) $\simeq$ 0.018 (used to estimate nb of ψ')

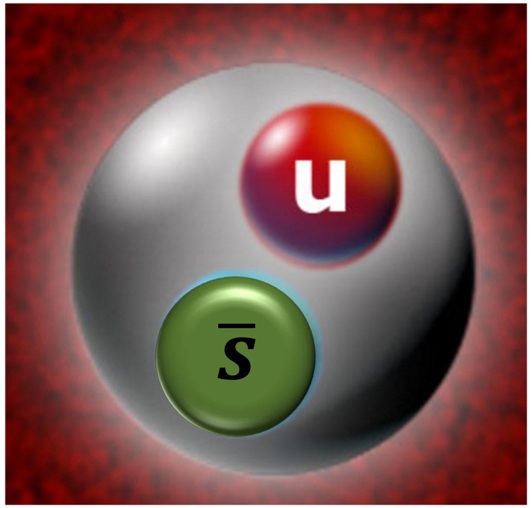
Target	Energy	Beam	Nb of ψ'
^{12}C	190 GeV	π^+	21 600
		π^-	32 400
		p	27 000
^{184}W		π^+	9 000
		π^-	12 600
		p	12 600

An order of magnitude better than previous experiments !



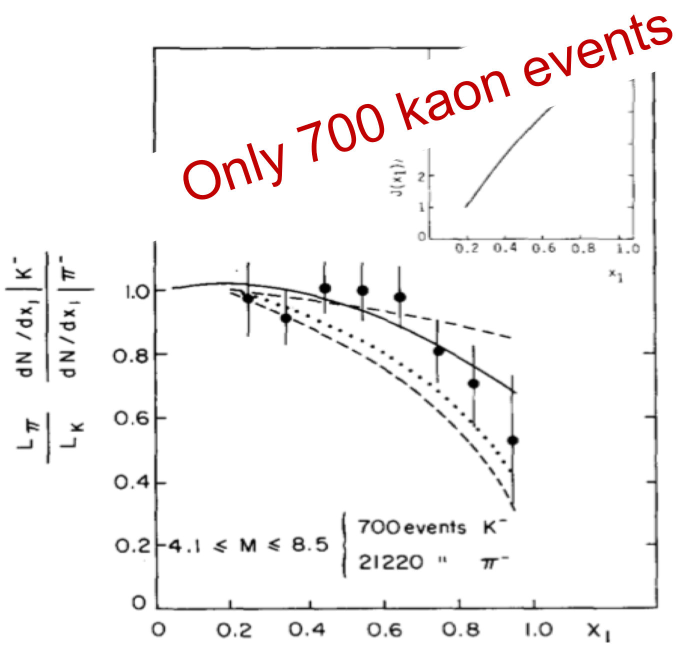


II. The kaon.



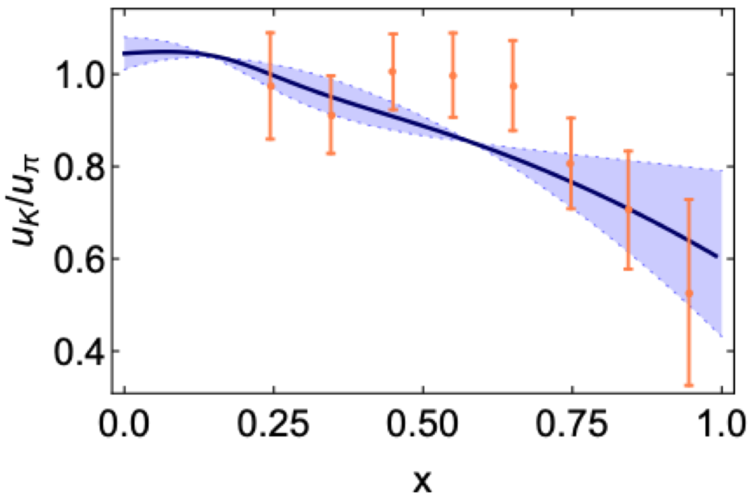
Kaon PDFs: present status

- 1980: Only available data:
  - NA3, PLB93, 1980



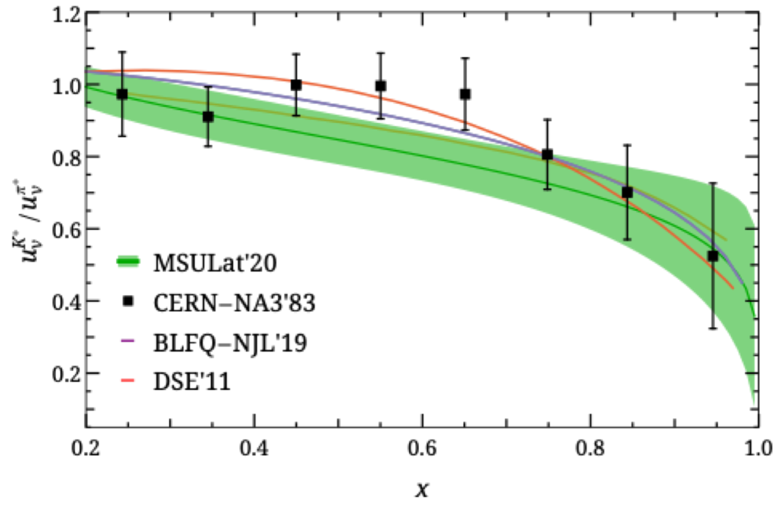
- 2020: First "ab-initio" calculations, no new data!

Dyson-Schwinger Equations
Cui et al., arXiv:2006.14075



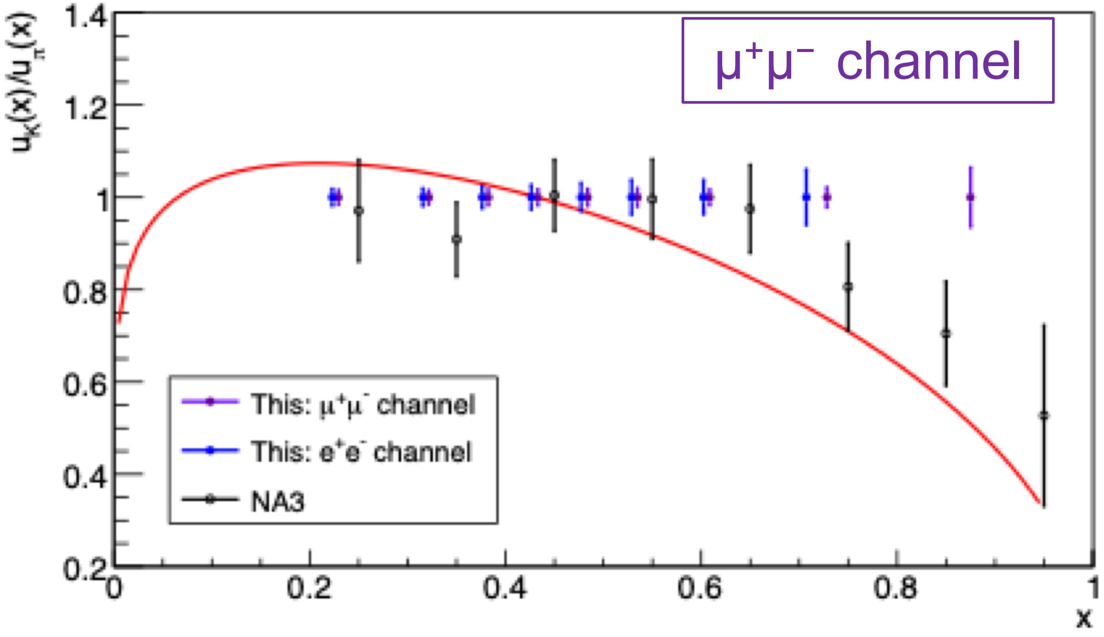
First ever calculation that predicts ALL kaon PDFs

Lattice QCD
Lin et al., arXiv:2003.14128



First ever lQCD calculation of the kaon valence PDF

Kaon PDF with Drell-Yan – expected results



Assumptions:

- Energy: 100 GeV
- Target: ^{12}C
- Data taking: 210 days of K^+; 70 days of K^-
- Intensity: 2.1 x 10^7/sec

Foreseen statistics with kaons (Drell-Yan) :
- ~ 40000 events K^-
- ~ 5200 events K^+

Good statistics for the valence PDF (factor of ~60)
Statistics is much larger for J/psi production…(x20-40)

J/ψ – model-independent access to the kaon valence PDF!

- Use the fact that: $K^+(u\bar{s})$ and $K^-(\bar{u}s)$
  - Only the $\bar{u}$ valence quark in the kaon annihilates with the u valence quark in the target
- Production cross section for K⁺ and K⁻ : $\sigma(K^-)-\sigma(K^+)\propto \bar{u}_v^K u_v^p$

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

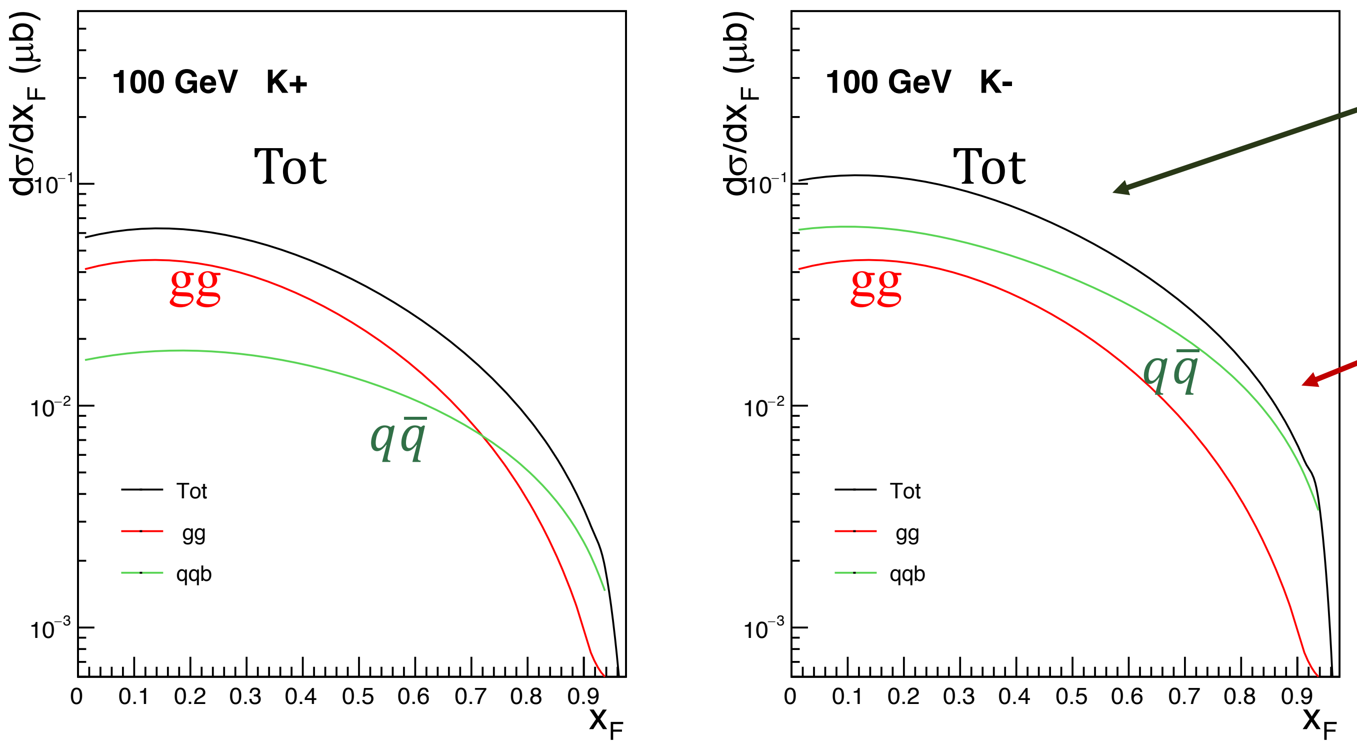
$$K^+(u\bar{s})+p(uud)\propto gg+\left[---\right]+\left[u_v^K\bar{u}_s^p+\bar{s}_v^K s_s^p\right]+\left[\bar{u}_s^K u_v^p\right]+\left[\bar{u}_s^K u_s^p+u_s^K\bar{u}_s^p+s_s^K\bar{s}_s^p+\bar{s}_s^K s_s^p\right]$$

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

The cross section difference singles out the valence-valence term

Kaon-induced J/ψ production

LO CEM calculation



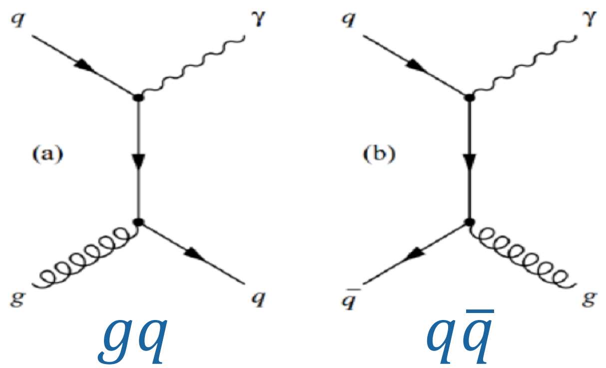
identical val-sea and sea-sea contributions

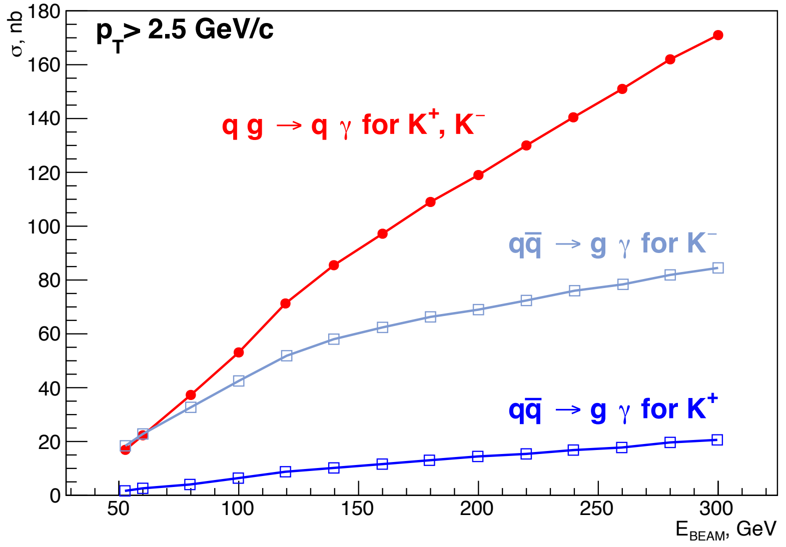
identical gg contributions

The valence PDF is measured mainly using the K^- data
The gluon PDF can be best determined using the K^+ data

Kaon-induced prompt-photon production (LoI, 1808.00848)

- Proposed measurement
  - Positive kaon beam $K^+(u\bar{s})$
  - Use AMBER calorimeters to detect photons
  - E = 100 GeV, 2m long H_2 target (1y data taking)
  - I = 2 x 10^7/s (about 50% kaons) + Beam PID
  - Access $g_K(x)$ via the $gq \rightarrow q\gamma$ process
  - p_T > 2.5 GeV/c

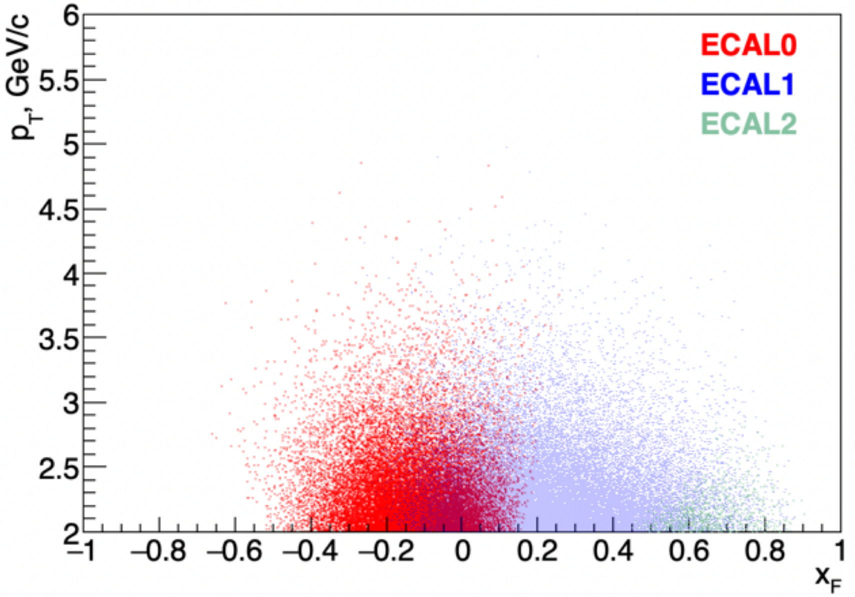




Kaon-induced prompt-photon production (LoI, 1808.00848)

- Advantages
  - $K^+(u\bar{s})$ minimizes the $q\bar{q}$ contribution
  - Fragmentation photons ~ 10%
  - Large x_F acceptance (down to $x_F \sim -0.5$)

AMBER calorimeters' coverage



  - Nb of events in the region ($-1.4 < y < +1.8$) : ~$3.4 \cdot 10^6$

Complementary to the gluon determination using J/psi production measurement

Summary

- Run-3 (Proposal): DY and J/ψ data with π+ and π− beams
  - DY data: pion PDFs, flavor dependence of the nuclear mean field
  - J/ψ and ψ' data: high-statistics FT data for production mechanism studies

- Run-4 (LoI): DY and J/ψ data with K^+ and K^- beams (RF separation needed)
  - DY data: kaon PDF measurements
  - J/ψ and ψ' data: comparison K^- and K^+ data – production mechanism, kaon structure
  - Direct-photon production: gluon PDF in the kaon

CERN + AMBER is unique for such measurements; no direct competition

Spare slides

Color Evaporation Model calculation at NLO

- Advantages
  - simple formalism: nice phenomenological success
  - good description of x_F dependent data
  - F-factor includes all J/ψ's (direct and Chi-decay)
- Drawbacks
  - too phenomenological
  - no p_T dependence -> ICEM model
  - not used at high energies

$$\frac{d\sigma}{dx_F}|_{J/\psi} = F \sum_{i,j=q,\bar{q},G} \int_{2m_c}^{2m_D} dM_{c\bar{c}} \frac{2M_{c\bar{c}}}{s\sqrt{x_F^2 + 4M_{c\bar{c}}{}^2/s}} \times f_i^{\pi}(x_1,\mu_F) f_j^N(x_2,\mu_F) \hat{\sigma}[ij \to c\bar{c}X](x_1 p_\pi, x_2 p_N, \mu_F, \mu_R), \quad (1)$$

The shape of the cross section is fully correlated to the shape of the beam and target PDFs

$$\begin{aligned}
q + \bar{q} &\to Q + \bar{Q}, \alpha_S^2, \alpha_S^3 \\
G + G &\to Q + \bar{Q}, \alpha_S^2, \alpha_S^3 \\
q + \bar{q} &\to Q + \bar{Q} + g, \quad \alpha_S^3 \\
G + G &\to Q + \bar{Q} + g, \quad \alpha_S^3 \\
G + q &\to Q + \bar{Q} + q, \quad \alpha_S^3 \\
G + \bar{q} &\to Q + \bar{Q} + \bar{q}, \quad \alpha_S^3.
\end{aligned}$$

Computer code from Mangano et al., Nucl.Phys. B405, 1993

Estimated J/ψ statistics

Experiment	Target type	Beam energy (GeV)	Beam type	J/ψ events
NA3 [76]	Pt	150	π^-	601000
		280	π^-	511000
		200	π^+	131000
			π^-	105000
E789 [127, 128]	Cu	800	p	200000
	Au			110000
	Be			45000
E866 [129]	Be, Fe, Cu	800	p	3000000
NA50 [130]	Be	450	p	124700
	Al			100700
	Cu			130600
	Ag			132100
	W			78100
NA51 [131]	p	450	p	301000
	d			312000
HERA-B [132]	C	920	p	152000
This exp	75 cm C	190	π^+	1200000
			π^-	1800000
			p	1500000
	12 cm W	190	π^+	500000
			π^-	700000
			p	700000

Comments

Cross sections not published, only plots available

x_F and p_T cross sections available

Only ratios of cross sections available

Only A-dependent studies of total cross sections

Only A-dependent studies of total cross sections

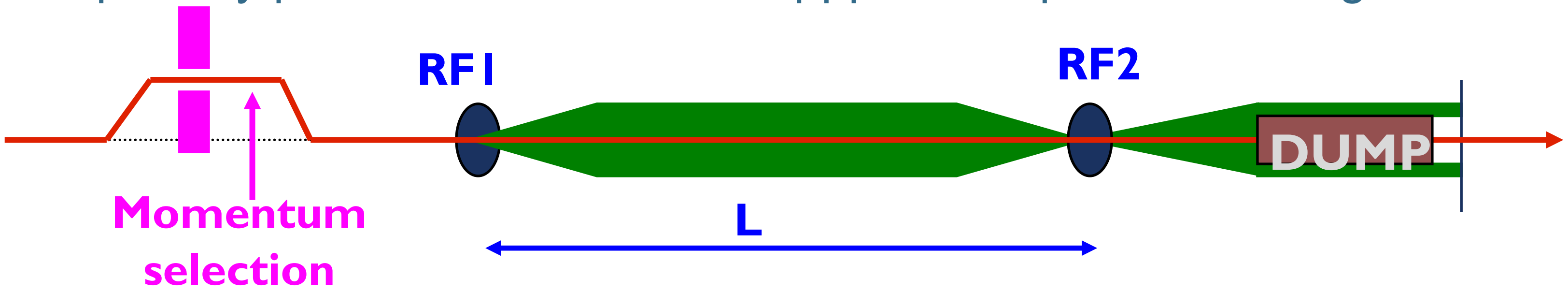
x_F and p_T cross sections available

…

Estimations based on Compass preliminary numbers

Run4++ : RF separated beams – high-intensity

- 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 : 100 GeV

Large improvement in kaon and antiproton intensities (> x 20- 40 !)