COMPASS++/AMBER Physics: preparing Phase-II

C. Quintans, LIP-Lisbon
on behalf of the COMPASS++/AMBER interested community

by petescully, UrbanSketchers, Lisboa

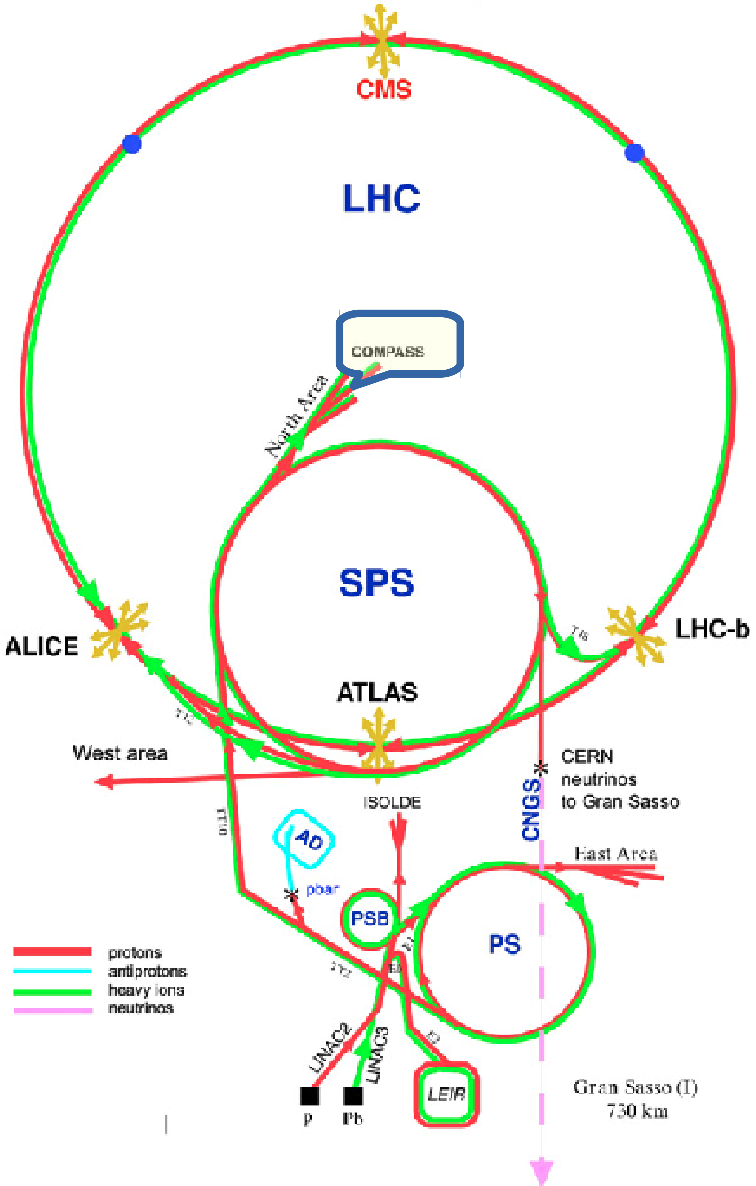
LABORATÓRIO DE INSTRUMENTAÇÃO E FÍSICA EXPERIMENTAL DE PARTÍCULAS

FCT Fundação para a Ciência e a Tecnologia

Outline

- COMPASS++/AMBER experiment
- Pion structure
- Kaon structure
- Proton (spin)-structure
- Strange meson spectroscopy

COMPASS++/AMBER: a unique opportunity



<u>The CERN-M2 beam line</u>:
$\mu^{\pm}$ beams and Hadron beams of both charges
in a wide range of momenta and with high intensities

Possible <u>upgrade of the M2 beam line</u>:
Using radio-frequency separation method,
obtain kaon-enriched and antiproton-enriched beams

Physics possibilities

Program	Physics Goals	Beam Energy [GeV]	Beam Intensity [s^{-1}]	Trigger Rate [kHz]	Beam Type	Target	Earliest start time, duration	Hardware additions
muon-proton elastic scattering	Precision proton-radius measurement	100	$4 \cdot 10^6$	100	$\mu^\pm$	high-pressure H2	2022 1 year	active TPC, SciFi trigger, silicon veto,
Hard exclusive reactions	GPD E	160	$2 \cdot 10^7$	10	$\mu^\pm$	$NH_3^\uparrow$	2022 2 years	recoil silicon, modified polarised target magnet
Input for Dark Matter Search	$\bar{p}$ production cross section	20-280	$5 \cdot 10^5$	25	p	LH2, LHe	2022 1 month	liquid helium target
$\bar{p}$-induced spectroscopy	Heavy quark exotics	12, 20	$5 \cdot 10^7$	25	$\bar{p}$	LH2	2022 2 years	target spectrometer: tracking, calorimetry
Drell-Yan	Pion PDFs	190	$7 \cdot 10^7$	25	$\pi^\pm$	C/W	2022 1-2 years	
Drell-Yan (RF)	Kaon PDFs & Nucleon TMDs	~100	10^8	25-50	$K^\pm$, $\bar{p}$	$NH_3^\uparrow$, C/W	2026 2-3 years	"active absorber", vertex detector
Primakoff (RF)	Kaon polarisa-bility & pion life time	~100	$5 \cdot 10^6$	> 10	K^-	Ni	non-exclusive 2026 1 year	
Prompt Photons (RF)	Meson gluon PDFs	≥ 100	$5 \cdot 10^6$	10-100	$K^\pm$ $\pi^\pm$	LH2, Ni	non-exclusive 2026 1-2 years	hodoscope
K-induced Spectroscopy (RF)	High-precision strange-meson spectrum	50-100	$5 \cdot 10^6$	25	K^-	LH2	2026 1 year	recoil TOF, forward PID
Vector mesons (RF)	Spin Density Matrix Elements	50-100	$5 \cdot 10^6$	10-100	$K^\pm$, $\pi^\pm$	from H to Pb	2026 1 year	

...as expressed in the COMPASS++/AMBER LoI:
https://arxiv.org/pdf/1808.00848.pdf

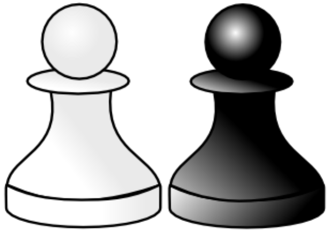
Phase-I

COMPASS++/AMBER Proposal Phase-I:
http://cds.cern.ch/record/2676885?ln=pt

Phase-II

Emergence of hadron mass

- leitmotiv for the various proposed measurements
- key for understanding QCD
- Pion plays a major role: lightest hadron, Nambu-Goldstone boson of the theory



- Kaon is a “window” to the interference region between Higgs mechanism and EHM mechanism

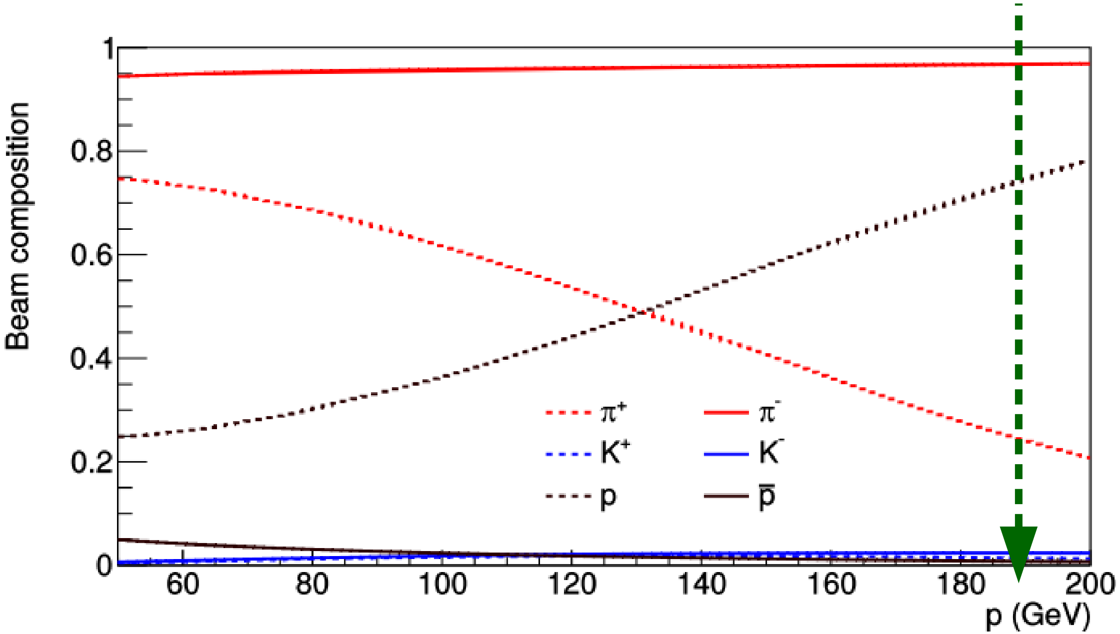
Several theory approaches address the issue of **pion and kaon structure**

But, what do we know from experimental measurements?

Experimental access to pion structure

- pion-induced Drell-Yan ✔ COMPASS++/AMBER
- Sullivan process ➡ **At JLab12, EIC, ...**
- prompt-photon production (induced by pion beam) ✔ COMPASS++/AMBER
- charmonium production (induced by pion beam) ✔ COMPASS++/AMBER
- pion diffractive scattering ? COMPASS++/AMBER

Conventional hadron beams

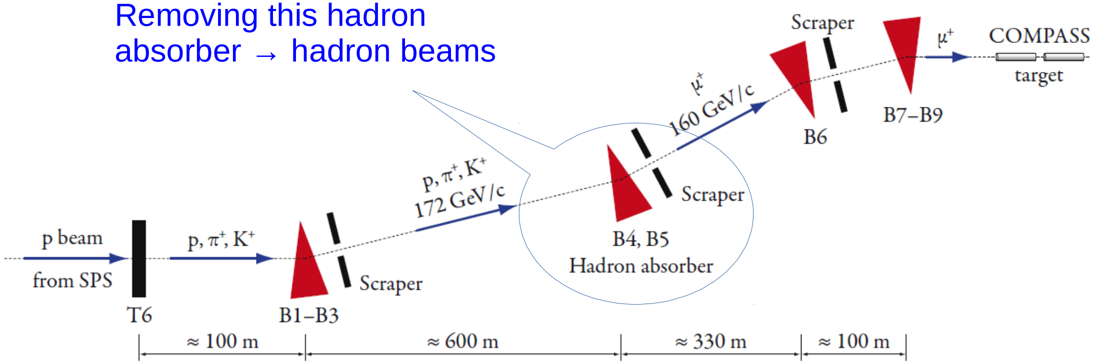


At 190 GeV/c:

- Negative: 97% **π^-** beam
- Positive: 24% **π^+** beam

Maximize Drell-Yan statistics
by having high beam momentum

The same beam line can
provide hadron or muon beams



Pion-induced Drell-Yan

- Mostly heavy target
  - ➜ nuclear effects
- Some did not publish cross-sections
- Some did not measure with both beam charges
  - ➜ no sea/valence separation

Table 7: Statistics collected by earlier experiments (top rows), compared with the achievable statistics of the proposed experiment (bottom rows), in 213 days (π^+ beam) + 67 days (π^- beam).

Experiment	Target type	Beam energy (GeV)	Beam type	Beam intensity (part/sec)	DY mass (GeV/c^2)	DY events
E615	20 cm W	252	π^+ π^-	17.6×10^7 18.6×10^7	4.05 – 8.55	5000 30000
NA3	30 cm H_2	200	π^+ π^-	2.0×10^7 3.0×10^7	4.1 – 8.5	40 121
	6 cm Pt	200	π^+ π^-	2.0×10^7 3.0×10^7	4.2 – 8.5	1767 4961
NA10	120 cm D_2	286 140	π^-	65×10^7	4.2 – 8.5 4.35 – 8.5	7800 3200
	12 cm W	286 194 140	π^-	65×10^7	4.2 – 8.5 4.07 – 8.5 4.35 – 8.5	49600 155000 29300
COMPASS 2015 COMPASS 2018	110 cm NH_3	190	π^-	7.0×10^7	4.3 – 8.5	35000 52000
COMPASS++/ AMBER	75 cm C	190	π^+	1.7×10^7	4.3 – 8.5 4.0 – 8.5	21700 31000
		190	π^-	6.8×10^7	4.3 – 8.5 4.0 – 8.5	67000 91100
	12 cm W	190	π^+	0.4×10^7	4.3 – 8.5 4.0 – 8.5	8300 11700
		190	π^-	1.6×10^7	4.3 – 8.5 4.0 – 8.5	24100 32100

Isoscalar target
Both beam charges
High statistics

Drell-Yan: experimental access to pion structure

Definitions:

$$u_{val}^{\pi^+} = u^{\pi^+} - \bar{u}^{\pi^+}$$ and $$d_{val}^{\pi^-} = d^{\pi^-} - \bar{d}^{\pi^-}$$

And assuming flavour-symmetry:

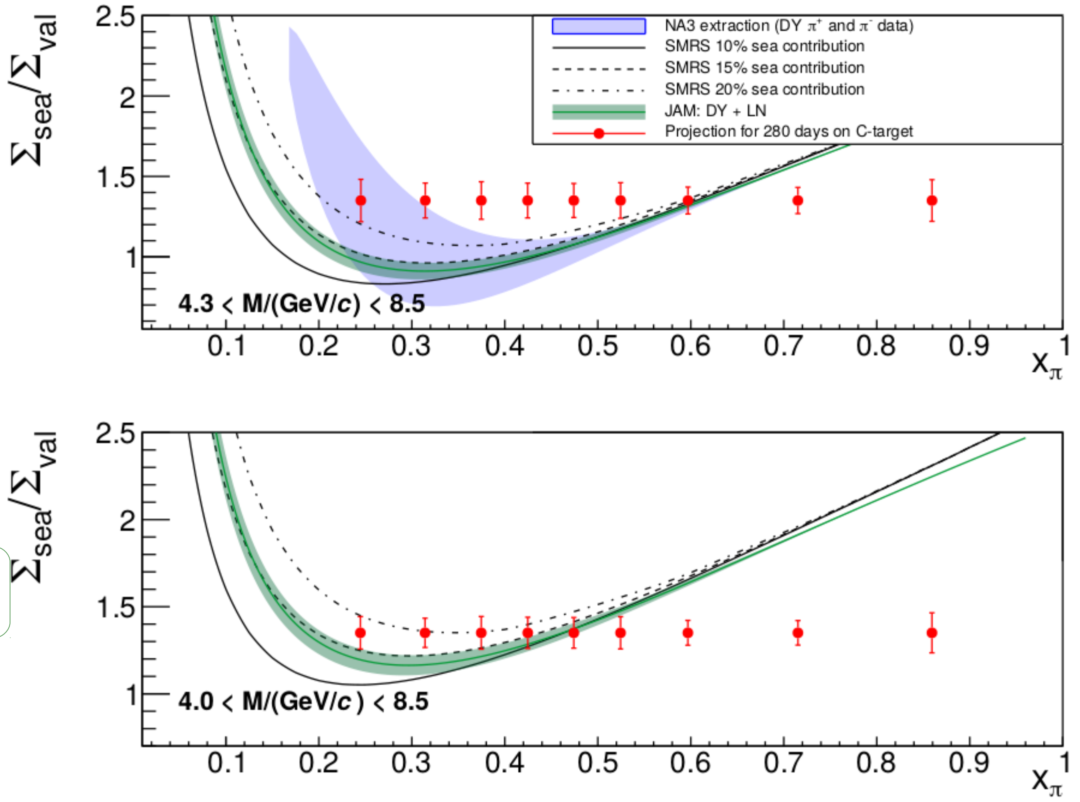
$$u_{val}^{\pi^+} = \bar{d}_{val}^{\pi^+} = \bar{u}_{val}^{\pi^-} = d_{val}^{\pi^-}$$

$$\bar{u}_{sea}^{\pi} = u_{sea}^{\pi} = \bar{d}_{sea}^{\pi} = d_{sea}^{\pi} = \bar{s}_{sea}^{\pi} = s_{sea}^{\pi}$$

$$\frac{\Sigma_{sea}}{\Sigma_{valence}} = \frac{4\sigma^{\pi^+C} - \sigma^{\pi^-C}}{-\sigma^{\pi^+C} + \sigma^{\pi^-C}}$$

LO: only sea-val and val-sea terms

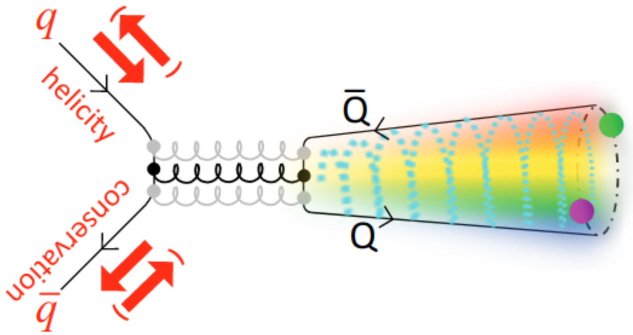
LO: only val-val terms

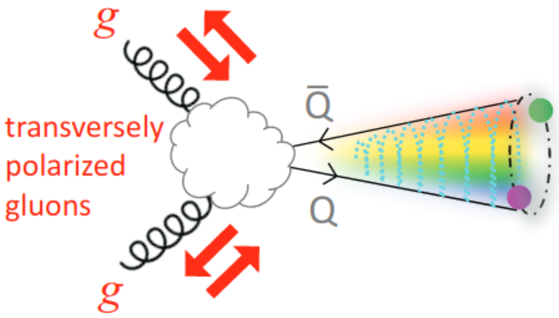


Gluon content of the pion
what can we learn from J/ψ production?

At COMPASS++/AMBER Phase-I:

- Large statistics on J/ψ production at dimuon channel
- Inclusive: due to the hadron absorber, we cannot distinguish prompt production from the rest
- In the low-pT regime, not described by NRQCD
- Expected significant feed-down: ψ(2S), χ_{c1}, χ_{c2}
- Expected to have dominant contribution from $2 \rightarrow 1$ processes

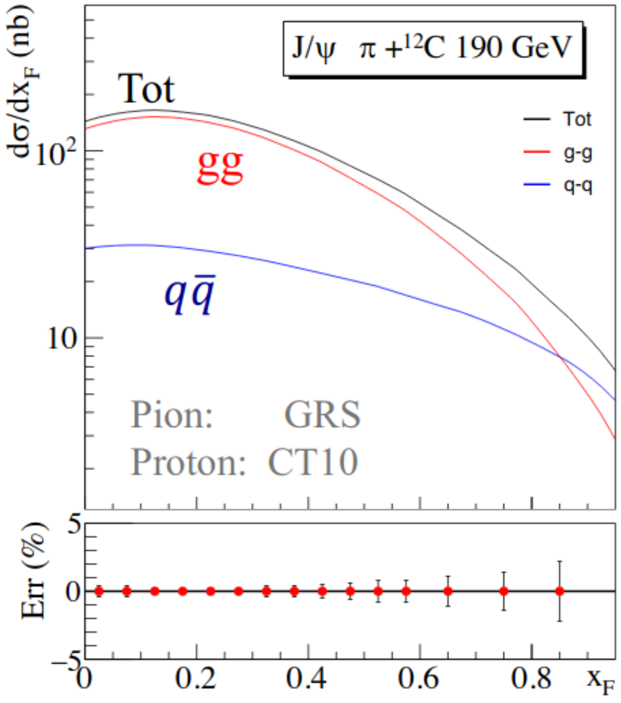


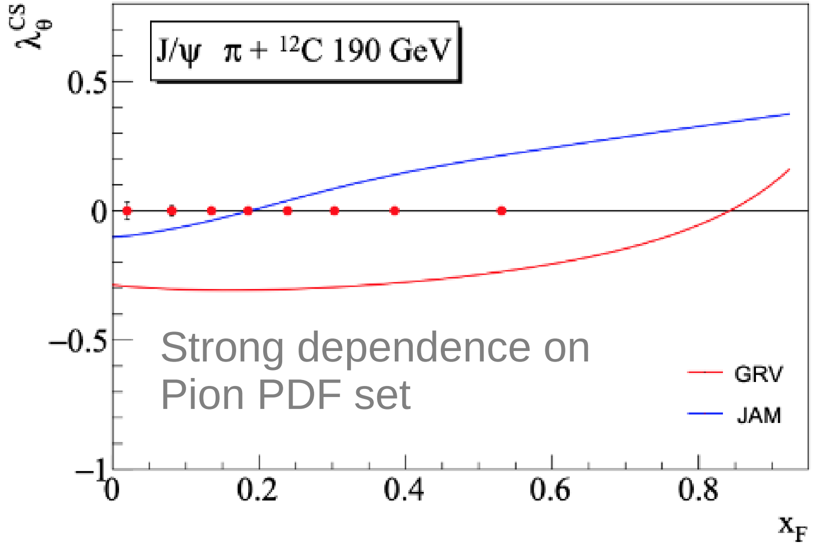


J/ψ production

The "naïve" picture:
J/ψ polarization, together with p_T and x_F behavior, will tell us about the dominant production mechanism

- If gluon-gluon fusion dominates, expect J/ψ longitudinal polarization
- If quark-antiquark annihilation dominates, expect J/ψ transverse polarization





Color Evaporation Model (ICEM)
Cheung and Vogt, PRD98, 114029 (2018)
and priv. comm.

Puzzling quarkonium results

P. Faccioli et al, EPJ C80 (2020) 623

Understanding Quarkonium production mechanisms remains challenging:

At the large-p_T regime of LHC experiments, all produced $c\bar{c}$ states follow a simple p_T/M scaling. But while J/ψ, $\psi(2S)$ and Υ are unpolarized, χ_{c1} and χ_{c2} are transversely and longitudinally polarized, as expected.

NRQCD model is able to describe these results, but only with a very specific linear combination of the octet terms…

How likely is this to happen? And what happens at low-p_T ?

NRQCD LDMEs are not tuned for low-p_T – and nor COMPASS, nor AMBER Phase-I data will allow to do it

Inclusive J/ψ measurements – Phase I

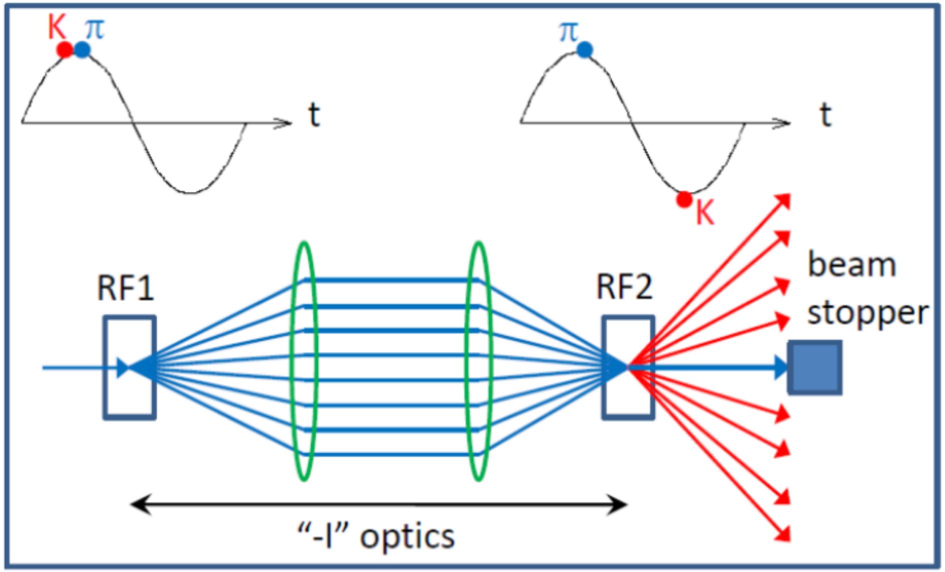
- We need to learn about J/ψ production mechanisms first
- Measurements in the low-p_T regime are missing
- ψ(2S) may be very relevant, as it has no feed-down contributions

COMPASS++/AMBER: large statistics, differential cross-section measurements, mostly to learn about quarkonia production mechanisms

Assessing the gluon content in the pion from this: likely to come only later, with AMBER Phase II

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 [129, 130]	Cu	800	p	200000
	Au			110000
	Be			45000
E866 [131]	Be, Fe, Cu	800	p	3000000
NA50 [132]	Be	450	p	124700
	Al			100700
	Cu			130600
	Ag			132100
	W			78100
NA51 [133]	p	450	p	301000
	d			312000
HERA-B [134]	C	920	p	152000
COMPASS 2015	110 cm NH_3	190	π^-	1000000
COMPASS 2018				1500000
COMPASS++/ AMBER	75 cm C	190	π^+	1200000
			π^-	1800000
			p	1500000
	12 cm W	190	π^+	500000
			π^-	700000
			p	700000

COMPASS++/AMBER PHASE II



Radio-frequency separation is a technique where some particle species end dumped in a beam stopper, while the chosen ones (dependent on distance "l") provide a **cleaner, still highly intense, beam**.

R&D from CERN Beams Department

- **$K^{\pm}$ beams with 60 – 100 GeV/c**
- **$\bar{p}$ beam with 80 – 110 GeV/c**

in both cases with some contamination from pions and muons

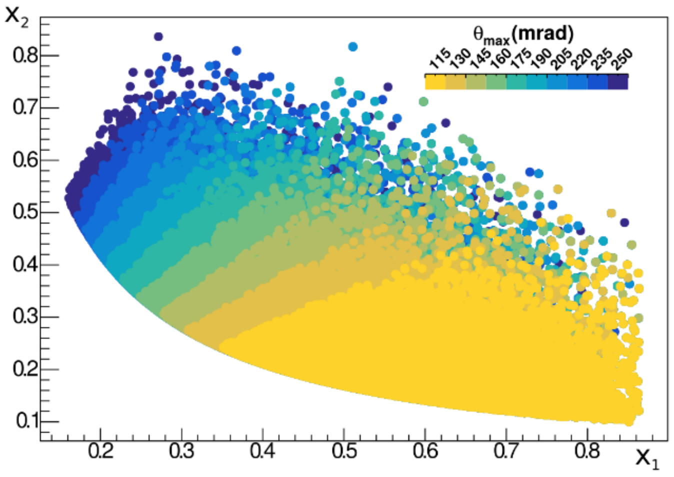
(Another) unique opportunity!

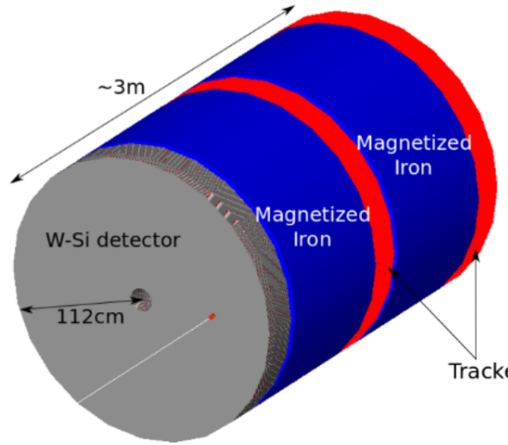
COMPASS++/AMBER PHASE II

- Lower beam energies → compressed spectrometer, in order to keep large angular acceptance (~40%)

- Active magnetized “absorber” → a calorimeter-like detector, under magnetic field and with high granularity, for muon pairs tracking and momentum measurement

- And what about a “pre-shower” detector, for dielectron measurement (…?)





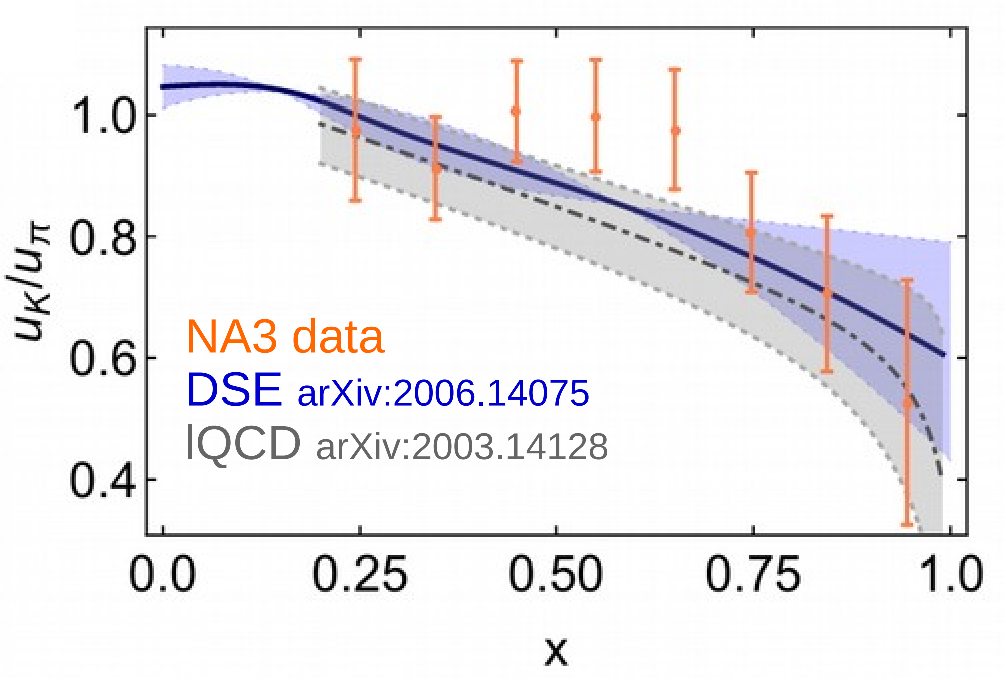
Kaon structure: u_K/u_π

Kaon structure: a window to the region of interference between Higgs mechanism and EHM mechanism.

Z.-F. Cui et al., arXiv:2006.14075

The only available experimental data:
NA3 → 200 GeV K^- beam on 6 cm Pt target

→ 700 kaon-induced Drell-Yan events



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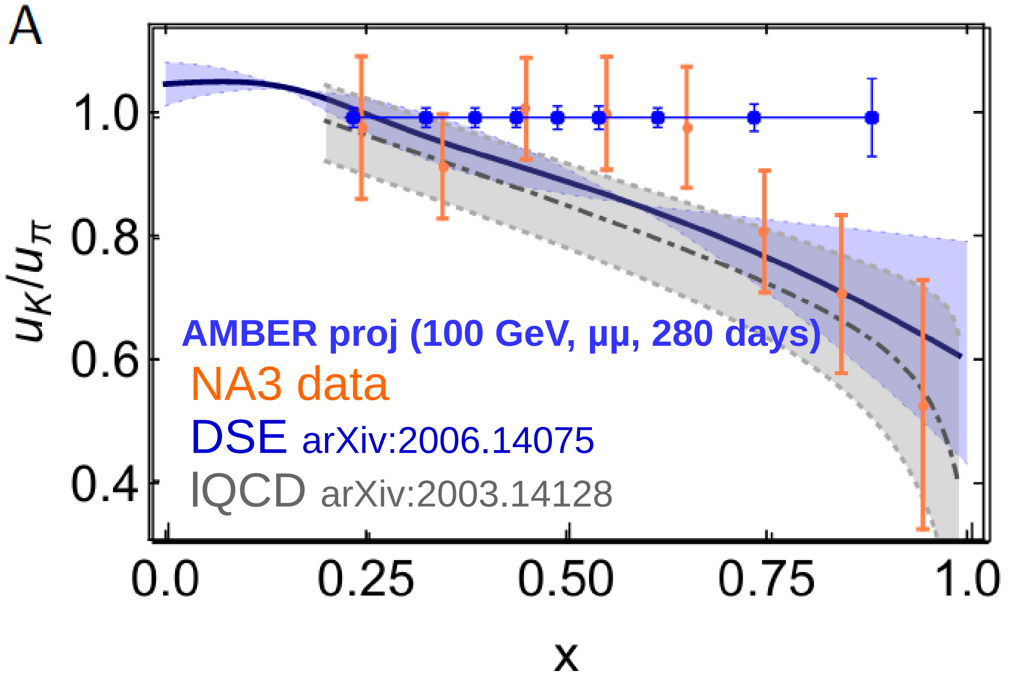
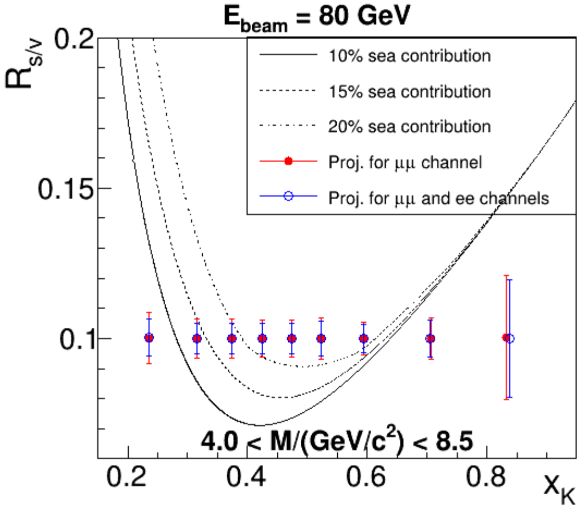
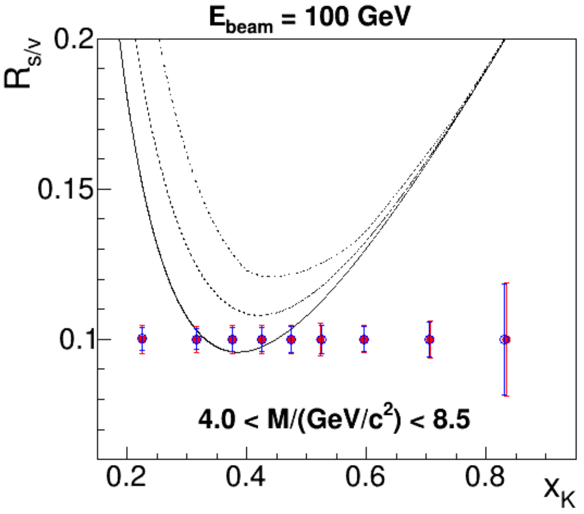
AMBER kaon-induced Drell-Yan

NEW



Kaon structure: valence and sea





Sea-valence separation:

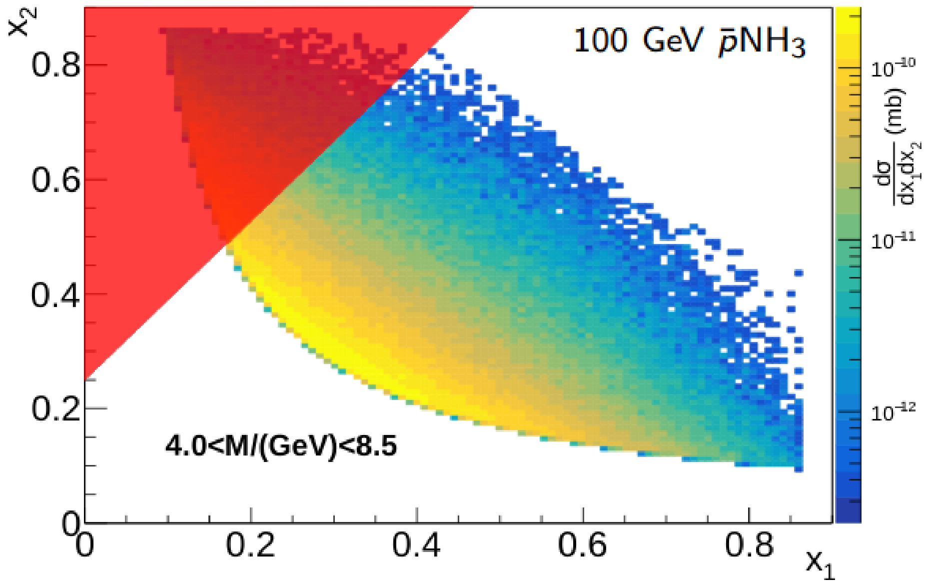
$$\Sigma_{val} = \sigma^{K^-A} - \sigma^{K^+A}$$

$$R_{s/v} = \sigma^{K^+A} / \Sigma_{val}$$

NEW

Experiment	Target type	Beam type	Beam intensity (part/sec)	Beam energy (GeV)	DY mass (GeV/c²)	DY events $\mu^+\mu^-$	DY events e^+e^-
NA3	6cm Pt	K^-	????	200	4.2 – 8.5	700	0
COMPASS++/ AMBER	100cm C	K^-	2.1×10^7	80	4.0 – 8.5	25,000	13,700
				100	4.0 – 8.5	40,000	17,700
		K^+	2.1×10^7	80	4.0 – 8.5	2,800	1,300
				100	4.0 – 8.5	5,200	2,000
COMPASS++/ AMBER	100cm C	π^-	4.8×10^7	80	4.0 – 8.5	65,500	29,700
				100	4.0 – 8.5	95,500	36,000

$\bar{p}$-induced Drell-Yan: proton TMD PDFs



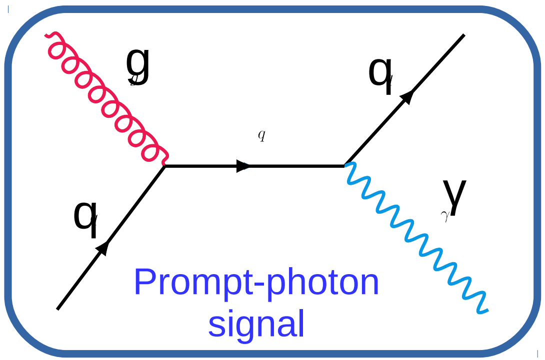
On a transversely polarized target: back to the **TMD PDFs of the nucleon**

- No dependence on PDFs of pion
  ↳ reduced systematics in accessing the proton spin structure
- Valence region: large x_{beam}
- Access to the Boer-Mulders TMD PDF:

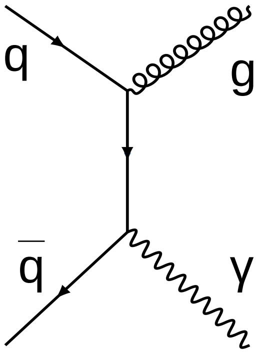
$$A_{UU}^{\cos(2\phi)} \propto h_{1,h}^{\perp q} \otimes h_{1,p}^{\perp q}$$
$$A_{UT}^{\sin(2\phi-\phi_S)} \propto h_{1,h}^{\perp q} \otimes h_{1,p}^{q}$$

Experiment	Target type	Beam type	Beam intensity (part/sec)	Beam energy (GeV)	DY mass (GeV/c^2)	DY events $\mu^+\mu^-$	DY events e^+e^-
COMPASS++/ AMBER	110cm NH_3	$\bar{p}$	3.5×10^7	100	4.0 – 8.5	28,000	21,000
				120	4.0 – 8.5	40,000	27,300

Kaon-induced prompt-photon production and the Gluon content in the kaon

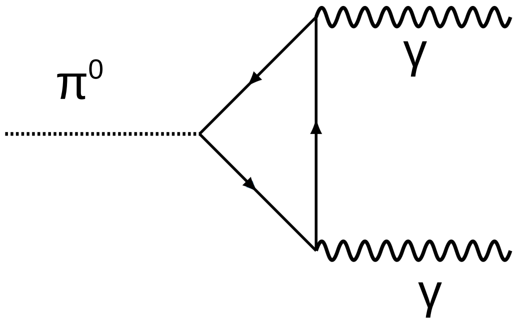


Direct access to the gluon PDF at $x_g^K > 0.05$, $Q^2 \sim p_T$



background

K^+ beam: minimize bkg

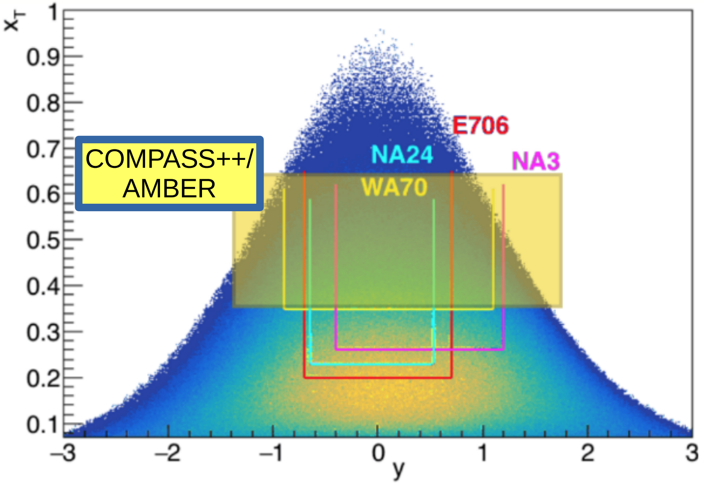


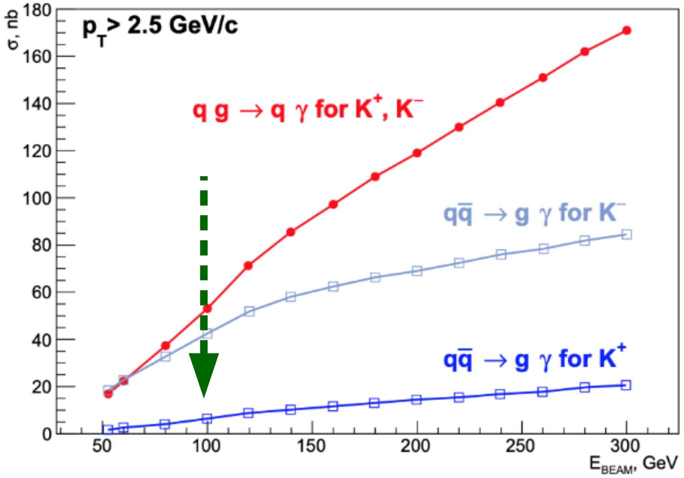
Minimum bias photons background

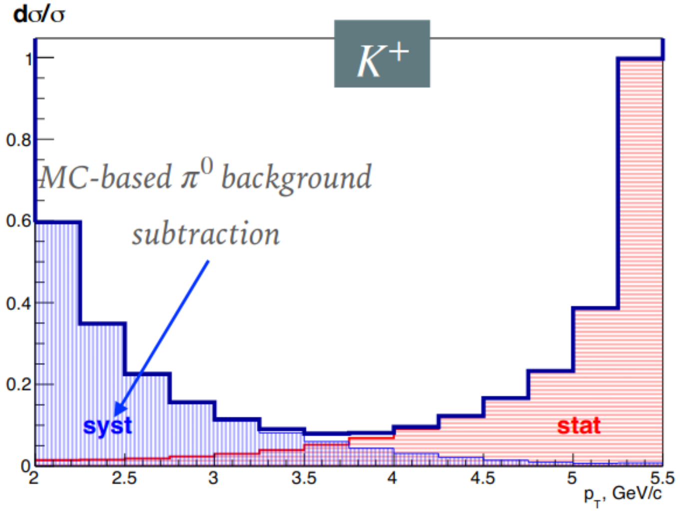
$p_T^\gamma > 2.5$ GeV/c: minimize photon background

100 GeV K^+ beam on a long lH_2 target

Kaon-induced prompt-photon production







$x_T = 2p_T/\sqrt{s}$

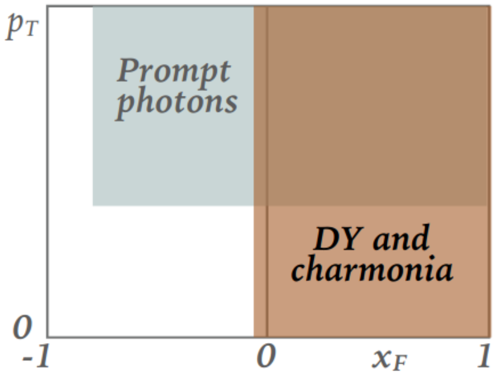
In 140 days

Experiment	Target type	Beam type	Beam Intensity (part/sec)	Beam Energy (GeV)	$\int \mathcal{L}$ (pb^{-1})	p_T range (GeV/c)	prompt-photon events
WA70	1m lH_2	π^+	2.5×10^6	280	1.3	$4 < p_T < 7$	—
		π^-	1.25×10^7	280	3.5	$4 < p_T < 7$	—
COMPASS++/ AMBER	2m lH_2	K^+	2×10^7	100	50	$p_T > 2.5$	3.4×10^6
		π^+	2×10^7	100	50	$p_T > 2.5$	3.4×10^6

Charmonium production and the gluon content in the kaon

Both the **Drell-Yan setup** and the **prompt-photon production setup** will provide significant statistics of charmonium samples

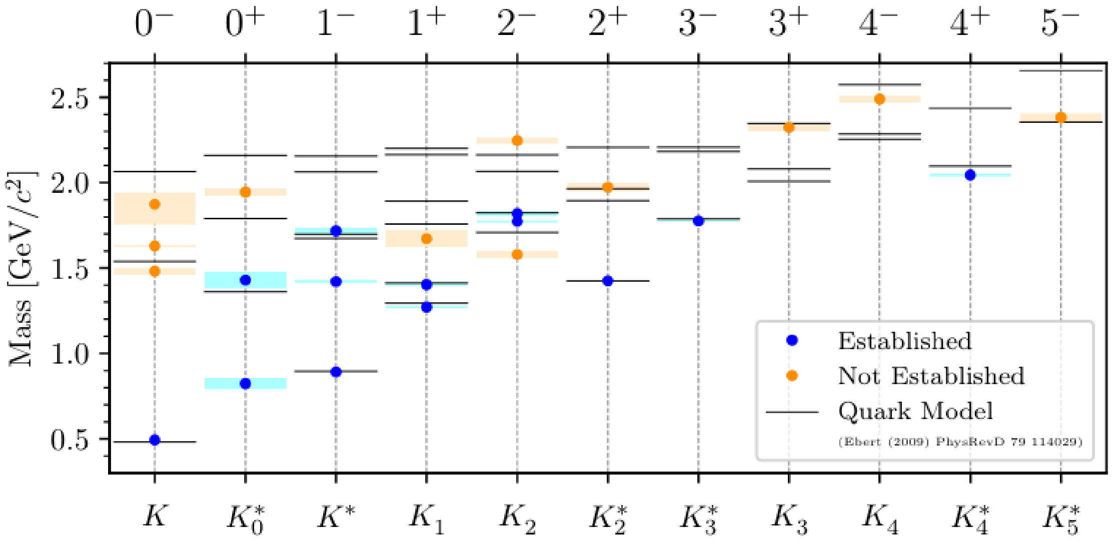
- No absorber: distinguish prompt from non-prompt production
- Possibility to detect accompanying photon: access to χ_{c1}, χ_{c2}
- Improved resolution: separate J/ψ from ψ(2S)



A thorough study of charmonium production mechanisms at low-p_T, via x_F and polarization information from the different states

A complementary input to the knowledge of gluon PDF in the kaon

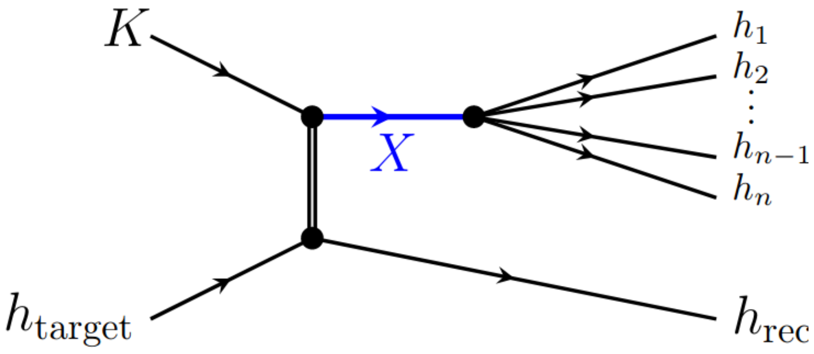
Kaon beam: an opportunity for strange-meson spectroscopy



From the 25 strange mesons listed presently in the PDG, 13 still need experimental confirmation:

- 3 predicted K^*_j states missing.
  Searches via $K^{\pm}p$ scattering, like
  $K^{\pm}p \rightarrow K\pi n$
  or through heavy meson and τ decays

- 11 predicted K_j states missing.
  Searches via heavy meson and τ decays to multi-body final states



X: strange-meson
Searched for and characterized with **Partial Wave Analysis**

Strange-meson spectroscopy with RF-separated kaon beam

COMPASS: the World's largest dataset of diffractively produced $K^{-}\pi^{-}\pi^{+}$

Observation of many well-known states, and also potential signals from excited states

With a RF-separated kaon beam:

- At least 10 times larger statistics
- Strange-meson spectrum detailed studies, reaching the same precision as for light non-strange mesons
- Use of advanced methods, that require large statistics, broad kinematic coverage and excellent beam and final state PID.

Summary

- COMPASS++/AMBER Phase-I was recommended for approval on 13th October 2020
- A broad physics program dedicated to the Emergence of Hadron Mass **and related topics**
- An ambitious Phase-II program is being planned, making use of novel RF-separated beams
- Experimentally challenging: intense hadron beams into fixed target, large kinematic coverage, good momentum and position resolutions and excellent PID required.
- Phase-II proposal must be anchored on solid theory fundament: