A NEW QCD FACILITY AT THE M2 BEAM LINE OF THE CERN SPS

PHYSICS SCOPE

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on behalf of the COMPASS++/AMBER collaboration

5.11.2019

Physics Beyond Collider Working Group meeting

COMPASS++/AMBER PHYSICS PROGRAM

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	$\overline{p}$ production cross section	20-280	$5 \cdot 10^5$	25	p	LH2, LHe	2022 1 month	liquid helium target
$\overline{p}$-induced spectroscopy	Heavy quark exotics	12, 20	$5 \cdot 10^7$	25	$\overline{p}$	LH2	2022 2 years	target spectrometer: tracking, calorimetry
Drell-Yan **charmonium**	Pion PDFs	190	$7 \cdot 10^7$	25	$\pi^\pm$	C/W	2022 1-2 years	
charmonium Drell-Yan (RF)	Kaon PDFs & Nucleon TMDs	∼100	10^8	25-50	$K^\pm, \overline{p}$	$NH_3^\uparrow$, 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	

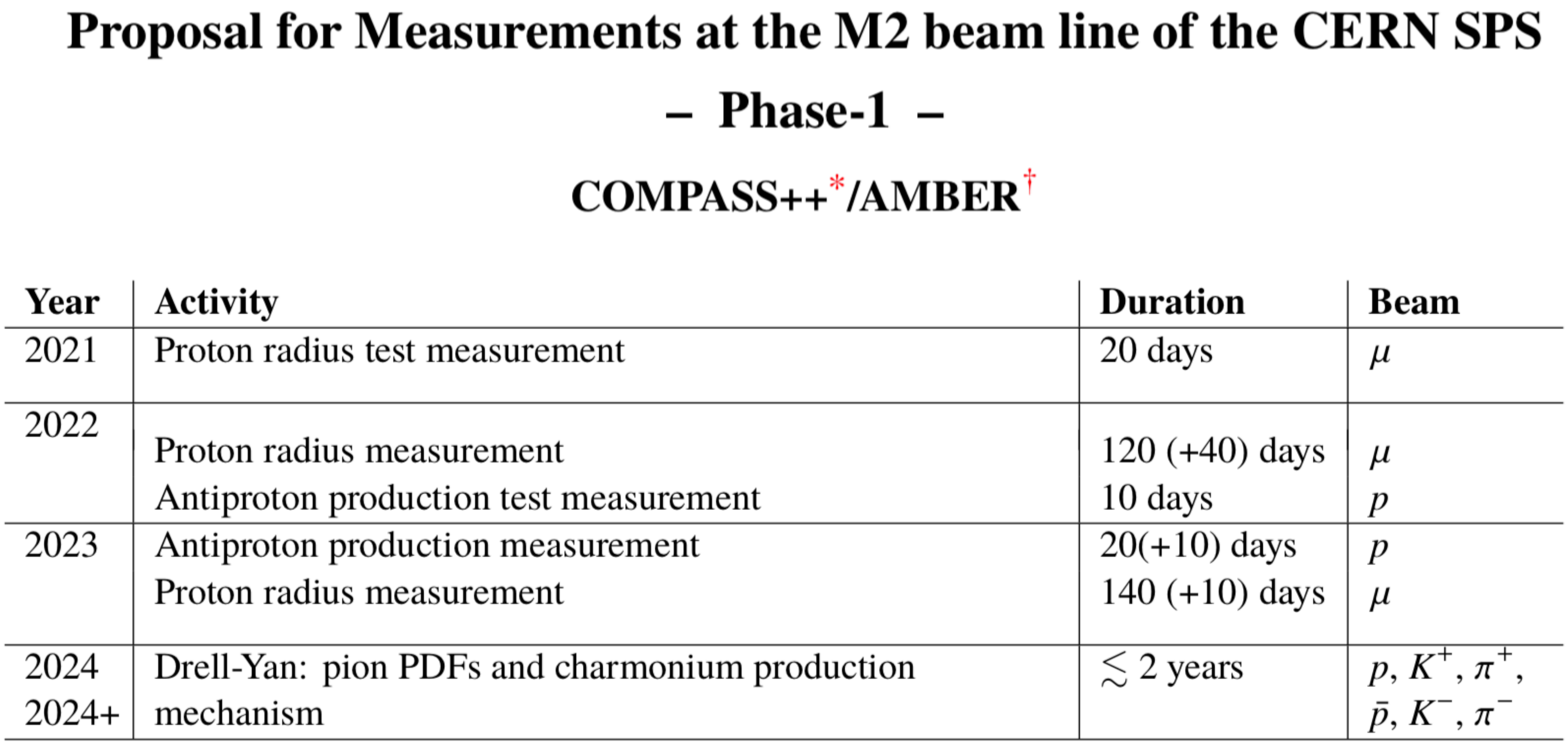
Phase-1
*conventional **muon** and **hadron** beams*

LS3

Phase-2
*conventional and RF-separated **hadron** beams*

SUBMISSION OF THE PROPOSAL FOR PHASE-1

Physics with conventional beams



Proposal for Measurements at the M2 beam line of the CERN SPS

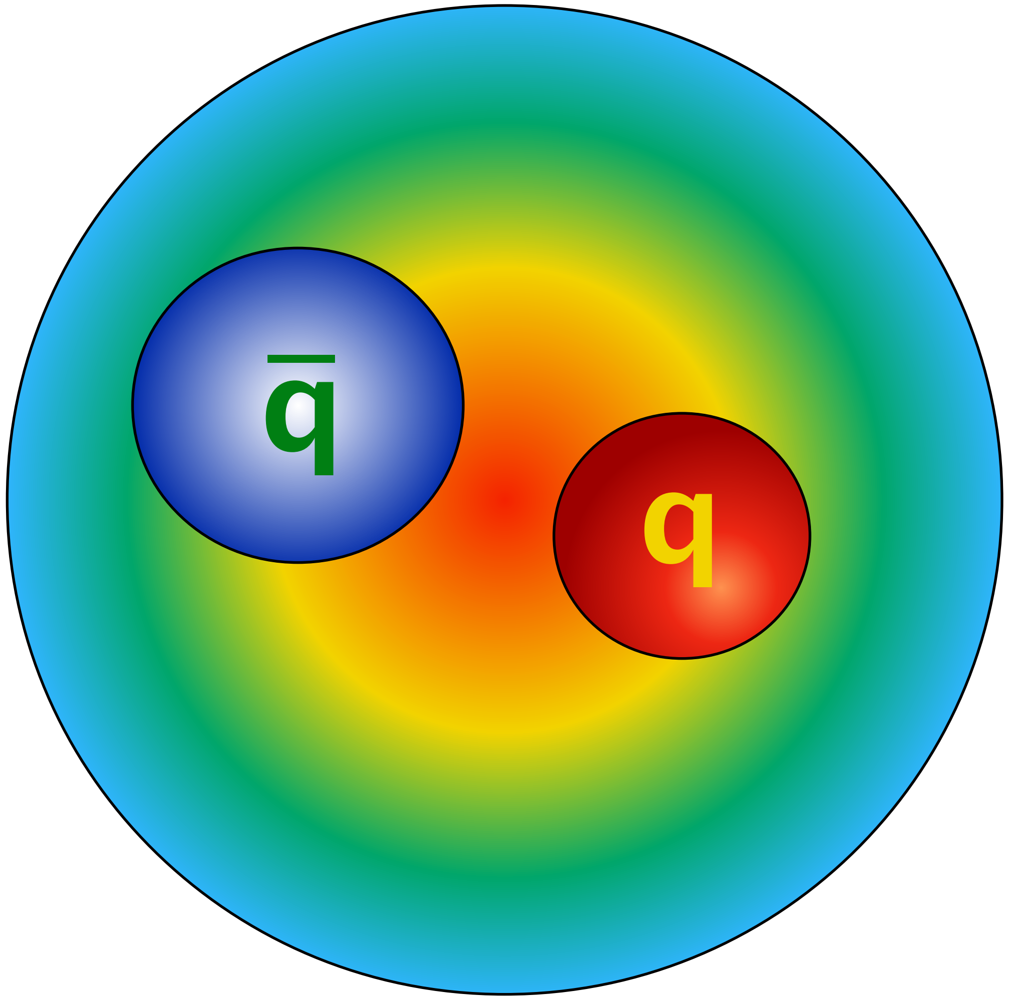
– Phase-1 –

COMPASS++[*]/AMBER[†]

Year	Activity	Duration	Beam
2021	Proton radius test measurement	20 days	μ
2022	Proton radius measurement	120 (+40) days	μ
	Antiproton production test measurement	10 days	p
2023	Antiproton production measurement	20(+10) days	p
	Proton radius measurement	140 (+10) days	μ
2024 2024+	Drell-Yan: pion PDFs and charmonium production mechanism	$\lesssim$ 2 years	p, K^+, π^+, $\bar{p}$, K^-, π^-

https://nqf-m2.web.cern.ch

MESON AS A COMPLEX QCD SYSTEM



Emergence of hadronic mass

Partonic structure

Drell-Yan

π K

Charmonia

π K

Prompt photons

π K

Resonant and dynamical properties of mesons

Spectroscopy

COMPASS π K

Pion and kaon as Nambu-Goldstone bosons

Low-t (Primakoff) reactions

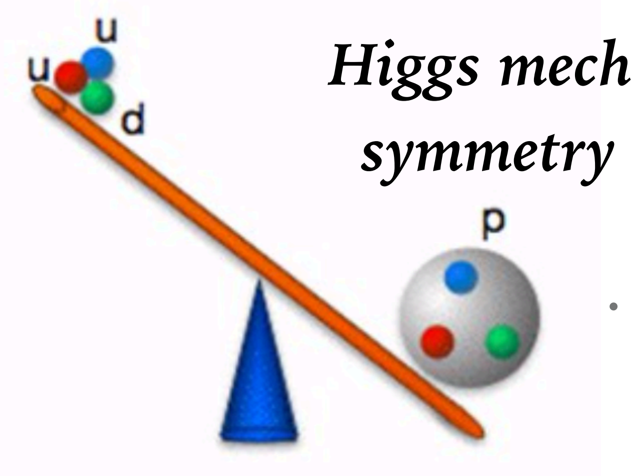
COMPASS π K

“Rigidity” of the meson as a complex system

Polarisability

COMPASS π K

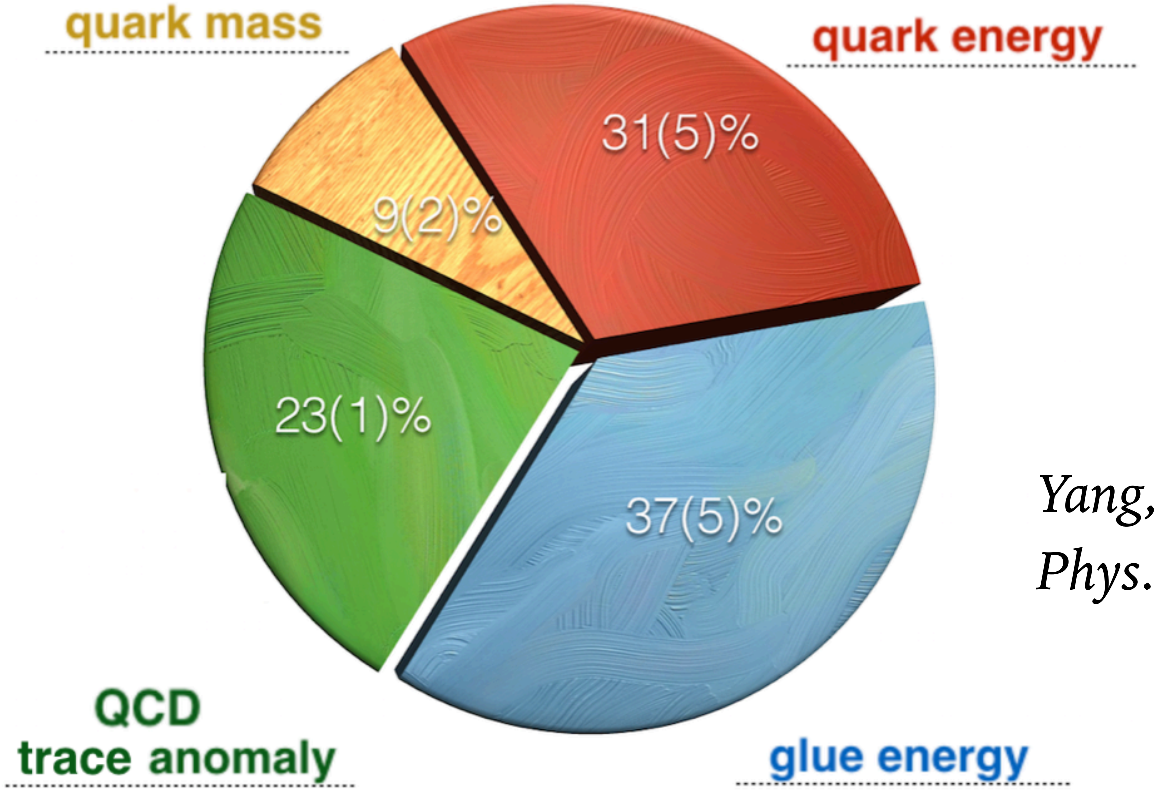
MASS BUDGET IN HADRONS



Higgs mechanism vs spontaneous symmetry breaking mechanism

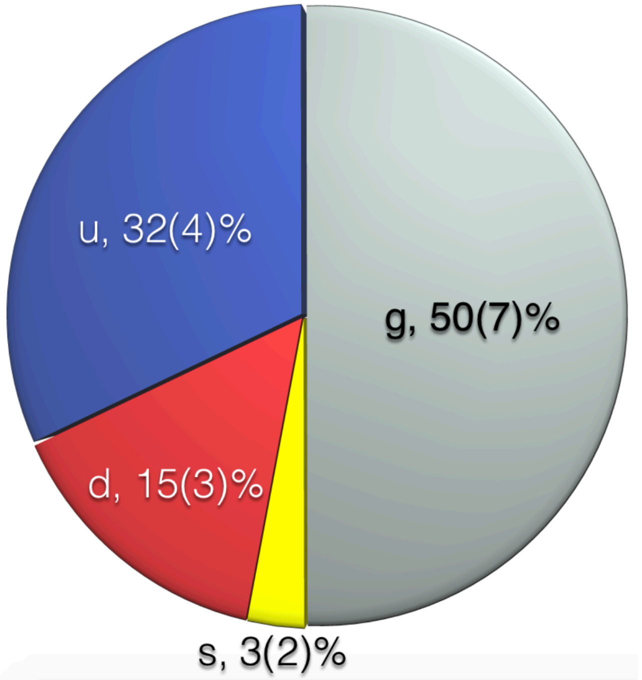
Higgs mechanism is not a main contributor to the mass of hadrons!

One of possible proton mass decompositions from the lattice calculations:



Yang, Yi-Bo et al. Phys.Rev.Lett. 121 (2018)

Contributions of quarks and gluons to the proton momentum fraction at Q=2 GeV/c

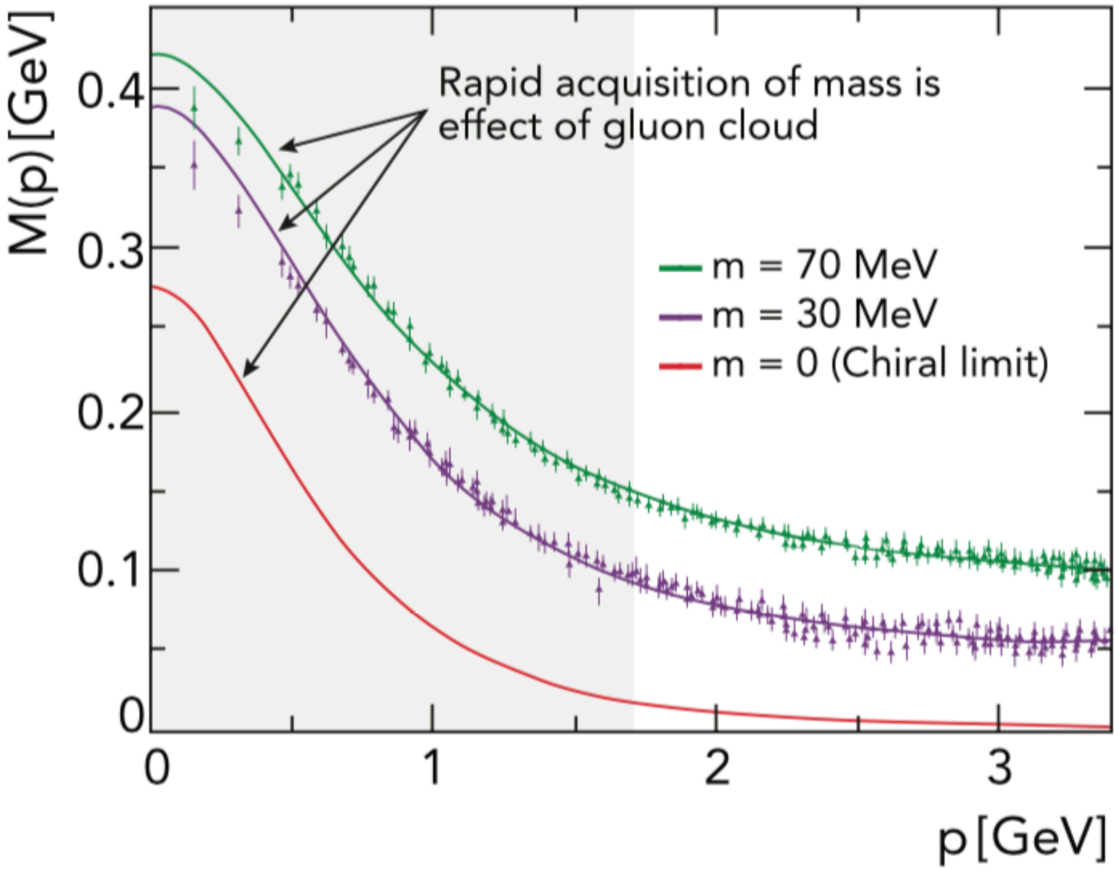


- ❑ Proton mass:

$$M = \overbrace{\underbrace{E_q}_{\text{Quark Energy}} + \underbrace{E_g}_{\text{Gluon Energy}}}^{\text{Relativistic motion}} + \overbrace{\underbrace{\chi_{m_q}}_{\text{Quark Mass}} + \underbrace{T_g}_{\text{Trace Anomaly}}}^{\text{Quantum fluctuation}}$$

MASS BUDGET IN HADRONS

Mass of dressed quark



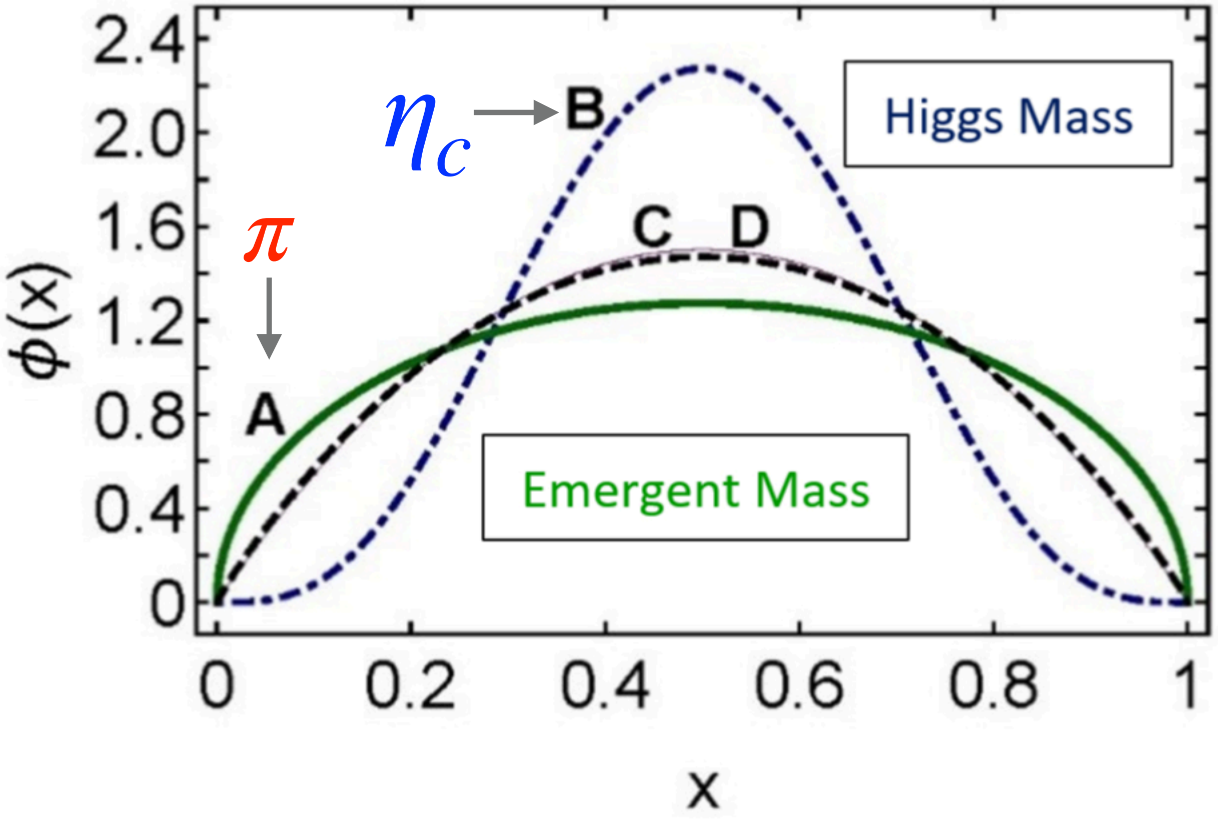
What are the relative contributions of Higgs and QCD mechanisms to meson masses?

PDFs

*While the proton mass in the chiral limit is close to its nominal mass, pion and kaon should become massless as **Nambu-Goldstone bosons**.*

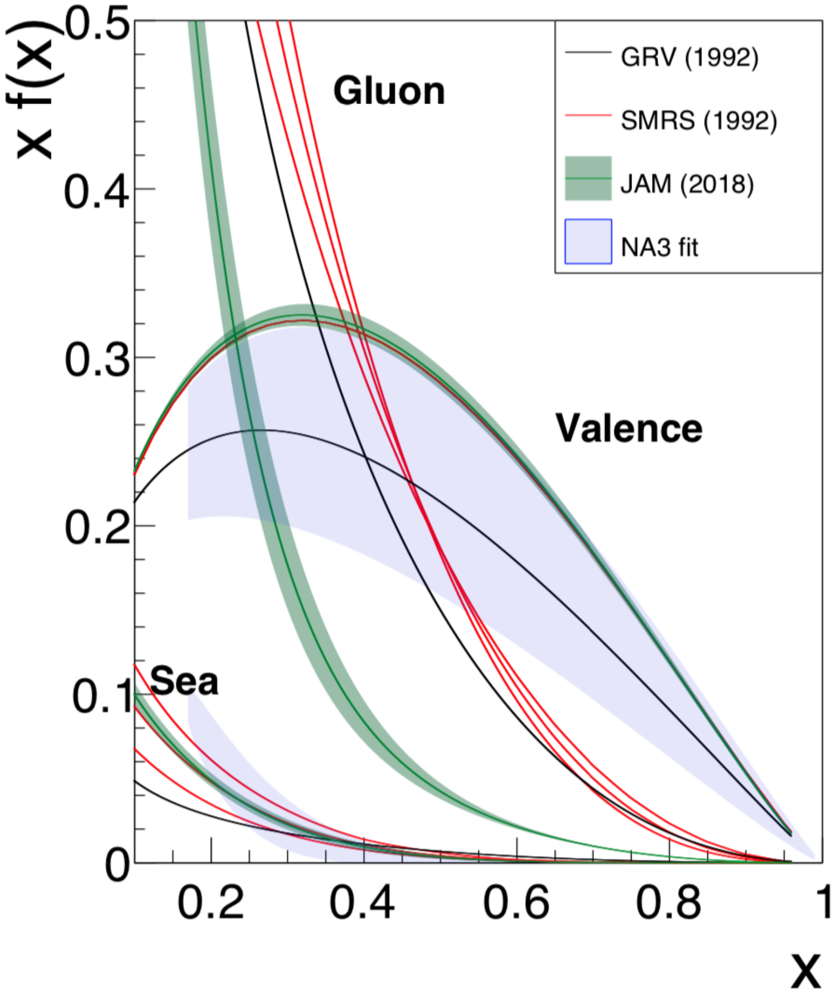
But what does this mean? Do mesons "contain" less gluons than proton?

Twist-two parton distribution amplitudes at scale 2 GeV



Arlene C. Aguilar et al. Eur. Phys. J. A **55** (2019) 190/1-15

MESON PDFs

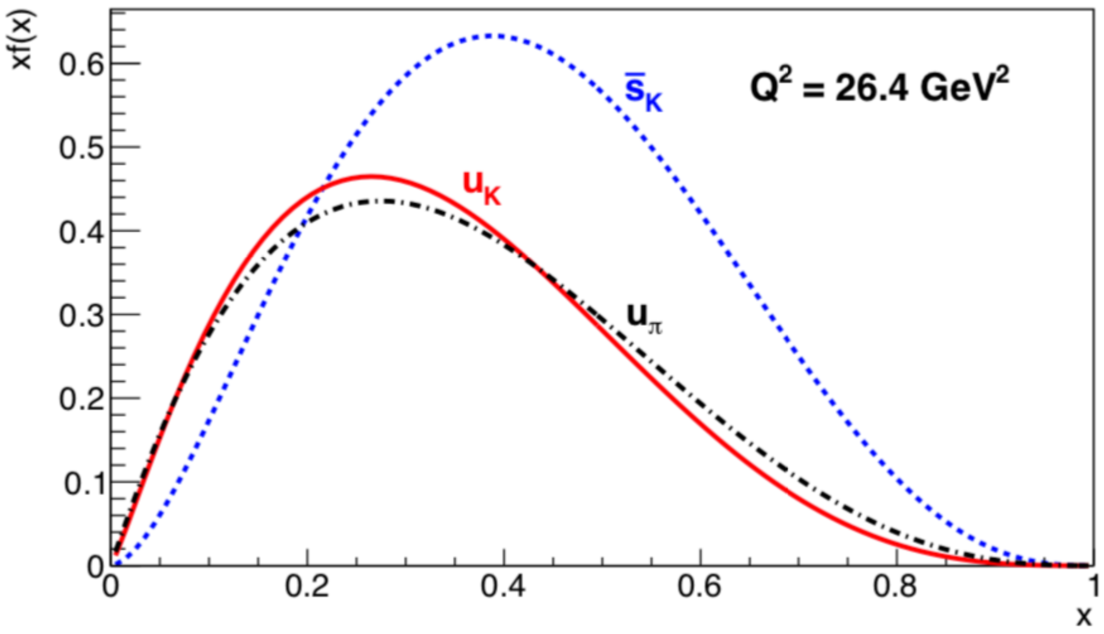


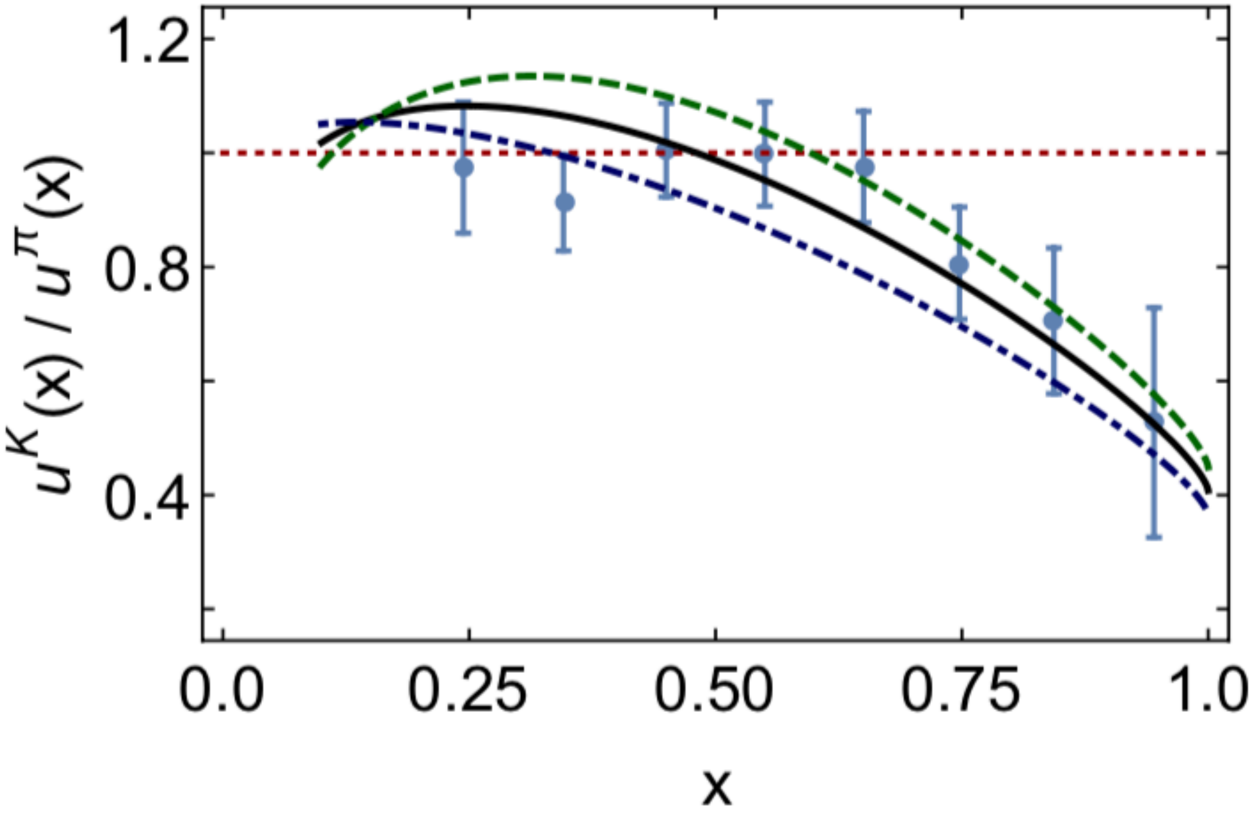
*GRV (1992) set of pion PDFs: Drell-Yan, charmonia and prompt photon production experiments (**E615, NA10, WA70, NA24**).*

SMRS (1992): basically the same old data.

*JAM (2018) set: production of leading neutrons in DIS at HERA (**ZEUS, H1**).*

*Kaon PDFs: just 700 kaon-induced DY events at **NA3***





PION-INDUCED DRELL-YAN

Phase-1

Valence/sea separation

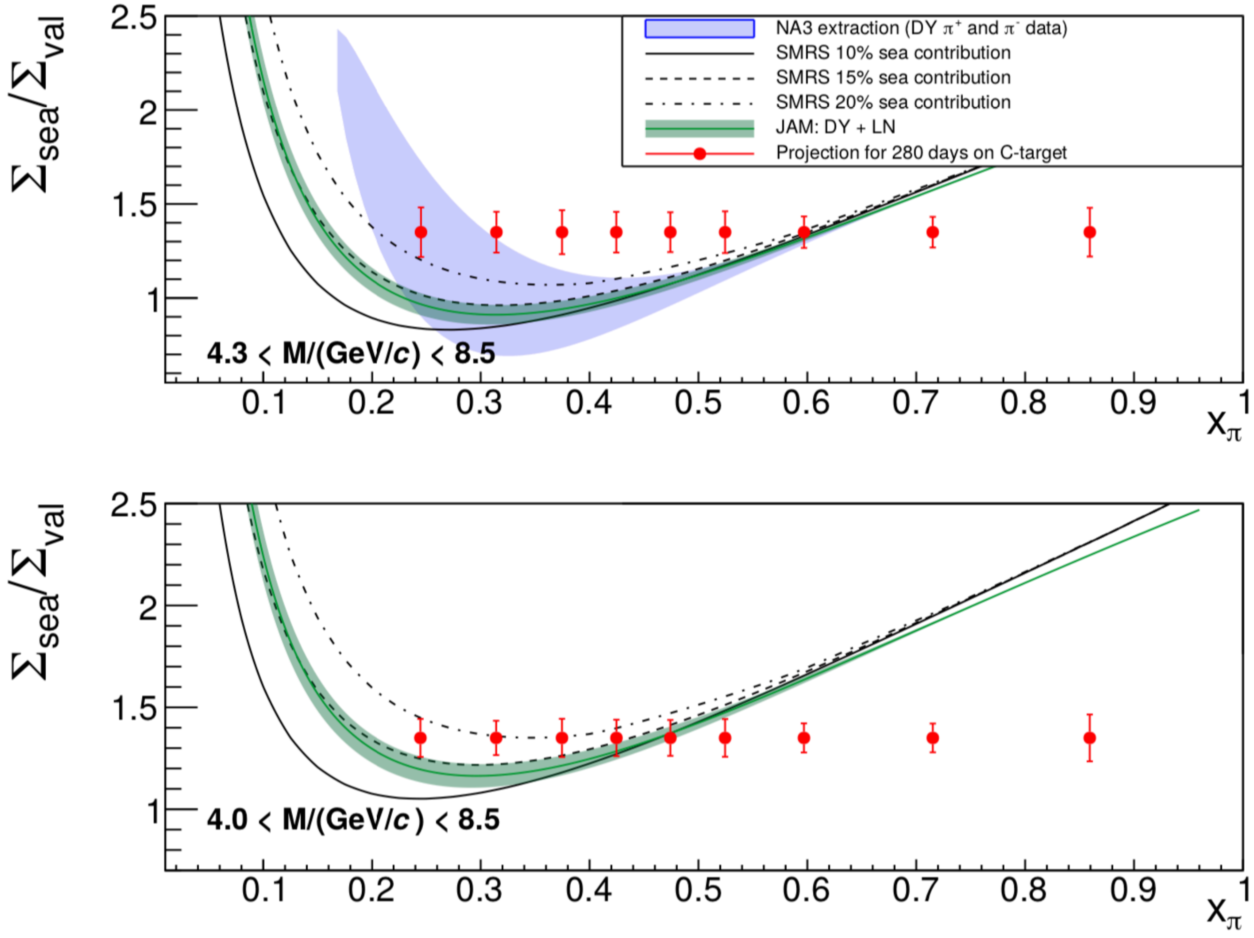
$$\Sigma_{val}^{\pi D} = -\sigma^{\pi^+ D} + \sigma^{\pi^- D}$$

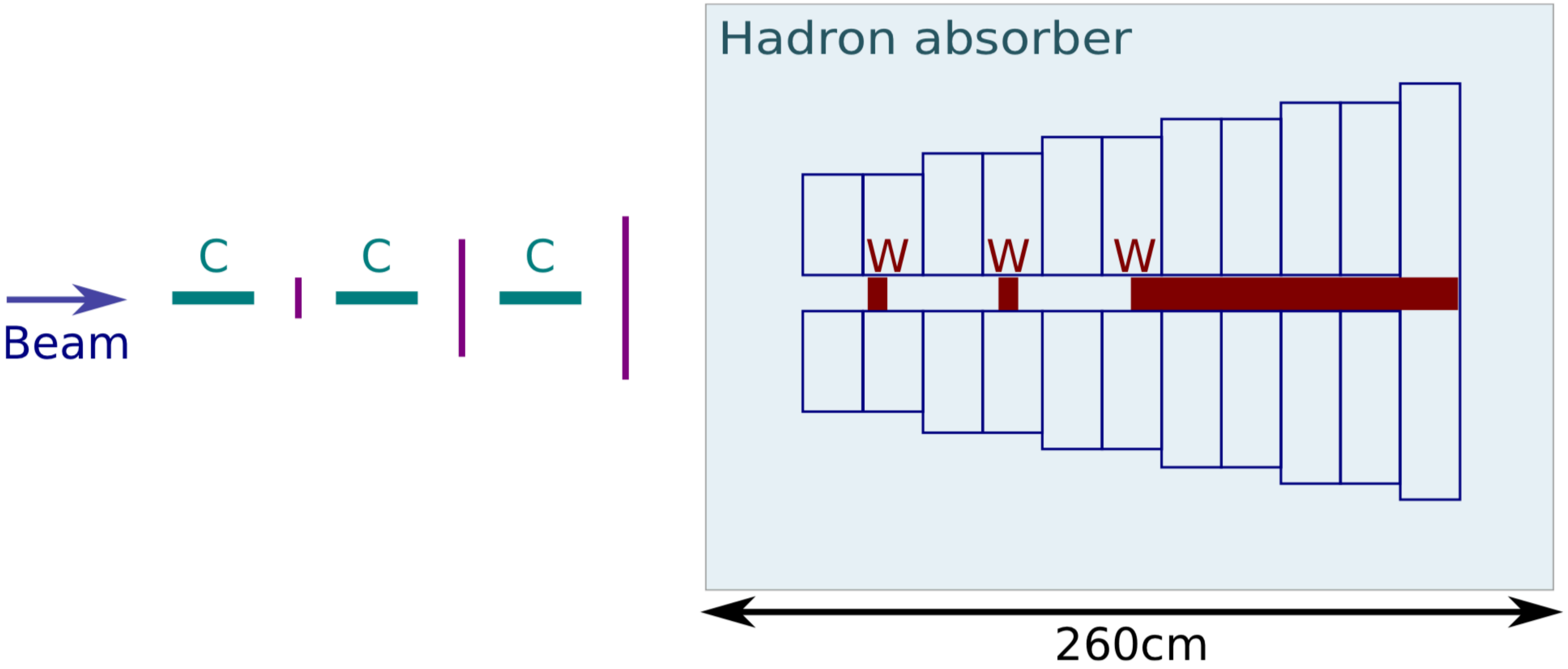
$$\Sigma_{sea}^{\pi D} = 4\sigma^{\pi^+ D} - \sigma^{\pi^- D}$$

under the assumption that

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

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





Tungsten targets will be added to study nuclear effects

PION-INDUCED DRELL-YAN

Phase-1

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
This exp	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 positive and negative beams* + *High statistics*

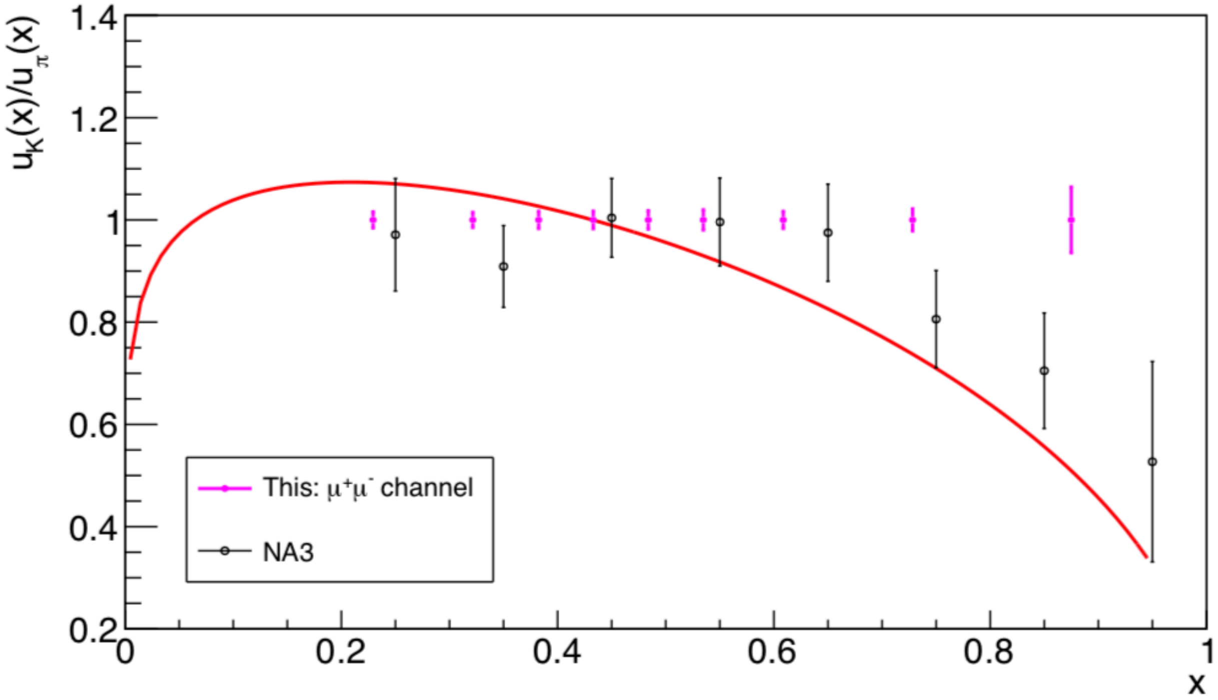
KAON-INDUCED DRELL-YAN

Phase-2

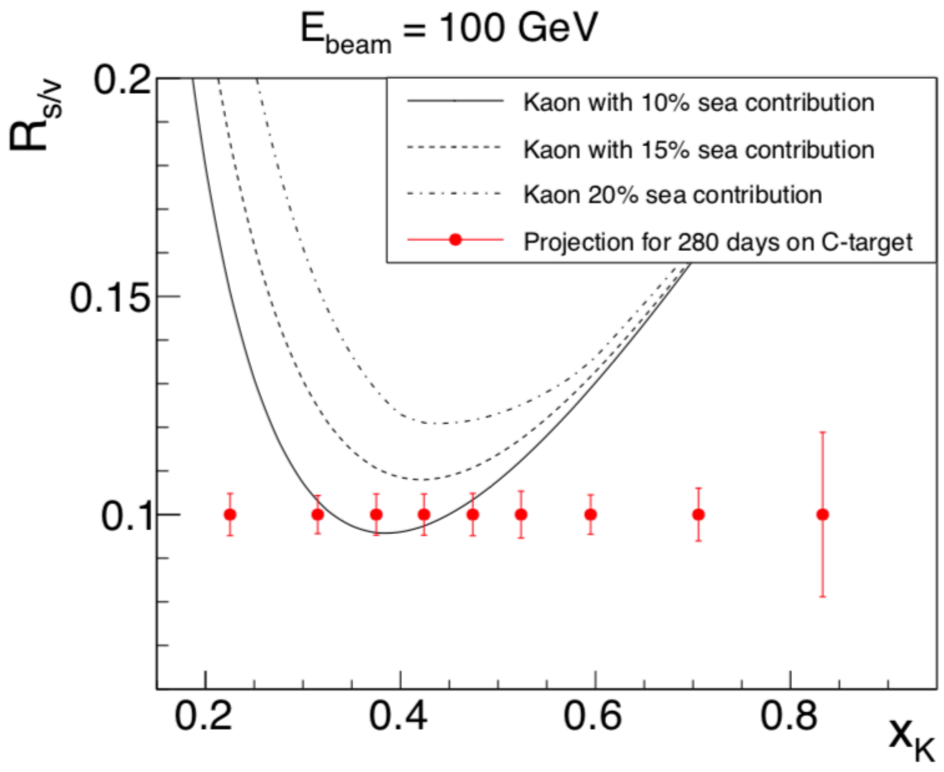
1) $u_K(x)/u_\pi(x)$ - ratio

2) *Valence/sea separation*

$$R_{S/V} = \frac{\sigma_{K^+}}{\sigma_{K^-} - \sigma_{K^+}}$$



Experiment	Target type	Beam type	Beam intensity (part/sec)	Beam energy (GeV)	DY mass (GeV/c^2)	DY events	
						$\mu^+\mu^-$	e^+e^-
NA3	6 cm Pt	K^-		200	4.2 – 8.5	700	0
This exp.	100 cm C	K^-	2.1×10^7	60	4.0 – 8.5	12,000	8,000
				70	4.0 – 8.5	18,000	10,900
				80	4.0 – 8.5	25,000	13,700
				100	4.0 – 8.5	40,000	17,700
				120	4.0 – 8.5	54,000	20,700
		K^+	2.1×10^7	60	4.0 – 8.5	1,000	600
				70	4.0 – 8.5	1,800	900
				80	4.0 – 8.5	2,800	1,300
				100	4.0 – 8.5	5,200	2,000
				120	4.0 – 8.5	8,000	2,400
This exp.	100 cm C	π^-	4.8×10^7	60	4.0 – 8.5	31,000	20,500
				70	4.0 – 8.5	50,800	25,400
				80	4.0 – 8.5	65,500	29,700
				100	4.0 – 8.5	95,500	36,000
				120	4.0 – 8.5	123,600	39,800



CHARMONIA PRODUCTION

Phase-1

Phase-2

Two main mechanisms of J/ψ production in hadron collisions:

$gg \rightarrow gJ/\psi$ and $q\bar{q} \rightarrow J/\psi$

1) *test of charmonia production mechanisms:* ***CEM*** *vs* ***NRQCD***

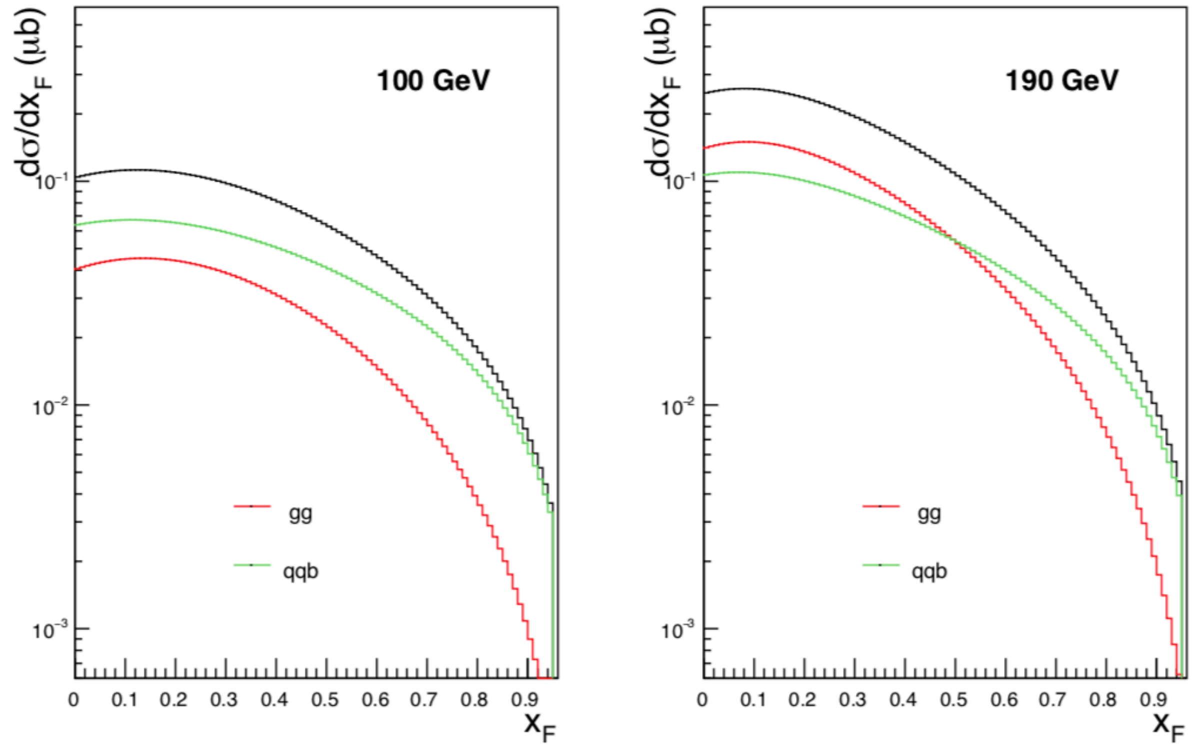
2) *probe of gluon and quark PDFs*

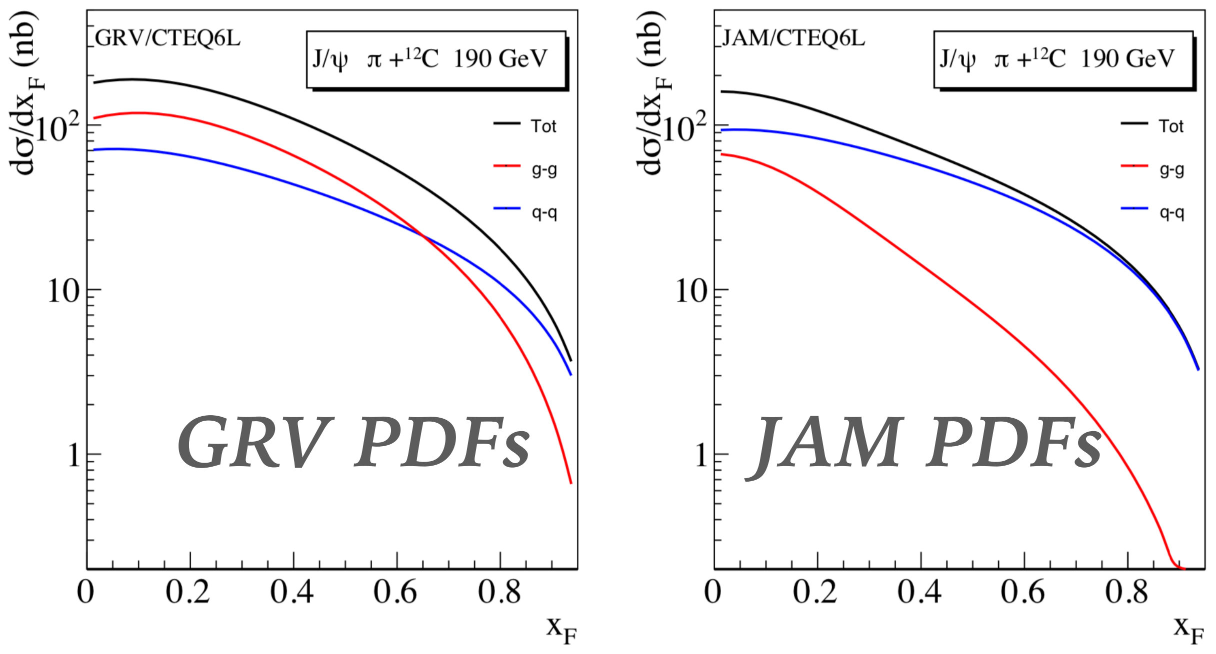
Model-dependent separation of gg and $q\bar{q}$ contributions using data collected with both positive and negative beams.

$$\sigma_{J/\psi}^{K^-} - \sigma_{J/\psi}^{K^+} \propto \bar{u}^{K^-} u^N$$

$\psi(2S)$ ***production*** *- free of feed-down effect from χ_{c1} and χ_{c2}*

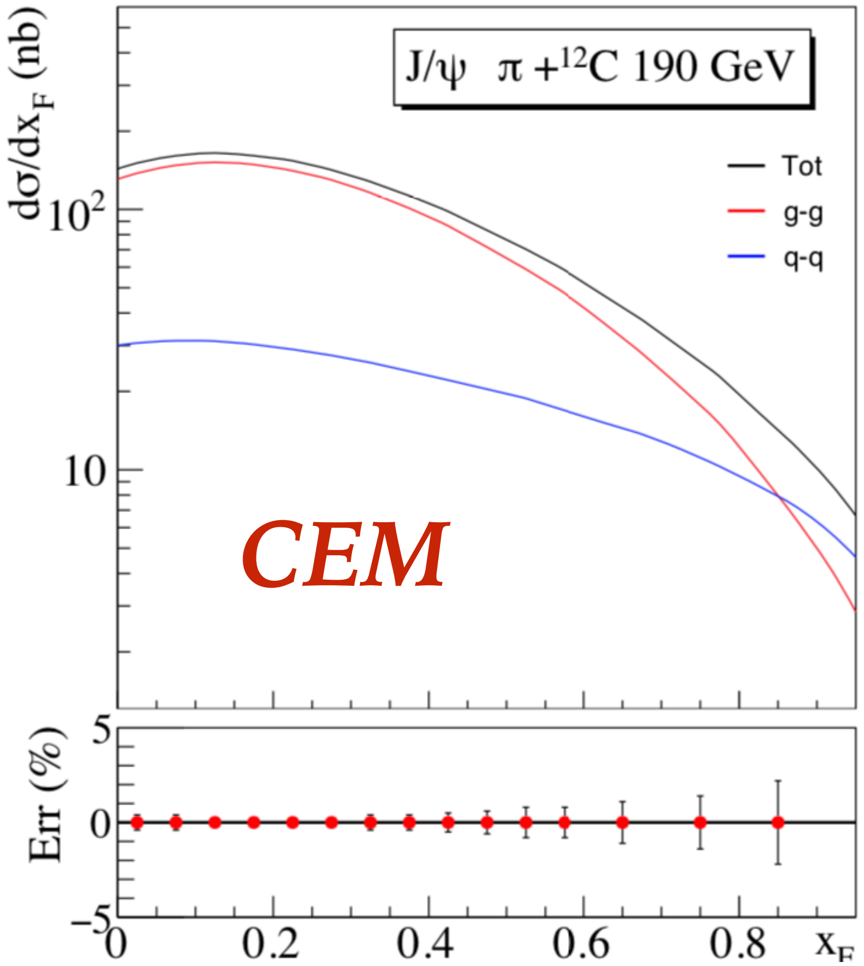
CEM, GRV PDFs for π

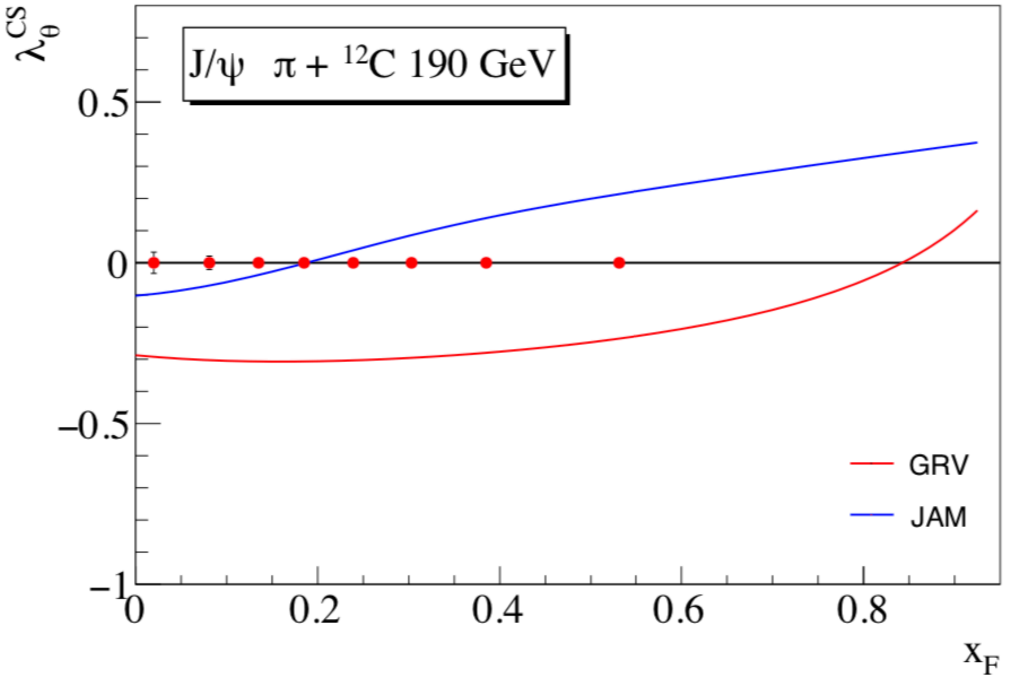




CHARMONIA PRODUCTION

Phase-1



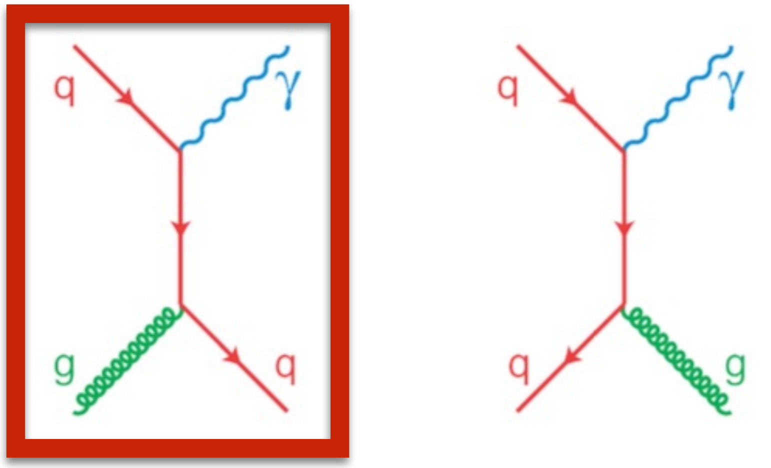


Experiment	Target type	Beam energy (GeV)	Beam type	J/ψ events
NA3 [76]	Pt	150	π^-	601000
		280	π^-	511000
		200	π^+	131000
			π^-	105000
E789 [129, 130]	Cu	800	p	200000
	Au			110000
	Be			45000
E866 [131]	Be Fe Cu	800	p	3000000
NA50 [132]	Be	450	p	124700
	Al			100700
	Cu			130600
	Ag			132100
	W			78100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

PRODUCTION OF PROMPT PHOTONS

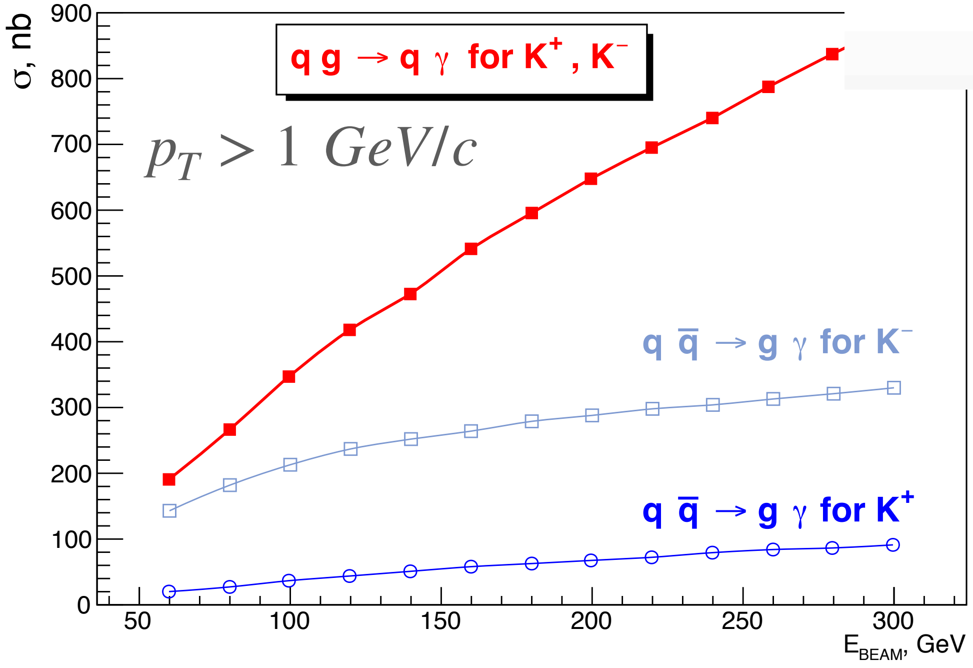
Phase-2

Gluon Compton scattering



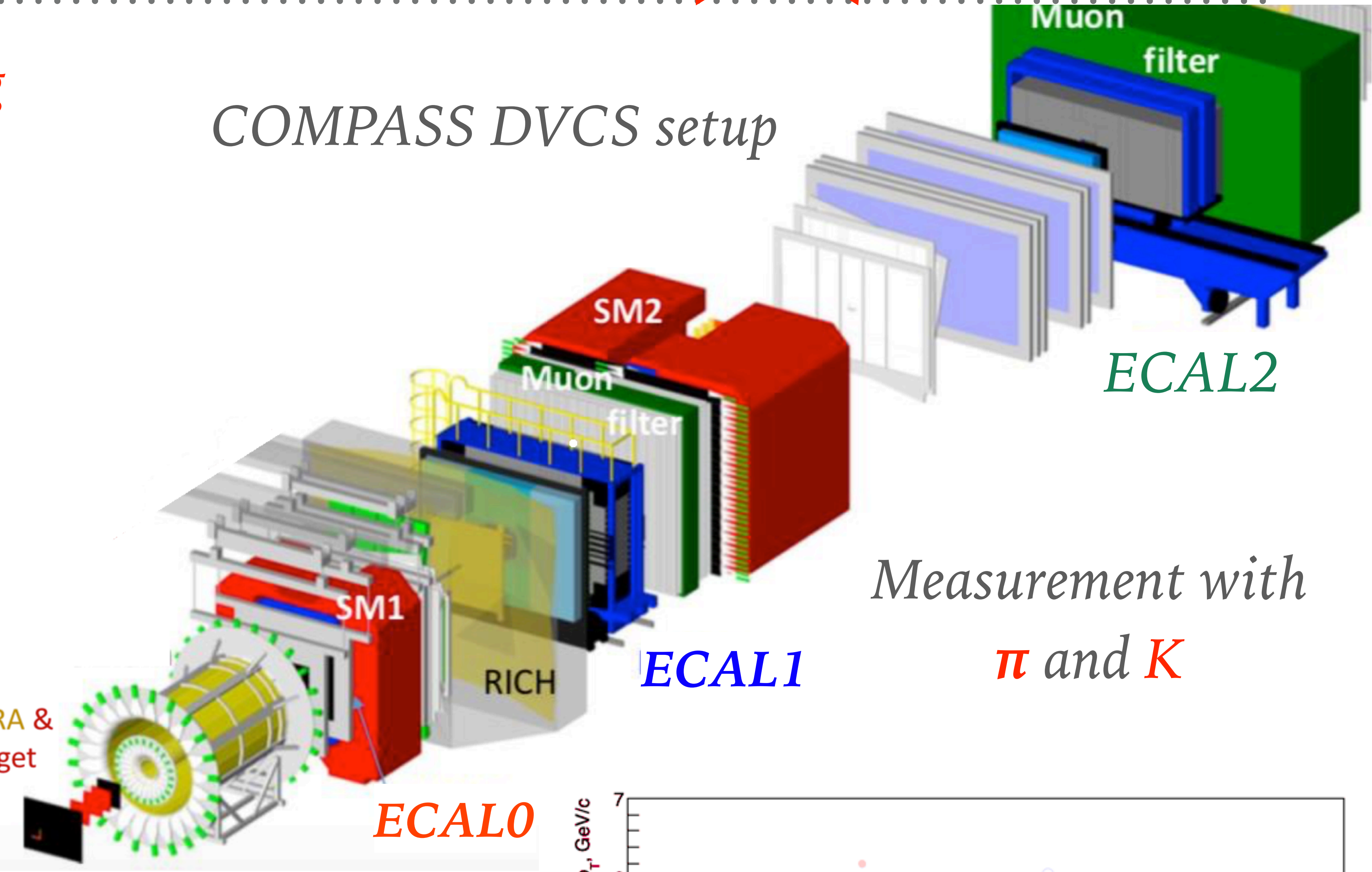
$qg \rightarrow q\gamma$ $\quad$ $q\bar{q} \rightarrow g\gamma$

Assumed for kaon similar PDFs as for pion (GRV)



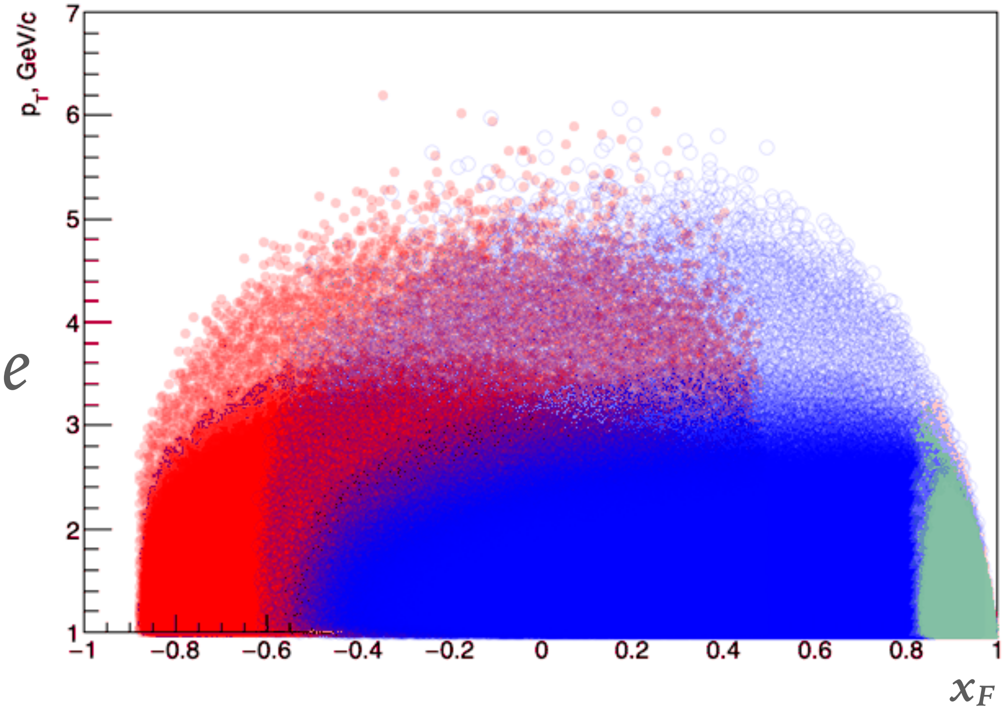
$p_T > 1$ *GeV/c*

COMPASS DVCS setup



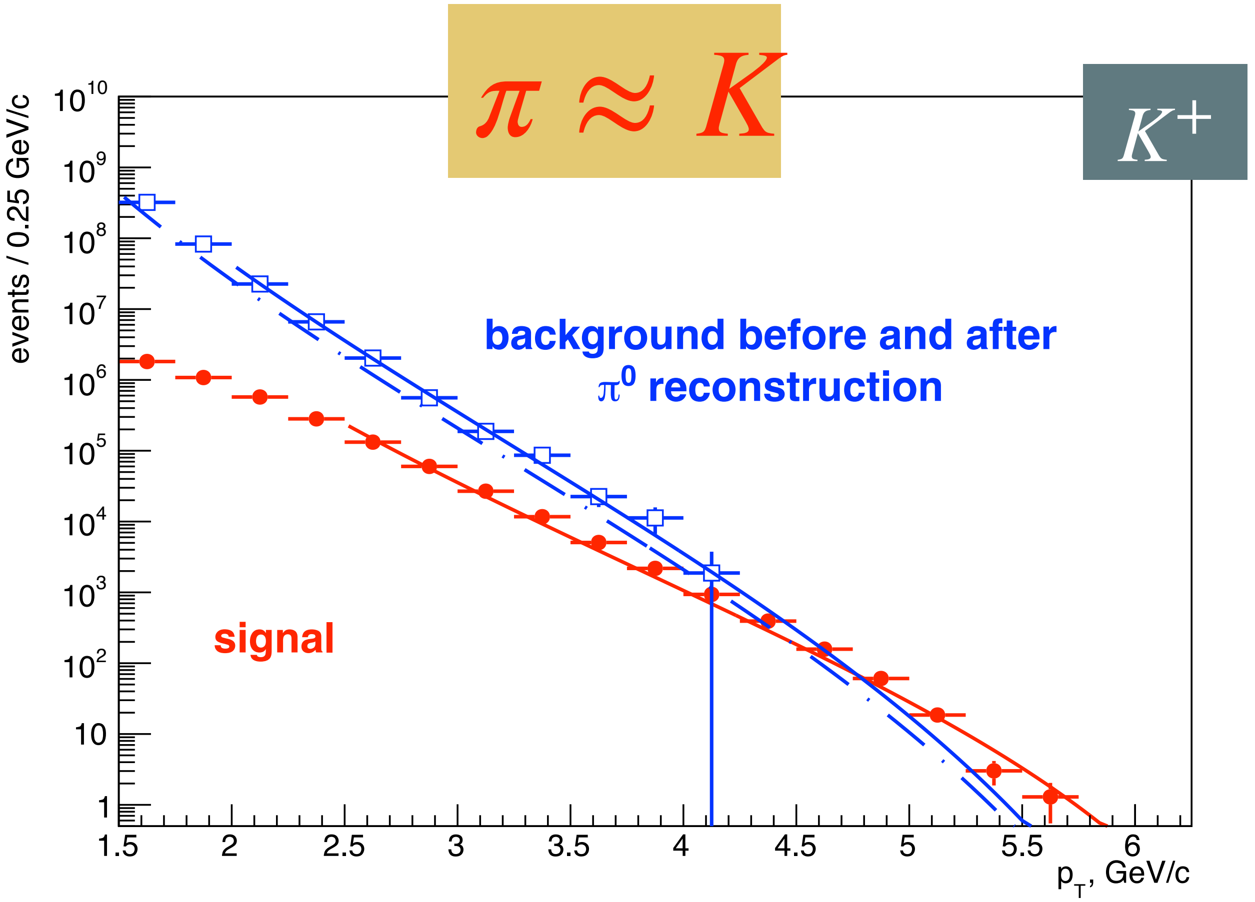
Measurement with π *and* K

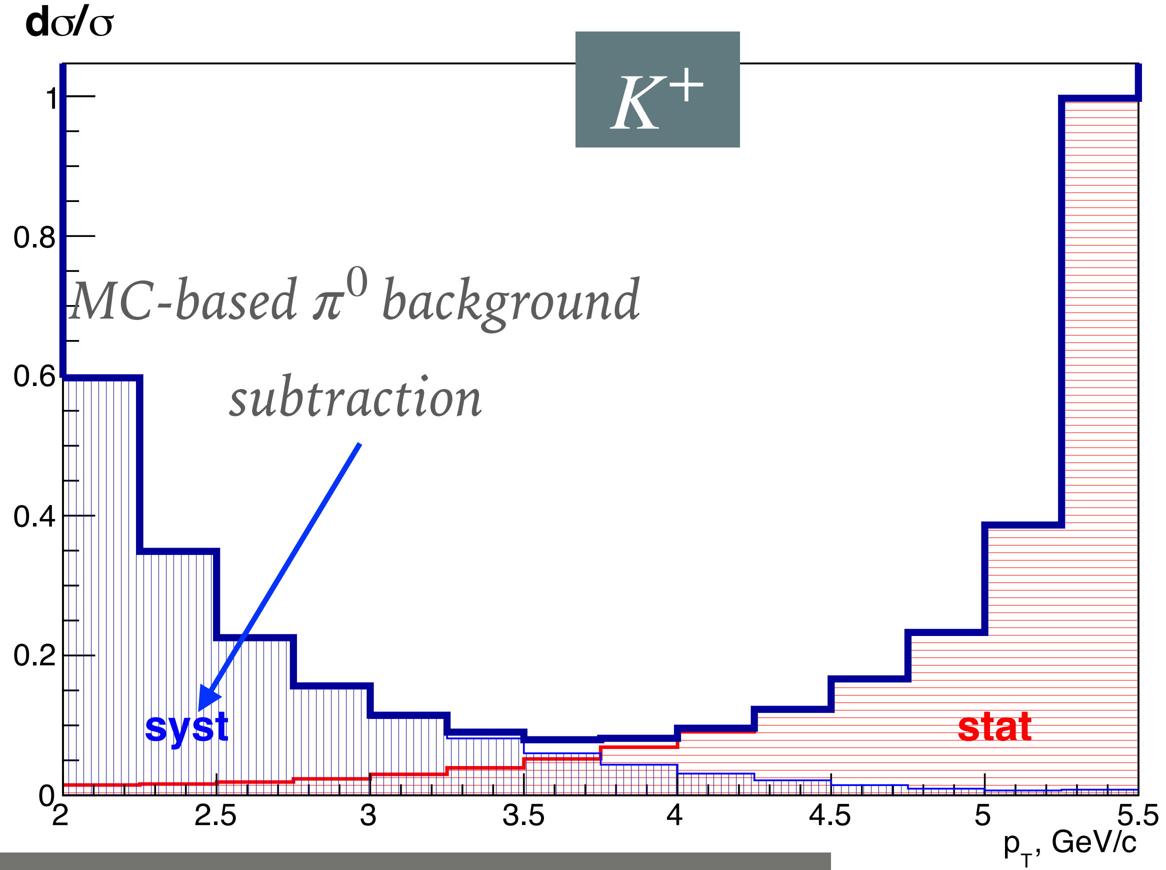
Open setup *- possibility for semi-inclusive and exclusive reactions!*

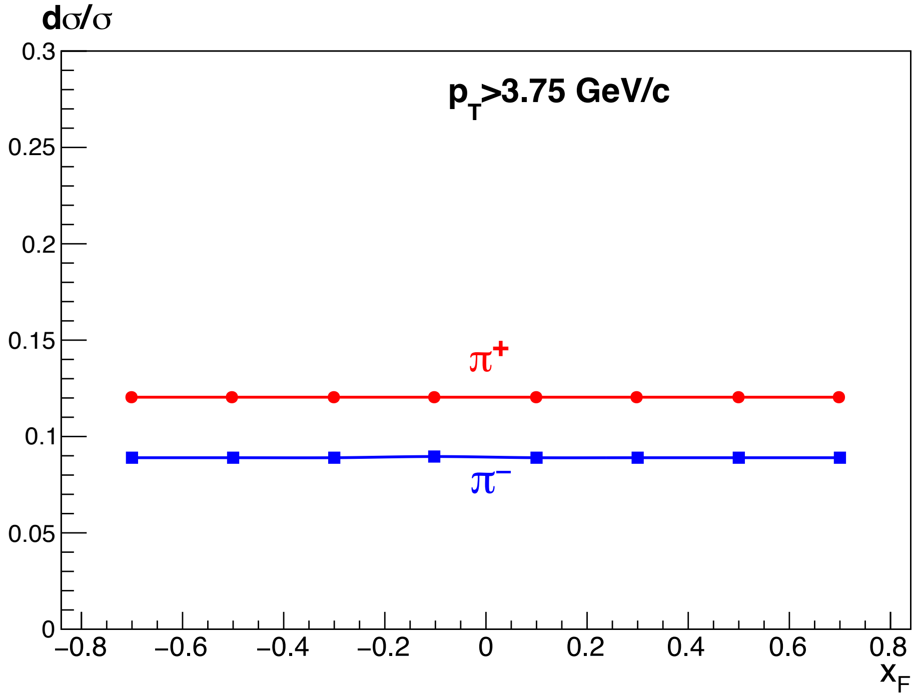


PRODUCTION OF PROMPT PHOTONS

Phase-2







# of photons	*p_T>2 GeV/c*	*p_T>3 GeV/c*
π^- total	*3.1×10^7*	*3.7×10^5*
π^- prompt	*1.3×10^6*	*6.8×10^4*
π^+ total	*3.3×10^7*	*3.6×10^5*
π^+ prompt	*1.1×10^6*	*4.7×10^4*

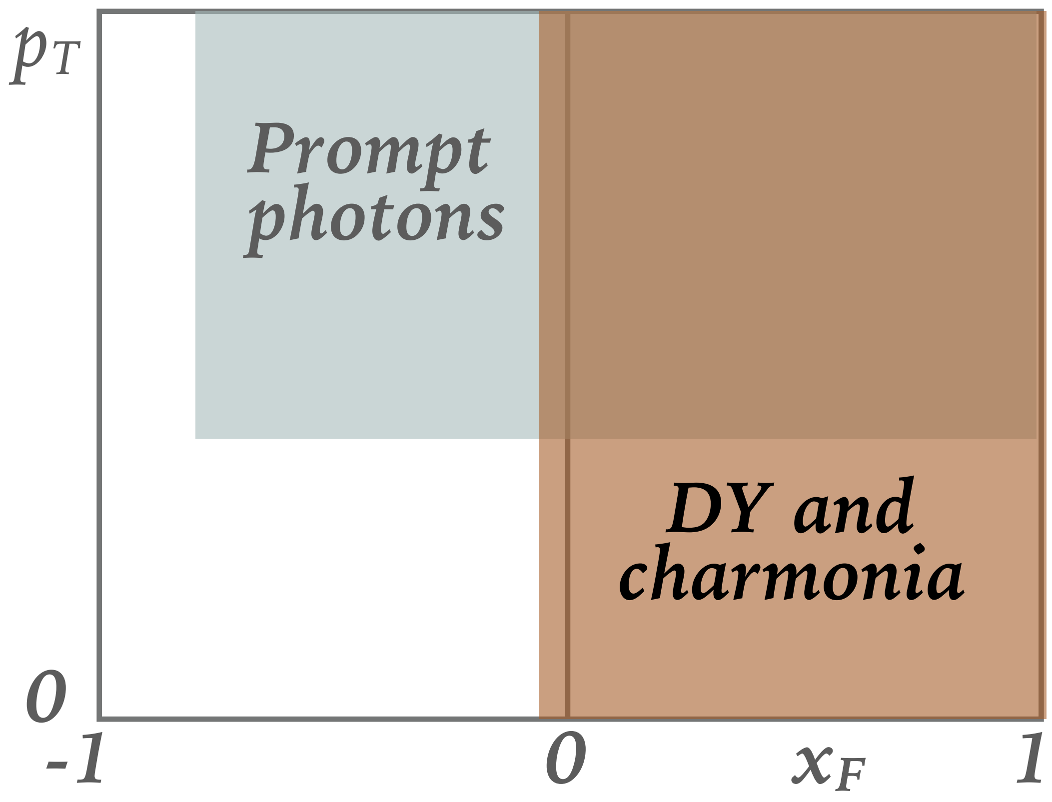
This experiment (100 GeV): 50 pb^{-1} (1 year)

WA70 (280 GeV):*1.3 pb^{-1} for π^+ and 3.5 pb^{-1} for π^-*

STUDY OF KAON STRUCTURE

Phase-2

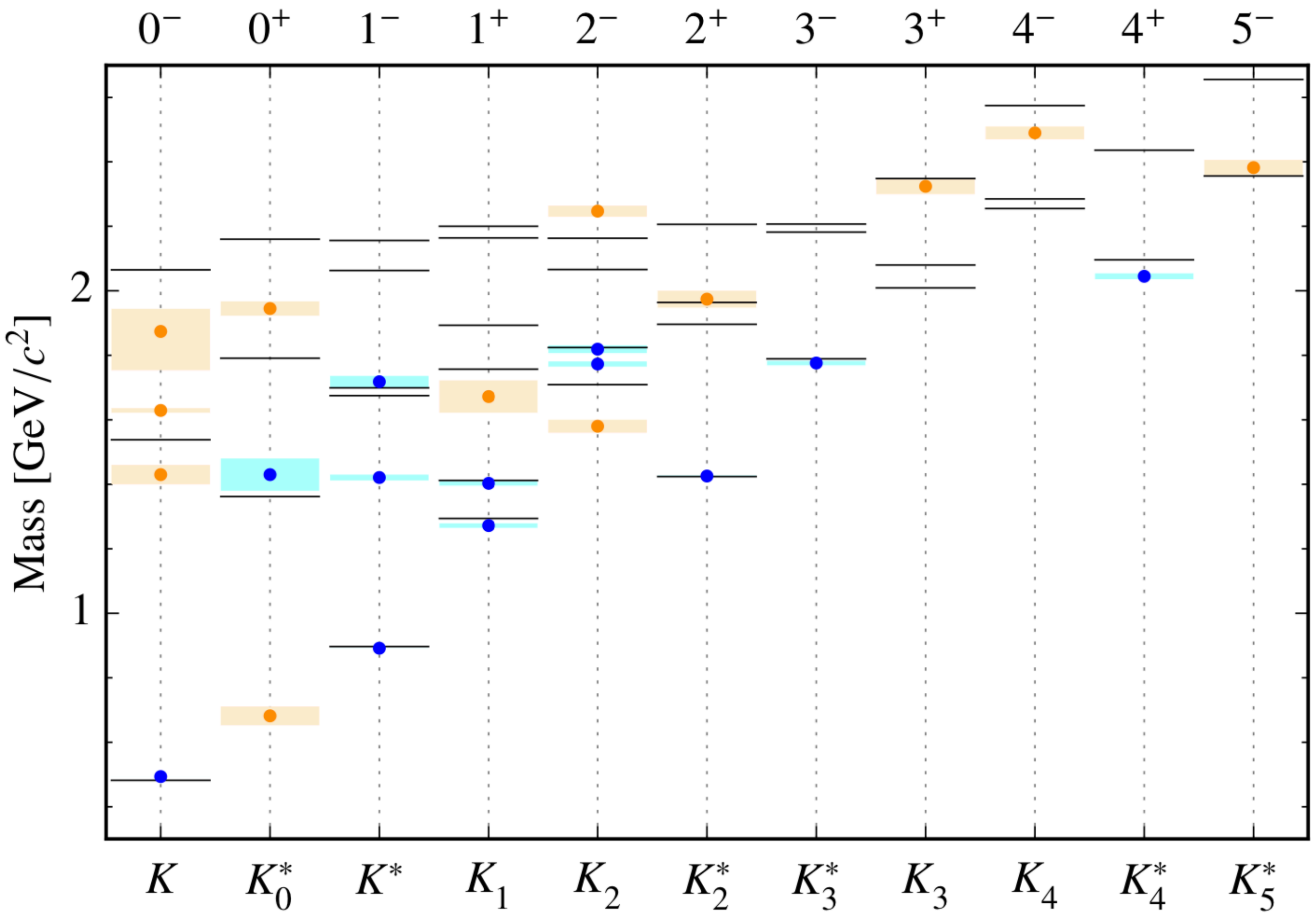
	Drell-Yan	Charmonia	Prompt photons
Main hard process (LO)	$q\bar{q} \rightarrow l^+l^-$	$gg \rightarrow J/\psi\ g$, $q\bar{q} \rightarrow J/\psi$	$q(\bar{q})g \rightarrow q(\bar{q})\gamma$, $q\bar{q} \rightarrow \gamma g$
Content to be tested	valence and sea quarks	gluons and quarks	gluons and quarks
Kinematic range	$x_F>0$	$x_F>0$	$p_T>2$ GeV/c
Main target	C	C	LH_2
Expected statistics, 10^6	π: ~0.1 (conv), K: ~0.06 (RF)	π: ~3 (conv), K: ~1 (RF)	π, K (RF) : ~10



Different but overlapping kinematic ranges

KAON SPECTROSCOPY

Phase-2

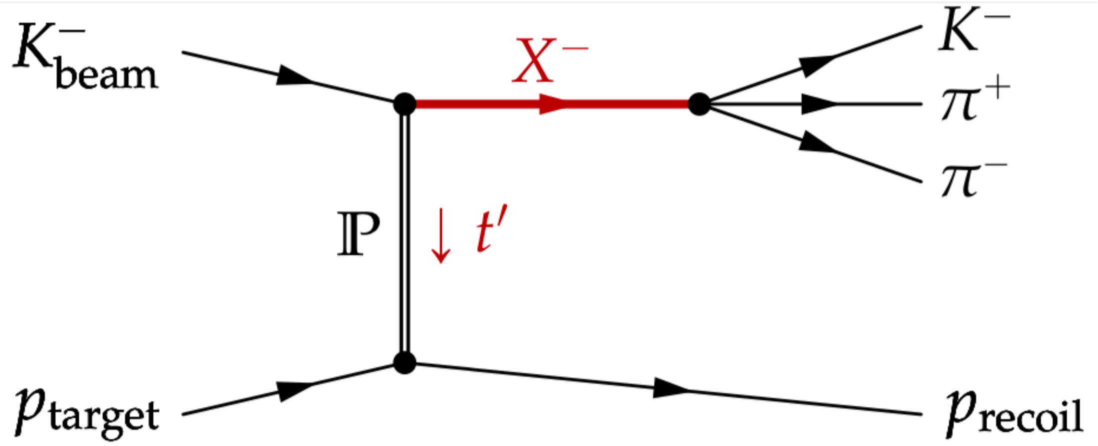


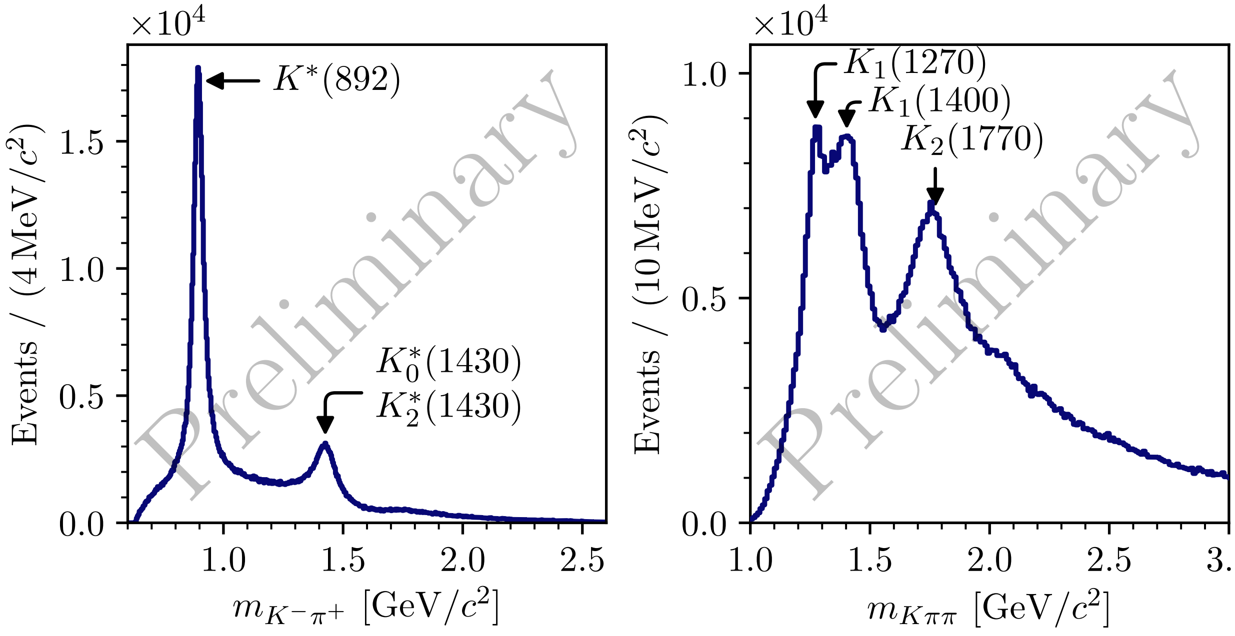
25 kaon states below 3.1 GeV can be found at PDG. But:

only 12 kaon states in summary table, 13 need confirmation;

most PDG entries more than 30 years old;

since 1990 only 4 kaon states added to PDG (only 1 to summary table)





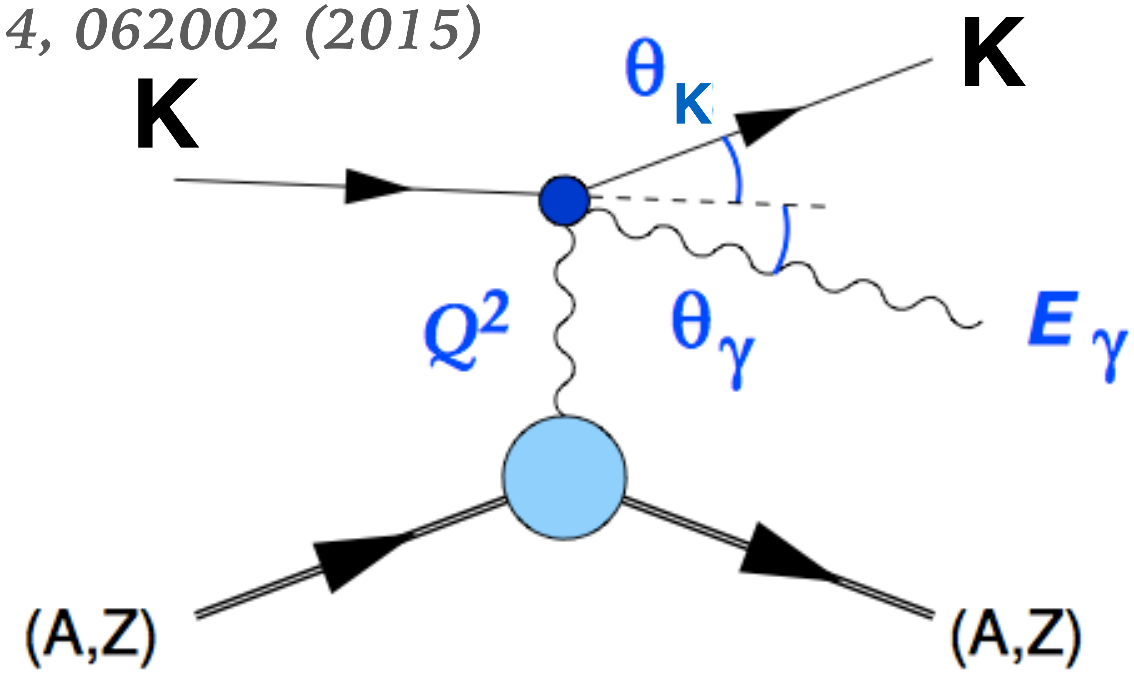
COMPASS: 7×10^5 $K^-\pi^+\pi^-$ events

AMBER: $> 1\times10^7$

KAON POLARISABILITY VIA PRIMAKOFF SCATTERING

Phase-2

Pion polarisability - *COMPASS, PRL 114, 062002 (2015)*



Theoretical predictions:

χPT prediction O(p⁴):

$$\alpha_K + \beta_K = 0$$

$$\alpha_K = \alpha_\pi \times \frac{m_\pi F_\pi^2}{m_K F_K^2} \approx \frac{\alpha_\pi}{5} \approx \underline{0.6 \times 10^{-4} fm}$$

Quark confinement model:

$$\alpha_K + \beta_K = 1.0 \times 10^{-4} fm^3$$

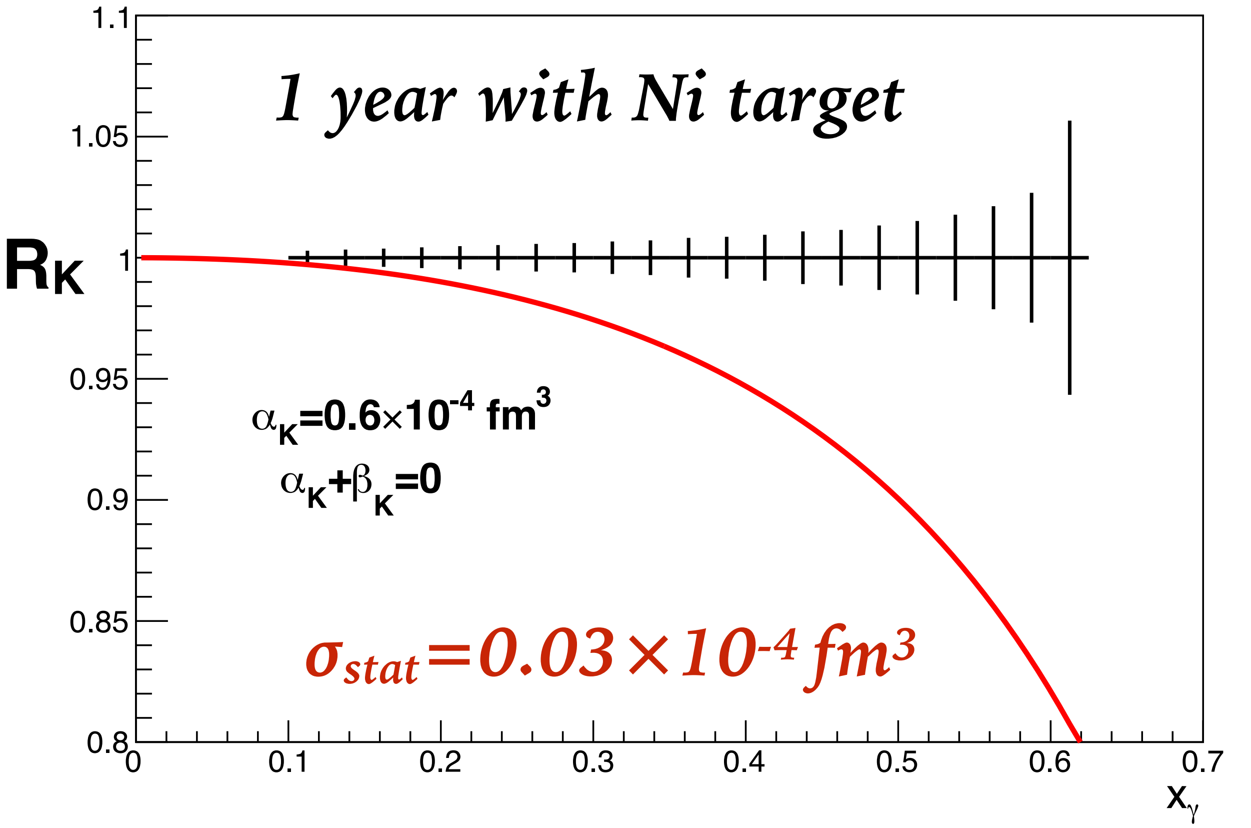
$$\alpha_K = \underline{2.3 \times 10^{-4} fm^3}$$

Experimental results:

$a_K < 200 \times 10^{-4}$ fm³ (1973)

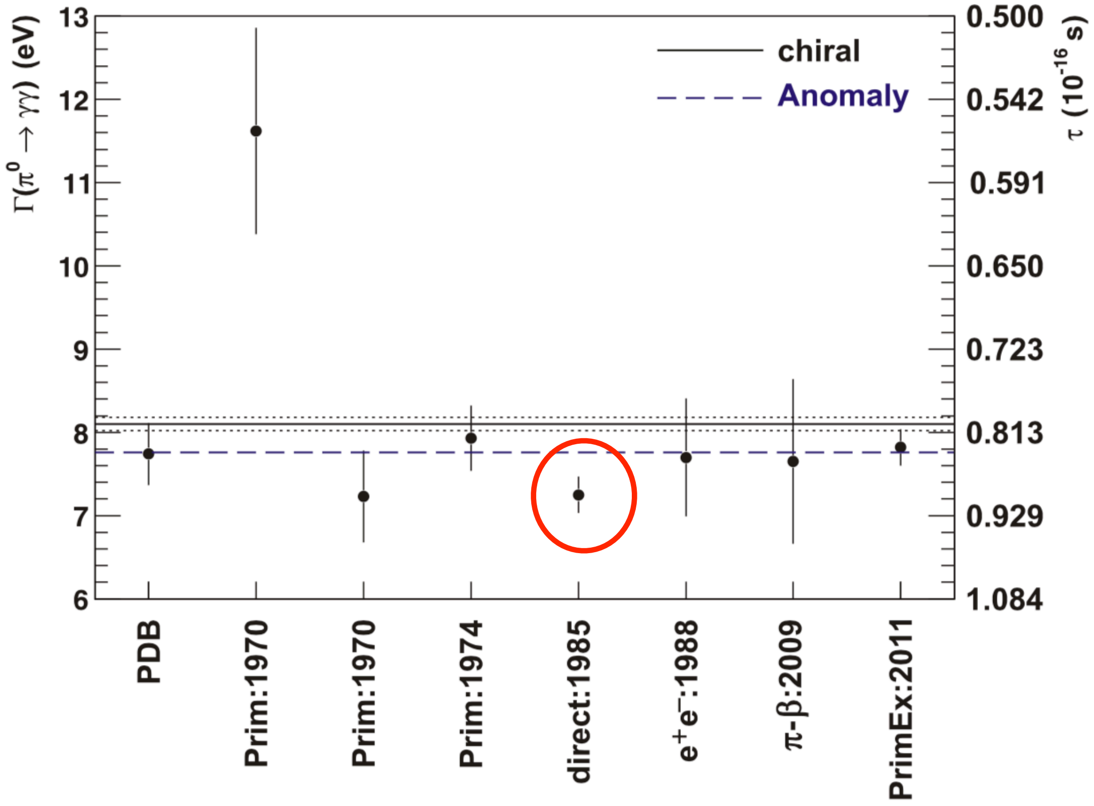
- from kaonic atoms spectra

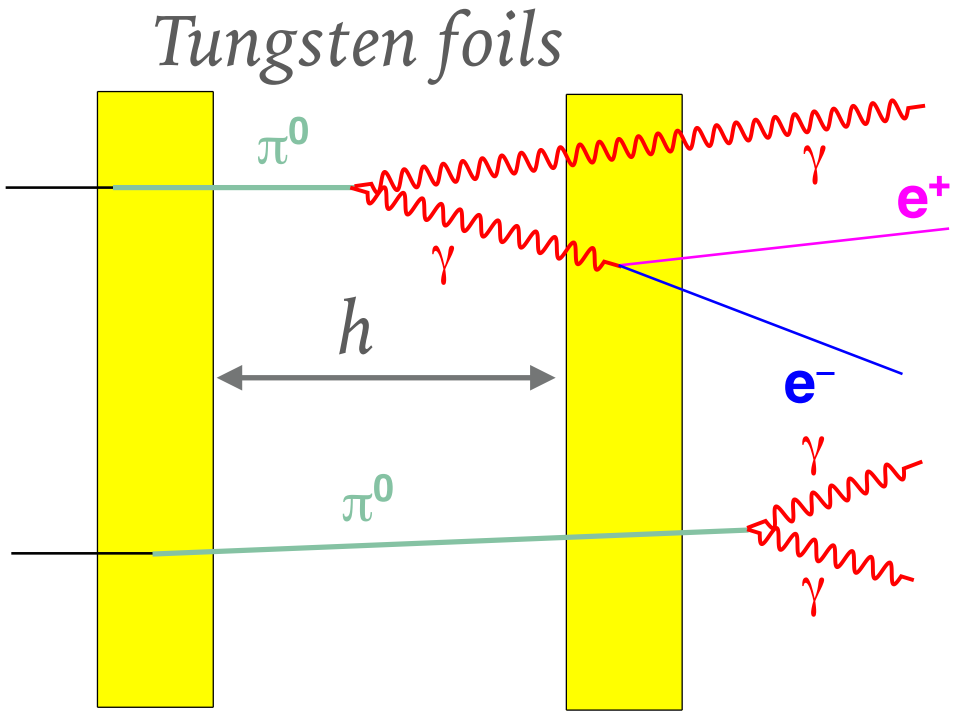
$$R_K \approx \frac{\sigma}{\sigma_{p.l.}} = 1 - \frac{3}{2} \cdot \frac{x_\gamma^2}{1 - x_\gamma} \cdot \frac{m_K^3}{\alpha} \cdot \alpha_K$$

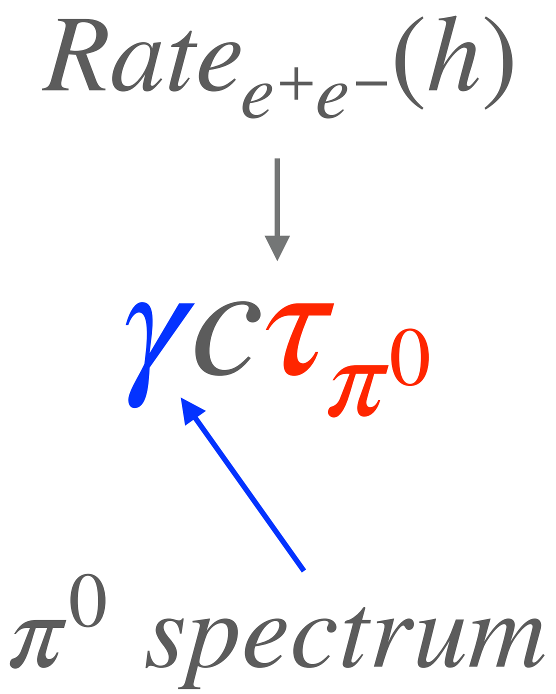


OTHER TESTS OF LOW-ENERGY QCD PREDICTIONS

Phase-2







$$Rate_{e^+e^-}(h)$$

$$\gamma c \tau_{\pi^0}$$

π^0 *spectrum*

Kaon-induced low-t reactions like

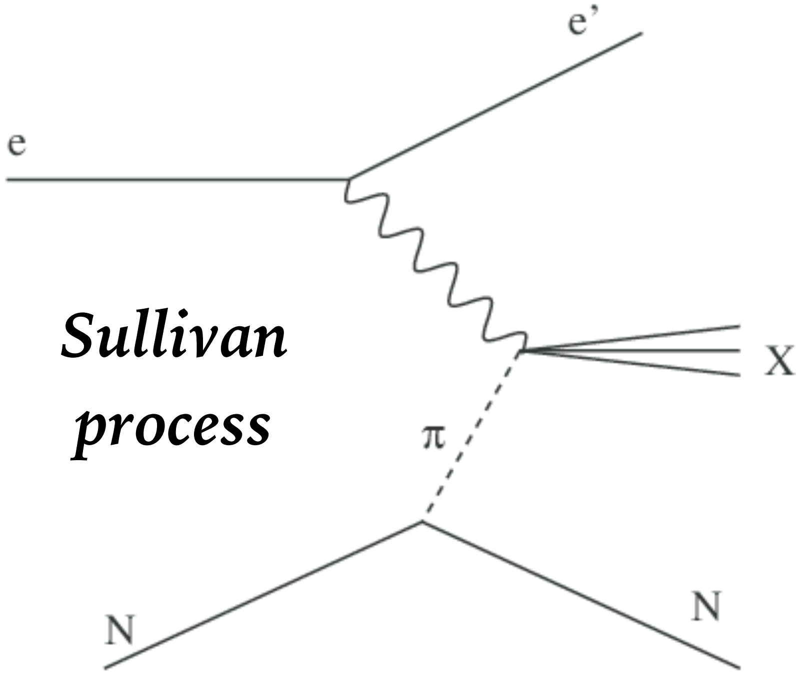
$$K^-(A,Z) \to K^-\pi^0(A,Z),$$

$$K^-(A,Z) \to \pi^-K^0(A,Z),$$

$$K^-(A,Z) \to K^-\pi^0\pi^0(A,Z)\ etc.$$

OUR COMPETITORS

Pion and kaon partonic structure can be accessed by model-dependent way via Sullivan process at JLab and EIC. The J-PARC kaon beam has too low momentum for such kind of measurements.



Sullivan process

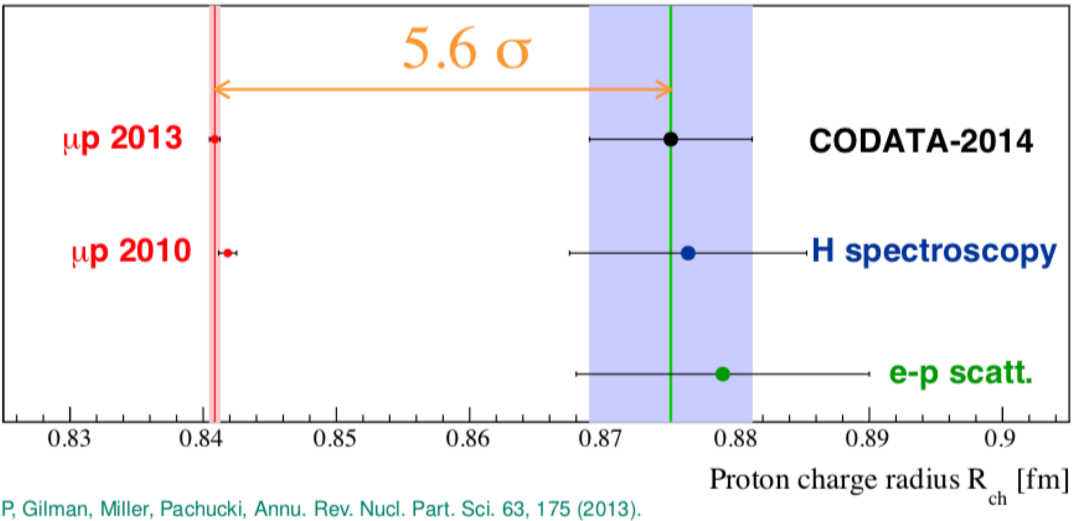
We are not aware of any other plans to measure kaon polarisabilities

Kaon spectroscopy: Belle II, BES III, LHCb: in decay of τ-lepton and D-mesons only states with mass below 1.8 GeV will be accessible. Limited dataset from decay of B-mesons. GlueX (JLab): photoproduction of $KK\pi\pi$ final state. J-PARC - spectroscopy with low-momentum kaon beam.

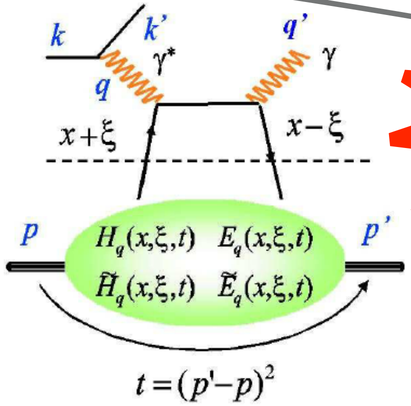
STUDY OF THE NUCLEON STRUCTURE AND PROPERTIES

Proton radius will be measured with accuracy of 0.01 fm in muon-proton elastic scattering

1



RP, Gilman, Miller, Pachucki, Annu. Rev. Nucl. Part. Sci. 63, 175 (2013).

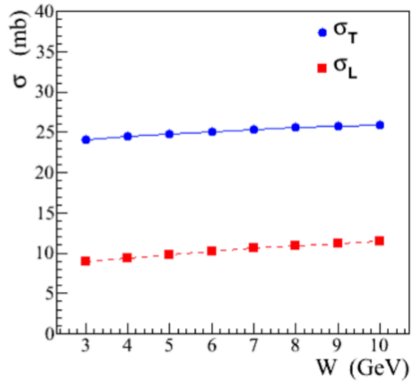


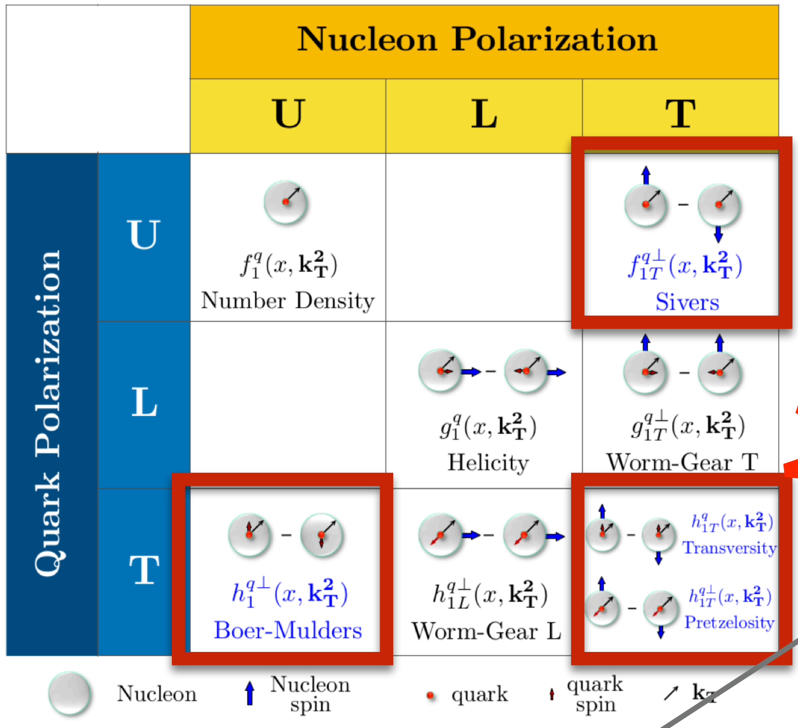
2

$$J^q = \tfrac{1}{2} \lim_{t\to 0} \int \left(H^q(x,\xi,t) + E^q(x,\xi,t)\right) x\, dx$$

*GPD E will be accessed and Ji sum rules will be tested with **DVCS** and **DVMP** processes using conventional positive and negative muon beams*

2





		Nucleon Polarization		
		U	L	T
Quark Polarization	U	$f_1^q(x,\mathbf{k}_T^2)$ Number Density		$f_{1T}^{\perp q}(x,\mathbf{k}_T^2)$ Sivers
	L		$g_1^q(x,\mathbf{k}_T^2)$ Helicity	$g_{1T}^{\perp q}(x,\mathbf{k}_T^2)$ Worm-Gear T
	T	$h_1^{\perp q}(x,\mathbf{k}_T^2)$ Boer-Mulders	$h_{1L}^{\perp q}(x,\mathbf{k}_T^2)$ Worm-Gear L	$h_{1T}^q(x,\mathbf{k}_T^2)$ Transversity $h_{1T}^{\perp q}(x,\mathbf{k}_T^2)$ Pretzelosity

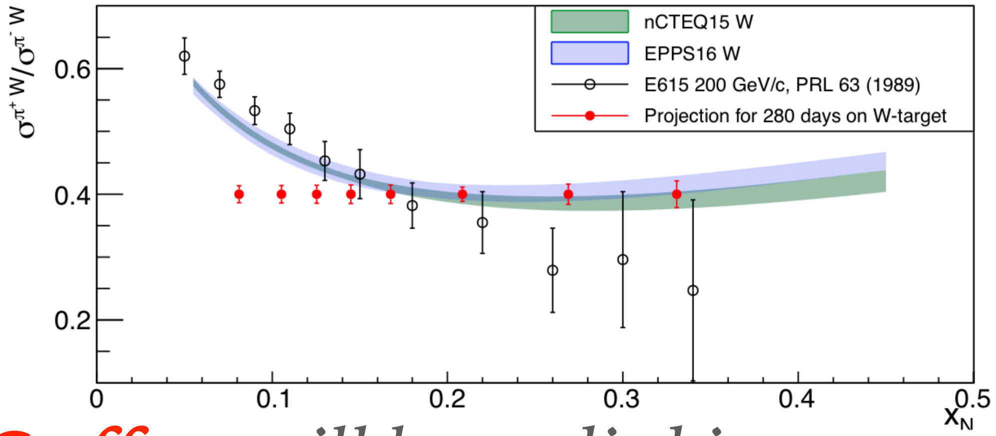
Nucleon · Nucleon spin · quark · quark spin · k_T

TMD PDFs will be accessed in DY process with $\bar{p}$ beam and polarised target

2

Production and propagation of polarised vector mesons in nuclear matter will be studied with π and K beams

1



The flavor-dependent EMC effect will be studied in pion-induced Drell-Yan process with C and W targets

SUMMARY

- ***No claim to have understood the Standard Model is supportable until an explanation is provided for the emergence and structure of Nambu-Goldstone modes.*** *The* ***meson as a complex QCD system*** *and, in particular,* ***the emergence of hadronic mass*** *is the central part of the proposed AMBER physics program with conventional pion and RF-separated beam, i.e. for both* ***Phase-1*** *and* ***Phase-2.*** *It will be attacked from several directions:*
    - *study of the parton structure of mesons via* ***Drell-Yan pair*** *production,* ***charmonia*** *and* ***prompt-photon*** *production;*
    - *investigation of resonant and dynamical properties in spectroscopy;*
    - *clarification of the Nambu-Goldstone nature of pion and kaon in low-t reactions.*
- *AMBER has intention to study structure and properties of nucleon. The proton-radius puzzle should be solved after precision measurement of proton radius in elastic* $\mu - p$ *scattering. GPD E should be touched via DVCS and DVMP processes. TMD PDFs will be accessed via* $\bar{p}$*-induced Drell-Yan. The flavor-dependent EMC effect will be investigated in pion-induced Drell-Yan process and C/W targets. Production and propagation of polarised vector mesons in nuclear matter will be studied with* π *and* K *beams*
- *The antiproton yield in* ***p-p*** *and p-He collisions will be measured for the purpose of dark matter search in astrophysics experiments.*
- *Study of charmonia production in* $p\bar{p}$ *annihilation will be performed with low-energy antiproton beam.*
- ***The proposal for Phase-1 of the COMPASS++/AMBER project was submitted to the SPSC in May 2019. It includes the proton radius measurement, Drell-Yan and charmonia production using conventional hadron beams and measurements of the antiproton yield in p-p and p-He collisions.***