Physics program of the COMPASS++/AMBER project

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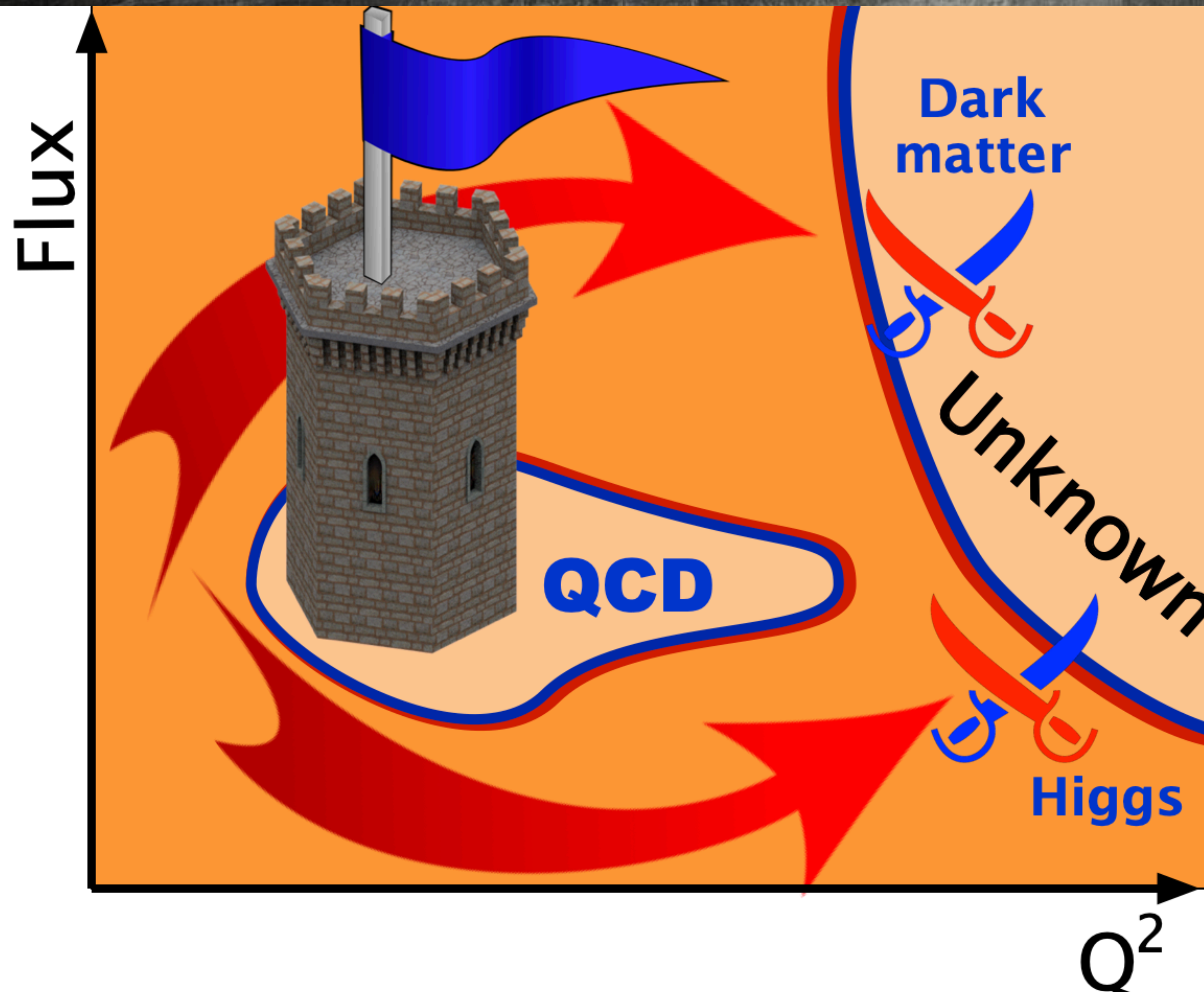
JINR, DLNP

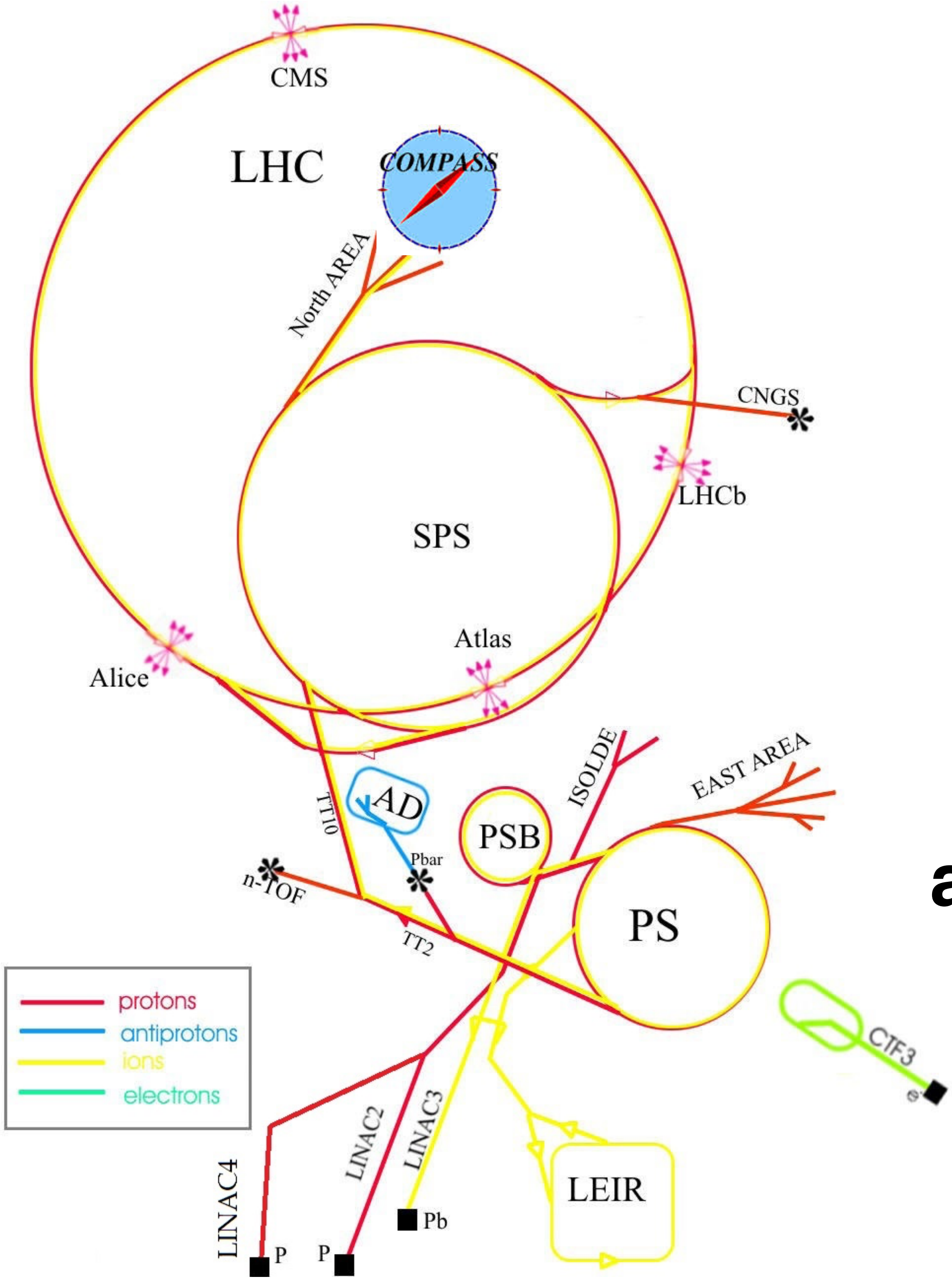
17.04.2019

on behalf of the COMPASS++/AMBER working team

Frontiers of HEP



COMPASS at CERN



COMPASS (NA58) is a fixed target experiment at CERN at the secondary beam line of the SPS at the North Area

COMPASS outside

COMPASS inside

COMPASS collaboration

COMPASS (**CO**mmon **M**uon **P**roton **A**pparatus for **S**tructure and **S**pectroscopy)

COMPASS

http://wwwcompass.cern.ch

13 states 24 institutes 220 scientists

The purpose of the experiment is the study of hadron structure and hadron spectroscopy with high intensity muon and hadron beams.

1996 - Proposal of the experiment

2002 - 2012 - COMPASS

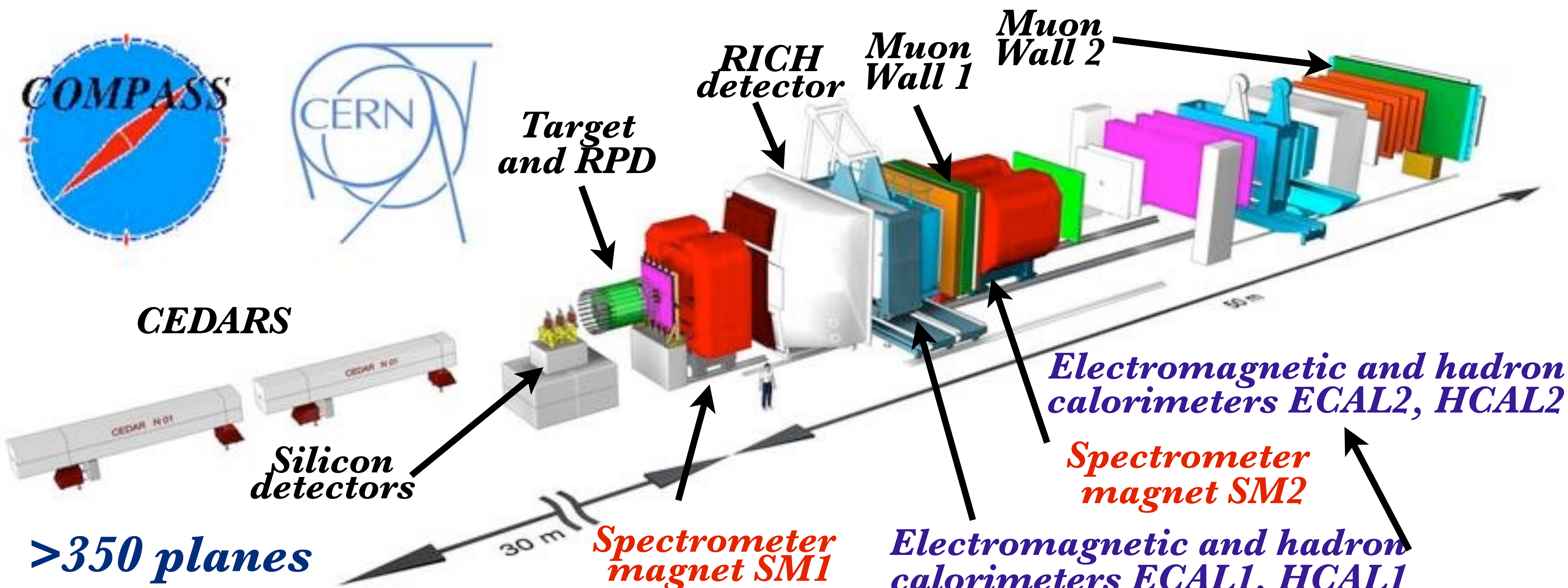
2012 - 2019 - COMPASS II

2021 - approved run

2022+ ??

ОИЯИ

The COMPASS setup



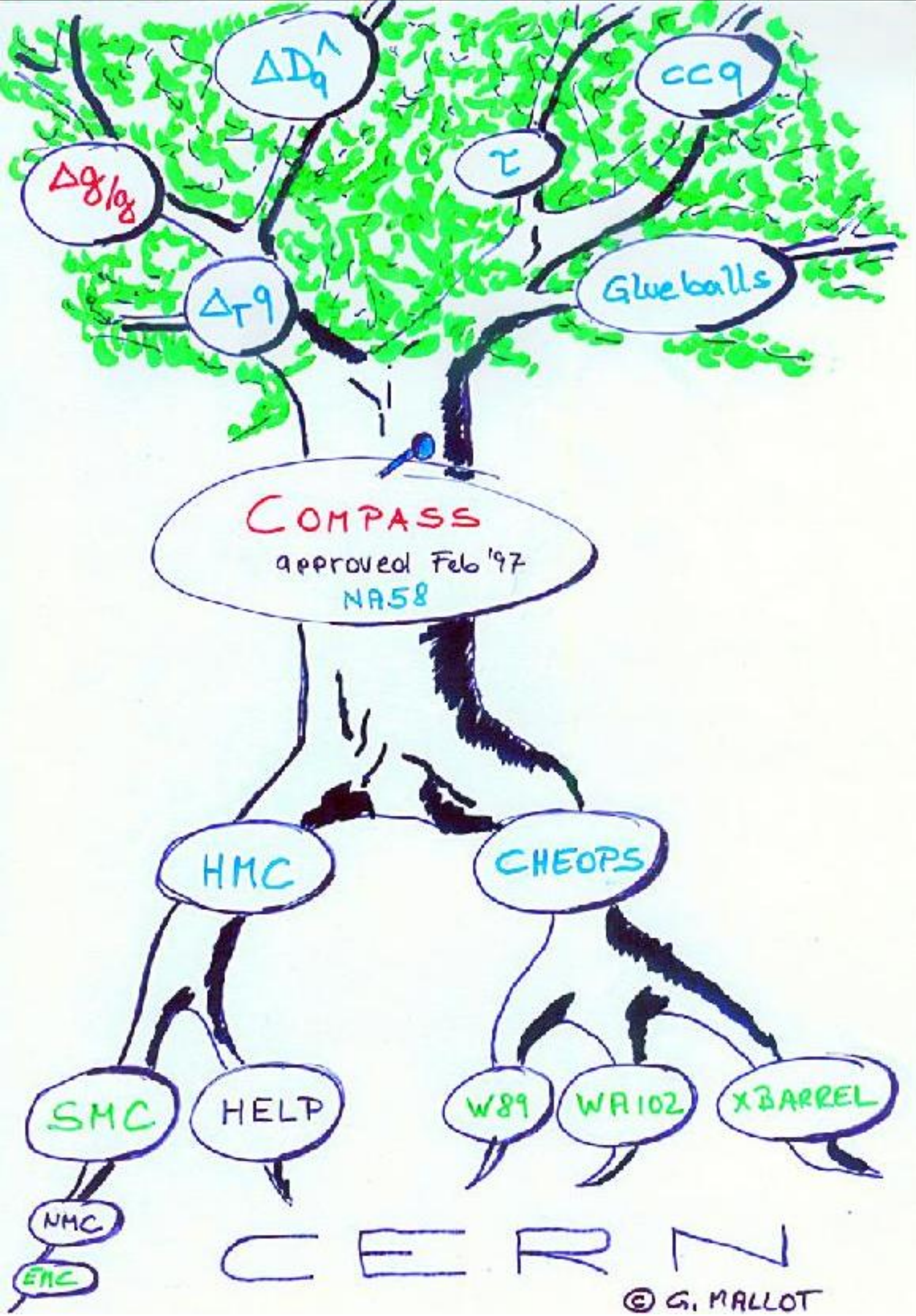
Muon beam: $\mu^{+/-}$, P=160-200 GeV/c

Hadron beam: $h^{+/-}$, P=190 GeV/c

Particles	Positive beam	Negative beam
π	0.240	0.968
K	0.014	0.024
p	0.746	0.008

Composition of the COMPASS hadron beam

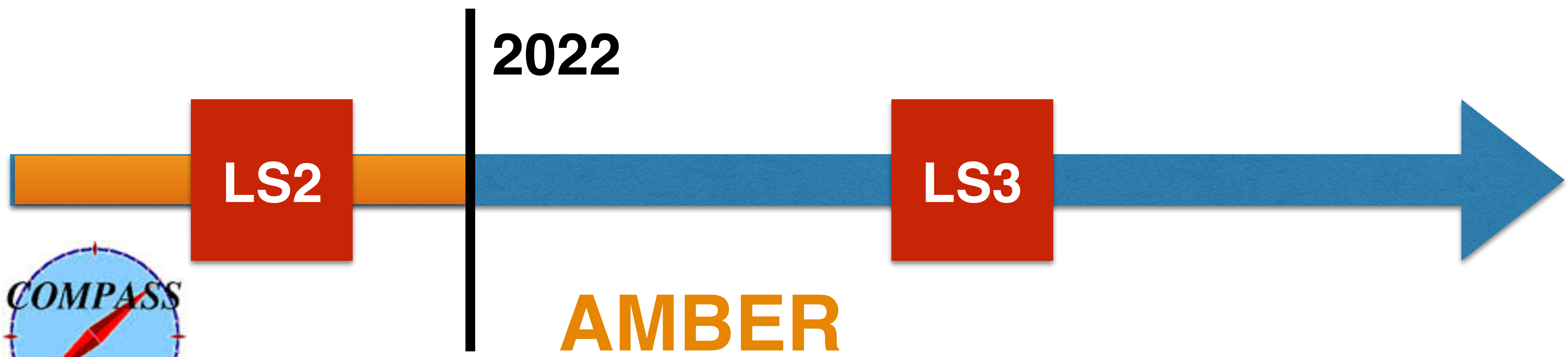
COMPASS roots



COMPASS → AMBER

Apparatus for Meson and Baryon Experimental Research

— a new QCD facility at the M2 beam line of the CERN SPS



AMBER LoI

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

COMPASS + ~15 new groups

CERN-SPSC-2019–003
SPSC-I-250
January 28, 2019

arXiv:1808.00848

with active participation of the JINR group!

Letter of Intent:

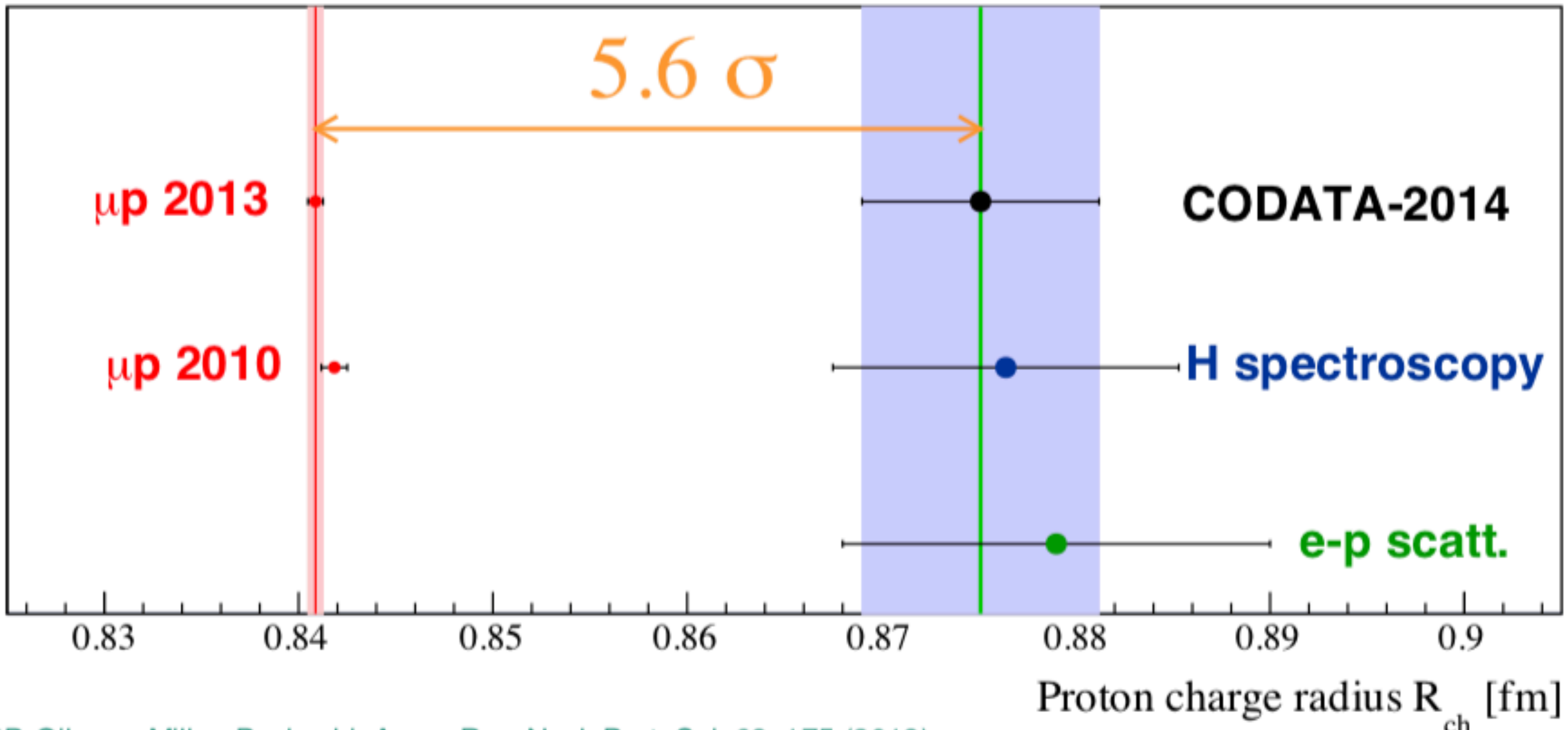
A New QCD facility at the M2 beam line of the CERN SPS[*]

COMPASS++[†]**/AMBER**[‡]

Proton radius measurement in μ-p elastic scattering

Competitors: unique

Proton radius puzzle

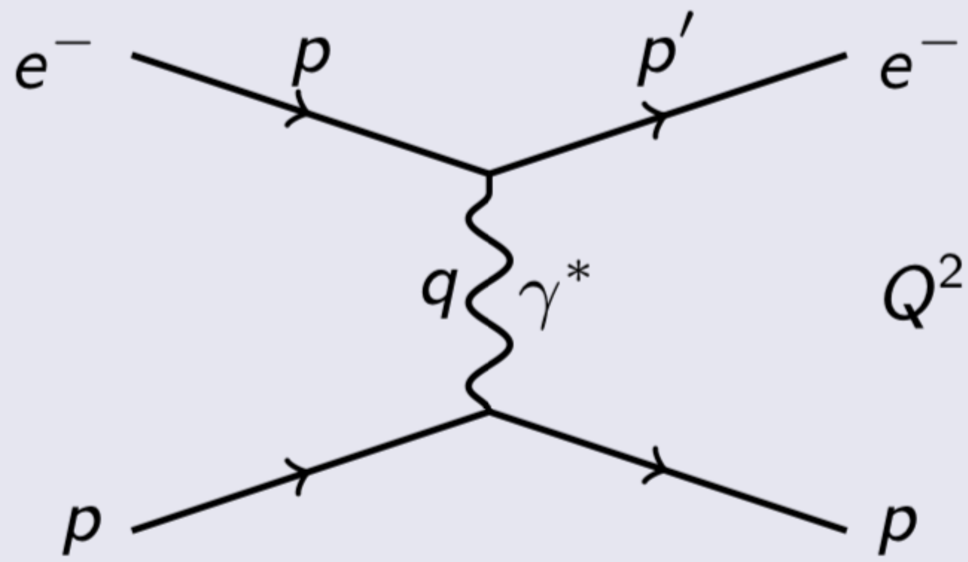


RP, Gilman, Miller, Pachucki, Annu. Rev. Nucl. Part. Sci. 63, 175 (2013).

proton radius "puzzle"

- discrepancy between scattering and spectroscopy data
  - measuring the same thing?
  - systematic effects for electron scattering, e.g. radiative corrections?
  - new physics? lepton non-universiality?
  - ...

Elastic scattering



$$Q^2 = -q^2$$

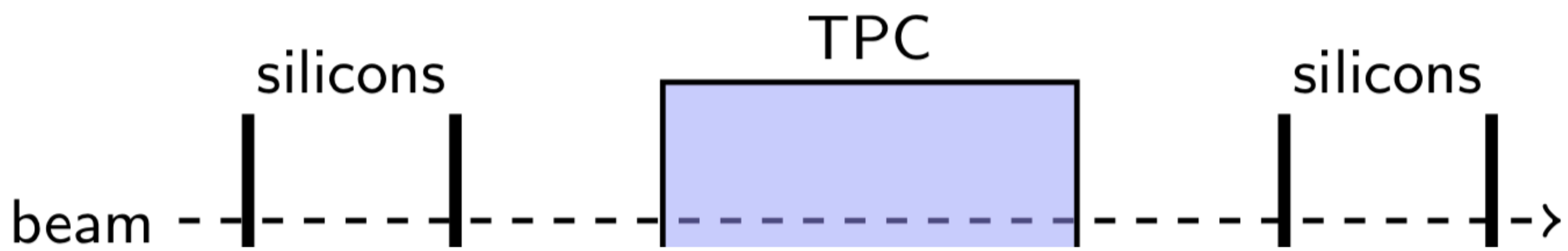
$$\frac{d\sigma}{dQ^2} = \frac{\pi\alpha^2}{Q^4 m_p^2 \vec{p}_e^{\,2}} \left[\left(G_E^2 + \tau G_M^2 \right) \frac{4E_e^2 m_p^2 - Q^2(s - m_\mu^2)}{1+\tau} - G_M^2 \frac{2m_e^2 Q^2 - Q^4}{2} \right]$$

with $\tau = Q^2/(4m_p^2)$

mean squared charge-radius

$$\langle r_E^2 \rangle = -6\hbar^2 \frac{dG_E(Q^2)}{dQ^2}\bigg|_{Q^2\to 0}$$

The proposed setup

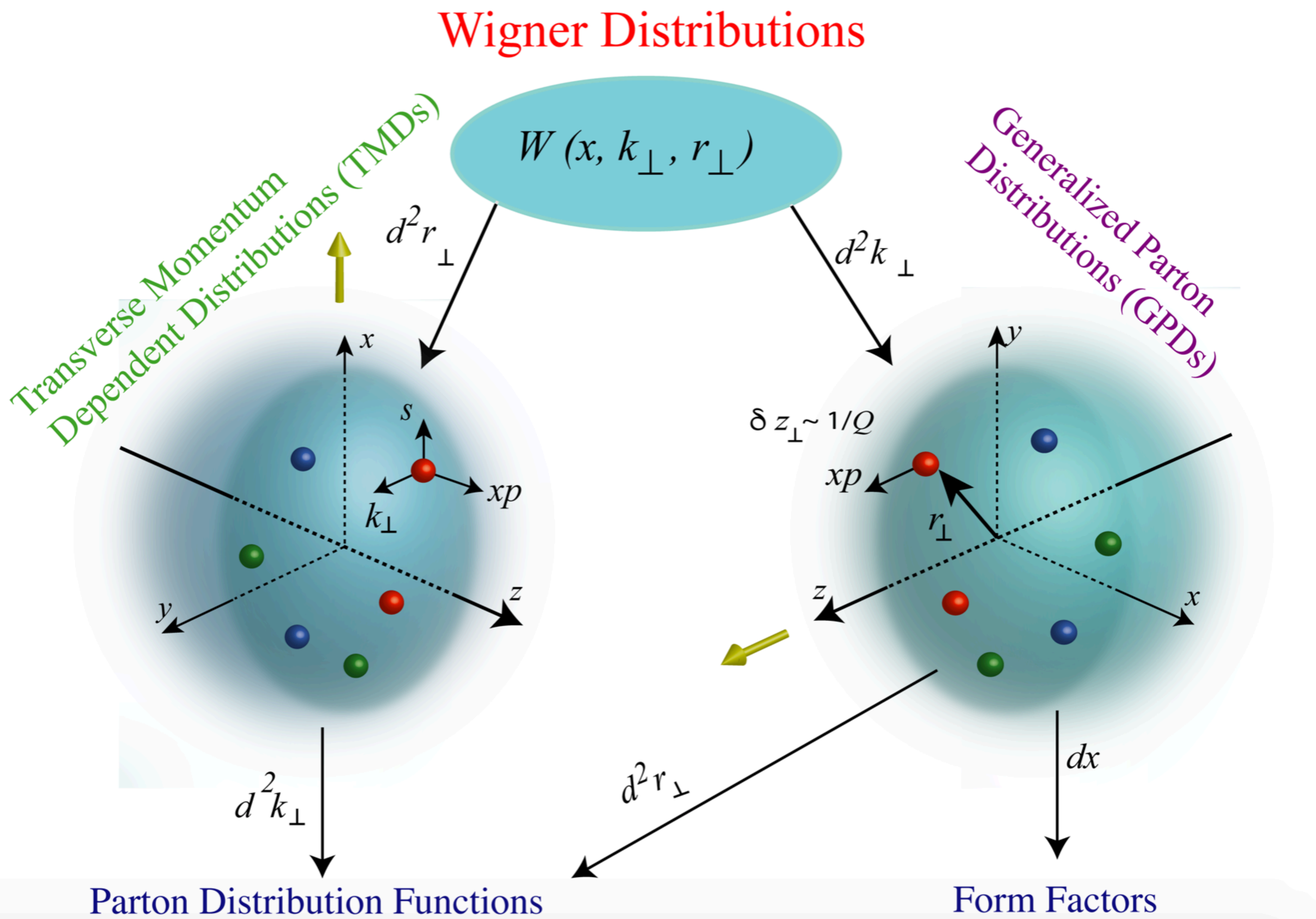


uncertainty on $\sqrt{\langle r_E^2 \rangle} \approx 0.01$ fm

Hard exclusive reactions with muon beam and transversely polarised target

Competitors: CLAS12 (JLab)

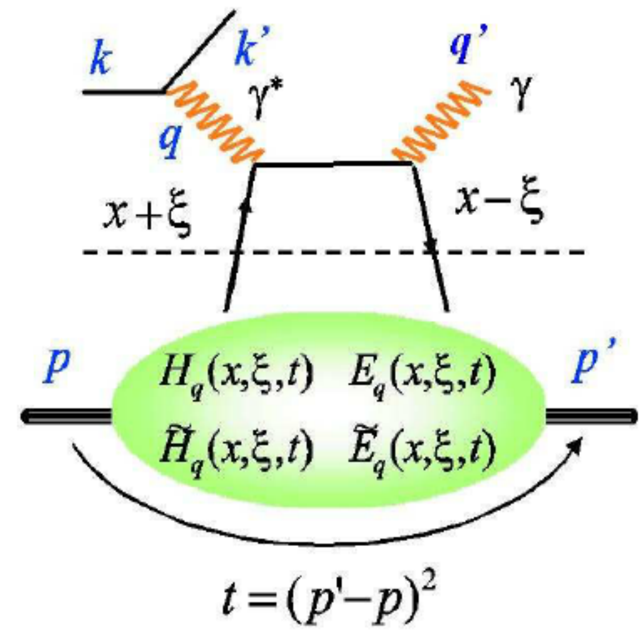
3D structure of proton



GPD E

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

Nucleon · Nucleon spin · quark · quark spin · $\mathbf{k_T}$



$\mathbf{H}(x, \xi, t) \xrightarrow{t\to 0} q(x)$ or $f_1(x)$

$\mathbf{E}(x, \xi, t) \longleftrightarrow f_{1T}^{\perp}(x, k_T)$

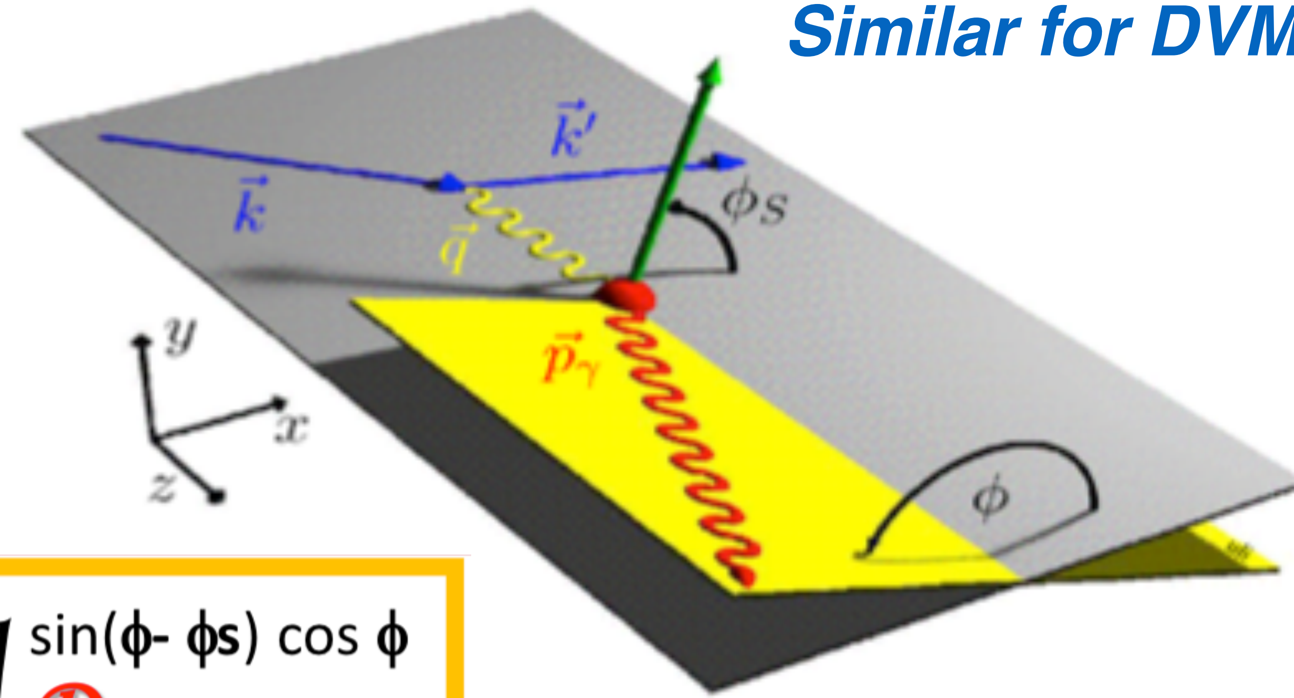
Ji sum rule

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

DVCS and GPD

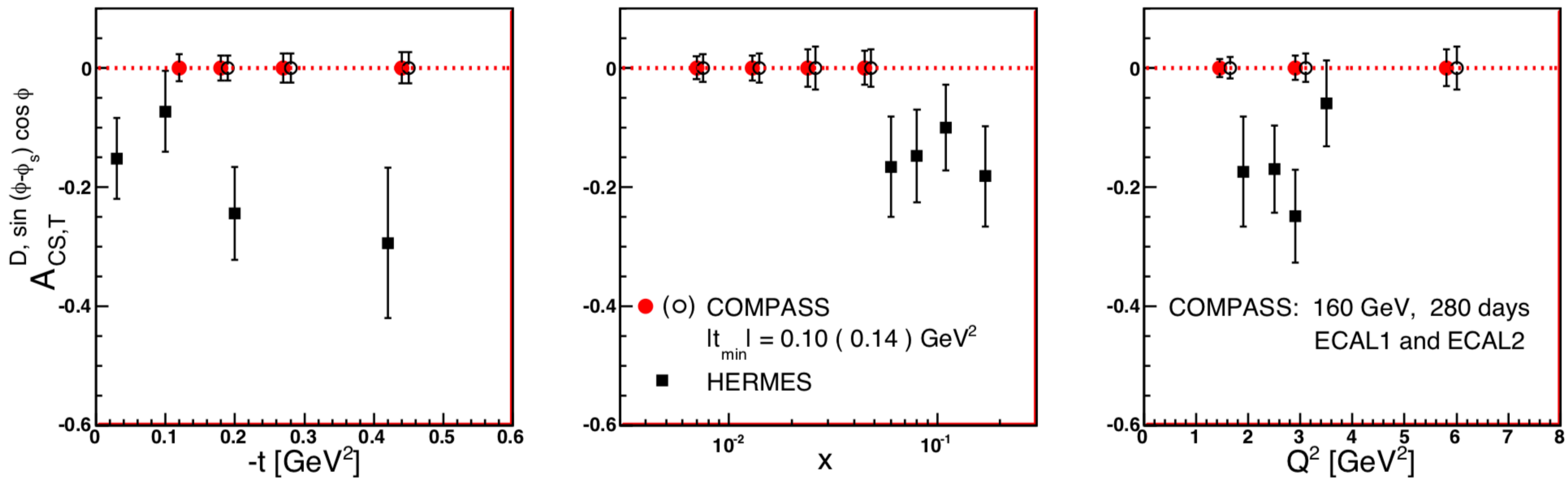
μ± beams
Transversely polarised NH_3 target
2 year of data taking

Similar for DVMP



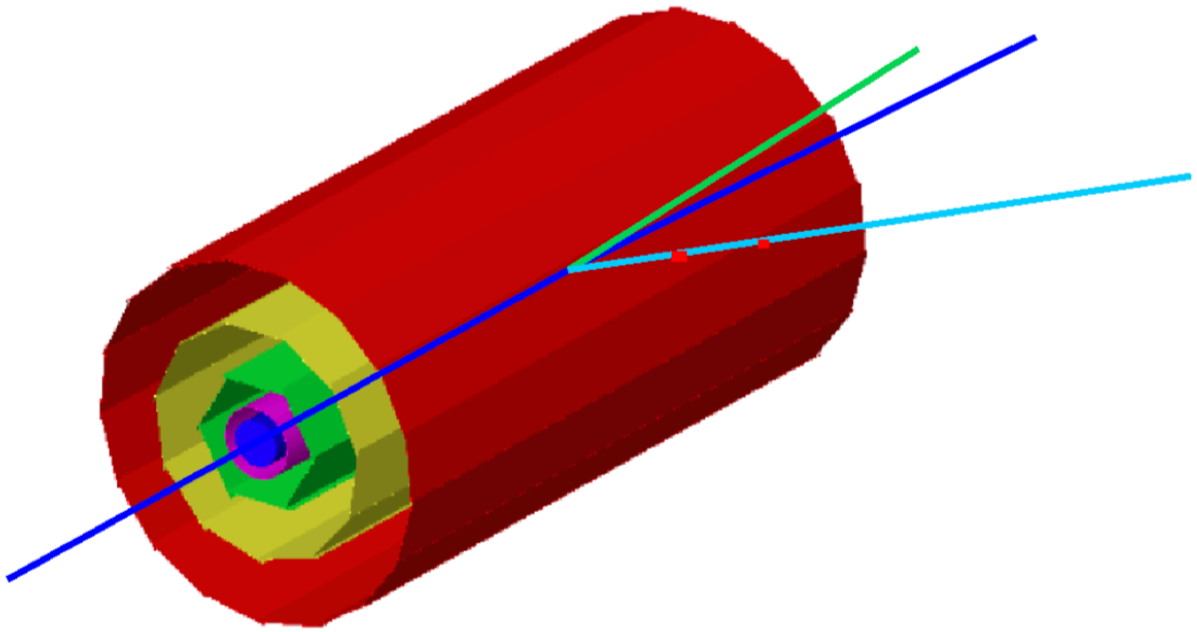
$$\mathcal{D}_{CS,T} \equiv \Delta\sigma_T(\mu^{+\downarrow}) - \Delta\sigma_T(\mu^{-\uparrow})$$
$$\rightarrow Im(F_2\mathcal{H} - F_1\mathcal{E})\ \sin(\phi-\phi s)\cos\phi$$

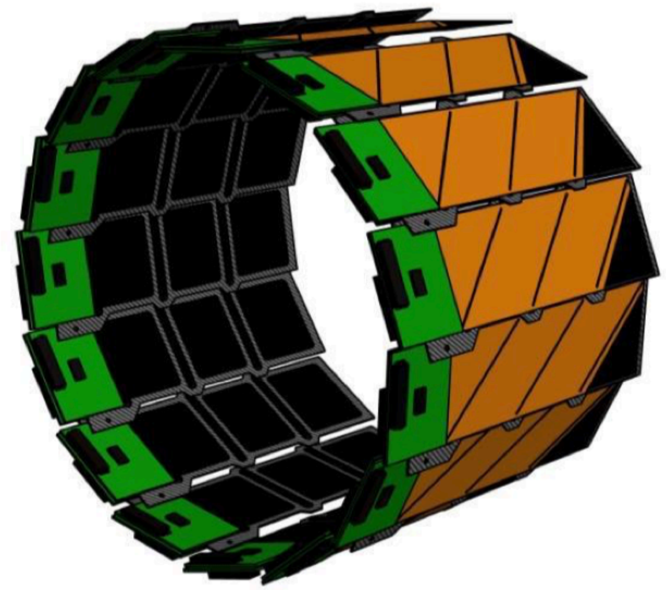
$$\mathcal{A}^{\sin(\phi-\phi s)\cos\phi}_{\mathcal{D}_{CS,T}}$$

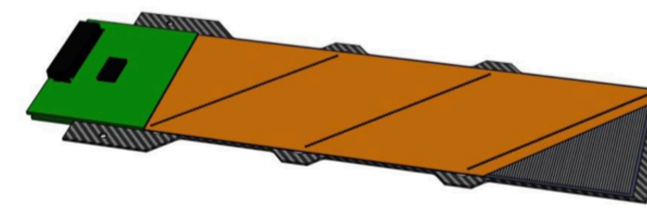


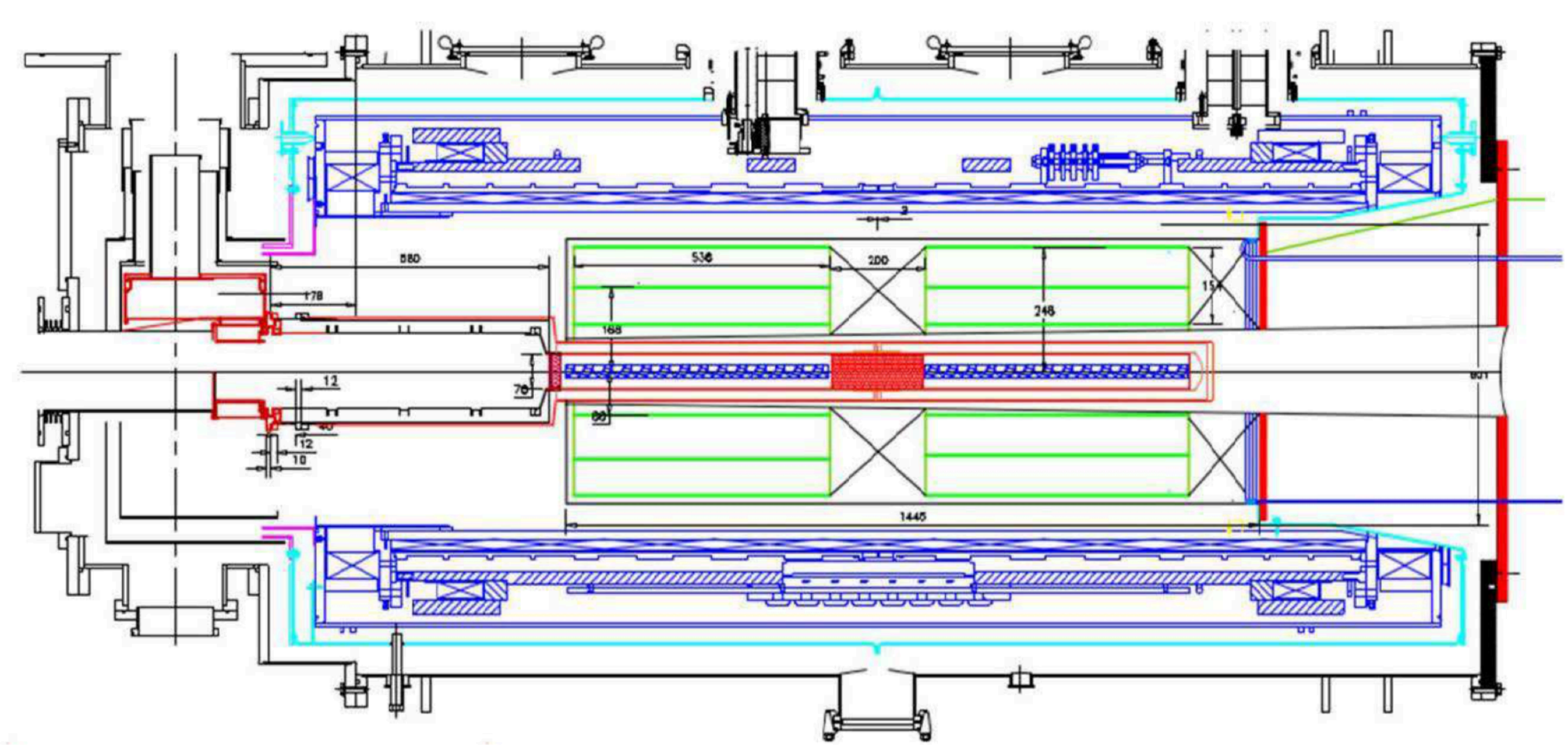
Silicon recoil detector

To enforce exclusivity selection the recoil detector for proton momentum measurement is proposed







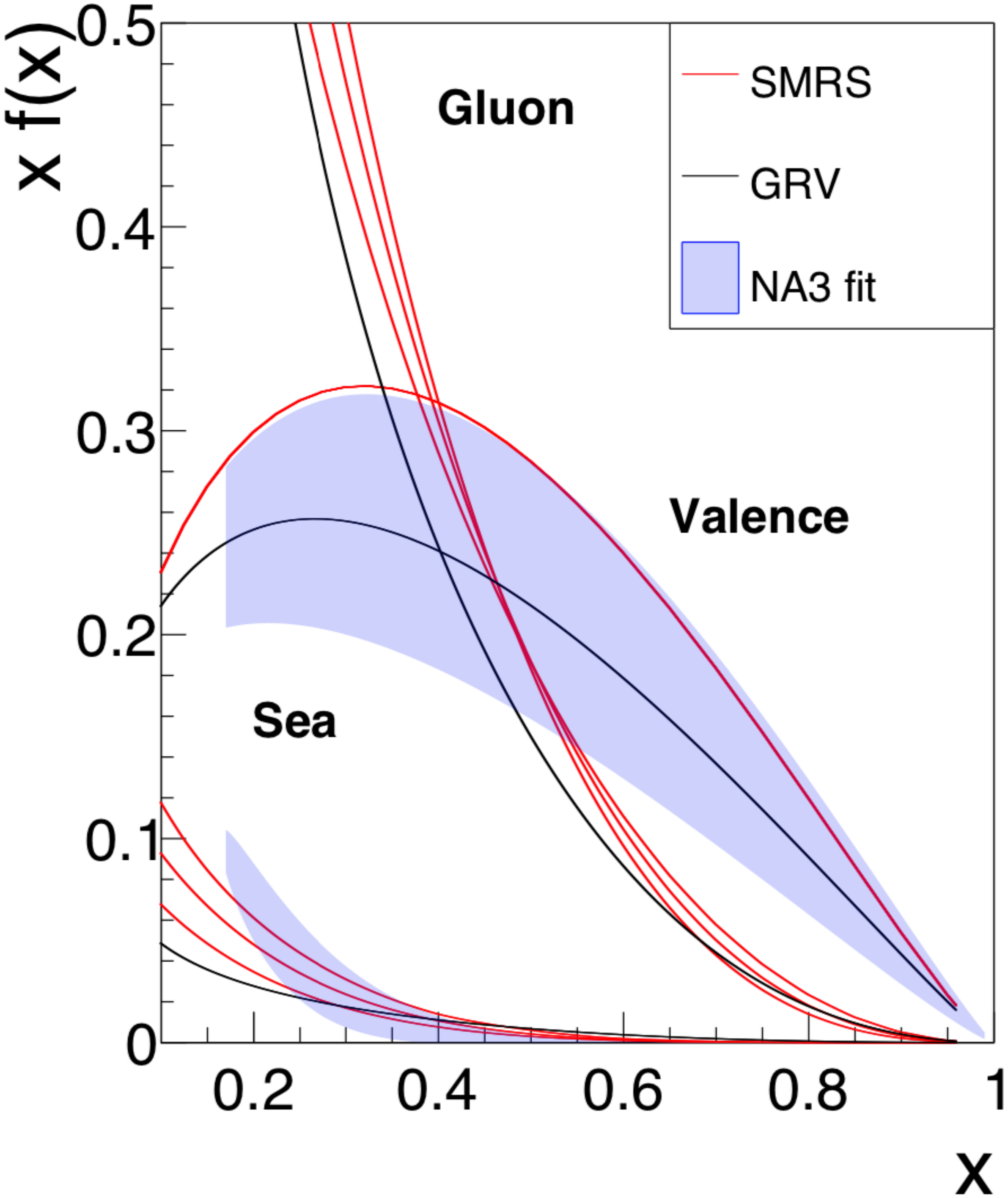


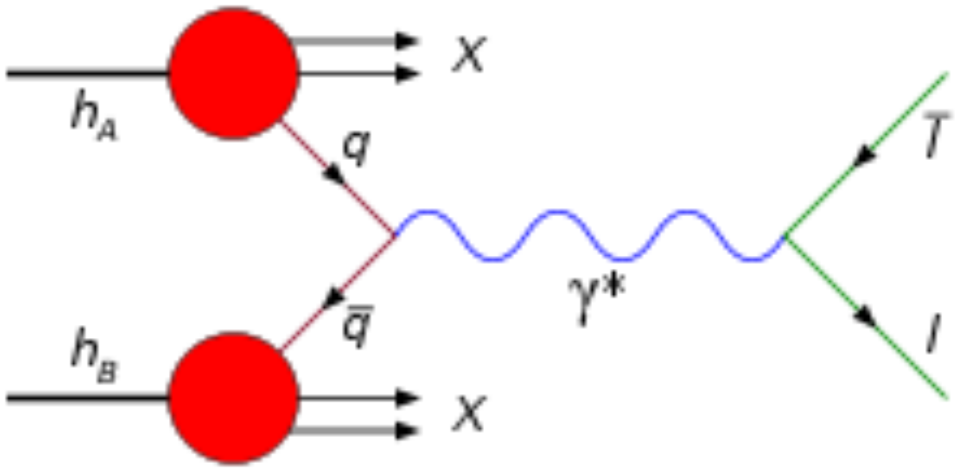
3 layers

Drell-Yan and charmonium production using conventional hadron beams

Competitors: EIC, PVDIS (JLab), SeaQuest (Fermilab)

Sea/valence in pion

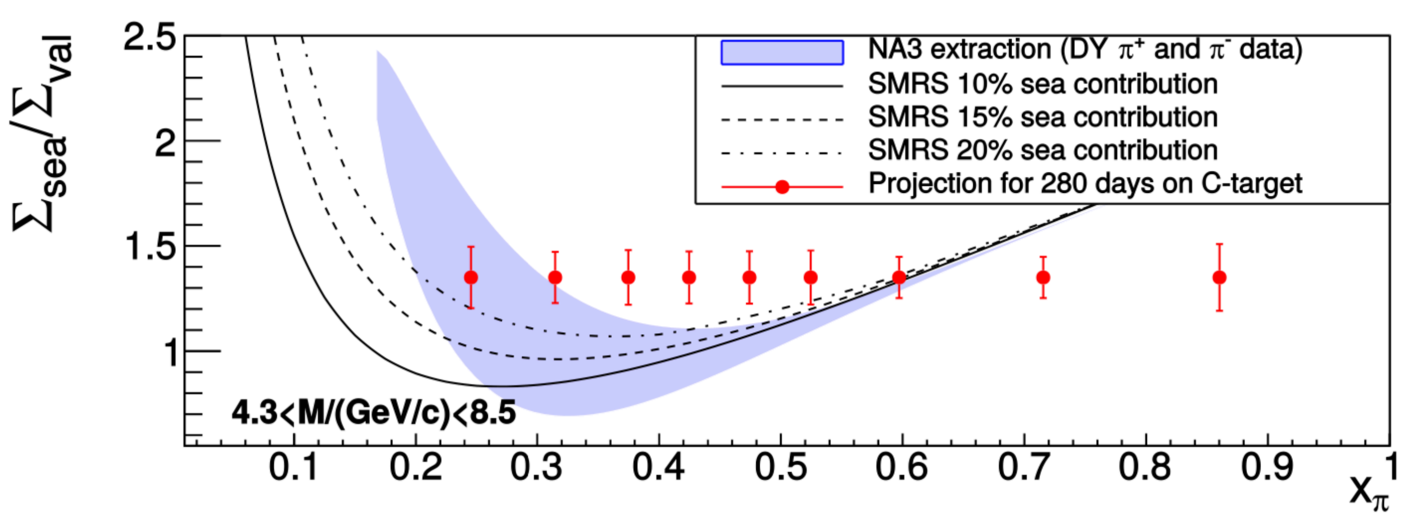




Sea/valence separation

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

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



Gluon PDFs

Z. Phys. C 72, 249–254 (1996)

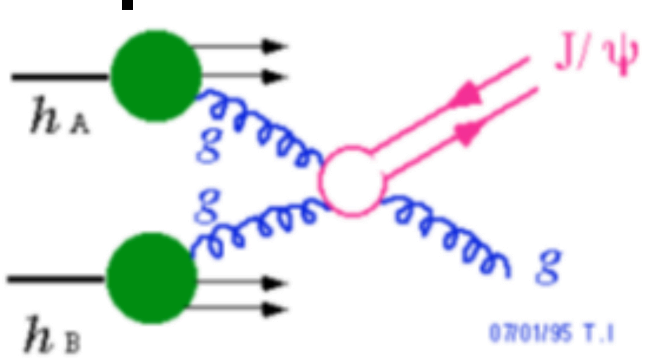
$xG(x)$	Reactions	Subprocess	Reference
$(1-x)^3$	$\pi N \to \psi$	$GG \to c\bar{c}$	[4], (1980)
$(1-x)^{1.9\pm0.3}$	$\pi^- Be \to \psi$	$GG \to c\bar{c}$	[5],(1983), WA11
$(1-x)^{2.38\pm0.06\pm0.1}$	$\pi^\pm Pt \to \psi$	$GG \to c\bar{c}$	[6], (1983)
$\sim(1-x)^{3.1}$, evolves with Q^2	$\pi p \to \psi, \pi^\pm X$	$GG \to c\bar{c}$	[7], (1984)
$(1-x)^{2.3^{+0.4+0.1}_{-0.3-0.5}}$	$\pi^- W \to \Upsilon$	$GG \to b\bar{b}$	[8], (1986) NA10
$(1-x)^{1.94^{+0.39}_{-0.17}}$	$\pi^\pm p \to \gamma X$	$QG \to \gamma Q$	[10], (1989) WA70
$(1-x)^{2.1\pm0.4}$	$\pi^+ p \to \gamma X$	$QG \to \gamma Q$	[11], (1991)
$(1-x)^{2.75\pm0.40\pm0.75}$	$\pi^- p \to dijets$	$QG, GG \to dijets$	This paper

$$xg(x) \sim (1-x)^\eta, \eta \approx 2$$

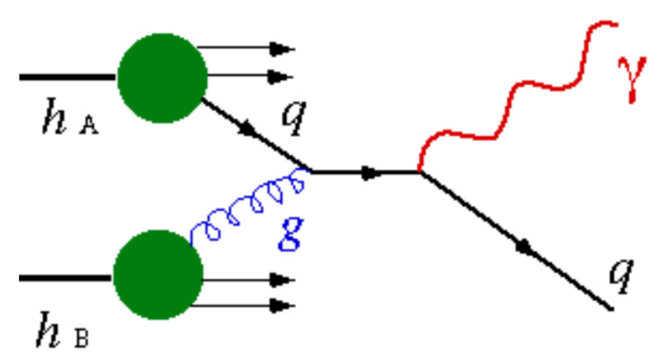
We have some minimal data for pion, for kaon there is no any experimental results!

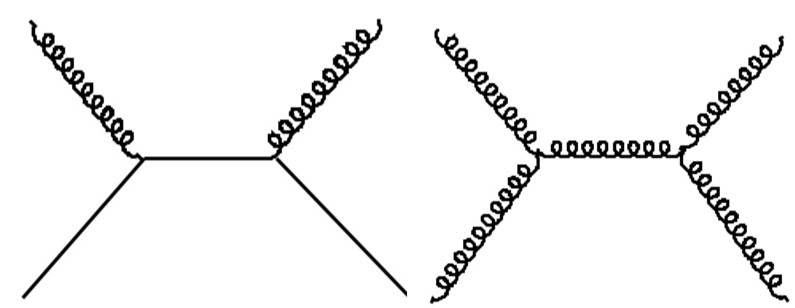
While there is a prediction that gluon content of kaon at hadronic scale is ~1/6 in respect to pion.

quarkonia production



prompt photons





jet production

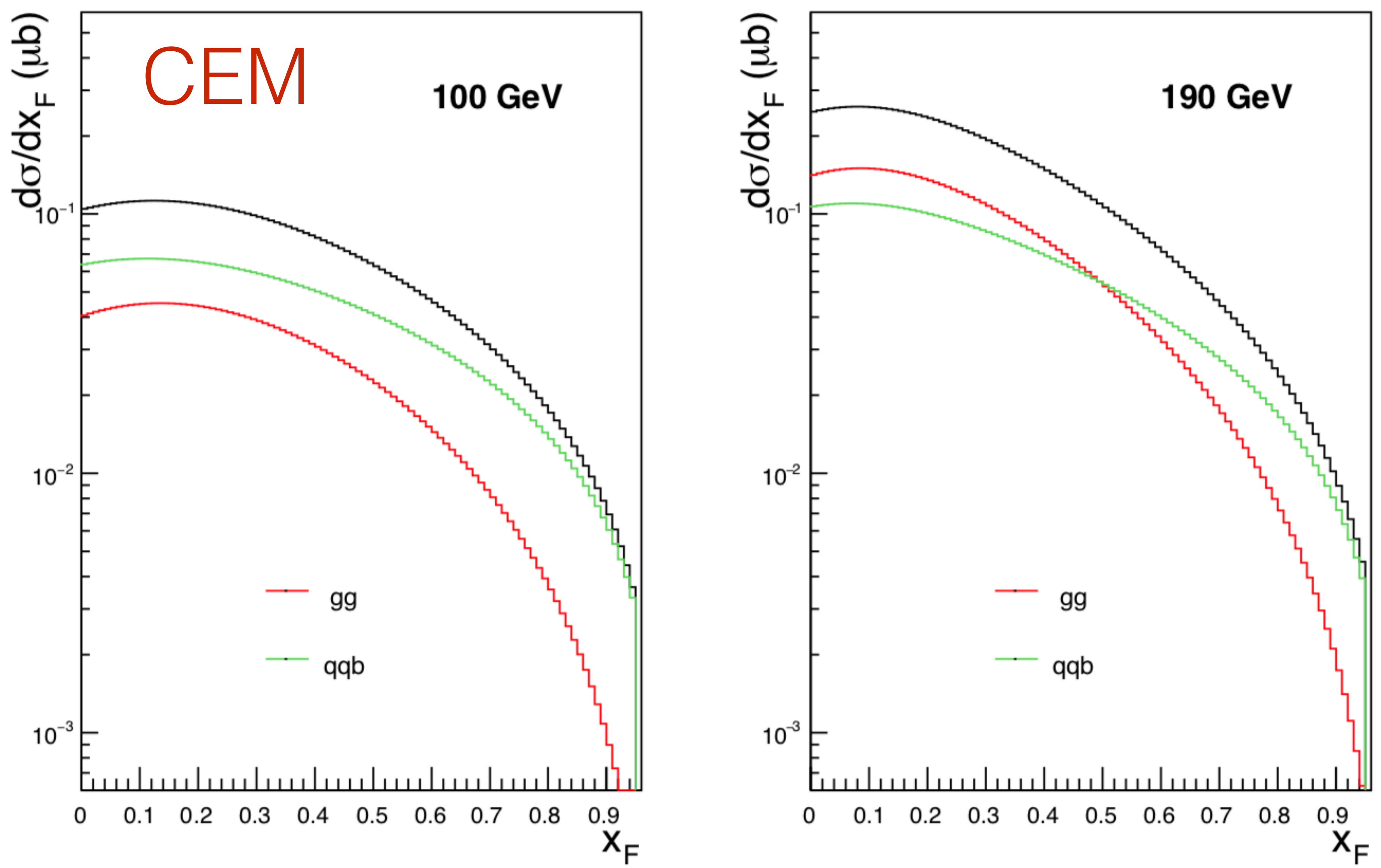
Complimentary approaches!

Gluon content & J/ψ

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

gg→J/ψ+…

$q\bar{q}$→J/ψ+…



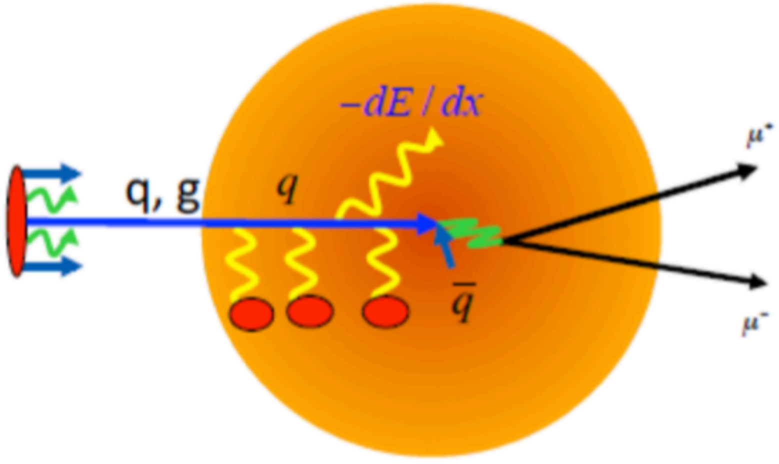
Model-dependent separation of gg and $q\bar{q}$ contributions using data collected with both positive and negative beams for pion.

Nuclear effects in DY

Energy loss:

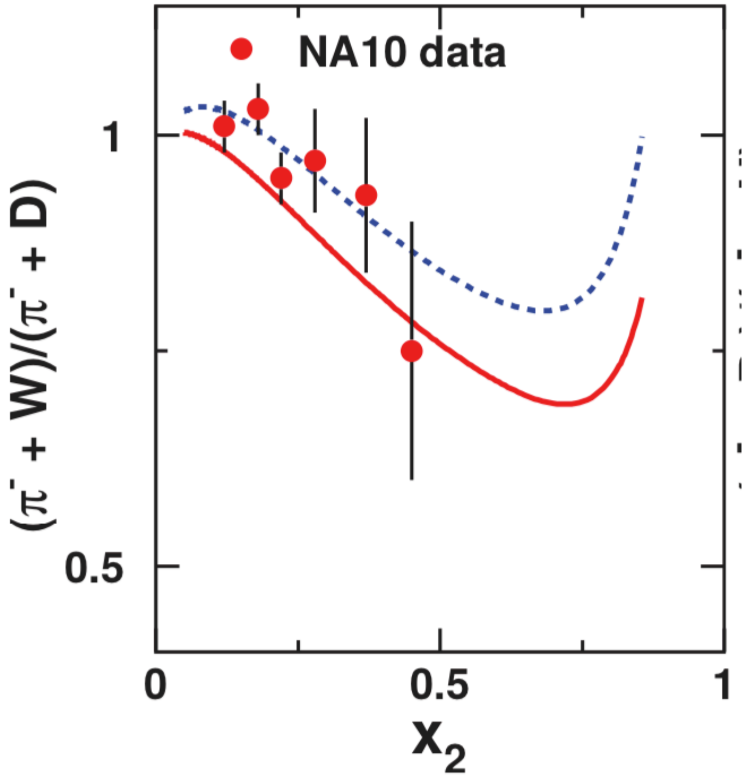
- Multiple scattering of incoming quark in large nuclei
- No energy loss in the final state

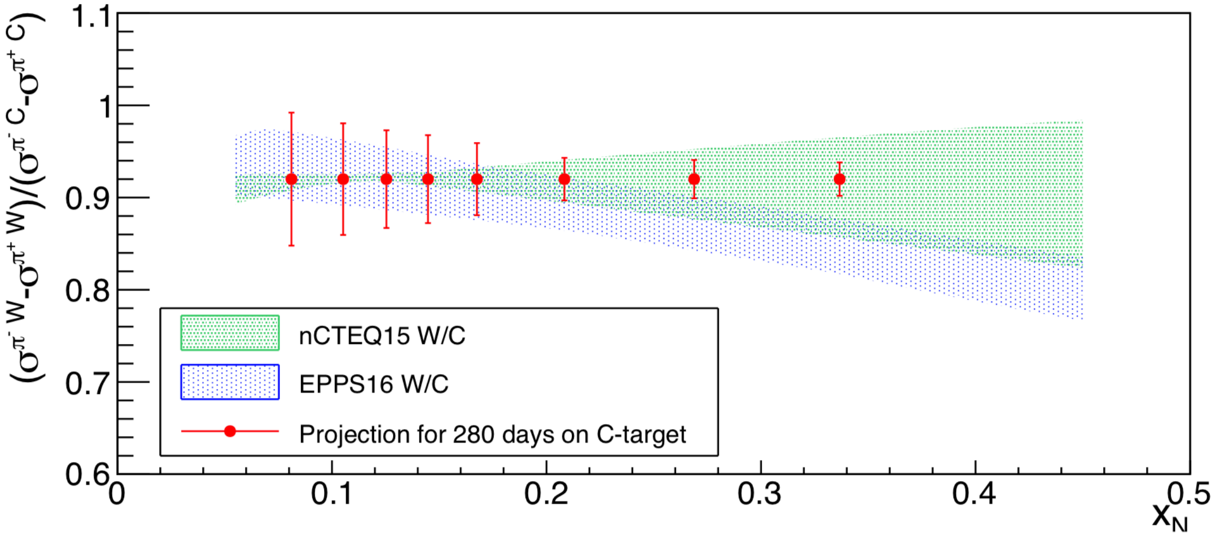
→ Comparison between DY and J/ψ complementary information

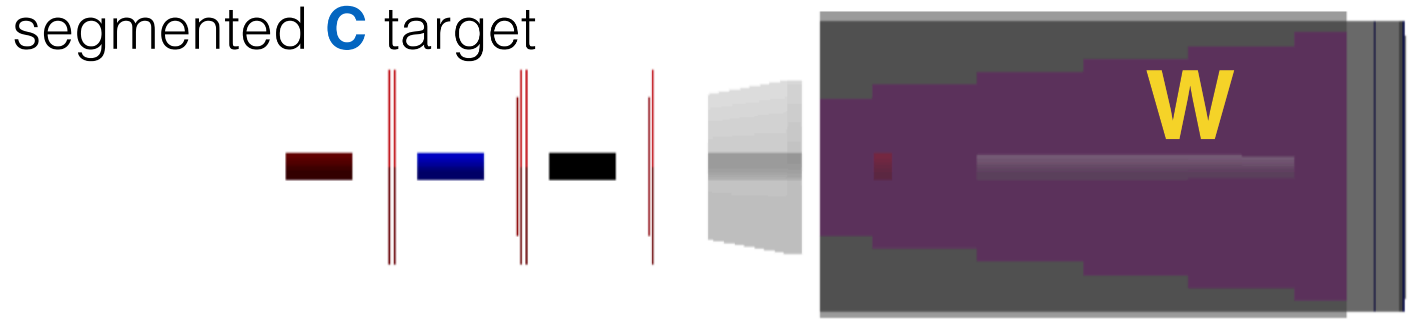


Flavour dependent EMC effect: Meson induced Drell-Yan process tags flavours

Using two π beam charges and two targets, one can add constraints on the EMC flavour dependence



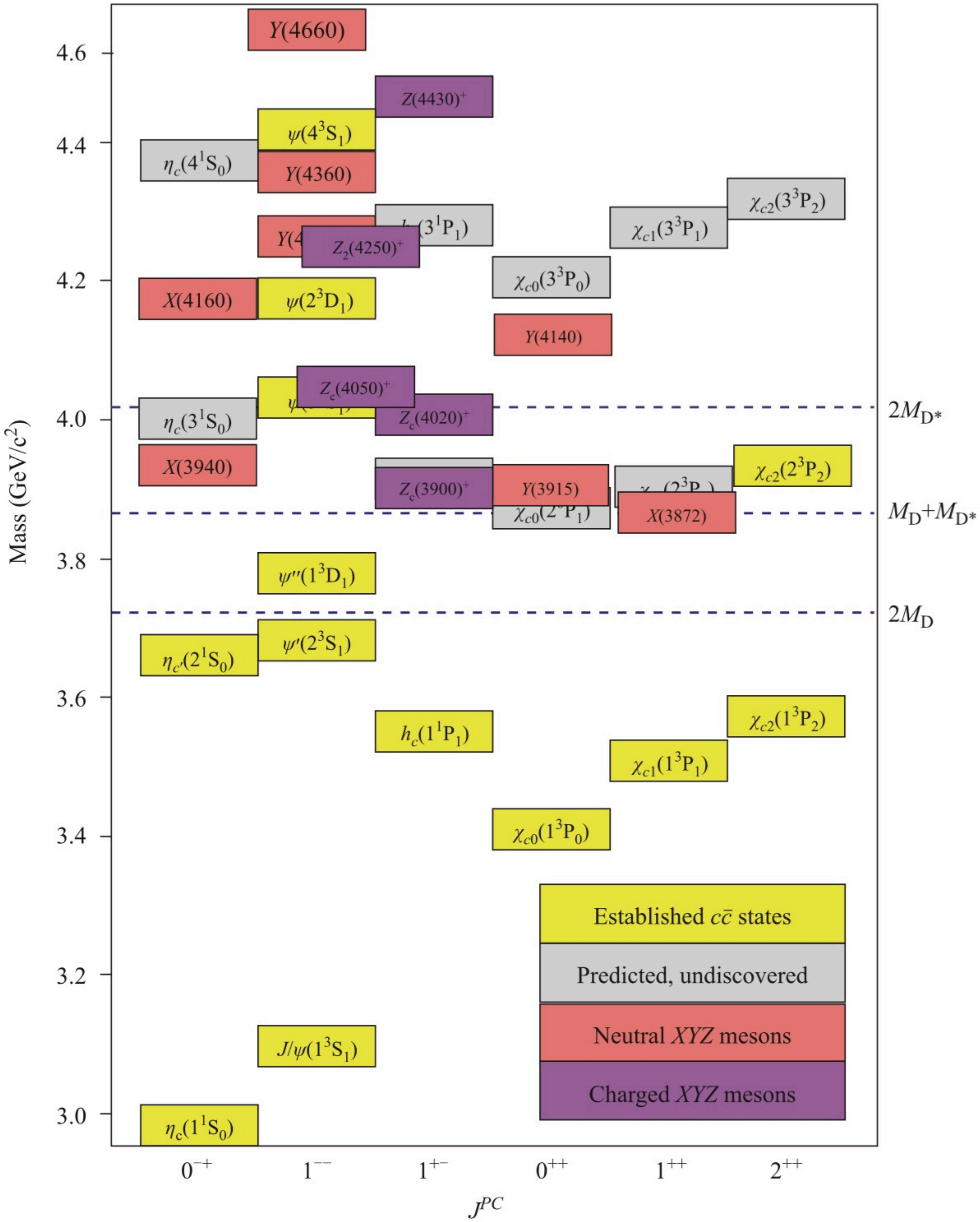


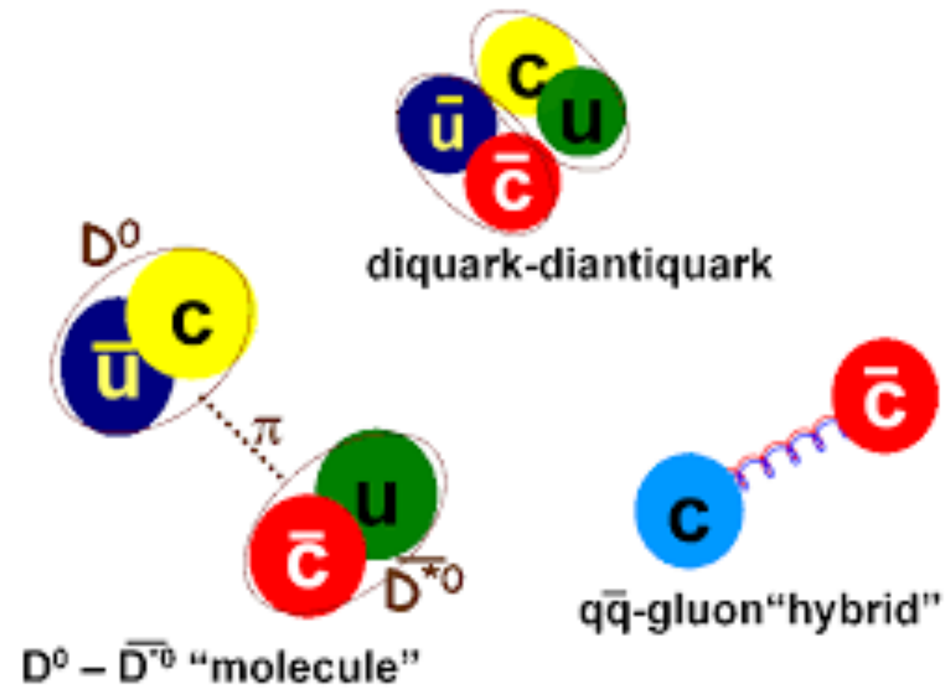


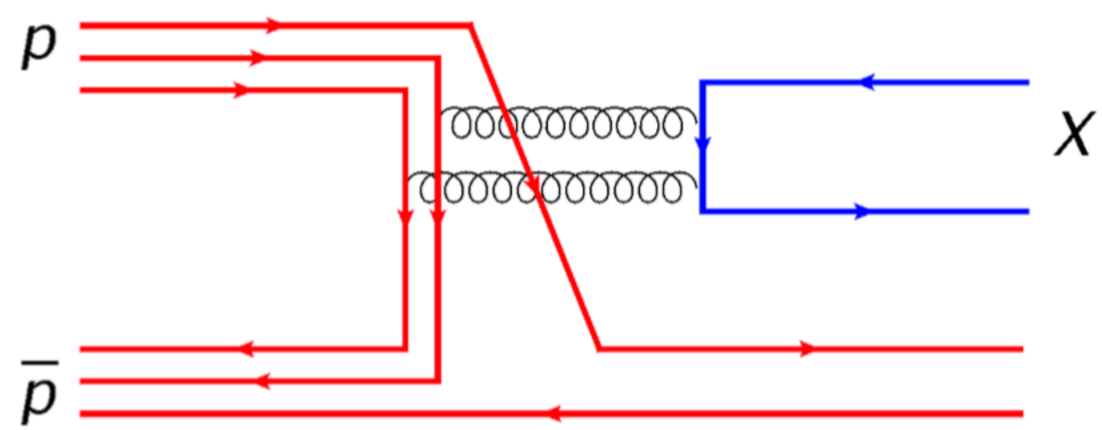
Spectroscopy with low-energy antiproton beam

Competitors: PANDA

Charmonia







Wide spectrum of quantum numbers!

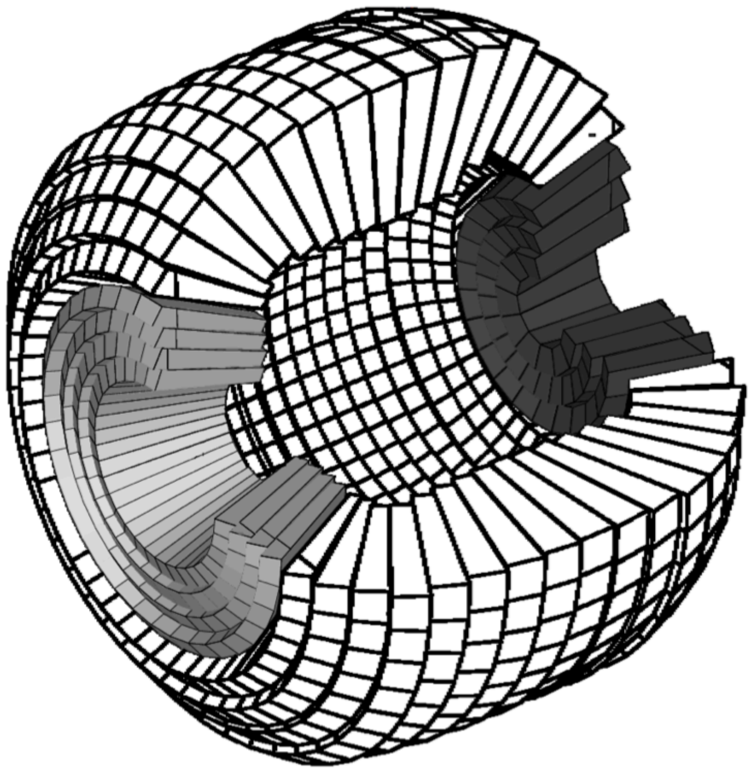
Charmonia at AMBER

12 and 20 GeV/c antiproton beam
40—100 cm LH_2 target

$$p\bar{p} \to \pi^- Z_c^+(4430), \text{ with } Z_c^+ \to \pi^+ J/\psi,$$

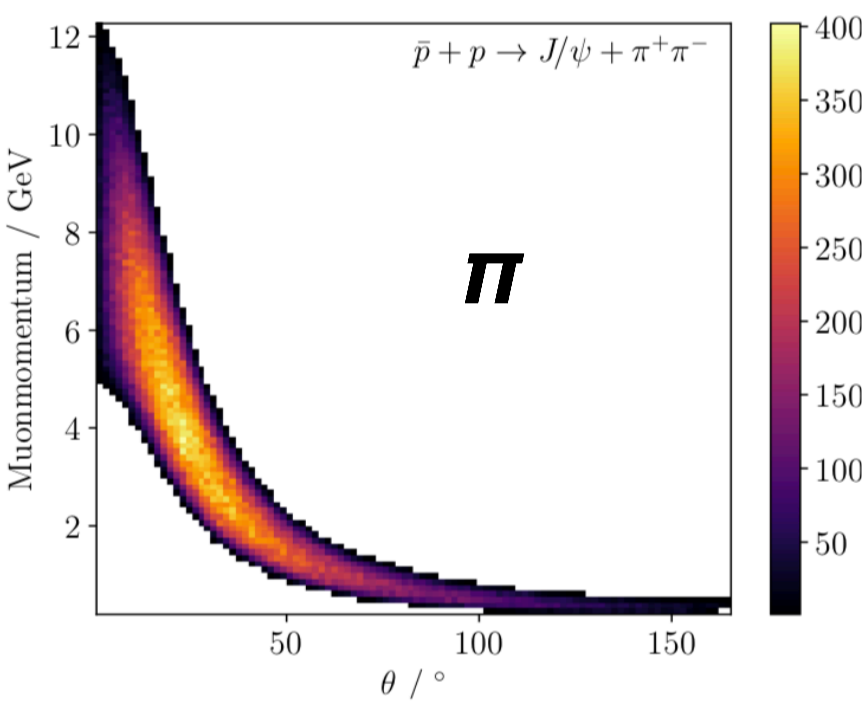
$$p\bar{p} \to \pi^0 Z_c^0(4430), \text{ with } Z_c^0 \to \pi^0 J/\psi,$$

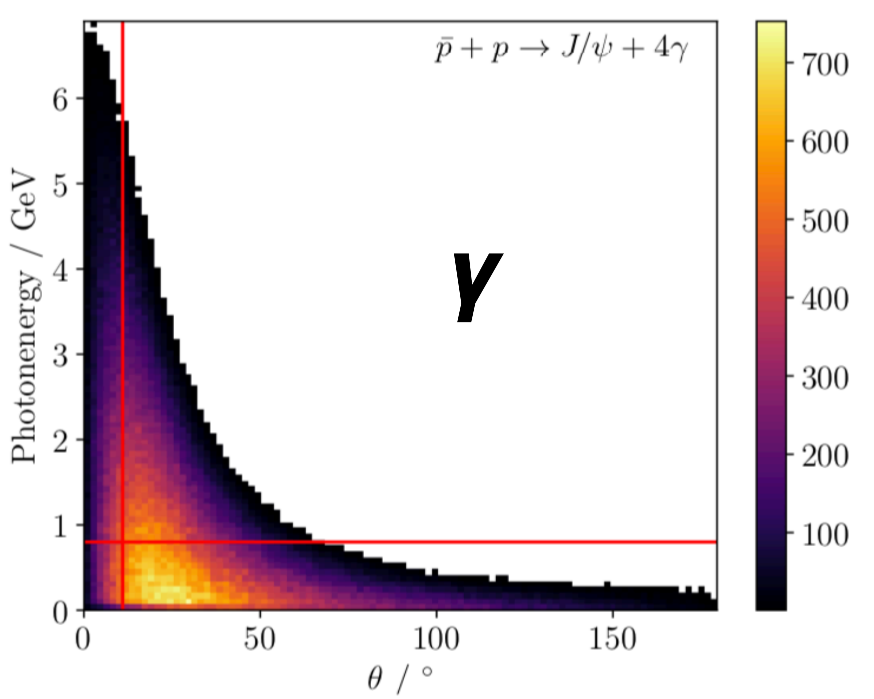
$$p\bar{p} \to \eta h(4300), \text{ with } h \to \pi^0 \pi^0 J/\psi$$

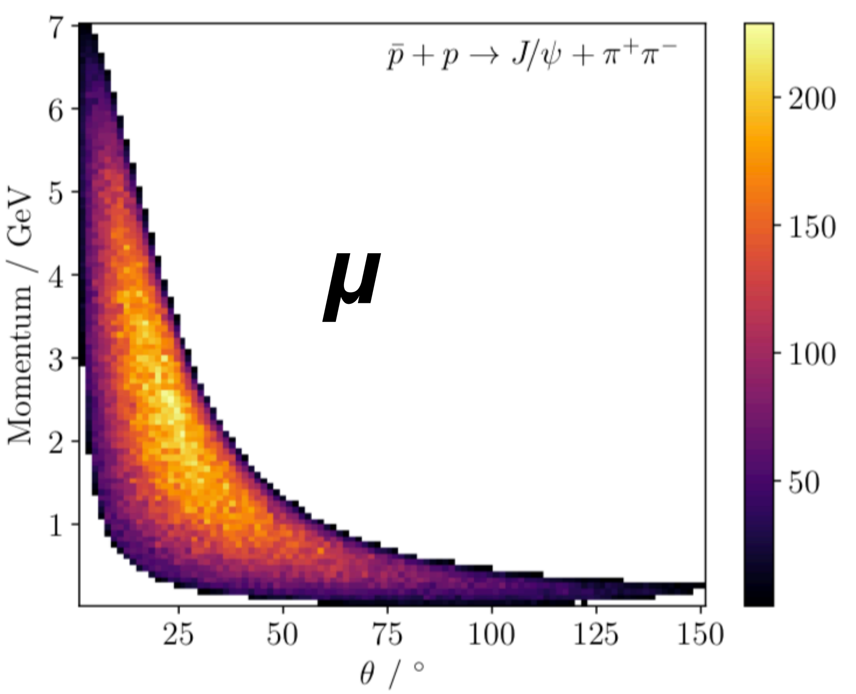


Calorimeter WASA (COSY)

Up to 7000 J/ψ→ μμ decays after 1 year of data taking

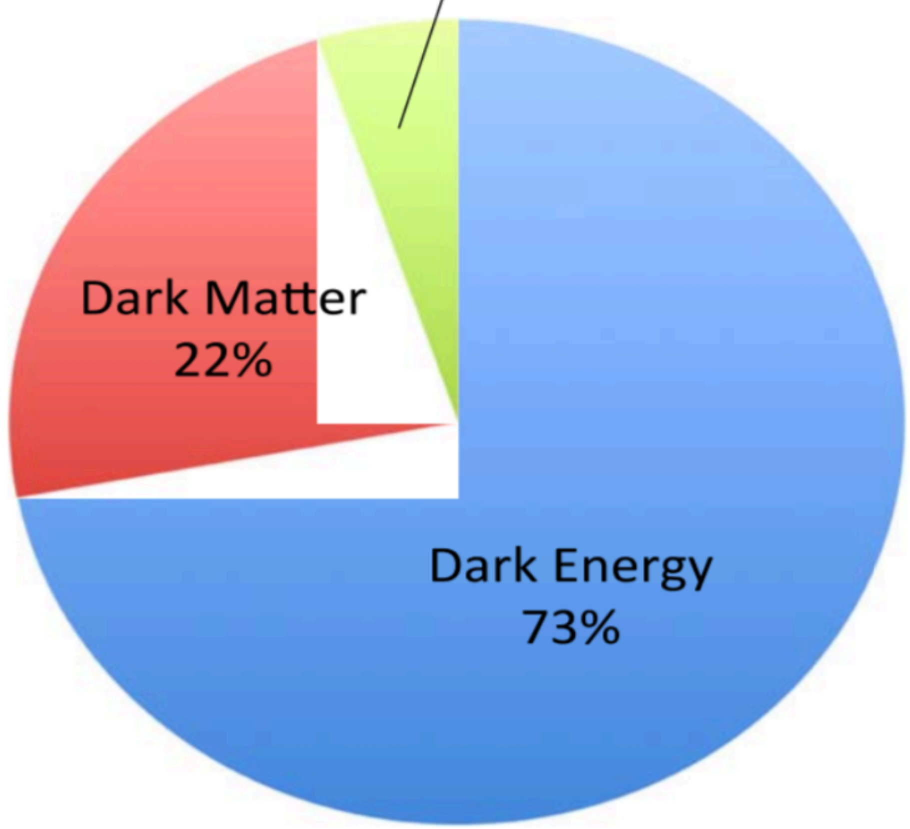


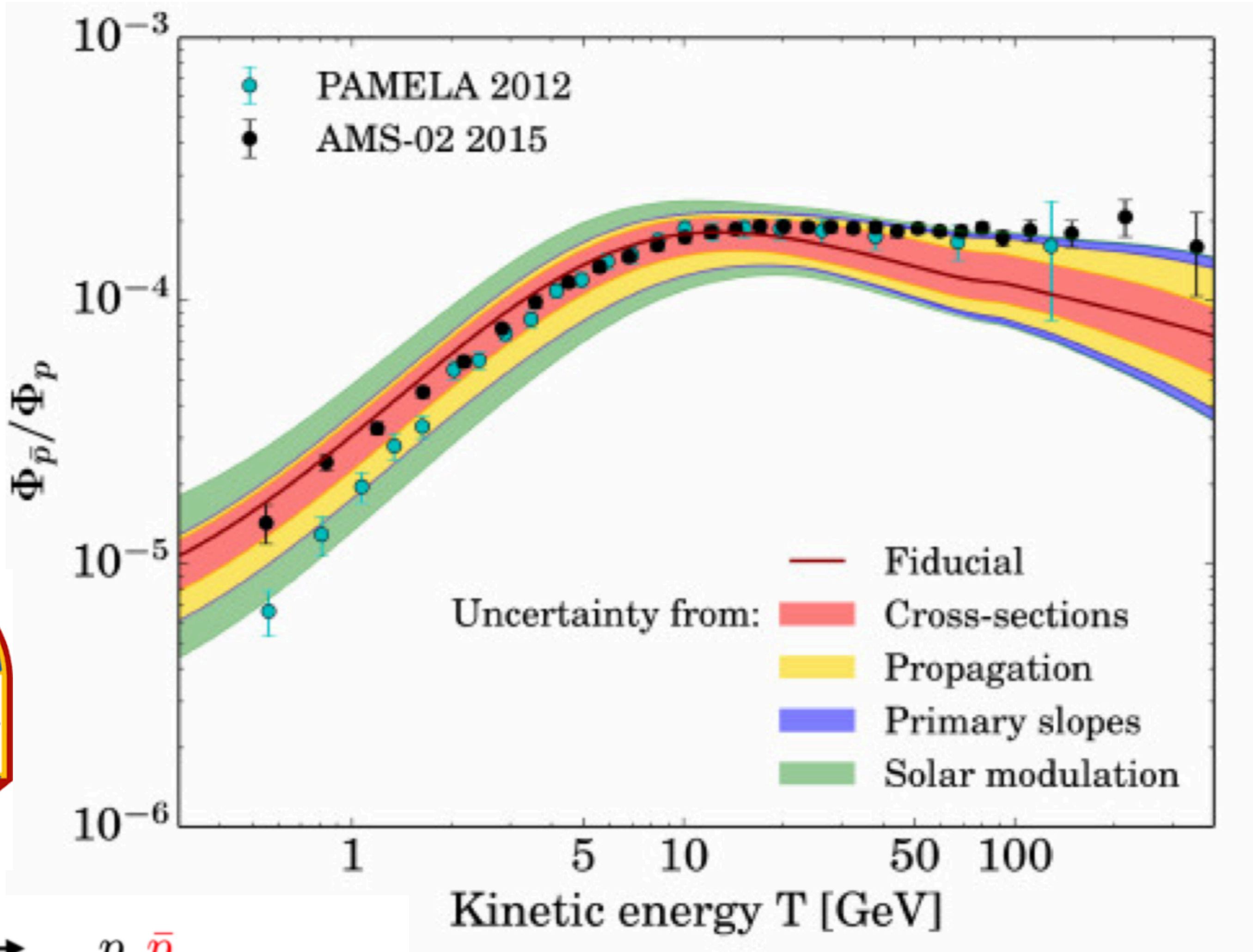


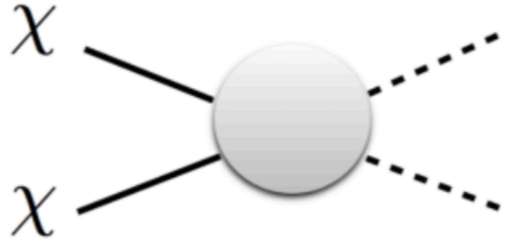


Measurement of antiproton production cross section for dark matter search

Physics case







$W^-, Z, b, \tau^-, t, h, \ldots \longrightarrow p, \bar{p}, \ldots$

annihilation channel — decay — final products

$W^+, Z, \bar{b}, \tau^+, \bar{t}, h, \ldots \longrightarrow p, \bar{p}, \ldots$

But the most of antiprotons are produced in interaction of primary CR with interstellar matter

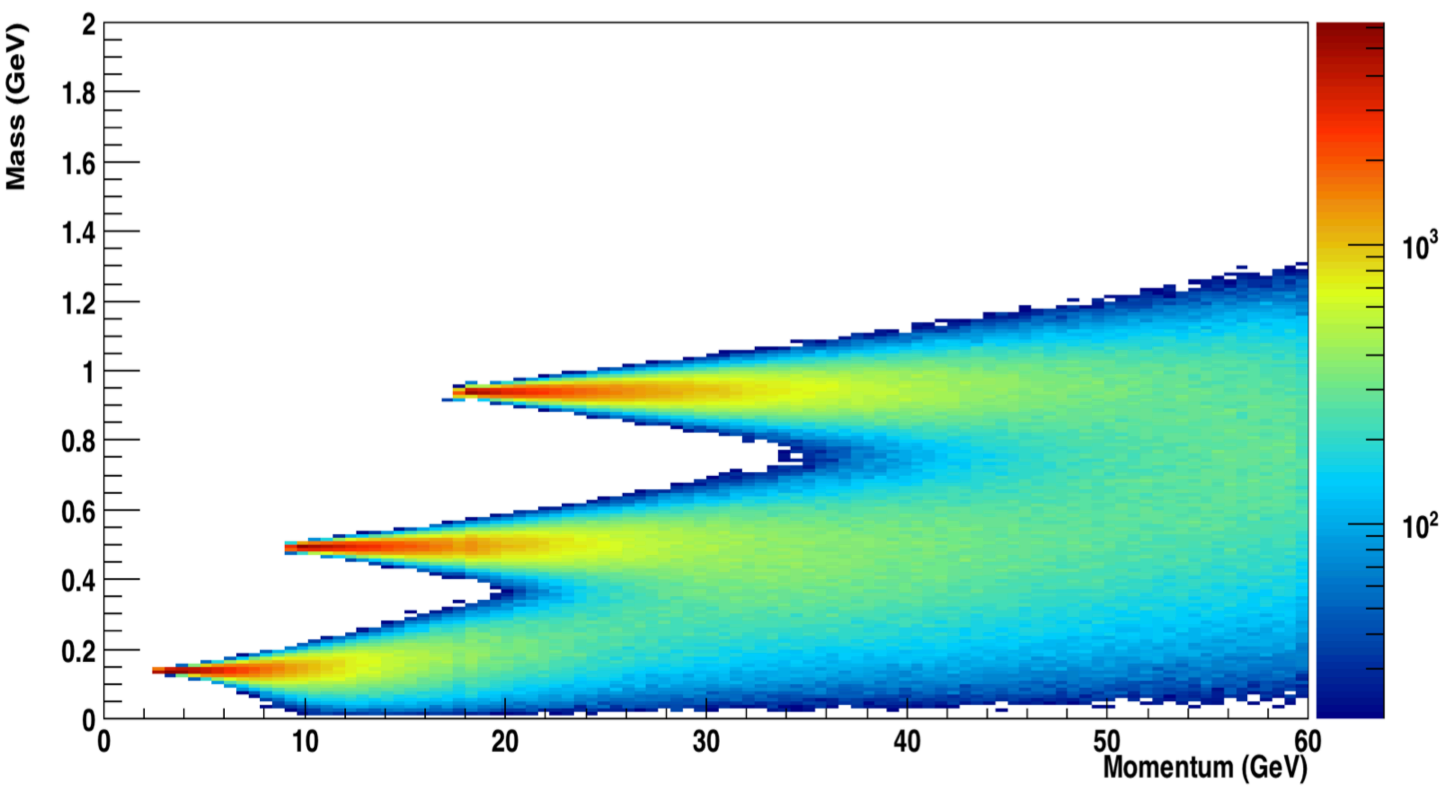
$$\begin{cases} p + H \to \bar{p} + X & \sim 70\% \\ \alpha + H \to \bar{p} + X & \sim 25\% \\ p + He \to \bar{p} + X & \sim 4\% \\ \alpha + He \to \bar{p} + X & \sim 1\% \end{cases}$$

Antiproton production

Existing data for antiproton production in p-p collisions

Experiment	$\sqrt{s}$ (GeV)	P_T (GeV)	x_R
Dekkers *et al.*, CERN 1965	6.1, 6.7	(0.00, 0.79)	(0.34, 0.65)
Allaby *et al.*, CERN 1970	6.15	(0.05, 0.90)	(0.40, 0.94)
Capiluppi *et al.*, CERN 1974	23.3, 30.6, 44.6, 53.0, 62.7	(0.18, 1.29)	(0.06, 0.43)
Guettler *et al.*, CERN 1976	23.0, 31.0, 45.0, 53.0, 63.0	(0.12, 0.47)	(0.036, 0.092)
Johnson *et al.*, FNAL 1978	19.4, 23.8, 27.4	(0.77, 6.15)	(0.08, 0.58)
Antreasyan *et al.*, FNAL 1979	23.0, 31.0, 45.0, 53.0, 63.0	(0.12, 0.47)	(0.036, 0.092)
BRAHMS, BNL 2008	200	(0.82, 3.97)	(0.11, 0.39)
NA49, CERN 2010	17.3	(0.10, 1.50)	(0.11, 0.44)
NA61, CERN 2017	6.3, 7.7, 8.8, 12.3, 17.3	—	—

Plans: p-He LHCb 86.7, 114.7 $2 < \eta < 5$

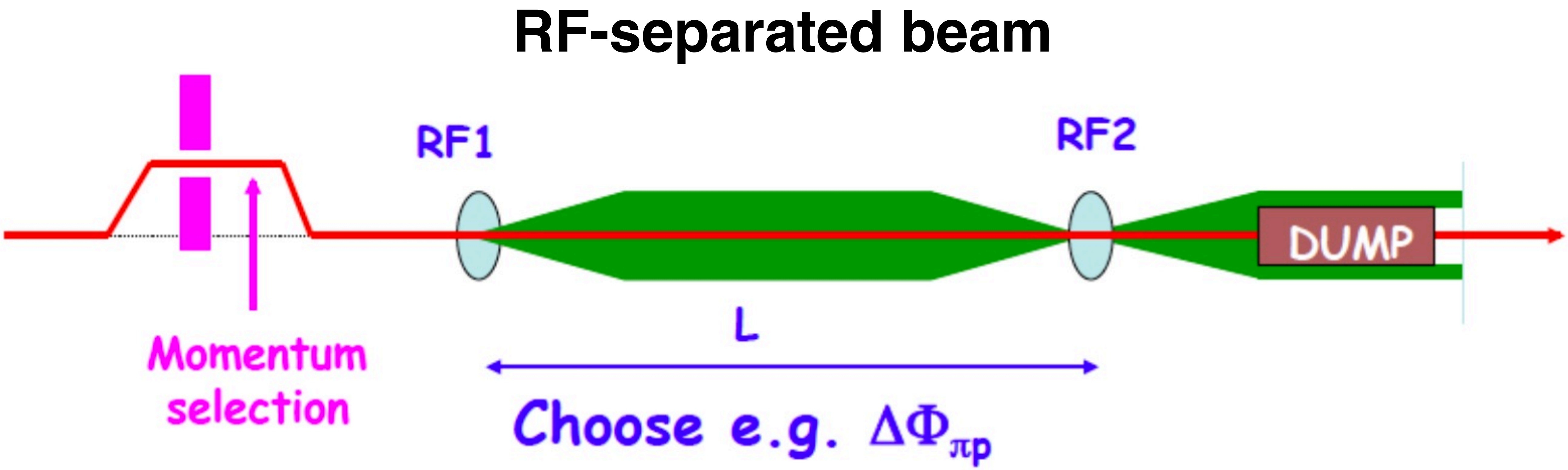


	pbar(18-45 GeV/c)	pbar (5-18 GeV/c)
p-p @ 0-280GeV/c	OK 2009 data @190GeV	RICH veto or RICH0
p-He @0-280GeV/c	new LHe target	RICH veto or RICH0

Also $\bar{p}$ from Λ and Σ decays

RF-separated hadron beam

RF-separated hadron beam



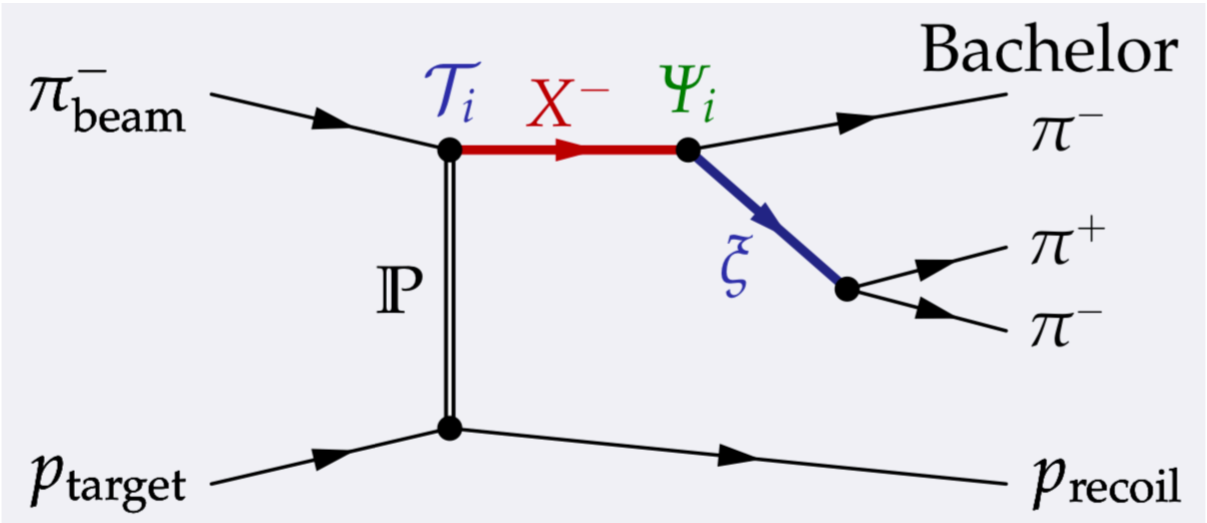
up to ~3×10^7 s^{-1} for antiprotons and kaons

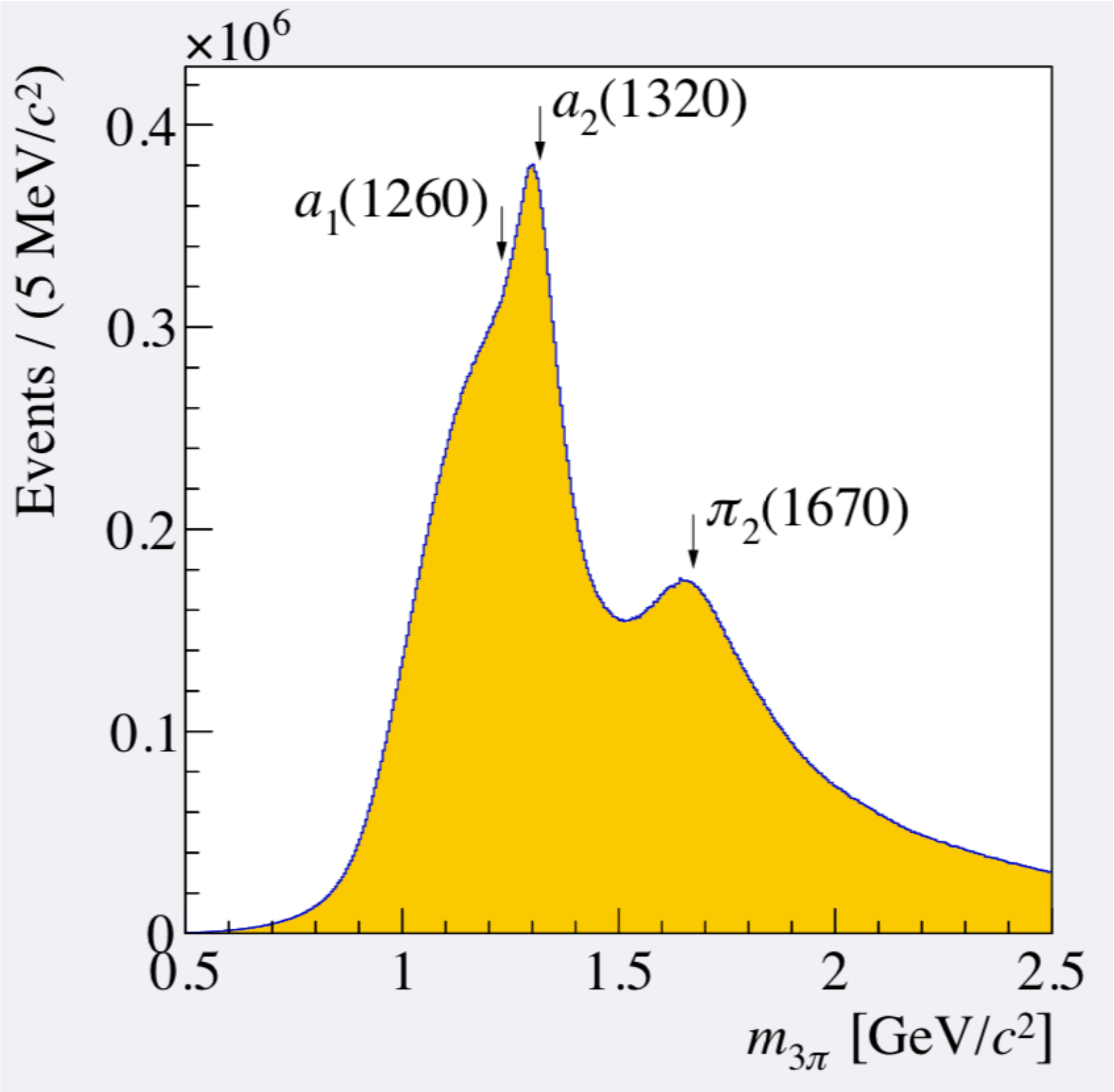
~80 GeV for kaons
~110 GeV for antiprotons

Spectroscopy of kaons

Competitors: GlueX, J-Parc

COMPASS with pions

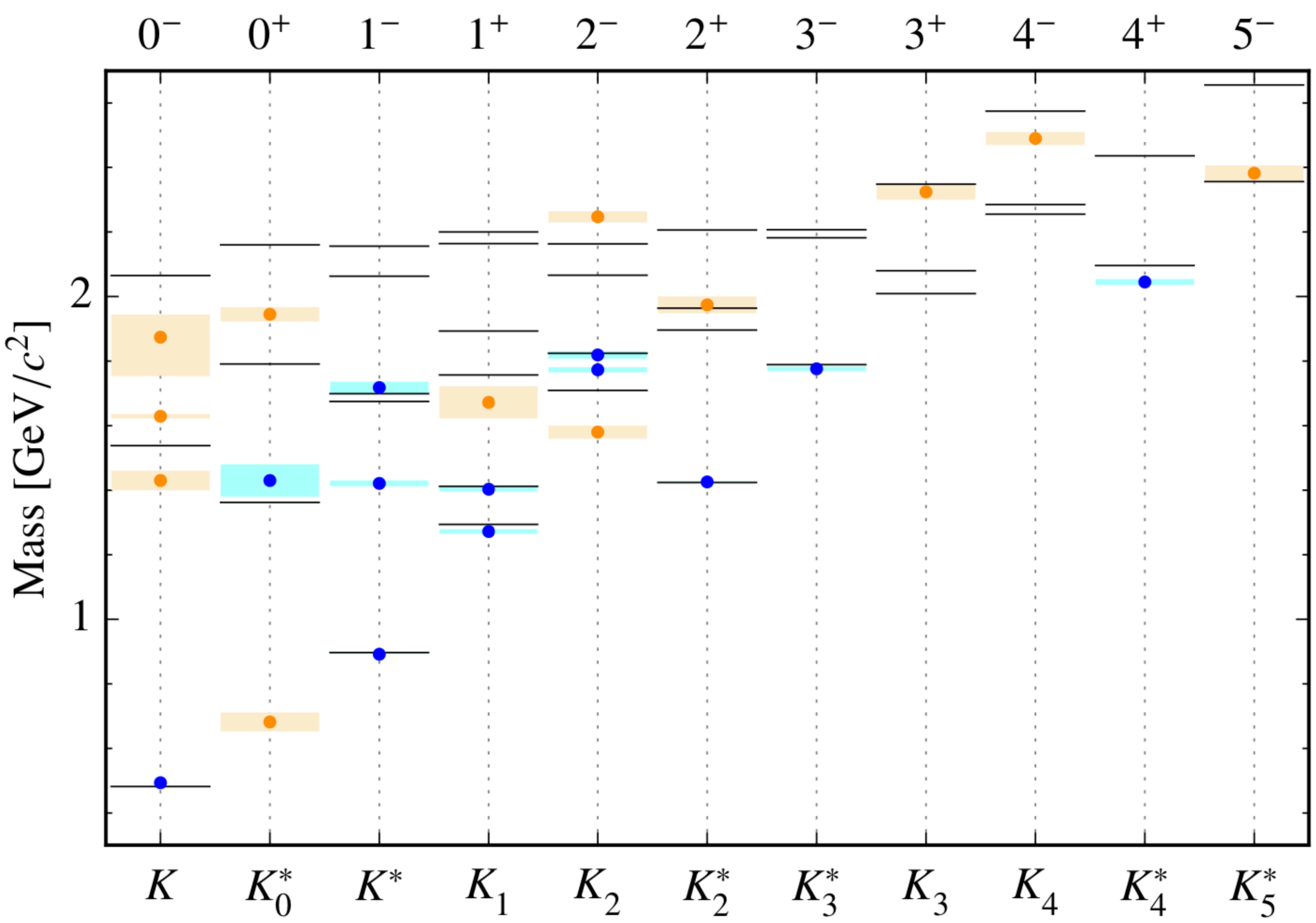


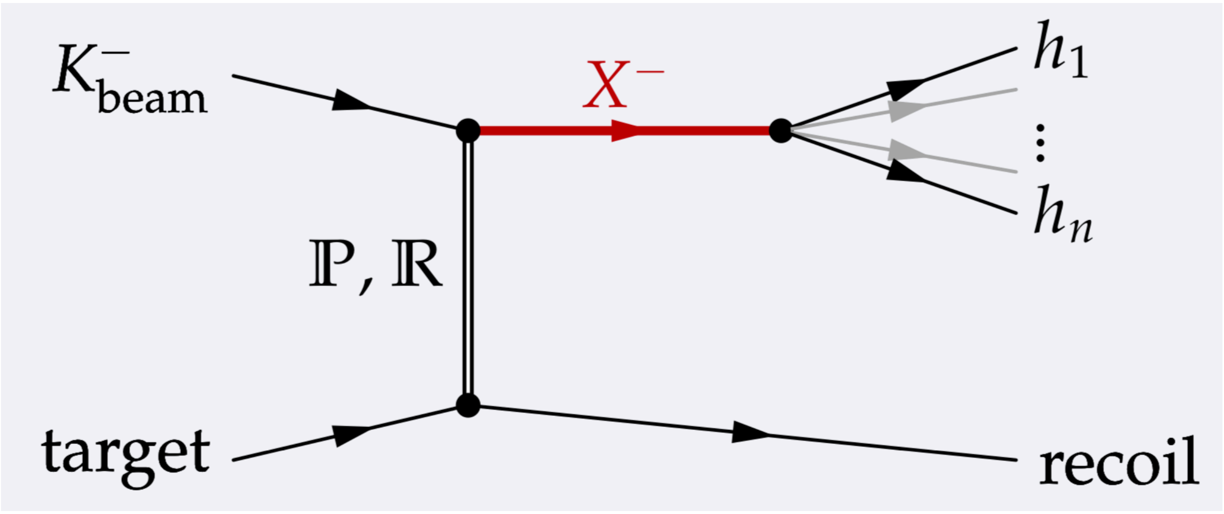


World largest sample:
46×10^6 $\pi^-\pi^+\pi^-$ events

Sophisticated PWA: 87 partial waves, J and L up to 6

Kaon spectroscopy





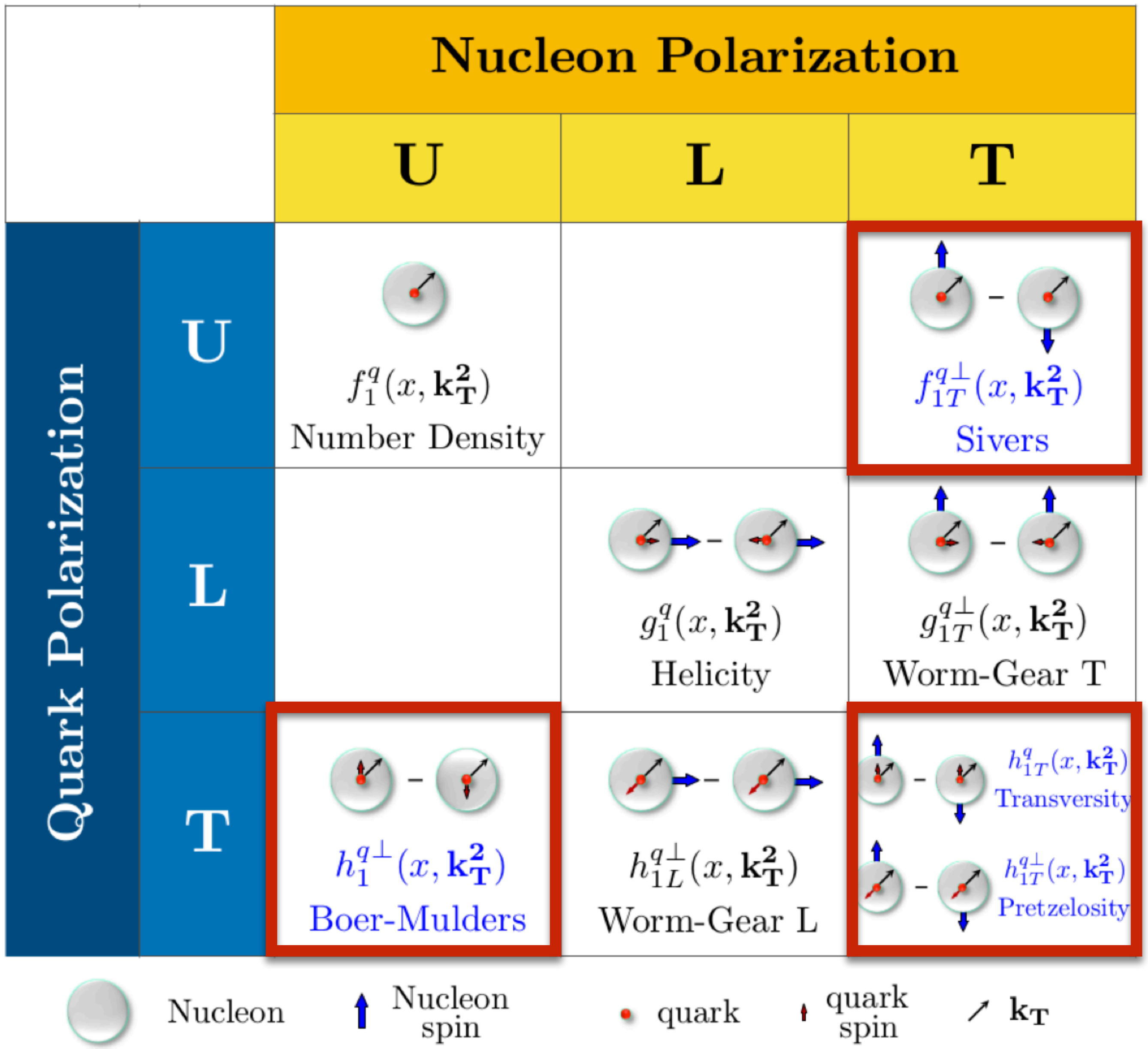
- Most PDG entries more than 30 years old
- Since 1990 only 4 kaon states added to PDG

We intend to rewrite completely the kaon section of PDG

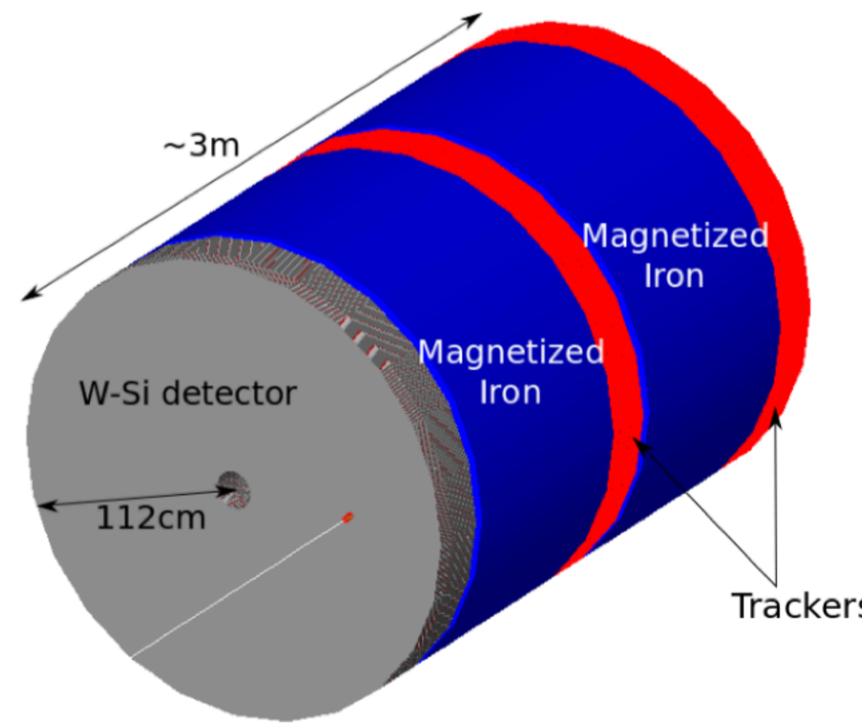
Drell-Yan and charmonium production using kaon and antiproton beams

Competitors:

Spin physics with antiproton beam



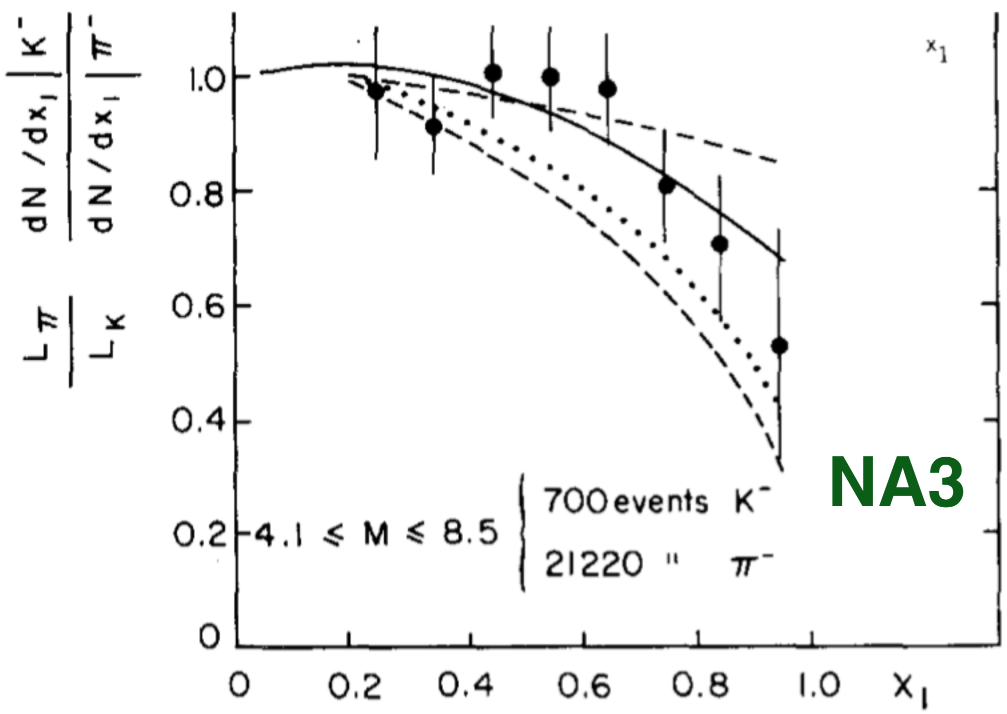
Antiproton beam and transversely polarised NH_3 target

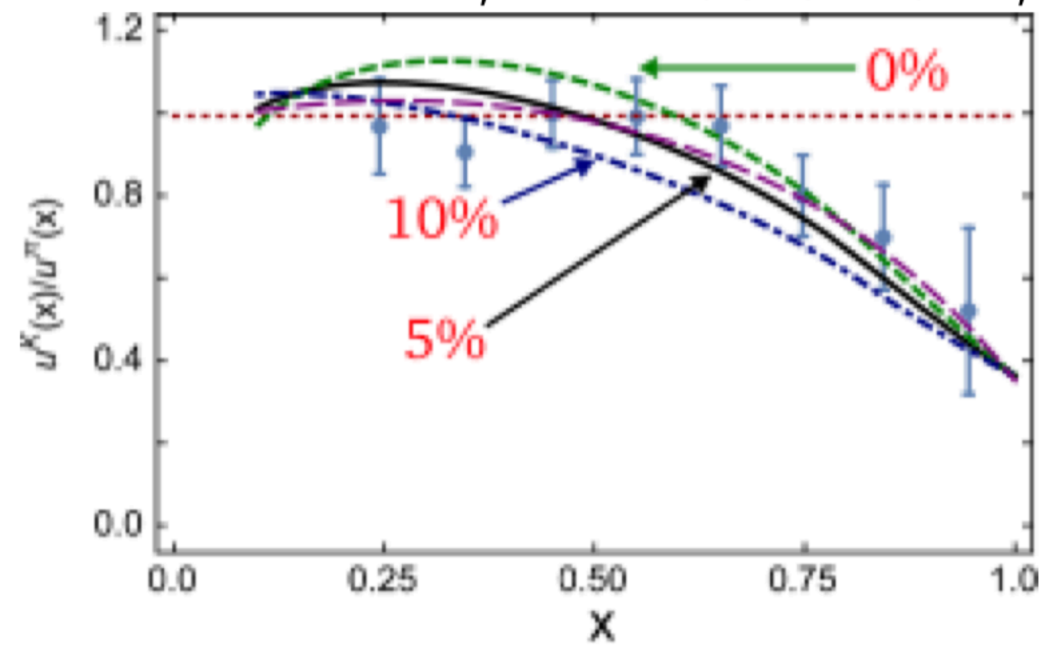


Active absorber

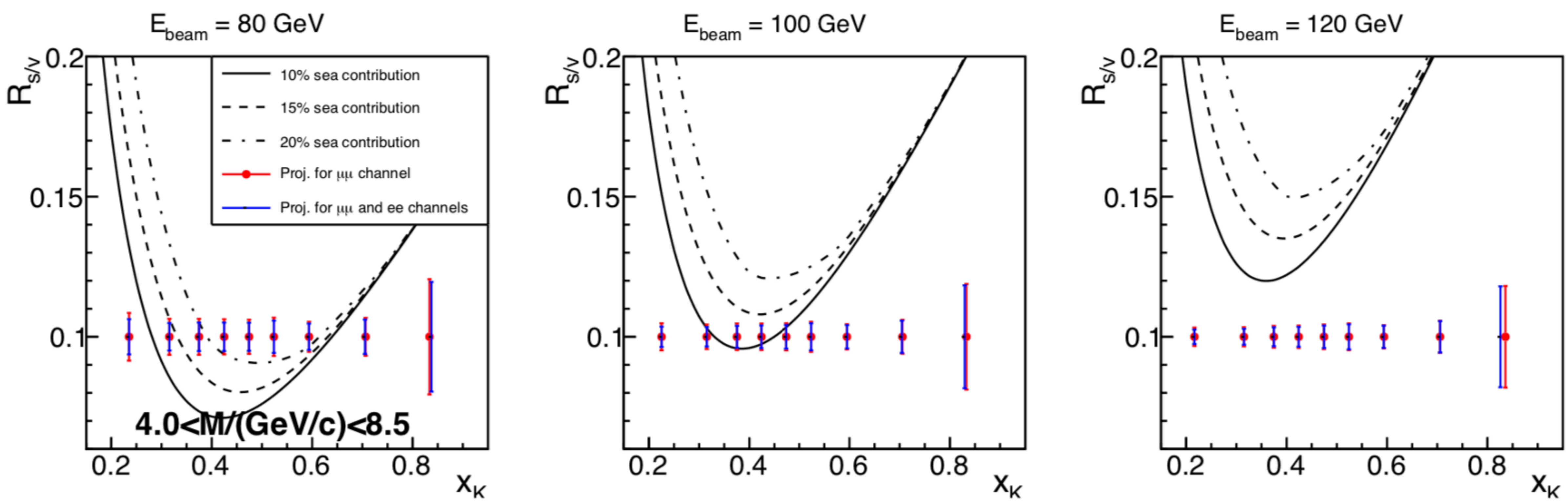
Experiment	Target type	Beam type	Beam intensity (part/sec)	Beam energy (GeV)	DY mass (GeV/c^2)	DY events $\mu^+\mu^-$	DY events e^+e^-
This exp.	110cm NH_3	$\bar{p}$	3.5×10^7	100	4.0 – 8.5	28,000	21,000
				120	4.0 – 8.5	40,000	27,300
				140	4.0 – 8.5	52,000	32,500

Sea/valence in kaon

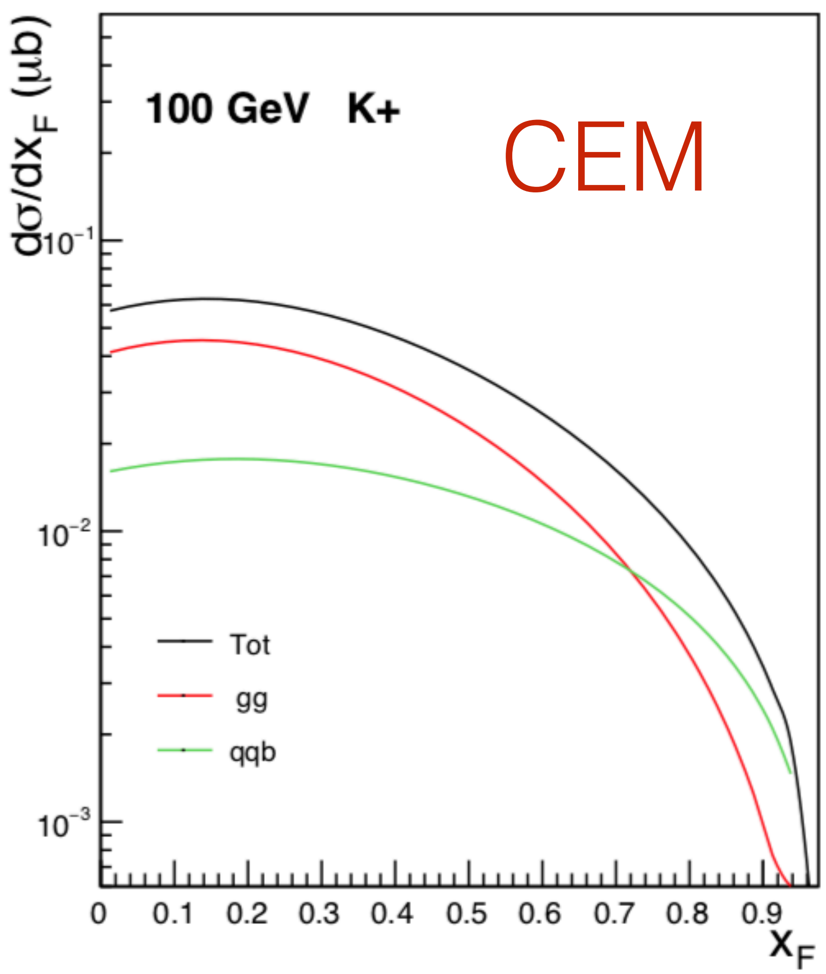


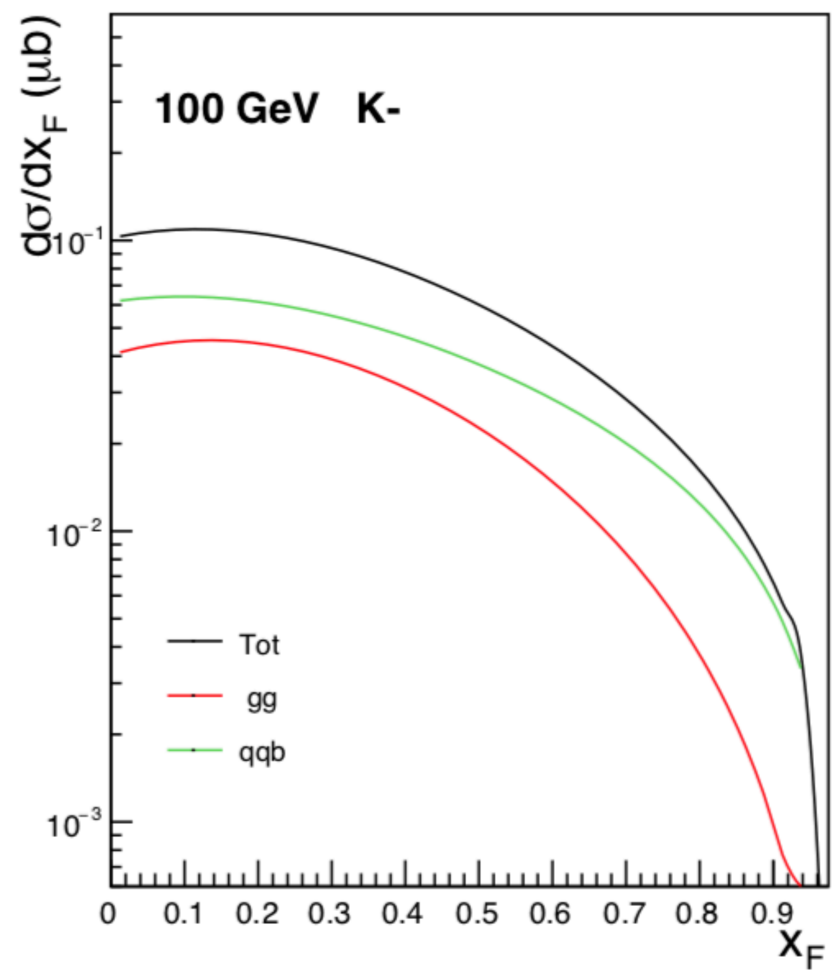


Poor knowledge of kaon valence PDFs, no info about sea



Gluon content & J/ψ





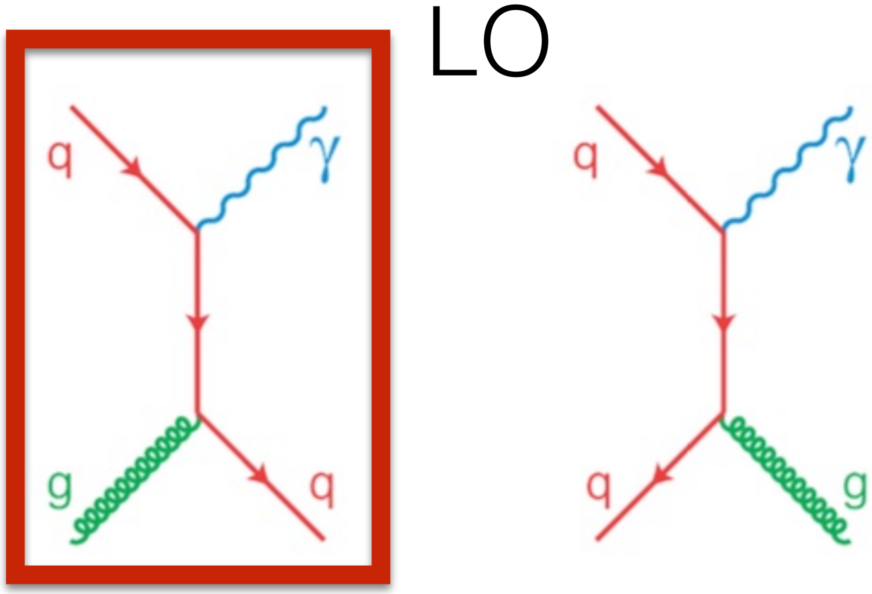
$$\sigma_{J/\psi}^{K^-} - \sigma_{J/\psi}^{K^+} \propto \bar{u}^{K^-} u^N$$

Study of gluon content of kaons with prompt photons

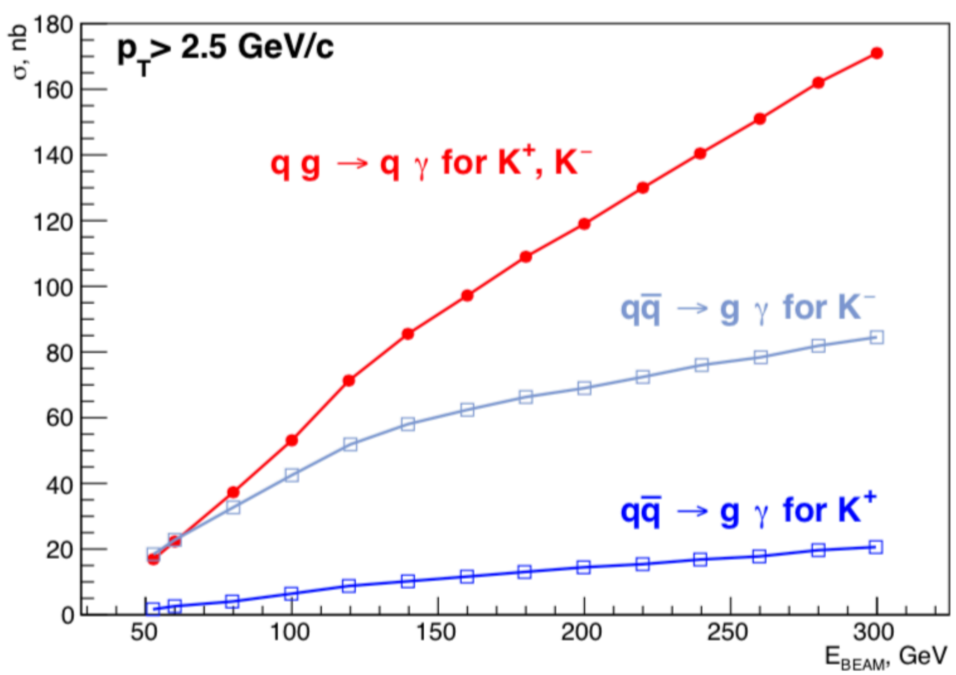
Competitors: COMPASS++/AMBER in J/ψ production

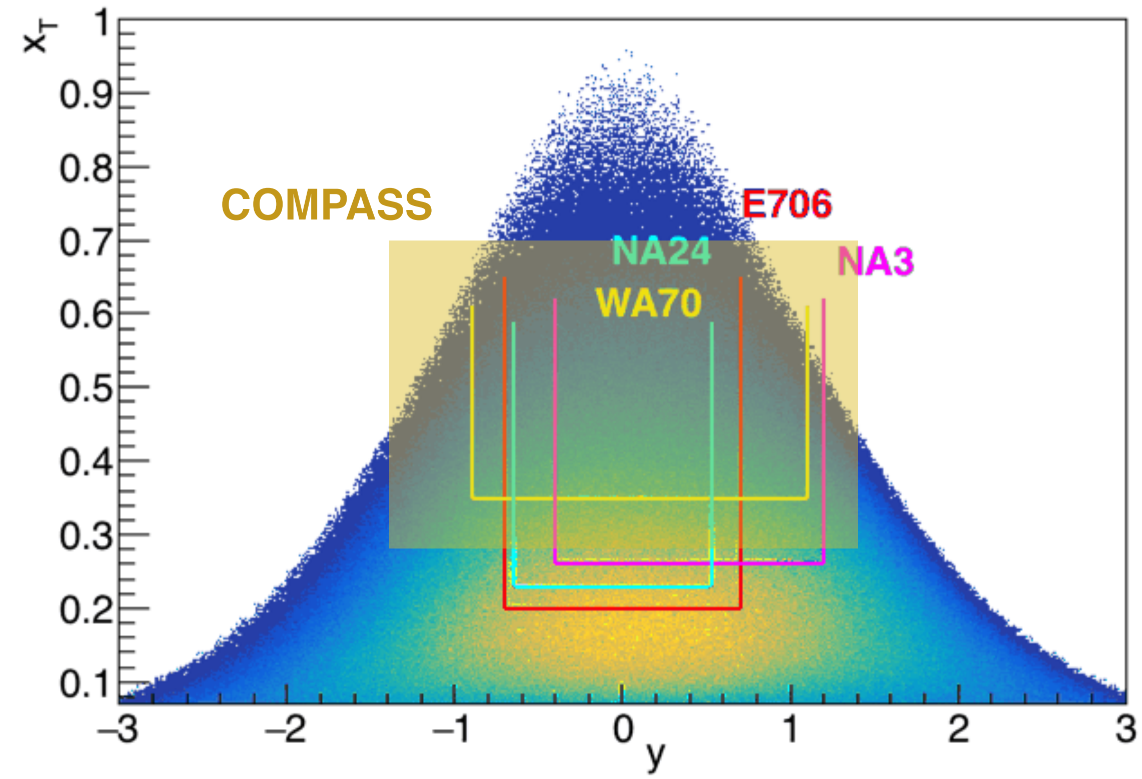
Gluon PDFs: prompt γ

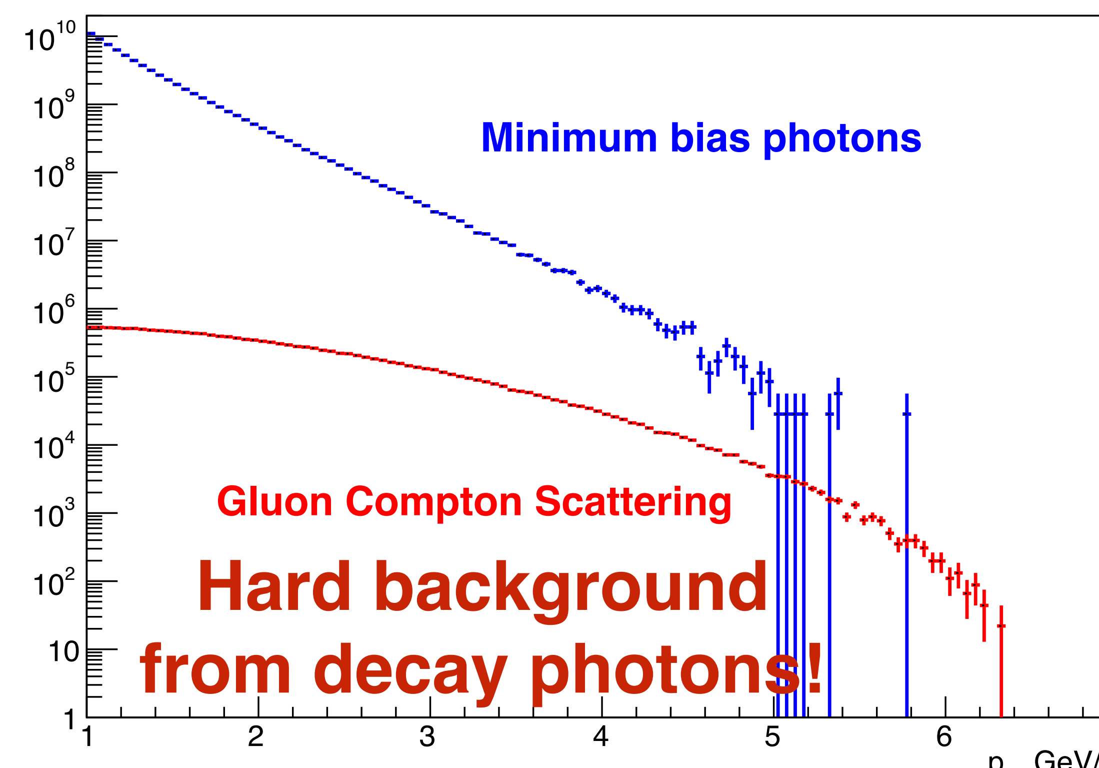
LO



$$d\sigma_{AB} = \sum_{a,b=q,\bar{q},g} \int dx_a dx_b f_a^A(x_a,\mu^2) f_b^B(x_b,\mu^2) d\sigma_{ab\to\gamma X}(x_a,x_b,\mu^2).$$

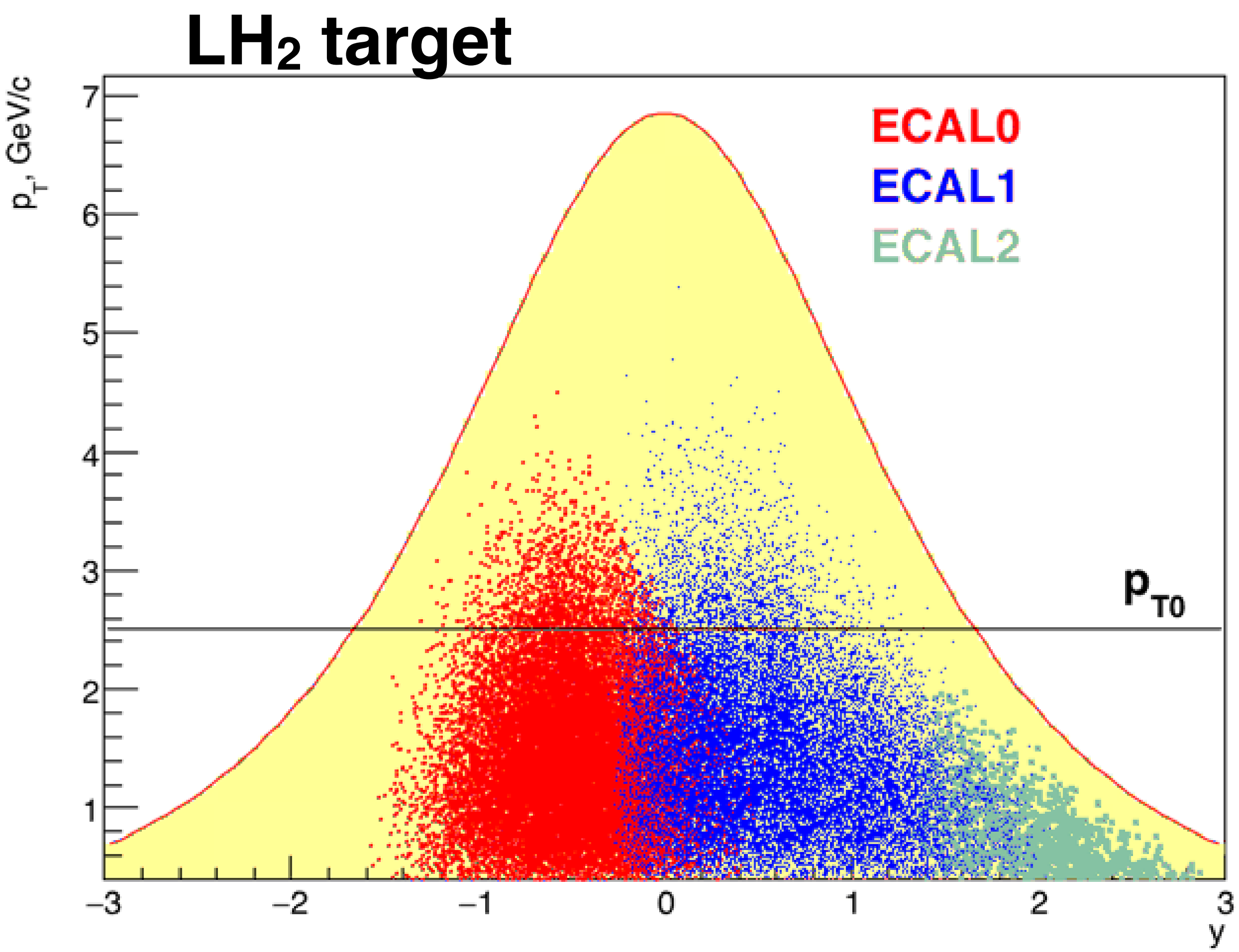




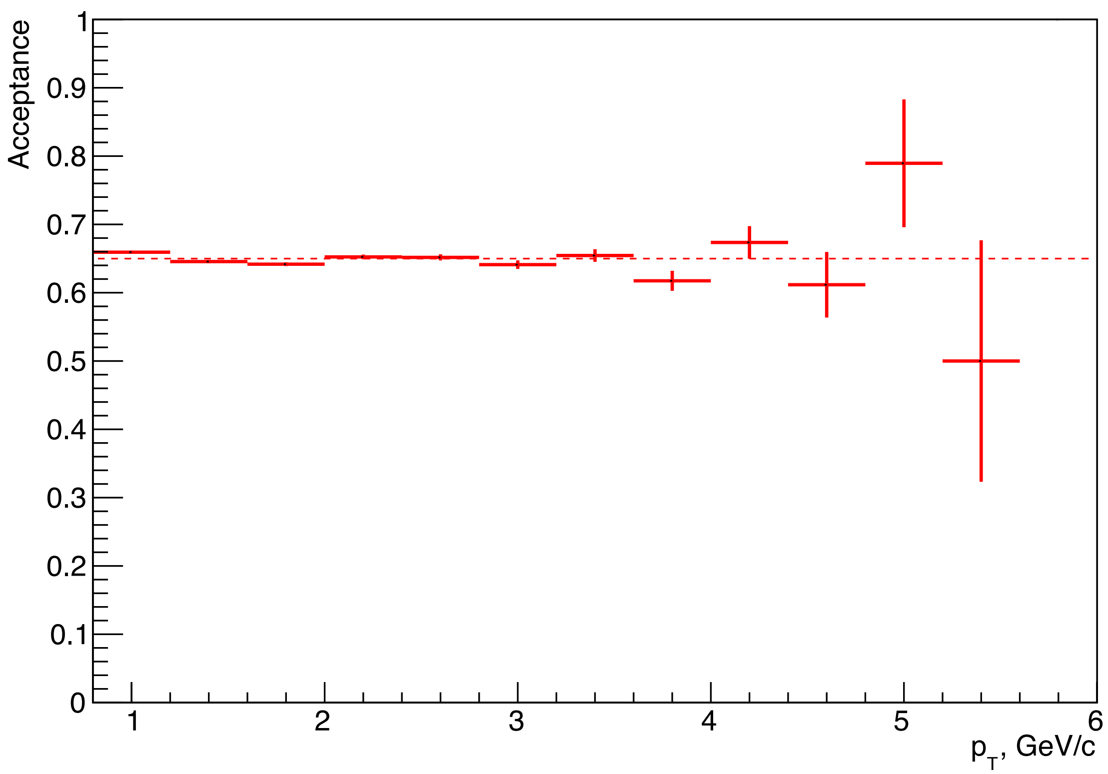


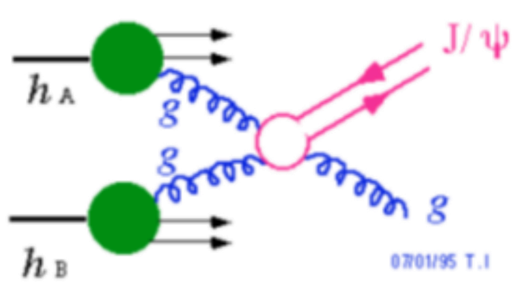
K+ for main sample, K−,π+,π− for reference and systematic studies.

Gluon PDFs: prompt γ

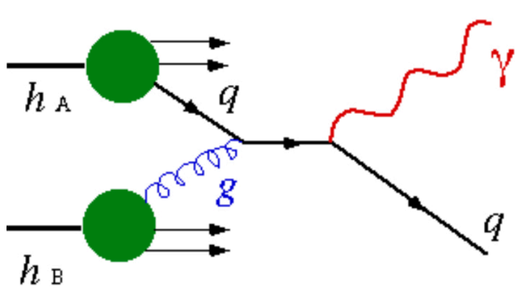


Flat acceptance in p_T





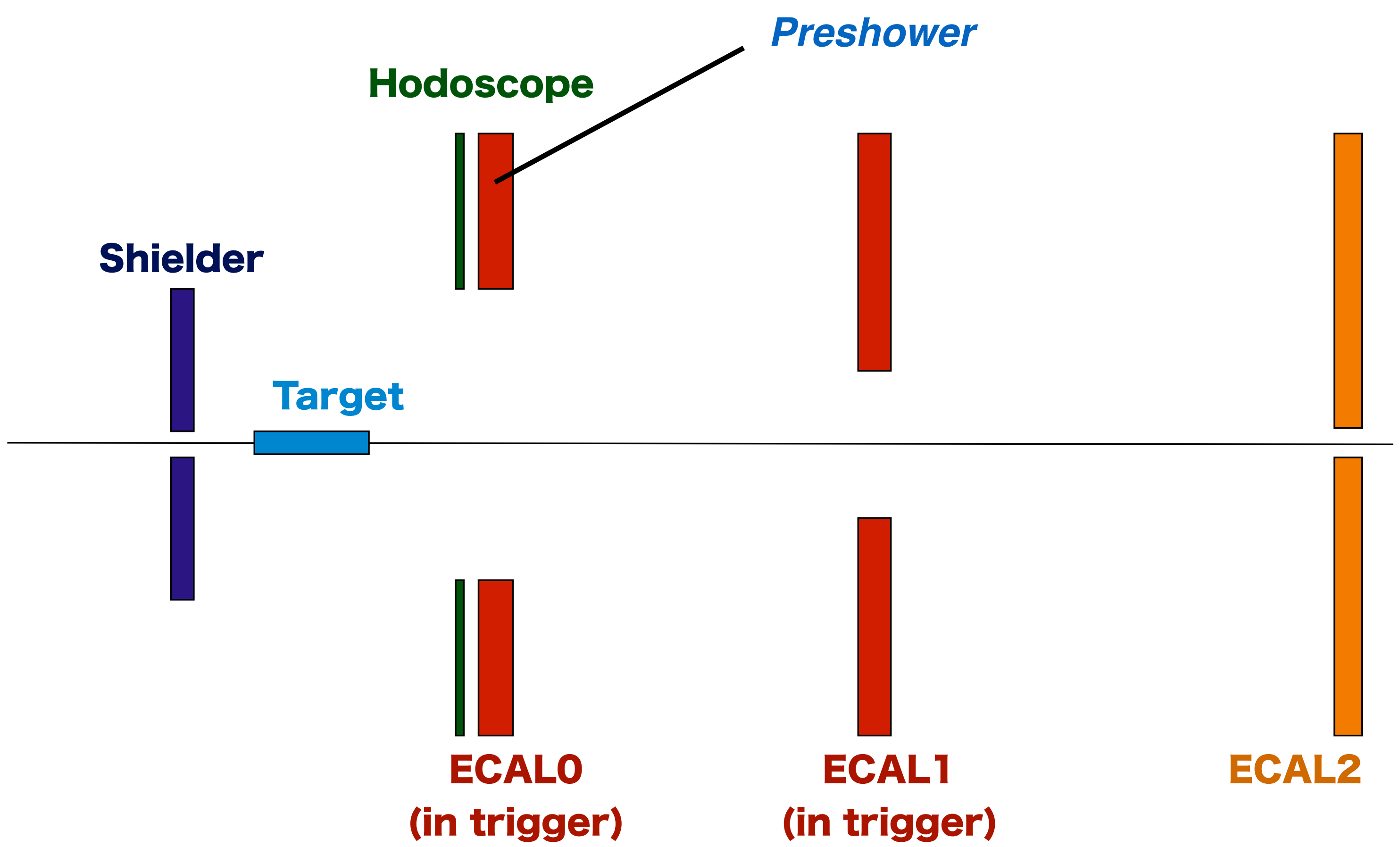
$x_{\pi,K} > 0.2$

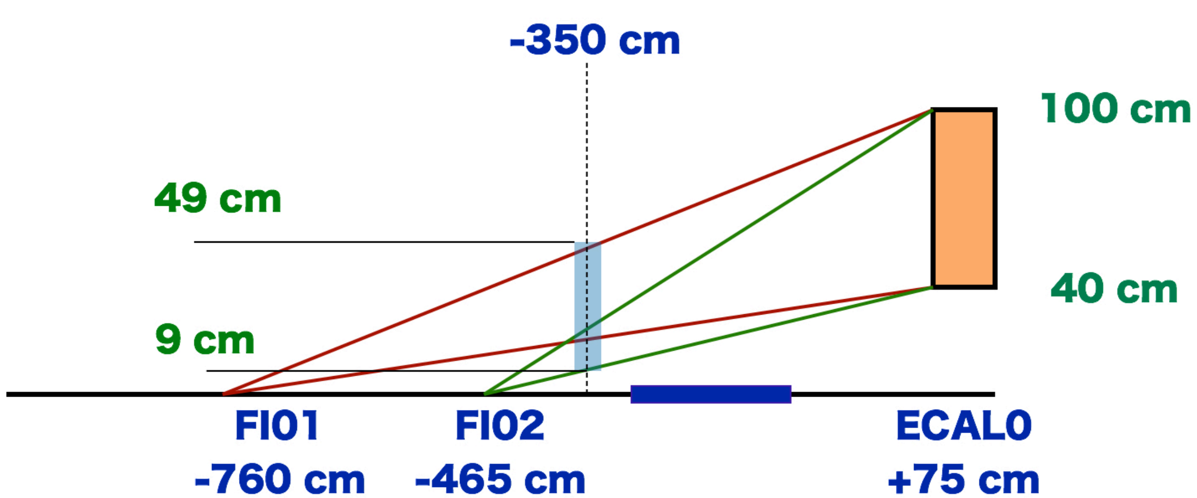


$x_{\pi,K} > 0.05$

Two different methods to touch g(x) — different systematics, different kinematic ranges.

Setup modification





Hydrogen target

K^+ beam of $5*10^6$ s^{-1}

"Transparent" setup

ECALs at low threshold

ECAL0,1 in trigger

XY hodoscope in front of ECAL0

Preshower in front of ECAL0

CEDARs

Shielder upstream the target (passive or active)

Low-energy QCD with kaon beam

Competitors: unique

Kaon polarizabilities

Theoretical predictions:

$_\chi$PT prediction O(p⁴):

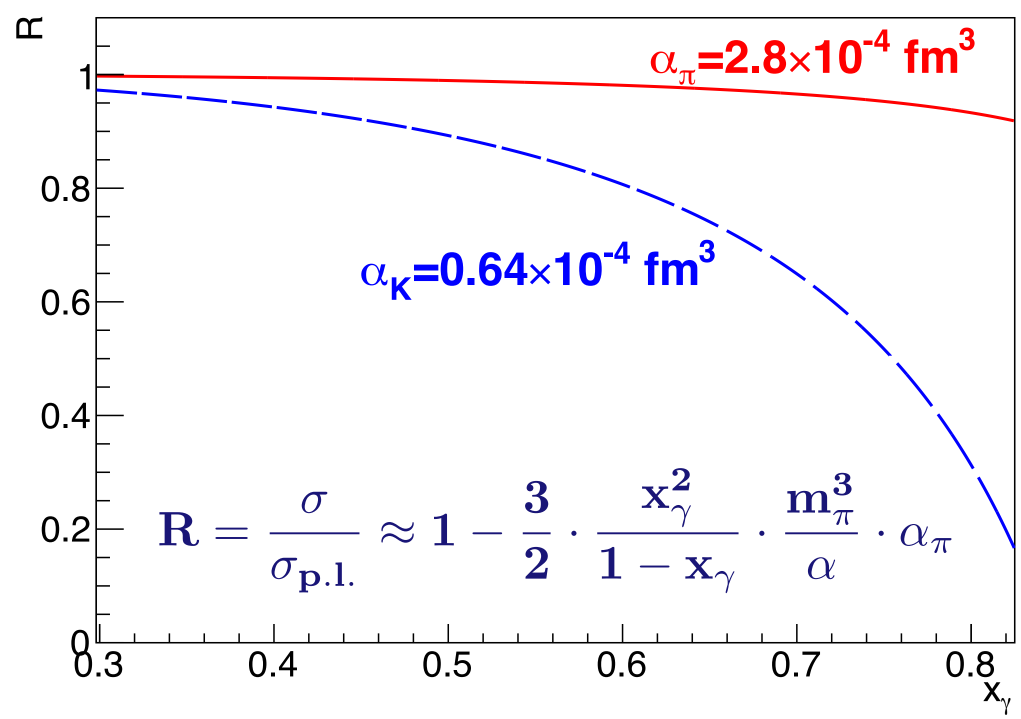
$$\alpha_K + \beta_K = 0$$

$$\alpha_K = \alpha_\pi \times \frac{m_\pi F_\pi^2}{m_K F_K^2} \approx \frac{\alpha_\pi}{5} \approx 0.6 \times 10^{-4} fm^3$$

Quark confinement model:

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

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



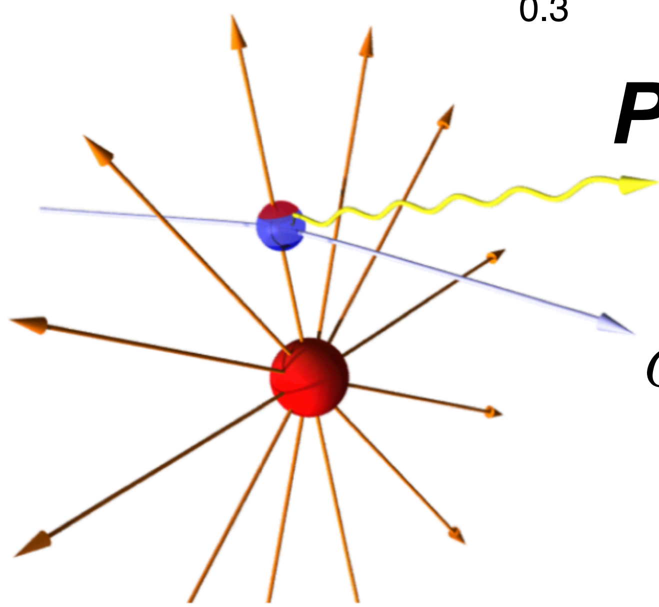
Polarization effects ~m^3

$$\sigma_{Prim} \sim \frac{1}{m^2}$$

Experimental results:

$\alpha_K < 200 \times 10^{-4}$ fm^3 (1973)

- from kaonic atoms spectra

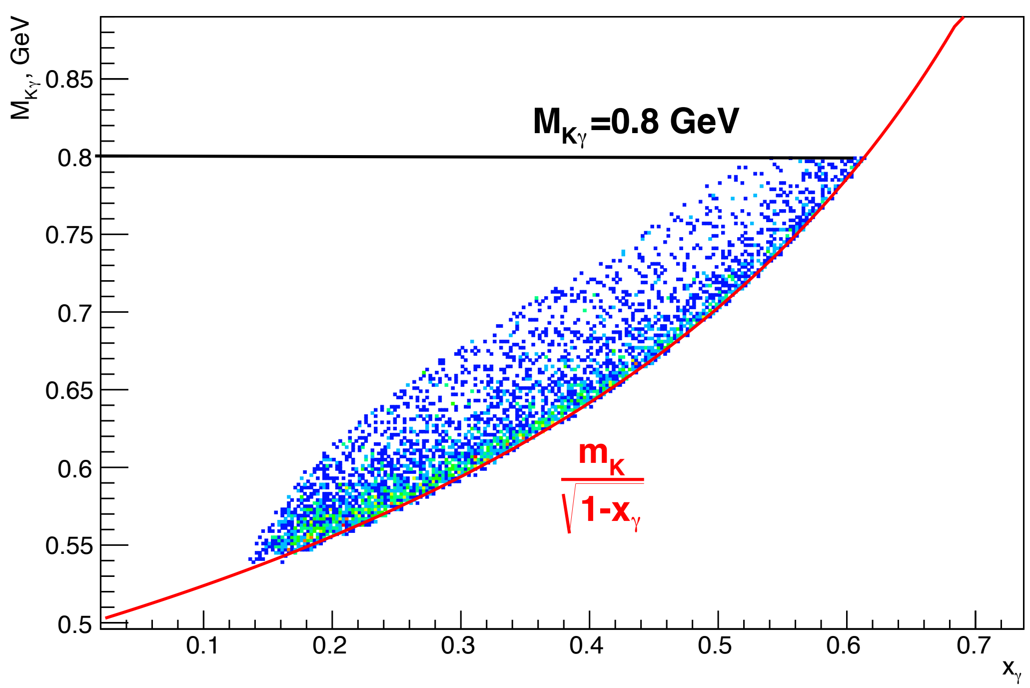


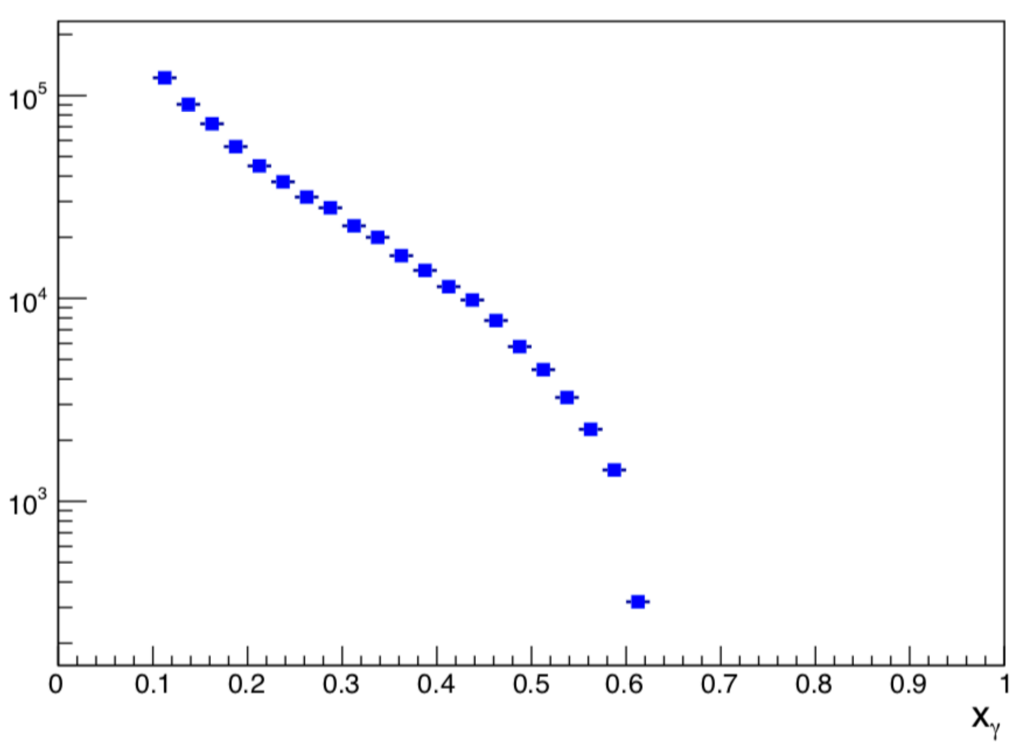
At COMPASS:

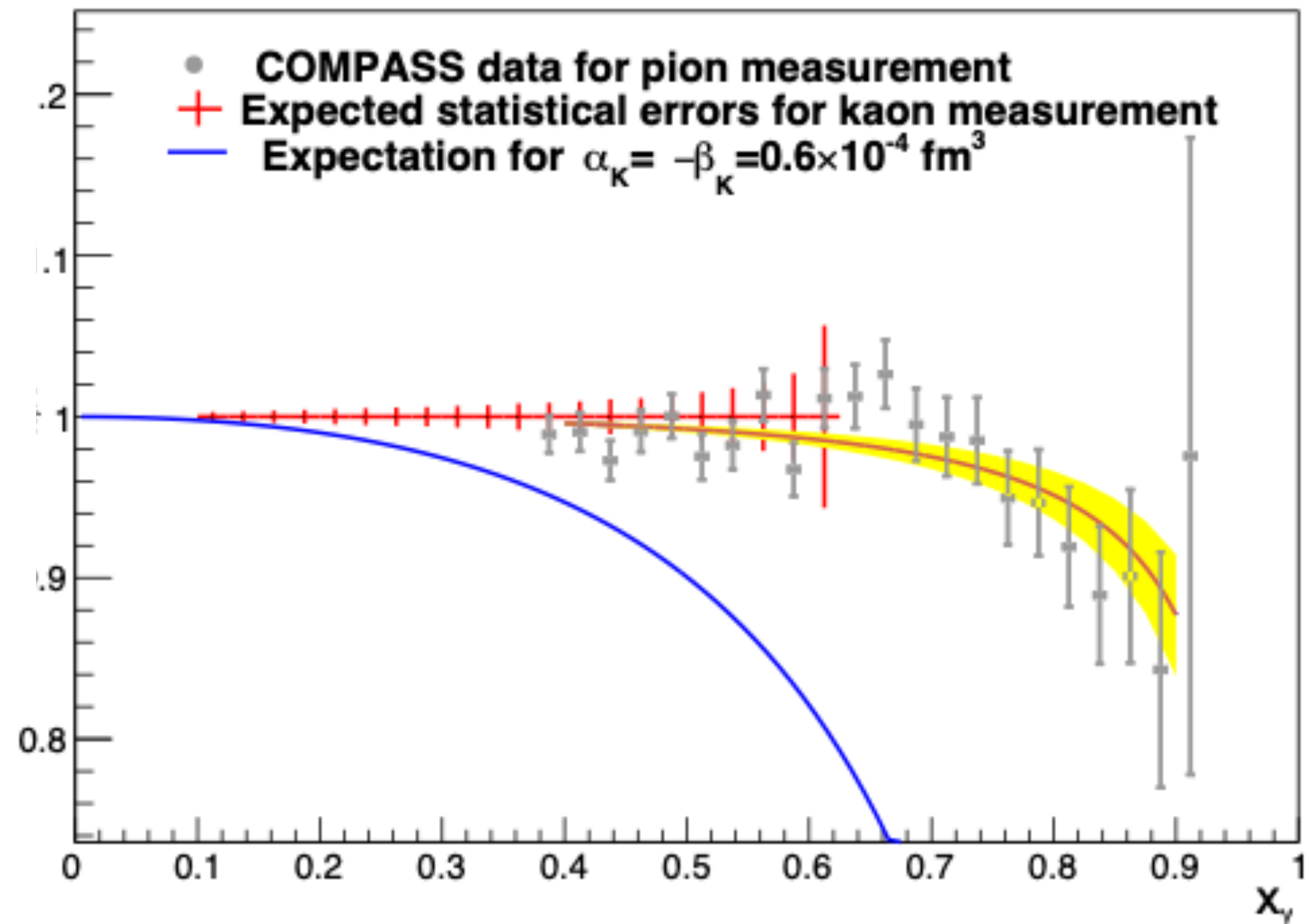
- ~2.4% of kaons in hadron beam
- CEDARs for beam kaons identification

1 Kγ event per 500 πγ

Expectations







$$5\times10^{12}\ K^- \ \rightarrow\ 6\times10^5\ K\gamma\ events$$

$$\sigma_{\alpha_K\ stat} = 0.03\times10^{-4}\ fm^3$$

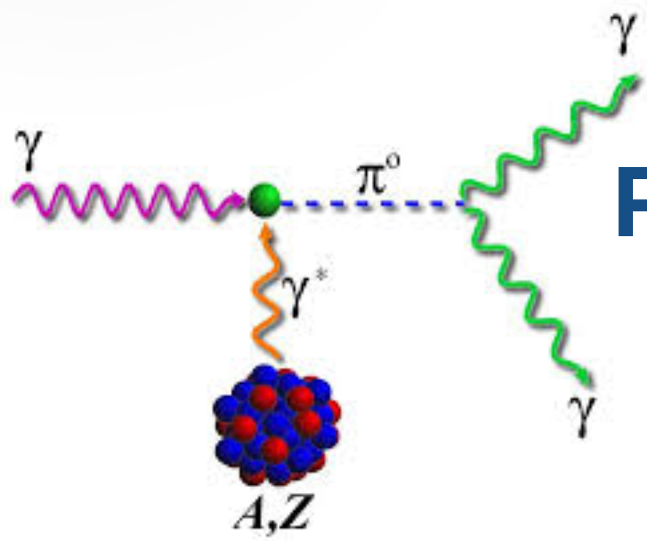
Pion lifetime: present experimental status

VALUE (10^{-17} s)	EVTS	DOCUMENT ID	TECN	COMMENT
8.52±0.18 OUR AVERAGE		Error includes scale factor of 1.2.		
8.32±0.15±0.18		[1] LARIN 11	PRMX	Primakoff effect
8.5 ±1.1		[2] BYCHKOV 09	PIBE	$\pi^+ \to e^+ \nu \gamma$ at rest
8.4 ±0.5 ±0.5	1182	[3] WILLIAMS 88	CBAL	$e^+ e^- \to e^+ e^- \pi^0$
8.97±0.22±0.17		ATHERTON 85	CNTR	Direct measurement
8.2 ±0.4		[4] BROWMAN 74	CNTR	Primakoff effect

2.1%

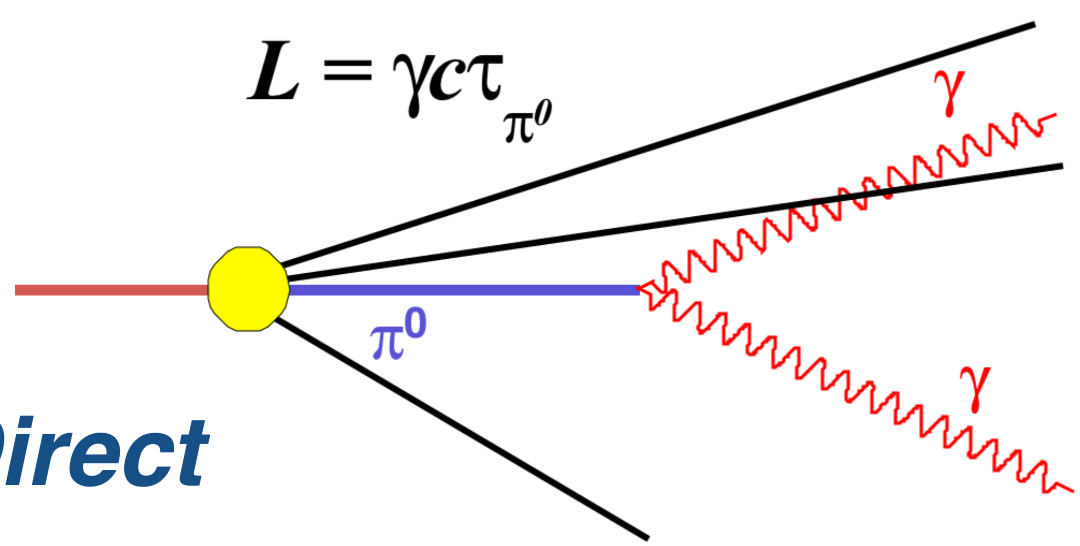
2.8%

3.1%

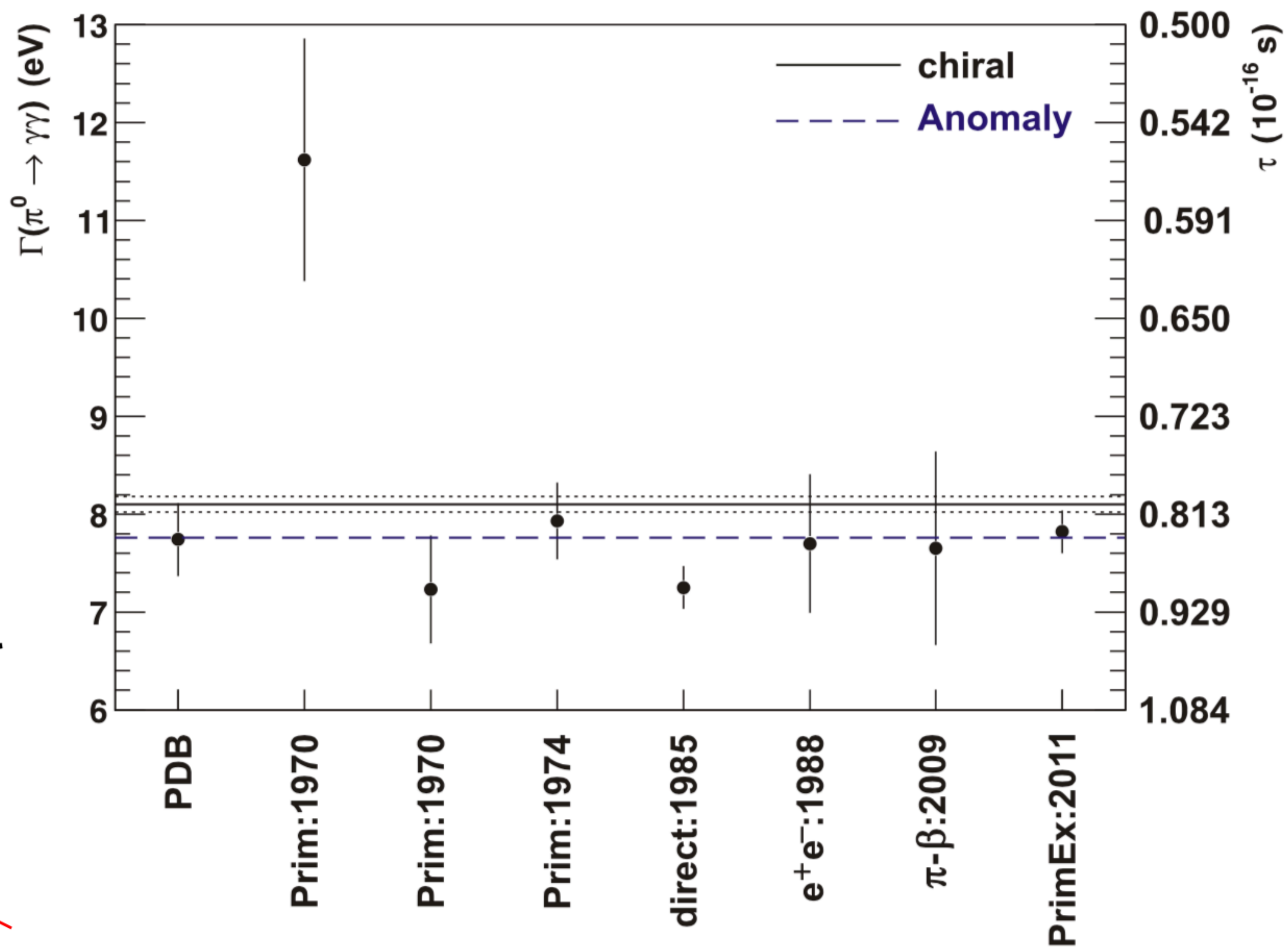


PrimEx

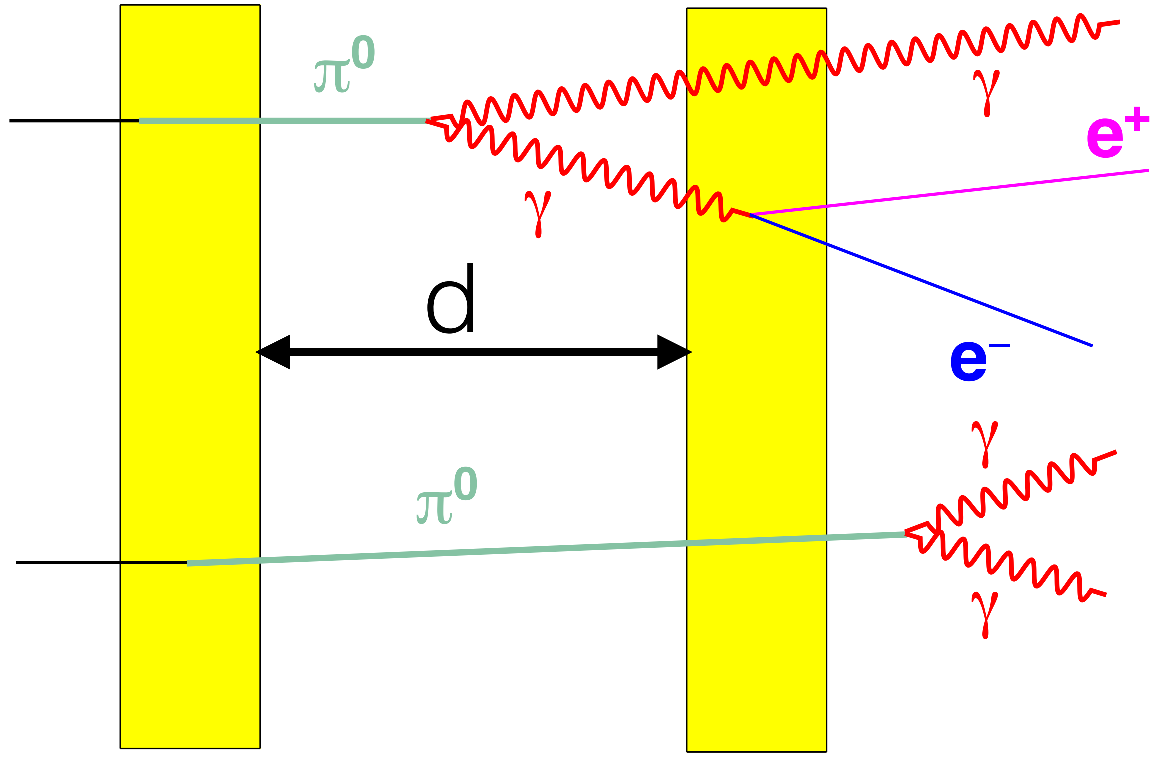
$$L = \gamma c \tau_{\pi^0}$$

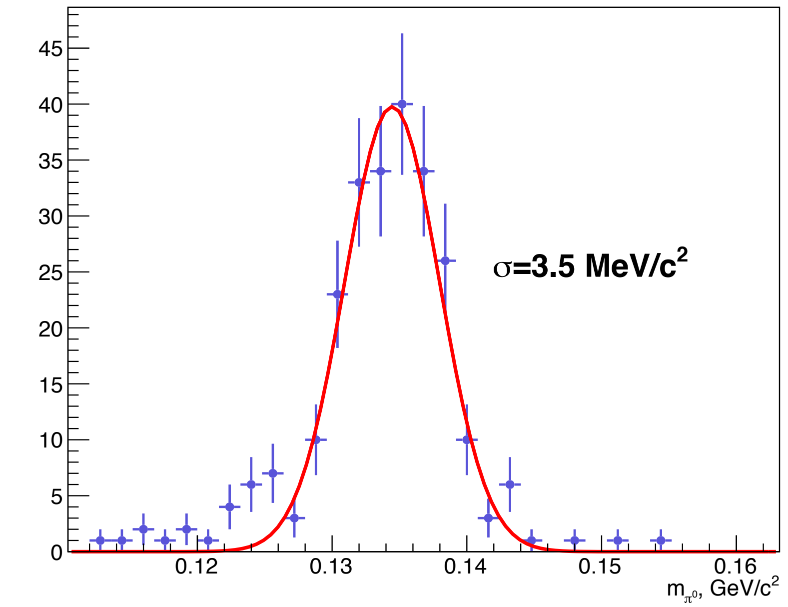


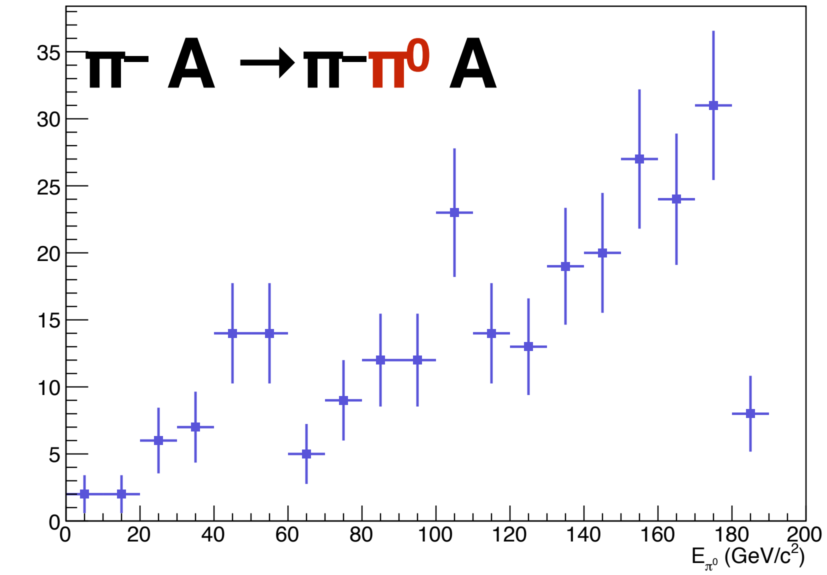
Direct



Pion lifetime: our possibilities







Strong points:

1) We can detect **both electrons and positrons from γ** conversion in the wide momentum range.
2) We can directly measure the **spectrum of produced π0** via reconstruction of γγ decay;
3) To control systematics we have the **known π0 spectrum from beam kaons decay** as a reference.

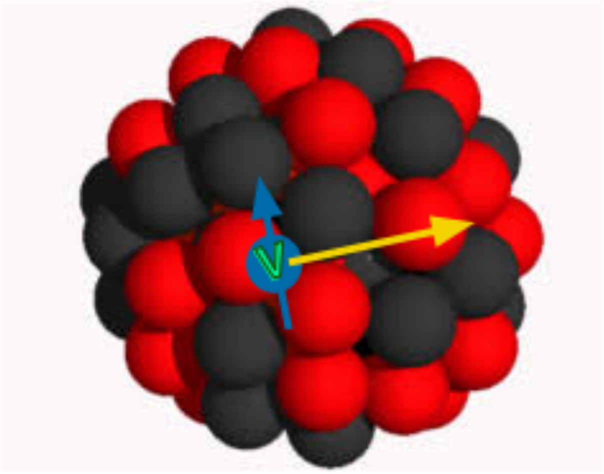
It would be nice to have the momentum of hadron beam as high as possible

Vector-meson production in nuclear matter

Competitors: GlueX

Vector mesons in nuclear matter: physics case

$\sigma_{L,T}=\sigma(V_{L,T}:\rho,\omega,\phi\ldots\ N)$

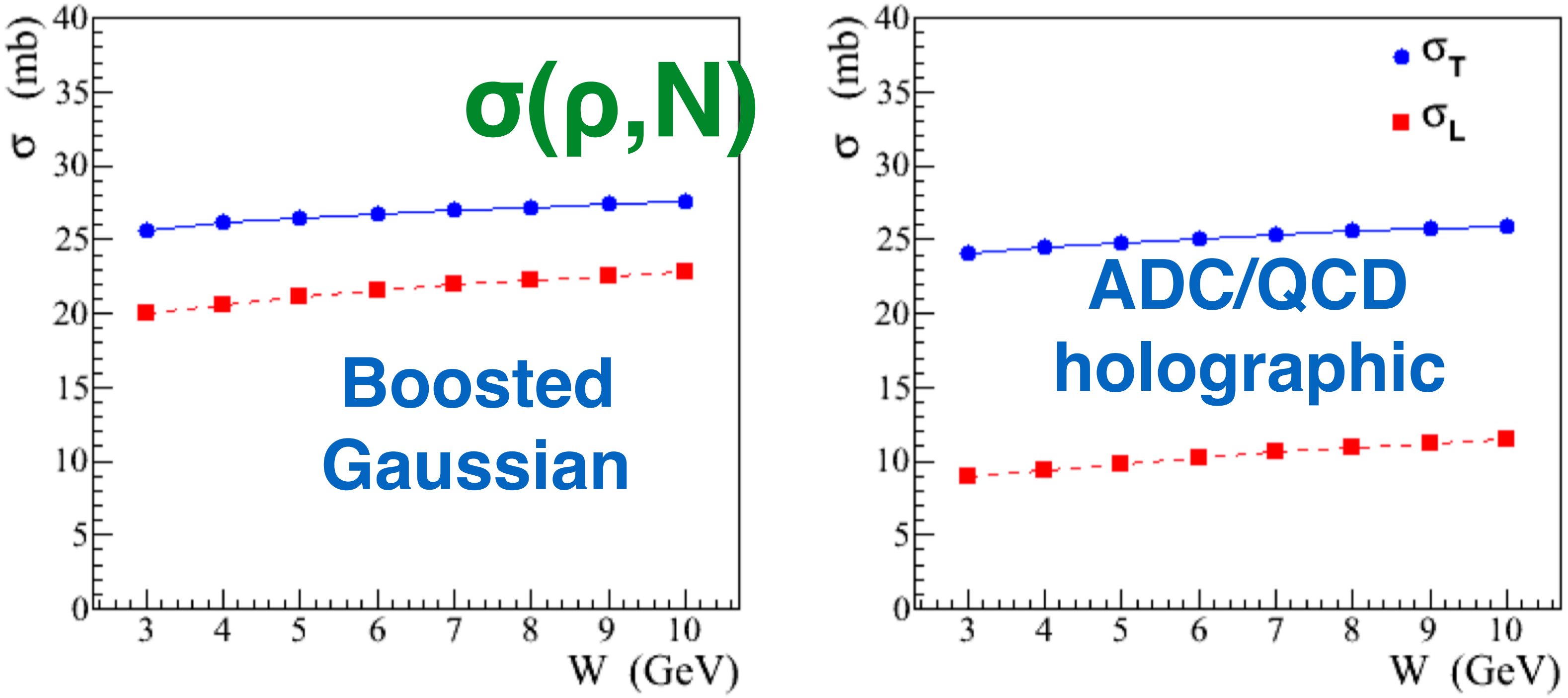


Important for:

- treating of the CT effect
- heavy ion collisions

Naive quark model: $\sigma_L=\sigma_T$

Color dipole model:



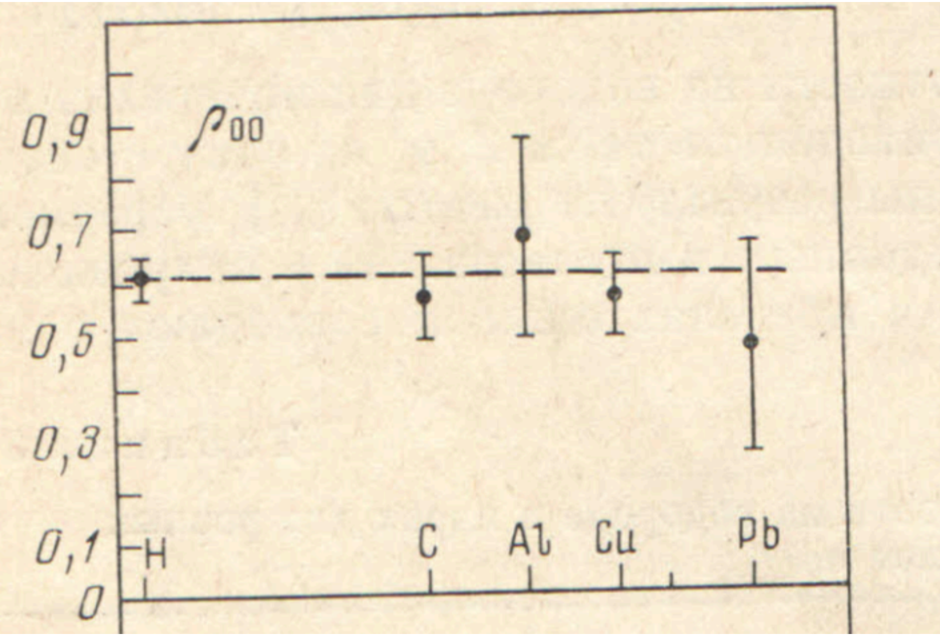
$\gamma A \rightarrow V\ A$ (coherent) – σ_T (proposed to be precisely measured at JLab)

$\pi^- A \rightarrow V\ A'$ – σ_L dominates (OUR CASE)

Vector mesons: previous results

A. V. Arefyev et.al, Sov. J. Nucl. Phys. 19, 304 (1974); 27, 85 (1978).

$\pi^- A \rightarrow \rho^0 A'$ E_π=3.7 GeV



σ(ρN)=27.6±4.5 mb

σ(ρN)=31.3±2.3 mb

from coherent photoproduction

So, $\sigma_L \approx \sigma_T$, but…

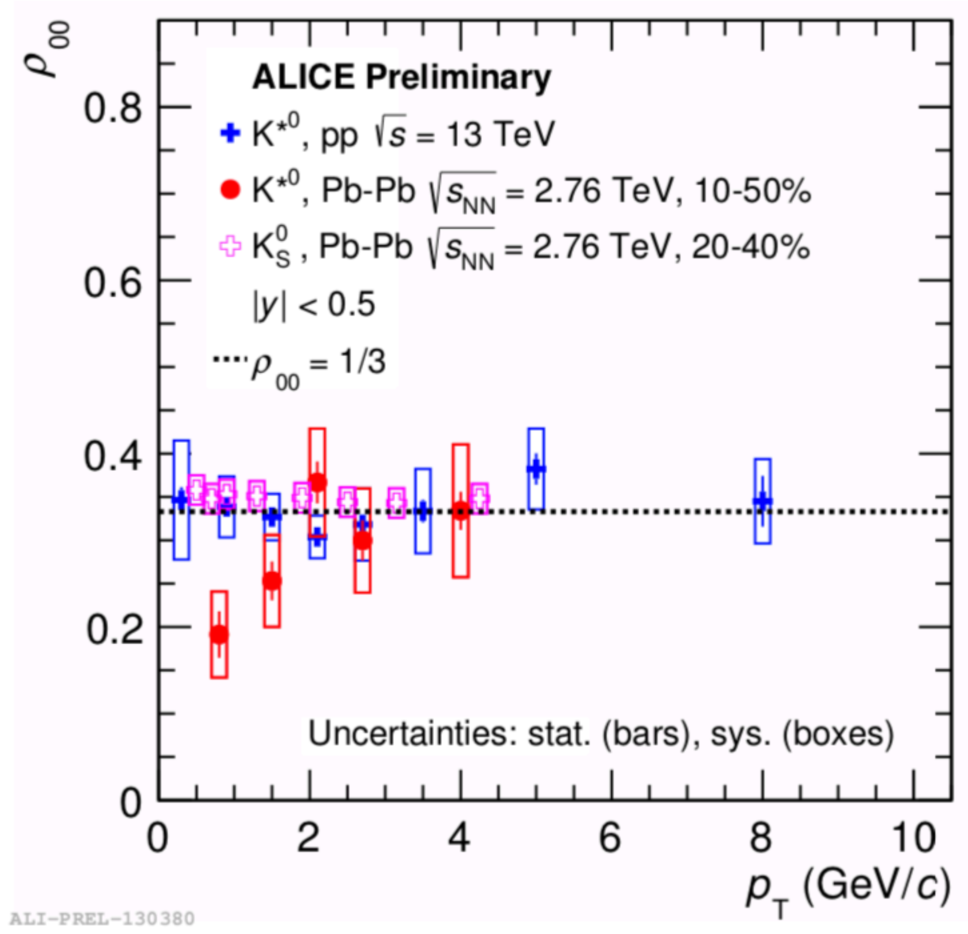
ρ-meson decay inside nucleus was not taken into account!

λ_{decay}=6.7 fm !

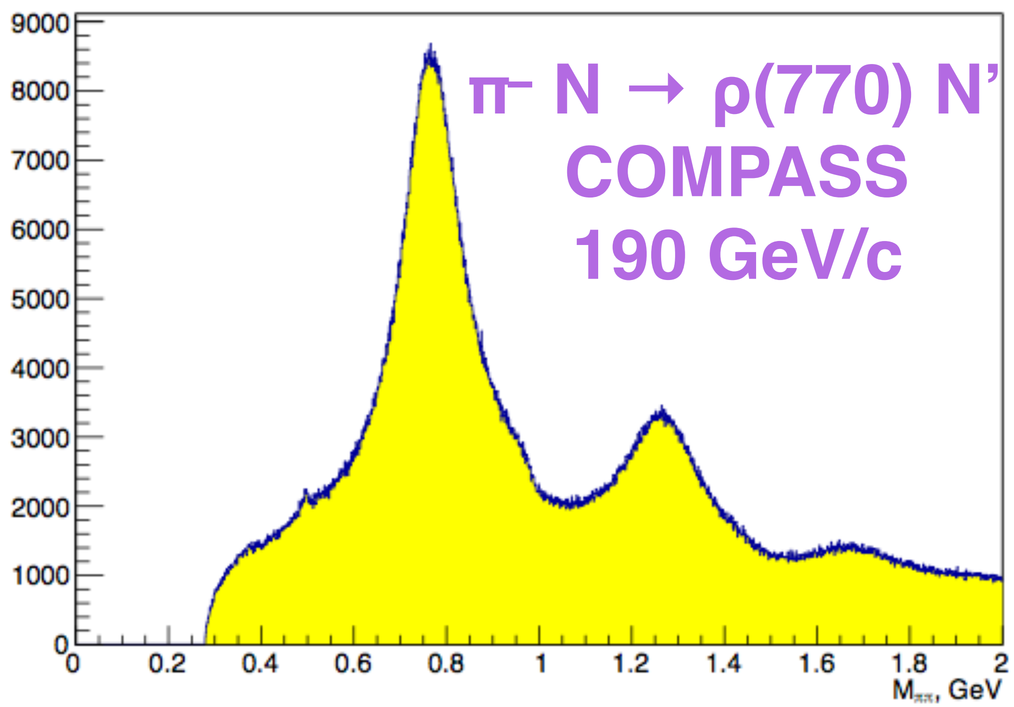
B. Chaudhary et al., Nucl. Phys. B67, 333 (1973)

$$\pi^+ + Ne \rightarrow \rho(f) + Ne'$$ E_π=3.2 GeV

σ(ρN)~12 mb that contradicts to photoproduction results



Vector mesons: requirements and compatibility



Exclusive charge exchange reactions:

$K^- A \rightarrow K^*(892) A'$

$\pi^- A \rightarrow \rho(770) A'$

$\pi^- A \rightarrow f_2(1270) A'$

...

Longitudinal polarisation of produced V-mesons (due to π^- exchange dominance)

So, we propose to measure the cross section of longitudinally polarised vector mesons interaction with nucleons σ_L and spin density matrix elements for the produced vector mesons.

Beam energy:

1) $\sigma_{OPE} \sim 1/E_{beam}$
2) $L \sim \gamma = E_V/m_V$

P_{beam} = 50-100 GeV/c looks as a reasonable compromise

Running with the set of different nuclear targets (Be - Pb). No special requirement for the spectrometer. Running in parasitic mode is also possible.

SUMMARY

COMPASS++/AMBER working team with active participation of the JINR group has presented in the Letter of Intent an extended physics program for the new QCD facility at CERN.

arXiv:1808.00848

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	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	$K^{\pm}, \overline{p}$	$NH_3^{\uparrow}$, C/W	2026 2-3 years	"active absorber", vertex detector
Primakoff (RF)	Kaon polarisability & 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	$K^{\pm}$	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	