Future meson structure studies with AMBER

Michela Chiosso
on behalf of the AMBER Collaboration

MENU2023 16 - 20 October 2023, Mainz

UNIVERSITÀ DI TORINO

INFN

History of AMBER

2018: Letter of Intent [arXiv:1808.00848]

2019: Formation of a Proto-Collaboration

2019: AMBER Phase–1 Proposal [CERN-SPSC-2019-02]

2020: Recommendation of the Proposal by SPSC and approval by Research Board

2021 and 2022: AMBER Pilot Run

2023: Start of AMBER data taking

Phase-2 proposal in preparation

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

Phase-1: 2022-2024

COMPASS++*/AMBER†

CERN-SPSC-2019-022 / SPSC-P-360
31/05/2019

B. Adams[14,13], C.A. Aidala[1], G.D. Alexeev[15], M.G. Alexeev[41,42], A. Amoroso[41,42], V. Andrieux[44,20], N.V. Anfimov[15], V. Anosov[15], A. Antoshkin[15], K. Augsten[15,31], W. Augustyniak[46], C.D.R. Azevedo[4], B. Badełek[47], F. Balestra[41,42], M. Ball[8], J. Barth[8], R. Beck[8], J. Berenguer Antequera[41,42], J.C. Bernauer[33,45], J. Bernhard[20,p], M. Bodlak[30], F. Bradamante[39], A. Bressan[38,39], M. Büchele[17], V.E. Burtsev[40], C. Butler[3], C. Chatterjee[38,39], M. Chiosso[41,42], A.G. Chumakov[40], S.-U. Chung[18,c], A. Cicuttin[39,d], M. Connors[3], A. Contin[6], P. Correia[4], M.L. Crespo[39,d], S. Dalla Torre[39], S.S. Dasgupta[11], S. Dasgupta[39,11], N. Dashyan[50], I. Denisenko[15], O.Yu. Denisov[42], L. Dhara[11], F. Donato[43], S.V. Donskov[32], N. Doshita[49], Ch. Dreisbach[18], W. Dünnweber[e], R.R. Dusaev[40], A. Dzyuba[19], A. Efremov[15], P. Egelhof[16], A. Elagin[14], P.D. Eversheim[8], P. Faccioli[22], M. Faessler[e], J. Fedotova[25], M. Finger[30], M. Finger jr.[30], H. Fischer[17], C. Franco[22], J.M. Friedrich[18], V. Frolov[15], A. Futch[44], F. Gautheron[44], O.P. Gavrichtchouk[15], S. Gerassimov[27,18], S. Gevorkyan[15], Y. Ghandilyan[50], J. Giarra[24], I. Gnesi[41,42], M. Gorzellik[17], A. Grasso[41,42], A. Gridin[15], M. Grosse Perdekamp[44], B. Grube[18], R.I. Gushterski[15,l], A. Guskov[15], G. Hamar[39], D. von Harrach[24], X. He[3], R. Heitz[44], F. Herrmann[17], M. Hoffmann[8], N. Horikawa[29,f], S. Huber[18], A. Inglessi[19], A. Ilyichev[25], S. Ishimoto[49,h], A. Ivanov[15], N. Ivanov[50], T. Iwata[49], M. Jadhav[2], M. Jandek[30], V. Jary[31], C.-M. Jen[23], R. Joosten[8], P. Jörg[17], K. Juraskova[31], E. Kabuß[24], F. Kaspar[18], D. Keller[12], A. Kerbizi[38,39], B. Ketzer[8], G.V. Khaustov[32], Yu.A. Khokhlov[32,i], M. Kim[1], O. Kiselev[16], Yu. Kisselev[15], F. Klein[9]

SPSC 139, Oct. 2020

The Committee **recommends** approval of the proposal SPSC-P-360 by the AMBER Proto-Collaboration to use the M2 beam-line before LS3 to perform measurements related to:

(i) Drell-Yan and J/Psi production using the conventional M2 hadron beam;
(ii) proton-induced antiproton production cross sections for dark matter searches;
(iii) the proton charge radius using muon-proton elastic scattering.

The proton-radius program is contingent on a successful pilot run previously approved for the first year of SPS operation after the Long Shutdown LS2.

AMBER: at the North Area of the CERN-SPS

In EHN2 (former COMPASS) experimental hall:

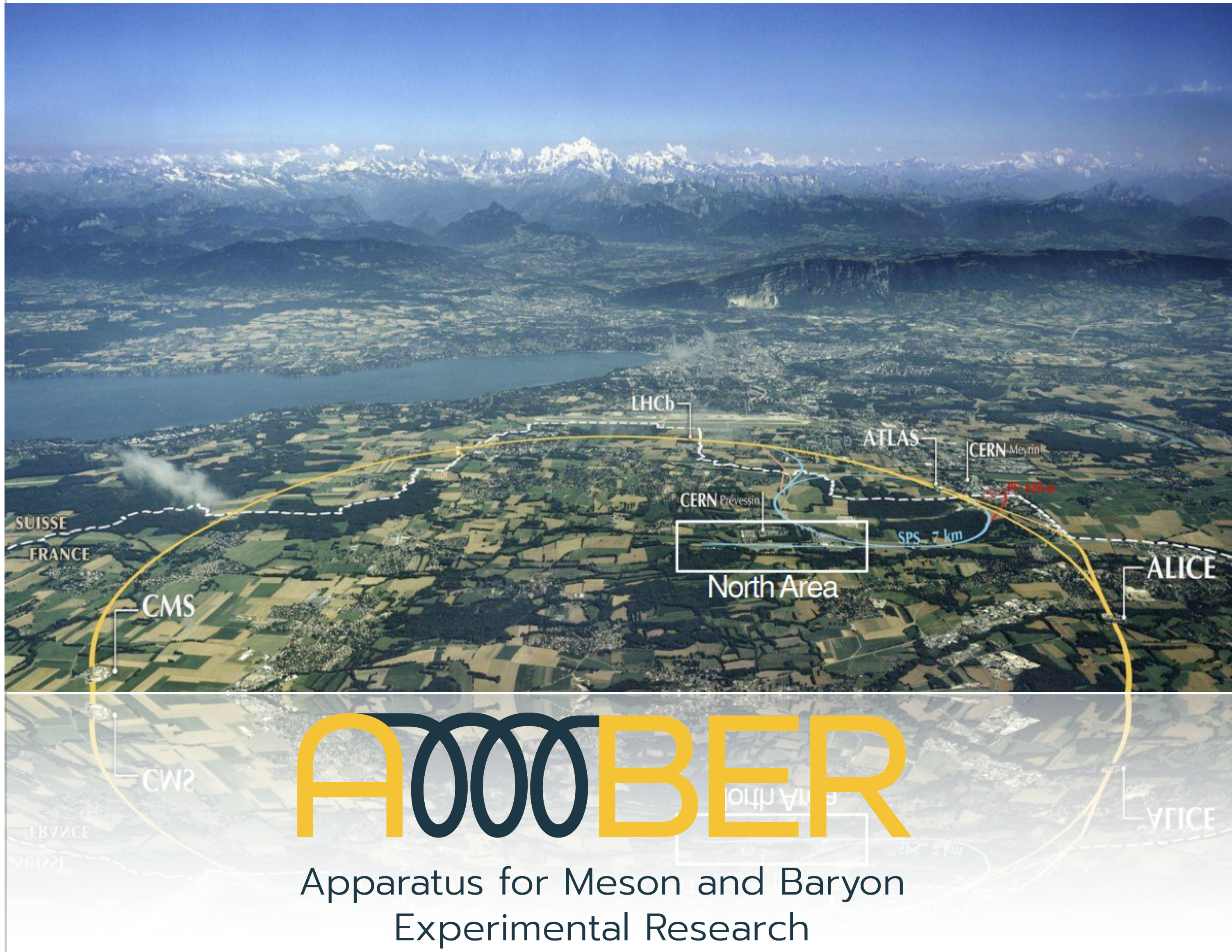
Availability of both hadron and muon beams

Both beam charges available, and in wide range of energies (~ 60 - 250 GeV/c)

Re-use of large aperture dipole magnets

Re-use of some of the most recent COMPASS detectors

To further exploit the M2 beam line at CERN and the unique COMPASS spectrometer for exploration of hadron structure and QCD physics

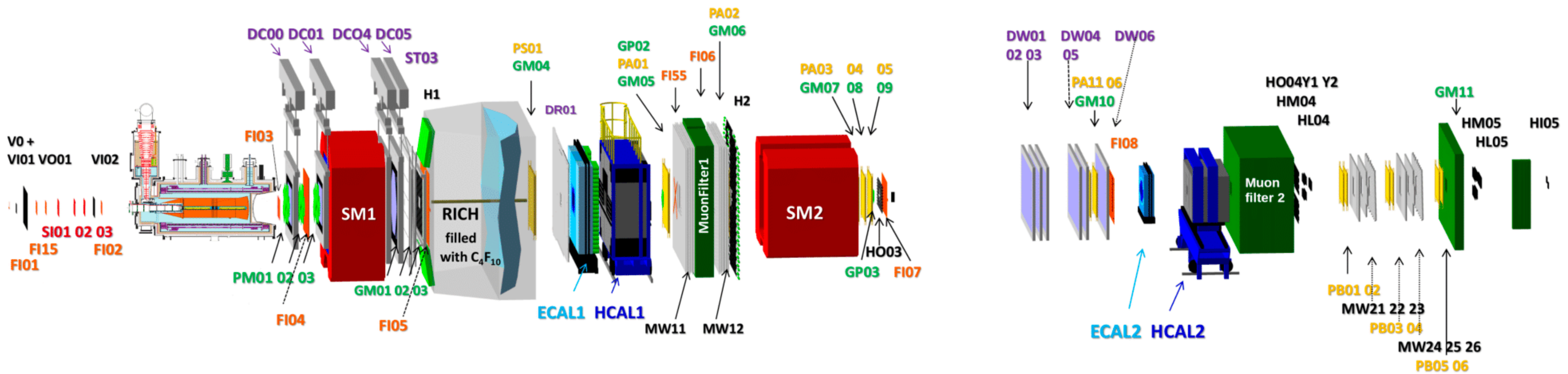


The AMBER Apparatus

AMBER
Apparatus for Meson and Baryon Experimental Research

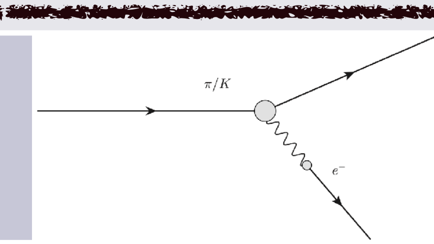
A high momentum resolution for charged particles provided by a two-stage magnetic spectrometer

- Redundant high-precision tracking
- RICH and Calorimeters for PID
- Muon identification
- CEDAR detectors for beam PID



The AMBER spectrometer (former COMPASS)

AMBER physics program

	Beam	Target	Additional Hardware	
Proton radius measurement	*100 GeV muons*	*high pressure Hydrogen*	*active target TPC, tracking stations (SciFi, Silicon)*	Phase 1 (approved)
Antiproton production cross section	*50 GeV - 280 GeV protons*	*LH_2, LHe*	*Liquid He target*	
Drell-Yan measurements with pions	*190 GeV charged pions*	*Carbon, Tungsten*	*vertex detector*	
Drell-Yan measurements with Kaons	*~100 GeV charged Kaons*	*Carbon, Tungsten*	*vertex detectors, 'active absorber'*	Phase 2 (in preparation)
Prompt photon measurements	*> 100 GeV charged Kaon/pion beams*	*LH_2, Nickel*	*hodoscopes*	
K-induced spectroscopy	*50 GeV - 100 GeV charged Kaons*	*LH_2*	*recoil ToF, forward PID*	
Meson radii	*50 GeV to 280 GeV charged pions and Kaons*			

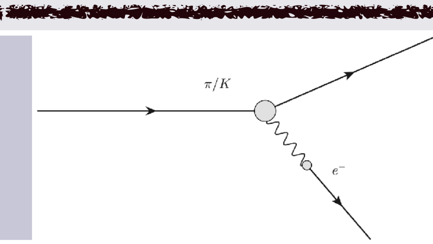
Phase-I
Proposal Phase-I:

Approved by CERN
2023 —> 2029

Phase-II
Proposal in preparation
Beyond 2029

AMBER physics program

Apparatus for Meson and Baryon Experimental Research

	Beam	Target	Additional Hardware
Proton radius measurement	***100 GeV muons***	***high pressure Hydrogen***	***acti[illegible]C***
Antiproton production cross section	***50 GeV - 280 GeV protons***	***LH_2, LHe***	
Drell-Yan measurements with pions	***190 GeV charged pions***	***Carbon, Tungsten***	***vertex detector***
Drell-Yan measurements with Kaons	***~100 GeV charged Kaons***	***Carbon, Tungsten***	***vertex detectors, 'active absorber'***
Prompt photon measurements	***> 100 GeV charged Kaon/pion beams***	***LH_2, Nickel***	***hodoscopes***
K-induced spectroscopy	***50 GeV - 100 GeV charged Kaons***	***LH_2***	***recoil ToF, forward PID***
Meson radii	***50 GeV to 280 GeV charged pions and Kaons***		

Meson Structure at AMBER

Phase 1 (approved)

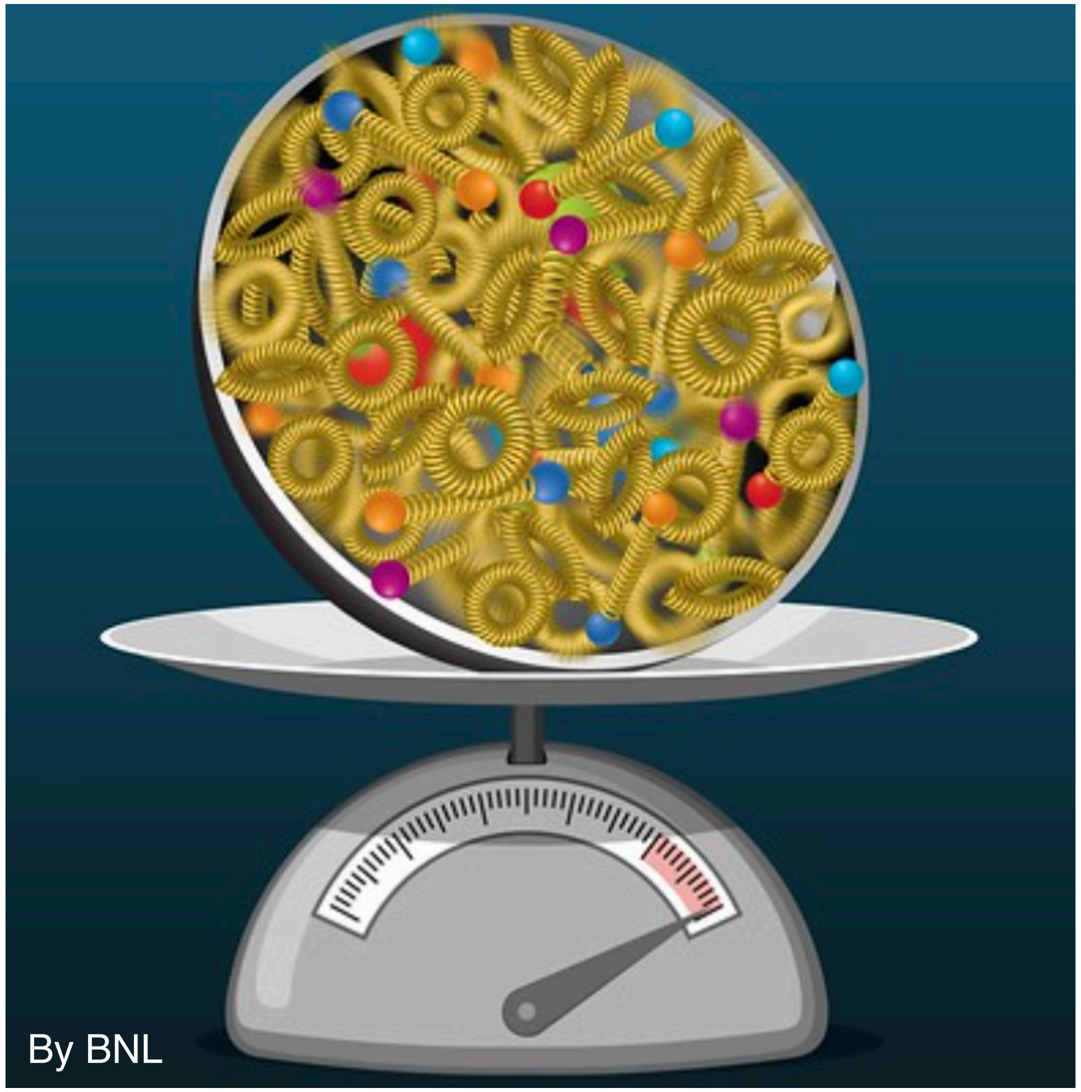
Phase 2 (in preparation)

Phase-I
Proposal Phase-I:

Approved by CERN
2023 —> 2029

Phase-II
Proposal in preparation
Beyond 2029

The meson structure and the origin of hadron masses



How does all the visible matter in the universe come about and what defines its mass scale?

Higgs mechanism produces a few percent of visible mass, where does the rest comes from?

The Higgs-generated mass scales explains neither the “huge” proton mass nor the ‘nearly masslessness’ of the pion

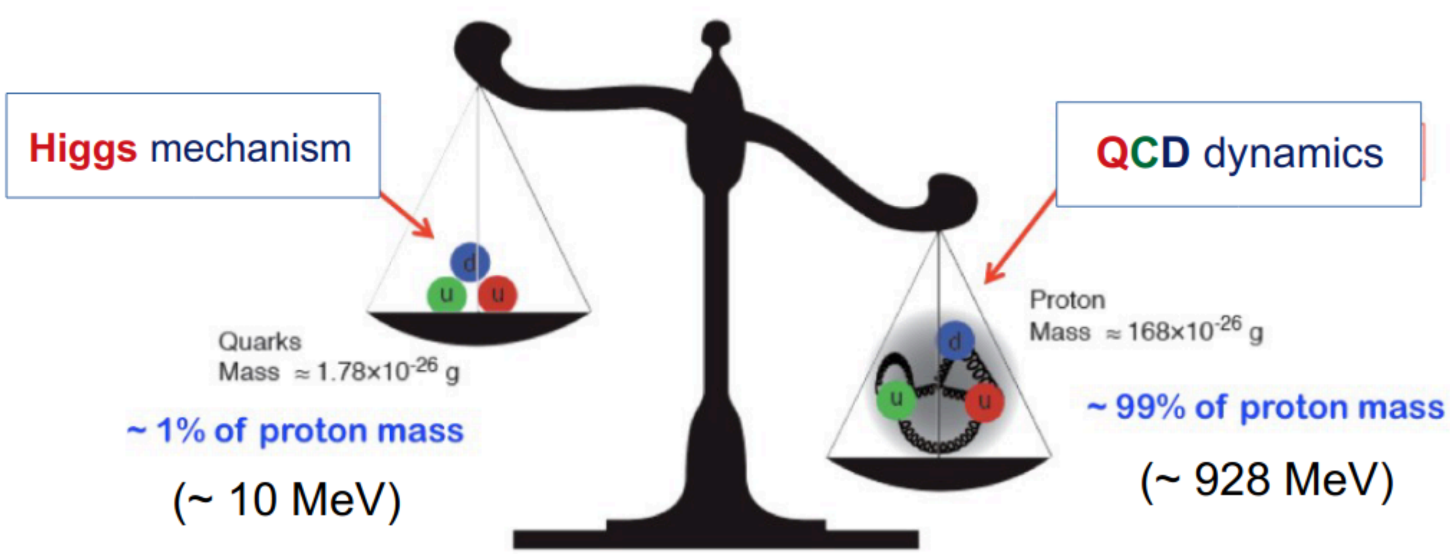
Emergence of hadron mass (EHM)

What are the underlying mechanisms?

The answer lies within SM, in particular within QCD
—> dynamical mass generation in continuum QCD

In order to “proof” that QCD underlies the EHM phenomenon we have to compare Lattice and Continuum QCD calculations with experimental data by measuring:

1. **Quark and Gluon PDFs of the pion/kaon/proton**
2. Hadron’s radii (confinement)
3. Excited-meson spectra



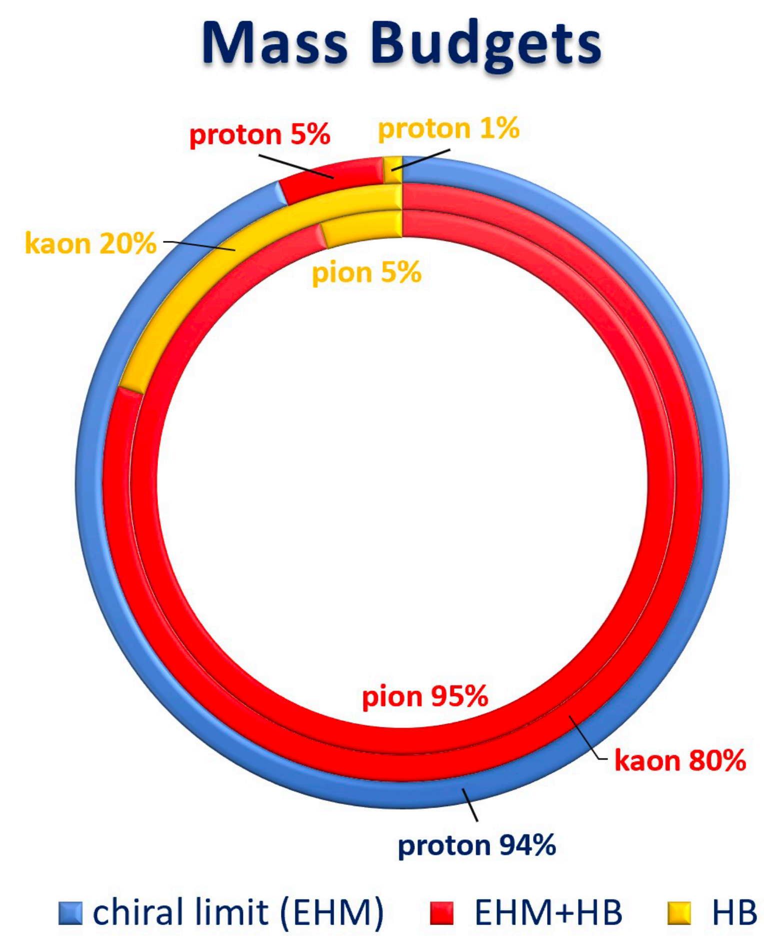


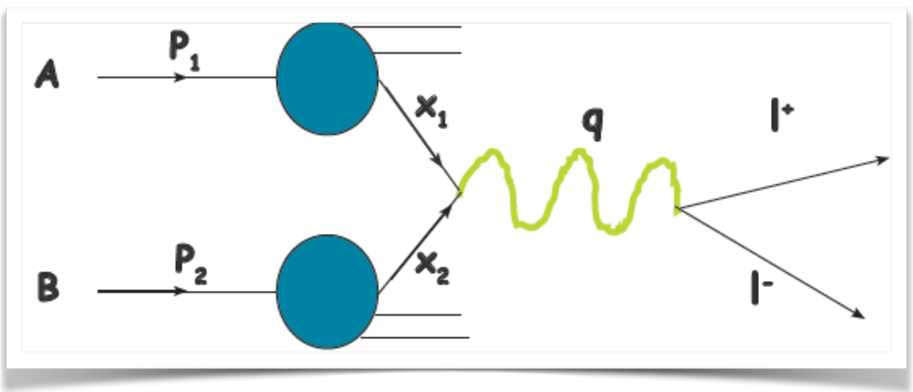
Figure taken from Craig Roberts "EHM via AMBER" at 5th AMBER EHM Workshop (2021)

Emergence of hadron mass

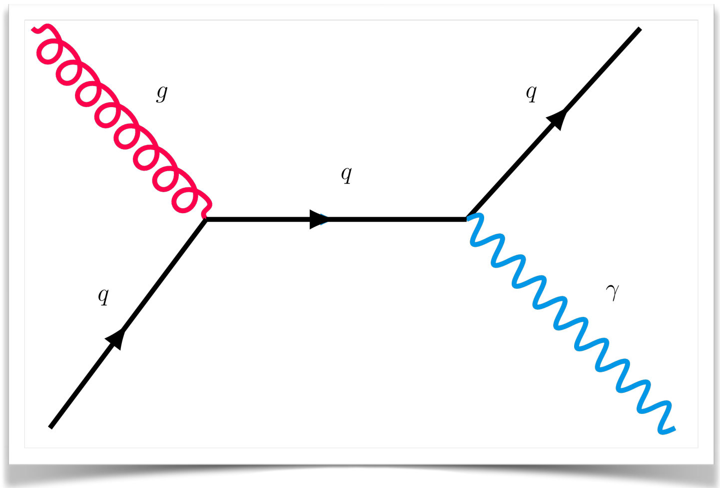
Questions to be answered:

- Mass difference pion/proton/kaon
- Mass generation mechanism (emergent mass .vs. Higgs)
- Gluon content, especially important pion/kaon striking difference

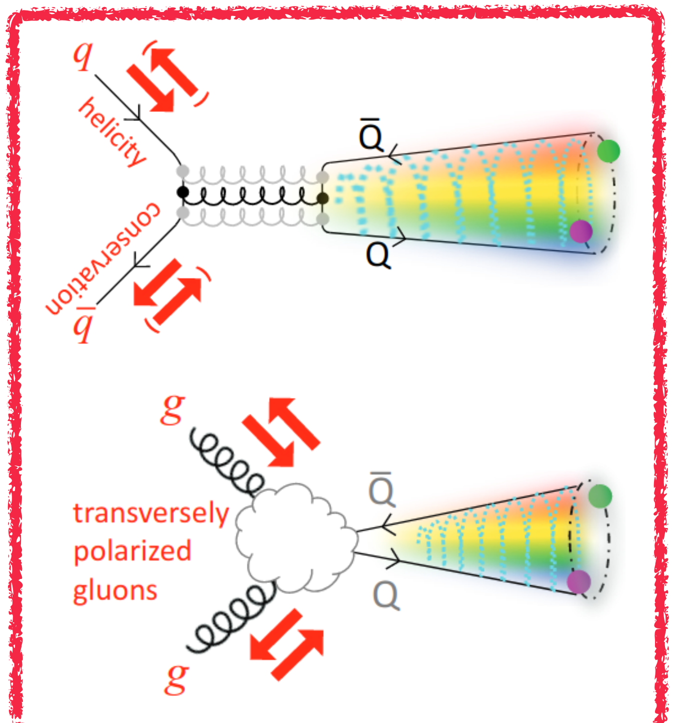
Experimental access @AMBER (with pion and kaon beams):



Drell-Yan



Prompt-photon production



Charmonium production

What do we know about pion structure?

Pion-induced Drell-Yan data collected by NA3, NA10, WA39 (CERN) and E615 (Fermilab), more than 30 years ago —> access valence and sea (NA3 and WA39) distributions in the pion

Available data from direct-photon production also obtained at that time, by WA70 and NA24 (CERN)

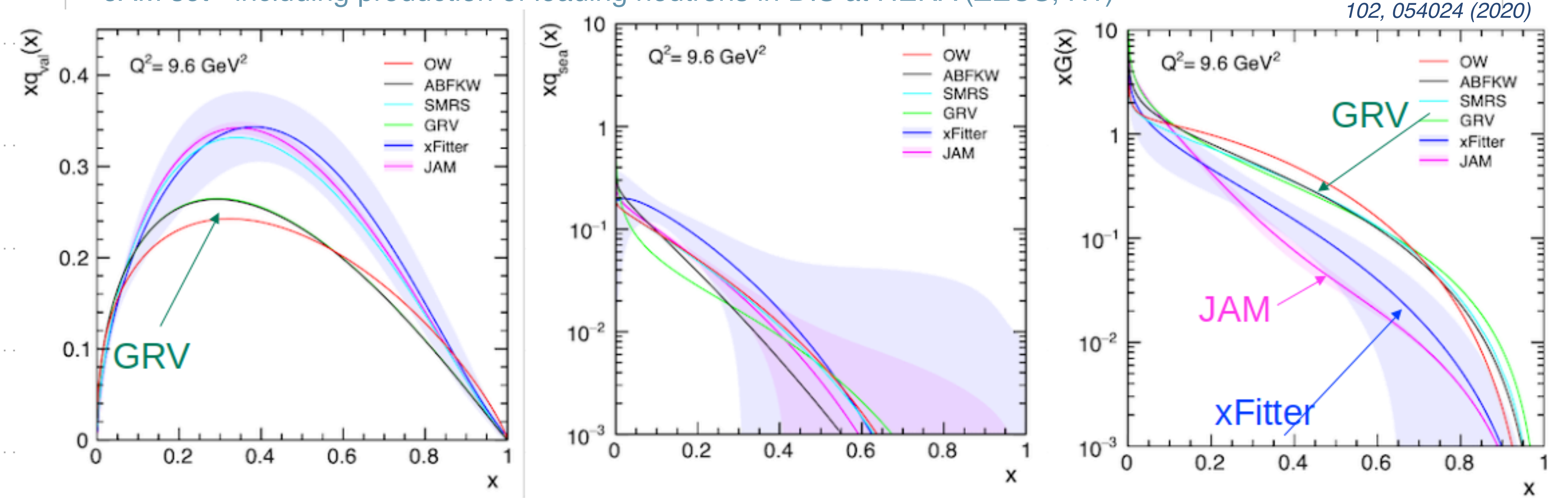
Limited data sets —> sea quark distribution was derived from momentum-sum-rule conservation

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

xFitter set: Drell-Yan, prompt photon production

JAM set - including production of leading neutrons in DIS at HERA (ZEUS, H1)

Chang et al. PRD 102, 054024 (2020)



What do we know about pion structure?

- Mostly heavy target
—> nuclear effects
- Some did not publish cross-sections
- Some did not measure with both beam charges

—> no sea/valence separation

Isoscalar target

Both beam charges

High statistics

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 37000
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

Pion-induced Drell-Yan at AMBER

➤ High energy and intensity pion beams

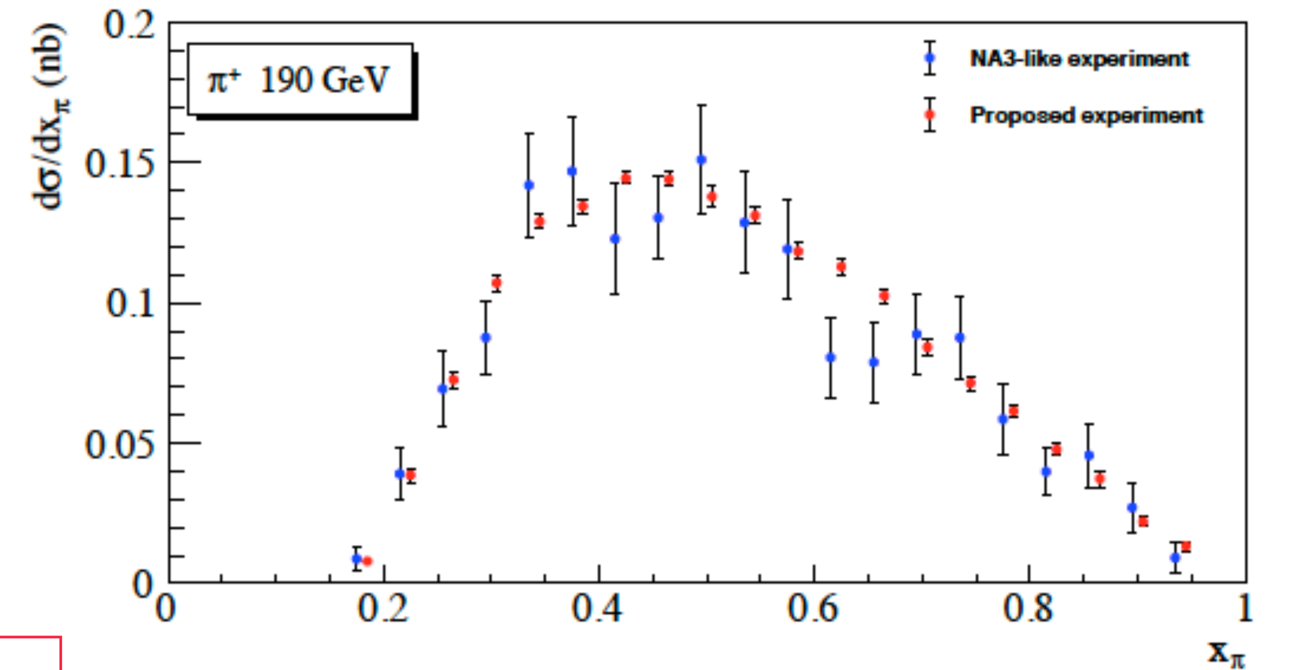
Example @ 190 GeV/c

$I_{\pi^-} \sim I_{beam} = 7.0\text{x}10^7/\text{s}$

$I_{\pi^+} \sim 25\%\ I_{beam} = 1.7\text{x}10^7/\text{s}$

➤ COMPASS-like apparatus

➤ Segmented Carbon target



Flavour dependent nuclear PDFs

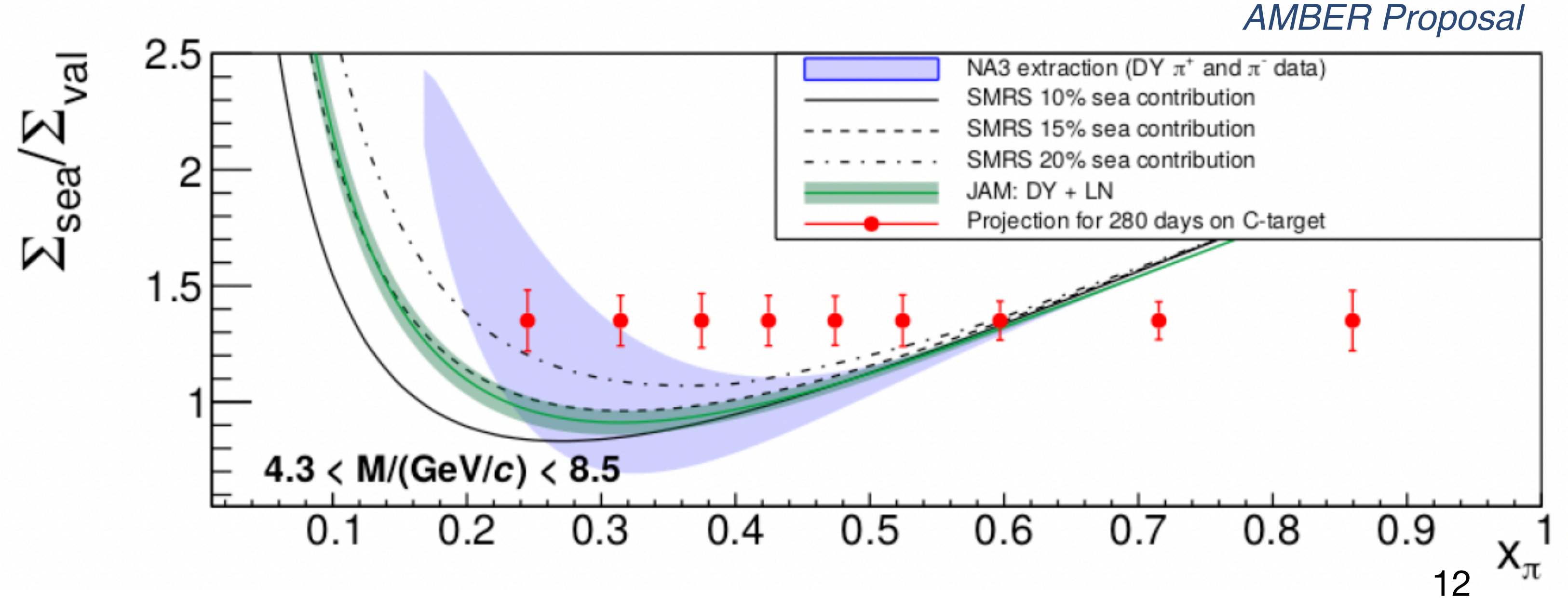
Positive and negative pion beam on Carbon and Tungsten target

➤ Aim at the first precise direct measurement of the pion sea contribution

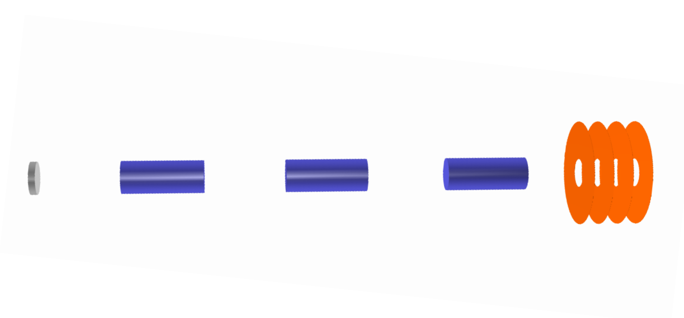
$$\frac{\Sigma_{sea}}{\Sigma_{valence}} = \frac{4\sigma^{\pi^+C} - \sigma^{\pi^-C}}{-\sigma^{\pi^+C} + \sigma^{\pi^-C}}$$

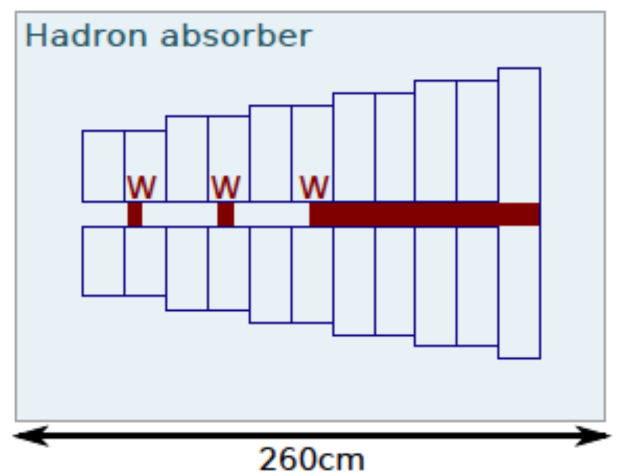
LO: only sea-val and val-sea terms
LO: only val-val terms

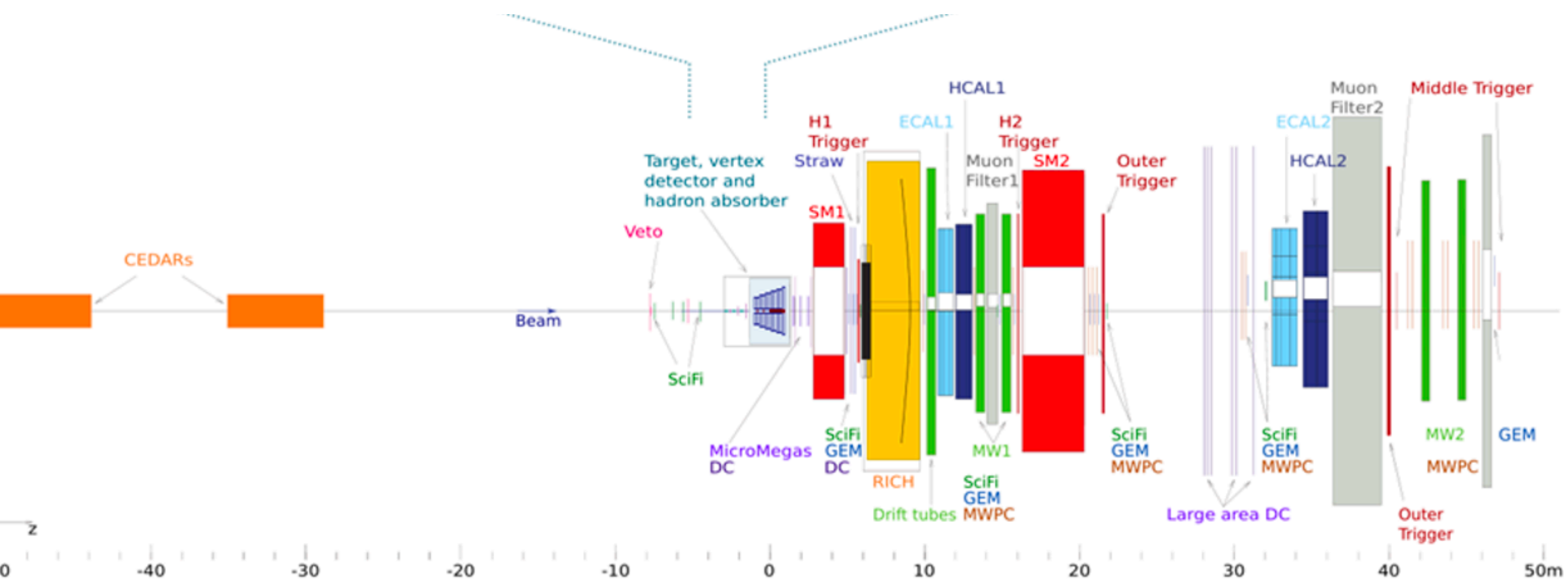
AMBER Proposal



Pion-induced Drell-Yan at AMBER







Drell-Yan process is a low cross-section process:

High intensity hadron beam

Hadron absorber to protect Spectrometer from a very high secondary flux

Vertex Detector to compensate losses in resolution because of the absorber, to improve mass and space resolution

Large surface: ±20cm

CEDARs

π-K separation beneficial for π-induced DY

Essential for K-induced DY

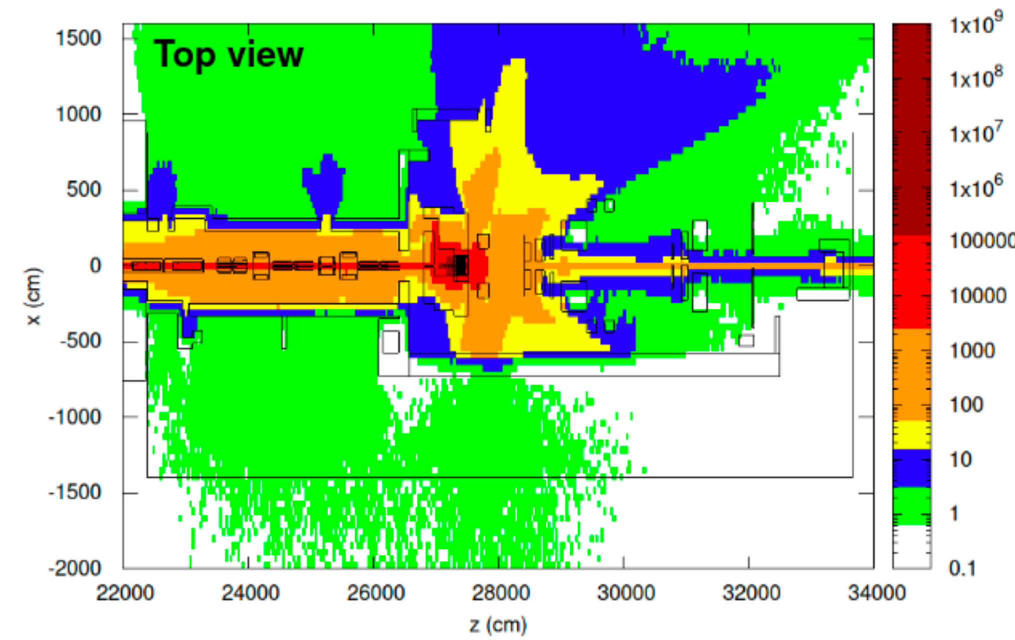
Efficient majority discrimination

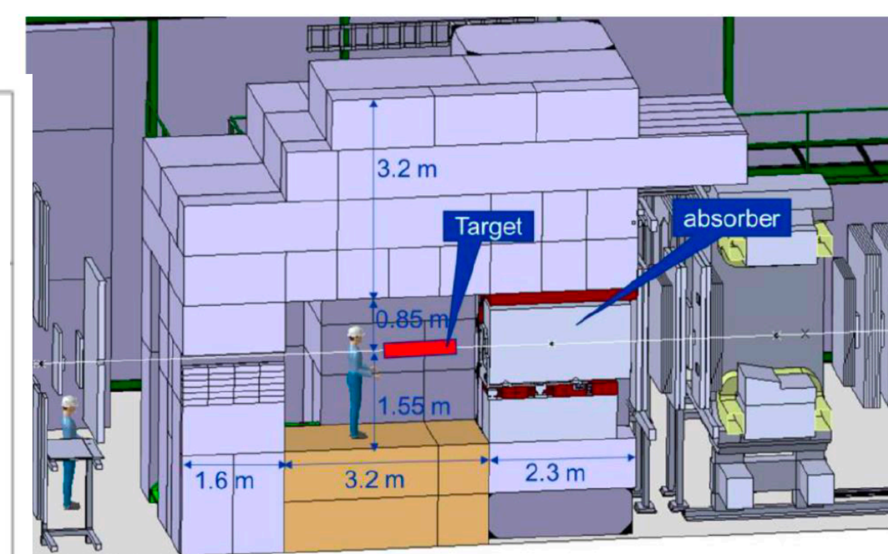
—> low divergence

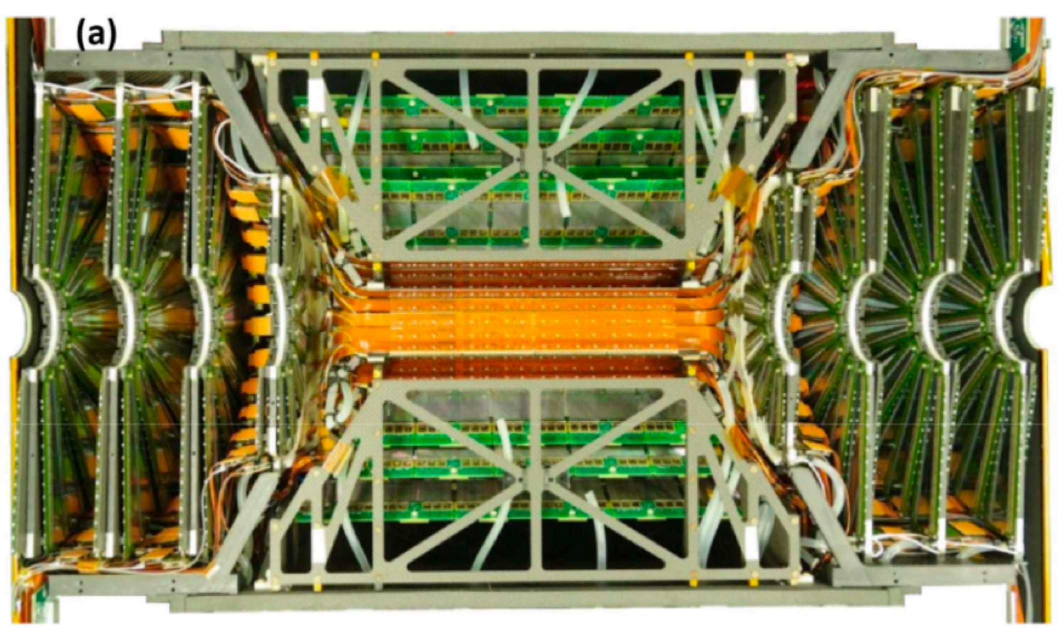
Experimental challenges

Required instrumental upgrades

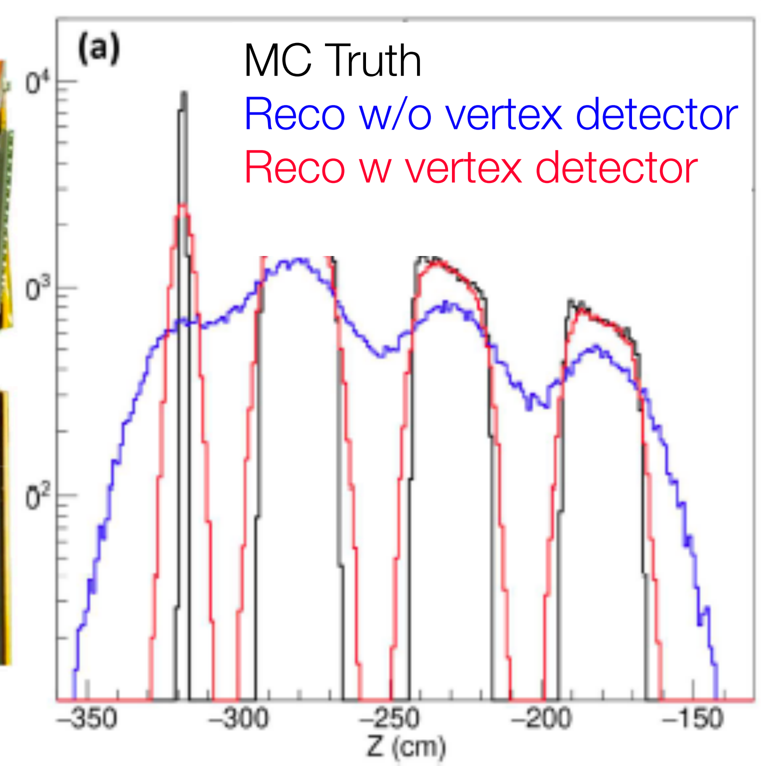
- Radioprotection upgrades for high intensity beam
- Verification of CEDAR-based beam-PID efficiency at high intensity
- Good vertex resolution by silicon vertex detectors -> improve mass resolution







FVTX detector from PHENIX@RHIC (LANL)



J/ψ production: an access to the pion gluon content

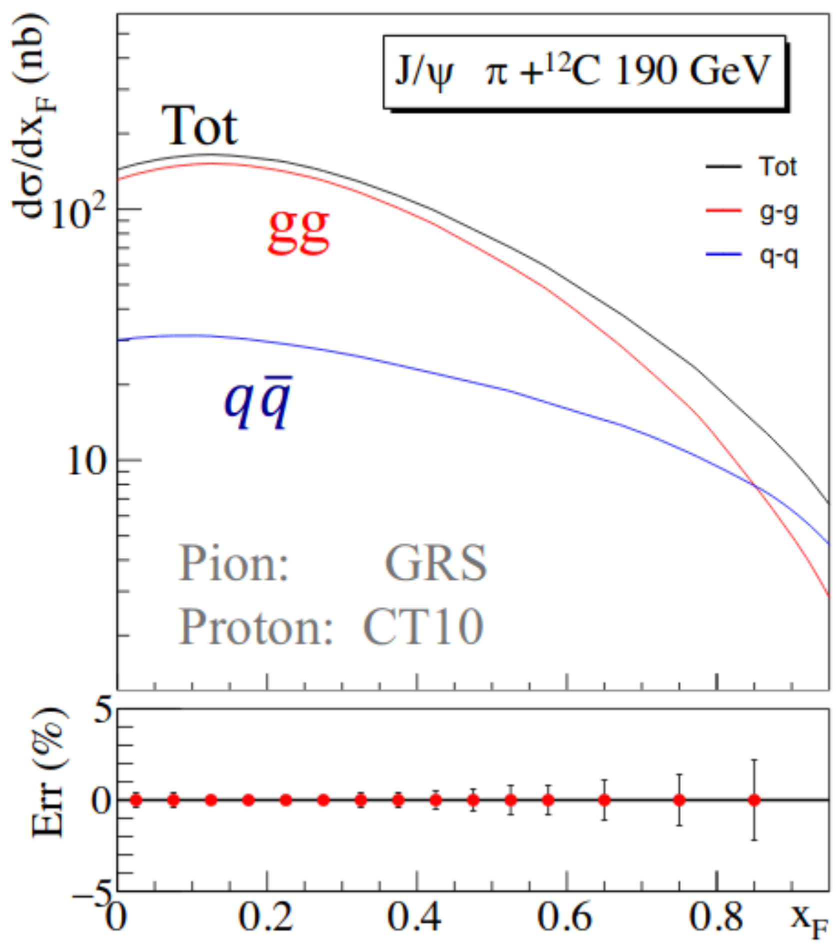
Two main mechanisms of J/ψ production in hadron collisions: *$gg \to gJ/\psi$ and $\bar{q}q \to J/\psi$*

1) test of charmonia production mechanisms: CEM vs NRQCD

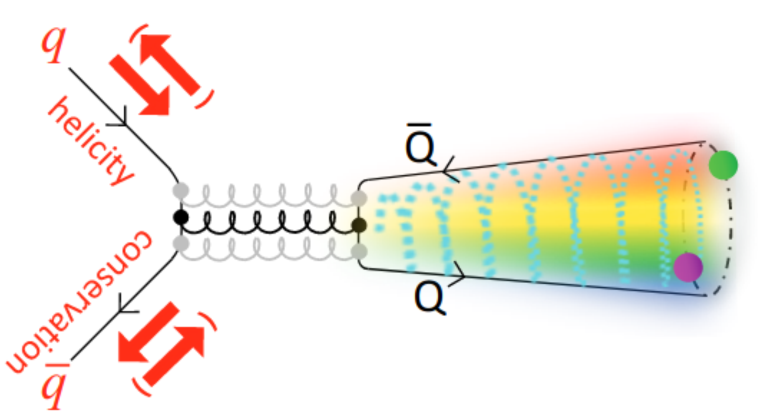
2) Model-dependent separation of gg and qq contributions using data collected with both positive and negative beams

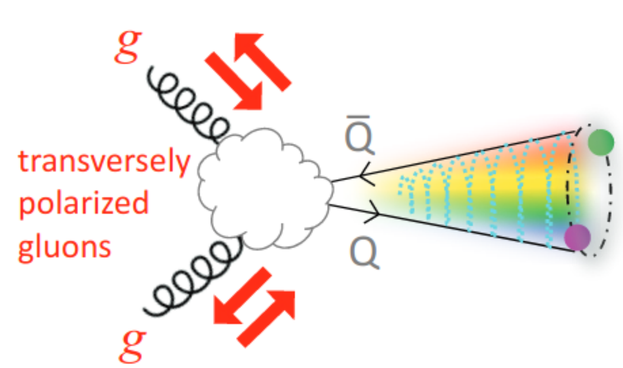
3) probe of gluon and quark PDFs

@AMBER: large statistics J/ψ production at dimuon channel, differential cross-section measurements, low-pT regime, expected significant feed-down: ψ(2S), χ_{c1}, χ_{c2}



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



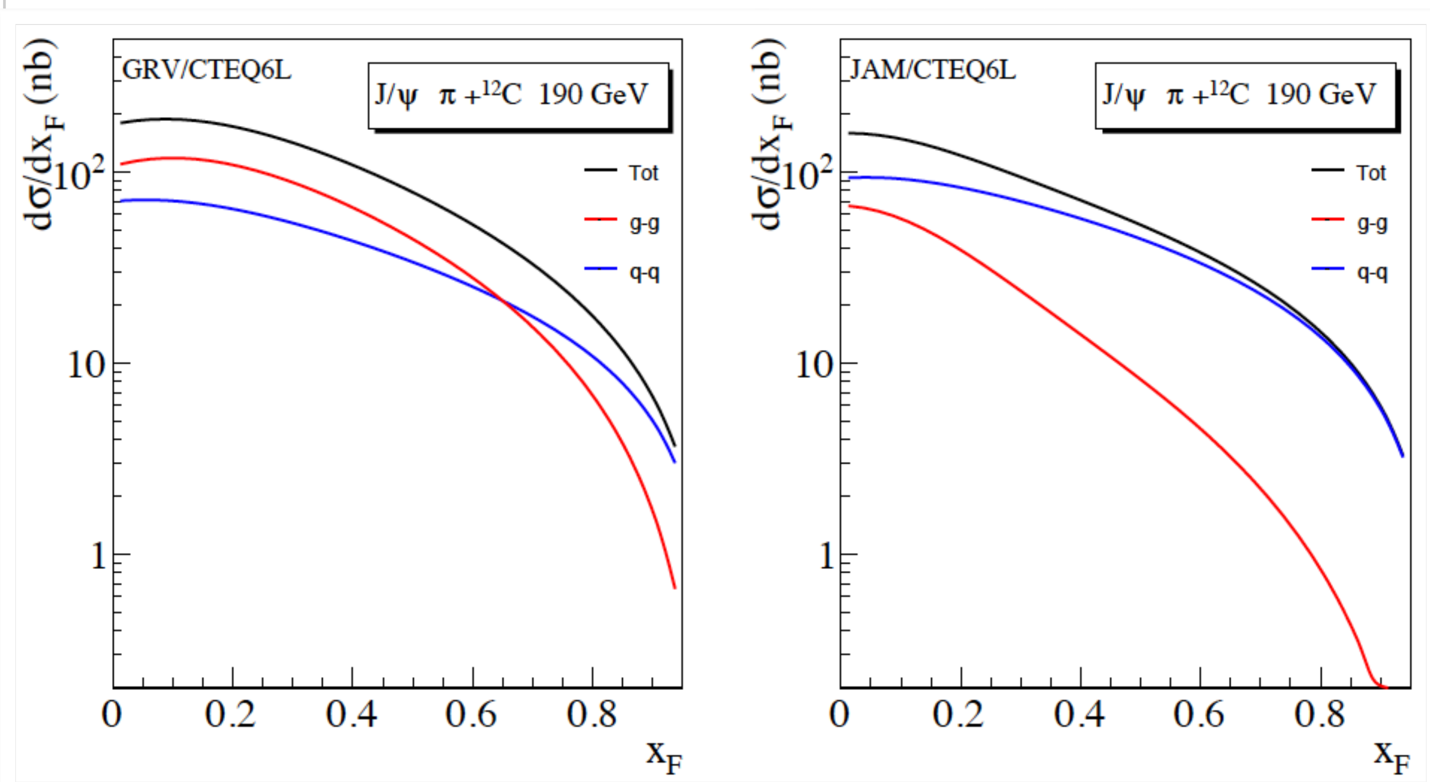


J/ψ production: an access to the pion gluon content

In the energy domain of AMBER and for sufficiently high x_F values, the $q\bar{q}$ component has a magnitude comparable or larger to that of the gg component.

The relative amount of both components is given by the overall amplitude and shape of the corresponding quark and gluon densities in the Bjorken-x region between 0.05 and 0.95 for the pion and between 0.05 and 0.4 for the nucleon.

Data may be used to infer the gluon distribution in the pion, within the uncertainties of the hadronization model.



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
AMBER	75 cm C	190	π^+	1200000
			π^-	1800000
			p	1500000
	12 cm W	190	π^+	500000
			π^-	700000
			p	700000

What do we know about kaon structure?

Sole measurement from NA3

J. Badier et al., PLB93 354 (1984)

- 200 GeV K^- beam on 6 cm Pt target
- 700 kaon-induced Drell-Yan events

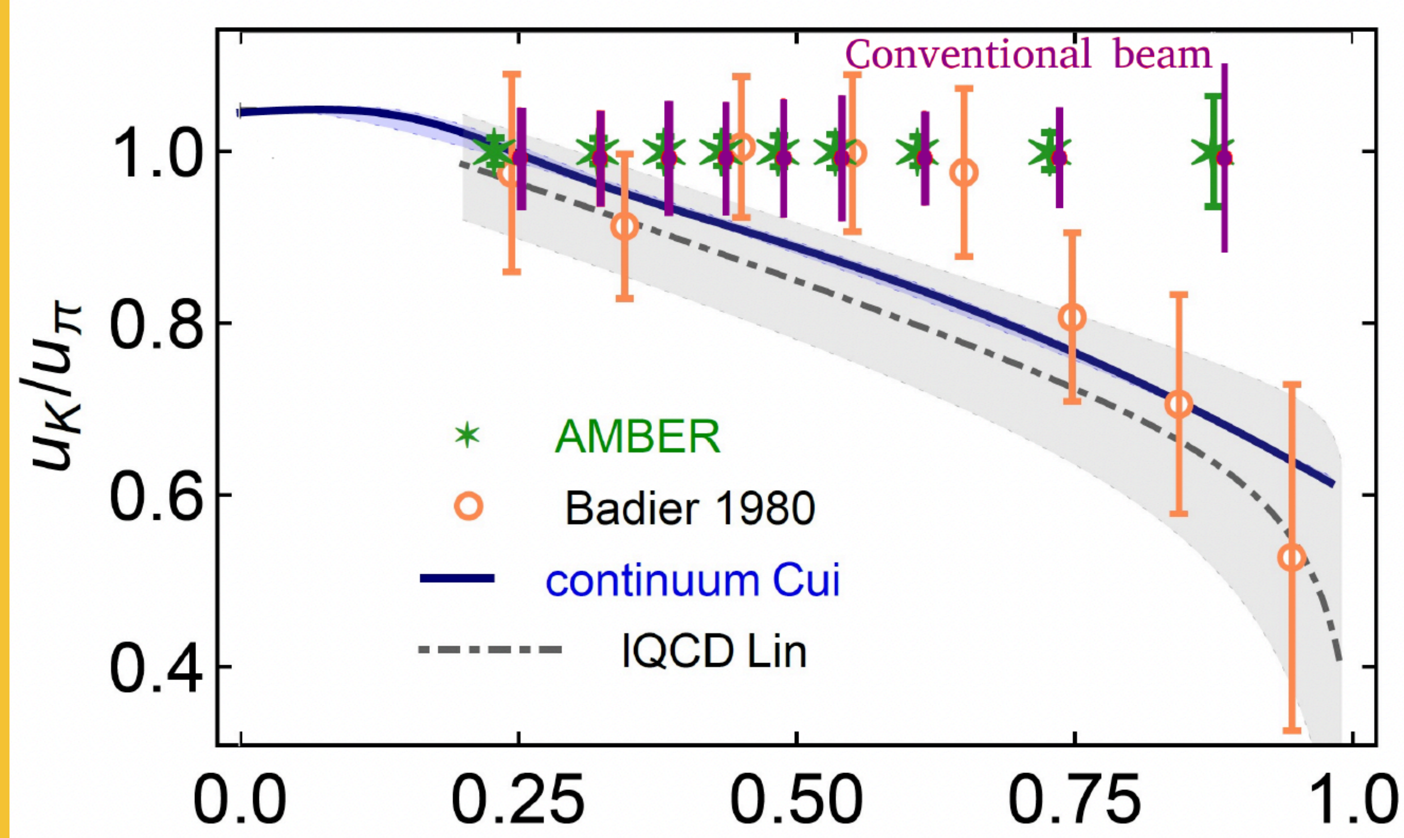
Interesting hint: At hadronic scale gluons carry only 5% of K's momentum vs 30% in π

- Scarce data on u-valence
- No measurements on gluons
- No measurements on sea quarks

➤ How to improve the situation?

With a conventional beam – from improved beamline and beam telescope – the AMBER statistics goal scales down, but there would be important gain wrt NA3.

Z-F. Cui, *et al.* EPJC80(2020)1064, H-W. Lin *et al.*, PRD103(2021)014516



* AMBER (LoI):
Assumed an RF-separated beam of 2 x 10^7 kaons/second.

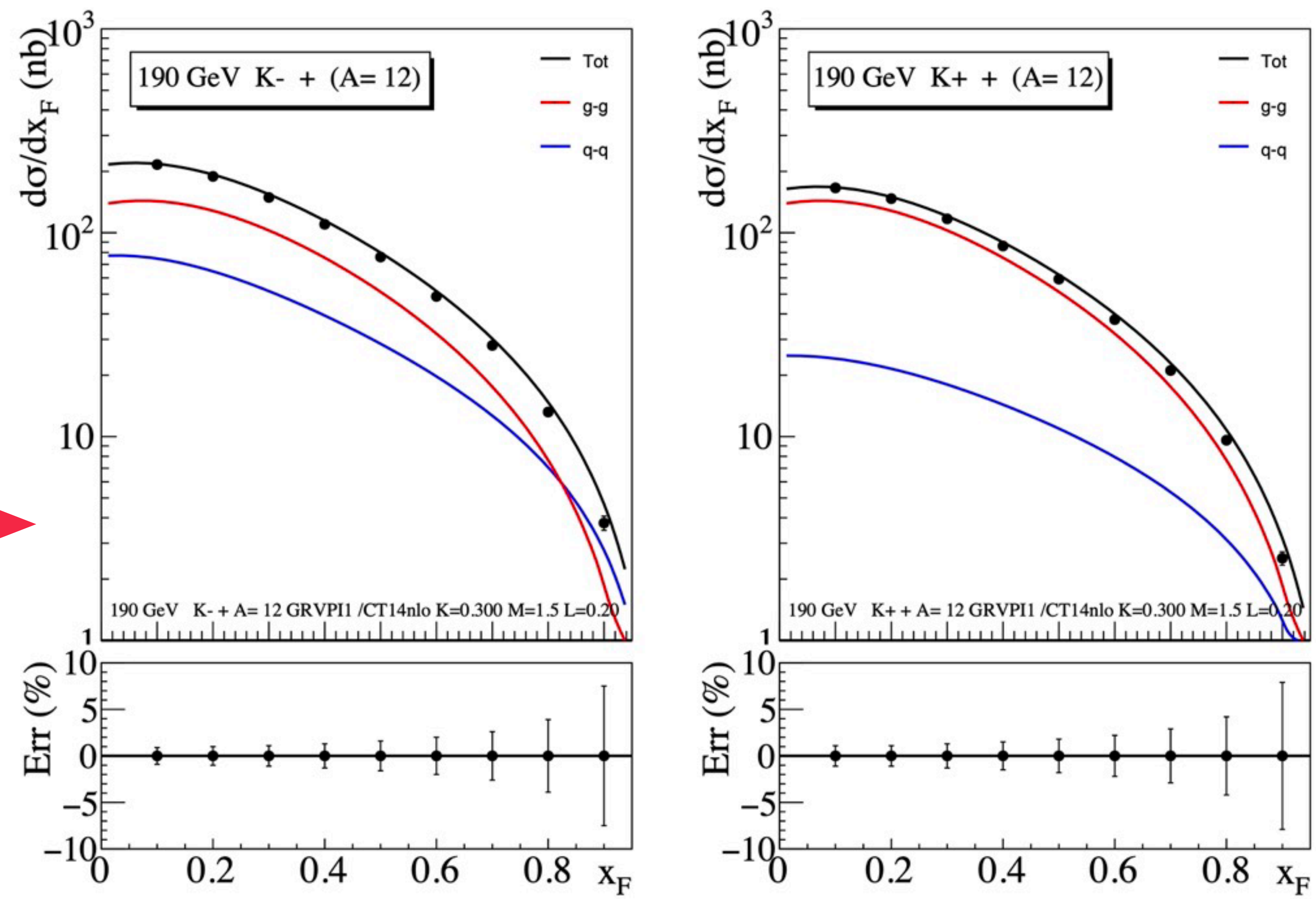
But: how high can the beam intensity be?
Not enough for kaon-induced Drell-Yan…

kaon-induced Drell-Yan and J/ψ production at AMBER

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%

J/Ψ data collected in parallel with kaon-induced Drell-Yan



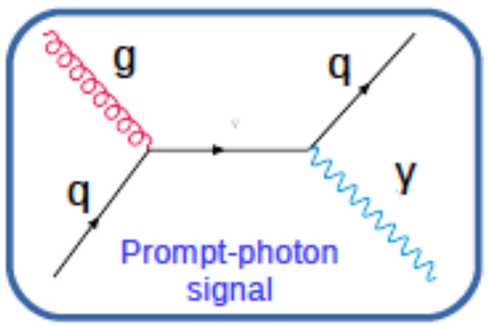
- Large statistics
- Model-dependent access to the gluon distribution in kaons

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

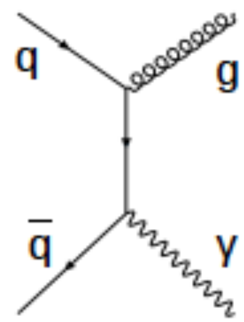
kaon-induced prompt-photon production at AMBER

clean access to the gluon distribution in kaon

- ➤ 100 GeV K+ beam on a long LH2 target

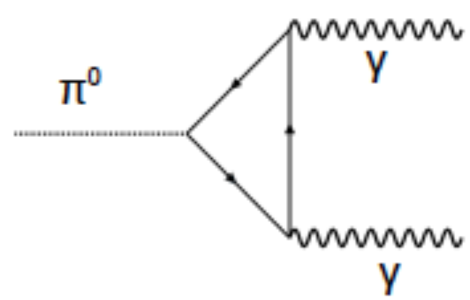


Direct access to the gluon PDF at $x_g^K > 0.05$, $Q^2 \sim p_T$



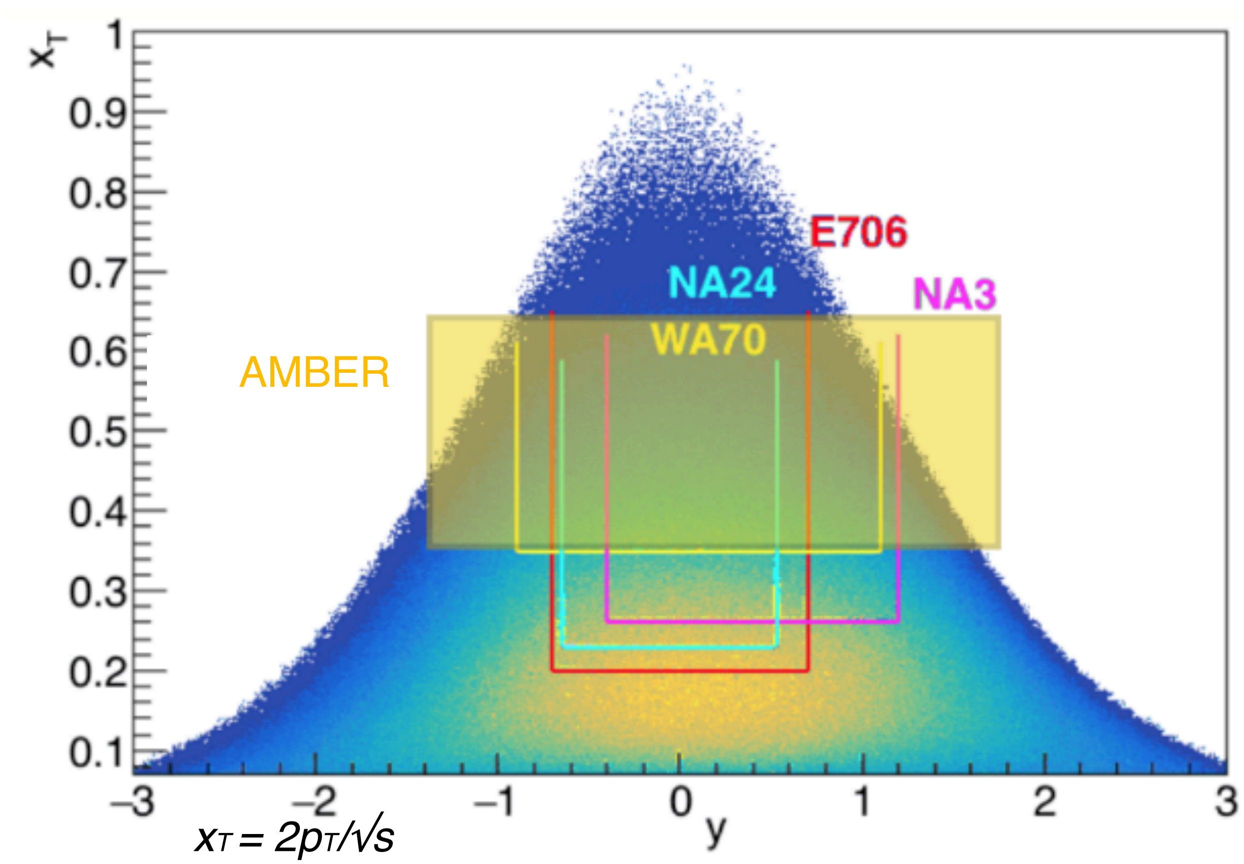
background

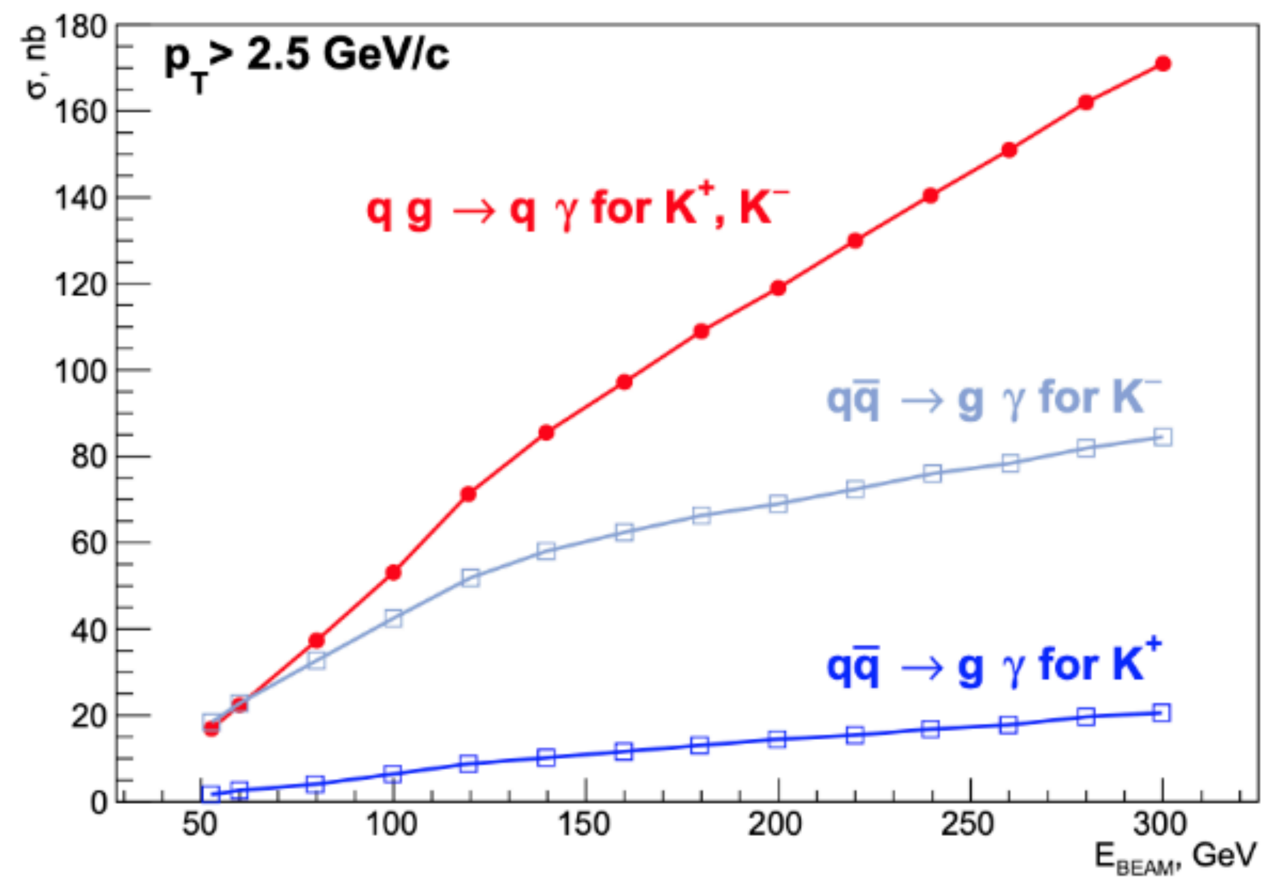
K^+ beam: minimize bkg



Minimum bias photons background

p_T^γ>2.5 GeV/c:
minimize photon bkg

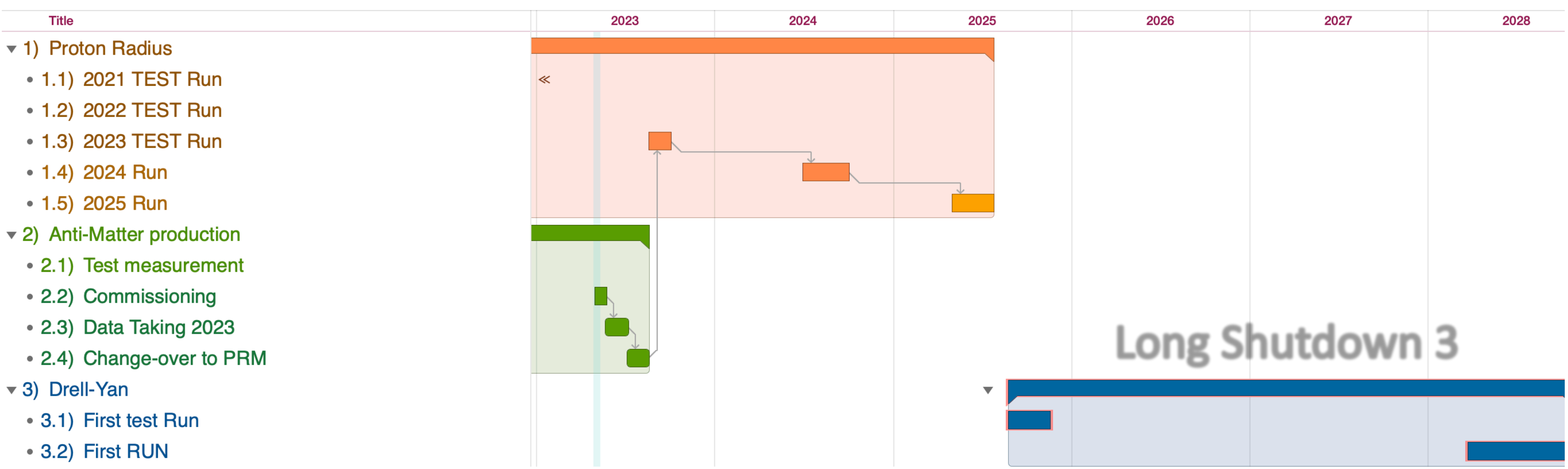




AMBER Phase-1 running plan

Milestones

1. May 1st 2023 – Antimatter production Run (Std. DAQ)
2. Sep. 1st 2023 – PRM pilot (FreeDAQ, very limited setup)
3. May 1st 2024 – PRM Run (FreeDAQ, limited setup)
4. Sep. 1st 2025 – DY Pilot (FreeDAQ, all trackers + mu id)
5. May 1st 2028 – DY Run (Full Spectr. Ex. RICH, Calorimeters)



Summary

@ AMBER

A future experiment to study meson structure

- Pion structure from pion-induced Drell-Yan and Charmonium production
- Kaon structure from kaon-induced Drell-Yan and Charmonium production, gluon content in the kaon from direct-photon production

Unique opportunity:

—> high-energy pion/kaon beams exclusively available at CERN so far

—> both positive and negative beams – very important!

—> large and uniform acceptance spectrometer

Thank you for your attention!