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Hadron Physics with AMBER at CERN

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Technical University of Munich

27 September 2021
On behalf of the AMBER Collaboration

Open Questions in Hadron Physics

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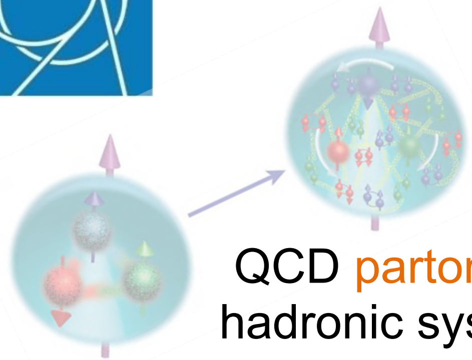
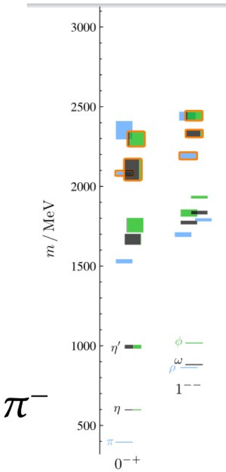
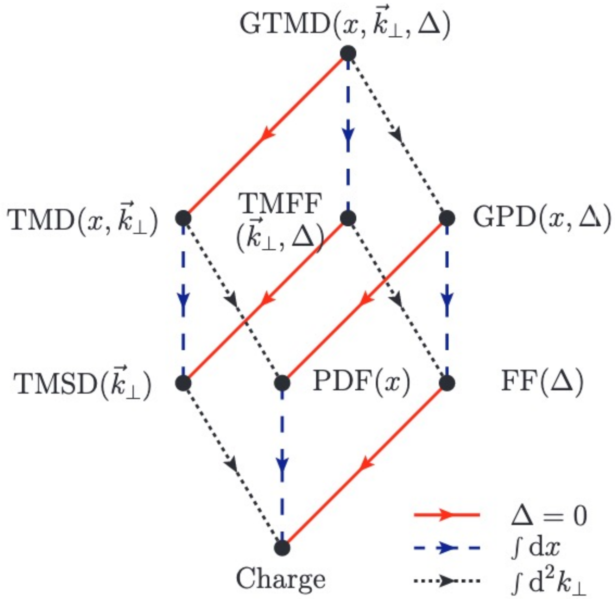
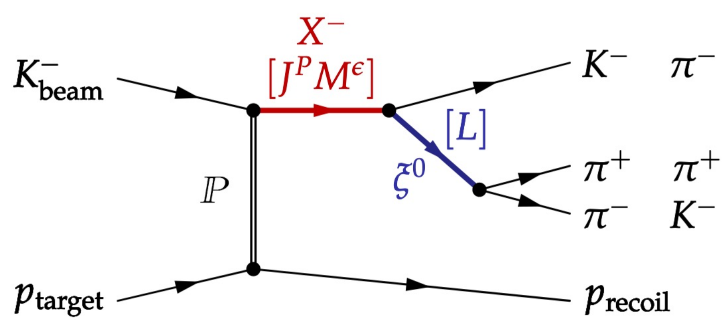


QCD partons in hadronic systems

The excitation scheme of hadronic systems







$$J^{PC}_{X^-} M^\varepsilon \xi \pi L$$

The complete picture: Wigner distributions

Measurable quantities: (iso)spin-parity, masses, couplings and decay widths

[from: Lorcé, Pasquini, Vanderhaeghen, JHEP05 (2011)]

[from: Grube, EHM workshop (2020)]

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A fundamental question: how do the hadron masses come about?

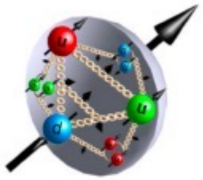
Pion

- $M_\pi \sim 140$MeV
- Spin 0
- 2 light valence quarks

Kaon

- $M_K \sim 490$MeV
- Spin 0
- 1 light and 1 “heavy” valence quarks

Proton



- $M_p \sim 940$MeV
- Spin 1/2
- 3 light valence quarks

- As composite systems, hadrons are to be understood in terms of their constituents: the QCD quarks and gluons
- The Higgs mass of the valence quarks contributes only little to the physical hadron masses
- Pion-to-proton mass ratio 1/7 much different from the constituent-quark inspired value of 2/3

Emergent Hadron Mass
and how to better understand it

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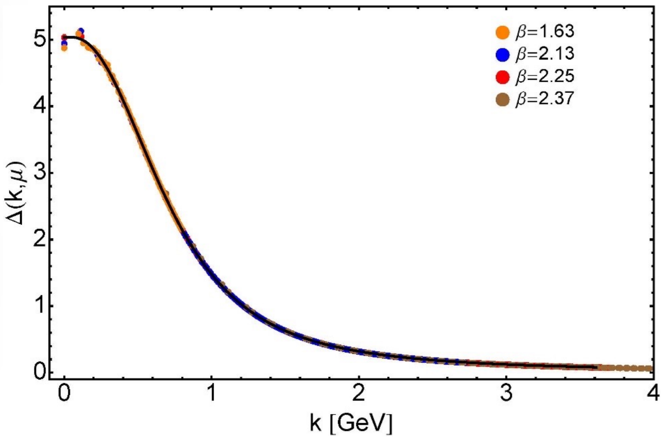
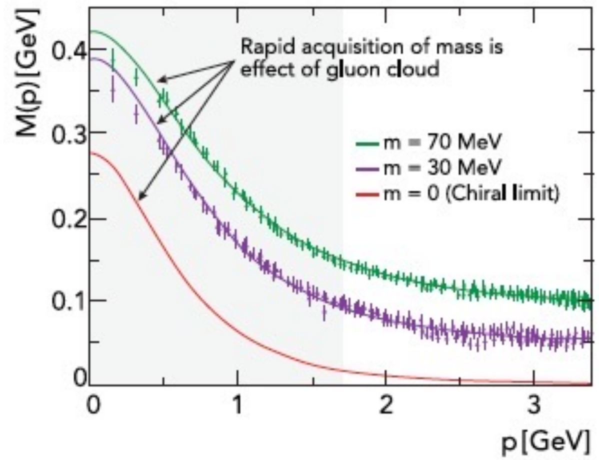
- Dynamic generation of mass in continuum QCD
- Gluon self-interaction in the infra-red leads to gluon "self-mass generation"





- Emergence of Hadron Mass is to some extent understood within continuum and lattice QCD calculations
- Prove and provide more input by measurement of
  - Quark and gluon PDFs of pion, kaon and proton
  - Hadron radii as consequence of confinement
  - Mass spectra of excited mesons

EHM for proton, pion and kaon

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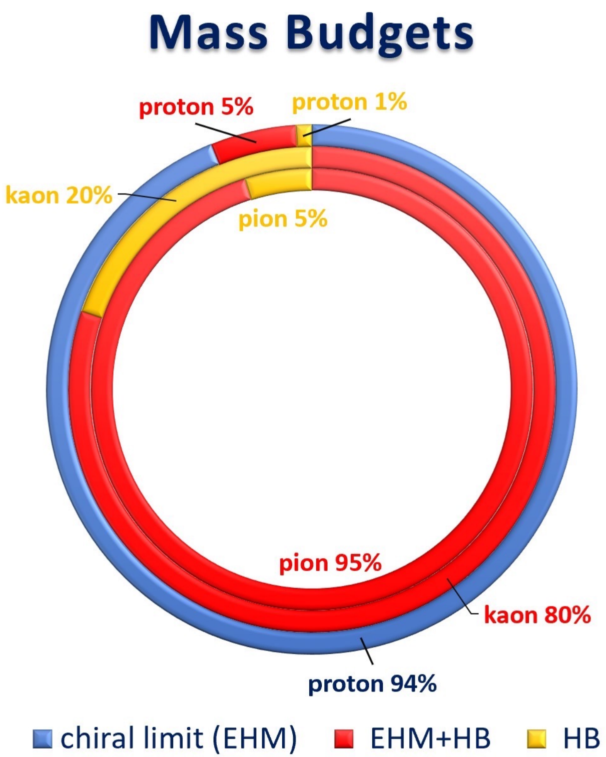
- The mass composition of the proton is structurally different from that of pions and kaons
- Pions and kaons are the Nambu-Goldstone bosons of the (approximate and spontaneously broken) chiral symmetry of strong interaction
- In the chiral limit
  - the mass of the proton remains basically unchanged
  - pions and kaons are massless

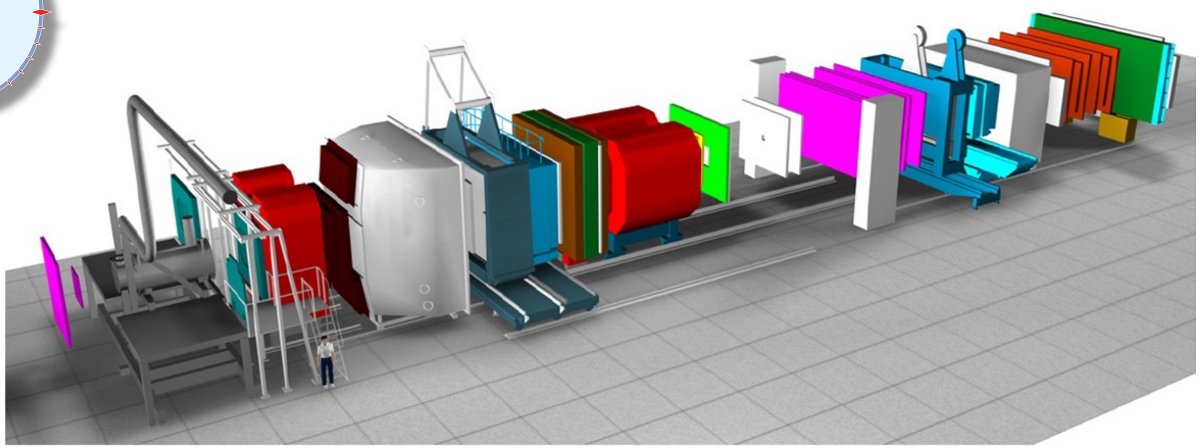
Thus for a full understanding the partonic structure of hadrons, the meson PDFs must be known on a similar level as those of the nucleon

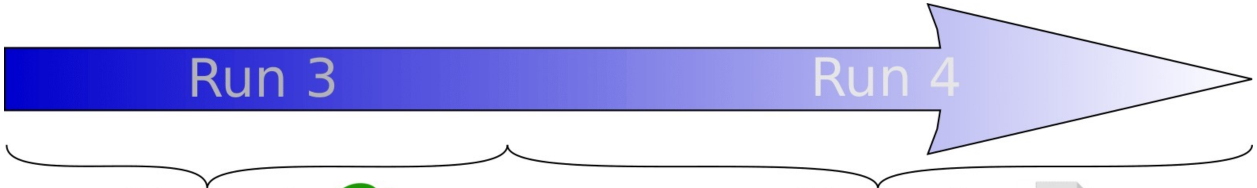


A new **AMBER**

Apparatus for **M**eson and **B**aryon **E**xperimental **R**esearch

- Successor of COMPASS
- with appropriate extensions and modernisations
- at the CERN M2 beamline





Phase-1 Proposal

- Submitted 2018
- Approved by the CERN Research Board in Dec 2020

Phase-2

- Submission planned for Jan 2022

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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	$4\cdot10^6$	100	$\mu^\pm$	high-pressure H2	2022 1 year	active TPC, SciFi trigger, silicon veto,
Hard exclusive reactions	GPD E	160	$2\cdot10^7$	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	$5\cdot10^5$	25	p	LH2, LHe	2022 1 month	liquid helium target
$\overline{p}$-induced spectroscopy	Heavy quark exotics	12, 20	$5\cdot10^7$	25	$\overline{p}$	LH2	2022 2 years	target spectrometer: tracking, calorimetry
Drell-Yan	Pion PDFs	190	$7\cdot10^7$	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	$5\cdot10^6$	> 10	K^-	Ni	non-exclusive 2026 1 year	
Prompt Photons (RF)	Meson gluon PDFs	≥ 100	$5\cdot10^6$	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	$5\cdot10^6$	25	K^-	LH2	2026 1 year	recoil TOF, forward PID
Vector mesons (RF)	Spin Density Matrix Elements	50-100	$5\cdot10^6$	10-100	$K^\pm, \pi^\pm$	from H to Pb	2026 1 year	

Table 2: Requirements for future programmes at the M2 beam line after 2021. Muon beams are in blue, conventional hadron beams in green, and RF-separated hadron beams in red.

Phase-1
with conventional hadron and muon beams
2022 → 2028

Phase-2
with conventional and rf-separated beams
2029 and beyond

Proton radius measurement

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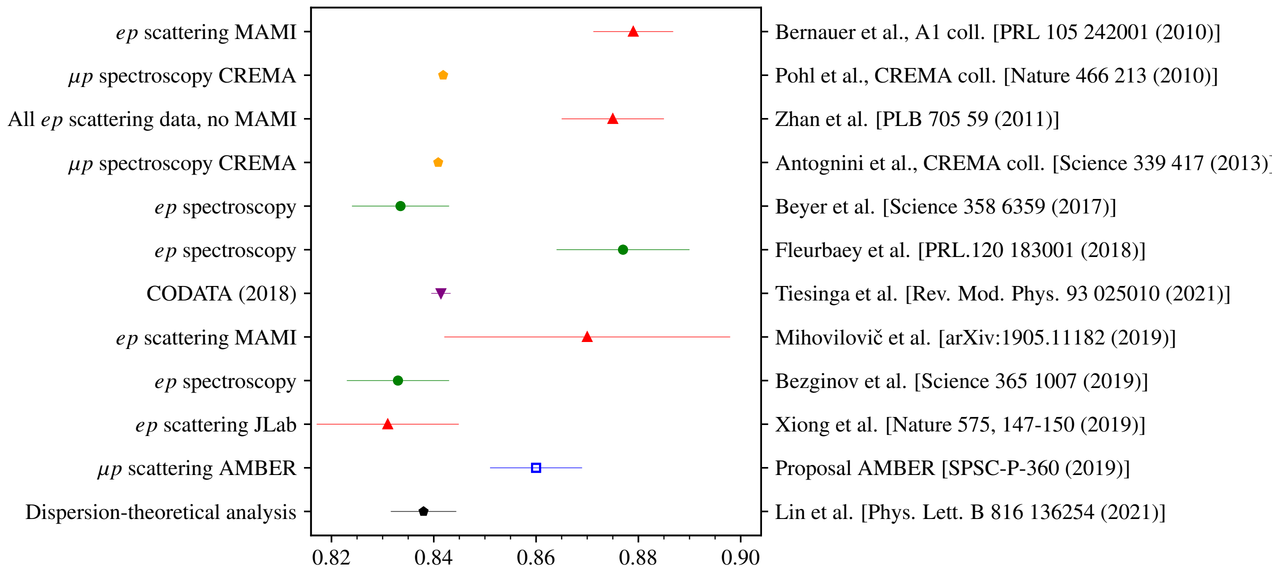

	ep	μp
Spectroscopy	New measurements with ▪ lower systematics ▪ new transitions	✔
Scattering	New measurements with ▪ lower systematics ▪ reaching lower Q^2 ProRAD, ULQ2, ISR @ MESA, PRad	No data yet. MUSE at PSI coming soon

μp scattering:

- Different systematic uncertainties
- small radiative corrections

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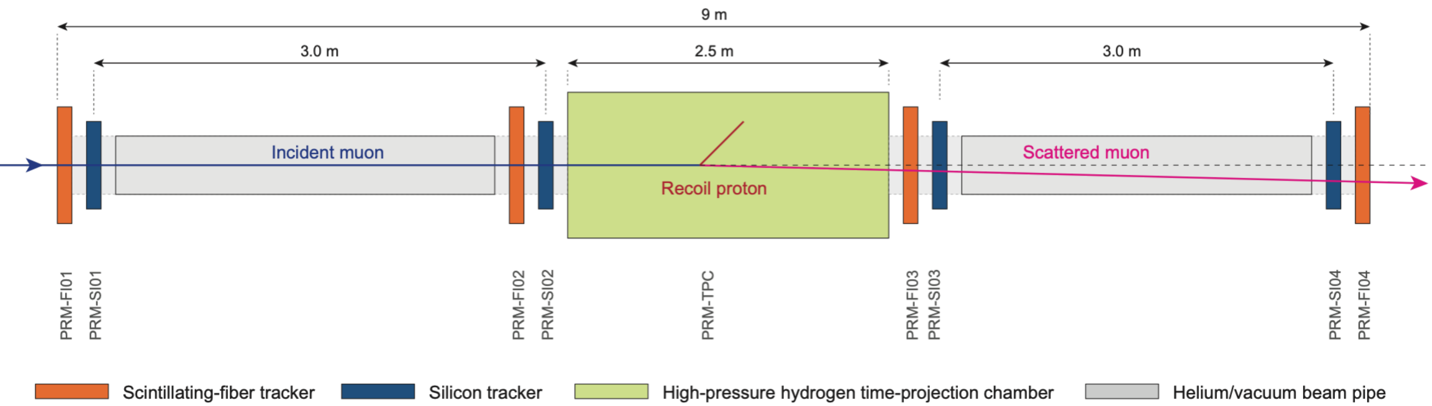
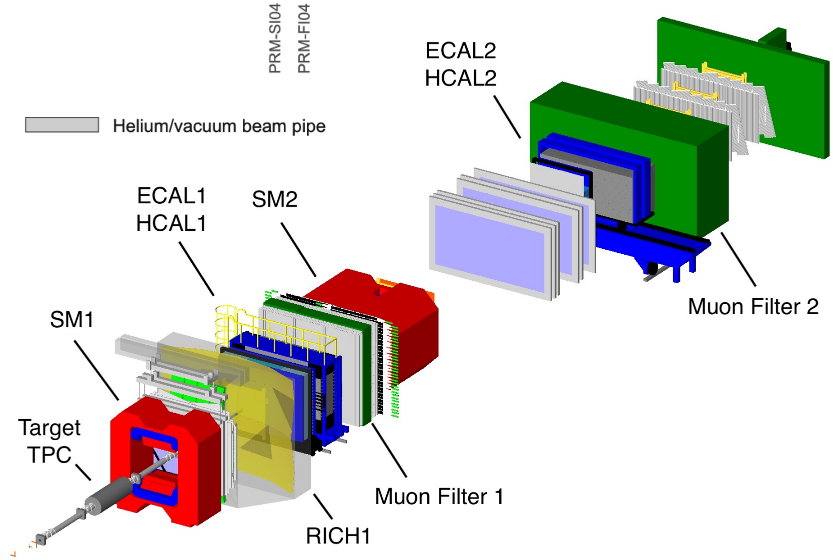
Muon-proton scattering at high energy





- 100 GeV muon beam
- Active-target TPC with high-pressure H_2
- goal: 70 million elastic scattering events in the $10^{-3} < Q^2 < 4 \cdot 10^{-2}$ GeV^2 range
- Precision on the proton radius ~0.01 fm
- Pilot run with smaller TPC in 2021

Precision on the proton form factor measurement with 100 GeV muons

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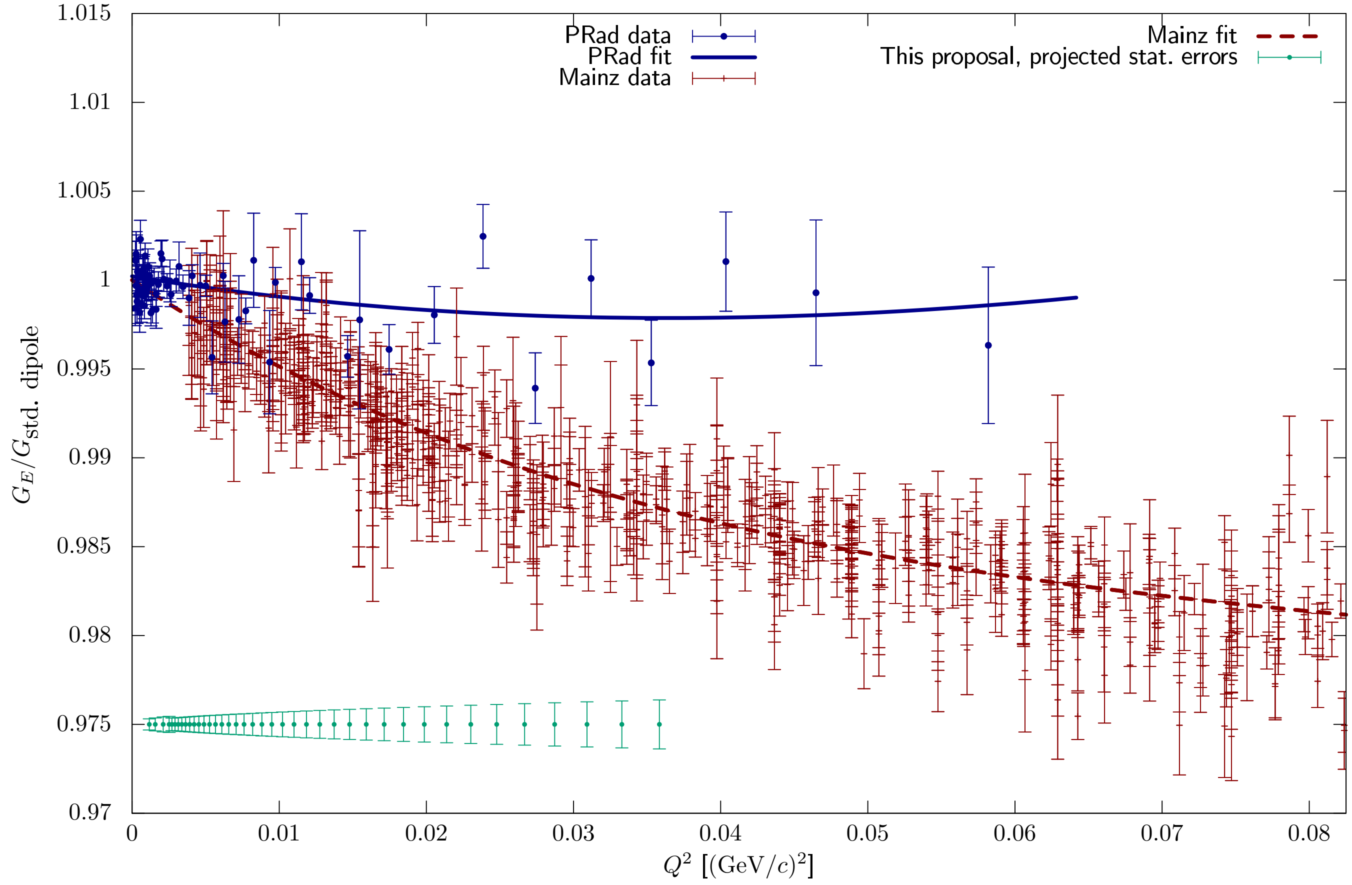

Search for Dark Matter

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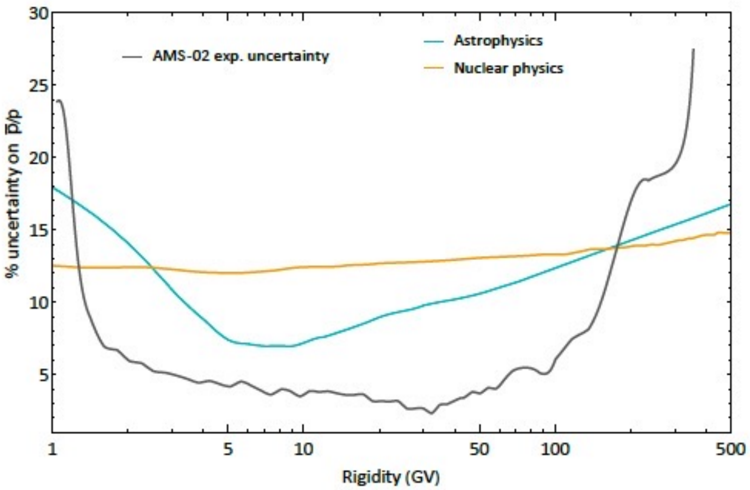
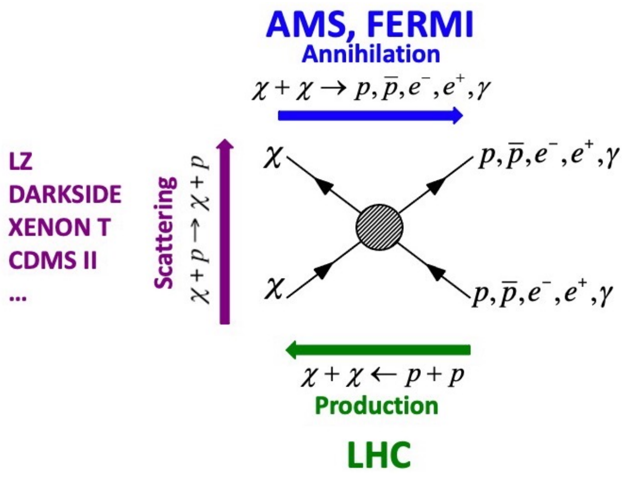
- New AMS(2) data – the antiparticle flux is well known now (few % prec.) (http://dx.doi.org/10.1103/PhysRevLett.117.091103)
- Two types of processes contribute – SM interactions (proton on the inter-stellar matter with the production for example of antiprotons) and contribution from dark particle – antiparticle annihilation;
- In order to detect a possible excess in the antiparticles flux a good knowledge of inclusive cross sections of p-He interaction with antiparticles in the final state is a must, currently the typical precision is of 30-50%.





AMBER proton beam: from a few tens of GeV/*c* up to 250 GeV/*c*, in the pseudo-rapidity range $2.4 < \eta < 5.6$. Goal is to measure the doubly differential (momentum and pseudo-rapidity) antiproton production cross section from p+H and p+He at different proton momenta (50, 100, 190, 250 *GeV/c*).

Antiproton production cross section

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The impact of the proposed p + p measurements on constraining the production of cosmic anti-protons versus their kinetic energy. Each curve represents the fraction of anti-proton production phase space as constrained by AMBER cross section measurements in p-p, p-He and He-p channels, compared to NA61 (p-p) and LHC-b (p-He) measurements

p-H channel, in three different energy ranges

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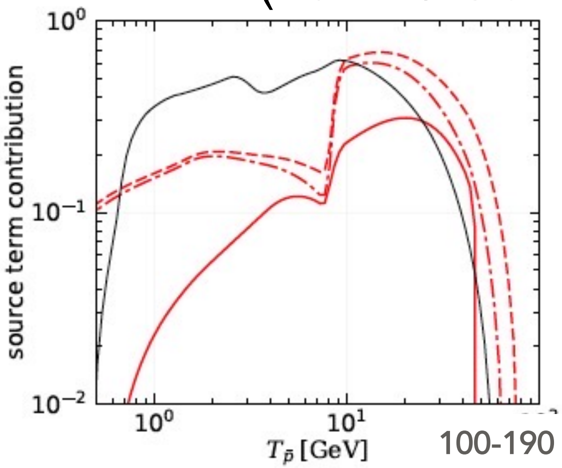
NA61 (20-158 GeV/c)



100-190 GeV/c

50-190 GeV/c

50 - 250 GeV/c

p-He and He-p channels

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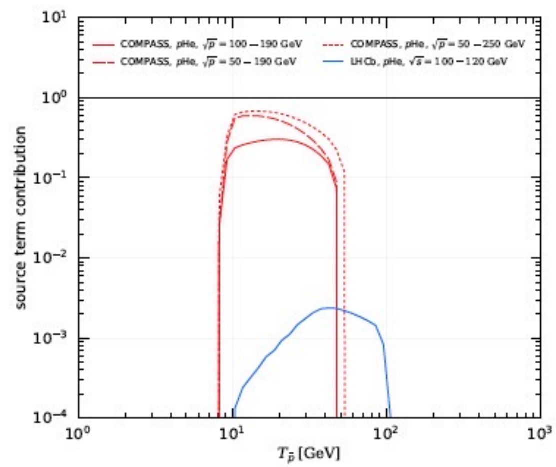
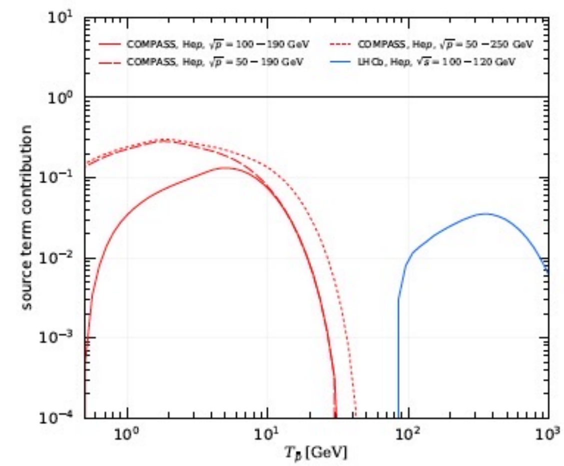
LHCb





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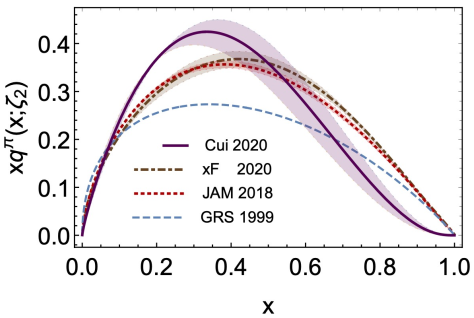
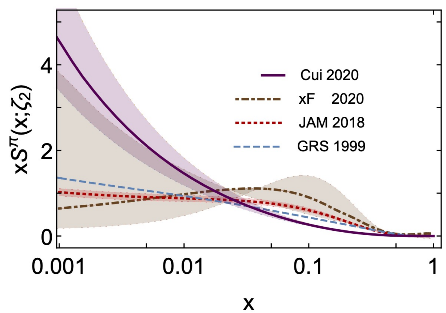
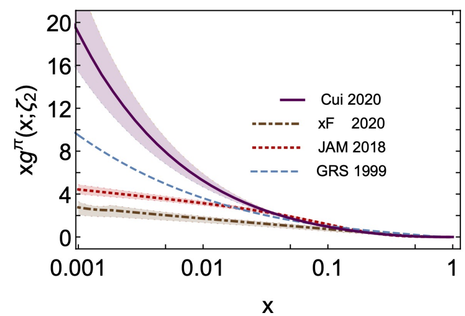
Pion-induced Drell-Yan
Status of knowledge of the pion structure

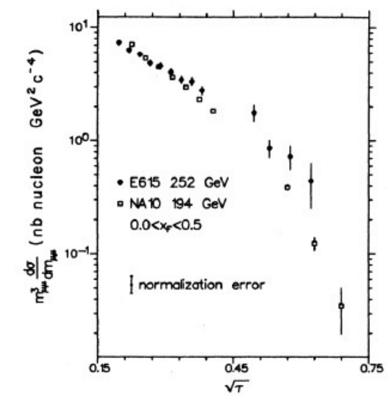
valence quarks *sea quarks* *gluons*







From: E615, PRD 1989



plots from: Chang & Roberts, arXiv:2106.08451v1

Pion structure status:

- Scarce data, poor knowledge of valence, sea and glue basically unknown
- Mostly heavy nuclear targets: large nuclear effects
- For some experiments, no information on absolute cross sections
- Two experiments (E615, NA3) have measured so far with both pion beam signs, but only one (NA3) has used its data to separate sea-valence quark contributions
- Discrepancy between different experiments (i.e. NA10, E615)
- Old data, no way to reanalyse them using modern approaches

Probing valence and sea quark distributions of the pion

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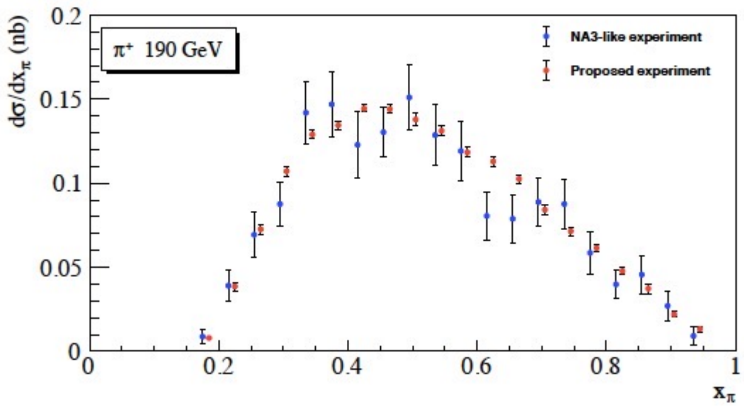
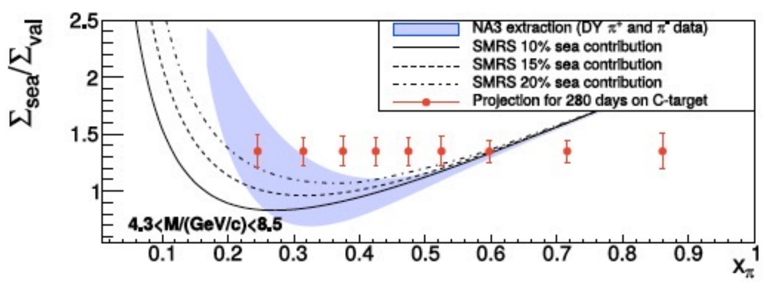
- Pion structure in pion induced DY
- Expected accuracy as compared to NA3





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*

Pion-induced J/ψ production

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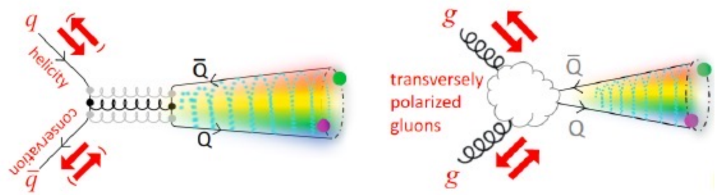
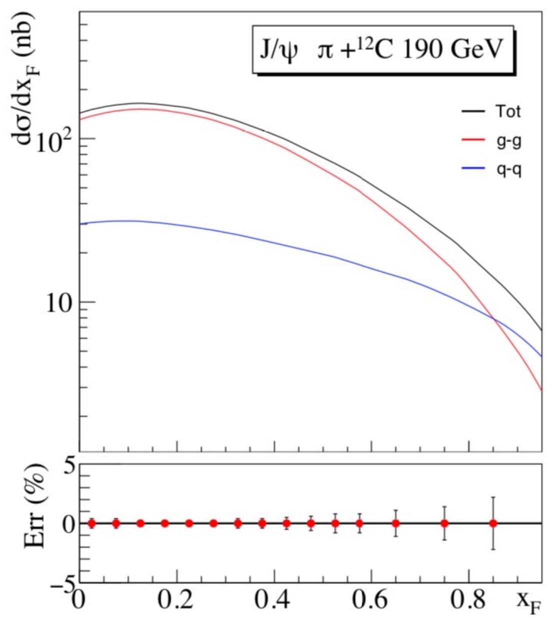


- simultaneously collected with DY data, with large counting rates

Cheung and Vogt, priv. comm.

Physics objectives:

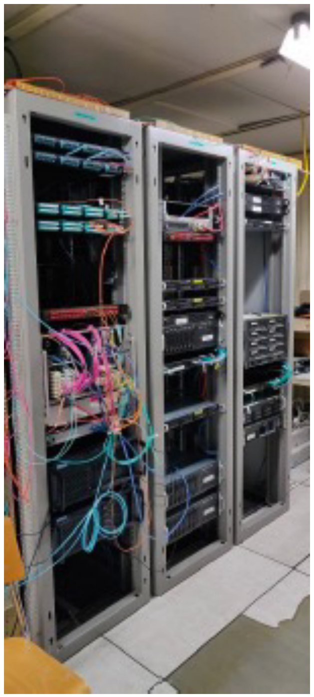
- Study of the J/ψ (charmonia) production mechanisms (gg–fusion vs $q\bar{q}$–annihilation), comparison of **CEM** and **NRQCD**
- Probe gluon and quark PDFs of pion
- arXiv:2103.11660v1
- Ψ(2S) signal study, free of feed-down effect from χ_{c1} χ_{c2}



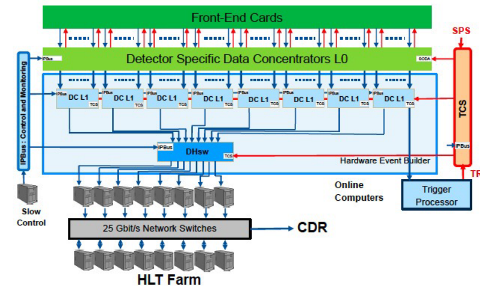
Improved CEM, CT10 + GRS99 global fit for proton/pion

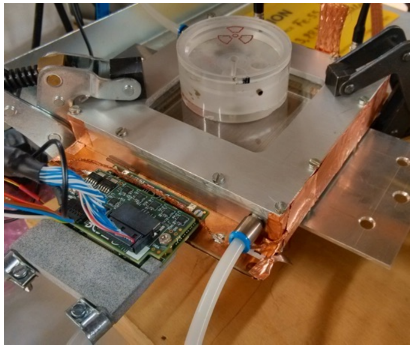
Experiment	Target type	Beam energy (GeV)	Beam type	J/ψ events
NA3 [76]	Pt	150	π^-	601000
		280	π^-	511000
		200	π^+	131000
			π^-	105000
E789 [129, 130]	Cu	800	p	200000
	Au			110000
	Be			45000
E866 [131]	Be, Fe, Cu	800	p	3000000
NA50 [132]	Be	450	p	124700
	Al			100700
	Cu			130600
	Ag			132100
	W		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

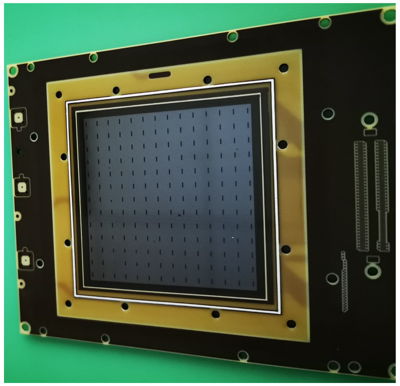
Hardware developments

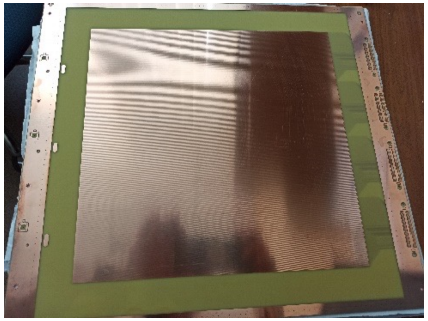


- New triggerless DAQ system, new front-end electronics and trigger logic compatible with triggerless readout
- New large-size PixelGEM detectors
- New large-area micro-pattern gaseous detectors (MPGD)
- High-rate-capable CEDARs detectors (beam line)
- A new RICH-0 detector to extend significantly phase space coverage (lower momenta)









Phase-1 hardware developments

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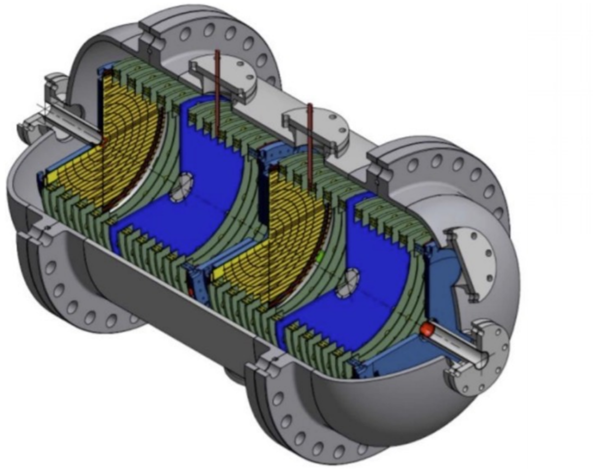
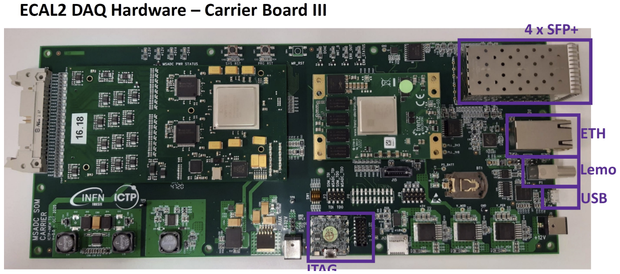
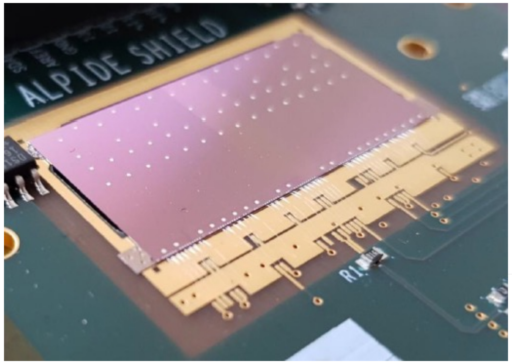
- High-pressure hydrogen filled active TPC (PRM)
- Combined scintillating fibres / silicon tracking system (4 stations) (PRM)
- Triggerless electromagnetic calorimeter electronics (PRM)

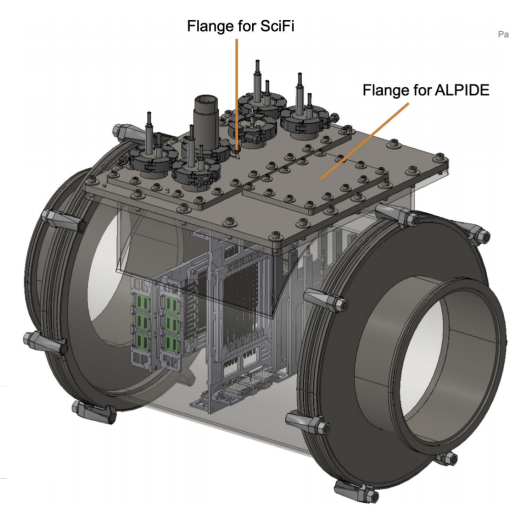
- High rate capable silicon-based vertex detector (DY)
- New high-purity and high efficiency di-muon trigger (DY)



ECAL2 DAQ Hardware – Carrier Board III







Collaboration founding

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- currently 189 full members (PhD and above) from 12 countries and ~40 institutions, growing up
- (proto-)Collaboration Board meetings since (April 2019) August 2020
- Since Feb 2021: Memorandum of Understanding writing group
- May 2021: First Collaboration Meeting

- Second Collaboration Meeting September 2021
- Initial annual budget (for 2022) ~400kCHF
- Submission of Phase-2 Proposal planned for beginning of 2022

Phase-2 Proposal: Focus on RF-separated beams

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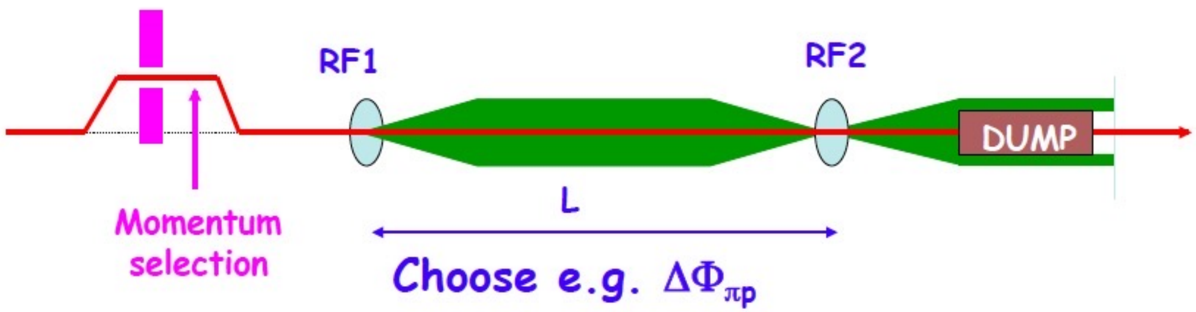
- Focus of the 1-day workshop of the CERN accelerator group on 30 September
- Major physics cases: Kaon-induced meson spectroscopy, Primakoff and Drell-Yan processes



$$\Delta\Phi = 2\pi\,(L\,f\,/\,c)\,(\beta_1^{-1} - \beta_2^{-1}) \text{ with } \beta_1^{-1} - \beta_2^{-1} = (m_1^2 - m_2^2)/2p^2$$

Particle species separation by radio-frequency modulation

A physics case with rf-separated kaon beam: kaon radius

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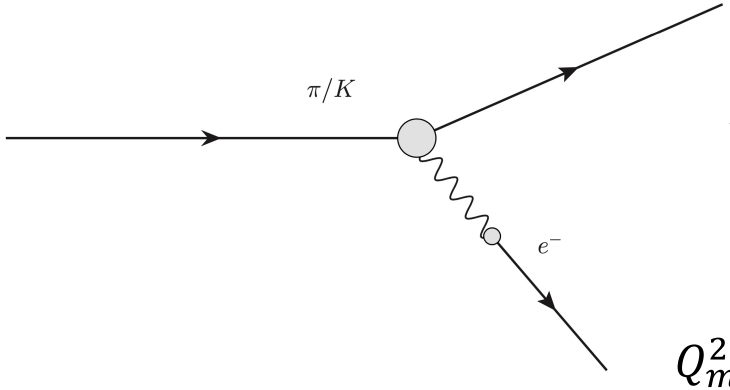

$$K^- \; e^-_{target} \rightarrow \; K^- \; e^-$$

$$s = 2E_b m_e + m_b^2 + m_e^2$$

$$Q^2_{max} = \frac{4p_b^2 \, m_e^2}{s}$$

S. R. Amendolia, et al. , Phys. Lett. B **178**, 435 (1986)

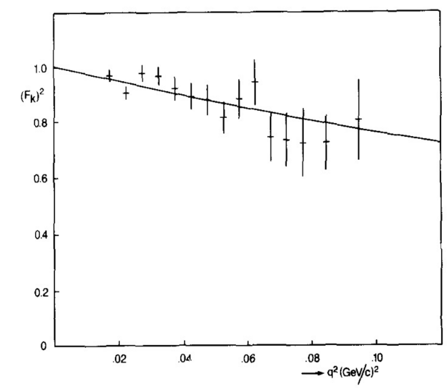

Fig. 3. The measured kaon form factor squared. The line corresponds to the pole fit with $\langle r^2 \rangle = 0.34\ \mathrm{fm}^2$.

Beam	E_b [GeV]	Q^2_{max} [GeV²]	$E'_{b,min}$ [GeV]	Relative charge-radius effect on c.s. at Q^2_{max}
π	190	0.176	17.3	~40%
K	190	0.086	105.7	~20%
	80	0.066	59.9	~15%
	50	0.037	41.3	~8%

- For kaons, a significant increase of the form factor knowledge in the range $0.001 < Q^2 < 0.07$ appears in reach with AMBER using an 80 GeV *rf-separated kaon beam*

Summary

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- NA66/AMBER is a new collaboration at CERN dedicated to hadron research at the M2 beamline
- Broad physics program from hadron radii to parton distributions in Drell-Yan processes
- Collaboration formation is ongoing - approach us if interested!

https://amber.web.cern.ch

https://home.cern/news/news/physics/meet-amber

CERN Accelerating science

ABOUT NEWS

Voir en français

Meet AMBER

The next-generation successor of the COMPASS experiment will measure fundamental properties of the proton and its relatives

8 MARCH, 2021 | By Ana Lopes

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Backup

Pion: Gluon PDF phenomenology and theory

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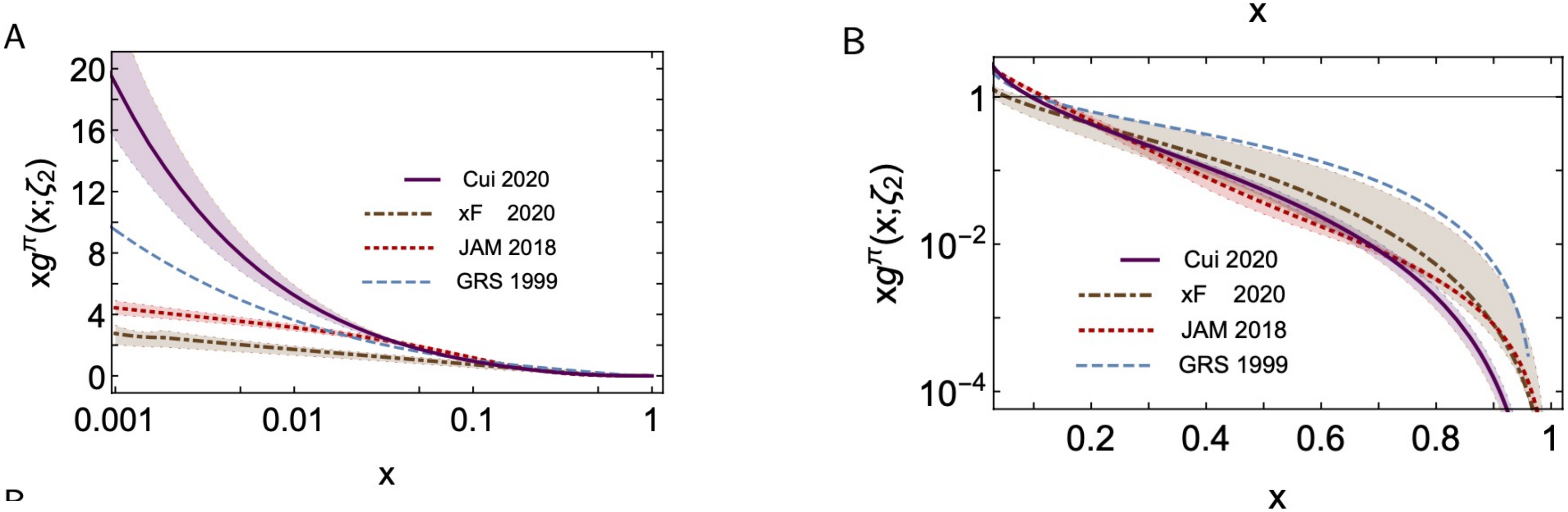

FIG. 4. Glue distribution, $xg^{\pi}(x, \zeta_2 = 2\,\text{GeV})$: solid purple curve, prediction from Ref. [43]. Panel A highlights low-x and Panel B, large-x. The band surrounding this curve expresses a conservative estimate of uncertainty in the prediction, obtained by varying ζ_H by $\pm 10\%$. Comparisons are selected fits to data: dashed blue curve, [32]; dotted red curve and associated band, [33]; dot-dashed brown curve and band, [34].

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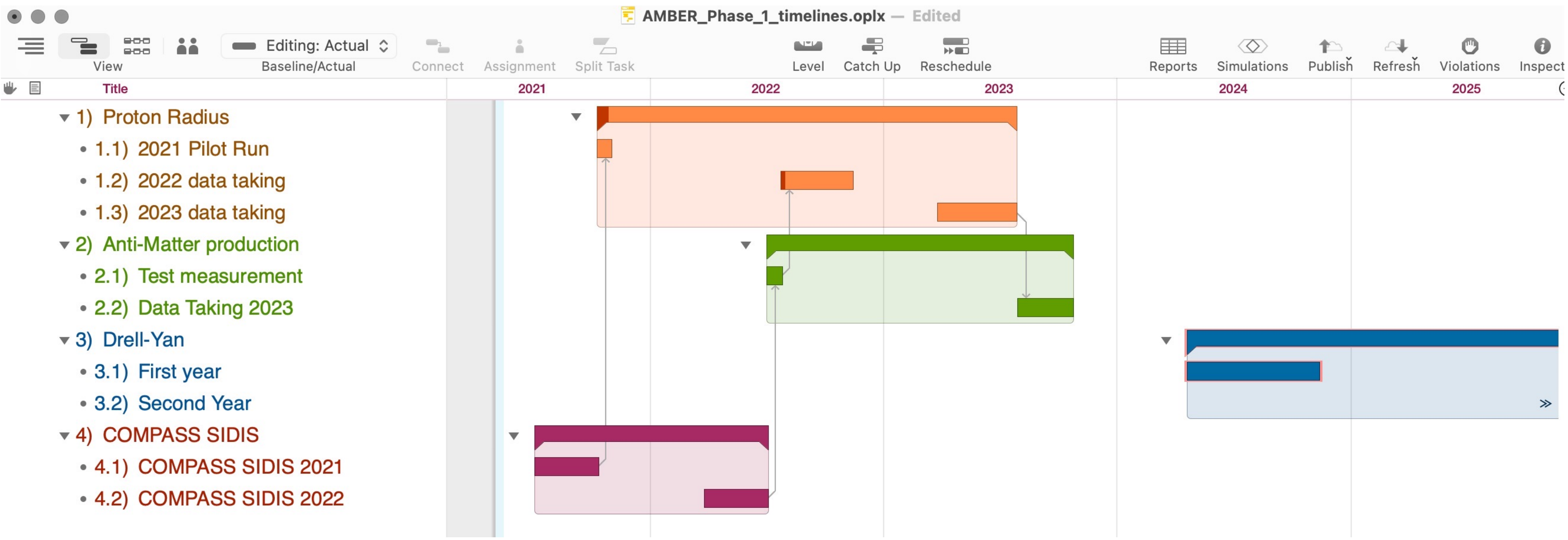
Possible timeline Phase-1



Precision in the context of the puzzle

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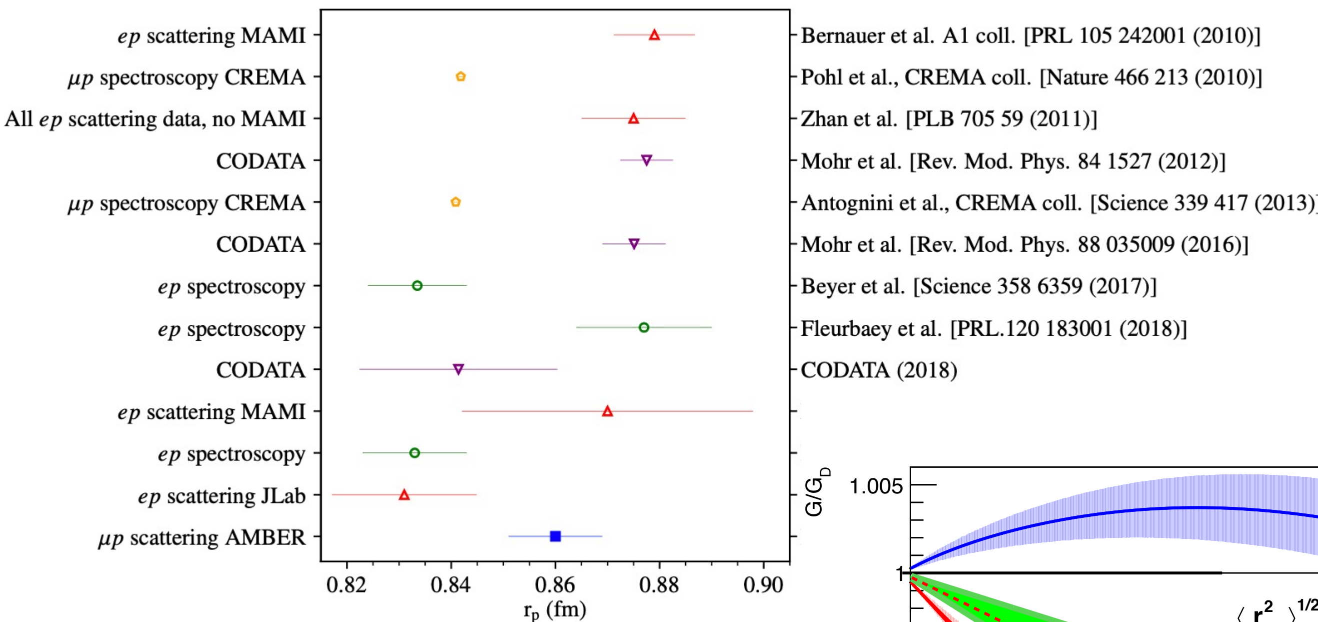
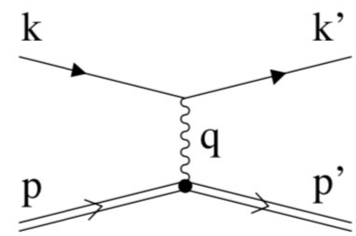
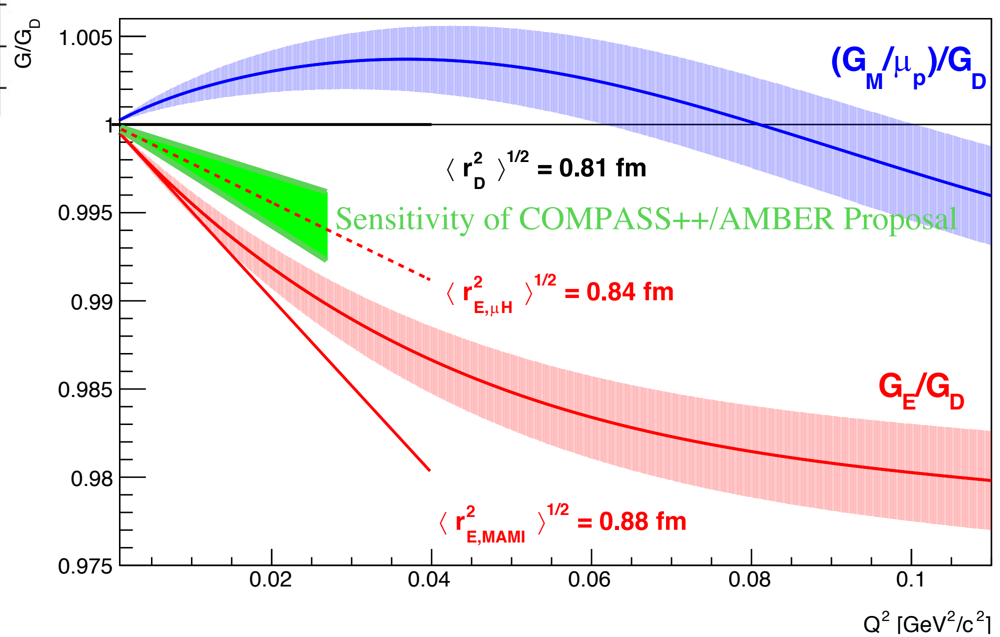




G_E, G_M



CERN-SPSC-2019-022; SPSC-P-360

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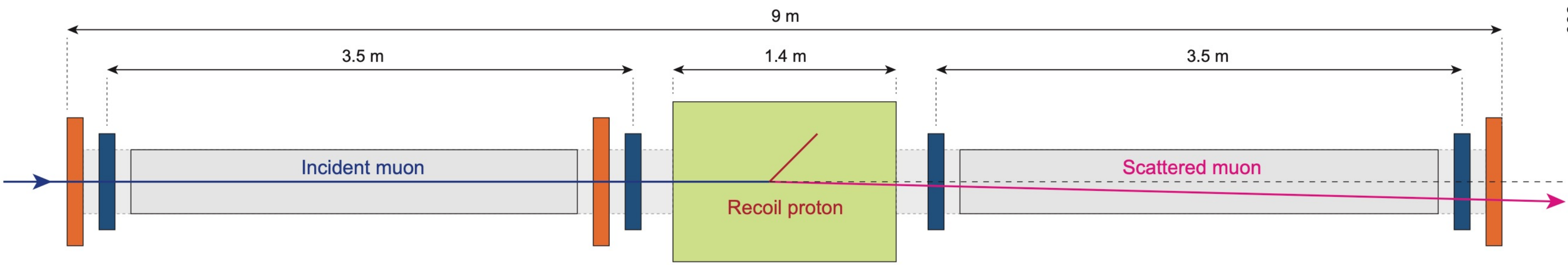
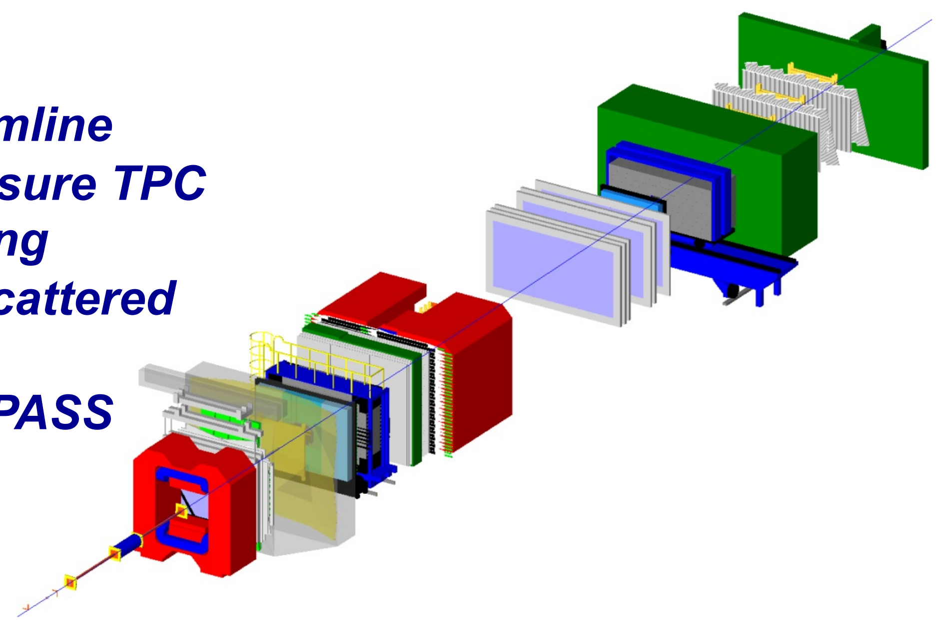
Proposal for Measurements at the M2 beam line of the CERN SPS

– Phase-1 –

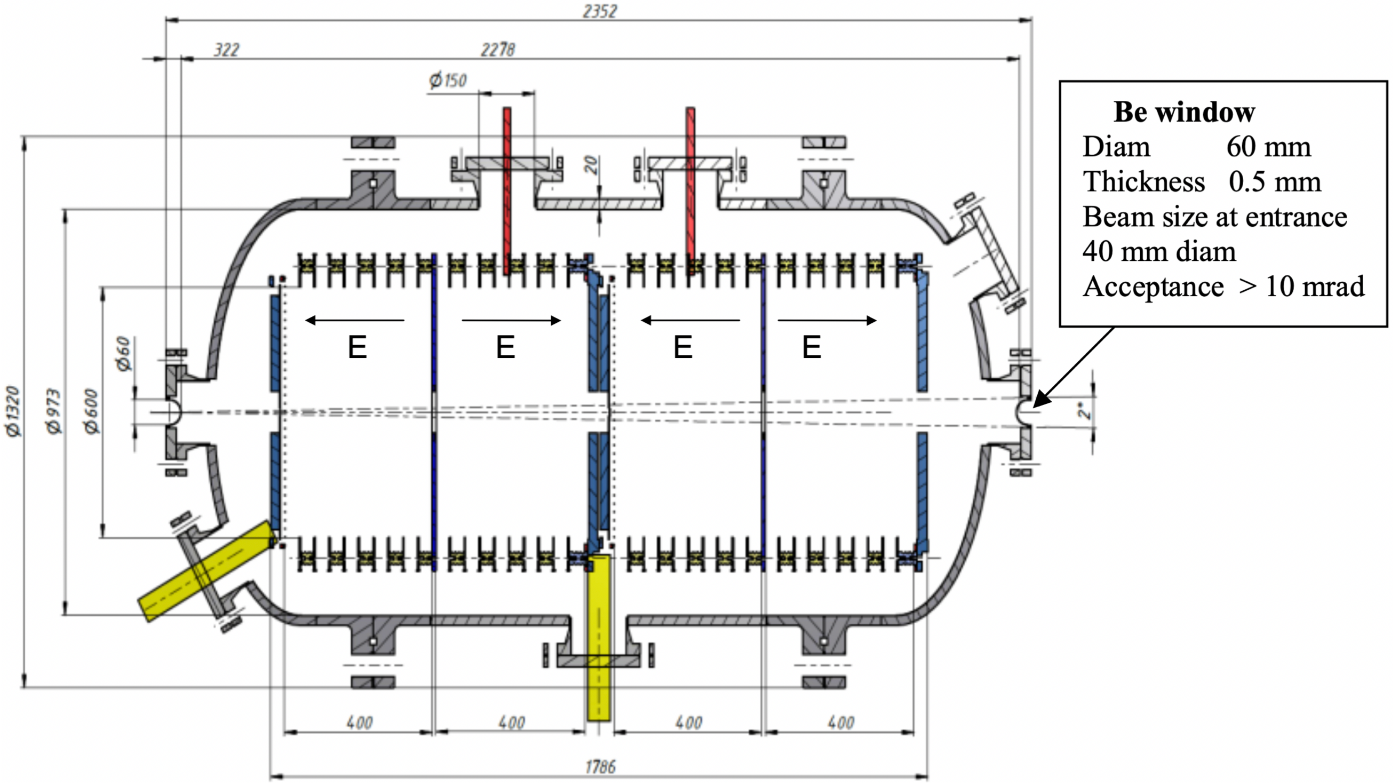
COMPASS++[*]/AMBER[†]



- ***100 GeV muons of the CERN M2 beamline***
- ***Protons in an active-target high-pressure TPC***
- ***Silicon detectors for precision tracking***
- ***200µm SciFi stations for trigger on scattered muons***
- ***inner tracking and ECAL of the COMPASS spectrometer***



Active target: high-pressure TPC AMBER



- up to 20 bar pressure
- 600mm diameter of active volume
- reconstruction of recoil energy 0.5-20 MeV (10^{-3}…4×10^{-2} GeV^2)

Schedule for Proton-Charge Radius Measurement

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- **Planning for the upcoming three years**
- Schedule for the setup, preparation and pilot run with the following main data taking and concluding systematic studies.

Preliminary feedback SPSC's April meeting:

"The AMBER proton radius experiment (core program) will likely run in 2022, keeping again in mind that at this point it is not at all clear how much NA operations will be delayed."

Phase	Year	Task	Time (days)	Particle	p (GeV)	Rate (μ/s)	Comment
Ia	2021	Preparation	100	μ^+/μ^-	160	$10^5 - 10^7$	Parasitic testing of single components
Ib	2021	Pilot run	20	μ^+/μ^-	100	$2 \cdot 10^6$	CEDAR location, down-scaled setup
IIa	2022	Data taking	43	μ^+/μ^-	100	$2 \cdot 10^6$	Q^2: $1.0 \cdot 10^{-3}$ – $8 \cdot 10^{-3}$ GeV$^2/c^2$
IIb	2022	Data taking	107	μ^+/μ^-	100	$2 \cdot 10^6$	Q^2: $2.5 \cdot 10^{-3}$ – $4 \cdot 10^{-2}$ GeV$^2/c^2$
IIIa	2023	Empty target	50	μ^+	100	$2 \cdot 10^6$	Empty TPC
IIIb	2023	Energy dep.	25	μ^+/μ^-	60	$2 \cdot 10^6$	Multiple scat. and scat. angle
IIIc	2023	Energy dep.	25	μ^+/μ^-	150	$2 \cdot 10^6$	Multiple scat. and scat. angle

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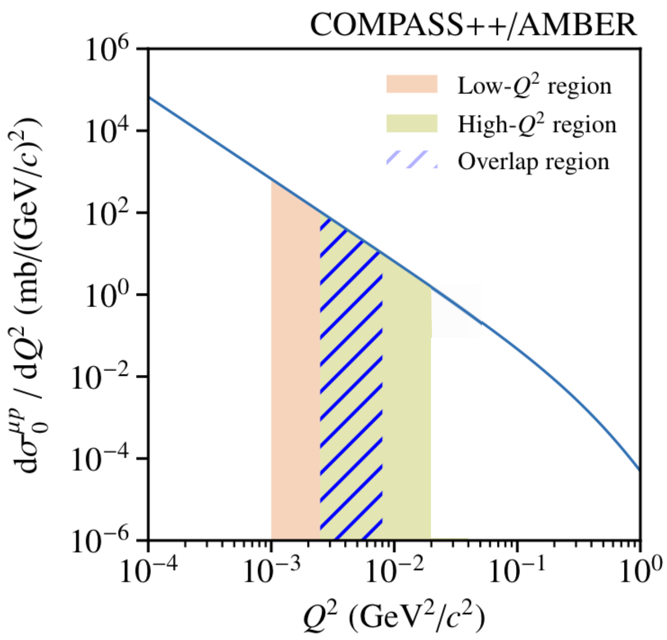
Proposed Q^2-Range Measurement

Measurement of elastic μ-p-scattering

Active-target pressurised hydrogen TPC combined with tracking and *COMPASS* spectrometer.

- Direct measurement of recoil-proton energy:
  $0.001 \leq Q^2 / (\mathrm{GeV}^2/c^2) \leq 0.02$
- Conservative scenario:
  → Low-Q^2: $0.001 \leq Q^2 / (\mathrm{GeV}^2/c^2) \leq 0.0025$
  → High-Q^2: $0.0025 \leq Q^2 / (\mathrm{GeV}^2/c^2) \leq 0.02$
- Data taking of 150 days - Phase II:
  → 43 days - low-Q^2 at 4 bar
  → 107 days - high-Q^2 at 20 bar
- Data set with $33 \cdot 10^6$ events:
  → stat. prec. on $\langle r^2 \rangle$: 1.6 %
  → fixed $\langle r^6 \rangle$ term: 0.7 %
  (values from simulation)



Stat. Prec.	fixed $< r^6 >$	Q^2 (GeV$^2/c^2$)	Statistics	Pressure	Comment
0.9 %	0.5 %	0.0010 - 0.04	70 mio.	20 bar	150 days
1.2 %	0.6 %	0.0025 - 0.04	37 mio.	20 bar	150 days
1.6 %	0.7 %	0.0010 - 0.04	6 + 27 mio.	4 + 20 bar	43 + 107 days
1.4 %	0.7 %	0.0010 - 0.04	12 + 27 mio.	4 + 20 bar	86 + 107 days

DAQ Status - Trigger-less System

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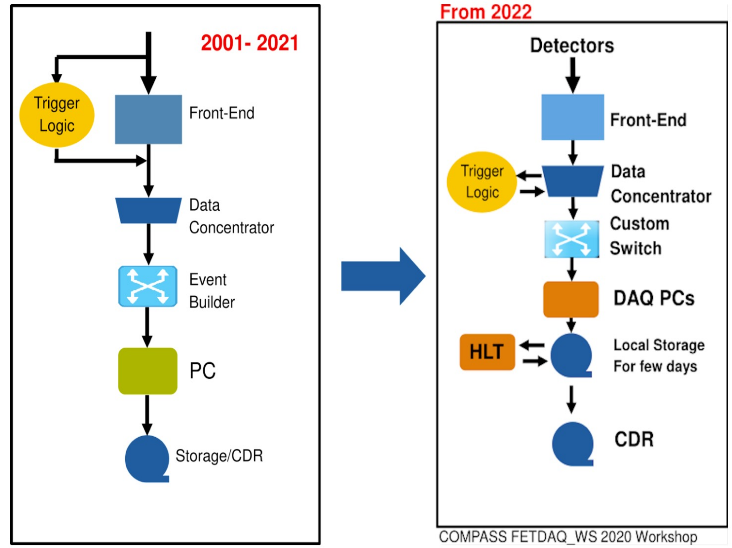
New DAQ development

A concept applying continuous DAQ based on the following principals:

- Trigger-less front-end electronics
- Front-end data can be forwarded to trigger processors
- Hardware event builder stores data until trigger decision
- Status and Plans:
  → Adaption of DAQ firmware and software (within 2020)
  → Increase of data rate capability (2/10 GB/s 2022/2023)
  → Development of digital trigger (iFTDC card since 2019)



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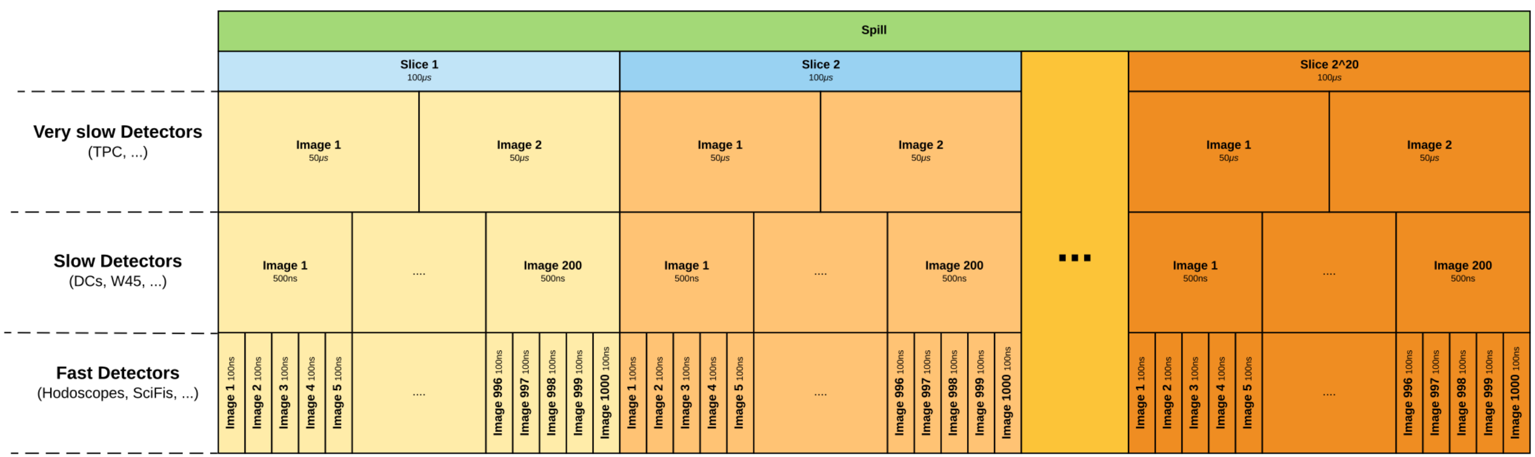

Bremsstrahlung: real-photon emission along the muon-proton scattering

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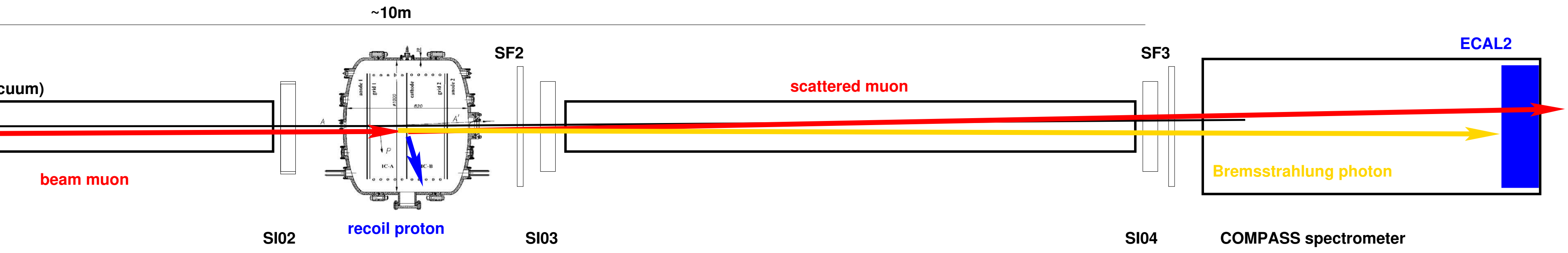
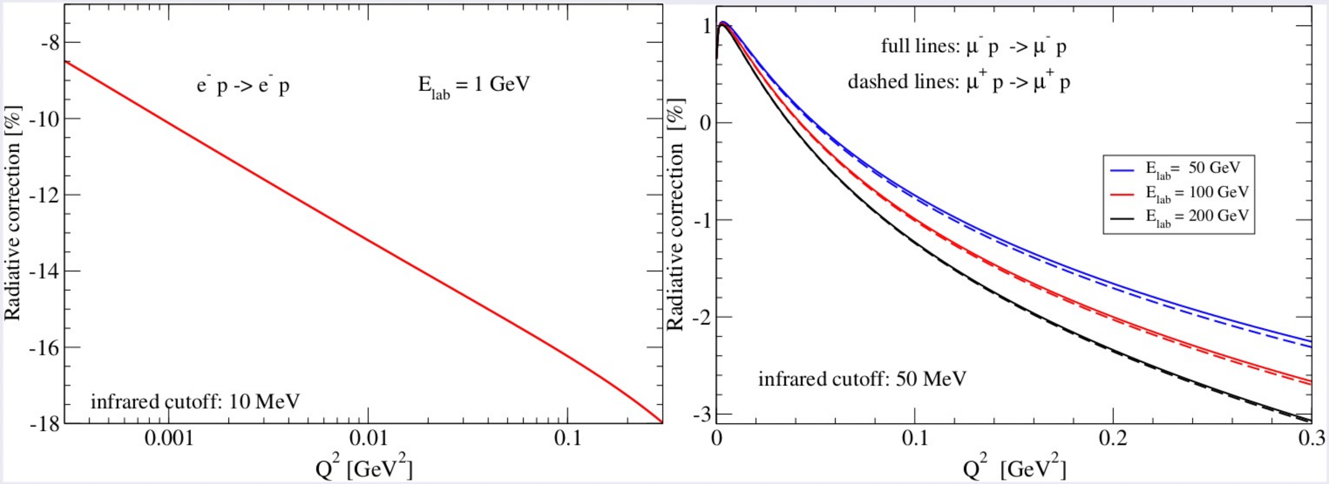


- Bremsstrahlung accompanies the elastic process
- for low-energy photons roughly $1/E_\gamma$ (‘infrared divergence‘)
- angular spectrum: peaking in the relativistic case, opening angle $1/\gamma$ [Lorentz factor]
- 100 GeV beam: E_γ between 50 MeV and 5 GeV emission probability at θ_μ =0.3mrad (Q^2=0.001): 5 x10^{-4}
- Bremsstrahlung events in Q^2=0.001…0.04 GeV^2/c^2 about 38000

Radiative corrections for electron and muon scattering

QED radiative corrections



- for soft bremsstrahlung photon energies ($E_\gamma / E_{beam} \sim 0.01$), QED radiative corrections amount to $\sim$ 15-20% for electrons, and to $\sim$ 1.5% for muons
- important contribution to the uncertainty of elastic scattering intensities: *change* of this correction over the kinematic range of interest
- check: impact of exponantiation procedure (stricty valid only for vanishing photon energies): e^-: $2 - 4\%$, μ^-: 0.1%
- integrating the radiative tail out to large fraction of beam energy: shifts the correction to smaller values, but only *increases* the uncertainty