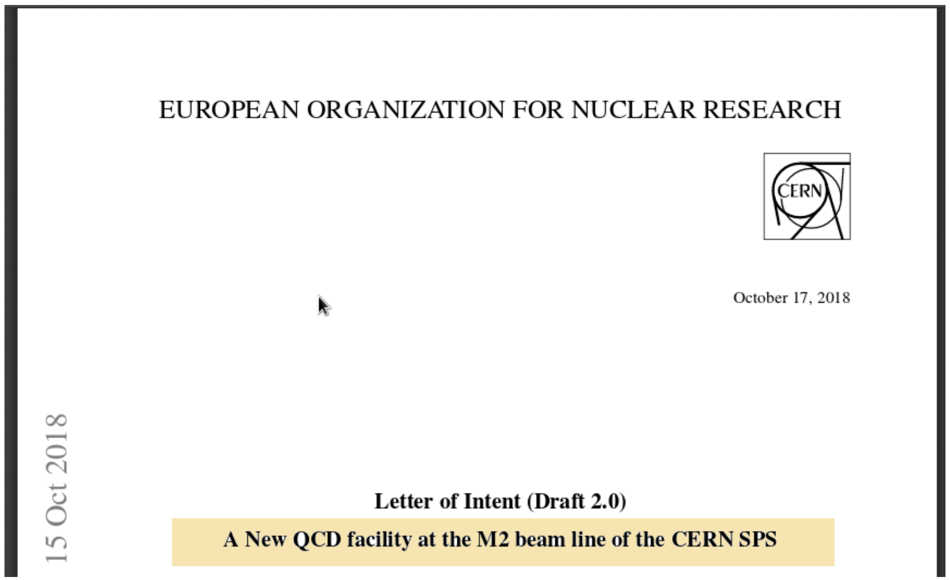
AMBER: Unravelling QCD mysteries

Catarina Quintans, LIP-Lisbon

21/02/2019

A new QCD facility at the M2 beam line of the CERN SPS

Apparatus for
Meson and
Baryon
Experimental
Research



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

October 17, 2018

15 Oct 2018

Letter of Intent (Draft 2.0)

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

Letter of Intent at arXiv:1808.00848 [hep-ex]

Approval of future experiments

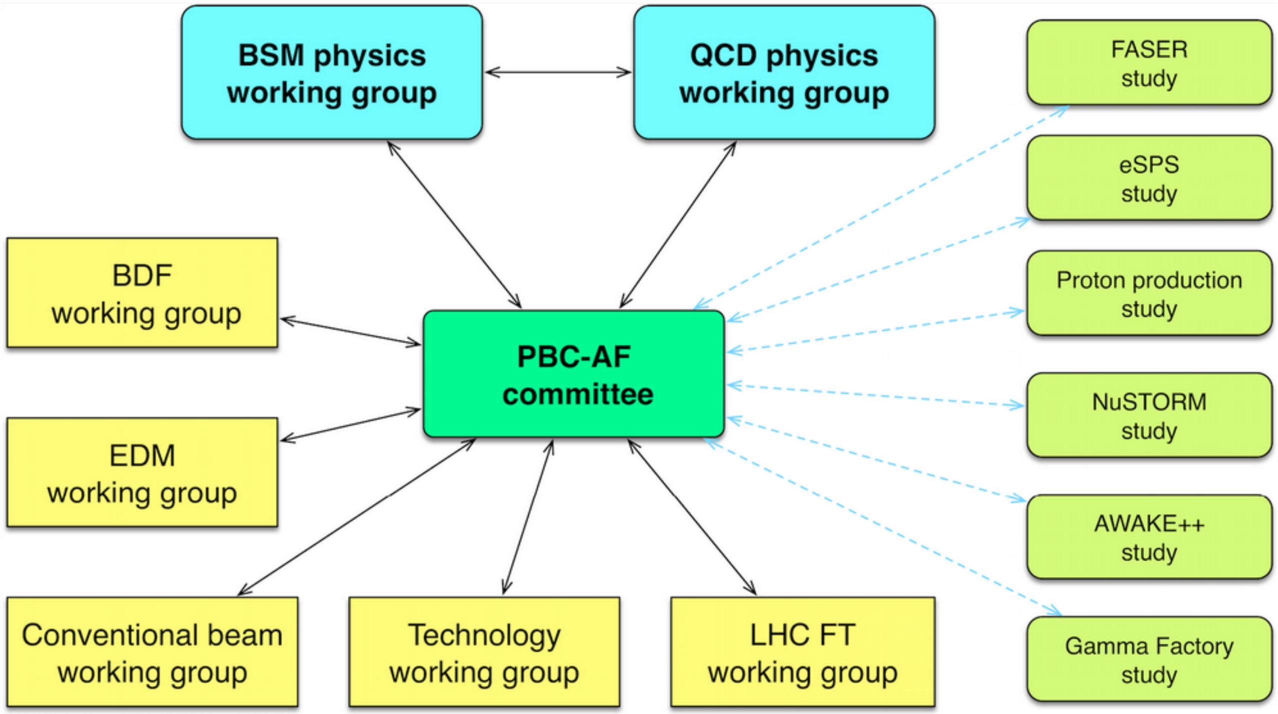
CERN created in 2016 the Physics Beyond Colliders - PBC study group, with a mandate to prepare the next European HEP strategy update (2019-20) on projects for future CERN non-collider experiments.

Coordinators: Joerg Jaeckel, Mike Lamont and Claude Vallée

Excerpt from the PBC mandate:
"Explore the opportunities offered by the CERN accelerator complex to address some of today's outstanding questions in particle physics through experiments complementary to high-energy colliders and other initiatives in the world."
Time scale: next 2 decades
pbc.web.cern.ch

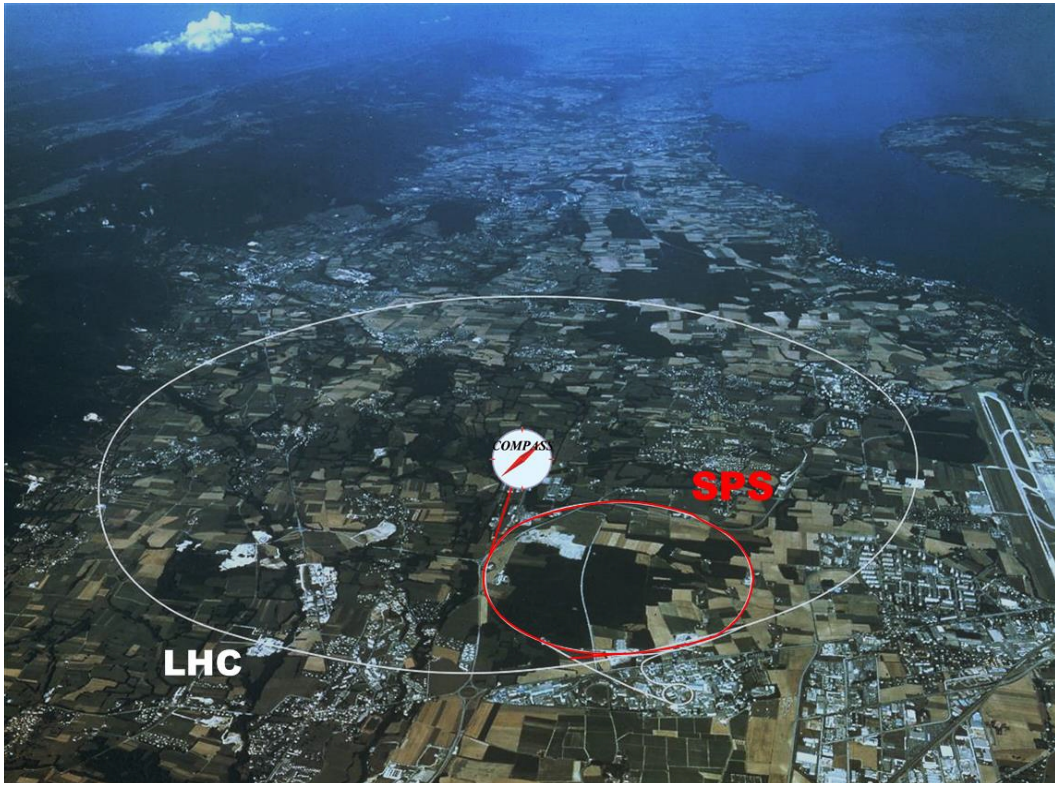
Last PBC annual workshop took place on 16-17 January:
PBC workshop 2019

PBC working groups



- **Physics Beyond Standard Model**: SHIP/NA64++/NA62++/KLEVER/IAXO/LSW/EDM
- **QCD Physics**: COMPASS++/μ-e/LHC-FT/DIRAC++/NA60++/NA61++

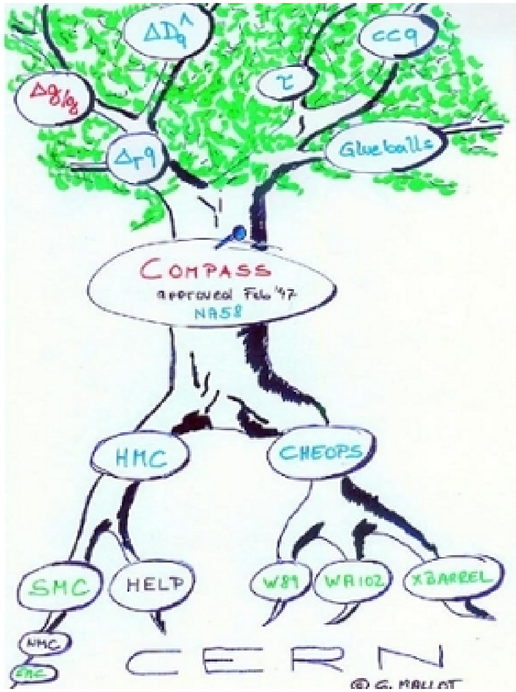
Where at CERN?



In the COMPASS/COMPASS-II experimental hall, since:

- Availability of both hadron and muon (unique!) beams (M2 beam line)
- Both beam charges available, and in wide range of energies (20-280 GeV)
- Re-use of large aperture dipole magnets from COMPASS
- Re-use of some of the most recent COMPASS detectors

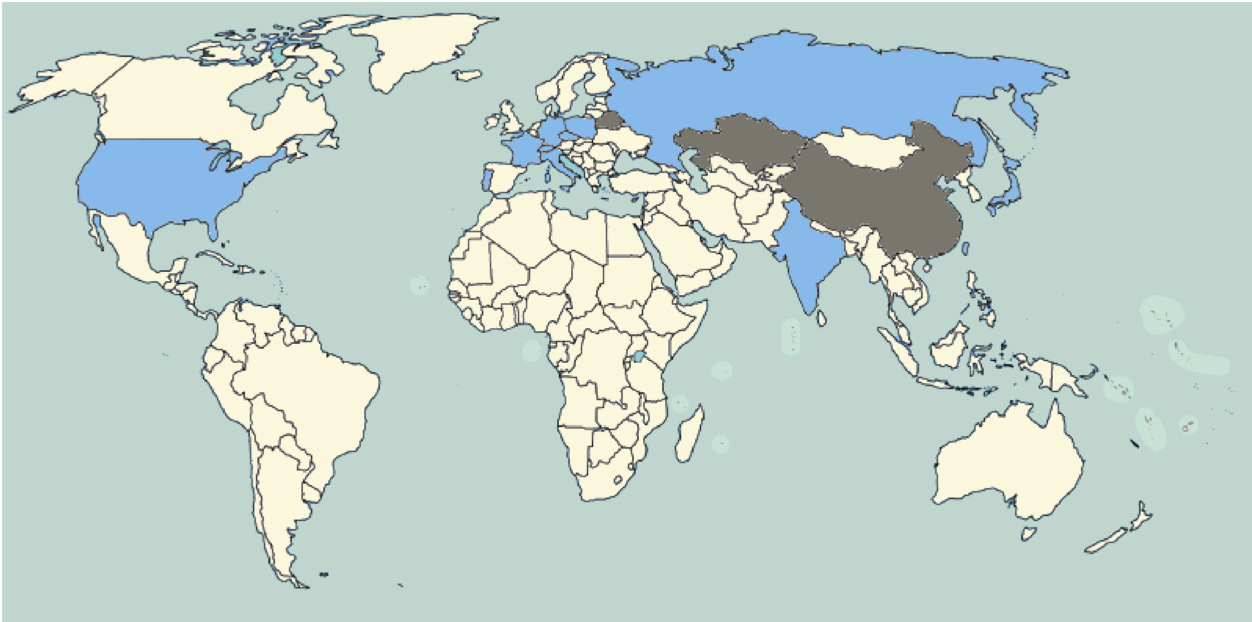
The origins



COMPASS **COMPASS–II** **AMBER**

2002 **2012** **2022**

A proto-Collaboration – ongoing



COMPASS + **AMBER**

- CERN
- Saclay, France
- Torino, Italy
- Trieste, Italy
- Lisbon, Portugal
- Aveiro, Portugal
- Bonn, Germany
- Munich, Germany
- Mainz, Germany
- Freiburg, Germany
- Bochum, Germany
- Prague, Czech Rep
- Kolkata, India
- Dubna, Russia
- Protvino, Russia
- Moscow, Russia
- Tel-Aviv, Israel
- Warsaw, Poland
- Yamagata, Japan
- Illinois, USA
- Taipei, Taiwan
- Tomsk, Russia
- Michigan, USA
- Chicago, USA
- Los Alamos, USA
- Tsinghua-Beijing, China
- Lanzhou, China
- Astana, Kazakhstan
- Bologna, Italy
- Trento, Italy
- Gatchina, Russia
- ...

AMBER physics programme

- **Hadron physics with muon beam**
  - Proton radius from muon-proton elastic scattering
  - Hard exclusive reaction with transversely polarized target

- **Hadron physics with conventional hadron beams**
  - Pion structure from Drell-Yan and charmonium production
  - Spectroscopy with low energy antiprotons
  - $\bar{p}$ production cross-sections for DM searches

- **Hadron physics with RF-separated beams**
  - Spectroscopy of kaons
  - Kaon structure from Drell-Yan and direct photon production
  - Kaon polarizability from Primakoff reaction
  - Pion and kaon-induced vector-meson production

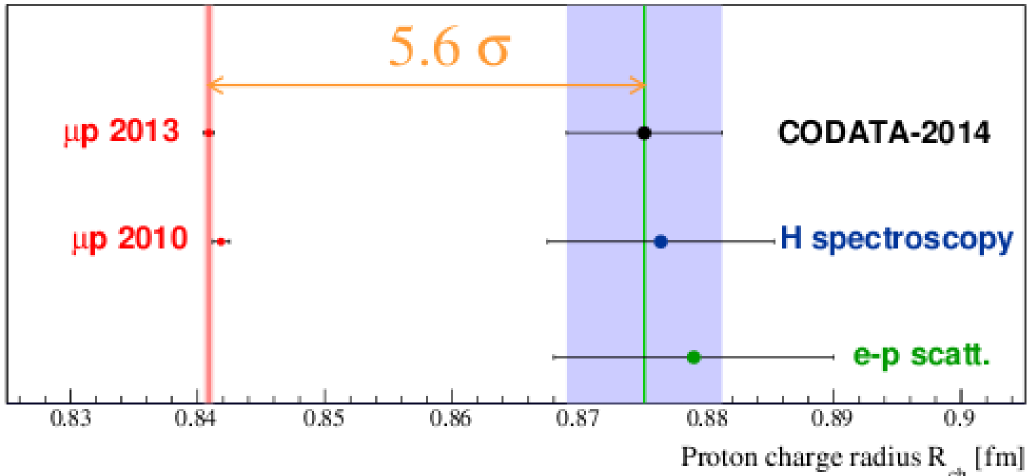
The proton radius puzzle: 2010

The proton radius puzzle (still)

The proton charge radius is accessed experimentally via two different methods: **lepton scattering** or **atomic physics** measurements.

But the obtained **results differ by 5.6 σ !**

- Elastic electron scattering and "Lamb shift" measurements (H spectroscopy) agree that the proton has a "large" radius
- Muonic hydrogen line splitting (spectroscopy on μonic-H) sees the proton much "smaller"



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

$R_E = 0.879 \pm 0.008$ fm (MAMI)
$R_E = 0.841 \pm 0.001$ fm (CREMA)

Proton form factors

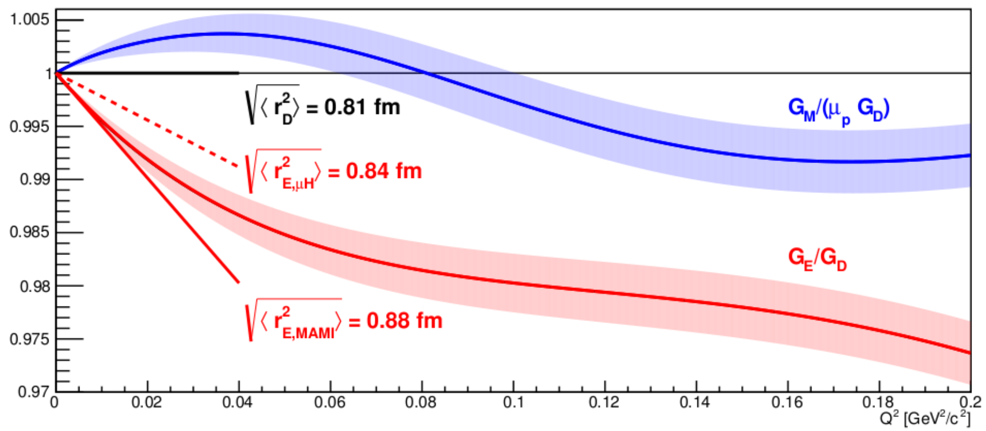
Proton form factors in the dipole approximation:

$$G_E(Q^2) \;=\; G_M(Q^2)/\mu_p \;=\; \frac{1}{(1+Q^2/a^2)^2}$$

with constant $a^2 \approx 0.71\ \mathrm{GeV}^2/c^2$
and the proton anomalous magnetic moment $\mu_p \approx 2.79$.

The electric charge radius of the proton is:

$$\langle r_E^2 \rangle = -6\hbar^2 \left. \frac{dG_E(Q^2)}{dQ^2} \right|_{Q^2 \to 0} \overset{dipole}{=} \frac{12\hbar^2}{a^2} \approx (0.81\mathrm{fm})^2 \equiv \langle r_D^2 \rangle$$



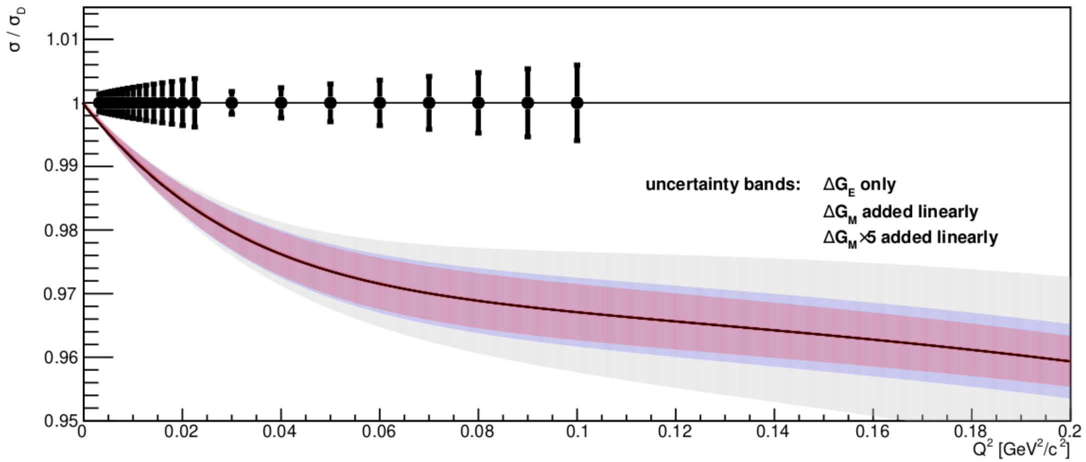
Muon-Proton elastic scattering

$$\mu p \to \mu' p$$

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

with $Q^2 = -(p_\mu - p_{\mu'})^2$, $\tau = Q^2/(4m_p^2)$ and $s = (p_\mu + p_p)^2$.

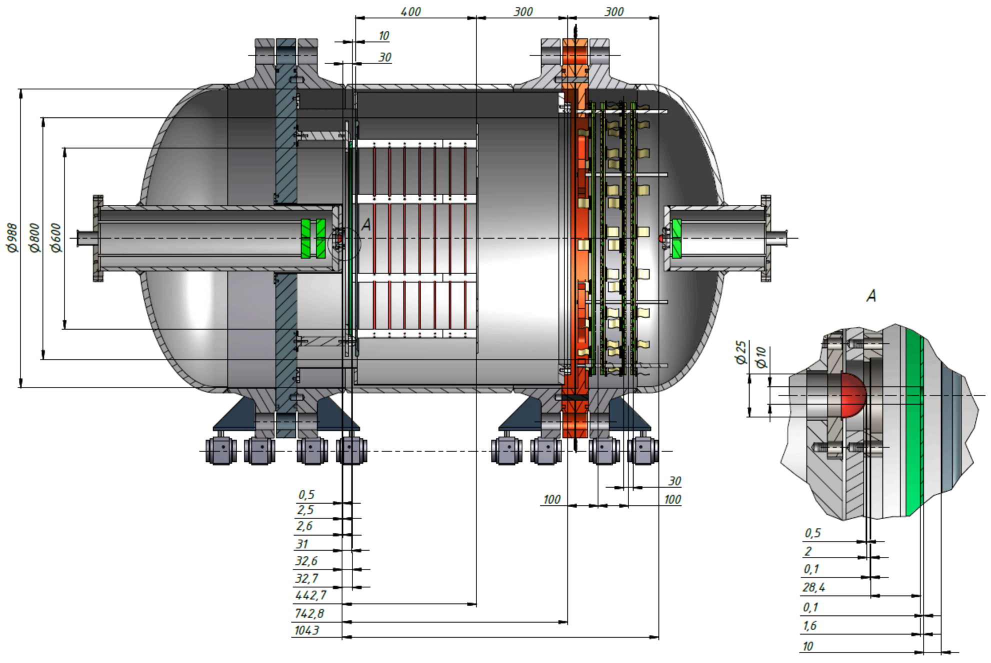
At high energy of the beam (160 GeV), the last term can be neglected. The sum $(G_E^2 + \tau G_M^2)$ can be accessed from the cross-section measurement, in the range $0.001 < Q^2 < 0.02\ (\mathrm{GeV}/c)^2$.



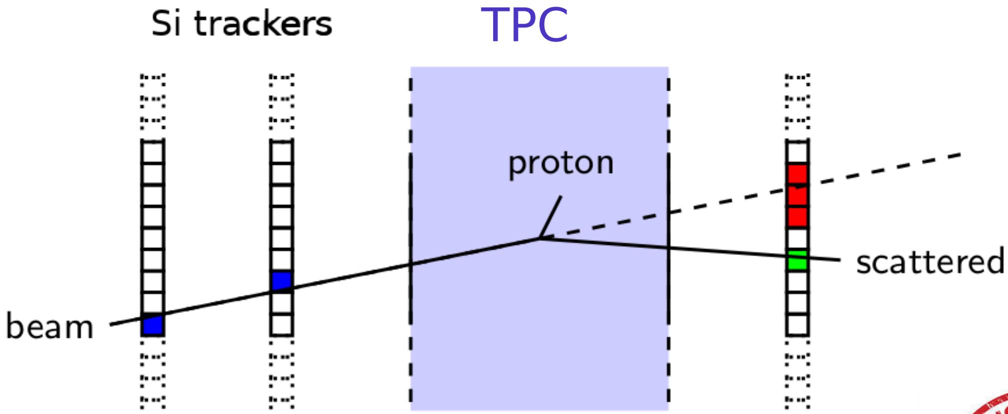
The measurement

- Advantageous wrt e-p scattering experiments like MAMI, since radiative corrections with muon $\ll$ with electron
- Radiative corrections $\ll$ than at low energy $\mu - p$ scattering, like proposed MUSE experiment (Coulomb distortion)

Active target: a **high-pressure hydrogen TPC**



Proton radius measurement setup



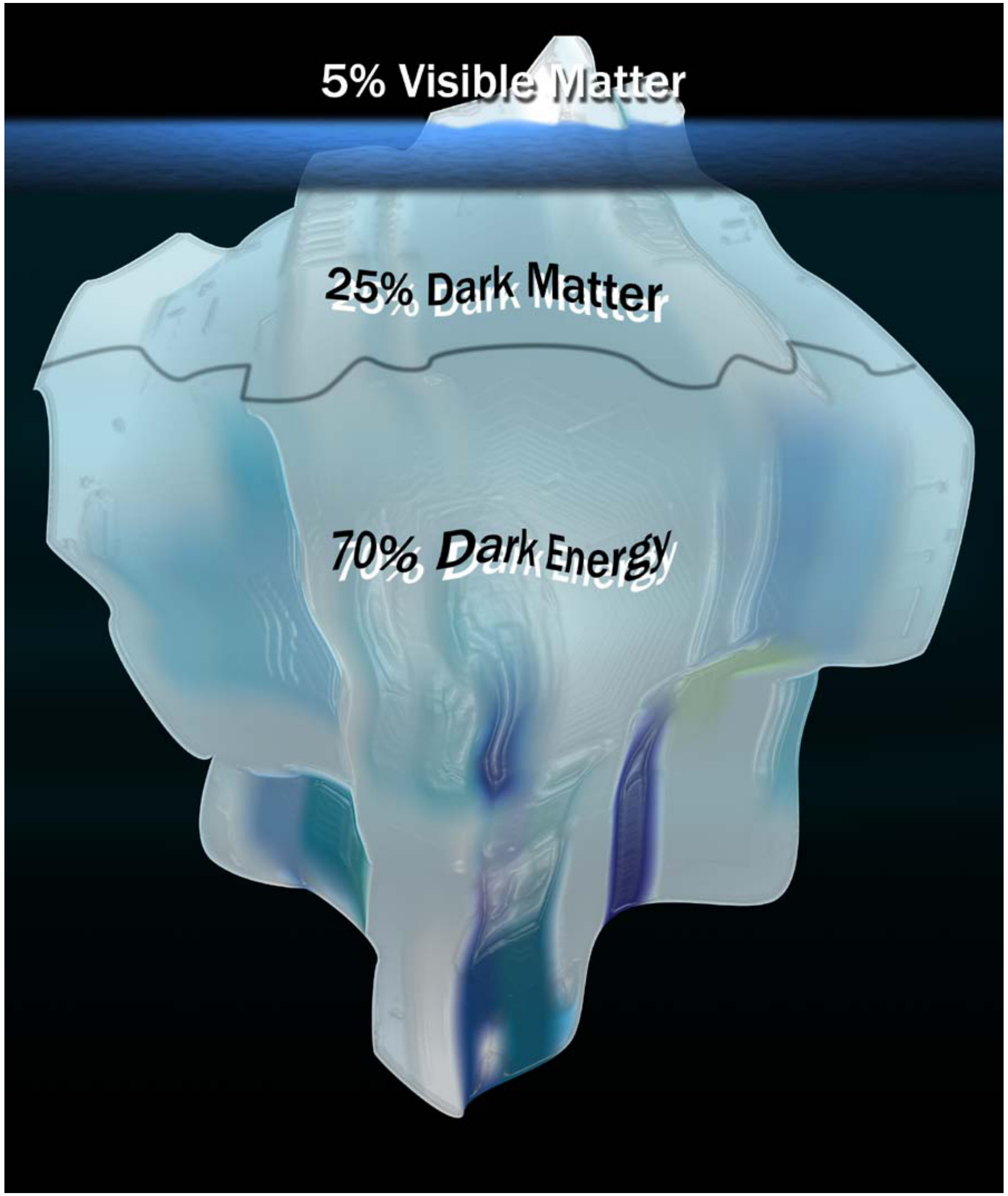
Elastic scattering:

- identify the recoil proton ($E_{p'}$: 100 keV - 100 MeV)
- measure the scattering angle of the muon ($\theta_\mu \sim 100\ \mu rad$)
- long target, for high luminosity (drift time $\sim 100\ \mu$s)
- trigger on the recoil proton signal and on the small kink of scattered muon

...followed by a COMPASS-like spectrometer

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

Dark matter searches: where can we help?



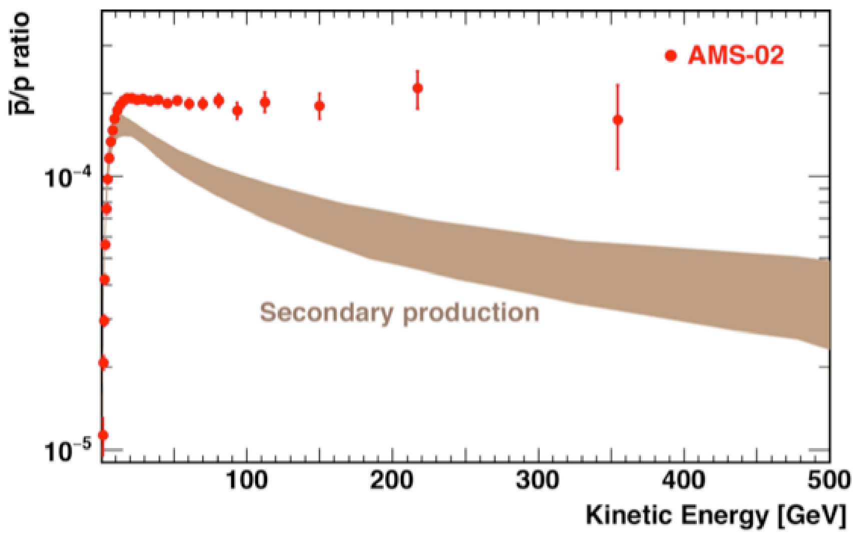
DM searches in astroparticle physics

Dark Matter:
- must exist
- interacts only weakly
- neutral

$\hookrightarrow$ WIMPs are a favorite!

Searches for dark matter via the products of its annihilation or decay

- $\bar{p}$ **primary production**: $\chi\chi \to q\bar{q}, W^+W^-, ... \to \bar{p}, \bar{D}, e^+, \gamma, \nu$
- $\bar{p}$ **secondary production**: scattering of primary cosmic rays (p,He) in interstellar medium.

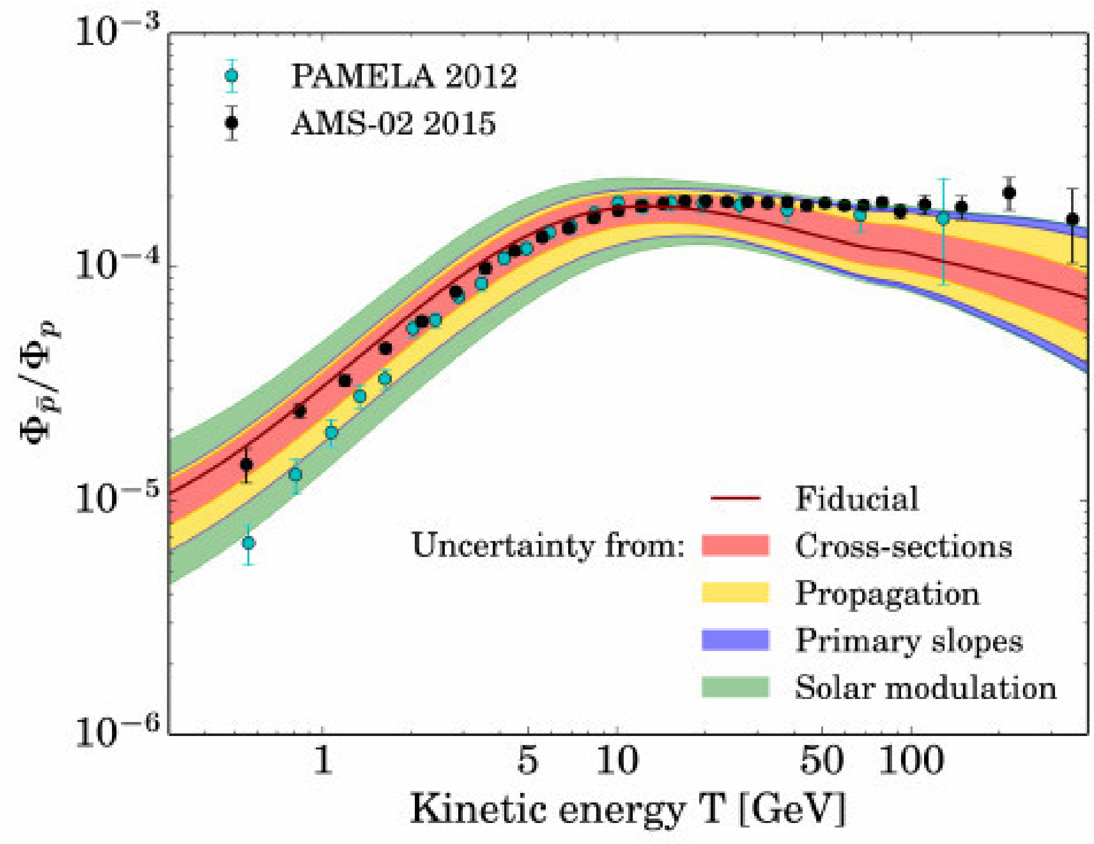


2008: exciting observation of $\bar{p}$ excess by the **PAMELA** satellite, later confirmed with high precision by **AMS-02**.

There must be an extra source of $\bar{p}$ in the Milky Way! WIMPs??

Antiprotons production cross-section

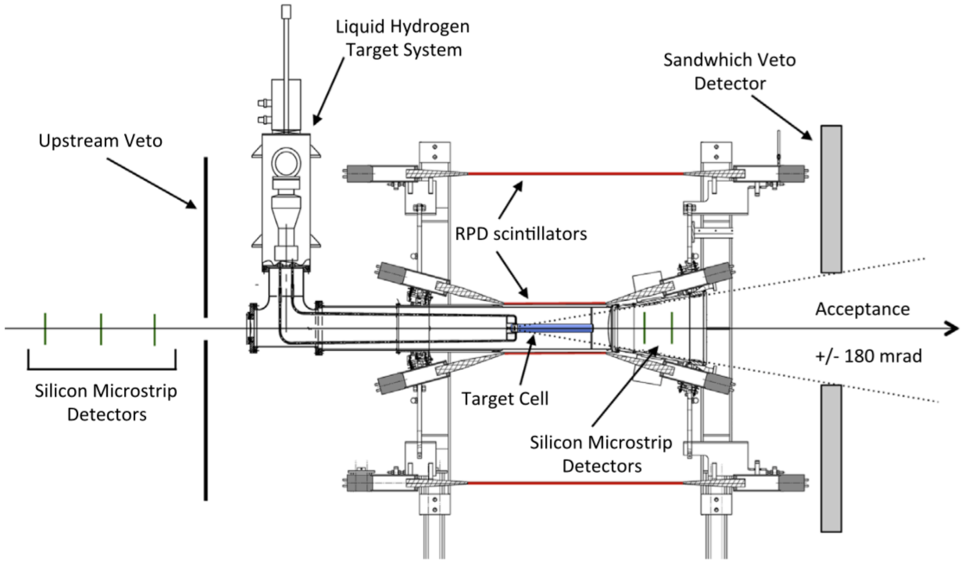
Most of the uncertainty in the $\bar{p}$ spectrum comes from: propagation model and production cross-section.



Motivation for a precise measurement of $\bar{p}$ production cross-section for incident energies in the range ∼30 to ∼250 GeV.

The measurement

	$p+p$	$p+{}^4$He
p_{beam} (GeV/c)	190	190
charged mult.	9.9	11.07
$\bar{p}$ event fraction (%)	7.1	7.7
$\langle p \rangle$ of $\bar{p}$ (GeV/c)	15.3	14.5

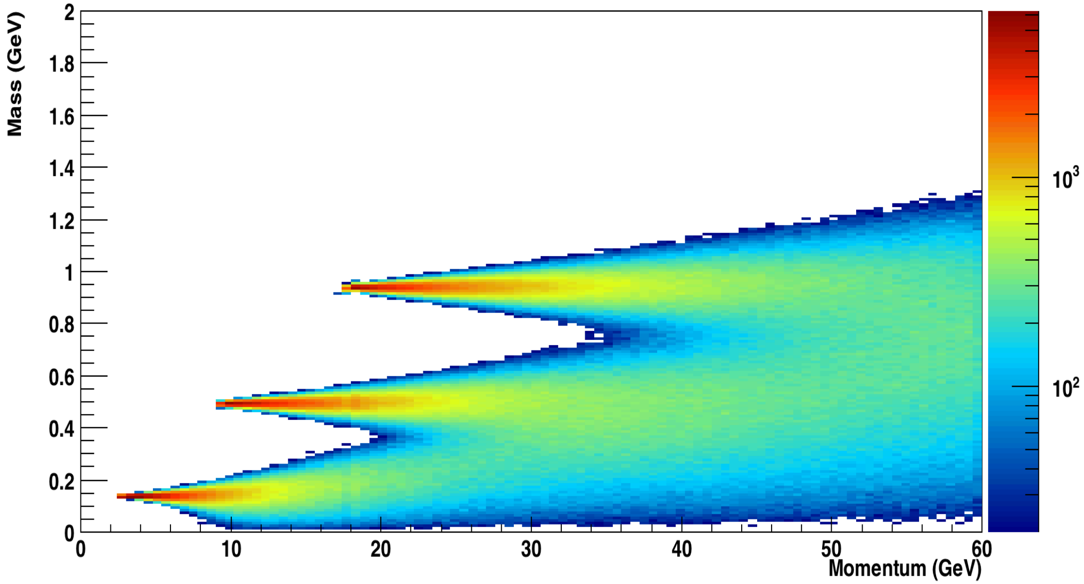


Measure **double differential cross-sections, in momentum and angle**

- Proton beam in the range $30 < p < 250$ GeV/c on liquid H_2 and ^{4}He targets.
- Low beam intensity: 10^5 p/second
- Beam particle identification from CEDARs
- $e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, p and $\bar{p}$ identified in the RICH
  - RICH signal for $\bar{p}$ in $18 < p < 45$ GeV/c
  - RICH as veto for $\bar{p}$ in $10 < p < 18$ GeV/c (not π and not K)

Goals on $\bar{p}$ production x-section

RICH mass reconstruction



Complementary to the measurements by LHCb in the TeV range.

Statistical precision ~1%, with point-to-point systematic uncertainty <5%

(present cross-sections uncertainty in this energy range is 20-30%)

Hadron mass hierarchy

Artwork by Sandbox Studio, Chicago with Corinne Mucha

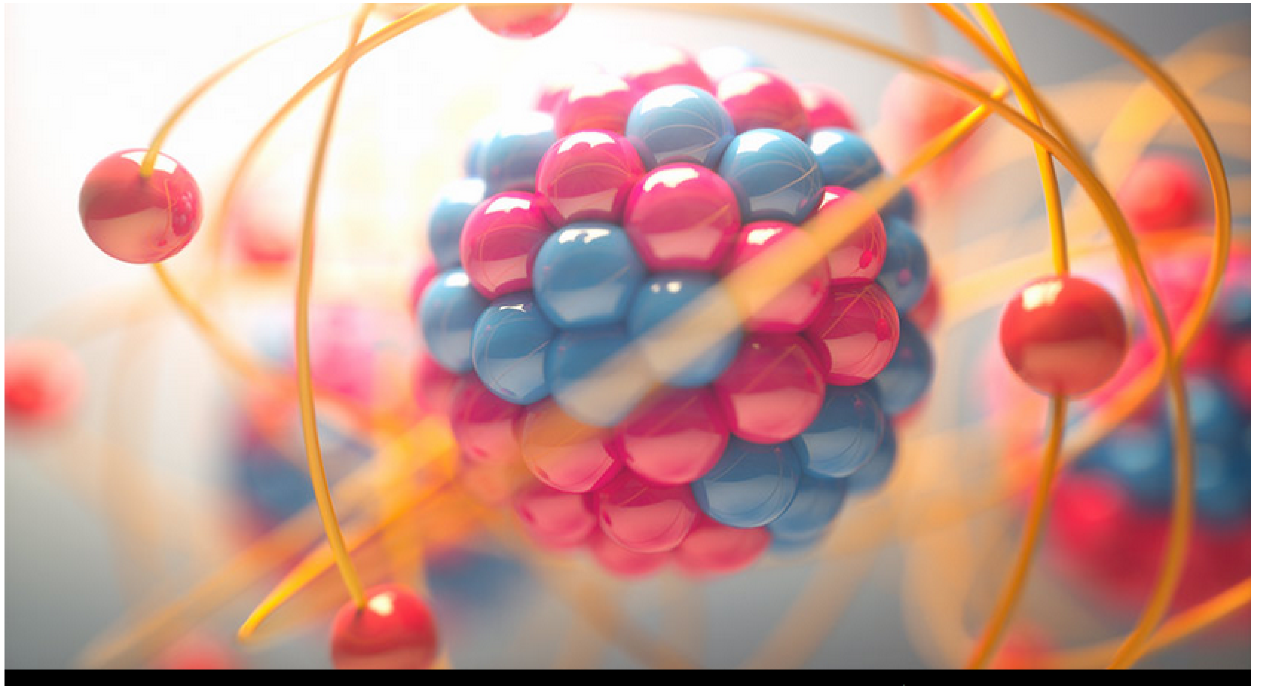
The proton mass from lattice QCD

NEWS PARTICLE PHYSICS

Physicists finally calculated where the proton's mass comes from

Only 9 percent of the subatomic particle's bulk comes from the mass of its quarks

BY EMILY CONOVER 6:00AM, NOVEMBER 26, 2018



MASSIVE UNDERTAKING Using a technique called lattice QCD, scientists figured out how protons (illustrated here in the nucleus of an atom) get their mass.

KTSDESIGN/SHUTTERSTOCK

Magazine issue: Vol. 194, No. 12, December 22, 2018, p. 8 in Science News

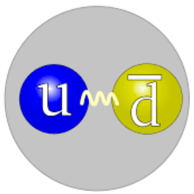
Hadron mass hierarchy

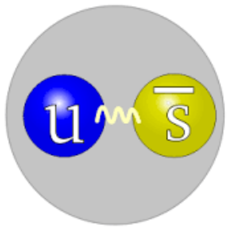
Over the last decades, the proton structure was thoroughly explored.

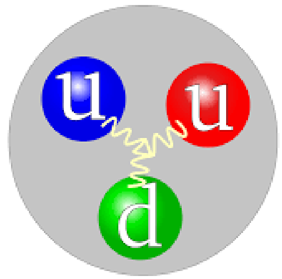
Other hadrons are still unexplored:

Pions and kaons are apparently simple, yet mysterious objects.

In their different structure (and internal dynamics) hides the answer to the **"mystery" of the hadron mass hierarchy**.

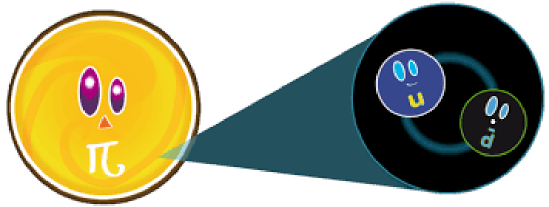






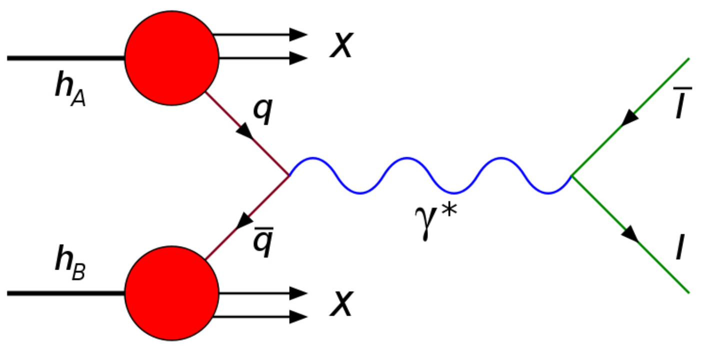
MASS	nearly massless – a near cancellation of dressed quarks	still 2 light quarks, but heavier bound state	3 light quarks – super heavy dressed ones
SPIN	S=0 implies an exact cancellation – a symmetry	S=0 – exact cancellation	S=1/2 – the good-old spin puzzle

What do we really know about the pion?



- the lightest pseudo-scalar meson (S=0, $m_\pi = 140$ MeV)
- described by 2 TMD PDFS of quarks: $f_{1,\pi}$ and $h_{1,\pi}^{\perp}$ (plus 2 for gluons)
- 95% of the pion mass comes from dynamics (gluons+sea)
- The valence is responsible for 50-60% of the pion momentum
- Pion structure information from only few DY experiments from the 80's

Pion-induced Drell-Yan process



$\bar{q}q \to \gamma^* \to \mu^+\mu^-$

$$\frac{d\sigma_{AB\to l\bar{l}X}}{dQ^2dy} = \sum_{ab}\int_0^1 dx_a \int_0^1 dx_b\; \Phi_a^A(x_a,\mu)\; \Phi_b^B(x_b,\mu)\; \frac{d\hat{\sigma}_{ab\to l\bar{l}}(x_a,x_b,Q,\mu)}{dQ^2dy}$$

COMPASS 2015 and 2018:

measured transverse spin asymmetries from pion-induced DY

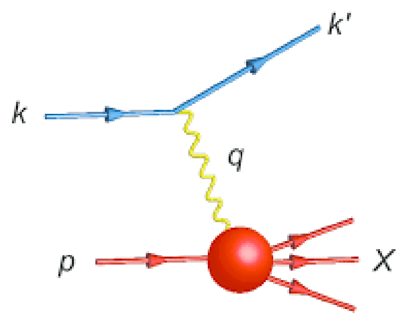
- Hadron A: π^- beam
- Hadron B: $p^\uparrow$ in polarized NH_3 target

$\hookrightarrow$ access convolutions of TMD PDFs of the u-quark (u-quark dominance)

How are PDFs determined?

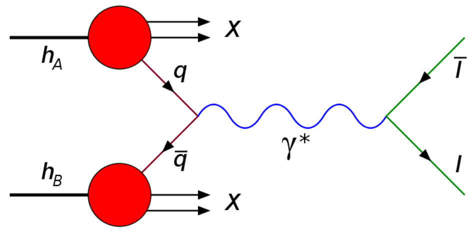
PDFs are universal – all available measurements are used together, in **global fits to world data**: DIS, pp, πp, e^+e^-, ...

DIS



$\sigma \propto PDF$

Drell-Yan



$\sigma \propto PDF \otimes PDF$

proton PDFs: Fractions of proton momentum carried by the constituent partons

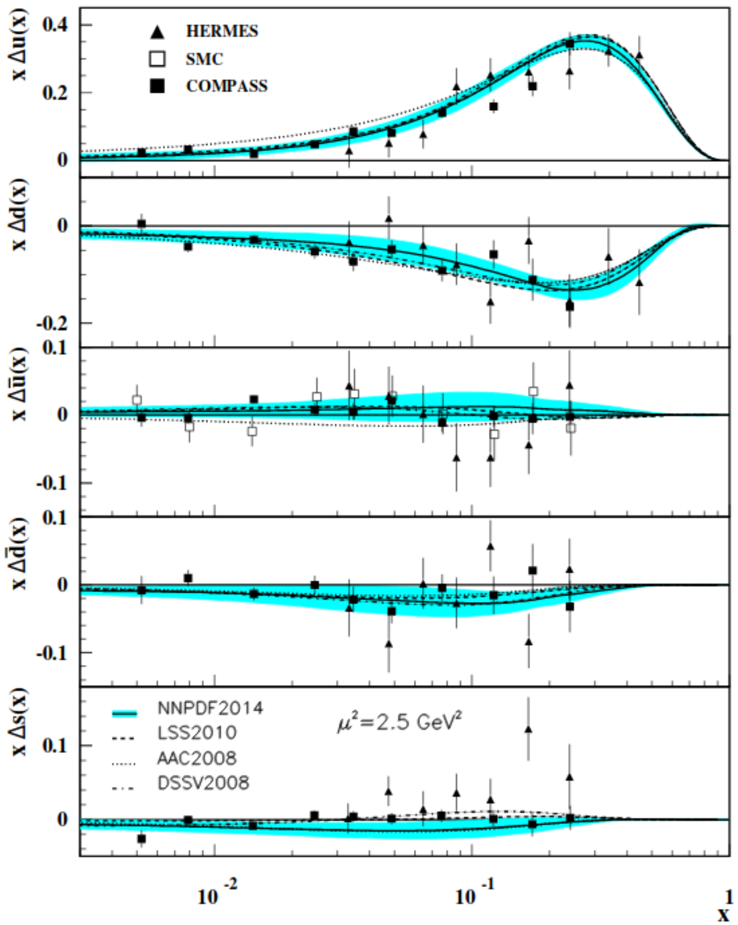
$$f_u = \int_0^1 dx[xu(x) + x\bar{u}(x)];\ f_d = \int_0^1 dx[xd(x) + x\bar{d}(x)]$$

Experimentally: $f_u^p \approx 0.36$ and $f_d^p \approx 0.18$

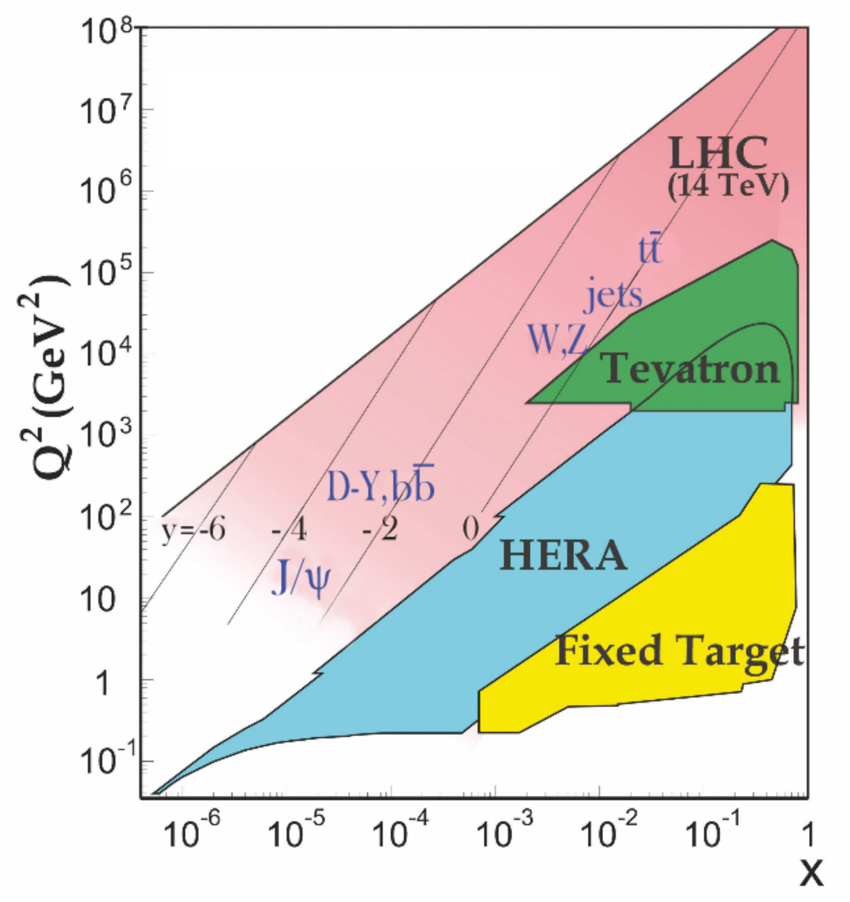
$\hookrightarrow$ u-quarks in the proton carry twice as much momentum than d-quarks.

$\hookrightarrow$ In total quarks carry only ≈50% of the proton momentum. The rest is carried by gluons!

Proton polarized PDFs



Phase-space of measurements (mostly unpolarized)



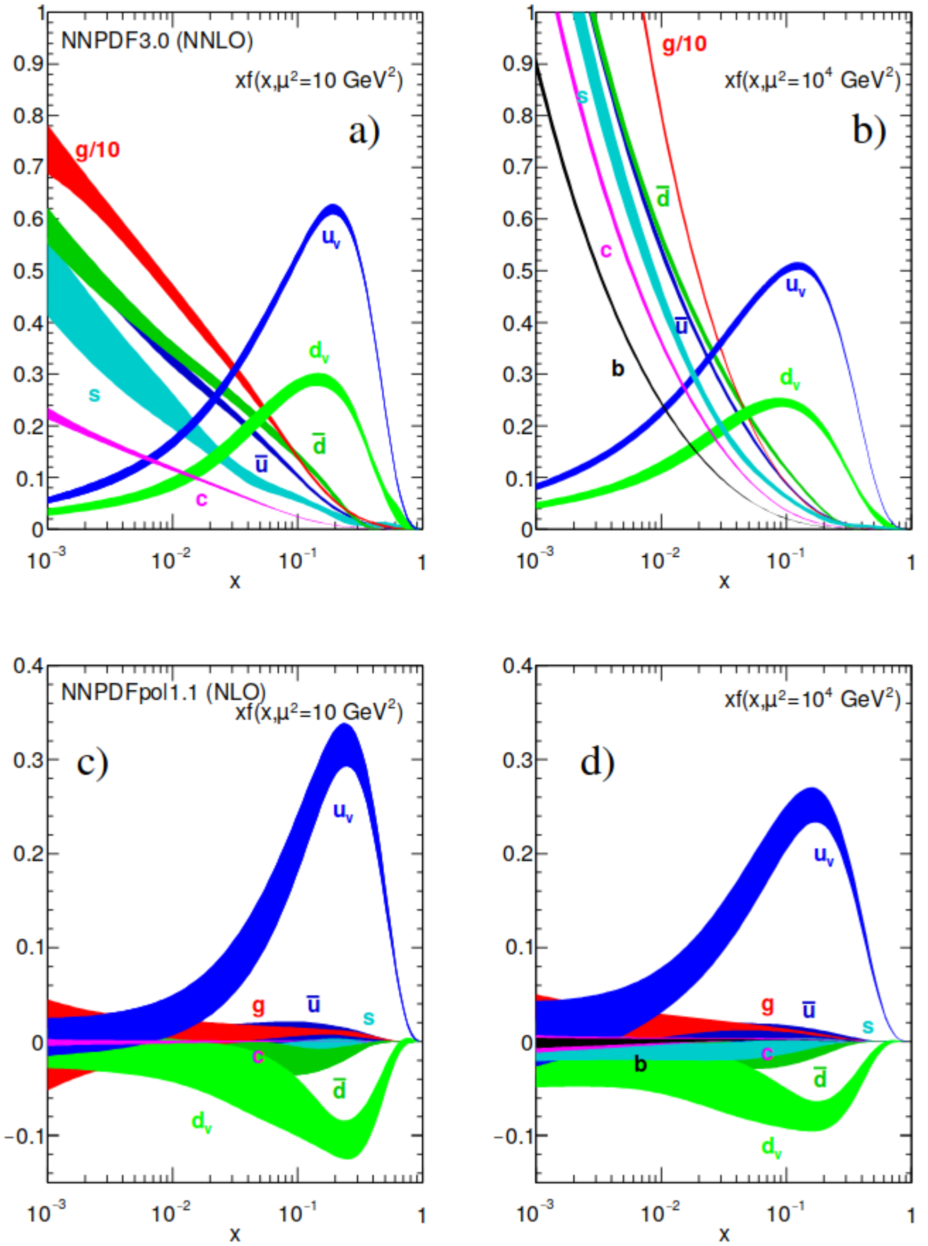
For the polarized PDFs there is much less data available, specially in some regions of phase-space. Mostly fixed-target, recently also RHIC-Spin.

Big projects for the future: EIC, EIC-China and maybe Spin@LHC

Proton PDFs

Unpolarized

Polarized



in PDG 2018

And what about the pion?

Much less studied. Experimentally, it is much more difficult:

- no such thing as "pion target"
- not so many pion beams of high energy in the world
- Few pion-induced Drell-Yan experiments, all performed in the '80s – access to pion valence
- scarce data on direct photon production in $\pi^{\pm} + p$, also from the '80s – access to gluon PDF

Pion induced Drell-Yan

Experiment	Target type	Beam energy (GeV)	Beam type	Beam intensity (part/sec)	DY mass (GeV/c^2)	DY events
E615	20cm W	252	π^+ π^-	17.6×10^7 18.6×10^7	4.05 – 8.55	5000 30000
NA3	30cm H_2	200	π^+ π^-	2.0×10^7 3.0×10^7	4.1 – 8.5	40 121
	6cm Pt	200	π^+ π^-	2.0×10^7 3.0×10^7	4.2 – 8.5	1767 4961
NA10	120cm D_2	286 140	π^-	65×10^7	4.2 – 8.5 4.35 – 8.5	7800 3200
	12cm 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	110cm NH_3	190	π^-	7.0×10^7	4.3 – 8.5	35000 > 35000

- After 30 years, finally new data on pion-induced DY
- W and Pt: non-negligible nuclear effects have to be considered
- NA3 did not publish cross-sections
- **COMPASS Drell-Yan cross-sections analysis ongoing**

A roadmap for progress in this field

Strong motivation for new Drell-Yan measurements, with ultimate goals:

- Contribute to the hadron mass hierarchy puzzle
- Contribute to the hadron spin puzzles

Measurements should include and be accompanied by:

- Meson-induced Drell-Yan with both beam charges: sea-valence separation
- (Un)polarized Drell-Yan: hadron TMDs characterisation
- Meson-induced prompt photon production: glue component

Pion structure: *valence + sea + glue*

Valence:

$$v^{\pi}(x_1) = \bar{u}_v^{\pi^-}(x_1) = d_v^{\pi^-}(x_1) = u_v^{\pi^+}(x_1) = \bar{d}_v^{\pi^+}(x_1)$$

Sea (SU(3) symmetry):

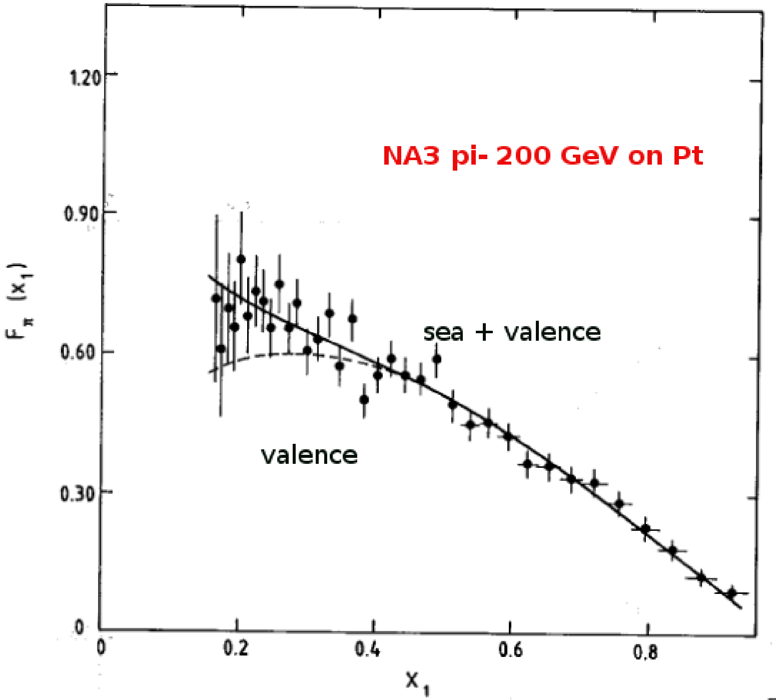
$$S^{\pi}(x) = \bar{u}_s^{\pi}(x) = u_s^{\pi}(x) = \bar{d}_s^{\pi}(x) = d_s^{\pi}(x) = \bar{s}_s^{\pi}(x) = s_s^{\pi}(x)$$

Assuming charge and isospin conjugation symmetry for valence and sea quarks:

$\Sigma_v^{\pi p} = \sigma^{\pi^- p} - \sigma^{\pi^+ p} \propto \frac{1}{3}\, u_v^{\pi}\, (u_v^p + d_v^p)$ → Only valence-valence terms

$\Sigma_s^{\pi p} = 4\sigma^{\pi^+ p} - \sigma^{\pi^- p}$ → No valence-valence terms

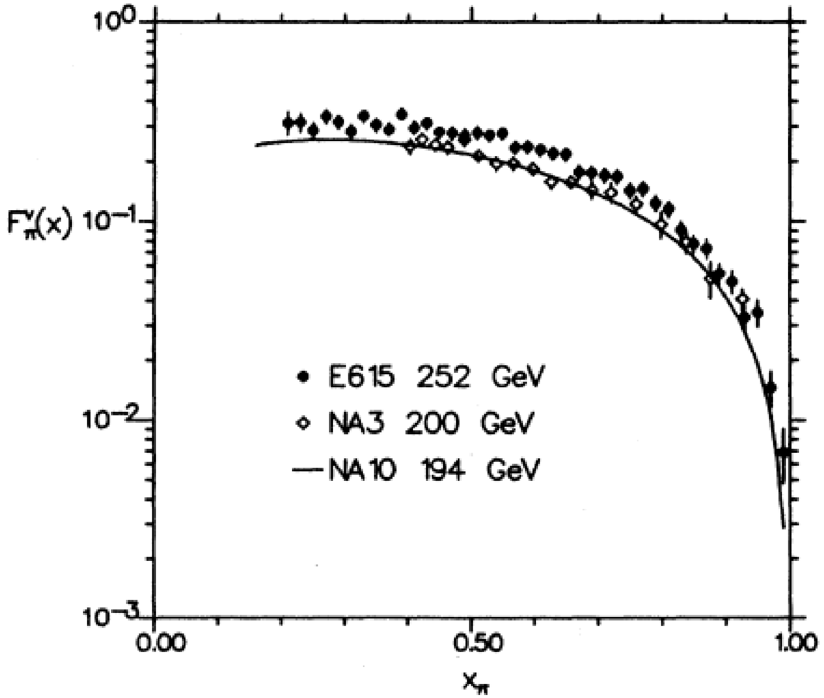
Pion Structure Function: $F_\pi(x_1)$



Simultaneous fit of NA3 π^+, π^- and p at 200 GeV Drell-Yan data, using CDHS nucleon PDF set.

NA3 Coll.; Z.Phys.C **18** (1983) 281-287

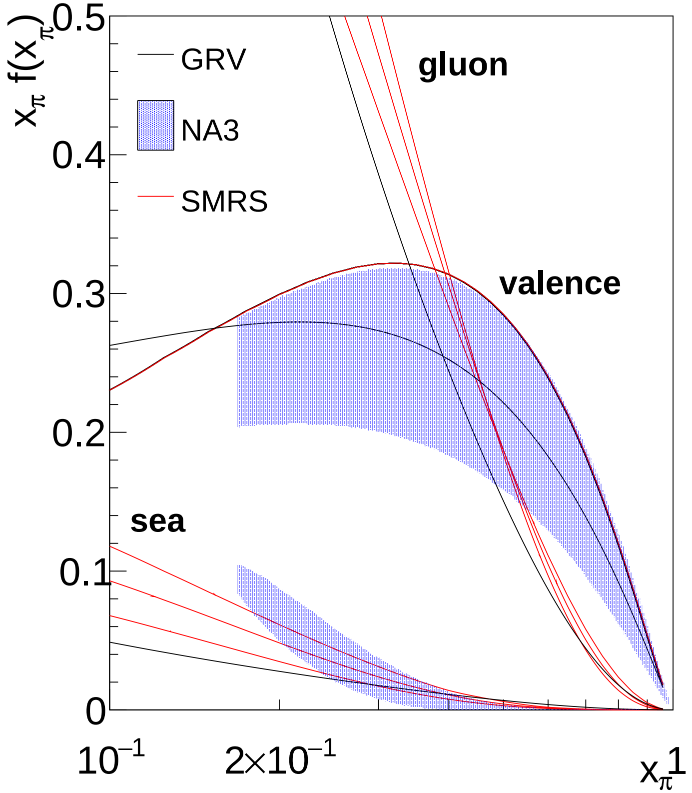
$v^\pi(x_1)$



Discrepancy by 20% between E615 and NA3/NA10, even if all 3 use the value extracted by NA3, $\langle g_\pi \rangle = 0.47$.

E615 Coll.; Phys.Rev. D **39** (1989) 92-122

Global fits



GRV: M. Gluck et al, Z.Phys.C **53** (1992) 651-655

SMRS: P.J. Sutton et al, Phys.Rev.D **45** (1992) 2349–2359

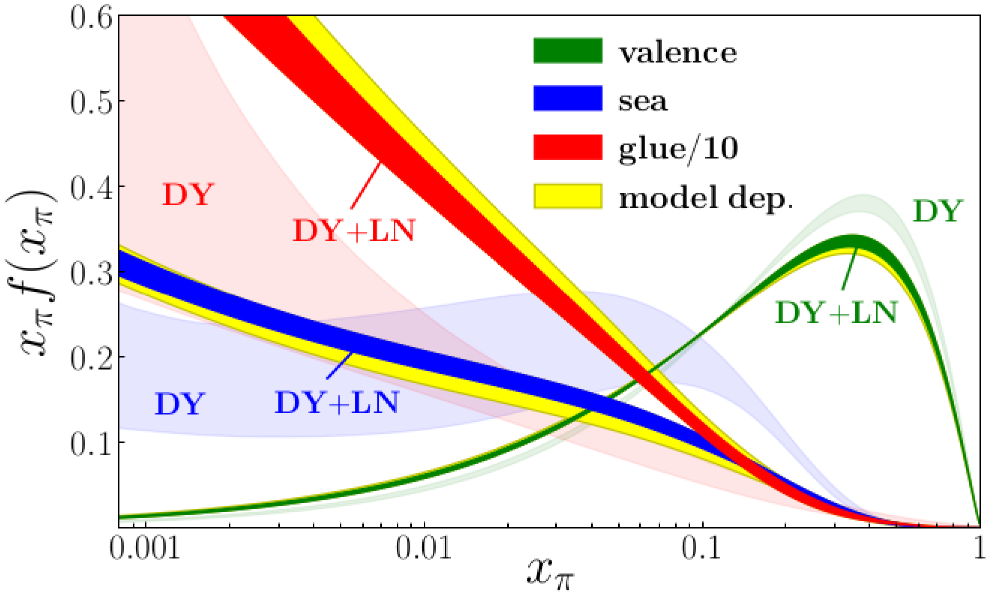
- SMRS did not use π^+ NA3 data. Instead, they assume 3 levels of sea: 10%, 15% or 20%.
- GRV neither. They constrain the pion gluon distribution from pion-induced direct photon production (NA24, WA70)
- NA3 did not publish cross-sections. They extract pion valence and sea based solely on their (scarce) data.
- Large discrepancies. No error treatment.

↪ **COMPASS data will provide new input on the pion valence.**

Recently: JAM pion structure extraction

JAM group revisited the old DY data, and added the leading neutron electroproduction from HERA:

at forward angles LN is expected to be dominated by pion exchange (...but indirect)



JAM, arXiv:1804.01965

Pion gluon distribution: g^π

The gluon distribution in the pion can be accessed from:

direct photons

- From gluon Compton scattering:
  $gq(\bar{q}) \to \gamma q(\bar{q})$
- From quark-antiquark annihilation:
  $q\bar{q} \to \gamma g$

First mechanism dominates.

Important background of minimum bias photons from π^o and η decays.

$\hookrightarrow$ Past measurements from WA70 and NA24.

J/ψ

Mechanism of charmonia production not well understood, models differ:

- NRQCD (color octet+singlet):
  gg fusion dominance.
- Color Evaporation Model:
  $q\bar{q}$ annihilation dominance.

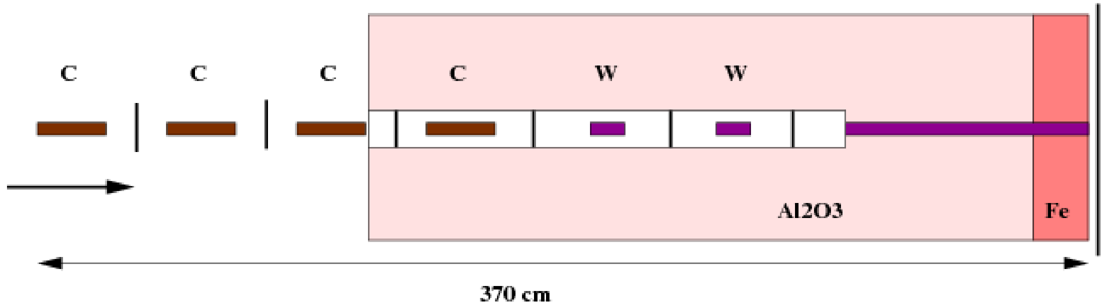
charmonia and their polarization may shed light into production mechanisms, eventually allow separation and access the gluon distribution.

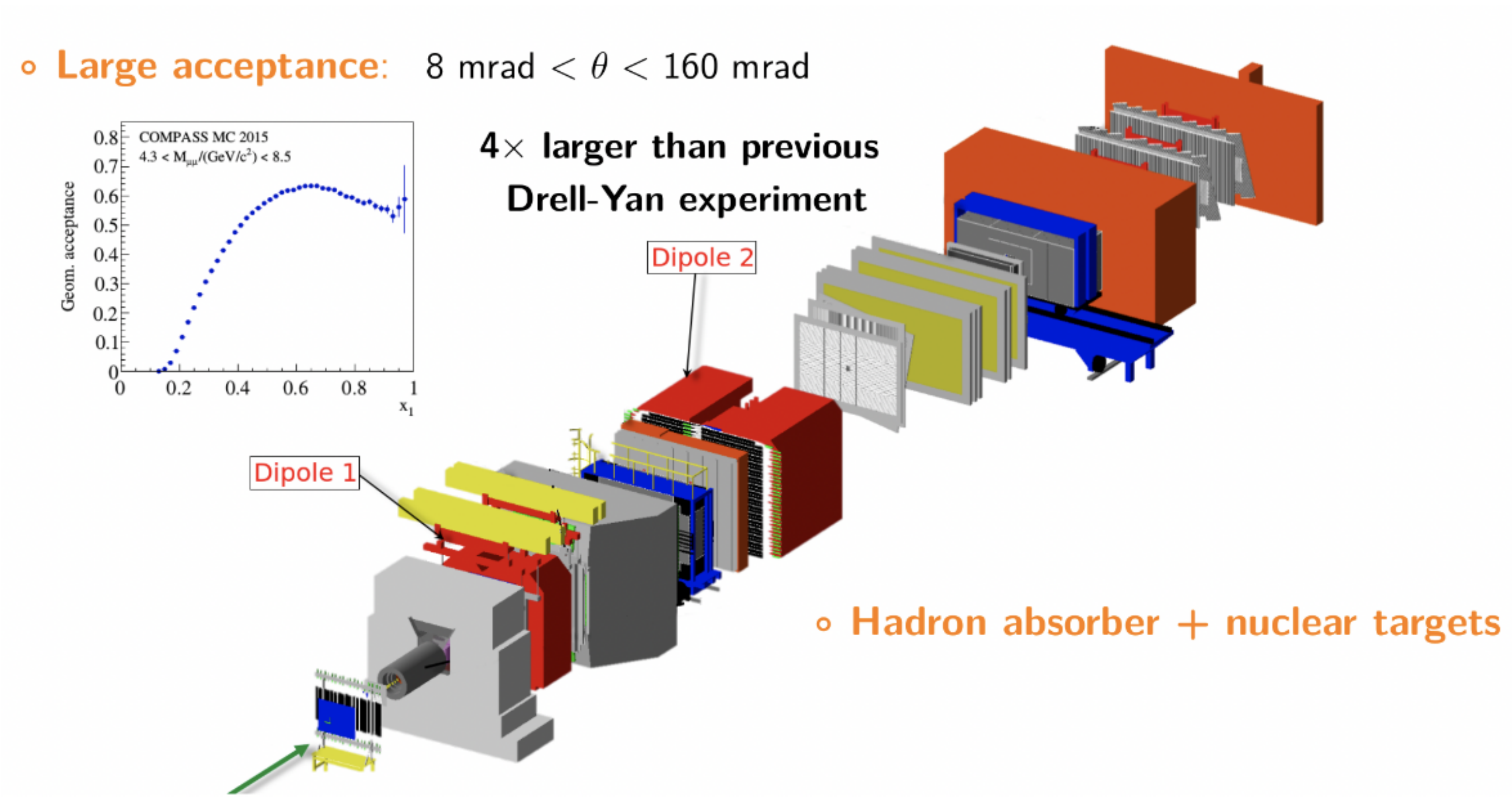
A new Drell-Yan experiment

- Both beam charges are needed
- A light isoscalar target is preferable, to avoid nuclear effects.
- DY has low cross-section (6 orders of magnitude below the hadronic cross-section) → high luminosity needed
- Lots of hadronic products flying in the forward direction → need a hadron absorber, to keep the spectrometer at reasonable occupancies

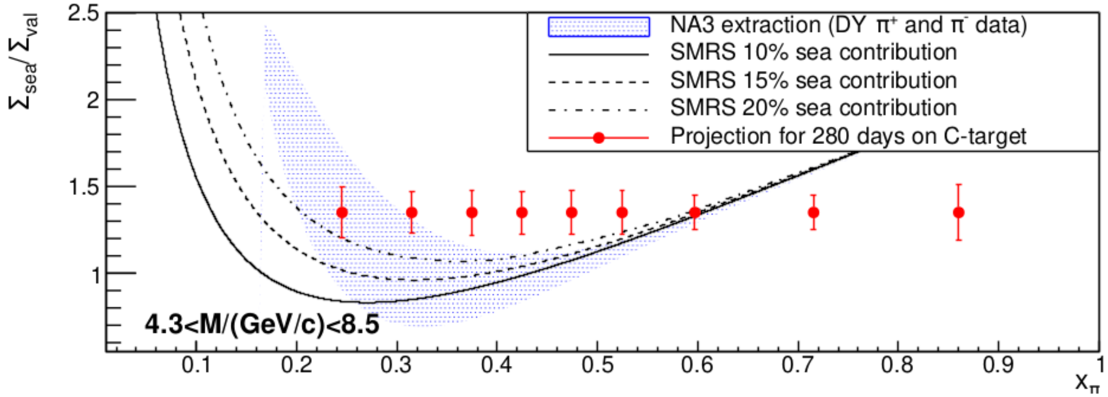
  ↪preferably an **active absorber**
- As large acceptance as possible – keep first part of spectrometer compact
- Good beam particle identification is mandatory

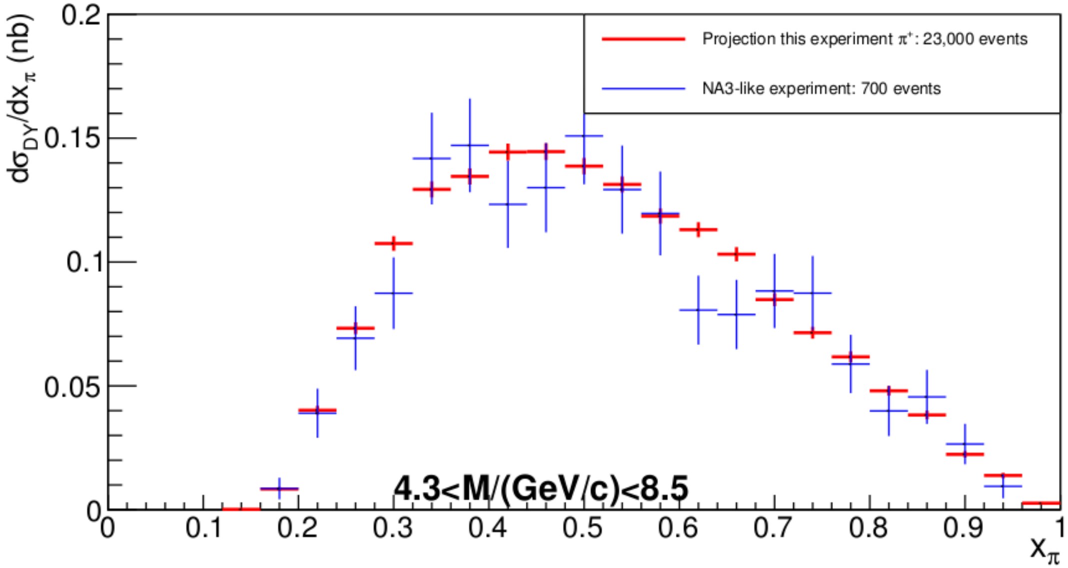
Target: possible (old-fashioned) design





New DY experiment: pion sea to valence ratio





- Collect at least a factor 10 more statistics than presently available
- Minimize nuclear effects on target side
  - Projection for 2 years of Drell-Yan data taking
  - π^+ to π^- 10:1 time sharing
  - 190 GeV beams on Carbon target ($1.9\lambda^{\pi}_{int}$)

Contribution to nuclear PDFs

The nuclear effects of $u_v(x)$ in Carbon are very **small**:

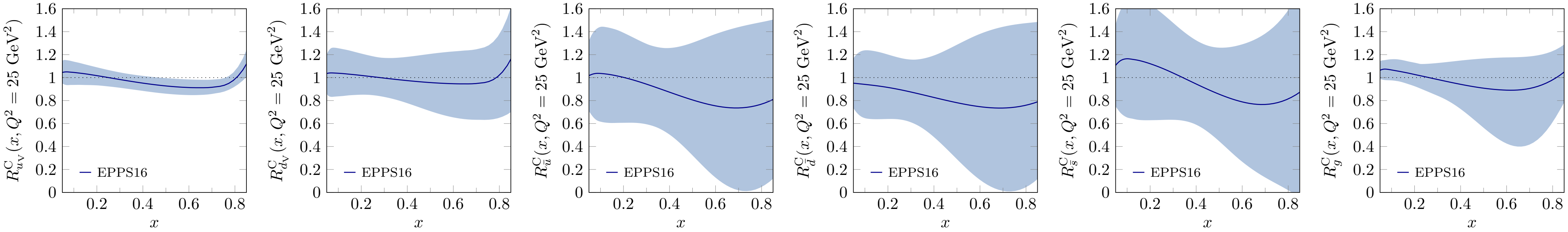
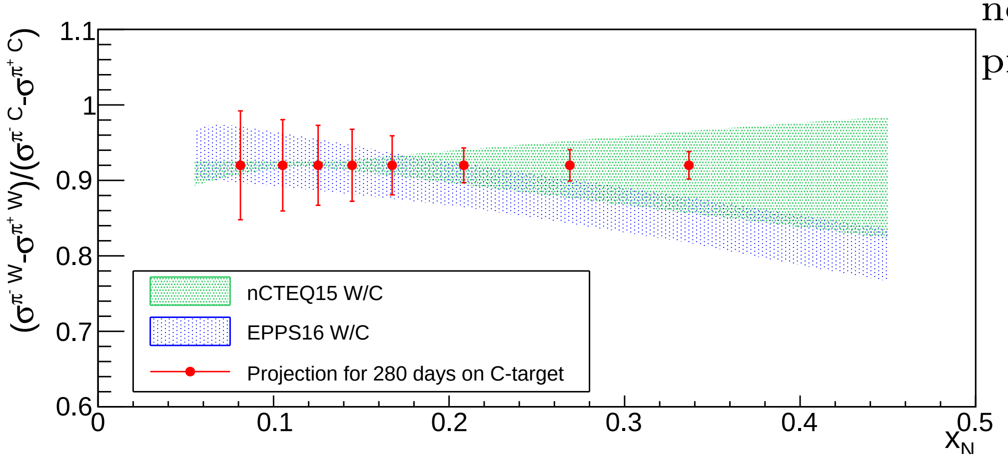


Figure provided by P. Paakkinen, EPPS16 (P. Paakkinen et al, arXiv:1612.05741v1)

Projections

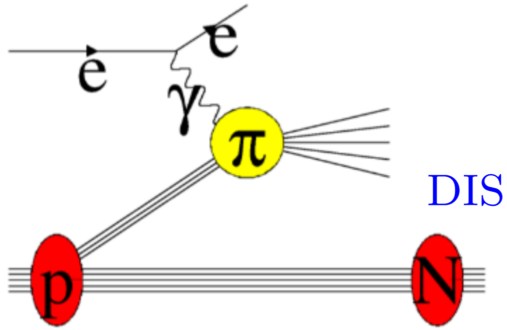


EPPS16: nuclear PDF effects from global fits, including pion-induced DY, and new data on neutrino DIS, and LHC p+Pb dijet, W and Z production.

- No tension in the fit when pion-induced DY data is added.
- But: the statistical weight of these data is not enough to add significant additional constraints to the nuclear PDFs.
- **The new experiment may have a large impact**

Competition/Complementarity: JLab 12 and EIC

At 12 GeV JLab, access **pion form factor** F_π: the electron beam can probe the **pion cloud** of the proton, at $Q^2 = 5 - 10$ GeV^2 – experiment approved for 2018/2019



DIS - Sullivan process

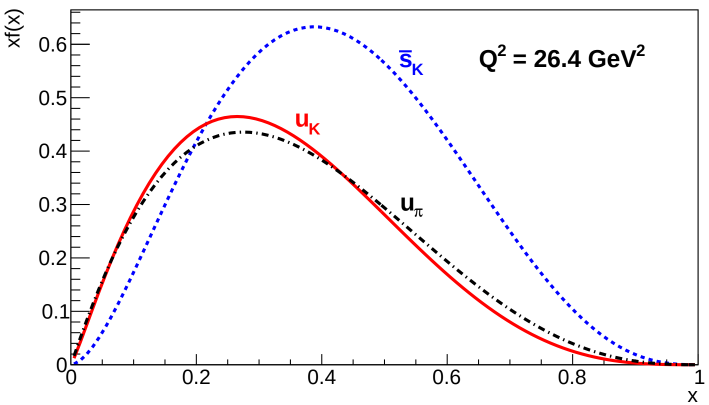
At EIC, apply the same idea to access the pion structure function, down to very low $x_\pi \approx 0.01$

The same process was already used at HERA to reach F_2^π at even lower x_π

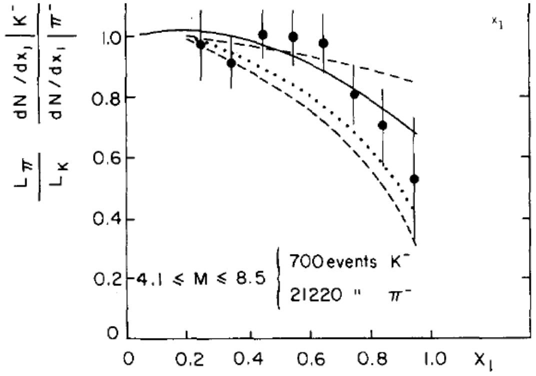
kaons are well-known everywhere, even to mexican graffiters

Kaon structure: mostly unknown

Heavier s-quark $\Longrightarrow$ different valence distribution: $\int V^K(x_1) > \int V^\pi(x_1) \Longrightarrow$ **much less glue carried by the kaons than by pions**.

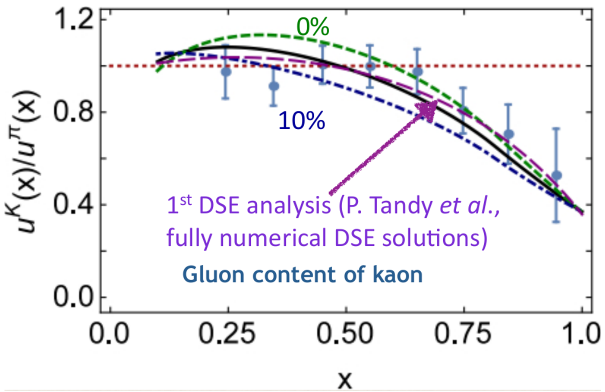


Expectation using Dyson-Schwinger Eq. framework



NA3, Phys.Lett.B 93 (1980) 354

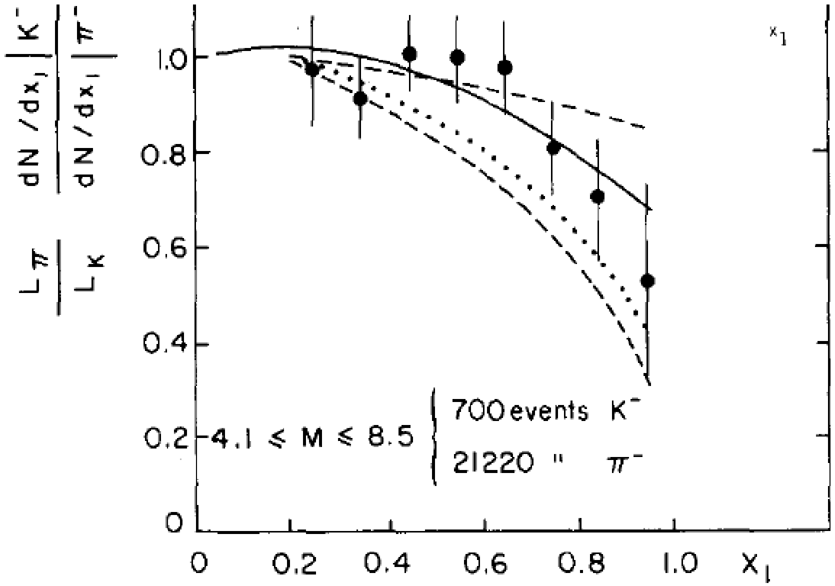
The DSE prediction from C. Chen et al., PRD 93 074021, 2016 indicates the best fit to data is for gluons in kaon to carry 5% of momentum only $\rightarrow$

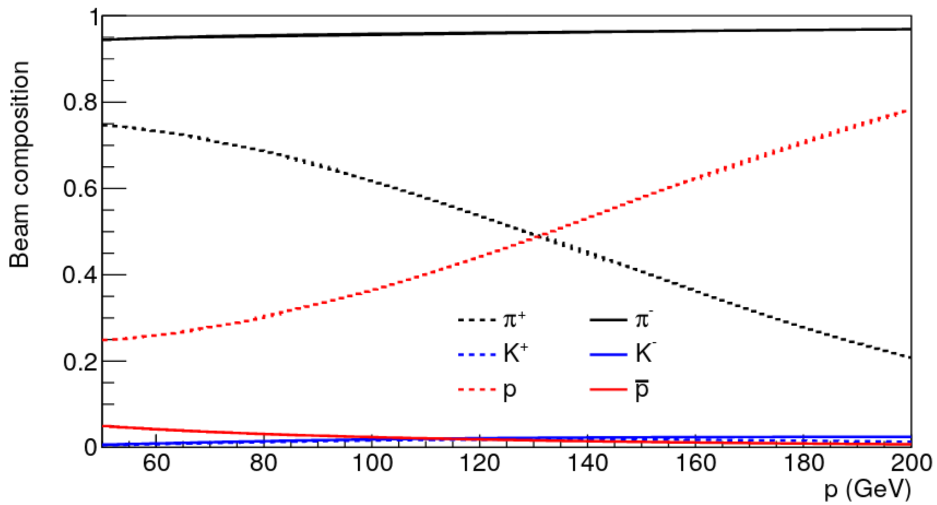


K^+-induced DY cross-section: no valence-valence terms

$$\Sigma_{val} = \sigma^{K^-C} - \sigma^{K^+C} \qquad R_{s/v} = \sigma^{K^+C}/\Sigma_{val}$$

The difficulty with kaons

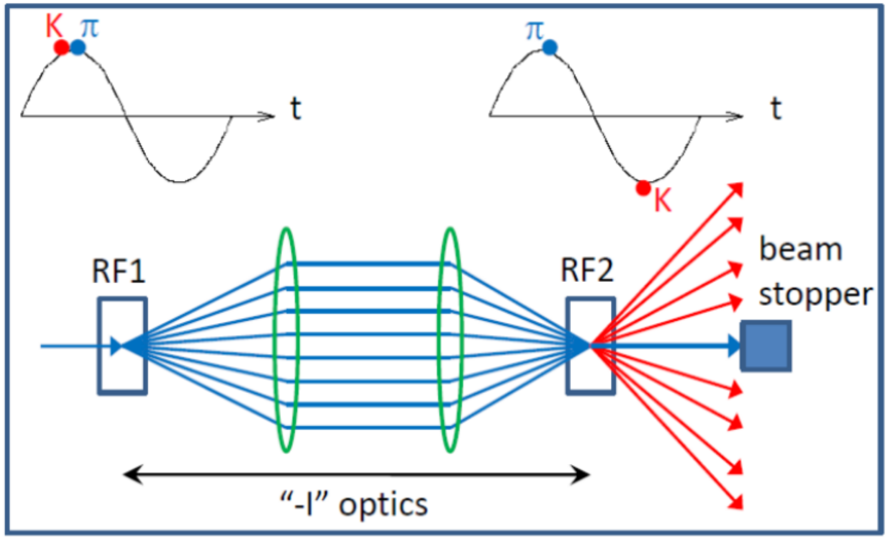




Secondary hadron beams produced from the 400 GeV SPS protons in a beryllium target. In a 190 GeV hadron beam we have:

- 2.5% of K^- in the h^- beam
- 4% of K^+ in the h^+ beam

A high-intensity kaon beam: RF-separated



- Play with particles deflection using 2 RF-cavities
- $\Delta\phi = 0 \rightarrow$ dumped on beam stopper
- Deflection of wanted particle given by: $\Delta\phi = \frac{\pi f L}{c} \frac{m_w^2 - m_u^2}{p^2}$
- Beam will not be pure. For good separation, L should increase as p^2, for given f
  $\hookrightarrow$As L is limited, present limit on beam momentum is
  - $\sim$ 80 GeV/c on kaon beam
  - $\sim$ 100 GeV/c on antiproton beam

Lower beam energy $\Longrightarrow$ for a DY geometrical acceptance $\approx$40% we need to cover 250 mrad.

$\hookrightarrow$ **new detector concept**

A detector with large dilepton acceptance

Magnetised active absorber

- $\mu^+\mu^-$ tracking
- momentum from Lorentz kink in the magnetic field
- Good vertexing resolution
- Associated to an upstream detector for e^+e^-, ECAL-like

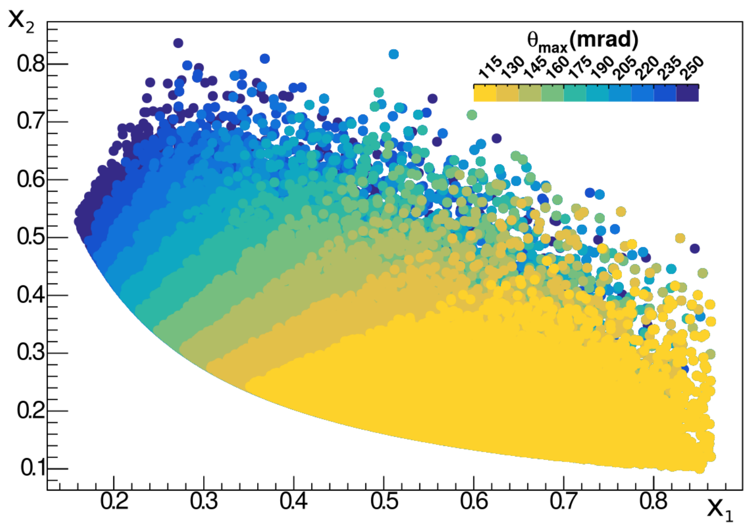
Starting point:

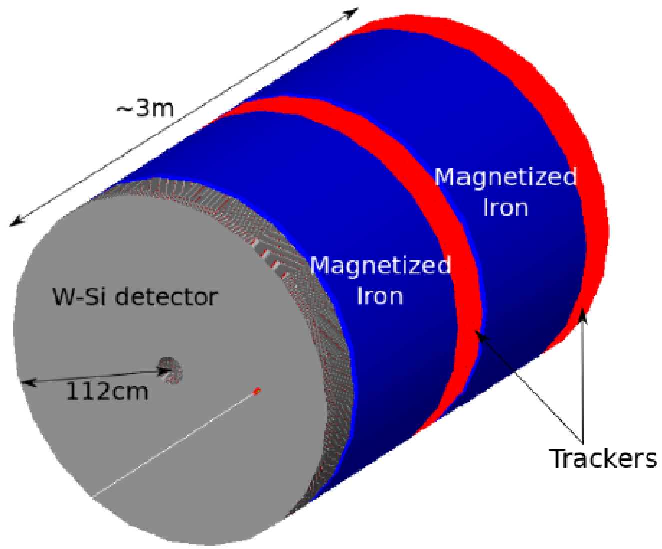
- BabyMIND detector

  M. Antonova et al., arXiv:1704.08079

- W-Si detectors for e^+e^- and photon, a la BNL

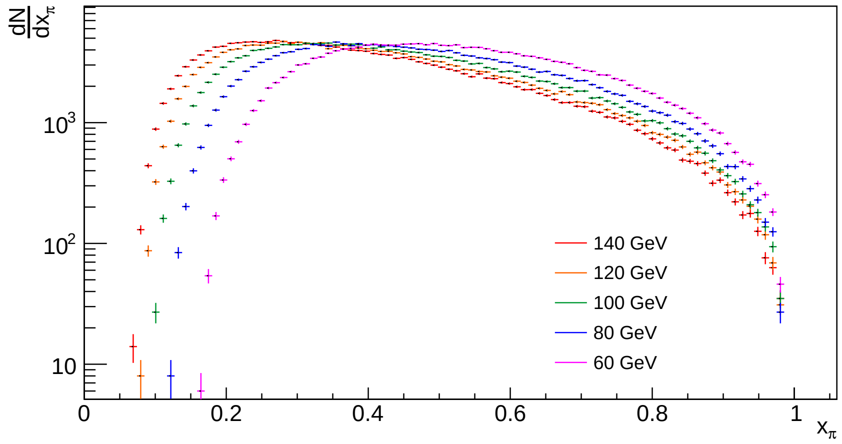
  (AnDY; PHENIX MPCEX; PHENIX NCC – all from RHIC)





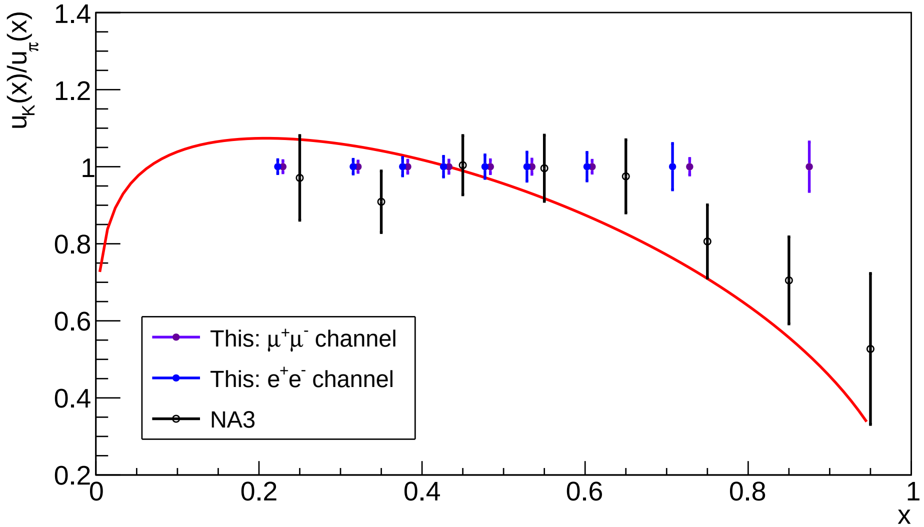
Precision on valence kaon/pion ratio

Pion case here. Expect identical for kaons.



Larger beam energy: larger DY cross-section and access to lower x_K

↪We need to maximize kaon beam energy: R&D needed



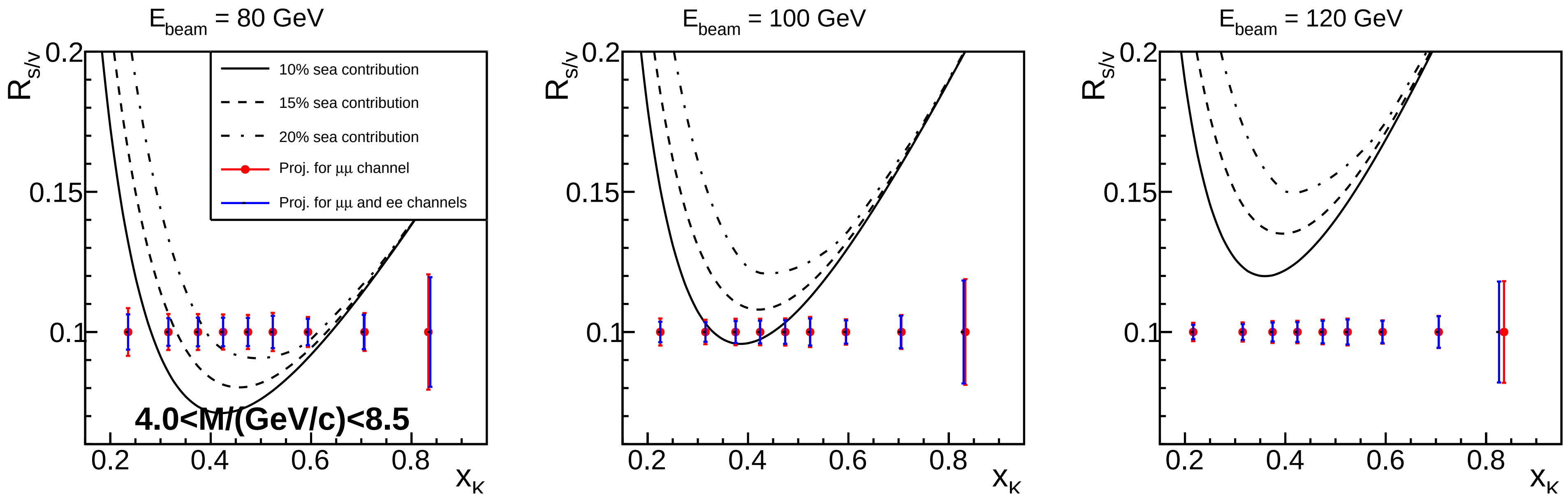
● ● 140 days of K^- beam of 100 GeV momentum

line: DSE prediction, following C. Chen et al., PRD 93 074021, 2016

↪Discriminating power between the existing kaon models

Kaon valence-sea separation

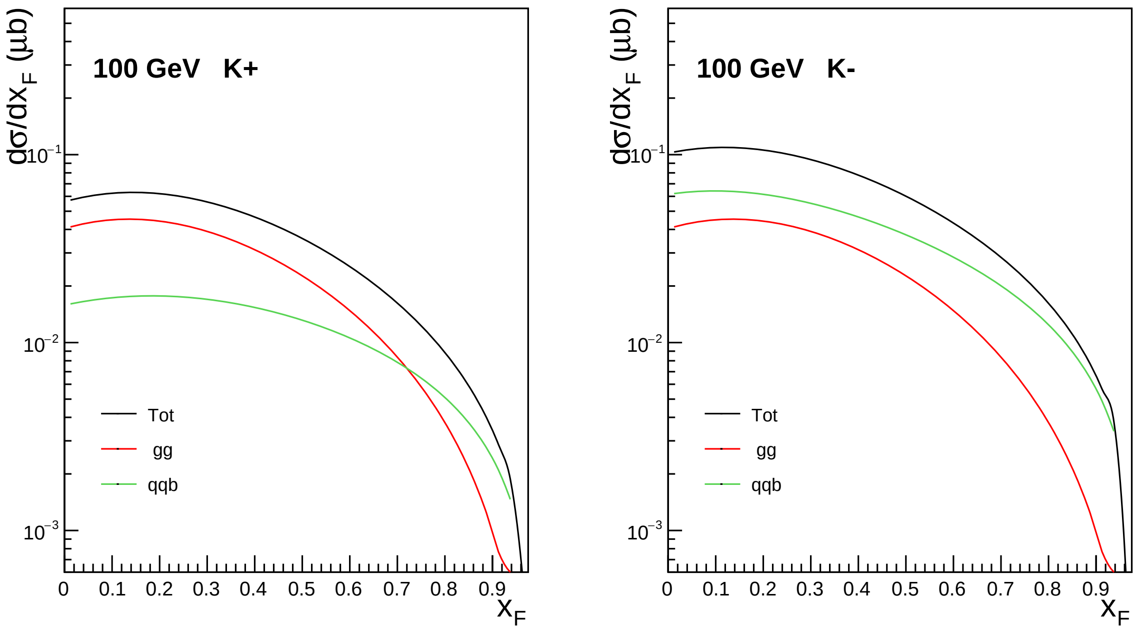
A **first ever** measurement



2 years measurement, 140 days for each kaon beam charge, with intensity 2×10^7 kaons/second

J/ψ production and the kaon gluon distribution

with Color Evaporation Model



While the gg contribution is the same for the 2 kaon beam charges, there is a factor 3 difference for the $q\bar{q}$ contribution. Thus:

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

From the knowledge of valence, within a given model we extract the $g^K g^N$ term.

Back at Spin Physics: closing the circle

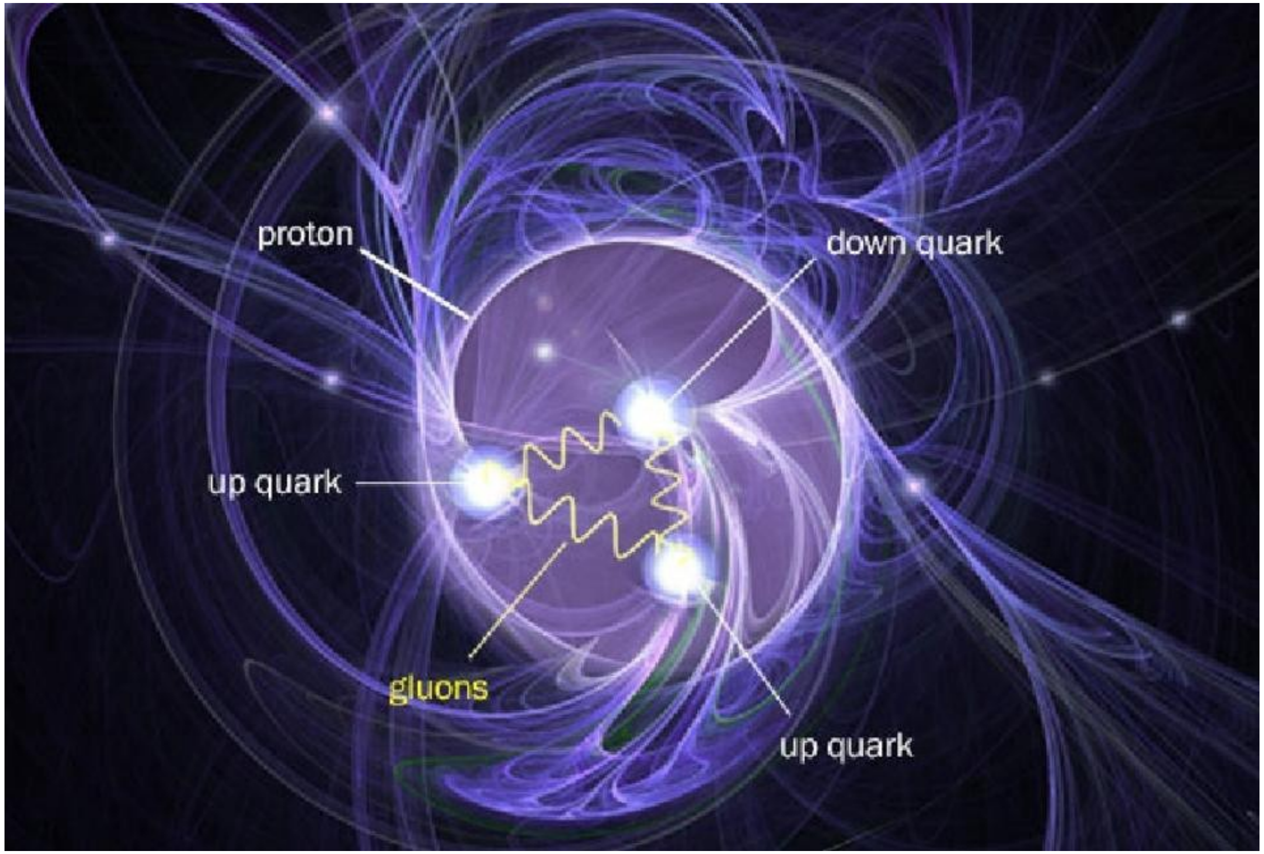


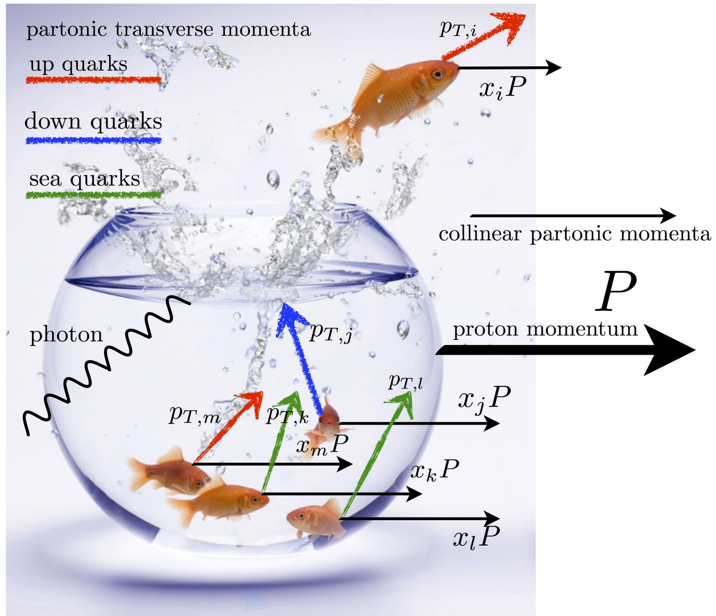
Image credit: Brookhaven National Laboratory

Going beyond the collinear approximation

		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 · $\mathbf{k_T}$

Taking into account the partons transverse motion (k_T), we need 8 TMD PDFs to describe the nucleon.



Quarks and gluons have not only a longitudinal momentum (fraction x of the proton momentum), but also an intrinsic transverse momentum k_T.

Spin physics with antiproton beam

The main uncertainty to access the proton TMD PDFs from COMPASS single spin asymmetries is that they come convoluted with pion TMD PDFs.

$\hookrightarrow$ **Single polarized Drell-Yan with antiproton beam** is cleaner

$$\frac{d\sigma}{dq^4 d\Omega} \propto \hat{\sigma}_U \Big\{ 1 + D_2 A_U^{\cos 2\phi} \cos 2\phi + S_T \Big[D_1 A_T^{\sin \phi_S} \sin \phi_S +$$

$$+ D_2 \Big(A_T^{\sin(2\phi - \phi_S)} \sin(2\phi - \phi_S) \qquad + A_T^{\sin(2\phi + \phi_S)} \sin(2\phi + \phi_S) \Big) \Big] \Big\}$$

- $A_U^{\cos 2\phi}$: $h_1^{\perp}(x_2, k_{T2}) \otimes \bar{h}_1^{\perp}(x_1, k_{T1})$
- $A_T^{\sin \phi_S}$: $f_1(x_2, k_{T2}) \otimes \bar{f}_{1T}^{\perp}(x_1, k_{T1})$
- $A_T^{\sin(2\phi - \phi_S)}$: $h_1^{\perp}(x_2, k_{T2}) \otimes \bar{h}_1(x_1, k_{T1})$
- $A_T^{\sin(2\phi + \phi_S)}$: $h_1^{\perp}(x_2, k_{T2}) \otimes \bar{h}_{1T}^{\perp}(x_1, k_{T1})$

5 "unknown" functions and 4 modulations from DY data. But on $f_1(x_2, k_{T2})$ we have some knowledge

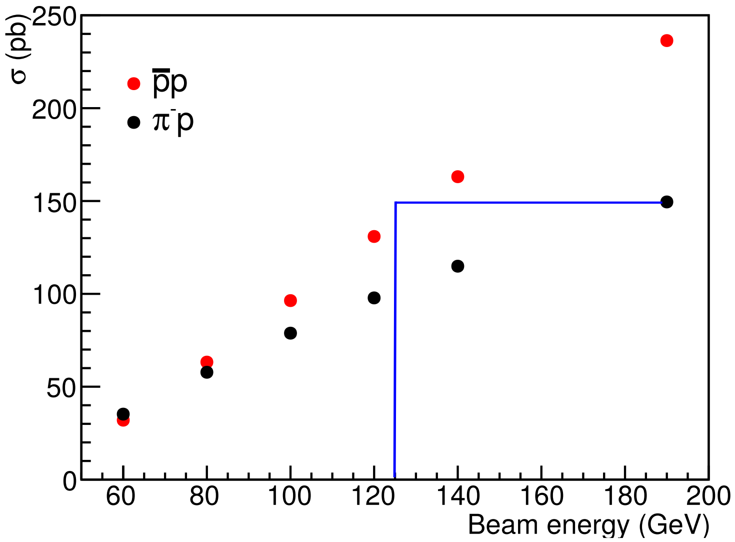
RF-separated antiproton beam

Same limitations as with kaon RF-separated beam:

- beam momentum ≈ 110 GeV, at most
- Purity of 30-50% – antiprotons come mixed with pions

⟹ **transversely polarized protons** using a NH_3 COMPASS-like target

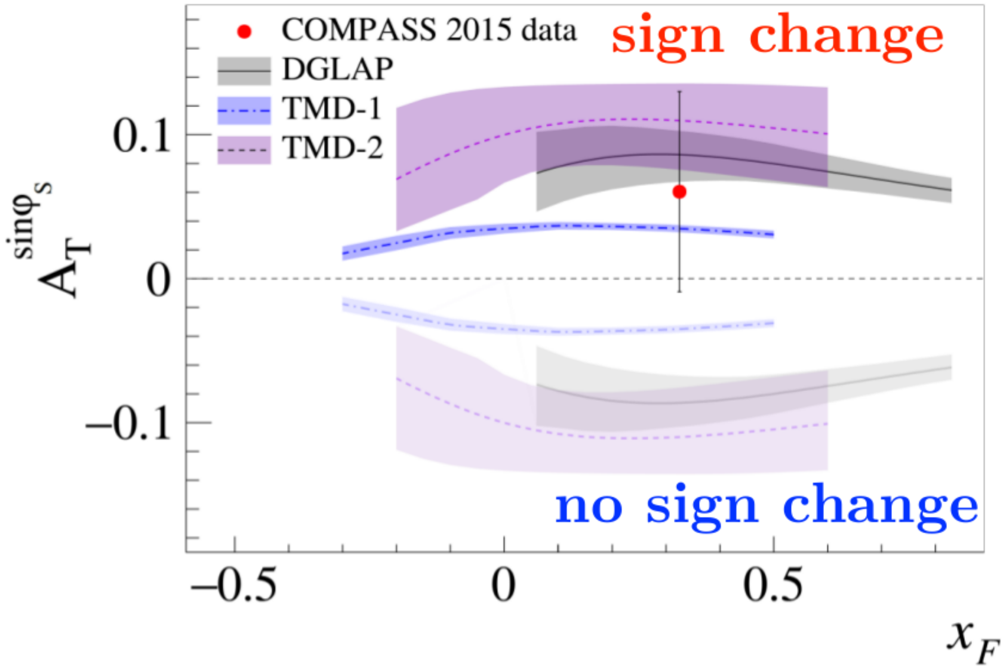
Use a mini-spectrometer active absorber, to access Drell-Yan $\mu^+\mu^-$ and e^+e^-



With antiproton beam at these energies one gets in the most favourable region to access valence distributions.

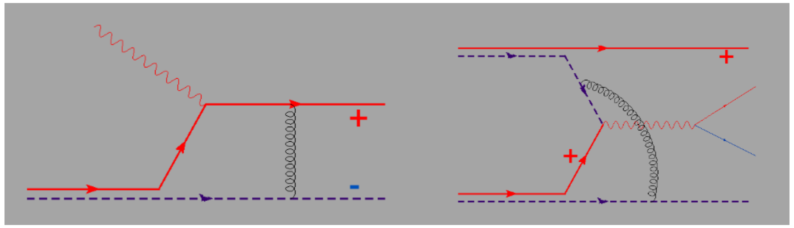
← For the same beam energy, the Drell-Yan cross-section is higher with antiproton beam than with pion beam (3 quarks vs 2 quarks)

Towards a Siver TMD extraction



COMPASS, Phys.Rev.Lett. **119**, 112002 (2017)

The Sivers TMD is naive time reversal odd! – i.e. depends on the process



$$f_{1T}^{\perp}(\text{SIDIS}) = - f_{1T}^{\perp}(\text{DY})$$

There is a "hint" that the Sivers TMD PDF has opposite sign in SIDIS and DY reactions, but statistically not yet conclusive → COMPASS 2018 data

Much lower systematics in the proton Sivers PDF extraction if using antiproton-induced DY.

Requirements for COMPASS++/AMBER

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 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	

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.

COMPASS++/AMBER at CERN

QCD Conveners at PBC workshop, 16/01/2019 (M. Diehl, J. Pawlowski, G. Schnell)

	LHC FT gas				LHC FT	COMPASS++	MUonE	NA61++	NA60++	DIRAC++
	ALICE	LHCb	LHCSpin	AFTER@LHC	crystals					
proton PDFs	×	×		×						
nuclear PDFs	×	×		×		×				
spin physics	×		×	×		×				
meson PDFs						×				
heavy ion physics	×			×				×	×	
elast. μ scattering						×	×			
chiral dynamics						×				×
magnet. moments					×					
spectroscopy						×				
measurements for cosmic rays and neutrino physics	×	×		×		×		×		

Table 1. Schematic overview of the physics topics addressed by the studies presented in the QCD working group.

Year	Activity	Duration	Beam
2019 2020	Long Shutdown 2	2 years	-
2021	COMPASS-II transversity with polarised deuteron target	1 year	muon
2022	proton radius	1 year	muon
2023 2024	Drell-Yan for π and K PDFs and charmonium production mechanism Antiproton cross section for Dark Matter Search	$\lesssim 2$ years 2 month	p, K^+, π^+ $\bar{p}, K^-, \pi^-$ p
2025	Long Shutdown 3 (for SPS)		

Some concluding remarks

- Progress in the field of QCD, with important contribution from COMPASS, lead to a bunch of new and old questions.
- A new experimental programme in the context of QCD physics is proposed
- More than an "experiment", we propose a modular setup, a "facility" to conduct a many QCD-related measurements
- Smooth transition from COMPASS-II to COMPASS++ and later finally to AMBER
- AMBER shall be a new Collaboration: new groups, new detector, new beam line

Preparing now the Physics Proposal