CERN

From COMPASS to AMBER

Hadron'23, Genova, Italia, 2023/06/09

AMBER
Apparatus for Meson and Baryon Experimental Research

HADRON 2023

Spin crisis? It is over.. Mass "crisis"? Knocking in the door…

(how much we have learned so far about proton spin (selected topics), what is next science question to be addressed?)

Outlook

1. Intro: Spin and Transverse Momentum Dependent PDFs
2. Polarised SIDIS:
   - Sivers function story
3. Crucial TMDs approach test:
   - SIDIS vs Drell-Yan
   - COMPASS results
4. Intro: EHM and pion – proton mass difference
5. CERN's road map main focus and contribution by AMBER
7. Summary

Dr. Oleg Denisov, senior researcher INFN section of Turin, Italy

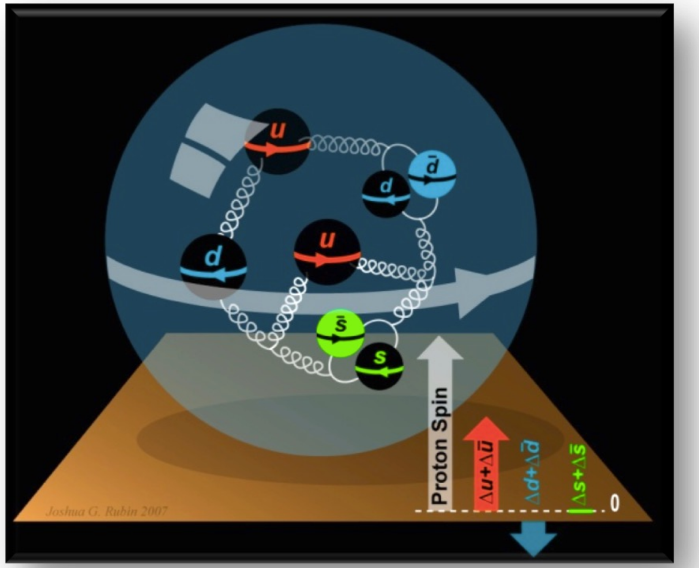
Only very selected results of COMPASS are shown – for more see talks by Bernhad Ketzer, Stefan Wallner, Dominik Ecker, Philipp Haas, Julien Beckers

Materials/slides of Vincent Andrieux, Craig Roberts, Bakur Parsamyan, Alessandro Bacchetta, Stefan Wallner , Jan Friedrich, Stephan Paul and others have been used

Introduction to the Spin I

On the one hand - Almost all visible matter of the universe we are able to observe consists of nucleons.

On the other hand - SPIN is a fundamental quantum number (Pauli principle), to some extent define a rules on how the atomic/nuclear matter is constructed.



Thus we better understand well how the spin of the nucleon (and hadron in general) is "constructed".

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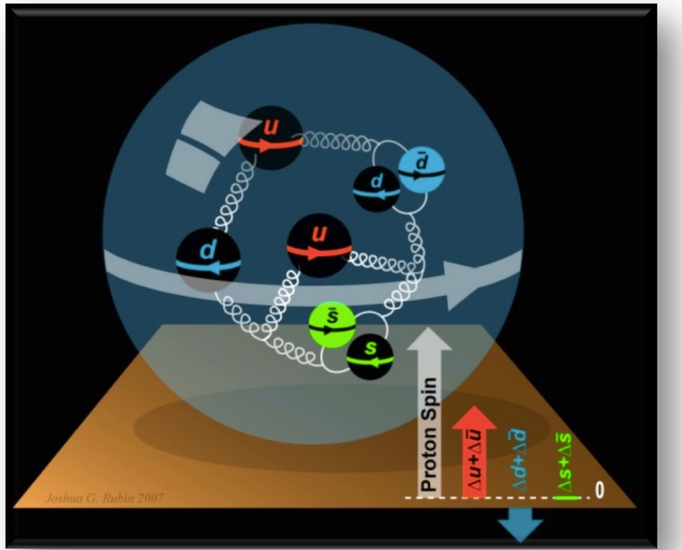
Nucleon spin ½ = ½ ΔΣ + ΔG + L

quark gluon orbital mom.

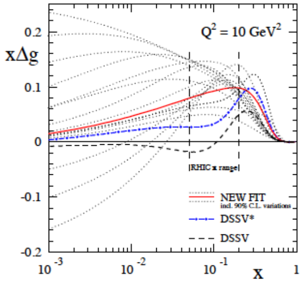


$\Delta\Sigma$: sum over u, d, s, $\bar{u}$, $\bar{d}$, $\bar{s}$
Can take any value: superposition of several states

$\Delta q = \vec{q} - \overleftarrow{q}$
Parton spin parallel or anti parallel to nucleon spin

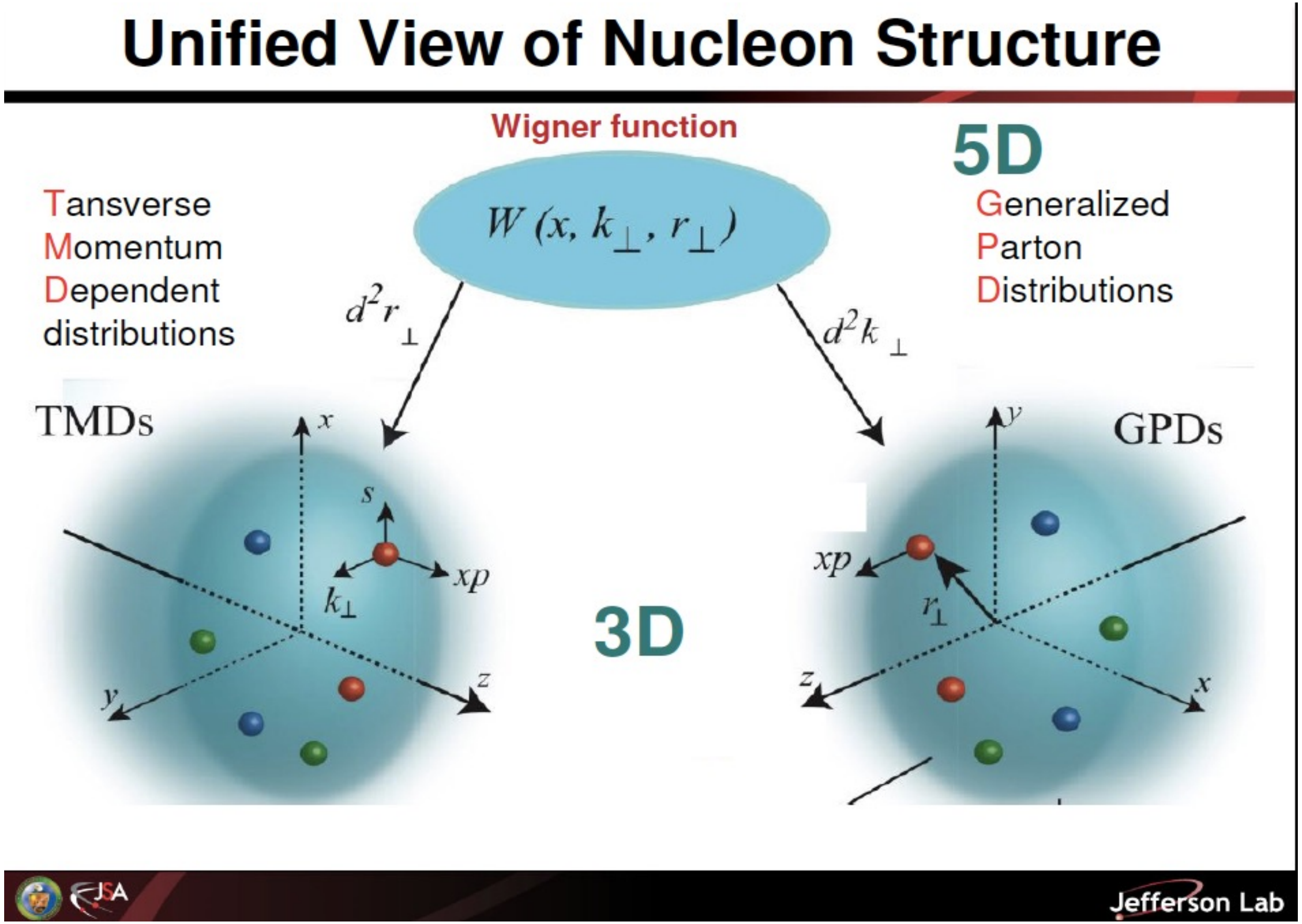
First two component were extensively studied in the SIDIS experiments with the longitudinally polarised target (collinear case approach): spin fraction carried by quarks and gluons is not sufficient to describe ½ nucleon spin (Spin Crisis, continued):

- Quark spin contribution ΔΣ=0.24 (Q^2=10 $(GeV/c)^2$ DSSV *arXiv:0804.0422)*
- RHIC and COMPASS Open charm measurement and other direct measurements ➔ ΔG/G is not sufficient ➔

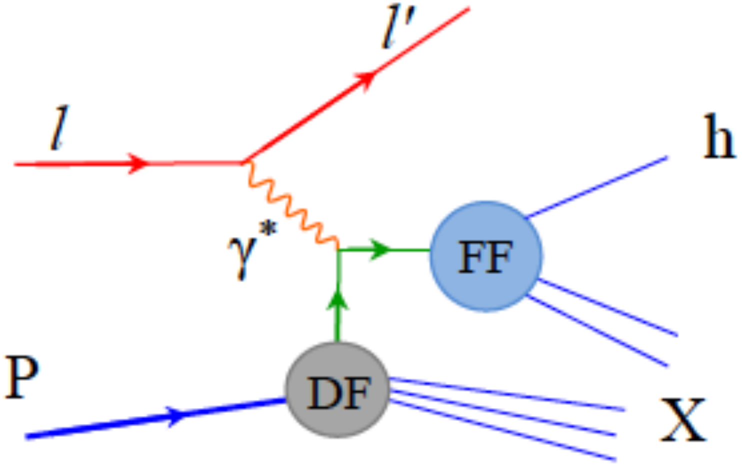


In order to create Angular Momentum of partons spin-orbit correlation has to be taken into account ➔ transverse momentum of the quark k_T appears ➔ **3D structure of the Nucleon has to be studied**

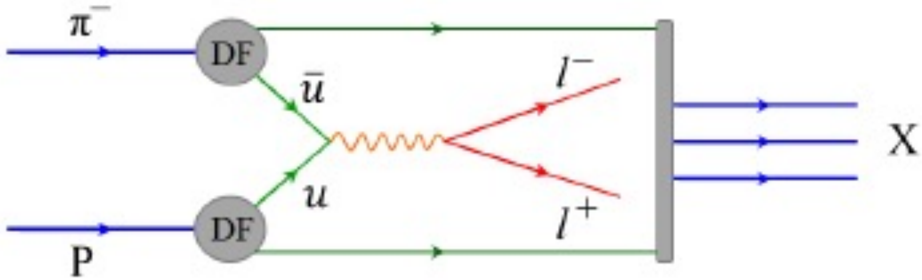
3D structure of nucleon II



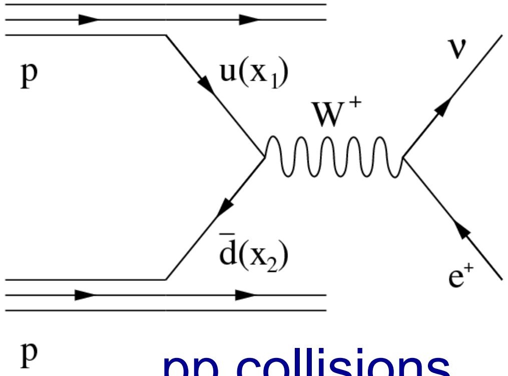
Four probes to access transverse hadron structure (TMD PDFs)



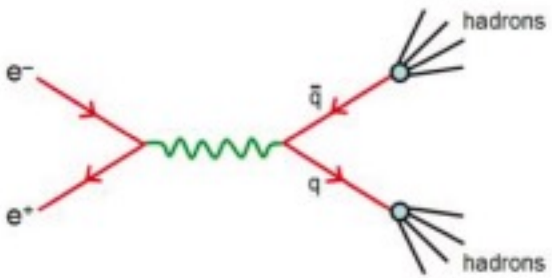
SIDIS



Drell-Yan



pp collisions



e^+e^- collisions

SIDIS ➔

18 structure functions
14 azimuthal modulations

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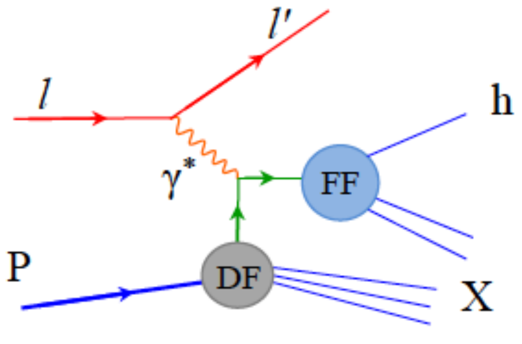
$$\frac{d\sigma}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\phi_S} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right](F_{UU,T}+\varepsilon F_{UU,L})$$

$$\times\Bigg\{1+\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h+\varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h + \lambda\sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\phi_h}\sin\phi_h$$

$$+S_L\left[\sqrt{2\varepsilon(1+\varepsilon)}A_{UL}^{\sin\phi_h}\sin\phi_h+\varepsilon A_{UL}^{\sin 2\phi_h}\sin 2\phi_h\right] + S_L\lambda\left[\sqrt{1-\varepsilon^2}A_{LL}+\sqrt{2\varepsilon(1-\varepsilon)}A_{LL}^{\cos\phi_h}\cos\phi_h\right]$$

$$+S_T\left[\begin{array}{l}A_{UT}^{\sin(\phi_h-\phi_S)}\sin(\phi_h-\phi_S)\\ +\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S)\\ +\varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S)\\ +\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin\phi_S}\sin\phi_S\\ +\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin(2\phi_h-\phi_S)}\sin(2\phi_h-\phi_S)\end{array}\right]$$

$$+S_T\lambda\left[\begin{array}{l}\sqrt{(1-\varepsilon^2)}A_{LT}^{\cos(\phi_h-\phi_S)}\cos(\phi_h-\phi_S)\\ +\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos\phi_S}\cos\phi_S\\ +\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos(2\phi_h-\phi_S)}\cos(2\phi_h-\phi_S)\end{array}\right]\Bigg\}$$



Nucleon \ Quark	U	L	T
U	$f_1^q(x,\boldsymbol{k}_T^2)$ number density		$h_1^{\perp q}(x,\boldsymbol{k}_T^2)$ Boer-Mulders
L		$g_1^q(x,\boldsymbol{k}_T^2)$ helicity	$h_{1L}^{\perp q}(x,\boldsymbol{k}_T^2)$ worm-gear L
T	$f_{1T}^{\perp q}(x,\boldsymbol{k}_T^2)$ Sivers	$g_{1T}^q(x,\boldsymbol{k}_T^2)$ Kotzinian-Mulders worm-gear T	$h_1^q(x,\boldsymbol{k}_T^2)$ transversity; $h_{1T}^{\perp q}(x,\boldsymbol{k}_T^2)$ pretzelosity

+ two FFs: $D_{1q}^h(z,P_\perp^2)$ and $H_{1q}^{\perp h}(z,P_\perp^2)$

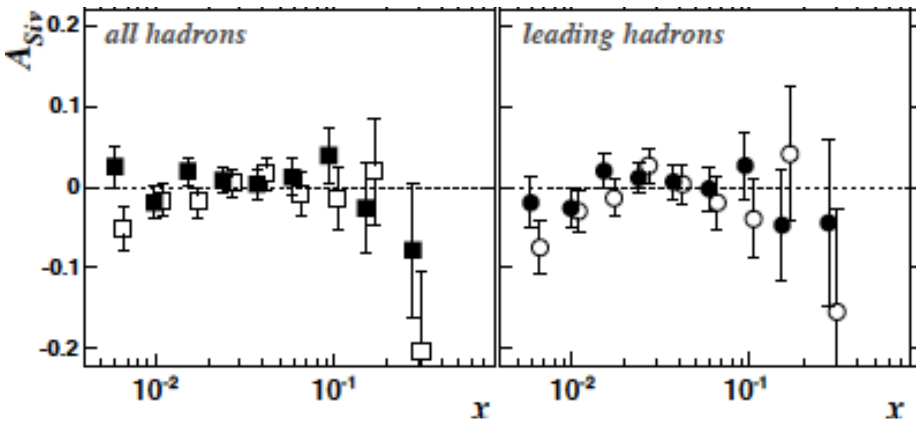
At leading order, three PDFs are needed to describe the nucleon in the collinear case.
If one admit a non-zero transverse quark momentum k_T in the nucleon five more PDFs (TMD PDFs) are needed.
In this talk dedicated attention to non zero structure function Sivers function $f^L_{1T}(x, k_T)$.
It describes the influence of the transverse spin of the nucleon onto the quark transverse momentum distribution ➔ provides model-dependent access to the orbital momentum

Sivers asymmetry: first round (earlier 2000):
Sivers 2004 – first Hermes data at proton – non zero asymmetry, COMPASS at deuteron - zero

COMPASS Results of 2005

Hep-ex/0503002

Solid state ^{6}LD polarised target



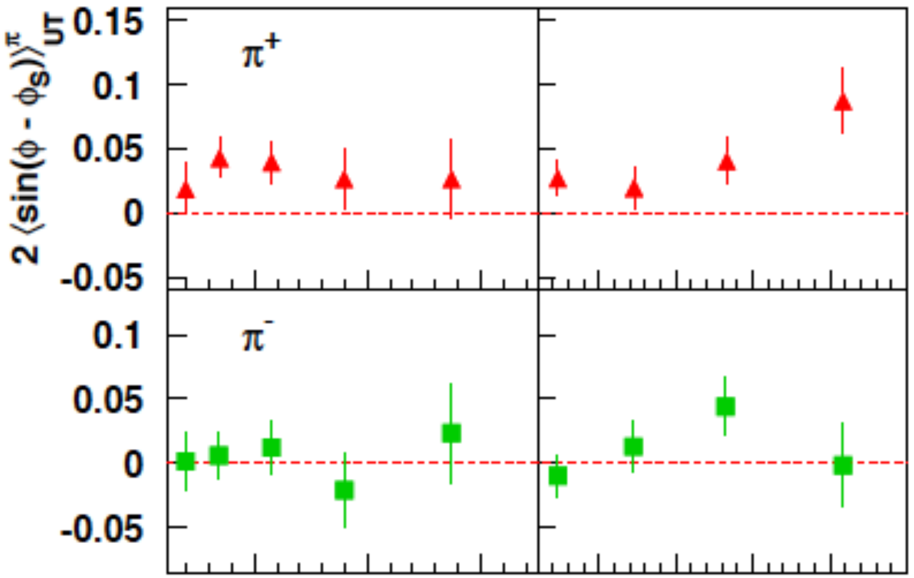
Full points – positive hadrons,
Open points – negative hadrons

DOUBTS…..

Hermes Results of 2004

hep-ph/0408013

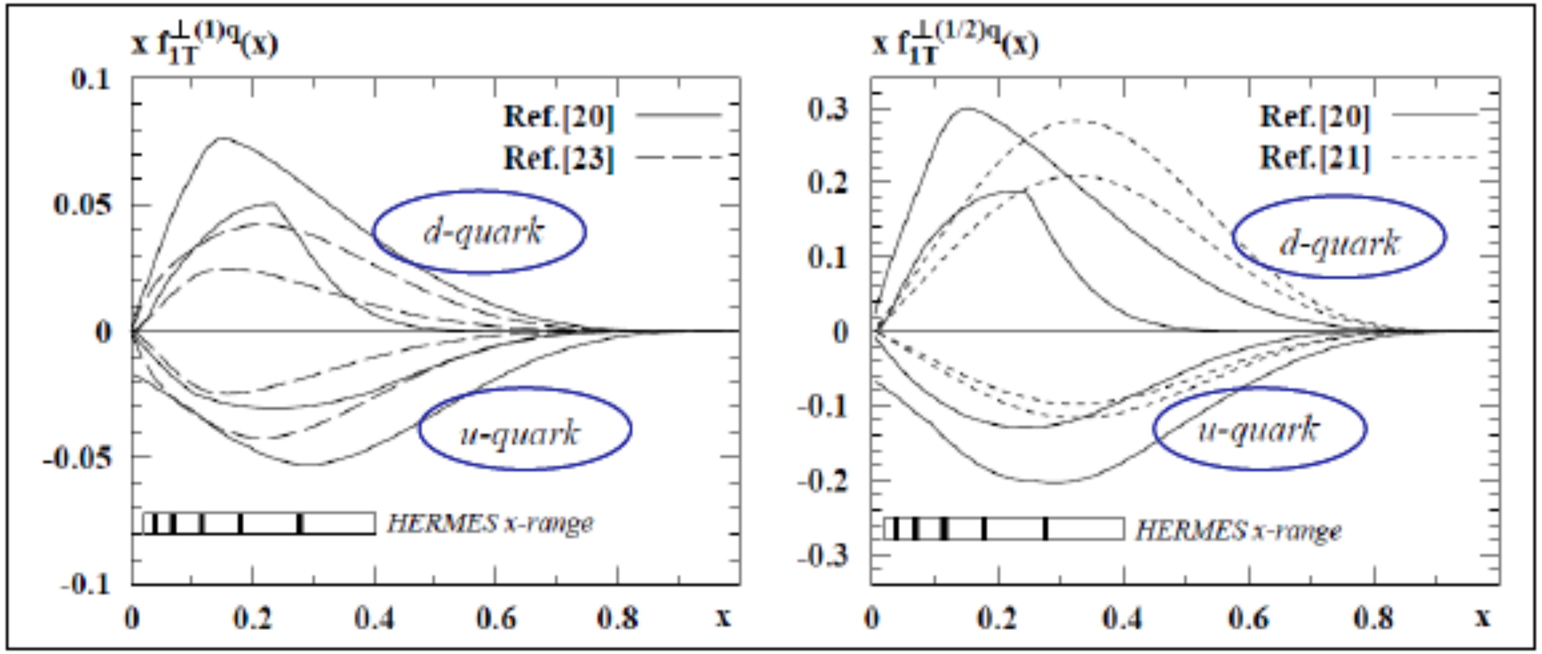
Gaseous H_2 polarized target



$$A_{UT}^{\sin(\phi_h-\phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^{h}$$

Joint data analysis form Hermes and COMPASS – no contradictions

As it was shown by Mauro Anselmino and Colleagues (second half of 2005) when first extraction of Sivers function has been performed from Hermes and COMPASS data (Transversity'2005, hep-ph/051101)) that the contributions from u- and d-quarks are opposite



Sivers 2009 – final results Hermes&COMPASS data perfectly fits together

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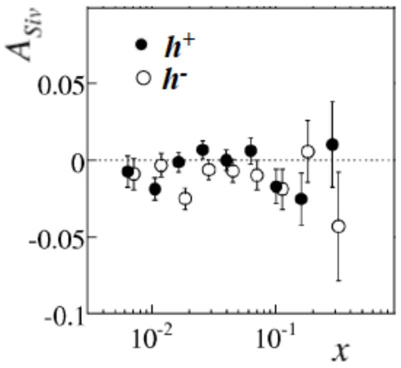
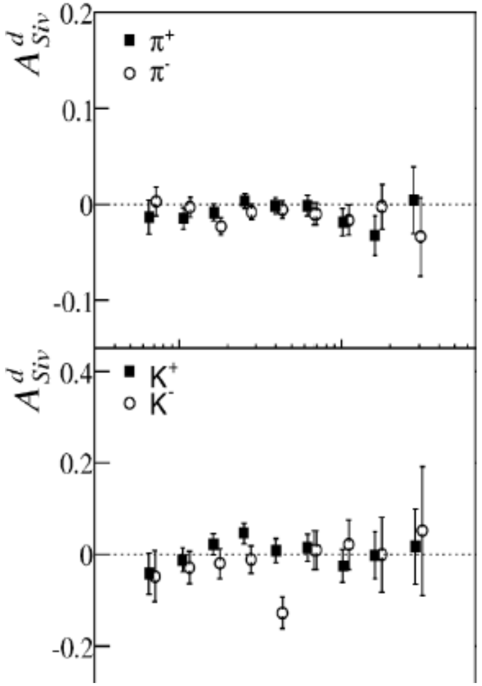
COMPASS Final results on deuteron

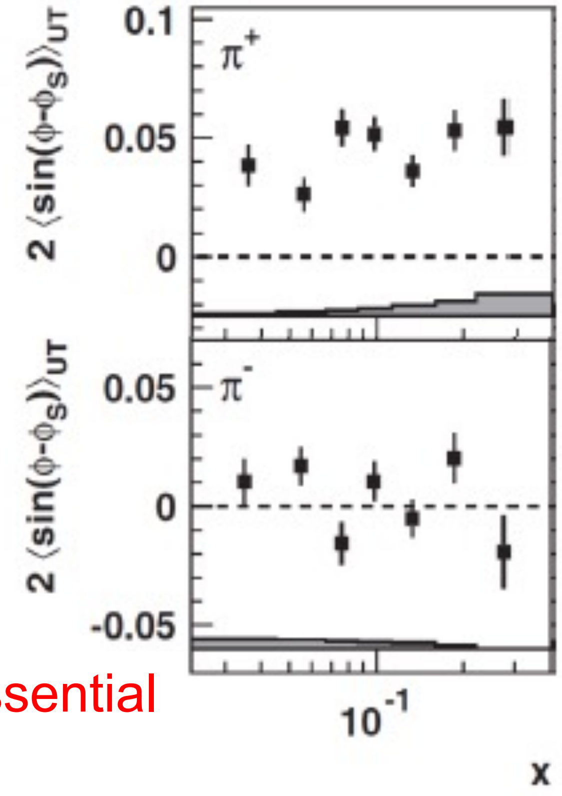
(data 2002-2004) PLB 673 (2009)

Hermes Final results on proton

PRL 103 (2009)



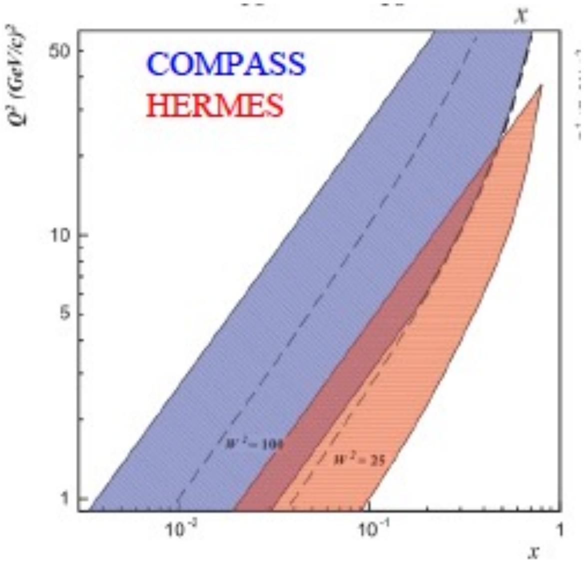


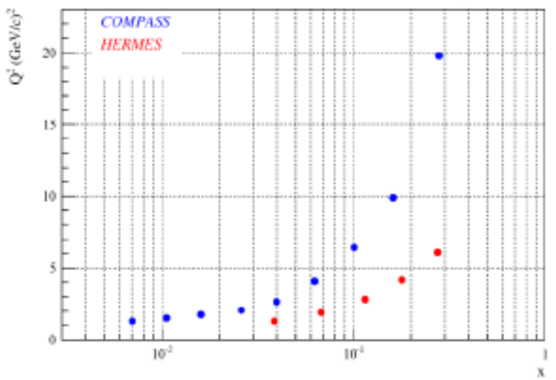


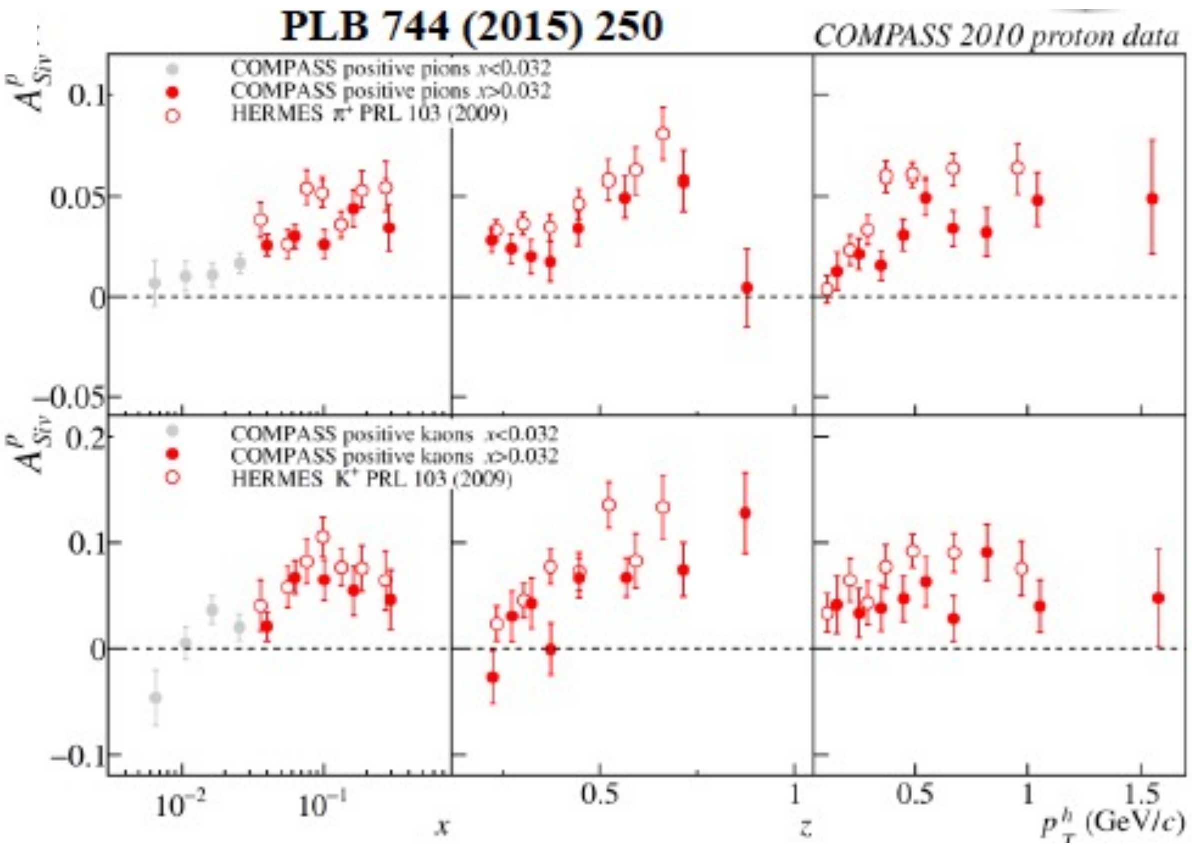
Flavour separation is essential

COMPASS ⇔ Hermes proton data
COMPASS Sivers is smaller – QCD evolution eff.?

Even if exist evolution has to be rather slow







TMDs universality SIDIS⟵⟶DY

The time-reversal odd character of the Sivers and Boer-Mulders PDFs lead to the prediction of a sign change when accessed from SIDIS or from Drell-Yan processes:

↪ Check the predictions:

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

$$h_{1}^{\perp}(DY) = -h_{1}^{\perp}(SIDIS)$$

Its experimental confirmation is considered a crucial test of non-perturbative QCD.

Universality test includes not only the sing-reversal character of the TMDs but also the comparison of the amplitude as well as the shape of the corresponding TMDs

SIDIS ←→ DY – QCD test

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Andreas Metz (Trento-TMD'2010):

Sign reversal of the Sivers function

- Prediction based on operator definition (Collins, 2002)

$$f_{1T}^{\perp}\big|_{DY} = -\, f_{1T}^{\perp}\big|_{DIS}$$

- What if sign reversal of $f_{1T}^{\perp}$ is not confirmed by experiment ?
  - Would not imply that QCD is wrong
  - Would imply that SSAs not understood in QCD
  - Problem with TMD-factorization
  - Problem with resummation of large logarithms
    - → Resummation relevant if more than one scale present
    - → CSS resummation in Drell-Yan (Collins, Soper, Sterman, 1985); resum logarithms of the type

$$\alpha_s^k \ln^{2k} \frac{\vec{Q}_T^2}{Q^2}$$

→ Has also implications for Fermilab and LHC physics

2005 – Anatoly Efremov brings my attention for the first time to this effect (discussed in the famous paper by John Collins *Phys.Lett.B* 536 (2002) 43-48)

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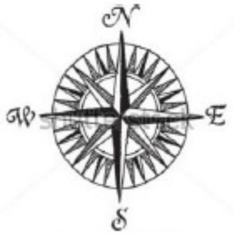
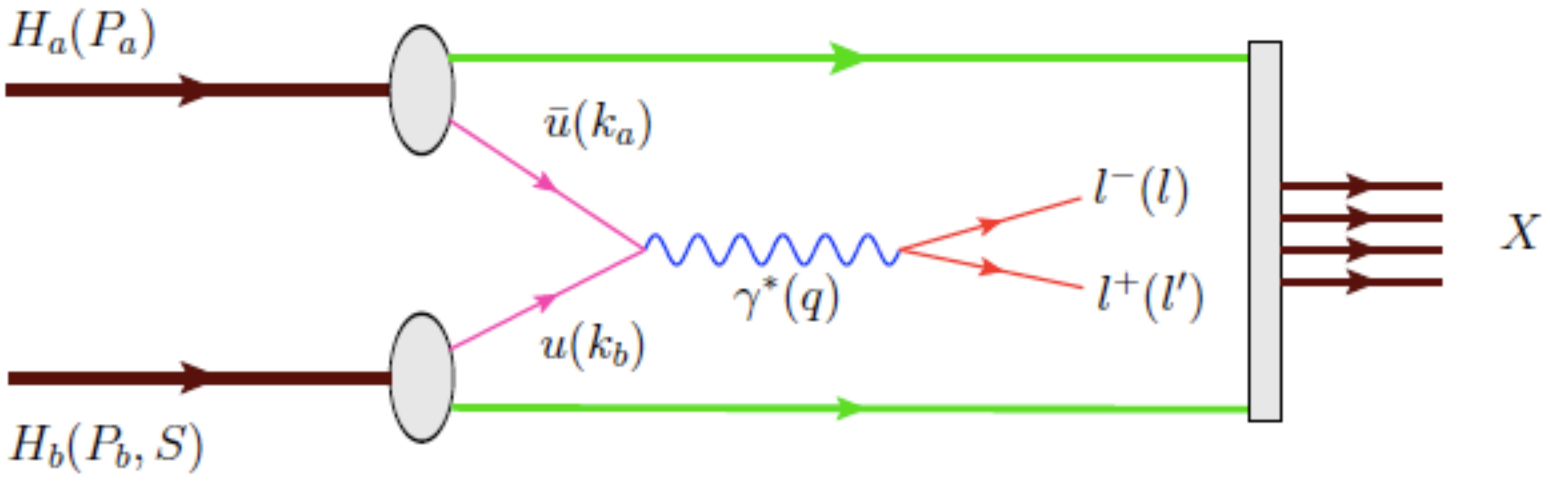


Drell-Yan process



$P_{a(b)}$	the momentum of the beam (target) hadron,
$s = (P_a + P_b)^2,$	the total centre-of-mass energy squared,
$x_{a(b)} = q^2/(2P_{a(b)} \cdot q),$	the momentum fraction carried by a parton from $H_{a(b)}$,
$x_F = x_a - x_b,$	the Feynman variable,
$M^2_{\mu\mu} = Q^2 = q^2 = s\ x_a\ x_b,$	the invariant mass squared of the dimuon,
$\mathbf{k}_{Ta(b)}$	the transverse component of the quark momentum,
$\mathbf{q}_T = \mathbf{P}_T = \mathbf{k}_{Ta} + \mathbf{k}_{Tb}$	the transverse component of the momentum of the virtual photon.

Sivers in SIDIS and Drell-Yan

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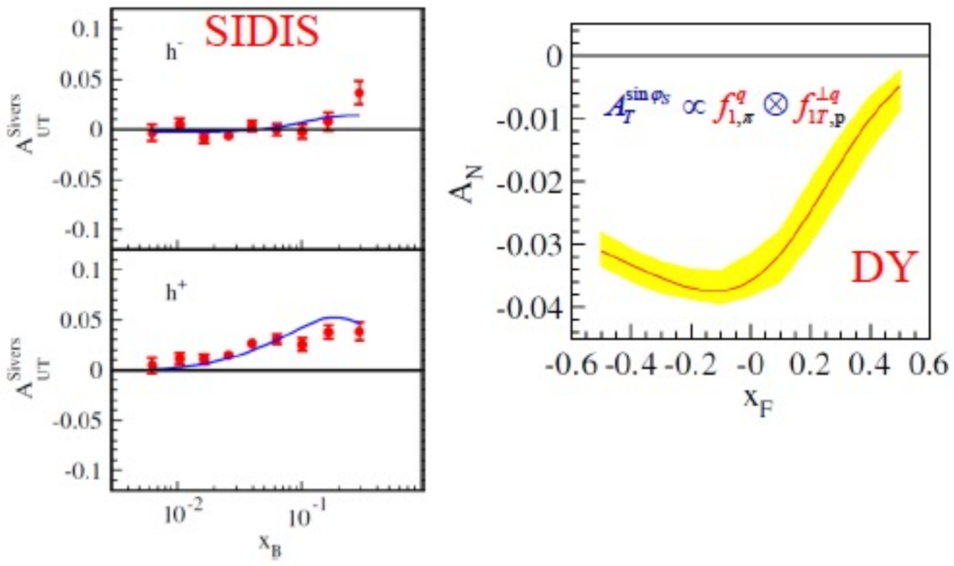
SIDIS data:

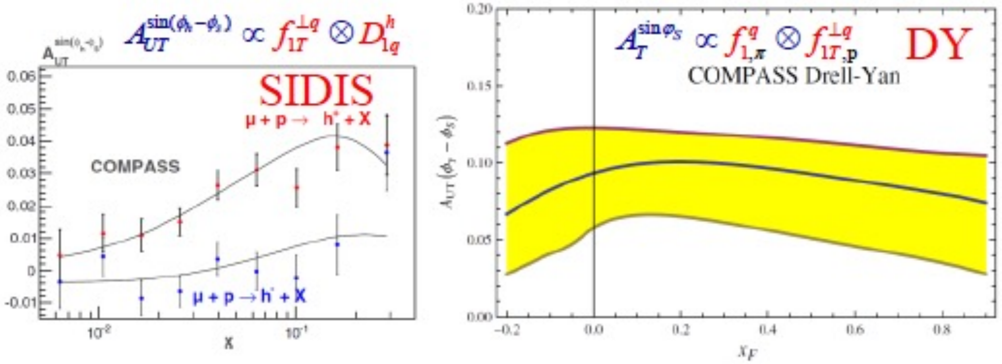
- Global fits of available 1-D SIDIS data
- Different TMD evolution schemes
- Different predictions for Drell-Yan

- Extremely important to extract Sivers in SIDIS in Drell-Yan Q^2 range

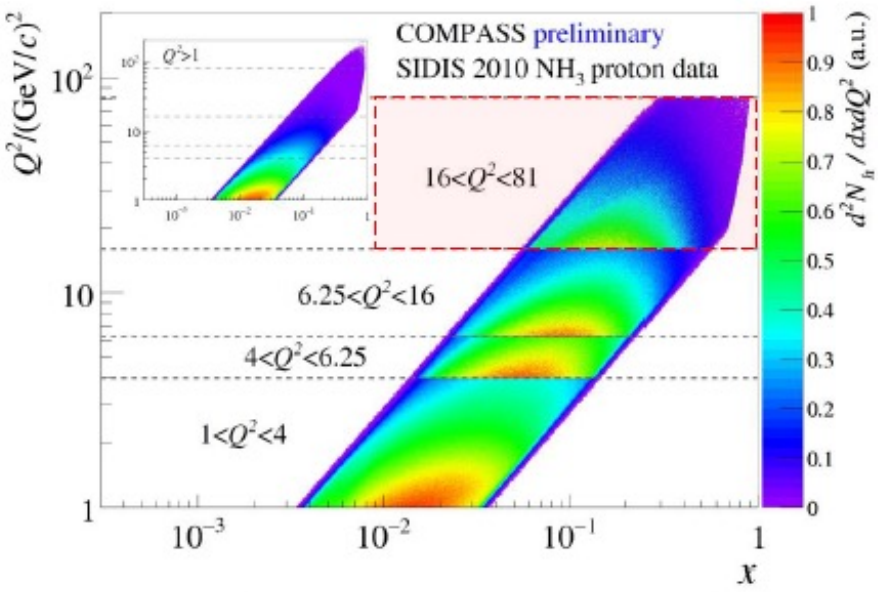
M.G. Echevarria, A.Idilbi, Z.B. Kang and I. Vitev, **PRD 89 074013 (2014)**

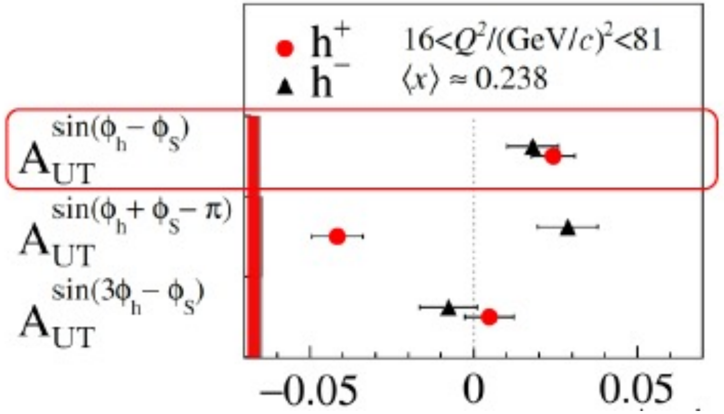


P. Sun and F. Yuan, **PRD 88 11, 114012 (2013)**

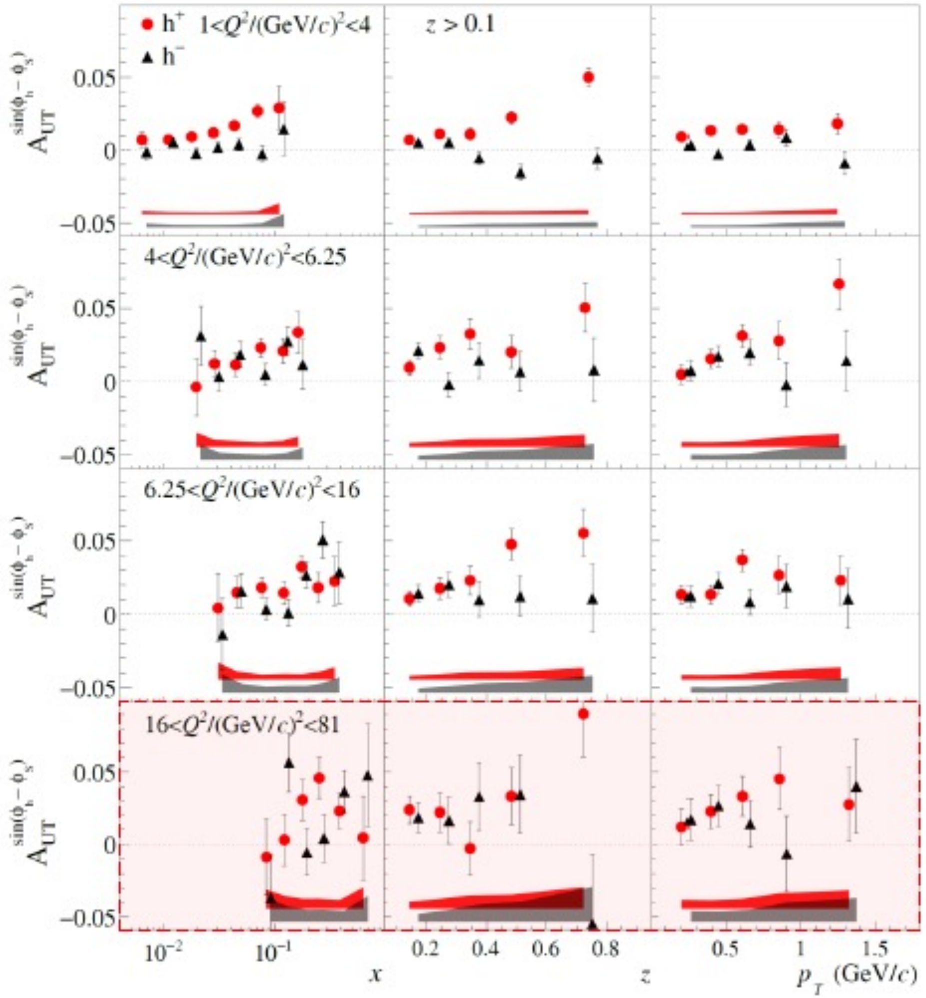


Sivers in SIDIS in Drell-Yan kinematic range





COMPASS PLB 770 (2017) 138



Drell-Yan at COMPASS

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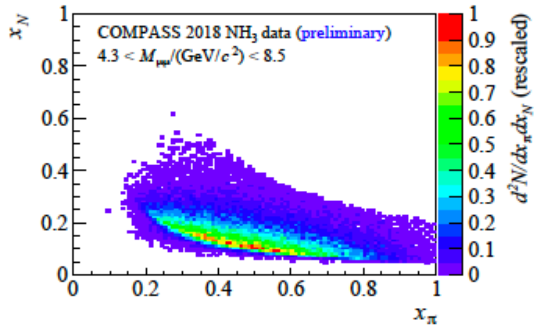
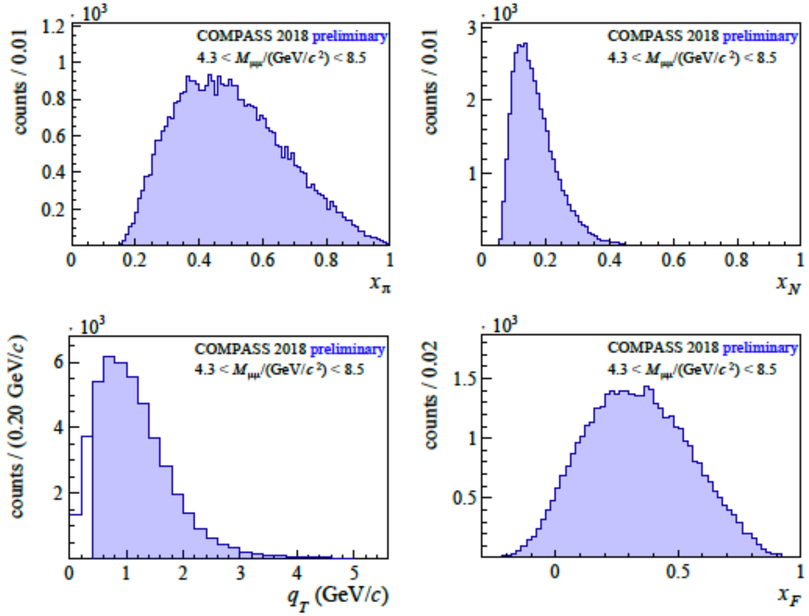
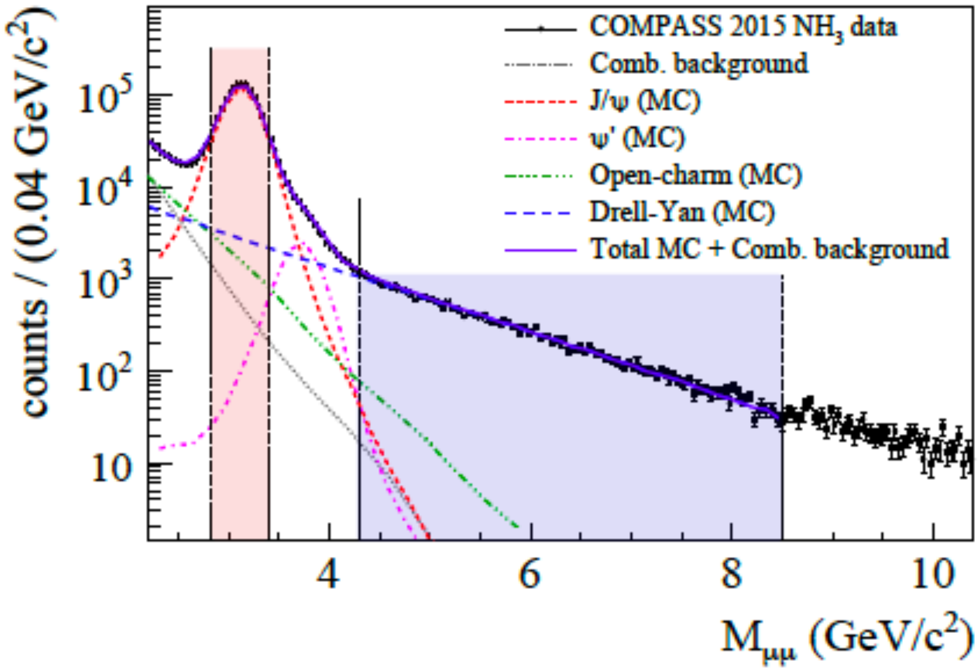
High mass Drell–Yan region: Kinematic coverage



$\langle x_\pi \rangle = 0.5, \quad \langle x_N \rangle = 0.17.$

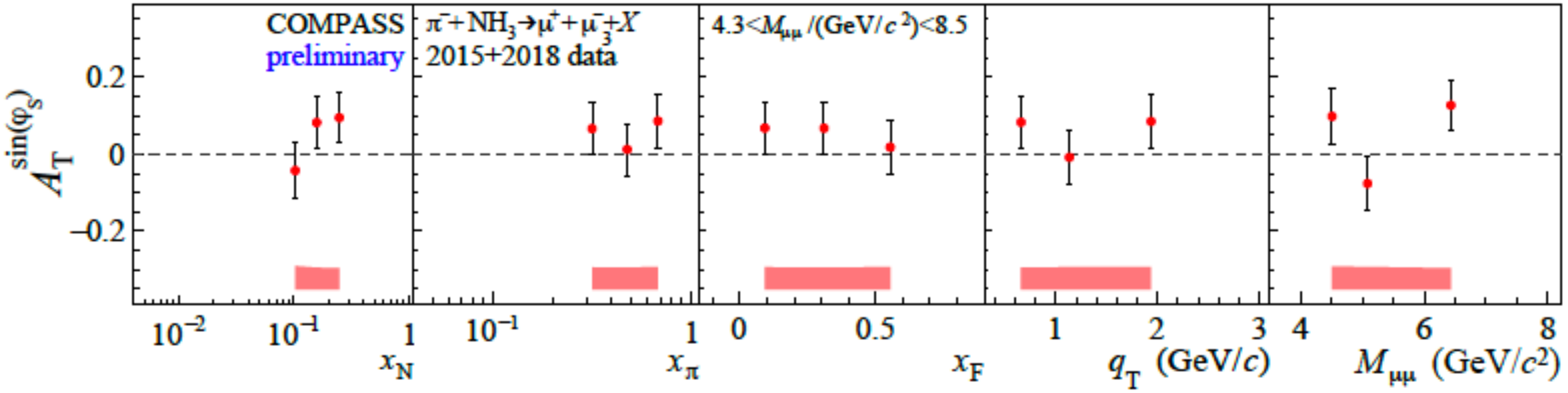
- Valence region ($u\bar{u}$ annihilation).
- $\langle M_{\mu\mu} \rangle = 5.3$ GeV/c^2.
- $q_T > 0.4$ GeV/c required.
- $\langle q_T \rangle = 1.17$ GeV/c.

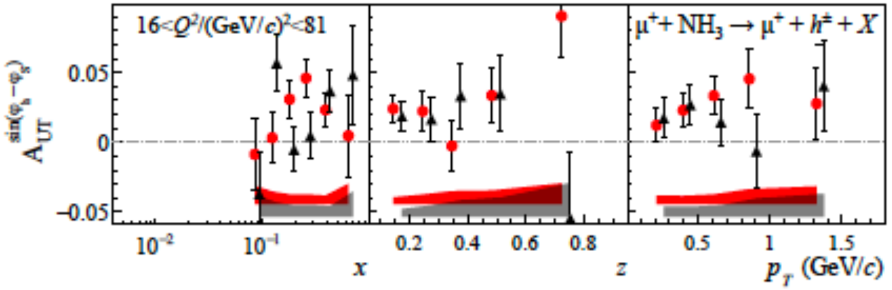




NEW!! Sivers in Drell-Yan

$A_T^{\sin\varphi_S} \propto f_{1,\pi}^q \otimes f_{1T,p}^{\perp q}$ (number density $\otimes$ Sivers function)





SIDIS in the corresponding Q^2 range.

$A_{UT}^{\sin(\varphi_h - \varphi_S)} = f_{1T,p}^{\perp q} \otimes D_{1,q}^h$

(Sivers $\otimes$ unpolarised FF)

[Phys.Lett.B770 (2017) 138]

NEW!! Sivers in Drell-Yan 2015 +2018

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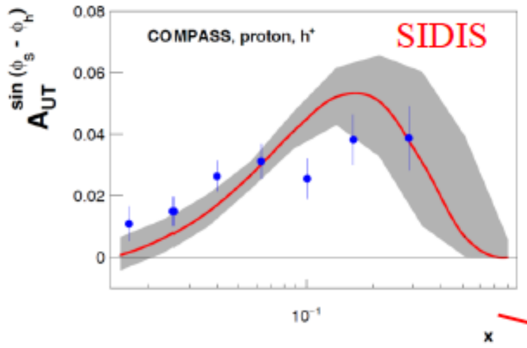
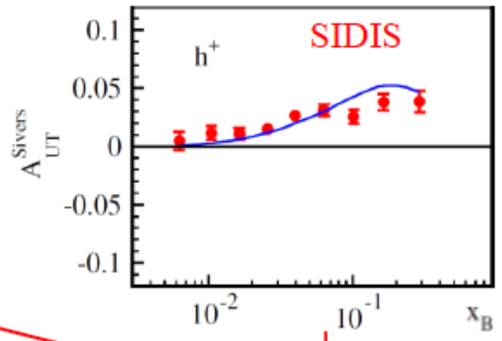
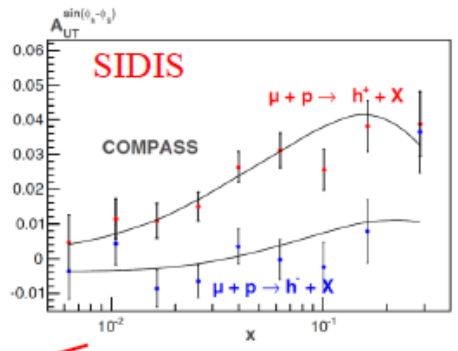
DGLAP (2016)
M. Anselmino et al., **arXiv:1612.06413**

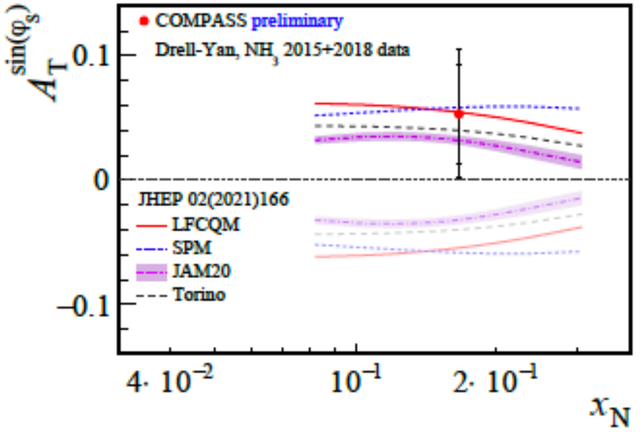


TMD-1 (2014)
M. G. Echevarria et al. **PRD89,074013**



TMD-2 (2013)
P. Sun, F. Yuan, **PRD88, 114012**





Integrated, compared to predictions.
Curves: [Bastami *et al.*, JHEP 02 (2021) 166]

In 2018 – 2nd round of polarized DY measurements at COMPASS

NEW!! TSAs in Drell-Yan compared to SIDIS

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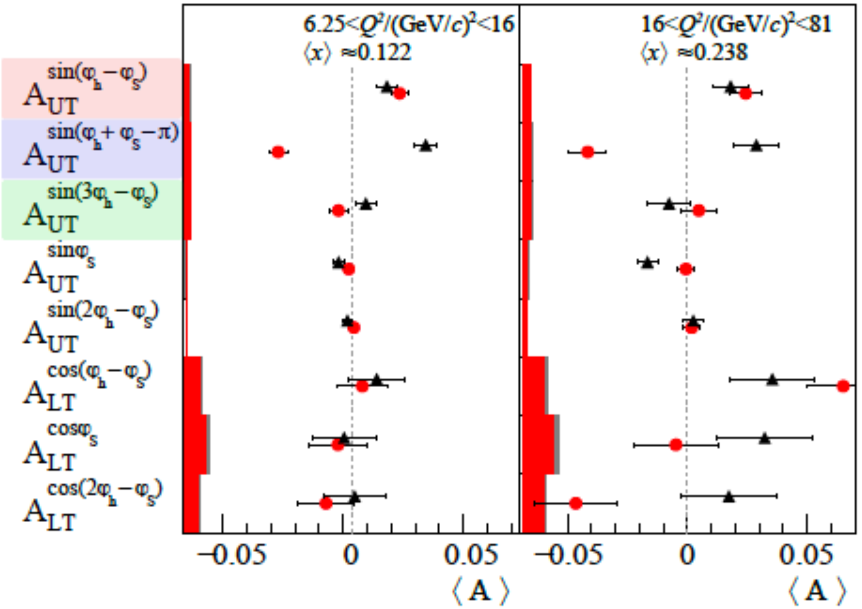
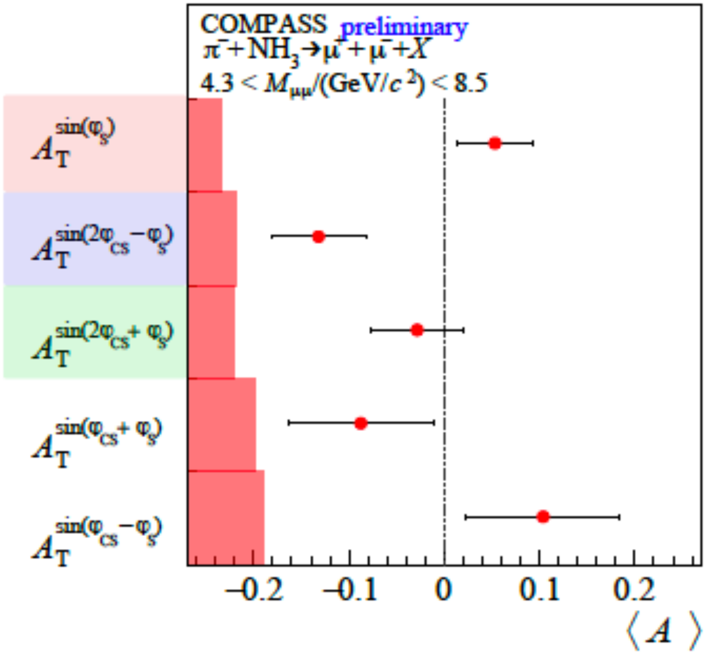
$$\frac{d\sigma}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{ 1+\ldots + S_T \left[\begin{array}{l} A_{UT}^{\sin(\phi_h-\phi_S)}\sin(\phi_h-\phi_S) \\ +\ \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S) \\ +\ \varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S) \\ +\ \sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin\phi_S}\sin\phi_S \\ +\ \sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin(2\phi_h-\phi_S)}\sin(2\phi_h-\phi_S) \end{array} \right] \right\}$$

$$\frac{d\sigma^{LO}}{d\Omega} \propto F_U^1\left(1+\cos^2\theta_{CS}\right)\left\{ 1+\ldots + S_T \left[\begin{array}{l} A_T^{\sin\varphi_S}\sin\varphi_S \\ +D_{[\sin^2\theta_{CS}]}\left(\begin{array}{l} A_T^{\sin(2\varphi_{CS}-\varphi_S)}\sin(2\varphi_{CS}-\varphi_S) \\ +\ A_T^{\sin(2\varphi_{CS}+\varphi_S)}\sin(2\varphi_{CS}+\varphi_S) \end{array} \right) \\ +D_{[\sin 2\theta_{CS}]}\left(\begin{array}{l} A_T^{\sin(\varphi_{CS}-\varphi_S)}\sin(\varphi_{CS}-\varphi_S) \\ +\ A_T^{\sin(\varphi_{CS}+\varphi_S)}\sin(\varphi_{CS}+\varphi_S) \end{array} \right) \end{array} \right] \right\}$$



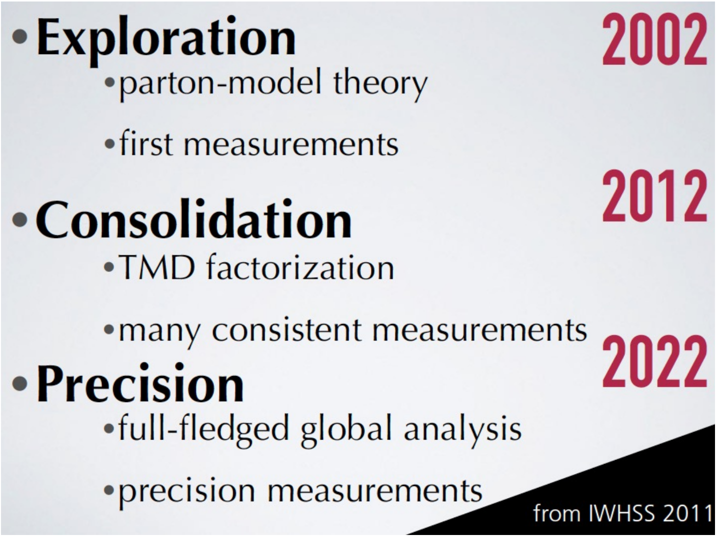


Summary 1

- There is a very clear recipe to fill up the missing part of the proton spin – angular momentum ➔ 3D case ➔ TMDs and GPDs
- TMDs study will provide essential input for 3-D structure of the hadron
- Experimental prove of the TMDs mechanism **validity is still missing**
- We found ourselves in Precision phase (Alessandro Bacchetta)
- More data to come in the next years from

  JLAB, COMPASS and later from EIC

➔



AMBER
more than 15 years-long effort

Apparatus for Meson and Baryon Experimental Research

We have started to work on physics program of possible COMPASS successor > 15 years ago.

A Number of Workshops has been organized, for detail see AMBER web page:

https://amber.web.cern.ch/

CERN Accelerating science — Signed in as: odenisov (CERN) — Sign out

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

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Welcome

Over the past four decades, measurements at the external beam lines of the CERN Super Proton Synchrotron (SPS) have received worldwide attention. The experimental results have been challenging Quantum Chromodynamics (QCD) as our theory of the strong interactions, thus serving as important input to develop improvements of the theory. As of today, these beam lines remain mostly unique and bear great potential for significant future advancements in our understanding of hadronic matter.

In the context of the Physics-beyond-colliders (PBC) initiative at CERN, the COMPASS++/AMBER (proto-) collaboration proposes to establish a "New QCD facility at the M2 beam line of the CERN SPS". Such an unrivalled installation would make the experimental hall EHN2 the site for a great variety of measurements to address fundamental issues of QCD. The proposed measurements cover a wide range in the squared four-momentum transfer Q^2: from lowest values of Q^2 where we plan to measure the proton charge radius by elastic muon-proton scattering, over intermediate Q^2 where we plan to study the spectroscopy of mesons and baryons by using dedicated meson beams, to high Q^2 where we plan to study the structure of mesons and baryons via the Drell-Yan process and eventually address the fundamental quest on the emergence of hadronic mass arxiv:1606.03909[nucl-th], arXiv:1905.05208[nucl-th].

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-SPSC-2019–003
SPSC-I-250
January 25, 2019

LoI submitted in January 2019
http://arxiv.org/abs/1808.00848
Apparatus for Meson and Baryon Experimental Research
> 270 authors

Letter of Intent:

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

COMPASS++[†]/AMBER[‡]

B. Adams[13,12], C.A. Aidala[1], R. Akhunzyanov[14], G.D. Alexeev[14], M.G. Alexeev[41], A. Amoroso[41,42],

AMBER PHASE-1 (proposal submitted in Sep. 2019, approved in Dec. 2020)

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Apparatus for Meson and Baryon Experimental Research

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.

PHASE-1

Conventional hadron and muon beams

2022 ➔ 2029

PHASE-2

Improved conventional Hadron/Hadron and muon beam

2029 and beyond

AMBER science questions

There are two bearing columns of the facility:

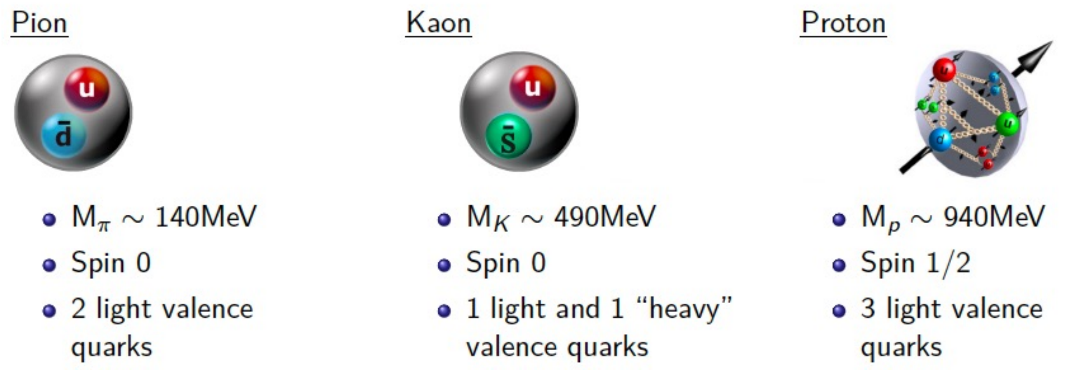
1. **Phenomenon of the Emergence of the Hadron Mass**
2. Proton spin? (largely addressed by COMPASS and others, Phase-2)

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

Great discovery of the Higgs-boson unfortunately does not help to answer this question, because:

✓ The Higgs-boson mechanism produces only a small fraction of all visible mass

✓ The Higgs-generated mass scales explain neither the "huge" proton mass nor the 'nearly-masslessness' of the pion



Higgs generated masses of the valence quarks:

$M_{(u+d)}$~7 MeV $M_{(u+s)}$~100 MeV $M_{(u+u+d)}$~10 MeV

As Higgs mechanism produces a few percent of visible mass, Where does the rest comes from (EHM phenomenon)?

EHM phenomenon
What are the underlying mechanisms?

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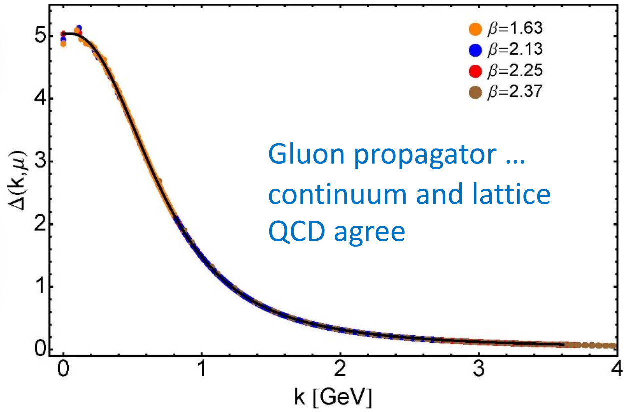
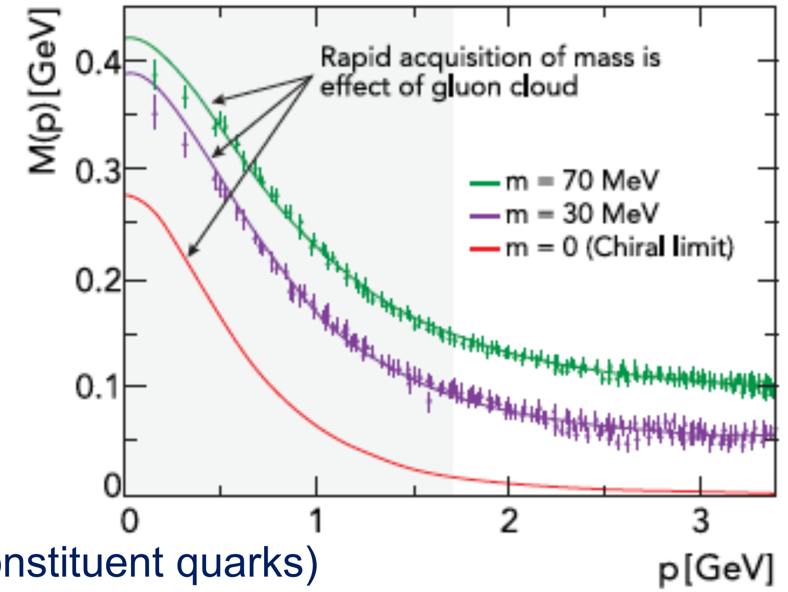
Intuitively one can expect that the answer to the question lies within SM, in particular within QCD. Why? Because of the dynamical mass generation in continuum QCD.



Truly "mass from nothing" phenomenon: Initially massless gluon produces dressed gluon fields which "generates" mass function that is large at infrared momenta

Dynamical mass generation in continuum quantum chromodynamics
J.M. Cornwall, Phys. Rev. D ***26*** *(1981) 1453*
… ~ 1000 citations

As quark can emit and absorb gluons It acquires its mass in infrared region because of the gluon "self-mass-generation" mechanism, so the visible (or emergent) mass of hadrons must be dominated by gluon component



(Constituent quarks)

Dressed-quark mass function M(p)

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

EHM phenomenon

Is it enough to study the proton to understand SM?

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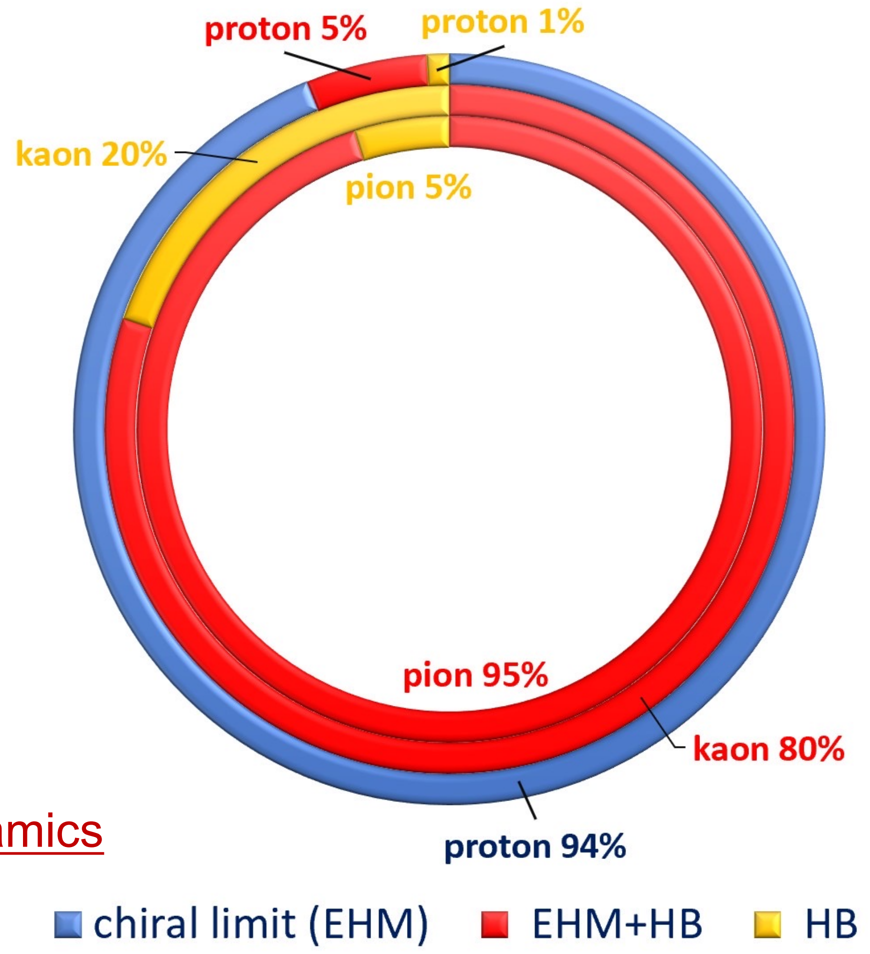
The answer is obviously NOT (SM paradigm):

- proton is described by QCD … 3 valence quarks
- pion is also described by QCD … 1 valence quark and 1 valence antiquark
- expect $m_p \approx 1.5 \times m_\pi$ … but, instead $m_p \approx 7 \times m_\pi$

Proton and pion/kaon difference:

- In the chiral limit the mass of the proton remains basically the same
- Chiral limit mass of pion and kaon is "0" by definition (Nambu-Goldstone bosons)
- Different gluon content expected for pion and kaon
- Contribution from interplay with Higgs mechanism is different

Mass Budgets



Thus it is equally important to study the internal structure and dynamics of pions, kaons and protons

AMBER physics program

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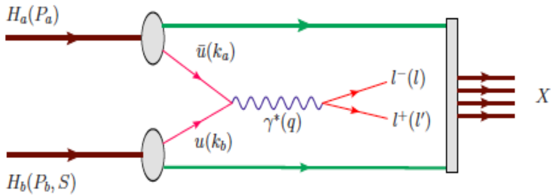
Questions to be answered:

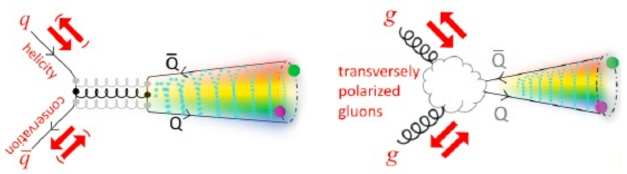
- Mass difference pion/proton/kaon
- Mass generation mechanism (emergent mass .vs. Higgs)
- Internal quark-gluon structure and dynamics,
  especially important pion/kaon/proton striking differences

A series of workshops entitled
"Perceiving of the EHM through
AMBER@CERN(SPS)":
https://indico.cern.ch/event/1021402/

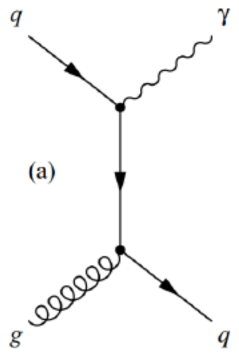
Methods:

Drell-Yan (compl. to Sullivan) and J/Ψ

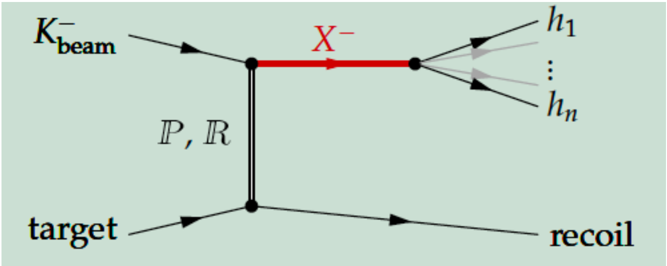


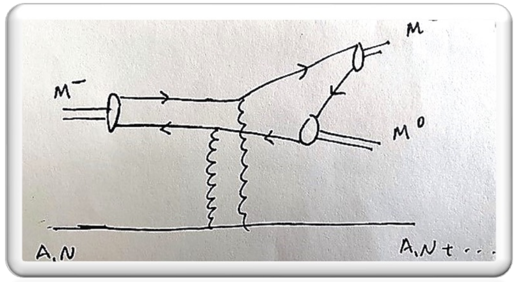


Prompt Photon Production

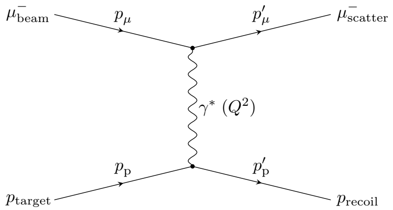


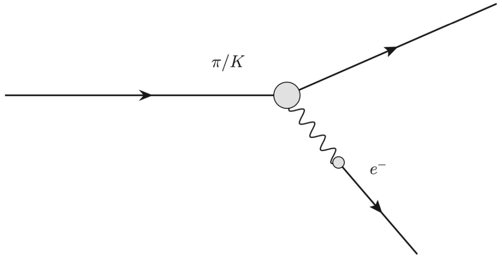
Diffractive scattering





Elastic scattering





General AMBER timeline

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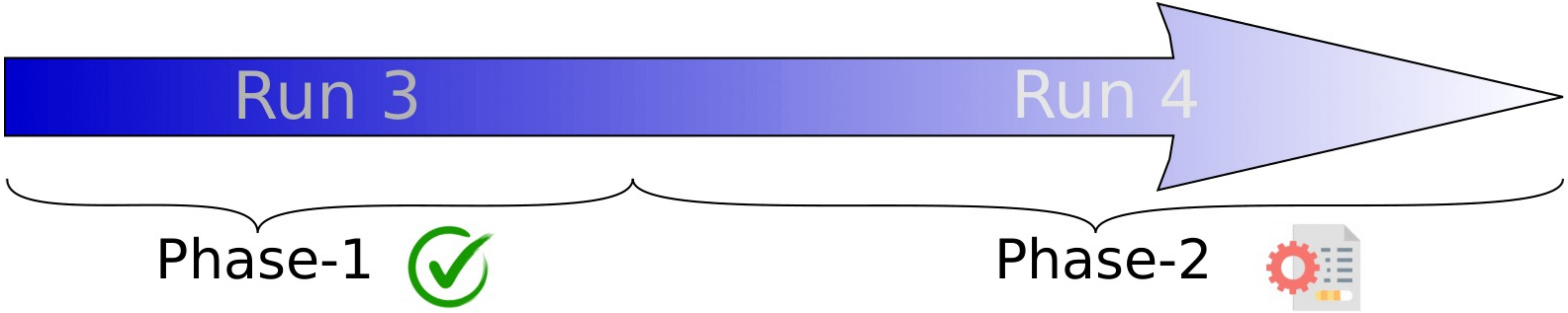
Conventional muon/hadron M2 beams

Improved conventional hadron M2 beams



Proton Radius Measurement
Antimatter production cross section
Pion structure (PDFs) via DY and charmonia
Kaon and pion structure (PDFs and PDAs)

High precision strange-meson spectrum
Kaon and pion charge radius
Kaon induced Primakoff reaction

Phase-1 Proposal approved by RB on 02/12/2020

Phase-2 Proposal submission in the beginning of 2024

Pion induced Drell-Yan at AMBER
Status of the knowledge of the Pion structure

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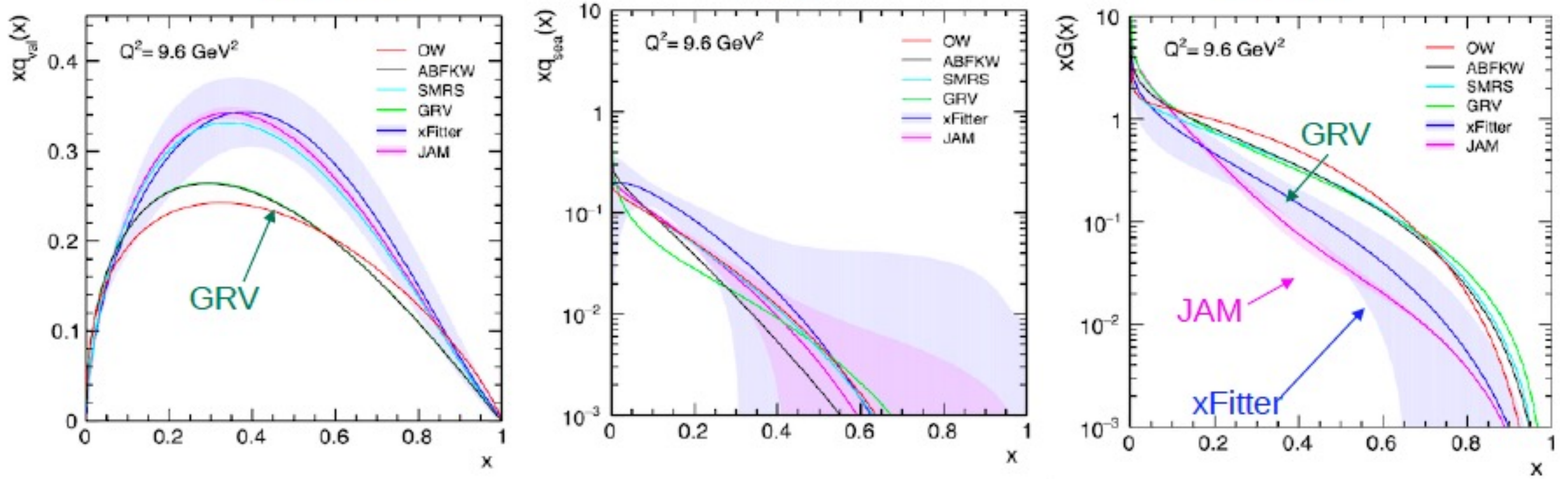
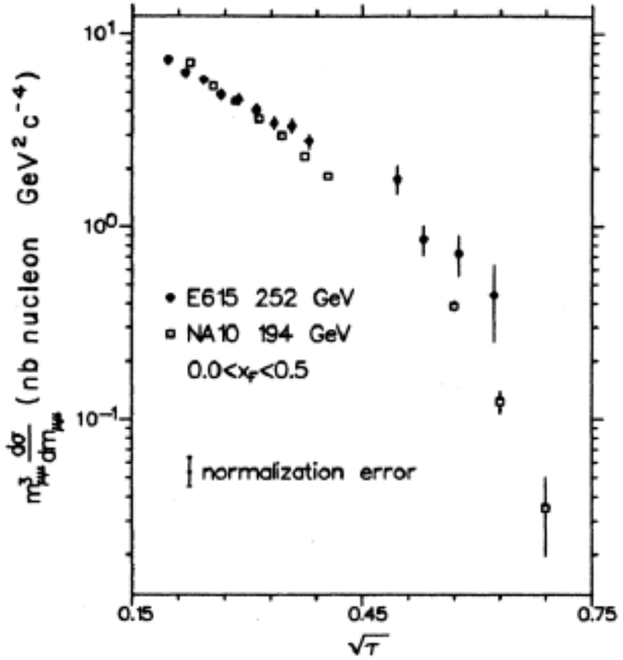
valence sea gluons



Chang et al, PRD 102, 054024 (2020)

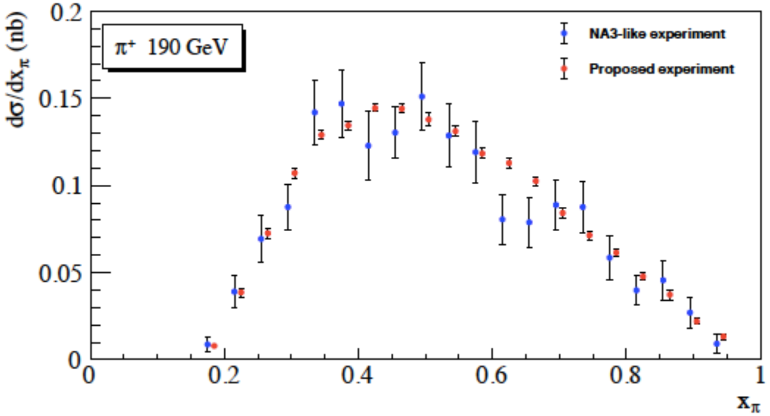
From: E615, PRD 1989

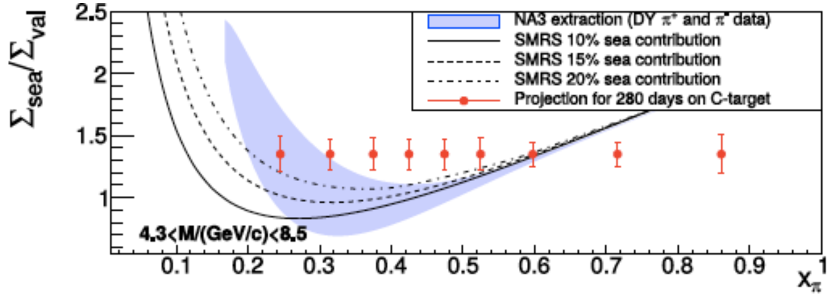


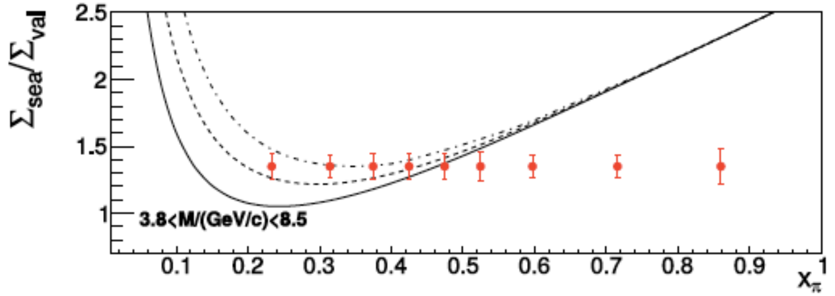
Pion structure status:

- 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 sign, 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 contents of pion at AMBER
Expected statistics 8 to 20 times higher than available







Sea quark content of pion can be accurately measured at AMBER for the first time

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

- $\Sigma_V = \sigma^{\pi^- C} - \sigma^{\pi^+ C}$: only valence-valence
- $\Sigma_S = 4\sigma^{\pi^+ C} - \sigma^{\pi^- C}$: no valence-valence
- Collect at least a **factor 10 more statistics** than presently available
- Minimize nuclear effects on target side
  - Projection for 2 × 140 days of Drell-Yan d 3:1 king
  - π^+ to π^- 10:1 time sharing
  - 190 GeV beams on Carbon target ($1.9\lambda_{int}^{\pi}$)
  - Improvement of shielding to double the intensity is under investigation

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
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

Isoscalar target + *Both positive and negative beams* + *High statistics*

Pion induced J/ψ at AMBER

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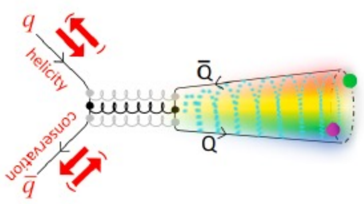
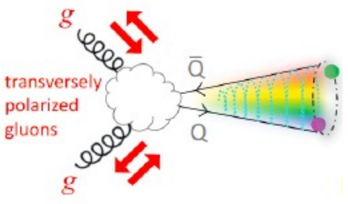


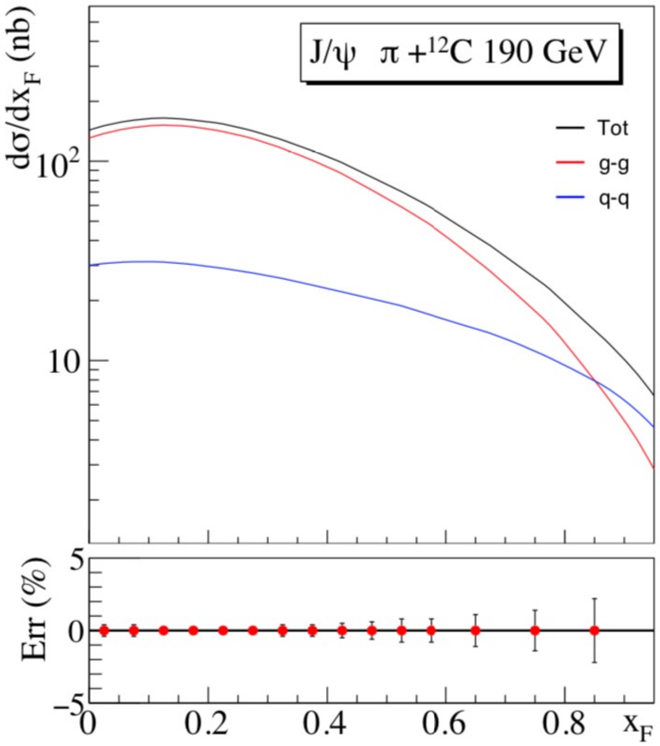


Collected simultaneously with DY data, with large counting rates

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 [hep-ph] 22 Mar 2021)
- ***Ψ***(2S) signal study, free of feed-down effect from χ_{c1} χ_{c2}

Cheung and Vogt, priv. comm.



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

Goal 2: gluon distribution in the pion through J/ψ production

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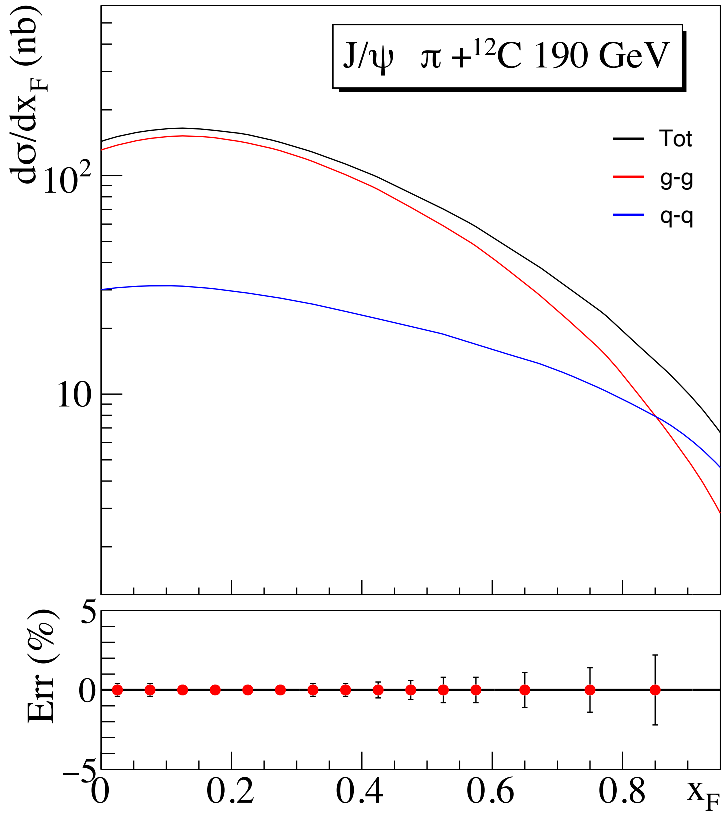
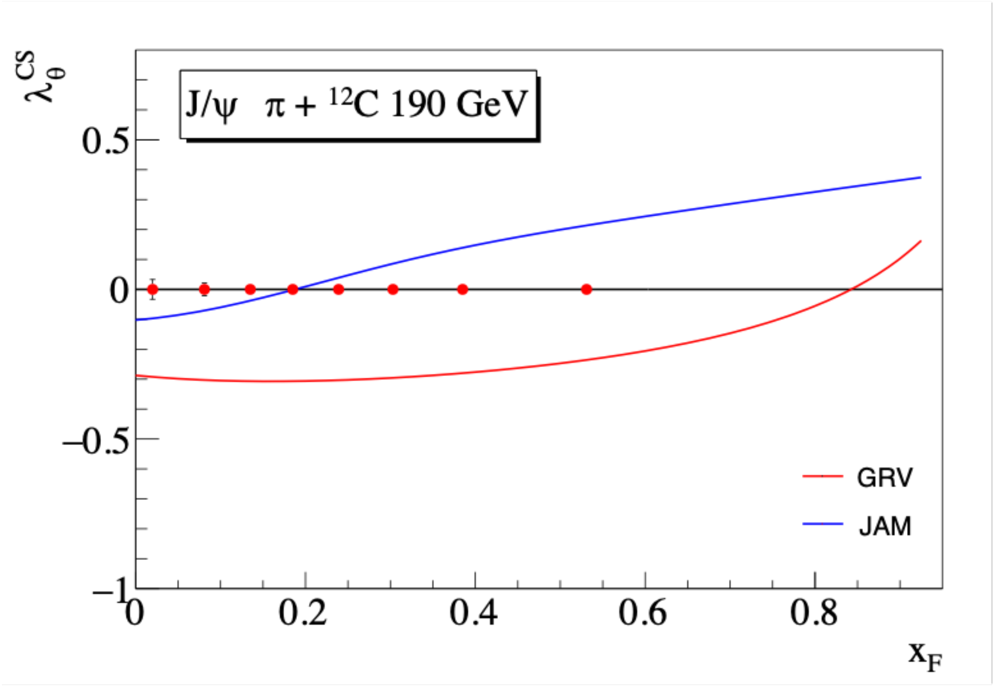
Cross section (ICEM)



Polarization (ICEM)

CHEUNG AND VOGT, PRIV. COMM., 2020



Both x_F-distribution and polarization depend on the relative amount of valence and glue

Huge statistics: π+, π−, p : 1.2 – 1.8 M J/ψ and 20 – 30 k ψ’

AMBER (kaon induced Drell-Yan and J/Psi production)

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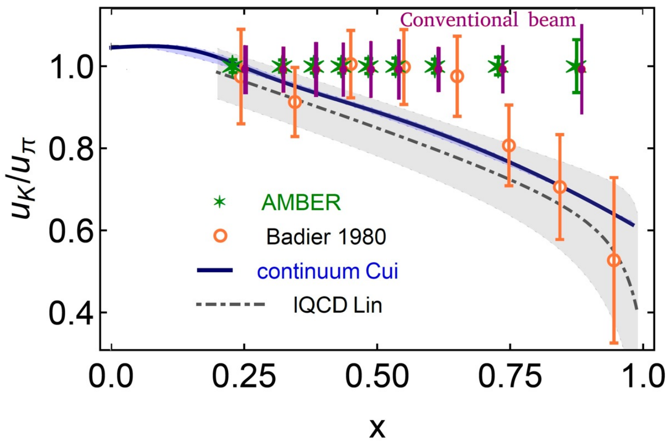
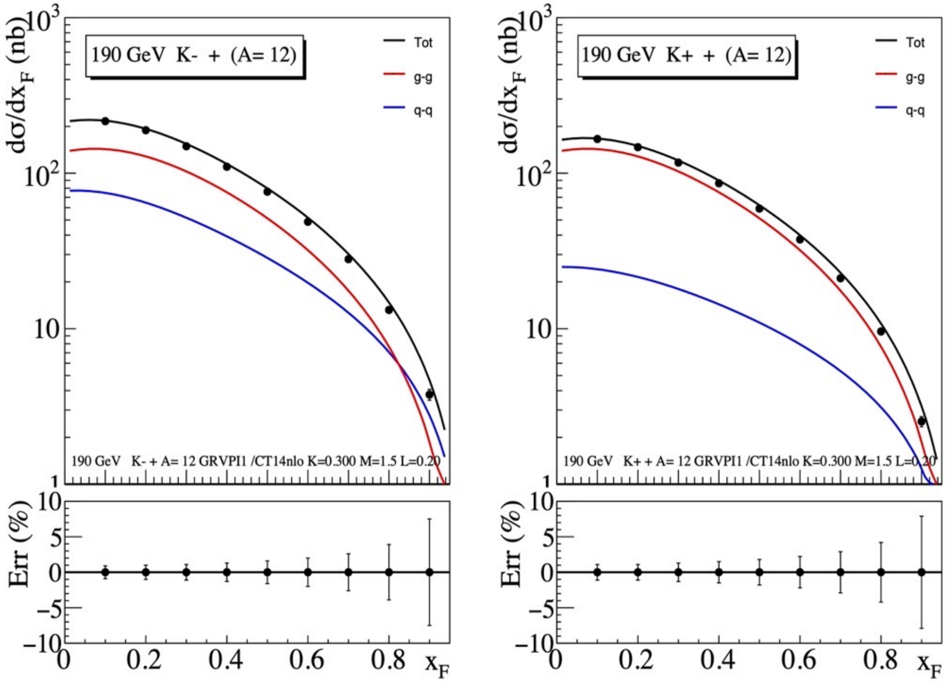
Extremely important to compare the gluon content of kaon and pion (emergent mass)

- 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%



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



Projected statistical errors after 280 days of running, compared to NA3 stat. errors

Proton Radius Measurement at AMBER (confinement)

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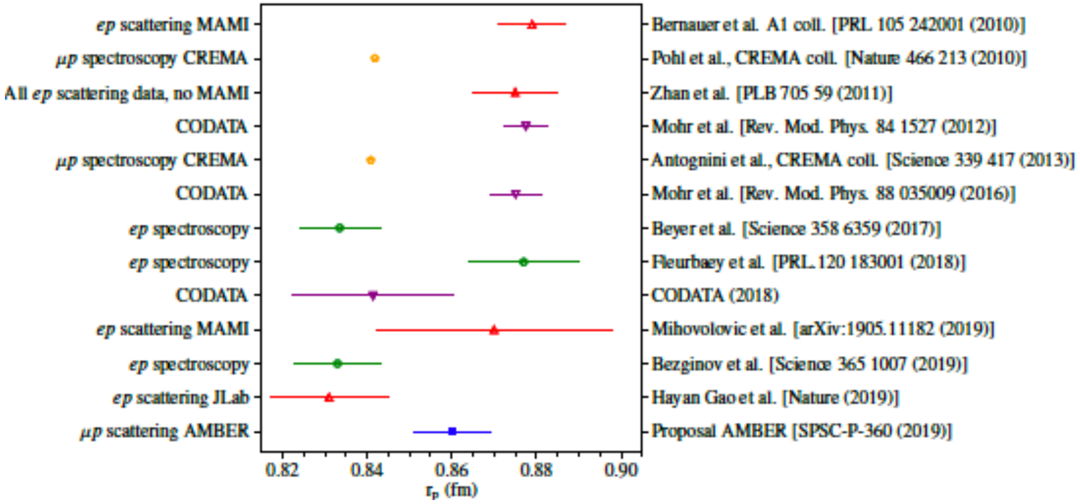
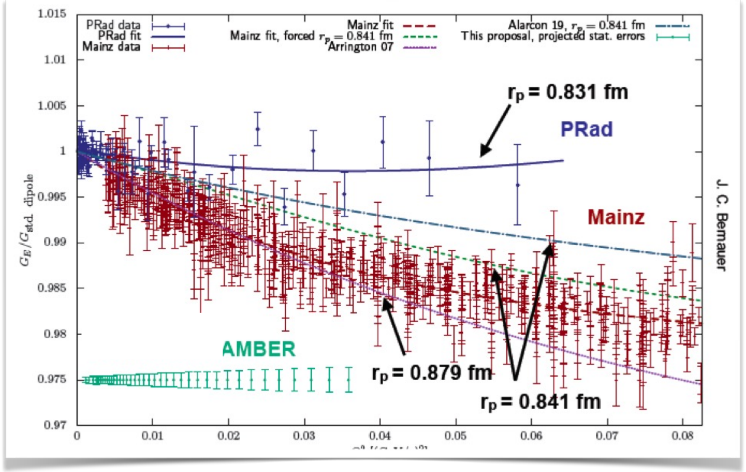


	ep	μp
Spectroscopy	New measurements with ▪ lower systematics ▪ new transitions	✔
Scattering	New measurements with ▪ lower systematics ▪ reaching lower Q^2 ProRAD, ULQ2, ISR @ MESA, PRad	No data yet. MUSE at PSI coming soon AMBER



statistical precision of the proposed measurement, down to Q^2 = 0,001 GeV^2/c^2, Cross section is normalised to the G_D - dipole form factor

$$< r_p^2 > = -6\hbar^2 \cdot \frac{dG_E(Q^2)}{dQ^2}\bigg|_{Q^2\to 0}$$

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

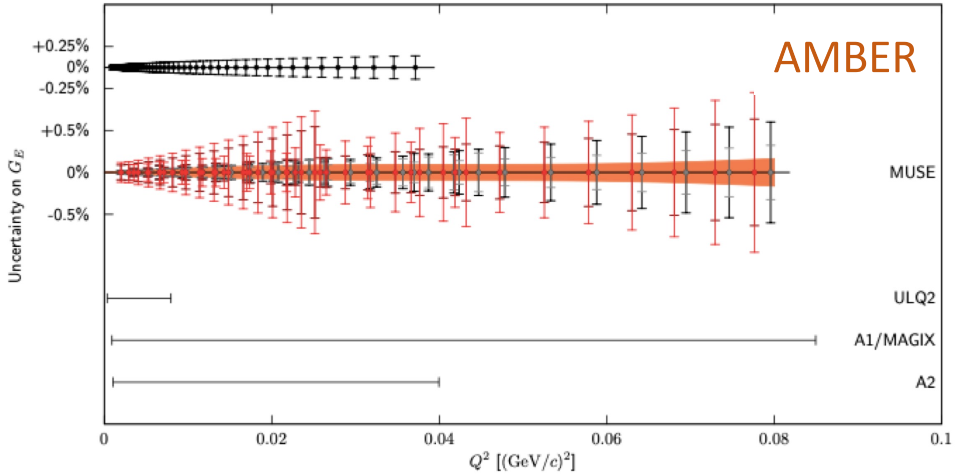
- Suppress magnetic form factor G_M^2
  → Requires $\tau \to 0$
  → Measurement at low-Q^2 values of $\mathcal{O}(<10^{-2})$
- Measurement at high-energy $\mathcal{O}$(10 - 100 GeV)
  → Results in $\varepsilon \to 1$
  → Cross-section directly proportional to G_E^2

Proton Radius Measurement at AMBER (confinement)

- A number of experiments is on the way in different laboratories
- There is a synergy between PRES at MAMI (E_e = 720 *MeV*) and AMBER ($E\mu = 100\ GeV$):
  - The same type of active target (hydrogen filled TPC) will be used for both experiment
  - The same Q^2 range will be covered (10^{-3} - 4×10^{-2} GeV^2)
  - Mutual calibration of the transferred momentum
- Significant advantage of the AMBER measurement is much lower radiative corrections: for soft bremsstrahlung photon energy $E\gamma/E_{beam}$ ~ 0.01 QED corrections amount to ~15-20% for electrons and to ~1.5% for muons (AMBER will be able to make a control measurement with Electromagnetic Calorimeters).

If compared to the muon scattering experiment at PSI (MUSE):

- Much cleaner experimental conditions (pure muon beam with less than 10^{-6} admixture of hadrons)
- Much higher beam momentum, thus contribution from magnetic form factor is suppressed (0.1-0.2 *GeV/c* vs 100 *GeV/c*)
- Small statistical errors achievable with the proposed running time



AMBER (Kaon and pion charge radius)

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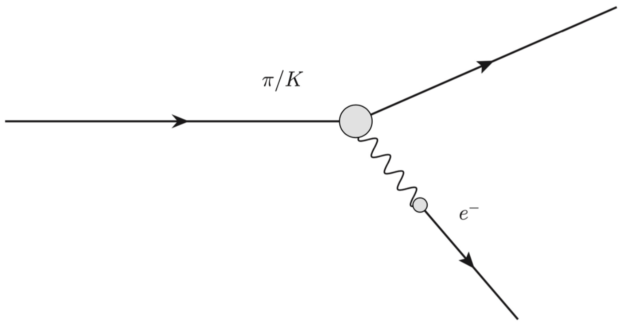
Precise measurements of pion and kaon radii will reveal the compositeness (confinement) scale for (near) Nambu-Goldstone bosons. At the moment there is basically no precise experimental information on kaon charge radius.



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

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

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

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

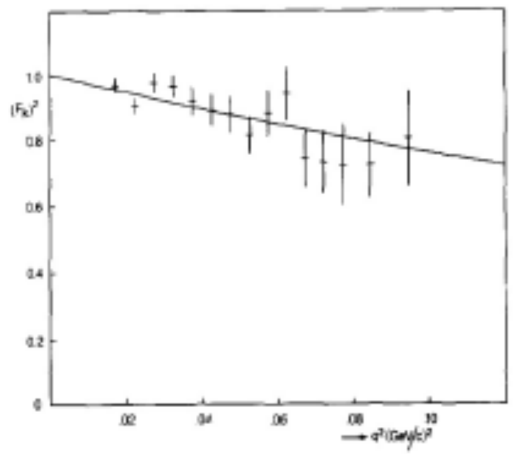


Fig. 3. The measured kaon form factor squared. The line corresponds to the pole fit with $\langle r^2 \rangle = 0.34\ \mathrm{fm}^2$.

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*

Hadron spectroscopy AMBER (kaon enriched beam)

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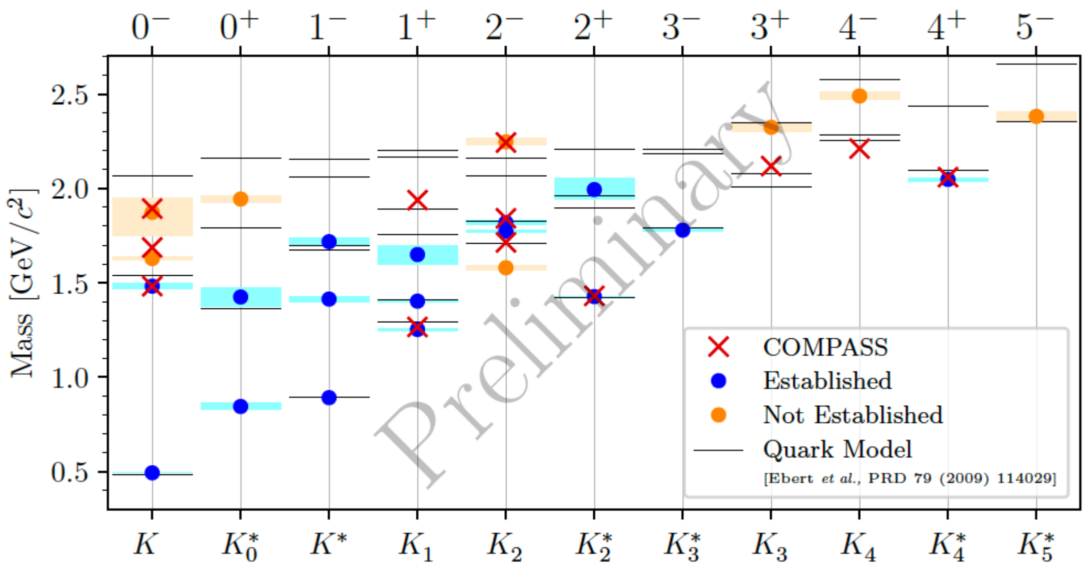
PDG lists 25 strange mesons

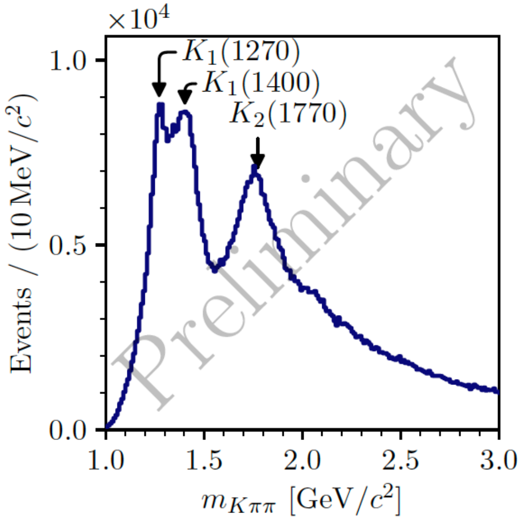
- 16 established states, 9 need further confirmation
- Missing states with respect to quark-model predictions
- Many measurements performed more than 30 years ago

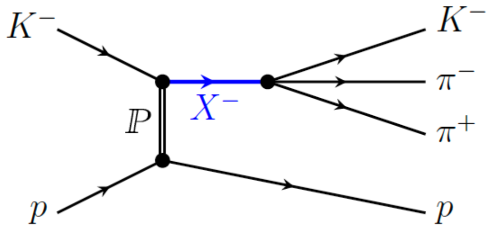


Stefan Wallner's talk of 08/06/23

Strange-Meson Spectroscopy with COMPASS

The $K^-\pi^-\pi^+$ Data Sample





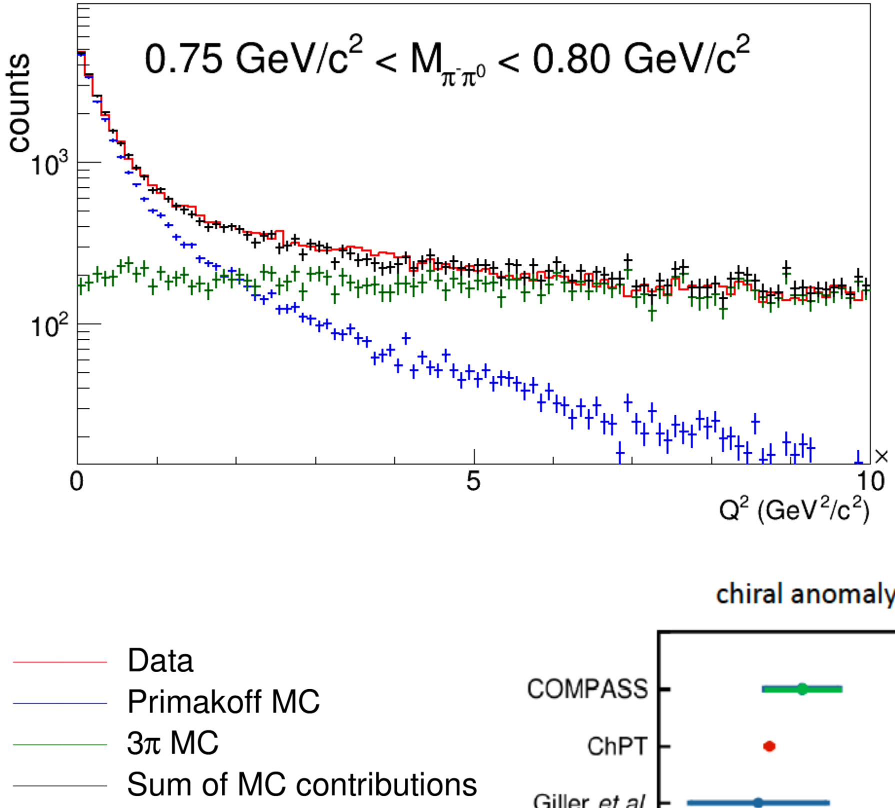
- World's largest data set of about 720 k events
- Rich spectrum of overlapping and interfering X^-
  - Dominant well known states
  - States with lower intensity are "hidden"

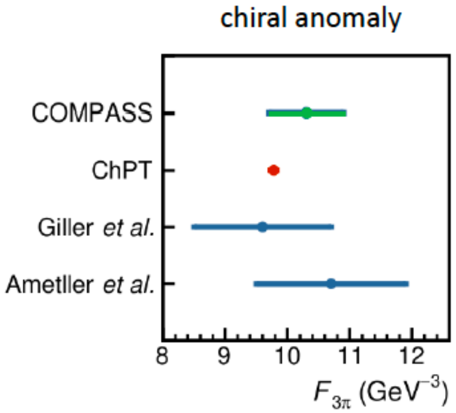
AMBER QCD Facility, goal for Kaon induced Spectroscopy to Collect 10-20x10^6 $K^-\ \pi^+\ \pi^-$ events using high-intensity high-energy kaon beam:

- Optimised Conventional Hadron beam line
- Higher wrt COMPASS beam intensity
- Better pion/kaon beam particles separation
- Much more powerful pid in the final state

Primakoff at AMBER:
Chiral Anomaly and Polarizabilities (kaon enriched beam)

Apparatus for Meson and Baryon Experimental Research

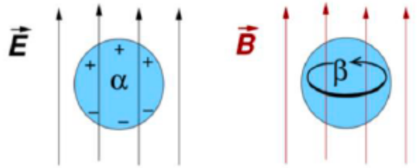




Dominik Ecker's talk of 08/06/23

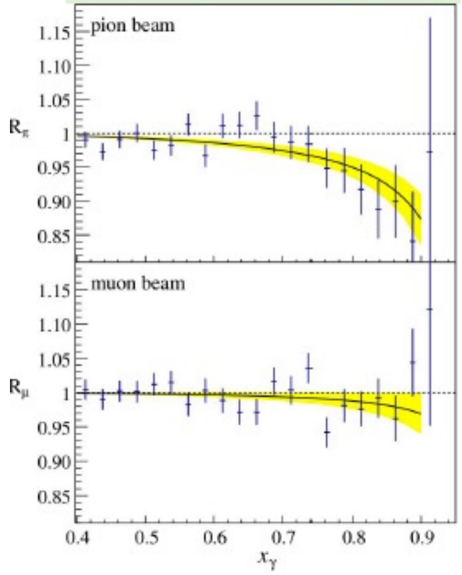
Polarizabilities

(Analogy from classical physics)

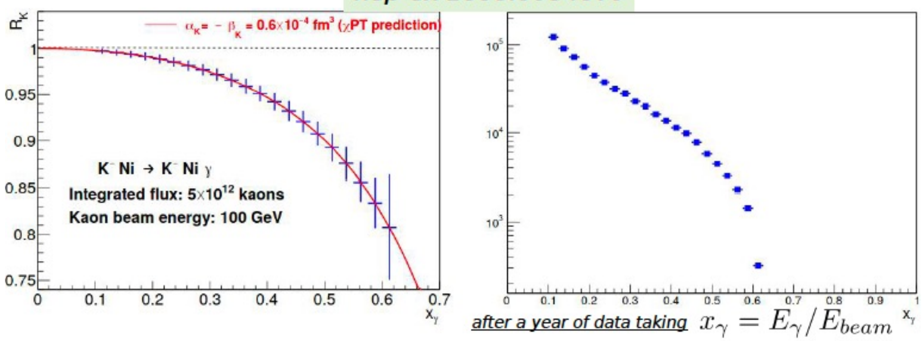


Interaction between **hadron** and **external electromagnetic field** described by parameters **α, β** (LO), encoding information about its internal structure

PRL 114, 062002 (2015)



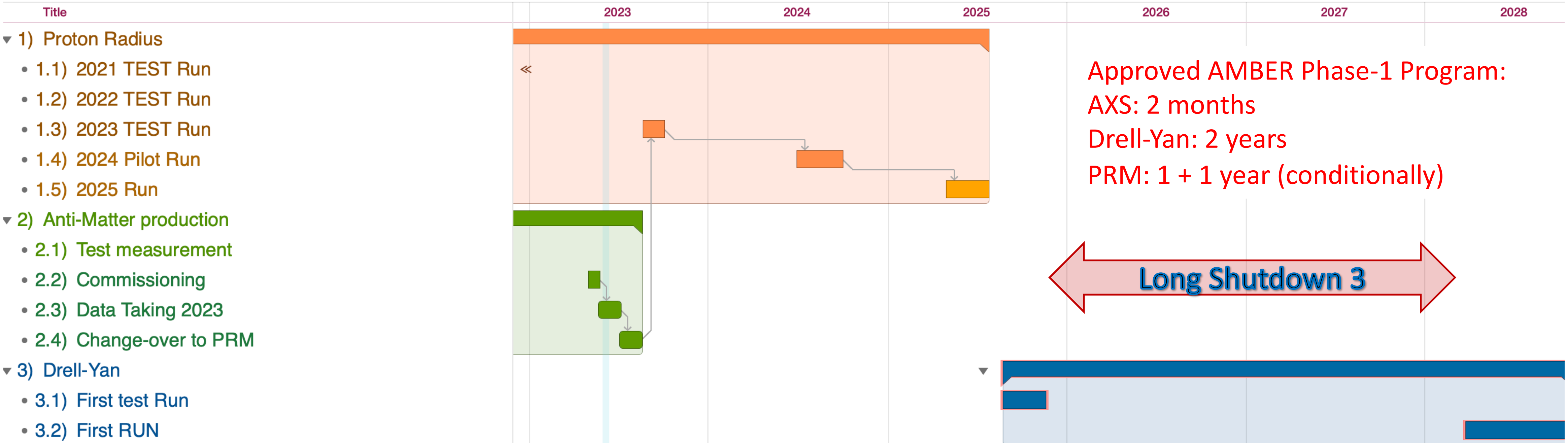
hep-ex 1808.00848v6



AMBER Phase-1 running plan

AMBER
Apparatus for Meson and Baryon Experimental Research

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)



Approved AMBER Phase-1 Program:
AXS: 2 months
Drell-Yan: 2 years
PRM: 1 + 1 year (conditionally)

Summary: AMBER at CERN SPS

Apparatus for Meson and Baryon Experimental Research

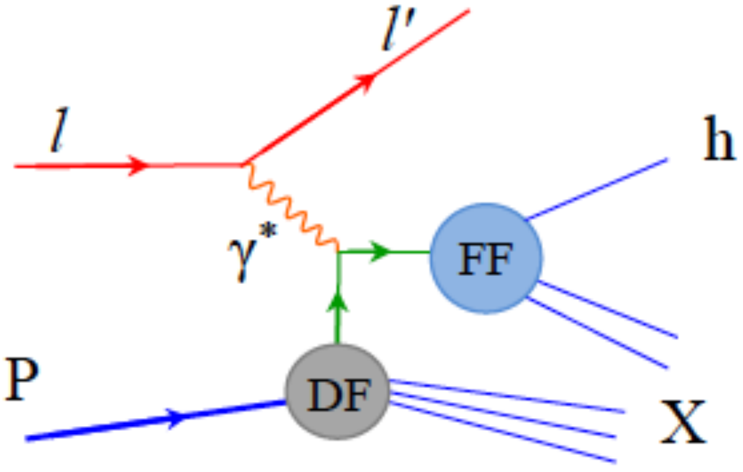
- A wide and extremely competitive physics program brought together, strong interest in the hadron physics community
- 33 Institutions and 13 countries, ~200 members
- Main goal of the AMBER Phase-1: high precision study of the pion structure as well as first study of the kaon structure via Drell-Yan and J/Psi production
- Improved hadron beam for Phase-2 ➔ unique new opportunities in Hadron Physics

Apparatus for Meson and Baryon Experimental Research

Spares

SIDIS ➔ access to TMD PDFs and FFs

Apparatus for Meson and Baryon Experimental Research



TMD Fragmentation Functions (FF)

factorization

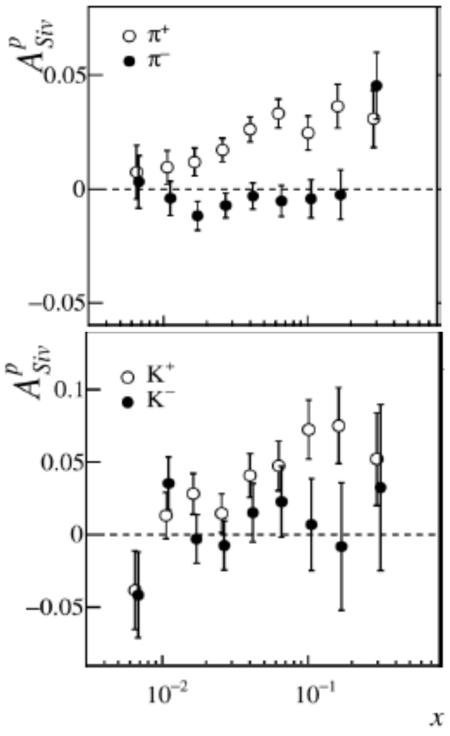
TMD Distribution Functions (DF)

$$\sigma^{\ell\, p \to \ell\, hX} = \Sigma_q \left(DF \otimes \sigma^{\ell\, q \to \ell\, q} \otimes FF \right)$$

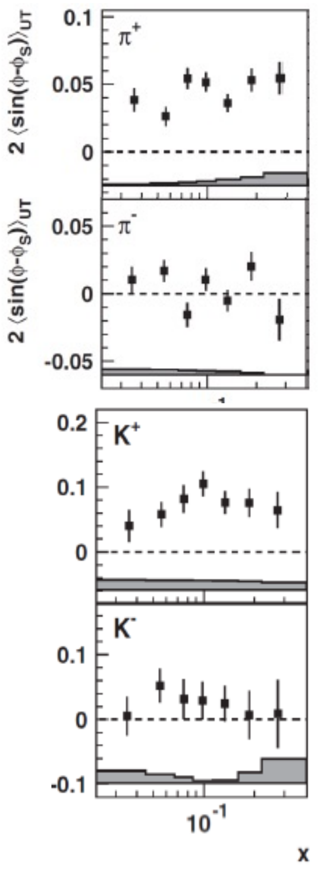
(Un)polarized SIDIS process allows to probes both TMD PDFs and FFs

Second round:
COMPASS ⇔ Hermes proton data

COMPASS final results on proton
(data 2007, 2010) PLB 744 (2015)



Hermes Final results on proton
PRL 103 (2009)



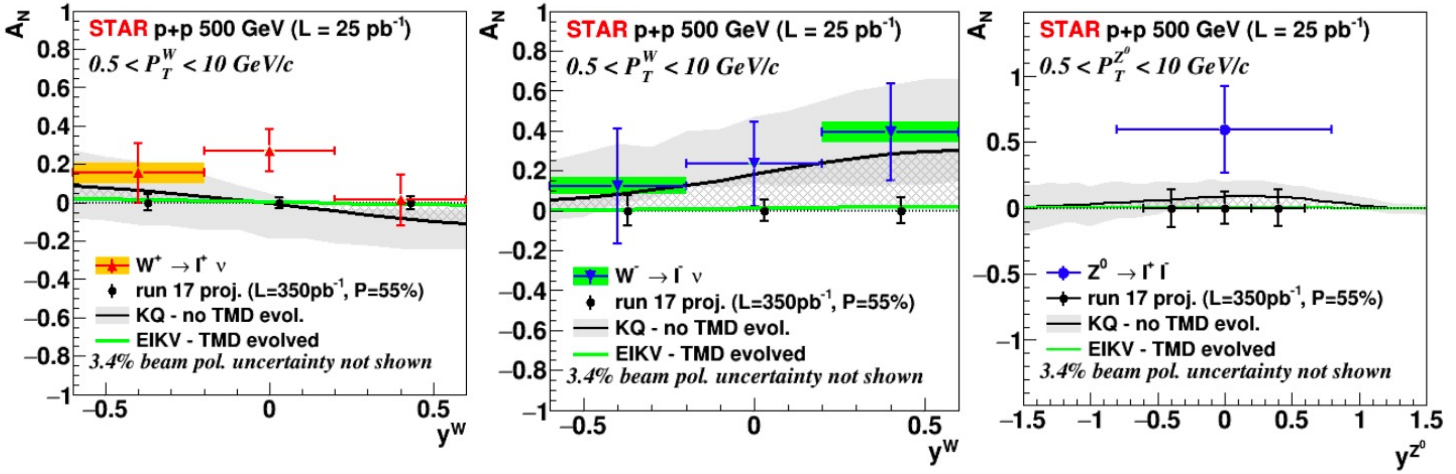
STAR: W-Boson Production in $p\uparrow+p$: $p+p\rightarrow W\pm\rightarrow e\pm+\nu$

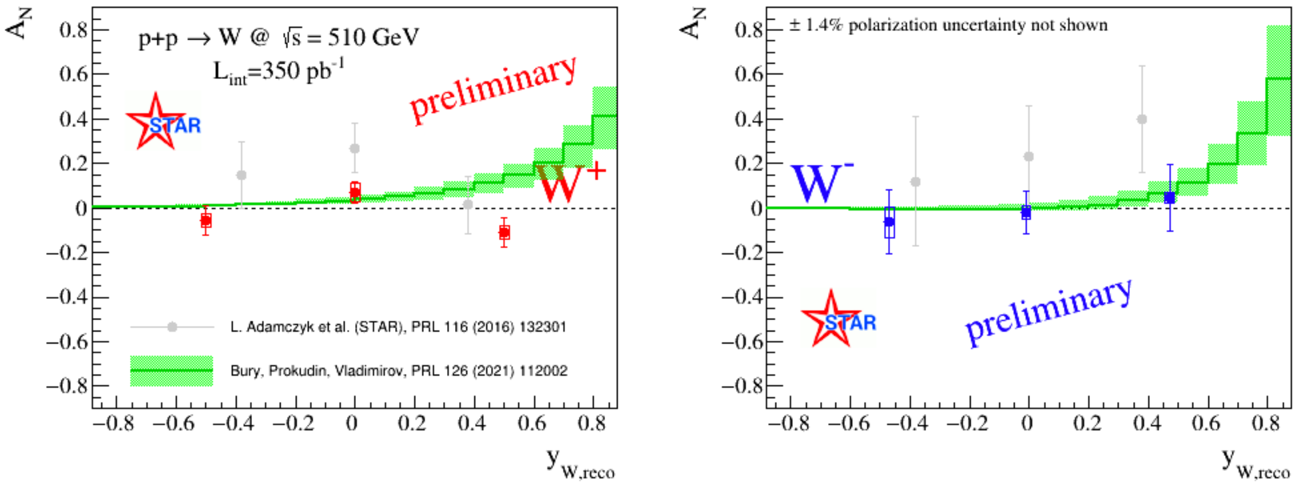
Apparatus for Meson and Baryon Experimental Research

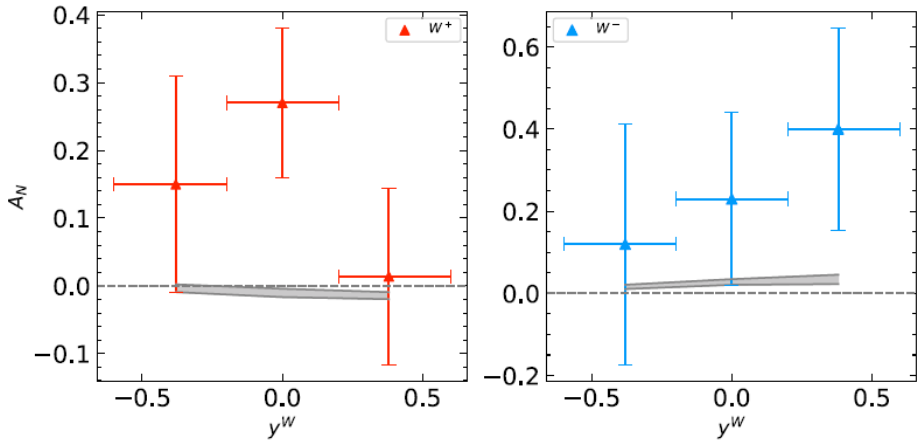
Very important STAR (RHIC) result:

- First experimental investigation of Sivers-non-universality in pp collision (W/Z production)
- Very different hard scale (Q^2) compared to the available SIDIS (FT) data
- QCD evolution effects may play a substantial role

Phys. Rev. Lett. 116, 132301 (2016)
Comparison with Phys. Rev. Lett. 103, 172001



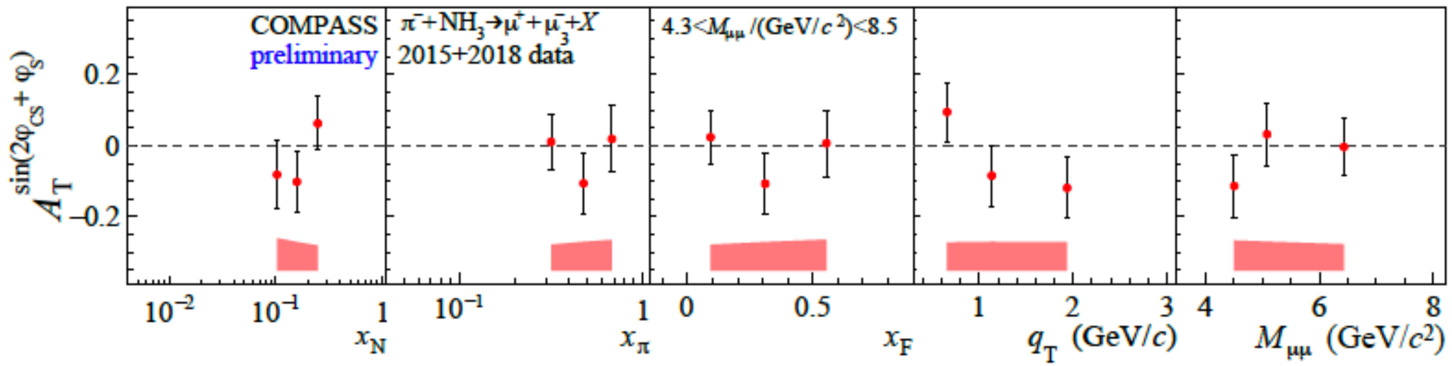




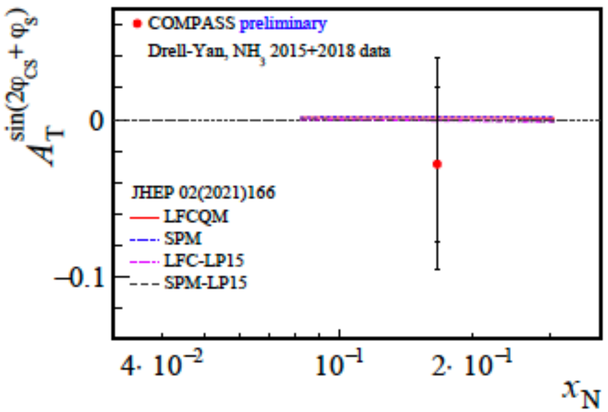
Bacchetta et al.,Phys. Lett. B . Lett. B 827 (2022) 136961
Comparison with PRL116(2016) 13201

NEW!! Pretzelocity in Drell-Yan

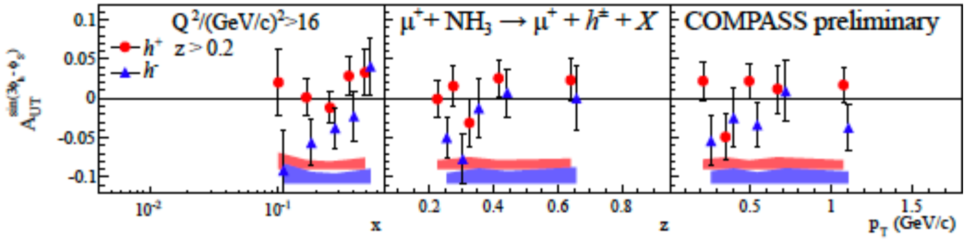
$$A_T^{\sin(2\varphi_{CS}+\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1T,p}^{\perp q} \quad \text{(Boer–Mulders} \otimes \text{pretzelosity)}$$



Compatible with zero, no significant kinematic dependence visible.
The error bars are statistical, the color bands show systematic uncertainty.
An additional scale uncertainty of 5% is not shown (dilution factor, λ, polarization).



Integrated, compared to predictions.



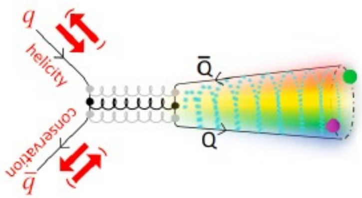
SIDIS in the corresponding Q^2 range.

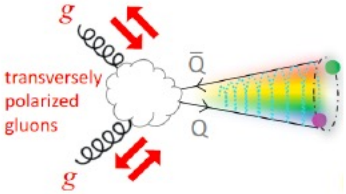
$$A_{UT}^{\sin(3\varphi_h-\varphi_S)} \propto h_{1T,p}^{\perp q} \otimes H_{1,q}^{\perp h}$$

(pretzelosity ⊗ Collins FF)

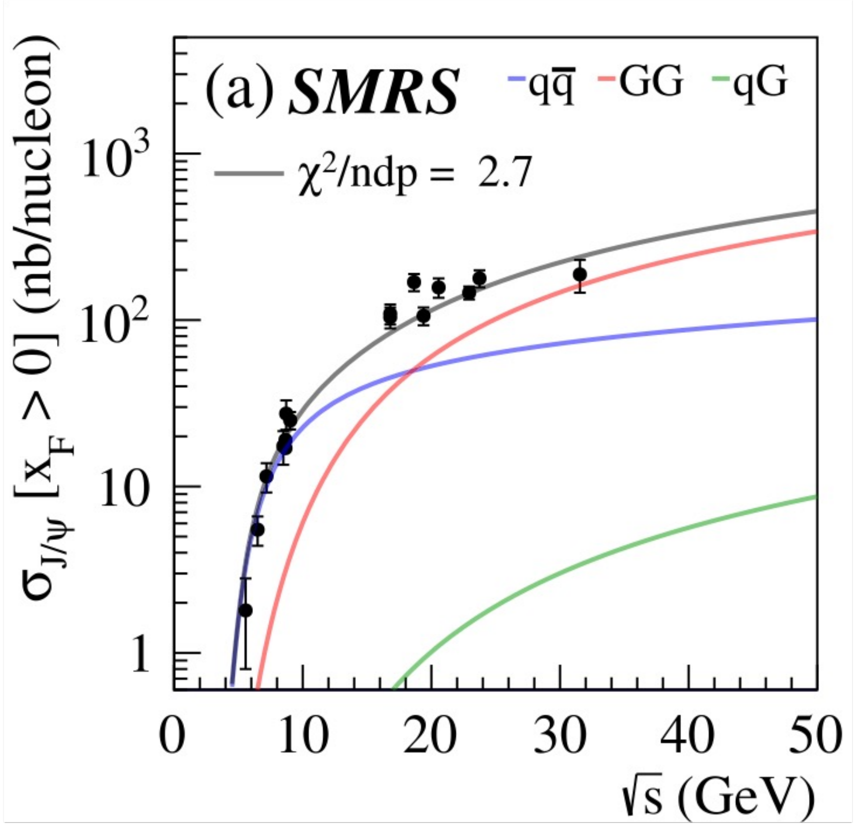
Curves: [Bastami *et al.*, JHEP 02 (2021) 166]

Pion induced J/ψ at AMBER

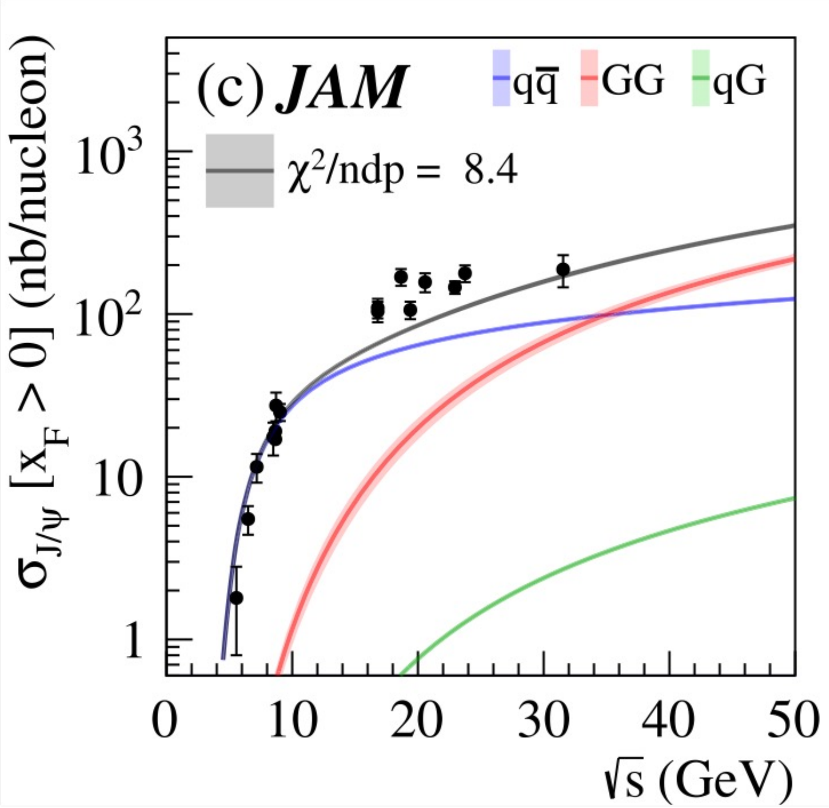




Model dependence of the J/ψ production cross section



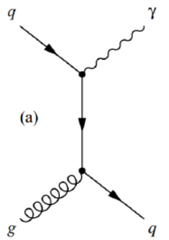
Relative contribution
From quarks and gluons
Very uncertain



SMRS vs JAM fits: strong dependence on the PDFs

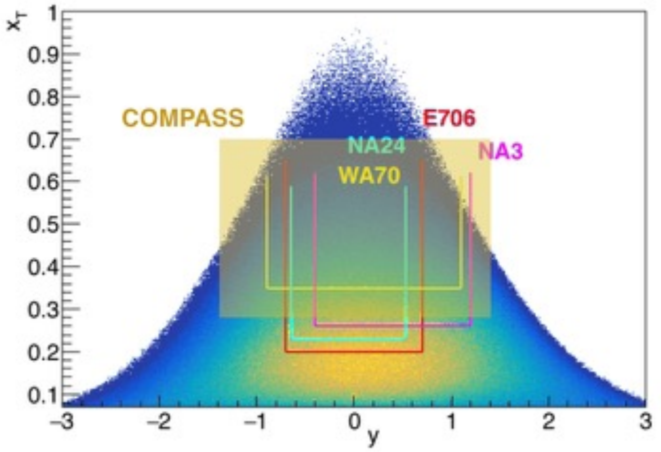
AMBER (Prompt Photons)

AMBER
Apparatus for Meson and Baryon Experimental Research

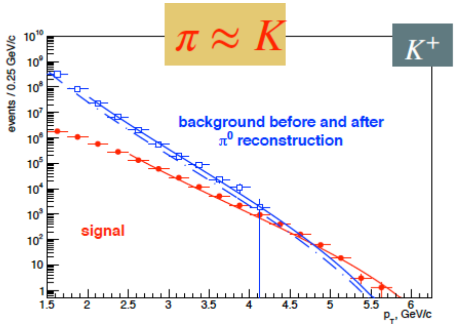


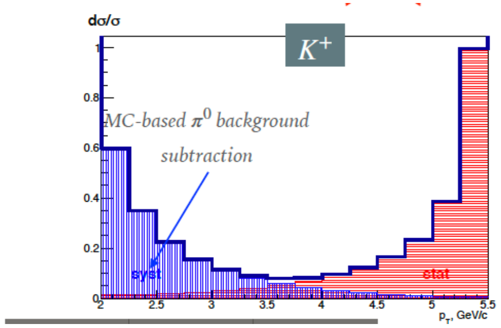
Prompt photons probe – direct access to the gluon content of the kaon.
At the moment there is no experimental information about gluon contribution in kaon.

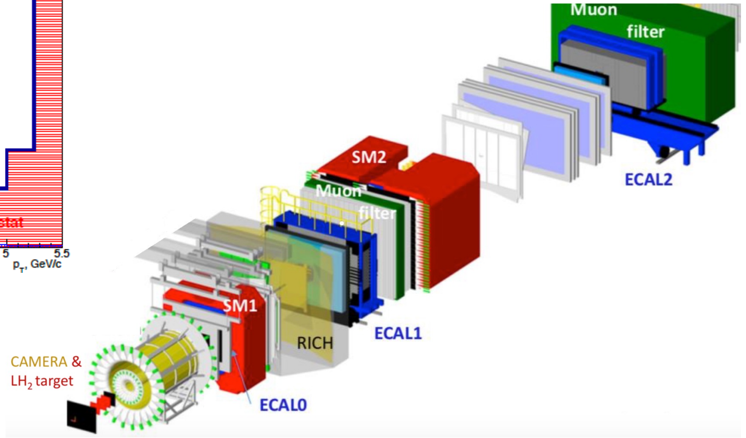
Pythia-based MC simulation for prompt photons production was used for preliminary estimation of kinematic range accessible at COMPASS. It was compared with corresponding ranges accessible by previous experiments with pion beams.

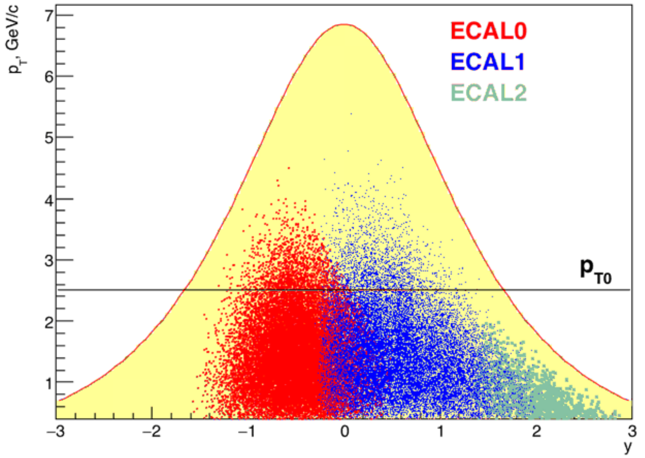


Possibilities to identify signal and reject background were tested. Some optimization of the setup from point of the material budget was tested.





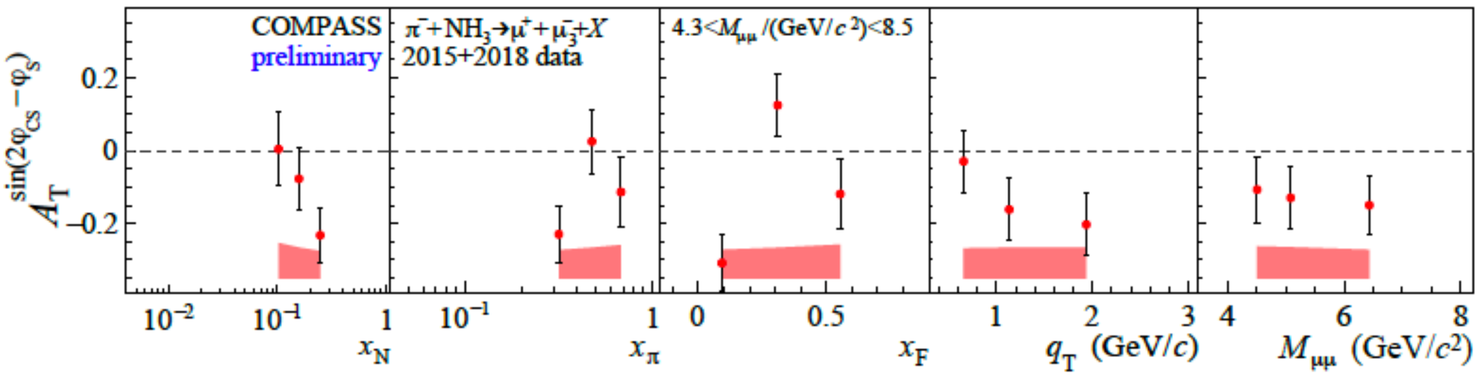




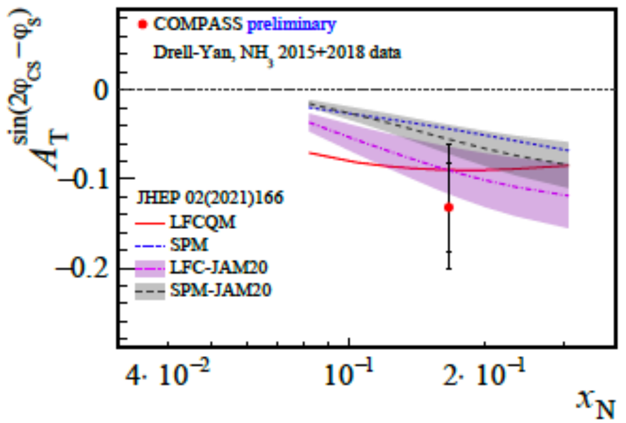
NEW!! Transversity in Drell-Yan

Apparatus for Meson and Baryon Experimental Research

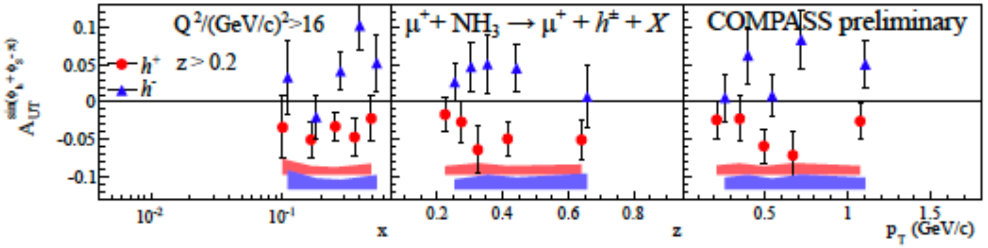
$A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{q}$ (Boer–Mulders function $\otimes$ transversity)



Negative (about 1.5σ significance), kinematic dependence not really significant.
The error bars are statistical, the color bands show systematic uncertainty.
An additional scale uncertainty of 5% is not shown (dilution factor, λ, polarization).



Integrated, compared to predictions.

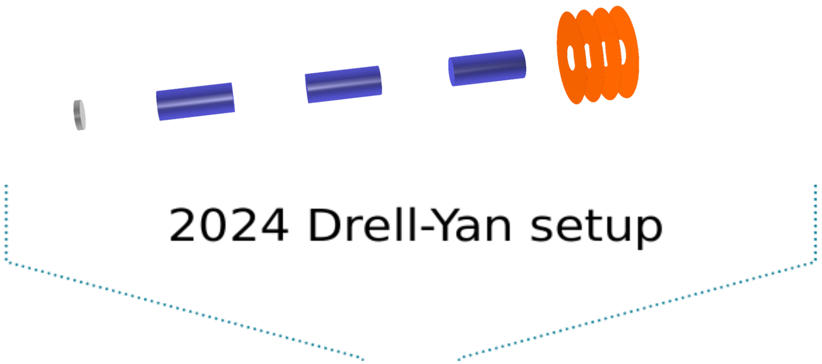


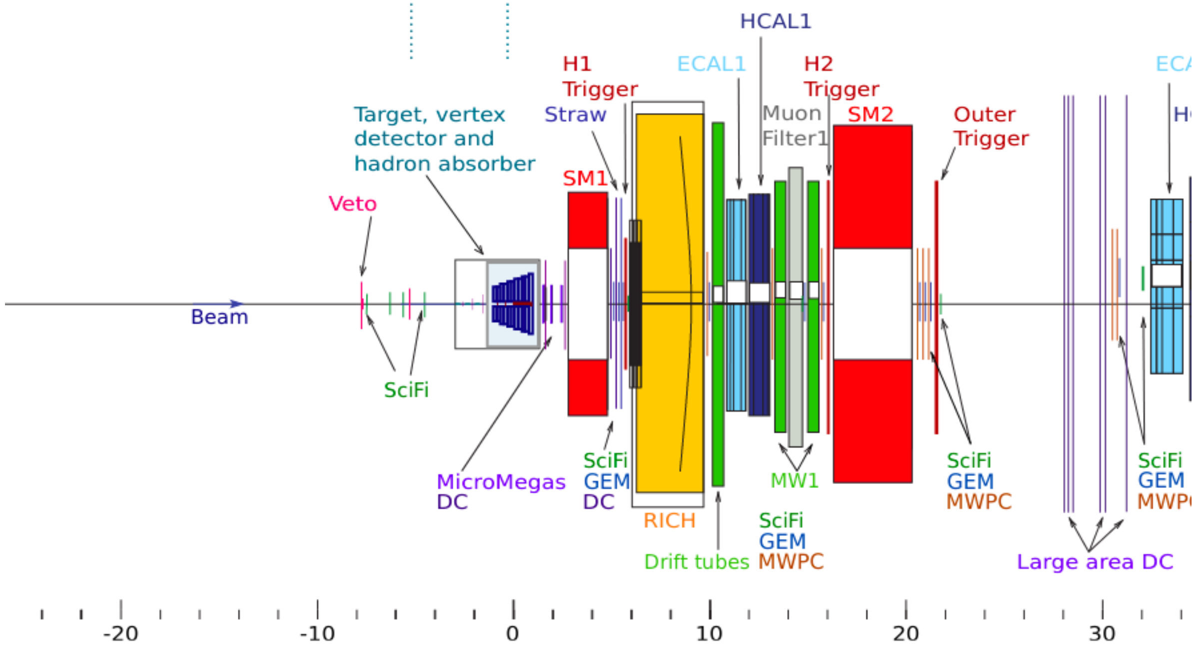
SIDIS in the corresponding Q^2 range.
$A_{UT}^{\sin(\varphi_h+\varphi_S-\pi)} \propto h_{1,p}^{q} \otimes H_{1,q}^{\perp h}$
(transversity $\otimes$ Collins FF)

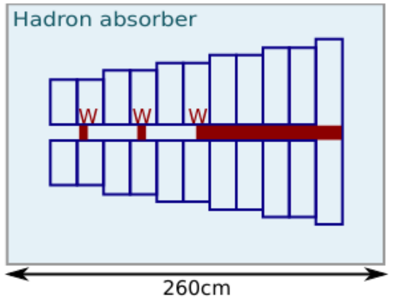
Curves: [Bastami *et al.*, JHEP 02 (2021) 166]

Drell-Yan experiment preparation I

AMBER
Apparatus for Meson and Baryon Experimental Research

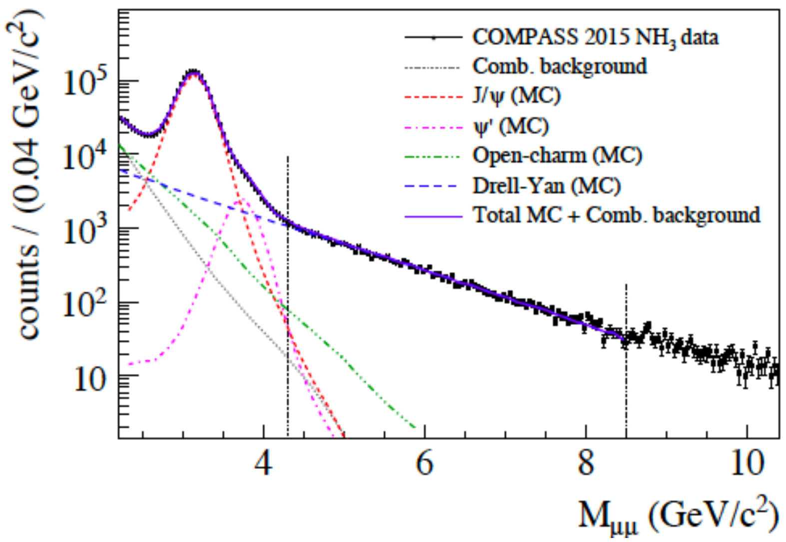






Drell-Yan process is a low cross-section process:

- High intensity hadron beam
- Hadron absorber to protect Spectrometer from a very high secondary flux
- Vertex Detector to compensate loses in resolution because of the absorber in order to improve mass and space resolution



Drell-Yan experiment preparation II
Proposal by LANL group to reuse PHENIX Silicon Vertex Detector

CERN

AMBER
Apparatus for Meson and Baryon Experimental Research

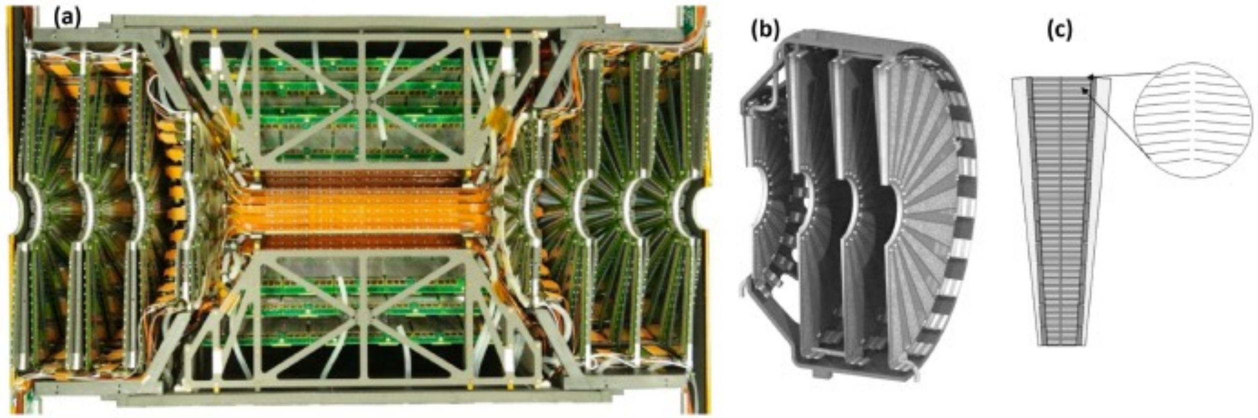
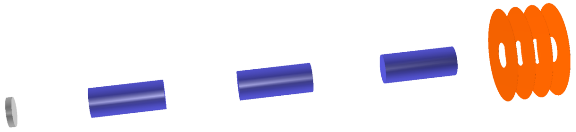
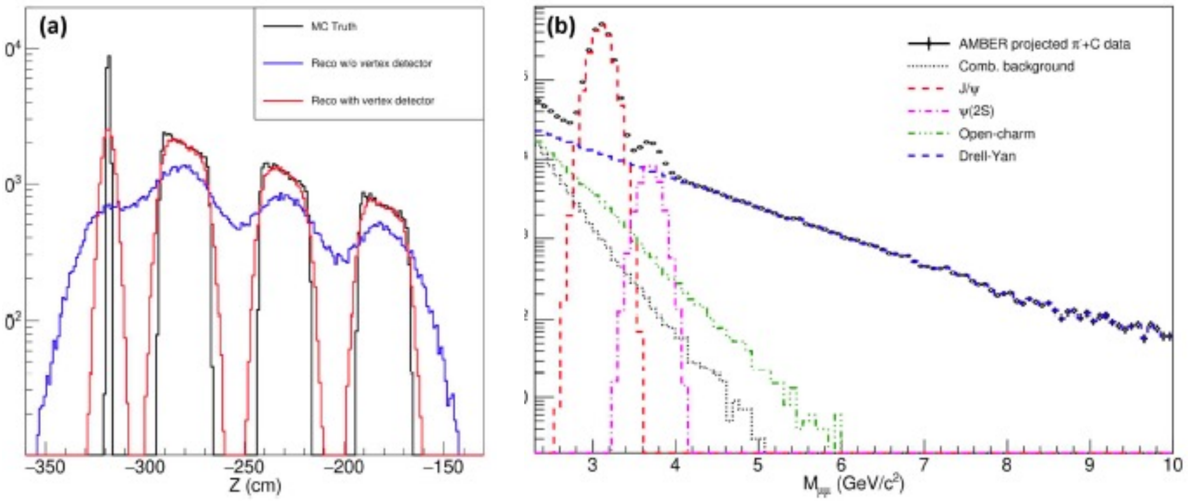


Figure 7 (a) A completed half FVTX detector, with sensors, frontend electronics, supporting structures, and cooling system. Two half FVTX endcaps are shown on either end. The overall length is about 80 cm. (b) A structural illustration of one endcap of the FVTX. One small disk and three large disks are included in one endcap. (c) A segment (wedge) of the FVTX sensor. Each wedge holds two columns of the silicon strips as shown in the zoomed-in portion.

Table 1 Summary of the FVTX specifications.

Silicon sensor thickness (μm)	320
Strip pitch (μm)	75
Number of strips per column	1664
Inner radius of silicon (mm)	44
Outer radius of silicon (mm)	168.8
Strip length at inner radius (mm)	3.4
Strip length at outer radius (mm)	11.5
Pulse timing (ns)	30
Number of wedges per disk	48





Active silicons mini-strip sensors plus front-end ASIC, the FPHX chip bonded directly on sensors

- Time resolution: $\sim$ ns
- Spatial resolution: $\sim 20\mu$m

Simulations and optimisation of the apparatus and reconstruction ongoing

Preliminary:
$\rightarrow \sigma_{\mu\mu} \sim 110$ MeV$/c^2$

$M_{\mu\mu} > 4.3$ GeV$/c^2 \rightarrow M_{\mu\mu} > 4.0$ GeV$/c^2$:
$\Rightarrow \sim 50\%$ gain in DY statistics

Drell-Yan experiment preparation III
Toward doubling of the incoming beam intensity (TO)

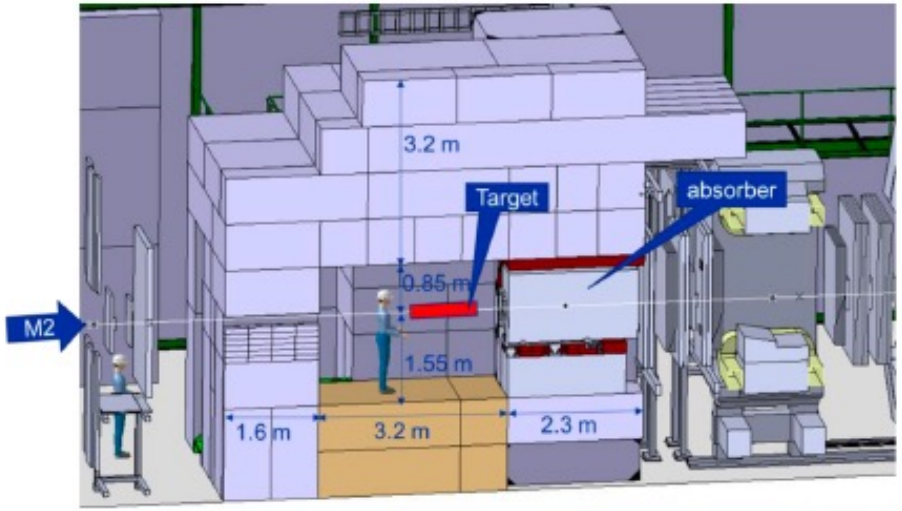
Study and optimisation of the shielding to:

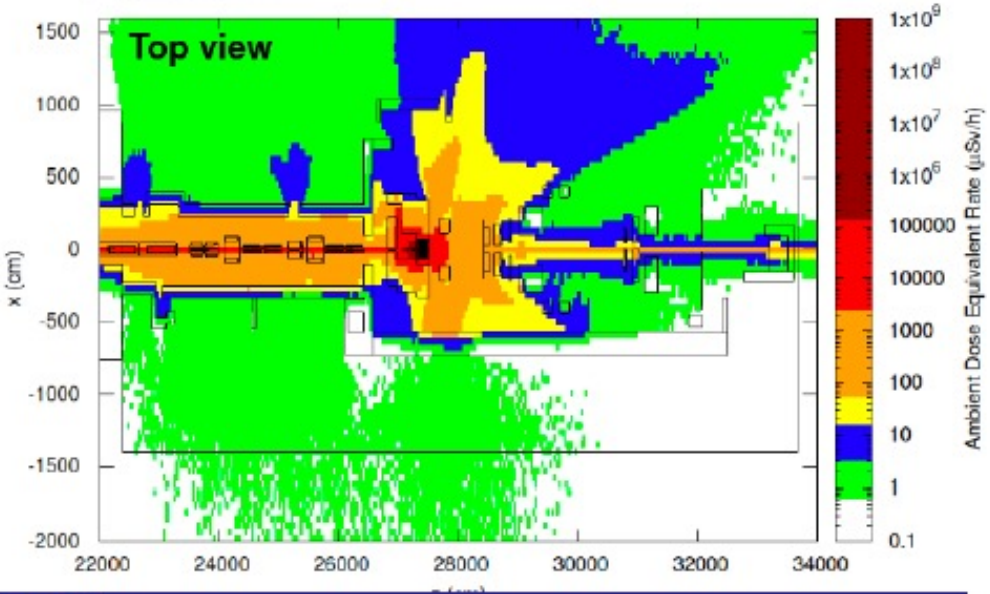
- Contain the radiation
- Minimise the environmental impact
- Comply with regulations

⇒ Compatible with 2×current Intensities

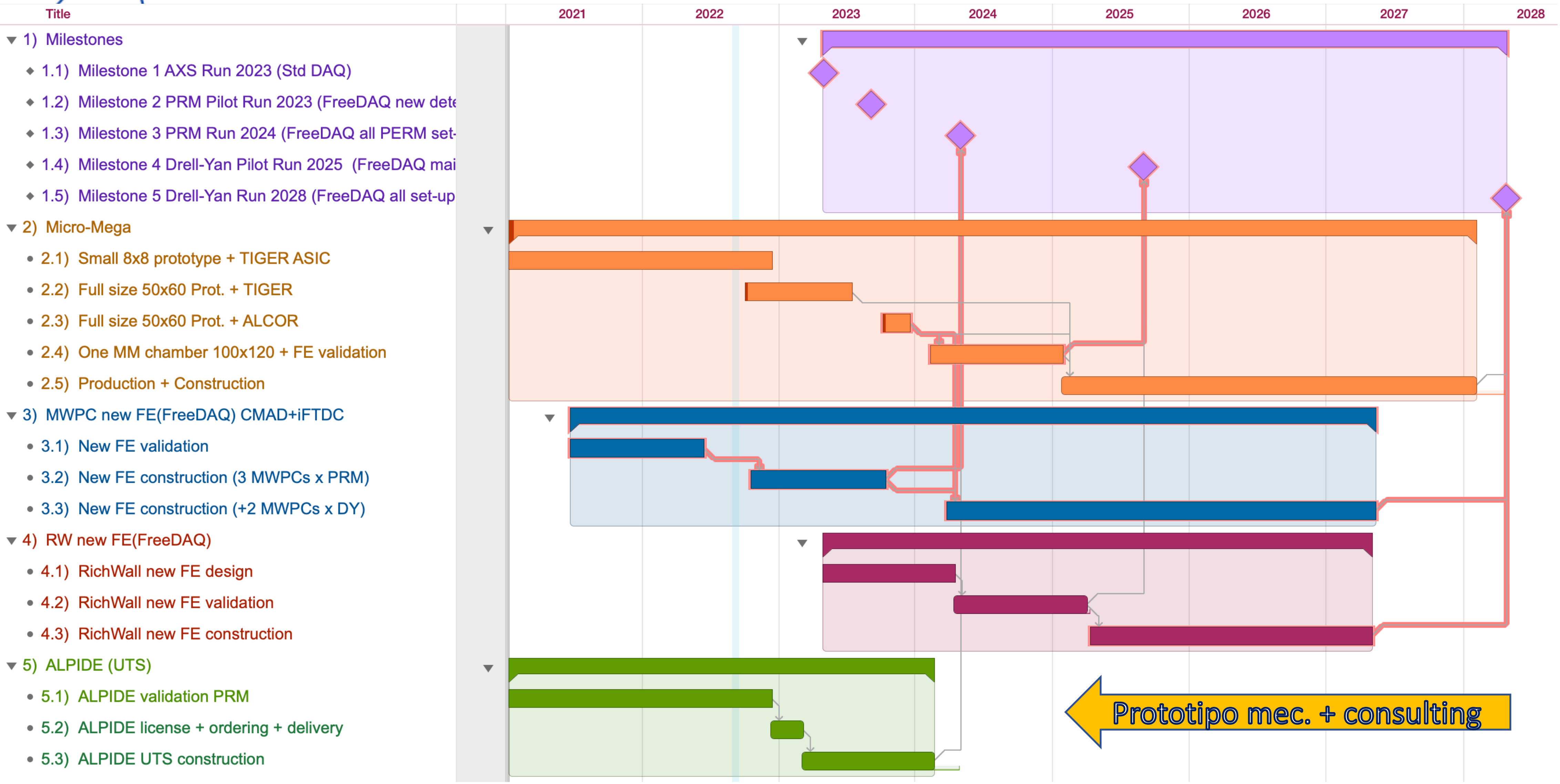
⇒ ECR to be submitted

	Area	Annual dose limit (year)	Ambient dose equivalent rate		Sign	
			permanent occupancy	low occupancy	RADIATION	
	Non-designated	1 mSv	0.5 µSv/h	2.5 µSv/h		
Radiation Area	Supervised	6 mSv	3 µSv/h	15 µSv/h		Controlled Area
Radiation Area	Simple Controlled	20 mSv	10 µSv/h	50 µSv/h		Controlled Area
Radiation Area	Limited Stay	20 mSv	-	2 mSv/h		Controlled Area
Radiation Area	High Radiation	20 mSv	-	100 mSv/h		Controlled Area
Radiation Area	Prohibited	20 mSv	-	> 100 mSv/h	NO ENTRY DÉFENSE D'ENTRER	Controlled Area





AMBER Phase-1 Torino construction plan



Unified Tracking Station