From COMPASS to AMBER  
Trento, Italia, 18-22/09/2023

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
6. Summary

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

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”.
Introduction to the Spin I

Nucleon spin \( \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L \)

- Quark spin contribution \( \Delta \Sigma = 0.24 \) (\( Q^2 = 10 \) (GeV/c)^2 DSSV \( \text{arXiv:0804.0422} \))
- RHIC and COMPASS Open charm measurement and other direct measurements \( \rightarrow \Delta G/G \) is not sufficient \( \rightarrow \)

In order to create Angular Momentum of partons spin-orbit correlation has to be taken into account \( \rightarrow \) transverse momentum of the quark \( k_T \) appears \( \rightarrow 3D \) structure of the Nucleon has to be studied
Unified View of Nucleon Structure

Wigner function

$W(x, k_{\perp}, r_{\perp})$

Transverse Momentum Dependent distributions

TMDs

3D

Generalized Parton Distributions

GPDs

$d^2 r_{\perp}$

$d^2 k_{\perp}$
Four probes to access transverse hadron structure (TMD PDFs)

SIDIS

Drell-Yan

pp collisions

e^+e^- collisions
18 structure functions
14 azimuthal modulations

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 $f_{1T}^q(x, k_T)$. 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

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

+ $\sqrt{2\varepsilon (1+\varepsilon)} A_{UU}^{\cos A_2} \cos \phi_h + \varepsilon A_{UU}^{\cos 2A_2} \cos 2\phi_h$

+ $\lambda \cdot \sqrt{2\varepsilon (1-\varepsilon)} A_{UU}^{\sin A_2} \sin \phi_h$

+ $\sqrt{1-\varepsilon^2} A_{LL} + \sqrt{2\varepsilon (1-\varepsilon)} A_{LL}^{\sin A_2} \cos \phi_h$

\[ A_{UL}^{\sin (A_1-A_2)} \sin (\phi_h - \phi_s) \]

\[ + A_{UL}^{\sin (A_1+A_2)} \sin (\phi_h + \phi_s) \]

+ $2\varepsilon (1+\varepsilon) A_{UL}^{\sin A_2} \sin \phi_s$

+ $2\varepsilon (1-\varepsilon) A_{UL}^{\sin A_2} \sin (2\phi_h - \phi_s)$

\[ + S_T \cdot \sqrt{1-\varepsilon^2} A_{UL}^{\cos A_2} \cos (\phi_h - \phi_s) \]

\[ + S_T \cdot 2\varepsilon (1+\varepsilon) A_{UL}^{\cos A_2} \sin \phi_s \]

+ $2\varepsilon (1-\varepsilon) A_{UL}^{\cos A_2} \sin (2\phi_h - \phi_s)$

\[ \times \{ \frac{\alpha}{xyQ^2 2(1-\varepsilon)} \left( 1 + \frac{\rho^2}{2x} \right) (F_{UU,T} + \varepsilon F_{UU,L}) \]

\[ = \frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_s} \]

\[ = \frac{\alpha}{xyQ^2 2(1-\varepsilon)} \left( 1 + \frac{\rho^2}{2x} \right) (F_{UU,T} + \varepsilon F_{UU,L}) \]

\[ + \sqrt{2\varepsilon (1+\varepsilon)} A_{UU}^{\cos A_2} \cos \phi_h + \varepsilon A_{UU}^{\cos 2A_2} \cos 2\phi_h \]

\[ + \lambda \cdot \sqrt{2\varepsilon (1-\varepsilon)} A_{UU}^{\sin A_2} \sin \phi_h \]

\[ + \sqrt{1-\varepsilon^2} A_{LL} + \sqrt{2\varepsilon (1-\varepsilon)} A_{LL}^{\sin A_2} \cos \phi_h \]

\[ A_{UL}^{\sin (A_1-A_2)} \sin (\phi_h - \phi_s) \]

\[ + A_{UL}^{\sin (A_1+A_2)} \sin (\phi_h + \phi_s) \]

\[ + 2\varepsilon (1-\varepsilon) A_{UL}^{\sin A_2} \sin (3\phi_h - \phi_s) \]

\[ + 2\varepsilon (1-\varepsilon) A_{UL}^{\sin A_2} \sin (2\phi_h - \phi_s) \]

\[ + S_T \cdot \sqrt{1-\varepsilon^2} A_{UL}^{\cos A_2} \cos (\phi_h - \phi_s) \]

\[ + S_T \cdot 2\varepsilon (1+\varepsilon) A_{UL}^{\cos A_2} \sin \phi_s \]

\[ + 2\varepsilon (1-\varepsilon) A_{UL}^{\cos A_2} \sin (2\phi_h - \phi_s) \]
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 $^6$Li polarised target

Hermes Results of 2004
hep-ph/0408013
Gaseous $H_2$ polarized target

Full points – positive hadrons,
Open points – negative hadrons

Doubts.....
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

COMPASS Final results on deuteron

Hermes Final results on proton
PRL 103 (2009)

Flavour separation is essential
Second round: COMPASS ↔ Hermes proton data


Hermes Final results on proton PRL 103 (2009)
COMPASS ↔ Hermes proton data
COMPASS Sivers is smaller – QCD evolution eff.?

Hint from the data: even if exist evolution has to be rather slow
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:

\[ f_{1T}^{\uparrow}(DY) = -f_{1T}^{\uparrow}(SIDIS) \]

\[ h_{1}^{\uparrow}(DY) = -h_{1}^{\uparrow}(SIDIS) \]

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.
Andreas Metz (Trento-TMD’2010):

Sign reversal of the Sivers function

- Prediction based on operator definition (Collins, 2002)
  \[ f_{1T}^{\perp}|_{DY} = - f_{1T}^{\perp}|_{DIS} \]

- 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
      \[ \alpha_s \ln^2 \frac{Q_T^2}{Q^2} \]
    - Has also implications for Fermilab and LHC physics

Drell-Yan process

\[ H_a(P_a) \rightarrow \bar{u}(k_a) \rightarrow l^-(l) \gamma^*(q) \rightarrow l^+(l') + X \]

\[ H_b(P_b, S) \rightarrow u(k_b) \]

\[ s = (P_a + P_b)^2, \]

\[ x_{a(b)} = q^2 / (2P_{a(b)} \cdot q), \]

\[ x_F = x_a - x_b, \]

\[ M_{\mu\mu}^2 = Q^2 = q^2 = s \cdot x_a \cdot x_b, \]

\[ k_{T(a)} = k_{T(a)} + k_{T(b)} \]

the momentum of the beam (target) hadron,
the total centre-of-mass energy squared,
the momentum fraction carried by a parton from \( H_{a(b)} \),
the Feynman variable,
the invariant mass squared of the dimuon,
the transverse component of the quark momentum,
the transverse component of the momentum of the virtual photon.
Sivers in SIDIS and Drell-Yan

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
Sivers in SIDIS in Drell-Yan kinematic range
Drell-Yan at COMPASS

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).
- \( \langle M_{\mu\mu} \rangle = 5.3 \text{ GeV/c}^2 \).
- \( q_T > 0.4 \text{ GeV/c} \) required.
- \( \langle q_T \rangle = 1.17 \text{ GeV/c} \).
NEW!! Sivers in Drell-Yan

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

**COMPASS preliminary**
\[ \pi^+ + \text{NH}_3 \rightarrow \mu^+ + \mu^+ + X \]
2015+2018 data
4.3 < \sqrt{s_{NN}}/(GeV/c^2) < 8.5

\[ A_T \] vs
\[ x_N, x_\pi, x_F, q_T^{\perp} (GeV/c), M_{\mu\mu} (GeV/c^2) \]

**SIDIS in the corresponding \(Q^2\) range.**
\[ A_{UT}^{\sin(\varphi_h - \varphi_S)} = f_{1 T,p}^{\perp q} \otimes D_{1, q}^h \]
(Sivers \otimes unpolarised FF)
NEW!! Sivers in Drell-Yan 2015 +2018

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

Curves: [Bastami et al., JHEP 02 (2021) 166]
NEW!! TSAs in Drell-Yan compared to SIDIS

\[
\frac{d\sigma}{dx dy dp_T^2 dp_\phi d\phi_3} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \ldots + S_T \right\}
\]

\[
\frac{d\sigma}{d\Omega} \propto F_U (1 + \cos^2 \theta_C) \left\{ 1 + \ldots + S_T \right\}
\]

\[
\begin{align*}
& A_{UT}^{\sin(\phi_\phi - \phi_3)} \sin(\phi_\phi - \phi_3) \\
+ & \varepsilon A_{UT}^{\sin(A_\phi + \phi_3)} \sin(\phi_\phi + \phi_3) \\
+ & \varepsilon A_{UT}^{\sin(3\phi_\phi - \phi_3)} \sin(3\phi_\phi - \phi_3) \\
+ & 2\varepsilon (1 + \varepsilon) A_{UT}^{\sin(4\phi_\phi)} \sin \phi_3 \\
+ & 2\varepsilon (1 + \varepsilon) A_{UT}^{\sin(4\phi_\phi - 2\phi_3)} \sin(2\phi_\phi - \phi_3)
\end{align*}
\]

\[
\begin{align*}
& A_{UT}^{\sin(\phi_\phi - \phi_3)} \sin \phi_3 \\
+ & D_{\sin^2 \theta_C} \left\{ A_{UT}^{\sin(2\phi_\phi - \phi_3)} \sin(2\phi_\phi - \phi_3) \\
& + A_{UT}^{\sin(2\phi_\phi + \phi_3)} \sin(2\phi_\phi + \phi_3) \\
& + A_{UT}^{\sin(2\phi_\phi + \phi_3)} \sin(\phi_\phi + \phi_3) \\
& + A_{UT}^{\sin(2\phi_\phi - \phi_3)} \sin(\phi_\phi - \phi_3) \right\}
\end{align*}
\]

\[
\begin{align*}
& \sin(\phi_\phi - \phi_3) \\
& \sin(\phi_\phi + \phi_3) \\
& \sin(3\phi_\phi - \phi_3) \sin(3\phi_\phi - \phi_3) \\
& \sin(4\phi_\phi) \sin \phi_3 \\
& \sin(4\phi_\phi - 2\phi_3) \sin(2\phi_\phi - \phi_3)
\end{align*}
\]

\[
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& \sin(4\phi_\phi) \sin \phi_3 \\
& \sin(4\phi_\phi - 2\phi_3) \sin(2\phi_\phi - \phi_3)
\end{align*}
\]
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
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/

Lol 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++²/AMBER²

B. Adams¹,12, C.A. Aidala¹, R. Akhunzhanov¹⁴, G.D. Alexeev¹⁴, M.G. Alexeev¹⁴, A. Amoroso⁴¹,4²,

<table>
<thead>
<tr>
<th>Program</th>
<th>Physics Goals</th>
<th>Beam Energy [GeV]</th>
<th>Beam Intensity [s⁻¹]</th>
<th>Trigger Rate [kHz]</th>
<th>Beam Type</th>
<th>Target</th>
<th>Earliest start time, duration</th>
<th>Hardware additions</th>
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<td>muon-proton elastic</td>
<td>Precision proton-radius measurement</td>
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<td>4 × 10⁶</td>
<td>100</td>
<td>μ⁺⁻</td>
<td>high-pressure H₂</td>
<td>2022 1 year</td>
<td>active TPC, SciFi trigger, silicon veto,</td>
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<td>scattering</td>
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<td>Hard exclusive reactions</td>
<td>GPD E</td>
<td>160</td>
<td>2 × 10⁷</td>
<td>10</td>
<td>μ⁺⁻</td>
<td>NH₃</td>
<td>2022 2 years</td>
<td>recoil silicon, modified polarised target magnet</td>
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<td>Input for Dark</td>
<td>ϒ production cross section</td>
<td>20-280</td>
<td>5 × 10⁵</td>
<td>25</td>
<td>μ⁺⁻</td>
<td>LH₂, LHe</td>
<td>2022 1 month</td>
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<td>Matter Search</td>
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<td>J- induced spectroscopy</td>
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<td>25</td>
<td>ϒ⁻</td>
<td>LH₂</td>
<td>2022 2 years</td>
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<td>Drell-Yan</td>
<td>Pion PDFs</td>
<td>190</td>
<td>7 × 10⁷</td>
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<td>π⁺⁻</td>
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<td>2022 1-2 years</td>
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<td>Drell-Yan (RF)</td>
<td>Kaon PDFs &amp; Nucleon TMDs</td>
<td>~100</td>
<td>10⁶</td>
<td>25-50</td>
<td>K⁺⁻, π⁻</td>
<td>NH₃, OW</td>
<td>2026 2-3 years</td>
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<td>Primakoff (RF)</td>
<td>Kaon polarisability &amp; pion lifetime</td>
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<td>Prompt Photons (RF)</td>
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<td>5 × 10⁶</td>
<td>10-100</td>
<td>K⁺⁻, π⁺⁻</td>
<td>LH₂, Ni</td>
<td>2026 non-exclusive 1-2 years</td>
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<td>K- induced Spectroscopy</td>
<td>High-precision strange-meson spectrum</td>
<td>50-100</td>
<td>5 × 10⁶</td>
<td>25</td>
<td>K⁻</td>
<td>LH₂</td>
<td>2026 1 year</td>
<td>recoil TOF, forward PID</td>
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<td>(RF)</td>
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<td>Vector mesons (RF)</td>
<td>Spin Density Matrix Elements</td>
<td>50-100</td>
<td>5 × 10⁶</td>
<td>10-100</td>
<td>K⁺⁻, π⁺⁻</td>
<td>from H to Pb</td>
<td>2026 1 year</td>
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</table>

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
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

**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?

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*  
... ~ 1000 citations

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  

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.

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?

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 \( m_p \approx 1.5 \times m_\pi \ldots \) 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

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

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

Methods:

- Drell-Yan (compl. to Sullivan) and $J/\Psi$
- Prompt Photon Production
- Diffractive scattering
- Elastic scattering

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

19/09/23

Oleg
General AMBER timeline

Conventional muon/hadron M2 beams

Run 3

Phase-1 ✓

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

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

Run 4

Phase-2

Improved conventional hadron M2 beams

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

Phase-2 Proposal submission in the beginning of 2024

19/09/23
Oleg Denisov
Pion induced Drell-Yan at AMBER
Status of the knowledge of the Pion structure

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

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

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

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Target type</th>
<th>Beam energy (GeV)</th>
<th>Beam type</th>
<th>Beam intensity (particles)</th>
<th>Drell-Yan mass (GeV/c^2)</th>
<th>Drell-Yan events</th>
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<td>E615</td>
<td>20 cm W</td>
<td>252</td>
<td>π^+</td>
<td>17.6 x 10^3</td>
<td>4.05 – 8.55</td>
<td>5000</td>
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<td>NA3</td>
<td>30 cm H_2</td>
<td>200</td>
<td>π^-</td>
<td>2.9 x 10^3</td>
<td>4.3 – 8.5</td>
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<td>4.2 – 8.5</td>
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<td>NA10</td>
<td>120 cm D_{2}</td>
<td>286</td>
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<td>65 x 10^3</td>
<td>4.2 – 8.5</td>
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<td>NA10</td>
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<td>COMPASS 2015</td>
<td>110 cm NH_{3}</td>
<td>190</td>
<td>π^-</td>
<td>7.9 x 10^3</td>
<td>4.3 – 8.5</td>
<td>35000</td>
</tr>
<tr>
<td>COMPASS 2018</td>
<td>75 cm C</td>
<td>190</td>
<td>π^-</td>
<td>1.7 x 10^7</td>
<td>4.3 – 8.5</td>
<td>21700</td>
</tr>
<tr>
<td></td>
<td></td>
<td>190</td>
<td>π^-</td>
<td>6.8 x 10^7</td>
<td>4.3 – 8.5</td>
<td>67000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>190</td>
<td>π^-</td>
<td>0.4 x 10^7</td>
<td>4.3 – 8.5</td>
<td>13000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>12 cm W</td>
<td>π^-</td>
<td>1.6 x 10^7</td>
<td>4.3 – 8.5</td>
<td>24100</td>
</tr>
</tbody>
</table>

Isoscalar target + Both positive and negative beams + High statistics

19/09/23

Oleg Denisov
Pion induced $J/\psi$ at AMBER

Collected simultaneously with DY data, with large counting rates

Physics objectives:
- Study of the $J/\psi$ (charmonia) production mechanisms ($gg$–fusion vs $q\bar{q}$–annihilation), comparison of CEM and NRQCD
- $\Psi(2S)$ signal study, free of feed-down effect from $X_{c1}$ $X_{c2}$

Improved CEM, CT10 + GRS99 global fit for proton/pion
Goal 2: gluon distribution in the pion through $J/\psi$ production

Cross section (ICEM)

Polarization (ICEM)

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

Huge statistics: $\pi^+$, $\pi^-$, $\rho$ : 1.2 – 1.8 M $J/\psi$ and 20 – 30 k $\psi'$
AMBER (kaon induced Drell-Yan and J/Psi production)

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)

- New measurements with lower systematics and new transitions
- ProRAD, ULQ2, ISR @ MESA, PRad

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.
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_μ = 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 x 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_γ/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)

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.

\[ K^- e_{\text{target}} \rightarrow K^- e^- \]
\[ s = 2E_b m_e + m_b^2 + m_e^2 \]
\[ Q_{\text{max}}^2 = \frac{4p_b^2 m_e^2}{s} \]

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)

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

Strange-Meson Spectroscopy with COMPASS

AMBER QCD Facility, goal for Kaon induced Spectroscopy to Collect 10-20x10^6 K^- π^+ π^- 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)

Polarizabilities

Interaction between hadron and external electromagnetic field described by parameters $\alpha$, $\beta$ (LO), encoding information about its internal structure.

Dominik Ecker’s talk at HADRON’23

19/09/23  Oleg Denisov
AMBER (Prompt Photons)

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.
AMBER Phase-1 running plan

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

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

Oleg Denisov
19/09/23
Summary: AMBER at CERN SPS

• 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
Spares
SIDIS $\rightarrow$ access to TMD PDFs and FFs

\[ \sigma^\ell p \rightarrow \ell hX = \sum_q (DF \otimes \sigma^\ell q \rightarrow \ell q \otimes FF) \]

(Un)polarized SIDIS process allows to probes both TMD PDFs and FFs
STAR: $W$-Boson Production in $p\uparrow+p\rightarrow W^\pm\rightarrow e^\pm+\nu$

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

Comparison with Phys. Rev. Lett. 103, 172001

Comparison with PRL116(2016) 13201
NEW!! Pretzelocity in Drell-Yan

\[ A_T^{\sin(2\varphi_{CS} + \varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1T,p}^{\perp q} \]  
(Boer–Mulders \otimes 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, \(\lambda\), polarization).

Integrated, compared to predictions.

Curves: [Bastami et al., JHEP 02 (2021) 166]
Pion induced $J/\psi$ at AMBER

Model dependence of the $J/\psi$ production cross section

(a) **SMRS**
- $q\bar{q}$
- $GG$
- $qG$

$\chi^2/ndp = 2.7$

(c) **JAM**
- $q\bar{q}$
- $GG$
- $qG$

$\chi^2/ndp = 8.4$

Relative contribution
From quarks and gluons
Very uncertain

SMRS vs JAM fits: strong dependence on the PDFs
NEW!! Transversity in Drell-Yan

\[ A_T^{\sin(2\varphi_{CS} - \varphi_S)} \propto h_{1,p}^{1/4} \otimes h_{1,h}^{q} \]

(Boer–Mulders function ⊗ 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.

Curves: [Bastami et al., JHEP 02 (2021) 166]
Drell-Yan experiment preparation

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

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>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon sensor thickness (µm)</td>
<td>320</td>
</tr>
<tr>
<td>Strip pitch (µm)</td>
<td>75</td>
</tr>
<tr>
<td>Number of strips per column</td>
<td>1664</td>
</tr>
<tr>
<td>Inner radius of silicon (mm)</td>
<td>44</td>
</tr>
<tr>
<td>Outer radius of silicon (mm)</td>
<td>168.8</td>
</tr>
<tr>
<td>Strip length at inner radius (mm)</td>
<td>3.4</td>
</tr>
<tr>
<td>Strip length at outer radius (mm)</td>
<td>11.5</td>
</tr>
<tr>
<td>Pulse timing (ns)</td>
<td>30</td>
</tr>
<tr>
<td>Number of wedges per disk</td>
<td>48</td>
</tr>
</tbody>
</table>

Table 1 Summary of the FVTX specifications.

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

- Time resolution: \(\sim\) ns
- Spatial resolution: \(\sim20\mu m\)

Simulations and optimisation of the apparatus and reconstruction ongoing

Preliminary:
\[\sigma_{\mu\mu} \sim 110\text{ MeV}/c^2\]
\[M_{\mu\mu} > 4.3\text{ GeV}/c^2 \rightarrow M_{\mu\mu} > 4.0\text{ GeV}/c^2:\]
\[\Rightarrow \sim50\%\text{ gain in DY statistics}\]
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

<table>
<thead>
<tr>
<th>Area</th>
<th>Annual dose limit (year)</th>
<th>Ambient dose equivalent rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>permanent occupancy</td>
</tr>
<tr>
<td>Non-designated</td>
<td>1 mSv</td>
<td>0.5 µSv/h</td>
</tr>
<tr>
<td>Supervised</td>
<td>8 mSv</td>
<td>3 µSv/h</td>
</tr>
<tr>
<td>Simple Controlled</td>
<td>20 mSv</td>
<td>10 µSv/h</td>
</tr>
<tr>
<td>Limited Stay</td>
<td>20 mSv</td>
<td>-</td>
</tr>
<tr>
<td>High Radiation</td>
<td>20 mSv</td>
<td>-</td>
</tr>
<tr>
<td>Prohibited</td>
<td>20 mSv</td>
<td>-</td>
</tr>
</tbody>
</table>

Top view

Vincent Andrieux (UIUC)  
EHM remote May-2022
AMBER Phase-1 Torino construction plan

1) Milestones
   1.1) Milestone 1 AXS Run 2023 (Std DAQ)
   1.2) Milestone 2 PRM Pilot Run 2023 (FreeDAQ new det)
   1.3) Milestone 3 PRM Run 2024 (FreeDAQ all PERM set-
   1.4) Milestone 4 Drell-Yan Pilot Run 2025 (FreeDAQ mai
   1.5) Milestone 5 Drell-Yan Run 2028 (FreeDAQ all set-up

2) Micro-Mega
   2.1) Small 8x8 prototype + TIGER ASIC
   2.2) Full size 50x60 Prot. + TIGER
   2.3) Full size 50x60 Prot. + ALCOR
   2.4) One MM chamber 100x120 + FE validation
   2.5) Production + Construction

3) MWPC new FE (FreeDAQ) CMAD+IFTDC
   3.1) New FE validation
   3.2) New FE construction (3 MWPCs x PRM)
   3.3) New FE construction (+2 MWPCs x DY)

4) RW new FE (FreeDAQ)
   4.1) RichWall new FE design
   4.2) RichWall new FE validation
   4.3) RichWall new FE construction

5) ALPIDE (UTS)
   5.1) ALPIDE validation PRM
   5.2) ALPIDE license + ordering + delivery
   5.3) ALPIDE UTS construction

Prototipo mec. + consulting

19/09/23
Oleg Denisov
Unified Tracking Station