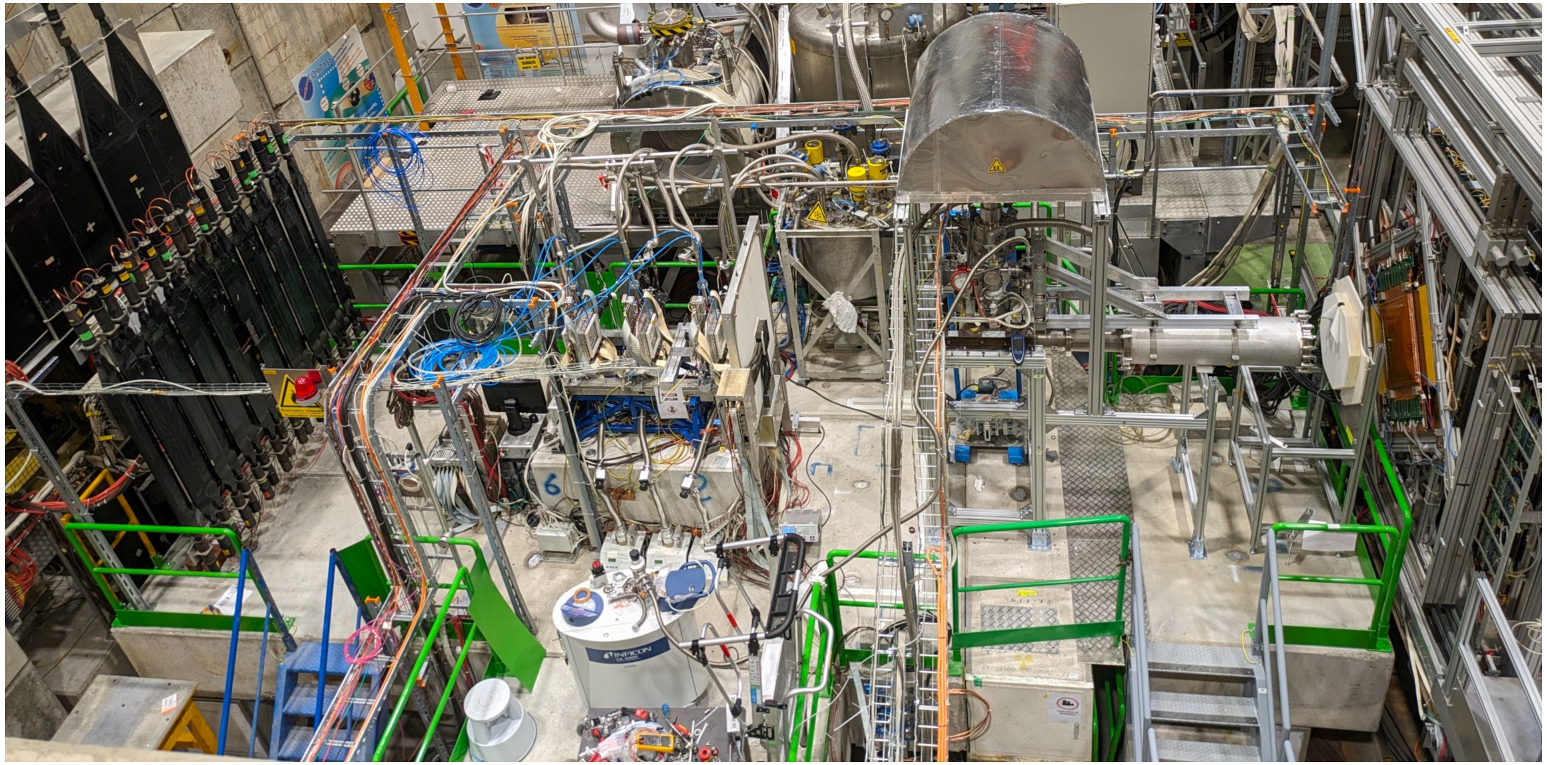
From COMPASS to AMBER
DLNP, JINR, Dubna, 10/07/2024

Apparatus for Meson and Baryon
Experimental Research

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

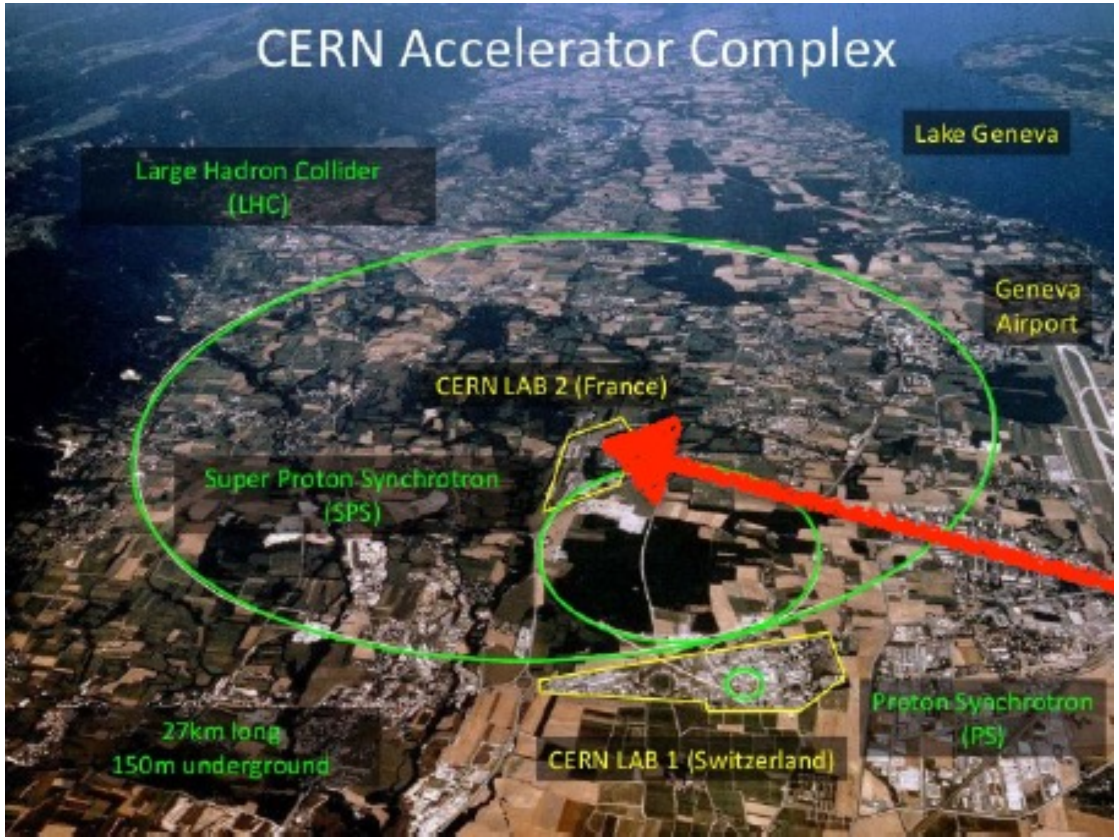
1. Intro: from NA4 to AMBER
2. Spin ➔ Mass
    - COMPASS: Sivers TMD journey
    - Some conclusions
3. AMBER QCD facility at CERN physics program
4. Current status and perspectives of the AMBER experiment & beam line
5. Summary

Dr. Oleg Yu. Denisov, senior researcher INFN section of Turin, Italy
On behalf of the AMBER Collaboration

Materials/slides of Vincent Andrieux, Craig Roberts, Alessandro Bacchetta, Paolo Zuccon, Stephane Platchkov, Alexey Guskov, Stefan Wallner , Jan Friedrich, Stephan Paul, Stefan Diehl and other Colleagues have been used in this talk

AMBER facility is a successor of the COMPASS in a long row of Experiments which took place in the EHN2 experimental hall of the CERN North Area Laboratory (aka CERN-Prevessin or CERN Lab 2)

NA4 → EMC → NMC → SMC → COMPASS → AMBER

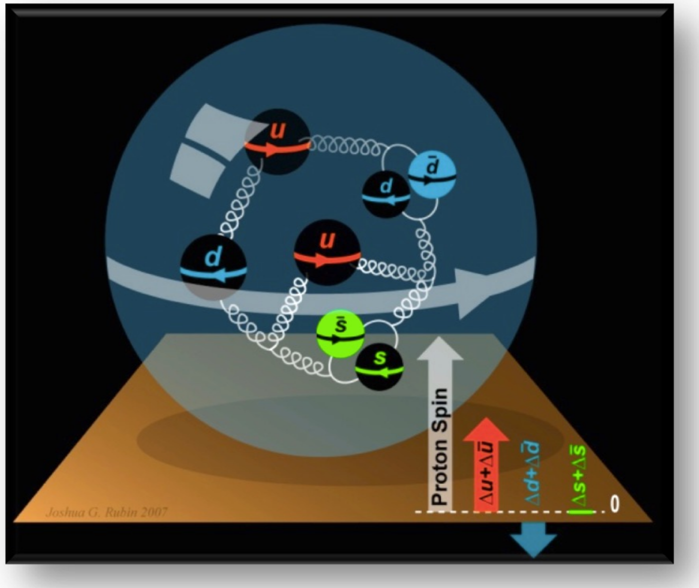


Most of them are known because of their contribution to the study of the proton structure and proton spin structure

Introduction to the Spin I

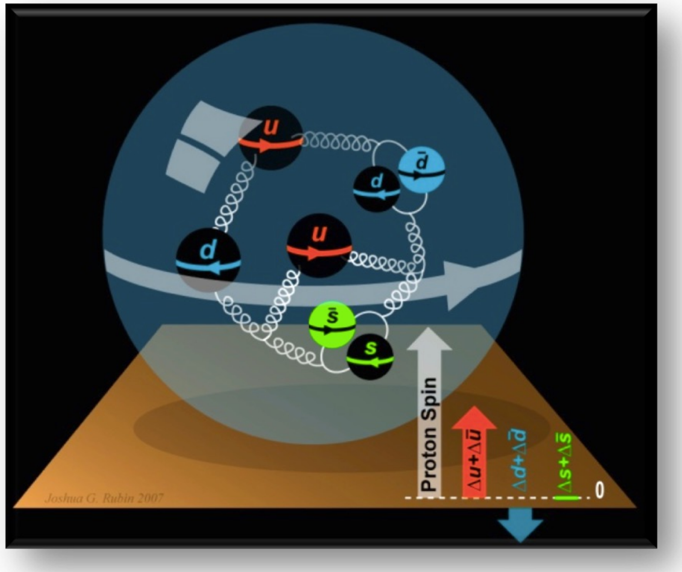
On the one hand - Almost all visible matter of the universe we are able to observe consists of nucleons.

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 ½ = ½ ΔΣ + ΔG + L

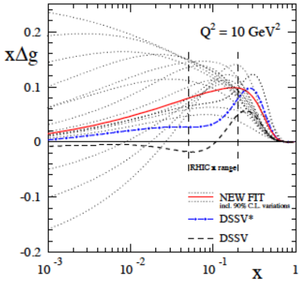
quark gluon orbital ang. mom.

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

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

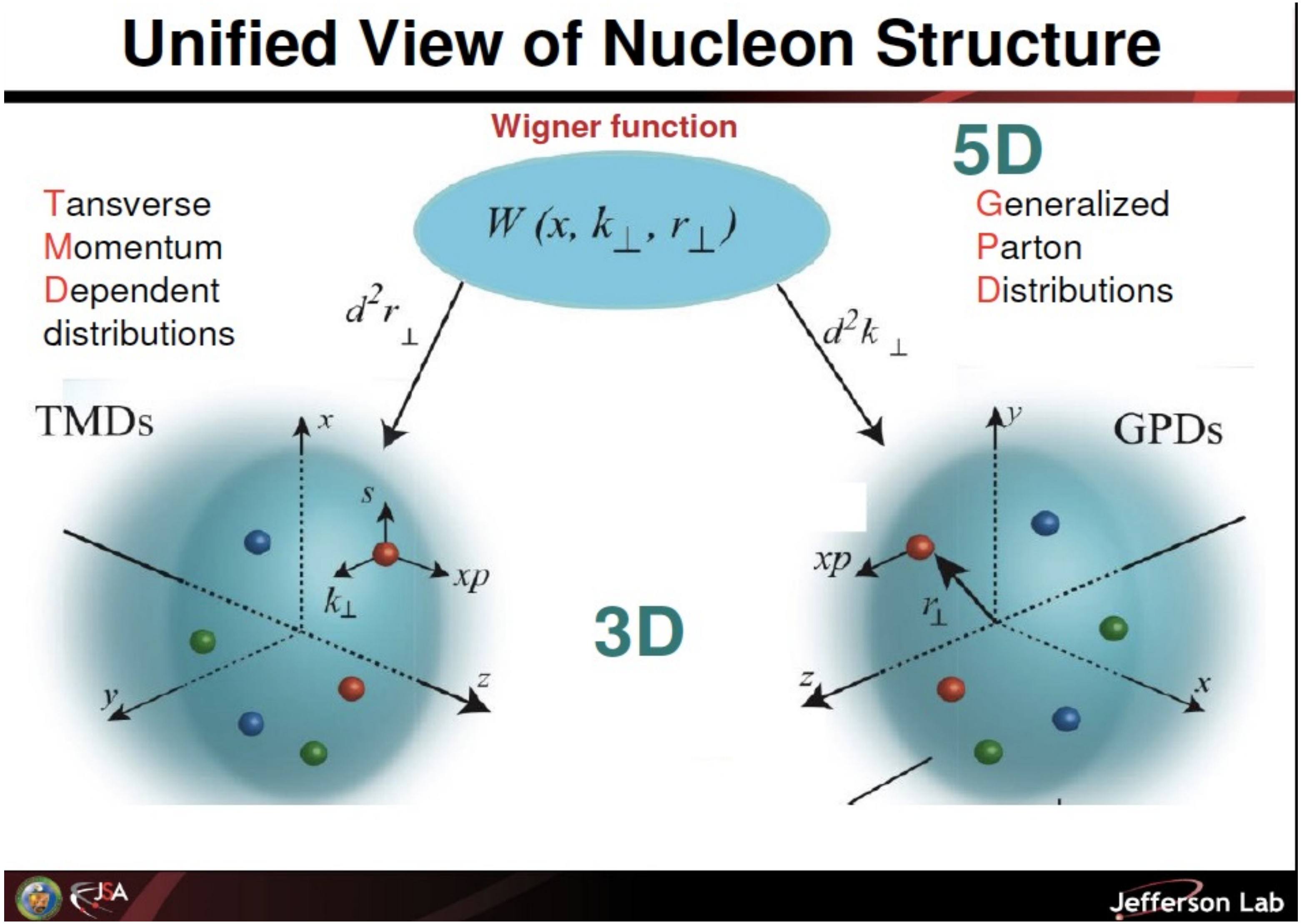
First two component were extensively studied in the SIDIS experiments with the longitudinally polarised target (collinear case approach): spin fraction carried by quarks and gluons is not sufficient to describe ½ nucleon spin:

- 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 Orbital 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



Unified View of Nucleon Structure

Wigner function

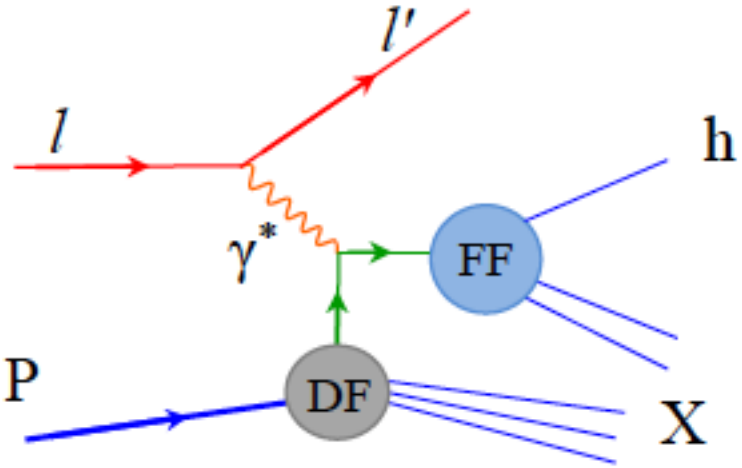
$W(x, k_\perp, r_\perp)$

Tansverse
Momentum
Dependent
distributions

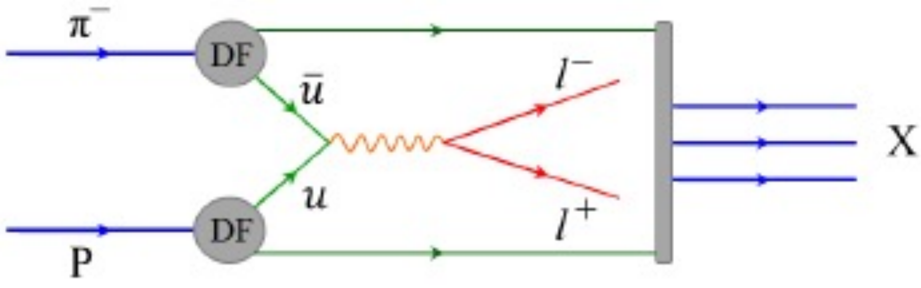
5D
Generalized
Parton
Distributions

3D

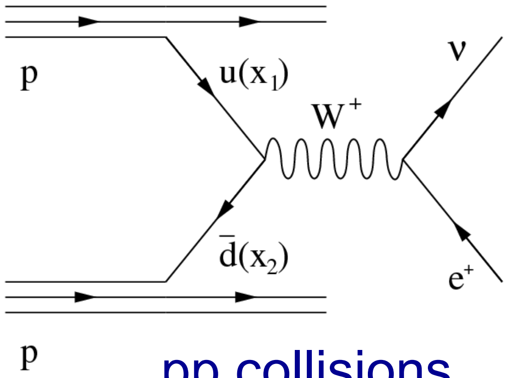
Four probes to access transverse hadron structure (TMD PDFs)



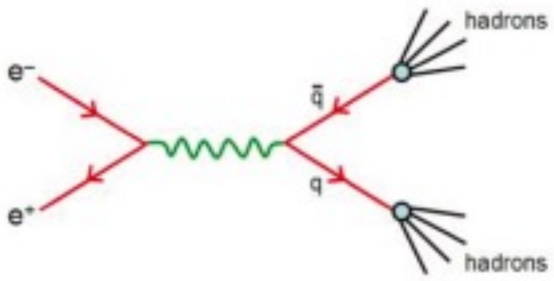
SIDIS



Drell-Yan



pp collisions



e^+e^- collisions

Contribution from COMPASS, Sivers TMD journey, SIDIS ➔

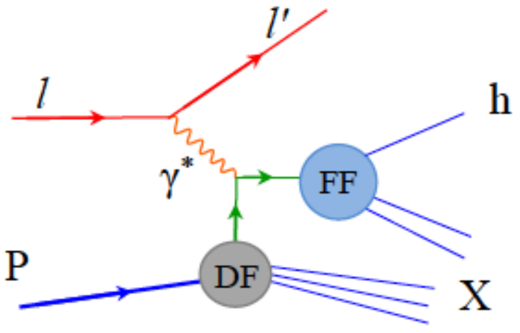
18 structure functions
14 azimuthal modulations

AMBER
Apparatus for Meson and Baryon
Experimental Research

$$\frac{d\sigma}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\phi_S} =$$

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

$$\times\left\{\begin{array}{l}
1+\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h+\varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h \\
+\ \lambda\sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\phi_h}\sin\phi_h \\
+\ S_L\left[\sqrt{2\varepsilon(1+\varepsilon)}A_{UL}^{\sin\phi_h}\sin\phi_h+\varepsilon A_{UL}^{\sin 2\phi_h}\sin 2\phi_h\right] \\
+\ S_L\lambda\left[\sqrt{1-\varepsilon^2}A_{LL}+\sqrt{2\varepsilon(1-\varepsilon)}A_{LL}^{\cos\phi_h}\cos\phi_h\right] \\
+\ S_T\left[\begin{array}{l}
\boxed{A_{UT}^{\sin(\phi_h-\phi_S)}\sin(\phi_h-\phi_S)} \\
+\ \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S) \\
+\ \varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S) \\
+\ \sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin\phi_S}\sin\phi_S \\
+\ \sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin(2\phi_h-\phi_S)}\sin(2\phi_h-\phi_S)
\end{array}\right] \\
+\ S_T\lambda\left[\begin{array}{l}
\sqrt{(1-\varepsilon^2)}A_{LT}^{\cos(\phi_h-\phi_S)}\cos(\phi_h-\phi_S) \\
+\ \sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos\phi_S}\cos\phi_S \\
+\ \sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos(2\phi_h-\phi_S)}\cos(2\phi_h-\phi_S)
\end{array}\right]
\end{array}\right\}$$



Quark / Nucleon	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

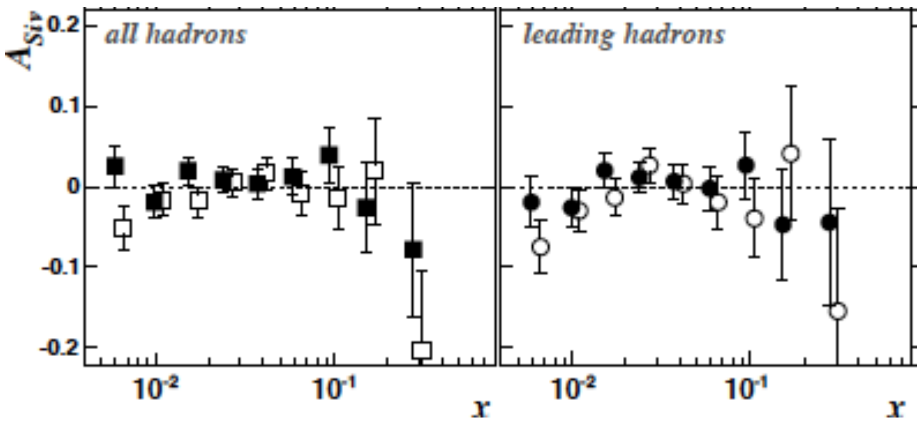
Hep-ex/0503002

Solid state ^{6}LD polarised target

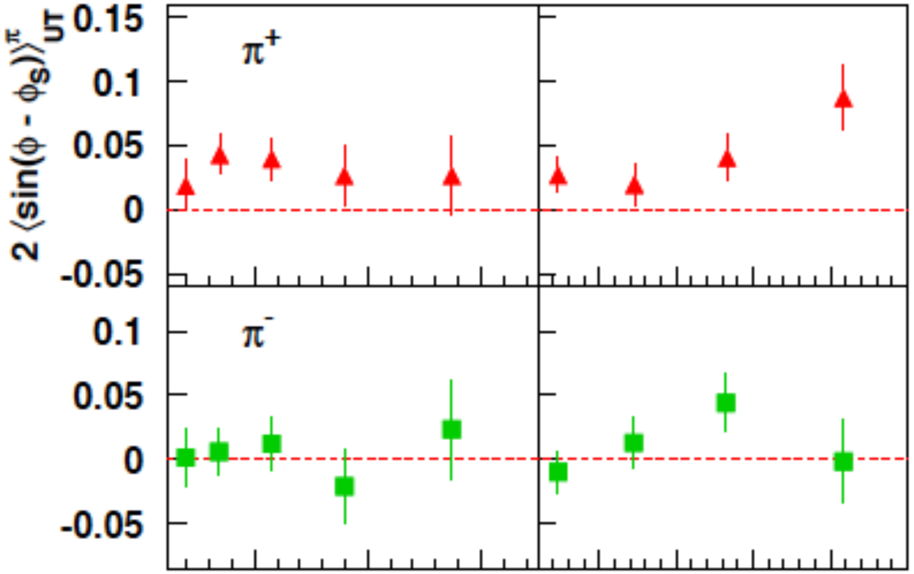
Hermes Results of 2004

hep-ph/0408013

Gaseous H_2 polarized target



Full points – positive hadrons,
Open points – negative hadrons

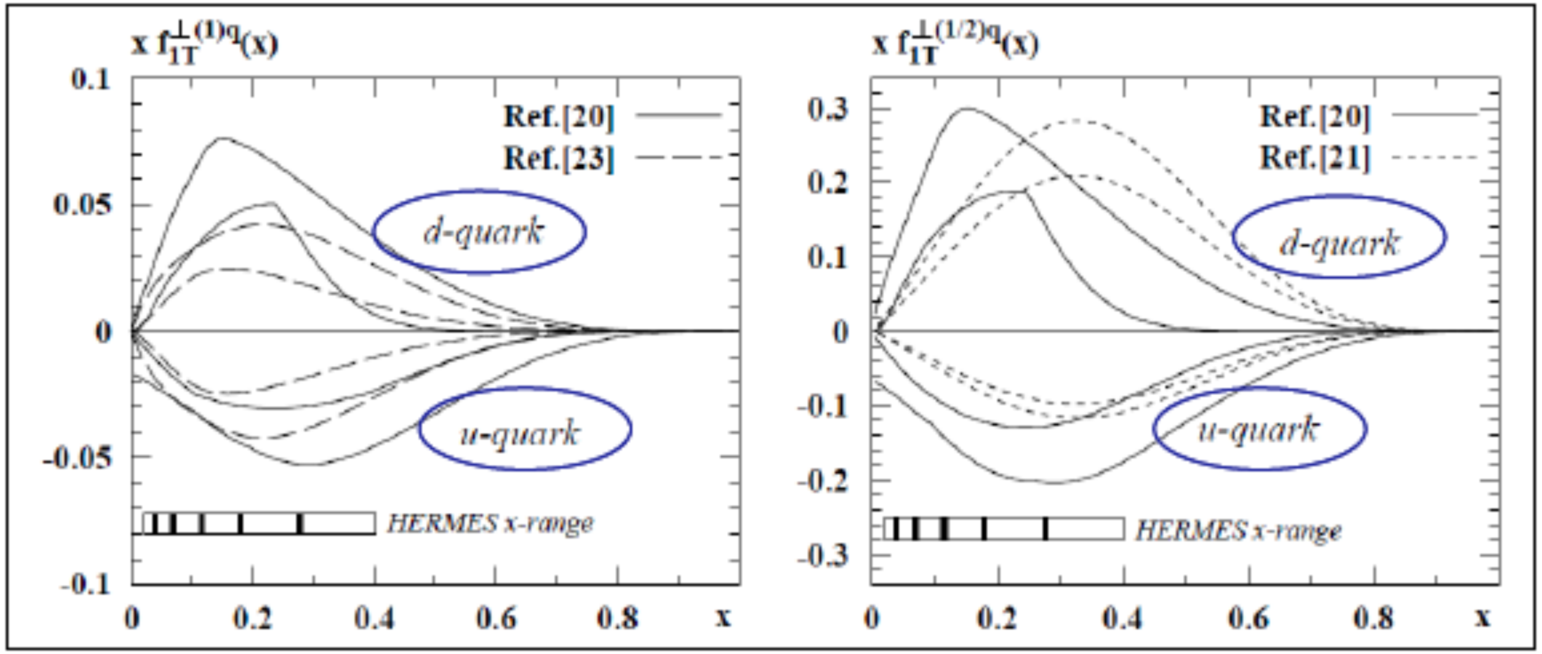


DOUBTS…..

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

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



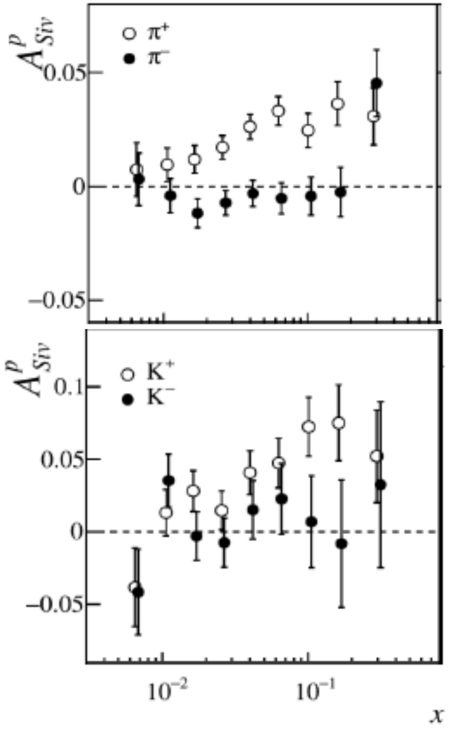
Second round(2010'):
COMPASS ←→ Hermes proton data

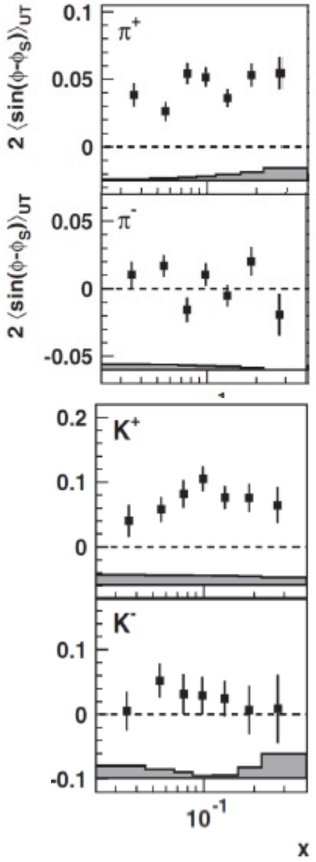
Apparatus for Meson and Baryon Experimental Research

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

Hermes Final results on proton

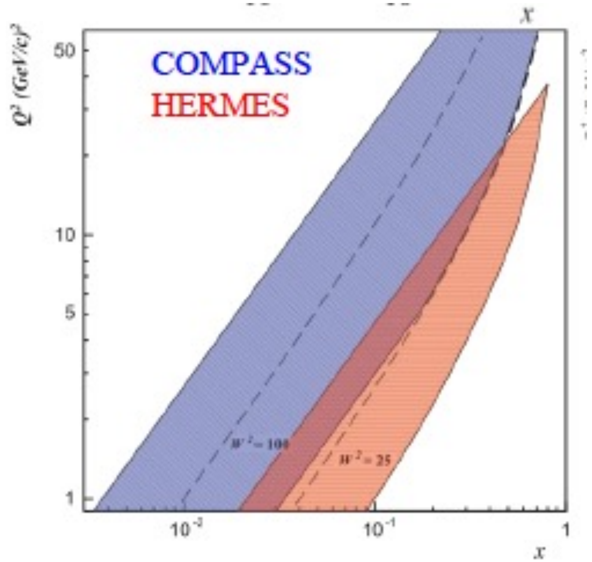
PRL 103 (2009)

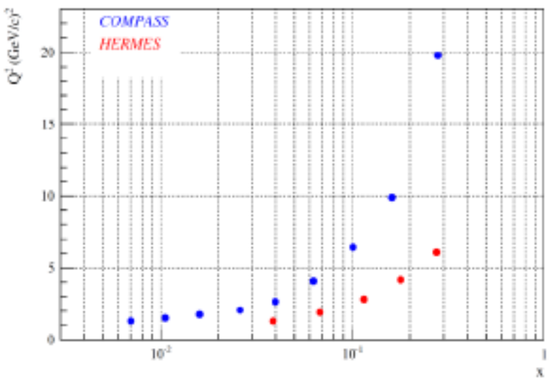


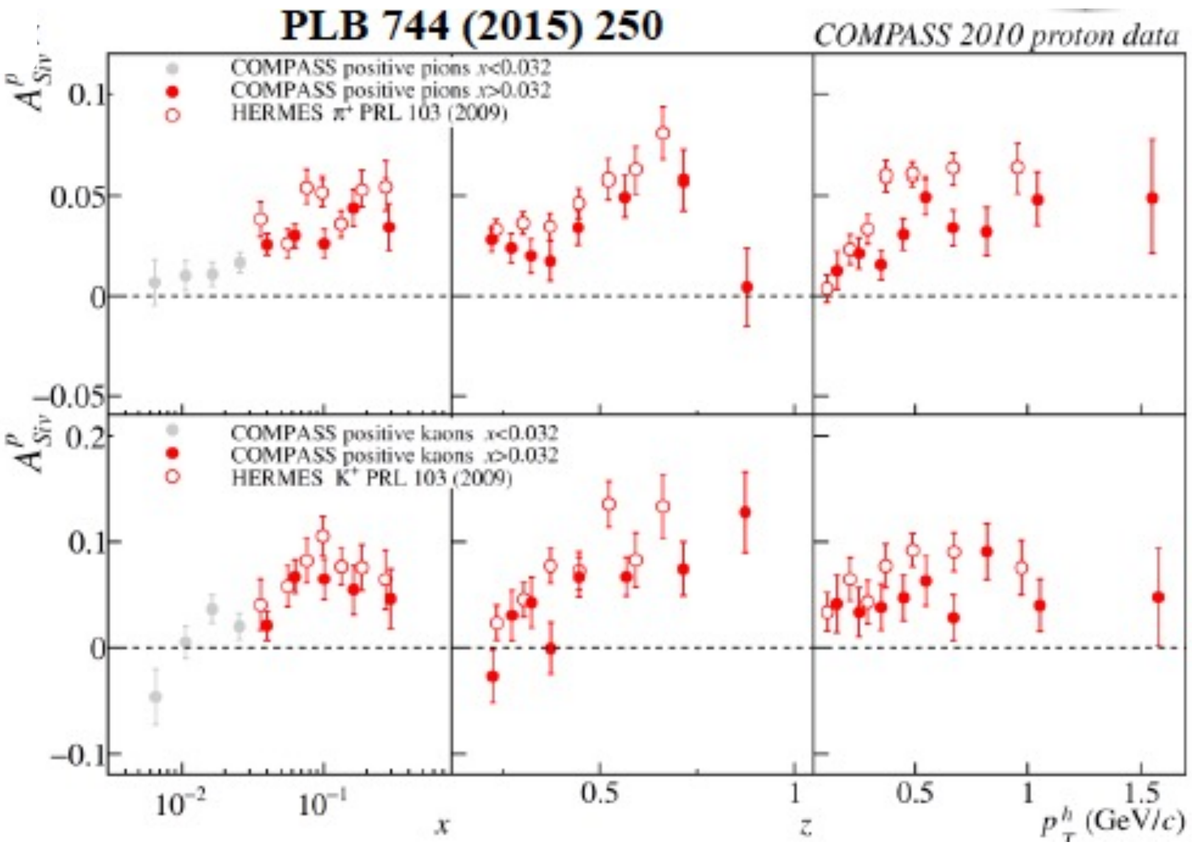


COMPASS ⇐⇒Hermes proton data
COMPASS Sivers is smaller – QCD evolution eff.?

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







Two lessons from COMPASS ⇐⇒ Hermes SIDIS data

- TMDs are flavour-dependent
- QCD evolution plays significant role

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:

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

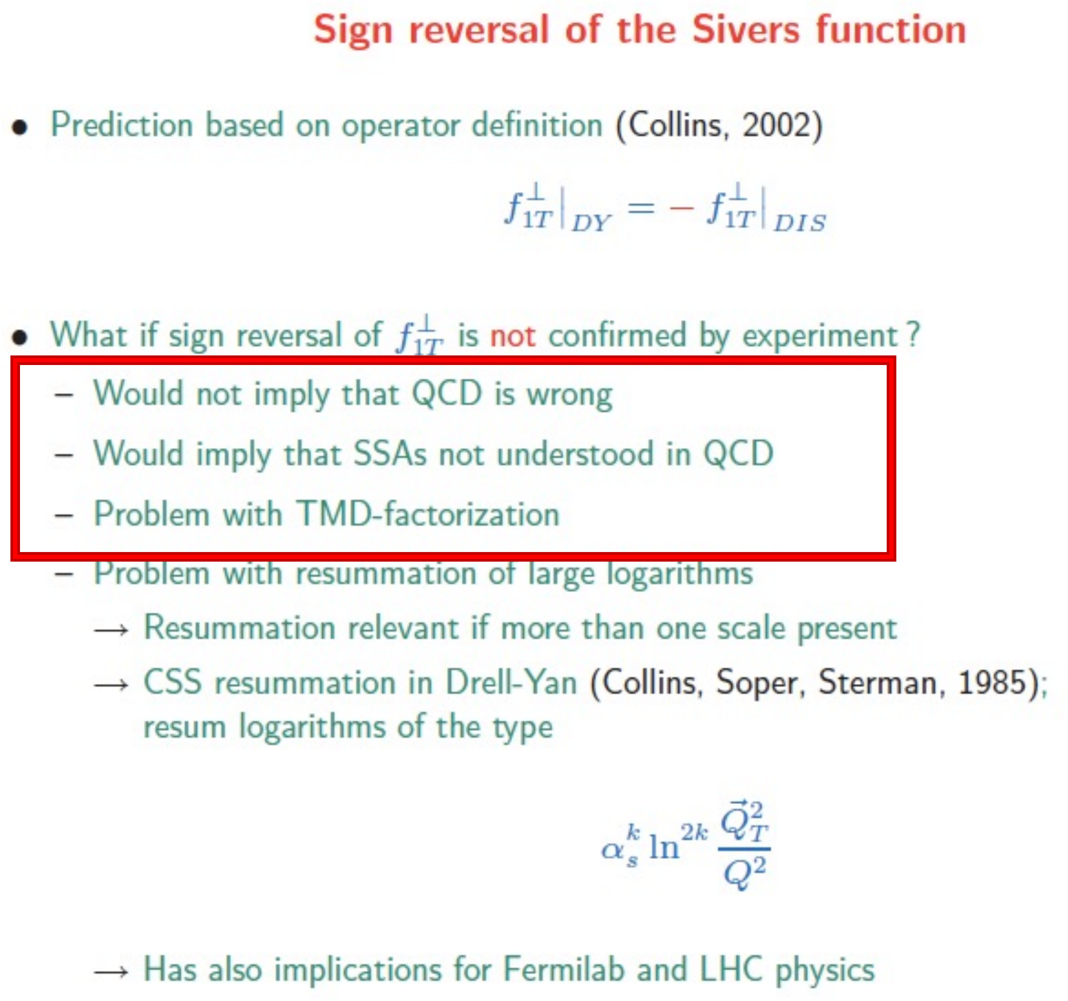
$$\boxed{h_{1}^{\perp}(DY) = -h_{1}^{\perp}(SIDIS)}$$

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

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

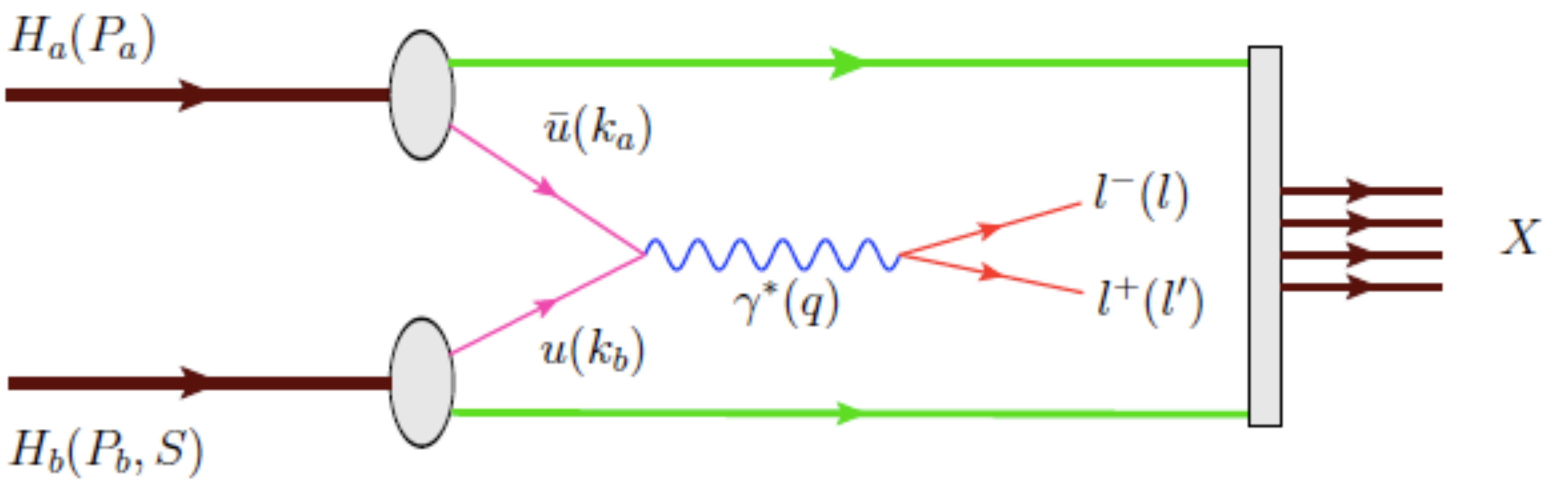
2005 – Anatoly Efremov brings my attention for the first time to this effect (discussed in the famous paper by John Collins *Phys.Lett.B* 536 (2002) 43-48)

COMPASS SIDIS⇔Drell-Yan bridge

Apparatus for Meson and Baryon Experimental Research

Different processes but the same spectrometer, Polarised Target, Analysis methods

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.

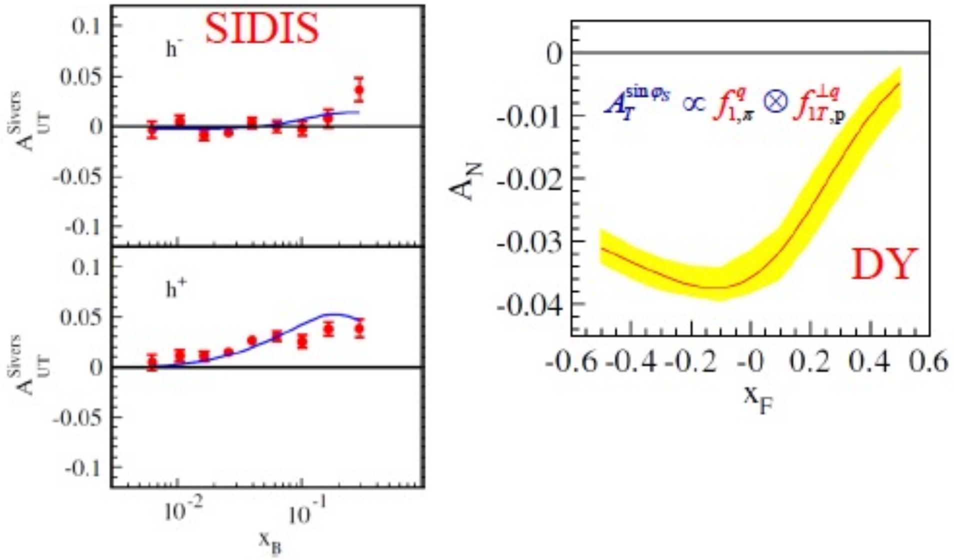
Sivers in SIDIS and Drell-Yan

SIDIS data:

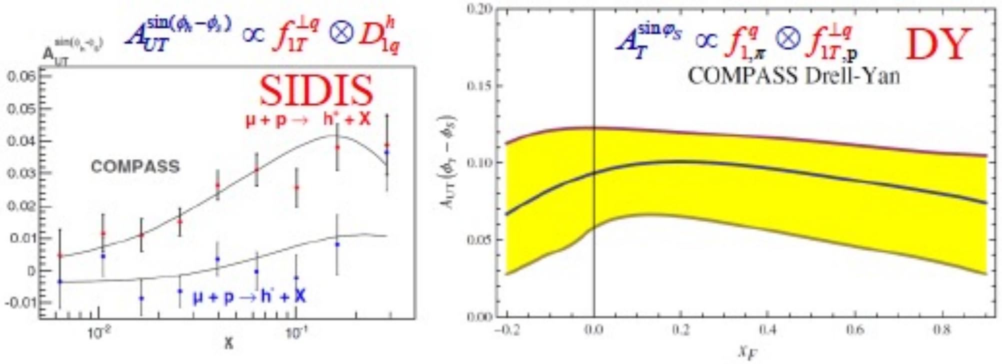
- Global fits of available 1-D SIDIS data
- Different TMD evolution schemes
- Different predictions for Drell-Yan

- 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

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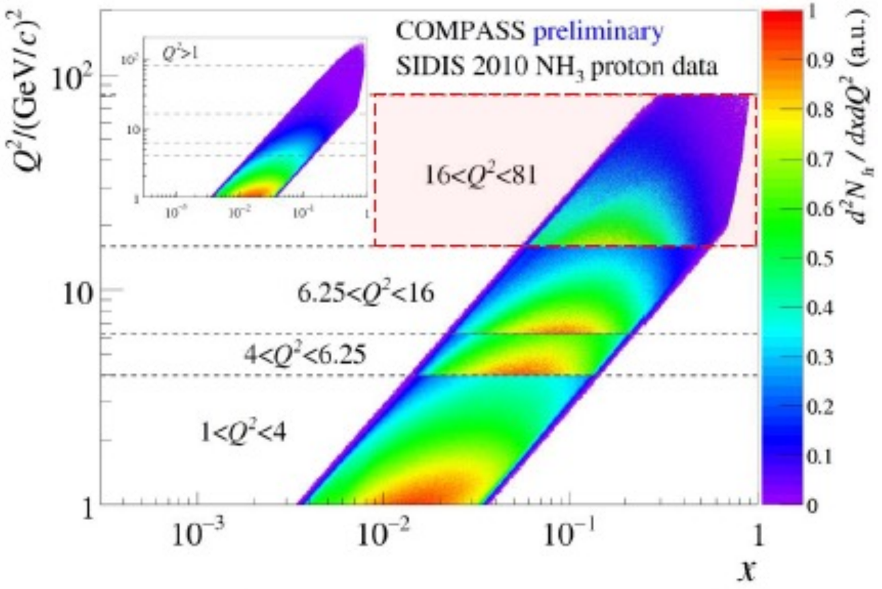
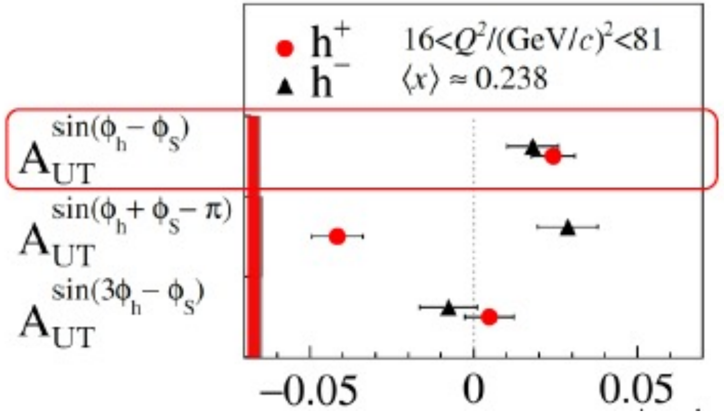
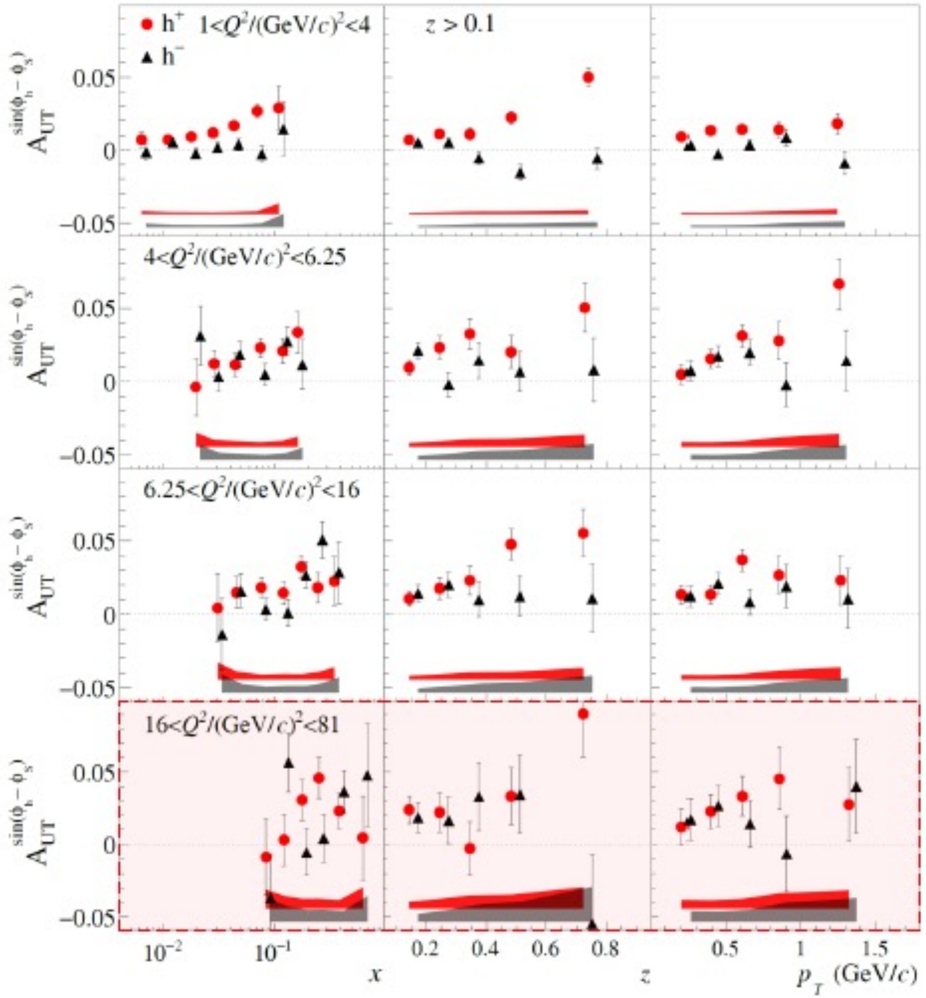
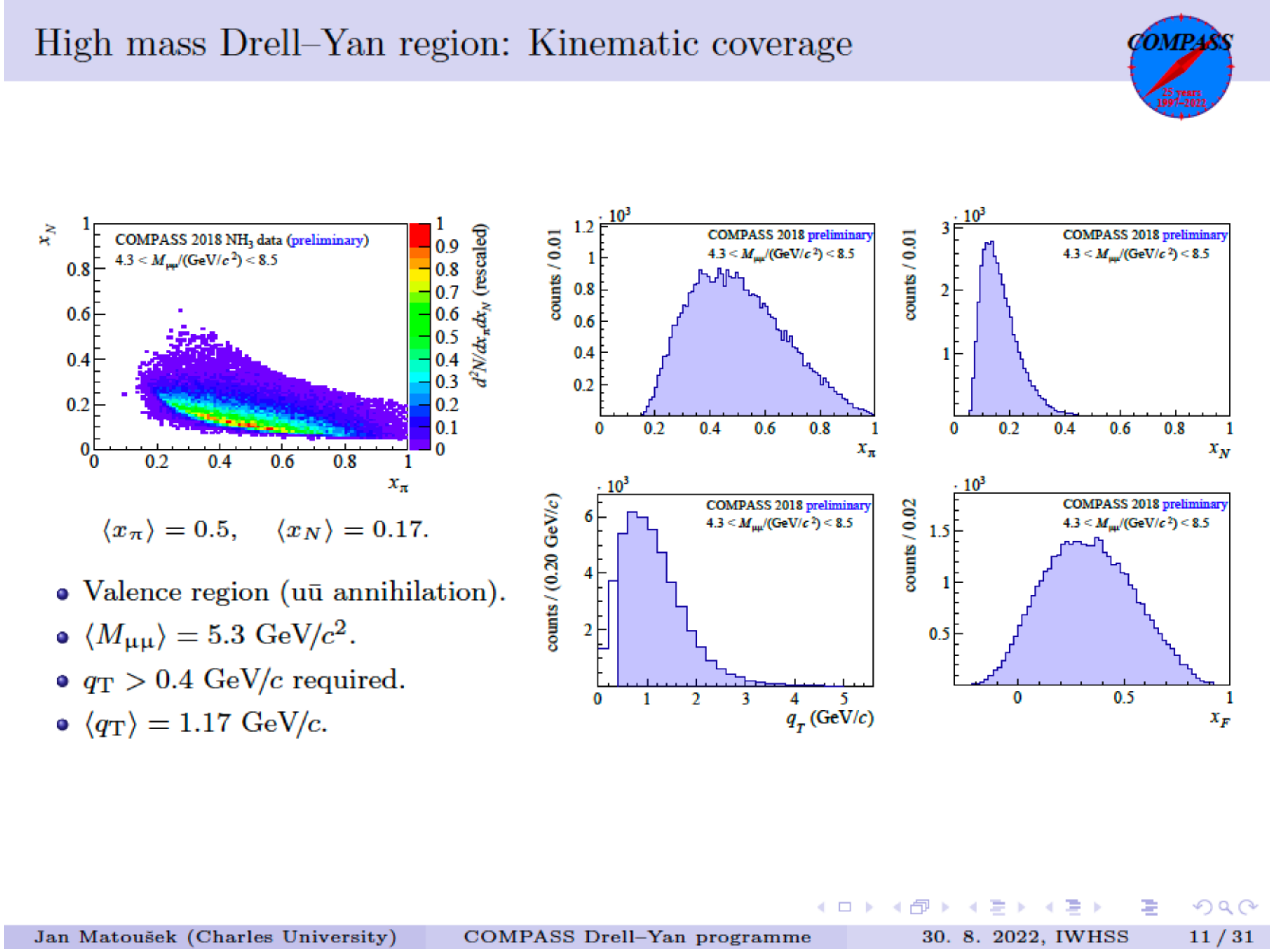




COMPASS PLB 770 (2017) 138



Drell-Yan at COMPASS

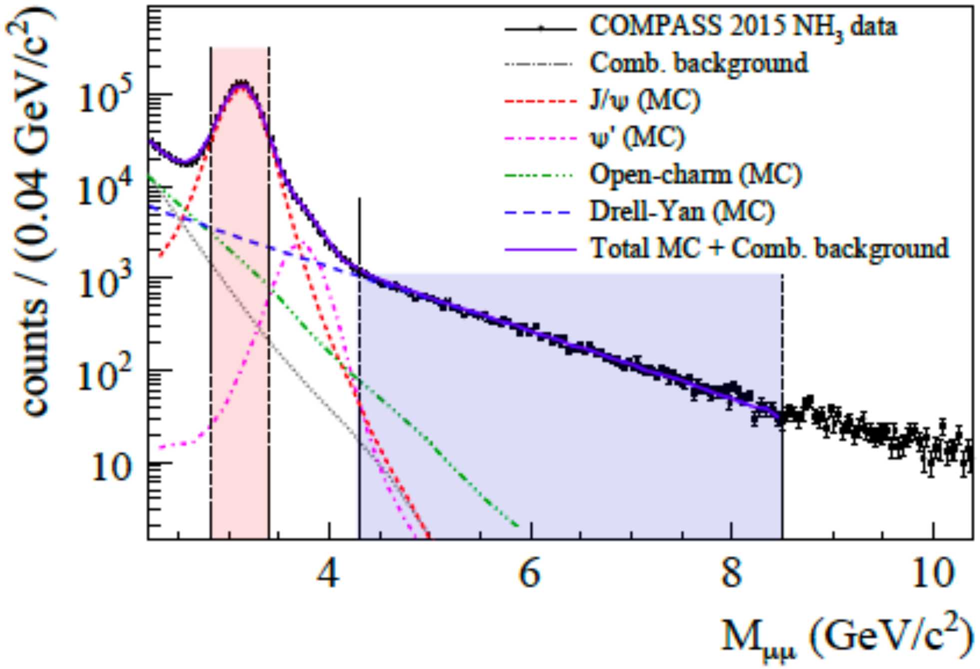


High mass Drell–Yan region: Kinematic coverage

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

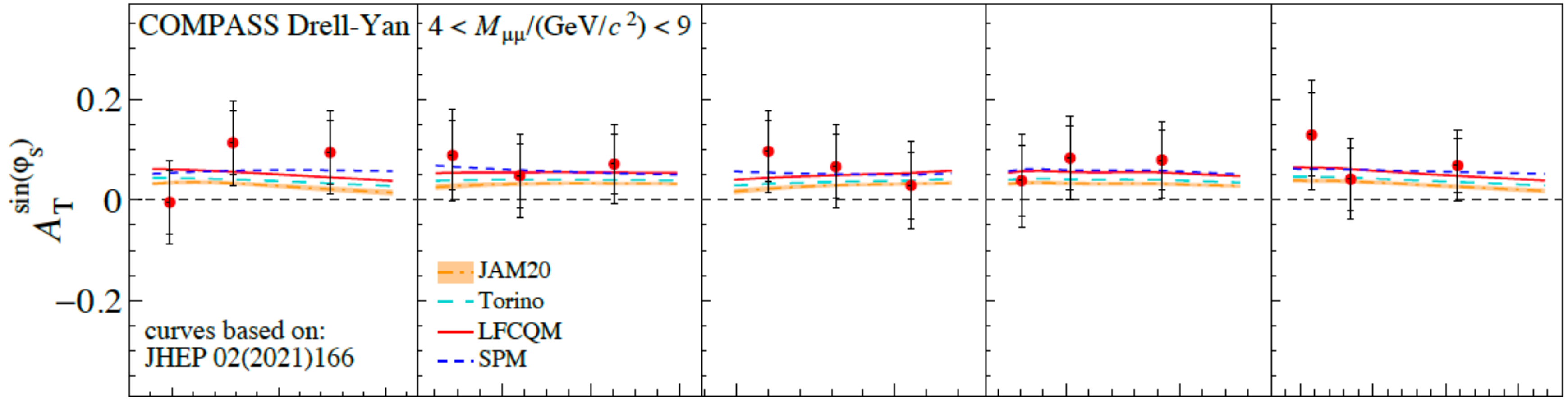
- Valence region ($u\bar{u}$ annihilation).
- $\langle M_{\mu\mu} \rangle = 5.3\ \mathrm{GeV}/c^2$.
- $q_T > 0.4\ \mathrm{GeV}/c$ required.
- $\langle q_T \rangle = 1.17\ \mathrm{GeV}/c$.

Jan Matoušek (Charles University) COMPASS Drell–Yan programme 30. 8. 2022, IWHSS 11 / 31

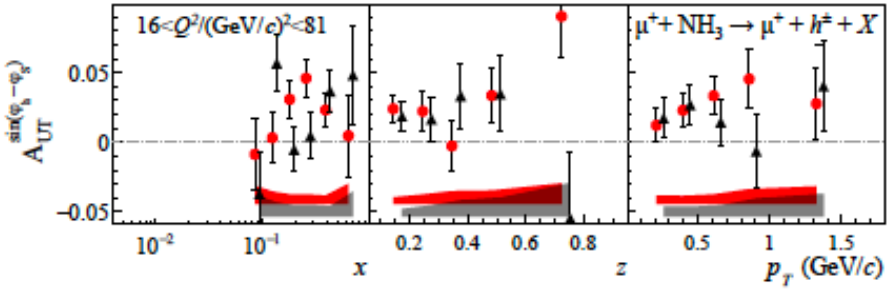


NEW!! Sivers in Drell-Yan

$A_{\mathrm{T}}^{\sin\varphi_{\mathrm{S}}} \propto f_{1,\pi}^{q} \otimes f_{1\mathrm{T},\mathrm{p}}^{\perp q}$ (number density $\otimes$ Sivers function)



curves based on:
JHEP 02(2021)166



SIDIS in the corresponding Q^2 range.

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

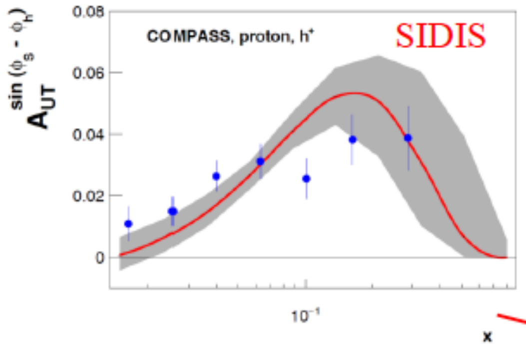
(Sivers $\otimes$ unpolarised FF)

[Phys.Lett.B770 (2017) 138]

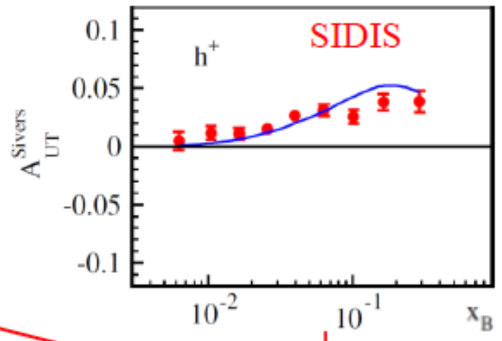
Apparatus for Meson and Baryon
Experimental Research

NEW!! Sivers in Drell-Yan 2015 +2018

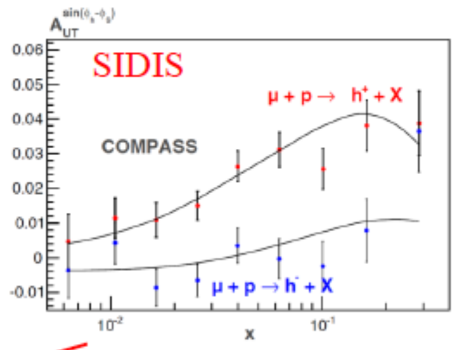
DGLAP (2016)
M. Anselmino et al., **arXiv:1612.06413**

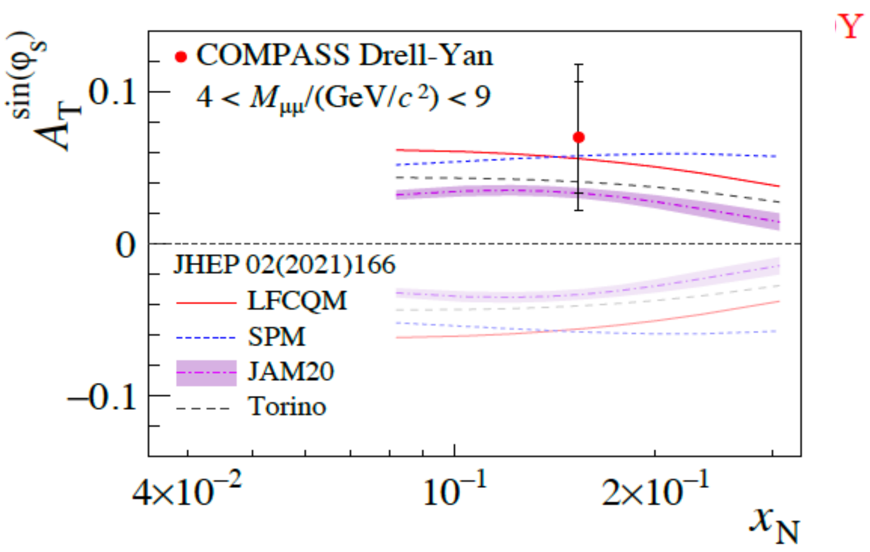


TMD-1 (2014)
M. G. Echevarria et al. **PRD89,074013**



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





AMBER Science Question

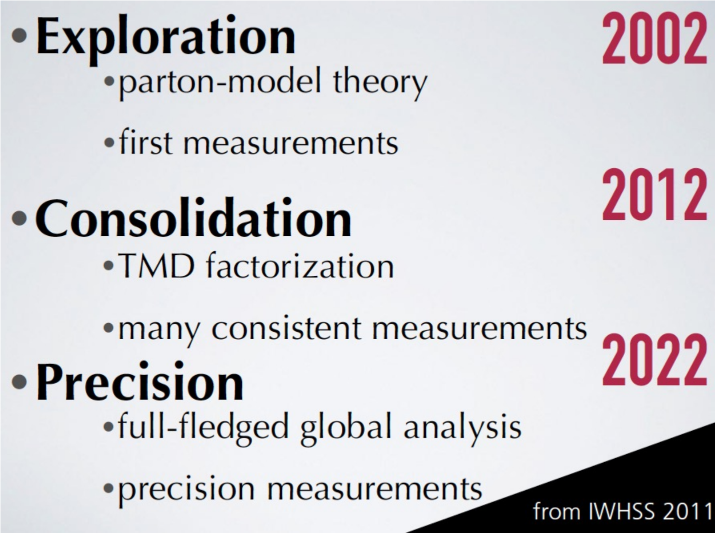
Apparatus for Meson and Baryon
Experimental Research

- COMPASS & Co legacy:
  - Proton spin crisis is over: much more precise data on ΔΣ + ΔG, there is a very clear recipe to fill up the missing part of the proton spin – angular momentum ➔ 3D case ➔ TMDs and GPDs
  - Huge progress on Transversity
- We found ourselves in Precision phase (Alessandro Bacchetta)
- More data to come in the next years from COMPASS, JLab, RHIC and later from high-luminosity facilities like NICA SPD and others

GPS compass

Precision

➔



- **Exploration** 2002
  - parton-model theory
  - first measurements
- **Consolidation** 2012
  - TMD factorization
  - many consistent measurements
- **Precision** 2022
  - full-fledged global analysis
  - precision measurements

from IWHSS 2011

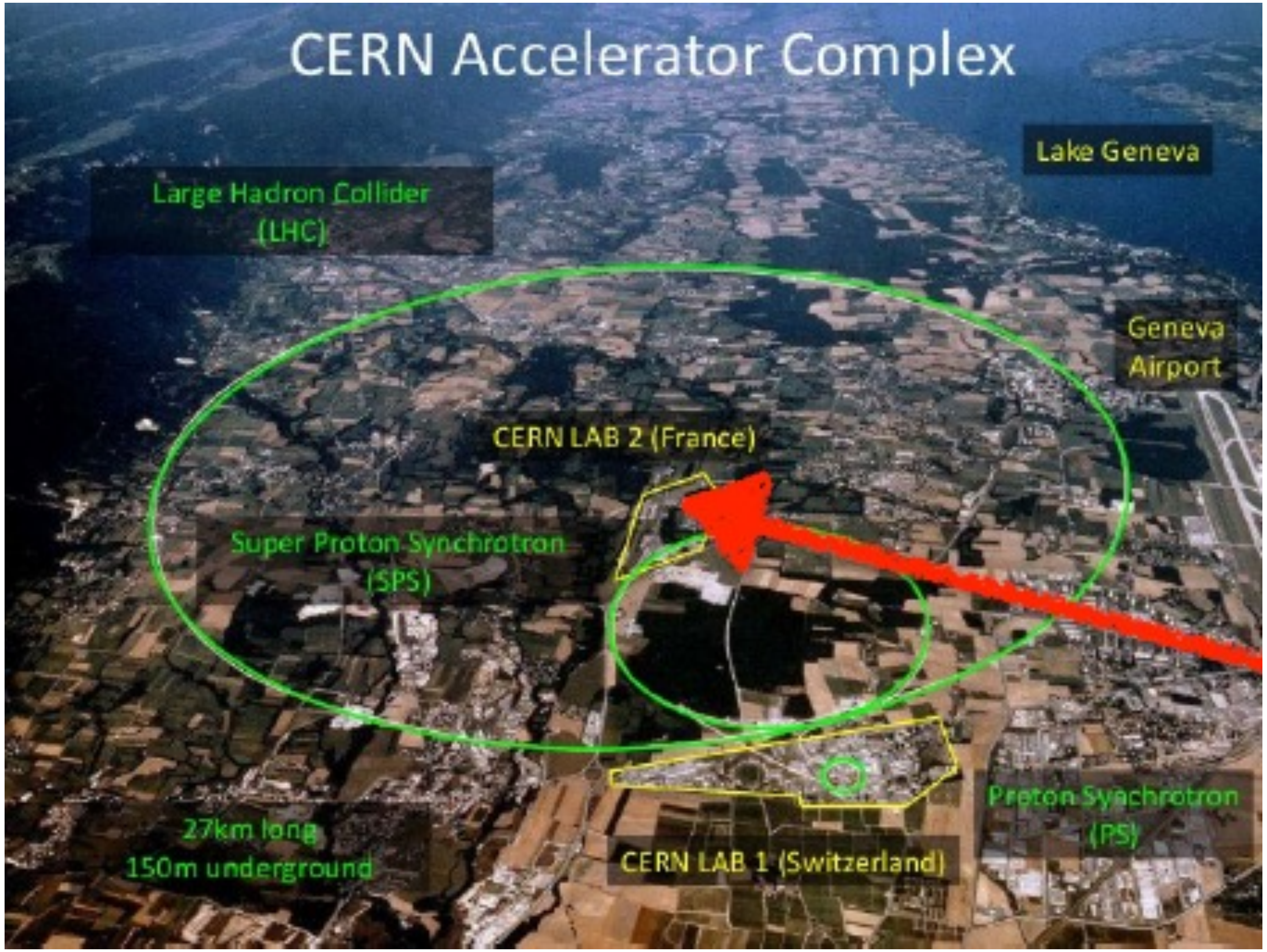
Proton SPIN can not be considered as a main AMBER Science Question because of:

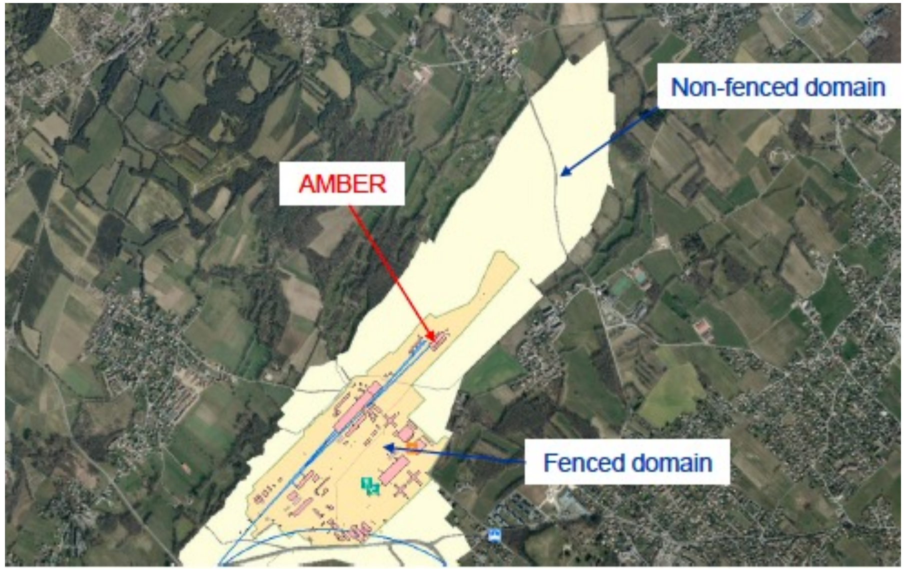
- Proton spin and structure are quite well known nowadays
- A number of high luminosity programs (NICA(SPD), Jlab, EiC, EicC) will provide data in a next years
- Everything what can be done elsewhere but at CERN must be done elsewhere
- Wider physics program to attract new groups

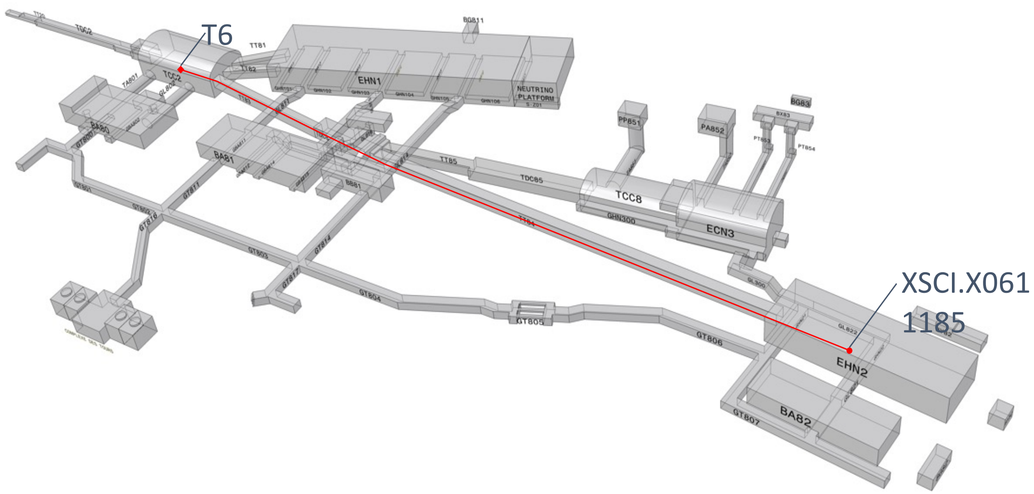
Location, environment and basic featured of the enterprise:

- CERN North Area (aka CERN-Prevessin, Lab 2)
- Fixed target facility using secondary SPS beams extracted on the ground level

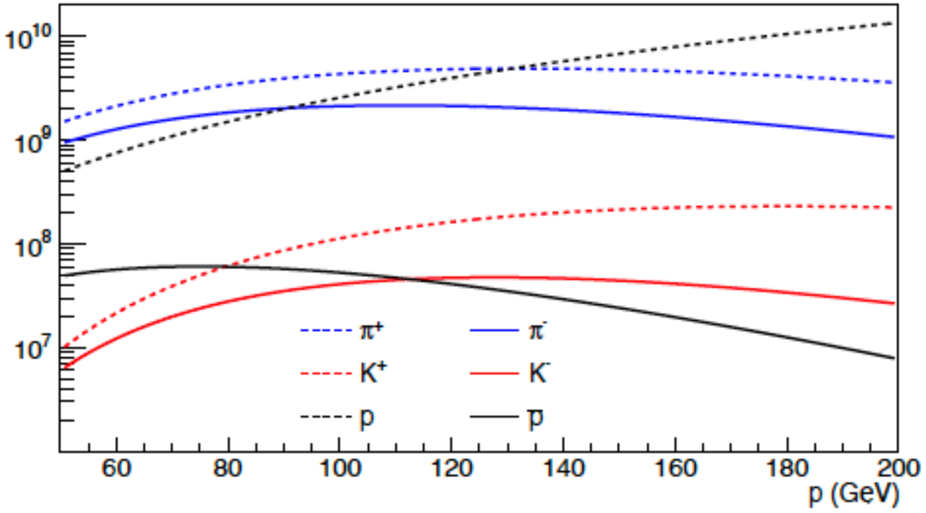
Apparatus for Meson and Baryon Experimental Research

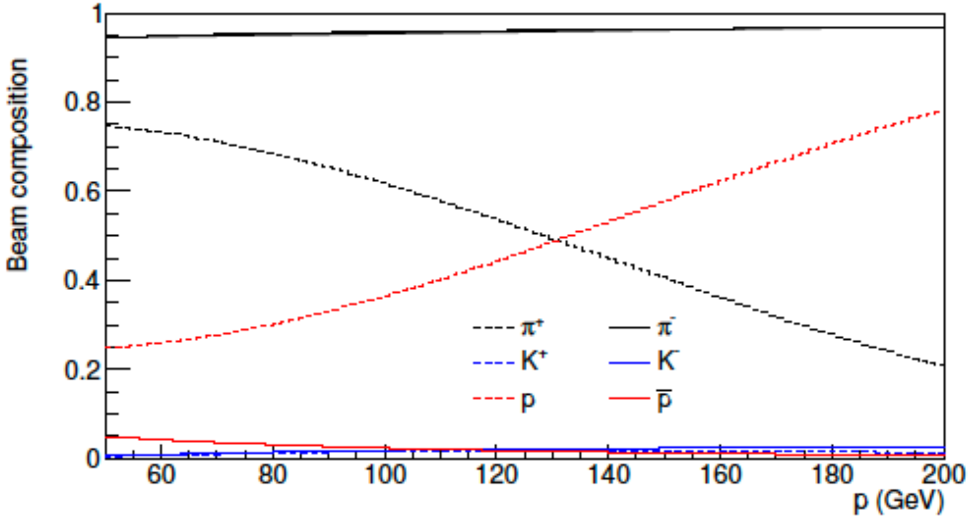






Setting up of the strong physics case for AMBER facility was greatly simplified by uniqueness of the CERN SPS AMBER/EHN2 secondary beams





Basic features of the AMBER/EHN2 secondary beams (CERN SPS 400 GeV primary proton beam):

- Hadron+/- beams, momentum range 50 – 250 GeV, up to 10^9 /sec
- Muon+/- beams, momentum range 50 – 250 Gev, up to $5x10^7$ /sec
- Electron/positron beams 20-60 GeV, up to 10^5 /sec

High energy/High intensity Pion+/- and Kaon+/- beams are UNIQUE to study UNSTABLE Particles Structure.

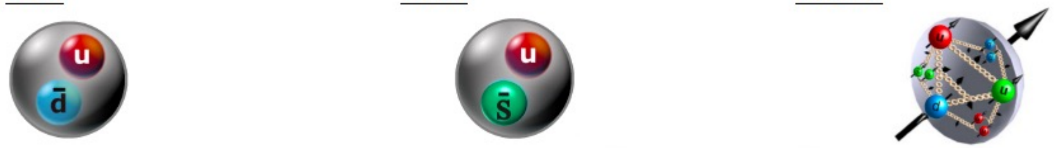
AMBER science questions
Emergence of the Hadron Mass Phenomenon

Taking into account unique meson beam opportunities at EHN2 we Identify AMBER as a key contributor to the study Of the Emergence of the Hadron Mass Phenomenon

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



Pion	Kaon	Proton
$M_\pi \sim 140$MeV	$M_K \sim 490$MeV	$M_p \sim 940$MeV
Spin 0	Spin 0	Spin 1/2
2 light valence quarks	1 light and 1 "heavy" valence quarks	3 light valence quarks

Higgs generated masses of the valence quarks:

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

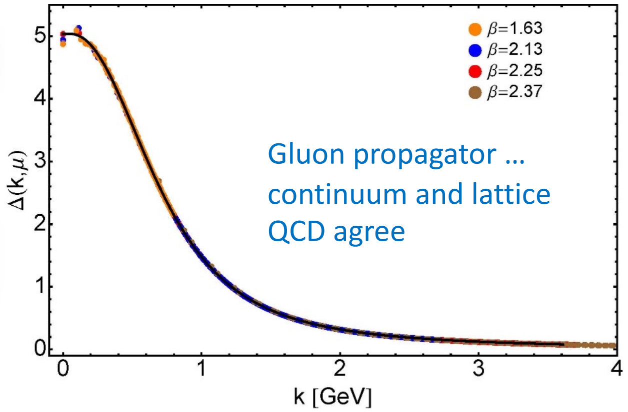
As Higgs mechanism produces a few percent of visible mass, Where does the rest comes from?

EHM phenomenon

What are the underlying mechanisms?

Apparatus for Meson and Baryon
Experimental Research

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

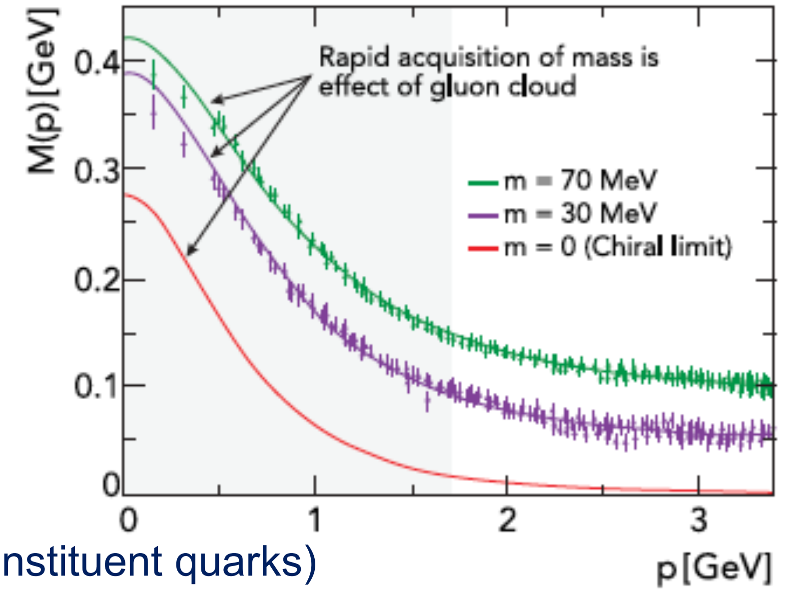


Gluon propagator … continuum and lattice QCD agree

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

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



Rapid acquisition of mass is effect of gluon cloud

(Constituent quarks)

Dressed-quark mass function M(p)

<u>In order to "proof" that QCD underlies the EHM phenomenon we have to compare Lattice and Continuum QCD calculations with experimental data by measuring:</u>

1. <u>Quark and Gluon PDFs and PDAs of the pion/kaon/proton</u>
2. <u>Hadron's radii (confinement)</u>
3. <u>Excited-meson spectra</u>

EHM phenomenon
Is it enough to study the proton to understand SM?

Apparatus for Meson and Baryon Experimental Research

The answer is obviously NOT (SM paradigm):

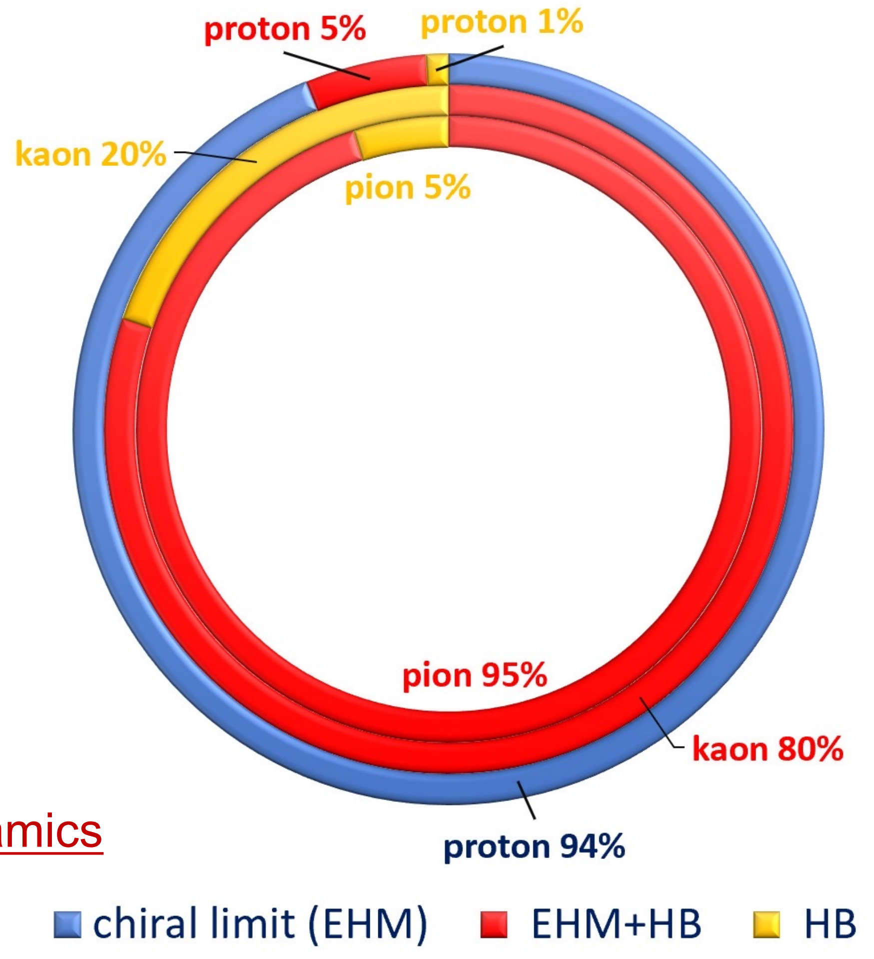
- proton is described by QCD … 3 valence quarks
- pion is also described by QCD … 1 valence quark and 1 valence antiquark
- expect $m_p \approx 1.5 \times m_\pi$ … but, instead $m_p \approx 7 \times m_\pi$

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

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

Mass Budgets



AMBER physics program

Apparatus for Meson and Baryon
Experimental Research

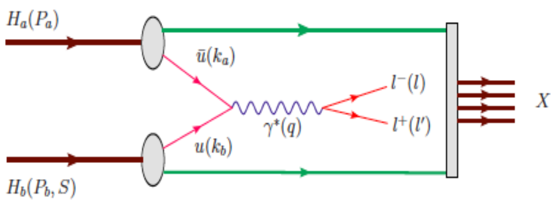
Questions to be answered:

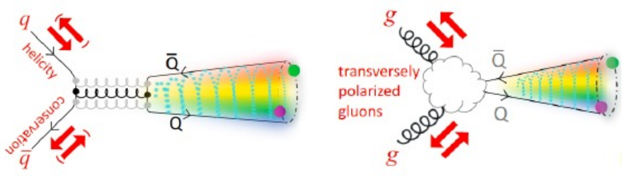
- Mass difference pion/proton/kaon
- Mass generation mechanism (emergent mass .vs. Higgs)
- Internal quark-gluon structure and dynamics, especially important pion/kaon/proton striking differences

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

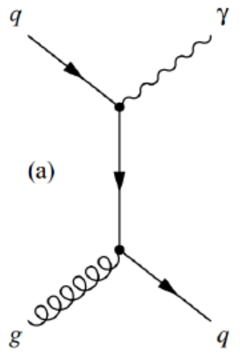
Methods:

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

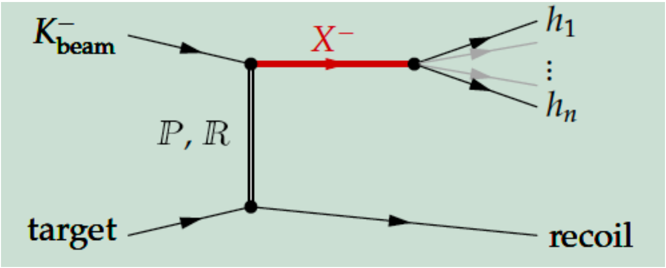


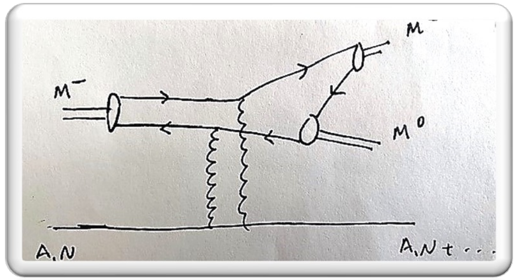


Prompt Photon Production

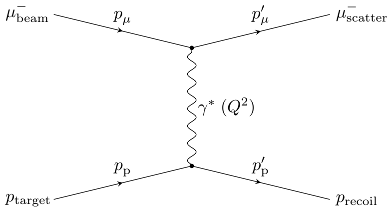


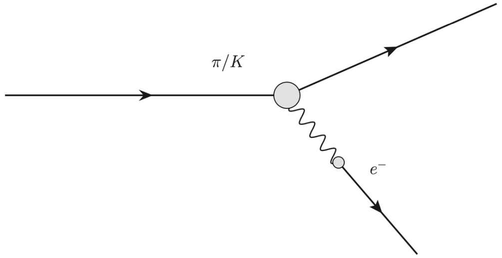
Diffractive scattering





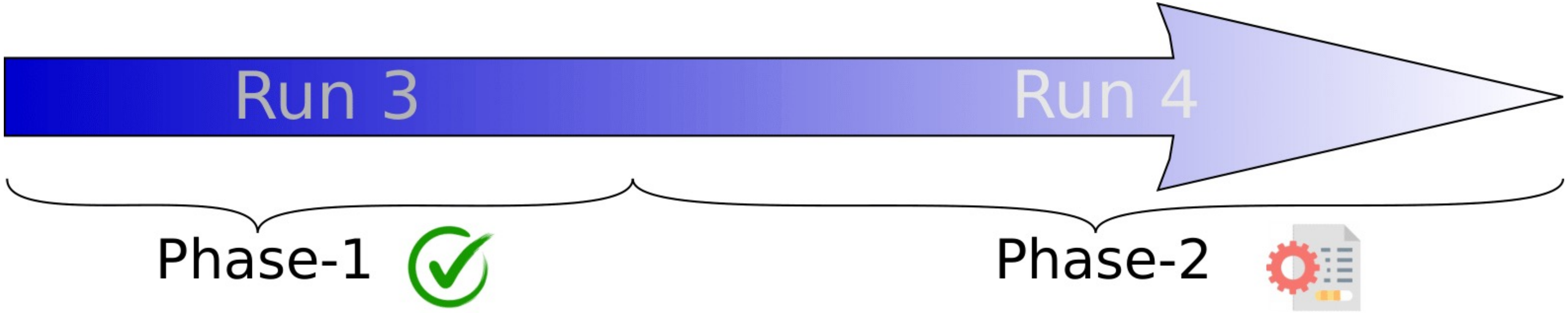
Elastic scattering





General AMBER timeline

Apparatus for Meson and Baryon Experimental Research



Conventional and Improved hadron beams, conventional muon beam

Phase-1 ✓

Proton Radius Measurement
Antimatter production cross section
Pion and kaon structure (PDFs) via DY and J/Psi production

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

Improved hadron beams, conventional muon beam

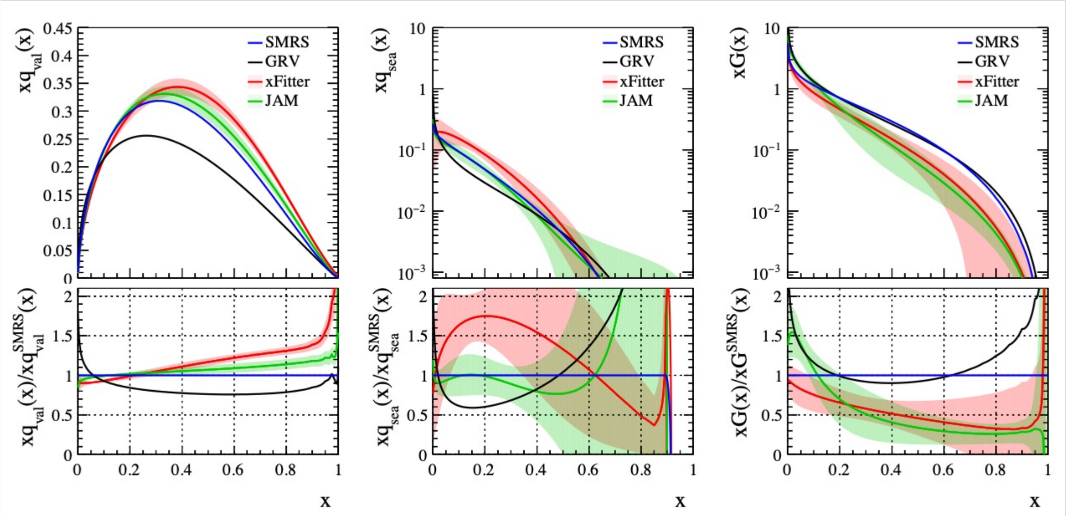
Phase-2

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

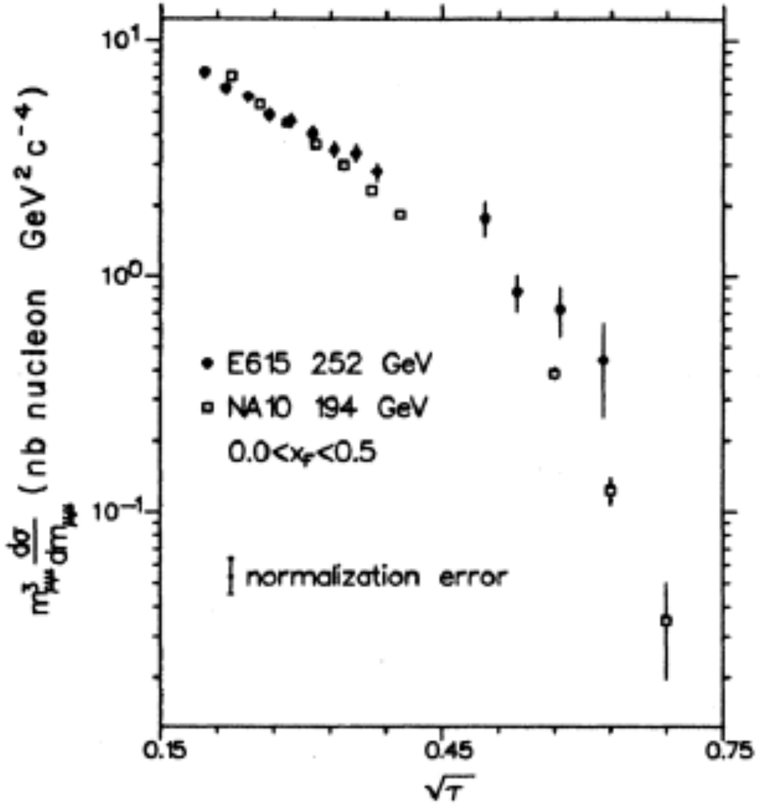
Phase-2 Proposal submission in the beginning of 2025

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

valence sea gluons



From: E615, PRD 1989

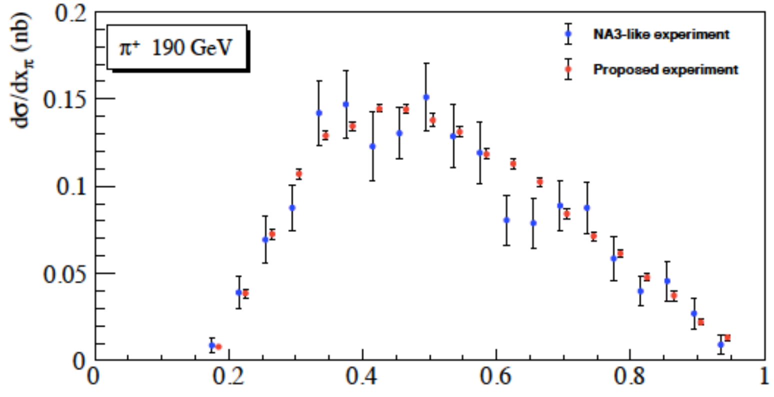


Pion structure status:

- 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

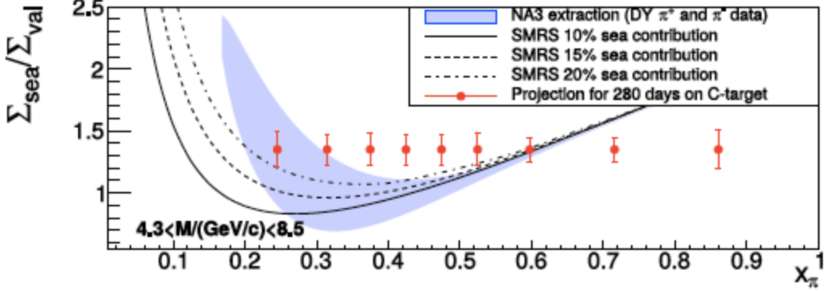
Apparatus for Meson and Baryon Experimental Research

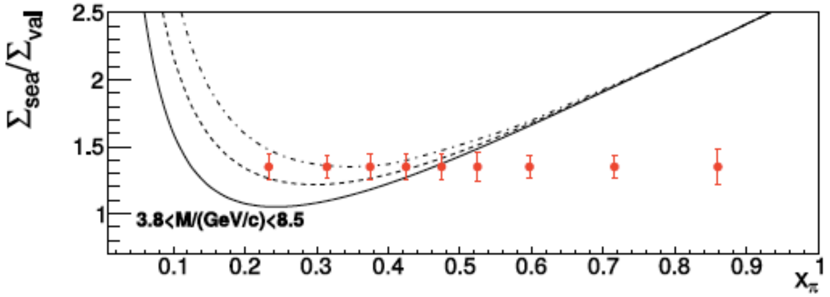


Pion structure in pion induced DY
Expected accuracy as compared to NA3

Studying of the di-muon angular distributions (λ, μ, υ) provides a direct input to the EHM

- $\Sigma_V = \sigma^{\pi^- C} - \sigma^{\pi^+ C}$: 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 data taking
  - π^+ to π^- 3:1 time sharing
  - 190 GeV beams on Carbon target ($1.9\lambda^{\pi}_{int}$)
  - Improvement of shielding to double the intensity is under investigation





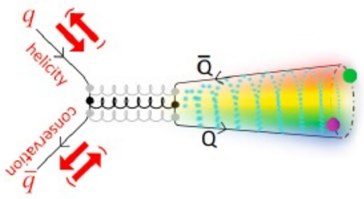
Experiment	Target type	Beam energy (GeV)	Beam type	Beam intensity (part/sec)	DY mass (GeV/c^2)	DY events
E615	20 cm W	252	π^+ π^-	17.6×10^7 18.6×10^7	4.05 – 8.55	5000 30000
NA3	30 cm H_2	200	π^+ π^-	2.0×10^7 3.0×10^7	4.1 – 8.5	40 121
	6 cm Pt	200	π^+ π^-	2.0×10^7 3.0×10^7	4.2 – 8.5	1767 4961
NA10	120 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

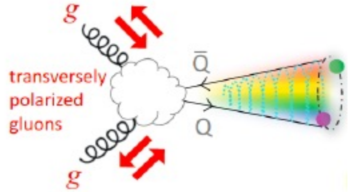
Isoscalar target + *Both positive and negative beams* + *High statistics*

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

Pion induced J/ψ at AMBER

Apparatus for Meson and Baryon Experimental Research



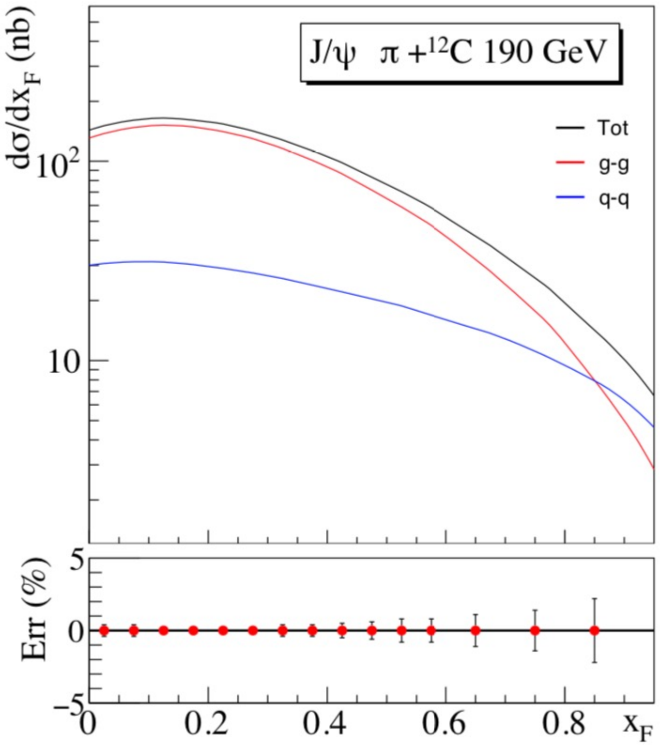


Collected simultaneously with DY data, with large counting rates

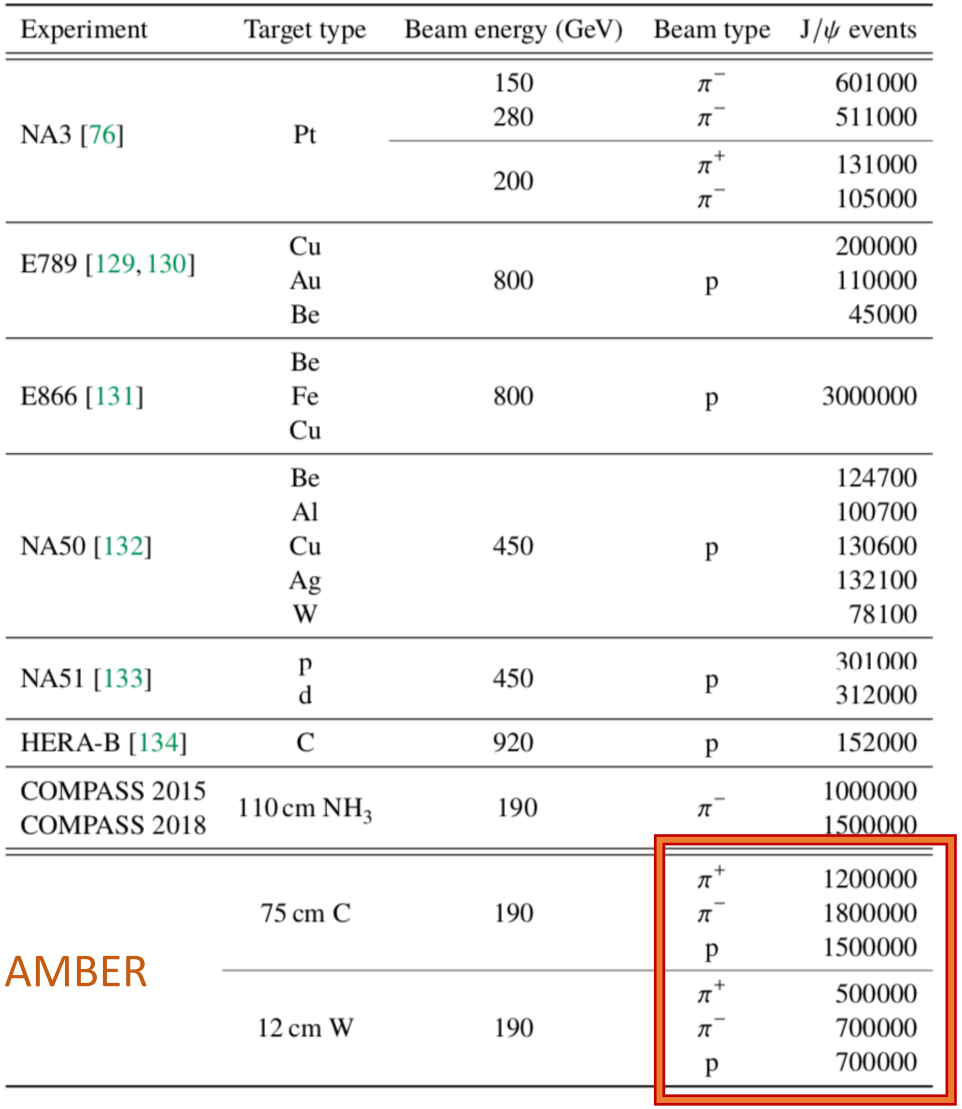
Physics objectives:

- 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.



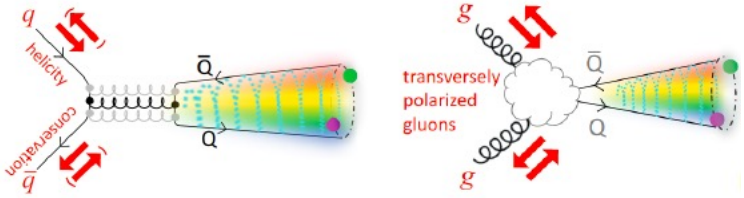
Improved CEM, CT10 + GRS99 global fit for proton/pion



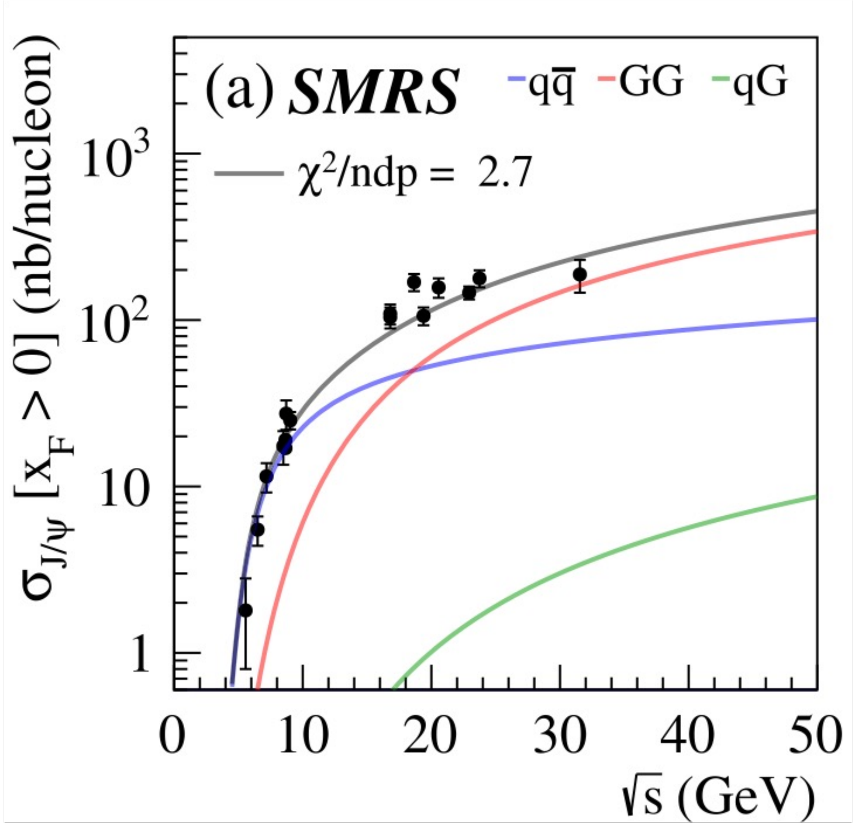
Experiment	Target type	Beam energy (GeV)	Beam type	J/ψ events
NA3 [76]	Pt	150	π^-	601000
		280	π^-	511000
		200	π^+	131000
			π^-	105000
E789 [129, 130]	Cu Au Be	800	p	200000 110000 45000
E866 [131]	Be Fe Cu	800	p	3000000
NA50 [132]	Be Al Cu Ag W	450	p	124700 100700 130600 132100 78100
NA51 [133]	p d	450	p	301000 312000
HERA-B [134]	C	920	p	152000
COMPASS 2015 COMPASS 2018	110 cm NH$_3$	190	π^-	1000000 1500000
AMBER	75 cm C	190	π^+	1200000
			π^-	1800000
			p	1500000
	12 cm W	190	π^+	500000
			π^-	700000
			p	700000

Pion induced J/ψ at AMBER

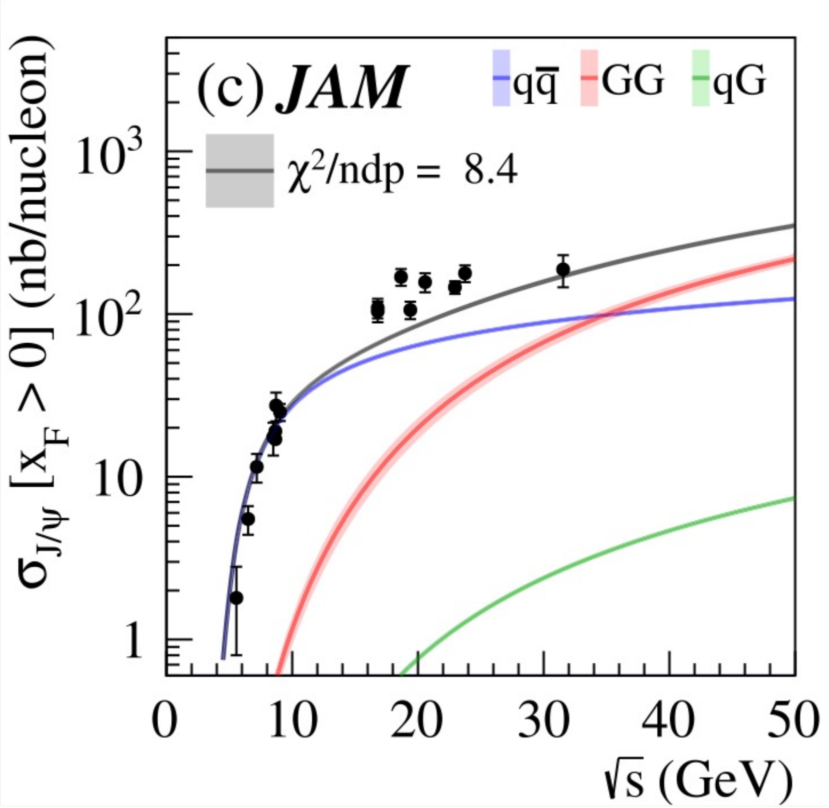
Apparatus for Meson and Baryon
Experimental Research



Model dependence of the J/ψ production cross section



Relative contribution
From quarks and gluons
Very uncertain

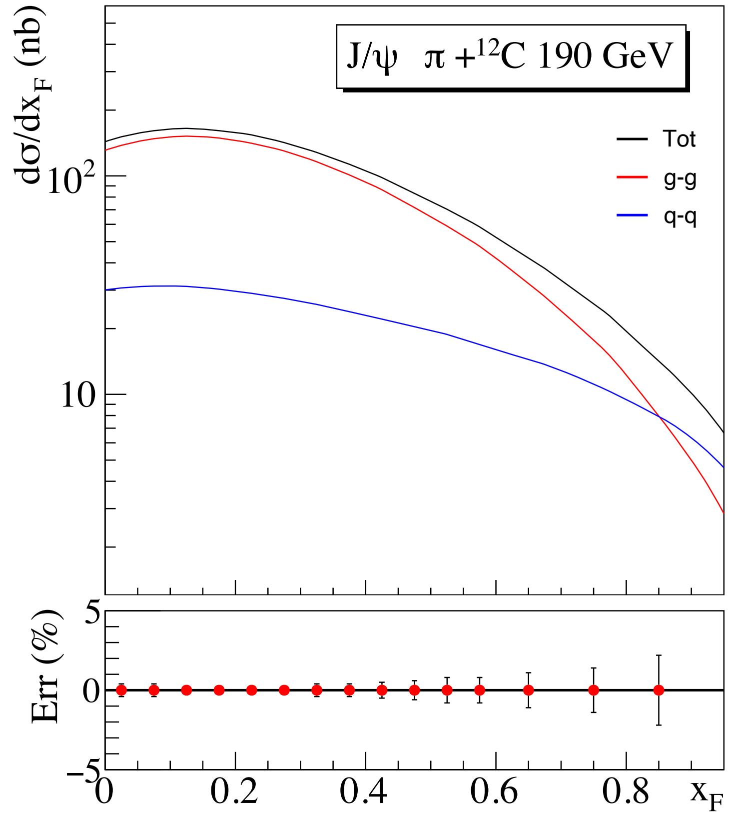


SMRS vs JAM fits: strong dependence on the PDFs

Gluon distribution in the pion through J/ψ production

Apparatus for Meson and Baryon Experimental Research

Cross section (ICEM)

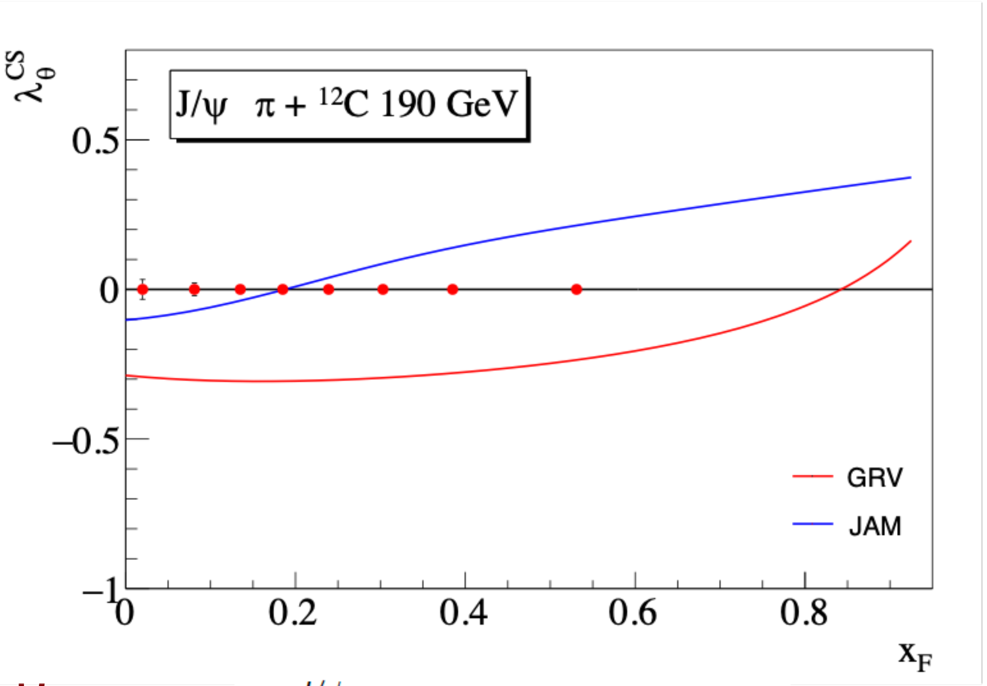


Both x_F-distribution and polarization depend on the relative amount of of quark/gluon content

Huge statistics: π^+, π^-, p:
1.2 – 1.8 M J/ψ and
20 – 30 k ψ'

Polarization (ICEM)

CHEUNG AND VOGT, PRIV. COMM., 2020



$$\frac{d\sigma^{J/\psi}}{d\Omega} \sim 1 + \lambda_\theta^{CS} cos^2(\theta)$$

- From $q\bar{q} \to J_z=\pm1 \to \lambda = -1$
- From $gg \to J_z=0 \to \lambda = 1$

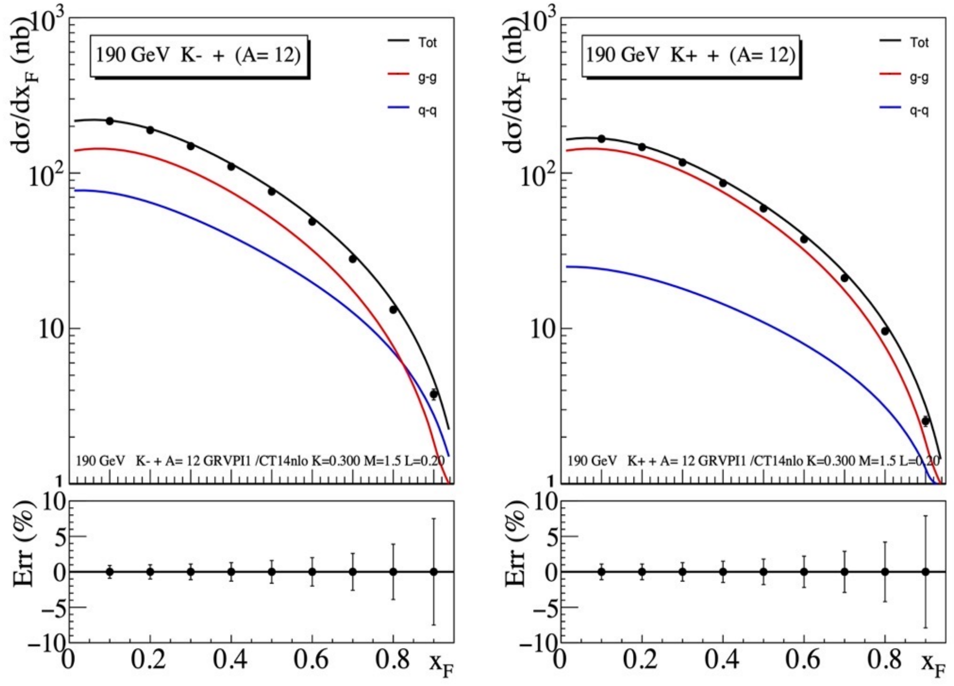
AMBER (kaon induced Drell-Yan and J/Psi production)

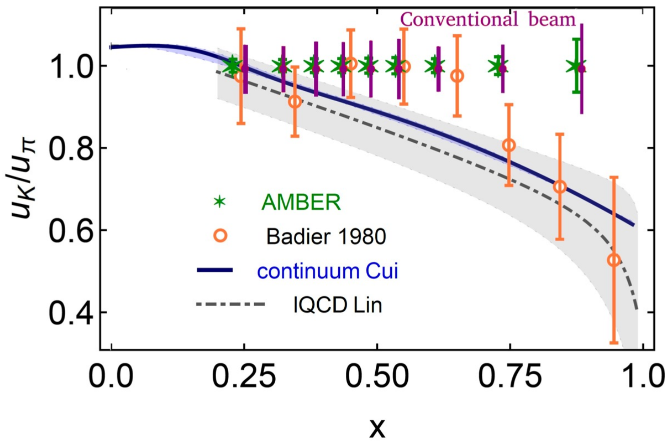
Extremely important to compare the gluon content of kaon and pion (EHM)

- 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^+

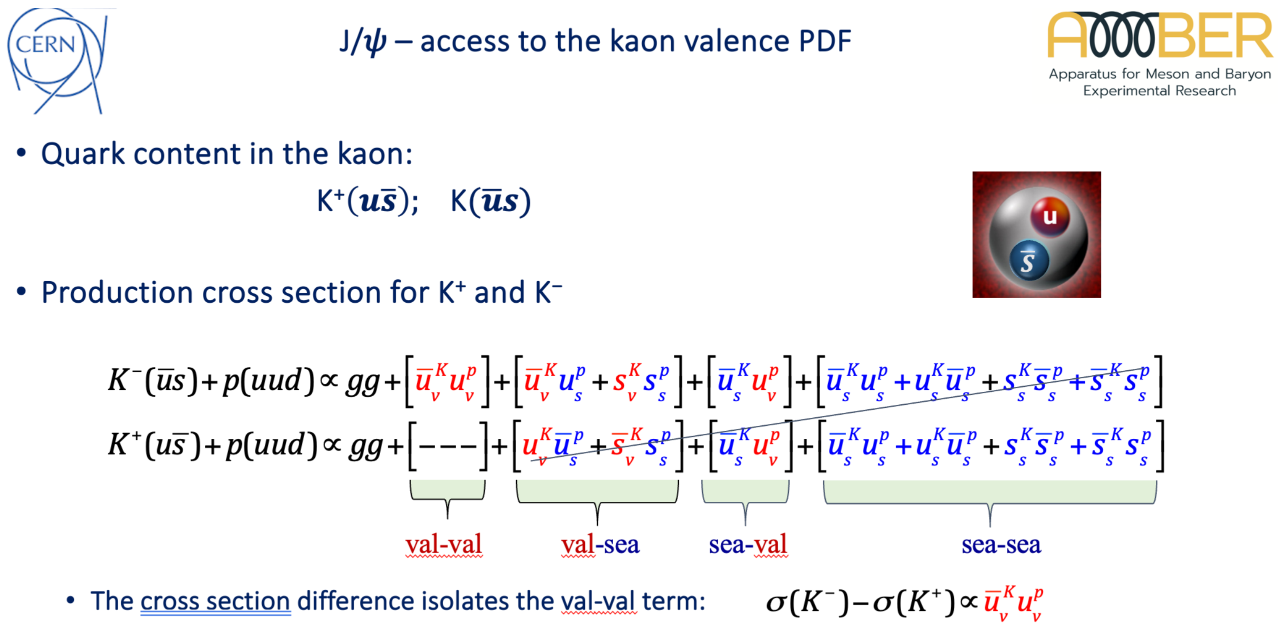




Projected statistical errors after 280 days of running, compared to NA3 stat. errors

K⁻ and K⁺ -induced J/ψ cross sections direct access to the kaon valence PDF

AMBER
Apparatus for Meson and Baryon Experimental Research



J/ψ – access to the kaon valence PDF

AMBER
Apparatus for Meson and Baryon Experimental Research

- Quark content in the kaon:

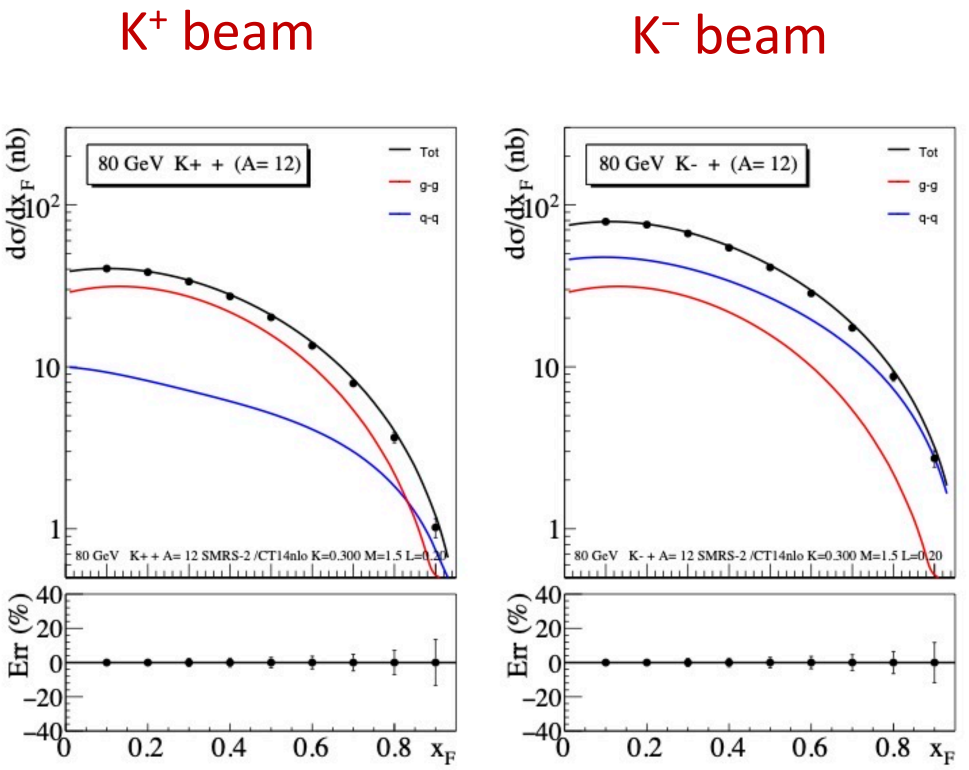
  K⁺($\boldsymbol{u\bar{s}}$); K($\boldsymbol{\bar{u}s}$)

- Production cross section for K⁺ and K⁻

$$K^{-}(\bar{u}s)+p(uud)\propto gg+\left[\bar{u}_v^K u_v^p\right]+\left[\bar{u}_v^K u_s^p+s_v^K s_s^p\right]+\left[\bar{u}_s^K u_v^p\right]+\left[\bar{u}_s^K u_s^p+u_s^K\bar{u}_s^p+s_s^K\bar{s}_s^p+\bar{s}_s^K s_s^p\right]$$

$$K^{+}(u\bar{s})+p(uud)\propto gg+\underbrace{\left[---\right]}_{\text{val-val}}+\underbrace{\left[u_v^K\bar{u}_s^p+\bar{s}_v^K s_s^p\right]}_{\text{val-sea}}+\underbrace{\left[\bar{u}_s^K u_v^p\right]}_{\text{sea-val}}+\underbrace{\left[\bar{u}_s^K u_s^p+u_s^K\bar{u}_s^p+s_s^K\bar{s}_s^p+\bar{s}_s^K s_s^p\right]}_{\text{sea-sea}}$$

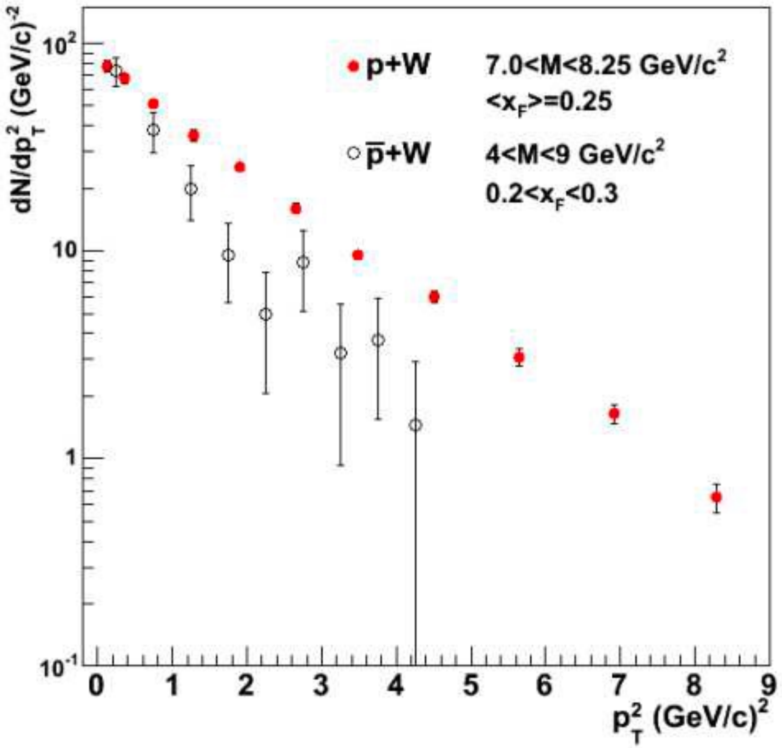
- The cross section difference isolates the val-val term: $\sigma(K^{-})-\sigma(K^{+})\propto\bar{u}_v^K u_v^p$



K⁺ beam

K⁻ beam

Antiproton induced Drell-Yan
(new idea by Guissen colleague – Stefan Diehl)



Study the difference between valence and sea quark TMD PDFs

Chiral quark soliton models suggest that the transverse momentum width of sea quarks in a proton may be as much as three times broader than that of the valence distribution

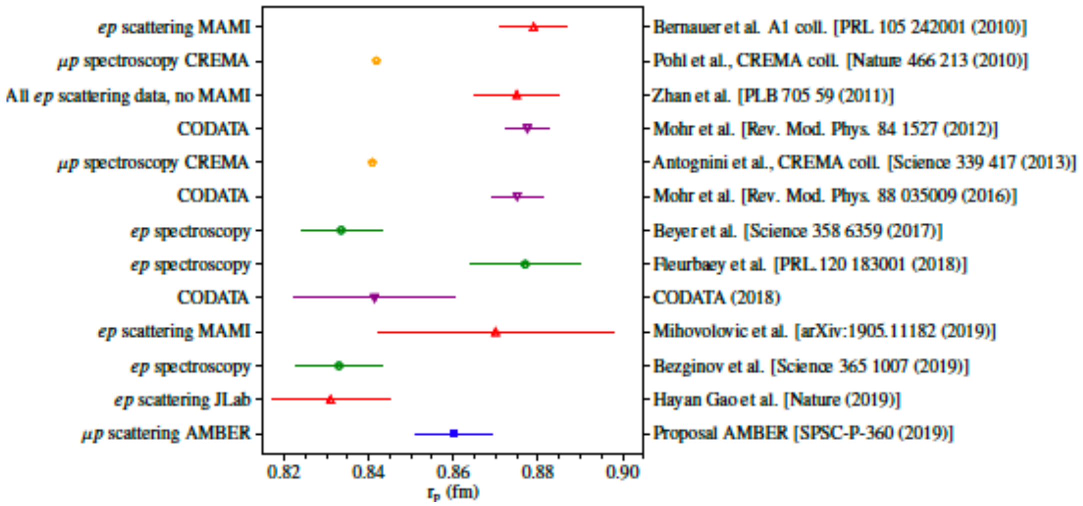
C. A. Aidala et al., Phys. Rev. D 89, 094002 (2014)

W. Oliver, H. R. Gustafson, L. W. Jones, M. Longo, T. Roberts, et al., AIP Conf.Proc. 45, 93 (1978).
E. Anassontzis, S. Katsanevas, E. Kiritsis, P. Kostarakis, C. Kourkoumelis, et al., Phys.Rev. D38, 1377 (1988).

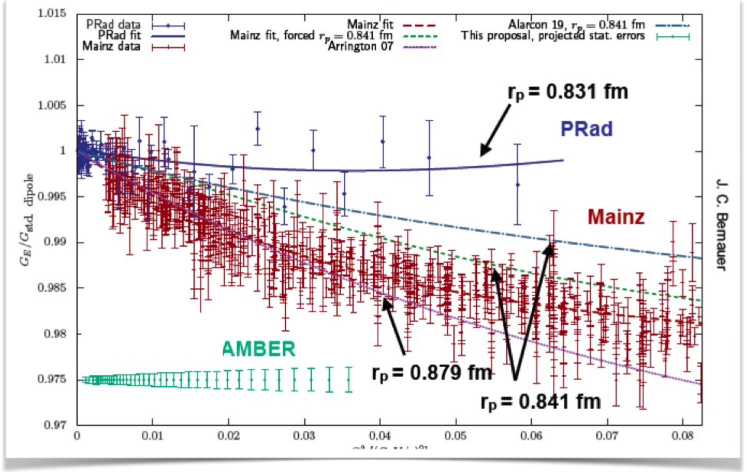
➔ *Compare transverse momentum distributions for pA and pbarA DY collisions*
　➔*Use exactly the same beam energy + same x1, x2 and Q.*
　　pA case: (quark-in-proton) X (antiquark-in-A) TMD PDFs
　　pbarA case: (antiquark-in-antiproton) X (quark-in-A) TMD PDFs
➔ *Difference pf PT distributions probes difference between valence and sea quarks*

Proton Radius Measurement at AMBER (hadron structure ➔ confinement ➔ EHM)

Apparatus for Meson and Baryon Experimental Research



	ep	μp
Spectroscopy	New measurements with - lower systematics - new transitions	✓
Scattering	New measurements with - lower systematics - reaching lower Q² ProRAD, ULQ2, ISR @ MESA, PRad	No data yet. MUSE at PSI coming soon AMBER



statistical precision of the proposed measurement, down to $Q^2 = 0{,}001\ \mathrm{GeV}^2/c^2$, 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)

Apparatus for Meson and Baryon Experimental Research

Proton Radius Experiment at Jefferson Lab

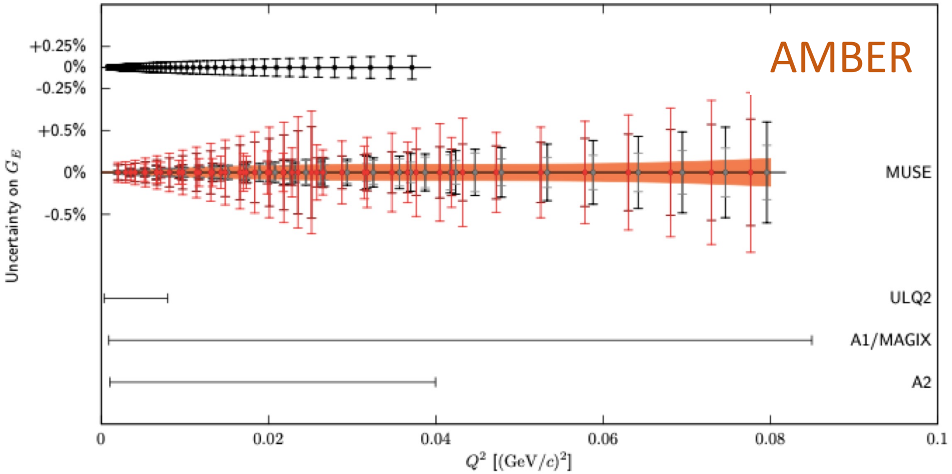
- A number of experiments is on the way in different laboratories
- There is a synergy between PRES at MAMI (E_e = 720 *MeV*) and AMBER ($E\mu = 100\ GeV$):
  - The same type of active target (hydrogen filled TPC) will be used for both experiment
  - The same Q^2 range will be covered (10^{-3} - $4x10^{-2}$ 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).

MESA Mainz Energy-recovering Superconducting Accelerator

PAUL SCHERRER INSTITUT

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

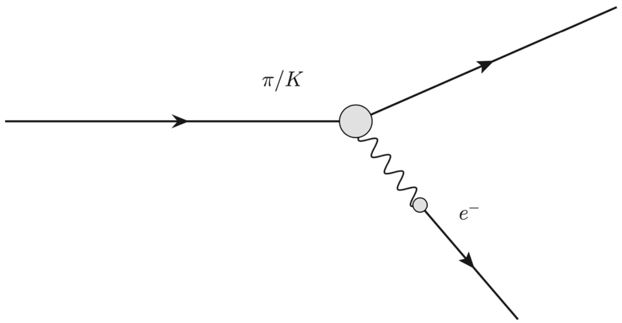
- Much cleaner experimental conditions (pure muon beam with less than 10^{-6} admixture of hadrons)
- Much higher beam momentum, thus contribution from magnetic form factor is suppressed (0.1-0.2 *GeV/c* vs 100 *GeV/c*)
- Small statistical errors achievable with the proposed running time



AMBER (Kaon and pion charge radius)

Apparatus for Meson and Baryon
Experimental Research

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)

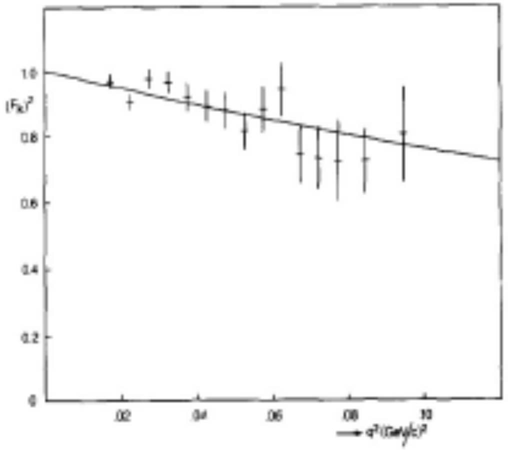


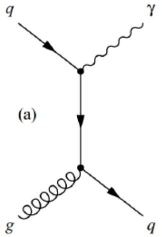
Fig. 3. The measured kaon form factor squared. The line corresponds to the pole fit with $\langle r^2 \rangle = 0.34$ fm^2.

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*

Prompt Photons Production measurement at AMBER

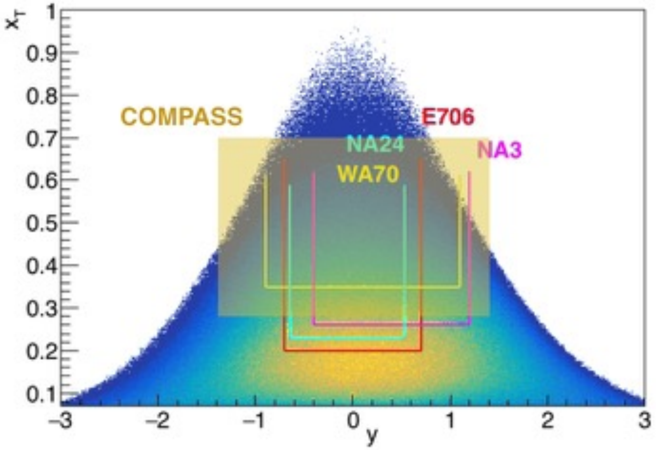
Apparatus for Meson and Baryon
Experimental Research

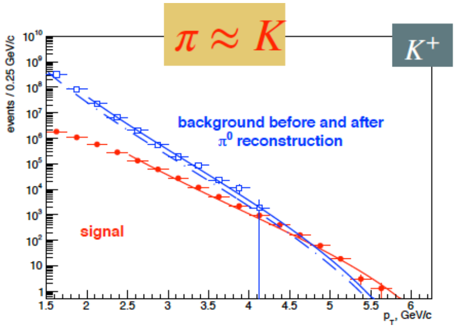


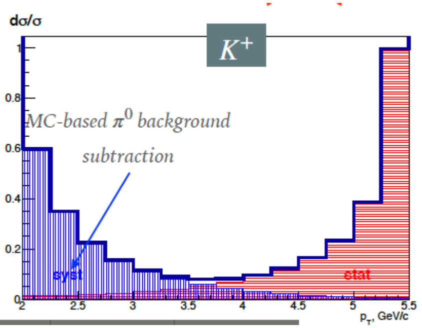
Prompt photons probe – direct access to the gluon content of the kaon.
At the moment there is no experimental information about gluon contribution in kaon.

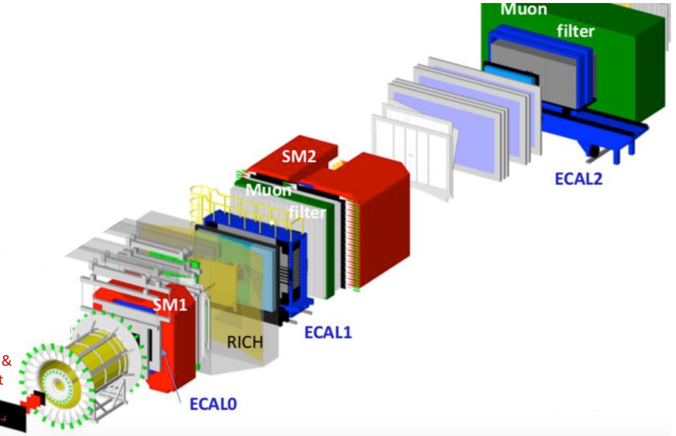
Pythia-based MC simulation for prompt photons production was used for preliminary estimation of kinematic range accessible at COMPASS. It was compared with corresponding ranges accessible by previous experiments with pion beams.

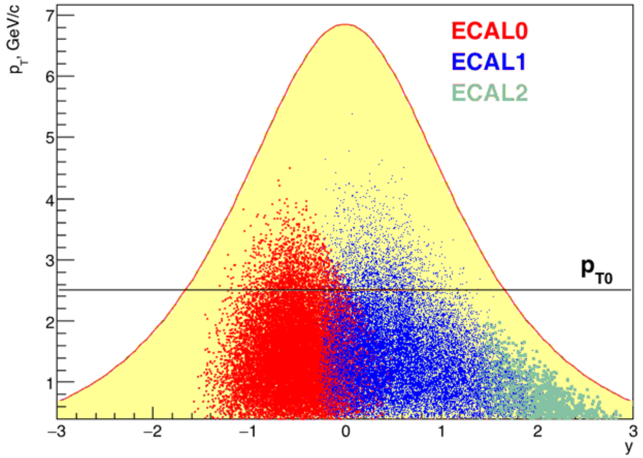
Possibilities to identify signal and reject background were tested. Some optimization of the setup from point of the material budget was tested.









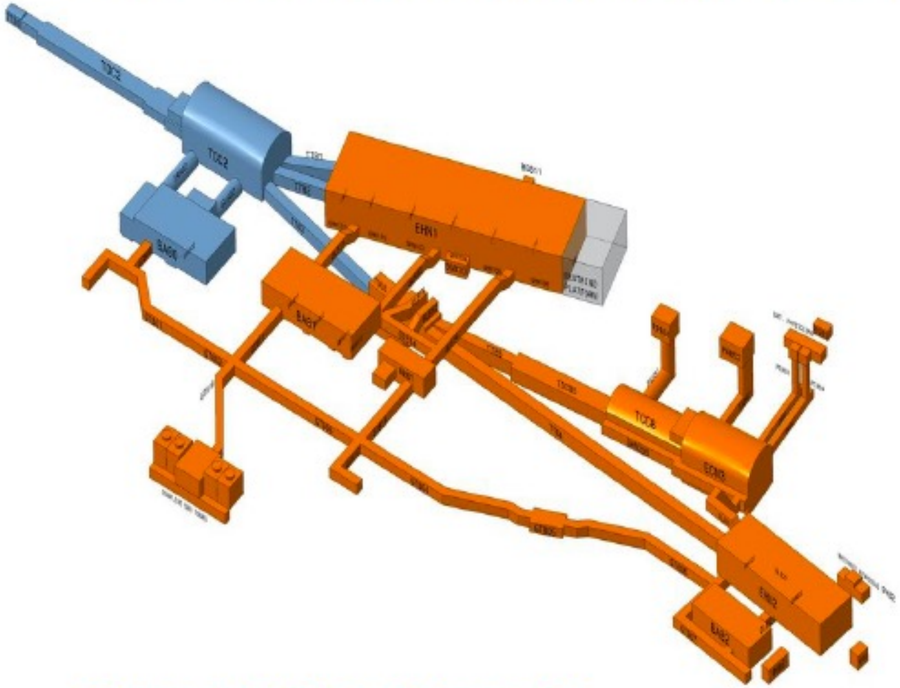


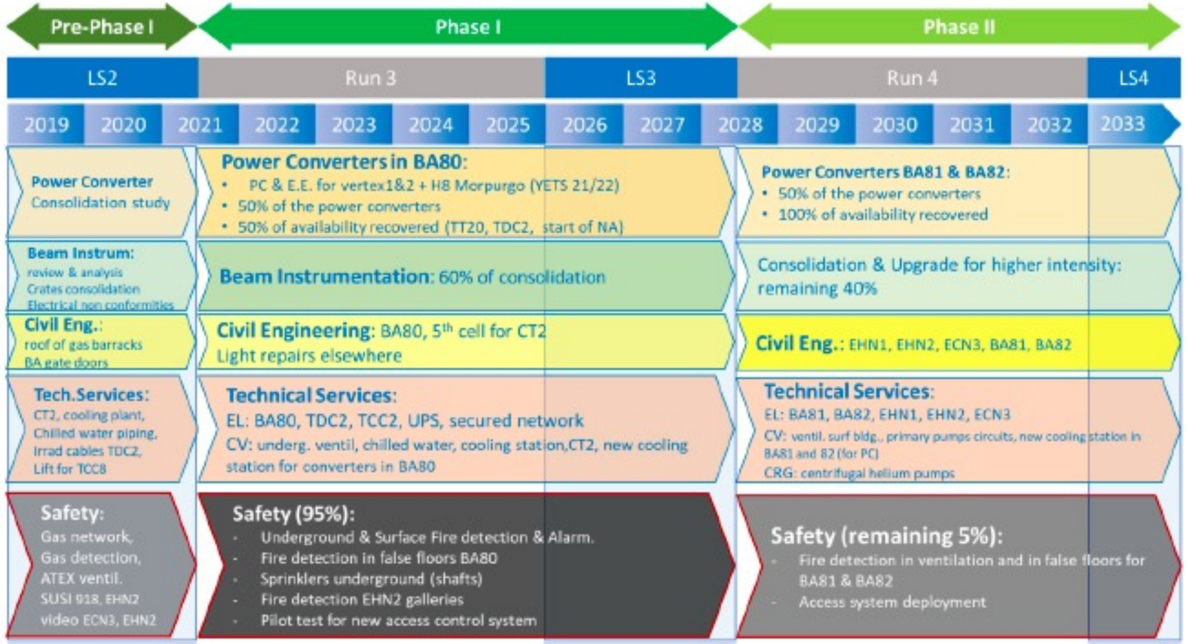
Oleg Denisov

NA-CONS Scope/Roadmap

EDMS 2458866

Consolidation Phase 1:
2019 – 2028: primary areas (incl. BA2), BA80 & beamlines towards EHN1 & TDC8





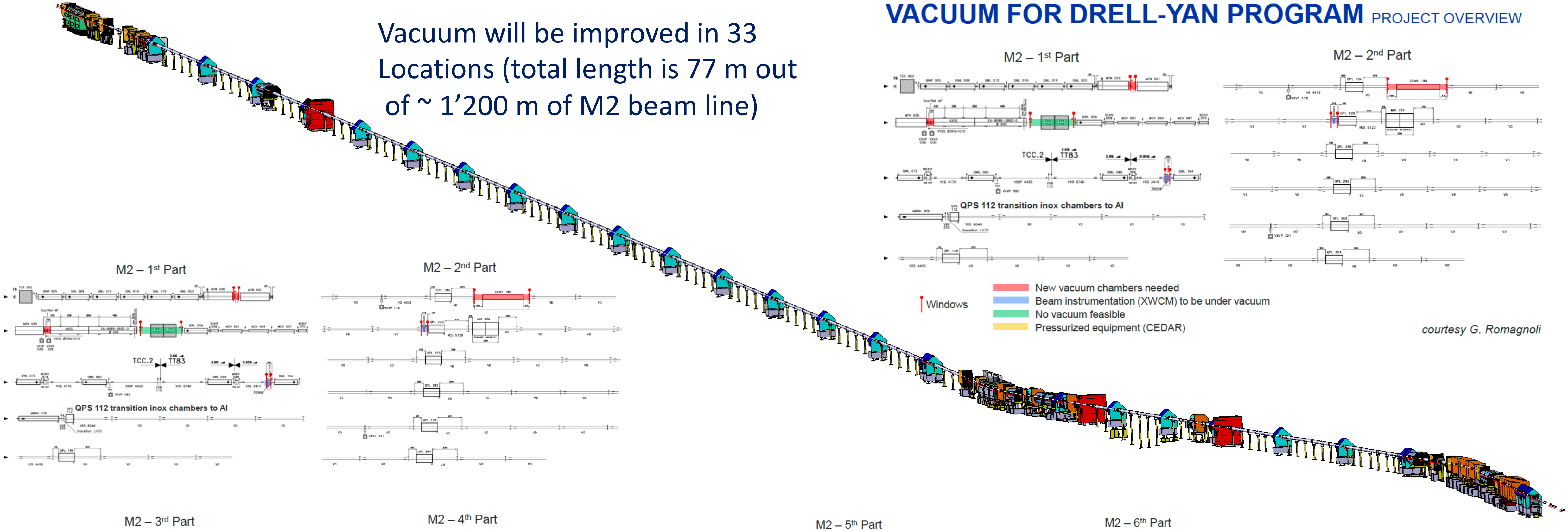
Pre-Phase I	Phase I	Phase II
LS2	Run 3 / LS3	Run 4 / LS4
2019, 2020	2021, 2022, 2023, 2024, 2025, 2026, 2027	2028, 2029, 2030, 2031, 2032, 2033
Power Converter Consolidation study	**Power Converters in BA80:** • PC & E.E. for vertex1&2 + H8 Morpurgo (YETS 21/22) • 50% of the power converters • 50% of availability recovered (TT20, TDC2, start of NA)	**Power Converters BA81 & BA82:** • 50% of the power converters • 100% of availability recovered
Beam Instrum: review & analysis Crates consolidation Electrical non conformities	**Beam Instrumentation:** 60% of consolidation	Consolidation & Upgrade for higher intensity: remaining 40%
Civil Eng.: roof of gas barracks BA gate doors	**Civil Engineering:** BA80, 5th cell for CT2 Light repairs elsewhere	**Civil Eng.:** EHN1, EHN2, ECN3, BA81, BA82
Tech.Services: CT2, cooling plant, Chilled water piping, Irrad cables TDC2, Lift for TCC8	**Technical Services:** EL: BA80, TDC2, TCC2, UPS, secured network CV: underg. ventil, chilled water, cooling station,CT2, new cooling station for converters in BA80	**Technical Services:** EL: BA81, BA82, EHN1, EHN2, ECN3 CV: ventil. surf bldg., primary pumps circuits, new cooling station in BA81 and 82 (for PC) CRG: centrifugal helium pumps
Safety: Gas network, Gas detection, ATEX ventil. SUSI 918, EHN2 video ECN3, EHN2	**Safety (95%):** - Underground & Surface Fire detection & Alarm. - Fire detection in false floors BA80 - Sprinklers underground (shafts) - Fire detection EHN2 galleries - Pilot test for new access control system	**Safety (remaining 5%):** - Fire detection in ventilation and in false floors for BA81 & BA82 - Access system deployment

Consolidation Phase 2:
2029 – 2034: BA81, BA82, EHN1, EHN2 & associated beamlines

Status of the AMBER Facility preparations: AMBER/EHN2 beam line upgrade: vacuum improvements and beam line instrumentation

AMBER
Apparatus for Meson and Baryon Experimental Research

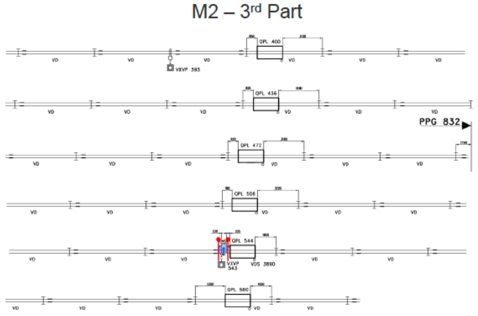
Vacuum will be improved in 33 Locations (total length is 77 m out of ~ 1’200 m of M2 beam line)

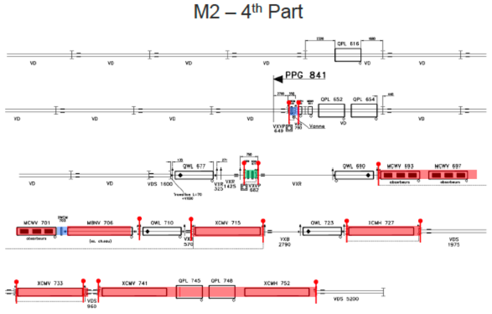


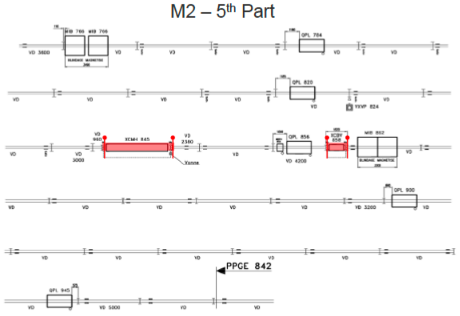
VACUUM FOR DRELL-YAN PROGRAM PROJECT OVERVIEW

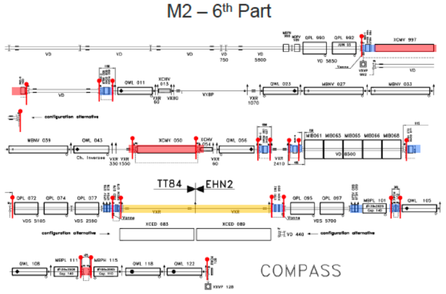
Windows
🟥 New vacuum chambers needed
🟦 Beam instrumentation (XWCM) to be under vacuum
🟩 No vacuum feasible
🟨 Pressurized equipment (CEDAR)

courtesy G. Romagnoli





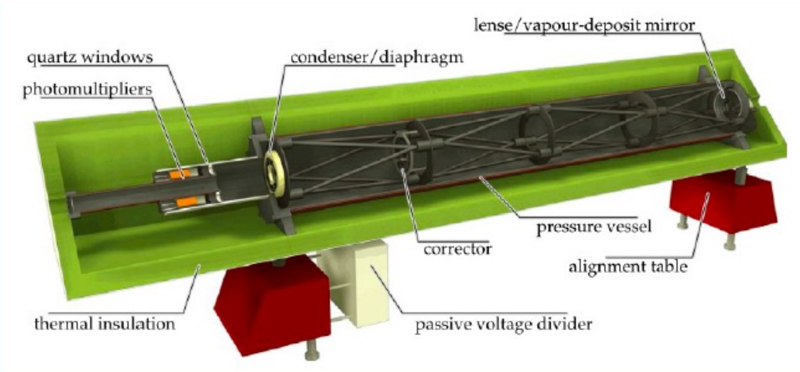


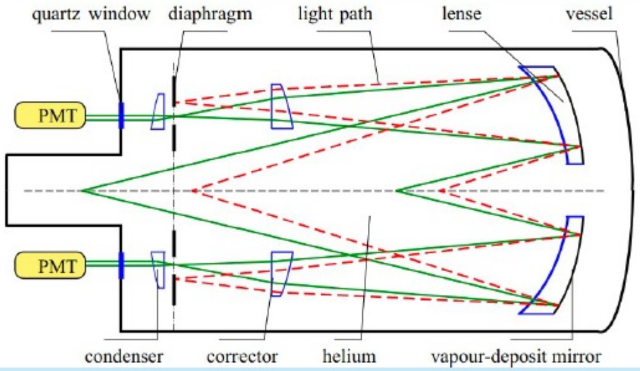


Status of the AMBER Facility preparations: Secondary Beam PId improvement

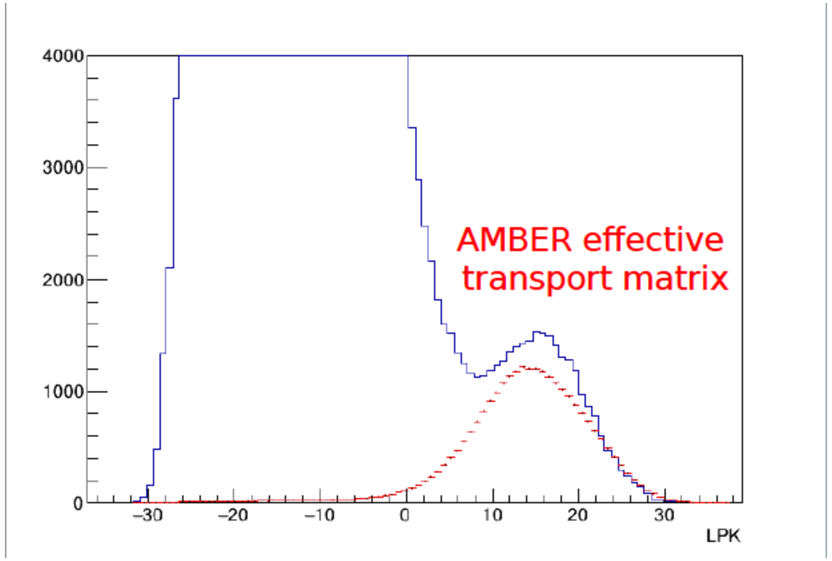
AMBER
Apparatus for Meson and Baryon Experimental Research

- Cherenkov Differential counter with Achromatic Ring Focus





We (AMBER and CERN Beam Dep.) are improving on both hardware (mechanics, read out electronics) and methods.
In 2023 we run a full hadron intensity beam test (~10^8 hadrons/s) for CEDARs & new beam telescope and for the first time we clearly see kaon peak in likelihood distribution



CEDAR refurbishment YETS 2023/2024

M. Lino Diogo Dos Santos

The CEDAR open issues were compiled and reported at the end of the 2023 run. The two M2 CEDARs have been prioritized and refurbished:

Courtesy: K. Bernhard-Novotny

M2 - SPXCEDN001 - CR000002
M2 - SPXCEDN001- CR0000020

- Diaphragm – Mechanics Refurbishment
- Motor + Switches – Replacement
- Gas – Gas pipes refurbishment (correct sized shape etc.)
- Joints – Replacement
- Optics – Alignment
- XY Table – Table precision check / replacement
- Alignment – Realignment of CEDAR

For all CEDARS

- Installing new pressure sensors
- Validating new diaphragm movement algorithm
- Measuring quantum efficiency of spare PMTs – To requalify or discard the spare park of PMTs

Status of the AMBER Facility preparation: Toward at least doubling of the incoming beam intensity

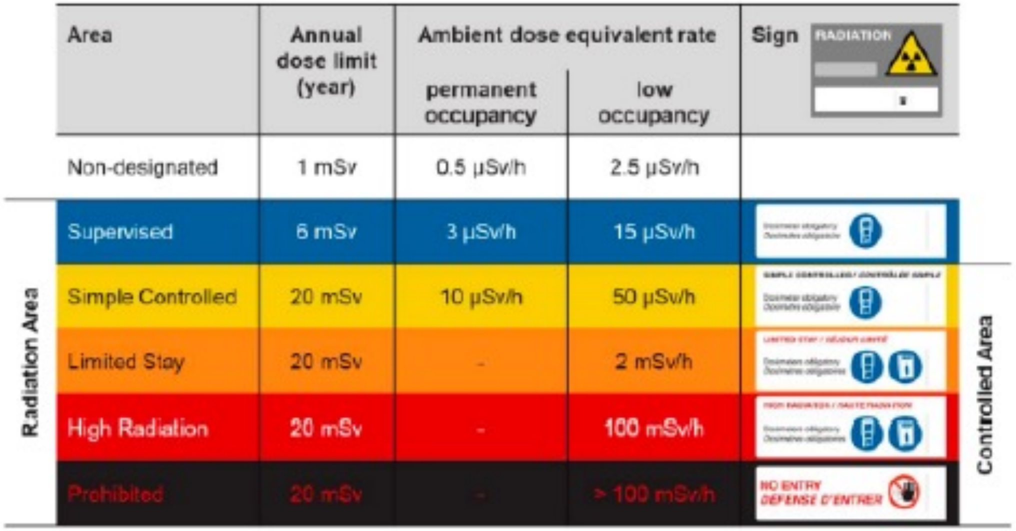
Apparatus for Meson and Baryon
Experimental Research

Study and optimisation of the shielding to:

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

⇒ Compatible with 2×current Intensities

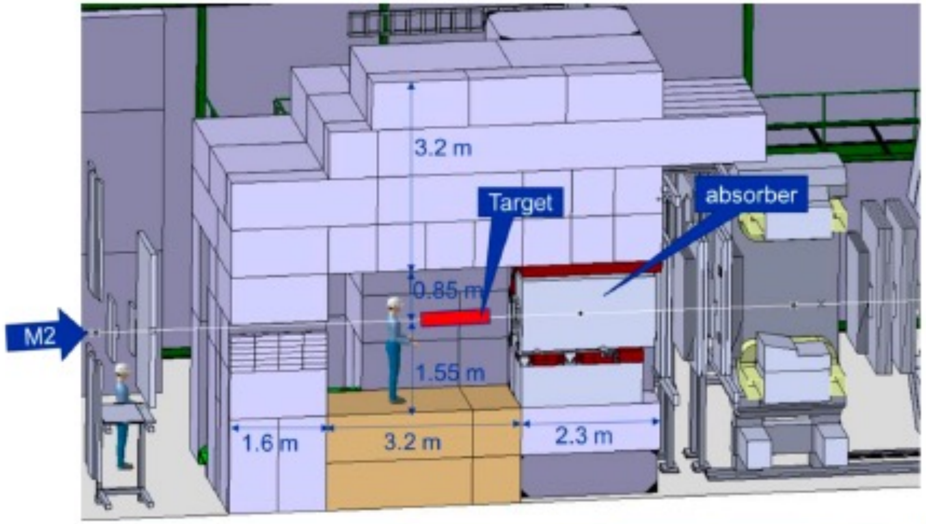
⇒ ECR to be submitted

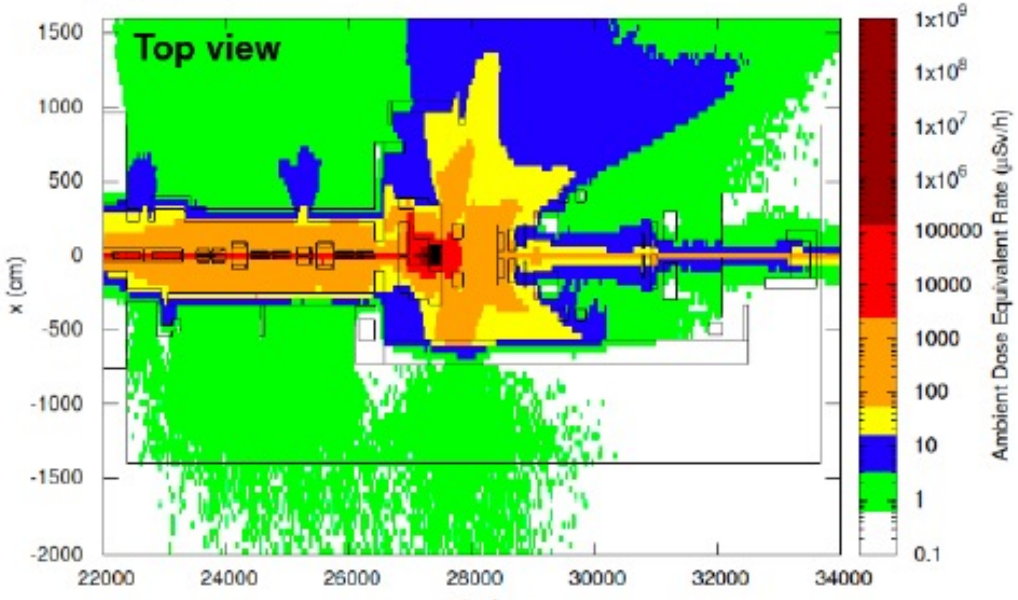


Area	Annual dose limit (year)	Ambient dose equivalent rate		Sign
		permanent occupancy	low occupancy	RADIATION
Non-designated	1 mSv	0.5 µSv/h	2.5 µSv/h	
Supervised	6 mSv	3 µSv/h	15 µSv/h	
Simple Controlled	20 mSv	10 µSv/h	50 µSv/h	
Limited Stay	20 mSv	-	2 mSv/h	
High Radiation	20 mSv	-	100 mSv/h	
Prohibited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

Radiation Area

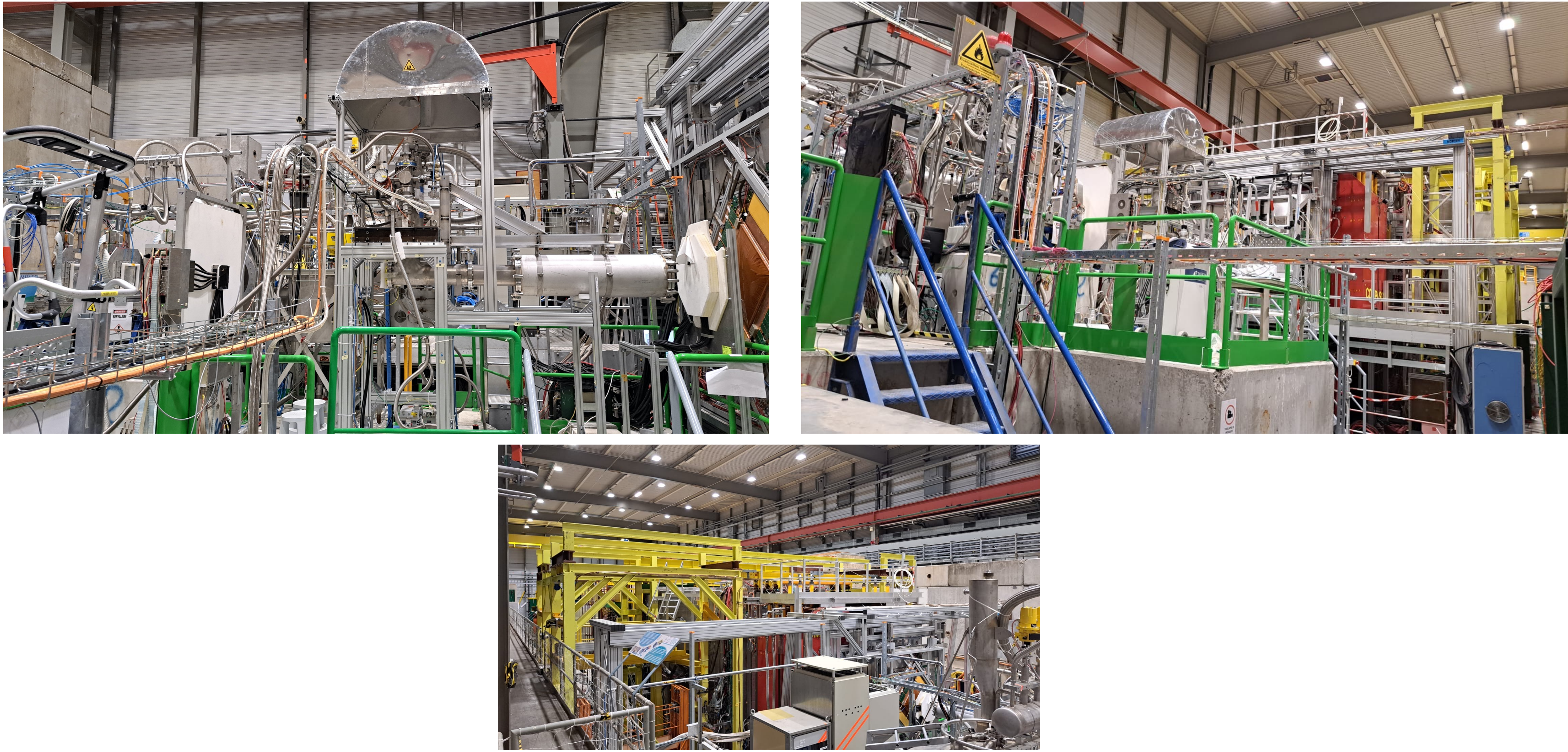
Controlled Area



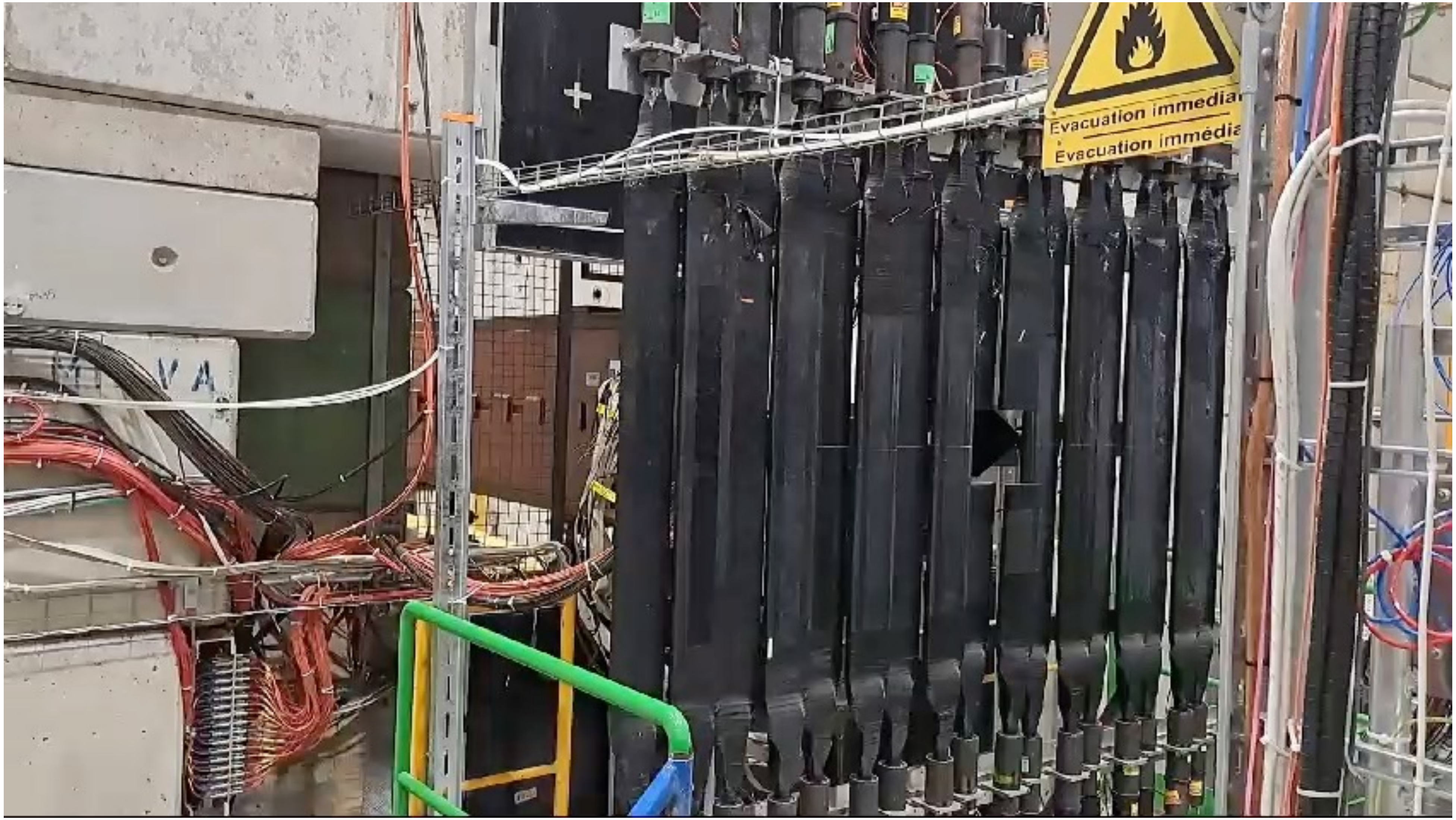


Status of the AMBER Facility preparations: 2024 APX run preparation

Apparatus for Meson and Baryon
Experimental Research



Status of the AMBER Facility preparations: 2024 APX run preparation

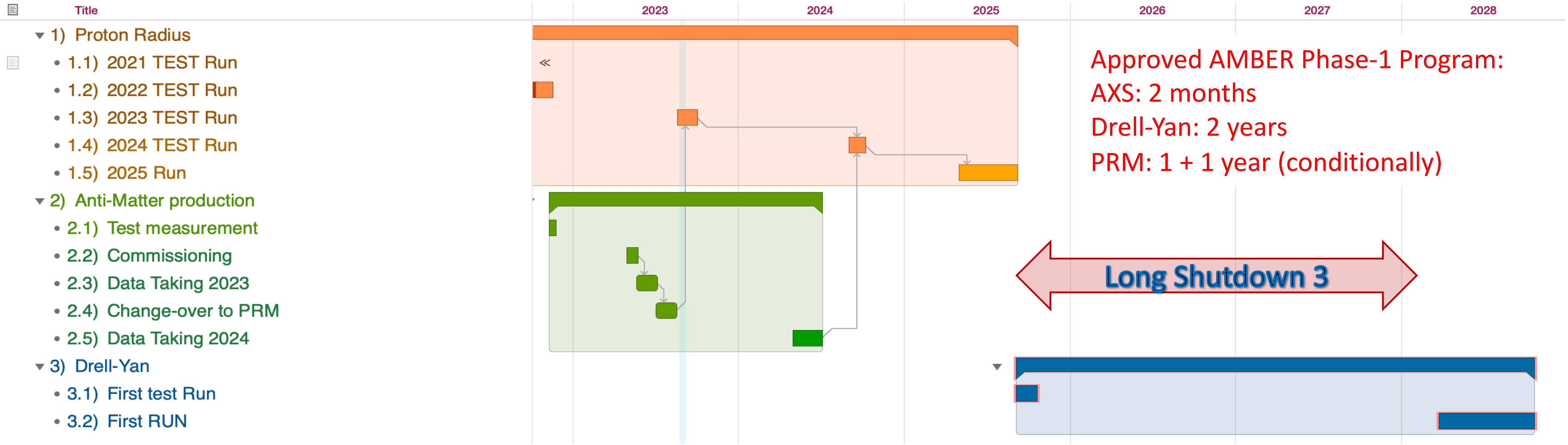


AMBER Phase-1 running plan (obsolete)

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)



Title

- 1) Proton Radius
  - 1.1) 2021 TEST Run
  - 1.2) 2022 TEST Run
  - 1.3) 2023 TEST Run
  - 1.4) 2024 TEST Run
  - 1.5) 2025 Run
- 2) Anti-Matter production
  - 2.1) Test measurement
  - 2.2) Commissioning
  - 2.3) Data Taking 2023
  - 2.4) Change-over to PRM
  - 2.5) Data Taking 2024
- 3) Drell-Yan
  - 3.1) First test Run
  - 3.2) First RUN

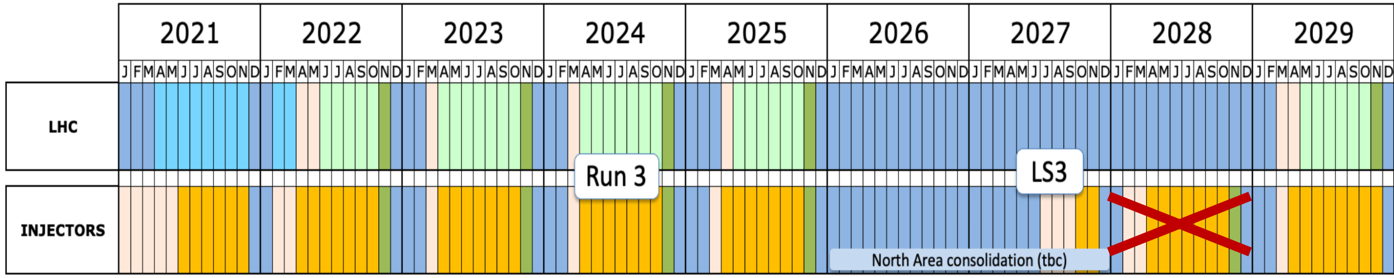
Approved AMBER Phase-1 Program:
AXS: 2 months
Drell-Yan: 2 years
PRM: 1 + 1 year (conditionally)

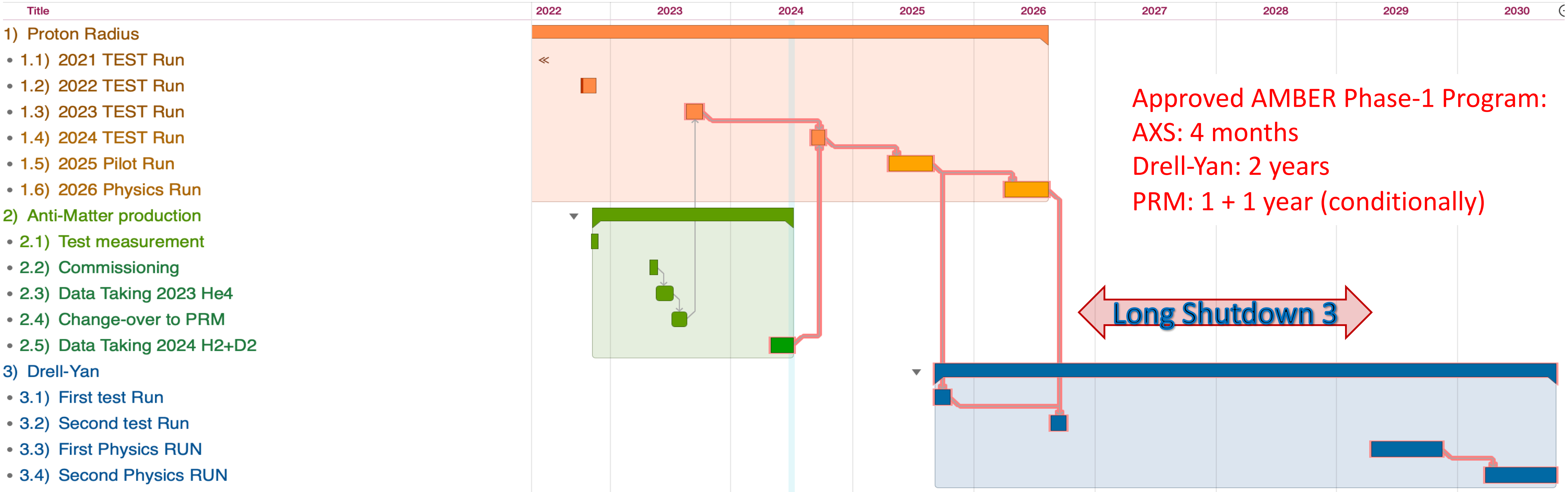
AMBER Phase-1 running plan - modified

Apparatus for Meson and Baryon Experimental Research

Milestones:

1. May 1st 2023, 2024 – Antimatter production Run (Std. DAQ)
2. Sep. 1st 2024 – PRM Test (FreeDAQ, very limited setup)
3. June. 1st 2025 – PRM Pilot (FreeDAQ, limited setup)
4. May. 1st 2026 – PRM Physics (FreeDAQ, PRM setup)
5. Sep. 1st 2025, 2026 – DY Test (FreeDAQ, all trackers + mu id)
6. May 1st 2029/30 – DY Run (FreeDAQ, full Drell-Yan setup)

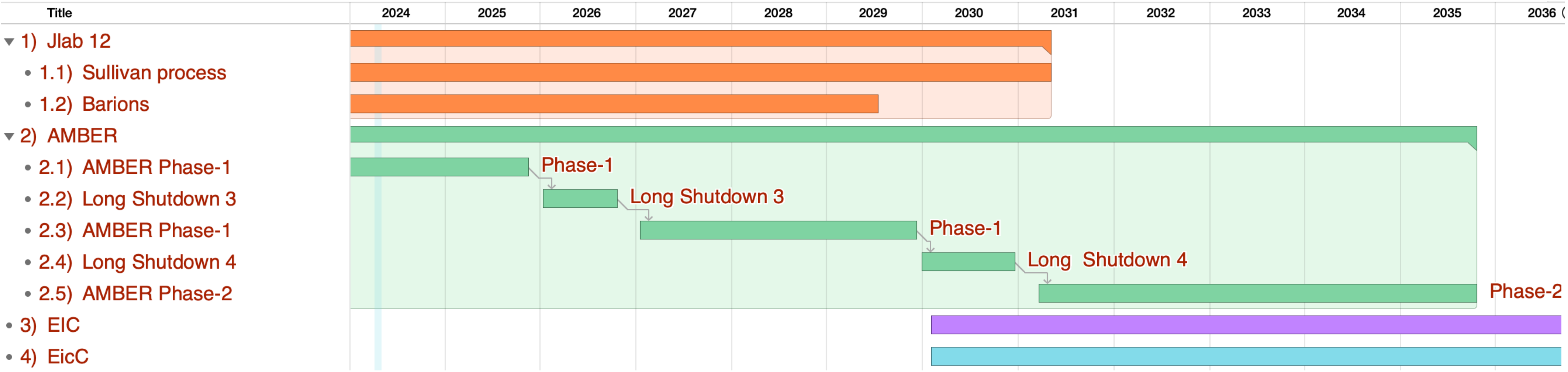




Approved AMBER Phase-1 Program:
AXS: 4 months
Drell-Yan: 2 years
PRM: 1 + 1 year (conditionally)

AMBER Phase-1&2 running plan

Apparatus for Meson and Baryon Experimental Research



We are in the beginning of a very long journey – consider to join if you see your insterests…

AMBER WEB Page:
https://amber.web.cern.ch/

Summary: AMBER at CERN SPS

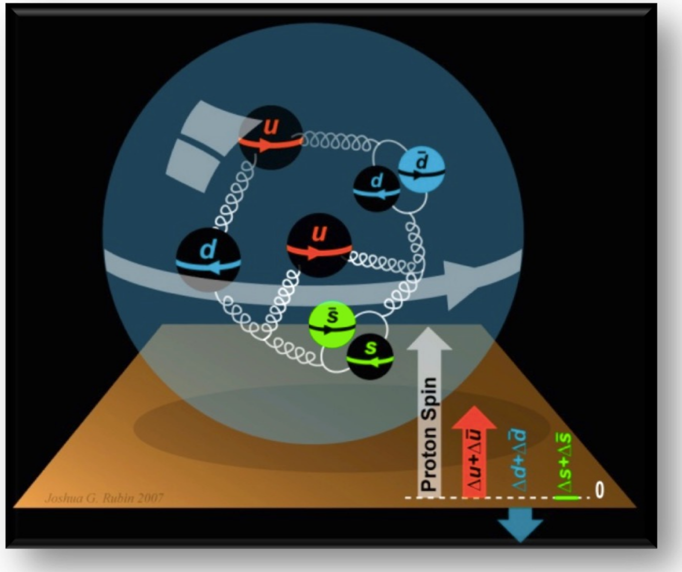
- We did a great job in COMPASS to understood better the proton spin structure, we are leaving a floor to the next generation high-luminosity facilities
- We are very happy that we managed with the approval of AMBER Phase-1 to provide long-term future for hadron physics at CERN (it was quite an effort taking into account uneasy neighbourhood of the LHC..)
- We are solid collaboration of 33 Institutions from 13 countries, ~150 physicists. Largest countries-contributors are already successfully went through their funding application processes
- Data taking of the AMBER Phase-1 is ongoing
- Focus is on EHM related studies but of course we will measure as well unpolarised TMD PDFs of unstable particles.

Apparatus for Meson and Baryon Experimental Research

Spares

All AMBER predecessors (at least most recent once) did a very significant contribution to the science question of the Proton Spin stating from initiation of Spin Crisis to its resolving.

Apparatus for Meson and Baryon Experimental Research



Nucleon spin ½ = ½ ΔΣ + ΔG + L

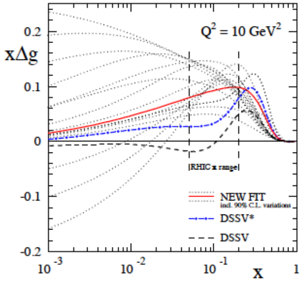
quark gluon orbital mom.

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

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

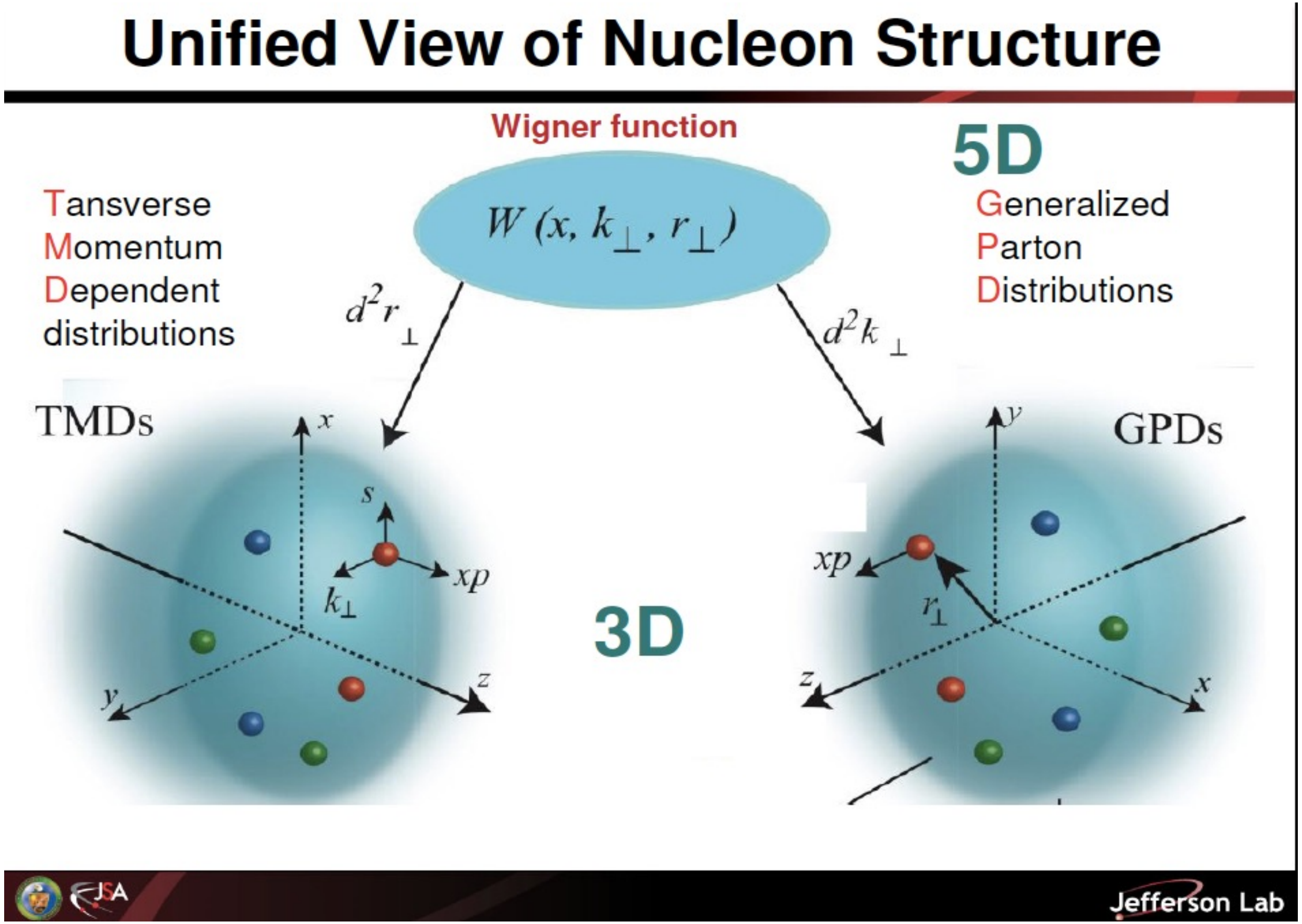
First two component were extensively studied in the SIDIS experiments with the longitudinally polarised target (collinear case approach): spin fraction carried by quarks and gluons is not sufficient to describe ½ nucleon spin (Spin Crisis):

- Quark spin contribution $\Delta\Sigma=0.24$ ($Q^2=10$ $(GeV/c)^2$ 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



Unified View of Nucleon Structure

Wigner function

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

5D

Tansverse
Momentum
Dependent
distributions

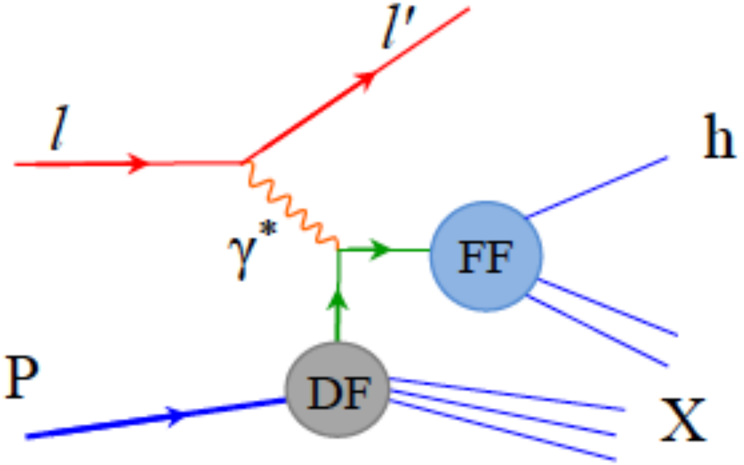
Generalized
Parton
Distributions

TMDs

GPDs

3D

Currently thanks to the contribution of number of Labs/Experiments (BEPC, BNL, CERN, Fermilab, JLab …) Spin puzzle is resolved



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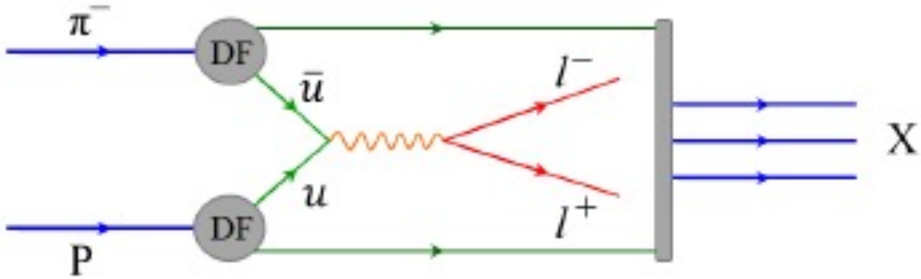
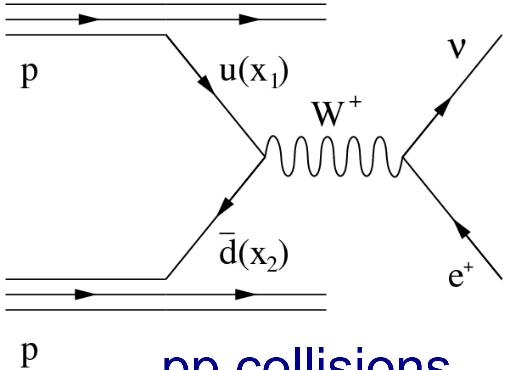
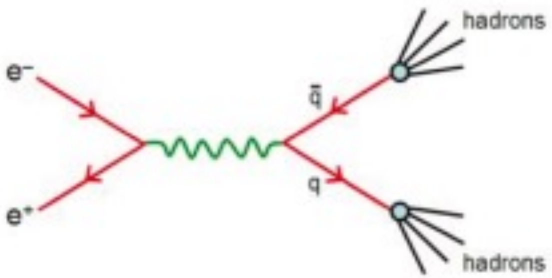


Drell-Yan



pp collisions



e^+e^- collisions

Principles to be respected while preparing new experiment at CERN

Once we are started to think about successor of COMPASS and continuation of hadron physics at CERN apart of reasoning mentioned above we were guided by few CERN-established principles:

1. High scientific value of the proposed measurements, i.e. importance of science questions to be addressed by the experiment
2. Results awaited by a broad scientific community
3. **Uniqueness of the proposed experiments, everything what could be done somewhere else but at CERN should be done somewhere else**
4. **Results, once achieved should define the state of the art in the field for a long time**

Former two are sort of common, latter two are rather CERN-specific.

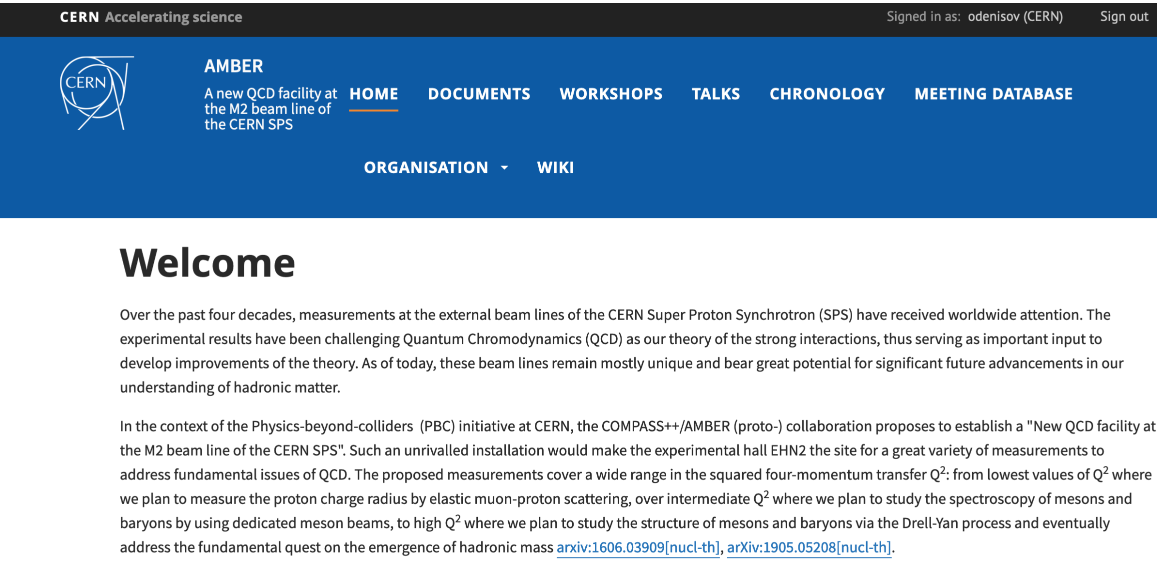
AMBER
more than 15 years-long effort

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:

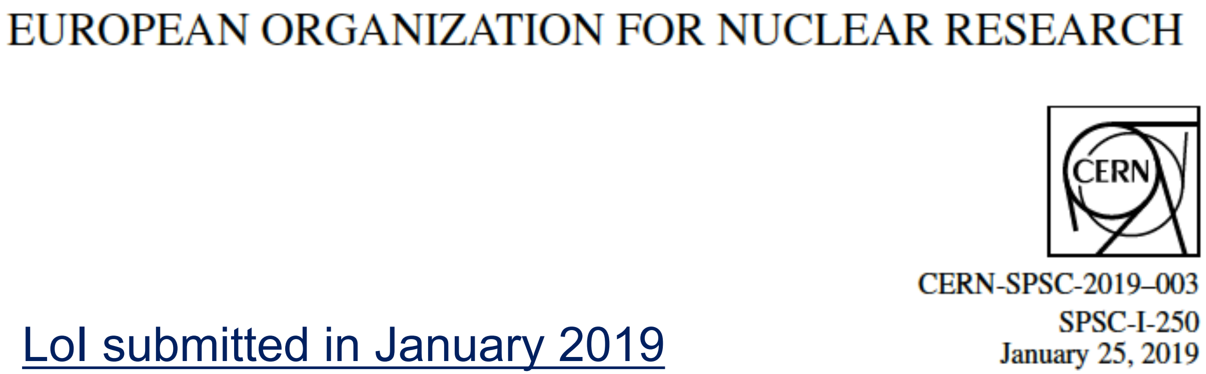
https://amber.web.cern.ch/



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.

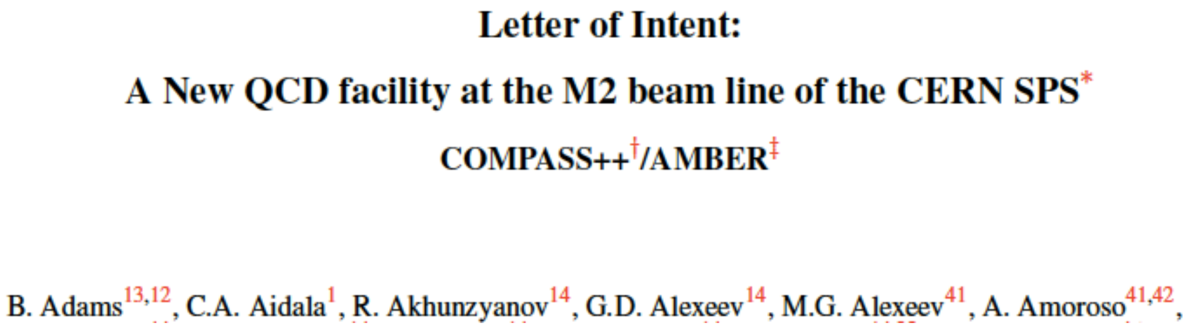
In the context of the Physics-beyond-colliders (PBC) initiative at CERN, the COMPASS++/AMBER (proto-) collaboration proposes to establish a "New QCD facility at the M2 beam line of the CERN SPS". Such an unrivalled installation would make the experimental hall EHN2 the site for a great variety of measurements 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‡

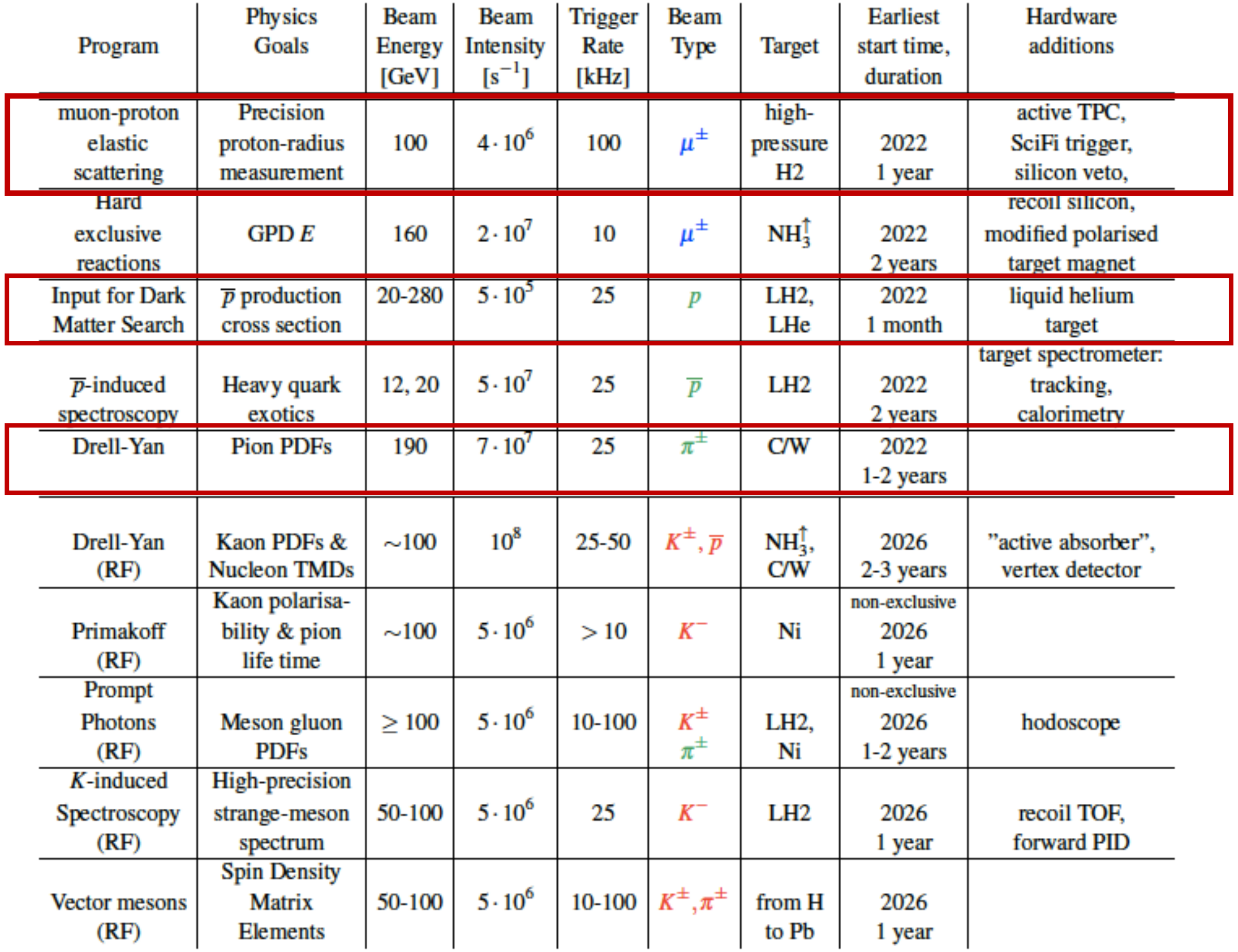
B. Adams[13,12], C.A. Aidala[1], R. Akhunzyanov[14], G.D. Alexeev[14], M.G. Alexeev[41], A. Amoroso[41,42],

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

Apparatus for Meson and Baryon Experimental Research

LoI submitted in January 2019 http://arxiv.org/abs/1808.00848

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 ➔ 2025

Improved conventional Hadron/Hadron beam

2027➔2030

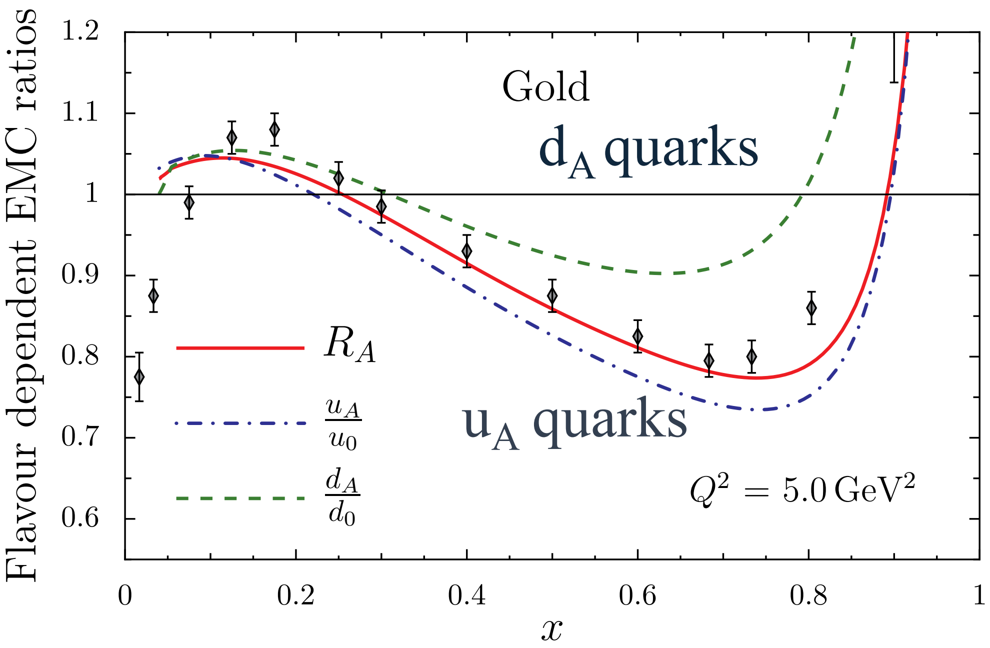
PHASE-2

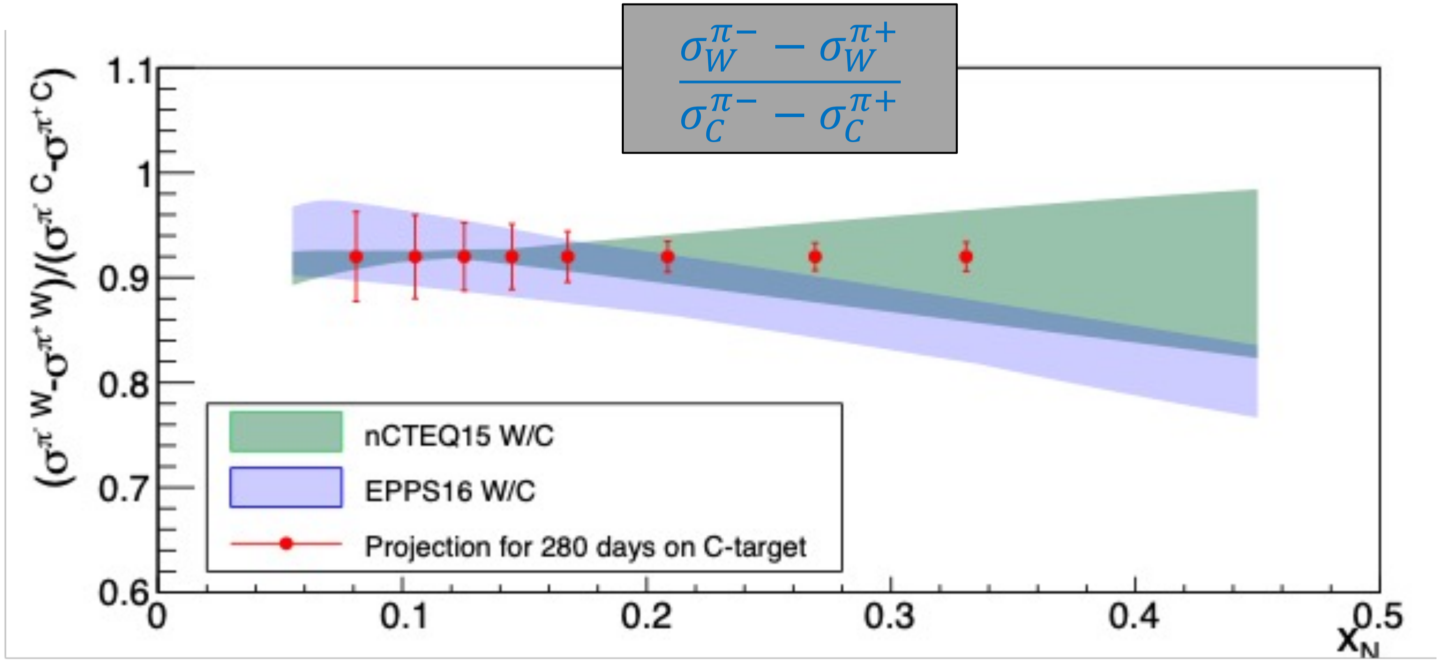
Improved conventional Hadron/Hadron and muon beam

2029 and beyond

Goal-4: Flavor dependence of the EMC effect

- Prediction: Cloët, Benz and Thomas (2009):
  - *"…for N≠Z nuclei, the u and d quarks have distinct nuclear modifications."*





$$\frac{\sigma_W^{\pi-} - \sigma_W^{\pi+}}{\sigma_C^{\pi-} - \sigma_C^{\pi+}}$$

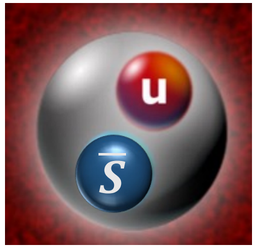
Can be accessed ONLY through parity-violating DIS (JLAB) or with AMBER@CERN

J/ψ – access to the kaon valence PDF

Apparatus for Meson and Baryon Experimental Research

- Quark content in the kaon:

$$K^+(u\bar{s});\quad K(\bar{u}s)$$



- Production cross section for K⁺ and K⁻

$$\begin{aligned}
K^-(\bar{u}s)+p(uud) &\propto gg+\left[\bar{u}_v^K u_v^p\right]+\left[\bar{u}_v^K u_s^p+s_v^K s_s^p\right]+\left[\bar{u}_s^K u_v^p\right]+\left[\bar{u}_s^K u_s^p+u_s^K\bar{u}_s^p+s_s^K\bar{s}_s^p+\bar{s}_s^K s_s^p\right]\\
K^+(u\bar{s})+p(uud) &\propto gg+\underbrace{\left[---\right]}_{\text{val-val}}+\underbrace{\left[\cancel{u_v^K\bar{u}_s^p+\bar{s}_v^K s_s^p}\right]}_{\text{val-sea}}+\underbrace{\left[\bar{u}_s^K u_v^p\right]}_{\text{sea-val}}+\underbrace{\left[\bar{u}_s^K u_s^p+u_s^K\bar{u}_s^p+s_s^K\bar{s}_s^p+\bar{s}_s^K s_s^p\right]}_{\text{sea-sea}}
\end{aligned}$$

- The cross section difference isolates the val-val term: $\sigma(K^-)-\sigma(K^+)\propto\bar{u}_v^K u_v^p$

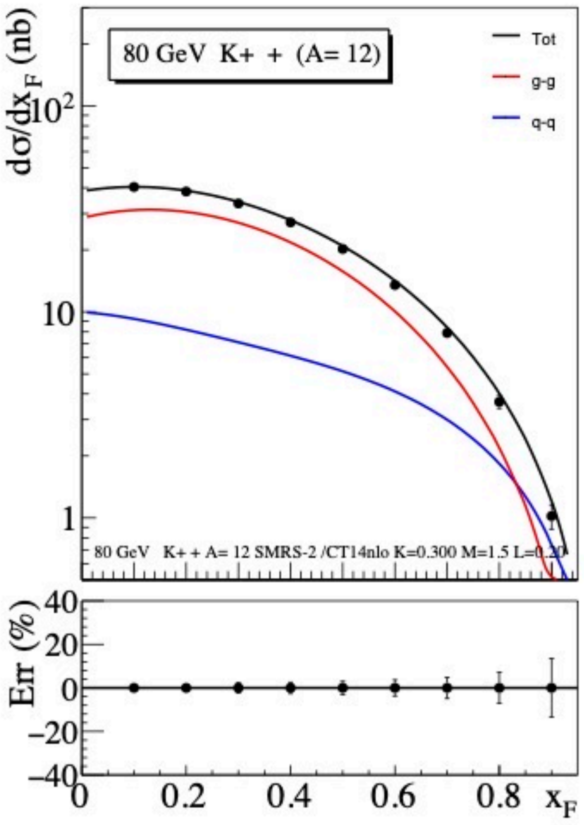
Error estimates: K⁻ and K⁺ -induced J/ψ cross sections

◆ Assumptions

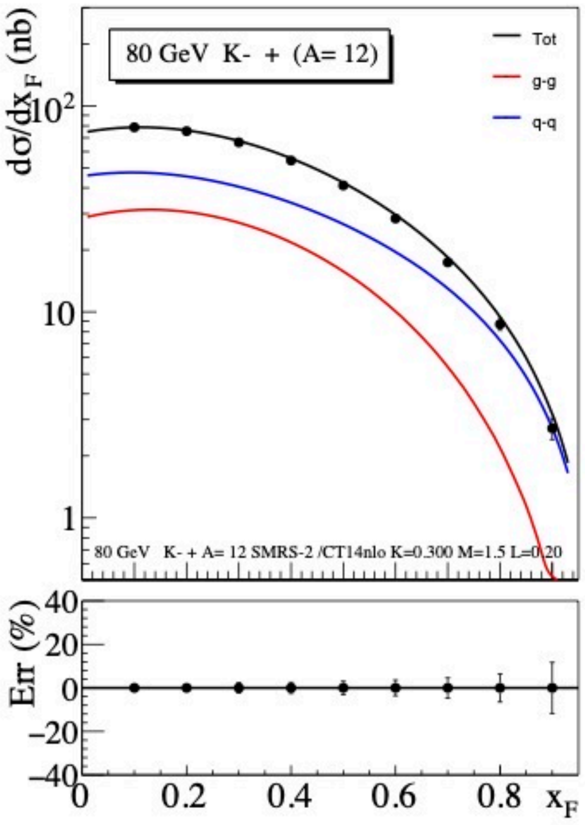
- Flux: 5.10^5/s
- ~10 000 events for each beam (conservative number)
- Beam sharing: ~70 d of K− and ~210 d of K+
- 3 carbon targets, length of 25cm each
- x_F coverage: 0.10 – 0.95

◆ Lower panel: statistical errors in %

K⁺ beam

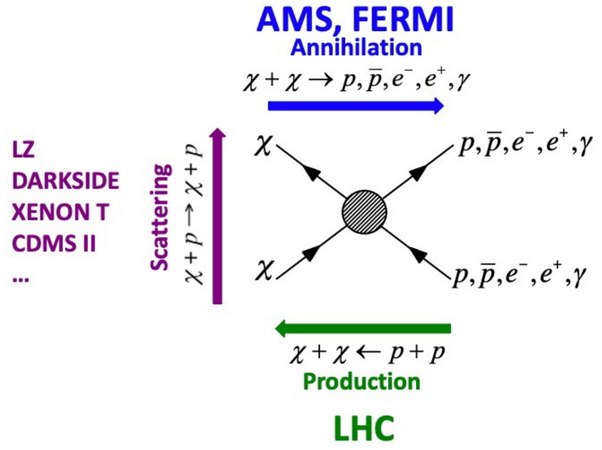


K⁻ beam

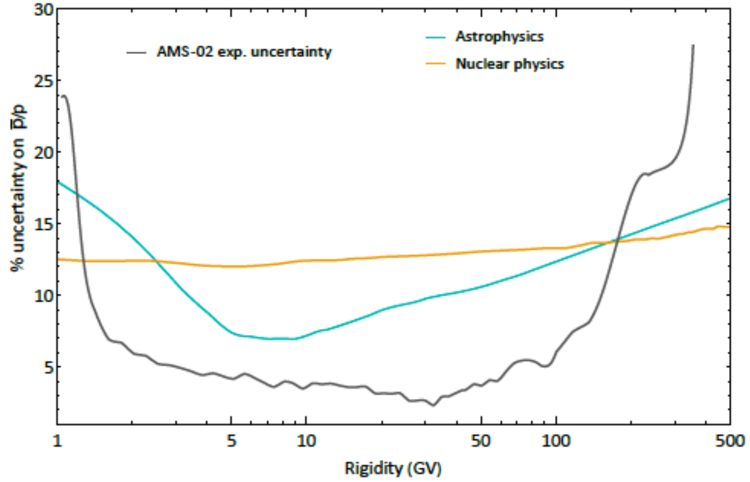


Antimatter Production Cross-Section measurement at AMBER

Apparatus for Meson and Baryon Experimental Research

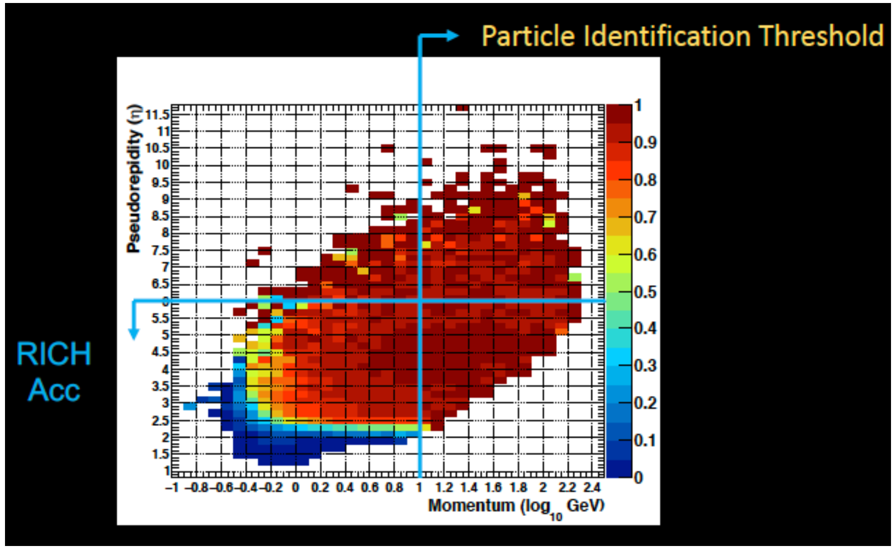


- New AMS(2) data – the antiparticle flux is well known now (few % pres.) (http://dx.doi.org/10.1103/PhysRevLett.117.091103)
- Two types of processes contribute – SM interactions (proton on the inter-stellar matter with the production for example of antiprotons) and contribution from dark particle –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



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

In 2023 we had successfully performed first data taking with He for six Incoming proton momentum in the range 60 – 250 GeV



AMBER antimatter production cross section

Apparatus for Meson and Baryon
Experimental Research

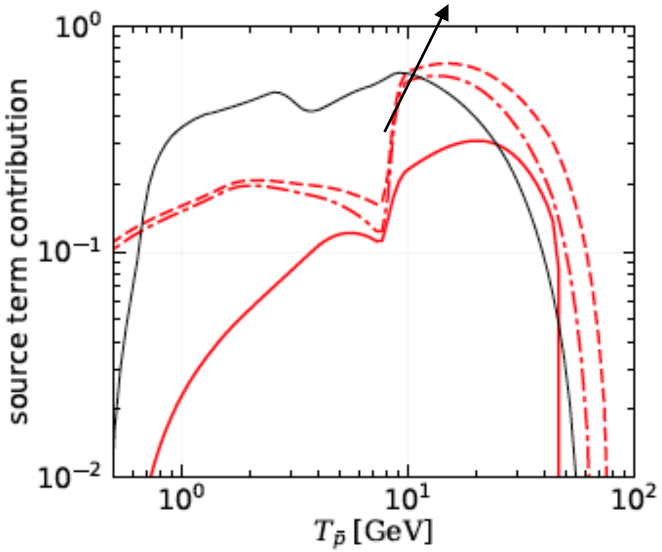
The impact of the proposed p + p measurements on constraining the production of cosmic anti-protons versus their kinetic energy. Each curve represents the fraction of anti-proton production phase space as constrained by AMBER cross section measurements in p-p, p-He and He-p channels, compared to NA61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

p-H channel, in three different energy ranges

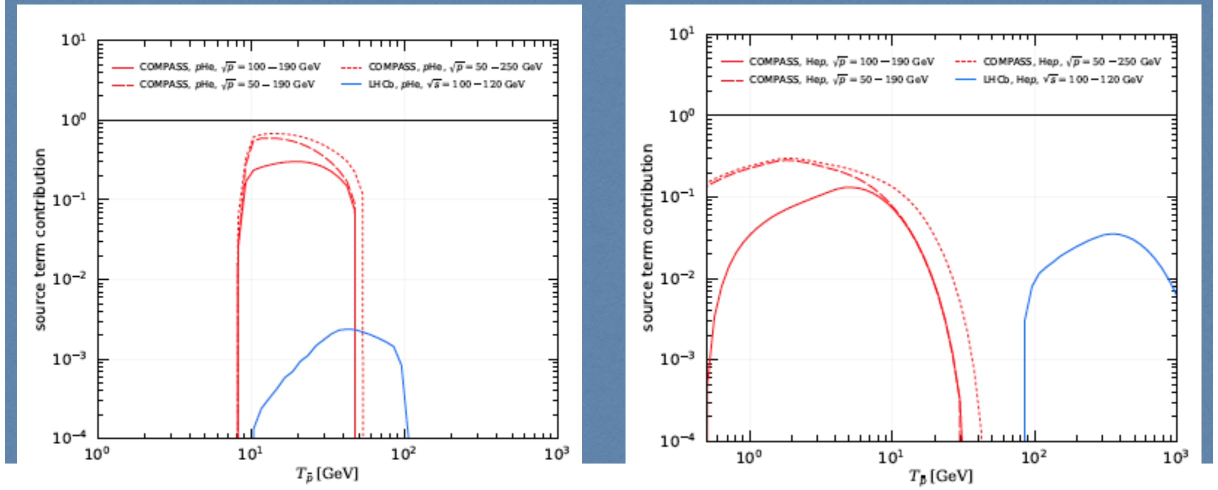
100-190 GeV/c
50-190 GeV/c
50 - 250 GeV/c

AMBER
LHCb

AMBER
NA61 (20-158 GeV/c)



p-He and He-p channels



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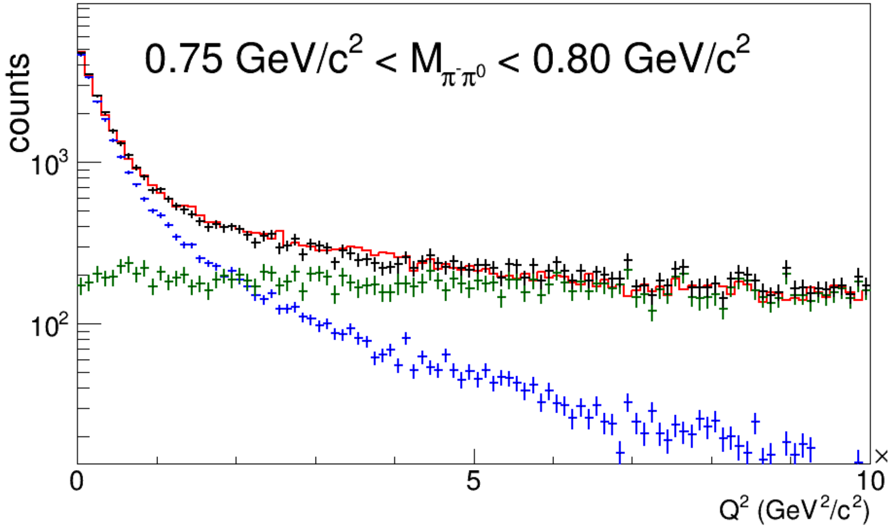
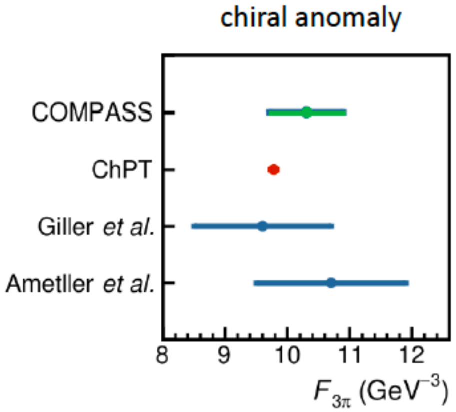
Apparatus for Meson and Baryon Experimental Research

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



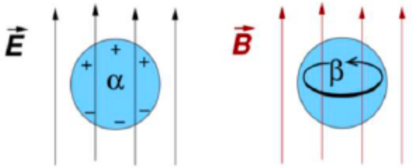
- Data
- Primakoff MC
- 3π MC
- Sum of MC contributions



Dominik Ecker's talk of 08/06/23

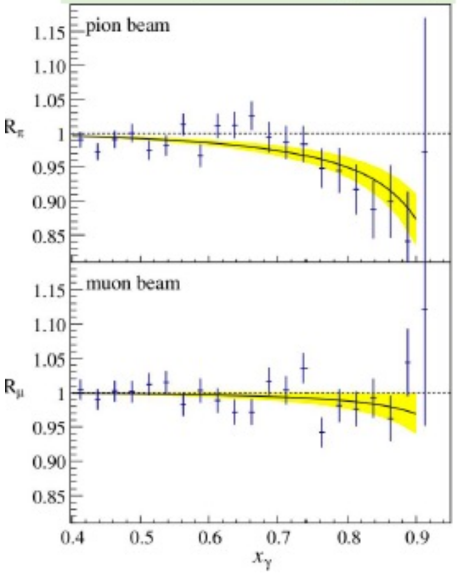
Polarizabilities

(Analogy from classical physics)

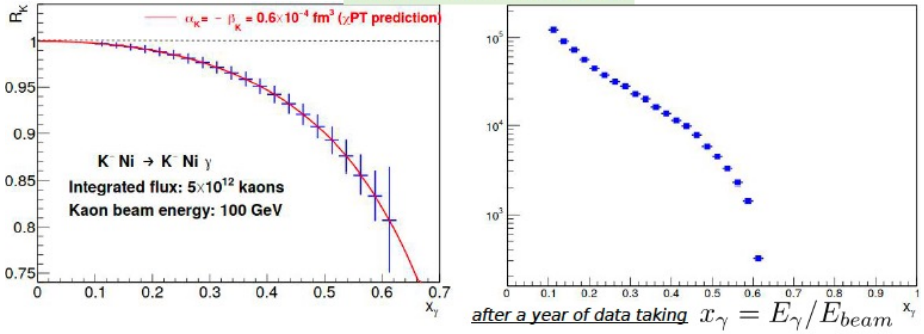


Interaction between **hadron** and **external electromagnetic field** described by parameters **α, β** (LO), encoding information about its internal structure

PRL 114, 062002 (2015)



hep-ex 1808.00848v6



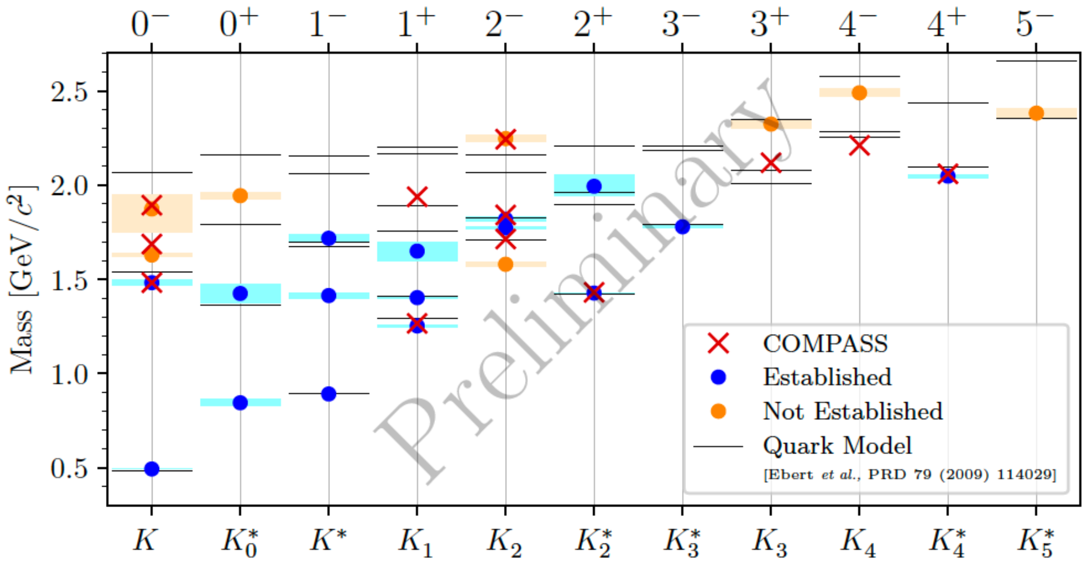
after a year of data taking $x_\gamma = E_\gamma/E_{beam}$

Hadron spectroscopy AMBER (kaon enriched beam)

Apparatus for Meson and Baryon
Experimental Research

PDG lists 25 strange mesons

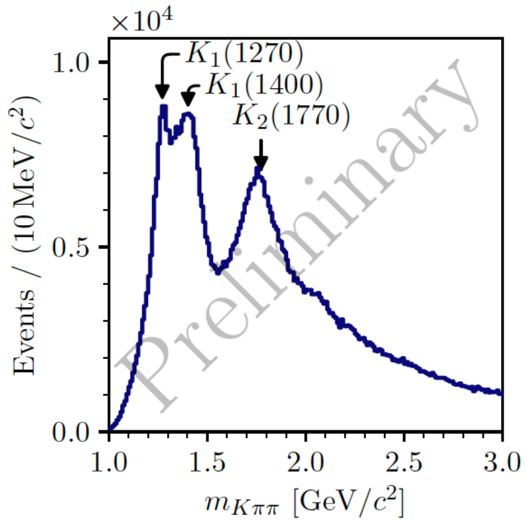
- 16 established states, 9 need further confirmation
- Missing states with respect to quark-model predictions
- Many measurements performed more than 30 years ago

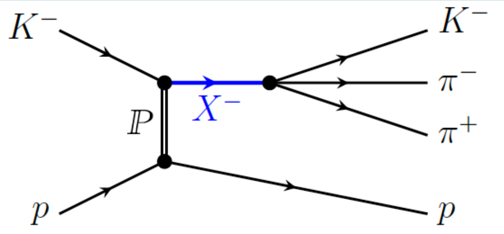


Stefan Wallner's talk of 08/06/23

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"

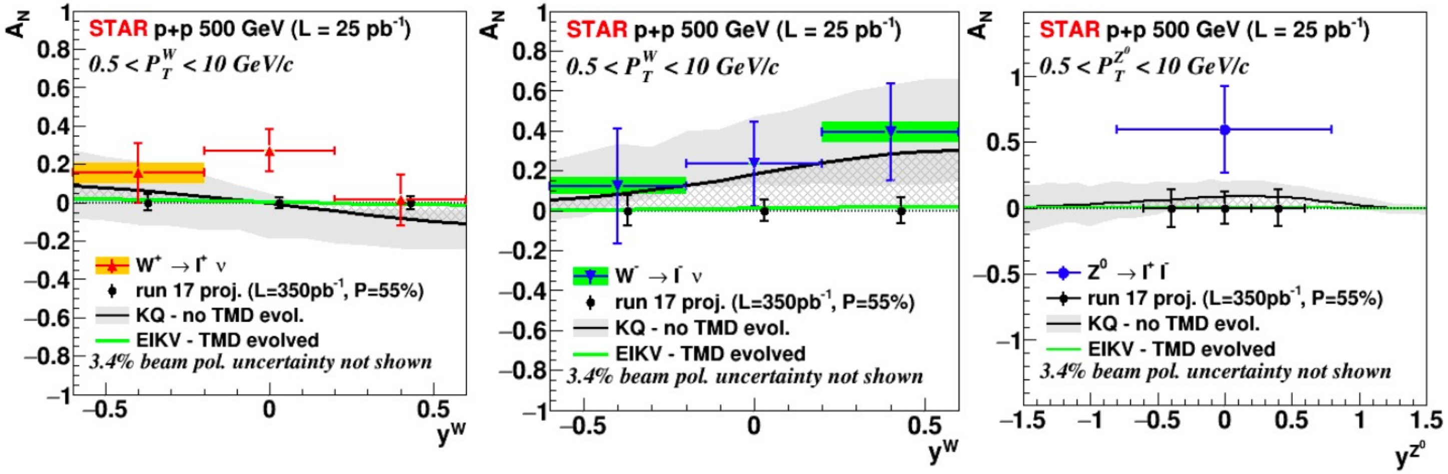
AMBER QCD Facility, goal for Kaon induced Spectroscopy to Collect 10-20x10^6 K^- π^+ π^- events using high-intensity high-energy kaon beam:

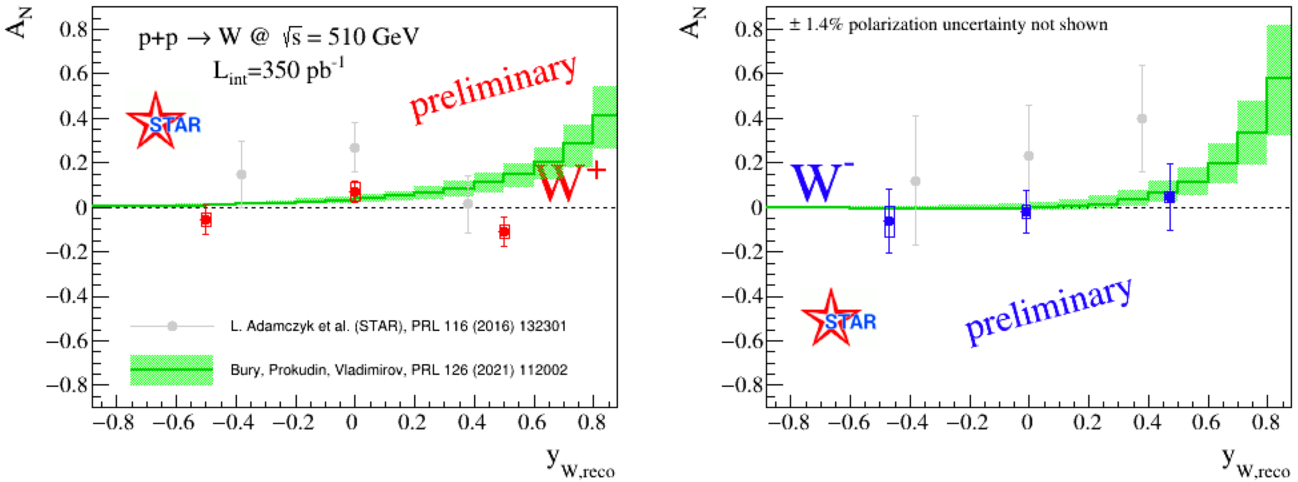
- Optimised Conventional Hadron beam line
- Higher wrt COMPASS beam intensity
- Better pion/kaon beam particles separation
- Much more powerful pid in the final state

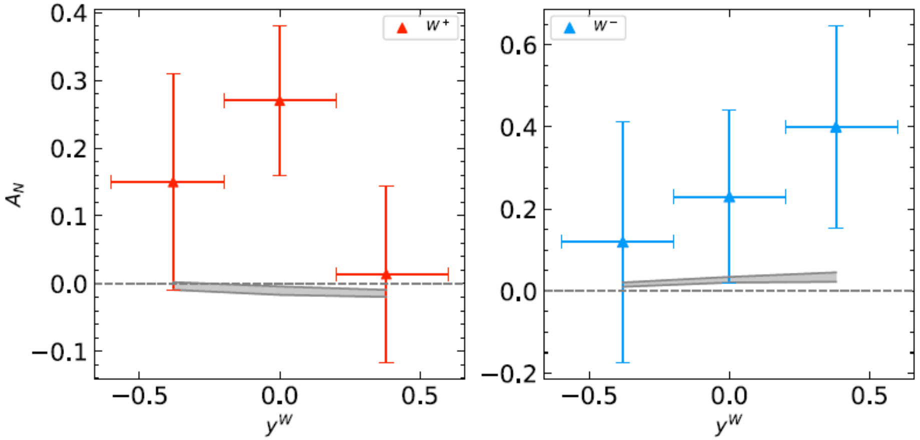
STAR: W-Boson Production in $p\uparrow+p$: $p+p\rightarrow W\pm\rightarrow e\pm+\nu$

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

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



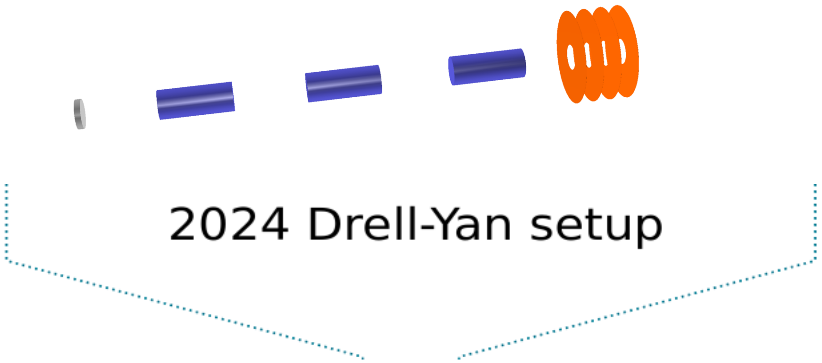


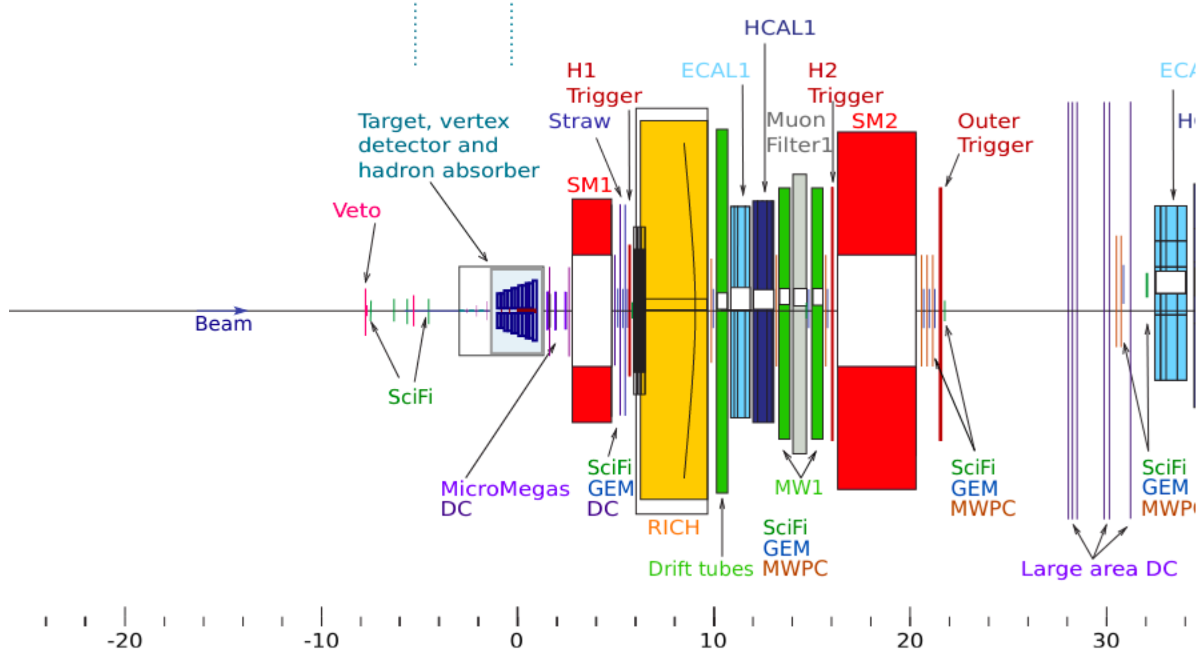


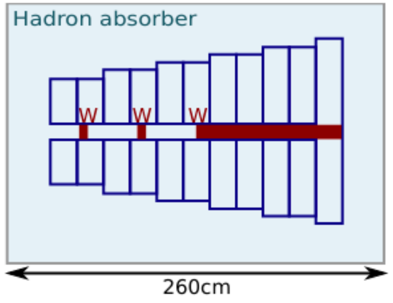
Bacchetta et al.,Phys. Lett. B . Lett. B 827 (2022) 136961
Comparison with PRL116(2016) 13201

Drell-Yan experiment preparation I

Apparatus for Meson and Baryon Experimental Research

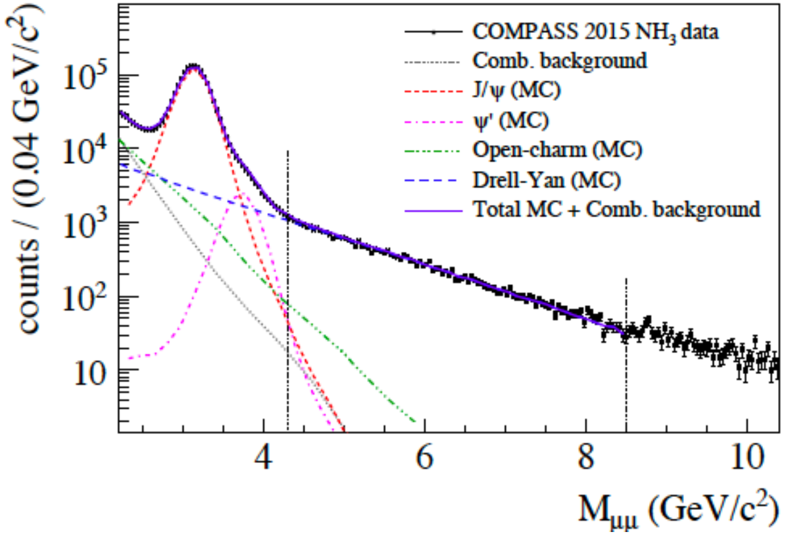






Drell-Yan process is a low cross-section process:

- 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

Apparatus for Meson and Baryon Experimental Research

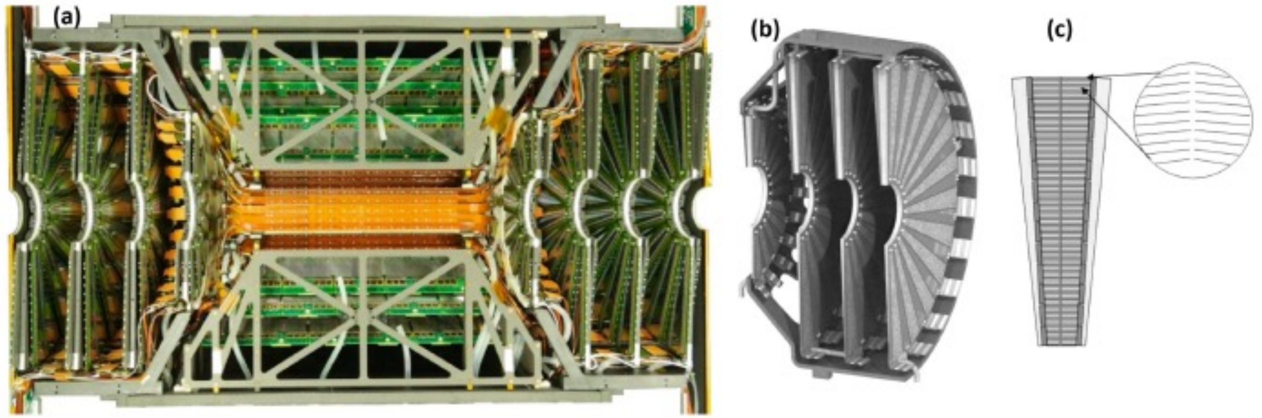
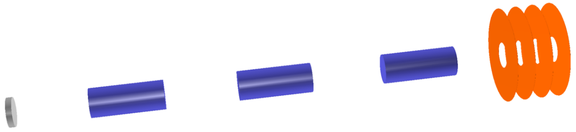
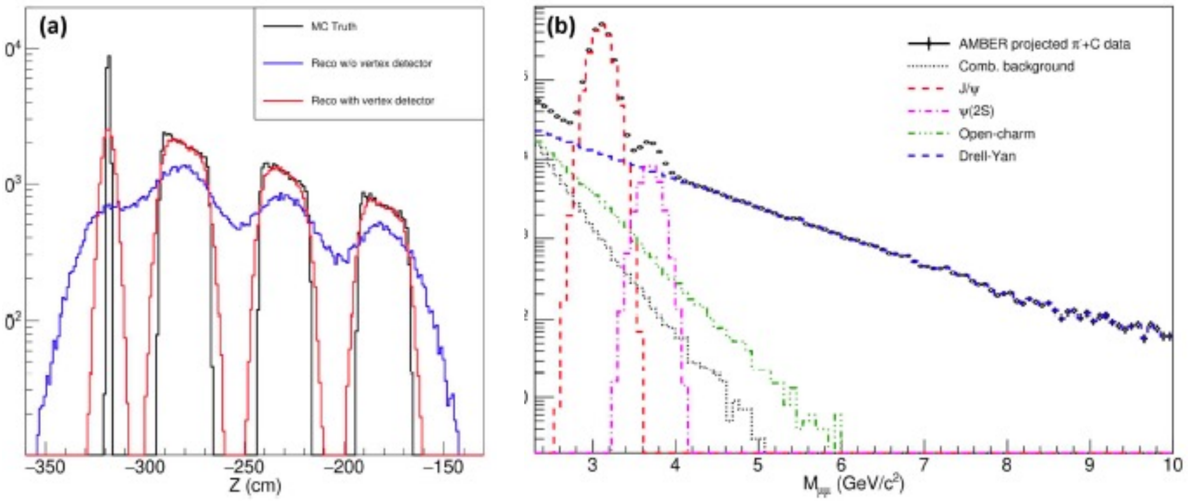


Figure 7 (a) A completed half FVTX detector, with sensors, frontend electronics, supporting structures, and cooling system. Two half FVTX endcaps are shown on either end. The overall length is about 80 cm. (b) A structural illustration of one endcap of the FVTX. One small disk and three large disks are 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: ∼ 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)

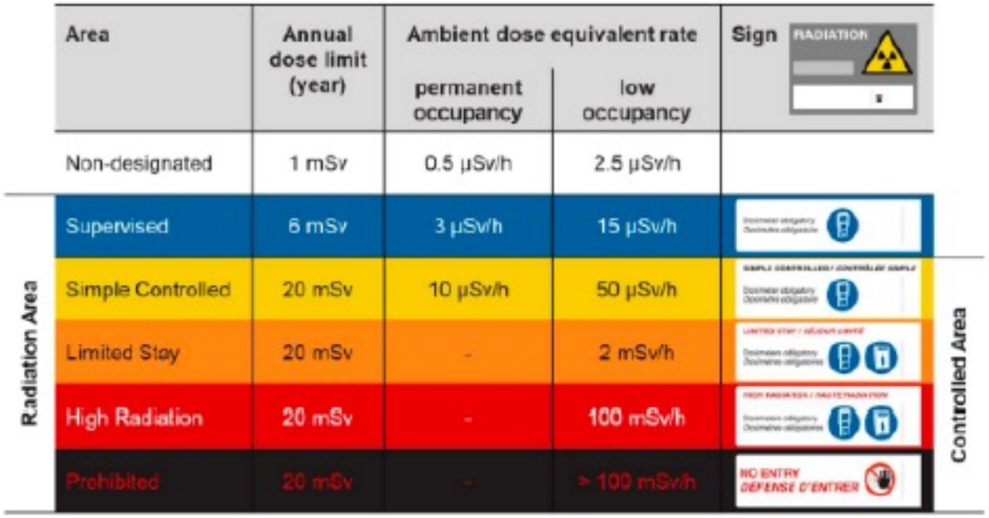
AMBER
Apparatus for Meson and Baryon Experimental Research

Study and optimisation of the shielding to:

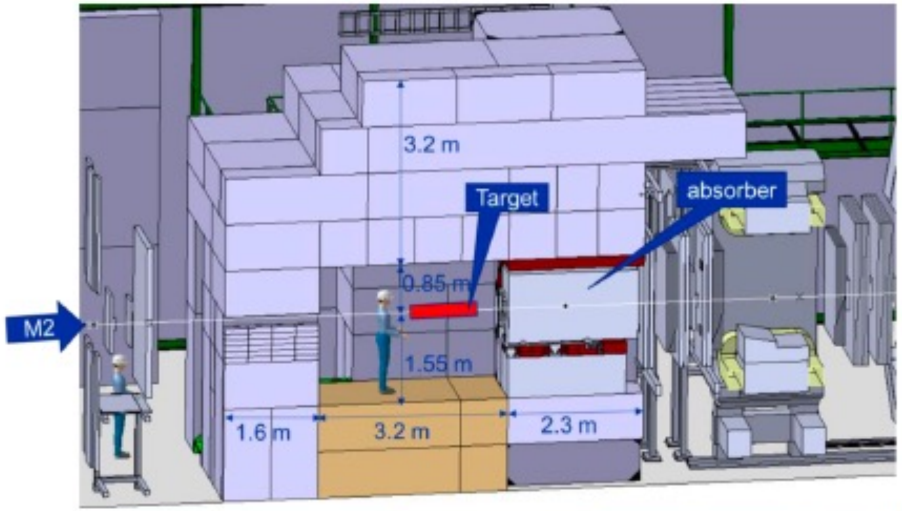
- Contain the radiation
- Minimise the environmental impact
- Comply with regulations

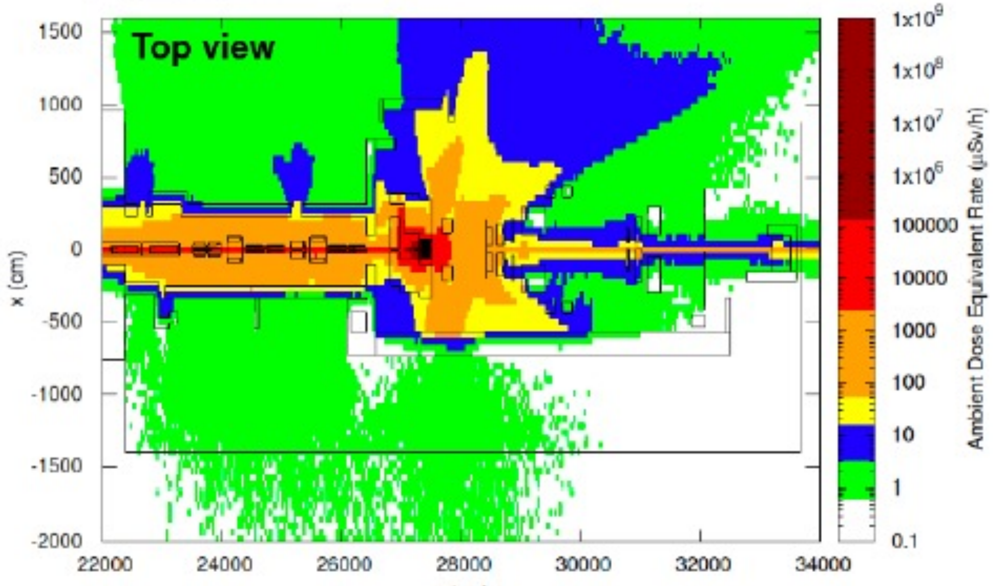
⇒ Compatible with 2×current Intensities

⇒ ECR to be submitted



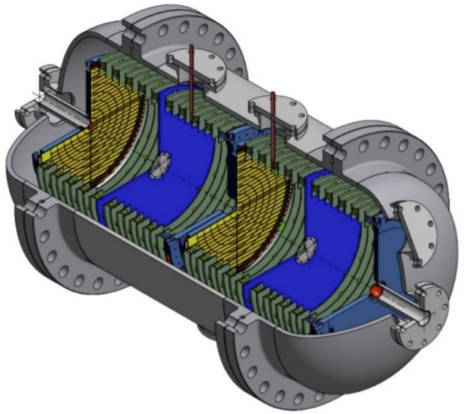
		Area	Annual dose limit (year)	Ambient dose equivalent rate		Sign RADIATION
				permanent occupancy	low occupancy	
		Non-designated	1 mSv	0.5 μSv/h	2.5 μSv/h	
Radiation Area		Supervised	6 mSv	3 μSv/h	15 μSv/h	
	Controlled Area	Simple Controlled	20 mSv	10 μSv/h	50 μSv/h	
		Limited Stay	20 mSv	-	2 mSv/h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



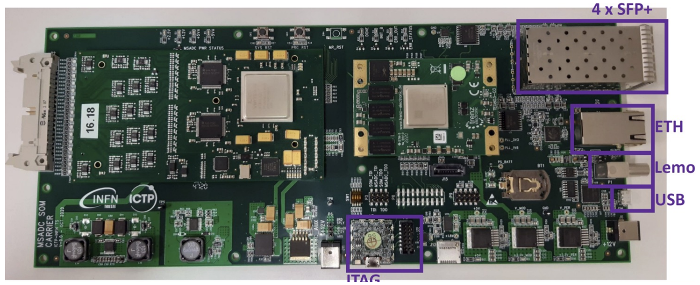


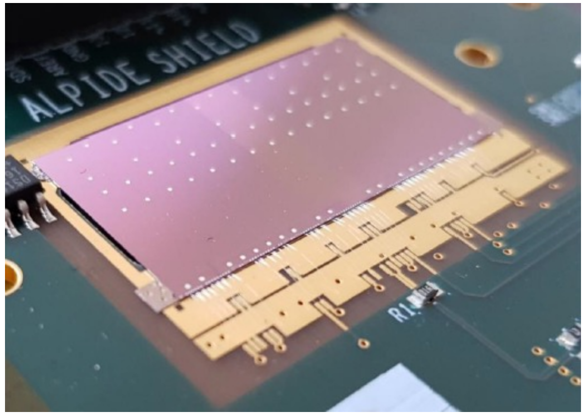
Status of the AMBER Facility preparations: AMBER Spectrometer Upgrades 2

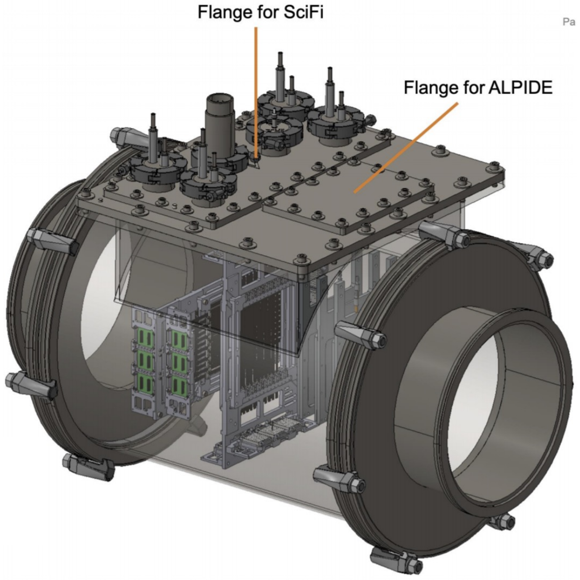
- High-pressure hydrogen filled active TPC (PRM)
- Combined scintillating fibres / silicon tracking system (4 stations) (PRM)
- Triggerless electromagnetic calorimeter electronics (PRM)
- High rate capable silicon-based vertex detector (DY)
- New high-purity and high efficiency di-muon trigger (DY)



ECAL2 DAQ Hardware – Carrier Board III

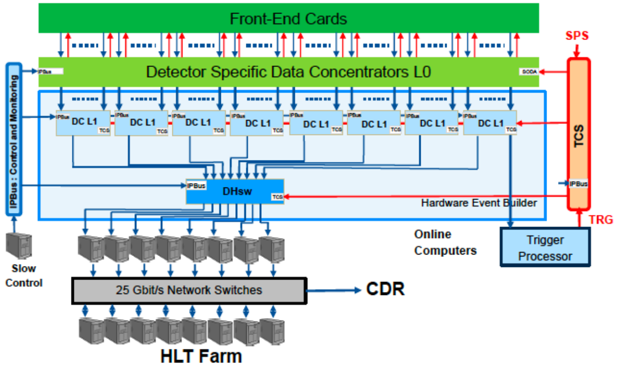




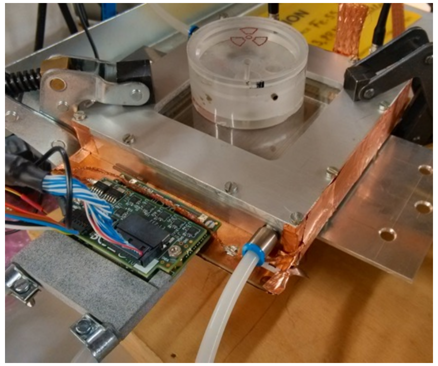


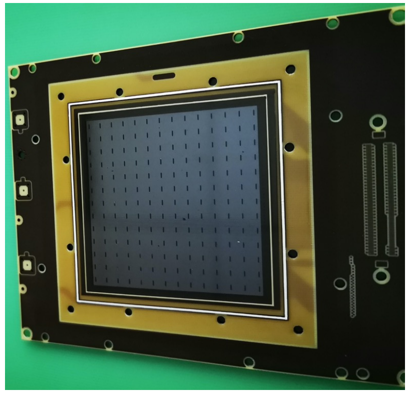
Status of the AMBER Facility preparations:
AMBER Spectrometer Upgrades 1

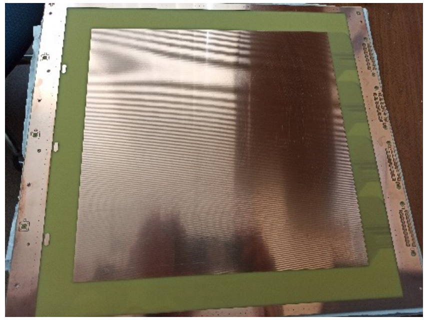
Apparatus for Meson and Baryon
Experimental Research



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

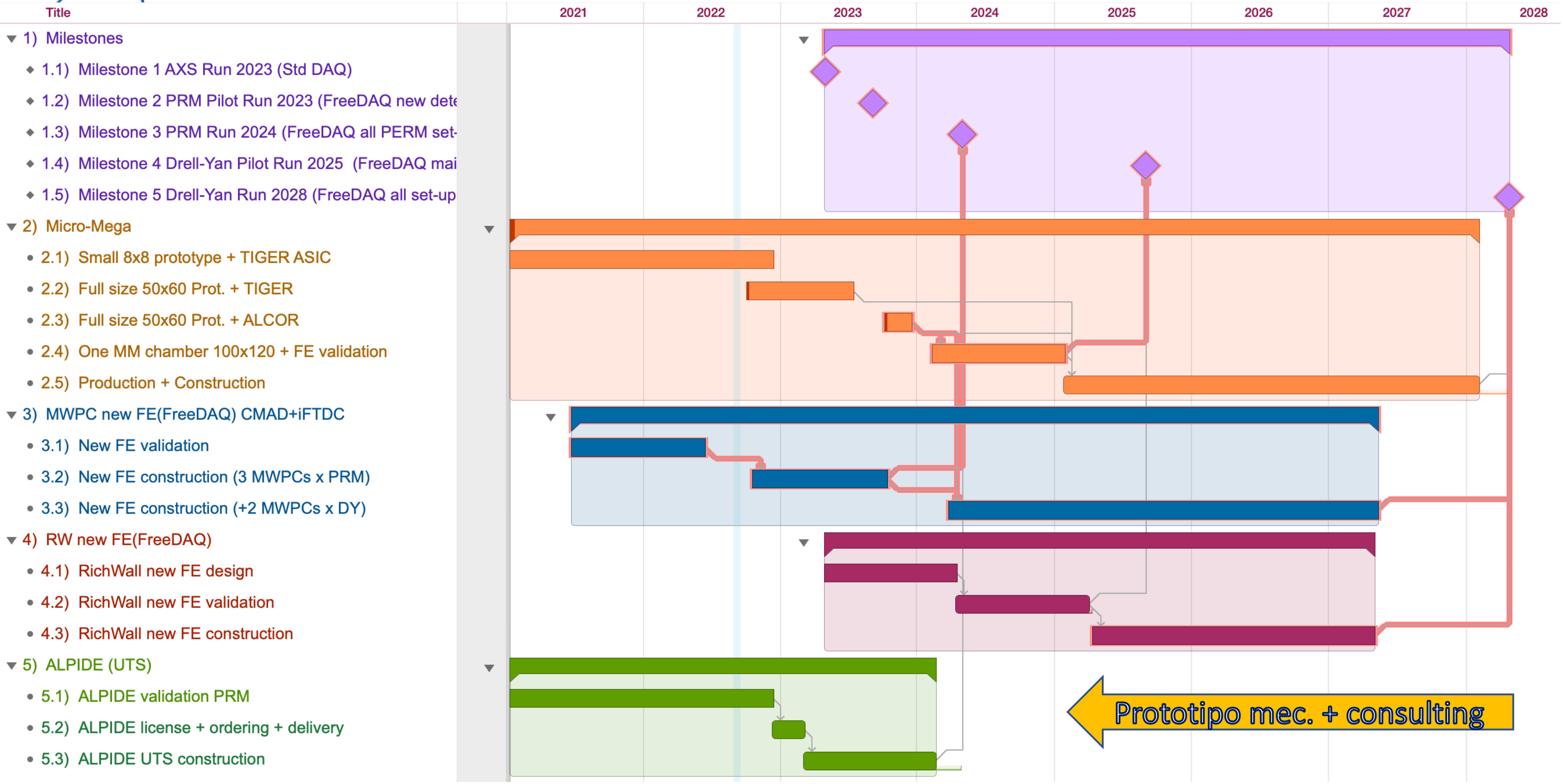






AMBER Phase-1 Torino construction plan

AMBER
Apparatus for Meson and Baryon Experimental Research



- 1) Milestones
  - 1.1) Milestone 1 AXS Run 2023 (Std DAQ)
  - 1.2) Milestone 2 PRM Pilot Run 2023 (FreeDAQ new dete
  - 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

Unified Tracking Station