Meson and proton structure in the new QCD facility at the M2 beam line at CERN

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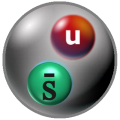
on behalf of COMPASS++/AMBER working team

Motivations

Pion

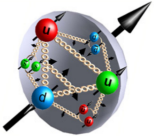
- $M_\pi \sim 140$MeV
- Spin 0
- 2 light valence quarks
- 2 TMD PDFs at LT

Kaon



- $M_K \sim 490$MeV
- Spin 0
- 1 light and 1 “heavy” valence quarks
- 2 TMD PDFs at LT

Proton



- $M_p \sim 940$MeV
- Spin 1/2
- 3 light valence quarks
- 8 TMD PDFs at LT

3 QCD objects, different structures, different properties, understanding differences and similarities teaches us about QCD

Almost all what we know about pion structure

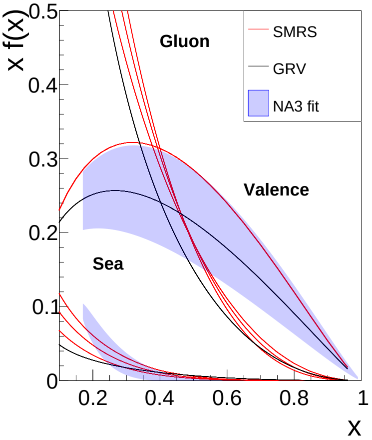
GRV: M. Gluck et al, Z.Phys.C **53** (1992) 651-655

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

Example with three fits:

- Large untainties or not even at all
- Not enough data to directly constrain all PDFs → use of: momentum sum rules, constituent quark model...
- Sea no direct constraints

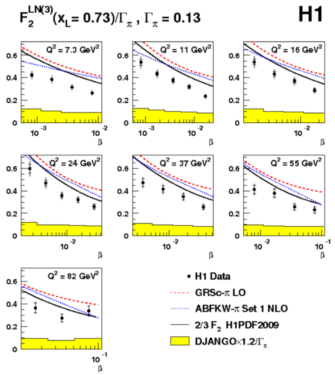
More data is needed, with better control of uncertainties, and full error treatment.



How to access the sea

DIS with di-jet and leading neutron

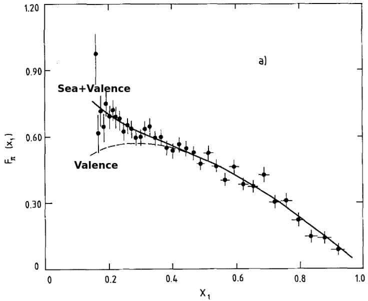
Aaron et al. Eur. Phys. J. C68, 2010



- Wide x coverage
- Estimation of pion flux introduces a strong model dependence

Drell-Yan NA3

Badier *et al.*, Z. Phys. C18, 1983



- Limited statistics:
  4.7k π^--event (shown)
  1.7k π^+-event
- Heavy nuclear target (Pt)

Pion Sea-Valence separation in Drell-Yan

With π^+ and π^- beam with an isoscalar target:

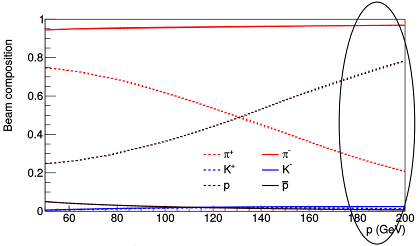
$$\sigma(\pi^+ d) \propto \frac{4}{9}[u^\pi \cdot (\bar{u}^p_s + \bar{d}^p_s)] + \frac{4}{9}[\bar{u}^\pi_s \cdot (u^p + d^p)] + \frac{1}{9}[\bar{d}^\pi \cdot (d^p + u^p)] + \frac{1}{9}[d^\pi_s \cdot (\bar{d}^p_s + \bar{u}^p_s)]$$

$$\sigma(\pi^- d) \propto \frac{4}{9}[u^\pi_s \cdot (\bar{u}^p_s + \bar{d}^p_s)] + \frac{4}{9}[\bar{u}^\pi \cdot (u^p + d^p)] + \frac{1}{9}[\bar{d}^\pi_s \cdot (d^p + u^p)] + \frac{1}{9}[d^\pi \cdot (\bar{d}^p_s + \bar{u}^p_s)]$$

- Assumption:
  - Charge conjugation and SU(2)$_f$ for valence:$u_v^{\pi^+} = \bar{u}_v^{\pi^-} = \bar{d}_v^{\pi^+} = d_v^{\pi^+}$
  - Charge conjugation and SU(3)$_f$ for sea:
    $u_s^{\pi^+} = \bar{u}_s^{\pi^-} = u_s^{\pi^-} = \bar{u}_s^{\pi^+} = \bar{d}_s^{\pi^+} = d_s^{\pi^+} = \bar{d}_s^{\pi^-} = d_s^{\pi^+} = s_s^{\pi^+} = s_s^{\pi^-} = \bar{s}_s^{\pi^+} = \bar{s}_s^{\pi^-}$
- Two linear combination
  - Only valence sensitive:$\Sigma_v^{\pi D} = -\sigma^{\pi^+ D} + \sigma^{\pi^- D} \propto \frac{1}{3} u_v^\pi (u_v^p + d_v^p)$
  - Sea sensitive :$\Sigma_s^{\pi D} = 4\sigma^{\pi^+ D} - \sigma^{\pi^- D}$

Opportunity at the CERN M2 beamline

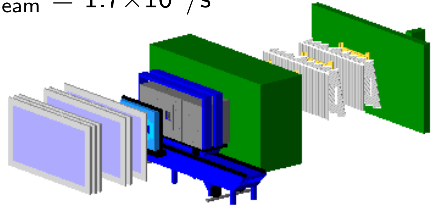
High energy and intensity pion beams

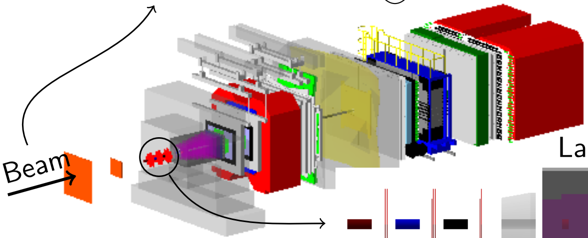


Example @ 190 GeV:

$I_{\pi^-} \sim I_{beam} = 7.0\times10^7/s$

$I_{\pi^+} \sim 25\%\ I_{beam} = 1.7\times10^7/s$

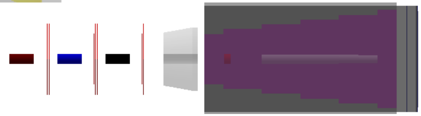


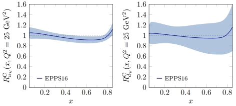


COMPASS-like apparatus

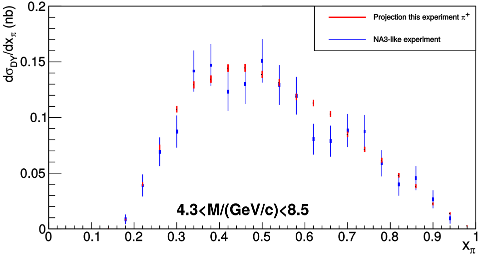
Large acceptance: $8mrad < \theta < 160mrad$

Segmented Carbon target:





Projection Pions (2 years)

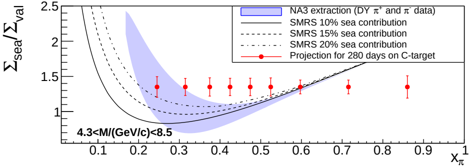


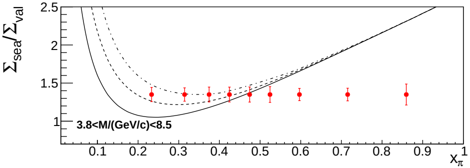
Expected accuracy compared to NA3 result

- Collect at least a **factor 10 more statistics** than presently available
- Aim at the first precise direct measurement of the pion sea contribution

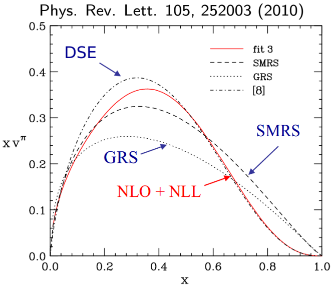
$\Sigma_{val} = \sigma^{\pi^- C} - \sigma^{\pi^+ C}$: only valence-valence

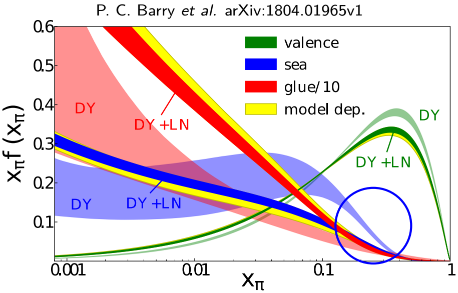
$\Sigma_{sea} = 4\sigma^{\pi^+ C} - \sigma^{\pi^- C}$: no valence-valence

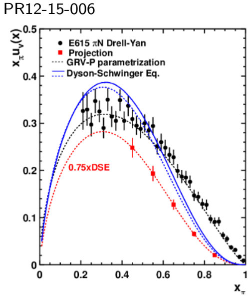




Renewed interest in pion structure







- Agreement restored between DSE and fit to data at NLL
- First extraction of PDFs with Hera data (DIS with leading neutron)
- Foreseen measurement of Tagged DIS at JLab and at EIC

Aim for direct data in the circled area and check the method for Tagged DIS

Pion induced Drell-Yan statistics

Experiment	Target type	Beam energy (GeV)	Beam type	Beam intensity (part/sec)	DY mass (GeV/c^2)	DY events
E615	20cm W	252	π^+ π^-	17.6×10^7 18.6×10^7	4.05 – 8.55	5,000 30,000
NA3	30cm H_2	200	π^+ π^-	2.0×10^7 3.0×10^7	4.1 – 8.5	40 121
NA3	6cm Pt	200	π^+ π^-	2.0×10^7 3.0×10^7	4.2 – 8.5	1,767 4,961
NA10	120cm D_2	286 140	π^-	65×10^7	4.2 – 8.5 4.35 – 8.5	7,800 3,200
NA10	12cm W	286 140	π^-	65×10^7	4.2 – 8.5 4.35 – 8.5	49,600 29,300
COMPASS 2015 COMPASS 2018	110cm NH_3	190	π^-	7.0×10^7	4.3 – 8.5	35,000 52,000
This exp	100cm C	190	π^+	1.7×10^7	4.3 – 8.5 3.8 – 8.5	**23,000** 37,000
This exp	100cm C	190	π^-	6.8×10^7	4.3 – 8.5 3.8 – 8.5	22,000 34,000
This exp	24cm W	190	π^+	0.2×10^7	4.3 – 8.5 3.8 – 8.5	7,000 11,000
This exp	24cm W	190	π^-	1.0×10^7	4.3 – 8.5 3.8 – 8.5	6,000 9,000

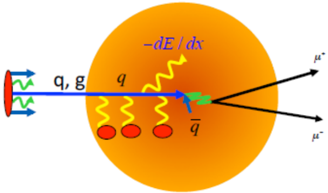
Also 100 of thousands of J/ψ available for free

Parallel measurements with an additional nuclear target

Energy loss:

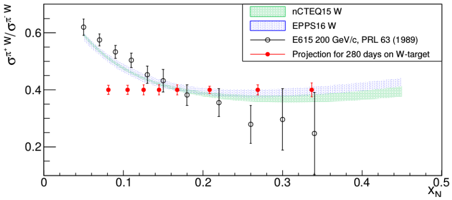
- Multiple scattering of incoming quark in large nuclei
- No energy loss in the final state

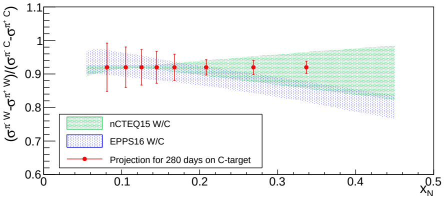
→ Comparison between DY and J/ψ complementary information



Flavour dependent EMC effect: Meson induced Drell-Yan process tags flavours

Using two π beam charges and two targets, one can add constraints on the EMC flavour dependence



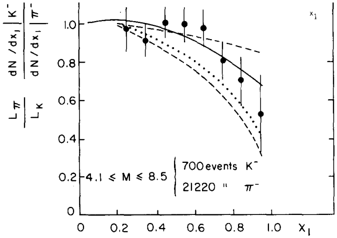


What do we know about kaon structure?

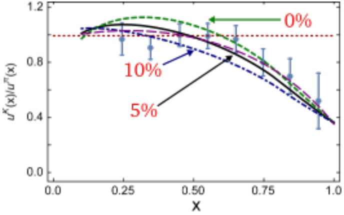
Sole measurement from NA3

J. Badier *et al.*, PLB93 354 (1984)

- Limited statistics: 700 events with K^-
- Sensitivity to $SU(3)_f$ breaking
- Mostly only model predictions



C. Chen *et al.*, PRD 93 074021, 2016

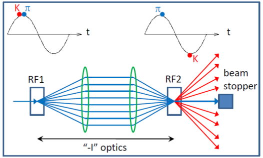


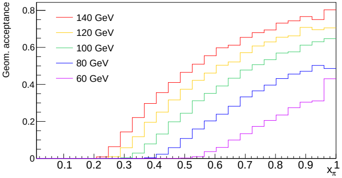
Interesting observation: At hadronic scale gluons carry only 5% of K's momentum *vs* ~30% in π

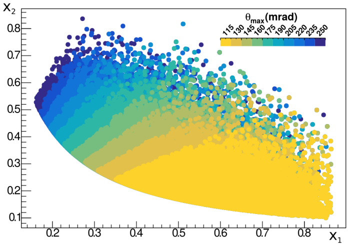
- Scarce data on *u*-valence
- No measurements on gluons
- No measurements on sea quarks

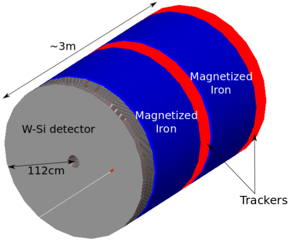
How to improve the situation?

Unique opportunities with RF separated beam







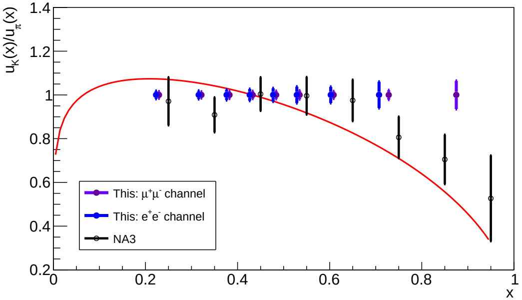


- Enriched K and $\bar{p}$ beams ($\sim 3 \times 10^7$/s)
- Expected energies: $\sim$ 80 (110) GeV for K($\bar{p}$)
  - Small cross-section in HM
  - Lepton pairs emmitted at large angles

Necessity to rethink the concept of DY absorber:

- Tracking with magnetic field
- Good resolution for vertexing
- Capability to collect e^+e^- DY pairs

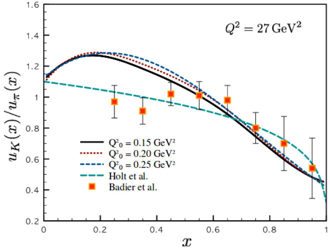
R&D necessary



- More data points and more precise compared to NA3
- Discriminating power between models
- 1 year with $2 \times 10^7\ s^{-1}$ 100 GeV K^- beam
- π taken simultanously

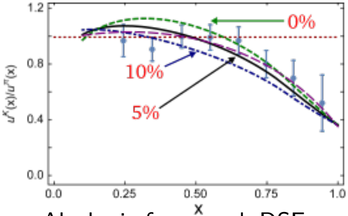
Unique and Promising

S-i. Nam PRD 86, 074005, 2012



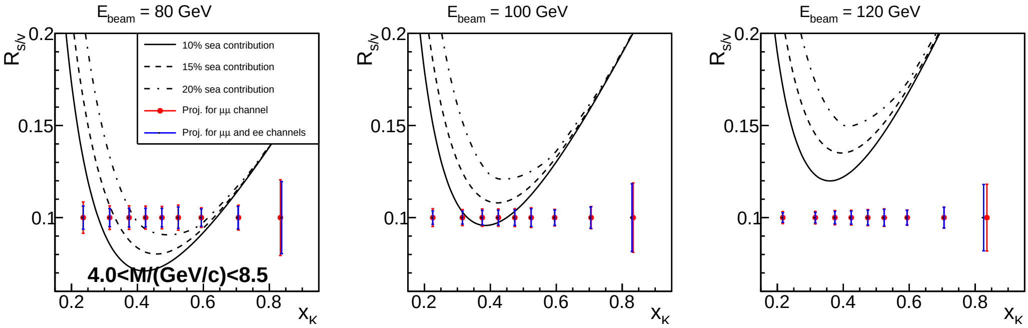
Gauge-invariant nonlocal chiral-quark model

C. Chen *et al.*, PRD 93 074021, 2016



Algebraic framework DSE

Projections for valence/sea separation for Kaons

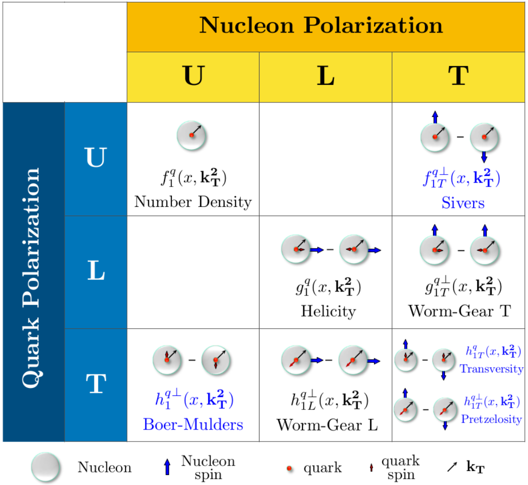


- **First measurement of sea in kaons**
- Requires an additional year with K^+ beam to complement the former K^- data
- Assuming the intensity for K^+ and K^-: $2 \times 10^7\ s^{-1}$

Gluon contribution addressed by prompt photon production → see Barbara Badelek

Transverse momentum dependent PDFs

So far, I talked only about mesons but what about the nucleon?



At LO QCD, the nucleon can be decomposed into 8 twist-2 TMD PDFs.

Using a transversally polarised target, one can access in SIDIS as well as in Drell-Yan:

- Sivers
- Transversity
- Pretzelosity

Synergy DY *vs* SIDIS

DY:					SIDIS:			
$A_{UU}^{\cos(2\phi)}$	$\propto h_{1,h}^{\perp q}$	$\otimes$	$h_{1,p}^{\perp q}$	Boer-Mulders	$A_{UU}^{\cos(2\phi_h)}$	$\propto h_{1,p}^{\perp q}$	$\otimes$	$H_{1q}^{\perp h}$
$A_{UT}^{\sin(\phi_S)}$	$\propto f_{1,h}^{q}$	$\otimes$	$f_{1T,p}^{\perp q}$	Sivers	$A_{UT}^{\sin(\phi_h-\phi_S)}$	$\propto f_{1T,p}^{\perp q}$	$\otimes$	D_{1q}^{h}
$A_{UT}^{\sin(2\phi-\phi_S)}$	$\propto h_{1,h}^{\perp q}$	$\otimes$	$h_{1,p}^{q}$	Transversity	$A_{UT}^{\sin(\phi_h+\phi_S)}$	$\propto h_{1,p}^{q}$	$\otimes$	$H_{1q}^{\perp h}$
$A_{UT}^{\sin(2\phi+\phi_S)}$	$\propto h_{1,h}^{\perp q}$	$\otimes$	$h_{1T,p}^{\perp q}$	Pretzelosity	$A_{UT}^{\sin(3\phi_h-\phi_S)}$	$\propto h_{1T,p}^{\perp q}$	$\otimes$	$H_{1q}^{\perp h}$

TMD PDFs are **universal** but
final state interaction (SIDIS) *vs.* initial state interaction (DY)
$\rightarrow$ **Sign flip** for naive T-odd TMD PDFs

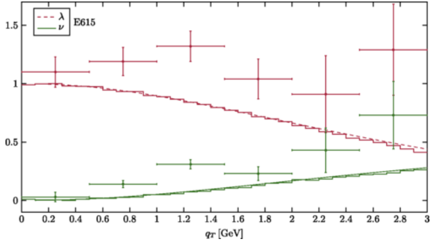
$$f_{1T}^{\perp q}|_{SIDIS} = -f_{1T}^{\perp q}|_{DY}$$
$$h_{1}^{\perp q}|_{SIDIS} = -h_{1}^{\perp q}|_{DY}$$

Crucial test of TMD framework in QCD addressed by COMPASS

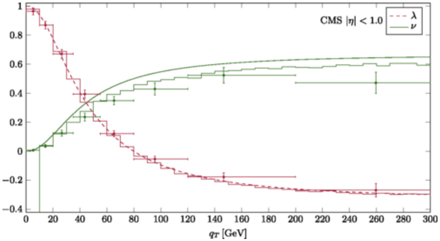
We propose to address the question again with:
$\rightarrow$ Anti-proton beam and polarised target
$\rightarrow$ Extra constraints on proton Boer-Mulders function

QCD effects *vs* Boer-Mulders effects

E615 PRD 39, 92 (1989)



CMS PLB 750, 154 (2015)



Recent evidence in terms of QCD: radiative effects describe well data at large q_T

J.-C. Peng *et al.* PLB 758, 384 (2016)

M. Lambertsen and W. Vogelsang PRD93, 114013 (2016)

- Boer Mulders expected at low q_T $\rightarrow$ fixed target regime
- To single out Boer Mulders effects very precise data are necessary

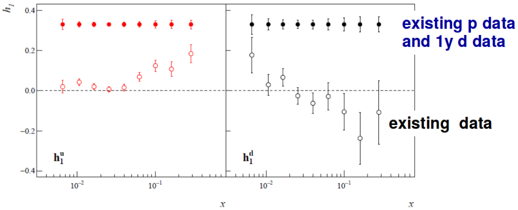
Anti-proton beam: Synergy DY and SIDIS

Additional insight with $\bar{p}$ on Boer Mulders (private exchange with Andreas Metz)

- Transversity modulation less affected by QCD effects
- Smooth matching between TMD approach and QCD

$\rightarrow$ Extract transversity from SIDIS $A_{UT}^{sin(\phi_h+\phi_S)} \propto h_{1,p}^{q} \otimes H_{1q}^{\perp h}$ measurements

u and d quark Transversity PDFs



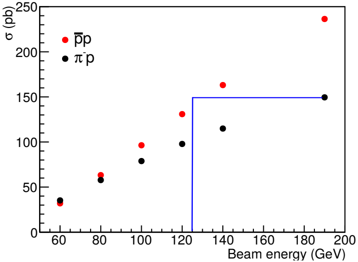
- Use DY measured $A^{sin(2\phi-\phi_S)} \propto h_{1,h}^{\perp q} \otimes h_{1,p}^{q}$ and SIDIS transversity knowledge

Obtain Boer-Mulders $h_1^{\perp q}$ for **proton and meson with antiproton and meson beams**

Complementary to SIDIS, where Cahn effects can be difficult to disentangle from Boer-Mulders effects

Anti-proton with a RF separated beam

Possibility to study valence proton TMD PDFs in a model free way

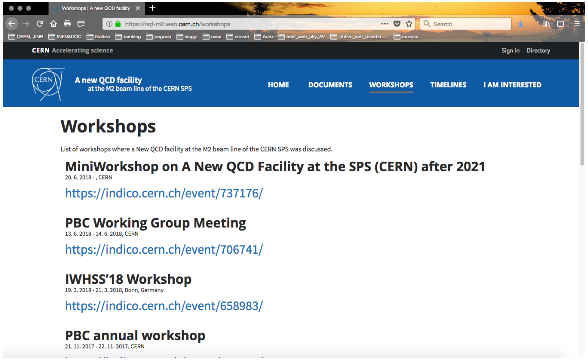


- cross-sections for $\bar{p}$ induced-DY at 120 GeV $\sim$ π^- induced-DY at 190 GeV
- Combined statistics from $\mu^+\mu^-$ and e^+e^- channels $\sim$ 2 years of COMPASS-II data taking
- With active absorber: better acceptance in θ_{CS}

Experiment	Target type	Beam type	Beam intensity (part/sec)	Beam energy (GeV)	DY mass (GeV/c^2)	DY events $\mu^+\mu^-$	DY events e^+e^-
This exp.	110cm NH_3	$\bar{p}$	3.5×10^7	100	4.0 – 8.5	28,000	21,000
				120	4.0 – 8.5	40,000	27,300
				140	4.0 – 8.5	52,000	32,500

A new QCD facility

- Letter of Intent
  arXiv:1808.00848
  DY, Spectroscopy, muon-p elastics scattering, . . .
- A web page
- Can register to stay informed



New ideas and collaborators are welcome

Proposal in preparation to be submitted this year

Outlook

Near term future: Current beams

- **Precise** determination of **pion structure** and valuable inputs for nuclear effects (nPDFs, EMC, J/ψ, ...)

Long term future: RF-separated beams

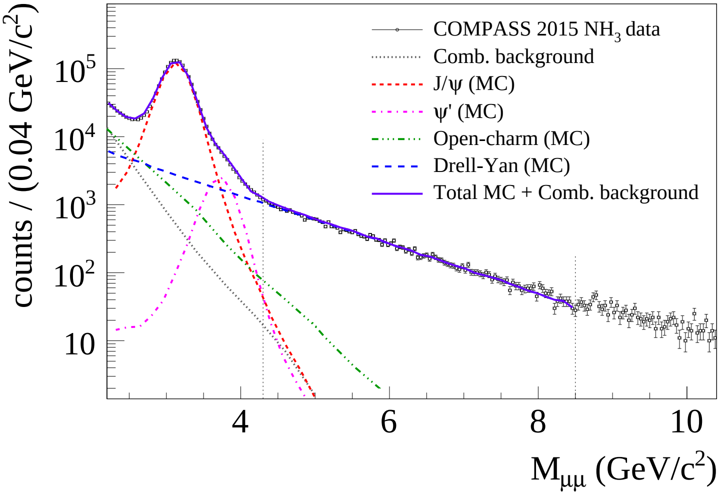
- **Unprecedented** studies of **Kaon structure**
- **Unique** opportunity to study **proton valence TMD PDFs** in a model free way

Many other valuables measurements described in the LoI for both short and long term future

$\rightarrow$ see also Barbara Badelek, Sergey Gevorkyan and Christian Dreisbach

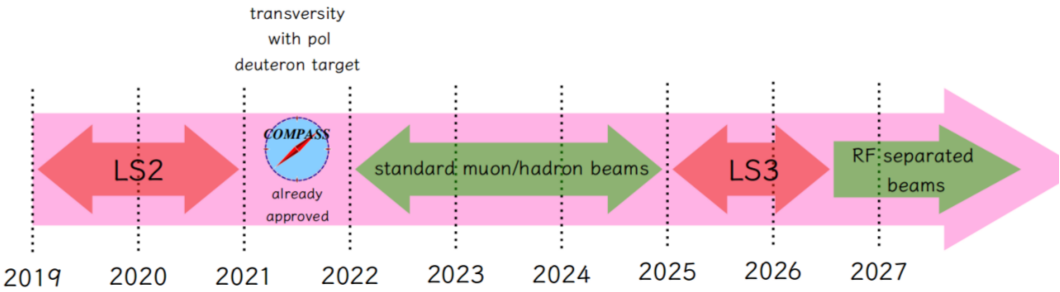
BACKUP

Mass spectrum



Background less than 4% in $4.3 < M_{\mu\mu}/(GeV) < 8.5$

Cern accelerator schedule



LS = long shutdown of CERN accelerators

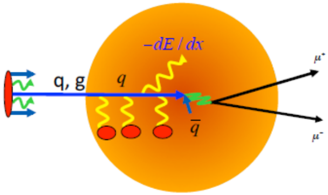
Parallel studies

Energy loss:

- Multiple scattering of incoming quark in large nuclei
- No energy loss in the final state

→ Fixed target regime especially suited

→ Comparison between DY and J/ψ complementary information

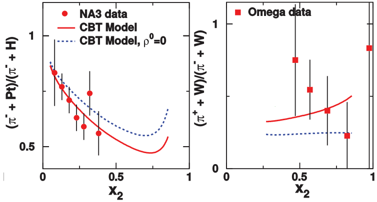


Flavour dependent EMC effect:

Iso-vector ρ^0 mean field generated in $N \neq Z$ nuclei can modify nucleon's u and d PDF differently

- NA3 π on Pt favours flavour dependence
- Omega π on W not conclusive

→ Meson induced Drell-Yan process tags flavours



Kaon induced Drell-Yan statistics

Experiment	Target type	Beam type	Beam intensity (part/sec)	Beam energy (GeV)	DY mass (GeV/c^2)	DY events $\mu^+\mu^-$	DY events e^+e^-
NA3	6 cm Pt	K^-		200	4.2 – 8.5	700	0
This exp.	100 cm C	K^-	2.1×10^7	80	4.0 – 8.5	25,000	13,700
				100	4.0 – 8.5	40,000	17,700
				120	4.0 – 8.5	54,000	20,700
		K^+	2.1×10^7	80	4.0 – 8.5	2,800	1,300
				100	4.0 – 8.5	5,200	2,000
				120	4.0 – 8.5	8,000	2,400
This exp.	100 cm C	π^-	4.8×10^7	80	4.0 – 8.5	65,500	29,700
				100	4.0 – 8.5	95,500	36,000
				120	4.0 – 8.5	123,600	39,800

Achievable statistics of the new experiment, assuming 2×140 days of data taking with equal time sharing between the two beam charges. For comparison, the collected statistics from NA3 is also shown.

Requirements per topic

Program	Beam Energy [GeV]	Beam Intensity [/s]	Trigger Rate [kHz]	Beam Type	Target	Hardware Additions	R	C
Proton radius	100	$4 \cdot 10^6$	100	$\mu^\pm$	high-pr. H2	active TPC, SciFi trigger, silicon veto		
GPD E	160	10^7	10	$\mu^\pm$	NH3↑	recoil silicon, modified PT magnet		
Anti-matter	190	$5 \cdot 10^5$	25	p	LH2, LHe	recoil TOF	×	×
Spectroscopy $\bar{p}$	12, 20	$5 \cdot 10^7$	25	$\bar{p}$	LH2	target spectrometer: tracking, calorimetry	×	×
Drell-Yan conv	190	$6.8 \cdot 10^7$	25	$\pi^\pm$	C/W	vertex detector		×
Drell-Yan RF	∼100	10^8	25-50	$K^\pm$, $\bar{p}$	NH_3 ↑, C/W	"active absorber", vertex detector		×
Primakoff	∼100	$5 \cdot 10^6$	> 10	K^-	Ni		×	×
Prompt photon	100	$5 \cdot 10^6$	10-100	K^+	LH2	hodoscope		×
Spectroscopy K^-	50-100	$3.7 \cdot 10^6$	25	K^-	LH2	recoil TOF	×	×

Requirements for the future programs at the M2 beam line after 2021.. Standard muon beams are in blue, standard hadron beams in orange, and RF-separated hadron beams in red. The common baseline is the COMPASS-II setup without RICH-1. “R” refers to RICH-1 and if possible RICH-0, “C” to CEDARs.