Hadron structure measurements at the M2 beamline at CERN

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on behalf of the AMBER collaboration

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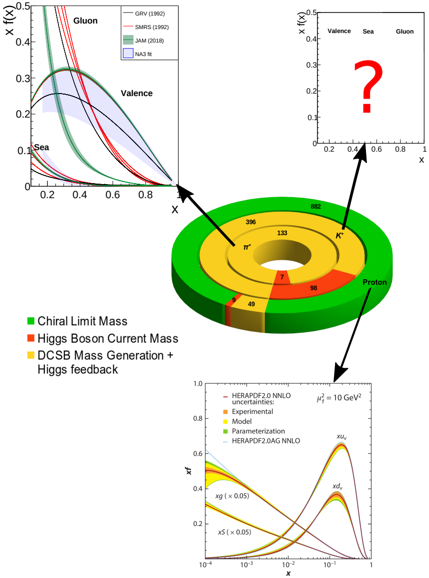
Perceiving the emergence of hadron mass

Different origin of the mass budget of π, K, p,
it must be reflected in the structure: PDF and PDA

What is the status?

- Proton: the best known particle
- Pion: basic but in improvement
- Kaon: basically nothing

Where and How can we contribute?

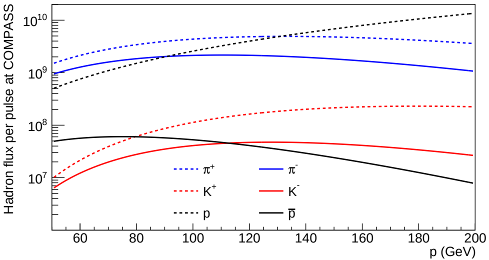


M2 beamline at CERN

Present beams:

- Unique high intensity meson beams
- High energy beams

$\Rightarrow$ Potential for π, K and $\bar{p}$ studies:
$\approx 10^8$K$/\bar{p}$ per spill



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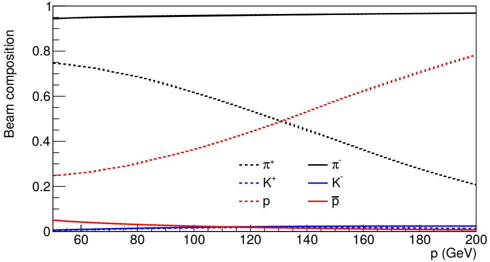
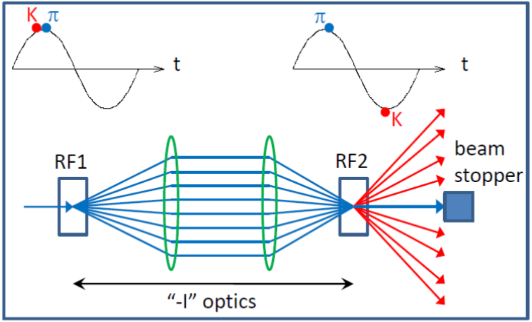


However, EHN2 is a surface area $\Rightarrow$ total intensity set by Radio-Protection limitation

We need to remove the unwanted particles before reaching the experimental hall

Opportunity with RF separated beam

- Deflection with 2 cavities
- Relative phase $= 0 \rightarrow$ dump
- Deflection of wanted particle given by
  $\Delta\phi \approx \frac{\pi f L}{c} \frac{m_w^2 - m_u^2}{p^2}$



To keep good separation:

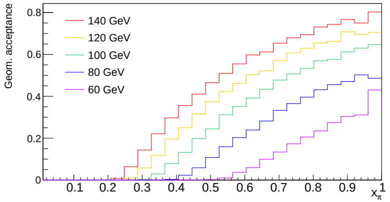
L should increase as p^2 for a given $f \rightarrow$ limits the beam momentum

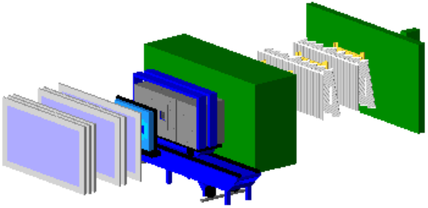
Initial expectations under study and *R&D*:

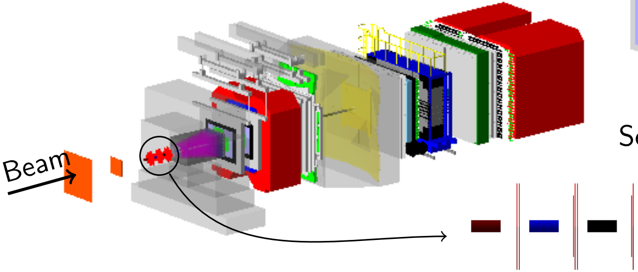
$\sim$ 80 GeV Kaon beam

$\sim$ 110 GeV Anti-proton beam

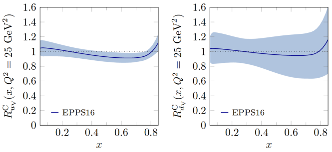
Dramatic effect on geometrical acceptance ⇒ to be redesigned for Phase-2







Segmented Carbon target:



Improvement of acceptance: Compress the spectrometer

<u>Requirements: Active absorber</u>

- Trackers
- Magnetic field
- Good resolution for vertexing
- Large area
- Capabilitity to collect e^+e^- DY pairs

<u>Initial detector consideration:</u>

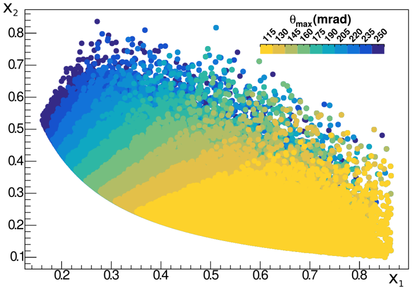
Combination of

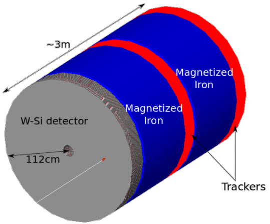
- Baby-Mind detector

  M. Antonova *et al.* arXiv:1704.08079

- W-Si detectors, a la BNL

  AnDY | Phenix MPCEX | Phenix NCC

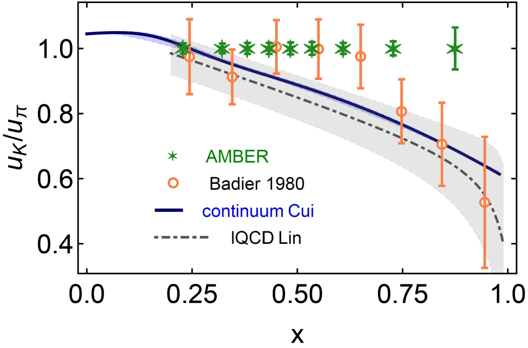




Kaon structure: up quark

140 days with $2 \times 10^7\ s^{-1}$ 100 GeV K^- beam:

Z-F. Cui, *et al.* EPJC80(2020)1064, H-W. Lin *et al.*, PRD103(2021)014516



$$\frac{\sigma_{DY}^{K^- C}}{\sigma_{DY}^{\pi^- C}} \approx \frac{u_K}{u_\pi}(x)$$

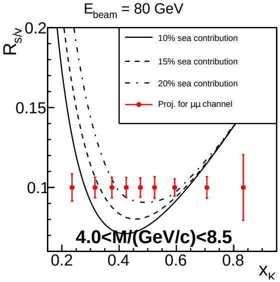
Experiment	Target type	Beam type	Beam intensity (part/sec)	Beam energy (GeV)	DY mass (GeV/c^2)	DY events $\mu^+\mu^-$
NA3	6 cm Pt	K^-		200	4.2 – 8.5	700
This exp.	100 cm C	K^-	2.1×10^7	80	4.0 – 8.5	**25,000**
				100	4.0 – 8.5	40,000
				120	4.0 – 8.5	54,000
This exp.	100 cm C	π^-	4.8×10^7	80	4.0 – 8.5	**65,500**
				100	4.0 – 8.5	95,500
				120	4.0 – 8.5	123,600

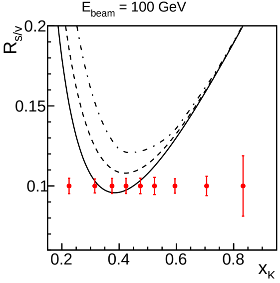
π data taken simultaneously (from beam impurity)

Enlarge world data statistics by a factor 30

Determine u_K/u_π within a few percent

Projections for valence/sea separation for Kaons





- **First measurement of sea in kaons**:
  $R_{s/v} = \frac{\sigma^{K^+C}}{\sigma^{K^-C} - \sigma^{K^+C}}$, Londergan, *et al.* PLB 380 (1996)
- Requires an additional year with K^+ beam to complement the former K^- data
- Assuming the intensity for K^+ and K^-: $2 \times 10^7\ s^{-1}$

Experiment	Target type	Beam type	Beam intensity (part/sec)	Beam energy (GeV)	DY mass (GeV/c^2)	DY events $\mu^+\mu^-$
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				100	4.0 – 8.5	40,000
				120	4.0 – 8.5	54,000
		K^+	2.1×10^7	80	4.0 – 8.5	**2,800**
				100	4.0 – 8.5	5,200
				120	4.0 – 8.5	8,000

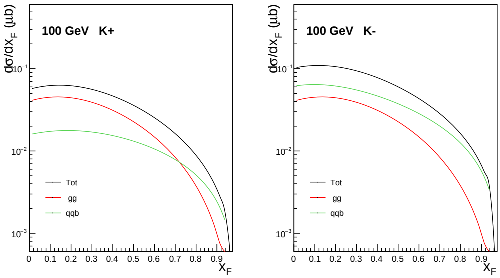
Parallel measurements with J/ψ production: up quark content

Purely strong interaction: all partons contribute on the same footing

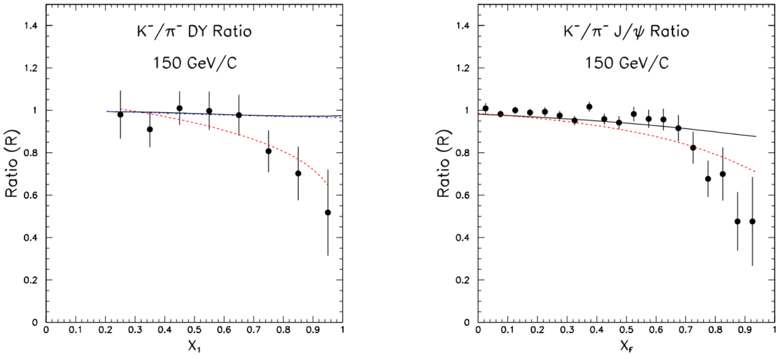
Using two kaon beam charges, one can access:

- $\bar{u}^K u^N \propto \sigma^{K^-}_{J/\psi} - \sigma^{K^+}_{J/\psi}$
- Infer the kaon gluon distribution from a model dependent way

J/ψ subprocess contribution as obtained from Color Evaporation Model



Parallel measurements with J/ψ production: up quark content



- NA3 experiment measured a similar suppression of K/π at large x_F

J. Badier *et al.* Phys. Lett. B93, 354 (1980), Z. Phys. C20, 101 (1983)

- Same modelisation of Kaon PDFs describe the cross-section ratios similarly well

J.C. Peng *et al.* arXiv:1711.00839

- AMBER will provide measurements at least 30 times more precise

Parallel measurements with J/ψ production: gluon content

Following the approach with a π beam: see talk from S. Platchkov

J/ψ polarisation can be used to determine the fraction of quark/gluon content

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

- ICEM prediction
  - $\lambda_{\theta}^{CS} \approx +0.4$ for $q\bar{q}$
  - $\lambda_{\theta}^{CS} \approx -0.6$ for gg
- Minimal model dependence

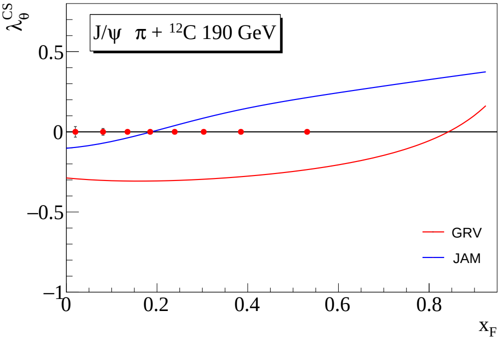
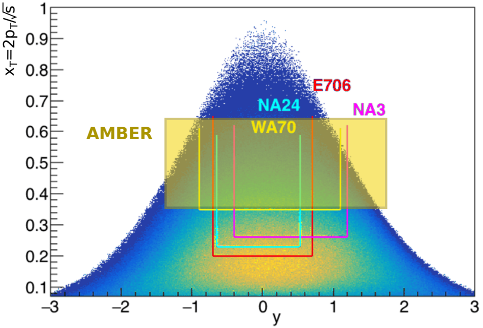
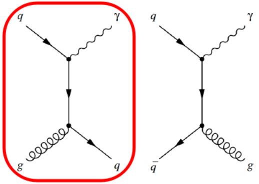


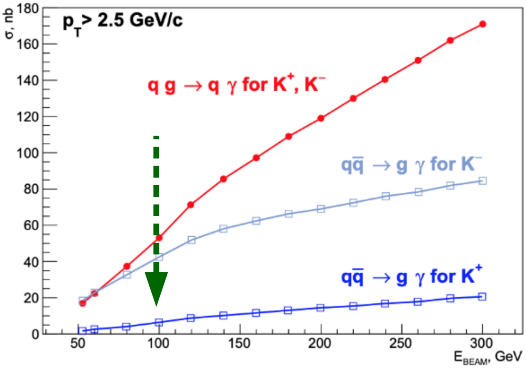
Illustration of the sensitivity with pion beam

Alternative access to gluon content: Prompt photon production

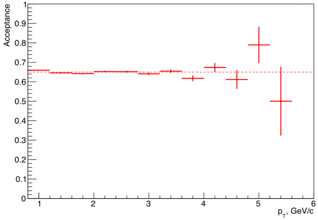
- Direct access to gluon via $gq \to q\gamma$
- $E_K \gtrsim 100$ GeV for signal dominance

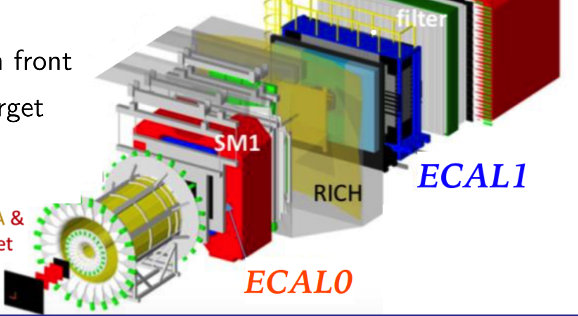






Acceptance for 100 GeV K beam

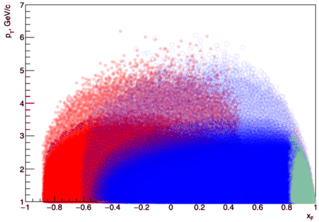


Shielding in front

of the target

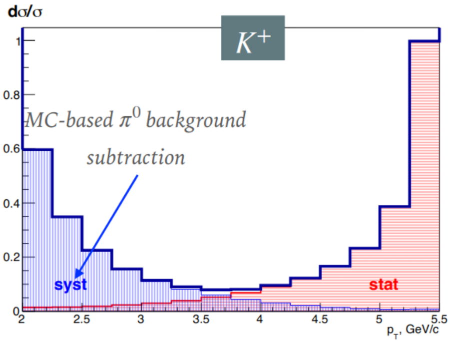
Calorimetry coverage



Experimental challenge

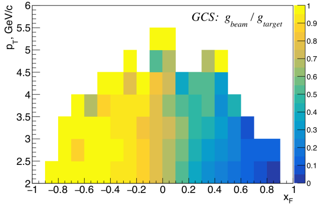
- Huge background from π^0, η, ... decays
- Precise MC simulations needed
- Precise knowledge of minimum bias photon

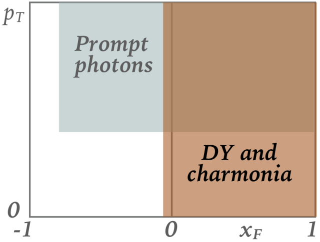
Measurement foreseen with K^+ and π to ensure systematics are under control



Experiment	Target type	Beam type	Beam Intensity (part/sec)	Beam Energy (GeV)	$\int \mathcal{L}$ (pb^{-1})	p_T range (GeV/c)	prompt-photon events
WA70	1m lH_2	π^+	2.5×10^6	280	1.3	$4 < p_T < 7$	—
		π^-	1.25×10^7	280	3.5	$4 < p_T < 7$	—
COMPASS++/AMBER	2m lH_2	K^+	2×10^7	100	50	$p_T > 2.5$	3.4×10^6
		π^+	2×10^7	100	50	$p_T > 2.5$	3.4×10^6

Complementarity between measurements and setups





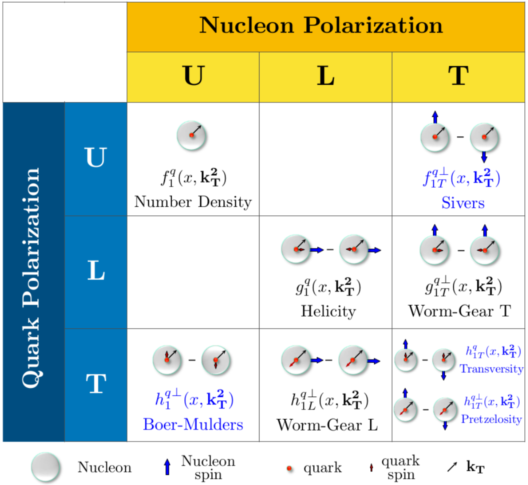
Charmonia and prompt photon production
$\Rightarrow$covering different phase-space

Open spectrometer $\rightarrow$ access to ψ' and χ_c states

- Extensive study of charmonia production mechanisms
- Additional input for gluon PDF in the Kaons

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

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

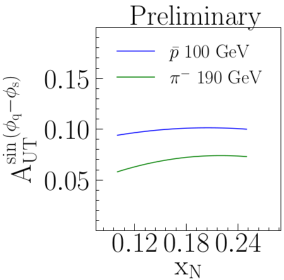
Crucial test of TMD framework in QCD addressed by COMPASS

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

Anti-proton with a RF separated beam

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

J. Terry, EHM 03/12/2020



- cross-sections for $\bar{p}$ induced-DY at 120 GeV $\sim \pi^-$ 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

Summary

Using an RF-separated beam and

- Drell-Yan lepton production
- Charmonia production
- Prompt photon production,

AMBER will map the Kaon structure with unprecedented statistics

Complementary measurements will be performed at the EIC

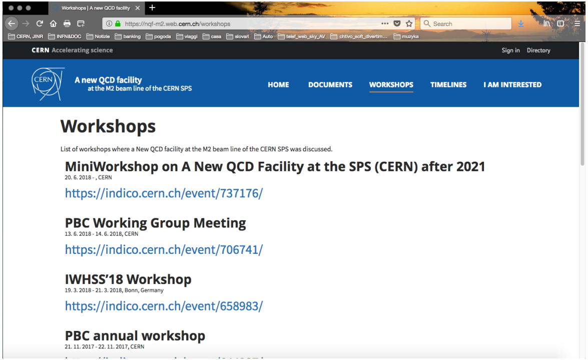
Using an antiproton beam, AMBER will address proton TMD PDFs in a minimised systematic way.

BACKUP

A new QCD facility

- Letter of Intent
  arXiv:1808.00848
  DY, Spectroscopy, muon-p elastics scattering, . . .

- A web page



New ideas and collaborators are welcome

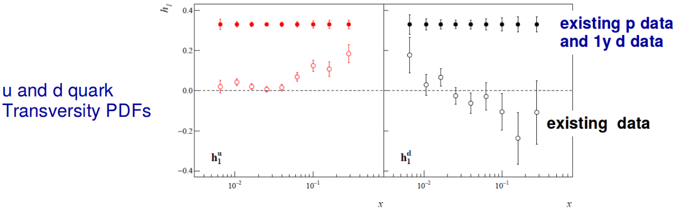
Proposal available

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 radiative effects
- Smooth matching between TMD approach and QCD

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



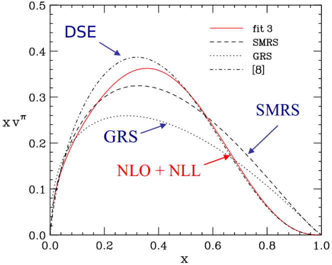
- Use DY measured $A^{sin(2\phi-\phi_S)} \propto h_{1,h}^{\perp q} \otimes h_{1,p}^{q}$ and SIDIS transversity knowledge

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

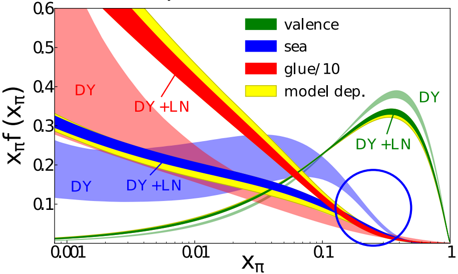
Complementary to SIDIS, where Cahn effects can be difficult to disentangle from Boer-Mulders effects

Renewed interest in pion structure

Phys. Rev. Lett. 105, 252003 (2010)



P. C. Barry *et al.* arXiv:1804.01965v1



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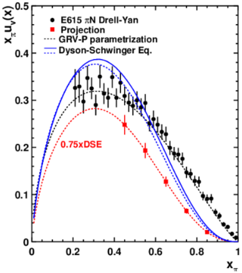

- Agreement between DSE and fit to E615 data at NLO+NLL
- First extraction of PDFs with Hera data (DIS with leading neutron)
- Foreseen measurement of Tagged DIS at JLab and at EIC

Aim for direct data in the circled area

Pion induced Drell-Yan statistics for 2 years

Experiment	Target type	Beam energy (GeV)	Beam type	Beam intensity (part/sec)	DY mass (GeV/c^2)	DY events
E615	20cm **W**	252	π^+	17.6×10^7	4.05 – 8.55	5,000
			π^-	18.6×10^7		30,000
NA3	30cm H_2	200	π^+	2.0×10^7	4.1 – 8.5	40
			π^-	3.0×10^7		121
	6cm **Pt**	200	π^+	2.0×10^7	4.2 – 8.5	1,767
			π^-	3.0×10^7		4,961
NA10	120cm D_2	286	π^-	65×10^7	4.2 – 8.5	7,800
		140			4.35 – 8.5	3,200
	12cm W	286	π^-	65×10^7	4.2 – 8.5	49,600
		140			4.35 – 8.5	29,300
COMPASS 2015	110cm NH_3	190	π^-	7.0×10^7	4.3 – 8.5	35,000
COMPASS 2018						45,000
This exp	100cm **C**	190	π^+	1.7×10^7	4.3 – 8.5	**23,000**
					3.8 – 8.5	37,000
		190	π^-	6.8×10^7	4.3 – 8.5	22,000
					3.8 – 8.5	34,000
	24cm W	190	π^+	0.2×10^7	4.3 – 8.5	7,000
					3.8 – 8.5	11,000
		190	π^-	1.0×10^7	4.3 – 8.5	6,000
					3.8 – 8.5	9,000

Use of lighter and isoscalar target as compared to past experiments