Pion and Kaon structure using Drell-Yan pair production at the M2 beam line at CERN

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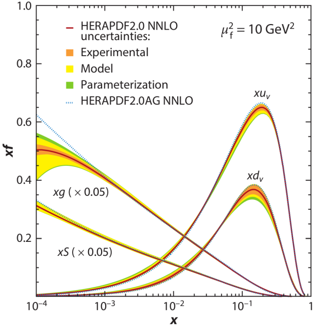
on behalf of COMPASS++/AMBER collaboration

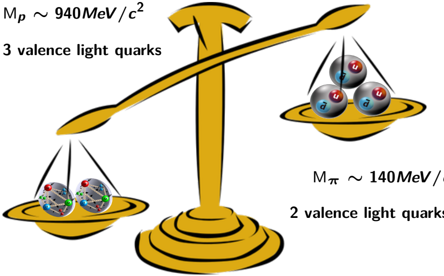
Center for Frontiers in Nuclear Science
Workshop series

How to explain the origin of the mass of composite hadrons?



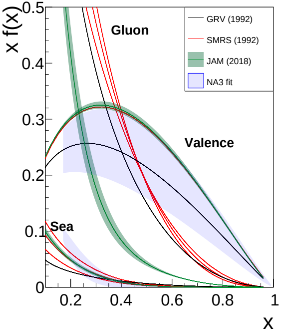
$M_p \sim 940 MeV/c^2$

3 valence light quarks



$M_\pi \sim 140 MeV/c^2$

2 valence light quarks



Knowledge of the nucleon and the **pion PDFs**
is **fundamental to understand the hadrons mass budget.**
Let us study their structure!

Focus on 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

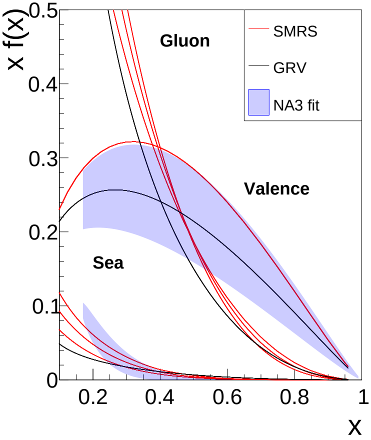
Different results among different groups

Using the same data for **GRV** and **SMRS**:

- π^-DY data from NA10 & E615
  $\rightarrow$ valence
- Prompt photon prod.: WA70 & NA24
  $\rightarrow$ gluon

Independently, **NA3**: π^-/π^+ DY data
$\rightarrow$ valence-sea

Not enough data to directly constrain all PDFs

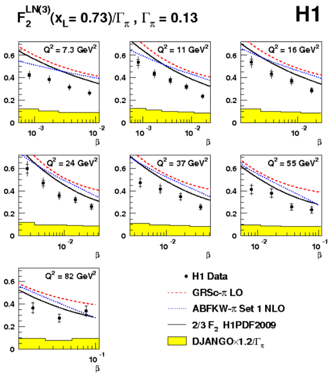


“Sea” means contribution per quark, *i.e.* $\sum_q f_q(x)/6$

How to access the sea

DIS with di-jet and leading neutron

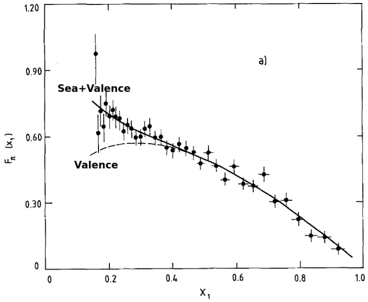
Aaron *et al.* Eur. Phys. J. C68, 2010



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

Drell-Yan NA3

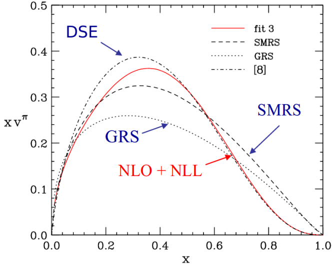
Badier *et al.*, Z. Phys. C18, 1983



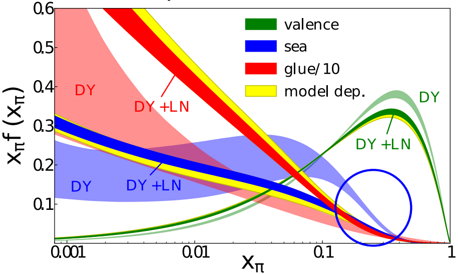
- Limited statistics:
  4.7k π^--event (shown)
  1.7k π^+-event
- Heavy nuclear target (Pt)

Renewed interest in pion structure

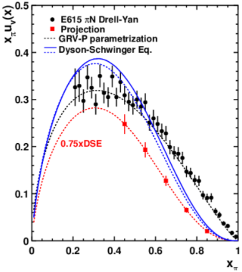
Phys. Rev. Lett. 105, 252003 (2010)



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



PR12-15-006

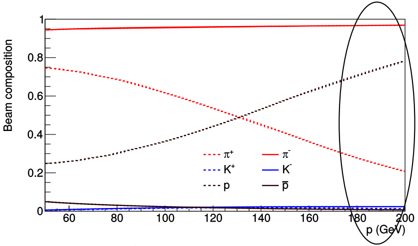


- Agreement between DSE and fit to E615 data at NLO+NLL
- First extraction of PDFs with Hera data (DIS with leading neutron)
- Foreseen measurement of Tagged DIS at JLab and at EIC

Aim for direct data in the circled area

Opportunity at the CERN M2 beamline

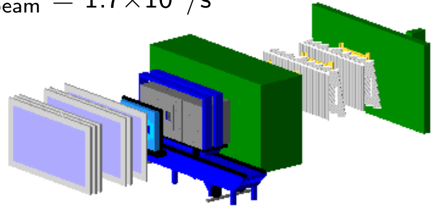
High energy and intensity pion beams

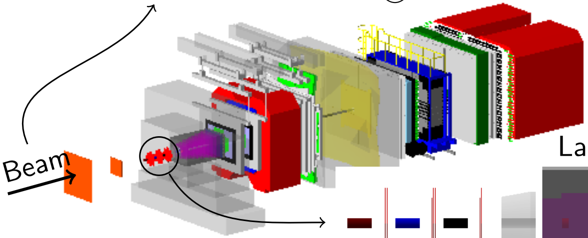


Example @ 190 GeV:

$I_{\pi^-} \sim I_{beam} = 7.0{\times}10^7/s$

$I_{\pi^+} \sim 25\%\ I_{beam} = 1.7{\times}10^7/s$

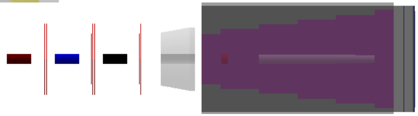


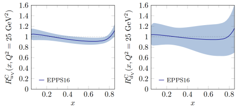


COMPASS-like apparatus

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

Segmented Carbon target:





Pion Sea-Valence separation in Drell-Yan

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

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

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

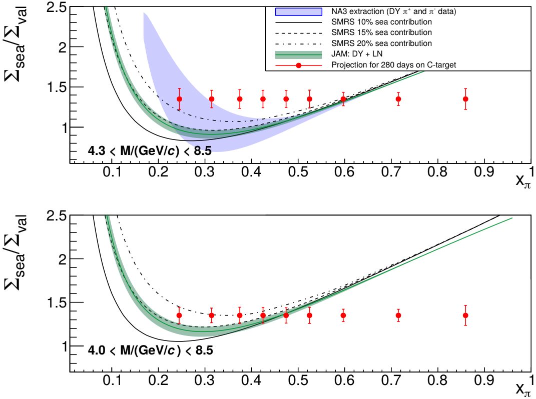
- Assumption:
  - Charge conjugation and SU(2)$_f$ for valence:$u_v^{\pi^+} = \bar{u}_v^{\pi^-} = \bar{d}_v^{\pi^+} = d_v^{\pi^+}$
  - Charge conjugation and SU(3)$_f$ for sea:
    $u_s^{\pi^+} = \bar{u}_s^{\pi^-} = u_s^{\pi^-} = \bar{u}_s^{\pi^+} = \bar{d}_s^{\pi^+} = d_s^{\pi^+} = \bar{d}_s^{\pi^-} = d_s^{\pi^+} = s_s^{\pi^+} = s_s^{\pi^-} = \bar{s}_s^{\pi^+} = \bar{s}_s^{\pi^-}$
- 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 :$\Sigma_s^{\pi D} = 4\sigma^{\pi^+ D} - \sigma^{\pi^- D}$

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^+ 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
	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
	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 45,000
This exp	100cm **C**	190	π^+	1.7×10^7	4.3 – 8.5 3.8 – 8.5	**23,000** 37,000
		190	π^-	6.8×10^7	4.3 – 8.5 3.8 – 8.5	22,000 34,000
	24cm W	190	π^+	0.2×10^7	4.3 – 8.5 3.8 – 8.5	7,000 11,000
		190	π^-	1.0×10^7	4.3 – 8.5 3.8 – 8.5	6,000 9,000

Use of lighter and isoscalar target as compared to past experiments

Projection Pions (2 years)



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

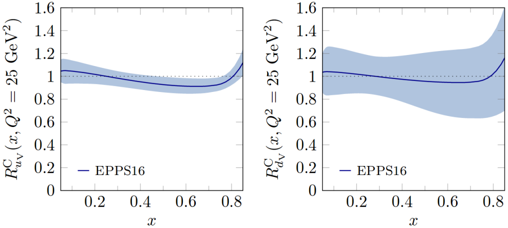
Two mass ranges:

- Safe range: background free top
- Extended with improved mass resolution → vertex detector

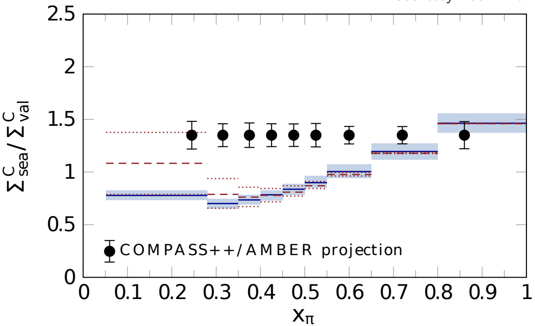
- Aim at the first precise direct measurement of the pion sea contribution
- Collect around a **factor 10 more statistics** than presently available

Impact of carbon target on the measurement

Carbon target is not free of nuclear effects:



Courtesy Paakkinen



However:

- π-PDF uncertainties are dominant in the region of interest
- nPDF mostly contributing in $x_\pi > 0.5$

SMRS: red dashed or dotted lines

EPPS16: blue shadded band

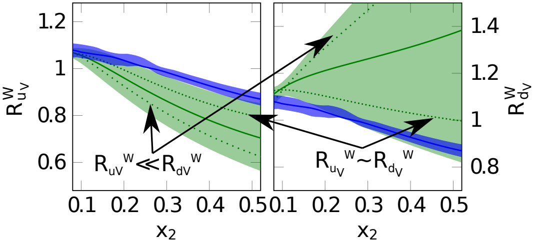
Nuclear dependence studies

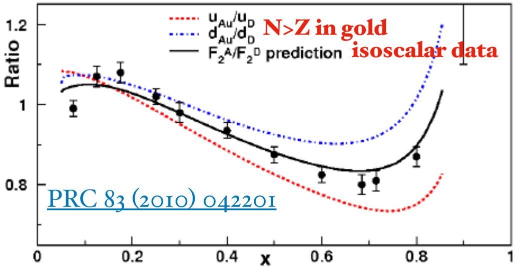
Flavour dependent EMC effect:

Unlike DIS, π-induced Drell-Yan process tags the quark flavour

nCTEQ15: unconstrained flavour dependence

EPS09: no flavour dependence





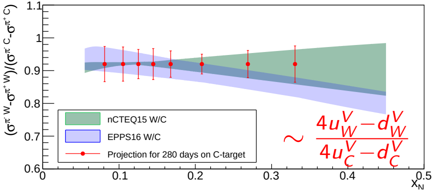
Energy loss:

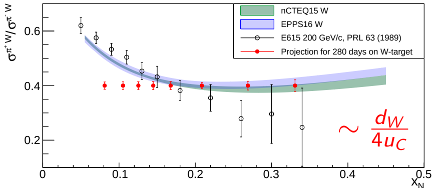
- Multiple scattering of incoming quark in large nuclei
- No energy loss in the final state

→ Comparison between DY and J/ψ complementary information

Nuclear PDFs

Applicability of DY πA measurements in global fit validated Paakkinen *et al.* PLB 768 (2017) 7

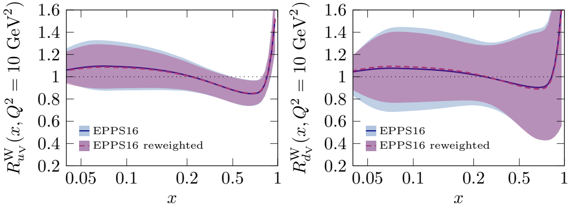




Parallel to pion structure measurement

	eDIS	νDIS	DY pA	RHIC	LHC	DY πA
nCTEQ15	✓		✓	✓		
EPPS16	✓	✓	✓	✓	✓	✓

Reduction of d_W^V uncertainties by 15% @ x∼0.1

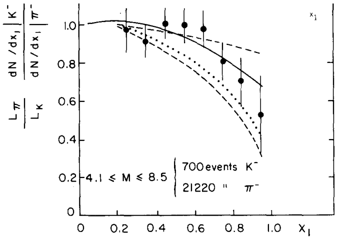


Courtesy Paakkinen

Sole measurement from NA3

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

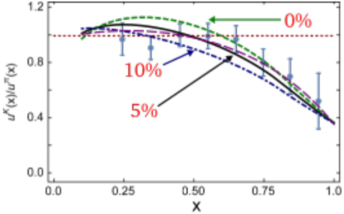
- Limited statistics: 700 events with K^-
- Sensitivity to $SU(3)_f$ breaking
- Mostly only model predictions



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

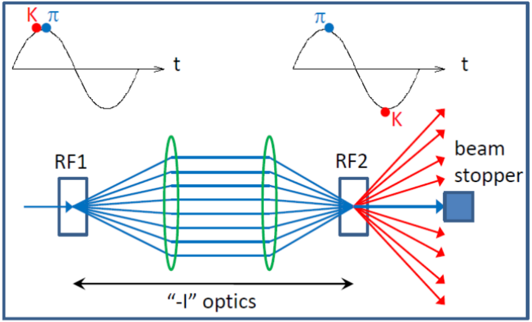
C. Chen *et al.*, PRD 93 074021, 2016



How to improve the situation?

Unique opportunities with RF separated beam

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



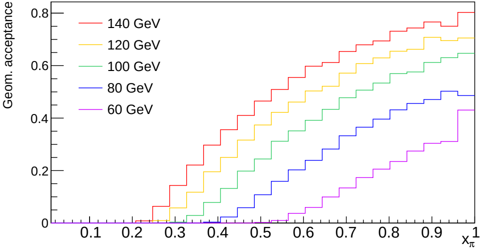
To keep good separation:

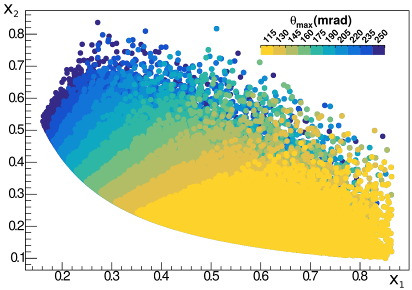
L should increase as p^2 for a given f → limits the beam momentum

Initial expectations before further *R&D*:

~ 80 GeV Kaon beam
~ 110 GeV Anti-proton beam

Opportunities for hardware development

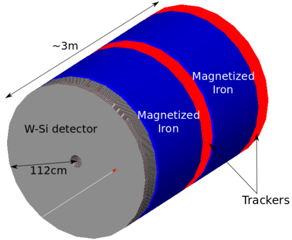




Necessity to compress the apparatus to keep an acceptance $\sim 40\%$

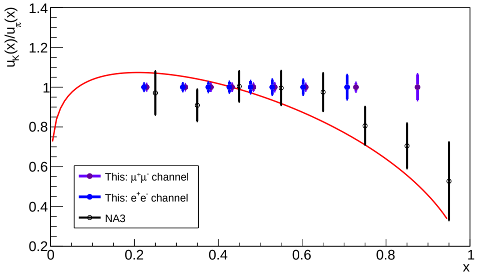
$\rightarrow$ rethink the concept of DY absorber:

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



R&D necessary

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



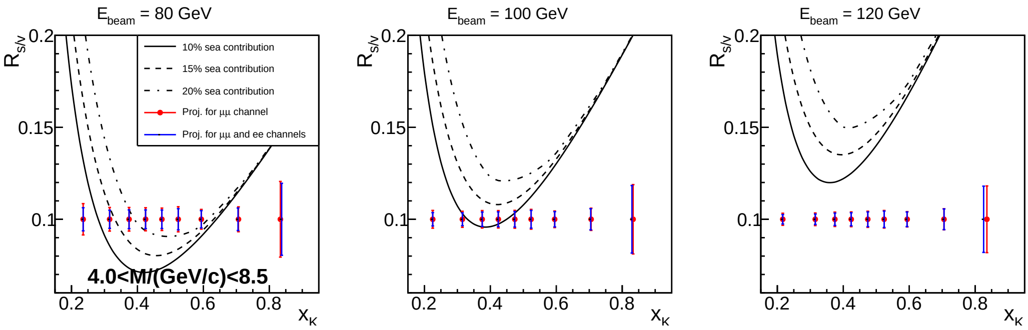
Experiment	Target type	Beam type	Beam intensity (part/sec)	Beam energy (GeV)	DY mass (GeV/c^2)	DY events $\mu^+\mu^-$
NA3	6 cm Pt	K^-		200	4.2 – 8.5	700
This exp.	100 cm C	K^-	2.1×10^7	80	4.0 – 8.5	**25,000**
				100	4.0 – 8.5	40,000
				120	4.0 – 8.5	54,000
		K^+	2.1×10^7	80	4.0 – 8.5	2,800
				100	4.0 – 8.5	5,200
				120	4.0 – 8.5	8,000
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

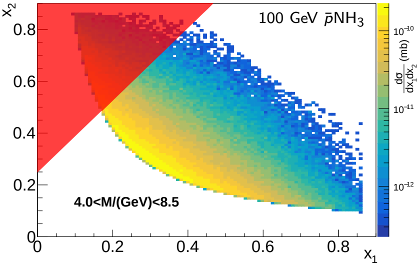


- **First measurement of sea in kaons**: $R_{s/v} = \frac{\sigma^{K^+C}}{\sigma^{K^-C} - \sigma^{K^+C}}$
- Requires an additional year with K^+ beam to complement the former K^- data
- Assuming the intensity for K^+ and K^-: $2 \times 10^7\ s^{-1}$

Gluon contribution addressed by prompt photon and J/ψ production → see C. Naïm

Anti-proton with a RF separated beam

Possibility to study valence proton TMD PDFs with a polarised NH_3 target



- No dependence upon π-PDF
- Access to large x value from the projectile
- Access Boer-Mulders function via:
  - $A_{UU}^{\cos(2\phi)} \propto h_{1,h}^{\perp q} \otimes h_{1,p}^{\perp q}$
  - $A_{UT}^{\sin(2\phi-\phi_S)} \propto h_{1,h}^{\perp q} \otimes h_{1,p}^{q}$

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

Outlook

Near term future: Current beams

- **Precise** determination of **pion structure** and valuable inputs for nuclear effects

Long term future: RF-separated beams

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

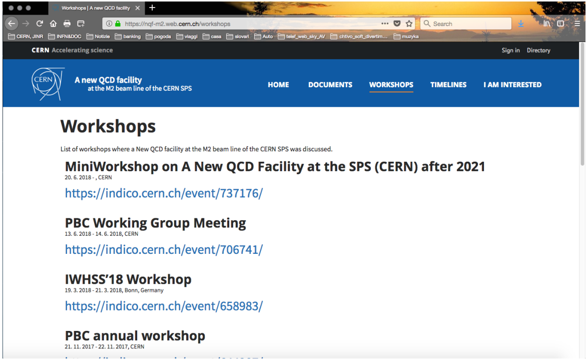
$\rightarrow$ see also O. Denisov, C. Naïm and A. Maltsev

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

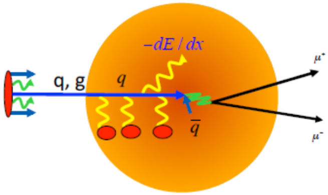
Parallel studies

Parton 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

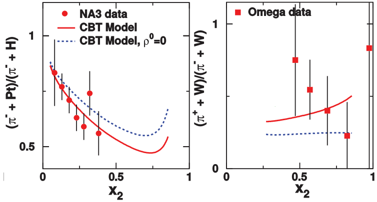


Flavour dependent EMC effect:

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



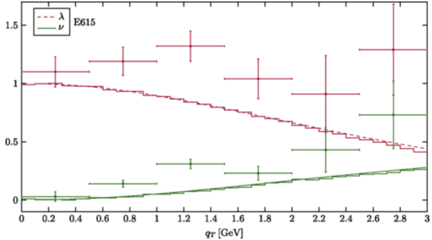
Kaon induced Drell-Yan statistics

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

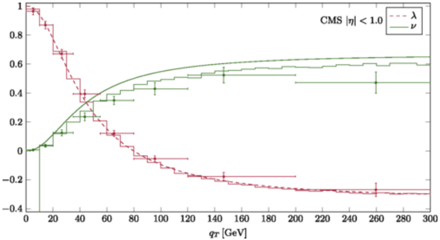
Achievable statistics of the new experiment, assuming 2×140 days of data taking with equal time sharing between the two beam charges. For comparison, the collected statistics from NA3 is also shown.

QCD radiative 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

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

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

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

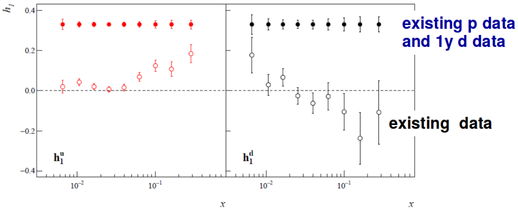
Anti-proton beam: Synergy DY and SIDIS

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

$\rightarrow$ 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