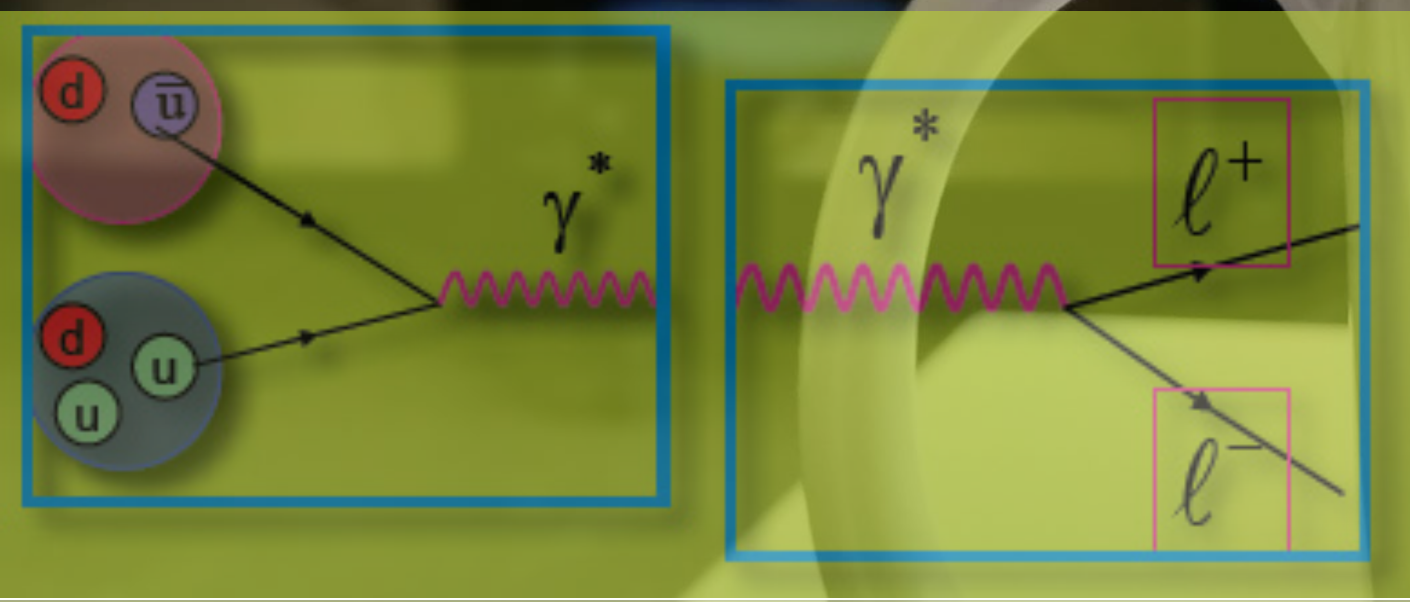
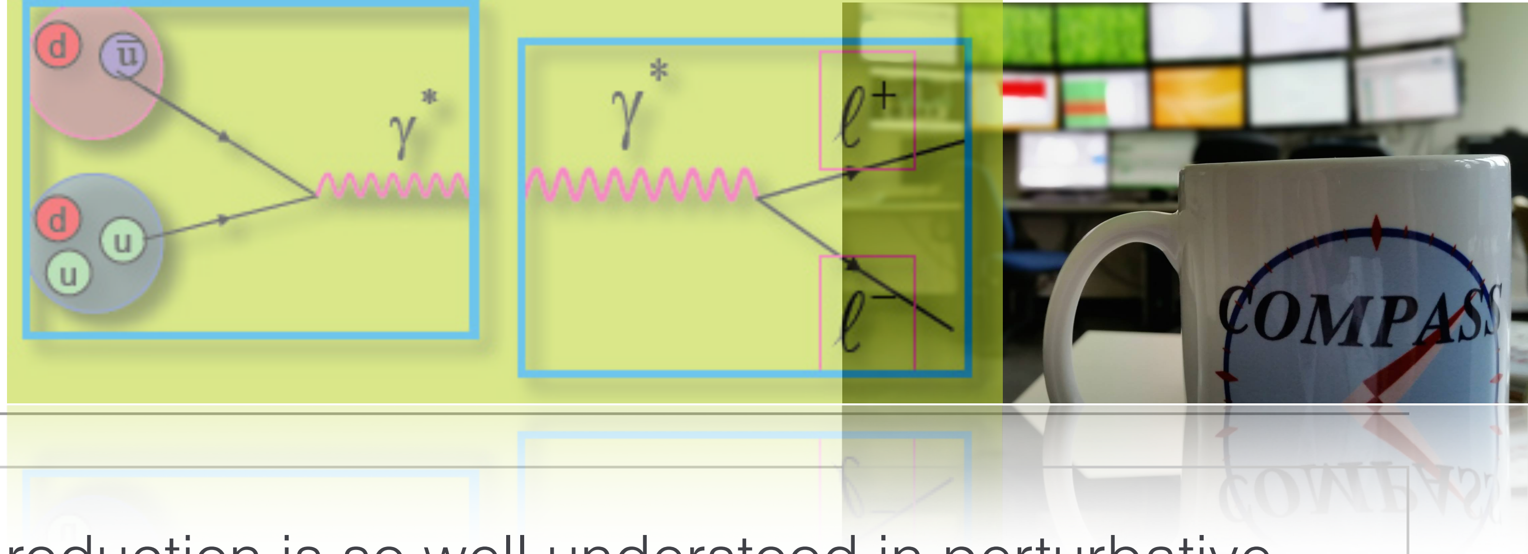
EINN2019 - Paphos, Cyprus
29/10-2/11



Drell-Yan Physics at COMPASS

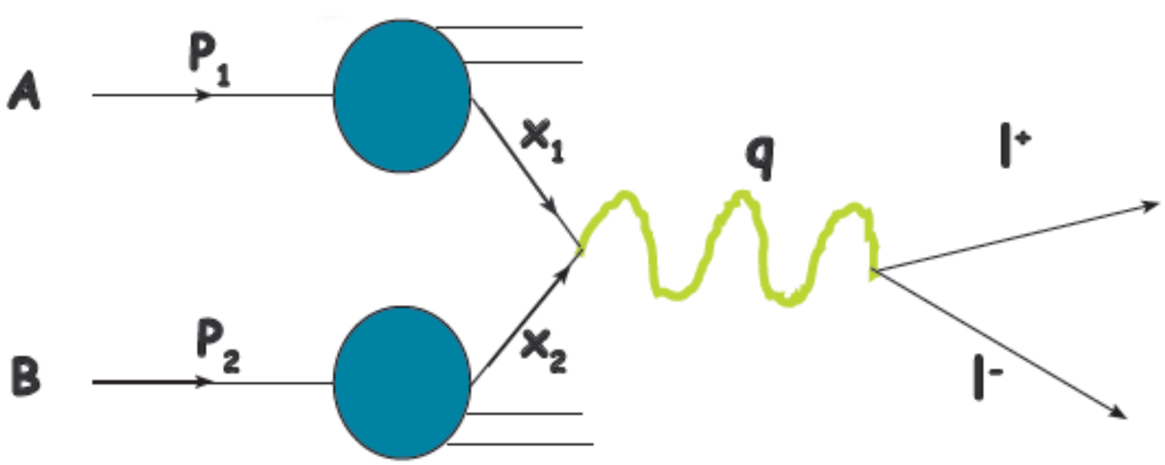
Michela Chiosso
On behalf of the
COMPASS Collaboration

Drell-Yan process



"The process of lepton pair production is so well understood in perturbative QCD that it has now become an important and powerful tool in search of new physics information"

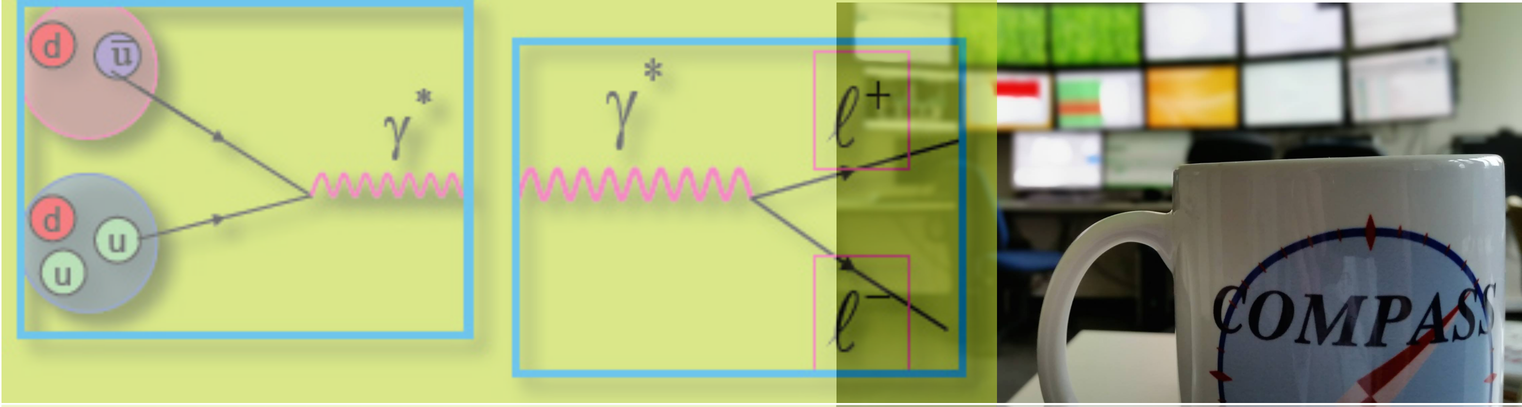
T-M. Yan, Talk given at the Drell Fest, July 31, 1998, SLAC on the occasion of Prof. Sid Drell's retirement
arXiv:hep-ph/9810268v1 6 Oct 1998



Kinematic variables:
$s^2 = (P_1 + P_2)^2$
$x_1 = Q^2/2P_1 \cdot q$
$x_2 = Q^2/2P_2 \cdot q$

$$x_F \approx 2p_L/\sqrt{s} = x_1 - x_2$$
$$M^2_{\mu^+\mu^-} = s x_1 x_2$$

Drell-Yan process



what can the Drell-Yan experiments offer in probing and understanding the nucleon and mesons structure?

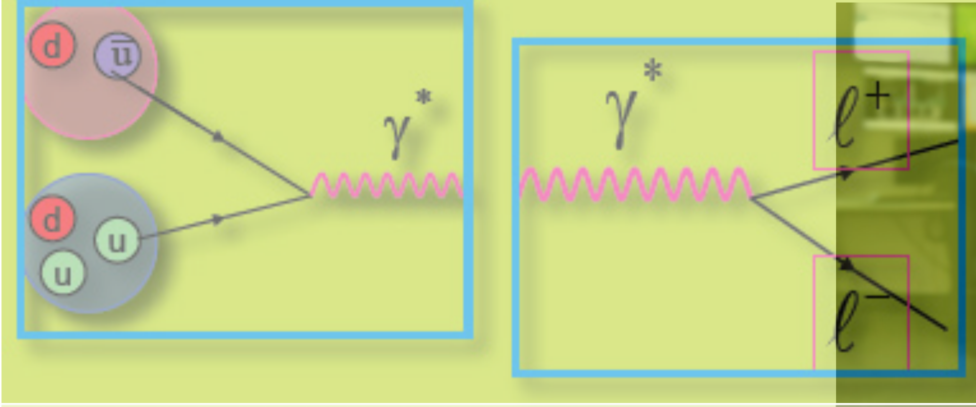
Convolution of two PDFs

DY

PDF $\otimes$ PDF

- Access to mesons and antiproton PDFs (with mesons and antiproton beam)
- Access to the nucleon PDFs
- Study of the modification of quark and gluon PDFs in bounded nucleons by a nuclear environment
- Study of the Lam-Tung Relation
- Crucial test of TMD formalism:
  experimental confirmation of the sign change prediction of the Sivers and the Boer-Mulders functions between SIDIS and Drell-Yan reactions

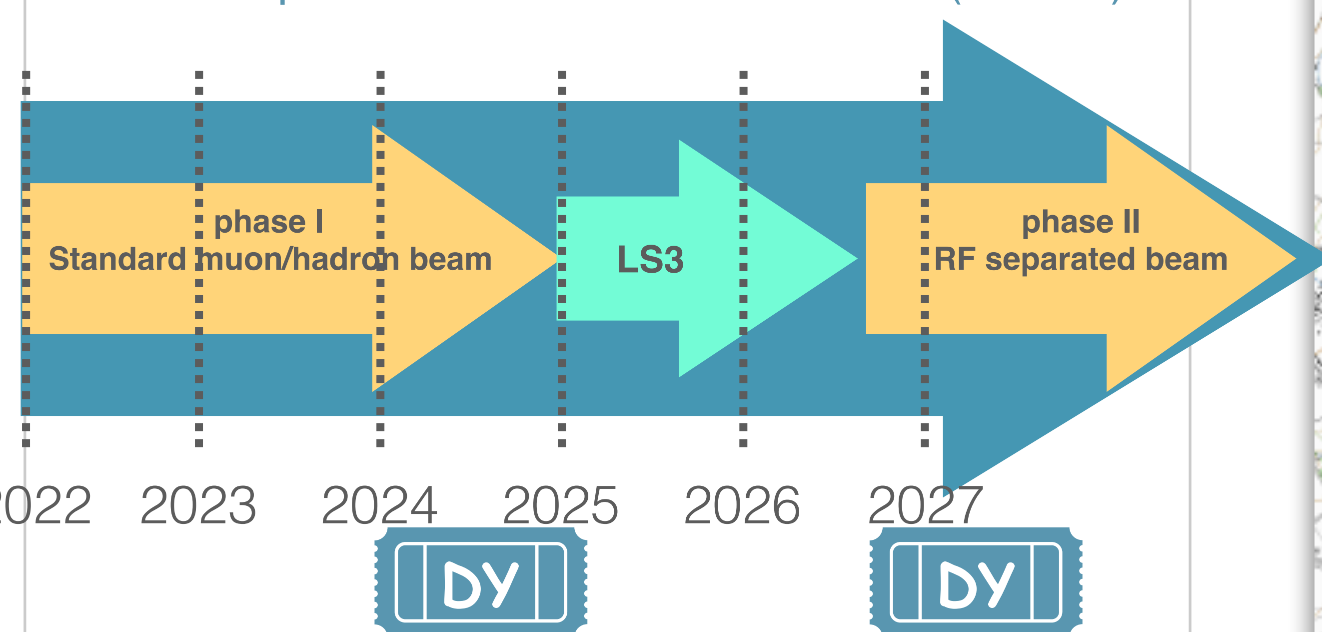
The COMPASS Experiment

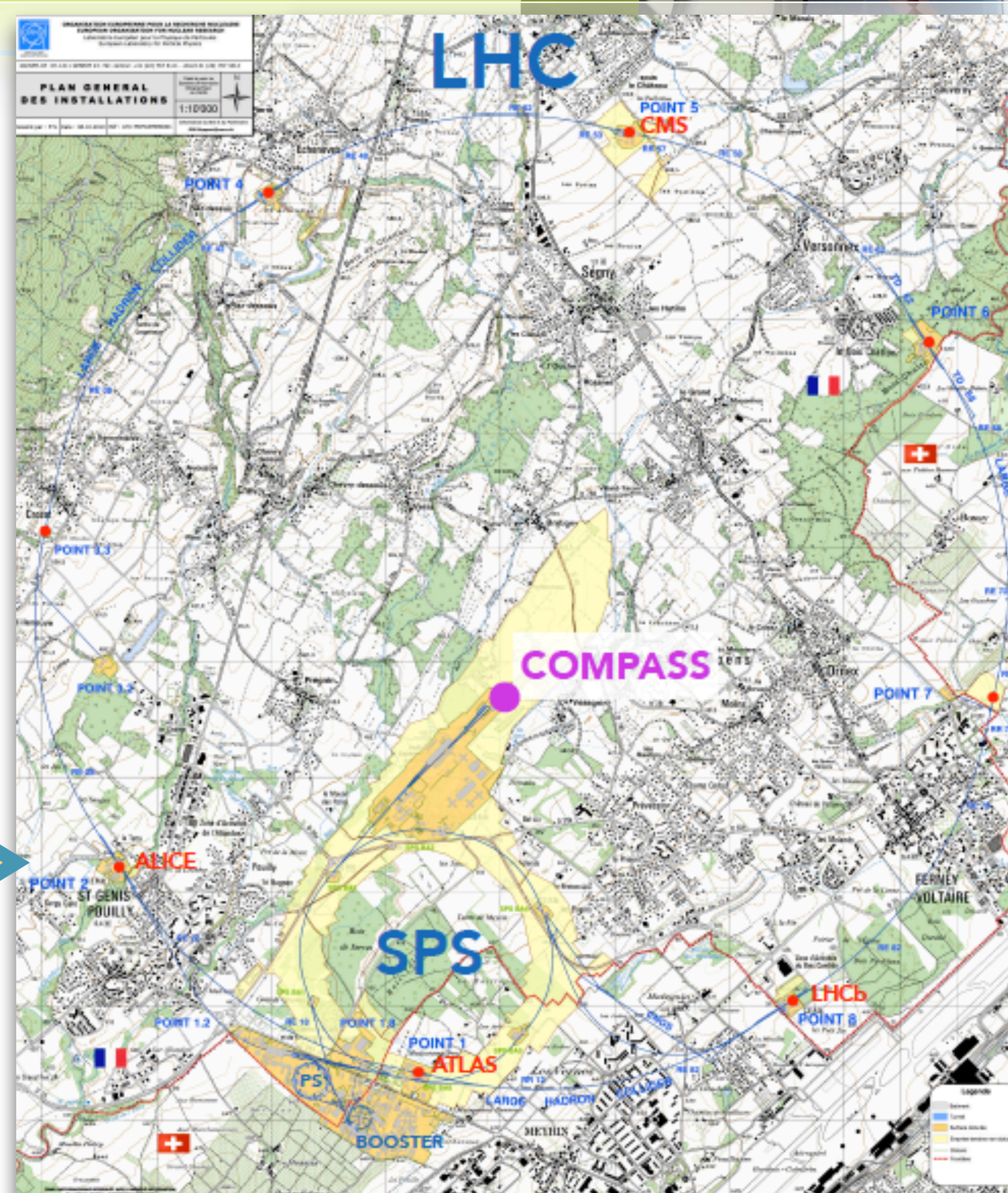


Phase I (2002 – 2011)
- Hadron spectroscopy
- Nucleon spin structure (L/T p/d Targets)

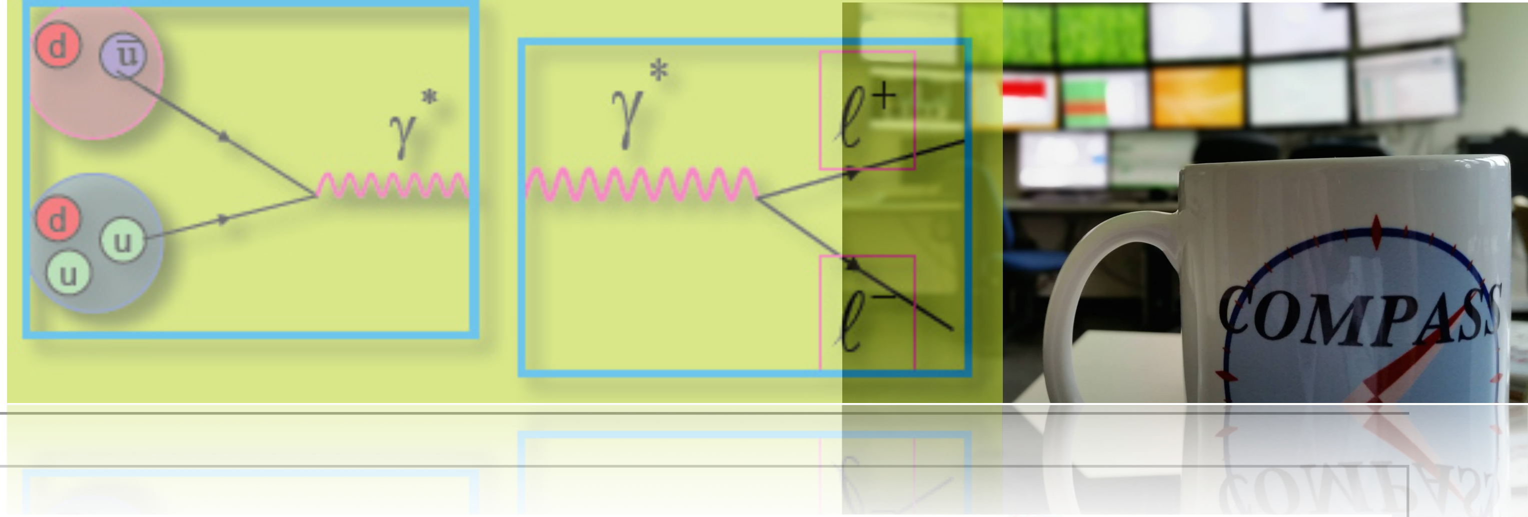
Phase II (2012 – 2018, 2021)
- Primakoff + DVCS pilot run (2012)
- **Drell-Yan (2015, 2018)**
- DVCS + Unpolarized SIDIS(2016-2017)
- T-polarized SIDIS (D target) (2021)

Future Perspective: COMPASS++/AMBER (> 2022)





The COMPASS DY Apparatus



negative hadron beam (π/K/p 97/2/1%)
(from 400 GeV/c SPS protons onto conversion target)

Average Beam Intensity: 10^8 particles / sec

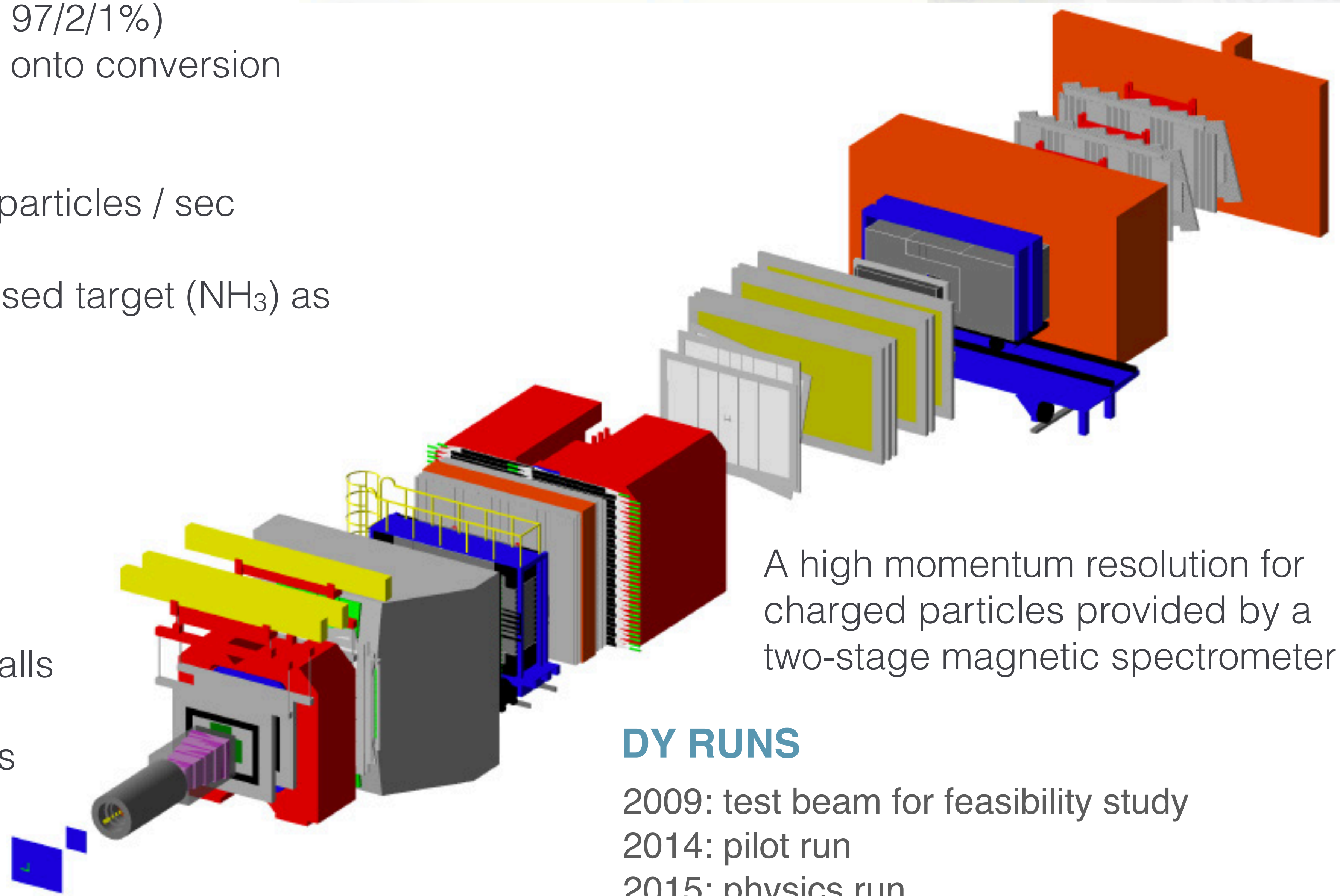
Solid state transversely polarised target (NH_3) as well as nuclear targets

Hadron absorber

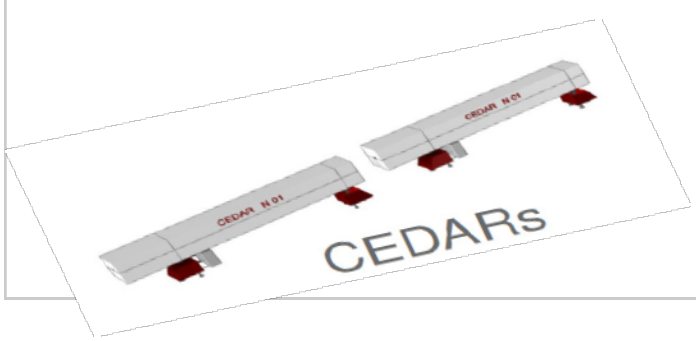
Powerful tracking system:
350 planes

Muon identification – Muon walls

Beam identification – CEDARs



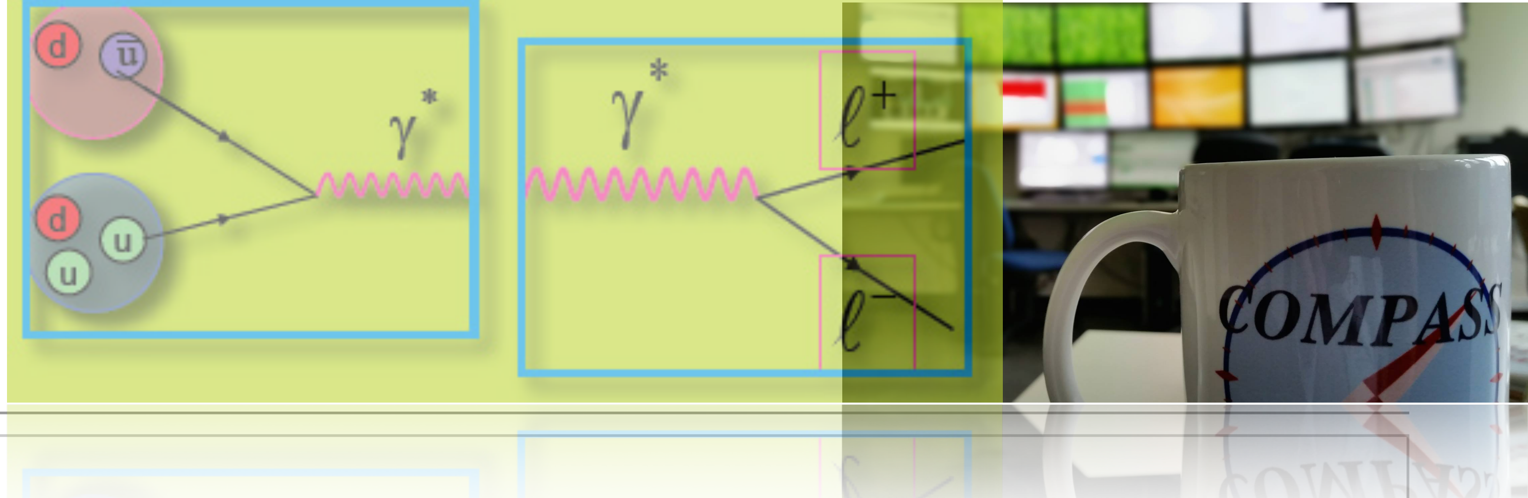
A high momentum resolution for charged particles provided by a two-stage magnetic spectrometer

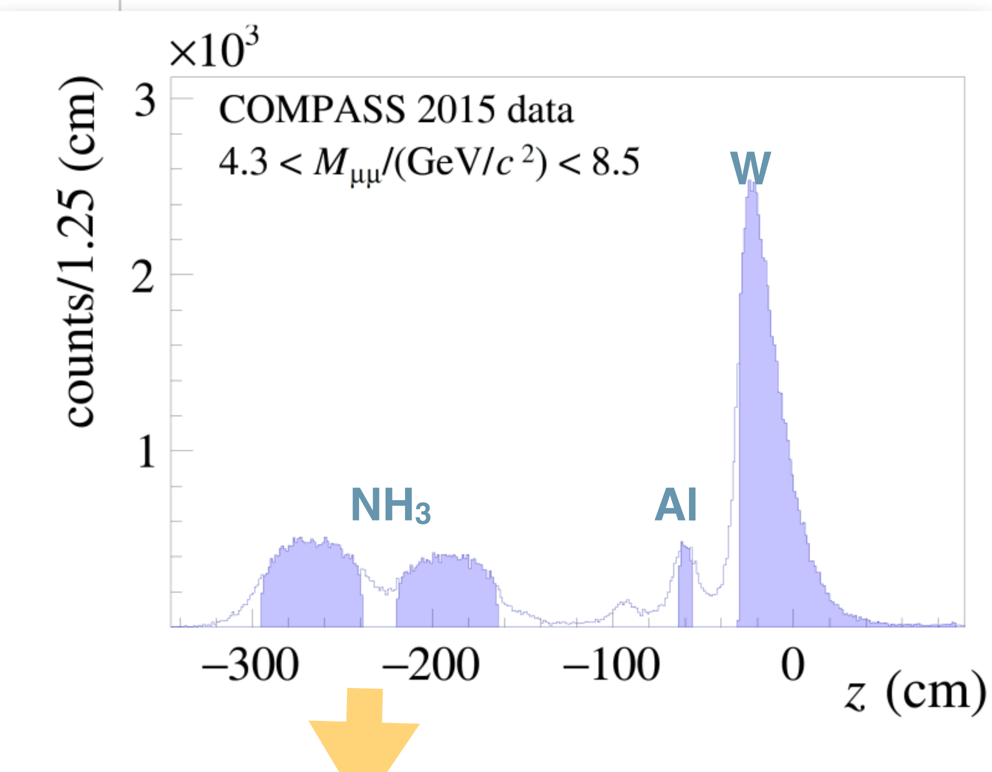


DY RUNS

2009: test beam for feasibility study
2014: pilot run
2015: physics run
(transversely polarized NH_3 target)
2018: physics run
(transversely polarized NH_3 target)

The COMPASS DY Apparatus

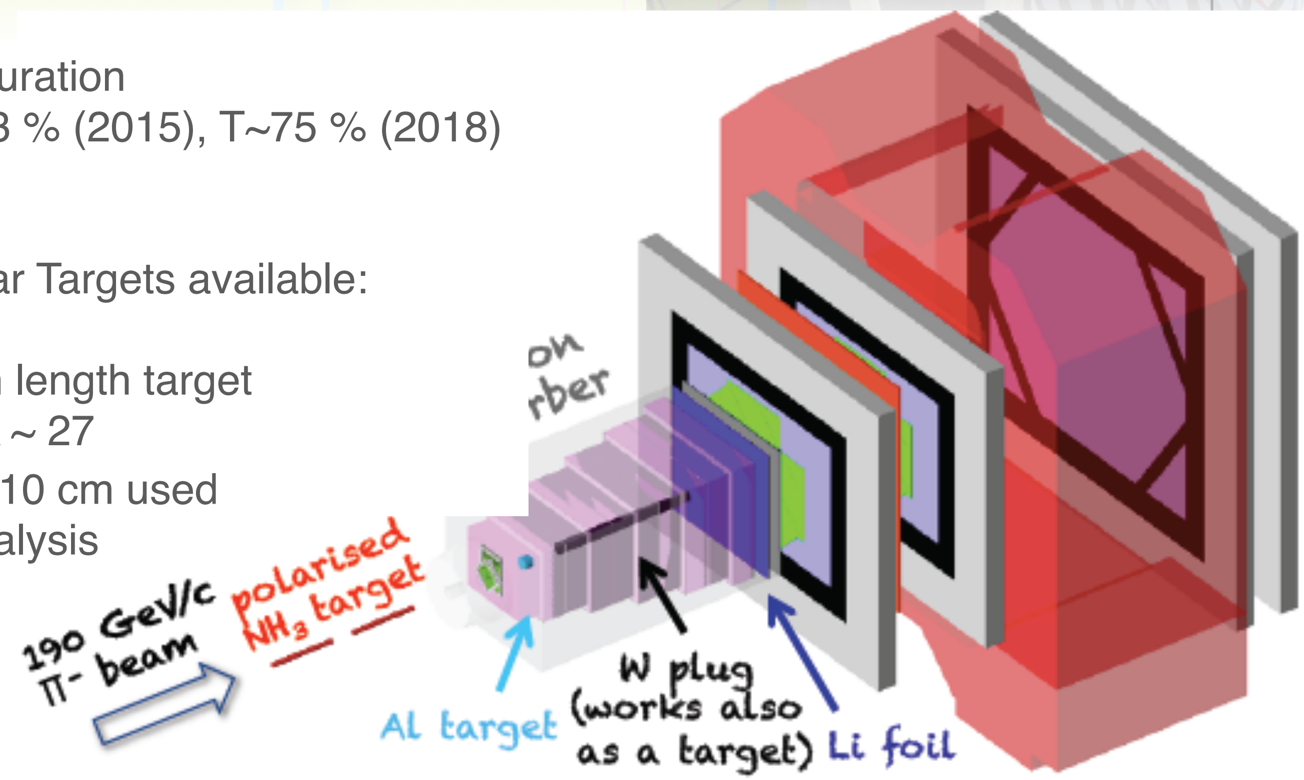




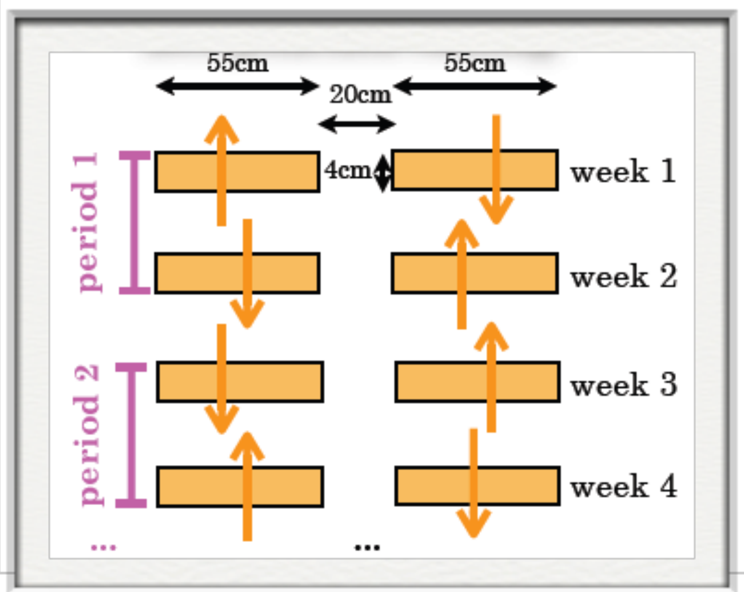
NH3 2-cell configuration
Polarization T~73 % (2015), T~75 % (2018)
f ~ 0.19

Additional Nuclear Targets available:

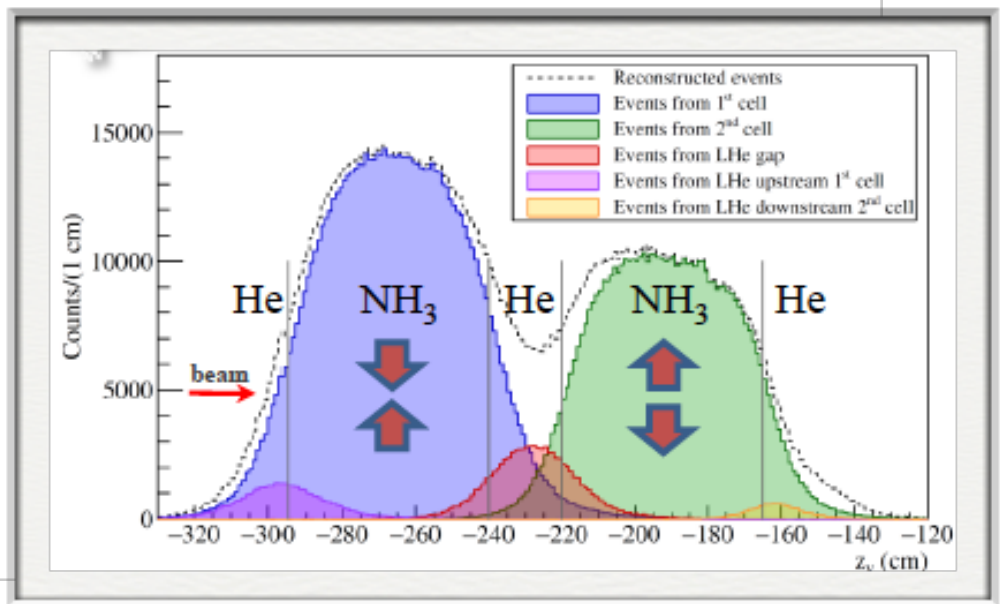
- Aluminum 7cm length target
  Intermediate A ~ 27
- Tungsten first 10 cm used
  for physics analysis
  Large A ~ 184



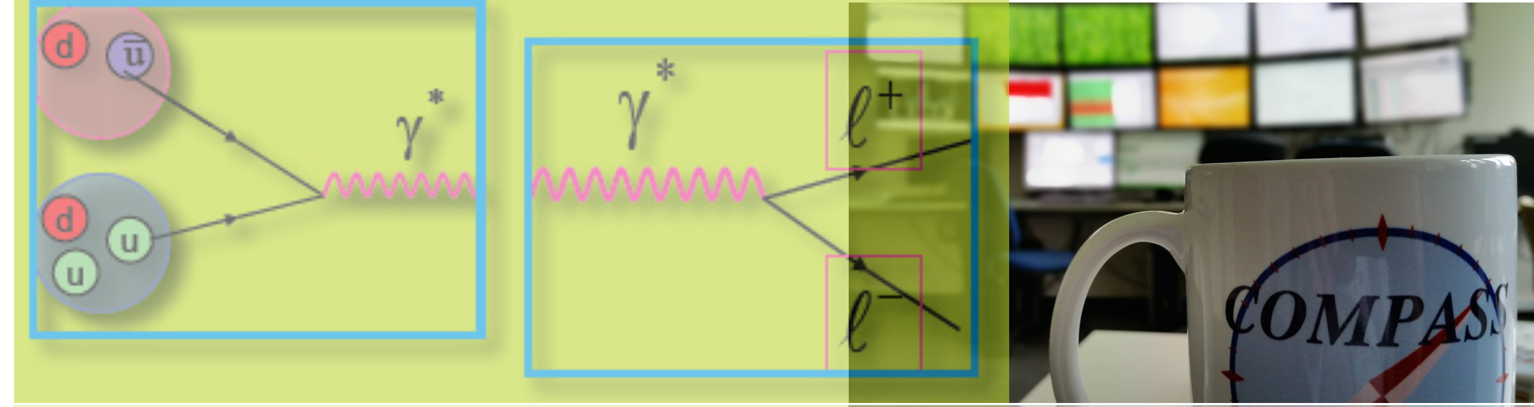
Periodic polarization reversal to minimise systematic effects



The dilution factor (the fraction of polarizable material in target) is corrected to account for the migration of events from one cell to the other (obtained with MC simulation)



Kinematic Coverage

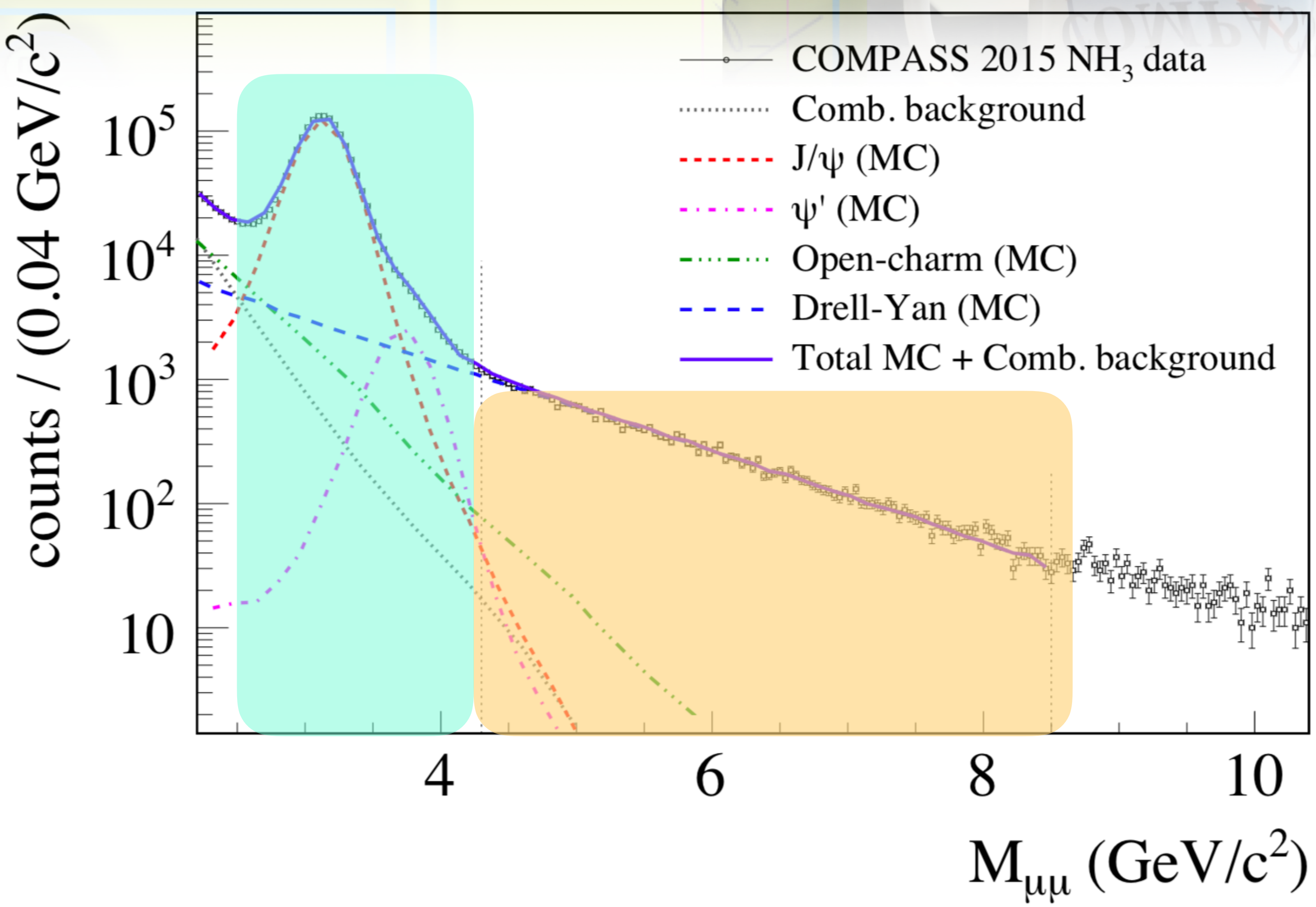


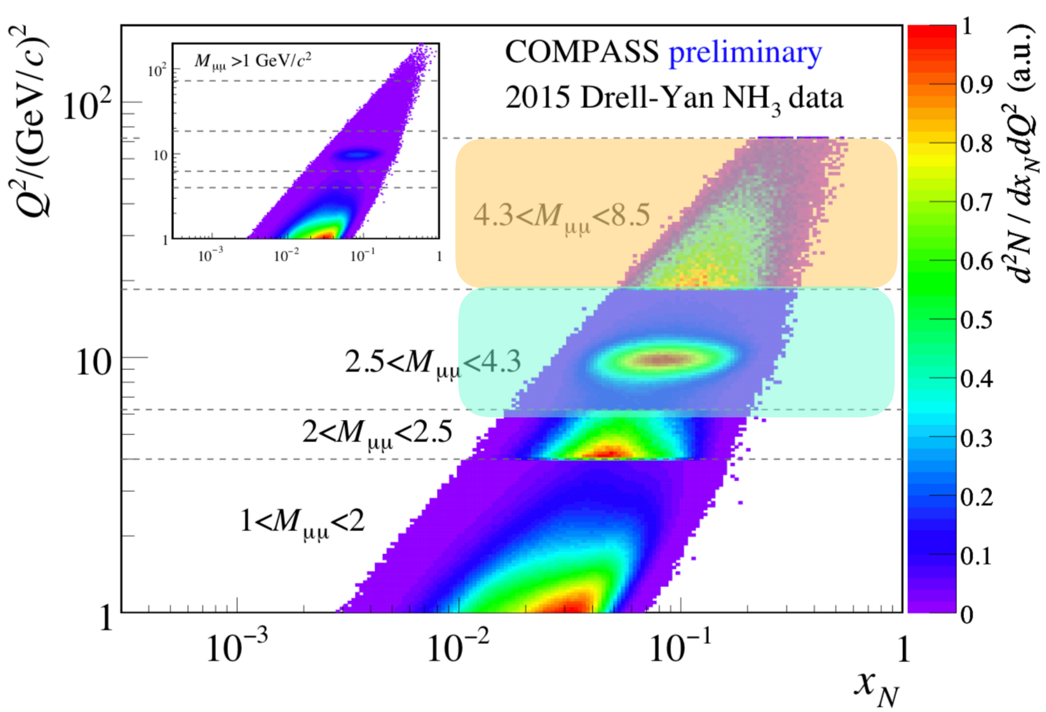
- $1 < M_{\mu\mu}/(\mathrm{GeV}/c^2) < 2$ — "Low Mass Region"
  - Large background contamination

- $2 < M_{\mu\mu}/(\mathrm{GeV}/c^2) < 2.5$ — "Intermediate mass"

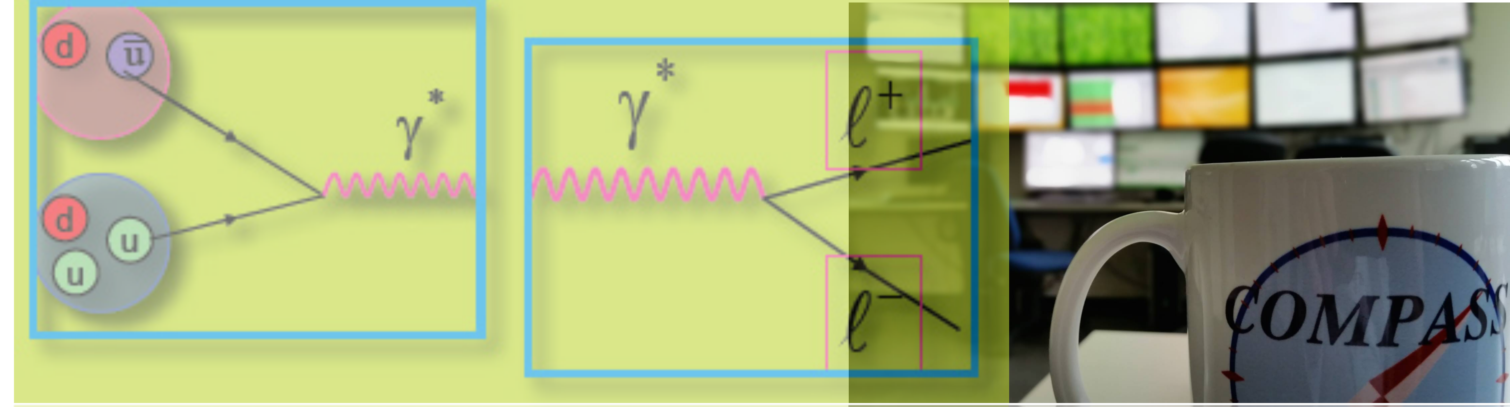
- $2.5 < M_{\mu\mu}/(\mathrm{GeV}/c^2) < 4.3$ — "Charmonia mass"
  - Good signal/background ratio (large statistics)
  - J/ψ peak — Production mechanism study

- $4.3 < M_{\mu\mu}/(\mathrm{GeV}/c^2) < 8.5$ — "DY High mass range"
  - Background contamination < 4%
  - Valence-quark region (Larger asymmetries)

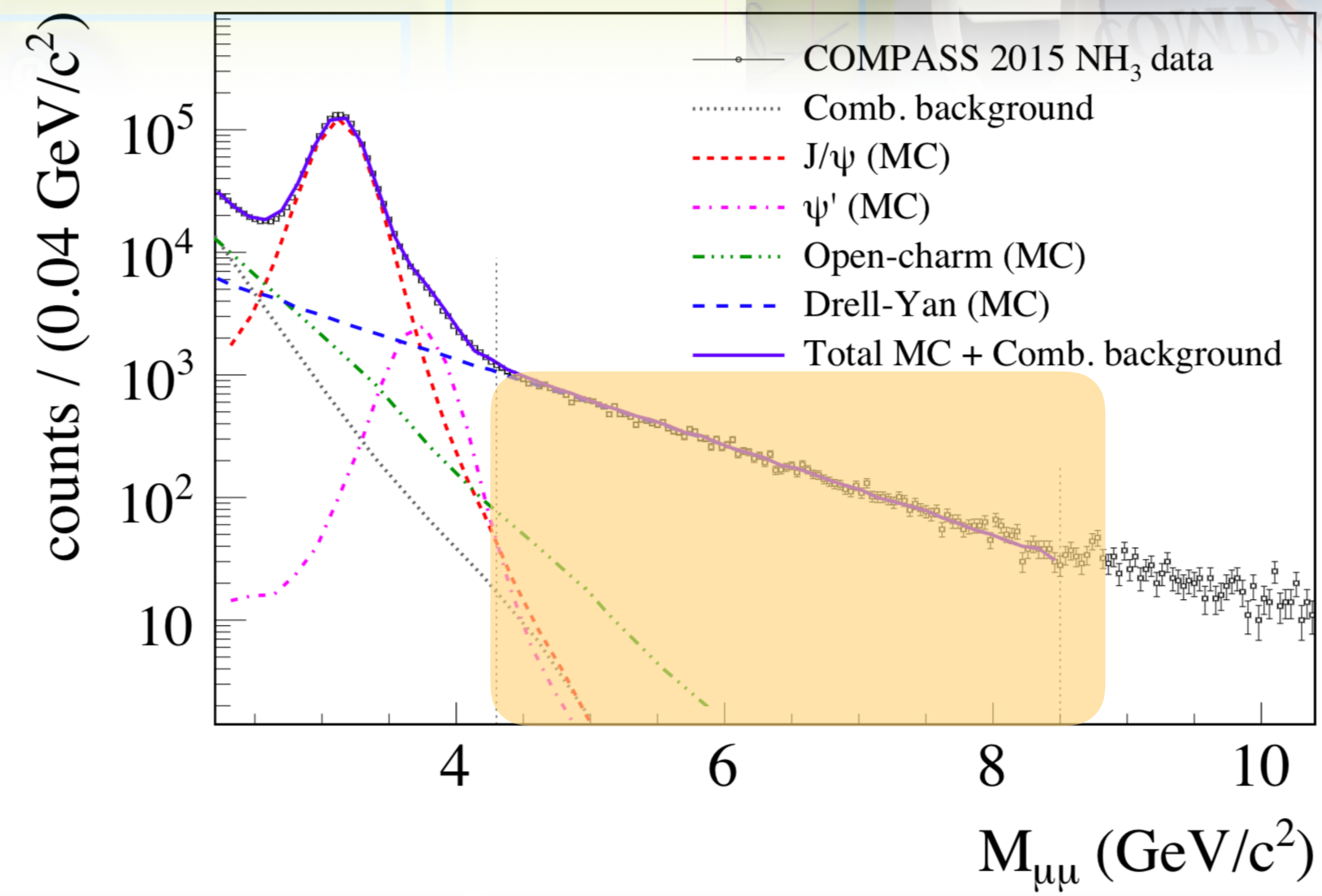




Kinematic Coverage

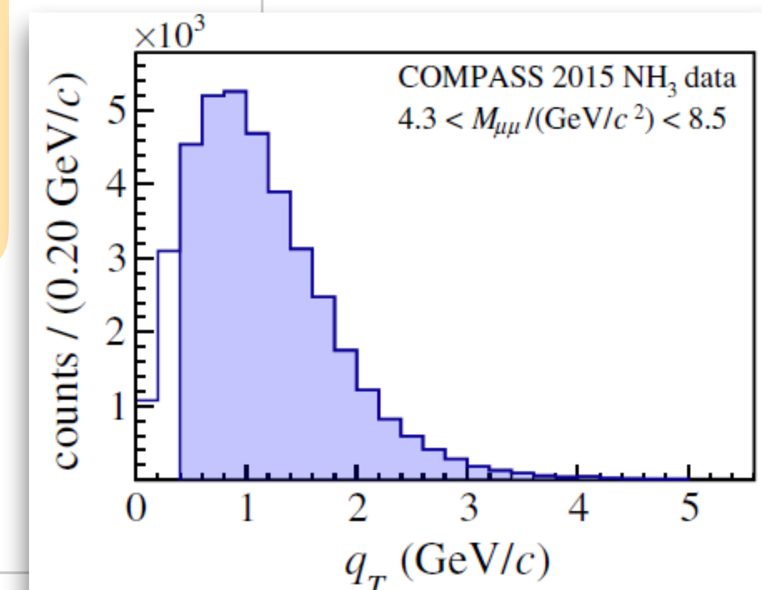


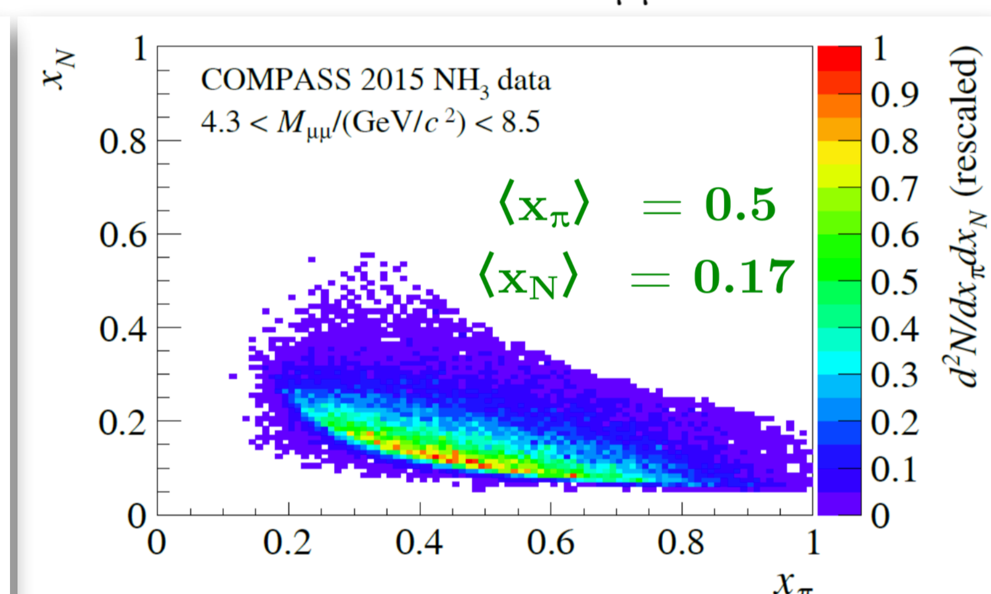
- ❋ $1 < M_{\mu\mu}/(GeV/c^2) < 2$ — “Low Mass Region”
  - Large background contamination
- ❋ $2 < M_{\mu\mu}/(GeV/c^2) < 2.5$ — “Intermediate mass”
- ❋ $2.5 < M_{\mu\mu}/(GeV/c^2) < 4.3$ — “Charmonia mass”
  - Good signal/background ratio (large statistics)
  - J/ψ peak — Production mechanism study
- ❋ $4.3 < M_{\mu\mu}/(GeV/c^2) < 8.5$ — “DY High mass range”
  - Background contamination < 4%
  - Valence-quark region (Larger asymmetries)



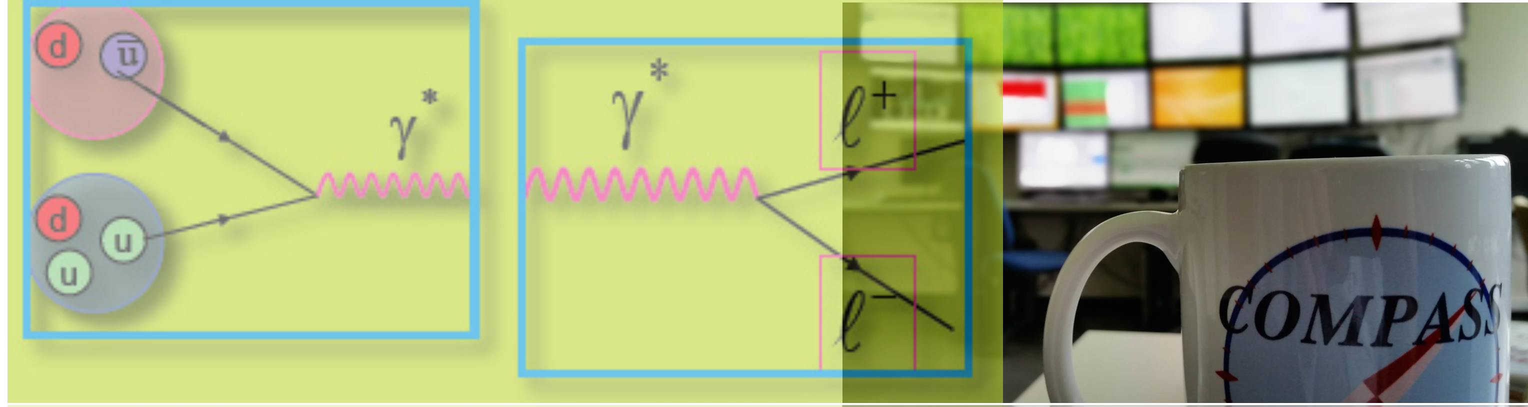
Valence region dominance $\bar{u}_\pi u_p$

$\langle q_T \rangle = 1.2$ GeV/c << $M_{\mu\mu} = 5.3$ GeV/c²
TMD approach validity



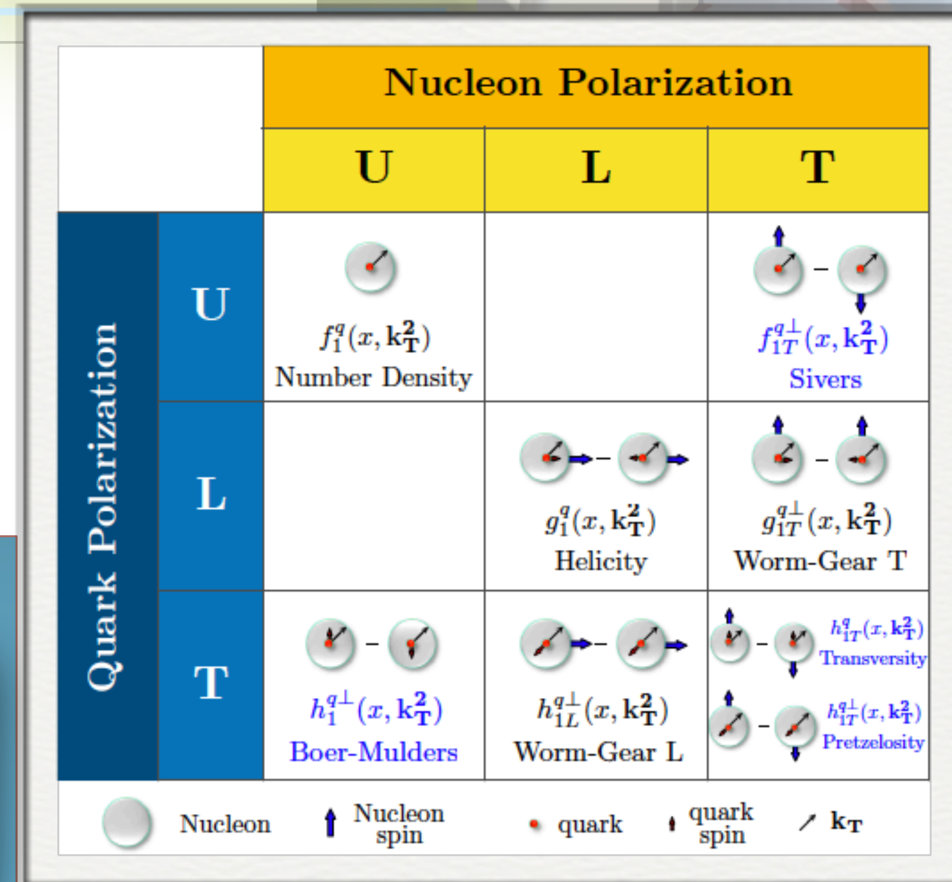


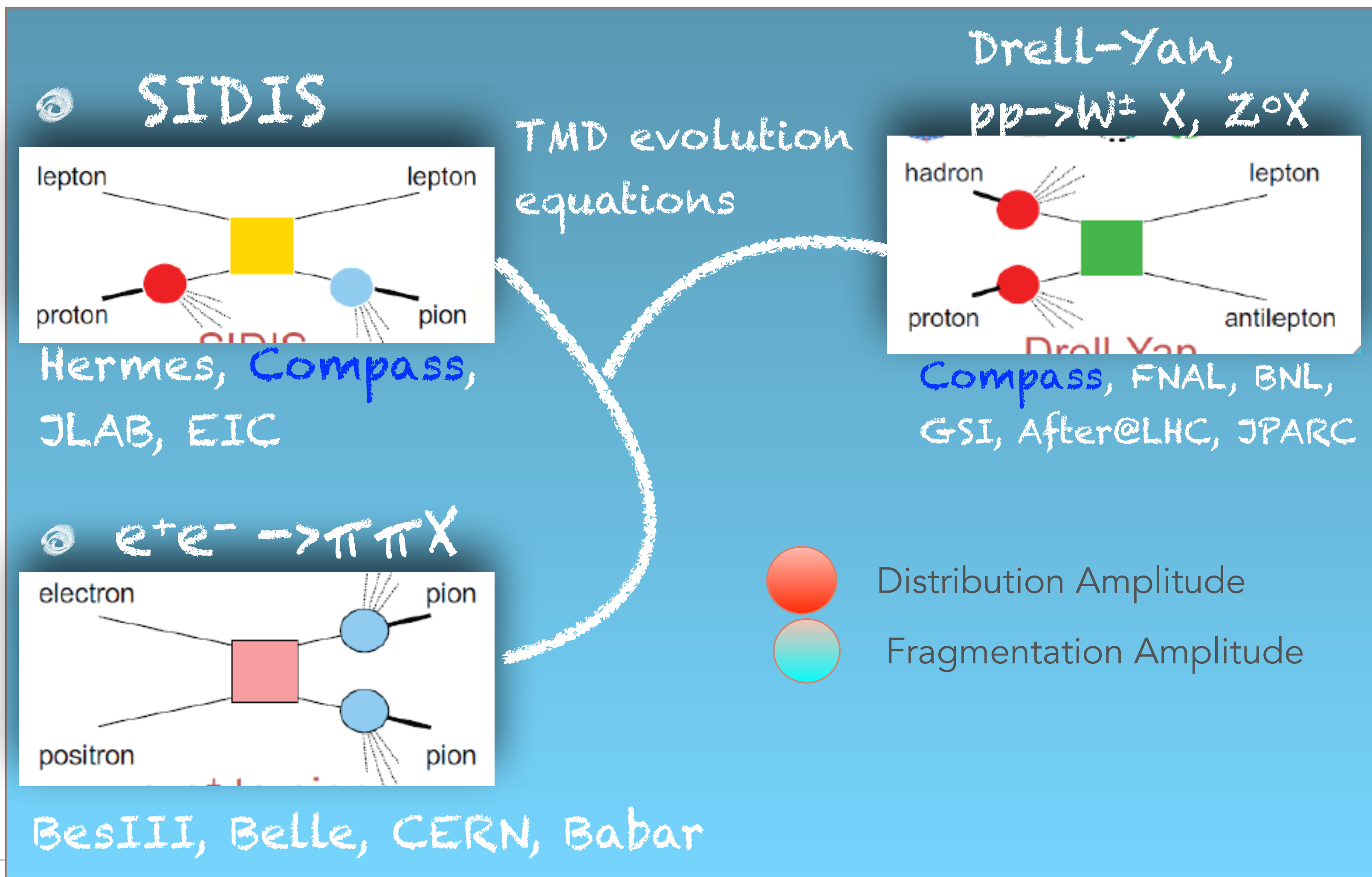
Which processes to probe TMDs?



“3-D imaging” hadrons encoded in transverse momentum dependent (TMD) PDFs

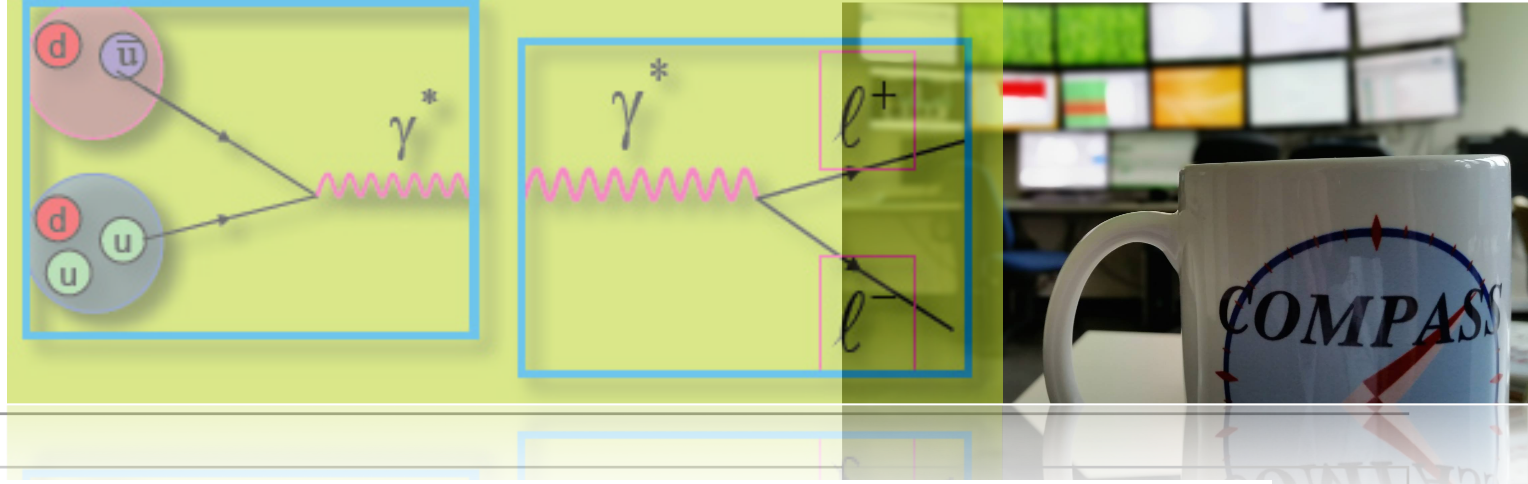
TMDs encode non perturbative information on hadron structure, including transverse momentum and polarization degrees of freedom, which is essential in the context of QCD factorization theorems



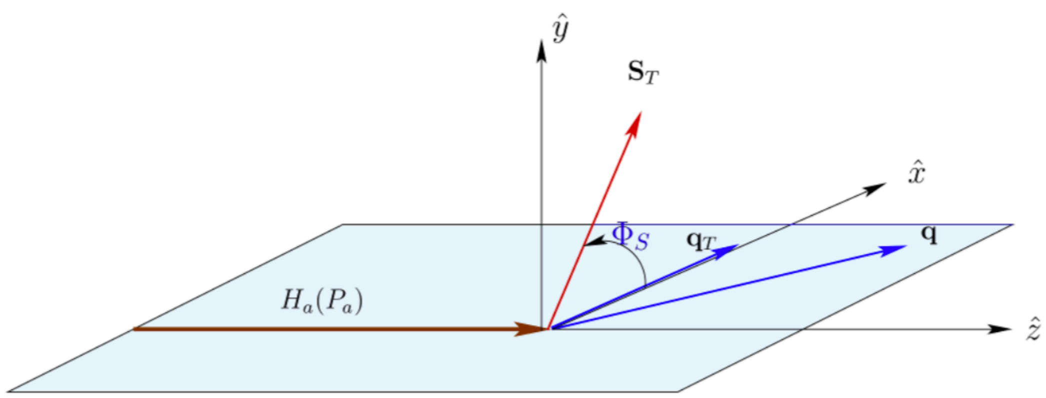


COMPASS Experiment :
Access to convoluted TMD PDFs via Polarized DY and SIDIS with the same apparatus

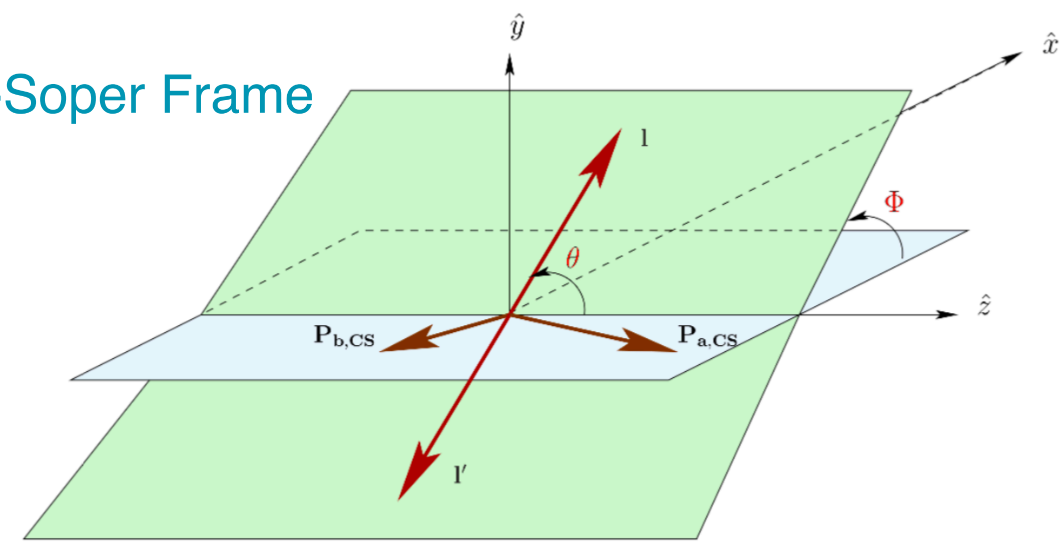
Single Polarized Drell-Yan @COMPASS



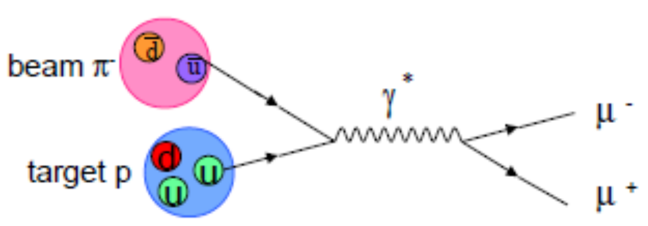
Target Rest Frame



Collins-Soper Frame



(b)



Measure magnitude of spin-dependent azimuthal modulations in cross section: "Single-Spin Asymmetries "

$$f_{\overline{u}|\pi} \otimes f_{u|p}$$

pion proton

At LO:

$$
\begin{aligned}
\mathrm{d}\sigma(\pi^- p^\uparrow \rightarrow \mu^+\mu^- X) = 1 &+ \boxed{\overline{h}_1^\perp} \otimes \boxed{h_1^\perp} \cos(2\phi) \\
&+ |S_T| \boxed{\overline{f}_1} \otimes \boxed{\overline{f}_{1T}^\perp} \sin\phi_S \\
&+ |S_T| \boxed{\overline{h}_1^\perp} \otimes \boxed{h_{1T}^\perp} \sin(2\phi + \phi_S) \\
&+ |S_T| \boxed{\overline{h}_1^\perp} \otimes \boxed{h_1} \sin(2\phi - \phi_S)
\end{aligned}
$$

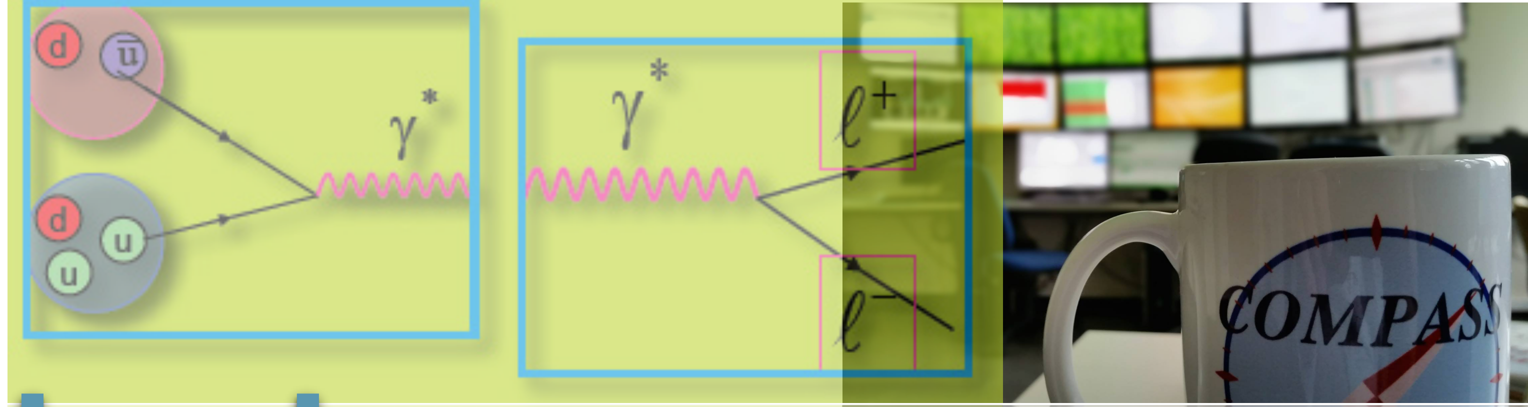
$(\mathrm{BM})_\pi \otimes (\mathrm{BM})_p$

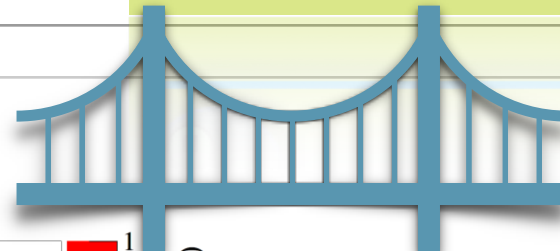
$(f_1)_\pi \otimes (\mathrm{Sivers})_p$

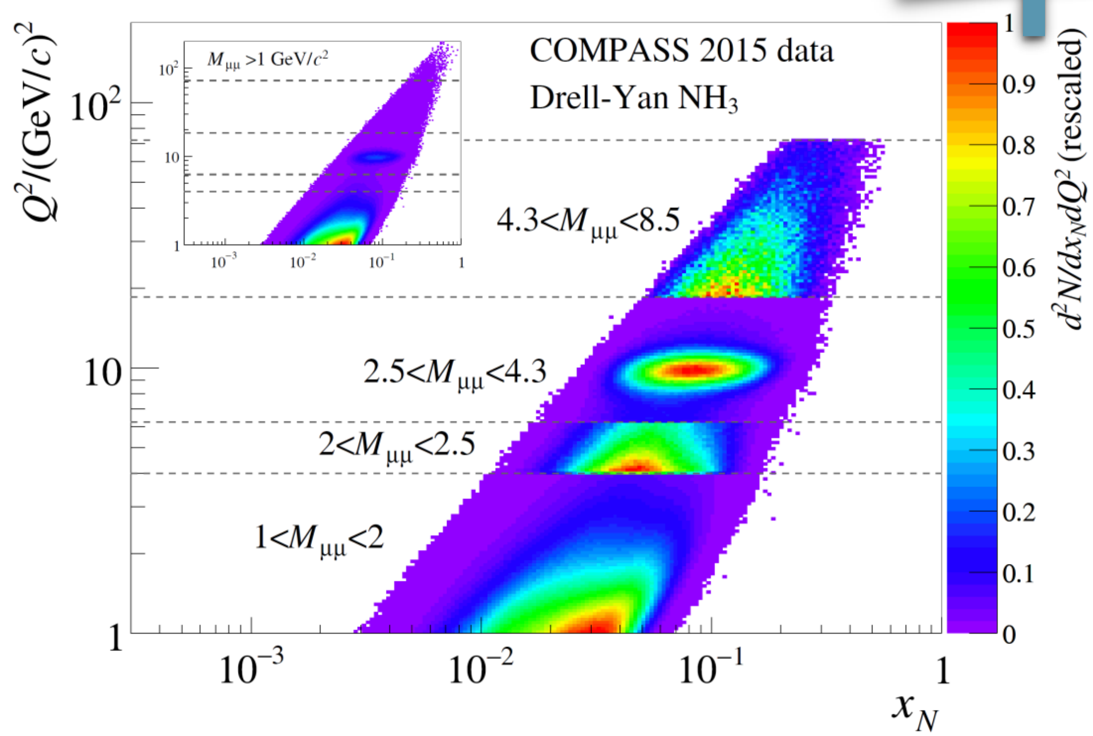
$(\mathrm{BM})_\pi \otimes (\mathrm{Pretzelosity})_p$

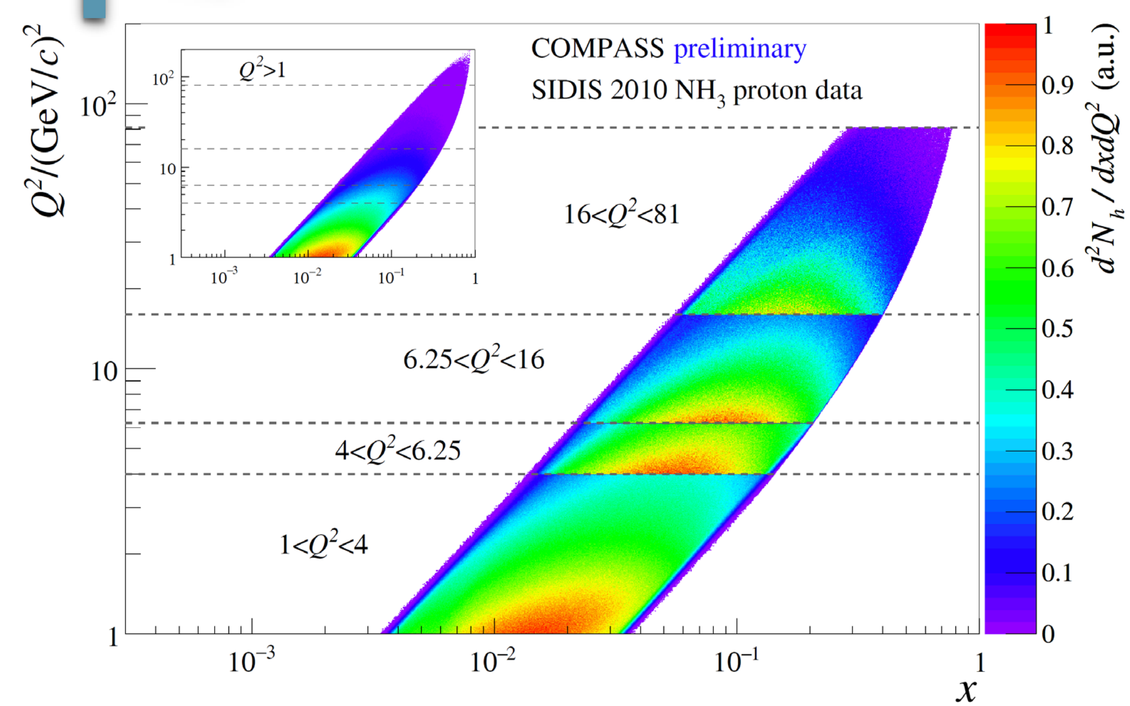
$(\mathrm{BM})_\pi \otimes (\mathrm{Transversity})_p$

DY-SIDIS Bridge at COMPASS









$$h_1^{q\perp}\Big|_{DY} = -\,h_1^{q\perp}\Big|_{SIDIS}$$

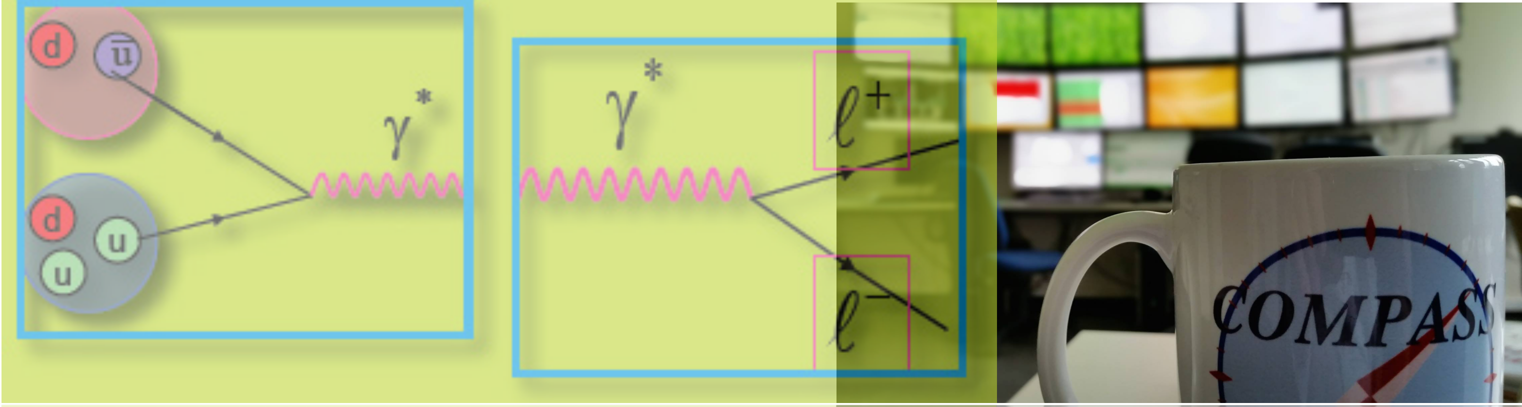
$$f_{1T}^{q\perp}\Big|_{DY} = -f_{1T}^{q\perp}\Big|_{SIDIS}$$

comparable x:Q² kinematic coverage

Unique experimental environment to perform crucial test of TMD formalism: experimental confirmation of the Sivers and the Boer-Mulders sign change prediction

minimization of possible Q² evolution effects

Sivers Asymmetry in High Mass Range

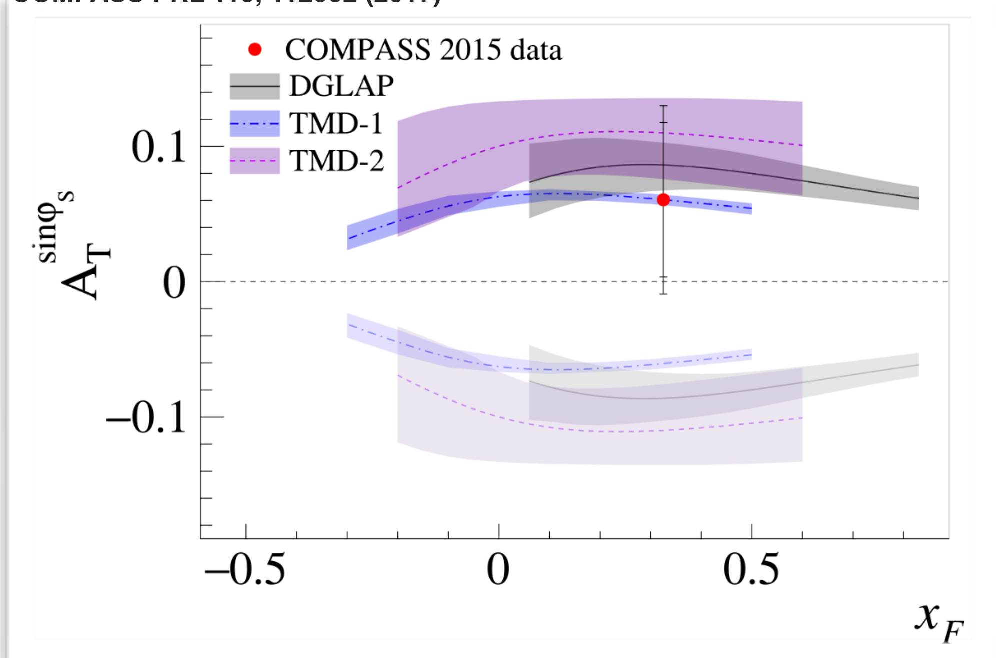


Sivers Asymmetry from COMPASS 2015 data:

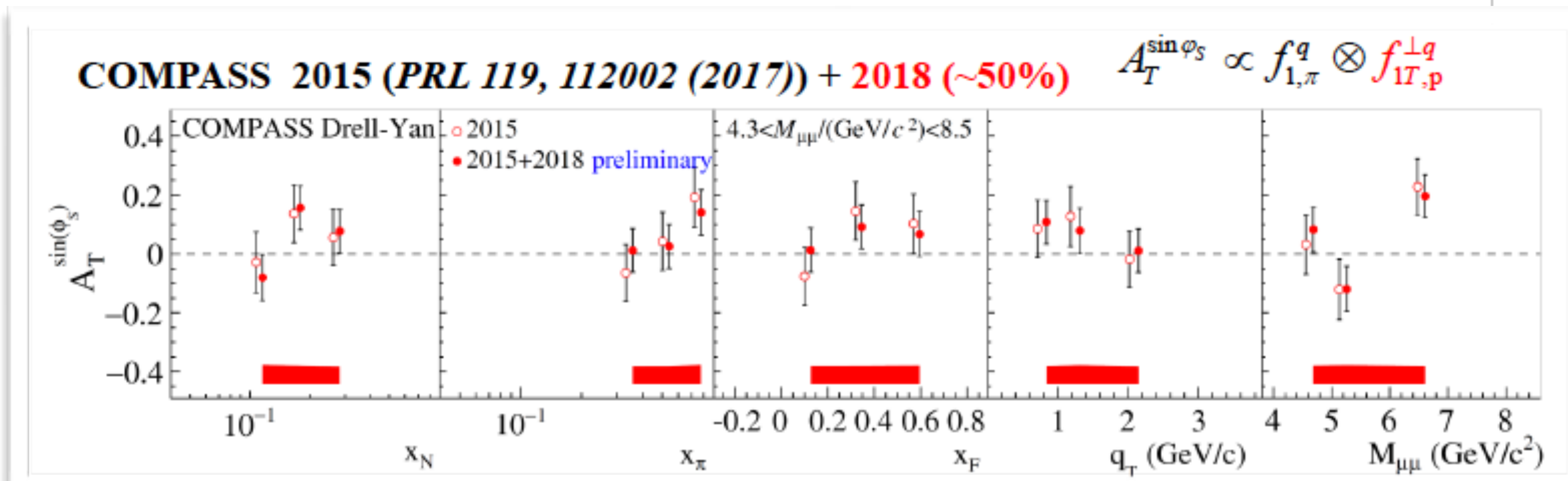
$\langle A_T^{\sin\phi_S} \rangle = 0.060 \pm 0.057(\mathrm{stat}) \pm 0.040(\mathrm{sys})$

➤ Requires more Drell-Yan data: Successful year of data taking in 2018

COMPASS PRL 119, 112002 (2017)

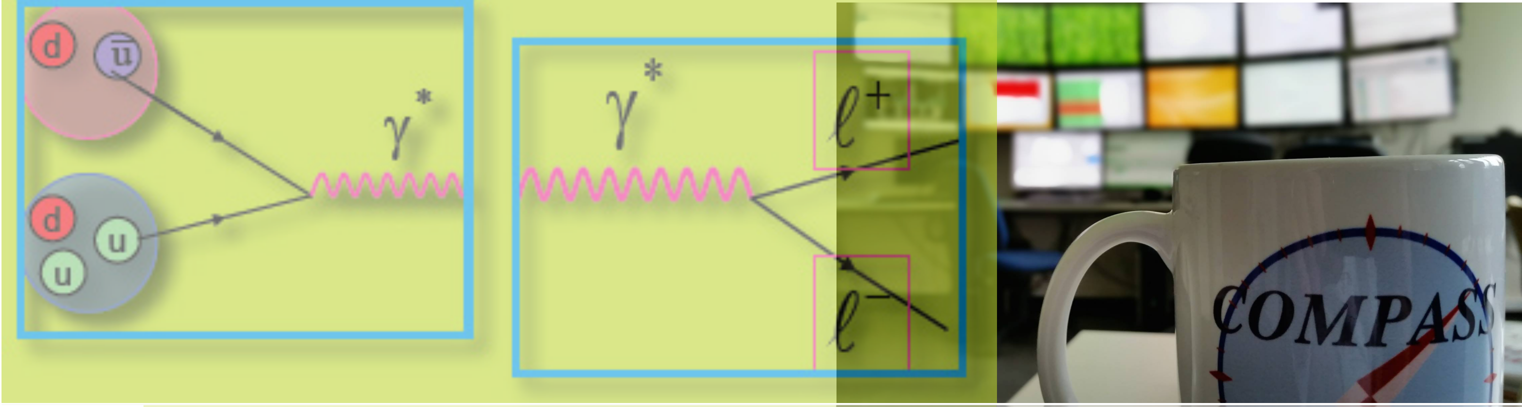


DGLAP (2016) M. Anselmino et al., arXiv:1612.06413
TMD-1 (2014) M. Echevarria et al., PRD 89 (2014) 074013
TMD-2 (2013) P. Sun and F. Yuan, PRD 88 (2013) 114012



➤ Updated results as function of x_N, x_π, x_F q_T, M
➤ Preliminary results including 50% of the 2018 data (2015 = 4 months; 2018 = 5 months of data taking)

DY TSAs : Results in High Mass Range

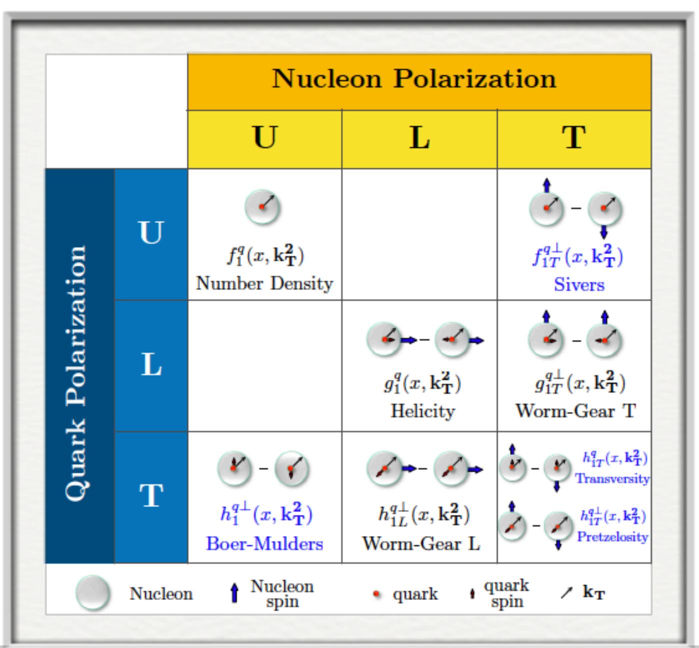


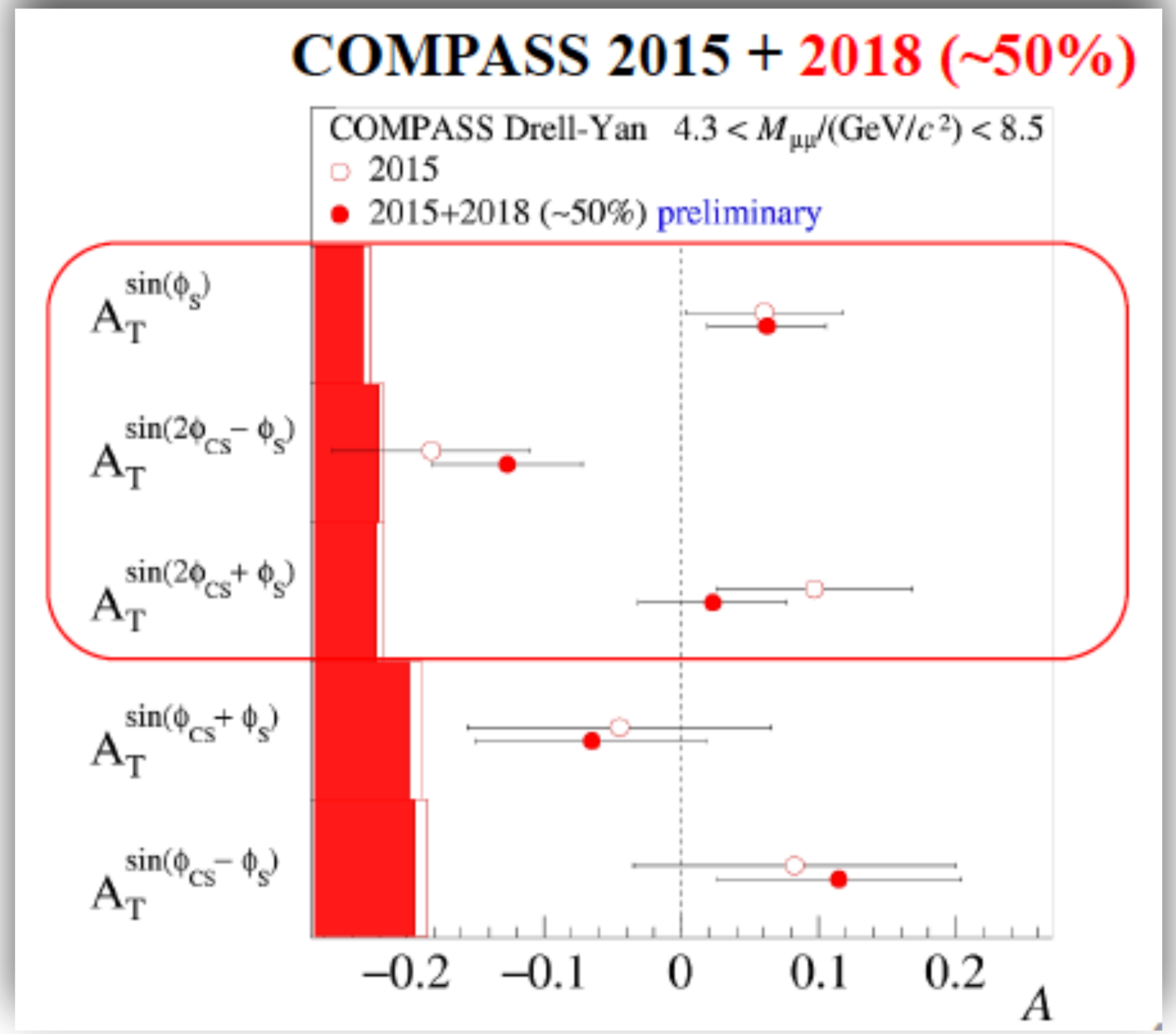
$$
\begin{aligned}
d\sigma^{DY} \propto\ & 1 + D_{[\sin 2\theta]} A_{UU}^{\cos\phi} \cos\phi + D_{[\sin^2\theta]} A_{UU}^{\cos 2\phi} \cos 2\phi \\
& + S_T \Big[D_{[1+\cos^2\theta]} A_{UT}^{\sin\phi_S} \sin\phi_S \\
& + D_{[\sin^2\theta]} \left(A_{UT}^{\sin(2\phi-\phi_S)} \sin(2\phi-\phi_S) + A_{UT}^{\sin(2\phi+\phi_S)} \sin(2\phi+\phi_S) \right) \\
& + D_{[\sin 2\theta]} \left(A_{UT}^{\sin(\phi-\phi_S)} \sin(\phi-\phi_S) + A_{UT}^{\sin(\phi+\phi_S)} \sin(\phi+\phi_S) \right) \Big]
\end{aligned}
$$

Unp. PDF $\otimes$ Sivers

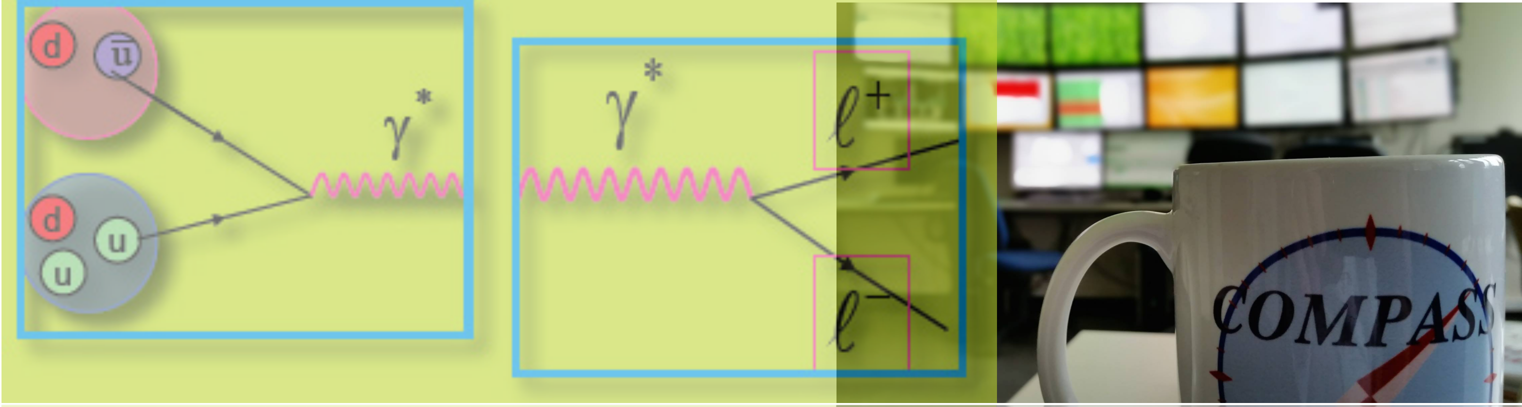
Boer-Mulders $\otimes$ Transversity

Boer-Mulders $\otimes$ Pretzelosity

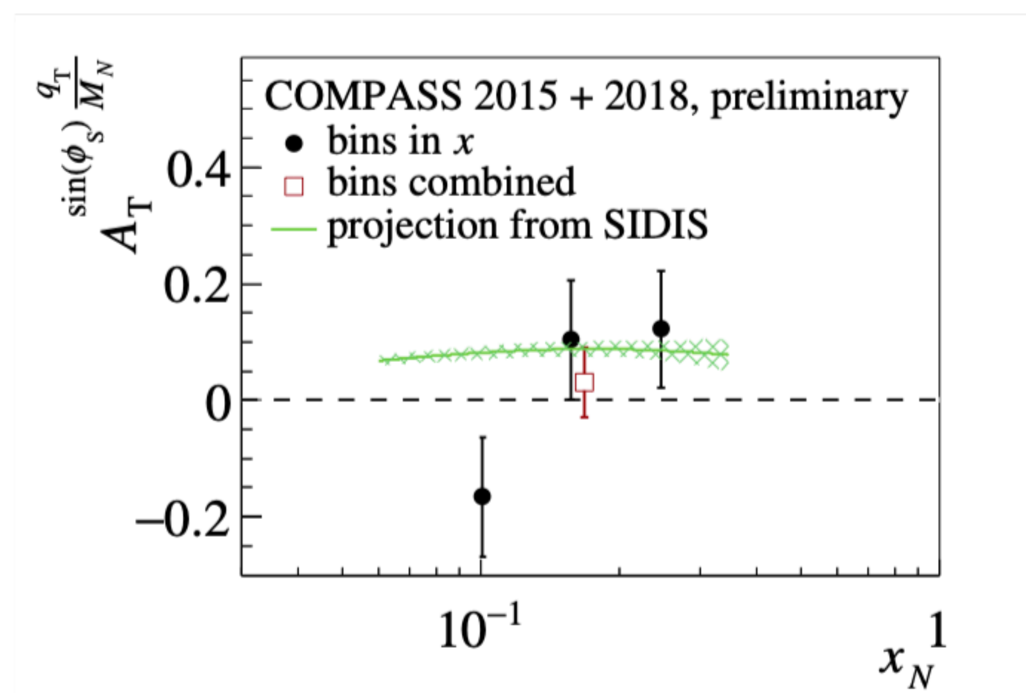




q_T weighted asymmetries



- General formalism firstly developed for SIDIS [A. Kotzinian & P. Mulders, PLB 406 (1997) 373];
- It allows to avoid assumptions on the functional form of the k_T dependence;
- Recently measured in SIDIS by COMPASS (COMPASS NPB 940 (2019) 34);
- Formalism extended to DY [A. Efremov et al., Phys.Lett. B612 (2005) 233, A. Sissakian et al., Phys.Rev. D72 (2005) 054027];
- Using appropriate q_T weights allows to access directly the first moment of TMDs;
- Recent wTSAs extraction by COMPASS from DY 2015 + 2018 (~50%) data;

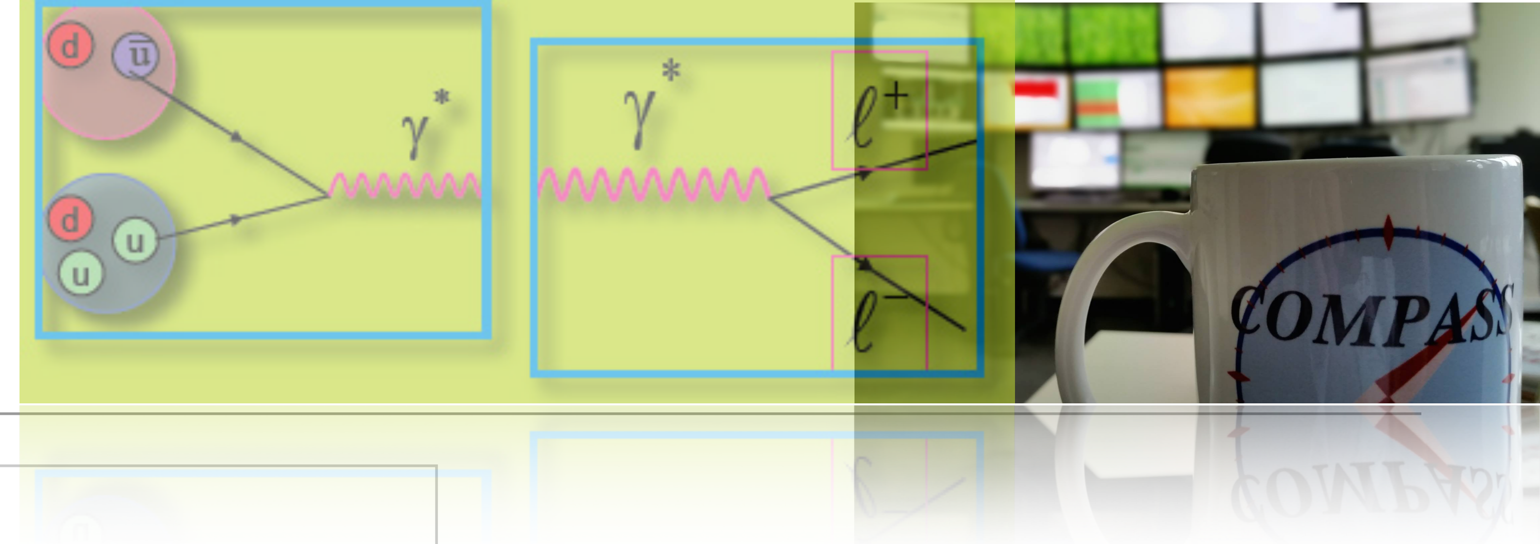


(c) 2015 + 2018 data

$$A_T^{\sin\varphi_S} \propto f_{1,\pi}^{q} \otimes f_{1T,p}^{\perp q}$$

$$A_T^{\sin\varphi_S \frac{q_T}{M_N}} \propto f_{1,\pi}^{q} \times f_{1T,p}^{\perp q(1)}$$

Unpolarized Drell-Yan

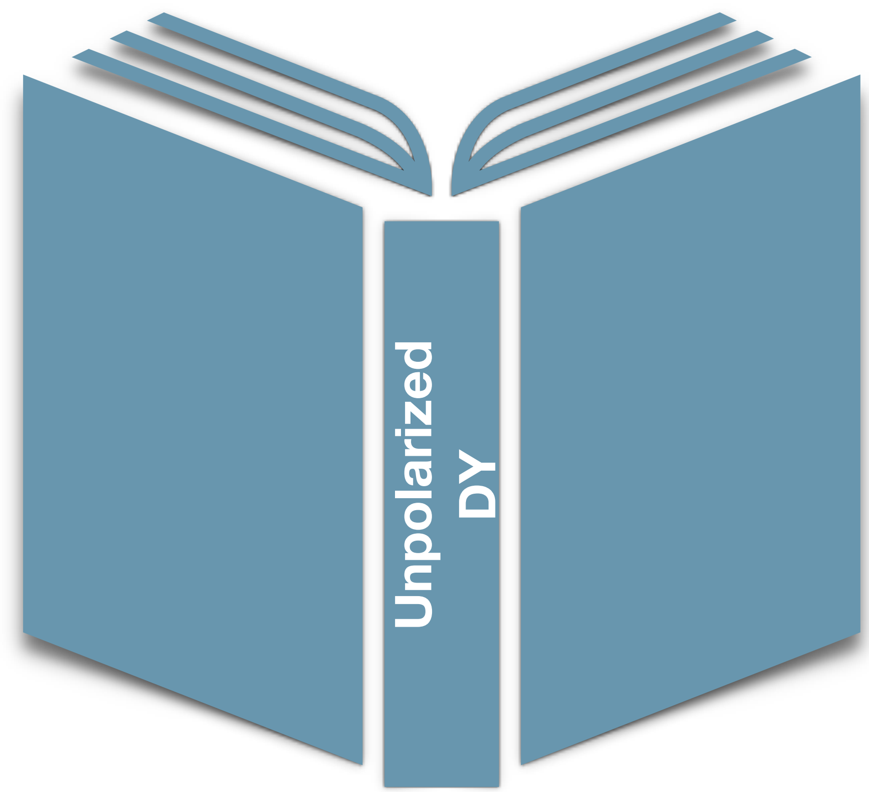


➤ Three targets available :

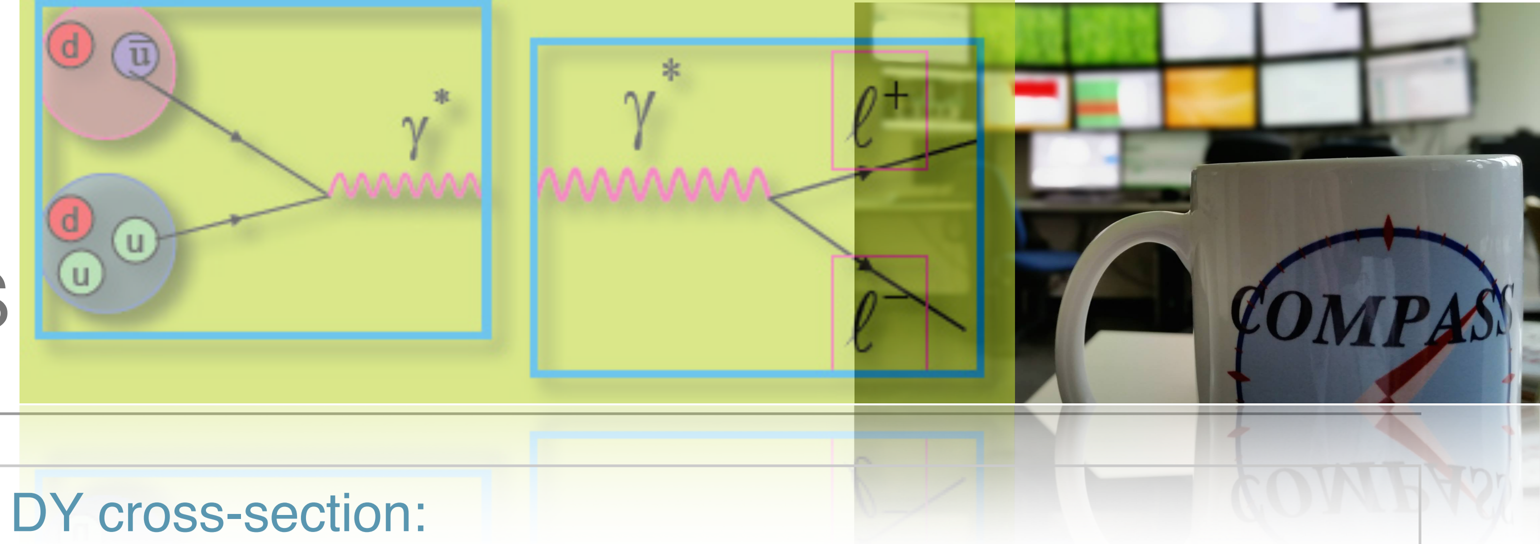
NH3, ^{27}Al, ^{184}W

➤ Motivations

- Study of unpolarized asymmetries, violation of the Lam-Tung relation
- Modification of the parton distributions within a nuclear medium —> EMC effect, parton energy loss
- Measurement of absolute Drell-Yan cross-sections



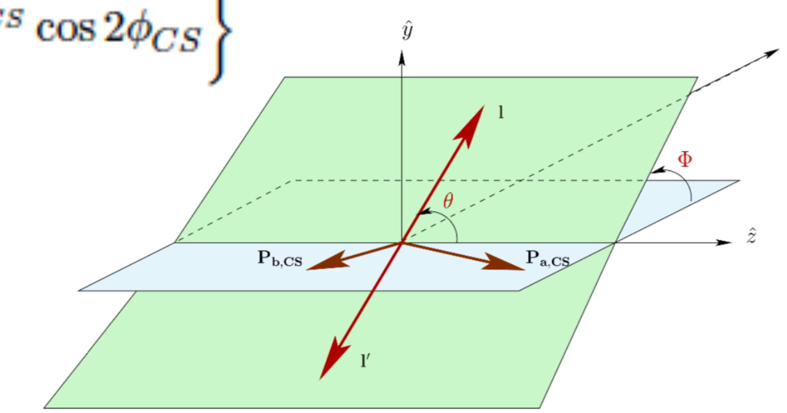
Unpolarized azimuthal asymmetries



Target polarization independent part of the DY cross-section:

$$\frac{d\sigma}{dq^4 d\Omega} \propto (F_U^1 + F_U^2)\left\{1 + A_U^1 \cos^2\theta_{CS} + \sin 2\theta_{CS} A_U^{\cos\phi_{CS}} \cos\phi_{CS} + \sin^2\theta_{CS} A_U^{\cos 2\phi_{CS}} \cos 2\phi_{CS}\right\}$$

$$\lambda = A_U^1, \qquad \mu = A_U^{\cos\phi_{CS}}, \qquad \nu = 2A_U^{\cos 2\phi_{CS}}$$



(b)

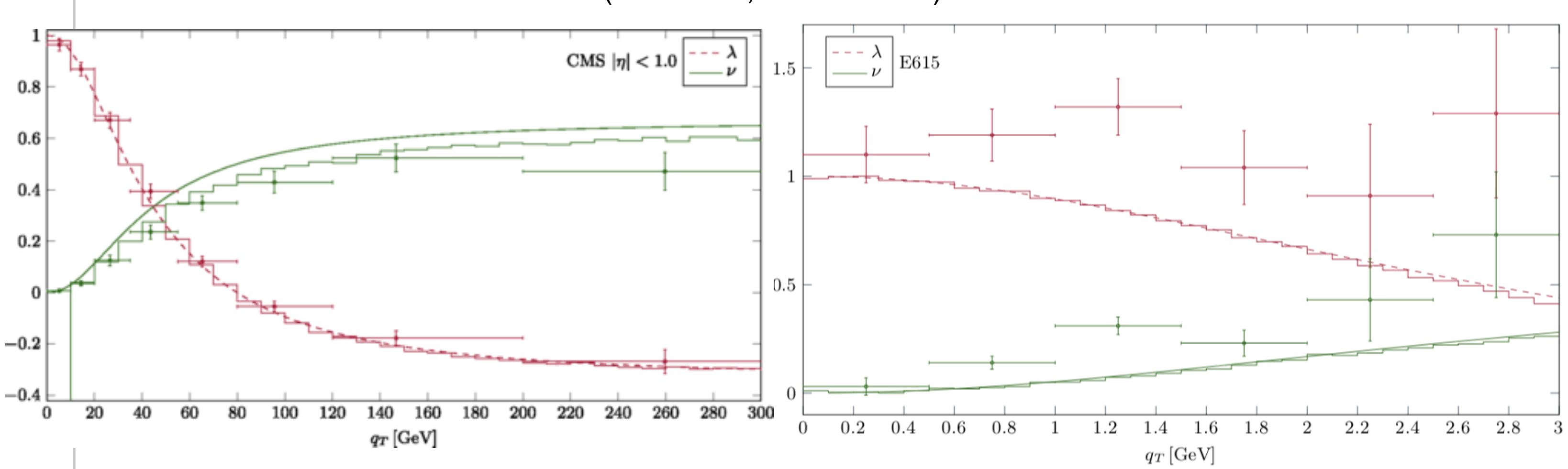
➤ Collinear hypothesis : λ = 1, μ = ν = 0 (assumed in early years)

Violation of the Lam-Tung relation : 1 - λ ≠ 2ν

➤ sizeable deviations of the Lam-Tung relation measured by several experiments:

(NA10) Z. Phys. C37 (1988) 545; (E615) PRD 39,(1989) 92;(CMS) Phys. Lett. B 750, 154 (2015); (ATLAS) JHEP 1608, 159 (2016)

(Line = LO, Dash = NLO)

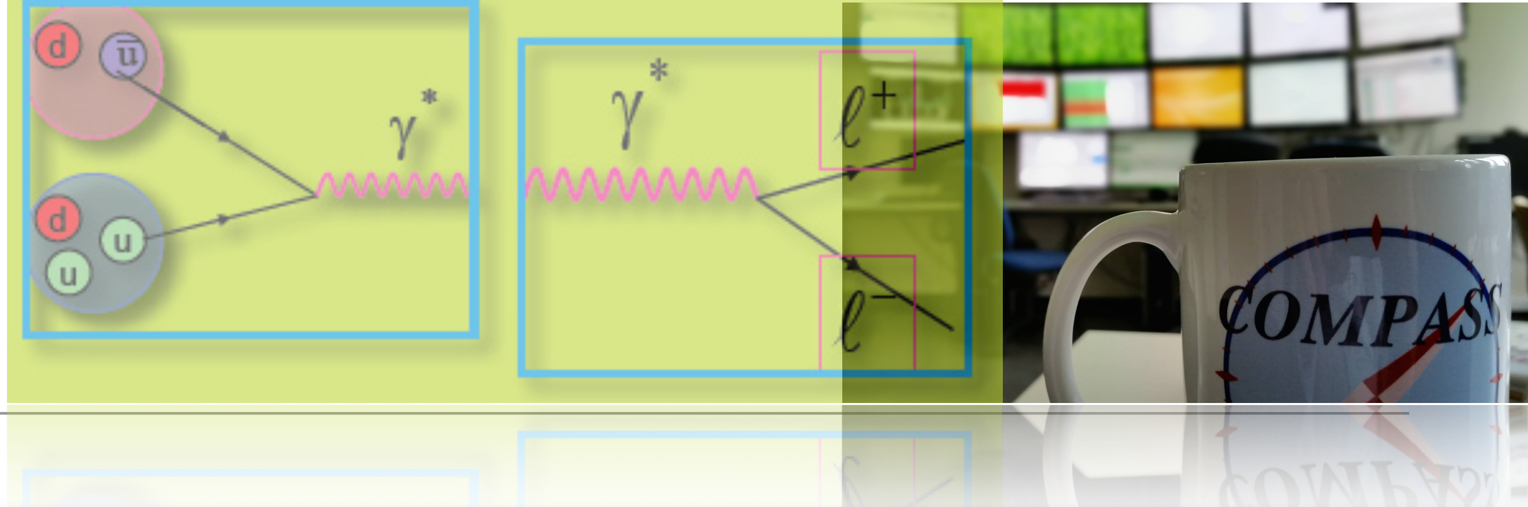


Recent evidence in terms of QCD: radiative effects describe well the data at large q_T
J.-C. Peng et al. PLB 758, 384 (2016)
M. Lambertsen and W. Vogelsang PRD93, 114013 (2016)

still space left for non-perturbative effects to play a role at lower q_T ?—> Boer-Mulders?

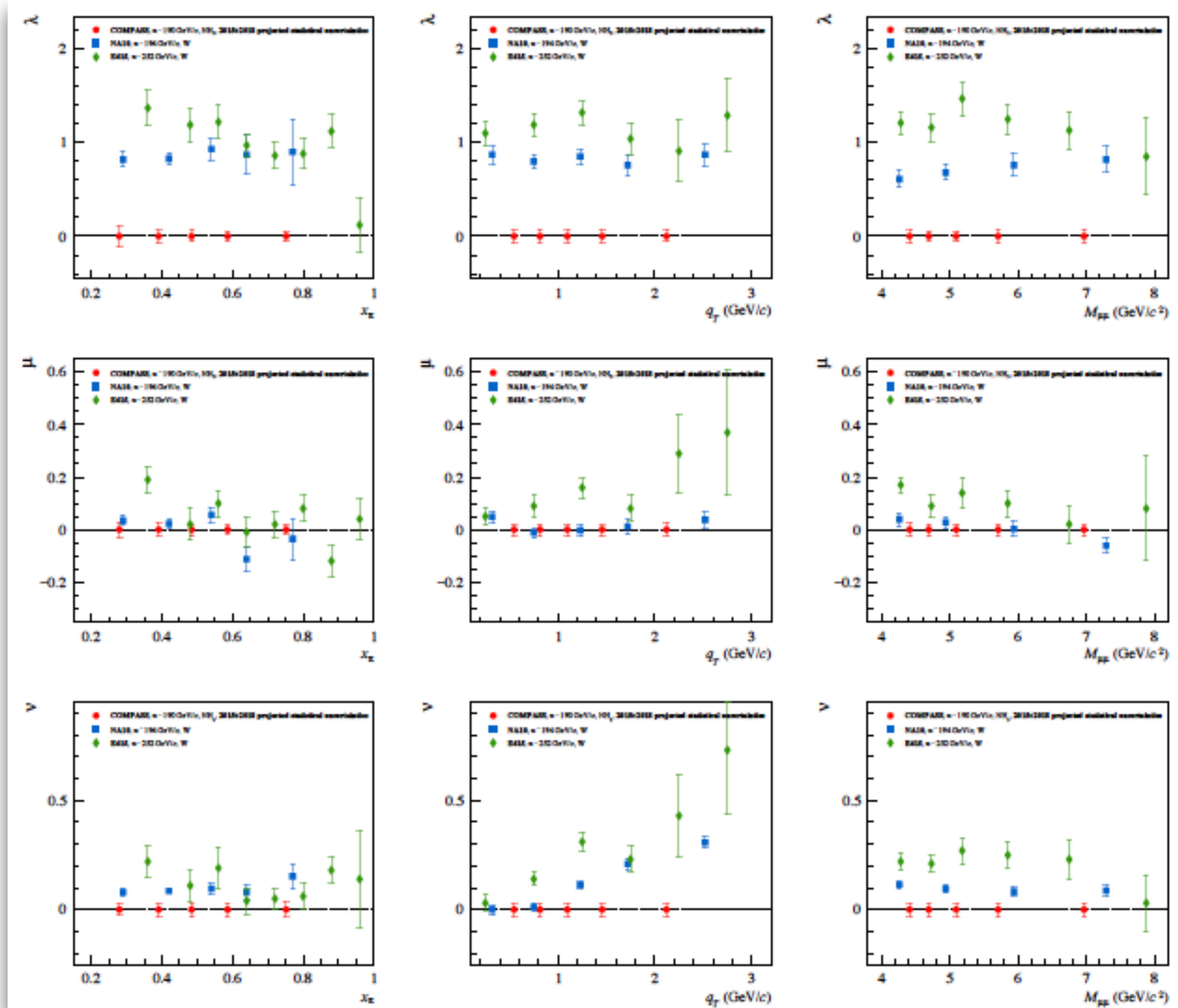
$$\boxed{\nu \propto h_1^{q\perp}(p) \otimes h_1^{q\perp}(\pi)}$$

Unpolarized azimuthal asymmetries

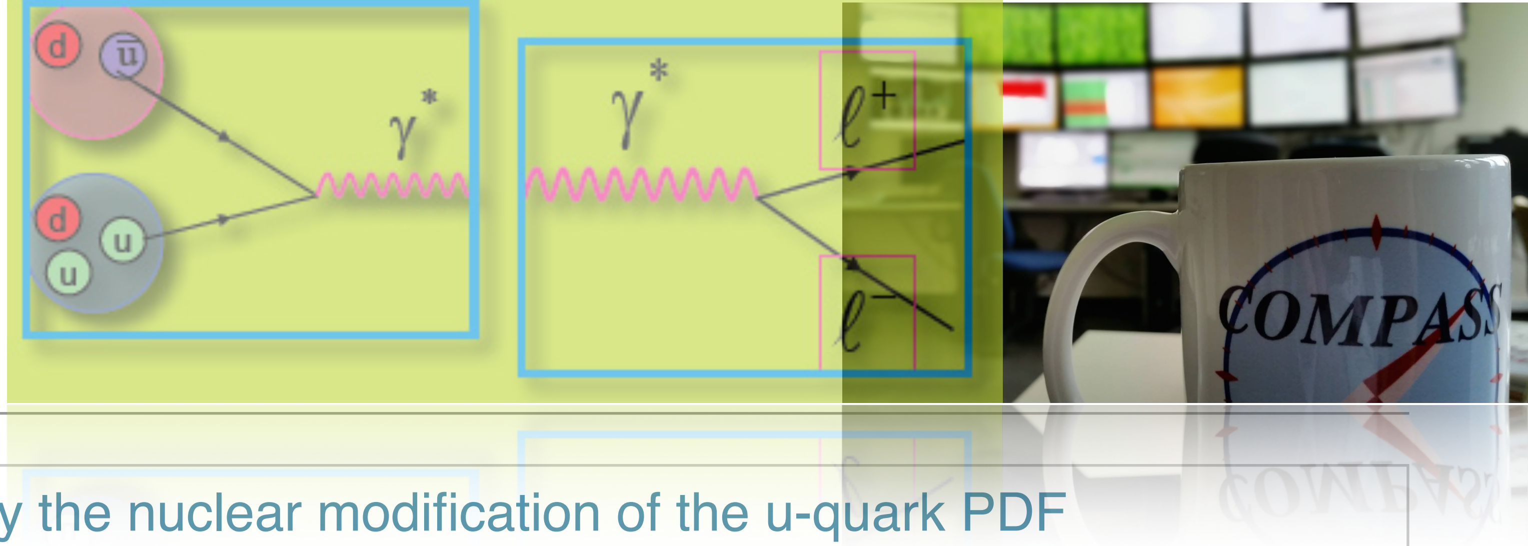


Expected statistical accuracy for DY UAs from COMPASS 2015 data collected with ammonia target

The published results from past experiments E615 and NA10 are also shown for comparison



Nuclear Dependence of Drell-Yan



➤ EMC effect : at COMPASS probes mainly the nuclear modification of the u-quark PDF

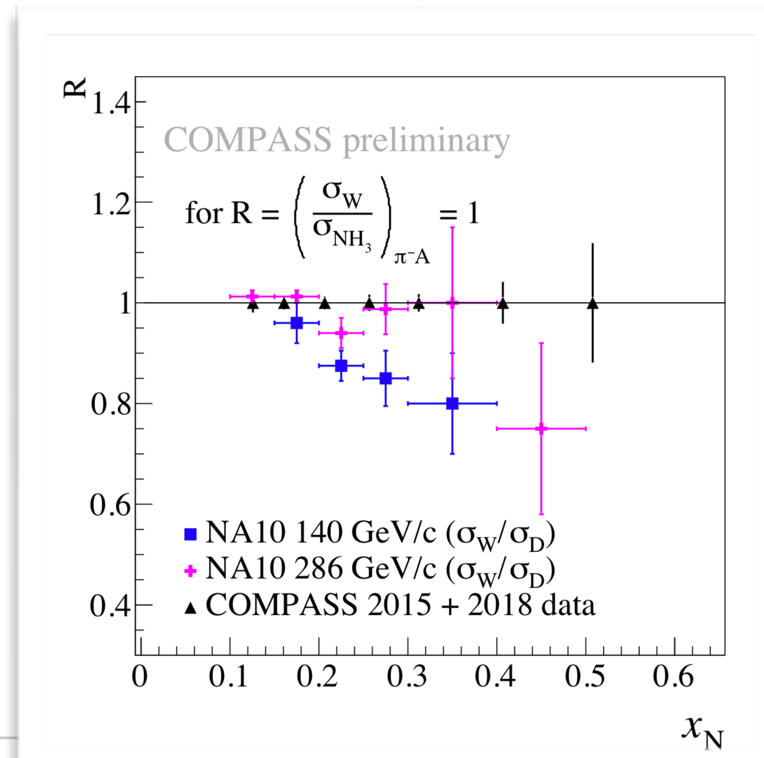
Study the A dependence of the Drell-Yan cross-sections per nucleon for the NH_3 and W targets:

$$R_{\pi^- A} = \frac{\sigma_W}{\sigma_{NH_3}} = \frac{\mathcal{L}_{NH_3}}{\mathcal{L}_W} k_{pn} \frac{N^W_{\mu\mu}\, Acc^{NH_3}}{N^{NH_3}_{\mu\mu} Acc^W} = C \frac{N^W_{\mu\mu}}{N^{NH_3}_{\mu\mu}}$$

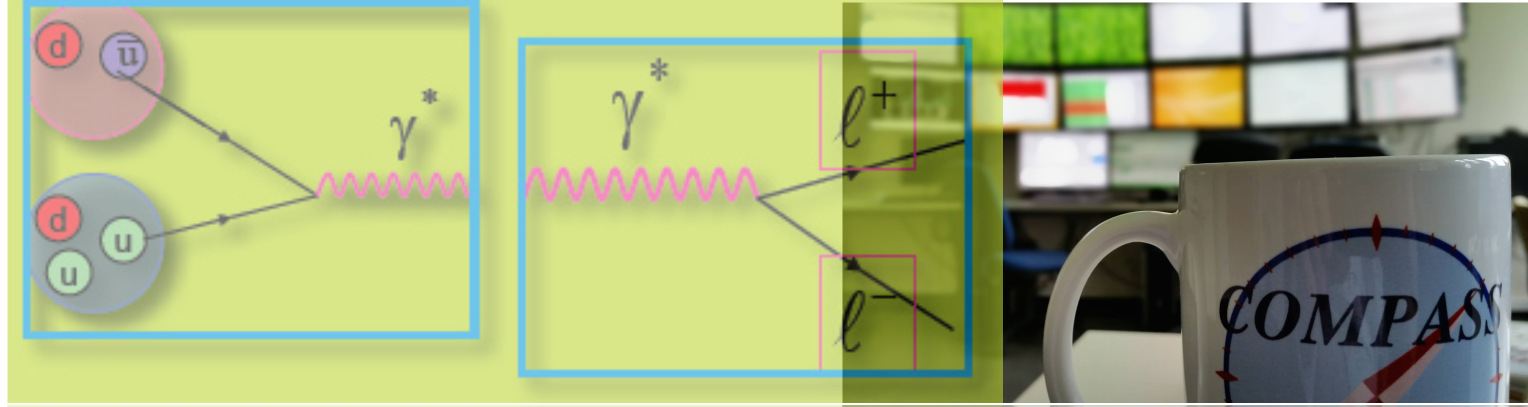
k_{pn} takes into account the different number of protons and neutrons in the targets.

➤ Recent release of the COMPASS preliminary projected uncertainties, ratio between NH_3 and W.

➤ Projected 2015 uncertainties + expected statistical uncertainty in 2018 (not from real data, based on simulation) compared with NA10



Future perspectives: COMPASS++/AMBER



Apparatus for Meson and Baryon Experimental Research

January 2019: Letter of Intent handed over to SPSC

April 2019: formation of Proto-Collaboration Board

May 2019: COMPASS++/AMBER Phase–1 Proposal (update September)

Phase–2 Proposal drafting to be started soon

250 authors,
51 institutions,
16 new institutions with respect to COMPASS (majority from USA, also Germany, Italy, Russia etc.)

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-SPSC-2019-003
SPSC-I-250
January 25, 2019

265 authors,
50 institutions

http://arxiv.org/abs/1808.00848

[hep-ex] 25 Jan 2019

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],

Proposal for Measurements at the M2 beam line of the CERN SPS

Phase-1: 2022-2024

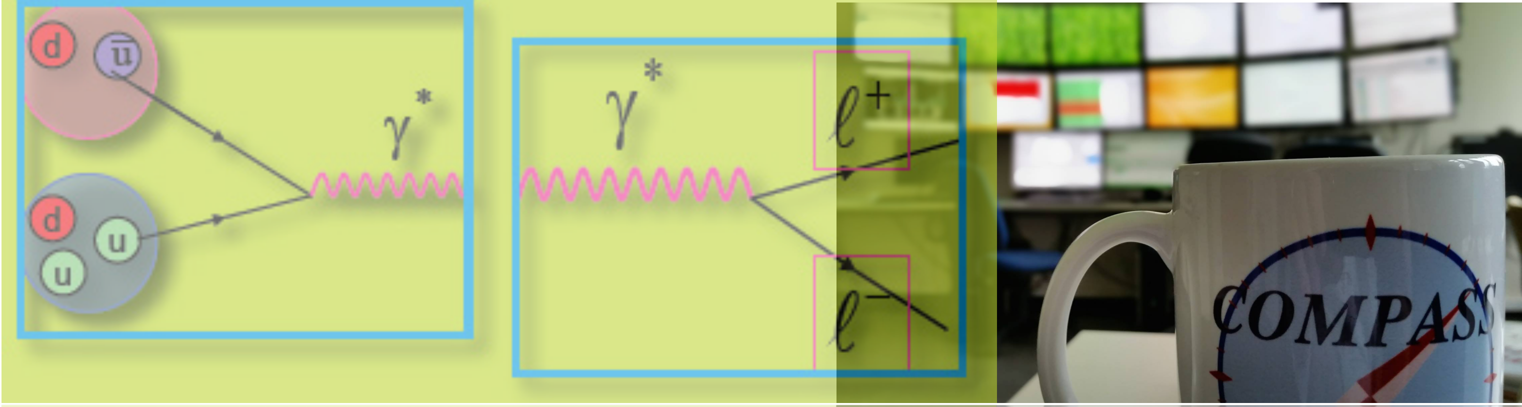
COMPASS++*/AMBER†

http://cds.cern.ch/record/2676885

CERN-SPSC-2019-022 / SPSC-P-360
31/05/2019

B. Adams[14,13], C.A. Aidala[1], G.D. Alexeev[15], M.G. Alexeev[41,42], A. Amoroso[41,42], V. Andrieux[44,20], N.V. Anfimov[15], V. Anosov[15], A. Antoshkin[15], K. Augsten[15,31], W. Augustyniak[46], C.D.R. Azevedo[4], B. Badełek[47], F. Balestra[41,42], M. Ball[8], J. Barth[8], R. Beck[8], J. Berenguer Antequera[41,42], J.C. Bernauer[33,45], J. Bernhard[20,p], M. Bodlak[30], F. Bradamante[39], A. Bressan[38,39], M. Büchele[17], V.E. Burtsev[40], C. Butler[3], C. Chatterjee[38,39], M. Chiosso[41,42], A.G. Chumakov[40], S.-U. Chung[18,c], A. Cicuttin[39,d], M. Connors[3], A. Contin[6], P. Correia[4], M.L. Crespo[39,d], S. Dalla Torre[39], S.S. Dasgupta[11], S. Dasgupta[39,11], N. Dashyan[50], I. Denisenko[15], O.Yu. Denisov[42], L. Dhara[11], F. Donato[43], S.V. Donskov[32], N. Doshita[49], Ch. Dreisbach[18], W. Dünnweber[e], R.R. Dusaev[40], A. Dzyuba[19], A. Efremov[15], P. Egelhof[16], A. Elagin[14], P.D. Eversheim[8], P. Faccioli[22], M. Faessler[e], J. Fedotova[25], M. Finger[30], M. Finger jr.[30], H. Fischer[17], C. Franco[22], J.M. Friedrich[18], V. Frolov[15], A. Futch[44], F. Gautheron[44], O.P. Gavrichtchouk[15], S. Gerassimov[27,18], S. Gevorkyan[15], Y. Ghandilyan[50], J. Giarra[24], I. Gnesi[41,42], M. Gorzellik[17], A. Grasso[41,42], A. Gridin[15], M. Grosse Perdekamp[44], B. Grube[18], R.I. Gushterski[15,l], A. Guskov[15], G. Hamar[39], D. von Harrach[24], X. He[3], R. Heitz[44], F. Herrmann[17], M. Hoffmann[8], N. Horikawa[29,f], S. Huber[18], A. Inglessi[19], A. Ilyichev[25], S. Ishimoto[49,h], A. Ivanov[15], N. Ivanov[50], T. Iwata[49], M. Jadhav [2], M. Jandek[30], V. Jary[31], C.-M. Jen[23], R. Joosten[8], P. Jörg[17], K. Juraskova[31], E. Kabuß[24], F. Kaspar[18], D. Keller[12], A. Kerbizi[38,39], B. Ketzer[8],

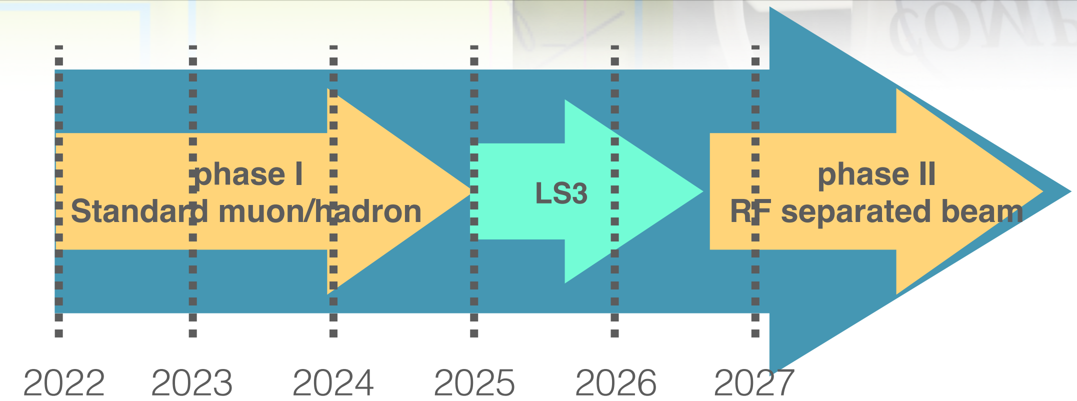
Future perspectives: COMPASS++/AMBER



Two phases program:

Phase I (shorter term) – current muon/hadron beam

Phase II (longer term) – RF-separated beam, after LS3



LOI complete program: phase I + phase II

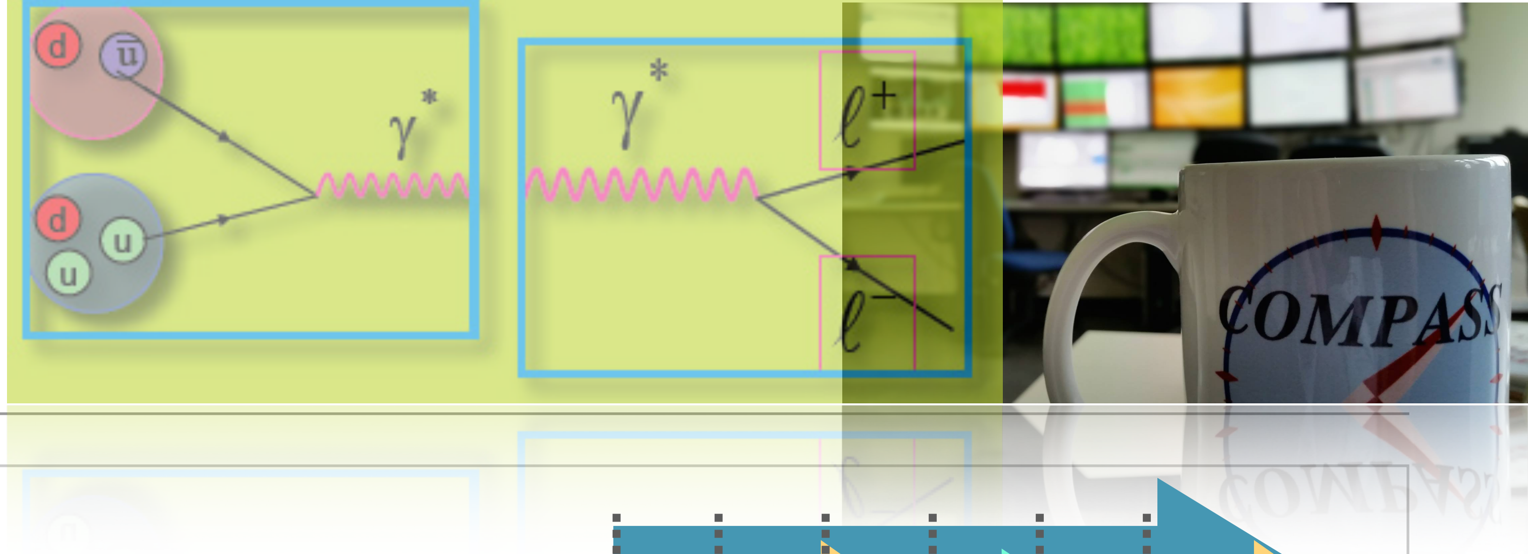
Program	Physics Goals	Beam Energy [GeV]	Beam Intensity [s^{-1}]	Trigger Rate [kHz]	Beam Type	Target	Earliest start time, duration	Hardware additions
muon-proton elastic scattering	Precision proton-radius measurement	100	$4 \cdot 10^6$	100	$\mu^\pm$	high-pressure H2	2022 2 years	active TPC, SciFi trigger, 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	$\bar{p}$ production cross section	20-280	$5 \cdot 10^5$	25	p	LH2, LHe	2022 1 month	liquid helium target
$\bar{p}$-induced spectroscopy	Heavy quark exotics	12, 20	$5 \cdot 10^7$	25	$\bar{p}$	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	$\sim$100	10^8	25-50	$K^\pm, \bar{p}$	$NH_3^\uparrow$, C/W	2026 2-3 years	"active absorber", vertex detector
Primakoff (RF)	Kaon polarisa-bility & pion life time	$\sim$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	

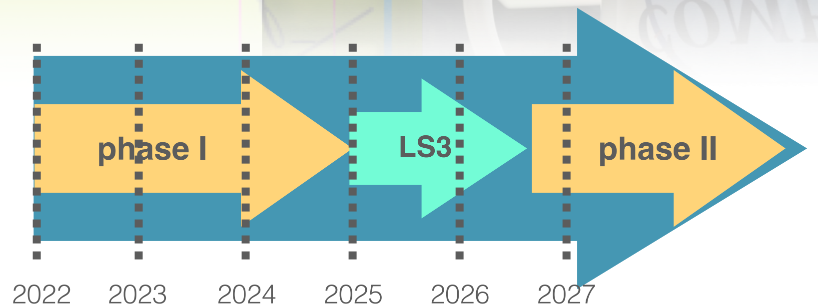
Proposal program: phase I

Year	Activity	Duration	Beam
2021	Proton radius test measurement	20 days	μ
2022	Proton radius measurement Antiproton production test measurement	120 (+40) days 10 days	μ p
2023	Antiproton production measurement Proton radius measurement	20(+10) days 140 (+10) days	p μ
2024 2024+	Drell-Yan: pion PDFs and charmonium production mechanism	$\lesssim$ 2 years	p, K^+, π^+, $\bar{p}, K^-, \pi^-$

DY program at COMPASS++/AMBER

DY program at COMPASS++/AMBER





Near term future: Current beams

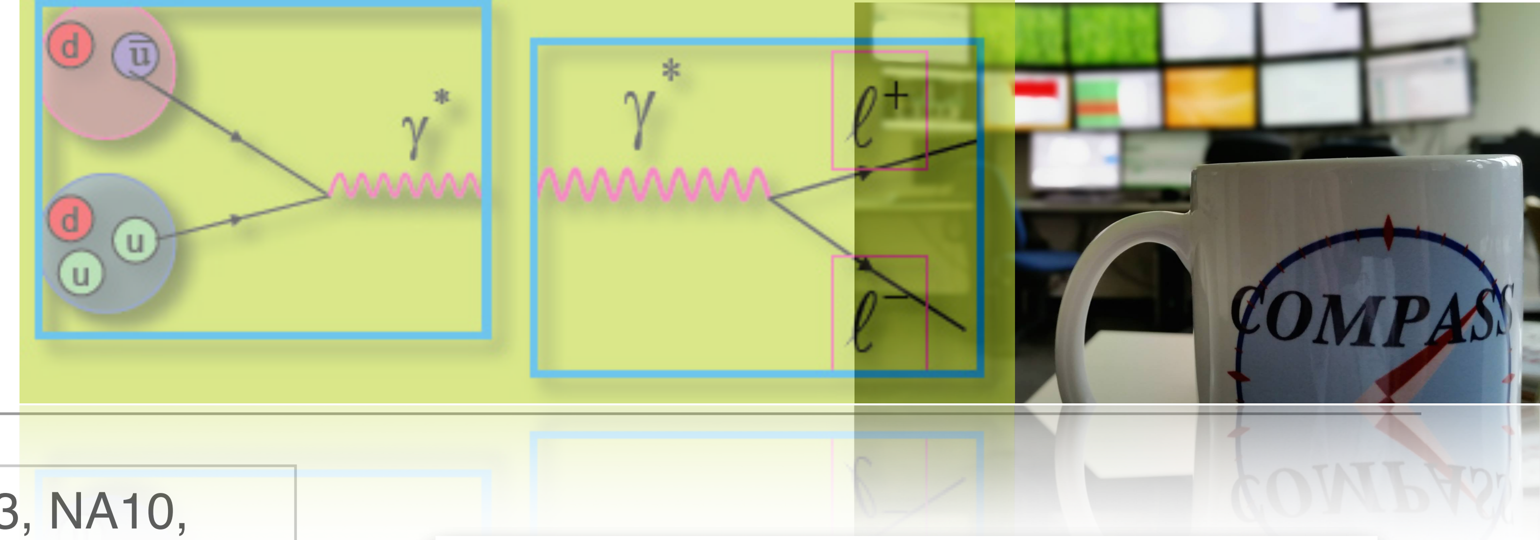
- The structure of the pion: determination of the pion valence and sea-quark distributions
- Investigation of flavour-dependent effects in nuclear targets

Long term future: RF-separated beams

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

Charmonia measurements —> study of the production mechanism and possible access to the pion and kaon gluon PDFs

What do we know about pion structure?

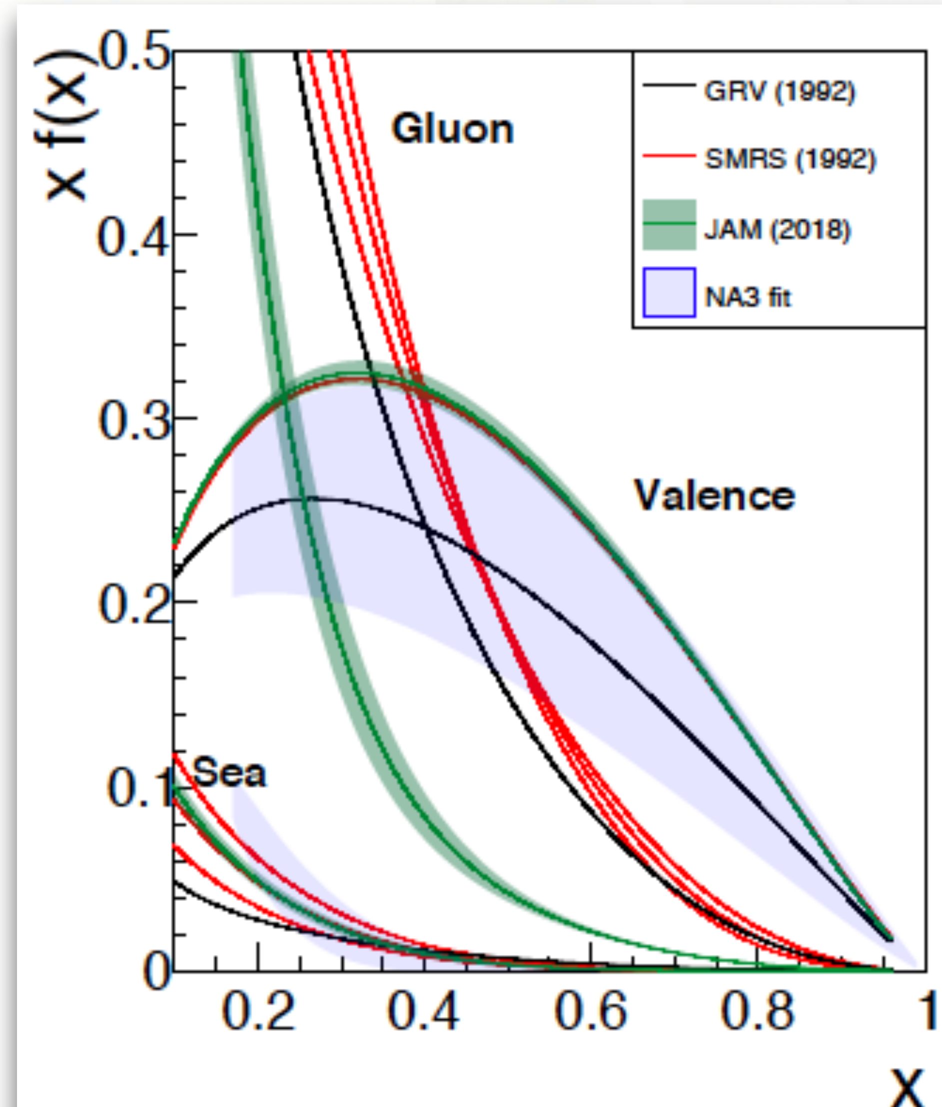


Pion-induced Drell-Yan data collected by NA3, NA10, and WA39 (CERN) and E615 (Fermilab), more than 30 years ago —> access valence and sea (NA3 and WA39) distributions in the pion

Available data from direct-photon production also obtained at that time, by WA70 and NA24(CERN)

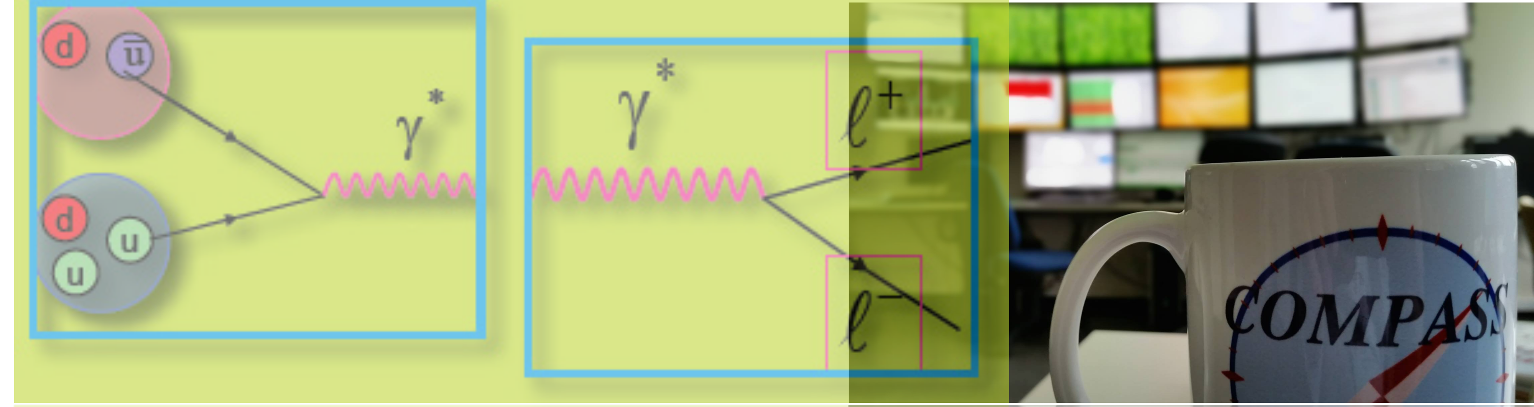
limited data sets —> sea quark distribution was derived from momentum-sum-rule conservation

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 52,000
This exp AMBER	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



GRV/S Z. Phys. C53 (1992) 651–656. ; Eur. Phys. J. C10 (1999)
SMRS Phys. Rev. D45 (1992) 2349–2359; Phys. Rev. Lett. 121 (2018) 152001
NA3 Z. Phys. C18 (1983) 281

The pion structure: COMPASS++/AMBER

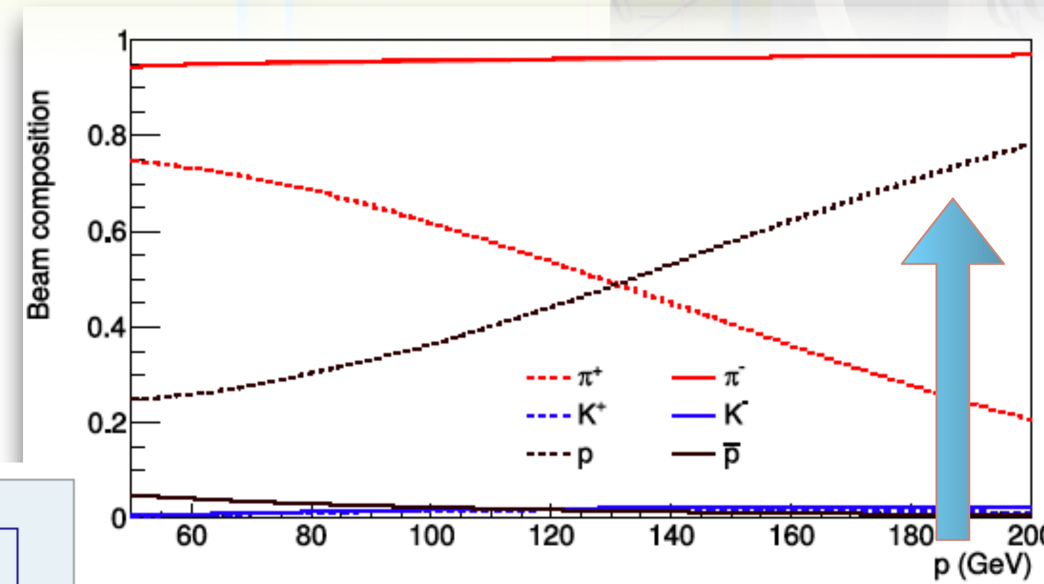


- High energy and intensity pion beams

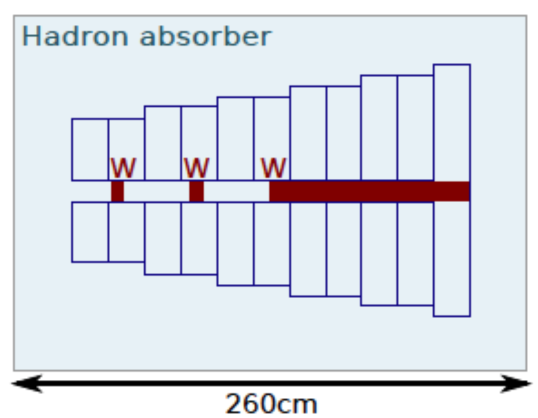
Example @ 190 GeV/c

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

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



- COMPASS-like apparatus
- Segmented Carbon target

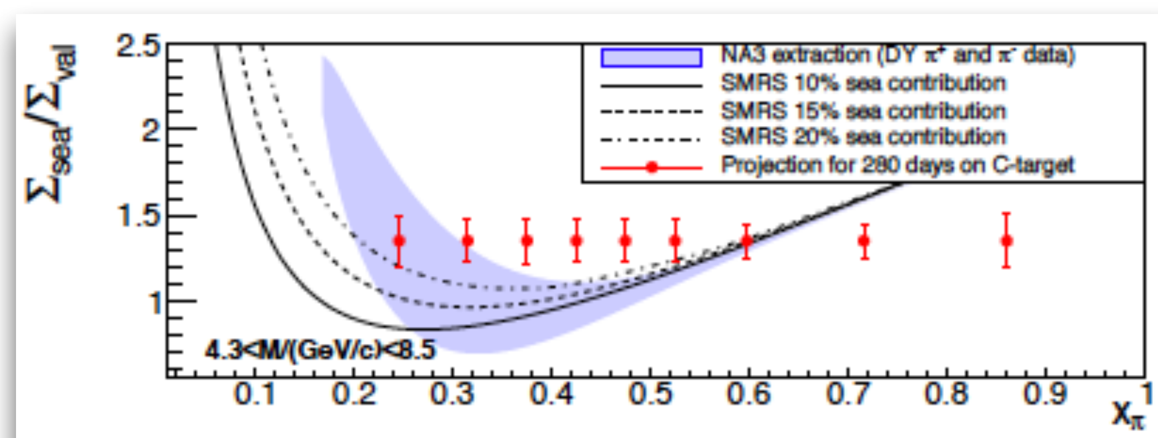


- Flavour dependent nuclear PDFs

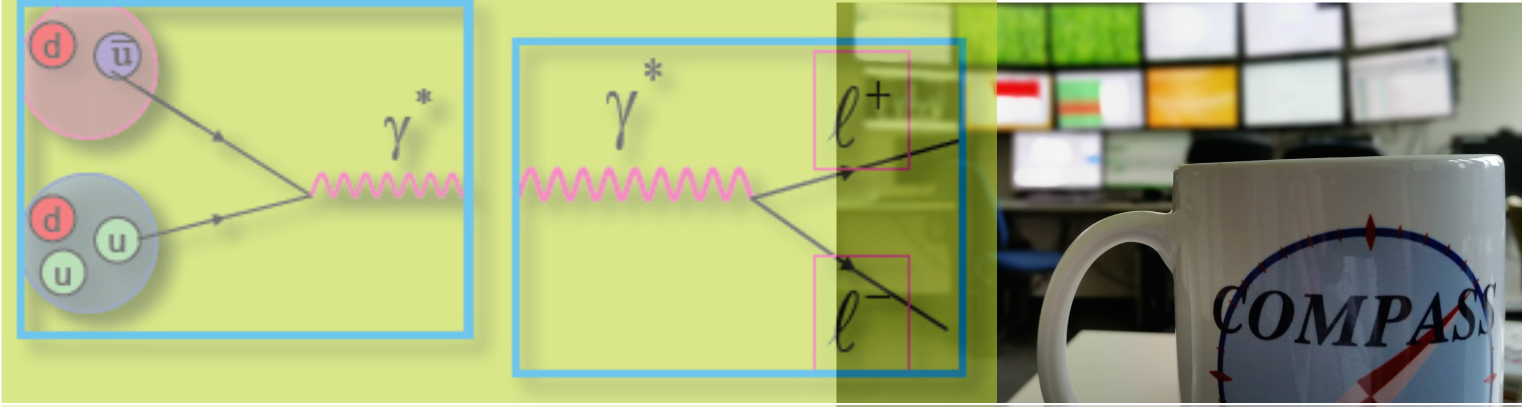
Positive and negative pion beam on Carbon and Tungsten target

- Aim at the first precise direct measurement of the pion sea contribution

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



What do we know about kaon structure?



Sole measurement from NA3

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

- Limited statistics: 700 events with K⁻
- Mostly only model predictions

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

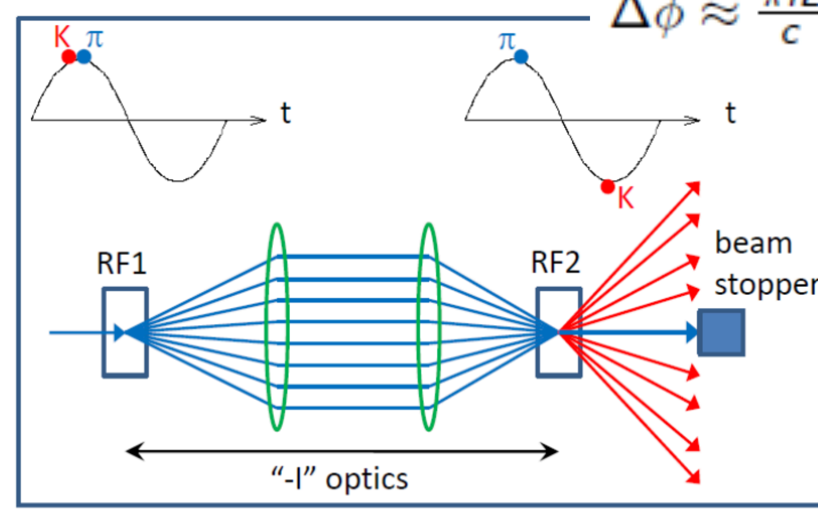
- Scarce data on u-valence
- No measurements on gluons
- No measurements on sea quarks

➤ How to improve the situation?

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. AMBER	100 cm C	K⁻	2.1×10^7	80 100 120	4.0 – 8.5 4.0 – 8.5 4.0 – 8.5	25,000 40,000 54,000	13,700 17,700 20,700
		K⁺	2.1×10^7	80 100 120	4.0 – 8.5 4.0 – 8.5 4.0 – 8.5	2,800 5,200 8,000	1,300 2,000 2,400
This AMBER	00 cm C	π⁻	4.8×10^7	80 100 120	4.0 – 8.5 4.0 – 8.5 4.0 – 8.5	65,500 95,500 123,600	29,700 36,000 39,800

Unique opportunities with RF separated beam

$$\Delta\phi \approx \frac{\pi f L}{c}\frac{m_w^2 - m_u^2}{p^2}$$



Enriched K⁻ and pbar beams (~ 3x10^7/s)

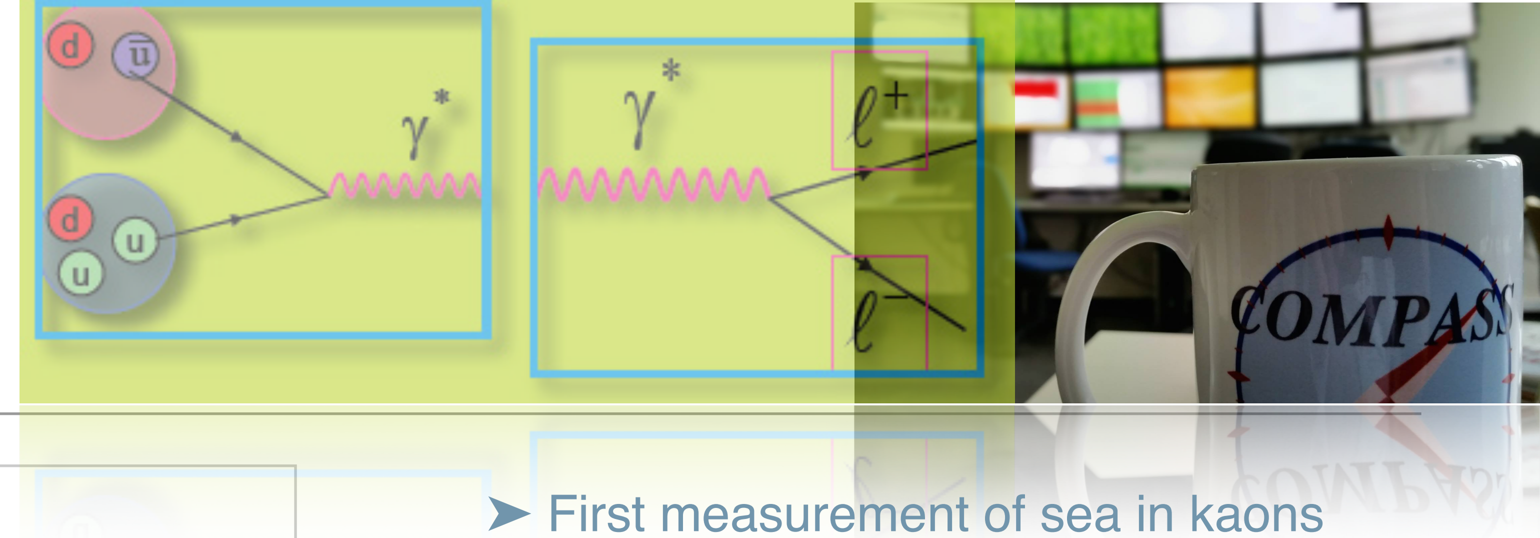
Expected energies: 80 (110) GeV for K⁻(pbar)

Small cross-section in HM

Lepton pairs emmitted at large angles

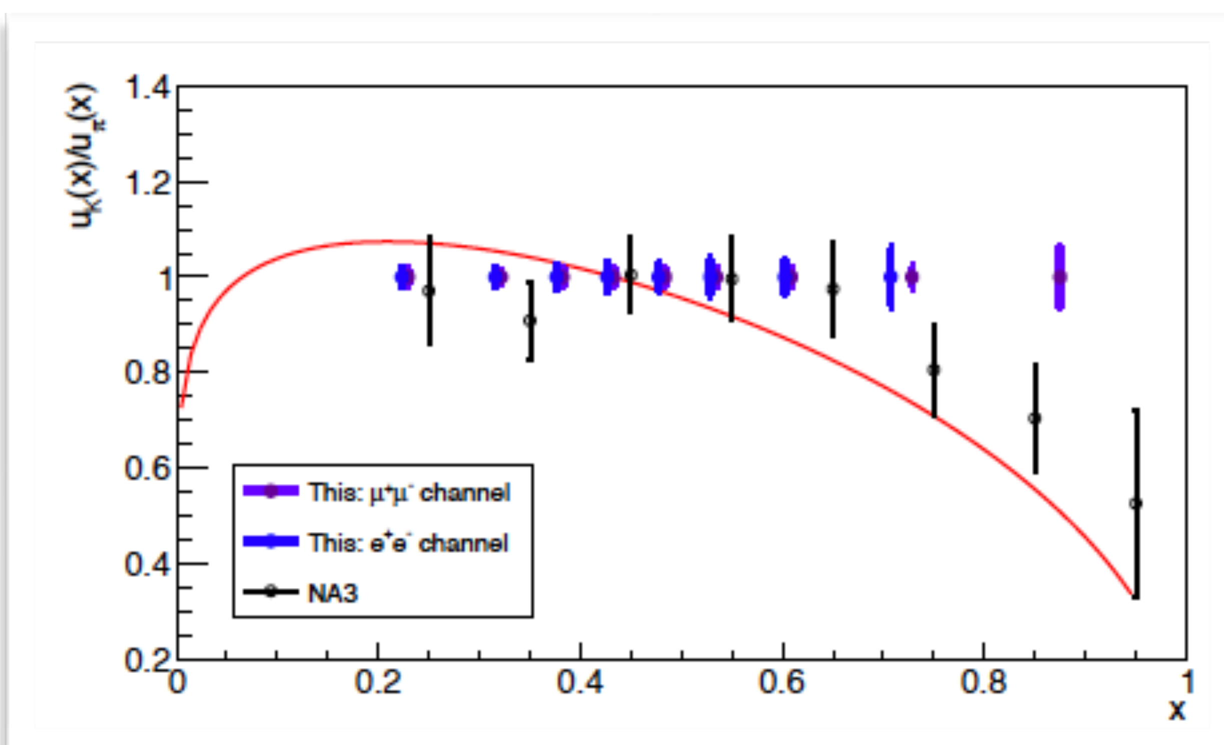
Active DY absorber:
Tracking with magnetic field
Good resolution for vertexing
Capability to collect e⁻e⁺ DY pairs

The pion structure: COMPASS++/AMBER



➤ More data points and more precise compared to NA3

- Discriminating power between models
- 1 year with ~ 2 x 10⁷/s 100 GeV/c K⁺ beam
- π taken simultaneously

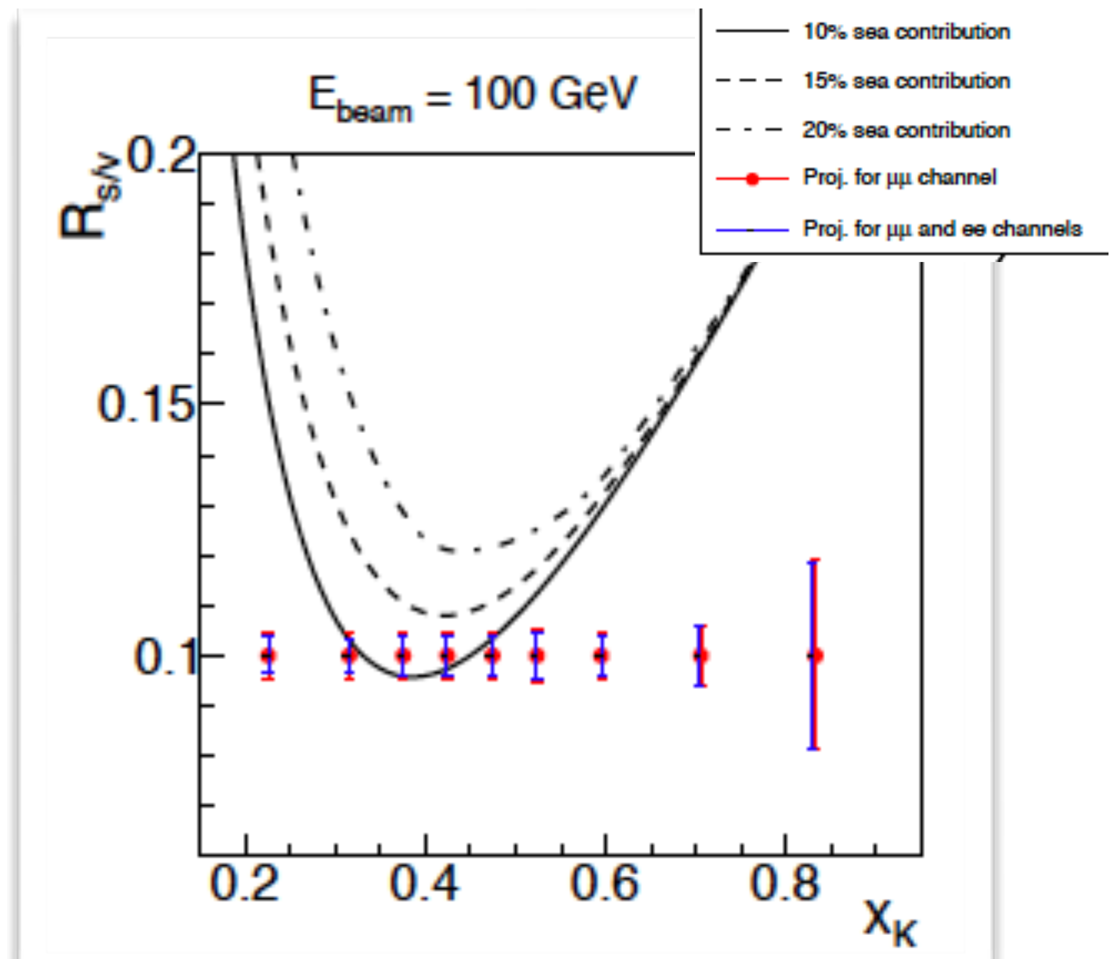


➤ First measurement of sea in kaons

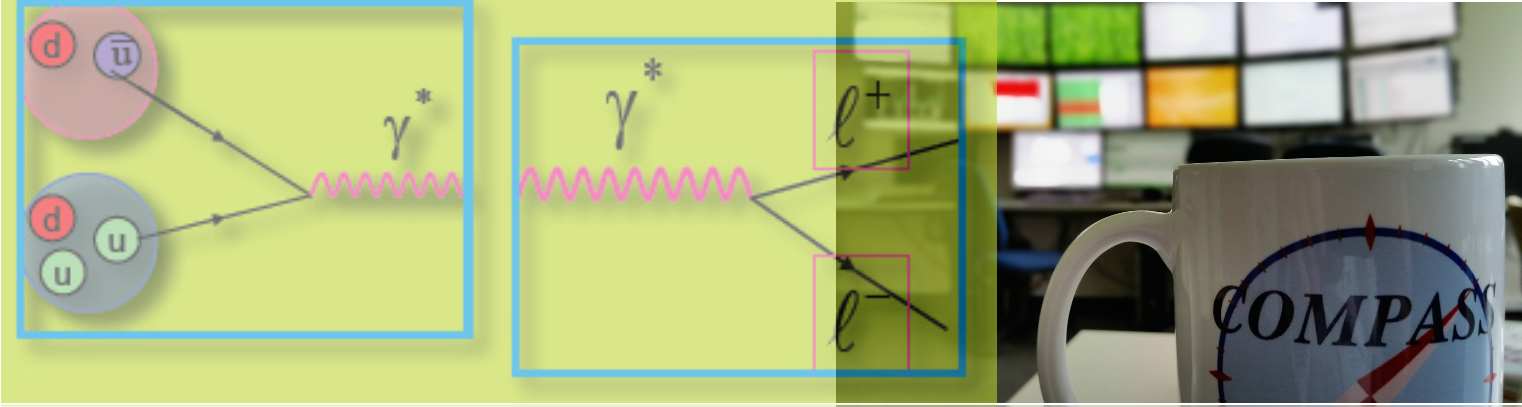
- Assuming the intensity for K^+ and K^- 2 x 10^7/s

$$\Sigma_{val} = \sigma^{K^-A} - \sigma^{K^+A}$$

$$R_{s/v} = \sigma^{K^+A}/\Sigma_{val}$$

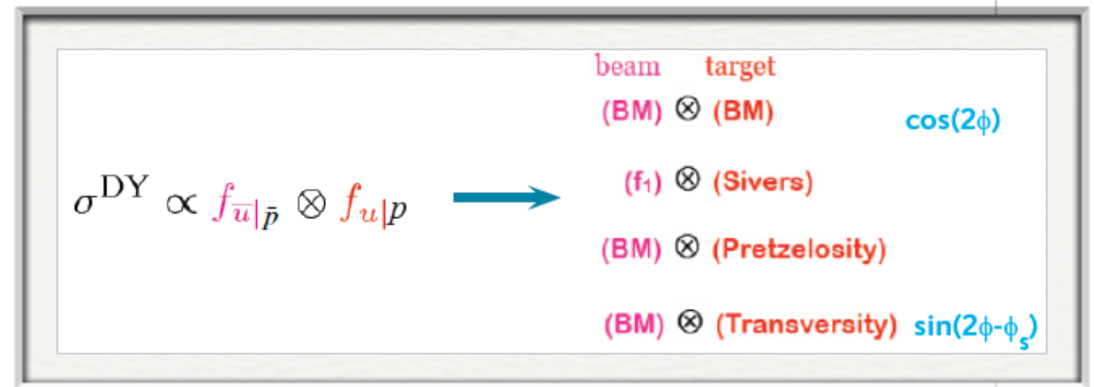


Single polarised DY with pbar beam



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

- prediction of a universal behaviour of the valence quark Boer-Mulders functions for pions and nucleons also awaits experimental confirmation
- Combining analysis of DY data with pion and antiproton beam an independent extraction of pion BM is achievable
- measurement of proton transversity entirely free of the uncertainty of fragmentation functions

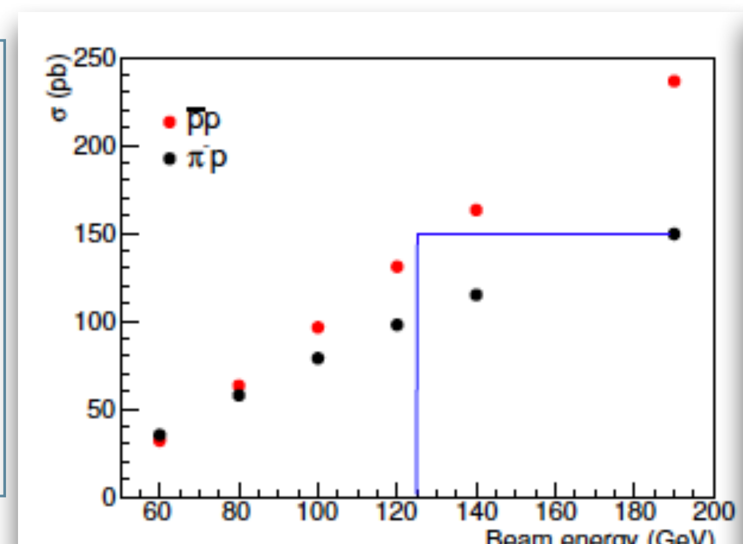


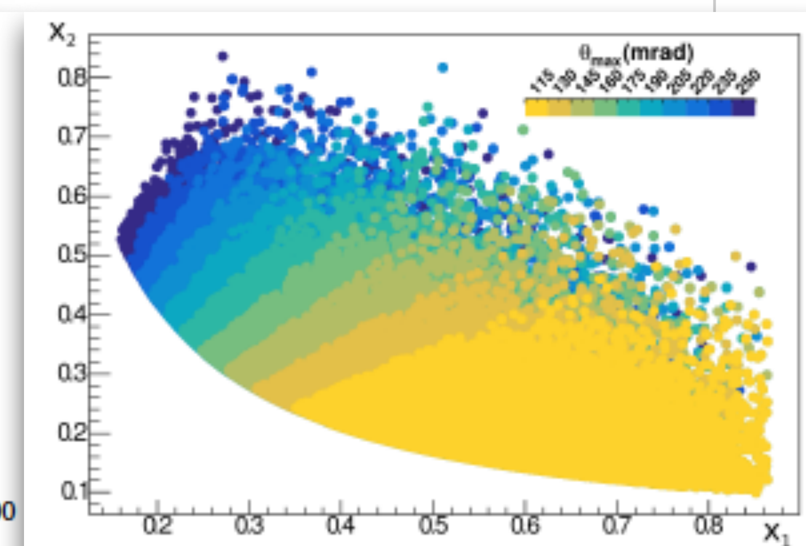
cross-sections for pbar induced-DY at 120 GeV

π^- induced-DY at 190 GeV

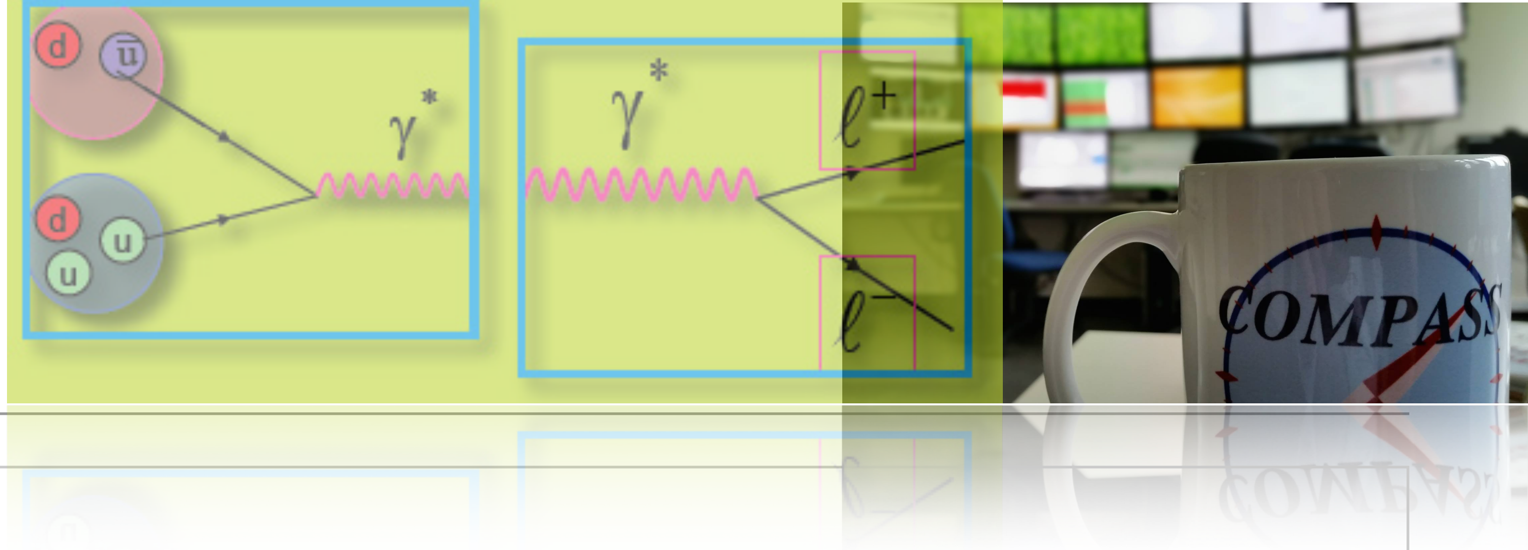
Combined statistics from $\mu^+\mu^-$ and e^+e^- channels

With active absorber: better acceptance in θ_{CS}





Summary



A rich Drell-Yan physics program: present and future

@ COMPASS

➤ COMPASS successfully collected new dimuon data in 2018:
The new 2018 Drell-Yan data are under analysis (preliminary results including 50% of these data)

➤ Transverse spin asymmetries:
TSAs measured both in polarized Drell-Yan and SIDIS processes

➤ Unpolarized studies:
- Measurement of absolute Drell-Yan cross-section on 3 different targets
- EMC effect, Energy loss
- Study of unpolarized asymmetries, violation of the Lam-Tung relation

@ COMPASS++/AMBER new QCD facility at CERN M2 beam line

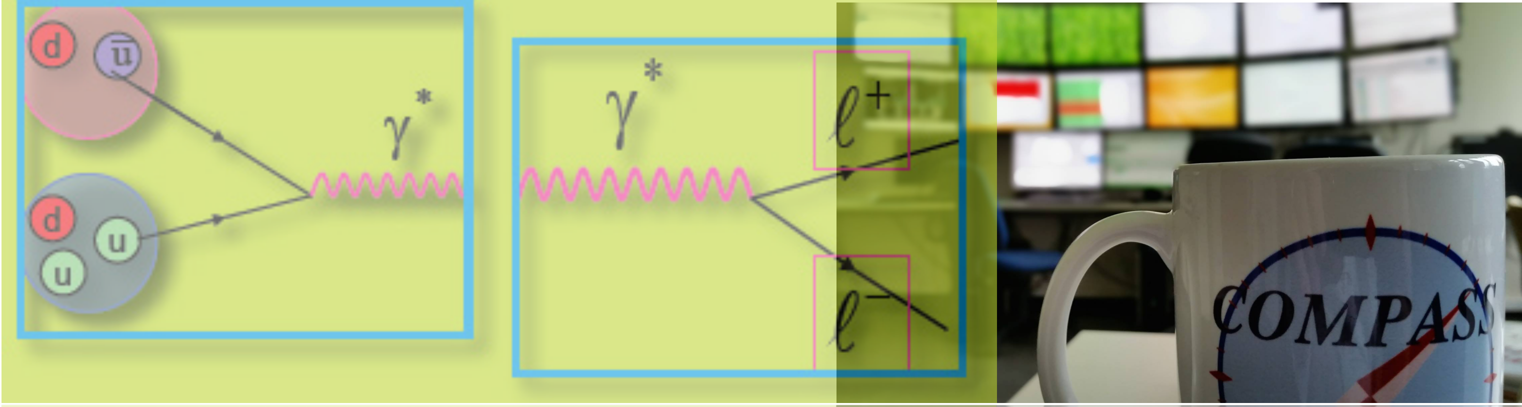
➤ A future Drell-Yan experiment is proposed, to study meson structure
- New, precise determination of the pion structure functions: valence, sea and gluon contributions
- The first-ever determination of the kaon PDFs, making use of RF-separated kaon beam of high intensity

➤ A unique opportunity to make antiproton-induced Drell-Yan with transversely polarized proton target, and measure TSAs with significantly reduced systematic error

Thank you for your attention

Michela Chiosso
On behalf of the
COMPASS Collaboration

DY TSAs : Results in High Mass Range



$$d\sigma^{DY} \propto 1 + D_{[\sin 2\theta]} A_{UU}^{\cos\phi} \cos\phi + D_{[\sin^2\theta]} A_{UU}^{\cos 2\phi} \cos 2\phi$$
$$+ S_T \Big[D_{[1+\cos^2\theta]} A_{UT}^{\sin\phi_S} \sin\phi_S$$
$$+ D_{[\sin^2\theta]} \left(A_{UT}^{\sin(2\phi-\phi_S)} \sin(2\phi-\phi_S) + A_{UT}^{\sin(2\phi+\phi_S)} \sin(2\phi+\phi_S) \right)$$
$$+ D_{[\sin 2\theta]} \left(A_{UT}^{\sin(\phi-\phi_S)} \sin(\phi-\phi_S) + A_{UT}^{\sin(\phi+\phi_S)} \sin(\phi+\phi_S) \right) \Big]$$

$$A_T^{\sin\varphi_S} \propto f_{1,\pi}^{q} \otimes f_{1T,p}^{\perp q}$$

$$A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{q} \qquad A_T^{\sin(2\varphi_{CS}+\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1T,p}^{\perp q}$$

→ Higher twist asymmetries

All 5 TSAs are extracted simultaneously using an Unbinned Maximum Likelihood Method

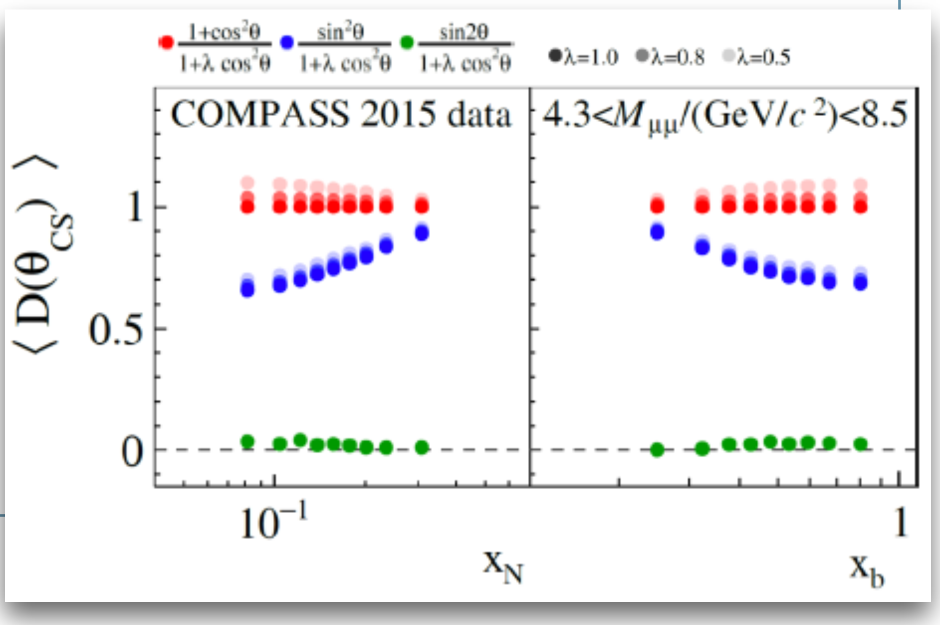
$$A_{raw} = P_T f D_{[f(\theta)]} A_{phy}$$

The asymmetries are weighted, event by event, according to the corresponding depolarization and dilution factors

The asymmetries resulting from the fit are corrected by the average P_T in the corresponding period

Depolarization factors are evaluated under assumption $\lambda = 1$

Possible impact of $\lambda \neq 1$ scenarios leads to a normalization uncertainty of at most 5%.

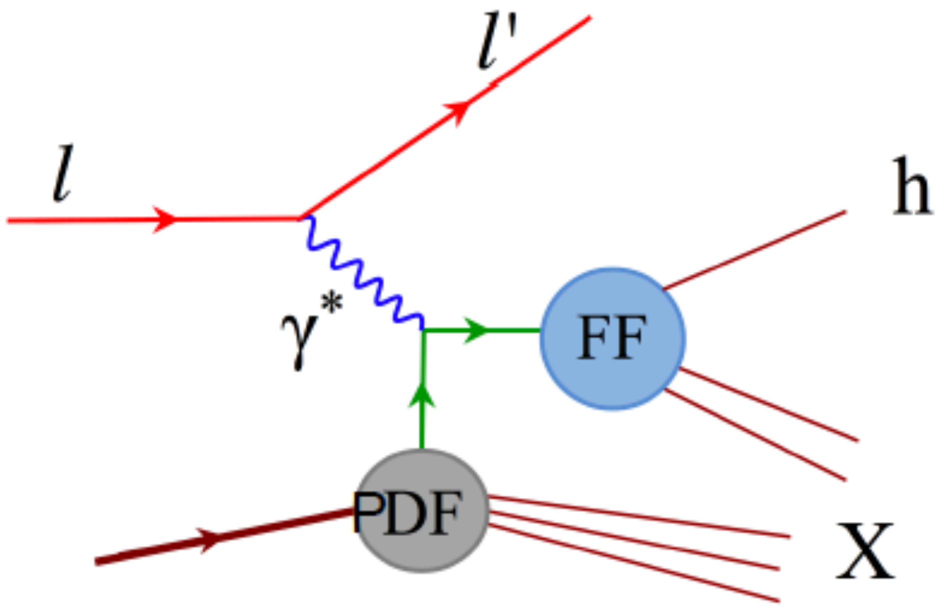


DY for TMDs

Future or planned Drell-Yan experiments: large variety of beam and target and kynematical ranges

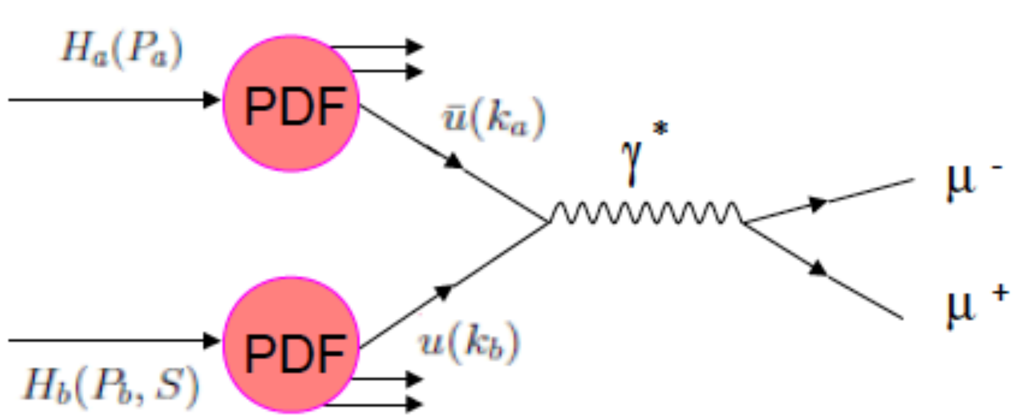
Experiment	particles	beam energy (GeV)	$\sqrt{s}$ (GeV)	$x^\uparrow$	$\mathcal{L}$ (cm^{-2}s^{-1})	$\mathcal{P}_{\mathrm{eff}}$	$\mathcal{F}$ (cm^{-2}s^{-1})
AFTER@LHCb	$p + p^\uparrow$	7000	115	$0.05 \div 0.95$	$1 \cdot 10^{33}$	80%	$6.4 \cdot 10^{32}$
AFTER@LHCb	$p + {}^3\mathrm{He}^\uparrow$	7000	115	$0.05 \div 0.95$	$2.5 \cdot 10^{32}$	23%	$1.4 \cdot 10^{31}$
AFTER@ALICE$_\mu$	$p + p^\uparrow$	7000	115	$0.1 \div 0.3$	$2.5 \cdot 10^{31}$	80%	$1.6 \cdot 10^{31}$
COMPASS (CERN) $\bar{p} + p^\uparrow$	$\pi^\pm + p^\uparrow$ $k^\pm + p^\uparrow$	190	19	$0.2 \div 0.3$	$2 \cdot 10^{33}$	18%	$6.5 \cdot 10^{31}$
PHENIX/STAR (RHIC)	$p^\uparrow + p^\uparrow$	collider	510	$0.05 \div 0.1$	$2 \cdot 10^{32}$	50%	$5.0 \cdot 10^{31}$
E1039 (FNAL)	$p + p^\uparrow$	120	15	$0.1 \div 0.45$	$4 \cdot 10^{35}$	15%	$9.0 \cdot 10^{33}$
E1027 (FNAL)	$p^\uparrow + p$	120	15	$0.35 \div 0.9$	$2 \cdot 10^{35}$	60%	$7.2 \cdot 10^{34}$
NICA (JINR)	$p^\uparrow + p$	collider	26	$0.1 \div 0.8$	$1 \cdot 10^{32}$	70%	$4.9 \cdot 10^{31}$
fsPHENIX (RHIC)	$p^\uparrow + p^\uparrow$	collider	200	$0.1 \div 0.5$	$8 \cdot 10^{31}$	60%	$2.9 \cdot 10^{31}$
fsPHENIX (RHIC)	$p^\uparrow + p^\uparrow$	collider	510	$0.05 \div 0.6$	$6 \cdot 10^{32}$	50%	$1.5 \cdot 10^{32}$
PANDA (GSI)	$\bar{p} + p^\uparrow$	15	5.5	$0.2 \div 0.4$	$2 \cdot 10^{32}$	20%	$8.0 \cdot 10^{30}$

Sign change of the Sivers function



SIDIS
PDF ⊗ FF

Probe Universality



Drell-Yan (DY)
PDF ⊗ PDF

Sign change of the Sivers function

Colored objects are surrounded by gluons, profound consequence of gauge invariance:

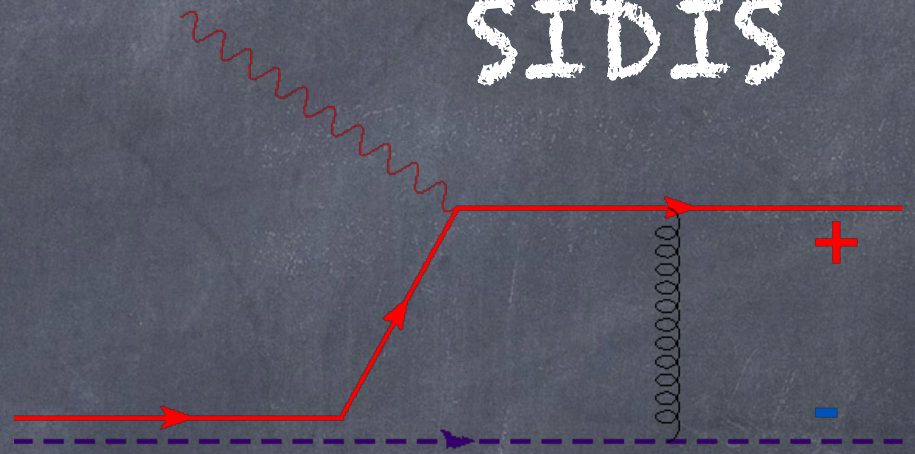
Sivers function has opposite sign when gluon couple after quark scatters (SIDIS) or before quark annihilates (Drell-Yan)

Crucial test of TMD factorization and collinear twist-3 factorization

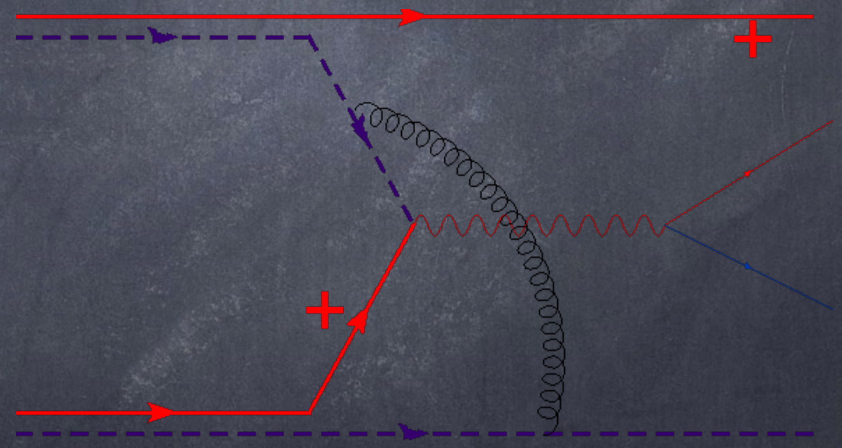
Several labs worldwide aim at measurement of Sivers effect in Drell-Yan

BNL, CERN, GSI, IHEP, JINR, FERMILAB etc

SIDIS



DY



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

First experimental hint on the sign change

STAR

$p^{\uparrow}p \to W^{\pm}\ X$

STAR Collaboration,
PRL 116 (2016) 132301

- Sign change $\chi^2/d.o.f \sim 1.2$
- No sign change $\chi^2/d.o.f \sim 3.$