# COMPASS facility beyond 2020

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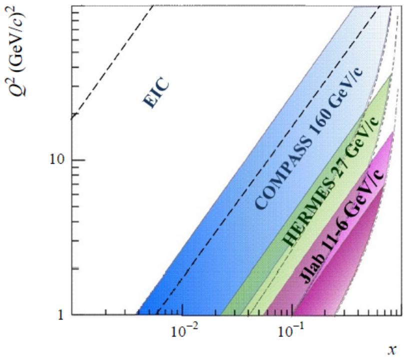
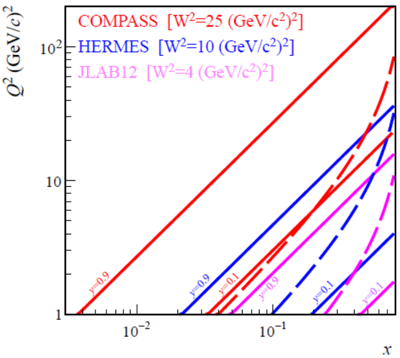
On behalf of COMPASS Collaboration

Kobe, April 16 – 20, 2018

# Acceptance of SIDIS experiments




EIC limits: $\sqrt{s}$ = 140 GeV, $y$ = 0.9
$\sqrt{s}$ = 40 GeV, $y$ = 0.1

Full lines: $y = 0.1$ and $y = 0.1$ boundaries; dashed – low $W^2$ boundaries

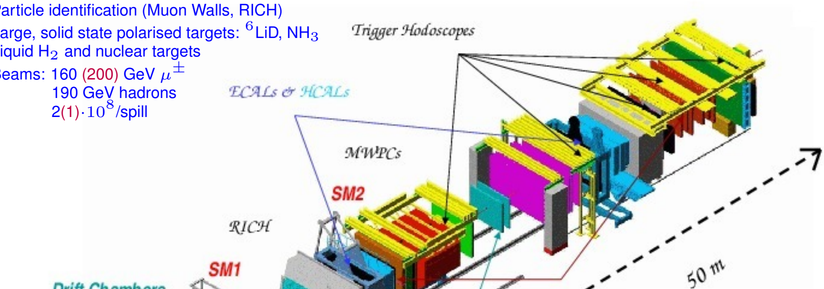
CERN-SPSC-2017-034

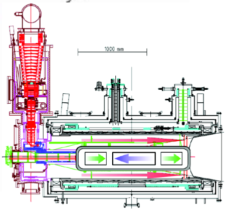
# Versatile COMPASS facility in the EHN2 at CERN

Two stages
Calorimetry
Particle identification (Muon Walls, RICH)
Large, solid state polarised targets: $^6$LiD, $NH_3$
Liquid $H_2$ and nuclear targets
Beams: 160 (200) GeV $\mu^{\pm}$
190 GeV hadrons
2(1)$\cdot 10^8$/spill

*COMPASS Spectrometer* (muon run)

Nucl. Instr. Meth. A577 (2007) 455

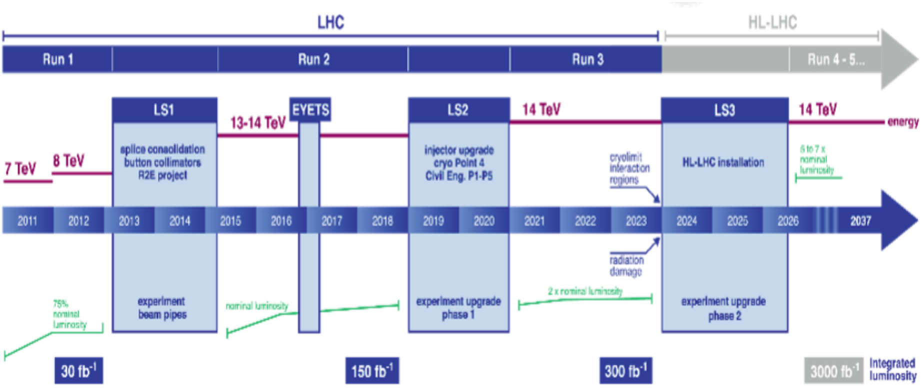


# COMPASS data taking until now

| | | |
|---|---|---|
| COMPASS I | 2002 – 2004 | nucleon structure $\mu$–d, 160 GeV, L and T polarised target |
| | 2005 | CERN accelerator shutdown, increase of acceptance |
| | 2006 | nucleon structure $\mu$–d, 160 GeV, L polarised target |
| | 2007 | nucleon structure $\mu$–p, 160 GeV, L and T polarised target |
| | 2008 – 2009 | hadron spectroscopy |
| | 2010 | nucleon structure $\mu$–p, 160 GeV, T polarised target |
| | 2011 | nucleon structure $\mu$–p, 200 GeV, L polarised target |
| | 2012 | Primakoff reaction; DVCS/SIDIS test |
| | 2013 | CERN accelerator shutdown, LS1 |
| COMPASS II | 2014 | Drell-Yan $\pi$–p reaction with T polarised target (test) |
| | 2015 | Drell-Yan $\pi$–p reaction with T polarised target |
| | 2016 – 2017 | DVCS/SIDIS $\mu$–p, 160 GeV, unpolarised target |
| | 2018 | Drell-Yan $\pi$–p reaction with T polarised target |
| | 2019 – 2020 | CERN accelerator shutdown, LS2 |
| | After 2020: | This talk |

# Future: CERN accelerator schedule




http://ls1ls2.web.cern.ch/

# COMPASS: the future

- Short term plans (immediately after LS2):
  extension of COMPASS II; proposal addendum $\rightarrow$ SPSC:

  one year (2021) SIDIS run with muons and $\perp$ polarised deuterium target;
  tests for the $\mu$p$\rightarrow$ $\mu$p

- Long term plans for future COMPASS-like experiment ($>$ 2021):
  $\Longrightarrow$ LoI to appear soon (in 2018)
  - renewed COMPASS-based collaboration
  - proton radius measurement in $\mu$p$\rightarrow$ $\mu$p
  - muon and hadron ($\pi$, K, $\bar{\mathrm{p}}$) beams
  - conventional- and newly designed RF-separated K and $\bar{\mathrm{p}}$ beams
  - 7–8 year endeavour

- Planning began in March 2016: "Beyond 2020" workshop at CERN

- Intertwined with "Physics Beyond Colliders" initiative at CERN (Sept. 2016);
  assessment by the European Strategy Group expected in 2020.

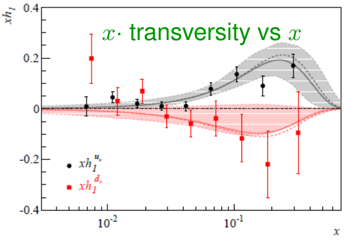
# Short term COMPASS future

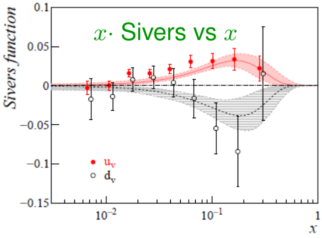
with transversely polarised deuterium target
(to commence in 2021, directly after LS2)

CERN-SPSC-2017-034

# Short term COMPASS future:
# Deuteron transversity $h_1^d$ and TMDs via SIDIS

- Goal: measurement of $h_1^d$, $h_1^p$ and TMD PDFs for separate flavours
- Optimal separation $\Longrightarrow$ comparable statistics on d ($^6$LiD) and p ($NH_3$) targets
- COMPASS d data sets have 4 times less statistics than p: cf an example below




CERN-SPSC-2017-034

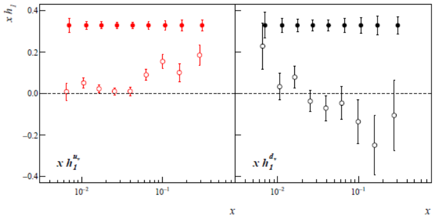
Curves: fits to COMPASS+HERMES +Belle (only for transversity)

- Conclusion: increase the d data set.

# Short term COMPASS future:
# $h_1^d$, TMDs and other SIDIS measurements

- After LS2, one year (150 days) SIDIS at 160 GeV/$c$, with $\perp$ polarised $^6$LiD target
  Apparatus upgrade: practically only increase of the target cells diameter

  Expected for asymmetries:
  $\sigma^d_{\text{stat.}} \approx 0.6 \times \sigma^p_{\text{stat.}}$,
  cf. $xh_1^{u_v}(x), xh_1^{d_v}(x)$ $\Longrightarrow$




CERN-SPSC-2017-034

- With new d data:
  - transversity and Sivers PDFs
  - full set of TSAs for the d data
  - determination of the (truncated) nucleon tensor charge

$$g_T = \delta u - \delta d \quad \text{where} \quad \delta q(Q^2) = \int_{x_{min}}^{x_{max}} \mathrm{d}x \left[h_1^q(x,Q^2) - h_1^{\bar{q}}(x,Q^2)\right],$$

    with accuracy 2$\times$ better than now ($\pm$0.044 vs $\pm$ 0.087).
  - hard exclusive production of $\rho$ and $\omega$ mesons
  - $g_2$ structure function

- Complementary data: JLab12 for p,n but for $0.1 < x < 0.6$

# Long term COMPASS future

preparations for proton radius measurements in $\mu$p$\rightarrow$ $\mu$p scattering
(to commence $>$2021)

CERN-SPSC-2017-034

# Proton radius measurement using $\mu p \to \mu p$

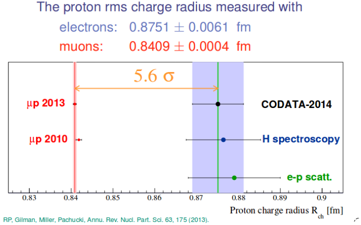
- Definition of the proton electric charge radius:

$$\langle r_E^2 \rangle = -6\hbar^2 \frac{dG_E(Q^2)}{dQ^2}\bigg|_{Q^2=0}$$

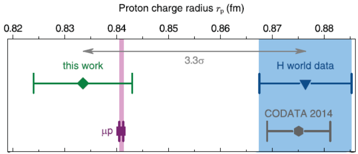
- Proton radius puzzle since a decade in e/$\mu$ spectroscopy and e scattering
- Reason still not clear see examples $\Longrightarrow$
- Missing piece: muon scattering needed!
  $\Longrightarrow$ MUSE @ PSI ($E_\mu \lesssim$ 0.5 GeV),
  $\Longrightarrow$ COMPASS (high energy $E_\mu$)

Goal of COMPASS:

$\Delta r_E \lesssim$ than 0.01 fm
in 180 days beam time




Pohl, FFK2017




Beyer et al., Science 358 (2017) 79

# Short term COMPASS future: preparation for $\mu$p$\rightarrow$ $\mu$p
# Advantages of the high energy muon beam

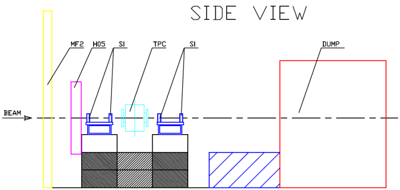
## Muon beam of about 100 GeV energy:

- momentum transfers of about 5 MeV/$c$
- radiative corrections $\ll$ than for electron beam (cf. JLab)
- at high energies Coulomb scattering angles $\ll$ than at low energies (cf. MUSE)
- muon energy loss negligible

## Measurement of the elastic reaction

- $\sigma(Q^2)$ measured for $10^{-4} \lesssim Q^2/(\mathrm{GeV}/c)^2 \lesssim 0.1$
- trigger on a proton recoil and muon kink
- active high-pressure hydrogen TPC target (IKAR, A. Vorobyev, St. Petersburg) + possibly also an active SciFi target

*Target region*




CERN-SPSC-2017-034

# $r_p$ experiment: TPC prototype at the test position

# Long term COMPASS future

hadron physics with standard muon and hadron beams
(after 2021)

Letter of Intent coming soon!

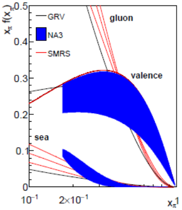
# Long term COMPASS future
# hadron physics with standard $\mu$ and hadron beams

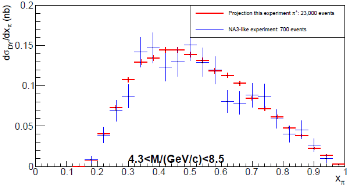
**1** Proton radius measurement using $\mu$p$\rightarrow$ $\mu$p

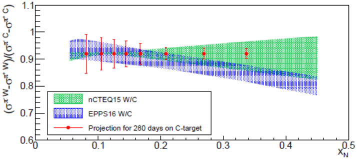
**2** New Drell-Yan experiment with 190 GeV $\pi^{\pm}$ beams and C, W targets

- Determine pion valence and sea quark distributions (both $\pi$ beams charges)
- Study direct photons and charmonium $\Longrightarrow$ gluons in $\pi$
- Study flavour dependent nuclear effects (2 beam charges, 2 targets: C, W)
- Important: good beam charge balance and PID in beams

projections: 2$\times$ 140 days; $\pi^+$ : $\pi^-$ time 10:1; C, W targets



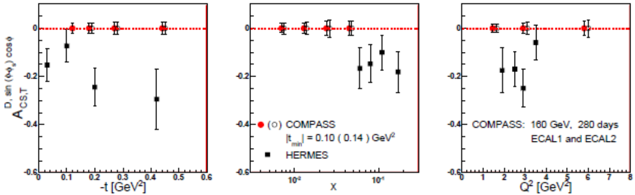



# Long term COMPASS future
# hadron physics with standard $\mu$ and hadron beams...

**3** Exclusive reactions with $\mu$ beam and $\perp$ polarised proton target:
GPD $E$ measurement $\Longrightarrow$ total $L_{\rm partons}$

- Now COMPASS measures $H$; $\perp$ polarised proton target will give $E$
  $\mu p^{\uparrow} \rightarrow \mu p\gamma, \quad \mu p^{\uparrow} \rightarrow \mu\rho(\omega)p$




- A flagship of JLab12 programme but in the valence region

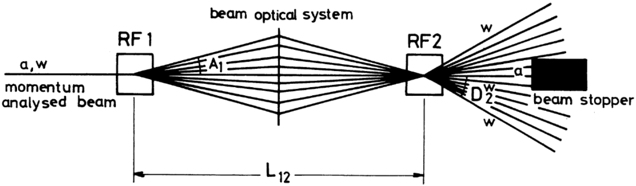
# Long term COMPASS future

hadron physics with RF-separated hadron beams
(after 2021)

Letter of Intent coming soon!

# RF-separated hadron beams

Panofsky-Schnell system with two RF cavities




P. Bernard et al., CERN 68-29

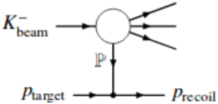
- Particles a,w are momentum-analysed
- Transverse kick by RF1 compensated/amplified by RF2
- Selection of a particle by selecting phase difference, $\Delta\phi$, e.g.$\Delta\phi_{\pi \mathrm{p}}$:

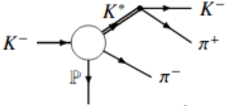
  $\Delta\phi = 2\pi(L_{12}f/c)(\beta_a^{-1} - \beta_w^{-1})$ for large $p$: $\beta_a^{-1} - \beta_w^{-1} = (m_a^2 - m_w^2)/2p^2$
- $L_{12}$ should increase as $p^2$ at given $f$; this limits beam momentum
- Expectations before further R & D: $\mathrm{p_K} \sim$ 80 GeV, $\mathrm{p_{\bar{p}}} \sim$ 110 GeV beams
- Intensity gains: $\sim$ 80 for K, $\sim$ 50 for $\bar{\mathrm{p}}$ beams
  (standard h$^-$ beam is $\sim$97% pions, $\sim$2.5% kaons, $\sim$0.5% antiprotons).

# Kaon spectroscopy with kaon beam

[COMPASS LoI]

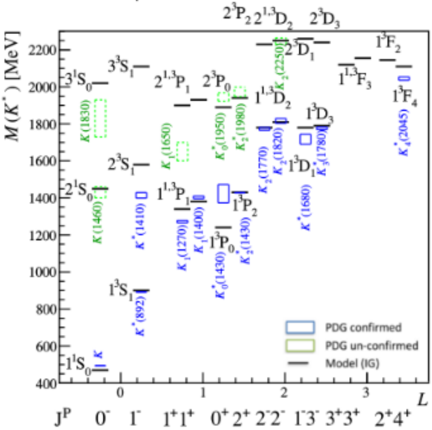
Diffractive production $K^- p \to K^- \pi^+ \pi^- p$




COMPASS can take a lead for *K*-spectroscopy

- Many kaonic states require confirmation and further studies
- COMPASS has collected $\sim 10^6$ $K^- p \to K^- \pi^+ \pi^- p$
  $\Rightarrow$ the analysis in progress
- We are aiming for 50M/y with the **RF separated beam**
  $\Rightarrow$ access for novel methods
- Requires uniform PID in a broad kinematic range



# RF separated beam – Drell-Yan (i)

**RF separated antiproton/kaon beam**, the maximal possible beam intensity (very rough estimate) of ~3-4x$10^7$ /s can be reached (antiprotons) and ~8x$10^6$ /s (kaons)

Assuming flux of 1x$10^7$ /s for kaon/antiproton,
background free high mass range $4 < M_{\mu\mu} < 9$ $GeV/c^2$ and
140 days of data taking with the efficiency of 2015 Drell-Yan Run.

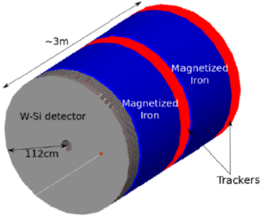
| | $NH_3$ | Al (7cm) | W | NA3 | NA10 | E537 | E615 |
|---|---|---|---|---|---|---|---|
| $K^-$ beam | 14,000 | 2,800 | 29,600 | 700 | | | |
| $\bar{p}$ beam | 15,750 | 2,750 | 22,500 | | | 387 | |

**The overall gain for RF separated beam compare to previous experiments is factor 50 to 100**

Courtesy of Oleg Denisov, Trento, Nov. 2017

# General features of a planned Drell-Yan experiment

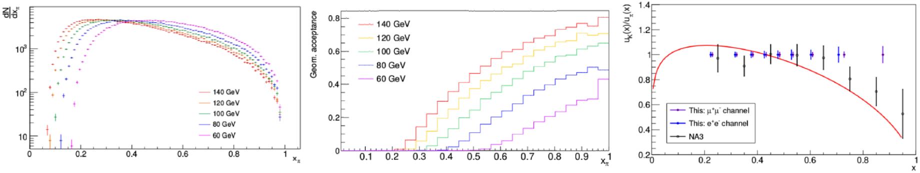
- The Drell-Yan cross sections are very small
  $\Longrightarrow$ high luminosities needed
- An isoscalar target, possibly light is preferable
- $\mu^+\mu^-$ angles may be large $\Longrightarrow$ large acceptance needed
- Incident hadrons separated from a beam $\Longrightarrow$ particle identification is crucial
- There is a copious forward production of hadrons $\Longrightarrow$ an (active) hadron absorber must be placed there, see e.g.
  BabyMIND detector M. Antonova et al., arXiv:1704.08079
  with W-Si detectors as in BNL (Phenix, AnDY):
  - very compact
  - good tracking resolution
  - momentum measurement
  - large acceptance, $\theta_{\mu\mu} > 250$ mrad



# RF-separated beam: kaon induced Drell-Yan

- A source of information on kaon structure (PDFs), presently unknown
- Kaons have heavier valence quarks $\Longrightarrow$ expect less glue in K
- RF-separated beams only 30–50% purity
- Sea-valence separation needs 3:1 time sharing between $K^+$, $K^-$.
- Two-year run gives PDF precision as in the pion

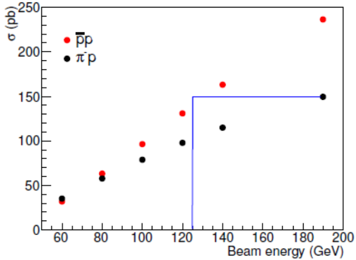
projections: 140 days; 100 GeV; C target



# RF-separated beam: antiproton induced Drell-Yan

- DY with antiprotons on $\perp$ polarised protons are ideal for TMD PDFs in the nucleon; no uncertainties due to $\pi$ structure

- $\bar{\text{p}}$–induced DY has a cross section higher than $\pi$–induced DY
- A new, active absorber with di-electron and di-muon tracking, covering wide angle, $\pm$250 mrad planned.




- Statistics for 140 days and active absorber

| 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 $NH_3$ | $\bar{p}$ | $3.5 \times 10^7$ | 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 |

# Requirements for the long term programme

| Program | Beam Energy [GeV] | Beam Intensity [/s] | Trigger Rate [kHz] | Beam Type | Target | S? | 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 $\overline{p}$ | 12, 20 | $5 \cdot 10^7$ | 25 | $\overline{p}$ | LH2 | | target spectrometer: tracking, calorimetry | × | × |
| Drell-Yan conv | 190 | $7 \cdot 10^7$ | 25 | $\pi^\pm$ | C/W | × | vertex detector | | × |
| Drell-Yan RF | ~100 | $10^8$ | 25-50 | $K^\pm, \overline{p}$ | 6LiD↑, 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 | $4 \cdot 10^6$ | 25 | $K^-$ | LH2 | × | recoil TOF | × | × |

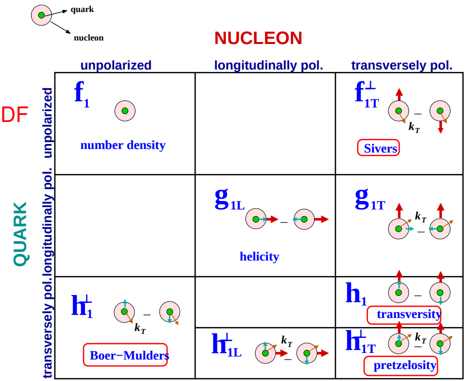
"S" – standard COMPASS spectrometer, "R" – RICH1 (RICH0 ?), "C" – CEDARs

# Outlook

- COMPASS facility is very successful in studies of nucleon structure and spectroscopy.
- "COMPASS Beyond 2020" (March 2016) and
  "Physics Beyond Colliders" (ongoing from Sept. 2016) workshops at CERN reveal a strong and active interest of the community in this physics.
- COMPASS submitted to SPSC a short-term proposal addendum, $>$ LS2
  effective after LS2 and concerning a SIDIS on $d^{\uparrow}$
  and tests for the proton radius measurements.
- COMPASS will soon present a Letter-of-Intent concerning the long-term future with a rich programme, chiefly on the D-Y physics and hadron spectroscopy. Apart of existing muon and hadron, new RF-separated K and $\bar{p}$ beams open new possibilities in hadron structure studies.
- New groups are welcome to join and contribute!

# SPARES

# Partonic structure of the nucleon; TMD distribution functions

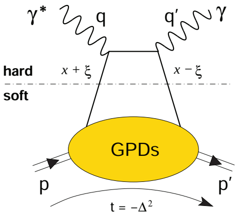



- In LT and considering $k_\mathrm{T}$,
  8 PDF describe the nucleon
  $\Longrightarrow$ Transverse Momentum Dependent PDF
- QCD-TMD approach valid if $k_\mathrm{T} \ll \sqrt{Q^2}$ (TMD factorisation)
- After integrating over $k_\mathrm{T}$
  only 3 survive: $f_1, g_1, h_1$
- TMD accessed in SIDIS and DY
  by measuring azimuthal asymmetries
  with different angular modulations
- SIDIS: e.g. $A_\mathrm{Sivers} \propto$ PDF $\otimes$FF
- DY: e.g. $A_\mathrm{Sivers} \propto$ PDF$^\mathrm{beam}\otimes$ PDF$^\mathrm{target}$
- OBS! Boer-Mulders and Sivers PDF are T-odd, i.e. process dependent

$$h_1^{\perp}(\mathrm{SIDIS}) = -h_1^{\perp}(\mathrm{DY}) \qquad f_{1\mathrm{T}}^{\perp}(\mathrm{SIDIS}) = -f_{1\mathrm{T}}^{\perp}(\mathrm{DY})$$

- TMD parton distributions need TMD Fragmentation Functions!

# Access GPD through the DVCS/DVMP mechanism

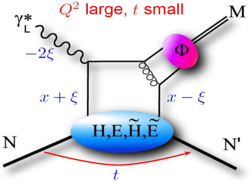


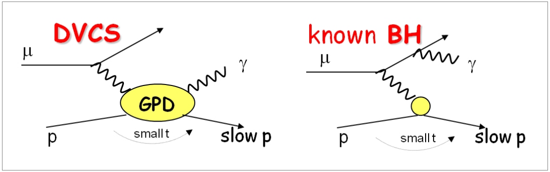

$Q^2 \to \infty$,
fixed $x_{\rm B}, t \implies |t|/Q^2$ small

- 4 GDPs $(H, E, \widetilde{H}, \widetilde{E})$ for each flavour and for gluons plus 4 chiral odd ones $(H_T, E_T, \widetilde{H}_T, \widetilde{E}_T)$
- DVMP: factorisation proven for $\sigma_L$ only
- All depend on 4 variables: $x, \xi, t, Q^2$; DIS @ $\xi = t = 0$; Later $Q^2$ dependence omitted. Careful ! Here $x \neq x_{\rm B}$!
- $H, \widetilde{H}$ conserve nucleon helicity
  $E, \widetilde{E}$ flip nucleon helicity
- $H, E$ refer to unpolarised distributions
  $\widetilde{H}, \widetilde{E}$ refer to polarised distributions
- $H^q(x,0,0) = q(x), \quad \widetilde{H}^q(x,0,0) = \Delta q(x)$

- $H, E$ accessed in vector meson production *via* $A_{UT}$ asymmetries
- $\widetilde{H}, \widetilde{E}$ accessed in pseudoscalar meson production *via* $A_{UT}$ asymmetries
- All 4 accessed in DVCS ($\gamma$ production) in $A_C, A_{LU}, A_{UT}, A_{UL}$
- Integrals of $H, E, \widetilde{H}, \widetilde{E}$ over $x$ give Dirac–, Pauli–, axial vector– and pseudoscalar vector form factors respectively.
- Important: $J_z^q = \frac{1}{2}\int dx\, x\,[H^q(x,\xi,t=0) + E^q(x,\xi,t=0)] = \frac{1}{2}\Delta\Sigma + L_z^q$ (X. Ji)

# DVCS/DVMP: $\mu p \to \mu p \gamma (M)$; observables

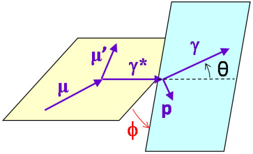



$$d\sigma^{\mu p \to \mu p \gamma} = d\sigma^{BH} + (d\sigma^{DVCS}_{unpol} + P_\mu d\sigma^{DVCS}_{pol}) + e_\mu(\mathrm{Re}I + P_\mu \mathrm{Im}I)$$

Observables (Phase 1):

- $S_{CS,U} \equiv \mu^{+\leftarrow} + \mu^{-\rightarrow} = 2\left(d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + e_\mu P_\mu \mathrm{Im}I\right)$
- $D_{CS,U} \equiv \mu^{+\leftarrow} - \mu^{-\rightarrow} = 2\left(P_\mu d\sigma^{DVCS}_{pol} + e_\mu \mathrm{Re}I\right)$
- $A_{CS,U} \equiv \dfrac{\mu^{+\leftarrow} - \mu^{-\rightarrow}}{\mu^{+\leftarrow} + \mu^{-\rightarrow}} = \dfrac{D_{CS,U}}{S_{CS,U}}$
- Each term $\phi$-modulated
  If $\phi$-dependence integrated over $\Longrightarrow$ twist-2 DVCS contribution;
  if $\phi$-dependence analysed: $\Longrightarrow$ Im $(F_1 H)$ and Re $(F_1 H)$; $H$ dominance @ COMPASS kin.




Analogously for transversely polarised target (Phase 2): $S_{CS,T}, D_{CS,T}, A_{CS,T} \Longrightarrow E$