



TMD studies at COMPASS: present and future

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SAR WORS 2021 – SARDINIAN WORKSHOP ON SPIN STUDIES
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Muon beam: SIDIS setup

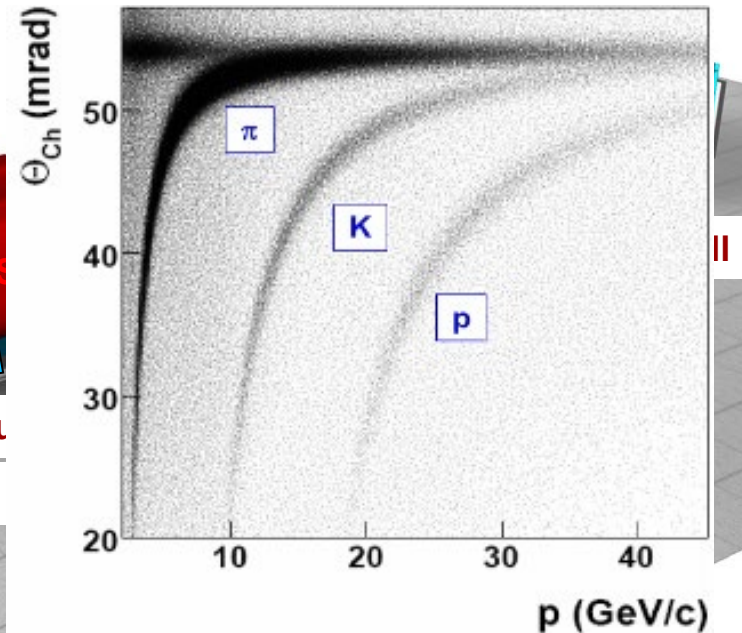
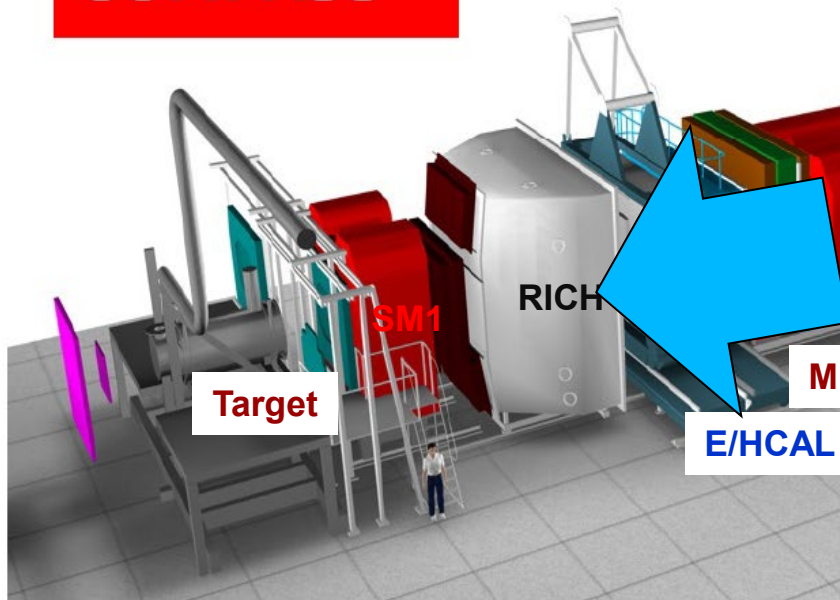
- high energy beam
- large angular acceptance
- broad kinematical range

two stages radiator Cu Filter

Large Angle Spectrometer $(SM1)$

Small Angle Spectrometer $(SM2)$

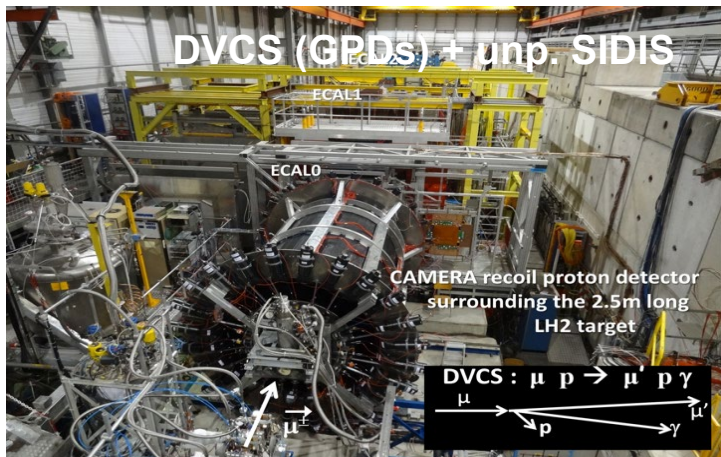
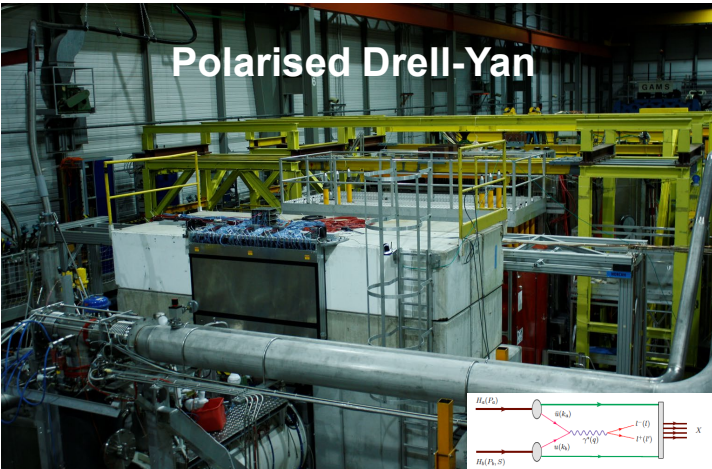
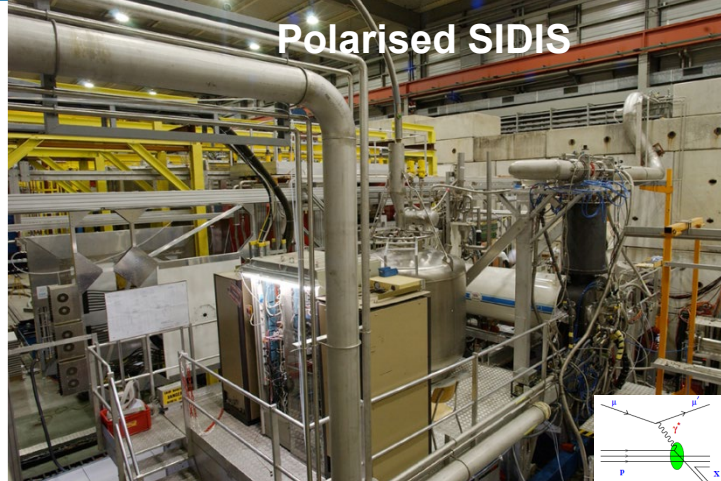
COMPASS



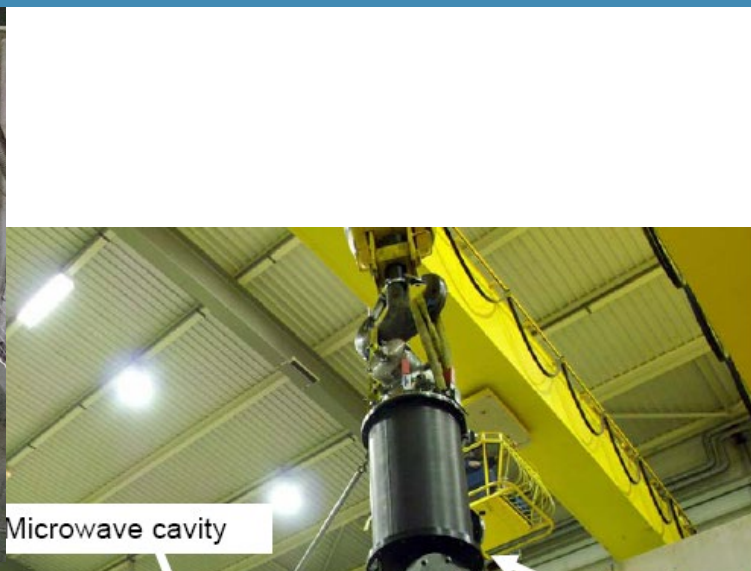
COMPASS target area

**COMPASS-I
1997-2011**

**COMPASS-II
2012-2020**



Operations on the target area



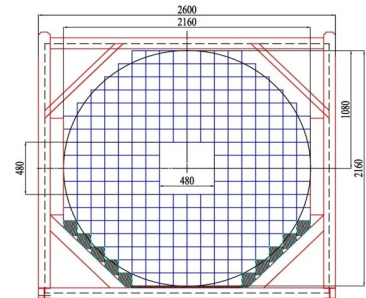
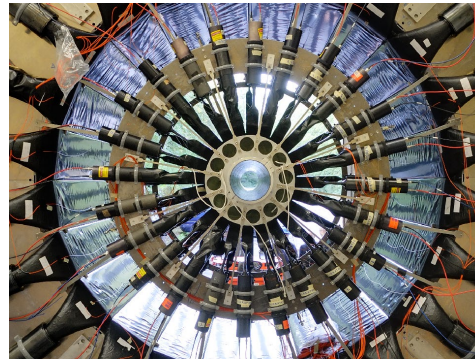
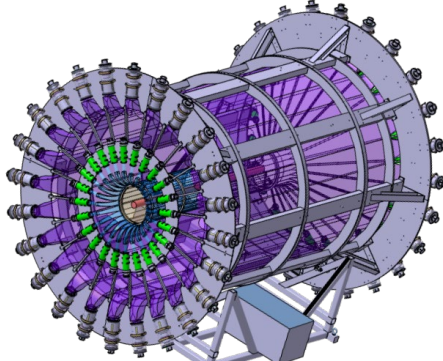
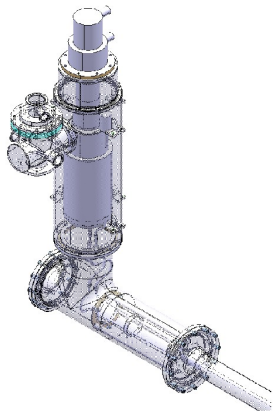
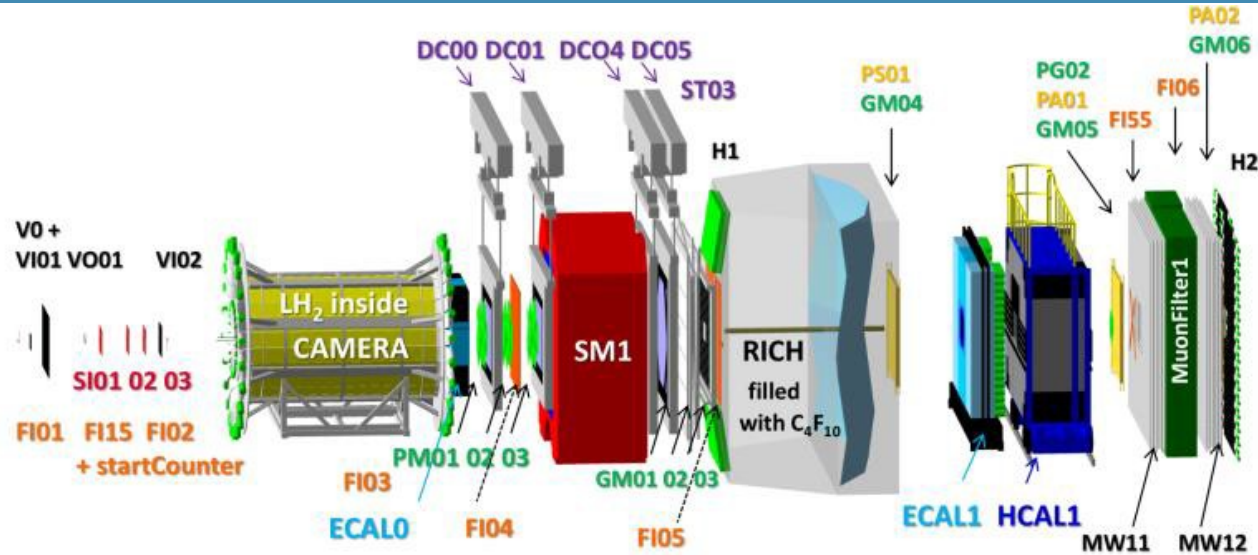
Microwave cavity

Dilution refrigerator



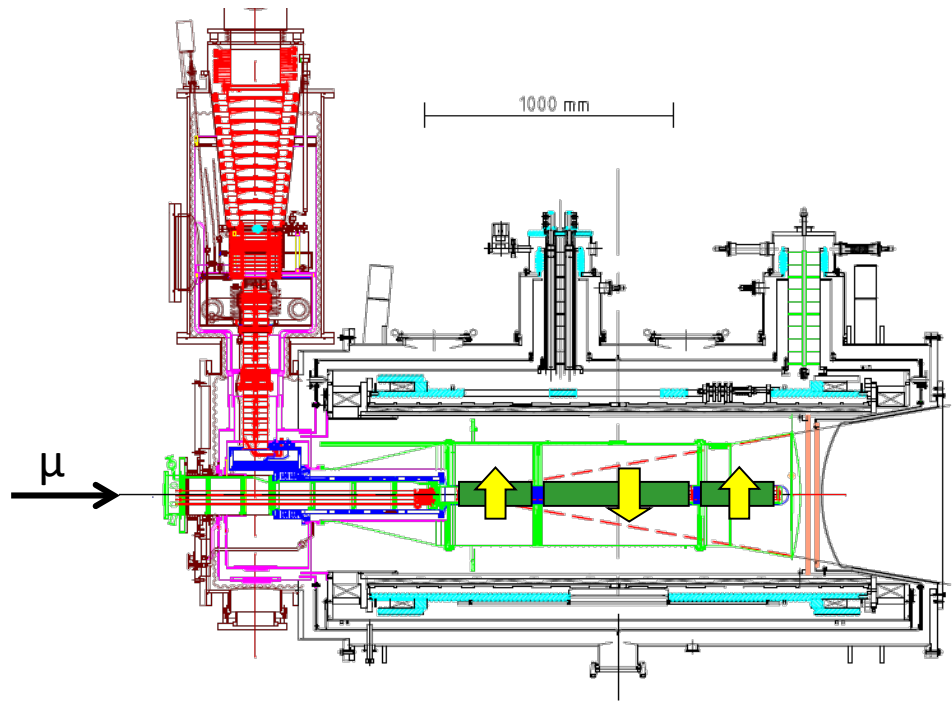
New Magnet

Muon beam – DVCS setup

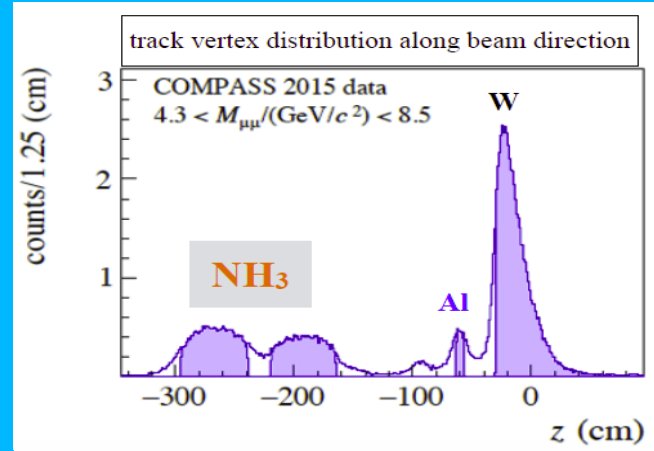
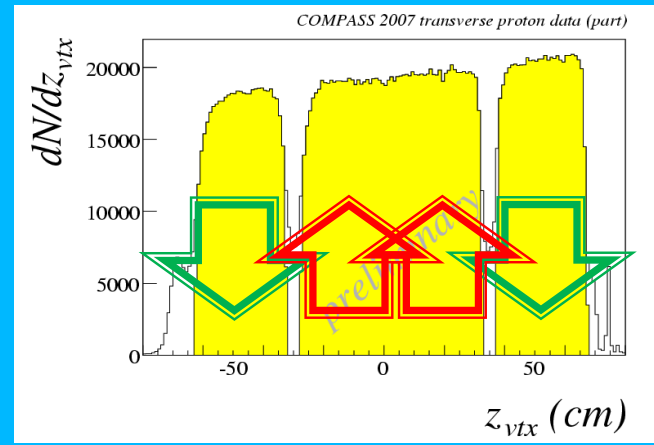


the polarized target system (>2005)

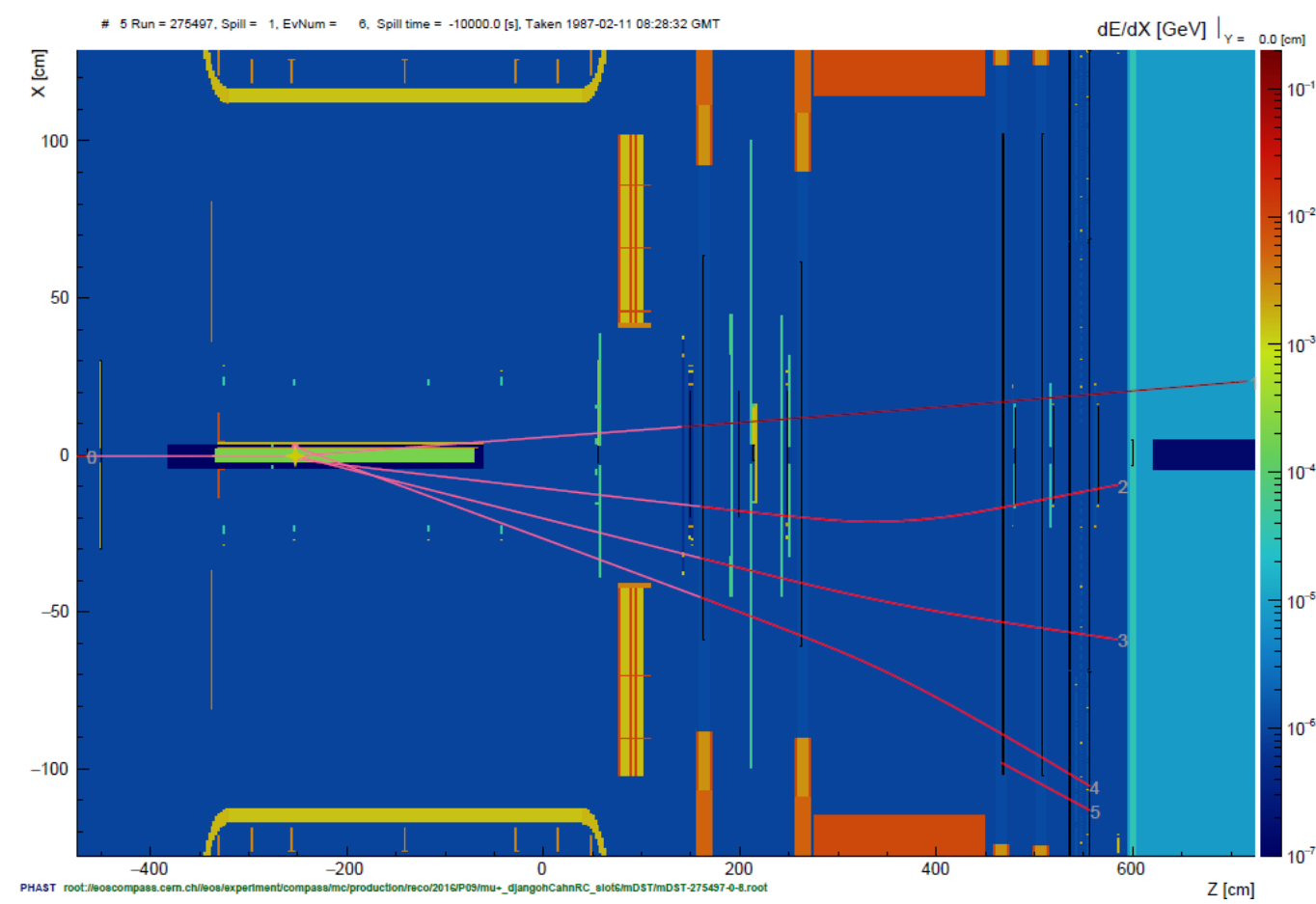
$^3\text{He} - ^4\text{He}$ dilution refrigerator ($T \sim 50\text{mK}$)



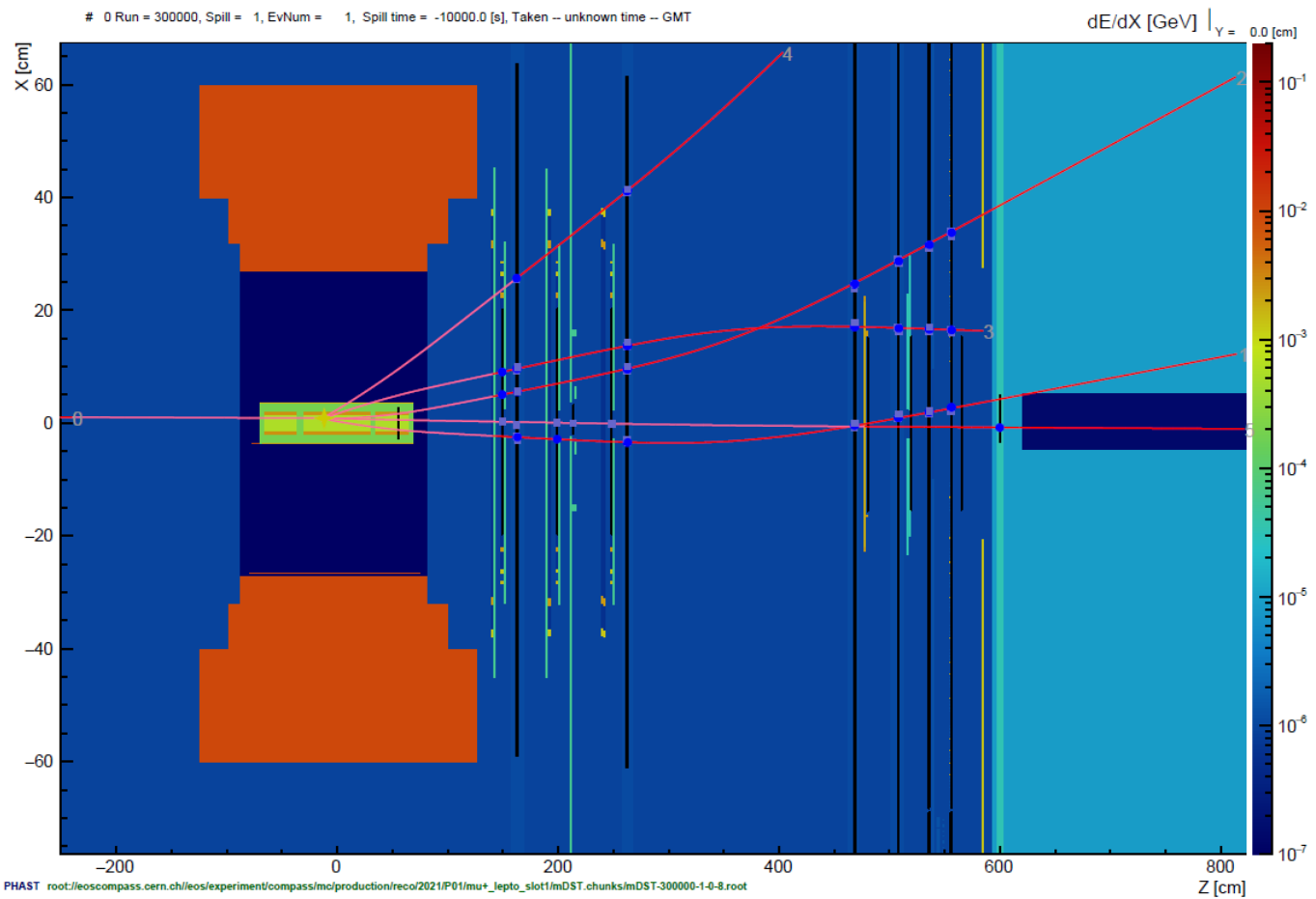
solenoid 2.5T
dipole magnet 0.6T



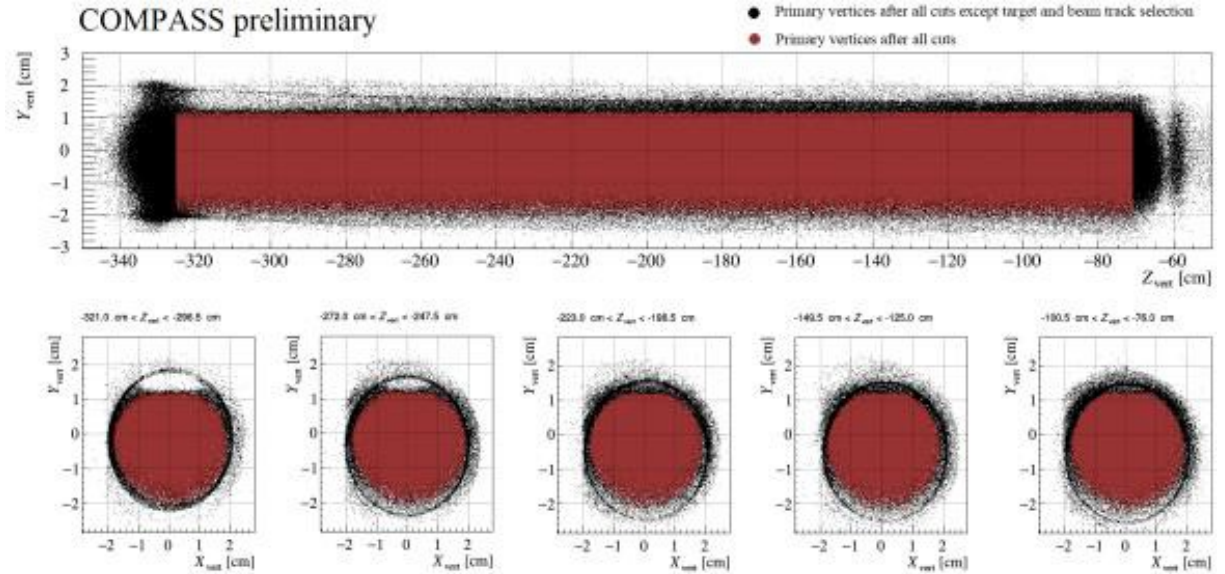
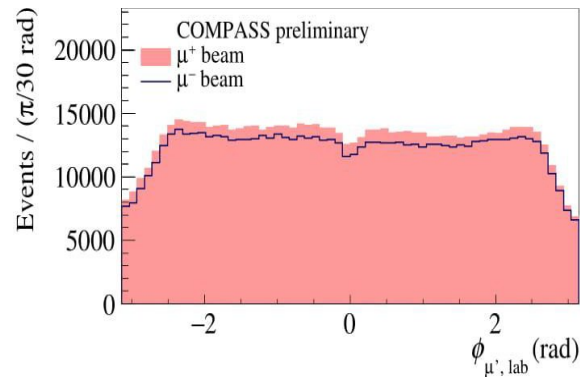
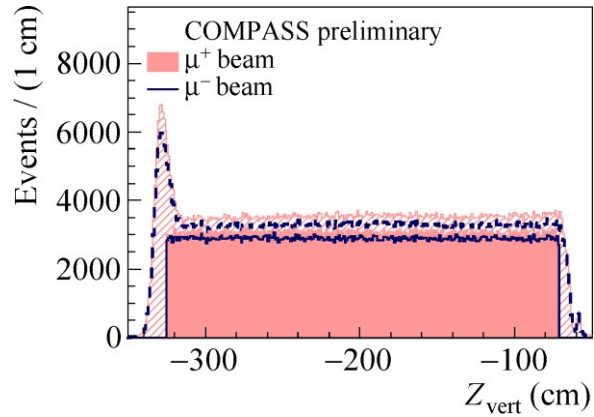
Spectrometer: 2016 event



Spectrometer: 2021 event

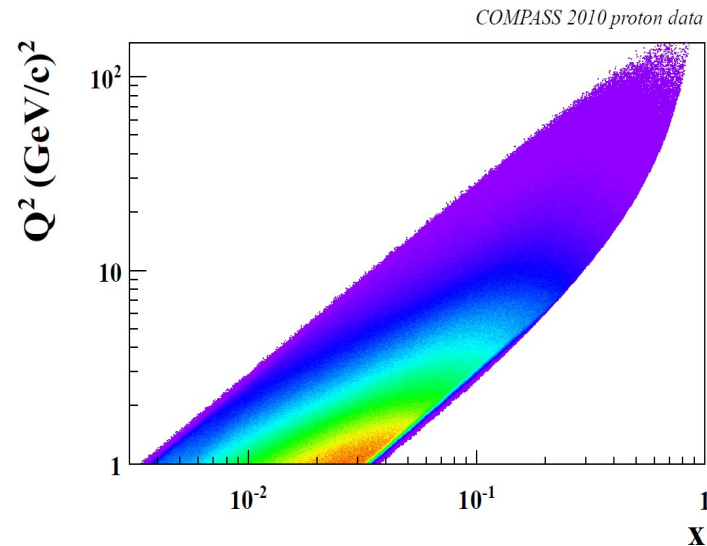
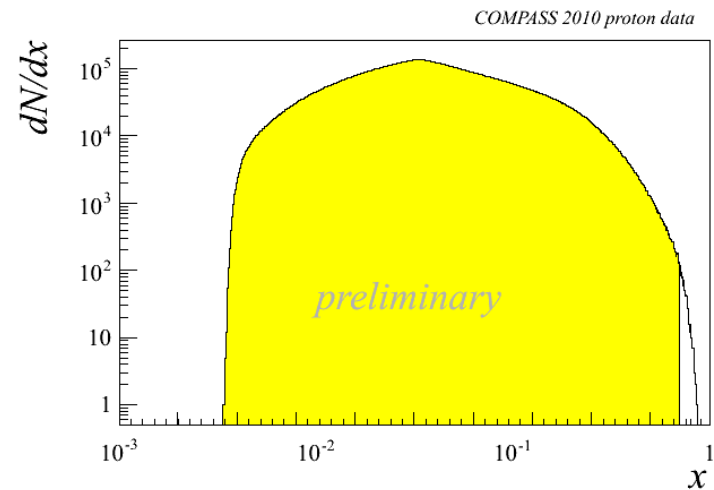
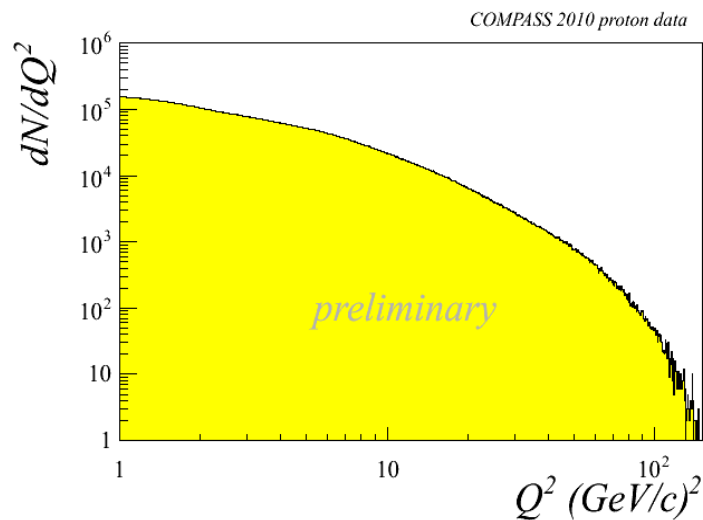


Vertex determination



Kinematic distributions

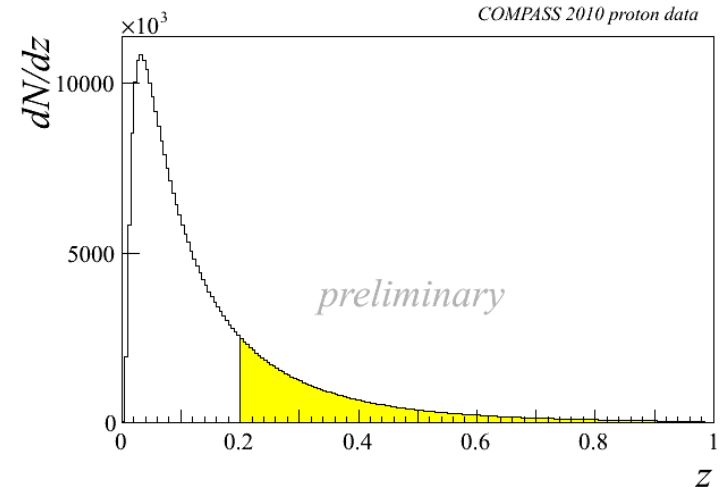
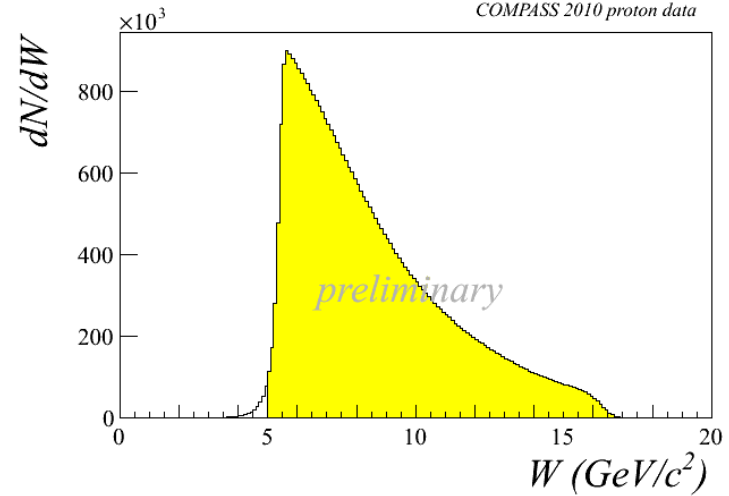
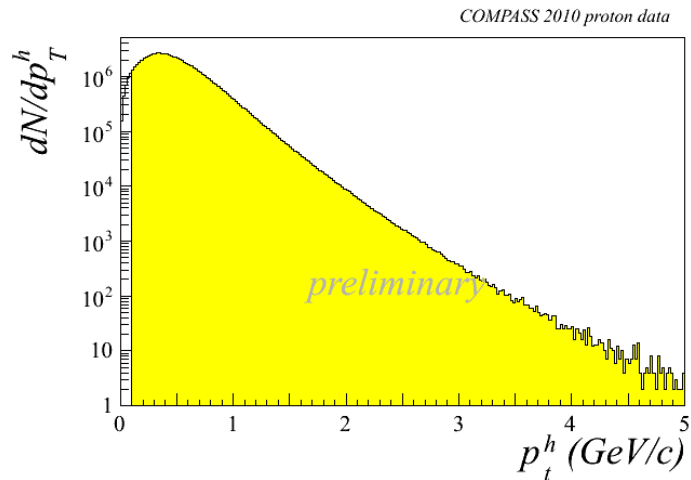
DIS cuts: $Q^2 > 1 \text{ (GeV/c)}^2$
 $0.1 < y < 0.9$
 $W > 5 \text{ GeV/c}^2$



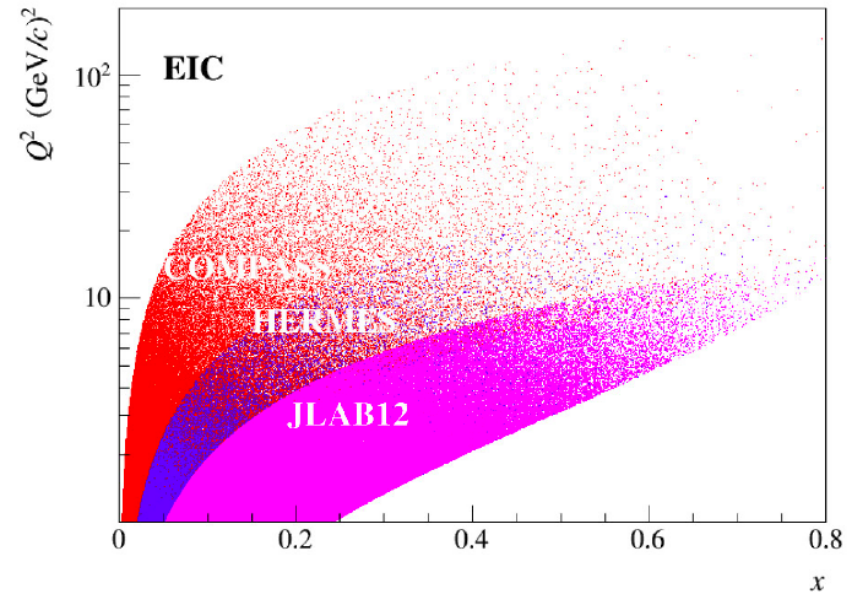
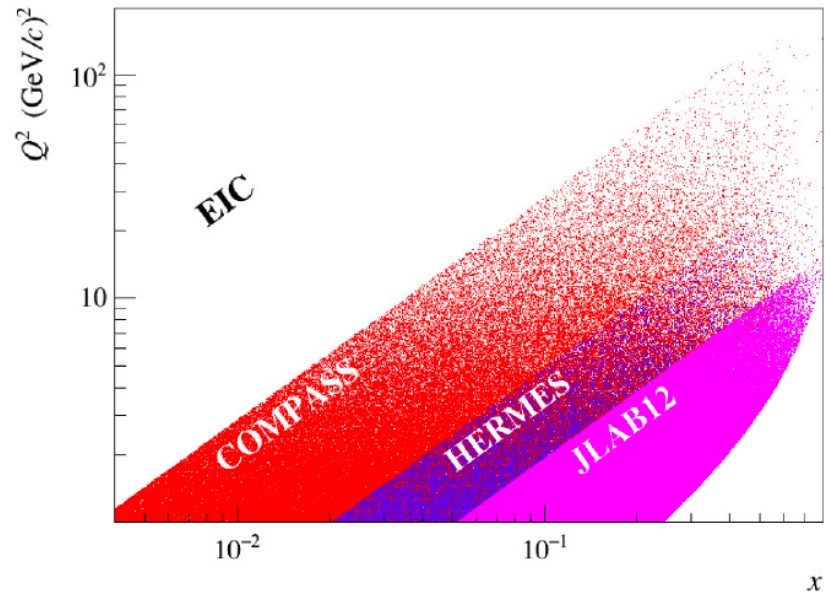
Kinematic distributions - 2

DIS cuts: $Q^2 > 1 \text{ (GeV/c)}^2$
 $0.1 < y < 0.9$
 $W > 5 \text{ GeV/c}^2$

hadron selection: $P_{hT} > 0.1 \text{ GeV/c}$
 $z > 0.2$



Kinematic coverage



COMPASS data taking

muon beam	deuteron (${}^6\text{LiD}$) PT	2002 2003 2004	80% L/20% T target polarisation
		2006	L target polarisation
	proton (NH_3) PT	2007	50% L /50% T target polarisation
Hadron	LH target	2008 2009	
muon beam	proton (NH_3) PT	2010	T target polarisation
		2011	L target polarisation
Hadron	Ni target	2012	Primakoff
muon beam	LH2 target	2012	Pilot DVCS & unpol. SIDIS
Hadron	Proton (NH_3) DT PT	2014 2015 2018	Pilot DY run DY run DY run
muon beam	LH2 target	2016 2017	DVCS & unpol. SIDIS
muon beam	deuteron (${}^6\text{LiD}$) PT	2021 2022	T target polarisation

Measurements with the target longitudinally polarized:

Year	Obs.	
2006	$A_{LL}^{2h}(Q^2 < 0)$	$\Delta g/g$
2007	$g_1^d(x)$,	$\Gamma_1^d, \Delta\Sigma$
2008	$A_{1,d}^{h^+-h^-}$	$\Delta u_v + \Delta d_v$
2009	$A_{1,d}, A_{1,d}^{\pi^\pm}, A_{1,d}^{K^\pm}$	$\Delta u_v + \Delta d_v, \Delta\bar{u} + \Delta\bar{d}, \Delta s (= \Delta\bar{s})$
2010	$g_1^p(x)$,	$\Gamma_1^{NS}, g_A/g_V $
2010	$A_{1,d}, A_{1,d}^{\pi^\pm}, A_{1,d}^{K^\pm}, A_{1,p}, A_{1,p}^{\pi^\pm}, A_{1,p}^{K^\pm}$	$\Delta u, \Delta d, \Delta\bar{u}, \Delta\bar{d}, \Delta\bar{s}, \Delta\bar{c}$
2010	$\sin\phi, \sin 2\phi, \sin 3\phi, \cos\phi$ asyms	$h_L, f_L^\perp, h_1, f_{1T}^\perp, h_{1L}^\perp, h_{1T}^\perp, h_{1L}^\perp, g_L^\perp, g_{1T}^\perp$
2013	A_{LL}^{2h}	$\Delta g/g$
2013	$A_D^{\gamma N}$	$\Delta g/g$ in LO and NLO
2015	$g_1^p(x)$	$\Gamma_1^{NS}, \Delta\Sigma, \Delta u + \Delta\bar{u} \dots$
2015	A_{LL}^p	NLO QCD fits for $\Delta g/g$

Target transversely polarized (1):

Year	Obs	
2005	$A_{Siv,d}^h, A_{Col,d}^h$	First ${}^6\text{LiD}$ data
2006	$A_{Siv,d}^h, A_{Col,d}^h$	Full ${}^6\text{LiD}$ statistics
2009	$A_{Siv,d}^{\pi^\pm, K^\pm, K_S^0}, A_{Col,d}^{\pi^\pm, K^\pm, K_S^0}$	Full ${}^6\text{LiD}$ statistics
2010	$A_{Siv,p}^h, A_{Col,p}^h$	2007 NH_3 data
2012	$A_{UT;p,d}^{\sin \phi_{RS}}$	Full ${}^6\text{LiD}$ and NH_3
	$A_{Siv,p}^h, A_{Col,p}^h$	Full NH_3 statistics
	$A_{UT;p,d}^{\sin(\phi_\rho - \phi_S)}$	Exclusive ρ^0
2013	$A_{UT;p,d}^{(\phi_\rho, \phi_S)}$	Exclusive ρ^0 , all asyms.

Target transversely polarized (2):

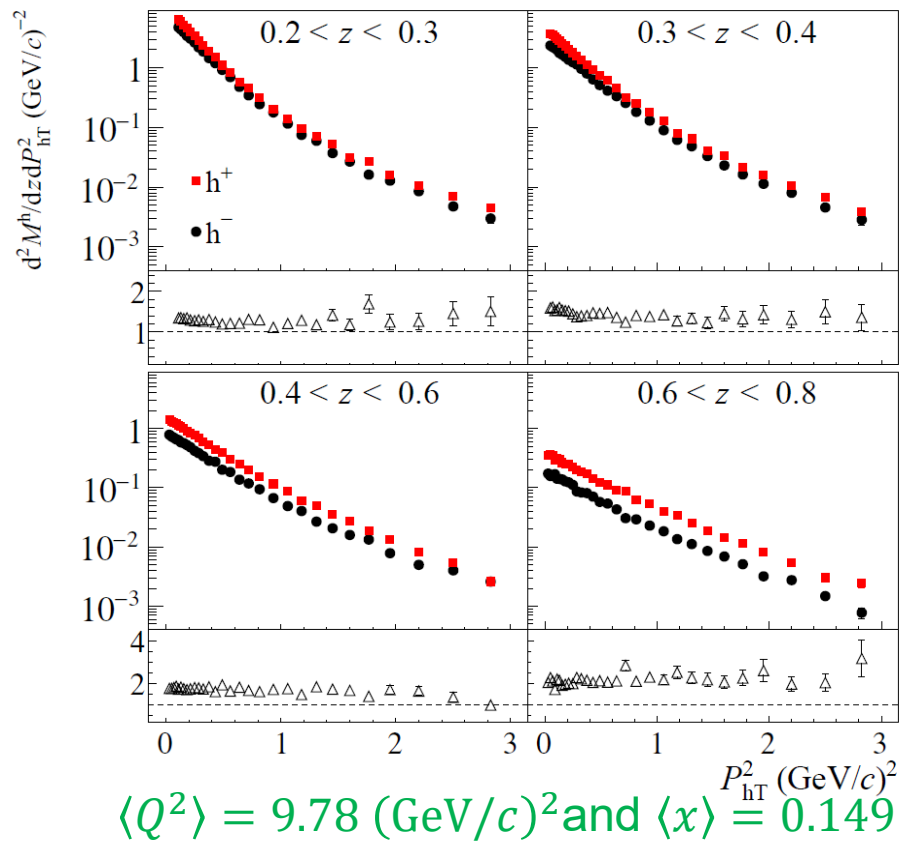
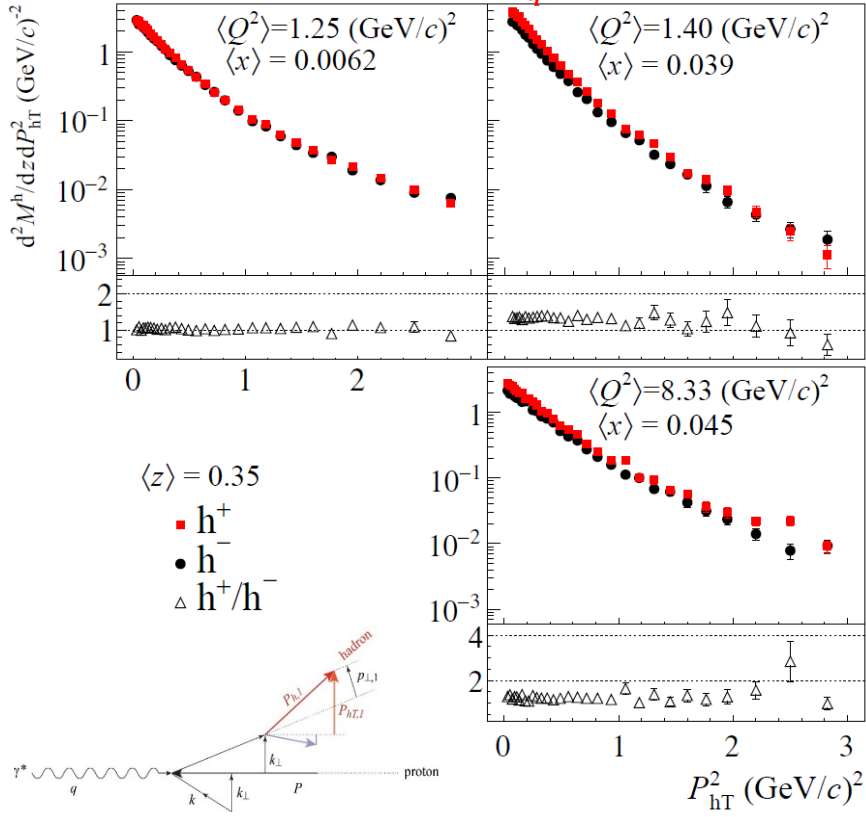
Year	Obs	
2014	$A_{UT,d}^{\sin \phi_{RS}}, A_{UT,p}^{\sin \phi_{RS}}$	Full ${}^6\text{LiD}$ and NH_3
	$A_{Siv,d}^{\pi^\pm, K^\pm, K_S^0}, A_{Col,d}^{\pi^\pm, K^\pm, K_S^0}$	Full NH_3 statistics
2015	Interplay $A_{UT,p}^{\sin \phi_{RS}}$ vs $A_{Col,p}^h$	Full NH_3 statistics
2016	TMDs in DY range	2010 NH_3 statistics
2017	$A_{PGF;p,d}^{\sin(\phi_p - \phi_S)}, A_{PGF;p,d}^{\sin(\phi_p - \phi_S)}$	Full ${}^6\text{LiD}$, NH_3 statistics
	$A_T^{\sin \phi_{CS}}, A_T^{\sin(2\phi_{CS} - \phi_S)}, A_T^{\sin(2\phi_{CS} + \phi_S)}$	2015 Drell-Yan run
2018	P_{hT} -weighted $A_{UT,p}^{\sin(\phi_h - \phi_S)}$	2010 NH_3 statistics
2021	$S_{\Lambda(\bar{\Lambda})}$	Full NH_3 statistics

Measurements with unpolarised targets:

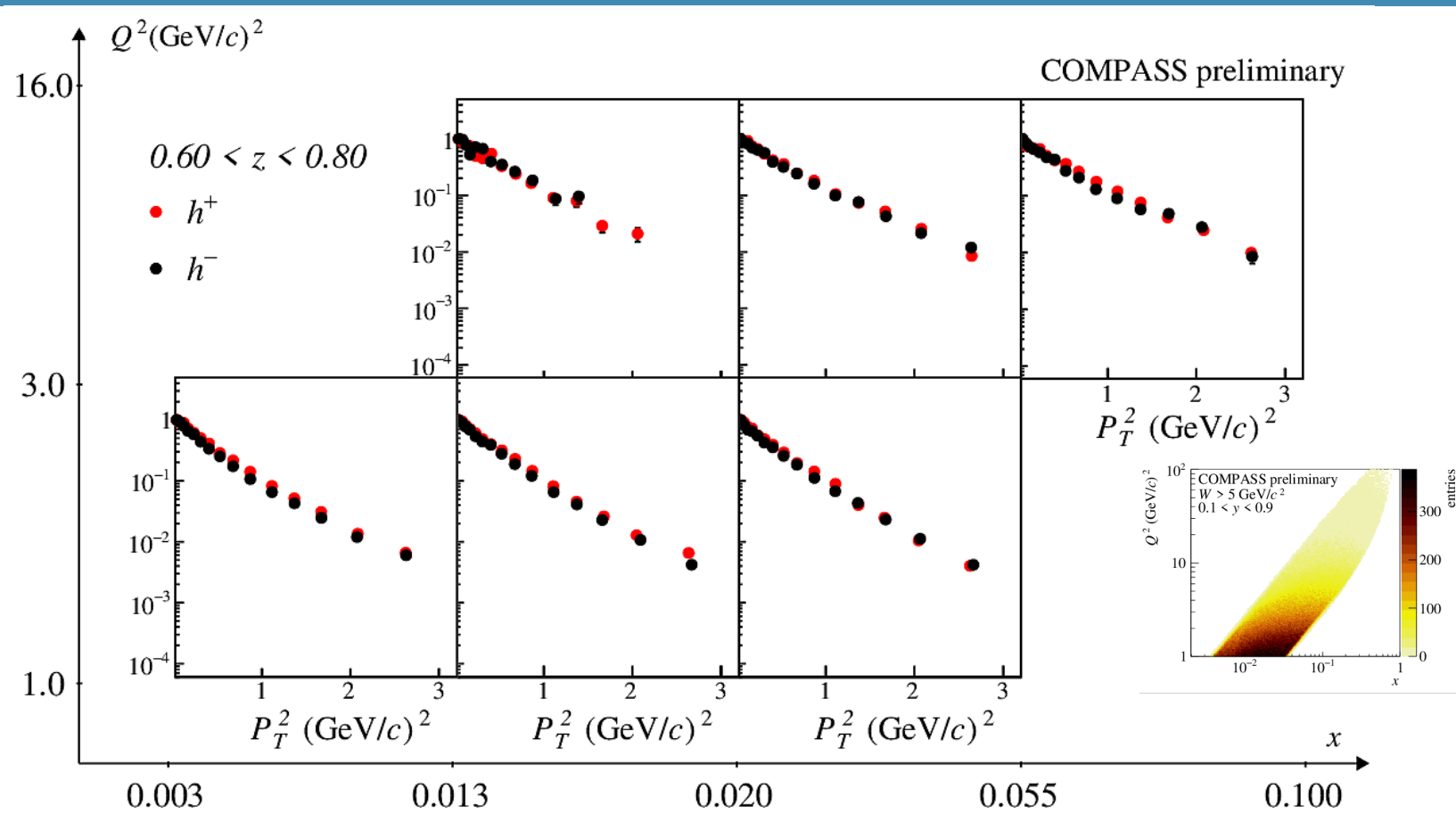
Year	Obs	
2013	$dn^h / (dN^\mu dz dp_T^2)$	Unpolarized multiplicities on d, 2004
2014	$A_{UU,d}^{\cos \phi_h}, A_{UU,d}^{\cos 2\phi_h}, A_{LU,d}^{\sin \phi_h}$	2004, part
2016	$dn^\pi / (dN^\mu dz)$	Unpolarized multiplicities on d, 2006
2016	$dn^h / (dN^\mu dz dp_T^2)$	Unpolarized multiplicities on d, 2006
2016	$dn^K / (dN^\mu dz)$	Unpolarized multiplicities on d, 2006
2020	$\sim dn^h / (dN^\mu dz dp_T^2)$	Unpolarized multiplicities on p, 2016
2020	$A_{UU,d}^{\cos \phi_h}, A_{UU,d}^{\cos 2\phi_h}, A_{LU,d}^{\sin \phi_h}$	Azimuthal mods' on p, 2016

Positive vs Negative charged hadrons (${}^6\text{LiD}$)

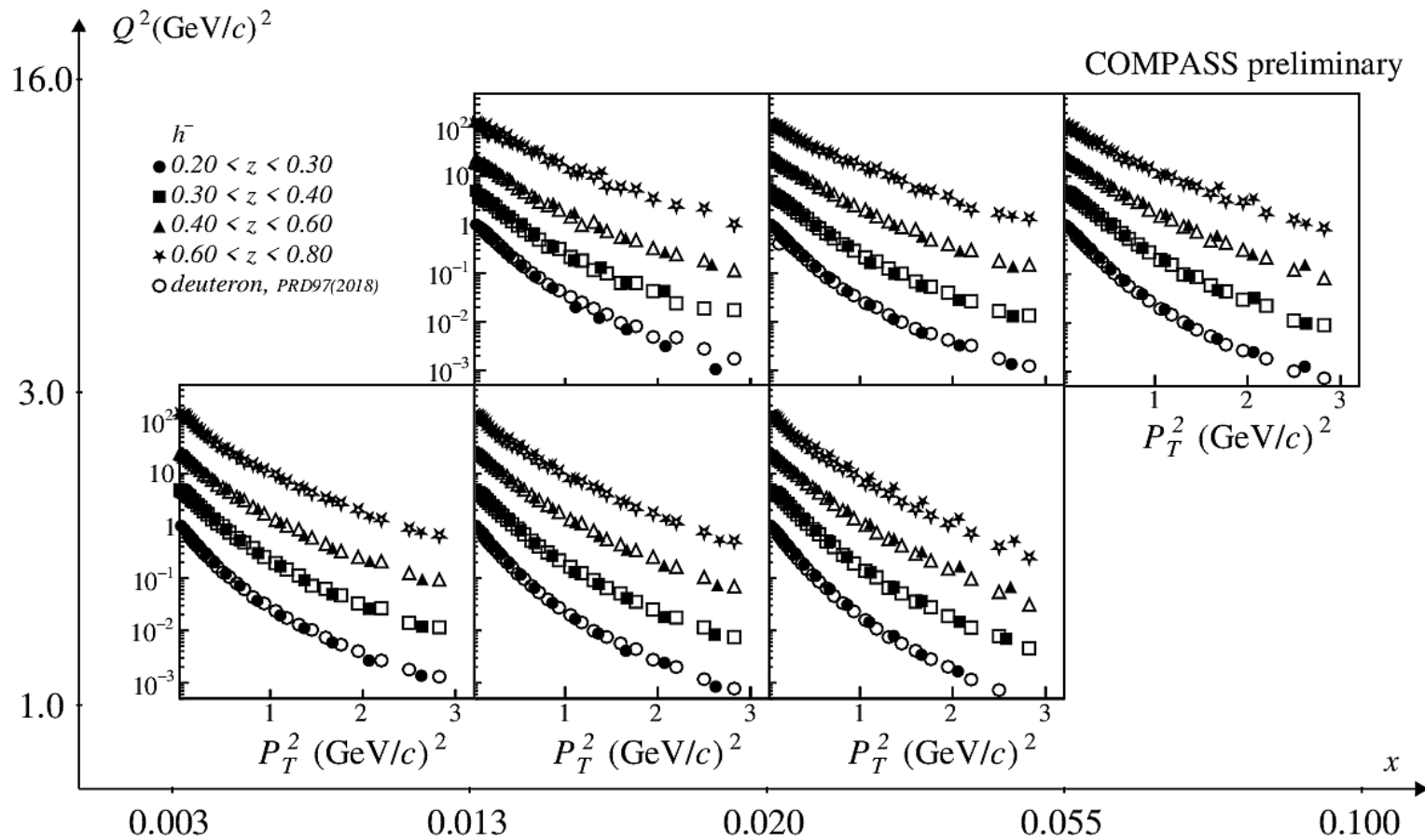
$$F_{UU}^{h}(x, z, P_{hT}^2; Q^2) = x \sum_q e_q^2 \int d^2\vec{k}_\perp d^2\vec{p}_\perp \delta(\vec{p}_\perp + z\vec{k}_\perp - \vec{P}_{hT}) f_1^q(x, k_\perp^2; Q^2) D_1^{q \rightarrow h}(z, p_\perp^2; Q^2)$$



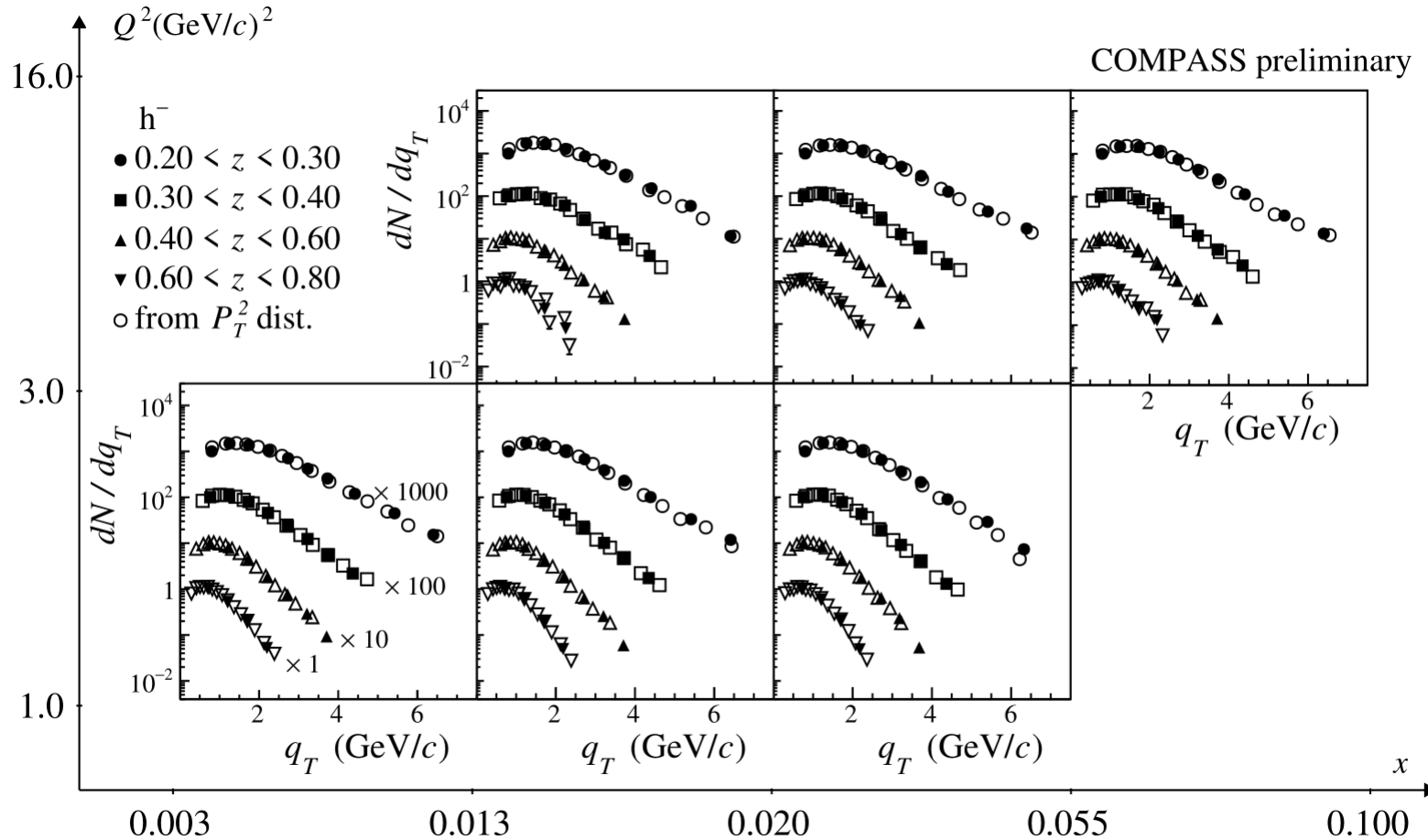
Positive vs Negative charged hadrons (LH_2)



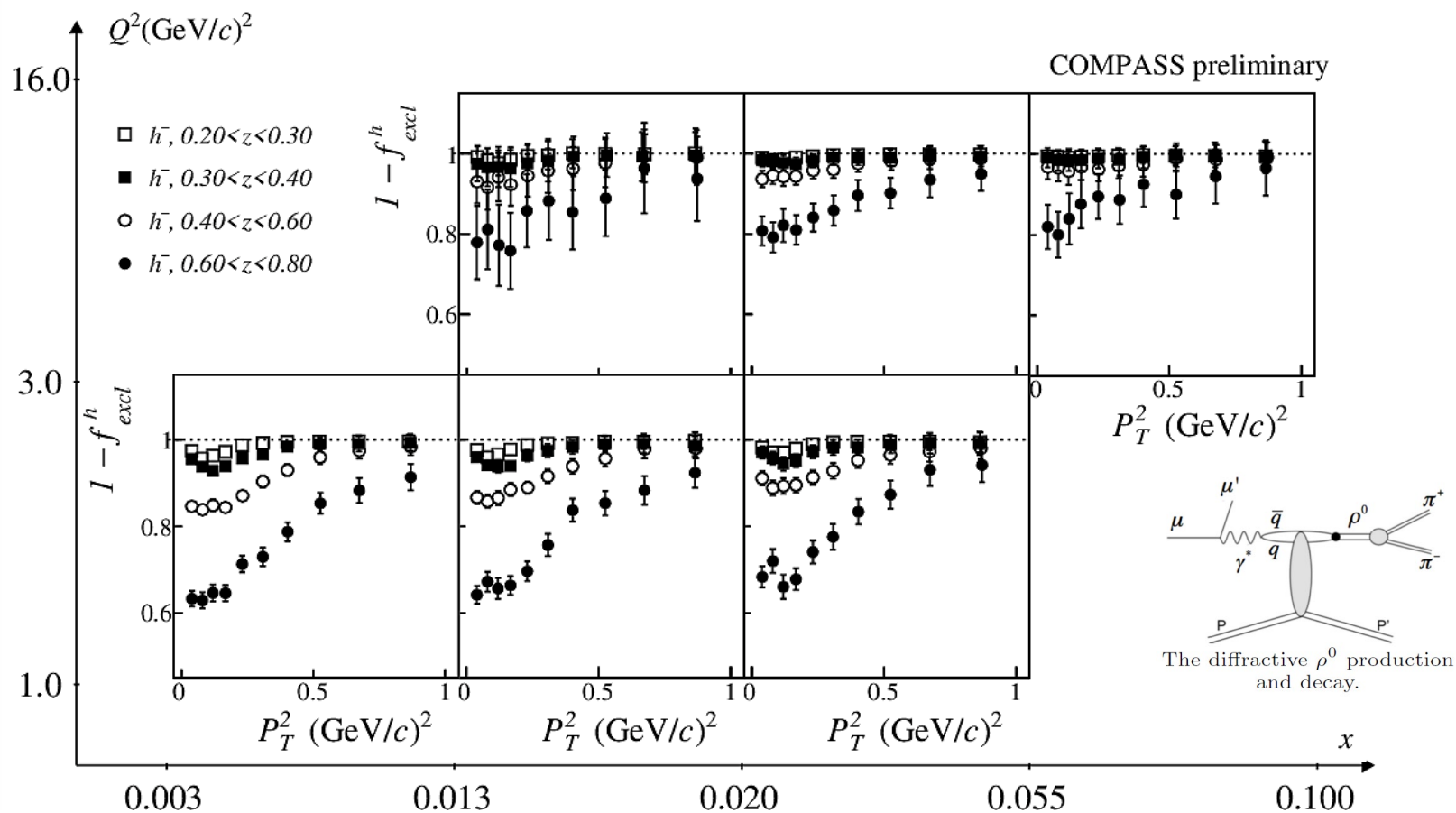
Comparison with the published deuteron



q_T distributions



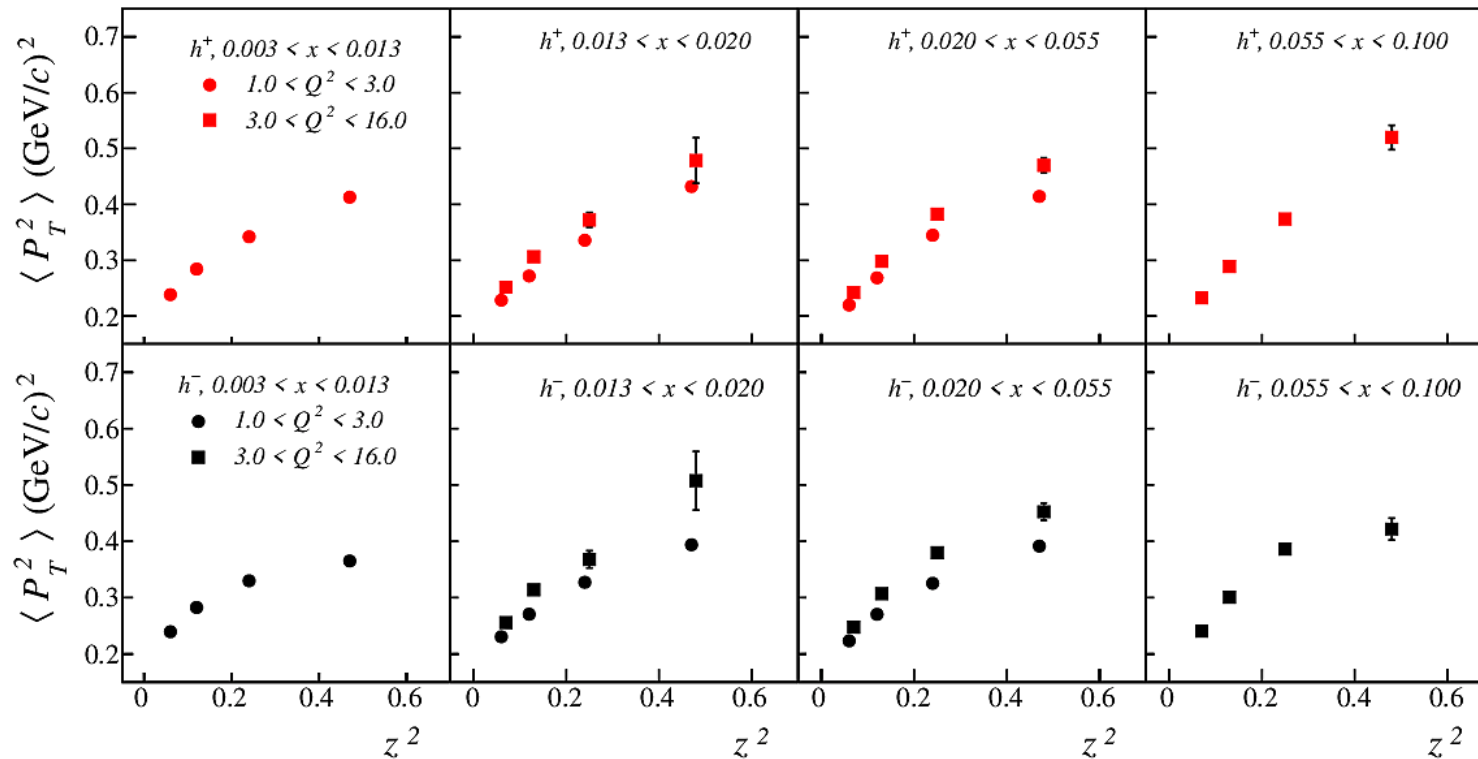
Contamination of hadrons from ρ^0 and ϕ produced in exclusive reactions



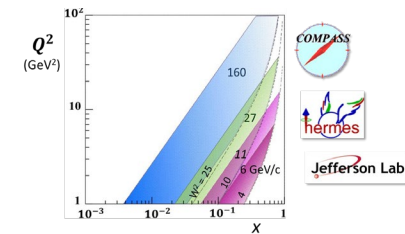
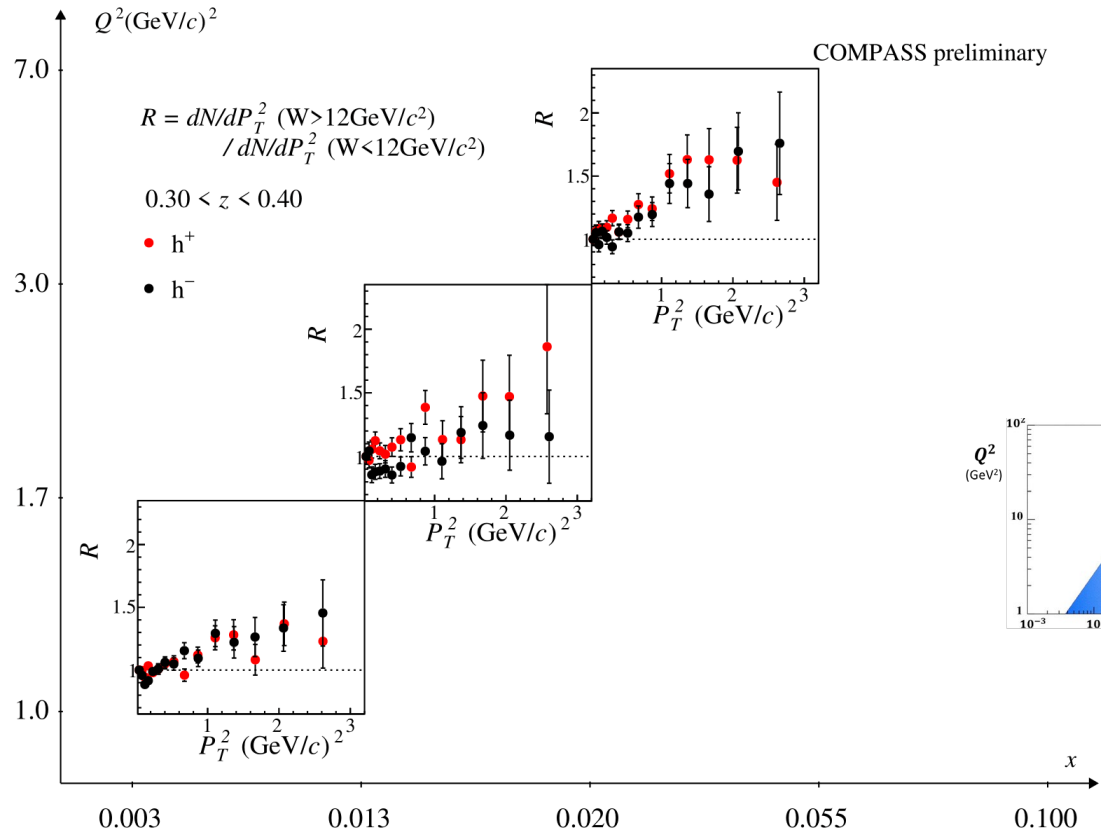
Slope dependence

A Gaussian ansatz for k_{\perp} and p_{\perp} leads to
 $\langle P_{hT}^2 \rangle = z^2 \langle k_{\perp}^2 \rangle + \langle p_{\perp}^2 \rangle$

COMPASS preliminary



P_{hT} distributions vs W



Unpolarised Azimuthal Modulation

When looking at the content of the structure functions/modulations in terms of TMD PDFs for the $\cos \phi_h$ and $\cos 2\phi_h$ we can write:

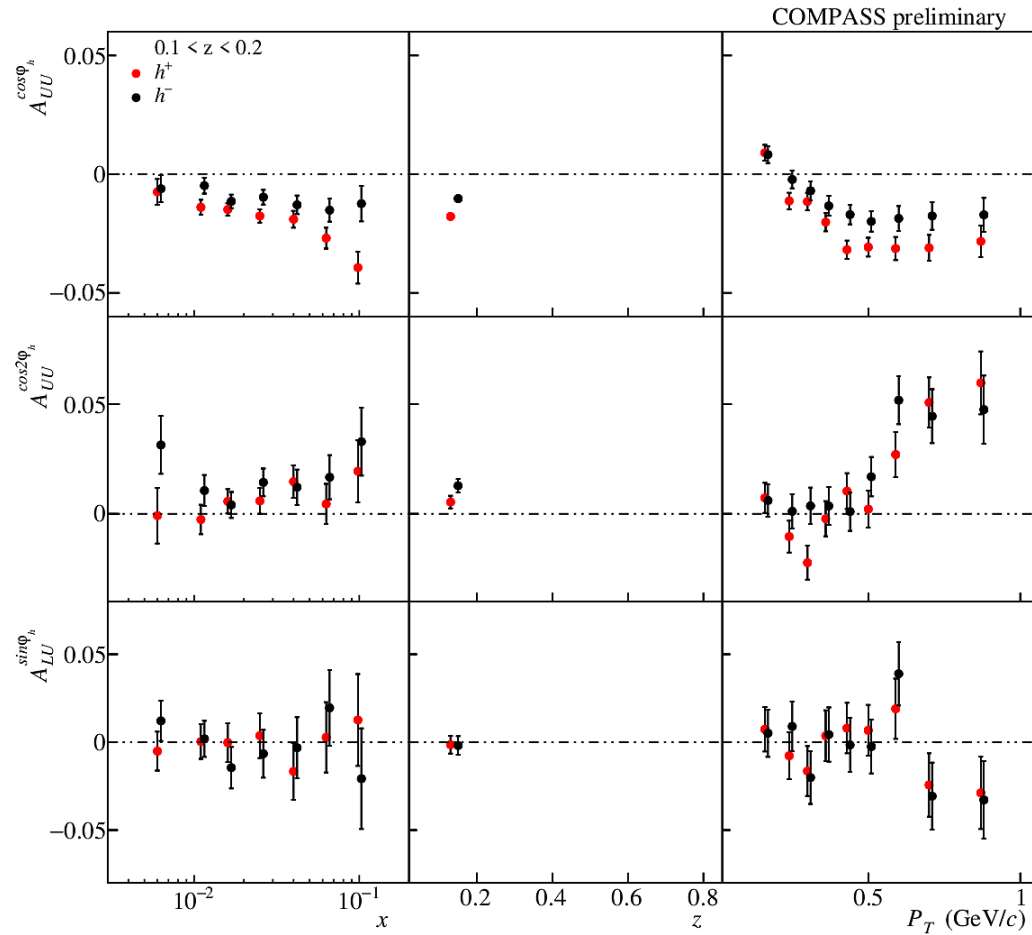
$$F_{UU}^{\cos \phi_h} = -\frac{2M}{Q} C \left[\frac{\hat{h} \cdot \vec{k}_\perp}{M} f_1 D_1 - \frac{p_\perp k_\perp \vec{P}_{hT} - z (\hat{h} \cdot \vec{k}_\perp)}{M z M_h M} h_1^\perp H_1^\perp \right] + \text{twists} > 3$$

$$F_{UU}^{\cos 2\phi_h} = C \left[\frac{(\hat{h} \cdot \vec{k}_\perp) (\hat{h} \cdot \vec{p}_\perp) - \vec{p}_\perp \cdot \vec{k}_\perp}{M M_h} h_1^\perp H_1^\perp \right] + \text{twists} > 3$$

In the $\cos 2\phi_h$ Cahn effects enters only at twist₄

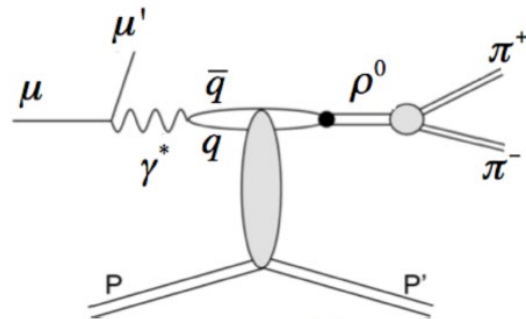
$$F_{\text{Cahn}}^{\cos 2\phi_h} \approx \frac{2}{Q^2} C \left[\left\{ 2 (\hat{h} \cdot \vec{k}_\perp)^2 - k_\perp^2 \right\} f_1 D_1 \right]$$

Azimuthal modulations on (LH₂) – 1D

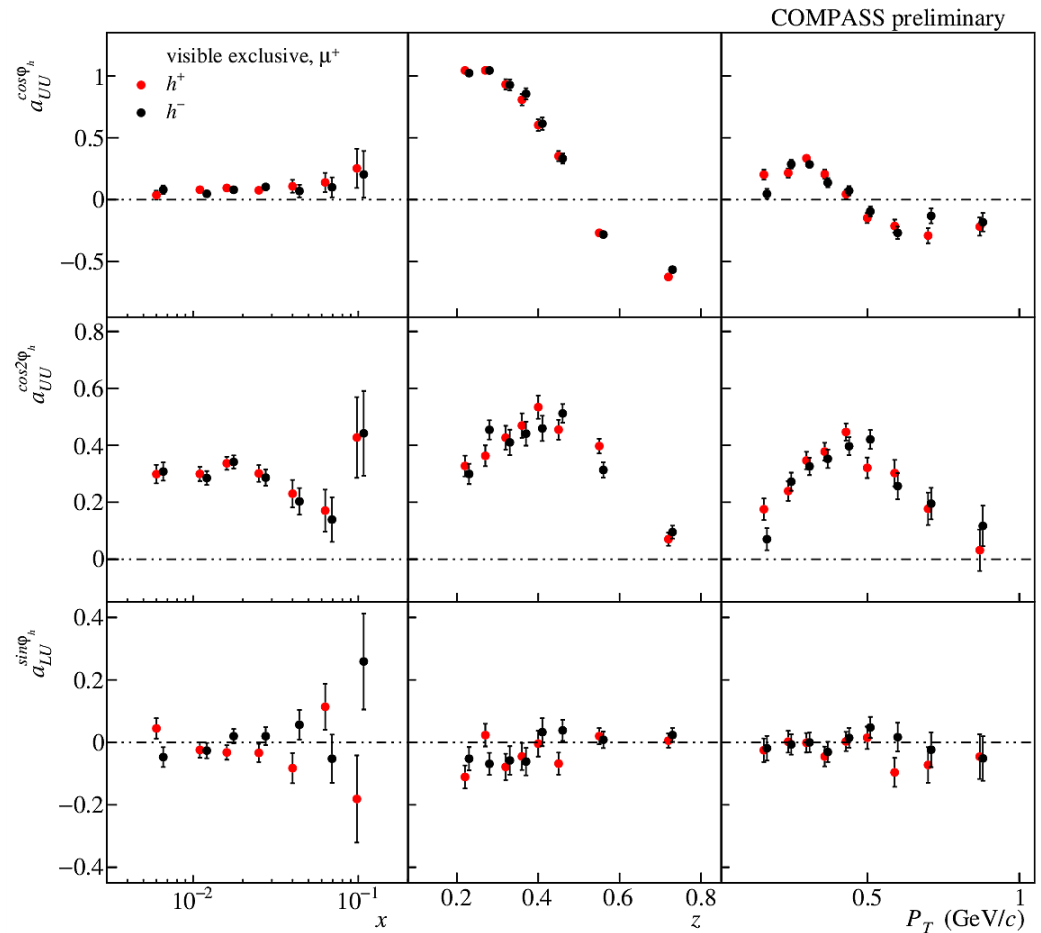


Contamination on (LH₂) – 1D

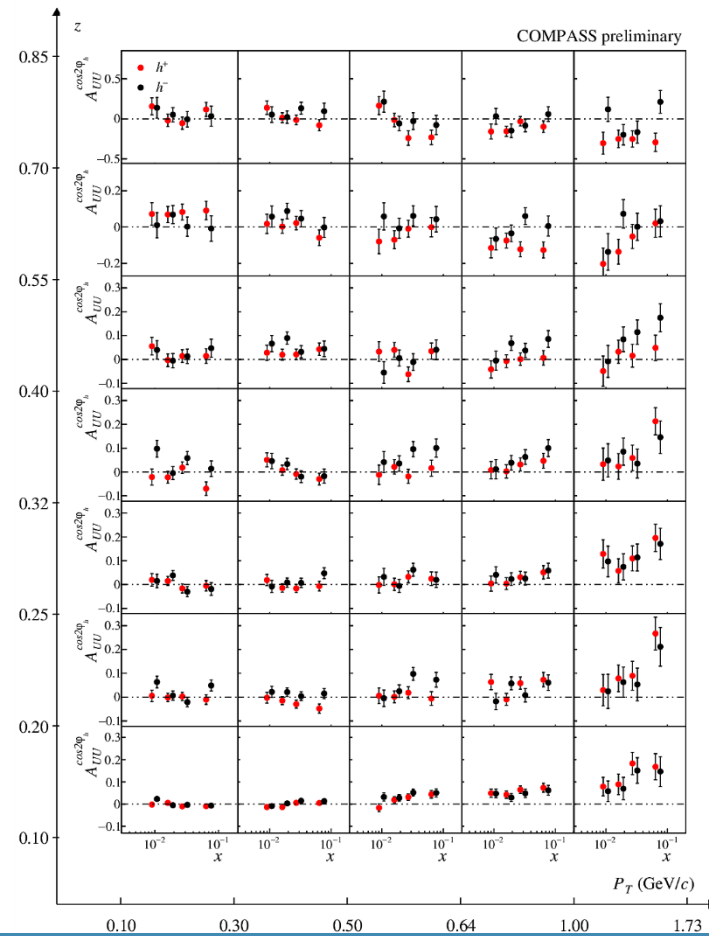
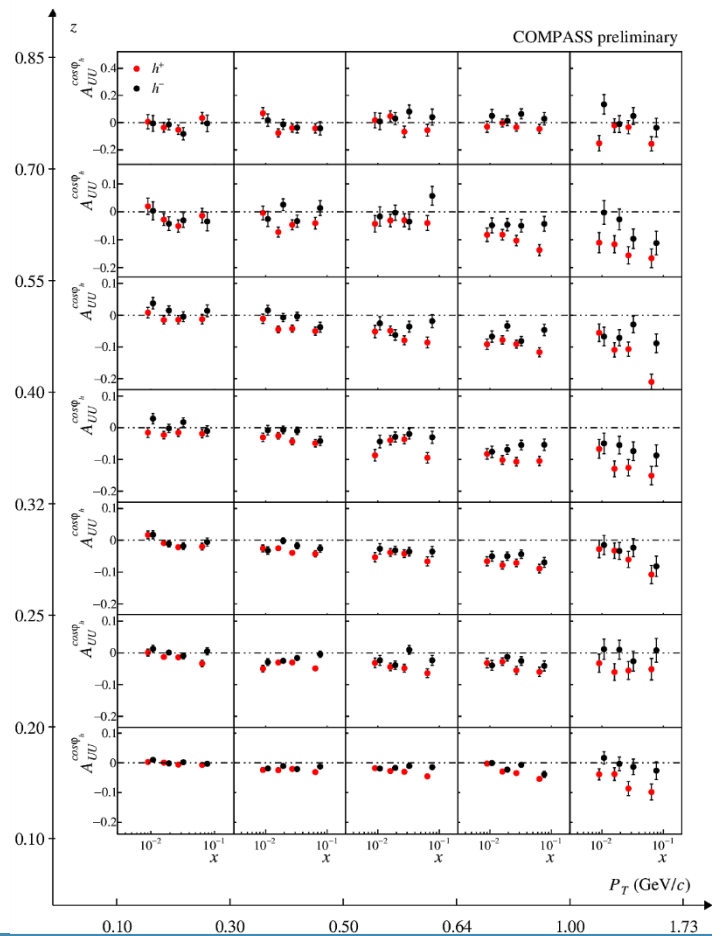
- Determined from $z_1 + z_2 > 0.95$
- Selecting ρ^0, ω and ϕ



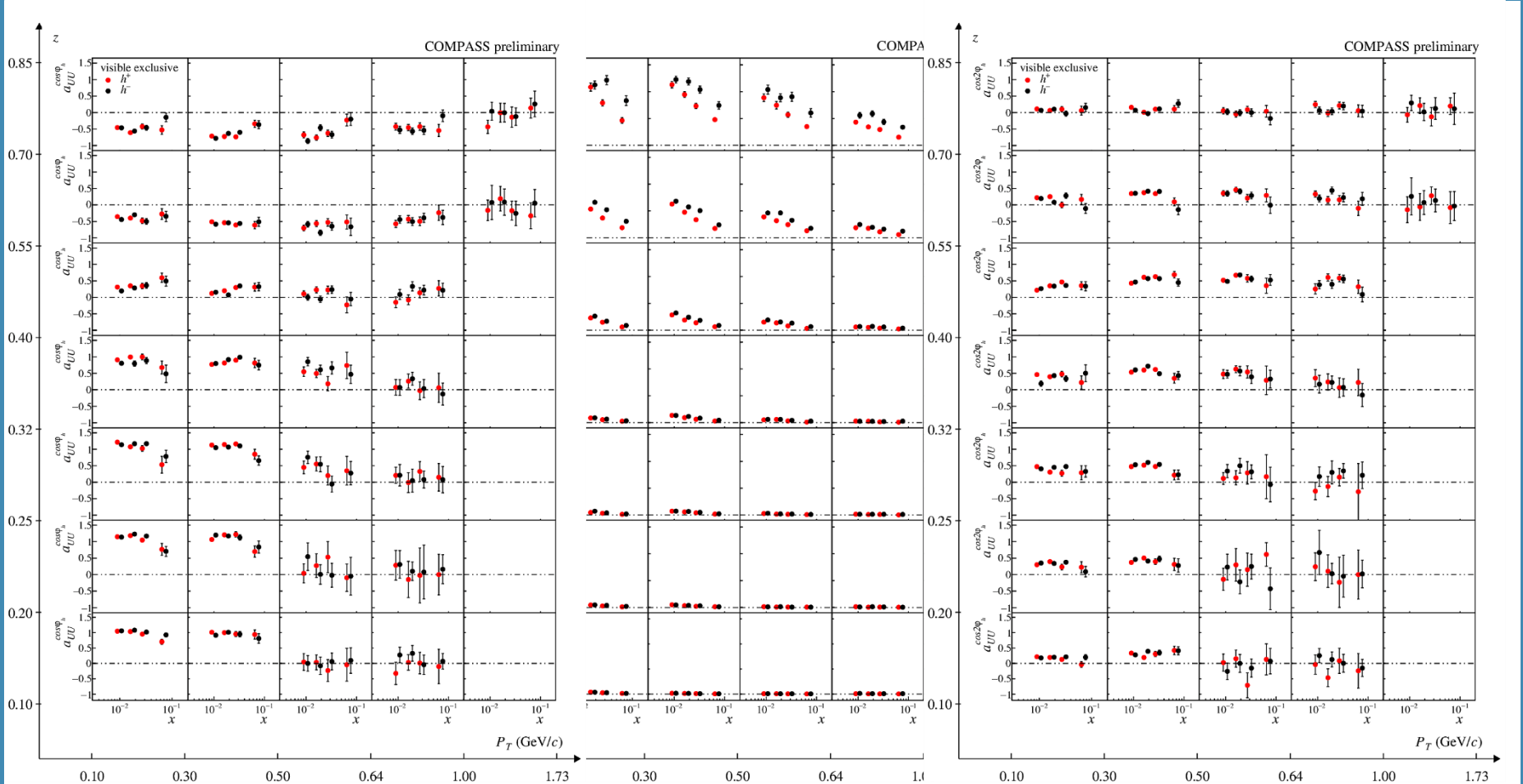
The diffractive ρ^0 production and decay.



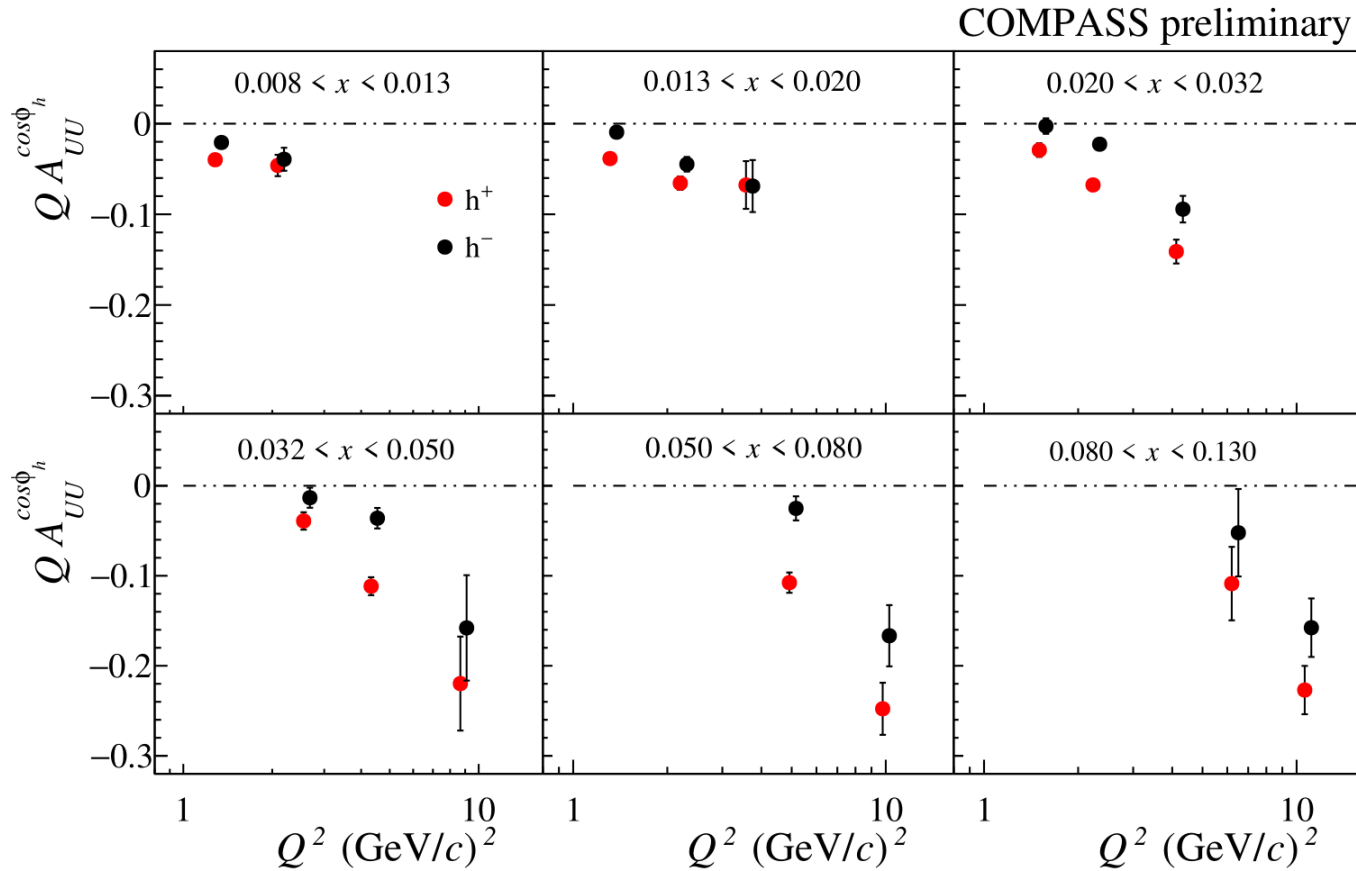
Azimuthal modulations on $(\text{LH}_2) - 3\text{D}$



Contamination on $(LH_2) - 3D$



Q^2 behavior

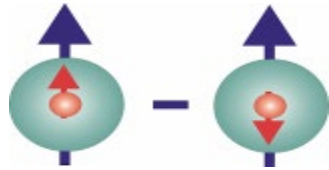


Polarized Nucleons



Transversity PDF

$$h_1^q(\mathbf{x}) = q^{\uparrow\uparrow}(\mathbf{x}) - q^{\uparrow\downarrow}(\mathbf{x})$$



$$q = u_v, d_v, q_{\text{sea}}$$

quark with **spin** parallel to the nucleon spin in a transversely polarised nucleon

- probes the relativistic nature of quark dynamics
- no contribution from the gluons \rightarrow simple Q^2 evolution
- Positivity: Soffer bound..... $2|h_1^q| \leq f_1^q + g_1^q$ *Soffer, PRL 74 (1995)*
- first moments: tensor charge..... $\delta q(Q^2) = \int_0^1 dx [h_1^q(x) - h_1^{\bar{q}}(x)]$
- is chiral-odd: decouples from inclusive DIS *Bakker, Leader, Trueman, PRD 70 (04)*

Transversity

is chiral-odd:

observable effects are given only by the product of $h_1^q(x)$ and an other chiral-odd function

Measured in **SIDIS** on a transversely polarised target via “quark polarimetry”

$$l N^\uparrow \rightarrow l' h X$$

“Collins” asymmetry

“Collins” Fragmentation Function

$$l N^\uparrow \rightarrow l' h h X$$

“two-hadron” asymmetry

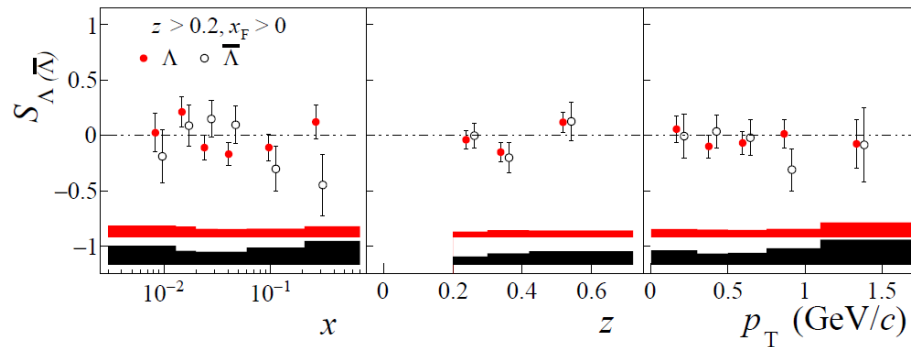
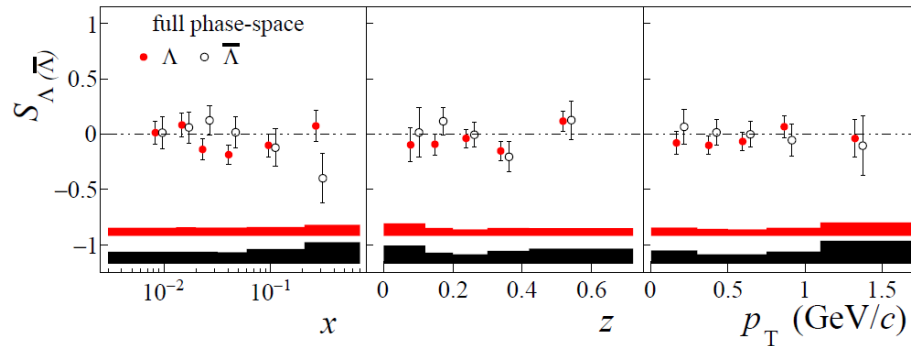
“Interference” Fragmentation Function

$$l N^\uparrow \rightarrow l' \Lambda X$$

Λ polarisation

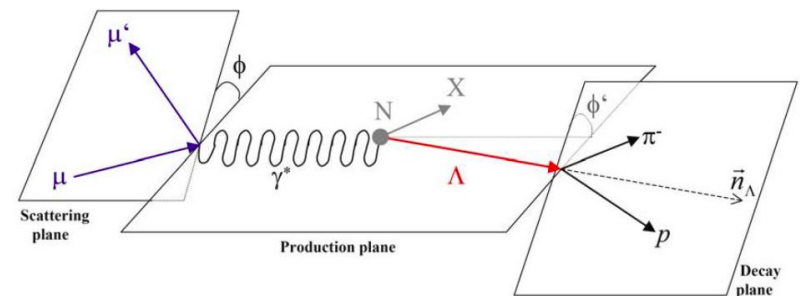
Fragmentation Function of $q^\uparrow \rightarrow \Lambda$

Λ transverse spin transfer from COMPASS



$$S_{\Lambda(\bar{\Lambda})}(x, z) = \frac{\sum_q e_q^2 h_1^q(x) H_1^{\Lambda(\bar{\Lambda})}(z)}{\sum_q e_q^2 f_1^q(x) D_1^{\Lambda(\bar{\Lambda})}(z)}$$

$$\frac{dN}{d \cos \theta^*} \propto A(1 + \alpha P_{\Lambda(\bar{\Lambda})} \cos \theta^*)$$



Sivers Asymmetry

Sivers: correlates nucleon spin & quark transverse momentum k_T / T-ODD

at LO:

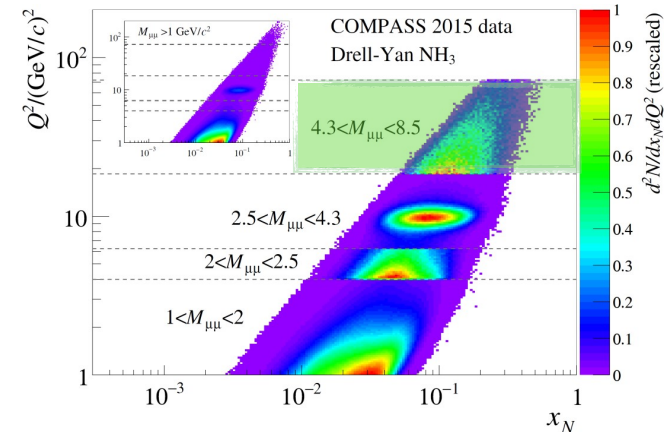
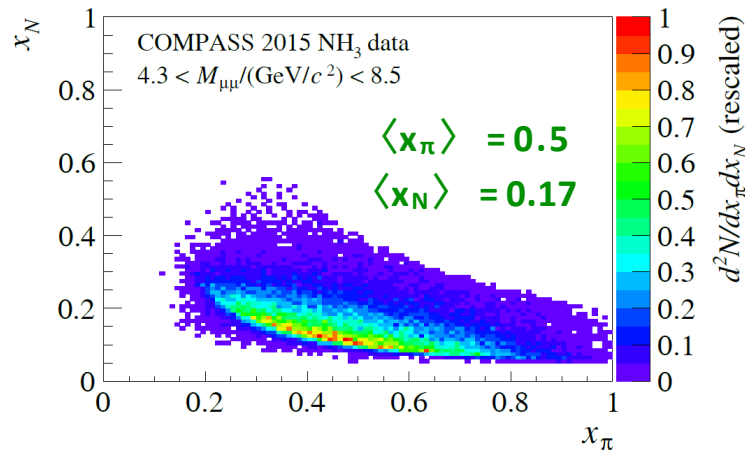
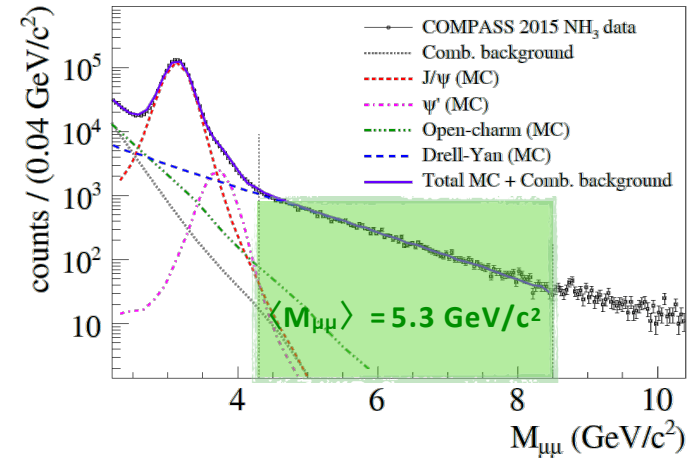
$$A_{Siv} = \frac{\sum_q e_q^2 f_{1Tq}^\perp \otimes D_q^h}{\sum_q e_q^2 q \otimes D_q^h}$$

$$\mu p^\uparrow \rightarrow \mu X h^\pm$$

The Sivers PDF	
1992	Sivers proposes f_{1T}^\perp
1993	J. Collins proofs $f_{1T}^\perp = 0$ for T invariance
2002	S. Brodsky, Hwang and Schmidt demonstrate that f_{1Tq}^\perp may be $\neq 0$ due to FSI
2002	J. Collins shows that $(f_{1T}^\perp)_{DY} = -(f_{1T}^\perp)_{SIDIS}$
2004	HERMES on p: $A_{Siv}^{\pi^+} \neq 0$ and $A_{Siv}^{\pi^-} = 0$
2004	COMPASS on d: $A_{Siv}^{\pi^+} = 0$ and $A_{Siv}^{\pi^-} = 0$
2008	COMPASS on p: $A_{Siv}^{\pi^+} \neq 0$ and $A_{Siv}^{\pi^-} = 0$

Drell-Yan measurements at COMPASS

- I. $1 < M_{\mu\mu}/(\text{GeV}/c^2) < 2$, "Low mass"
 - Large background contamination
- II. $2 < M_{\mu\mu}/(\text{GeV}/c^2) < 2.5$, "Intermediate mass"
 - High DY cross section.
 - Still low DY-signal/background ratio
- III. $2.5 < M_{\mu\mu}/(\text{GeV}/c^2) < 4.3$, "Charmonia mass"
 - Strong J/ψ signal: J/ψ physics.
 - Good signal/background.
- IV. $4.3 < M_{\mu\mu}/(\text{GeV}/c^2) < 8.5$, "High mass" background $< 4\%$
 - Valence quark region \rightarrow Largest asymmetries!
 - Low DY cross-section



Transverse Spin Asymmetry in Drell-Yan

190 GeV/c π^- beam, transversely polarized NH_3 target

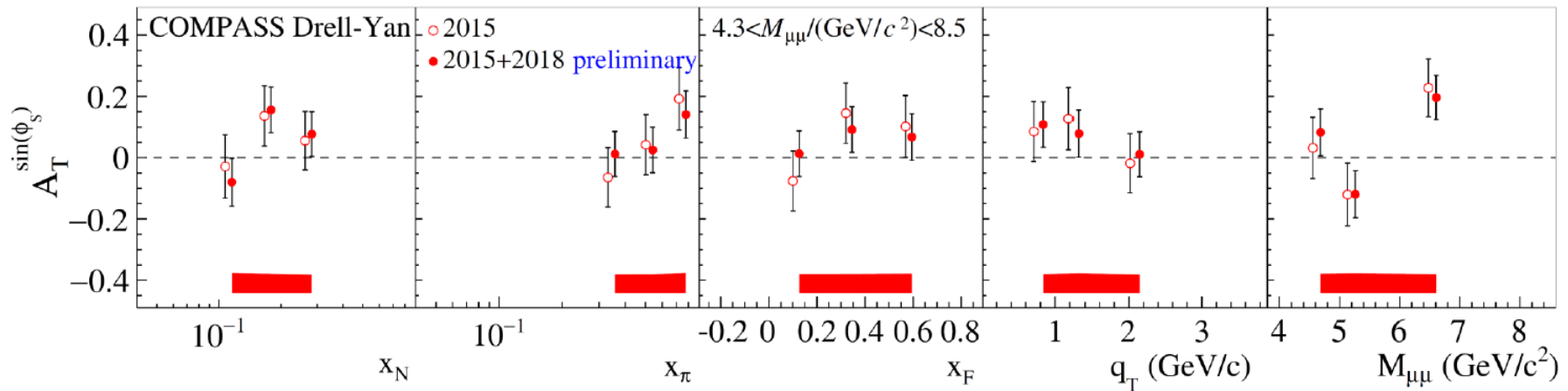
$$f_{1T, \text{DY}}^\perp = -f_{1T, \text{SIDIS}}^\perp$$

$$\frac{d\sigma}{dq^4 d\Omega} \propto 1 + \dots + S_T \left[A_T^{\sin\phi_S} \sin\phi_S + \dots \right]$$

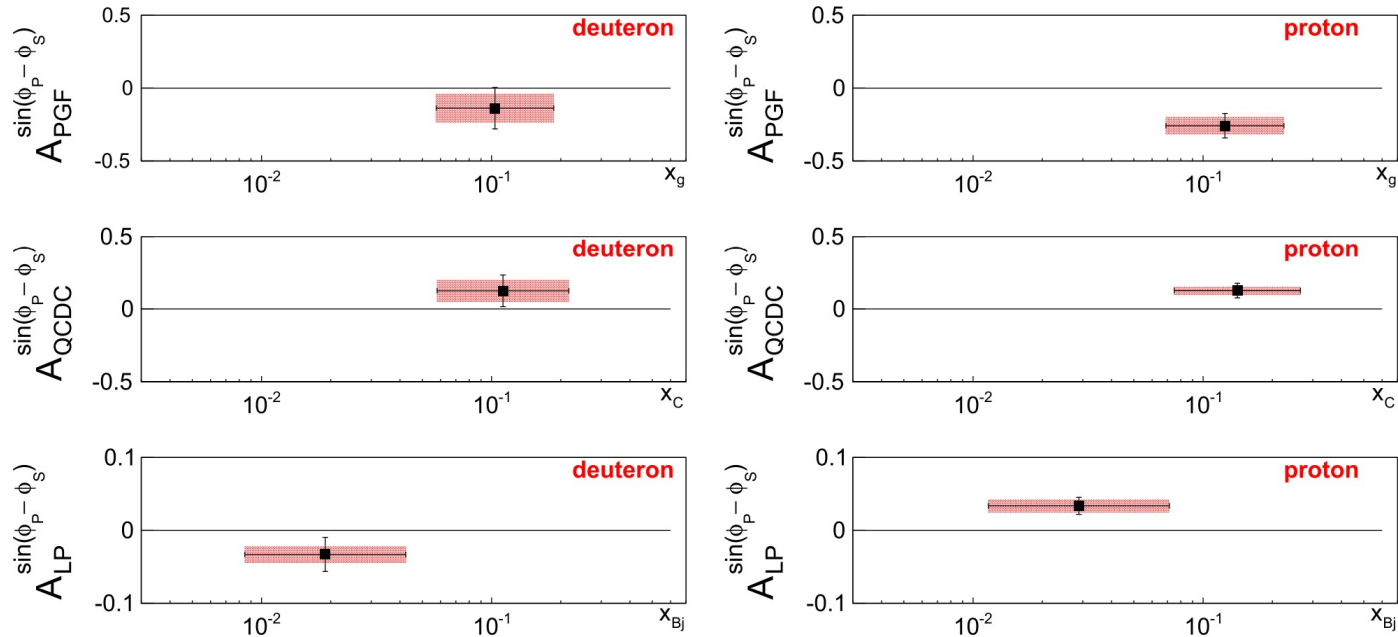
Sivers DY TSA

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

COMPASS 2015 (PRL 119, 112002 (2017)) + 2018 (~50%)



Sivers Asymmetry for Gluon from SIDIS



$$A_{PGF}^{Siv,d} = -0.14 \pm 0.15(\text{stat.}) \pm 0.10(\text{syst.})$$

$$\langle x_g \rangle = 0.13$$

$$A_{PGF}^{Siv,p} = -0.26 \pm 0.09(\text{stat.}) \pm 0.06(\text{syst.})$$

$$\langle x_g \rangle = 0.15$$

C. Adolph et al. (COMPASS Collaboration), *Phys. Lett. B* 772, 854 (2017).

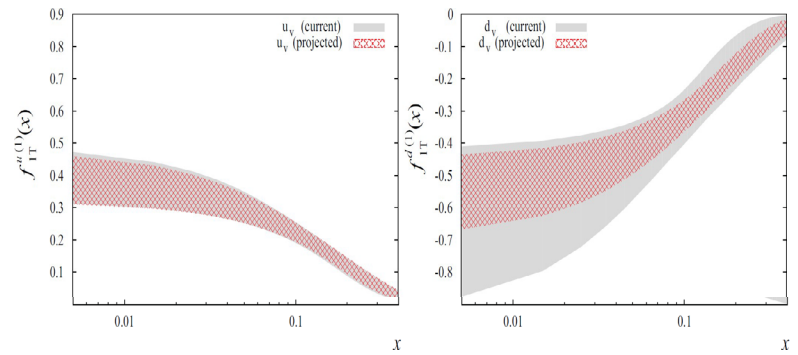
the 2021/22 run – transversely polarised deuteron

150 days of data taking with 160 GeV muons to measure SIDIS off transversely polarised

- the missing measurement to complete the COMPASS exploratory programme
- collecting the same statistics as in 2010, the deuteron asymmetries will have a statistical uncertainty $\sigma_d \simeq 0.6 \sigma_p^{2010}$ in a kinematic range that only COMPASS can cover, as long as EIC will not start, complementary to JLab12
 - important impact on the knowledge of TMD PDFs
 - and in particular transversity and tensor charge

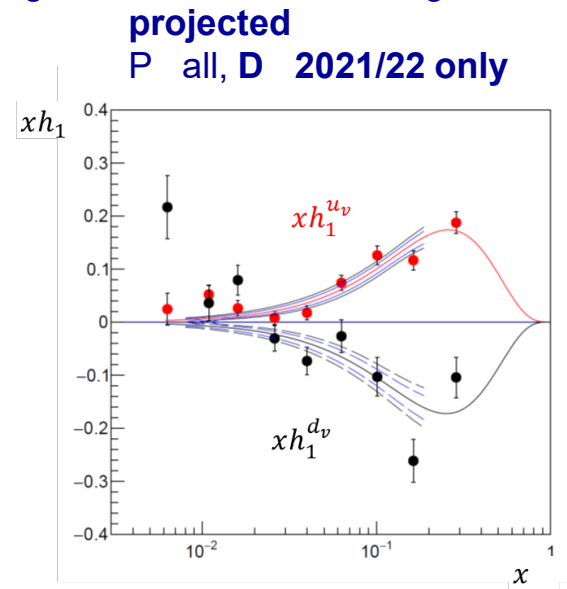
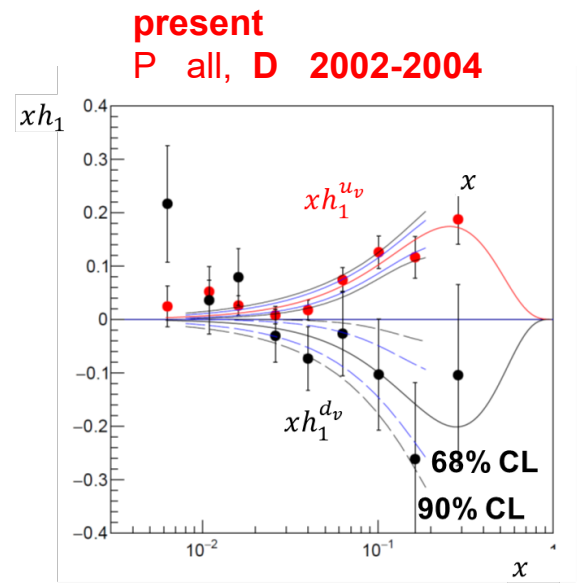


Sivers functions from global fits
M. E. Boglione and J. O. Gonzalez



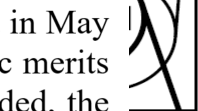
the 2021/22 run: impact on the tensor charge

for the proposal, we have evaluated the tensor charge in the measured x range



	$\delta_u = \int_{\Omega_x} dx h_1^{uv}(x)$	$\delta_d = \int_{\Omega_x} dx h_1^{dv}(x)$	$g_T = \delta_u - \delta_d$
Present	0.201 ± 0.032	-0.189 ± 0.108	0.390 ± 0.087
Projected	0.201 ± 0.019	-0.189 ± 0.040	0.390 ± 0.044

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

- 
- (b) On the basis of an Experimental Proposal (“the Experimental Proposal”) submitted in May 2019 (CERN-SPSC-2019-022; SPSC-P-360), and a detailed review of the scientific merits of the Experiment, the technological feasibility and estimates of the resources needed, the SPS Committee (SPSC) has recommended approval of the Experimental Proposal to the CERN Research Board (minutes of the 139th meeting of the SPSC held on 13th October 2020);
- (c) Based on the recommendation by the SPSC, the Research Board approved the Experiment under the reference number NA66;
- (d) The Director General accepted the Research Board recommendation and approved the Experiment (minutes of the 235th meeting of the Research Board held on 2 December 2020);

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

Phase-1: 2022-2024

COMPASS^{++*}/AMBER[†]

Italia all'avanguardia nell'Electron-Ion Collider

Il numero degli scienziati italiani che lavorano al progetto di questo nuovo collisore è secondo solo a quello degli statunitensi, e coinvolge una dozzina di università pubbliche e l'Istituto nazionale di fisica nucleare

Un risultato che alle Olimpiadi ci farebbe inorgogliare: secondi solo agli Stati Uniti. Questi sono i numeri del coinvolgimento italiano nell'impresa Electron-Ion Collider, descritta nell'articolo di Abhay Deshpande e Rikutarō Yoshida. Per ora l'Electron-Ion Collider, o EIC, è solo un progetto, ma raccoglie già una comunità di più di 850 scienziati, organizzati in un gruppo di lavoro, l'EIC User Group. L'Italia è presente con più di 80 ricercatori e docenti, afferenti a 12 atenei pubblici e all'Istituto nazionale di fisica nucleare (INFN), l'ente pubblico demandato a sostenere la ricerca italiana in fisica nucleare e delle particelle. Solo gli Stati Uniti hanno un numero di partecipanti superiore.

L'EIC potrebbe diventare l'acceleratore di particelle più potente al mondo dopo il Large Hadron Collider del CERN di Ginevra. Sarebbe l'unico acceleratore con questa potenza ad avere la capacità di sondare con altissima precisione la materia nucleare in stati molto ricchi di informazione (in gergo «polarizzati», oppure in condizioni di «saturazione»). Inoltre potrebbe essere l'unico nuovo acceleratore di particelle costruito nel prossimo decennio, e sarà sicuramente il maggior progetto statunitense nel campo della fisica nucleare. L'Italia ha l'interesse, le competenze e la voglia di partecipare con entusiasmo a questa avventura.

Una massima priorità

L'idea di realizzare un collisore di elettroni e ioni per studiare la struttura interna di protoni e neutroni ha radici lontane. L'unico collisore protone-elettrone mai realizzato è stato l'Hadron-Elektron-Ringanlage (HERA), al Deutsches Elektronen-Synchrotron (DESY) di Amburgo, che ha funzionato fino al 2007. Fin dalla fine degli anni novanta sono state avanzate proposte di «polarizzare» gli spin dei protoni circolanti, ovvero di orientarli in modo coerente. Tra il 2005 e il 2010 si è discusso senza successo di realizzare un anello di elettroni polarizzati all'interno del complesso della Facility for Antiproton and Ion Research (FAIR), attualmente in costruzione a Darmstadt, in Germania. Questi auspici della comunità scientifica si stanno ora realizzando, speriamo, con l'EIC, grazie alla forte spinta statunitense e al supporto internazionale che è riuscita a raccogliere.

Negli anni scorsi il gruppo di lavoro ha formulato innanzitutto la proposta di realizzare il collisore, identificando gli obiettivi scientifici che ne giustificano la costruzione. È poi riuscito a convincere tutta la comunità dei fisici nucleari statunitensi, che ha riconosciuto l'EIC come «massima priorità» nel suo ultimo documento di programmazione strategica pluriennale, e la comunità scientifica più ampia, rappresentata dalle National Academies of Sciences, Engineering and Medicine, che di recente hanno pubblicato una valutazione positiva sul progetto con lusinghieri commenti. Ora bisogna convincere il governo federale e il Congresso degli Stati Uniti a finanziare il progetto. Una prima decisione in merito è attesa nei prossimi mesi: sarà l'inizio concreto del progetto, con i primi importanti finanziamenti.

La costruzione dell'EIC dovrebbe iniziare entro i prossimi cinque anni, il funzionamento dovrebbe cominciare nel 2030 e proseguire per anni, aprendo nuove prospettive per un'intera generazione di giovani fisici.



Un ingegnere del Brookhaven National Laboratory lavora alle LEReC, sezioni di raffreddamento per elettroni del Relativistic Heavy Ion Collider (RHIC). La tecnologia delle LEReC potrebbe essere applicata all'Electron-Ion Collider.

I ricercatori italiani hanno dato e continueranno a dare contributi su molti fronti: innanzitutto, la definizione degli obiettivi generali, ben illustrati nell'articolo di Deshpande e Yoshida. Nel 2011 una dozzina di italiani hanno firmato il primo documento in cui è stato sviluppato il cosiddetto «Science Case» del collisore, cioè la definizione degli aspetti più importanti da investigare per giungere alla comprensione della struttura interna dei nuclei.

In pratica e in teoria

I ricercatori sperimentali porteranno la loro esperienza, fondamentale nel successo di esperimenti nei laboratori DESY in Germania, CERN in Svizzera, Jefferson Lab negli Stati Uniti. Le competenze che saranno inserite nel progetto sono relative sia alle complesse tecniche di analisi (software) necessarie in esperimenti del genere sia alla realizzazione di rivelatori con tecnologie all'avanguardia sviluppate in Italia. Il progetto EIC-NET, finanziato dall'INFN, raccoglie gruppi di fisici sperimentali a Torino, Padova, Bologna, Ferrara, Genova, Trieste, Roma, Frascati, Bari e Catania. Per Silvia Dalla Torre, dirigente di ricerca all'INFN, sezione di Trieste, e responsabile di EIC-NET, «il coinvolgimento dei fisici italiani che studiano la struttura del protone è una naturale continuazione di un convinto impegno scientifico. Molti di noi sono attivi in questo campo già da anni. Oggi la nostra partecipazione è formalizzata grazie al supporto dell'INFN. Sarà quindi possibile, per i fisici italiani, contribuire in maniera sostanziale a questo progetto di scoperta scientifica».

I ricercatori teorici italiani sono impegnati nello studio della distribuzione tridimensionale dei costituenti interni del protone (quark e gluoni). Da anni sono tra i pionieri a livello mondiale nella ricostruzione di queste mappe tridimensionali. Sono organizzati nel progetto National Initiative on PHysics of hAdrons (NINPHA) dell'INFN, coordinato da Mariacelena Boglione, professore associato all'Università di Torino, e il team comprende i gruppi di Torino, Cagliari, Genova, Roma, Perugia e Pavia. «L'EIC sarà letteralmente una miniera di informazioni, che ci aiuterà a comprendere alcuni tra i più affascinanti misteri della fisica subnucleare, come l'origine della massa e dello spin del protone», ha dichiarato Barbara Pasquini, professore associato all'Università di Pavia.

Nei prossimi anni proseguirà l'attività di ricerca e sviluppo sui rivelatori che verranno usati nell'EIC, mentre è in atto già da anni una proficua collaborazione tra sperimentali e teorici per ottimizzare l'analisi dei dati, testimoniata dalla partecipazione a progetti comuni di ricerca italiani e, soprattutto, europei. Oltre ad avere una fondamentale importanza per la comprensione dei costituenti della materia, l'EIC porterà a risultati utili anche per altri settori della fisica, e a ricadute tecnologiche e applicazioni in campi diversi, tra cui quello medico.

«L'Italia ha dato contributi rilevanti alla fisica nucleare negli Stati Uniti, fin dalla sua nascita per opera di Enrico Fermi. Il coinvolgimento in un grande progetto negli Stati Uniti sarà un'importante occasione per rafforzare la dimensione globale della ricerca scientifica italiana. L'INFN sarà in prima linea», ha detto Eugenio Nappi, vicepresidente dell'INFN.

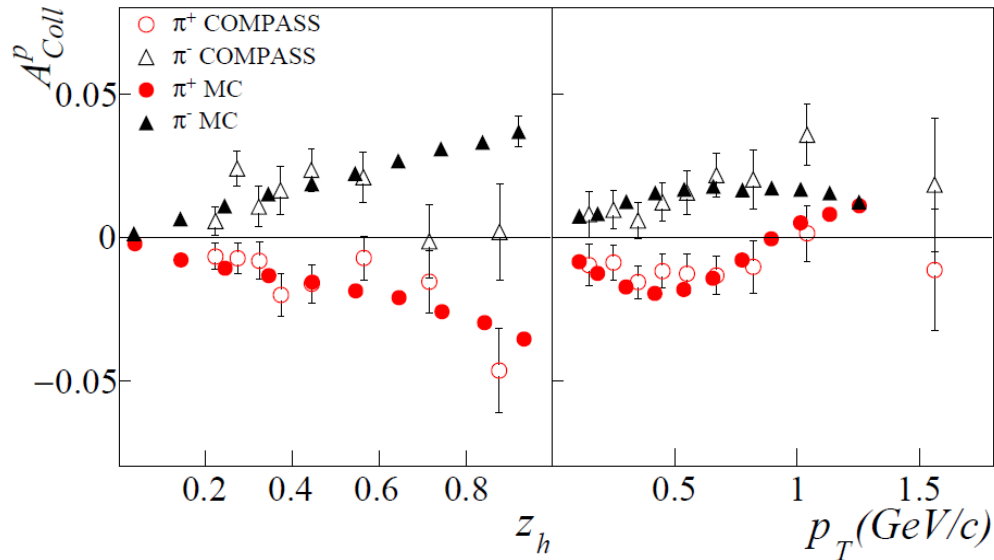
Alessandro Bacchetta,
professore associato, Università degli Studi di Pavia e INFN - Pavia
Andrea Bressan,
professore associato, Università degli Studi di Trieste e INFN - Trieste,
vicepresidente dell'Institutional Board dell'EIC User Group
Marco Radici,
primo ricercatore INFN - Pavia, membro dello Steering Committee
e dell'Institutional Board dell'EIC User Group

Thank you



A_{Coll}^p on proton and 3P_0 model for FF

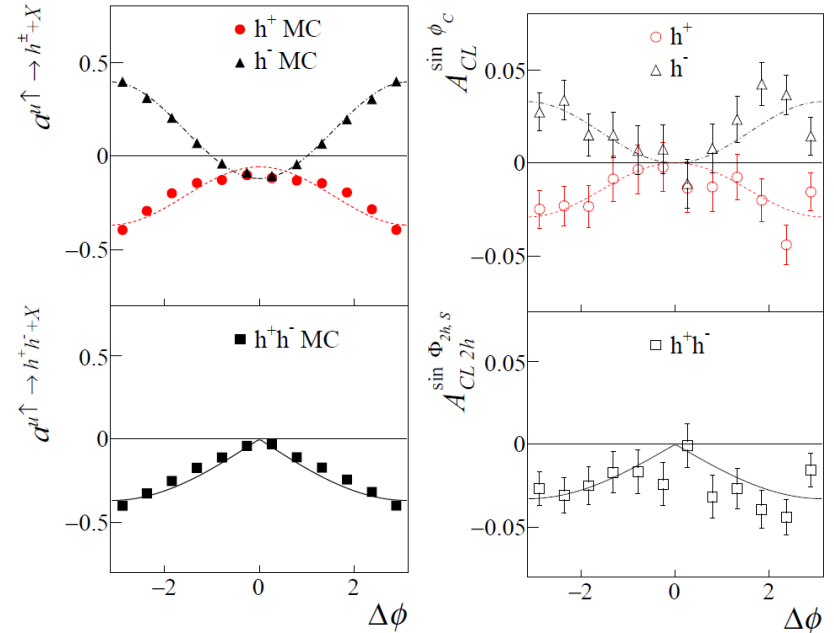
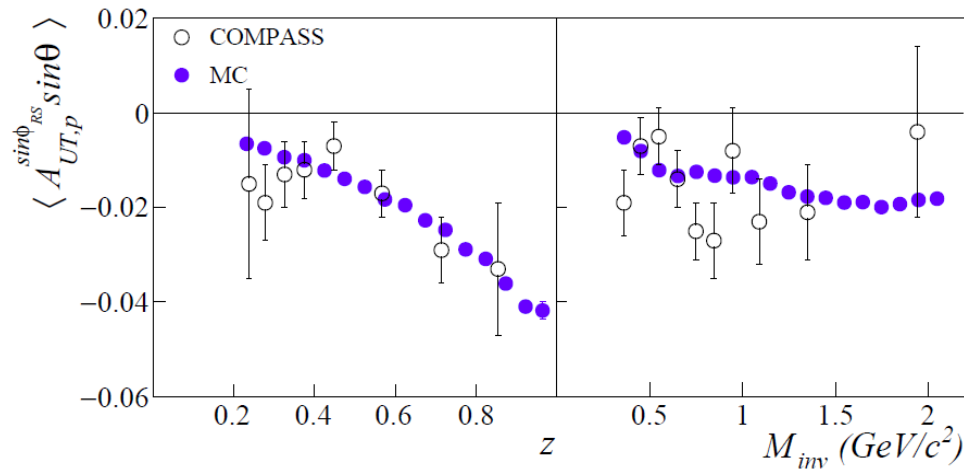
Albi Kerbizi @ DSPIN17 <http://theor.jinr.ru/~spin/2017/>
 Phys. Rev. D 97, 074010 (2018)/[arXiv:1802.00962](https://arxiv.org/abs/1802.00962)



- The curves are fits of the Monte Carlo data, scaled by $\lambda \sim \langle h_1^u / f_1^u \rangle \sim 0.055$
- Agreement with the measured Collins asymmetry is quite satisfactory

2h asymmetries on p and 3P_0 model for FF

$$A_{UT}^{\sin(\phi_R + \phi_S - \pi)} = \frac{\sum_q e_q^2 h_1^q(x) H_{q \rightarrow h_1 h_2}^{\not{z}}(z, \mathcal{M}_{h_1 h_2}^2)}{\sum_q e_q^2 q(x) D_a^{h_1 h_2}(z, \mathcal{M}_{h_1 h_2}^2)}$$



$$\alpha_P^{u \uparrow \rightarrow h^+ h^- X} = \langle \sin(\phi_R + \phi_S - \pi) \rangle \quad \text{and} \quad \vec{R} = \frac{z_2 \vec{P}_{h_1} - z_1 \vec{P}_{h_2}}{z_1 + z_2} \quad \text{and as before } \lambda \sim \langle h_1^u / f_1^u \rangle \sim 0.055$$

Sivers Asymmetry

$$A_{Siv}(x, z) = \frac{F_{UT}^{\sin\Phi_{Siv}}(x, z)}{F_{UU}(x, z)} = \frac{\sum_q e_q^2 x f_{1T}^{\perp q}(x, k_{\perp}^2) \otimes D_{1q}^h(z, p_{\perp}^2)}{\sum_q e_q^2 x f_1^q(x, k_{\perp}^2) \otimes D_{1q}^h(z, p_{\perp}^2)}$$

- To evaluate it we need to solve the convolutions (i.e. make hypothesis on the transverse momenta dependences of the TMDs)

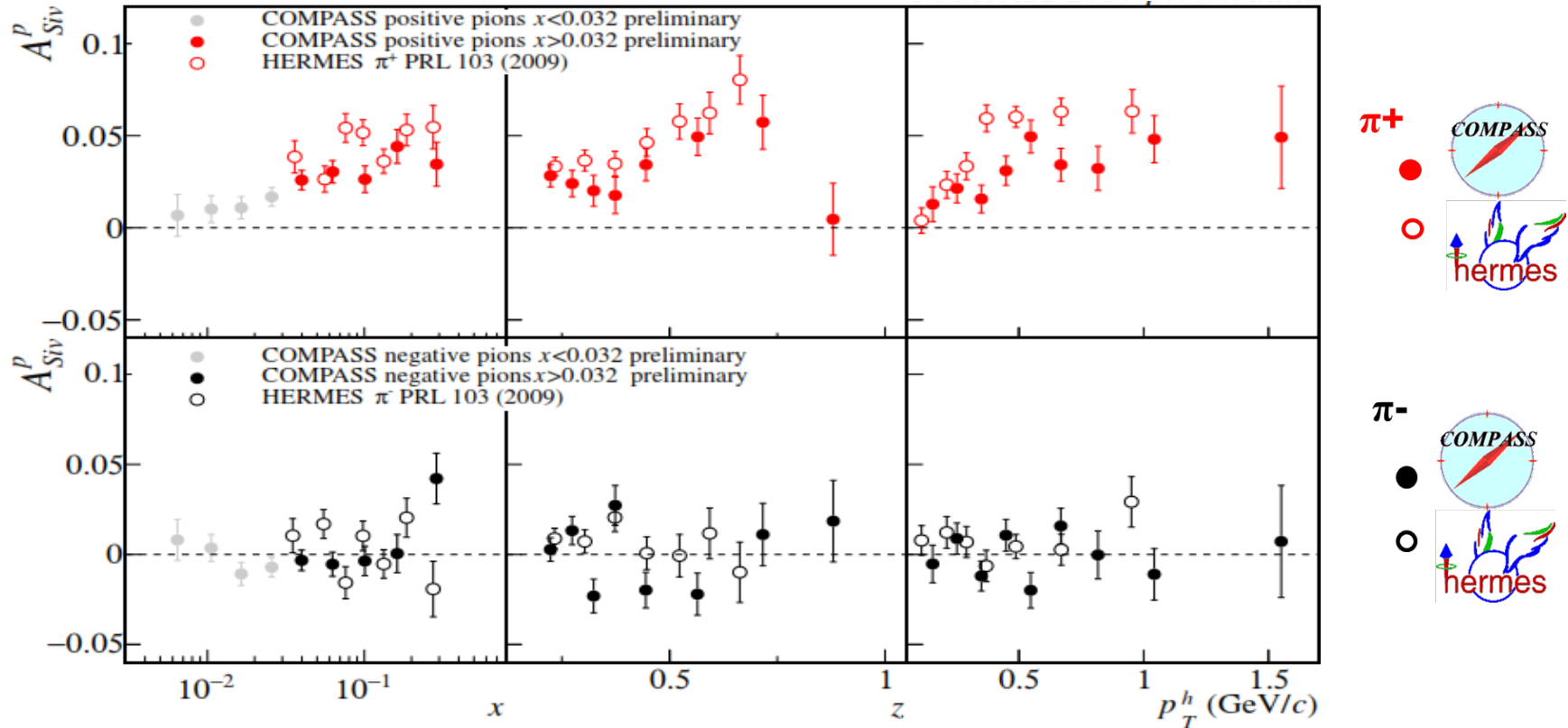
- Gaussian ansatz: $f_{1T}^{\perp q}(x) \frac{e^{-k_{\perp}^2/\langle k_{\perp}^2 \rangle_S}}{\pi \langle k_{\perp}^2 \rangle_S} \quad D_{1q}^h(z) \frac{e^{-p_{\perp}^2/\langle p_{\perp}^2 \rangle}}{\pi \langle p_{\perp}^2 \rangle}$

- Leading to: $A_{Siv,G}(x, z) = \frac{\sqrt{\pi} M}{\sqrt{z^2 \langle k_T^2 \rangle_S + \langle p_T^2 \rangle}} \frac{\sum_q e_q^2 x f_{1T}^{\perp(1)q}(x) z D_{1q}^h(z)}{\sum_q e_q^2 x f_1^q(x) D_{1q}^h(z)}$ with $f_{1T}^{\perp(1)q}(x) =$

$$\int d^2 \vec{k}_T \frac{k_T^2}{2M^2} f_{1T}^{\perp q}(x, k_T^2)$$

Sivers asymmetry on p

charged pions (and kaons), HERMES and COMPASS



The weighted Sivvers asymmetry

- If we **weight** the spin dependent part of the cross-section

$$F_{UT}^{\sin\Phi_{Siv}}(x, z) = \Sigma_q e_q^2 \int d^2\vec{P}_T P_T F_q(x, z, P_T^2)$$

- with $w = P_T/zM$, i.e.

$$F_{UT}^{\sin\Phi_{Siv,w}}(x, z) = \Sigma_q e_q^2 \int d^2\vec{P}_T \frac{P_T^2}{zM} F_q(x, z, P_T^2) = 2 \Sigma_q e_q^2 x f_{1T}^{\perp(1)q}(x) D_{1q}^h(z)$$

and $F_q(x, z, P_T^2) = \int d^2\vec{k}_T \int d^2\vec{p}_T \delta^2(\vec{P}_T - z\vec{k}_T - \vec{p}_T) \frac{\vec{P}_T \cdot \vec{k}_T}{MP_T^2} x f_{1T}^{\perp q}(x, k_T^2) D_{1q}(z, p_T^2)$

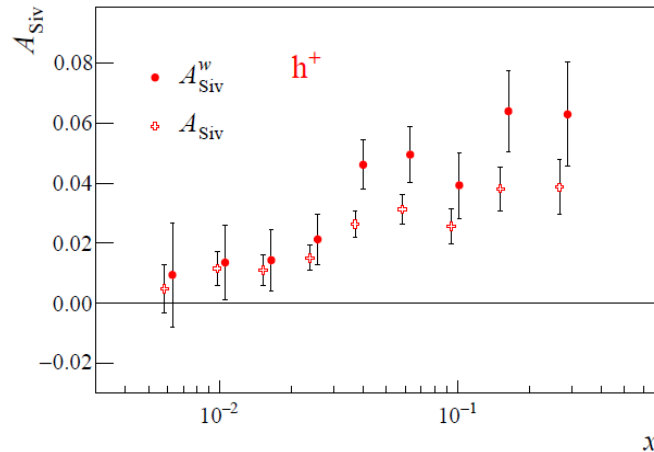
- we have no longer a convolution but a product of two integrals and we can write

$$A_{Siv}^w(x, z) = \frac{F_{UT}^{\sin\Phi_{Siv,w}}(x, z)}{F_{UU}(x, z)} = 2 \frac{\Sigma_q e_q^2 x f_{1T}^{\perp(1)q}(x) D_{1q}^h(z)}{\Sigma_q e_q^2 x f_1^q(x) D_{1q}^h(z)}$$

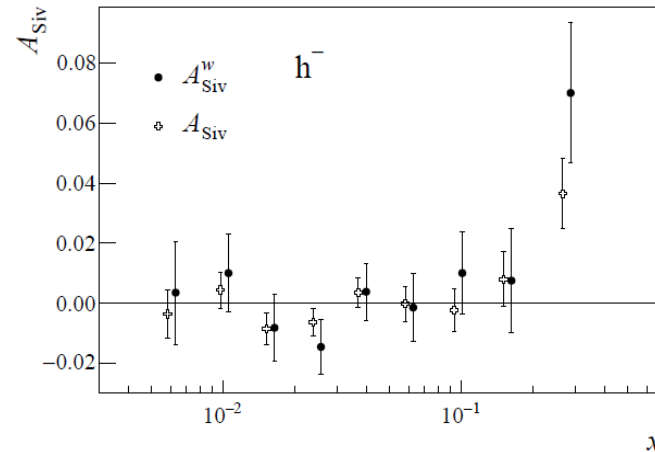
with $f_{1T}^{\perp(1)q}(x) = \int d^2\vec{k}_T \frac{k_T^2}{2M^2} f_{1T}^{\perp q}(x, k_T^2)$

The weighted Siverts asymmetry

$$A_{Siv}^w(x) = 2 \frac{\sum_q e_q^2 x f_{1T}^{\perp(1)q}(x) \int D_{1q}^h(z) dz}{\sum_q e_q^2 x f_1^q(x) \int D_{1q}^h(z) dz} \quad w = P_T/zM \quad \text{standard cuts } z > 0.2$$



$$\sim 2 \frac{f_{1T}^{\perp(1)u}(x)}{f_1^u(x)}$$

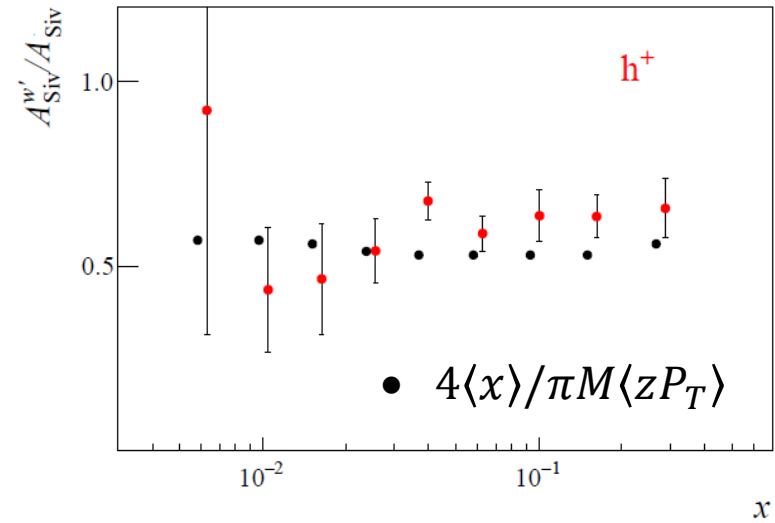
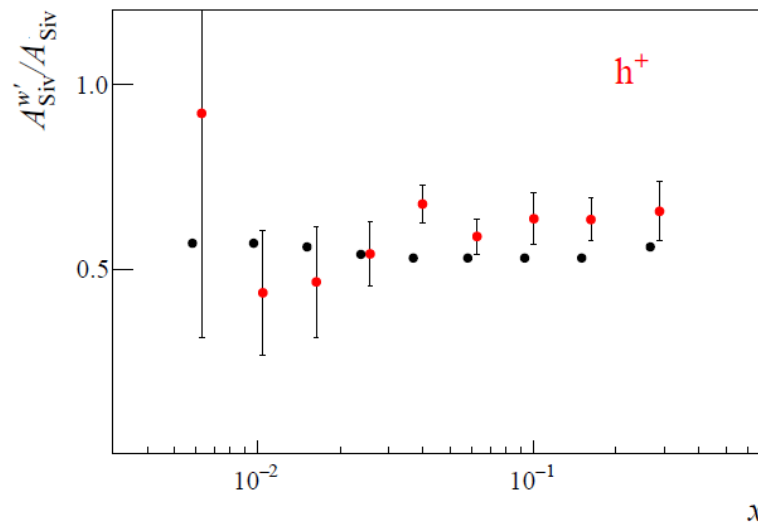


both $f_{1T}^{\perp(1)u}$ and $f_{1T}^{\perp(1)d}$ contribute

The weighted Sivvers asymmetry

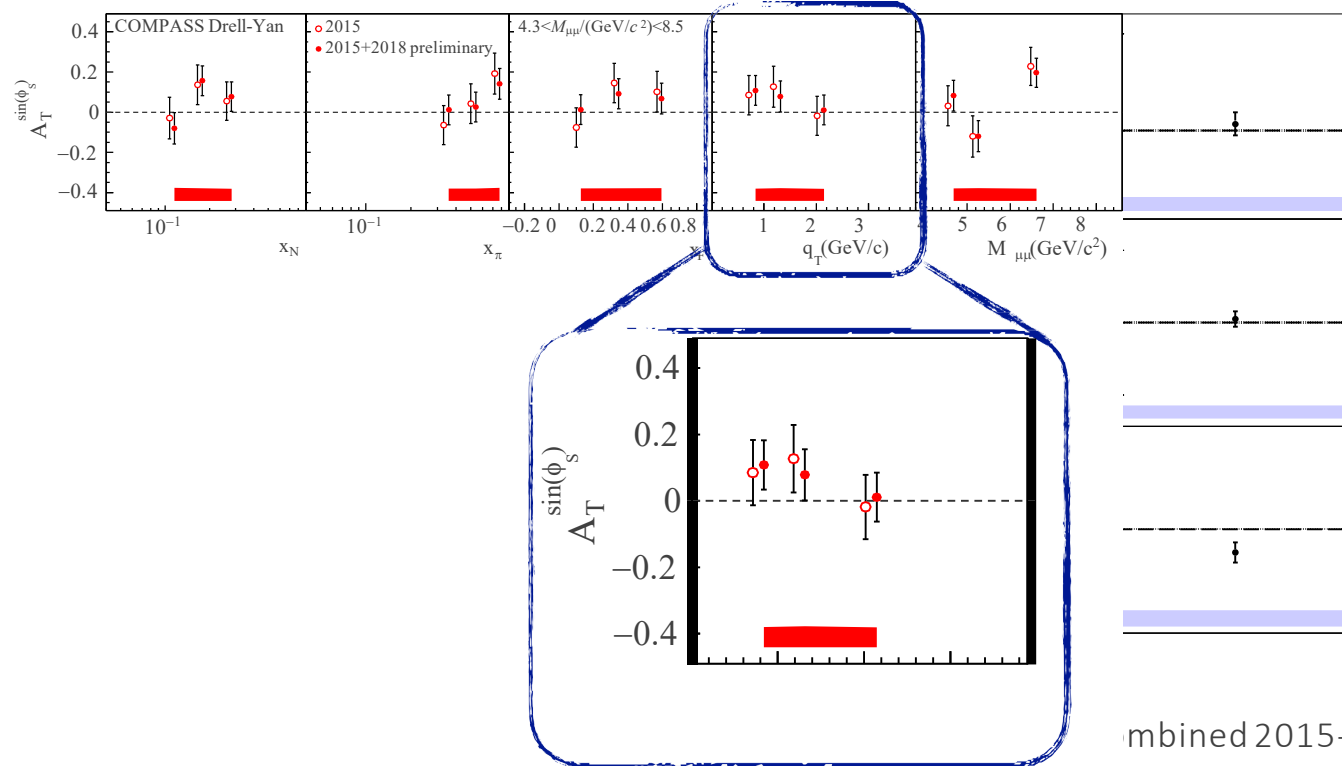
$$A_{Siv}^w(x) = 2 \frac{\sum_q e_q^2 x f_{1T}^{\perp(1)q}(x) \int D_{1q}^h(z) dz}{\sum_q e_q^2 x f_1^q(x) \int D_{1q}^h(z) dz} \quad w = P_T/zM$$

standard cuts
z>0.2



The ratio between weighted and unweighted Sivvers asymmetries follows the average of $4\langle x \rangle / \pi M \langle z P_T \rangle$ of the unpolarised sample

q_T weighted asymmetries: 2015+2018



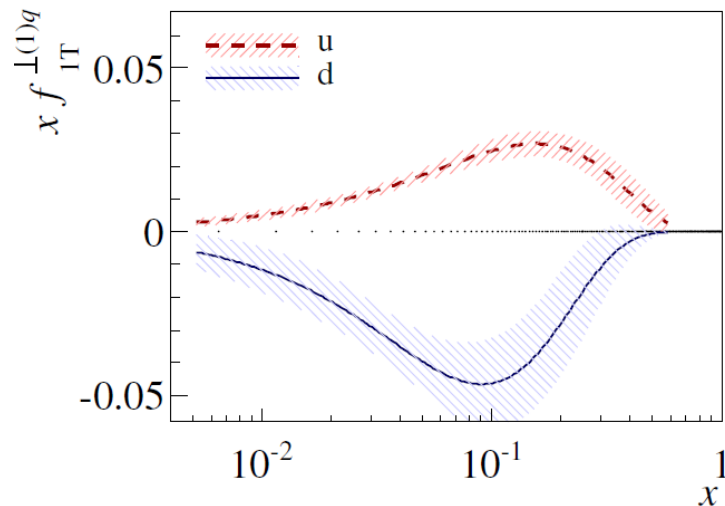
Combined 2015-2018

Drell-Yan data samples. For 2015, only 9% of the data have been used.

- Additional uncertainties of about 5% from the polarization and 8% from dilution factor calculation have to be added to the systematic errors.

Weighted asymmetries: from SIDIS to DY

1st k_{\perp}^2 -moment of the Sivers function from SIDIS data at $Q_{SIDIS}^2(x)$



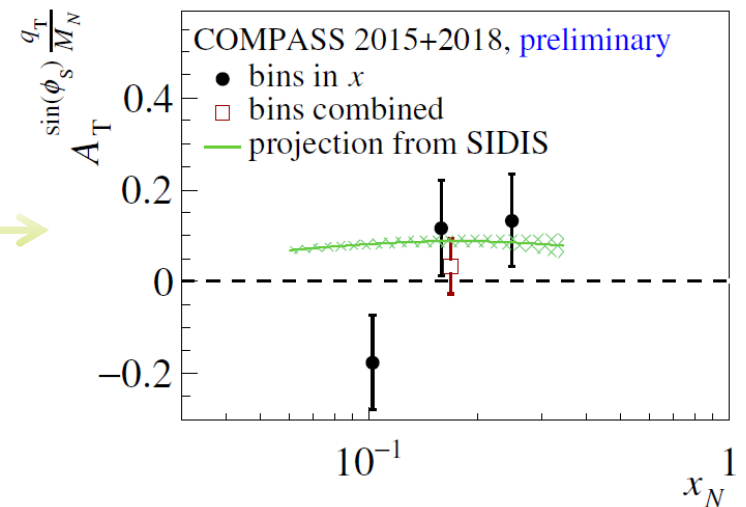
Assuming:

- u -dominance

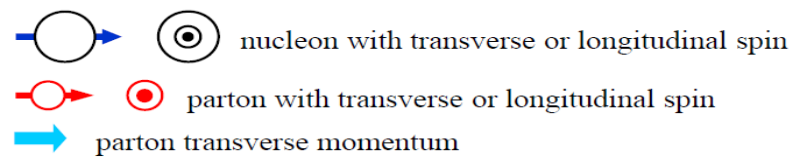
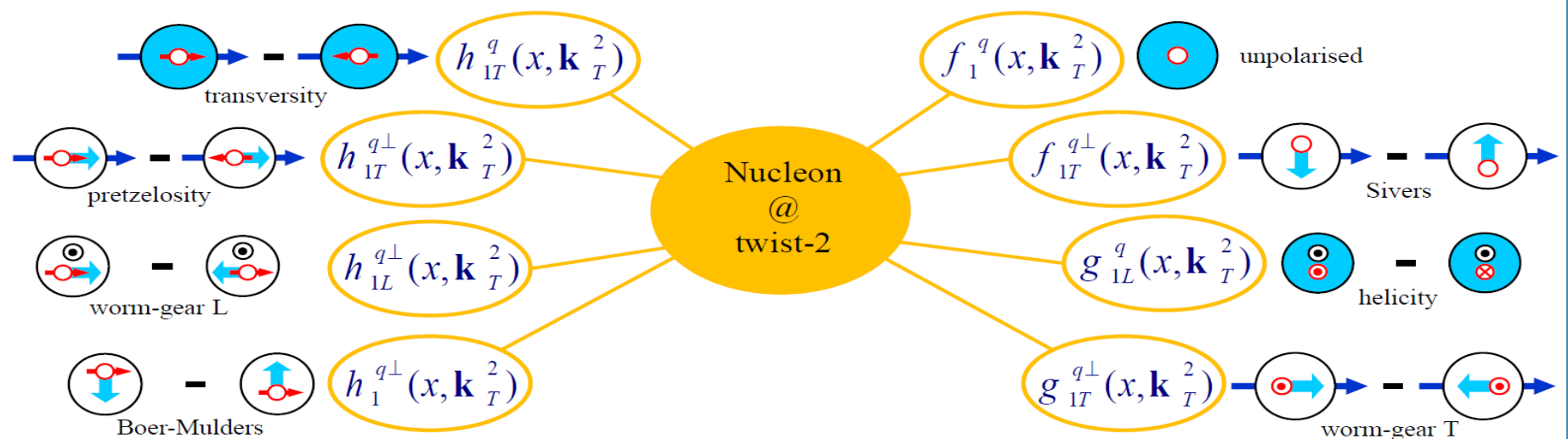
$$A_T^{\sin(\phi_s) \frac{q_T}{M_N}} \sim \frac{f_{1T}^{\perp(1)u}}{f_1^u}$$

- Same Q^2 for SIDIS and DY

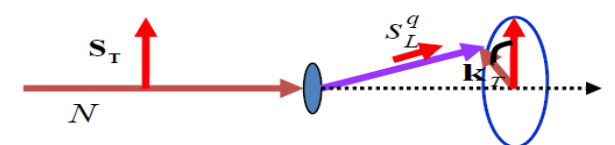
- Sine change $f_{1T}^{\perp(1)u} \Big|_{DY} = f_{1T}^{\perp(1)u} \Big|_{DIS}$



TMD Distribution Functions



Proton goes out of the screen. Photon goes into the screen



\mathbf{k}_T – intrinsic transverse momentum of the quark

From Collins asymmetries to transversity

- Following Physical Review D 91, 014034 (2015), in the valence region

$$xh_1^u = \frac{1}{5} \frac{1}{\tilde{\alpha}_p^h (1 - \tilde{\alpha})} \left[(xf_p^+ A_p^+ - xf_p^- A_p^-) + \frac{1}{3} (xf_d^+ A_d^+ - xf_d^- A_d^-) \right]$$

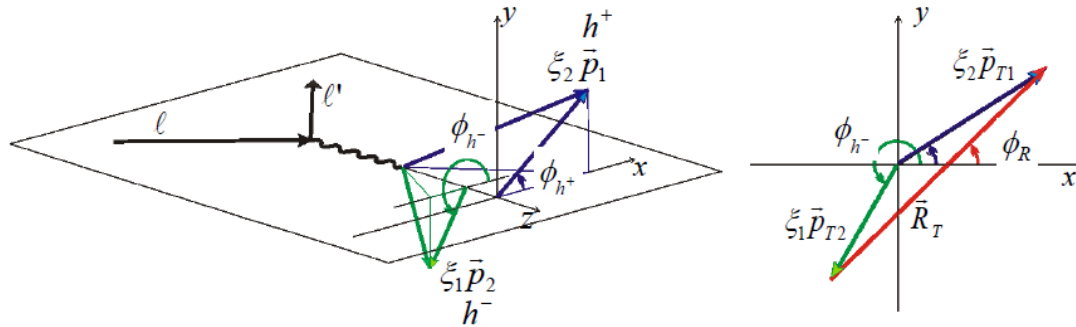
$$xh_1^d = \frac{1}{5} \frac{1}{\tilde{\alpha}_p^h (1 - \tilde{\alpha})} \left[\frac{4}{3} (xf_d^+ A_d^+ - xf_d^- A_d^-) - (xf_p^+ A_p^+ - xf_p^- A_p^-) \right]$$

With $\tilde{\alpha}_p^h$ and $\tilde{\alpha}$ constants

$$\pi^+ \text{ in } p: f_p^+ = 4 \left(f_1^u + \frac{\tilde{D}_{unf}}{\tilde{D}_f} f_1^{\bar{u}} \right) + \left(\frac{\tilde{D}_{unf}}{\tilde{D}_f} f_1^d + f_1^{\bar{d}} \right) + \frac{\tilde{D}_{unf}}{\tilde{D}_f} (f_1^s + f_1^{\bar{s}})$$

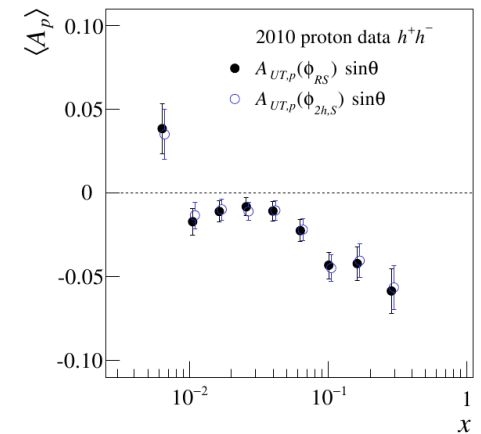
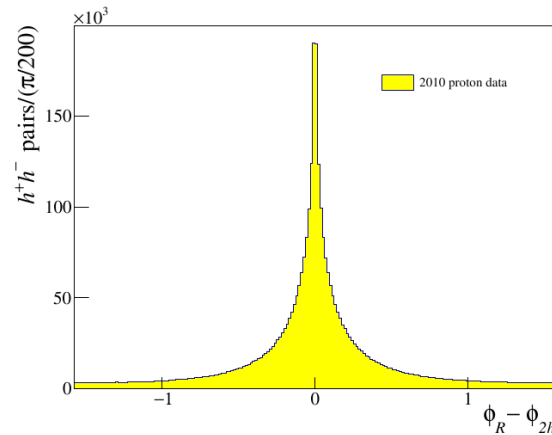
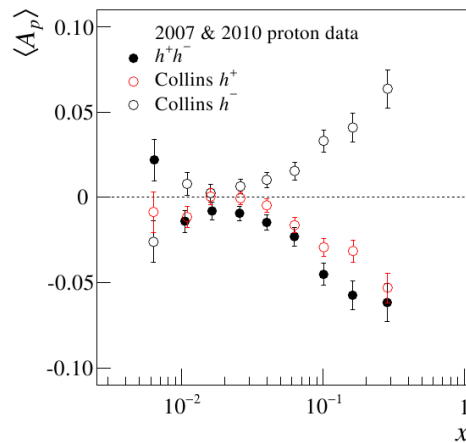
$$\pi^- \text{ in } p: f_p^+ = 4 \left(\frac{\tilde{D}_{unf}}{\tilde{D}_f} f_1^u + f_1^{\bar{u}} \right) + \left(f_1^d + \frac{\tilde{D}_{unf}}{\tilde{D}_f} f_1^{\bar{d}} \right) + \frac{\tilde{D}_{unf}}{\tilde{D}_f} (f_1^s + f_1^{\bar{s}})$$

Hadron correlations

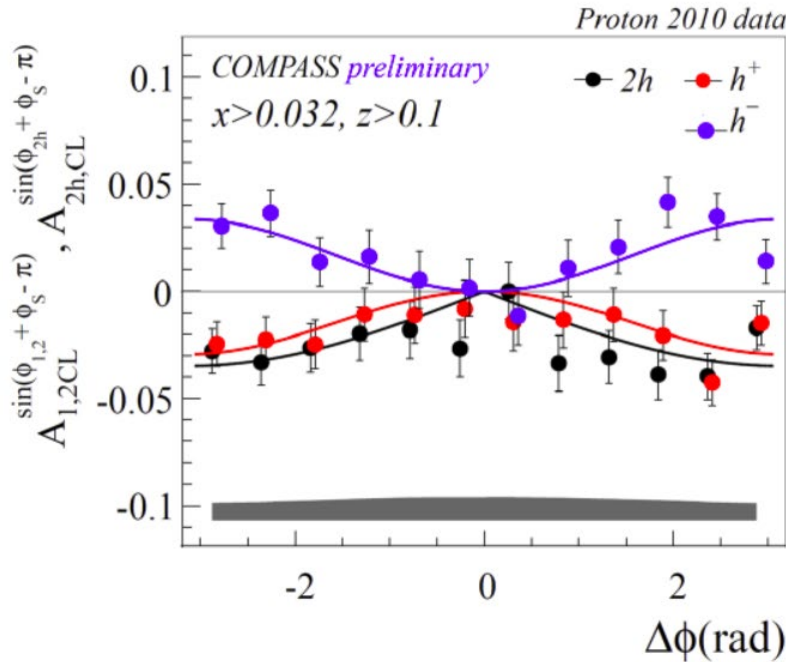


Interplay between Collins and IFF asymmetries

common hadron sample for Collins and 2h analysis



Asymmetries for $x > 0.032$ vs $\Delta\phi = \phi_{h^+} - \phi_{h^-}$



— $a \sqrt{2(1 - \cos \Delta\phi)}$
 — $a (1 - \cos \Delta\phi)$
 — $a (1 - \cos \Delta\phi)$

$a = -0.017 \pm 0.002, \chi^2/\text{n.d.f.} = 0.98$

$a = -0.015 \pm 0.003, \chi^2/\text{n.d.f.} = 0.65$

$a = 0.017 \pm 0.003, \chi^2/\text{n.d.f.} = 0.80$

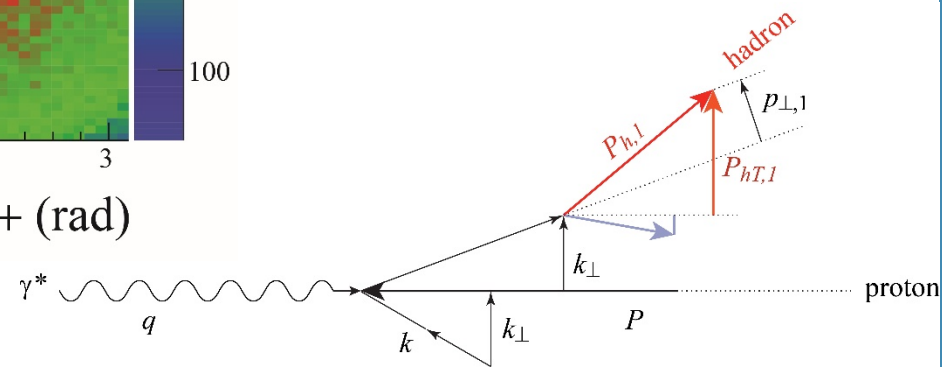
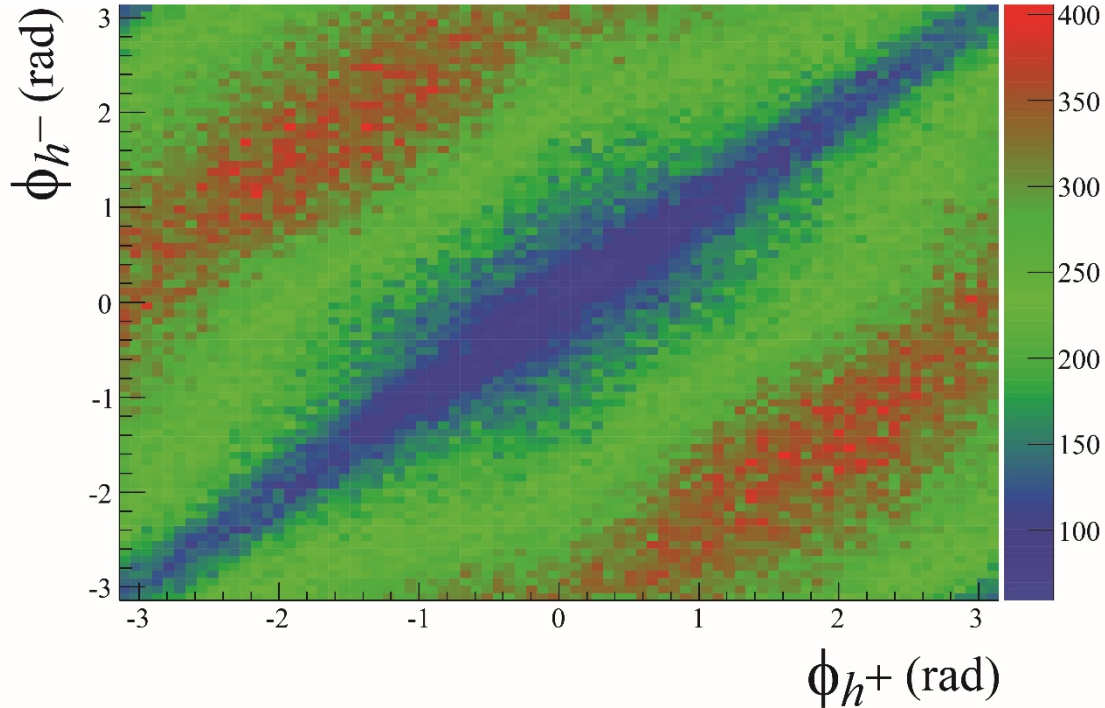
$$a = \frac{\sigma_{1C}^{h^+h^-}(\Delta\phi)}{\sigma_U(\Delta\phi)}$$

$$= - \frac{\sigma_{2C}^{h^+h^-}(\Delta\phi)}{\sigma_U(\Delta\phi)}$$

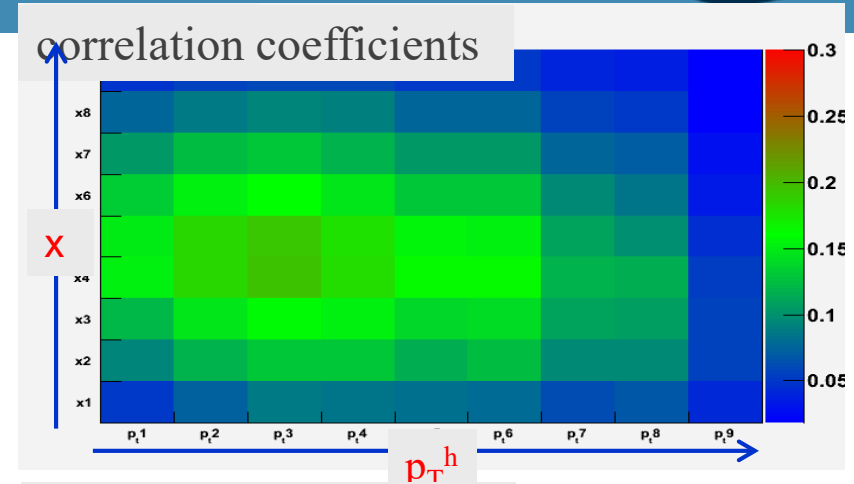
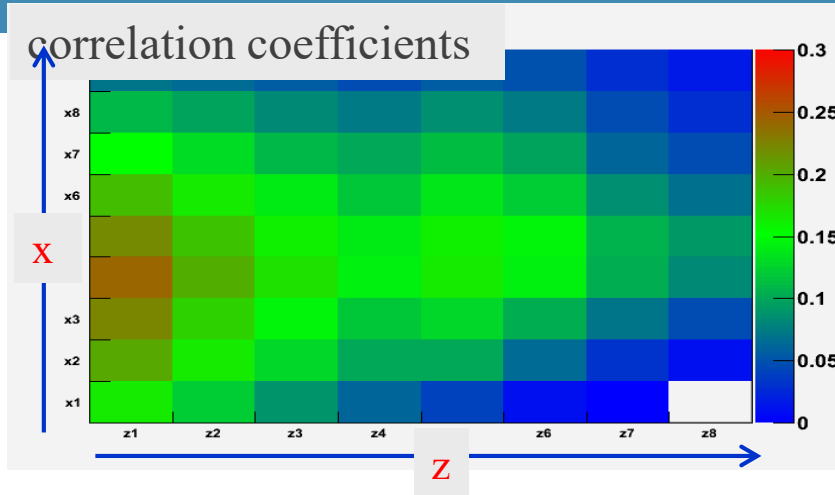
ratio of the integrals compatible with $4/\pi$

Hints for a common origin of 1h
and 2h mechanisms

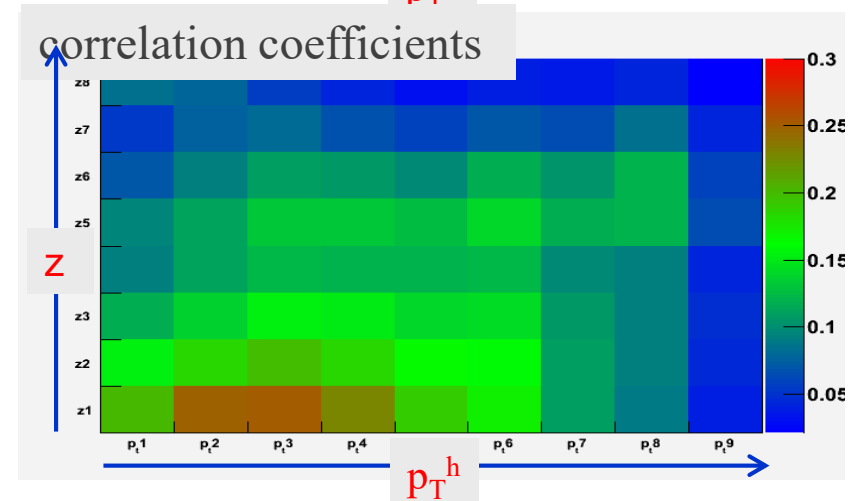
Is correlation having an impact?



Statistical correlations

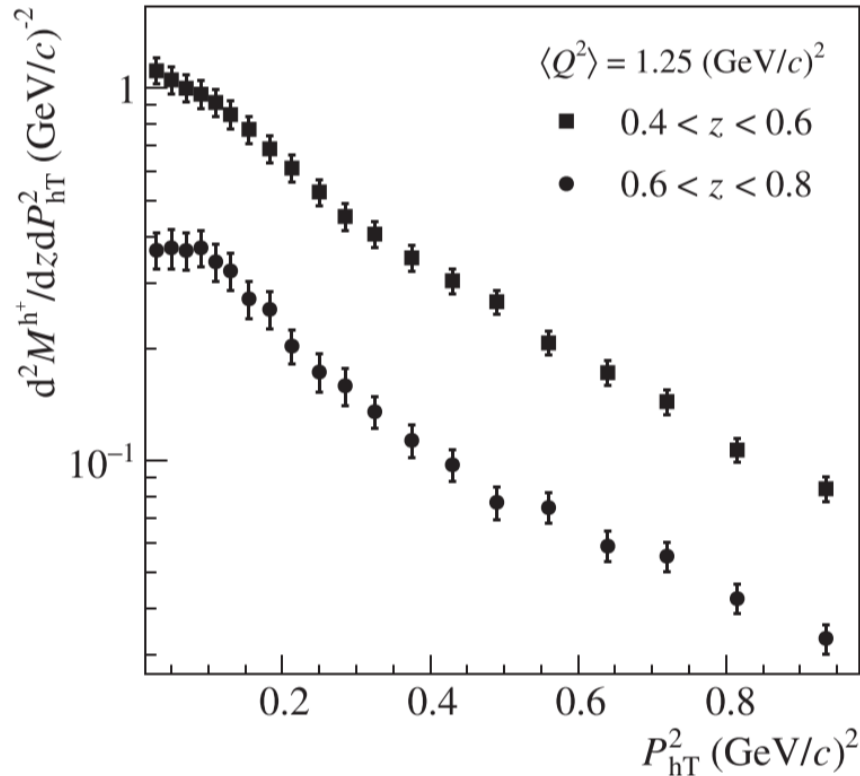


charged pions
 also available for
 charged hadrons
 charged kaons
 have to be taken into account

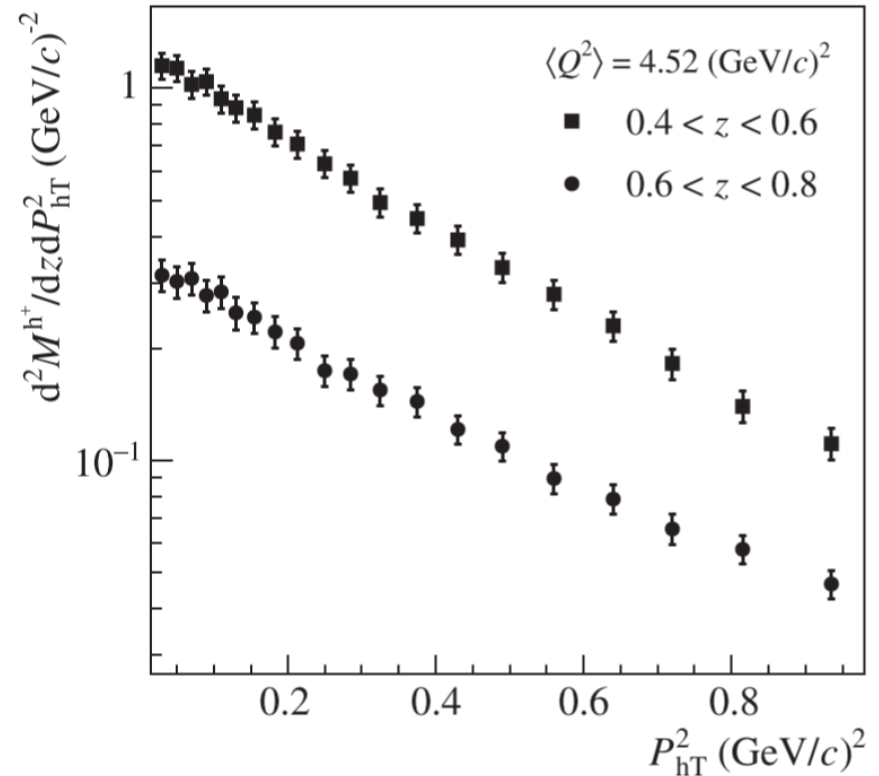


Low P_{hT} behavior

$\langle x \rangle = 0.006$



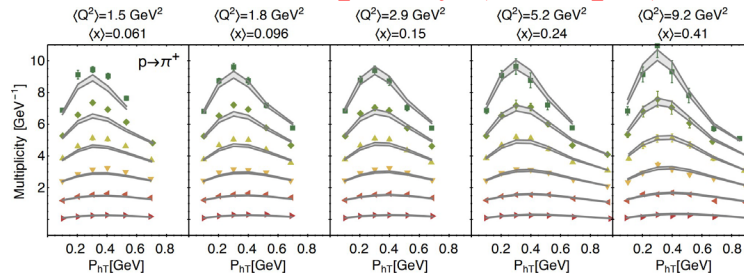
$\langle x \rangle = 0.043$



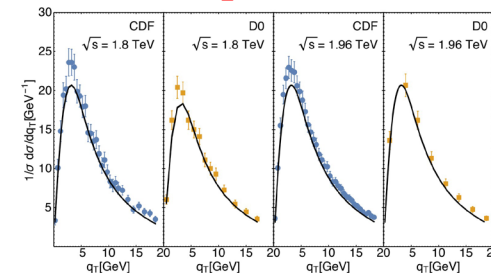
Global Analysis: Unpolarized TMD

Global analysis of semi-inclusive DIS, Drell-Yan and Z production data with TMD evolution

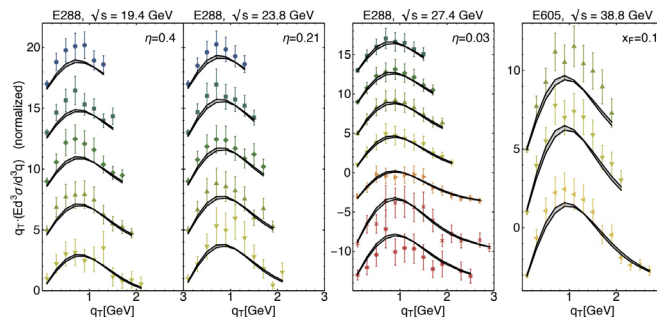
SIDIS multiplicity (example)



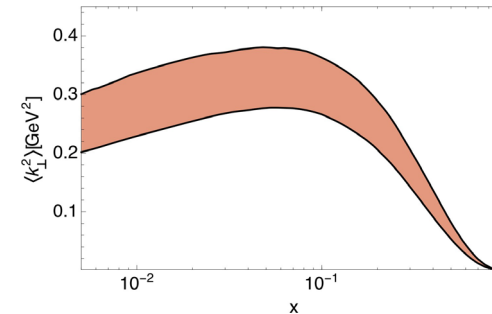
Z production



Drell-Yan cross section

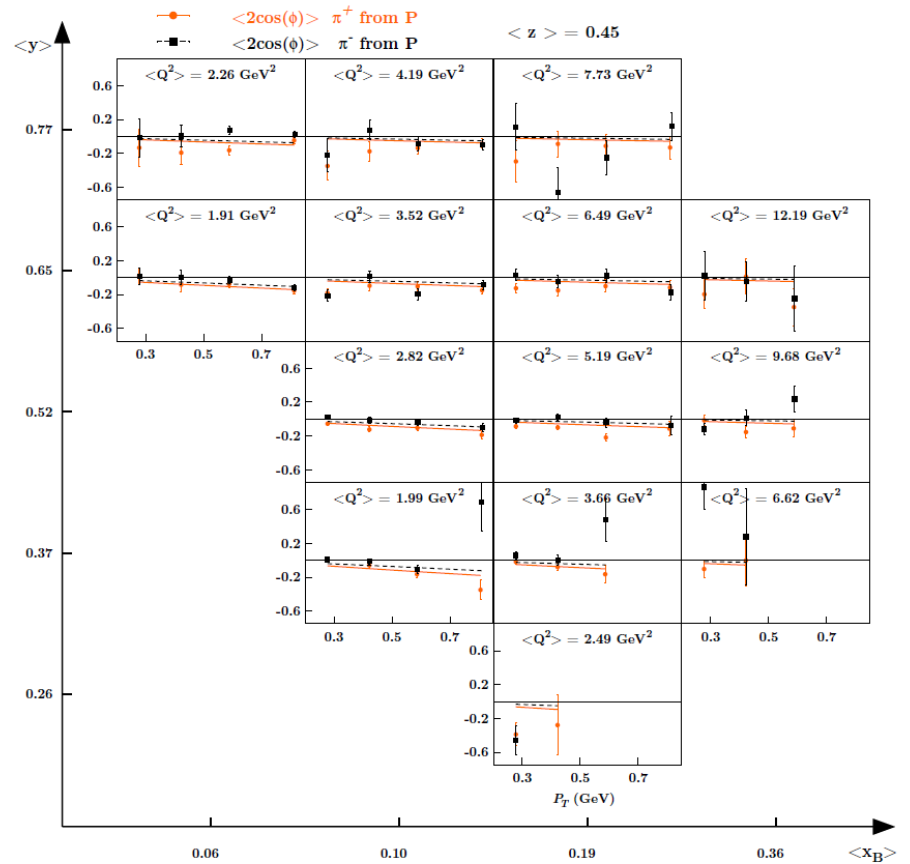
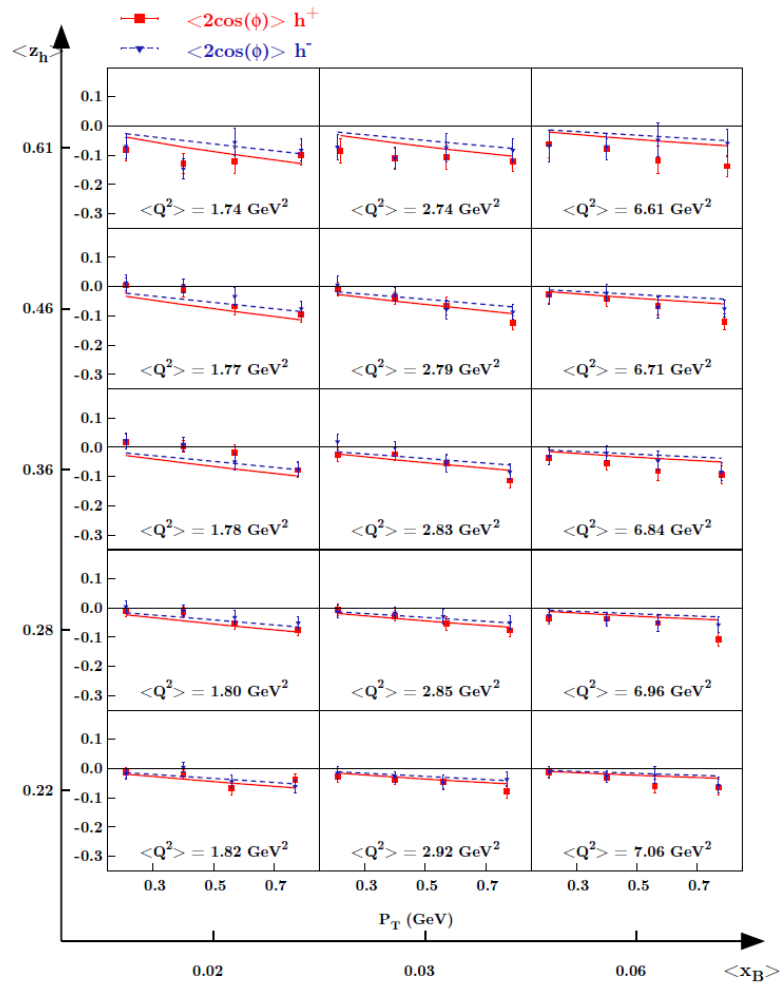


Transverse momentum distribution

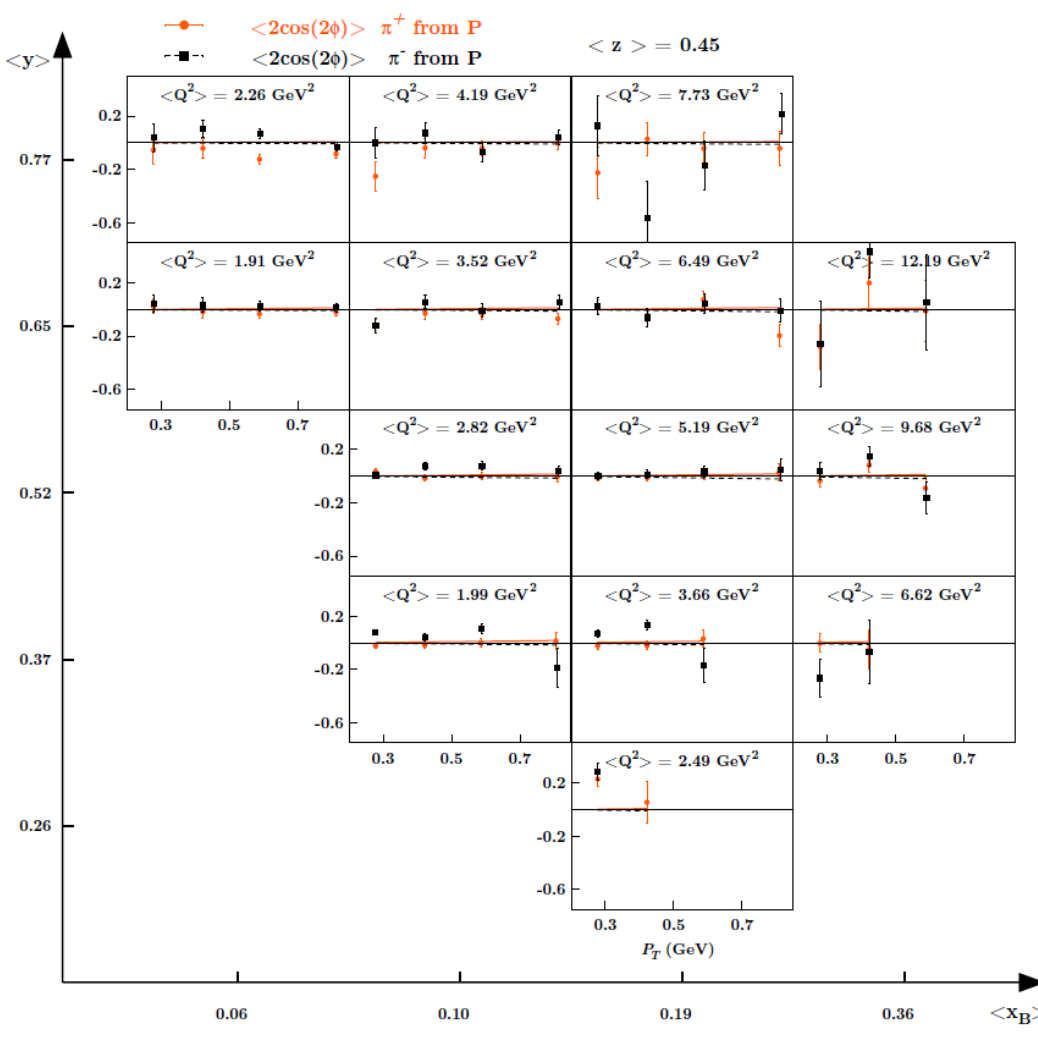
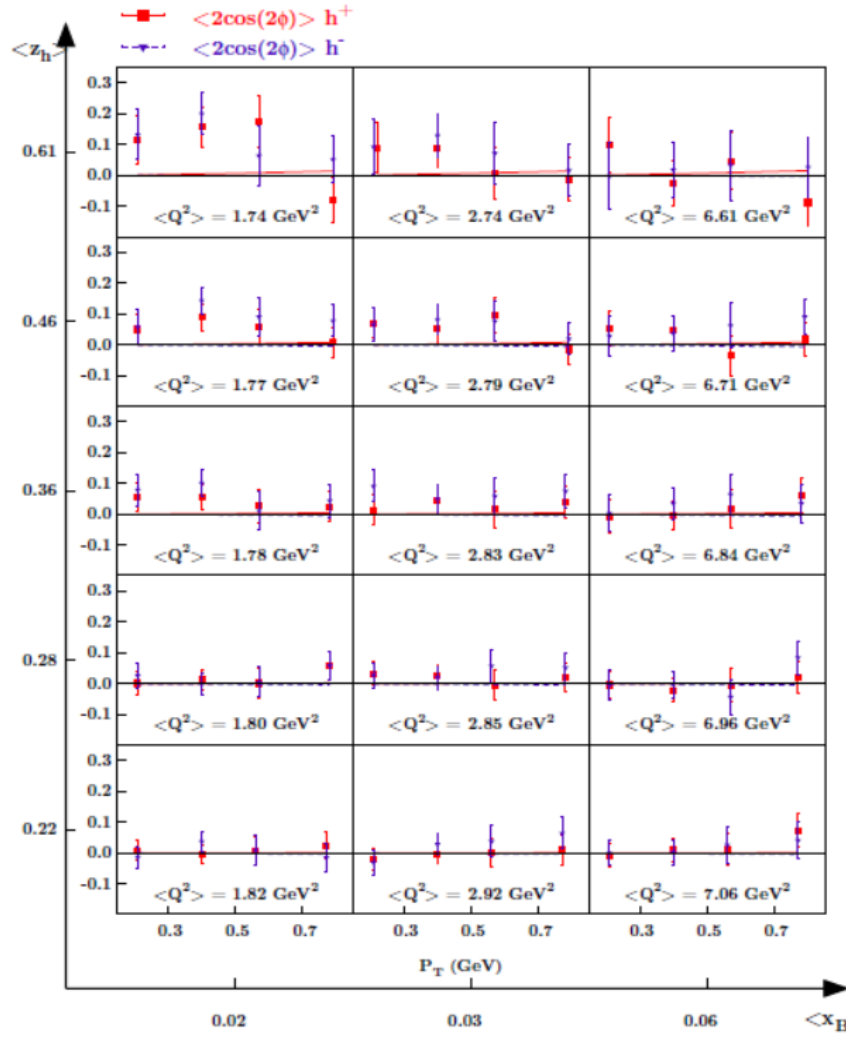


A. Bacchetta *et al.*, J. High Energy Phys. 06 (2017) 081.

cos ϕ modulation



Boer-Mulders in $\cos 2\phi$ and in $\cos \phi$



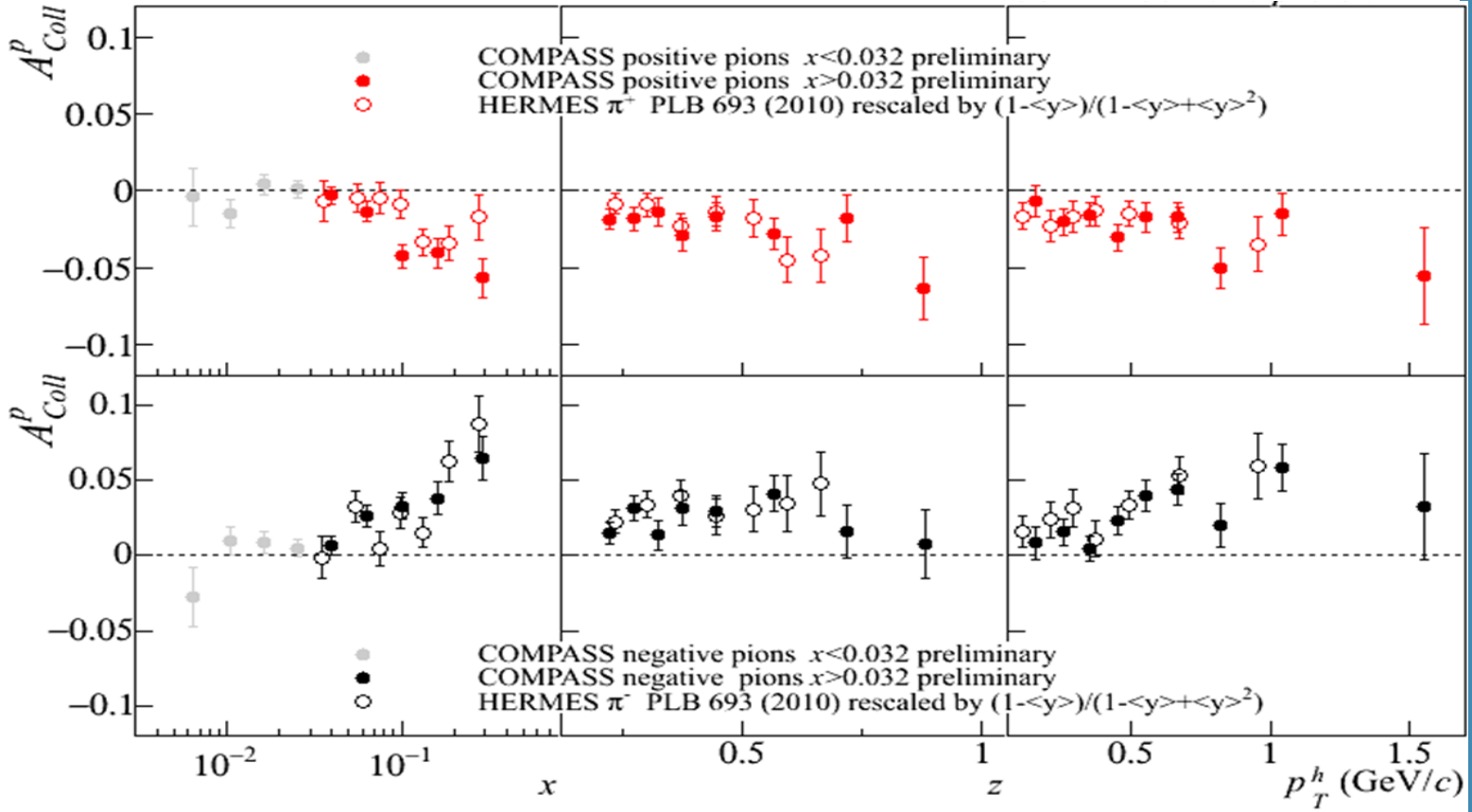
Collins asymmetry on proton

$x > 0.032$ region

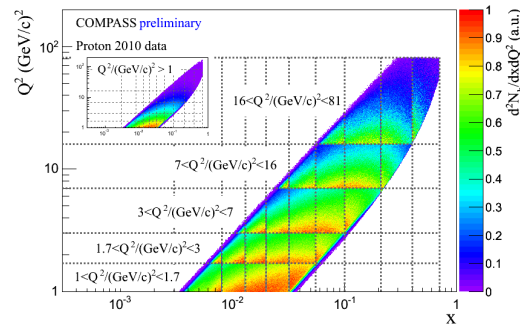
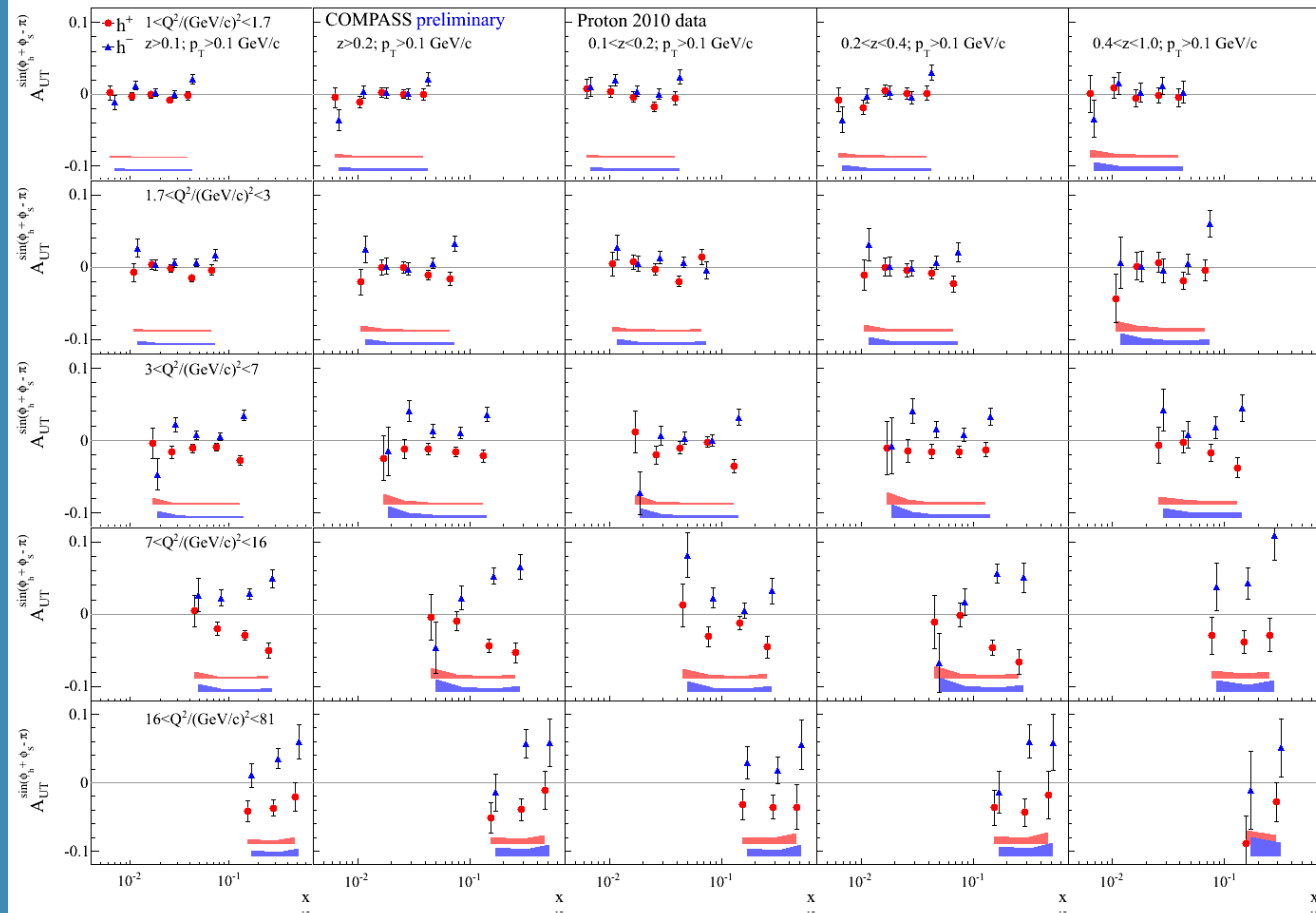


charged pions

COMPASS and HERMES results



Collins asymmetry on proton. Multidimensional Extraction of TSAs with a Multi-D ($x: Q^2: z: p_T$) approach



One dense plot out of many

