NINETEENTH LOMONOSOV CONFERENCE ON ELEMENTARY PARTICLE PHYSICS

August, 22-28, 2019

MOSCOW STATE UNIVERSITY

The COMPASS experiment at CERN

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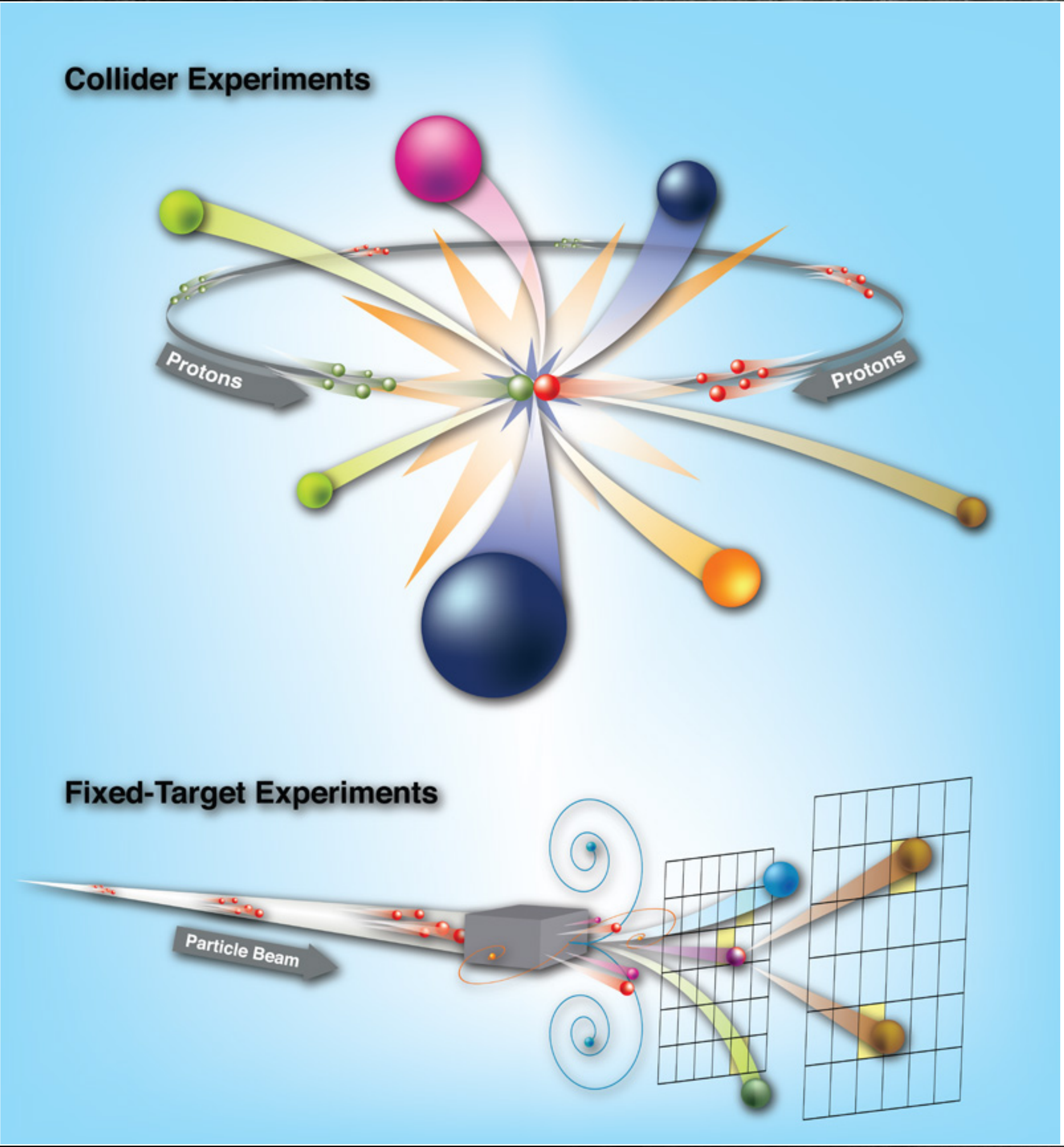
on behalf of the COMPASS collaboration

COMPASS

Moscow, 24.09.2019

JINR

Fixed-target experiments in the LHC era



High energy

High luminosity

Beams of unstable particles

COMPASS at CERN

The COMPASS experiment

COMPASS (COmmon Muon Proton Apparatus for Structure and Spectroscopy)

is a fixed target experiment on a secondary beam of Super Proton Synchrotron at CERN

13 countries,
24 institutions,
~220 physicists

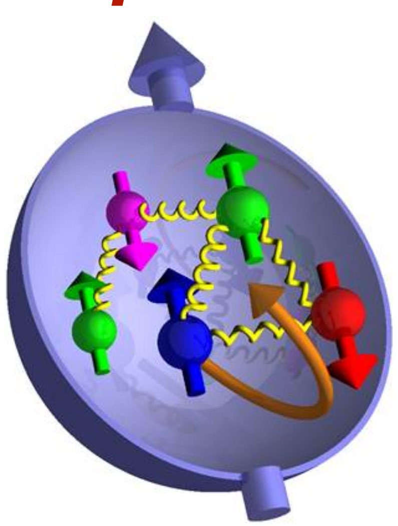
1996 - Proposal
2002-now - Physical data taking

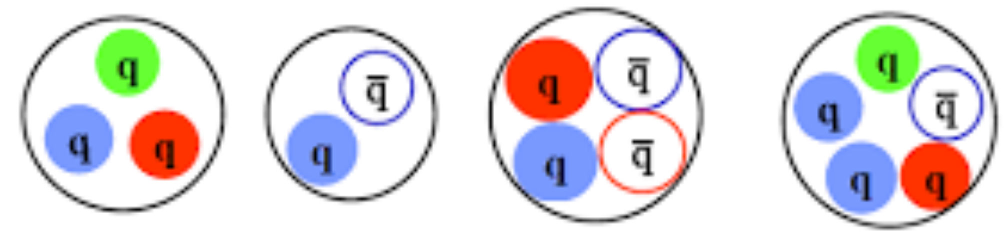
Main points of physics programme

COMPASS ≈ SPIN PHYSICS + SPECTROSCOPY

Study of spin structure of nucleon with muon and pion beam and polarized target:

- *(un)polarized and Transverse Momentum Dependent (TMD) PDFs and FFs*
- *Generalized PDFs*
- *TMD PDFs via Drell-Yan process*





baryon meson tetraquark pentaquark

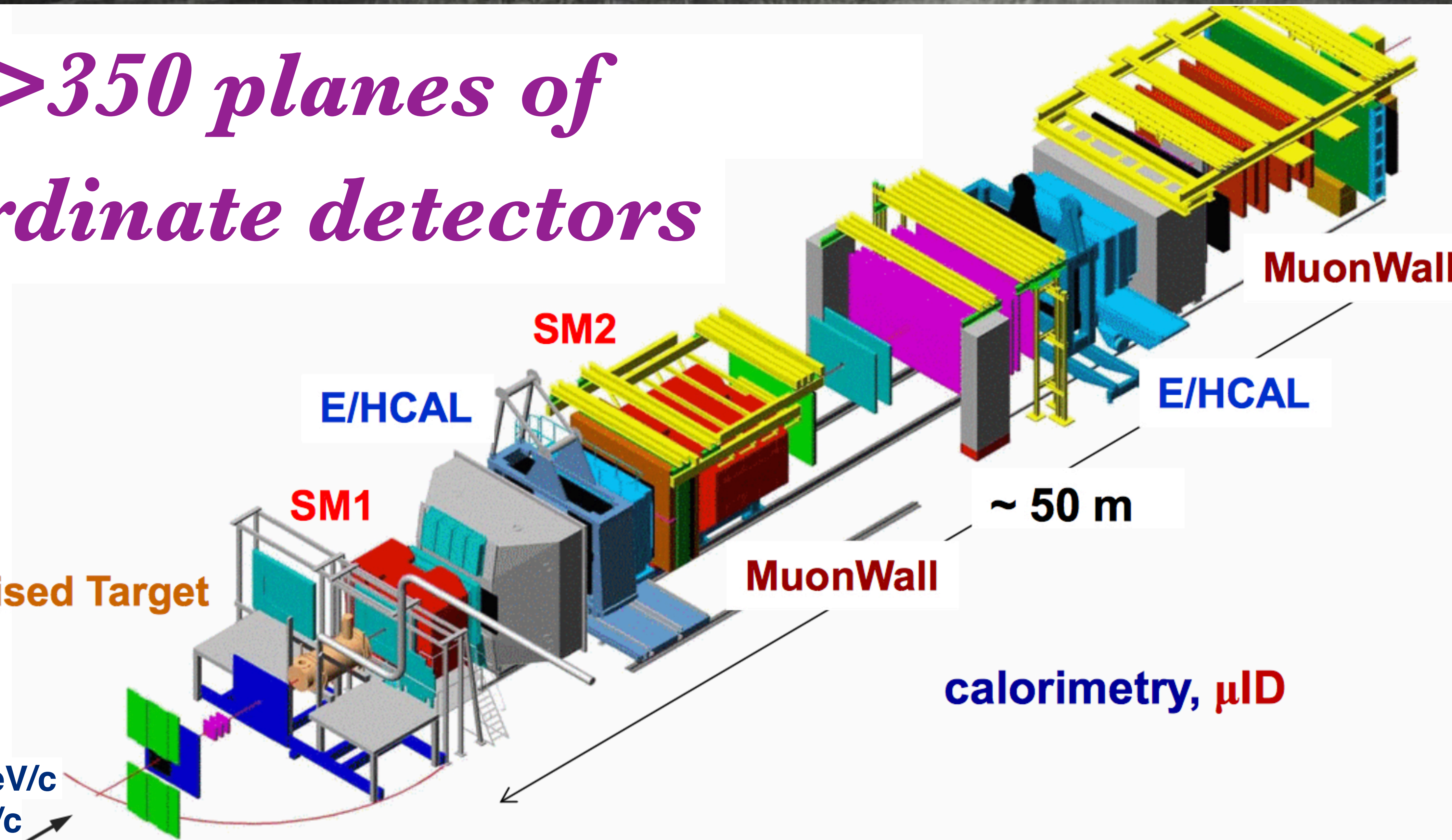
baryonium hybrid glueball

Hadron spectroscopy and tests of Chiral Perturbation Theory predictions:

- *Primakoff, diffractive and central production of light hadrons*
- *Dynamics of Primakoff cross sections, pion polarizability*
- *Muoproduction of charmonium-like states*

The COMPASS setup

>350 planes of coordinate detectors



Configuration of the beam and target region depends on the particular physics programme

COMPASS history and future

Year	Beam	Target	Physics
2002	muon, 160 GeV/c	^{6}LiD	SIDIS
2003	muon, 160 GeV/c	^{6}LiD	SIDIS
2004	muon, 160 GeV/c	^{6}LiD	SIDIS
2006	muon, 160 GeV/c	^{6}LiD	SIDIS
2007	muon, 160 GeV/c	NH_3	SIDIS
2008	hadron, 190 GeV/c	LH_2	Spectroscopy
2009	hadron, 190 GeV/c	LH_2, Ni, W, Pb	Spectroscopy, Primakoff
2010	muon, 160 GeV/c	NH_3	SIDIS
2011	muon, 200 GeV/c	NH_3	SIDIS
2012	hadron, 190 GeV/c	Ni, C, W, Pb	Primakoff, Spectroscopy
	muon, 160 GeV/c	LH_2	DVCS
2014	hadron, 190 GeV/c	NH_3	Drell-Yan
2015	hadron, 190 GeV/c	NH_3	Drell-Yan
2016	muon, 160 GeV/c	LH_2	DVCS
2017	muon, 160 GeV/c	LH_2	DVCS
2018	hadron, 190 GeV/c	NH_3	Drell-Yan
2021	muon, 160 GeV/c	^{6}LiD	SIDIS
2022			

COMPASS

Phase I

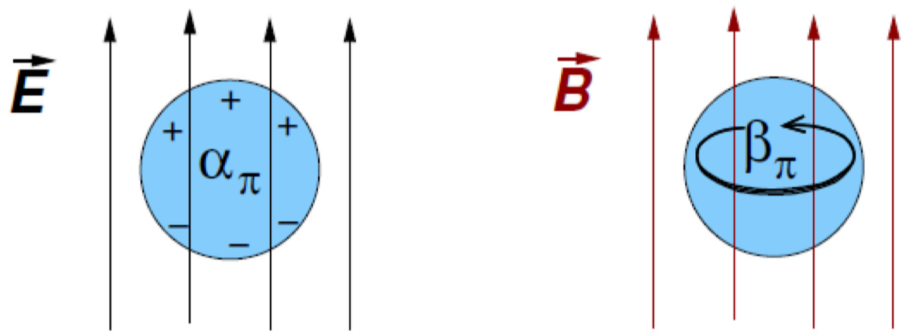
Phase II

We are there

COMPASS++/AMBER

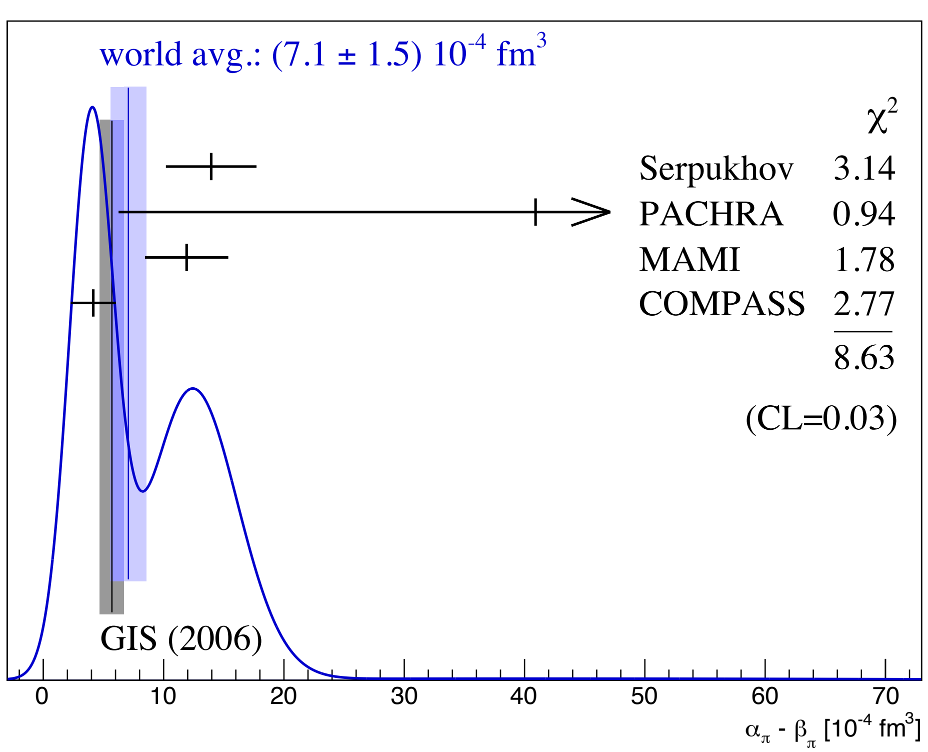
Pion polarizability

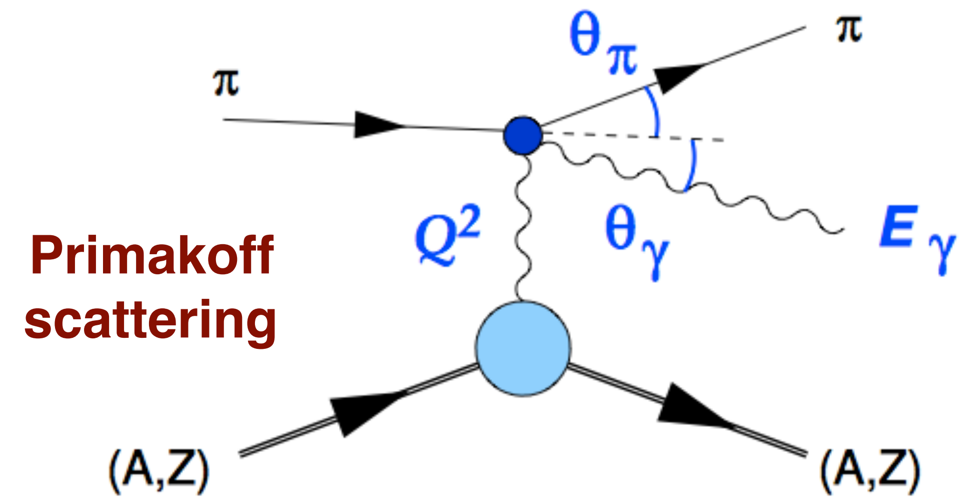
in classical electrodynamics



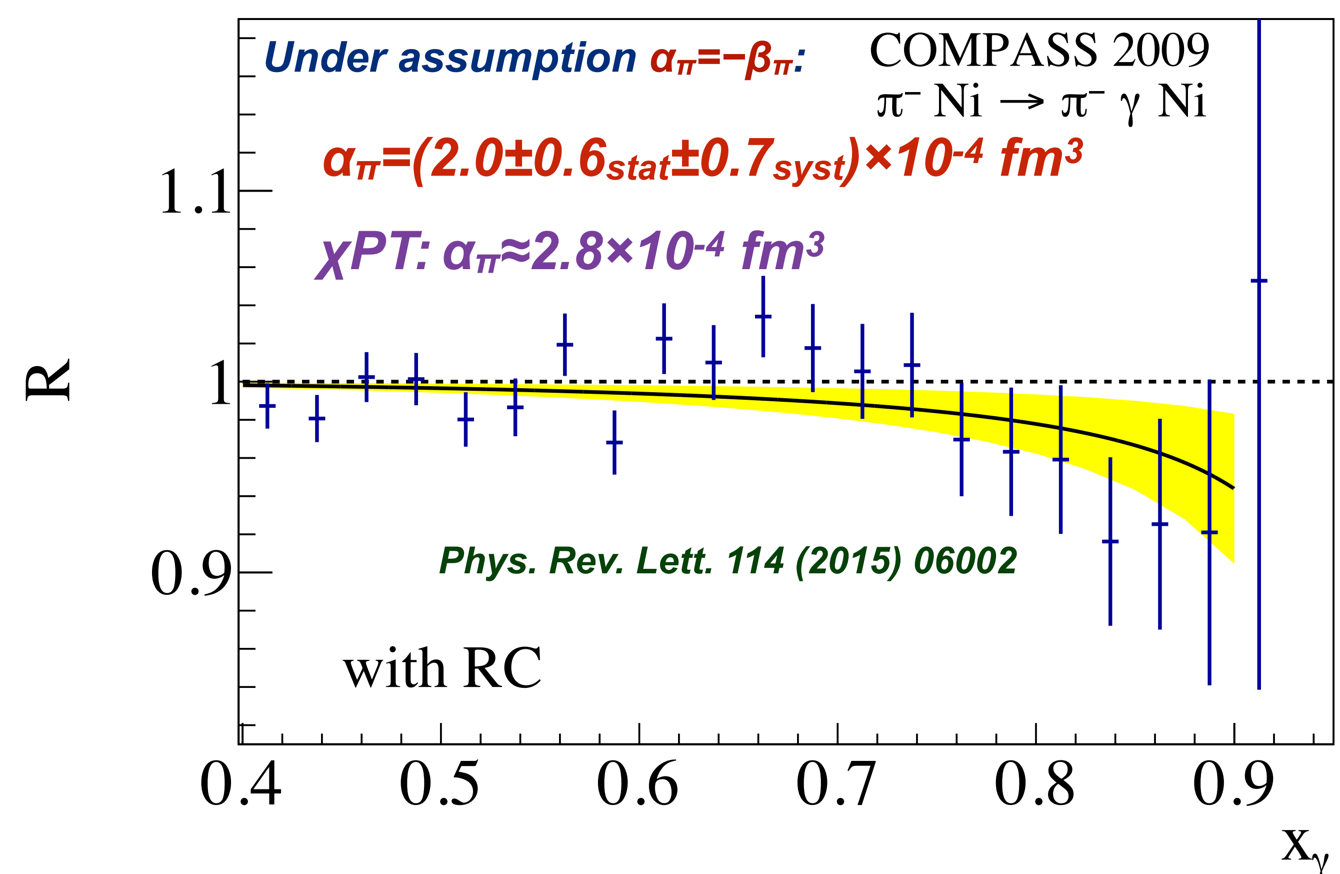
in QED

$$A(\gamma X \to \gamma X) =$$
$$(-\frac{\alpha}{m}\delta_{o\pm} + \alpha_X \omega_1\omega_2)\hat{e}_1 \cdot \hat{e}_2 +$$
$$+\beta_X \omega_1\omega_2(\hat{e}_1 \times \hat{q}_1)(\hat{e}_2 \times \hat{q}_2) + \ldots$$





$$\mathbf{R} = \frac{\sigma}{\sigma_{\mathbf{p.l.}}} \approx \mathbf{1} - \frac{\mathbf{3}}{\mathbf{2}} \cdot \frac{\mathbf{x}_\gamma^2}{\mathbf{1}-\mathbf{x}_\gamma} \cdot \frac{\mathbf{m}_\pi^3}{\alpha} \cdot \alpha_\pi$$
$$x_\gamma = E_\gamma / E_{beam}$$



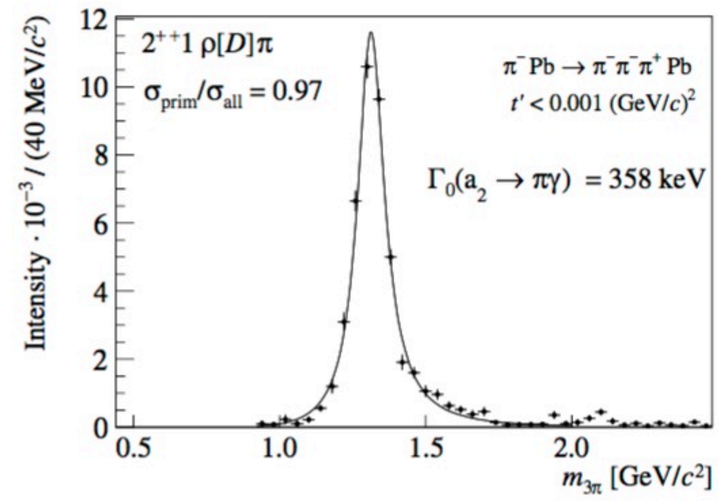
Radiative widths of mesons and chiral dynamics of cross sections

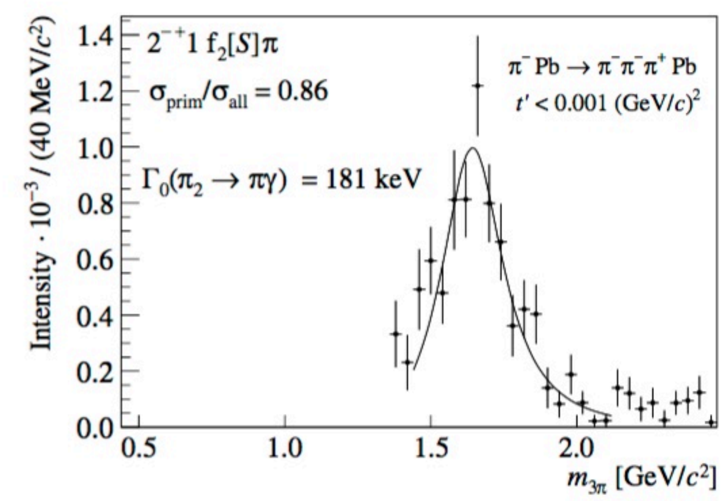
$a_2(1320)^- \to \pi^-\gamma$

$\pi_2(1670)^- \to \pi^-\gamma$

$\pi^-\gamma \to a_2(1320)^- \to \pi^-\pi^+\pi^-$

$\pi^-\gamma \to \pi_2(1670)^- \to \pi^-\pi^+\pi^-$





	$a_2(1320)$	$\pi_2(1670)$
This measurement	$(358 \pm 6 \pm 42)$ keV	$(181 \pm 11 \pm 27)$ keV $\cdot\ (0.56/BR_{f_2\pi})$
SELEX [21]	$(284 \pm 25 \pm 25)$ keV	
S. Cihangir *et al.* [24]	(295 ± 60) keV	
E.N. May *et al.* [25]	(0.46 ± 0.11) MeV	
VMD model [1]	(375 ± 50) keV	
Relativ. Quark model [2]	324 keV	
Cov. Osc. Quark model [3]	235 keV	
Cov. Osc. Quark model [4]	237 keV	2 values: 335 keV and 521 keV

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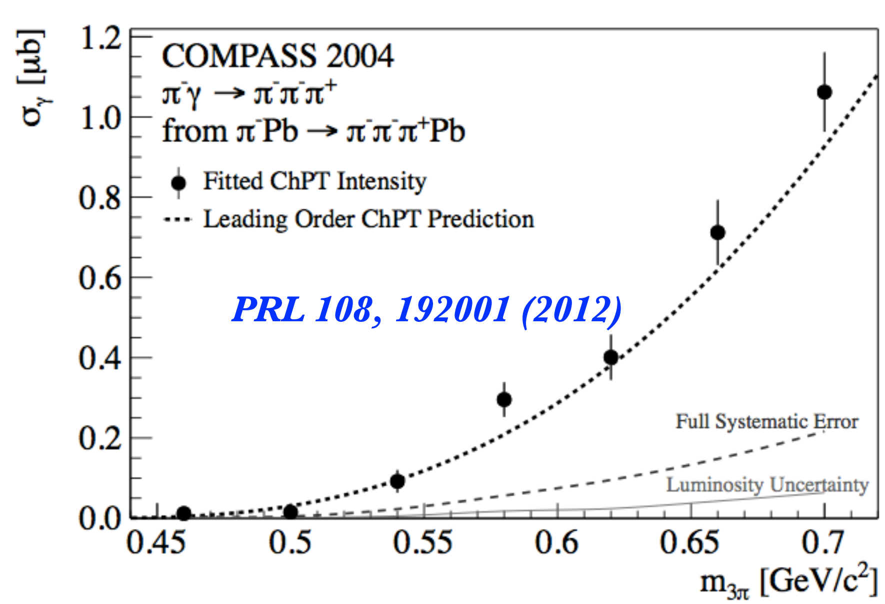
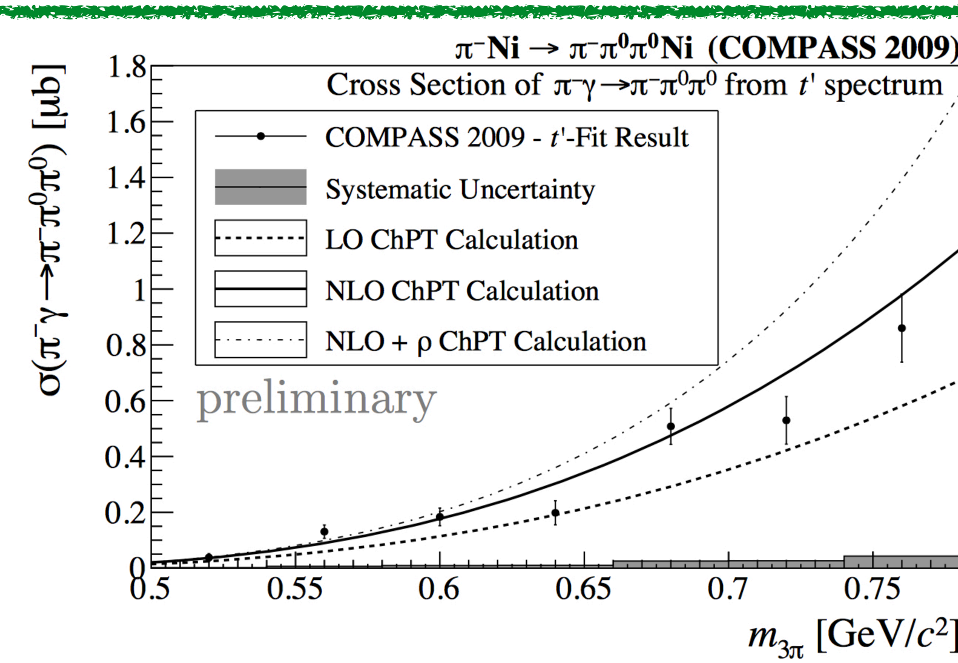
$$\sigma_{\mathrm{Primakoff},X} = \int_{m_1}^{m_2}\int_0^{t'_{\max}} \frac{d\sigma}{dm\,dt'}\,dt'\,dm = \Gamma_0(X \to \pi\gamma)C_X.$$

$\pi\gamma \to 3\pi$





Spectroscopy: light mesons

h^- **beam:** $97\,\%\ \pi^-, 2\,\%\ K^-, 1\,\%\ \bar{p}$
h^+ **beam:** $75\,\%\ p, 24\,\%\ \pi^+, 1\,\%\ K^+$

190 GeV/c

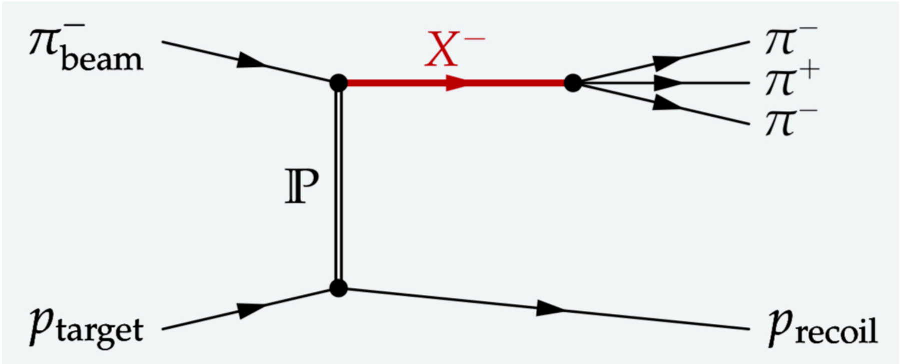
Targets: LH2, Ni, Pb, W, …

3 different beam particles, many final states:

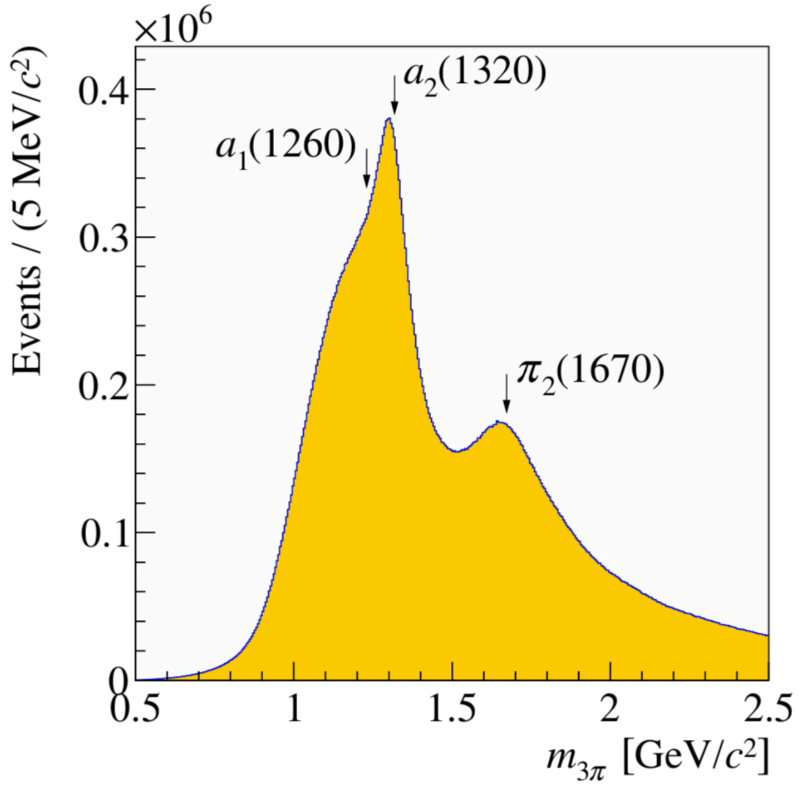
$\pi^0\pi^0\pi^-, \pi^-\pi^+\pi^-, \eta\pi^-, \eta'\pi^-, \eta\eta\pi^-, \pi^0\omega\pi^-, K\bar{K}\pi^-, K\bar{K}\pi^0\pi^- \ldots, K^-\pi^+\pi^- \ldots$

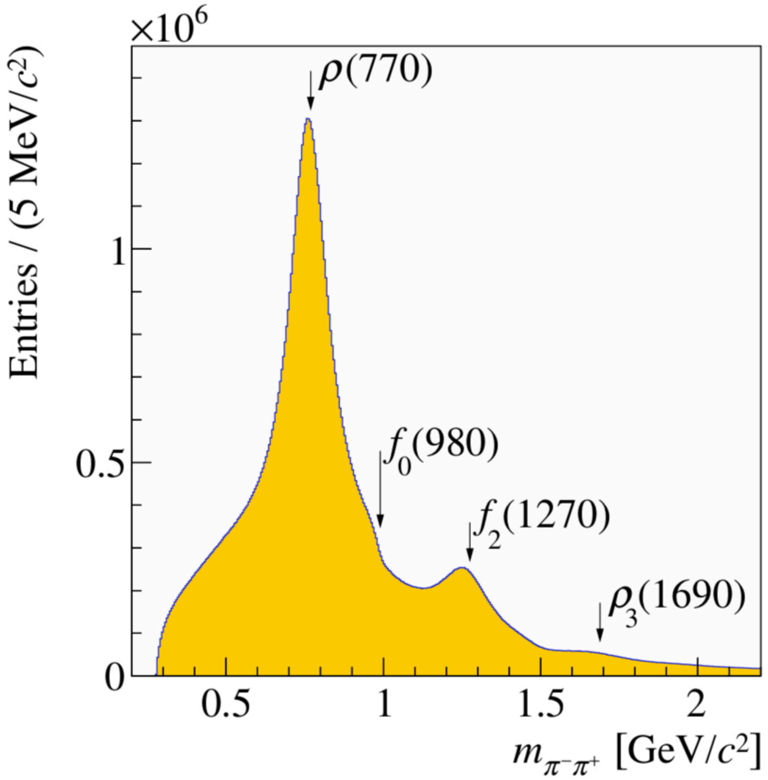
Production mechanisms: diffractive dissociation, central production, Primakoff production…

$\pi^- \to \pi^-\pi^+\pi^-$



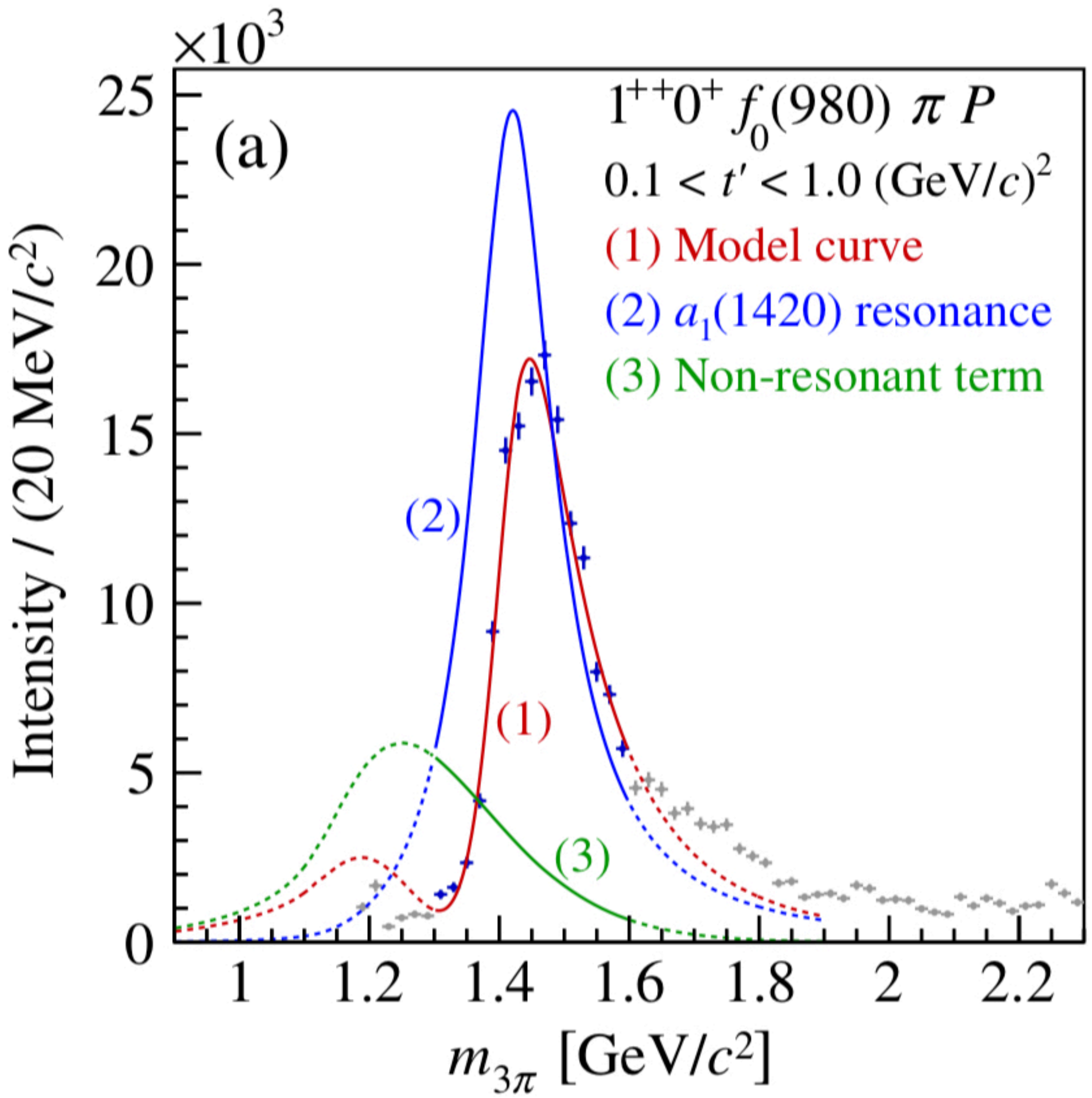
50M events





Partial wave analysis (PWA) with set of 88 waves, spin and orbital angular moment up to 6.

New state $a_1(1420)$



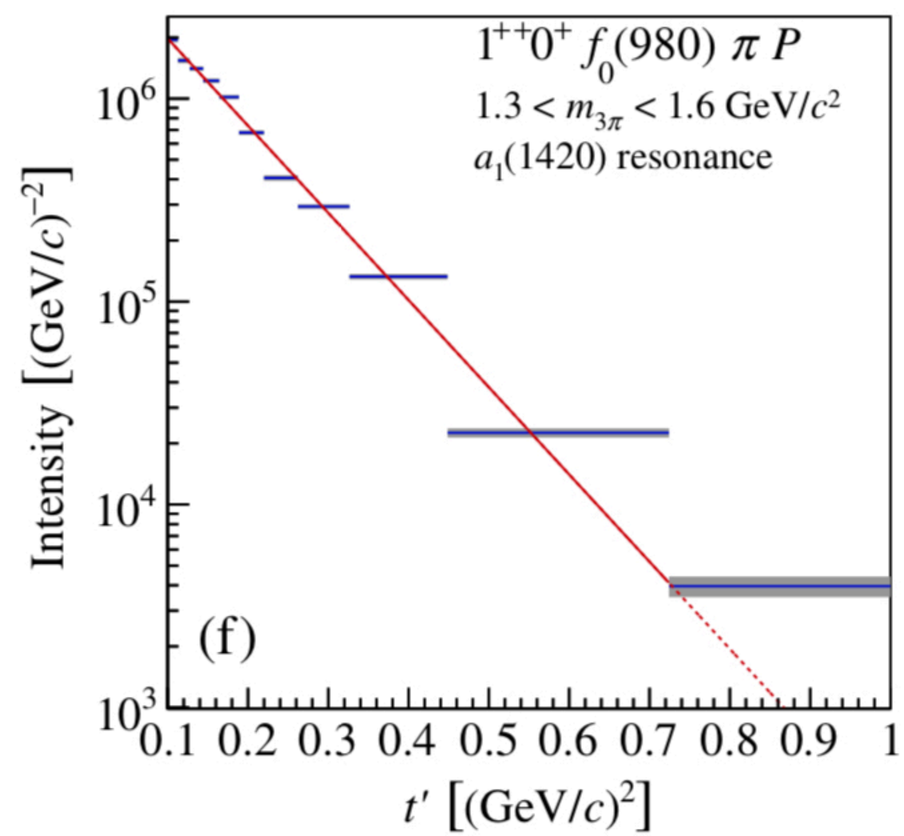
New axial-vector signal:

Narrow peak

$J^{PC}=1^{++}$

$M=1414^{+15}_{-13}$ MeV

$\Gamma=153^{+8}_{-23}$ MeV



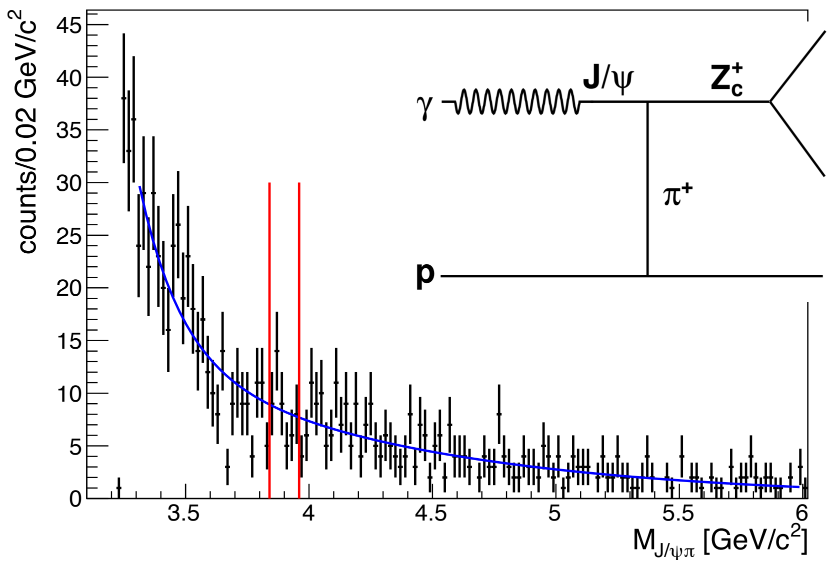
No quark-model states expected at 1.4 GeV
Ground state $a_1(1260)$ is very close and wider
Why only in $f_0(980)\pi$ decay mode?
Suspiciously close to KK* threshold
Isospin partner of narrow $f_1(1420)$?

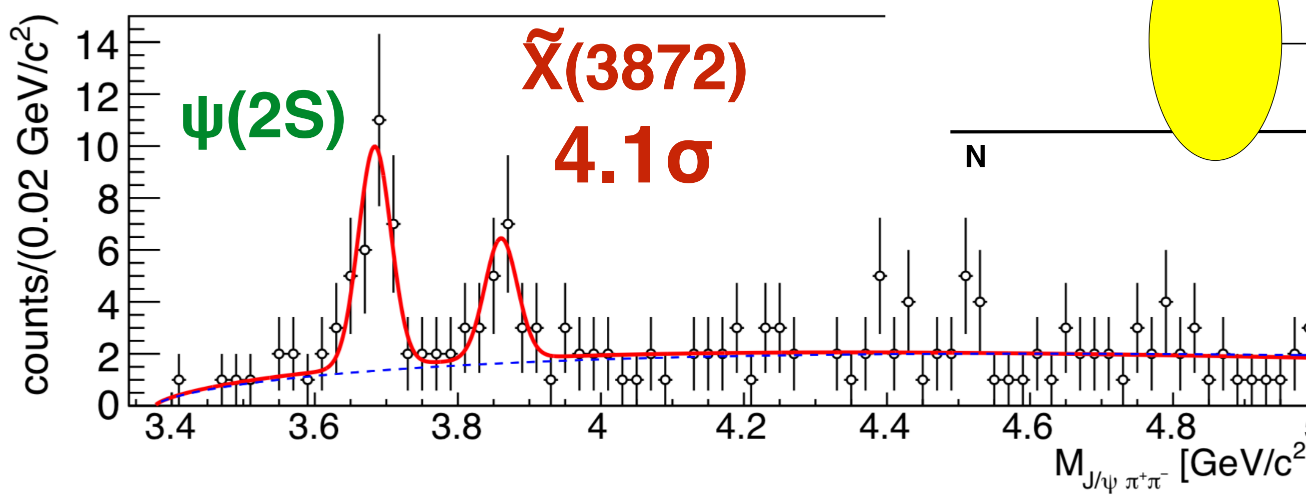
see PRL 115 (2015) 082001
and PRD 98 (2018) 092003

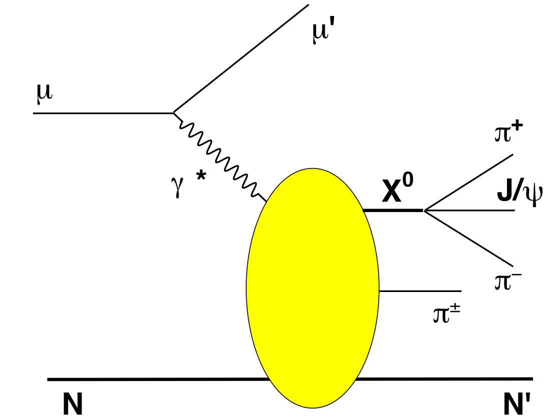
Spectroscopy: XYZ states

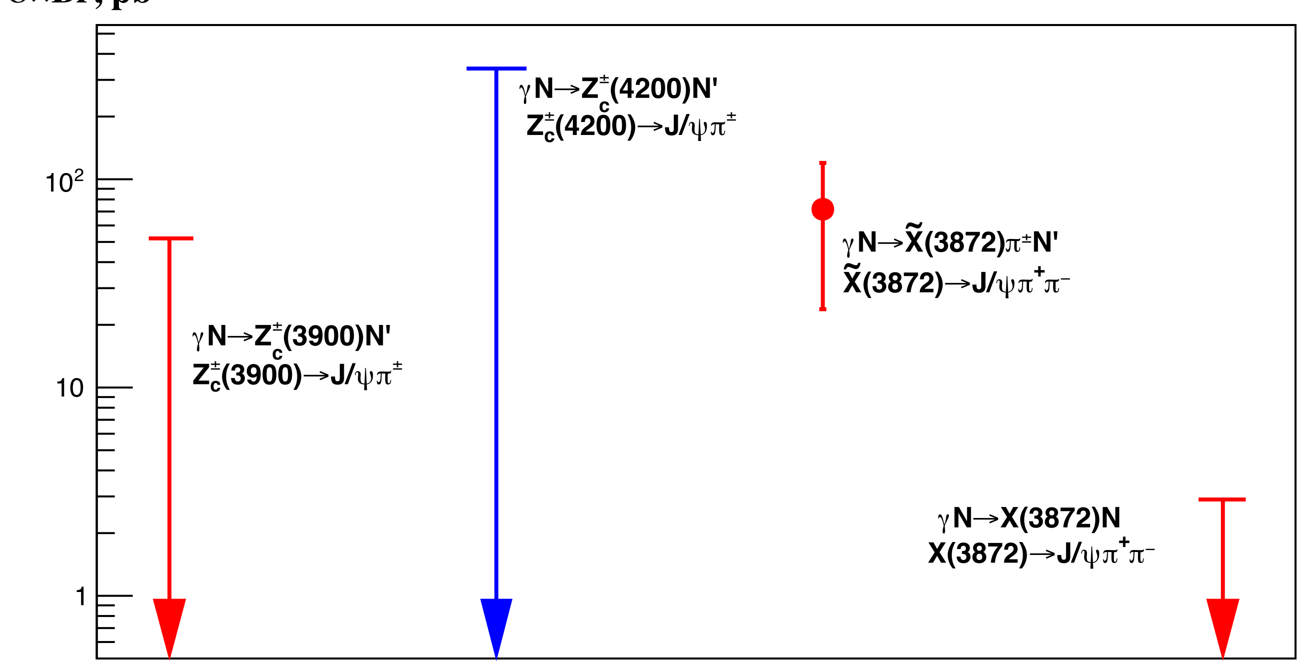
New instrument: lepto(photo)production

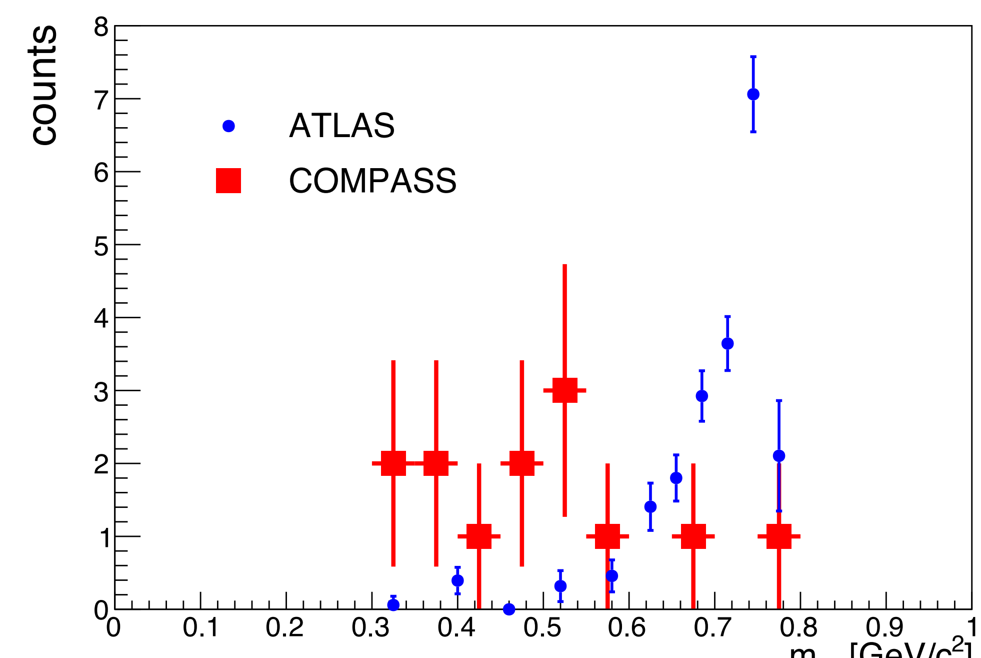
50k inclusive J/ψ sample











Phys.Lett. B742 (2015) 330 **Phys.Rev. D92 (2015) 094017** **Phys.Lett. B783 (2018) 334**

$$\widetilde{X}(3872) \neq X(3872)\ 1^{++}\ !$$

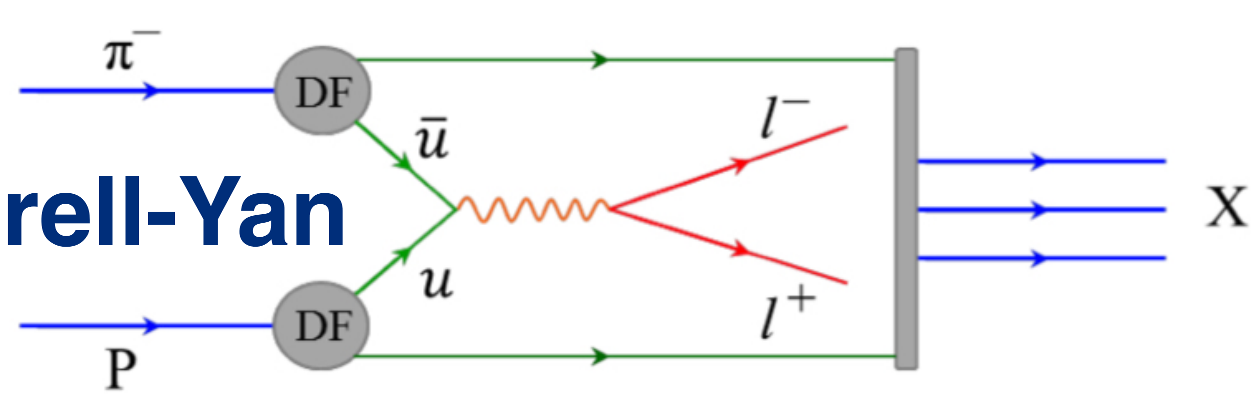
TMD PDFs

Quark \ Nucleon	U	L	T
U	$f_1^q(x,k_T^2)$ Number density		$f_{1T}^{q\perp}(x,k_T^2)$ Sivers
L		$g_1^q(x,k_T^2)$ Helicity	$g_{1T}^{q\perp}(x,k_T^2)$ Kotzinian-Mulders or Worm-gear T
T	$h_1^{q\perp}(x,k_T^2)$ Boer-Mulders	$h_{1L}^{q\perp}(x,k_T^2)$ Worm-gear L	$h_1^q(x,k_T^2)$ Transversity $h_{1T}^{q\perp}(x,k_T^2)$ Pretzelosity

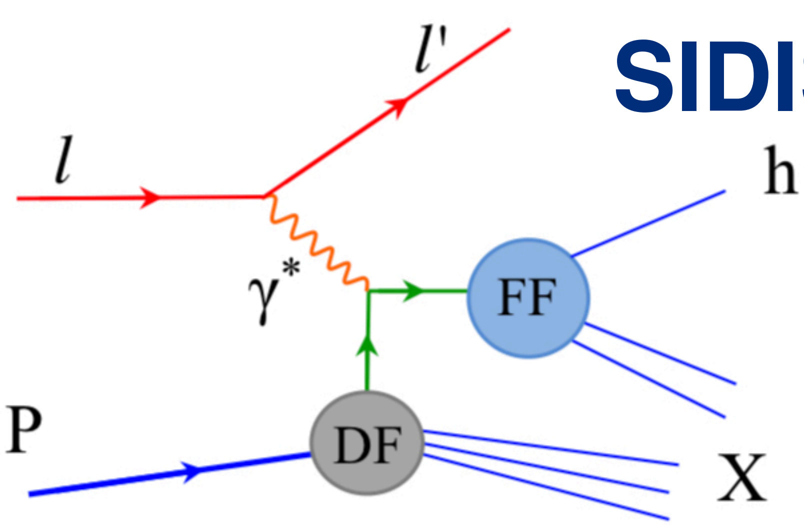
3 PDFs are needed to describe nucleon structure in collinear approximation

8 PDFs are needed if we want to take into account intrinsic transverse momentum k_T of quarks - **Transverse Momentum Dependent PDFs**

Drell-Yan



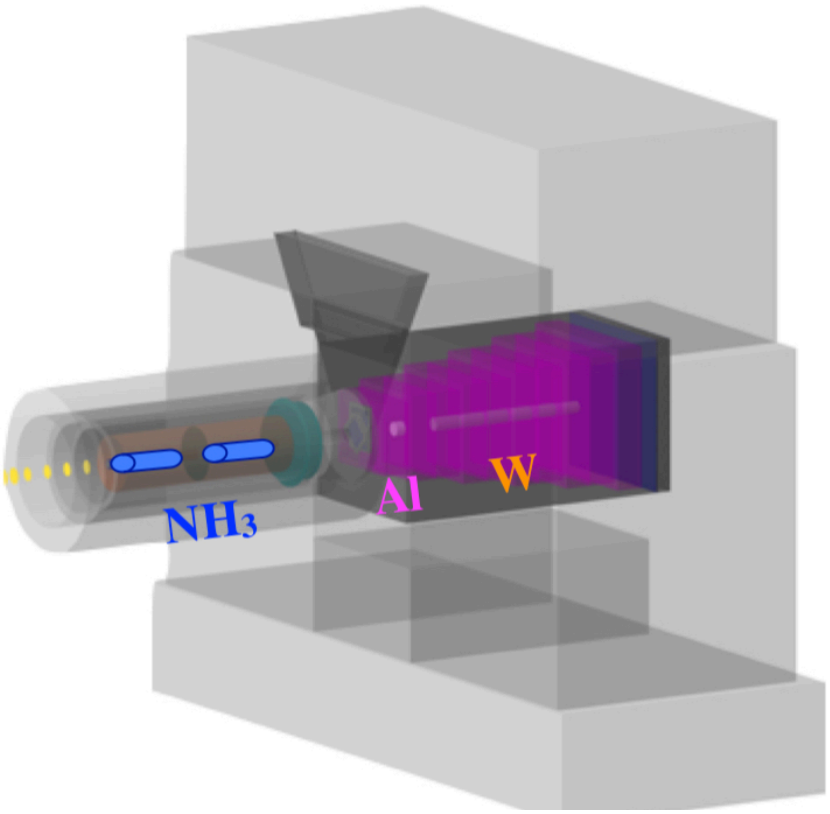
SIDIS



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

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

Drell-Yan at COMPASS

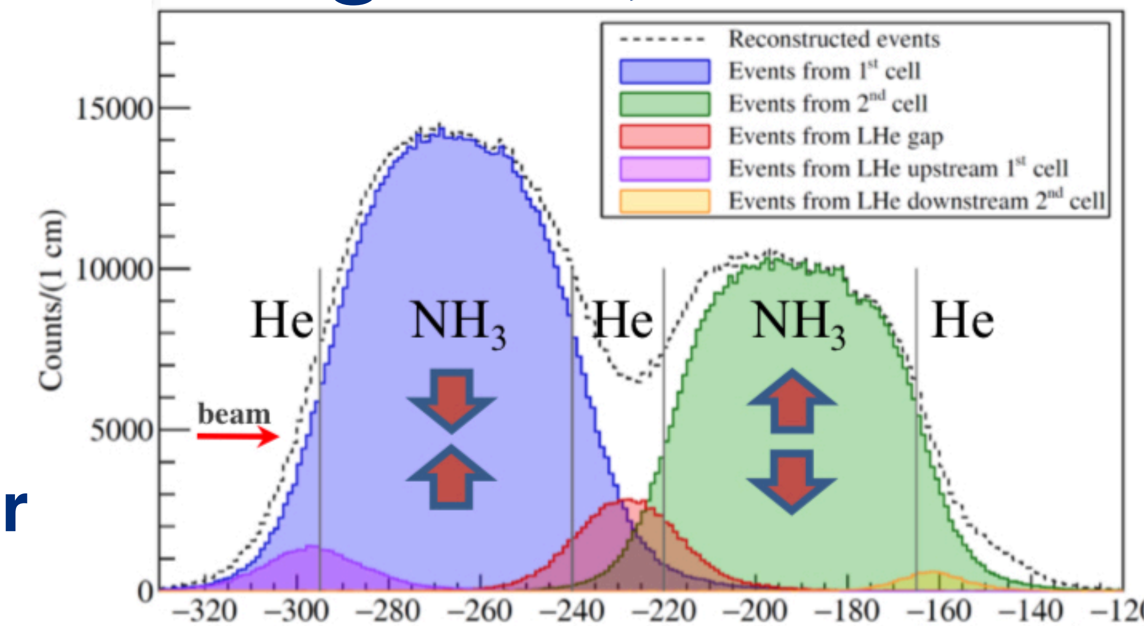


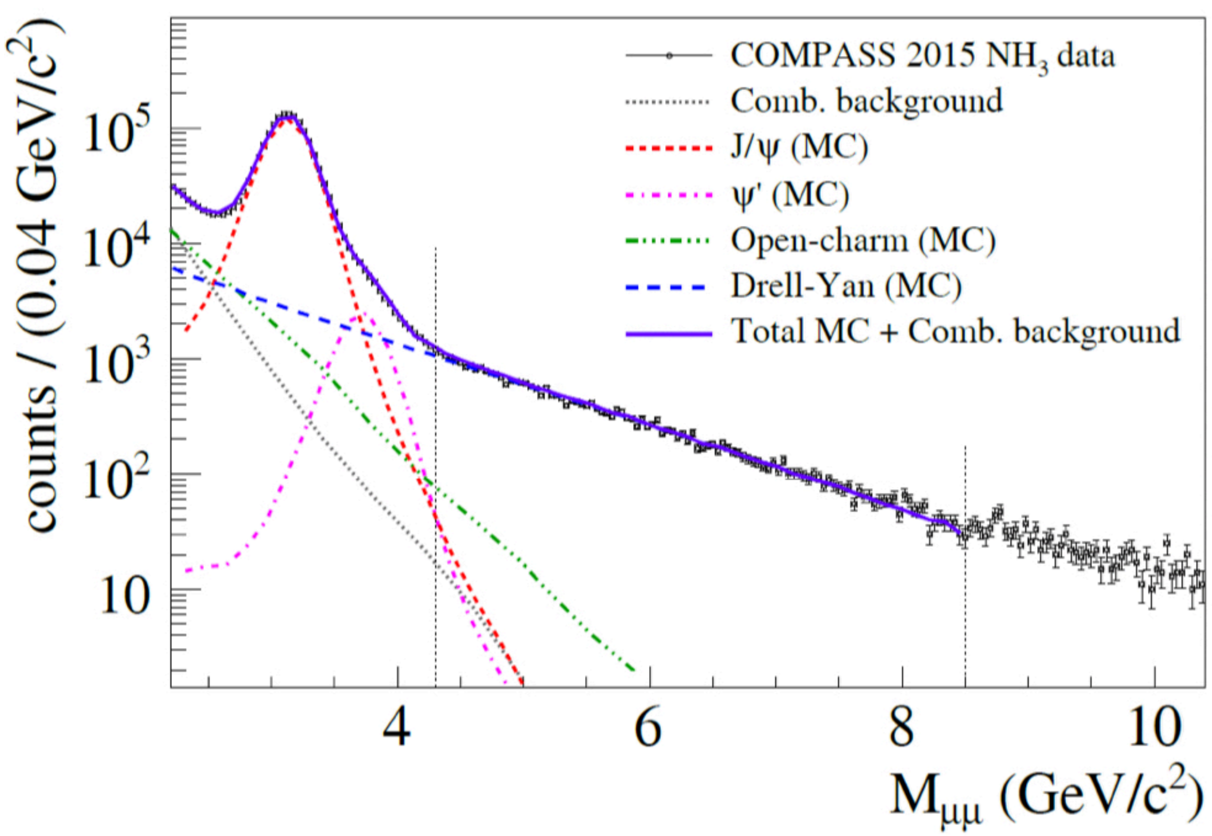
Data taking 2015, 2018

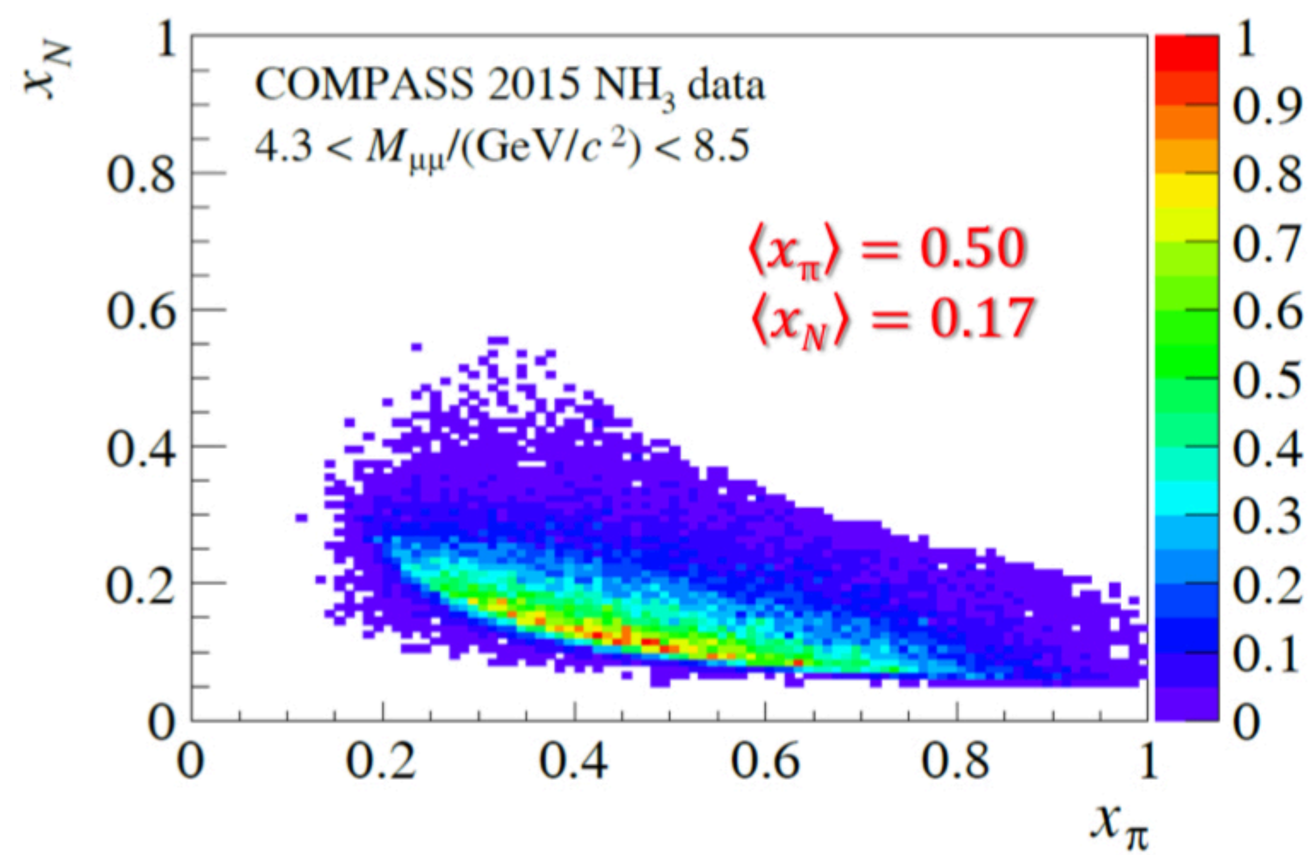
Target zone:

NH3 polarized target (2 cells)

Hadron absorber

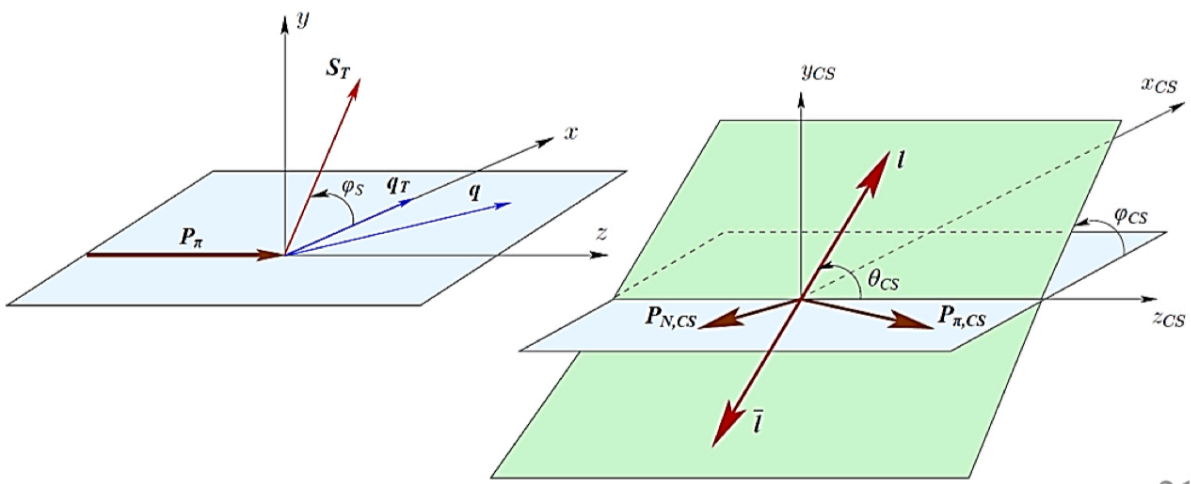






Azimuthal asymmetries

Azimuthal asymmetries - way to access TMD PDFs

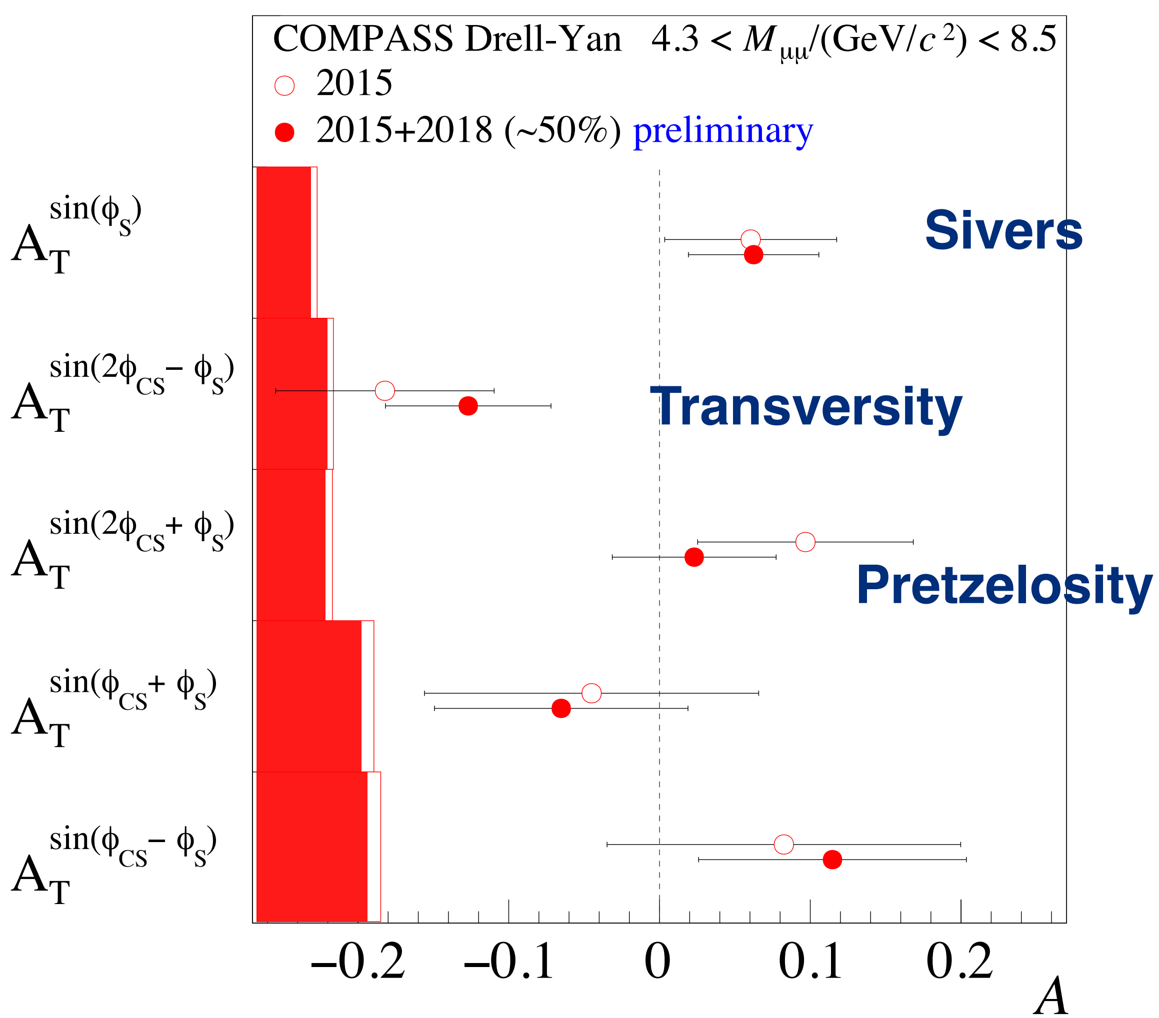


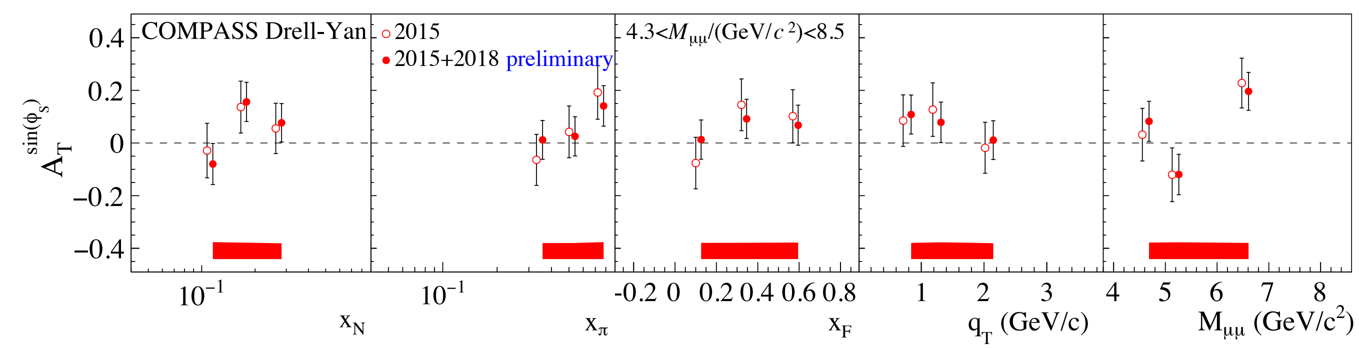
Boer-Mulders → $A_U^{\cos(2\varphi_{CS})} \propto h_{1,\pi}^{\perp,q} \otimes h_{1,p}^{\perp q}$

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

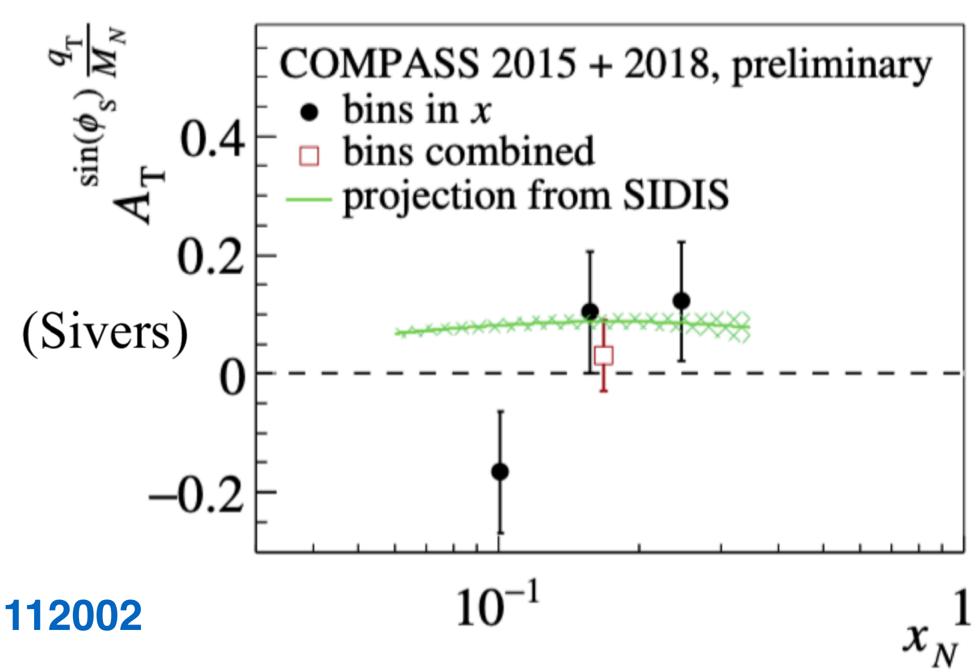
Pretzelosity → $A_T^{\sin(2\varphi_{CS}+\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1T,p}^{\perp q}$

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





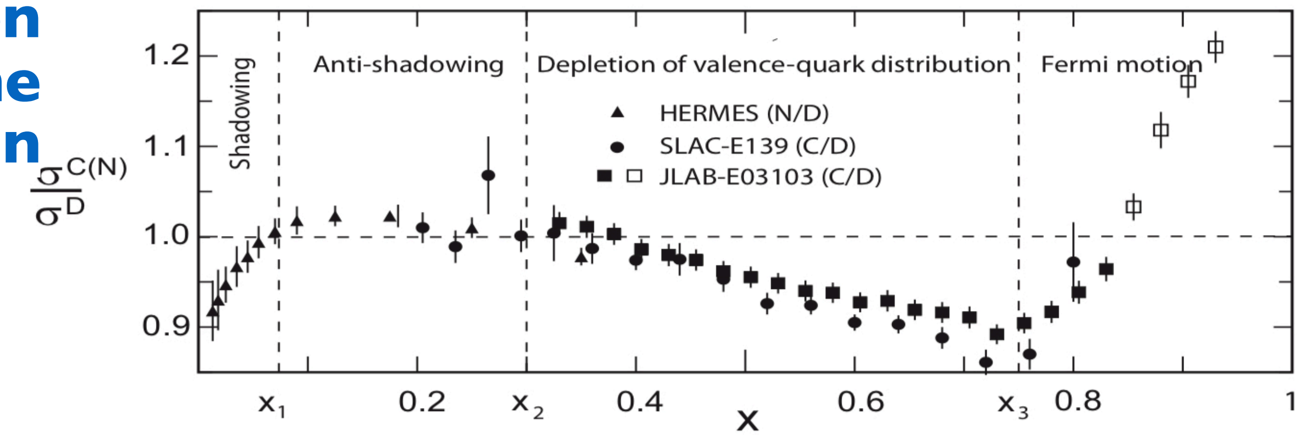
$$f_{1T}^{q\perp}\Big|_{\rm DY} = -f_{1T}^{q\perp}\Big|_{\rm SIDIS} \quad \text{(Sivers)}$$

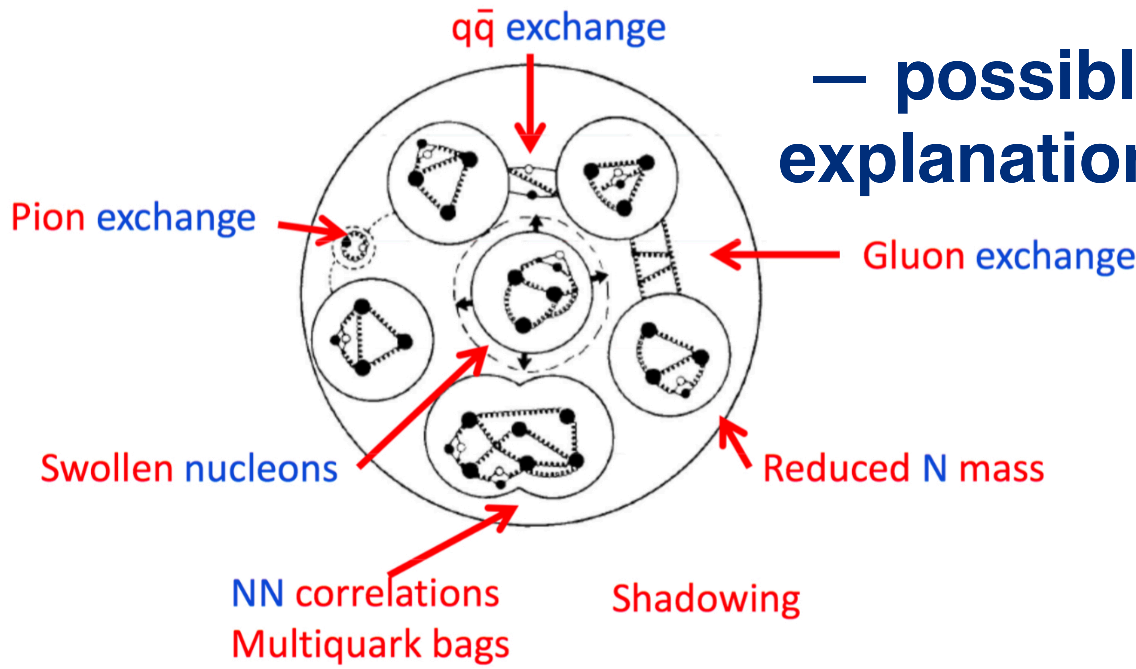


see also PRL 119 (2017) 112002

EMC effect in π-induced Drell-Yan

The EMC effect – a modification of parton distributions in bound nucleons by the nuclear environment, first observed in DIS by the EMC collaboration in 1983



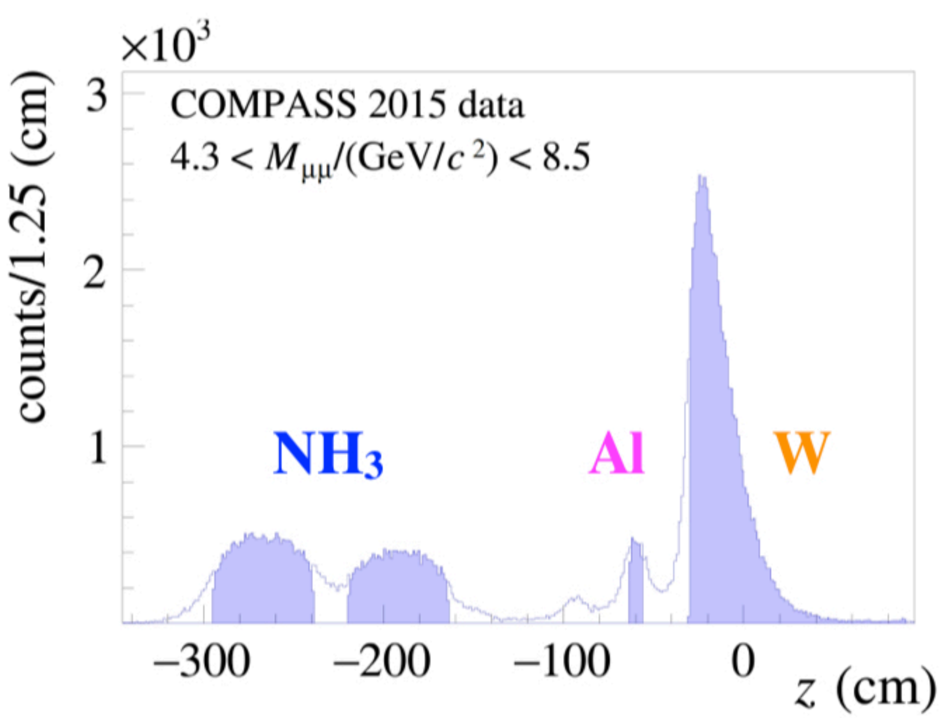


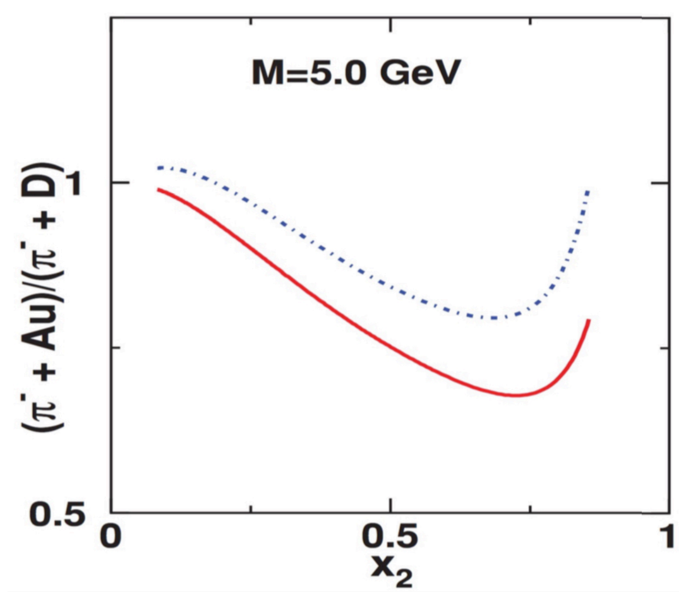
— possible explanations

$$\sigma_{DIS} \sim \frac{4}{9}u(x) + \frac{1}{9}d(x)$$

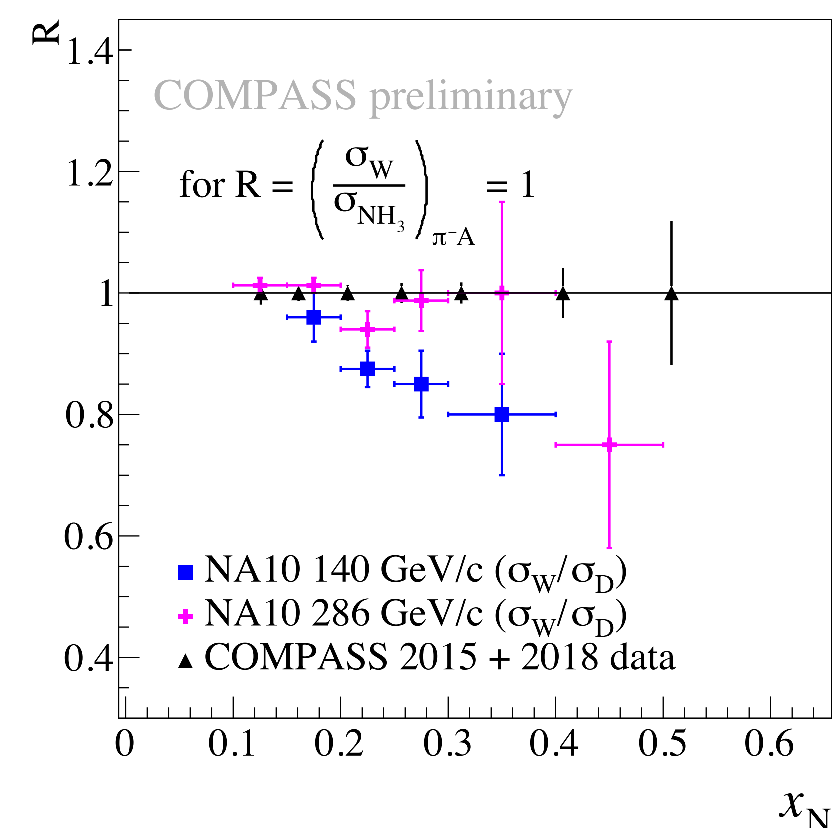
$$\sigma_{\pi^- DY} \sim u(x)$$

u/d contributions can be separated!

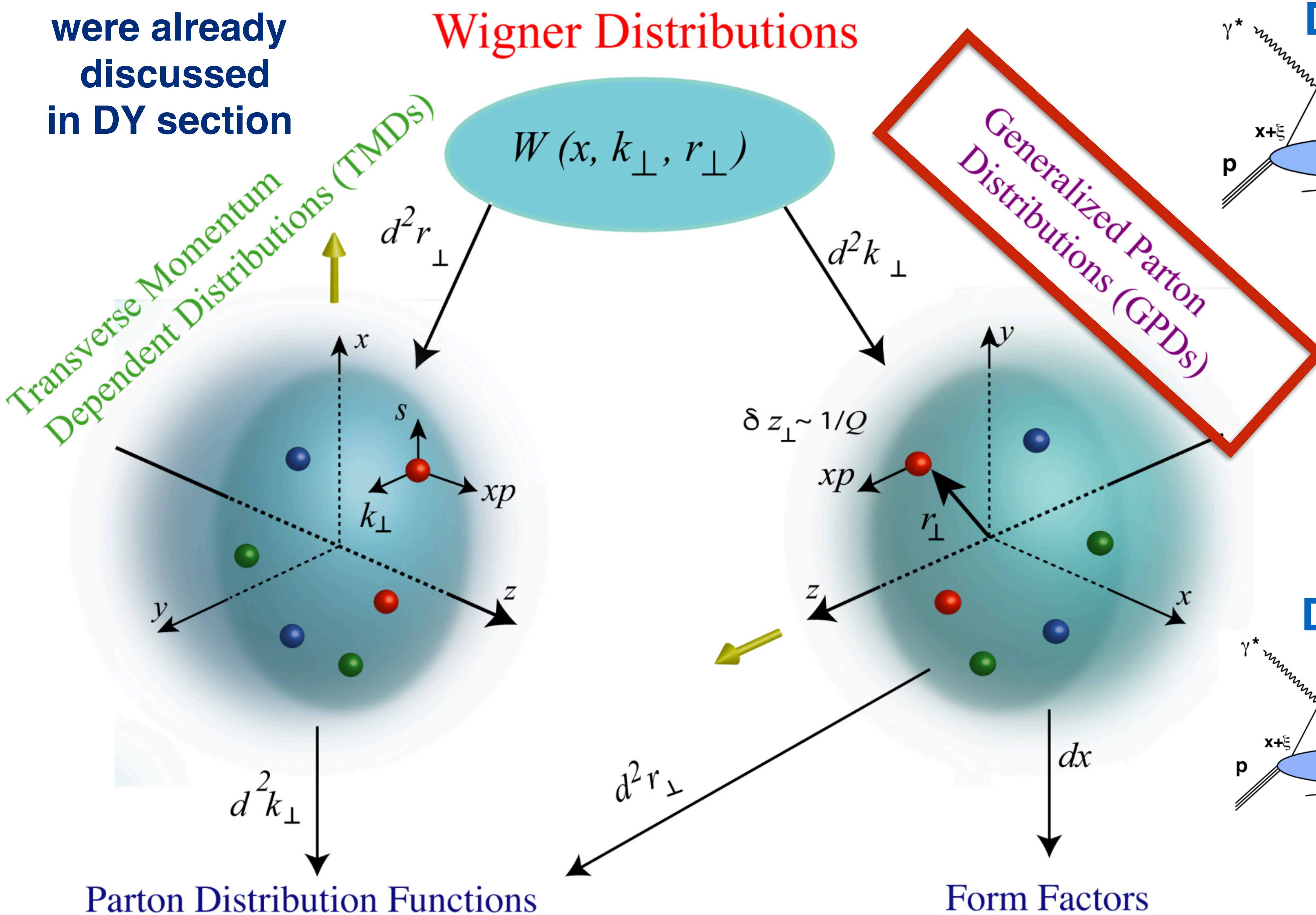


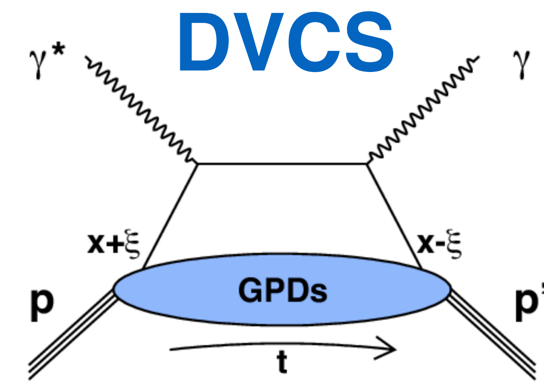


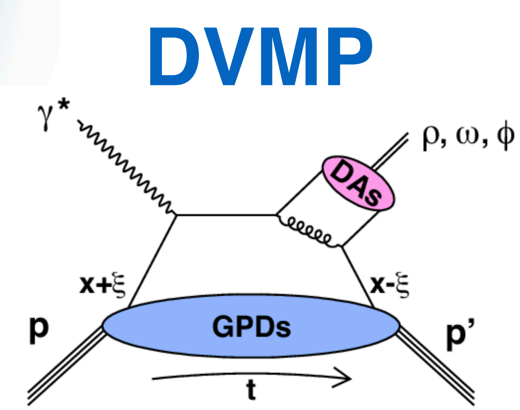
Phys. Rev. C 83, 042201 (2011);
Phys. Rev. Lett. 102, 252301 (2009)



3D picture of proton

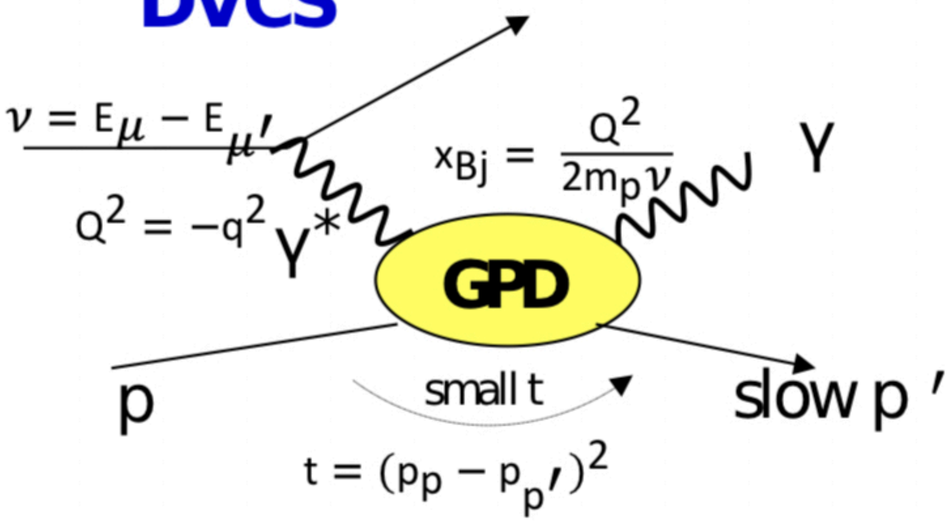




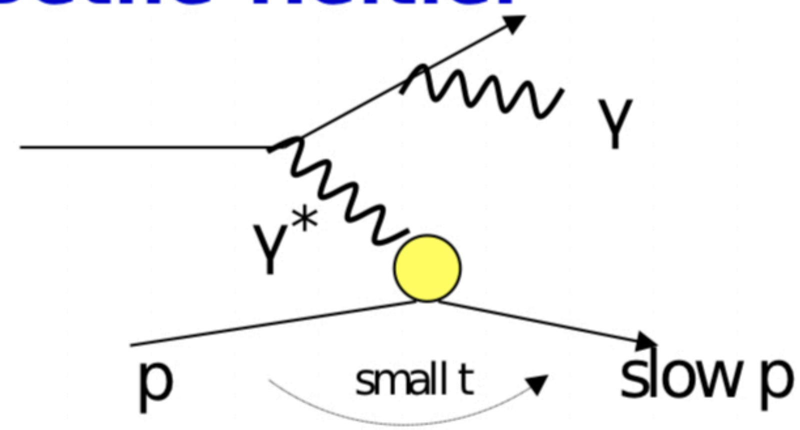


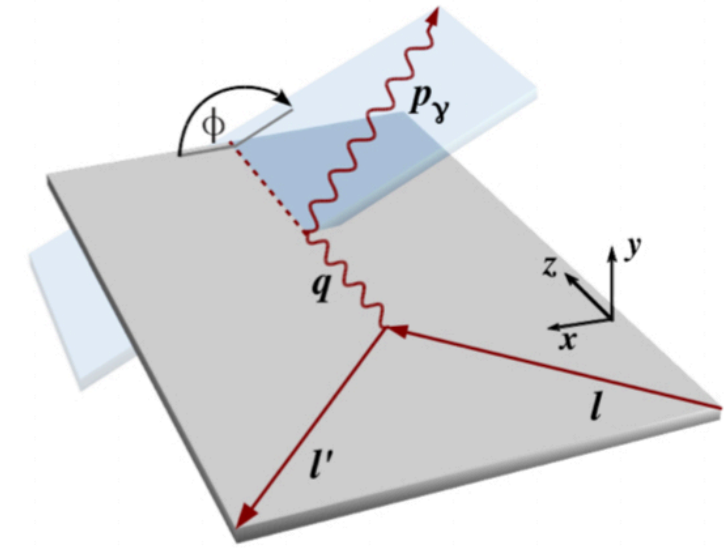
DVCS and BH

DVCS



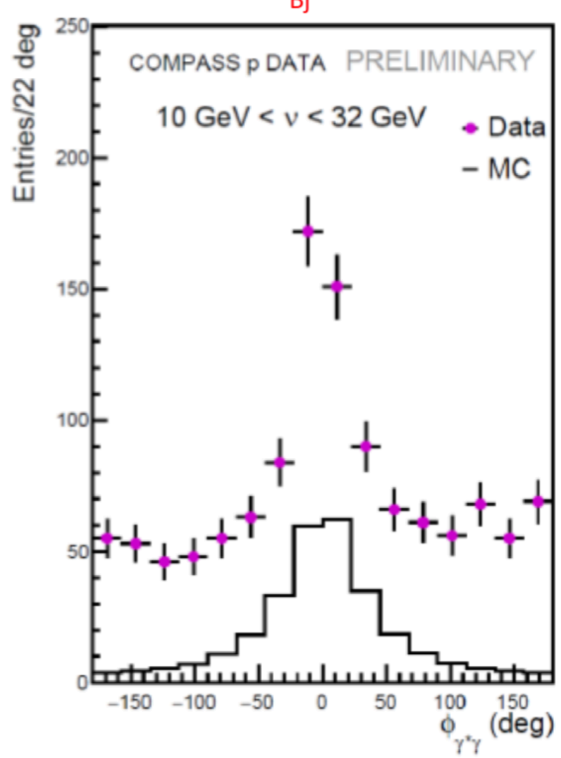
Bethe-Heitler



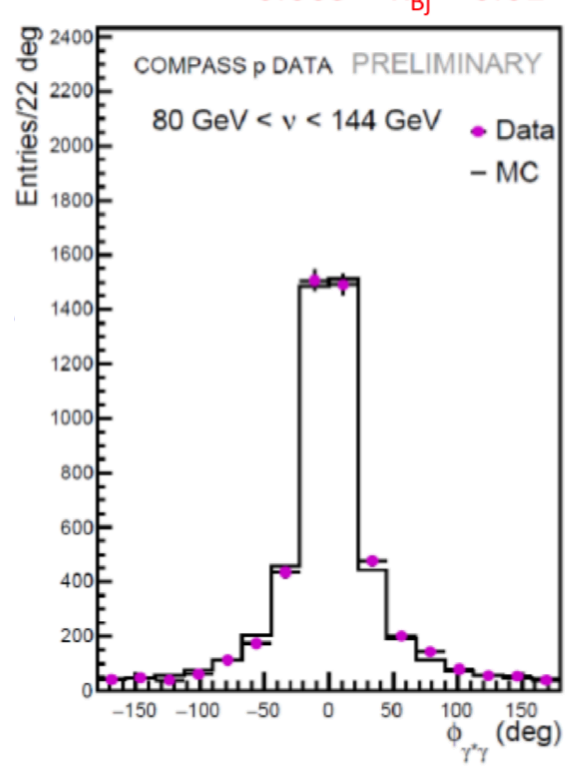


$d\sigma \propto \underbrace{|T_{DVCS}|^2}_{\text{bilinear combination of GPDs}} + \underbrace{|T_{BH}|^2}_{\text{known to 1 \%}} + \underbrace{\text{interference term}}_{\text{linear combination of GPDs}}$

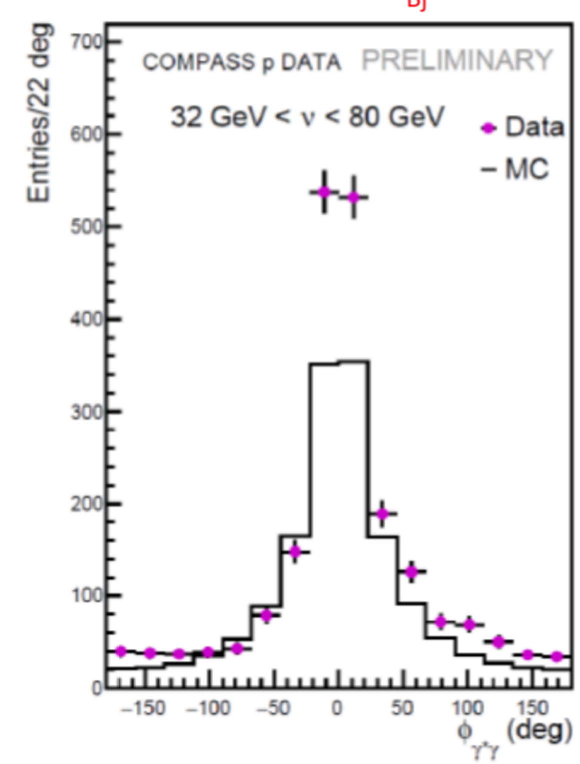
$x_{Bj} > 0.03$



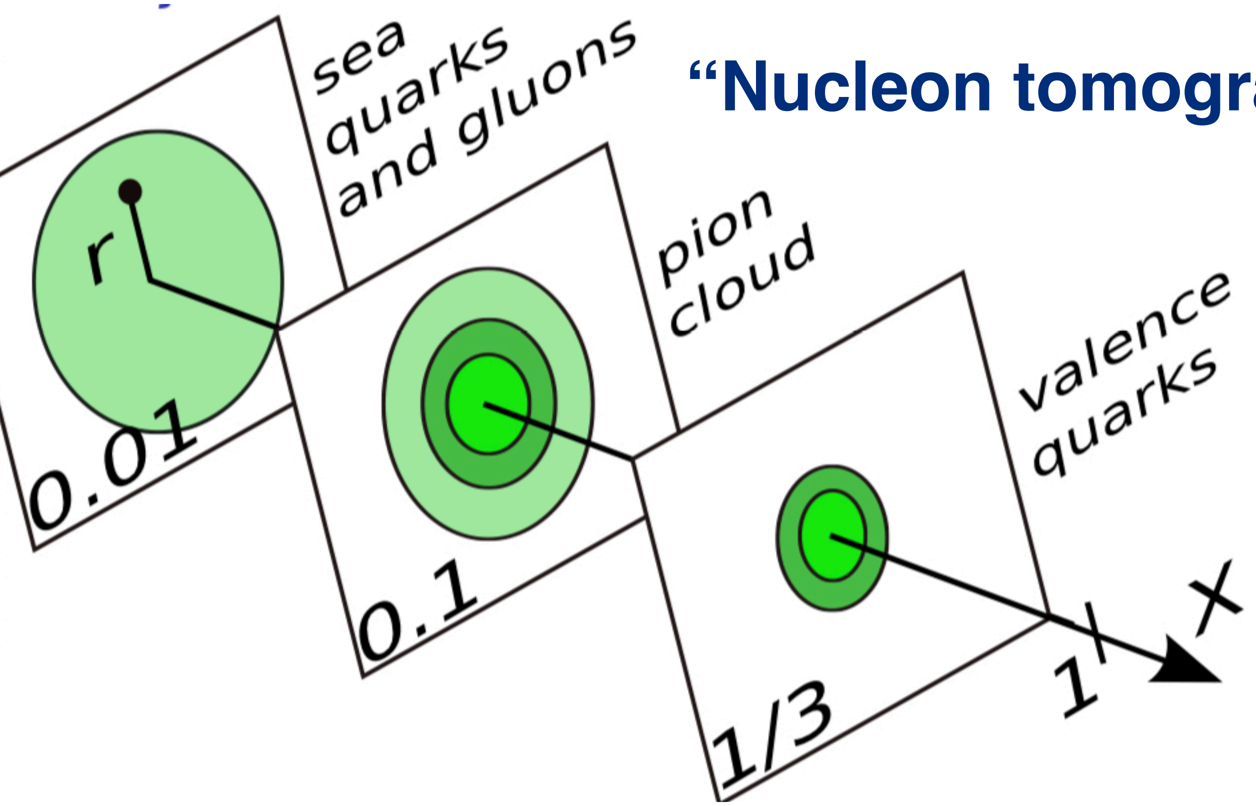
$0.005 < x_{Bj} < 0.01$



$0.01 < x_{Bj} < 0.03$



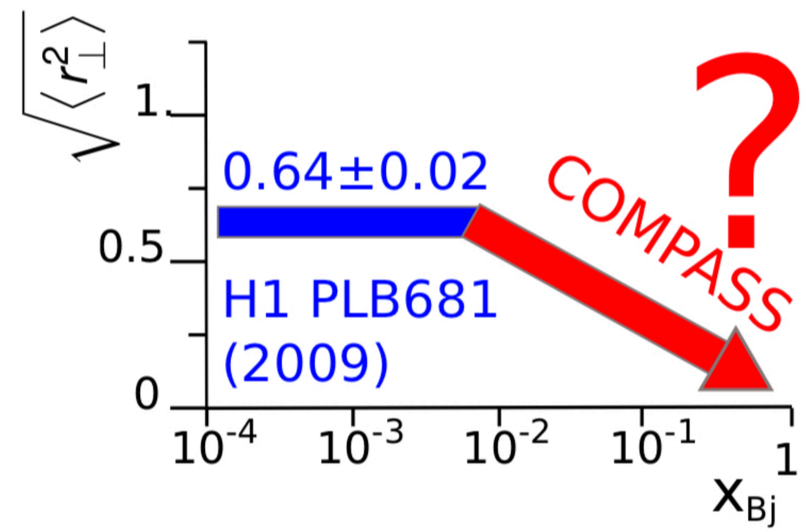
Sea quark imaging

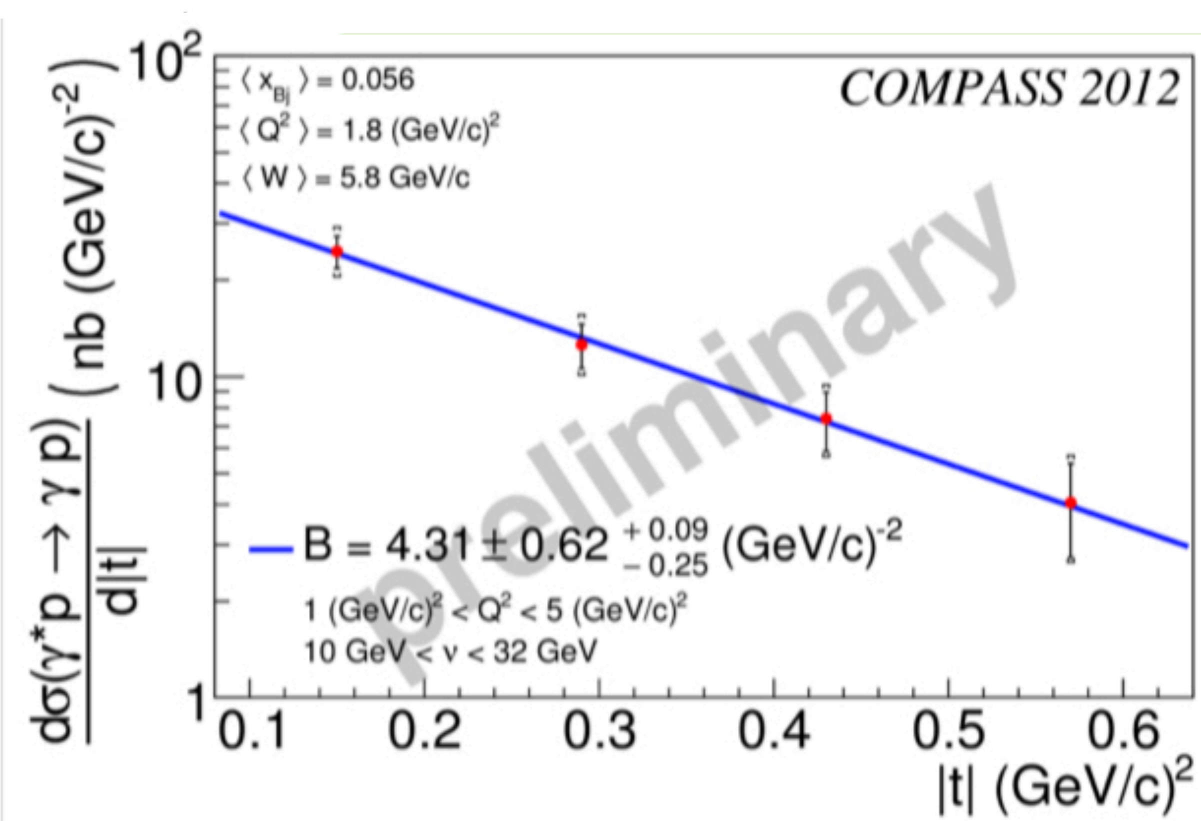


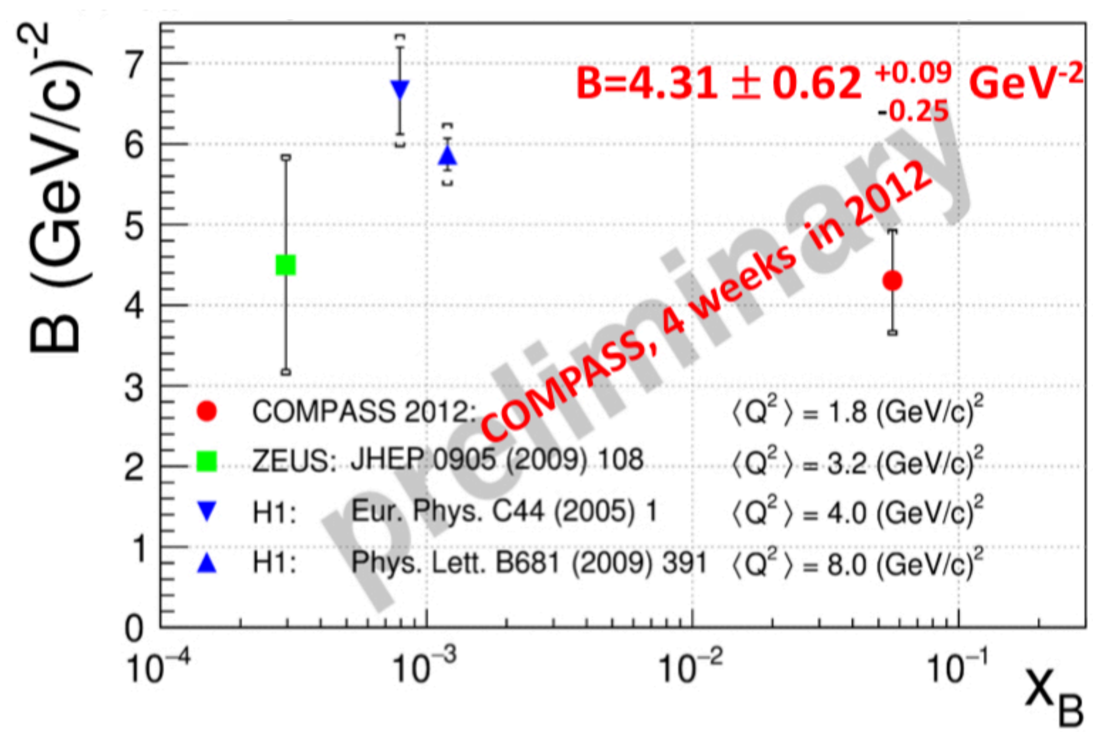
"Nucleon tomography"

$$\frac{d\sigma^{DVCS}}{d|t|} \propto e^{-B|t|}; \; < r_{\perp}^{2} > \sim 2B(x_{Bj})$$

at small x_{Bj}

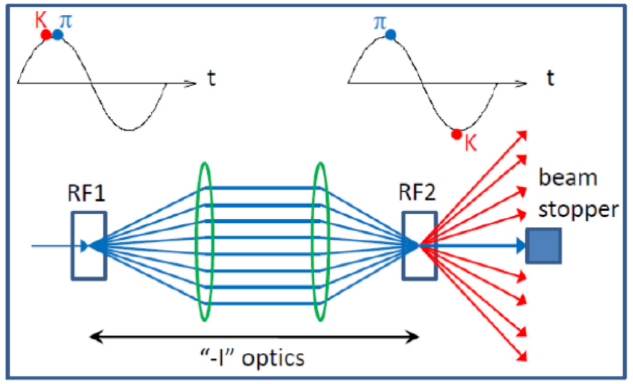






COMPASS++/AMBER

Apparatus for Meson and Baryon Experimental Research
- a new QCD facility at the M2 beam line of the CERN SPS



COMPASS — LS2 — 2022 **AMBER** — LS3

conventional beams

RF-separated hadron beam

- Proton-radius puzzle
- Hadron spectroscopy
- Nucleon structure
- Pion and kaon structure
- Low-energy QCD tests
- $\bar{p}$ yield for astrophysical dark matter search

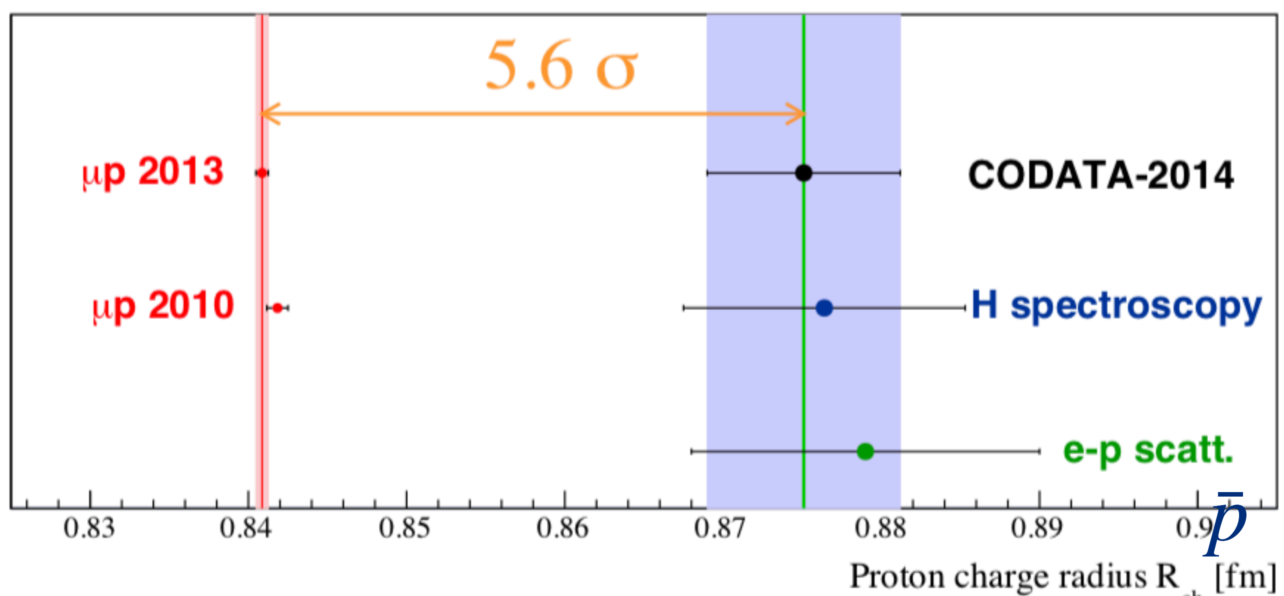
arXiv:1808.00848

https://nqf-m2.web.cern.ch

CERN-SPSC-2019-022 ; SPSC-P-360

COMPASS++/AMBER

Proton radius puzzle

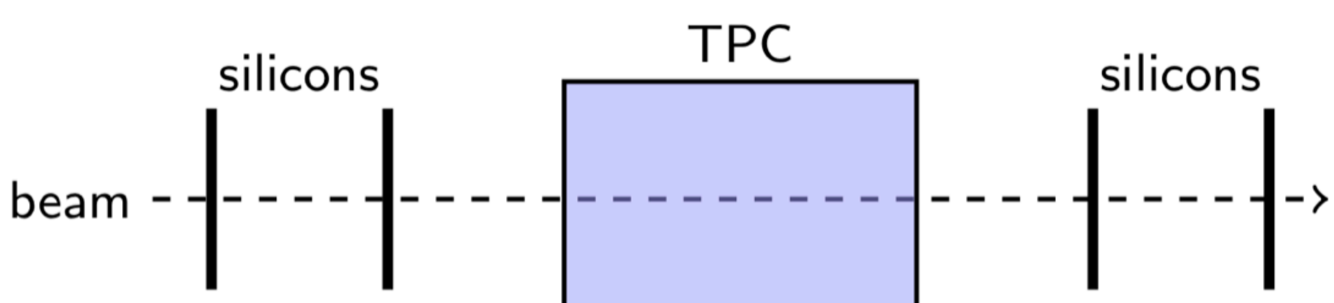


RP, Gilman, Miller, Pachucki, Annu. Rev. Nucl. Part. Sci. 63, 175 (2013).

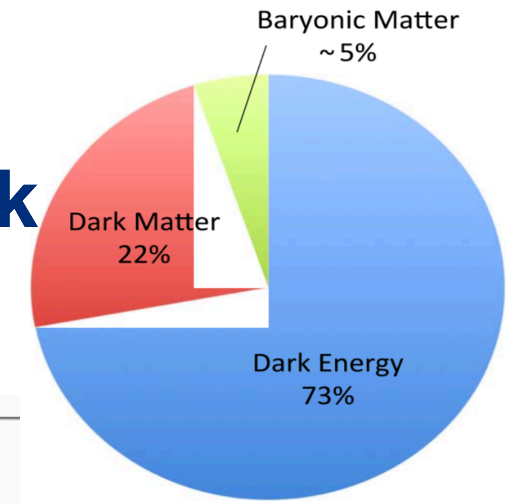
proposed set-up

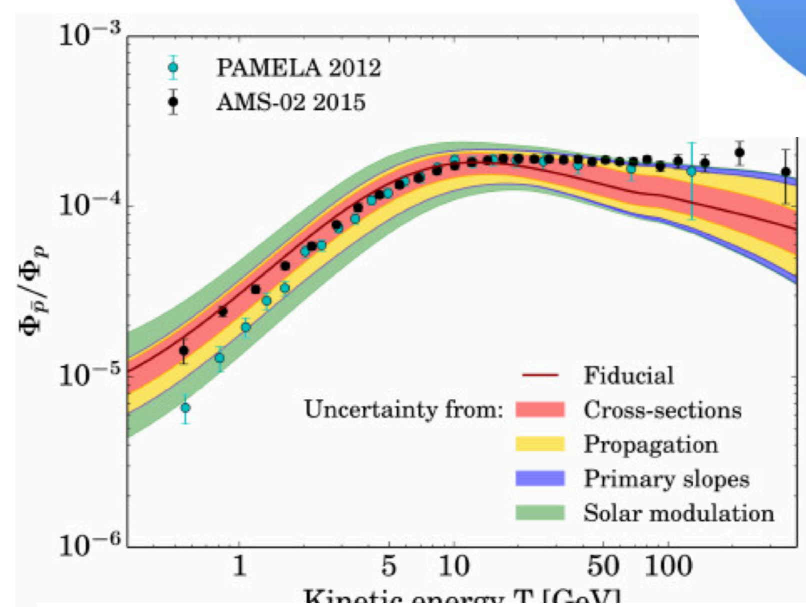
- hydrogen TPC acting as active target
  - measurement of energy of recoil proton
  - between 0.5 and 100 MeV
  - required resolution: $\Delta \approx 60$ keV)
- silicon telescopes up- and downstream of target
  - measurement of muon scattering angles
  - 300 μrad at $Q^2 \approx 10^{-3}$ $(\mathrm{GeV}/c)^2$
  - required resolution $\sigma \lesssim 100$ μrad

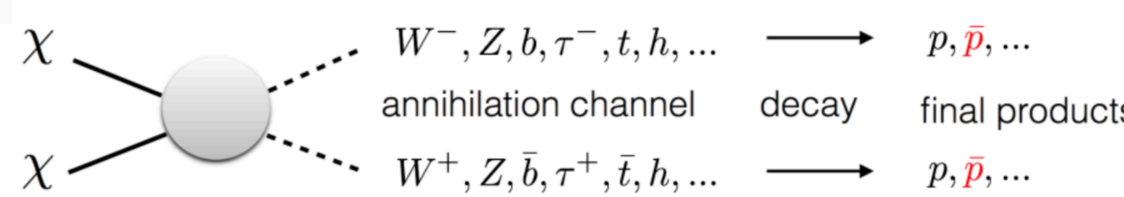
uncertainty on $\sqrt{\langle r_E^2 \rangle} \approx 0.01$ fm



$\bar{p}$ yield for astrophysical dark matter search







	pbar(18-45 GeV/c)	pbar (5-18 GeV/c)
p-p @ 0-280GeV/c	OK 2009 data @190GeV	RICH veto or RICH0
p-He @0-280GeV/c	new LHe target	RICH veto or RICH0

Nucleon structure

GPD E with DVCS

$\mathbf{H}(x, \xi, t) \xrightarrow{t \to 0} q(x)$ or $f_1(x)$

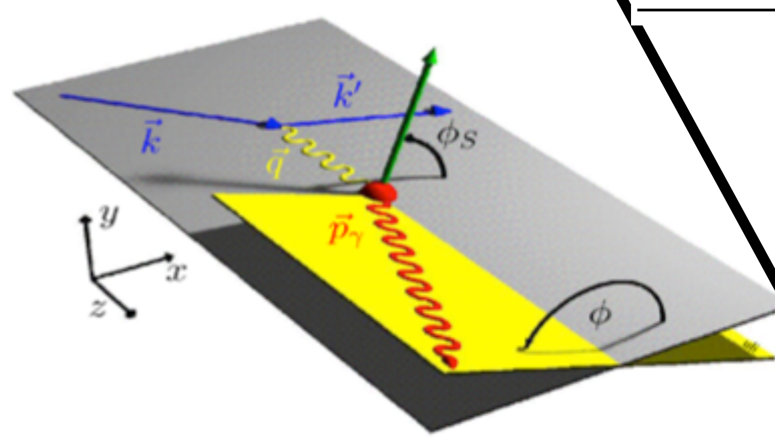
"Elusive"

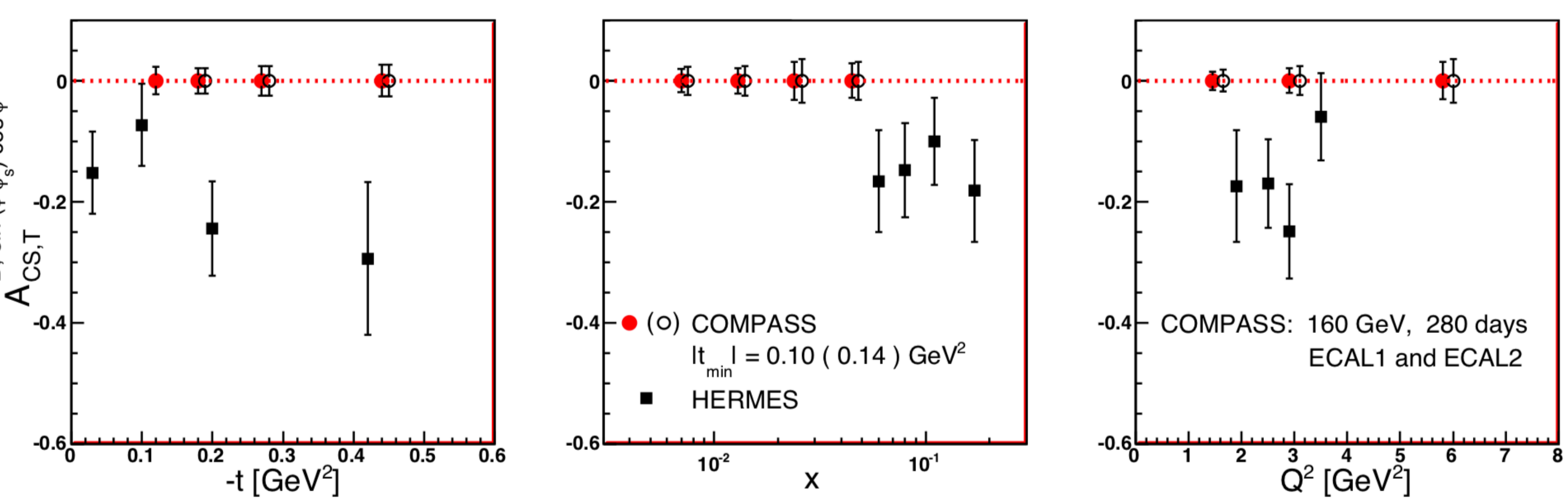
$\mathbf{E}(x, \xi, t) \longleftrightarrow f_{1T}^{\perp}(x, k_T)$ -

Ji sum rule

$$J^q = \frac{1}{2} \lim_{t \to 0} \int \left(\mathbf{H}^q(x, \xi, t) + \mathbf{E}^q(x, \xi, t)\right) x \, dx$$

$$\mathcal{D}_{CS,T} \equiv \Delta\sigma_T(\mu^{+\downarrow}) - \Delta\sigma_T(\mu^{-\uparrow})$$
$$\rightarrow Im(F_2 \mathcal{H} - F_1 \mathcal{E}) \sin(\phi - \phi_s) \cos\phi$$

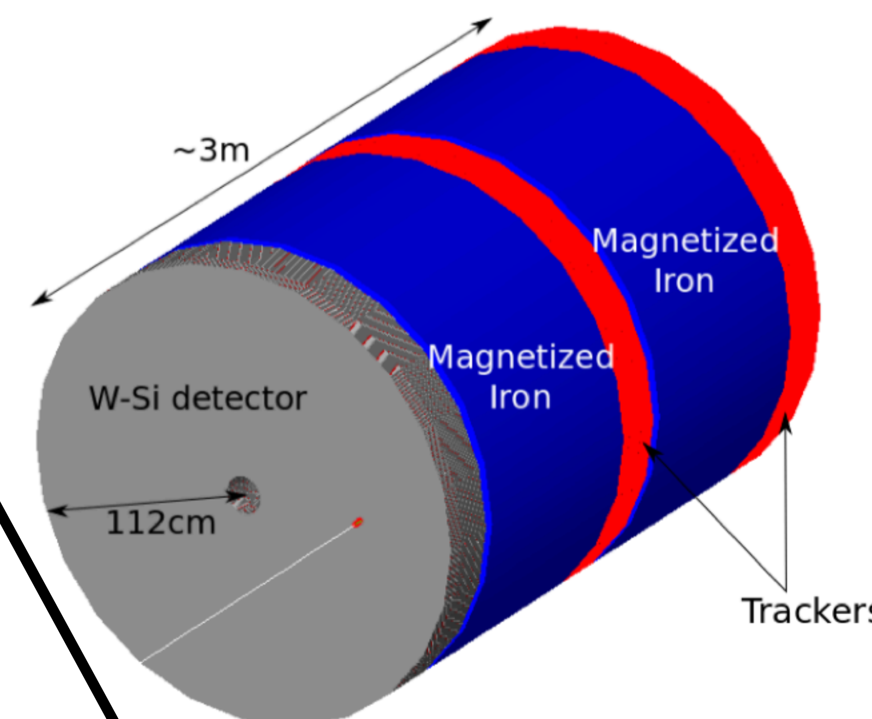




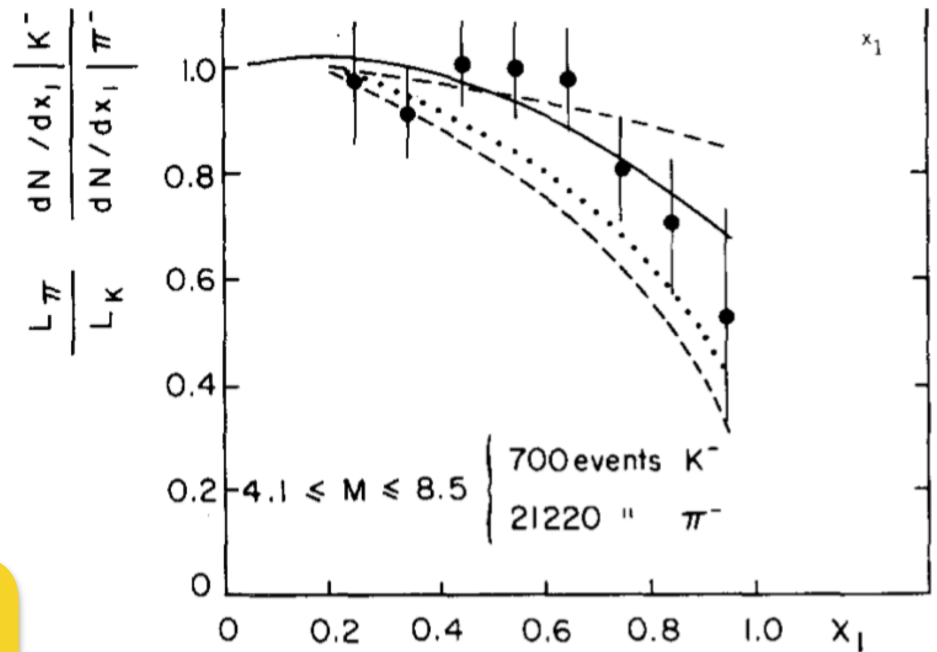
TMD PDFs with antiproton-induced DY and transversely polarised target

Experiment	Target type	Beam type	Beam intensity (part/sec)	Beam energy (GeV)	DY mass (GeV/c^2)	DY events $\mu^+\mu^-$	e^+e^-
This exp.	110cm NH_3	$\bar{p}$	3.5×10^7	100	4.0 – 8.5	28,000	21,000
				120	4.0 – 8.5	40,000	27,300
				140	4.0 – 8.5	52,000	32,500

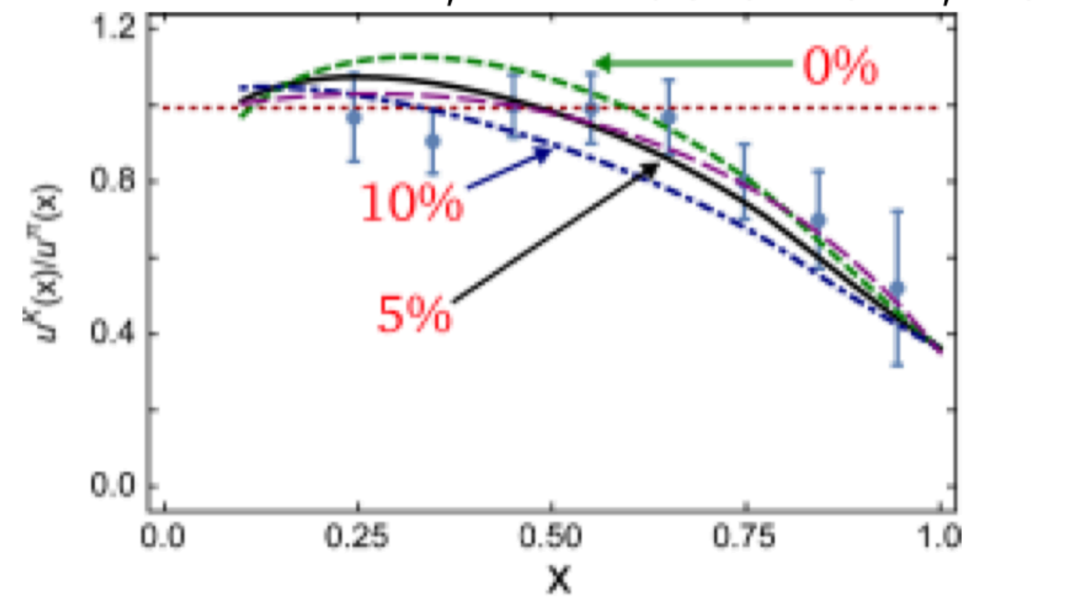
Active absorber



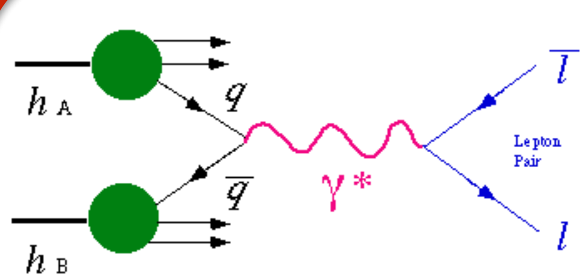
Pion and kaon PDFs



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



quarks

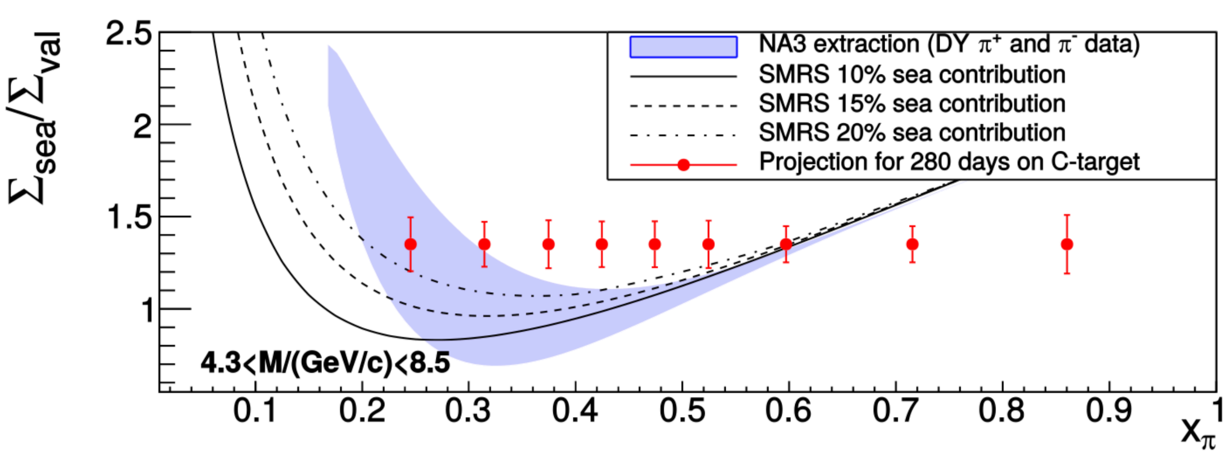


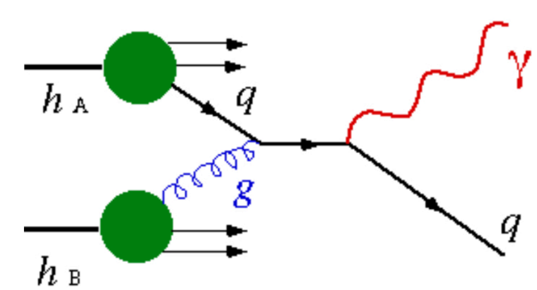
Drell-Yan

Sea/valence separation

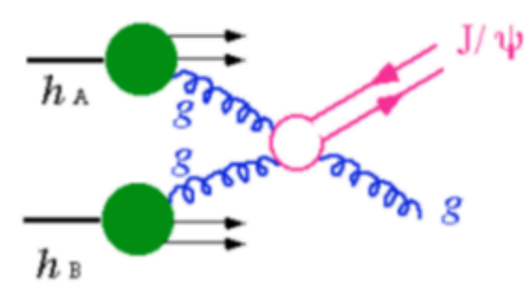
$$\Sigma_{val}^{\pi D} = -\sigma^{\pi^+ D} + \sigma^{\pi^- D}$$

$$\Sigma_{sea}^{\pi D} = 4\sigma^{\pi^+ D} - \sigma^{\pi^- D}$$





Prompt photos



Charmonia

gluons

QCD tests with RF-separated hadron beam

Kaon polarizability

$_\chi$PT prediction $O(p^4)$:

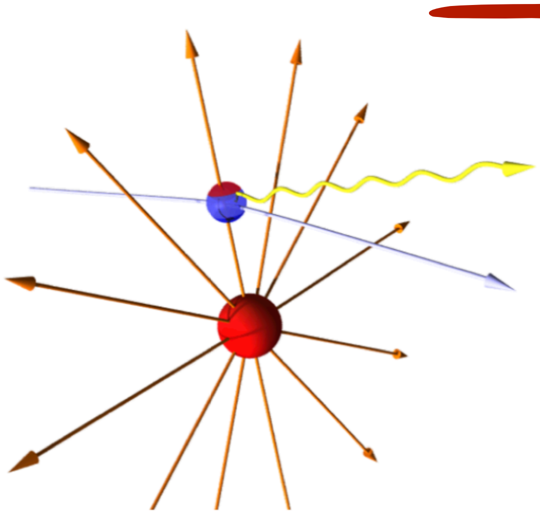
$$\alpha_K + \beta_K = 0$$

$$\alpha_K = \alpha_\pi \times \frac{m_\pi F_\pi^2}{m_K F_K^2} \approx \frac{\alpha_\pi}{5} \approx 0.6 \times 10^{-4} fm^3$$

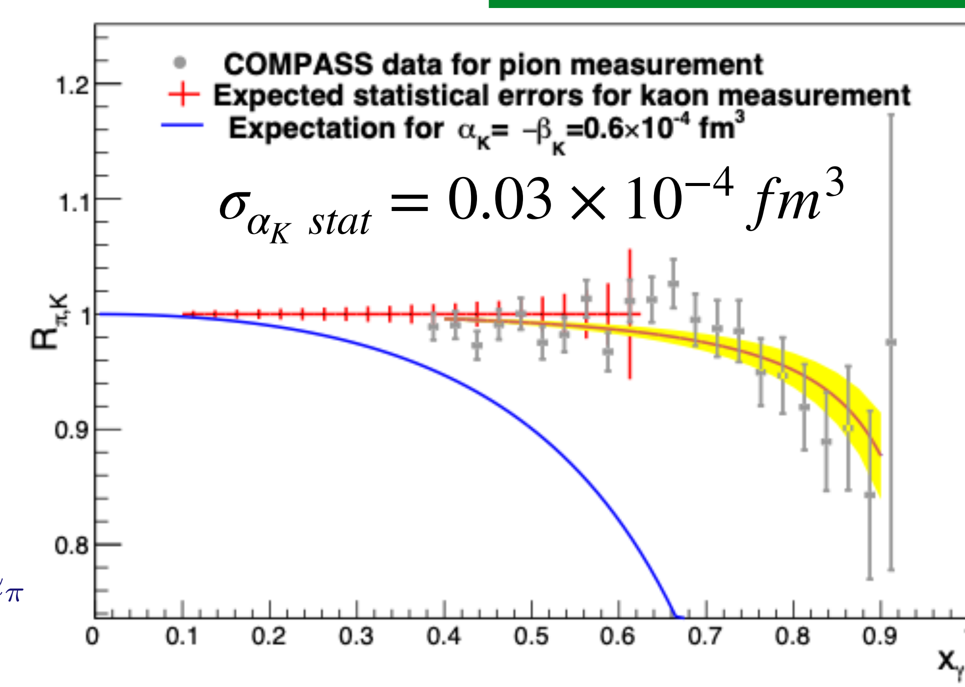
Quark confinement model:

$$\alpha_K + \beta_K = 1.0 \times 10^{-4} fm^3$$

$$\alpha_K = 2.3 \times 10^{-4} fm^3$$

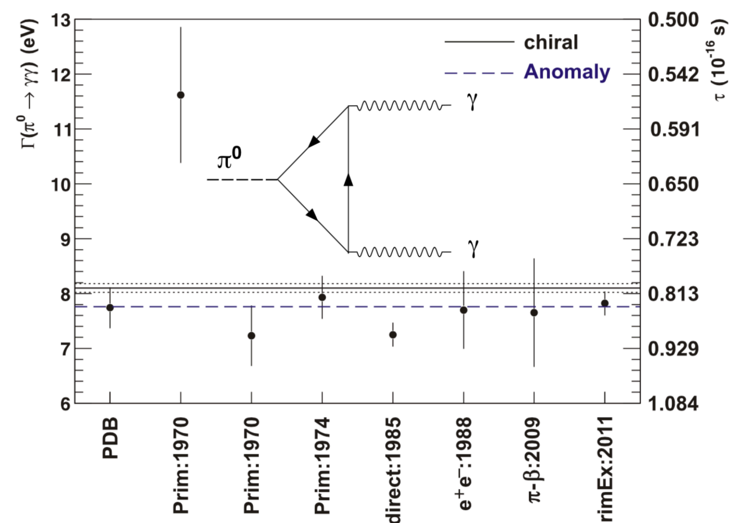


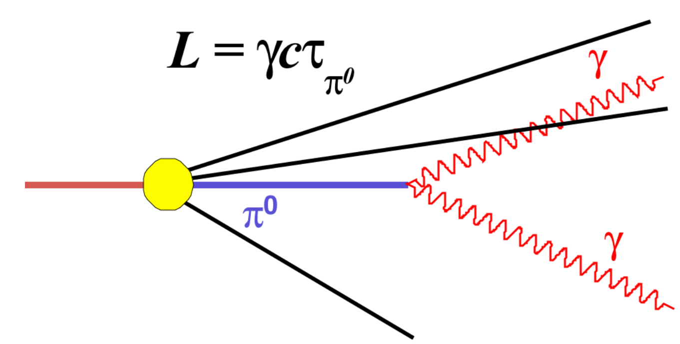
$$R = \frac{\sigma}{\sigma_{p.l.}} \approx 1 - \frac{3}{2} \cdot \frac{x_\gamma^2}{1 - x_\gamma} \cdot \frac{m_\pi^3}{\alpha} \cdot \alpha_\pi$$



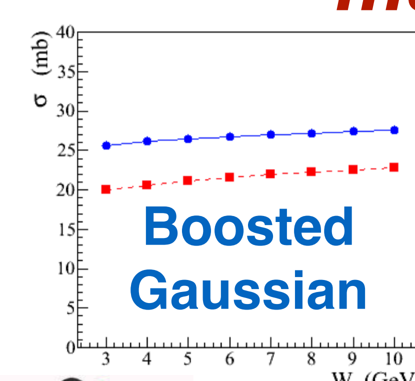
π^0 lifetime

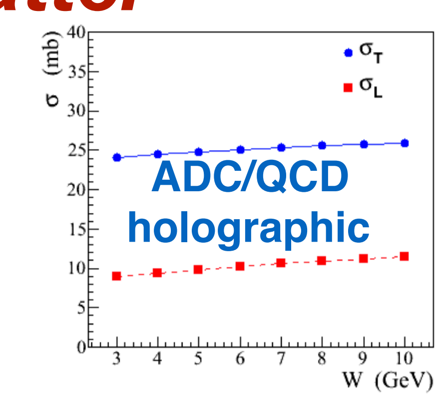
VALUE (10^{-17} s)	EVTS	DOCUMENT ID		TECN	COMMENT
8.52±0.18 OUR AVERAGE		Error includes scale factor of 1.2.			
8.32±0.15±0.18		[1] LARIN	11	PRMX	Primakoff effect
8.5 ±1.1		[2] BYCHKOV	09	PIBE	$\pi^+ \to e^+ \nu \gamma$ at rest
8.4 ±0.5 ±0.5	1182	[3] WILLIAMS	88	CBAL	$e^+ e^- \to e^+ e^- \pi^0$
8.97±0.22±0.17		ATHERTON	85	CNTR	Direct measurement
8.2 ±0.4		[4] BROWMAN	74	CNTR	Primakoff effect

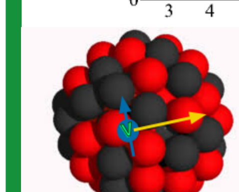




Vector mesons in nuclear matter





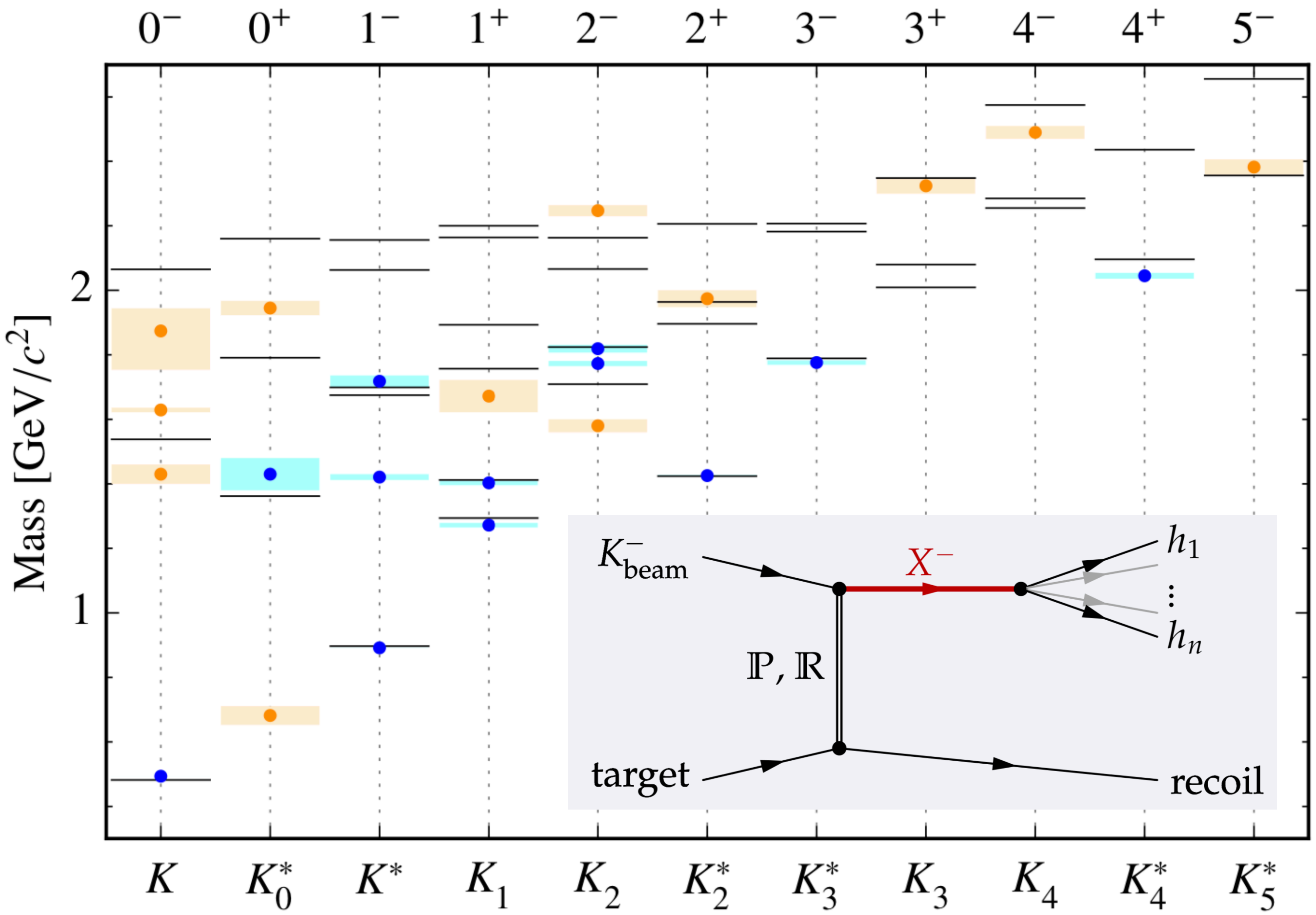


γA → V A (coherent) – σ_T

π⁻A → V A' – σ_L dominates

Hadron spectroscopy

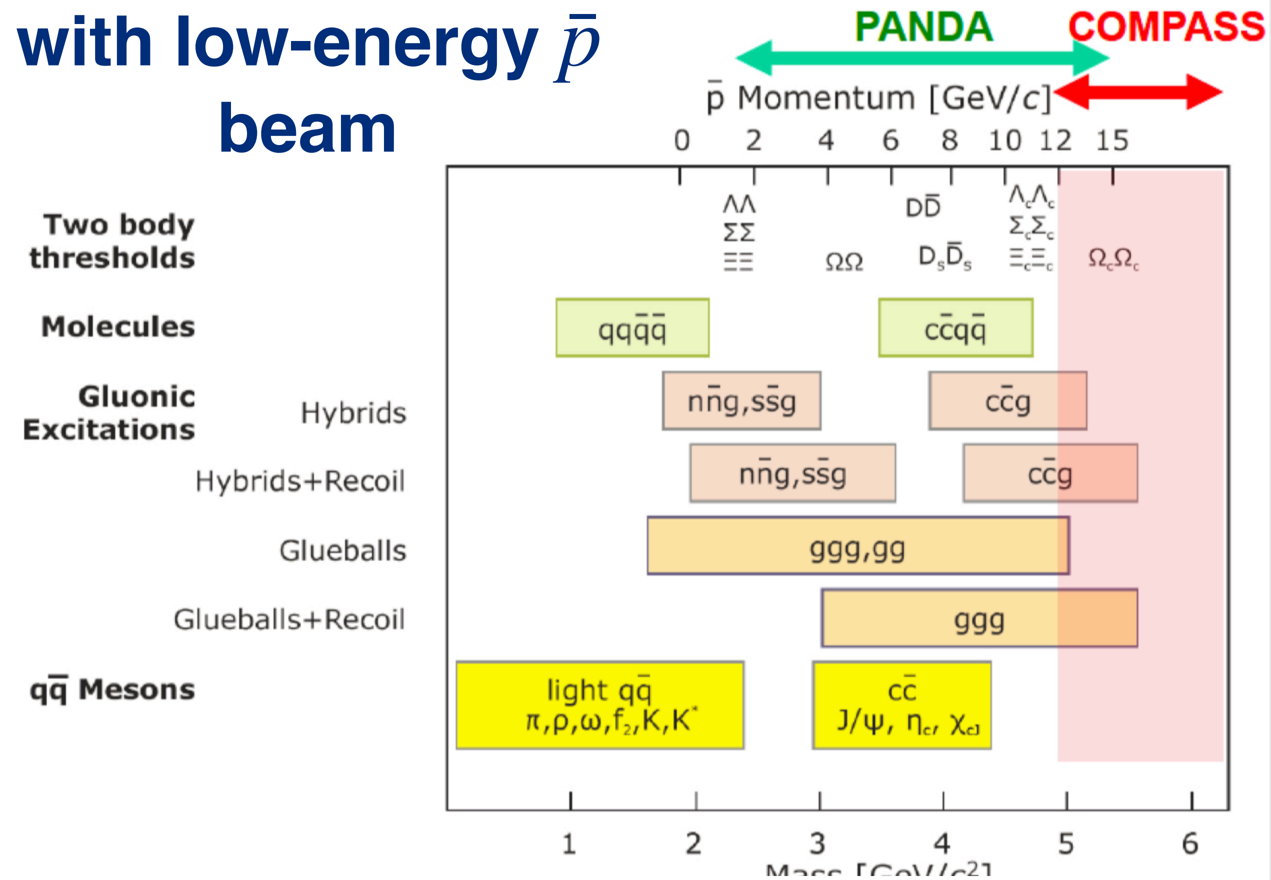
Kaon spectroscopy with kaon beam

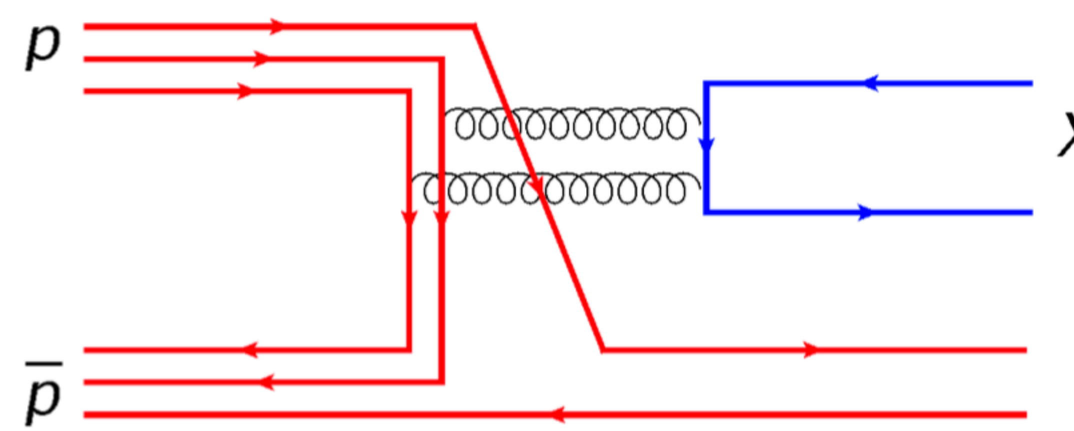


- Most PDG entries more than 30 years old
- Since 1990 only 4 kaon states added to PDG

The kaon section of PDG could be rewritten completely

Exotic charmonia with low-energy $\bar{p}$ beam





Wide spectrum of quantum numbers!

SUMMARY

- COMPASS is a modern fixed-target experiment at CERN with long history.
- Extensive COMPASS physics programme covers such fields as study nucleon spin structure, hadron spectroscopy and photon-meson interactions.
- COMPASS has a versatile setup and unique possibility to operate with both hadron and muon beams.
- A lot of important results have been already published.
- COMPASS continues to collect data according to the approved programme.
- COMPASS has rich plans to continue after 2021 as the COMPASS++/AMBER project with new interesting ideas.