Highlights from the COMPASS Experiment and the AMBER Proposal

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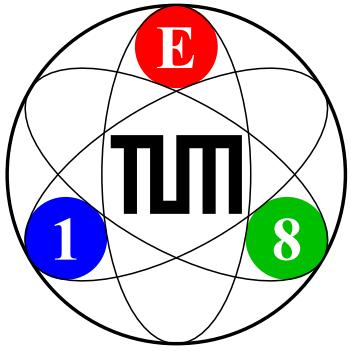
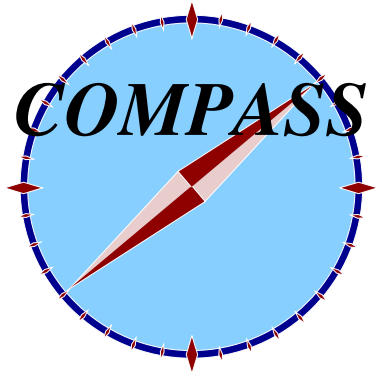
Garching, Germany

Virtuelle DPG-Tagung der Sektion Materie und Kosmos
30.08.2021, HK 1.2





The COMPASS Experiment at the CERN SPS

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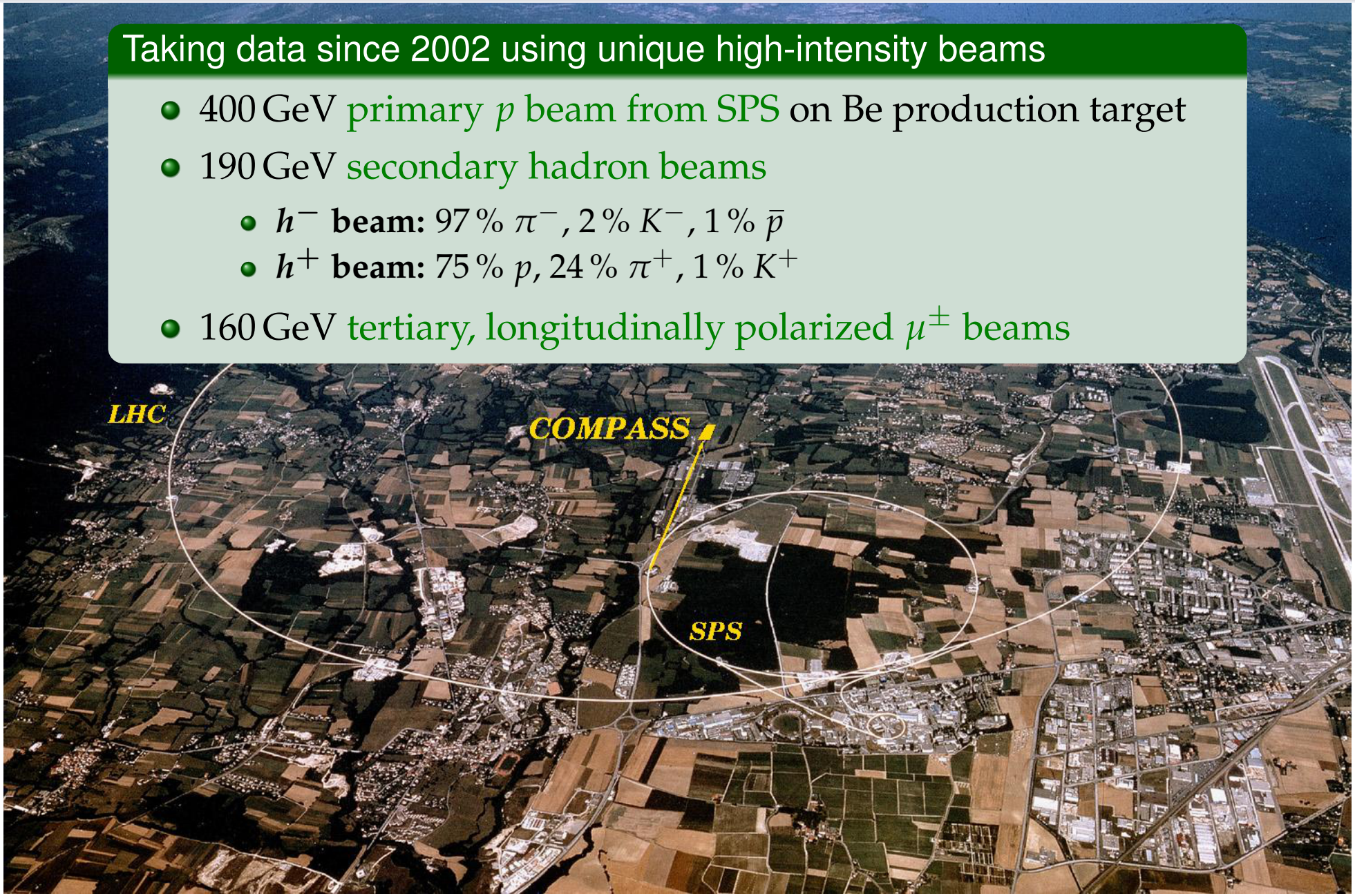
Taking data since 2002 using unique high-intensity beams

- 400 GeV primary p beam from SPS on Be production target
- 190 GeV secondary hadron beams
  - h^- **beam:** 97 % π^-, 2 % K^-, 1 % $\bar{p}$
  - h^+ **beam:** 75 % p, 24 % π^+, 1 % K^+
- 160 GeV tertiary, longitudinally polarized $\mu^\pm$ beams



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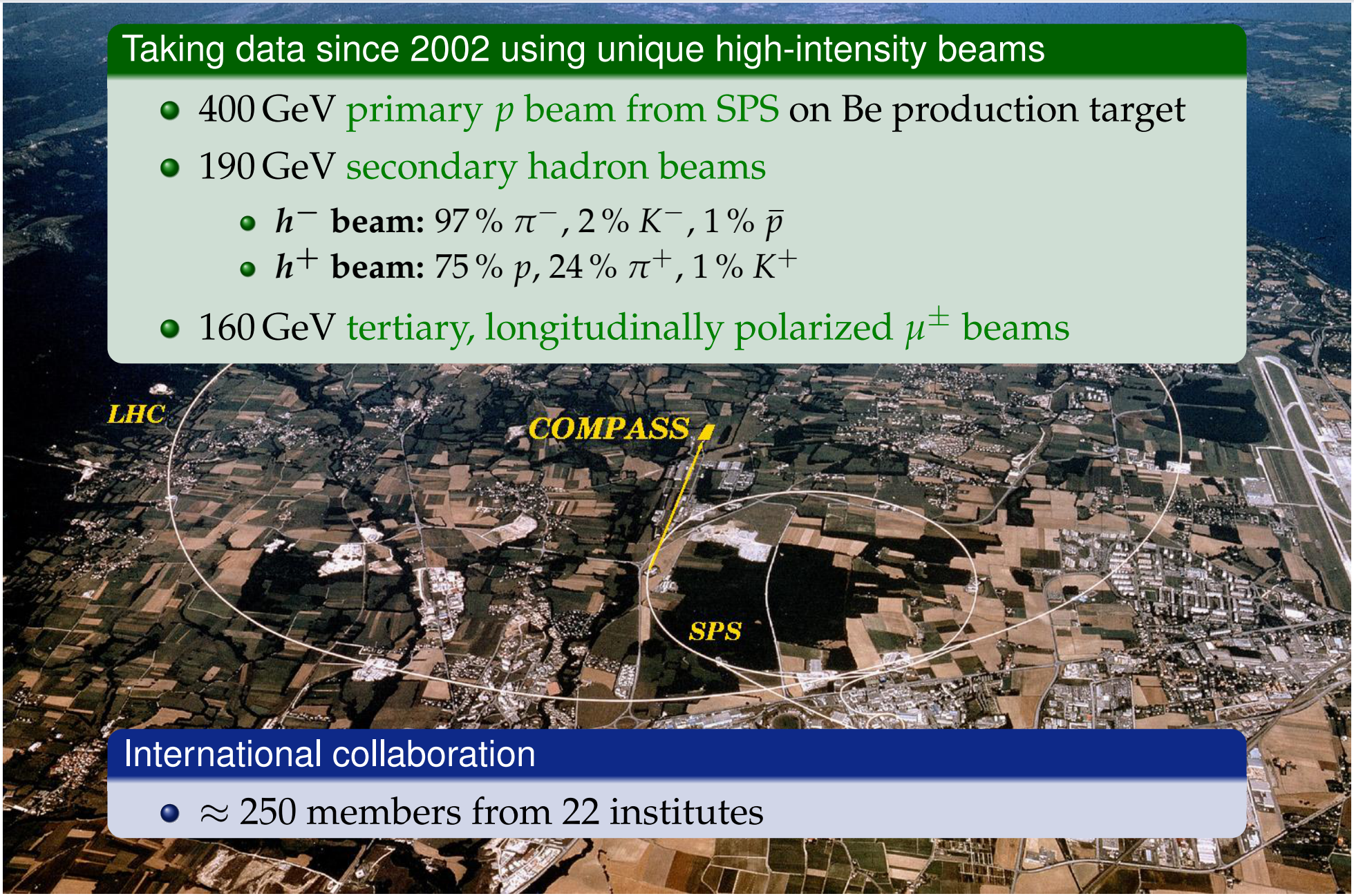


International collaboration

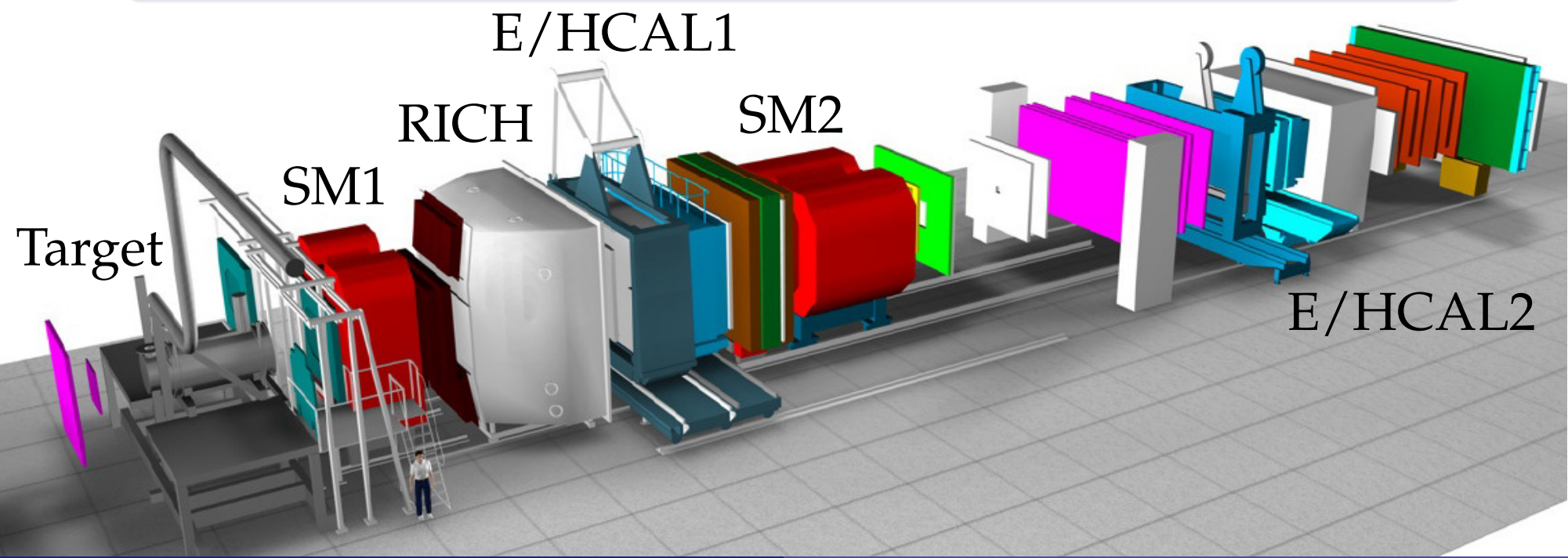
- $\approx$ 250 members from 22 institutes

The COMPASS Experiment at the CERN SPS

Versatile Experimental Setup

P. Abbon *et al.*, NIMA **577** (2007) 455, NIMA **779** (2015) 69

- Large-acceptance two-stage spectrometer
- Precise tracking ($\approx$ 350 planes) and PID (CEDAR, RICH, calorimeters, muon system)
- Various targets
  - Polarized solid-state NH_3 or ^6LiD
  - Liquid H_2
  - Solid-state nuclear targets (e.g. Ni, W, Pb)



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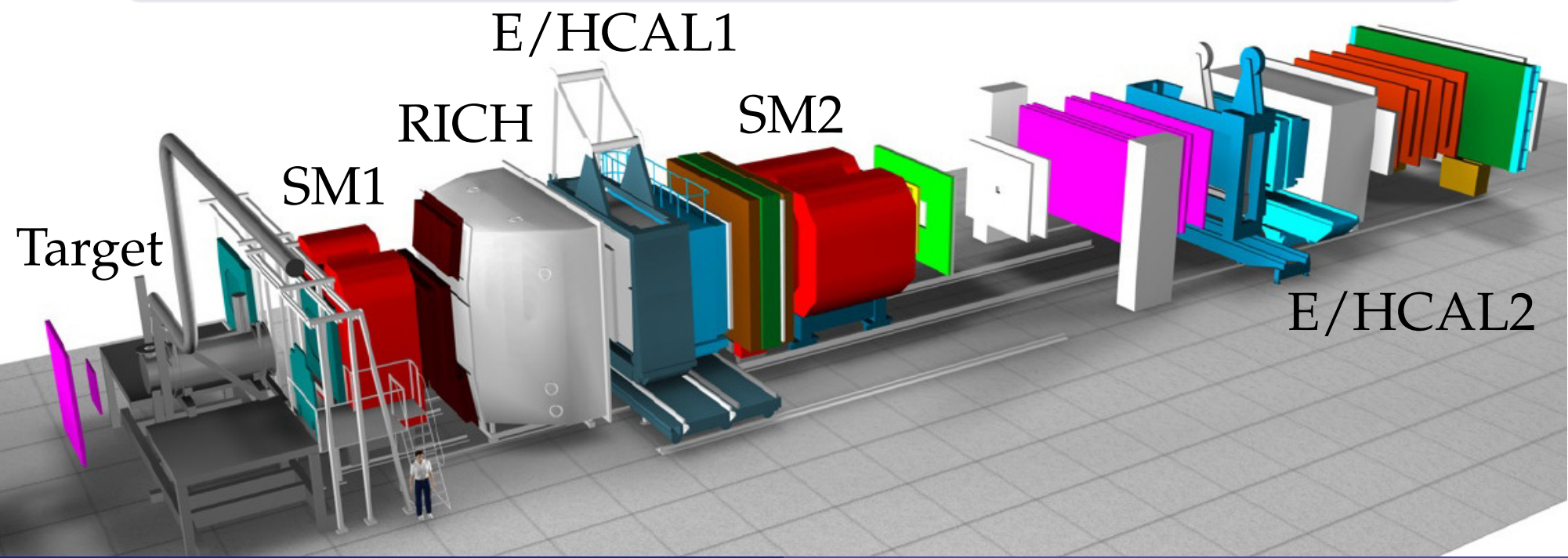

The COMPASS Experiment at the CERN SPS

Broad Physics Program to study Structure and Excitation Spectrum of Hadrons

Increasing resolution scale (momentum transfer) →

Chiral dynamics

- Test chiral perturbation theory in $\pi\gamma$ and $K\gamma$ reactions using π and K beams
- $\pi^{\pm}$ and $K^{\pm}$ polarizabilities
- Chiral anomaly $F_{3\pi}$

Hadron spectroscopy

- Diffractive scattering of π and K beams
- High-precision measurement of light-meson spectrum
- Exotic hadrons

Nucleon structure

- Hard scattering of $\mu^{\pm}$ and π^{-} off polarized nucleons
- Study of nucleon spin structure
- Extraction of parton distribution functions and fragmentation functions

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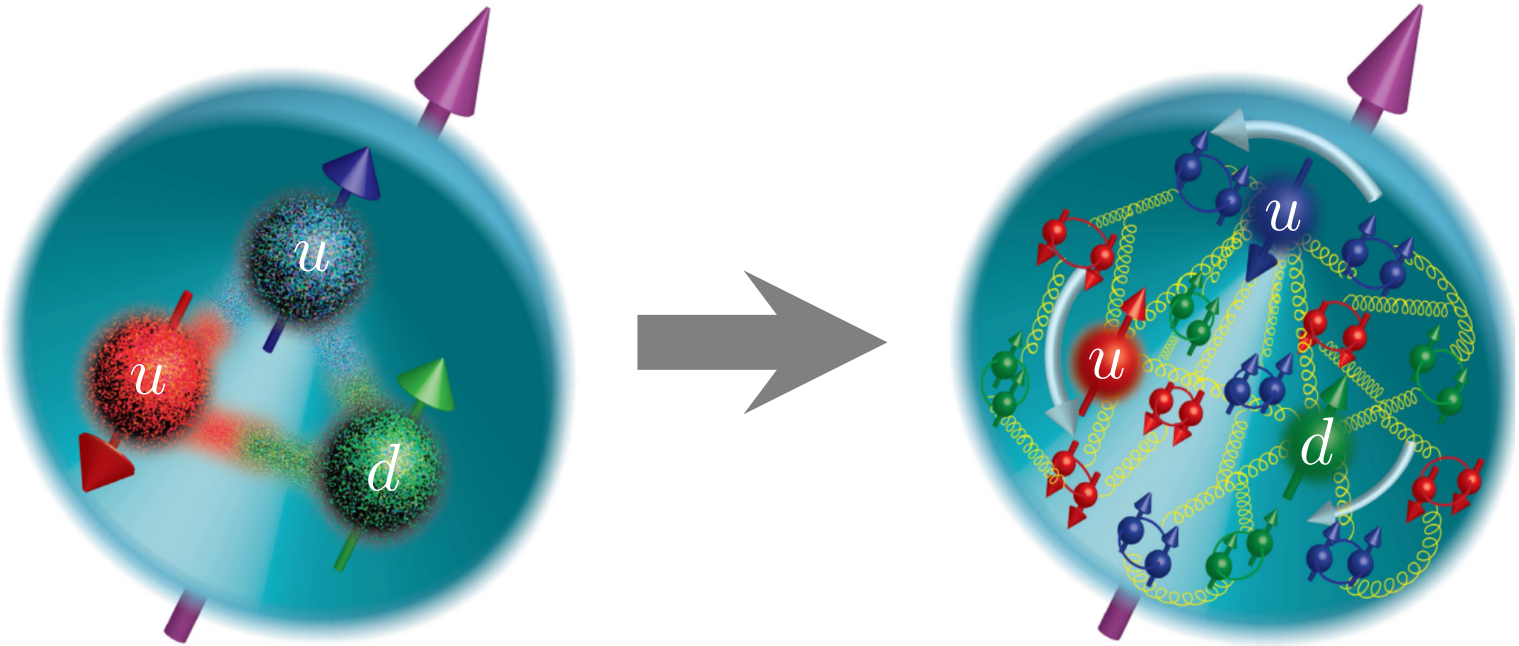
Studying the Nucleon Spin Structure at COMPASS

The Structure of the Nucleon

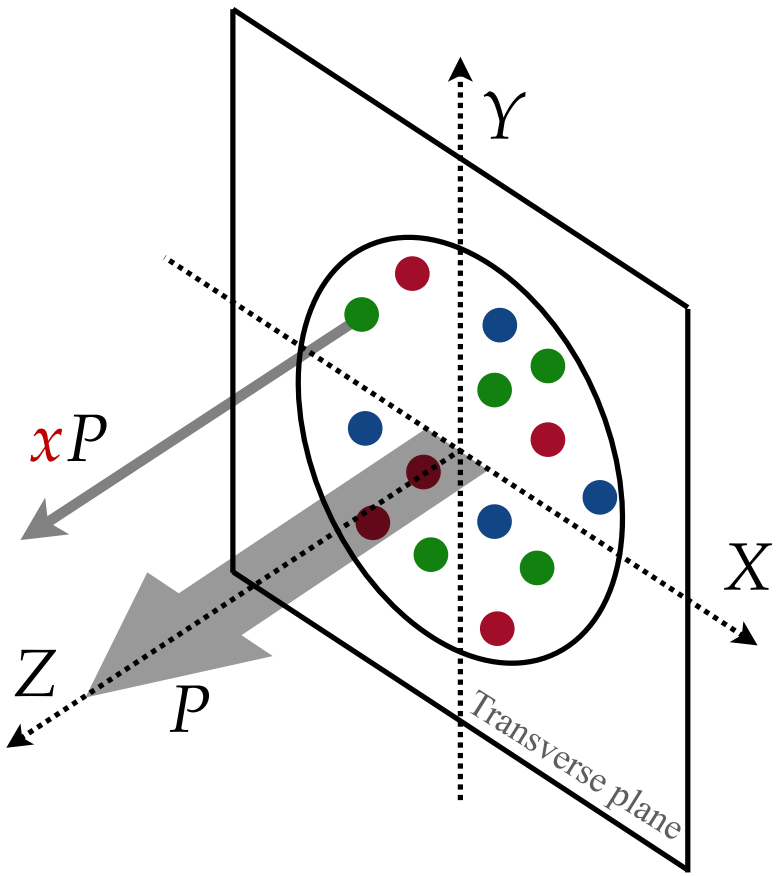


Many open questions

- How do spins of quarks and gluons (partons) and their orbital angular momenta make up the nucleon spin?
- How is nucleon spin correlated with the motion of partons?
- How does nucleon spin influence the spatial distribution of partons?

"Infinite-momentum frame"

- Neglect transverse movement of partons in nucleon
- All partons move parallel to nucleon and carry momentum fraction x
- Parton distribution functions (PDFs)
  $f_1^q(x) =$ probability for parton
  $q = \{g, u, d, s, \bar{u}, \bar{d}, \bar{s}, \ldots\}$ in nucleon
  to carry momentum fraction x
  - Not directly calculable from QCD Lagrangian $\Longrightarrow$ extraction from:
  - Process-independent
  - Very well known



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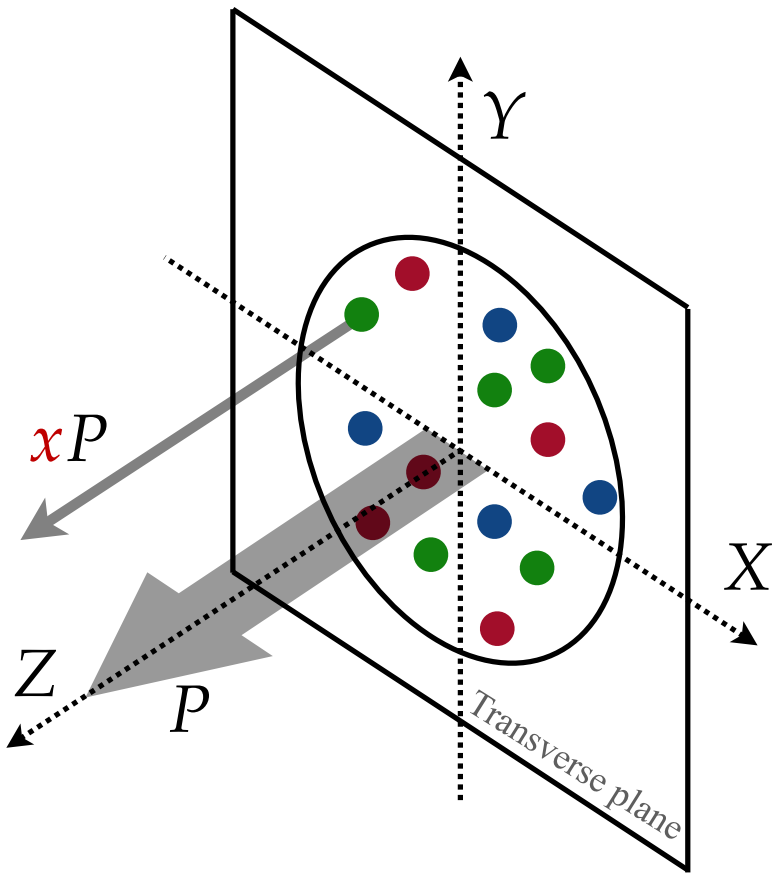

Parton Distribution Functions of the Nucleon

Unpolarized Partons in unpolarized Nucleon: Momentum Distributions

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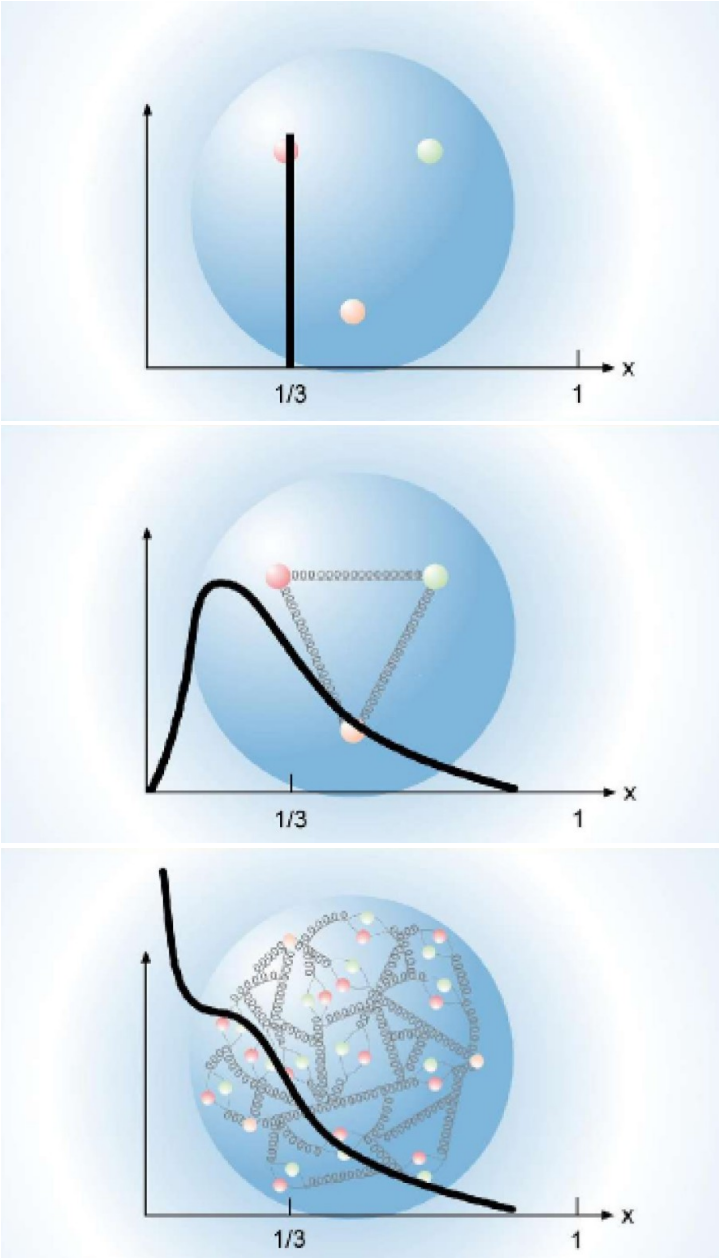

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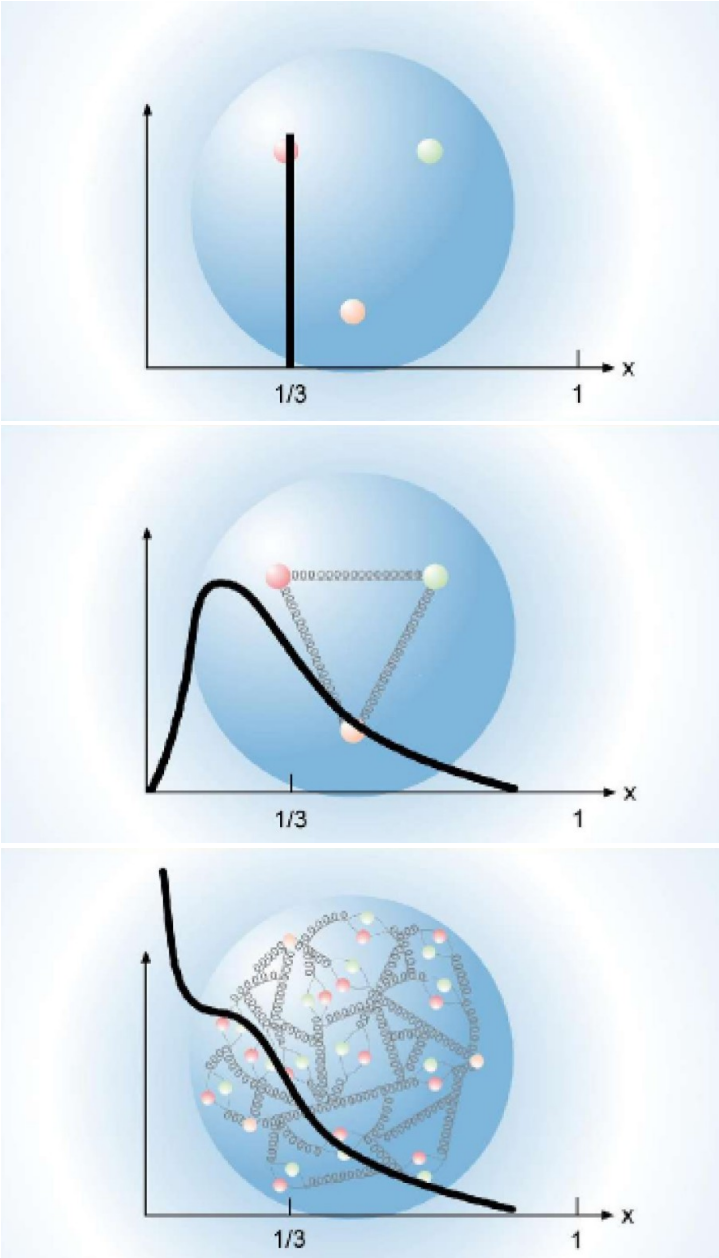

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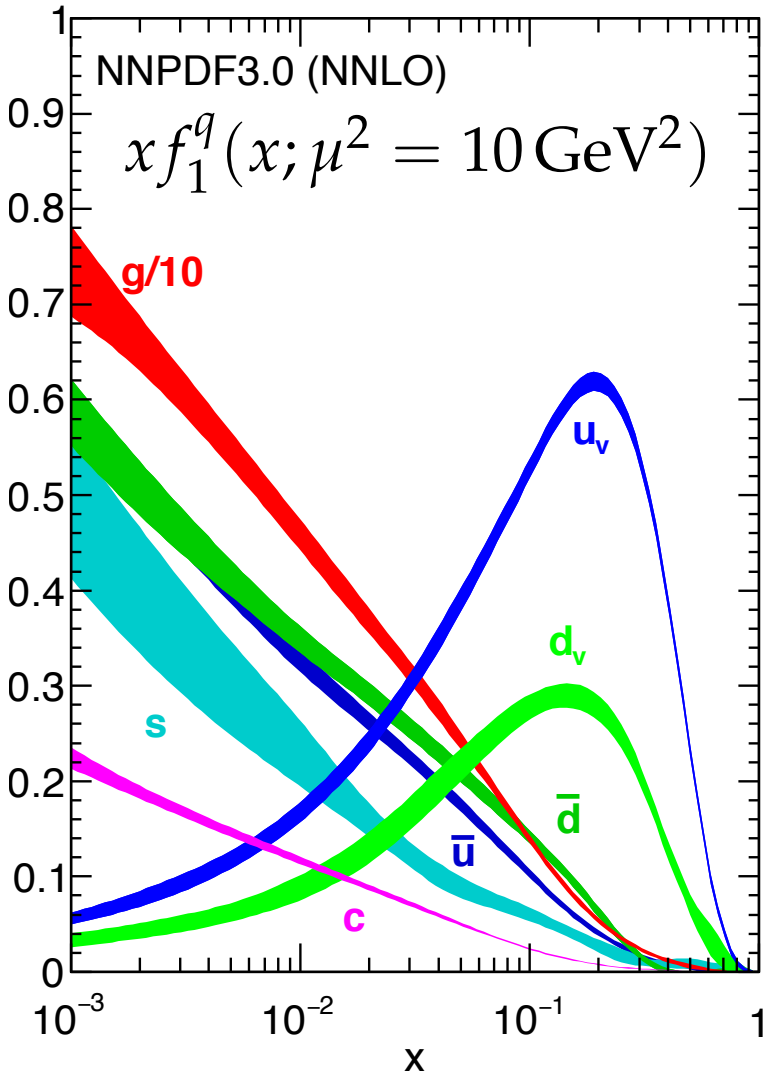

PDG, PTEP **2020** (2020) 083C01

Parton Distribution Functions of the Nucleon

Parton Polarization in polarized Nucleon: Spin Distributions

- Helicity distribution functions
  $g_1^q(x) = q^{\vec{\Rightarrow}}(x) - q^{\overleftarrow{\Rightarrow}}(x)$
  longitudinal polarization of parton q with x in nucleon with fixed longitudinal polarization
  - Well known
- Transversity distribution functions
  $h_1^q(x) = q^{\uparrow\Uparrow}(x) - q^{\downarrow\Uparrow}(x)$
  transverse polarization of parton q with x in nucleon with fixed transverse polarization
  - First measurement in 2005 (HERMES and COMPASS)
- *Collinear approximation:* nucleon structure described by 3 PDFs
  - Insufficient to explain all data

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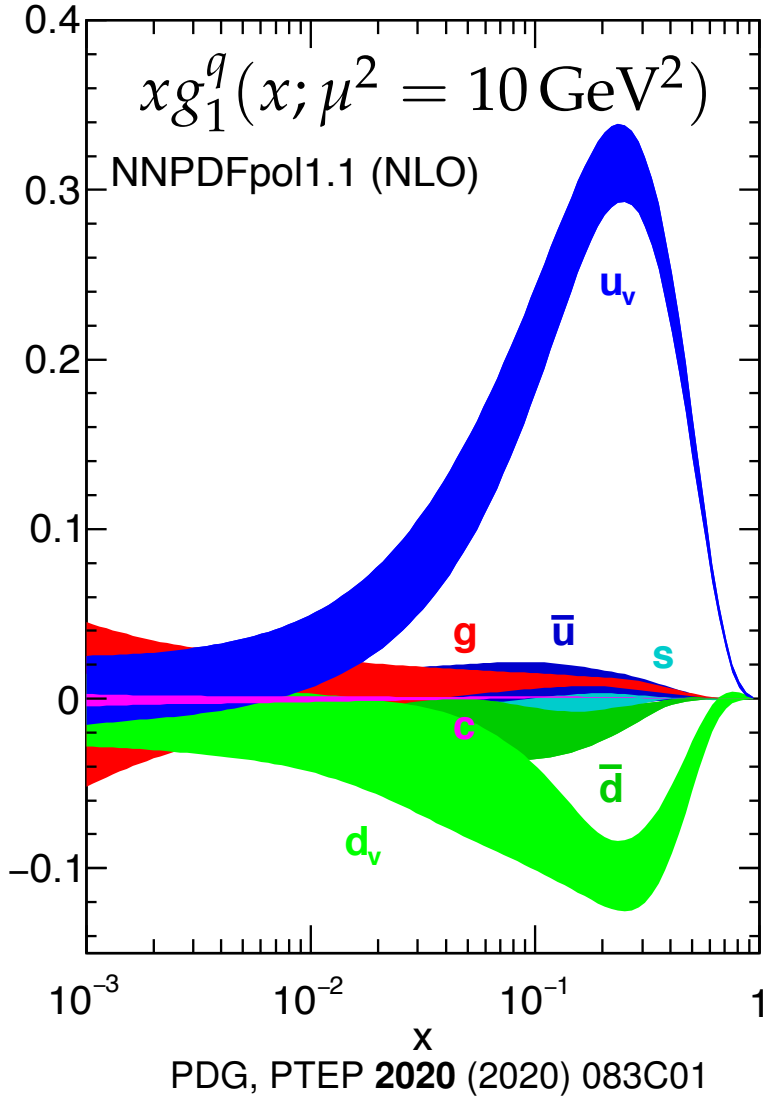

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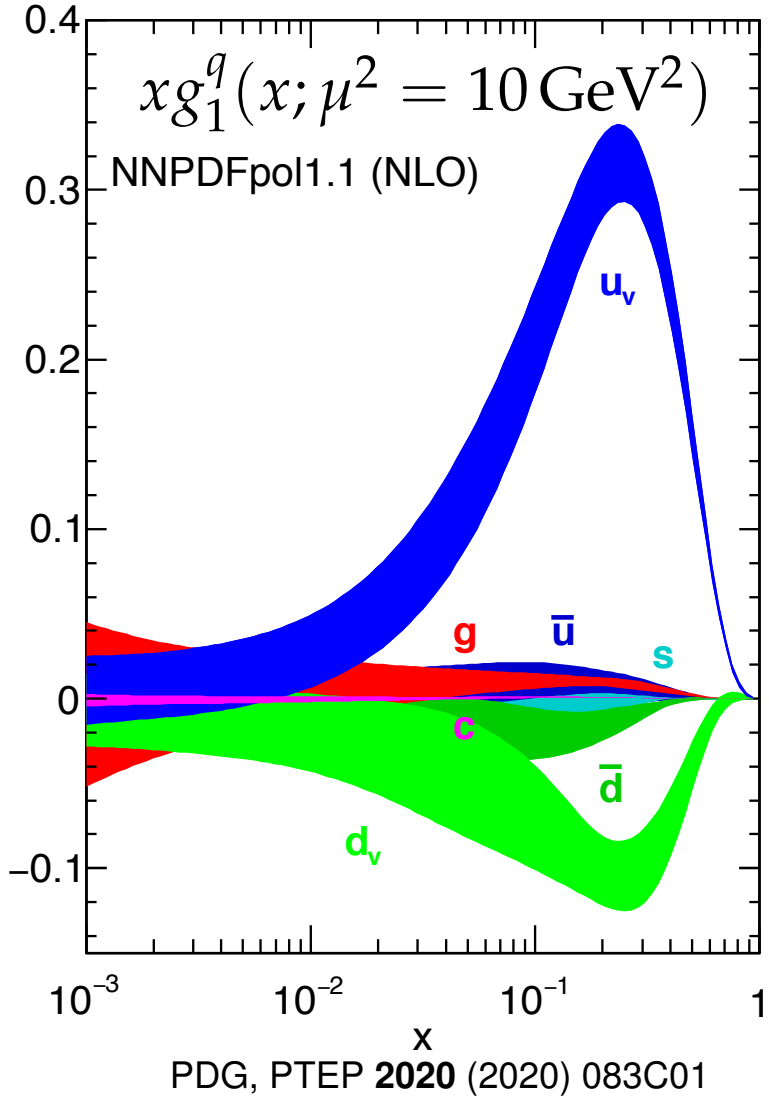

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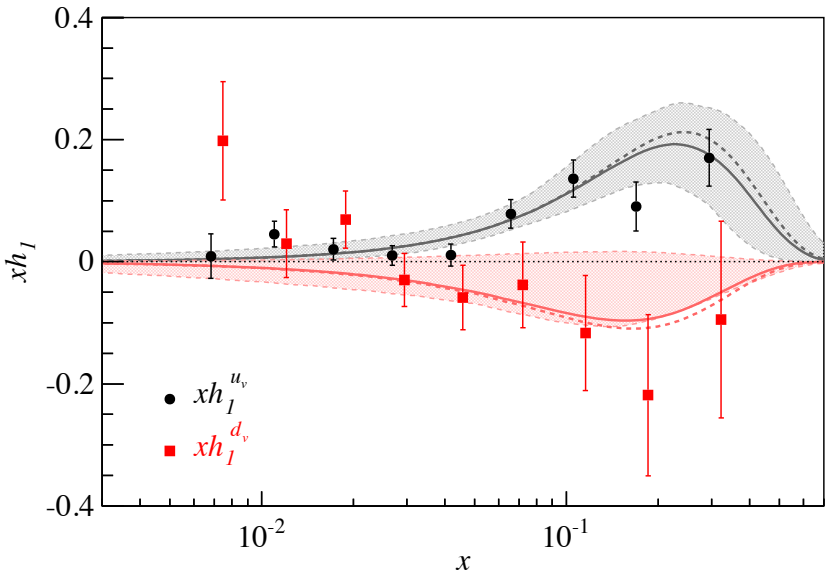

Points:
A. Martin *et al.*, PRD **91** (2015) 014034

Curves:
M. Anselmino *et al.*, PRD **87** (2013) 094019

Goal of COMPASS run 2021

Halve uncertainties on h_1^d

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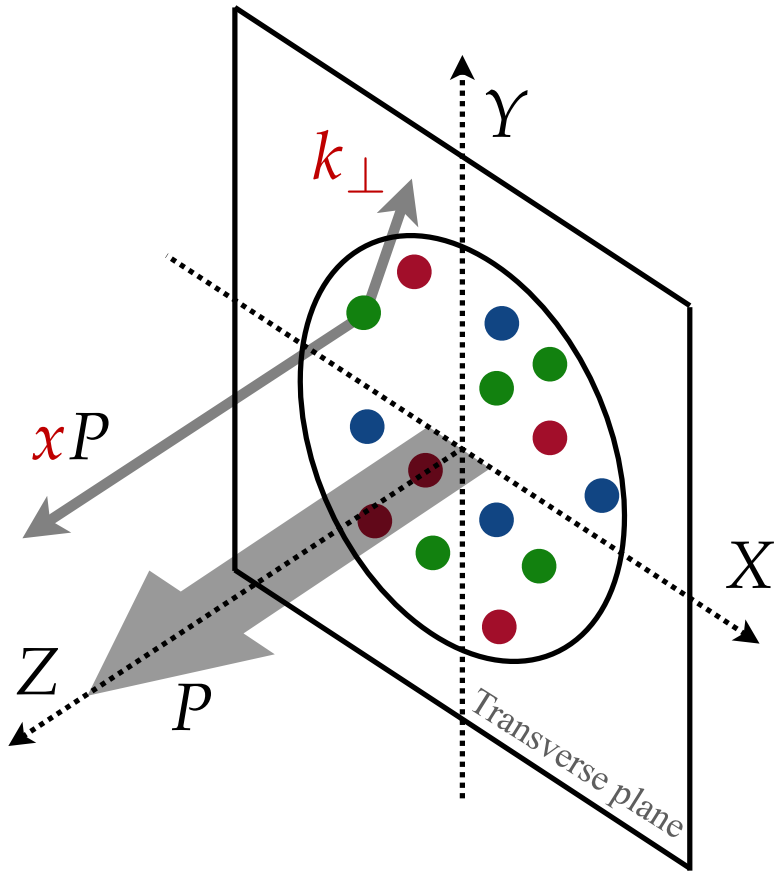
Nucleon \ Parton	U	L	T
U	$f_1(x)$		
L		$g_1(x)$	
T			$h_1(x)$

Parton Distribution Functions of the Nucleon

Extension: Transverse-Momentum-Dependent PDFs

- Additional information:
  - Transverse momentum $k_\perp$ of parton in nucleon
  - Correlation of $k_\perp$ with transverse spin of parton in nucleon
  - Correlation of both with transverse spin of nucleon
- 8 Transverse-Momentum-Dependent (TMD) PDFs
  - Mostly unknown
- COMPASS measures TMD PDFs using two reactions:
  - Semi-inclusive deep inelastic scattering (SIDIS): $\mu + N \rightarrow \mu + h + X$
  - Drell-Yan process (DY): $\pi^- + N \rightarrow \mu^+\mu^- + X$



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U	$f_1(x)$		
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Nucleon \ Parton	U	L	T
U	$f_1(x, k_\perp^2)$		$h_1^\perp(x, k_\perp^2)$
L		$g_1(x, k_\perp^2)$	$h_{1L}^\perp(x, k_\perp^2)$
T	$f_{1T}^\perp(x, k_\perp^2)$	$g_{1T}(x, k_\perp^2)$	$h_1(x, k_\perp^2)$ $h_{1T}^\perp(x, k_\perp^2)$

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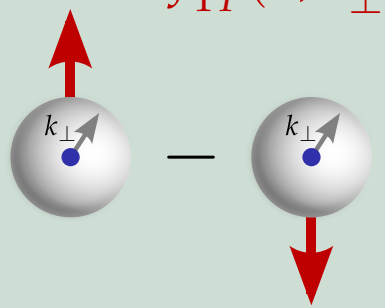
Example

- Sivers PDF $f_{1T}^\perp(x, k_\perp^2)$



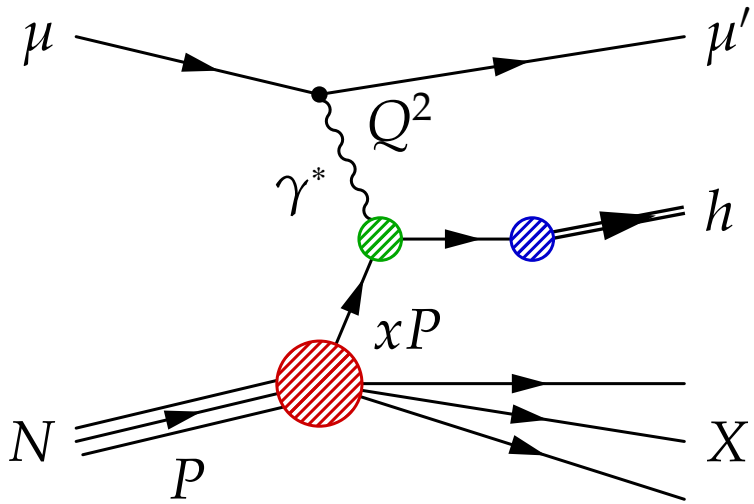
- Correlation of $k_\perp$ of unpolarized parton with nucleon spin

Sivers Function: Semi-Inclusive Deep Inelastic Scattering

Factorization of leading-order cross section

$$\mathrm{d}\sigma(\mu\, N \to \mu'\, h\, X)$$
$$\propto \sum_q \mathrm{PDF}_q \otimes \mathrm{d}\sigma(\mu\, q \to \mu'\, q') \otimes \mathrm{FF}_{q\to h}$$

- Parton distribution function
- Hard muon-quark cross section
- Fragmentation function



- Disentangle terms via their different angular dependence
- $\mathrm{d}\sigma \propto \left[1 + S_T\, A_{UT}^{\sin(\phi_h - \phi_S)}\, \sin(\phi_h - \phi_S) + \ldots\right]$
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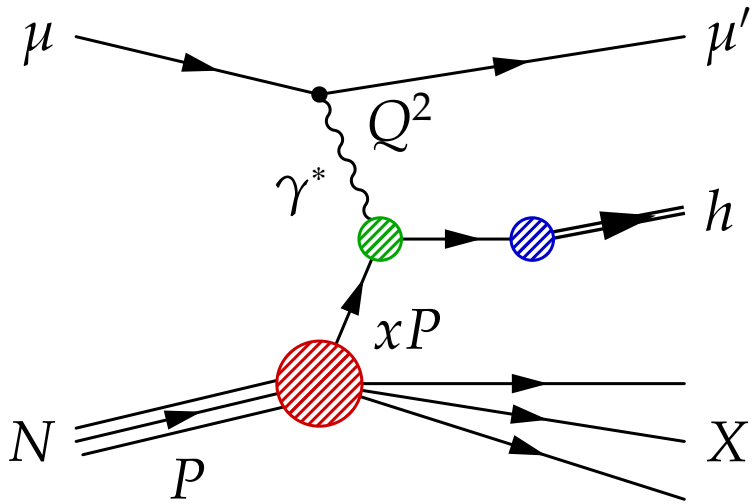

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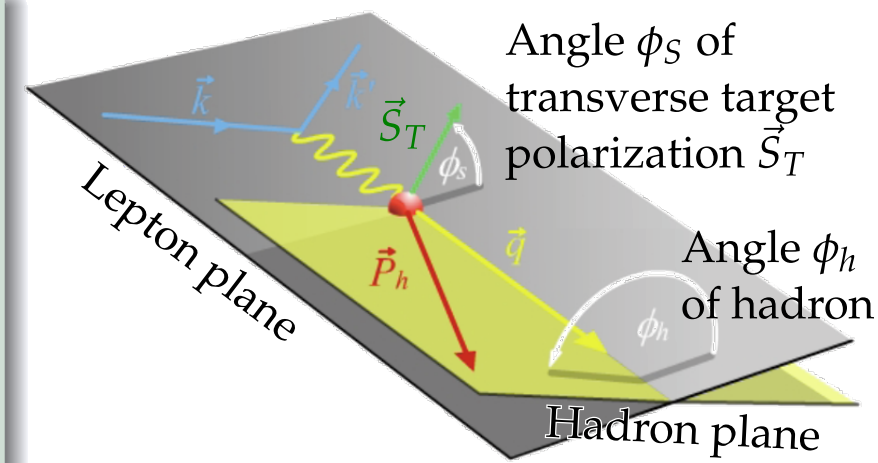

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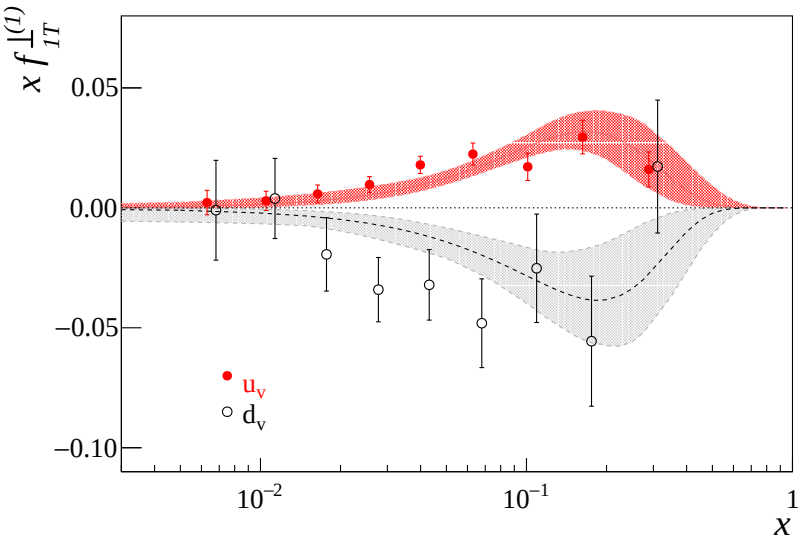


Points:

COMPASS, NPB **940** (2019) 34

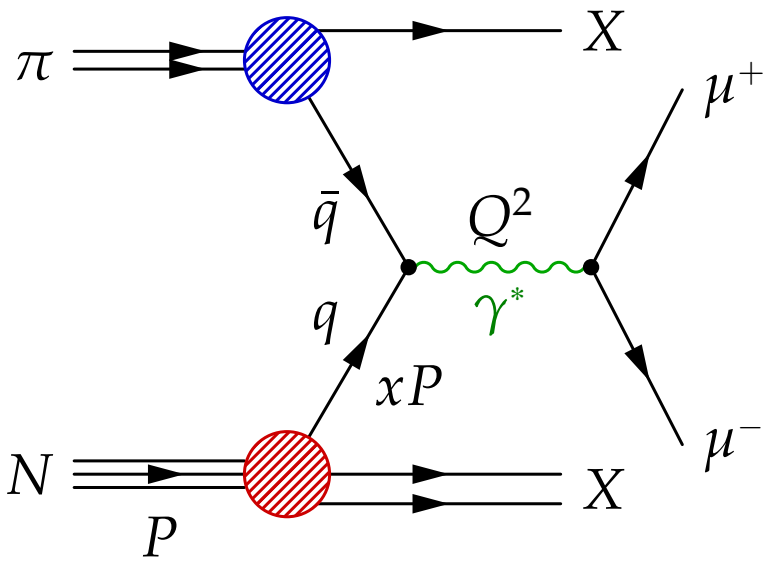
Curves:

M. Anselmino *et al.*, PRD **86** (2012) 014028

Sivers Function: Drell-Yan Process

Factorization of cross section

- Convolutions $\mathrm{PDF}_{q,N} \otimes \mathrm{PDF}_{\bar{q},\pi^-}$ of distribution functions for nucleon and pion
- Hard $q\bar{q} \to \mu^+\mu^-$ cross section



- Disentangle terms via their different angular dependence
- $\mathrm{d}\sigma \propto \left[1 + S_T\, A_T^{\sin\phi_S}\, \sin\phi_S + \ldots\right]$
- Asymmetry $A_T^{\sin\phi_S} \propto f_{1T,N}^{\perp q} \otimes f_{1,\pi}^{\bar{q}}$

Sivers Function: Drell-Yan Process

Factorization of cross section

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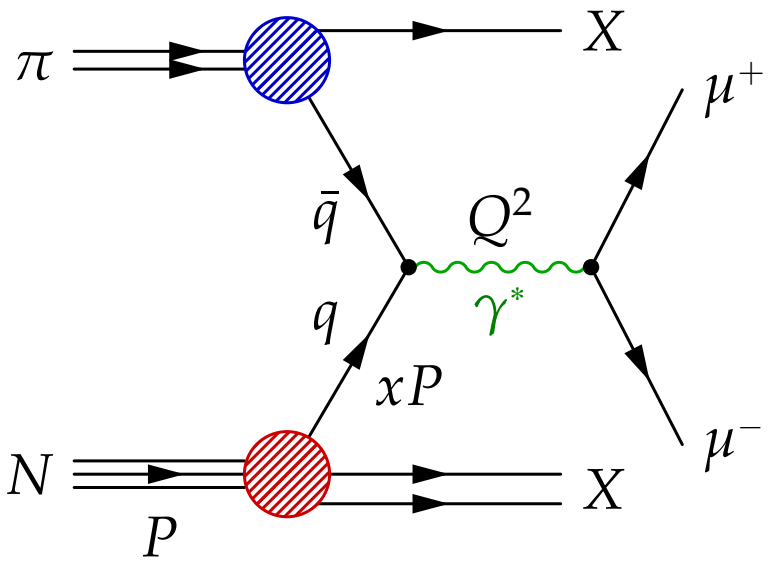

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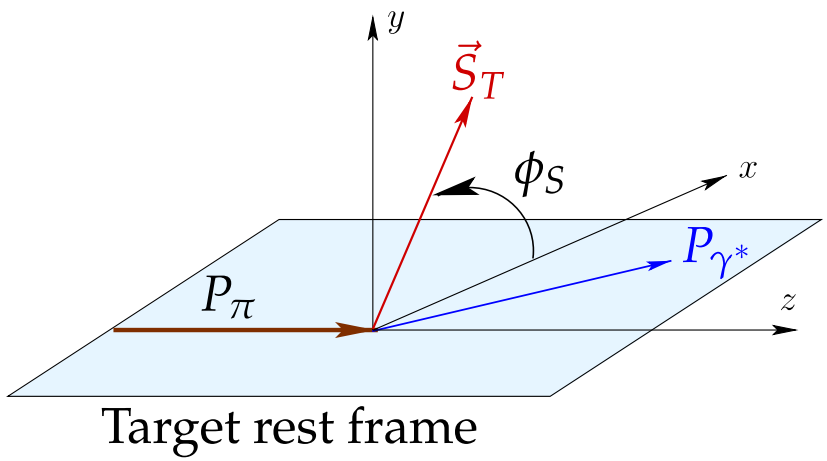

Target rest frame

Sivers Function

- Complementary information from semi-inclusive deep inelastic scattering and Drell-Yan process

Semi-incl. deep inelastic scatt.

- Asymmetry
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- Fundamental prediction following from QCD gauge invariance
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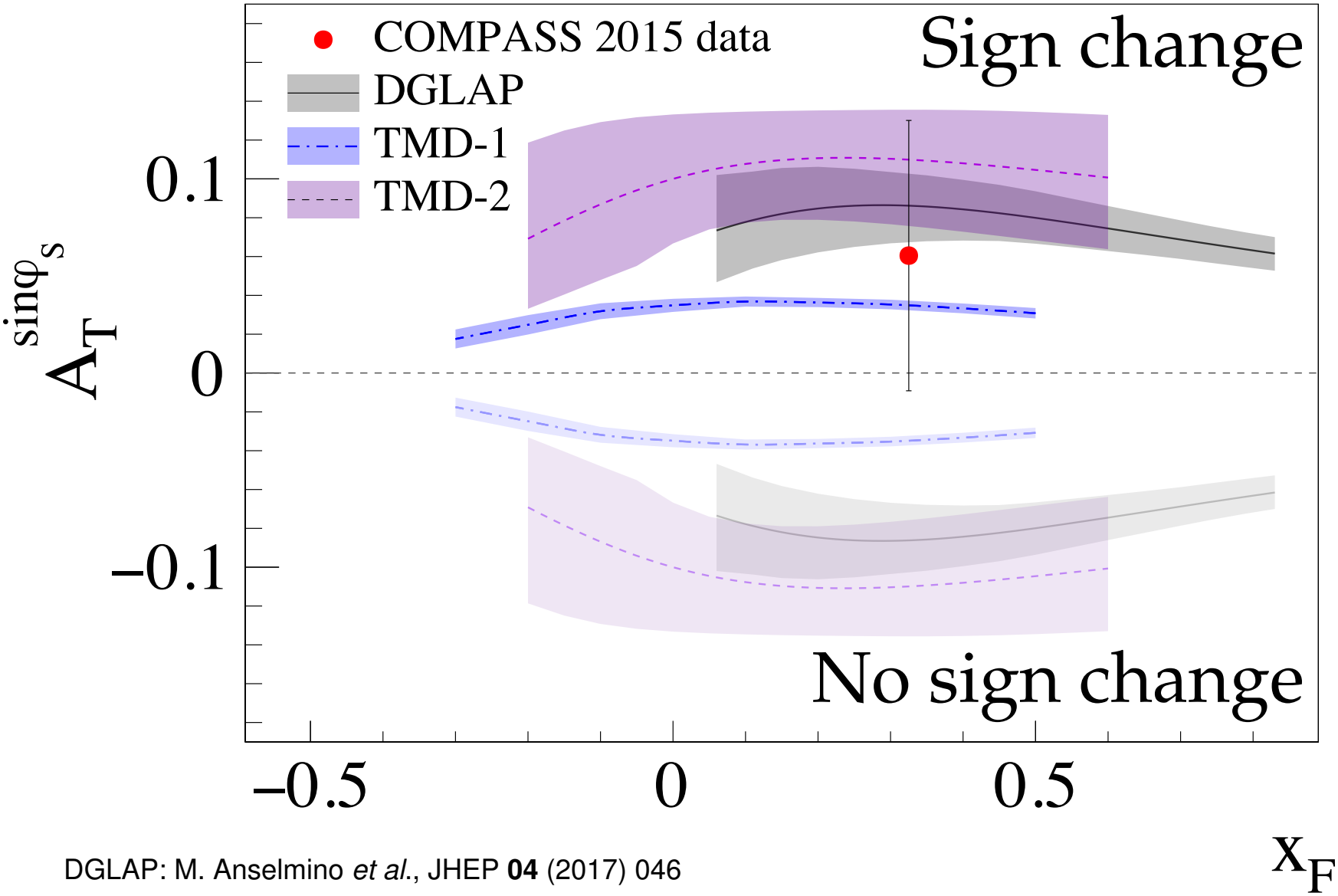
Sign Change of Sivers Function

Drell-Yan data in favor of sign-change hypothesis

COMPASS, PRL **119** (2017) 112002



DGLAP: M. Anselmino *et al.*, JHEP **04** (2017) 046

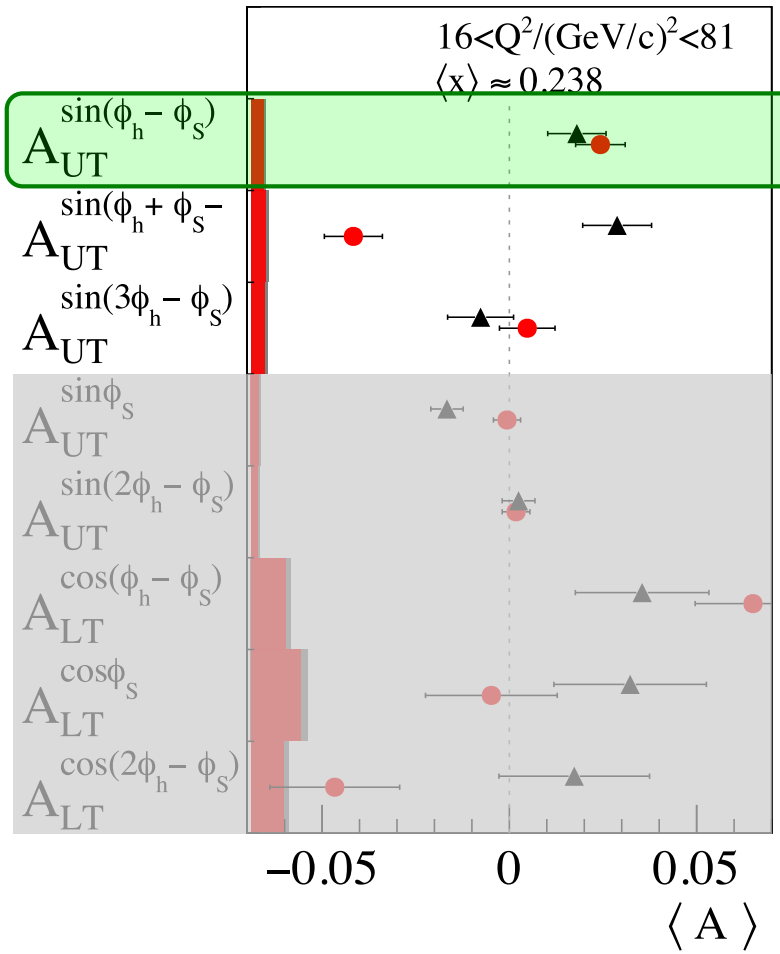
TMD1: M.G. Echevarria *et al.*, PRD **89** (2014) 074013

TMD2: P. Sun *et al.*, PRD **88** (2013) 114012

Sign Change of Sivers Function

Work in Progress: Combined Analysis of all COMPASS Drell-Yan Data

Semi-inclusive deep inelastic scattering

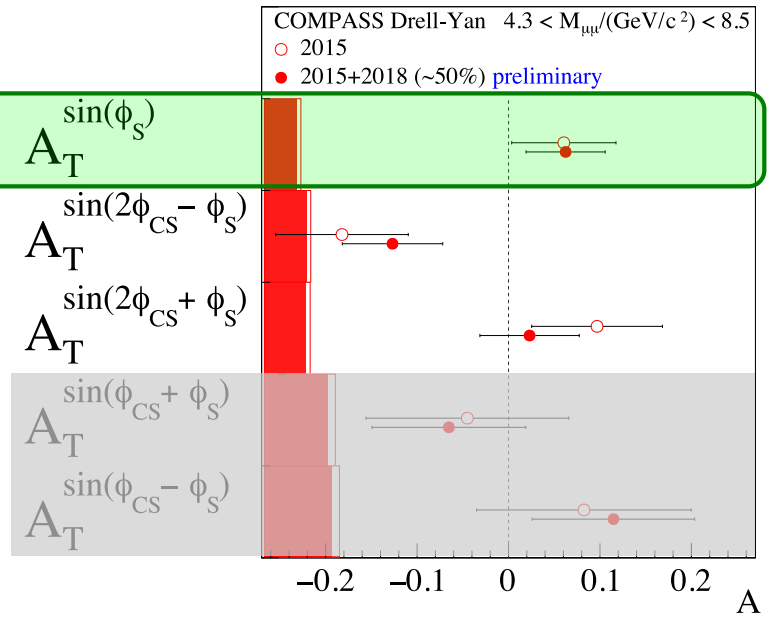


Sivers

Transversity

Pretzelosity

Drell-Yan process



- Additional 2018 data
  $\approx 1.2\times$ 2015 data

COMPASS, PLB **770** (2017) 138

Parton Distribution Functions of the Nucleon

Extension: Generalized Parton Distribution Functions

- Additional information:
  - Transverse position $r_\perp$ of parton in nucleon $\Longrightarrow$ spatial distribution
  - Correlation between $r_\perp$ and x of parton in nucleon
  - Complementary to TMD PDFs
- 8 generalized parton distribution functions (GPDs)
  - Mostly unknown
  - Contain information about parton orbital angular momentum
- Measured in exclusive processes:
  - Deeply virtual Compton scattering (DVCS): $\mu + N \rightarrow \mu + \gamma + N$
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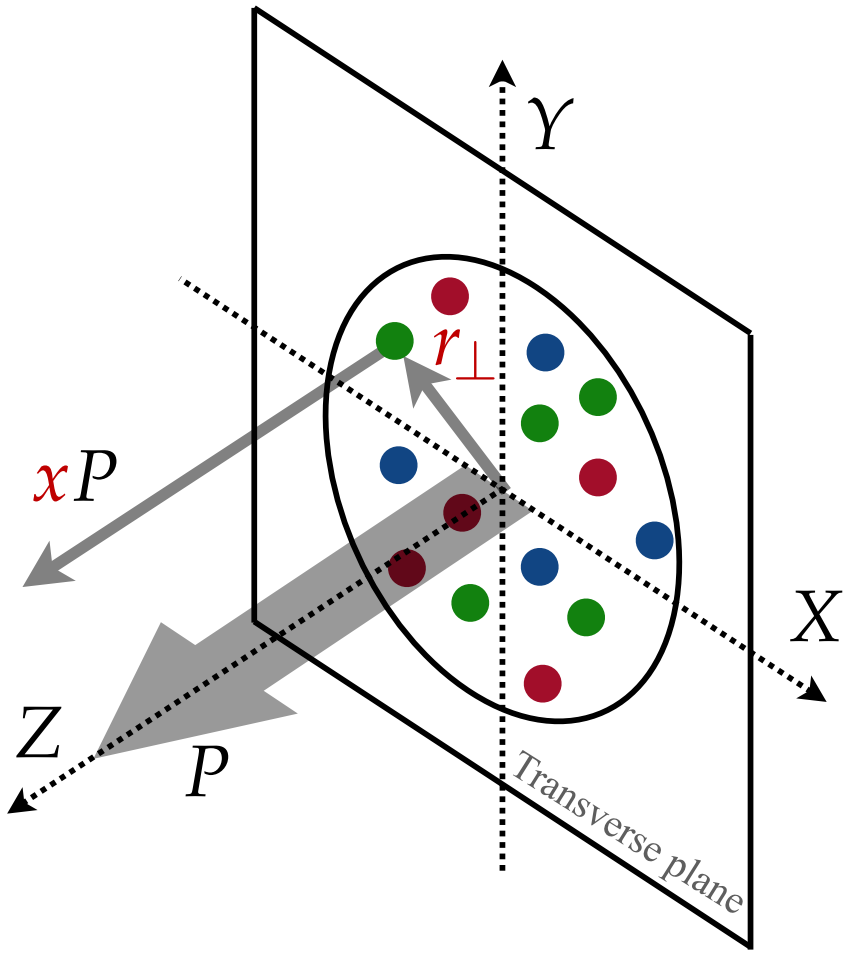

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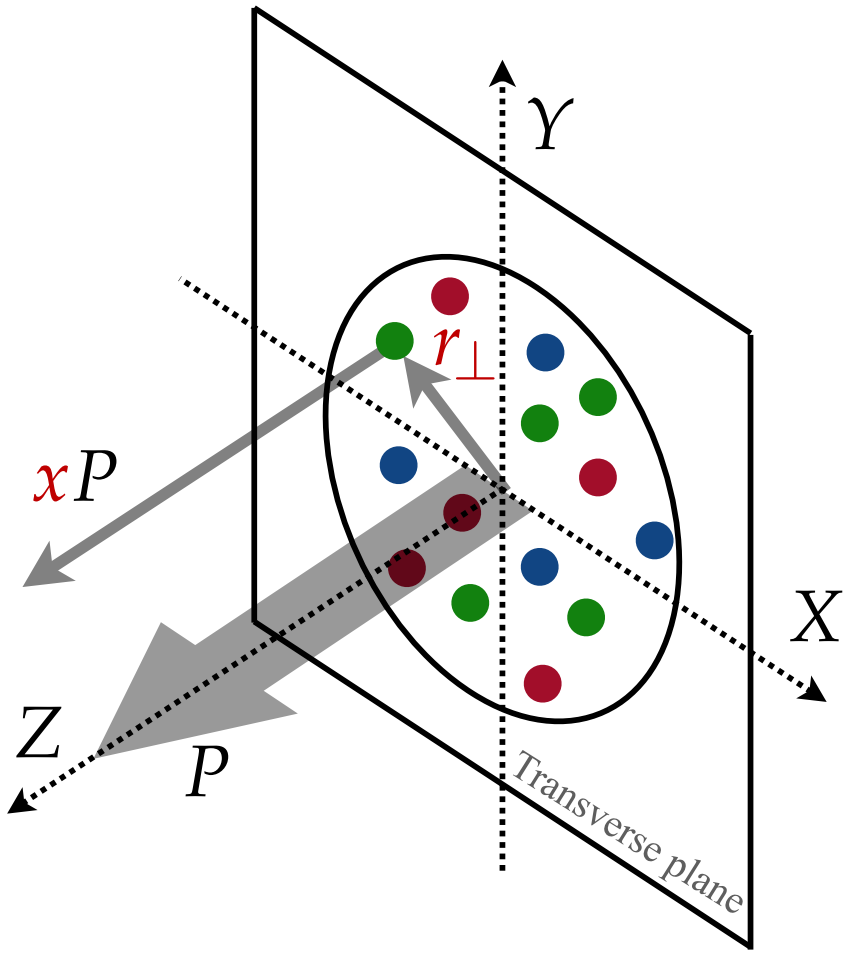

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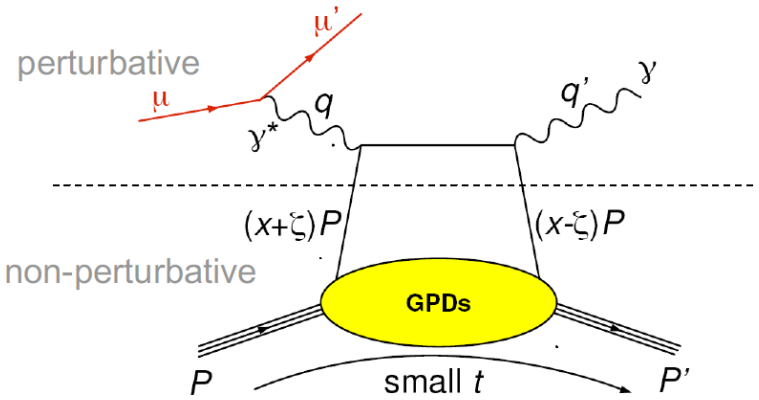
Deeply virtual Compton scattering



see talk by J. Giarra (HK 14.2, Tue 17:00)

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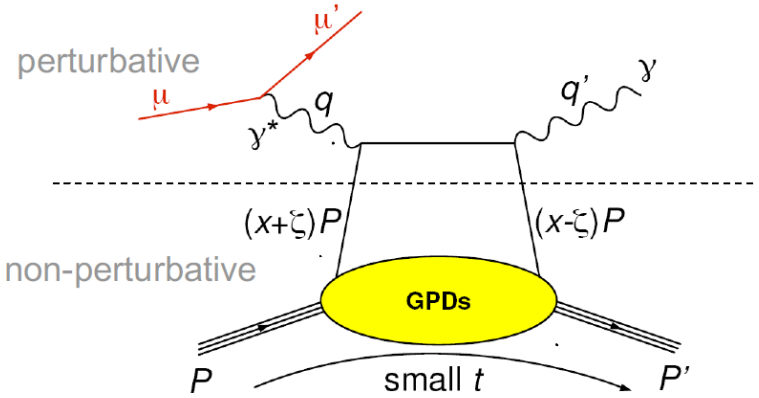

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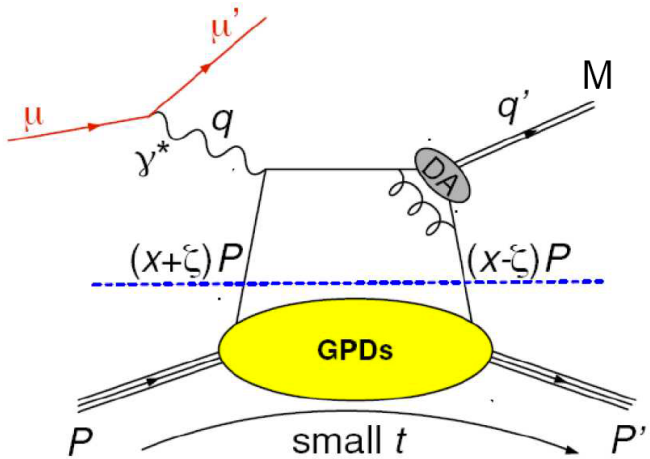
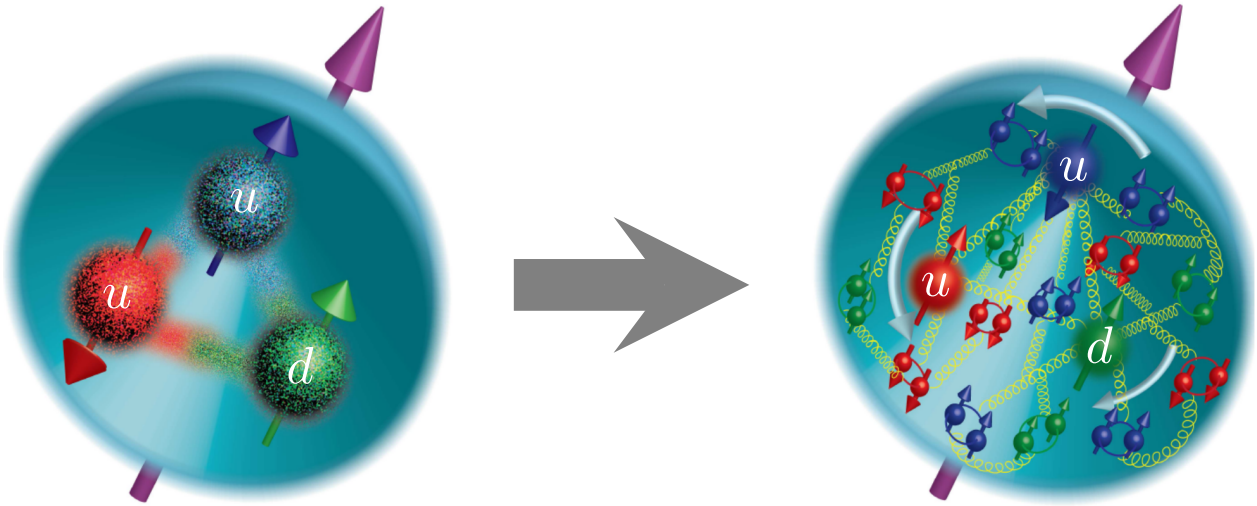
Hard exclusive meson production



Nucleon Structure at COMPASS

Summary



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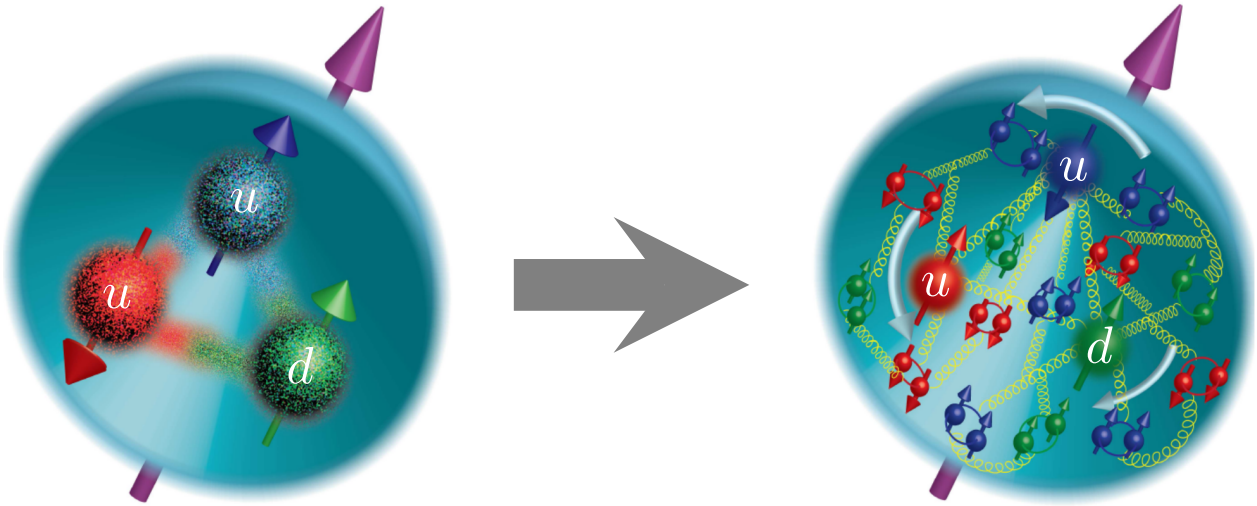

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Studying the Excitation Spectrum of light Mesons at COMPASS

The light-Meson Frontier

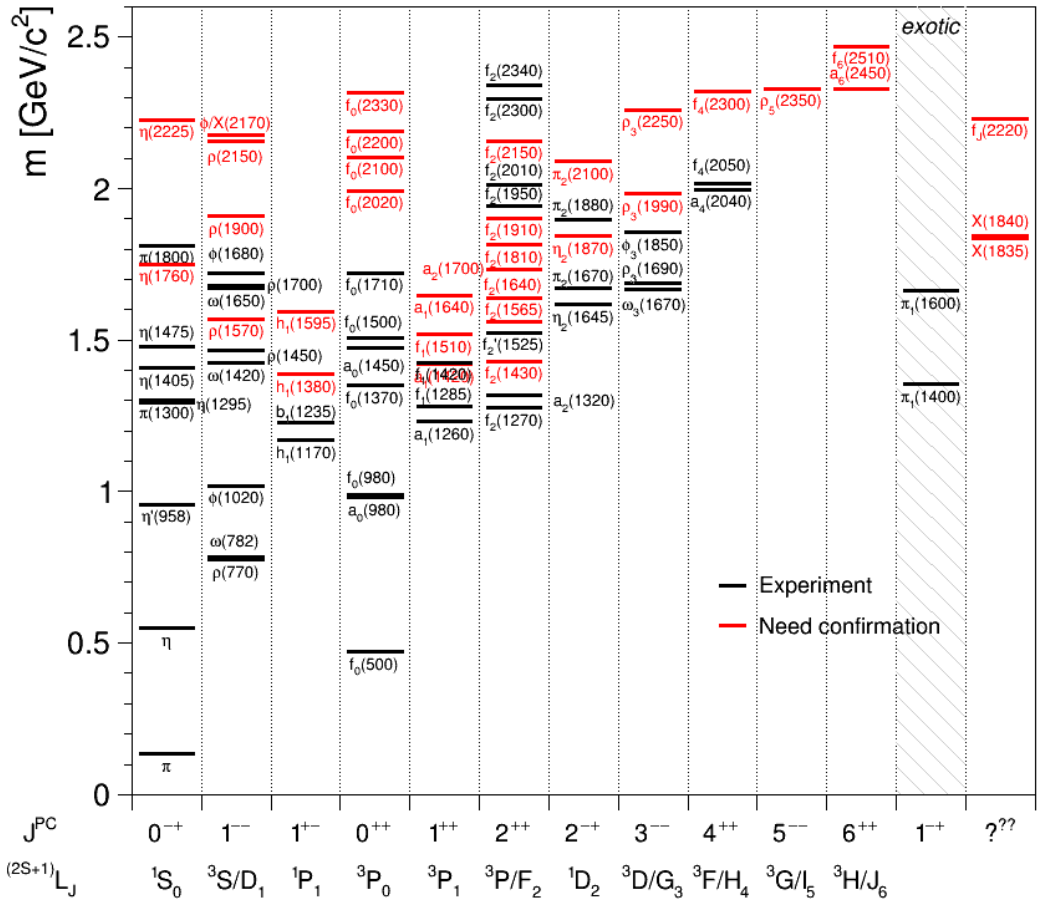
Light mesons

- $|q\bar{q}\rangle$ states made of u, d, and s (anti)quarks
- States characterized by
  - Isospin I
  - Spin J
  - Parity P
  - Charge conjugation C
  - Mass
  - Total width (lifetime)
  - Partial widths (decay modes)

The light-Meson Frontier

- Many states need confirmation in mass region $m \gtrsim 2\,\mathrm{GeV}/c^2$
- Many wide states $\Longrightarrow$ overlap and mixing
- Identification of higher excitations becomes exceedingly difficult

Spectrum of light non-strange mesons



[Courtesy K. Götzen, GSI]

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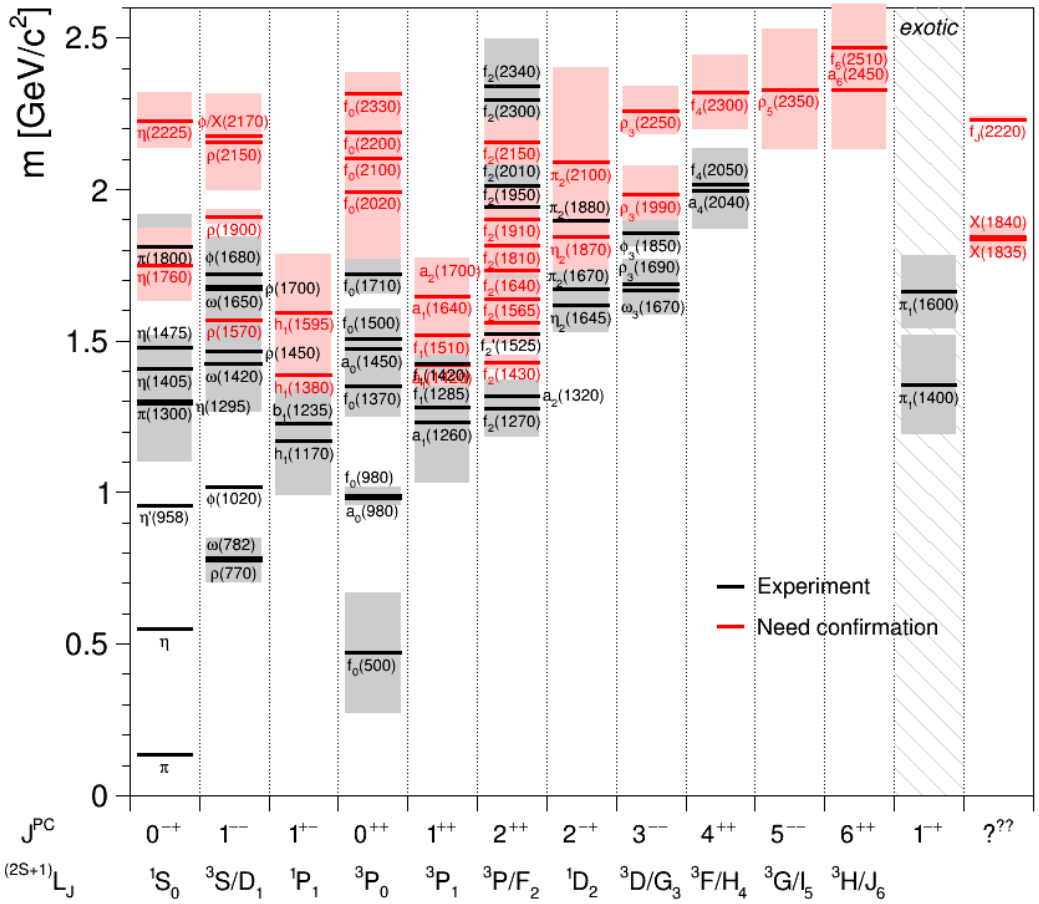

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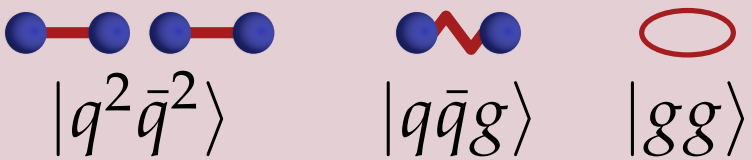
Goal: precision measurement

- Confirm higher excitations
- Search for exotic states



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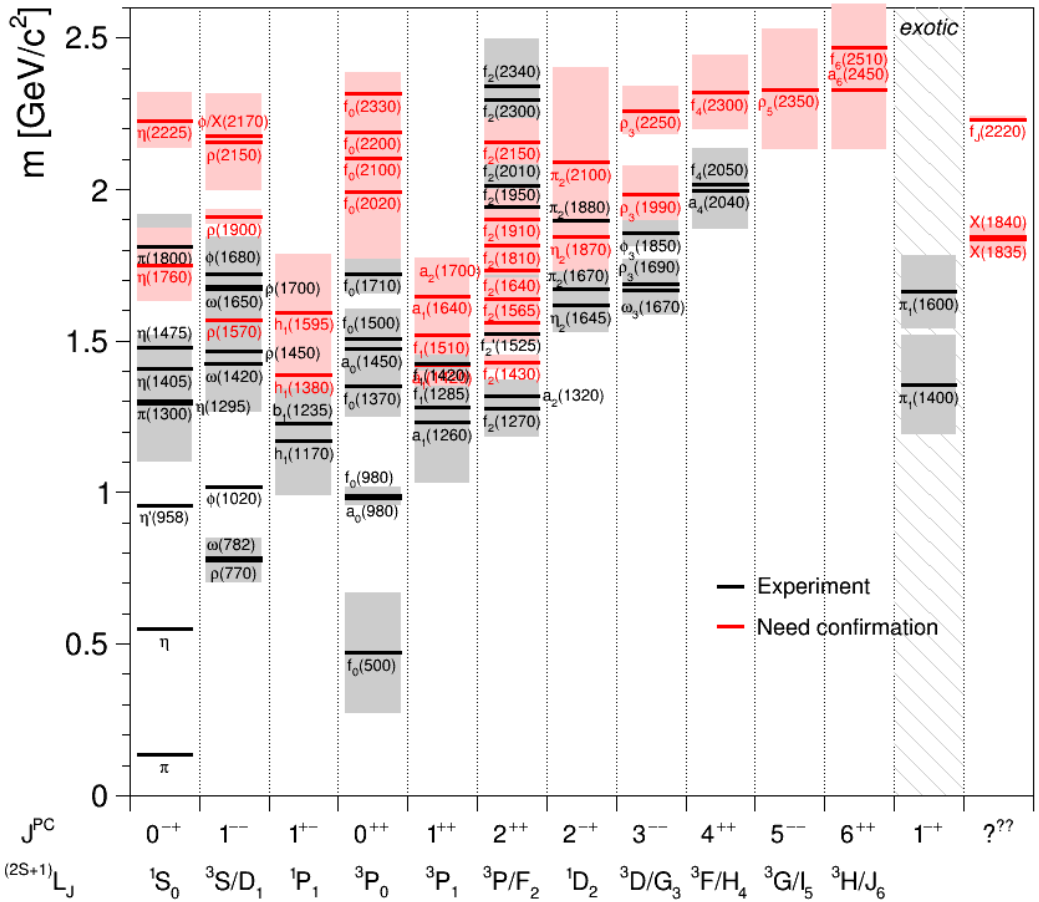

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Goal: precision measurement

- Important input for theory and phenomenology
- Understand QCD at low energies, i.e. nature of confinement

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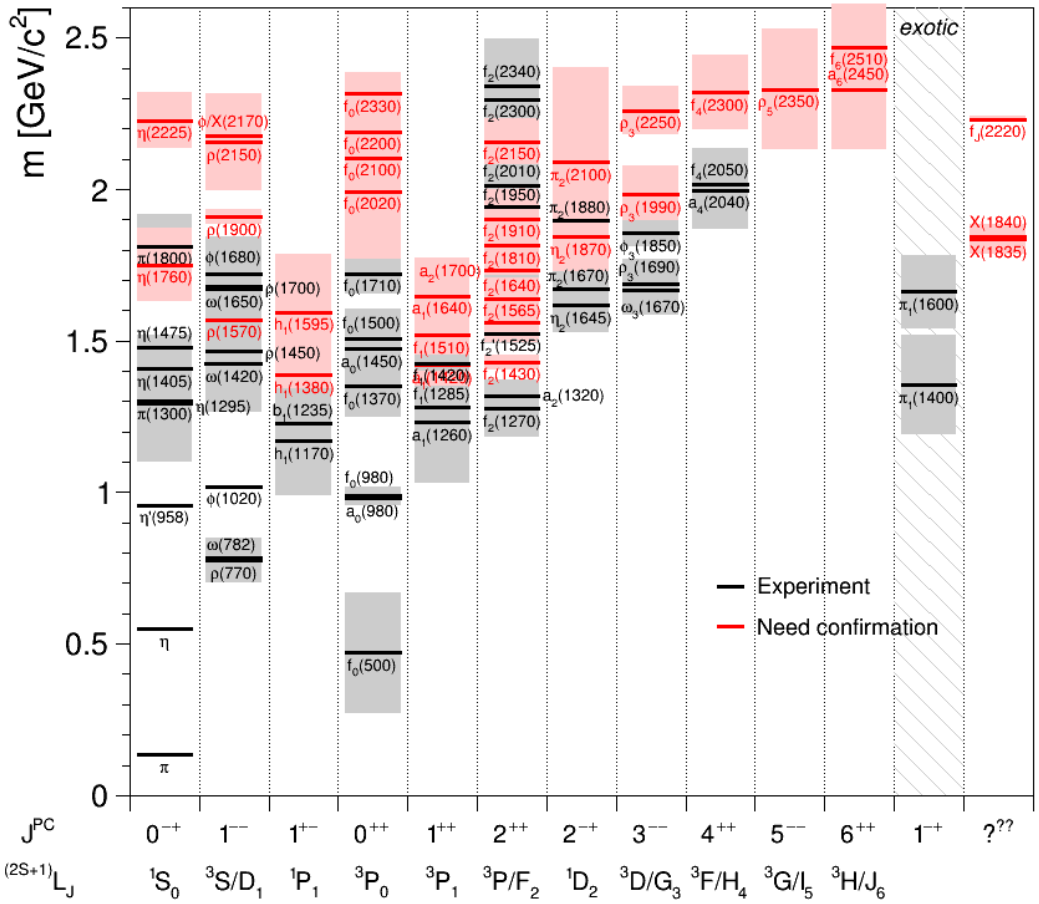

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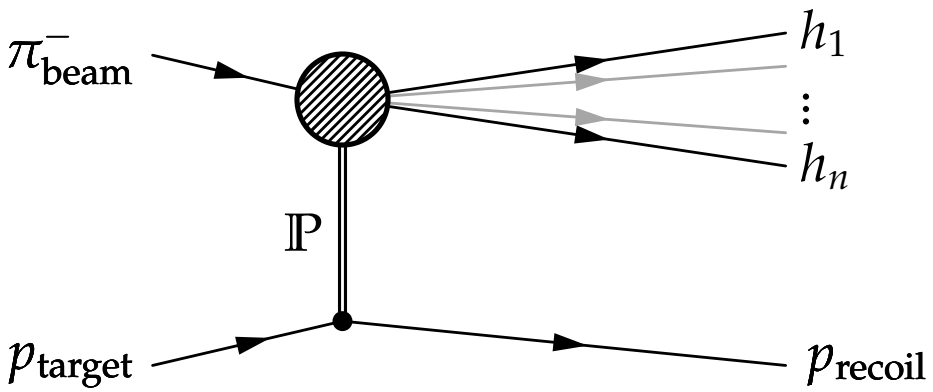
Production of excited light Mesons at COMPASS

Example: $\pi^-\pi^-\pi^+$ Final State COMPASS, PRD **95** (2017) 032004



- Diffractive production
- "Golden" channel
- 46×10^6 $\pi^-\pi^-\pi^+$ events
  - Ca. $10\times$ more data than previous experiments
- Well-known 3π mesons appear as enhancements in $m_{3\pi}$ spectrum

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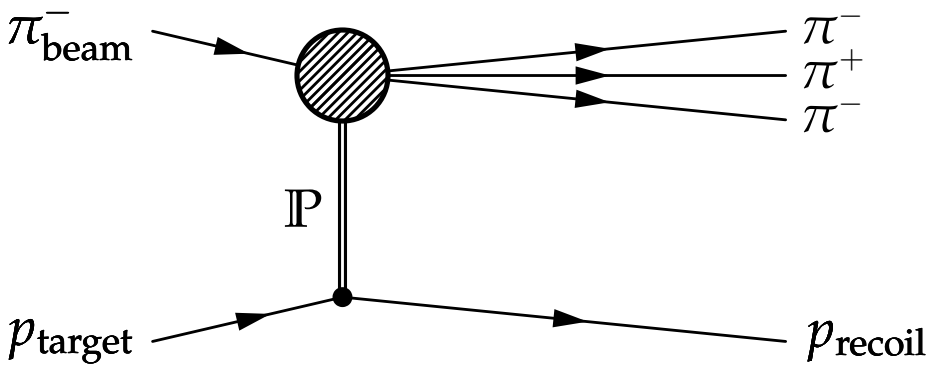

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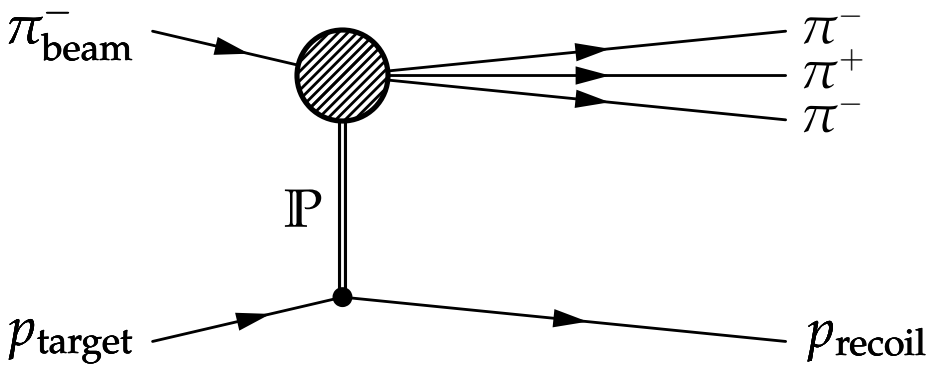

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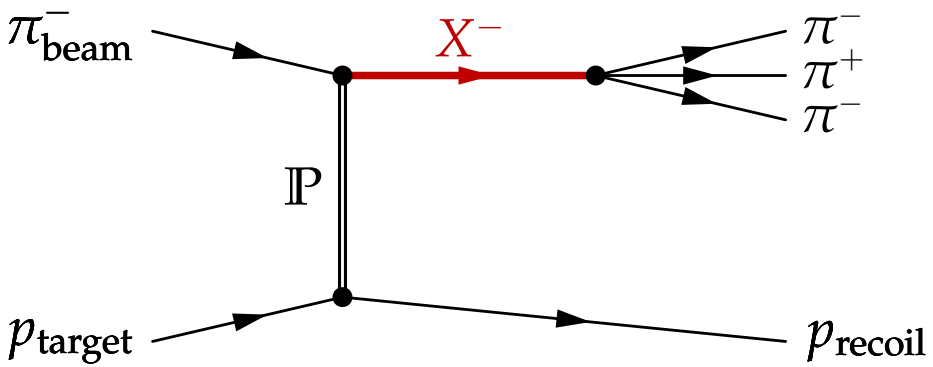

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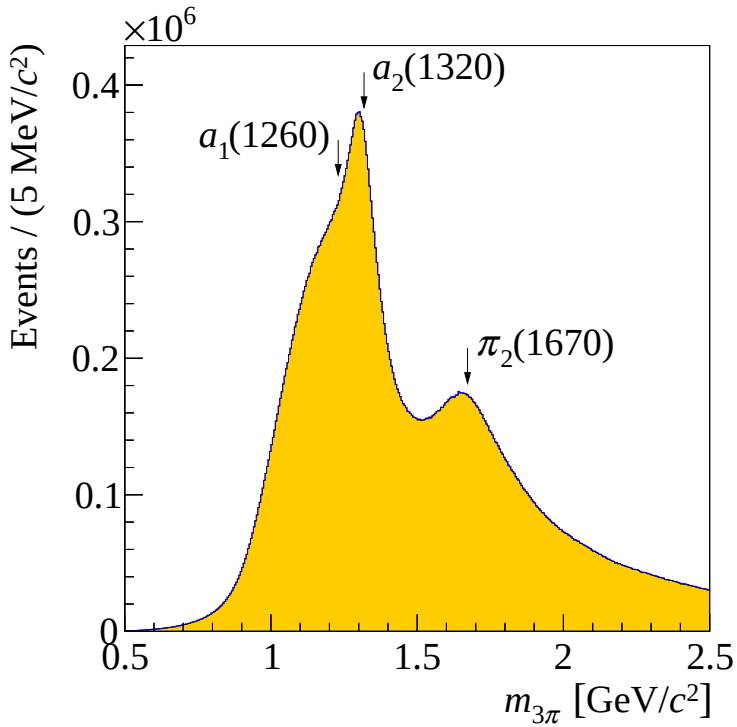

Experimental Signature of a Resonance

- All excited light mesons decay via strong interaction
  $\Longrightarrow$ extremely short-lived $\Longrightarrow$ "resonances"

Analogy: driven harmonic oscillator

- Amplitude peaks at resonance frequency $\omega_{\text{resonance}}$
- Phase rises from $0°$ to $180°$ and is $90°$ at $\omega_{\text{resonance}}$

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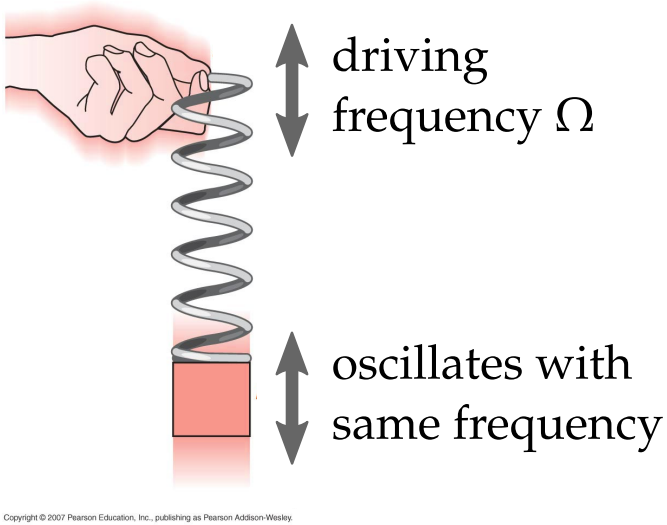

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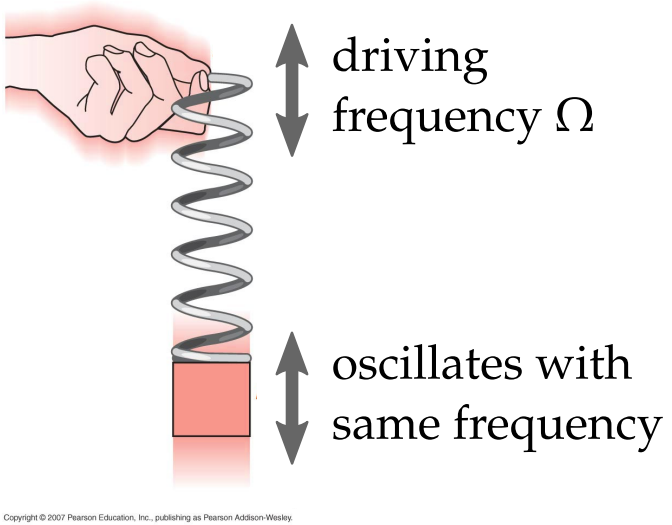

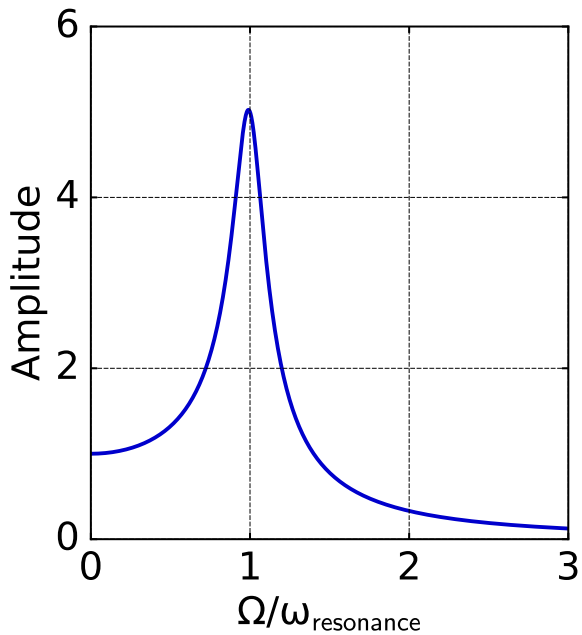

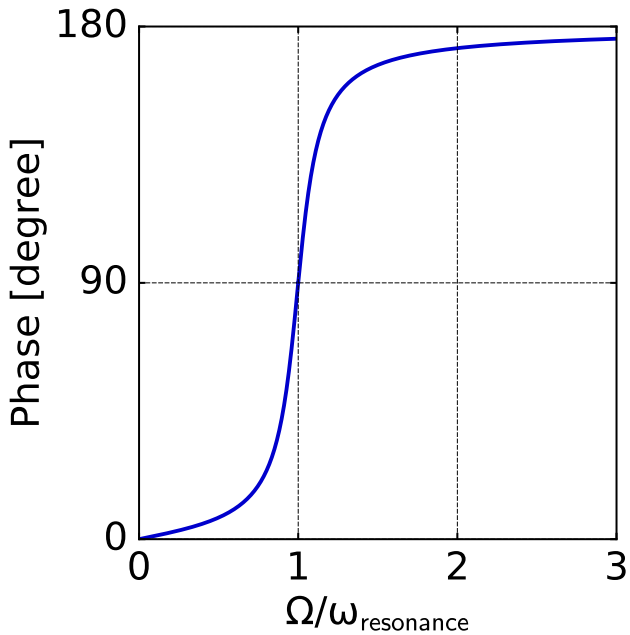

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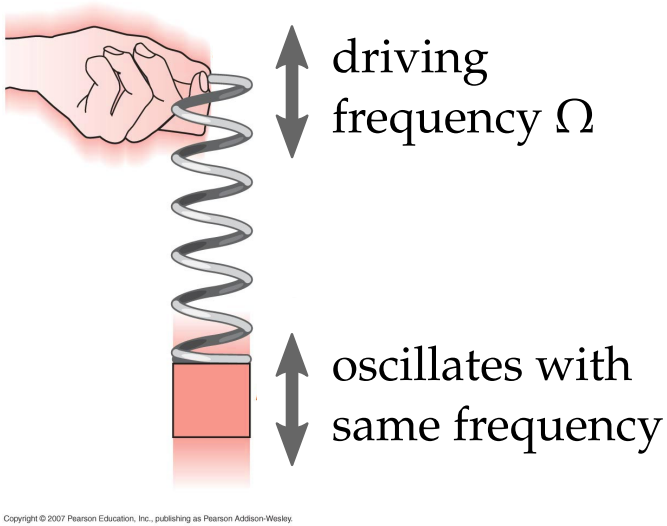
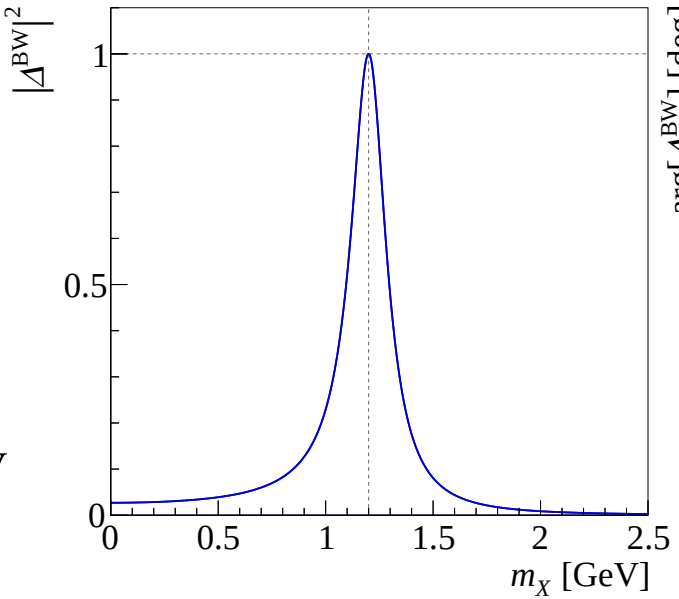
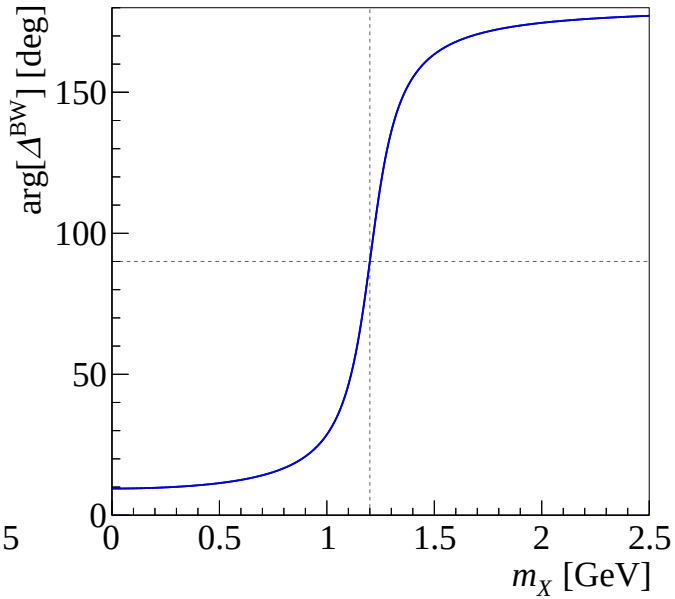
Quantum mechanical amplitude of hadronic resonance (Breit-Wigner)

- Intensity (probability) peaks at resonance mass m_0
- Phase rises from 0° to 180° and is 90° at m_0



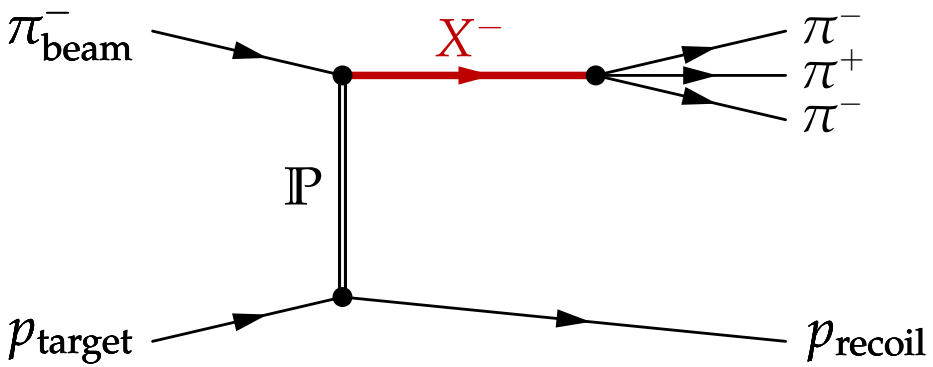




Partial-Wave Analysis Model

$\pi^-\pi^-\pi^+$ Final State

COMPASS, PRD **95** (2017) 032004

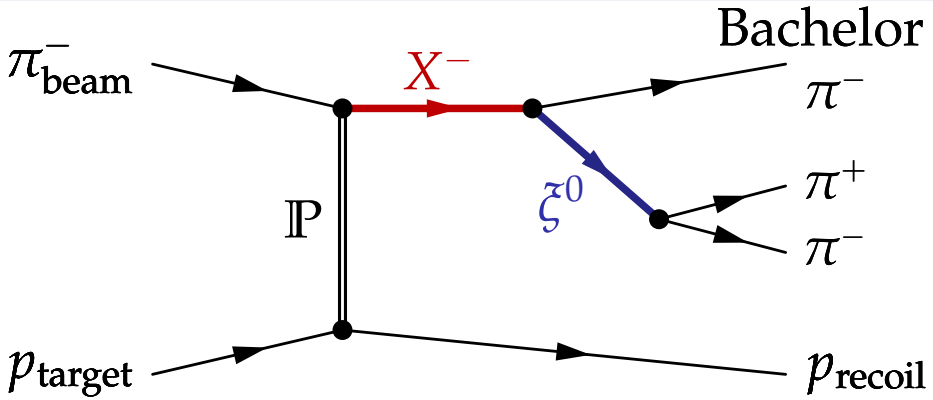


- *Goal:* disentangle all contributing 3π resonances $X \Longrightarrow$ mass, width, and quantum numbers
- *Method:* **partial-wave analysis**
- *Model:* chain of two-body decays
- Determine J^P of intermediate resonances X and ξ from measured angular distribution of pions
- *Analogy:* multipole radiation in classical electrodynamics

Partial-Wave Analysis Model

$\pi^-\pi^-\pi^+$ Final State

COMPASS, PRD **95** (2017) 032004



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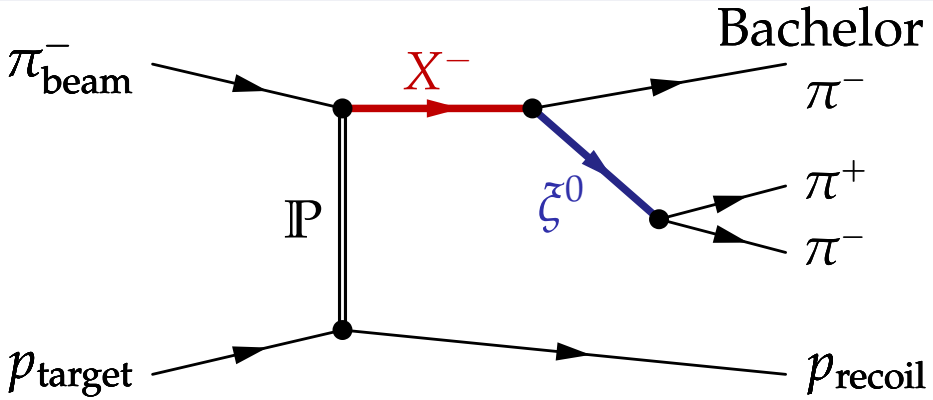
- *Method:* **partial-wave analysis**
- *Model:* chain of two-body decays
- Determine J^P of intermediate resonances X and ξ from measured angular distribution of pions
- *Analogy:* multipole radiation in classical electrodynamics

Partial-Wave Analysis Model

$\pi^-\pi^-\pi^+$ Final State

COMPASS, PRD **95** (2017) 032004



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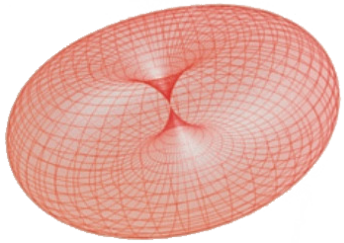
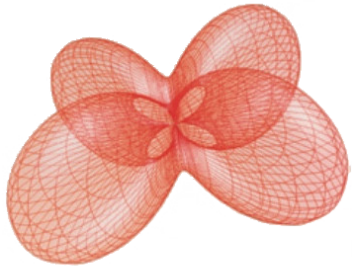
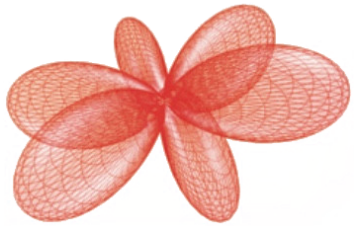
Dipole ($J = 1$)



Quadrupole ($J = 2$)



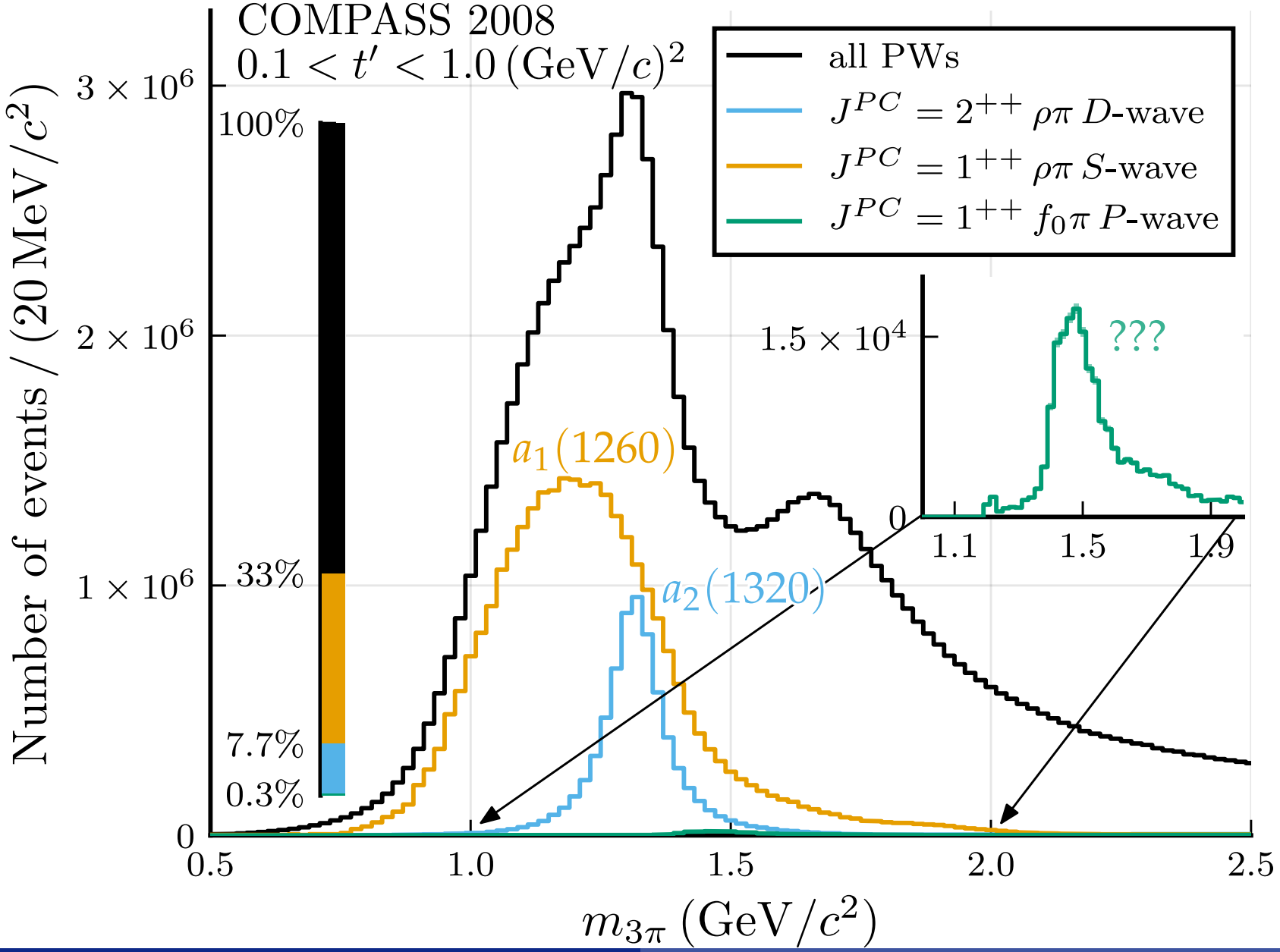
Octupole ($J = 3$)



Partial-Wave Analysis of $\pi^-\pi^-\pi^+$ Final State

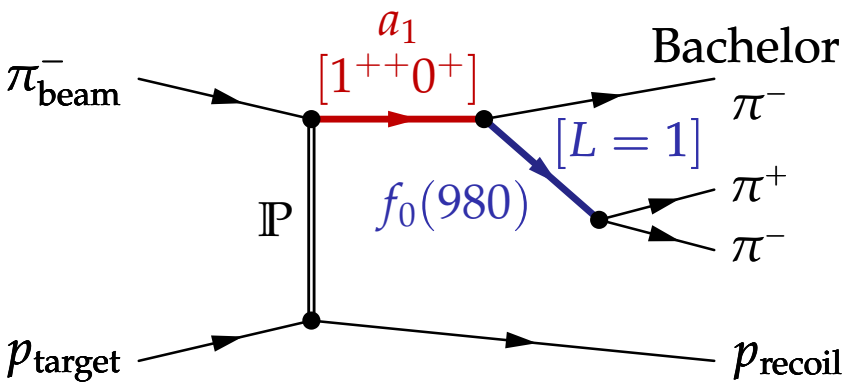
Example: Surprising Signal with $J^{PC} = 1^{++}$

COMPASS, PRD **95** (2017) 032004



A new $a_1(1420)$ State?

COMPASS, PRL **115** (2015) 082001, PRD **98** (2018) 092003, and PRL **127** (2021) 082501



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- Small relative intensity of only $0.3\,\%$
- Peak and phase motion well described by Breit-Wigner

$a_1(1420)$ resonance parameters

- $m_0 = (1411\,^{+4}_{-5})\,\text{MeV}/c^2$ and $\Gamma_0 = (161\,^{+11}_{-14})\,\text{MeV}/c^2$

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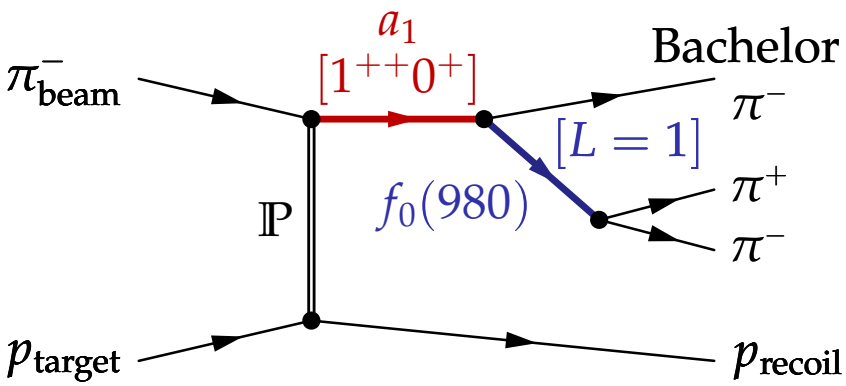

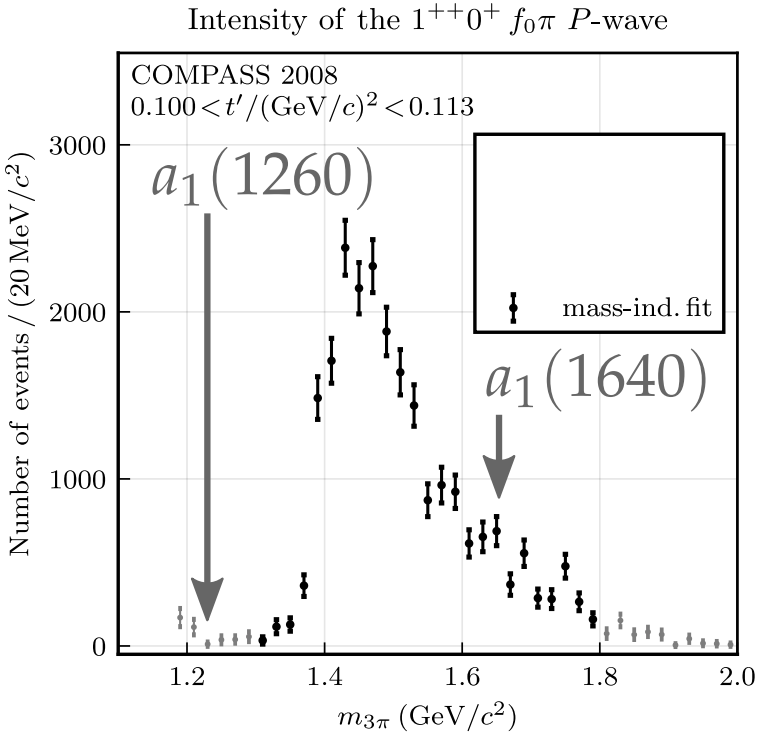

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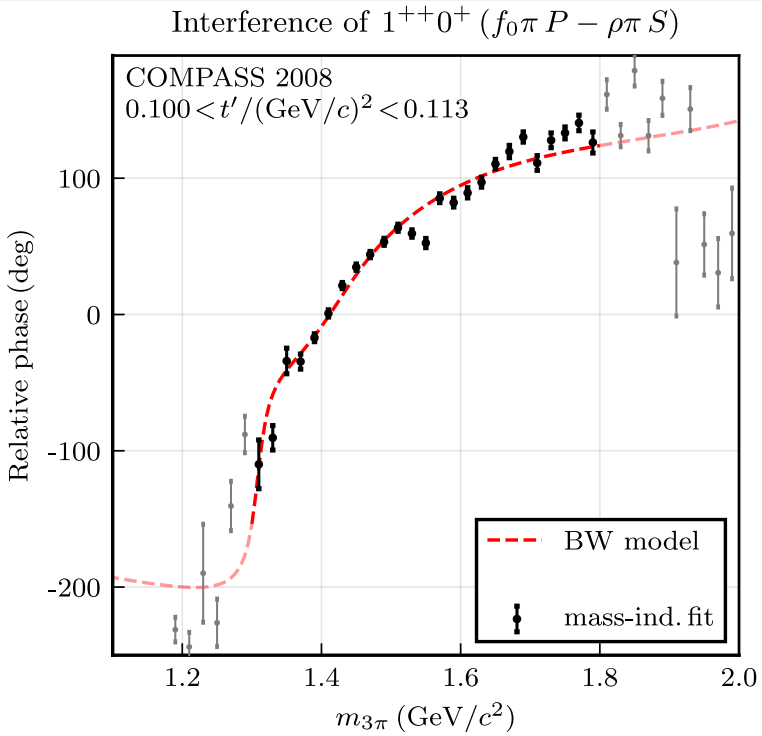

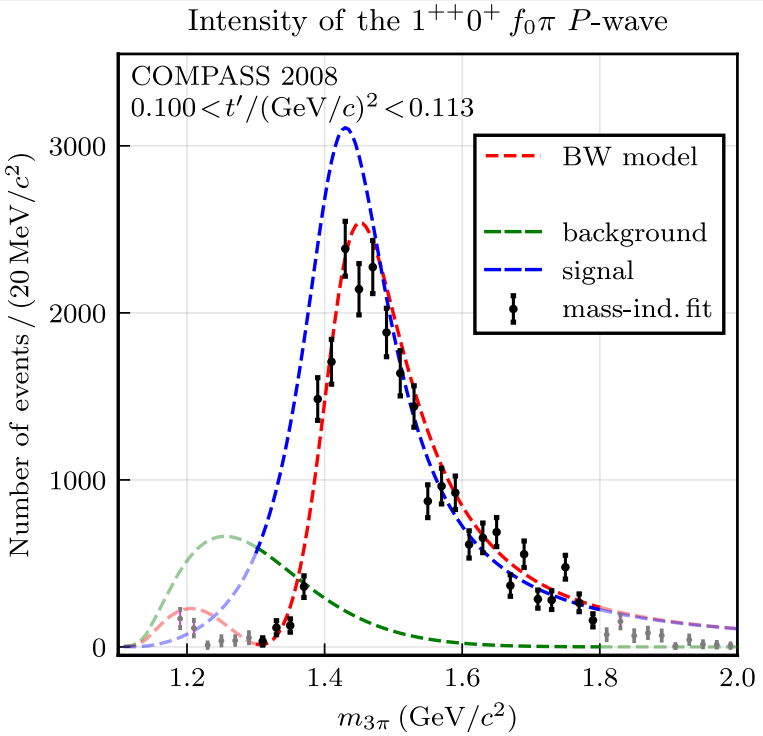

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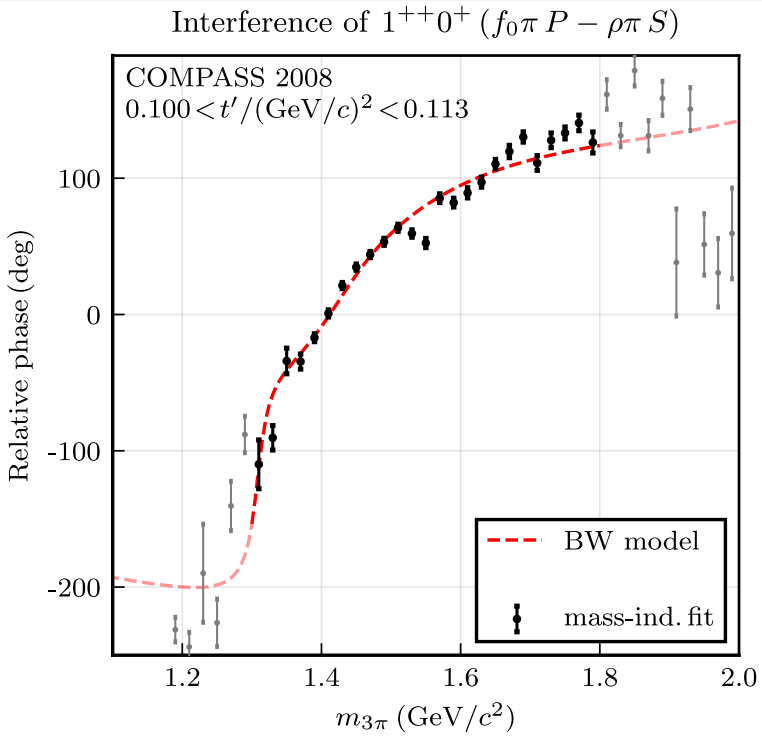

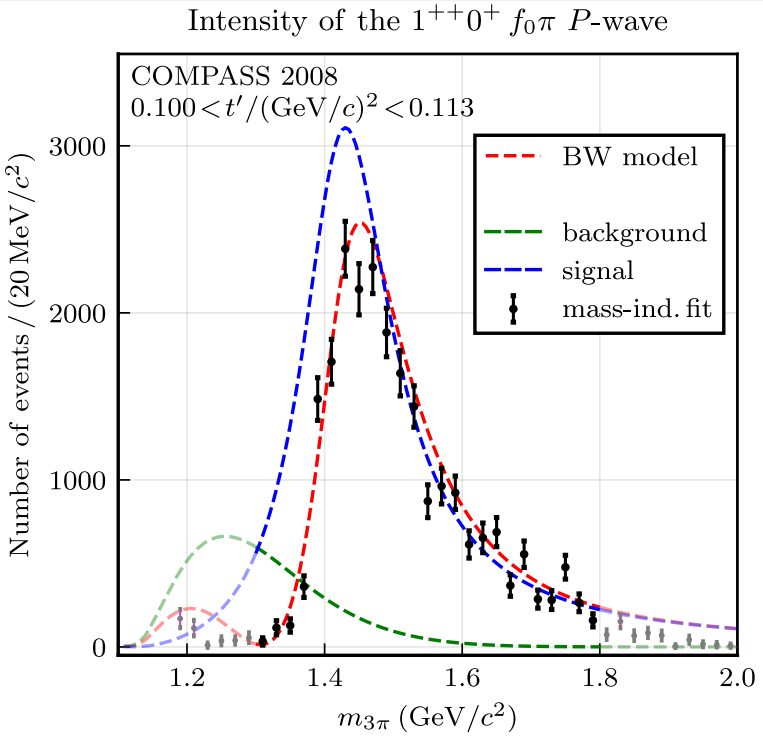

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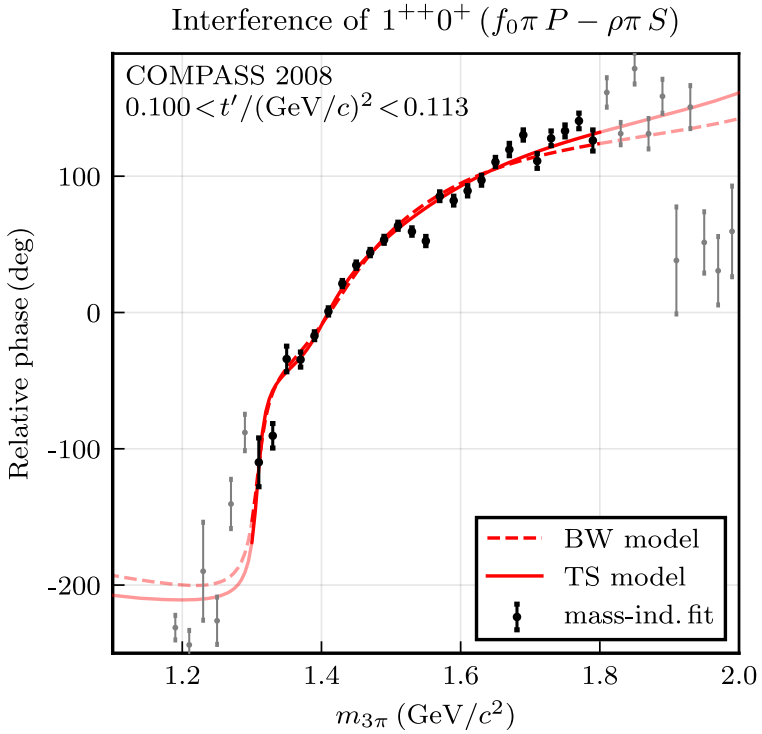
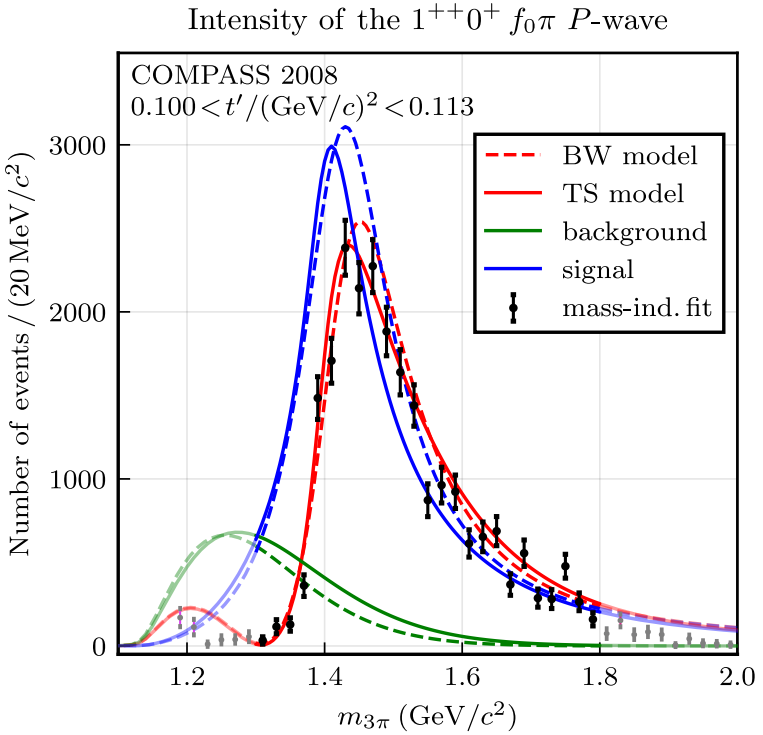
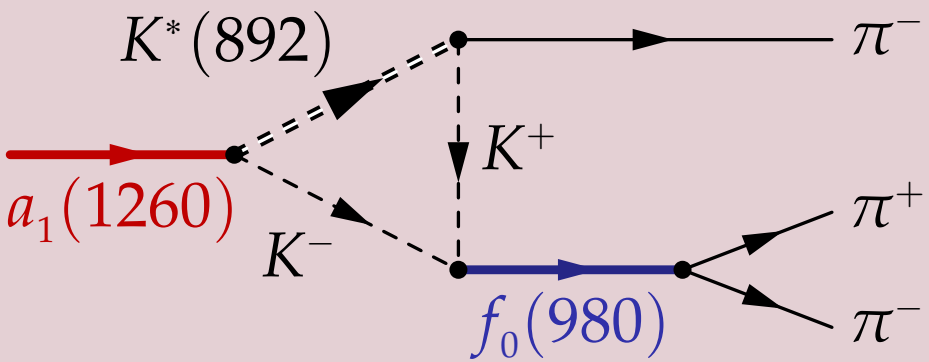




Data equally well-described by triangle diagram

M. Wagner, HK 29.7, Fri 15:45



Light-Meson Spectroscopy at COMPASS

Summary

Example: high-precision data on $\pi^- + p \to \pi^-\pi^-\pi^+ + p$

- Most detailed and comprehensive analysis so far

Discovery of an unexpected resonance-like $a_1(1420)$

- Consistent with triangle diagram
  - First fit of triangle diagram to amplitude data in light-meson sector
  - Triangle diagrams may also explain some exotic states in the heavy-meson sector

Further results from analysis of $\pi^- + p \to \pi^-\pi^-\pi^+ + p$

- Detailed study of $\rho(770)\pi$ decay of exotic resonance $\pi_1(1600)$

  see talk by F. Krinner, HK 29.6, Fri 15:30

- Surprising excited pion signal decaying to $f_2(1270)\pi$

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Other analyzed final states

- π^- diffraction into $\pi^-\eta^{(\prime)}, K^-K^0_S, \pi^-\pi^0\omega(782), \ldots$
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The future AMBER Experiment at CERN

Rich physics program addressing fundamental QCD questions

Phase 1: after Long Shutdown 2 of LHC (2022 to 2024)

- Elastic μp scattering: precision measurement of proton charge radius
- Drell-Yan and charmonium production: determination of pion PDFs
- Measurement of p-induced $\bar{p}$ production cross sections for indirect dark matter searches

Phase 2: after Long Shutdown 3 of LHC (from 2026 on)

- Radio-frequency-separated kaon and antiproton beams
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The AMBER Proposal

Apparatus for **M**eson and **B**aryon **E**xperimental **R**esearch

[CERN-SPSC-2019-022]

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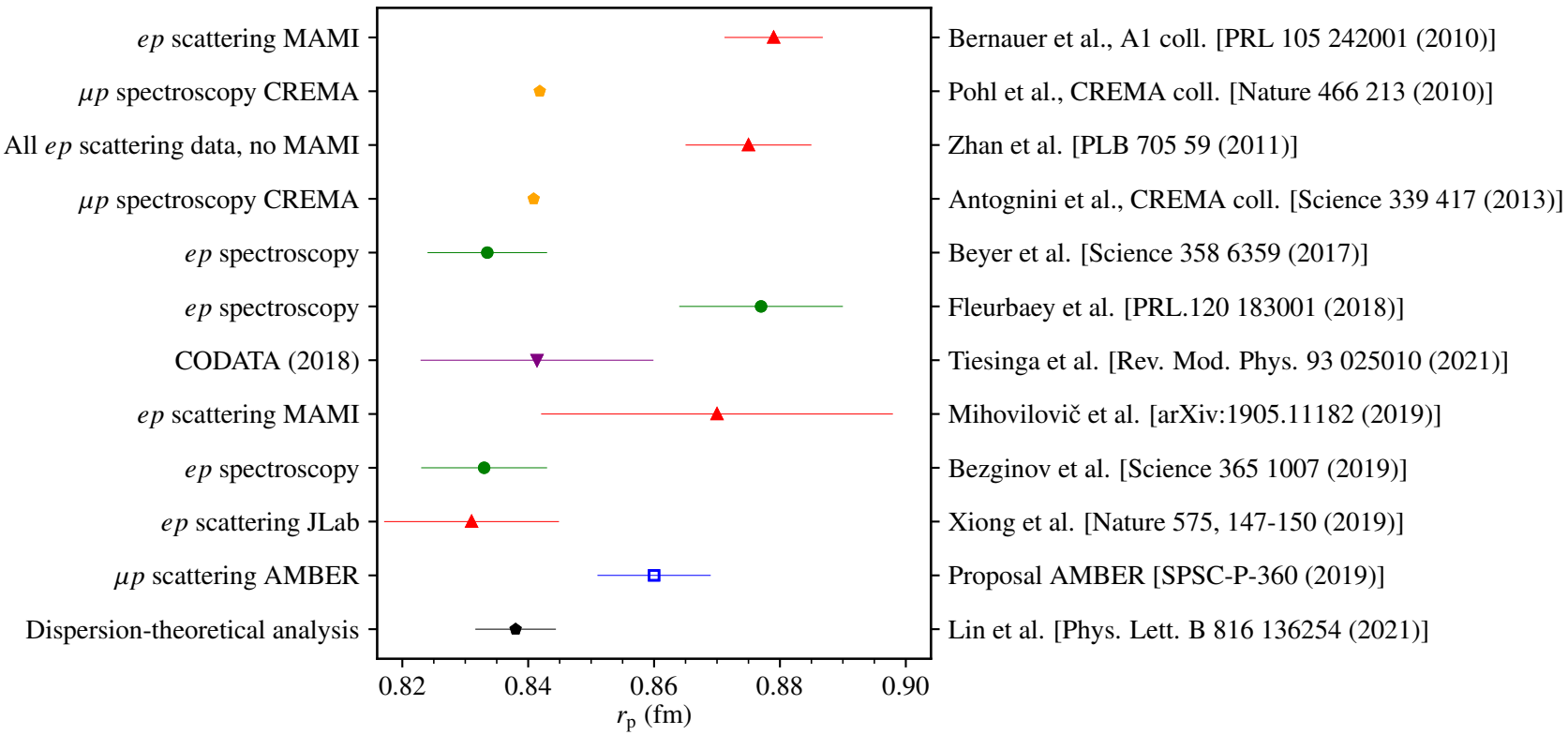
The Proton-Radius Puzzle

Measured values for proton radius r_p (root mean square of charge distribution)

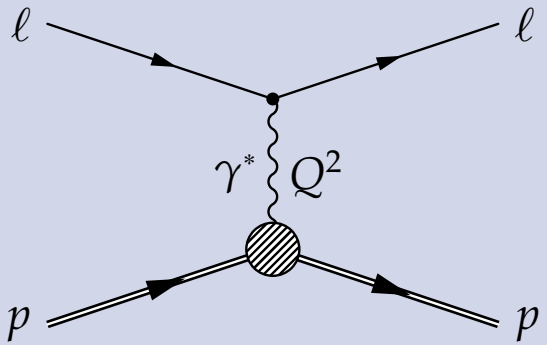


Contradictory proton-radius values from

- finite-size effects in spectroscopy of ordinary and muonic hydrogen
- slope of form-factor measured in elastic *ep* scattering

The Proton Charge Radius from Lepton Scattering

- Response of proton to external electromagnetic fields encoded in
  - electric form factor G_E and
  - magnetic form factor G_M



$$G_E(Q^2) \approx \frac{G_M(Q^2)}{\mu_p} \approx G_{\text{dipole}}(Q^2) = \frac{1}{\left(1 + Q^2/a^2\right)^2}$$

with magnetic moment $\mu_p = 2.79$ and $a^2 = 0.71\,(\text{GeV}/c)^2$

- Taylor expansion of G_E for spherically symmetric charge distribution

$$\langle r_E^2 \rangle = -6\hbar \left.\frac{\mathrm{d}G_E(Q^2)}{\mathrm{d}Q^2}\right|_{Q^2=0} \quad \text{with} \quad r_p = \sqrt{\langle r_E^2 \rangle}$$

- At high energy and low Q^2

$$\frac{\mathrm{d}\sigma}{\mathrm{d}Q^2} \propto G_E^2 + \tau G_M^2 \quad \text{with} \quad \tau = Q^2/(4m_p^2) \quad \text{small}$$

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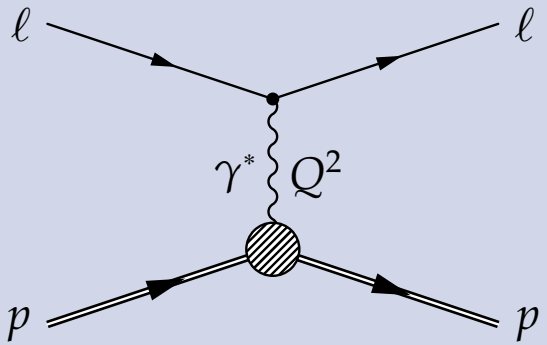

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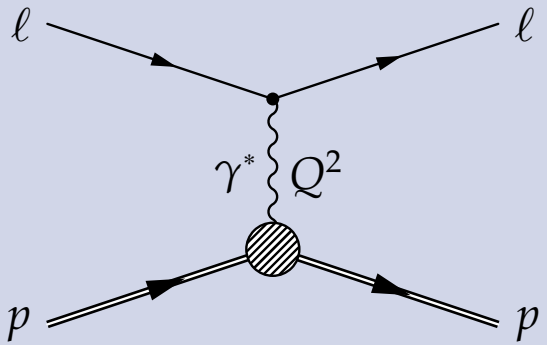

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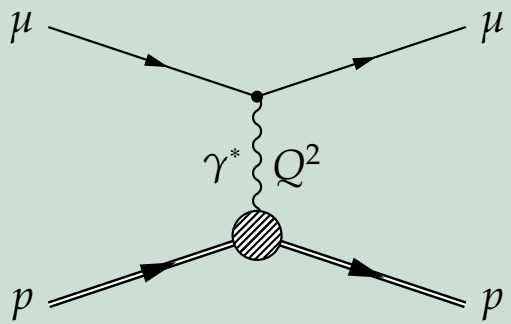
AMBER Proposal

Precision measurement of proton charge radius in high-energy elastic μp scattering



- Advantageous/complementary systematics compared to other techniques
- Small radiative corrections

Goals

- Cover range $10^{-3} < Q^2 < 4 \times 10^{-2}\,(\mathrm{GeV}/c)^2$
- Statistical precision of ≈ 0.01 fm or smaller
- Requires 70×10^6 elastic events
- Resolution $\Delta Q^2/Q^2 \lesssim 15\,\%$ at $Q^2 = 10^{-3}\,(\mathrm{GeV}/c)^2$

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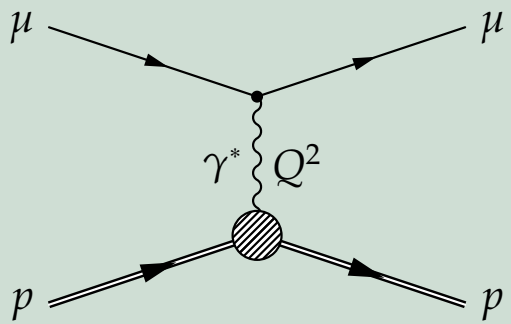

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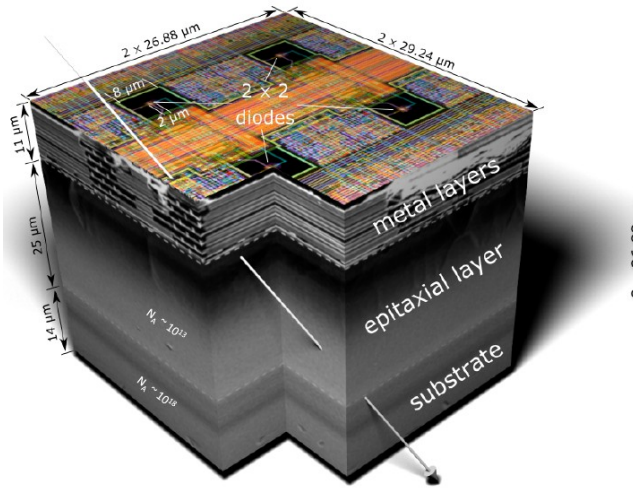
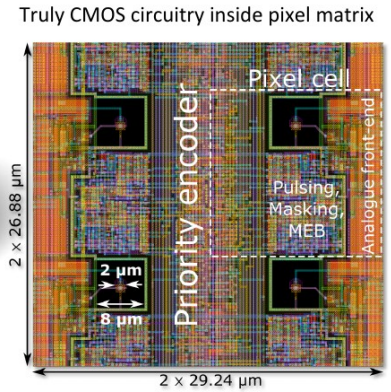
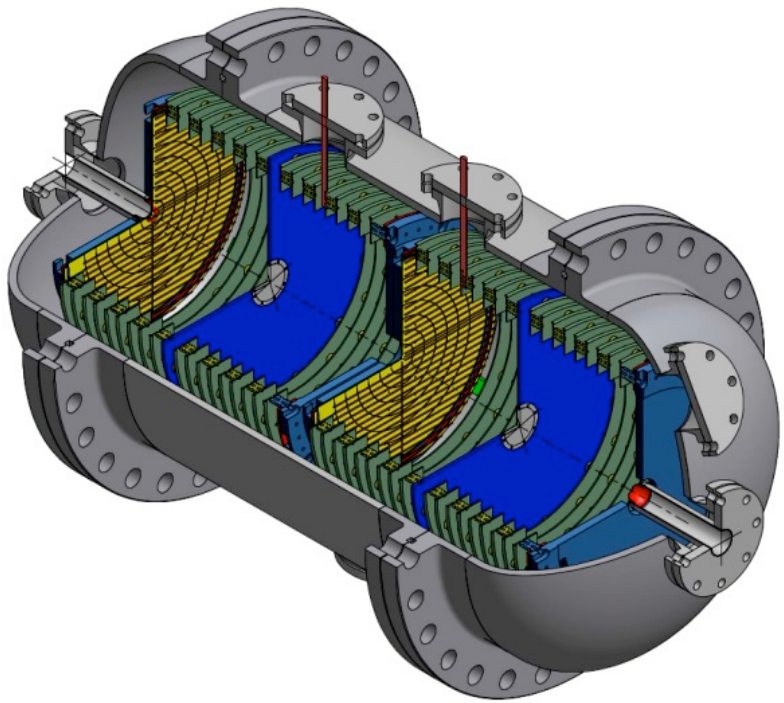
AMBER Experimental Setup

Challenging measurement

- 100 GeV muon beam with high-intensity $2 \times 10^6\ \mathrm{s}^{-1}$
- High Q^2 resolution down to $Q^2 = 10^{-3}\ (\mathrm{GeV}/c)^2$
  - Redundant measurement of scattered muon and recoil proton
  - High-precision forward tracking (ALPIDE silicon pixel detector)
  - Active-target high-pressure (20 bar) hydrogen TPC







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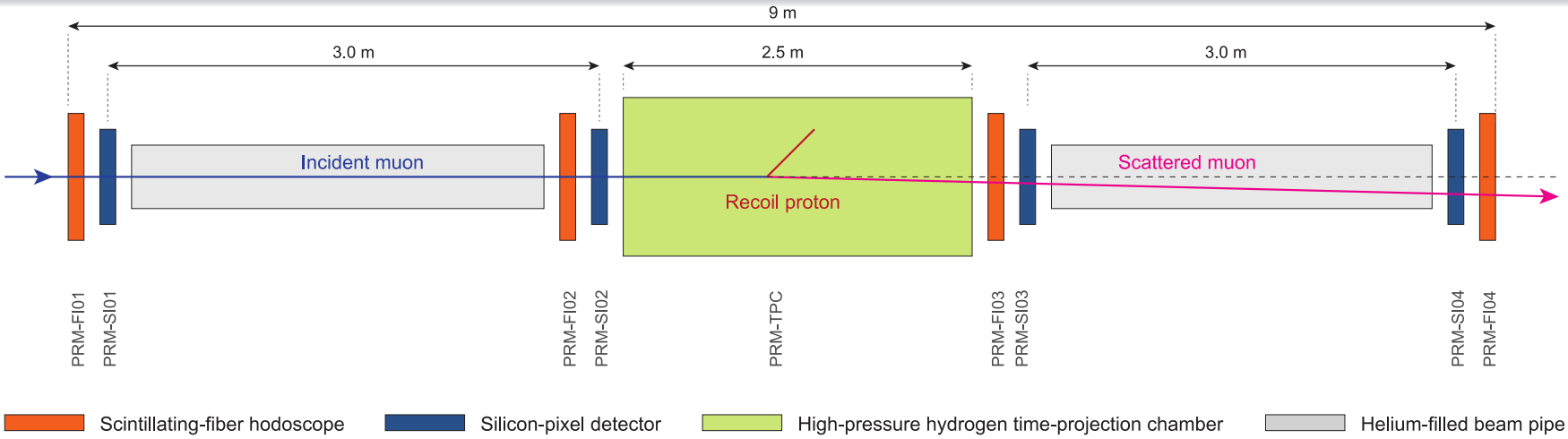
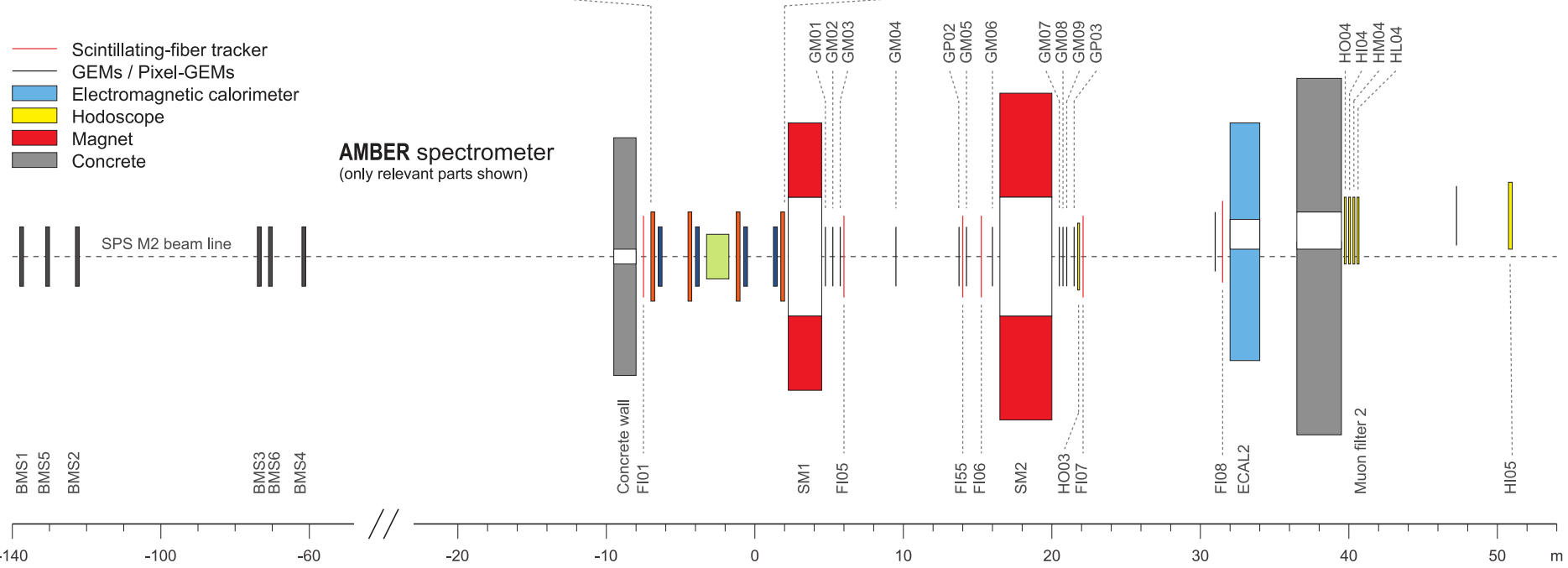
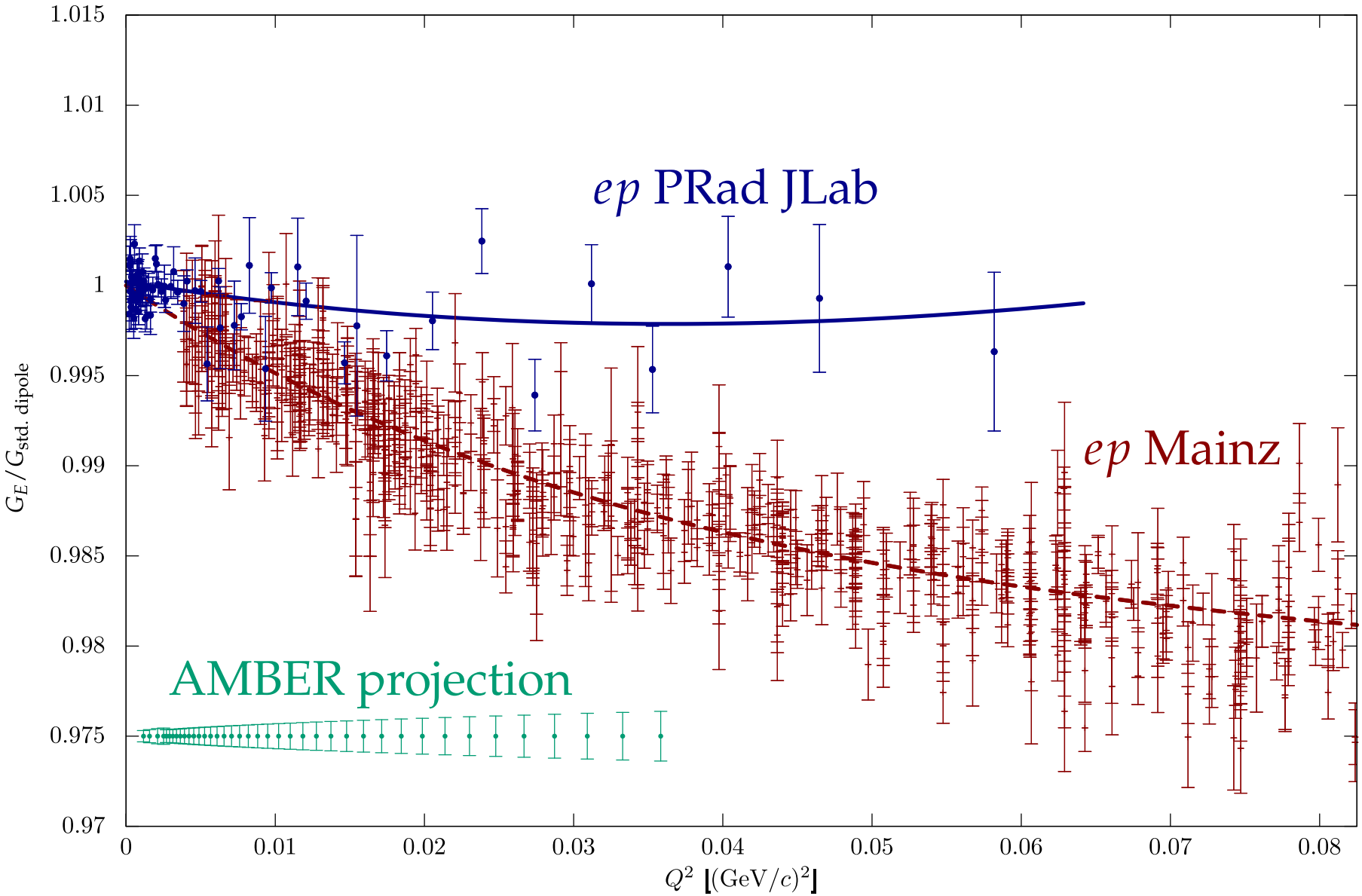


2022–24 setup for proton-radius measurement



AMBER Projected Performance (2 Years of Running)



AMBER

A New QCD Facility at the M2 Beam Line of the CERN SPS

3 Measurements proposed for phase 1 (2022-24)

1. Proton radius in high-energy muon-proton scattering
2. Pion PDFs in pion-induced Drell-Yan
3. Antiproton production in pp and pHe collisions

- New collaboration formed recently
- Various hardware developments and upgrades are ongoing

Phase 2 (after Long Shutdown 3)

- Broad physics program using conventional and radio-frequency-separated beams
- Proposal is being drafted

New ideas and collaborators are welcome!

`https://amber.web.cern.ch/`

AMBER

A New QCD Facility at the M2 Beam Line of the CERN SPS

3 Measurements proposed for phase 1 (2022-24)

1. Proton radius in high-energy muon-proton scattering
2. Pion PDFs in pion-induced Drell-Yan
3. Antiproton production in pp and pHe collisions

- New collaboration formed recently
- Various hardware developments and upgrades are ongoing

Phase 2 (after Long Shutdown 3)

- Broad physics program using conventional and radio-frequency-separated beams
- Proposal is being drafted

New ideas and collaborators are welcome!

https://amber.web.cern.ch/

Thank you!