# Production of mesons and related hadron physics

# 介子产生和相关的强子物理

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第一届介子束流物理研讨会
兰州大学，2024年12月27~30日

# 介子产生和相关的强子物理



Out of QCD vacuum, (anti-)quarks are born;
Out of (anti-)quarks, mass;
Out of mass, particles;
Out of particles, the created universe
--- modified from Tao Te Ching

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# Introduction

## 1 Missing resonances

More states are predicted in 3-quark models than seen in the $\pi N$ scattering

## 2 Redundant resonances

Less states are present in diquark models than seen in the $\pi N$ and $\gamma N$ scattering

($P_{13}$(1900) and $F_{15}$(2000): remedy?)

## 3 First-principles calculation

Lattice QCD and Dyson-Schwinger calculations

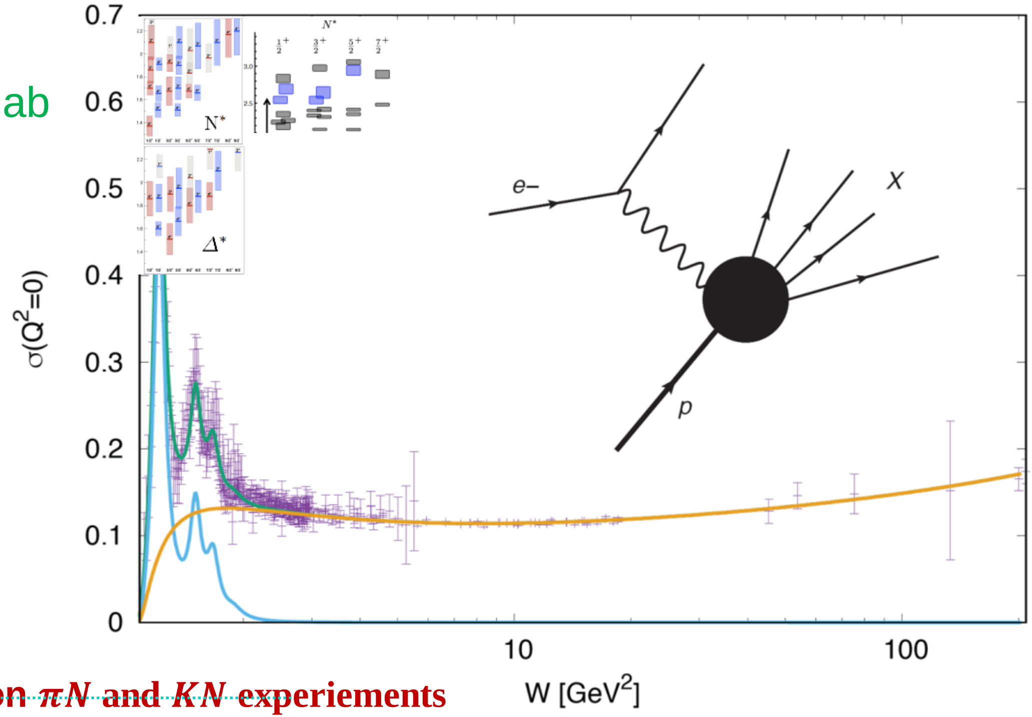
| $(D, L_N^P)$ | $S$ | $J^P$ | Singlet | Octet | | | Decuplet | |
|---|---|---|---|---|---|---|---|---|
| $(56, 0_0^+)$ | $\frac{1}{2}$ | $\frac{1}{2}^+$ | | $N(939)$ | $\Lambda(1116)$ | $\Sigma(1193)$ | | |
| | $\frac{3}{2}$ | $\frac{3}{2}^+$ | | | | | $\Delta(1232)$ | $\Sigma(1385)$ |
| $(70, 1_1^-)$ | $\frac{1}{2}$ | $\frac{1}{2}^-$ | $\Lambda(1405)$ | $N(1535)$ | $\Lambda(1670)$ | $\Sigma(1620)$ | $\Delta(1620)$ | $\Sigma(1900)$[a] |
| | | $\frac{3}{2}^-$ | $\Lambda(1520)$ | $N(1520)$ | $\Lambda(1690)$ | $\Sigma(1670)$ | $\Delta(1700)$ | $\Sigma(1910)$[a] |
| | $\frac{3}{2}$ | $\frac{1}{2}^-$ | | $N(1650)$ | $\Lambda(1800)$ | $\Sigma(1750)$ | | |
| | | $\frac{3}{2}^-$ | | $N(1700)$ | - | - | | |
| | | $\frac{5}{2}^-$ | | $N(1675)$ | $\Lambda(1830)$ | $\Sigma(1775)$ | | |
| $(56, 0_2^+)$ | $\frac{1}{2}$ | $\frac{1}{2}^+$ | | $N(1440)$ | $\Lambda(1600)$ | $\Sigma(1660)$ | | |
| | $\frac{3}{2}$ | $\frac{3}{2}^+$ | | | | | $\Delta(1600)$ | $\Sigma(1780)$ |
| $(70, 0_2^+)$ | $\frac{1}{2}$ | $\frac{1}{2}^+$ | $\Lambda(1710)$ | $N(1710)$ | $\Lambda(1810)$ | $\Sigma(1880)$ | $\Delta(1750)$ | - |
| | $\frac{3}{2}$ | $\frac{3}{2}^+$ | | - | - | - | | |
| $(56, 2_2^+)$ | $\frac{1}{2}$ | $\frac{3}{2}^+$ | | $N(1720)$ | $\Lambda(1890)$ | $\Sigma(1940)$ | | |
| | $\frac{1}{2}$ | $\frac{5}{2}^+$ | | $N(1680)$ | $\Lambda(1820)$ | $\Sigma(1915)$ | | |
| | $\frac{3}{2}$ | $\frac{1}{2}^+$ | | | | | $\Delta(1910)$ | - |
| | $\frac{3}{2}$ | $\frac{3}{2}^+$ | | | | | $\Delta(1920)$ | $\Sigma(2080)$ |
| | $\frac{3}{2}$ | $\frac{5}{2}^+$ | | | | | $\Delta(1905)$ | $\Sigma(2070)$ |
| | $\frac{3}{2}$ | $\frac{7}{2}^+$ | | | | | $\Delta(1950)$ | $\Sigma(2030)$ |
| $(70, 2_2^+)$ | $\frac{1}{2}$ | $\frac{3}{2}^+$ | $\Lambda(2070)$ | - | - | - | - | - |
| | | $\frac{5}{2}^+$ | $\Lambda(2110)$ | $N(1860)$ | - | - | $\Delta(2000)$ | - |
| | $\frac{3}{2}$ | $\frac{1}{2}^+$ | | $N(1880)$ | - | - | | |
| | | $\frac{3}{2}^+$ | | $N(1900)$ | - | - | | |
| | | $\frac{5}{2}^+$ | | $N(2000)$ | - | - | | |
| | | $\frac{7}{2}^+$ | | $N(1990)$ | $\Lambda(2085)$ | - | | |
| $(20, 1_2^+)$ | $\frac{1}{2}$ | $\frac{1}{2}^+$ | - | - | - | - | | |
| | | $\frac{3}{2}^+$ | - | - | - | - | | |
| | | $\frac{5}{2}^+$ | - | | | | | |
| $(56, 1_3^-)$ | $\frac{1}{2}$ | $\frac{1}{2}^-$ | | $N(1895)$ | $\Lambda(2000)$ | $\Sigma(1900)$[a] | | |
| | | $\frac{3}{2}^-$ | | $N(1875)$ | $\Lambda(2050)$ | $\Sigma(1910)$[a] | | |
| | $\frac{3}{2}$ | $\frac{1}{2}^-$ | | | | | $\Delta(1900)$ | $\Sigma(2110)$[a] |
| | | $\frac{3}{2}^-$ | | | | | $\Delta(1940)$ | $\Sigma(2010)$[a] |
| | | $\frac{5}{2}^-$ | | | | | $\Delta(1930)$ | - |
| $(70, 3_3^-)$ | $\frac{1}{2}$ | $\frac{5}{2}^-$ | $\Lambda(2080)$ | $N(2060)$[b] | - | - | - | - |
| | | $\frac{7}{2}^-$ | $\Lambda(2100)$ | $N(2190)$[b] | - | $\Sigma(2100)$ | $\Delta(2200)$ | - |
| $(70, 3_3^-)$ | $\frac{3}{2}$ | $\frac{3}{2}^-$ | | $N(2120)$ | - | - | - | - |
| | | $\frac{5}{2}^-$ | | $N(2060)$[b] | - | - | - | - |
| | | $\frac{7}{2}^-$ | | $N(2190)$[b] | - | - | - | - |
| | | $\frac{9}{2}^-$ | | $N(2290)$ | - | - | - | - |

# Introduction

- **Baryon spectrum around and above 2.0 GeV:**
- Transition from resonant region to asymptotic range?
- significant five-quark or gluonic components?
- Many (hybrid) states predicted by LQCD PRD 85(2012)054016 and QCD sum rules 2412.14878

- **New data:**
- Photo- and electron-production at Jlab
- xsection and polarizations
- Burkert *et al*, 2212.08980; 2211.12906

- **New technique:**
- A crowd of resonances  and channels
- Model analysis:
- MAID
- SAID
- Bonn-Gatchina
- Juelich-Bonn-GW
- ANL-Osaka
- Giessen K-matrix

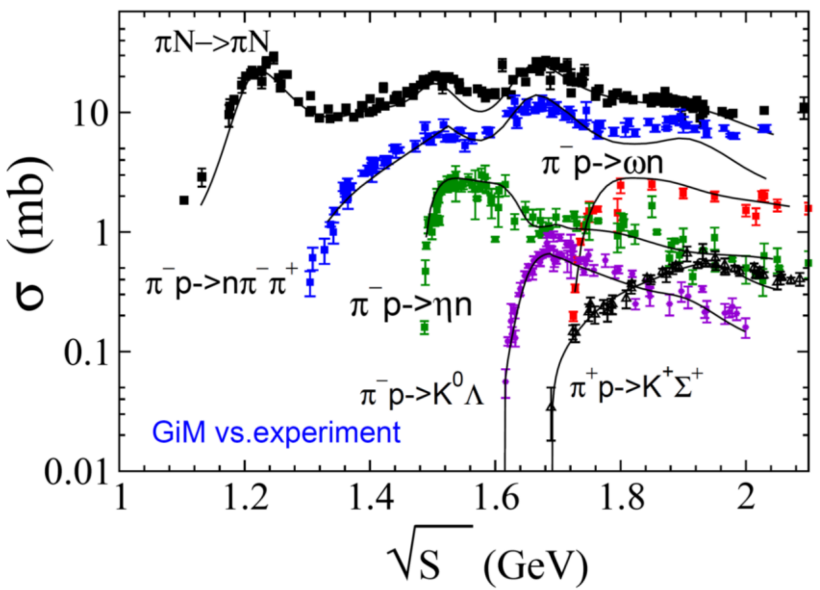


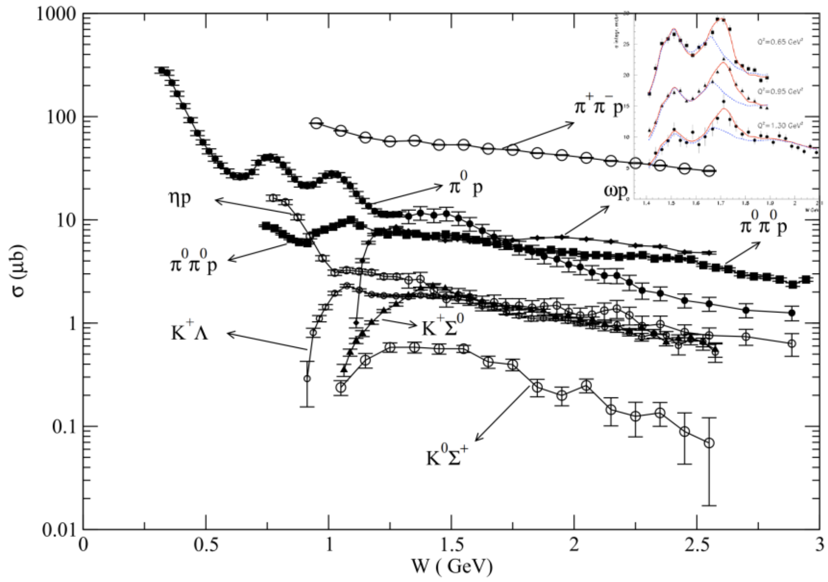

**Rise of the interest on $\pi N$ and $KN$ experiements**

# Introduction

- **Meson beams:**
- probe nucleon's excitation via pion/kaon
- …… absence of $K^*\Lambda$、$K\Lambda^*$、$K\Sigma^*$、 $K^*\Sigma$ …

- **Photon/Electron beams:**
- probe nucleon's excitation via photon
- …… also $K^*\Lambda$、$K\Lambda^*$、$K\Sigma^*$、 $K^*\Sigma$




For kaon, see BnGn, PRC 90, 065204, 2014; 92, 025205, 2015;
ANL-Osaka, Eur. Phys. J. A 55, 179; 55, 180, 2019

… many polarization observables

# Introduction

- **Historic Meson Factories:**
- Los Alamos Meson Physics Facility (LAMPF) with $P_\pi \in 190 \sim 730$ MeV: update failed (neutrino& meson beam)
- TRI University Meson Facility (TRIUMF) in Vancouver: KAON at TRIUMF failed (neutrino& meson beam)
- Swiss Institute for Nuclear Research (SIN) (now the Paul Scherrer Institute (PSI))
- Other experiments:
- optical spark chambers at the 7-GeV proton accelerator NIMROD in the UK: $\pi^- p \to K^0 \Lambda +$ ...
- Dubna with large statistical uncertainties: $\pi^- p \to e^+ e^- n$
- bubble chamber at the Saturne accelerator in Saclay: $\pi^- p \to \pi\pi N$
- HADES at GSI: unpolarized data of $\pi^- p \to \pi^- p,\ \pi^+\pi^- n,\ \pi^0\pi^- p,\ \pi^0\pi^0 n,\ e^+e^- n$
- EPECUR at ITEP: $\pi^\pm p \to \pi^\pm p, K^0\Lambda$
- BNL at the 30 GeV AGS: kaon beam
- COMPASS at the CERN SPS: $\mu$-beam, 190 GeV $\pi$-beam (Drell-Yan, DVCS, SIDIS)

- **Proposed facility: JLab, J-PARC, HADES, COMPASS, PANDA(suspended), and HIAF(?)**
- KLF Collaboration (approved) at GlueX of Hall D Jlab (2026-2028): $e\ (12GeV) \to \gamma \to K_L (10^4/s)$ 1604.02141, 2008.08215
- J-PARC: < 2 GeV update to 10 GeV? $\pi^\pm p \to \pi^\pm p, \pi\pi N, KY, \eta n, \eta' n, \varphi n, \omega n, \rho n, D^*\Lambda_c^*; K^- p \to K^+ K \Xi^{*-}, \mathrm{Kd}, K^3\mathrm{He}$
- COMPASS++/AMBER at the CERN SPS: first results in August, 2024 (Dark matter, meson PDF, proton radius)
- Strange Meson Spectrum through diffractive scattering of Kaon beams (1808.00848)

- **Virtual meson beams at future electron-ion colliders: Sullivan process**

- …… limited future facilities

# Real meson beams

- **I: Production of mesons via pN reactions:**

- Probe nucleon resonances coupling to those channels other than $\pi N$ and $\gamma N$

- Basic ingredient of 2π production in pd & pd & dd reactions (dibaryons?)

  H. Clement, PPNP93(2017)195: C. Wilkin, EPJA53(2017)144: also series of work by Yu-Bing Dong. Fei Huang et al.

- An input to transport model (at SIS energies)

  J. Weil, H. van Hees, U. Mosel, EPJA48(2012)111

- An input to baryon and baryon resonances in nuclear matter

  H. Lenske, M. Dhar,T.Gaitanos,X.C.. PPNP98(2018)119

- An input to heavy-ion induced Double Charge Exchange (DCE) reactions:

  $nn \rightarrow ppe^- \ e^-$: similar to Nuclear Matrix Elements Z,N → Z+2,N-2

  NUMEN project, EPJA54(2018)72,PLB807(2020)135528:

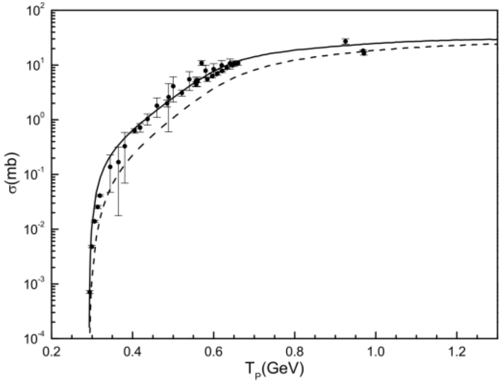
# Real meson beams

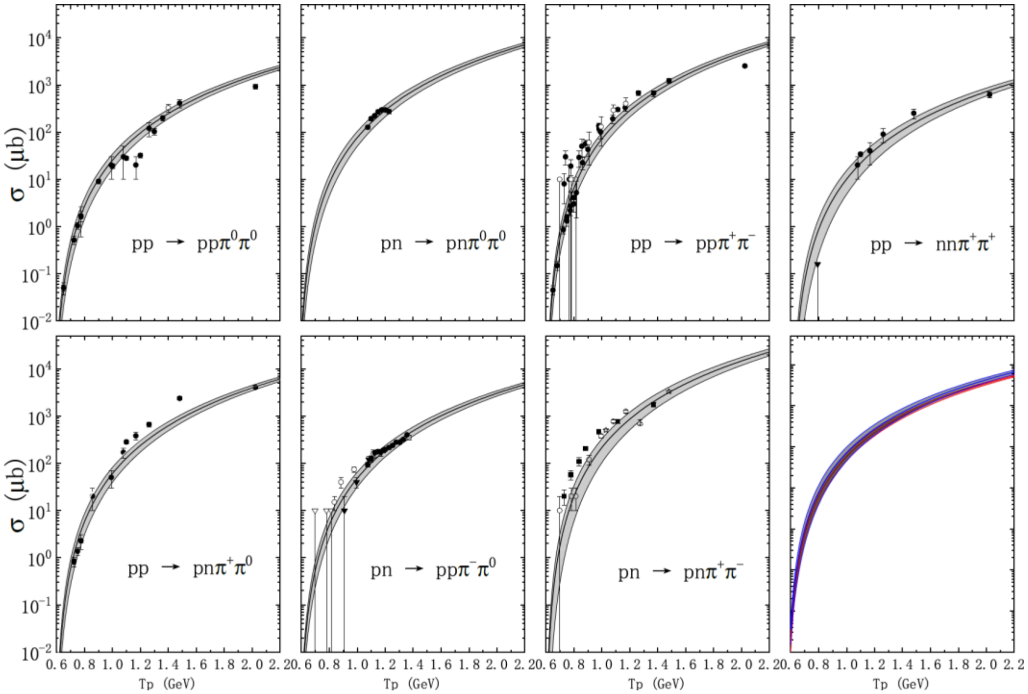
- **I: Production of mesons via pN reactions:**

$$2[\sigma(pp \to pp\pi^+\pi^-) + \sigma(pn \to pn\pi^+\pi^-) + \sigma(pp \to nn\pi^+\pi^+)] =$$
$$4\sigma(pp \to pp\pi^0\pi^0) + 4\sigma(pn \to pn\pi^0\pi^0) + \sigma(pp \to pn\pi^+\pi^0) + 2\sigma(pn \to pp\pi^-\pi^0)$$

- X. C., Bing-Song Zou, Hu-Shan Xu, PRC81(2010)065201;
  X.C. IJMPA26(2011)505

- For single pion production, see:
Z. Ouyang, J. J. Xie, B. S. Zou, H. S. Xu, IJMPE18(2009)281, NPA821(2009)220

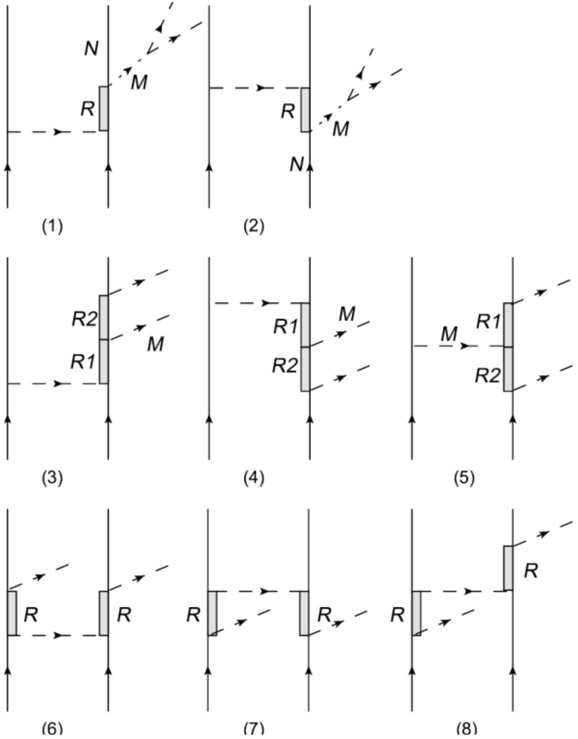


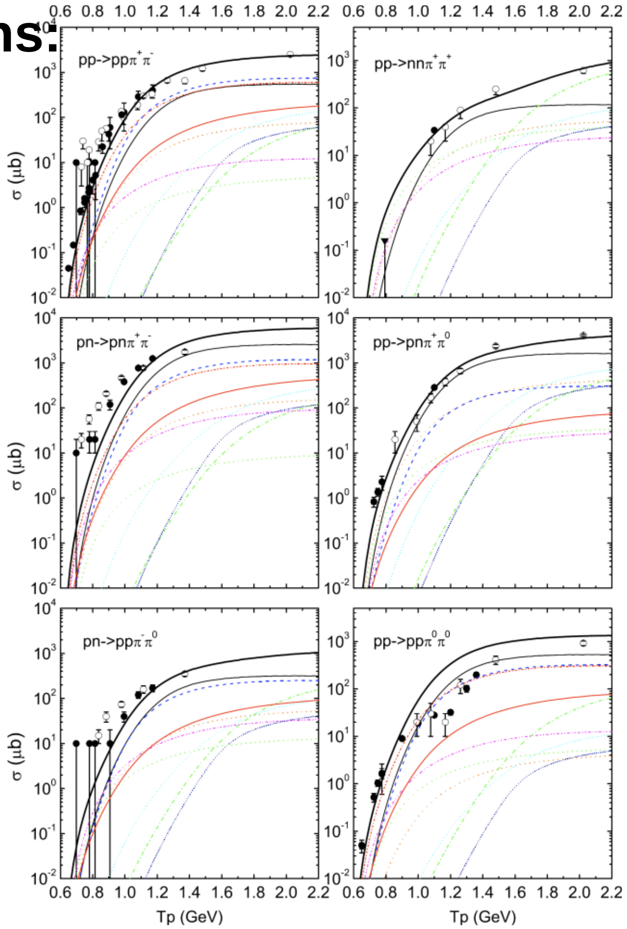



# Real meson beams

- **I: Production of mesons via pN reactions:**

- Single decay
- Cascade decay
- Double excitation



# Real meson beams

- **I: Production of mesons via pN reactions:**

- Negligible contributions at low energies:
- small branching ratios of double pion channel: $S_{11}(1535), S_{11}(1650), D_{13}(1700)$
- higher partial waves: $D_{13}(1520), D_{15}(1675)$
- lying beyond the considered energies: $F_{15}(1680), D_{33}(1700), P_{11}(1710), P_{13}(1720)$
- Resonances with mass bigger than 1720MeV: the two pion branching ratios have large uncertainties
- but would be important at higher energies, e.g. HIAF
- Portable with flexible energies&amplitudes to produce MC events

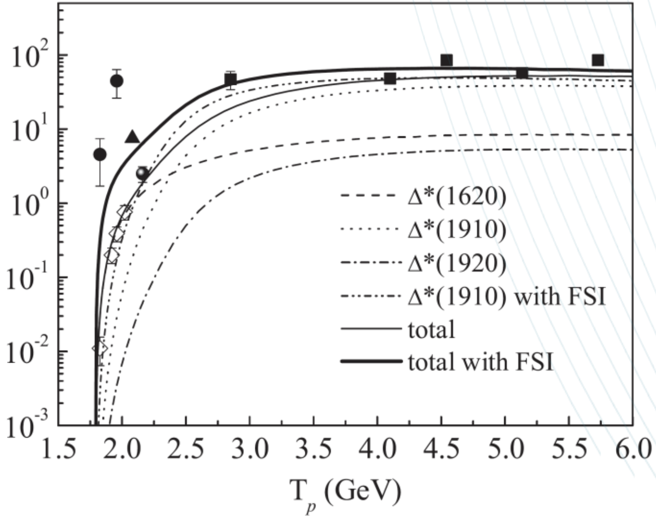
| Resonance | BW Width | Decay mode |
|---|---|---|
| $\Delta^*(1232)P_{33}$ | 118 | $N\pi$ |
| $N^*(1440)P_{11}$ | 300 | $N\pi$ |
| | | $N\sigma$ |
| | | $\Delta\pi$ |
| $\Delta^*(1600)P_{33}$ | 350 | $N\pi$ |
| | | $\Delta\pi$ |
| | | $N^*(1440)\pi$ |
| $\Delta^*(1620)S_{31}$ | 145 | $N\pi$ |
| | | $N\rho$ |
| | | $\Delta\pi$ |

# Real meson beams

- **I: Production of mesons via pN reactions:**

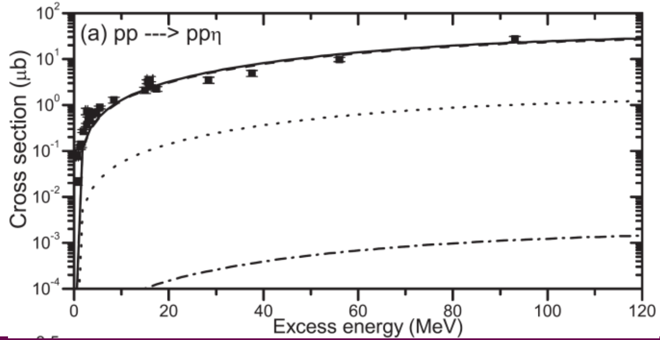
$$pp \to nK^+\Sigma^+$$

- X.-Y. Wang, X. C., J.-J. Xie, X.-R. Chen, Phys. Rev. C 92, 015202 (2015);
  X. C., Xi-Guo Lee, Qing-Wu Wang, Chin. Phys. Lett. 25, 888 (2008)




| Resonances | channel | Branching ratio (%) |
|---|---|---|
| $\Delta^*(1620)$ | $\pi N$ | 25.0 |
| | $K\Sigma$ | – |
| $\Delta^*(1750)$ | $\pi N$ | 10.0 |
| | $K\Sigma$ | 7.1 |
| $\Delta^*(1910)$ | $\pi N$ | 22.5 |
| | $K\Sigma$ | 14.0 |
| $\Delta^*(1920)$ | $\pi N$ | 12.5 |
| | $K\Sigma$ | 2.14 |
| $N^*(1535)$ | $\pi N$ | 0.35–0.55 |
| | $\rho N$ | $0.02 \pm 0.01$ |
| | $\eta N$ | 0.45–0.60 |
| | $\eta' N$ | – |

- For η & η' production, see:
  X. C., Xi-Guo Lee, Phys. Rev. C 78, 035207 (2008)

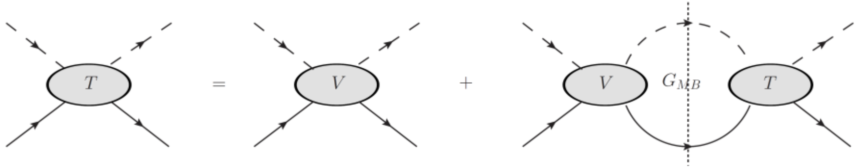


# Real meson beams

- **II: Physics of meson beams:**

K-matrix Coupled-Channel model

$T_{fi} = V_{fi} + V_{fa} G_{ab} T_{bi} \Longrightarrow T_{fi} = K_{fi} + iK_{fa} ImG_{ab} T_{bi}$




- $G_{ab} = \cancel{ReG_{ab}} + iImG_{ab} \Rightarrow T_{fi}^{J\pm,I} = \frac{K_{fi}^{J\pm,I}}{1 - iK_{fi}^{J\pm,I}}$
- Unitarity holds easily with technical simplicity and flexibility but at the cost of analyticity.
- final states: $\gamma N, \pi N, \pi\pi N, \eta N, \omega N, K\Lambda, K\Sigma$

I=1/2&3/2, J≤5/2, $\sqrt{s}$<2.0 GeV

1. coupled-channel (T-matrix) equation is first solved for $\pi N \to MN$
2. In an independent second step, the $\gamma N \to MN$ can be extracted
3. Finally, the Compton scattering amplitudes are calculated without free parameters

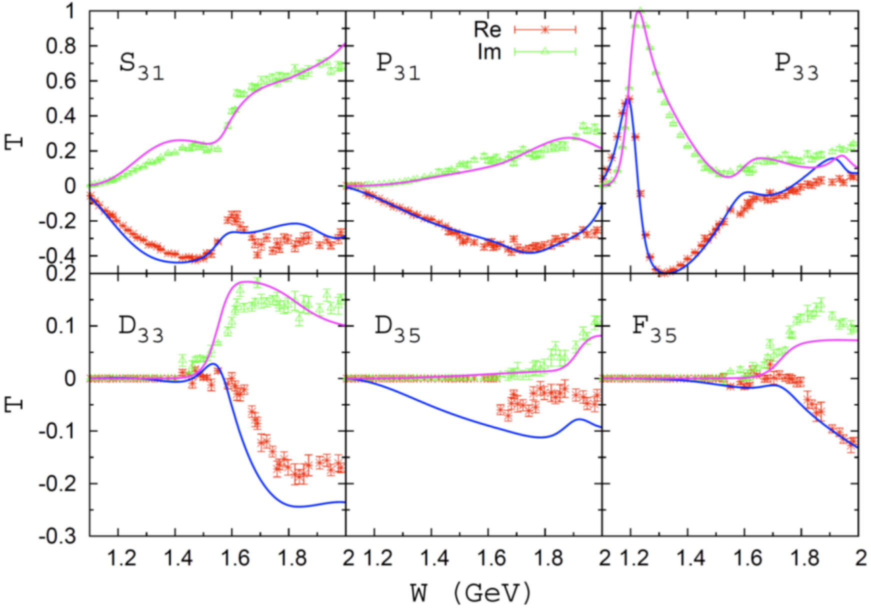

- See: Feuster &Penner &Shklyar &CAO &Lenske & Mosel:
- PRC58,457;59,460(1999);PRC66,055211;055212(2002);EPJA21,445(2004); PRC71,055206;72,015210(2005);
- PLB650,172(2007);PRC80,058201(2009);87,015201(2013);88,055204(2013),PLB772,274(2017);PRC93,045206(2016)

# Real meson beams

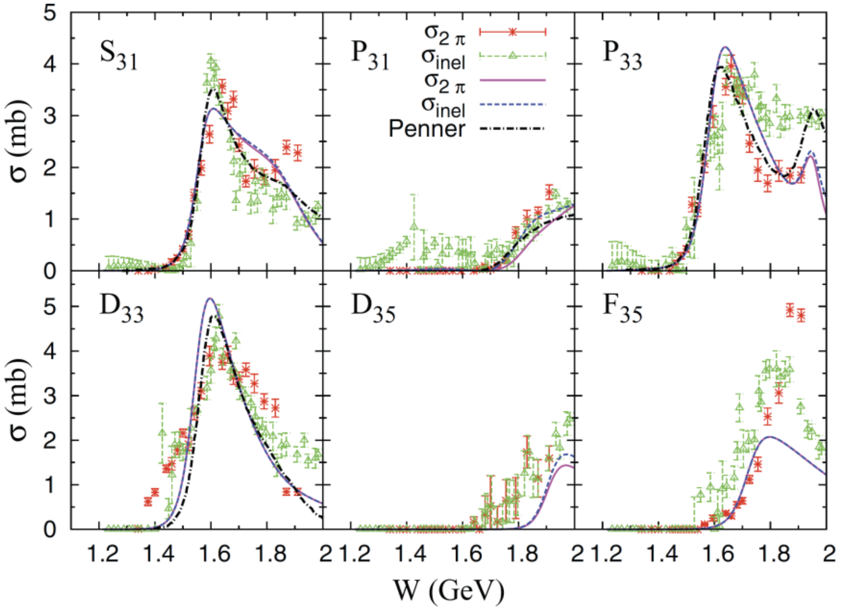
- **II: Physics of meson beams:**

- X. C., V. Shklyar and H. Lenske, Phys. Rev. C 88, 055204 (2013)

Elastic πN partial waves for I = 3/2




Inelastic 2πN total partial wave cross sections for I = 3/2



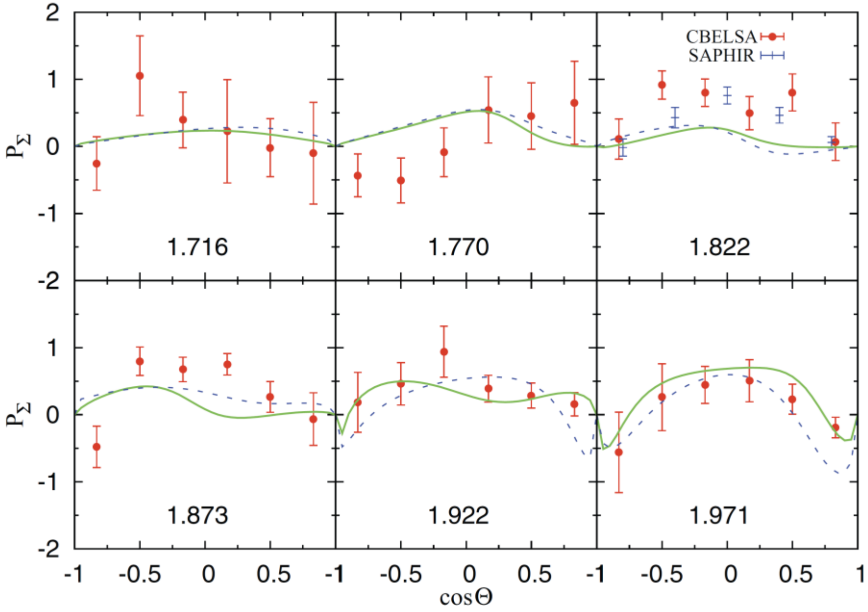
# Real meson beams

- **II: Physics of meson beams:**
  - X. C., V. Shklyar and H. Lenske, Phys. Rev. C 88, 055204 (2013)

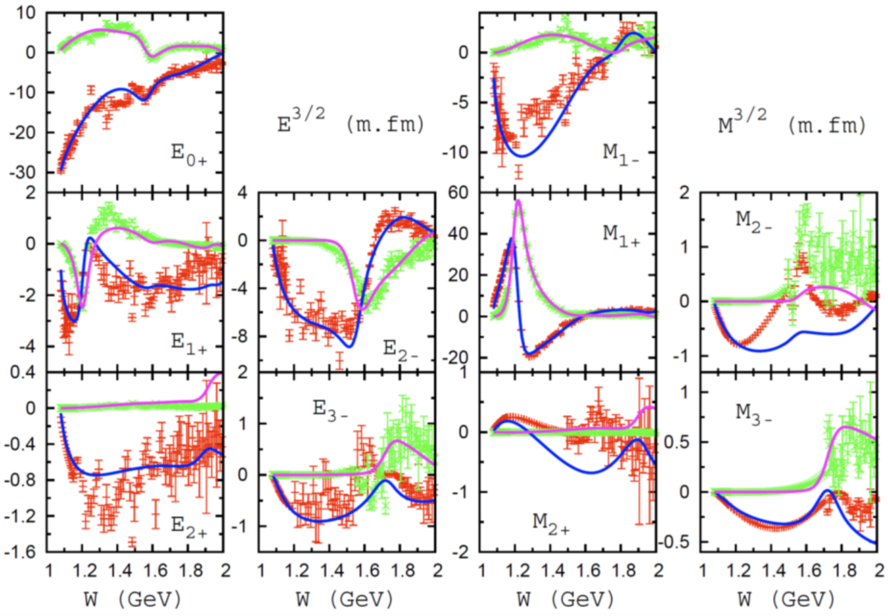
γp →$K^+\Sigma^0$ requires

| $g_{NK\Sigma}$ | $g_{NK^*\Sigma}$ |
|---|---|
| -5.41 | 0.83 |
| 2.48 | 4.33 |

recoil polarization of the γp →$K^0\Sigma^+$




γN → πN multipoles for I = 3/2

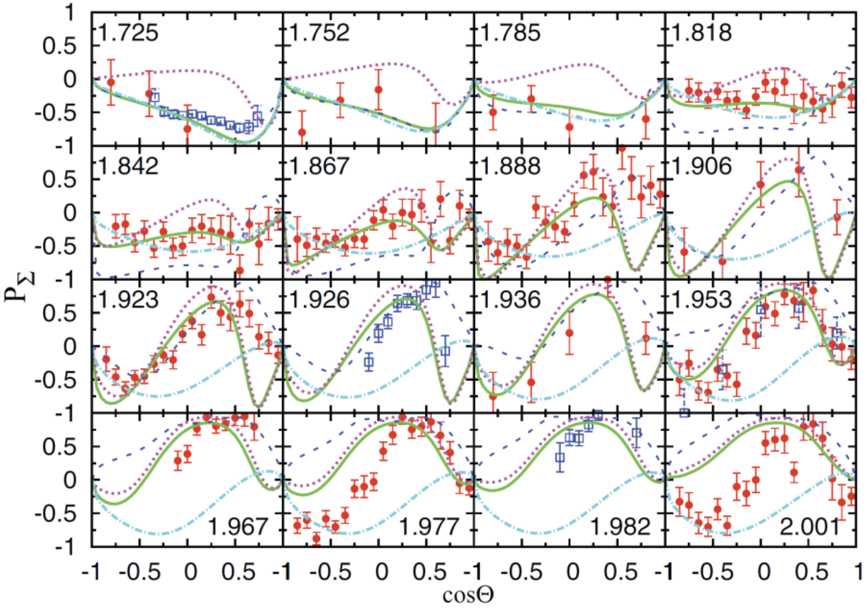


# Real meson beams

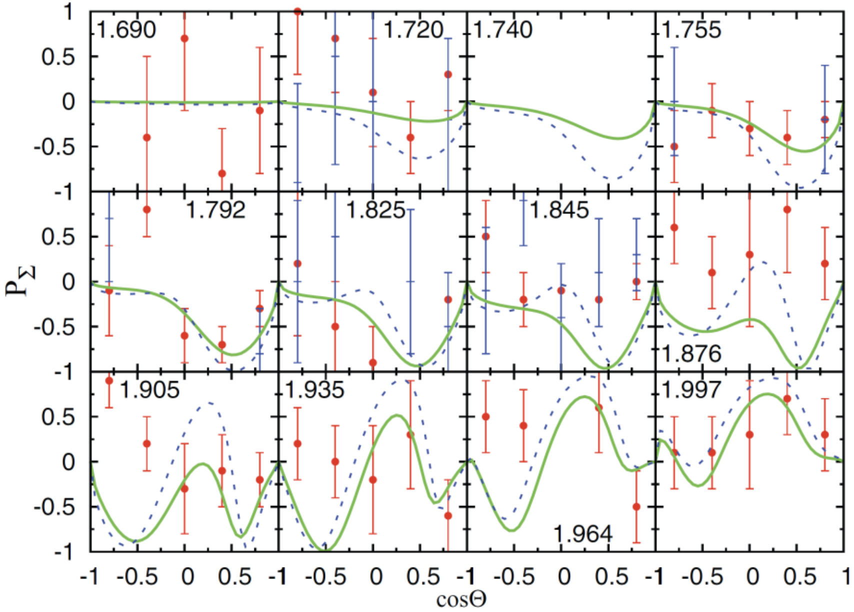
- **II: Physics of meson beams:**

  - X. C., V. Shklyar and H. Lenske, Phys. Rev. C 88, 055204 (2013)    $P_{31}$ (1750) is indispensable, * in PDG

$\Sigma^+$ polarization of the $\pi^+ p \rightarrow K^+\Sigma^+$




$\Sigma^0$ polarization of the $\pi^- p \rightarrow K^0\Sigma^0$



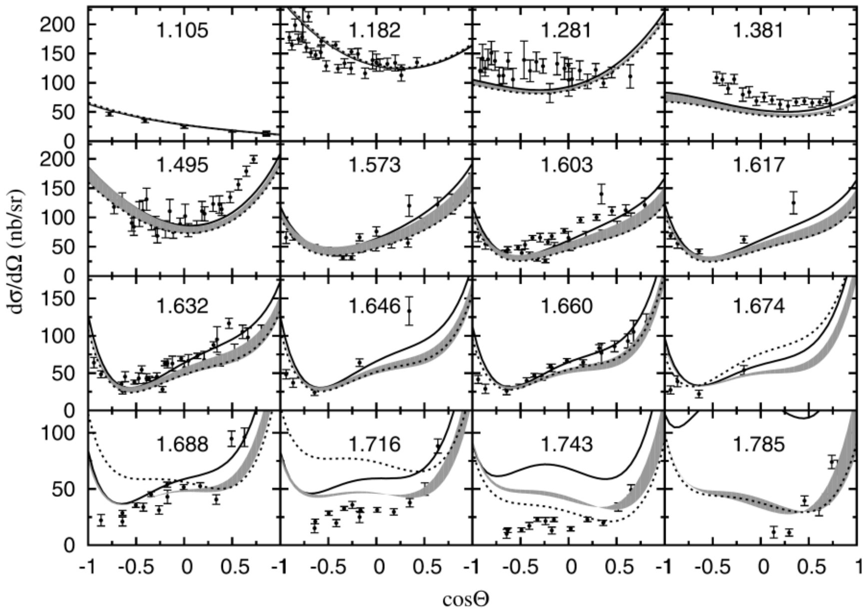
# Real meson beams

- **II: Physics of meson beams:**

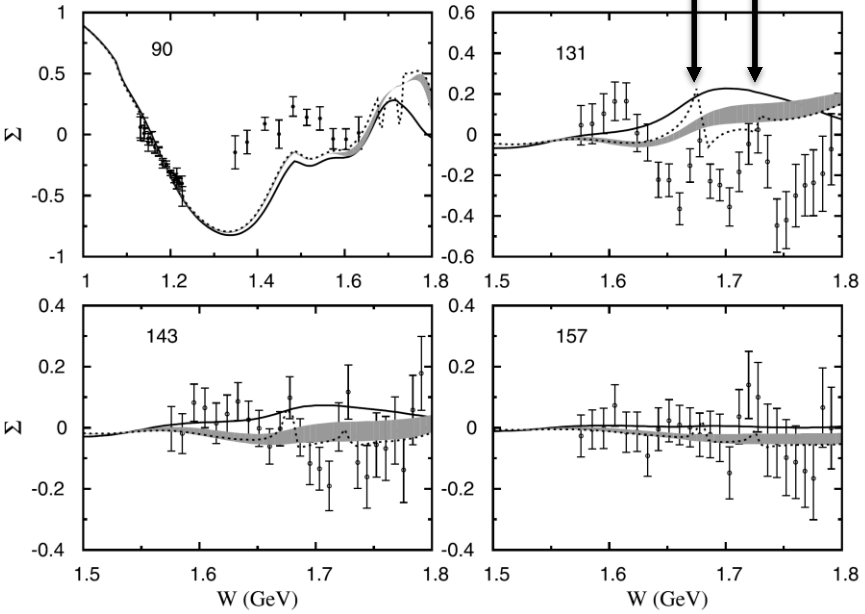
- X. C,H.Lenske, PhysicsLettersB772(2017)274
- X. C., Front. Phys. (Beijing) 18, 44600 (2023)

$D_{33}(1700)$ and $F_{35}(1905)$ are indispensable, $S_{11}(1680)$ $P_{11}(1720)$

Differential cross sections



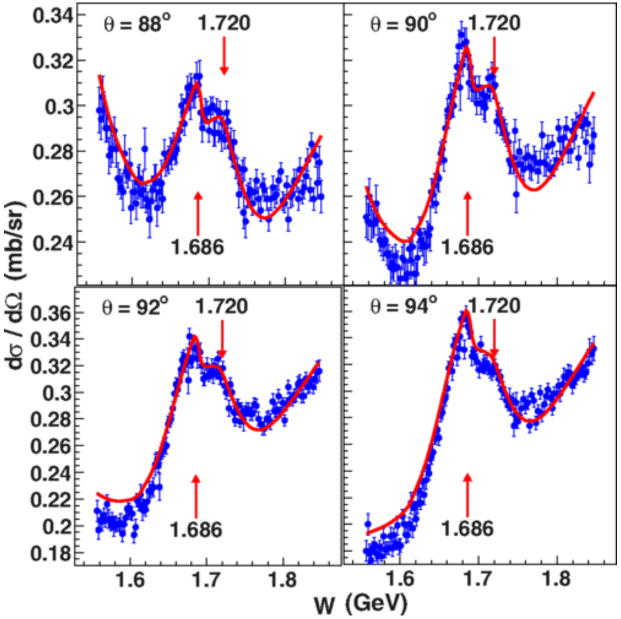

Beam polarization



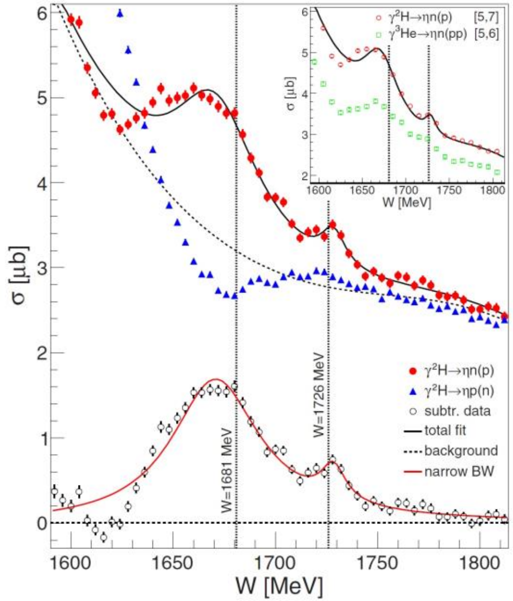
# ● II: Physics of meson beams:

- Evidence of two exotic narrow states: $S_{11}(1680)$ and $P_{11}(1720)$?

EPECUR'2015
$\pi^{\pm}p \to \pi^{\pm}p$




Graal, confirmed by A2@MAMI
$\gamma p \to \eta p$ & $\gamma n \to \eta n$



# Virtual meson beams

- **Polarized Electron-ion collider in China (EicC)**
- **Energy:**

  electron + proton: 3.5 GeV × 20 GeV

  electron + $^3$He: 3.5 GeV × 40 GeV

**中国科学: 物理学力学天文学, 50: 112005 (2020)**

**核技术, 43(2): 020001 (2020)**

**Front. Phys. 16, 64701 (2021)**

- **Luminosity:**

  Instantaneous Lumi: 2 x $10^{33}$ $cm^{-2}$ $s^{-1}$

  Integrated Lumi for simulation = 50 $fb^{-1}$

TMD: k ⊥ & longi. Momentum

GPD: trans. spatial position b⊥ & longi. Momentum

- **Polarization:**

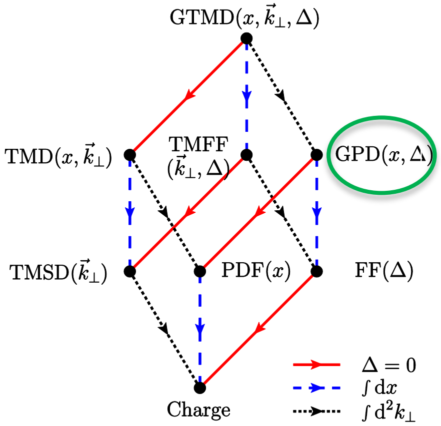
  electron: 80% L

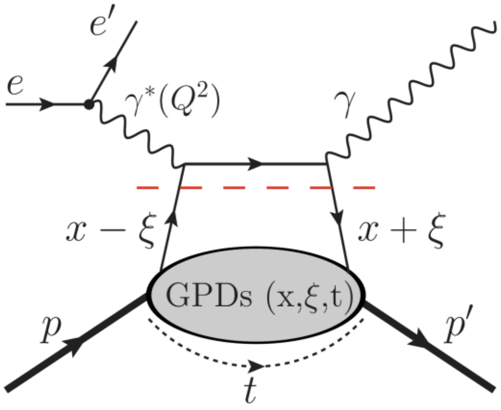
  proton& $^3$He: 70% L&T

- **Phase space coverage**

  **√s ~ 16.7 (15 ~ 20)GeV**

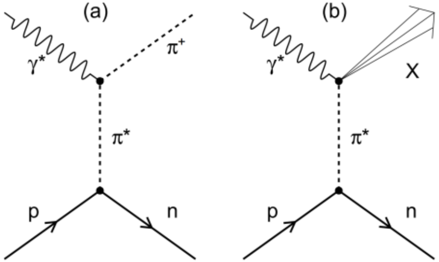
  **$4\times10^{-3}$ < x < ~ 0.1**



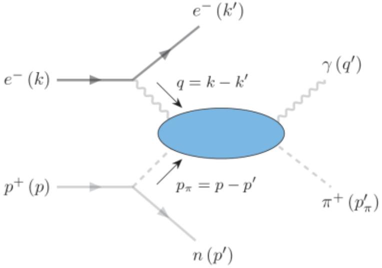



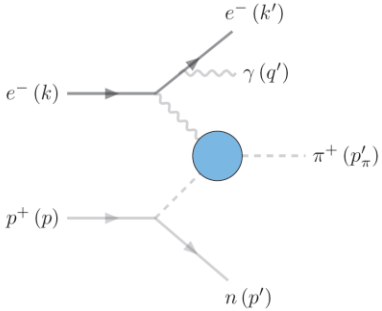
# Virtual meson beams

- **From 1D to 3D structure of pions & kaons:**
- Pions/Kaons as the approximate Nambu–Goldstone bosons of spontaneously broken chiral symmetries associated with the (near) masslessness of quarks
- Probed by Drell-Yan process with high energy pion beams at HERA
- Sullivan process: Detection of leading neutron/Lambda (Phys. Rev. D, 5:1732, 1972)
- Validity: S.-X. Qin *et al.*, Phys. Rev. C97:015203, 2018; Shastry *et al.*, Phys.Rev.D108(2023)114024; Leao *et al.*, Phys.Rev.D110.074035




- Structure function
- **Sensitivity to elastic form factor and Parton Distribution Functions**



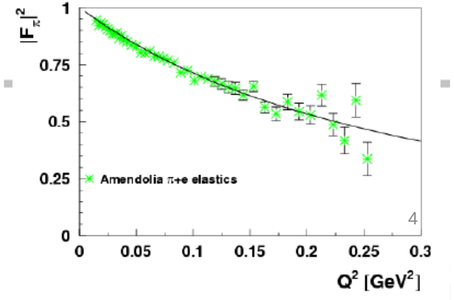

- $\pi^+$-DVCS
- **quarks and gluons interfere destructively**
- see: D. Amrath *et al.*, Eur. Phys. J. C (2008) 58: 179
  J. M. Morgado Chávez *et al.*, Phys.Rev.Lett. 128 (2022) 202501

# Virtual meson beams

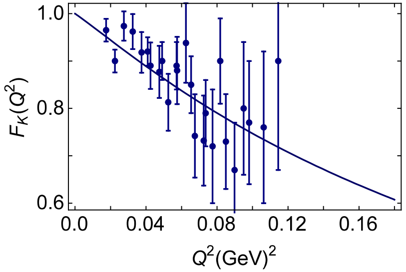
- **Status: structure of pions & kaons:**

## Meson Form Factor

- Elastic scattering of high energy meson beam from atomic electron target
  - Model independent way to measure form factor
  - Limited at low $Q^2$, need TeV meson to reach $Q^2$ = ~1GeV$^2$
  - $r_\pi$ = 0.657 ± 0.012 fm
  - $r_K$ = 0.560 ± 0.031 fm




Amendolia et al, NPB277,168 (1986)

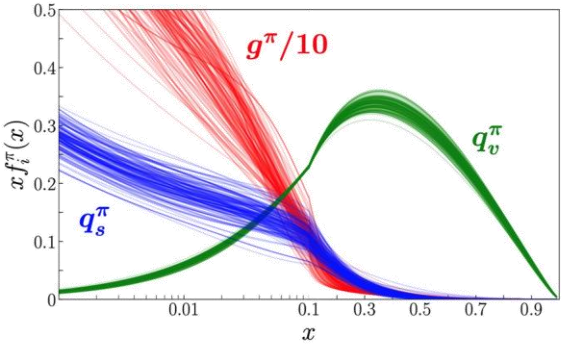



T. Horn and C. D. Roberts. J. Phys. G 43 (2016) 7, 073001

## Meson Structure Function

- Drell-Yan process: quark-antiquark annihilation between pion's and proton's, virtual photon decays into lepton pair
- Information about the quark-gluon momentum fractions

$$\frac{d^2\sigma}{dx_\pi dx_N} = \frac{4\pi\alpha_{em}^2}{9M_\gamma^2}\sum_q e_q^2[q_\pi(x_\pi)\bar{q}_N(x_N) + \bar{q}_\pi(x_\pi)q_N(x_N)]$$

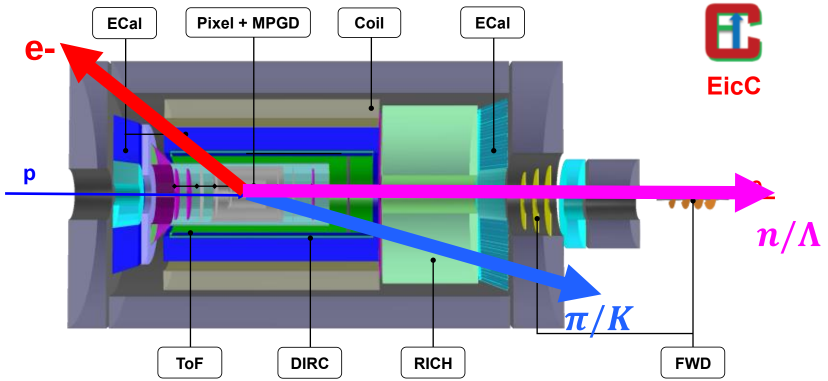


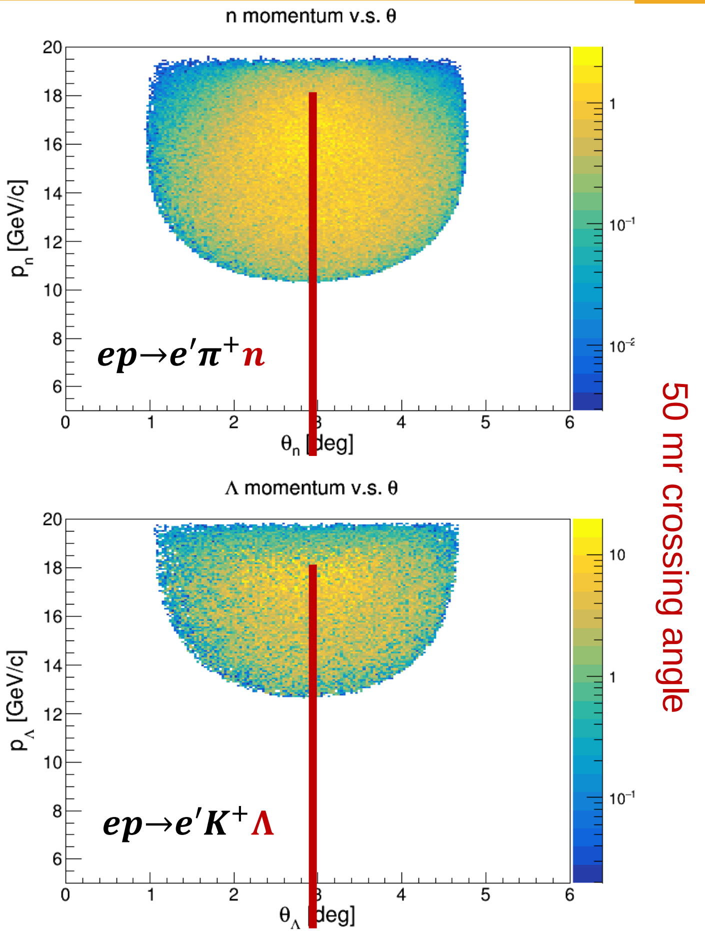
# Virtual meson beams

- Form Factors Measurement

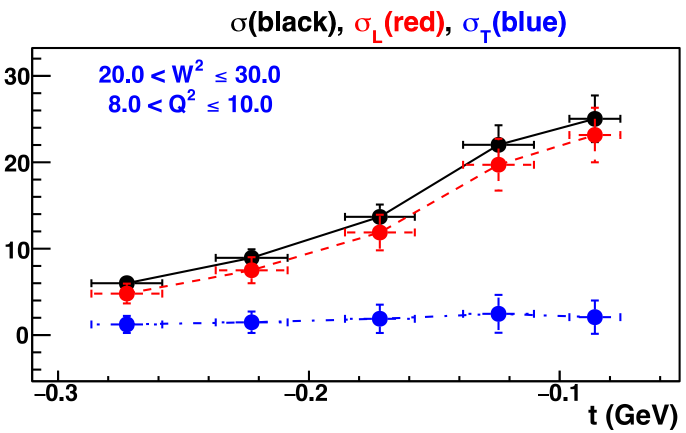
- Scattered electron and meson very well covered by central detector: Eff. > 95%
- “Spectator” neutron and $\Lambda$ move very close to the initial p-beam: far-forward detectors

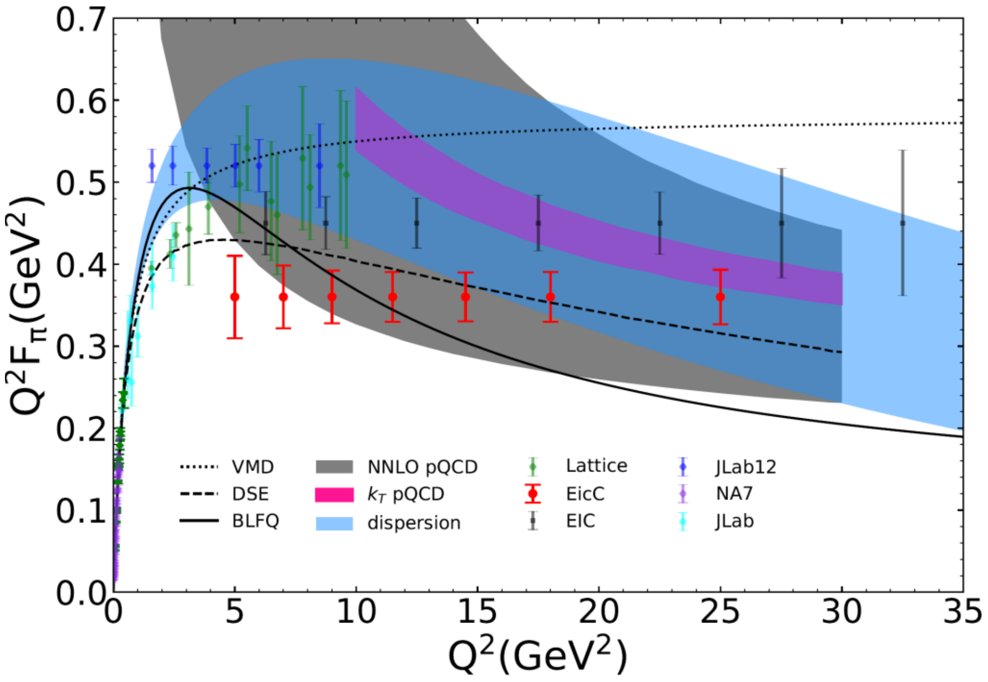
- Pion FF and SF require ZDC for neutron detection
- Kaon FF and SF need all detectors in far-forward region for $\Lambda$ neutral & charged decay



# Virtual meson beams



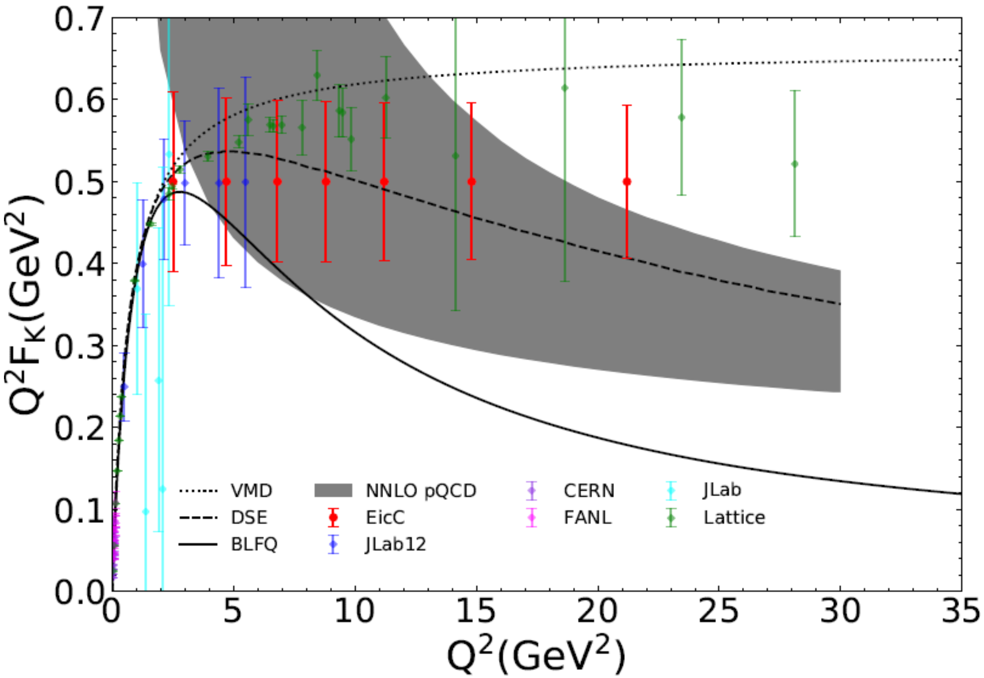




- In hard scattering regime, QCD scaling predicts $\sigma_L \propto Q^{-6}, \ \sigma_T \propto Q^{-8}$
- 100% uncertainty in R = $\sigma_T / \sigma_L$ from model subtraction
- 2.5% point-to-point syst. uncertainty
12% scaling syst. uncertainty

Eicc prelim. Compared to EIC(arXiv:2403.06000)

# Virtual meson beams

- energy setting: 3.5 GeV e x 20 GeV p
- Integrated luminosity: 50 $fb^{-1}$
- Include full detector acceptance
- 100% uncertainty in $R = \sigma_T / \sigma_L$ from model subtraction
- 2.5% point-to-point syst. uncertainty
  12% scaling syst. Uncertainty



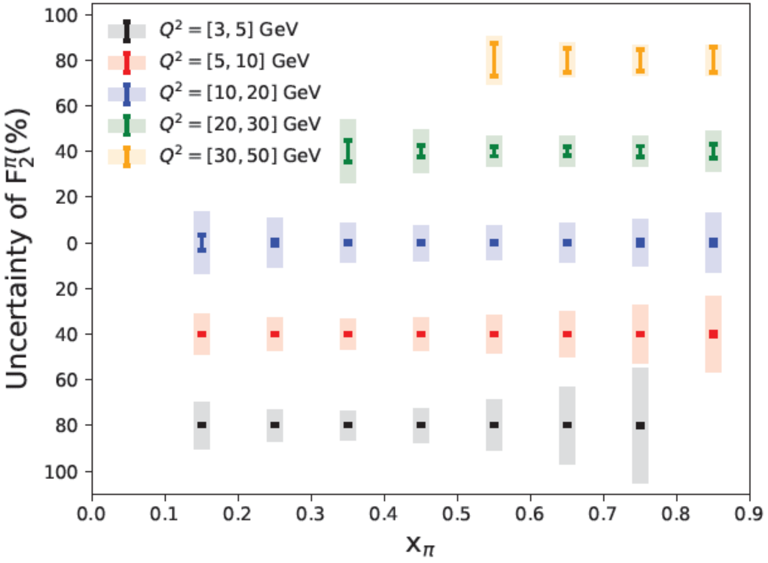

- Courtesy: Ting Lin, Weizhi Xiong (Shandong U.), Yutie Liang, Aiqiang Guo (IMPCAS)

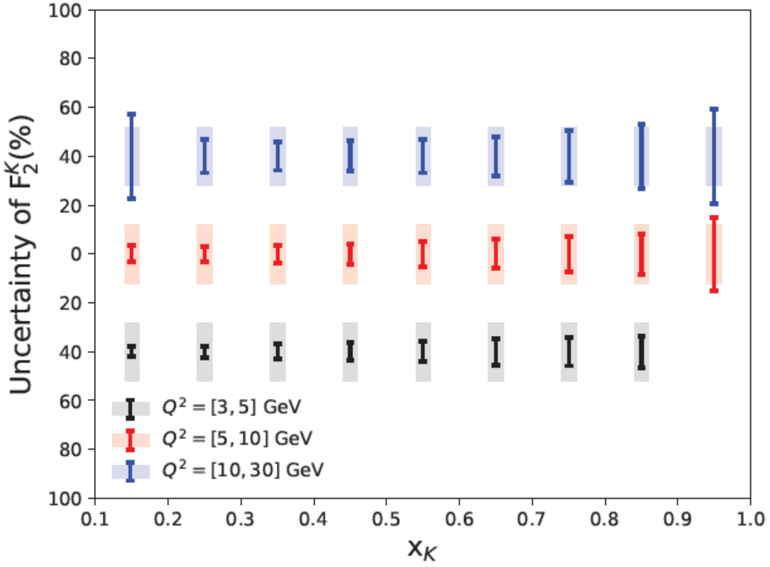
# Virtual meson beams

- RAPGAP generator
- Impact on the PDF extraction: in progress

$x_L > 0.75$, $P_T^n < 0.5$ GeV, $\theta_n$<15 mrad
EicC 50 fb$^{-1}$ $M_X > 0.5$ GeV

Stat. uncertainty only
systematic studies ongoing



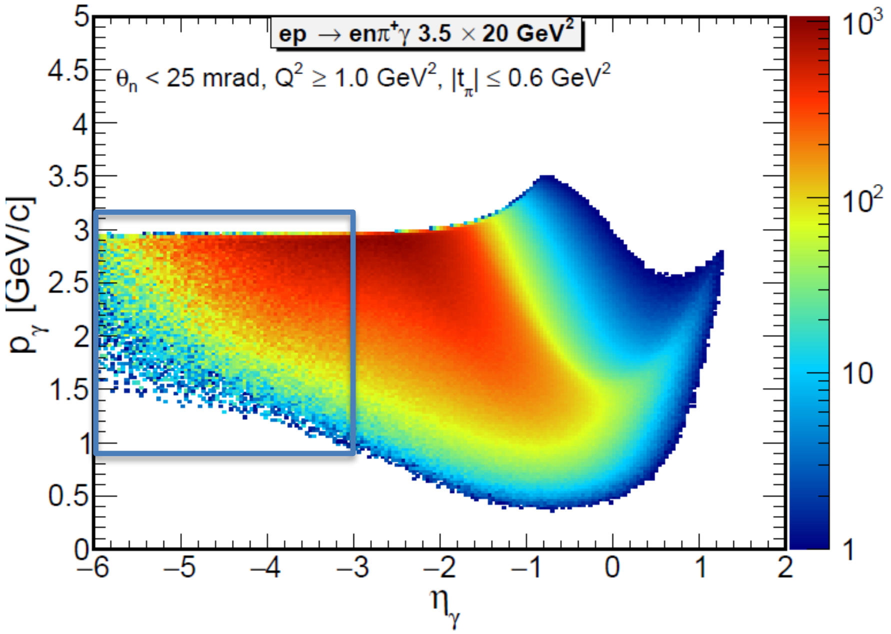

- Pion Meson Structure Function

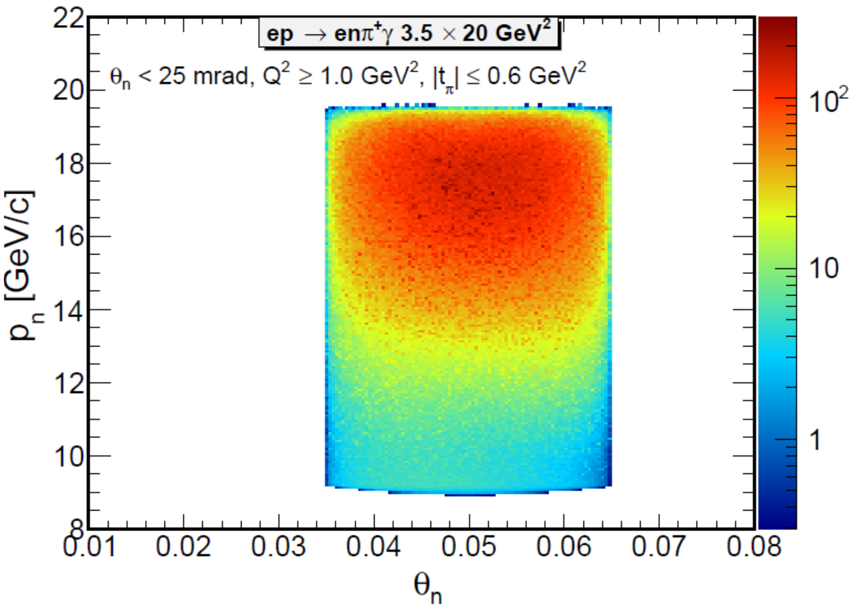
Kaon Meson Structure Function

# Virtual meson beams

- $\pi^+$-DVCS through Sullivan process: Meson GPD

X. C., Maxime Defurne, Ai-Qiang Guo, Yu-Tie Liang, Dexu Lin, Cédric Mezrag, José Manuel Morgado, Wei-Zhi Xiong *et al.*



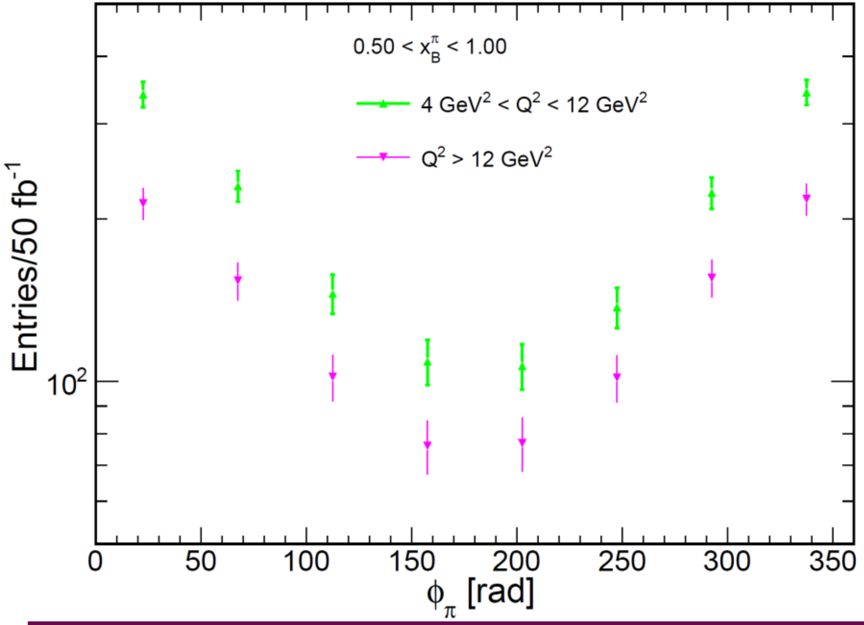



# Virtual meson beams

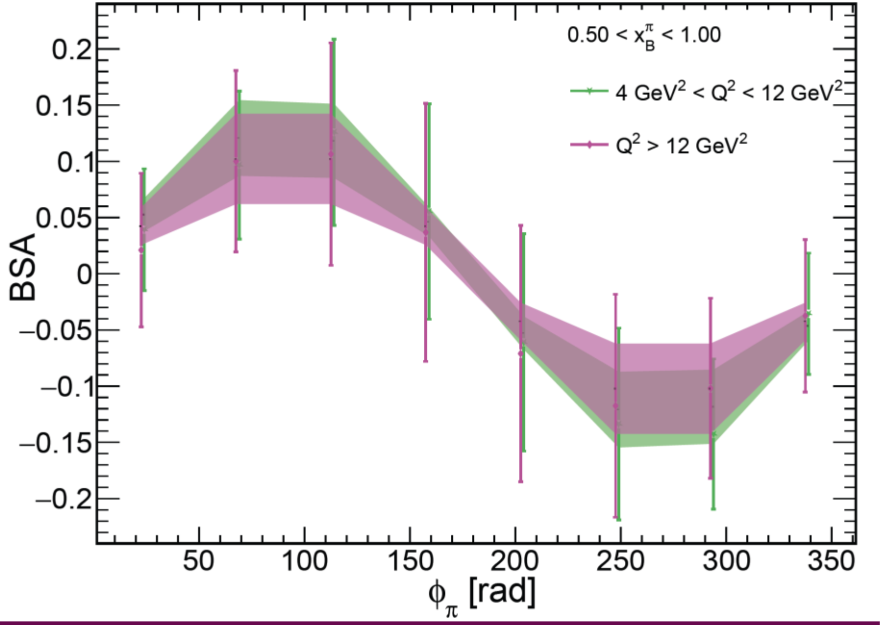
- $\pi^+$-DVCS through Sullivan process (filtered by detector at EicC)
- Over eff. ~ 45.9% Asy. 0.13 ± 0.04

  ~ 42.6% 0.11 ± 0.04

$$F_\pi(t_\pi)\,\mathrm{Re}\,\mathcal{H}_\pi \cos\phi_\pi$$




$$\mathcal{A}(\varphi_{\mathrm{Trento}}) = \frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow} \propto \mathrm{Im}(\mathcal{H}_\pi)\sin(\varphi_{\mathrm{Trento}}),$$

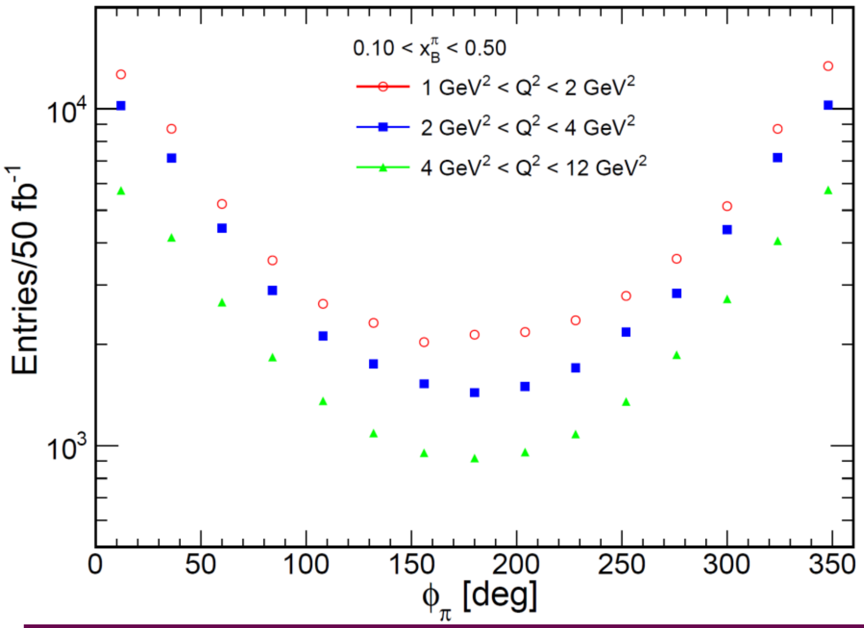


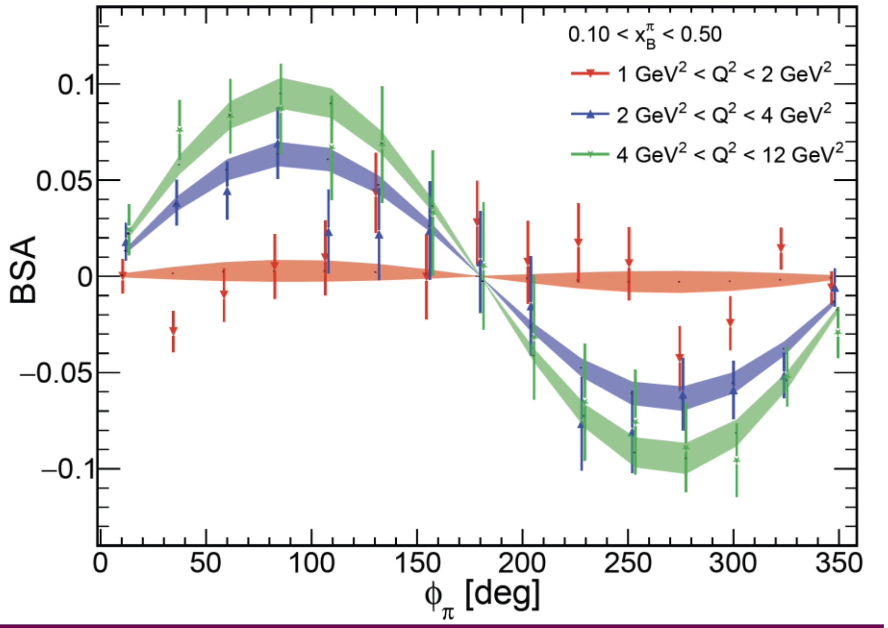
# Virtual meson beams

- $\pi^+$-DVCS through Sullivan process (filtered by detector at EicC)
- Over eff. ~ 35.0% Asy. 0.003±0.006
  - ~ 36.0% 0.064±0.006
  - ~ 33.9% 0.095±0.008

$$F_\pi(t_\pi)\,\mathrm{Re}\,\mathcal{H}_\pi \cos\phi_\pi$$

$$\mathcal{A}(\varphi_{\mathrm{Trento}}) = \frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow} \propto \mathrm{Im}(\mathcal{H}_\pi)\sin(\varphi_{\mathrm{Trento}}),$$



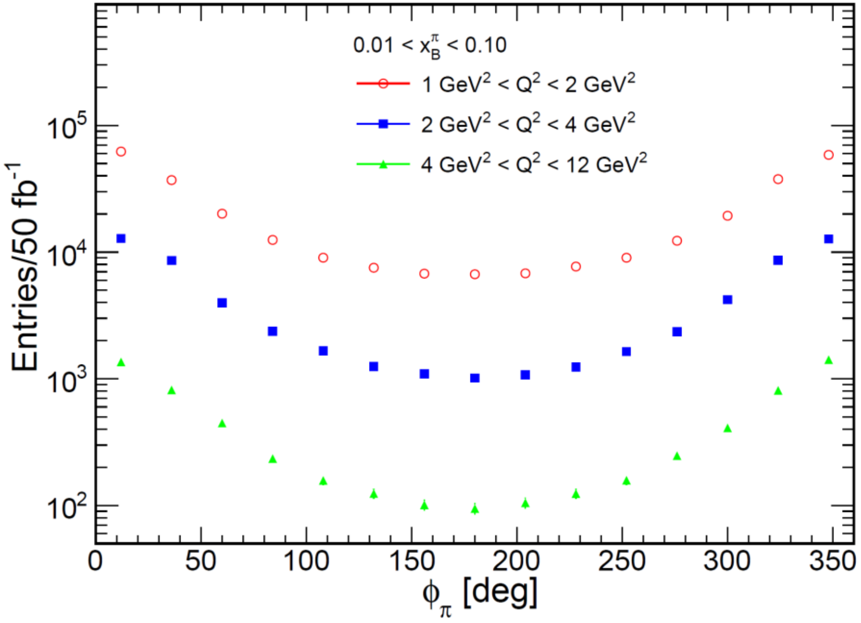



# Virtual meson beams

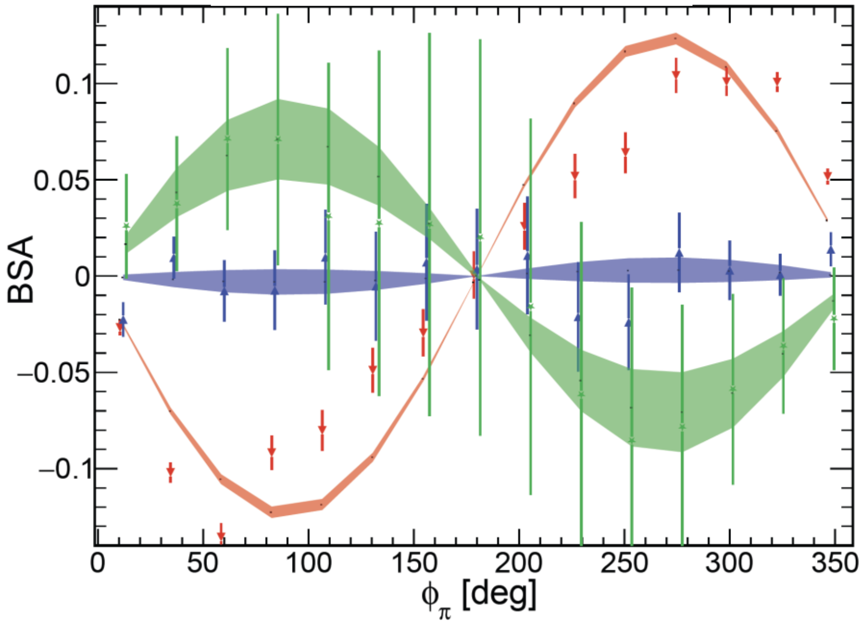
- $\pi^+$-DVCS through Sullivan process (filtered by detector at EicC)
- Over eff. ~ 17.8% / ~ 19.9% / ~ 20.6%

Asy. -0.124±0.003 / -0.003±0.007 / 0.07 ± 0.02

$$F_\pi(t_\pi)\,\mathrm{Re}\,\mathcal{H}_\pi \cos\phi_\pi$$

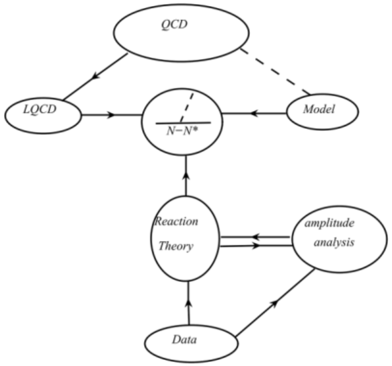



$$\mathcal{A}(\varphi_{\mathrm{Trento}}) = \frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow} \propto \mathrm{Im}(\mathcal{H}_\pi)\sin(\varphi_{\mathrm{Trento}}),$$



# Summary

- **Rise of the worldwide interest on meson beams:**




- Low energies: JLab, J-PAC
- High energies: COMPASS@CERN

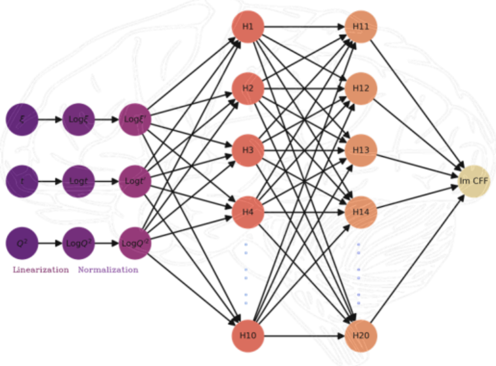
… challenge the CC model construction above 2.0 GeV:

A crowd of resonances and channels

- Future electron-ion colliders: virtual meson beams

… challenge the facility design and theory: inverse problem, extract GPDs from CFFs

$$\mathcal{H}(x_B,t,Q^2) = \sum_{a=u,d,\dots,g} \int_{-1}^{1} \frac{dx}{2\xi} T^a_{\text{DVCS}}(x,\xi,Q^2)\, H^a(x,\xi,t,Q^2)\,,$$

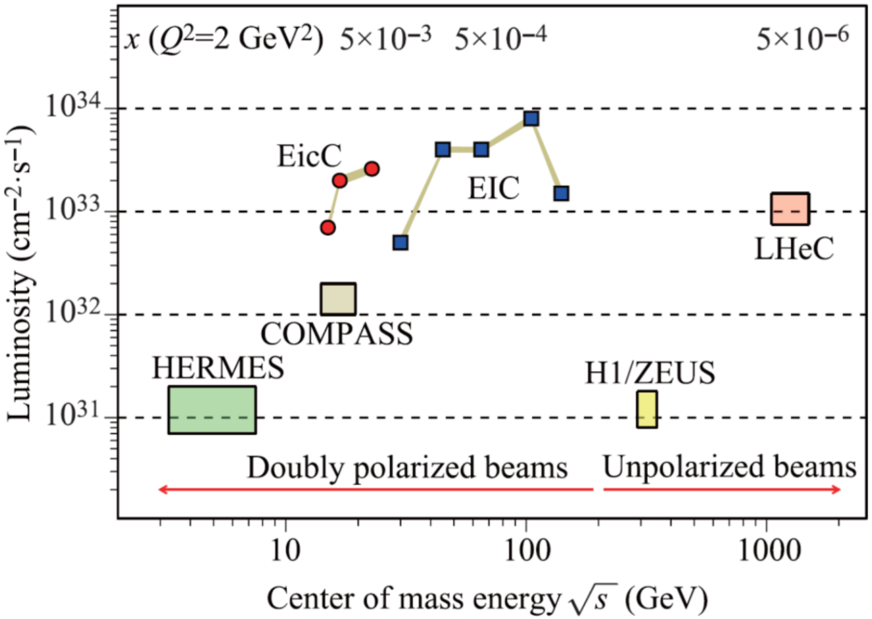


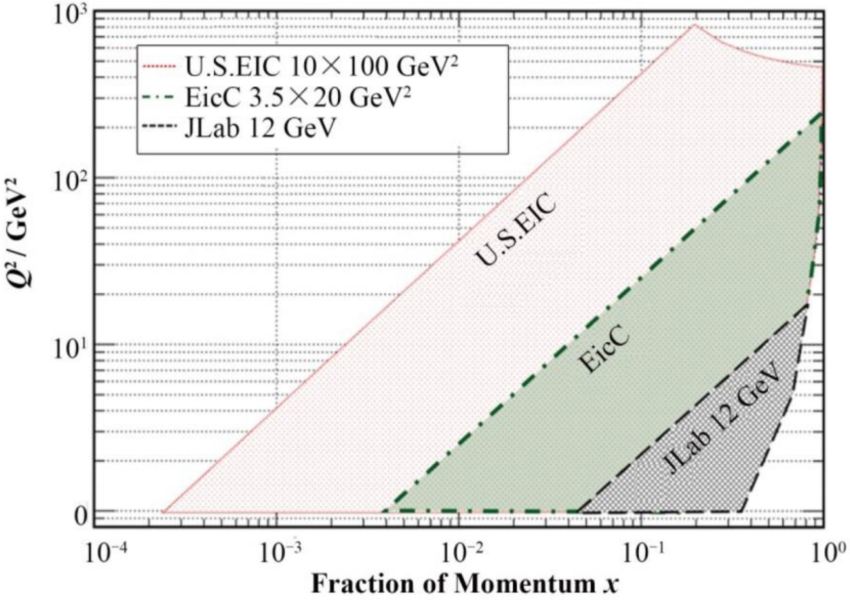

- Artificial Intelligence, e.g. Neural Network, would be helpful

- **HIAF:** Beams? Energies? Polarized Targets? Detector？

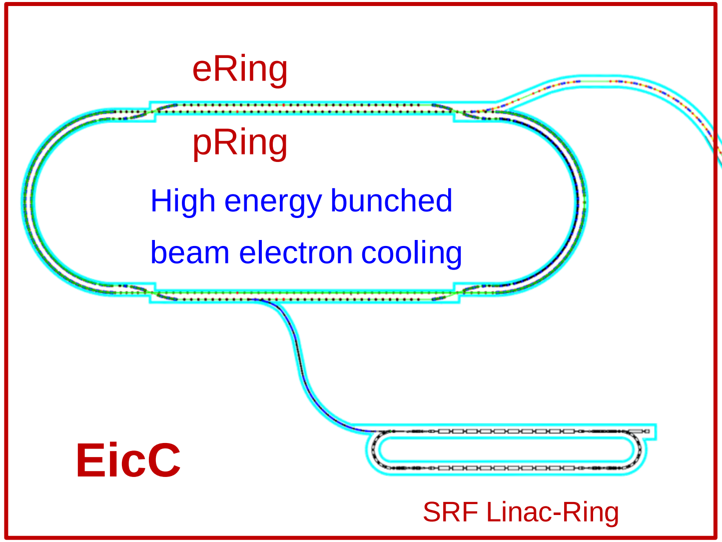
# Thanks

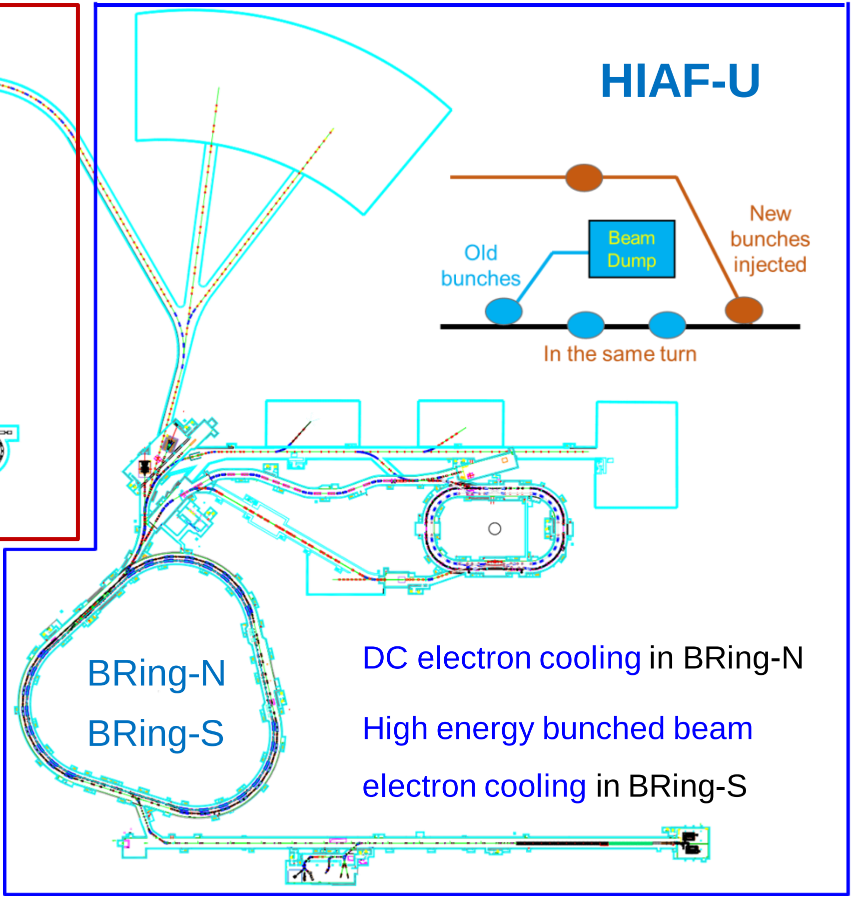
# Status&Agenda of EicC



# Status&Agenda of EicC

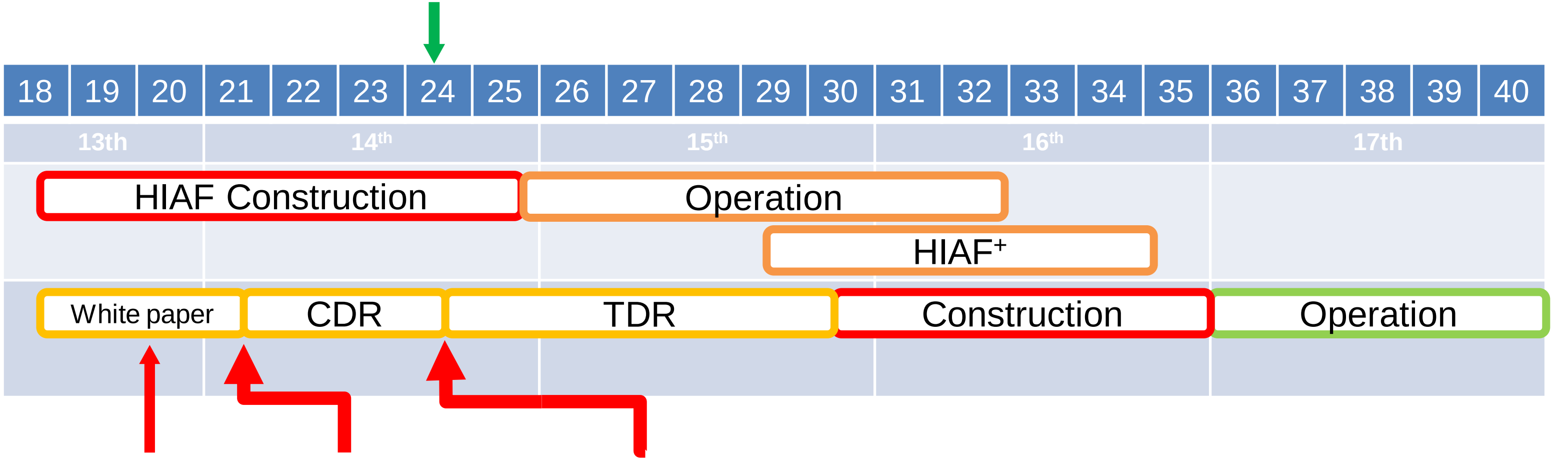



Upgrade from High Intensity Heavy-ion Accelerator Facility

- ✓ Four potential interaction points
- ✓ Full energy injection for online bunch replacement
- ✓ Multi-stage electron cooling leading to smaller emittance

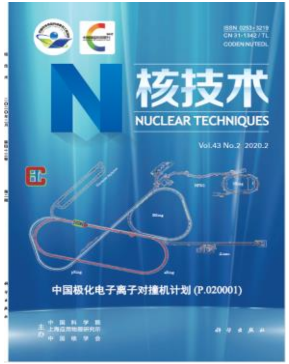
# Status&Agenda of EicC

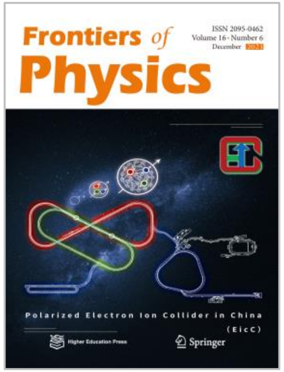


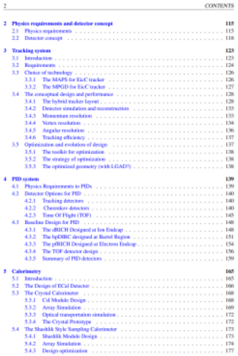

2020.02

2021.06

2024.08 CDR




**Fundings for detector and accelerator R&D:**

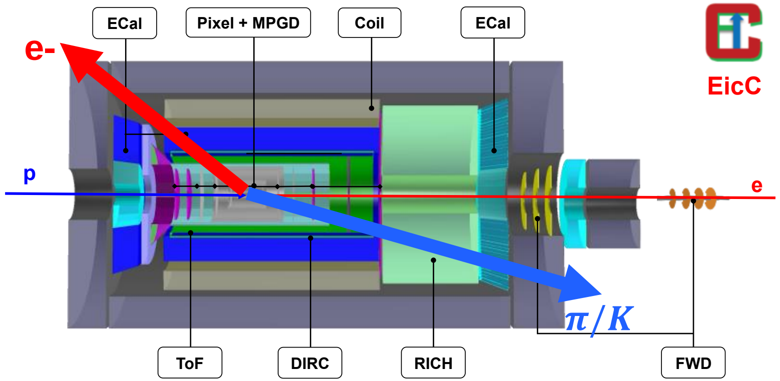
**Forward detectors: ZDC, OMD, EDT**

**proton polarimetry**

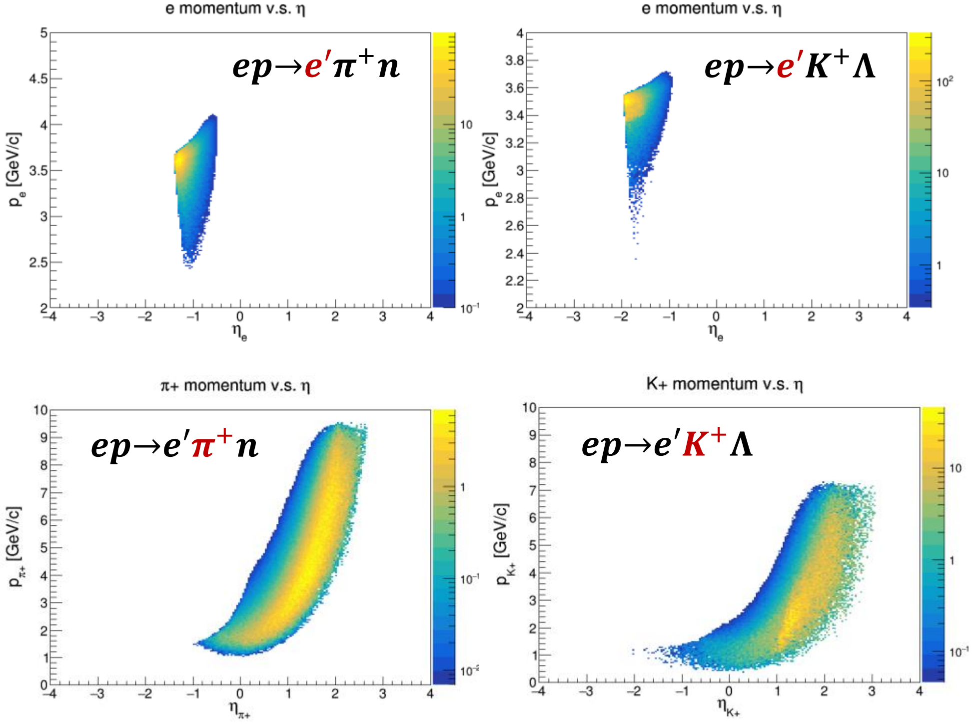
**Polarized proton beam**

# Meson Form Factor

- Scattered electron and meson very well covered by central detector
- Acceptance and resolution studied extensively for central detector, fast simulation exist
  - Eff. > 95% for both particles




3.5 GeV (e) x 20 GeV (p)



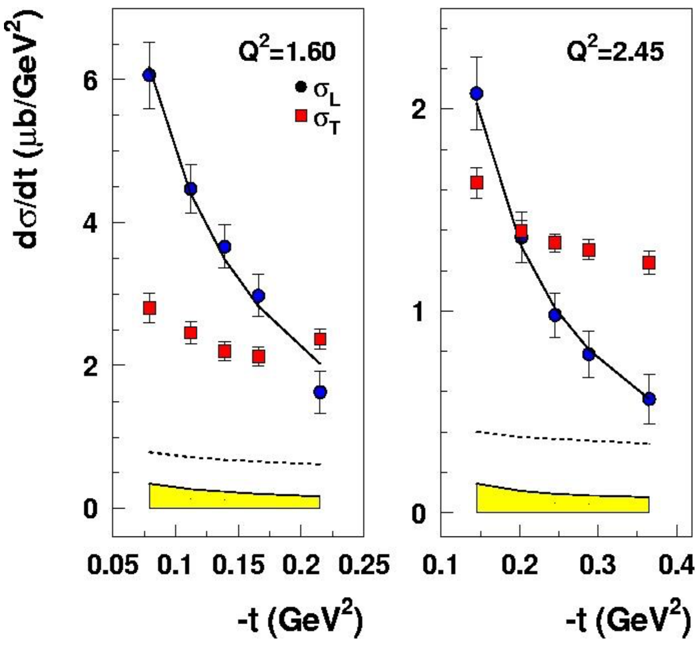
# Meson Form Factor

- Generally, one can apply L-T separation (like JLab) and isolate $\sigma_L$, where the meson factors live

$$\sigma_L \propto F_\pi^2$$

$$2\pi \frac{d^2\sigma}{dt\,d\varphi} = \epsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\epsilon(\epsilon+1)}\,\frac{d\sigma_{LT}}{dt}\cos\varphi + \epsilon\frac{d\sigma_{TT}}{dt}\cos 2\varphi.$$

[Horn et al., PRL **97**, (2006) 192001]




- Measure two CS at same $Q^2$ and W, and solve for $\sigma_L$ and $\sigma_T$

$$\sigma_1 = \sigma_T + \epsilon_1\sigma_L, \quad \sigma_2 = \sigma_T + \epsilon_2\sigma_L$$

$$\frac{\Delta\sigma_L}{\sigma_L} = \frac{1}{(\epsilon_1-\epsilon_2)}\frac{1}{\sigma_L}\sqrt{\Delta\sigma_1^2+\Delta\sigma_2^2}.$$

- *Δε* amplifies uncertainty, ideally need *Δε* > 0.2 (need small center-of-mass energy), difficult for EIC

- Alternatively, one may also use models to isolate $\sigma_L$ (with additional uncertainties)

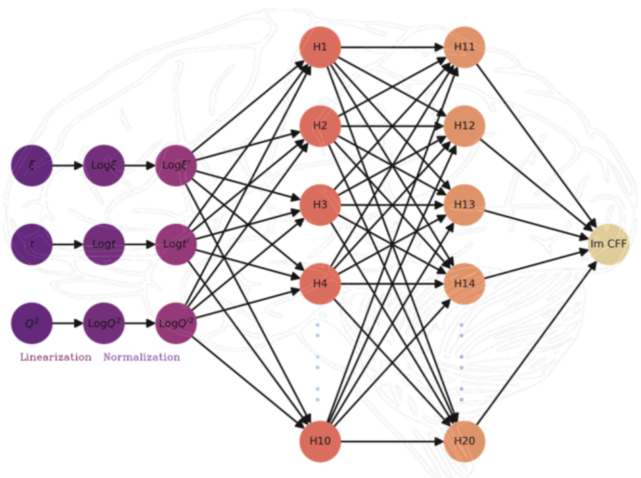
- L-T separation possible at EicC, but definitely not the entire kinematic region

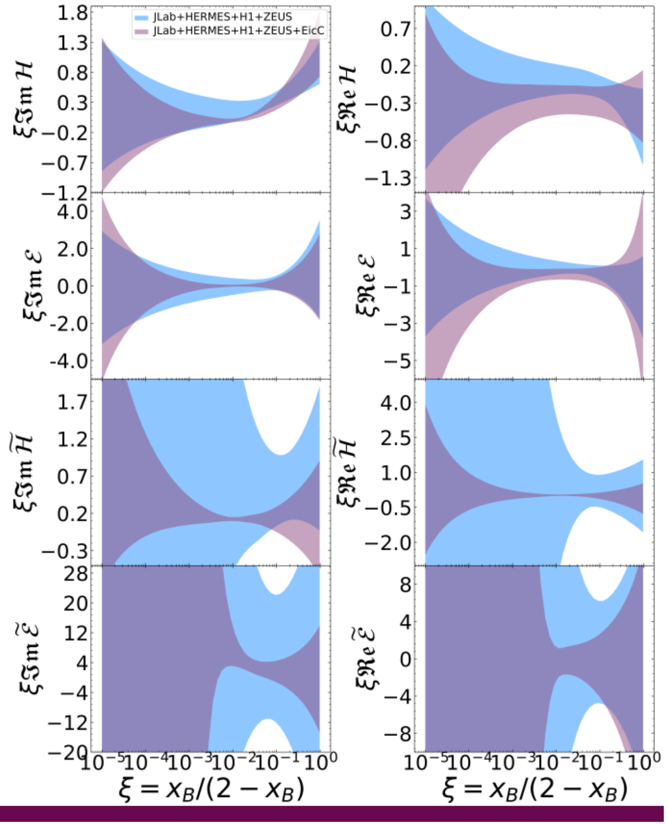
# proton DVCS

- **3D structure of nucleon (GPDs) @ EicC**
- Accessing Compton Form Factors by all pseudo-data of asymmetry at the EicC

~ 1 day running surpasses old data of $A_{UT}$

X. C, Jinlong Zhang, EPJC 83 (2023) 505




- Re-training (less-biased) within
- Gepard + neural network (PyTorch)
- in collaboration Krešimir Kumerički, Yuanyuan Huang *et. al*