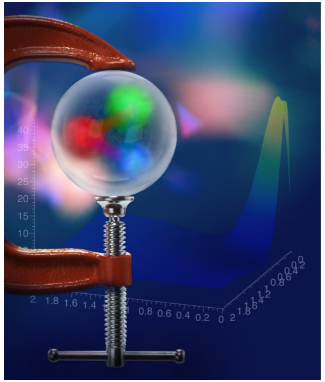
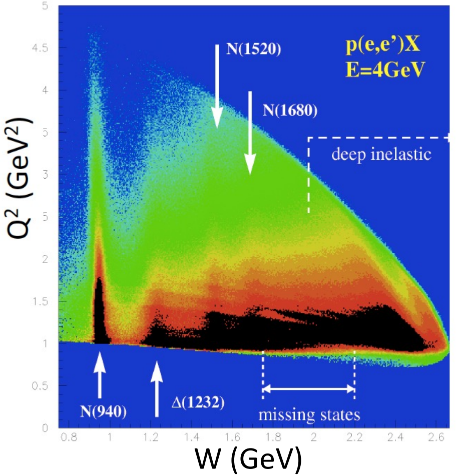
Hadron spectroscopy in the light sector: the on-going experimental programs

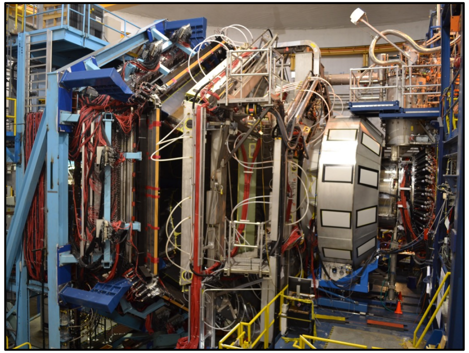
Lucilla Lanza
University of Rome Tor Vergata & INFN Rome Tor Vergata Rome – Italy

Outline



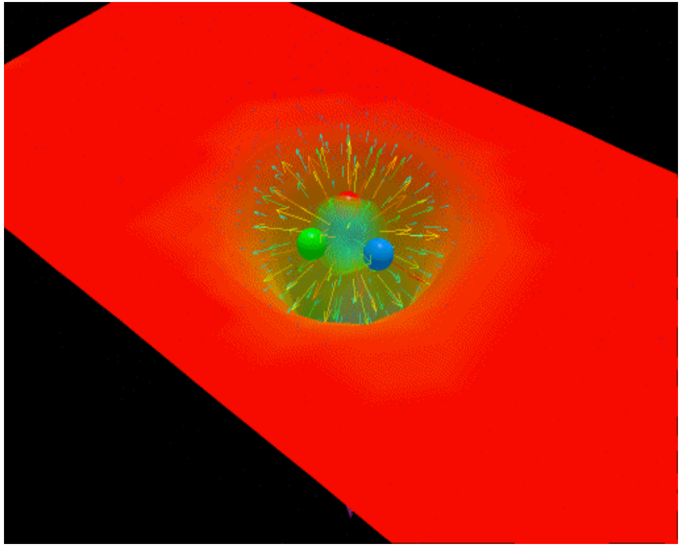


- Open questions in QCD
- Experiments with large INFN involvement:
  - A2 @ MAMI in Mainz
  - BGOOD @ ELSA in Bonn
  - CLAS @ JLab in Newport News (VA, USA)
- Latest results overview
- The future: EIC and the role of the glue
- Summary and Outlook



Critical QCD Questions Addressed

- The light N* spectrum: what is the role of glue?



Derek B. Leinweber – University of Adelaide

"Nucleons are the stuff of which our world is made.

As such they must be ***at the center of any discussion of why the world*** *we actually experience* ***has the character it does."***

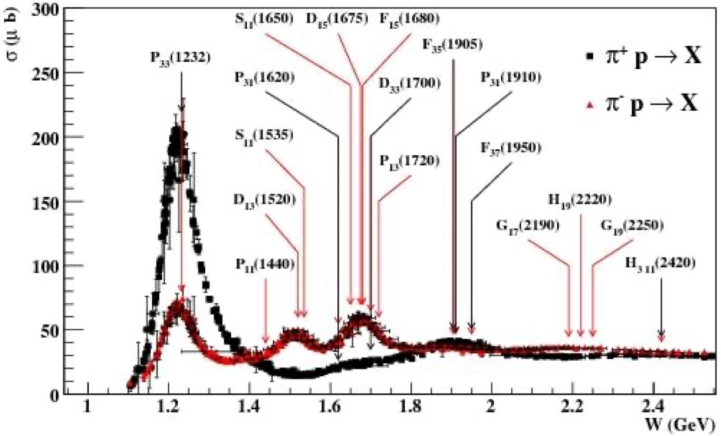
Nathan Isgur, NStar2000, Newport News, Virginia

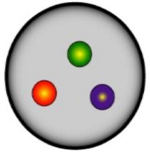
→ **Search for new baryon states**

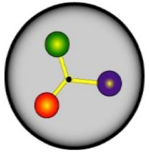
Why N*? From the N* Spectrum to QCD

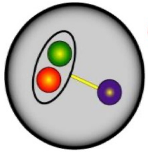
- Understanding the proton's ground state requires understanding its excitation spectrum.

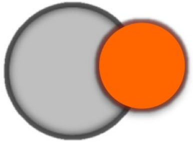
- The N* spectrum reflects the effective degrees of freedom and the forces.




CQM


CQM+flux tubes


Quark–diquark clustering


Baryon-meson system

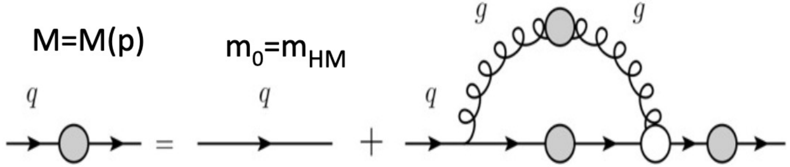
→ From the Constituent Quark model to QCD.

Mass Acquisition

Effective quark mass depends on its momentum

M=M(p)

$m_0=m_{HM}$



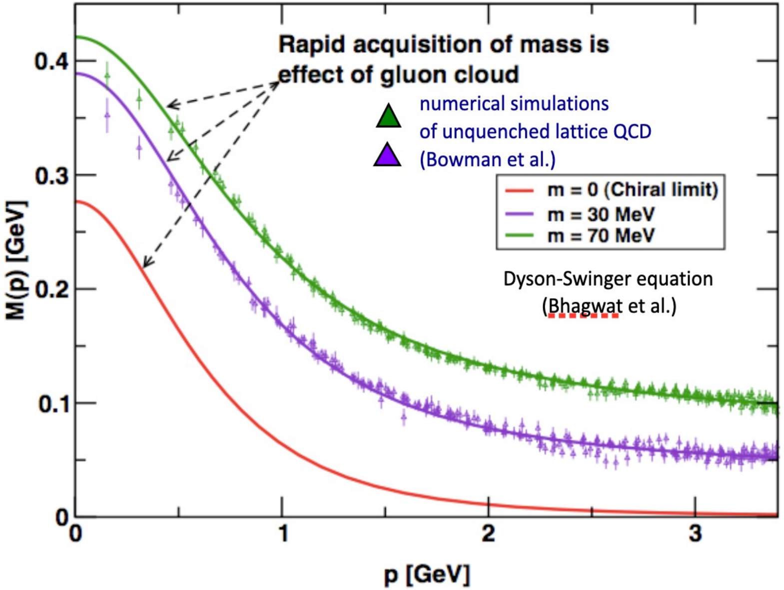
dressed quark

bare quark

dressing kernel

mass composition

<2%	Higgs mechanism
>98%	non-perturbative strong interaction



We need more information about the working of QCD in the non-perturbative regime

Exotic Hadrons

Standard Hadrons come in two varieties: Baryons & Mesons

Exotic Hadrons ⇨

Meson and baryon states whose properties cannot be described in terms of q anti-q or qqq degrees of freedom only

Hybrid mesons/baryons:
qqq or $q\bar{q}$ valence quarks plus a valence gluon

Multiquark states:

- Baryons with more than 3 valence quarks: **pentaquarks or di-baryons**
- Mesons with more than a quark-antiquark pair: **tetraquarks**

Glueballs:
Particles made up of gluonic degrees of freedom only

Molecules…

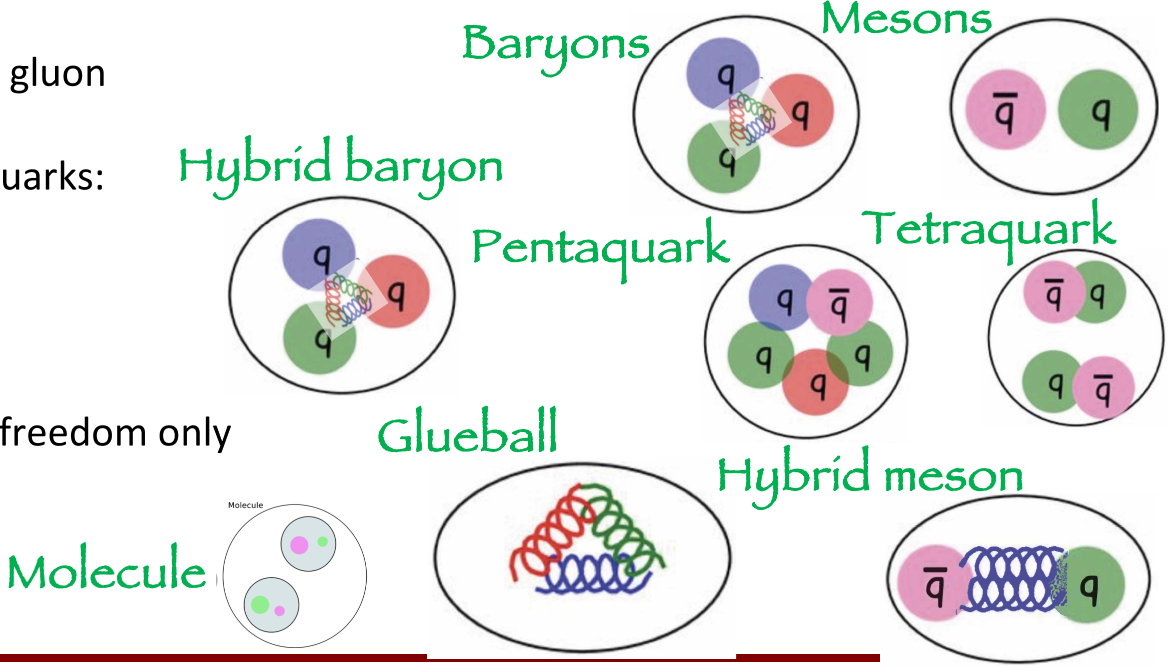


Photo- and Electro- production of mesons on nucleon targets

Meson photo- and electro-production reactions

for

Light quark baryon spectroscopy

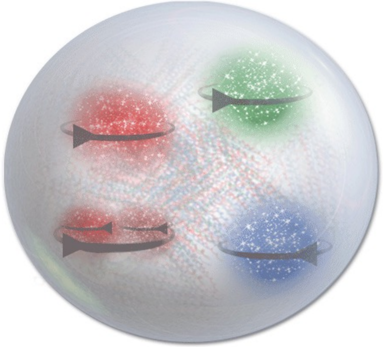
Two elements provided a crucial boost in the field:

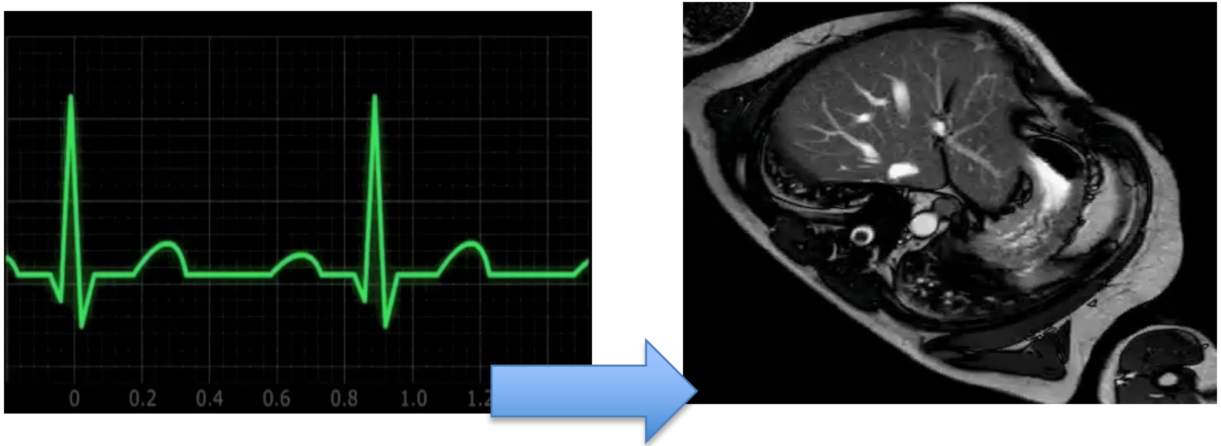
- advent of large solid angle detectors
- polarized beam and targets → single and double polarization observables

Powerful tool to study the internal structure of the nucleon

Critical QCD Questions Addressed

How are the quarks and gluons, and their intrinsic spins distributed in space & momentum inside the nucleon? What is the role of the angular momentum ?





→ **SIDIS and TMDs measurements toward a 3D imaging of the proton**

QCD: a list of questions

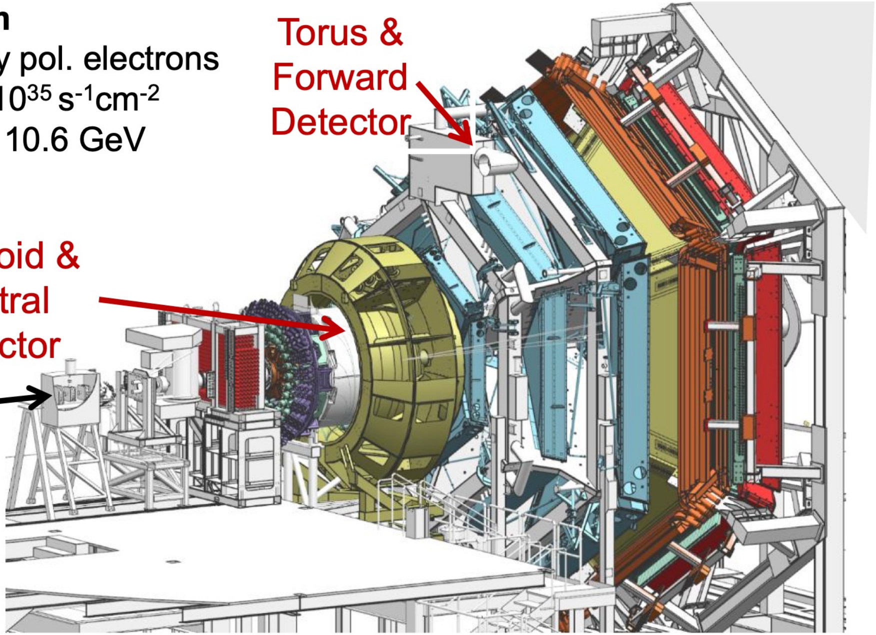
- **Which is the exact dynamics of the quarks and gluons inside the nucleon?**
- **How does QCD work in the non-perturbative regime?**
- **What is the origin of the nucleon spin and the charge and density distributions inside the nucleon?**
- **How do massless quarks acquire mass?**
- **How are the quarks and gluons, and their intrinsic spins distributed in space & momentum inside the nucleon? What is the role of the angular momentum ?**

Experiments at CLAS12, BGOOD and A2 are designed to address these questions.

CLAS12

Beam

- 85% longitudinally pol. electrons
- Max. luminosity: $10^{35}\,s^{-1}cm^{-2}$
- Energies: up to ~ 10.6 GeV


Torus & Forward Detector

Solenoid & Central Detector

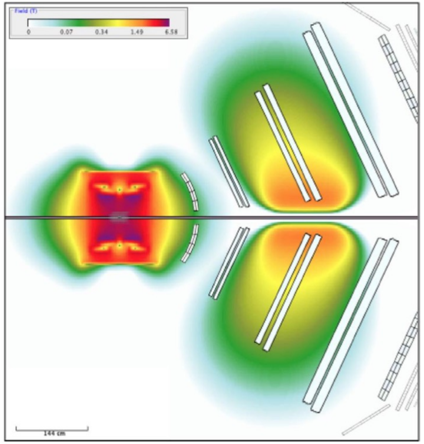
beam

[V.D. Burkert et al., Nucl. Inst. and Meth. A 959, 163419 (2020)]

Targets (org. by Run Groups)

- Proton (RG-A/K)
- Deuteron (RG-B)
- Nuclei (RG-M/D/E)
- Long. pol. NH_3/ND_3 (RG-C)

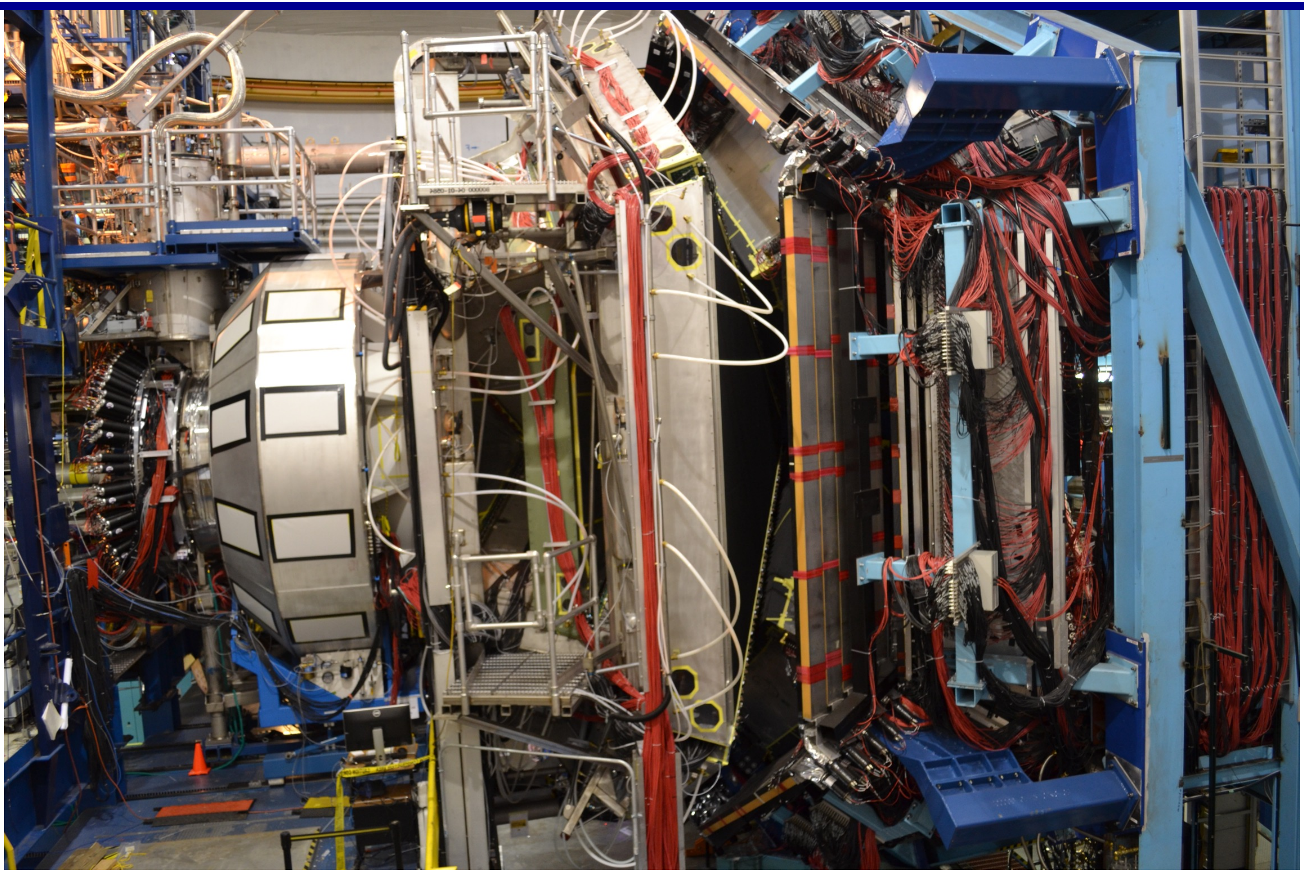
Magnetic Field



Ideal instrument to study exclusive meson electroproduction in the nucleon resonance region

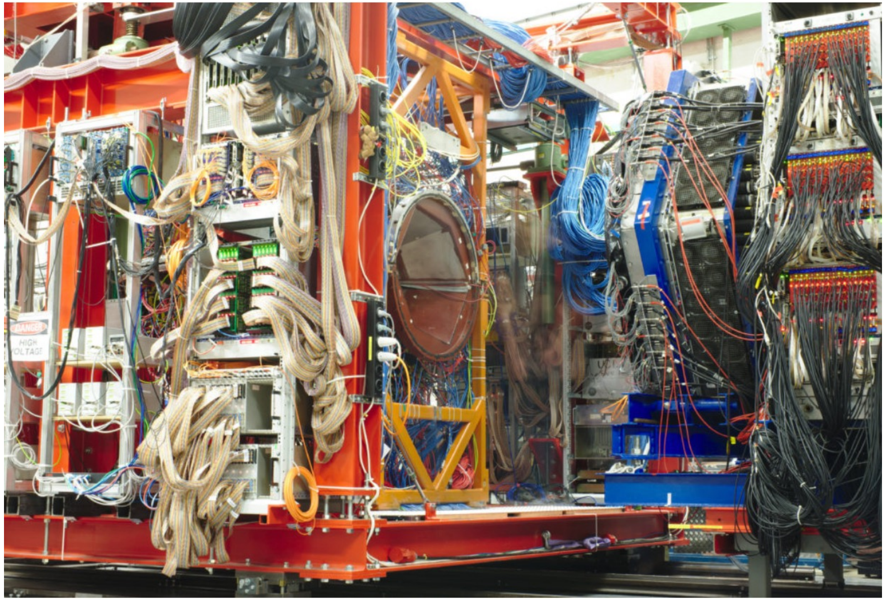
CLAS12 Spectrometer

beam

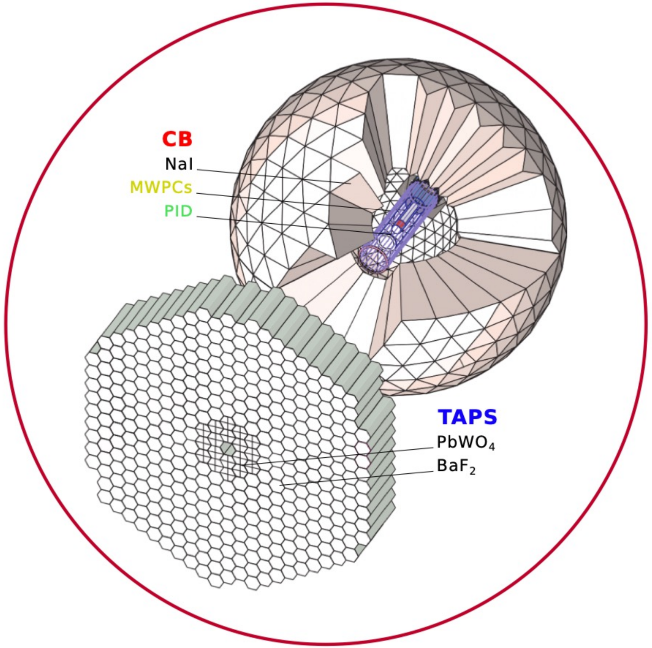


MAMBO: A2@MAMI AND BGOOD@ELSA

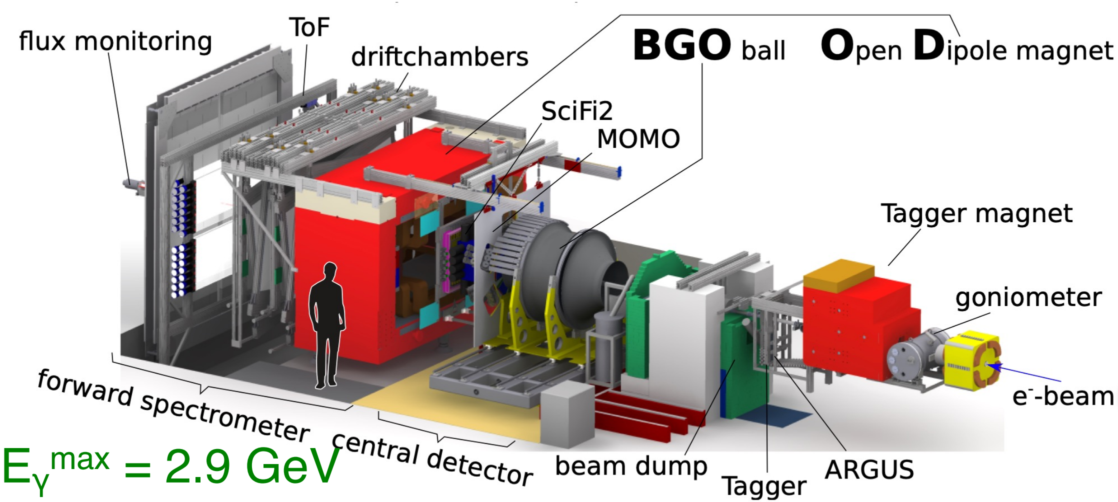
E_{γ}^{max} = 1.6 GeV
I_{γ} = 2.5 10^8 s^{-1}



A2@MAMI

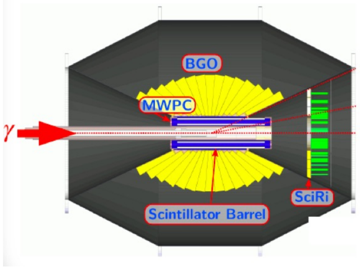


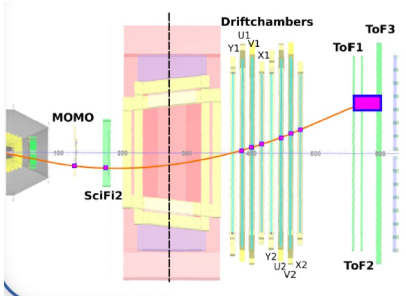
MAMBO: A2@MAMI AND BGOOD@ELSA

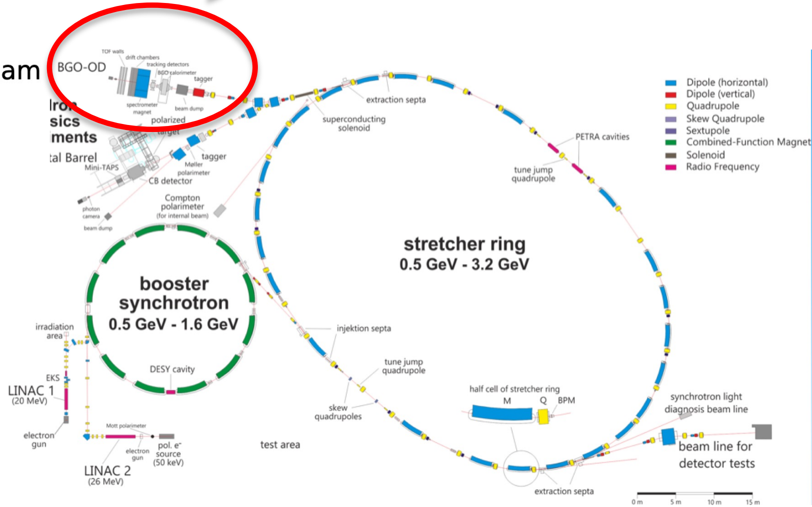


$E_\gamma^{max} = 2.9$ GeV

$I_\gamma = 3\ 10^7\ s^{-1}$







Polarizabilities @ MAMI

Properties of the nucleon, like the mass or the charge, they describe the response of the nucleon's internal structure to an external electromagnetic field

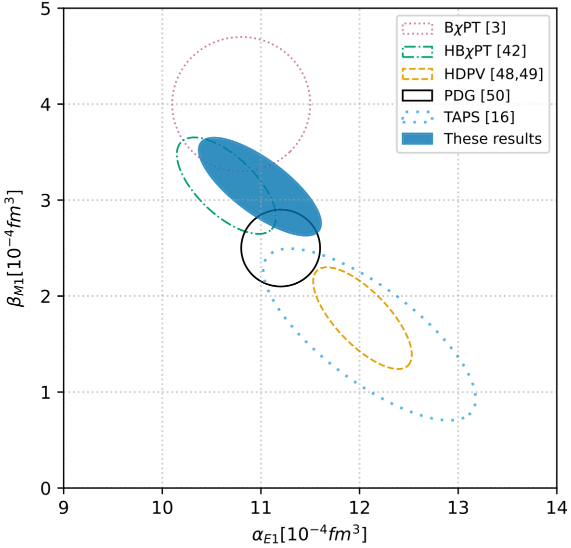
A precise measurement of:

- differential cross sections dσ/dΩ
- linearly polarized photon beam asymmetry Σ_3

for Compton scattering on the proton

$$\gamma + p \rightarrow \gamma' + p'$$

has been performed with a tagged photon beam and almost 4π detector at the Mainz Microtron.



E. Mornacchi (A2), Phys. Rev. Lett. 128, 132503 (2022)

Compton Scattering Hamiltonian - II order term:

$$H_{\text{eff}}^{(2)} = -4\pi\left[\frac{1}{2}\alpha_{E1}\vec{E}^2 + \frac{1}{2}\beta_{M1}\vec{H}^2\right]$$

Two proton scalar polarizabilities

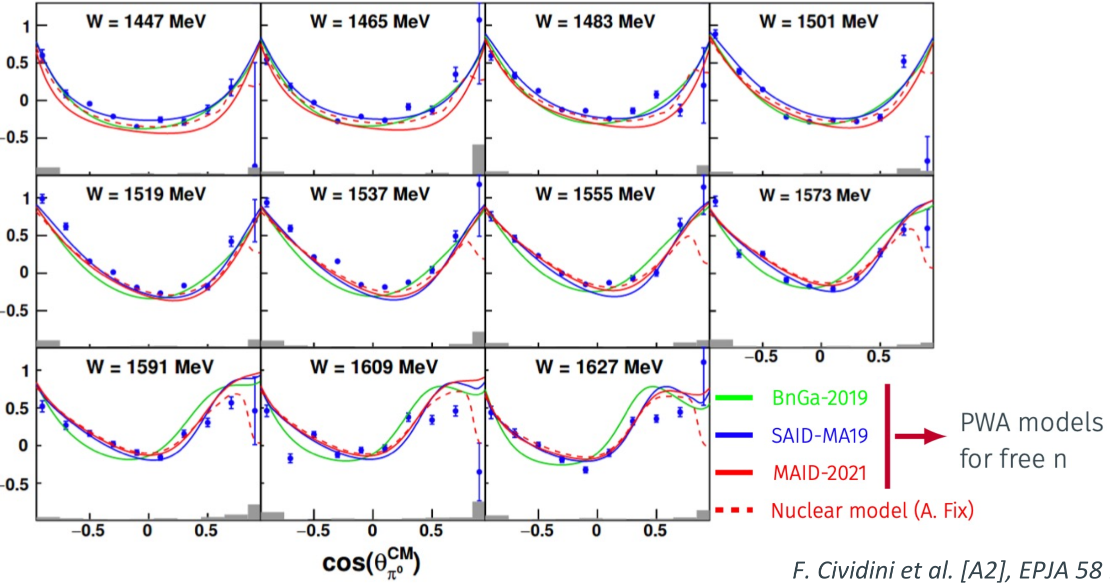
$$\alpha_{E1} = 10.99 \pm 0.16_{\text{stat.}} \pm 0.47_{\text{sys.}} \pm 0.17_{\gamma_S} \pm 0.34_{\text{mod.}}$$
$$\beta_{M1} = 3.14 \pm 0.21_{\text{stat.}} \pm 0.24_{\text{sys.}} \pm 0.20_{\gamma_S} \pm 0.35_{\text{mod.}}$$

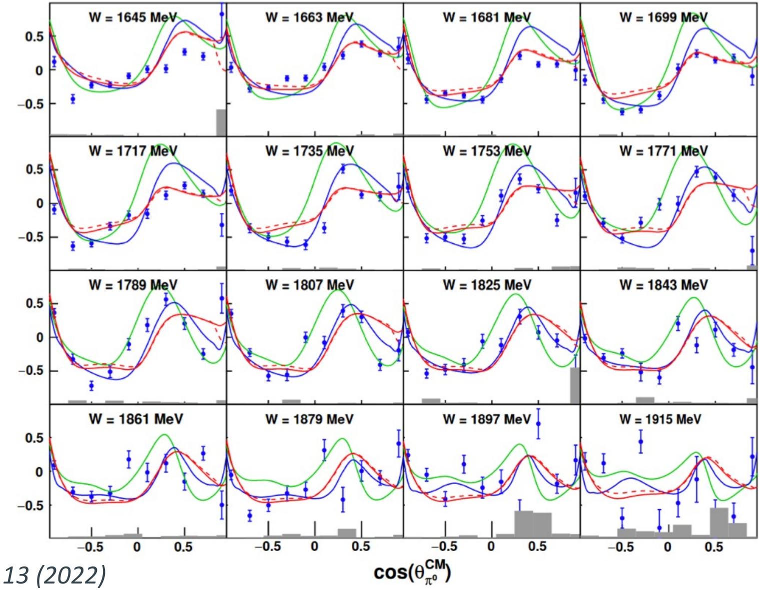
Polarization Observables @ MAMI

$$\gamma N \rightarrow \pi(\eta)N$$

Beam		Target			Recoil		Both	
		x	y	z			x	
					x'	z'	x'	z'
Unpolarized	σ		T				$T_{x'}$	$T_{z'}$
Linear	Σ	H	P	G	$O_{x'}$	$O_{z'}$	$L_{z'}$	$L_{x'}$
Circular		F		E	$C_{x'}$	$C_{z'}$		

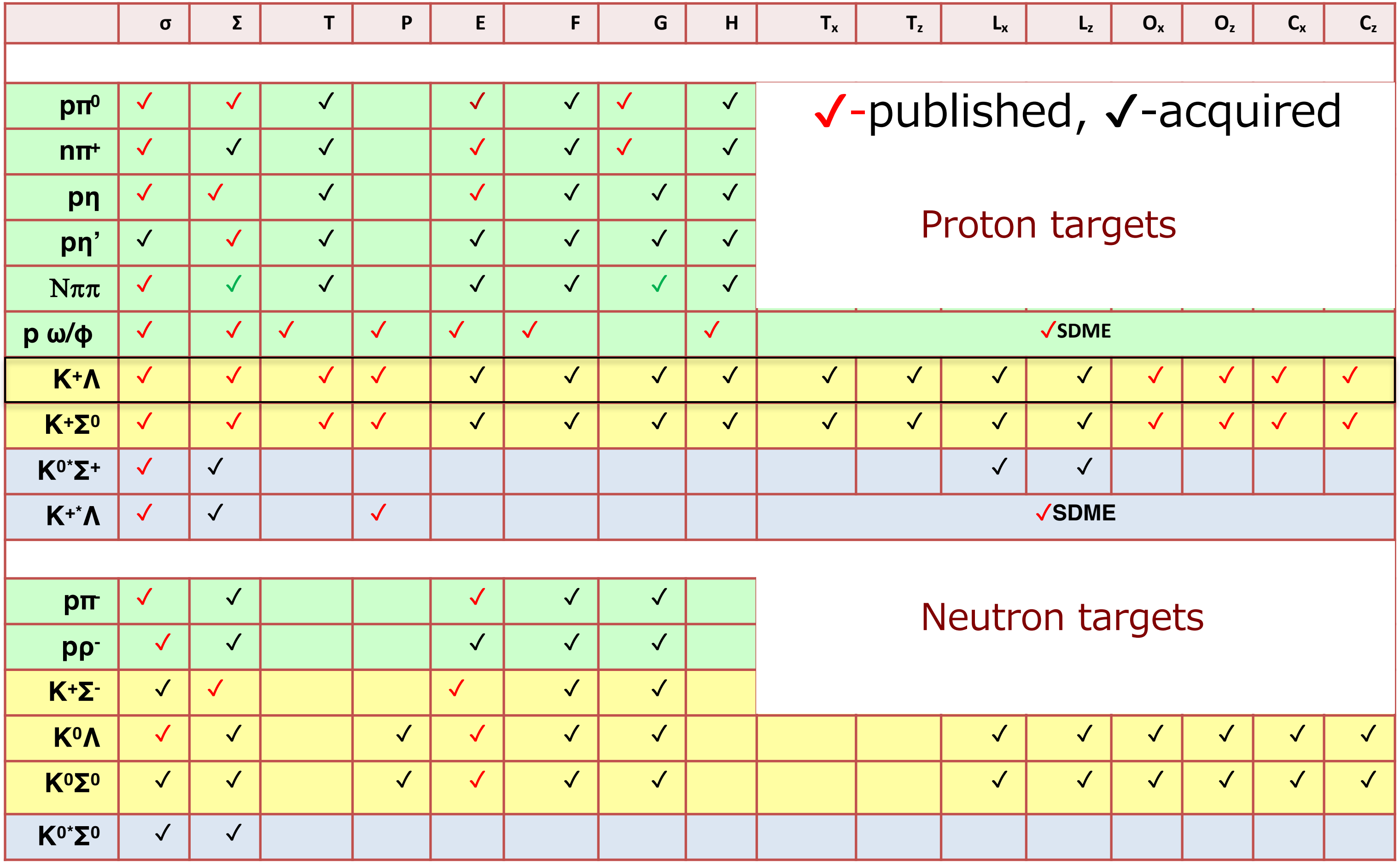
E asymmetry for π^0 photoproduction on quasi free neutron





F. Cividini et al. [A2], EPJA 58 113 (2022)

CLAS N* Experimental Program



✓-published, ✓-acquired

Proton targets

	σ	Σ	T	P	E	F	G	H	T_x	T_z	L_x	L_z	O_x	O_z	C_x	C_z
$p\pi^0$	✓	✓	✓		✓	✓	✓	✓								
$n\pi^+$	✓	✓	✓		✓	✓	✓	✓								
$p\eta$	✓	✓	✓		✓	✓	✓	✓								
$p\eta'$	✓	✓	✓		✓	✓	✓	✓								
$N\pi\pi$	✓	✓	✓		✓	✓	✓	✓								
$p\ \omega/\phi$	✓	✓	✓	✓	✓	✓		✓	✓SDME							
$K^+\Lambda$	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
$K^+\Sigma^0$	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
$K^{0*}\Sigma^+$	✓	✓									✓	✓				
$K^{+*}\Lambda$	✓	✓		✓					✓SDME							

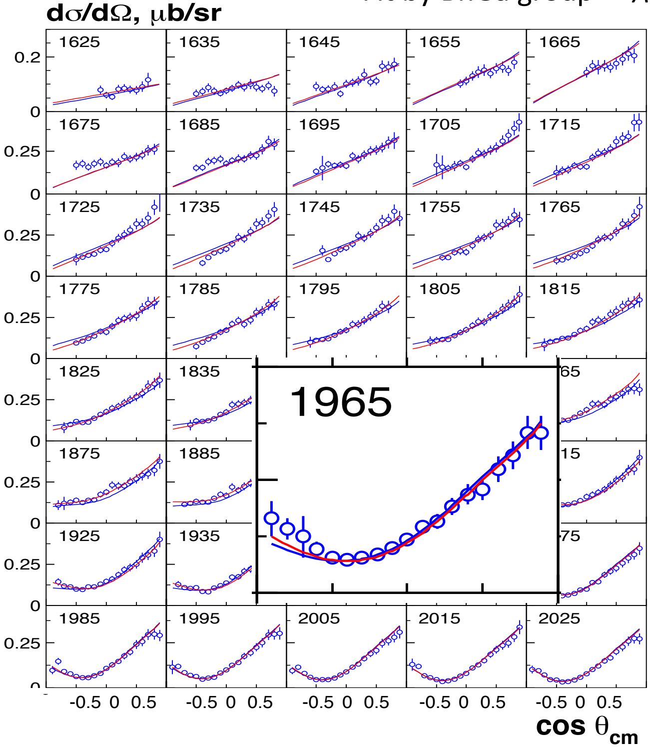
Neutron targets

	σ	Σ	T	P	E	F	G	H	T_x	T_z	L_x	L_z	O_x	O_z	C_x	C_z
$p\pi^-$	✓	✓			✓	✓	✓									
$p\rho^-$	✓	✓			✓	✓	✓									
$K^+\Sigma^-$	✓	✓			✓	✓	✓									
$K^0\Lambda$	✓	✓		✓	✓	✓	✓				✓	✓	✓	✓	✓	✓
$K^0\Sigma^0$	✓	✓		✓	✓	✓	✓				✓	✓	✓	✓	✓	✓
$K^{0*}\Sigma^0$	✓	✓														

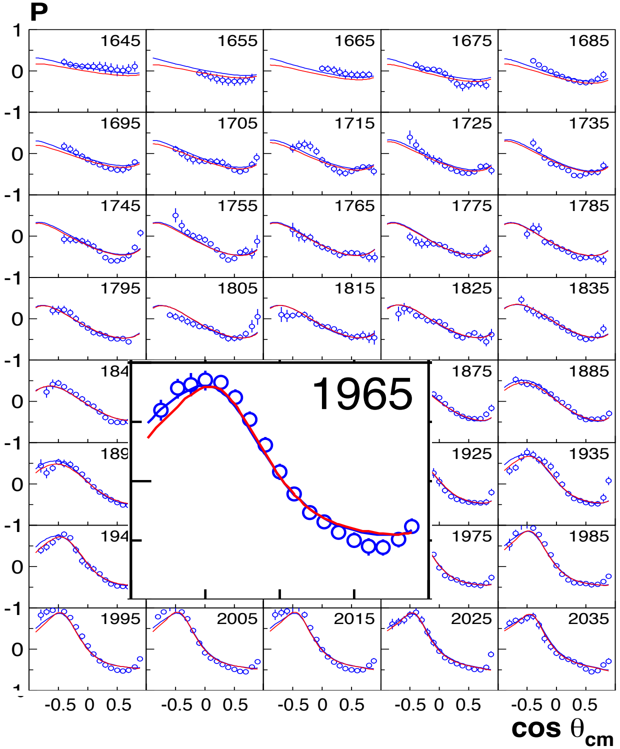
Establishing the N* spectrum – Precision & Polarization are essential

Hyperon photoproduction $\gamma p \to K^+\Lambda \to K^+ p\pi^-$

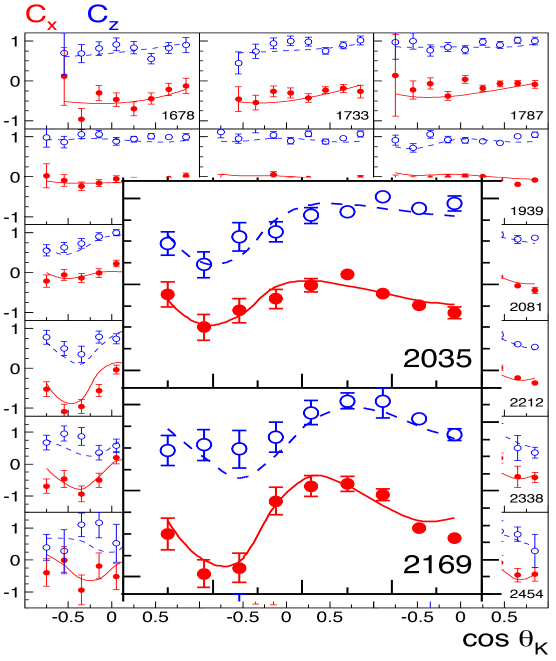
Fit by BnGa group *A.V. Anisovich et al, EPJ A48, 15 (2012)*



M. Mc Cracken et al.(CLAS), Phys.RevC81,025201,2010



γ->Λ **Polarization** transfer



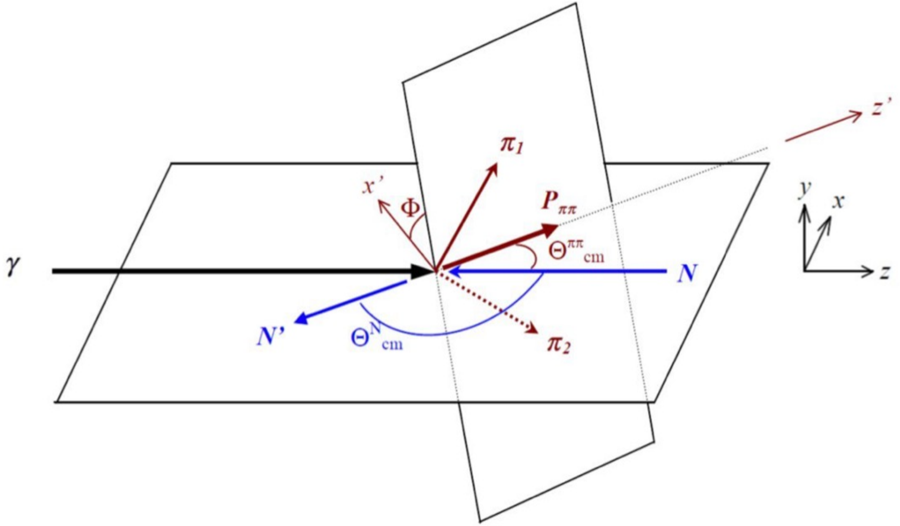
D. Bradford et al. (CLAS), Phys.Rev. C75, 035205, 2007

Polarization Observables @ JLab

g14 HD-ICE run period (CLAS):

- circularly polarized photons
- HD frozen spin polarized target

$$\boxed{\vec{\gamma}\vec{N} \to \pi^+\pi^- N}$$



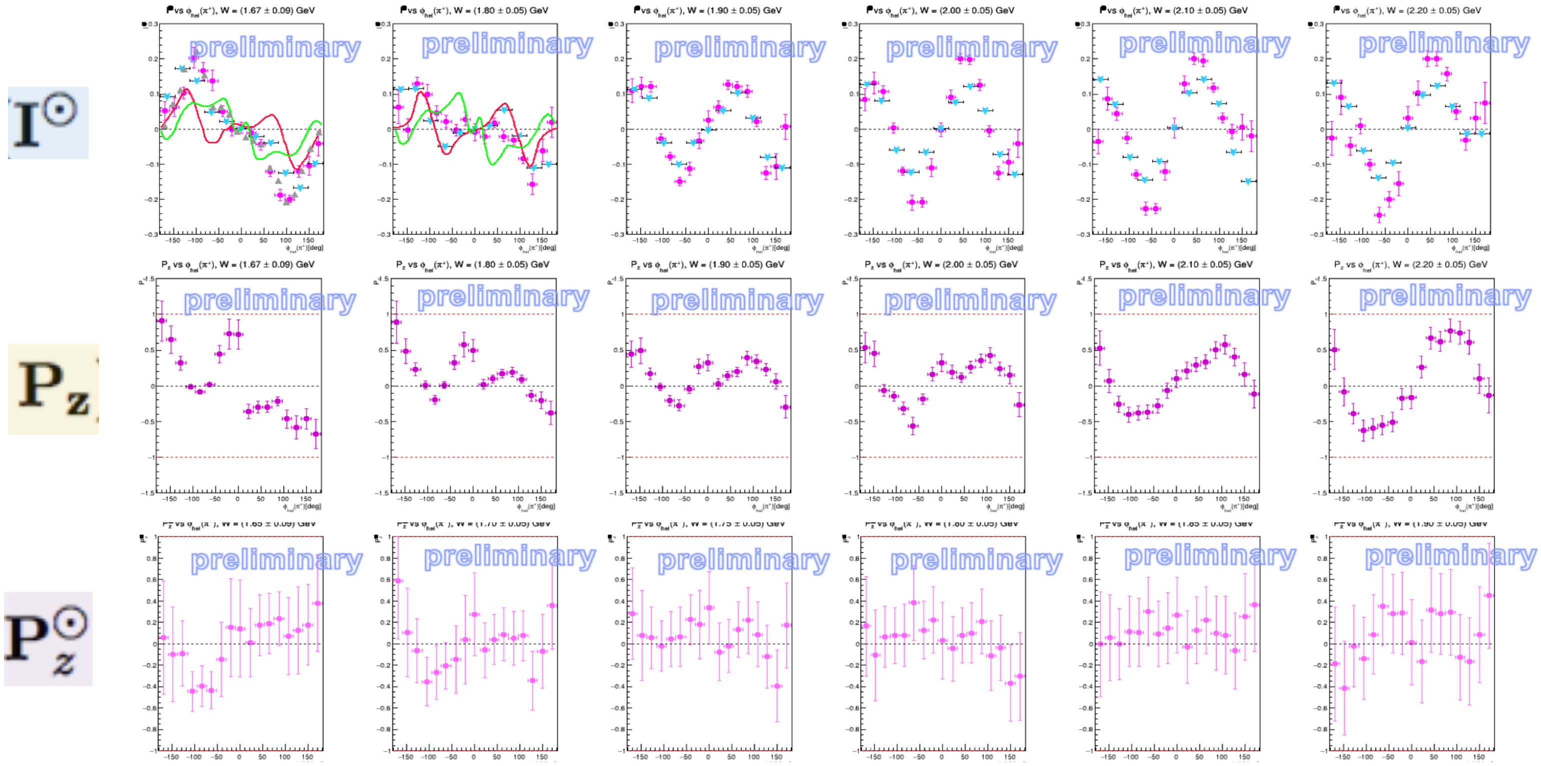
$$P_z = \frac{1}{\Lambda_z}\frac{[N(\rightarrow\Rightarrow)+N(\leftarrow\Rightarrow)]-[N(\rightarrow\Leftarrow)+N(\leftarrow\Leftarrow)]}{[N(\rightarrow\Rightarrow)+N(\leftarrow\Rightarrow)]+[N(\rightarrow\Leftarrow)+N(\leftarrow\Leftarrow)]}$$

$$I^{\odot} = \frac{1}{\delta_{\odot}}\frac{[N(\rightarrow\Rightarrow)+N(\rightarrow\Leftarrow)]-[N(\leftarrow\Rightarrow)+N(\leftarrow\Leftarrow)]}{[N(\rightarrow\Rightarrow)+N(\rightarrow\Leftarrow)]+[N(\leftarrow\Rightarrow)+N(\leftarrow\Leftarrow)]}$$

$$P_z^{\odot} = \frac{1}{\Lambda_z\delta_{\odot}}\frac{[N(\rightarrow\Rightarrow)+N(\leftarrow\Leftarrow)]-[N(\rightarrow\Leftarrow)+N(\leftarrow\Rightarrow)]}{[N(\rightarrow\Rightarrow)+N(\leftarrow\Leftarrow)]+[N(\rightarrow\Leftarrow)+N(\leftarrow\Rightarrow)]}$$

$$\boxed{\frac{d\sigma}{dx_i} = \sigma_0\{(1+\Lambda_z\cdot\mathbf{P_z})+\delta_{\odot}(\mathbf{I}^{\odot}+\Lambda_z\cdot\mathbf{P}_{\mathbf{z}}^{\odot})\}}$$

Polarization Observables @ JLab

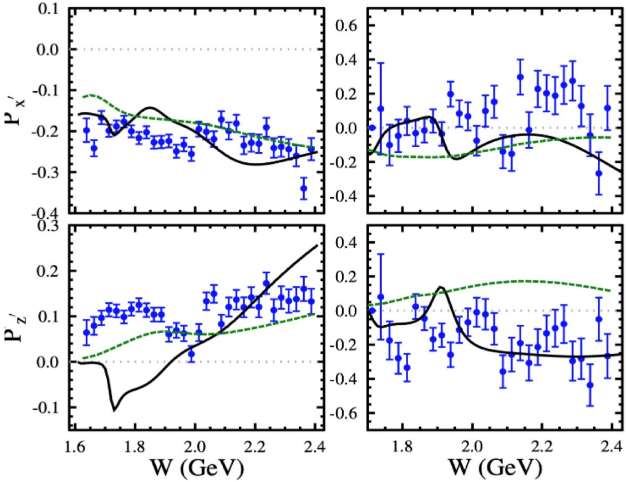


By Alessandra Filippi, INFN Torino

K^+Y Transferred Polarization CLAS12 vs. CLAS

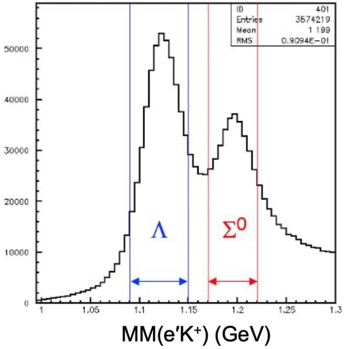
CLAS12 (RG-K)

$ep \rightarrow e'K^+\Lambda$ $ep \rightarrow e'K^+\Sigma^0$



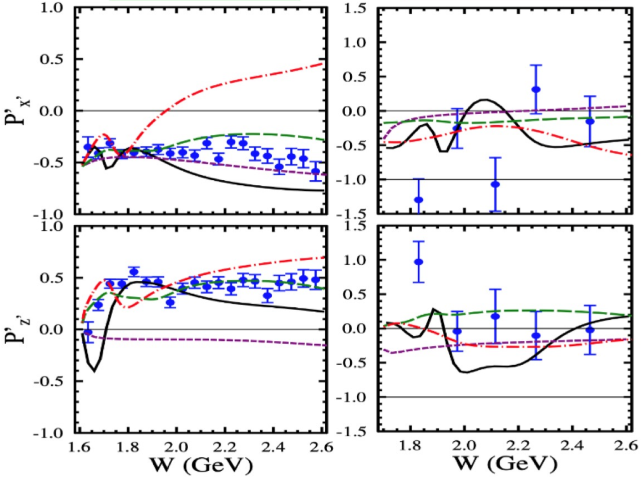
[D.S. Carman et al., Phys. Rev. C 105, 065201 (2022)]

$ep \rightarrow e'K^+Y$



CLAS (e1-6)

$ep \rightarrow e'K^+\Lambda$ $ep \rightarrow e'K^+\Sigma^0$



[D.S. Carman et al., Phys. Rev. C 79, 065205 (2009)]

KAON-MAID
RPR

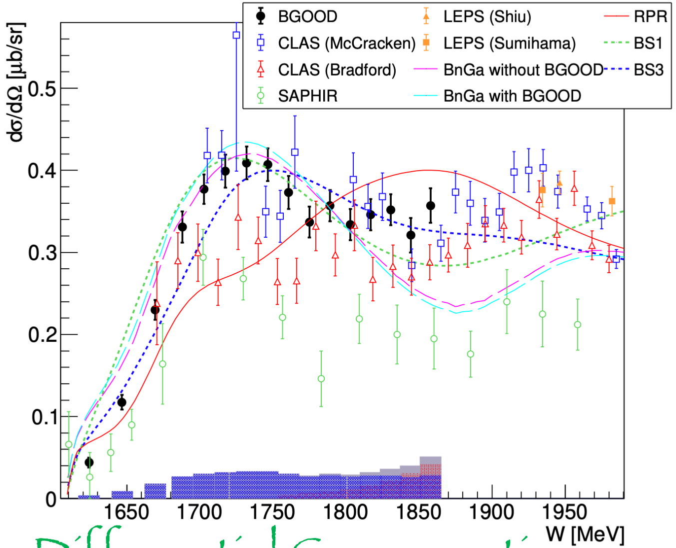
World data set will get extended by orders of magnitude

Mart/Bennhold RPR-2
RPR-1 Regge

K$^+$Y Induced Polarization @ BGOOD

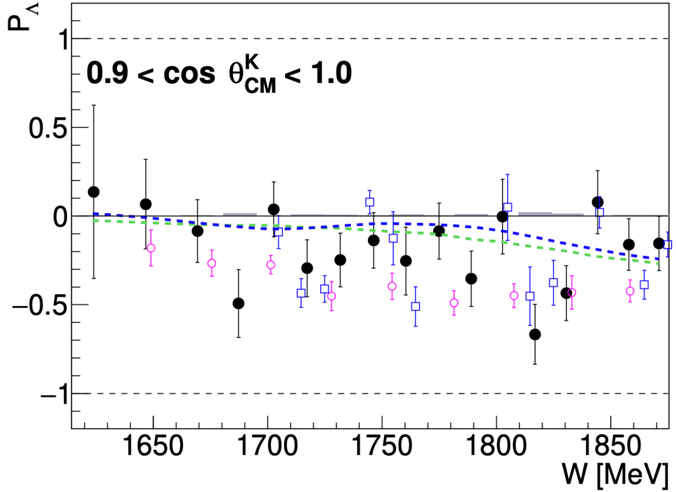
Study of $\gamma p \rightarrow \mathrm{K}^+\Lambda \rightarrow \mathrm{K}^+\pi^0 n$ channel:

- K^+ Detected in the Forward Detector
- $\pi^0 \rightarrow \gamma\gamma$ Detected by BGO



Differential Cross section

Recoil polarisation



Results achieved

- Very good angular resolution in the **forward direction**
- Very **high statistics**
- Structure at 1720 MeV

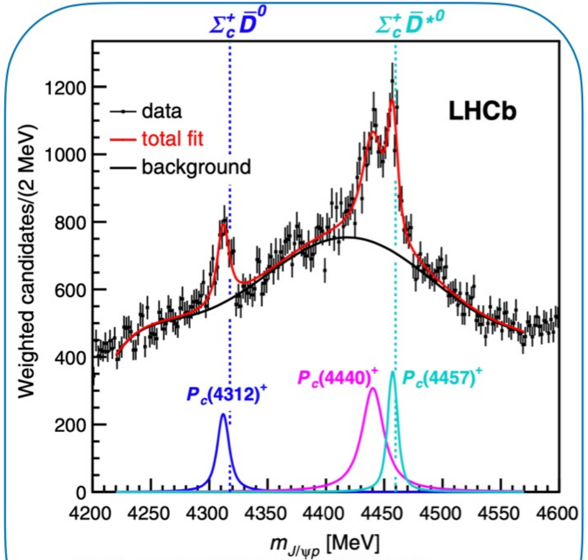
S. Alef *et al.* Eur. Phys. J. A (2021) 57:80

Pentaquark Search

PARTICLE PHYSICS 16 JULY 2015 | VOL 523 | NATURE | 267

Forsaken pentaquark particle spotted at CERN

Exotic subatomic species confirmed at Large Hadron Collider after earlier false sightings.

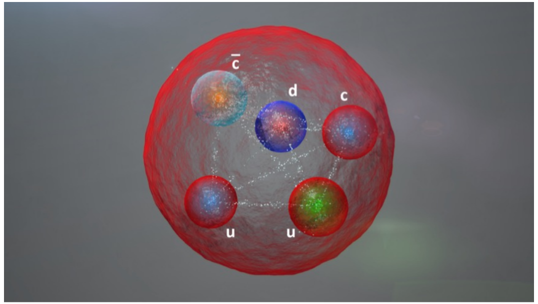


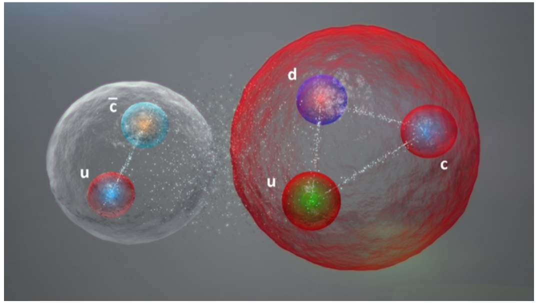
PRL 115, 072001 (2015)
PRL 112, 222001 (2019)

<u>Structure/binding mechanism is under debate</u>

Most of these pentaquarks have been interpreted as bound (or molecular) states.

Similarities in the strange & charmed quark sectors?



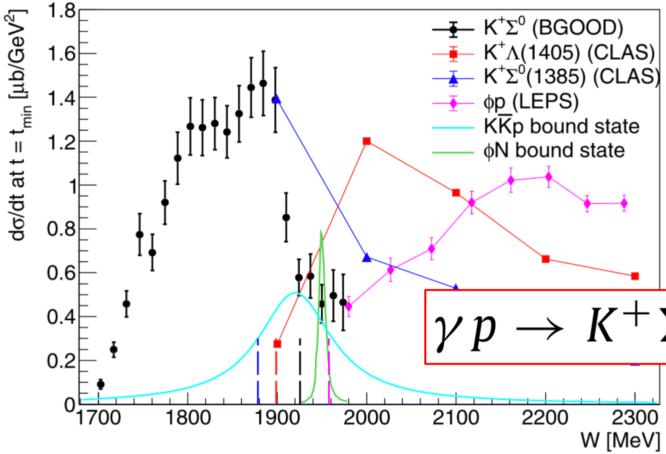


Pentaquark Search

Similarities in the strange & charmed quark sectors?

uds sector explored by BGOOD

Cusp-like structure at W ≈ 1900 MeV – In this region there are multiple predictions of hadronic bound states

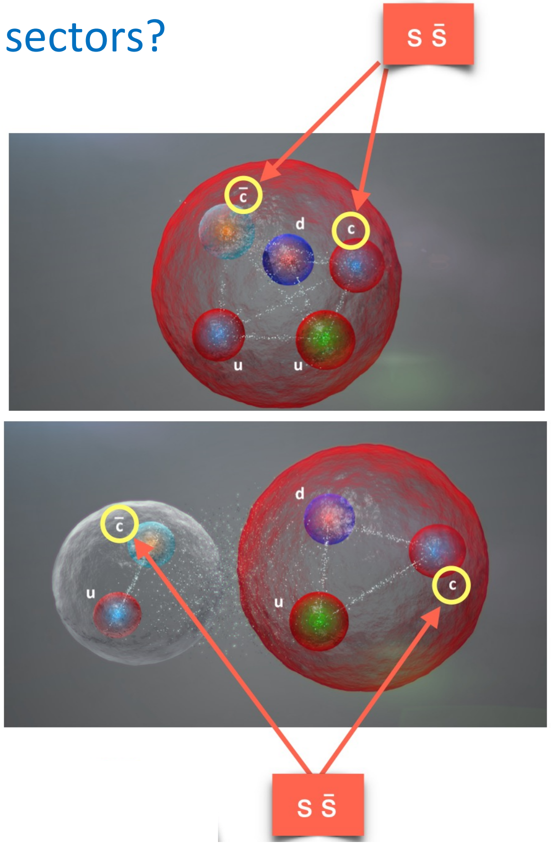


$$\gamma\, p \rightarrow K^{+}\Sigma^{0}$$

T. Jude et al. [BGOOD collab.] Phys. Lett B 820 (2021) 136559

This signature may be indicative of re-scattering effects close to open and hidden strange thresholds

Has to be investigated



Hybrid Hadrons

Hybrid hadrons with dominant gluonic contributions are predicted to exist by QCD.

Experimentally:

- **Hybrid mesons** $|q\bar{q}g>$ states may have exotic quantum numbers J^{PC} not available to pure $|\ q\bar{q}>$ states
  GlueX, MesonEx, COMPASS, PANDA ….
- **Hybrid baryons** |qqqg> have the same quantum numbers J^P as |qqq> electroproduction with CLAS12 (Hall B).

Theoretical predictions:

✧ MIT bag model - T. Barnes and F. Close, Phys. Lett. 123B, 89 (1983).

✧ QCD Sum Rule - L. Kisslinger and Z. Li, Phys. Rev. D 51, R5986 (1995).

✧ Flux Tube model - S. Capstick and P. R. Page, Phys. Rev. C 66, 065204 (2002).

✧ LQCD - J.J. Dudek and R.G. Edwards, PRD85, 054016 (2012).

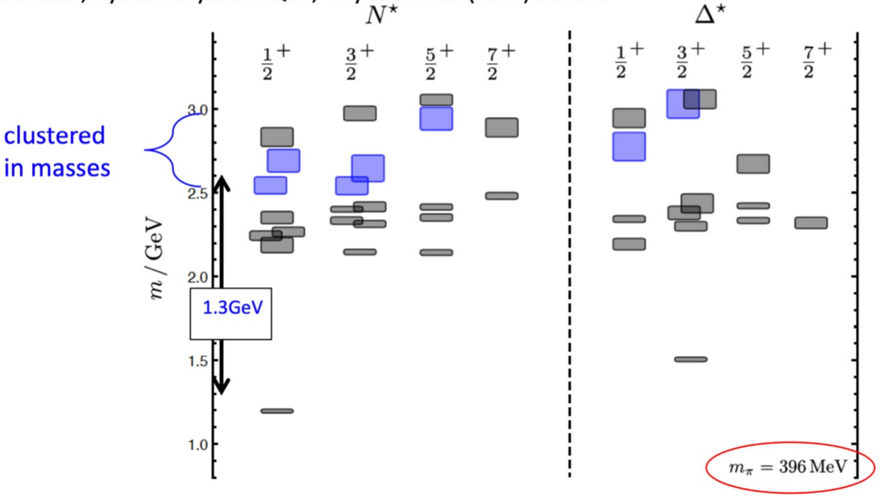
Hybrid Baryons

Hybrid baryons emerge as **gluonic excitations of the nucleon** to states where a **constituent gluon** combines with **three quarks**

QCD allows for the existence of Hybrid Baryons.

LQCD predicts several hybrid baryons states.

Dudek et al, Hybrid Baryons in QCD, Phys.Rev. D85 (2012) 054016



▬ Regular states

🟦 Hybrid states

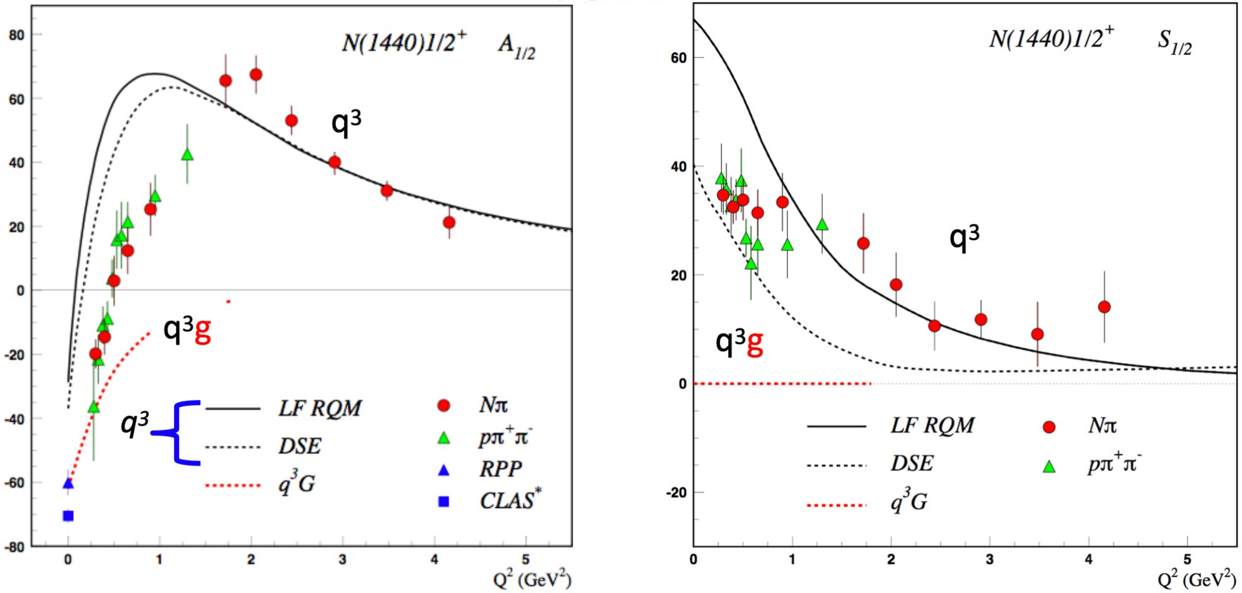
The nucleon mass is shifted ~300 MeV to higher masses

Differently from the case of hybrid mesons, hybrid baryons are predicted to have **same quantum numbers** of N* resonances

Hybrid Baryons

CLAS results on electrocouplings clarified nature of the Roper.

Will CLAS12 data be able to identify gluonic contributions ?



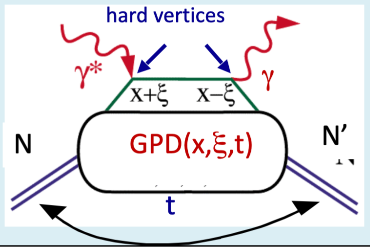
For hybrid "Roper", $A_{1/2}(Q^2)$ drops off faster with Q^2 and $S_{1/2}(Q^2)$ ~ 0.

DVCS and DVMP to get GPDs

Study GPDs and their moments

Generalized Parton distributions (GPDs) correlate the transverse position and the longitudinal momentum fraction of the partons in the nucleon → Provide a 3D structure of N

Deeply Virtual Compton Scattering



x – longitudinal quark momentum fraction

2ξ – longitudinal momentum transfer

t – four momentum transfer to final N

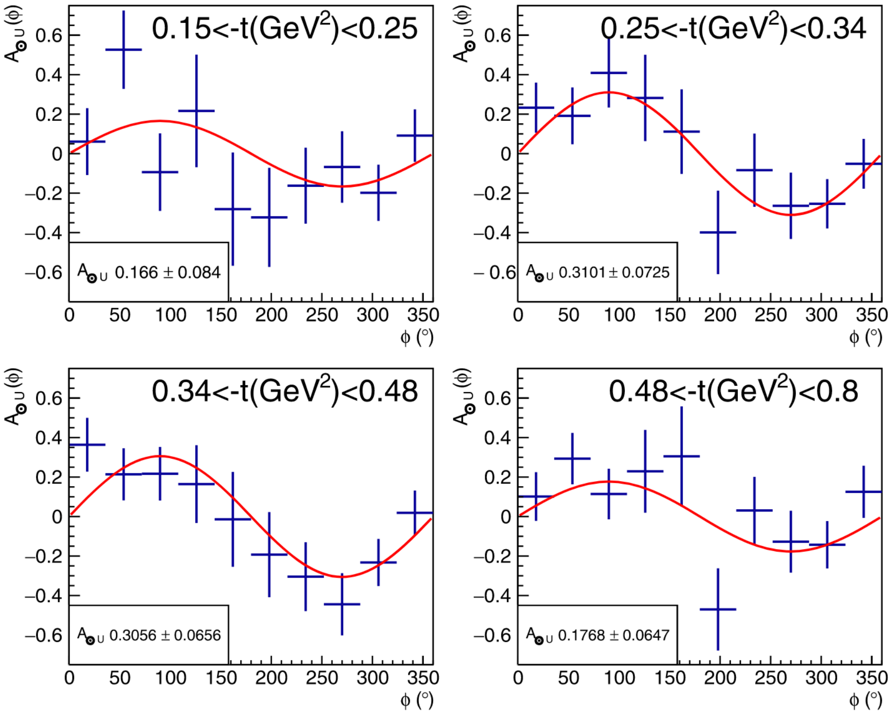
"handbag" mechanism

Deeply Virtual Compton Scattering (DVCS) and **Deeply Virtual Meson Production (DVMP)** are the most established reactions to study GPDs

DVCS Beam Spin Asymmetry

P_e=85%

CLAS12



P. Chatagnon et al. Phys. Rev Lett 127, 262501 (2021)

$\vec{e}\,\mathrm{p} \rightarrow e'p'\gamma$

Extraction of GPDs is a major goal of the CLAS12 program

x_B

SIDIS to get TMDs

Semi-Inclusive Deep Inelastic Scattering: toward a 3D imaging of the proton

SIDIS allows to probe Nucleon Internal Structure:

Single Hadron SIDIS

Access the TMDs

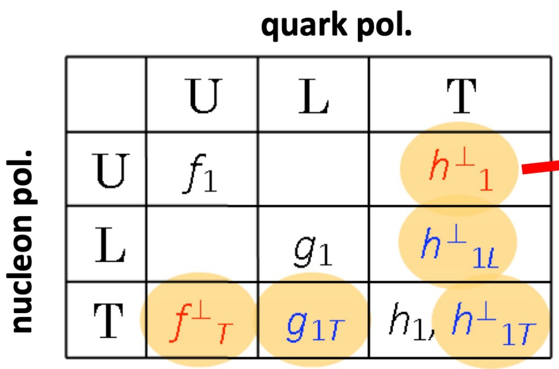
Transverse Momentum Distributions contain information about longitudinal and transverse motion of partons

Knowledge of TMDs reveals:

- the **orbital motion of quarks** within the parent nucleon;
- **correlations** between **parton momentum** and **spin**;
- additional effects driven by emergent hadron mass

Transverse Momentum Distributions (TMDs)

- **Spin-dependent 3D momentum space images**

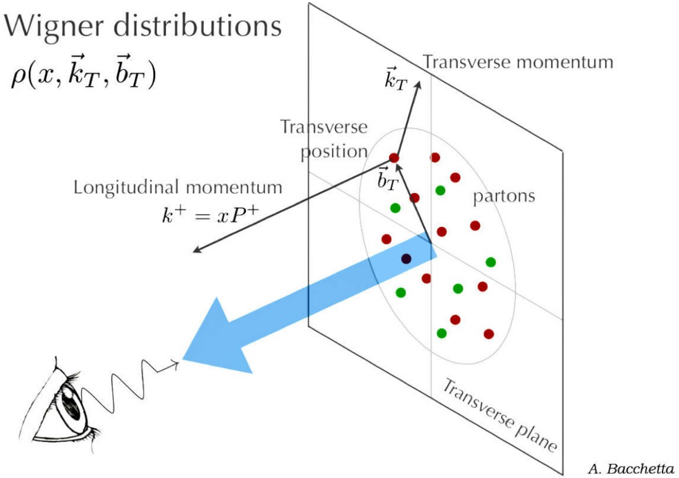


quark pol.

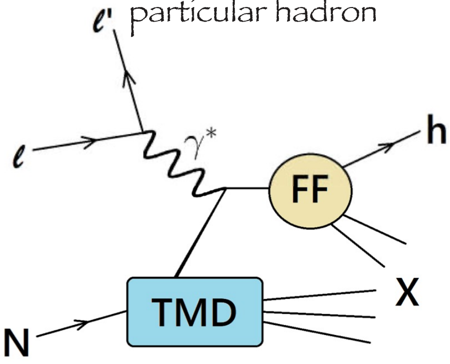
nucleon pol.

	U	L	T
U	f_1		$h^{\perp}_{1}$
L		g_1	$h^{\perp}_{1L}$
T	$f^{\perp}_{T}$	g_{1T}	h_1, $h^{\perp}_{1T}$

Boer-Mulders

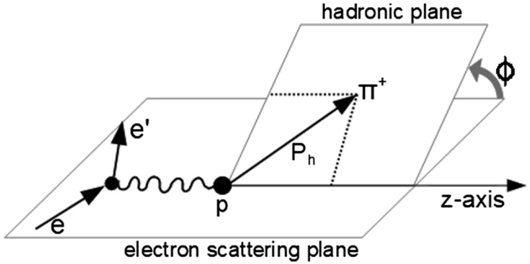


Fragmentation Functions parametrize the probability for a given struck parton to emit a particular hadron



TMDs can be accessed in semi-inclusive deep-inelastic scattering (SIDIS)

At least one specified hadron in the final state plus the scattered lepton

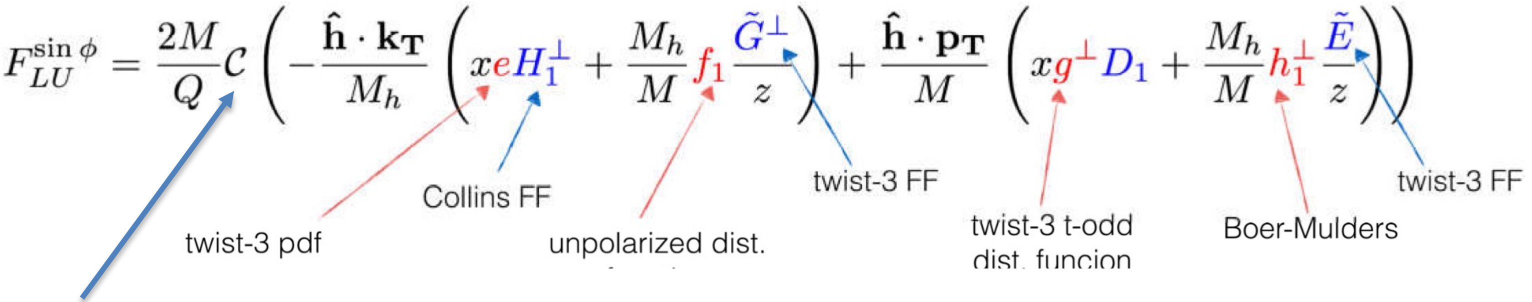


Observables dependent on TMDs

Longitudinally polarized beam and unpolarized target:

$$\frac{d\sigma}{dx\,dQ^2\,dz\,dP_{h\perp}^2\,d\phi_h} \sim F_{UU,T} + \epsilon\, F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)}\ \cos\phi_h\ F_{UU}^{\cos\phi_h} + \epsilon\ \cos 2\phi_h\ F_{UU}^{\cos 2\phi_h} + \lambda_e\ \sqrt{2\epsilon(1-\epsilon)}\ \sin\phi_h\ F_{LU}^{\sin\phi_h}$$

$F_{LU}^{sin\varphi}$ **structure function** can reveal novel aspects of emergent hadron mass and quark-gluon correlations within the nucleon:



$$F_{LU}^{\sin\phi} = \frac{2M}{Q}\mathcal{C}\left(-\frac{\hat{\mathbf{h}}\cdot\mathbf{k_T}}{M_h}\left(xeH_1^\perp + \frac{M_h}{M} f_1 \frac{\tilde{G}^\perp}{z}\right) + \frac{\hat{\mathbf{h}}\cdot\mathbf{p_T}}{M}\left(xg^\perp D_1 + \frac{M_h}{M} h_1^\perp \frac{\tilde{E}}{z}\right)\right)$$

➔ TMDs and Fragmentation functions

convolution of TMDs and FFs

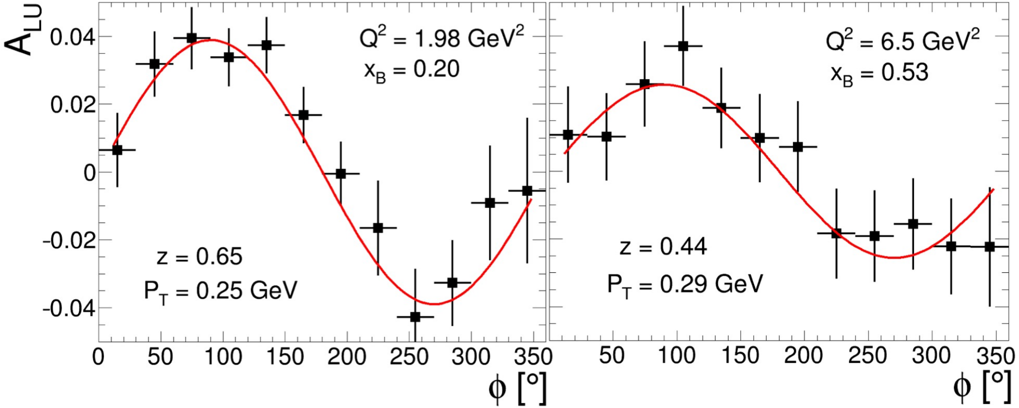
Observables dependent on TMDs

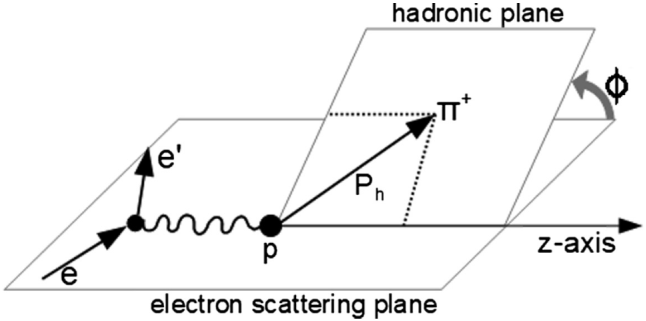
Structure function ratio

$$A_{LU}(x_B, Q^2, z, P_T, \phi) = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} = \frac{\sqrt{2\epsilon(1-\epsilon)}\,\boxed{\frac{F_{LU}^{\sin\phi}}{F_{UU}}}\sin\phi}{1 + \sqrt{2\epsilon(1+\epsilon)}\,\frac{F_{UU}^{\cos\phi}}{F_{UU}}\cos\phi + \epsilon\,\frac{F_{UU}^{\cos 2\phi}}{F_{UU}}\cos 2\phi}$$

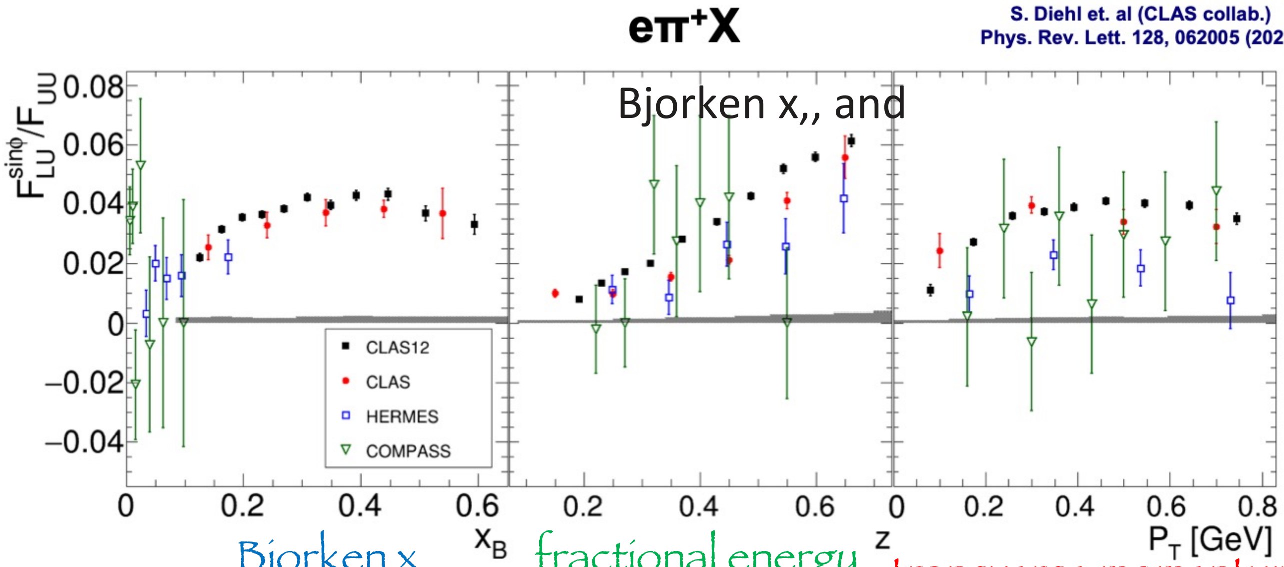
Beam Spin Asimmetry **BSA**

π^+:





Observables dependent on TMDs



S. Diehl et. al (CLAS collab.)
Phys. Rev. Lett. 128, 062005 (2022)

Bjorken x,, and

Bjorken x fractional energy transverse momentum

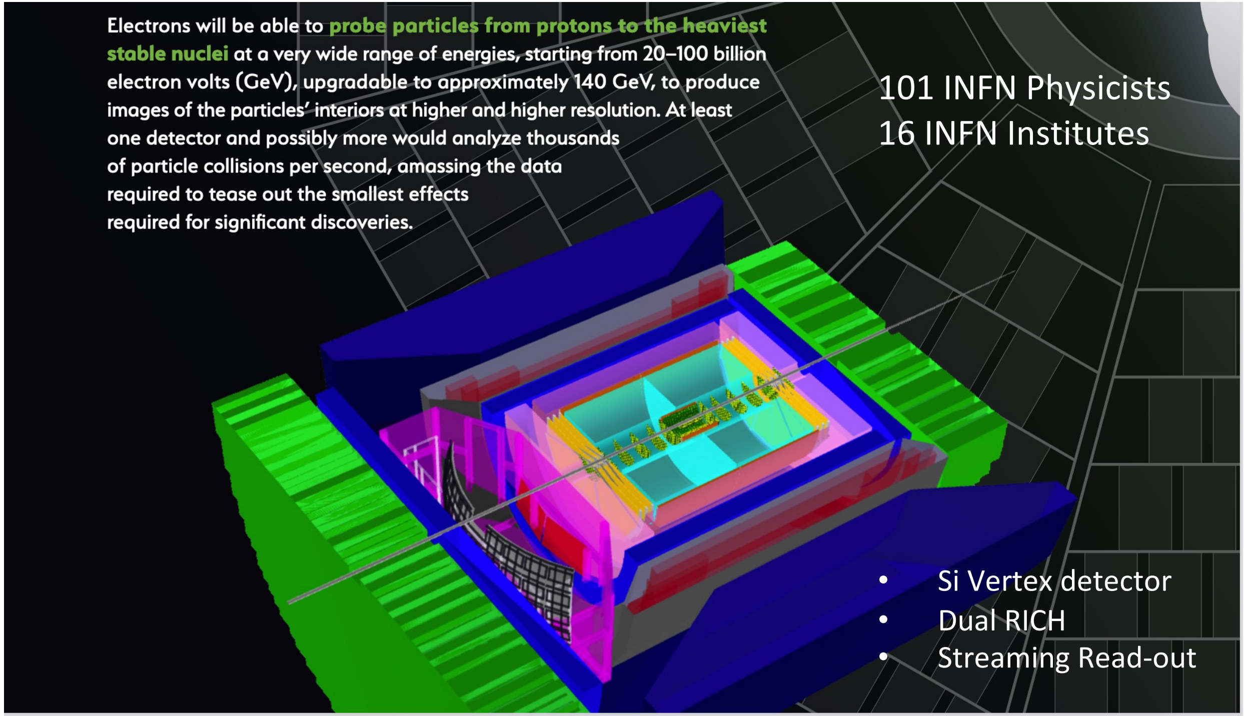
■ **CLAS12** [PRL 128 (2022)] 🟥 **CLAS** [PRD 98 (2014)]

□ **HERMES** [Phys. Let. B 797 (2019)] ▽ **COMPASS** [Nucl. Phys. B 886 (2014)]

CLAS12: A multidimensional study in Q^2, x_B, z and P_T for $\pi^\pm$, π^0 and $K^\pm$

THE FUTURE: EIC @ BNL

E_e =100-140 GeV

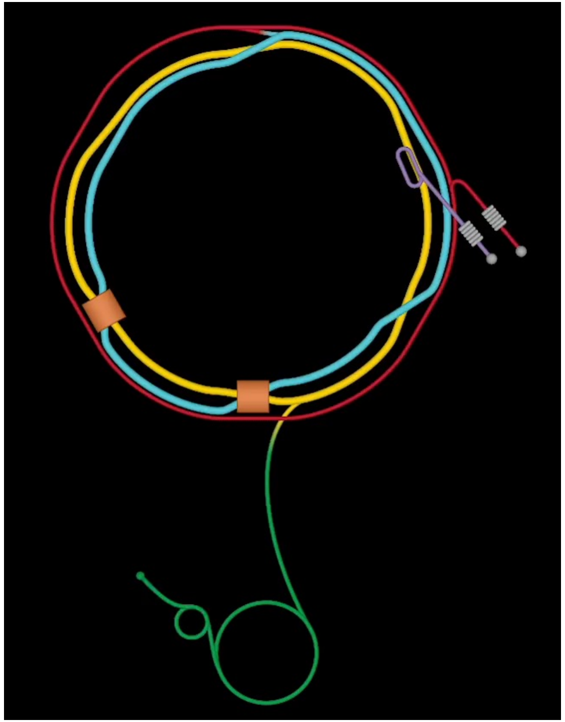


Electrons will be able to **probe particles from protons to the heaviest stable nuclei** at a very wide range of energies, starting from 20–100 billion electron volts (GeV), upgradable to approximately 140 GeV, to produce images of the particles' interiors at higher and higher resolution. At least one detector and possibly more would analyze thousands of particle collisions per second, amassing the data required to tease out the smallest effects required for significant discoveries.

101 INFN Physicists
16 INFN Institutes

- Si Vertex detector
- Dual RICH
- Streaming Read-out

Electron-Ion Collider



THE FUTURE: EIC @ BNL

EIC will study important topics, including:

- **The parton structure of hadrons**

How quarks and gluons contribute to the global properties of nucleon such as spin and mass

- **The multidimension imaging of nucleons, nuclei and mesons**

GPDs (generalized parton distributions) & **TMDs** (transverse momentum dependent parton distributions) to provide a 3D structure of N.

- **Nucleon structure**

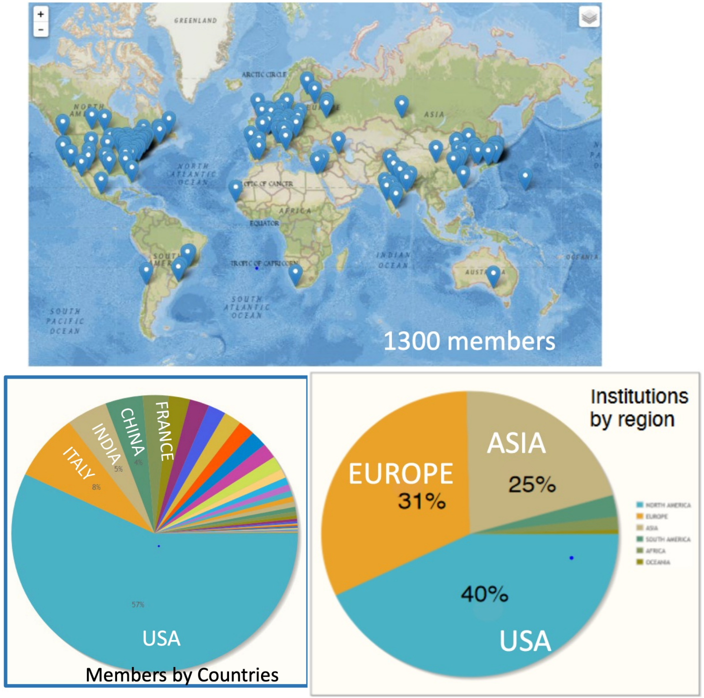
Effect of binding of nucleons on nuclear parton distributions; spatial distributions of partons in a nucleus.

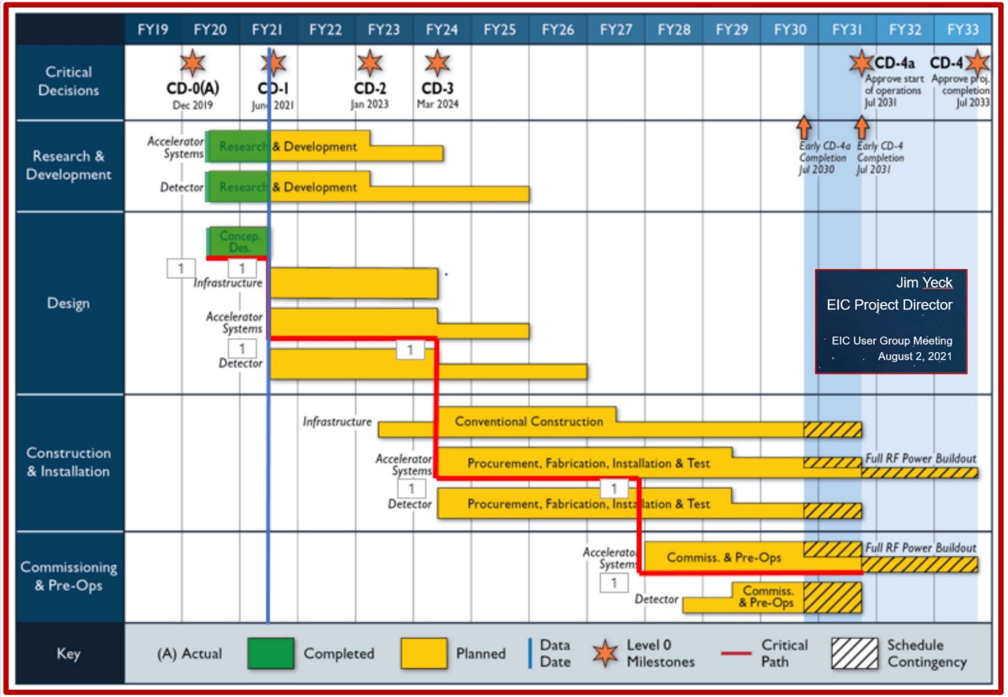
- **The mechanisms of hadronization**

Study of hadronization mechanisms production in lepton-hadron collisions, including parton fragmentation, threshold production, etc...

THE FUTURE: EIC @ BNL

The EICUG (User Group)





Summary and Outlook

Summarizing:

- Features of structure formation in QCD? **Pentaquark**
- How can we determine the properties of the nucleon resonances? **Polarization observables**
- The N* spectrum: what is the role of glue? **Hybrid Baryons**
- How is color confinement realized in the force and pressure distributions and stabilize nucleons? **DVCS and DVMP to get GPDs**
- How are the quarks and gluons, and their intrinsic spins distributed in space & momentum inside the nucleon? What is the role of the angular momentum ? **SIDIS to get TMDs via BSA**

And in the future

- The future EIC will allow to study the gluonic content of the nucleon
- Upgrades of CLAS12 (high luminosity), of A2 and of BGOOD will allow a deeper study of the processes under analysis

Stay tuned for further updates…

Summary and Outlook

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Thank you for the attention!

And in the fu

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