QCD, Hadron Spectroscopy, and Exotics

Summary

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Feng Yuan (LBNL)
Marian Stahl (RUB),

June 13, 2025
CIPANP, UW, Madison

Overview

Two blocks on Wednesday.

First one spectroscopy-focussed, second with focus on QCD observables.

Sessions well attended.

Thanks to the speakers for excellent talks, and attendees for lively discussions!

Won't go in chronological order.

Contribution list | Timetable

Wed 11/06

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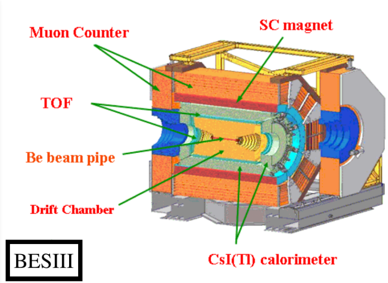
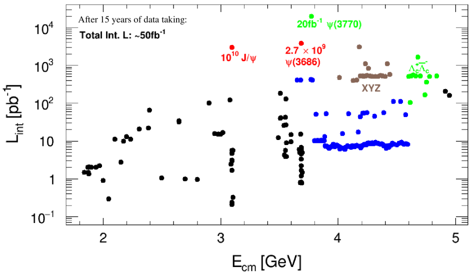
14:00	Hadron Spectrosocpy at GlueX	*Capital View*	*Volker Crede*	14:00 - 14:20
	Recent results on hadron spectroscopy from the lattice	*Capital View*	*Felipe Ortega Gama*	14:20 - 14:40
	Recent Hadron Spectroscopy Highlights from BESIII	*Capital View*	*Ryan Mitchell*	14:40 - 15:00
15:00	Amplitude analyses in hadron spectroscopy experiments	*Capital View*	*Vanamali Shastry*	15:00 - 15:20
	Charged Pion Polarizability at Jefferson Lab	*Beefeaters*	*Albert Fabrizi*	19:20 - 19:40
	Accessing Spin-1 Structure Functions and TMDs of the Deuteron	*Beefeaters*	*Nathaly Santiesteban*	19:40 - 20:00
20:00	Nuclear Calculations for Neutrino-Nucleus and Dark Matter-Nucleus Scattering	*Beefeaters*	*Baishan Hu*	20:00 - 20:20

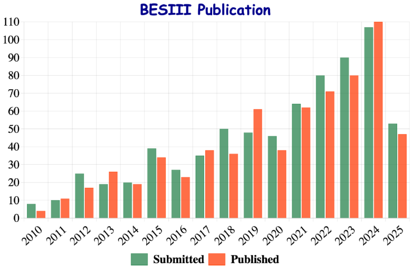


+ new CGEM inner tracker (2025)

http://english.ihep.cas.cn/bes/ui/ds/202109/t20210923_284001.html

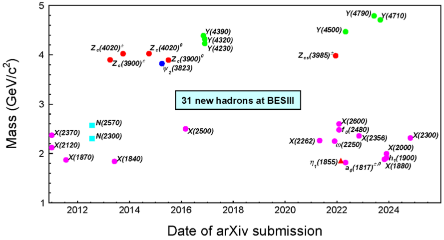


Nsubmitted = 721, Npublished = 677



"New hadrons discovered at BESIII," Z. Q. Liu, R. E. Mitchell, Sci.Bull. 68 (2023) 2148-2150

updates: http://english.ihep.cas.cn/bes/re/pu/NewParticles/



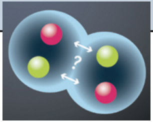
<u>This Talk *(a small subset of recent results)*:</u>

1. Glueball Candidates in Radiative ψ Decays
2. The $\pi_1(1600)$ in χ_{c1} Decays
3. Updates on the $X(3872)$ *(aka $\chi_{c1}(3872)$)*
4. Updates on the Y States *(aka ψ states)*
5. Updates on the $Z_c(3900)$ *(aka $T_{c\bar{c}1}(3900)$)*

Using a Flatte parameterization with $\bar{D}D^*$ and $\rho J/\psi$ coupled channels…

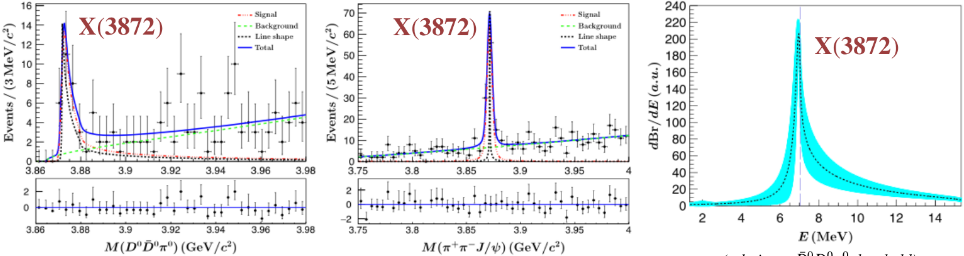
T-matrix pole position: $(3871.70 \pm 0.15^{+0.07}_{-0.08}) - i(0.19 \pm 0.08^{+0.14}_{-0.19})$ MeV

The real part is still consistent with the $\bar{D}^0D^{*0}$ threshold (3871.70 ± 0.11 MeV/c^2), and the imaginary part leads to a width of 0.38 MeV.



Using both $X(3872) \to \bar{D}^0D^{*0}$ and $X(3872) \to \pi^+\pi^-J/\psi$ gives access to the T-matrix pole position…

BESIII $e^+e^- \to \gamma(\bar{D}^0D^{*0})$ and $e^+e^- \to \gamma(\pi^+\pi^-J/\psi)$ (2024)



(relative to $\bar{D}^0D^0\pi^0$ threshold)

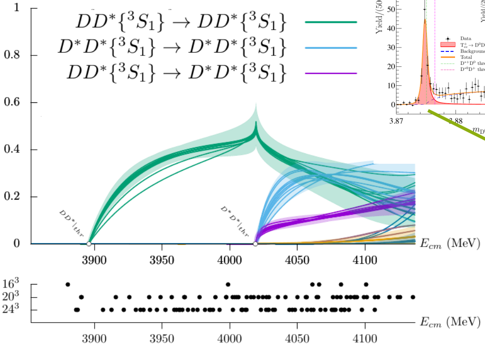
<u>BESIII, Phys.Rev.Lett. 132 (2024) 15, 151903</u>

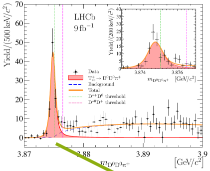
[Travis et al. (HadSpec) 2405.15741]

Double charmed tetraquark $T_{cc}\,(I=0)$

	m/MeV
π	390
D	1,886
D^*	2,009

$$\rho_a \rho_b \left| \mathcal{M}_{a,{}^{2S+1}\ell_J;b,{}^{2S'+1}\ell'_J} \right|^2$$

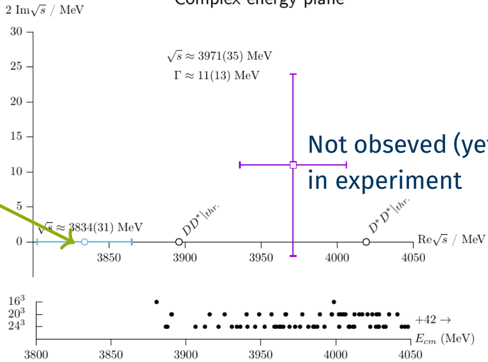




[(LHCb) 2109.01038]

Pole singularities

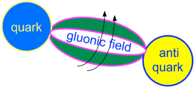
Complex energy plane



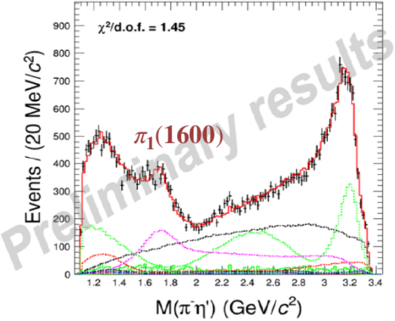
Not obseved (yet) in experiment

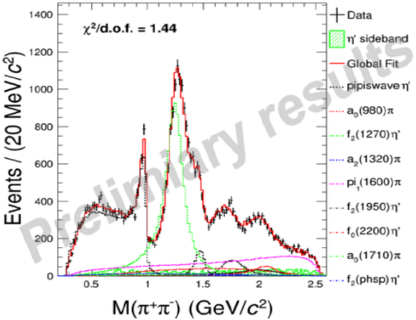
109 energy levels across 3 vols, 9 irreps

BESIII has access to the spin-exotic $\pi_1(1600)$ in χ_{c1} decays…



BESIII $\psi(2S) \to \gamma\chi_{c1};\ \ \chi_{c1} \to \pi^+\pi^-\eta'$ (2025, preliminary)

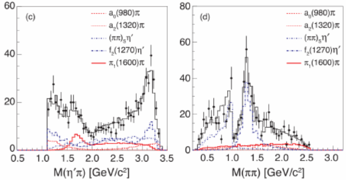




With 2.7 billion $\psi(2S)$ decays, this is a factor of 100 more statistics than CLEOc.

This production mode gives BESIII access to more decays of the $\pi_1(1600)$ [eg $b_1\pi$].

CLEOc $\psi(2S) \to \gamma\chi_{c1};\ \ \chi_{c1} \to \pi^+\pi^-\eta'$ (2011)



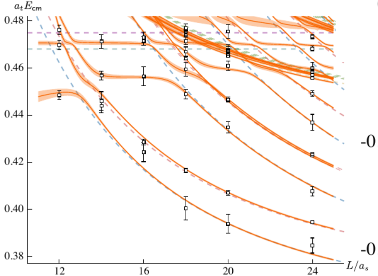
Phys.Rev.D 84 (2011) 112009

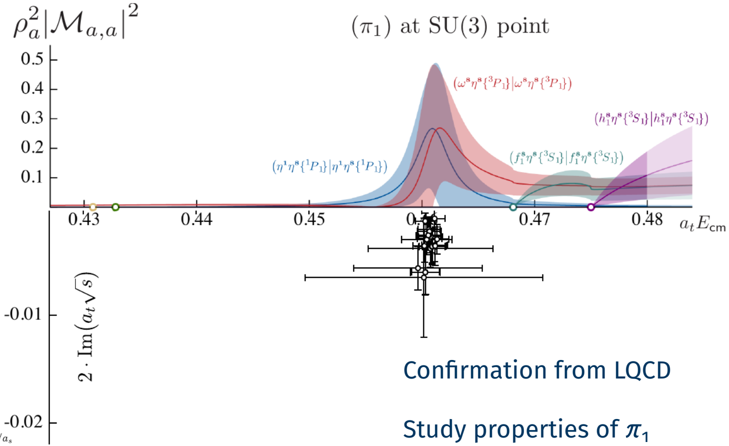
[Woss et al. (HadSpec) 2009.10034]

Lowest lying hybrid meson

	m/MeV
π	~ 700
K	~ 700

- Meson-meson and qqbar
- 6 volumes [$12a_s,\ldots,24a_s$]
- Spectrum for P=[000]
- 53 energy levels





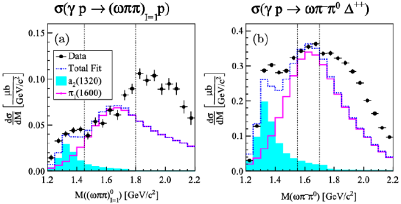
Confirmation from LQCD

Study properties of π_1

Production mechanisms

Goal: understand the mechanism behind the photoproduction of $\pi_1(1600)$

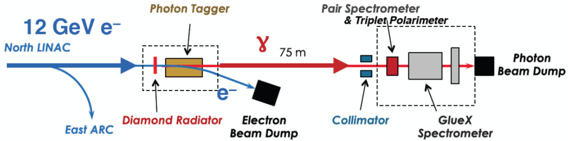
One pion $\Rightarrow$ Two pions $\Rightarrow$ ρp / $\boxed{\pi\Delta}$ / $\pi\pi p$ $\Downarrow$ $\omega\pi p(b_1 p)$ $\Leftarrow$ $\omega\pi\pi p$ $(b_1\Delta, \pi_1 p)$ $\Leftarrow$ $\pi_1\Delta$



GlueX, *Phys.Rev.Lett.* 133 (2024) 26, 26

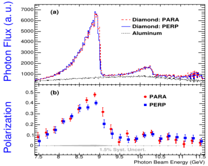
Why is the $\pi_1(1600)$ more likely to be produced in a charge exchange reaction?

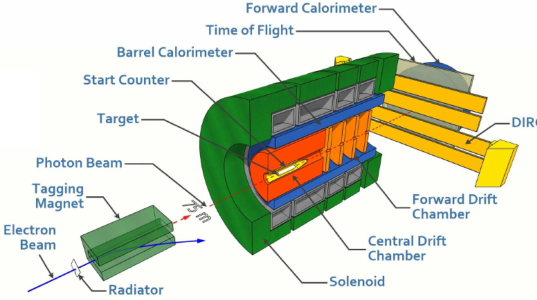
Understand i.a. $\pi\Delta$ photoproduction along the journey...

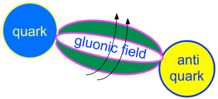


Polarized photon beam produced via coherent bremsstrahlung off thin diamond radiator:

- Tagging system with $\Delta E < 25$ MeV.
- Linear photon polarization of $P_\gamma \approx 40\,\%$ in the coherent peak.
- Phase-I intensity of 5×10^7 γ/s in peak.

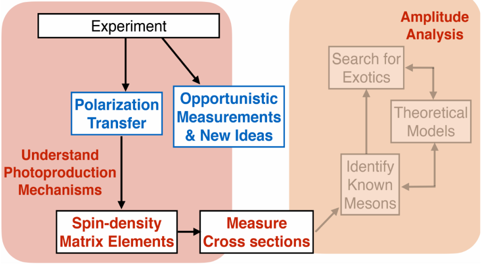




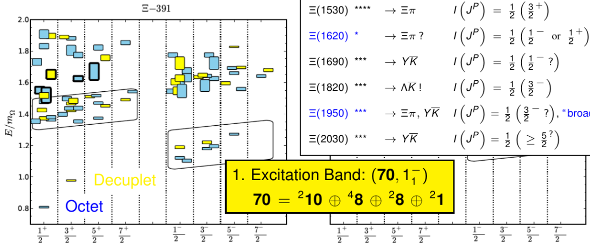


12 GeV CEBAF upgrade has high priority
(DOE Office of Science, Long Range Plan)
"[key area] is experimental verification of the powerful force fields *(flux tubes)* believed to be responsible for quark confinement."

Courtesy of Sean Dobbs



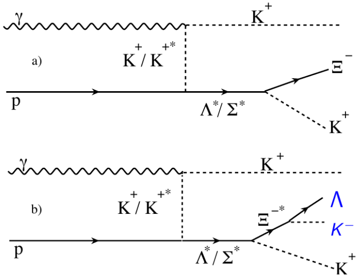
R. Edwards *et al.*, PRD **87**, 054506 (2013)

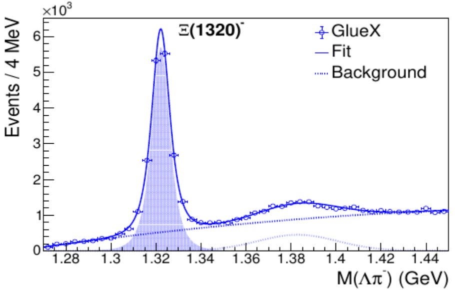


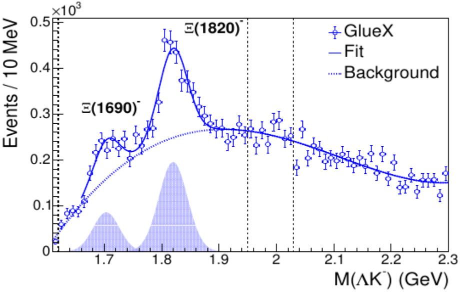
Ξ(1320)	****	$\to \Lambda\pi$	$I(J^P) = \frac{1}{2}\left(\frac{1}{2}^+\right)$
Ξ(1530)	****	$\to \Xi\pi$	$I(J^P) = \frac{1}{2}\left(\frac{3}{2}^+\right)$
Ξ(1620)	*	$\to \Xi\pi$?	$I(J^P) = \frac{1}{2}\left(\frac{1}{2}^- \text{ or } \frac{1}{2}^+\right)$
Ξ(1690)	***	$\to Y\overline{K}$	$I(J^P) = \frac{1}{2}\left(\frac{1}{2}^- ?\right)$
Ξ(1820)	***	$\to \Lambda\overline{K}$!	$I(J^P) = \frac{1}{2}\left(\frac{3}{2}^-\right)$
Ξ(1950)	***	$\to \Xi\pi, Y\overline{K}$	$I(J^P) = \frac{1}{2}\left(\frac{3}{2}^- ?\right)$, "broad"
Ξ(2030)	***	$\to Y\overline{K}$	$I(J^P) = \frac{1}{2}\left(\geq \frac{5}{2}^?\right)$

Exhibits broad features expected of $SU(6) \otimes O(3)$ symmetry

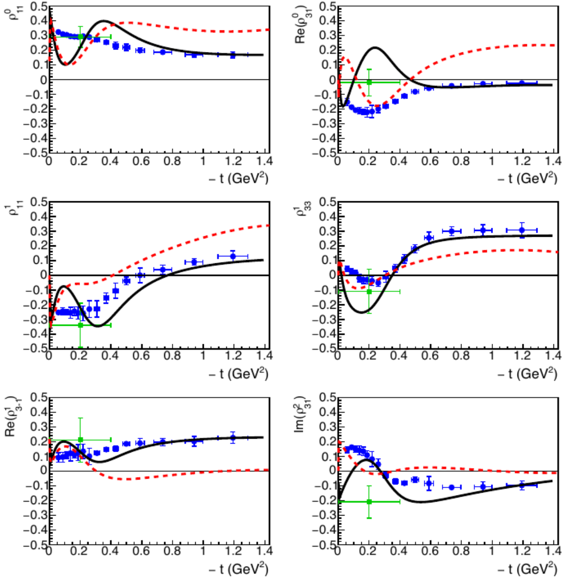
➜ Counting of states of each flavor and spin consistent with QM for the lowest negative- and positive-parity bands.







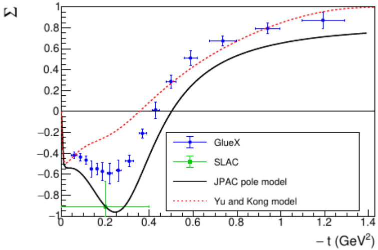
Spin-Density Matrix Elements: $\gamma p \to \Delta^{++}\pi^-$



[GlueX] PL B **863**, 139368 (2025)

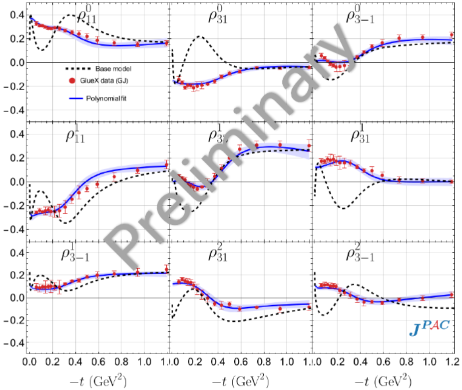
$$\rho_{ij}^{N/U} = \rho_{ij}^0 \pm \rho_{ij}^1$$

$$\Sigma = \left(\rho_{11}^N + \rho_{33}^N\right) - \left(\rho_{11}^U + \rho_{33}^U\right)$$
$$= 2\left(\rho_{11}^1 + \rho_{33}^1\right)$$



Two pion photoproduction – $\pi\Delta$ (V. Shastry *et al* (JPAC) *In progress*)

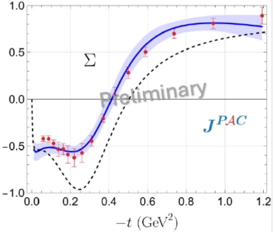
Spin density matrix elements when one of the pions comes from the lower vertex



- Instead of Lagrangians, chose polynomials (linear in *t*).
- Fit the coefficients to the data
  - Takes care of any higher order term left out of the model.
- Can be used in any future work involving Δ
- EXD broken for natural exchange
- Very forward region ($|t| \leq 0.1\ GeV^2$) shows absorption
- Not effectively described by PMA
- More analysis needed and in progress.

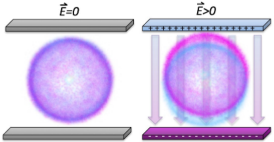
Structure of the amplitudes and their singularities

t-channel Residues and scalar amplitudes



GlueX data from F. Afzal *et al* (GlueX), *Phys.Lett.B* 863 (2025) 139368

Hadron surrounded by Pion Cloud



Hadron surrounded by displaced Pion Cloud

Electric Polarizability $= \alpha \approx 10^{-4} \times$ **Volume** $\vec{p} = -\alpha\vec{E}$

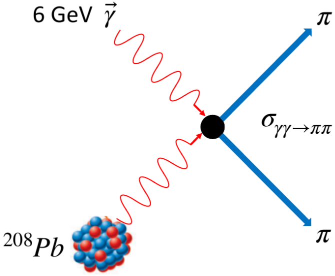
Magnetic Polarizability $= \beta \approx 10^{-4} \times$ **Volume** $\vec{\mu} = \beta\vec{H}$

Measurements of Pion Polarizability provide a test of chiral symmetry

Chiral Perturbation Theory Prediction for Charged Pions:*

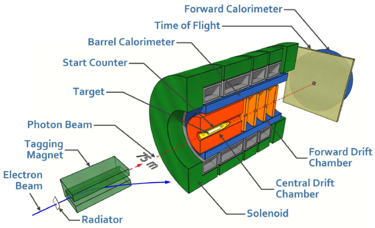
$$\alpha_\pi = -\beta_\pi = \frac{4\alpha}{m_\pi F_\pi^2}(L_9^r - L_{10}^r) = \boxed{2.8 \times 10^{-4} \mathrm{fm}^3}$$

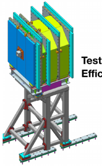
*Gasser et al. Annals Phys. 158, 142



$$\frac{d^2\sigma_{Prim}}{d\Omega dM_{\pi\pi}} = \frac{2\alpha Z^2}{\pi^2}\frac{E_\gamma^2\beta^2}{M_{\pi\pi}}\frac{sin^2\theta}{Q^4}\left|F_{EM}(Q^2)\right|^2\left(1 + P_\gamma cos2\phi_{\pi\pi}\right)\sigma_{\gamma\gamma\to\pi\pi}$$

Photon polarization





New detector for μ/π identification

Test Efficiency: 99.7%
Efficiency During Experiment: 99.9%

Compare $\mu^+\mu^-$production with respect to $\pi^+\pi^-$ production

Status of the JLab GlueX CPP and NPP measurements

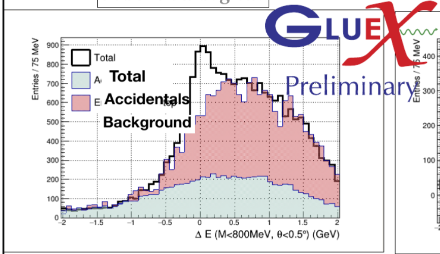
- Data was taken in summer 2022 with 6 GeV linearly polarized photons on ^{208}Pb target, ~ 80% polarization
- Calorimeter and charged particle tracking calibrations have been completed
- Data processing was concluded October 2024
- Currently working on Neural Nets for separation of $e^+e^-, \pi^+\pi^-, \mu^+\mu^-$Particle ID
- We expect to have preliminary physics distributions at end of summer.
- Neutral Pion Polarizability has Preliminary physics distributions

Observed and Expected $\pi^0\pi^0$ Signal

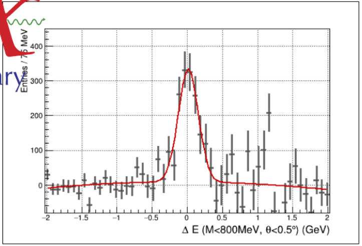
- The experimental background conditions are favorable for the angular range below 0.5°
- For 4.5÷5.9 GeV photon beam energy, $M_{\pi\pi} < 800 MeV$ and $\theta_{\pi\pi} < 0.5°$:
  - –Observed yield: 1.6K ± 8% (very preliminary)
  - –Expected Primakoff yield based on Crystal Ball $\sigma(\gamma\gamma \to \pi^0\pi^0)$ data: 1.7K ± 16%

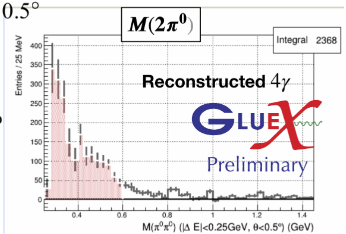
We are close to our expectations

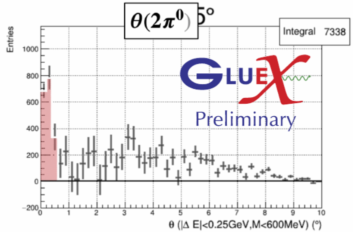
observed signal

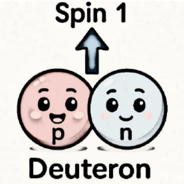


backgound subtracted

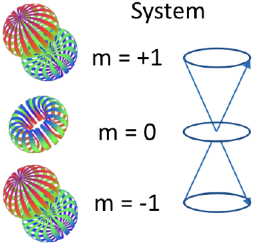






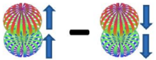


Spin-1
System



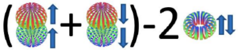
Deuteron in a magnetic field

Vector Polarization:



$$P = N(+1) - N(-1)$$

Tensor Polarization:



$$Q = N(+1) + N(-1) - 2N(0)$$

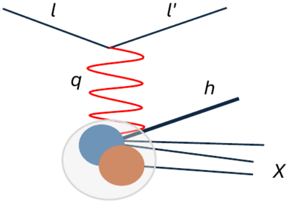
N(m): population density

$$N(+1) + N(-1) + N(0) = 1$$

Normalization

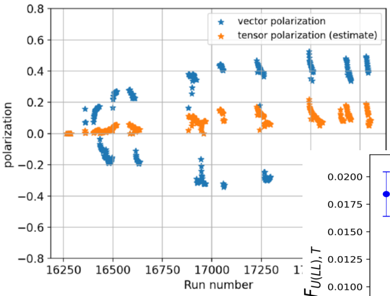
Transverse-momentum-dependent (TMD) tensor distribution functions describe quark- and gluon dynamics inside the deuteron.

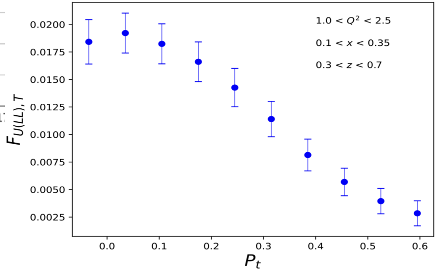
Multi-differential cross-section measurements of semi-inclusive deep-inelastic scattering (SIDIS) off tensor-polarized deuteron targets.

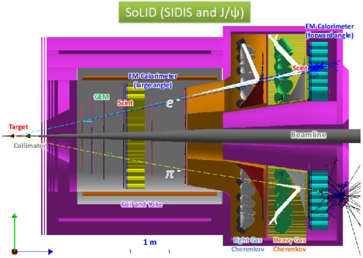


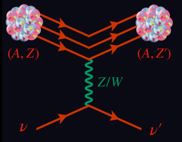
Deuteron TMDs – Nathaly Santiesteban

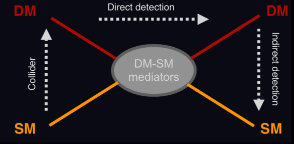
Exploratory Measurement CLAS12 → Dedicated Measurement Hall C → Full Program SOLID

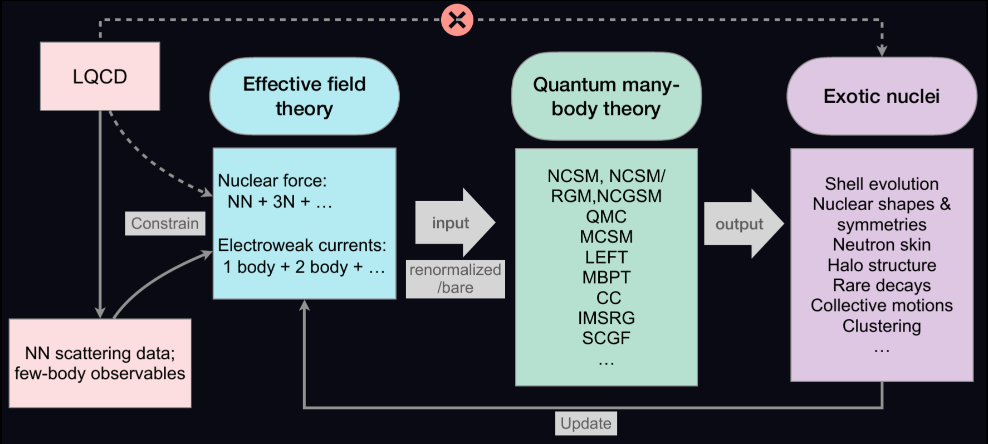












Y L Ye, X F Yang, H Sakurai and BSHu. Nature Reviews Physics 7, 21 (2025)

Spin-Dependent Dark Matter Direct Detection

PHYSICAL REVIEW LETTERS **131**, 041002 (2023)

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