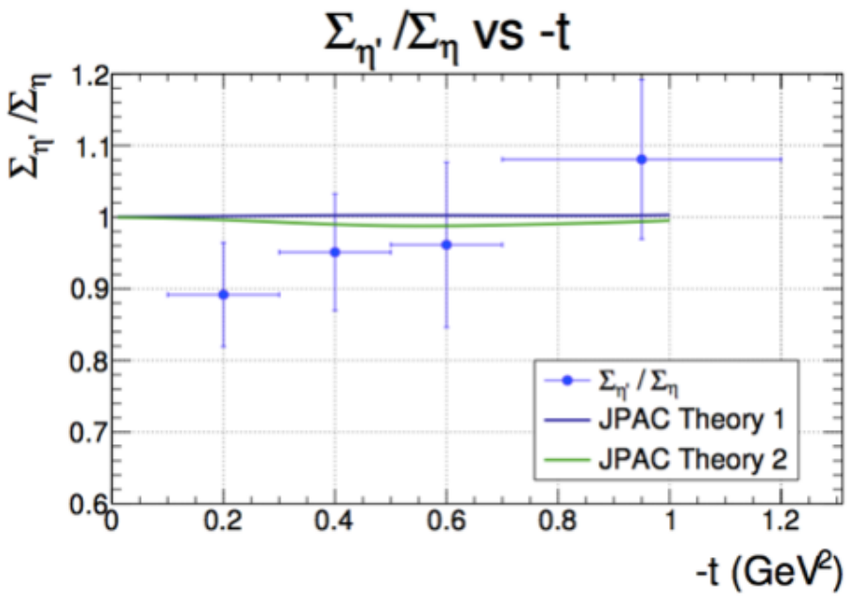

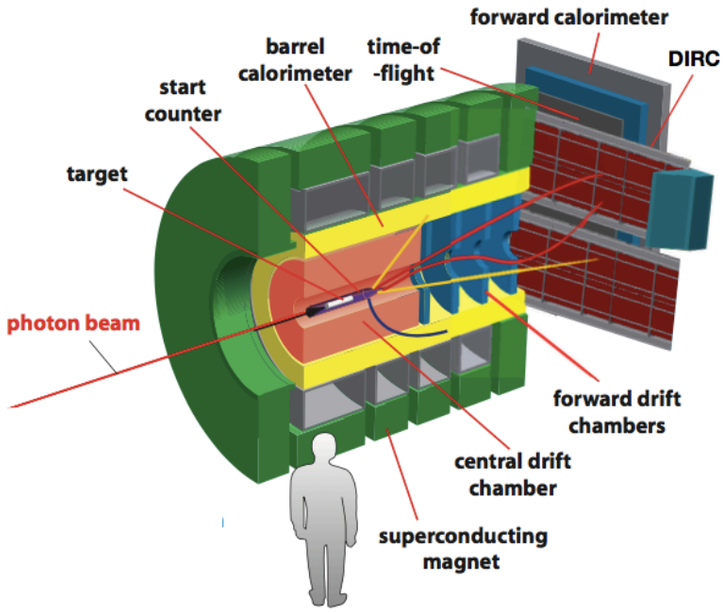

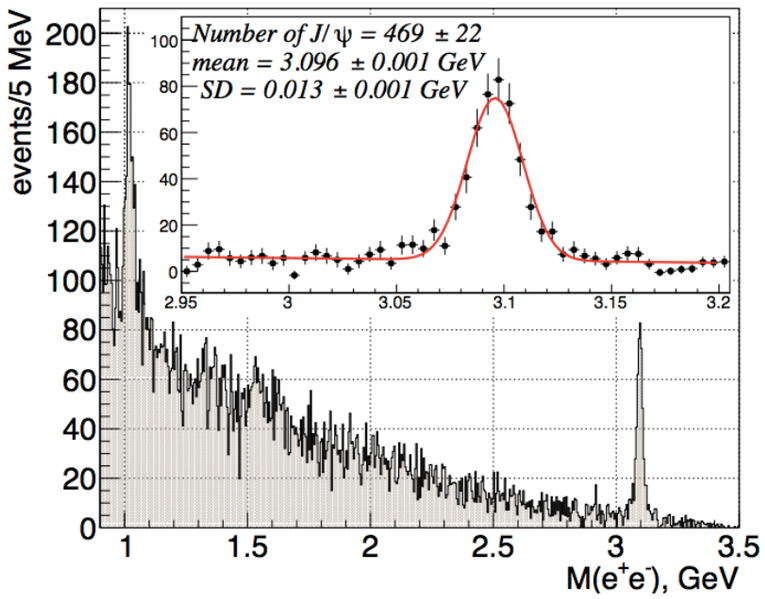

The GlueX Experiment:
A Search for Exotic Matter

Dr. Zisis Papandreou

University of Regina

CAP Congress 2019

June 5, 2019

Outline

- Physics Motivation
- The Experiment
- Beam Asymmetry: η, η′
- Other Analyses

Physics Motivation

Confined States of Quarks and Gluons

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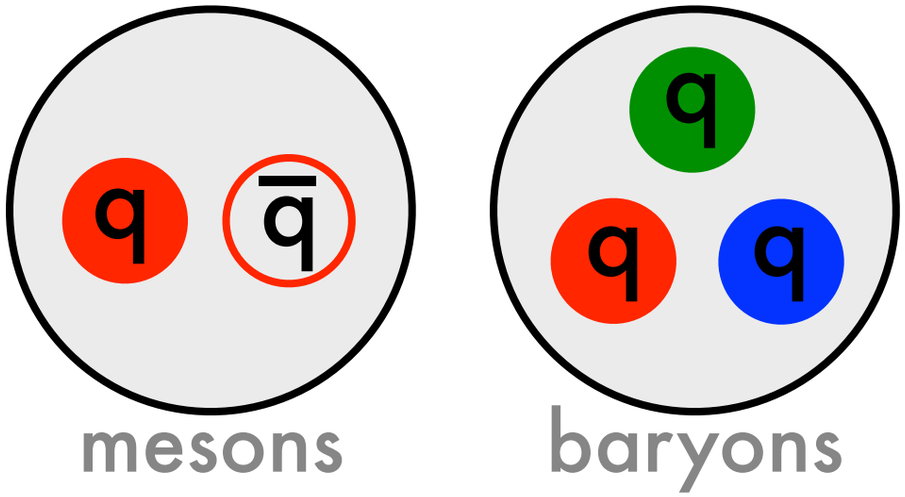

QCD predicts more types
of states than
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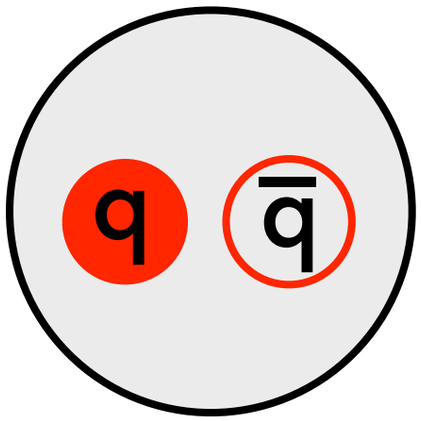
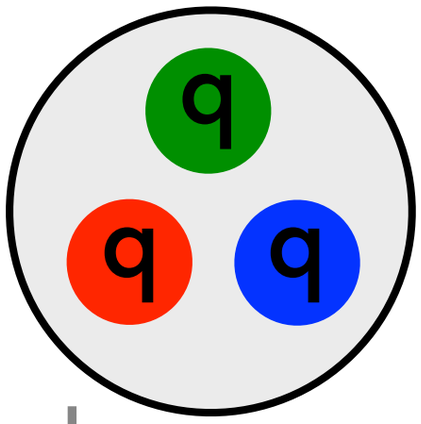
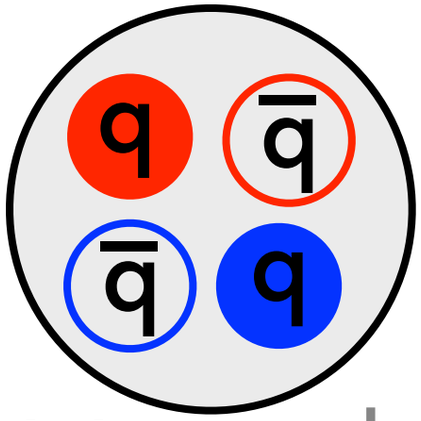


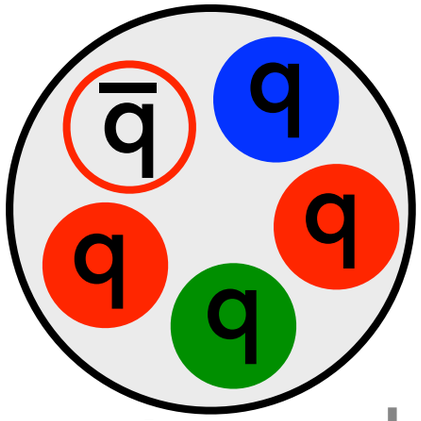
mesons



baryons



tetraquark



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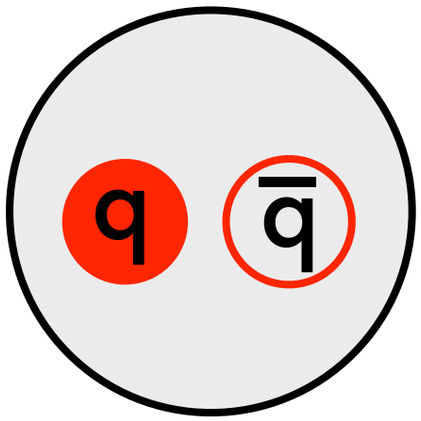

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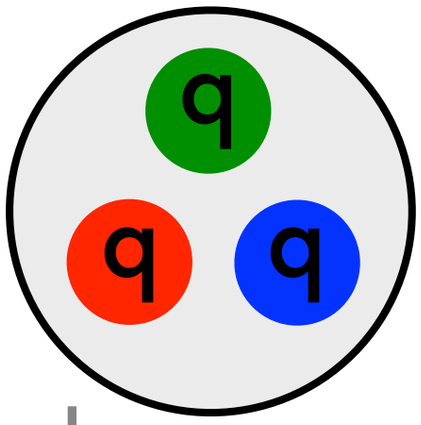

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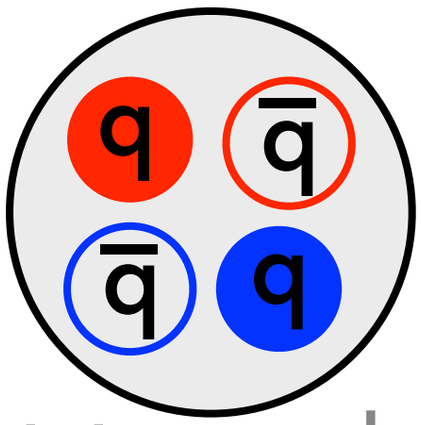

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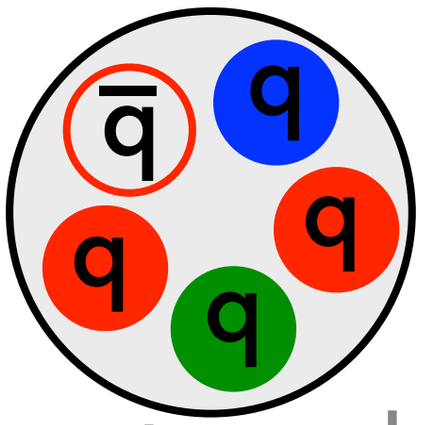

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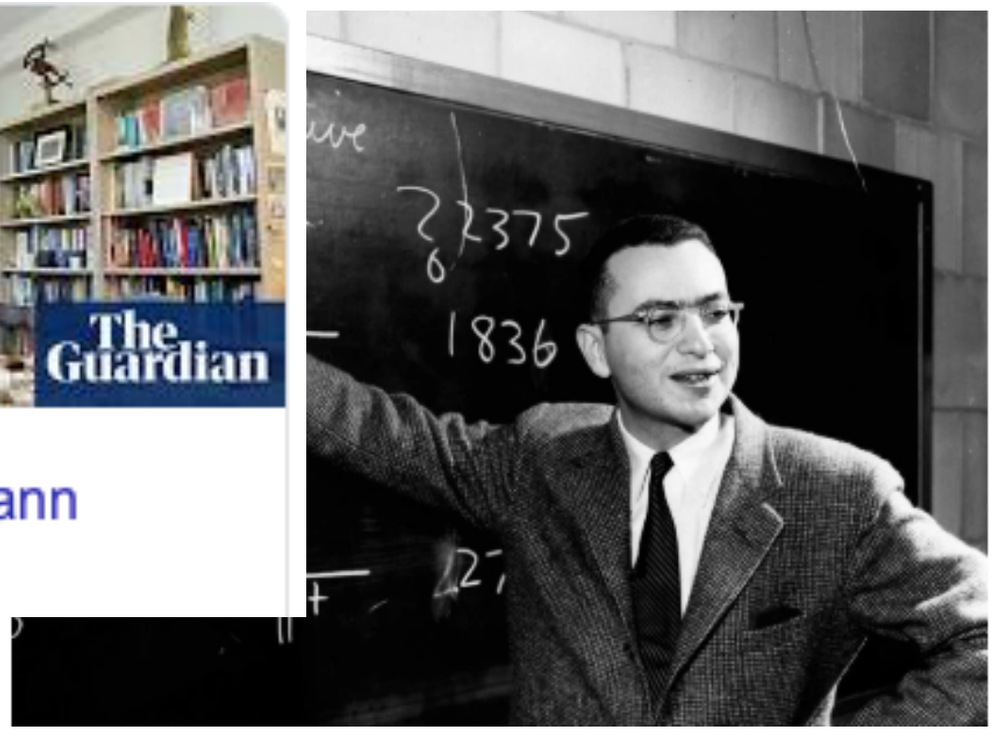
The New York Times

Murray Gell-Mann, Who Peered at Particles and Saw the Universe, Dies at 89

Murray Gell-Mann obituary



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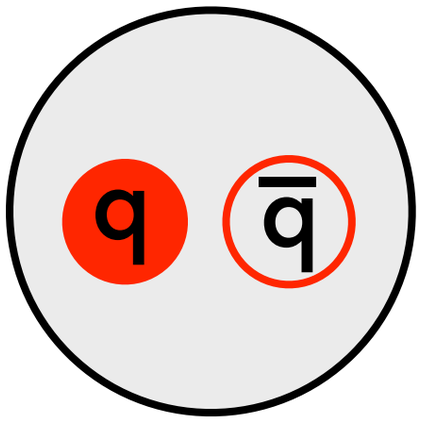

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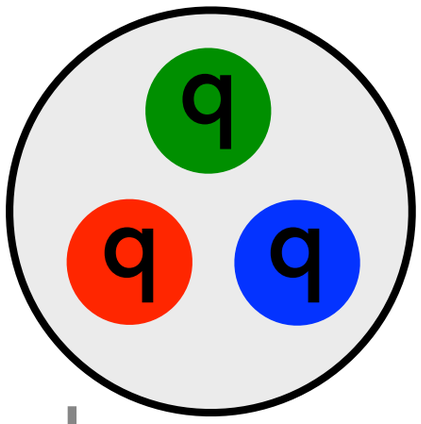

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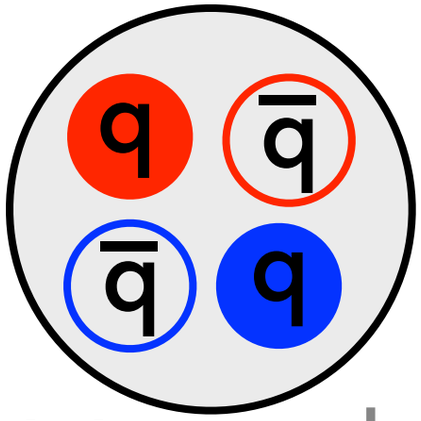

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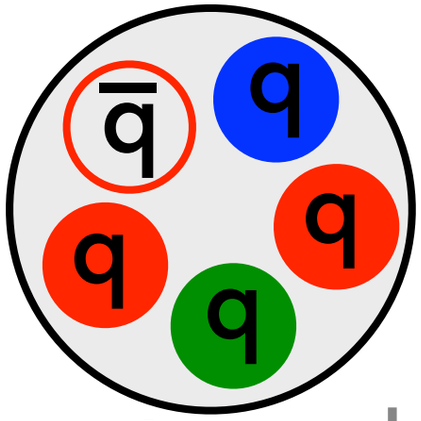

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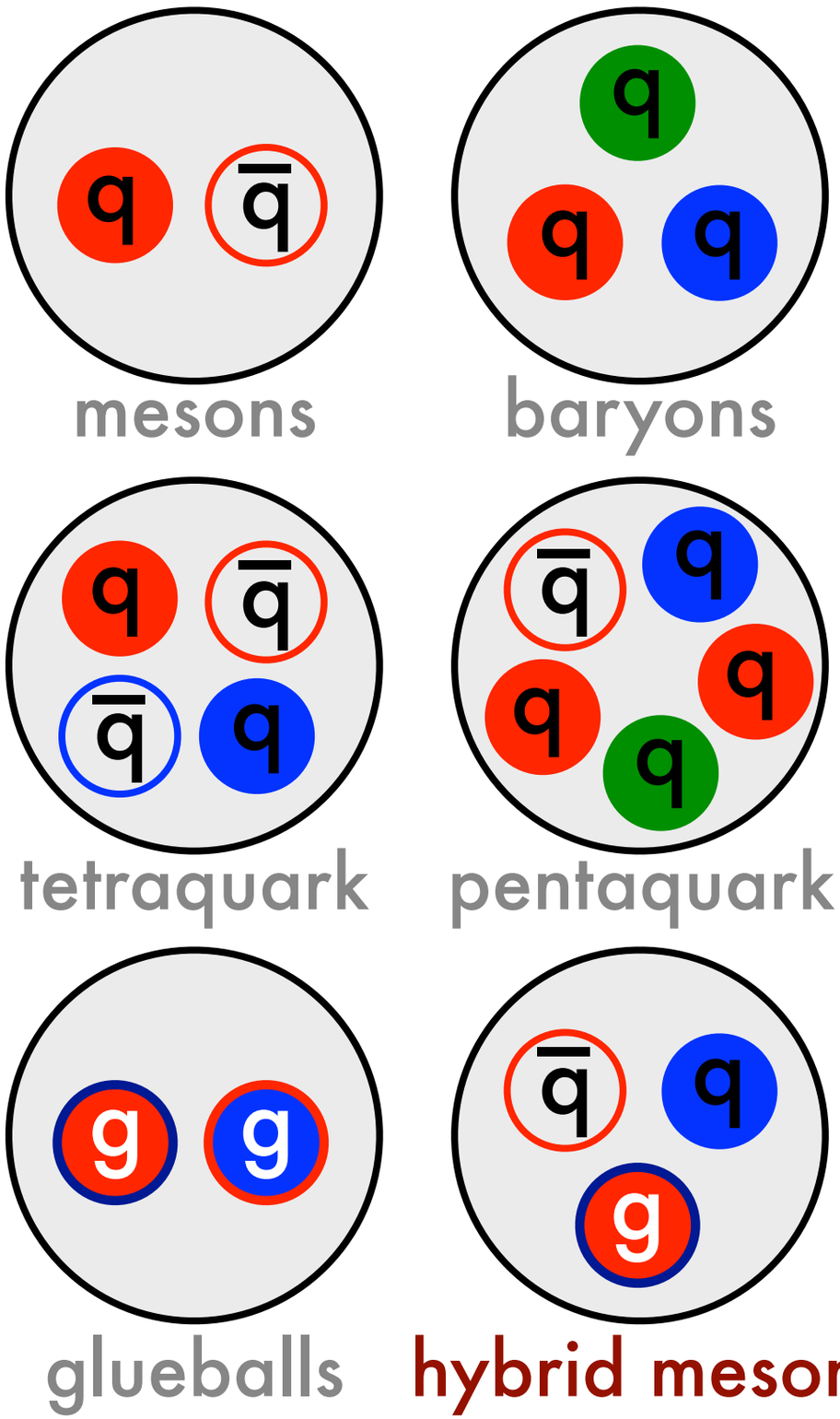

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Can we observe explicit gluonic degrees of freedom in nature's bound states?

Spectroscopy

How do we look for gluonic degrees of freedom in spectroscopy?

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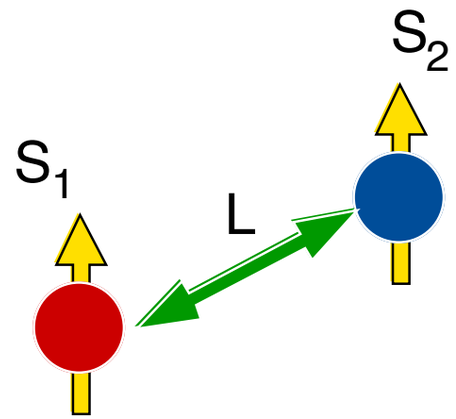
Nonets characterized by given J^{PC}



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$$J = L + S$$

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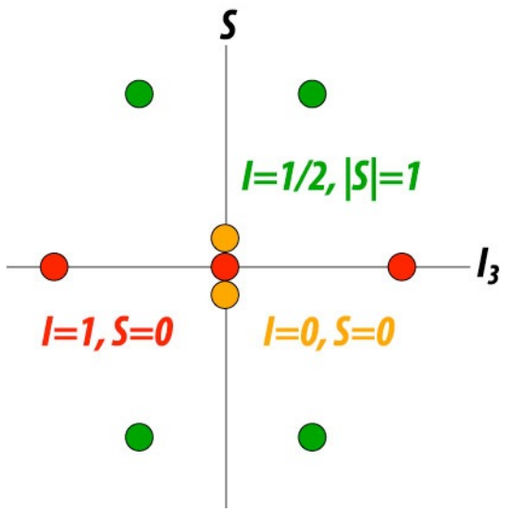

symmetry groups

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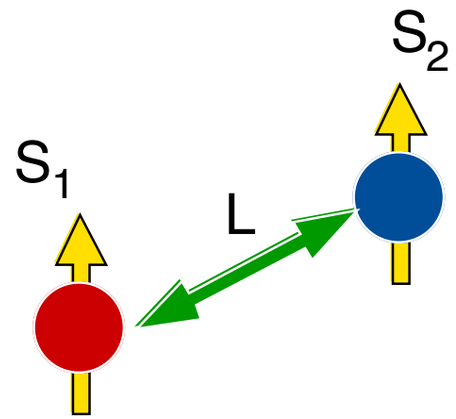

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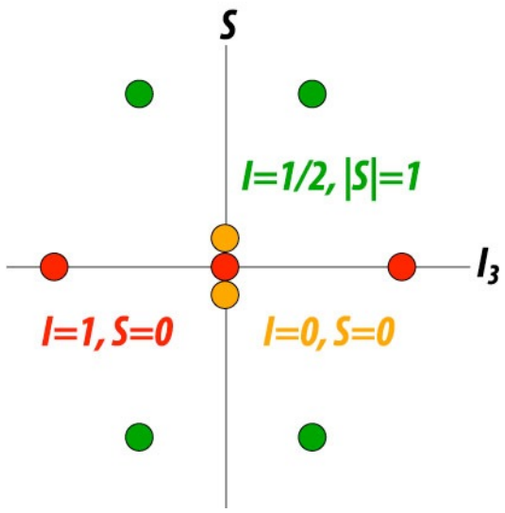


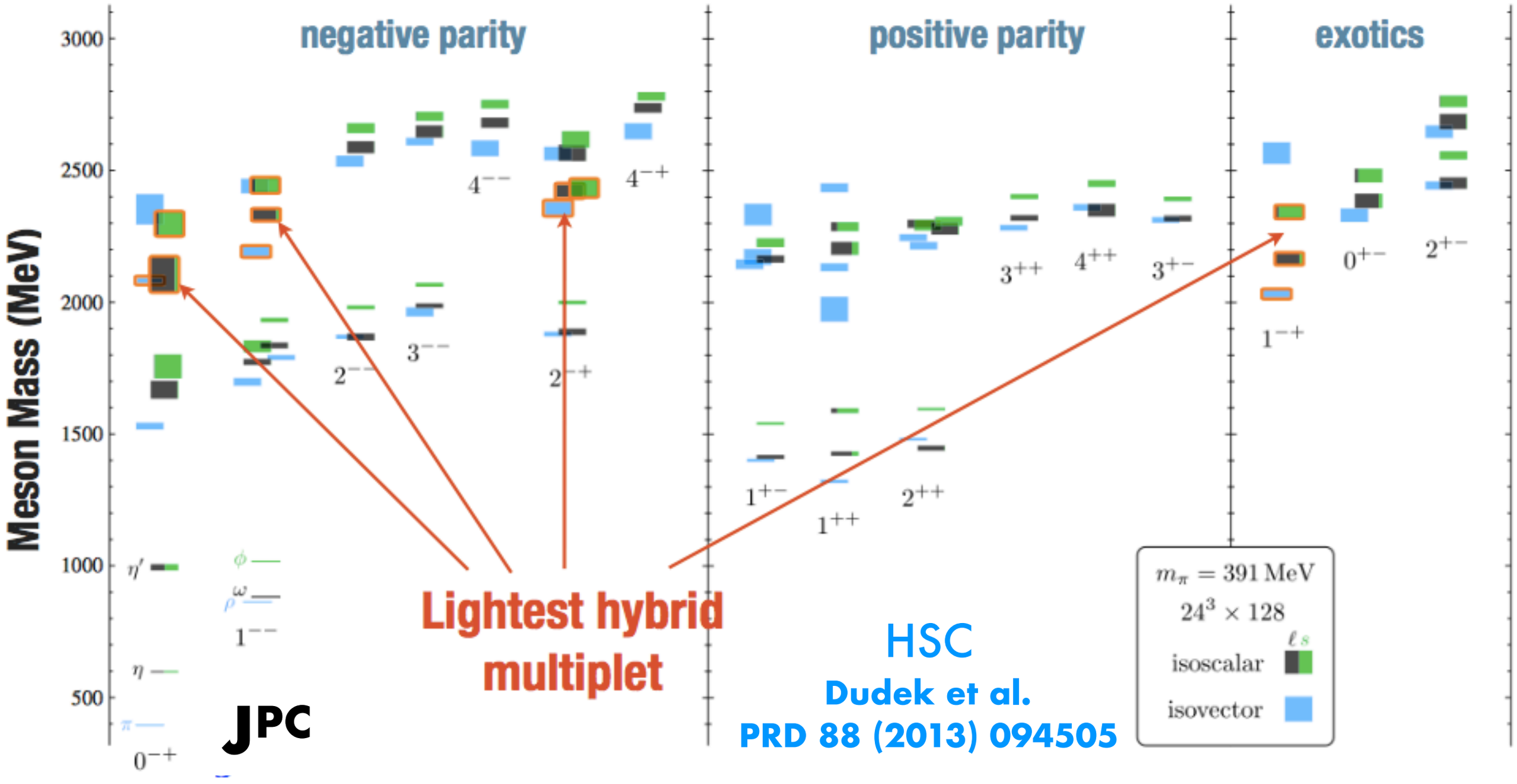
symmetry groups

Non-rel. quark model has allowed and non-allowed (exotic) QNs

$$J^{PC} = 0^{+-},\ 1^{-+},\ 2^{+-}$$

Determine quantum numbers and pole parameters via Amplitude Analysis

LQCD Full Spectrum



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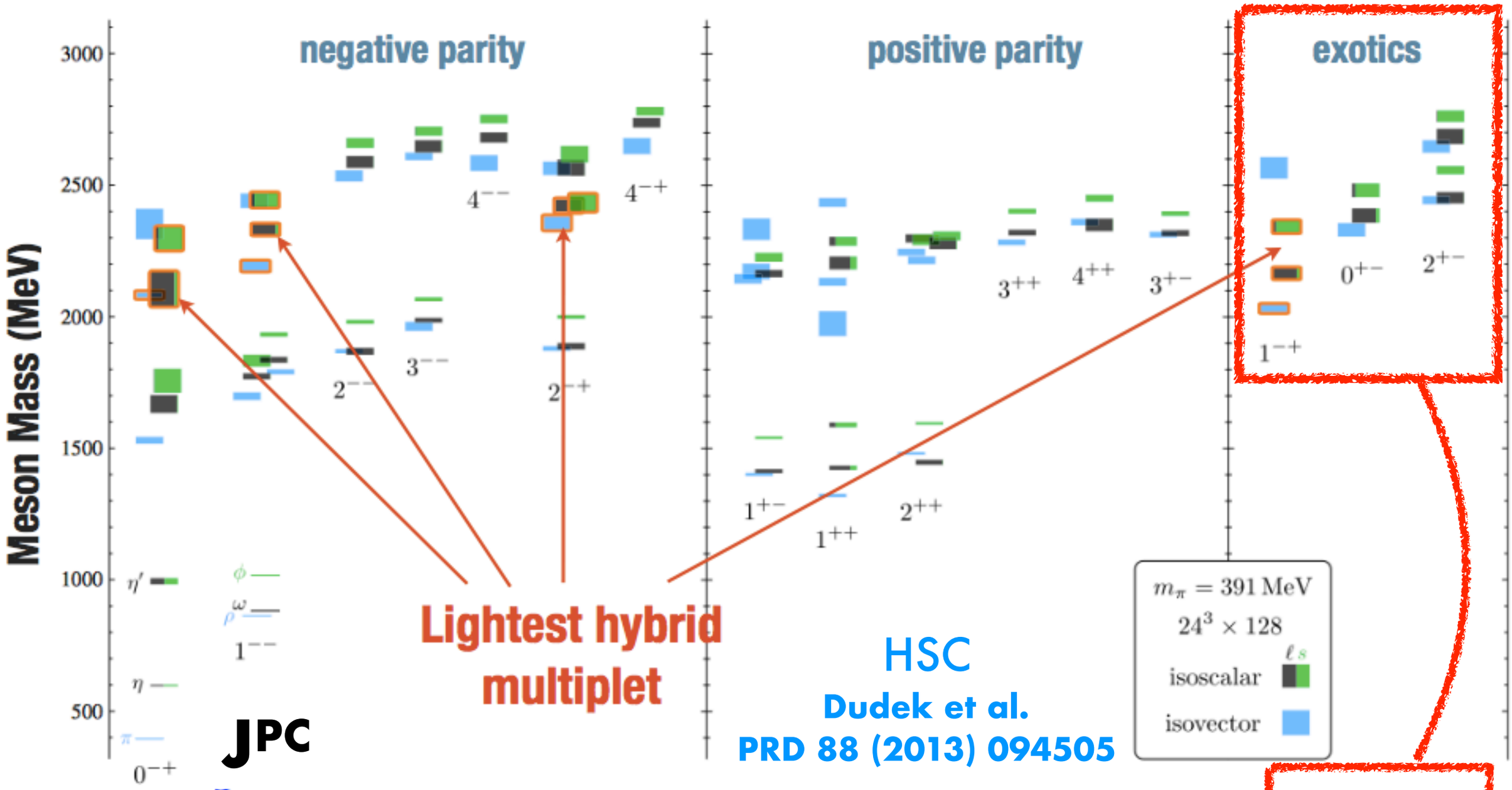


Lightest hybrid multiplet

JPC

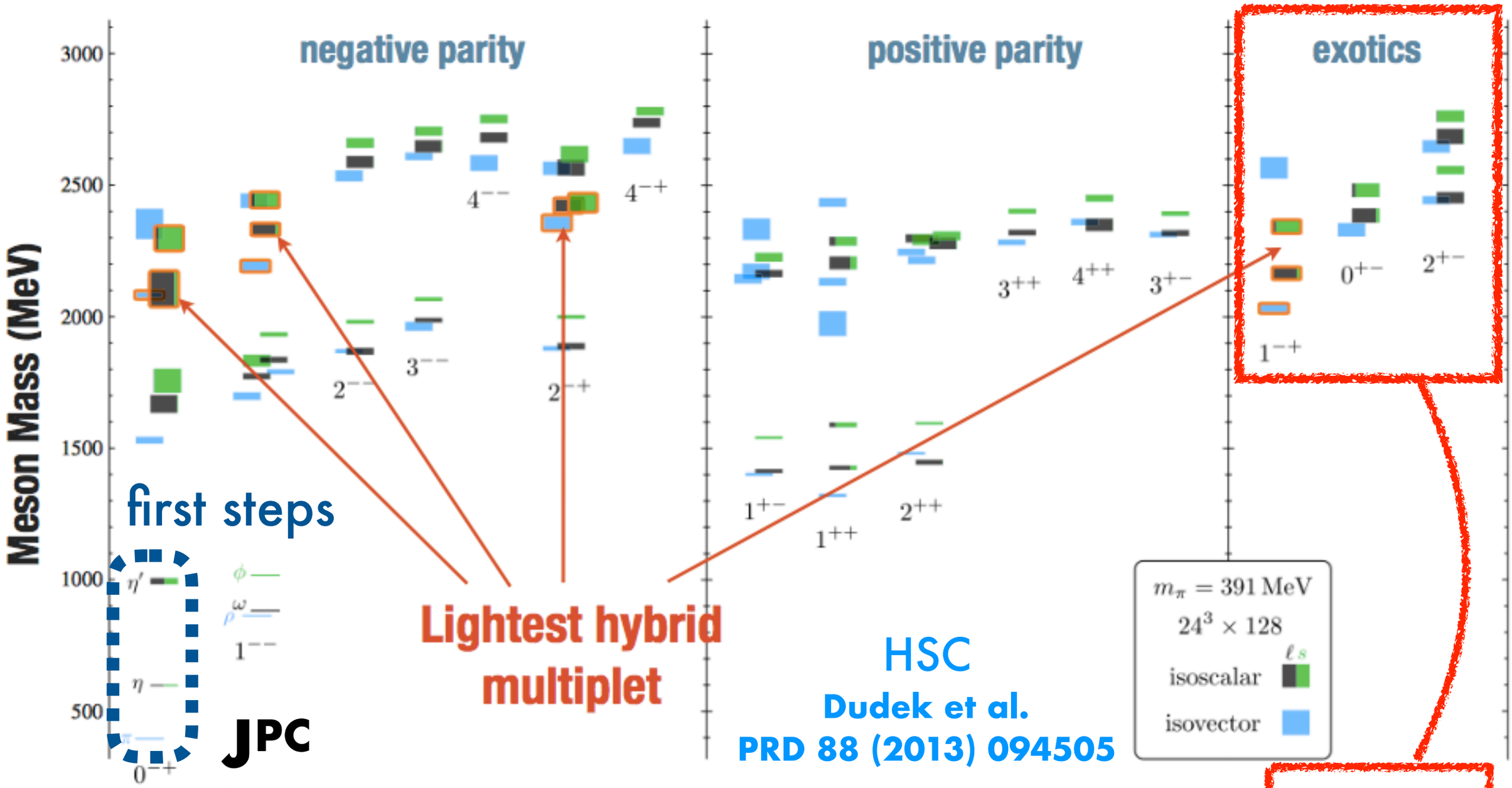
HSC

Dudek et al.

PRD 88 (2013) 094505

GlueX goal: look for hybrid patterns incl. exotics

LQCD Full Spectrum



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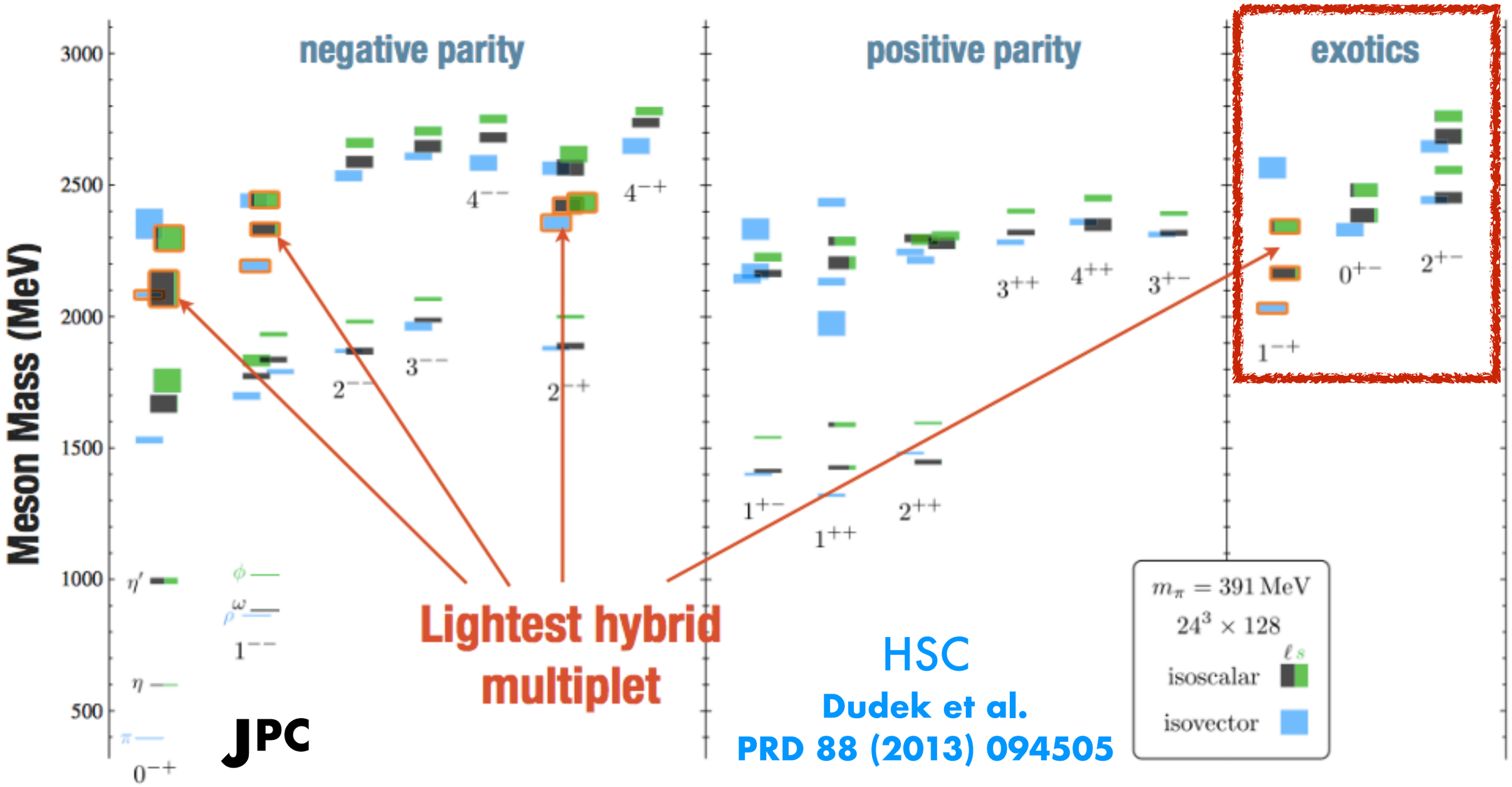

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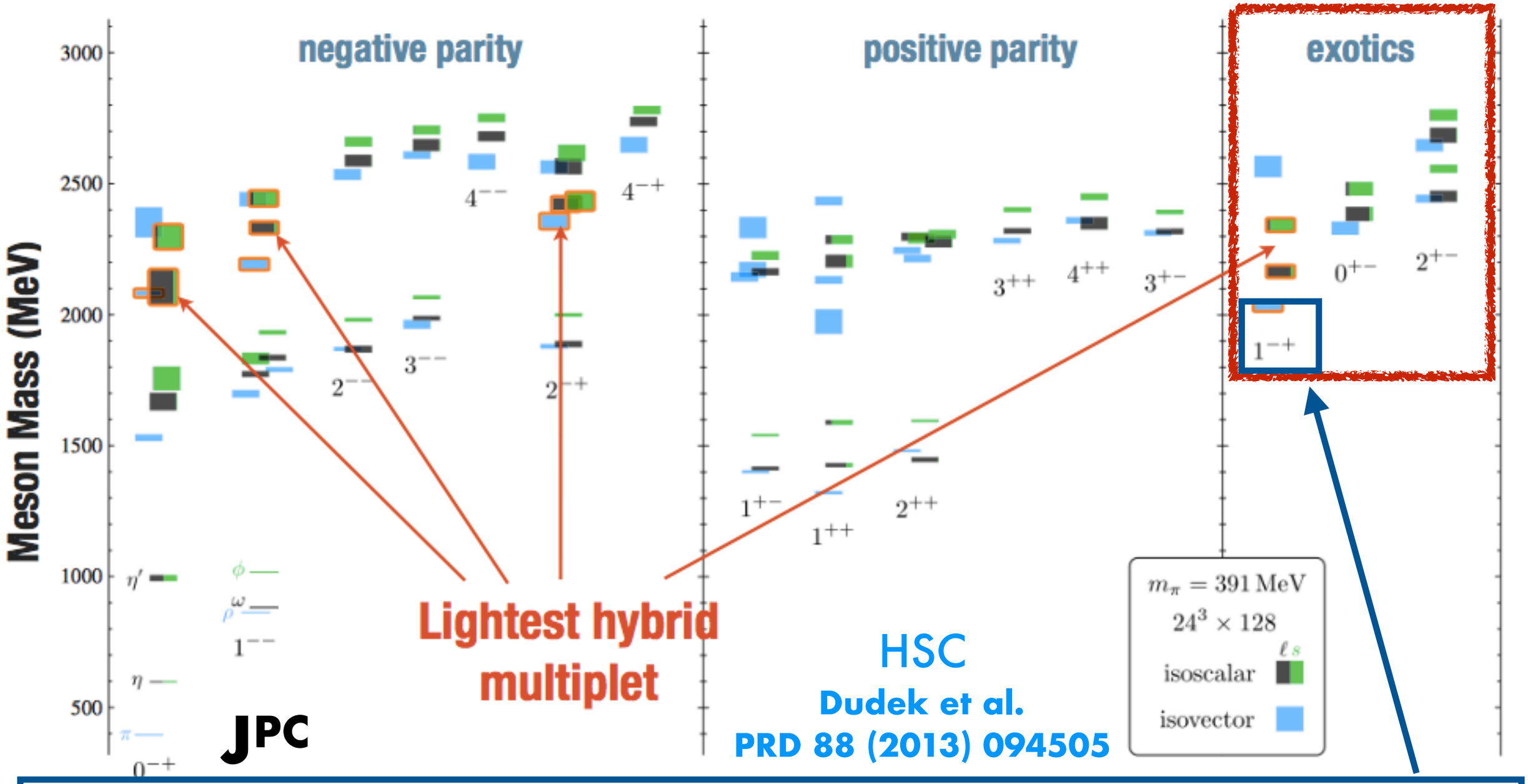

Most searches have focused on the lightest hybrid $\pi_1(1600)$ with 1^{-+}

Where are the Exotic hybrids?

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Candidates

(older experiments)

State	Mass (GeV)	Width (GeV)
$\pi_1(1400)$	1.351 ± 0.03	0.313 ± 0.040
$\pi_1(1600)$	1.662 ± 0.015	0.234 ± 0.050
$\pi_1(2015)$	2.01 ± 0.03	0.28 ± 0.05

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$\pi_1(1600)$	$\pi^- p, \bar{p}p$	$\eta' \pi, b_1 \pi, f_1 \pi, \rho \pi^\ddagger$
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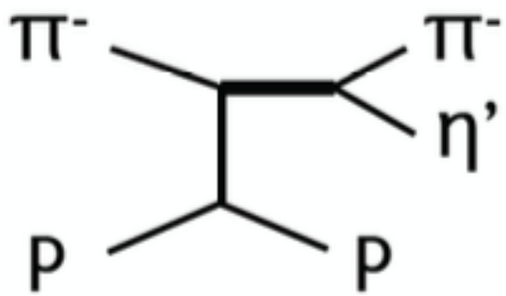

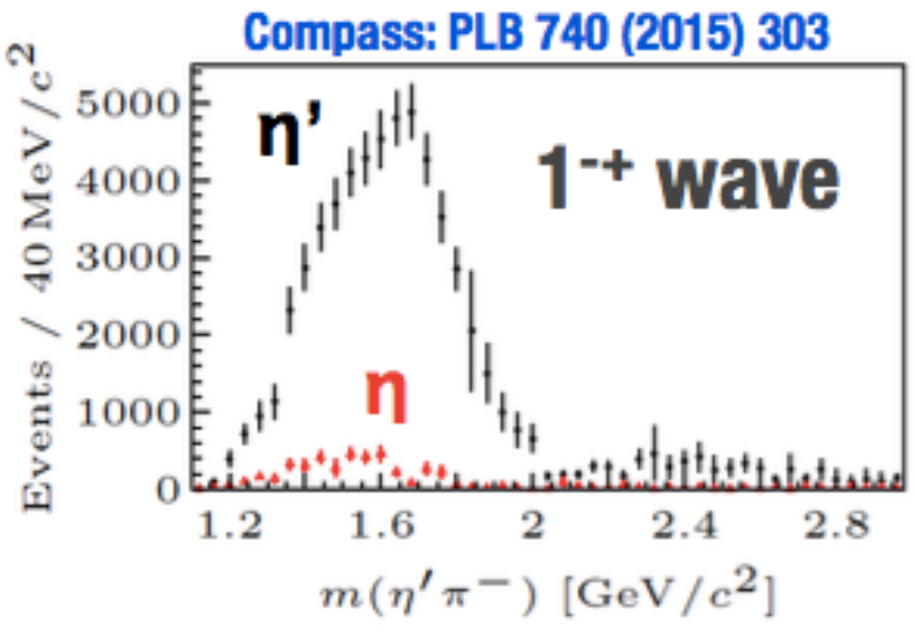

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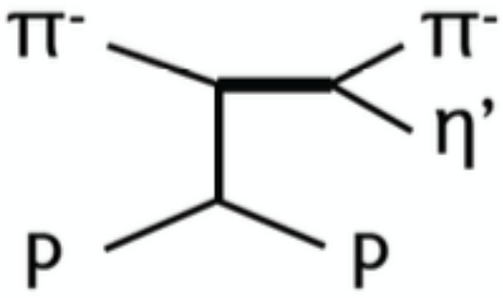
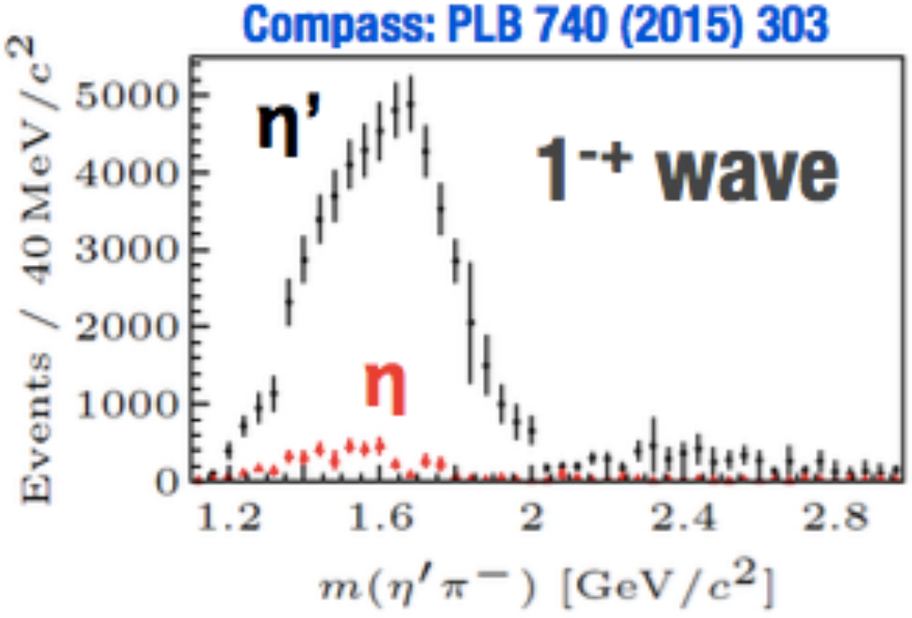


Compass: PLB 740 (2015) 303



Past: Two different candidates $\pi_1(1400)/\pi_1(1600)$ that couple separately to $\eta\pi$ and $\eta'\pi$.
Not compatible with LQCD estimates for hybrid states, nor with most phenomenological models.

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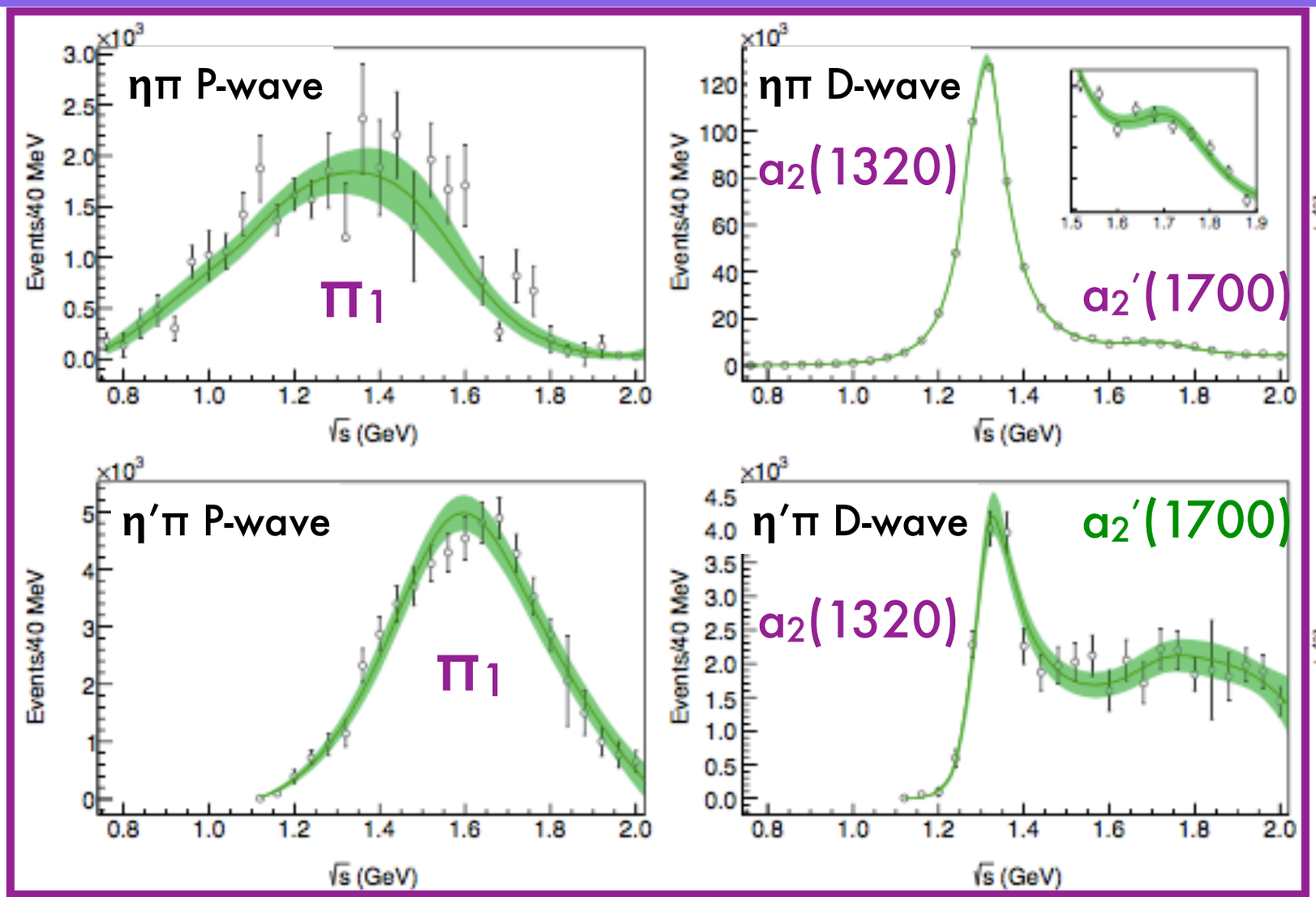

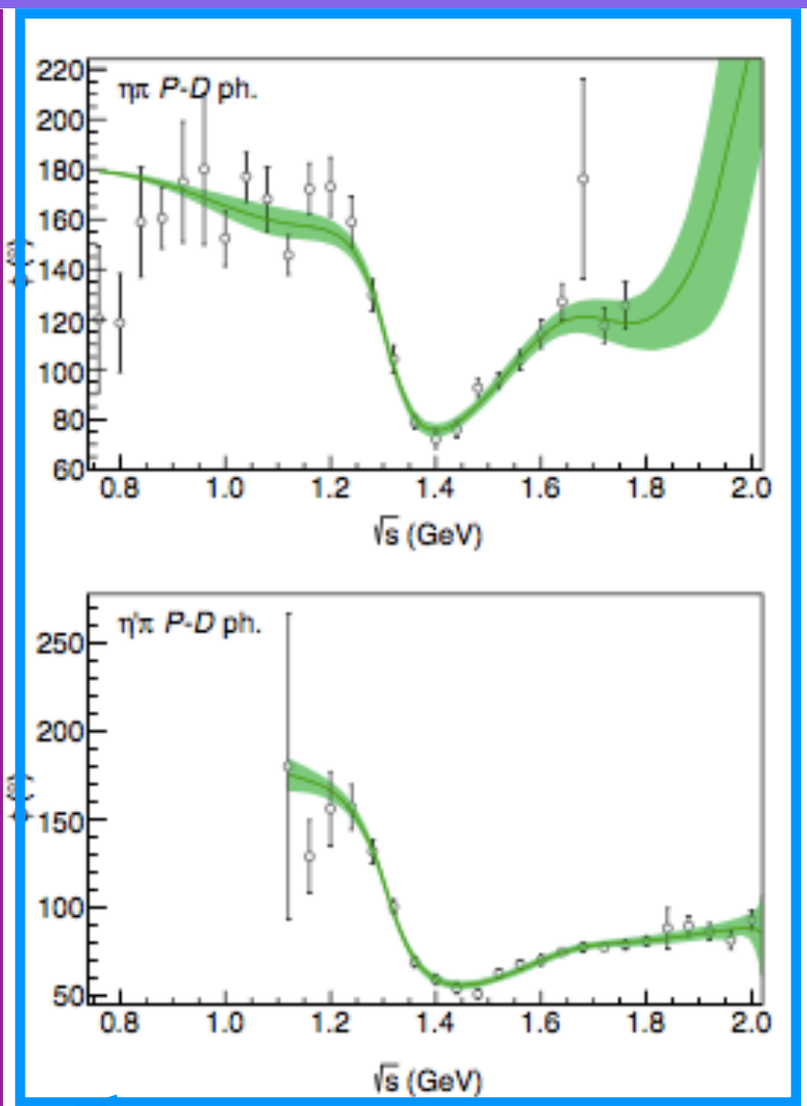

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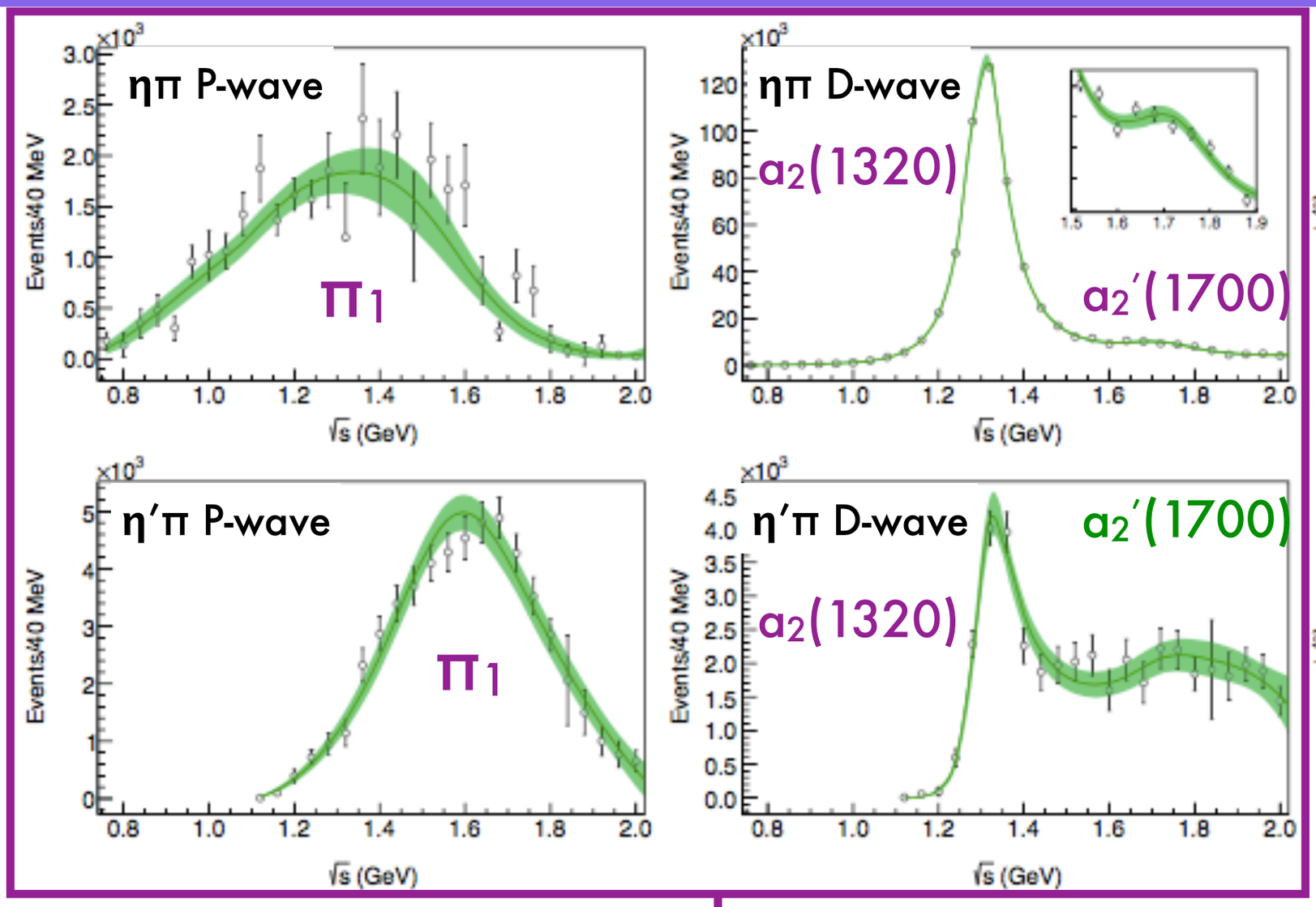

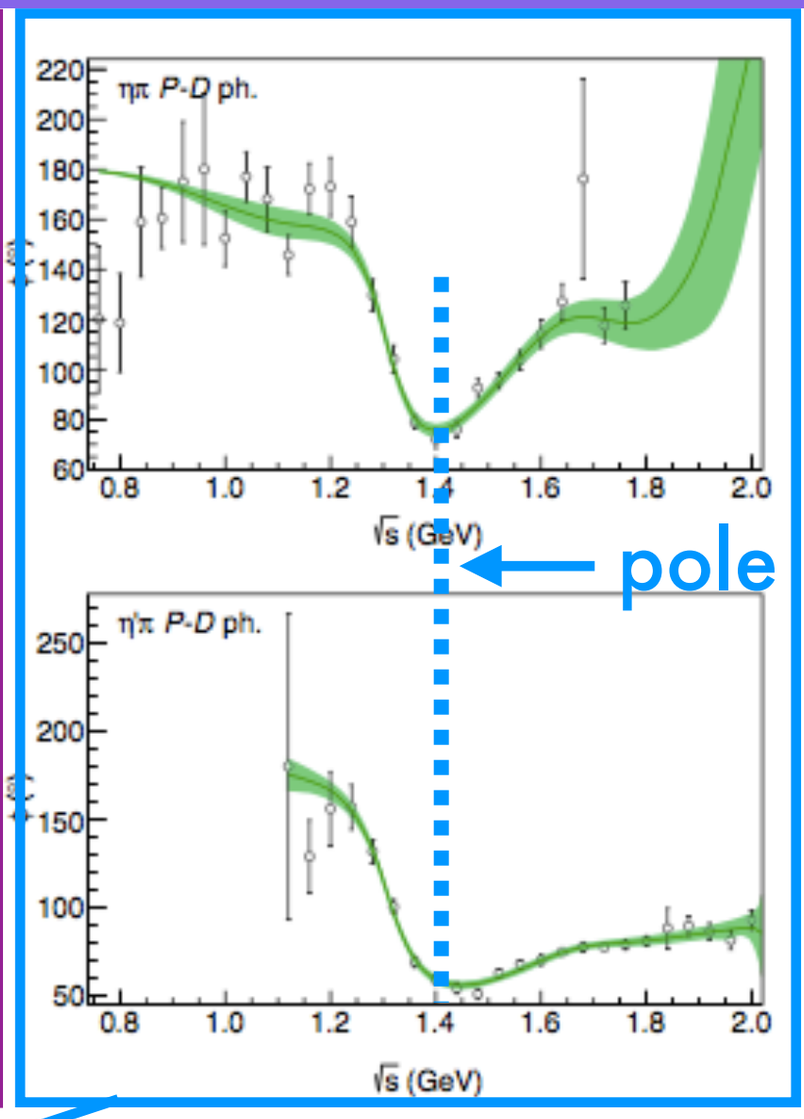

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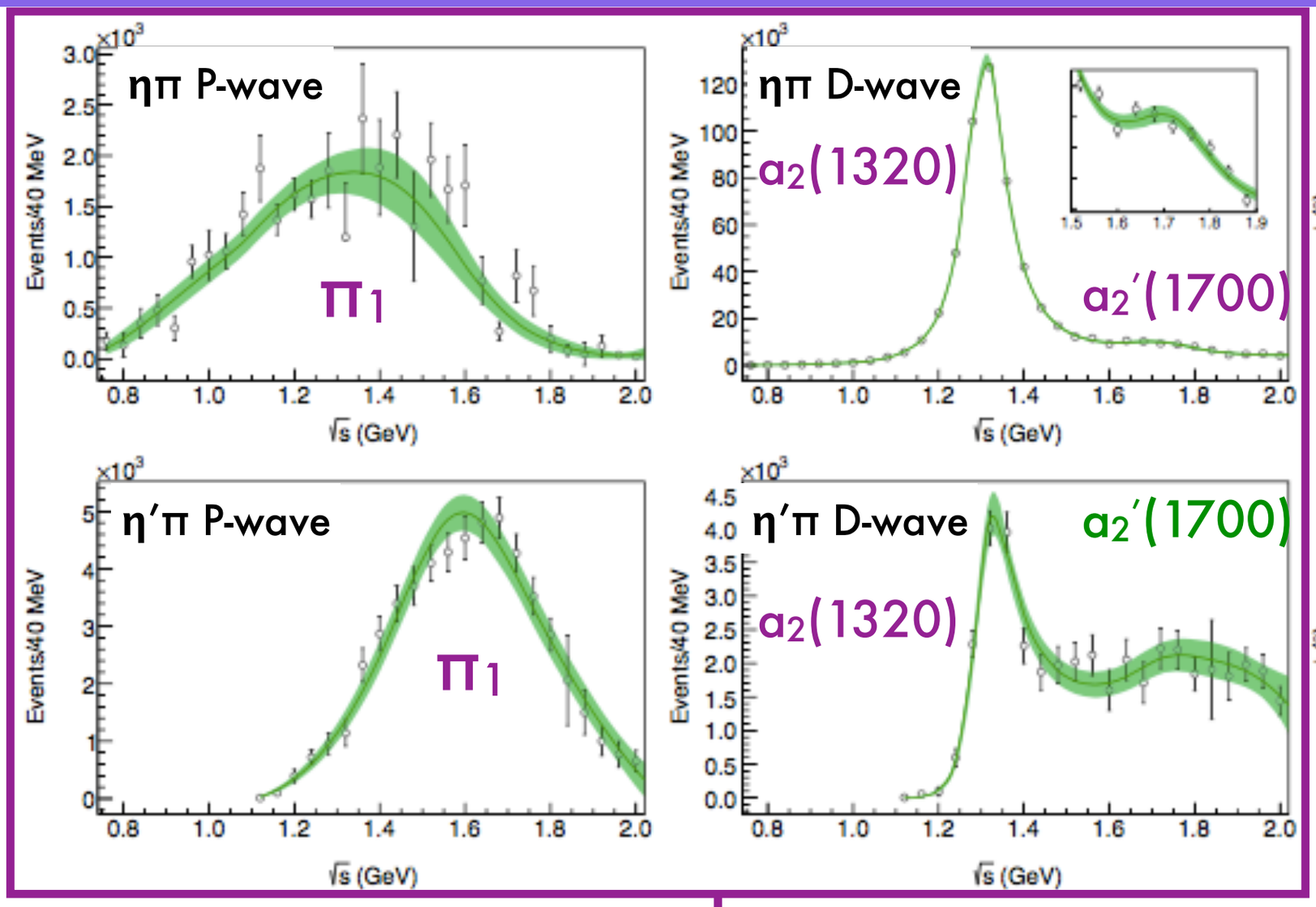

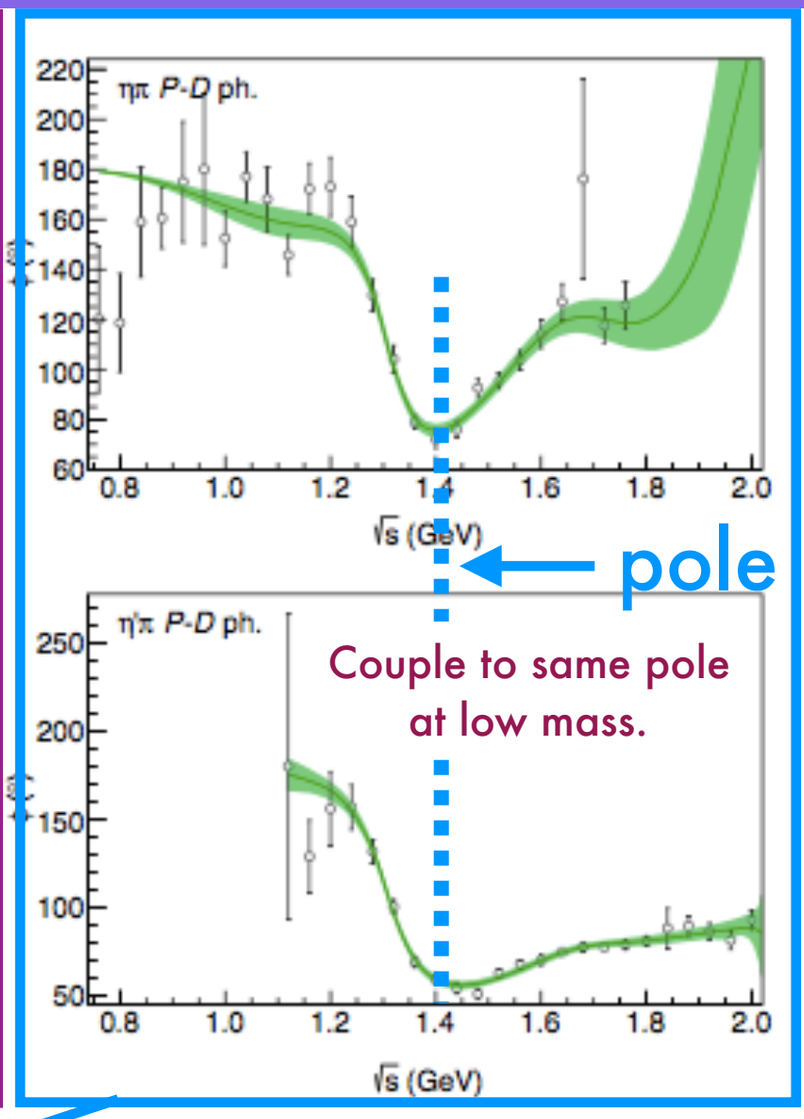

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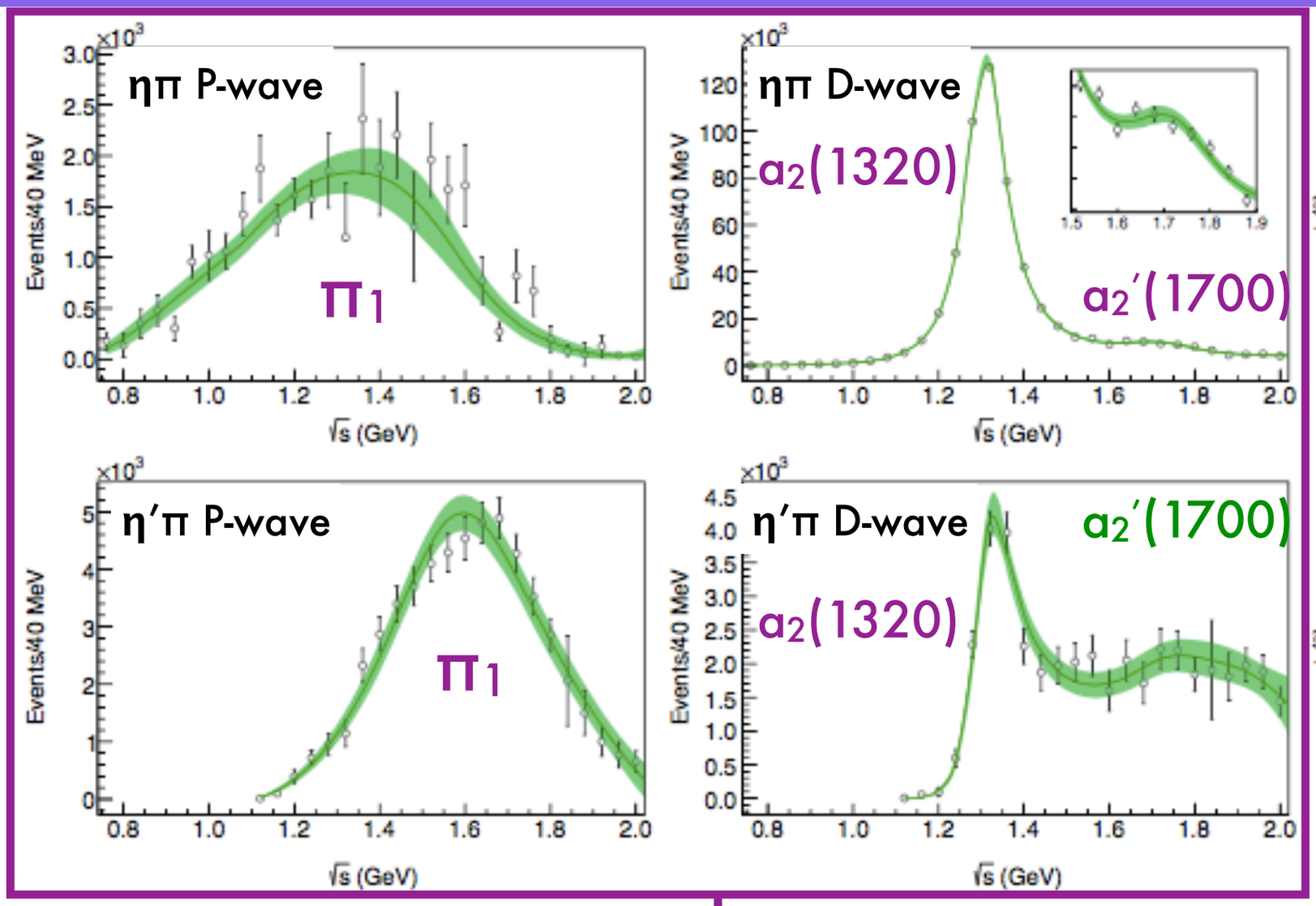
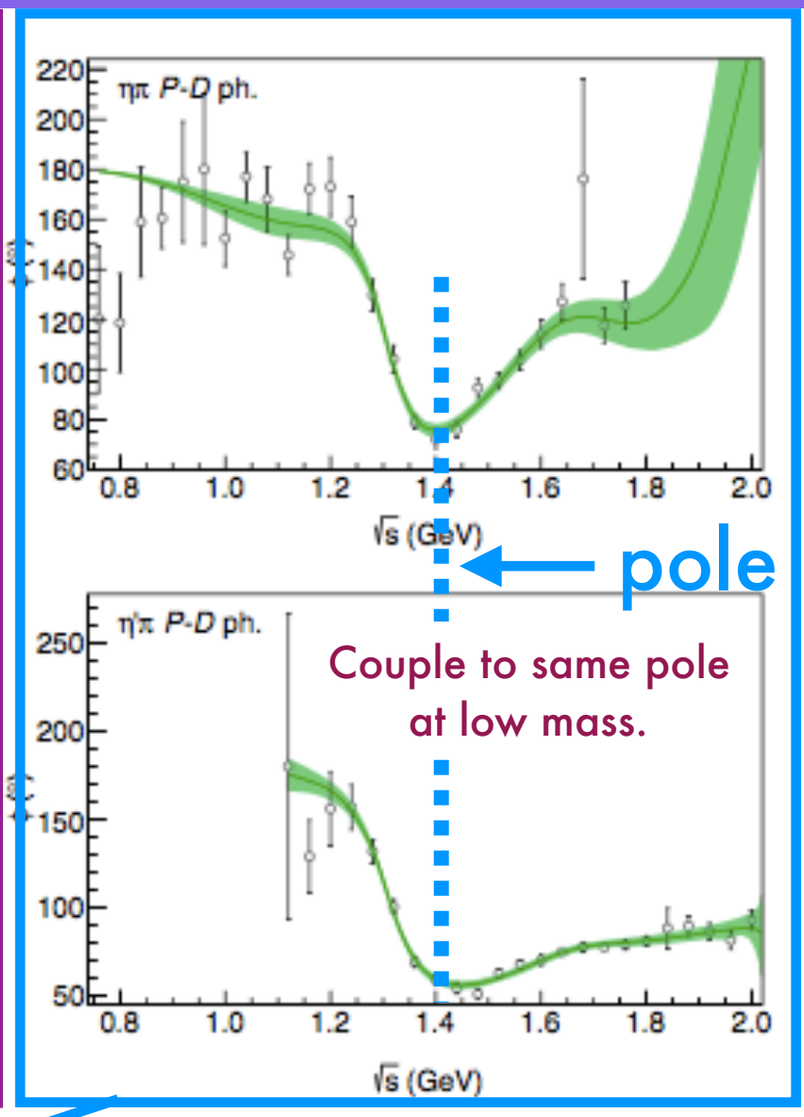
single exotic π1 (1564) resonant pole which couples to both η/η′π channels





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- Combine the QN

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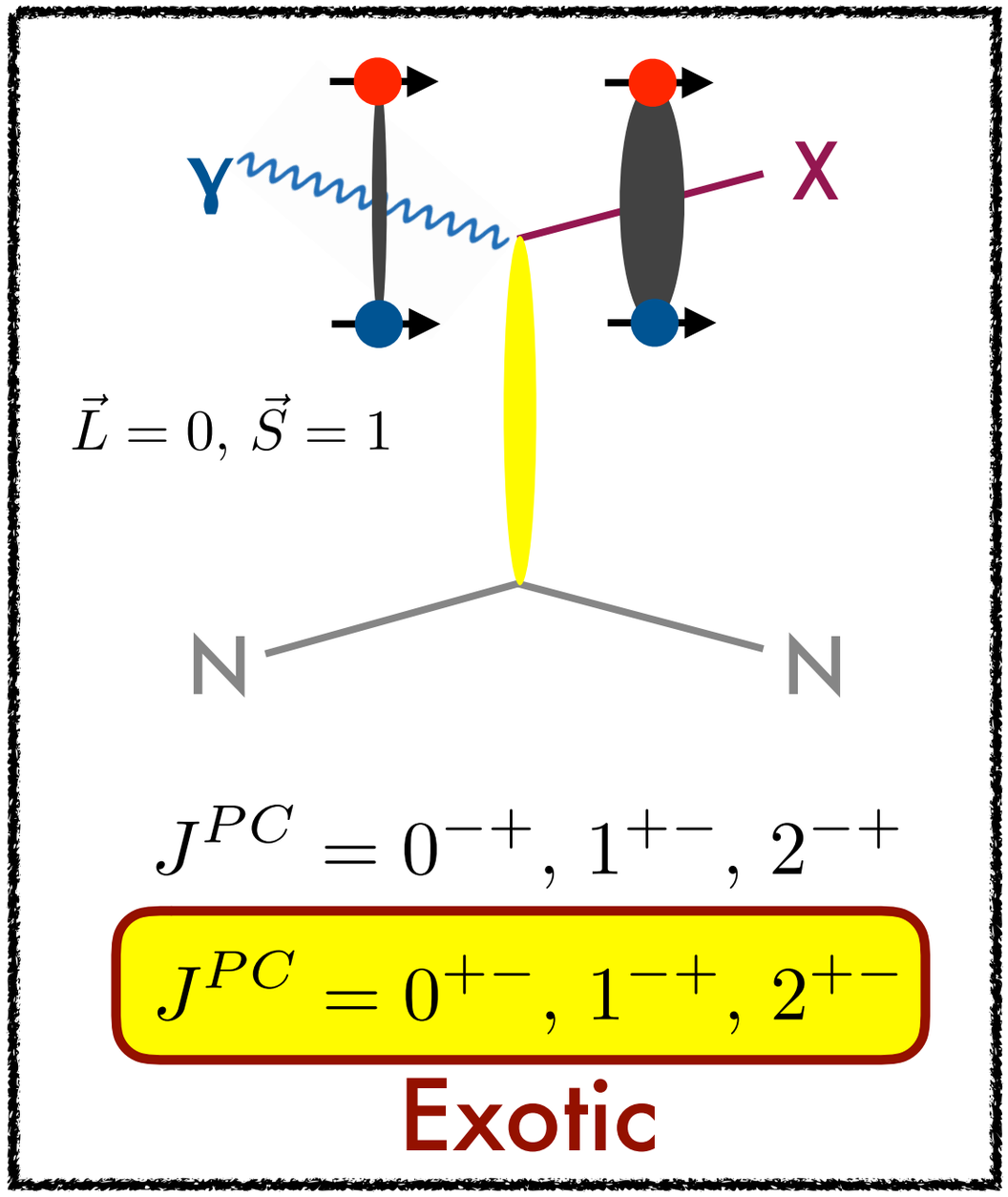

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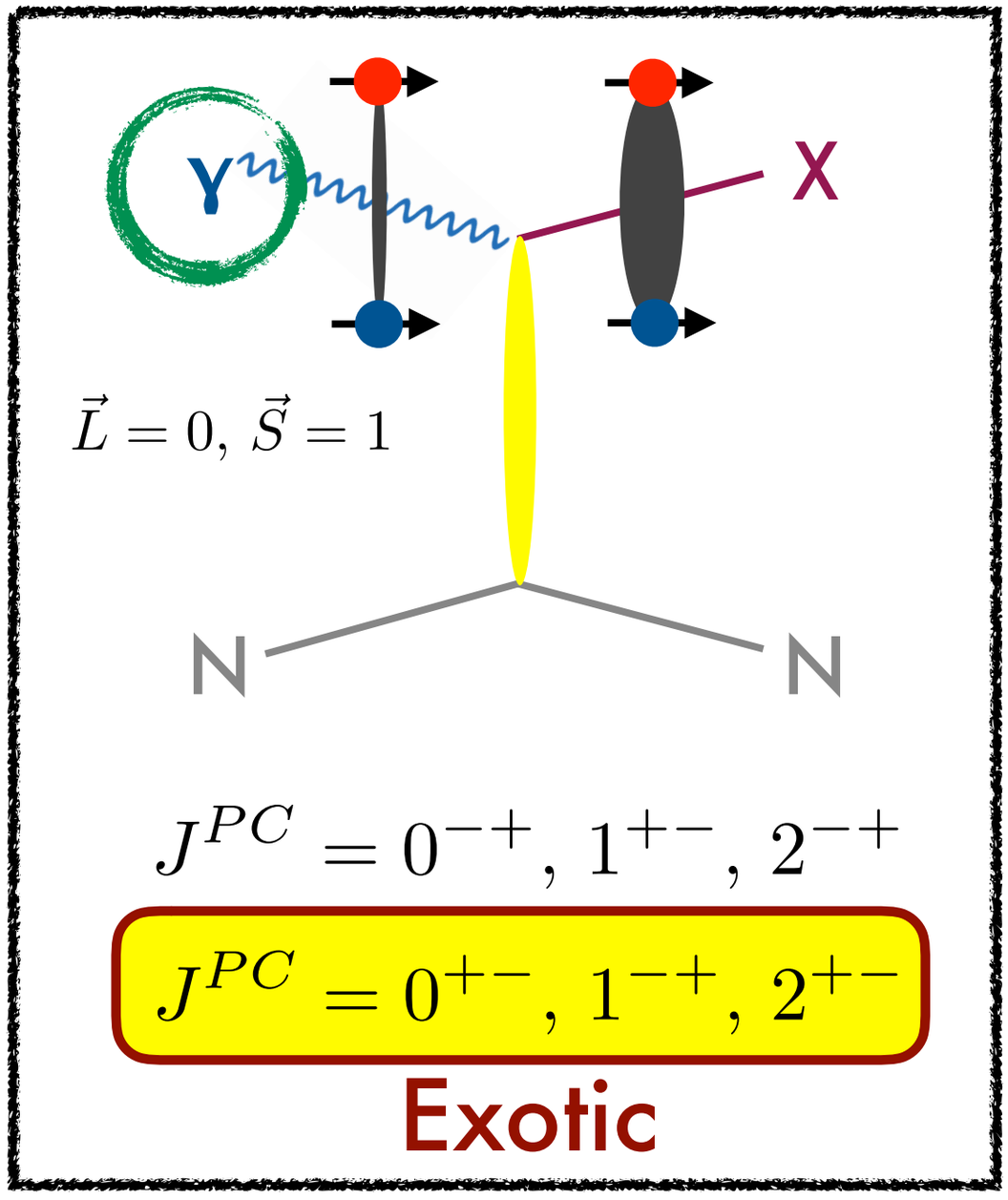


Photoproduction: Exotics

	Approximate Mass (MeV)	J^{PC}
π_1	1900	1^{-+}
η_1	2100	1^{-+}
η_1'	2300	1^{-+}
b_0	2400	0^{+-}
h_0	2400	0^{+-}
h_0'	2500	0^{+-}
b_2	2500	2^{+-}
h_2	2500	2^{+-}
h_2'	2600	2^{+-}

$\rho\pi,\rho\omega \rightarrow \pi_1$

$\omega\omega,\rho\rho \rightarrow \eta_1$

$\omega\omega,\rho\rho,\phi\omega \rightarrow \eta'_1$

$\rho P \rightarrow b_0$

$\omega P \rightarrow h_0$

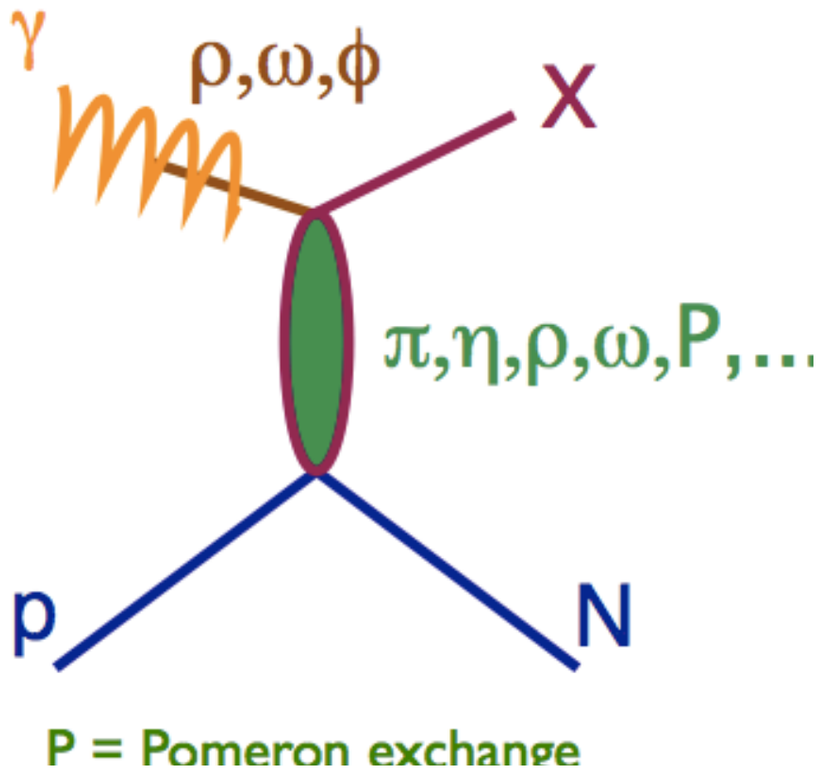
$\omega P, \phi P \rightarrow h'_0$

$\omega\pi,\rho\eta,\rho P \rightarrow b_2$

$\rho\pi,\omega\eta,\omega P \rightarrow h_2$

$\rho\pi,\omega\eta,\phi P \rightarrow h'_2$

Possible quantum numbers from Vector Meson Dominance and t-channel exchange: $(I^G)J^{PC}$

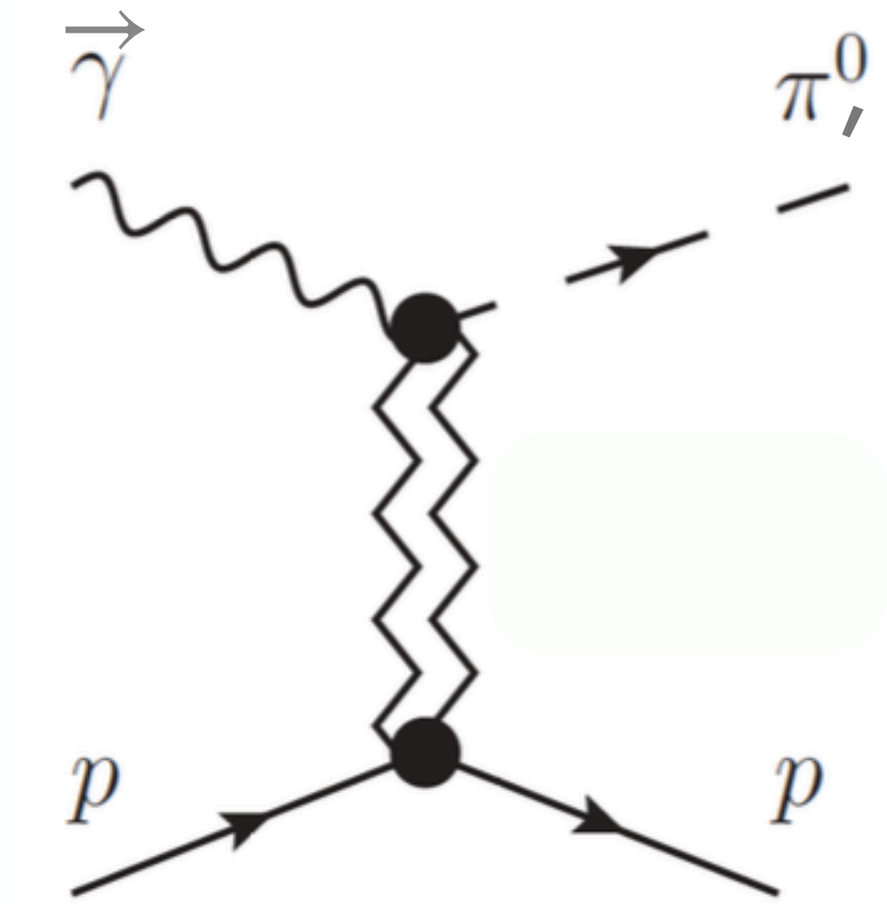


P = Pomeron exchange

- Can couple to all states in the lightest hybrid multiplet through t-channel exchange and photoproduction (via Vector Meson Dominance)

Photoproduction: Non-exotics

linear polarization



Exchange J^{PC}

$$1^{--} : \omega, \rho$$

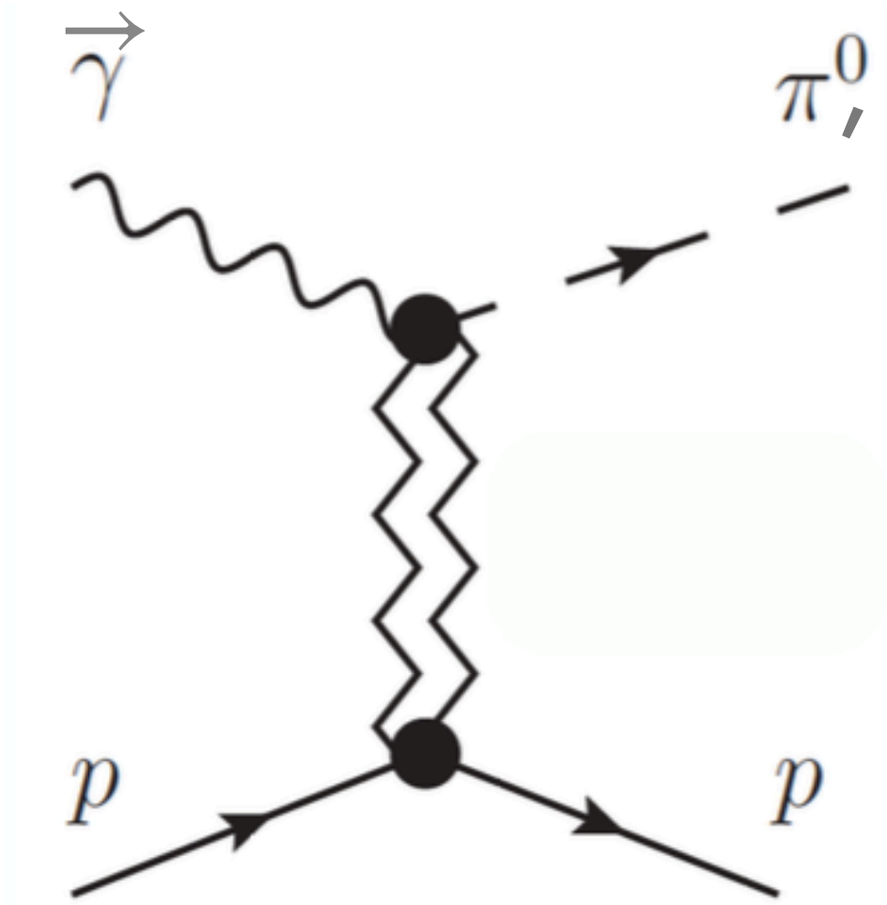
$$1^{+-} : b, h$$

- Photon beam polarization filters the "naturality" of the exchange particle

le

Photoproduction: Non-exotics

linear polarization



π^0, η, η' This talk

Exchange J^{PC}

1^{--} : ω, ρ

1^{+-} : b, h

- Photon beam polarization filters the "naturality" of the exchange particle

le

Worldwide Spectroscopy

Worldwide Spectroscopy

	hadron probes		electromagnetic probes	
colliding beam	CDF, DØ, ATLAS, CMS, LHCb		BESIII, Belle II, BaBar, Belle	
	completed/analysis	ongoing/future	ongoing/future	completed/analysis
fixed target	COMPASS	PANDA	GlueX, CLAS12	CLAS

Worldwide Spectroscopy

colliding beam

hadron probes

completed/analysis

ongoing/future

electromagnetic probes

ongoing/future

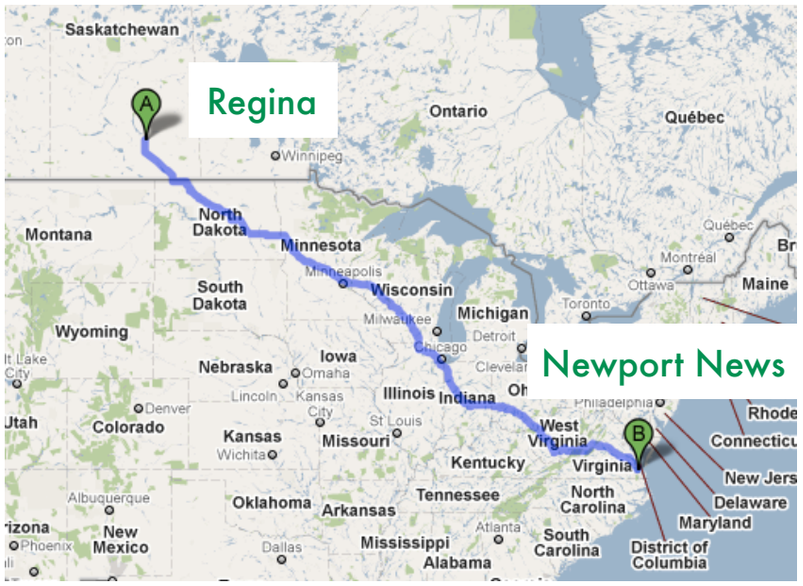
completed/analysis

fixed target

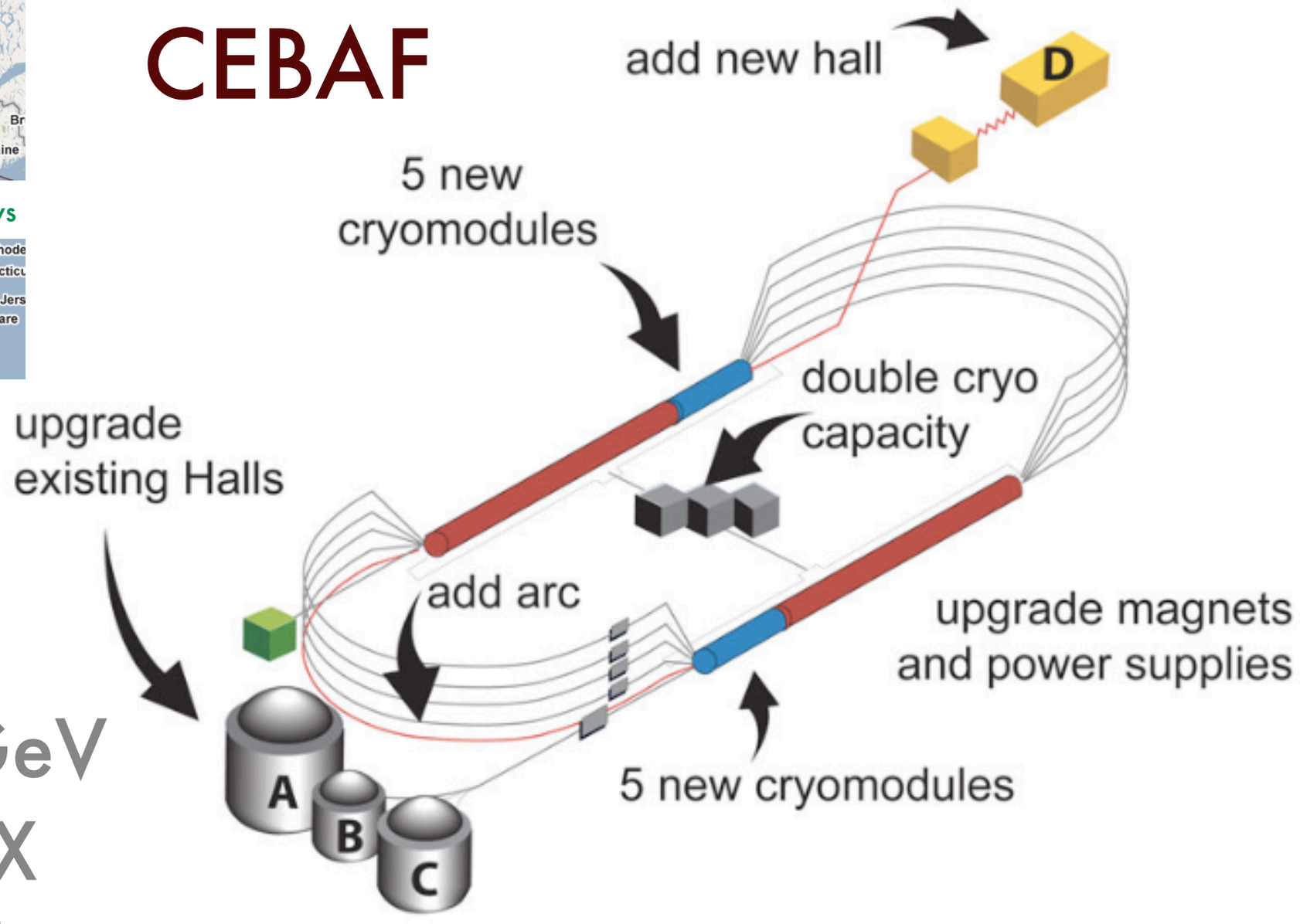
The GlueX Experiment


120 scientists, 27 Institutions
GlueX Collaboration

Jefferson Lab



CEBAF



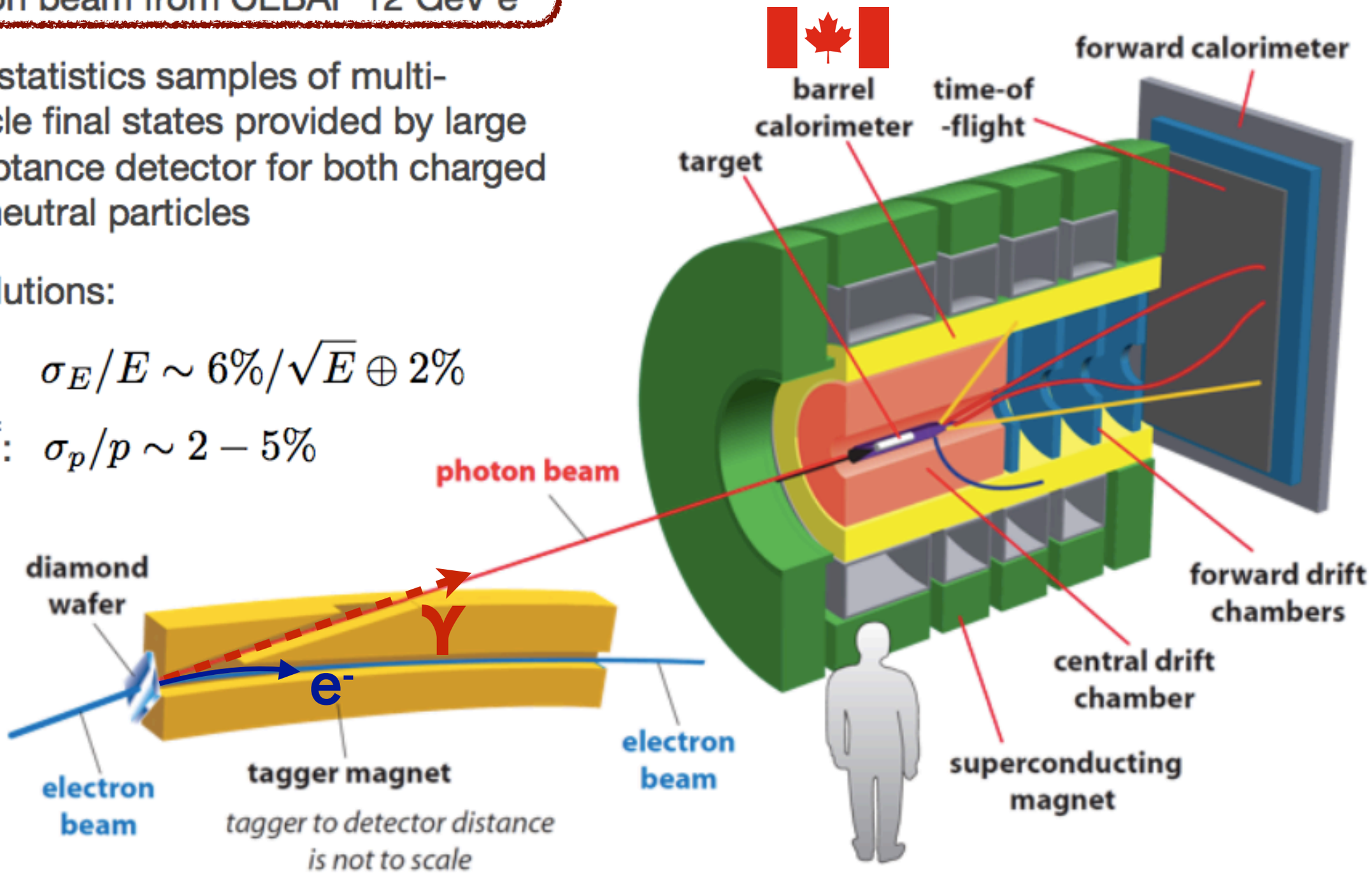
Upgraded: 12 GeV

4th Hall: GlueX

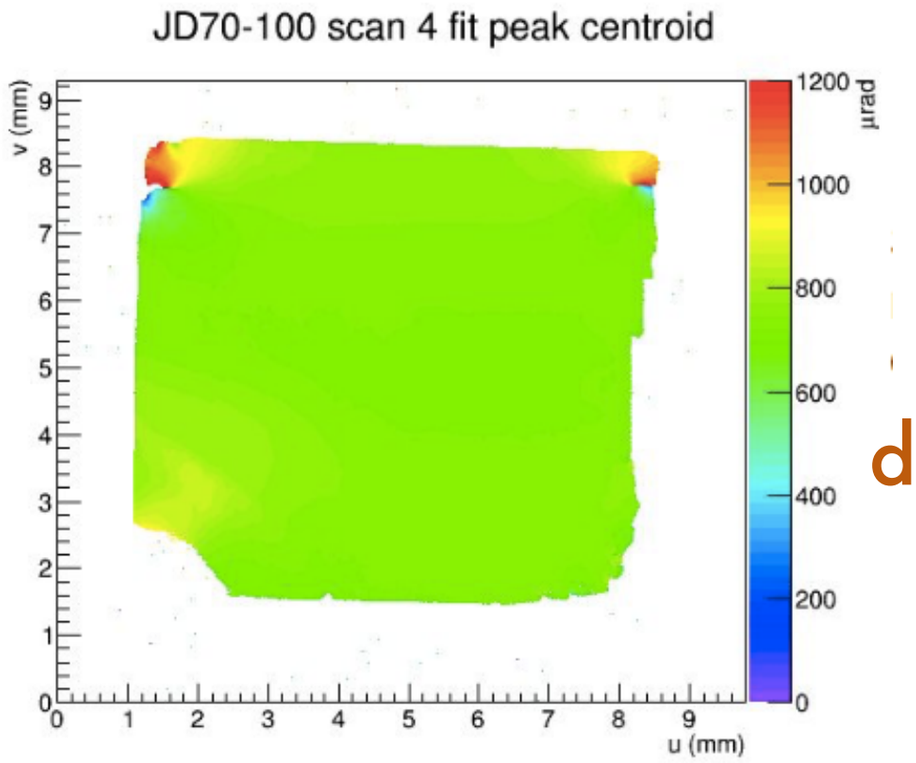
Cost > $310M

The Experiment

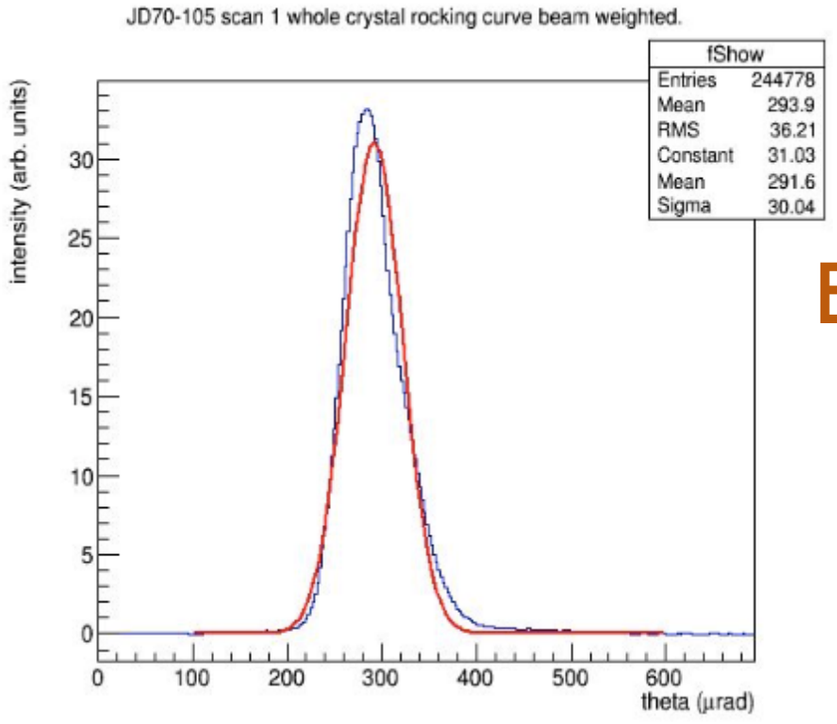
- Linearly polarized bremsstrahlung photon beam from CEBAF 12 GeV e⁻
- High statistics samples of multi-particle final states provided by large acceptance detector for both charged and neutral particles
- Resolutions:
  - γ: $\sigma_E/E \sim 6\%/\sqrt{E} \oplus 2\%$
  - $q^{\pm}$: $\sigma_p/p \sim 2-5\%$



The Diamonds

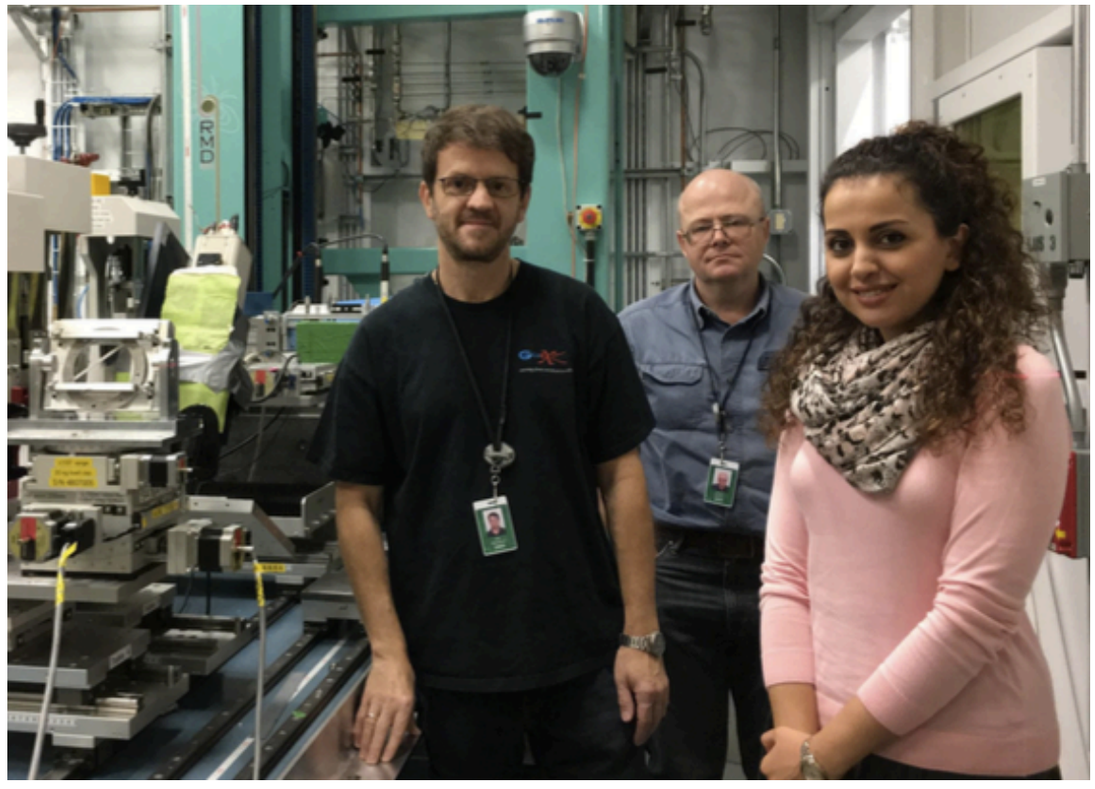


diamond scan

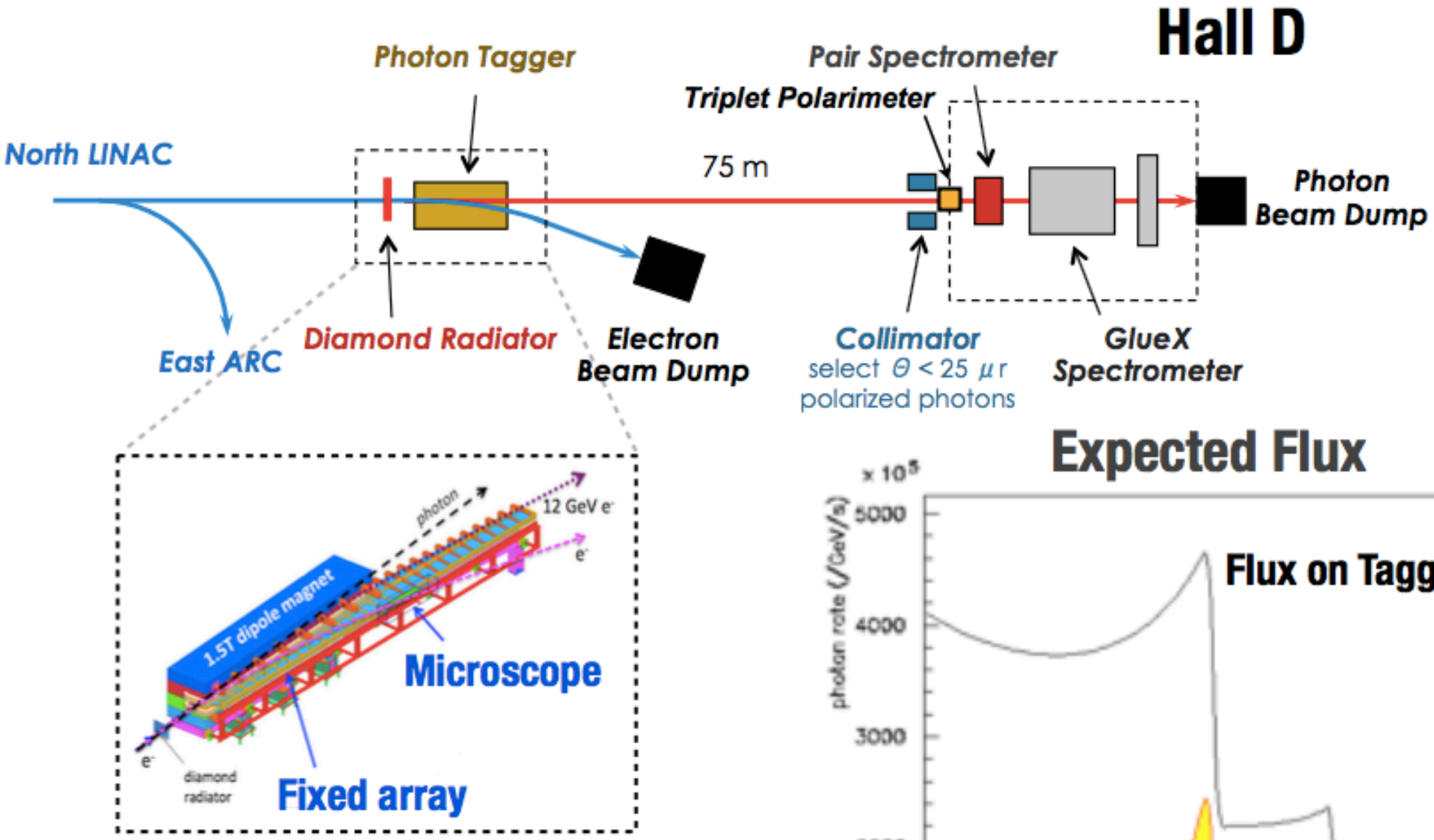


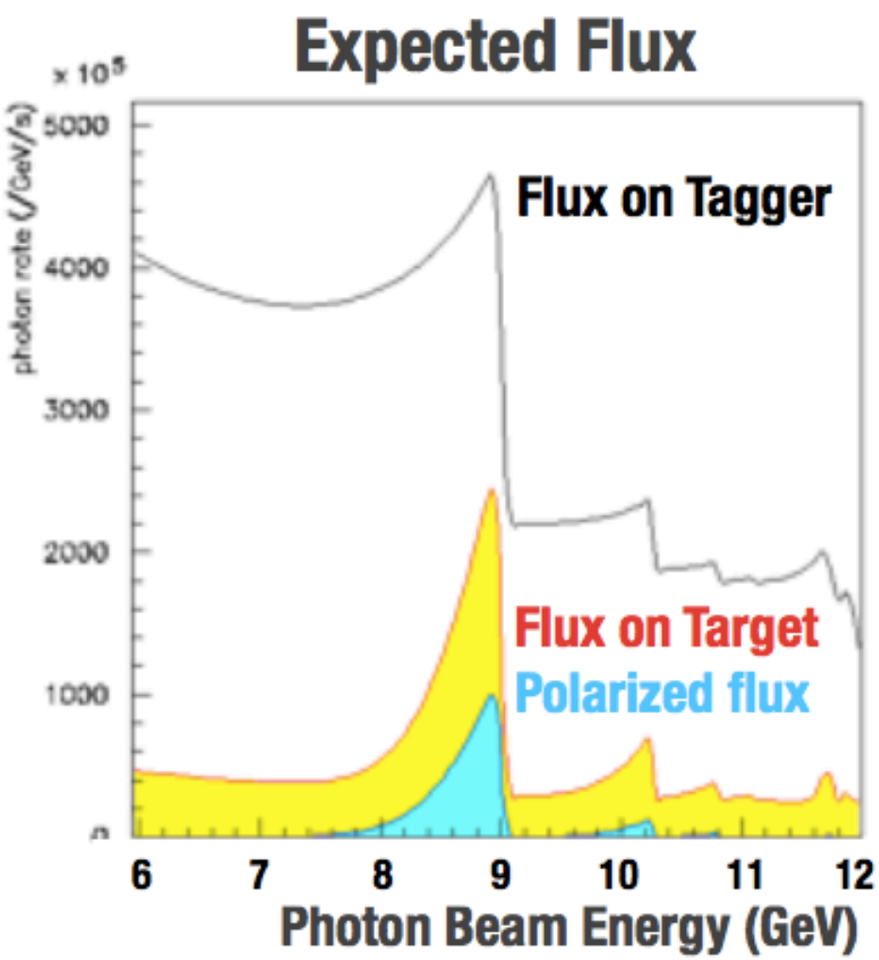
Excellent rocking curve widths

- 50 µm diamond radiators
- Bragg/Laue: "rock that curve"
- At BMIT beam line



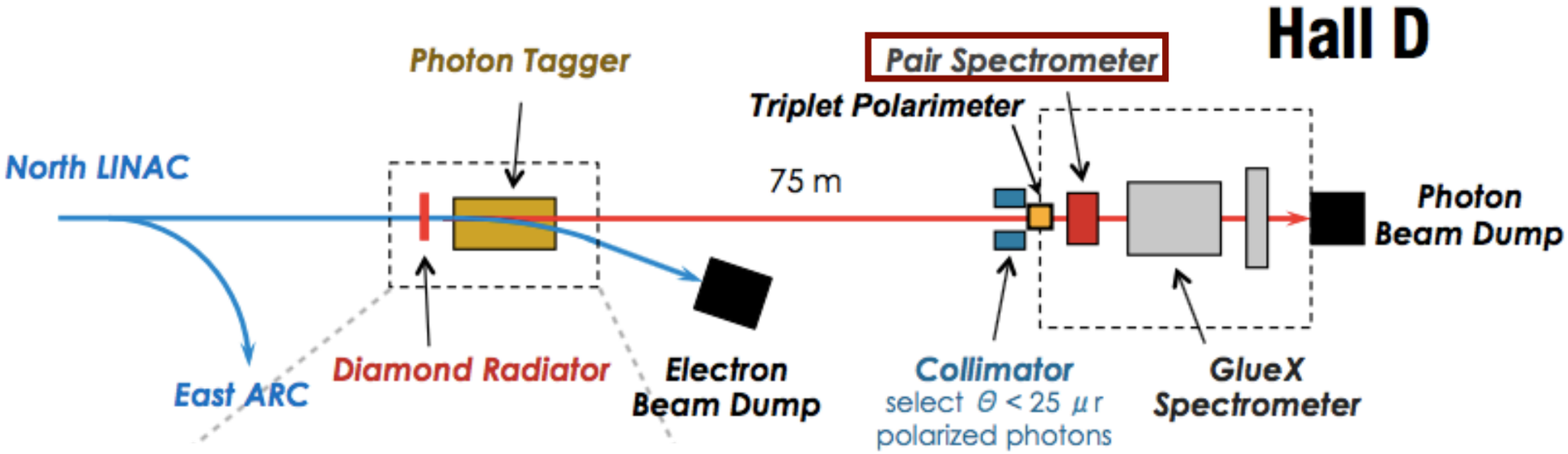
The Beam Line



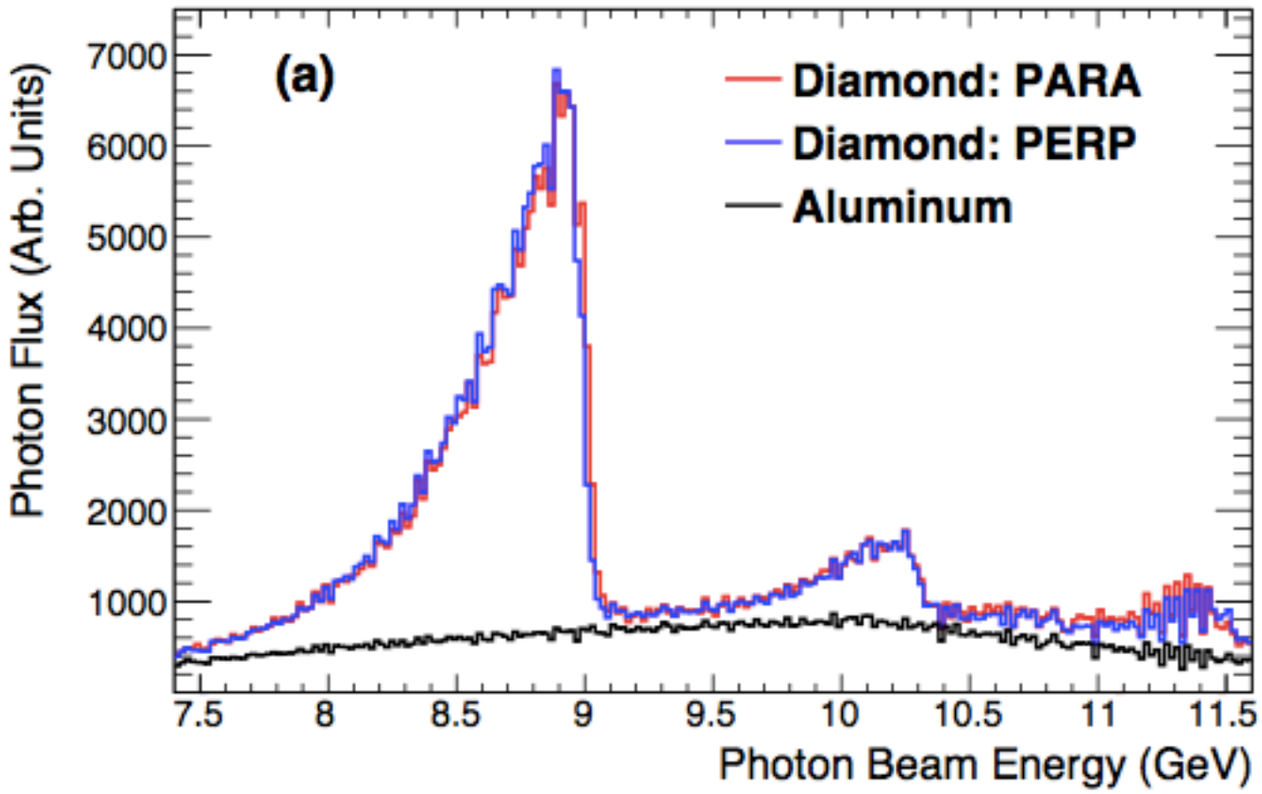


- Linearly polarized photons via coherent bremsstrahlung from diamond radiator
- Design intensity of 10^8 γ/s in coherent peak between E_γ = 8.4 and 9 GeV

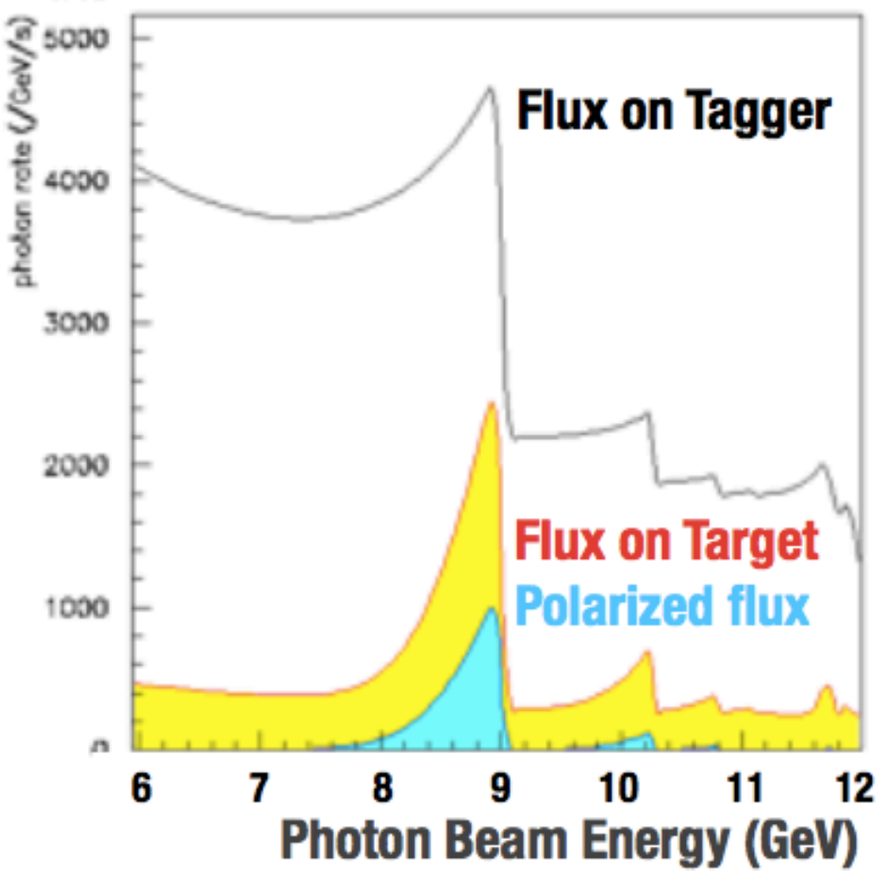
The Beam Line



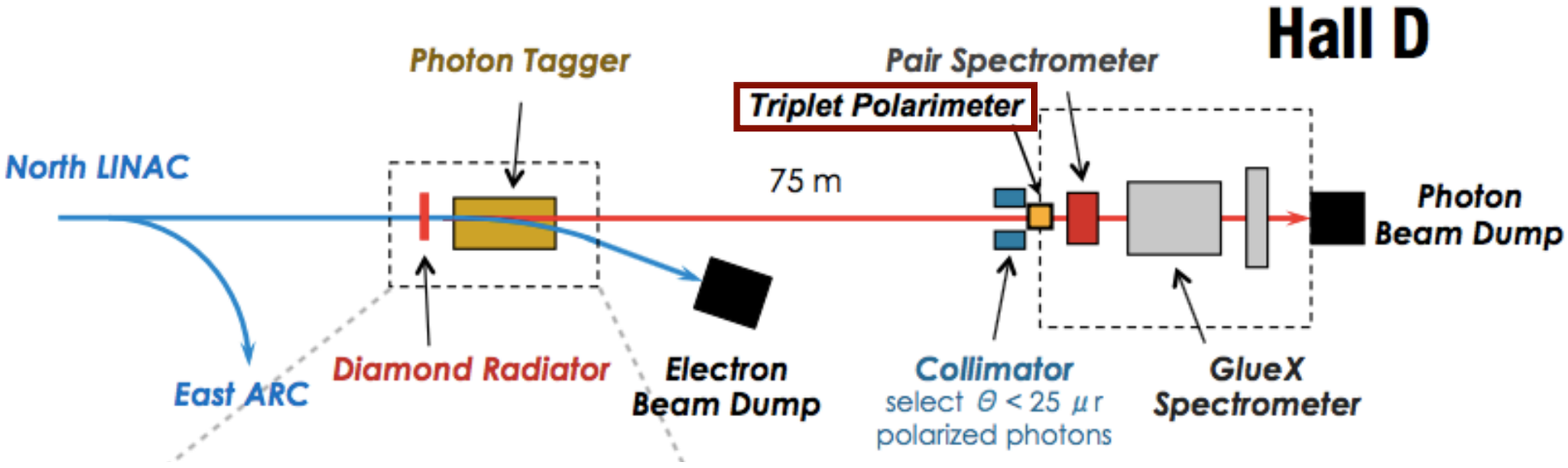
Measured Flux



Expected Flux



The Beam Line



- **Triplet production**

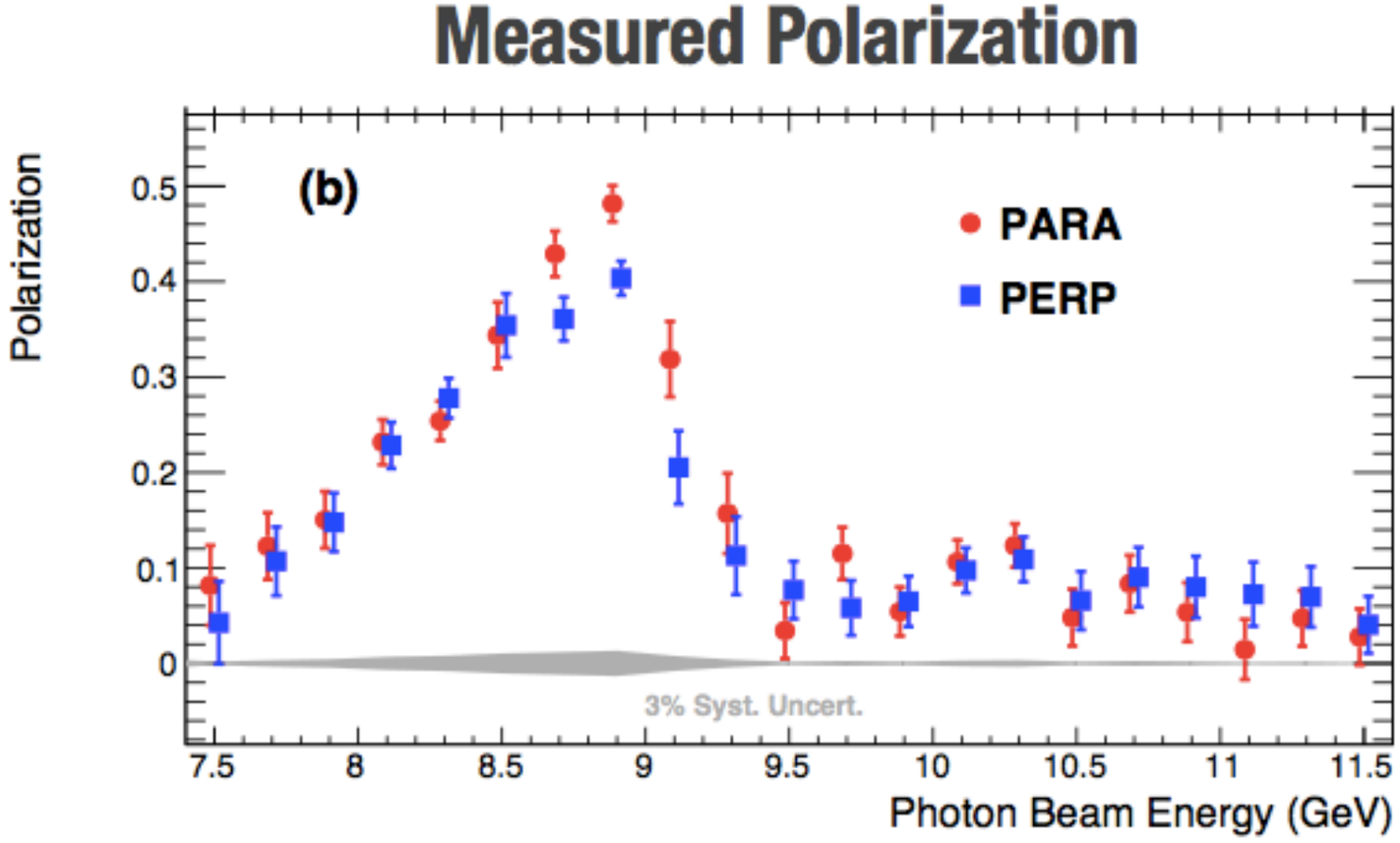
$$\gamma e^- \rightarrow e^- e^+ e^-$$

  - Known analyzing power

$$d\sigma \sim 1 \pm P\Sigma cos(2\phi_{e^-})$$

  - Measure beam polarization independent of spectrometer

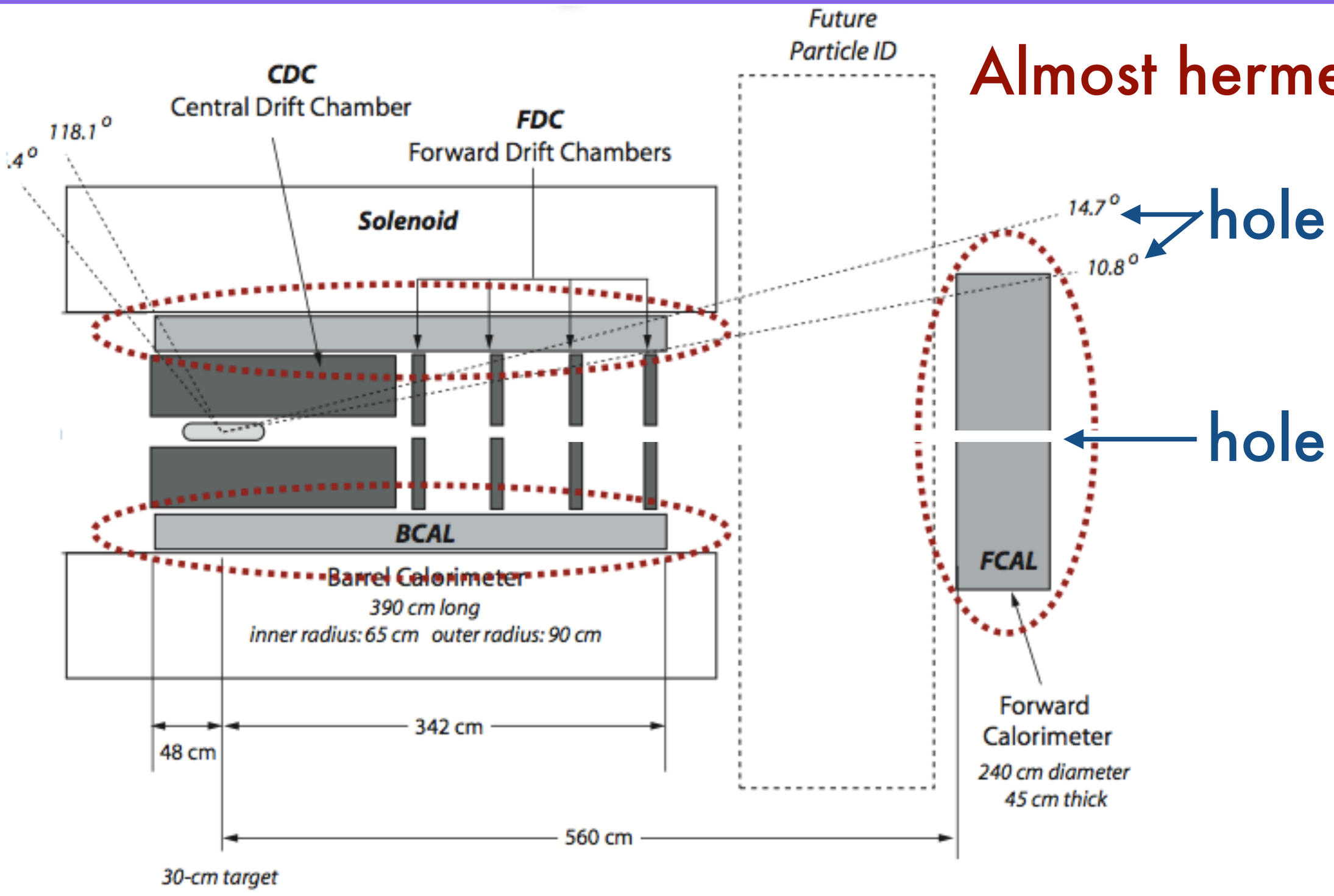
arXiv:1703.07875



The Detector

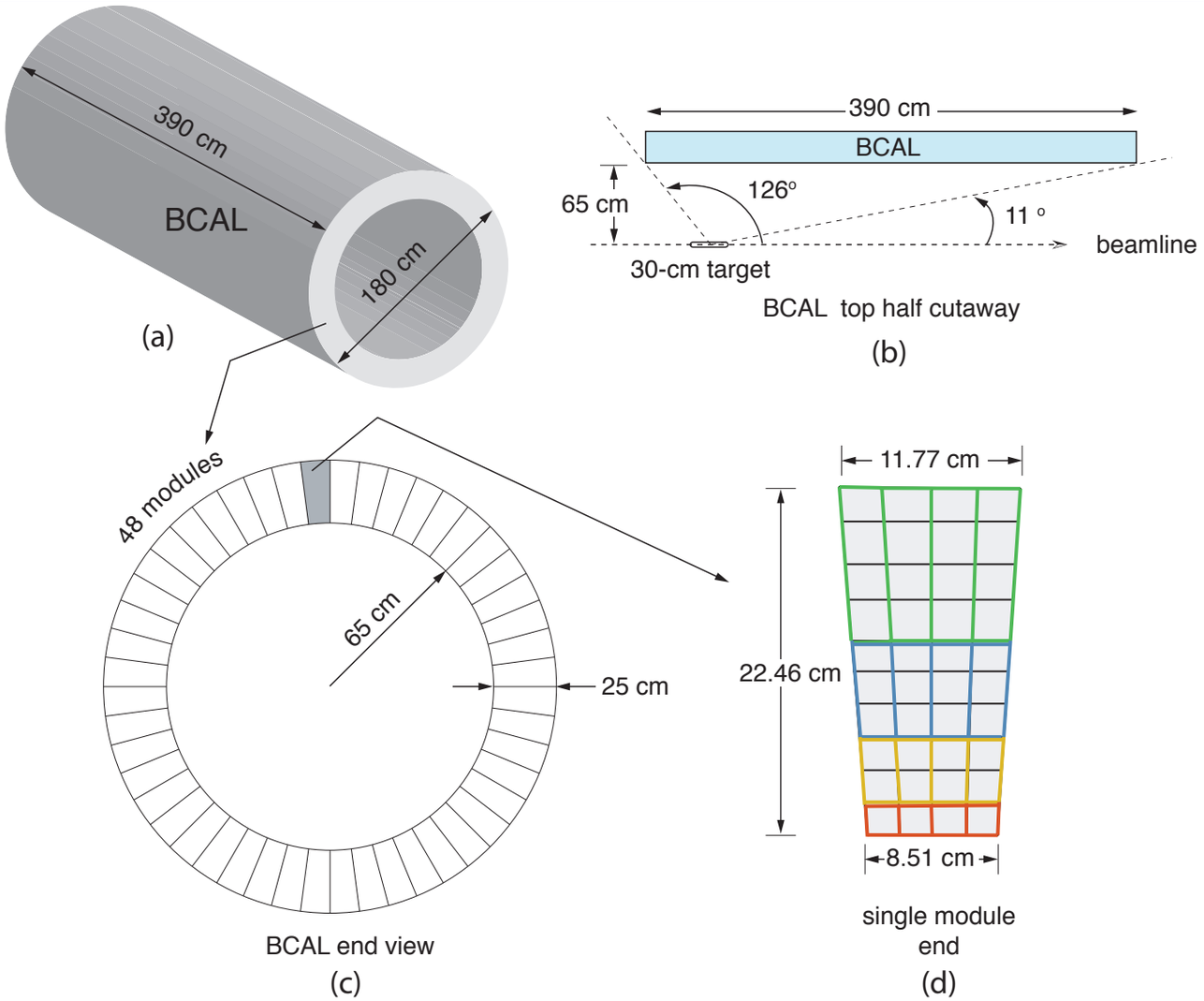
Data:
to date: 3.8 Pb
annually: 8 Pb

The Calorimeters

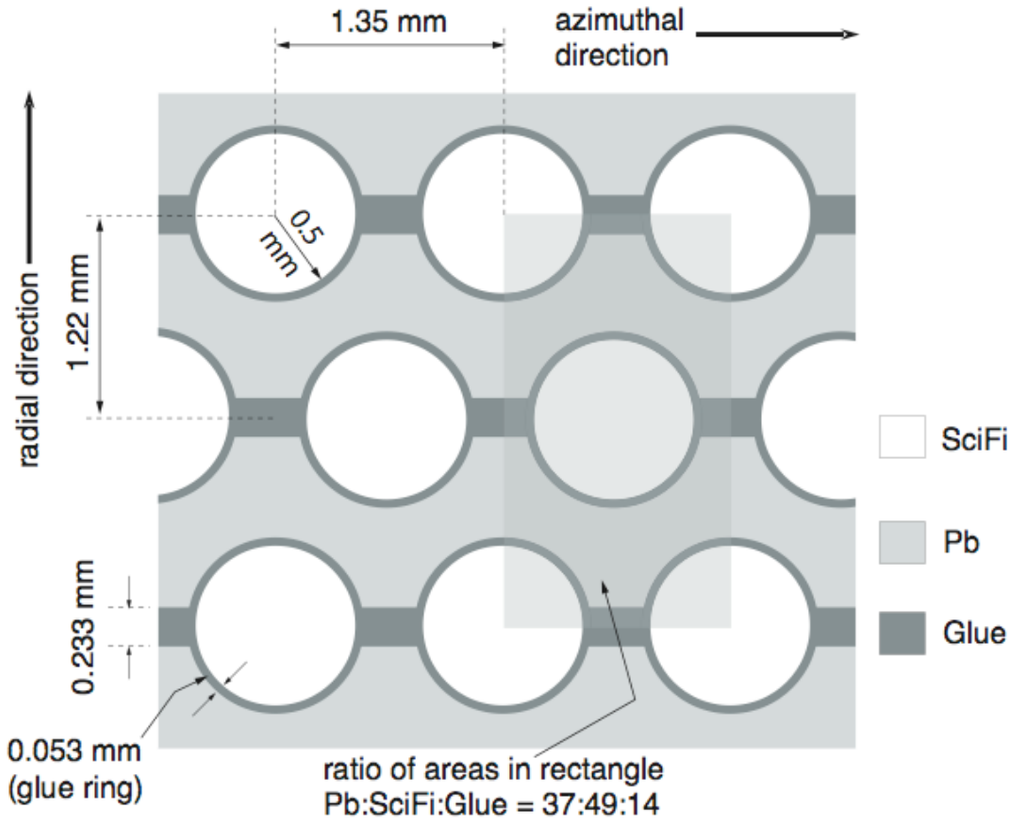


Almost hermetic

The Barrel Calorimeter



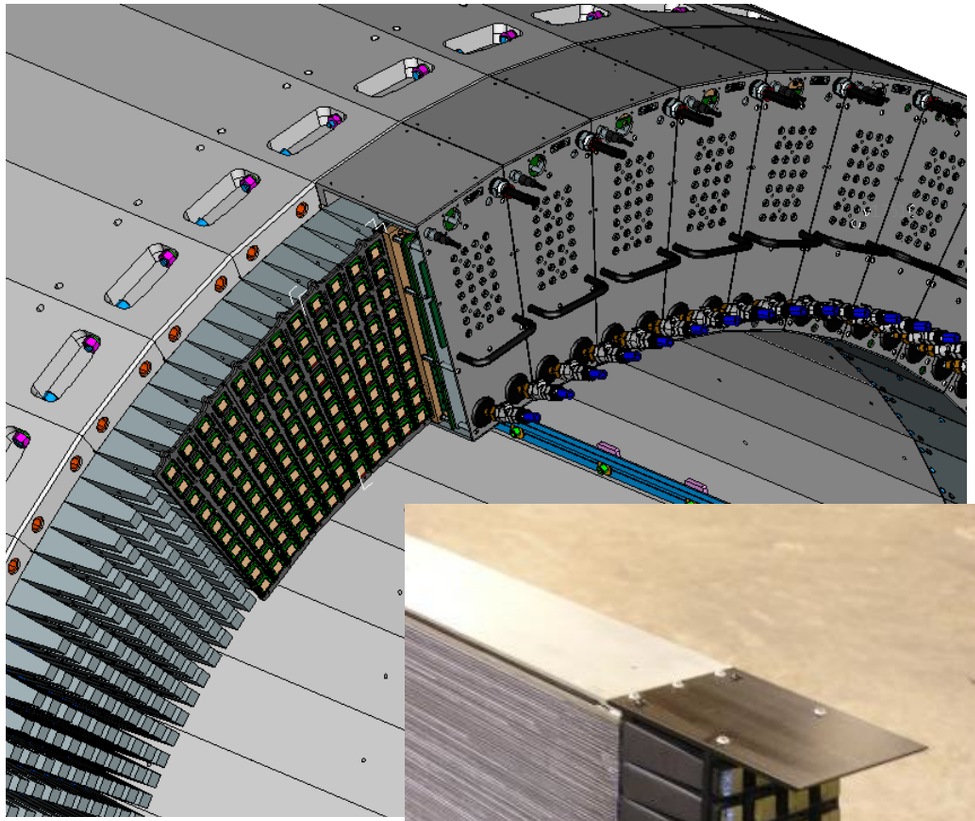
- 48 azimuthal sections (modules)
- Reconstructs γ showers from π^0 and η decays
- Provides timing information (neutrals/charged)
- With the CDC it provides charged particle PID



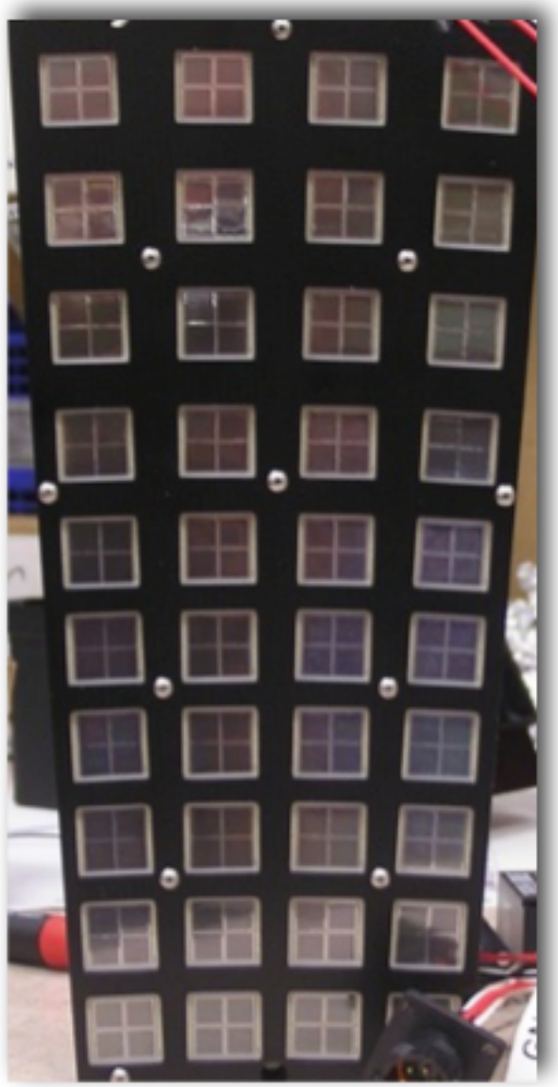
- Sampling calorimeter (9.5% sampling fraction)
- 750,000 double-clad scintillating fibers
- BCAL: 28 tonnes

T.D. Beattie et al.,
NIM A 896 (2018) 24–42

SiPM Readout Assemblies

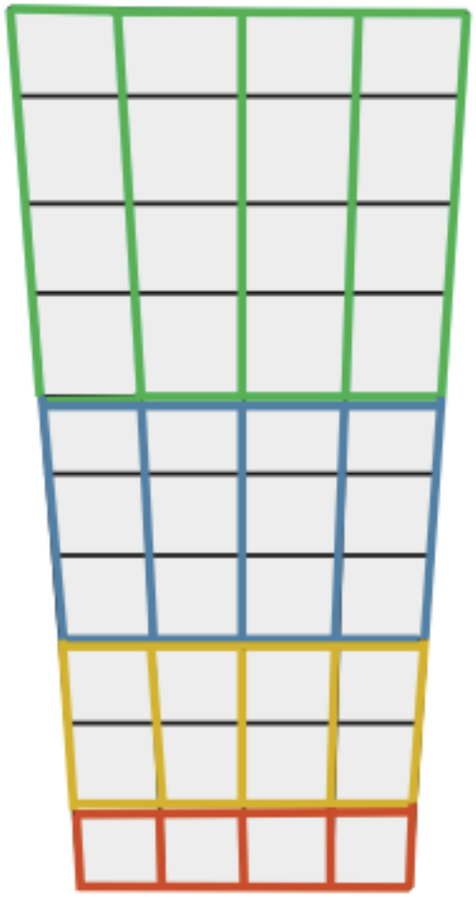


Light guides



Assembly

Electronics



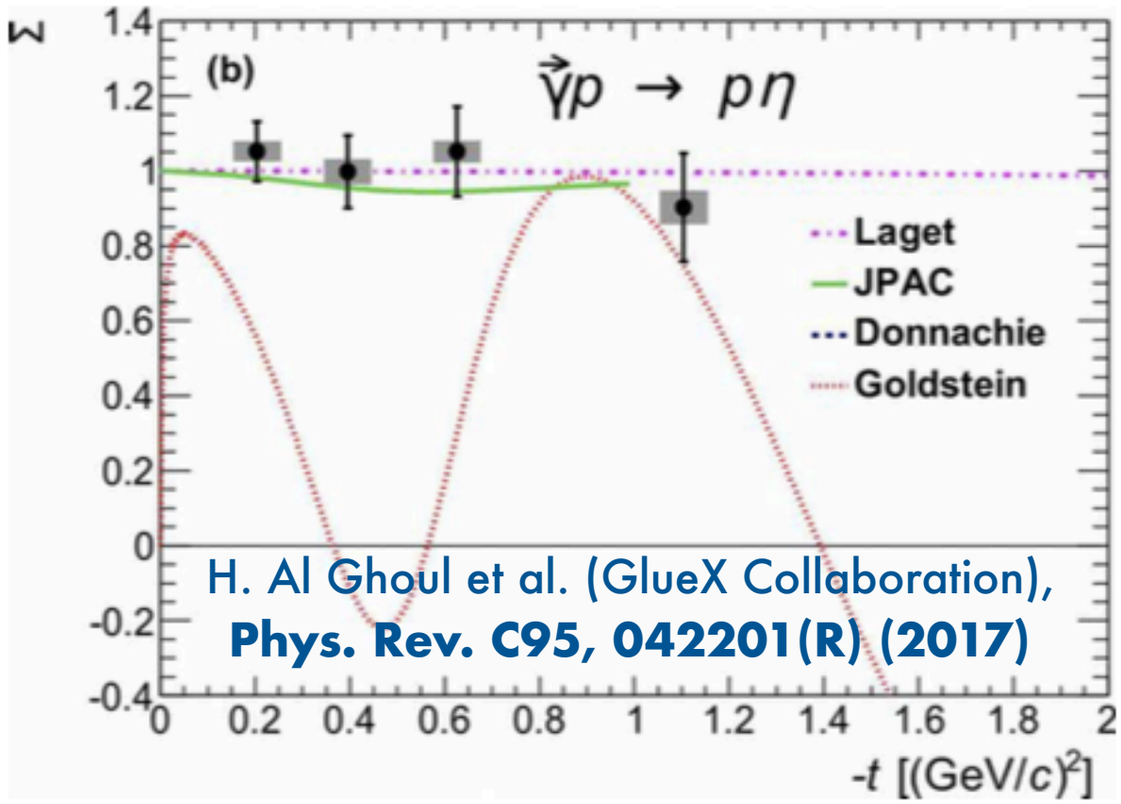
Summing Scheme

Beam Asymmetry

Tegan Beattie (Regina), Will McGinley (CMU)

Motivation: γp→pη

- First steps toward mapping exotics: study observables of likely decay particles
  - $\pi\eta$ and $\pi\eta'$ resonances high on list of possibly-accessible exotics/hybrids
  - Σ for η measured by GlueX at E_γ = 9 GeV
  - Σ for η' not yet measured at E_γ = 9 GeV
  - Σ sensitive to four-momentum transfer squared (Mandelstam t)
    - $t = (P_{target} - P_{recoil})^2$



H. Al Ghoul et al. (GlueX Collaboration), **Phys. Rev. C95, 042201(R) (2017)**

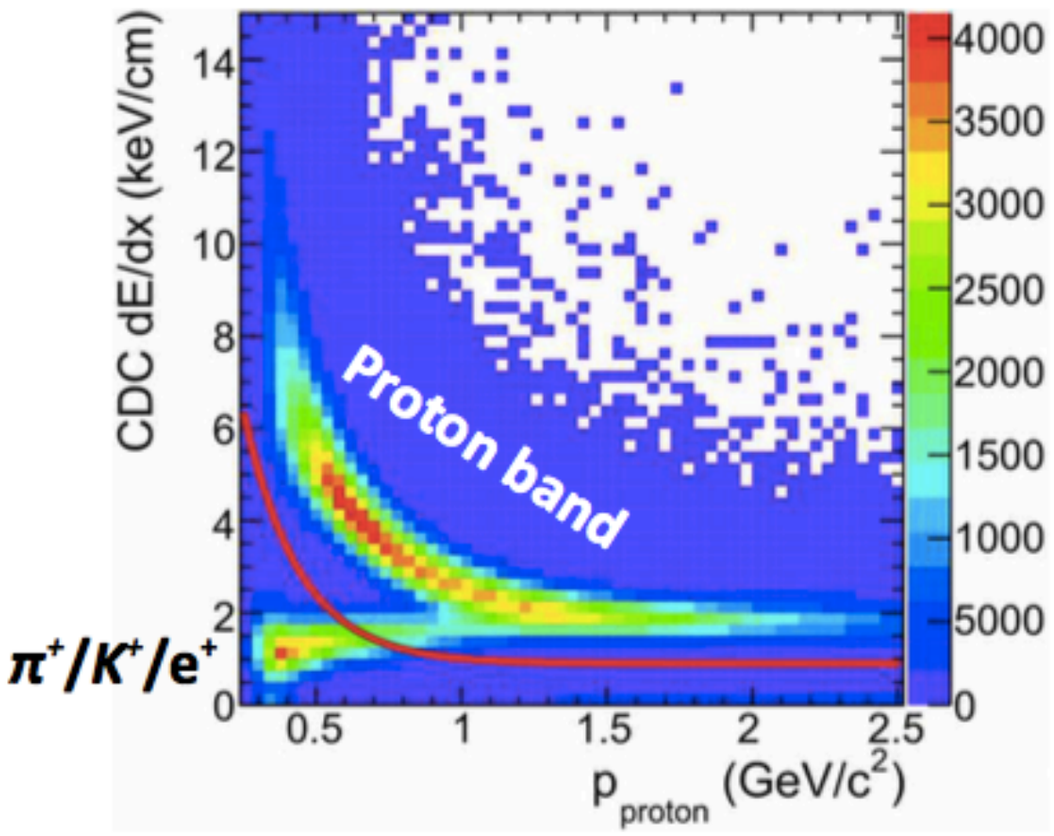
Measure Σ asymmetry of η' and η as functions of t

$\eta \rightarrow \pi^+\pi^-\pi^0$	$\eta \rightarrow 3\pi^0$	$\eta \rightarrow 2\gamma$	$\eta' \rightarrow \pi^+\pi^-\eta$
$\pi^0 \rightarrow 2\gamma$	$\pi^0 \rightarrow 2\gamma$		$\eta \rightarrow 2\gamma$
(BR ≈ 22.9 %)	(BR ≈ 32.7 %)	(BR ≈ 39.4 %)	(BR ≈ 42.9 % * 39.4 %)

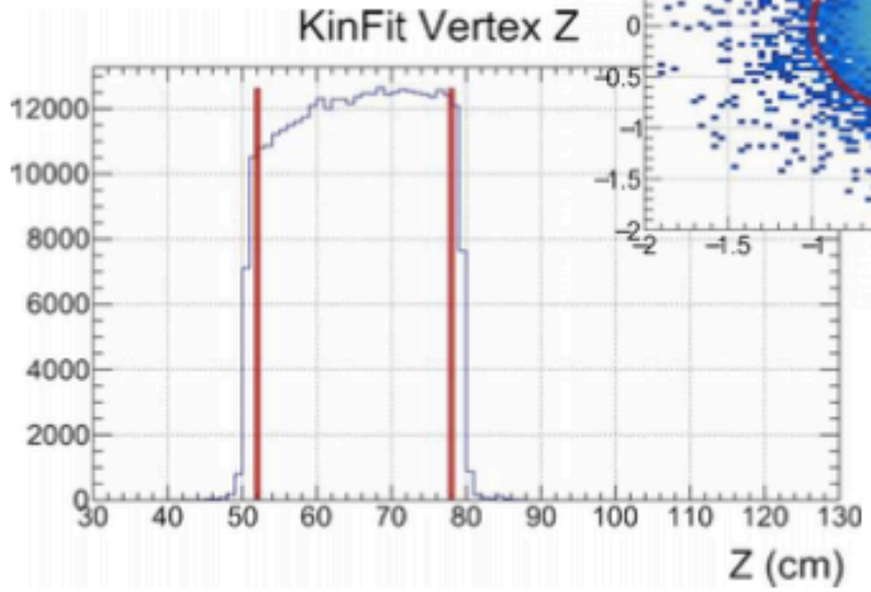
- Re-measuring Σ for η lends confidence to the new η' measurements

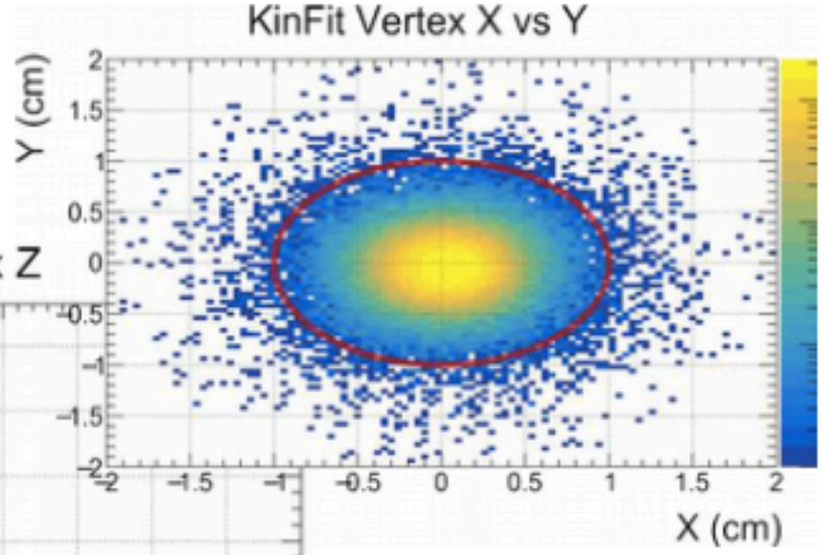
Event Filtering / Accidentals

- Select combinations of particles which match our topology (e.g., $\pi^+\pi^-\eta$)
  - 2 pos. tracks (p, π^+), 1 neg. track (π^-), 2 neutral showers ($\eta \rightarrow 2\gamma$)
- Loose dE/dx cut for Proton/Pion separation
- Missing mass cut to select exclusive η or η' production
  - Ensure invariant mass of beam + target ≈ invariant mass of candidate particle
- Kinematic fit constrains 2γ mass and tests for conservation of E and P
  - 'Pulls' particle positions and momenta to fit hypothesis
  - Outputs 'Confidence Level' (CL), a measure of goodness-of-fit
- Vertex cuts remove candidates with decay vertices outside target volume



Cuts shown in RED





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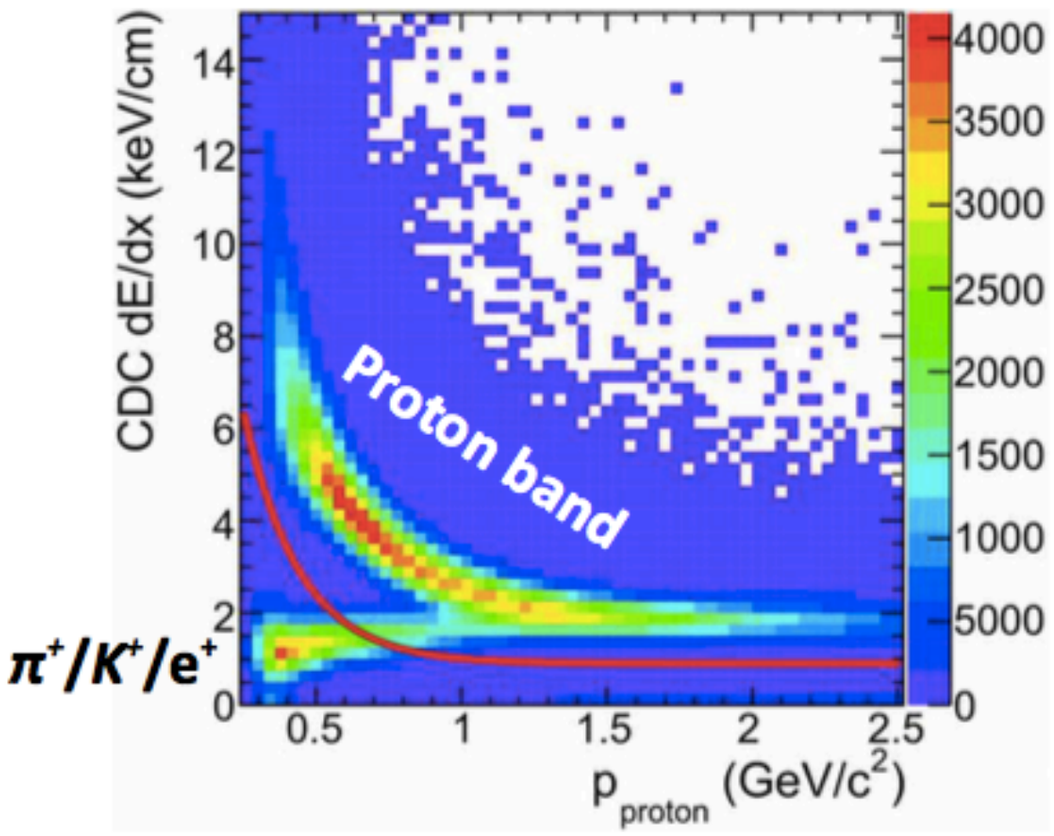
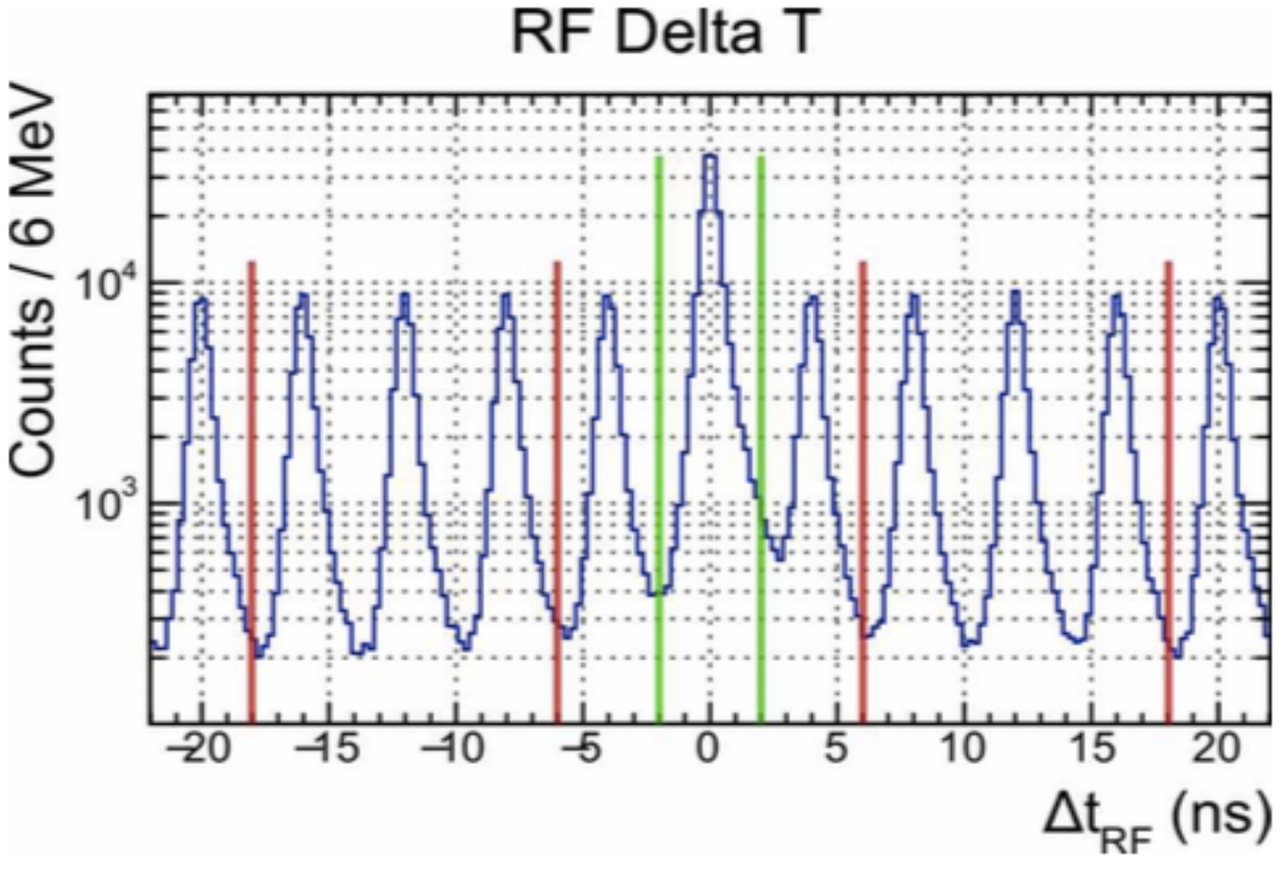
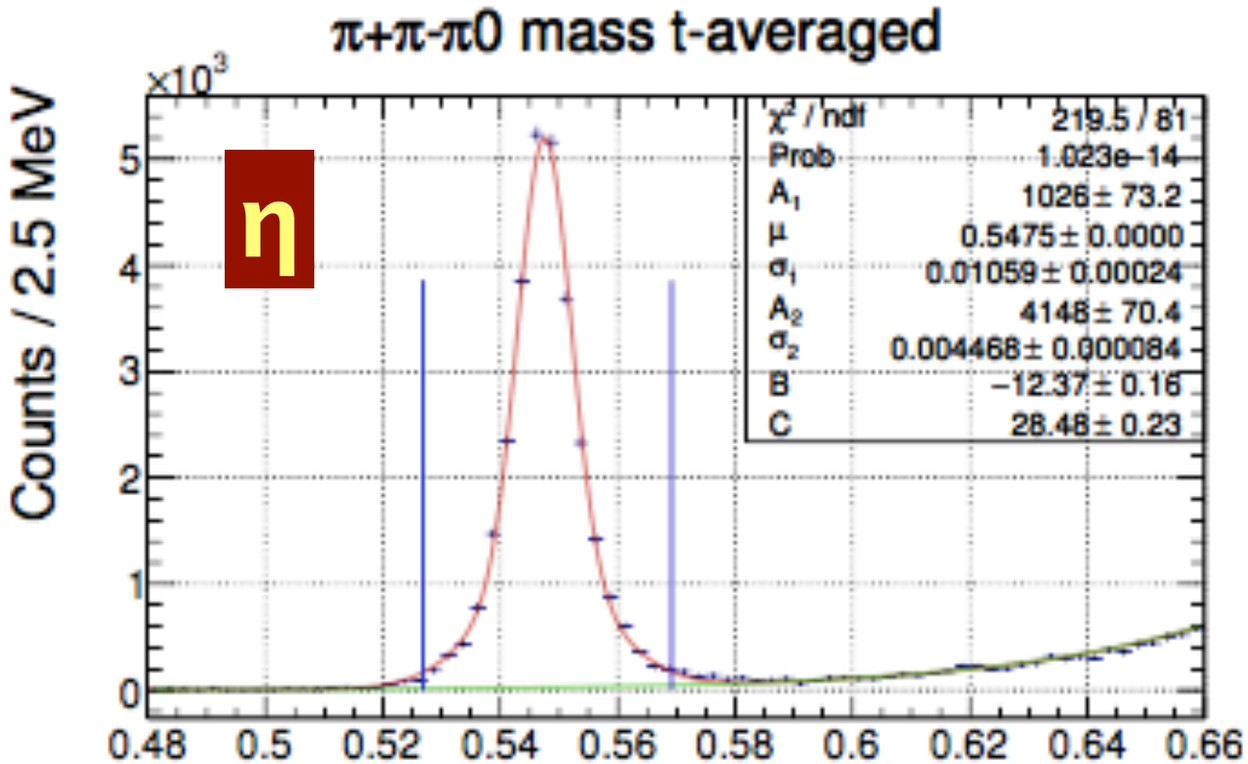
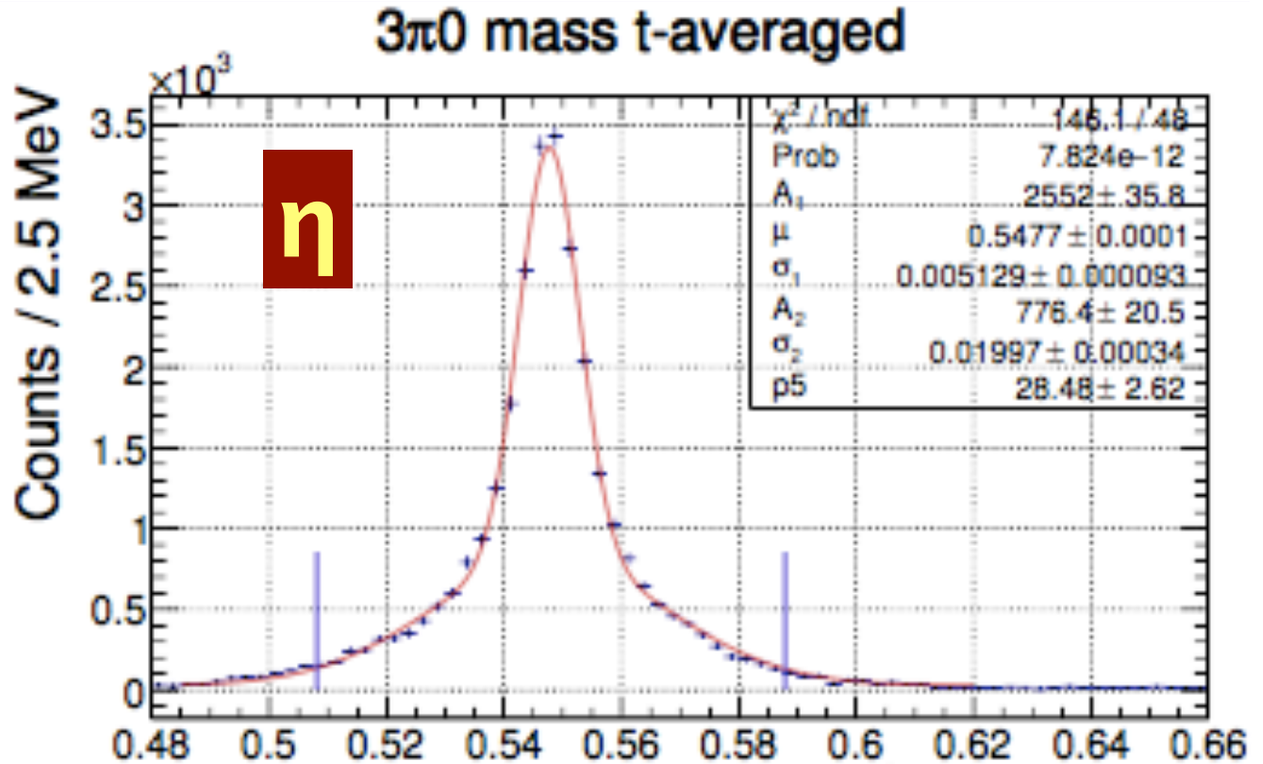
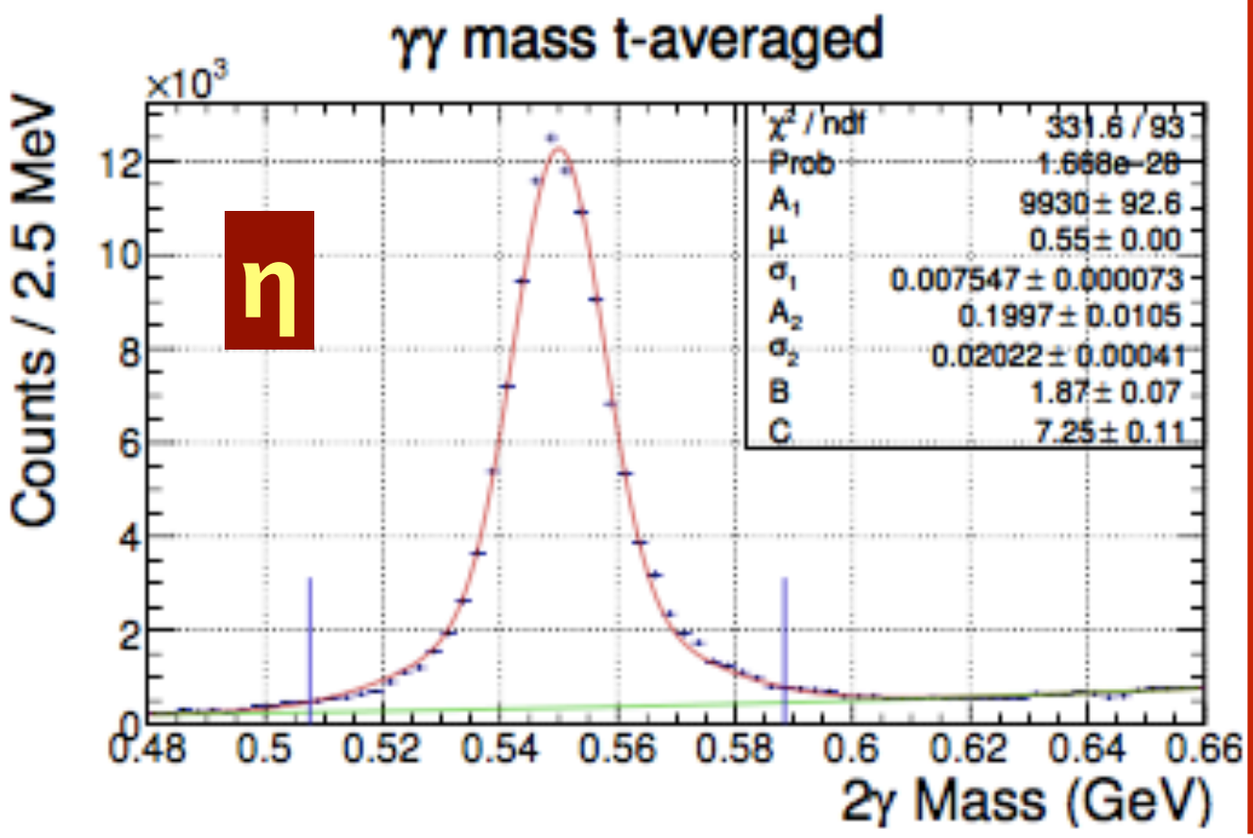


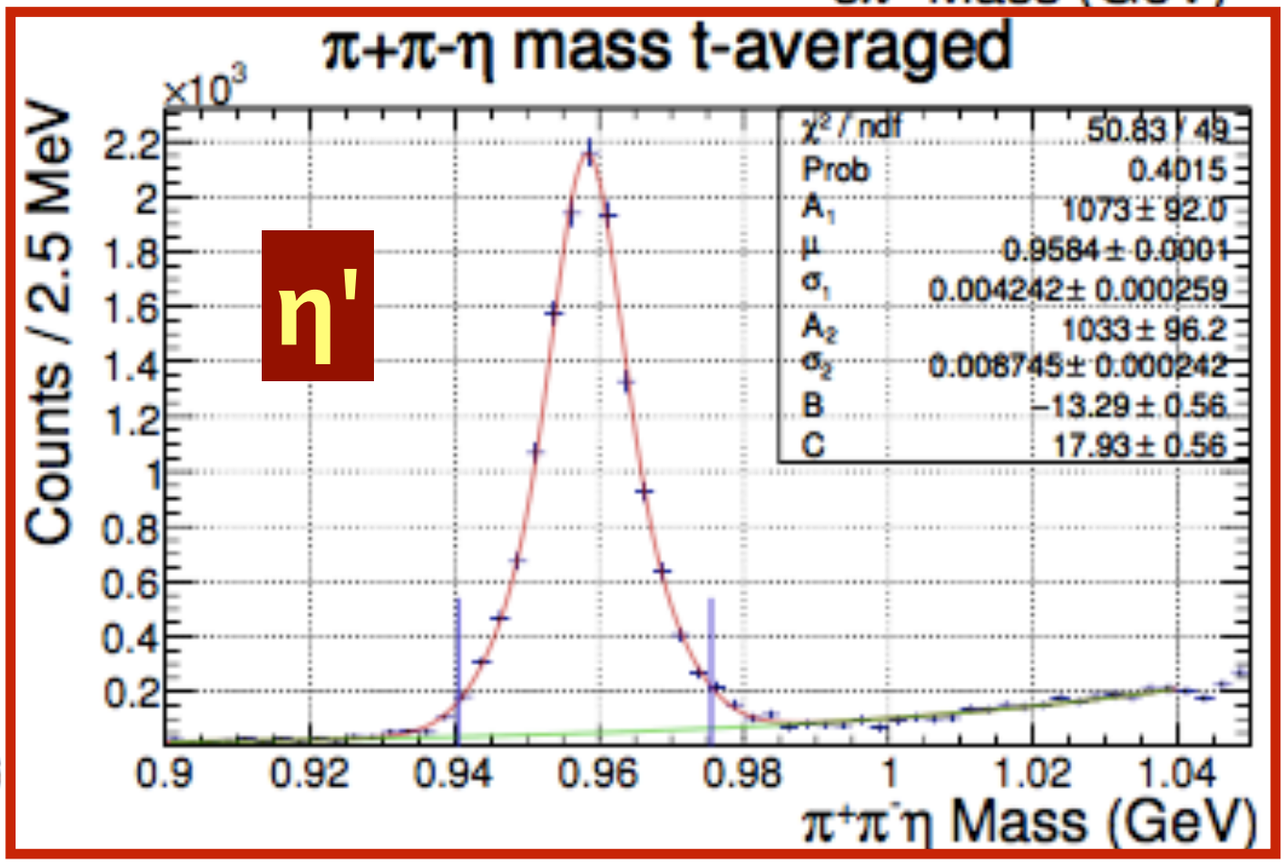


Invariant Masses









η,η′ Beam Asymmetries

- Defined such that:
  - Natural parity exchange contributes positively
    - Exchange of vector, ρ and ω ($J^P = 1^-$)
  - Unnatural parity exchange contributes negatively
    - Exchange of pseudovector, b and h ($J^P = 1^+$)

$$\Sigma = \frac{\sigma_{\text{nat.}} - \sigma_{\text{unnat.}}}{\sigma_{\text{nat.}} + \sigma_{\text{unnat.}}}$$

- In terms of yields

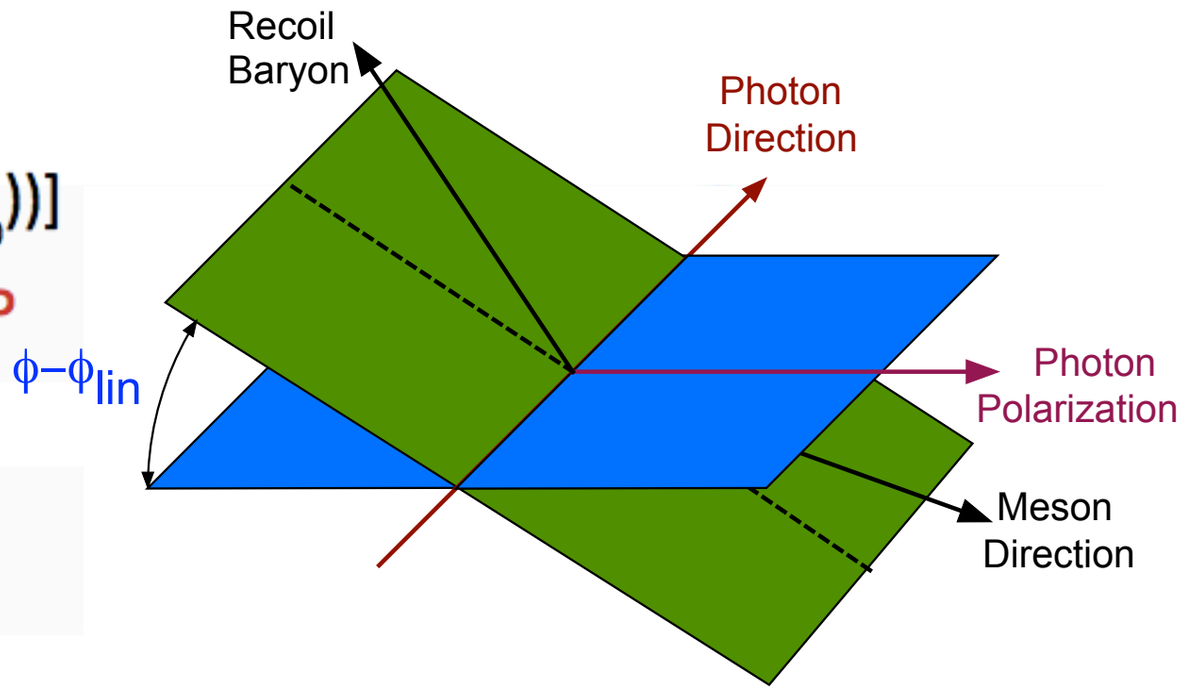
$$Y_\gamma(\phi) \approx N_\gamma A(\phi)\, \sigma_0[1 - P_\gamma \Sigma \cos(2(\phi - \phi_\gamma - \phi_0))]$$

- 2 polarization configurations: PARA, PERP
- 2 data sets: 0/90, 45/135

$$Y_{\parallel}(\phi) \approx N_{\parallel} A(\phi)\, \sigma_0[1 - P_{\parallel} \Sigma \cos(2(\phi - \phi_0))]$$
$$Y_{\perp}(\phi) \approx N_{\perp} A(\phi)\, \sigma_0[1 + P_{\perp} \Sigma \cos(2(\phi - \phi_0))]$$

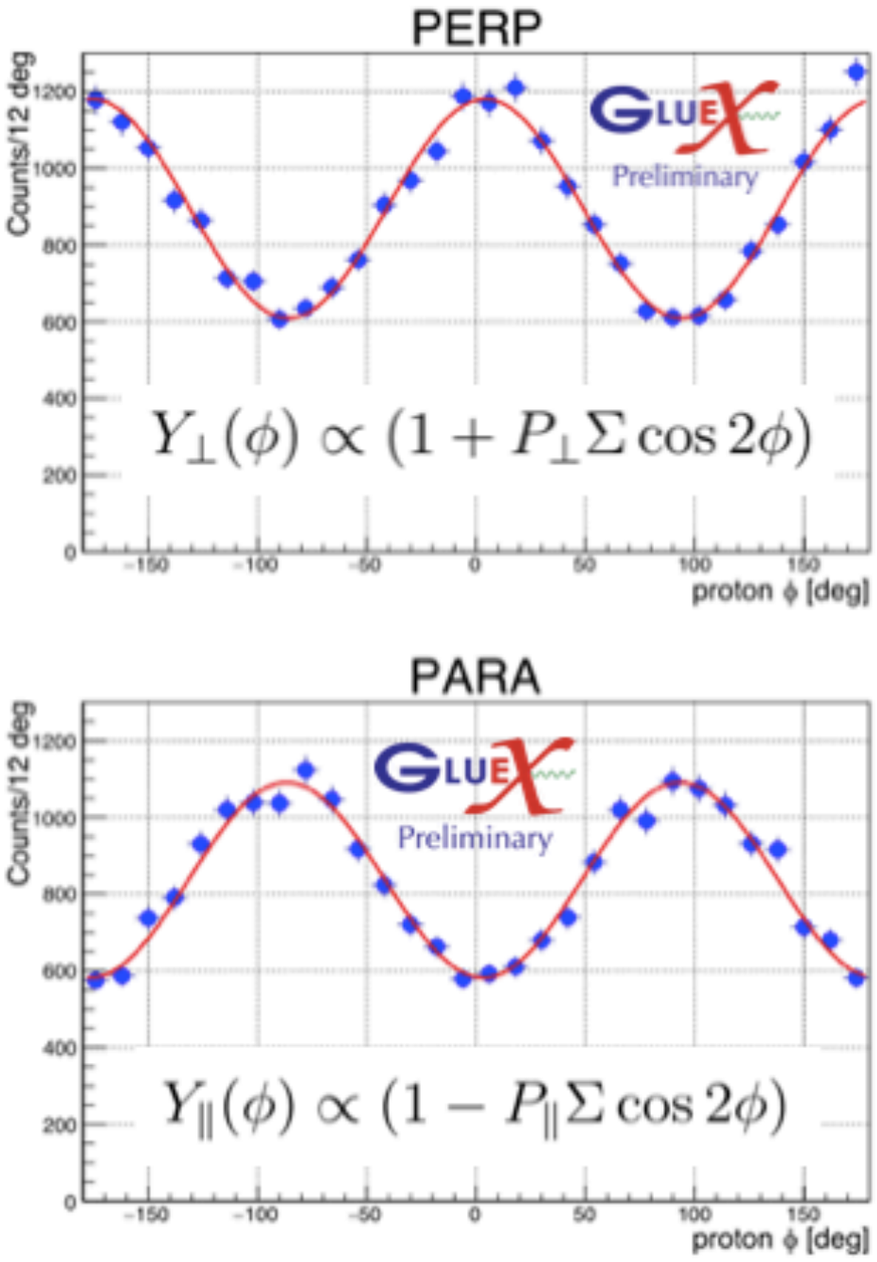
- 'Yield Asymmetry' eliminates σ_0 and $A(\phi)$

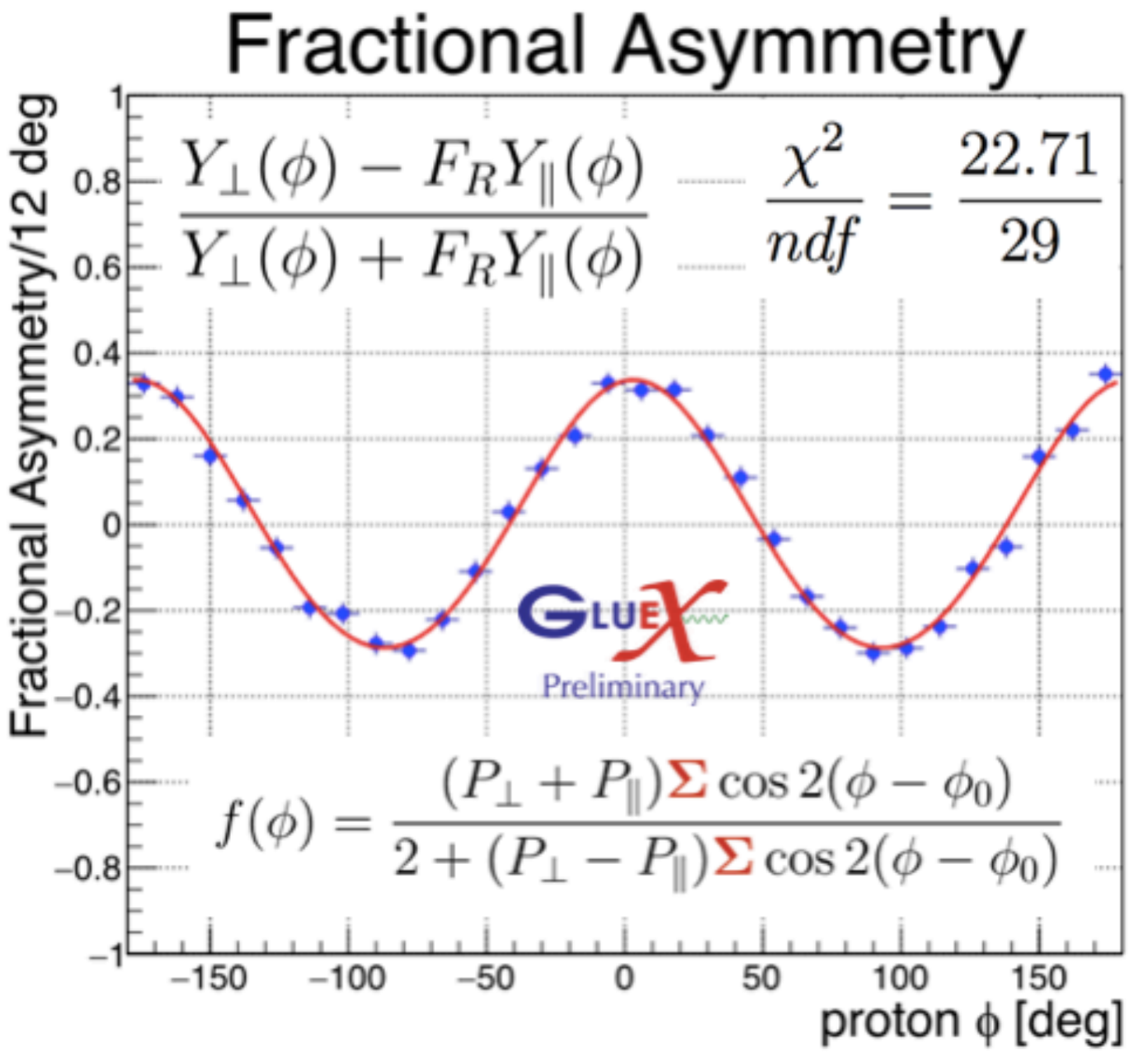
$$\text{ASYM} = \frac{Y_\perp - F_R Y_\parallel}{Y_\perp + F_R Y_\parallel} = \frac{(P_\perp + P_\parallel)\Sigma \cos(2(\phi - \phi_0))}{2 - (P_\perp - P_\parallel)\Sigma \cos(2(\phi - \phi_0))}$$



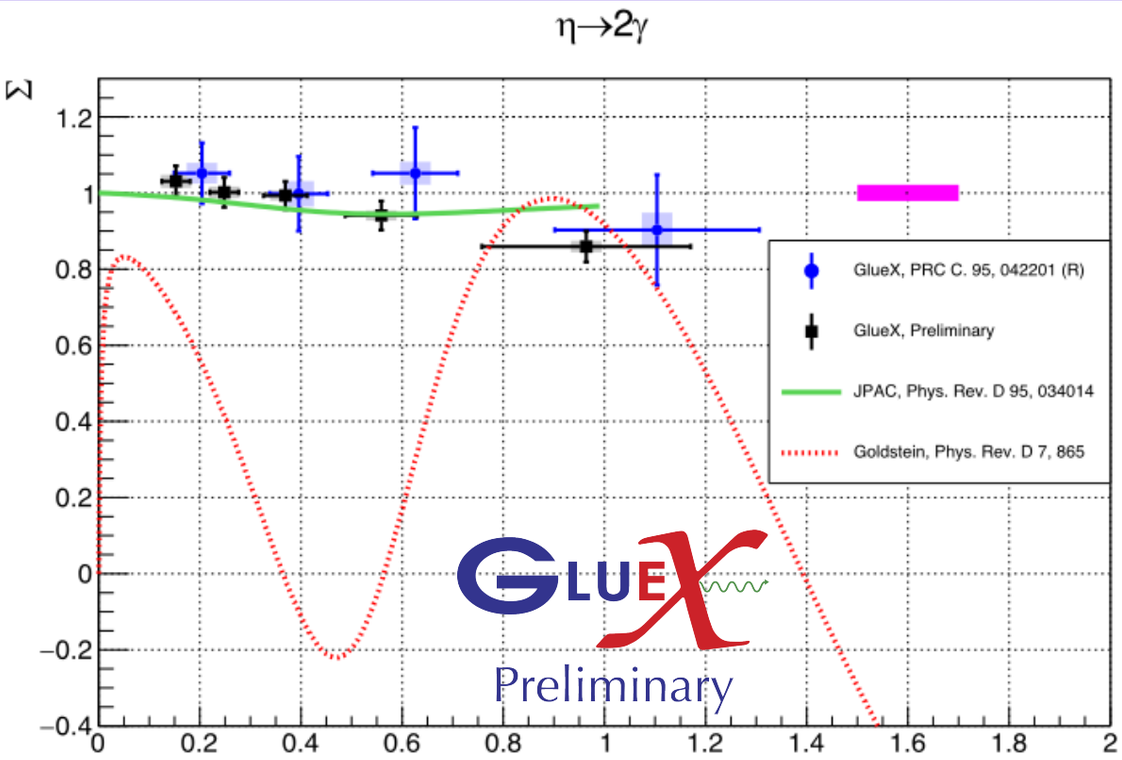
- F_R: Pair Spectrometer yields
- ϕ_0: $\eta \to 2\gamma$ asymmetry fit / $\rho \to \pi^+\pi^-$
- $P_\perp$ and $P_\parallel$: Triplet Polarimeter
- Σ is the only free parameter

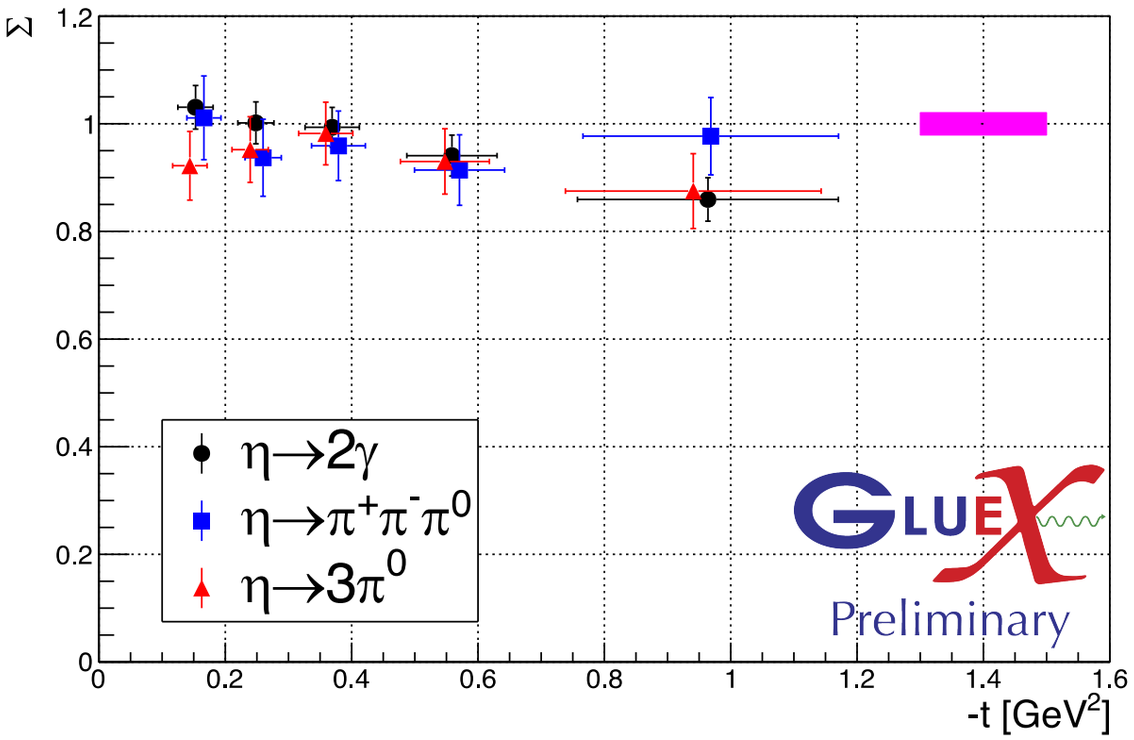
η,η′ Asymmetry Method

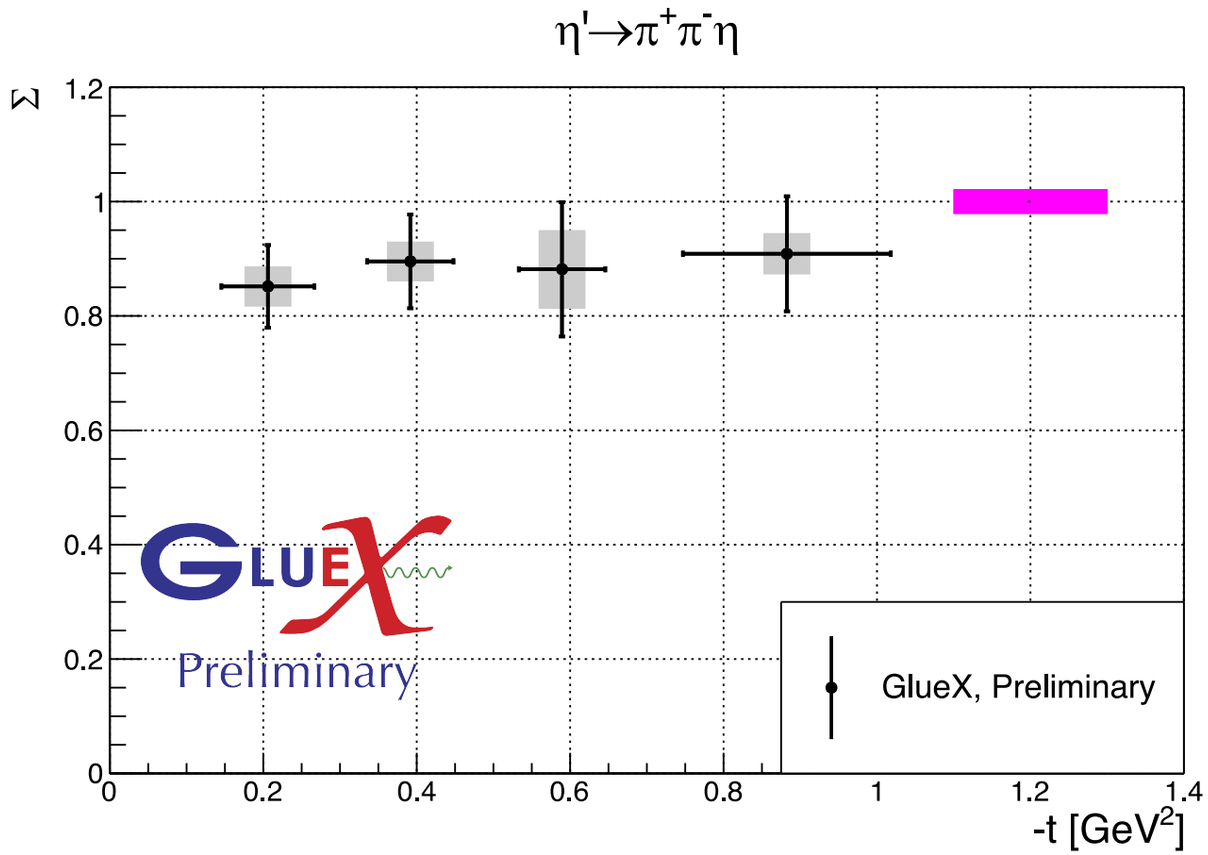




GlueX: Beam Asymmetries η,η′

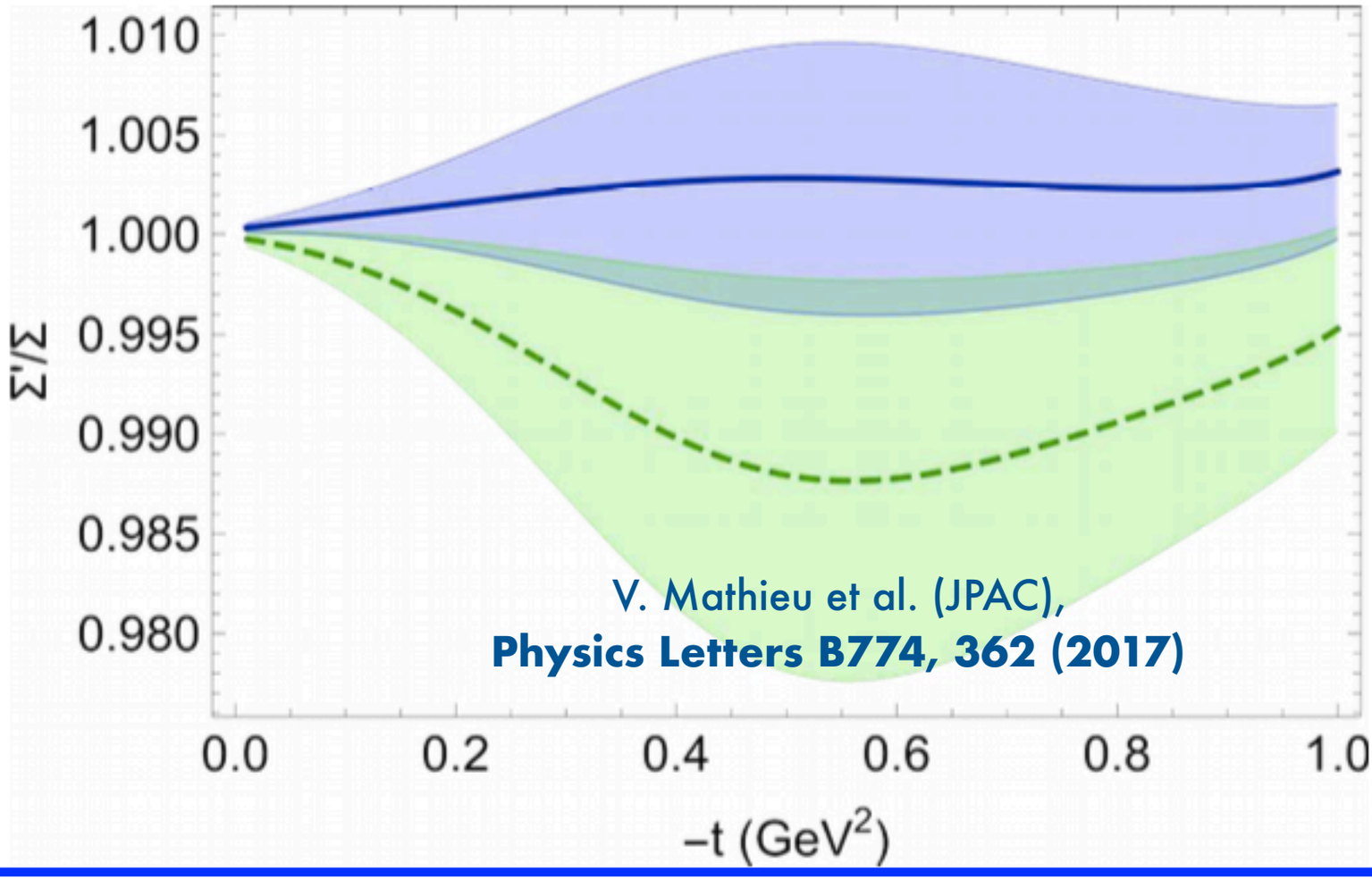






Theory: Beam Asymmetry Ratio

- η' beam-target exchanges dominated by ρ, ω, b, and h mesons
- Assuming no contribution from hidden strangeness exchange of ϕ and h' mesons implies that the Σ asymmetry of the η' and η will be equal
- JPAC predictions for two model assumptions for $\Sigma_{\eta'}/\Sigma_{\eta}$ allowing ϕ exchange:

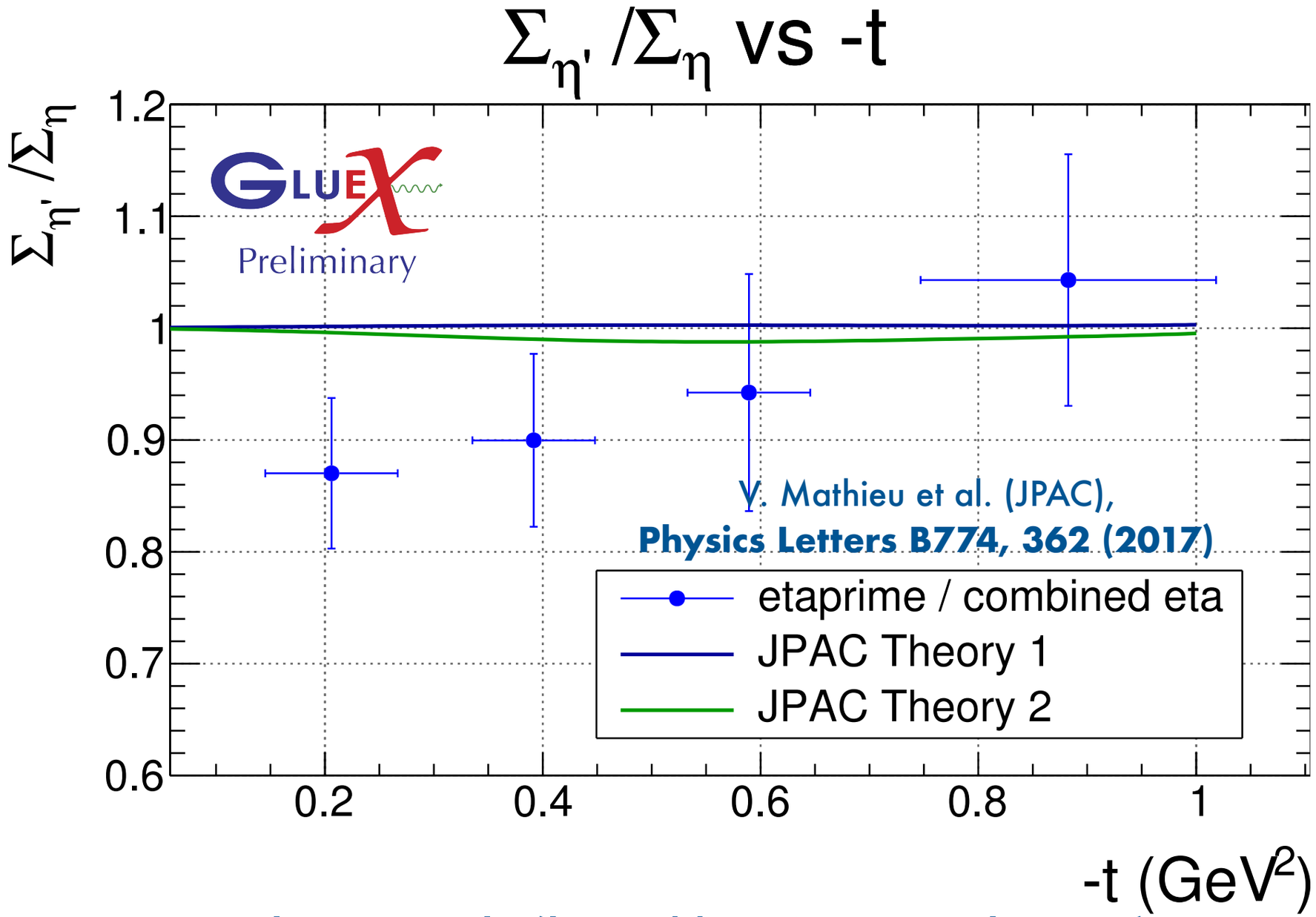


V. Mathieu et al. (JPAC),
Physics Letters B774, 362 (2017)

These two model predictions use different assumptions for the axial vector (b, h) coupling strengths

- Significant deviation from 1 may imply non-negligible ϕ/h' contributions or more complicated interactions between the proton and produced meson

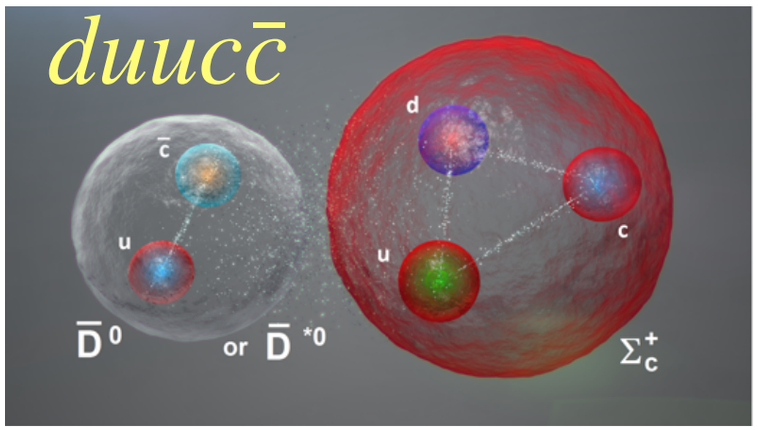
GlueX: Beam Asymmetry Ratio

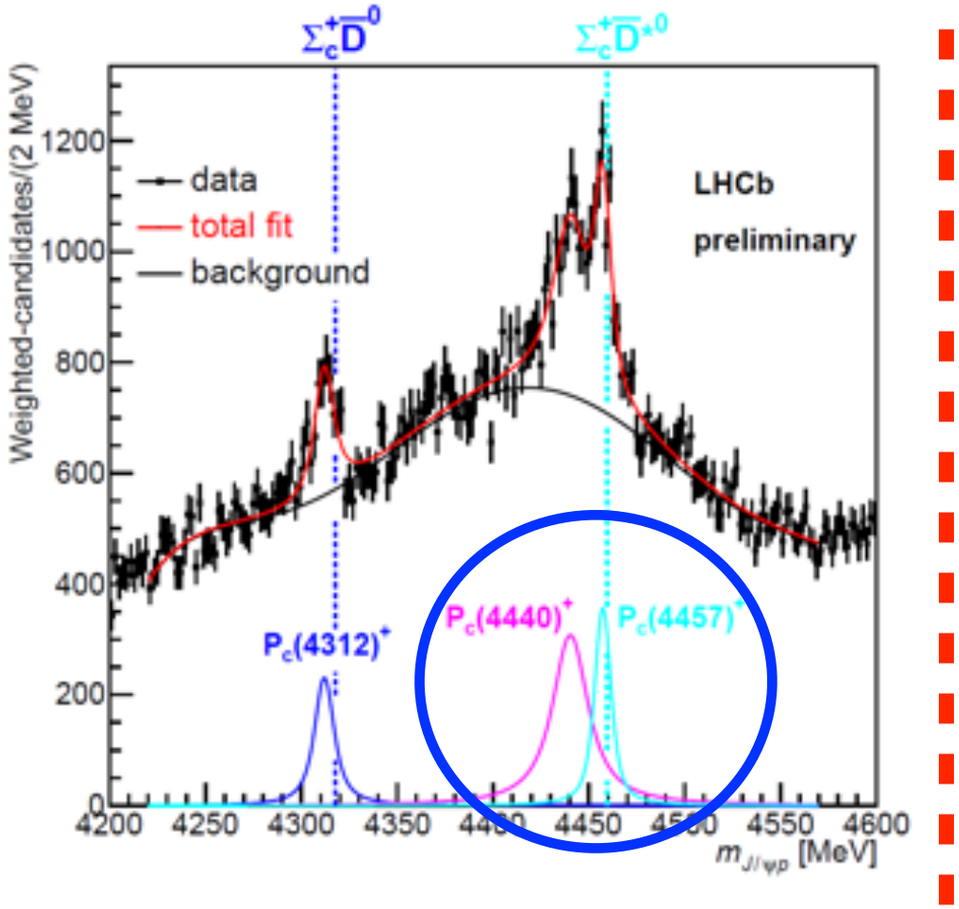


- Statistical errors only (limited by η′ statistical errors)
- No statistically-significant deviations from unity are observed

Other Analyses

J/psi Threshold Production





LHCb, arXiv 1904.03947 (2019)

J/psi Threshold Production

- **GLUEX** Results
  (2 citations)

- threshold (11.8-8.2 GeV) production is clean; s-channel photoproduction probes 5-quark interaction!

- probes gluon distributions in the proton and trace anomaly term [Kharzeev et al., NPA 661, 568 (1999)]

-

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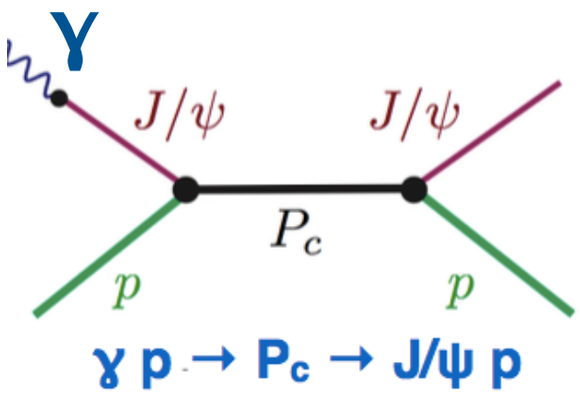
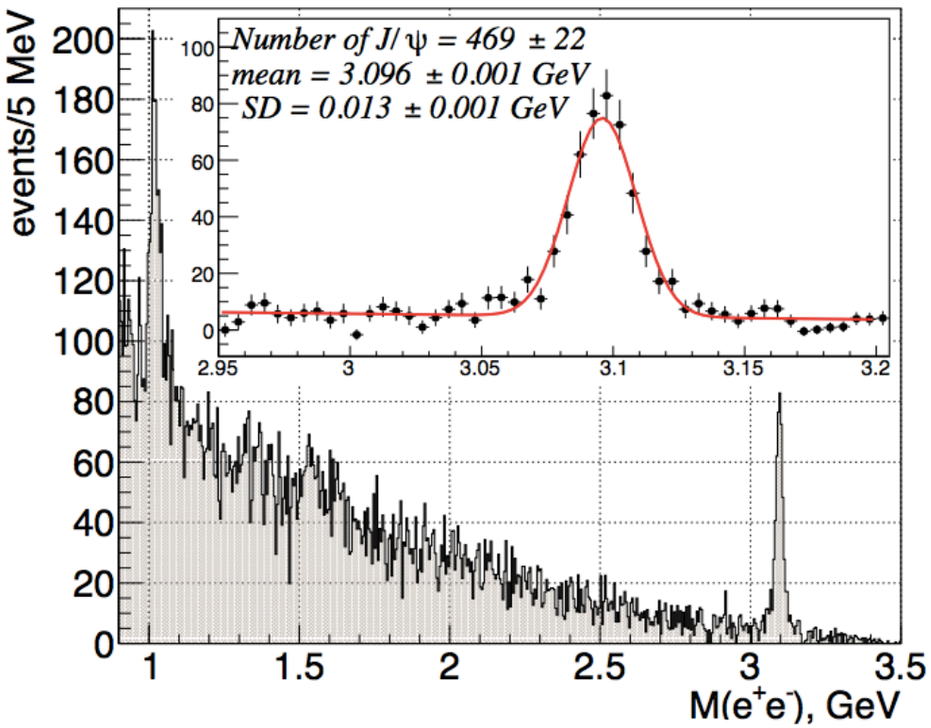
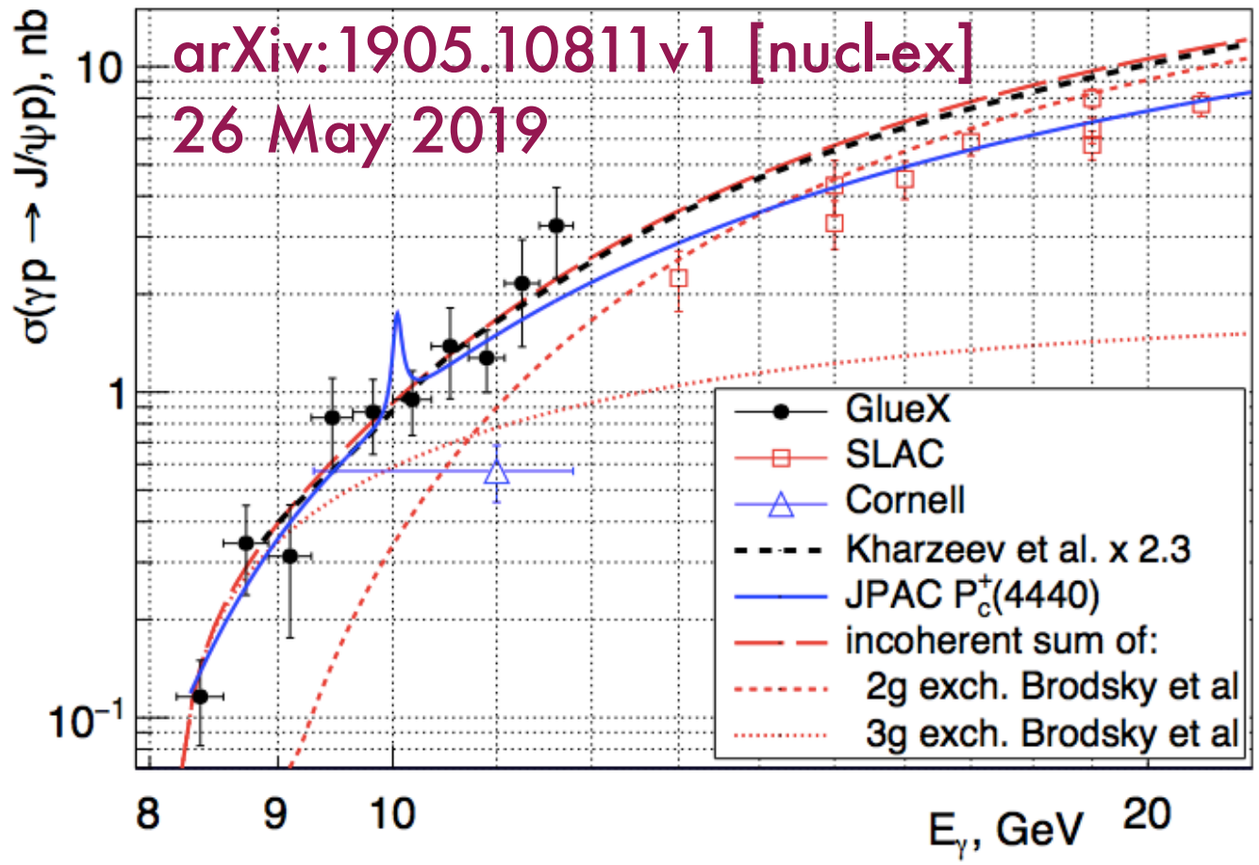






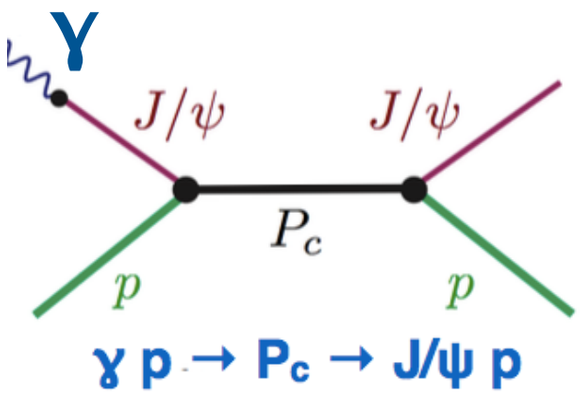
J/psi Threshold Production

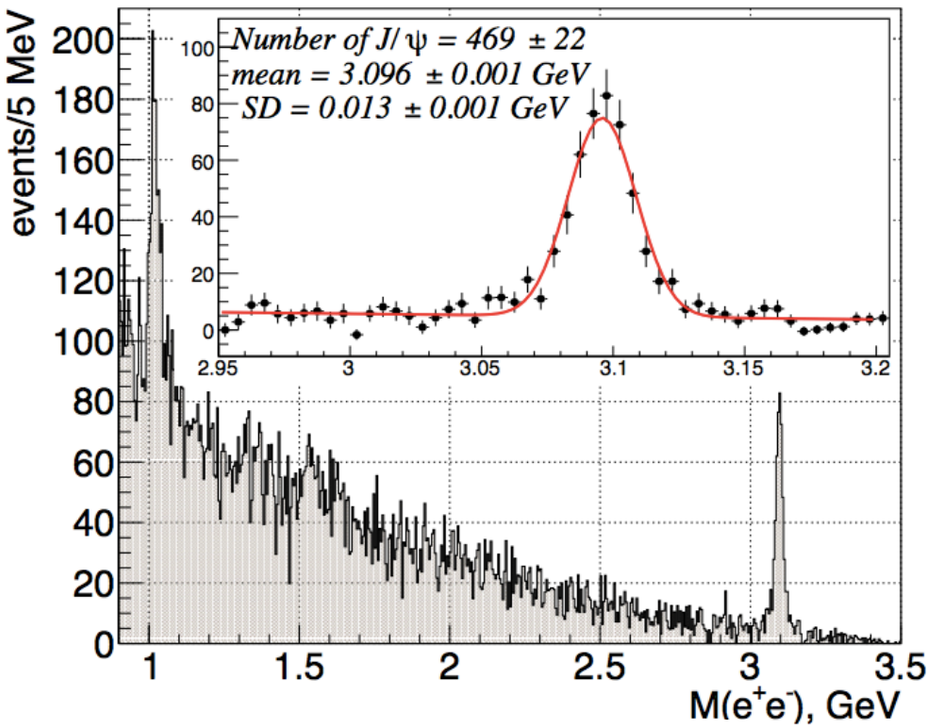
- **GLUEX** Results
  (2 citations)

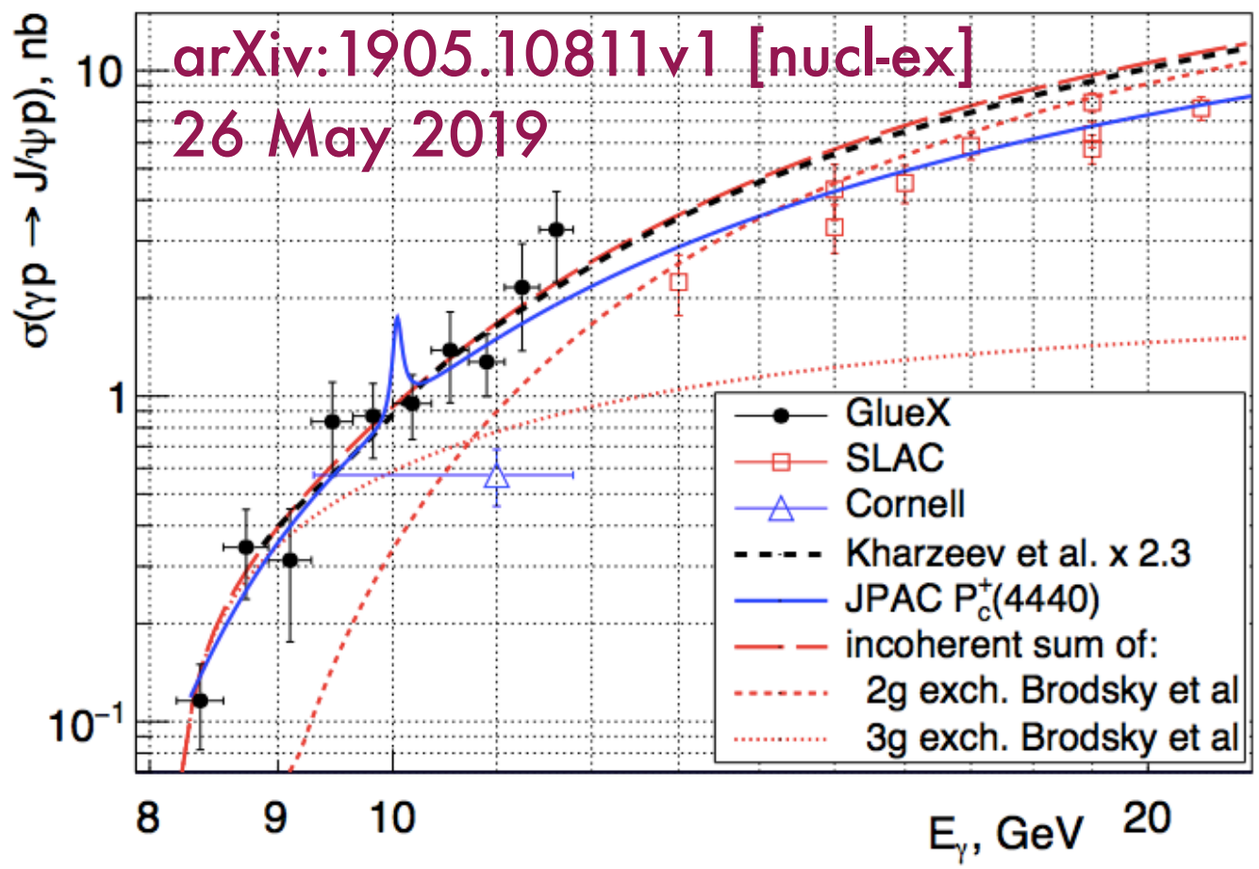
- threshold (11.8-8.2 GeV) production is clean; s-channel photoproduction probes 5-quark interaction!

- probes gluon distributions in the proton and trace anomaly term [Kharzeev et al., NPA 661, 568 (1999)]

- Don't see LHCb pentas!







GlueX talks at MENU 2019

Plenary

Searching for Exotic Hadrons at GlueX	*Sean Dobbs*	
McConomy Auditorium, CMU Cohen University Center	09:15 - 09:45	

Hadron Spectroscopy

Exclusive eta and eta' photoproduction and beam asymmetries at GlueX	*William McGinley*	
Rangos 1	15:00 - 15:30	
Beam Asymmetries from Light Scalar Meson Photoproduction on the Proton at GlueX	*Dr Stuart Fegan*	
Rangos 1	17:00 - 17:30	
Measurement of the Photon Beam Asymmetry Σ for $\gamma + p\to K^+\Sigma^0$ at E_{γ} = 8.5 GeV in GlueX	*Mr Nilanga Wickramaarachchi*	
Rangos 2	17:30 - 18:00	
Photoproduction of Ξ Baryons at GlueX	*Ashley Ernst*	
Rangos 2	09:45 - 10:15	
Spin-Density Matrix Elements for Vector Meson Photoproduction at GlueX	*Alexander Austregesilo*	
Rangos 2	14:30 - 15:00	

Meson-Nucleon

Photoproduction of Baryon-anti-Baryon Pairs at GlueX.	*Hao Li*	
Rangos 1	09:15 - 09:45	

Future Facilities

Physics with the GlueX DIRC	*Justin Stevens*	
Rangos 3	13:30 - 14:00	

Summary & Outlook

- Gluonic-field excitation leads to a **complete spectrum** of mesons.
- LQCD predicts hybrid multiplets; GlueX will map them out.

✓Reaction channels: $\gamma p \to (\rho,\omega,\varphi)p$, $\gamma p \to (\pi^0,\eta,\eta')p$, etc.

✓Early physics analyses: beam asymmetries of η, η' mesons

- Next: other asymmetries, **SDMEs**, **cross sections**, **PWA**
- Future:
  - Primakoff program for η decay width and $\pi^{\pm}$ polarizability
  - DIRC Detector upgrade for improved K/π separation fall 2019

Acknowledgements

LEARN MORE

- **portal.gluex.org**
- **www.halld.org**
- **www.gluex.org**

Acknowledgements

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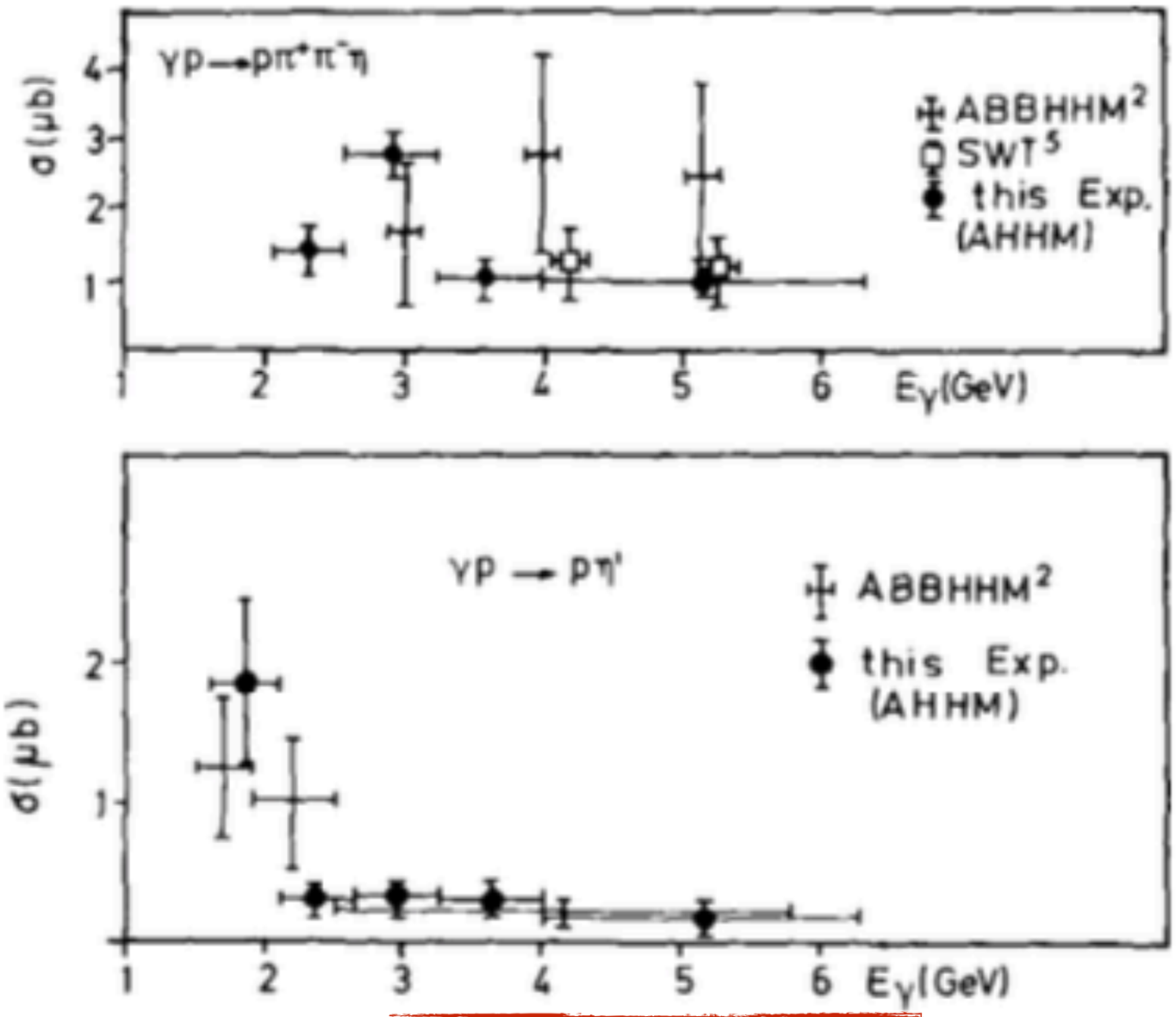
Thank you!

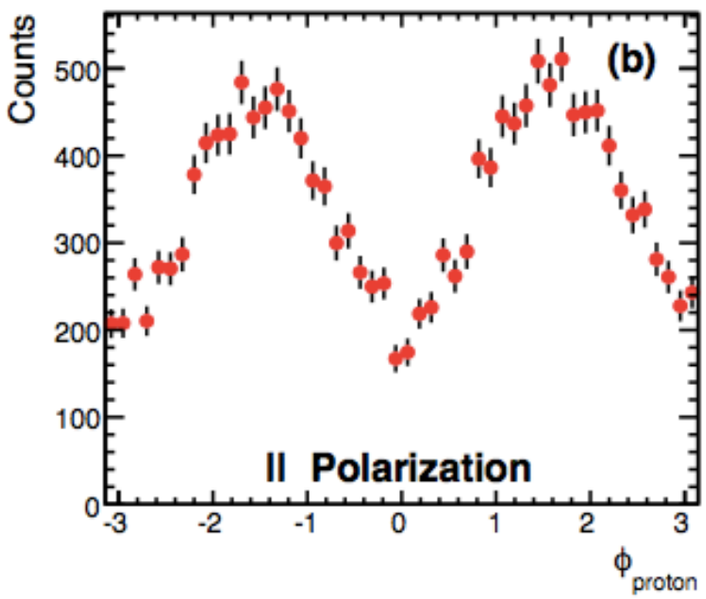
Backup Slides

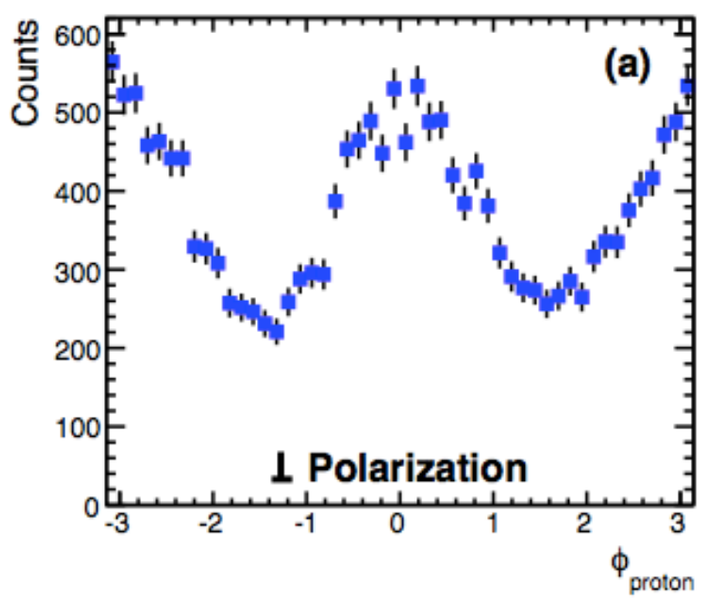
Old Data: $\gamma p \rightarrow p\eta, p\eta'$



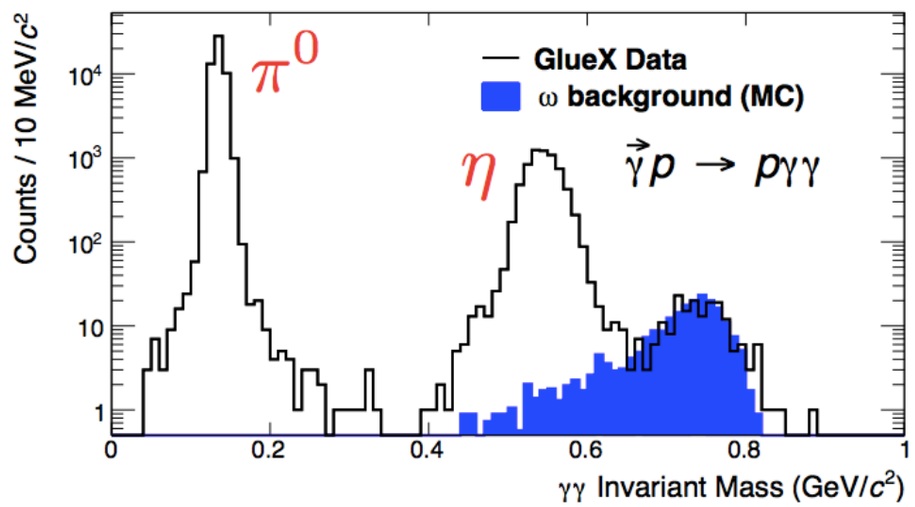
Struczinski et al., 1976

π^0 and η Beam Asymmetries

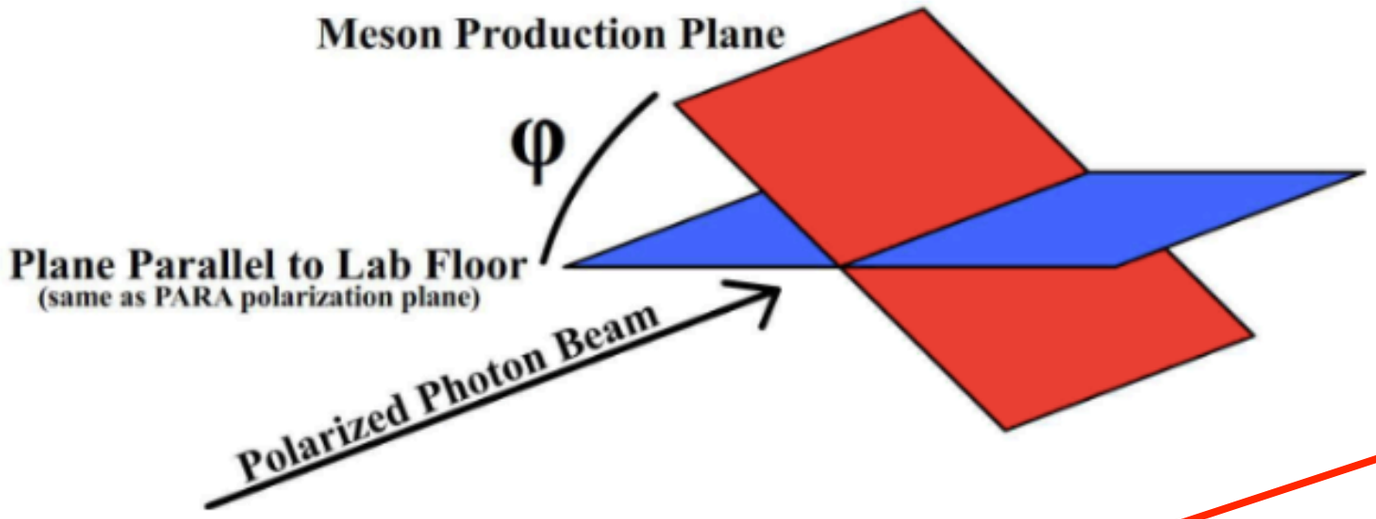




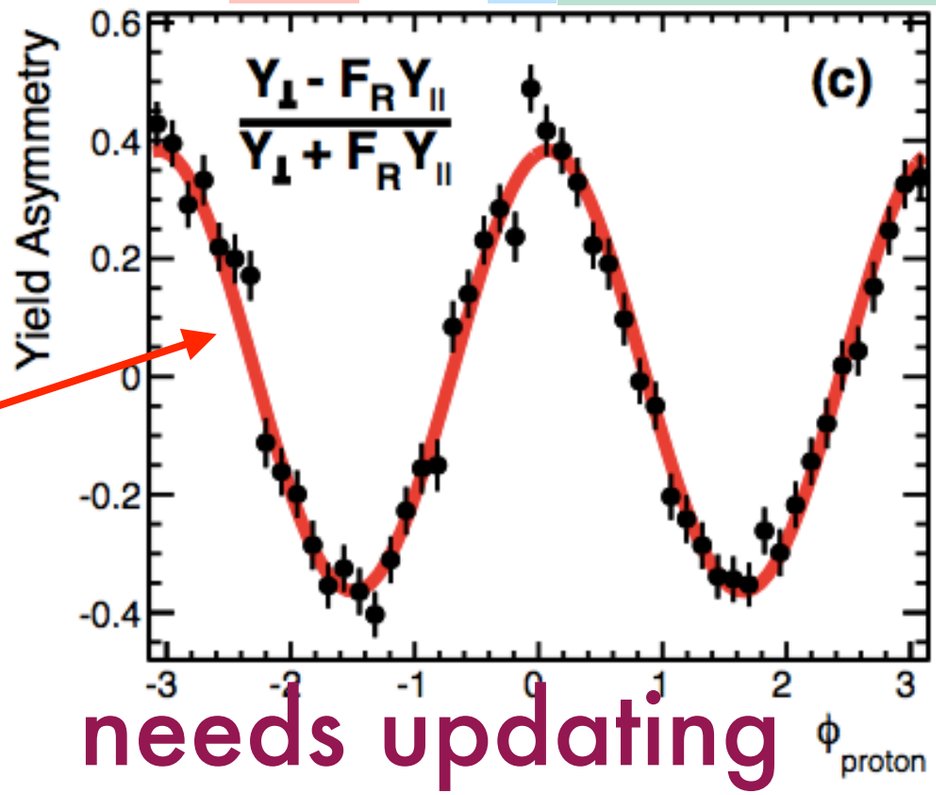
$$\gamma p \to p\gamma\gamma$$



$$Y_{\parallel} \propto A(\phi)(1 - P_\gamma \Sigma cos(2(\phi - \phi_\gamma^{lin}))$$



$$\sigma = \sigma_0 \left(1 - P_\gamma \Sigma \cos 2(\phi_p - \phi_\gamma^{\text{lin}})\right)$$

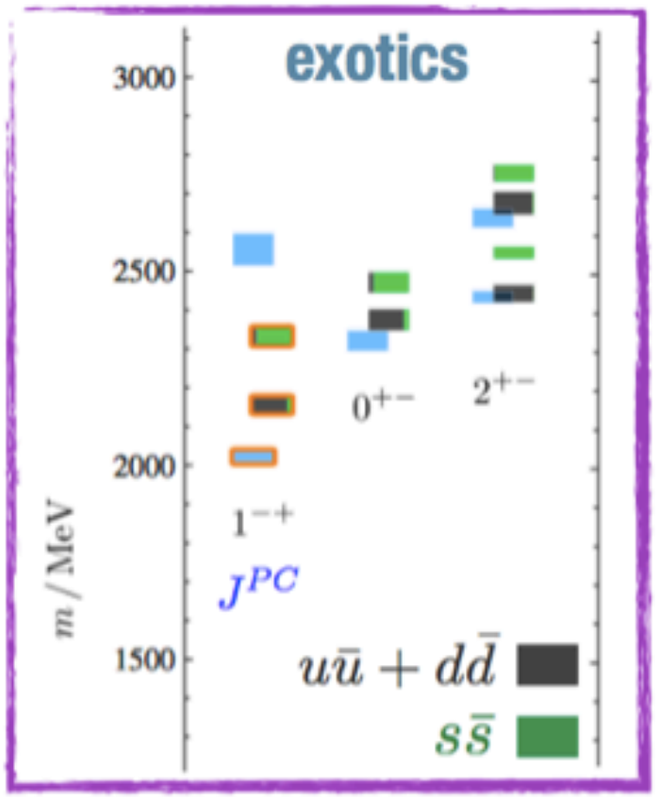


needs updating

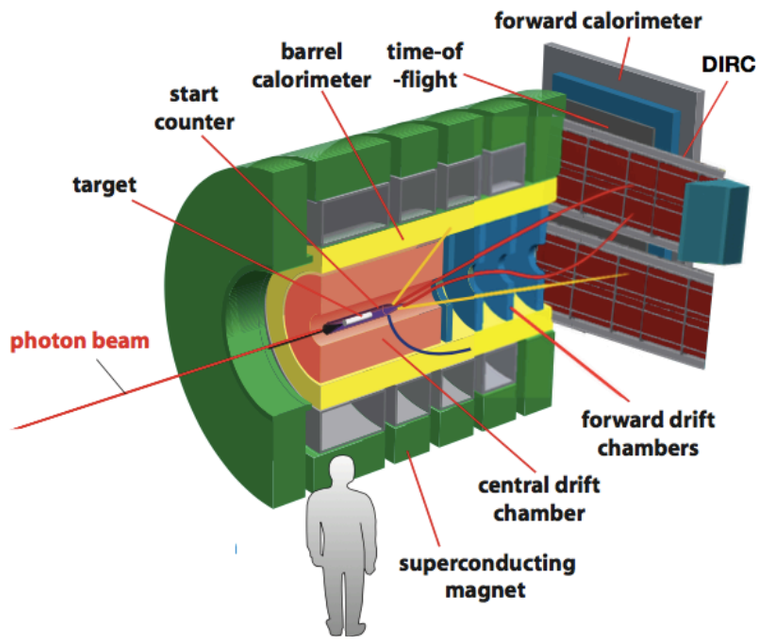
Future GlueX with Strangeness

Strangeness program

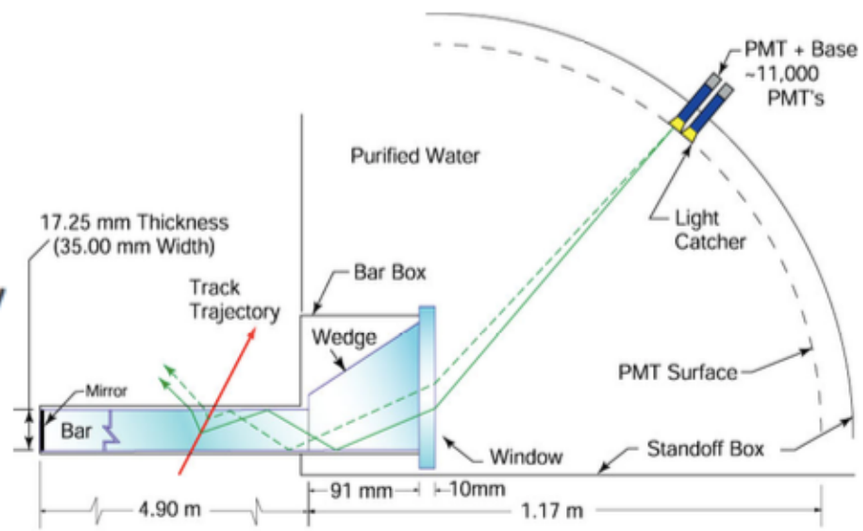
	J^{PC}	Allowed Decay Modes
π_1	1^{-+}	$b_1\pi$, $\pi\rho$, πf_1, $\pi\eta$, $\pi\eta'$, ηa_1, $\pi\eta(1295)$
η_1	1^{-+}	πa_1, πa_2, ηf_1, ηf_2, $\pi\pi(1300)$, $\eta\eta'$, KK_1^A, KK_1^B
η_1'	1^{-+}	KK_1^B, KK_1^A, KK^*, $\eta\eta'$
b_0	0^{+-}	$\pi\pi(1300)$, πh_1, ρf_1, ηb_1
h_0	0^{+-}	πb_1, ηh_1, $KK(1460)$
h_0'	0^{+-}	$KK(1460)$, KK_1^A, ηh_1
b_2	2^{+-}	πa_1, πa_2, πh_1, $\eta\rho$, ηb_1, ρf_1
h_2	2^{+-}	$\pi\rho$, πb_1, $\eta\omega$, ωb_1
h_2'	2^{+-}	KK_1^B, KK_1^A, KK_2^*, ηh_1



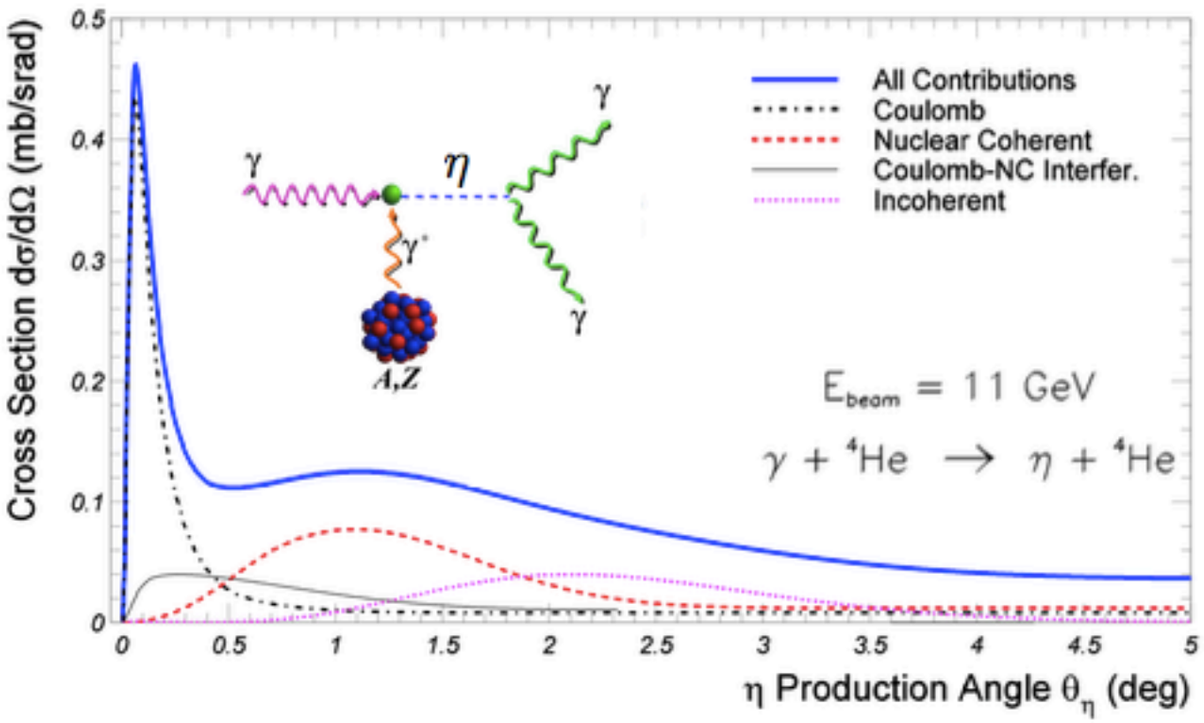
DIRC (fall 2019)



- Mapping the hybrid spectrum requires: large statistics samples of many particle final states in **strange** and **non-strange** decay modes
- Experimentally access to strangeness content of the state by comparing strange vs non-strange decay modes



Primakoff program



- η → γγ decay width through Primakoff production
- Test discrepancy between measurements at e^+e^- colliders and previous Primakoff results

- Extract charge pion polarizability from Primakoff production of pion pairs
- Comparison to other processes, eg. COMPASS's recent $\pi^-\gamma \to \pi^-\gamma$ and further test χPT predictions