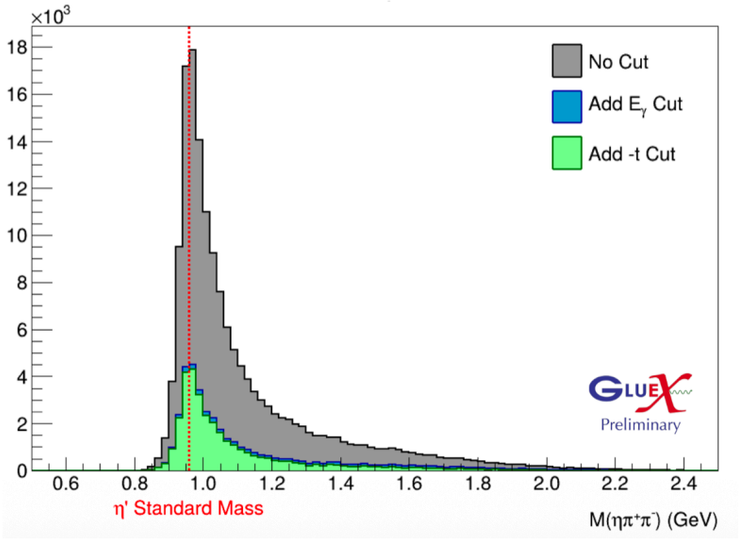
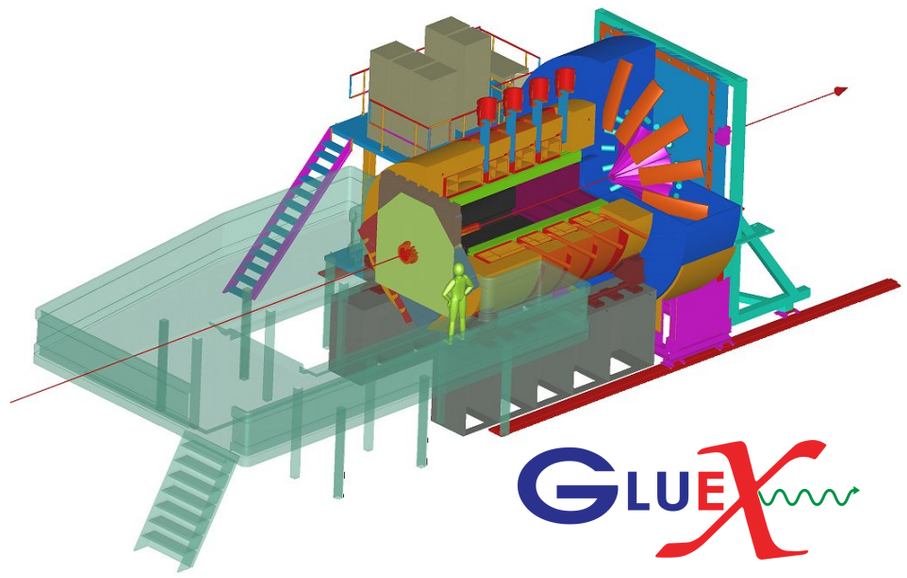
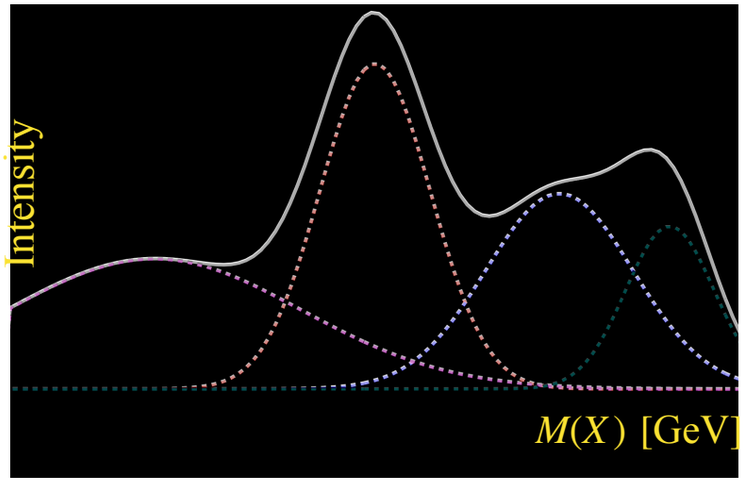






EXOTIC TWO-PSEUDOSCALAR MESON DECAYS IN GLUEX

Z. Papandreou[1], H. Singh[1], J. Stevens[2], W. Imoehl[3]
on behalf of the GlueX Collaboration

CAP Congress 2026, June 22, 2026

1 University of Regina | Faculty of Science
2 William & Mary
3 Jefferson Lab

Physics

Experiment

Methodology

two-pseudo

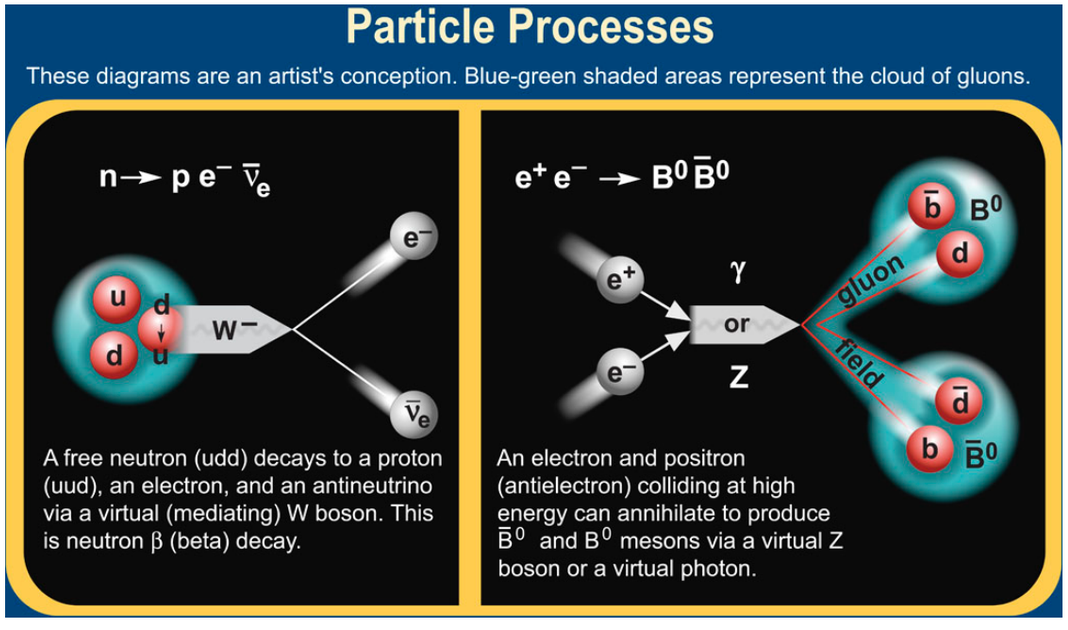
Colossal Energy Scale

Asymptotic Freedom

High energy, short distance

Perturbative

Gluon Jets Observed



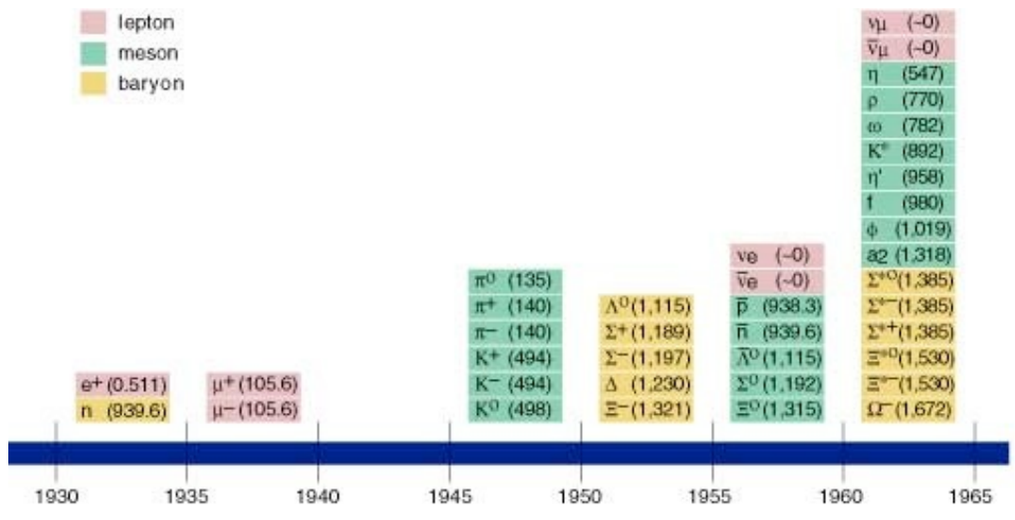
High-energy scattering

Confinement

Low energy, large distance

Non-perturbative

Gluonic Degrees of Freedom Missing!



Spectroscopy

Colossal Energy Scale

Asymptotic Freedom
High energy, short distance

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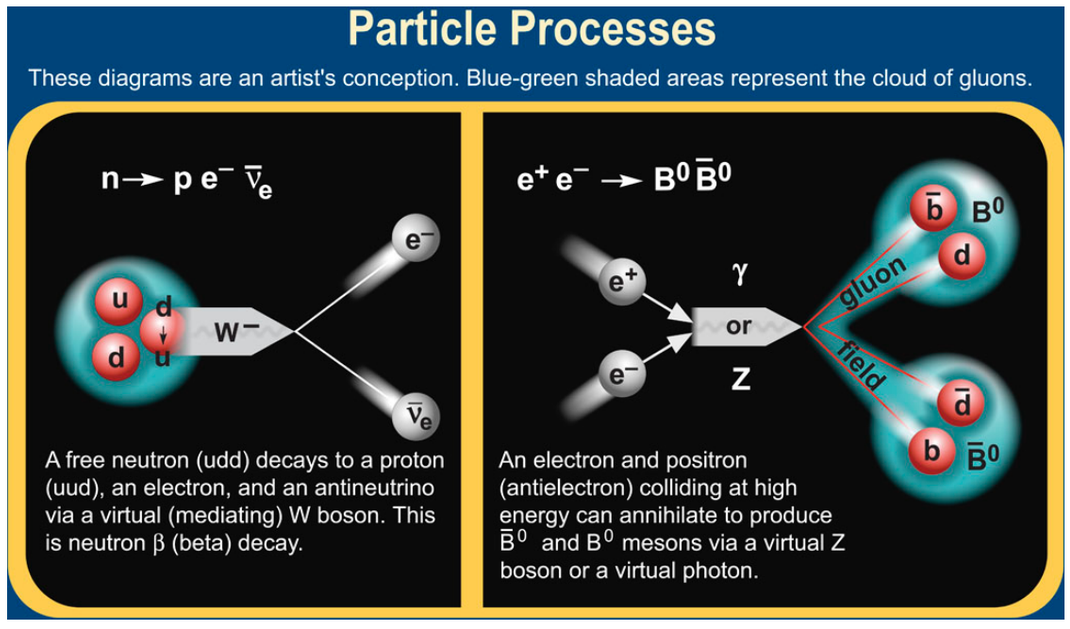

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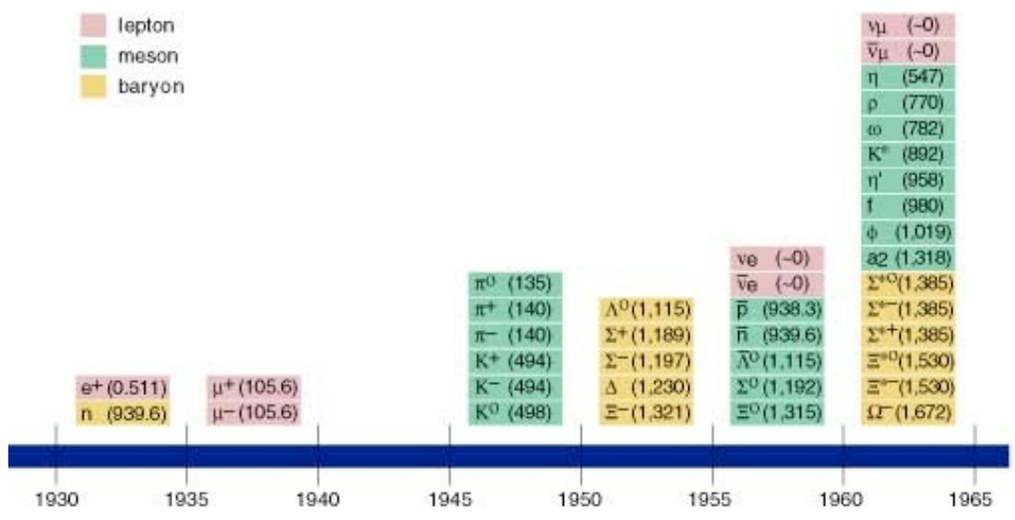
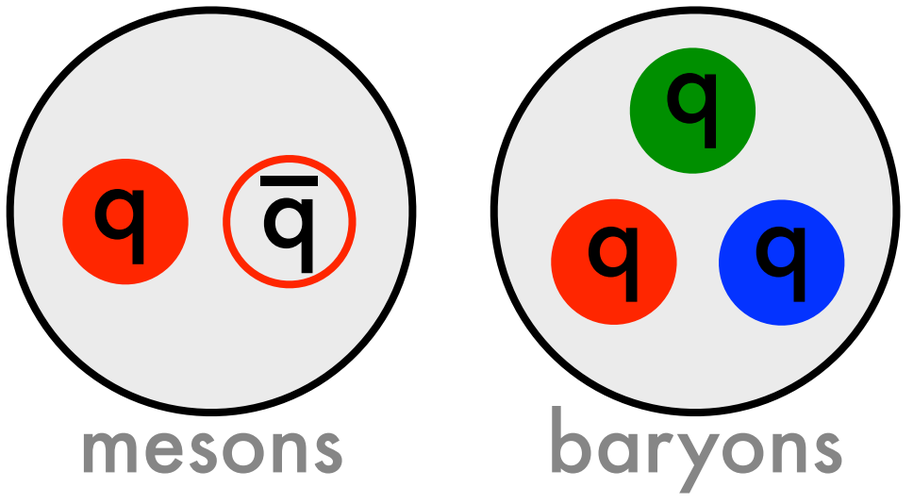


Spectroscopy

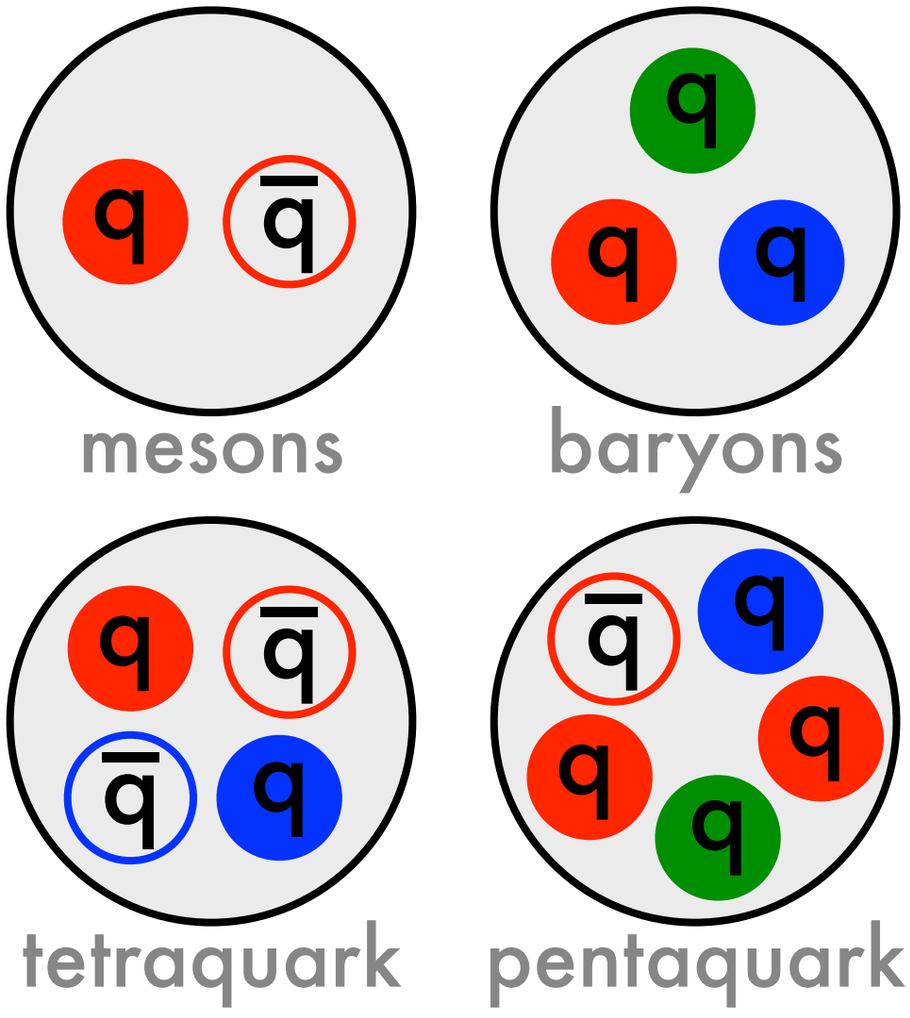
Confined States of Quarks and Gluons

Confined States of Quarks and Gluons



QCD predicts more types of states than just mesons & baryons

Confined States of Quarks and Gluons



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A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

... Baryons can now be constructed from quarks by using the combinations (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. ... **Phys.Let.8 (1964) 214**

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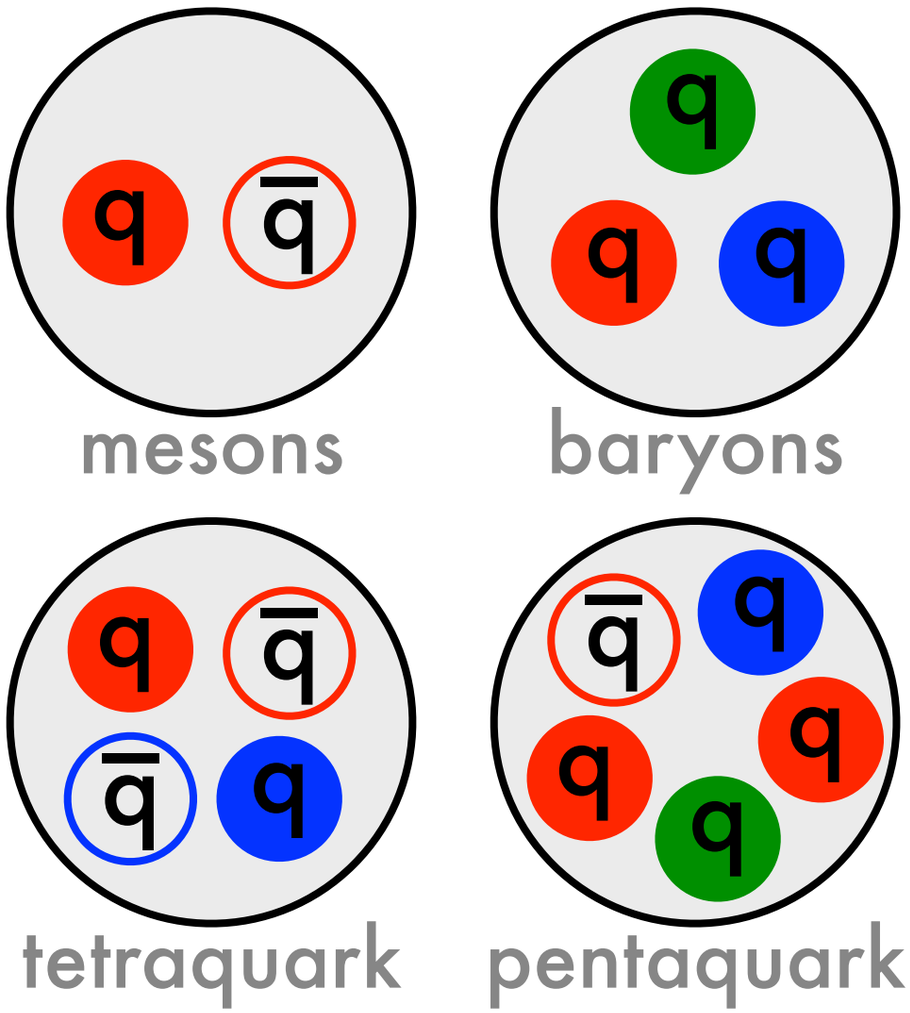

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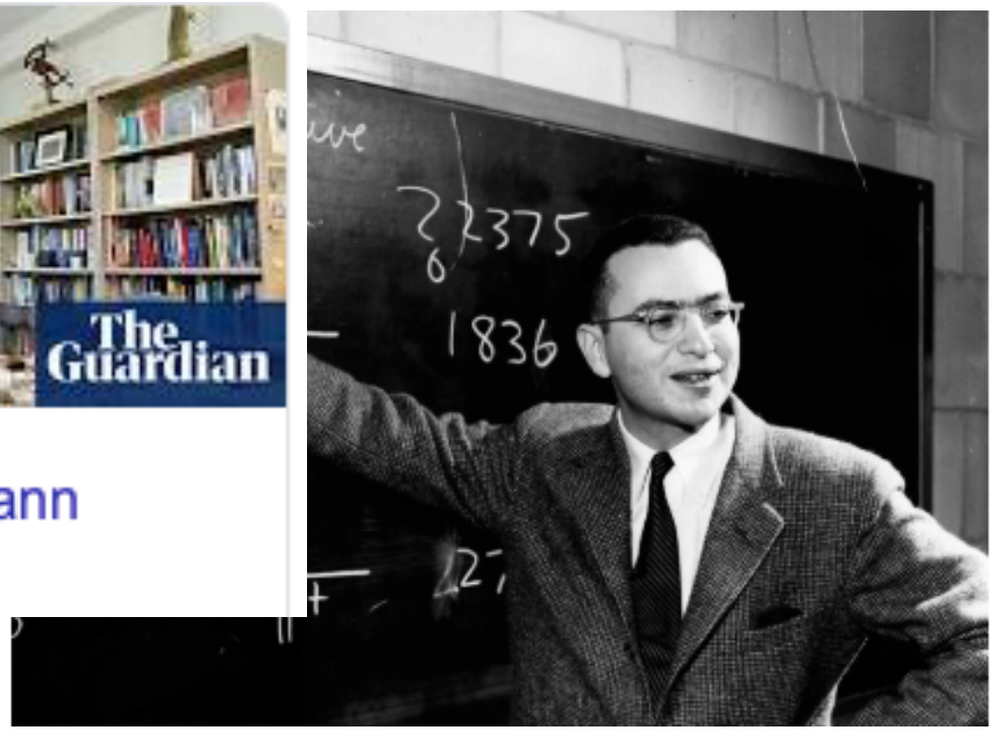
The New York Times

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

Murray Gell-Mann obituary



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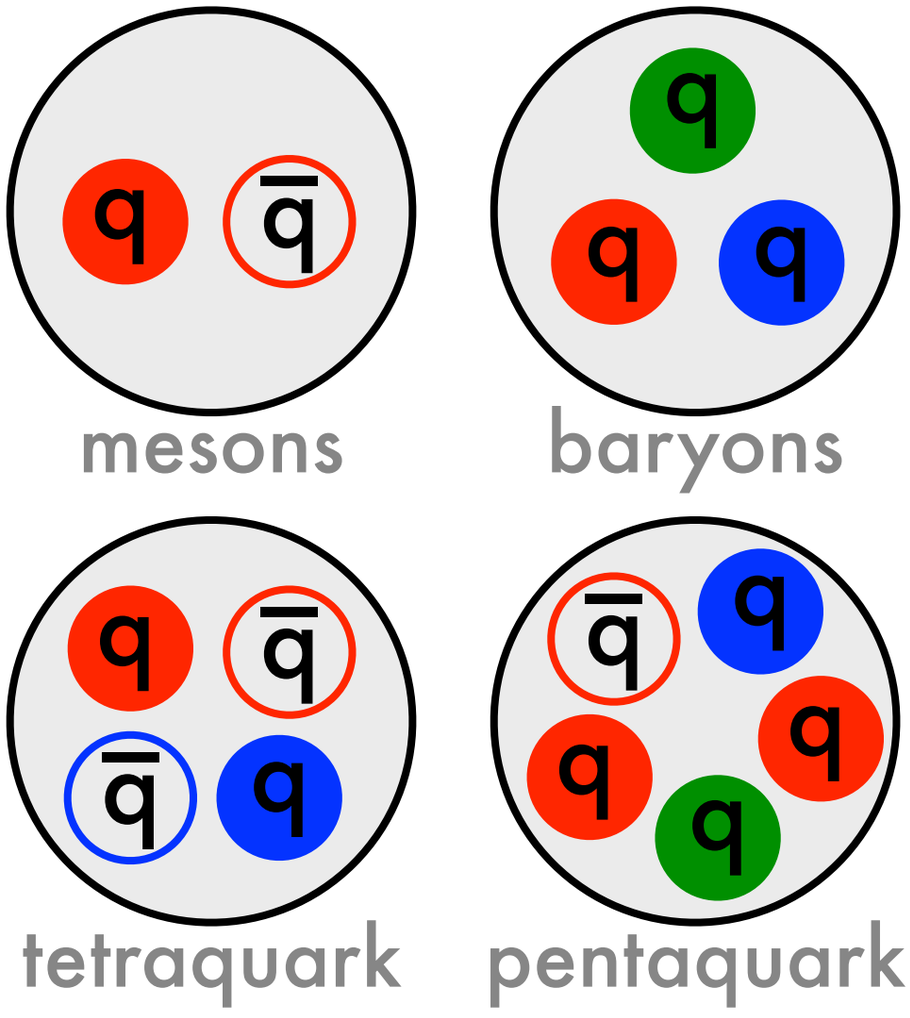

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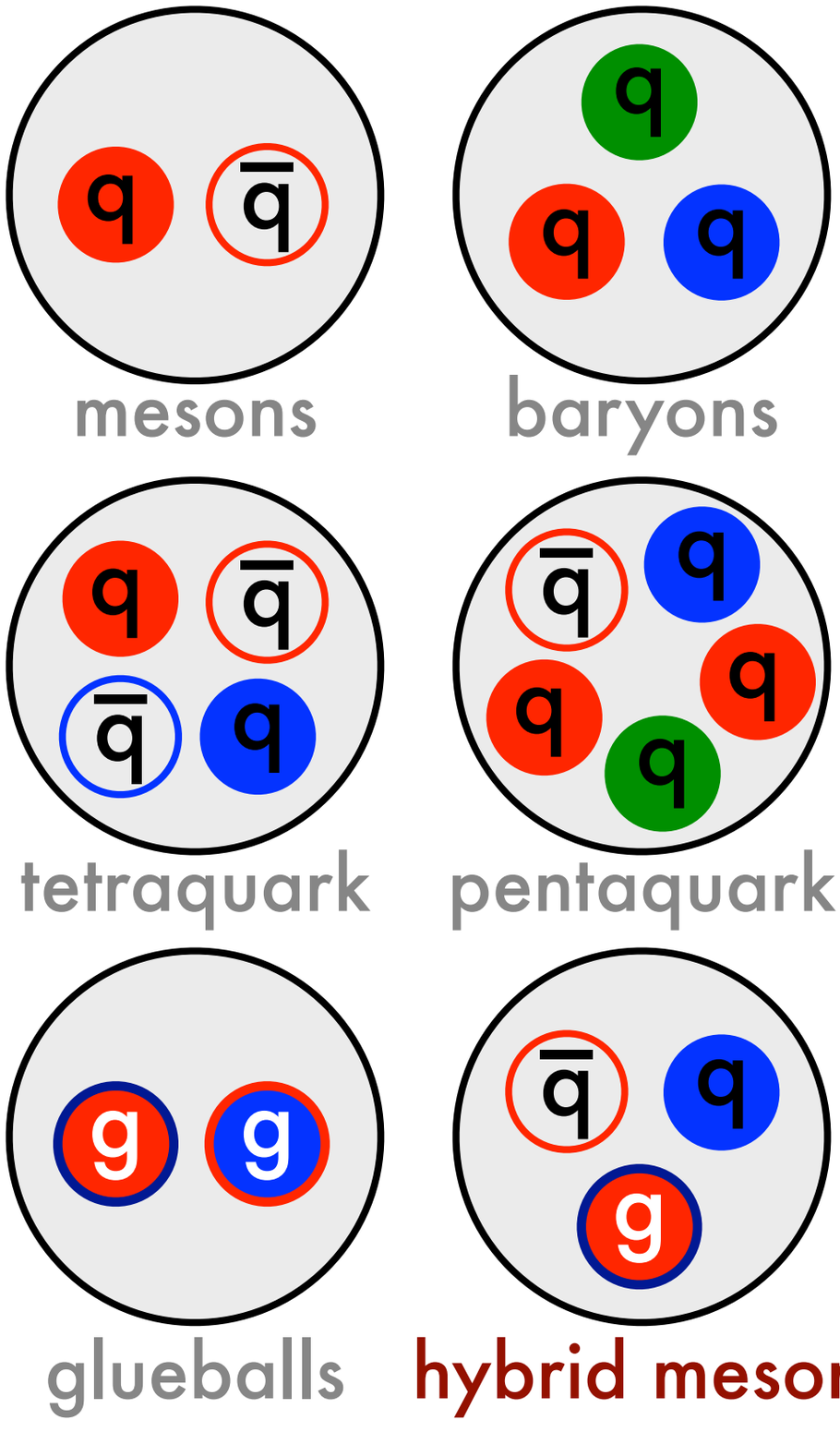

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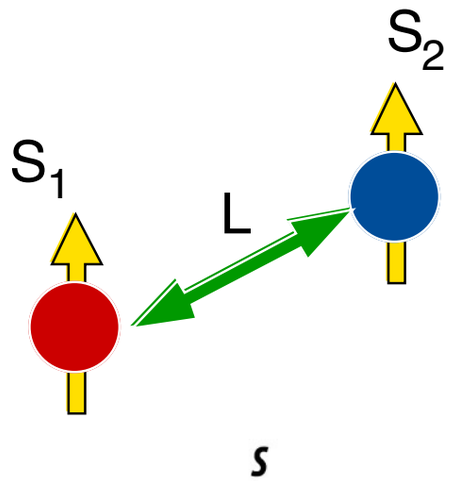
Can we observe explicit gluonic degrees of freedom in nature's bound states?

Gluonic DOF in Spectroscopy?

Gluonic DOF in Spectroscopy?

Nonets characterized by given J^{PC}



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$$J = L + S$$

$$P = (-1)^{L+1}$$

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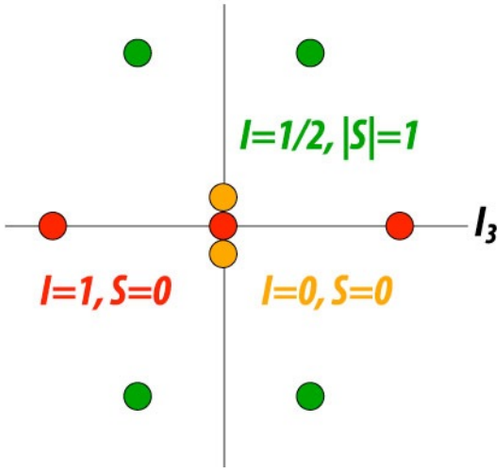

symmetry groups

J: the quantum mechanical spin of the particle
P: represents its property under parity (inversion of spatial co-ordinates)
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Gluonic DOF in Spectroscopy?

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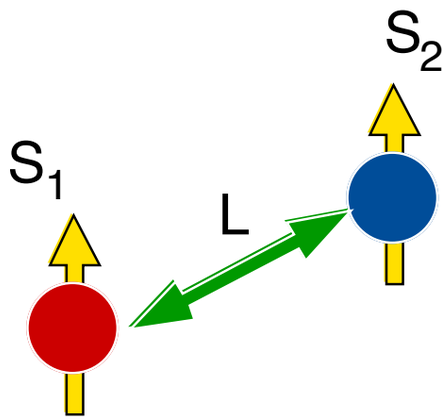

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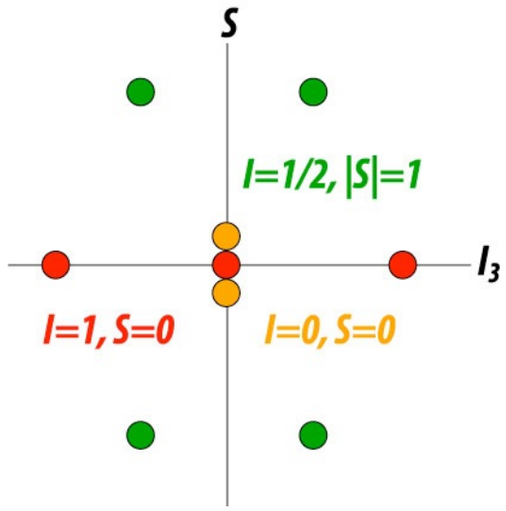
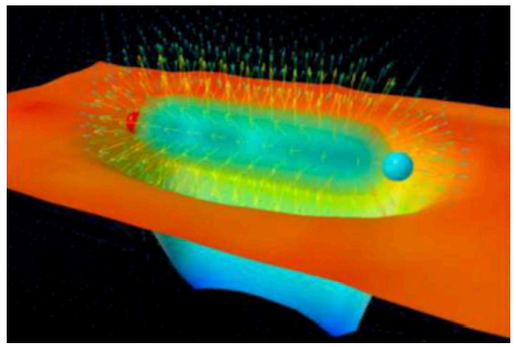
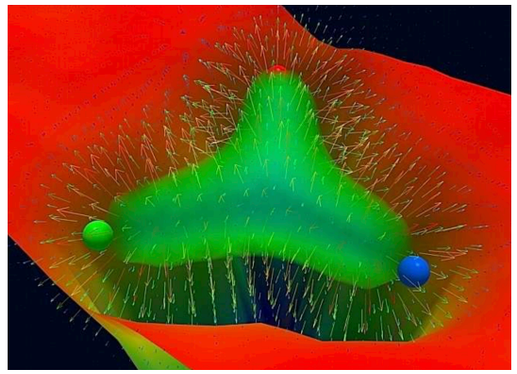


Flux tube:





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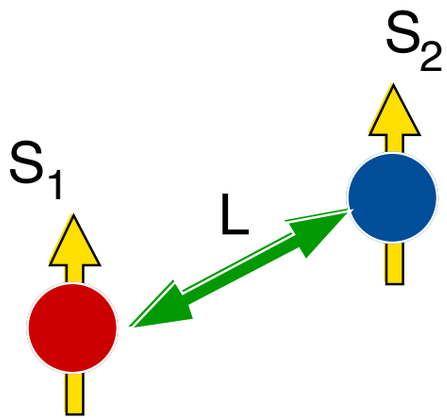

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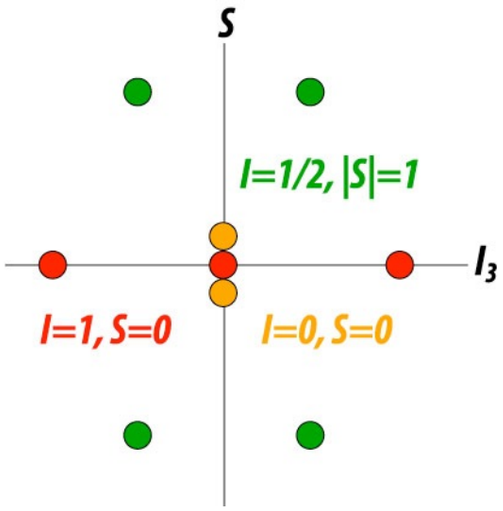

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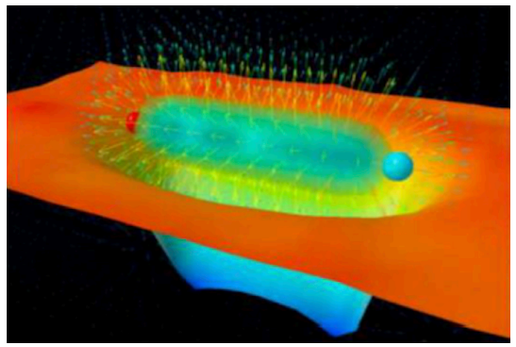
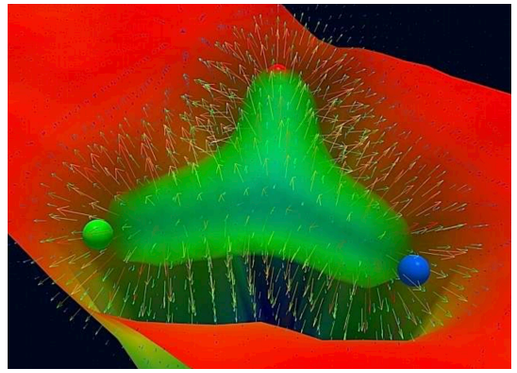
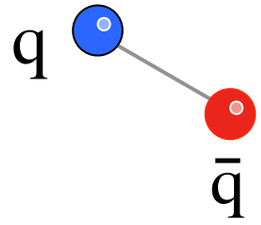




Normal meson:
flux tube in ground state
m=0
$PC=(-1)^{S+1}$



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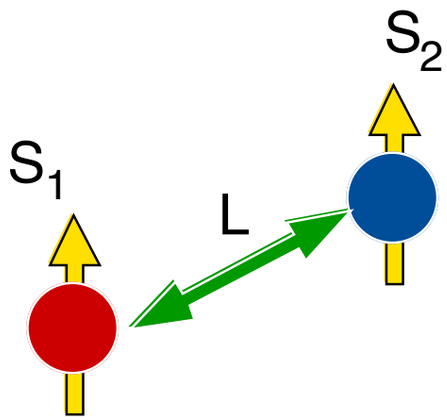

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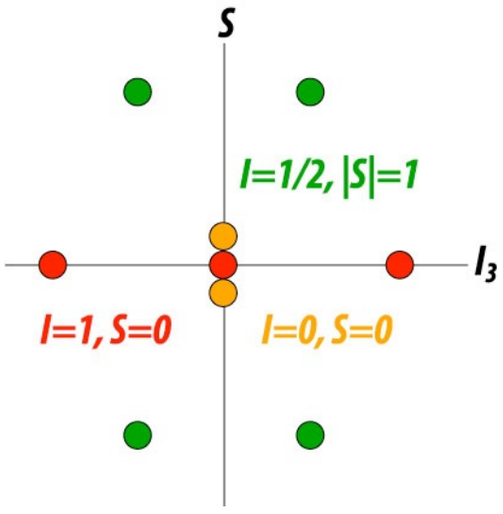

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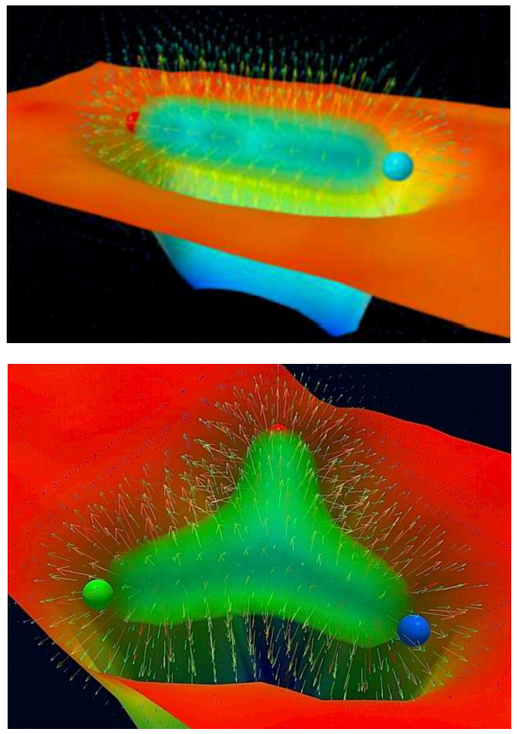
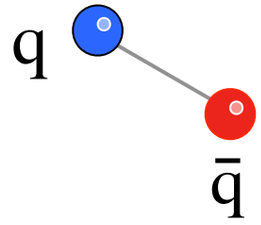
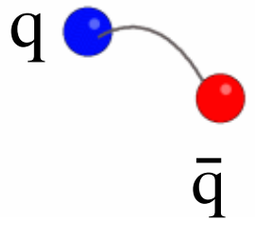


Normal meson:
flux tube in ground state
m=0
PC=(-1) S+1



Hybrid meson:
flux tube in excited state
m=1
PC=(-1) S



In the first-excited state we have two degenerate transverse modes – clockwise and counter-clockwise – that lead to

$J^{PC} = 1^{+-}$ or $J^{PC}=1^{-+}$

for the excited glue string.

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Production of Hybrid Mesons

Combine the QN $J^{PC} = 1^{+-}, 1^{-+}$ of the excited gluonic field with those of the quarks:

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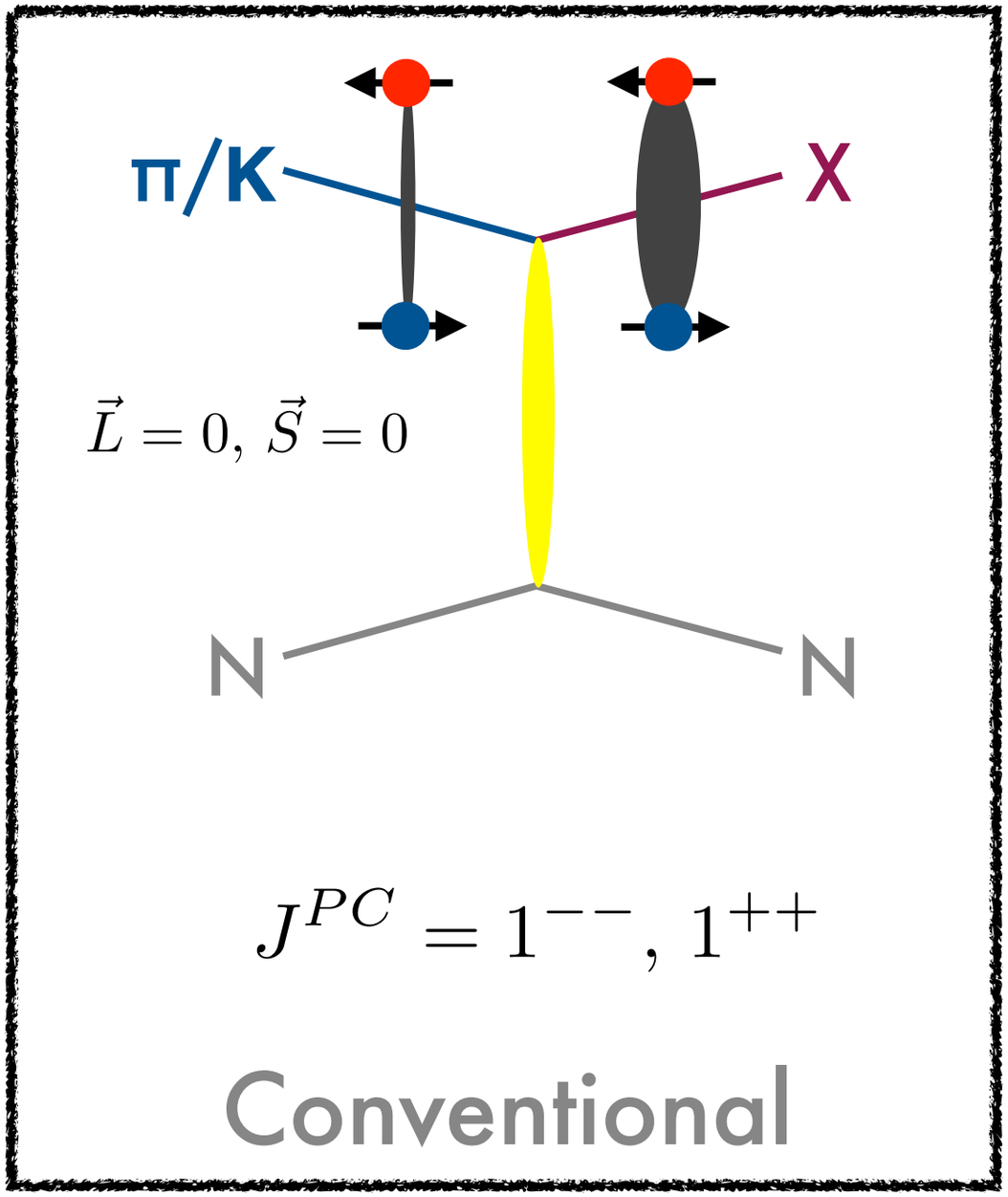

$J^{PC} = 1^{--}, 1^{++}$

Conventional

Production of Hybrid Mesons

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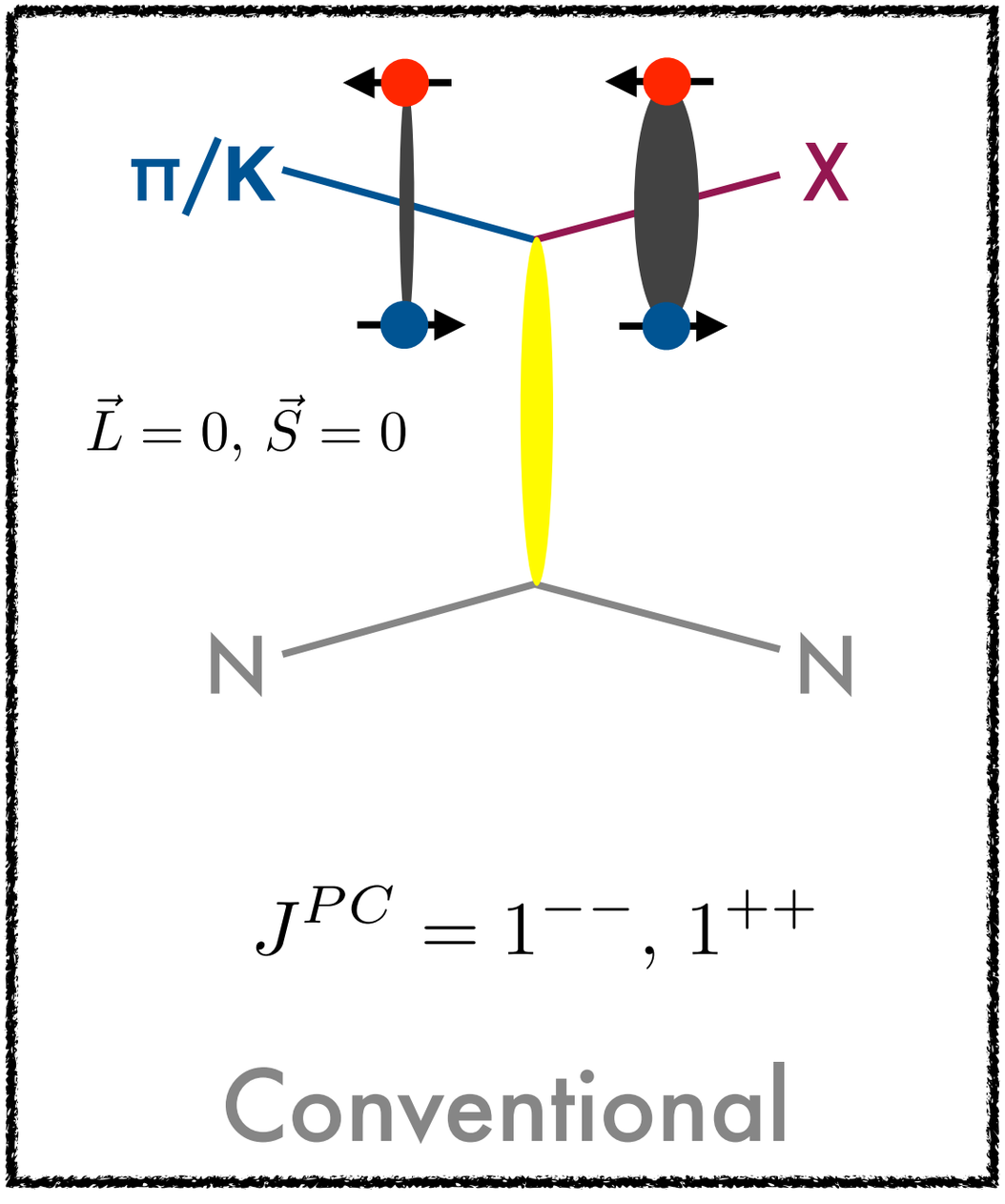
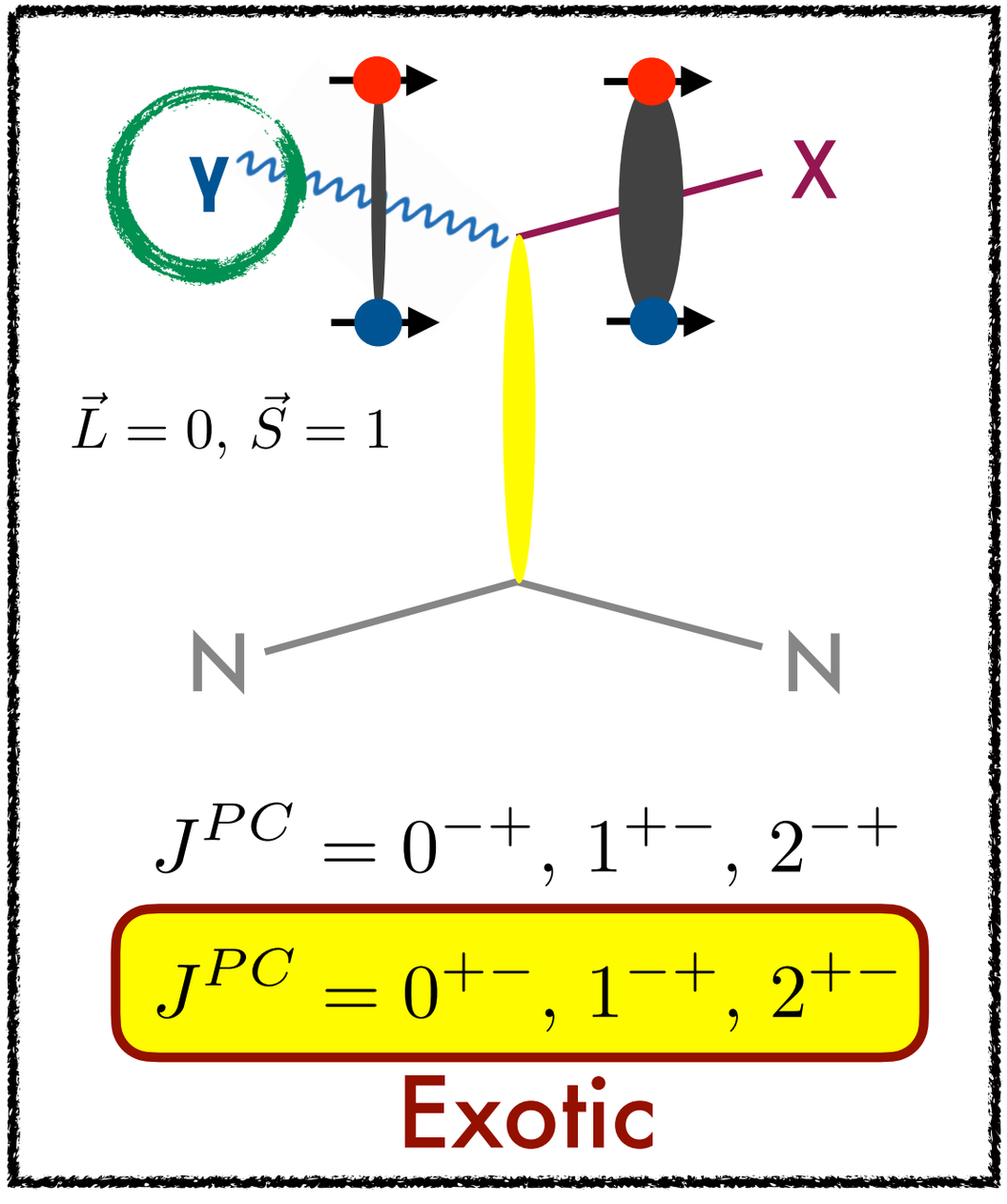
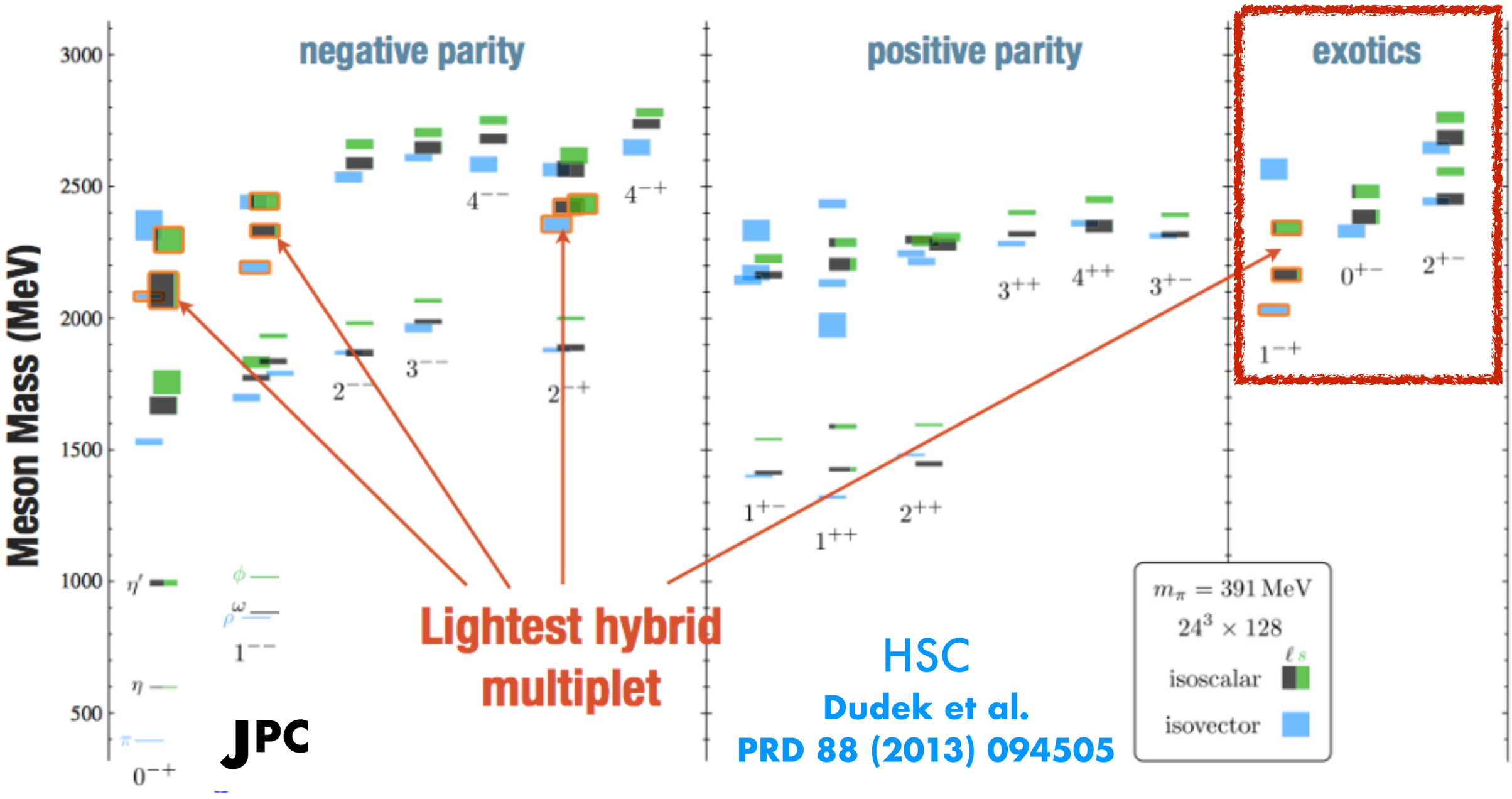




LQCD Meson Spectrum



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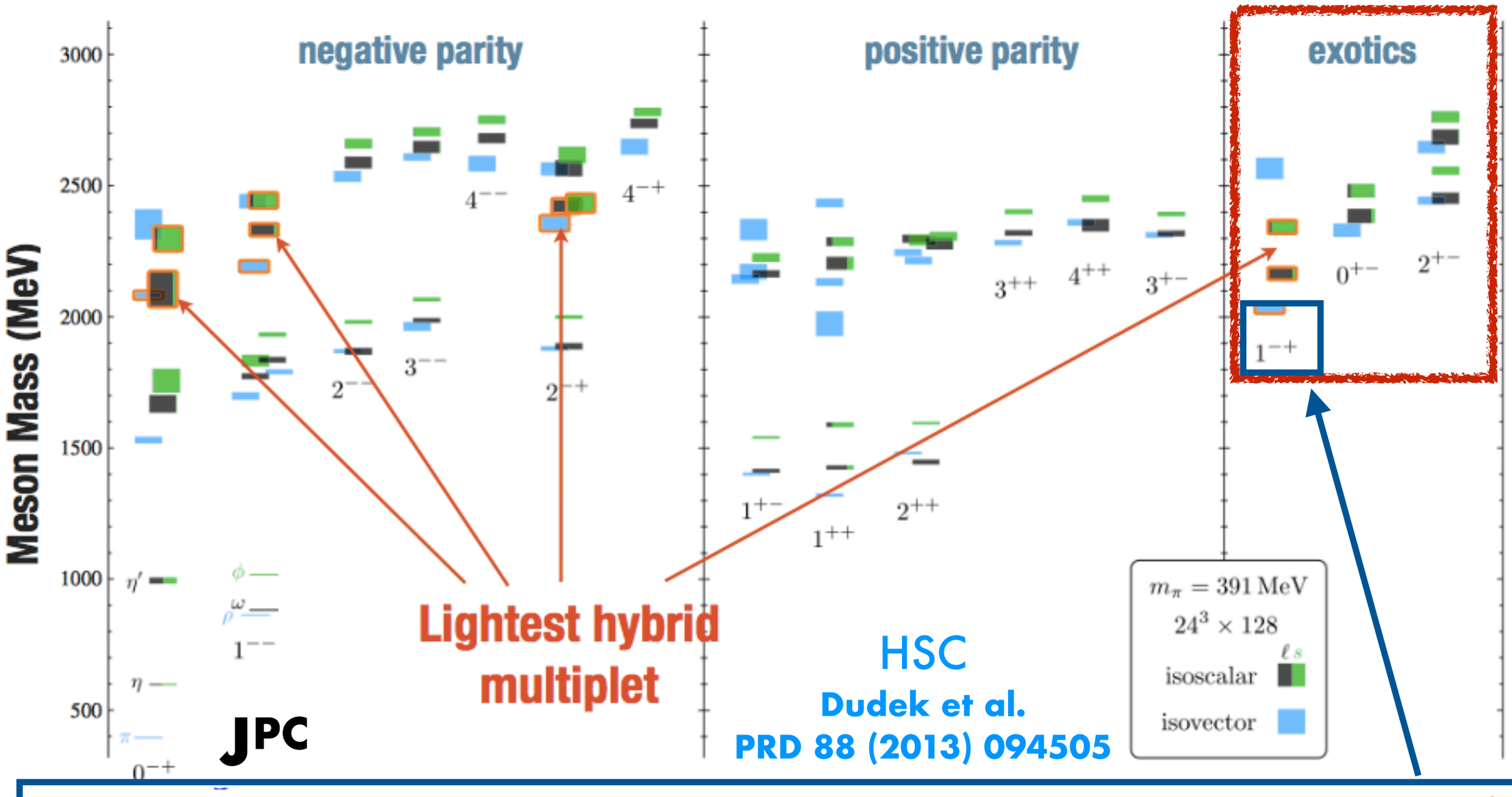

Past searches have focused on the lightest hybrid $\pi_1(1600)$ with 1^{-+}

History: Google reveals

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- **Hall-D Collaboration formed in 1998**
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- 2004: Google
  - GlueX player – Scripting Language (JPN)
  - GlueX – Active X software (JPN)
  - Gluex – Enzyme (DE)
  - glueX – public static java.awt.Component
  - Glue X – Preschool Ideas for teaching alphabet
    - glue X's using colored paper, make an X ray
  - X-Logic Glue - enables diverse languages and logical tools to be integrated in the solution of complex problems.
- 2010: 98/100 of first Google links are related to 'our' GlueX.
- **2026: all about 'the' GlueX except for one "competitor"**

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GlueX Collaboration

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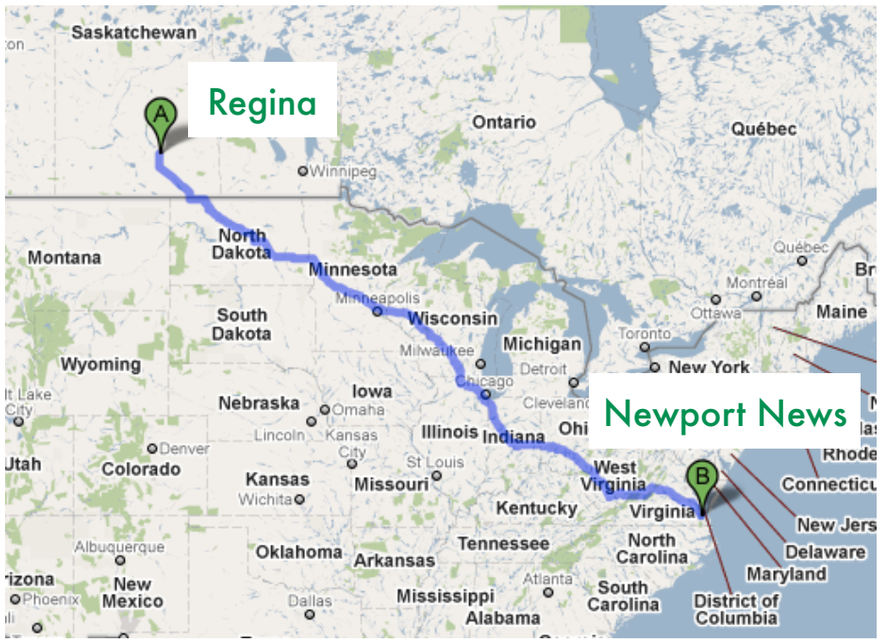
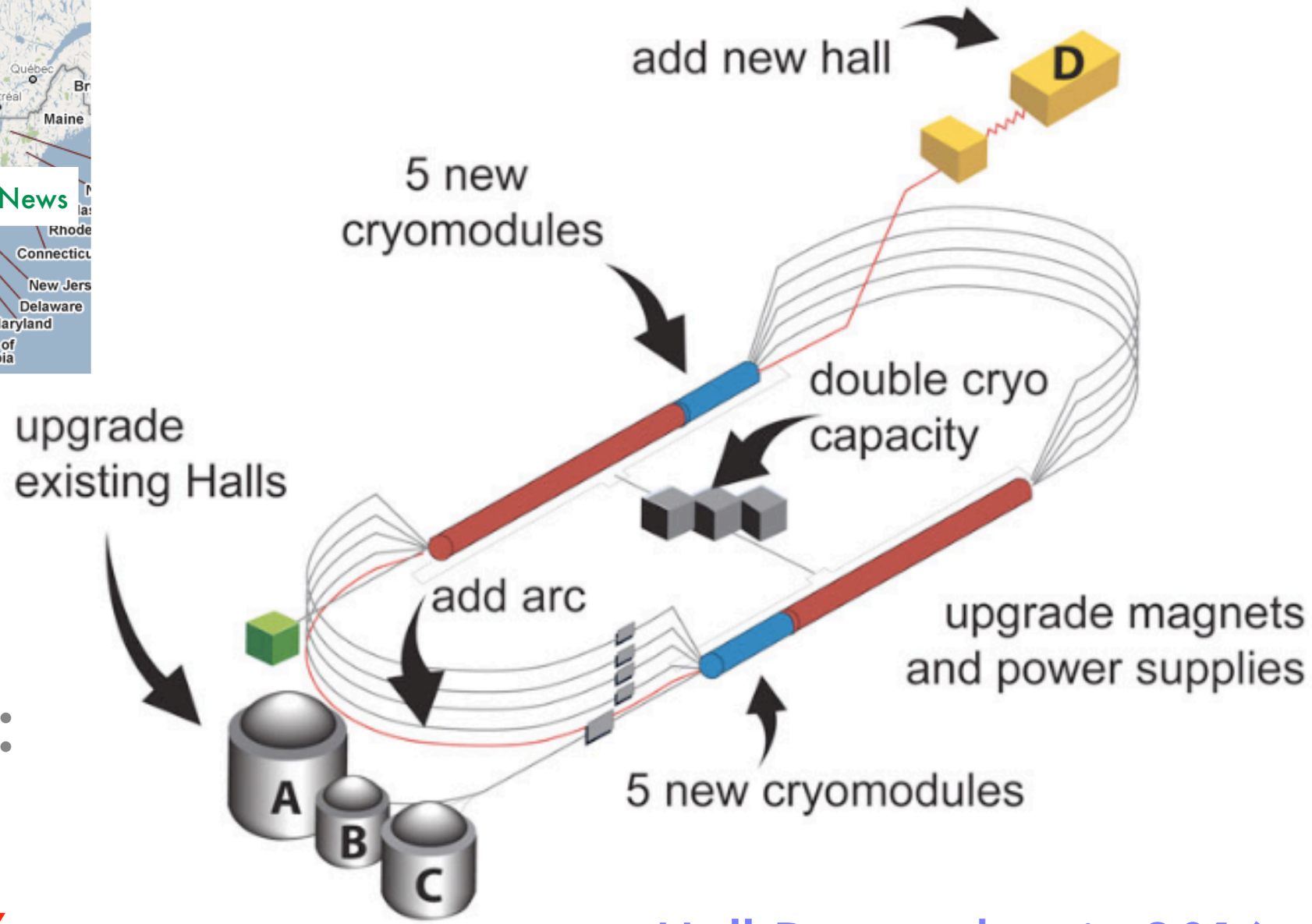
Jefferson Lab



Electron linear accelerator



CEBAF

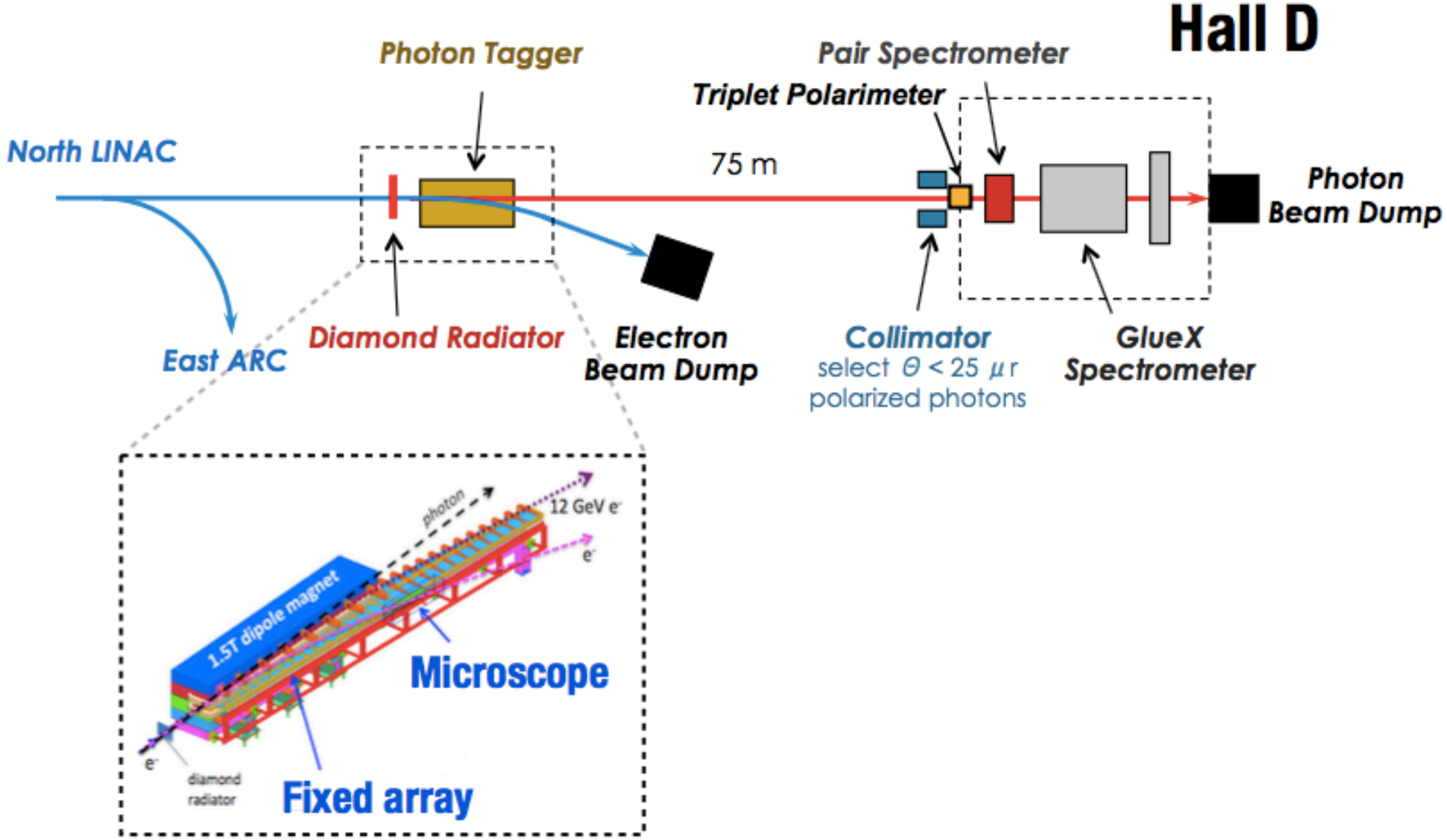
2012 Upgrade:

6→12 GeV

4th Hall GlueX

Hall D turned-on in 2016

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

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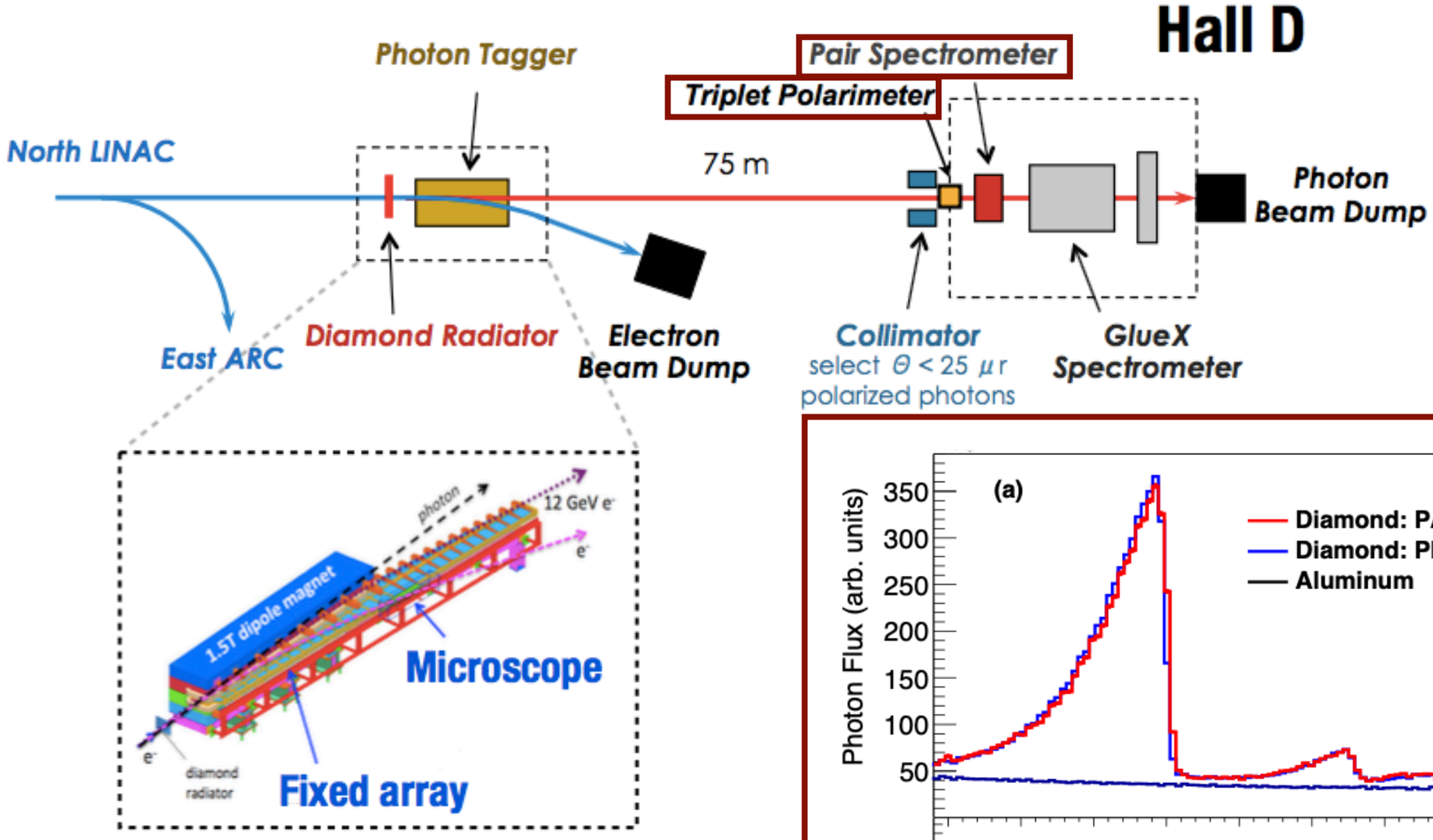
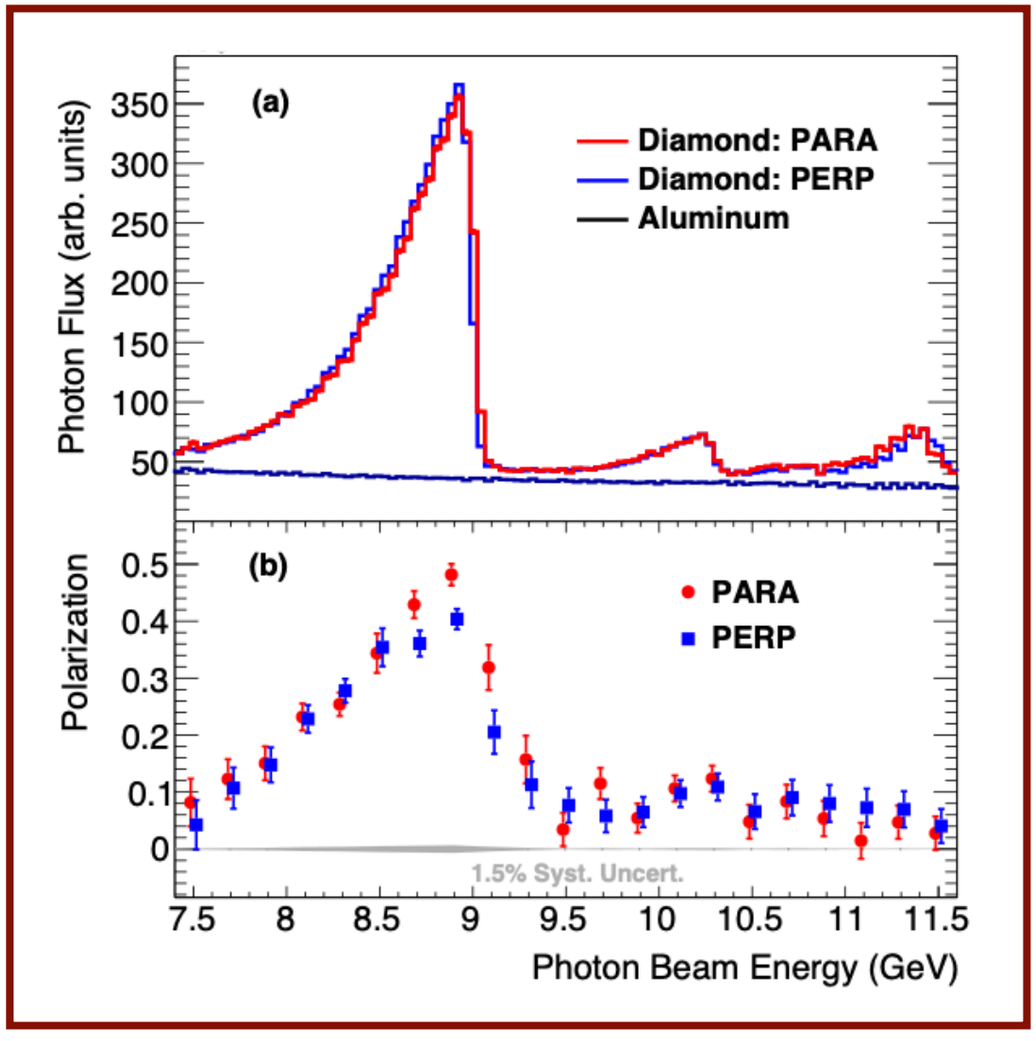
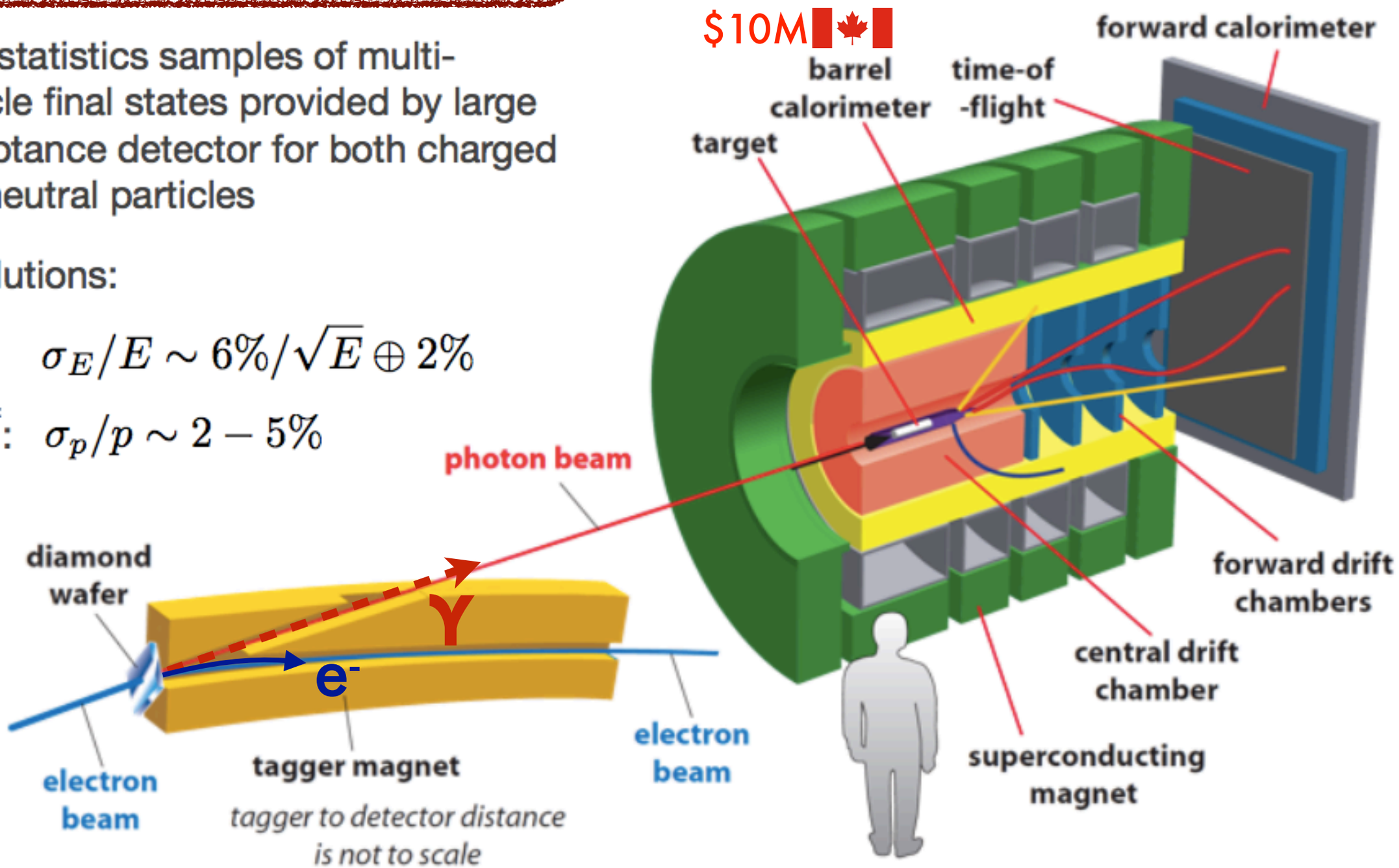




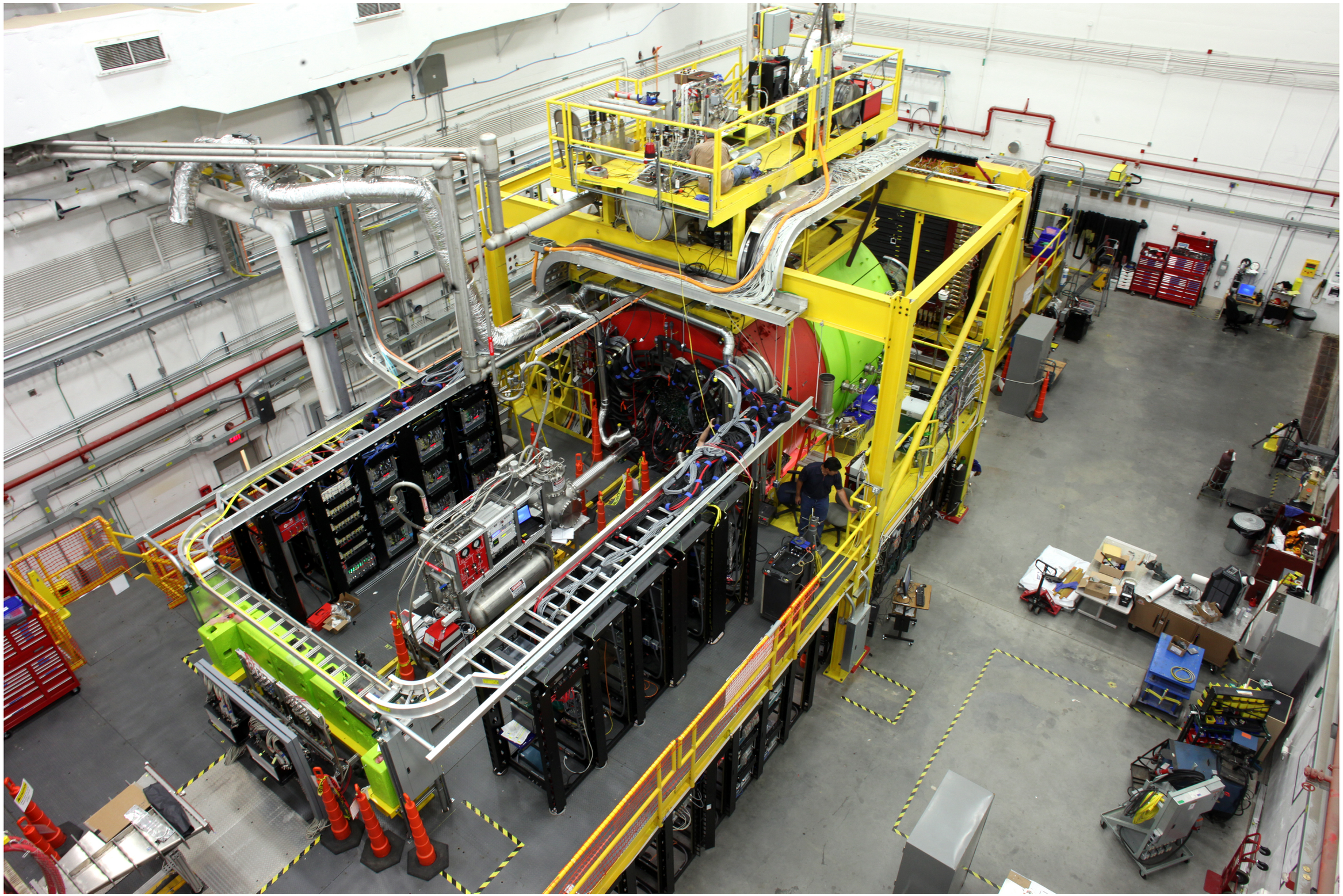
- Linearly polarized photons via coherent bremsstrahlung from diamond radiator
- Design intensity of 10^8 γ/s in coherent peak between E_γ = 8.4 and 9 GeV

The 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 Detector



GlueX Productivity

~ 23 Peta bytes of data collected

Year	Theses	Physics	Techical
2019	4	2	1
2020	5	1	5
2021	4	1	3
2022	4	2	3
2023	6	2	3
2024	10	1	3
2025	5	4	3
2026	3	2	3
Total	56 (12)	15 (3)	59 (8)

Many new analyses underway

Roadmap to exotics

Roadmap to exotics

GlueX Reconstruction, Analysis, and Simulation Framework
GlueX Collaboration

Systematics Task Forces
S. Dobbs + 8 Comitttees

Validated Model for Beam and Detector

Data Analysis Framework
Sean Dobbs

Cross Section Measurements
>10 collaborators

Review of the Strategy for Searching for Exotic Mesons
Outline of Talks and Activities

direct path of publications: from results on beam asymmetries to first results on exotic hybrids

measurements of beam asymmetries of meson production

spin-density matrix element measurements for ρ, ω, ϕ, and Λ(1520) photoproduction

results on cross-sections and mechanisms of $a_2(1320)^{0,-}$ photoproduction

observables that characterize Double-Regge production of the $\eta\pi^0$ system

results on cross-sections and mechanisms of $b_1^{0,-}$ photoproduction and properties of $b_1^{0,-}$ decays

extraction of the *P*-wave amplitude in $\eta\pi^{0,-}$ and $\eta'\pi^{0,-}$

first results on the exotic π_1 in photoproduction

results on the spectrum of hadrons, including hybrid mesons

Spin-Density Matrix Elements
Alex Austregesilo

Λ(1520) SDMEs
P. Pauli

ρ SDMEs
A. Austregesilo
J. Fitches

ω SDMEs using both $\gamma\pi^0$ and $\pi^+\pi^-\pi^0$
M. Dalton

ϕ SDMEs
N. Jarvis

$\eta^{(\prime)}\pi$ Analysis
Malte Albrecht

$\eta\pi^0$ Event Selection
L. Ng
Z. Baldwin
M. Albrecht

$\eta\pi^-$ Event Selection
C. Gleason

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$\pi^+\pi^-$
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K_SK_S
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G. Rodriguez

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J. Barlow

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?

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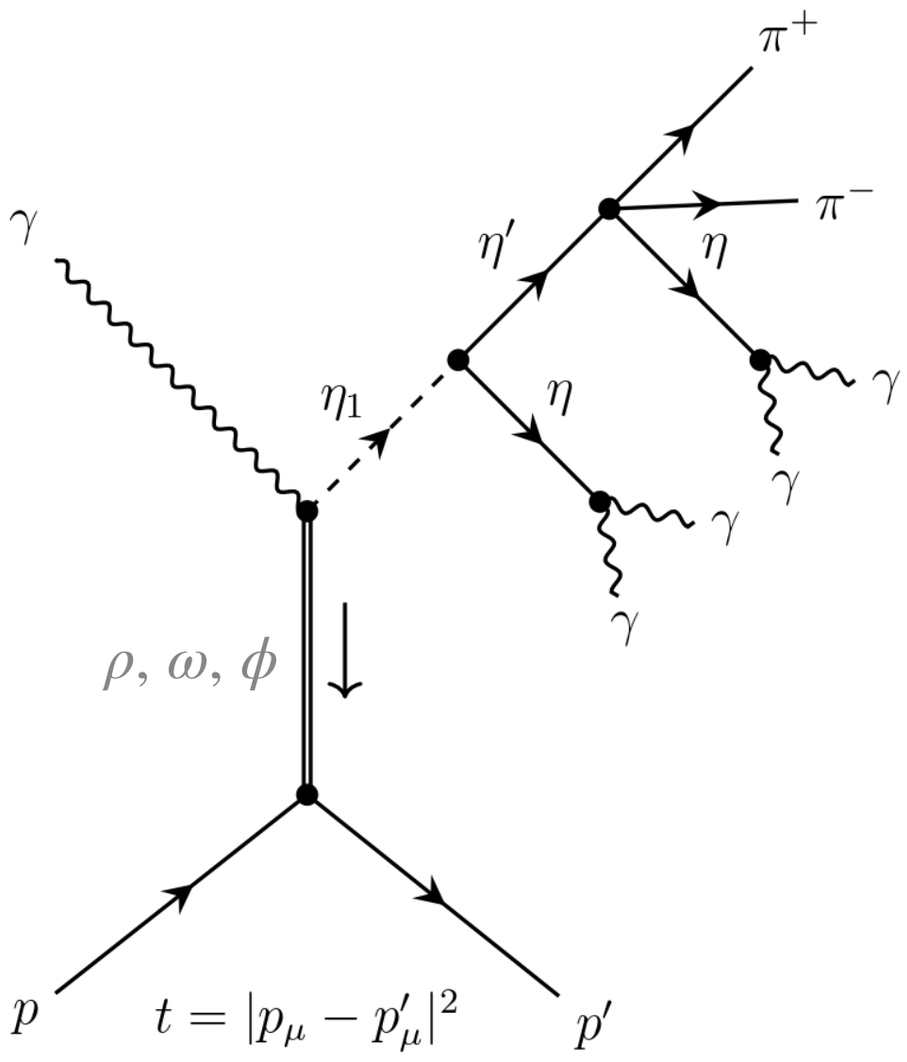
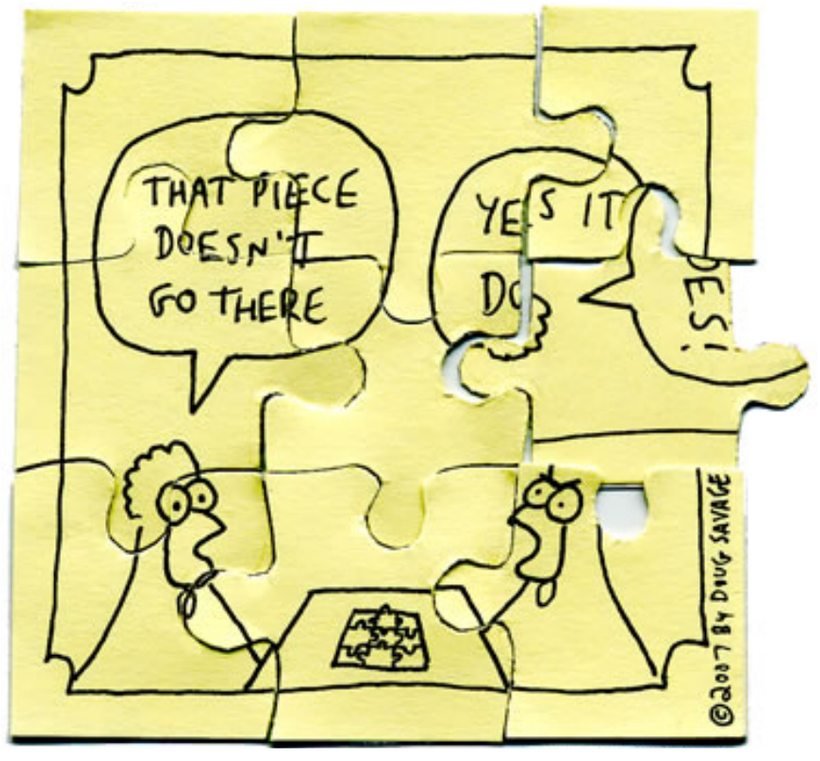
η_1 Reconstruction

$$\gamma p \to (\eta_1) p' \to (\eta \eta') p' \to (\eta(\eta \pi^+ \pi^-)) p' \to (\gamma\gamma(\gamma\gamma\pi^+\pi^-)) p'$$



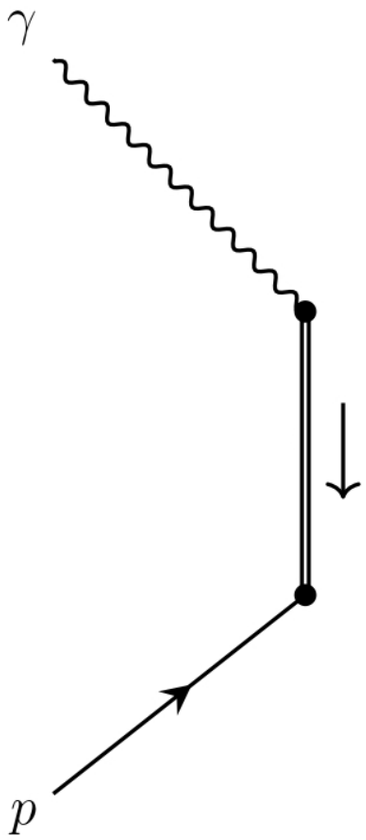
- Final states is: $\gamma\gamma\gamma\gamma\pi^+\pi^- p$
- Event reconstruction: putting the pieces of a puzzle together.



Source: savagechickens.com

η_1 Reconstruction

$$\gamma\gamma\gamma\gamma\pi^+\pi^- p'$$



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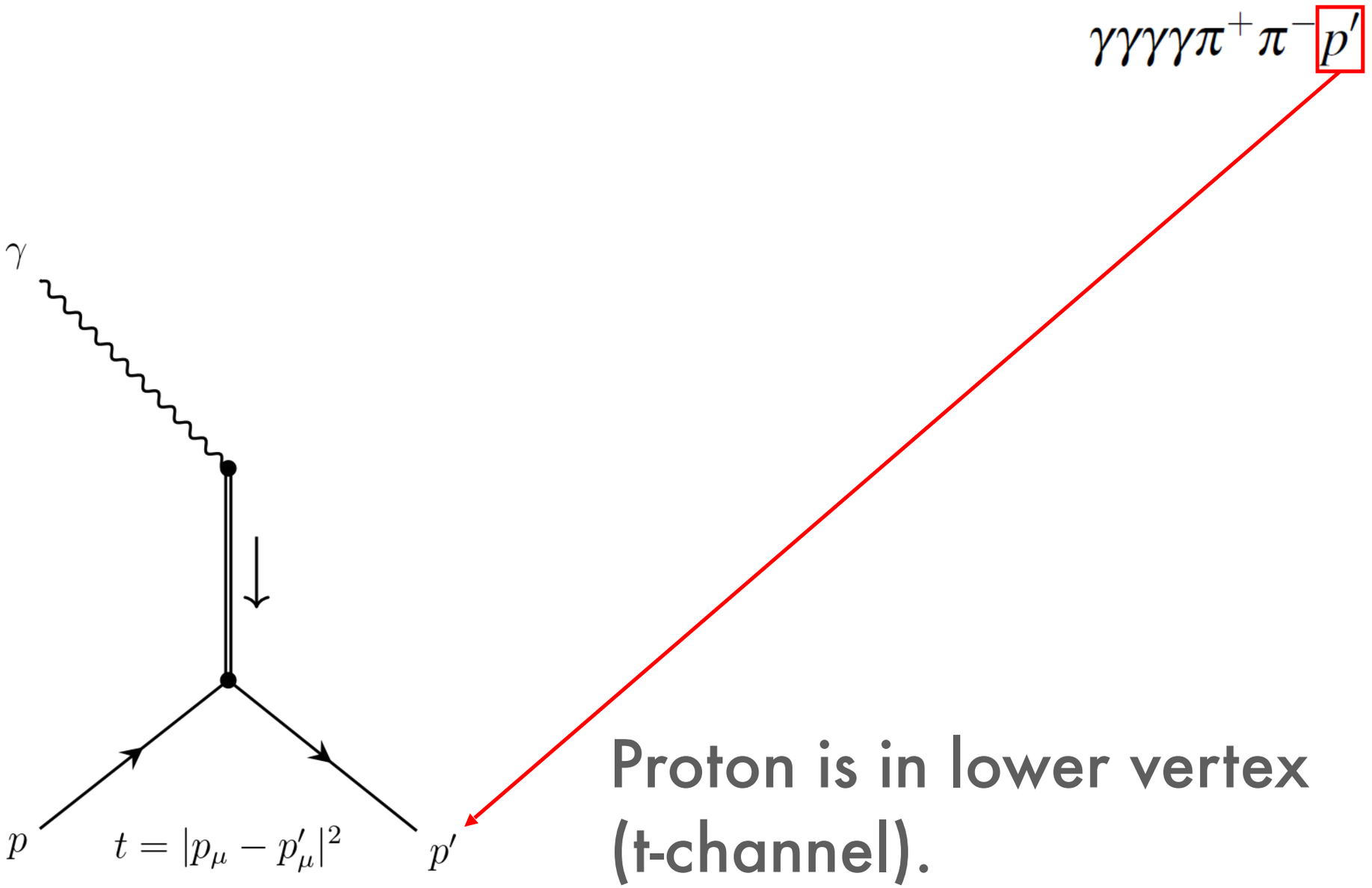
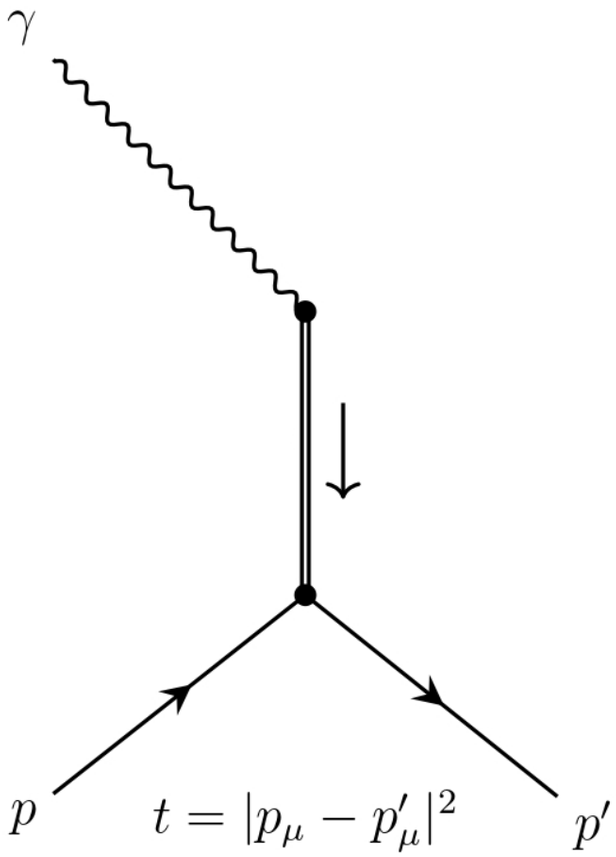


Proton is in lower vertex (t-channel).

η_1 Reconstruction

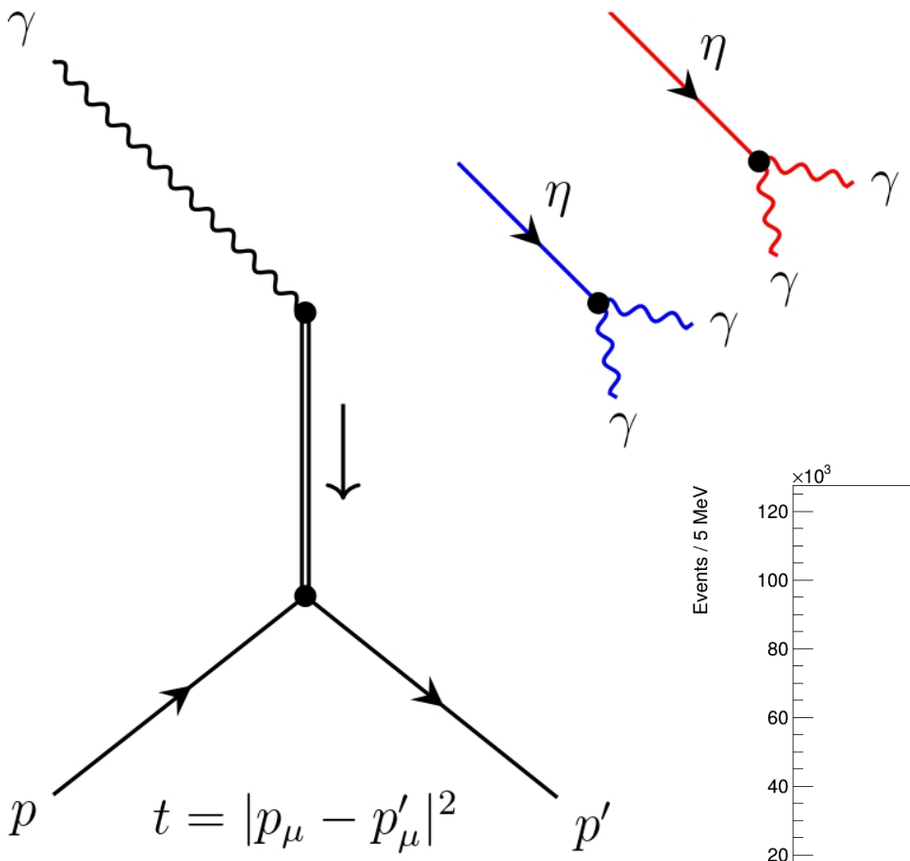
$$\gamma\gamma\gamma\gamma\pi^+\pi^- p'$$



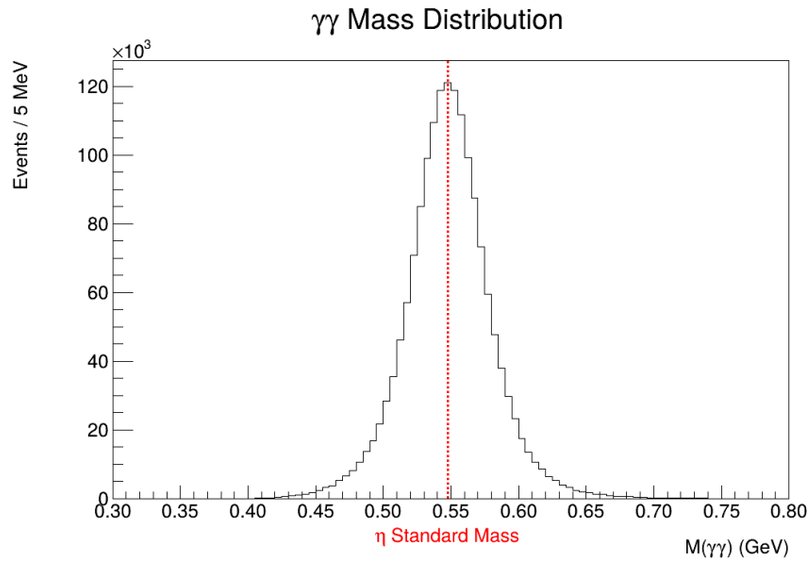
$$\eta \to \gamma\gamma$$

Combinatorics to decide how 4 γ should be combined to form 2 η

η_1 Reconstruction



$$\gamma\gamma\gamma\gamma\pi^+\pi^- p'$$
$$\downarrow$$
$$\gamma\gamma\gamma\gamma\pi^+\pi^- p'$$
$$\downarrow$$
$$\eta\,\eta\,\pi^+\pi^- p'$$



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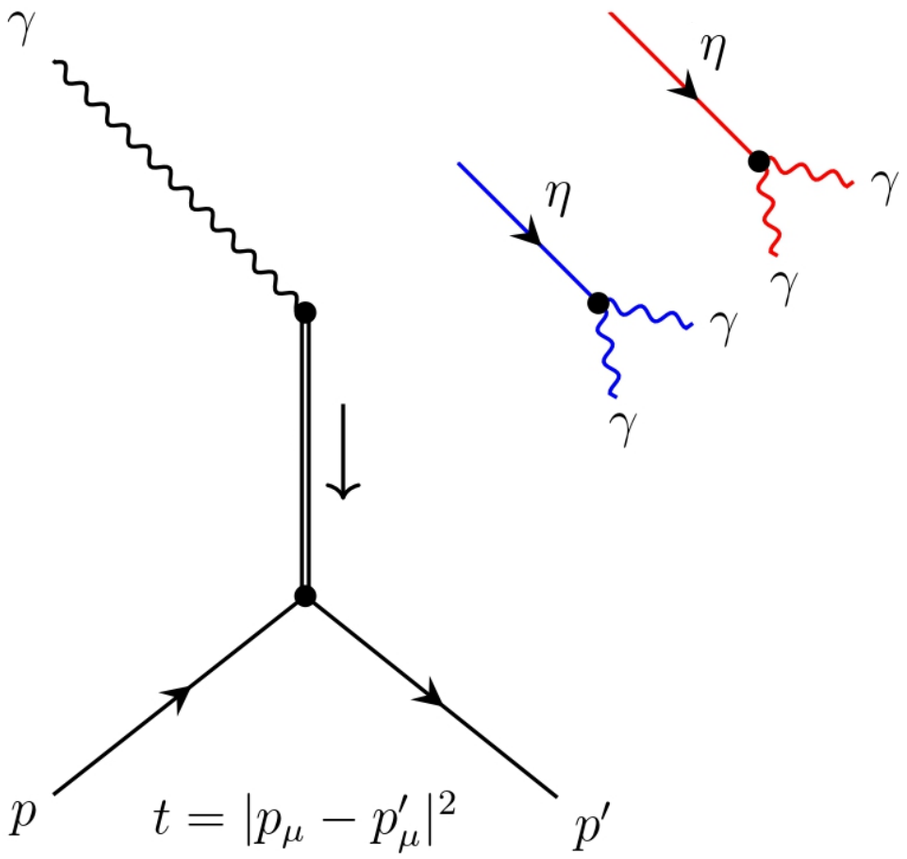

$$\gamma\gamma\gamma\gamma\pi^+\pi^- p'$$
$$\downarrow$$
$$\gamma\gamma\gamma\gamma\pi^+\pi^- p'$$
$$\downarrow$$
$$\eta\,\eta\,\pi^+\pi^- p'$$

$$\eta' \to \eta\,\pi^+\pi^-$$

Combinatorics to decide which η has decayed from the η'

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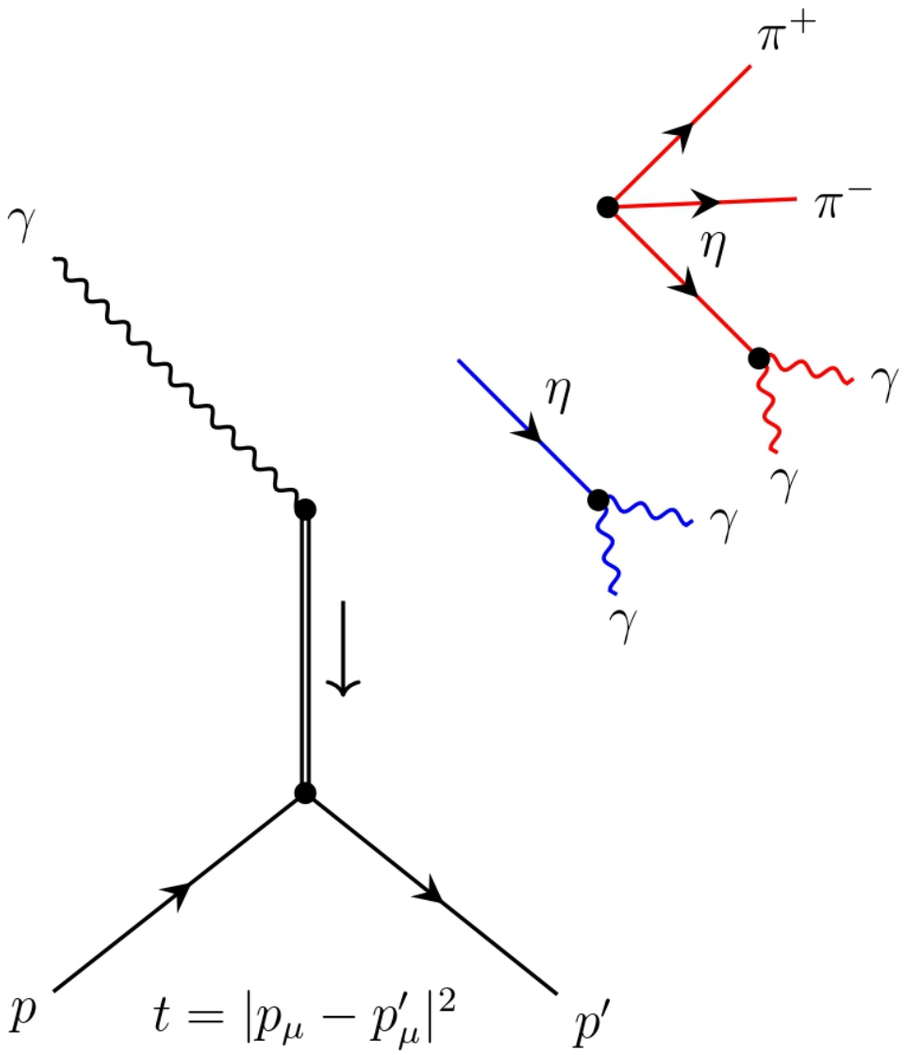

$$\gamma\gamma\gamma\gamma\pi^+\pi^- p'$$
$$\downarrow$$
$$\gamma\gamma\gamma\gamma\pi^+\pi^- p'$$
$$\downarrow$$
$$\eta\,\eta\,\pi^+\pi^- p'$$
$$\downarrow$$
$$\eta\,(\eta\,\pi^+\pi^-)\,p'$$

$$\eta' \to \eta\,\pi^+\pi^-$$

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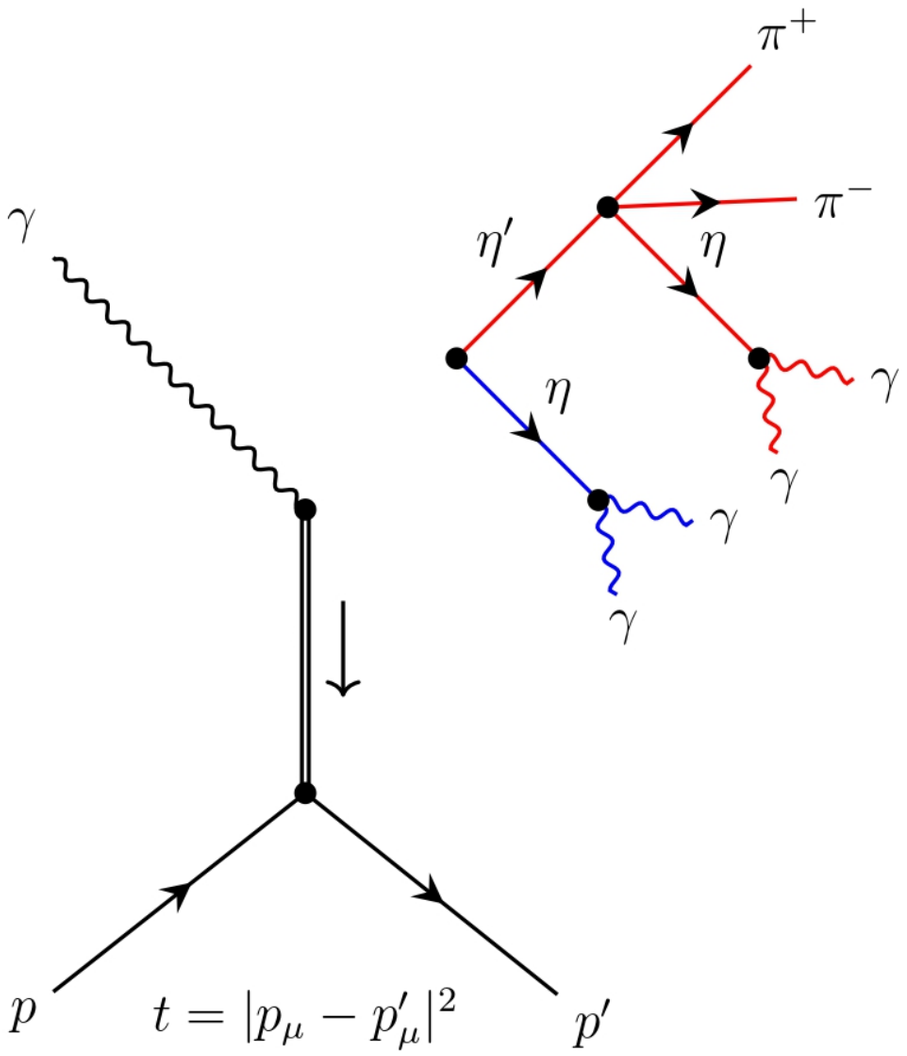

$$\gamma\gamma\gamma\gamma\pi^+\pi^- p'$$
$$\downarrow$$
$$\gamma\gamma\gamma\gamma\pi^+\pi^- p'$$
$$\downarrow$$
$$\eta\,\eta\,\pi^+\pi^- p'$$
$$\downarrow$$
$$\eta\,(\eta\,\pi^+\pi^-)\,p'$$
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$$\eta\,\eta'\,p'$$

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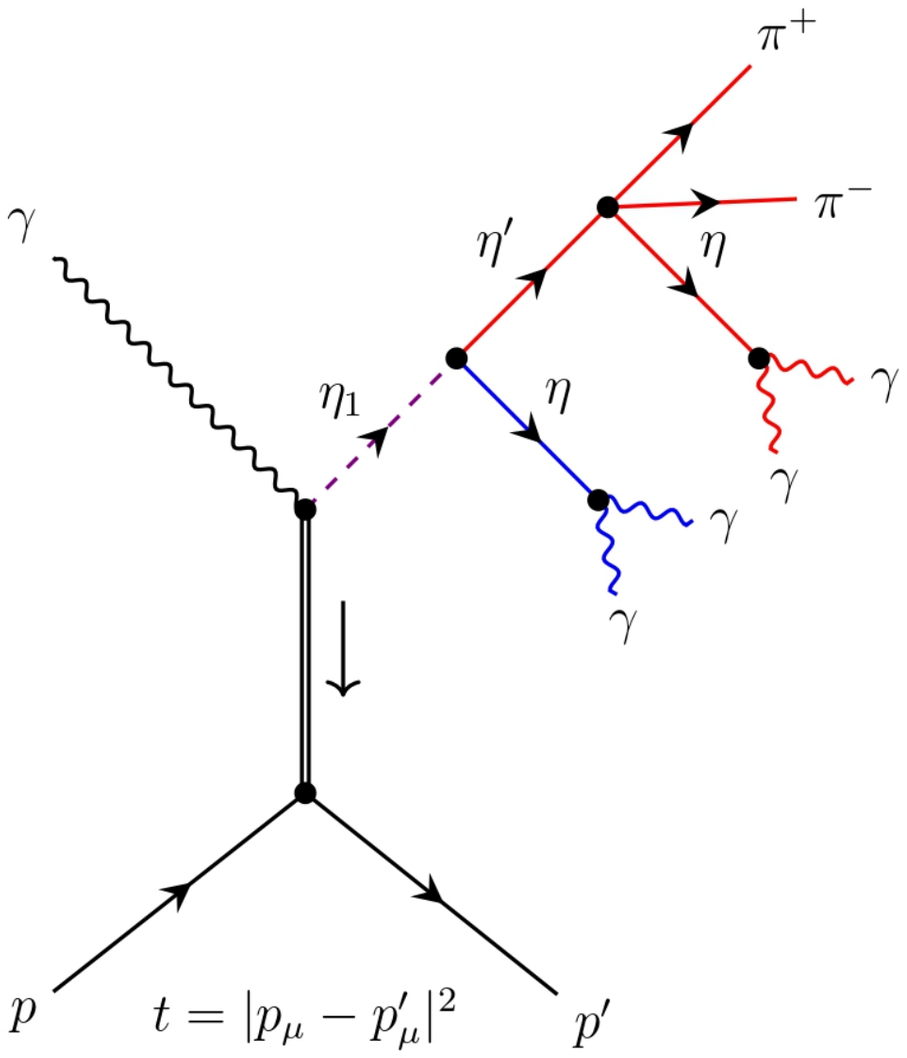

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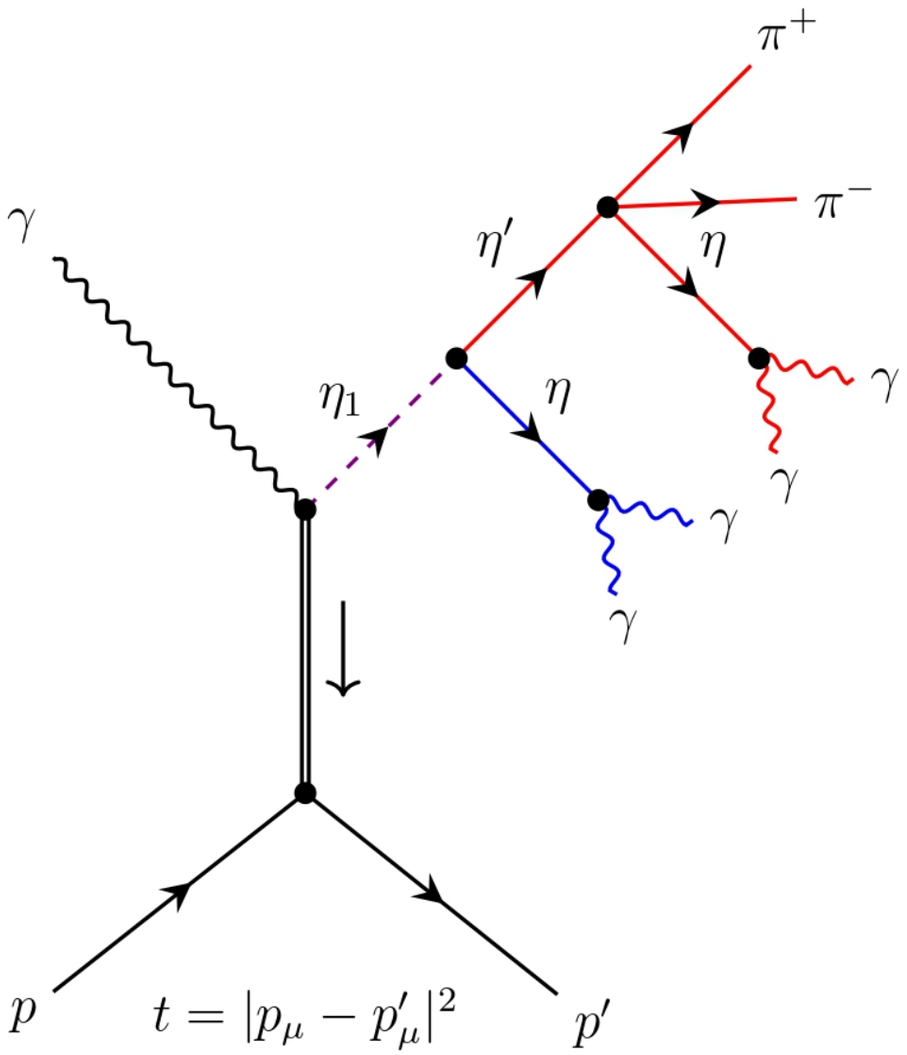
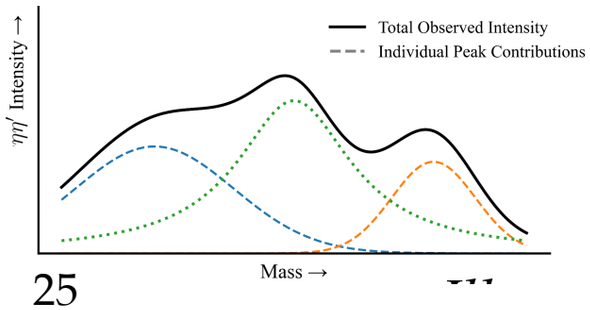
$$\downarrow$$
$$\gamma\gamma\gamma\gamma\pi^+\pi^- p'$$
$$\downarrow$$
$$\eta\,\eta\,\pi^+\pi^- p'$$
$$\downarrow$$
$$\eta\,(\eta\,\pi^+\pi^-)\,p'$$
$$\downarrow$$
$$\eta\,\eta'\,p'$$
$$\downarrow$$
$$\eta_1 p'$$

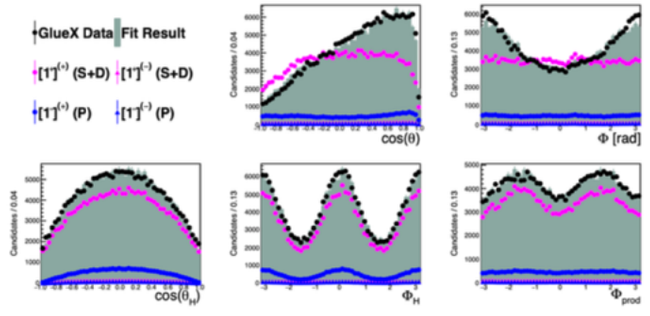
η_1 Reconstruction



$$\gamma\gamma\gamma\gamma\pi^+\pi^- p'$$
$$\downarrow$$
$$\gamma\gamma\gamma\gamma\pi^+\pi^- p'$$
$$\downarrow$$
$$\eta\,\eta\,\pi^+\pi^- p'$$
$$\downarrow$$
$$\eta\,(\eta\,\pi^+\pi^-)\,p'$$
$$\downarrow$$
$$\eta\,\eta'\,p'$$
$$\downarrow$$
$$\eta_1 p'$$

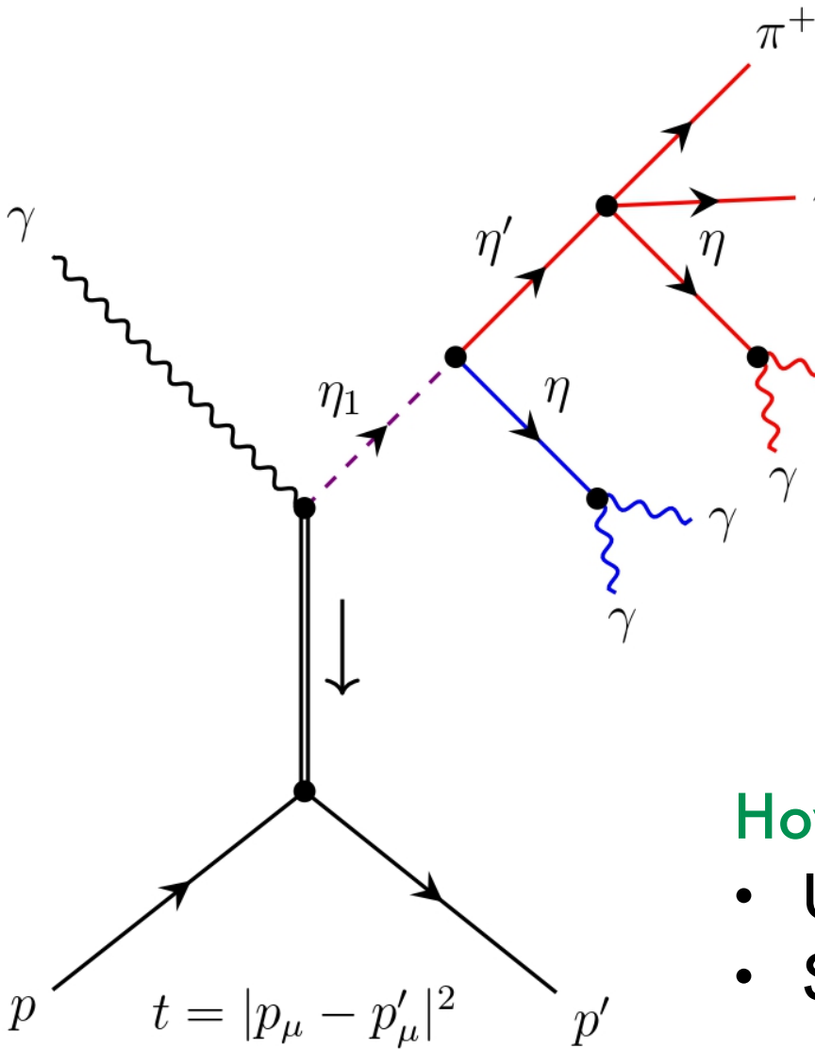
Multi-dimensional fits of spectra

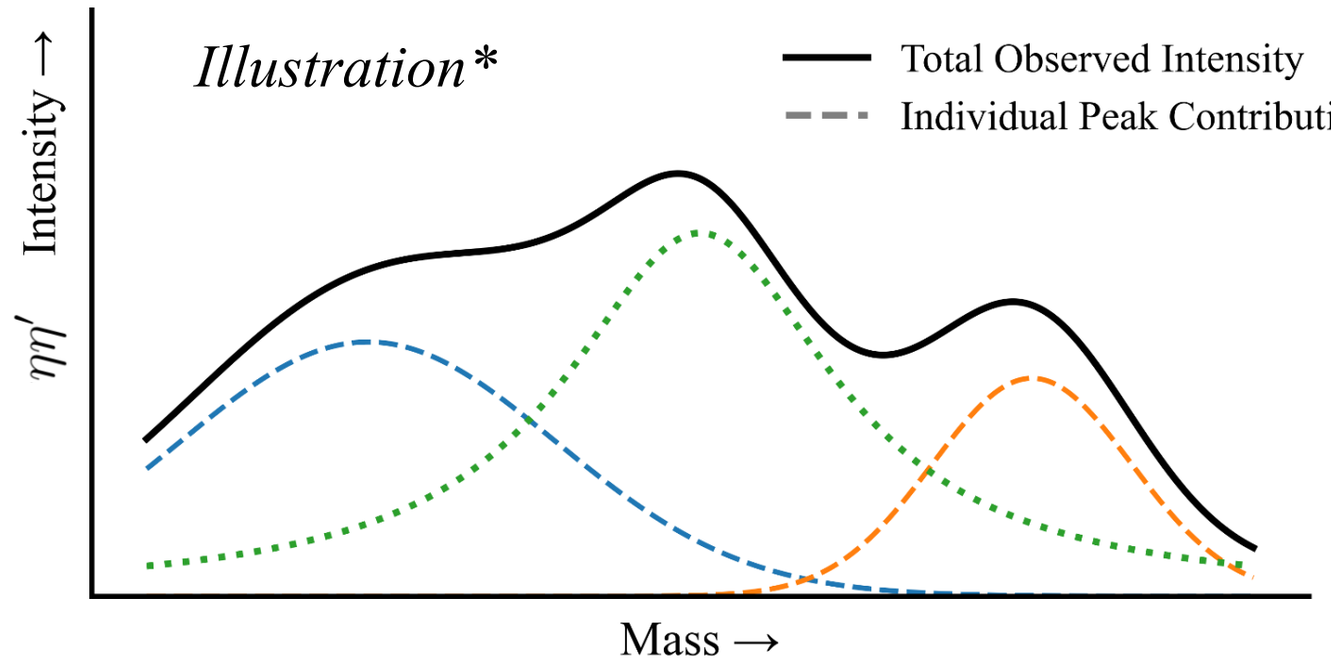




Methodology: Partial Wave Analysis

$$\gamma p \to (\eta_1) p' \to (\eta\eta') p' \to (\eta(\eta\pi^+\pi^-)) p' \to (\gamma\gamma(\gamma\gamma\pi^+\pi^-)) p'$$





How does one extract J^{PC} contributions from this spectrum?

- Using only mass spectrum is insufficient.
- Study and analyze intensity in more "dimensions":
  - →decay angles of the constituent particles.
- Develop model from scattering theory.

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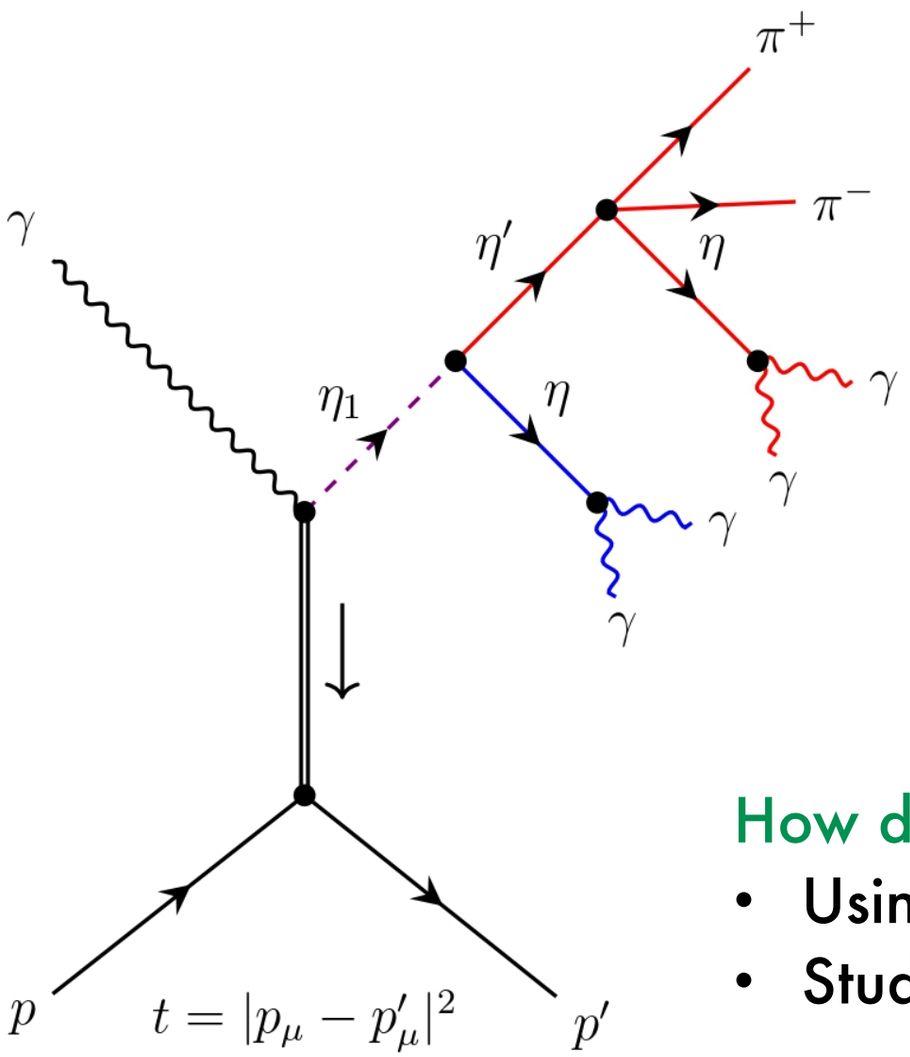

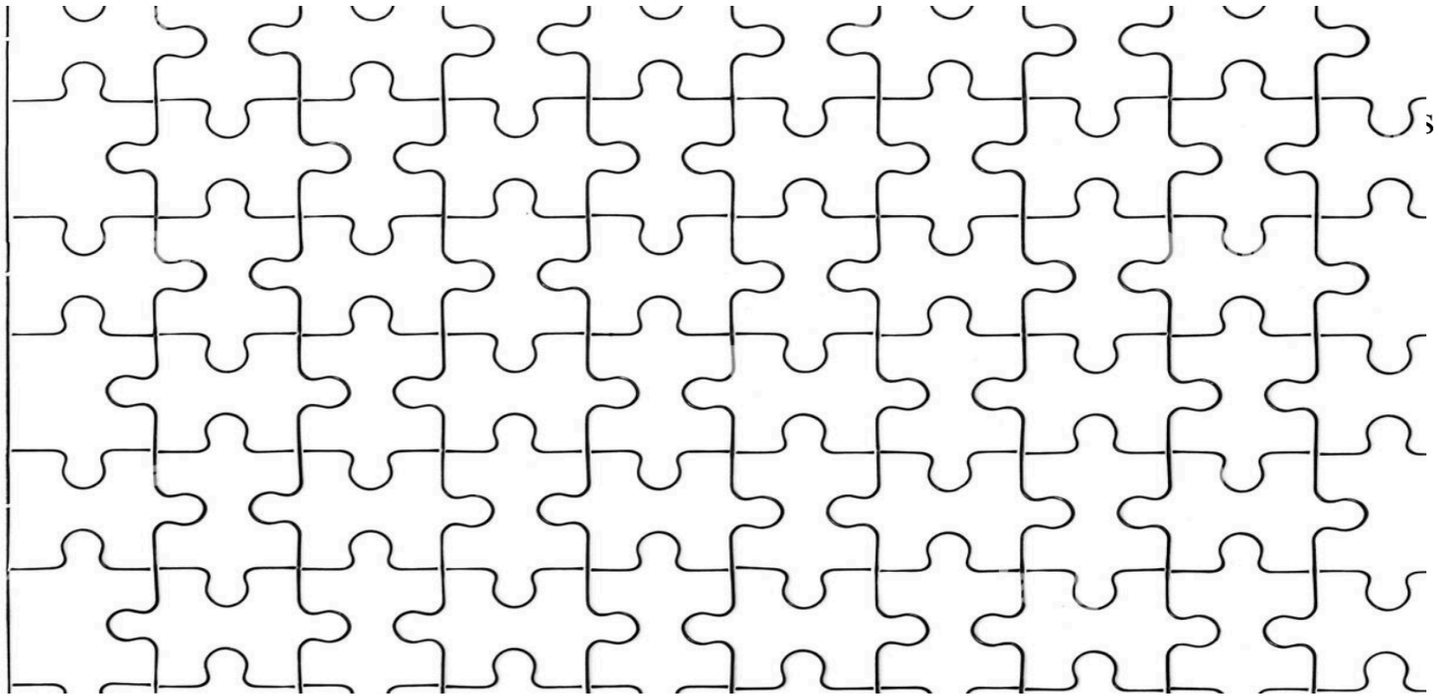

Source: alamy.com

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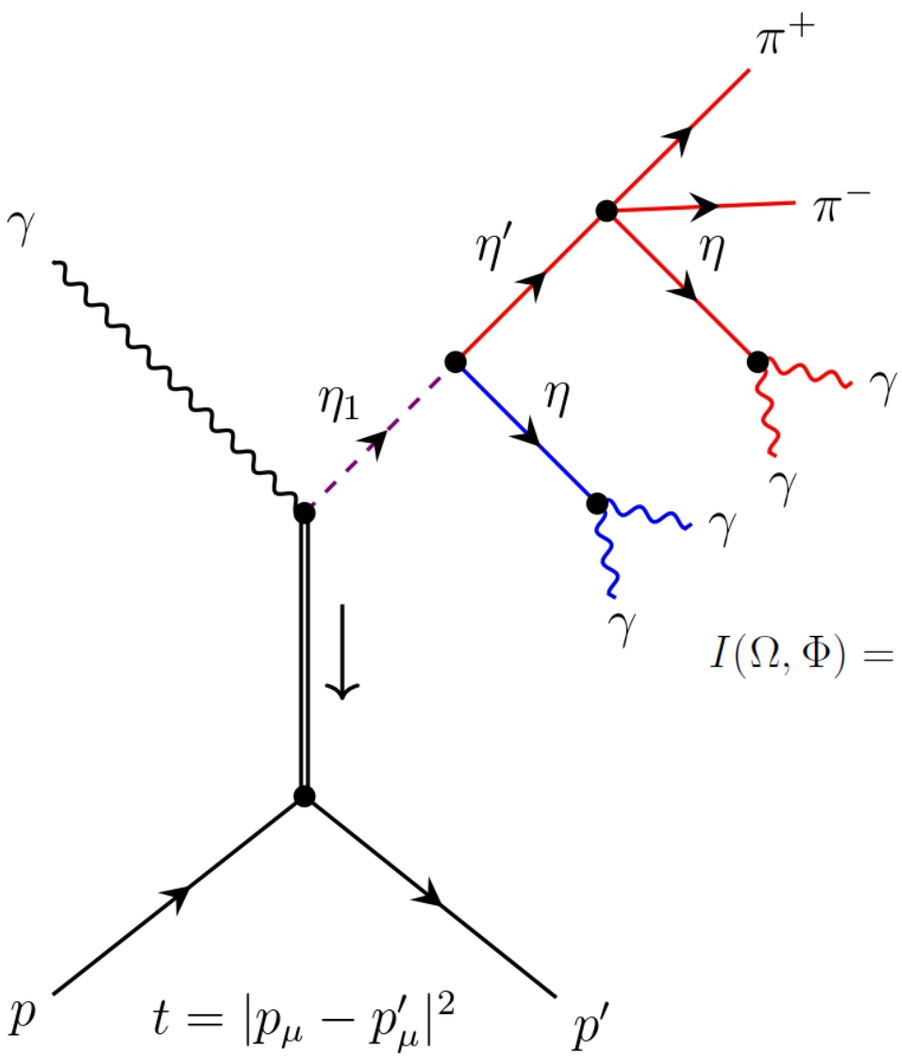


Partial Wave Analysis (PWA):

Intensity distribution under amplitude analysis framework can be written as:

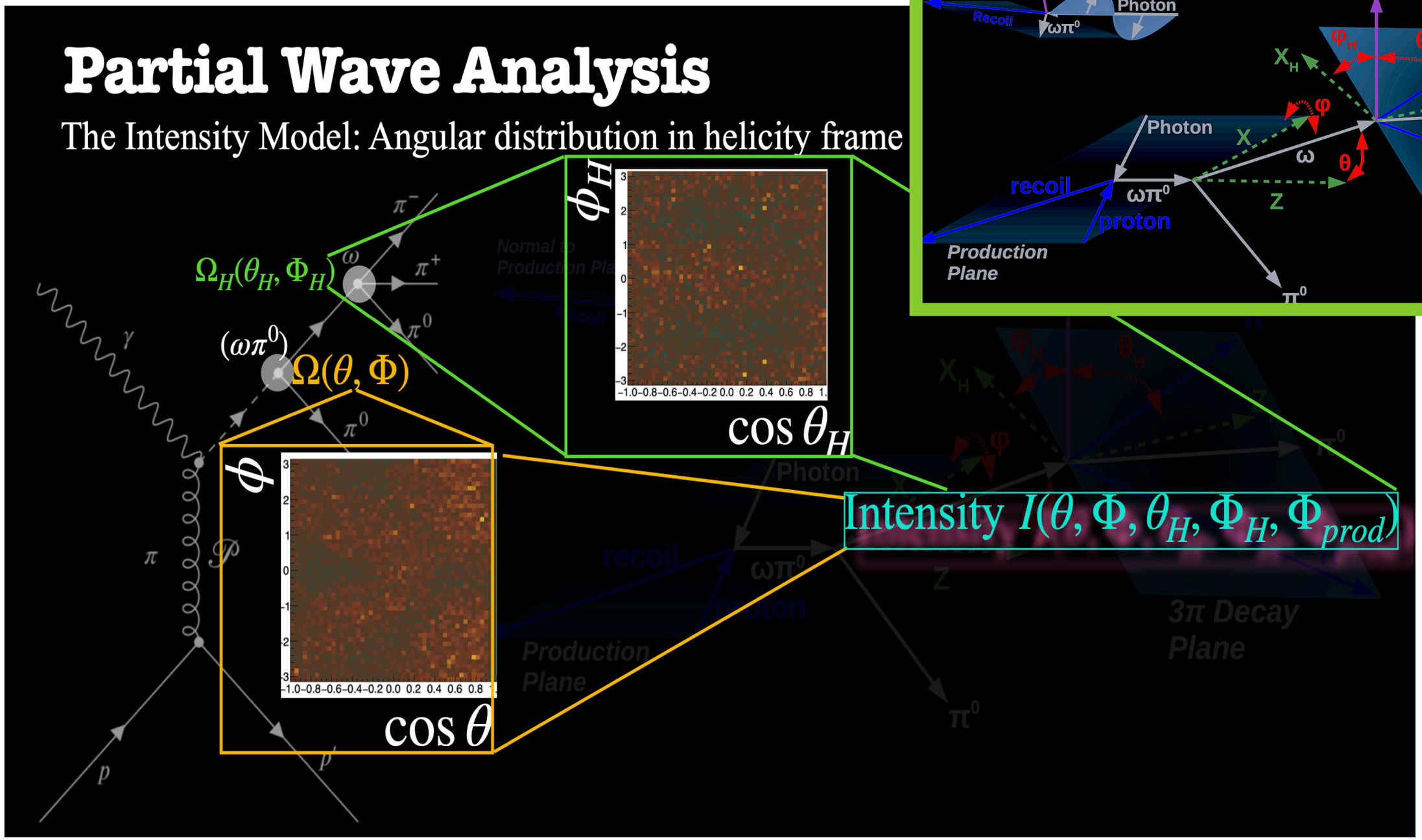
$$I(\Omega, \Phi) \equiv \frac{d\sigma}{dt dm_{\eta\eta'} d\Omega d\Phi}$$

which can be solved to give:

$$I(\Omega,\Phi) = 2\kappa \sum_k \Big\{ (1-P_\gamma) \Big| \sum_{l,m} [l]^{(-)}_{m;k} \Re[Z^m_l(\Omega,\Phi)] \Big|^2 + (1-P_\gamma) \Big| \sum_{l,m} [l]^{(+)}_{m;k} \Im[Z^m_l(\Omega,\Phi)] \Big|^2$$
$$+ (1+P_\gamma) \Big| \sum_{l,m} [l]^{(+)}_{m;k} \Re[Z^m_l(\Omega,\Phi)] \Big|^2 + (1+P_\gamma) \Big| \sum_{l,m} [l]^{(-)}_{m;k} \Im[Z^m_l(\Omega,\Phi)] \Big|^2 \Big\}$$

PWA - A framework to solve a scattering problem by extracting J^{PC}s via spectrum intensity and multiple decay angles

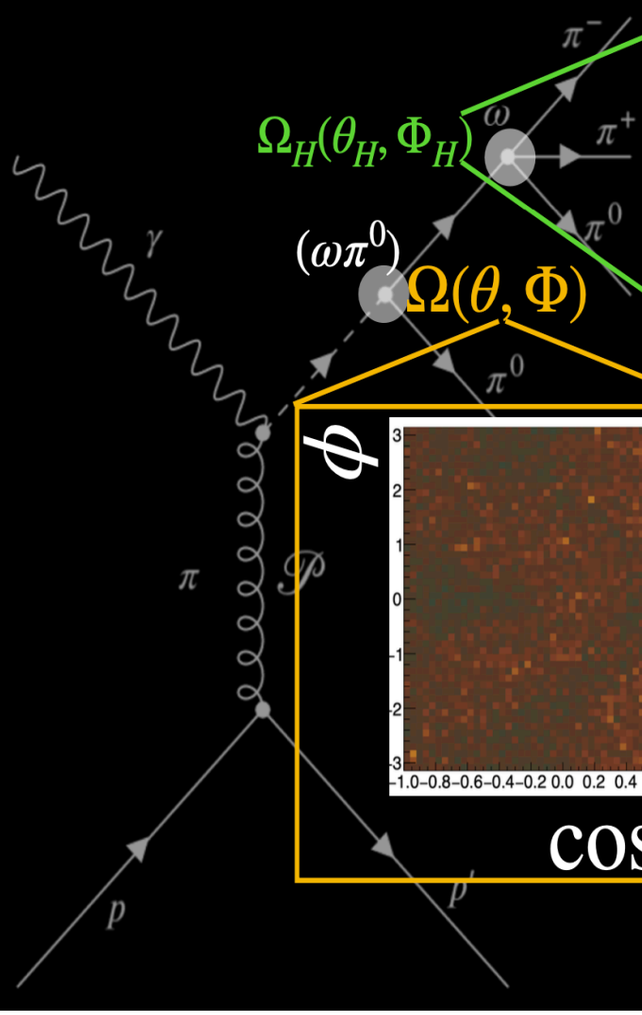
Angular Distributions

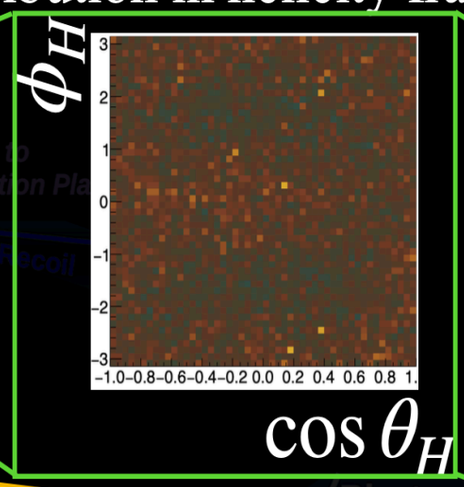


Angular Distributions

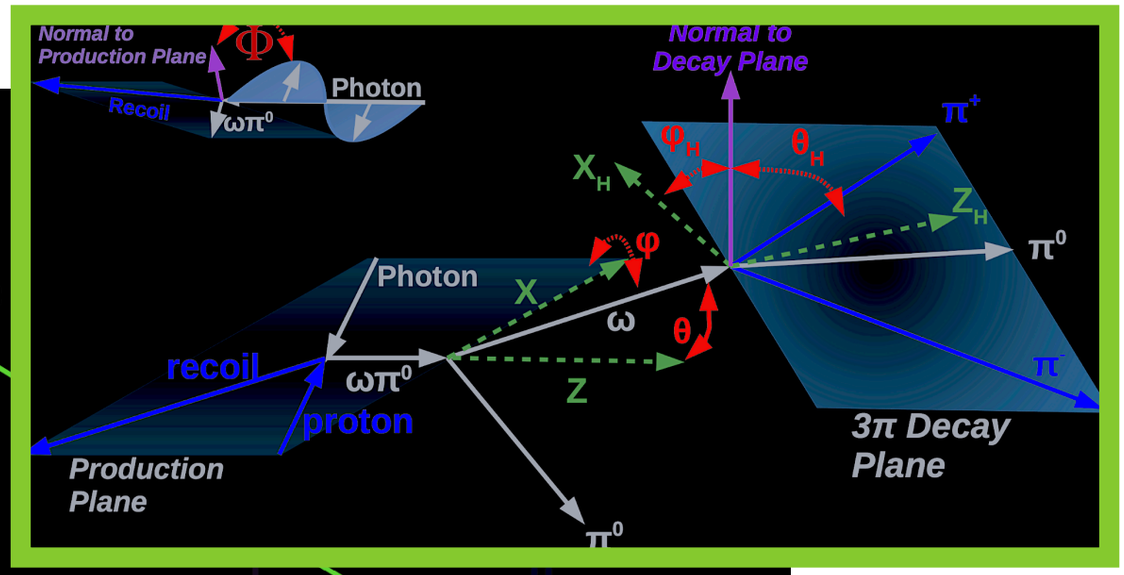
Partial Wave Analysis

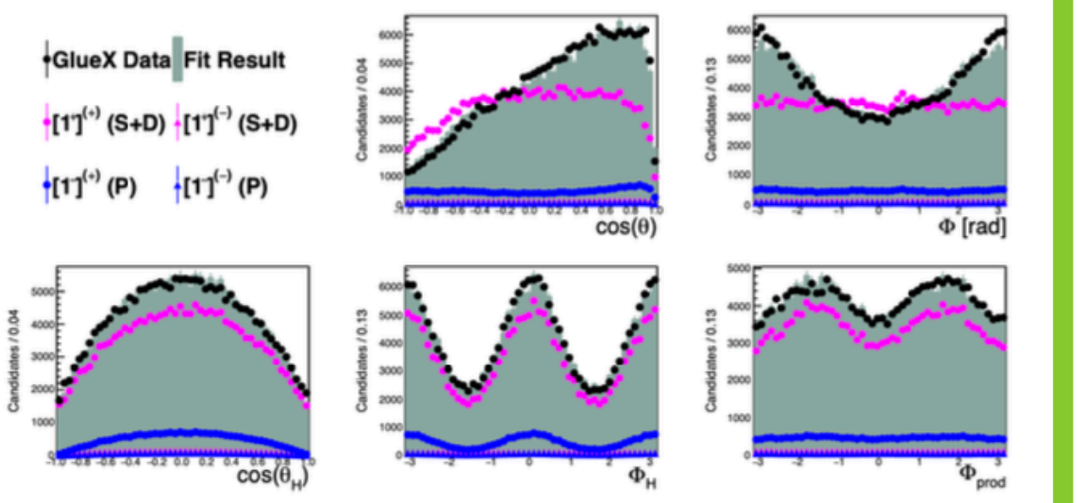
The Intensity Model: Angular distribution in helicity frame



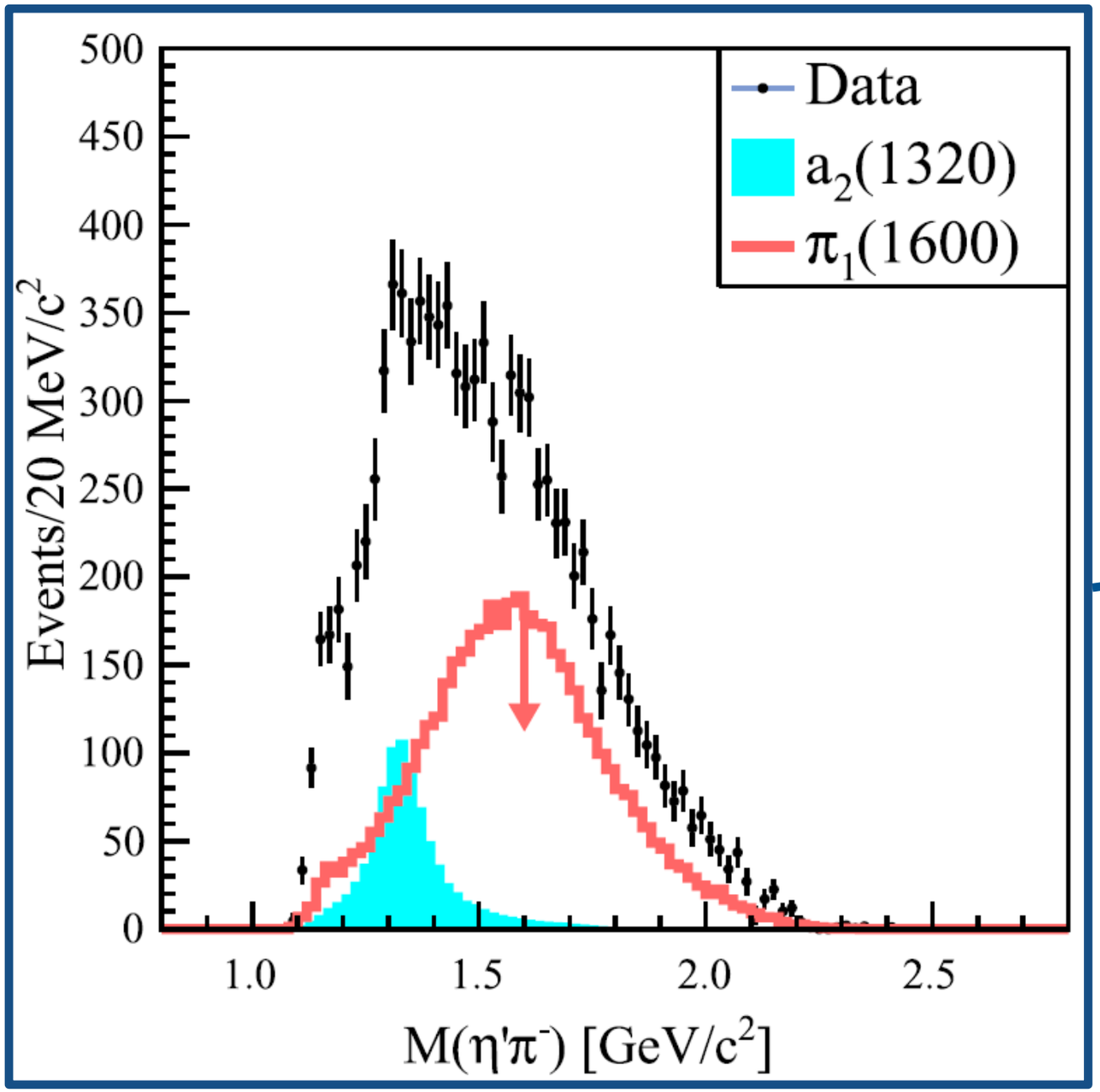


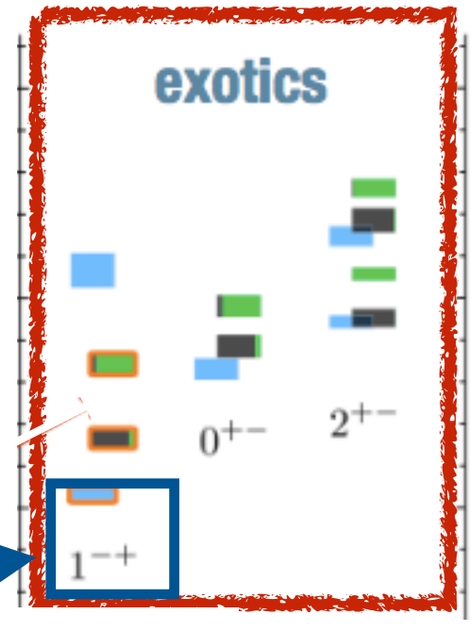
Intensity $I(\theta, \Phi, \theta_H, \Phi_H, \Phi_{prod})$





GlueX published - a_2, π_1





- GlueX Machinery works:
  - π1 upper limit - xsection

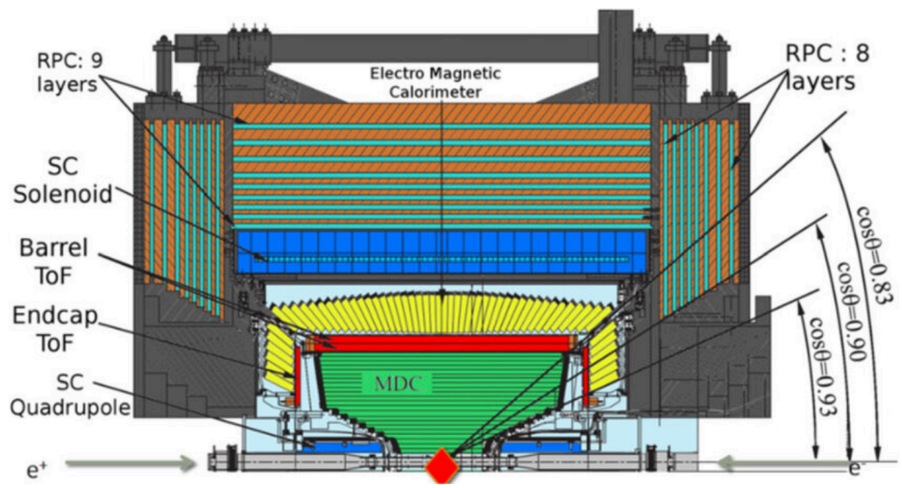
    PRL 133, 261903 (2024)
  - a2 meson - PWA

    PRC 112, 015204 (2025)

η_1 meson

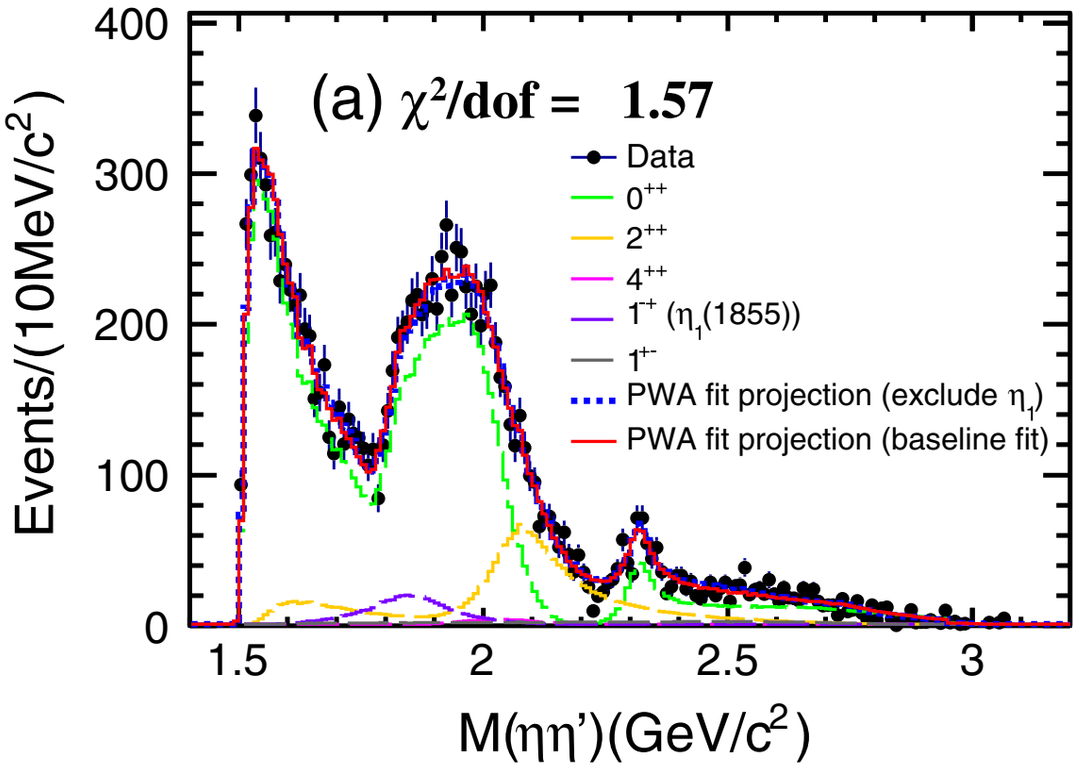
- The η_1 has $(I^G)J^{PC} = (0^+)(1^{-+})$ that are **exotic**.
- Goal: test whether $\gamma p \to \eta\eta' p$ events in GlueX are consistent with the $\eta_1(1855)$ state discovered by **BESIII**.
- This is a **two-pseudo scalar meson** decay.

Beijing Electron-Positron Collider II operates at c.o.m. energy of 2.0-4.6 GeV, optimized at 1.89 GeV to study the J/ψ resonance and others.



Schematic of the BESIII detector

BESIII: η_1 in $J/\psi \to \gamma\eta\eta'$

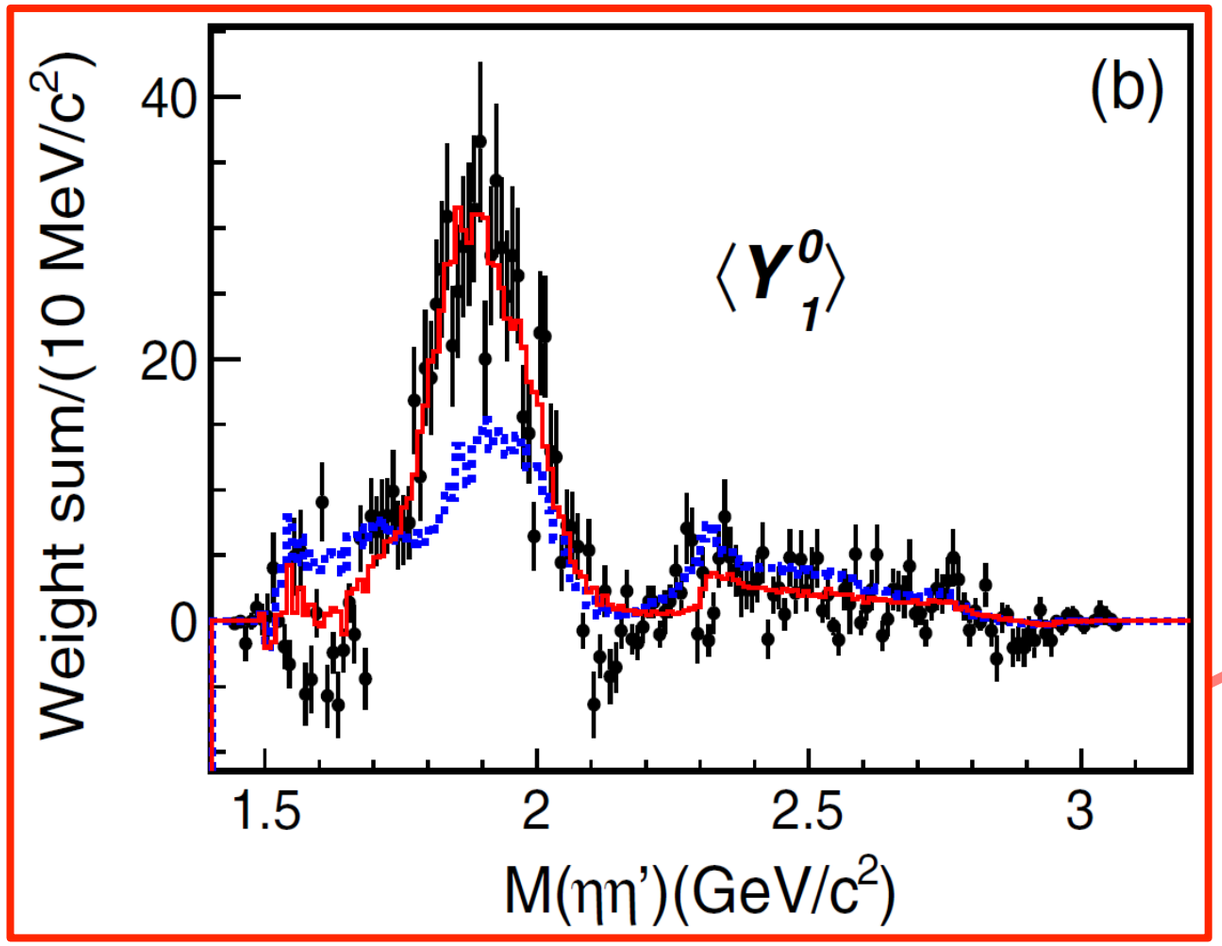


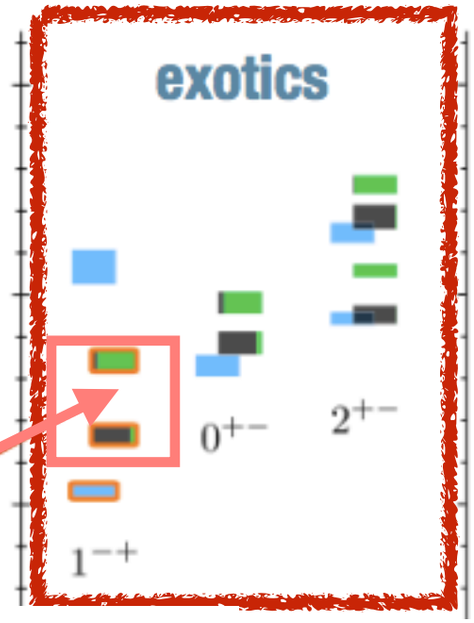
Phys.Rev.D.106.072012 (2022)

Resonance	M (MeV/c^2)	Γ (MeV)	B.F.($\times 10^{-5}$)	Sig.
$f_0(1500)$	1506	112	$1.81 \pm 0.11^{+0.19}_{-0.13}$	$> 30\sigma$
$f_0(1810)$	1795	95	$0.11 \pm 0.01^{+0.04}_{-0.03}$	11.1σ
$f_0(2020)$	$2010 \pm 6^{+6}_{-4}$	$203 \pm 9^{+13}_{-11}$	$2.28 \pm 0.12^{+0.29}_{-0.20}$	24.6σ
$f_0(2330)$	$2312 \pm 7^{+7}_{-3}$	$65 \pm 10^{+3}_{-12}$	$0.10 \pm 0.02^{+0.01}_{-0.02}$	13.2σ
$\eta_1(1855)$	$1855 \pm 9^{+6}_{-1}$	$188 \pm 18^{+3}_{-8}$	$0.27 \pm 0.04^{+0.02}_{-0.04}$	21.4σ
$f_2(1565)$	1542	122	$0.32 \pm 0.05^{+0.12}_{-0.02}$	8.7σ
$f_2(2010)$	$2062 \pm 6^{+10}_{-7}$	$165 \pm 17^{+10}_{-5}$	$0.71 \pm 0.06^{+0.10}_{-0.06}$	13.4σ
$f_4(2050)$	2018	237	$0.06 \pm 0.01^{+0.03}_{-0.01}$	4.6σ
0^{++} PHSP	...	...	$1.44 \pm 0.15^{+0.10}_{-0.20}$	15.7σ
$h_1(1415)$	1416	90	$0.08 \pm 0.01^{+0.01}_{-0.02}$	10.2σ
$h_1(1595)$	1584	384	$0.16 \pm 0.02^{+0.03}_{-0.01}$	9.9σ

- Nominal model given in the table - includes significant $\eta_1(1855)$ component.
- Solid red line contains $\eta_1(1855)$ contribution, dashed blue does not.
- Need for exotic component most obvious looking at the moments.

BESIII: η_1 PWA





BESIII Collaboration:

signature of an exotic $\eta_1(1855)$

$$e^- e^+ \to J/\psi \to (\eta_1)\gamma \to (\eta\eta')\gamma$$

Phys.Rev.D.106.072012 (2022)

$$M(\eta\eta')(GeV/c^2) = \sqrt{E^2_{\eta\eta'} - p^2_{\eta\eta'}}$$

Moment analysis= decomposition of angular distribution into spherical harmonics $Y_L^M(\theta, \phi)$; Expansion coefficients are the moments H(L, M) with L, M $\in Z \geq 0$

GlueX Two-pronged Approach

Will Jefferson Lab

- Measure cross section for $\gamma p \to \eta\eta' p$
- Use to set upper limit on $\eta_1(1855)$ production rate
- Note: many phenomenological models predict $\mathcal{B}(\eta_1 \to \eta\eta') = 0$
- Combine with moment analysis: greater sensitivity to exotic hybrid meson waves if we include angular moment info in the limit of the cross section

Harsimran University of Regina

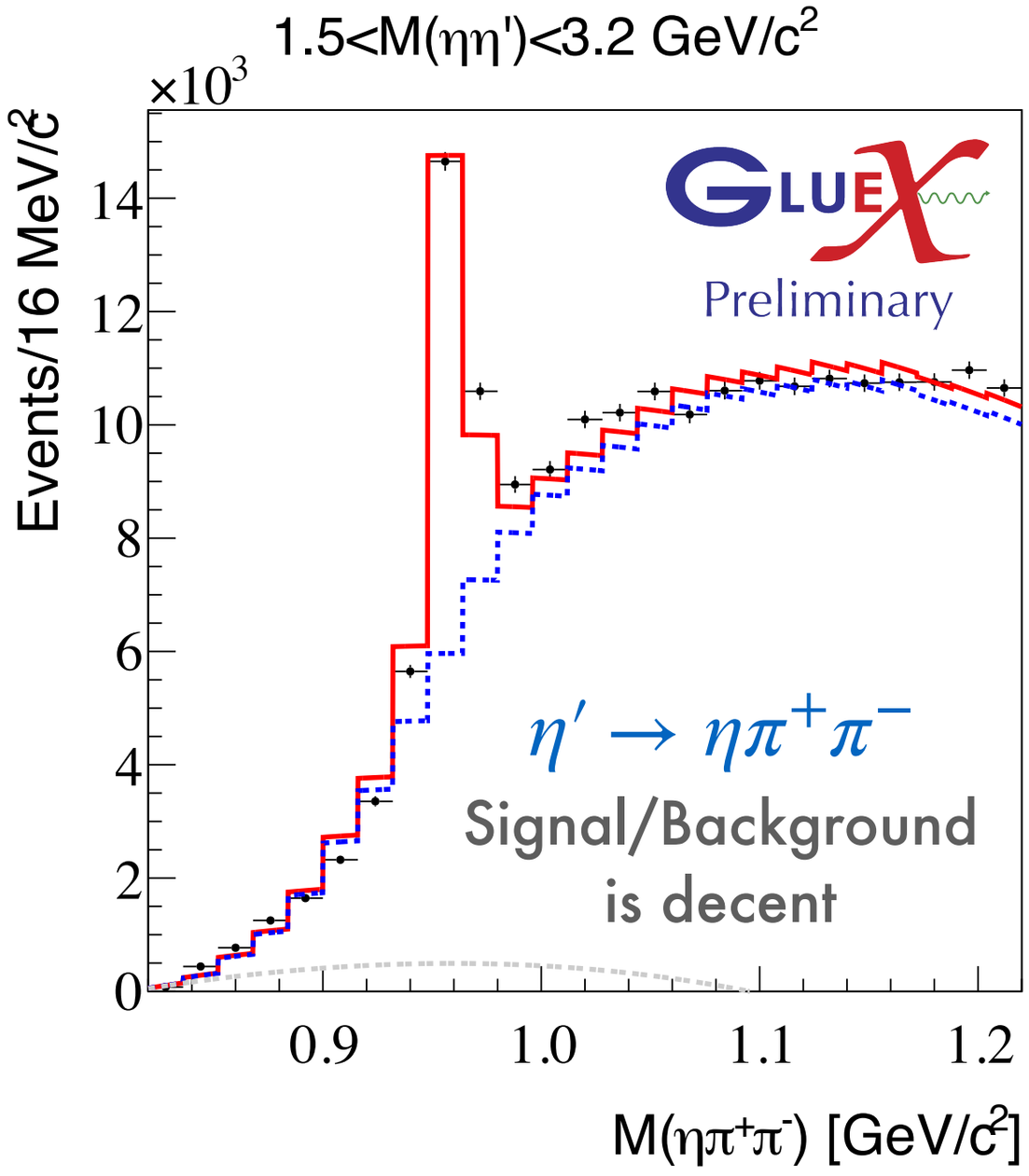
- Pursue PWA AmpTools analysis
- Start with input/output tests:
  - Use machinery from a_2 and b_1
- Examine event selection
- Carry out mass-independent analysis
- Longer time scale

GlueX: η_1 cross section

Will Jefferson Lab

- BESIII used both $\eta' \to \gamma\pi^+\pi^-$ and $\eta' \to \pi^+\pi^-\eta$
  - 15,000 signal events across both decay modes
- GlueX shows 12,000 events in Phase-I + Spring 2020 + Spring 2023 (much more data available in Phase-II and -III)
- Use additional decay modes:

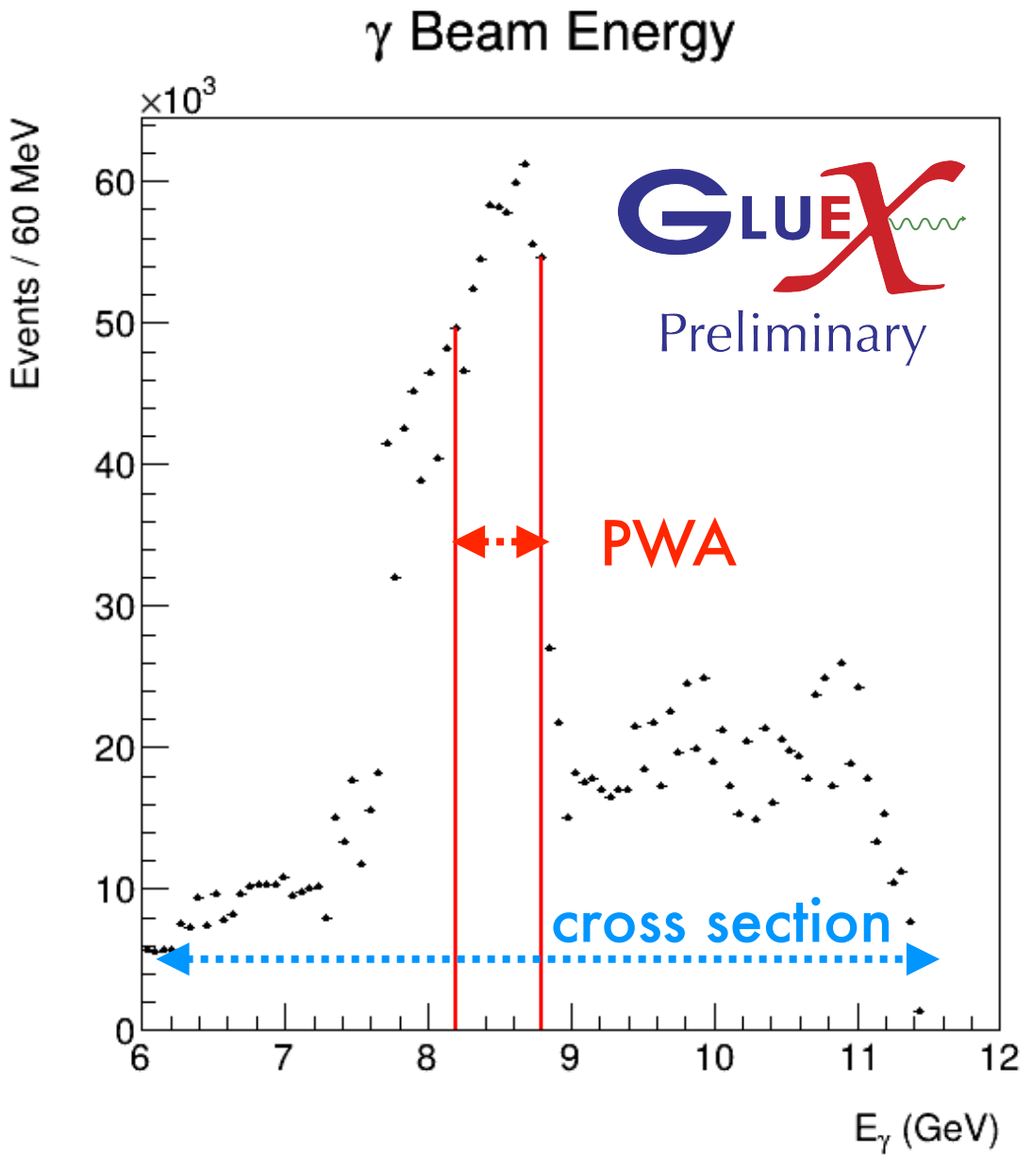
η' Decay	Branching Fraction
$\pi^+\pi^-\eta$	$(42.5 \pm 0.5)\%$
$\gamma\rho$	$(29.48 \pm 0.35)\%$
$\pi^0\pi^0\eta$	$(22.4 \pm 0.5)\%$
$\gamma\omega$	$(2.52 \pm 0.07)\%$
$\gamma\gamma$	$(2.307 \pm 0.033)\%$



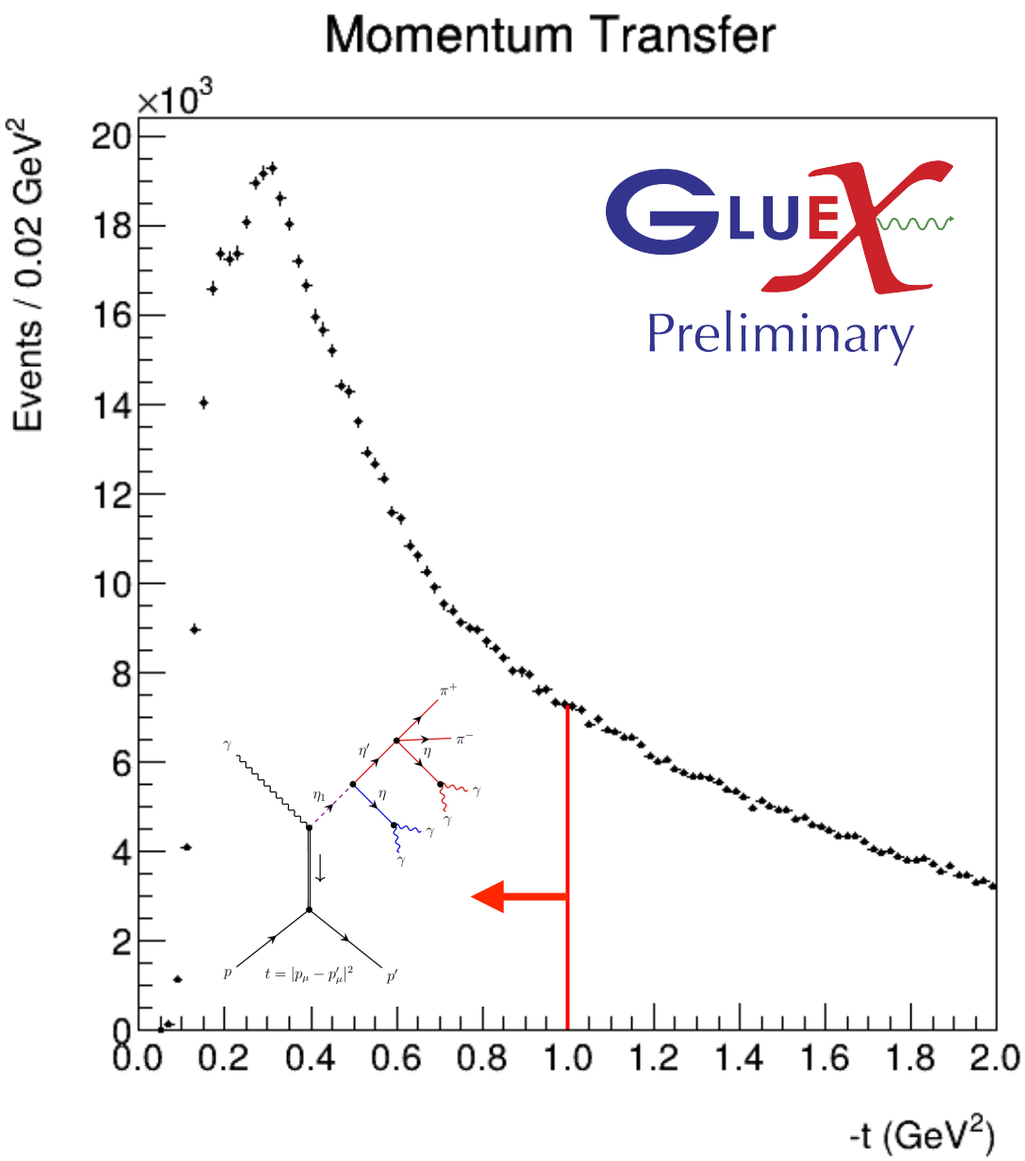
GlueX: η_1 PWA

Harsimran

University of Regina



highest polarization

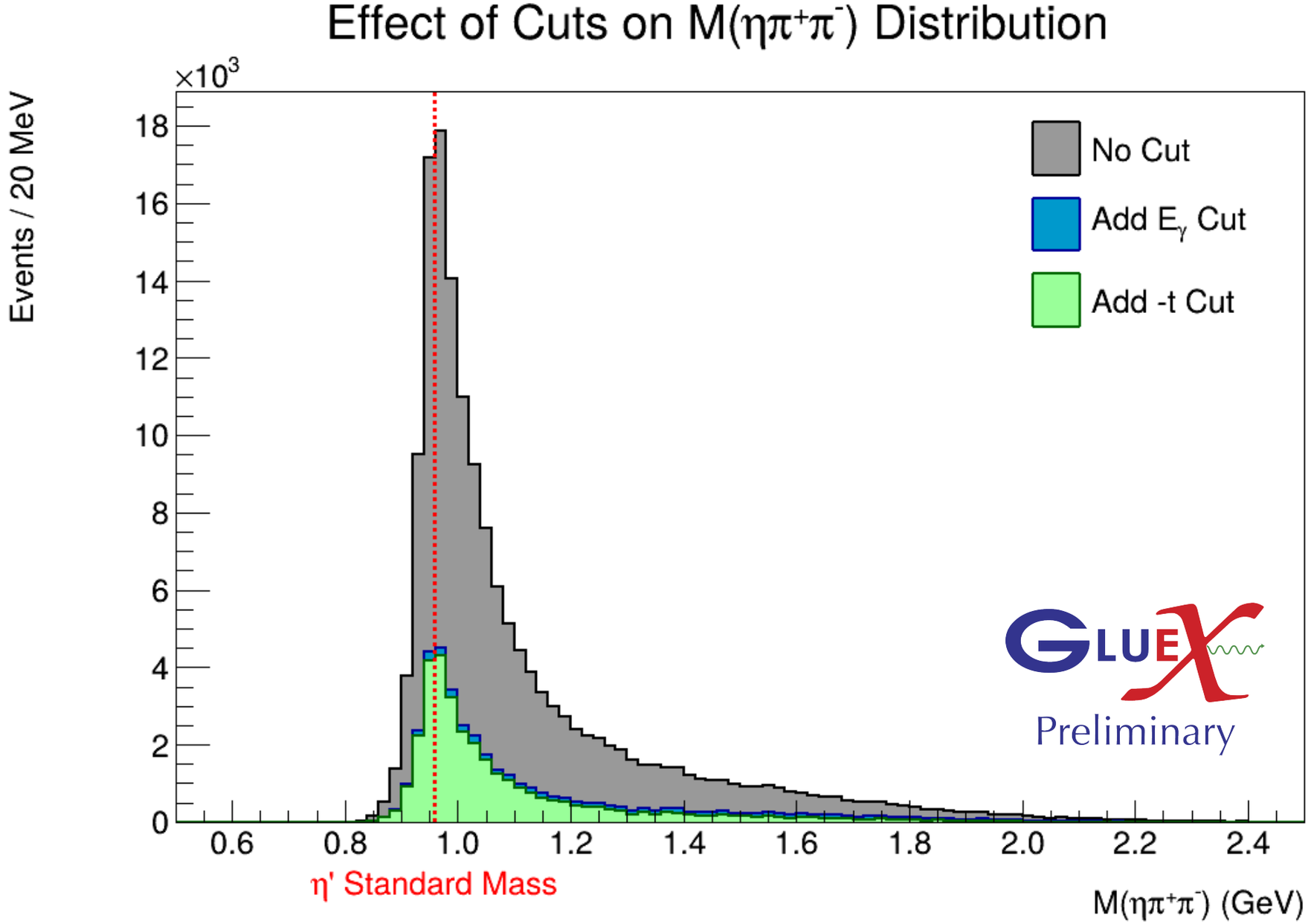


t-channel physics

GlueX: η_1 PWA

Harsimran

University of Regina



Summary & Outlook

- Hybrid mesons help explore role of gluons in hadron dynamics.
- PWA can extract individual J^{PC} contributions.
- exotic $\eta_1(1855)(1^{-+}) \rightarrow \eta\eta'$ is accessible in GlueX.
- Next steps (cross section and PWA):
  - Study signal and background Monte Carlo; optimize S/B.
  - Extract a clean $\eta\eta'$ signal from data.
  - Examine constrained and unconstrained η mass fits.
  - Project moments from cross section fits.
  - Fit that data with PWA to find signatures of η_1.

NSERC CRSNG

GlueXperiment
gluexperiment
Glue_X

https://gluex.org/thanks.html

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Thank you / Merci

NSERC CRSNG

GlueXperiment
gluexexperiment
Glue_X

https://gluex.org/thanks.html