Scalar photoproduction on the proton at CLAS and GlueX

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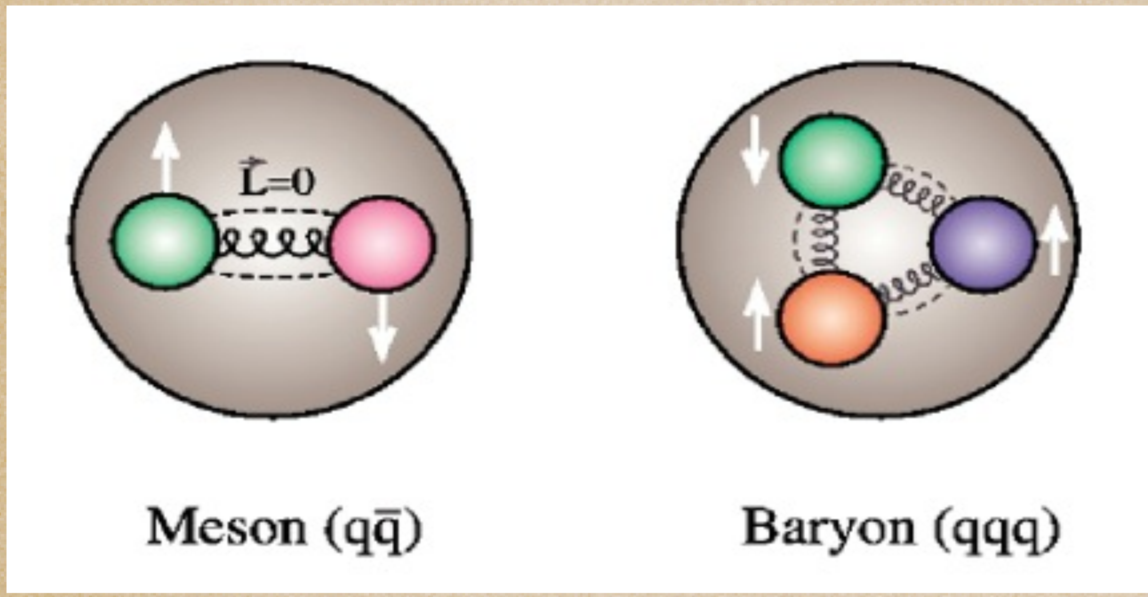
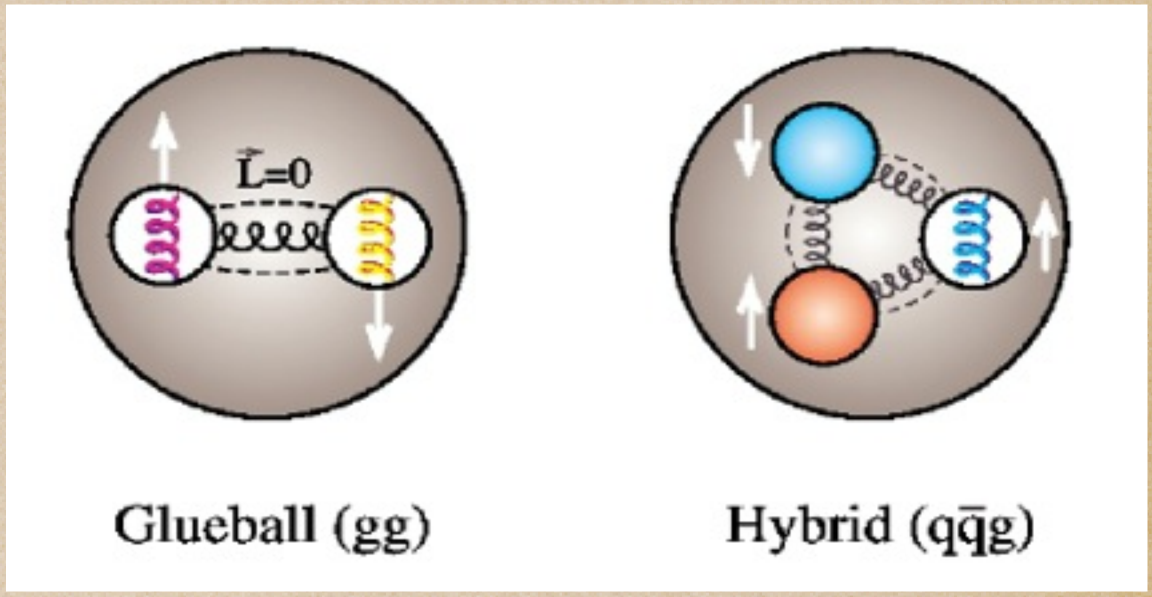
Outline

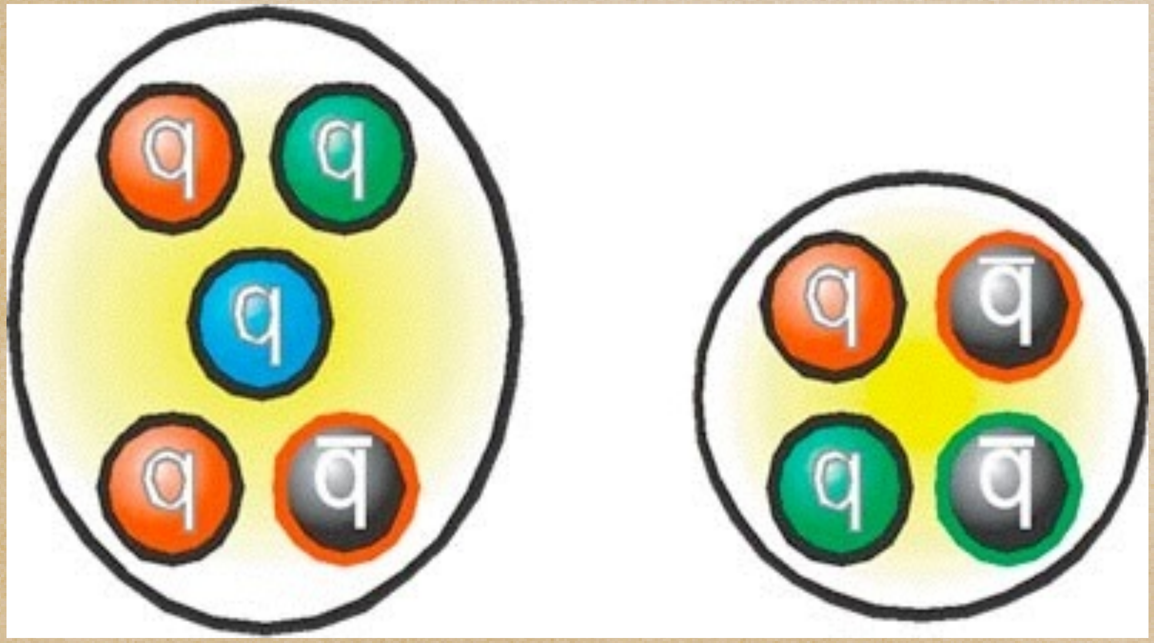
- Motivation
- Photoproduction of scalar mesons
  - Differential cross section
  - Regge trajectories
  - Results
- Summary and conclusions

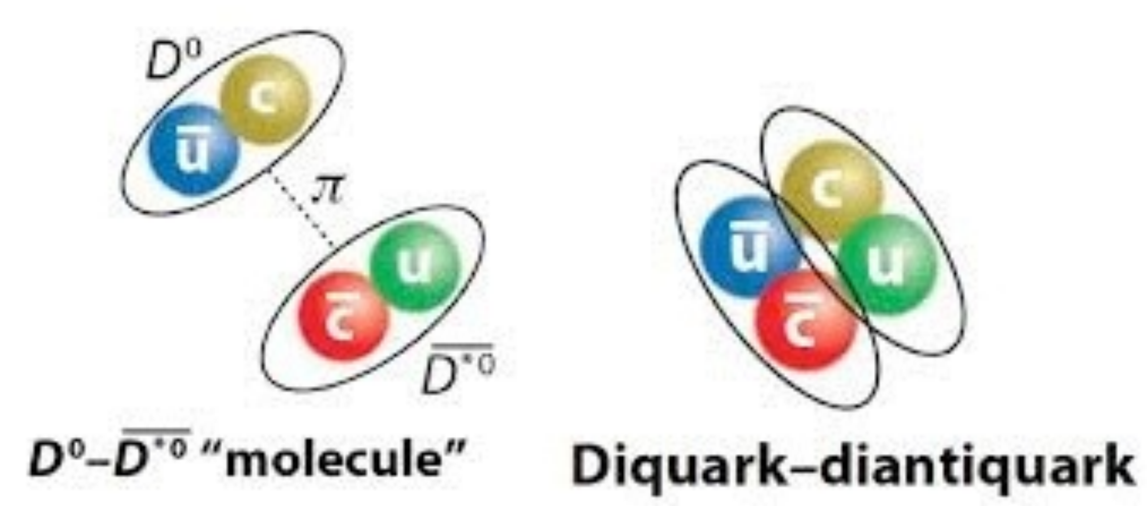
Motivation

Hadron Structure:









Motivation

Meson Quantum Numbers:

$$J^{PC}$$

$$\vec{J} = \vec{L} + \vec{S}; \qquad C = (-1)^{L+S}$$

$$P = (-1)^{L+1}; \qquad G = (-1)^{L+S+I}$$

- Possible quantum numbers for quark-antiquark

Exotic States

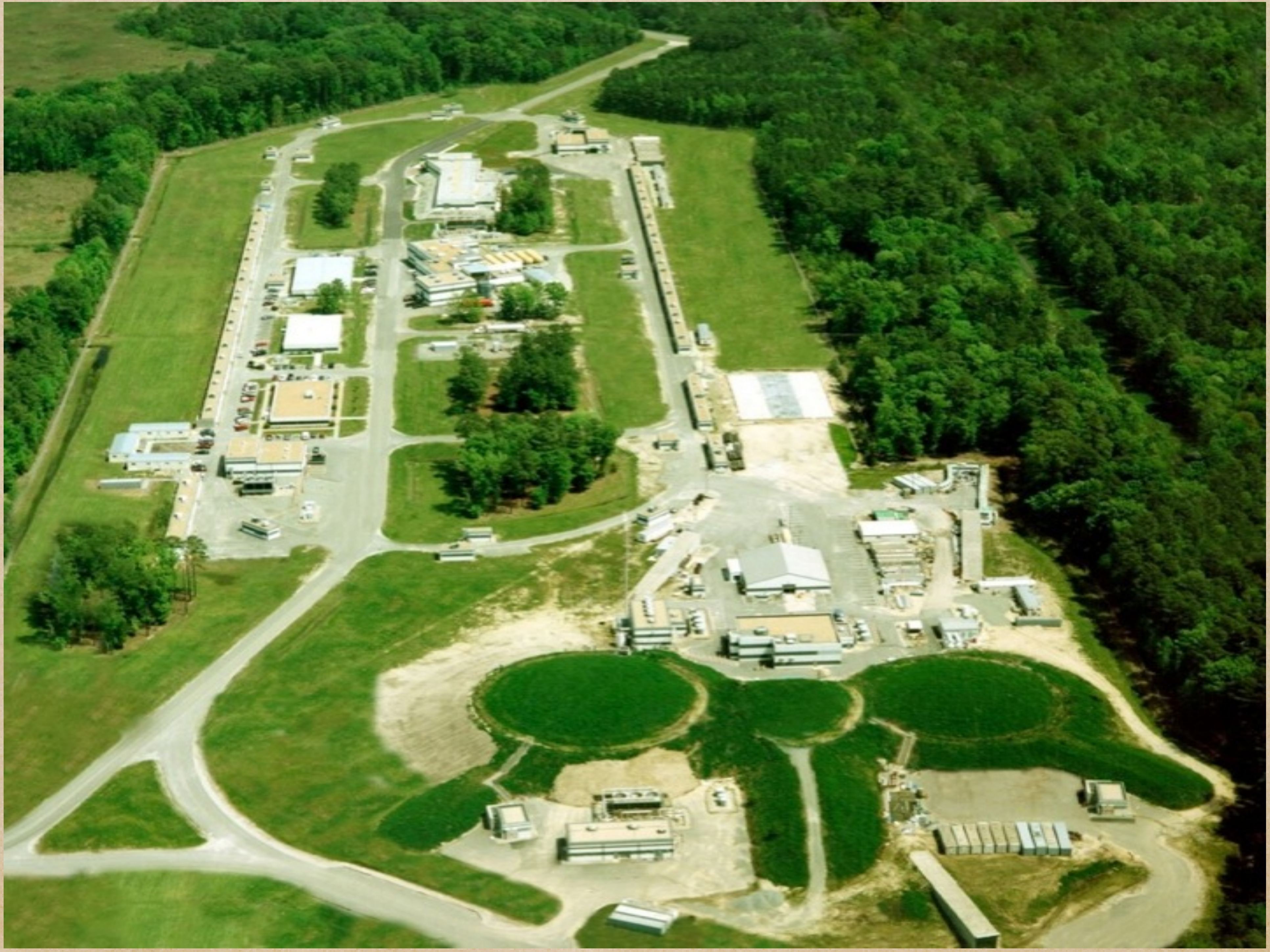
0^{--}	0^{++}	0^{-+}	0^{+-}
1^{--}	1^{++}	1^{-+}	1^{+-}
2^{--}	2^{++}	2^{-+}	2^{+-}
3^{--}	3^{++}	3^{-+}	3^{+-}
4^{--}	4^{++}	4^{-+}	4^{+-}
5^{--}	5^{++}	5^{-+}	5^{+-}

Motivation

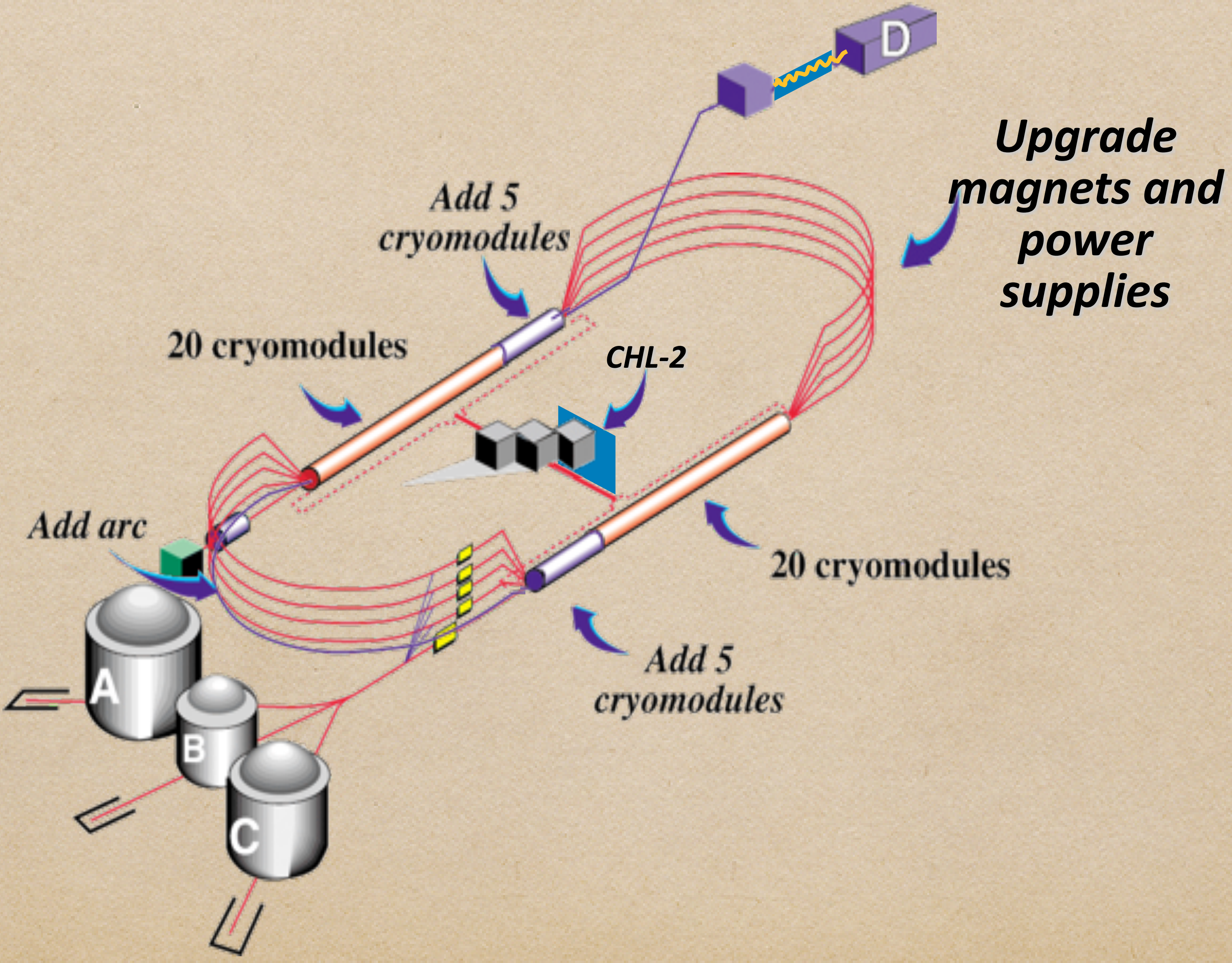
Light mesons:

$n\,^{2s+1}\ell_J$	J^{PC}	I = 1 $u\bar{d}$, $\bar{u}d$, $\frac{1}{\sqrt{2}}(d\bar{d} - u\bar{u})$	I = $\frac{1}{2}$ $u\bar{s}$, $d\bar{s}$; $\bar{d}s$, $-\bar{u}s$	I = 0 f'	I = 0 f	θ_{quad} [°]	θ_{lin} [°]
$1\,^1S_0$	0^{-+}	π	K	η	$\eta'(958)$	−11.5	−24.6
$1\,^3S_1$	1^{--}	$\rho(770)$	$K^*(892)$	$\phi(1020)$	$\omega(782)$	38.7	36.0
$1\,^1P_1$	1^{+-}	$b_1(1235)$	$K_{1B}{}^\dagger$	$h_1(1380)$	$h_1(1170)$		
$1\,^3P_0$	0^{++}	$a_0(1450)$	$K_0^*(1430)$	$f_0(1710)$	$f_0(1370)$		
$1\,^3P_1$	1^{++}	$a_1(1260)$	$K_{1A}{}^\dagger$	$f_1(1420)$	$f_1(1285)$		
$1\,^3P_2$	2^{++}	$a_2(1320)$	$K_2^*(1430)$	$f_2'(1525)$	$f_2(1270)$	29.6	28.0
$1\,^1D_2$	2^{-+}	$\pi_2(1670)$	$K_2(1770)^\dagger$	$\eta_2(1870)$	$\eta_2(1645)$		
$1\,^3D_1$	1^{--}	$\rho(1700)$	$K^*(1680)$		$\omega(1650)$		
$1\,^3D_2$	2^{--}		$K_2(1820)$				
$1\,^3D_3$	3^{--}	$\rho_3(1690)$	$K_3^*(1780)$	$\phi_3(1850)$	$\omega_3(1670)$	32.0	31.0
$1\,^3F_4$	4^{++}	$a_4(2040)$	$K_4^*(2045)$		$f_4(2050)$		
$1\,^3G_5$	5^{--}	$\rho_5(2350)$					
$1\,^3H_6$	6^{++}	$a_6(2450)$			$f_6(2510)$		
$2\,^1S_0$	0^{-+}	$\pi(1300)$	$K(1460)$	$\eta(1475)$	$\eta(1295)$		
$2\,^3S_1$	1^{--}	$\rho(1450)$	$K^*(1410)$	$\phi(1680)$	$\omega(1420)$		

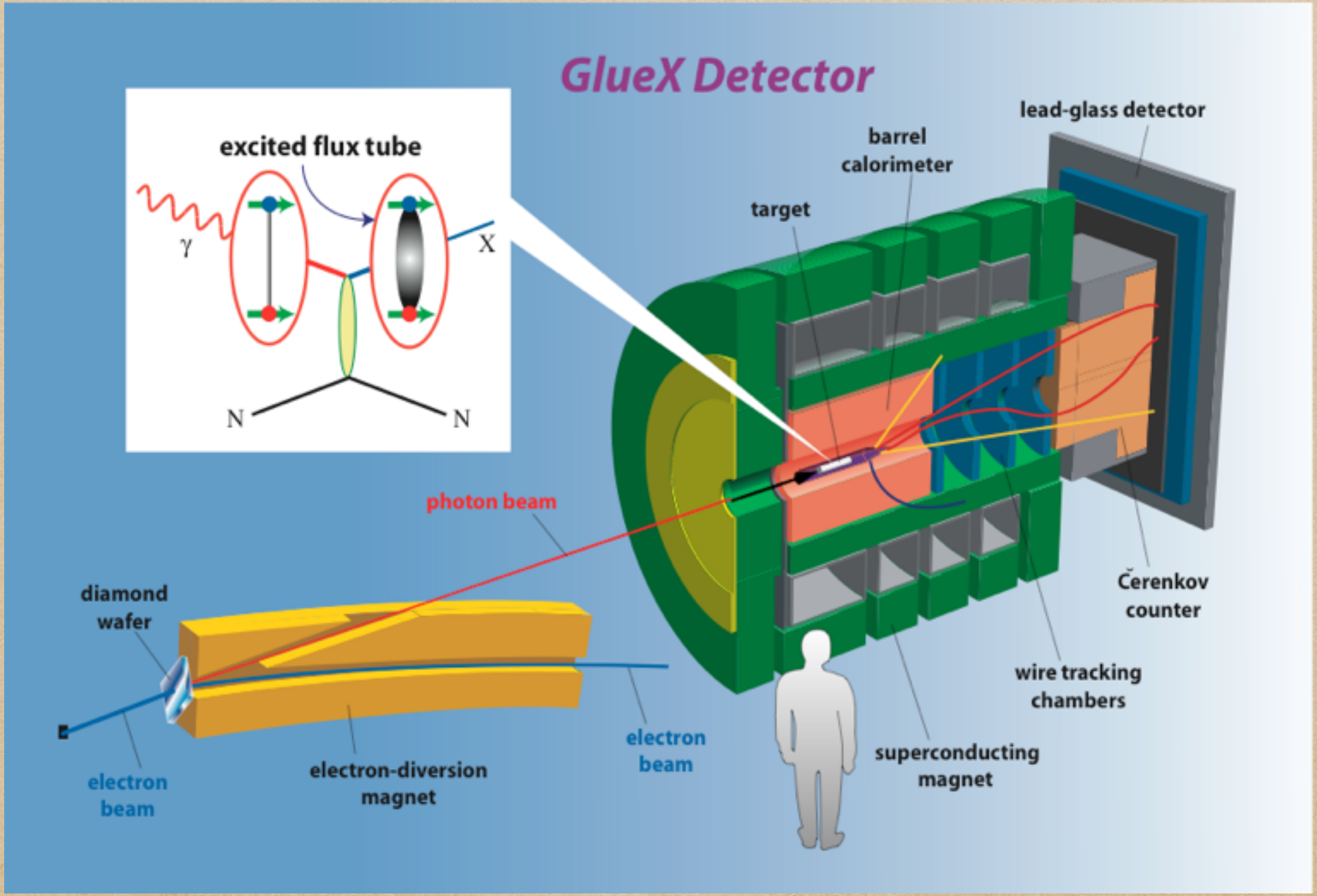
GlueX



GlueX


D
Upgrade magnets and power supplies
Add 5 cryomodules
20 cryomodules
CHL-2
Add arc
20 cryomodules
Add 5 cryomodules
A
B
C

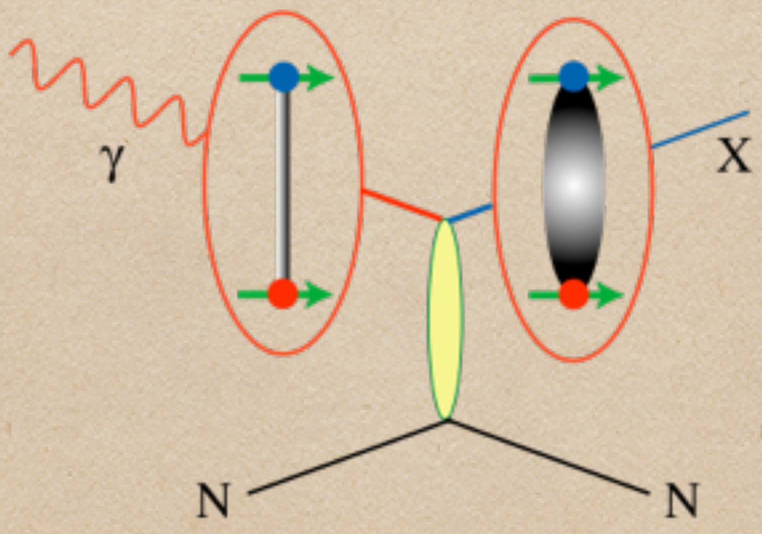
GlueX



GlueX Detector
excited flux tube
γ
X
N
N
lead-glass detector
barrel
calorimeter
target
photon beam
diamond
wafer
Čerenkov
counter
wire tracking
chambers
superconducting
magnet
electron
beam
electron-diversion
magnet
electron
beam

GlueX

- Electron beam: 12 GeV
- Photon beam: 9 GeV
- Photon-Proton interaction



- Starts operating in 2014

Scalar Mesons

- Scalars:
  - $a_0(980)$
  - $f_0(980)$
  - $f_0(1500)$
  - $f_0(1710)$
- Glueballs

$$|f_0(M)\rangle = c_1 |N\rangle + c_2 |S\rangle + c_3 |G\rangle$$

Mixing Scheme

$$\begin{pmatrix} | f_0(1370)\rangle \\ | f_0(1500)\rangle \\ | f_0(1710)\rangle \end{pmatrix} = \mathcal{U} \begin{pmatrix} | G\rangle \\ | S\rangle \\ | N\rangle \end{pmatrix}$$

Weingarten

$$\begin{pmatrix} -0,46 & 0,28 & 0,84 \\ 0,19 & -0,9 & 0,40 \\ 0,87 & 0,34 & 0,36 \end{pmatrix}$$

Close & Kirk

$$\begin{pmatrix} -0,61 & 0,13 & 0,78 \\ 0,70 & -0,38 & 0,61 \\ 0,37 & 0,92 & 0,14 \end{pmatrix}$$

Scalar Photoproduction

Process → $\gamma p \to p\, M$

M → $a_0(980)$, $f_0(980)$, $f_0(1500)$, $f_0(1710)$

Differential cross section

$$\frac{d\sigma}{dt}(\gamma p \to pM) = \frac{|\mathcal{M}(s,t)|^2}{64\pi\,(s-m_p^2)^2}$$

Scattering amplitude

This is the scattering amplitude for the exchange of single vector meson (ρ or ω)

$$
\begin{aligned}
|\mathcal{M}(s,t)|^2 &= -\frac{1}{2}\mathcal{A}^2(s,t)\Big[s(t-t_1)(t-t_2) \\
&\qquad + \frac{1}{2}t(t^2 - 2(m_S^2+s)t + m_S^4) \Big] \\
&- \mathcal{A}(s,t)\mathcal{B}(s,t) m_p s(t-t_1)(t-t_2) \\
&- \frac{1}{8}\mathcal{B}^2(s,t) s(4m_p^2 - t)(t-t_1)(t-t_2).
\end{aligned}
$$

$$
\begin{aligned}
t_{1,2} &= \frac{1}{2s}\Big[-(m_p^2-s)^2 + m_S^2(m_p^2+s) \\
&\pm (m_p^2-s)\sqrt{(m_p^2-s)^2 - 2m_s^2(m_p^2+s) + m_S^4}\Big]
\end{aligned}
$$

where t and s are Mandelstam variables

Regge Trajectories

Linear Regge Trajectories

$$\alpha_V(t) = \alpha_V(0) + \alpha'_V t$$

$$\mathcal{A}(s,t) \;=\; g_A \left(\frac{s}{s_0}\right)^{\alpha_V(t)-1} \frac{\pi\alpha'_V}{\sin(\pi\alpha_V(t))}\frac{1-e^{-i\pi\alpha_V(t)}}{2\,\Gamma(\alpha_V(t))}$$

$$\mathcal{B}(s,t) \;=\; -\frac{g_B}{g_A}\mathcal{A}(s,t)$$

$\rho \longrightarrow \alpha_V(0) = 0.55 \quad \alpha'_V = 0.8$

$\omega \longrightarrow \alpha_V(0) = 0.44 \quad \alpha'_V = 0.9$

Couplings

$$g_A = g_S(g_V + 2m_p g_T) \qquad g_B = 2 g_S g_T$$

$$g_V^\rho = 3.4 \qquad g_T^\rho = 11$$

$$g_V^\omega = 15 \qquad g_T^\omega = 0$$

$$\Gamma(S \to \gamma V) = g_S^2 \frac{m_S^3}{32\pi}\left(1 - \frac{m_V^2}{m_S^2}\right)^3$$

PRC73, 045203

$$\Gamma(S \to \gamma V) = g_S^2 \frac{(m_S^2 - m_V^2)^3}{8\,\pi\, m_S^3}$$

NPA833, 138

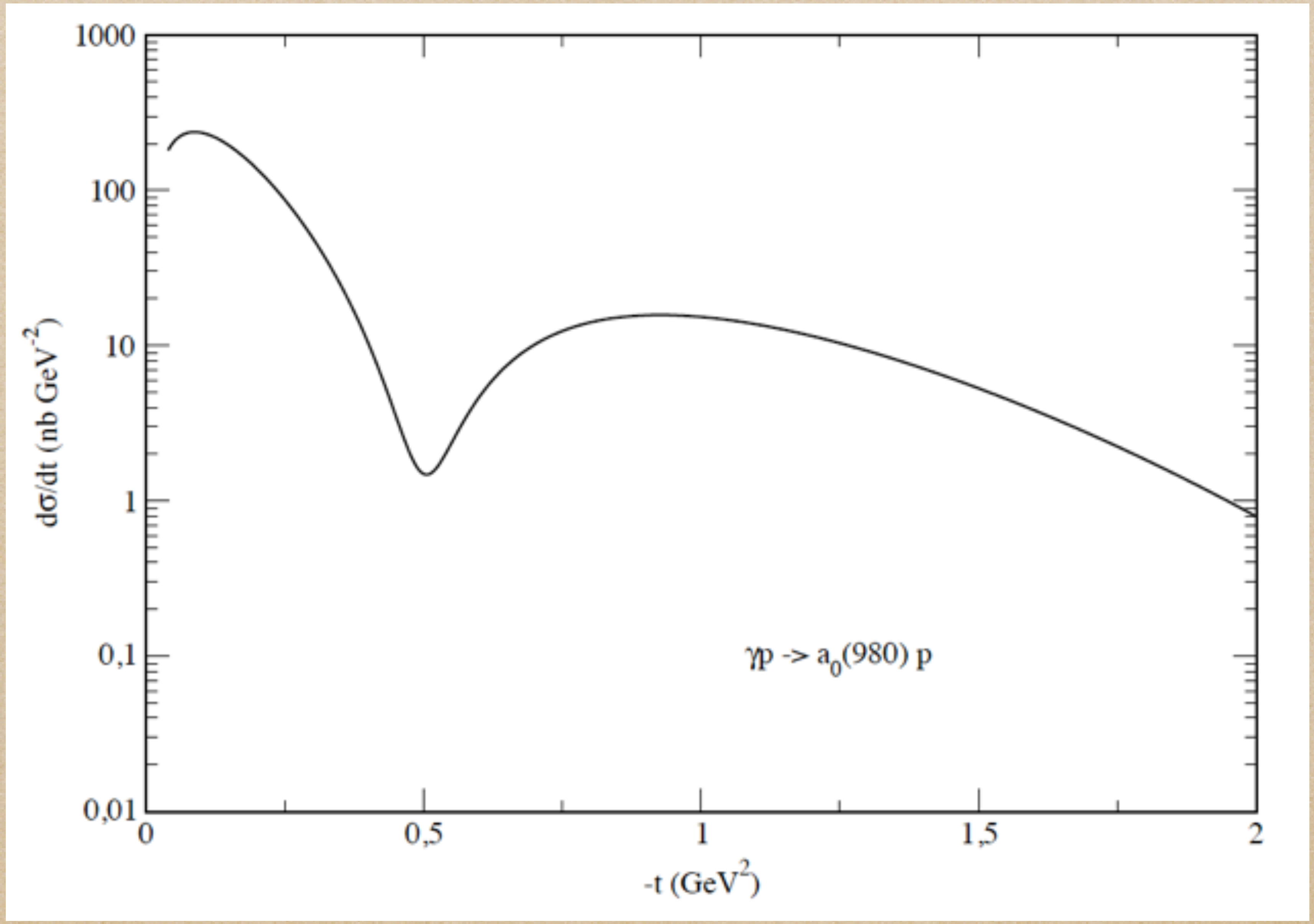
Decay width

I - The glueball is lighter than N
II - The glueball mass is between N e S
III - The glueball is heavier than S

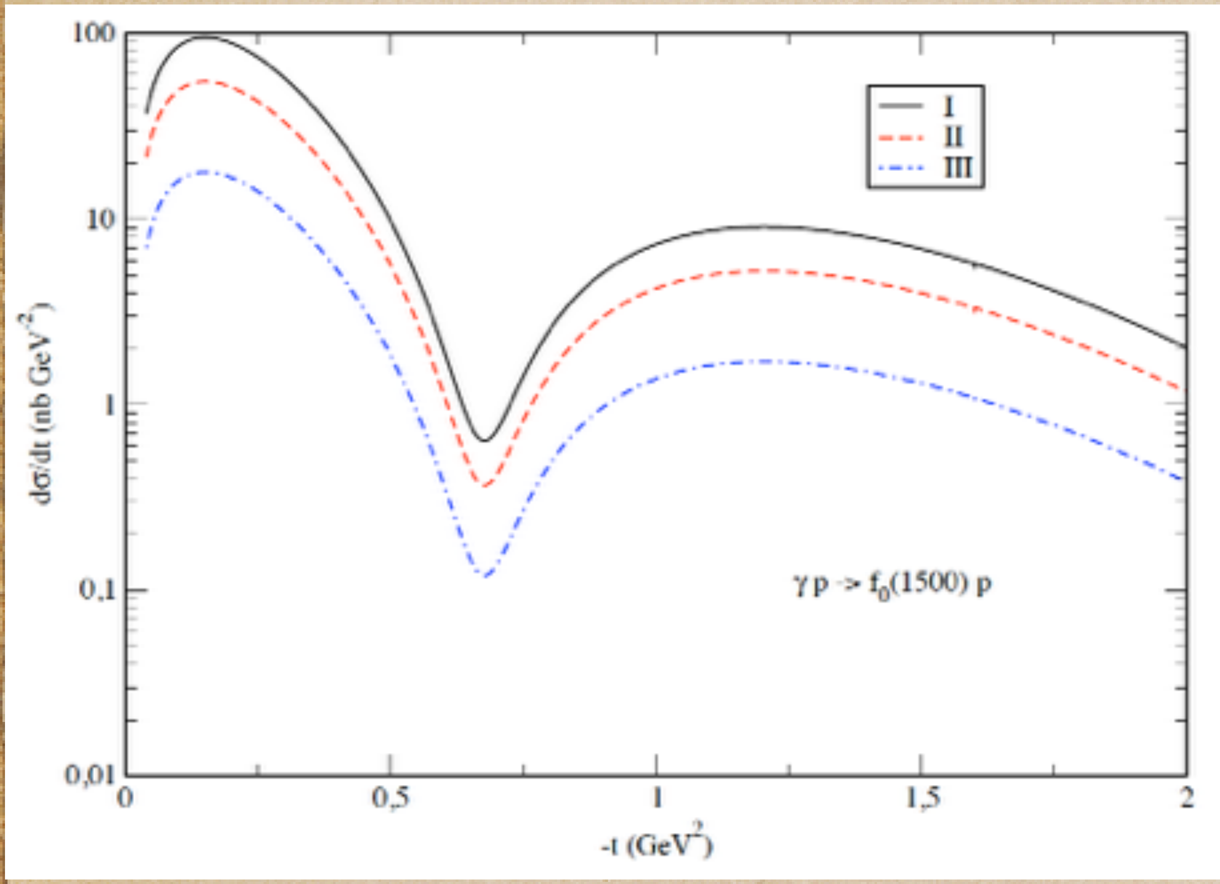
$$\Gamma(a_0(980) \to \gamma\rho(\omega)) = 14(126)\,\mathrm{keV}$$

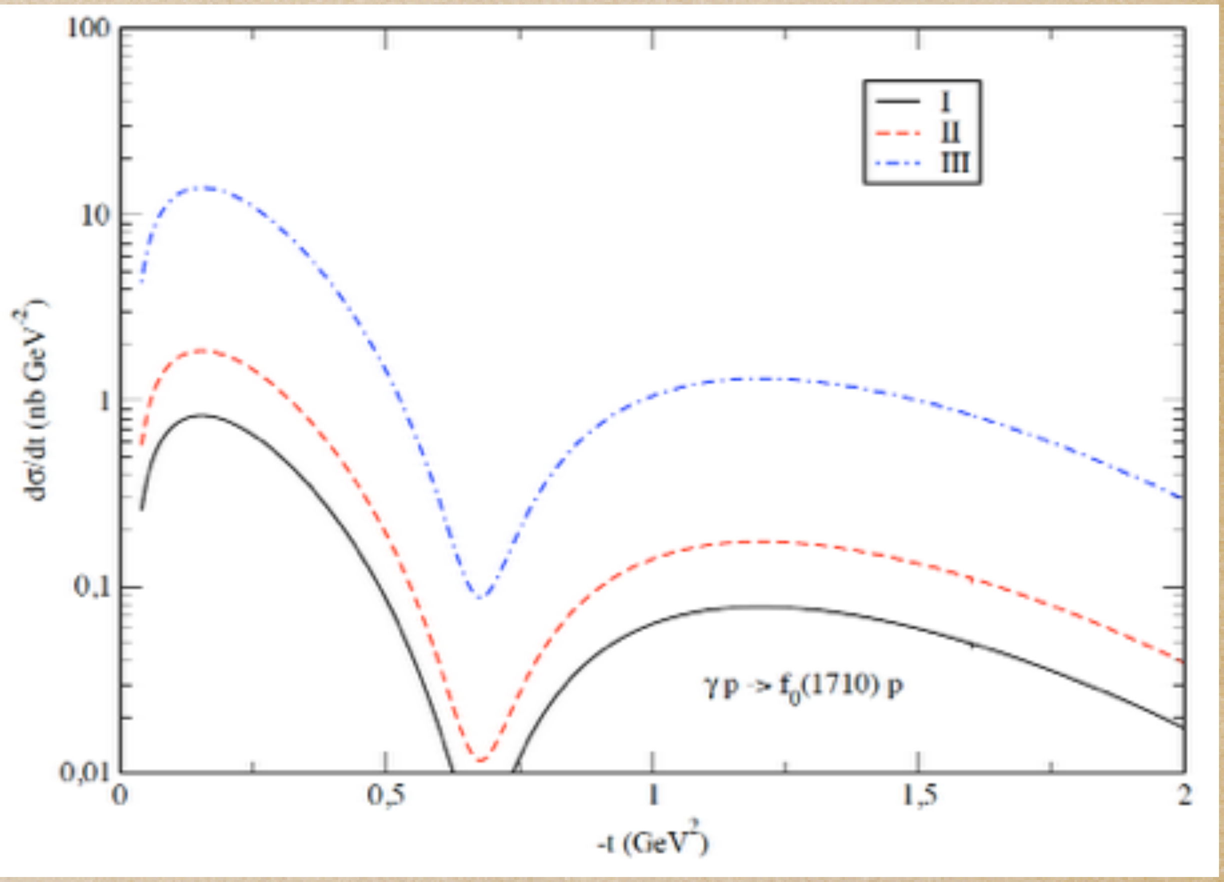
Scenario	$f_0(1500) \to \gamma V$	$f_0(1710) \to \gamma V$
(I)	2519 (280)	42 (4.7)
(II)	1458 (162)	94 (10.4)
(III)	476 (53)	705 (78)

Differential cross section



Differential cross section





Total cross section

For $a_0(980)$ the total cross section is:

59,22 nb

For $f_0(1500)$ and $f_0(1710)$ we have (nb):

Scenario	(I)	(II)	(III)
$f_0(1500)$	34.98	20.25	6.61
$f_0(1710)$	0.30	0.68	5.08

MLLS, M V T Machado, PRC 86, 015209 (2012).

Cross section for $f_0(980)$

- The differential cross section for the photoproduction of a scalar is

$$\frac{d\sigma}{dt\,dM} = \frac{d\hat{\sigma}(t, m_S)}{dt}\frac{2m_S^2}{\pi}\frac{\Gamma_i(M)}{(m_S^2 - M^2)^2 + (m_S\Gamma_{\mathrm{Tot}})^2}$$

- where the Breit-Wigner decay width of $f_0(980)$ to pseudoscalar-pseudoscalar final state is given by:

$$\Gamma(M) = \frac{g_{\pi\pi}^2}{8\pi M^2}\sqrt{\frac{M^2}{4} - M_{\pi\pi}^2} + \frac{g_{K\bar{K}}^2}{8\pi M^2}\left[\sqrt{\frac{M^2}{4} - M_{K^+K^-}^2} + \sqrt{\frac{M^2}{4} - M_{K^0\bar{K}^0}^2}\right]$$

becomes imaginary below KK threshold

KK thresold

- The Breit-Wigner width can be calculated through the Flattè formula.
- Another way to solve this matter is to use experimental data for strong decay of $f_0(980)$.
  - From PDG, the total width is in the range of 40 to 100 MeV.
  - From LHCb collaboration (PRD87, 052001)

$$\mathcal{B}(f_0(980) \to \pi^+\pi^-) = 46 \pm 6\%$$

Parameters

Radiative decay width

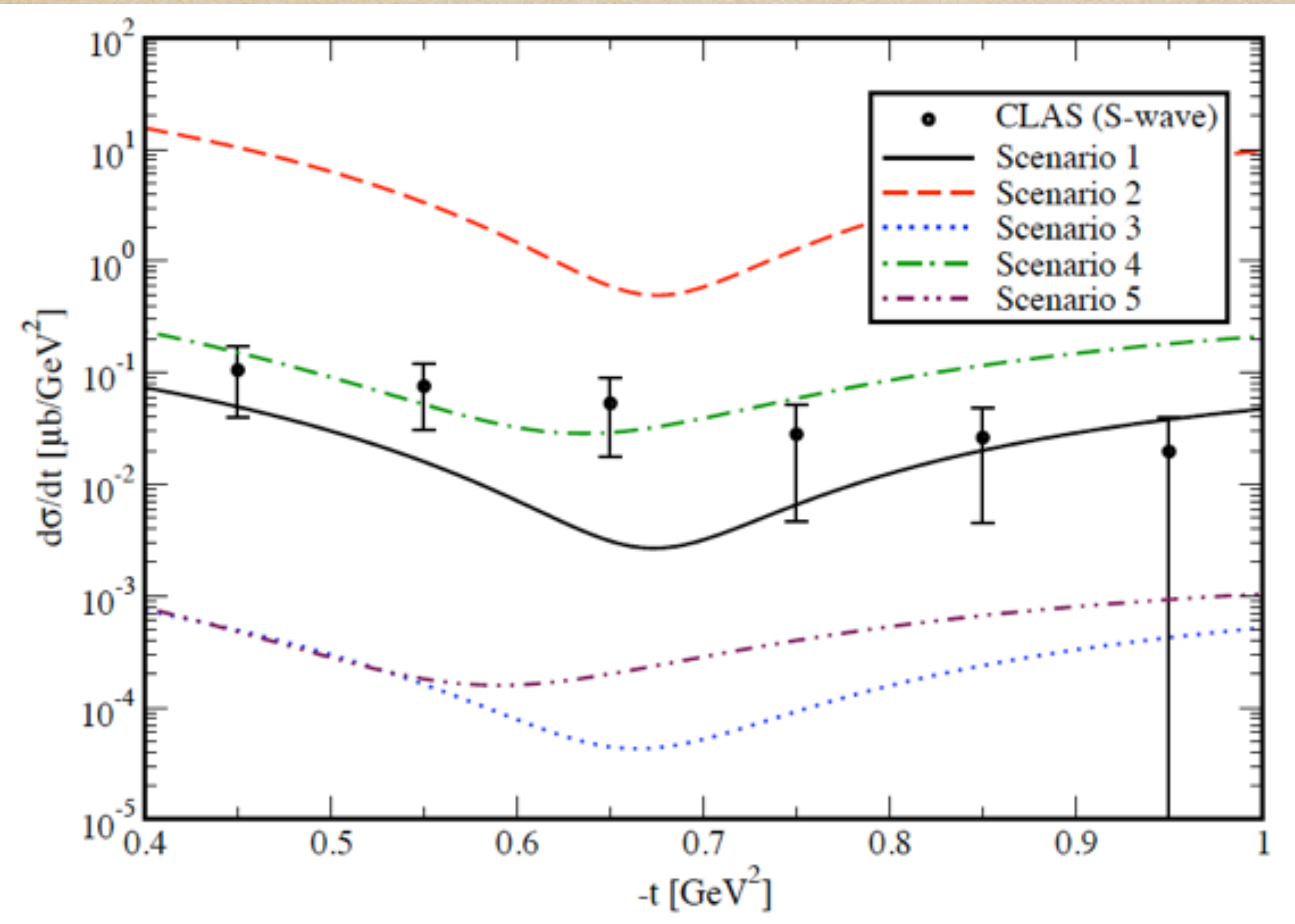
Scenario	f_0	Nature
1	83(9.2)	quarkonium
2	69880(6730)	quarkonium
3	3.3(0.61)	quarkonium
4	1005(463)	tetraquark
5	3.1(3.4)	tetraquark

*PRC78, 064603.

†NPA833, 138.

3 and 5 including vector meson dominance.

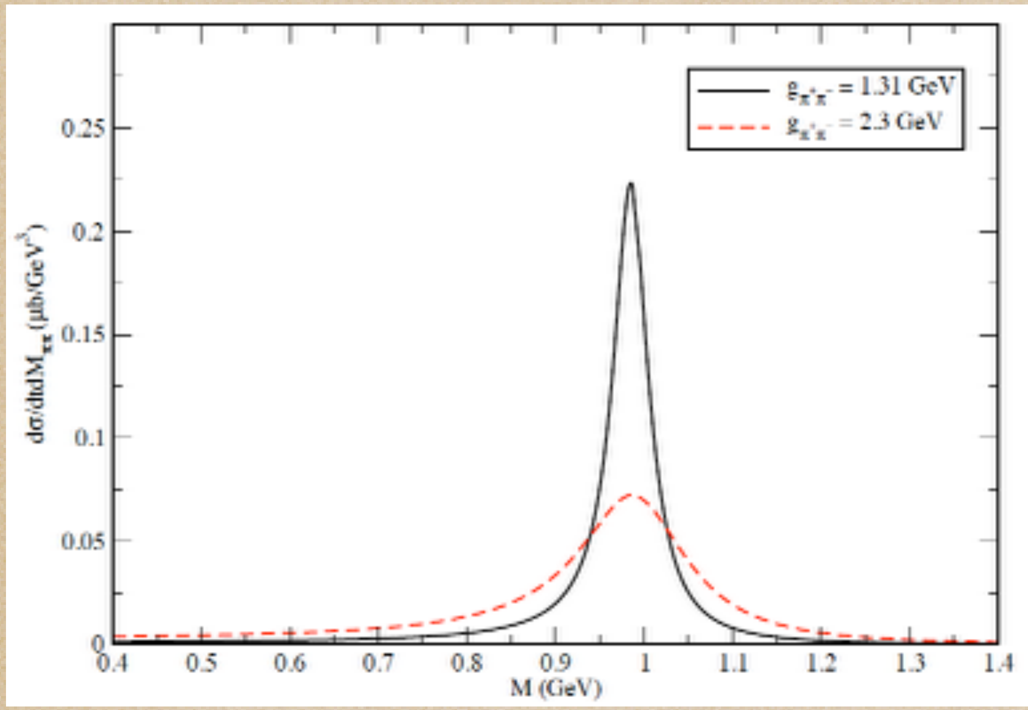
Results for CLAS energy

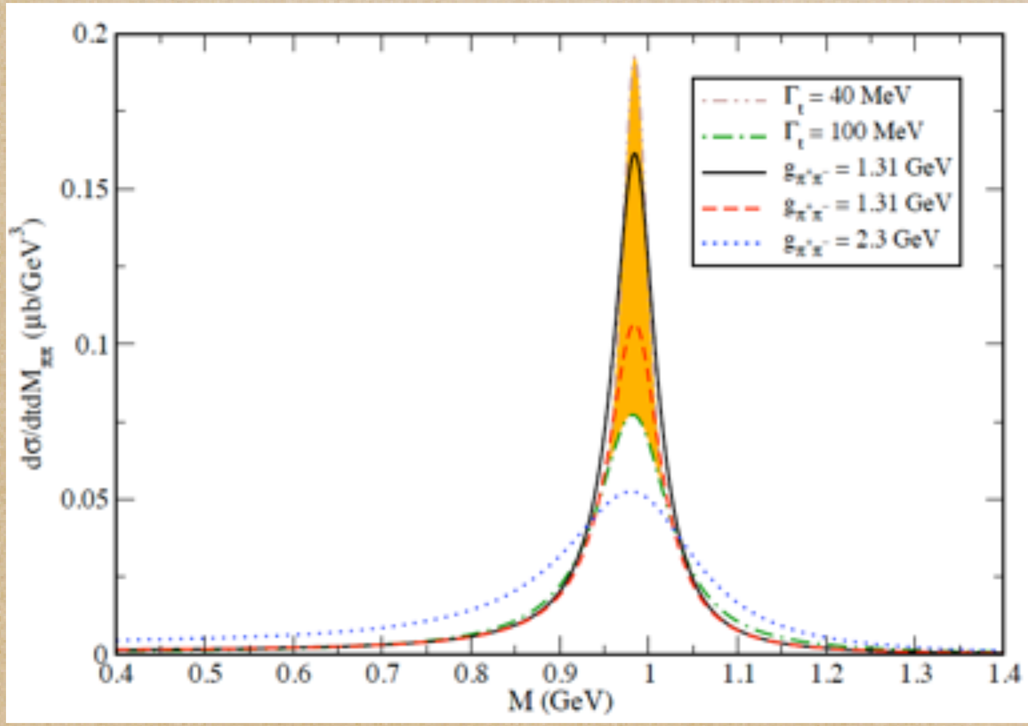


$E_\gamma = 3.4$ GeV

Data from PRL102, 102001.

Invariant mass distribution





Flattè formula

Scenario 1

g_{KK} = 0.4 GeV

Branching ratios

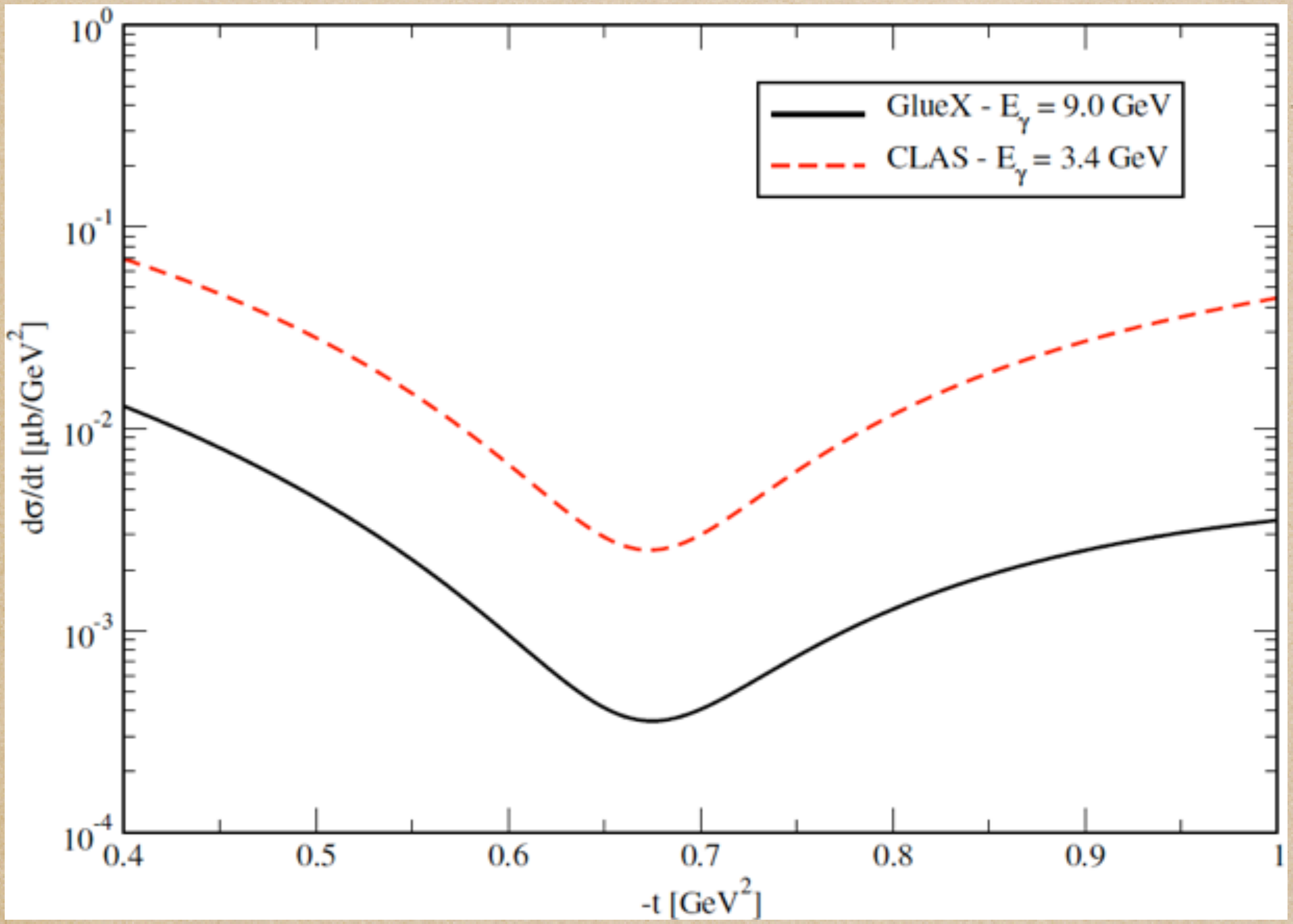
Scenario 1

g_{KK} = 0.4 GeV

$\mathfrak{B}(f_0(980) \to \pi\pi) = 85\%$

$\mathfrak{B}(f_0(980) \to \pi^+\pi^-) = 46 \pm 6\%$

Results for GlueX energie



Scenario 1

Summary and Conclusions

- We have studied the photoproduction of scalar resonance for CLAS and GlueX energies.
- We can distinguish the different mixing schemes.
- The effect of distinct scenarios in the calculation of coupling $S \to V\gamma$ was investigated.
- We also show the large dependence on the model parameters.

Thanks!