Photoproduction of Mesons

K. Hicks (Ohio U.)

July 28, 2021

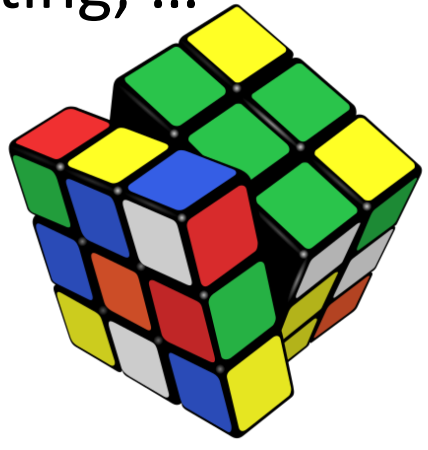
Hadron 2021 International Conf.

Outline

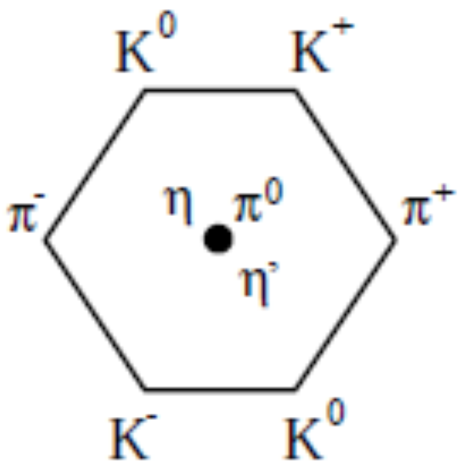
- Reminder of some group theory
- Theoretical tools / Experimental tools
- Why photoproduction?
- Two particular examples:
    1. Photoproduction of K_sK_s: scalar mesons/glueball
    2. Photoproduction of $\pi^0\pi^0$: $f_2(1270)$ t-dependence

Origins of Group Theory

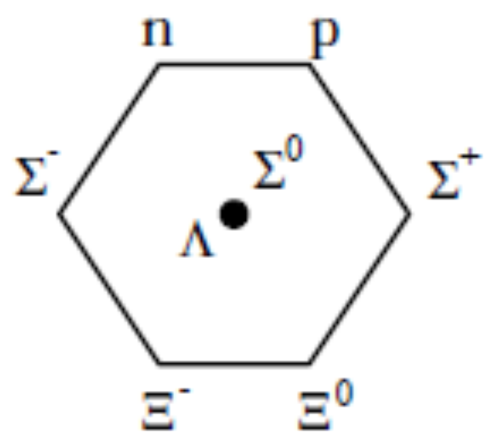
- Group theory grew out of mathematician's desire to solve the quintic equation (x^5+…).
  - Evarist Galois developed group theory from nill.
- Applications of group theory abound
  - Found in most areas of physics: CM, GR, particle,…
  - Also found in music, art, games, forecasting, …
  - Basically, wherever symmetry exists!



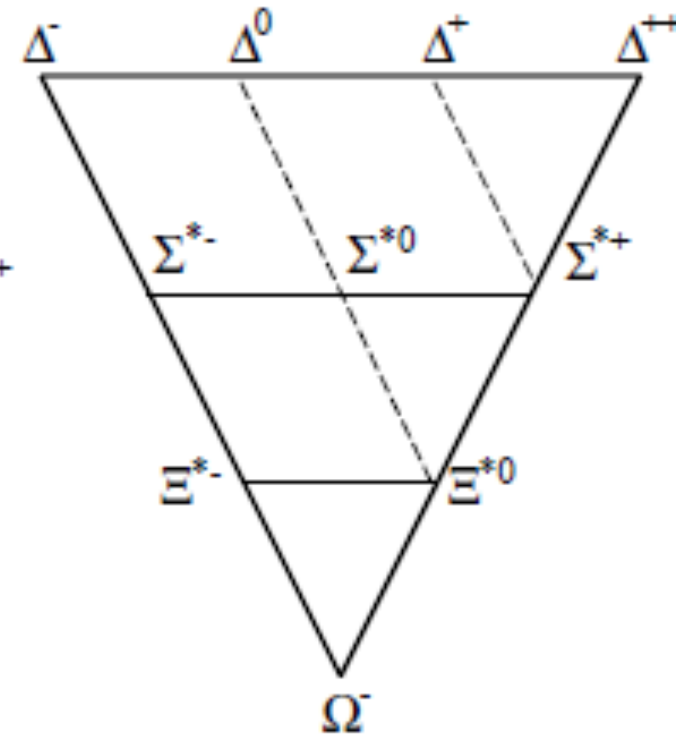
Group Theory: Flavor SU(3)



NONET

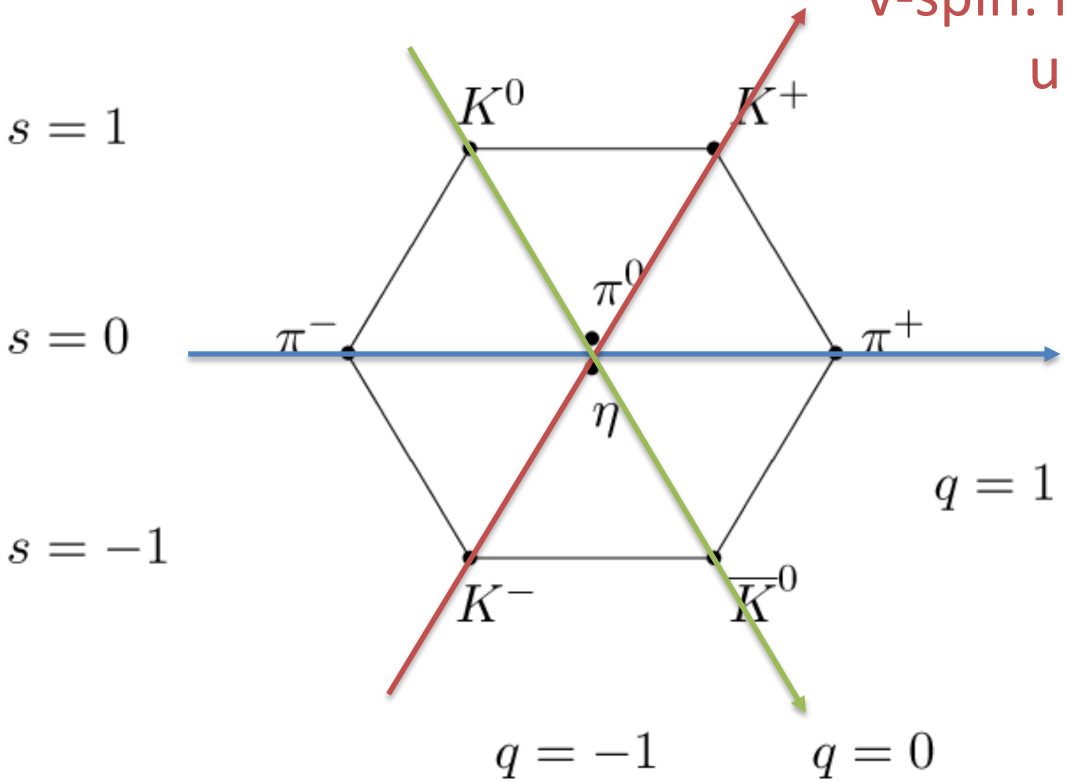


OCTET



DECUPLET

I-spin, U-spin, V-spin



V-spin: not as useful

u ⟷ s

Isospin: conserved in strong interactions.

u ⟷ d

U-spin: conserved in EM interactions.

s ⟷ d

U-spin predictions for EM decays

Eur. Phys. J. A (2013) **49**: 53
DOI 10.1140/epja/i2013-13053-4

THE EUROPEAN PHYSICAL JOURNAL A

Letter

U-spin predictions of the transition magnetic moments of the electromagnetic decay of the $\Sigma^*(1385)$ baryons

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[2] Ohio University, Athens, Ohio 45701, USA

Transitions	$1/N_c$	QM [16]	U-spin	Experiment
$\mu_{\Sigma\Sigma^{*+}}$	2.96 ± 0.04	2.33	3.22 ± 0.05	3.22 ± 0.45
$\mu_{\Lambda\Sigma^{*0}}$	2.96 ± 0.04	2.28	2.68 ± 0.04	2.75 ± 0.25
$\mu_{\Sigma\Sigma^{*0}}$	1.34 ± 0.04	1.02	1.61 ± 0.07	
$\mu_{\Sigma\Sigma^{*-}}$	-0.27 ± 0.04	-0.30	0.0 ± 0.20	
$\mu_{\Xi\Xi^{*0}}$	2.96 ± 0.04	2.33	3.21 ± 0.15	

Can similarly good results be obtained for mesons? (Open question)

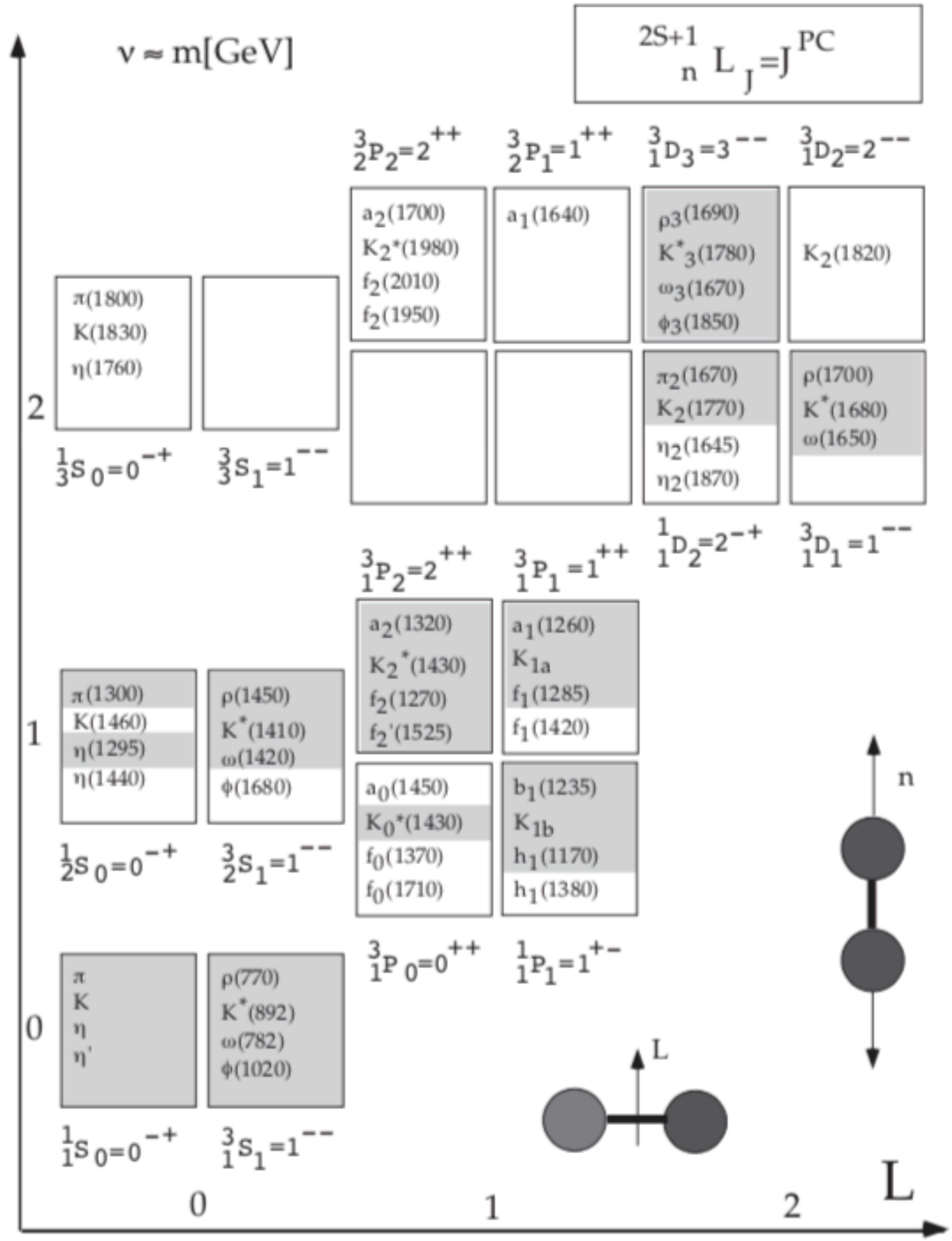
Quark Model: mesons (u,d,s)

$n^{2s+1}\ell_J$	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	$\eta'(958)$	−11.3	−24.5
1^3S_1	1^{--}	$\rho(770)$	$K^*(892)$	$\phi(1020)$	$\omega(782)$	39.2	36.5
1^1P_1	1^{+-}	$b_1(1235)$	$K_{1B}{}^\dagger$	$h_1(1415)$	$h_1(1170)$		
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^{--}	$\rho(1700)$	$K^*(1680)^\ddagger$		$\omega(1650)$		
1^3D_2	2^{--}		$K_2(1820)^\dagger$				
1^3D_3	3^{--}	$\rho_3(1690)$	$K_3^*(1780)$	$\phi_3(1850)$	$\omega_3(1670)$	31.8	30.8
1^3F_4	4^{++}	$a_4(1970)$	$K_4^*(2045)$	$f_4(2300)$	$f_4(2050)$		
1^3G_5	5^{--}	$\rho_5(2350)$	$K_5^*(2380)$				
2^1S_0	0^{-+}	$\pi(1300)$	$K(1460)$	$\eta(1475)$	$\eta(1295)$		
2^3S_1	1^{--}	$\rho(1450)$	$K^*(1410)^\ddagger$	$\phi(1680)$	$\omega(1420)$		
2^3P_1	1^{++}	$a_1(1640)$					
2^3P_2	2^{++}	$a_2(1700)$	$K_2^*(1980)$	$f_2(1950)$	$f_2(1640)$		

reference: PDG review

Amsler & Tornqvist:

known states (shaded) and prospective states (2004)

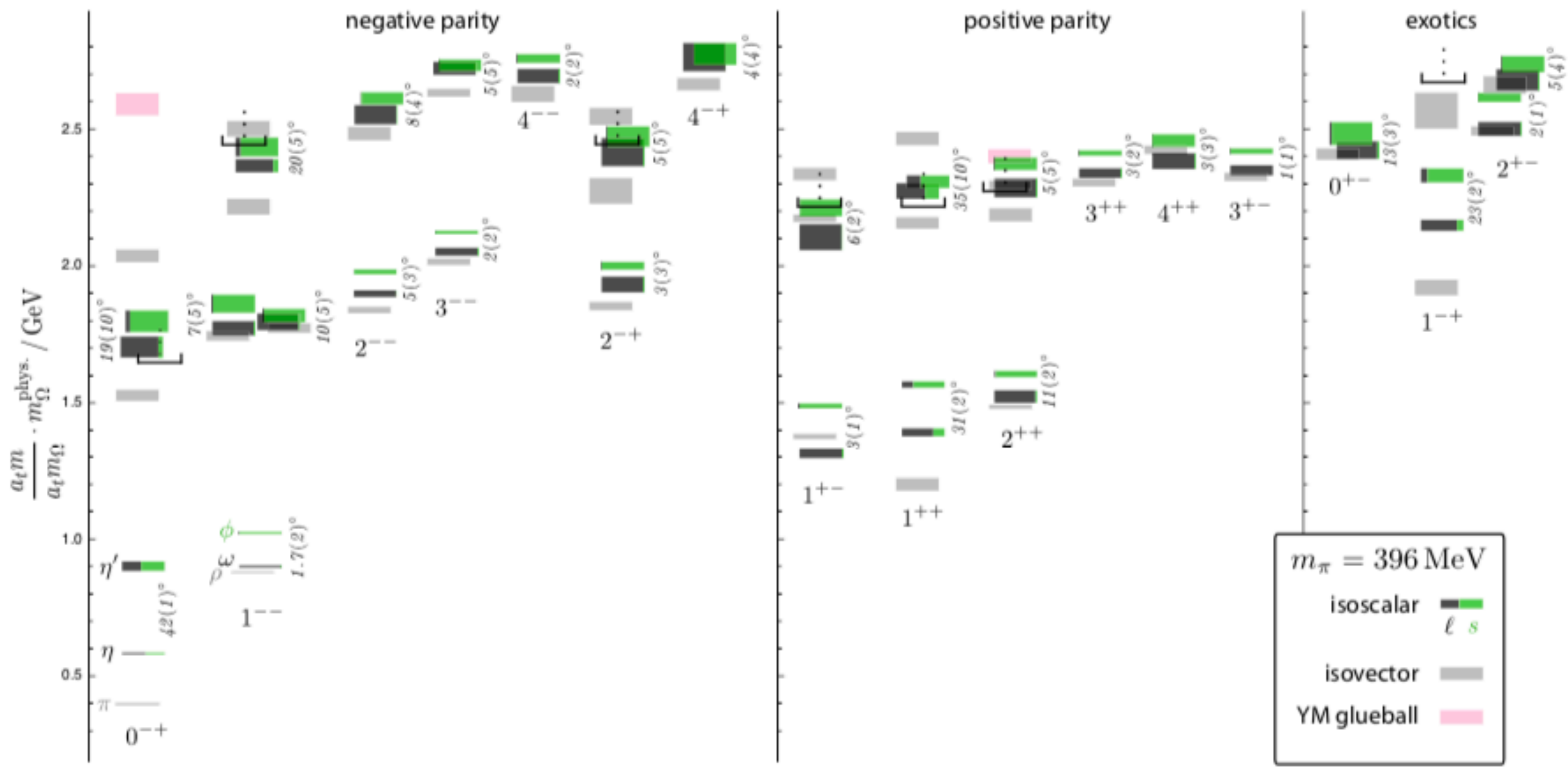


Theoretical Tools

- Lattice QCD: direct calculations of QCD using the concept of Feyman path integrals.
  - With advances in computers, these calculations are finally possible to predict hadron resonances
  - One difference from the quark model is that gluon excitations can also form "hybrid" resonances.
  - Today, one can even extract phase shifts from scattering states of two mesons (Luescher).

Lattice spectrum of mesons

J. Dudek et al., PRD 83, 111502 (2011)



Can we find the missing states from experiments?

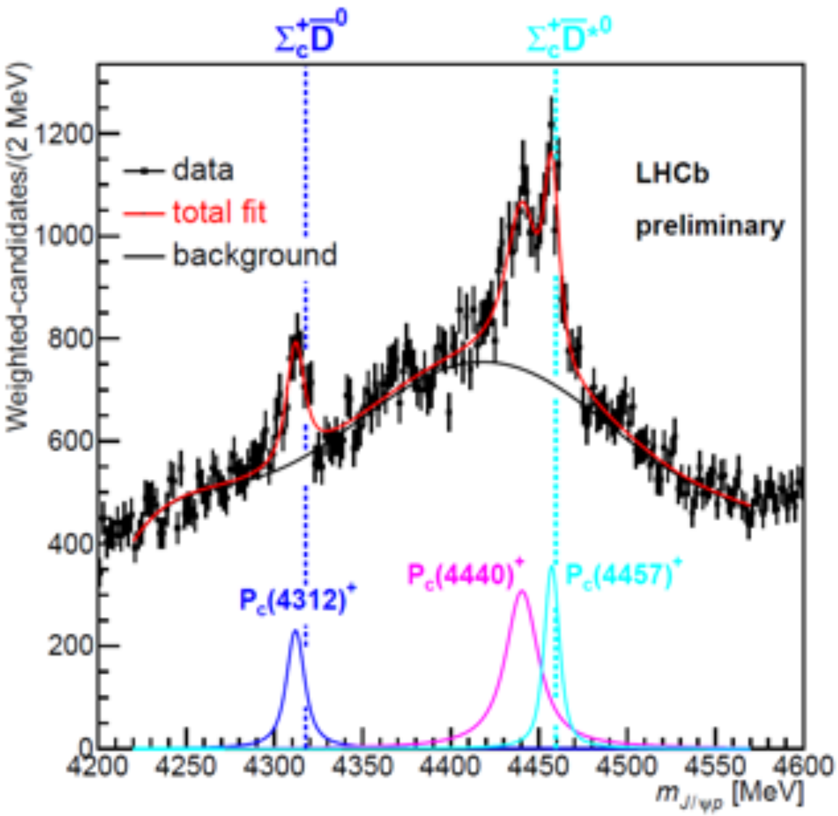
Why Photoproduction?

- Photoproduction couples with a different strength than for hadron beams.
- If a meson resonance is a typical QM (q-qbar) excited state, then it should be seen in a variety of production mechanisms.
- If the photocoupling is small, then this tells us more about the resonance properties.

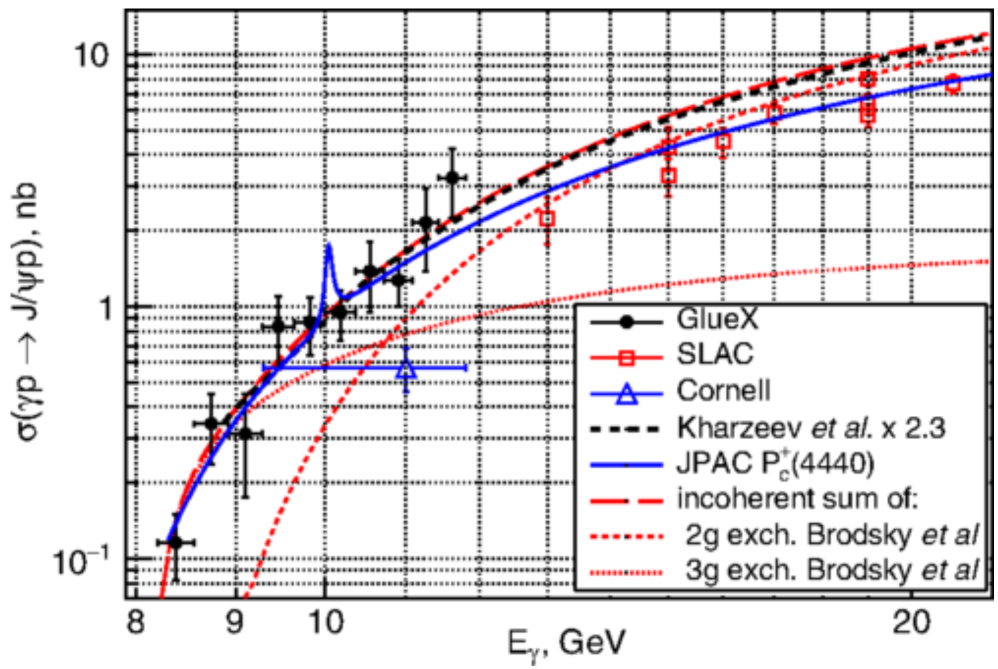
Example: $P_c(4440)^+$ pentaquark

(shown earlier in this conference by Astrid Hiller Blin)

LHCb result: PRL 122, 222001 (2019)



GlueX result: PRL 123, 072001 (2019)



Why is the peak at 4440 seen in B-decay, but not in photoproduction?

Experimental Tools

- Large acceptance detectors:
  - Need full coverage for Partial Wave Analysis
- Polarized photon beams:
  - Linear polarization, Circular polarization
- Polarized targets:
  - Double-polarization observables possible
- Higher-energy photon beams
  - t-channel dominance above N* region.

Some photoproduction facilities:

Germany: MAMI-A2 and Bonn-CBELSA/TAPS

USA: CLAS/CLAS12 and GlueX

Japan: LEPS, LEPS2 and ELPH

1. Search for Glueball decay to $K_s K_s$

Double K_S^0 Photoproduction off the Proton at CLAS

Shloka Chandavar
(PhD, OhioU, 2015)

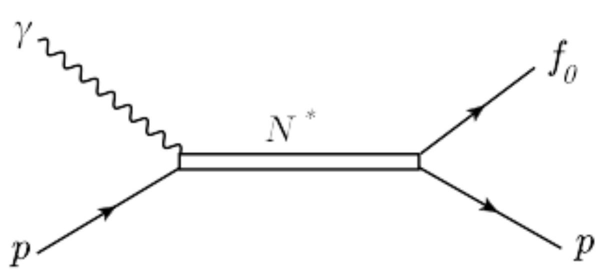
S. Chandavar[1] and K. Hicks[1]
[1] Ohio University
(Dated: September 19, 2017)

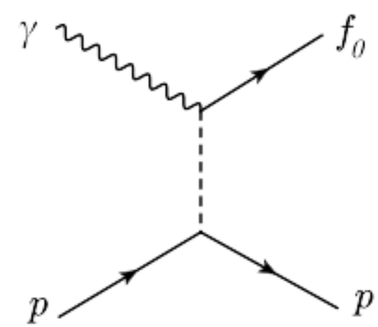
S. Chandavar et al.,
PRC 97, 025203 (2018)

Name	Mass [MeV/c^2]
$f_0(600)$ *	400 – 1200
$f_0(980)$ *	980 ± 10
$f_0(1370)$ *	1200 – 1500
$f_0(1500)$ *	1507 ± 5
$f_0(1710)$ *	1718 ± 6

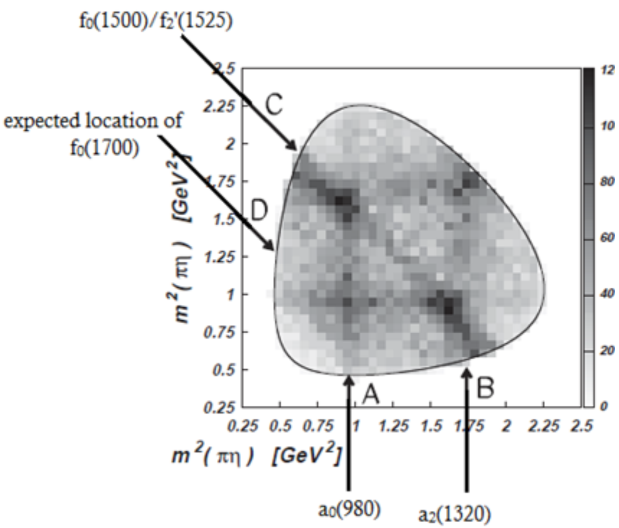
- There are 5 **isoscalar** states identified by experiment: f0(600),$f_0(980)$, $f_0(1370)$, $f_0(1500)$ and $f_0(1710)$
- There are only 2 slots for the f_0 states in the quark model

Photoproduction can give info on the coupling of the f_0 meson to the photon.





What previous experiments observed

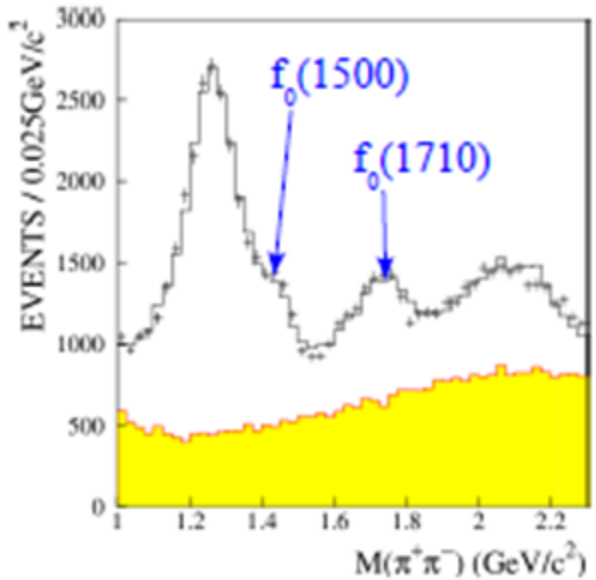


$p\bar{p} \to \pi^0\eta\eta$

$p\bar{p}$ annihilation : Crystal Barrel

$f_0(1500)$ is seen in the ηη mass projection

C. Amsler and N.A. Tornqvist, Phys. Rept. 389 (2004) 61.



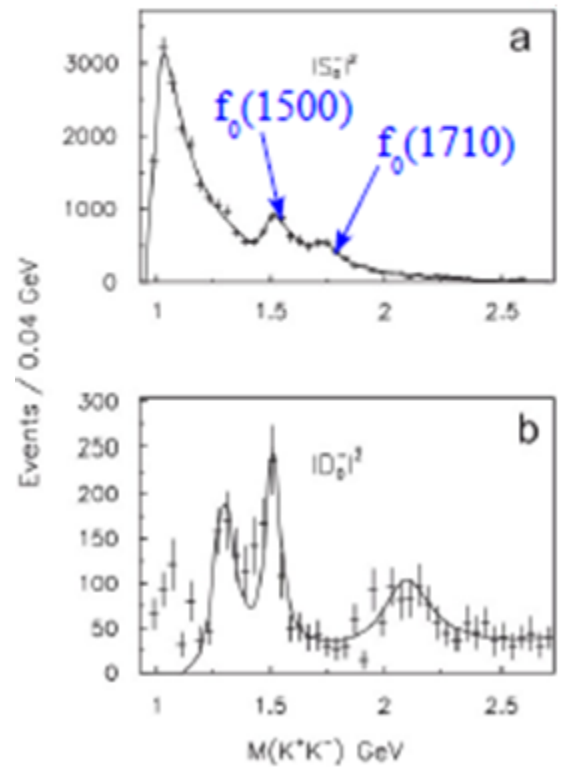
BES II

J/Ψ –> γππ

PWA: J=0 -> $f_0(1500)$

Shaded region = J/Ψ –> $\pi^+\pi^-\pi^0$

D. Barberis et al., [WA102 Collaboration], Phys. Lett. B462 (1999) 462, hep-ex/9907055

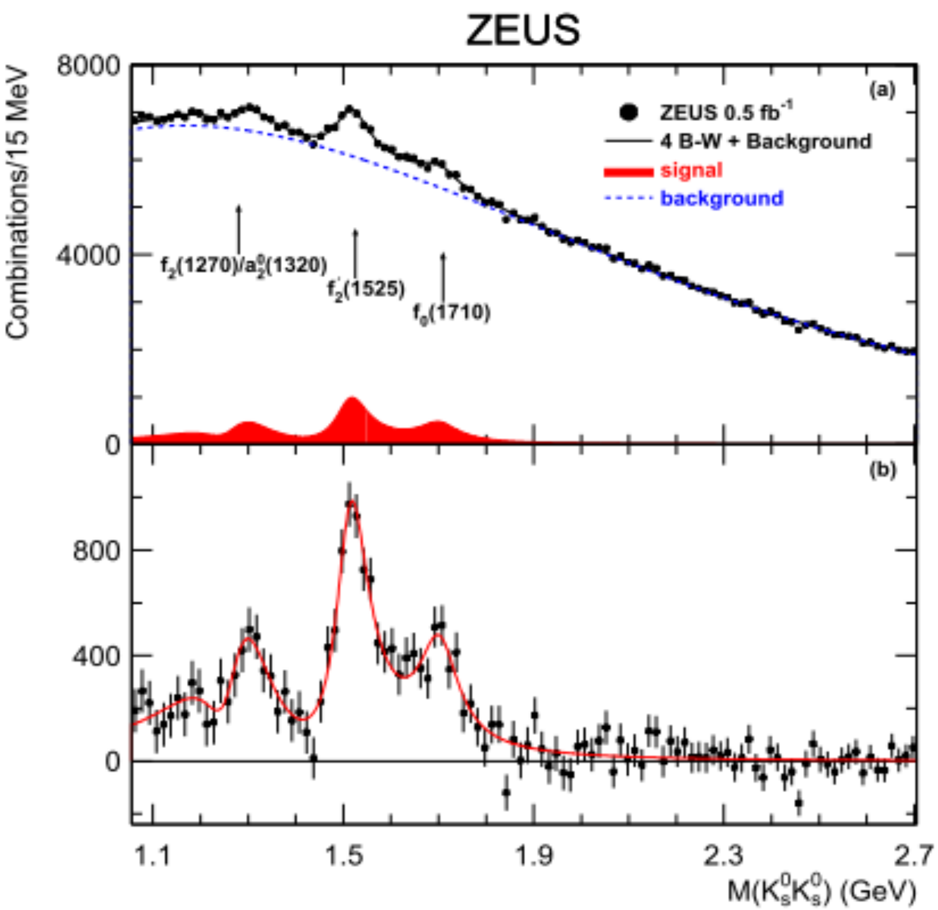


WA102 Central production

The $f_0(1500)$ is clearly seen

M. Ablikim et al., [BES Collaboration] Phys. Lett. B 642 (2006) 441

ZEUS Experiment: detected $K_s^0K_s^0$



ZEUS Collaboration: S. Chekanov, et al, *Inclusive $K^0_SK^0_S$ resonance production in ep collisions at HERA, Phys.Rev.Lett.101:112003,2008, arXiv:0806.0807v2*

Why choose strange decay?

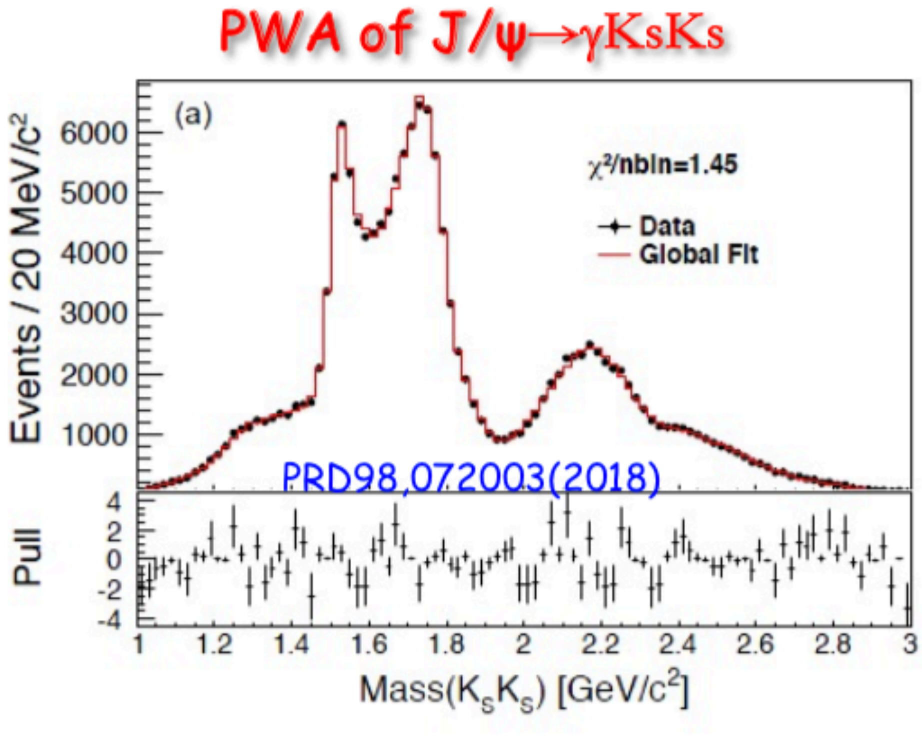
M.Chanowitz suggests in PRL 95, 172001 (2005) that glueballs are more likely to decay to strange channels

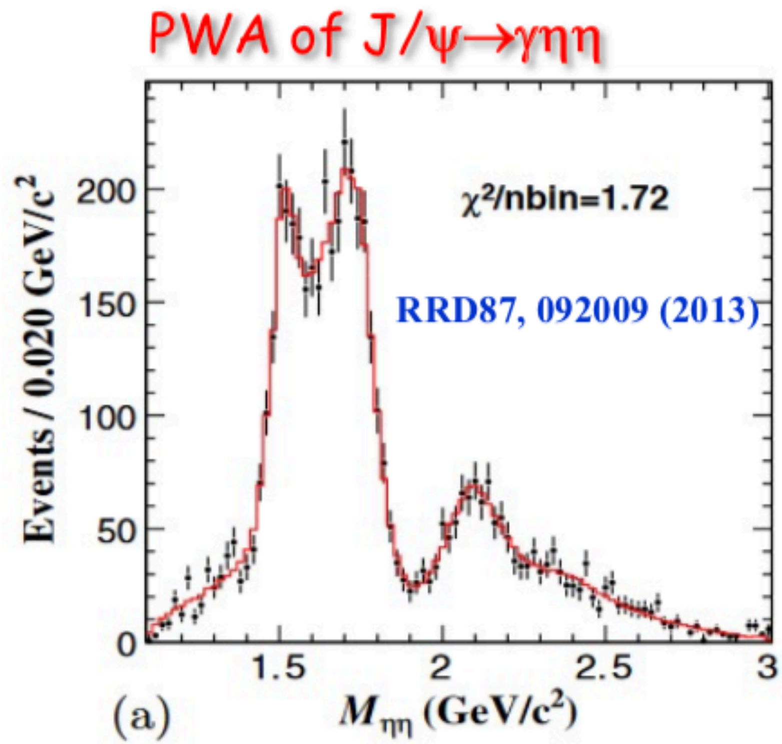
Why choose $K_s^0K_s^0$?

Ensure that the final state has the same PC =++ as the lightest glueball

BES-III: recent spectra

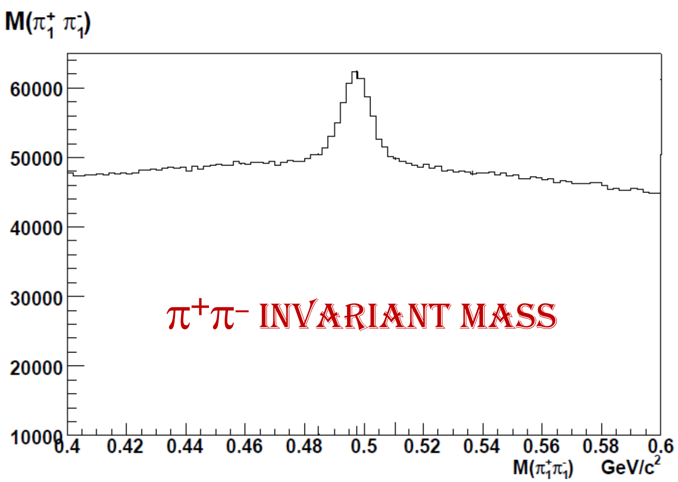
(shown earlier in this conference by Shuangshi Fang)

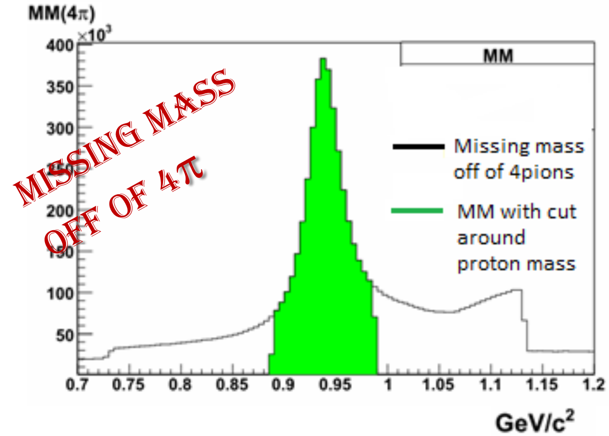


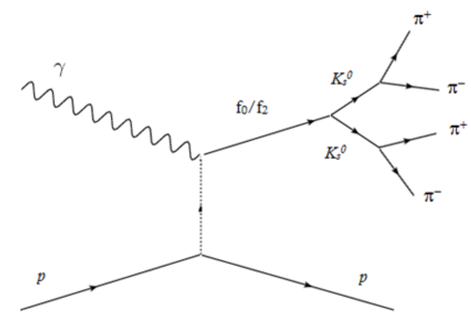


Peaks at $f_0(1500)$ and $f_0(1700)$ are dominant. Why different than $M(\pi\pi)$ and Zeus?
→ shows the value in having different production mechanisms!

CLAS: $\gamma p \rightarrow K_s^0 K_s^0 p$ (g12 run)



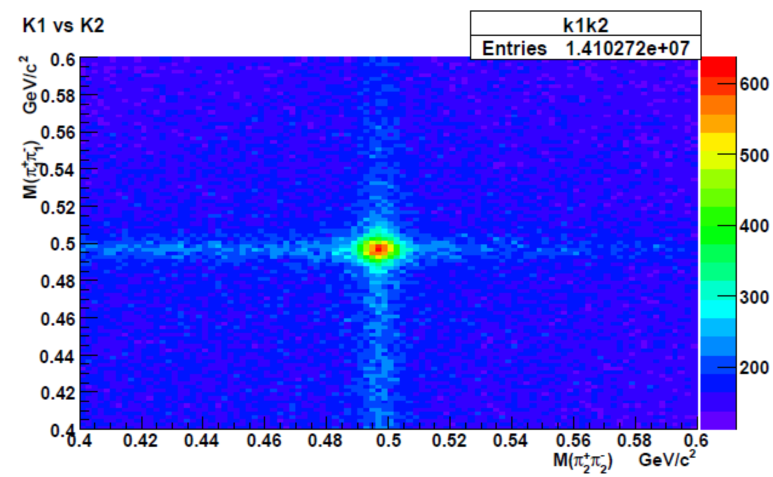




There is a clear kaon peak above the combinatorial background

Only those events are selected which have a missing mass of the proton

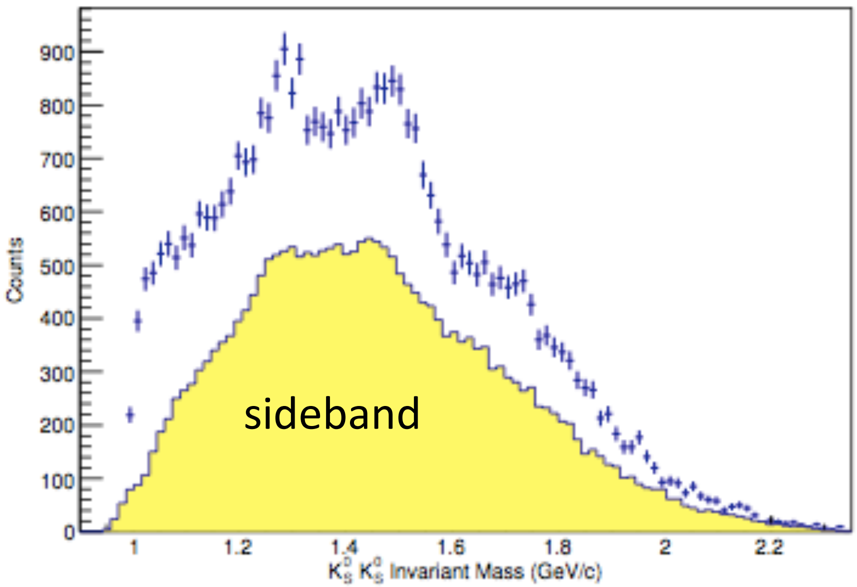
The plot of the two K_s^0 plotted against each other shows the high correlation between them.



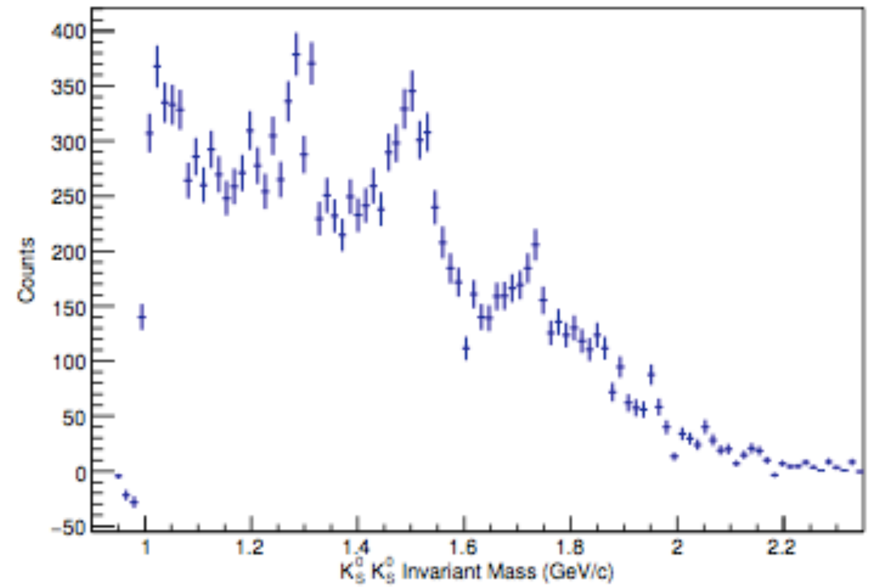
4 combinations of $\pi^+\pi^-$ are possible. We select the 2 combinations that most closely match the value of the Ks mass.

Invariant mass: $f_0 \rightarrow K_s^0 K_s^0$

All events: $M(4\pi)$: $M(K_s K_s)$ + sidebands



Sideband-subtracted events



Cut Level	Type of Cut	Size of Cut
1	Timing Cut for identification of pions	± 1 ns
2	Fiducial Cut	Fit to CLAS acceptance
3	Missing mass (proton)	± 0.0497 GeV (3σ)
4	Photon beam energy	2.7-3.0 and 3.1-5.1 GeV
5	K_S^0 peak and sideband subtraction	0.01614 GeV (3σ)

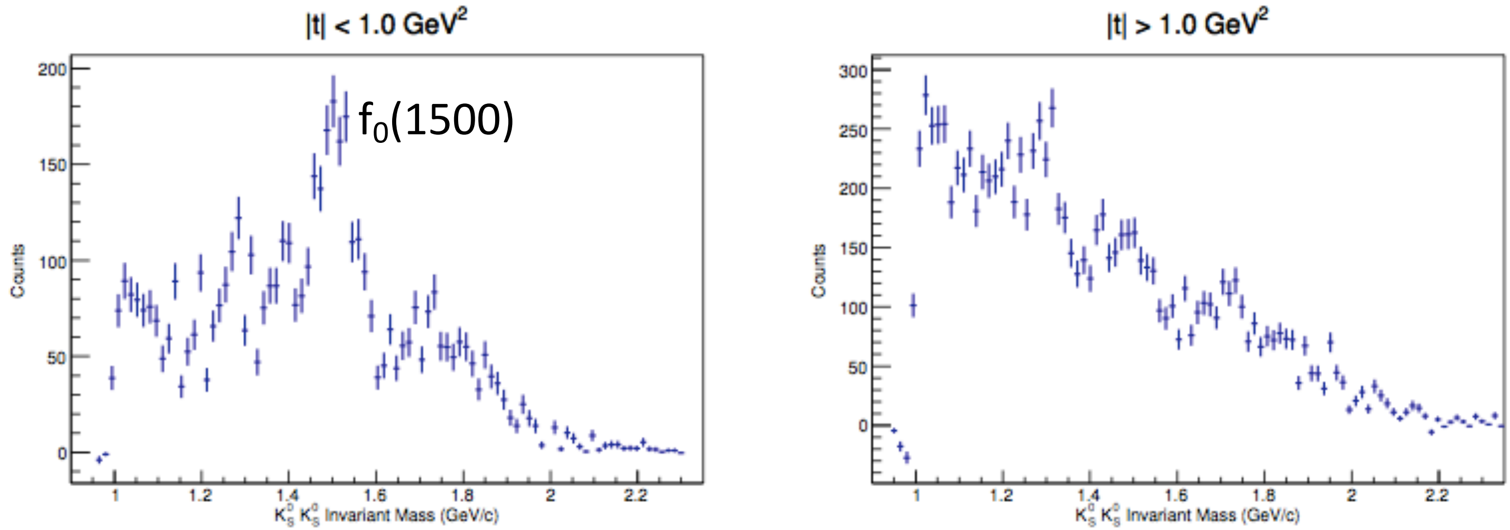
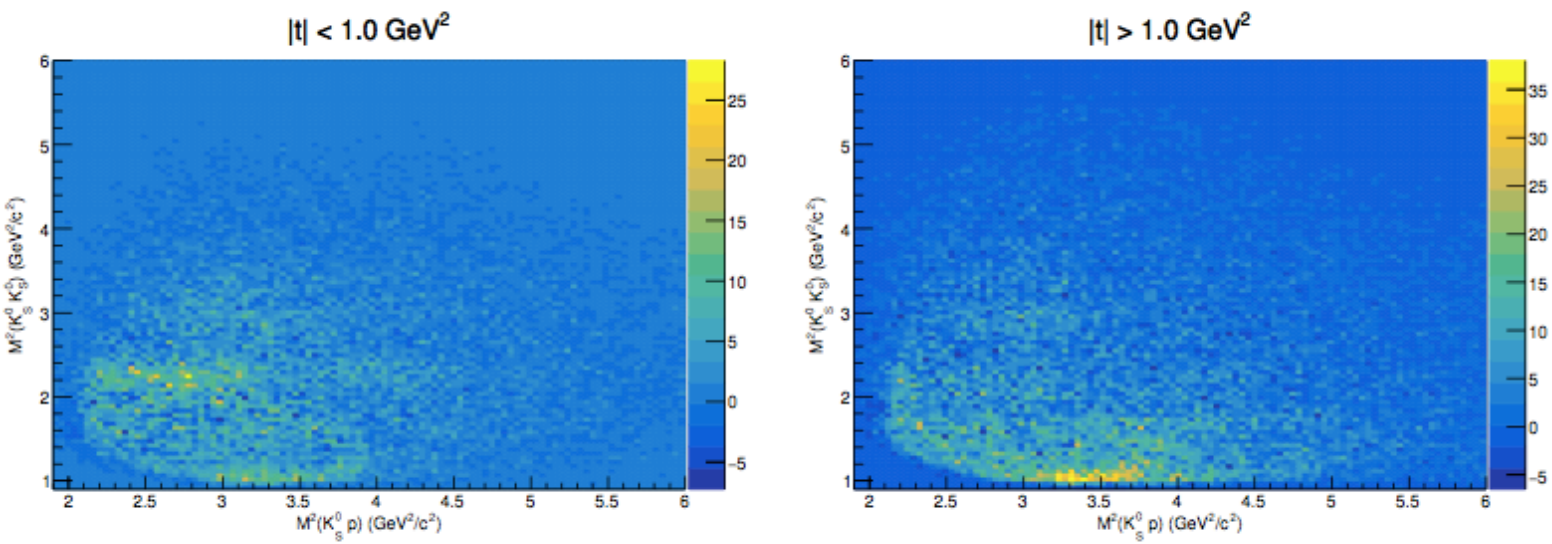
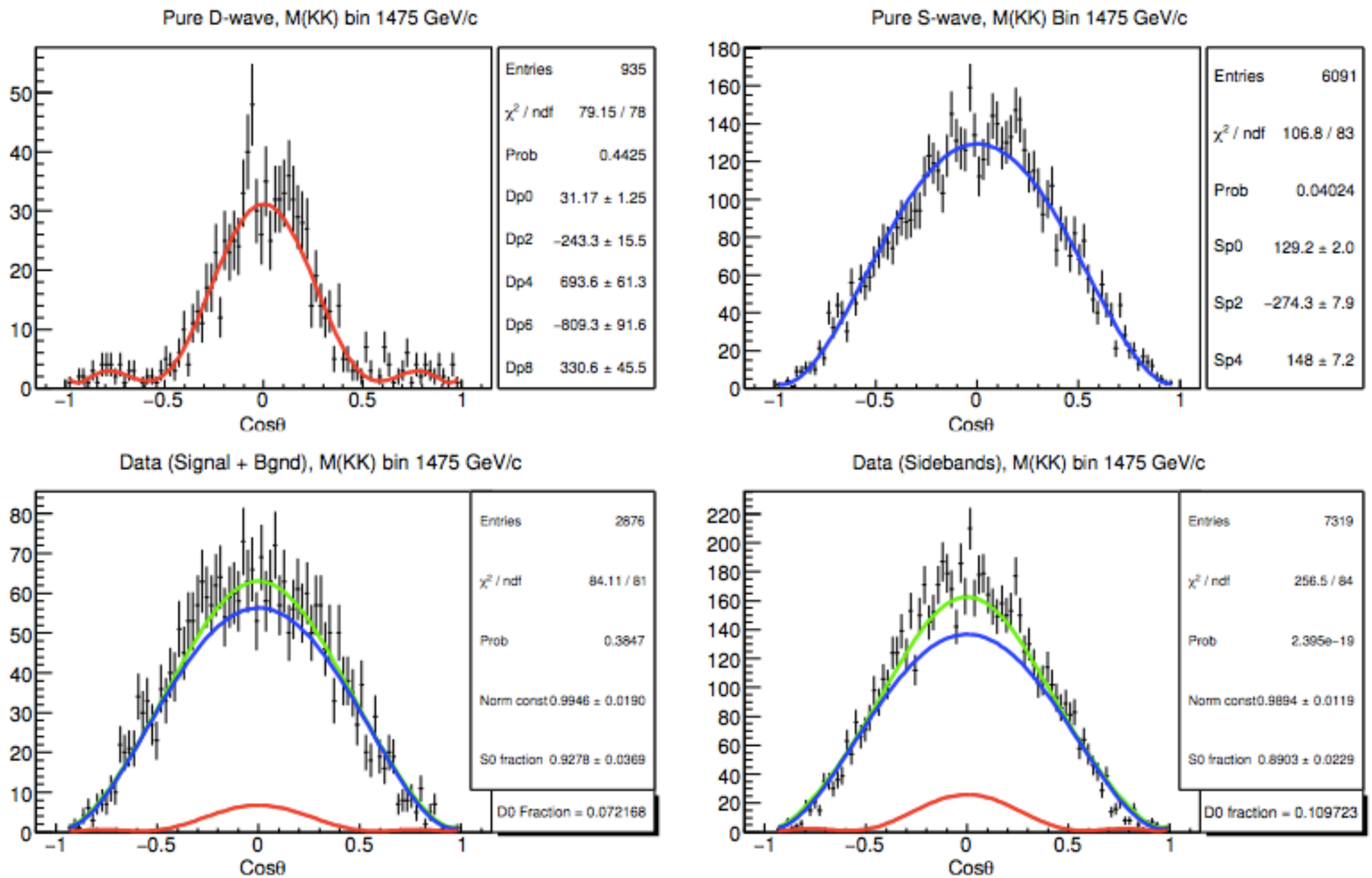


Figure 6. Background subtracted plots for the 4π invariant mass for $|t| < 1$ GeV^2 (left) and $|t| > 1$ GeV^2 (right).



t-channel photoproduction dominates for $f_0(1500)$ peak.

Angular distributions (G.J.-frame)



Fits to 1500 MeV mass region show S-wave dominance → $f_0(1500)$.

Summary of K_sK_s mass spectrum

- Clear peak seen in $M(K_sK_s)$ at 1500 MeV in the CLAS photoproduction data.
  - smaller peaks: likely $f_2(1270)$, $f_0(1710)$.
  - main peak enhanced at small $|t|$.
  - decay angular distribution fits -> S-wave.
- Suggests that the photon couples more strongly to the $f_0(1500)$.
  - Less glueball content? (pure glueball: no charge)

2. t-dependence of $f_2(1270)$: $\pi^0\pi^0$

Undergraduate at Ohio U.

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Photoproduction of the $f_2(1270)$ Meson Using the CLAS Detector

M. Carver,[1] A. Celentano,[2] K. Hicks,[1] L. Marsicano,[2] V. Mathieu,[3] A. Pilloni,[4,2,5] K. P. Adhikari,[6] S. Adhikari,[7] M. J. Amaryan,[6] G. Angelini,[8] H. Atac,[9] N. A. Baltzell,[10,11] L. Barion,[12] M. Battaglieri,[10,2] I. Bedlinskiy,[13] F. Benmokhtar,[14] A. Bianconi,[15,16] A. S. Biselli,[17] M. Bondi,[2] F. Bossù,[18] S. Boiarinov,[10] W. J. Briscoe,[8] W. K. Brooks,[19] D. Bulumulla,[6] V. D. Burkert,[10] D. S. Carman,[10] J. C. Carvajal,[7] P. Chatagnon,[20] T. Chetry,[21] G. Ciullo,[12,22] L. Clark,[23] B. A. Clary,[24] P. L. Cole,[25,26] M. Contalbrigo,[12] V. Crede,[27] A. D'Angelo,[28,29] N. Dashyan,[30] R. De Vita,[2] M. Defurne,[18] A. Deur,[10] S. Diehl,[31,24] C. Djalali,[1,11] M. Dugger,[32] R. Dupre,[20] H. Egiyan,[10,33] M. Ehrhart,[34] A. El Alaoui,[19] L. El Fassi,[21,34] P. Eugenio,[27] G. Fedotov,[35] S. Fegan,[36] A. Filippi,[37] G. Gavalian,[10,6] N. Gevorgyan,[30] G. P. Gilfoyle,[38] F. X. Girod,[10,18] R. W. Gothe,[11] K. A. Griffioen,[39] K. Hafidi,[34] H. Hakobyan,[19,30] M. Hattawy,[6] T. B. Hayward,[39] D. Heddle,[40,10] M. Holtrop,[33] Q. Huang,[18] C. E. Hyde,[6] Y. Ilieva,[11] D. G. Ireland,[23] E. L. Isupov,[35] D. Jenkins,[41] H. S. Jo,[42] K. Joo,[24] S. Joosten,[34] D. Keller,[43,1] A. Khanal,[7] M. Khandaker,[44,*] A. Kim,[24] C. W. Kim,[8] F. J. Klein,[45] A. Kripko,[31] V. Kubarovsky,[10] L. Lanza,[28] M. Leali,[15,16] P. Lenisa,[12,22] K. Livingston,[23] I. J. D. MacGregor,[23] D. Marchand,[20] V. Mascagna,[46,16] M. E. McCracken,[47] B. McKinnon,[23] Z. E. Meziani,[34] V. Mokeev,[10,35] A. Movsisyan,[12] E. Munevar,[8] C. Munoz Camacho,[20] P. Nadel-Turonski,[10,45] K. Neupane,[11] S. Niccolai,[20] G. Niculescu,[48] M. Osipenko,[2] A. I. Ostrovidov,[27] M. Paolone,[9] L. L. Pappalardo,[12,22] R. Paremuzyan,[10] E. Pasyuk,[10] W. Phelps,[40] O. Pogorelko,[13] Y. Prok,[6,43] D. Protopopescu,[23] M. Ripani,[2] B. G. Ritchie,[32] J. Ritman,[49] A. Rizzo,[28,29] G. Rosner,[23] J. Rowley,[1] F. Sabatié,[18] C. Salgado,[44] A. Schmidt,[8] R. A. Schumacher,[47] Y. G. Sharabian,[10] U. Shrestha,[1] D. Sokhan,[23] O. Soto,[50] N. Sparveris,[9] S. Stepanyan,[10] I. I. Strakovsky,[8] S. Strauch,[11] N. Tyler,[11] R. Tyson,[23] M. Ungaro,[10,24] L. Venturelli,[15,16] H. Voskanyan,[30] E. Voutier,[20] D. P. Watts,[36] K. Wei,[24] X. Wei,[10] B. Yale,[39] N. Zachariou,[36] J. Zhang,[43,6] and Z. W. Zhao[51,11]

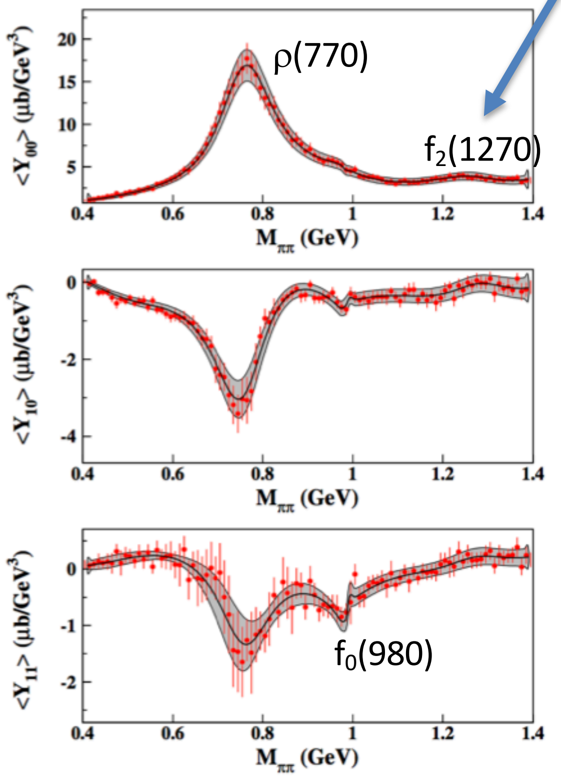
(CLAS Collaboration)

Interest in the $f_2(1270)$

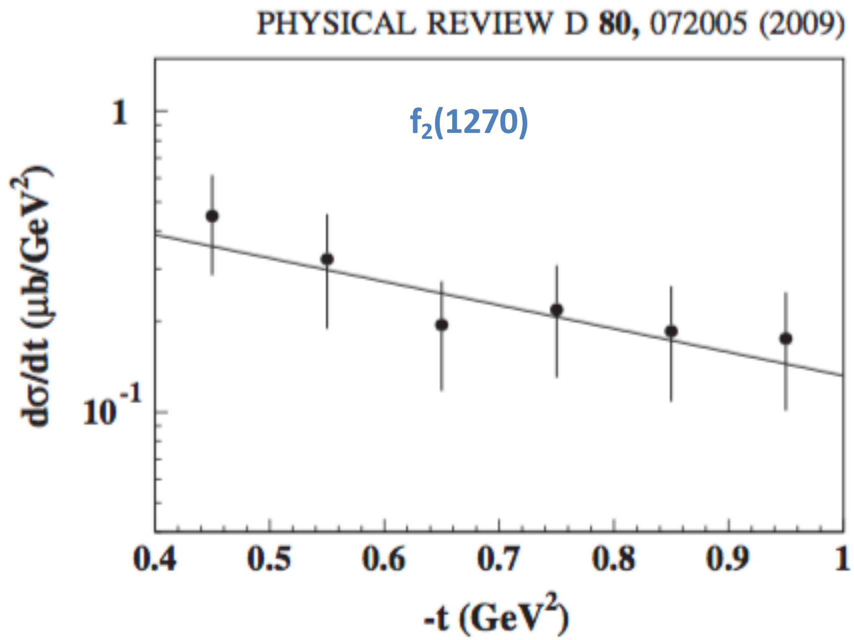
- Is that the $f_2(1270)$ is a $\rho-\rho$ molecule?
  - Ref: Xie and Oset, Eur. Phys. J. A 51, 111 (2015)
  - Based on fits to older CLAS data: Battaglieri et al., PRD 80, 072005 (2009).
  - The CLAS data had large (>20%) error bars, based on $\pi^+\pi^-$ final state from g11.
  - Xie and Oset predicted an E_γ dependence to the total cross section based on $\rho-\rho$ molecule model.

CLAS g11 $\pi^+\pi^-$ analysis: Multipole Fits

For one bin: E_γ=3.2-3.4 GeV, |t|=0.5-0.6.



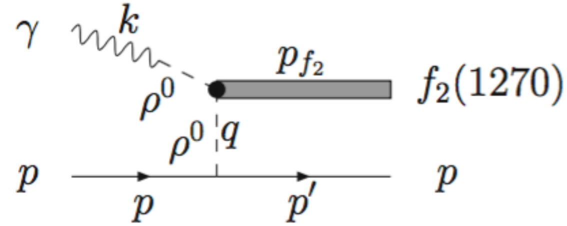
$M_{\pi\pi}$ = 1.19-1.46 GeV, for E_γ = 3.0-3.8 GeV



Theory predictions

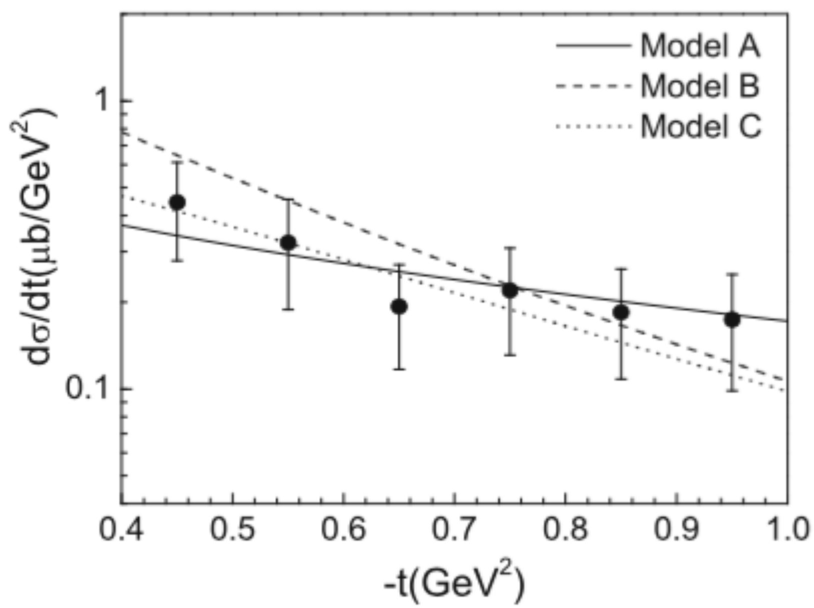
Xie and Oset: EPJ A 51, 111 (2015)

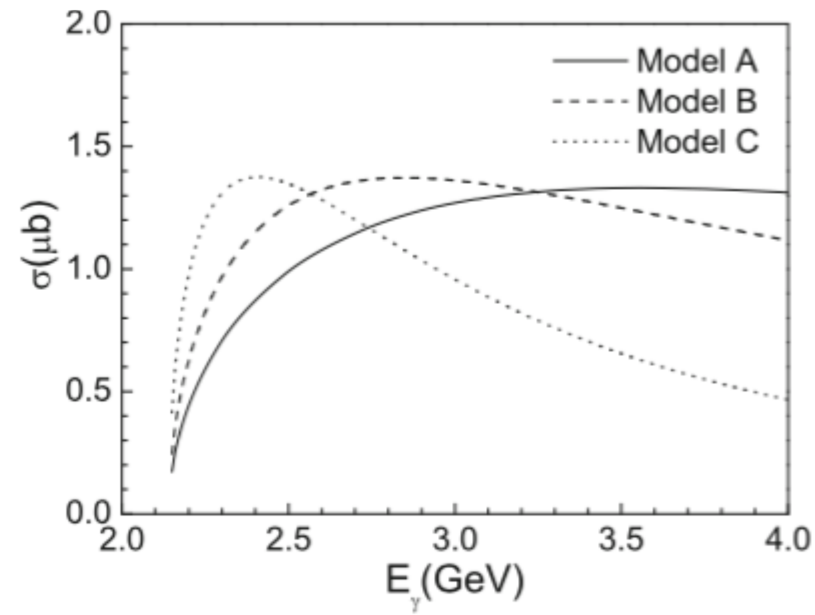
Data from Battaglieri, PRD 80 (2009)



which gives a $\rho^0 pp$ vertex

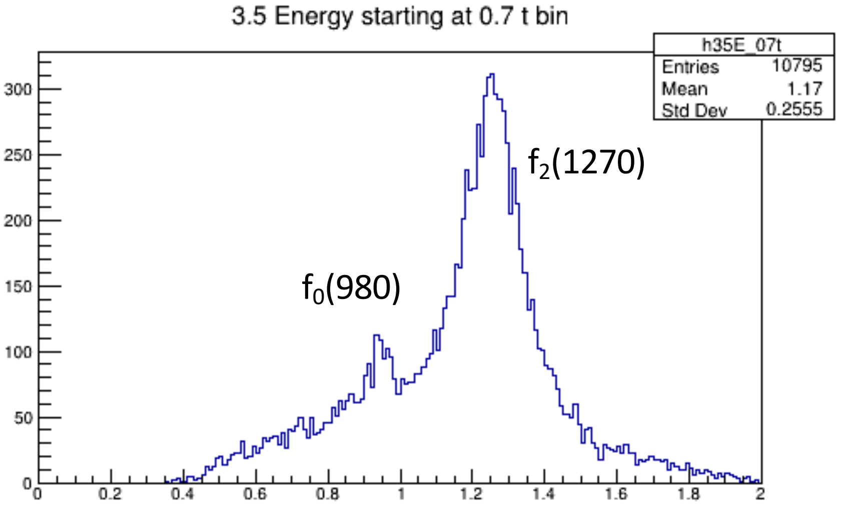
$$-it_{\rho^0 pp} = ig_{\rho NN}\bar{p}\left(\gamma^\mu + \frac{i\kappa_\rho}{2m_N}\sigma^{\mu\nu}q_\nu\right)p\epsilon_\mu(\rho^0),$$



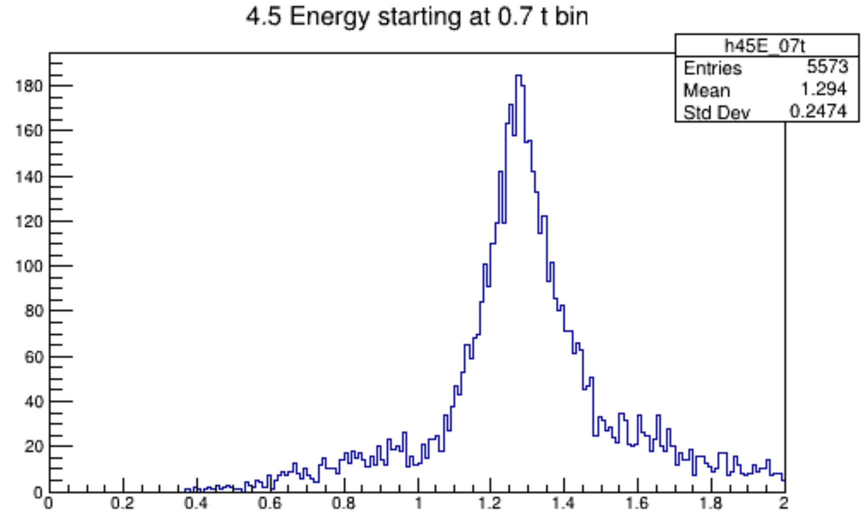


New g12 data using $\pi^0\pi^0$: no ρ background

$E_\gamma > 3.5$ GeV to remove background from baryon resonances!



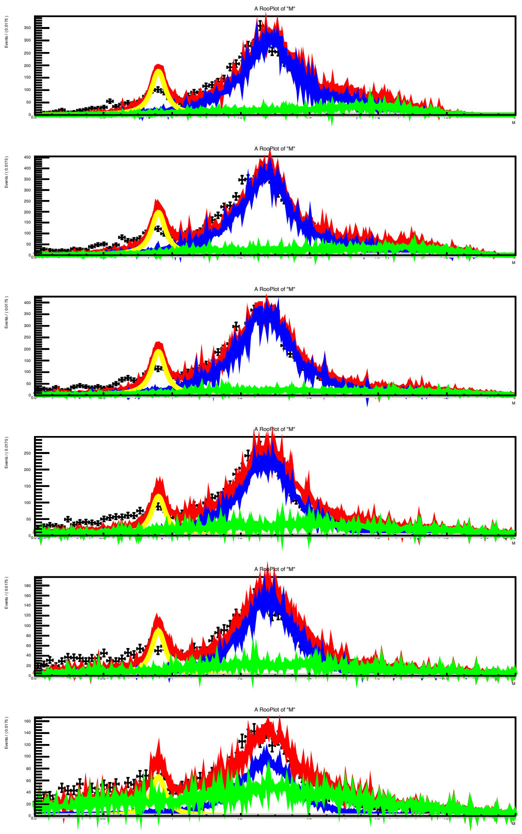
$M_{\pi\pi}$ (GeV)



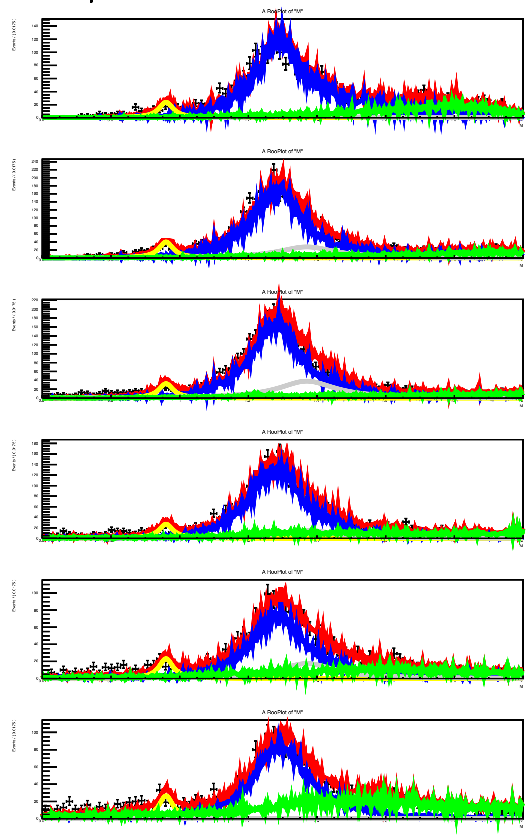
$M_{\pi\pi}$ (GeV)

Fits to the new $\pi^0\pi^0$ data

E_γ = 3.5-4.5 GeV, |t| bins



E_γ = 4.5-5.5 GeV, |t| bins



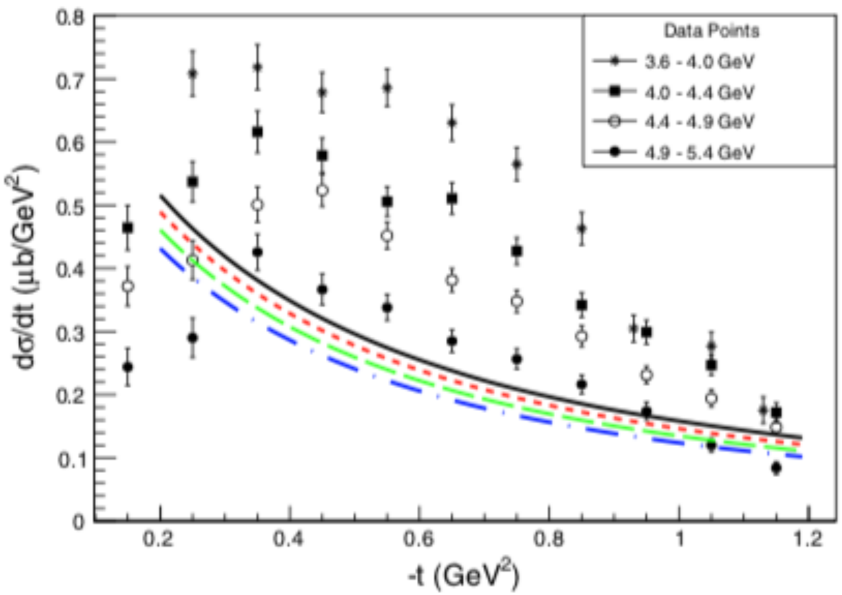
Red: sum of all parts
Blue: $f_2(1270)$ peak
Green: phase space

increasing |t|

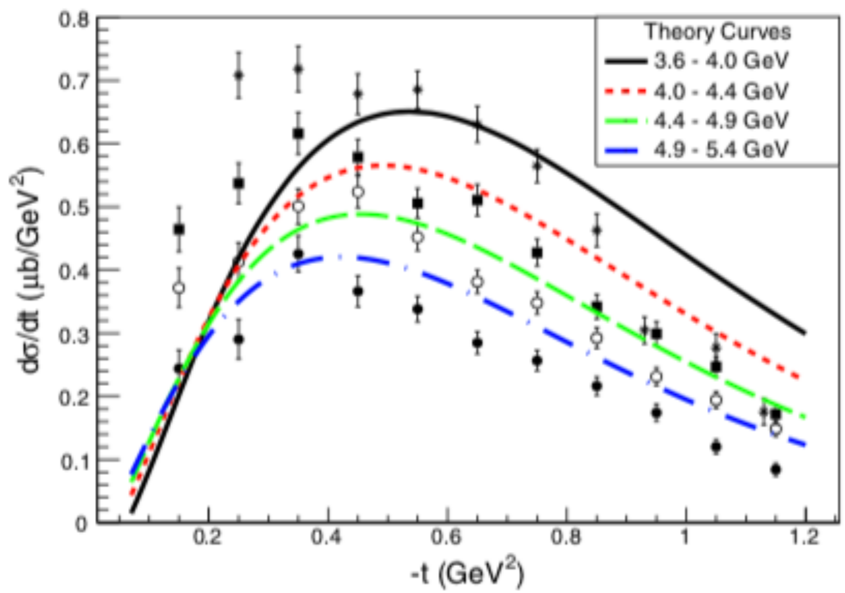
Results: t-dependence (bins of E_γ)

Note: the data is the SAME for both plots. Only theory curves change.

Theory curves: (left) Xie and Oset; (right) JPAC, Vincent Mathieu.



Predictions of model A of Xie and Oset: EPJ A 51, 111 (2015).



Tensor Meson Dominance model of JPAC: PRD 102, 014003 (2020). Scaled by factor of 0.6.

Summary of $f_2(1270)$ photoproduction

- Using $\pi^0\pi^0$ final state: no ρ-background.
  - $f_2(1270)$ cross sections much more precise!
  - t-dependence peaks at about 0.4 GeV^2, in agreement with trend of TMD model.
    - Nearly linear shape of ρ–ρ model disagrees.
- Results suggest that $f_2(1270)$ is a quark model state, not a tetraquark.
  - More theoretical studies are needed.

Backup

What have we learned?

- The quark model works well for the ground states with L=0.
- When n>0, not all of the quark model predictions are found.
- This may be because the energy required to excite a quark into higher orbitals is greater than the pion mass.
  - Is it more efficient to create pions than meson resonances?