Light Exotics
-
Have we observed mesons beyond ?

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Bonn

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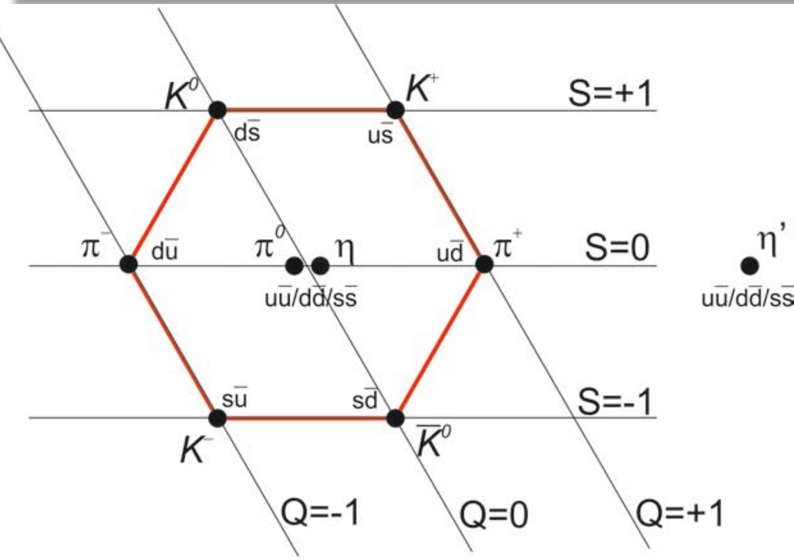
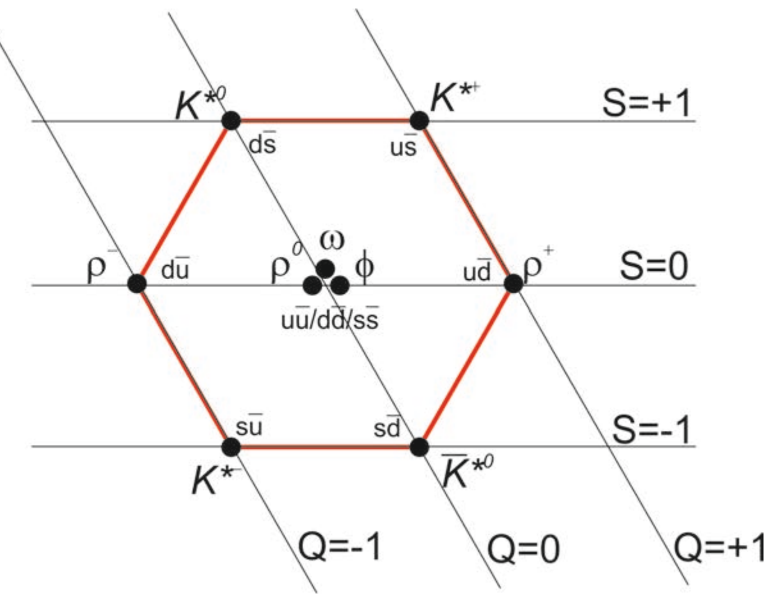
Light Mesons





Quark model:

- bound state of qq
- SU(3)$_{\text{flavor}}$: $q \otimes \bar{q}' = 3 \otimes \bar{3} = 8 \oplus 1$
- color singlets

Quantum numbers:

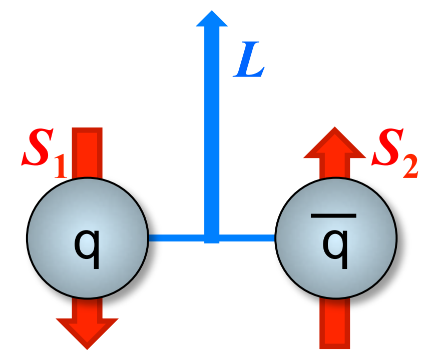
- measured: $I^G\ (J^{PC})$
- quark model: ${}^{2S+1}L_J$

$\boldsymbol{S}=\boldsymbol{S}_1+\boldsymbol{S}_2\ ,\quad \boldsymbol{J}=\boldsymbol{L}+\boldsymbol{S}$

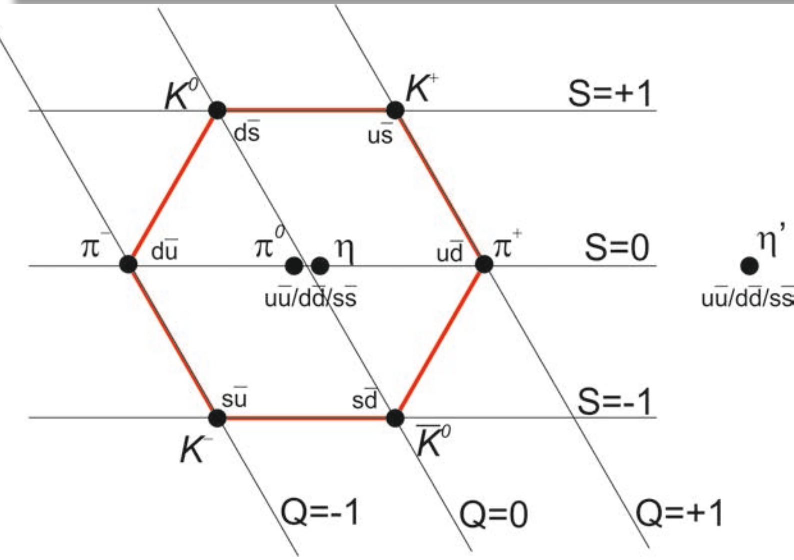
$$P = (-1)^{L+1}$$

$$C = (-1)^{L+S}$$

$$G = (-1)^{L+S+I}$$



Light Mesons



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Allowed combinations

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

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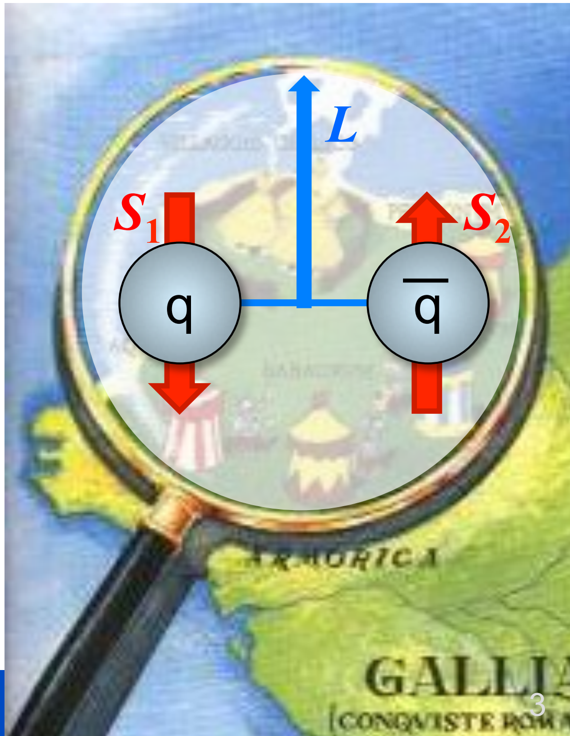
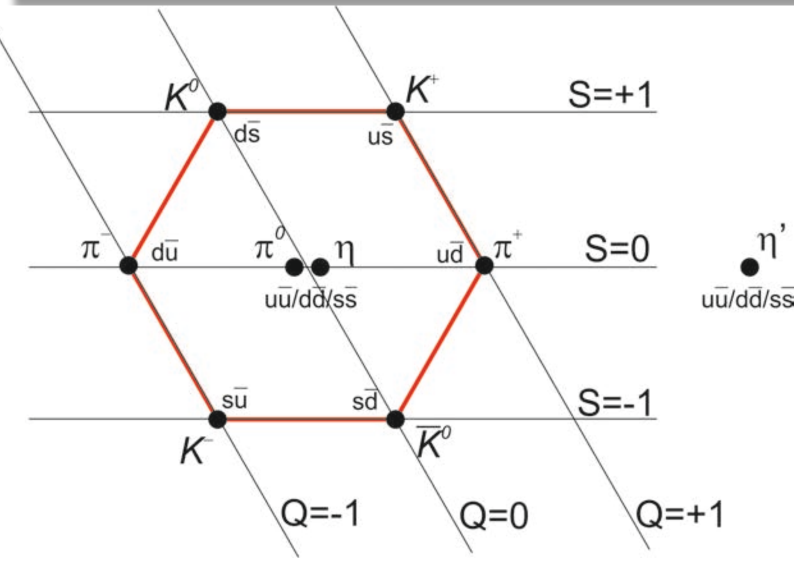


Light Mesons



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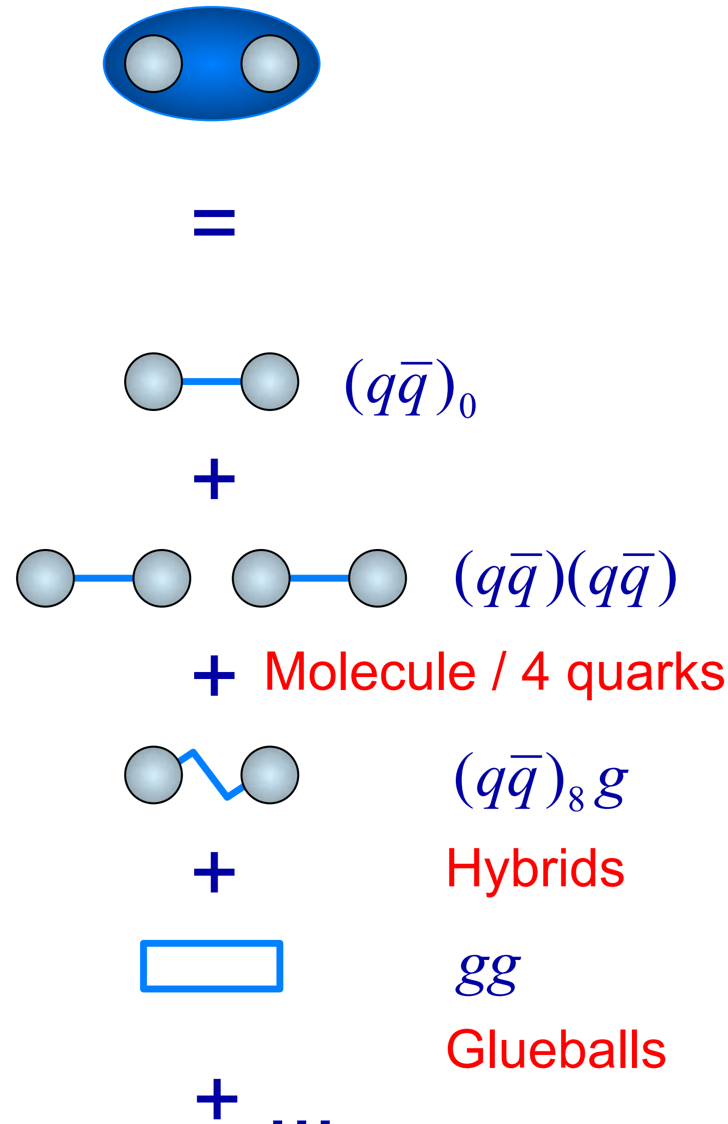
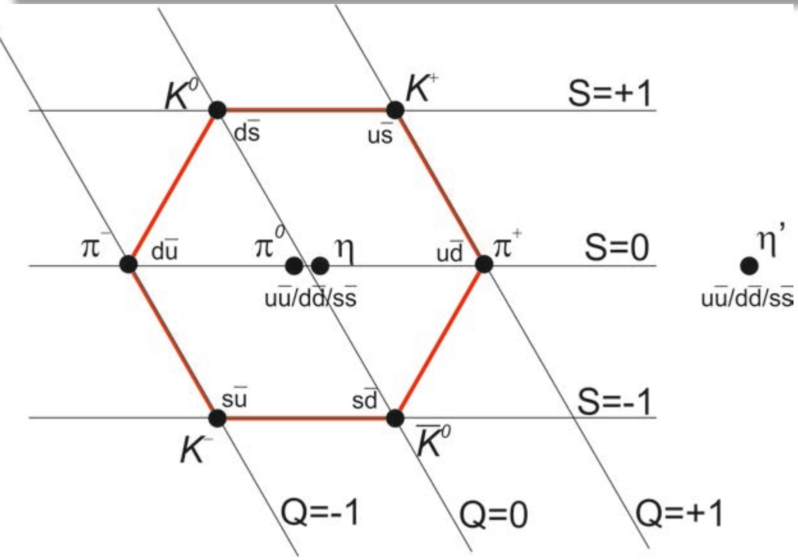
"Forbidden" combinations

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



Light Mesons



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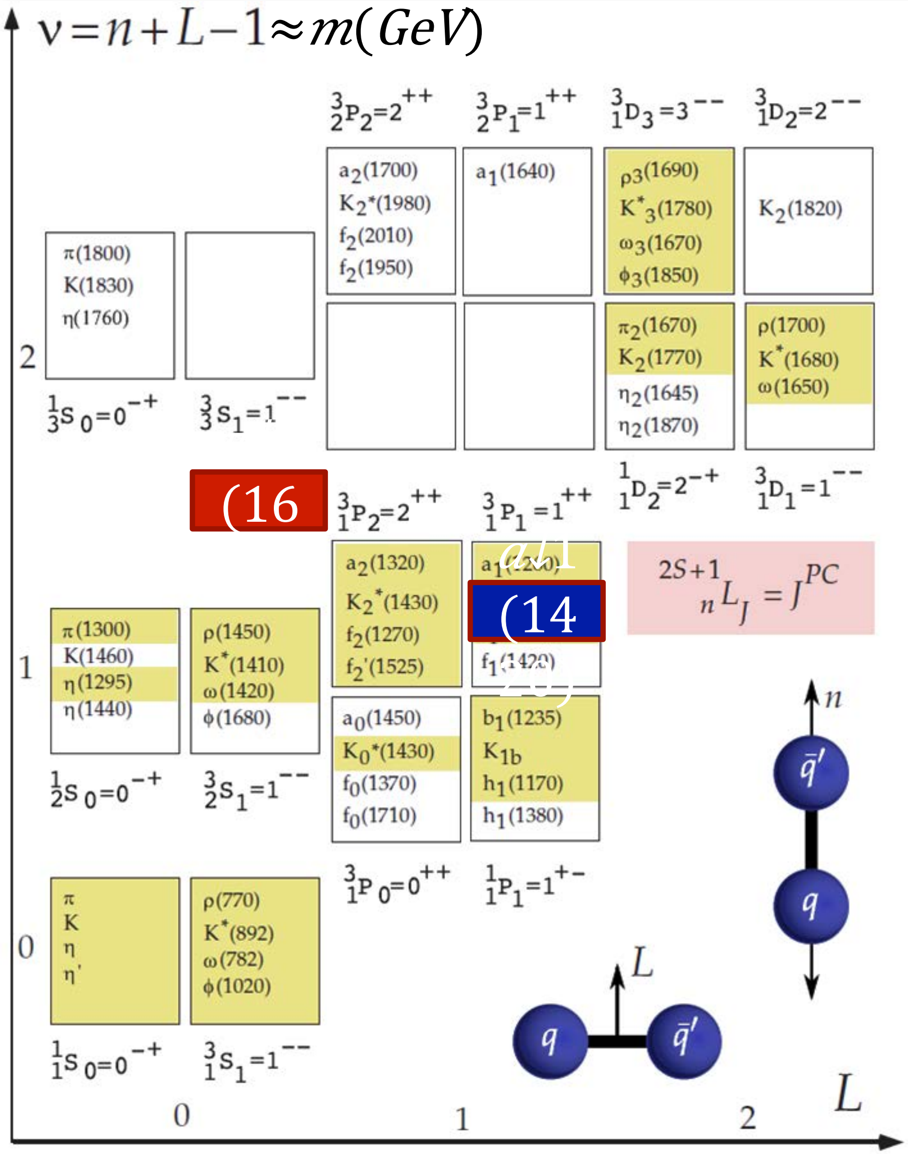
Light Meson Spectrum



- Ground state 0^{-+} , 1^{--} nonets ok
- Many predicted radial and orbital excitations missing / unclear
- Identification of exotics
  - overpopulation of meson spectrum
  - spin-exotic quantum numbers

In this talk: 2 examples

- $a_1(1420)$: $J^{PC}=1^{++}$
- $\pi_1(1600)$: $J^{PC}=1^{-+}$

[Amsler et al., Phys. Rept. 389, 61 (2004)]

What is a Resonance?

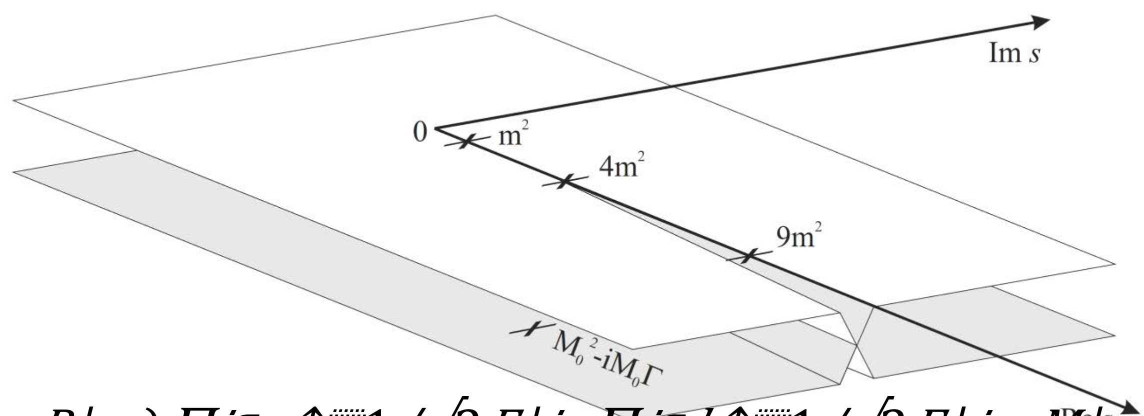
- “Not every bump is a resonance, and not every resonance is a bump”
- Resonances have complex properties like mass and width, which do not depend on the experiment or the specific model
- Resonances correspond to poles in the S-matrix on unphysical Riemann sheets

Proc. Roy. Soc. Lond. A. **318**, 279–298 (1970)
Printed in Great Britain

What is resonance?

By R. H. Dalitz, F.R.S.
Department of Theoretical Physics, Oxford University,
and R. G. Moorhouse
Department of Natural Philosophy, Glasgow University

- S-matrix: $\mathbb{S} = \mathbb{I} + i\mathbb{T}$
  - unitary
  - analytic



Transition (reaction) matrix:

$$T_{ab} = (2\pi)^4 \delta^4(P_b - P_a) \prod_{i\in a} \frac{1}{\sqrt{2E_i}} \prod_{j\in b} \frac{1}{\sqrt{2E_j}} \mathcal{M}_{ab}$$

Partial Wave Expansion

For a 2-body reaction: expand scattering amplitude in partial waves

$$M_{ab} \equiv A(s,t) = \sum_{\ell=0}^{\infty} (2\ell+1)\, A_\ell(s)\, P_\ell(\cos\theta)$$

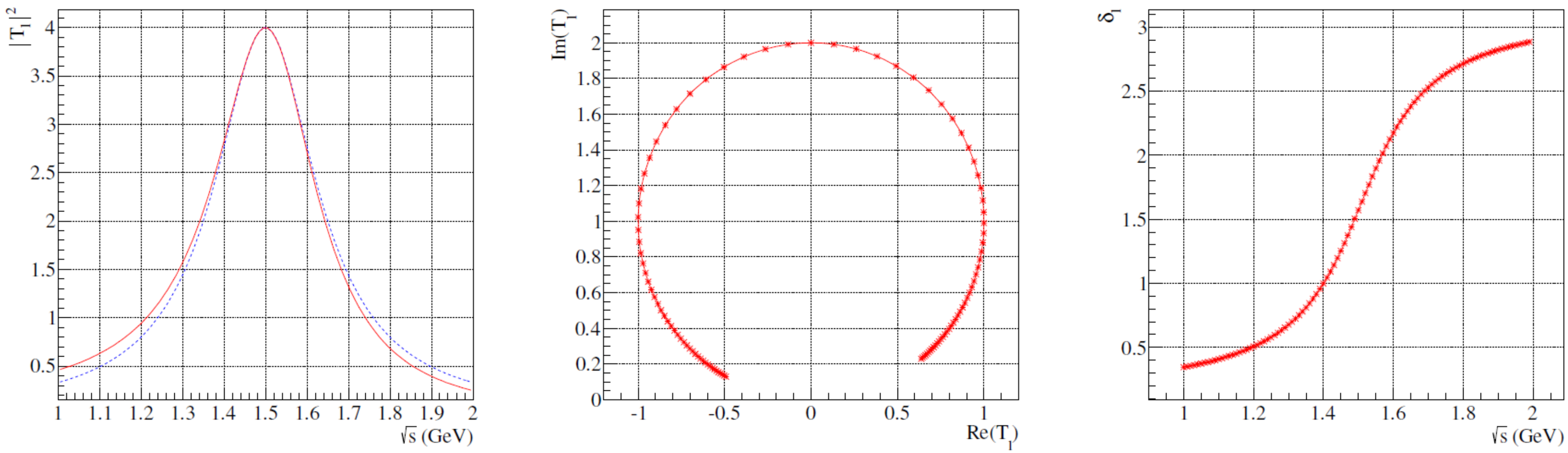
- P_ℓ Legendre polynomials ⇨ angular distribution
- A_ℓ transition amplitudes ⇨ dynamics
- General parameterization for scattering through resonance

$$A_\ell(s) = \frac{8\pi\sqrt{s}}{k} \cdot \frac{\eta_\ell(s)\, e^{2i\delta_\ell(s)} - 1}{2i} = \frac{8\pi\sqrt{s}}{k}\, f_\ell(s)$$

- For isolated, narrow resonance: Breit-Wigner parameterization

$$f_\ell(s) \cong \frac{m_0\,\Gamma}{m_0^2 - s - i m_0\,\Gamma}$$

Partial Wave Expansion



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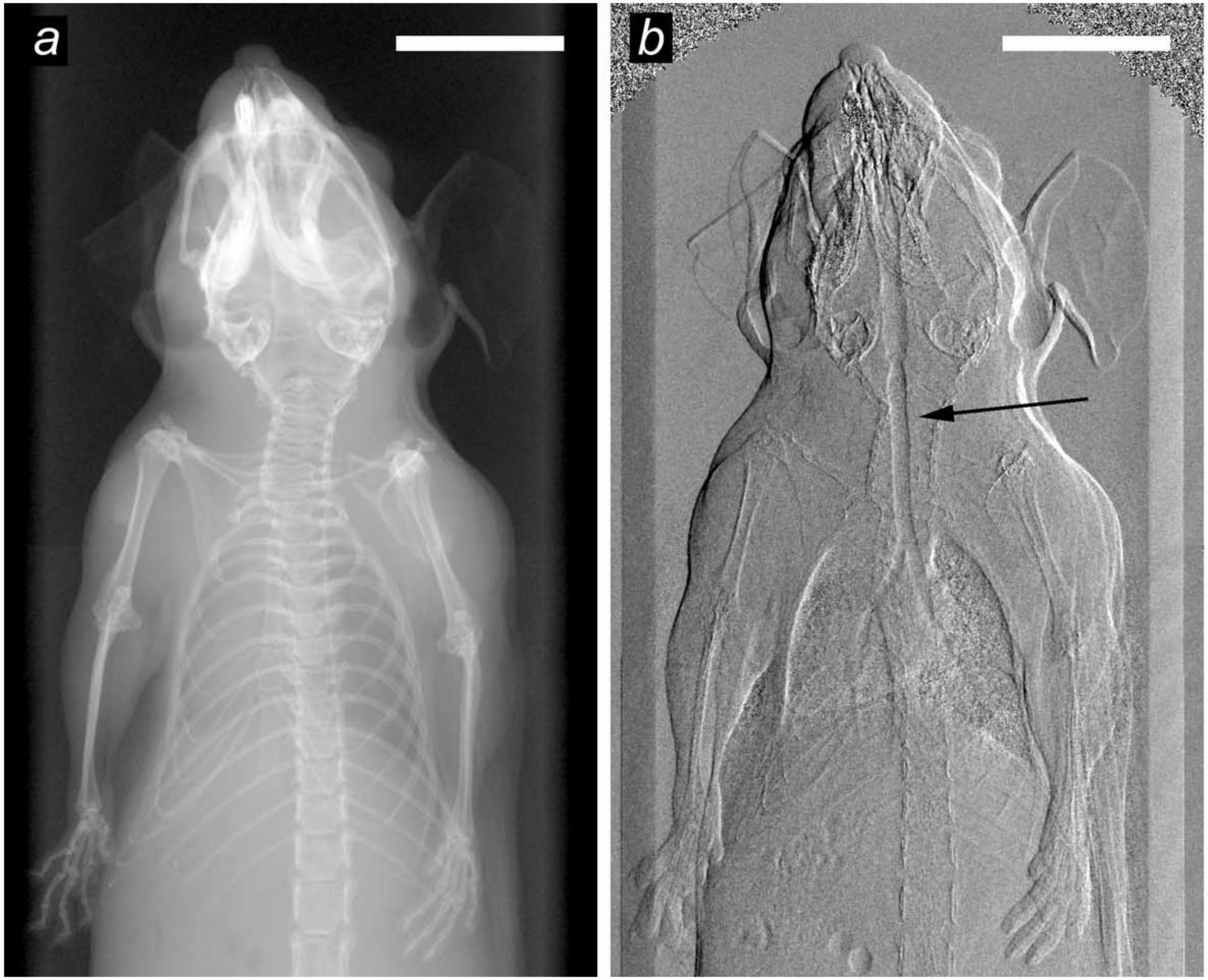
The Virtue of Phase Information



[M. Beck et al., Sci. Rep. 3, 3209; DOI:10.1038/srep03209 (2013).

Partial Wave Analysis

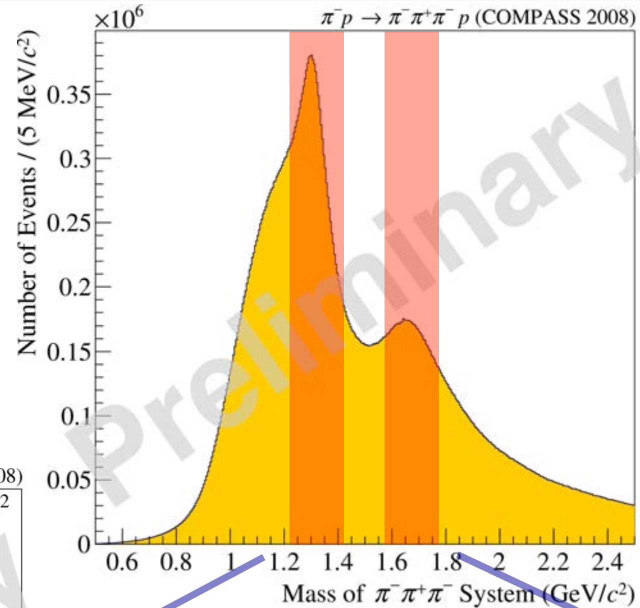
- Many different resonances are produced which decay into same final state
- Goal:
  - find and disentangle (all) contributing resonances
  - determine **mass, width** and **quantum numbers** J^P of resonances

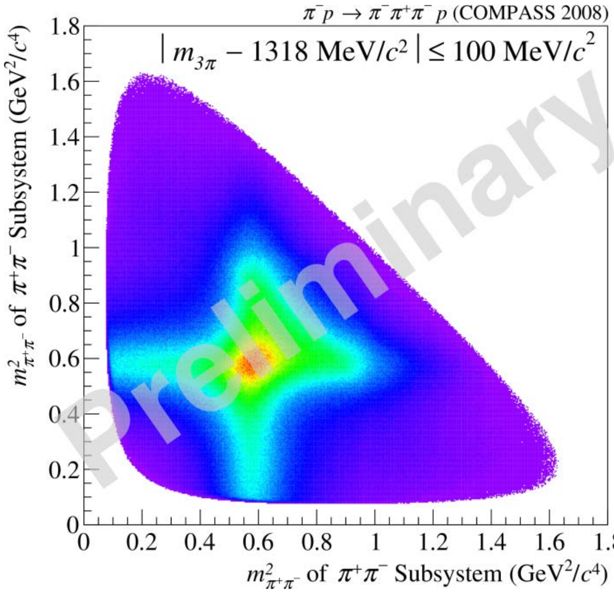
    ⇨ angular distributions of decay products
- Interference effects ⇨ small resonances may be enhanced
- Take into account experimental acceptance

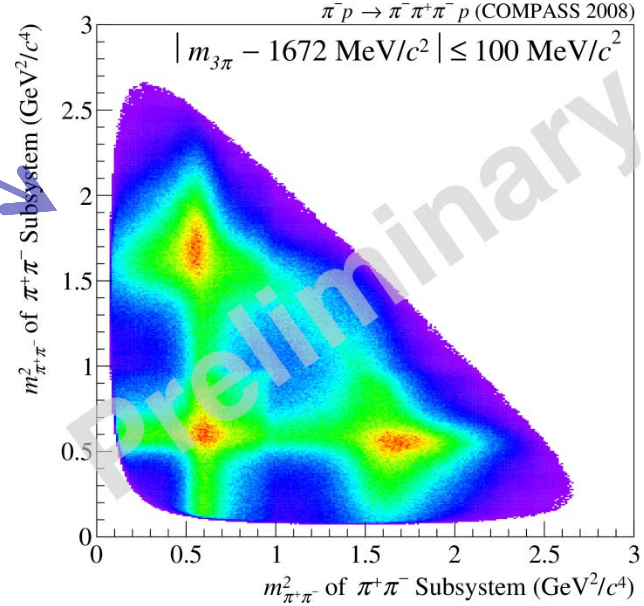
Assumptions:

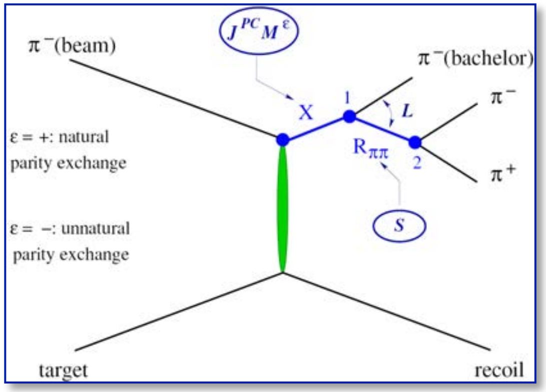
- Production and decay of a state factorize
- Decay into multi-particle final state can be described by a sequence of 2-body decays

Isobar Model









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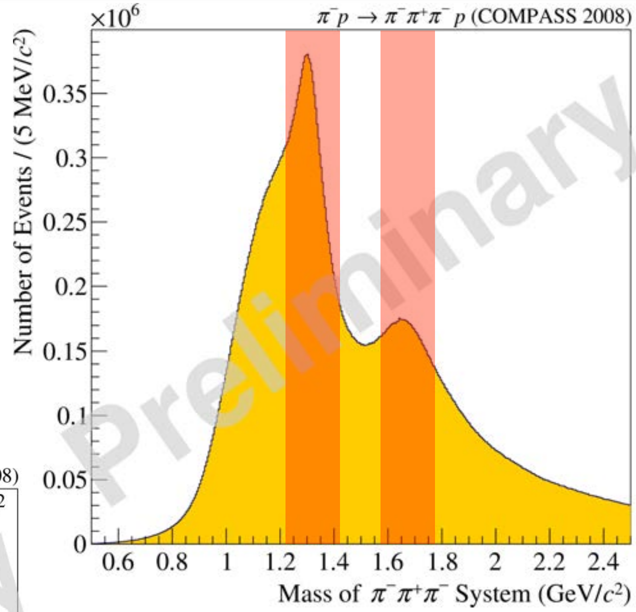

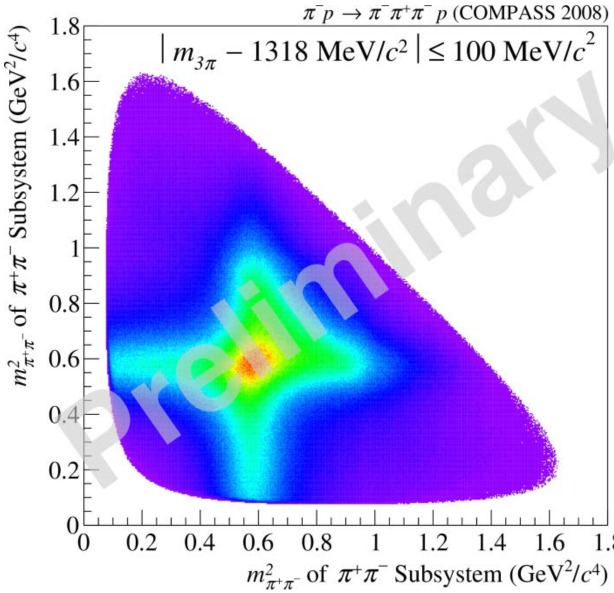

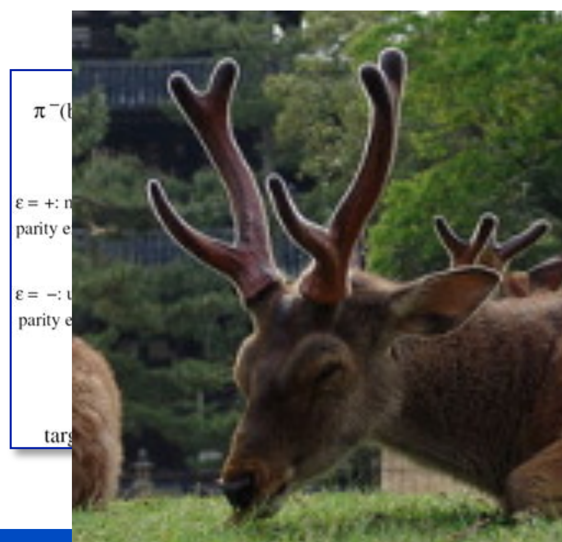

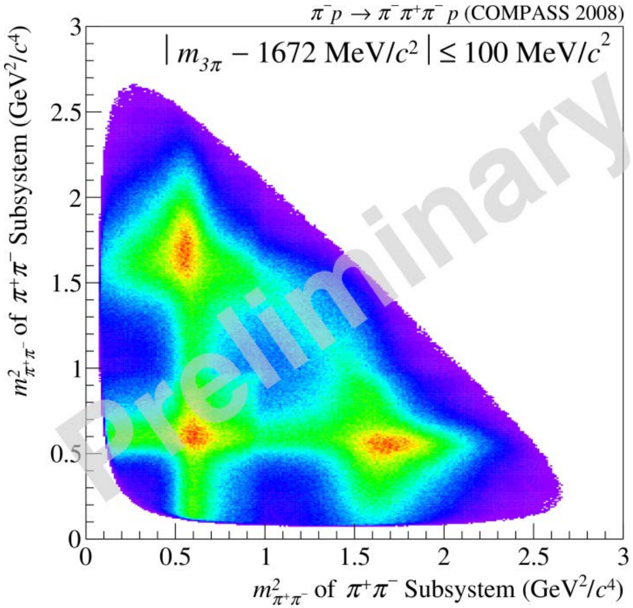

Partial Wave Analysis

1. **PWA** of angular distributions in **mass bins** and **t' bins**

$$I(\tau) = \left| \sum_{\xi} T_{\xi} A_{\xi}(\tau) \right|^2$$

- $T_\xi =$ production amplitude for state with $\chi = I^G(J^{PC})M$ decaying to ξ
- $A_\xi(\tau) =$ decay amplitude (calculable without free parameters)
- Result: spin-density matrix $\rho_{\xi\xi'} = T_\xi T_{\xi'}^*$

Assumptions:

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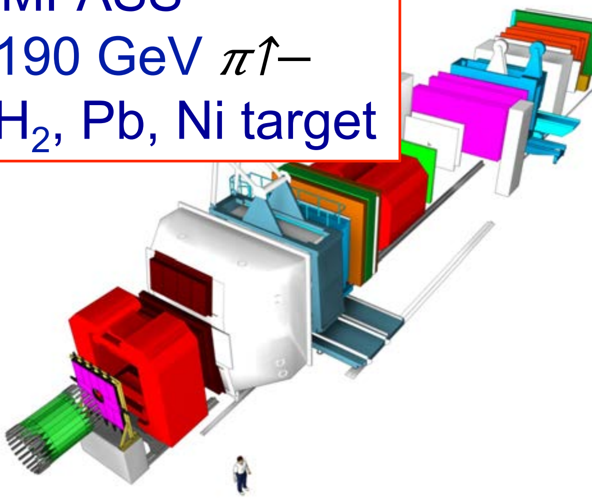
2. χ^2 **-Fit of mass- and t-dependence** of spin-density matrix

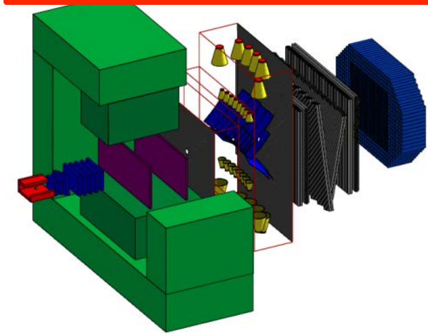
- Resonant contributions: Breit-Wigner functions
- Non-resonant contributions: empirical functions
- Only subset of spin-density matrix is considered for computational reasons

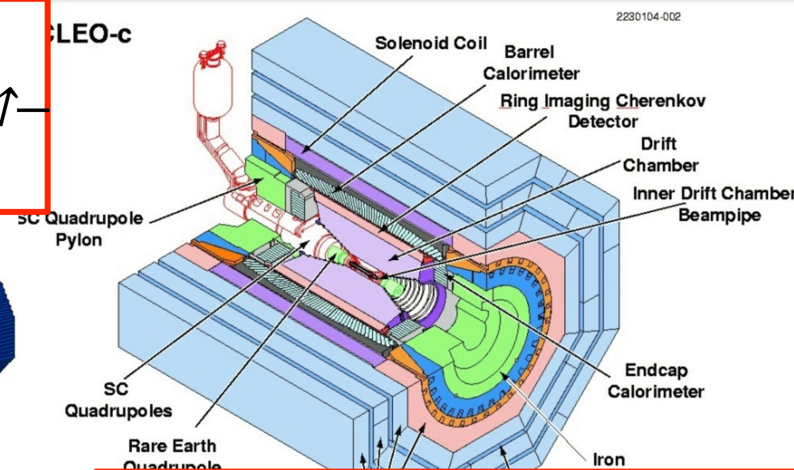
Key Players

COMPASS
- 190 GeV $\pi\uparrow-$
- H_2, Pb, Ni target

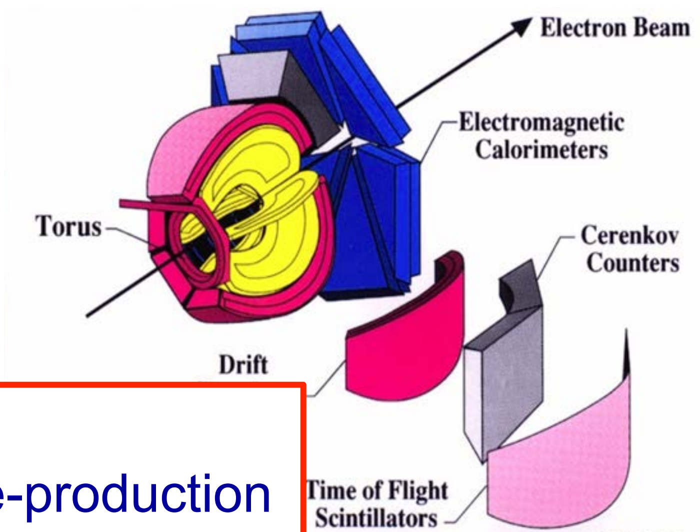


VES:
- 37/29 GeV $\pi\uparrow-$
- Be target

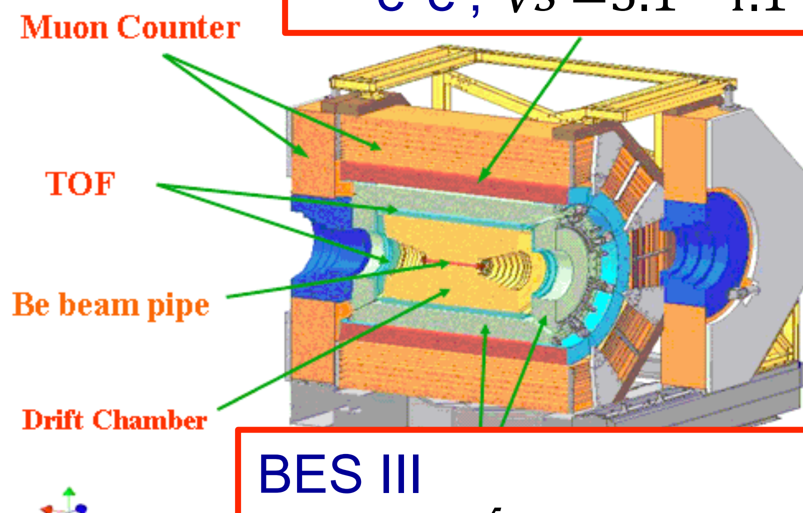




CLEO-c:
- e^+e^-, $\sqrt{s} = 3.1 - 4.1$ GeV



CLAS:
- γ-, e-production
- p target

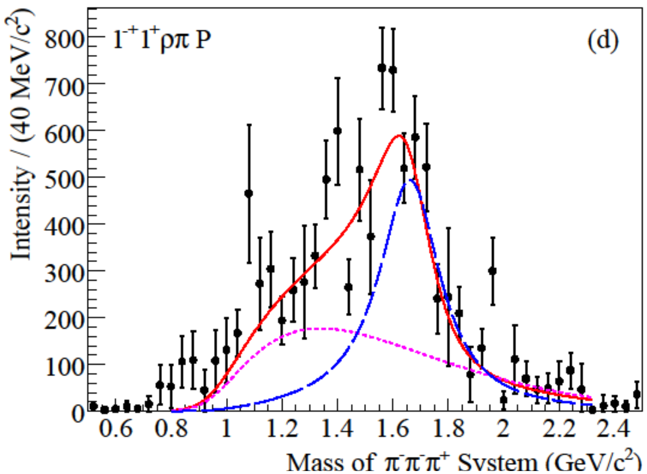


BES III
- e^+e^-, $\sqrt{s} = 3.1 - 4.6$ GeV

The $\pi_1(1600)$

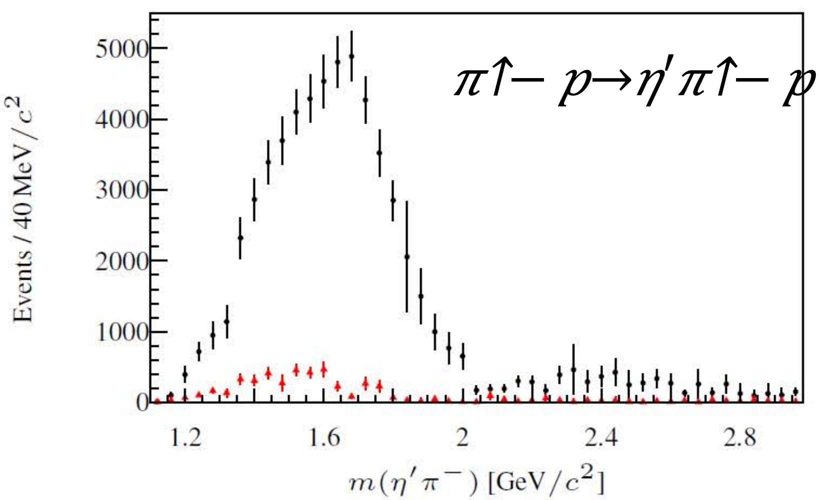
$J^{PC}=1^{-+}$ Wave

$\pi^- \ \mathrm{Pb} \rightarrow \pi^-\pi^-\pi^+ \ \mathrm{Pb}$



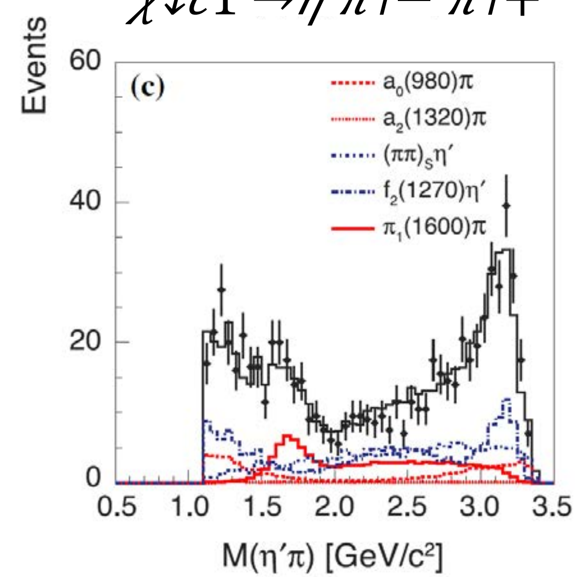
- Resonance-like signal observed
- Large contribution of non-resonant background
- Need to understand origin for a reliable fit of spin-density matrix of high-statistics H_2 data

[Alekseev et al., Phys. Rev. Lett. 104, 241803 (2010)]



[C. Adolph et al., subm. PLB, arXiv:1408.4286]

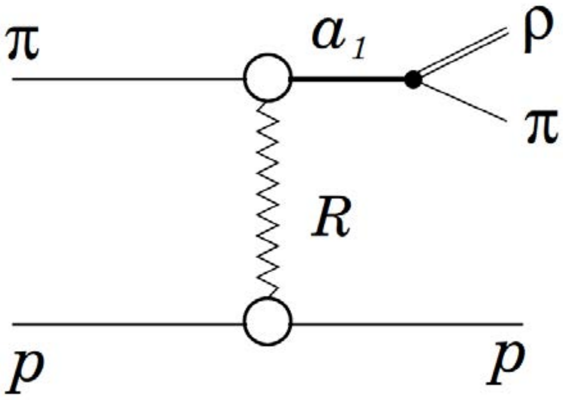
$\chi_{c1} \rightarrow \eta' \pi^- \pi^+$



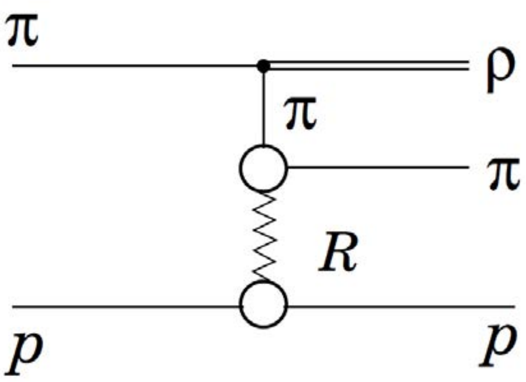
[G.S. Adams et al., Phys. Rev. D **84**,112009 (2011)]

Deck Effect

Resonant production



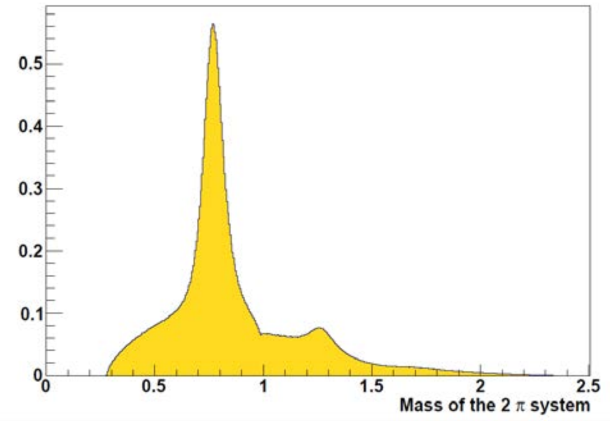
Non-resonant production



- Generate pure Deck-like events

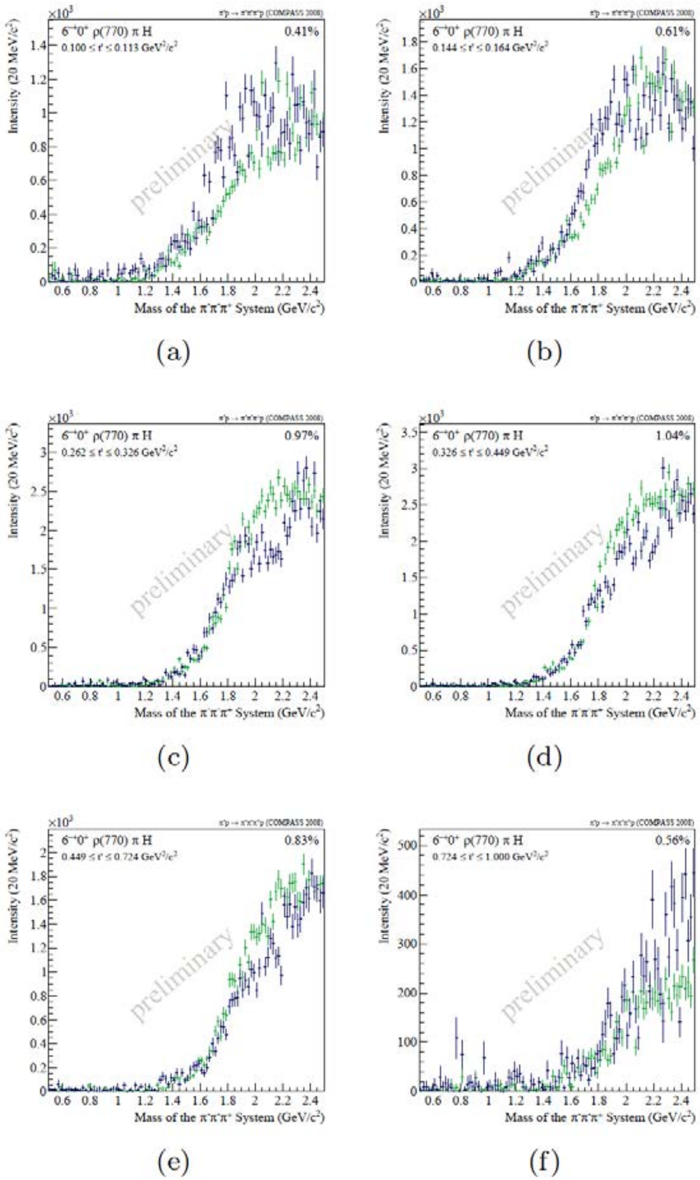
$$\psi(M_{\pi\pi}, t_\pi, t) = \frac{A_{\pi\pi}(M_{\pi\pi}, t_\pi) A_{\pi p}(s_{\pi p}, t)}{m_\pi^2 - t_\pi}$$

[G. Ascoli et al., Phys. Rev. D 8, 3894 (1973)]



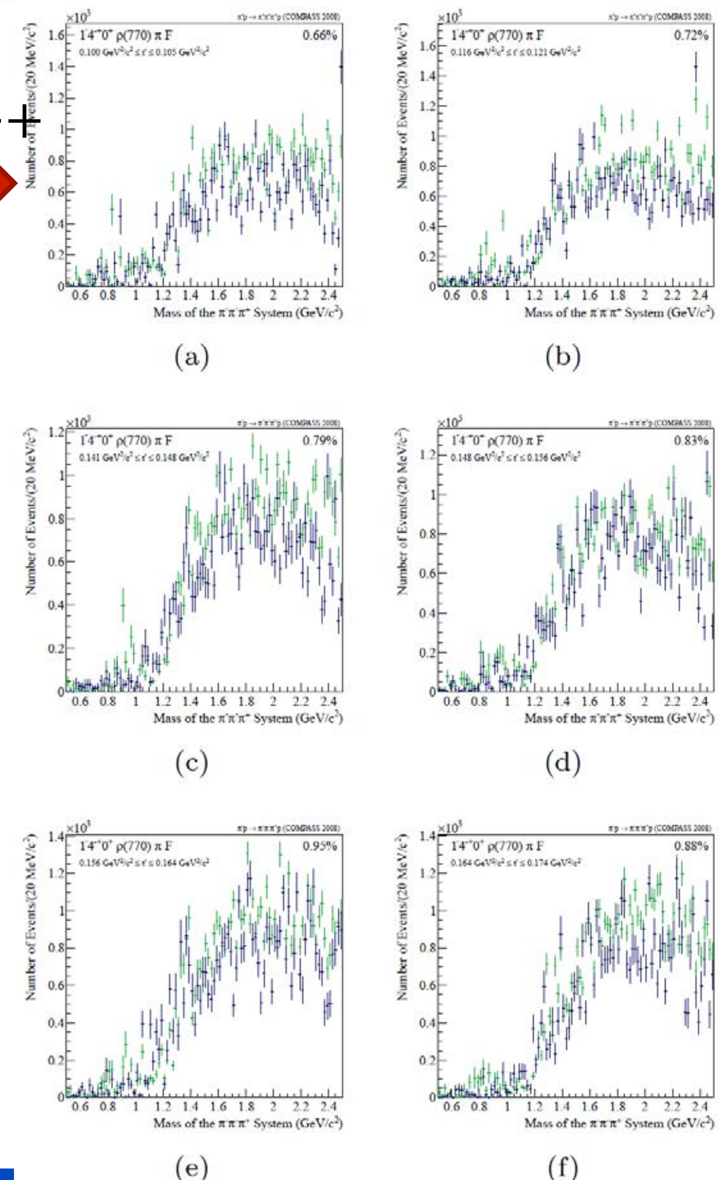
- Pass through Monte Carlo & PWA
- Normalize intensity to data for each wave and sum over t'
- Benchmark on waves w/o resonances, test on exotic wave

Data vs Deck



$6 \uparrow -+$ ←

→ $4 \uparrow -+$

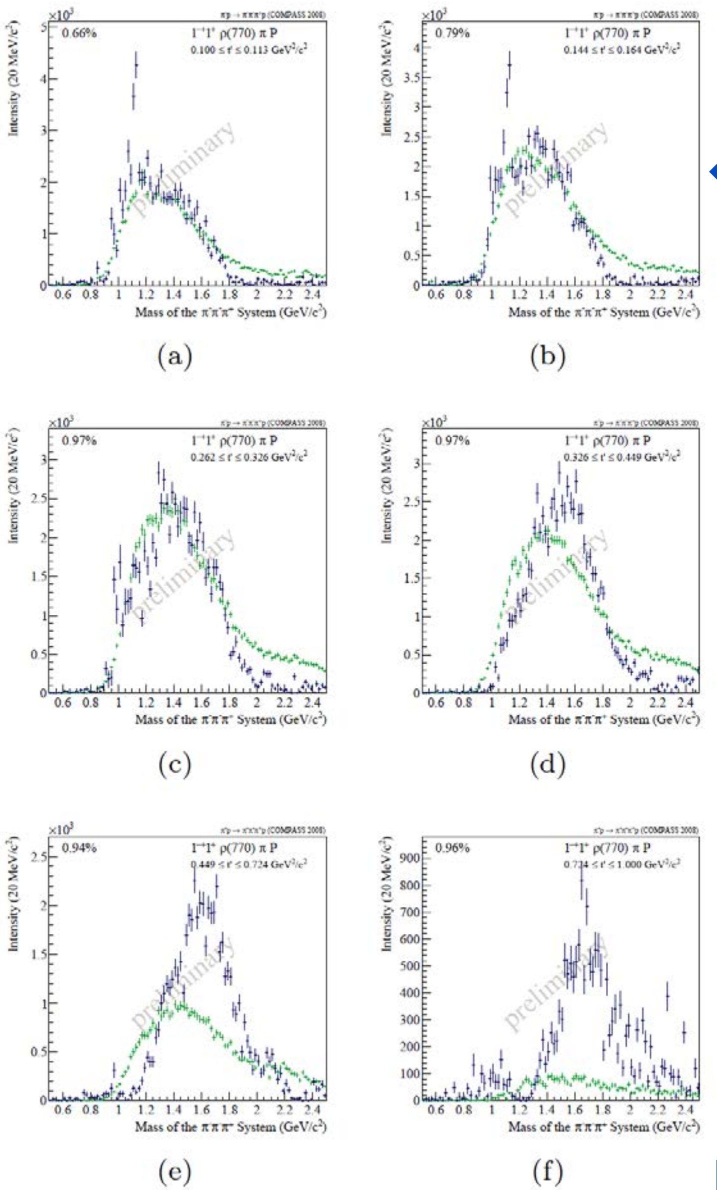


↓ t'

— Data

— Deck

Data vs Deck



1^{-+} ←

↓ t'

— Data
— Deck

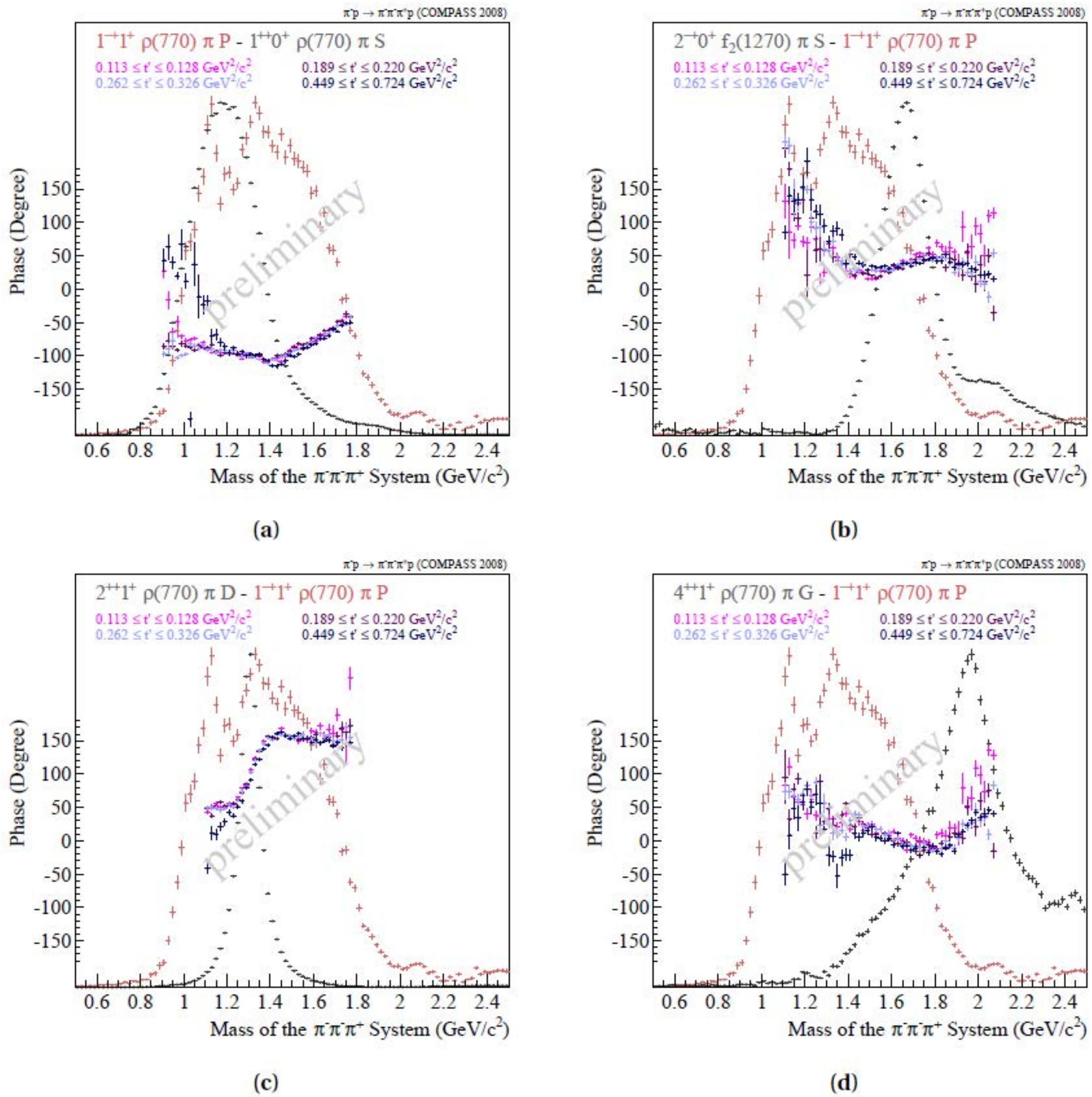
Low values of t':

- Mostly non-resonant production
- Good description by Deck model

High values of t':

- Resonance appears
- Dominates highest t' - bin

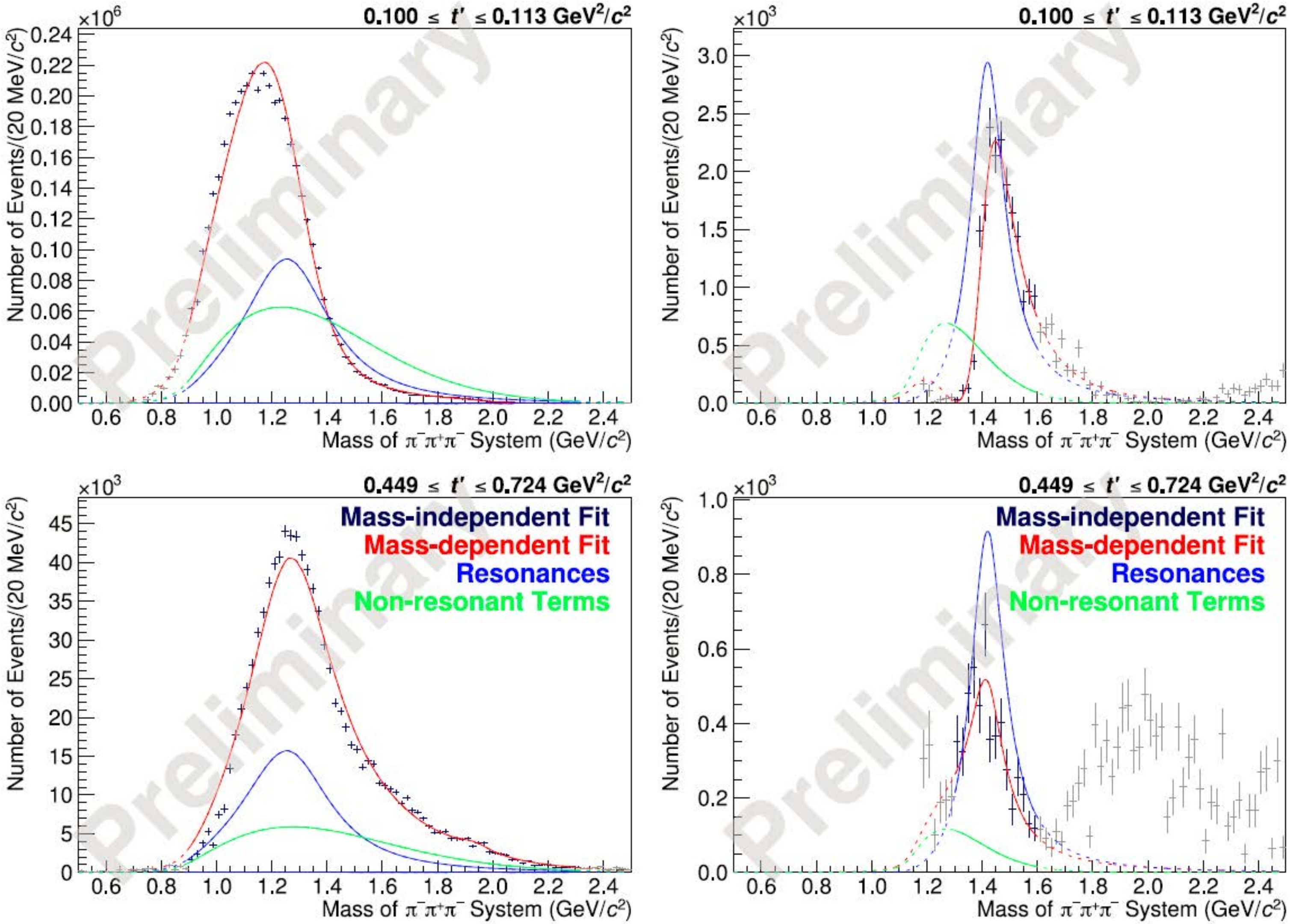
Phase of 1^{-+} Wave



- Clear phase variation
- Variation $\mathcal{O}(50°)$
- Mild variation with t'

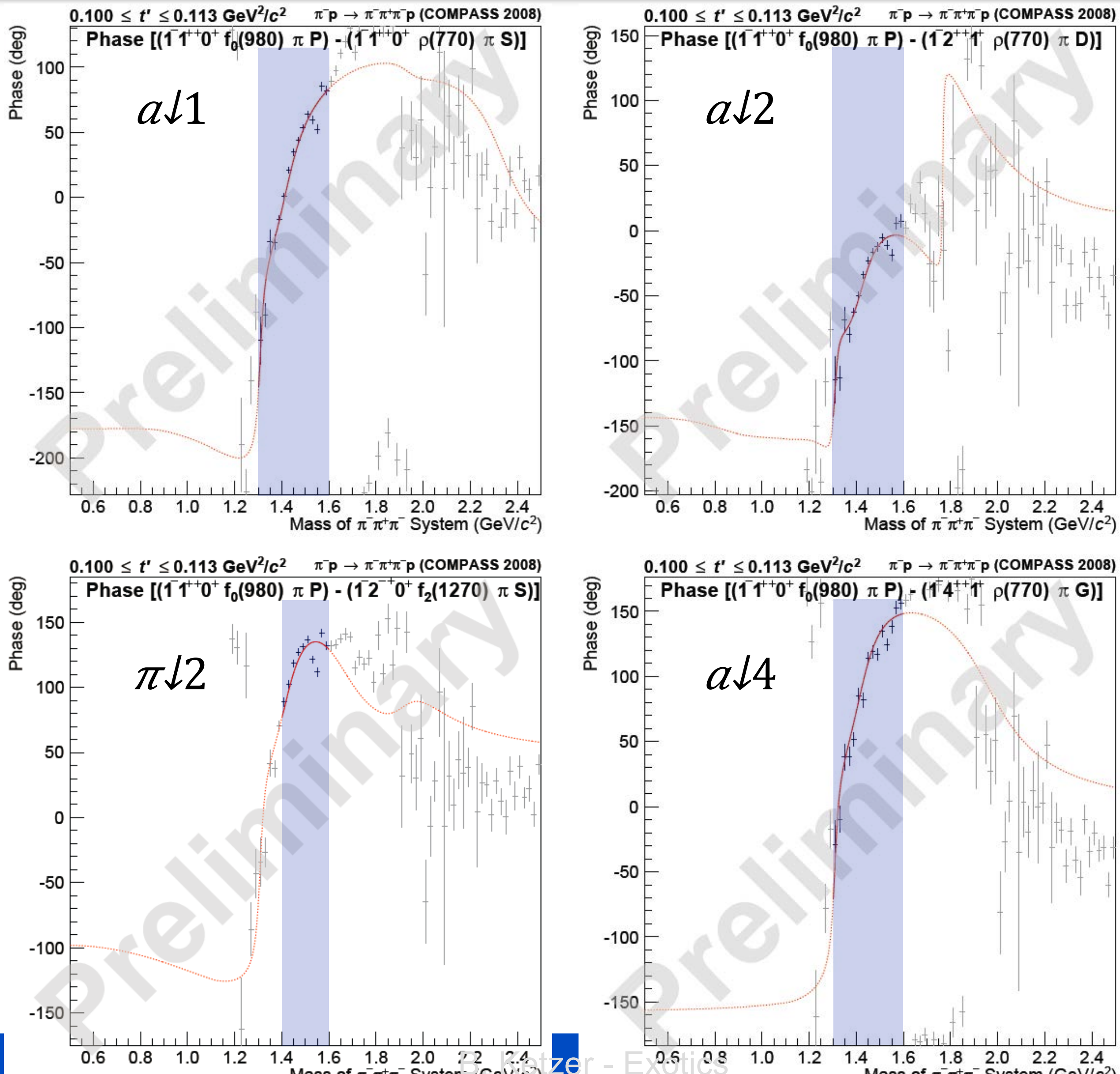
The $a_1(1420)$

New a_1 - $1^{++}0^+$ $f_0(980)\pi$ P



[C. Adolph et al., COMPASS, subm. PRL, arXiv:1501.05732]

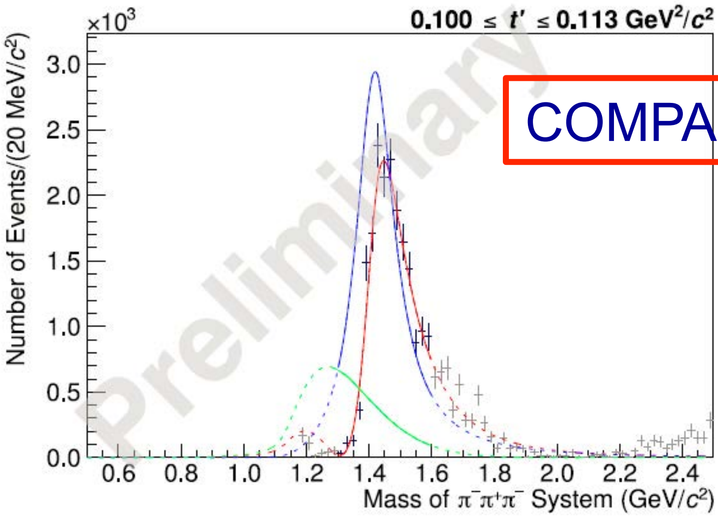
New $a_1(1420)$ - Phase Differences

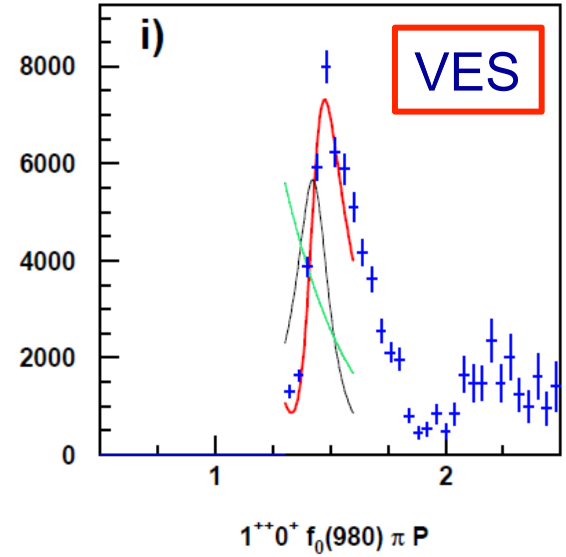


fit range

Low t'

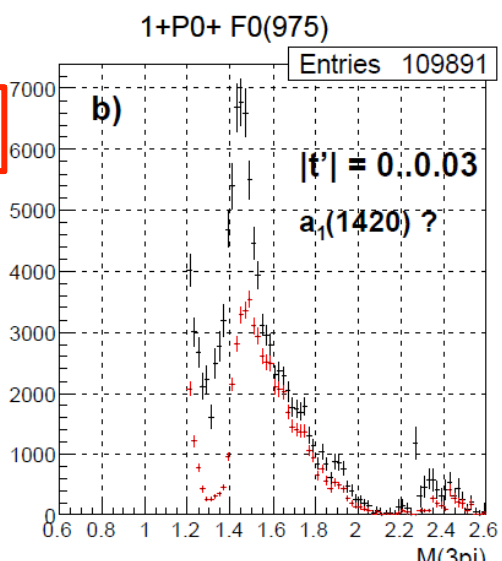
New a_1 - $1^{++}0^+$ $f_0(980)\pi$ P





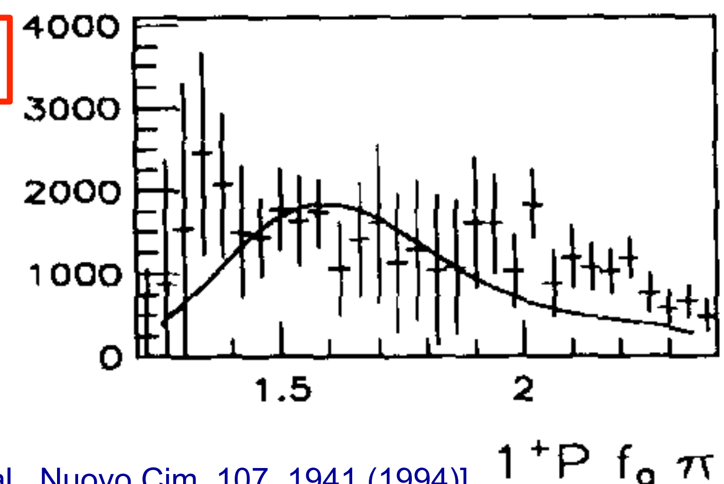
[Yu. Khokhlov, PoS Hadron 088 (2014)]

VES



[I. Kachaev, PANIC 2014]

VES



[E.B. Berdnikov et al., Nuovo Cim. 107, 1941 (1994)]

Nature of $a_1(1420)$

- Has all features of resonance!
  - Narrow peak in intensity
  - Sharp phase motion
  - Description with Breit-Wigner gives

$$M_{a_1} = 1412 - 1422\,\mathrm{MeV}/c^2$$
$$\Gamma_{a_1} = 130 - 150\,\mathrm{MeV}/c^2$$

- Does not fit into quark model
  - Mass difference to a1(1260) only 160 MeV
  - Much narrower than ground state

Interpretation:

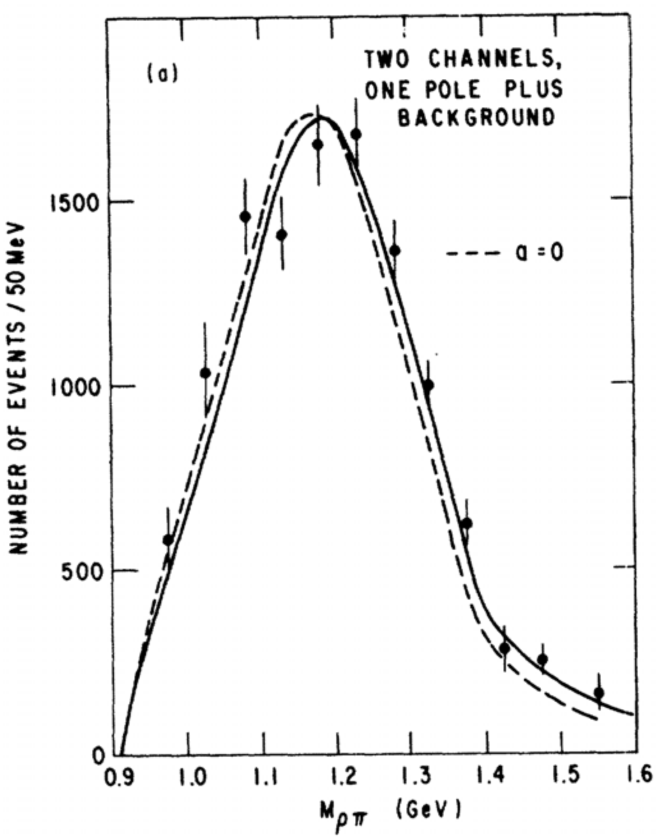
- 4-quark / molecular state, isospin partner of $f_1(1420)$?
- Dynamic interpretation?

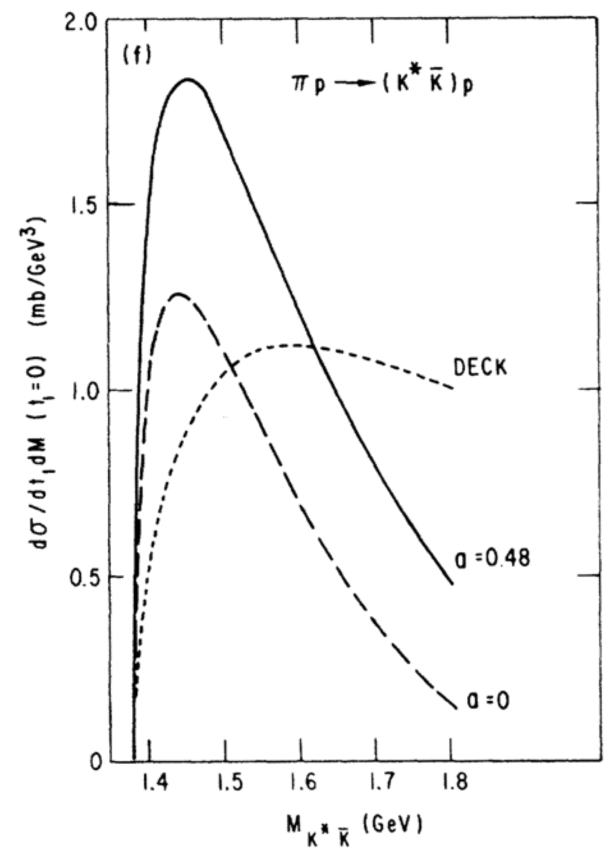
Dynamic Interpretation

$a_1(1260) \to \rho\pi, K^* K$

[J.L. Basdevant et al., PRD 16, 657 (1977)]

- Unitary coupled-channel analysis
- Gives sharp rise at $K^* K$ threshold
- Phase motion inherited from $a_1(1260)$?

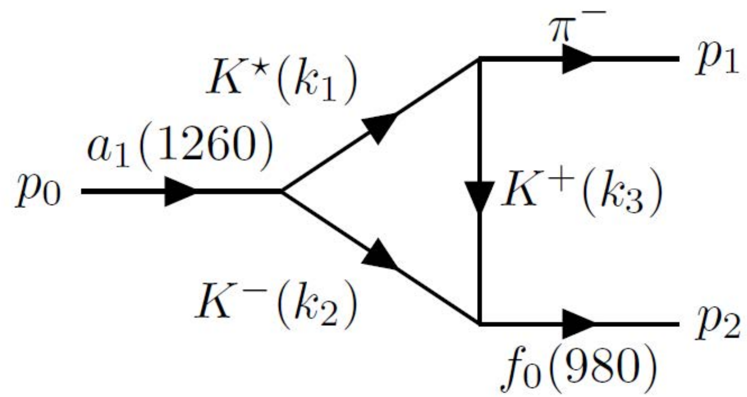




Dynamic Interpretation

$a_1(1260) \to K^* K + c.c. \to f_0(980)\pi$

- Decay of $a_1(1260) \to K^* K$
- Rescattering of K's to $f_0(980)$
- Triangle diagram
- Logarithmic singularity in amplitude



Two isospin combinations contribute

- $a_1^-(1260) \to K^{\star 0} K^- \to \pi^- K^+ K^- \to \pi^- f_0,$
- $a_1^-(1260) \to K^{\star -} K^0 \to \pi^- \bar{K}^0 K^0 \to \pi^- f_0.$

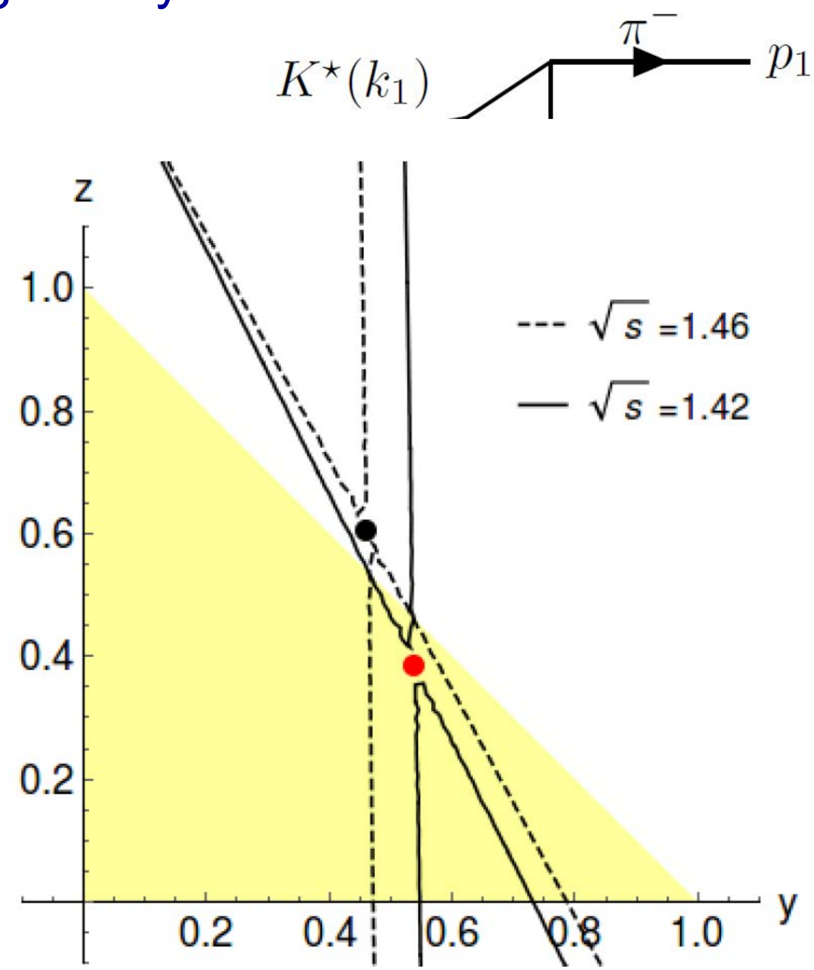
Kinematic Conditions

Landau, 1959:

- Positions of singularity in scalar theory given by

$$\begin{cases} k_i^2 = m_i^2, & i = 1 \ldots 3, \\ x\,k_{1\mu} - y\,k_{2\mu} + z\,k_{3\mu} = 0, & x, y, z \in [0,1], \\ x + y + z = 1, & \end{cases}$$

- For case of $a_1\,(1260)$:
  - $E_1 = 1.42\ GeV$
  - $E_2 = 1.46\ GeV$



Interpretation:

- All intermediate particles on mass shell
- Collinear to each other
- K and K have same velocity only for E↓

Calculation of Amplitude

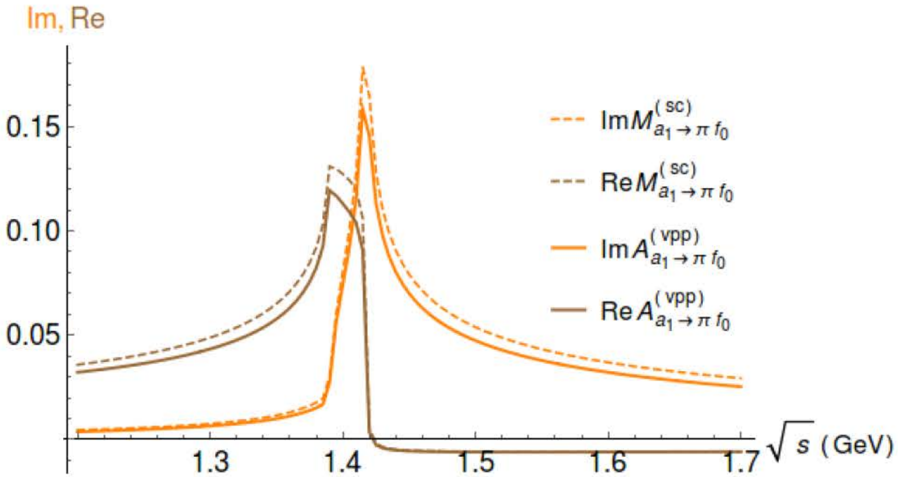
Feynman rules for hadronic processes:

- Scalar case

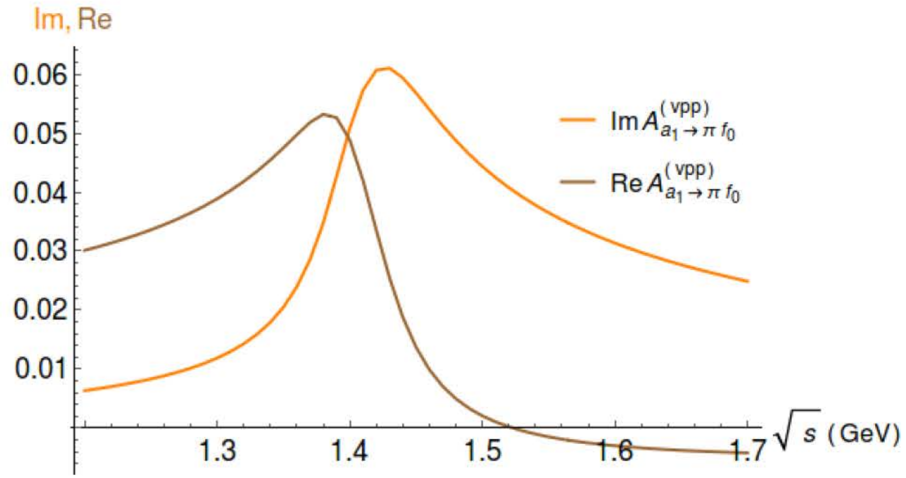
$$\mathbb{M}^{(\mathrm{sc})}_{a_1\to f_0\pi} = g^3 \int \frac{\mathrm{d}^4 k_1}{(2\pi)^4 i} \frac{1}{(m_1^2 - k_1^2 - i\epsilon)(m_2^2 - (p_0 - k_1)^2 - i\epsilon)(m_3^2 - (k_1 - p_1)^2 - i\epsilon)}$$

- VPP case: denominator carries spin structure

Scalar vs VPP

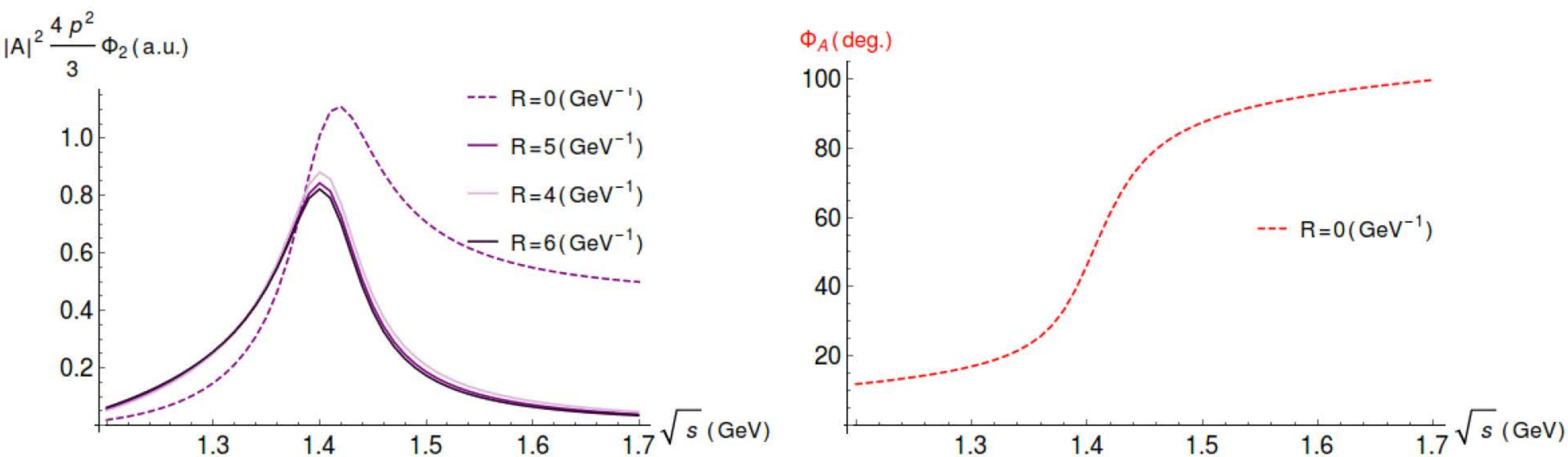


+ finite width of K^*



Corrections to Vertices

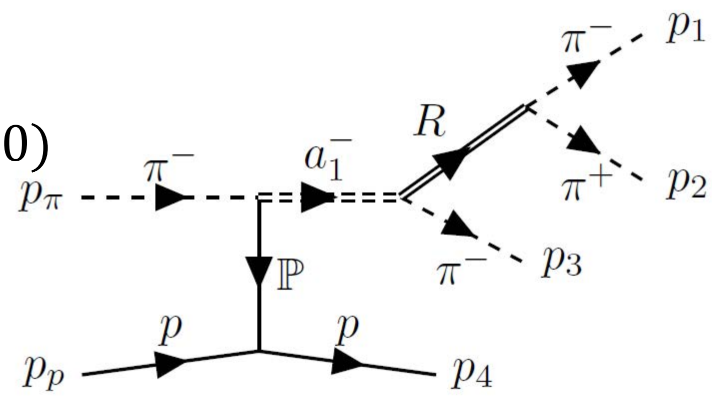
- Finite width of K^{*}
- Suppression of P-wave tail due to $K^{*} \to K\pi$ decay
  - Blatt-Weisskopf barrier factors
  - Exponential correction factors for finite meson-size
  - Introduce left-hand singularity in the amplitude

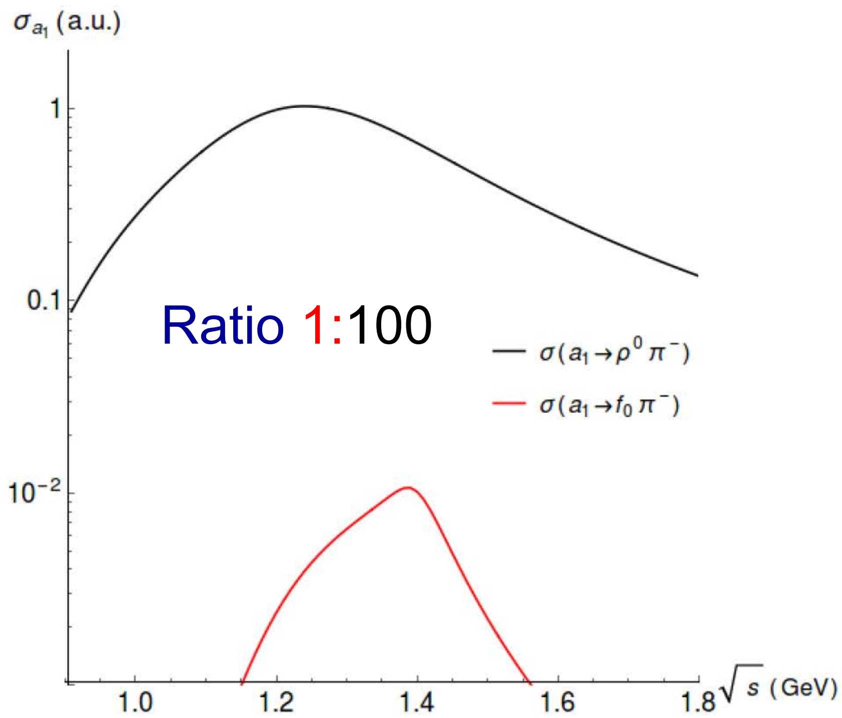


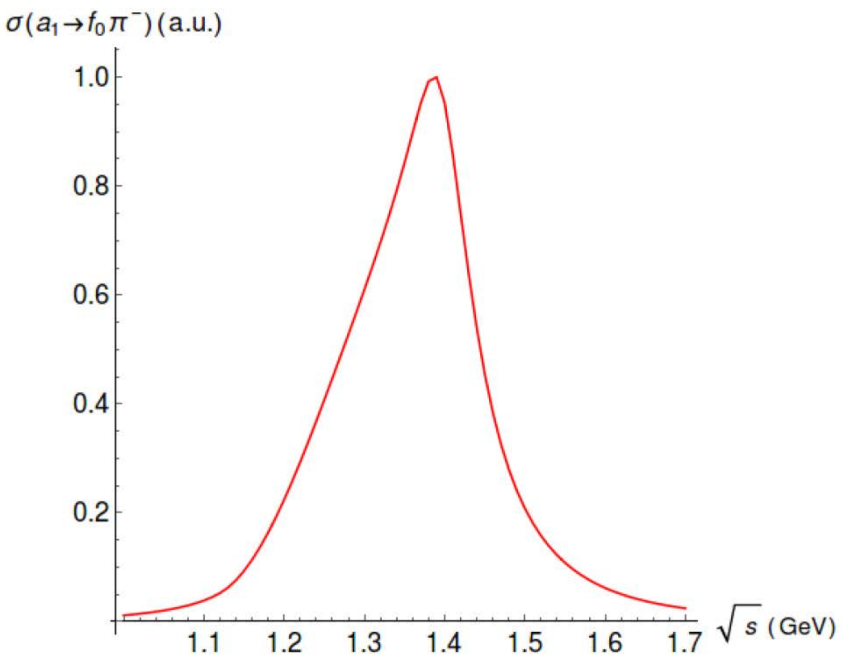
Cross Section Ratio

Consider full process:

- Diffractive production of resonant $a_1(1260)$
- Direct decay to $\rho\pi$
- Decay to $f_0\,\pi$ only via triangle diagram







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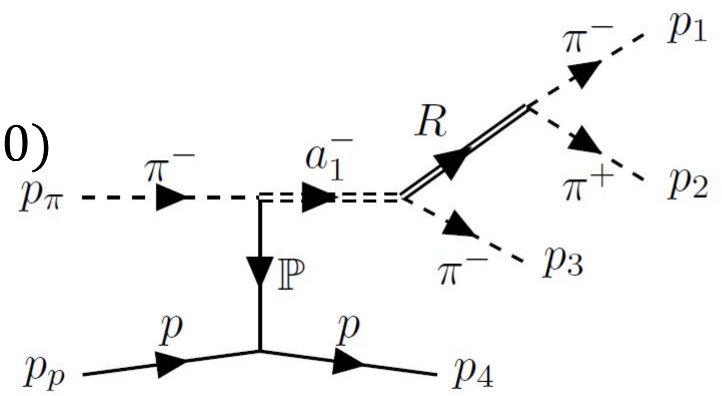

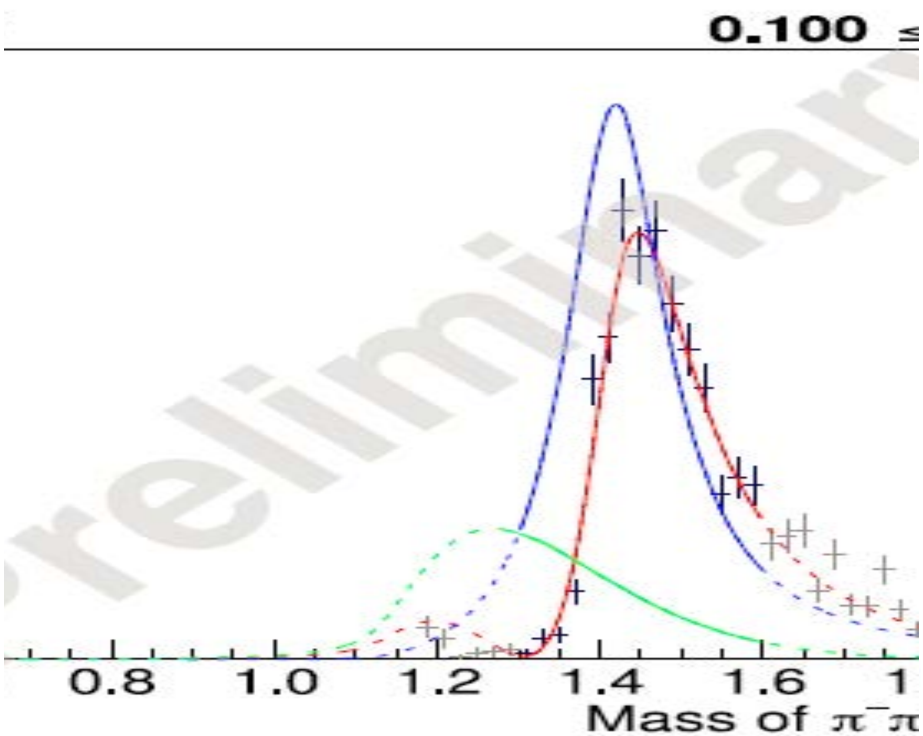

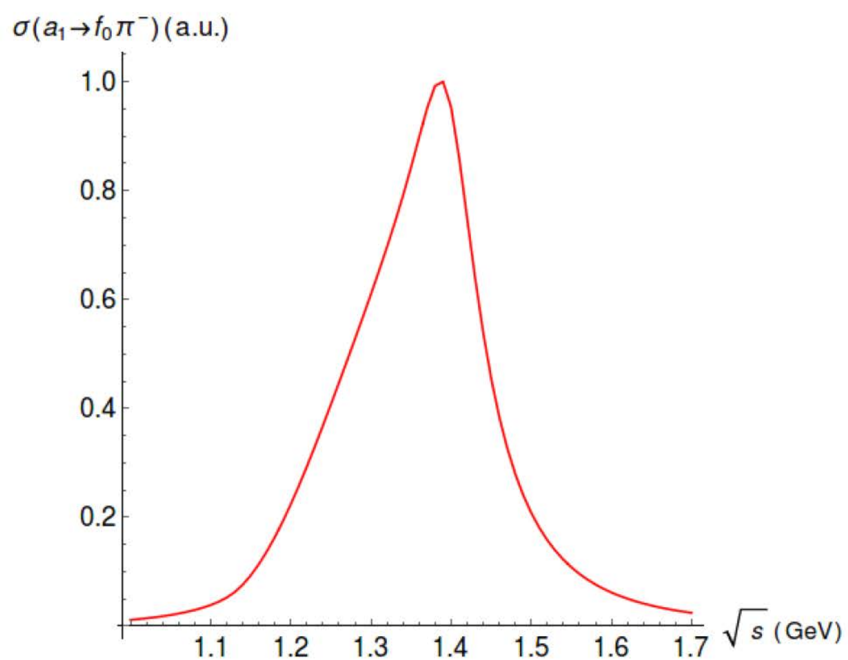

Conclusions

- Hadron spectroscopy is entering precision era
- Statistical uncertainties very small
- Systematic model uncertainties become dominant
- Spin-exotic $\pi_1(1600)$: (re-) observed by COMPASS, VES, CLEO-c
  - Large statistics of COMPASS ⇨ 2D-PWA in bins of m_X and t'
  - ⇨ Strong non-resonant contribution to $\rho\pi$, $\eta'\pi$
  - ⇨ Can be well described by Deck effect
  - ⇨ Resonant part dominates at high t'
- New axial vector meson observed in $a_1(1420)\to f_0(980)\pi$?
  - Has all features of a genuine resonance
  - Possible explanation: pseudo-resonance due to triangle singularity

- Future: identify exotic multiplets and measure decay pattern
- General: amplitudes need to satisfy analyticity and unitarity!

Spare Slides