Departamento de Física Teórica. Universidad Complutense de Madrid

pion-kaon scattering at KLF

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For KLF Collaboration

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Motivation to study πK scattering

- π,K appear as final products of almost all hadronic strange processes:
  Examples: B and D decays, CP violation studies, etc…

- π,K are Goldstone Bosons of QCD → Test Chiral Symmetry Breaking

- Many light resonances appear → Strange SPECTROSCOPY

Particularly interesting at KLF:

- $\kappa/K_0^*(800)$ light scalar meson. “Needs confirmation”@PDG.
  Light scalar mesons longstanding candidates for non-ordinary mesons.
  Settle multiplet classification?

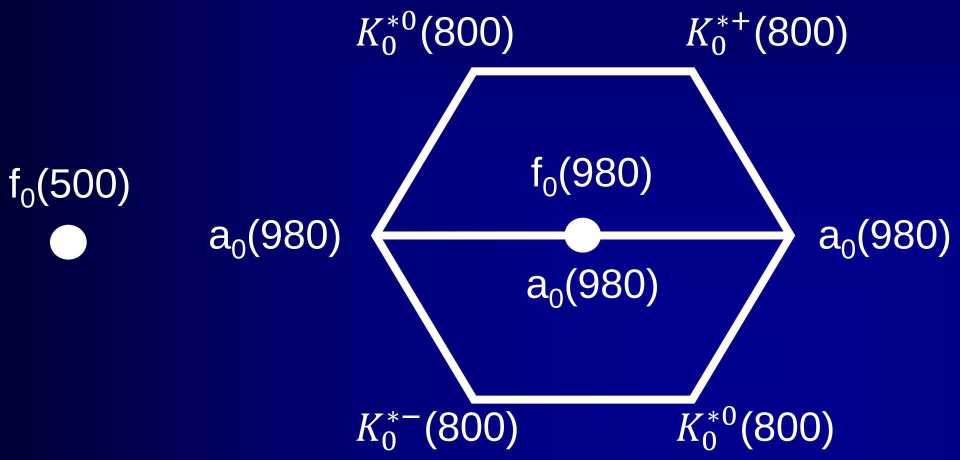
- Scattering lengths for SU(3) Chiral Perturbation Theory (ChPT)

- K_1^*(892) interesting for CP violation studies
- K_1^*(1410) and K_0^*(1430) smaller discussion on parameters and nature

The light scalar controversy. The theory side... classification

- Scalar lightest SU(3) nonet controversial for decades

  … but a picture is emerging



$K_0^{*0}(800)$ $K_0^{*+}(800)$

$f_0(500)$

$f_0(980)$

$a_0(980)$ $a_0(980)$

$a_0(980)$

$K_0^{*-}(800)$ $K_0^{*0}(800)$

Non-strange heavier!!

Inverted hierarchy problem

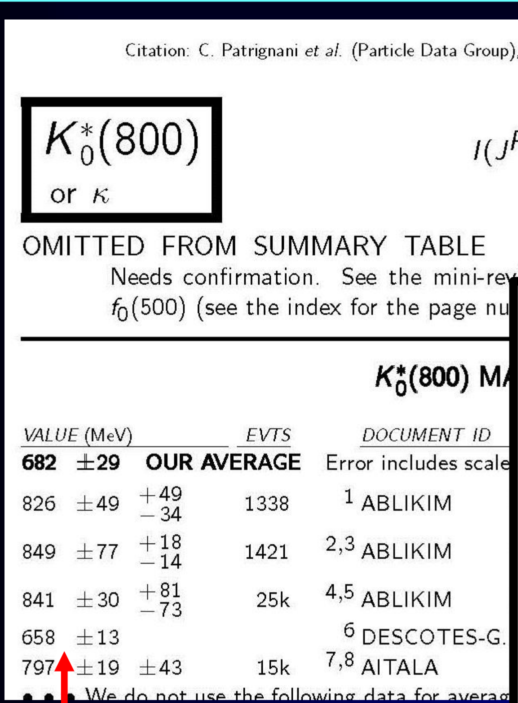
For quark-antiquark

f_0(500) and f_0(980) are really octet/singlet mixtures

Oldest candidates for **non-ordinary $q\bar{q}$ mesons** (Jaffe 76)

Only the κ(800) or K0*(800) still "Needs Confirmation" @ PDG

The resonance is NO LONGER the κ nor the $K_0^*(800)$,



Citation: C. Patrignani *et al.* (Particle Data Group), Chin. Phys. C, **40**, 100001 (2016)

$K_0^*(800)$ or κ

$I(J^P) = \frac{1}{2}(0^+)$

OMITTED FROM SUMMARY TABLE

Needs confirmation. See the mini-review on scalar mesons under

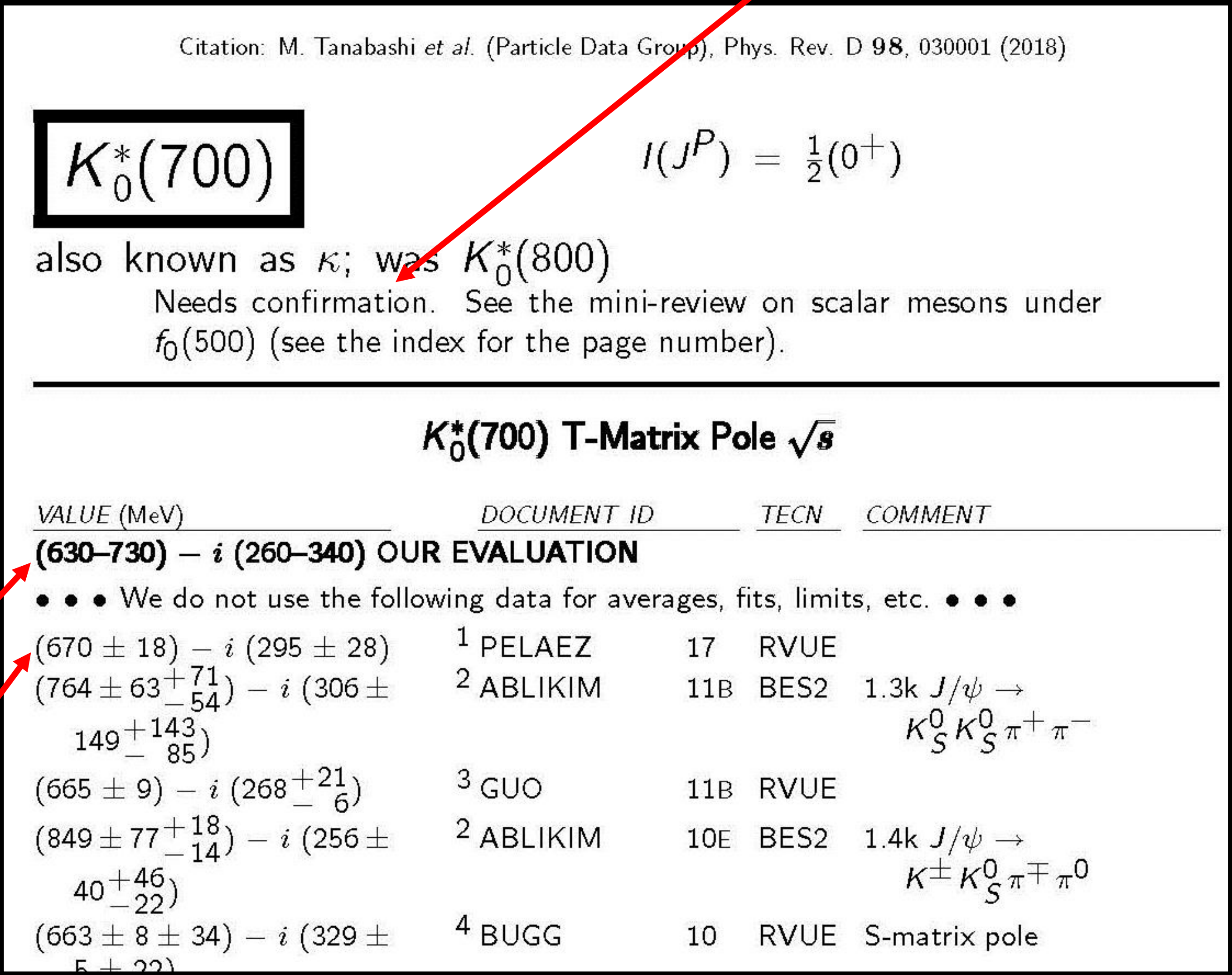
$f_0(500)$ (see the index for the page nu

$K_0^*(800)$ MA

VALUE (MeV)			*EVTS*	*DOCUMENT ID*
682	**±29**	**OUR AVERAGE**		Error includes scale
826	±49	$^{+49}_{-34}$	1338	[1] ABLIKIM
849	±77	$^{+18}_{-14}$	1421	[2,3] ABLIKIM
841	±30	$^{+81}_{-73}$	25k	[4,5] ABLIKIM
658	±13			[6] DESCOTES-G.
797	±19	±43	15k	[7,8] AITALA

• • • We do not use the following data for averag

Still "Needs Confirmation" !



Citation: M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018)

$K_0^*(700)$

$I(J^P) = \frac{1}{2}(0^+)$

also known as κ; was $K_0^*(800)$

Needs confirmation. See the mini-review on scalar mesons under $f_0(500)$ (see the index for the page number).

$K_0^*(700)$ T-Matrix Pole $\sqrt{s}$

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
(630–730) − *i* (260–340) OUR EVALUATION				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$(670 \pm 18) - i\,(295 \pm 28)$	[1] PELAEZ	17	RVUE	
$(764 \pm 63^{+71}_{-54}) - i\,(306 \pm 149^{+143}_{-85})$	[2] ABLIKIM	11B	BES2	1.3k $J/\psi \to K^0_S K^0_S \pi^+ \pi^-$
$(665 \pm 9) - i\,(268^{+21}_{-6})$	[3] GUO	11B	RVUE	
$(849 \pm 77^{+18}_{-14}) - i\,(256 \pm 40^{+46}_{-22})$	[2] ABLIKIM	10E	BES2	1.4k $J/\psi \to K^\pm K^0_S \pi^\mp \pi^0$
$(663 \pm 8 \pm 34) - i\,(329 \pm 5 \pm 22)$	[4] BUGG	10	RVUE	S-matrix pole

Best analysis: Roy-Steiner dispersion relations

Plenty of room for improvement on parameters

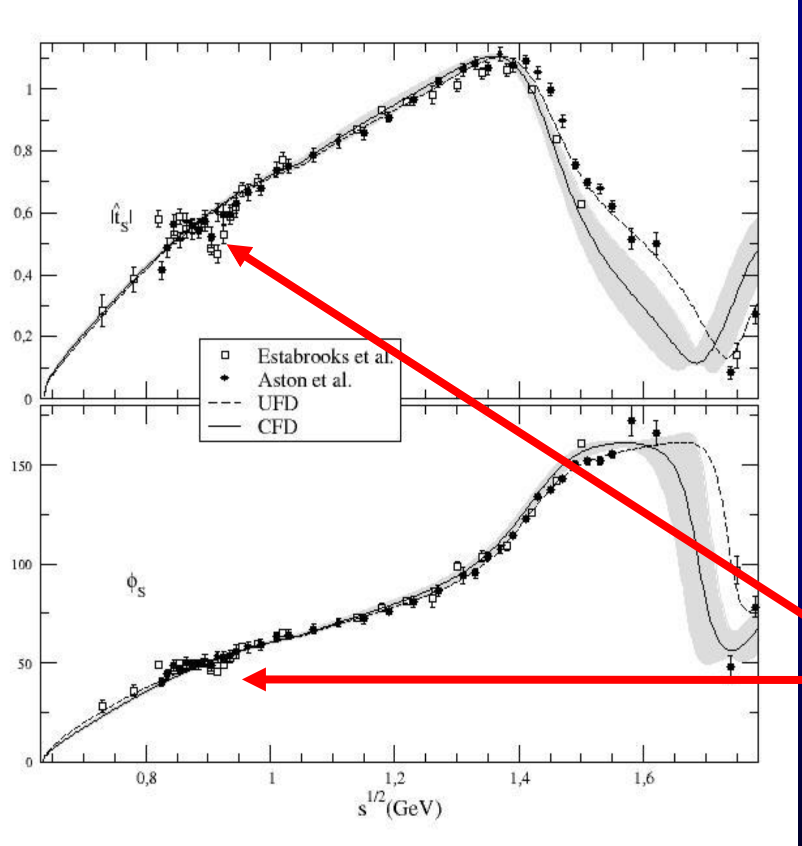
Pade sequences

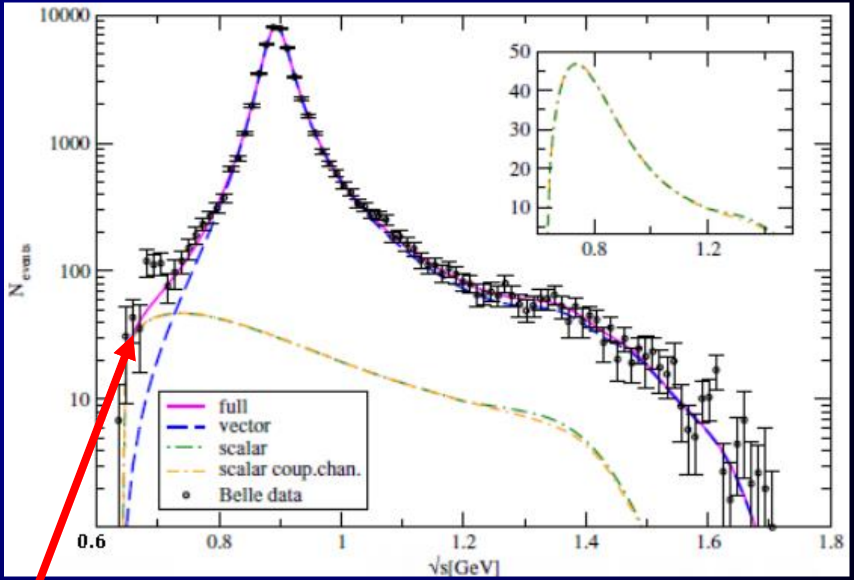
The problem with the kappa

It is a very wide resonance close to threshold

Either from scattering (SLAC)

Or produced in decays (Belle)





No clear “peak” or phase movement for $\kappa/K_0^*(800)$ resonance, less so $K_0^*(700)$

Definitely **NO BREIT-WIGNER shape**

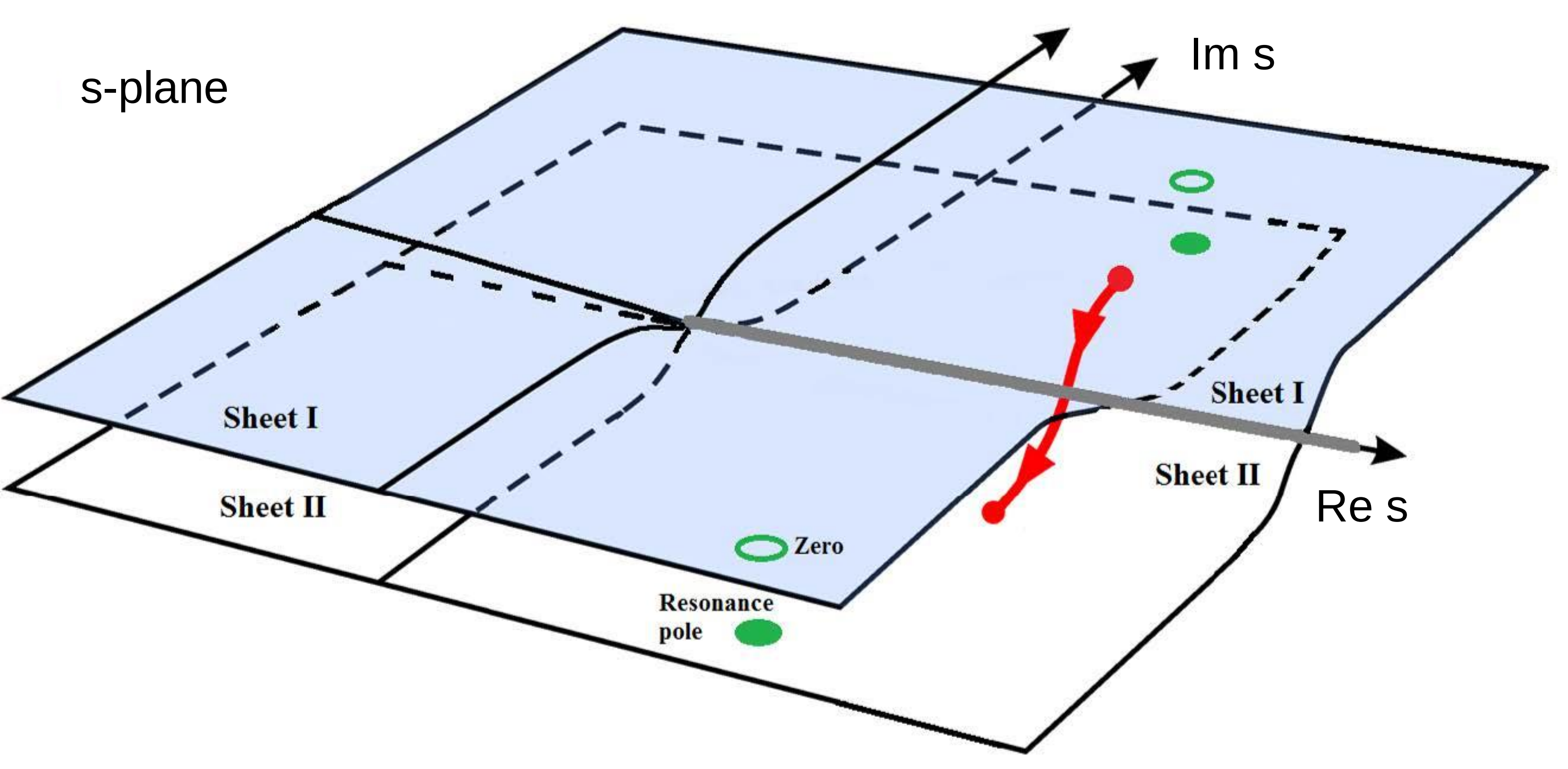
Mathematically correct to use **POLES**

Resonances as poles

The Breit-Wigner shape is just an approximation for narrow and isolated resonances

The universal features of resonances are their
pole positions and residues *
$\sqrt{s_{pole}} \approx M-i\,\Gamma/2$

*in the Riemann sheet obtained from an analytic continuation through the physical cut

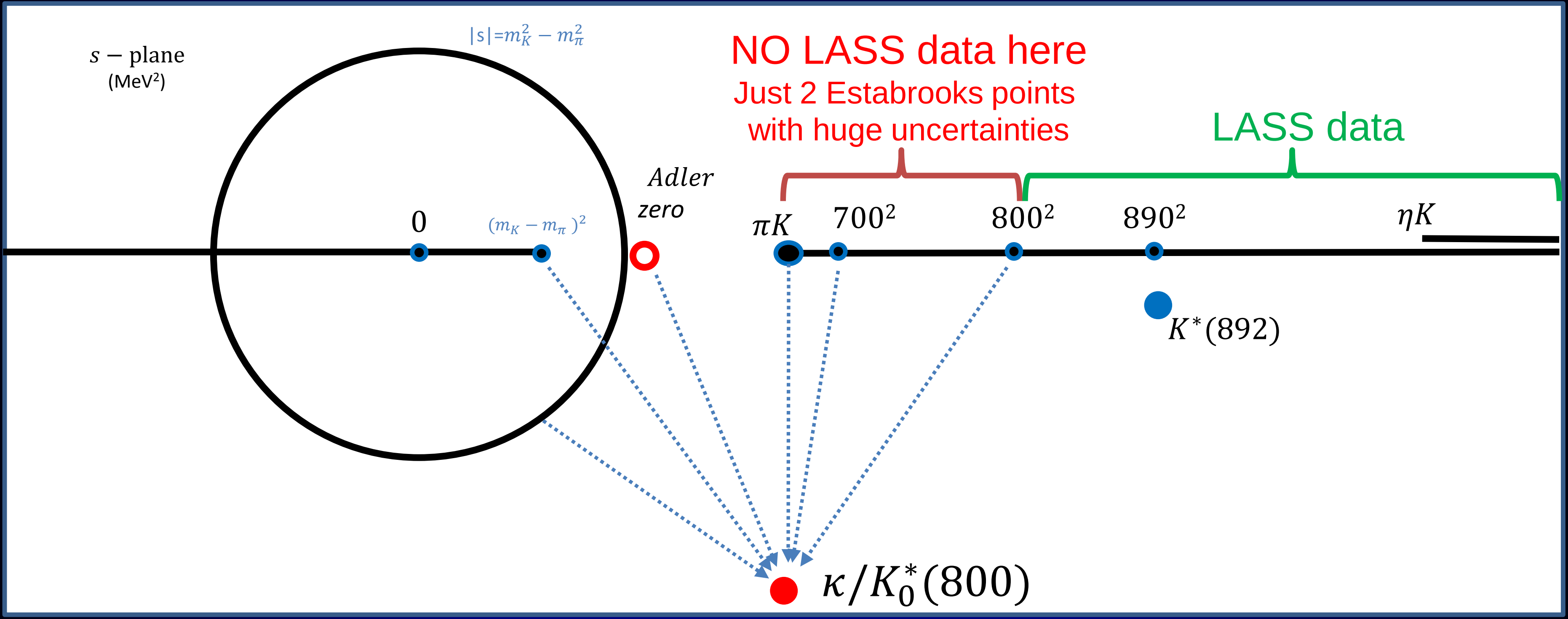


Why so much worries about low energy and CORRECT ANALYTIC STRUCTURE?

Analyticity is expressed in the s-variable, not in $\sqrt{s}$

Why so much worries LOW ENERGY and CORRECT ANALYTIC STRUCTURE?

Analyticity is expressed in the *s*-variable, not in $\sqrt{s}$

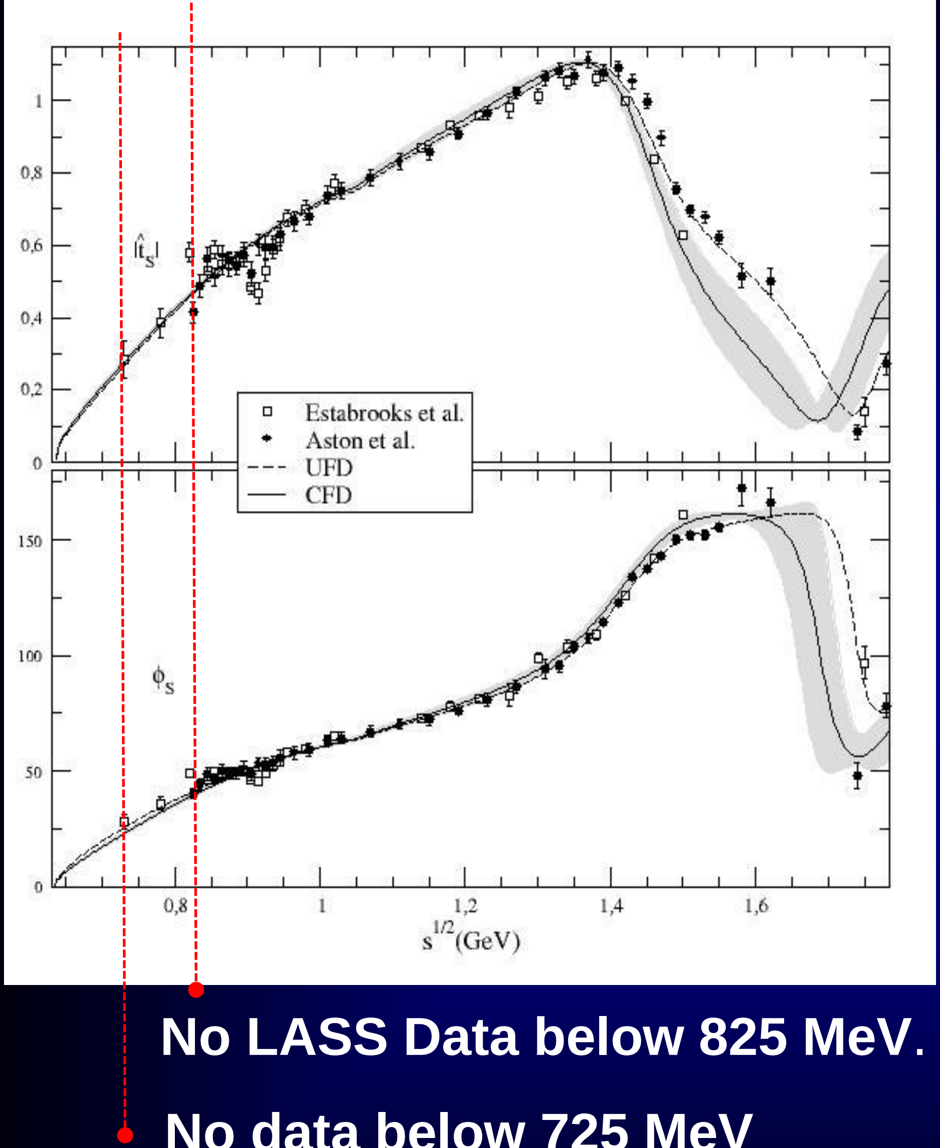


Important for the $\kappa/K_0^*(800)$

- Threshold behavior (Theory: chiral symmetry)
- Subthreshold behavior (Theory: chiral symmetry →Adler zeros)
- Other cuts (Theory: Left & circular)

- **LOW ENERGY REGION data very relevant for the kappa**

The problem with data on S-WAVE



No LASS Data below 825 MeV. Only 2 points with huge uncertainties from Estabrooks et al. 78 below 800 MeV

No data below 725 MeV

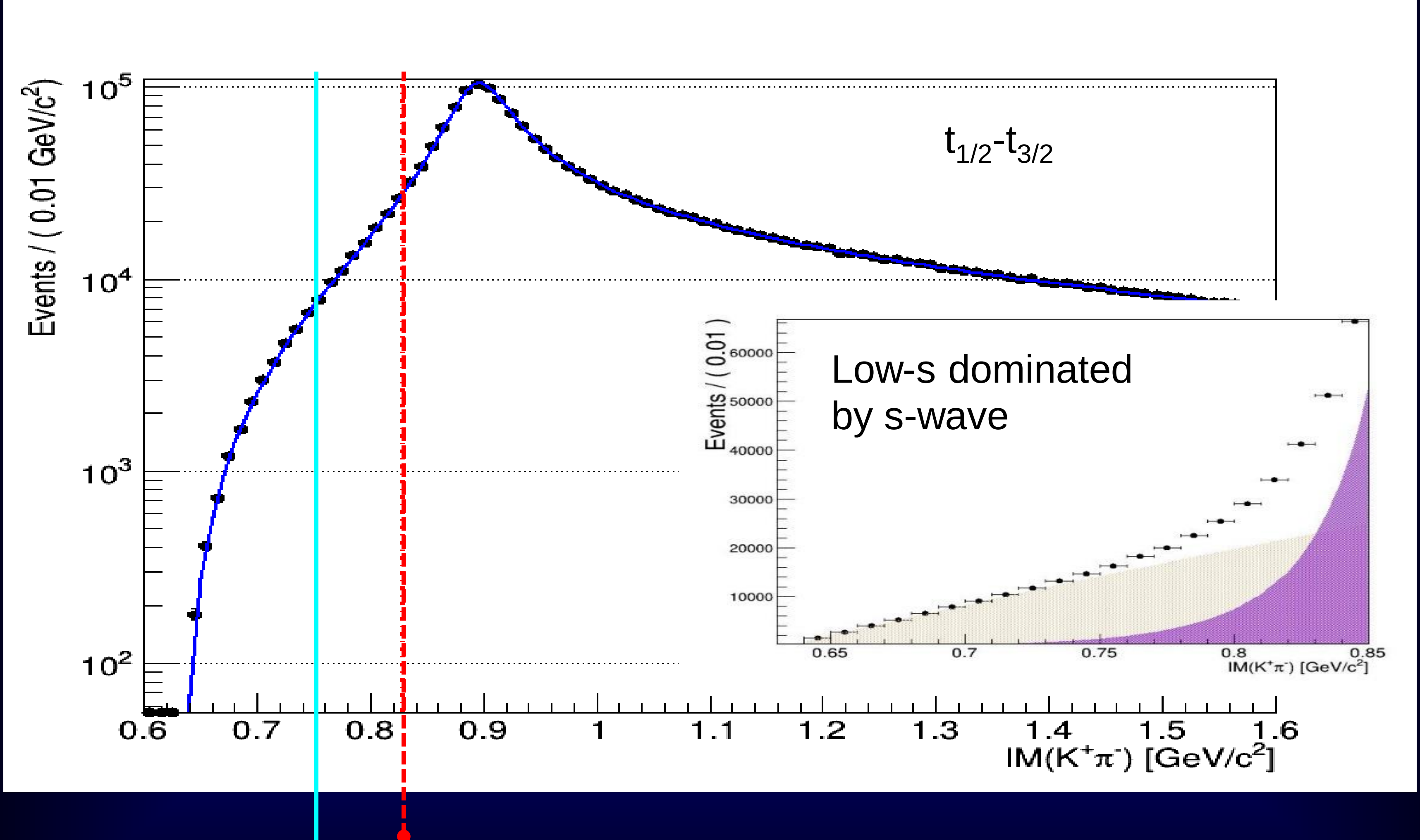
Most reliable sets:

- Estabrooks et al. 78 (SLAC)
- **Aston et al.88 (SLAC-LASS)** Largest statistics. But measures $t_{1/2}+t_{3/2}/2$

KLF will improve this

Expected number of events after 100-day run @ KLF

1) FOUR ORDERS of MAGNITUDE larger tan previous data set



Low-s dominated by s-wave

2) 18 NEW energy bins below 825 MeV (there were 2)

3) 11 NEW energy bins below 725 MeV (there were NONE)

Isospin separation @KLF

- KLF will measure

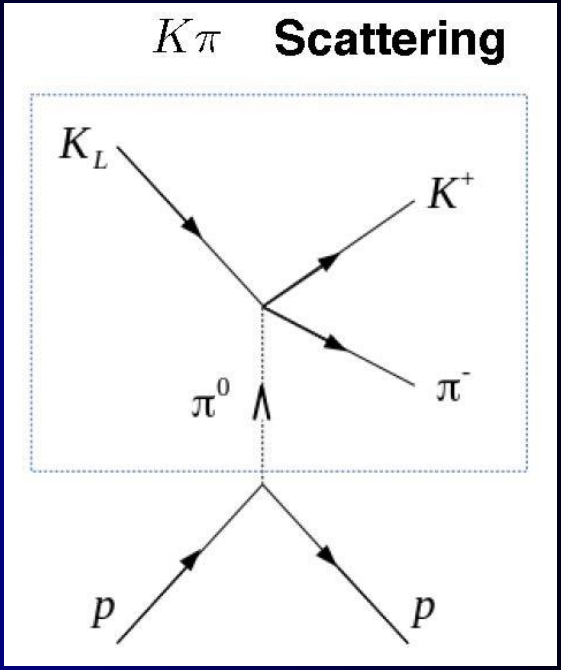
$$K_L p \to (K^{*0})p \to K^+\pi^- p$$
$$K_L p \to (\bar{K}^{*0})p \to K^-\pi^+ p$$

which are sensitive to $t_{1/2}$-$t_{3/2}$.

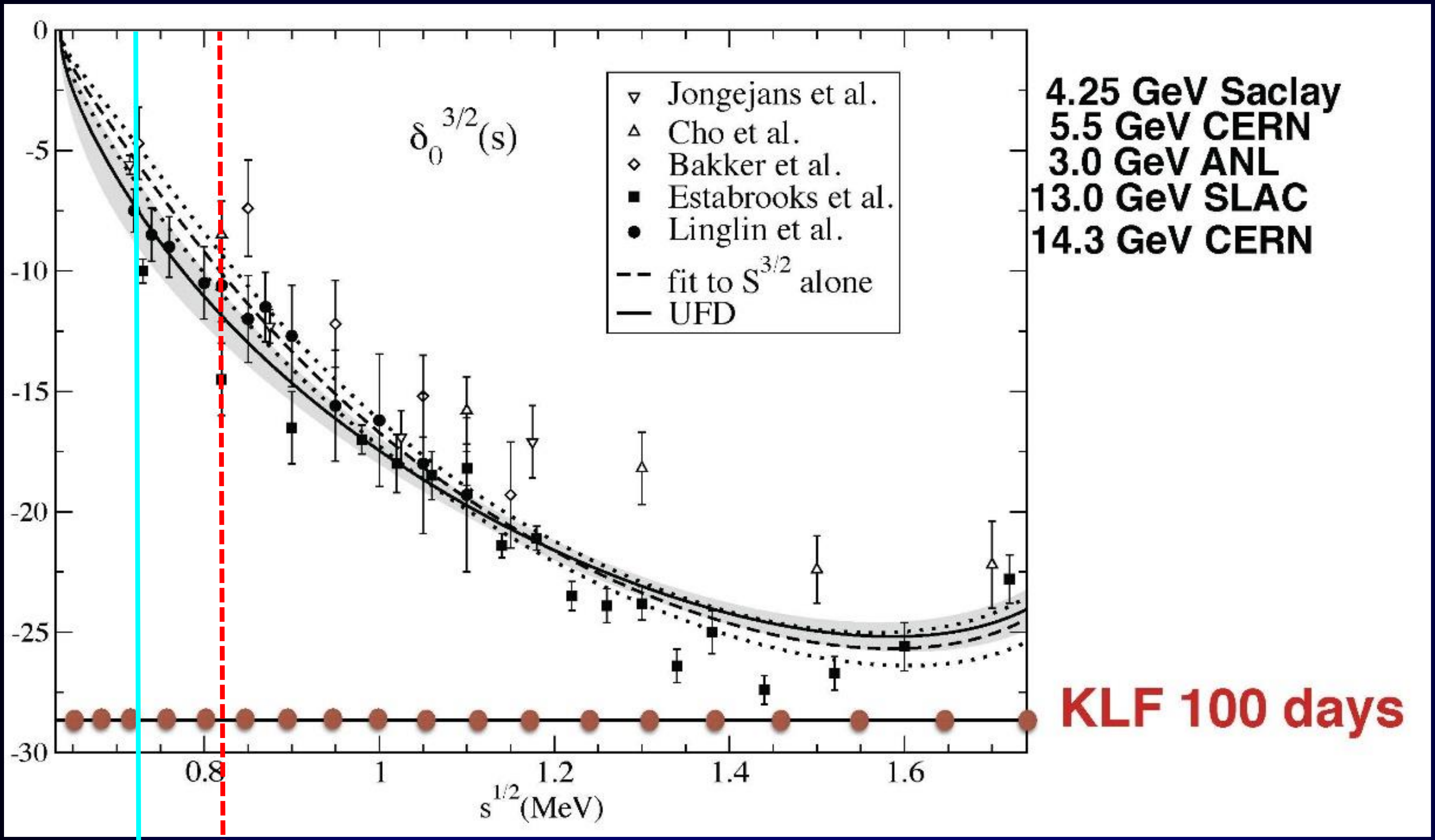
But also

$$K_L p \to (K^{*0})p \to K_L\pi^0 p$$

which is sensitive to $t_{1/2}+2\ t_{3/2}$



In this way the two isospin states can be separated.
For the latter the K_L will be reconstructed from the missing mass of the proton and the π^0 and the invariant mass of the $K_L\pi^0$ in the missing mass of the proton.

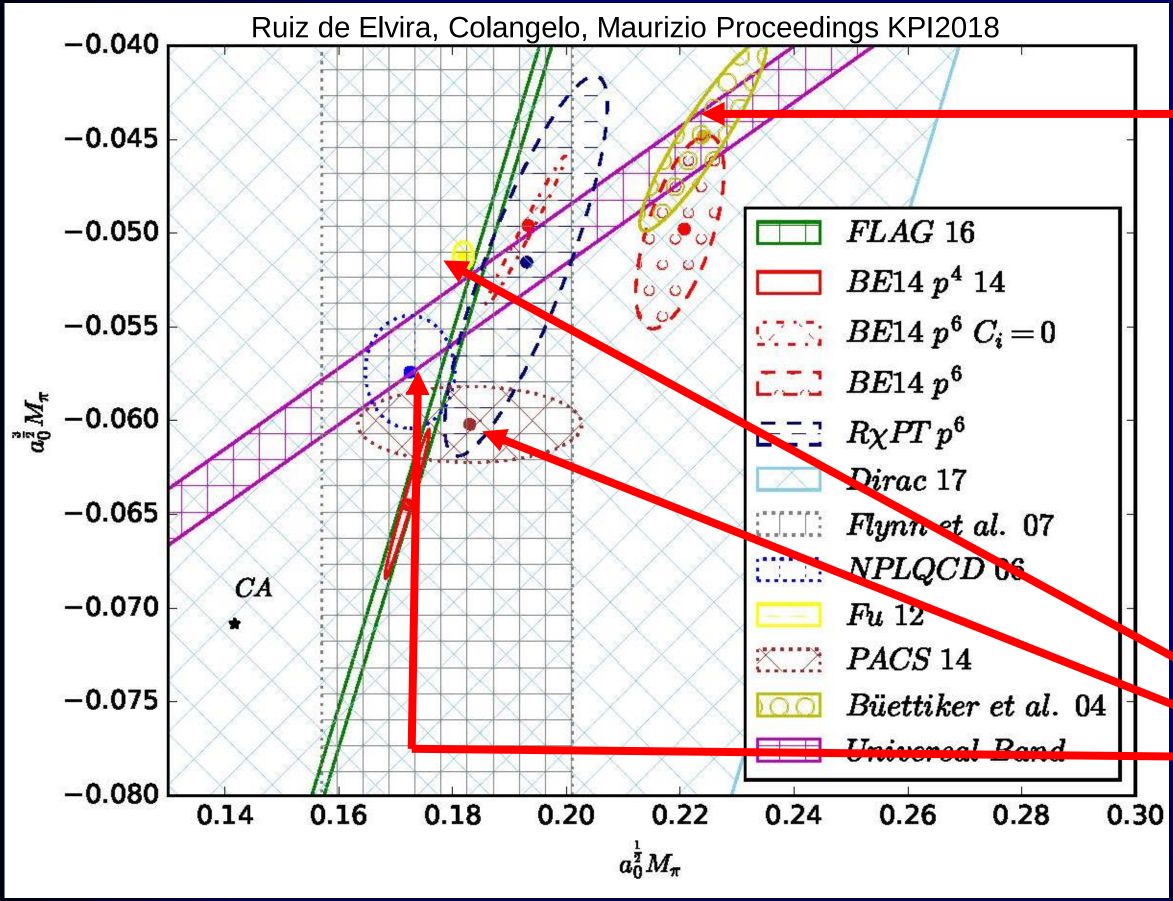


- With the missing mass reconstruction one expects 5 points below 825MeV
- 3 points below the existing data.
- With some timing improvement KLF could double the points.
- 100 x statistics than Estabrooks et al. **Stat. Error bars invisible with KLF**.
- Systematic uncertainties expected at ~5% level

Relevance for threshold parameters and ChPT

Present tension between exp+dispersion theory vs. lattice.

Important to understand applicability of SU(3) ChPT & size of strange condensate.



Ruiz de Elvira, Colangelo, Maurizio Proceedings KPI2018

Dispersive solution or with dispersive constrained fit to data

Lattice

No reliable extraction from DATA. All rely on extrapolations from 750MeV to threshold

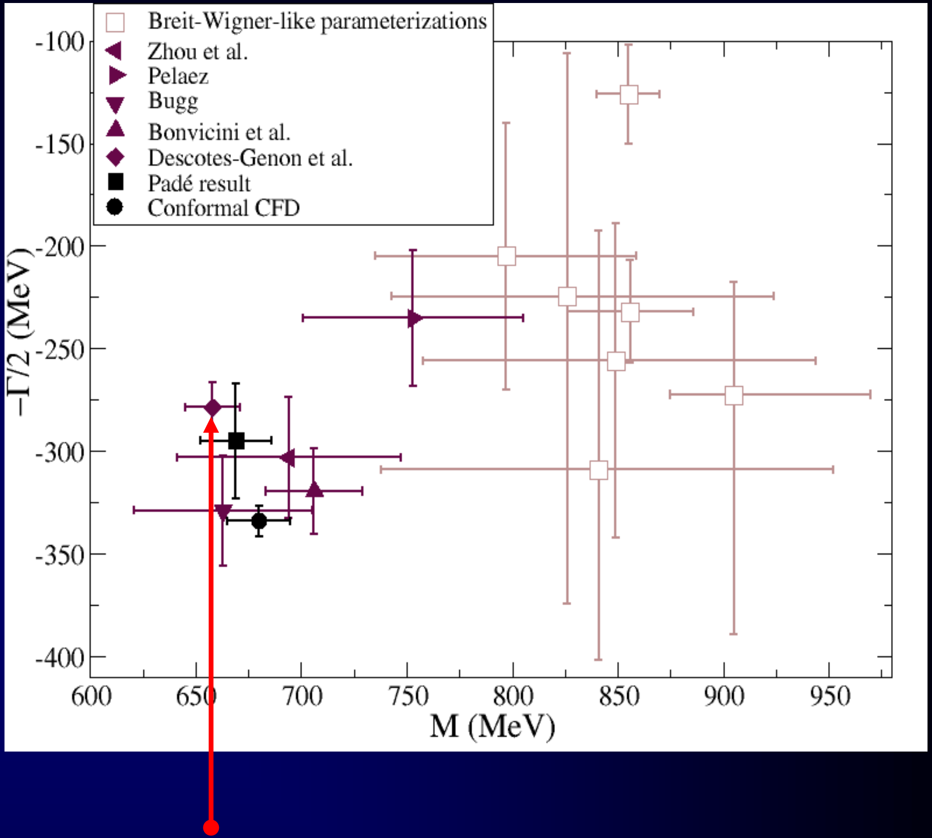
Low-enery and isospin separation @KLF crucial

The theory problem for the kappa

Much confusion from
too simple theoretical models:

- Breit Wigners !!
- No Adler zeros
- No left cuts, no circular cuts, etc…

The rigorous way to extract the pole is with partial wave dispersión relations (Roy-Steiner eqs.)



The only Roy-Steiner calculation so far DOES NOT USE DATA on S-wave below 900 MeV
(In a sense is a prediction)

Even Lattice + K-matrix gets a kappa

Resonances in coupled $\pi K, \eta K$ scattering from quantum chromodynamics

Jozef J. Dudek,[1,2,*] Robert G. Edwards,[1] Christopher E. Thomas,[3] and David J. Wilson[2]
(for the Hadron Spectrum Collaboration)
[1] *Theory Center, Jefferson Lab, 12000 Jefferson Avenue, Newport News, VA 23606, USA*
[2] *Department of Physics, Old Dominion University, Norfolk, VA 23529, USA*
[3] *DAMTP, University of Cambridge, Cambridge, UK*
(Dated: June 18, 2014)

Phys.Rev.Lett. 113 (2014) 18, 182001

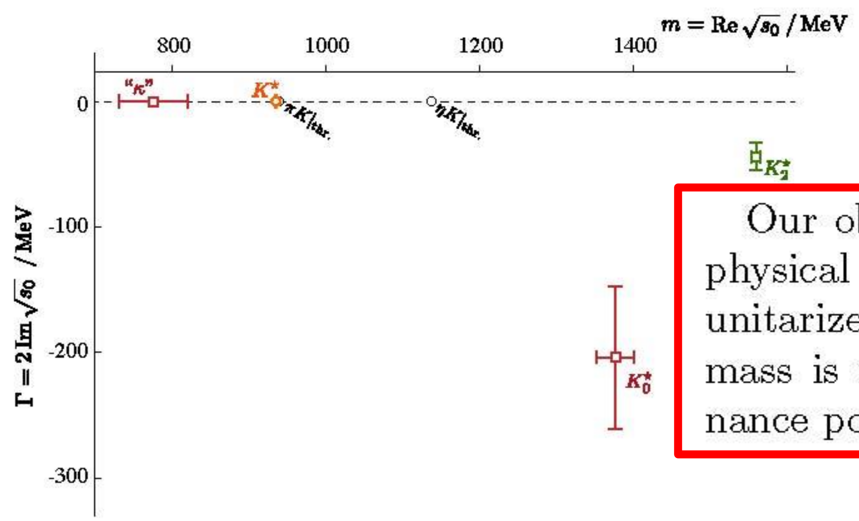


FIG. 3. Pole singularities of partial-wave t-matrices in the complex plane for $J^P = 0^+$(red), 1^-(orange) and 2^+(green). Squares correspond to poles found on unphysical sheets, circle is a physical sheet bound-state.

M_π=391 MeV

M_K=549 MeV

Our observation of a 0^+ pole below threshold on unphysical sheets agrees with the qualitative prediction of unitarized chiral perturbation theory that as the pion mass is increased above its physical value, the κ resonance pole becomes a virtual bound state [13].

around the πK threshold. Points determined
umes: 16^3(boxes), 20^3(circles) and 24^3(triangles).
$\cot\delta_1 = (m_R^2 - s)\frac{6\pi\sqrt{s}}{g_R^2}$. (c) $J^P = 2^+$ amplitudes –

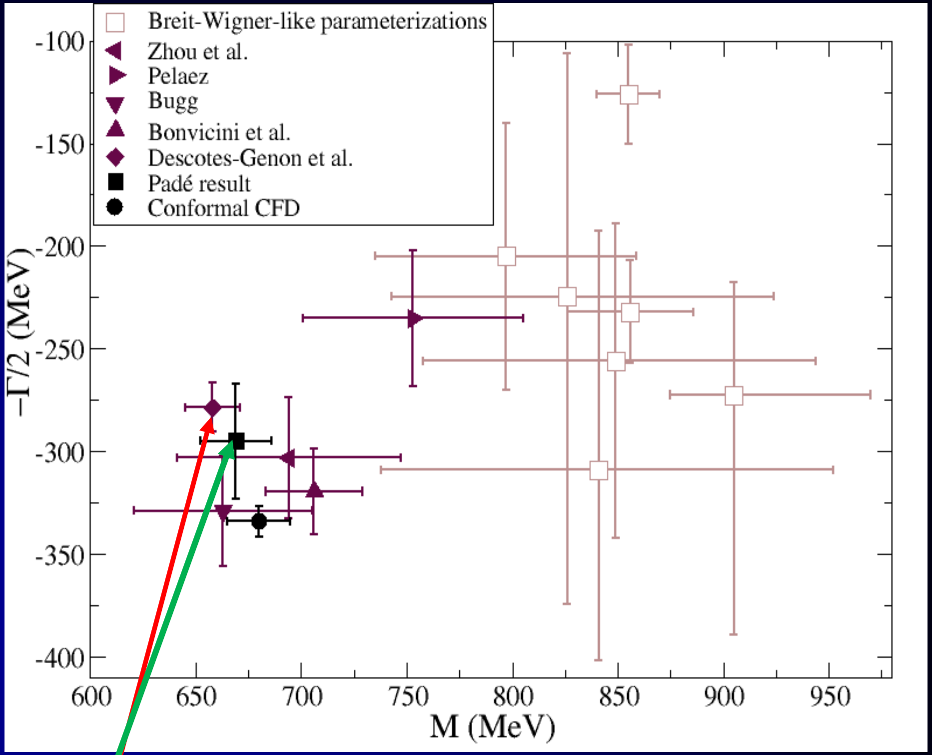
- So, there seems to be a virtual kappa on the lattice…

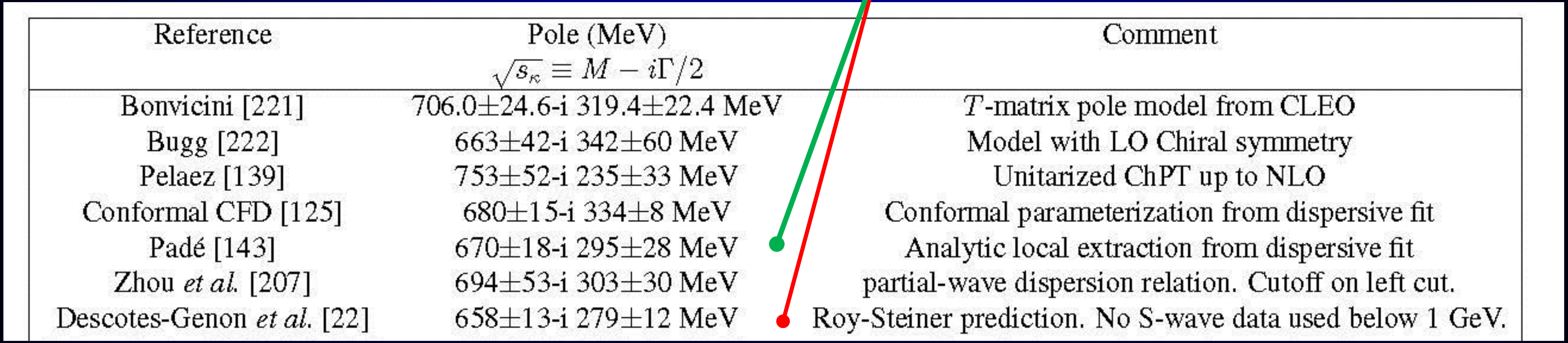
but at high masses!!

The theory problem for the kappa

There are some sound extractions,
with good chiral and analyticity properties,
but still with some model dependence
and without low-energy data…

NOT GOOD FOR PRECISION





Reference	Pole (MeV) $\sqrt{s_\kappa} \equiv M - i\Gamma/2$	Comment
Bonvicini [221]	706.0±24.6-i 319.4±22.4 MeV	T-matrix pole model from CLEO
Bugg [222]	663±42-i 342±60 MeV	Model with LO Chiral symmetry
Pelaez [139]	753±52-i 235±33 MeV	Unitarized ChPT up to NLO
Conformal CFD [125]	680±15-i 334±8 MeV	Conformal parameterization from dispersive fit
Padé [143]	670±18-i 295±28 MeV	Analytic local extraction from dispersive fit
Zhou *et al.* [207]	694±53-i 303±30 MeV	partial-wave dispersion relation. Cutoff on left cut.
Descotes-Genon *et al.* [22]	658±13-i 279±12 MeV	Roy-Steiner prediction. No S-wave data used below 1 GeV.

Ongoing dispersive study USING EXISTING DATA

- Impose Forward Dispersion Relations on fits to data.

(García-Martín, Kaminski,JRP, Ruiz de Elvira, Ynduráin, Rodas)

Use any parameterization to **fit DATA** imposing FDR within uncertainties.

(But you can use physical inspiration for clever choices of parameterizations)

Also needs input on other waves and high energy.

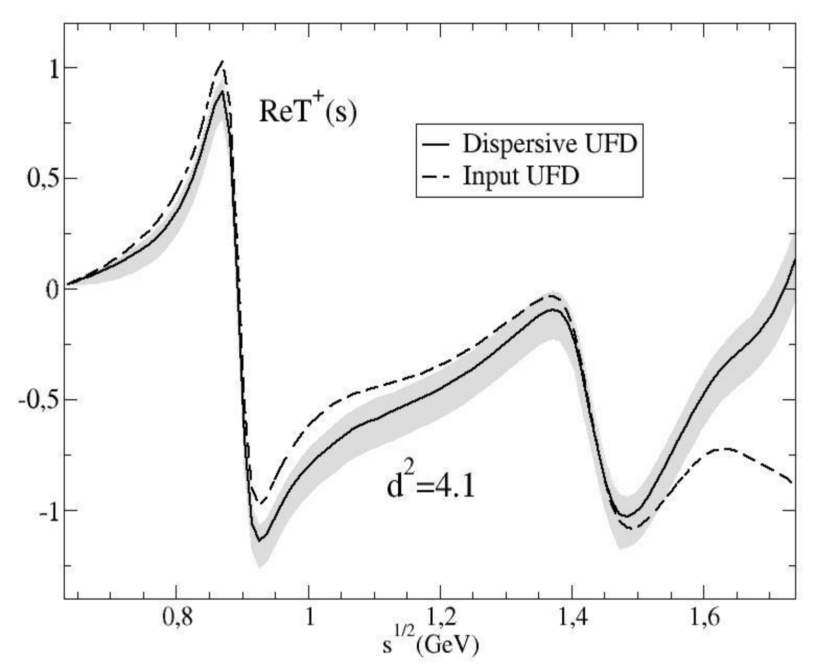
USE ROY-STEINER EQUATIONS TO DETERMINE THE POLE

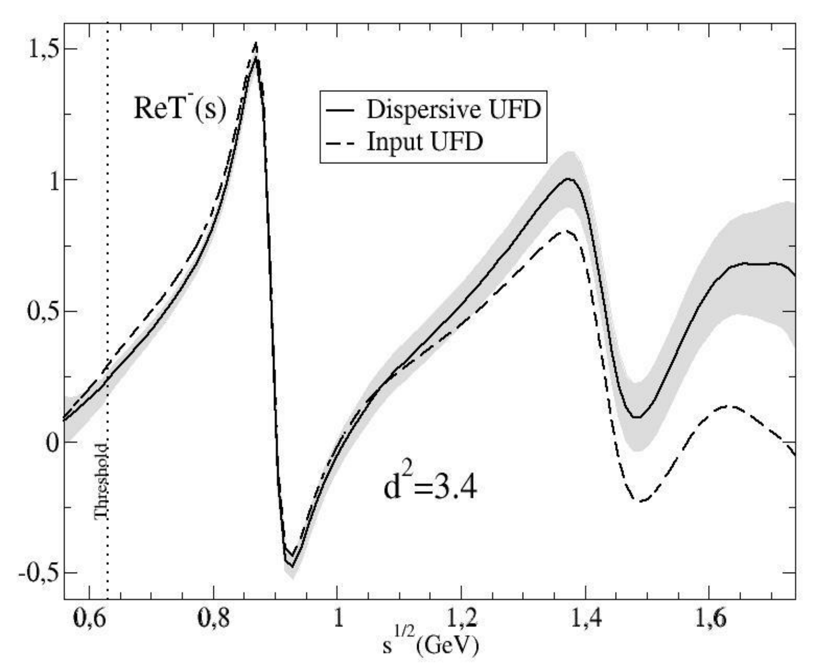
(but not the parameterizations)

Dispersive analysis of πK scattering DATA up to 1.6 GeV

(**not a solution** of dispersión relations, but a constrained fit)

A.Rodas & JRP, PRD93,074025 (2016)





First observation:
Forward Dispersion relations
Not well satisfied by data
Particularly at high energies

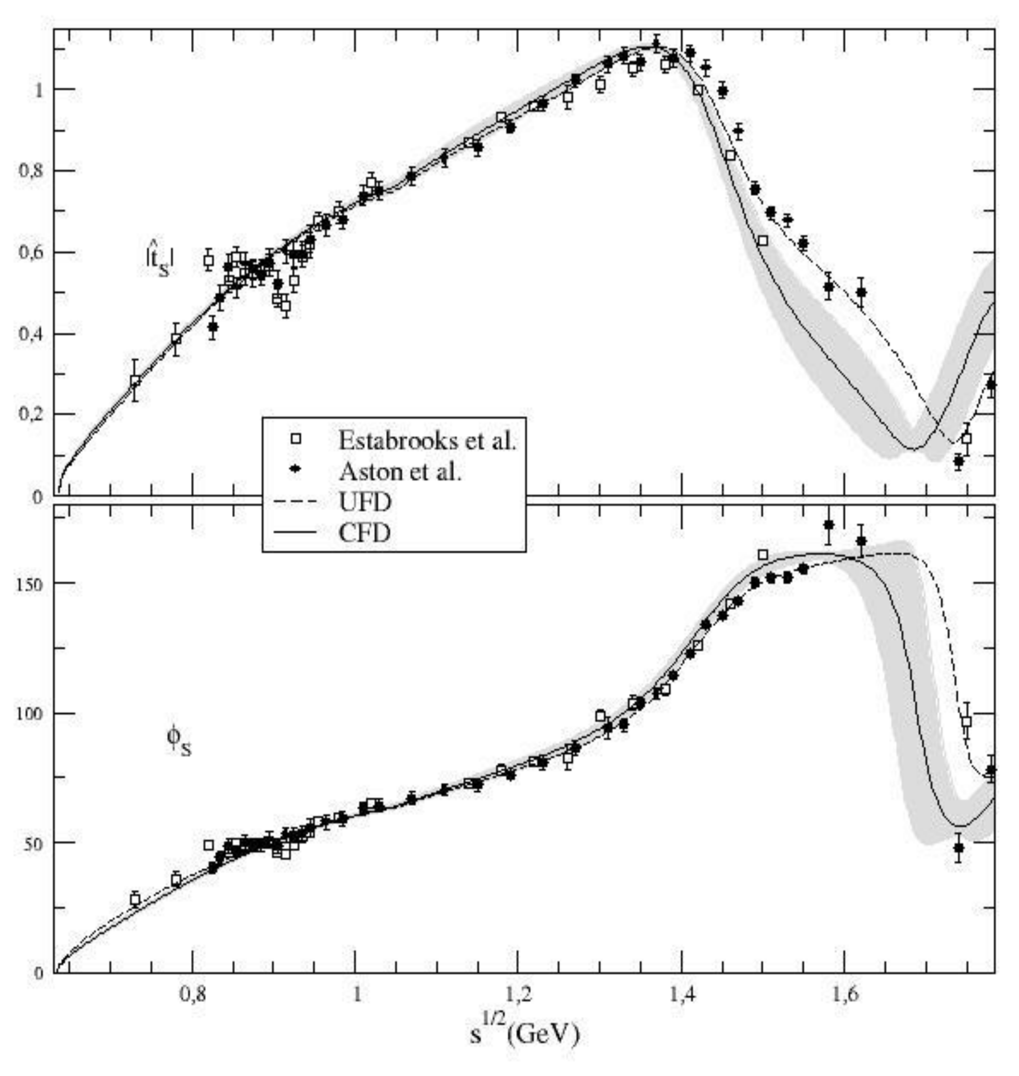
So we use
Forward Dispersion Relations
as CONSTRAINTS on fits

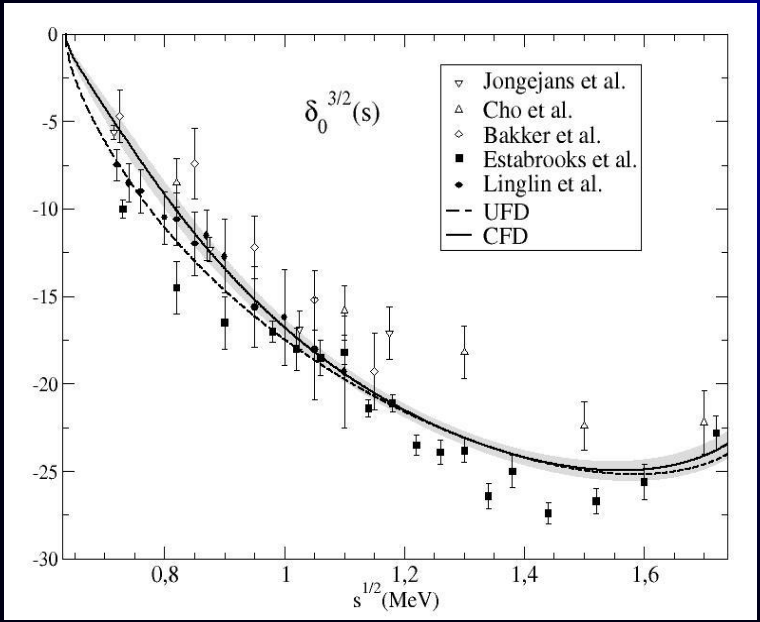
From Unconstrained (UFD) to Constrained Fits to data (CFD)

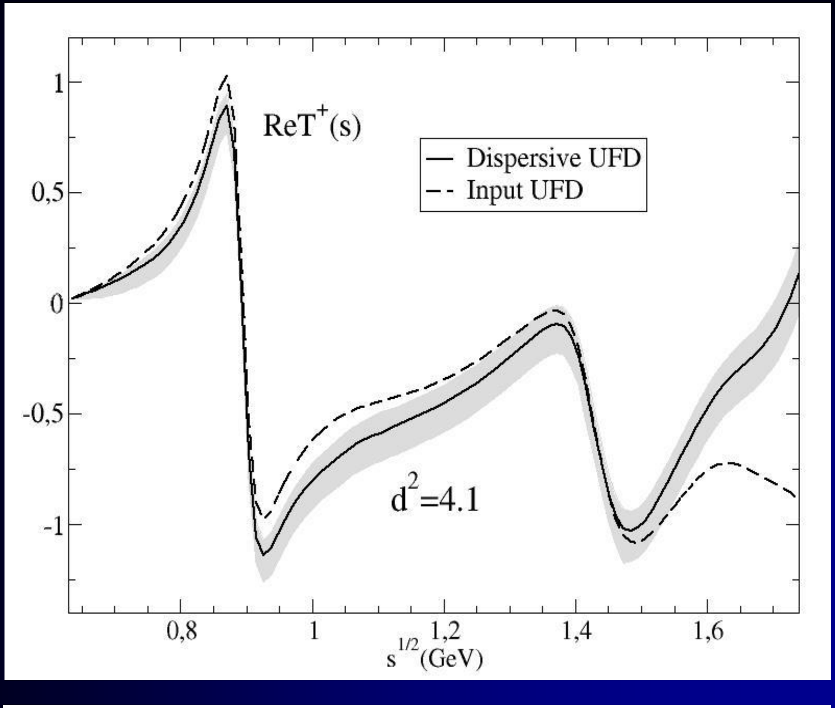
S-waves. The most interesting for the K_0* resonances

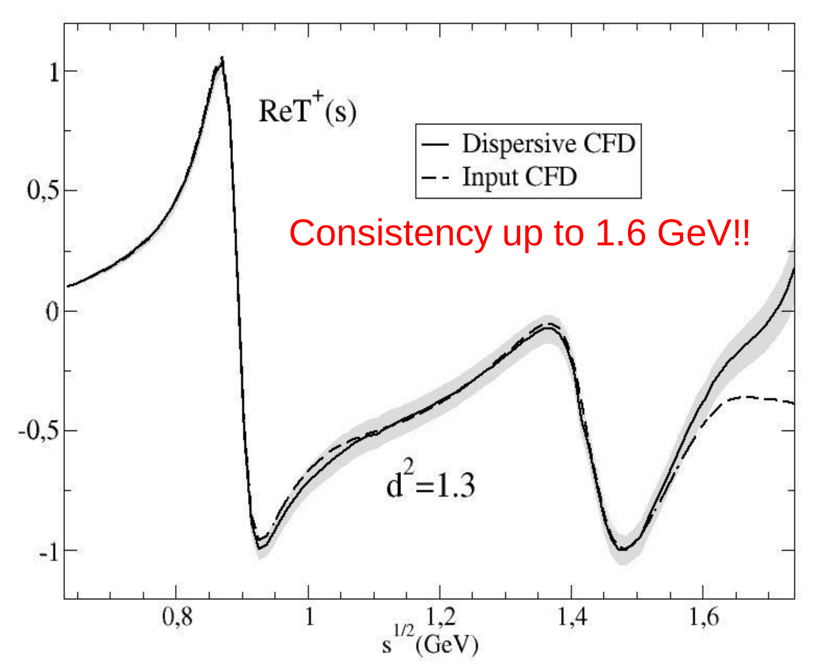
Largest changes from UFD to CFD

at higher energies

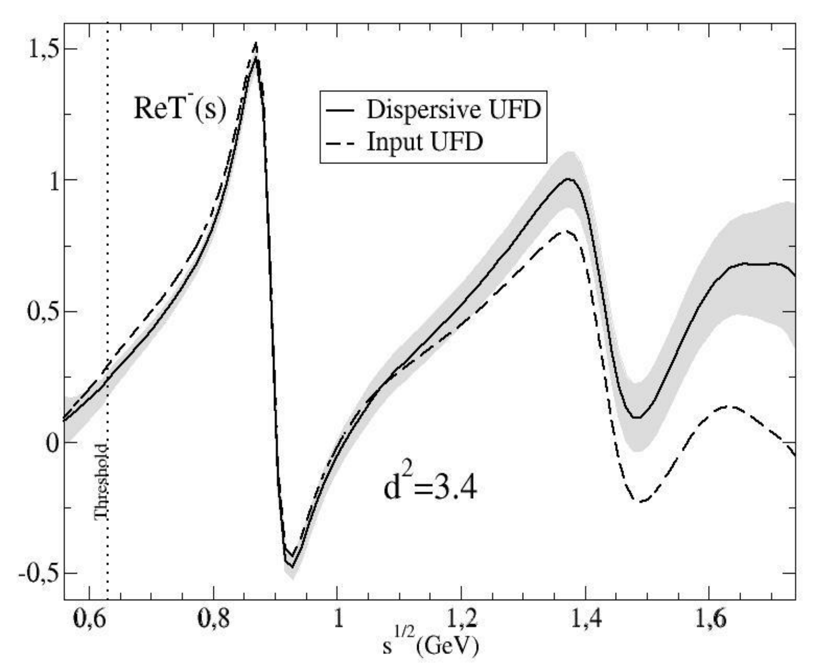


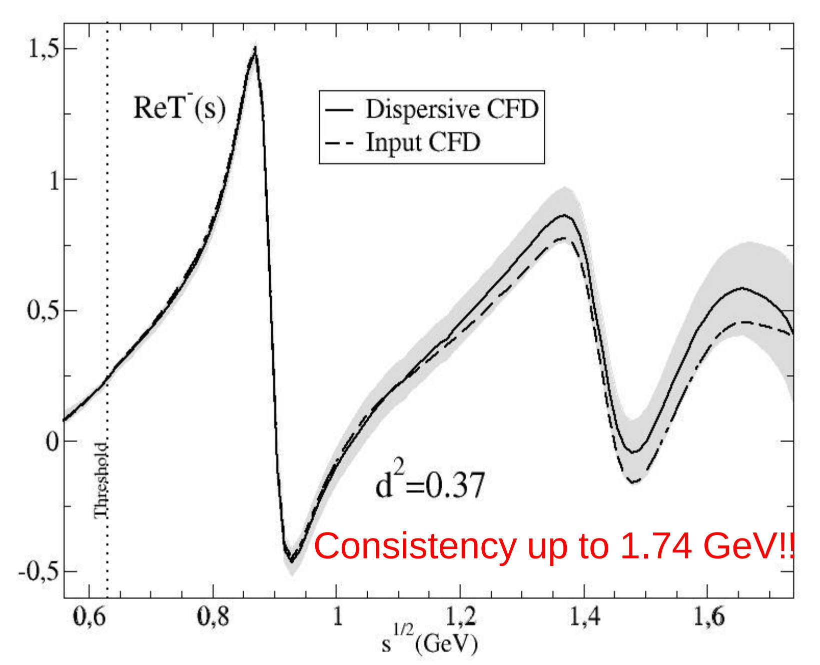






Consistency up to 1.6 GeV!!





Consistency up to 1.74 GeV!!

Model independent analysis with existing data

Roy-Steiner SOLUTION from Paris group
Decotes-Genon-Moussallam 2006

(658±13)-i(278.5±12) MeV

Our Roy-Steiner analysis of FIT to data
JRP, A. Rodas, in preparation

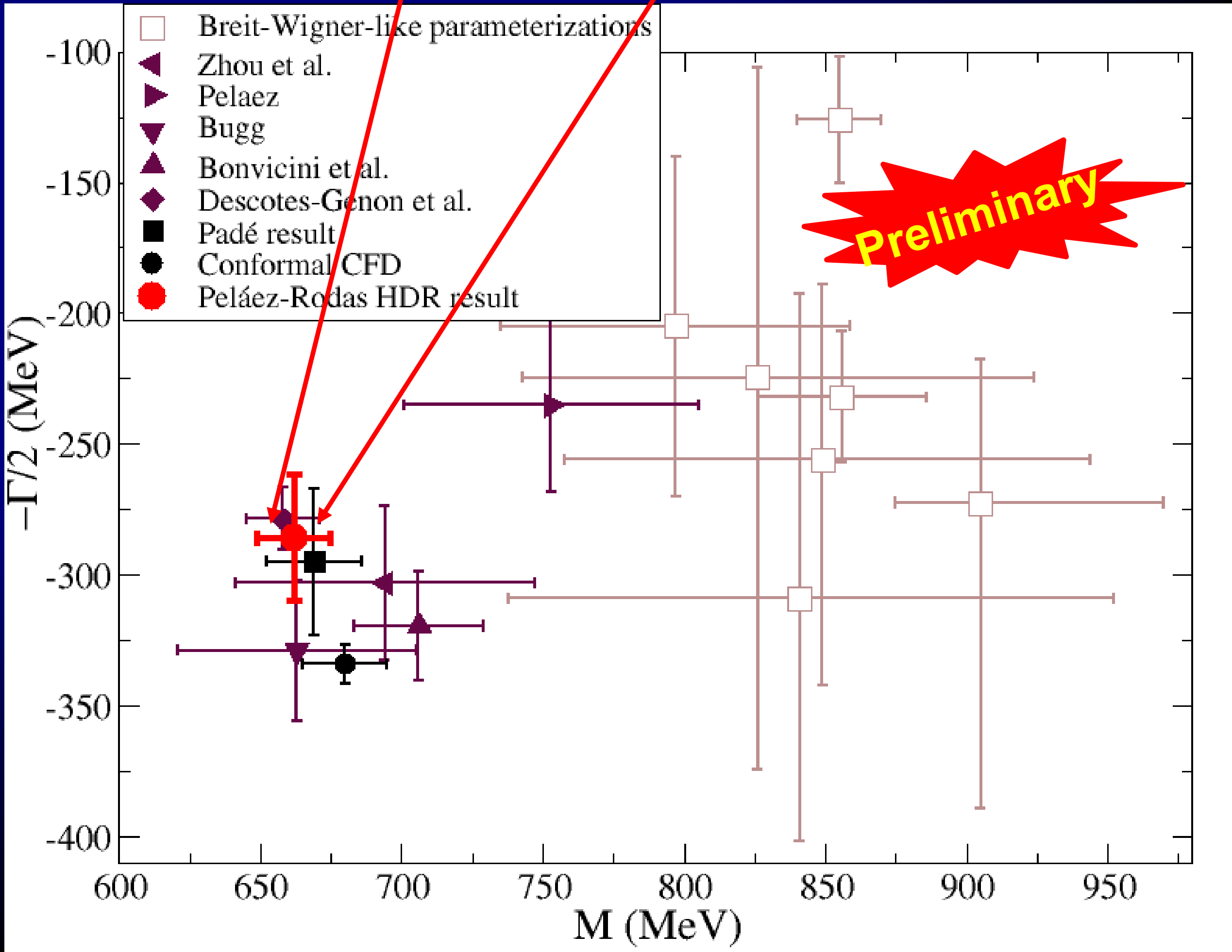
(663±14)-i(288±27) MeV

NEW!!

We have:

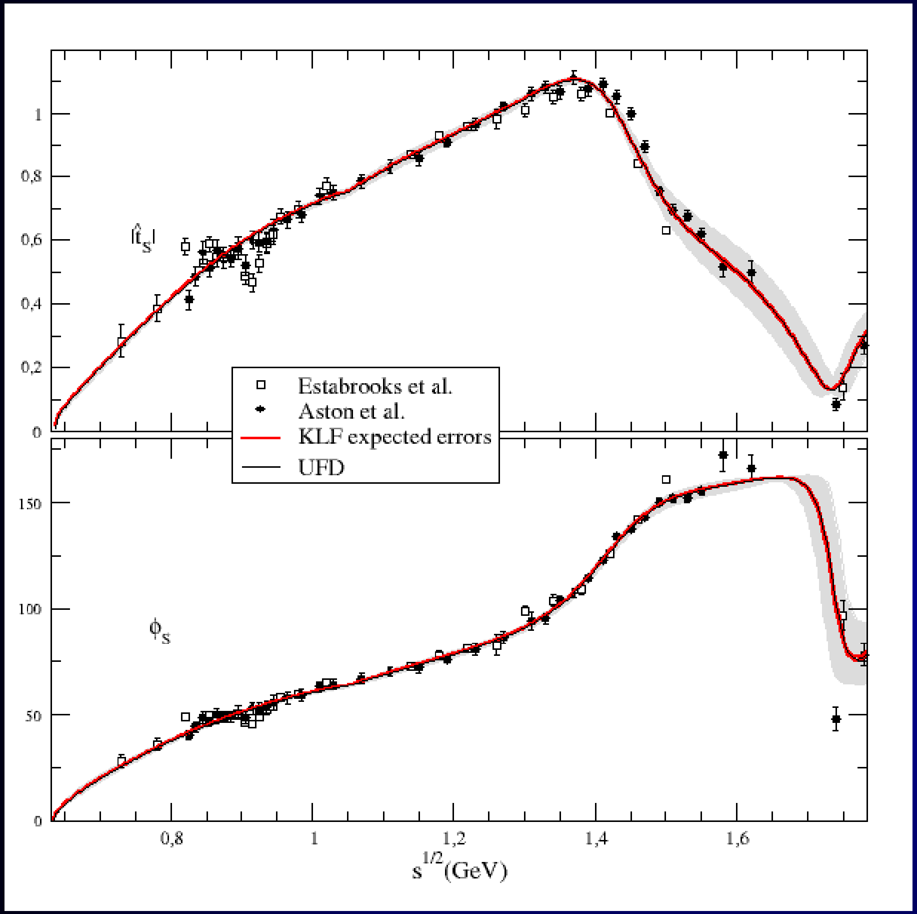
- Constrained Fit to data (not solved)
- Improved P-wave (data OK)
- Used Hyperbolic DR both in real axis and complex plane.
- Improved Pomeron
- Constrained ππ→KK input with DR
- Other technicalities

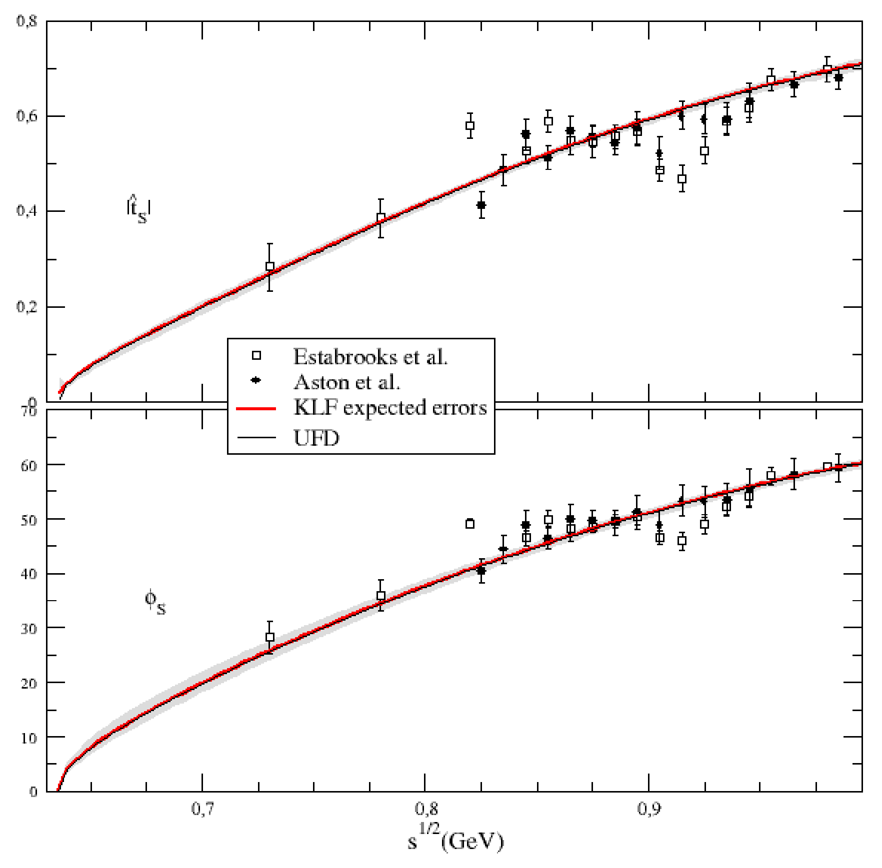
Independent dispersive $K_0^*(800)$ determination
USING EXISTING DATA



Model independent analysis **WITH EXPECTED KLF DATA**

We have run the same procedure but with 50x statistics of KLF on LASS data



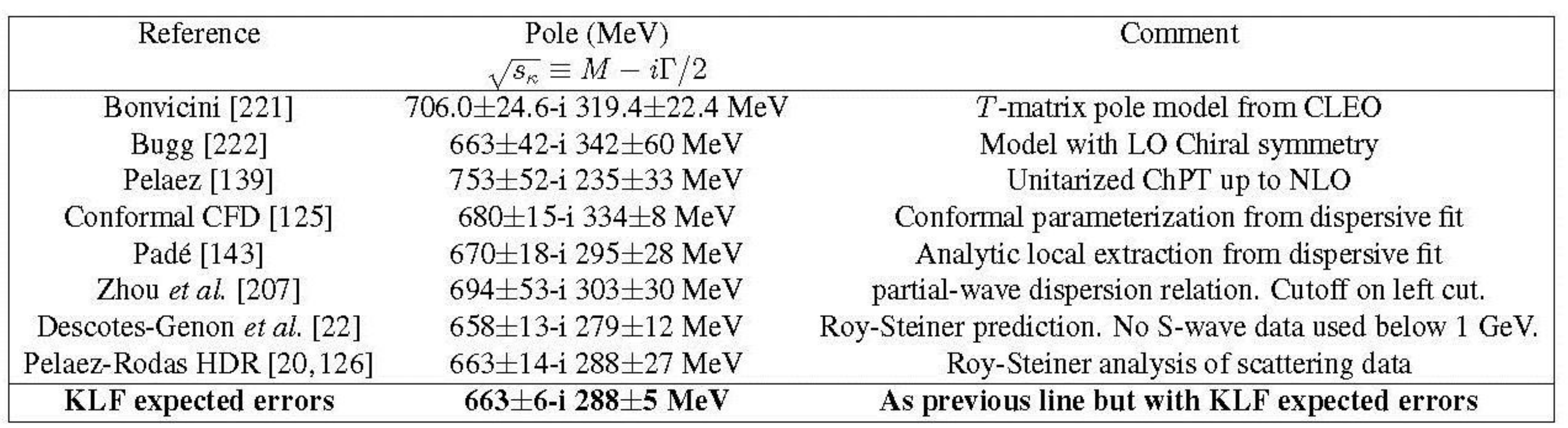


Uncertainty bands of the size of red line (not vanishing due to systematics)

Note we are NOT CONSIDERING NEW POINTS AT LOW ENERGIES

(that will decrease systematics)

Model independent analysis **WITH EXPECTED KLF DATA**



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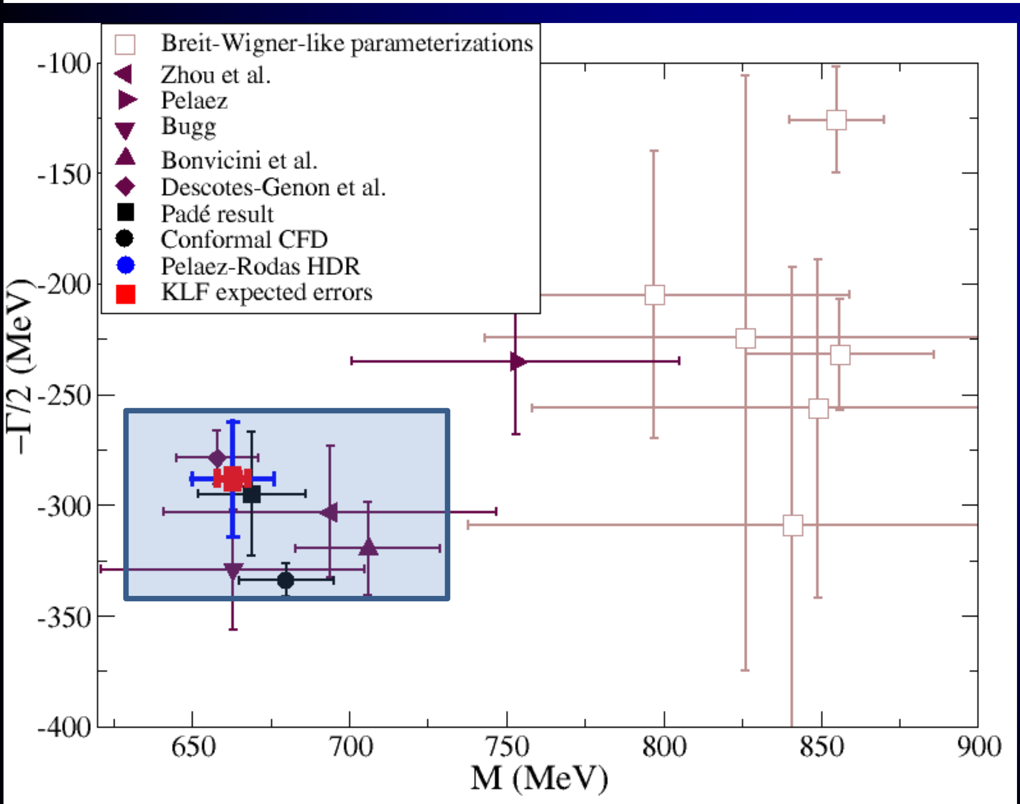
Pelaez-Rodas HDR [20,126]	663±14-i 288±27 MeV	Roy-Steiner analysis of scattering data
KLF expected errors	**663±6-i 288±5 MeV**	**As previous line but with KLF expected errors**



with EXISTING DATA

(663±14)-i(288±27) MeV

WITH KLF

(663±6)-i(288±5) MeV

HUGE IMPROVEMENT!!

Systematic errors should be reduced with further points near threshold

Remarks: Alternative/simpler methods

Dispersion relations needed to extract pole, but also to complete the region where there is no data.

They need data from other partial waves, high energies, etc… which induce systematic uncerrtainties

However, with additional points below 800 or 750 MeV one might not even need to use Dispersion Relations in the real axis or to continue to the complex plane.

Other analytic methods, like sequences of Padé approximants, which need dense grids of data points, could be used.

In that case, **kappa determinations based on KLF data alone**, will become competitive with dispersion relations.

Summary I

- KLF plans to measure Kπ with very high statistics (estimated 50x existing data)
- Will provide isospín 1/2 and 3/2 separation. This will require K_L reconstruction
- Will provide: 18 data points below 825 MeV (LASS reach) for charged final state.
  11 of them below 725 where data does not exist
- Will provide: 5 data points below 825 MeV (LASS reach) for neutral final state.
  3 of them below 725 where data does not exist
- The points near threshold and the large statistics will determine precisely the value of the scattering lengths and determine the convergence radius and applicability of SU(3) ChPT, size of the strange condensate, etc…

Summary II

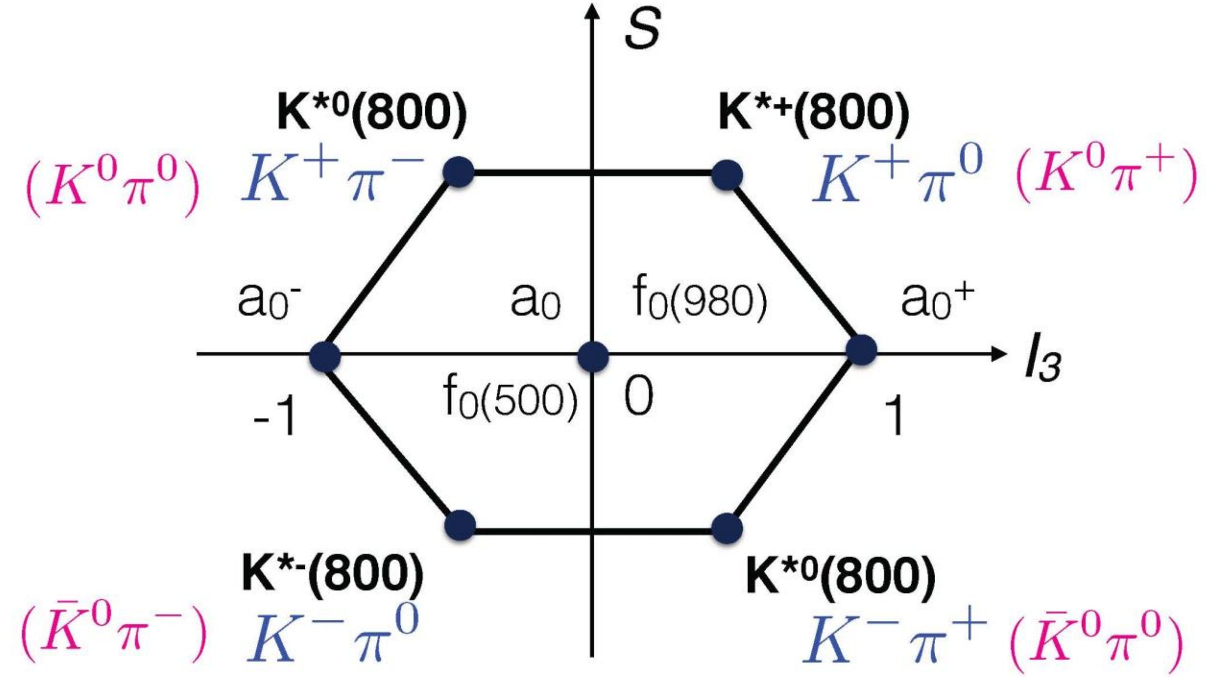
- Just with the statistical improvement + dispersion theory+ other input, a model independent analysis of the much debated $\kappa/K_0^*(800)$ will reduce the uncertainties in its mass by more than 2 and the width (coupling) by more than 5
- Systematic effects will be reduced with the new data points close to threshold.
- This may allow for a precise determination with KLF data only with other rigorous methods based on analyticity.

This should finally settle the controversy confirming the existence of the $\kappa/K_0^*(800)$ and determining precisely the value of its parameters. It will also fix the controversy about the existence of a light scalar nonet and its non-ordinary nature.

- KLF will also improve the precision of the K_1^*(892), K_1^*(1410) and K_0^*(1430)

SPARE SLIDES

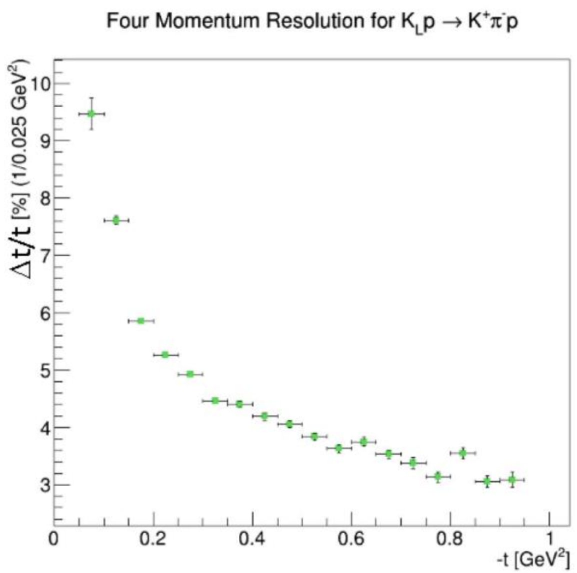
Scalar Meson Nonet



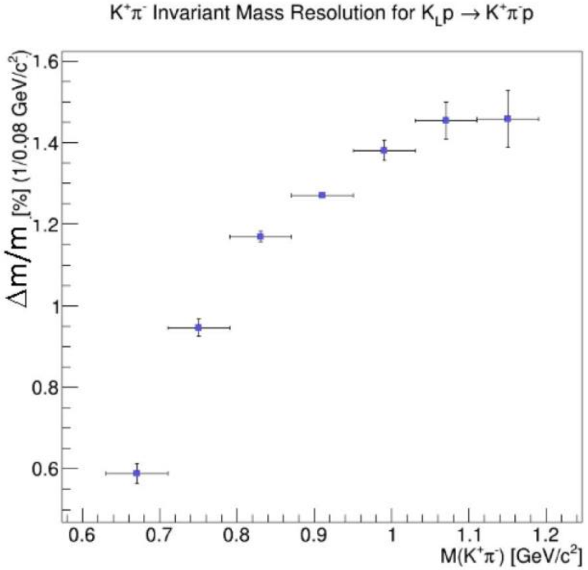
Four states called κ

still need further confirmation(PDG)

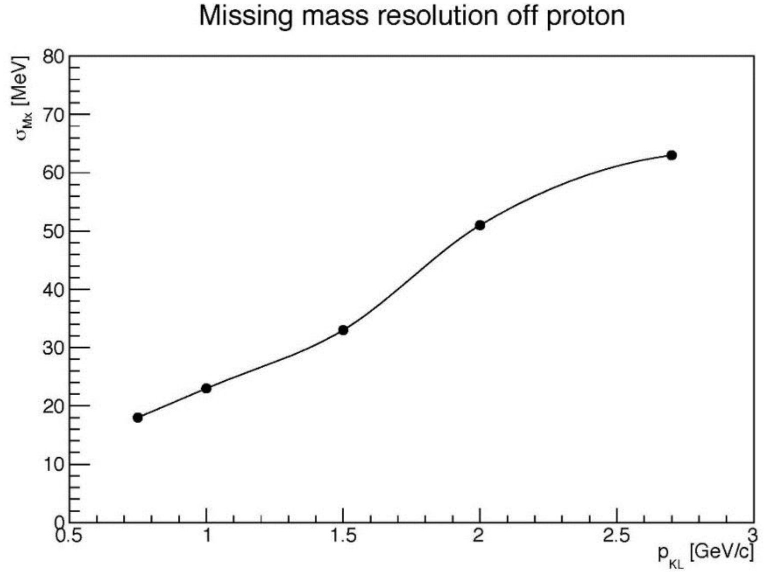
We can mesure all of them



-Good resolution at low-t is needed to be on pion pole



-Binning in ~10 MeV will cover almost entire elastic K-pi scattering range



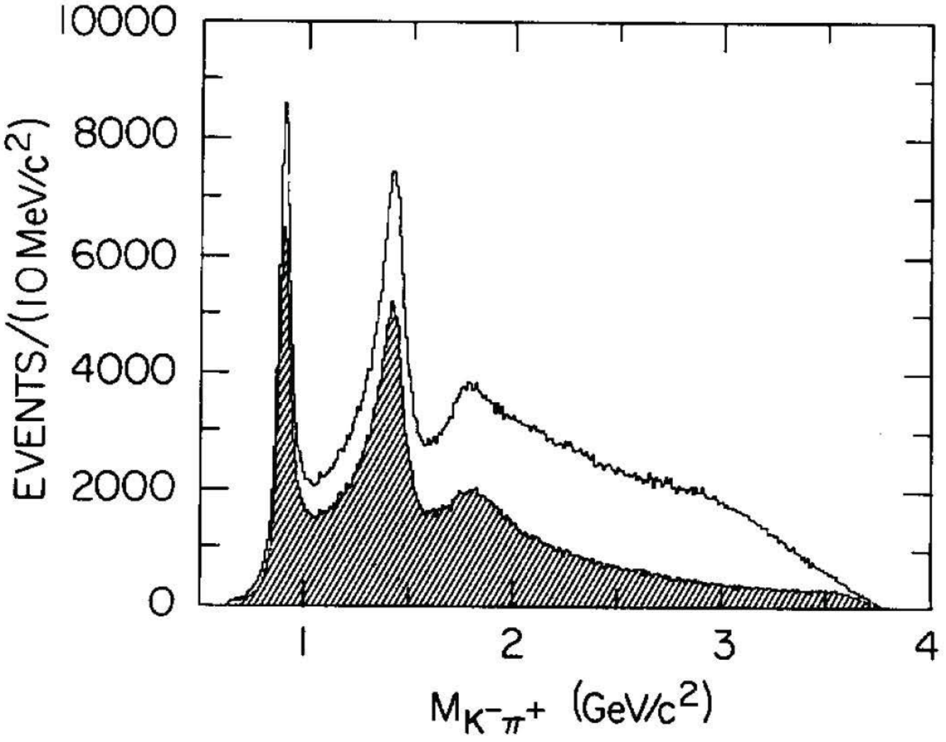
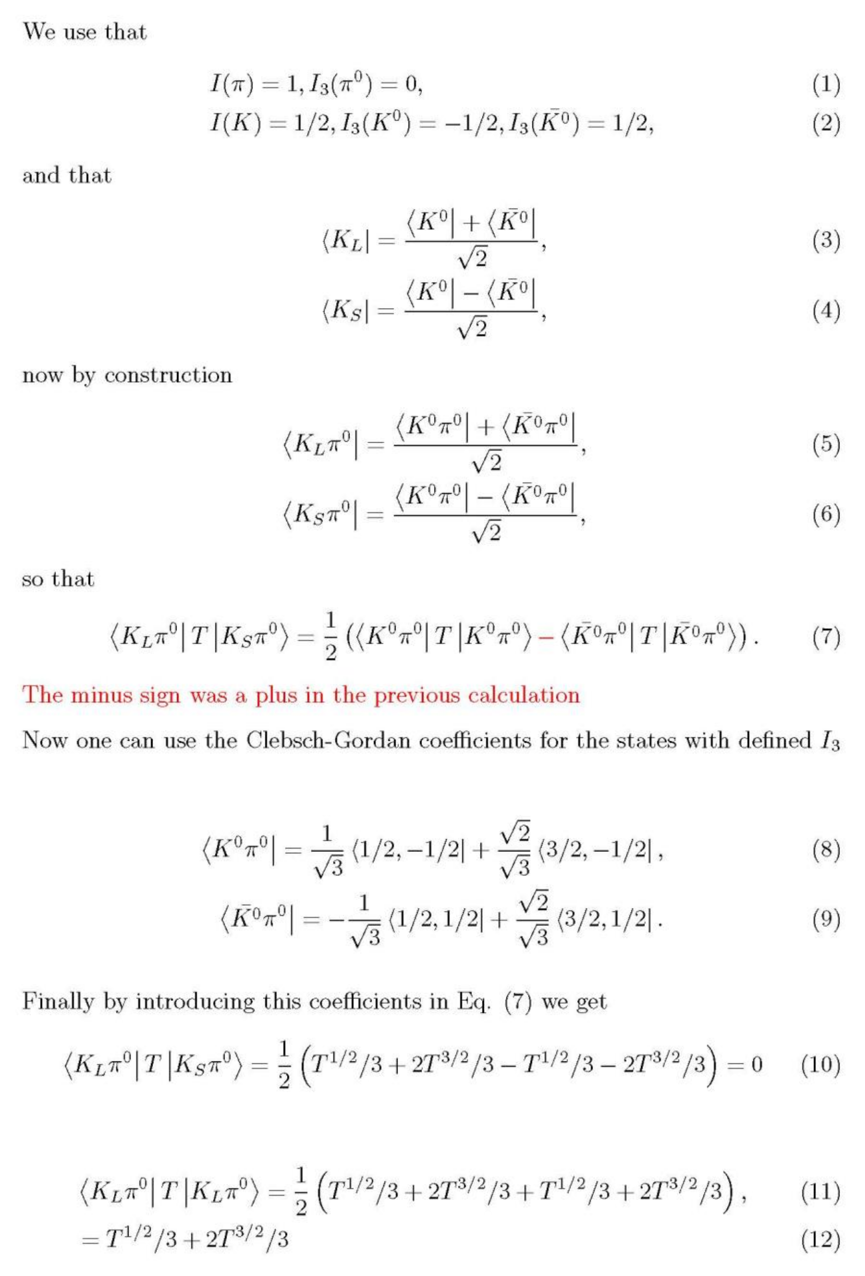


FIG. 1. The $K^{-}\pi^{+}$ invariant mass distribution for events with $|t'| \leq 1.0\ (GeV/c)^2$. The unshaded curve contains all events while the cross-hatched curve contains events with $n\pi^{+}$ mass greater than $1.7\ (GeV/c)^2$.



We use that

$$I(\pi) = 1, I_3(\pi^0) = 0, \tag{1}$$

$$I(K) = 1/2, I_3(K^0) = -1/2, I_3(\bar{K}^0) = 1/2, \tag{2}$$

and that

$$\langle K_L| = \frac{\langle K^0| + \langle \bar{K}^0|}{\sqrt{2}}, \tag{3}$$

$$\langle K_S| = \frac{\langle K^0| - \langle \bar{K}^0|}{\sqrt{2}}, \tag{4}$$

now by construction

$$\langle K_L\pi^0| = \frac{\langle K^0\pi^0| + \langle \bar{K}^0\pi^0|}{\sqrt{2}}, \tag{5}$$

$$\langle K_S\pi^0| = \frac{\langle K^0\pi^0| - \langle \bar{K}^0\pi^0|}{\sqrt{2}}, \tag{6}$$

so that

$$\langle K_L\pi^0| T |K_S\pi^0\rangle = \frac{1}{2}\left(\langle K^0\pi^0| T |K^0\pi^0\rangle - \langle \bar{K}^0\pi^0| T |\bar{K}^0\pi^0\rangle\right). \tag{7}$$

The minus sign was a plus in the previous calculation

Now one can use the Clebsch-Gordan coefficients for the states with defined I_3

$$\langle K^0\pi^0| = \frac{1}{\sqrt{3}}\langle 1/2, -1/2| + \frac{\sqrt{2}}{\sqrt{3}}\langle 3/2, -1/2|, \tag{8}$$

$$\langle \bar{K}^0\pi^0| = -\frac{1}{\sqrt{3}}\langle 1/2, 1/2| + \frac{\sqrt{2}}{\sqrt{3}}\langle 3/2, 1/2|. \tag{9}$$

Finally by introducing this coefficients in Eq. (7) we get

$$\langle K_L\pi^0| T |K_S\pi^0\rangle = \frac{1}{2}\left(T^{1/2}/3 + 2T^{3/2}/3 - T^{1/2}/3 - 2T^{3/2}/3\right) = 0 \tag{10}$$

$$\langle K_L\pi^0| T |K_L\pi^0\rangle = \frac{1}{2}\left(T^{1/2}/3 + 2T^{3/2}/3 + T^{1/2}/3 + 2T^{3/2}/3\right), \tag{11}$$

$$= T^{1/2}/3 + 2T^{3/2}/3 \tag{12}$$