On the importance of Kpi scattering for Phenomenology

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Physics with Neutral Kaon Beam at JLab Workshop
Thomas Jefferson National Accelerator Facility

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Outline

1. Introduction and Motivation
2. Test of ChPT
3. Hadron spectroscopy
4. Test of the SM and new physics
5. Conclusion and outlook

1. Introduction and Motivation

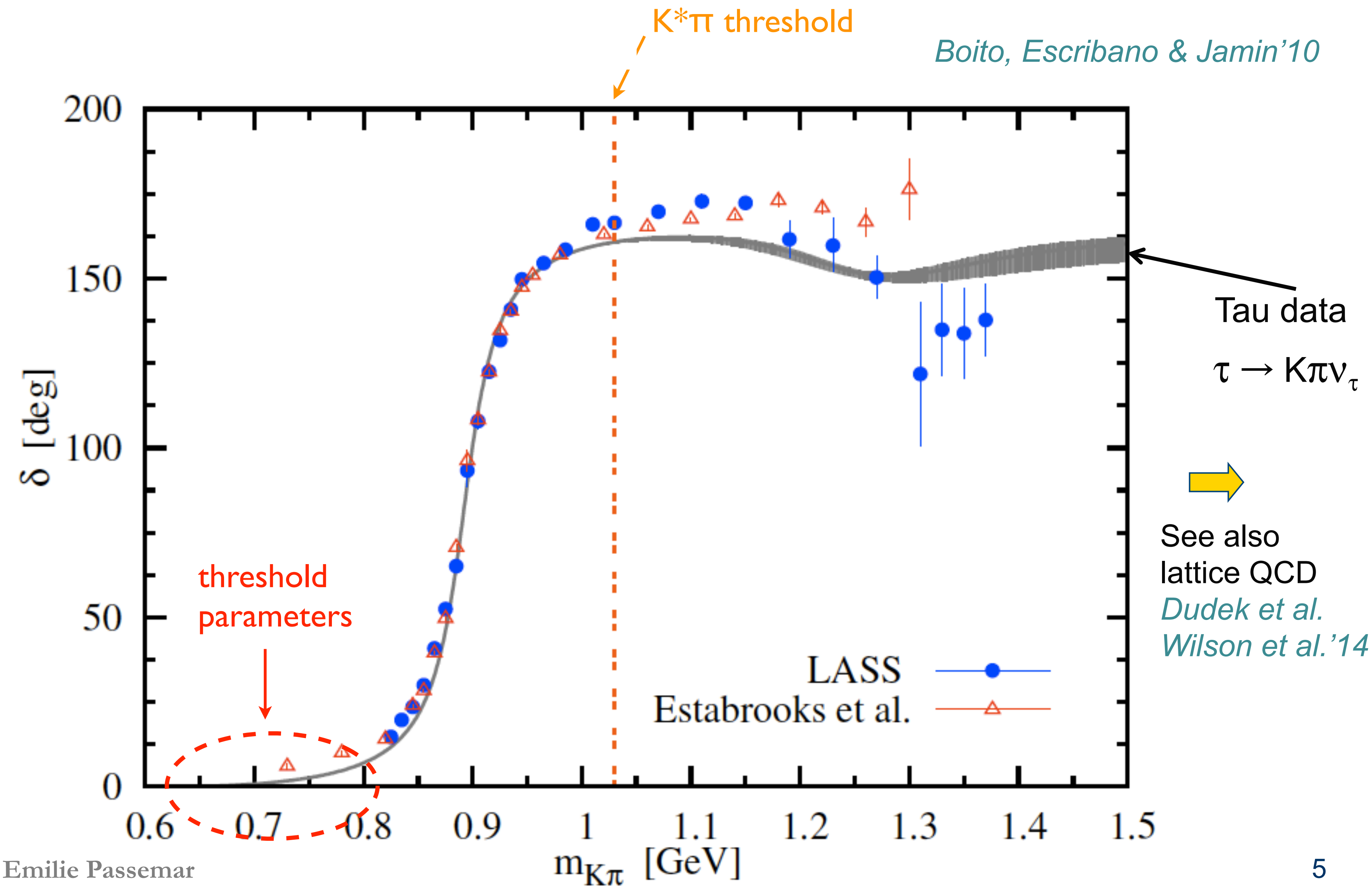
1.1 Why Kπ scattering is important?

- Hadron spectroscopy: determine resonances and their nature
  - P-wave: K*(892), K*(1410), K*(1680), …
  - S-wave: "κ(~800)", …
  - Exotics,…

- ππ and *Kπ* building blocks for hadronic physics:
  - Test of Chiral Dynamics
  - Extraction of fundamental parameters of the Standard Model
  - Look for physics beyond the Standard Model: High precision at low energy as a key to new physics?

⇨ Very important when *Final State Interactions* at play!

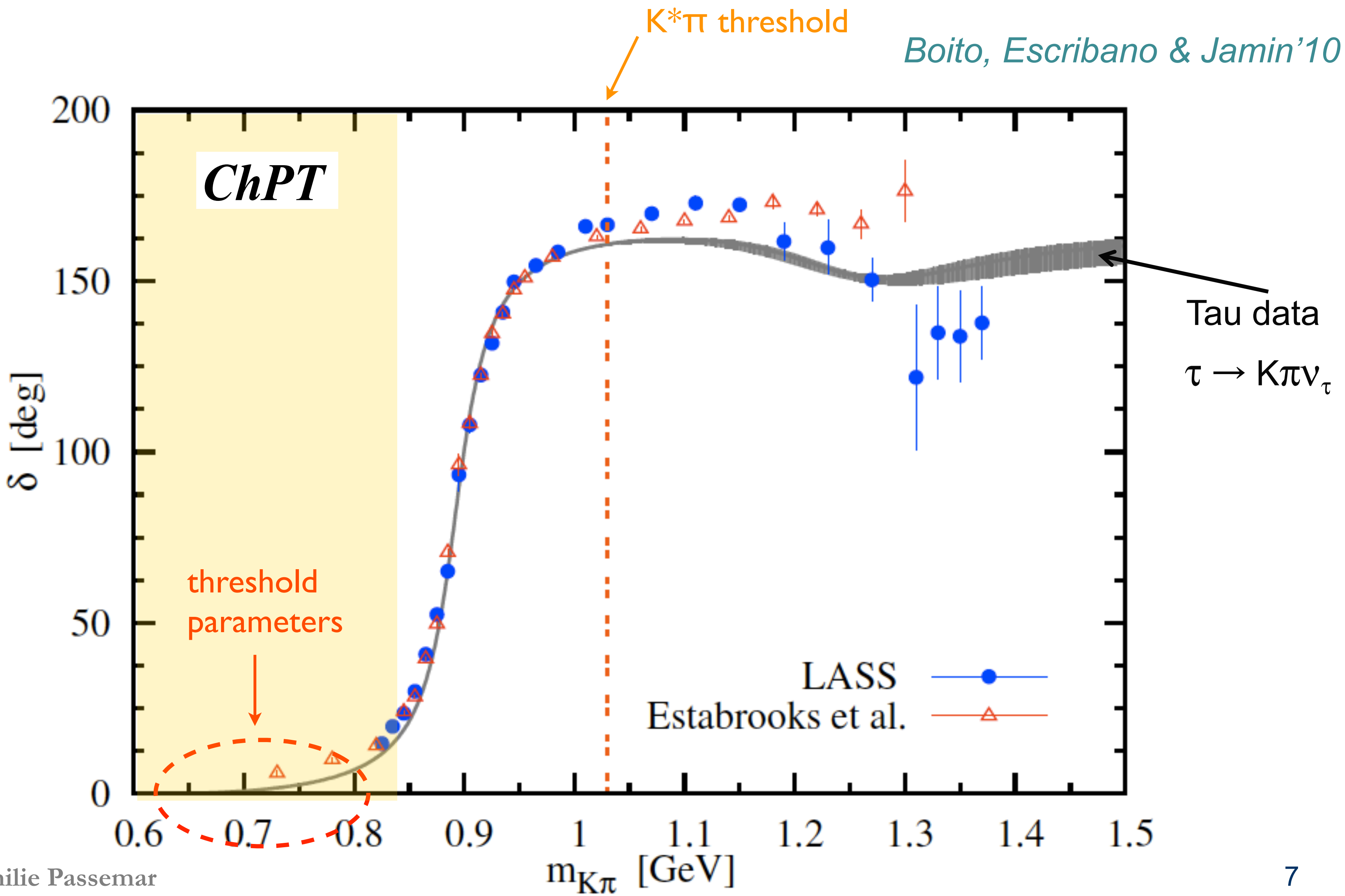
1.2 Ex: Kπ scattering: P-wave



See also lattice QCD
Dudek et al.
Wilson et al.'14

2. Using Kπ scattering to test ChPT

Kπ scattering: P-wave



2.1 Chiral Symmetry

- Limit $m_k \to 0$

$$\mathcal{L}_{QCD} \to \boxed{\mathcal{L}^0_{QCD} = -\frac{1}{4}G_{\mu\nu}G^{\mu\nu} + \bar{q}_L i\gamma^\mu D_\mu q_L + \bar{q}_R i\gamma^\mu D_\mu q_R}, \quad q = \begin{pmatrix} u \\ d \\ s \end{pmatrix}$$

with $q_{L/R} \equiv \frac{1}{2}\left(1 \mp \gamma_5\right) q$

Symmetry: $\boxed{G \equiv SU(3)_L \otimes SU(3)_R \to SU(3)_V}$

- Chiral Perturbation Theory: dynamics of the Goldstone bosons (kaons, pions, eta)

- Goldstone bosons interact weakly at low energy and $m_u, m_d \ll m_s < \Lambda_{QCD}$
Expansion organized in external momenta and quark masses

Weinberg's power counting rule

$$\boxed{\mathcal{L}_{eff} = \sum_{d \geq 2} \mathcal{L}_d \; , \; \mathcal{L}_d = \mathcal{O}\left(p^d\right) \; , p \equiv \left\{q, m_q\right\}}$$

$$\boxed{\mathrm{p} << \Lambda_H = 4\pi F_\pi \sim 1 \text{ GeV}}$$

2.2 Chiral expansion

- $$\mathcal{L}_{ChPT} = \underbrace{\mathcal{L}_2}_{\text{LO}:\ \mathcal{O}(p^2)} + \underbrace{\mathcal{L}_4}_{\text{NLO}:\ \mathcal{O}(p^4)} + \underbrace{\mathcal{L}_6}_{\text{NNLO}:\ \mathcal{O}(p^6)} + \ldots.$$

- The structure of the lagrangian is fixed by chiral symmetry but not the coupling constants → LECs appearing at each order

- The method has been rigorously established and can be formulated as a set of calculational rules:

LO : tree level diagrams with $\mathcal{L}_2$

$\mathcal{L}_2 :\ F_0, B_0$

NLO: tree level diagrams with $\mathcal{L}_4$
1-loop diagrams with $\mathcal{L}_2$

$$\mathcal{L}_4 = \sum_{i=1}^{10} L_i\, O_4^i,$$

NNLO: tree level diagrams with $\mathcal{L}_6$
2-loop diagrams with $\mathcal{L}_2$
1-loop diagrams with one vertex from $\mathcal{L}_4$

$$\mathcal{L}_6 = \sum_{i=1}^{90} C_i\, O_6^i$$

- Renormalizable and unitary order by order in the expansion

2.3 ChPT in the meson sector: precision calculations

- Today's standard in the meson sector: 2-loop calculations

- Main obstacle to reaching high precision: determination of the LECs: $\mathcal{O}(p^6)$ LECs proliferation makes the program to pin down/ estimate all of them prohibitive

- In a specific process, only a limited number of LECs appear

- The LECs calculable if QCD solvable, instead
  - Determined from experimental measurement
  - Estimated with models: Resonances, large N_C
  - Computed on the lattice

2.4 Test of SU(3) ChPT

- Interesting framework to test ChPT is offered by the kaons: K_{l3}, K_{l4}, $K \to 3\pi$, etc

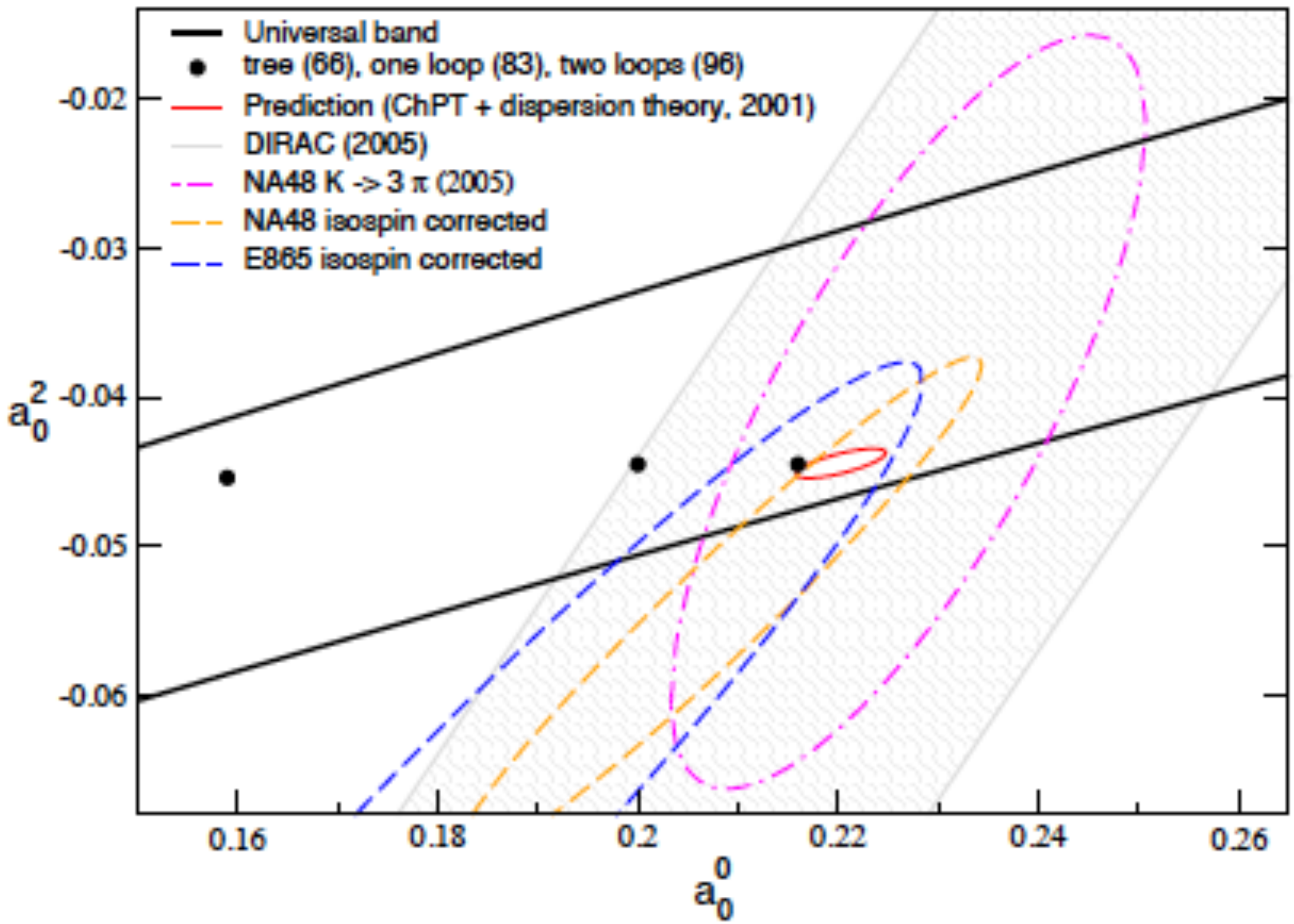
- A very interesting quantity is the scattering length: first term in the expansion:

$$\frac{2}{\sqrt{s}} \mathrm{Re}\, t_l^I(s) = \frac{1}{2q} \sin 2\delta_l^I(q) = q^{2l} \left[\underline{a_l^I} + b_l^I\, q^2 + c_l^I\, q^4 + \mathcal{O}(q^6) \right]$$

- For ππ: SU(2) ChPT very successful!

ππ scattering lengths

H. Leutwyler



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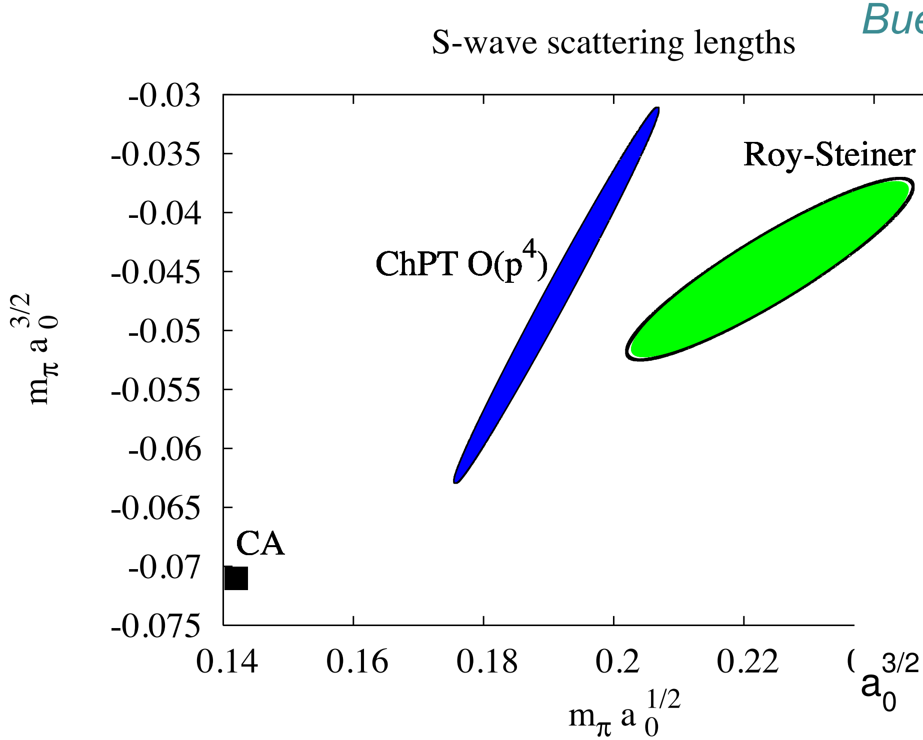
- For ππ: SU(2) ChPT very successful!

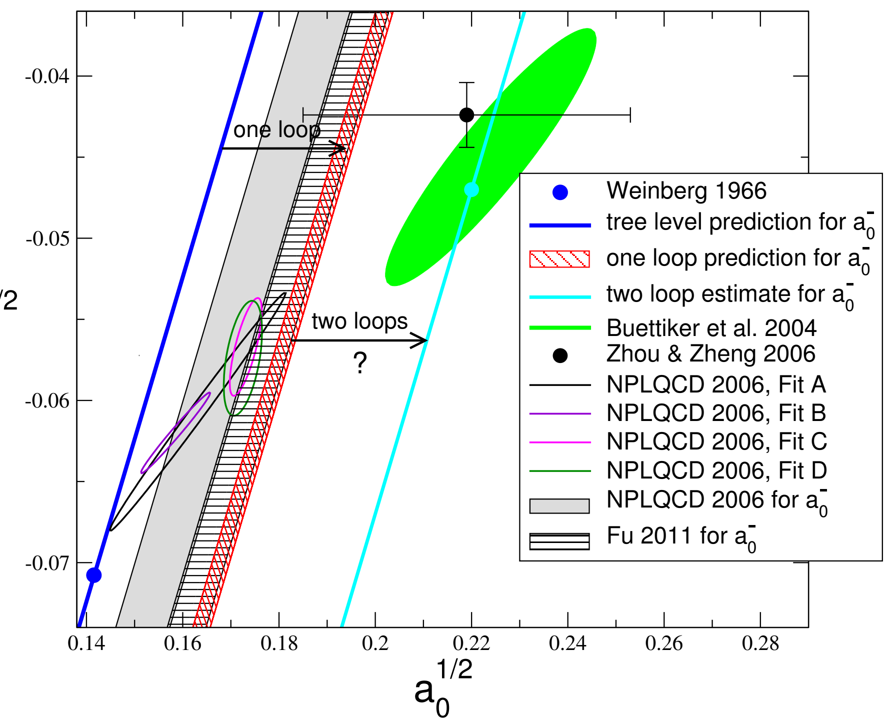
- What about SU(3) ChPT?
  In principle slower convergence if convergence at all!

Kπ scattering lengths: S-wave

Buettiker, Descotes-Genon, Moussallam'04



Janowski'14



Roy-Steiner equations for Kπ

- Unitarity effects can be calculated *exactly* using dispersive methods

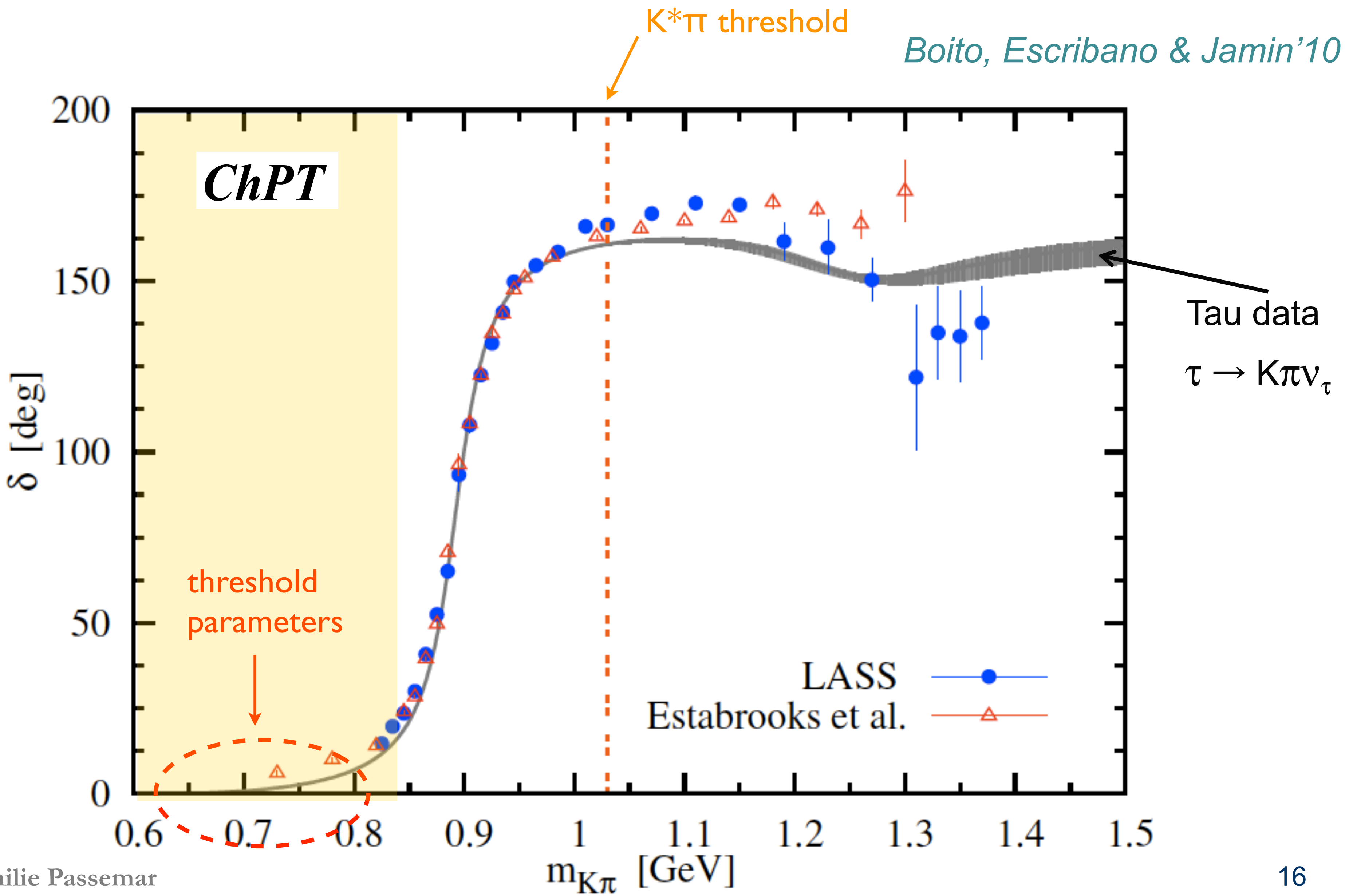
- Unitarity, analyticity and crossing symmetry ≡ *Roy-Steiner equations*

- Input: Data on $K\pi \to K\pi$ and $\pi\pi \to KK$ for E ≥ 1 GeV
  two subtraction constants, e.g. a_0^0 and a_2^0

- Output: the full Kπ scattering amplitude below 1 GeV
  ⇨ In *poor* agreement with the experimental data

- Numerical solutions of the Roy-(Steiner) equations:
  - ππ: *Pennington-Protopopescu, Basdevant-Froggatt-Petersen (70s)*
    Bern group: Ananthanarayan et al.'00, Caprini et al.'11
    Orsay group: Descotes-Genon, Fuchs, Girlanda and Stern'01
    Madrid-Cracow group: Garcia-Martin,et al.'11
  - Kπ: *Buettiker, Descotes-Genon, Moussallam'04*
  - KN: *Ruiz de Elvira et al'15*

Kπ scattering lengths: P-wave



$K\pi$ scattering lengths: P-wave

Boito, Escribano & Jamin'10

$$\frac{2}{\sqrt{s}}\text{Re}\, t_l^I(s) = \frac{1}{2q}\sin 2\delta_l^I(q) = q^{2l}\left[a_l^I + b_l^I\, q^2 + c_l^I\, q^4 + \mathcal{O}(q^6)\right]$$

	Tau data	ChPT $\mathcal{O}(p^4)$	RChPT $\mathcal{O}(p^4)$	ChPT $\mathcal{O}(p^6)$	Roy-Steiner
$m_\pi^3\, a_1^{1/2} \times 10$	0.166(4)	0.16(3)	0.18(3)	0.18	0.19(1)
$m_\pi^5\, b_1^{1/2} \times 10^2$	0.258(9)	-	-		0.18(2)
$m_\pi^7\, c_1^{1/2} \times 10^3$	0.90(3)	-	-		0.71(11)

➡ Recent analysis combining K_{l3}, tau and D data : 0.249 ± 0.011 *Bernard'14*

- *Bernard, Kaiser, Meissner'91* (ChPT $\mathcal{O}(p^4)$)
- *Bernard, Kaiser, Meissner'91* (RChPT $\mathcal{O}(p^4)$)
- *Bijnens, Dhonte, Talavera'04* (ChPT $\mathcal{O}(p^6)$)
- *Buettiker, Descotes-Genon, Moussallam'04* (Roy-Steiner)

- Poor agreement ➡ need *more data*

3. Hadron spectroscopy

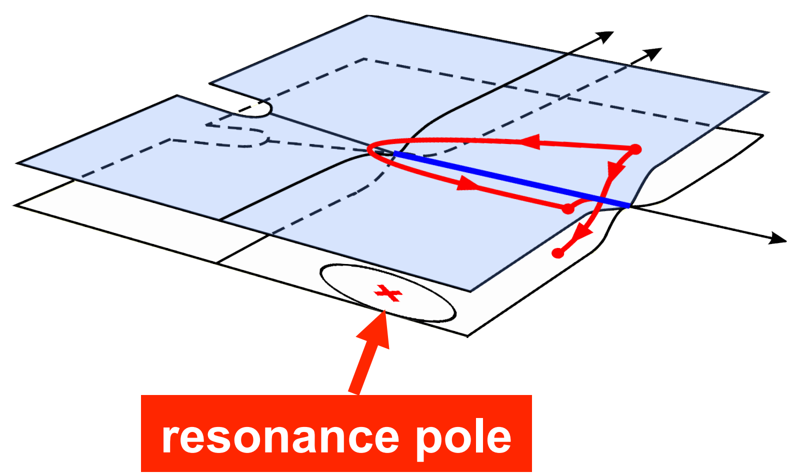
3.1 Determining of pole and width

- Once one gets Kpi scattering amplitude

  ⇨ analytical continuation into the complex plane

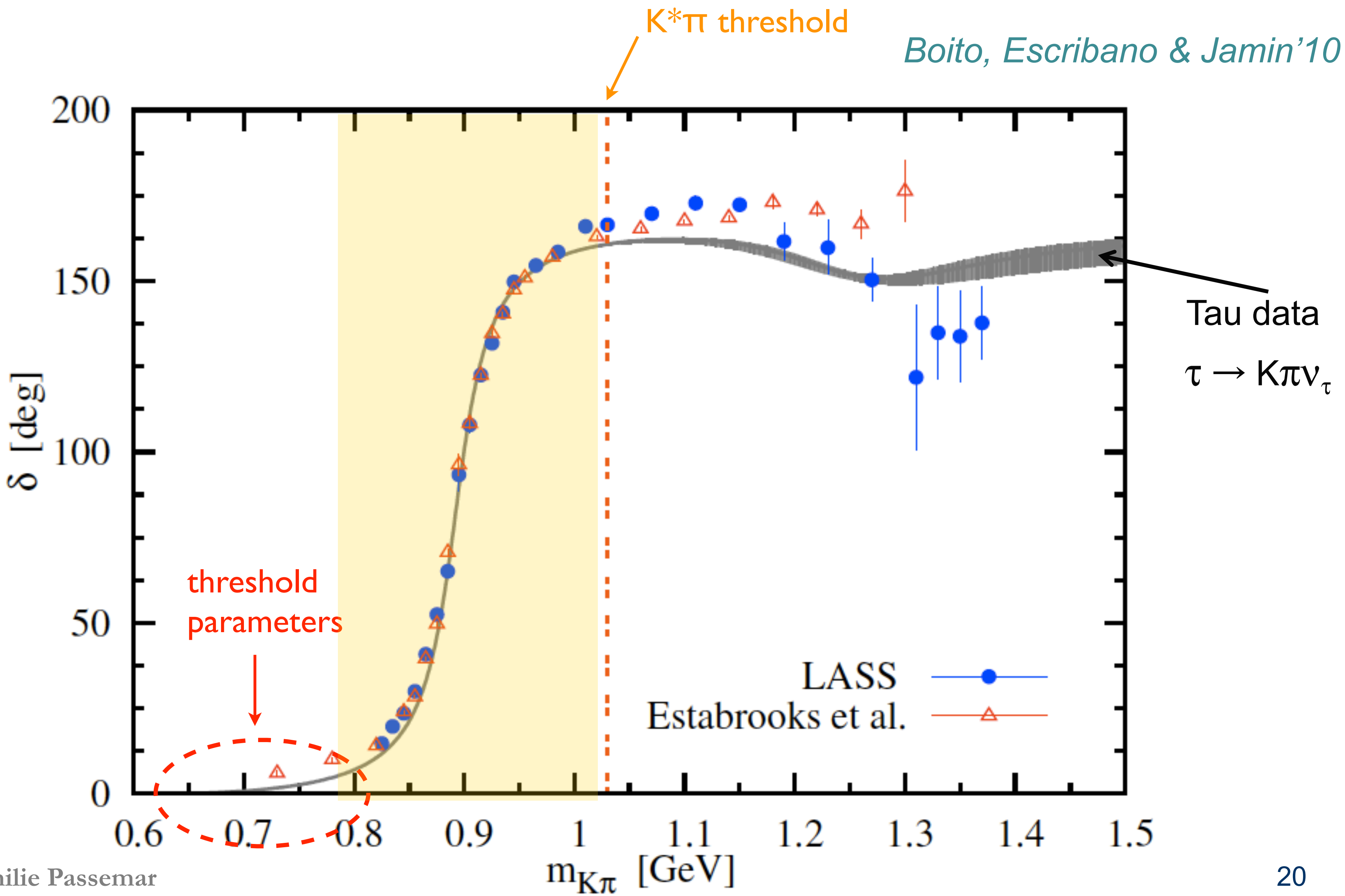
Poles on the second sheet correspond to zeros on the first sheet!

Plot from M. Pennington



Dispersive analytic continuation

Kπ scattering lengths: P-wave



3.2 K*(892) mass and width

PDG'15

$K^*(892)$ MASS

CHARGED ONLY, HADROPRODUCED

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
891.66±0.26 OUR AVERAGE					
892.6 ±0.5	5840	BAUBILLIER 84B	HBC	−	8.25 $K^- p \to \overline{K}^0 \pi^- p$
888 ±3		NAPIER 84	SPEC	+	200 $\pi^- p \to 2K^0_S X$
891 ±1		NAPIER 84	SPEC	−	200 $\pi^- p \to 2K^0_S X$
891.7 ±2.1	3700	BARTH 83	HBC	+	70 $K^+ p \to K^0 \pi^+ X$
891 ±1	4100	TOAFF 81	HBC	−	6.5 $K^- p \to \overline{K}^0 \pi^- p$
892.8 ±1.6		AJINENKO 80	HBC	+	32 $K^+ p \to K^0 \pi^+ X$
890.7 ±0.9	1800	AGUILAR-... 78B	HBC	±	0.76 $\overline{p} p \to K^\mp K^0_S \pi^\pm$
886.6 ±2.4	1225	BALAND 78	HBC	±	12 $\overline{p} p \to (K\pi)^\pm X$
891.7 ±0.6	6706	COOPER 78	HBC	±	0.76 $\overline{p} p \to (K\pi)^\pm X$
891.9 ±0.7	9000	[1] PALER 75	HBC	−	14.3 $K^- p \to (K\pi)^- X$
892.2 ±1.5	4404	AGUILAR-... 71B	HBC	−	3.9,4.6 $K^- p \to (K\pi)^- p$
891 ±2	1000	CRENNELL 69D	DBC	−	3.9 $K^- N \to K^0 \pi^- X$
890 ±3.0	720	BARLOW 67	HBC	±	1.2 $\overline{p} p \to (K^0 \pi)^\pm K^\mp$
889 ±3.0	600	BARLOW 67	HBC	±	1.2 $\overline{p} p \to (K^0 \pi)^\pm K \pi$
891 ±2.3	620	[2] DEBAERE 67B	HBC	+	3.5 $K^+ p \to K^0 \pi^+ p$
891.0 ±1.2	1700	[3] WOJCICKI 64	HBC	−	1.7 $K^- p \to \overline{K}^0 \pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
893.5 ±1.1	27k	[4] ABELE 99D	CBAR	±	0.0 $\overline{p} p \to K^+ K^- \pi^0$
890.4 ±0.2 ±0.5	80±0.8k	[5] BIRD 89	LASS	−	11 $K^- p \to \overline{K}^0 \pi^- p$
890.0 ±2.3	800	[2,3] CLELAND 82	SPEC	+	30 $K^+ p \to K^0_S \pi^+ p$
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896.0 ±1.9	380	DELFOSSE 81	SPEC	+	50 $K^\pm p \to K^\pm \pi^0 p$
886.0 ±2.3	187	DELFOSSE 81	SPEC	−	50 $K^\pm p \to K^\pm \pi^0 p$
894.2 ±2.0	765	[2] CLARK 73	HBC	−	3.13 $K^- p \to \overline{K}^0 \pi^- p$
894.3 ±1.5	1150	[2,3] CLARK 73	HBC	−	3.3 $K^- p \to \overline{K}^0 \pi^- p$
892.0 ±2.6	341	[2] SCHWEING... 68	HBC	−	5.5 $K^- p \to \overline{K}^0 \pi^- p$

CHARGED ONLY, PRODUCED IN τ LEPTON DECAYS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
895.47±0.20±0.74	53k	[6] EPIFANOV 07	BELL	$\tau^- \to K^0_S \pi^- \nu_\tau$
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892.0 ±0.5		[7] BOITO 10	RVUE	$\tau^- \to K^0_S \pi^- \nu_\tau$
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895.3 ±0.2		[8,10] JAMIN 08	RVUE	$\tau^- \to K^0_S \pi^- \nu_\tau$
896.4 ±0.9	11970	[11] BONVICINI 02	CLEO	$\tau^- \to K^- \pi^0 \nu_\tau$
895 ±2		[12] BARATE 99R	ALEP	$\tau^- \to K^- \pi^0 \nu_\tau$

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895.81±0.19 OUR AVERAGE		Error includes scale factor of 1.4. See the ideogram below.		
895.4 ±0.2 ±0.2	243k	[13] DEL-AMO-SA..11I	BABR	$D^+ \to K^- \pi^+ e^+ \nu_e$
895.7 ±0.2 ±0.3	141k	[14] BONVICINI 08A	CLEO	$D^+ \to K^- \pi^+ \pi^+$
$895.41 \pm 0.32^{+0.35}_{-0.43}$	18k	[15] LINK 05I	FOCS	$D^+ \to K^- \pi^+ \mu^+ \nu_\mu$
896 ±2		BARBERIS 98E	OMEG	450 $pp \to p_f p_s K^* \overline{K}^*$
895.9 ±0.5 ±0.2		ASTON 88	LASS	11 $K^- p \to K^- \pi^+ n$

3.2 K*(892) mass and width

PDG'15

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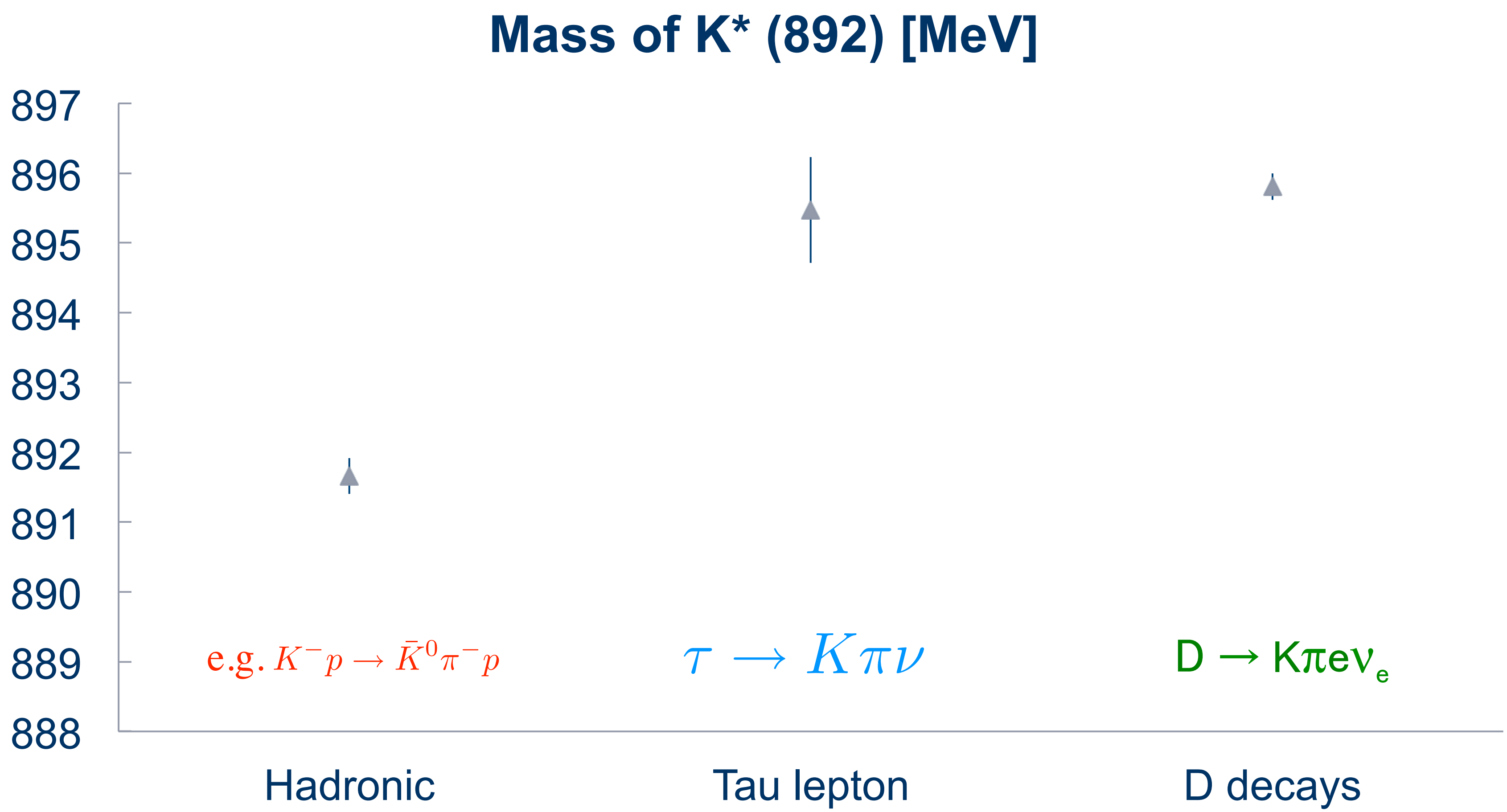
3.2 K*(892) mass and width

PDG'15



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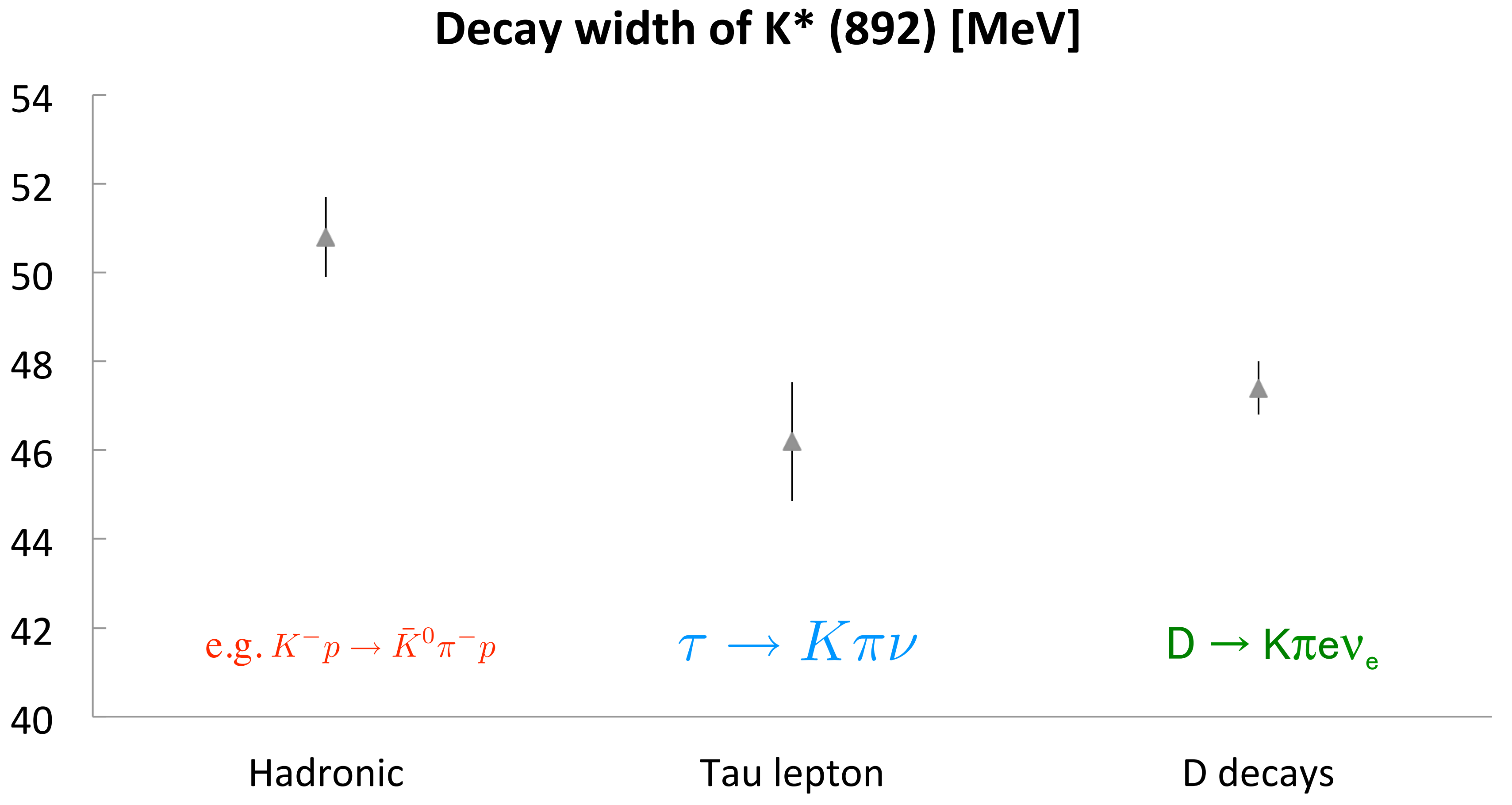
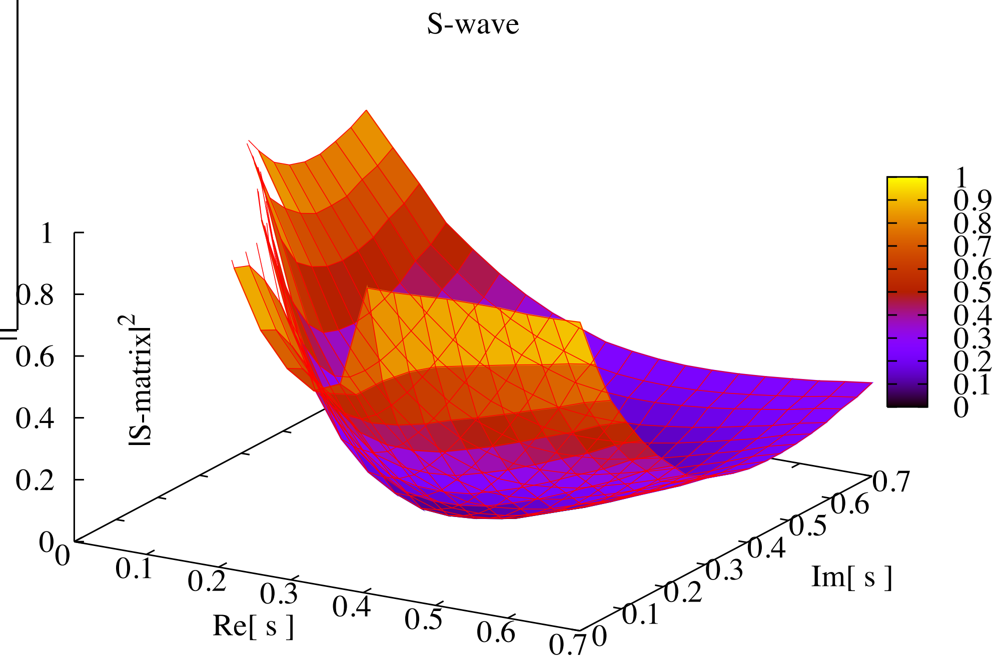


3.3 Kappa(800)

- The results coming from Roy-Steiner and data at higher energy not in agreement with low energy experimental data ⇨ need improvement!
  Problem: no other precise data

Descotes-Genon, Moussallam'06

	M_κ (MeV)	Γ_κ (MeV)
This work	658 ± 13	557 ± 24
Zhou, Zheng [16]	694 ± 53	606 ± 89
Jamin et al. [18]	708	610
Aitala et al. [7]	$721 \pm 19 \pm 43$	$584 \pm 43 \pm 87$
Pelaez [19]	750 ± 18	452 ± 22
Bugg [9]	750^{+30}_{-55}	684 ± 120
Ablikim et al. [20]	$841 \pm 23^{+64}_{-55}$	$618 \pm 52^{+55}_{-87}$
Ishida et al. [14]	877^{+65}_{-30}	668^{+235}_{-110}

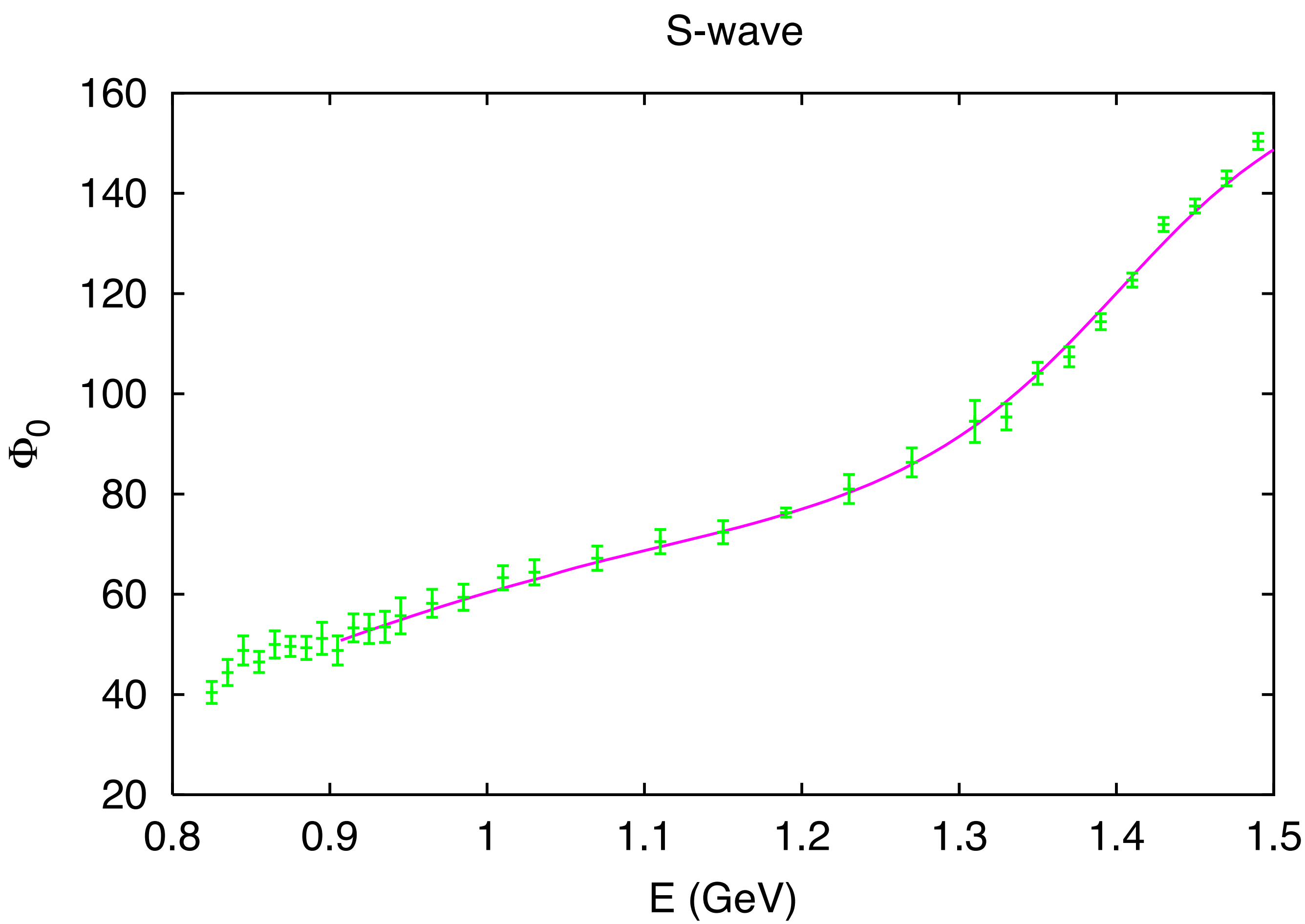


- Existence would suggest κ not a glueball

3.3 Kappa(800)

- Inputs for S wave in Roy-Steiner analysis from LASS

Buettiker, Descotes-Genon, Moussallam'04



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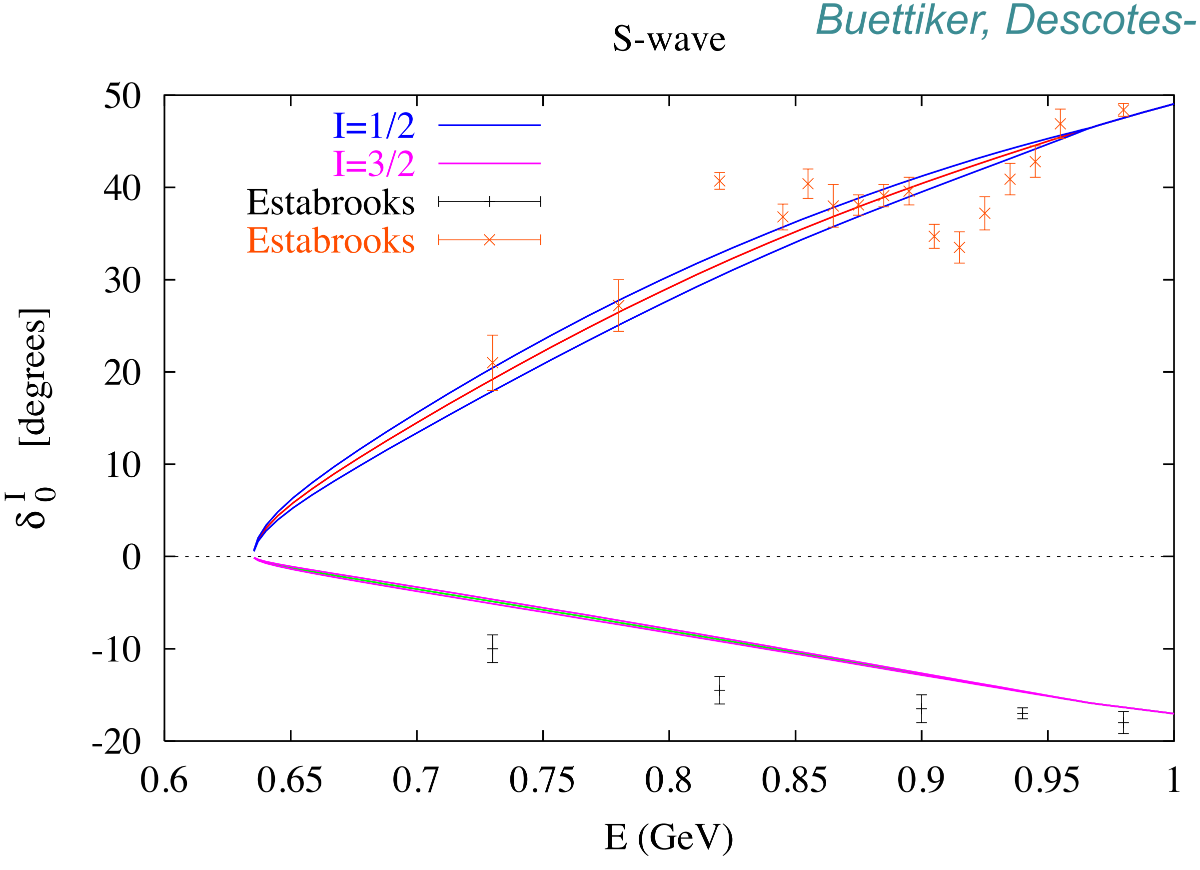
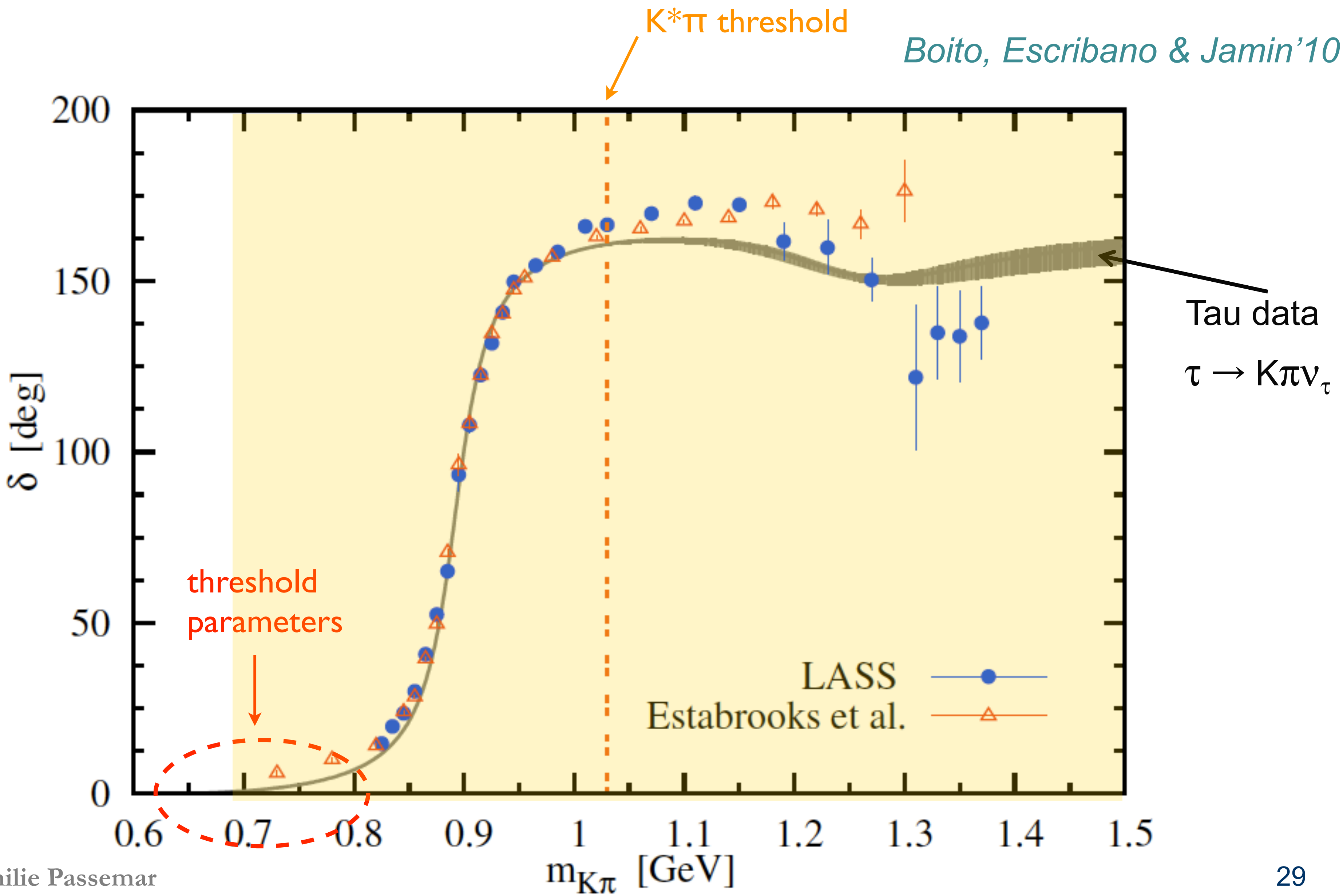


4. Test sof the SM and new physics

Kπ scattering lengths: P-wave



4.1 Determination of fundamental parameters: V_{us}

- Master formula for K $\rightarrow$ $\pi l \nu_l$:

$$\Gamma\left(K\rightarrow \pi l \nu[\gamma]\right)=\frac{G_F^2 m_K^5}{192\pi^3}C_K^2 S_{EW}^K \left|V_{us}\right|^2 \left|f_+^{K^0\pi^-}(0)\right|^2 I_K^l \left(1+\delta_{\mathrm{EM}}^{Kl}+\delta_{\mathrm{SU(2)}}^{K\pi}\right)^2$$

4.1 Determination of fundamental parameters: V_{us}

- Master formula for $K \to \pi l \nu_l$:

$$\Gamma(K \to \pi l \nu [\gamma]) = \frac{G_F^2 m_K^5}{192\pi^3} C_K^2 S_{EW}^K |V_{us}|^2 \left| f_+^{K^0\pi^-}(0) \right|^2 I_K^l \left(1 + \delta_{\mathrm{EM}}^{Kl} + \delta_{\mathrm{SU(2)}}^{K\pi}\right)^2$$

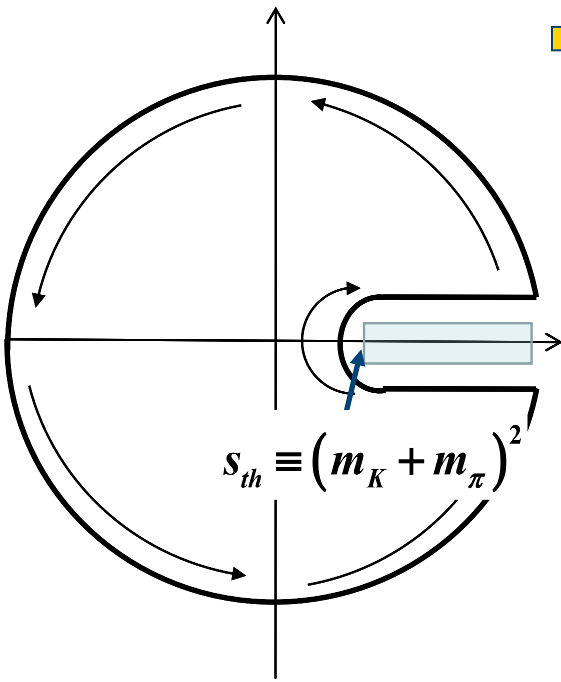
$$\langle \pi(p_\pi) | \, \bar{\mathrm{s}} \gamma_\mu \mathrm{u} \, | \mathrm{K}(\mathrm{p_K}) \rangle = \left[(p_K + p_\pi)_\mu - \frac{\Delta_{K\pi}}{t} (p_K - p_\pi)_\mu \right] f_+(t) + \frac{\Delta_{K\pi}}{t} (p_K - p_\pi)_\mu f_0(t)$$

vector: $f_+(t)$; scalar: $f_0(t)$

Dispersive representation for the form factors

Bernard, Oertel, E.P., Stern'06, '09

- Omnès representation:



$$\bar{f}_{+,0}(s) = \exp\left[\frac{s}{\pi}\int_{s_{th}}^{\infty} \frac{ds'}{s'} \frac{\phi_{+,0}(s')}{s' - s - i\varepsilon}\right]$$

$\phi_{+,0}$ (s): phase of the form factor

$$s < s_{in} \; : \; \phi_{+,0}(s) = \delta_{K\pi}(s)$$

$K\pi$ scattering phase

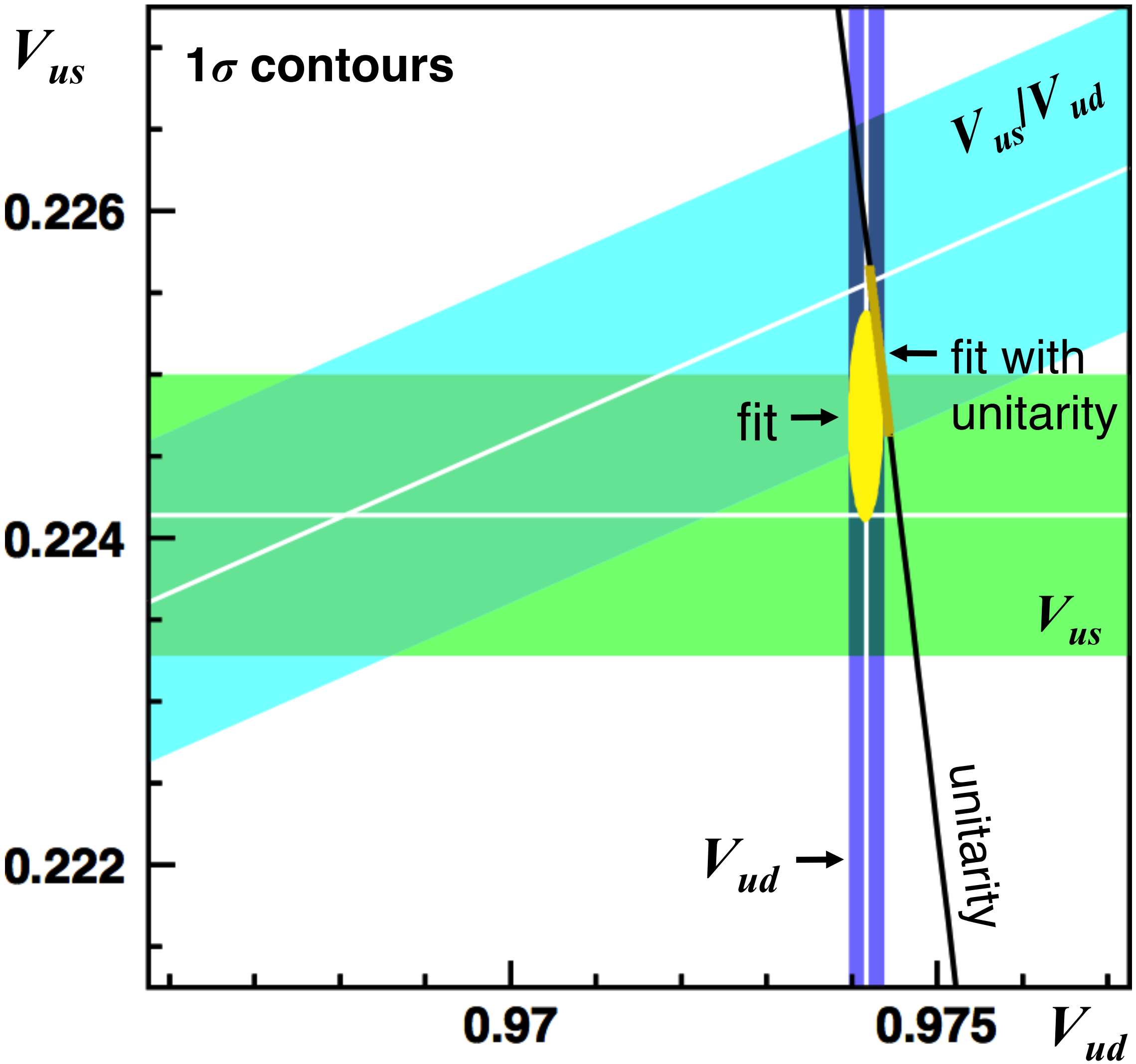
$$s \geq s_{in} \; : \; \phi_{+,0}(s)$$

$$\phi_{+,0}(s) = \phi_{+,0as}(s) = \pi \pm \pi \; \left(\bar{f}_{+,0}(s) \to 1/s\right)$$

[Brodsky&Lepage]

- Subtract dispersion relation to weaken the high energy contribution of the phase. Improve the convergence but sum rules to be satisfied.

Global fit to V_{us} & V_{ud}



FlaviaNet KaonWG'10 Updated by Moulson@CKM2014

V_{ud} = **0.97416(21)**

V_{us} = **0.2248(7)**

χ^2/ndf = 1.16/1 (28.1%)

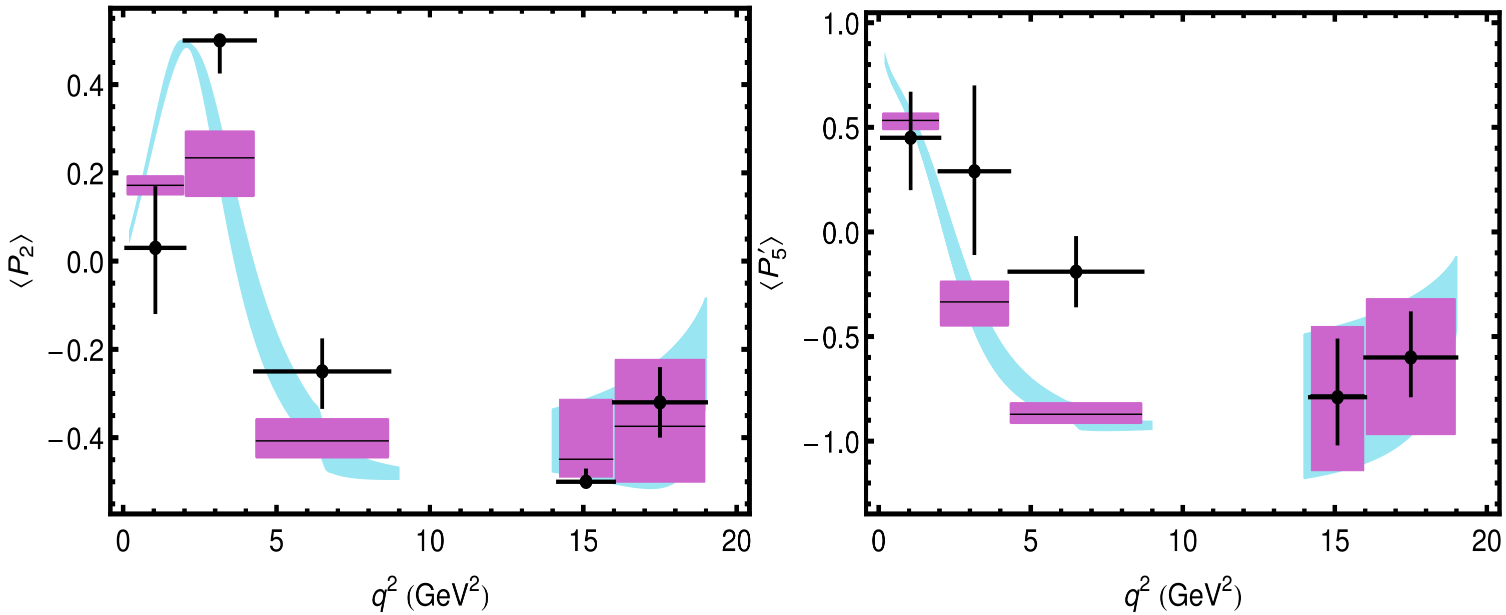
Δ_{CKM} = **–0.0005(5)**

–1.0σ

4.2 FSI in the quest for New Physics

- Ex: CP violating asymmetries: B → K^* ll

Matthias et al'12
Camalich&Jaeger'11
Doering, Meissner, Wang'13 etc..



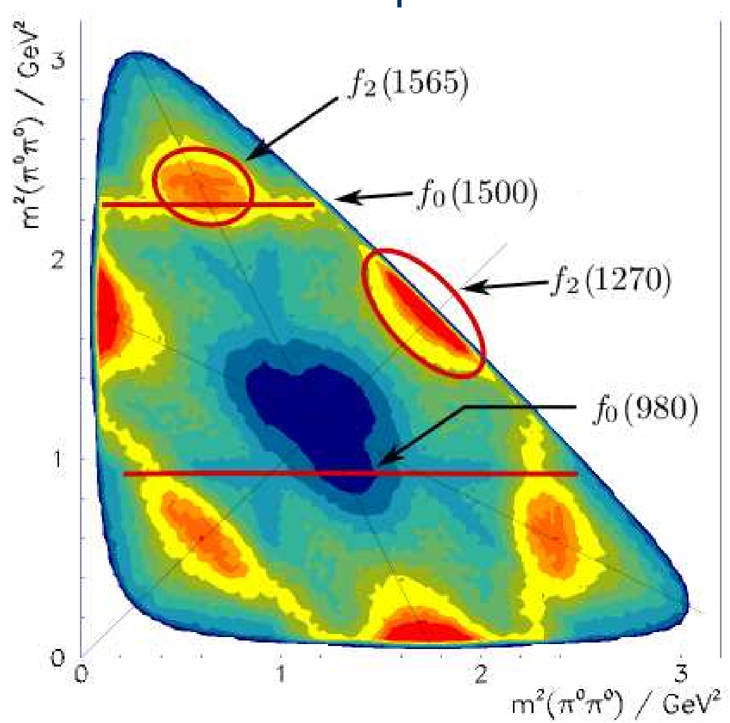
LHCb at EPS13 : 2.9 σ discrepancy in P_2, 4.0 σ in P_5' !

[blue: SM unbinned, purple: SM binned, crosses: LHCb]

4.2 FSI in the quest for New Physics

- Ex: CP violation in D → Kππ

Ex: Dalitz plot



4.2 FSI in the quest for New Physics

- Ex: CP violation in D → Kππ

Niecknig & Kubis'15

Full set of equations

$$S^2_{\pi\pi}(u) = \Omega^2_0(u)\left\{u^2\int_{4M_\pi^2}^\infty \frac{\hat{S}^2_{\pi\pi}(u')}{u'^2(u'-u)}d\mu^2_0\right\}$$

$$P^1_{\pi\pi}(u) = \Omega^1_1(u)\left\{c_0 + c_1 u + u^2\int_{4M_\pi^2}^\infty \frac{\hat{P}^1_{\pi\pi}(u')}{u'^2(u'-u)}d\mu^1_1\right\}$$

$$S^{1/2}_{\pi K}(s) = \Omega^{1/2}_0(s)\left\{c_2 + c_3 s + c_4 s^2 + c_5 s^3 + s^4\int_{(M_K+M_\pi)^2}^\infty \frac{\hat{S}^{1/2}_{\pi K}(s')}{s'^4(s'-s)}d\mu^{1/2}_0\right\}$$

$$S^{3/2}_{\pi K}(s) = \Omega^{3/2}_0(s)\left\{s^2\int_{(M_K+M_\pi)^2}^\infty \frac{\hat{S}^{3/2}_{\pi K}(s')}{s'^2(s'-s)}d\mu^{3/2}_0\right\}$$

$$P^{1/2}_{\pi K}(s) = \Omega^{1/2}_1(s)\left\{c_6 + s\int_{(M_K+M_\pi)^2}^\infty \frac{\hat{P}^{1/2}_{\pi K}(s')}{s'(s'-s)}d\mu^{1/2}_1\right\}$$

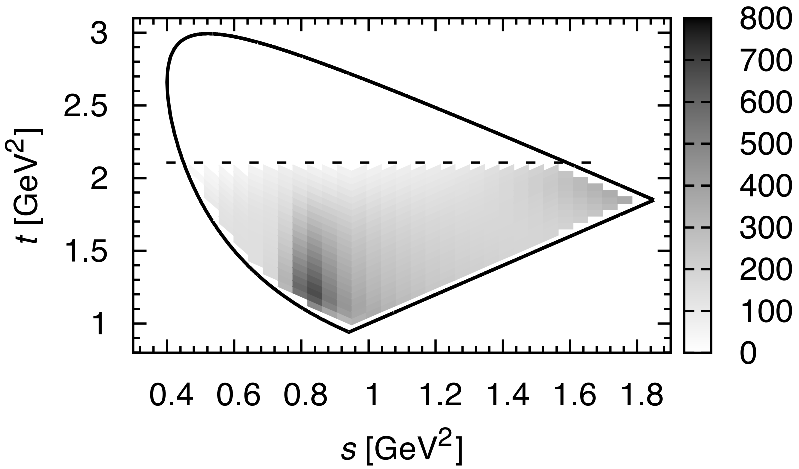
$$D^{1/2}_{\pi K}(s) = \Omega^{1/2}_2(s)\left\{\int_{(M_K+M_\pi)^2}^\infty \frac{\hat{D}^{1/2}_{\pi K}(s')}{(s'-s)}d\mu^{1/2}_2\right\}$$

- Ex: CP violation in D → Kππ

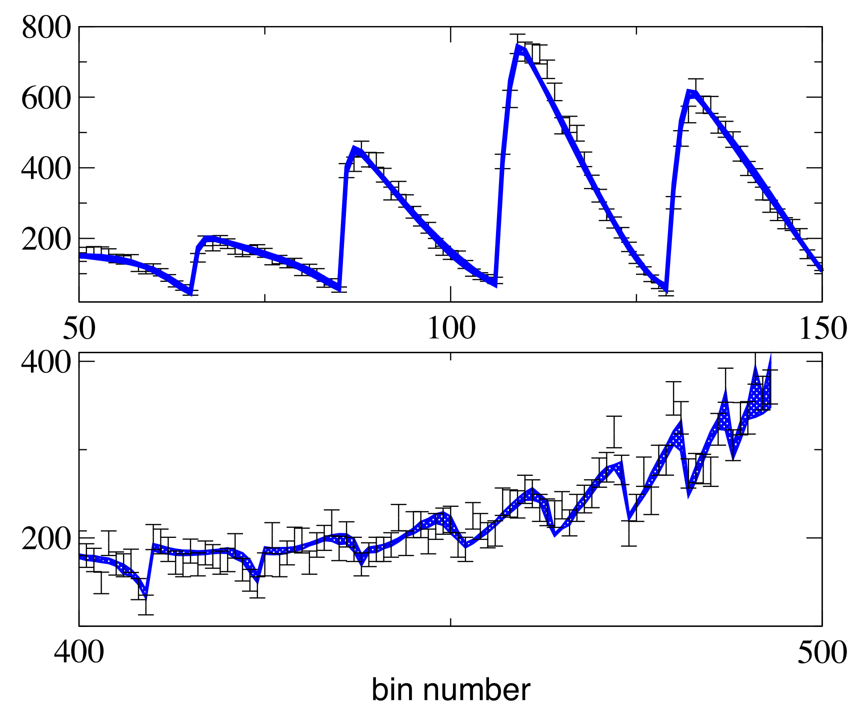
Niecknig & Kubis'15

Dalitz plot

CLEO'08



slices



- full fit: $\chi^2/\text{ndof} \approx 1.1$

4.2 FSI in the quest for New Physics

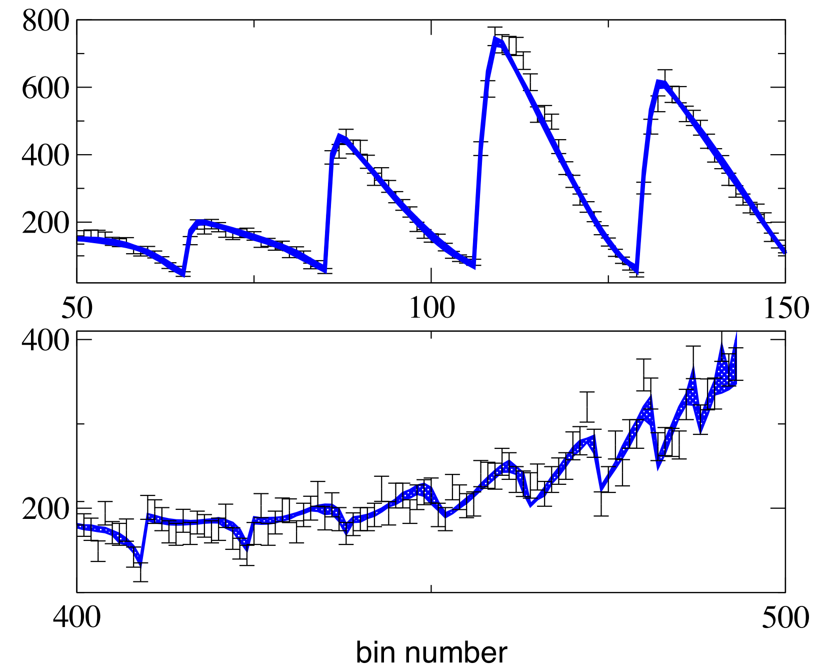
- Ex: CP violation in D → Kππ

Niecknig & Kubis'15

fit fractions

	Full fit
$S^2_{\pi\pi}$	$(8 \pm 3)\%$
$S^{1/2}_{\pi K}$	$(72 \pm 12)\%$
$P^{1/2}_{\pi K}$	$(10 \pm 2)\%$
$S^{3/2}_{\pi K}$	$(16 \pm 3)\%$
$D^{1/2}_{\pi K}$	$(0.15 \pm 0.1)\%$
Σ	$(106 \pm 20)\%$

slices



- full fit: $\chi^2/\text{ndof} \approx 1.1$
- fit fractions: hierachy of partial-wave amplitudes compare to previous analyses

5. Conclusion and Outlook

Conclusion and Outlook

- Determining $K\pi$ scattering reliably very important:
  - Low energy: test of Chiral Dynamics
  - Intermediate energy: Determination of Resonance parameters
  - Very important to help taking into account final state interactions and hunting for new physics ⇨ CP violation in heavy meson decays

- Hadronic data on which most of the analyses rely not in good agreement with more recent data coming mainly from tau decays
  ⇨ worth remeasuring it.

- Possibility at Jlab with KL?
  ⇨ Major advantage: pure I=1/2 measurement

6. Back-up

2.5 Determination of some low energy constants

	πK Roy-Steiner	πK sum-rules	$Kl_4,\ O(p^4)$	$Kl_4,\ O(p^6)$
$10^3\, L_1$	1.05 ± 0.12	0.84 ± 0.15	0.46 ± 0.24	0.53 ± 0.25
$10^3\, L_2$	1.32 ± 0.03	1.36 ± 0.13	1.49 ± 0.23	0.71 ± 0.27
$10^3\, L_3$	-4.53 ± 0.14	-3.65 ± 0.45	-3.18 ± 0.85	-2.72 ± 1.12
$10^3\, L_4$	0.53 ± 0.39	0.22 ± 0.30		-0.2 ± 0.9

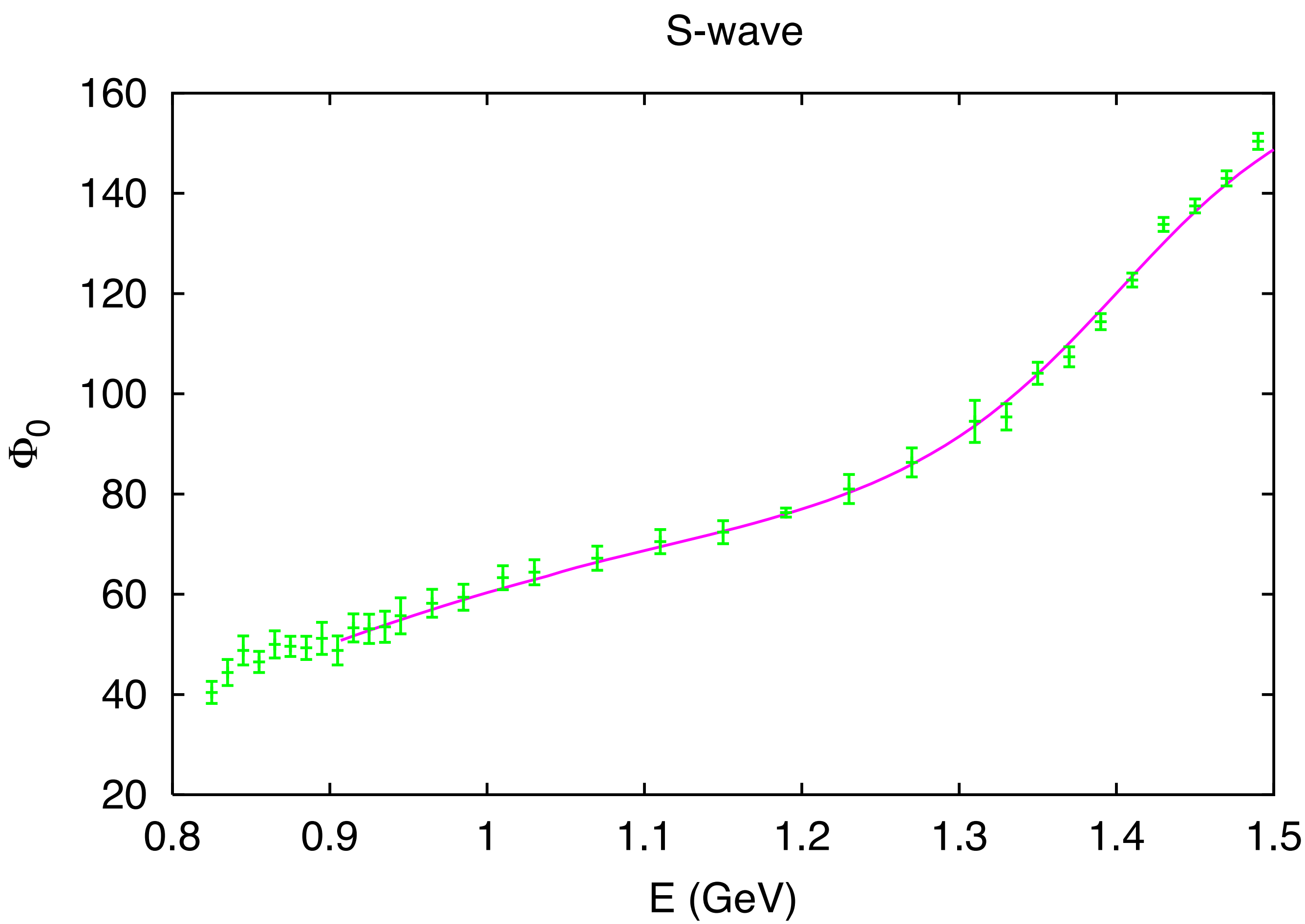
- Significant violation of OZI rule in the scalar sector

⇨ Large values for the condensates!

3.2 Kappa(800)

- Inputs for S wave in Roy-Steiner analysis from LASS

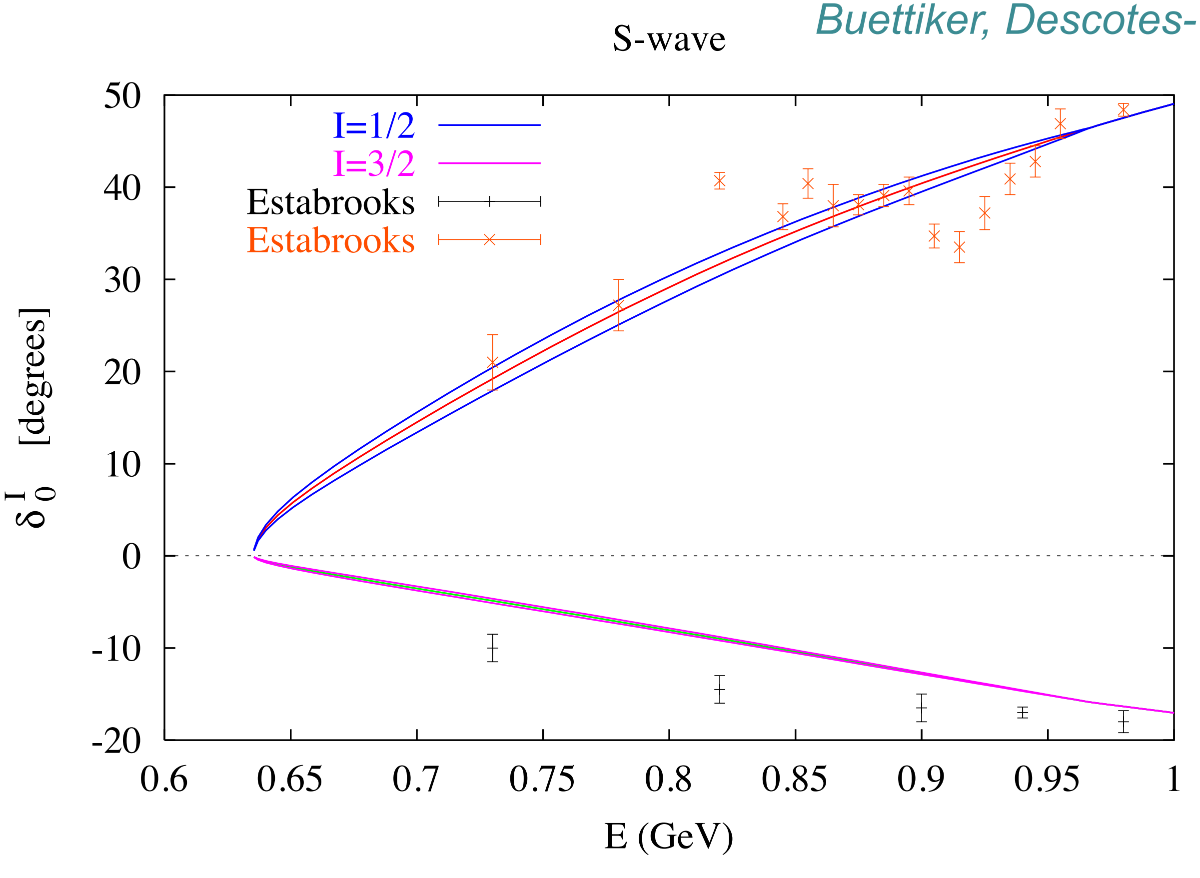
Buettiker, Descotes-Genon, Moussallam'04



3.2 Kappa(800)

- The results coming from Roy-Steiner and data at higher energy not in agreement with low energy experimental data ⇒ need improvement!

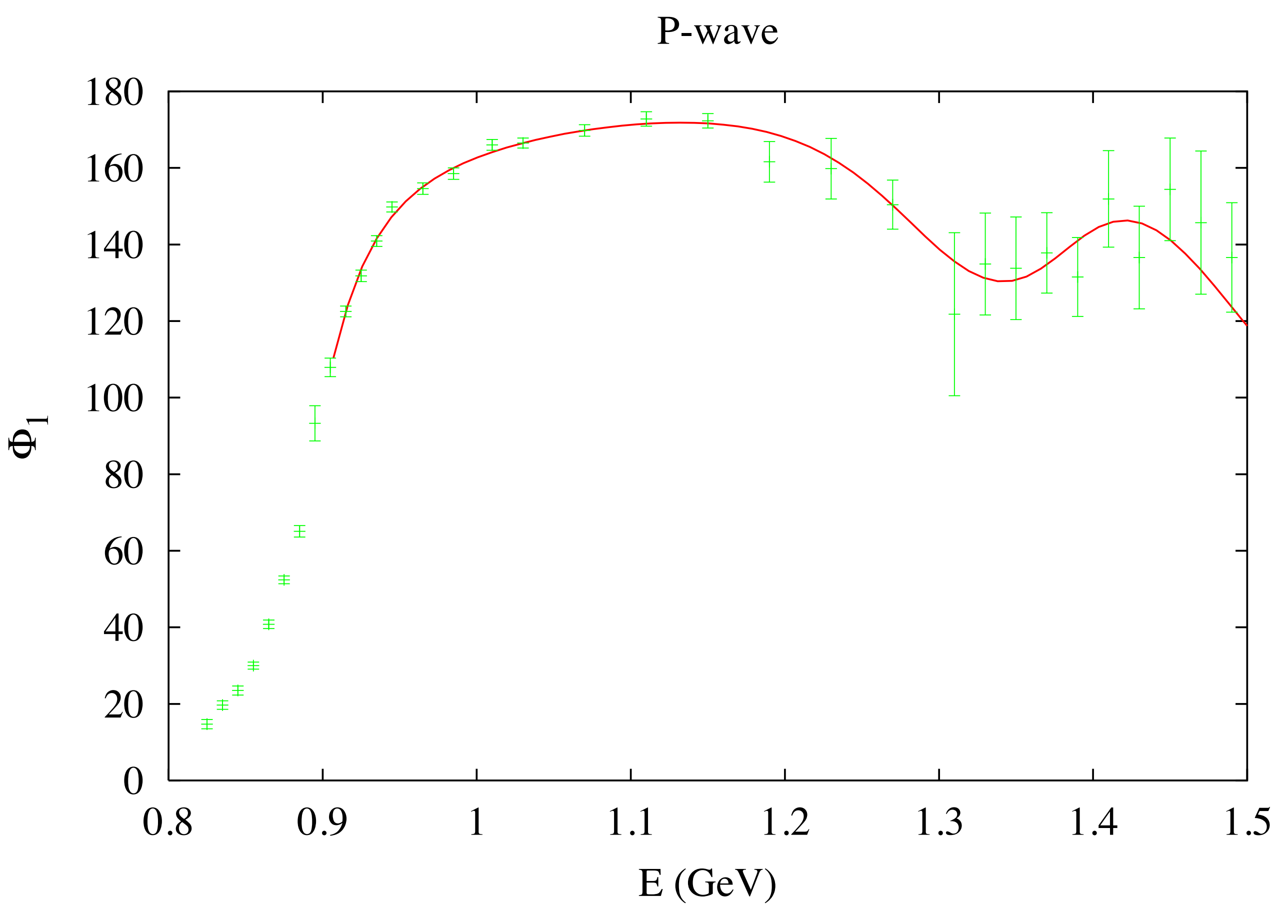
Buettiker, Descotes-Genon, Moussallam'04



P wave

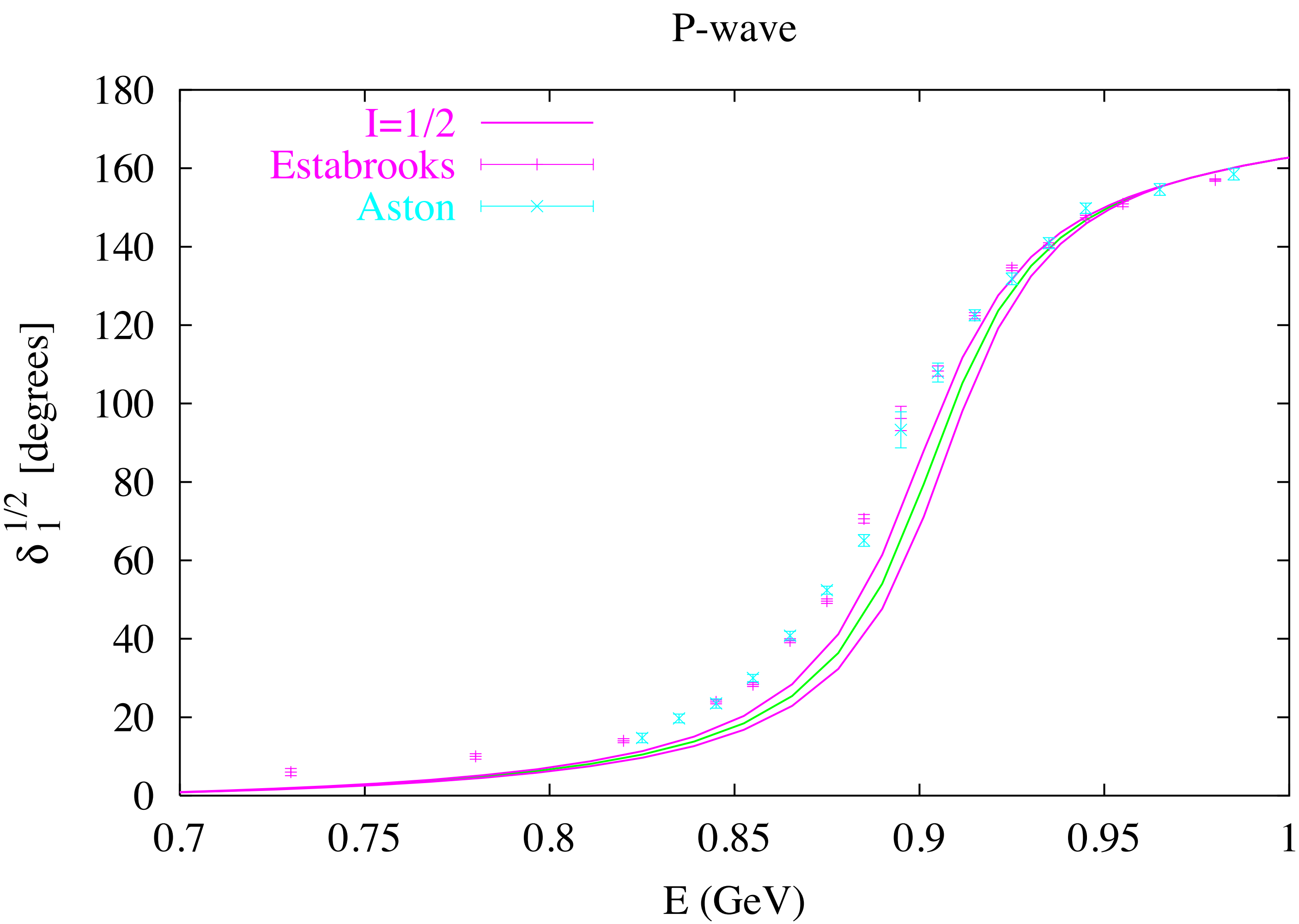
Buettiker, Descotes-Genon, Moussallam'04

Inputs:



P wave

Buettiker, Descotes-Genon, Moussallam'04



P wave

Buettiker, Descotes-Genon, Moussallam'04