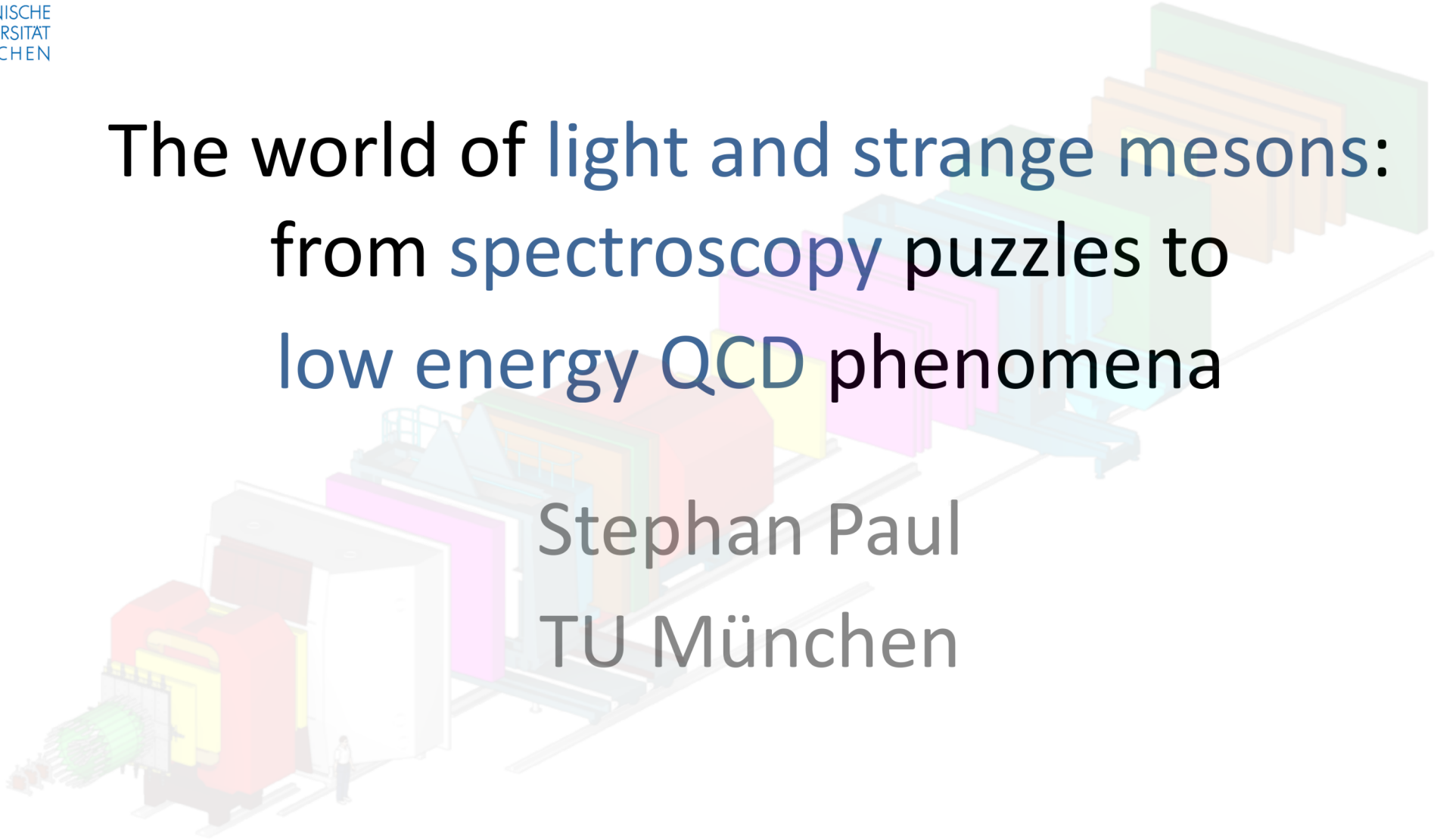
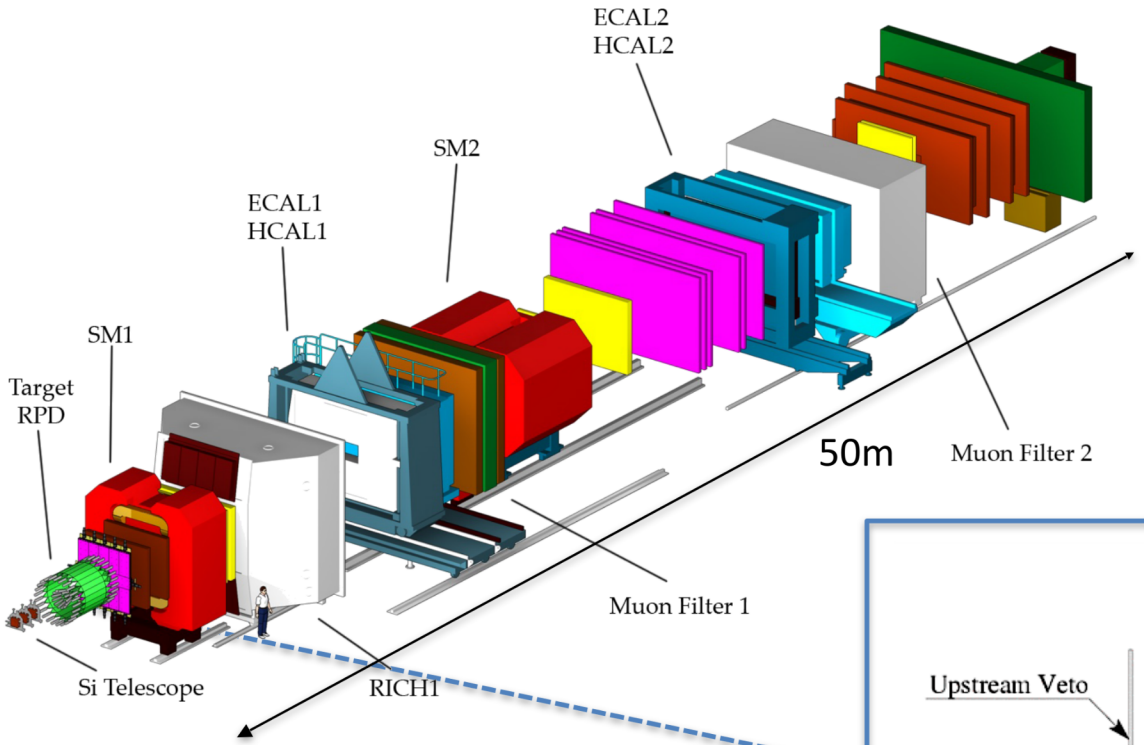
The world of light and strange mesons: from spectroscopy puzzles to low energy QCD phenomena

Stephan Paul

TU München



The COMPASS Experiment

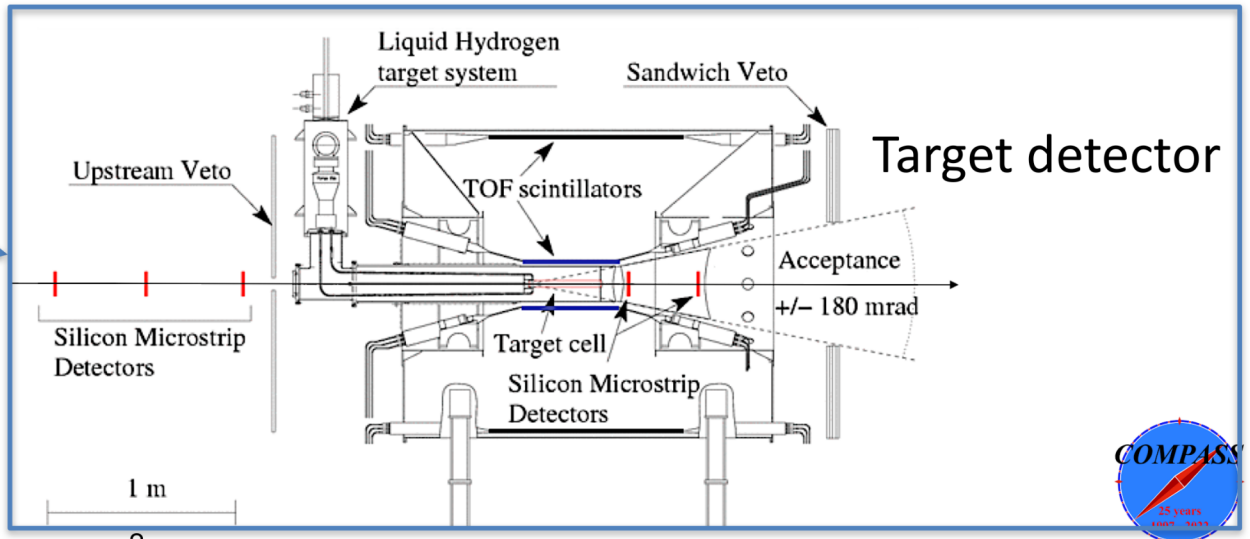


CERN SPS

Hadron beam:

- 190 GeV/c π, K, p
- $5 \cdot 10^7$ particles/SPS-spill
- LH_2 or Ni/W-target

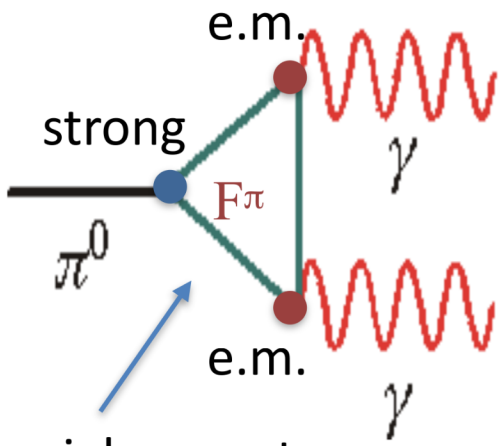
operated 2002-2022



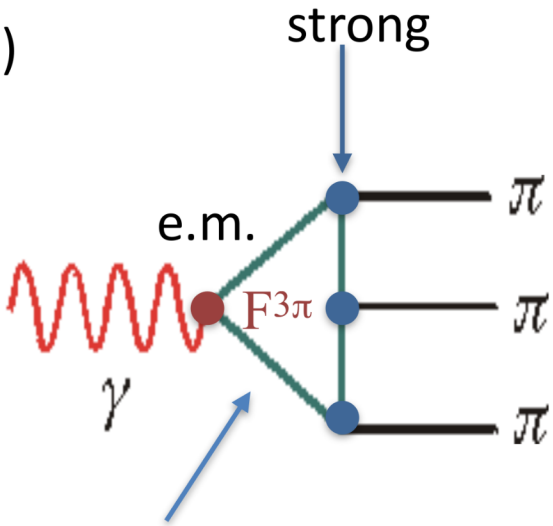
COMPASS Nucl.Instrum.Meth.A 779 (2015) 69-115

The Chiral Anomaly

in QCD axial-vector current is not conserved (PCAC)



Quark axial current

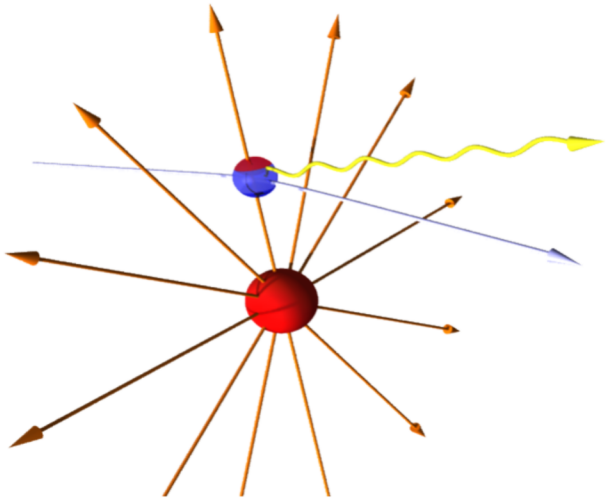


Quark axial current

- triangle diagram reveals breaking of classical symmetries → chiral anomaly
- Chiral anomaly taken into account χEFT by Wess-Zumino-Witten term:
  Describes coupling of odd number of Goldstone bosons (π, η, K)
  $\pi^0 \to \gamma\gamma$ and $\gamma \to 3\pi$ $(\pi^-\gamma \to \pi^-\pi^0)$ determined by chiral anomaly of QCD

Principle of Measurement

$\pi^- + \gamma^* \rightarrow \pi^-\pi^0$ via $\pi^- + (A,Z) \rightarrow \pi^-\pi^0 + (A,Z)$ at $Q^2 < 10^{-3}$



Primakoff process

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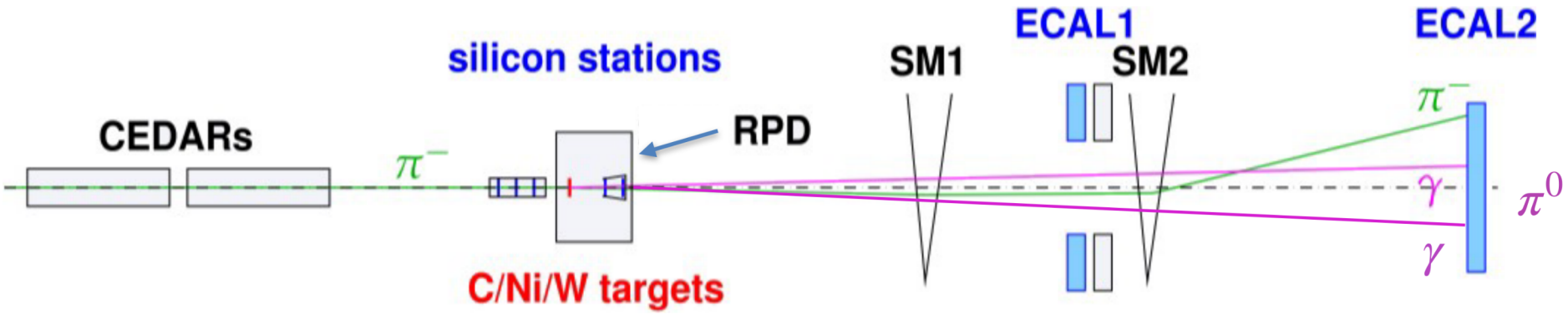


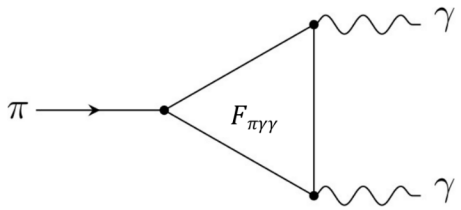
- identify beam particle: 96.8% π^- or 2.4% K^- (190 GeV)
- 4mm Ni target disk ≈ 25% X/X_0
- select exclusive $\pi^-\gamma$ final state at very low Q^2
- Luminosity determination via beam Kaon decay

($K^- \longrightarrow \pi^-\pi^0$ or $K^- \longrightarrow \pi^-\pi^0\pi^0$)

$\pi^- \gamma^* \to \pi^- \pi^0$

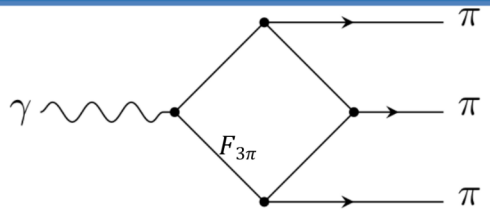
$F_{\pi\gamma\gamma}$

$N_c = 3$

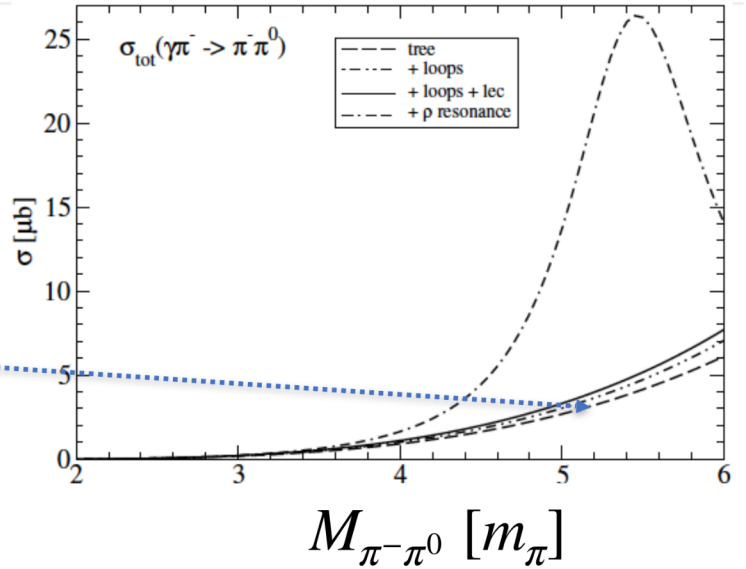


$$F_{\pi\gamma\gamma} = \frac{e^2 N_c}{12\pi^2 f_\pi} = 2.52 \cdot 10^{-2}\ \text{GeV}^{-1}$$

$F_{3\pi}$

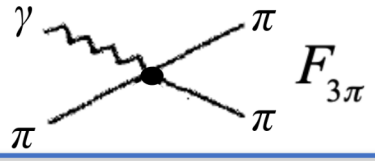


$$F_{3\pi} = \frac{eN_c}{12\pi^2 f_\pi^3} = (9.78 \pm 0.05)\ \text{GeV}^{-3}$$



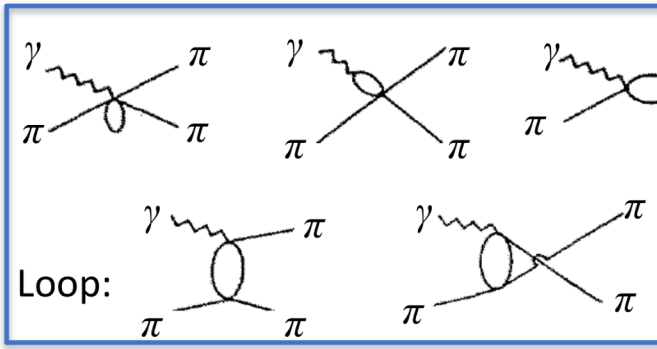
$\pi^- \gamma^* \to \pi^- \pi^0$

Tree:



$F_{3\pi}$

Loop:



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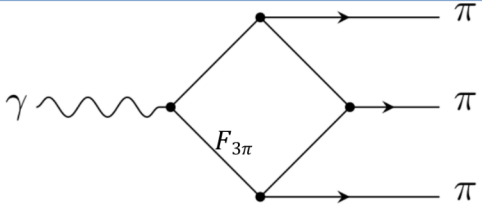

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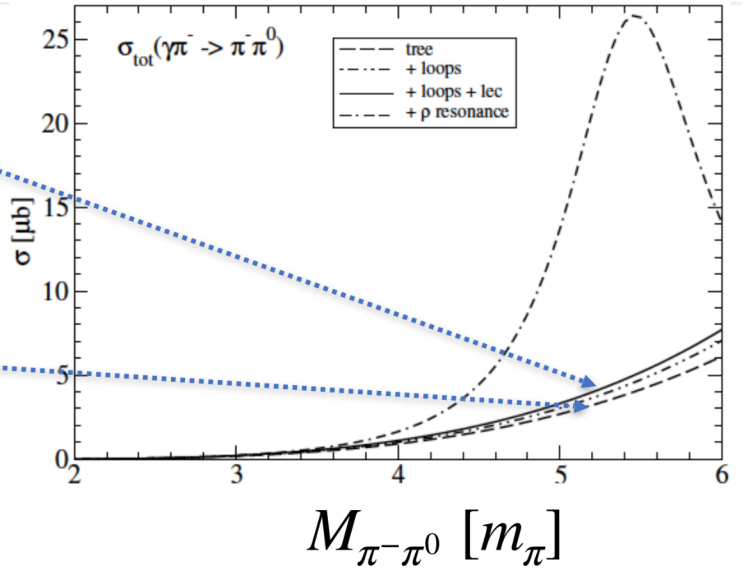

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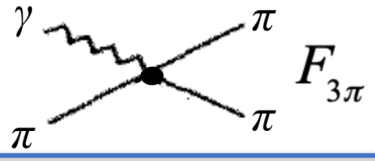

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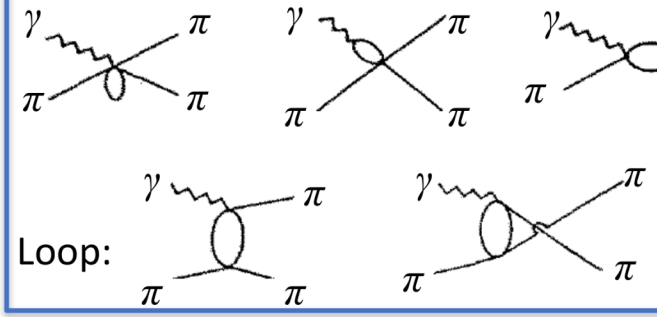

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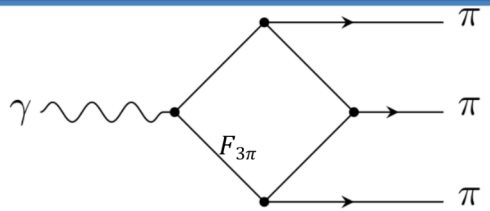

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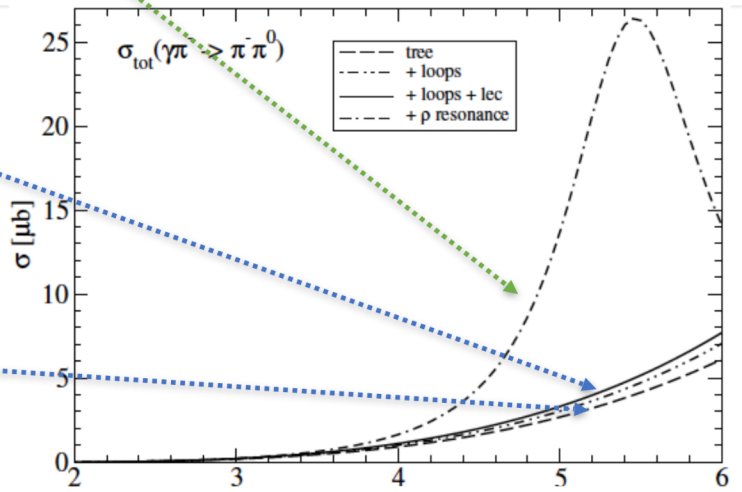
Strong final state interaction (FSI)

$$\pi^-\pi^0 \to \rho \to \pi^-\pi^0$$



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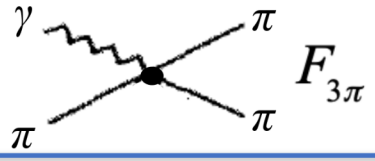

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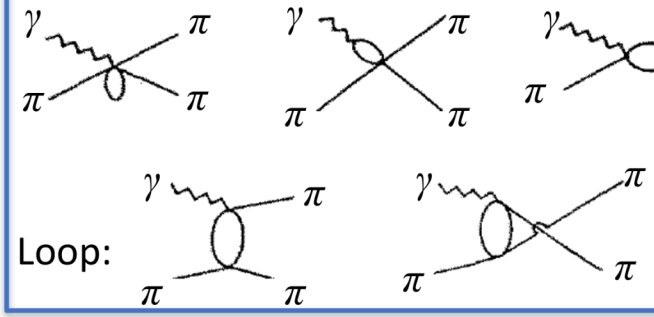

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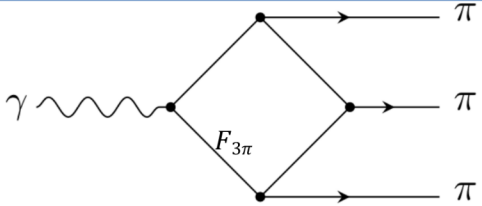

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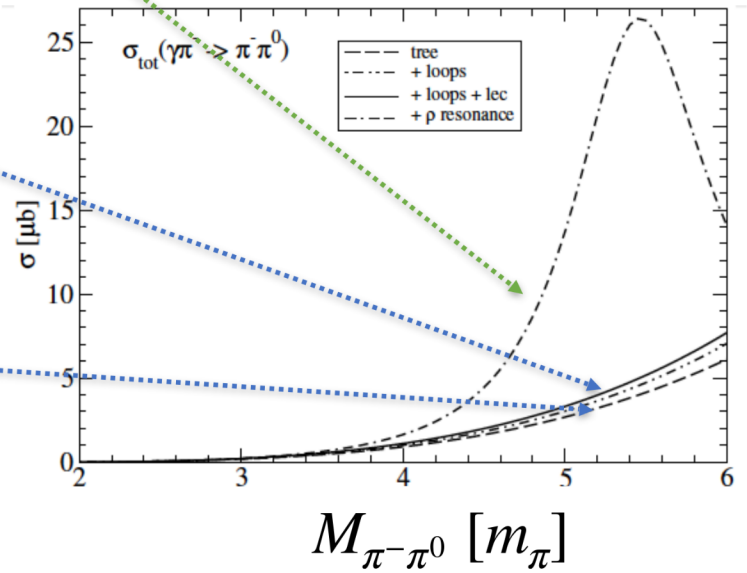
Strong final state interaction (FSI)

$$\pi^-\pi^0 \to \rho \to \pi^-\pi^0$$

Antipov et al in Serpukhov:

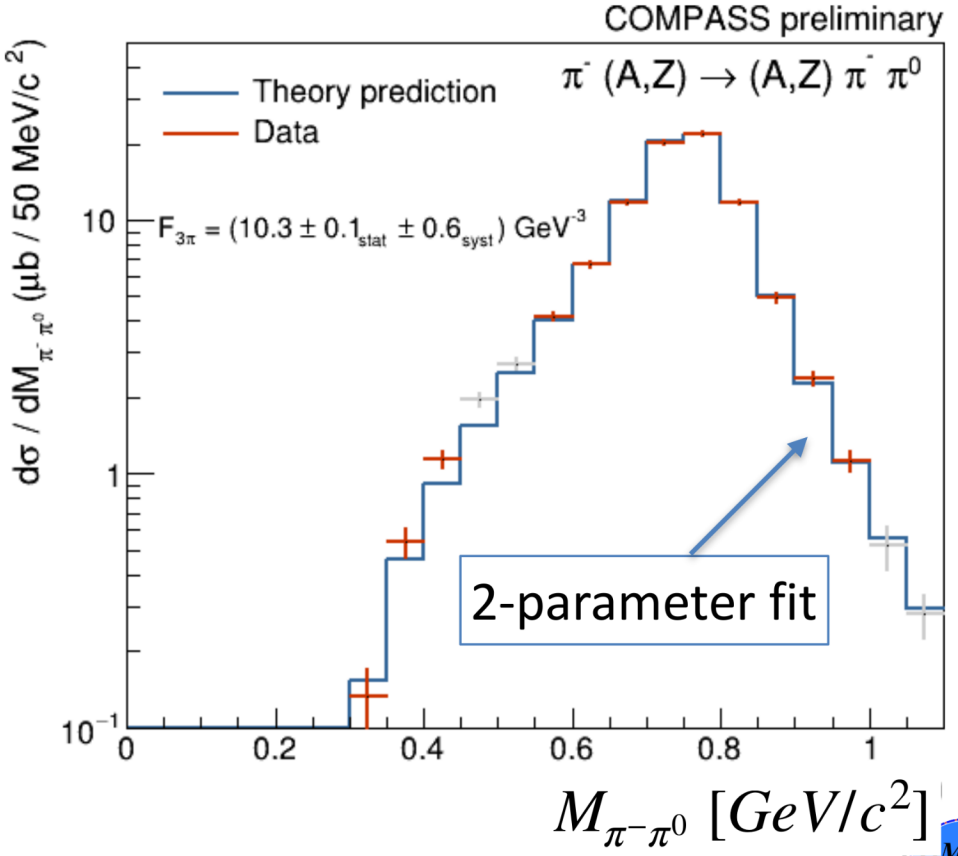
$F^{3\pi} = 12.9 \pm 0.9 \pm 0.5\ \text{GeV}^{-3}$

reanalyzed - many systematics



Results of Dispersive fits $\pi^-\gamma^* \rightarrow \pi^-\pi^0$

- Selection: $Q^2 < 1.3 \cdot 10^{-3}\ \mathrm{GeV}^2/c^2$
- Dispersive framework*: deduce $F_{3\pi}$ and $\Gamma_{\rho\to\pi\gamma}$ from fit to $\pi^-\pi^0$ mass distribution up to 1.0 GeV with FSI including $\rho(770)$-resonance:



*M. Hoferichter, B. Kubis, and D. Sakkas, *PRD* **86** (2012) 116009

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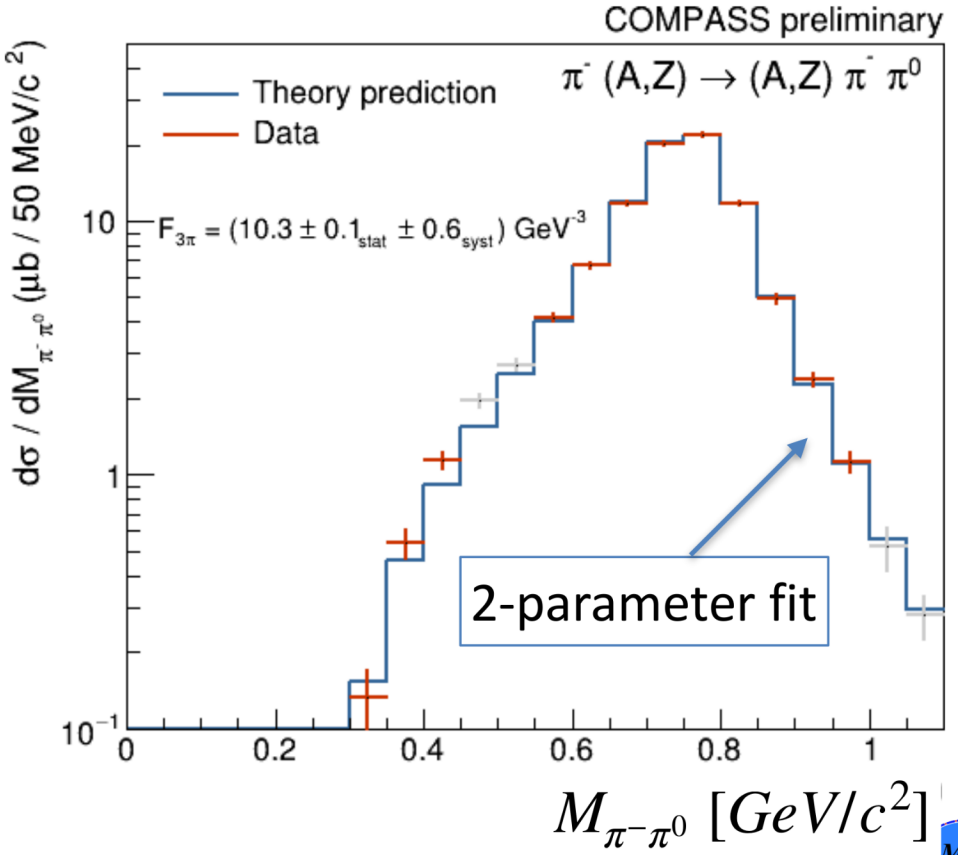
$$F_{3\pi} = (10.3 \pm 0.1_{stat} \pm 0.6_{syst})\mathrm{GeV}^{-3}$$

$$\Gamma_{\rho\to\pi\gamma} = \left(76 \pm 1_{stat}{}^{+10}_{-8}{}_{syst}\right)\mathrm{keV}$$

- Preliminary result for $F_{3\pi}$ in agreement with χPT prediction

$$F_{3\pi}^{\mathrm{Th}} = (9.78 \pm 0.05)\ \mathrm{GeV}^{-3}$$

- Final systematic uncertainties expected: 4-5%



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χPT is consistent low energy effective theory for strong interaction

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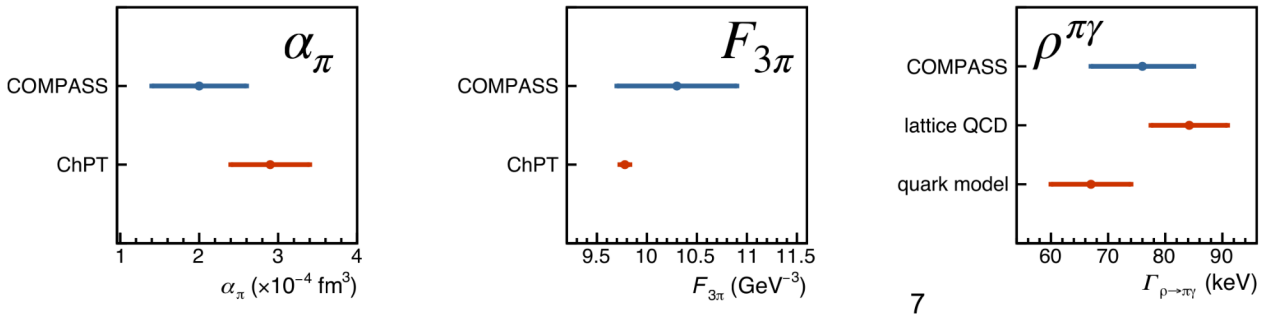
  - Now: Excellent agreement with O(p⁶) for $\pi-$polarisability ($\alpha_\pi - \beta_\pi$ not shown)
  - Now: First „precision“ tests of hadron-hadron dynamics ($\pi^-\gamma^* \to \pi^-\pi^-\pi^+$not shown)



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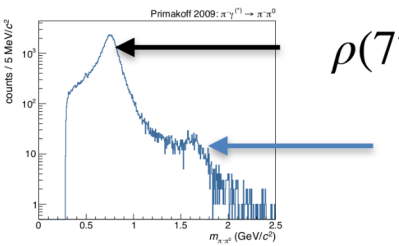

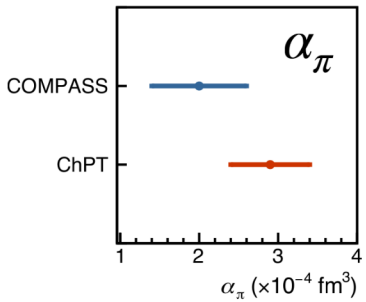

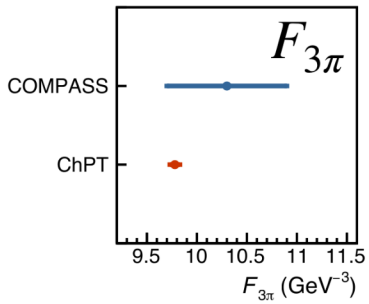

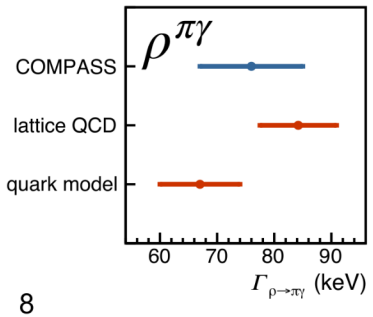

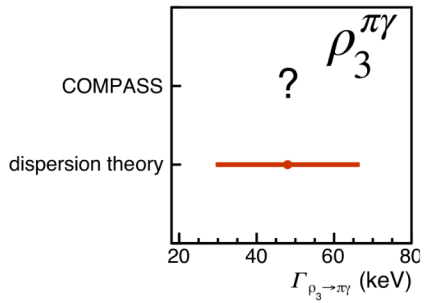

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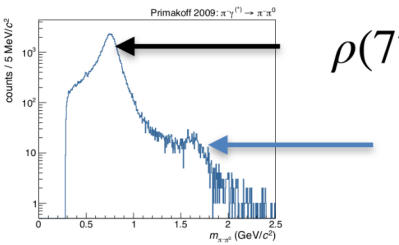
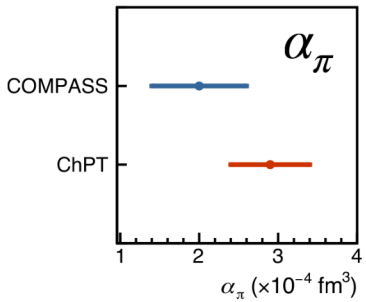
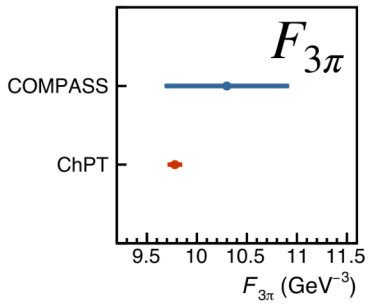
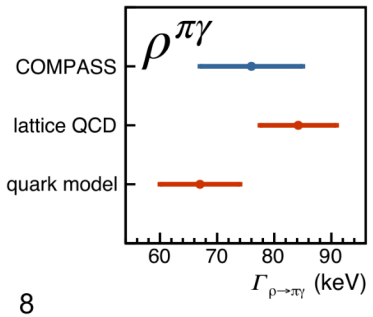
  - Now: First „precision“ tests of hadron-hadron dynamics
  - Radiative width of $\rho(770)$ extracted „model independently“
- Pions are Goldstone bosons of spontaneous chiral symmetry breaking
- Pions are the only active degrees of freedom

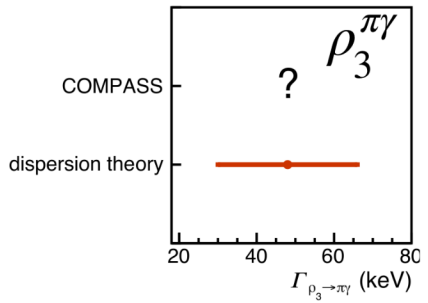
$$\pi^-\gamma^* \to \pi^-\pi^0$$











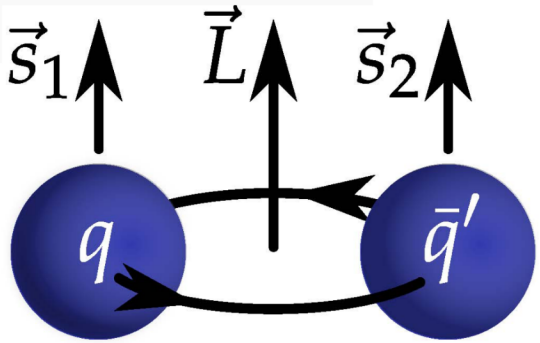
Meson Spectroscopy

Constituent Quark Model Mesons

Spin-Parity selection rules for bound $q\bar{q}'$ system

- Quark spins couple to total intrinsic spin S : $S = 0$ (singlet) or $S=1$ (triplet)
- Relative orbital angular momentum L couples with total spin S to Meson spin: $\vec{J} = \vec{L} + \vec{S}$

- Parity: $P = (-1)^{L+1}$
- Charge conjugation: $C = (-1)^{L+S}$
- G-parity: $G = C \cdot e^{i\pi I_z} = (-1)^{I+L+S}$



- Allowed J^{PC} combinations:

  $L = 0$ → pseudo-scalar 0^{-+}, Vector 1^{--}

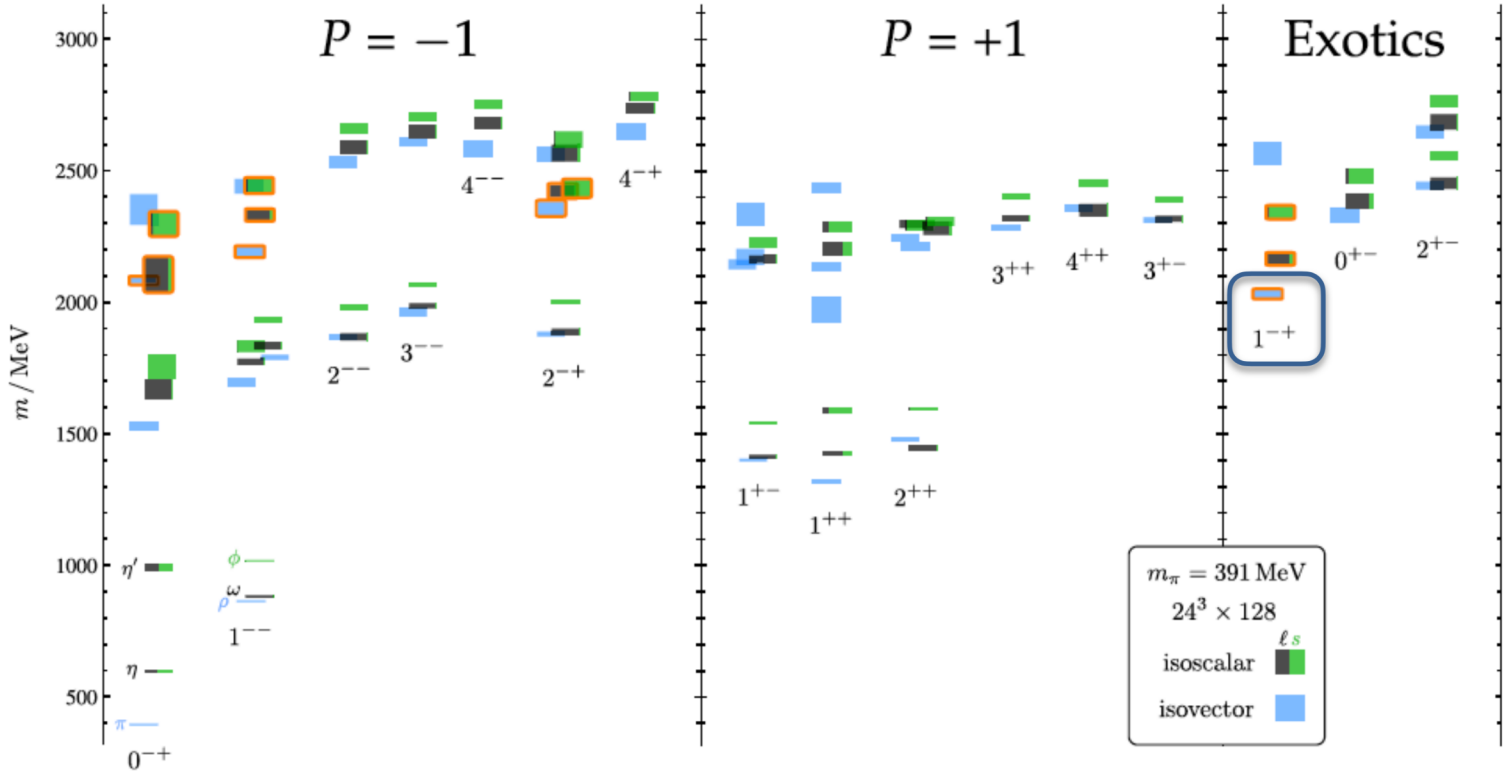
  $L = 1$ → scalar 0^{++}, axial-vector 1^{+-}, 1^{++} and tensor 2^{++}

- Forbidden J^{PC} combinations: 0^{--} , 0^{+-} , 1^{-+} , 2^{+-} , 3^{+-} .....

Theory Input is Quantitative

Exzellenzcluster ORIGINS

- lattice calculations predict mass spectrum (also for exotics)
- future: lattice predicts width and couplings



Why Searching for Light Mesons II

At high energies:

- Restoration of chiral symmetry $\mathrm{E} > 4\pi \cdot f_\pi \approx 1.2 GeV$
- Degeneration of different parity states
- Disappearance of mass-splitting of parity multiplets

Requires precise spectroscopy at higher masses (M > 2 GeV/c^2)

Meson Spectroscopy

- Most reactions studied with COMPASS are diffractive beam dissociation;

  $h^- p \rightarrow$ 3 hadrons e.g. $h' \pi \; \pi + p$ 3-body final state

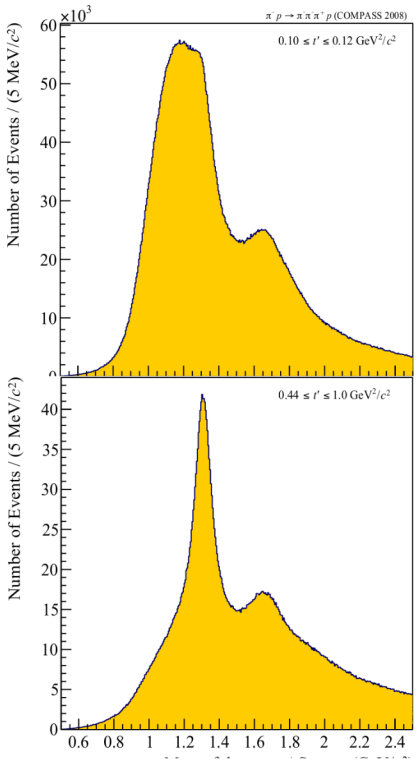
  $h^- p \rightarrow$ 2 hadrons e.g. $\pi^- \eta^{(')} + p$ 2-body final state

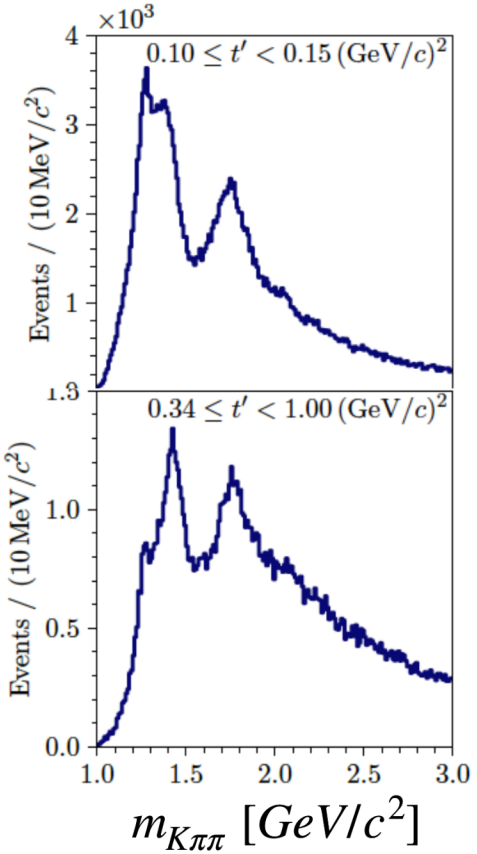
How to Search: Final State Examples

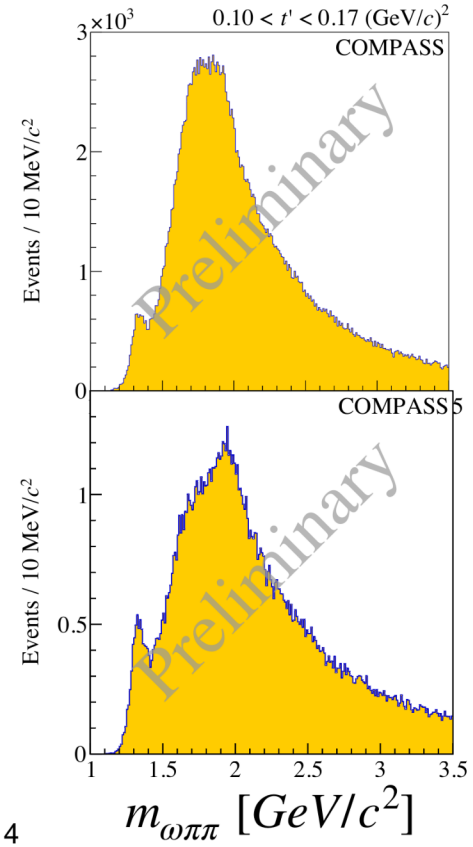
- Mass spectra of inclusive final states give small fraction of information
  - Production dependence (4-momentum transfer) adds separation power
  - Final states contain 10-20 different resonances - from peak hunting to PWA

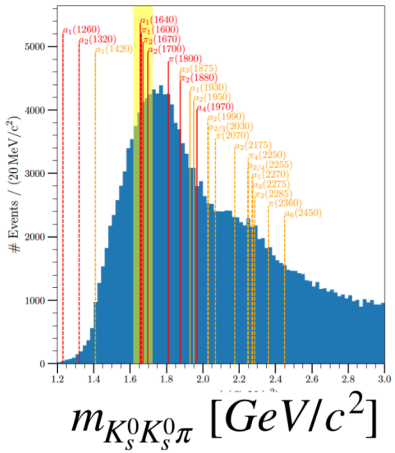
low t'

high t'









Hass HK 29.4

Wagner HK 29.3

Partial Wave Analysis

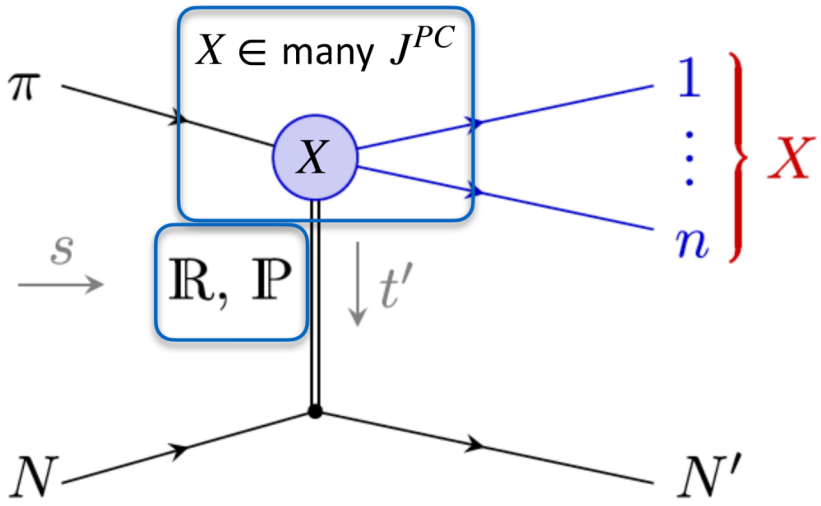
- Decomposition of a complex System (without interference)

inspired by M. Pennington

Art taken from Urs Wehrli: “Kunst aufgeräumt”

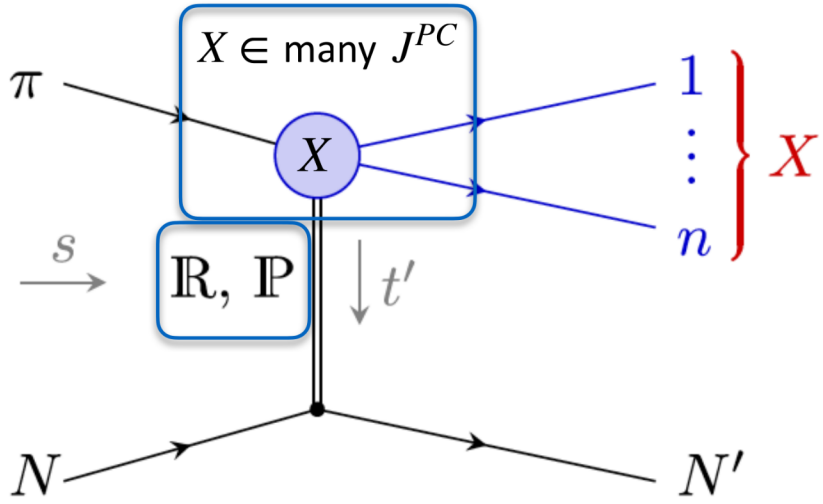
Partial Wave Analysis

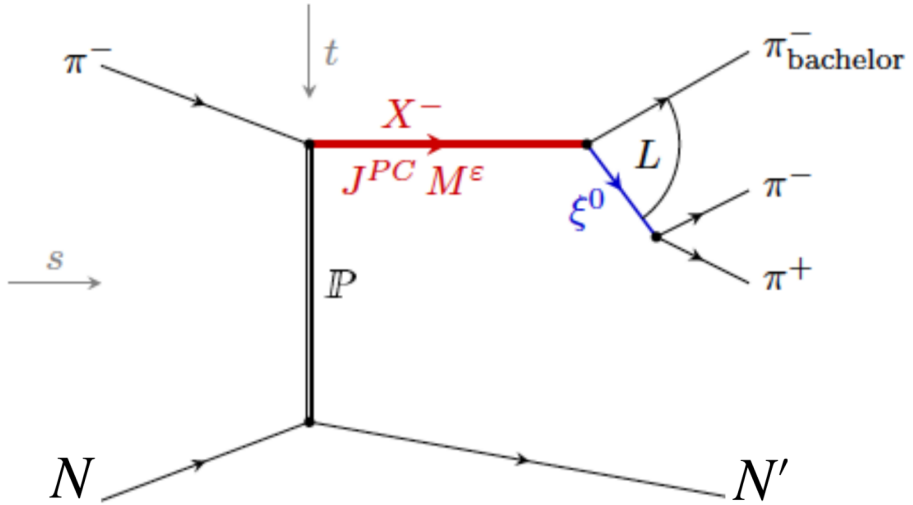
- Decomposition of a complex System (without interference)
- But: quantum mechanics involves interference



Partial Wave Analysis

- Decomposition of a complex System (without interference)
- But: quantum mechanics involves interference
- Model reaction as multi-step process: production X and subsequent 2-body decays

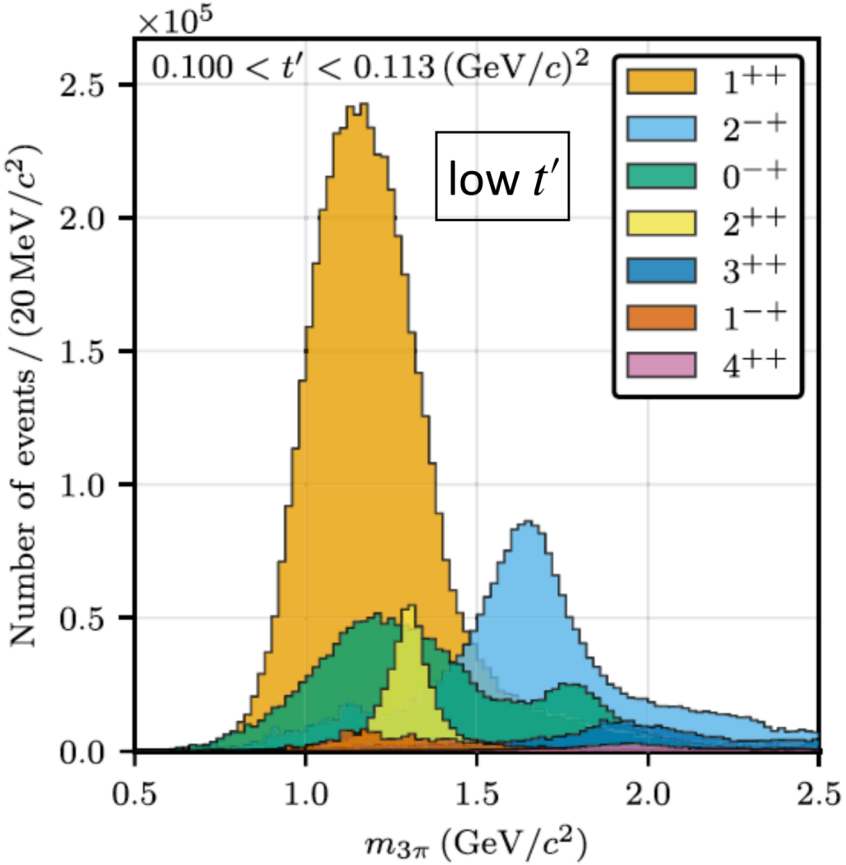


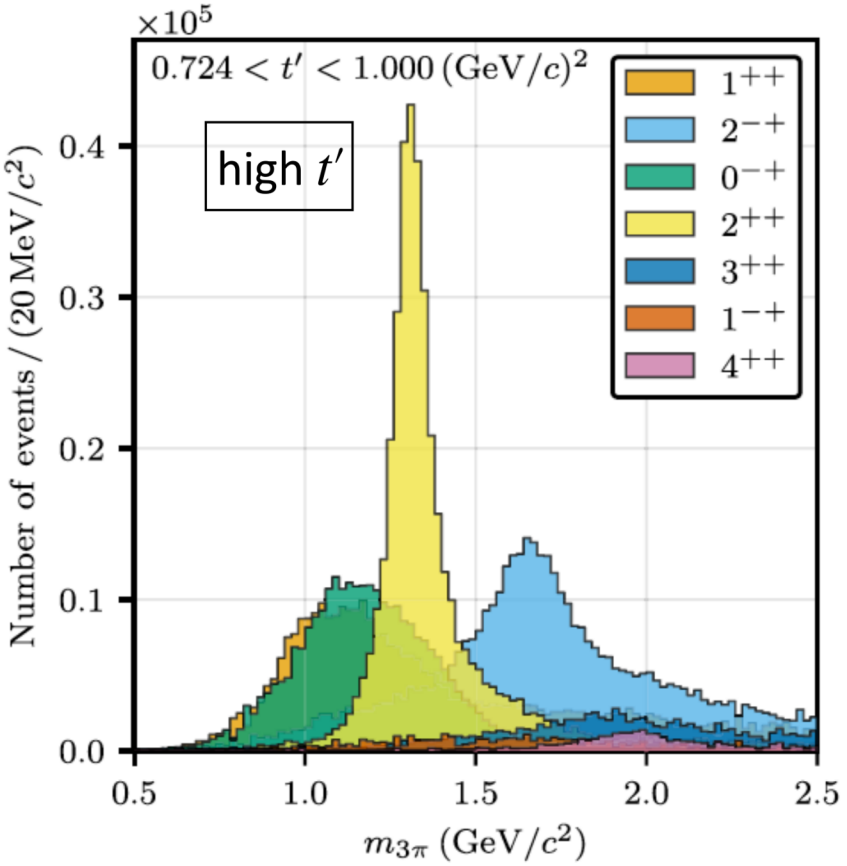


$J^{PC}(X^-)M^\epsilon \to \xi\pi \to 3\pi$ is called "wave"

PWA Result („spin totals“)

- Decomposition of the mass spectrum in terms of J^{PC}

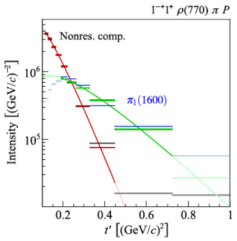


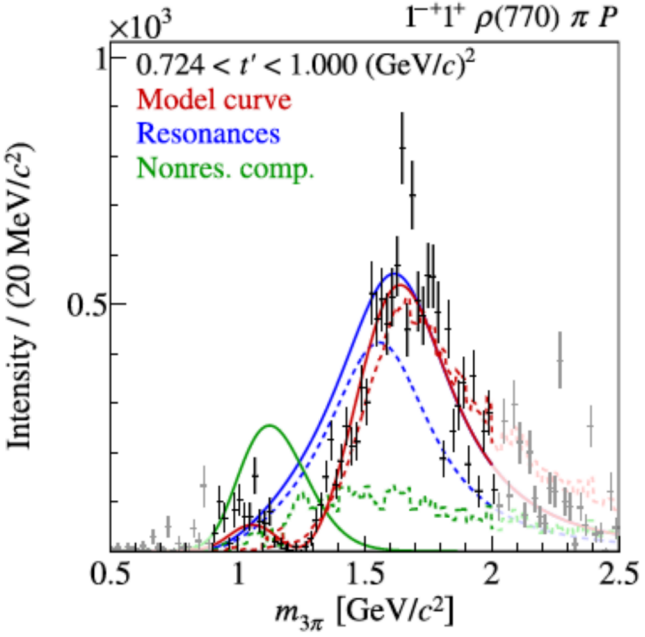


Exotics in COMPASS : Spin Exotic $J^{PC} = 1^{-+}$

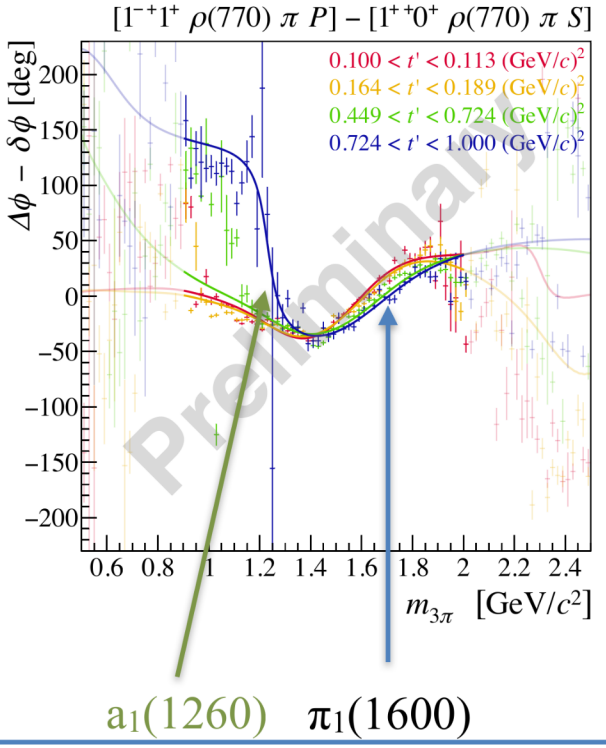
Exzellenzcluster ORIGINS

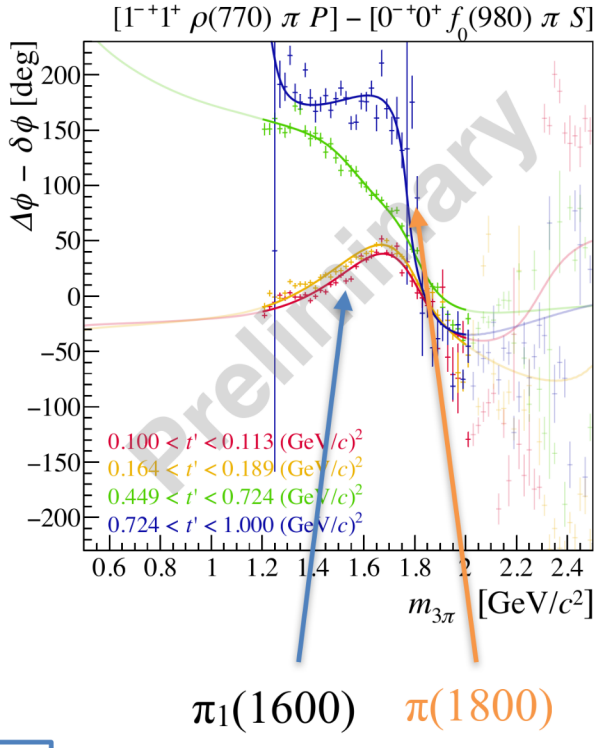
Intensity





Relative Phases (interference terms)





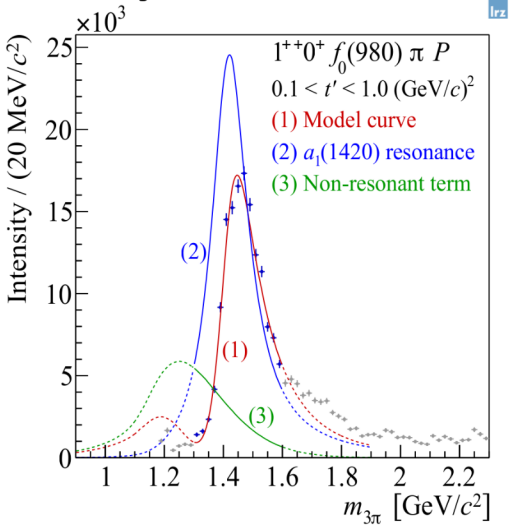
Clear Establishment of exotic meson !
COMPASS could reconcile dispute from previous experiment : analysis artifact

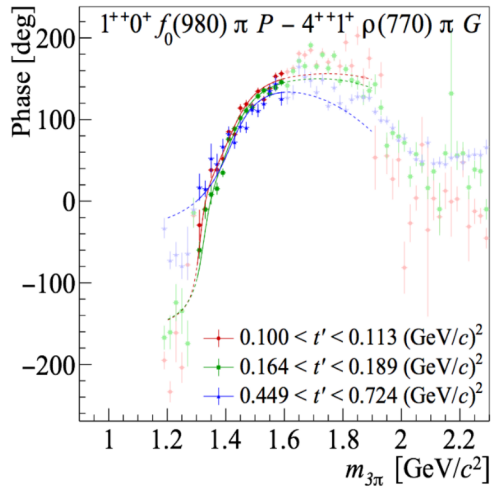
COMPASS *Phys.Rev.D* 98 (2018) 9, 092003 - *Phys.Rev.D* 105 (2022) 1

Exotic: Observation of $a_1(1420)$

axialvector ($J^{PC} = 1^{++}$) decaying into $f_0(980)\pi$ (P-wave)

- small signal (10^{-3}) compared to dominant $\rho(770)\pi$ (S-wave)
- large phase variation
- „narrow“ signal : $\Gamma/M \approx 10\,\%$





Observation*:*

- Decay only : [$f_0(980)$] π P
- *Mass : 1413 ± 15± 13 MeV/c²*
- *Width: 157 ± 8 ± 23 MeV/c²*

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Observation of $a_1(1420)$

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Various explanations proposed for interpretation:

- Dynamics
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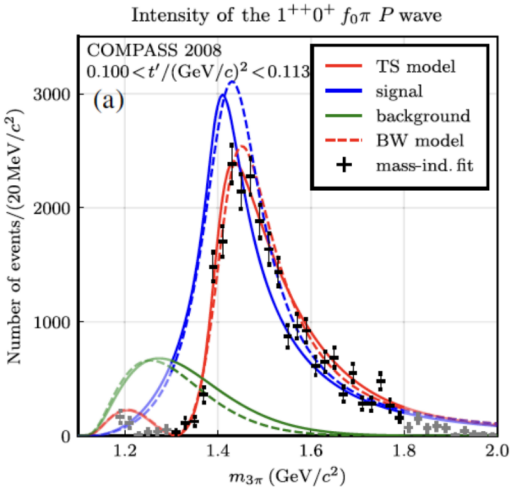
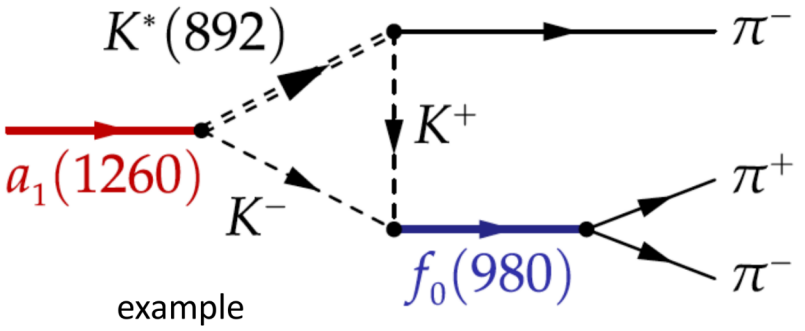
  $a_1(1260) \rightarrow f_0(980)\pi$ decay shows up 200 MeV above $a_1(1260)$ (Mikhasenko et al.; Aceti et al.)
- Requires same kinematic t dependence for $a_1(1260)$ and $a_1(1420)$

– Molecular structure





example

COMPASS Phys.Rev.Lett. 127 (2021) 8

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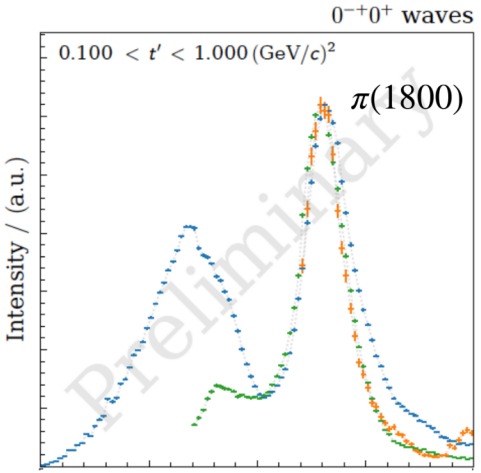
Analysis of 3π τ lepton decays crucial

- ongoing using Belle/Belle 2 data (TUM)

Rabusov HK 29.2

Exotic: A New Pionic State ?

- Ground state and radially excited pions have $J^{PC} = 0^{-+}$
- known states: π(140), π(1300), π(1800)



$M_{3\pi}$ [GeV/c^2]

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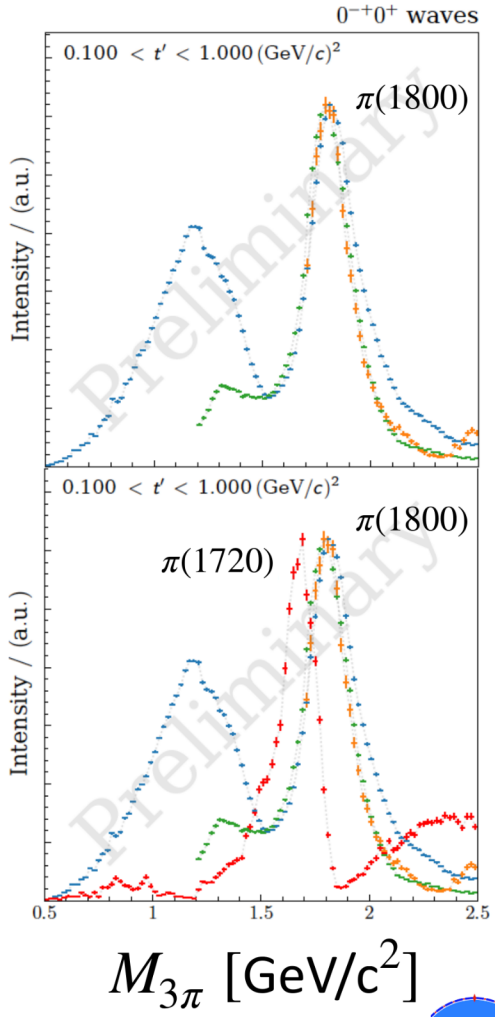

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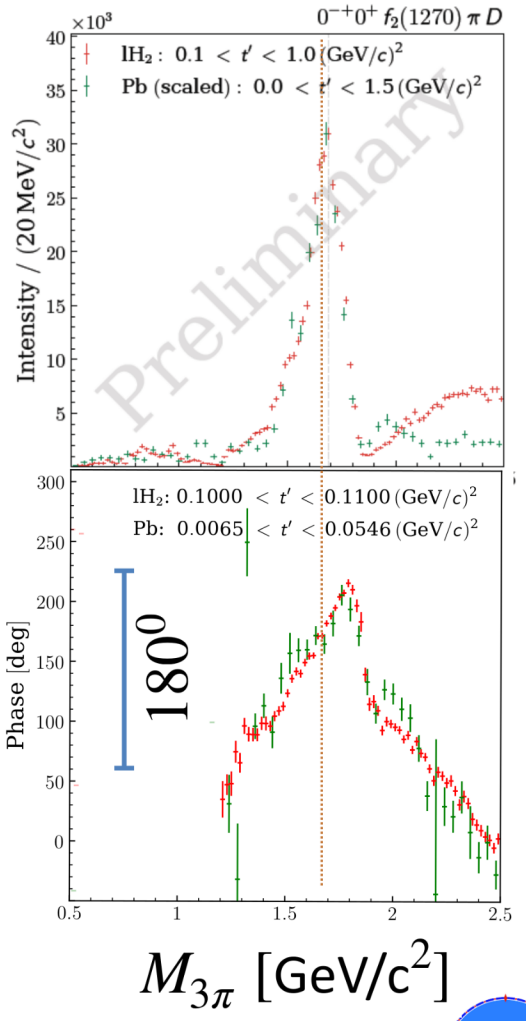

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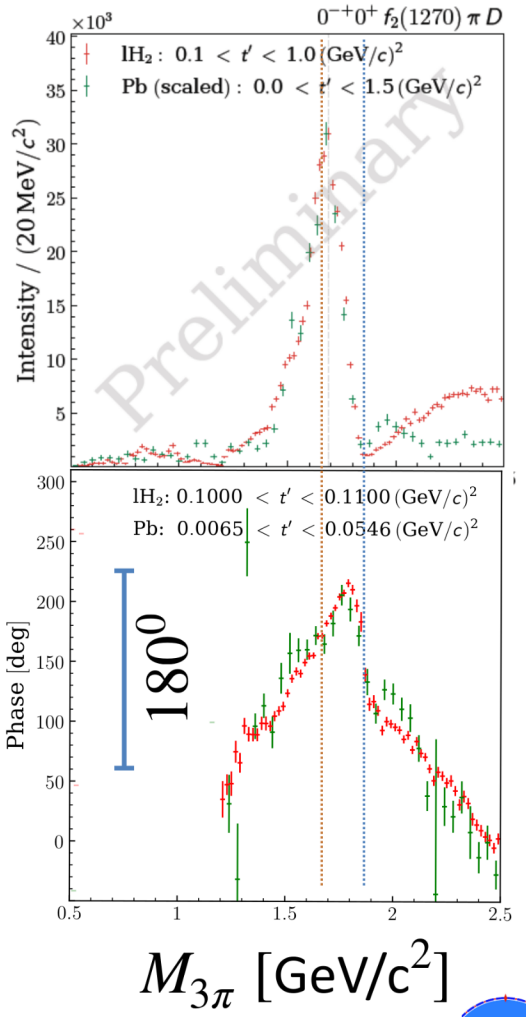

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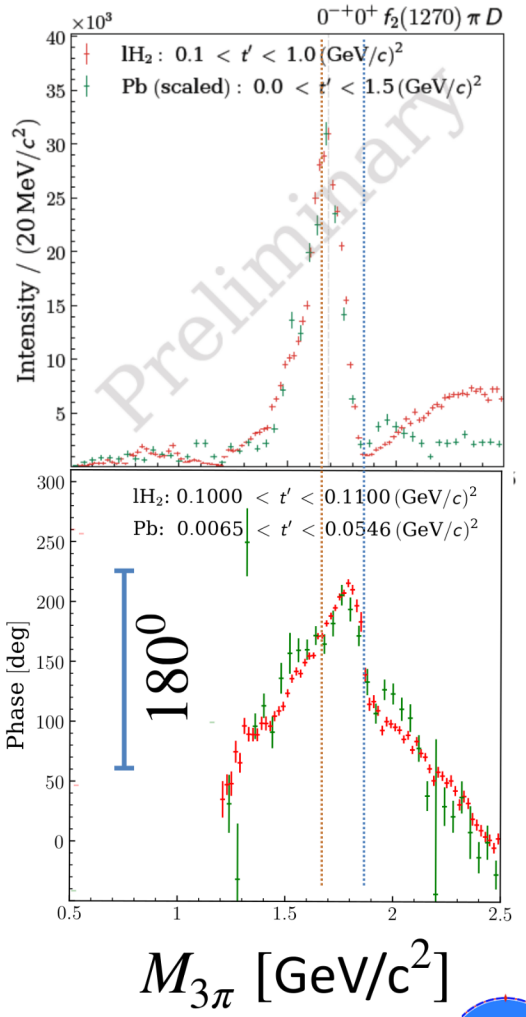
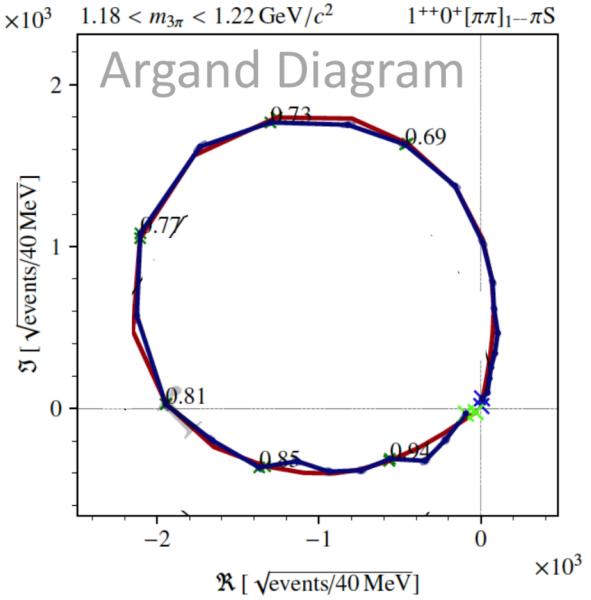
- Interpretation unclear



Analyzing the Isobaric Structure

- Novel analysis technique to extract complex amplitudes for 2-body isobars from data
- example: $J^{PC} = 1^{--}$ (e.g. $\rho(770)$ in π $[\pi\pi]_{1^{--}}$)
- fit unitary and analytic amplitude models (Hanhart et al.) and extract pole mass and width for all $m_{3\pi}, t'$
- Extend to $\pi\pi$ – S-wave and strange systems



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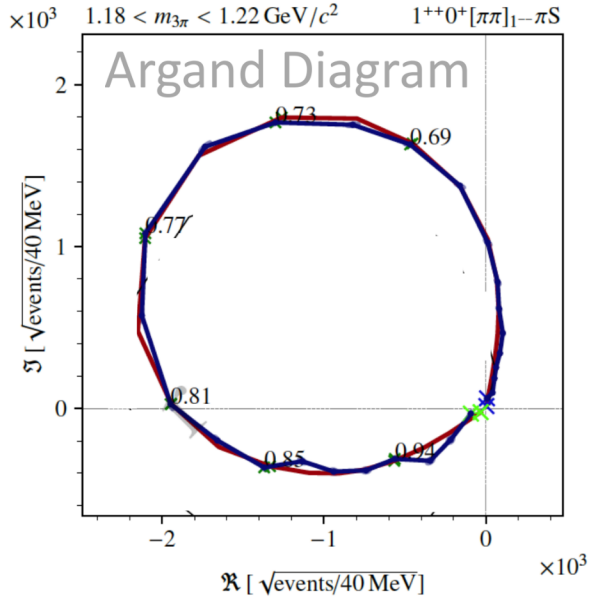

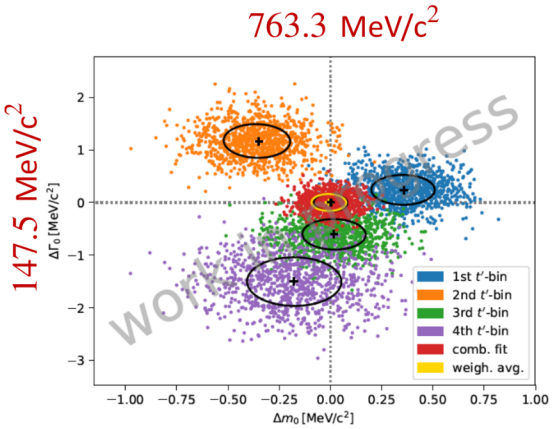

Theory*: $m_0 \in [761,764]$; $\Gamma_0 \in [143.4,146.4]$

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Bartl HK 74.33

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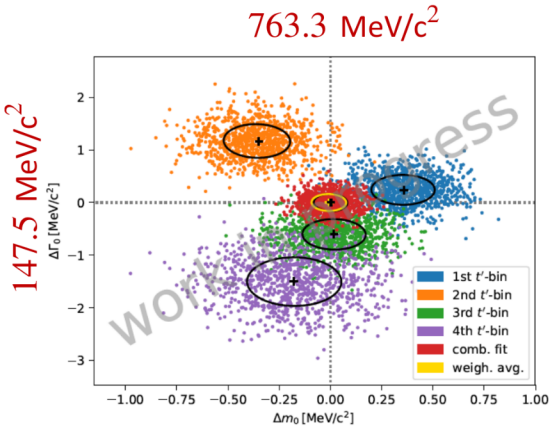
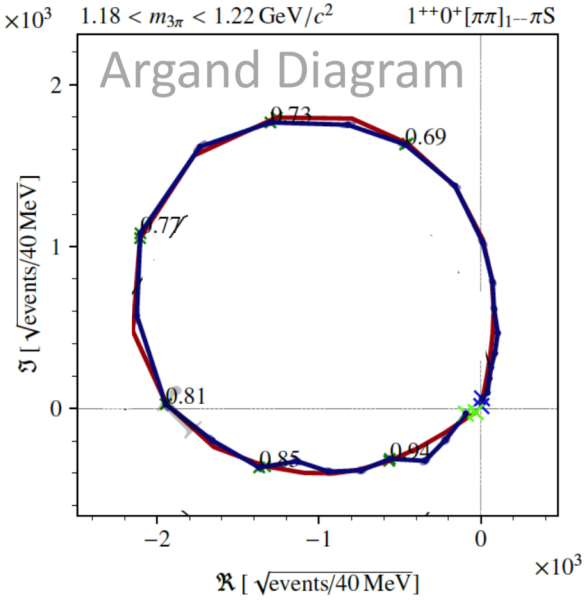
3-body systematics to be understood





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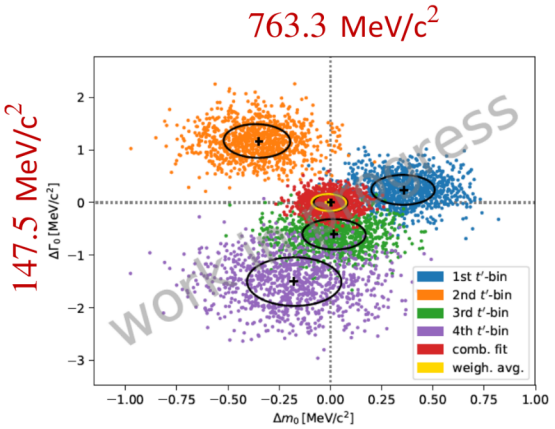

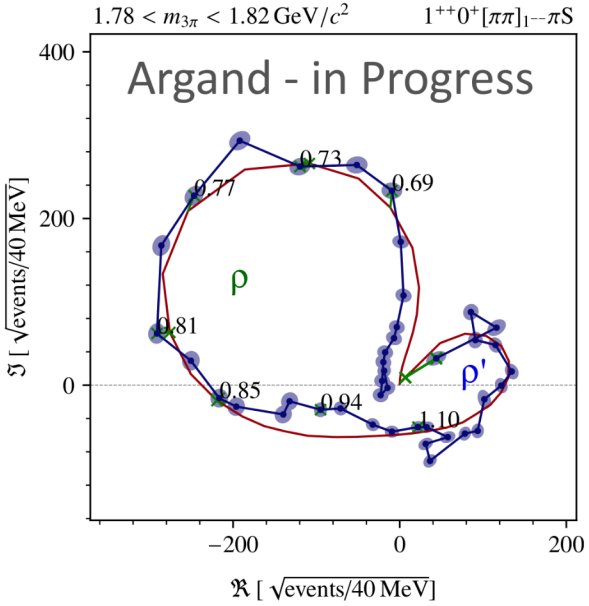

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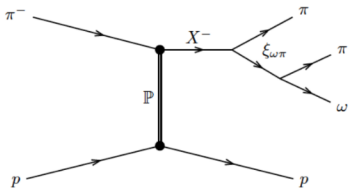
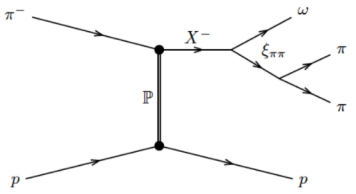
$\omega\pi\pi \to 2\pi^-2\pi^0\pi^+$

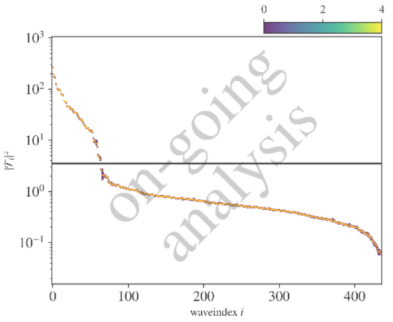


(a) $\omega\pi$ isobar



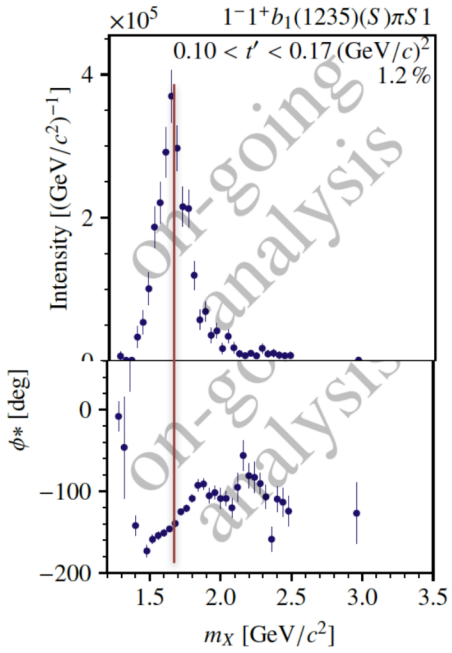
(b) $\pi\pi$ isobar

- PWA: automatic wave selection: select 80(*) waves from pool of 434

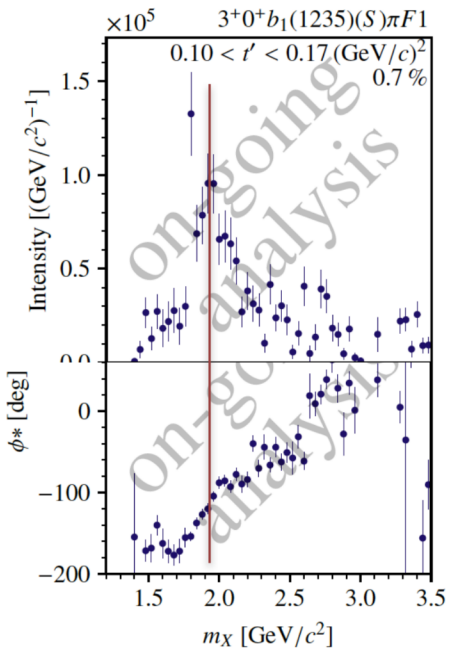


- most exciting examples in $b_1(1235)\pi \to (\omega\pi)\pi$:

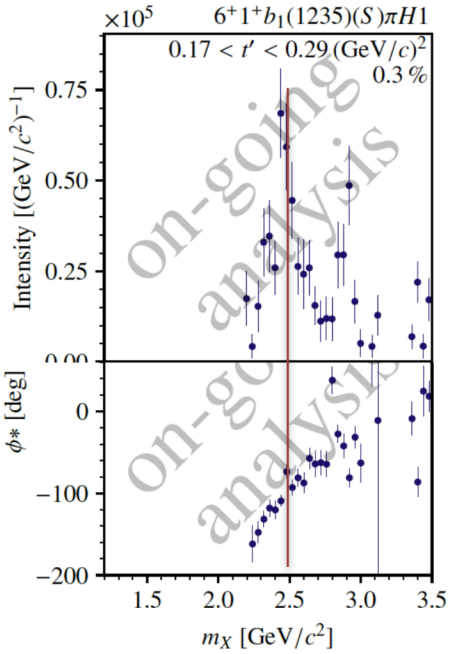
1^{-+} spin-exotic



a_3



a_6



* in total 150 waves appear in various mass ranges

Haas HK 29.4

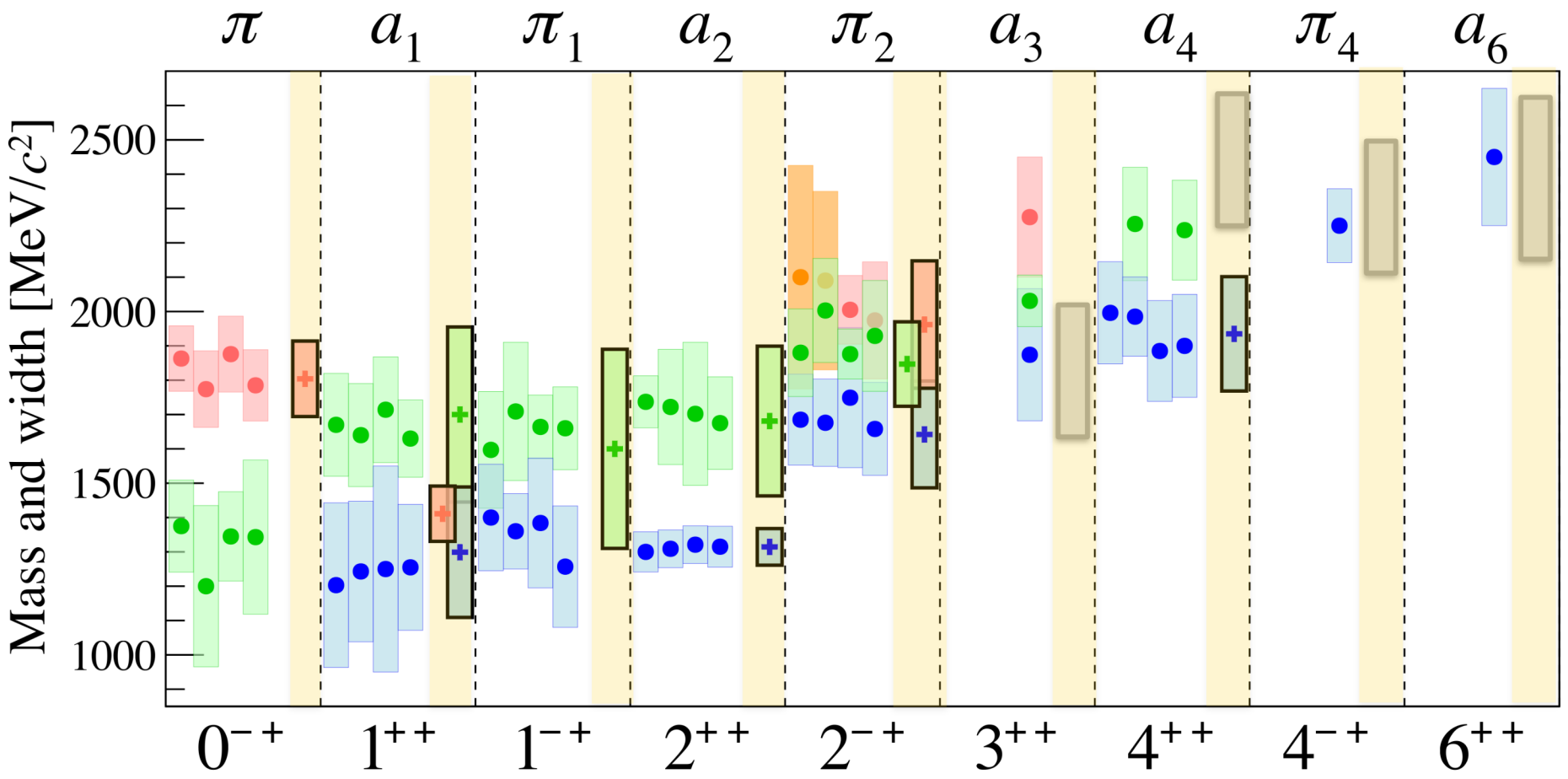
Developments

1. Wave selection: use computer algorithm and regularization on very large „wave pools“
2. bin-correlated analysis using NIFTY* (program package used by cosmology)
3. One step data fitting for resonances (parametric) and non-parametric background across full mass range
4. Variational inference (variational Bayes) to estimate uncertainties

*numerical information field theory

Kaspar HK 7.2

The Light Isovector Meson System



COMPASS Phys.Rev.D 98 (2018) 9, 092003

- COMPASS found 15 states in a consistent analysis (more on the horizon)

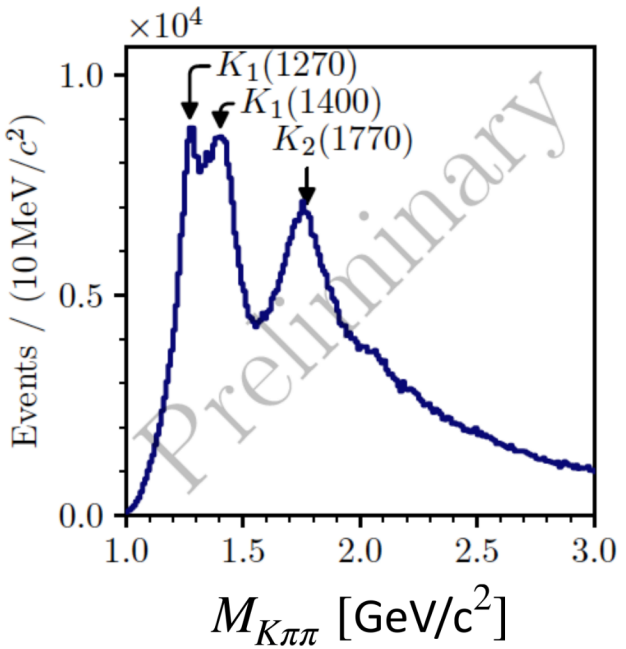
Strangeness

Strange-Meson Spectroscopy

COMPASS hadron beam contains $2.4\,\%$ kaons

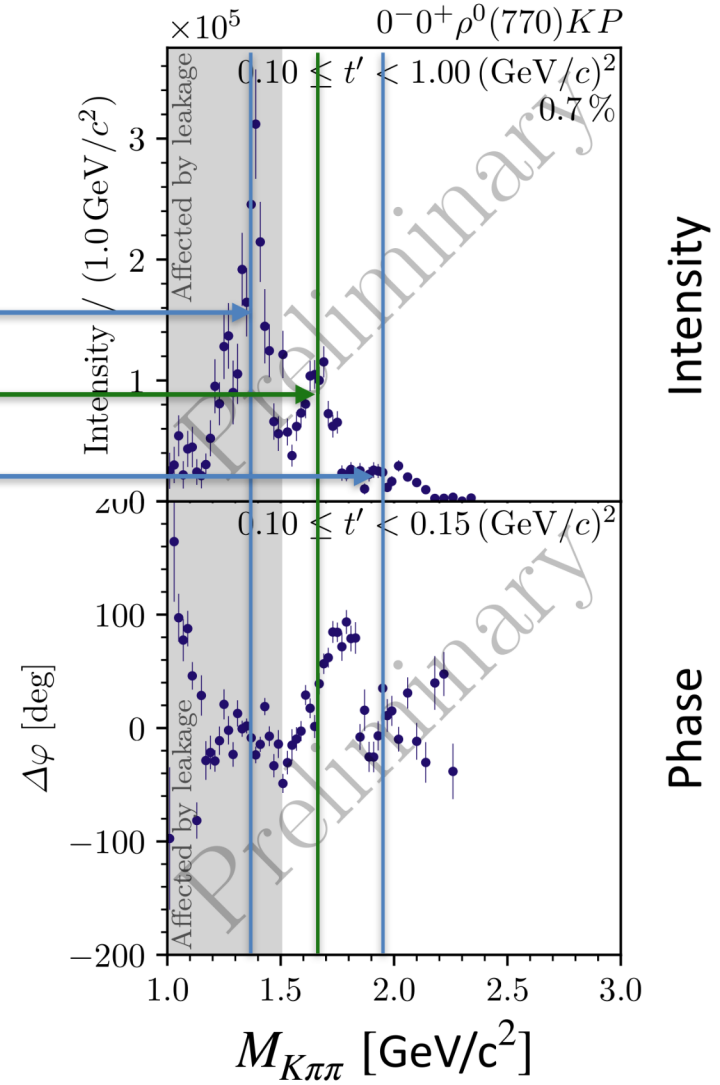
- first analysis: $K^- + p \to K^-\pi^+\pi^- + p'$
- $0.7 \cdot 10^6$ events in $t' \in [0.1,1.0]$ GeV/c^2
- use automatic wave selection to build PWA model (novel)

  selection of 15-80 waves ($m_{K\pi\pi}$ dependent) - 596 waves offered
- treat pion background reaction $\pi^- + p \to \pi^-\pi^+\pi^- + p'$ through incoherent wave set in PWA (novel)



Examples for Excited (and Exotic) Kaons

- $J^P = 0^-$: $K^*(892)\pi$ and $[K\pi]_S\pi$ and $\rho(770)K$
  - $K(1460)$
  - $K(1630)$ (supernumerous)
  - $K(1830)$ (weak)



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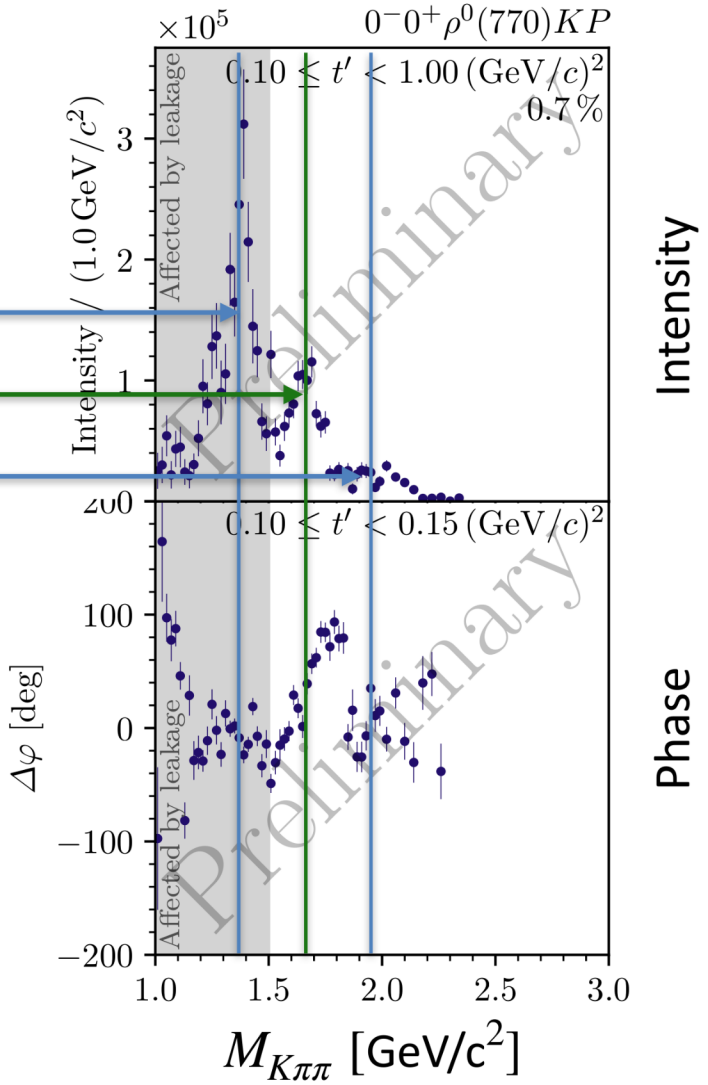
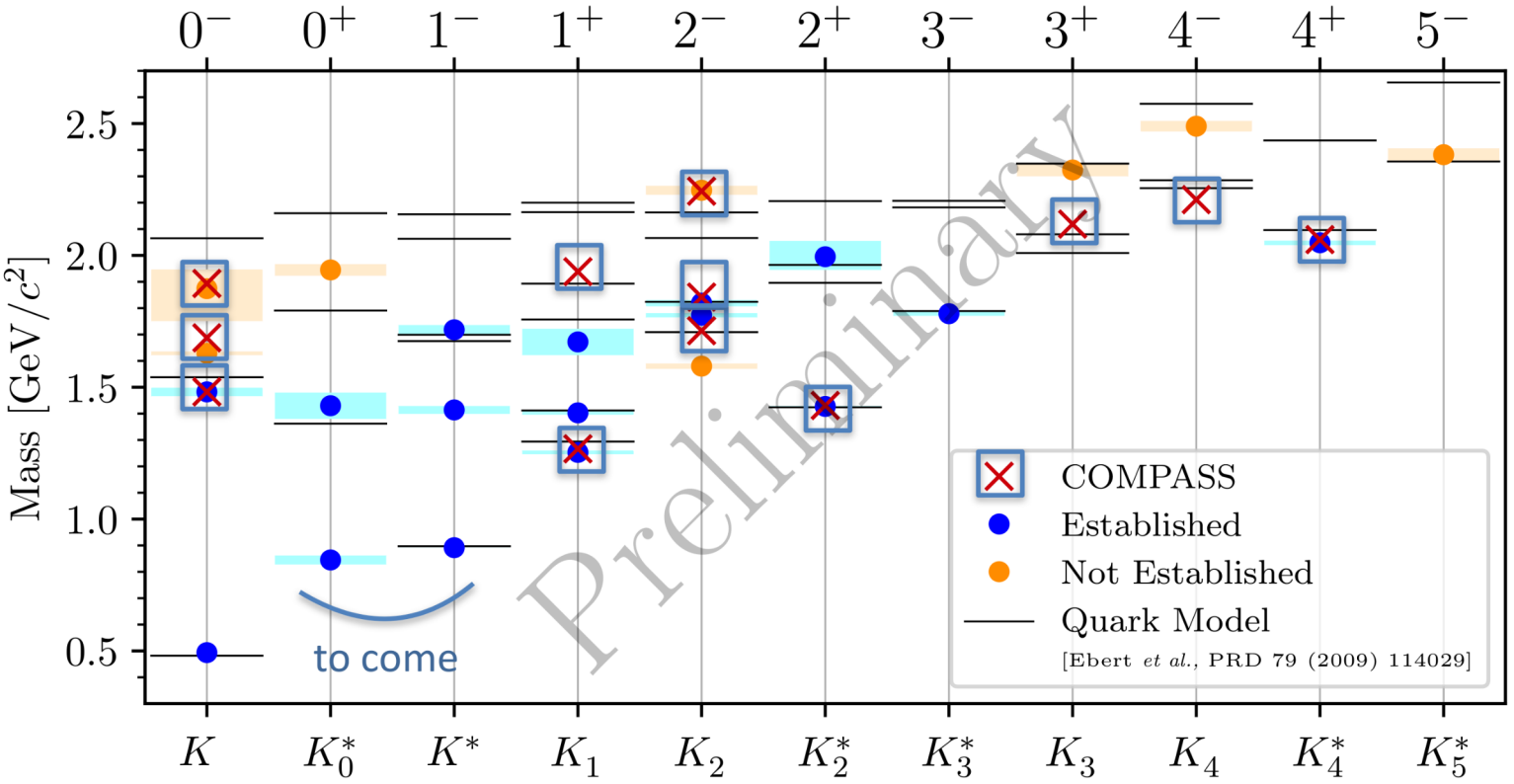
- supernumerous state likely to be of exotic nature



Summary Strange Mesons

COMPASS will release m_0/Γ of 11 strange mesons using $K^-\pi^-\pi^+$

- $K,\ K_1,\ K_2^*,\ K_2,\ (K_3^*),\ K_3,\ K_4^*,\ K_4$



- COMPASS found 11 strange mesons - ONE supernumerous State (exotic ?)

Topics Not Mentioned

- Measurement of pion polarizability ✓ — COMPASS Phys.Rev.Lett. 114 (2015) 062002
- Measurement of $\gamma\pi^- \to \pi^-\pi^+\pi^-, \pi^-\pi^0\pi^0$ (χEFT fit) ✓ — COMPASS Phys.Rev.Lett. 108 (2012) 192001
- Measurement of radiative width of excited mesons $a_2(1320)$ and $\pi_2(1670)$ ✓ — COMPASS *Eur.Phys.J.A* 50 (2014) 79
- $\eta\pi, \eta'\pi$ analysis and the state of $\pi_1(1400)$ and $\pi_1(1600)$ ✓ — COMPASS Phys.Rev.Lett. 114 (2015) 062002, JPAC-COMPASS Phys.Lett.B 779 (2018) 464-472
- Kaon polarizability ✓
- SU(3) χEFT ✓
- Nuclear effects in π scattering ✓
- Determination of $(K\pi)$ $S-$, $P-$, $D-$ wave scattering ✓
- Spectroscopy in 16+ final states ✓

Vast number of measurements with polarized muons and polarized target on longitudinal and transversal structure of the nucleon

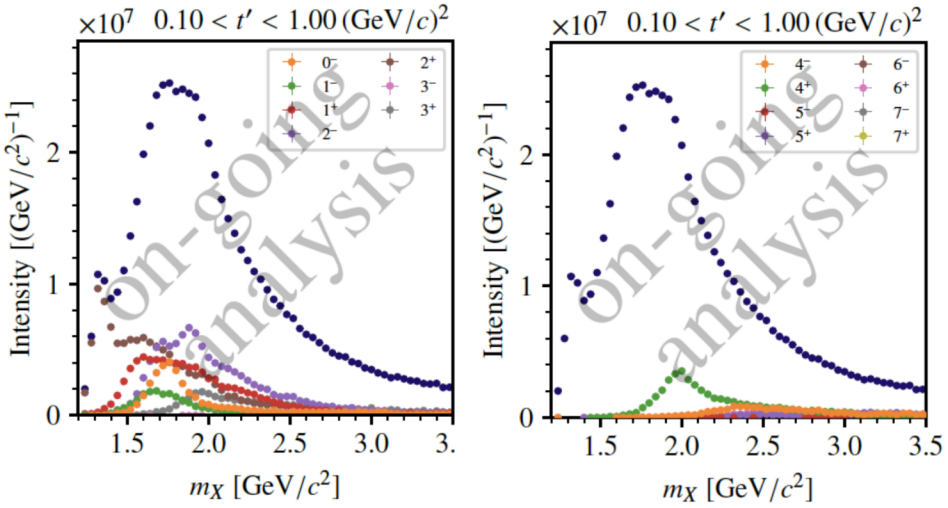
Summary

- COMPASS has made numerous key measurements
  - low energy QCD phenomena
  - light meson spectroscopy
    - systematic exploration of ordinary meson systems
    - exotic mesons
    - new undiscovered phenomena
- Development of tools necessary
  - precision measurements around χEFT
  - complex partial wave analysis and high mass mesons
  - export technology to heavy flavor facilities (e.g. D, B-meson decays, τ-lepton decays)
- COMPASS explores full $SU(3)$ flavor space (many results to come)
- AMBER II offers extension to strangeness sector (10-fold data sample)

Backup $\omega\pi\pi \rightarrow 2\pi^{-}2\pi^{0}\pi^{+}$

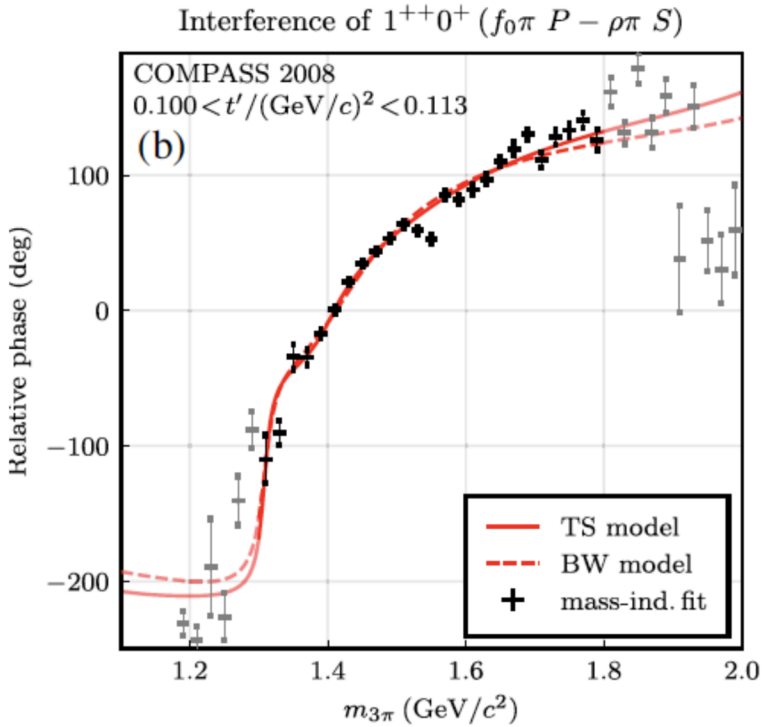
- include $L \leq 7$ for $\xi'\xi$ and use the following isobars

Isobar	Decay channel	m [MeV/c^2]	Γ [MeV/c^2]
$\rho(770)^0$	$\pi\pi$	769.0	150.9
$\rho(770)^-$	$\pi\pi$	766.5	150.2
$\rho(1450)$	$\omega\pi$	1465	400
$\rho_3(1690)$	$\omega\pi, \pi\pi$	1688.8	161
$b_1(1235)$	$\omega\pi$	1229.5	142



Backup a1(1420)

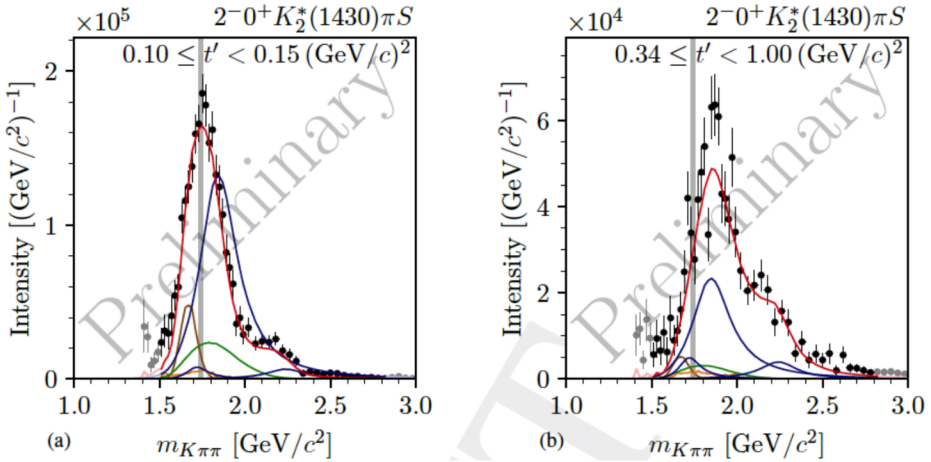
- phase variation w.r.t. main wave



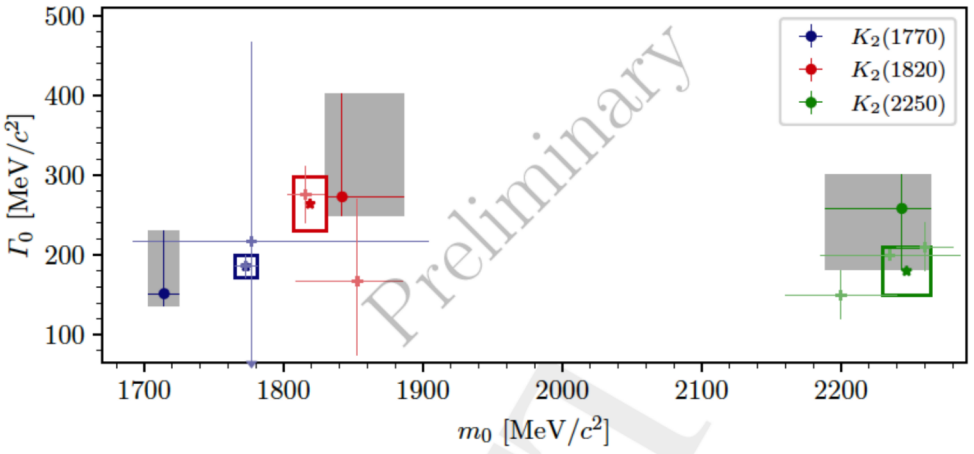
- same fit quality for resonance and triangular singularity

Backup strange mesons K_2

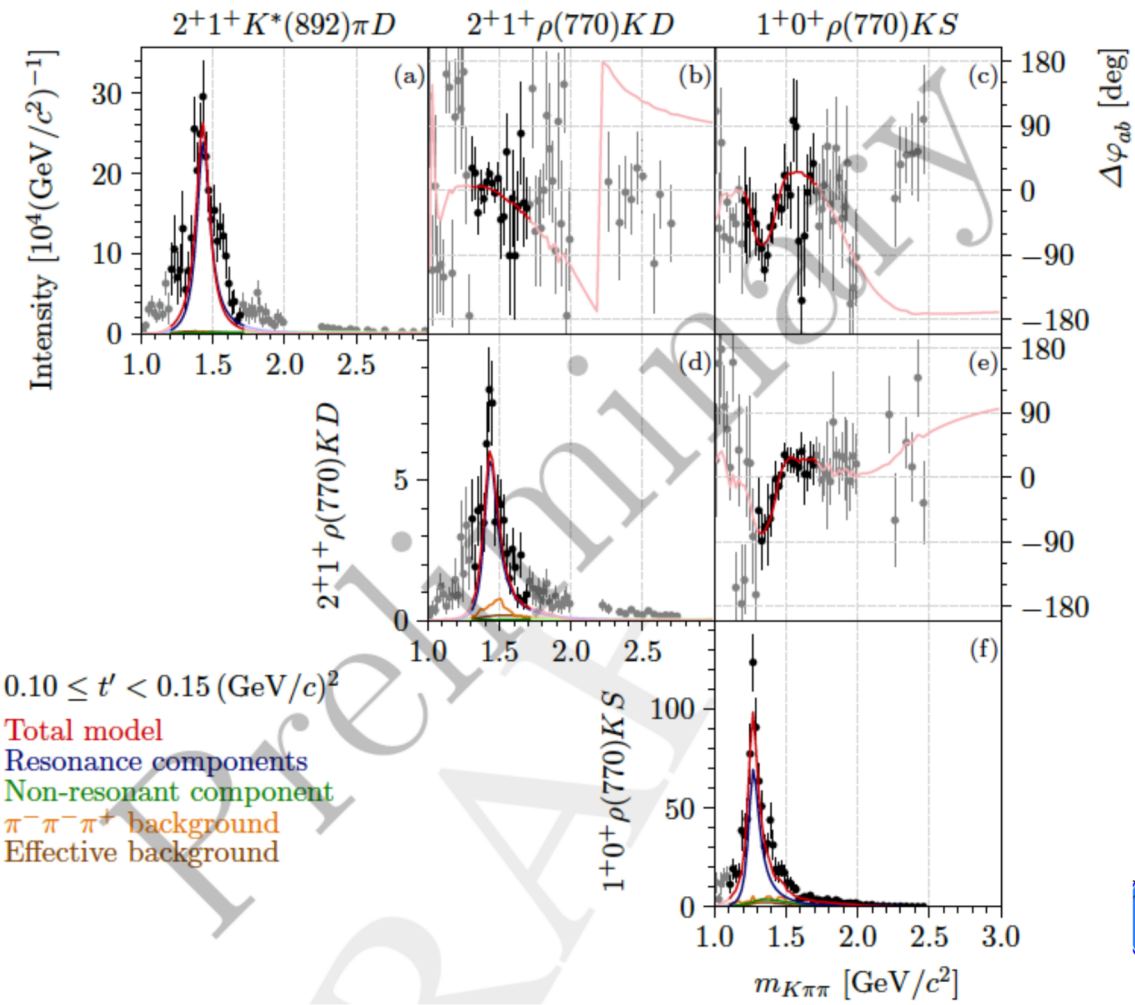
- K_2 : t' dependence (4 t 'bins)



- BW parameters: Systematics of fit:



Backup strange mesons K_2^*

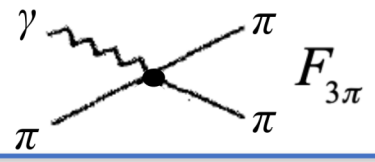


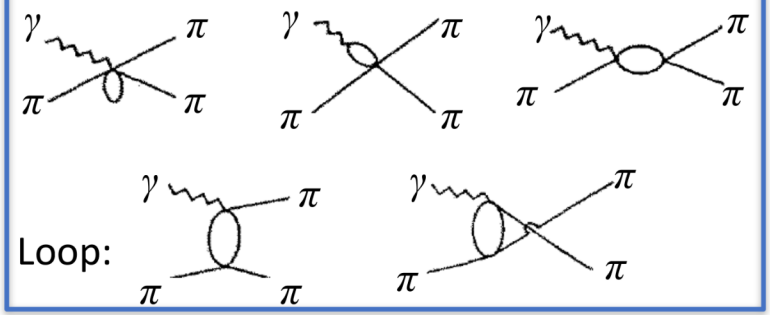
$\pi^- \gamma^* \to \pi^- \pi^0$

$$T_{\gamma 3\pi} \propto \frac{e}{4\pi^2 f_\pi^2} = F_{3\pi}$$ determined by chiral anomaly of QCD

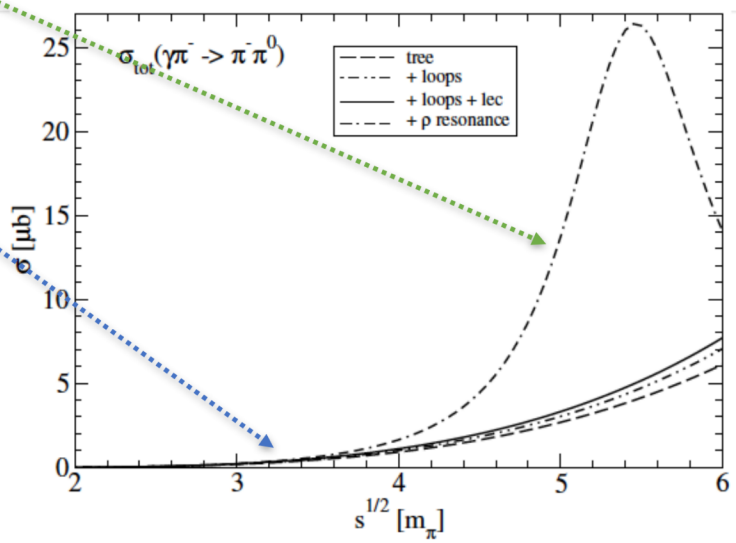
Antipov et al in Serpukhov:
$F^{3\pi} = 12.9 \pm 0.9 \pm 0.5\ \mathrm{GeV}^{-3}$
reanalyzed - many systematics

- strong final state interaction:

Tree:  $F_{3\pi}$

Loop: 

$\pi^- \pi^0 \to \rho \to \pi^- \pi^0$



Comparison to Previous Measurements

- COMPASS: First combined measurement of

$F_{3\pi}$ and $\Gamma_{\rho\to\pi\gamma}$

$$F_{3\pi} = (10.3 \pm 0.1_{stat} \pm 0.6_{syst})\,\mathrm{GeV}^{-3}$$

$$\Gamma_{\rho\to\pi\gamma} = (76 \pm 1\ (\mathrm{stat})\ ^{+10}_{-8}\ (\mathrm{syst}))\ \mathrm{keV}$$

- Intensive study of systematics:
  - multiple K^- decay modes
  - Various background studies (ω and π exchange)
- Detailed π^- Ni $\rightarrow \pi^-\pi^0\pi^0$ Ni analysis for diffractive background subtraction

Expect final uncertainties ~ 4%

Previous measurements (80's):

$$^{*}\Gamma_{\rho\to\pi\gamma} = (81 \pm 4 \pm 4)\ \mathrm{keV}$$

separation of nuclear and Coulomb processes from $\mathrm{d}\sigma/\mathrm{d}t$

- Neglect chiral contribution to $\pi^-\pi^0$
- No detailed 3π diffractive background study
- Unresolved beam composition

$$^{**}F_{3\pi} = (10.7 \pm 1.2)\ \mathrm{GeV}^{-3}$$

- Neglect s-channel production of ρ meson
- No proper consideration of systematics

* Capraro, L. *et al.* NPB 288 (1987) 659-680 at CERN (SPS):
**Y. *et al.* PRD 36 (1987) 101103 and reanalyzed by Ametller, L. *et al.* PRD 64 (2001) 094009

Examples for Excited (and Exotic) Kaons

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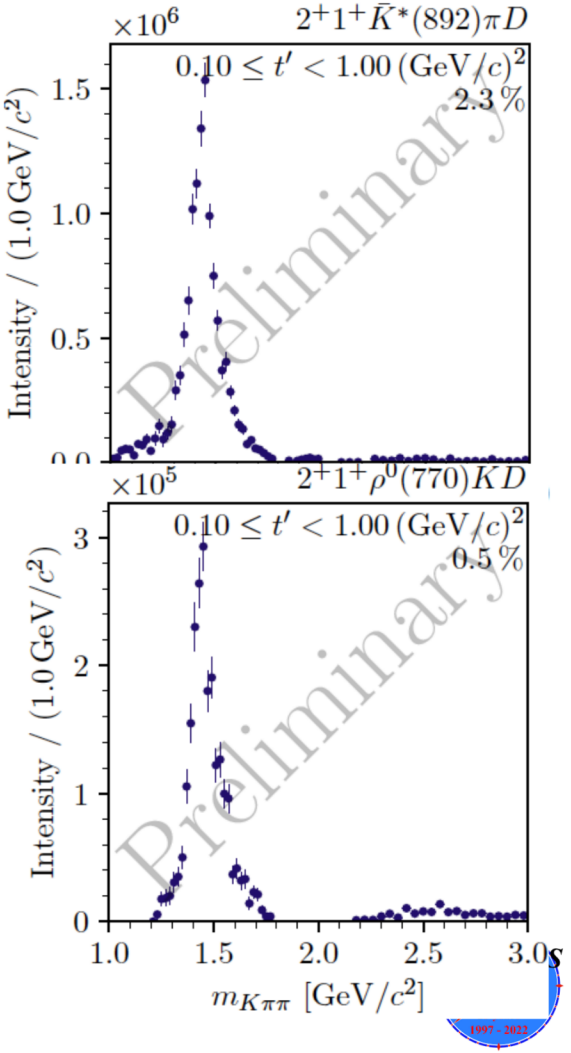
- $J^P = 2^+$: $K_2^*(1430)$ in $K^*(892)\pi$ and $\rho(770)K$



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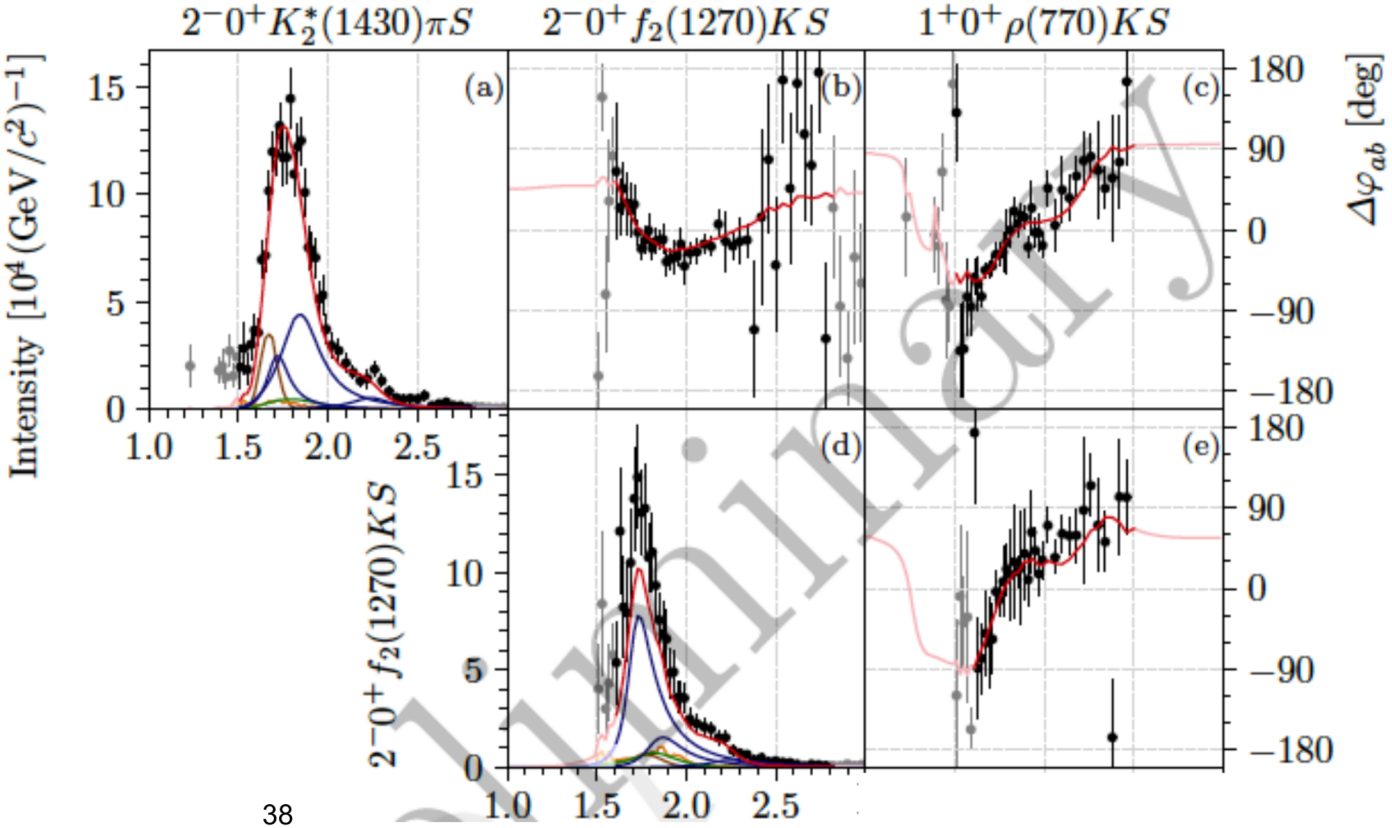
  - $K_2(1820)$
  - $K_2(2250)$ (confirmation)
  - coherent fit including all



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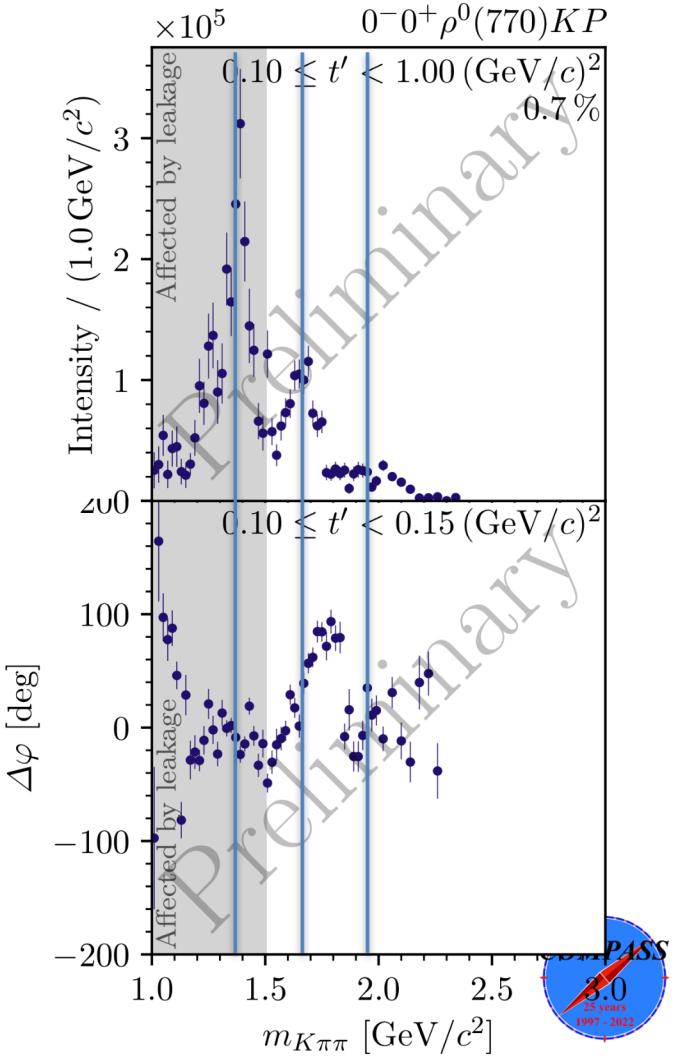
  - $K_2(1770)$
  - $K_2(1820)$
  - $K_2(2250)$ (confirmation)
  - coherent fit including all
- $J^P = 0^-$: $K^*(892)\pi$ and $[K\pi]_S\pi$ and $\rho(770)K$
  - $K(1460)$
  - $K(1630)$ (supernumerous)
  - $K(1830)$ (weak)



Strange-Meson Spectroscopy

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COMPASS hadron beam contains $2.4\,\%$ kaons

- first analysis: $K^- + p \rightarrow K^-\pi^+\pi^- + p'$
- $0.7 \cdot 10^6$ evts in $t' \in [0.1,1.0]$ GeV/c^2

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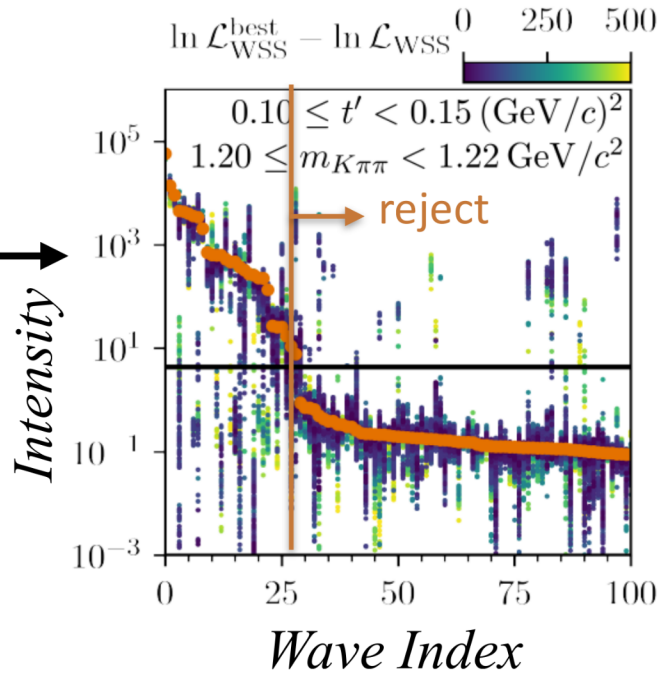
  selection of 15-80 waves ($m_{K\pi\pi}$ dependent) - 596 waves offered



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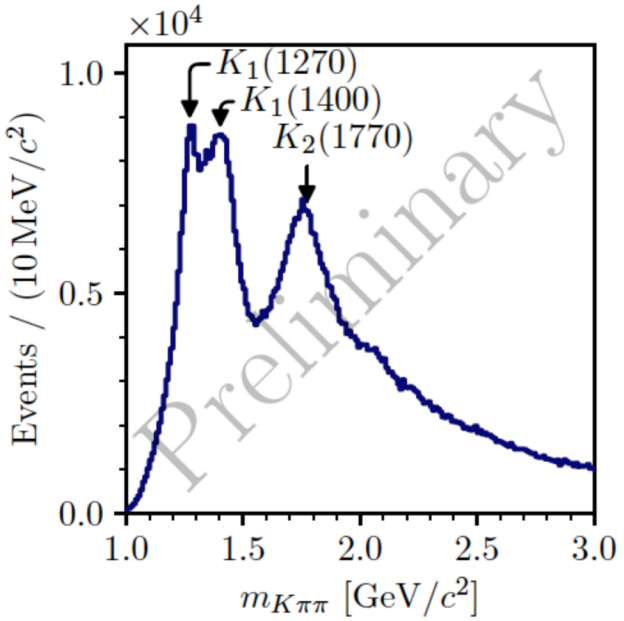
- treat pion background reaction $\pi^- + p \to \pi^-\pi^+\pi^- + p'$ through incoherent wave set in PWA (novel)

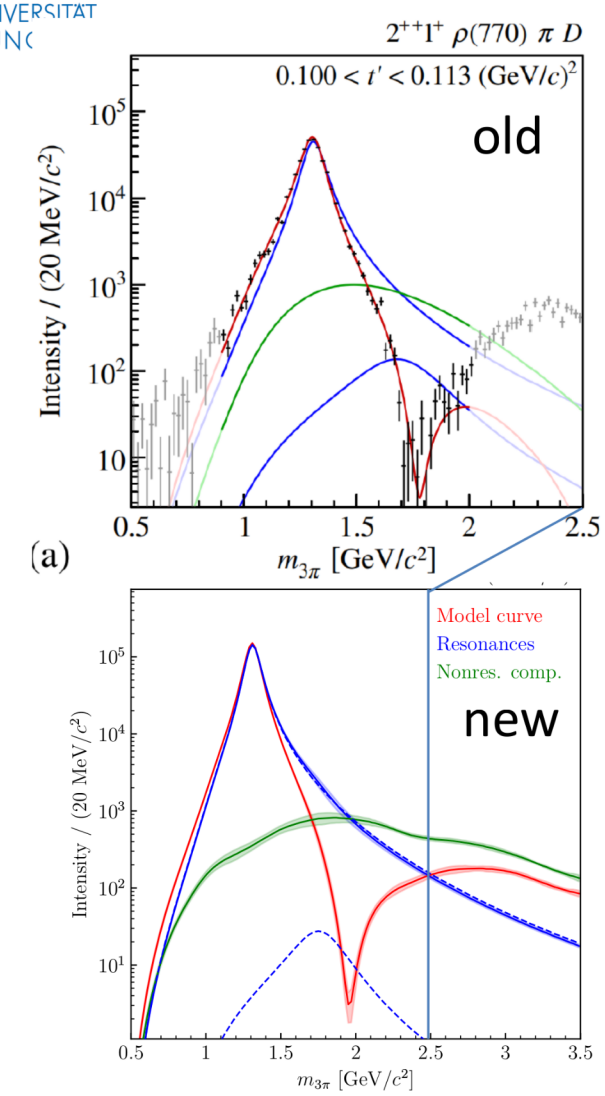


COMPASS Spectroscopic reactions

- $\pi^- p \to \pi^-\pi^-\pi^+ + p$ ✓
- $\pi^- p \to \pi^-\pi^0\pi^0 + p$ ✓
- $\pi^- p \to \omega\pi^-\pi^0 + p$ ✓
- $\pi^- p \to \pi^-\pi^-\pi^+\eta + p$ ✓
- $\pi^- p \to \pi^-\eta + p$ ✓
- $\pi^- p \to \pi^-\eta' + p$ ✓
- $\pi^- p \to \pi^- f_1(1285) + p$ ✓
- $\pi^- p \to K_s^0 K_s^0 \pi^- + p$ ✓
- $\pi^- p \to K^- K_s^0 + p$ ✓
- $K^- p \to K^-\pi^-\pi^+ + p$ ✓
- $K^- p \to K_s^0\pi^- + p$ ✓
- $K^- p \to \Lambda\bar{p} + p$ ✓

- $\pi^-\gamma^* \to \pi^-\pi^-\pi^+$ ✓
- $\pi^-\gamma^* \to \pi^-\pi^0\pi^0$ ✓
- $\pi^-\gamma^* \to \pi^-\pi^0$ ✓
- $K^-\gamma^* \to K^-\pi^0$ ✓

Prove of new PWA-Scheme



Prove of new PWA-Scheme

Error bands obtained from variational Bayes