Excitations of flavorless and strange mesons

The case of Isovectors

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Excitations of the Ground State

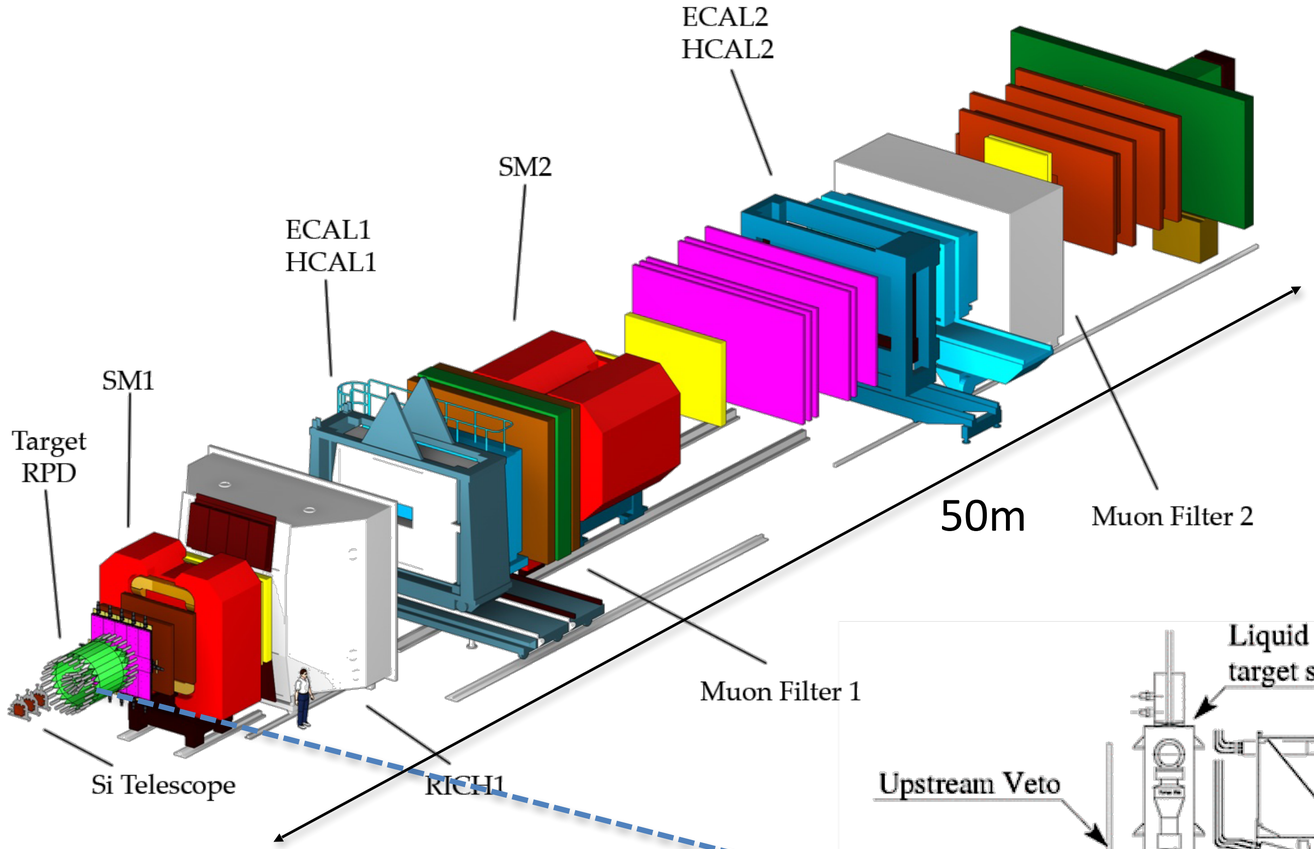
The spectroscopy of mesons

Light mesons (excitations of the pion)

Strange mesons (excitations of the kaon)

What is the excitation spectrum of the ground state ?
How stable are excitations ?
How do they couple the quarks and gluons ?
What happened to its chiral partner and its excitation ?
At which energy (mass) will the parity splitting disappear ?

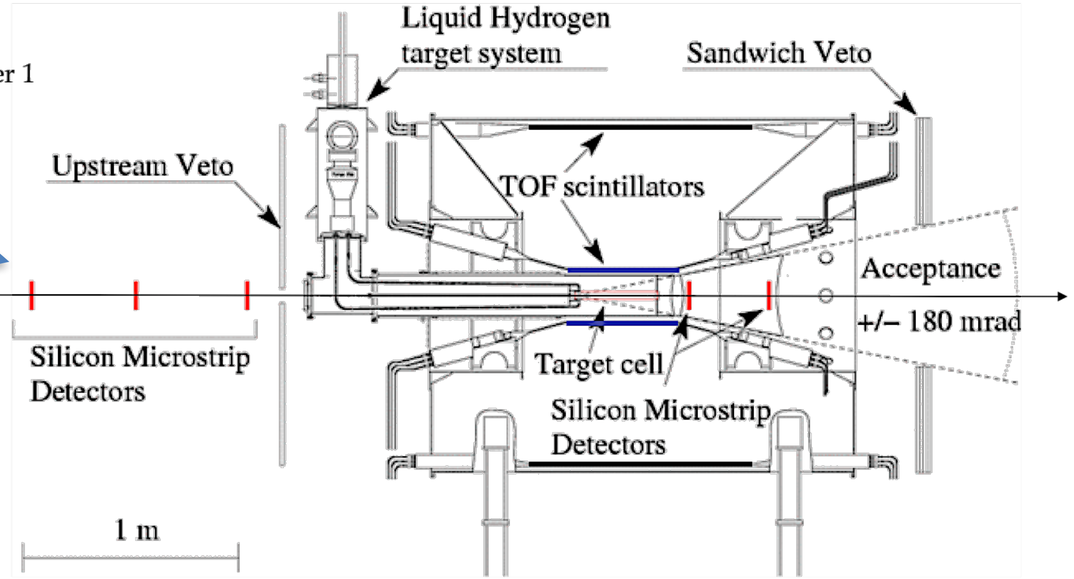
The COMPASS Experiment



CERN SPS

Hadron beam:

- 190 GeV/c π, K, p
- $5 \cdot 10^7$ particles/SPS-spill
- 60 days data taking 2008
- Trigger: RPD hit, beam veto



Selected 2-, 3- and 4-body final states from diffractive scattering of π^- and K^-

In diffractive scattering :

$$beam + p \rightarrow \boxed{X^-} + p \rightarrow \boxed{final\ state} + p$$

information on X^- obtained from partial wave analysis of the final state hadrons

COMPASS investigates numerous multi-body final states

- 2-body
  - $\boxed{K_s^0 K^-}$, $\eta\pi$, $\eta'\pi$, $f_1(1285)\pi$
  - $K_s^0\pi^-$, $\Lambda\bar{p}$
- 3-body
  - $\boxed{\pi^-\pi^+\pi^-}$, $\pi^-\pi^0\pi^0$
  - $\boxed{K^-\pi^+\pi^-}$
- effective 3-body
  - $\boxed{\omega\pi^-\pi^0}$
- 4-body
  - $\boxed{\eta\pi^+2\pi^-}$
- 5-body
  - $\pi^-2\pi^+2\pi^-$

Partial Wave Analysis

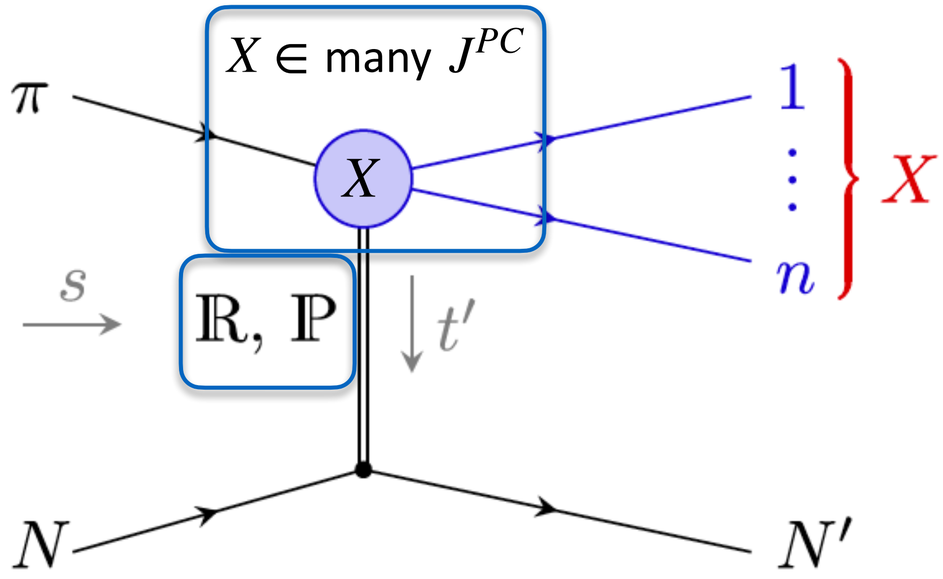
- Decomposition of a complex System (without interference)

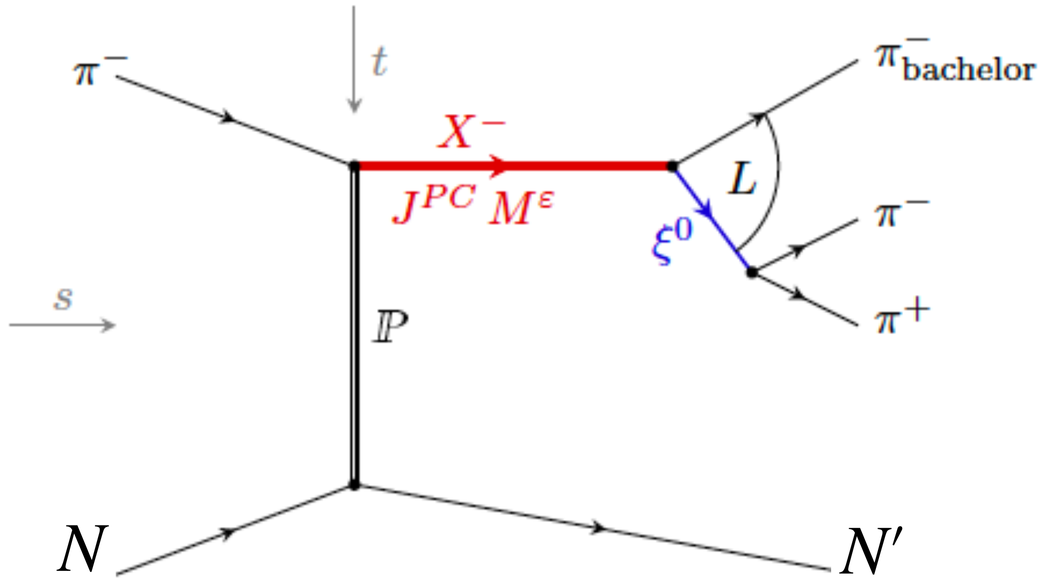
inspired by M. Pennington

Art taken from Urs Wehrli: “Kunst aufgeräumt”

Partial Wave Analysis

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

Classical Partial Wave Analysis

step 1

Example: 3-body - describe population in 5-dimensional phase space of final state by model

Define a set of quantum numbers J^{PC}

Define a set of decay channels for each J^{PC}

($X^- \rightarrow$ isobar + π; isobar$\rightarrow\pi\pi$) : wave (n waves used)

each such "wave" has a pre-determined population in phase space

each wave may have alignment of *J* described by quantum number *M*

For each bin of 20 MeV/c^2 mass of final state: determine which coherent combination of waves fits distribution best

Obtain spin-density matrix

likelihood

step 2

- Describe spin density matrix (submatrix) by model containing resonances and non-resonant contributions connecting all mass bins
- Determine resonance parameters

χ^2

New Fit Scheme

$$\sigma(m_X, \tau) = \sigma_0 \left| \sum_{\text{waves}} T_{\text{wave}}(m_X)\, A_{\text{wave}}(m_X, \tau) \right|^2$$

partial wave decomposition: exact only for $n_{waves} \to \infty$

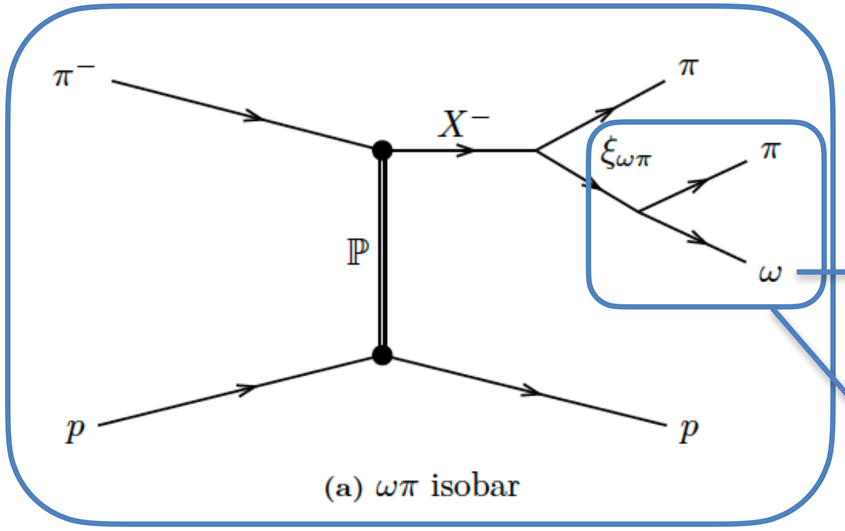
impractical ⇨ cut off needed

New Fit Scheme

- Two new procedures introduced
- Automatic model selection
  - increase model space to over 332 -860 waves (depending on final state)
  - novel algorithm for selection of individual waves (thresholding, detection destructive interference of small waves, regularisation via Cauchy or double Pareto)
  - resulting model space varies across mass range
- „All-in-One“-Fit (AoI) (extended NIFTY (**N**umerical **I**nformation **F**ield **T**heor**y**“) technique)
  - smoothing of fit variations across neighboring mass bins
  - simultaneous extraction of complex amplitudes from data and separation of components

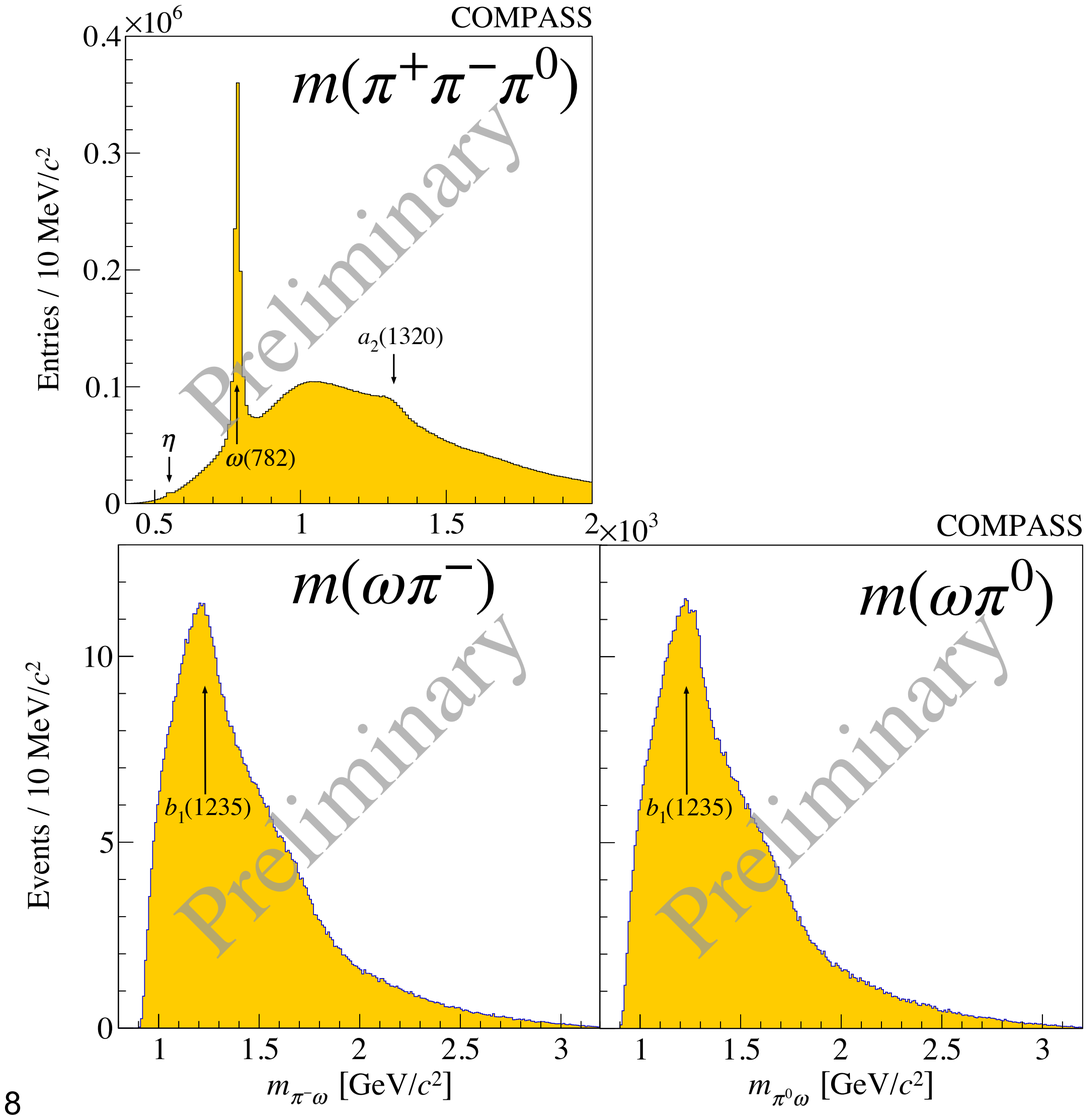
$\pi^- p \to \omega\pi\pi\, p \to 2\pi^- 2\pi^0 \pi^+\, p$

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



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

$b_1 \to \omega\pi^{0,\pm}$



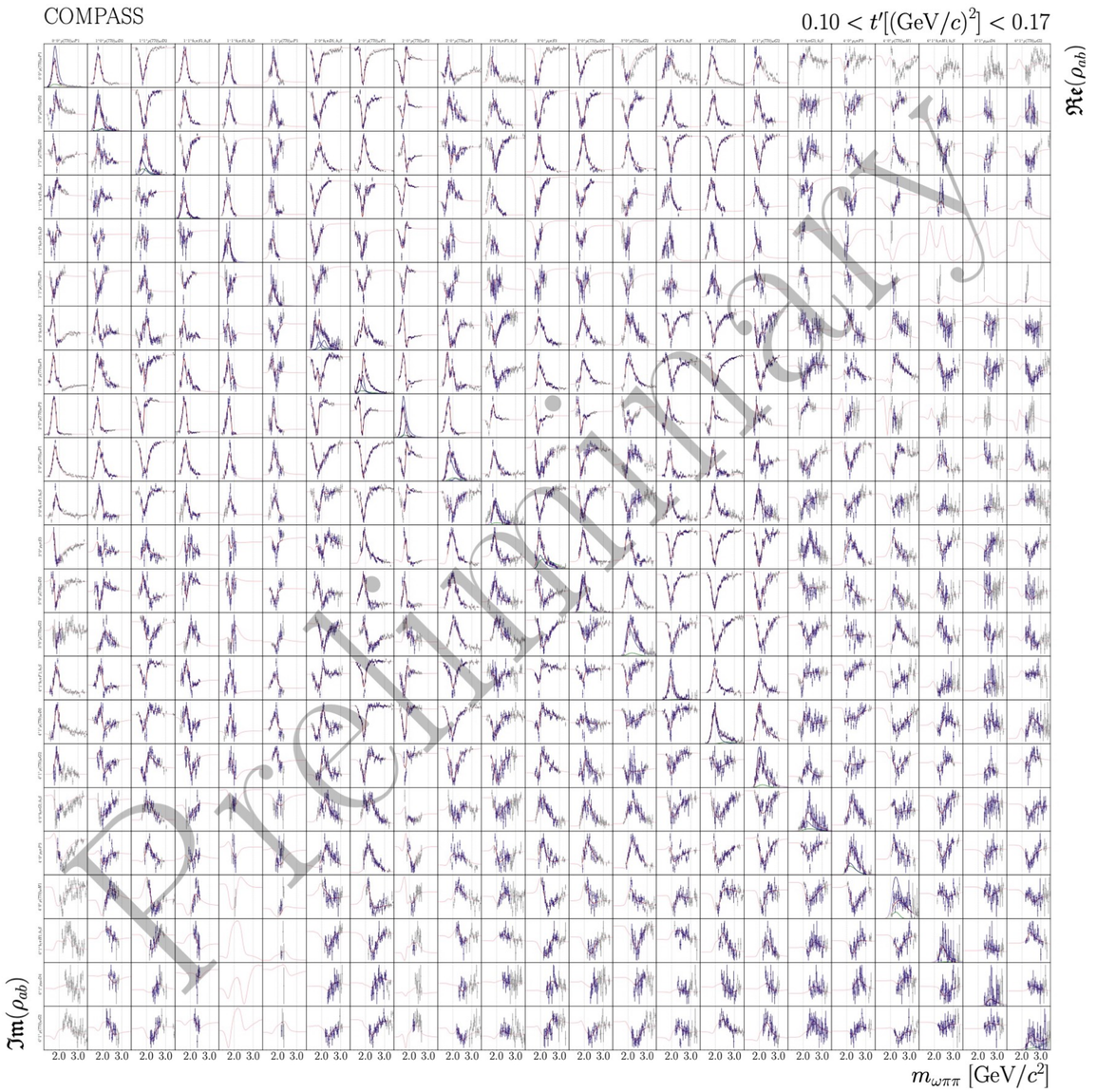
select 40 waves

Spin density Matrix $\pi^- p \rightarrow \omega\pi\pi\ p$

Fit 23x23x4 elements of $\rho_{\omega\pi\pi}(m, t')$

4500 data points

350 free parameters

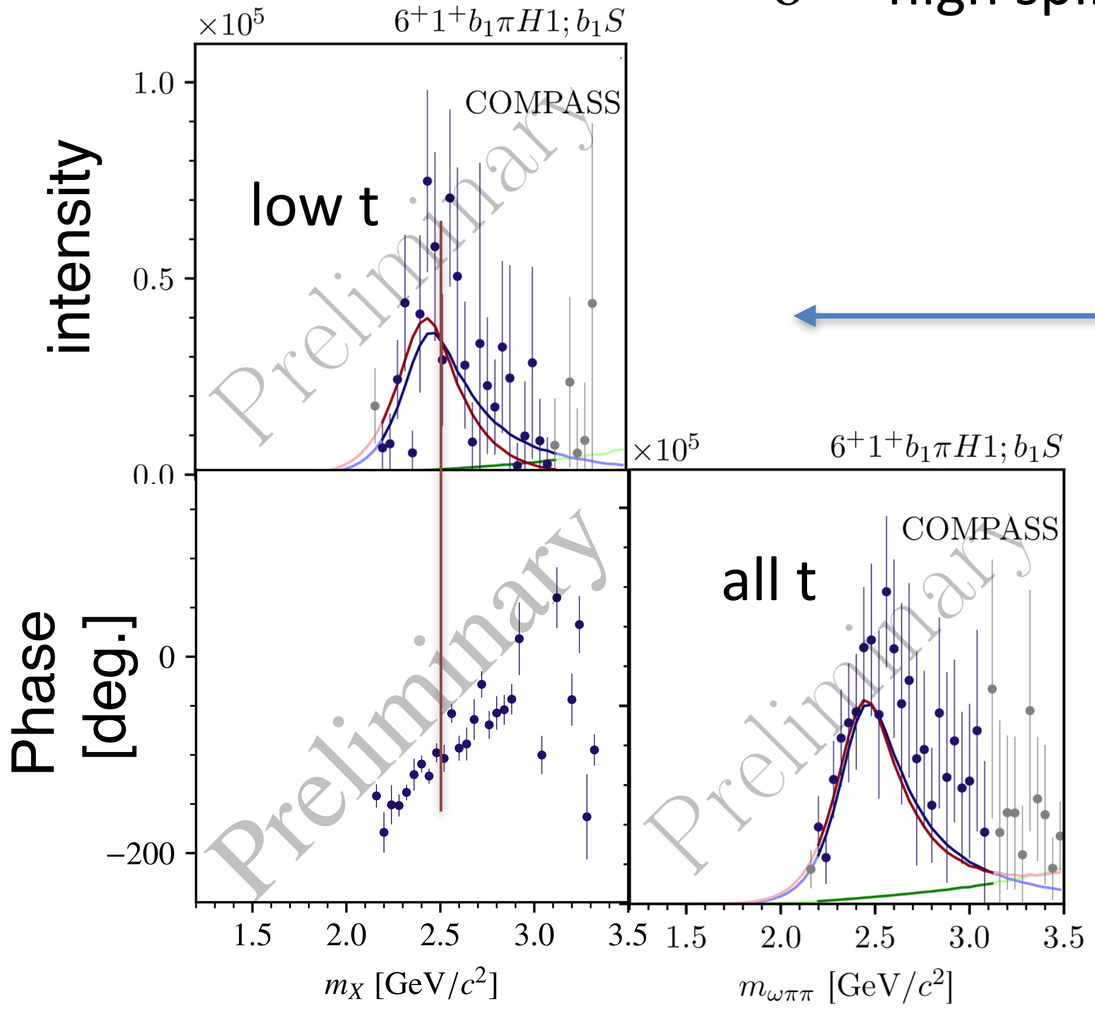


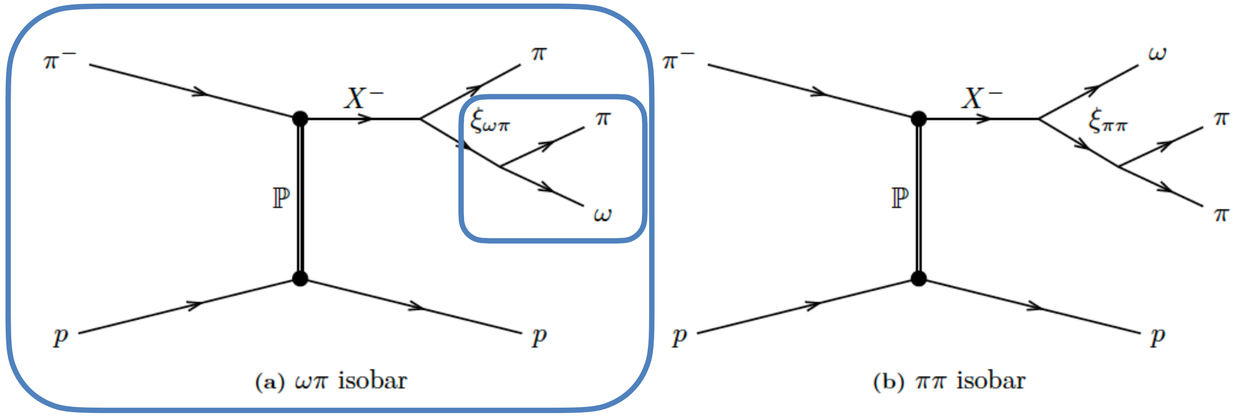
3π analysis: fit 64 x 64 x 11 elements of $\rho_{\pi\pi\pi}(m, t')$

45000 elements $\rho_{\pi\pi\pi}(m, t')$!!

$\pi^- p \to \omega\pi\pi\, p$

exciting example in $a_6(2500) \to [b_1(1235)\pi]\ (L = 5) \to (\omega\pi)\pi$:
6^{++} high spin system

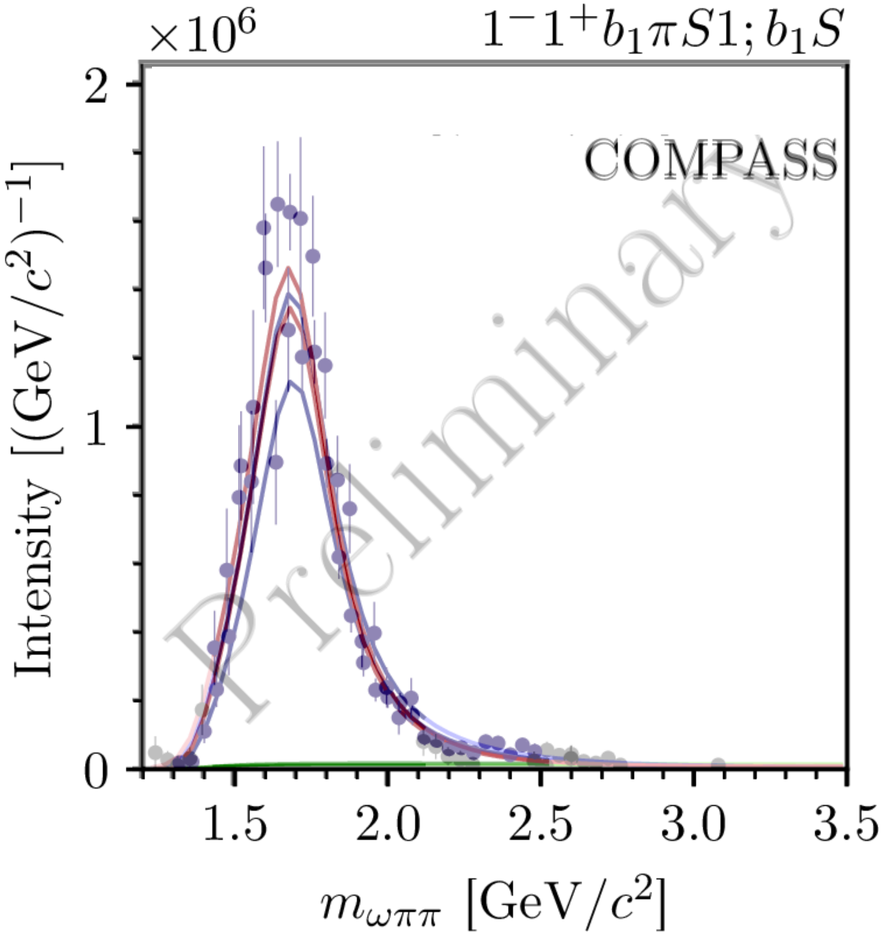




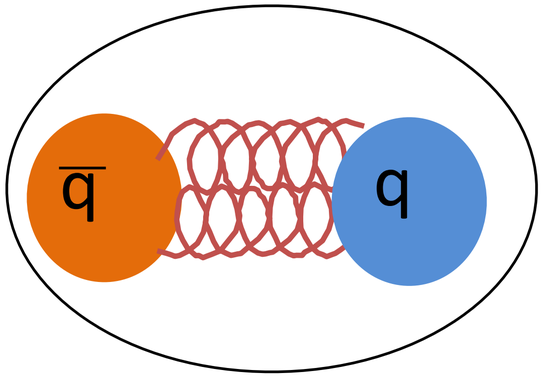
* in total 150 waves appear in various mass ranges
(from the pool of 830 waves)

1^{-+} Exotic in $\pi^- p \to b_1\pi\, p \to \omega\pi\pi\, p$

- Two decay modes possible passing through L = 0 and L = 2:

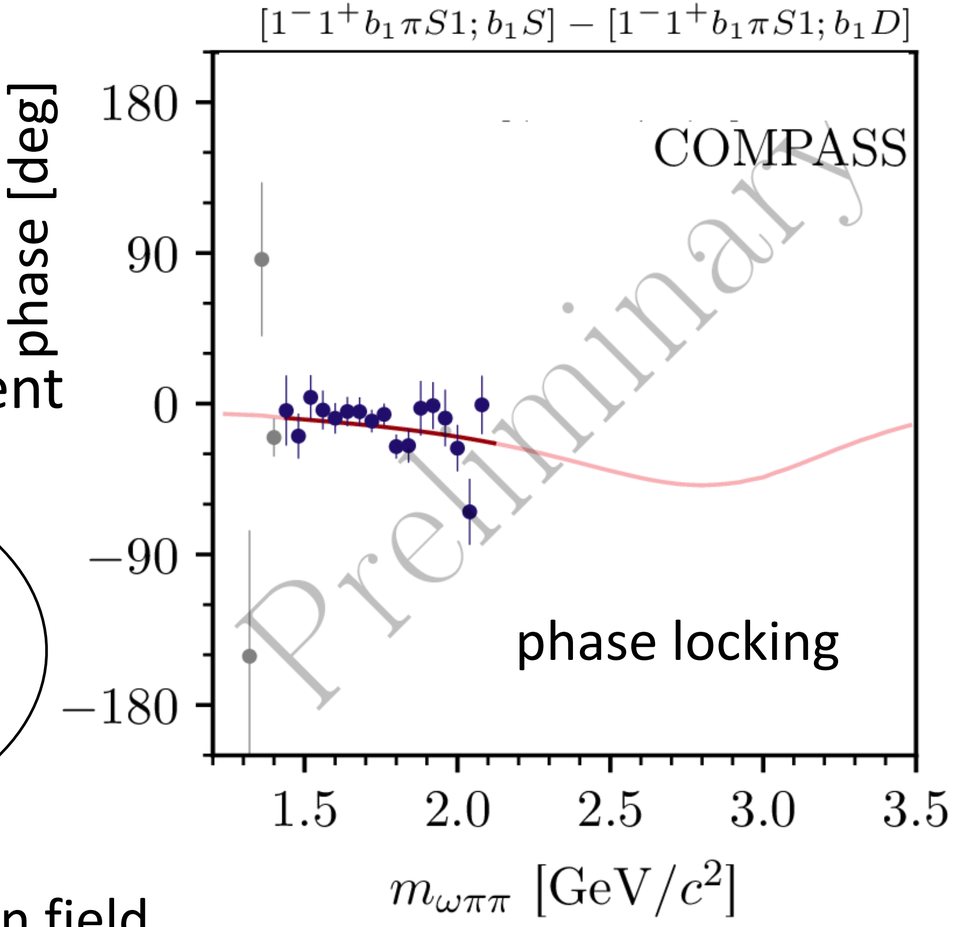


Results are consistent



Excitation of the gluon field

$\pi_1(1600)$



Summary $\pi^- p \to \omega\pi\pi\ p$

Resonance	m_0 [MeV/c^2]	Γ_0 [MeV/c^2]	
$\pi(1800)$	$1768 \pm 6^{+21}_{-16}$	$320 \pm 9^{+14}_{-16}$	
$a_1(1640)$	$1660 \pm 20^{+30}_{-50}$	$370 \pm 30^{+20}_{-50}$	
$a_1(1930)$	$1970 \pm 20^{+30}_{-40}$	$230 \pm 30^{+140}_{-40}$	new
$\pi_1(1600)$	$1723 \pm 6^{+37}_{-14}$	$336 \pm 10^{+96}_{-33}$	new decay channel - spin exotic
$\pi_2(1670)$	$1698 \pm 6^{+18}_{-7}$	$296 \pm 11^{+30}_{-15}$	
$\pi_2(1880)$	$1876 \pm 4^{+4}_{-4}$	$166 \pm 8^{+8}_{-18}$	
π_2''	$2142 \pm 12^{+15}_{-21}$	$304 \pm 21^{+14}_{-34}$	new
a_3	$2080 \pm 10^{+40}_{-40}$	$560 \pm 20^{+100}_{-100}$	new
$a_4(1970)$	$1973 \pm 3^{+15}_{-8}$	$311 \pm 8^{+10}_{-46}$	
$\pi_4(2250)$	$2198 \pm 12^{+25}_{-27}$	$550 \pm 30^{+90}_{-40}$	new
$a_6(2450)$	$2558 \pm 31^{+12}_{-73}$	$600 \pm 90^{+60}_{-170}$	new

Look at $\pi^- p \to \eta\pi^-\pi^+\pi^- p$

involves three decay chains:

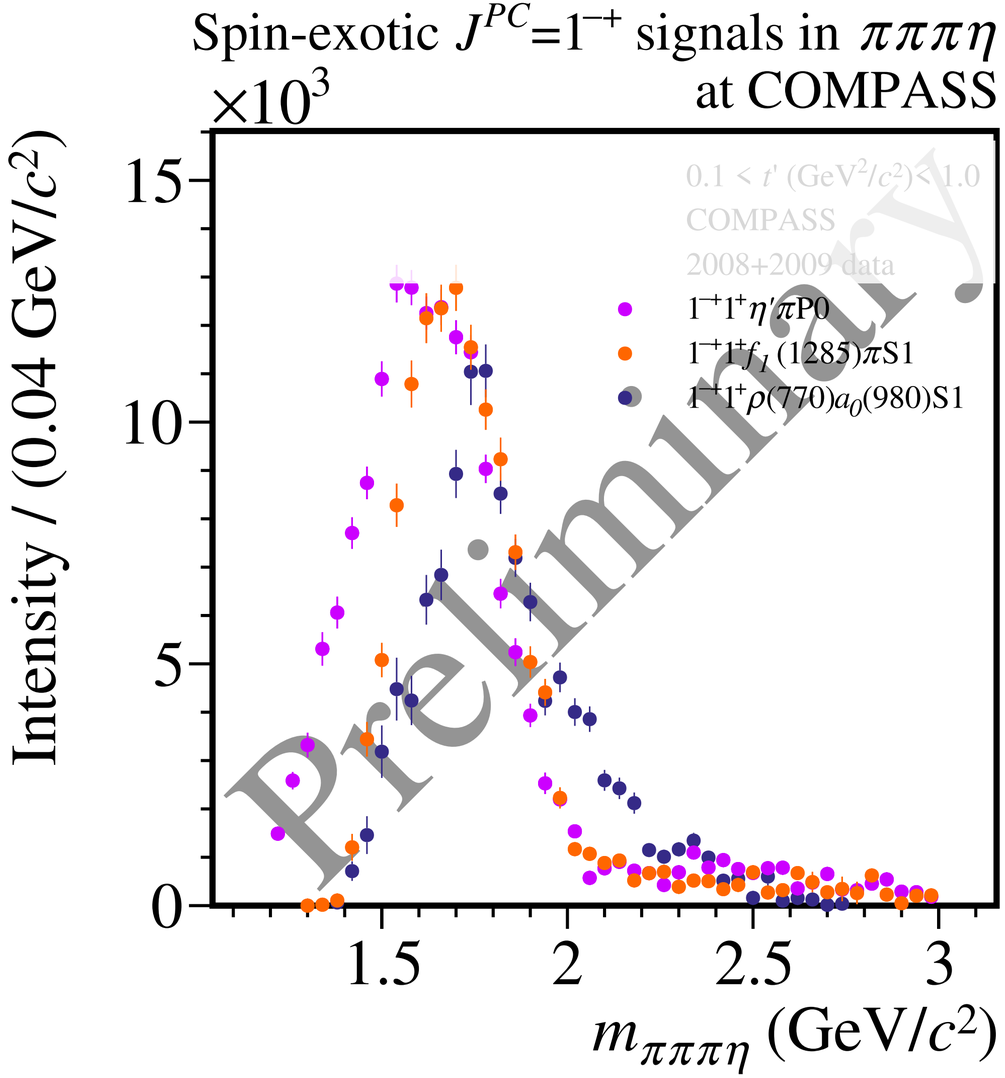
Primary Decay	Secondary Decay	Tertiary Decay
$X^- \to f_1(1285)\pi^-$	$f_1(1285) \to a_0^{\pm}(980)\pi$	$a_0^{\pm}(980) \to \pi^{\pm}\eta$
$X^- \to f_1(1285)\pi^-$	$f_1(1285) \to (\pi\pi)_S\eta$	$(\pi\pi)_S \to \pi^-\pi^+$
⋮		

use 16 isobar combinations

high mass isobars

- distortions for low mass systems (phase space)

750k events



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$X^- \to f_1(1285)\pi^-$	$f_1(1285) \to (\pi\pi)_S\eta$	$(\pi\pi)_S \to \pi^-\pi^+$
⋮		

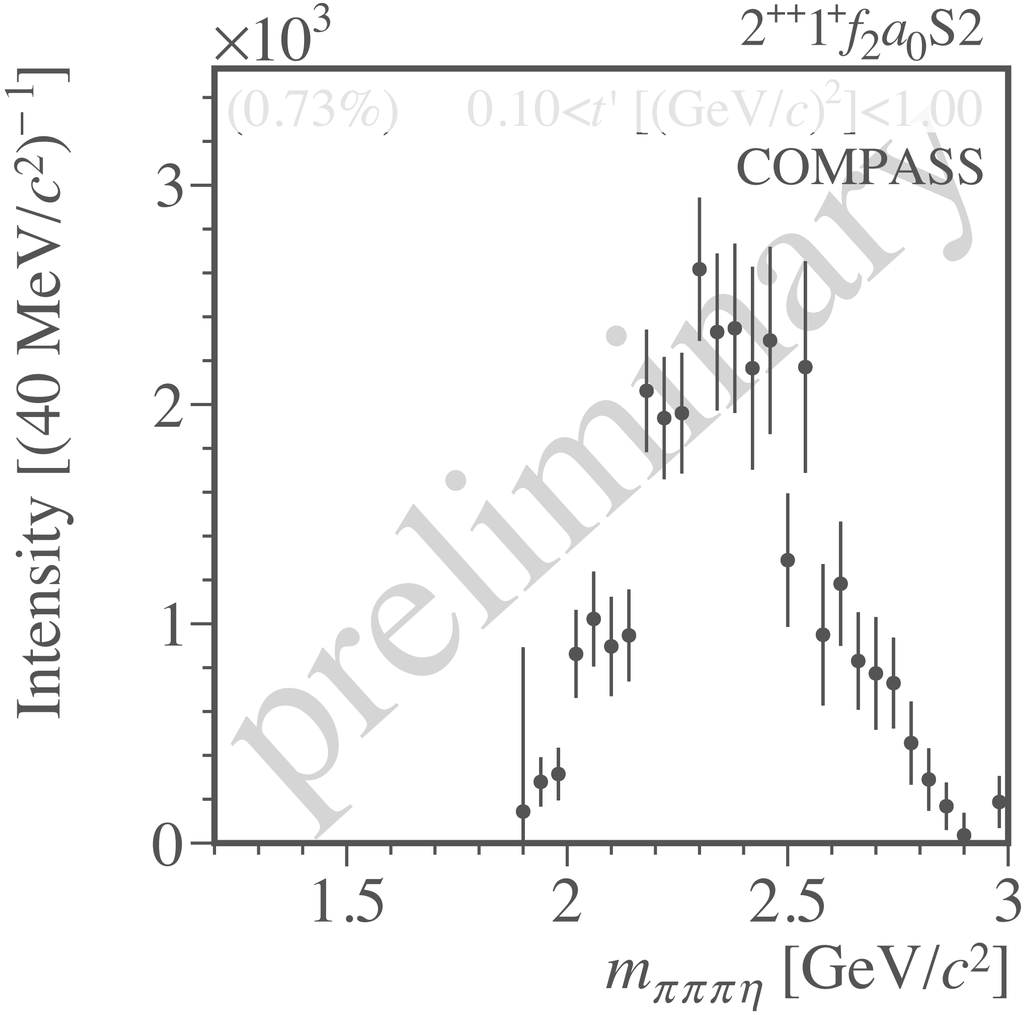
use 16 isobar combinations

high mass isobars

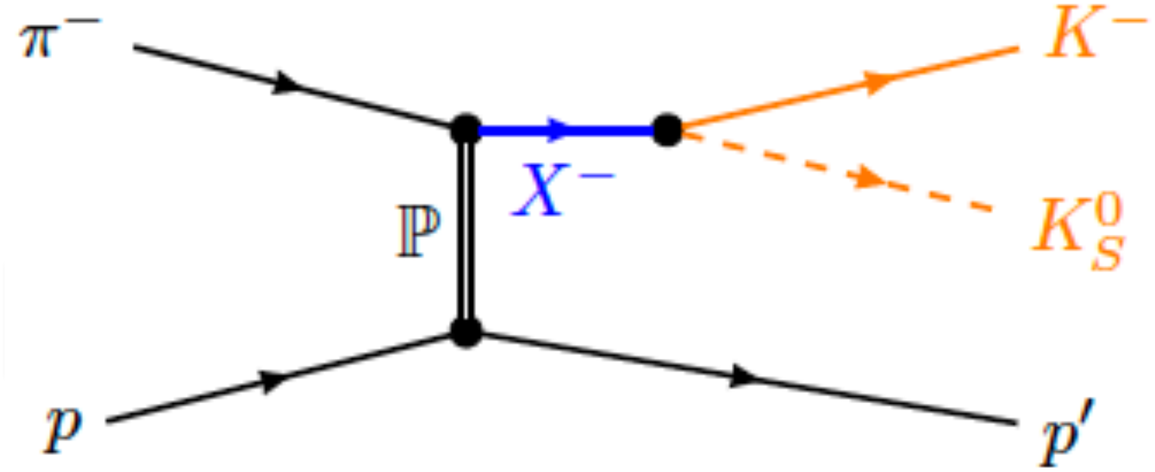
- distortions for low mass systems (phase space)
- excellent to study high mass light flavors M > 2 GeV/c²

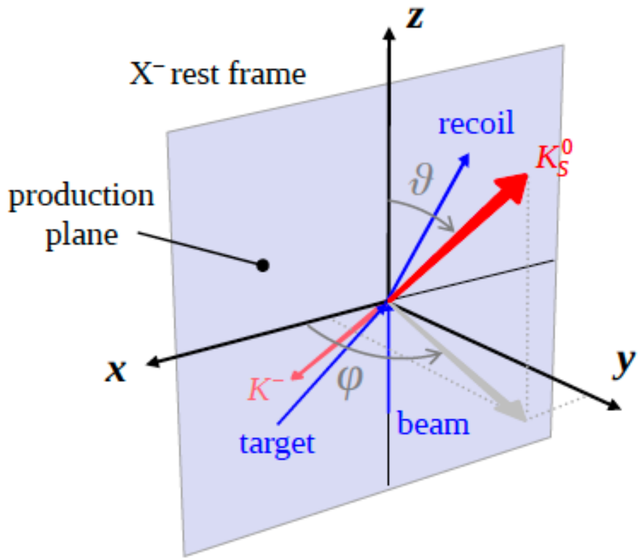
750k events

high mass a_2 - $J^{PC} = 2^{++}$ in $\pi\pi\pi\omega$



$$\pi^- p \to K_s^0 K^- + p$$


π^-
K^-
X^-
$\mathbb{P}$
K_S^0
p
p'


z
X⁻ rest frame
recoil
K_S^0
ϑ
production
plane
x
y
K^-
φ
target
beam

$\pi^- p \to K_s^0 K^- + p$

- Perform PWA
- Decay amplitudes **simple** - spherical harmonics

$$A(m_{KK}, t'; \theta, \phi) = \sum_{J,M} T_{J,M}(m_{KK}, t')\, \psi_{J,M}(\theta, \phi)$$

  - Partial-wave amplitudes split into
  - Production and propagation $T_{J,M}(m_{KK}, t')$
  - decay $\psi_{J,M}(\theta, \phi)$

- Fit: $\frac{dN}{d\Phi(\theta,\phi)} \sim I(m_{KK}, t'; \theta, \phi) = \left| \sum_{J,M} T_{J,M}(m_{KK}, t')\, Y_J^M(\theta, \phi) \right|^2$

  - separate in bins of m_{KK} and t’

- ambiguities !!

$\pi^- p \to K_s^0 K^- + p$

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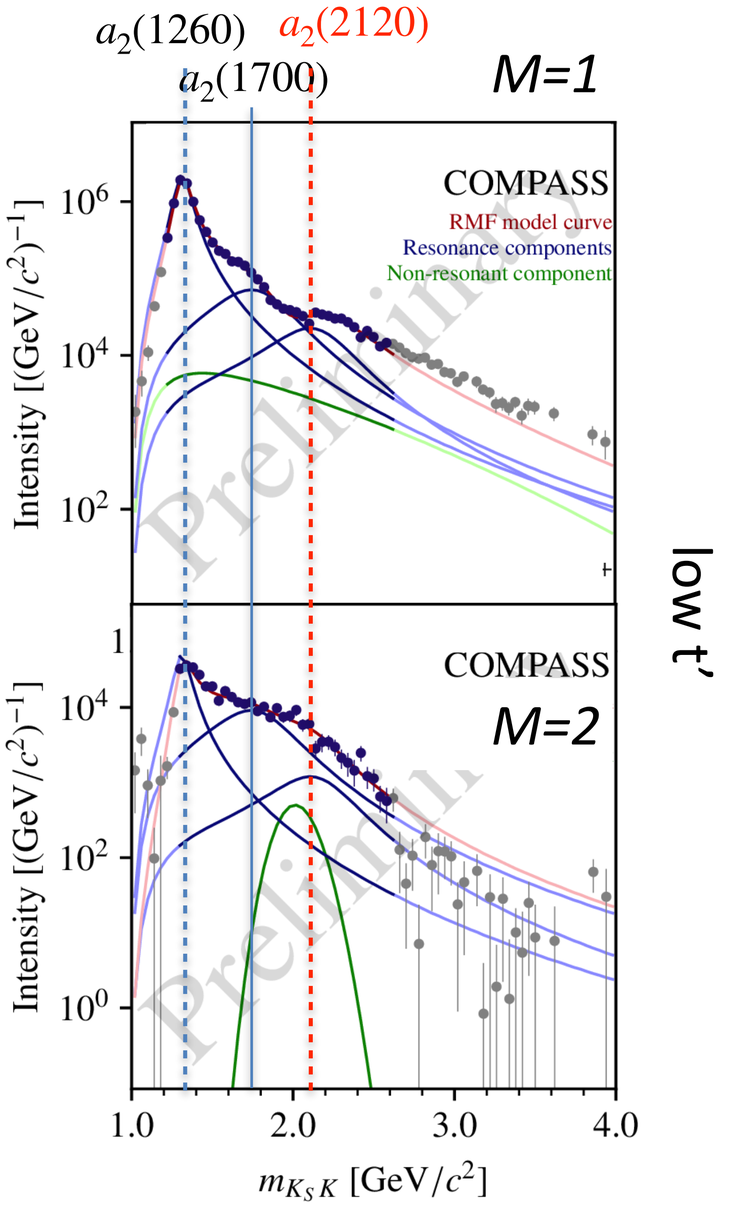


450kevts

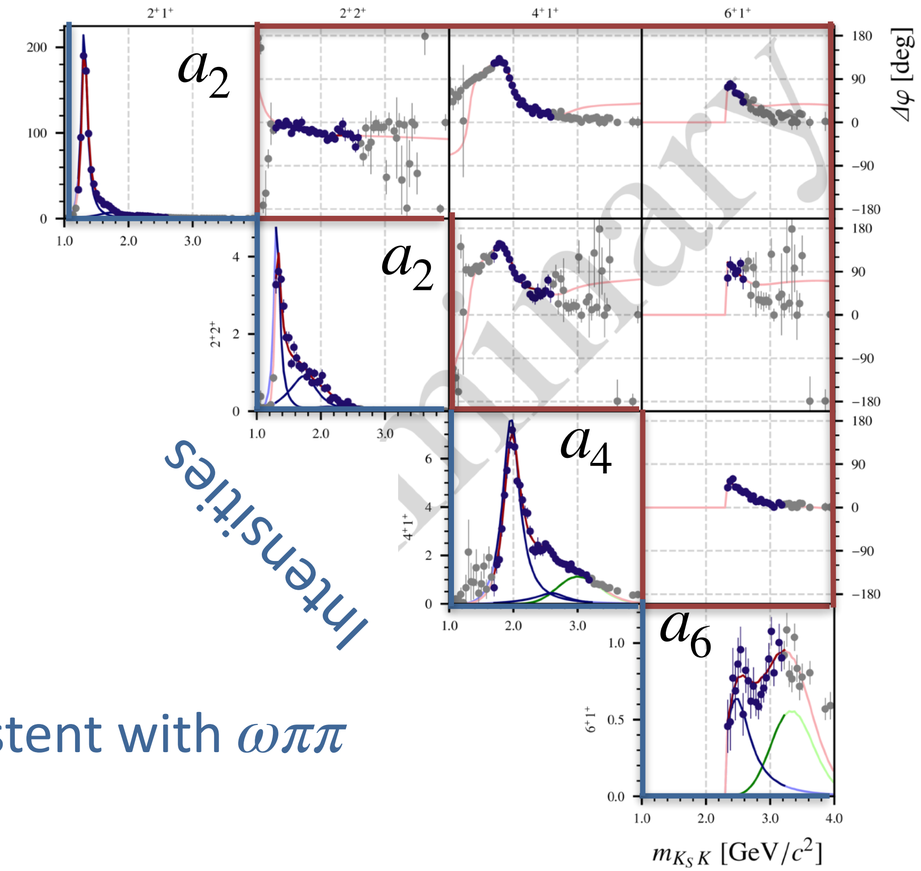
News at High Mass - a_2'', a_4', a_6

Resonance	Parameter value	
	m_0 [MeV/c^2]	Γ_0 [MeV/c^2]
$a_2(1320)$	$1316.63 \pm 0.20^{+2.23}_{-2.33}$	$109.5 \pm 0.4^{+2.6}_{-2}$
$a_2(1700)$	$1748 \pm 4^{+13}_{-86}$	$534 \pm 9^{+26}_{-230}$
a_2''	$2124 \pm 5^{+37}_{-9}$	$527 \pm 13^{+55}_{-250}$
$a_4(1970)$	$1952.2 \pm 1.8^{+3}_{-3.5}$	$327 \pm 4^{+6}_{-6}$
a_4'	$2608 \pm 9^{+5}_{-38}$	$609 \pm 22^{+35}_{-311}$
$a_6(2450)$	$2430 \pm 9^{+21}_{-25}$	$523 \pm 22^{+39}_{-119}$

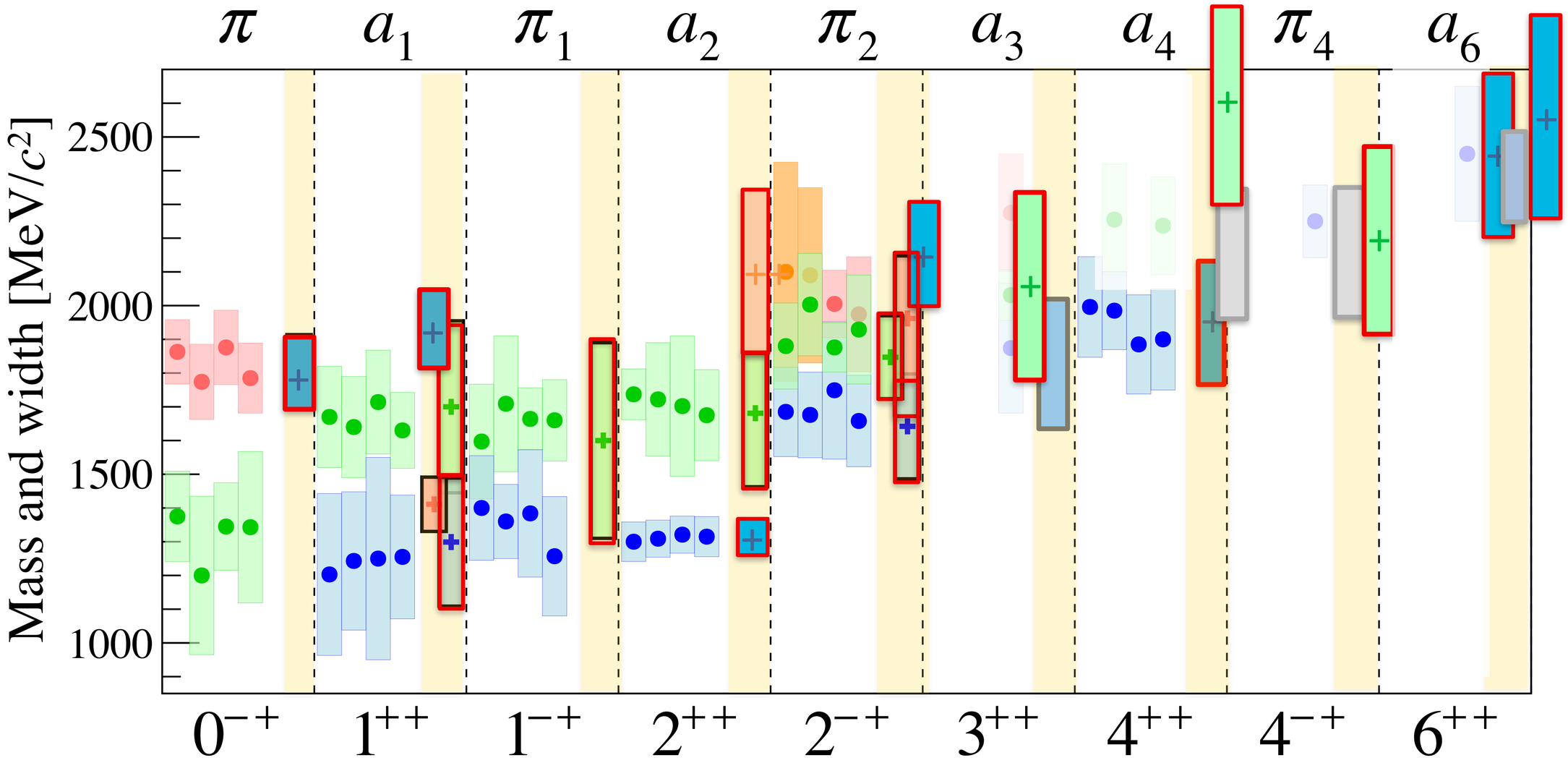
new

new

new - consistent with $\omega\pi\pi$



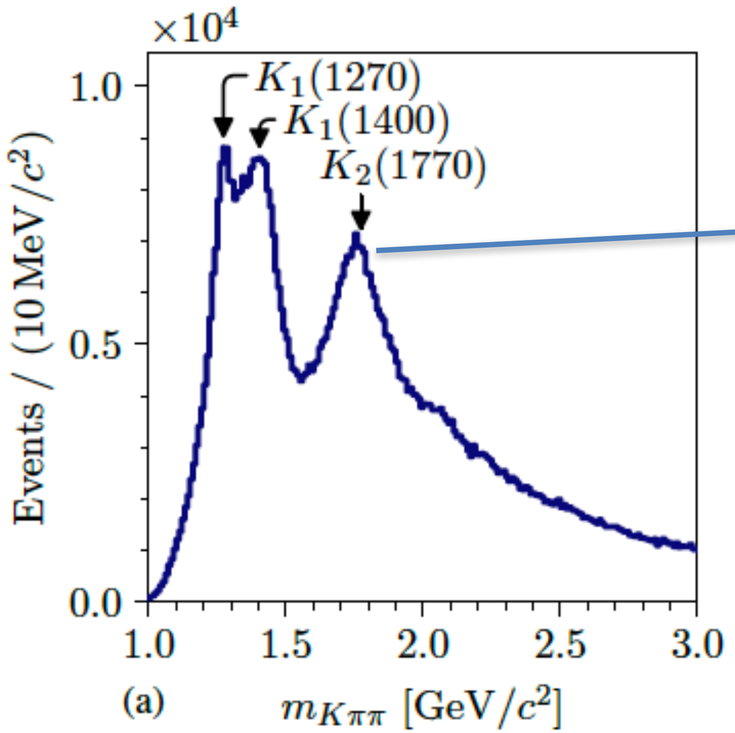
The Light Isovector Meson System



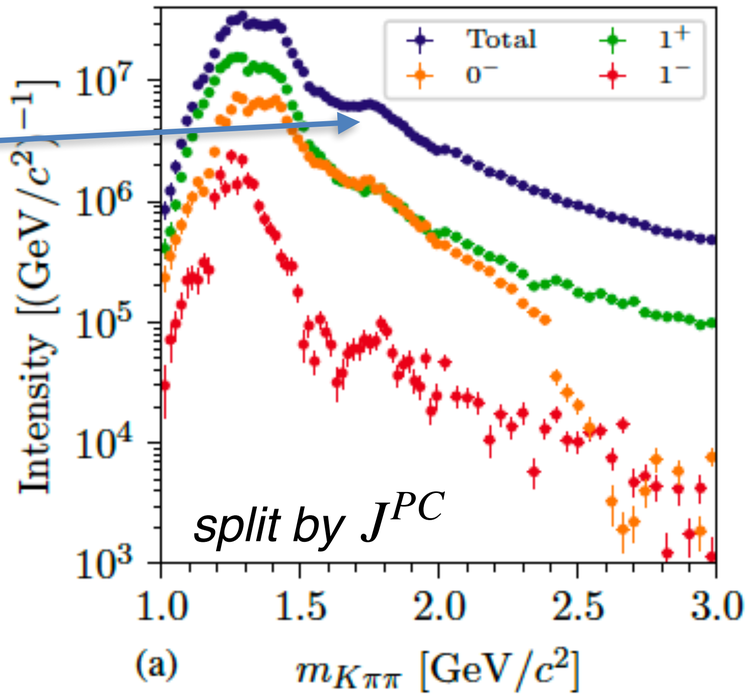
COMPASS Phys.Rev.D 98 (2018) 9, 092003

- COMPASS found 18 states in a consistent analysis (more on the horizon)

- COMPASS beam contains 2% kaons
- Identified through beam-Cherenkov detectors
- Perform analysis of reaction $K^- + p \rightarrow K^-\pi^-\pi^+ \; + \; p$ (720 kevts)

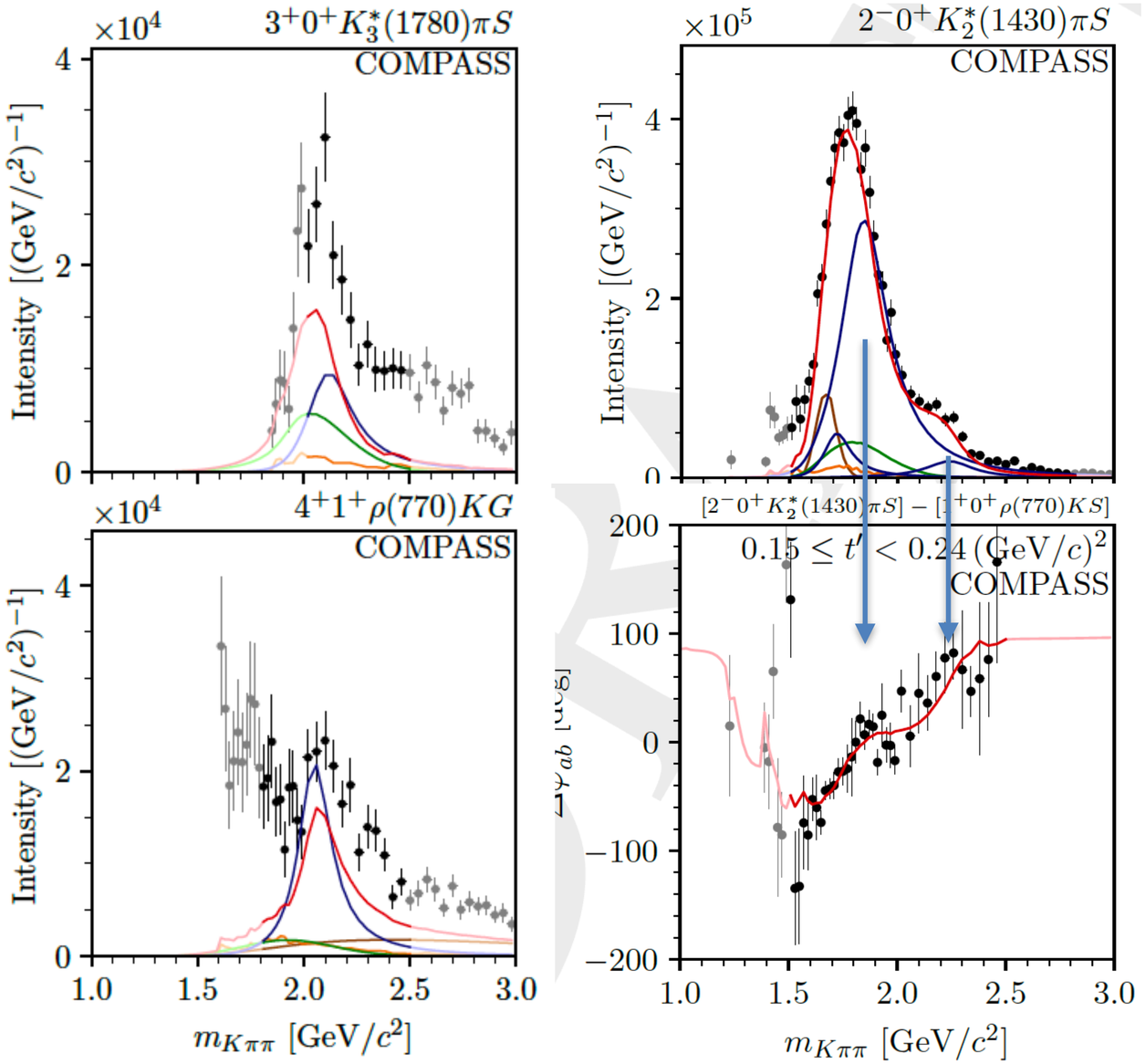


following partial wave analysis



Examples 3^+, 4^+, 2^-

- Kinematic spectrum subdivided in 4 bins of t': $[0.1,1]$ *GeV/c*^{2}
- automatic wave selection (from a 238 wave set)
- „classical“ 2-stage fit
- (14x14x4 $\rho(m_{K\pi\pi}, t')$)
- novel treatment of beam-pion background - incoherent addition
  - take 3π spectrum from COMPASS
  - analyse a $K\pi\pi$
  - scale according to known contamination ($\approx 6{,}7\,\%$)



Examples for Excited (and Exotic) Kaons

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

Calculations expect 3 states M < 2GeV/c²

Meson	J^P	Dom.	The.
K	0^-	1^1S_0	481
		2^1S_0	1512
		3^1S_0	2018
		4^1S_0	2318
		5^1S_0	2488
		6^1S_0	2567

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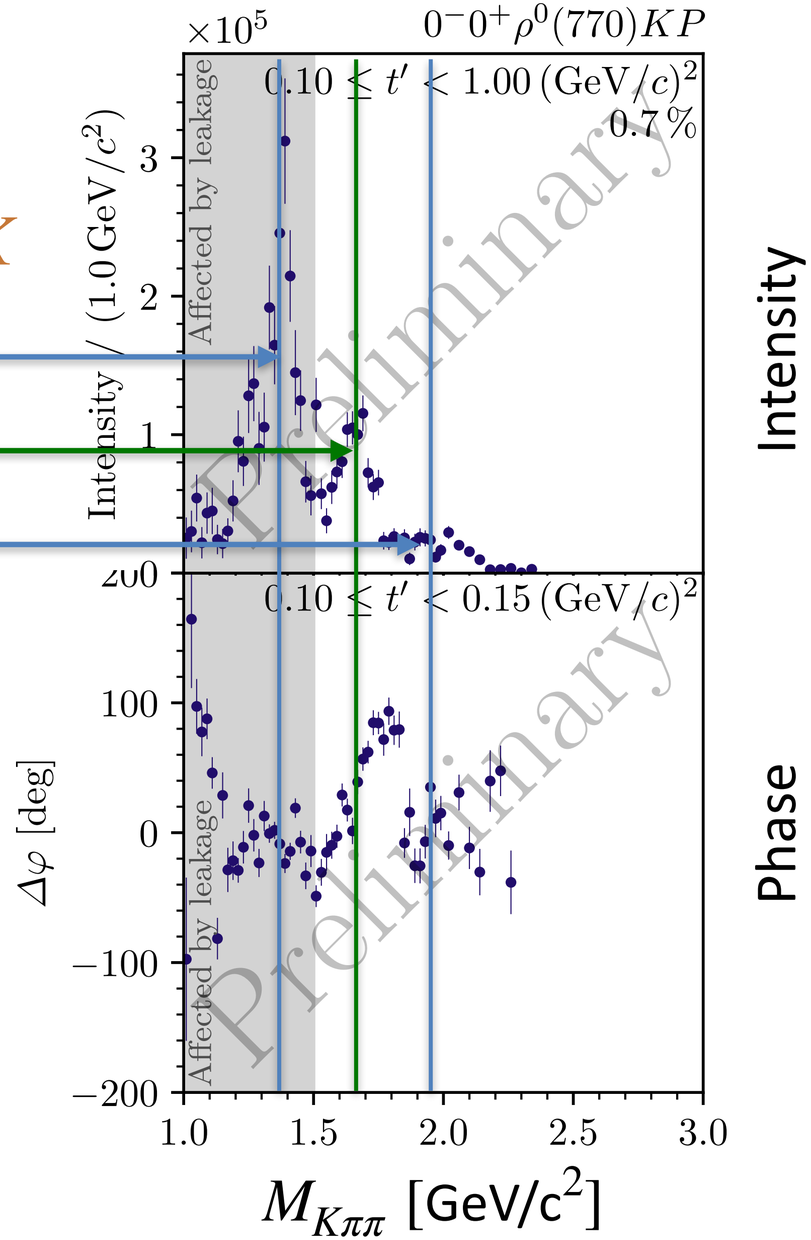
- $K(1460)$
- $K(1630)$ (supernumerous)
- $K(1830)$ (weak)



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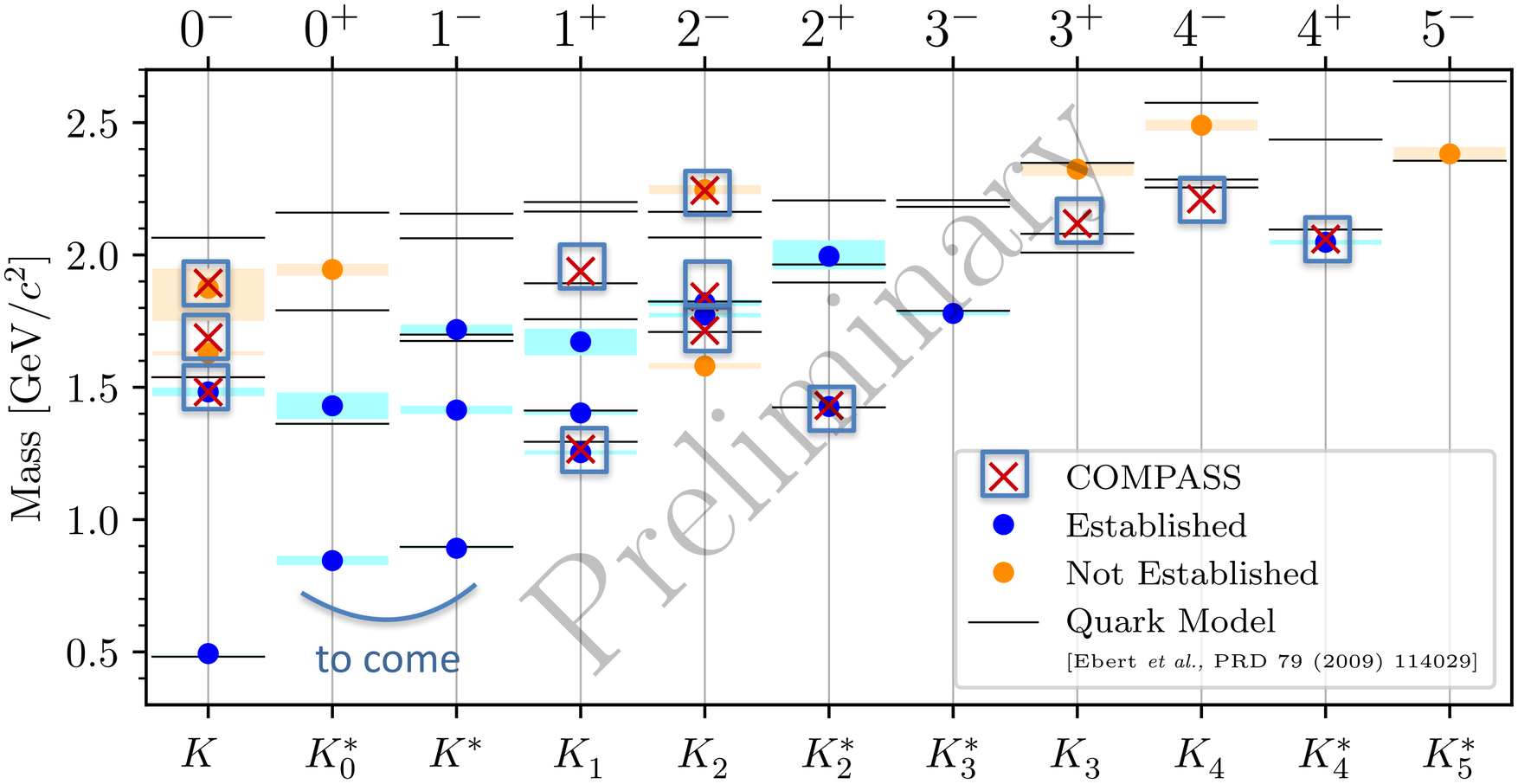
$K(1680)$ is supernumerous state → candidate for Crypto-exotic meson
First exotic meson with strangeness

Summary Strange Mesons

COMPASS observes m_0/Γ of 11 strange mesons using $K^-\pi^-\pi^+$ (publ. submitted)

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



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

Summary

Results due to excellent data and novel analysis techniques

- New analysis scheme allows to disentangle complex light mesons excitations
  - Soon resonance fits in > 100 different waves simultaneously
- Full proof of hybrid meson (gluonic excitation in pion)
  - details of decays studied extensively
- First solid observation of high mass 2^{++}
- Solid observation of medium-spin meson ($J = 3$) and excited 4^{++}
- First observation of high-spin pion (4^{-+})
- First observation of high-spin meson ($J = 6$)
- First observation of $a_1(1420)$
- First observation of „crypto“ exotic strange meson

Summary

Results due to excellent data and novel analysis techniques

- New analysis scheme allows to disentangle complex light mesons excitations
  - Soon resonance fits in > 100 different waves simultaneously
- Full p
  - deta
- First s
- Solid

Its amazing that starting from two valence quarks with mass around 5 **MeV** you can generate structures at masses of 2.6 **GeV**

- First observation of high-spin pion (4^{-+})
- First observation of high-spin meson $(J = 6)$
- First observation of $a_1(1420)$
- First observation of „crypto“ exotic strange meson