Diffractive resonance production in the reaction $\pi^- + p \to K_S^0 K_S^0 \pi^- + p$ at $190\,\text{GeV}/c$ from COMPASS

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for the COMPASS-Collaboration

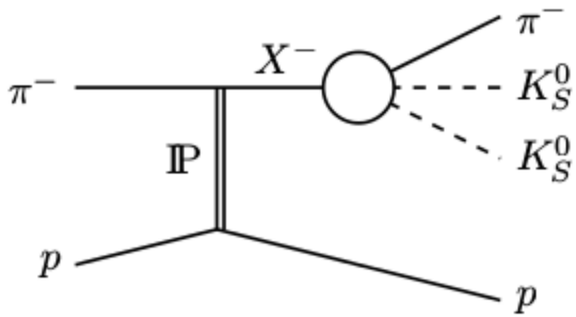
at the 86^{th} DPG Spring Meeting - HK 29.3

22nd March 2023

GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

The Reaction

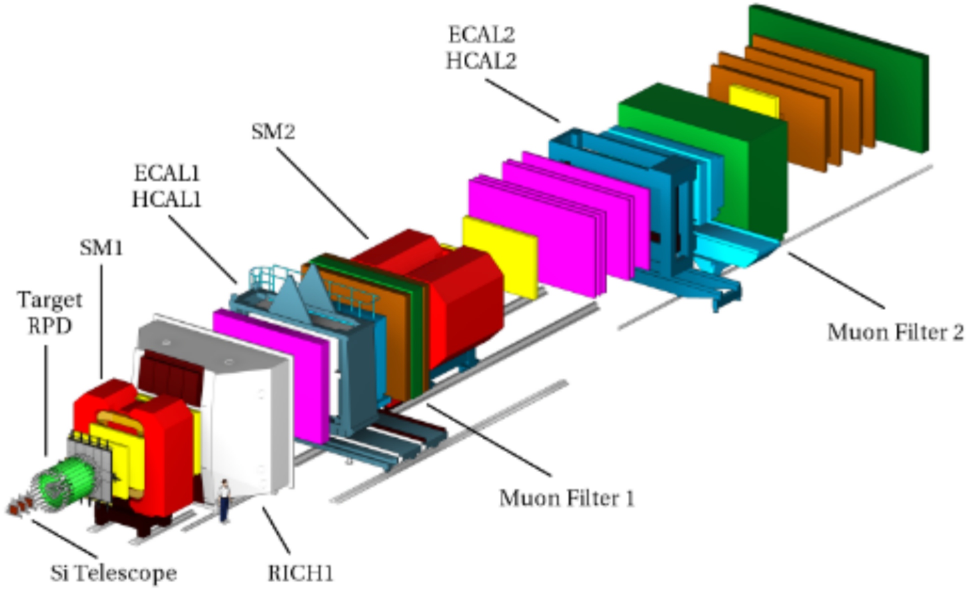
- $\pi^- + p \rightarrow X^- + p_{\text{recoil}} \rightarrow K_S^0 K_S^0 \pi^- + p_{\text{recoil}}$



- a_J and π_J mesons are accessible
- K_J^* and f_J mesons are accessible as isobars (two-body resonances)
- Threshold at $m_X \geq 1.135\,\text{GeV}/c^2$
  $\Rightarrow$ easier access to higher radial excitations

Diffractive Scattering at COMPASS

- **CO**mmon **M**uon **P**roton **A**pparatus for **S**tructure and **S**pectroscopy
- Fixed-target experiment at the SPS-CERN
- Spectroscopy via secondary hadron beam, mostly π^- ($\sim 97\,\%$) of $190\,\text{GeV}/c$
- Liquid-hydrogen target ($40\,\text{cm}$)



[COMPASS, **NIM A 779** (2015), pp. 69-115]

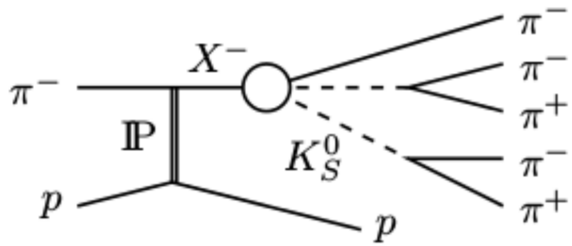
Motivation for $K_S^0 K_S^0 \pi^-$ Final State

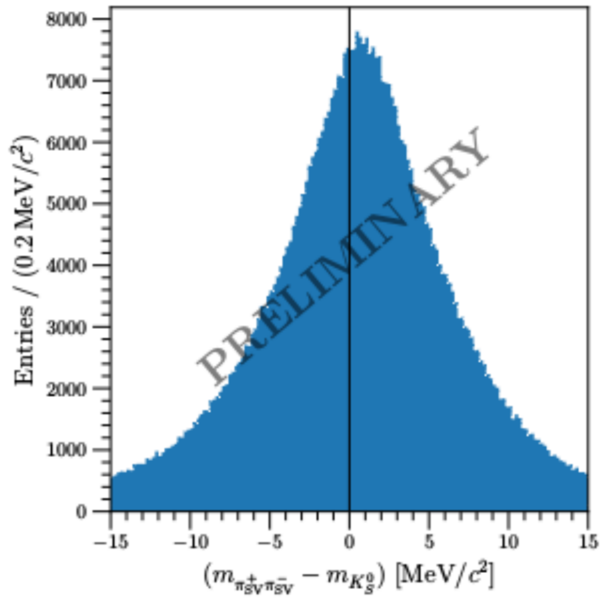
- Decay channels to (neutral) kaons not yet well established
- Complementary to $\pi^-\pi^+\pi^-$ final state
- Rescattering effect $a_1(1420)$ should be present in $f_0(980)\pi^-$ decay channel [COMPASS, **PRL 127** (2021), p. 082501]
- Spin-exotic $\pi_1(1600)$ hybrid candidate accessible
- Extraction of branching fraction ratios between $X^- \to K_J^{*-} K_S^0$ and $X^- \to f_J \pi^-$ possible within same data set

Event Selection

K_S^0 Selection

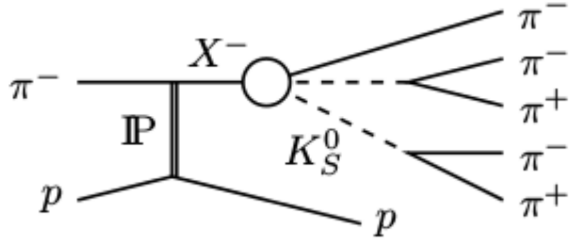
- Main decay channel:
  $K_S^0 \to \pi^+ + \pi^-$ (69 %)
- Require minimal decay-vertex separation from primary vertex
- Require invariant mass within $\sim 15\,\text{MeV}/c^2$ of nominal K_S^0 mass
- Resolution of $\sim 5\,\text{MeV/c}^2$
- Employ kinematic fit to correct for it

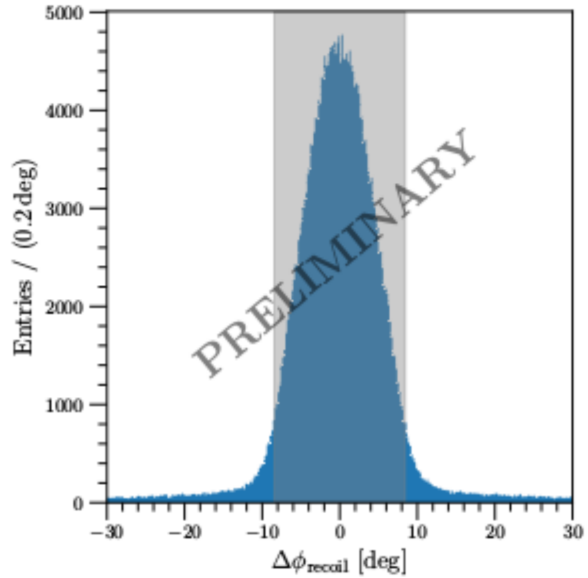


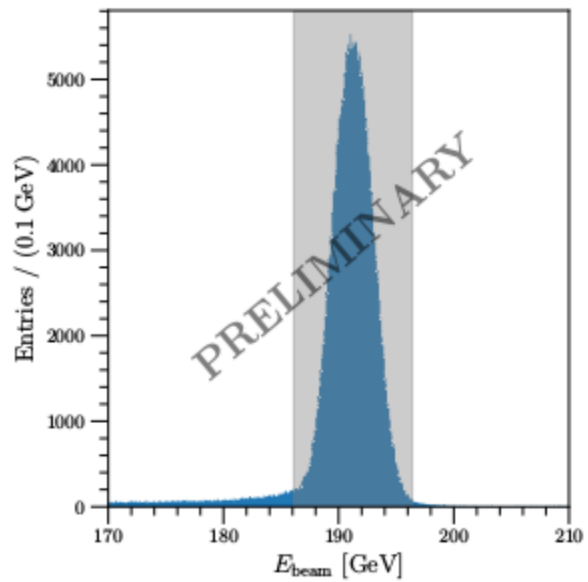


EXCLUSIVITY & 4-MOMENTUM CONSERVATION

- Use measured recoil proton track for check of exclusivity
- Reconstruct beam energy from final state





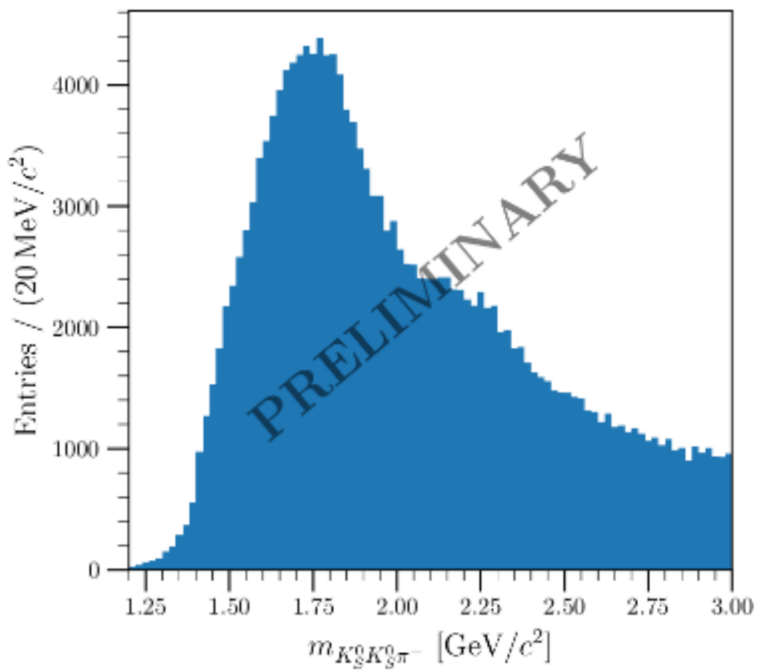


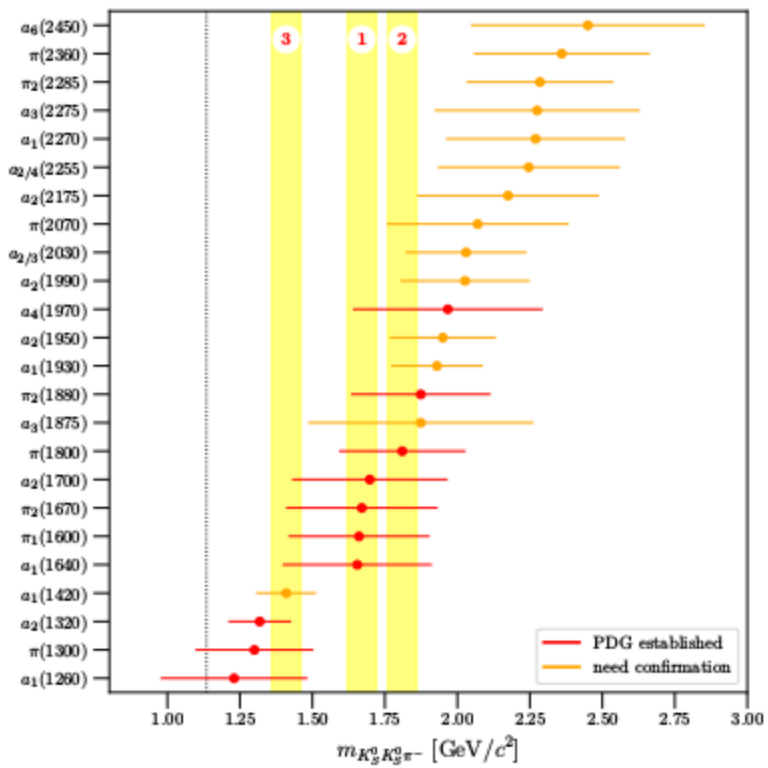
Results

of

$\sim 240\,000$ exclusive events

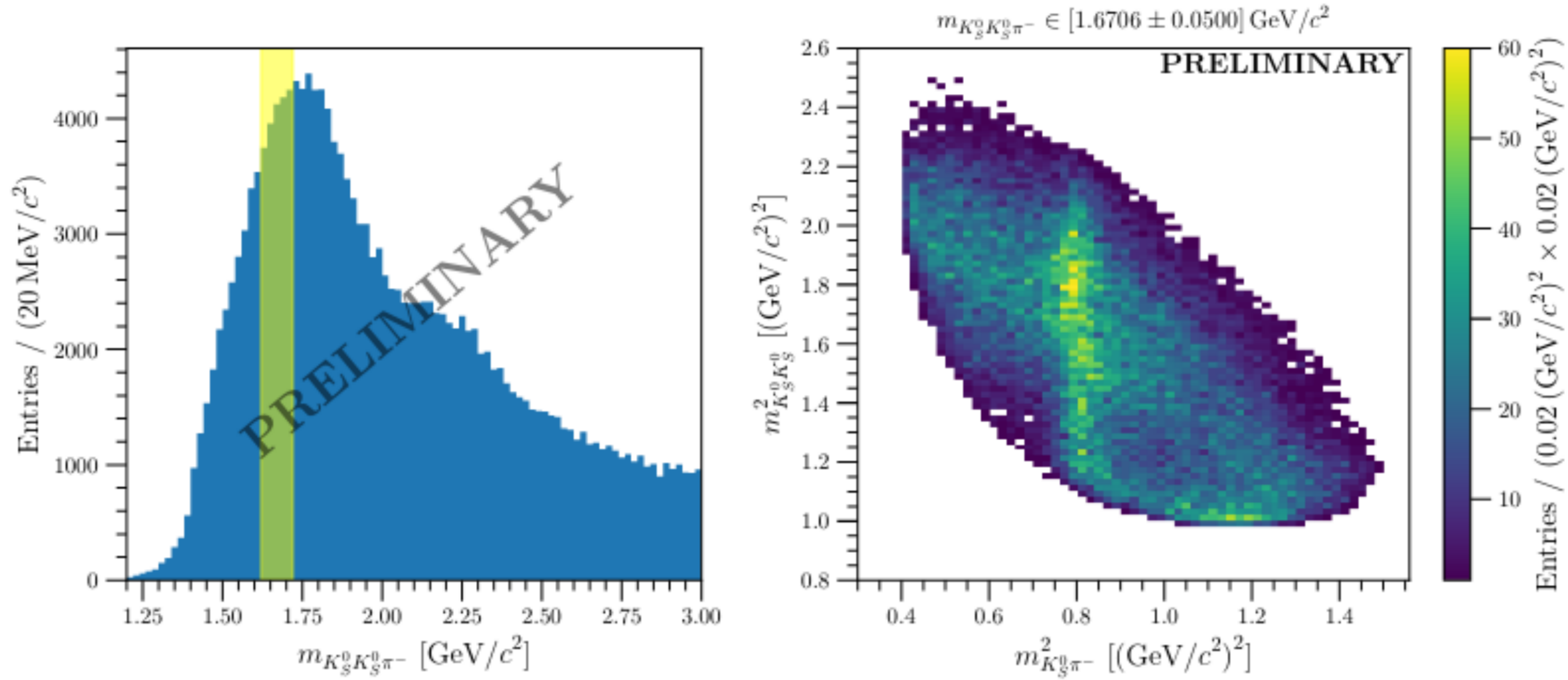
Resonance Spectrum





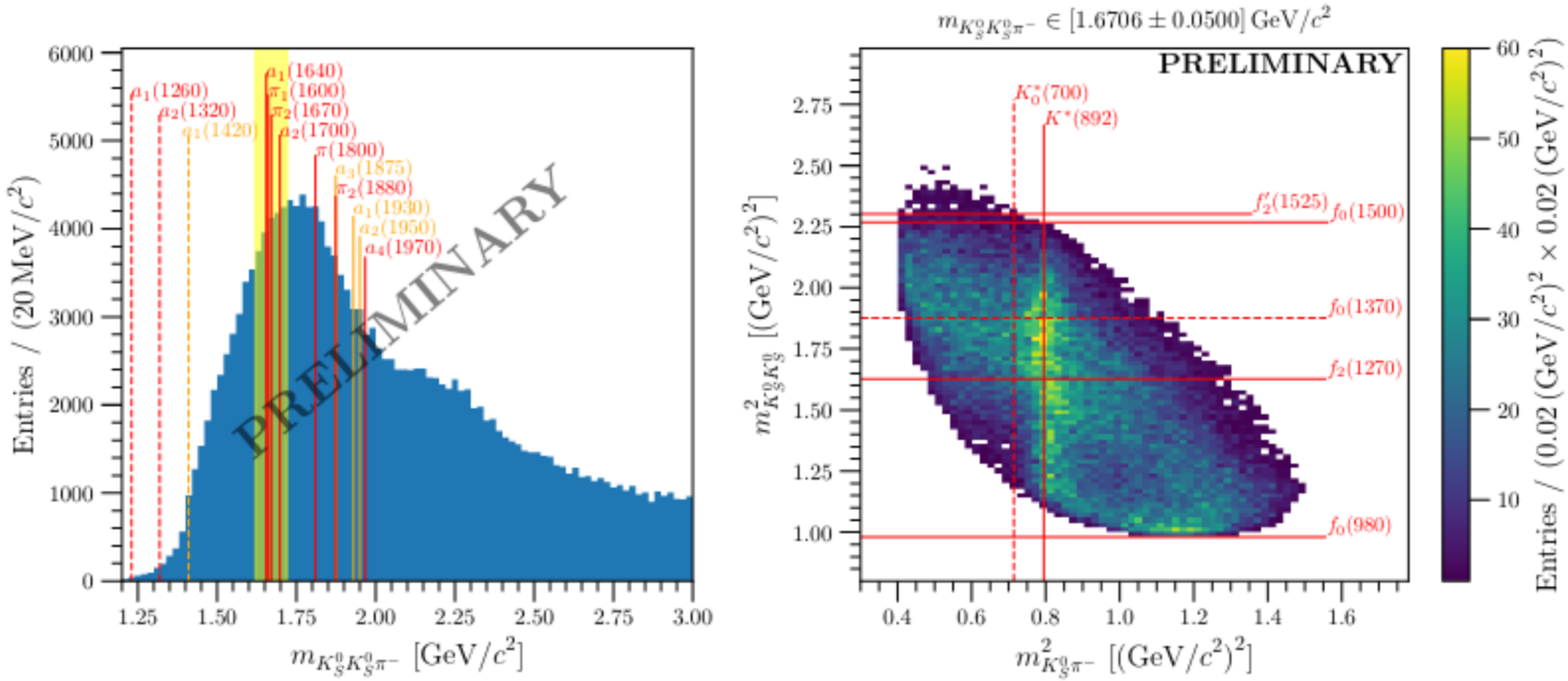
DALITZ PLOT AROUND 1.67 GeV/c^2

Dalitz plot is filled with both $K_S^0\pi^-$ combinations

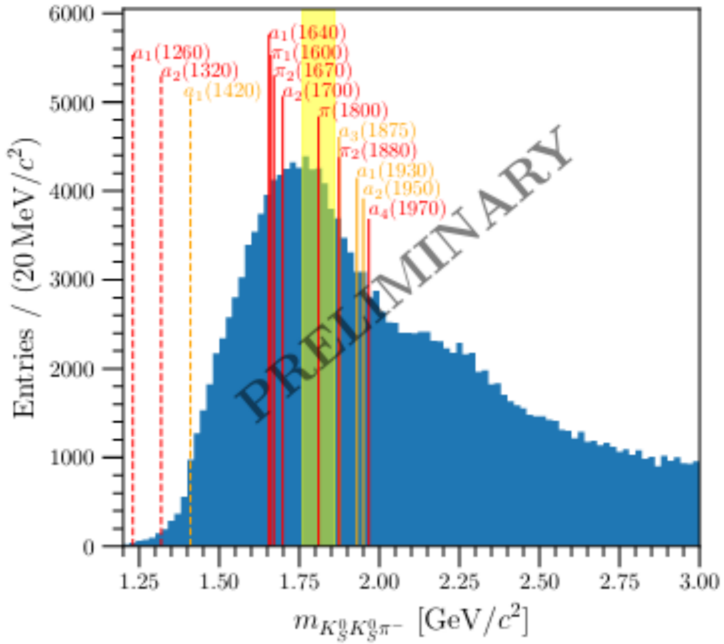


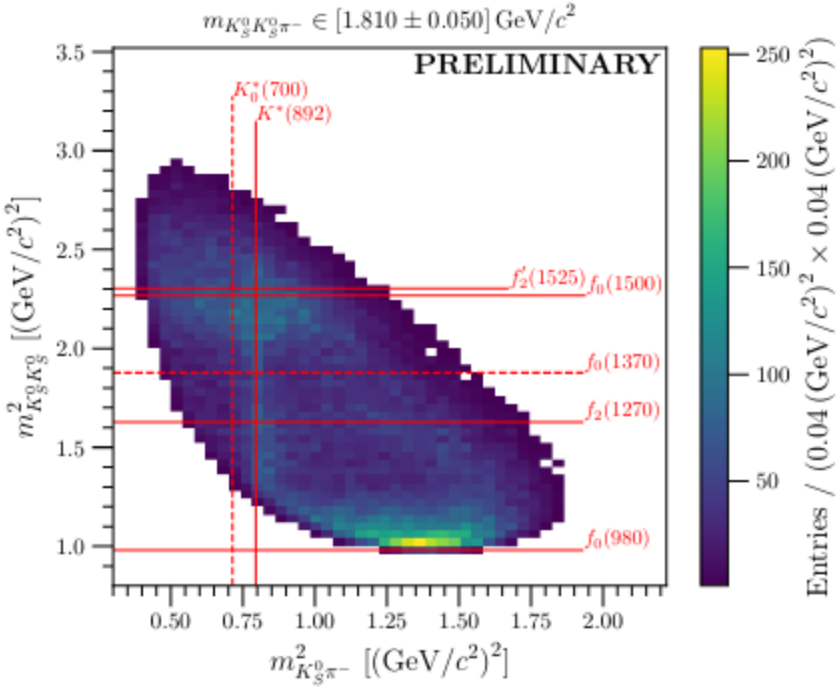
Dalitz Plot around 1.67 GeV/c^2

Possible signals: $a_1(1640) \to K^{*-}K_S^0$ and $\pi_2(1670) \to f_2\pi^-$



Possible signal: $\pi(1800) \to f_0\pi^-$

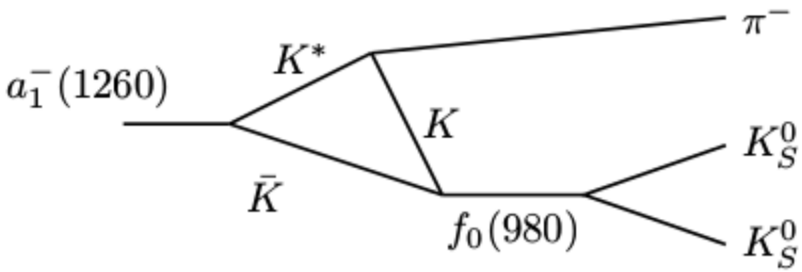




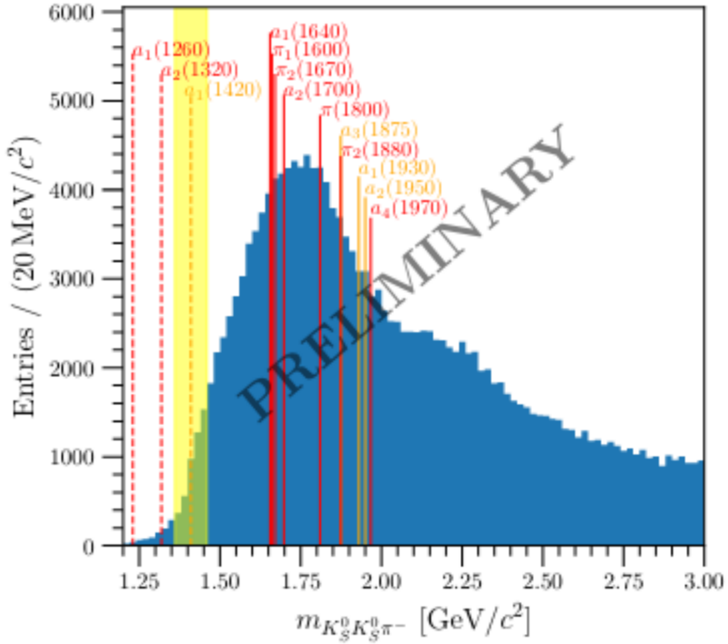
Rescattering Effect $a_1(1420)$

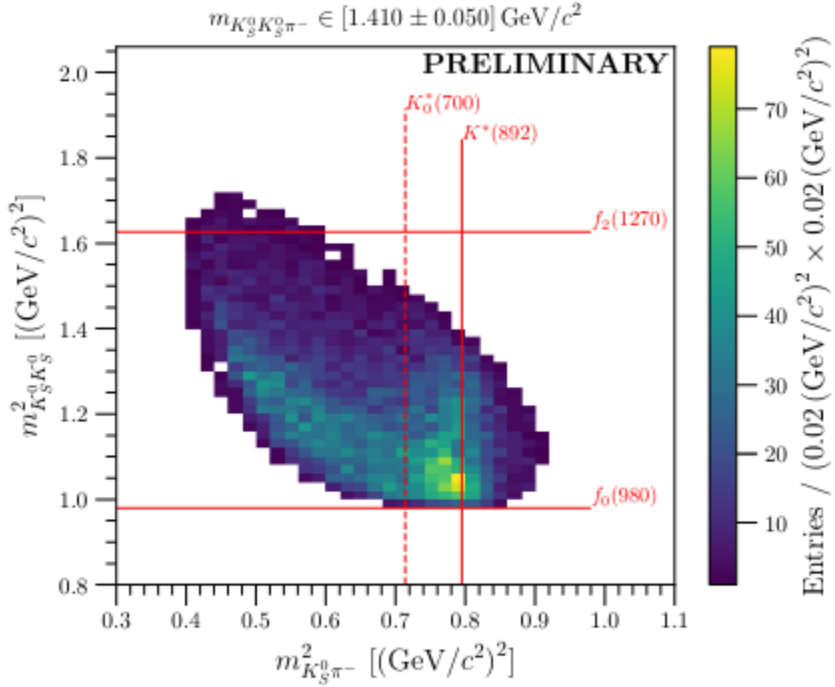
- $a_1(1420)$ signal found at COMPASS in $\pi^-\pi^+\pi^-$ final state at $1.41\,\text{GeV}/c^2$
- Can be explained via rescattering effect
  [COMPASS, **PRL 127** (2021), p. 082501]
- Should also appear in $K_S^0 K_S^0 \pi^-$

But: Close to threshold $m_{K_S^0 K_S^0 \pi^-} \geq 1.135\,\text{GeV}/c^2$



Dalitz Plot around $1.41\,\mathrm{GeV}/c^2$





- Overlap of $K^*(892)$ and $f_0(980)$ band
- Need PWA to separate contributions

Summary and Outlook

Summary and Outlook

Summary:

- $\sim 240\,000$ exclusive $K_S^0 K_S^0 \pi^-$ events
- Rich but densely populated resonance spectrum $\Rightarrow$ need PWA
- Clear hints for $a_1(1640)$ and $\pi(1800)$
- Good intensity at the $a_1(1420)$ and $\pi_1(1600)$ locations

Outlook:

- Partial-wave analysis
- Resonance model fit to extract resonance parameters

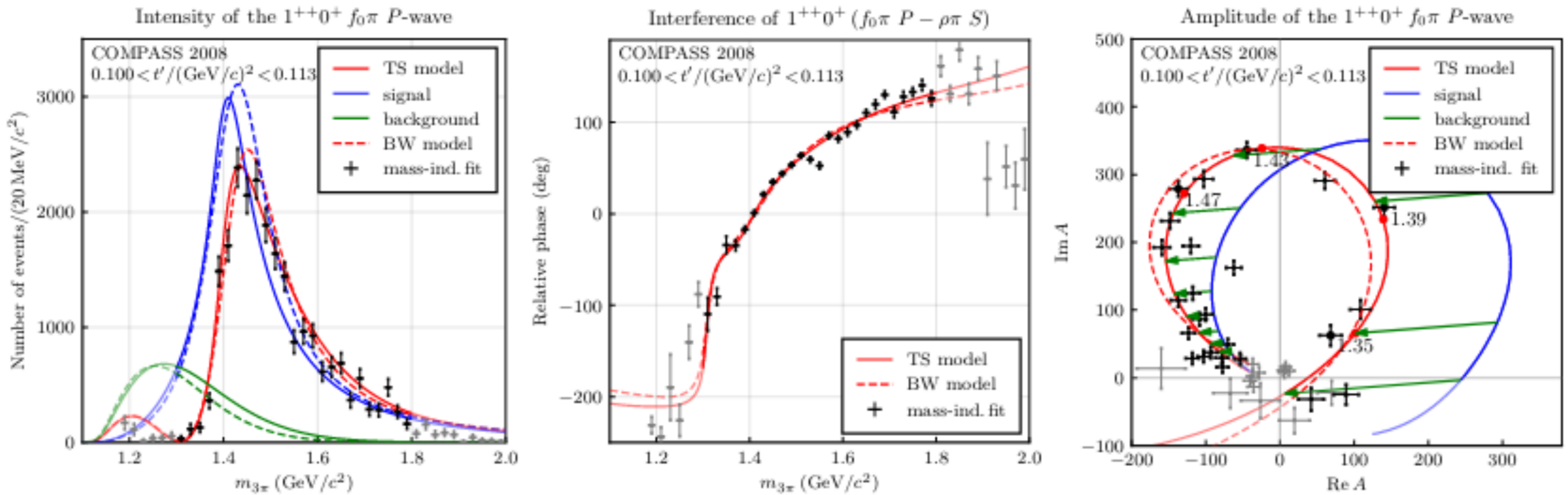
Thanks for your attention!

Backup

Event Number Comparison

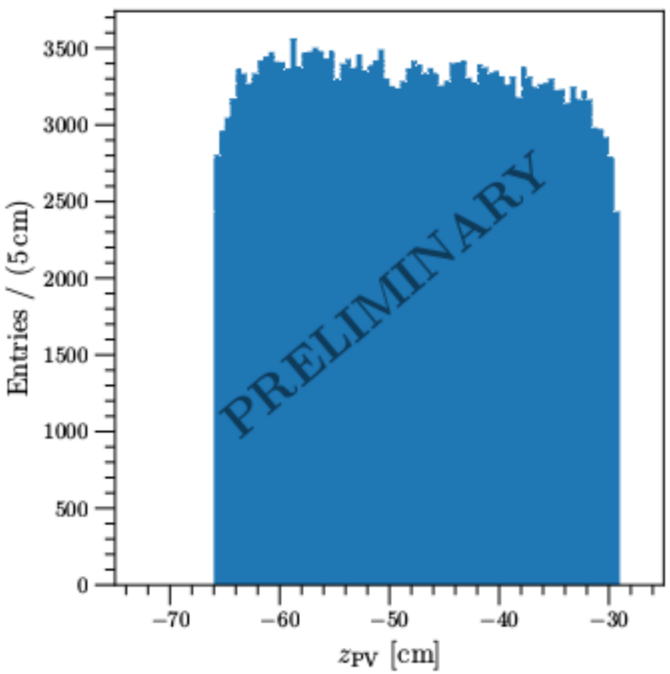
- $\sim 240\,000$ exclusive $K_S^0 K_S^0 \pi^-$ events selected
- $\sim 240\times$ E580 experiment via diffractive scattering at Fermilab
  [T. Y. Chen et al., **PRD 28** (1983), p. 2304]
- $\sim 42\times$ Crystal Barrel experiment in $\bar{p}n$ annihilations at LEAR
  [CB collab., **Nucl. Phys. A 692.1** (2001), p. 326]
- $\sim 9\times$ BaBar experiment via τ^- decays ($m_{K_S^0 K_S^0 \pi^-} < 1.75\,\text{GeV}/c^2$)
  [J. P. Lees et al., **PRD 86** (2012), p. 092013]

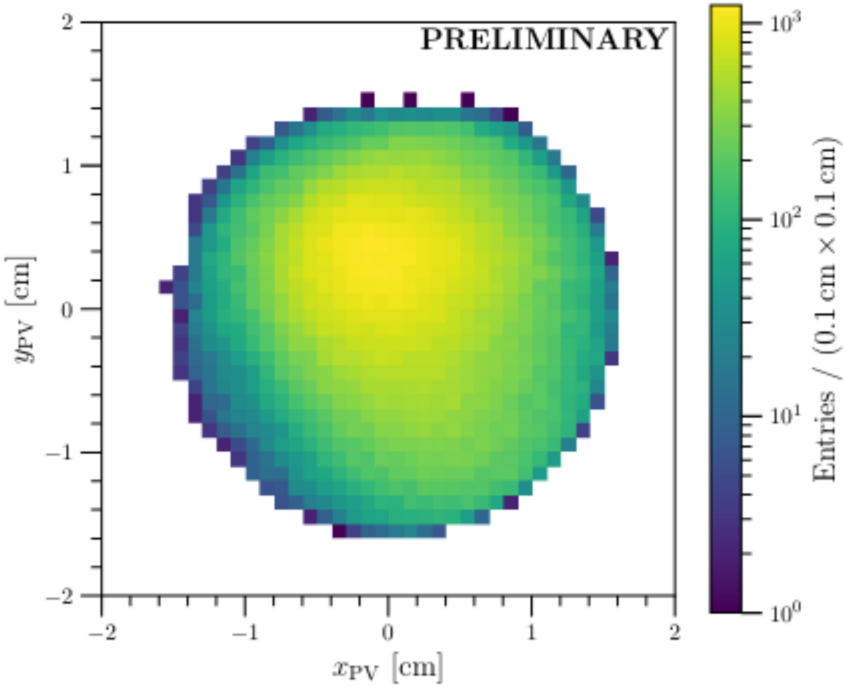
$a_1(1420)$ as a Rescattering Effect



[COMPASS, **PRL 127** (2021), p. 082501]

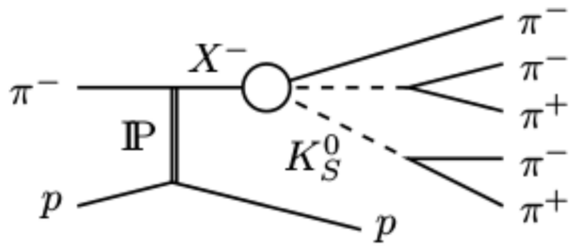
Primary Vertex Distributions

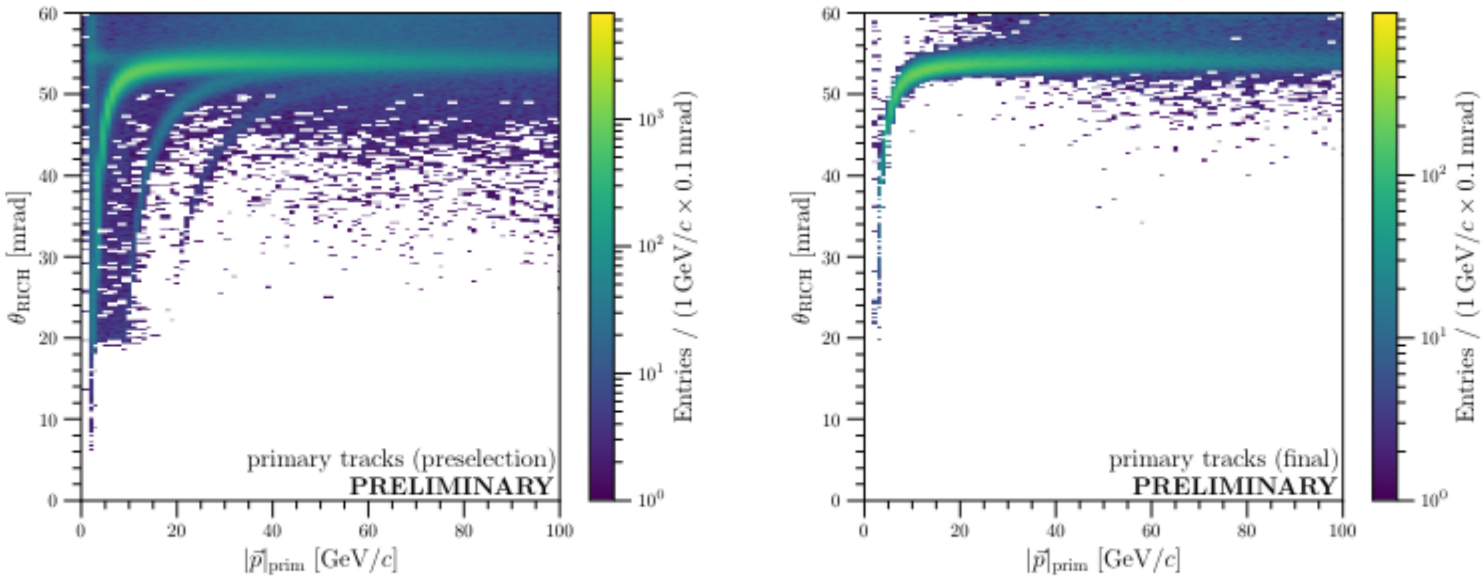




Particle Identification

- RICH detector to veto on K and p





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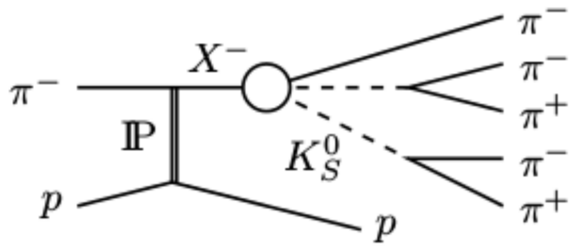
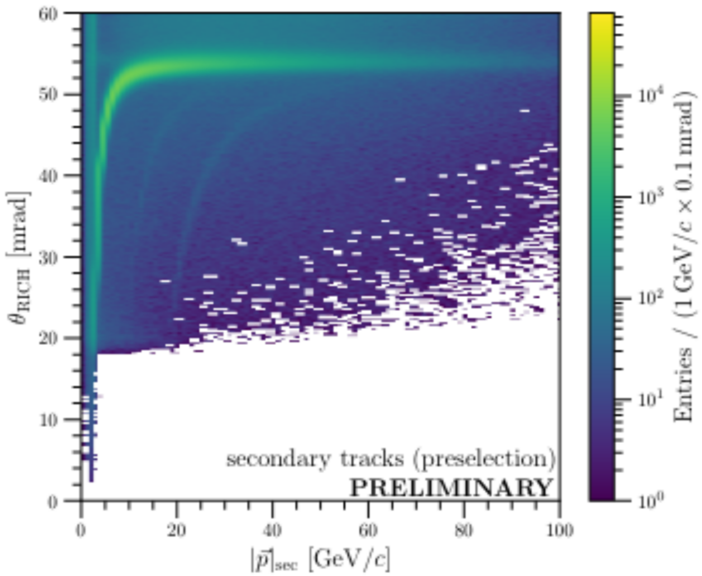
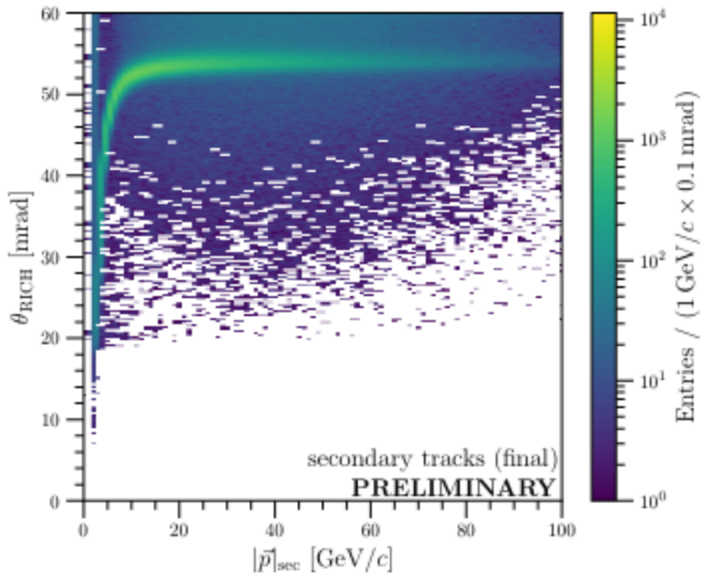
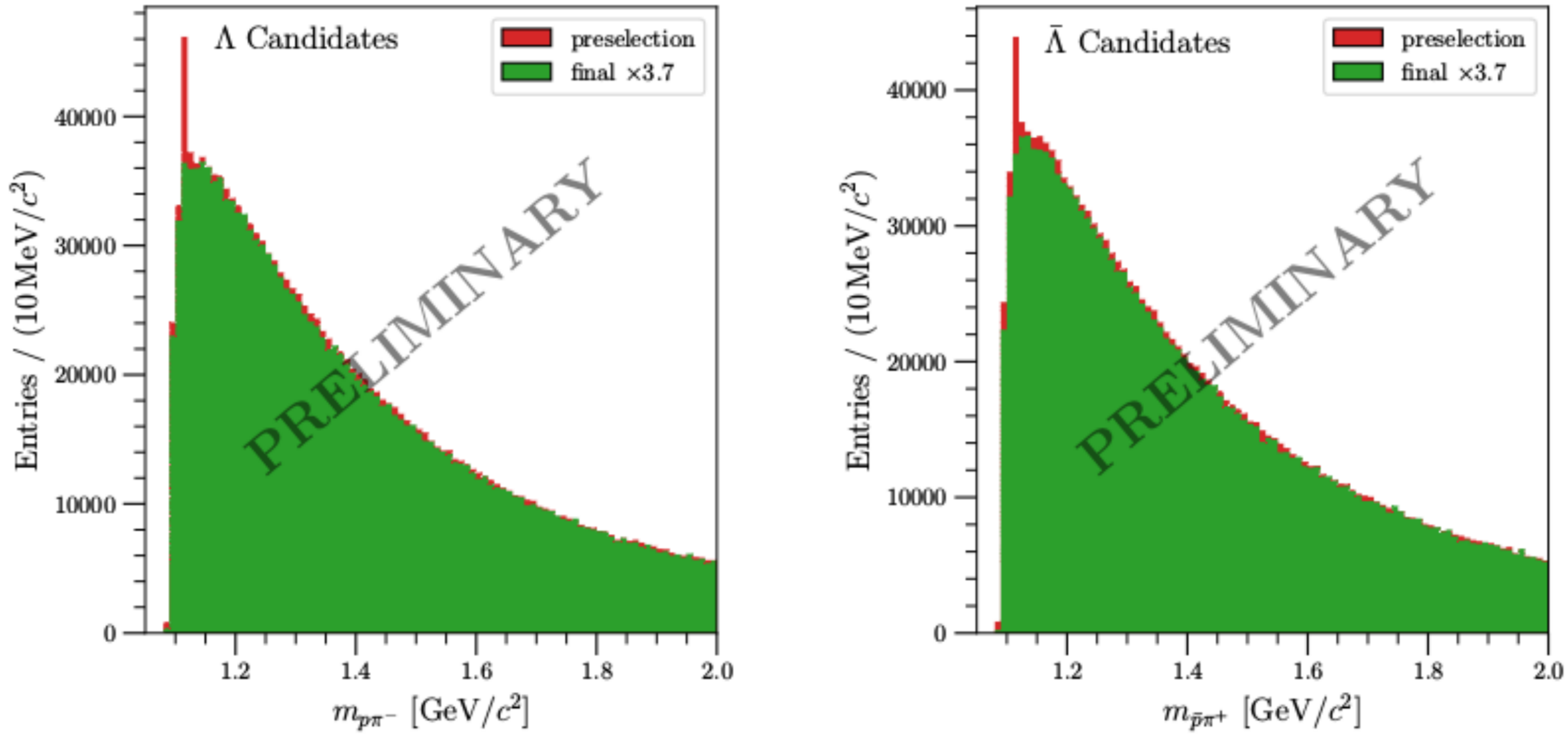




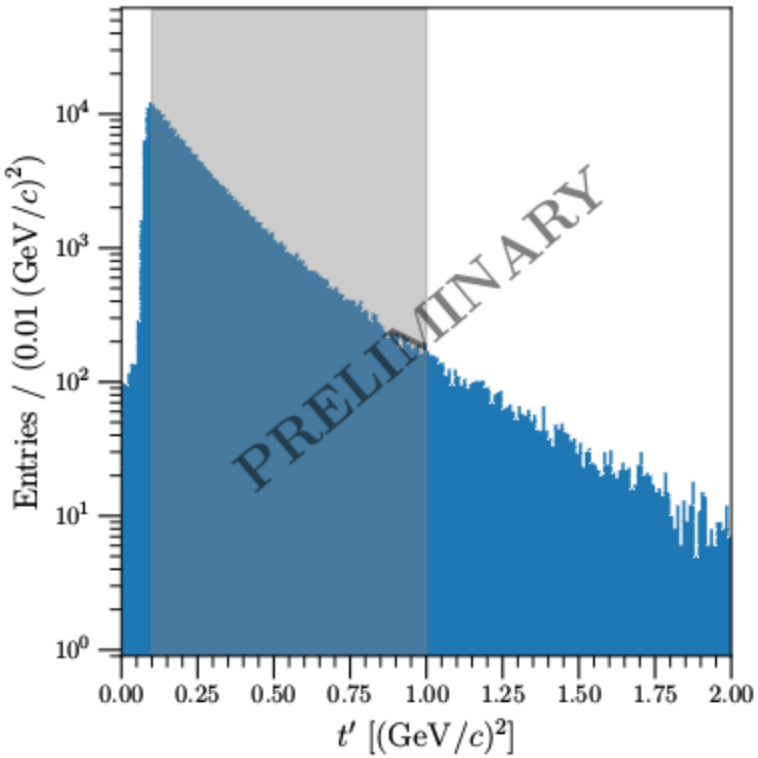


Λ and $\bar{\Lambda}$ Contamination

Assuming (anti)proton and pion mass for outgoing tracks from SV

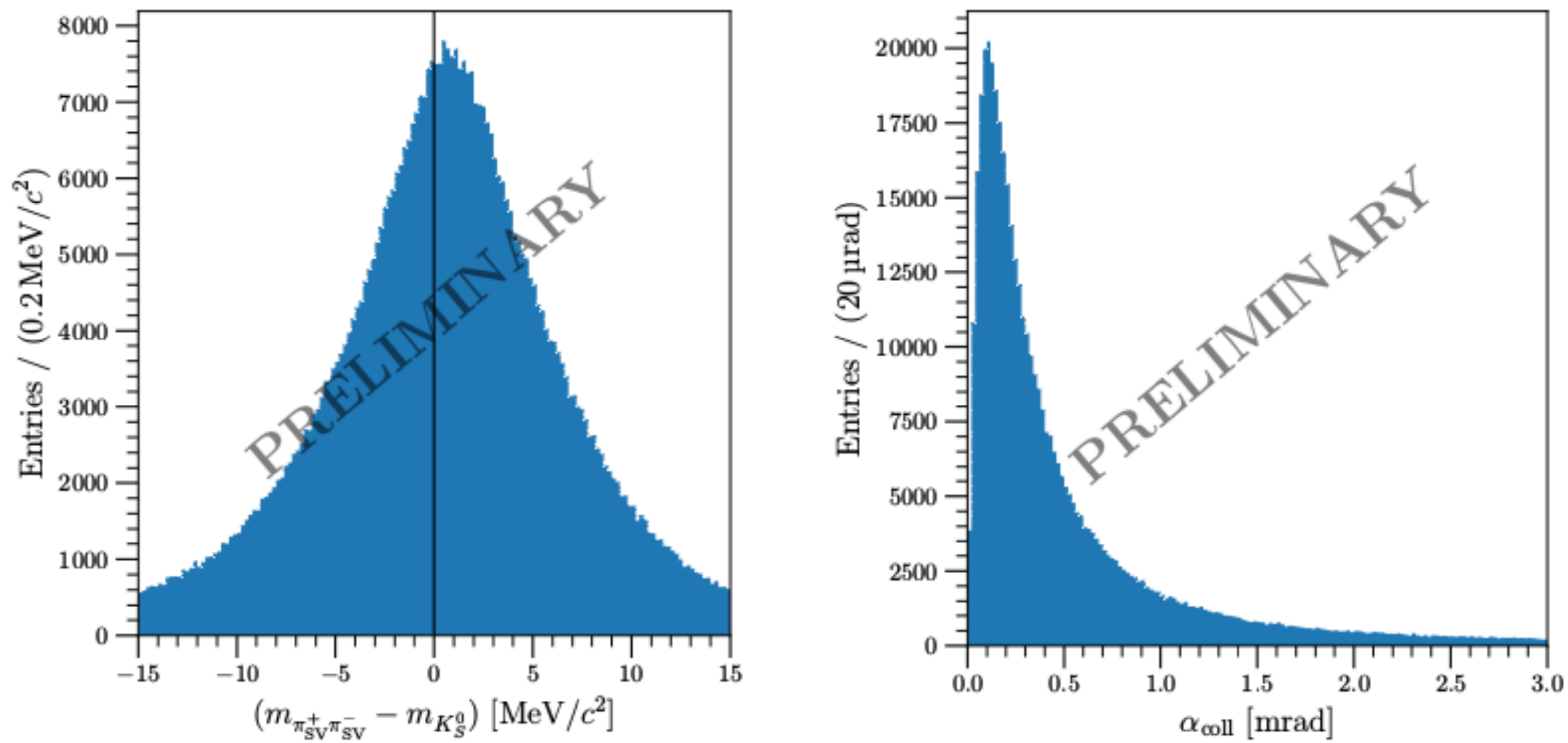


Four-Momentum Transfer



$$t' := |t| - |t|_{\mathsf{min}}$$

K_S^0 Properties



Kinematic Fit

- Special case of constrained fitting
  [F. James, Statistical Methods in Experimental Physics]

- Constraint $F(y) = (p_1 + p_2)^2 - m^2_{K^0_S} = 0$
  with $y = \left(\frac{p_{1x}}{|\vec{p}_1|}, \frac{p_{1y}}{|\vec{p}_1|}, E_1, \frac{p_{2x}}{|\vec{p}_2|}, \frac{p_{2y}}{|\vec{p}_2|}, E_2\right)$

- Minimize $\chi^2 := \epsilon^T C^{-1} \epsilon$ with $F(y + \epsilon) = 0$
  with covariance matrix C

- Failure rate $< 0.02\,\%$

No ρ_J Isobars

The decay $\rho_J \to K_S^0 K_S^0$ demands $M = 0$ since both K_S^0 are scalars. Bose-symmetry demands symmetrized wave function $|p_1, p_2\rangle + |p_2, p_1\rangle$. Partial-wave expansion of theses wave functions yields:

$$\begin{aligned} |p_1, p_2\rangle &= \sum_J \sqrt{2J+1} D^J_{0,0}(\phi_1, \theta_1, 0) |J, 0\rangle \\ |p_2, p_1\rangle &= \sum_J \sqrt{2J+1} D^J_{0,0}(\phi_2, \theta_2, 0) |J, 0\rangle \end{aligned}$$

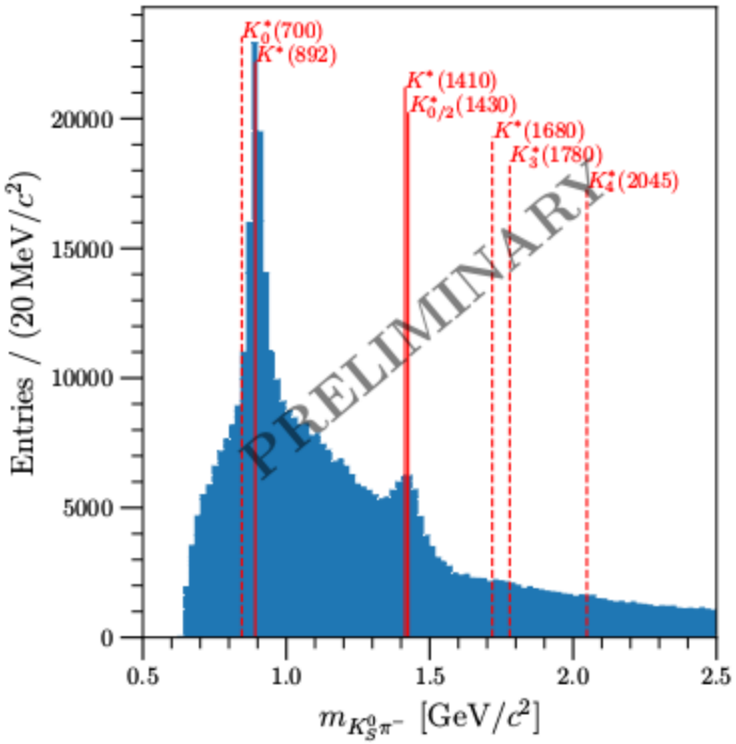
Now we use $\theta_2 = \pi - \theta_1$ and $\phi_2 = \phi_1 + \pi$ as well as $d^J_{0,0}(\pi - \theta) = (-1)^J d^J_{0,0}(\theta)$:

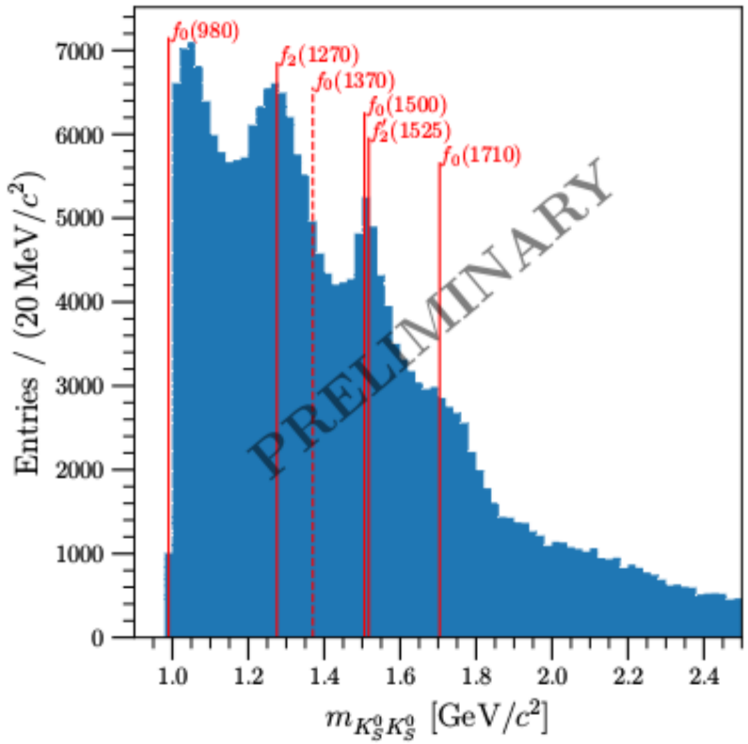
$$\begin{aligned} D^J_{0,0}(\phi_2, \theta_2, 0) &= d^J_{M,0}(\theta_2) = d^J_{0,0}(\pi - \theta_1) \\ &= (-1)^J d^J_{0,0}(\theta_1) \end{aligned}$$

Therefore we obtain for the symmetrized wave function

$$\frac{1}{\sqrt{2}} \left(|p_1, p_2\rangle + |p_2, p_1\rangle \right) = \frac{1}{\sqrt{2}} \sum_J \sqrt{2J+1} \underbrace{\left[1 + (-1)^J \right]}_{0 \text{ for odd } J} d^J_{0,0}(\theta_1) |J, 0\rangle$$

Isobar Spectra

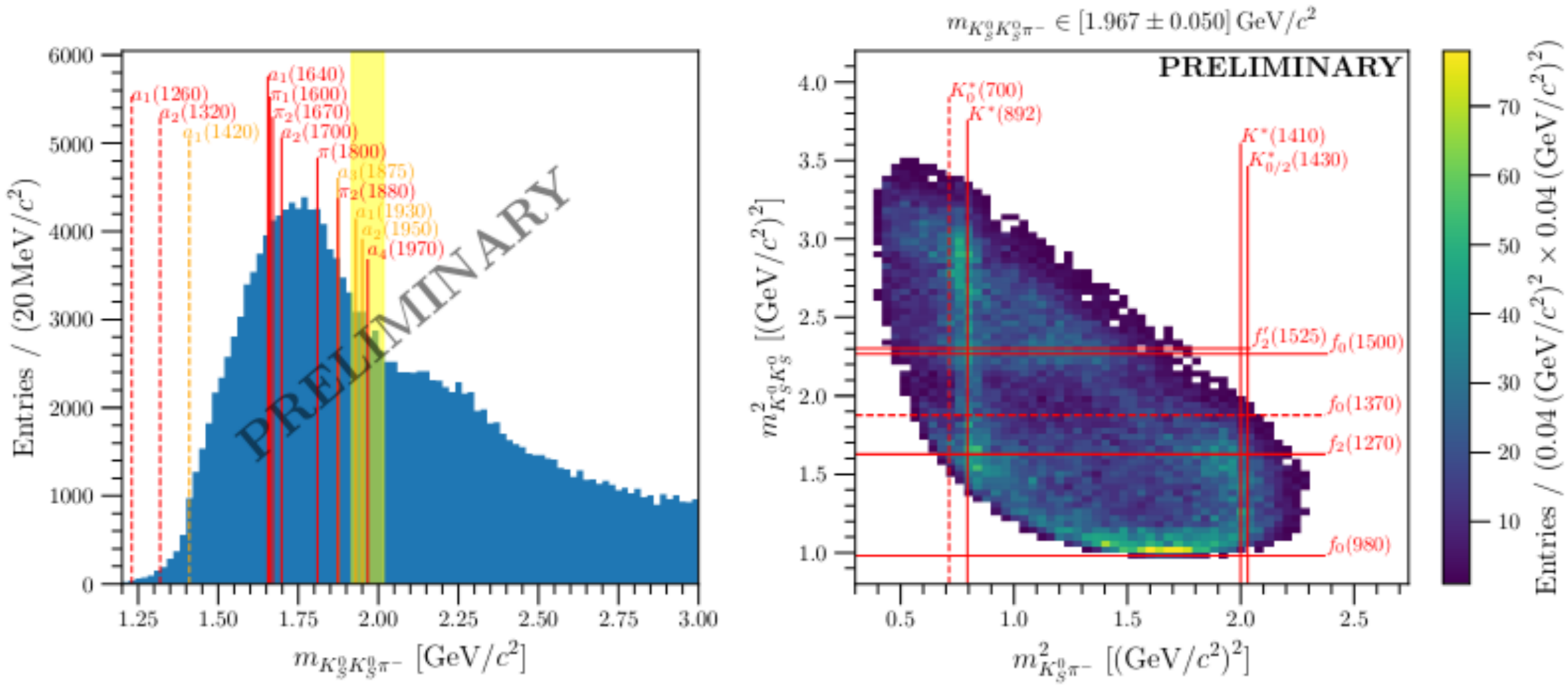




Resonance Decay Modes

$X \to \xi b$	$f_0\pi^-$, $K_0^{*-}K_S^0$	$K^{*-}K_S^0$	$f_2\pi^-$, $K_2^{*-}K_S^0$	$K_3^{*-}K_S^0$	$f_4\pi^-$, $K_4^{*-}K_S^0$
a_1	P	S, D	P, F	D, G	F
a_2	$--$	D	P, F	D, G	F
a_3	F	D, G	P, F	S, D, G	P, F
a_4	$--$	G	F	D, G	P, F
π	S	P	D	F	G
π_1	$--$	P	D	F	G
π_2	D	P, F	S, D, G	P, F	D, G
π_3	$--$	F	D, G	P, F	D, G
π_4	G	F	D, G	P, F	S, D, G

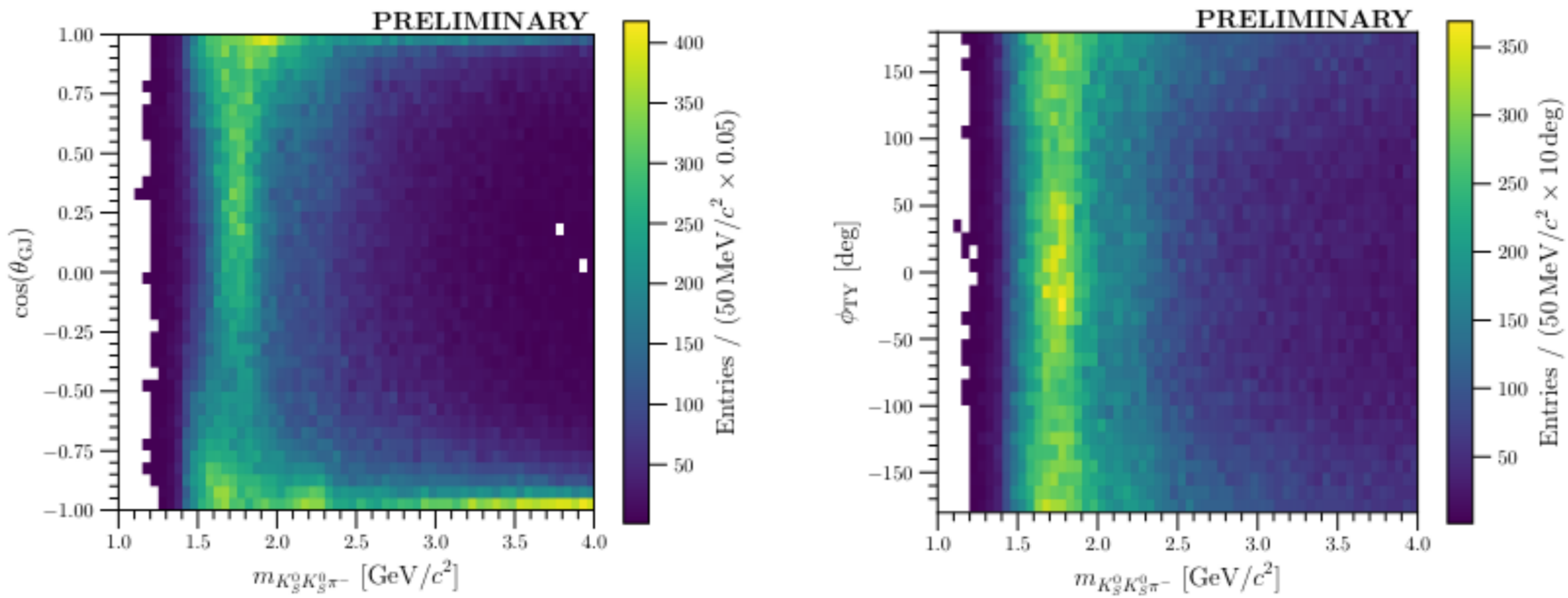
Dalitz Plot around $a_4(1970)$



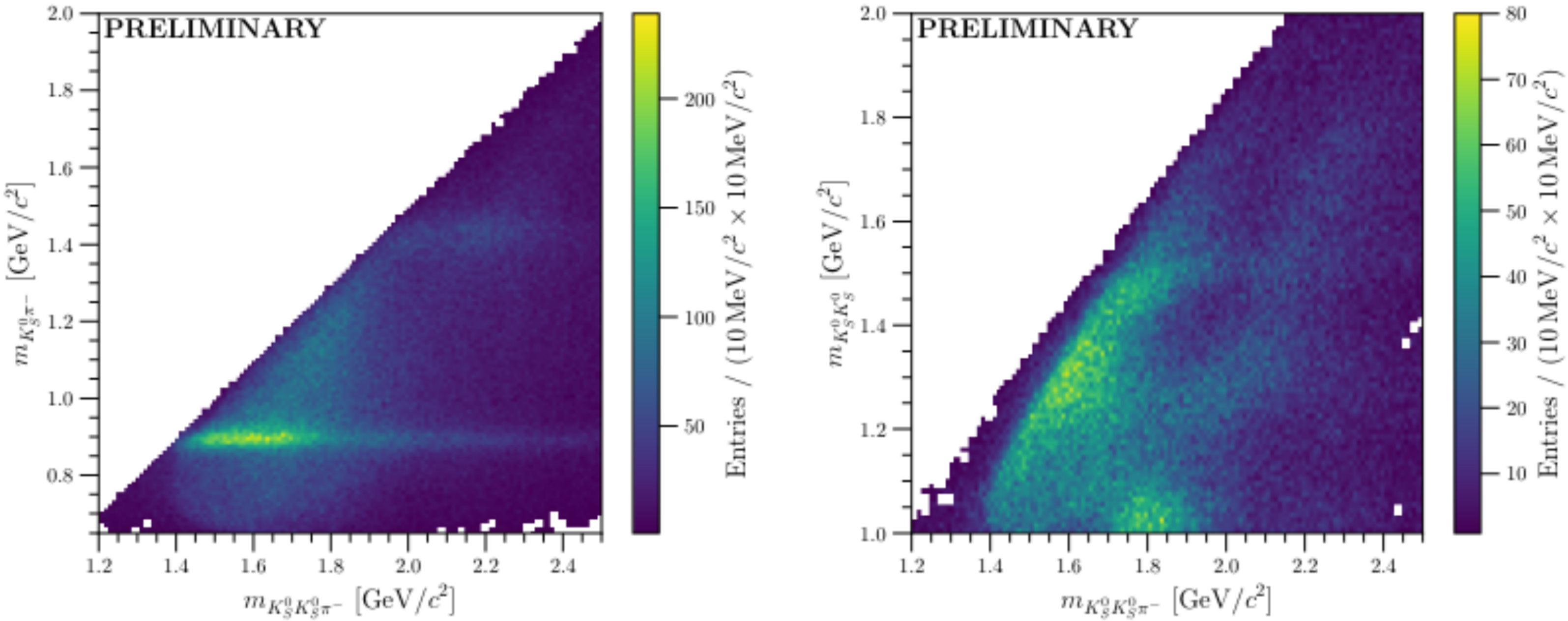
Dominant decay: $a_1(1930) \to K^{*-} K_S^0$

$a_4 \to f_2 \pi^-$ or $a_4 \to K_2^{*-} K_S^0$ only via F-wave

Gottfried-Jackson Frame



Isobar Mass vs. Resonance Mass



Isobar Mass vs. Resonance Mass