Updates on $pp \longrightarrow \Lambda + K_S^0 + p + \pi^+$ at T = 4.5 GeV

Snehankit Pattnaik[1,2]

HADES Analysis Meeting

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[1]GSI Helmholtzzentrum für Schwerionenforschung GmbH
[2]Ruhr-Universität Bochum

Previous Baryonic Studies with HADES

- $pp \rightarrow p + K^+ + \Lambda/\Sigma^0$ at T = 3.5 GeV [Waleed Esmail PhD Thesis @ RUB]
- $pp \longrightarrow \Lambda + K_S^0 + p + \pi^+$ at T = 4.5 GeV **This work**

Total cross section: ~ 38μb for $pK^+\Lambda$ final state.

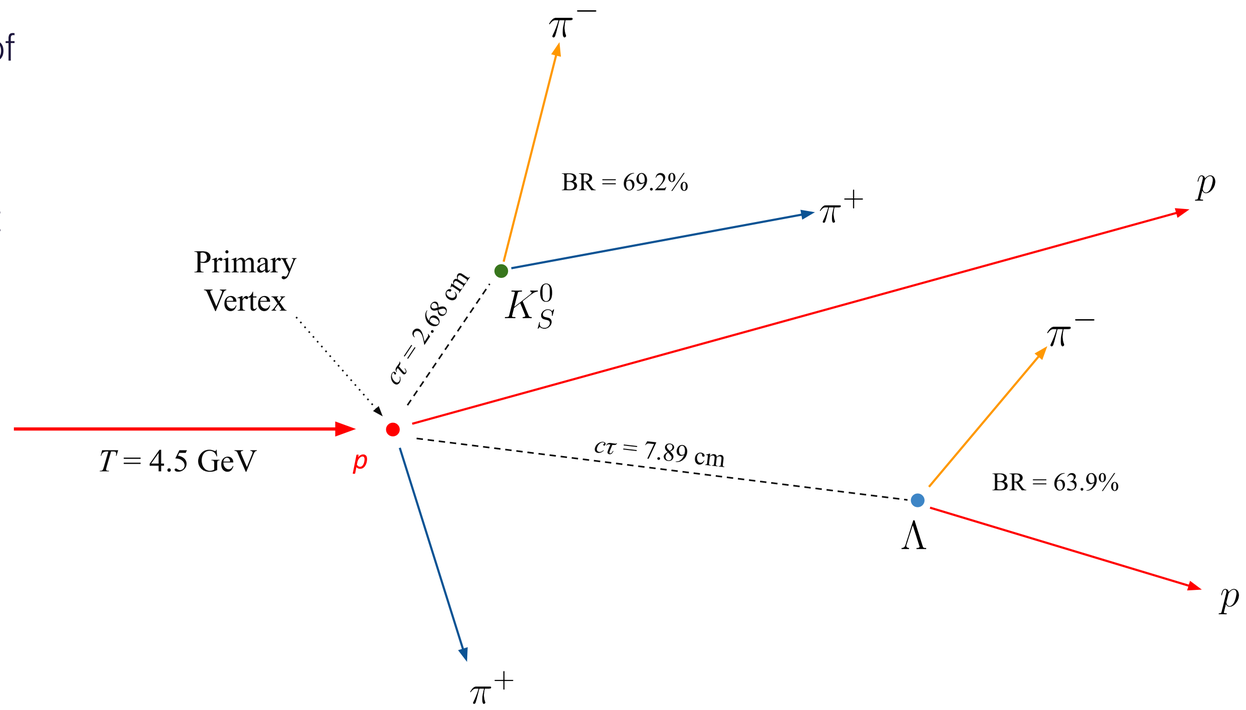
Phase-space deviations: Hints of resonances within mass range of 1.6 GeV/c^2 to 2.0 GeV/c^2 at 3.5 GeV [1-2].

Dalitz plots: Show enhancements near $p\Lambda$ and $K^+\Lambda$ thresholds, not consistent with uniform phase space.

No exotic states: No evidence for a deeply bound ppK^- state

Served as a reference channel

Additional pion enables access to other intermediate resonances.



[1] G. Agakishiev *et al.* 2015 Phys.Lett. B 742 242-248.
[2] R. Munzer *et al.* 2018 Phys. Lett. B 785, 574–580.

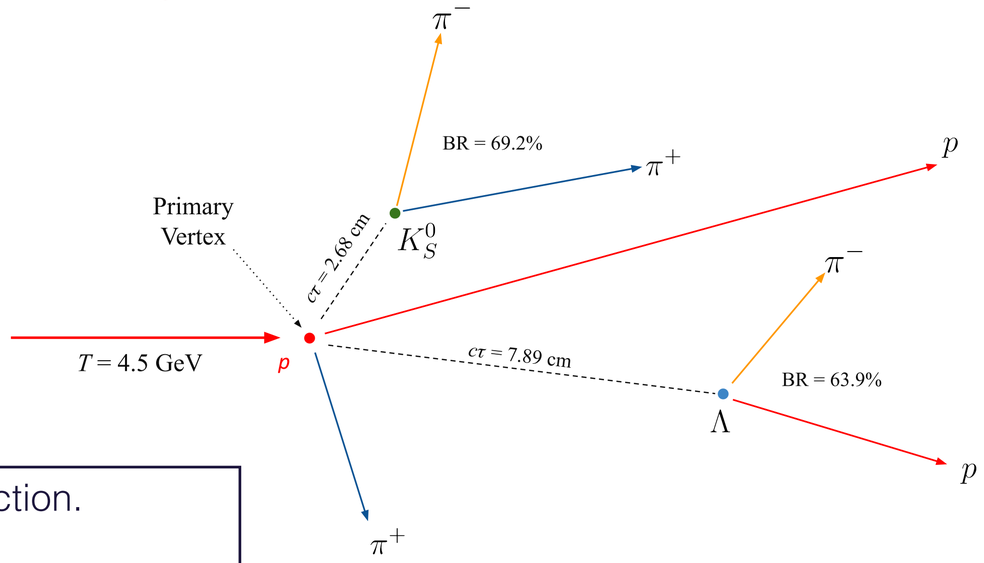
Probing Baryon Resonances with Exclusive Final States

This work at kinetic energy of 4.5 GeV

$$pp \longrightarrow \Lambda + K_S^0 + \Delta^{++}\,[p\pi^+]$$
$$pp \longrightarrow \Lambda + K^+(892)\,[K_S^0\pi^+] + p$$
$$pp \longrightarrow \Sigma^+(1385)\,[\Lambda\pi^+] + K_S^0 + p$$

$$\Rightarrow \quad pp \longrightarrow \Lambda + K_S^0 + p + \pi^+$$

- Investigating the production mechanism of *N** resonances within mass range of 1.6 GeV/c^2 to 2.0 GeV/c^2 at 3.5 GeV [1-2].
- Coupling of *N** resonance decays to strangeness with K_S^0 and Λ as final state particles [1-2].



- Total and differential cross section measurements at 4.5 GeV with proton-proton reaction.
- Extract spin degrees of freedom via measurements of spin density matrix elements of *K**.

[1] G. Agakishiev *et al.* 2015 Phys.Lett. B 742 242-248.
[2] R. Munzer *et al.* 2018 Phys. Lett. B 785, 574–580.

Higher Level Analysis Strategy

Previous presentations

- ☑ Incoherent combined fit on different parameters to describe the data
- ☑ Extract spin density matrix elements via the angular distributions
- ☑ Cross section estimates

Current Focus

- ☐ Dynamic Coupled Channel Approach
- ☐ Jülich-Bonn Model describes meson-baryon interactions from various channels
- ☐ Estimating contributions from meson-baryon channels

$M(p\,\pi^-)$ vs $M(\pi^-\,\pi^+)$

Analysis	Step	S	B	S/B	$S/\sqrt{S+B}$
Fully exclusive $(S, B \text{ in } \times 10^4)$	1	6.35	57.4	1.11	182.7
	2	3.07	0.89	3.44	154.3
	3	3.03	0.81	3.75	154.7
	4	2.68	0.35	7.69	154.1
	5	2.0	0.15	13.1	136.2

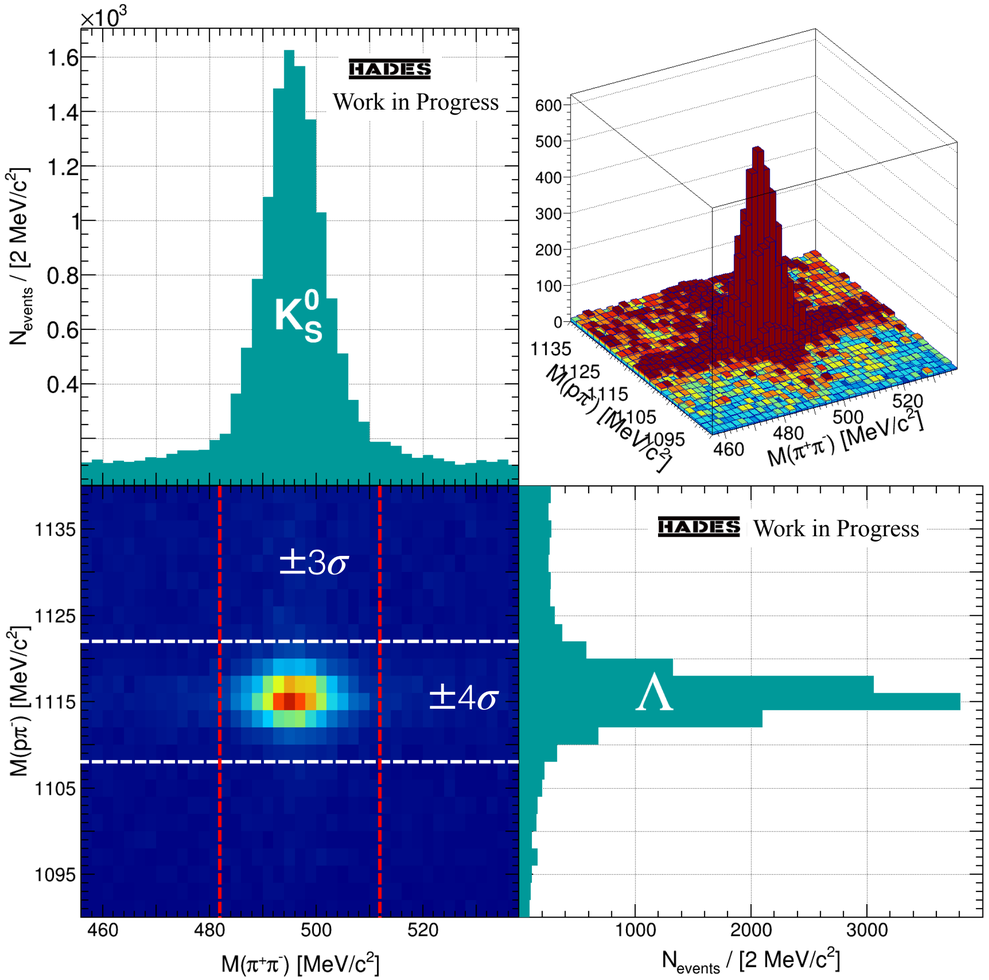
Selection steps: (1) no cuts, (2) best χ^2_{DCA} combination, (3) χ^2_p and χ^2_{DCA} cut, (4) downstream decay-vertex requirement, (5) $4C$ kinematic refit.

The fitted peak positions and widths are consistent across all the steps:

$$\mu_\Lambda = 1115.67 \pm 0.03 \text{ MeV}/c^2, \sigma_\Lambda = 2.15 \pm 0.03 \text{ MeV}/c^2$$

$$\mu_{K^0_S} = 497.43 \pm 0.05 \text{ MeV}/c^2, \sigma_{K^0_S} = 5.31 \pm 0.04 \text{ MeV}/c^2$$

HADES at $\sqrt{s} = 3.46$ GeV

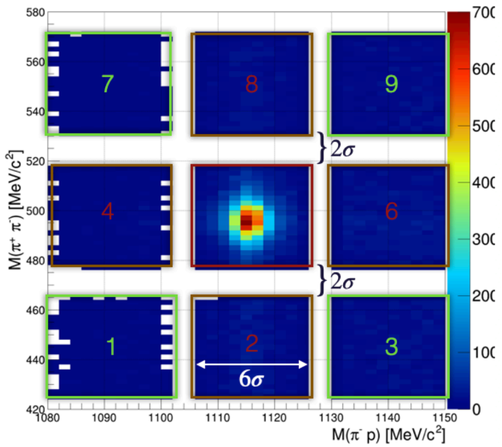


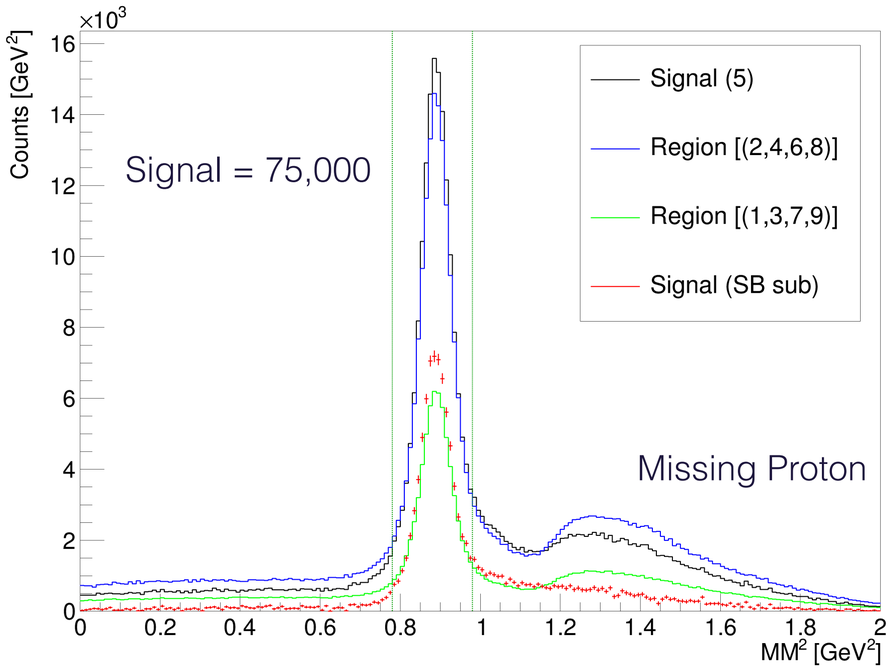
Missing Proton Analysis

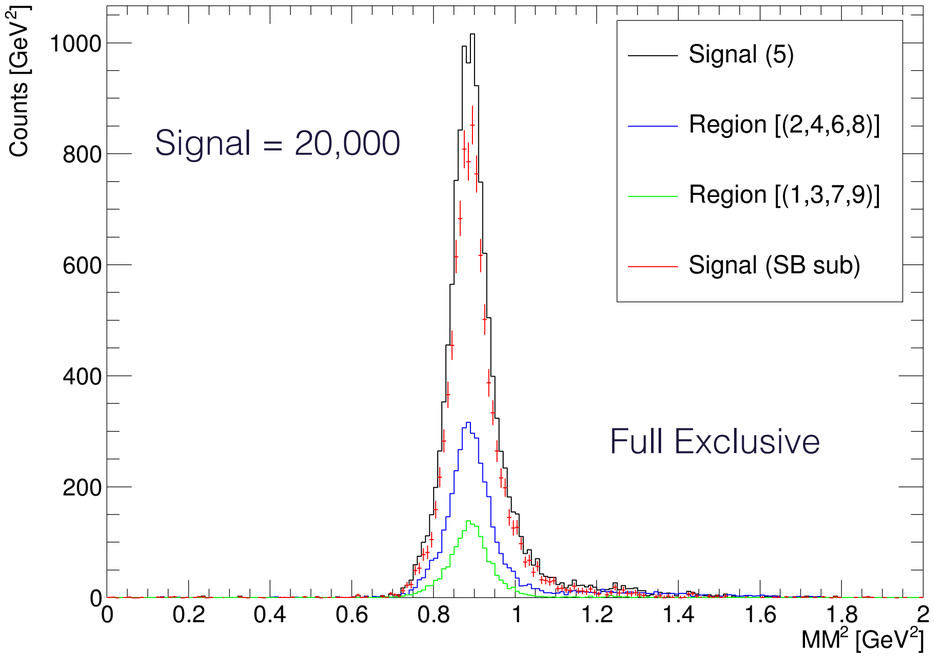
$$pp \longrightarrow \Lambda + K_S^0 + \pi^+ + X$$

$$\Lambda \rightarrow p + \pi^-$$

$$K_S^0 \rightarrow \pi^- + \pi^+$$







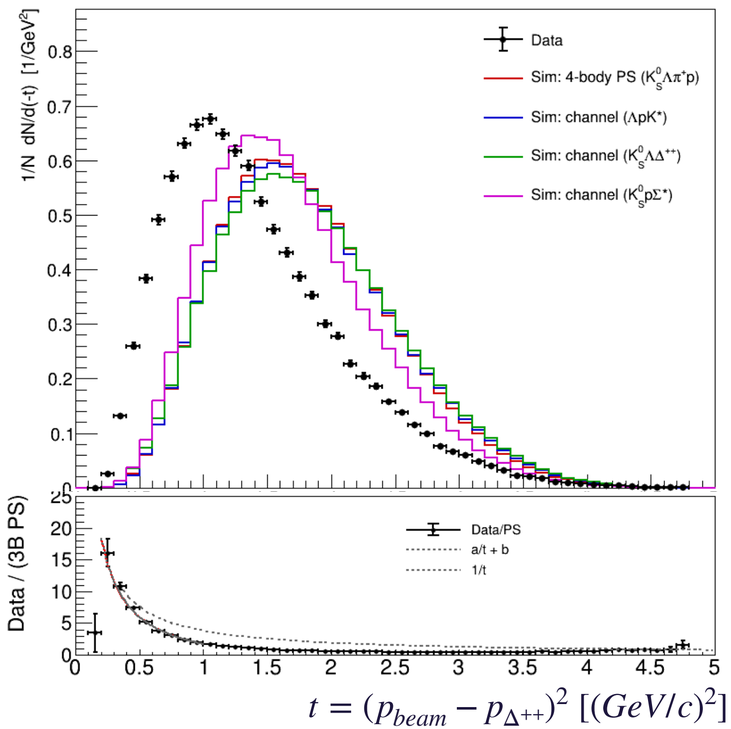
In the case of fully exclusive analysis, background contribution is low

Factor 3 more statistics by including events with a missing primary proton

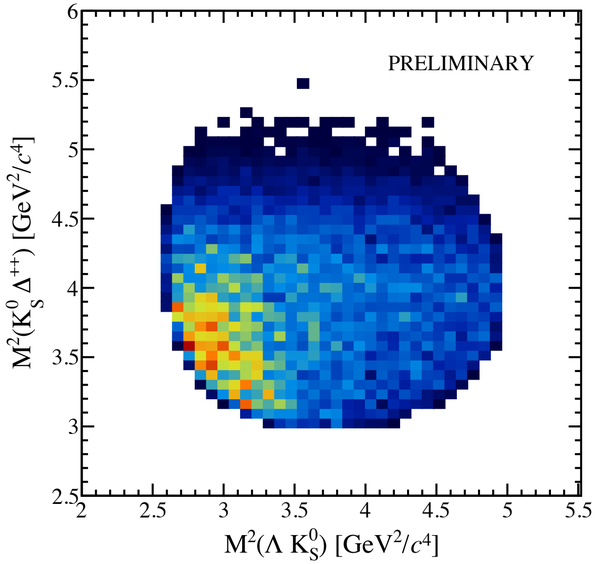
Provides a better dataset to perform MB interaction studies

$pp \longrightarrow \Lambda + K_S^0 + \Delta^{++}\,[p\pi^+]$

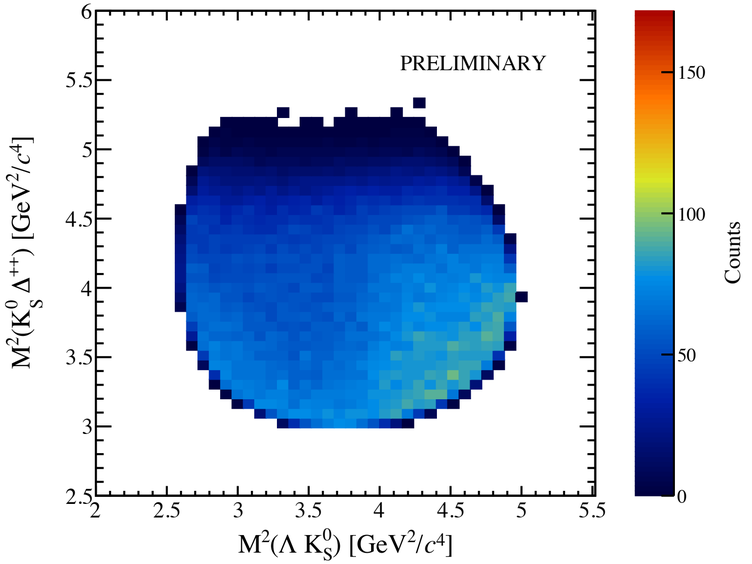
Data vs Simulations



Data

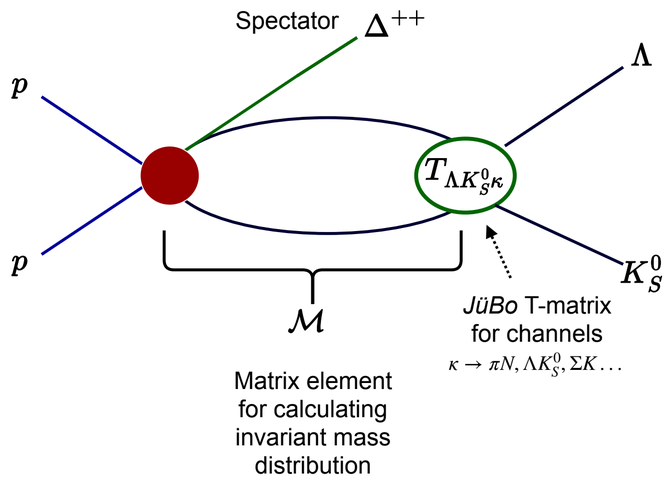


Simulations



- Data comparison with 3 body and 4 body simulations
- A ratio between data and $\Lambda K_S^0 \Delta^{++}$ shows an exchange like mechanism in low *t* range
- Dalitz distributions has enhancement in low invariant mass region

Jülich-Bonn Dynamic Coupled Channel Approach



Jülich-Bonn Model

ϵ - c.m energy of $pp \to \Lambda K_S^0 \Delta^{++}$

$$\mathcal{M}_{\mu\nu}(q, p', \epsilon) = V_{\mu\nu}(q, p', \epsilon) + \sum_{\kappa} \int_0^{\infty} dp\, p^2 T_{\mu\kappa}(q, p, \epsilon) G_{\kappa}(p, \epsilon) V_{\kappa\nu}(p, p', \epsilon)$$

$\mu = \Lambda K_S^0$

$\nu = pp$

Kernel responsible for the coupling of resonances to the final states

All possible meson baryon couplings

D. Rönchen et al. 2014 Eur. Phys. J. A 50 101

- Jülich-Bonn Dynamic Coupled Channel (JuBo) - to extract the production mechanism of resonances which decay via strangeness in their final states
- Used for hadronic scattering and photoproduction processes such as $pp \to \Lambda K_S^0 \Delta^{++}$ (with a spectator), $pp \to p\Lambda K$ [Óscar Cytron] , $pp \to pn\pi^+$ [Saket Sahu] or $N\pi \to \pi N, K\Lambda$
- $T_{\mu\nu}(s)$ simultaneously describes every meson-baryon channel
- Work in progress - understanding MB contribution to $pp \to \Lambda K_S^0 \Delta^{++}$ channel

JüBo Fit Results

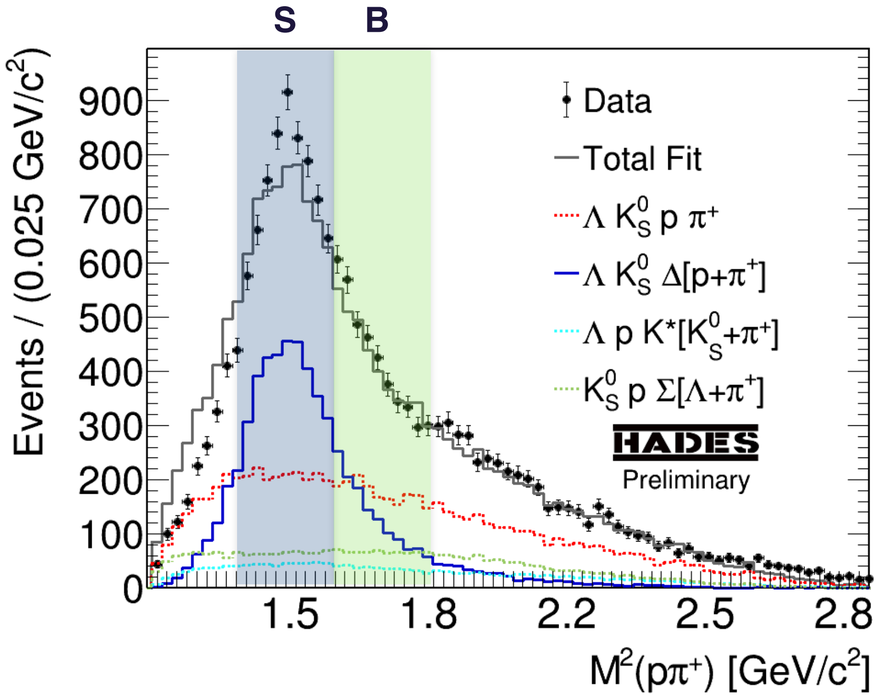
$$pp \longrightarrow \Lambda + K_S^0 + \Delta^{++}\,[p\pi^+]$$

Data selection on fully exclusive events :

- mass constraint - $M(\pi^+p)$ to 1.23 GeV
- Kinematic refit:
  - ➡ individual mass constraints - $\Lambda, K_S^0, \Delta^{++}$
  - ➡ initial *pp* system energy momentum conservation - 4C

Signal events selected - $1.4\ GeV^2 < M^2(\pi^+p) < 1.6\ GeV^2$

Background - $1.6\ GeV^2 < M^2(\pi^+p) < 1.8\ GeV^2$

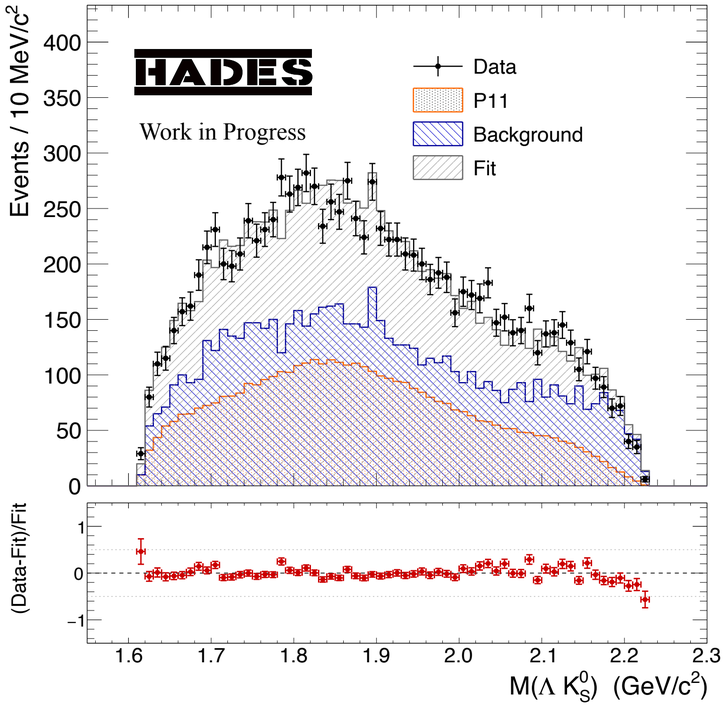


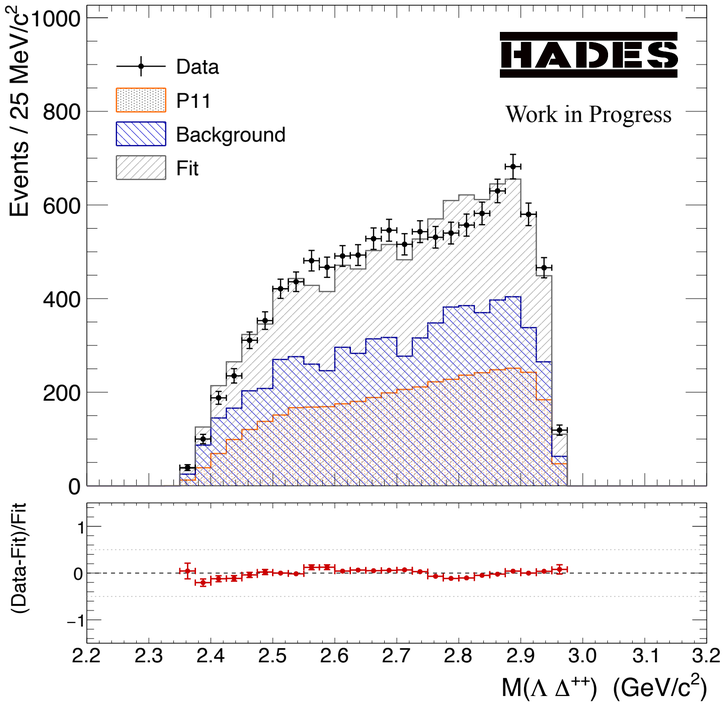
JüBo Fit Results

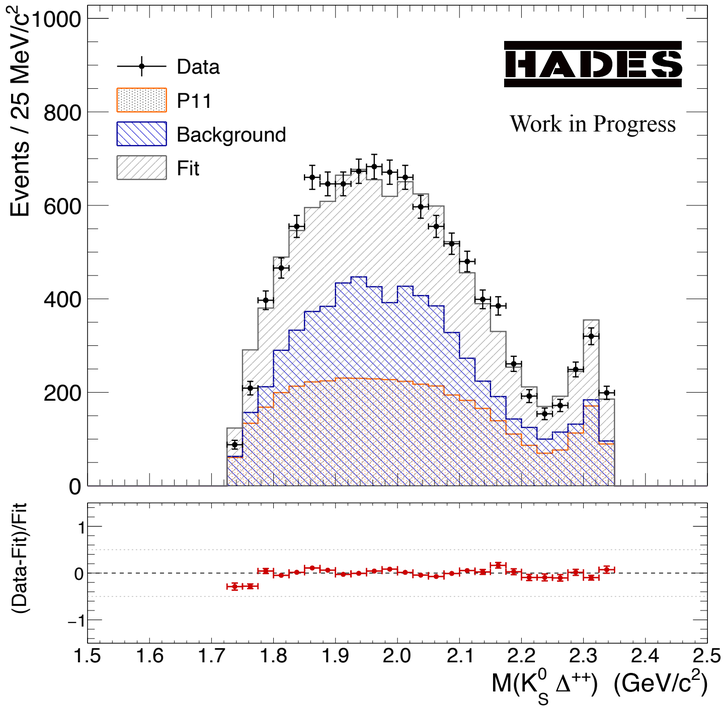
$$pp \longrightarrow \Lambda + K_S^0 + \Delta^{++}\,[p\pi^+]$$

Model applicability :

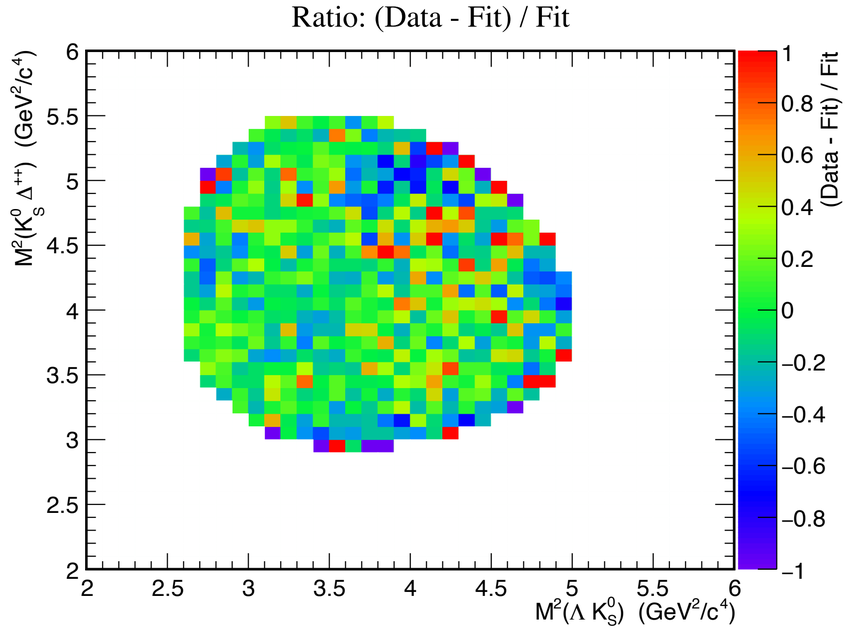
- JüBo fit on $M(\Lambda K_S^0)$
- **Signal events** - $1.4\ GeV^2 < M^2(\pi^+ p) < 1.6\ GeV^2$
- Background - $1.6\ GeV^2 < M^2(\pi^+ p) < 1.8\ GeV^2$

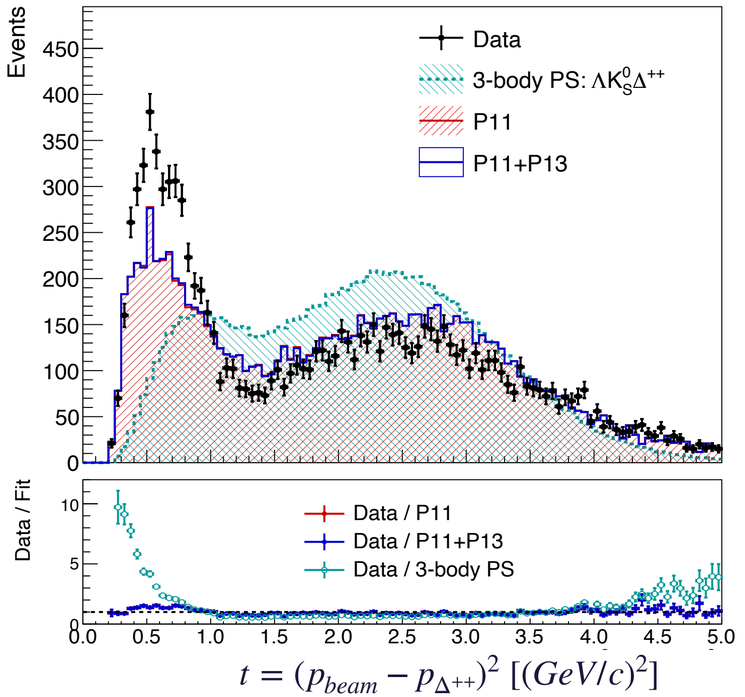






P_{11} Fit vs Data





The ratio of the Dalitz distribution has tiny deviations

The model applicability is performed across the entire *t* range

The fit with an additional P_{13} wave does not improve the ratio

Fit with Higher Waves

Ratio: $\frac{Data - Fit}{Fit}$

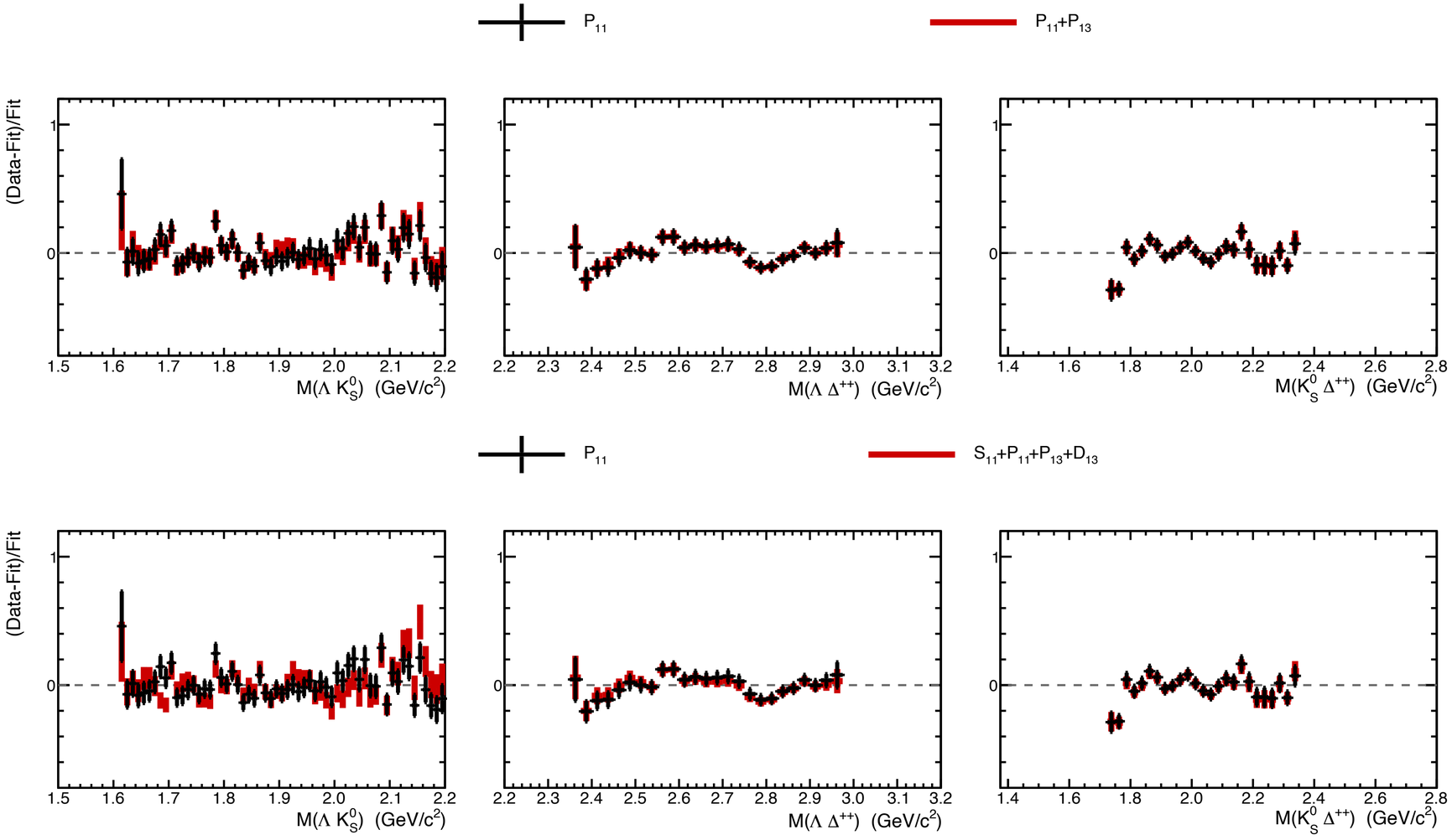
Ratios are compared to the base case - P_{11} results in black.

Adding higher waves doesn't improve the results.

The sideband events -

$1.6\ GeV^2 < M^2(\pi^+ p) < 1.8\ GeV^2$

are taken as background in the fit.



Summary

- JüBo model applied to study contributions for N* resonances in $pp \rightarrow \Delta^{++} N*$, with $N* \rightarrow \Lambda K_S^0$
- P_{11} wave is sufficient to understand the data.

Outlook

➡ Short term: Systematic uncertainties

➡In progress: JüBo model application to missing proton analysis.

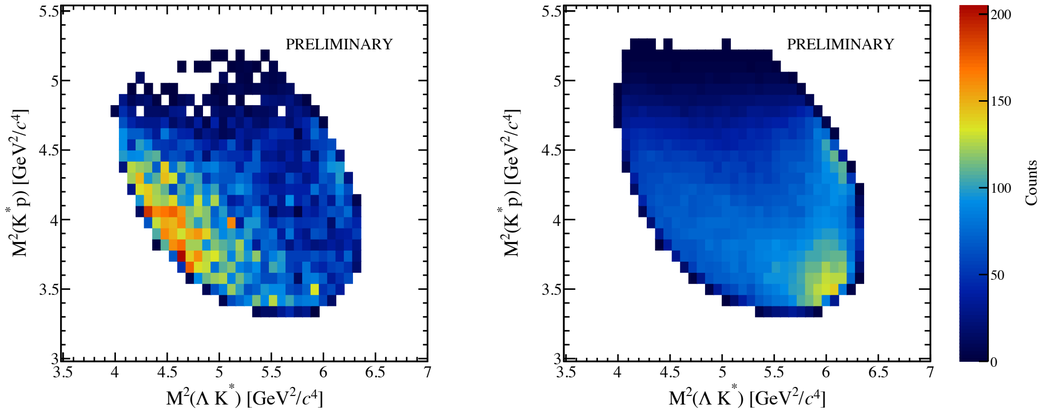
➡Long term: complete partial wave analysis.

Thank you

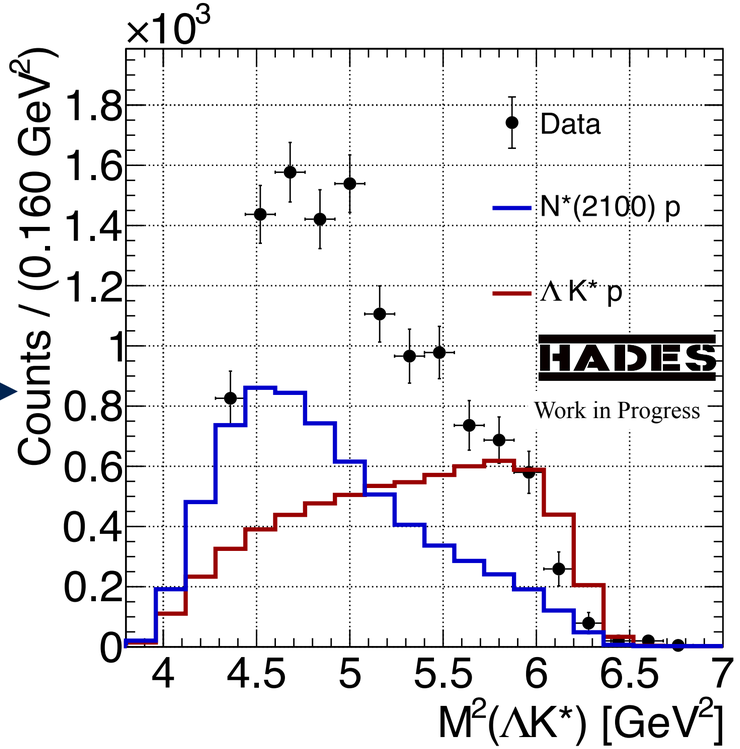
Missing Proton Analysis

$$pp \longrightarrow \Lambda + K^{+}(892)\,[K_S^0\pi^+] + p$$

Data **Simulations**



p_p (GeV/c)	N^* (%)
3.65 [1]	-
This work 5.35	?
6.70 [2]	*seen*
7.87 [3]	15.6



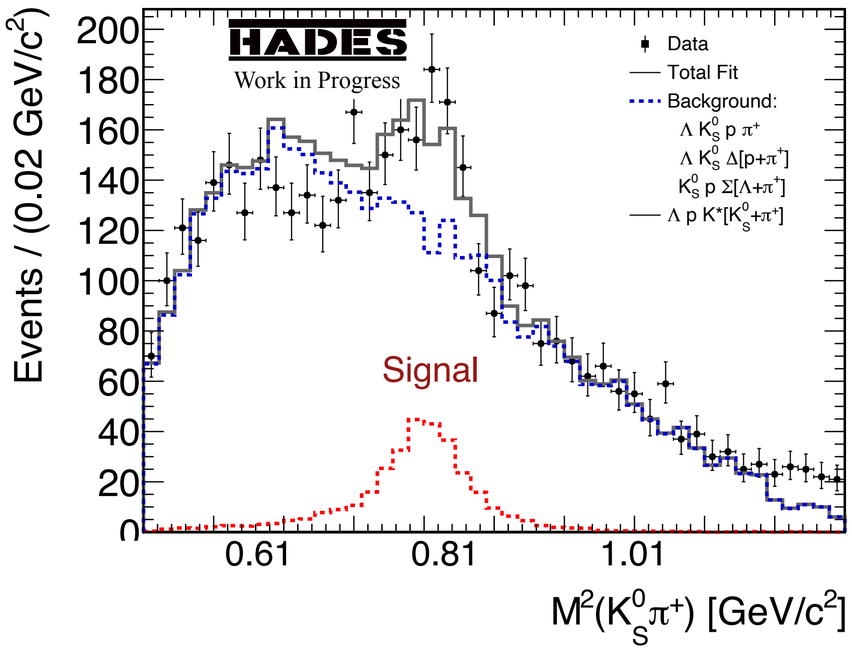
- Data comparison with 3 body simulations
- A Breit-Wigner with N(2100) is used to model low invariant mass region
- Data points to dynamics more than a simple 3 body phase space behavior
- A dynamic coupled channel approach to be implemented to draw further conclusions

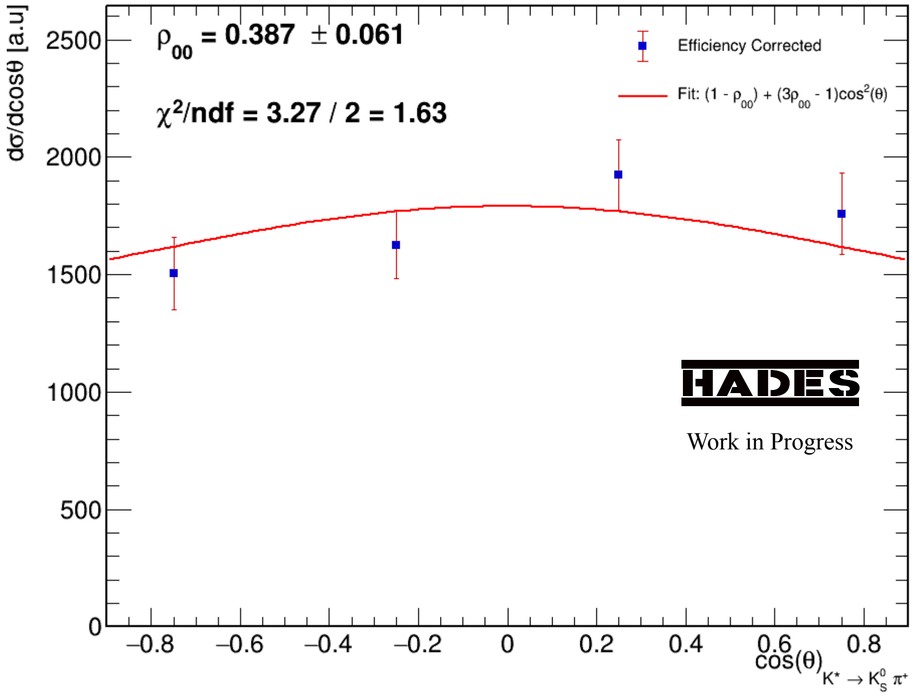
[1] M. Nekipelov et al 2007 J. Phys. G: Nucl. Part. Phys. 34 627.

[2] S. Klein et al. 1970 Phys. Rev. D 1 3019.

[3] M. Firebaugh et al. 1968 Phys. Rev. 172 1354.

K^* Angular Distributions





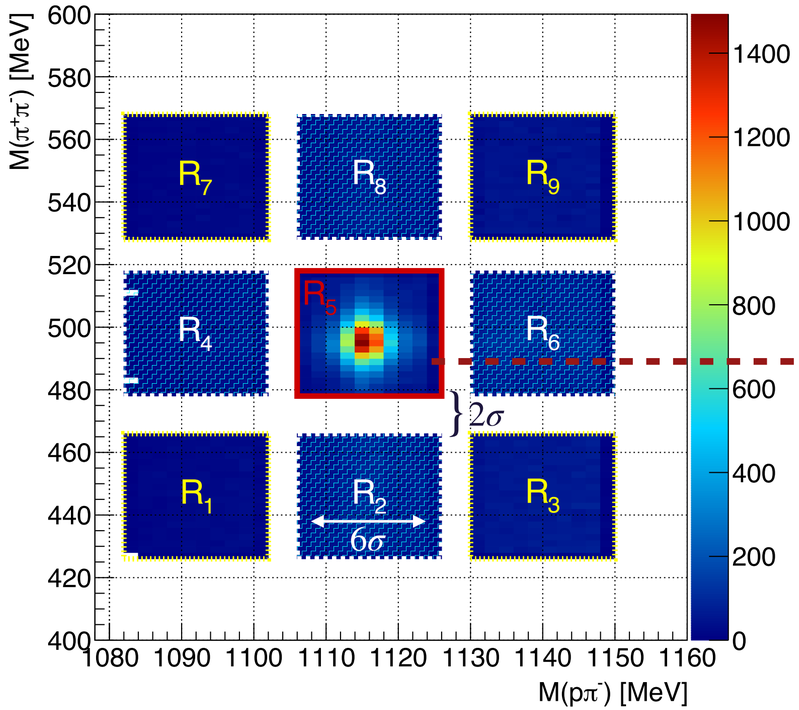
- Differential angular distribution of K*$^+$ decays
- The ratio between reconstructed over phase space generated map - acc x efficiency correction
- Helicity frame used for estimating ρ_{00}

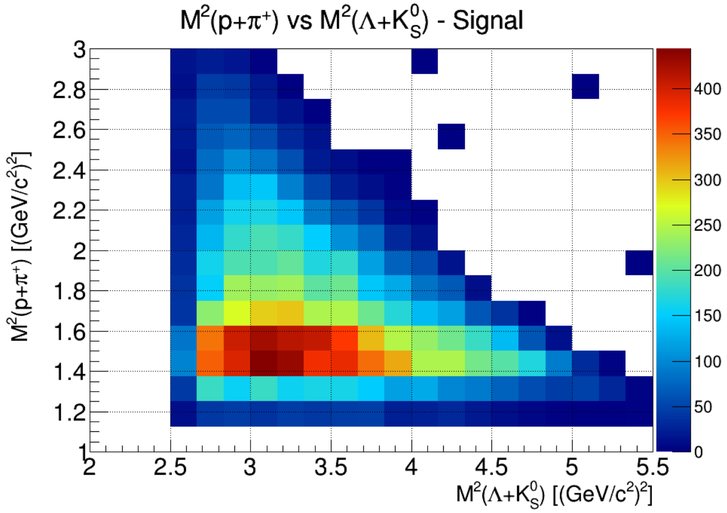
Within the our energy range ρ_{00} seems to independent of the cm energy

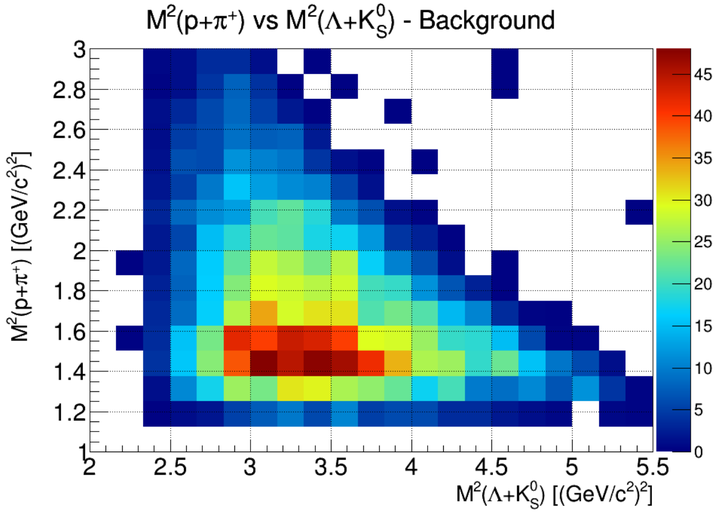
Previously ρ_{00} = 0.39 ± 0.09(stat.) $^{+0.10}_{-0.09}$ (syst.) at $\sqrt{s} \sim 3.18$ with HADES.

G. Agakishiev et al. Phys. Rev. C 92, 024903

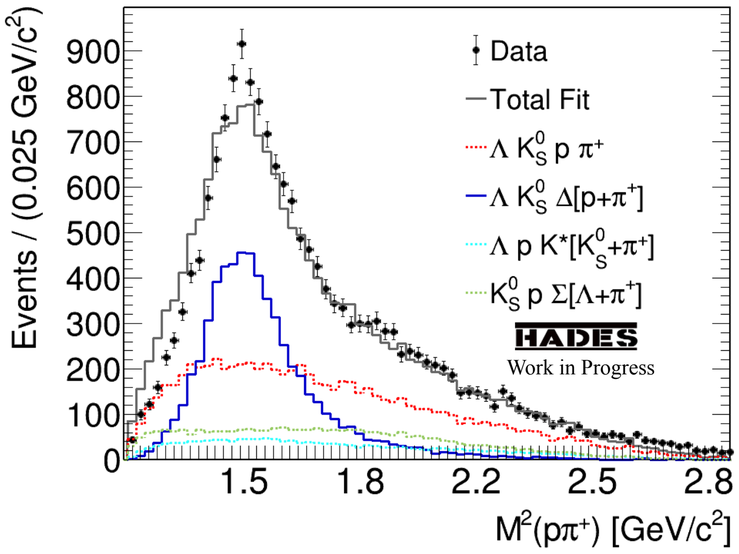
Sideband Subtraction



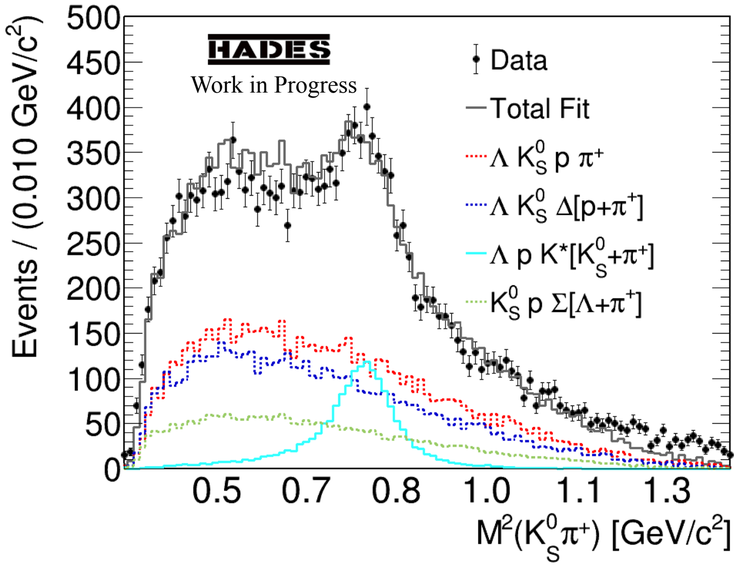




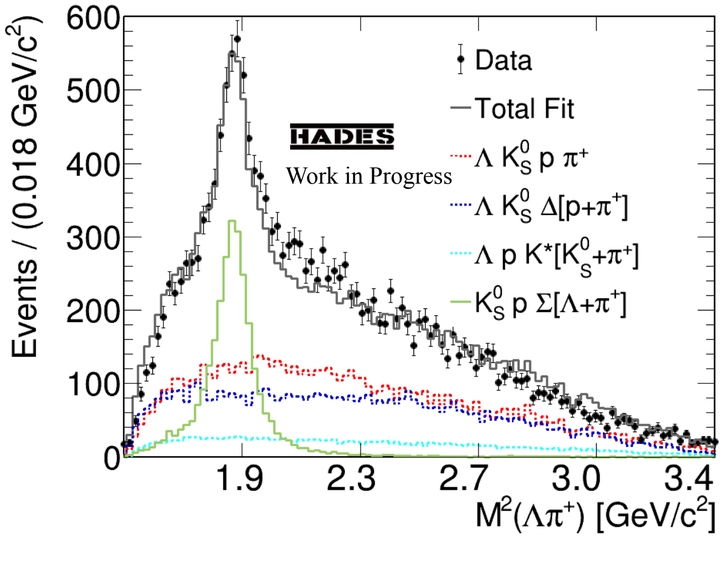
- Signal region ± 3σ from the nominal mass peak.
- A gap of ± 2σ is kept to avoid overlap with signal window.
- Sideband regions of size 6σ are taken from ± 3σ from the gap window.
- Region **2, 4, 6, 8** have a weight of -1/2, region **1, 3, 7, 9** have a weight of +1/4.
- Region **5** has a weight of 1.



$$pp \longrightarrow \Lambda + K_S^0 + \Delta^{++}\,[p\pi^+]$$



$$pp \longrightarrow \Lambda + K^+(892)\,[K_S^0\pi^+] + p$$



$$pp \longrightarrow \Sigma^+(1385)\,[\Lambda\pi^+] + K_S^0 + p$$

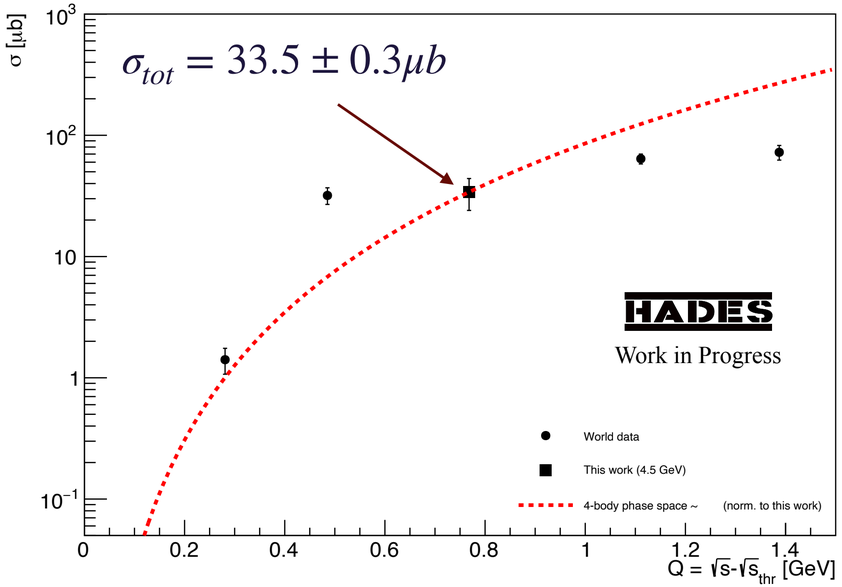
- A simultaneous incoherent fit is performed to the three different invariant mass distributions.
- The presented mass distributions are well described by the combined fit.

I. Fröhlich et al., J. Phys Conf. Ser. 219 032039 (2010).

Preliminary Total Cross Section

p_p (GeV/c)	N_{events} (Counts/1000)	σ_{tot} (μb)	NR (%)	Δ^{++} (%)	Σ^{+*} (%)	K^{+*} (%)	N^* (%)	ρ_0 [a.u]
3.65 [1]	1.04	1.41	65	35	seen	-	-	-
This work 5.35	8.8	34	20	44	16	20	Hints	0.39
6.70 [2]	1.0	64	36	36	18	10	*seen*	-
7.87 [3]	0.83	72.4	5.7	34.2	29.1	15.5	15.6	-

$$pp \longrightarrow \Lambda + K^0 + p + \pi^+$$



Cross section vs beam momentum, adapted from [1].

- Observables from earlier experiments based on a one-pion-exchange model [2-3].
- Previous experiments had lower statistics.
- Preliminary cross sections values (total and differential) from this work compatible with earlier results [1-3].
- Partial wave analysis necessary to extract couplings and intermediate resonances.

[1] M. Nekipelov et al 2007 J. Phys. G: Nucl. Part. Phys. 34 627.
[2] S. Klein et al. 1970 Phys. Rev. D 1 3019.
[3] M. Firebaugh et al. 1968 Phys. Rev. 172 1354.
[4] K. Tsushima et al 1999, Phys. Rev. C 59, 369.
[5] G.Agakishiev et al 2014 Phys.Rev.C 90 015202.