Analysis of the production mechanism of $p + p \rightarrow p + K + \Lambda$ using PWA

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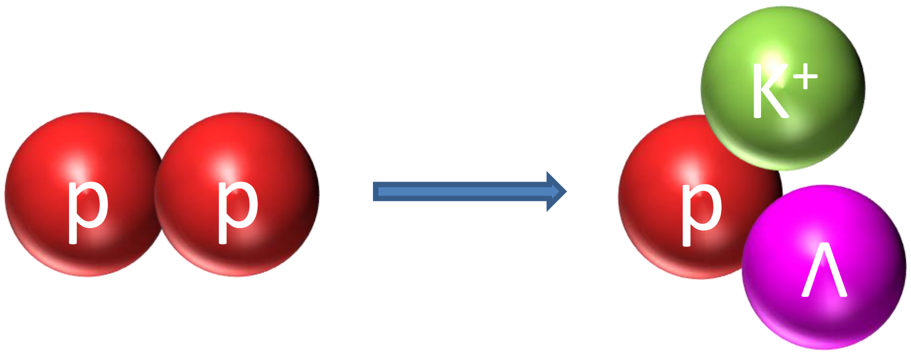
CERN

Outline

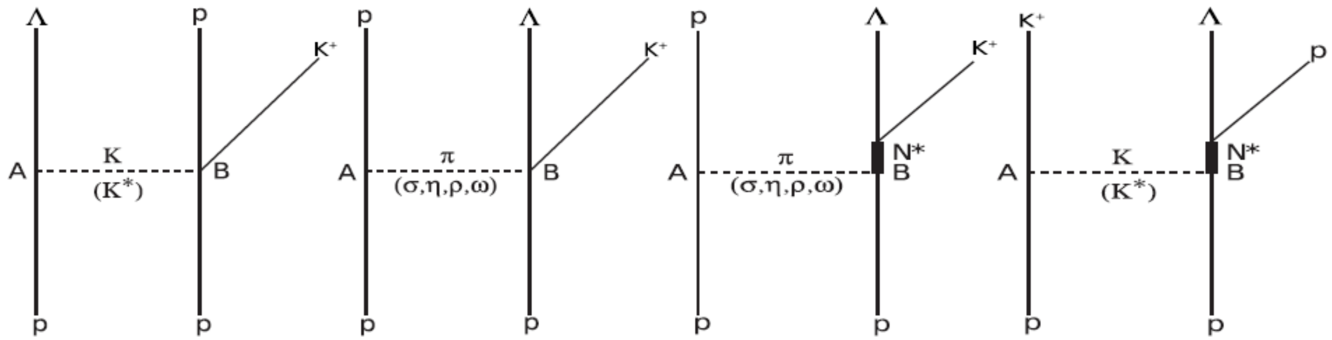
- Introduction - Strangeness Production
- Experimental Data
- Method of Partial Wave Analysis
- Results of Combined Analysis
  - Excitation Function
  - Scattering Length
- Summary
- Outlook

Strangeness Production

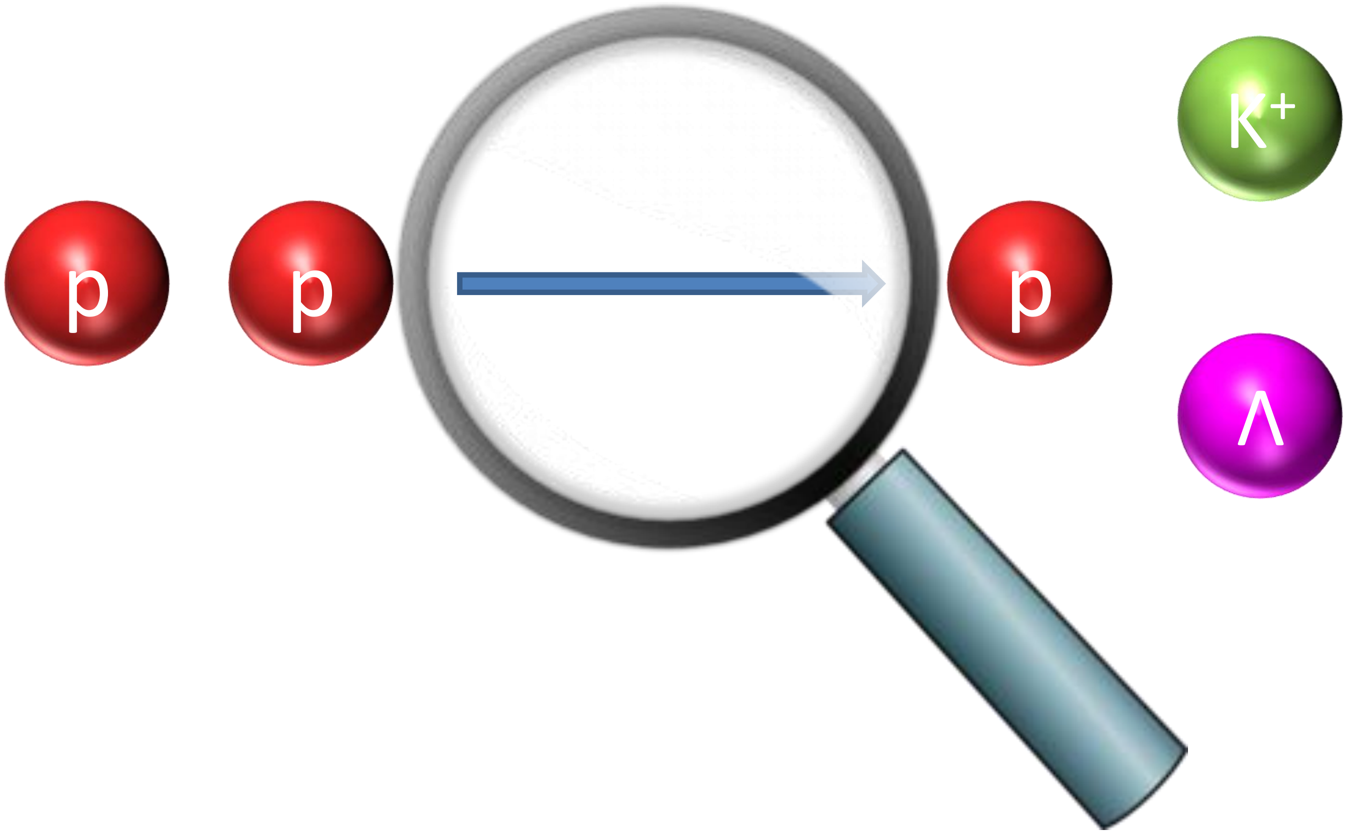


Detailed Understanding required:
- Transport Model
- Production of Exotic

One – Boson Exchange Modell

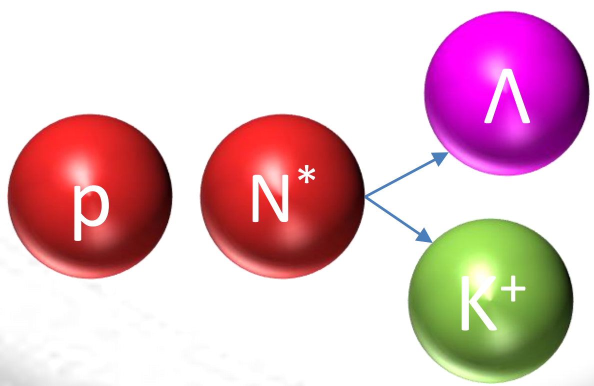


Strangeness Production



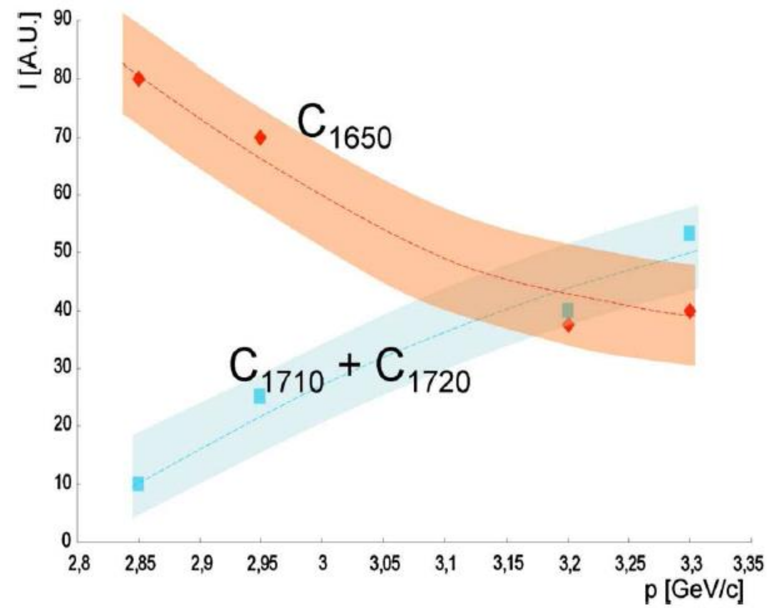
Strangeness Production

Resonance	J^P	Mass (GeV/c^2)	Γ (MeV/c^2)
N*(1650)	$1/2^-$	1.655	0.150
N*(1710)	$1/2^+$	1.710	0.100
N*(1720)	$3/2^+$	1.720	0.250
N*(1875)	$3/2^-$	1.875	0.220
N*(1880)	$1/2^+$	1.870	0.235
N*(1895)	$1/2^-$	2.090	0.090
N*(1900)	$3/2^+$	1.900	0.0250

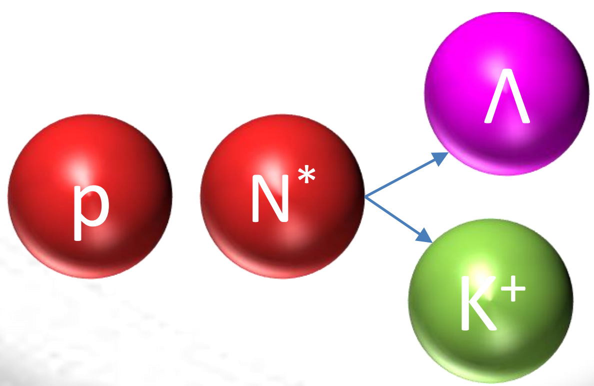


S. Abd El-Samad et al.
Phys.Lett B688 (2010)

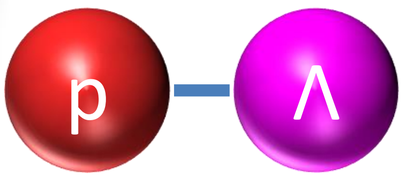
Strangeness Production



S. Abd El-Samad et al.
Phys.Lett B688 (2010)

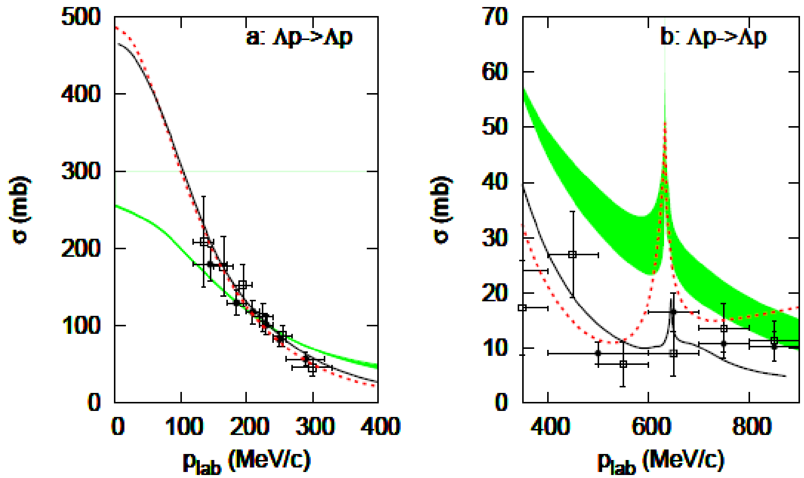


Strangeness Production



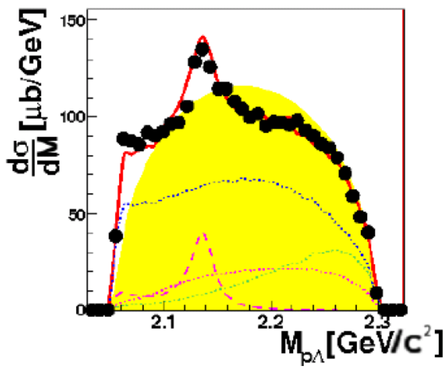
Final State Interaction

LO – NLO Calculations

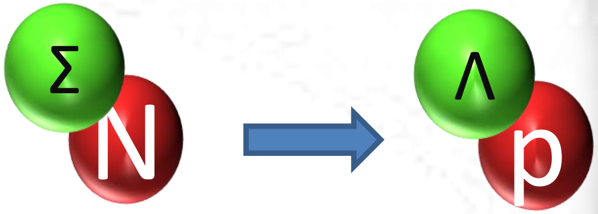


J. Haidenbauer et al., Nucl. Phys. **A915**, 24 (2013)

Strangeness Production

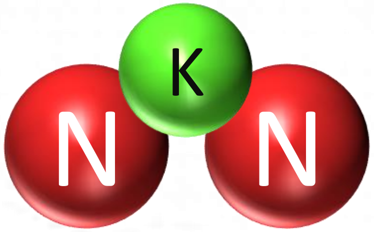


S.Abd El-Samad, Eur.Phys.J A49(2013)

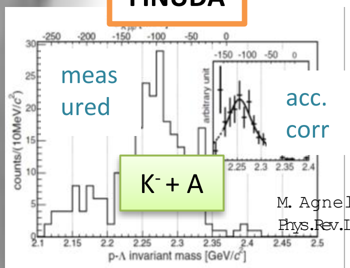


At Threshold : 2130 MeVc^{-2}

Strangeness Production

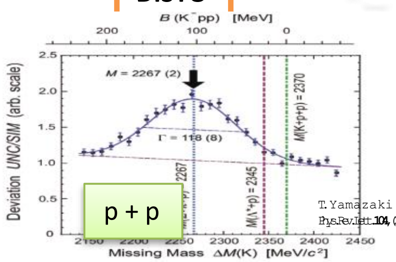


FINUDA



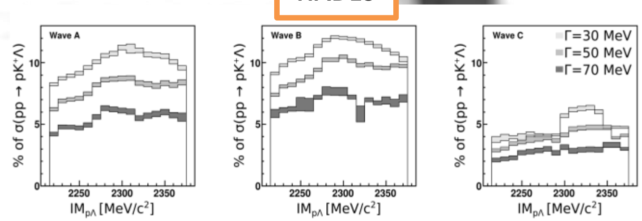
M. Agnello et al. Phys.Rev.Lett.94 (2005)

DISTO



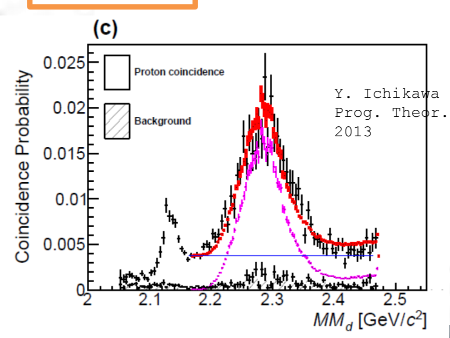
T. Yamazaki et al. Phys.Rev.Lett.104 (2010)

HADES



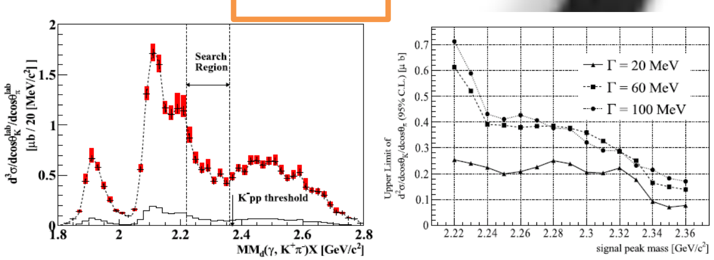
G. Agakishiev, Phys.Lett. B742 (2015) 242-248

E-27 JParc



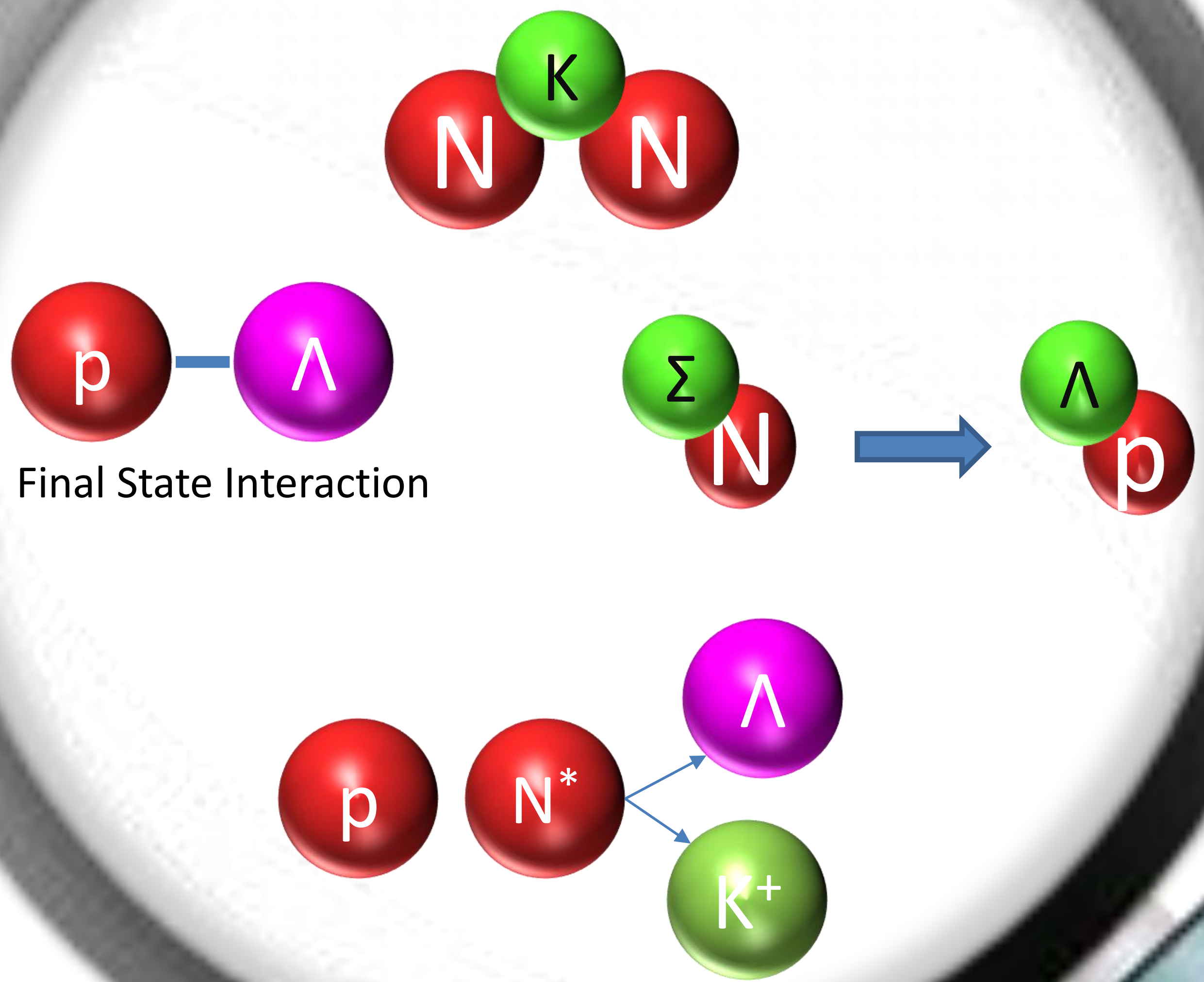
Y. Ichikawa et al. Prog. Theor. Exp. Phys. 2013

LEPS/ SPRING8

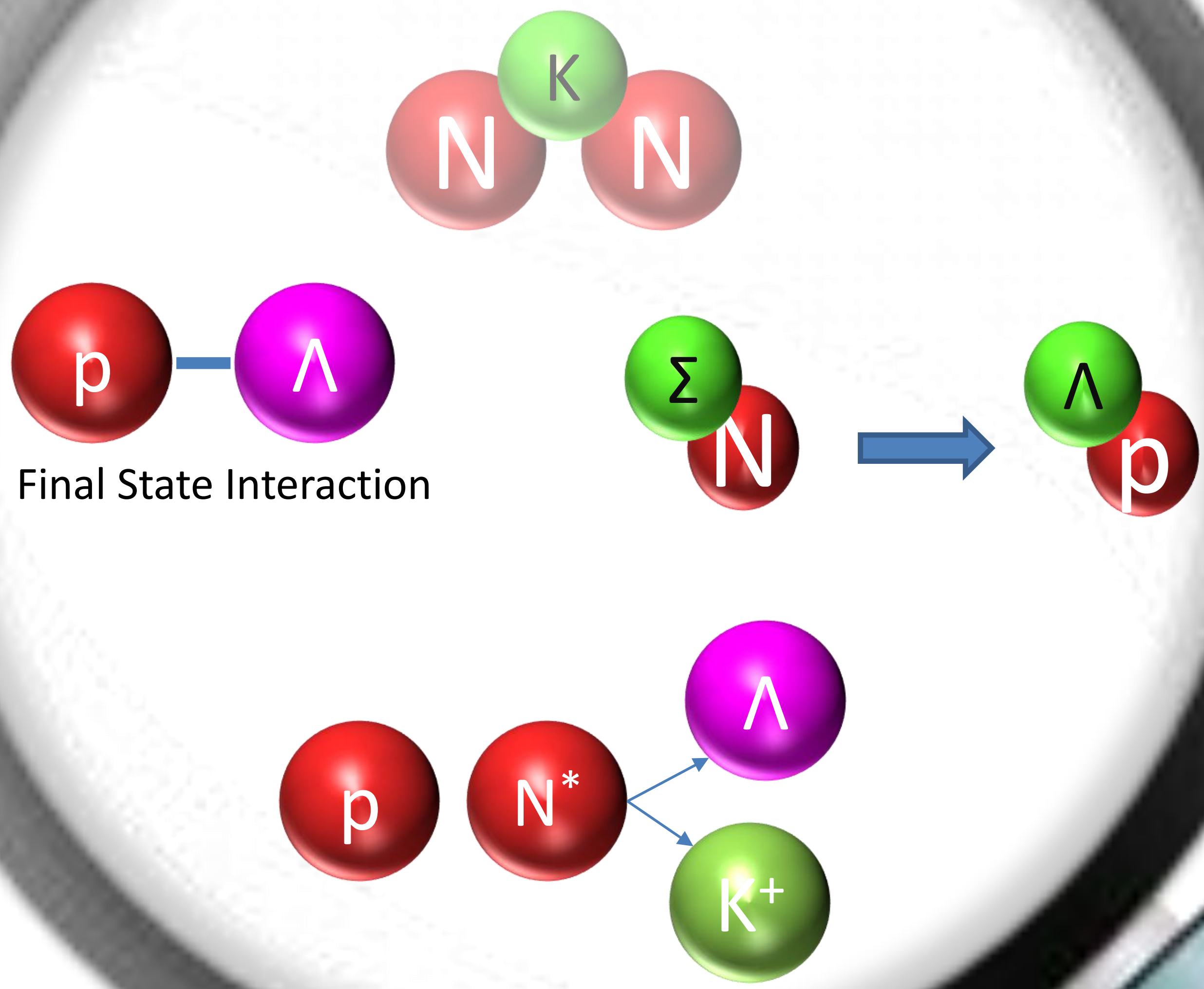


A.O. Tokayasu et al. Phys.Lett. B728, (2014)

Strangeness Production



Strangeness Production



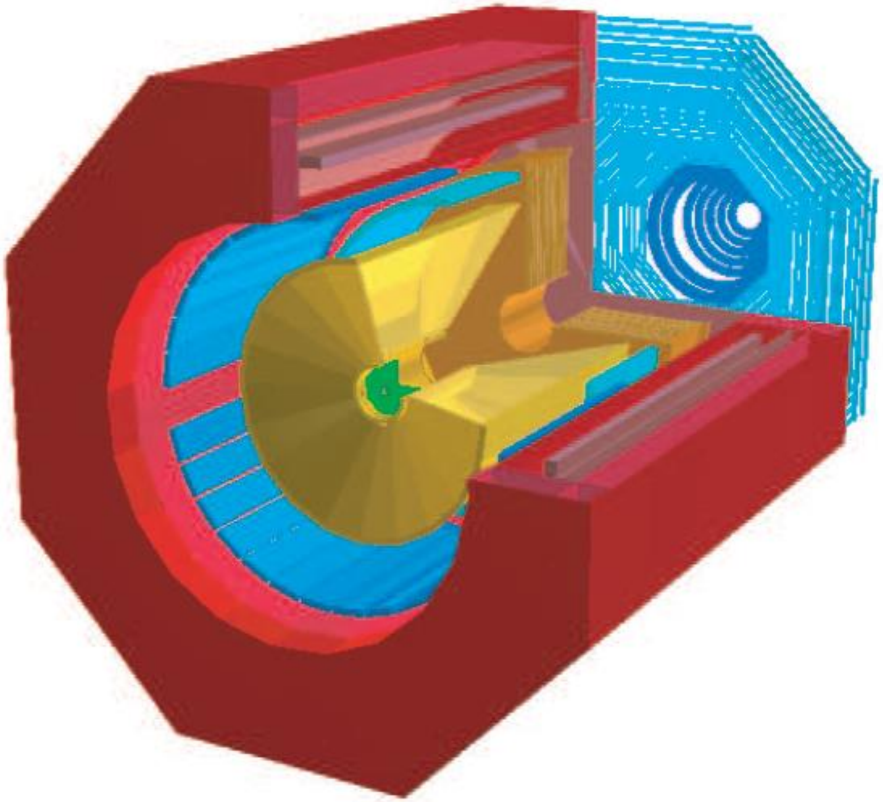
Experimental Data

Data Sets

Experiment	E_B [GeV]	Statistics	Reference
DISTO	2.15	121k	M. Maggiora et al. Nucl Phys. A835, 43 (2010) M.Maggiora, Nucl Phys. A691, 329 (2001)
COSY-TOF	2.16	43k	M. Roeder et al., Eur. Phys..J. A49, 157 (2013) S. Jowzaee et al., Eur. Phys. J. A52, 7 (2016)
DISTO	2.5	304k	M. Maggiora et al. Nucl Phys. A835, 43 (2010) M.Maggiora, Nucl Phys. A691, 329 (2001)
DISTO	2.85	424k	M. Maggiora et al. Nucl Phys. A835, 43 (2010) M.Maggiora, Nucl Phys. A691, 329 (2001) F. Balestra et al. , Phys.Rev.Lett.83. 1534 (1999)
FOPI	3.1	903	R. Münzer, Hyp. Int., 233,1-3,159-166 (2015)
HADES	3.5	21k	G. Agakishiev,Phys.Lett. B742 (2015) 242-248

The FOPI Experiment

SIS18 GSI Darmstadt



Beam Energy: 3.1 GeV

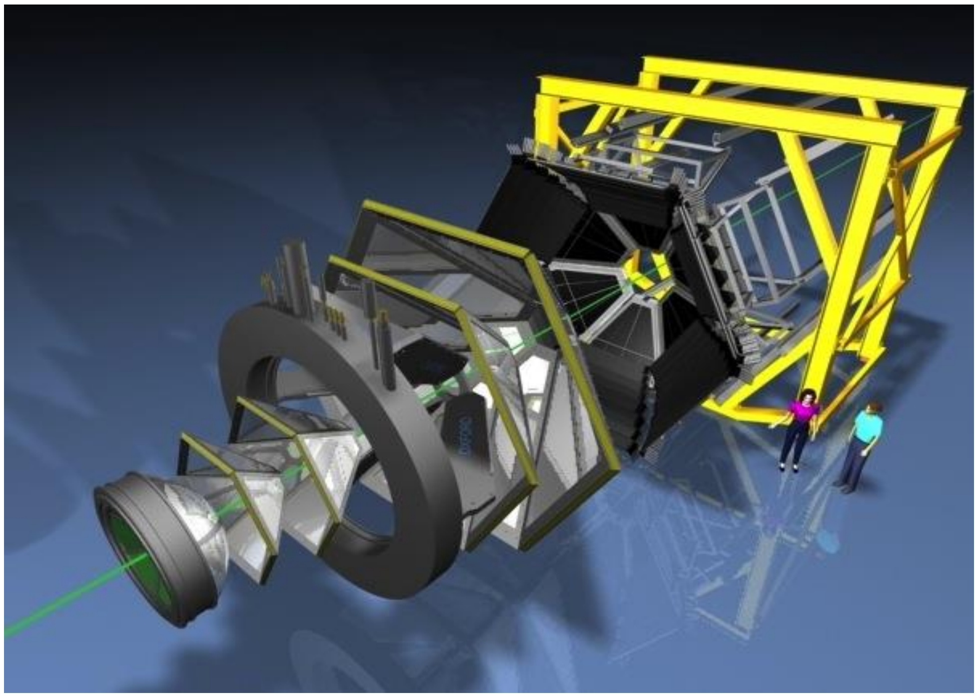
- Fixed-target Setup
- Full azimuthal coverage, 5˚- 110˚ in polar angle
- Momentum resolution ≈ 7% - 15 %
- Particle identification via dE/dx & ToF

Trigger Detector – SiΛViO:

Λ – Enhancement: $14.1 \pm 7.9(stat)^{+4.3}_{-0.6}$

The HADES experiment

High **A**cceptance **D**i-electron **S**pectrometer
GSI, Darmstadt

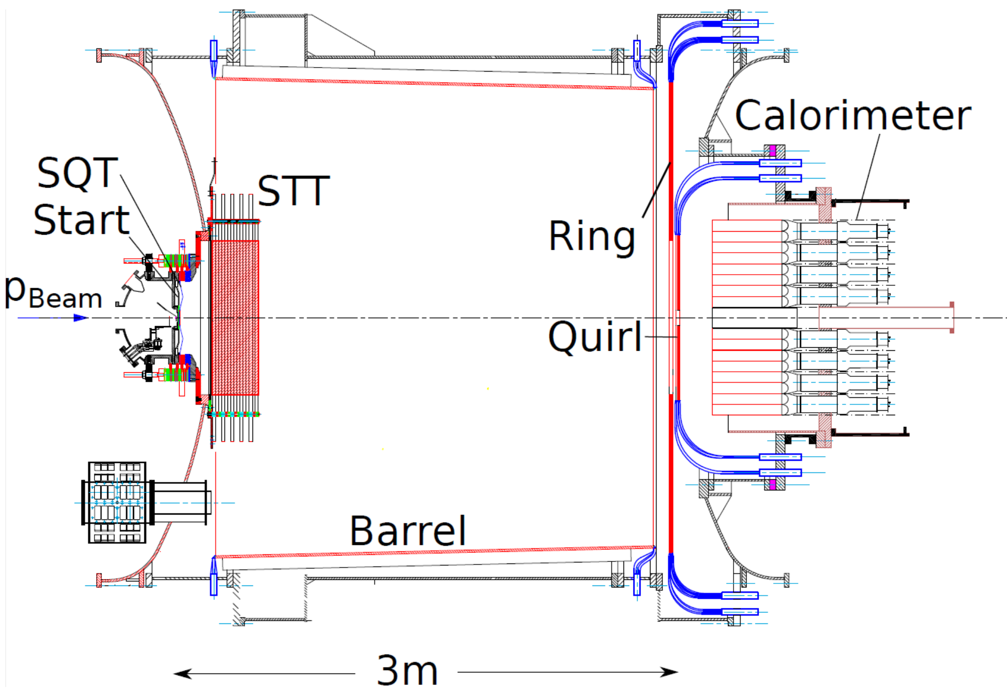


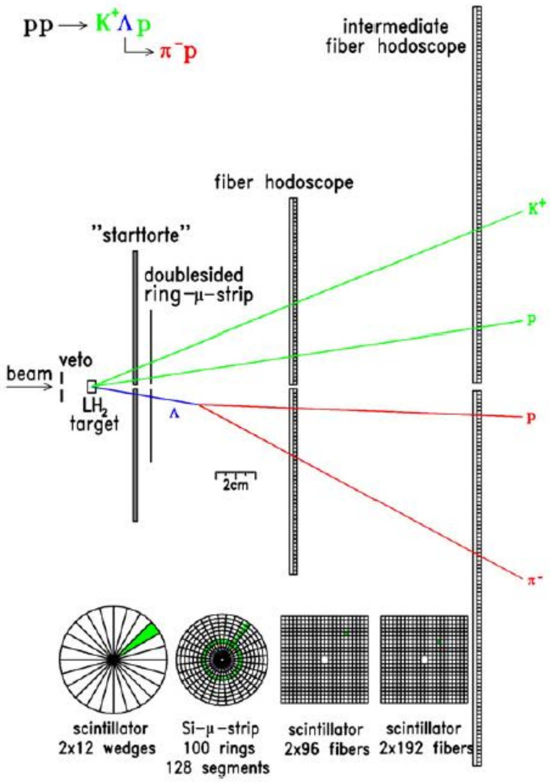
HADES Coll. (G. Agakishiev et al.), Eur. Phys. **J. A41** (2009)

Beam Energy: 3.5 GeV

- Fixed-target Setup
- Full azimuthal coverage, 15˚- 185˚ in polar angle
- Momentum resolution ≈ 1% - 5 %
- Particle identification via dE/dx & ToF

COSY-TOF Spectrometer





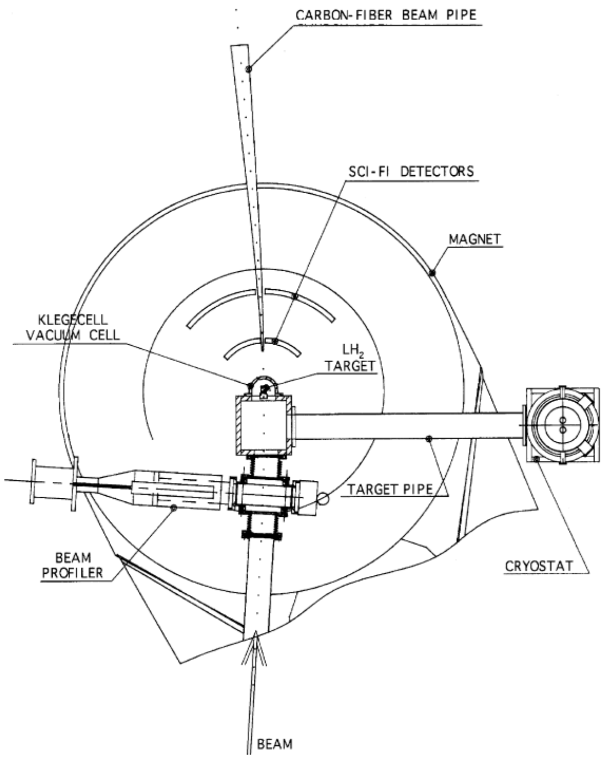
Acceptance: 1°-60° (polar), 2π (azimuthal)

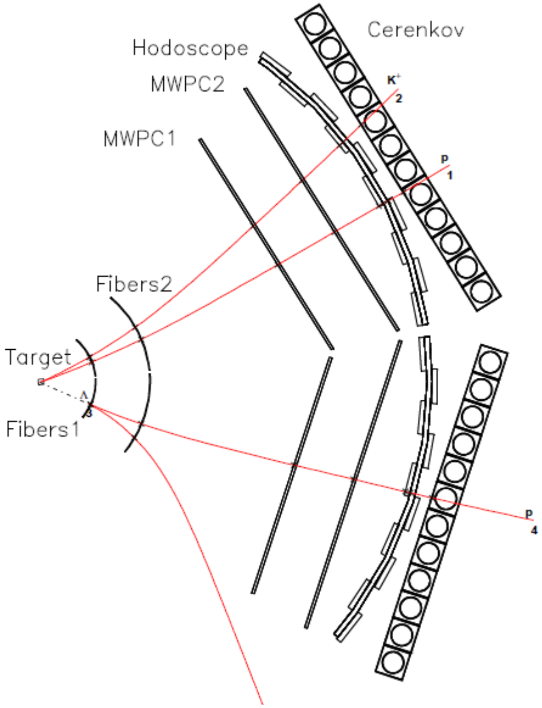
Sec. Vertex: $\sigma_{x,y} < 0.5mm, \sigma_z < 2.5mm$

Momentum resolution ≈ 1% - 1.5 %

$$\sigma_{MM(pK)} = 1.5\ MeV/c^2$$

DISTO Spectrometer





Acceptance: 23°-43° (polar), 2π (azimuthal)

$$\sigma_p = 5\%$$

$$\sigma_{MM(pK)} = 30\ MeV/c^2$$

Partial Wave Analysis

Bonn-Gatchina PWA Framework

A. Sarantsev et.al., Eur.Phys J A 25 2005

Cross-section Decomposition

$$d\sigma = \frac{(2\pi)^4|A|^2}{4|k|\sqrt{s}} d\phi(P, q_1, q_2, q_3), \qquad P = k_1 + k_2$$

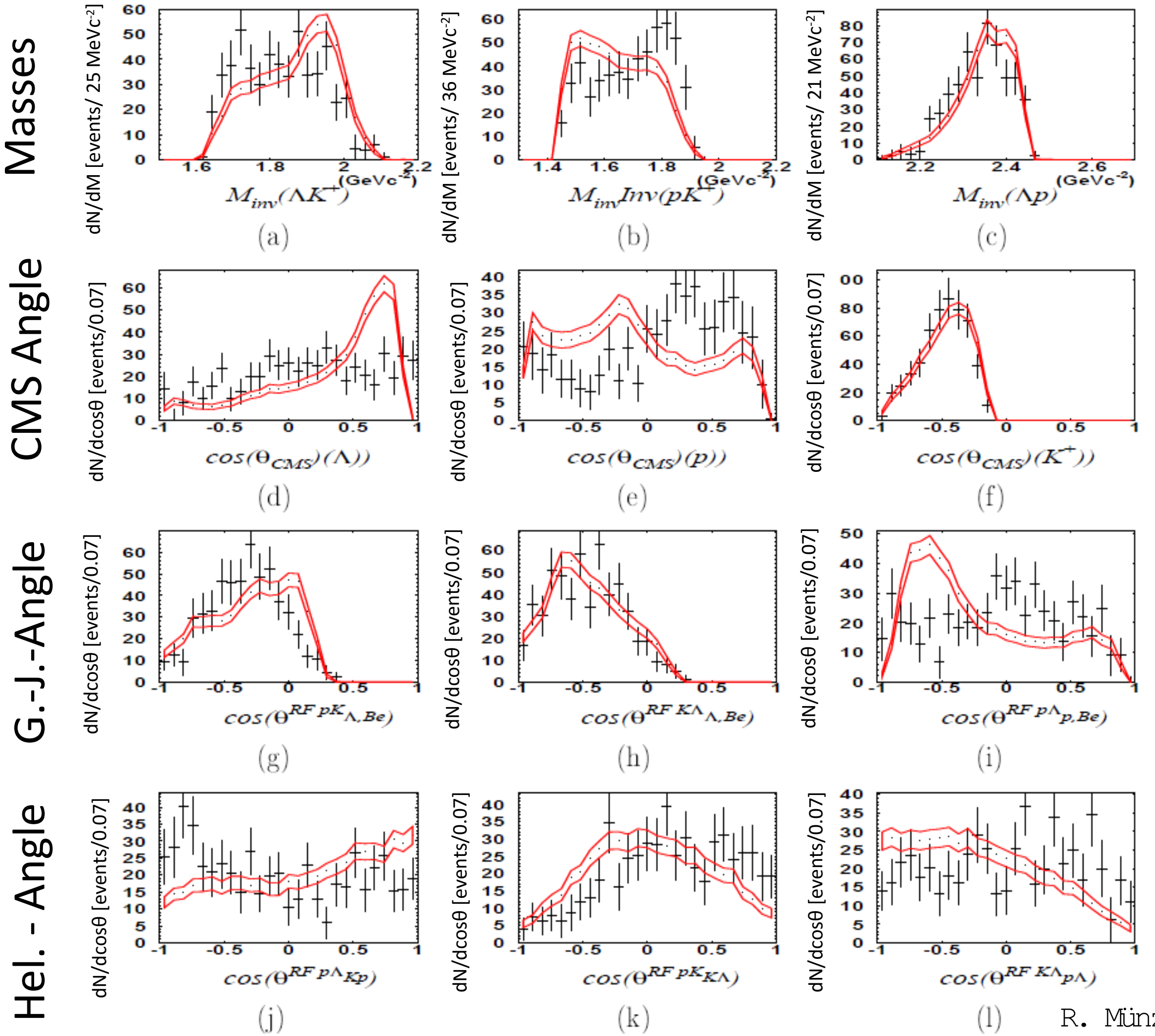
A : reaction amplitude A ∝ $A \propto A^{\alpha}_{tr}$ (s) (Transition amplitude of wave α)
k : 3-momentum of the initial particle in the CM
$s - P^2 : (k_1 + k_2)^2$
$d\phi(P, q_1, q_2, q_3)$: invariant three-particle phase space

Parameterization of the Transition

$$A^{\alpha}_{tr}(s) = (a^{\alpha}_1 + a^{\alpha}_3\sqrt{s})e^{ia^{\alpha}_2}$$

a^{α}_1 Constant amplitude
a^{α}_2 Phase
a^{α}_3 Energy dependent amp.

Why PWA?

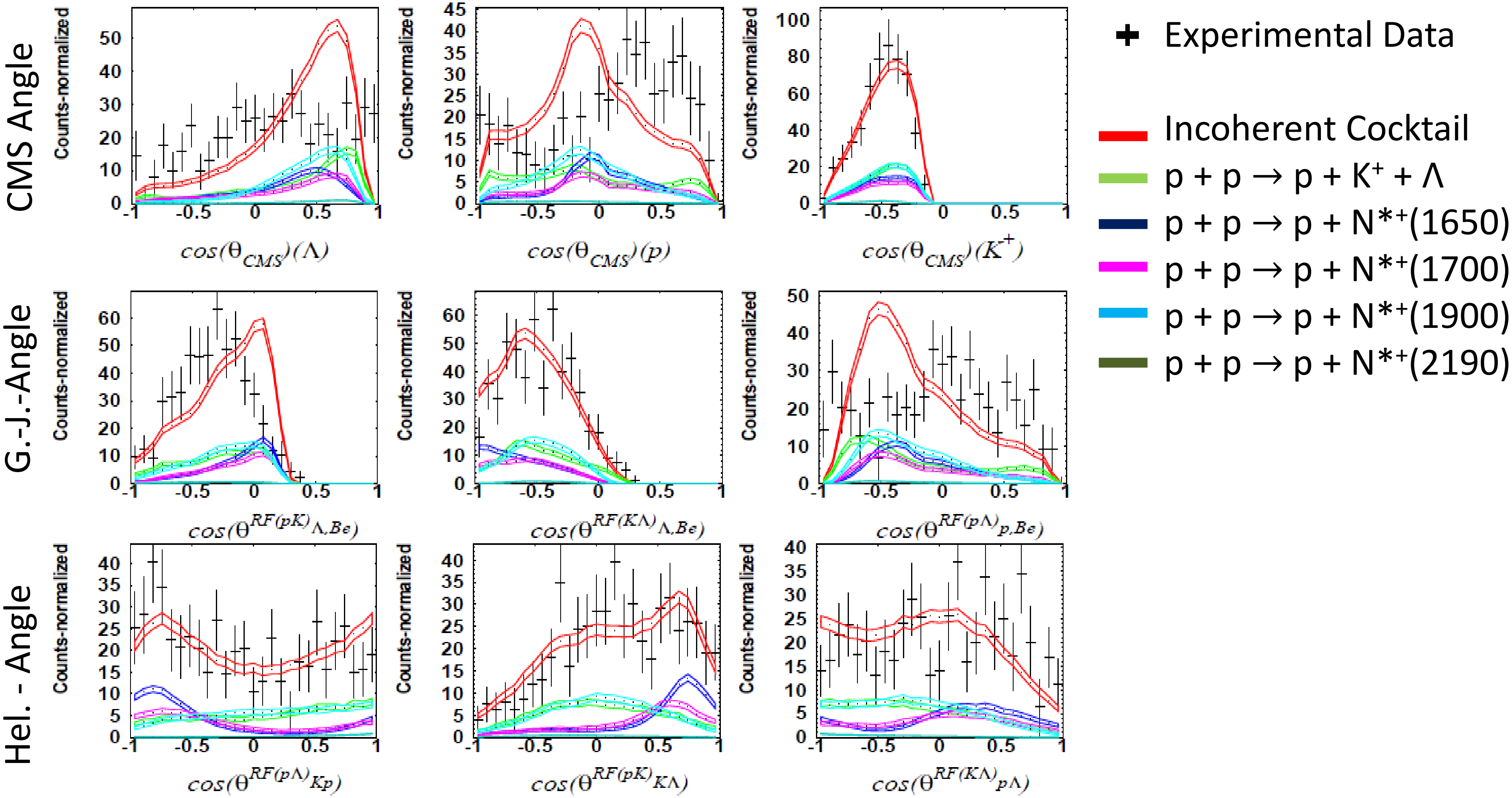


✚ Experimental Data

pp→ p K^+ Λ Phase Space

R. Münzer, Hyp. Int., 233,1-3,159-166 (2015)

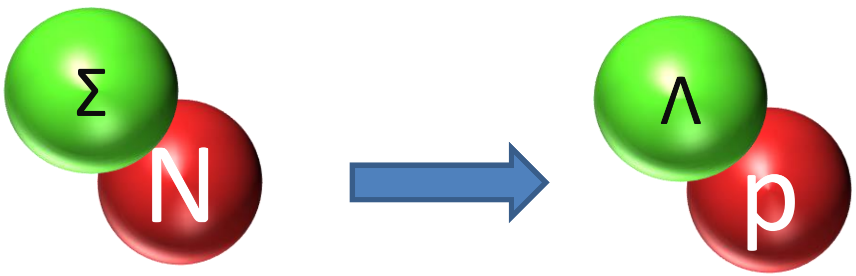
Why PWA?

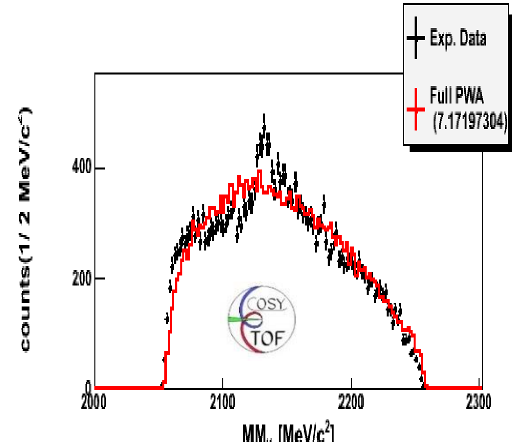


R. Münzer, PhD Thesis, TU Munich 2014

The ΣN Cusp Effect

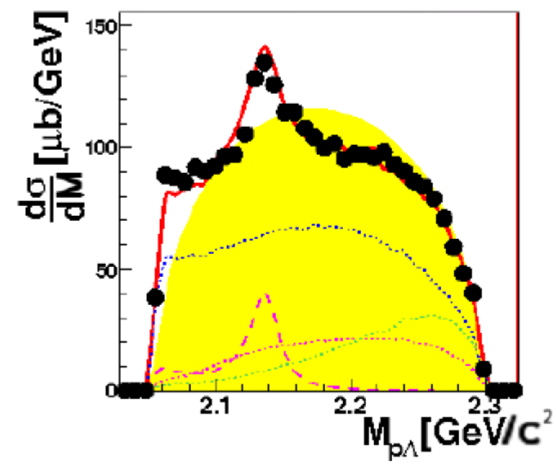
Coupled Channel:





At Threshold : 2130 $MeVc^{-2}$

Quantum Number of Cusp: 0^{+} / 1^{+} (L=0,2)



S.Abd El-Samad, Eur.Phys.J A49(2013)

Cusp Spectral Function

The Breit-Wigner:

$$\frac{d\sigma_{p\Lambda}}{dm_{p\Lambda}} \approx \frac{1}{\left|m_R^2 - m_{p\Lambda}^2 - i\, m_{p\Lambda} \Gamma\right|^2}$$

$Mass\ M_{cusp} = 2.13\mathrm{GeV}$, $With\ \Gamma = 0.02\mathrm{GeV}$

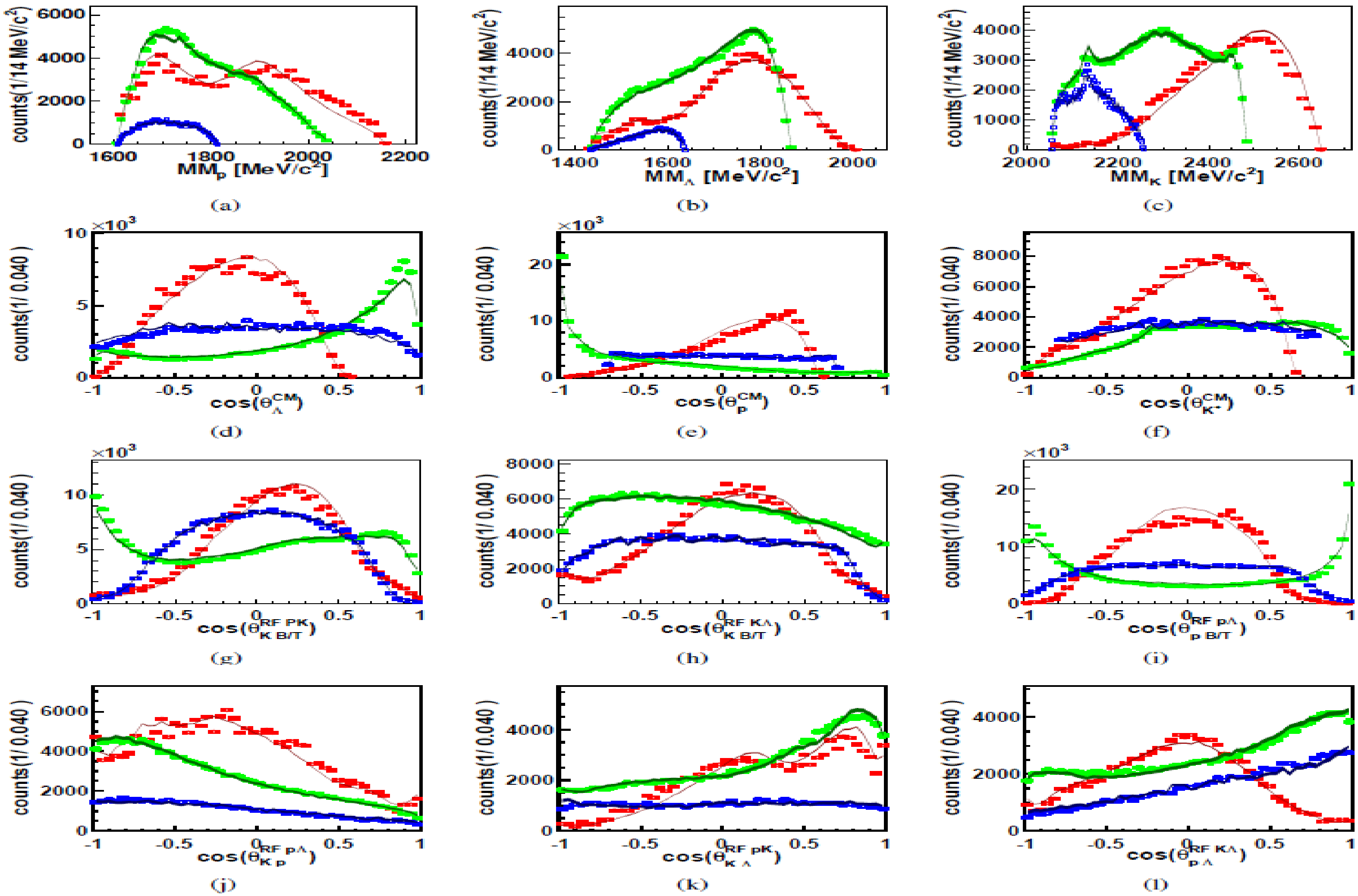
Combined Analysis

Parameter Scan

Variation of Included N* Resonances
Five best solution used to obtain systematical error

Solution	A	B	C	D	E
Loglike	-67142	-67018	-66878	-66405	-66393
N*(1650)	+	+	+	+	+
N*(1710)	+	+	+	+	+
N*(1720)	+	+	+	-	-
N*(1875)	+	+	-	+	+
N*(1880)	+	+	+	+	+
N*(1895)	+	+	+	+	+
N*(1900)	-	+	+	+	-
$\Sigma N - Cusp$	+	+	+	+	+

PWA Results



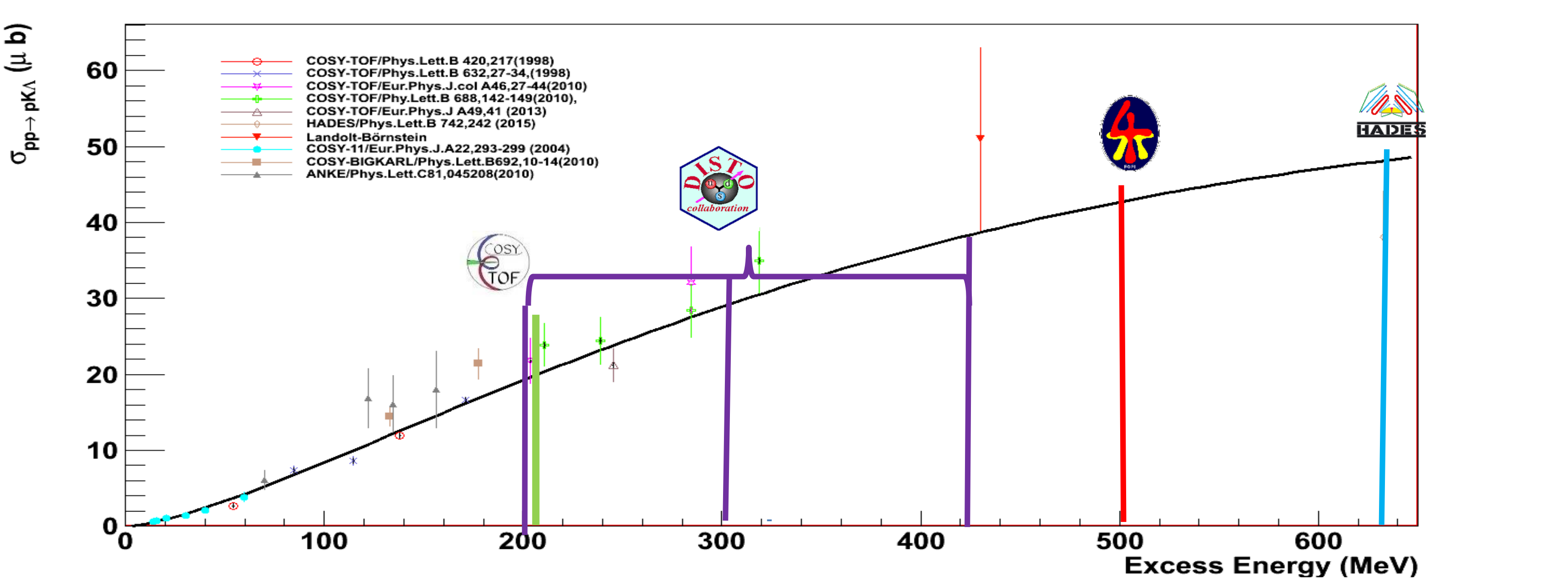
counts(1/14 MeV/c^2)
MM_p [MeV/c^2]
(a)
MM_Λ [MeV/c^2]
(b)
MM_K [MeV/c^2]
(c)
counts(1/ 0.040)
$\cos(\theta_\Lambda^{CM})$
(d)
$\cos(\theta_p^{CM})$
(e)
$\cos(\theta_{K^+}^{CM})$
(f)
$\cos(\theta_{K\,B/T}^{RF\,pK})$
(g)
$\cos(\theta_{K\,B/T}^{RF\,K\Lambda})$
(h)
$\cos(\theta_{p\,B/T}^{RF\,p\Lambda})$
(i)
$\cos(\theta_{K\,p}^{RF\,p\Lambda})$
(j)
$\cos(\theta_{K\,\Lambda}^{RF\,pK})$
(k)
$\cos(\theta_{p\,\Lambda}^{RF\,K\Lambda})$
(l)

PWA Results

- Comparison of Experimental Data and Results of PWA
- Using 3 Mass and 9 Angular Spectra
- ➢ Good Agreement between experimental data and PWA Result

Experiment	E_B [GeV]	X^2 /ndf
DISTO	2.15	1.52
COSY-TOF	2.16	0.44
DISTO	2.5	2.56
DISTO	2.85	3.55
FOPI	3.1	0.91
HADES	3.5	2.14

Total Cross Section



R.Muenzer et al.,Hyperfine 233, 159-166 (2016)

$$\sigma_{pK\Lambda} = C_1\left(1-\frac{s_0}{\left(\sqrt{s_0}+\epsilon\right)^2}\right)^{C_2}\left(\frac{s_0}{\left(\sqrt{s_0}+\epsilon\right)^2}\right)^{C_3}$$

A. Sibirtsev et.al. Nucl.Phys. A632,131 (1998)

Value:

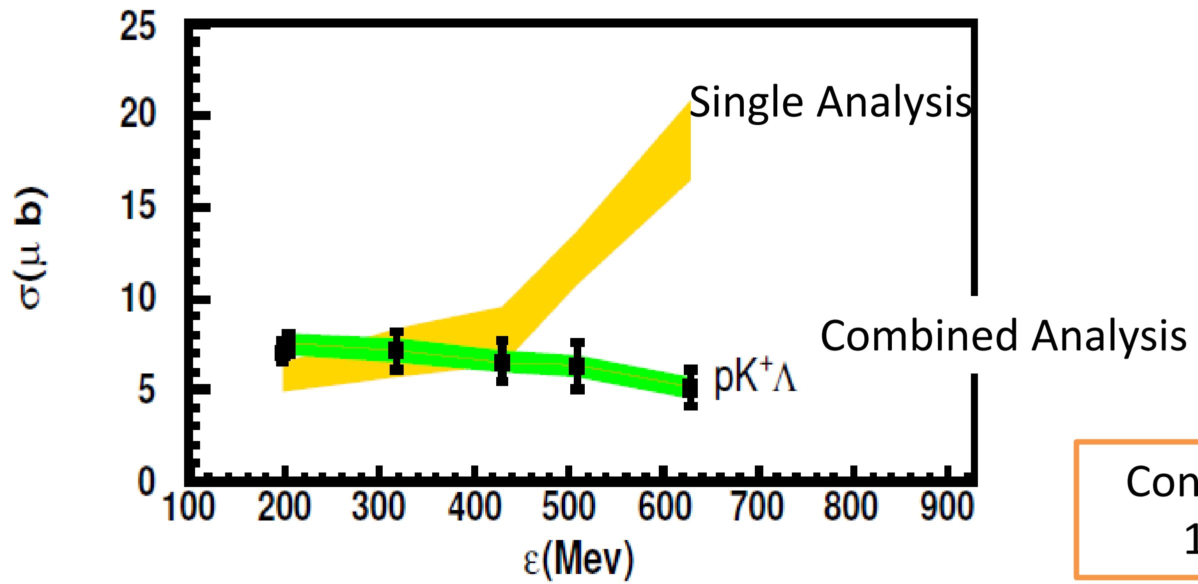
$C_1 = 1.18 \pm 0.42\ 10^3$

$C_2 = 1.88 \pm 0.12$

$C_3 = 3.28 \pm 0.71$

Excitation Function

P + p → p + K^+ + Λ (non resonant)

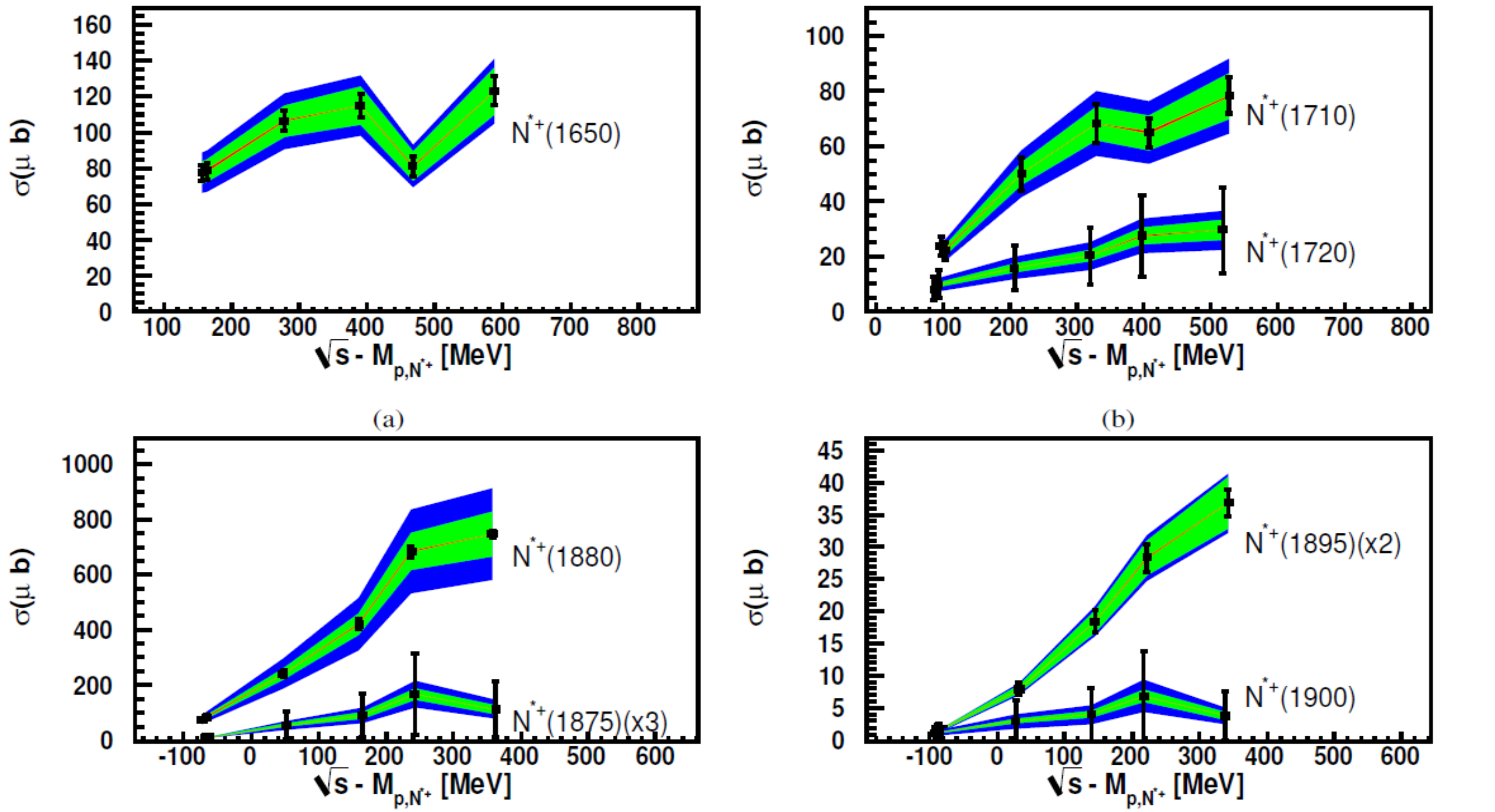


Contribution:
15-40%

Combined data set of data samples, provide required constraint on contributions

Cross Section

P + p → p + N* (-> K^+ + Λ)



Final State Interaction in PWA

$$A_{2b}^{\beta}=\frac{\sqrt{s_i}}{1+\frac{1}{2}r^{\beta}q^2a_{p\Lambda}^{\beta}+iqa_{p\Lambda}^{\beta}q^{2L}/F(q,r^{\beta},L)}$$

$a_{p\Lambda}^{\beta}$ Scattering Length

r^{β} Effective Range of System

$\alpha_s = -1.43 \pm 0.36 \pm 0{,}09\, fm$ $\alpha_t = -1.88 \pm 0.38 \pm 0.10 fm$

$r_s = 1.31 \pm 0.24 \pm 0{,}16\, fm$ $r_t = 1.04 \pm 0.78 \pm 0.15 fm$

Source	${}^1S_0\ \alpha_{\Lambda-p}$	${}^1S_0\ r_{\Lambda-p}$	${}^3S_1\ \alpha_{\Lambda-p}$	${}^3S_1\ r_{\Lambda-p}$	$<\alpha_{\Lambda-p}>$
NLO[1]	$-2.91\ fm$	$2.78\ fm$	$-1.54\ fm$	$2.72\ fm$	$-1.88\ fm$
LO[2]	$-1.91\ fm$	$1.40\ fm$	$-1.23 fm$	$2.13\ fm$	$-1.4\ fm$
[2]	$-1.8_{-4.2}^{+2.3}\ fm$		$-1.6_{-0.8}^{+1.1}\ fm$		
COSY-TOF[3]					$-1.25 \pm 0.08 \pm 0.03\ fm$
COSY-TOF[4]			$-1.31_{-0.49}^{+3.2} \pm 0.3 \pm 0.16\ fm$		$-1.233 \pm 0.014 \pm 0.3 \pm 0.12\ fm$

[1] Nucl.Phys. A915, 24(2013) [2] Phys.Rev. 173,1452 (1968)
[3] Eur. Phys.J. A49, 157 (2013) / [4] F.Hauenstein, PhD Thesis (2014)

Summary

- Strangeness production has to understood in elementary reaction
- Different contribution Channels (N*, Cusp Effect, FSI)
- Description requires Partial Wave Analysis.

  Allow to analyze different beam data in parallel.

  Combined analysis necessary to provide sufficient information
- Extraction of Excitation Function of N*
  - N* play dominate role in the production at GeV Energies
- Scattering Length and effective extraction
  - Values for Singlet and Triplet separately
  - Separation between LO and NLO difficult.

Outlook – Σ-N Cusp

The Breit-Wigner:

$$\frac{d\sigma_{p\Lambda}}{dm_{p\Lambda}} \approx \frac{1}{\left| m_R^2 - m_{p\Lambda}^2 - i\, m_{p\Lambda} \Gamma \right|^2}$$

$$Mass\ M_{cusp} = 2.13\text{GeV},\ With\ \Gamma = 0.02\text{GeV}$$

$$g_{p\Sigma} \ll g_{p\Lambda}\ Symmetric$$

$$g_{p\Sigma} \gg g_{p\Lambda}\ Antisymmetric$$

The Flatté parametrization:

$$\frac{d\sigma_{p\Lambda}}{dm_{p\Lambda}} \approx \frac{\Gamma_{p\Lambda}}{\left| m_R^2 - m_{p\Lambda}^2 - i\, m_{p\Lambda} (\Gamma_{p\Lambda} + \Gamma_{p\Sigma}) \right|^2}$$

$$\Gamma_{p\Lambda} = g_{p\Lambda} * q_{p\Lambda} \qquad \Gamma_{p\Sigma} = g_{p\Sigma} * q_{p\Sigma}$$

Above the threshold

$$q_{p\Sigma} = \frac{\sqrt{(m_{p\Sigma}^2 - (m_\Sigma + m_p)^2) * (m_{p\Sigma}^2 - (m_p - m_\Sigma)^2)}}{2 m_{p\Sigma}}$$

Below the threshold

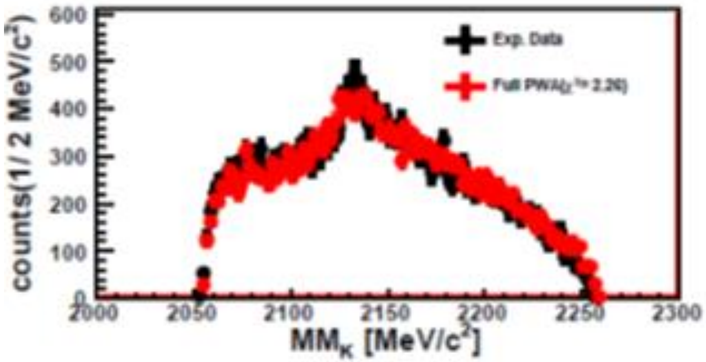
$$q_{p\Sigma} = i * \frac{\sqrt{((m_\Sigma + m_p)^2 - m_{p\Sigma}^2) * (m_{p\Sigma}^2 - (m_p - m_\Sigma)^2)}}{2 m_{p\Sigma}}$$

Incoherent Analysis by COSY-TOF

S. Jowzaee et al., Eur. Phys. J. A52, 7 (2016)

Outlook – Σ-N Cusp : Combined Analysis

Experiment	E_B [GeV]	Statistics
DISTO	2.15	121k
COSY-TOF	2.16	43k
DISTO	2.5	304k
DISTO	2.85	424k



Resulting value:

$$g_{p\Lambda} = 0.38 \pm 0.06 \pm 0.008 \quad 10^{-2}$$
$$g_{p\Sigma} = 1.60 \pm 0.07 \pm 0.03 \quad 10^{-2}$$

Thank You

HADES Collaboration

FOPI Collaboration

DISTO Collaboration
M. Maggiora

COSY-TOF Collaboration
J. Ritman, E. Roderburg
F. Hauenstein, D. Gronzka

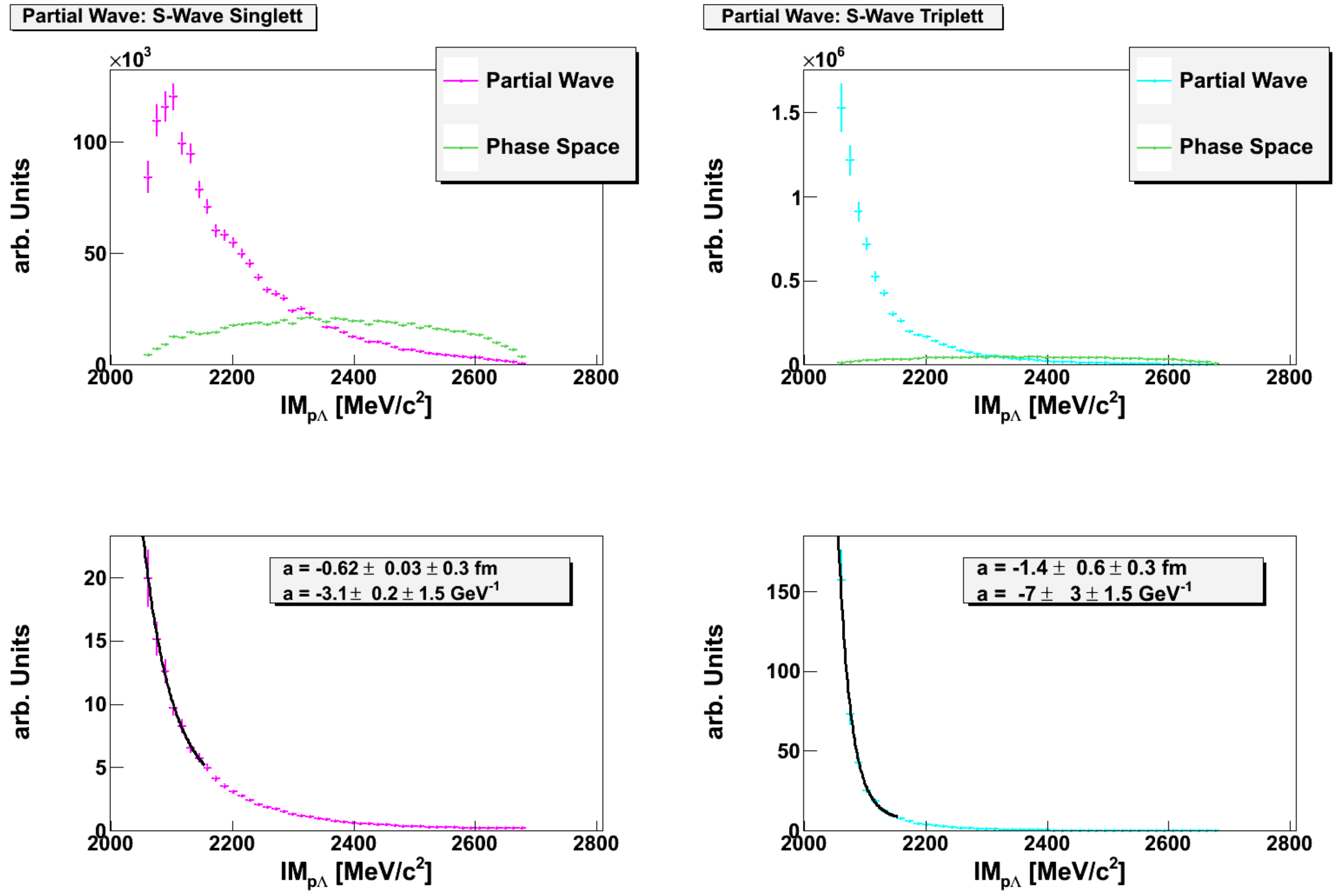
Petersburg Nuclear Physics Institute

Bonn Gatchina Group
A. Sarantsev

K-Cluster – Excellence Cluster Universe – TU Munich
L. Fabbietti, E. Epple, P. Klose, S.Lu, J. Siebenson, D. Soliman

Thank for your attention

Final State Interaction



Branching Ratio

	Mass [GeV/c^2]	Width [GeV/c^2]	$\Gamma_{\Lambda K}/\Gamma_{All}$ %
N(1650)S_{11}	1.655	0.150	3-11
N(1710)P_{11}	1.710	0.200	5-25
N(1720)D_{13}	1.720	0.250	1-15
N(1875)D_{13}	1.875	0.220	4 ± 2
N(1880)P_{11}	1.870	0.235	2 ± 1
N(1895)S_{11}	1.895	0.090	18 ± 5
N(1900)P_{13}	1.900	0.250	0-10