Review of strangeness physics programme at HADES – past and future perspectives

HYP2022

June 29, 2028

Rafał Lalik

Jagiellonian University, Kraków

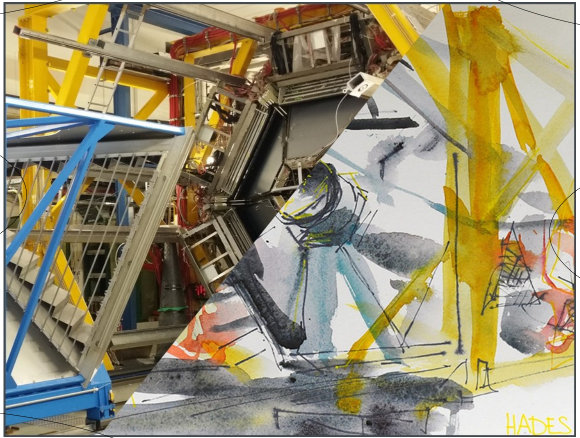
HADES Strangeness Physics Programme

Strangeness Production
(in pp, πA and HIC)

Hyperon Structure
(Λ(1405), Hyperon eFF)

Mesons interactions
(K/φ absorption,
KN potential)

See L. Tolos's talk



© Clara Schuster

Hyperon-nucleon interactions
(via correlation functions)

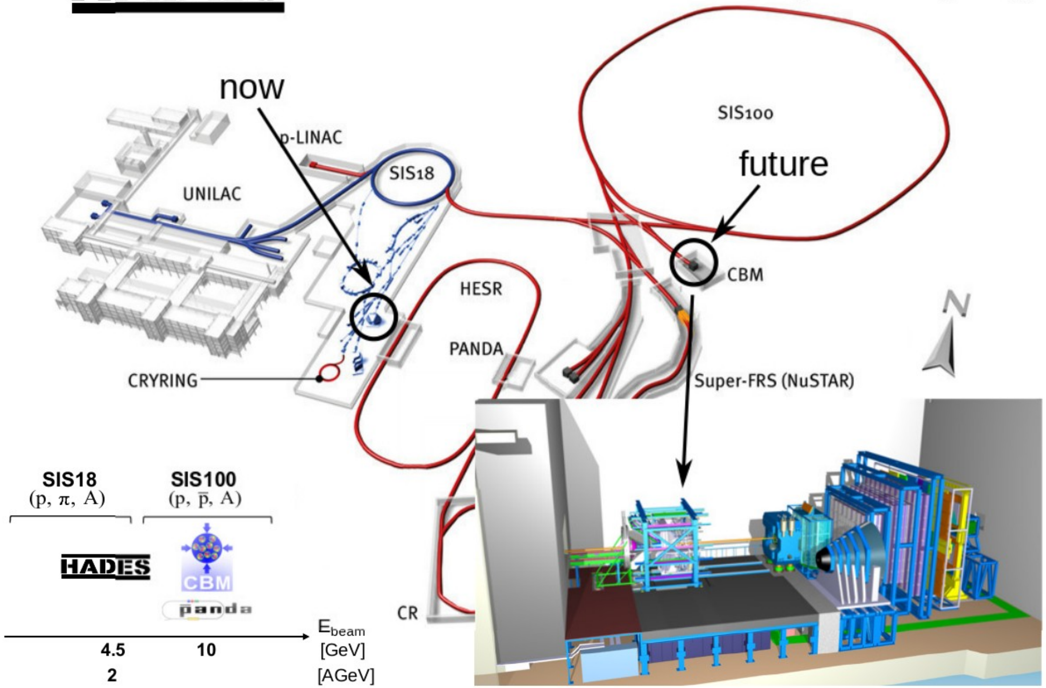
Hypernucleai

See S. Spies's talk

Hyperon polarization
(from pp to AA)

HADES at FAIR PHASE-0

HADES - first detector of FAIR Phase-0 (2018-ongoing)



Major HADES upgrades:

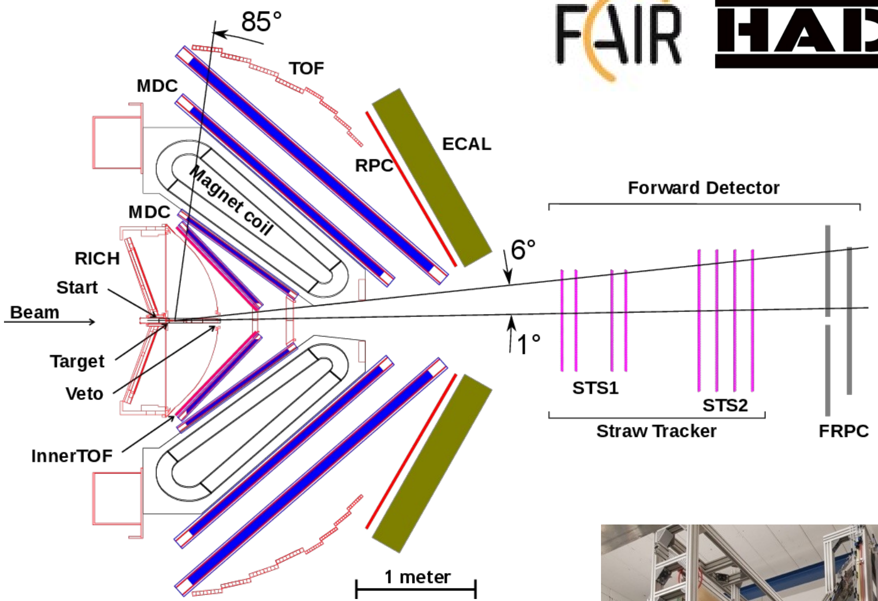
- RPC (2010)
- Pion Tracker (2014)
- ECAL (2017-2021)
- RICH (2018)
- Forward Detector (2021)
- iTOF (2021)
- START

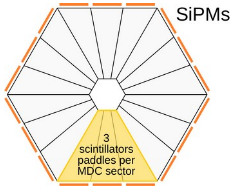
- various HI beams (Au+Au, Ag+Ag) in the meantime
- light system beams: p+p@3.5 GeV ('07), π+p/A ('14)
- the next beam: p+p@4.5 GeV

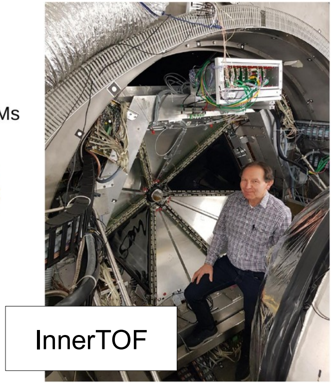
HADES Forward Detector upgrade

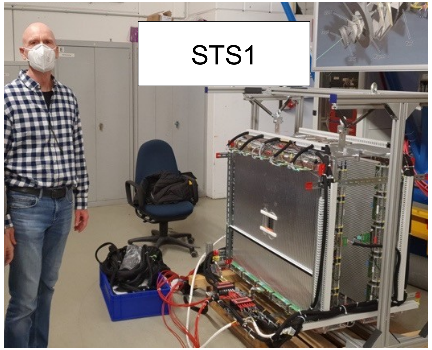
- STS/FRPC
  - Instruments the field-free forward hemisphere
  - Straw Tube Stations (STS) compatible with Phase-1 PANDA STT and FT
  - Boost physics capability for hyperon e/m transition FFs

- InnerTOF improves triggering efficiency and purity









Feb22 beam time – p+p@4.5 GeV beam energy

- **G-PAC 44: HADES III**
- *Production and decay of hyperons, and inclusive hadron and dilepton production in p+p reaction at 4.5 GeV*

1) Hyperon electromagnetic decays $Y \to \Lambda\gamma^{*}$ and $Y \to \Lambda\gamma$
2) Hyperon hadronic decays
3) Production of double (Ξ^{-} , $\Lambda\Lambda$) and hidden strangeness (φ)
4) Inclusive hadron and dilepton production as a reference for p+A and heavy-ion data

FEB22 experiment from February 2022

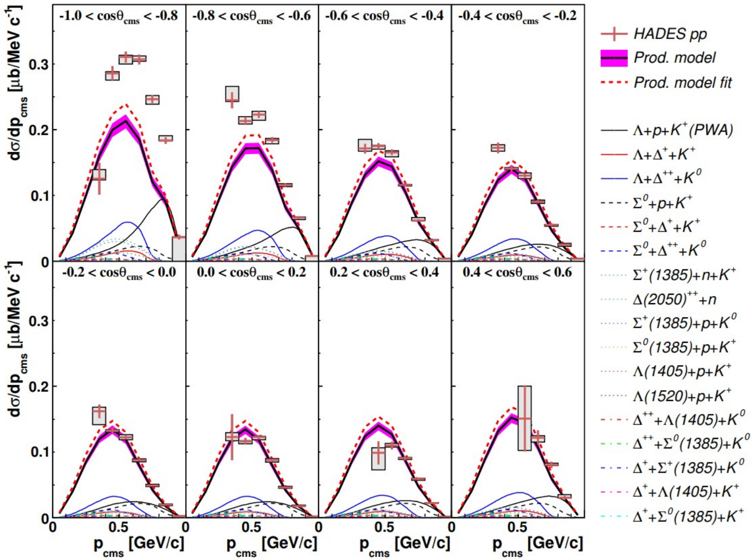
p+p @ 4.5 beam energy

Strangeness production
Hyperon production

Measurements of Λ in p+p@3.5 GeV

(Mainly) data driven model based on exclusive measurements in HADES

HADES, Phys. Rev. C 95, 015207 (2017)



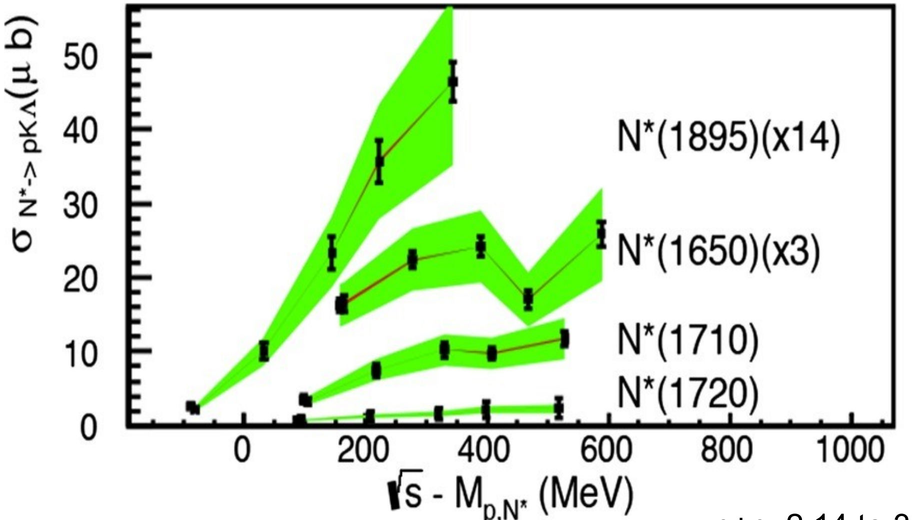
id	pp→ reaction	$\sigma_0^{(id)}$ cross section [μb]	∡ var.	∡(a_2, a_4)		H	notes	fit result	
		3-body channels							
1	$\Lambda p K^+$	$35.26 \pm 0.43\ ^{+3.55}_{-2.83}$	θ^{cms}_{Λ}	0.798	0.134	✓	[16]	38.835 ± 0.026	⊤
2	$\Sigma^0 p K^+$	$16.5 \pm 20\,\%$	$\theta^{cms}_{\Sigma^0}$	0.034 ± 0.241	—		[21]+calc.	19.800 ± 0.094	⊤
3	$\Lambda\Delta^{++}K^0$	$29.45 \pm 0.08\ ^{+1.67}_{-1.46} \pm 2.06$	$\theta^{cms}_{\Delta^{++}}$	1.49 ± 0.3	—	✓	[13]	32.10 ± 0.11	⊤
4	$\Sigma^0\Delta^{++}K^0$	$9.26 \pm 0.05\ ^{+1.41}_{-0.31} \pm 0.65$	$\theta^{cms}_{\Delta^{++}}$	0.08 ± 0.02	—	✓	[13]	8.5 ± 2.1	⊥
5	$\Lambda\Delta^+K^+$	$9.82 \pm 20\,\%$	$\theta^{cms}_{\Delta^+}$	from $\Lambda\Delta^{++}K^0$			res. mod.	11.78 ± 0.15	⊤
6	$\Sigma^0\Delta^+K^+$	$3.27 \pm 20\,\%$	$\theta^{cms}_{\Delta^+}$	from $\Sigma^0\Delta^{++}K^0$			res. mod.	2.6 ± 1.3	⊥
7	$\Sigma(1385)^+nK^+$	$22.42 \pm 0.99 \pm 1.57\ ^{+3.04}_{-2.23}$	$\theta^{cms}_{\Sigma^{+*}}$	1.427 ± 0.3	0.407 ± 0.108	✓	[17]	17.905 ± 0.075	⊥
8	$\Delta(2050)^{++}n$	33 % feeding for $\Sigma^* nK^+$	θ^{cms}_{n}	1.27	0.35	✓	[17]	8.82 ± 0.13	⊤
9	$\Sigma(1385)^+pK^0$	$14.05 \pm 0.05\ ^{+1.79}_{-2.14} \pm 1.00$	$\theta^{cms}_{\Sigma^{+*}}$	1.42 ± 0.3	—	✓	[13]	16.101 ± 0.072	⊤
10	$\Sigma(1385)^0pK^+$	$6.0 \pm 0.48\ ^{+1.94}_{-1.06}$	$\theta^{cms}_{\Sigma^{0*}}$	from $\Sigma(1385)^+nK^+$		✓	[17]	7.998 ± 0.069	⊤
11	$\Lambda(1405)pK^+$	$9.2 \pm 0.9 \pm 0.7\ ^{+3.3}_{-1.0}$	—	—	—	✓	[18]	7.7 ± 3.0	⊥
12	$\Lambda(1520)pK^+$	$5.6 \pm 1.1 \pm 0.4\ ^{+1.1}_{-1.6}$	—	—	—	✓	[18]	7.2 ± 3.6	⊤
13	$\Delta^{++}\Lambda(1405)K^0$	$5.0 \pm 20\,\%$	—	—	—		[23]	6.0 ± 1.6	⊤
14	$\Delta^{++}\Sigma(1385)^0K^0$	$3.5 \pm 20\,\%$	—	—	—		[23]	4.90 ± 0.46	⊤
15	$\Delta^+\Sigma(1385)^+K^0$	$2.3 \pm 20\,\%$	—	—	—		[23]	3.2 ± 1.1	⊤
16	$\Delta^+\Lambda(1405)K^+$	$3.0 \pm 20\,\%$	—	—	—		compl. to above	4.2 ± 1.9	⊤
17	$\Delta^+\Sigma(1385)^0K^+$	$2.3 \pm 20\,\%$	—	—	—		compl. to above	3.2 ± 1.1	⊤
		4-body channels							
18	$\Lambda p\pi^+K^0$	$2.57 \pm 0.02\ ^{+0.21}_{-1.98} \pm 0.18$		—		✓	[13]	2.8 ± 1.5	⊤
19	$\Lambda n\pi^+K^+$	from $\Lambda p\pi^+K^0$		—				2.8 ± 1.5	⊤
20	$\Lambda p\pi^0K^+$	from $\Lambda p\pi^+K^0$		—				2.8 ± 1.4	⊤
21	$\Sigma^0 p\pi^+K^0$	$1.35 \pm 0.02\ ^{+0.10}_{-1.35} \pm 0.09$		—		✓	[13]	1.48 ± 0.76	⊤
22	$\Sigma^0 n\pi^+K^+$	from $\Sigma^0 p\pi^+K^0$		—				1.48 ± 0.84	⊤
23	$\Sigma^0 p\pi^0K^+$	from $\Sigma^0 p\pi^+K^0$		—				1.48 ± 0.75	⊤

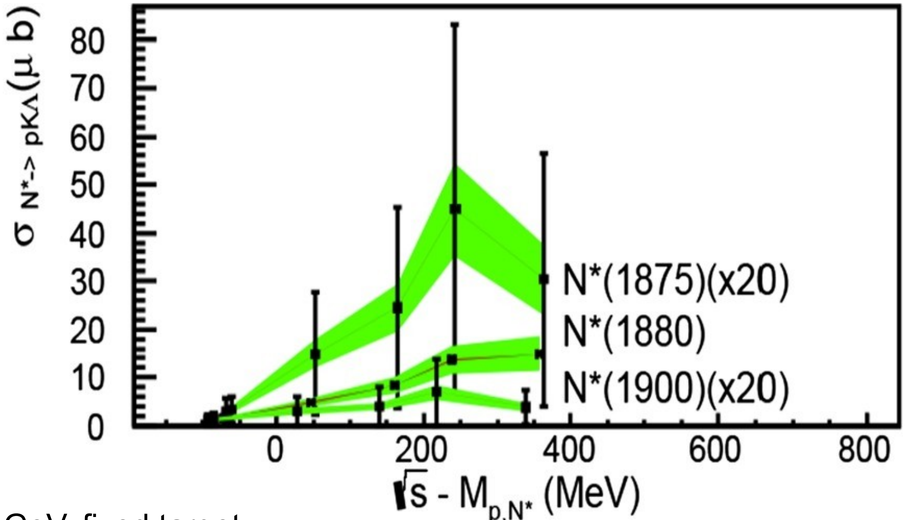
Resonant production of hyperons in p+p

- Combined PWA analysis of COSY-TOF, DISTO, FOPI and HADES data
- Contribution of seven N* resonances to $pK^+\Lambda$

- 90% of pKΛ goes via resonances (at HADES energy)

Phys. Lett. B 785, 574-580 (2018)

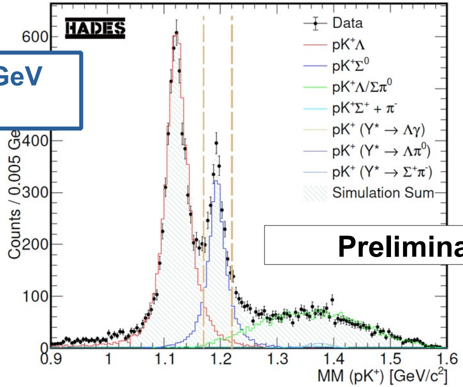




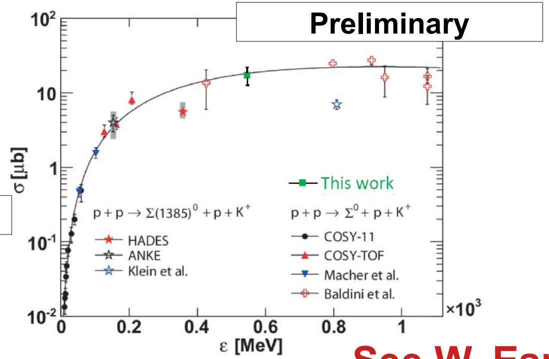
p+p: 2.14 to 3.5 GeV, fixed target

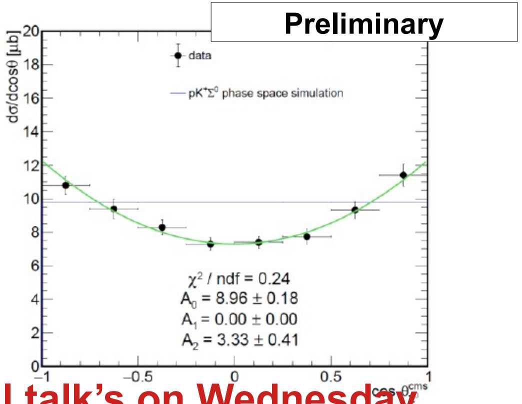
Σ^0 production

p+p@3.5 GeV data



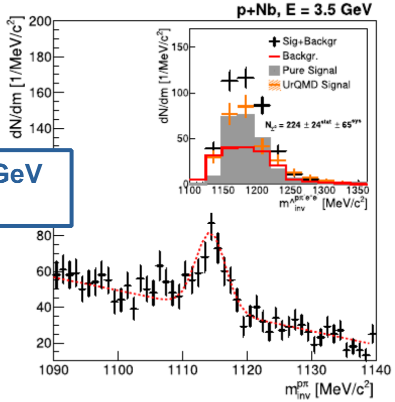
$$\sigma(pK^+\Sigma^0)[\mu b] = 18.74 \pm 1.01(stat) \pm 1.71(syst)$$



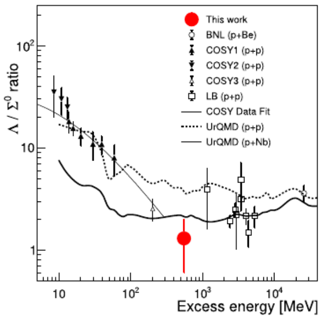


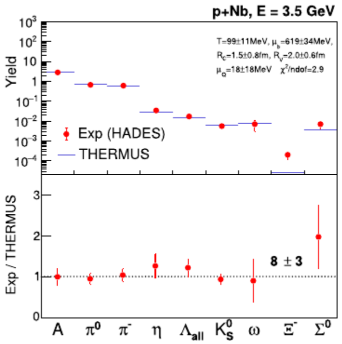
See W. Esmail talk's on Wednesday

p+Nb@3.5 GeV data



$$\sigma_{p+Nb}(\Sigma^0) = 5.8 \pm 2.3 \text{ mb}$$





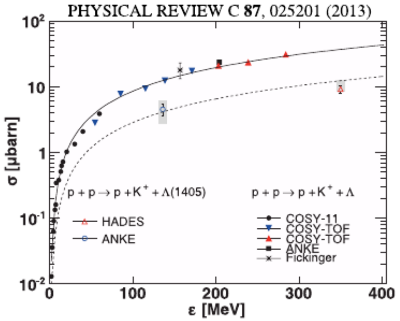
Phys. Lett. B 781, 735-740 (2018)

Heavier hyperons production

p+p@3.5 GeV data

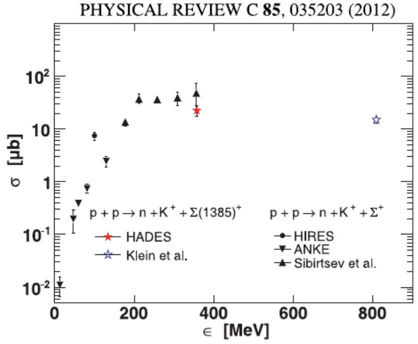
Λ(1405), Λ(1520)

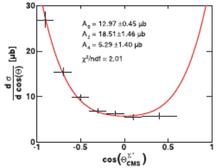
$$\sigma_{pp\to\Lambda(1405)pK^+} = 9.2 \pm 0.9 \pm 0.7^{+3.3}_{-1.0}\ \mu\text{b},$$
$$\sigma_{pp\to\Lambda(1520)pK^+} = 5.6 \pm 1.1 \pm 0.4^{+1.1}_{-1.6}\ \mu\text{b},$$
$$\sigma_{pp\to\Sigma^+\pi^- pK^+} = 5.4 \pm 0.5 \pm 0.4^{+1.0}_{-2.1}\ \mu\text{b},$$
$$\sigma_{pp\to\Delta^{++}\Sigma^- K^+} = 7.7 \pm 0.9 \pm 0.5^{+0.3}_{-0.9}\ \mu\text{b}.$$

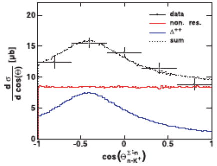


Σ(1385)

$$\sigma_{pp\to\Sigma(1385)^+ pK^+} = 22.27 \pm 0.89 \pm 1.56^{+3.07}_{-2.10}\ \mu b$$



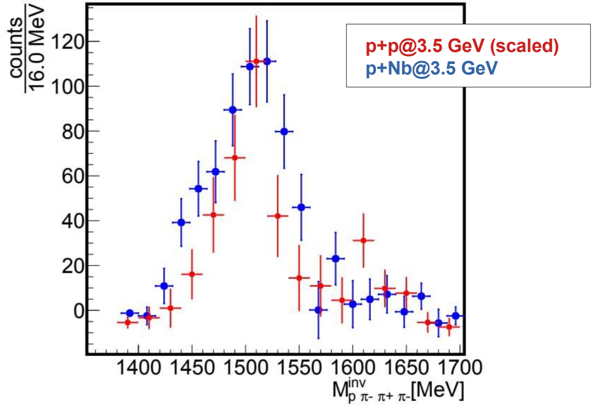


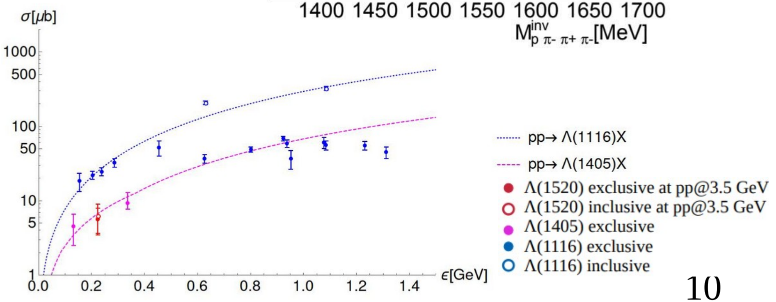


p+p@3.5 GeV
p+Nb@3.5 GeV
data

Λ(1520) in pp and pNb

HADES Preliminary



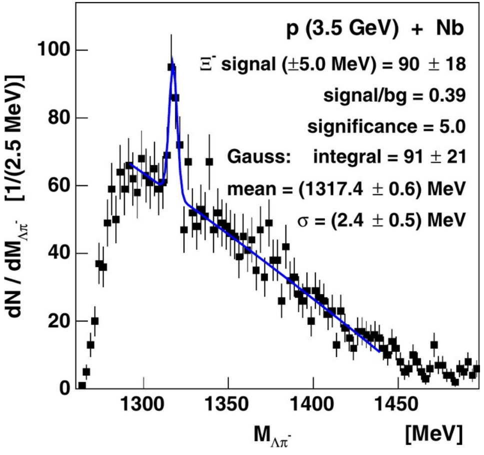


Ξ⁻ hyperon

Multi-strange baryons - historically a signature for QGP
An impressive set of data, however data below AGS energies are missing for less abundant particles (Ξ,Ω)!

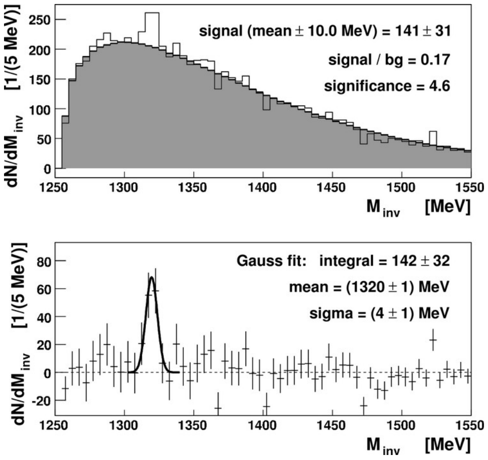
Ξ^- (far below NN production threshold) is observed by HADES

p+Nb $\sqrt{s_{NN}} = 3.2\,GeV$



HADES, PRL 114 (2015) 212301

Ar+KCl $\sqrt{s_{NN}} = 2.6\,GeV$



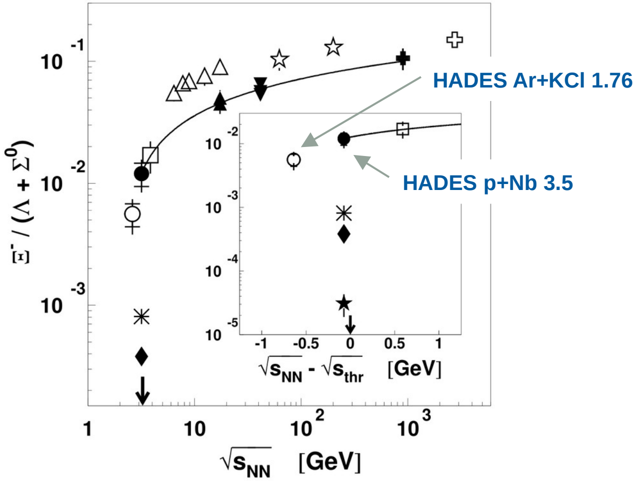
HADES, PRL 103 (2009) 132301

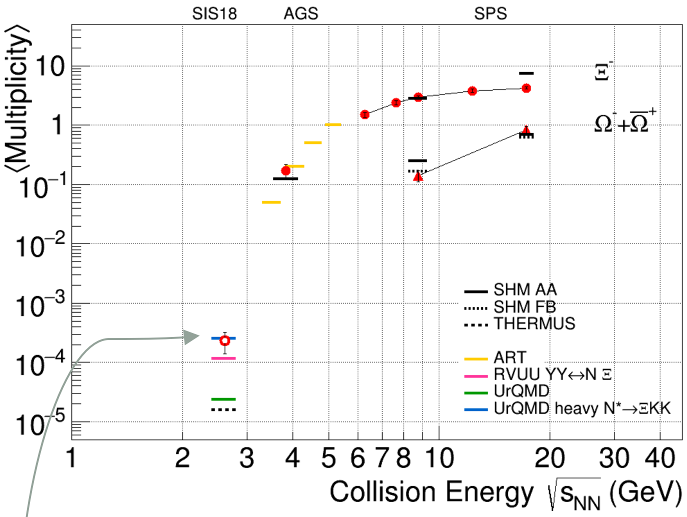
Ag+Ag $\sqrt{s_{NN}} = 2.55\,GeV$

Work in progress

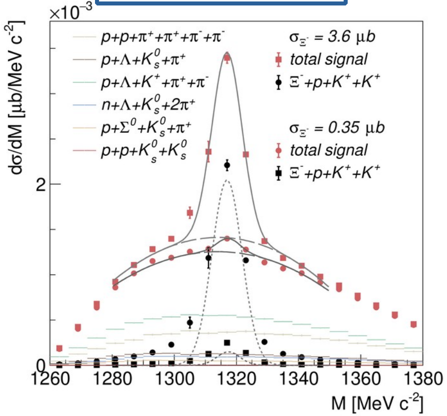
Ξ⁻ hyperon, model comparison

HADES, PRL 103 (2009) 132301
RVUU: F. Li et al., PRC 85 (2012) 064902
UrQMD: J. Steinheimer et al., J.Phys. G43 (2016) 015104
ART: C.M. Ko et al., PLB595 (2004) 158-164





p+p@4.5 GeV sim



Observations:

Double strange hyperon multiplicity above expectation of Statistical Hadronization Model (SHM)

- Not in equilibrium?
- Role of YY interaction, high mass baryonic resonances?

Observations:

Does UrQMD microscopic transport models Ξ⁻ dominant role of high mass baryonic resonances?

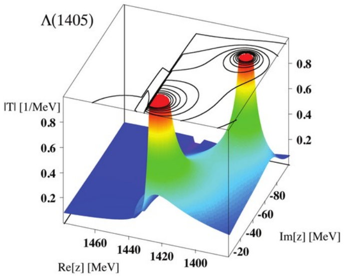
Spectroscopy of N* → Ξ+K+K is badly needed

Hyperon structure

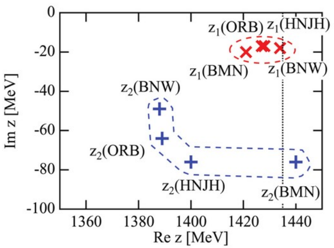
Λ(1405) structure

p+p@3.5 GeV data

- $\Sigma\pi$ decays of Λ(1405) are sensitive tests of its structure (Σπ/KN poles)
- Line shape of Λ(1405):
  - Σ-π (pp beams [HADES, ANKE])
  - K-N (K beams [LEPS] and electro-production [CLAS])
- Λ(1405) measured in HADES in p+p@3.5 GeV via $\Sigma^{\pm}\pi^{\mp}$, but $\Sigma^{\pm}\pi^{\mp}$ are also allowed for $\Sigma(1385)^{+}$ → overlap of mass peaks
- **HADES ECAL allows to measure Λ(1405) via $\Sigma^0\pi^0 \rightarrow p\pi^-3\gamma$, which is not allowed for $\Sigma(1385)^0$**
- Previous pp data suffered from low statistics, HADES can improve statistical precision by two orders of magnitude

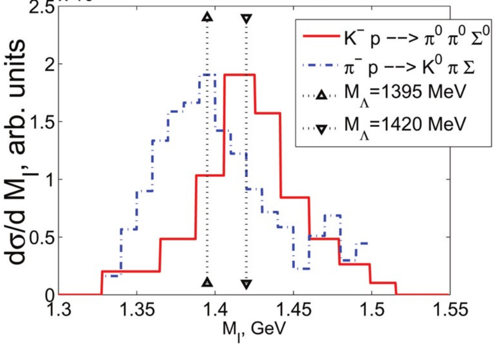


Prog.Part.Nucl.Phys., 67:55–98, 2012.

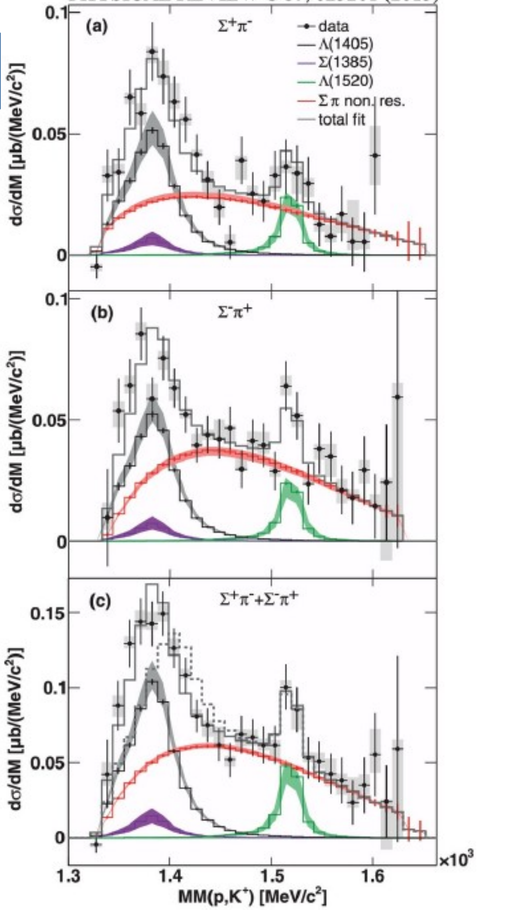


Phys.Rev., C77:035204, 2008.

Phys.Rev.Lett., *95:052301*, *2005*



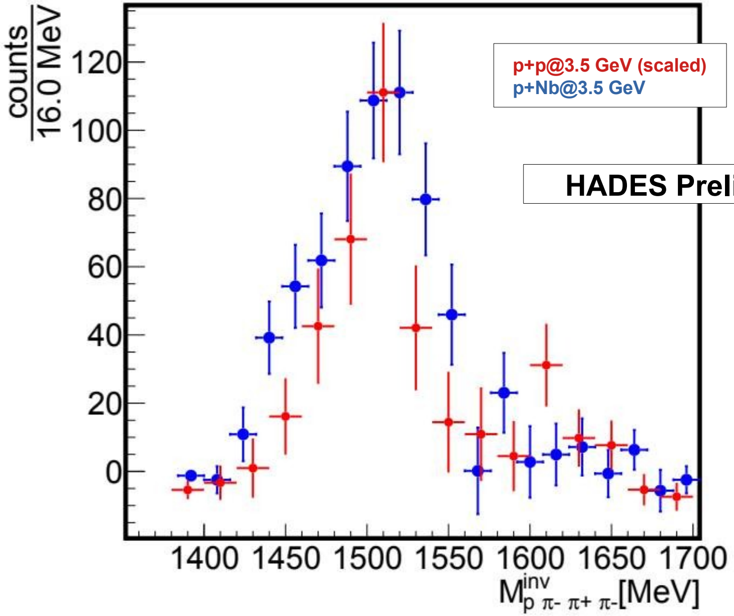
PHYSICAL REVIEW C **87**, 025201 (2013)



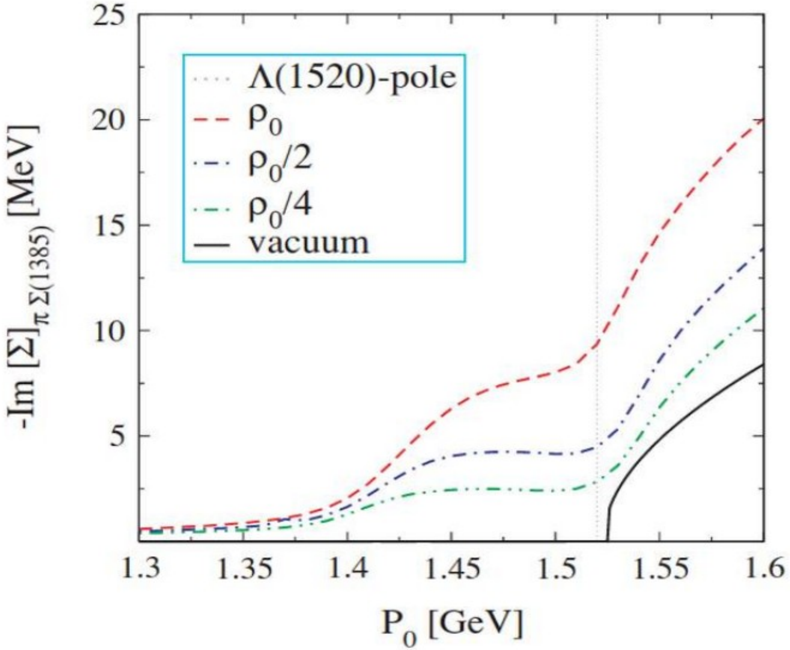
Cold matter effects on Λ(1520)

p+p@3.5 GeV
p+Nb@3.5 GeV
data

- is Λ(1520) a Σ(1385)π molecule?
- studies of in-medium modifications of Λ(1520)

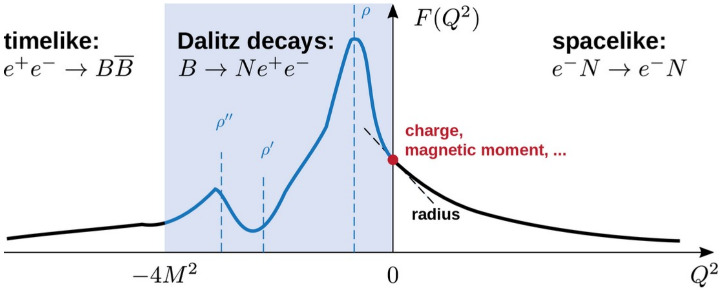


Phys. Rev. C 73, 045213 (2006)

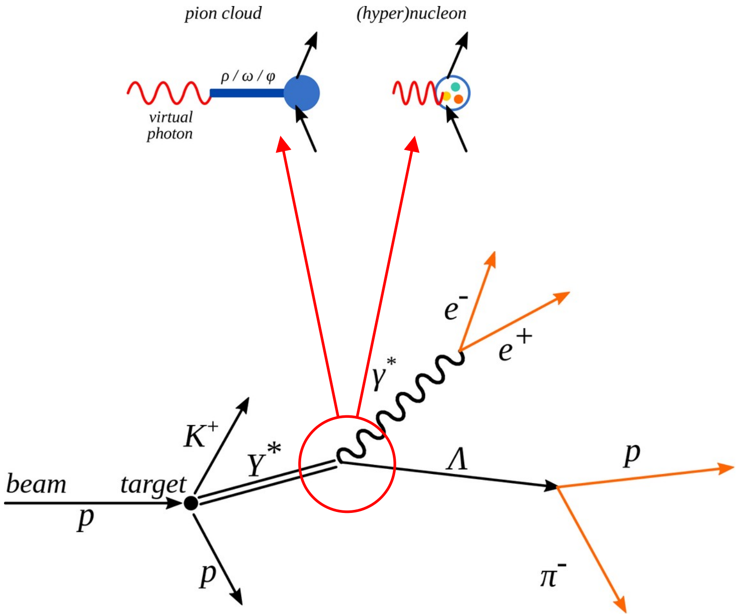


Hyperons electromagnetic decays Y → Λγ* and Y → Λγ

- eTFF are sensitive probes oh hyperon internal structure
- Measurements of eTFF

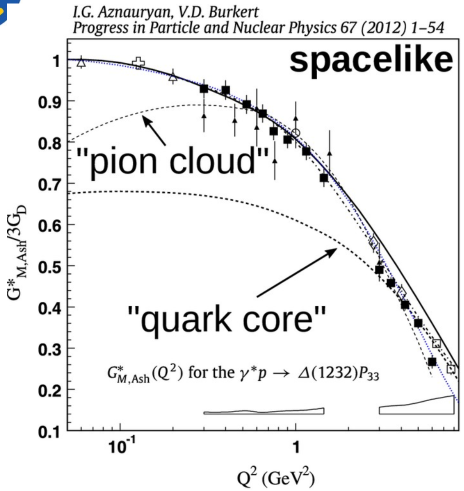


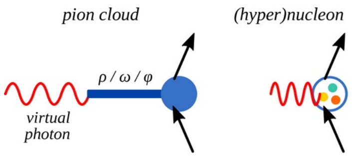
- Space-like region $|Q^2|>0$ is inaccessible for excited hyperons (as target or beam)
- Time-like high $|Q^2|$ is probed by electron-positron annihilation (BaBar, CLEO_C, BESIII)
- Time-like low $|Q^2|$ available via Dalitz decays in HADES



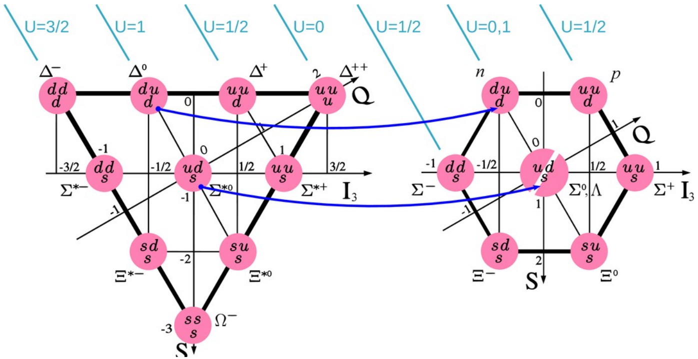
$$\mathrm{d}\Gamma(R_{J\geq 3/2} \to N\gamma^*) = F(m, M_{l^+l^-})^{\pm} \left(\frac{l}{l+1} \left| G^{\pm}_{M/E}(M_{l^+l^-}) \right|^2 + (l+1)(l+2) \left| G^{\pm}_{E/M}(M_{l^+l^-}) \right|^2 + \frac{M^2_{l^+l^-}}{m^2} \left| G_C(M_{l^+l^-}) \right|^2 \right)$$

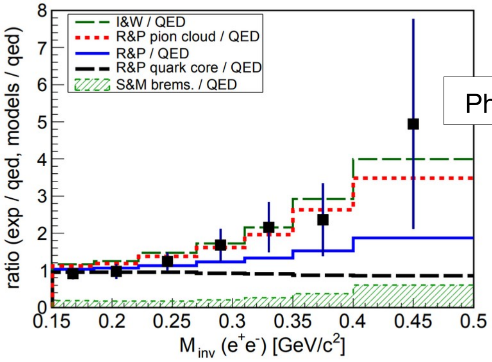
Hyperons electromagnetic decays Y→Λγ* and Y→Λγ





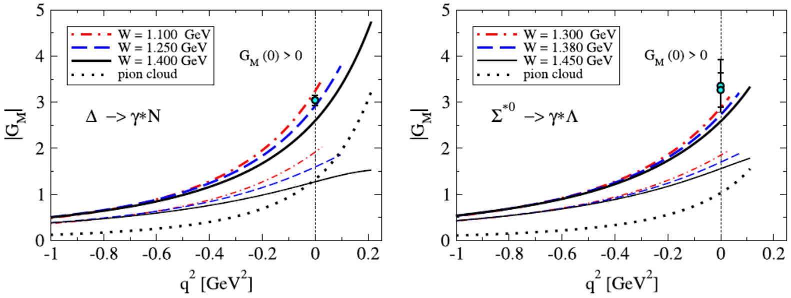
- Comparison of strange and non-strange baryons: i.e. Δ(1232)→ Ne^+e^- with $\Sigma(1385)^0 \to \Lambda e^+e^-$ (flavor symmetry partner of Δ in SU(3))





Phys. Rev. C 95, 065205 (2017)

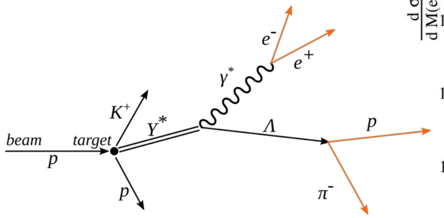
p+p@3.5 GeV data

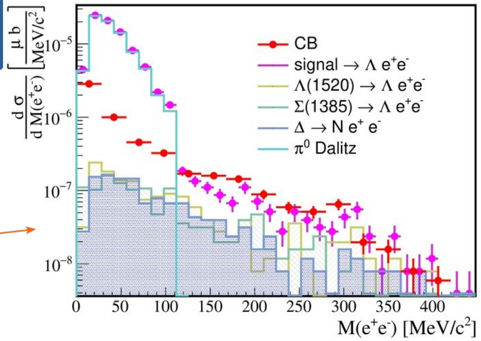


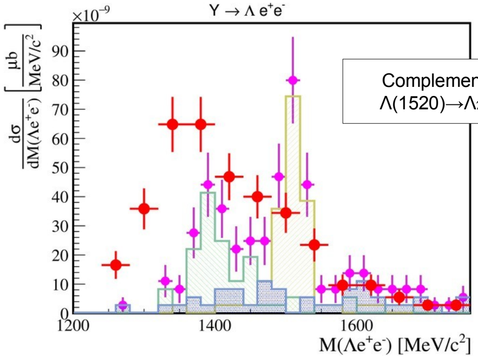
Phys. Rev. D 102, 054016 (2020)

Hyperons electromagnetic decays $Y \rightarrow \Lambda\gamma^*$ and $Y \rightarrow \Lambda\gamma$

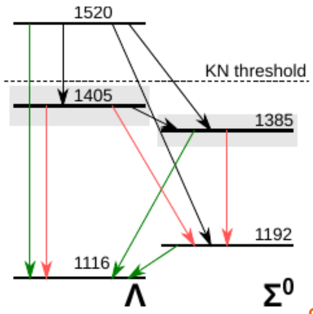
p+p@4.5 GeV sim



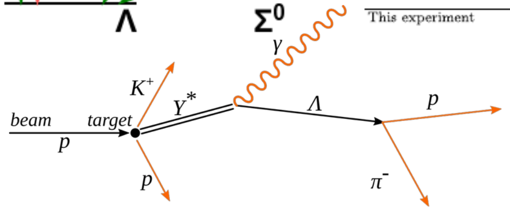


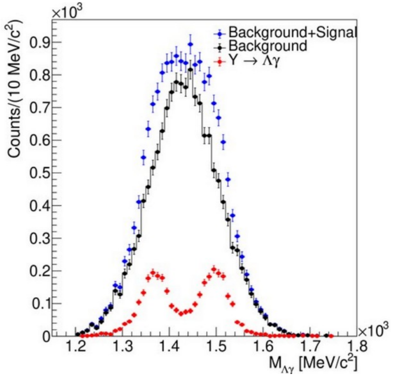


Complementary HADES results for $\Lambda(1520)\rightarrow\Lambda\pi^+\pi^-$ from p+p@3.5 GeV



Model	Δ(1232) $p\gamma$	Σ⁰(1385) Λ(1116)γ	Σ⁰(1385) Σ⁰(1193)γ	Λ(1405) Λ(1116)γ	Λ(1405) Σ⁰(1193)γ	Λ(1520) Λ(1116)γ	Λ(1520) Σ⁰(1193)γ
NRQM[3, 4]	360[14]	273	22	200	72	156	55
RCQM[5]		267	23	118	46	215	293
χCQM[6]	350	265	17.4				
MIT Bag[3]		152	15	60, 17	18, 2.7	46	17
Chiral Bag[7]				75	1.9	32	51
Soliton[8]		243, 170	19, 11	44, 40	13, 17		
Skyrme[9, 10]	309-348	157-209	7.7-16				
Algebraic model[11]	343.7	221.3	33.9	116.9	155.7	85.1	180.4
HBχPT[12]†	(670-790)	290-470	1.4-36				
$1/N_c$ expansion[13]		298 ± 25	24.9 ± 4.1				
Previous Experiments	640-720[30]	<2000[22]	<1750[22]	27±8[19]	10±4[19] 23±7[19]	33±11[17] 134±23[16] 159±33±26[18]	47±17[17]
This experiment		$479 \pm 120^{+81}_{-100}$				$167 \pm 43^{+26}_{-12}$	



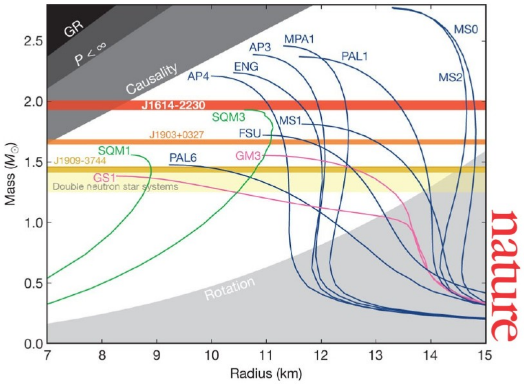


E. Kaxiras et al., Phys. Rev. D32, p. 695–700 (1985)
C. Granados et al., arXiv:1701:09130 (2017) 113014.
G. Ramalho et al., Phys. Rev. D93 (2016) 033004
S. Taylor et al. (CLAS Collaboration), Phys. Rev. C71, 054609

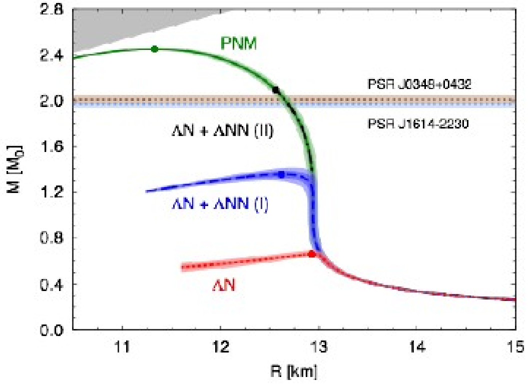
Hyperon-nucleon interactions

ΛN interactions

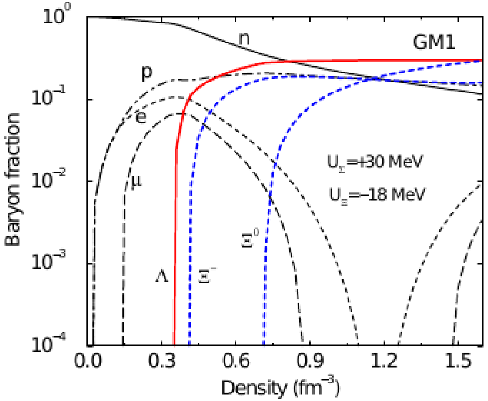
- EOS and “neutron star” puzzle
- purely nucleonic neutron star agrees with measurements
- strangeness softens EOS
- repulsive core of ΛN interaction is crucial for description



PB Demorest *et al. Nature* **467**,
1081-1083 (2010) doi:10.1038/nature09466

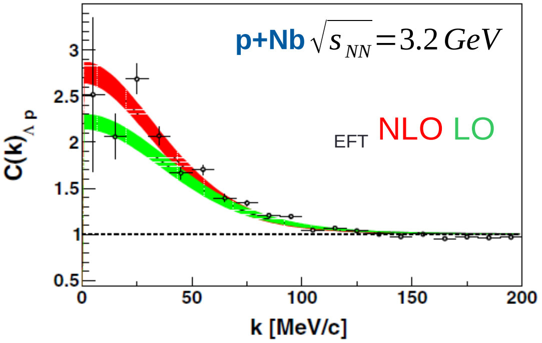


Phys. Rev. Lett. 114, 092301

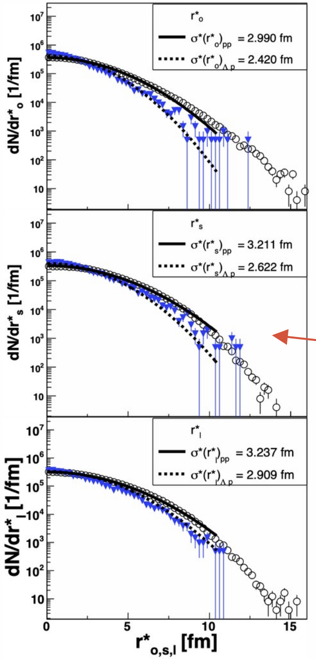


Phys. Rev. C 53 (1996) 1416

ΛN interactions



HADES, PRC 94 (2016) 025201
J. Haidenbauer et al., NPA915 (2013) 24



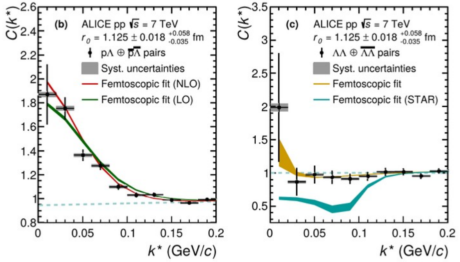
Λp interaction studied (for the first time) via femtoscopy

$$C(\mathbf{p}_1, \mathbf{p}_2) \equiv \frac{P(\mathbf{p}_1, \mathbf{p}_2)}{P(\mathbf{p}_1) \cdot P(\mathbf{p}_2)}$$

Access the region of very low relative hyperon-nucleon momentum (k < 50 MeV/c)

Source size uncertain

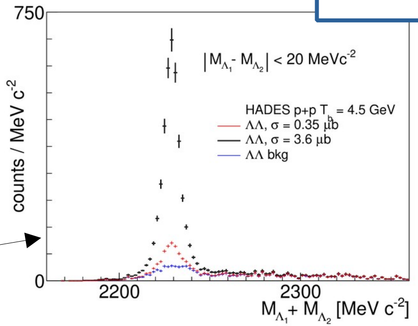
ΛN, ΞN further studies in high statistic p+p and p+Ag in 2022+

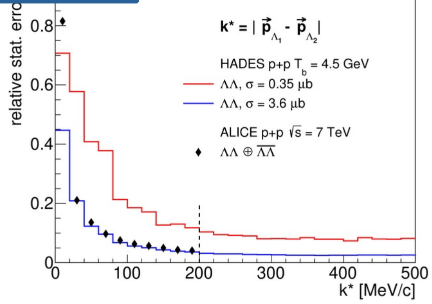


Phys. Rev. C 99, 024001 (2019)

ΛΛ interactions

p+p@4.5 GeV sim





Hyperon polarization

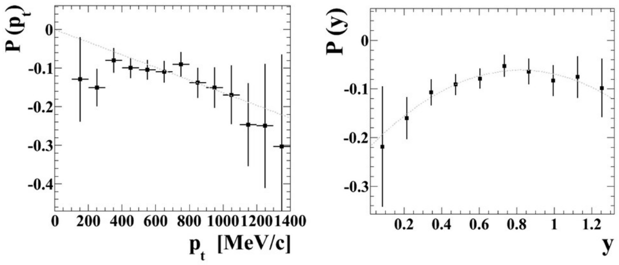
Λ polarization

Ag+Ag $\sqrt{s_{NN}} = 2.55\, GeV$

non-central heavy-ion collisions ☑
large orbital angular momenta ☑
vortical structure of the system?
global spin polarization of the particles

$$P_\Lambda = \frac{8}{\pi \alpha_\Lambda} \frac{\langle sin(\Psi_{EP} - \phi_p^*)\rangle}{R_{EP}}$$

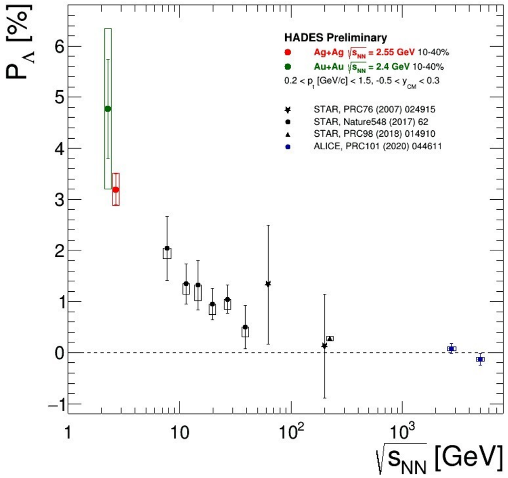
p+Nb $\sqrt{s_{NN}} = 3.2\, GeV$



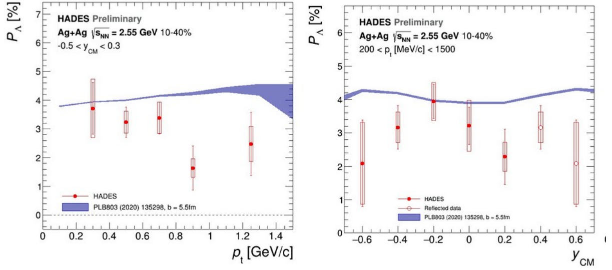
$$\langle \mathcal{P} \rangle = -0.119 \pm 0.005\,(\text{stat}) \pm 0.016\,(\text{syst})$$

Negative values of the polarization in the order of 5 − 20% over the entire phase space

HADES, Eur.Phys.J.A 50 (2014) 81



P_Λ still shows the increasing trend from 7.7 GeV down to 2.4 GeV



F. Kornas et al., HADES, Springer Proc.Phys. 250 (2020) 435-439

Feb22 beam time – p+p@4.5 GeV beam energy

- **G-PAC 44: HADES III**
- Production and decay of hyperons, and inclusive hadron and dilepton production in p+p reaction at 4.5 GeV
  1) Hyperon electromagnetic decays Y→Λγ* and Y→Λγ
  2) Hyperon hadronic decays
  3) Production of double (Ξ− , ΛΛ) and hidden strangeness (φ)
  4) Inclusive hadron and dilepton production as a reference for p+A and heavy-ion data

Table 2: Projected number of events reconstructed during 84 shifts.

Electromagnetic hyperon decays ($\Lambda\gamma^*$ and $\Lambda\gamma$)				
$\Sigma(1385)^0 \to \Lambda e^+e^-$	$\Lambda(1520) \to \Lambda e^+e^-$	$\Sigma(1385) \to \Lambda\gamma$	$\Lambda(1520) \to \Lambda\gamma$	
302	352	1484	1559	
Hyperon hadronic decays				
$\Lambda(1405) \to \Sigma^0\pi^0 \to \Lambda\ 3\gamma$	$\Lambda(1405) \to \Sigma^\pm\pi^\mp$	$\Lambda(1520) \to \Lambda\pi^-\pi^+$		
3.6×10^4	7.2×10^4	5.2×10^5		
Production of double and hidden strangeness				
$\Xi^- \to \Lambda\pi^-$	$\Lambda\Lambda$	$\phi \to K^+K^-$		
$(4.7 - 47.6) \times 10^4$	$(0.62 - 6.17) \times 10^4$	3.1×10^6		
Inclusive measurement of hadrons and dielectrons				
$M_{ee} < 0.15\,\mathrm{GeV}/c^2$	$M_{ee} > 0.15\,\mathrm{GeV}/c^2$	$\omega \to e^+e^-$	$\phi \to e^+e^-$	$M_{ee} > 1.1\,\mathrm{GeV}/c^2$
5.72×10^6	7.41×10^5	5.8×10^4	1.86×10^3	69

Eur. Phys. J. A (2021) 57:138