Hyperons@FAIR | HADES

Mini-symposium

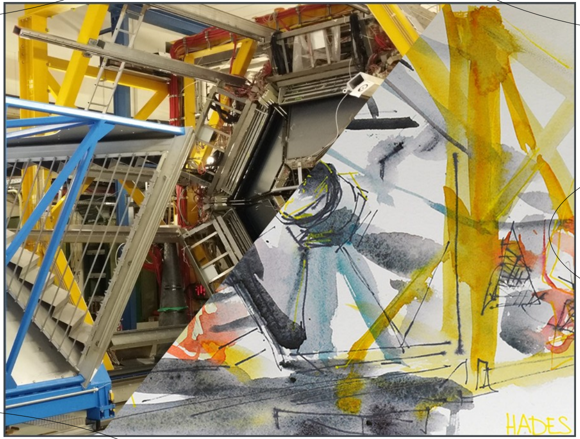
October 25, 2021

Rafał Lalik

HADES Hyperons Physics Program

Hyperon Production
(in pp and HI collisions)

Hyperon Structure
(Λ(1405), Hyperon eFF)



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Hyperon-nucleon interactions
(via correlation functions)

Hypernucleai

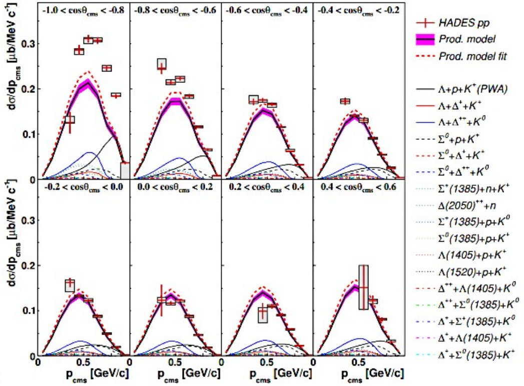
Hyperon polarization
(from pp to AA)

Measurements of Λ in p+p@3.5 GeV

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

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

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



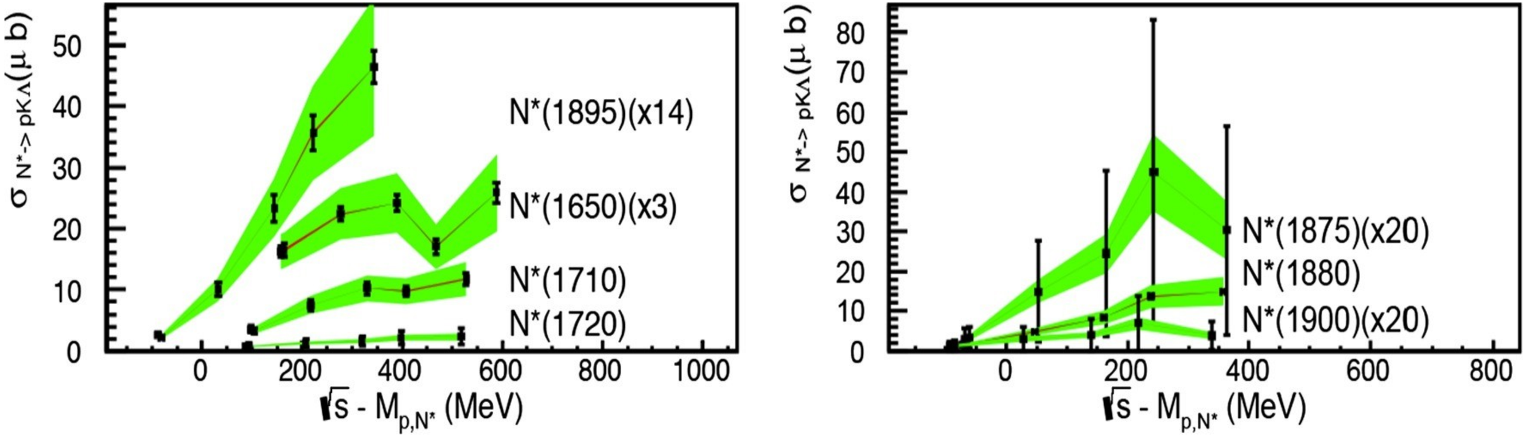
Resonant production of strangeness in p+p

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

- 90% of $pK\Lambda$ goes via resonances (at HADES energy)

p+p: 2.14 to 3.5 GeV, fixed target

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



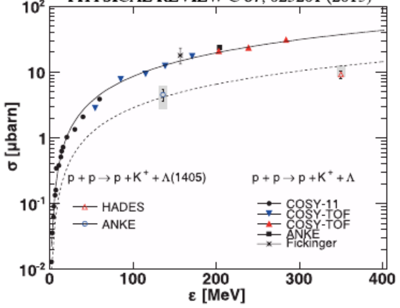
Heavy hyperons production

p+p@3.5 GeV data

Λ(1405), Λ(1520)

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

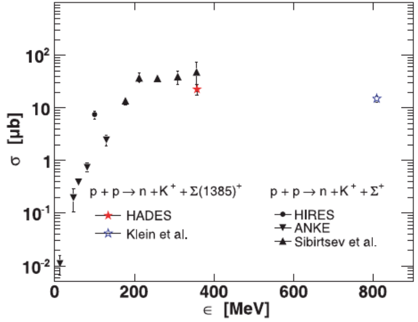
PHYSICAL REVIEW C 87, 025201 (2013)

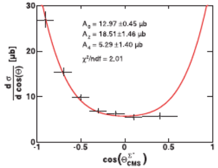


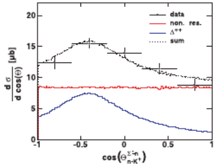
Σ(1385)

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

PHYSICAL REVIEW C 85, 035203 (2012)



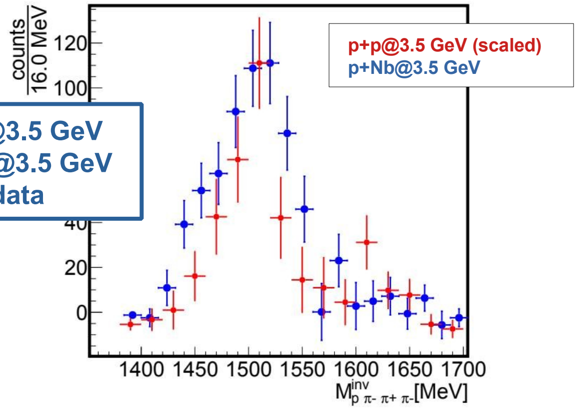


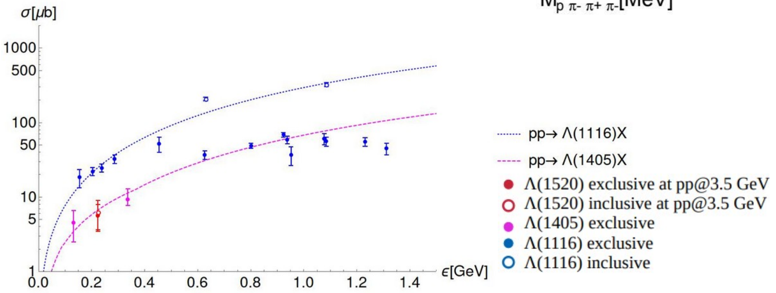


Λ(1520) in pp and pNb

HADES Preliminary

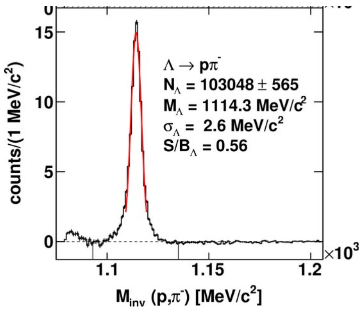
p+p@3.5 GeV p+Nb@3.5 GeV data

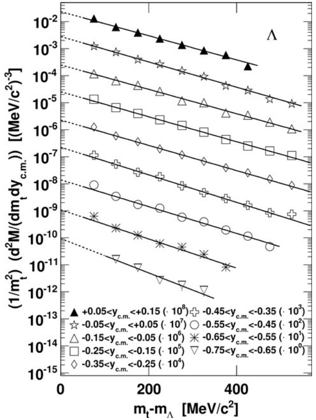




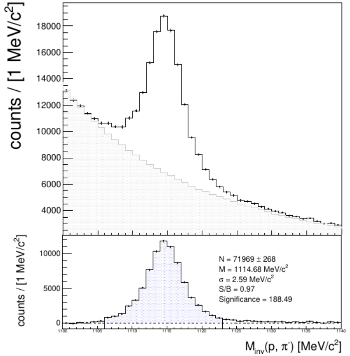
Λ hyperon

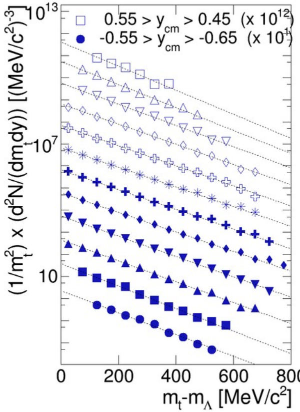
Ar+KCl $\sqrt{s_{NN}} = 2.6\,GeV$



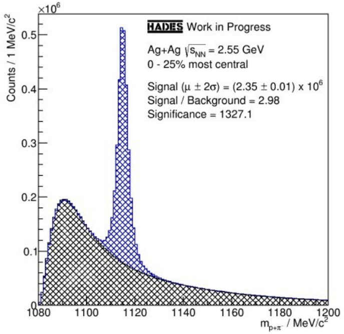


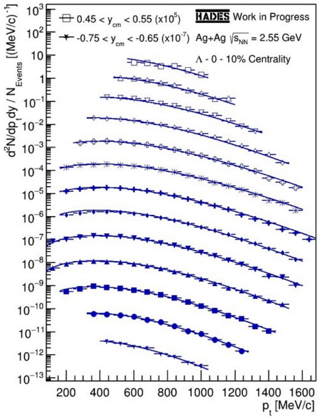
Au+Au $\sqrt{s_{NN}} = 2.42\,GeV$





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





High statistics

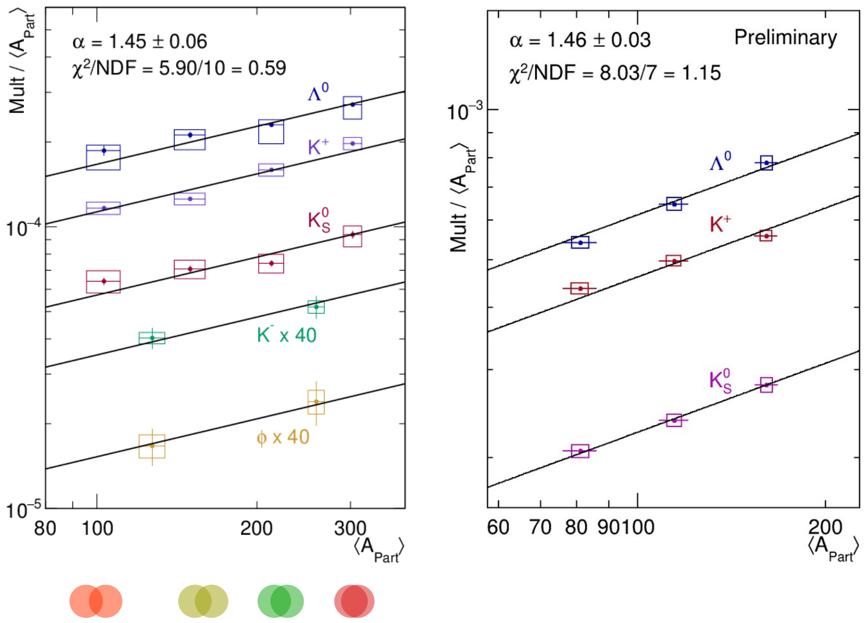
Large phase-space coverage

- *Eur.Phys.J.A* 47 (2011) 21
- *Phys.Lett.B* 793 (2019) 457-463

Strangeness production in HIC at SIS18

Strangeness production is an important probe for the QCD matter formed in HIC at SIS18
No dedicated “strangeness runs”, anticipated statistics in A+A runs dictated by dielectron program

Au+Au $\sqrt{s_{NN}}=2.42\,GeV$ **Ag+Ag** $\sqrt{s_{NN}}=2.55\,GeV$



HADES, Phys.Lett.B 793 (2019) 457

Observation:

Universal centrality dependence of multiplicities $M \sim \langle A_{part} \rangle^{\alpha}$

- Au+Au $\sqrt{s_{NN}}=2.42\,GeV : \alpha = 1.45 \pm 0.06$
- Ag+Ag $\sqrt{s_{NN}}=2.55\,GeV : \alpha = 1.46 \pm 0.03$

Scaling with absolute amount of strangeness not with individual hadron states

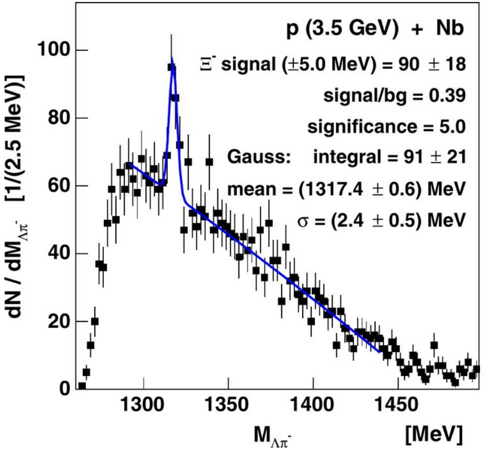
- *Phys. Lett. B* 778 (2018) 403-407
- *Phys. Lett. B* 793 (2019) 457-463

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)!

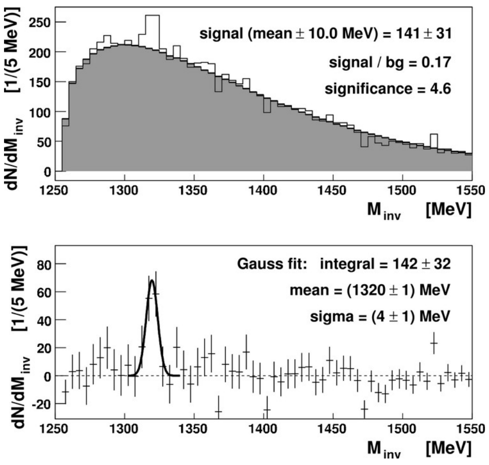
Ξ^- (far below NN production threshold) is observed by HADES

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



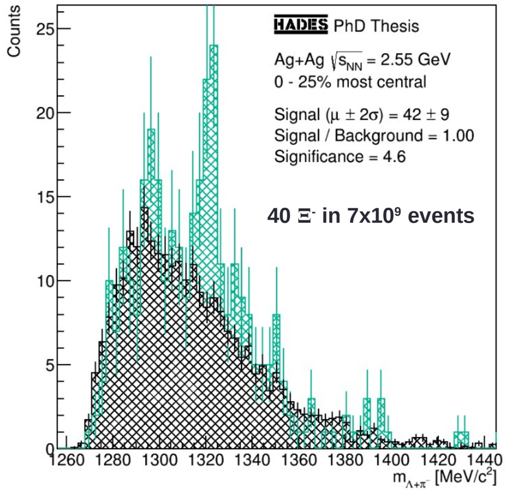
HADES, PRL 114 (2015) 212301

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



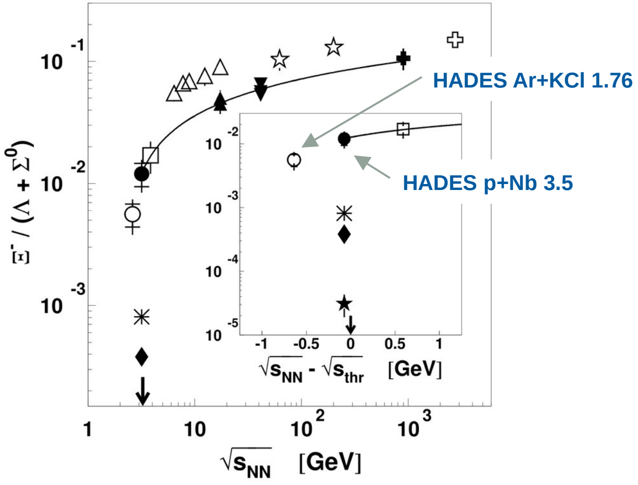
HADES, PRL 103 (2009) 132301

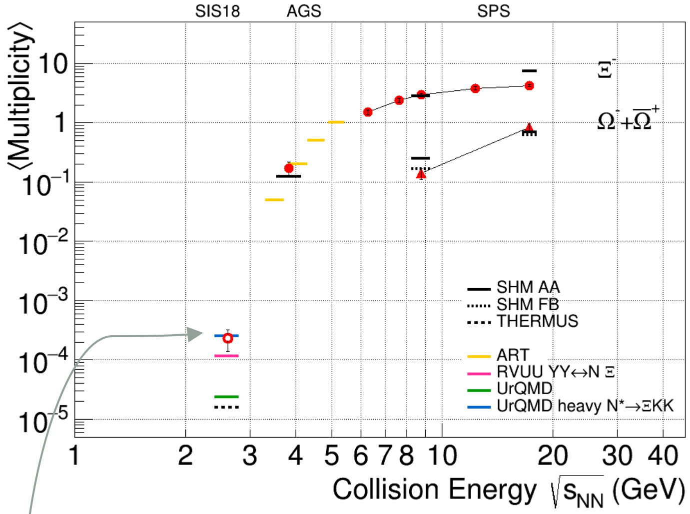
Ag+Ag $\sqrt{s_{NN}} = 2.55\,GeV$



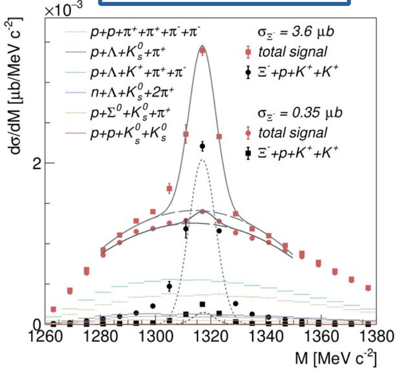
Ξ^- hyperon, model comparison

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?

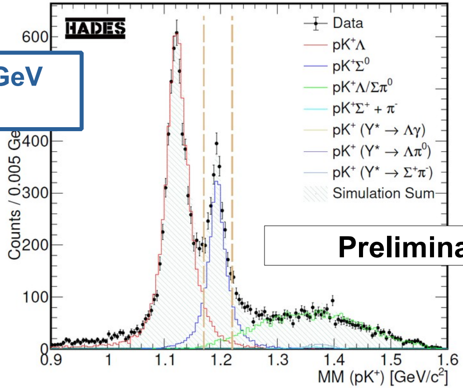
Observations:

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

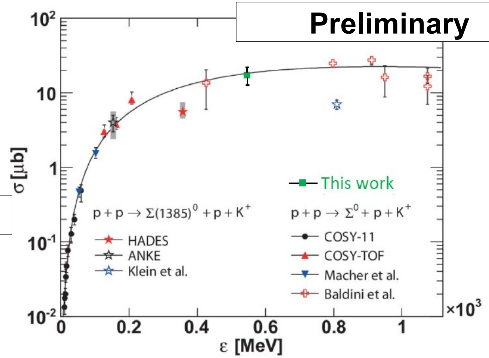
Spectroscopy of $N^* \rightarrow \Xi$+K+K is badly needed

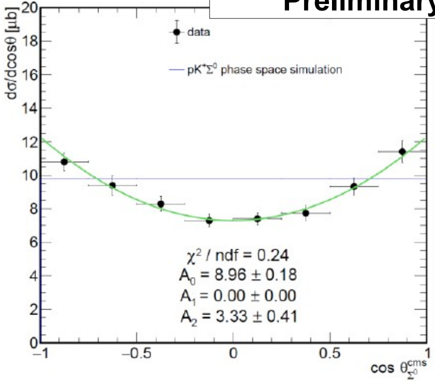
Σ^0 production

p+p@3.5 GeV data

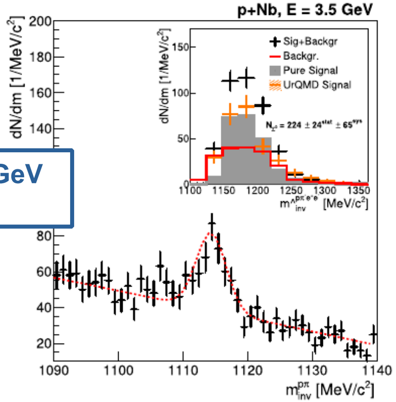


$$\sigma(pK^+\Sigma^0)[\mu b] = 18.74 \pm 1.01(stat) \pm 1.71(syst)$$

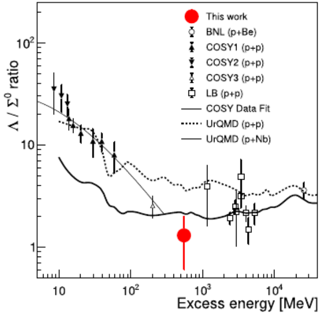


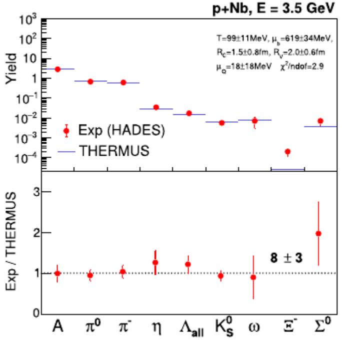


p+Nb@3.5 GeV data



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



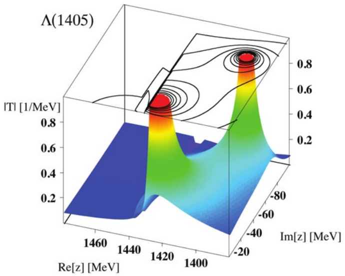


Phys. Lett. B 781, 735-740 (2018)

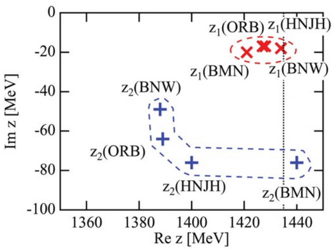
$\Lambda(1405)$ structure

- $\Sigma\pi$ decays of $\Lambda(1405)$ are sensitive tests of its structure ($\Sigma\pi$/KN poles)
- Line shape of $\Lambda(1405)$:
  - Σ-π (pp beams [HADES, ANKE])
  - K-N (K beams [LEPS] and electro-production [CLAS])
- $\Lambda(1405)$ 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 $\Lambda(1405)$ 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

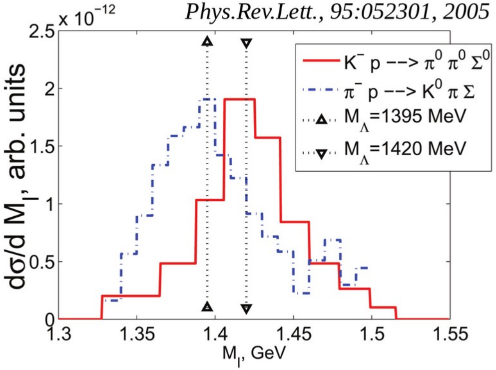
p+p@3.5 GeV data

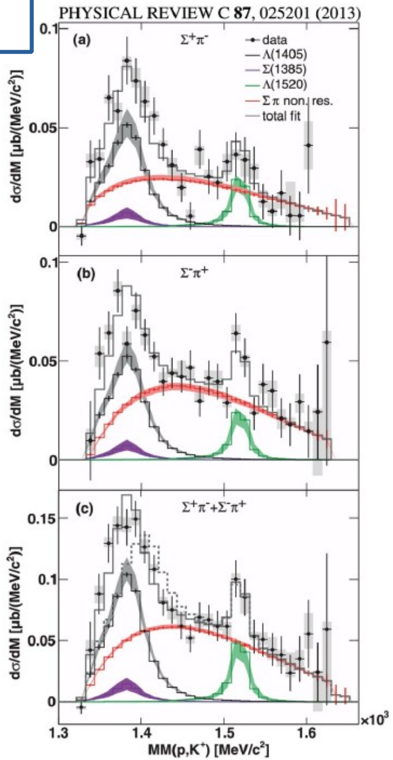


Prog.Part.Nucl.Phys., 67:55–98, 2012.



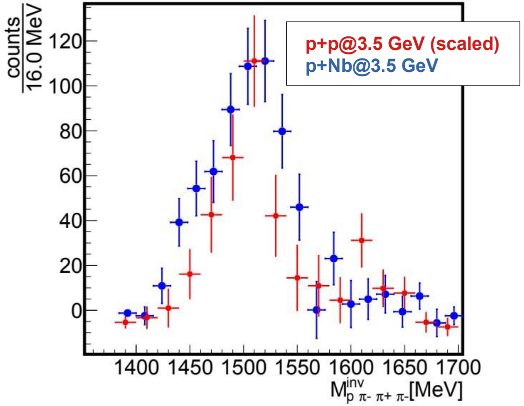
Phys.Rev., C77:035204, 2008.



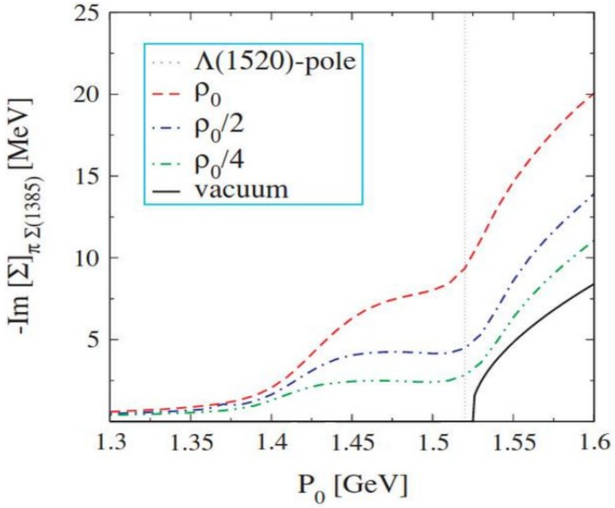


Cold matter effects on Λ(1520)

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



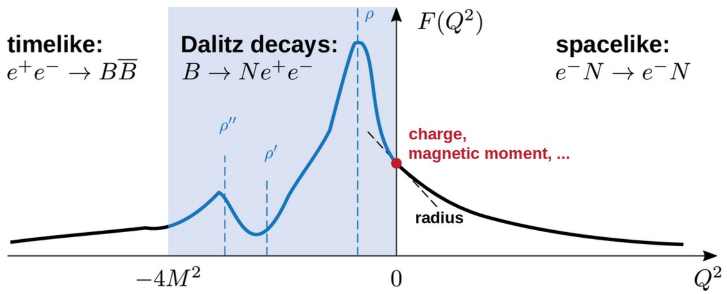
Phys. Rev. C 73, 045213 (2006)

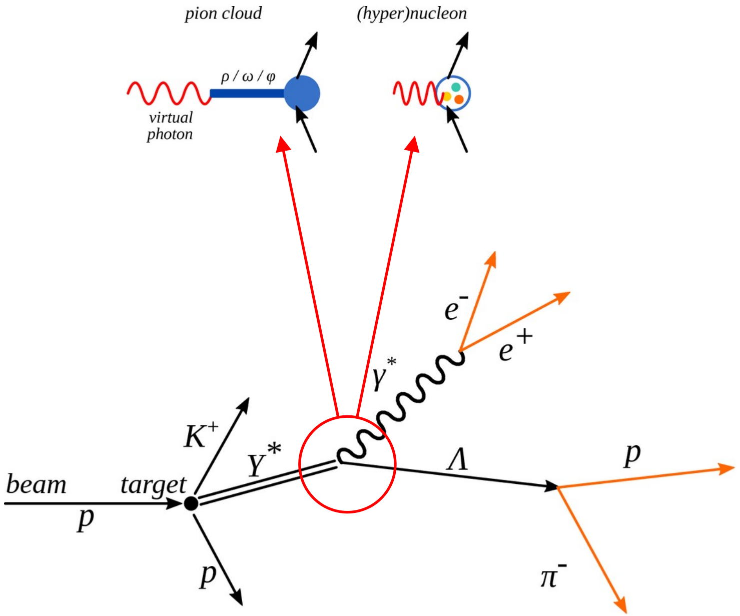


- is Λ(1520) a Σ(1385)π molecule?
- studies of in-medium modifications of Λ(1520)

Hyperons electromagnetic decays Y→Λγ* and Y→Λγ

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



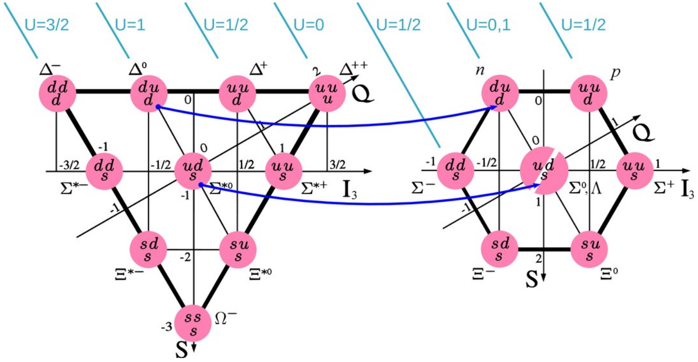


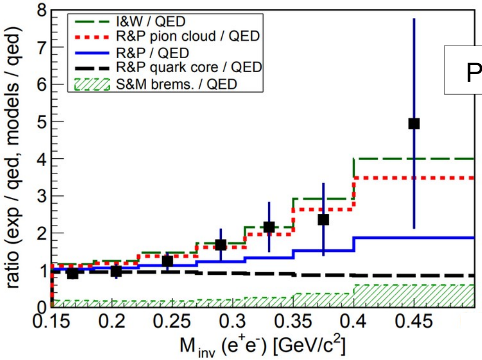
- Space-like region $|Q^2|>0$ is inaccessible for excited hyperons (as target or beam)
- Time-like high $|Q^2|$ is probed by electron-positron annihilation (BaBar, CLEO_C, BESIII)
- Time-like low $|Q^2|$ available via Dalitz decays in HADES

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

Hyperons electromagnetic decays Y→Λγ* and Y→Λγ

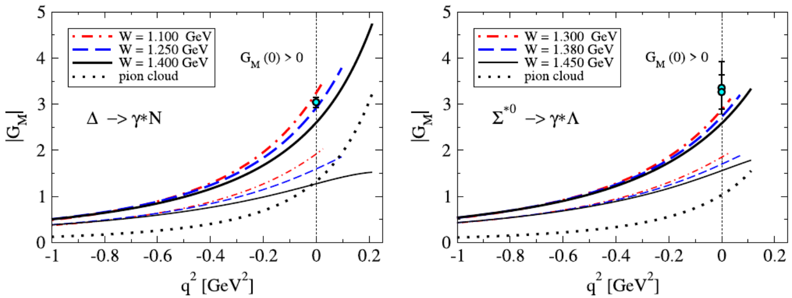
- Comparison of strange and non-strange baryons: i.e. Δ(1232)→ Ne^+e^- with $\Sigma(1385)^0 \to \Lambda e^+e^-$ (flavor symmetry partner of Δ in SU(3))



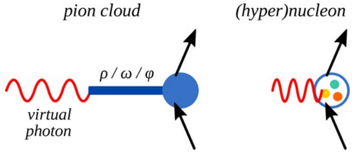


Phys. Rev. C 95, 065205 (2017)

p+p@3.5 GeV data

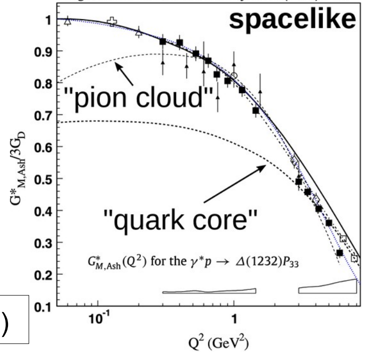


Phys. Rev. D 102, 054016 (2020)



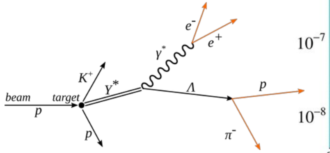
Prog. Part. Nucl. Phys. 67, 1 (2012)

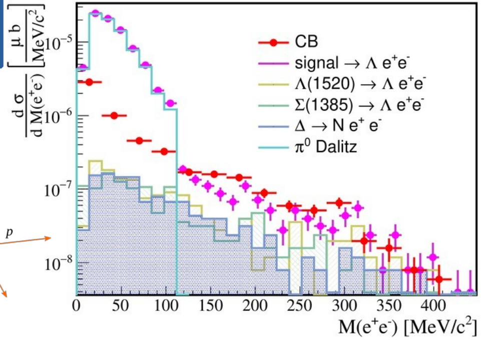
I.G. Aznauryan, V.D. Burkert
Progress in Particle and Nuclear Physics 67 (2012) 1–54

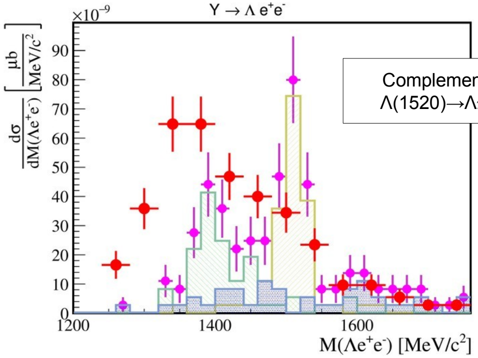


Hyperons electromagnetic decays Y→Λγ* and Y→Λγ

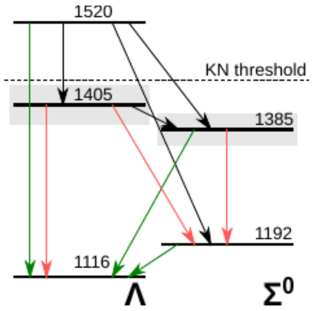
p+p@4.5 GeV sim



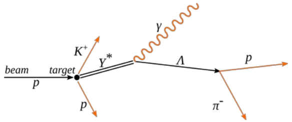


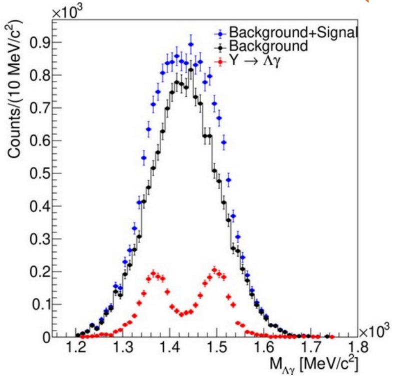


Complementary HADES results for Λ(1520)→Λ$\pi^+\pi^-$ from p+p@3.5 GeV



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		$479 \pm 120^{+81}_{-100}$				$167 \pm 43^{+26}_{-12}$	

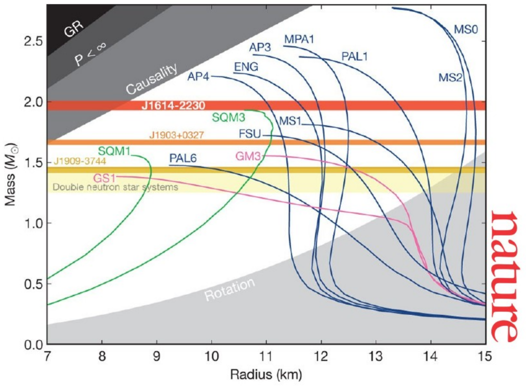




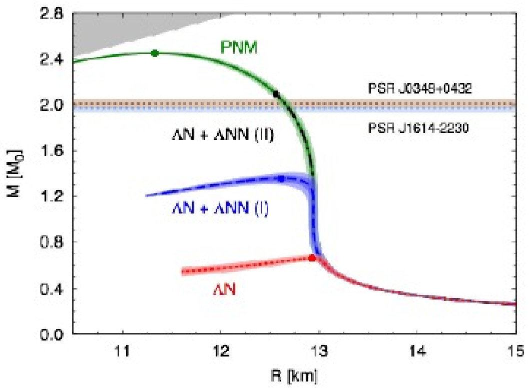
E. Kaxiras et al., Phys. Rev. D32, p. 695–700 (1985)
C. Granados et al., arXiv:1701:09130 (2017) 113014.
G. Ramalho et al., Phys. Rev. D93 (2016) 033004
S. Taylor et al. (CLAS Collaboration), Phys. Rev. C71, 054609

ΛN interactions

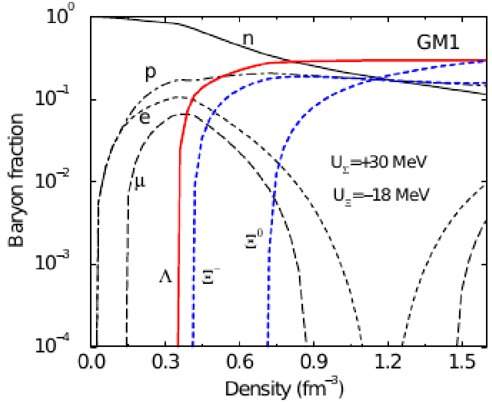
- EOS and “neutron star” puzzle
- purely nucleonic neutron star agrees with measurements
- strangeness softens EOS
- repulsive core of ΛN interaction is crucial for description



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

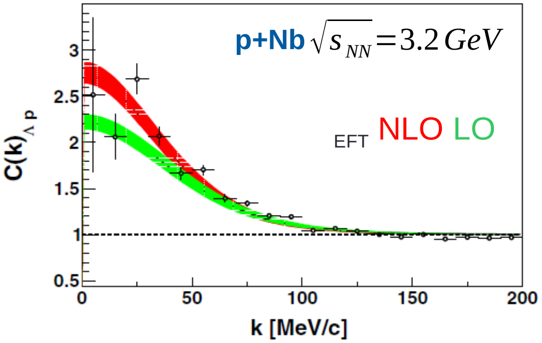


Phys. Rev. Lett. 114, 092301

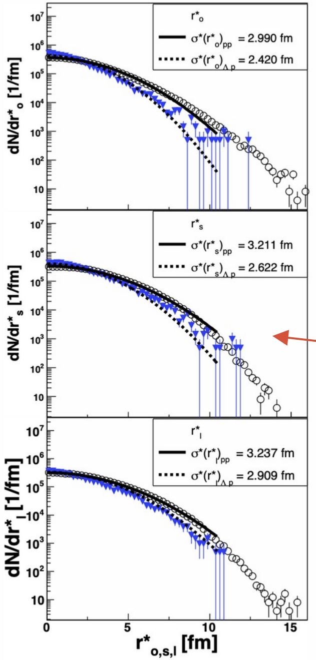


Phys. Rev. C 53 (1996) 1416

ΛN interactions



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



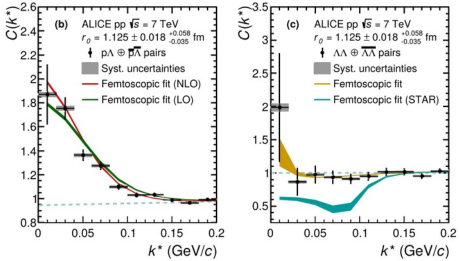
Λp interaction studied (for the first time) via femtoscopy

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

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

Source size uncertain

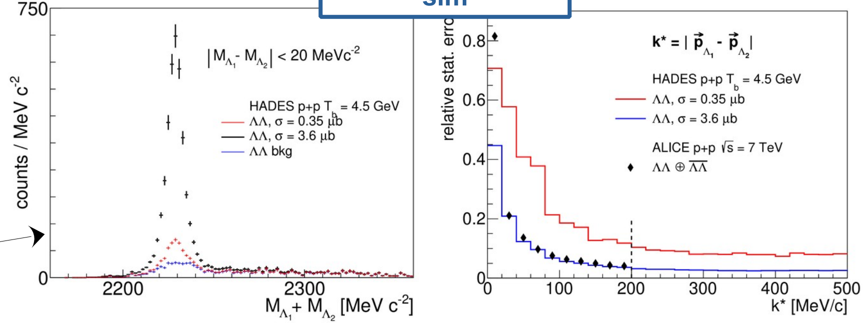
ΛN, ΞN further studies in high statistic p+p and p+Ag in 2022+



Phys. Rev. C 99, 024001 (2019)

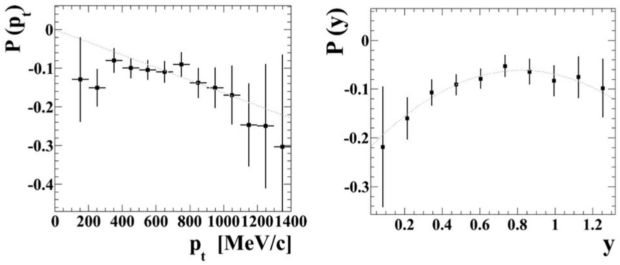
ΛΛ interactions

p+p@4.5 GeV sim



Λ polarization

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

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

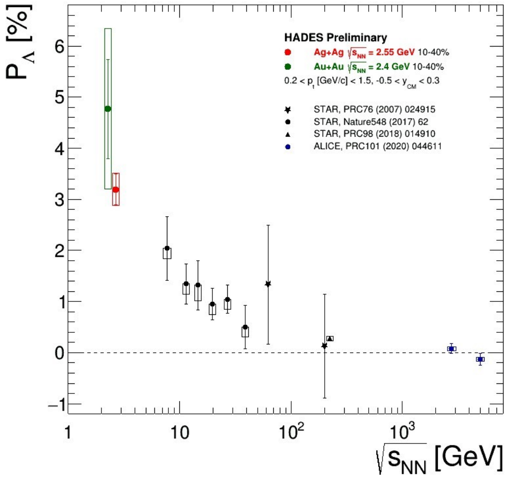
non-central heavy-ion collisions ☾

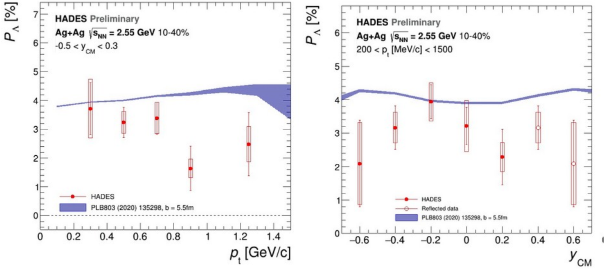
large orbital angular momenta ☾

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_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

Hypernuclei in HADES

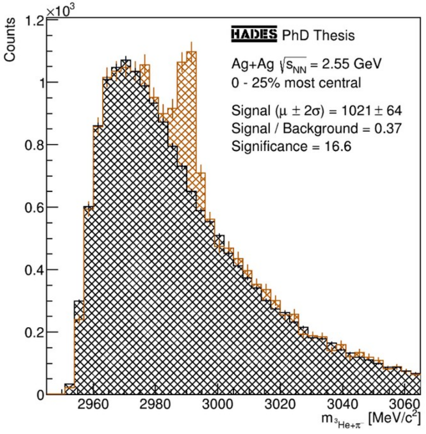
arXiv:2110.09531v1

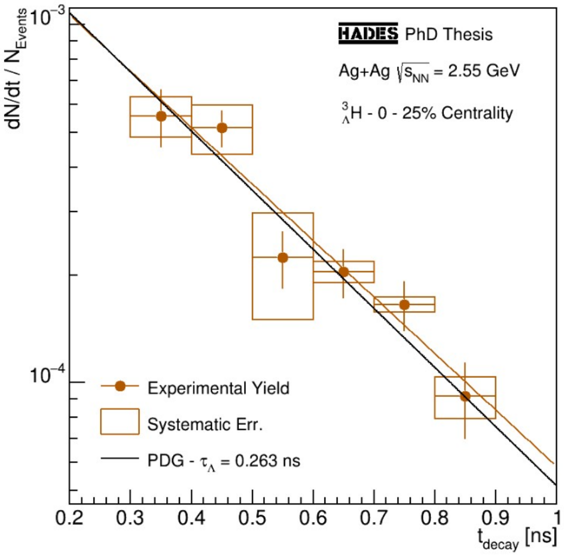
STAR, Au+Au $\sqrt{s_{NN}}=3\,GeV$

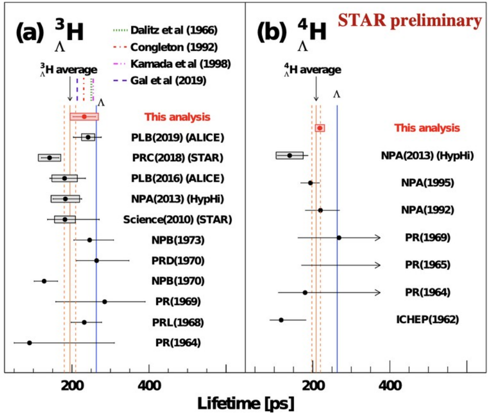
Sensitivity to hypernuclei production in the mid-rapidity region
First observation in HADES in the Ag+Ag run $\sqrt{s_{NN}}=2.55\,GeV$:

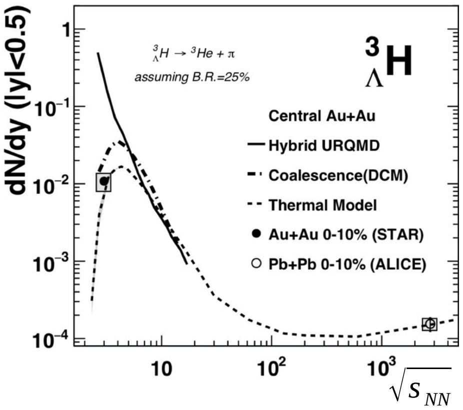
~1000 ${}^{3}_{\Lambda}H$ in 7x10^{9} events

allows lifetime measurement, understanding the production mechanism



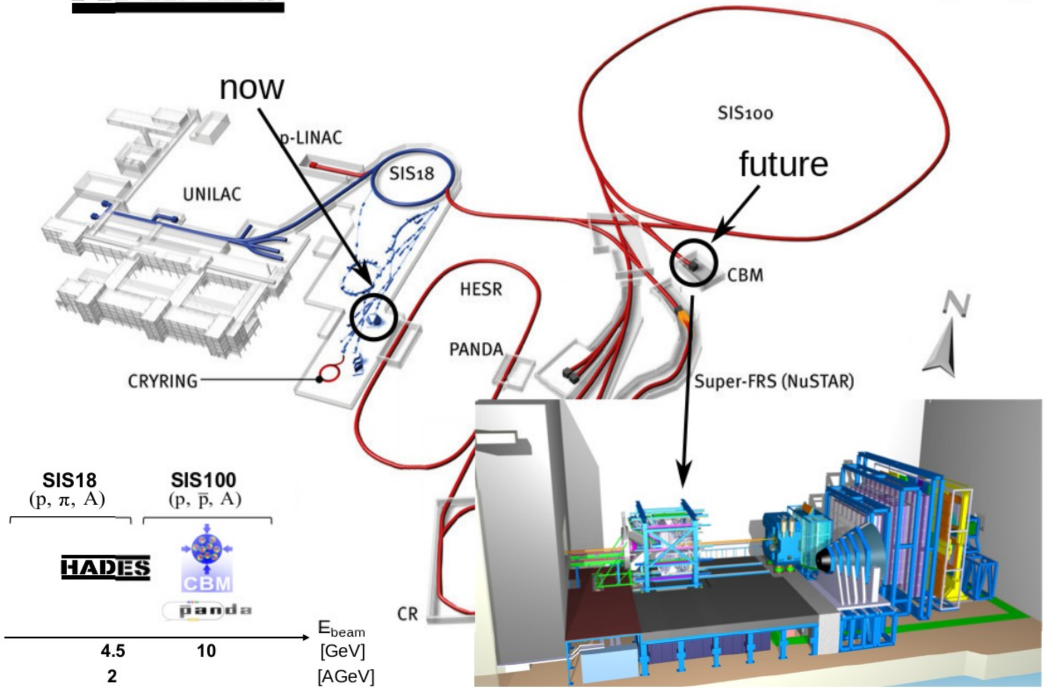






FAIR PHASE-0: HADES Forward Detector upgrade

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

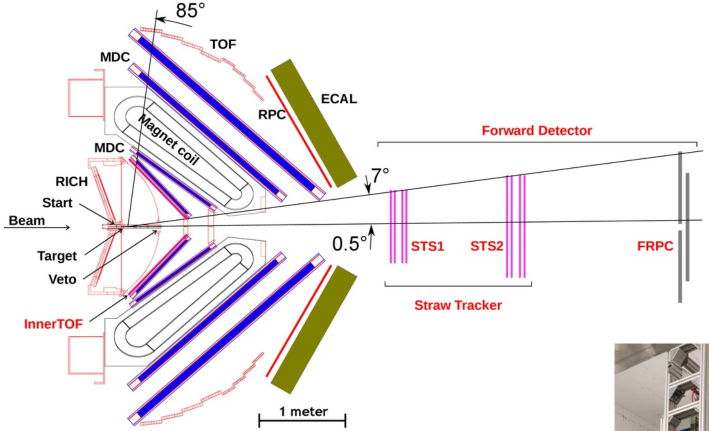
- various HI beams (Au+Au, Ag+Ag) in the meantime
- light system beams: p+p@3.5 GeV ('07), π+p/A ('14)
- the next beam: p+p@4.5 GeV

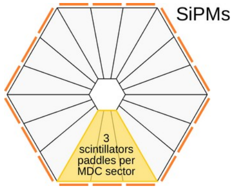
HADES Forward Detector upgrade: STS

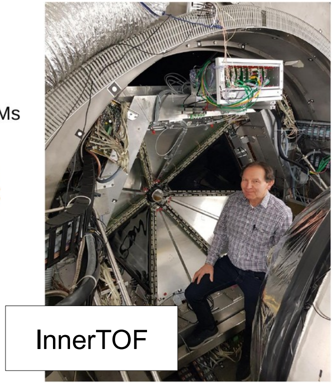
- Instruments the field-free forward hemisphere
- Straw Tube Stations (STS) compatible with Phase-1 PANDA STT and FT
- Boost physics capability for hyperon e/m transition Ffs

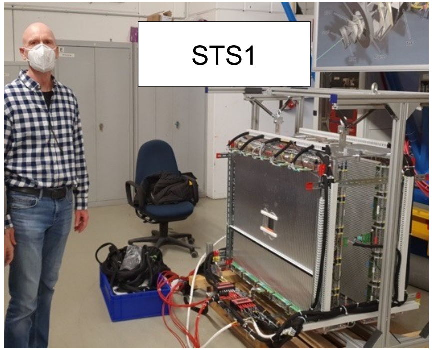
- STS1 and STS2 installed and tested in HADES
- fRPC full installation in Nov ‘21 (half setup tested)

- InnerTOF project to improve triggering efficiency (Q4/2021)



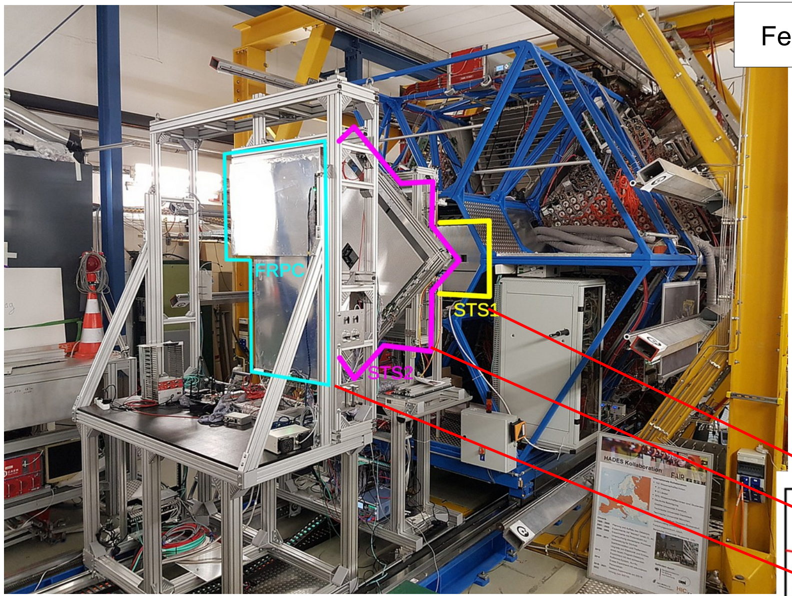


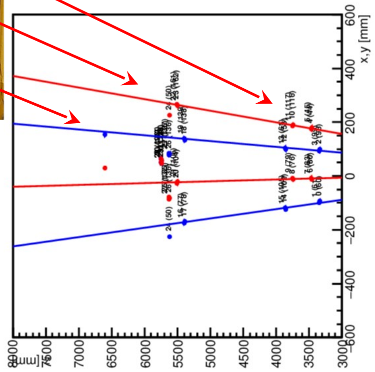




FAIR PHASE-0: HADES Forward Detector upgrade

February ‘21 test beam





Summary

- **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

p+p@4.5 GeV beam scheduled for February 2022

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

PRODUCTION AND DECAY OF HYPERONS, AND INCLUSIVE HADRON AND DILEPTON PRODUCTION

in p+p Reactions at 4.5 GeV

The HADES and HADES-PANDA Collaborations

HADES

Spokespersons: J. Stroth (j.stroth@gsi.de), P. Tlusty (tlusty@ujf.cas.cz)
GSI contact: J. Pietraszko (j.pietraszko@gsi.de)

Infrastructure: SIS18, LH_2 target, HADES cave

Beam: protons at 4.5 GeV, beam intensity 7.5×10^7 p/s, slow extraction

Abstract

In this FAIR Phase-0 proposal, we request proton beam to perform a group of experiments mostly involving hyperons or hidden strangeness. This run group will make very effective and efficient use of the available beamtime since four investigations require the same beam/trigger conditions and improved detector set-up, thus they will be measured concurrently. This proposal addresses the following main physics topics: (1) Hyperon electromagnetic decays $Y \to \Lambda\gamma^*$ and $Y \to \Lambda\gamma$. (2) Hyperon hadronic decays. (3) Production of double strangeness ($\Xi^-(1321)$, $\Lambda\Lambda$) and hidden strangeness (ϕ). (4) Inclusive hadron and dilepton production as a reference for p+A and heavy-ion data. These measurements will provide first results in this energy region and an important benchmark for the future physics program at FAIR. The measurements of hyperon production and electromagnetic decays during Phase-0 are complementary to the Phase-1 studies at PANDA with antiproton-proton interactions, and will enable some PANDA detector systems to be setup and commissioned already now.
Below is a description of the proposed study with proton beam using the HADES spectrometer combined with the new forward detection system.

This is a new experiment proposal.
We request 84 shifts plus 4 shifts in a separate proposal for commissioning.

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