Hyperons with HADES

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EMMI Workshop
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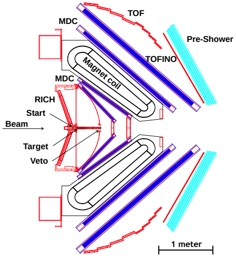
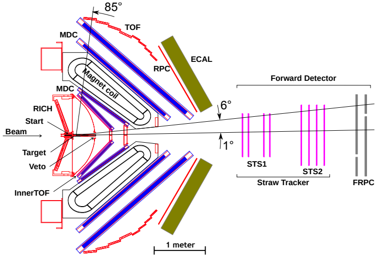
HADES – High Acceptance Dielectron Spectrometer

HADES in 2007



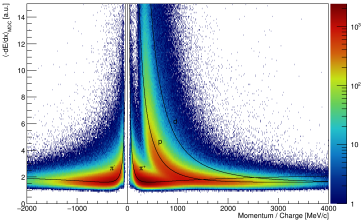
HADES in 2022

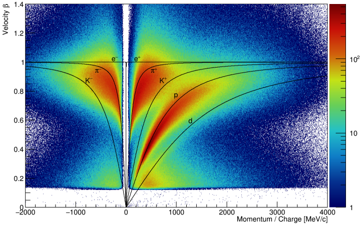


Major HADES upgrades:

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

Particle identification: dEdx, β vs momentum





Previous experiments:

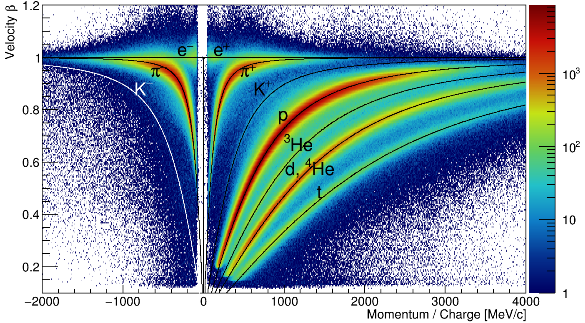
- various HI beams (Ar+KCl, Au+Au, Ag+Ag)
- light system beams:
  - p+p@3.5 GeV ('07)
  - p+Nb@3.5 GeV ('07)
  - π^-+p / π^-+A ('14)
  - p+p@4.5 GeV ('22)

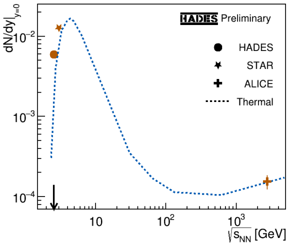
Hyperons in Heavy Ions Collisions at HADES

- 2012: Au+Au @ 1.23 AGeV ($\sqrt{s_{NN}}$ = 2.42 GeV)
  7 billion events
- 2019: Ag+Ag @ 1.58 AGeV ($\sqrt{s_{NN}}$ = 2.55 GeV)
  14 billion events

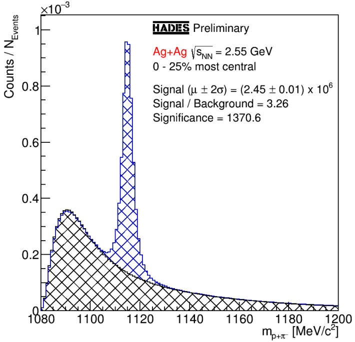
- Strangenes production close to free NN threshold:
  $N+N \rightarrow Y+N+K$ – $\sqrt{s_{NN}}$ = 2.55 GeV
  $N+N \rightarrow N+N+K+\overline{K}$ – $\sqrt{s_{NN}}$ = 2.86 GeV
- Strangeness exchange process:
  $Y+\pi \rightarrow N+\overline{K}$

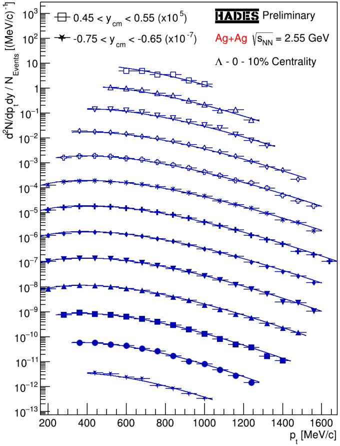
- Production of Hypernuclei favored by baryon dominance of the fireball:
  1. Produce Λ
  2. Λ must find nucleons
- Sweet spot for hypernuclei production is below 10 GeV – FAIR energies

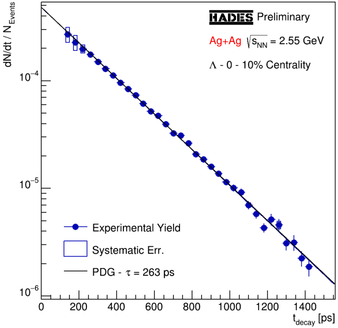




Λ hyperon in Ag+Ag

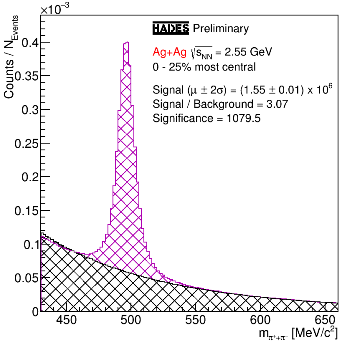


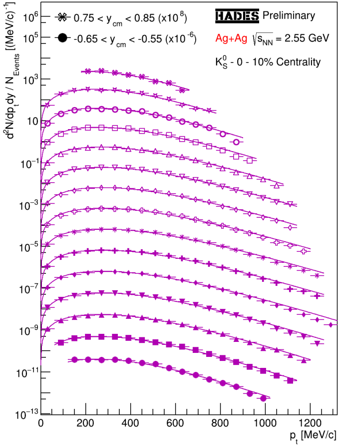


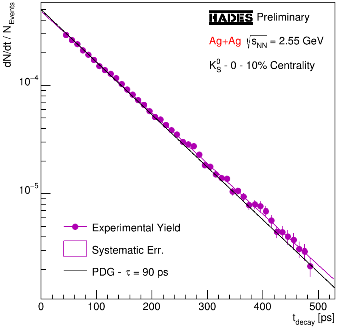


$\tau = 262 \pm 2 \pm 3$ ps
compatible with PDG

K^0 meson in Ag+Ag







$\tau = 91 \pm 1 \pm 1$ ps
compatible with PDG

hypertriton – ${}^{3}_{\Lambda}$H

- mass = 2991 MeV c^{-2}
- binding energy $B({}^{3}_{\Lambda}\mathrm{H})$ = 0.79 MeV/A
- decay branches:

decay channel	BR [%]
${}^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi^{-}$	27
${}^{3}_{\Lambda}\mathrm{H} \rightarrow \mathrm{t} + \pi^{0}$	13
${}^{3}_{\Lambda}\mathrm{H} \rightarrow \mathrm{d} + \mathrm{p} + \pi^{-}$	40
${}^{3}_{\Lambda}\mathrm{H} \rightarrow \mathrm{d} + \mathrm{n} + \pi^{0}$	20

- world average lifetime 211 ± 9 ps

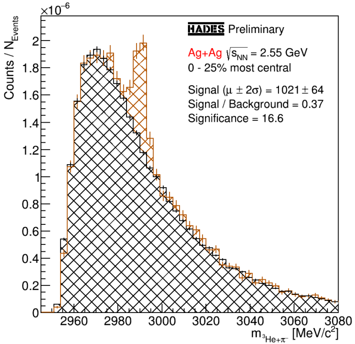
hyperhydrogen-4 – ${}^{4}_{\Lambda}$H

- mass = 3923 MeV c^{-2}
- binding energy $B({}^{4}_{\Lambda}\mathrm{H})$ = 2.63 MeV/A $\approx$ 3.3 $\mathrm{B}({}^{3}_{\Lambda}\mathrm{H})$
- decay branches:

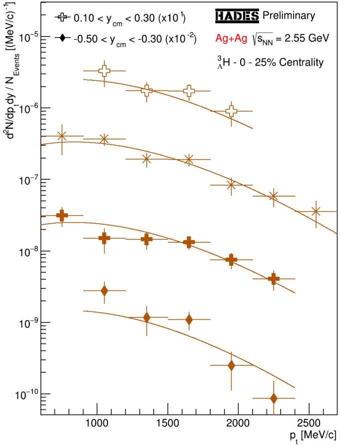
decay channel	BR [%]
${}^{4}_{\Lambda}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + \pi^{-}$	50
${}^{4}_{\Lambda}\mathrm{H} \rightarrow \mathrm{t} + \mathrm{p} + \pi^{-}$	33
${}^{4}_{\Lambda}\mathrm{H} \rightarrow \mathrm{t} + \mathrm{n} + \pi^{0}$	17

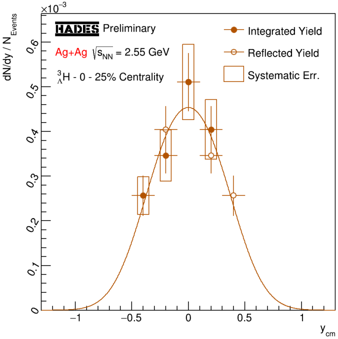
- world average lifetime 218 ± 5 ps

Hypertriton in HIC: ${}^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^{-}$



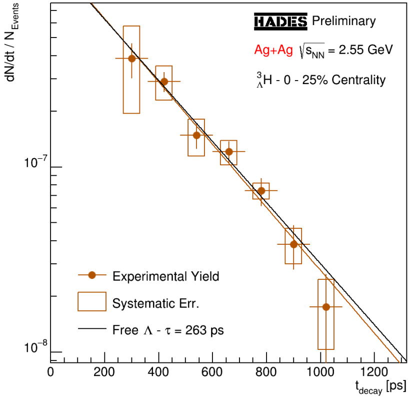
Multidifferential analysis possible

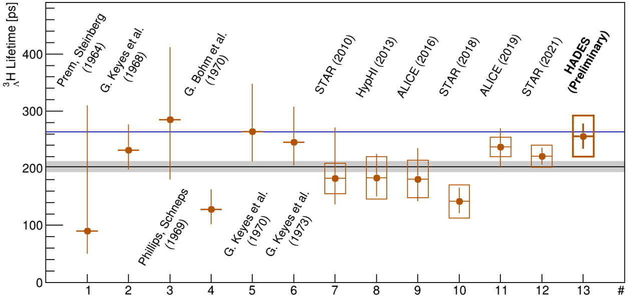




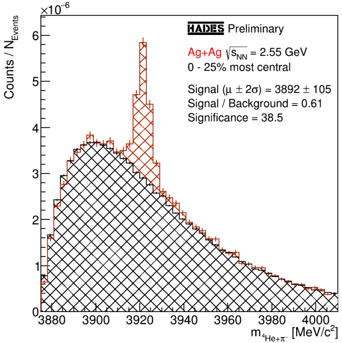
First measurement at mid-rapidity at this energy

Hypertriton in HIC: ${}^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^{-}$ – lifetime

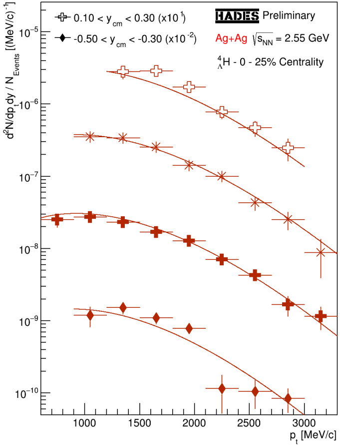


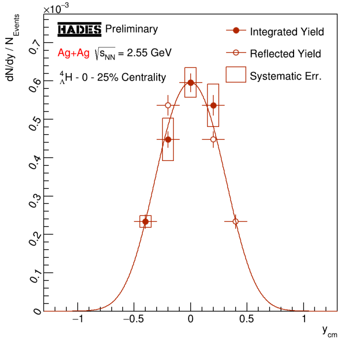


lifetime of 256 ± 22 ± 36 ps compatible with free Λ



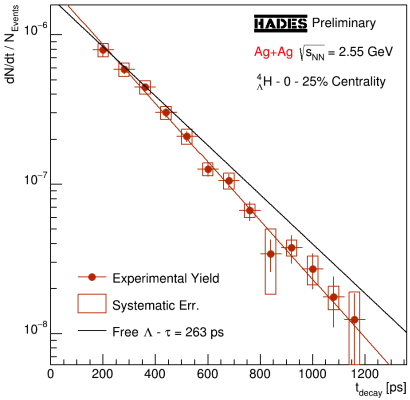
Multidifferential analysis possible

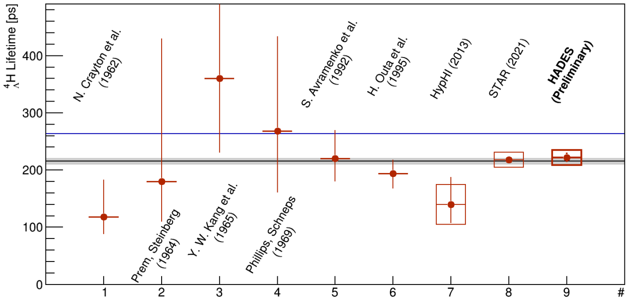




First measurement at mid-rapidity at this energy

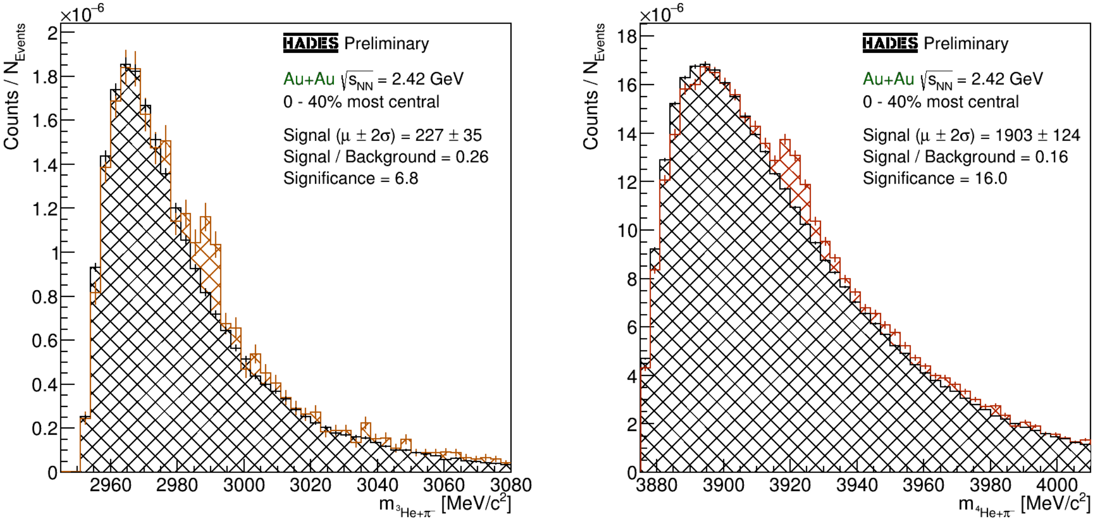
Hyperhydrogen-4 in HIC: ${}^{4}_{\Lambda}H \rightarrow {}^{4}He + \pi^{-}$ – lifetime





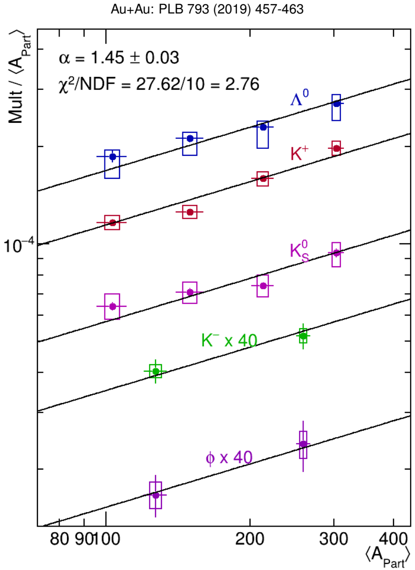
lifetime of 222 ± 8 ± 13 ps compatible with earlier measurements

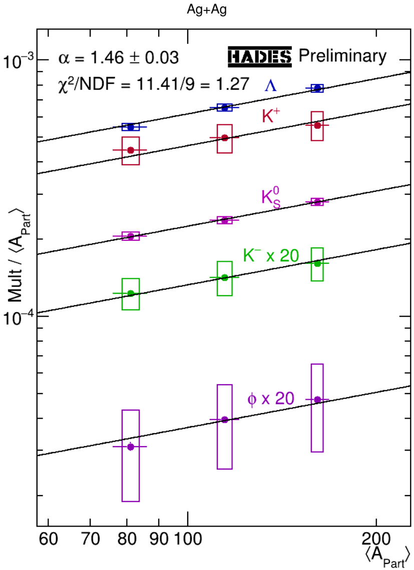
Hypernuclei in HIC: Au+Au



Lowest energy at which Hypernuclei were ever reconstructed in HIC

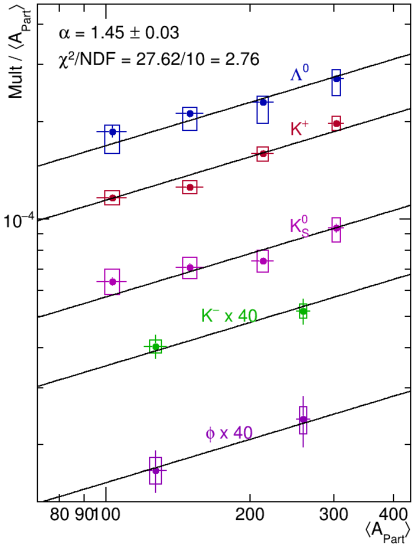
Strangeness yields



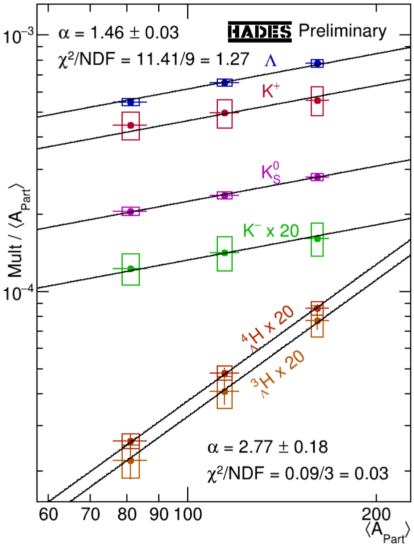


Strangeness yields

Au+Au: PLB 793 (2019) 457-463



Ag+Ag



id	pp→ reaction	$\sigma_0^{(id)}$ cross section [μb]	∡ var.	$\measuredangle(a_2, a_4)$		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	$\Sigma(1385)^+ n K^+$	$22.42 \pm 0.99 \pm 1.57\ ^{+3.04}_{-2.23}$	$\theta^{cms}_{\Sigma^{+*}}$	1.427 ± 0.3	0.407 ± 0.108	✓	[17]	17.905 ± 0.075	⊥
8	$\Delta(2050)^{++} n$	33 % feeding for $\Sigma^* n K^+$	θ^{cms}_{n}	1.27	0.35	✓	[17]	8.82 ± 0.13	⊤
9	$\Sigma(1385)^+ p K^0$	$14.05 \pm 0.05\ ^{+1.79}_{-2.14} \pm 1.00$	$\theta^{cms}_{\Sigma^{+*}}$	1.42 ± 0.3	—	✓	[13]	16.101 ± 0.072	⊤
10	$\Sigma(1385)^0 p K^+$	$6.0 \pm 0.48\ ^{+1.94}_{-1.06}$	$\theta^{cms}_{\Sigma^{0*}}$	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	$\Delta^{+} \Lambda(1405) K^+$	$3.0 \pm 20\,\%$	—	—	—		compl. to above	4.2 ± 1.9	⊤
17	$\Delta^{+} \Sigma(1385)^0 K^+$	$2.3 \pm 20\,\%$	—	—	—		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	$\Lambda p \pi^0 K^+$	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	⊤

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

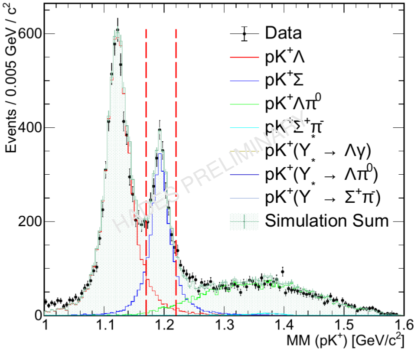
New results from 3.5 GeV

- though 15 years old, data from p+p @3.5 GeV still can help us a lot
- new reactions are analyzed → new anaylsis tools for HADES are being developped (HADES + PANDA cooperation):

→ Neural networks (K. Sumara, W. Esmail, K. Nowakowski)

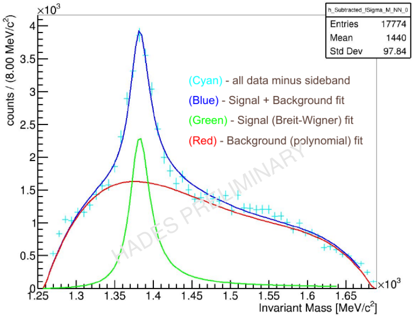
→ Kinematic refit (W. Esmail, J. Riegier. J. Regina)

Σ^0 exclusive (!) (W. Esmail)



$\Sigma(1385)^+$ inclusive (K. Sumara)

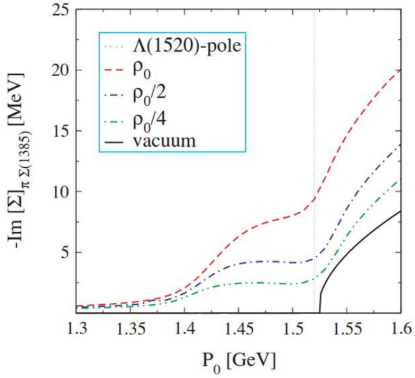
Inclusive analysis



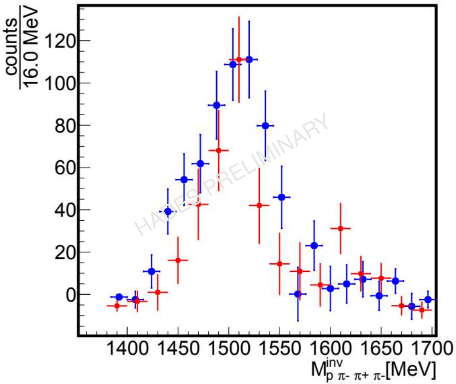
$$M_0 = 1382.96 \pm 0.59\ \mathrm{MeV/c^2}$$

$$\Gamma_0 = 32.7 \pm 1.9\ \mathrm{MeV/c^2}$$

- is $\Lambda(1520)$ a $\Sigma(1385)\pi$ molecule?
- studies of in-medium modifications of $\Lambda(1405)$



Phys. Rev. C 73, 045213 (2006)



of $\Lambda(1520)$	M [MeV/c^2]	σ [MeV/c^2]	Γ [MeV/c^2]
p+p	1504.5 ± 4.7	14.7 ± 6.7	15.6 ± 1.0
p+Nb	1507.7 ± 3.3	14.7 ± 6.7	34.6 ± 5.2

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 experiment executed in February-March 2022

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

Production and electromagnetic decay of hyperons: a feasibility study with HADES as a phase-0 experiment at FAIR

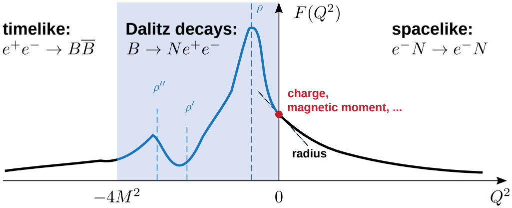
Production and electromagnetic decay of hyperons: a feasibility study with HADES as a Phase-0 experiment at FAIR

HADES + HADES@PANDA collaborations

`Eur.Phys.J.A57,138(2021)`

Electromagnetic transitions form-factors (eTFF)

- Sensitive probe of hyperon internal structure
- Measurements of eTFF

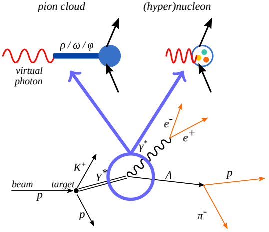


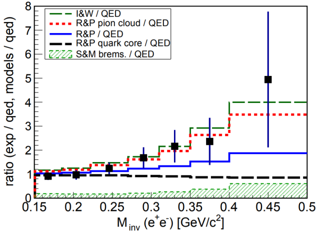
→ Space-like region $|Q^2| > 0$ is inaccessible for excited hyperons (as a target or beam)

→ Time-like high $|Q^2|$ is probed by electron-positron anihillation (BaBar, CLEO-C, BESIII)

→ Time-like low $|Q^2|$ available via Dalitz decays

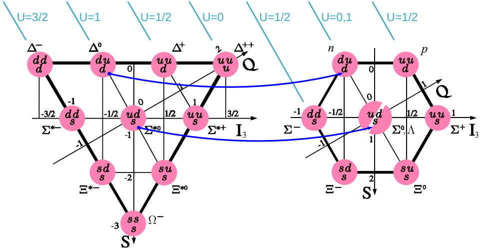
HADES is an excellent experiment for a Dalitz decay measurements

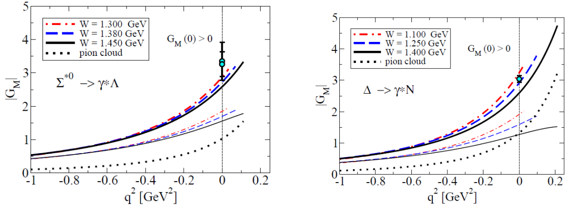




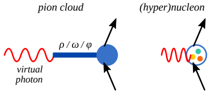
Phys.Rev. C95 (2017) no.6, 065205

i.e. $\Delta(1232)\to Ne^+e^-$ (measured by HADES) with $\Sigma(1385)^0\to\Lambda e^+e^-$ - (flavor sym. partner of Δ in SU(3))





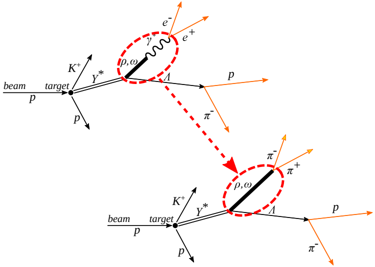
G. Ramahlo, arXiv: 2002.07280v1



Importance of pion cloud at small q^2

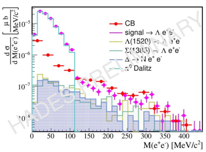
Hyperon electromagnetic/hadronic decays

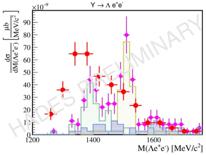
- Tests VDM hypothesis (coupling to ρ,ω) for hyperons.
- $\pi\pi$ decays complementary to dileptons.



- Independent $\Lambda(1520)$ reconstruction via $\Lambda\pi^-\pi^+$ decay (BR = 6 %), and
- $\Sigma(1385)$ via $\Lambda\pi$ (BR = 87 %)

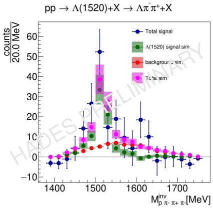
Radiative decay $Y\rightarrow\Lambda e^+e^-$

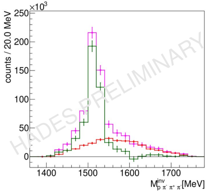




Projections for HADES with p+p @4.5 GeV; Expected: ~300 events/Y

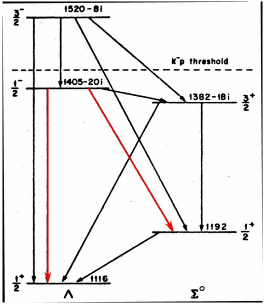
Hadronic decay $\Lambda(1520)\rightarrow\Lambda\pi^+\pi^-+X$





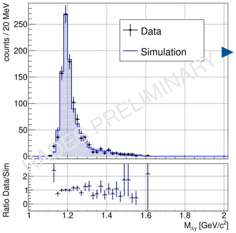
Reference HADES results from p+p @3.5 GeV (t.b.pub.)

Projections for HADES p+p @4.5 GeV; Expected: ~500k events



- Complementary to Dalitz decay
- Y internal structure sensitive to $\Lambda\gamma/\Sigma^0\gamma$ transition rates
- $\Sigma(1385)^0$ and $\Lambda(1520)\rightarrow\Lambda\gamma$ measured by CLAS

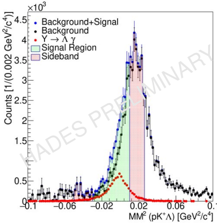
Σ^0 production

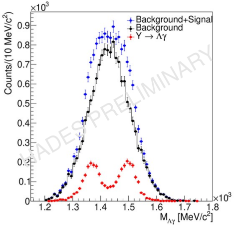


- Reconstruction of Σ^0 as reference for Λ production and feed-down in $Y\rightarrow\Lambda e^+e^-$

Recent HADES results for $\Sigma^0\rightarrow\Lambda\gamma$ with p+p @3.5 GeV (t.b.p)

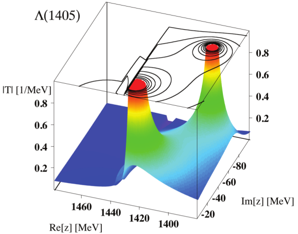
Radiative decays of $Y\rightarrow\Lambda\gamma$



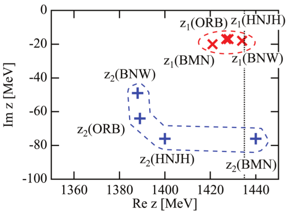


Projections for HADES with p+p @4.5 GeV;
Expected: 1500 events

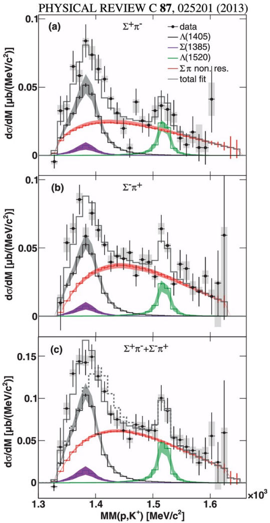
Hyperon hadronic decays - $\Lambda(1405)$



Prog.Part.Nucl.Phys., 67:55–98, 2012.



Phys.Rev., C77:035204, 2008.

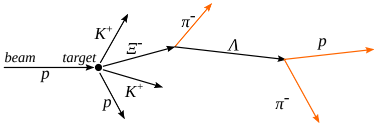


- $\Sigma\pi$ decays of $\Lambda(1405)$ are sensitive tests of its structure
- Line shape of $\Lambda(1405)$ ruled by two poles:
  - Σ-π (pp beams [HADES, ANKE])
  - K-N (K beams [LEPS] and electro-production [CLAS])
- $\Lambda(1405)$ measured in HADES in pp@3.5 GeV via $\Sigma^{\pm}\pi^{\mp}$
- $\Sigma^{\pm}\pi^{\mp}$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

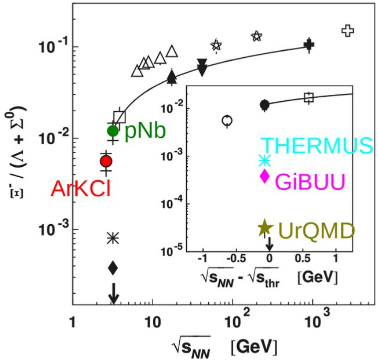
Reference HADES results with p+p @3.5 GeV

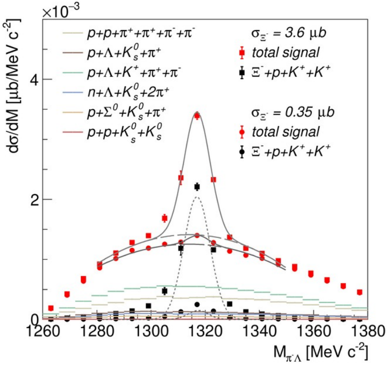
Double strangeness reactions – Ξ^- production

- Motivated by HADES-puzzle of Ξ^- enhancement in p+Nb and Ar+KCl
- Production through intermediate high mass (>2 GeV c^{-2}) baryonic or hyperon resonance ?? → pp data needed



PRL **114,** 212301 (2015)

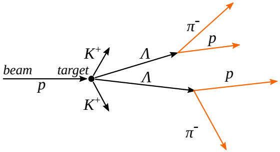




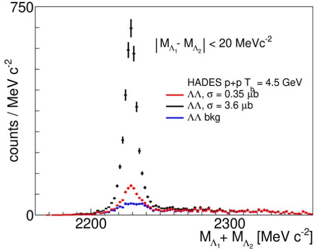
Reference HADES results with p+Nb @3.5 GeV and Ar+KCl @1.76 GeV

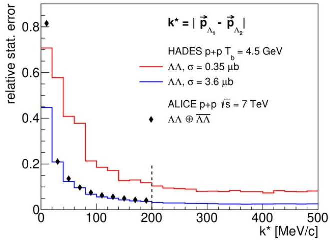
Projections for HADES with p+p @4.5 GeV

Double strangeness reactions – $\Lambda\Lambda$ production



- Sensitive to Y-N and Y-Y interaction
- Complementary to PANDA program of $\Lambda\Lambda$ at p+$\overline{\text{p}}$
- HADES measured pΛ correlations (Phys.Rev. C94 (2016) no.2, 025201), coherent studies with ALICE for pΛ and $\Lambda\Lambda$ (Phys. Rev. C 99, 024001)
- ALICE identified 6M Λ and $\overline{\Lambda}$, but only a small fraction in the interesting region of $k^{?} < 200\,\text{MeV}\,c^{-1}$
- In HADES smaller contribution from feed-down of higher excited states, and smaller source-size corrections





Projections for HADES with p+p @4.5 GeV

Expected count rates in p+p@4.5 GeV

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		
$\Xi^- \to \Lambda \pi^-$	$\Lambda\Lambda$	$\varphi \to K^+ K^-$
$(4.7 - 47.6) \times 10^4$	$(0.62 - 6.17) \times 10^4$	3.1×10^6

Inclusive measurement of hadrons and dielectrons				
$M_{ee} < 0.15\,\mathrm{GeV}/c^2$	$M_{ee} > 0.15\,\mathrm{GeV}/c^2$	$\omega \to e^+ e^-$	$\varphi \to e^+ e^-$	$M_{ee} > 1.1\,\mathrm{GeV}/c^2$
5.72×10^6	7.41×10^5	5.8×10^4	1.86×10^3	69

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Summary

- HADES has rich hyperon program in HIC and elementary reactions.
- HADES can provide first data of hyperon Dalitz decay.
- The p+p@3.5 GeV, p+p@4.5 GeV and Au+Au and Ag+Ag for HIC data are still being analyzed.