Proton-proton reactions and hyperon physics at HADES

Physics program and quick summary of detector development

Rafał Lalik

Jagiellonian University
Faculty of Physics, Astronomy and Applied Computer Science

mailto:rafal.lalik@uj.edu.de

UJ Particle Physics Phenomenology and Experiments Seminar
15.03.2021

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 665778

National Science Centre, Poland 2016/23/P/ST2/04066 POLONEZ

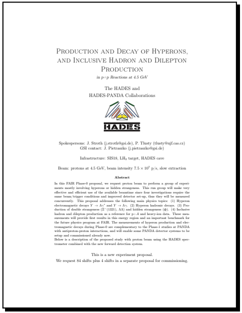
Hyperons at HADES

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

pp beam scheduled for February 2022 (4 weeks)



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

HADES + HADES@PANDA collaborations

`https://arxiv.org/abs/2010.06961` – accepted for EPJA

Hyperons and strange baryonic resonances

Inclusive Λ production in p+p@3.5 GeV (2007)

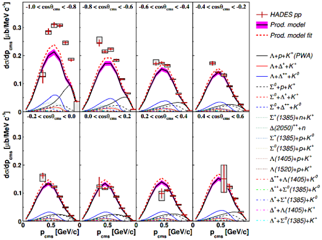
id	pp→ reaction	$\sigma_0^{(\mathrm{id})}$ cross section [μb]	∡ var.	∡(a_2, a_4)		H	notes	fit result	
			3-body channels						
1	$\Lambda p K^+$	$35.26 \pm 0.43\ ^{+3.55}_{-2.83}$	$\theta^{\mathrm{cms}}_{\Lambda}$	0.798	0.134	✓	[16]	38.835 ± 0.026	$\top$
2	$\Sigma^0 p K^+$	$16.5 \pm 20\,\%$	$\theta^{\mathrm{cms}}_{\Sigma^0}$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

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

Hyperons and strange baryonic resonances

Inclusive Λ production in p+p@3.5 GeV (2007)

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	$\Sigma(1385)^+ n K^+$	$22.42 \pm 0.99 \pm 1.57\, ^{+3.04}_{-2.23}$	$\theta^{cms}_{\Sigma^{+*}}$	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	$\Delta^{+} \Lambda(1405) K^+$	$3.0 \pm 20\,\%$					ol. to above	4.2 ± 1.9	⊤
17	$\Delta^{+} \Sigma(1385)^0 K^+$	$2.3 \pm 20\,\%$					ol. 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	⊤



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

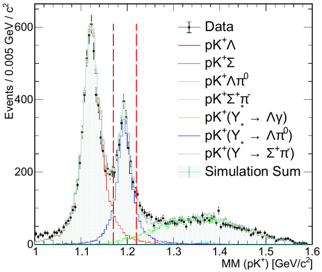
New results from 3.5 GeV

- though 14 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):

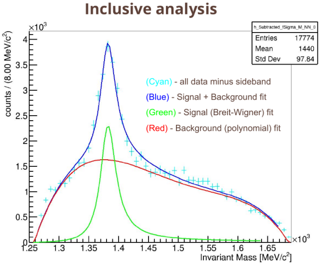
→ Neural networks (K. Sumara, W. Esmail, K. Nowakowski)

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

Σ^0 exclusive (!) (W. Esmail)



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



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

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

Yield = 15010 ± 540 counts

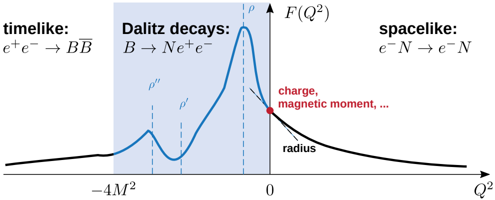
- data from p+p@3.5 GeV are most important sources for projections for p+p@4.5 GeV

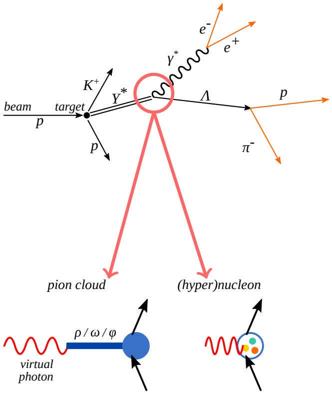
Hyperon electromagnetic decays Y→Λγ* and Y→Λγ

Electromagnetic transitions form-factors (eTFF)

- Sensitive probe of hyperon internal structure
- Measurements of eTFF

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



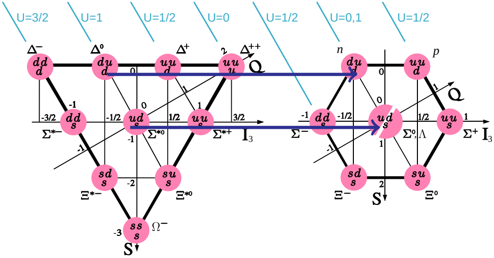


→ Space-like region $|Q^2| > 0$ is inaccessible for excited hyperons (as target or beam)

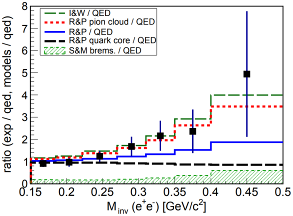
→ Time-like high $|Q^2|$ is probed by electron-positron anihillation (BaBar, CLEO-C, BESIII)

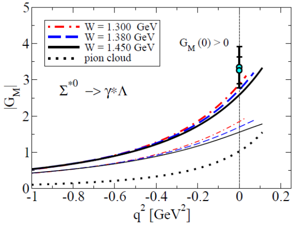
Hyperon electromagnetic decays $Y \rightarrow \Lambda\gamma^*$ and $Y \rightarrow \Lambda\gamma$

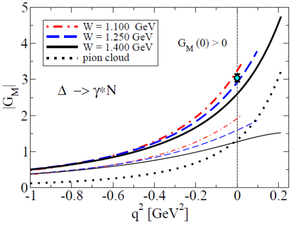
Comparison of strange and non-strange baryons: i.e. $\Delta(1232) \rightarrow N e^+ e^-$ (measured by HADES) with $\Sigma(1385)^0 \rightarrow \Lambda e^+ e^-$- (flavor sym. partner of Δ in SU(3))



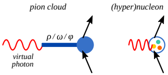
Phys.Rev. C95 (2017) no.6, 065205







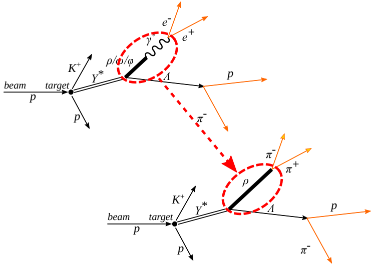
G. Ramahlo
arXiv: 2002.07280v1



Important role of pion cloud at small q^2

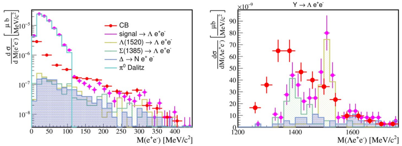
Hyperon electromagnetic/hadronic decays

- Tests VDM hypothesis (coupling to $\varrho/\omega/\pi$) 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 %)

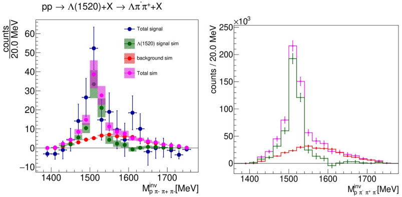
Radiative decay $Y \to \Lambda e^+ e^-$



Expected: ~300 events/Y

Projections for HADES with p+p@4.5 GeV

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

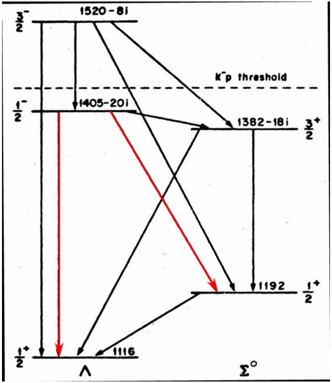


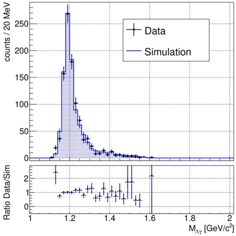
Reference HADES results with p+p@3.5 GeV (t.b.pub.)

Projections for HADES with p+p@4.5 GeV

~500k events

Hyperon electromagnetic decays



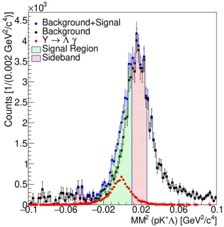


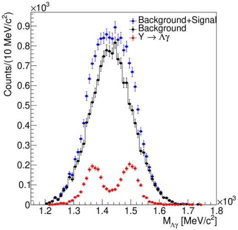
Reconstruction of Σ^0 as reference for Λ production and feed-down $Y\to\Lambda e^+e^-$

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

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

Radiative decay $Y\to\Lambda\gamma$



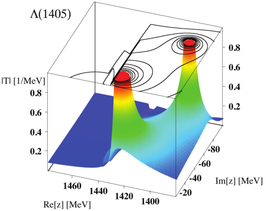


Expected: 1500 events

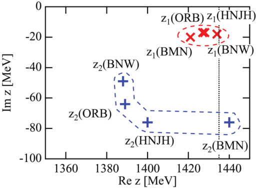
Projections for HADES with p+p@4.5 GeV

~500k events/Y

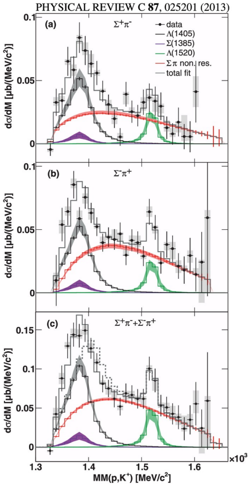
Hyperon hadronic decays - $\Lambda(1405)$



Prog.Part.Nucl.Phys., 67:55–98, 2012.



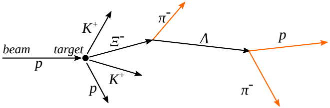
Phys.Rev., C77:035204, 2008.



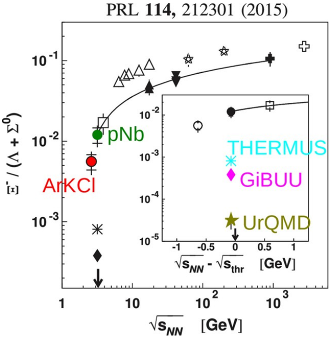
Reference HADES results with p+p@3.5 GeV

- $\Sigma\pi$ 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 $\Sigma(1385)^0$
- Previous pp data suffered from low statistics, HADES can improve statistical precision by two orders of magnitude

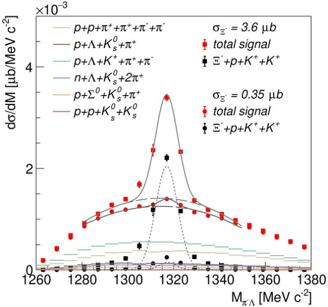
Double strangeness reactions – Ξ⁻ production



- Motivated by "HADES"-puzzle of Ξ⁻ enhancement in pNb and ArKCl
- Production through intermediate high mass (>2 GeV c^{-2}) baryonic or hyperon resonance ?? → pp data needed

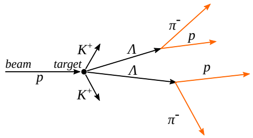


Reference HADES results with
p+Nb@3.5 GeV and Ar+KCl@1.76 GeV

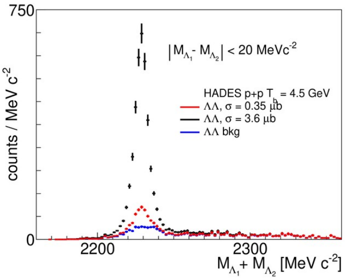


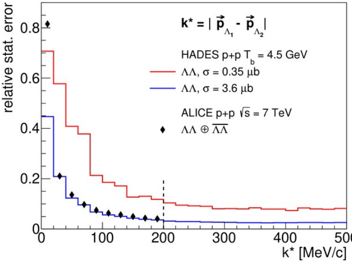
Projections for HADES with p+p@4.5 GeV

Double strangeness reactions – ΛΛ production



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

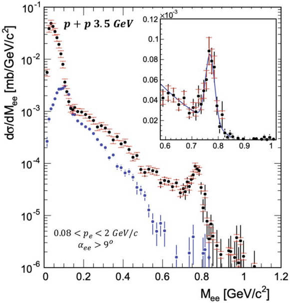




Projections for HADES with p+p@4.5 GeV

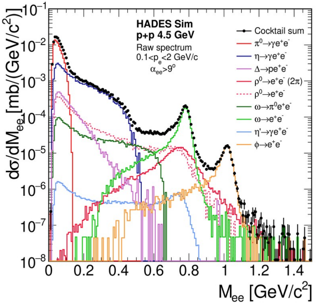
Dilepton spectra

- Model-independent reference spectra for studies of cold nuclear matter (p+A collisions) and hot and dense matter (A+A collisions) at higher (SIS100) energies: modification of ϱ spectral function, φ and ω production
- First measurements in Intermediate Mass Range: coupling of high mass resonances to Nγ* or multi πs contributions?
- Important reference for studies of ϱ-a1 mixing in dense hadronic medium (SIS100)



Reference HADES results with p+p@3.5 GeV

- 260 pairs in ω region
- no clear φ



Projections for HADES with p+p@4.5 GeV

- 5.8×10^4 pairs in ω region
- 1.9×10^3 pairs in φ region
- ∼70 counts in IMR

Expected count rates

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

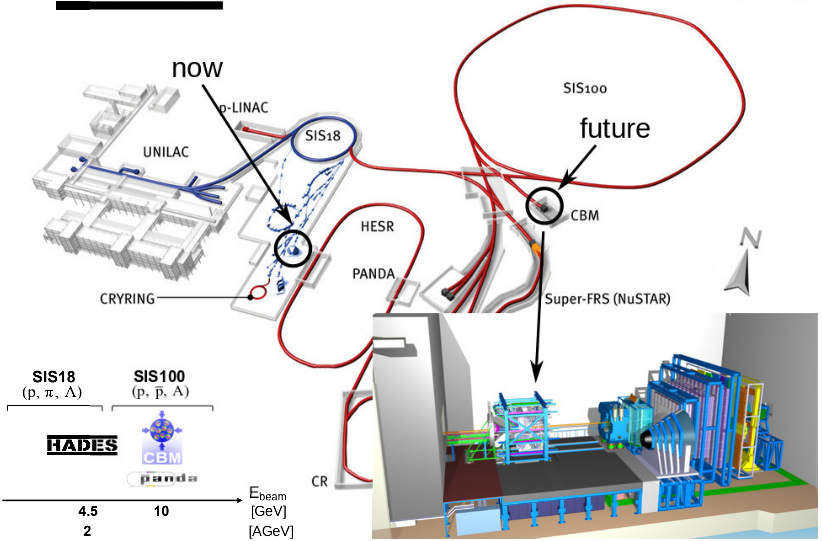
Hyperon hadronic decays		
$\Lambda(1405) \to \Sigma^0 \pi^0 \to \Lambda\ 3\gamma$	$\Lambda(1405) \to \Sigma^{\pm} \pi^{\mp}$	$\Lambda(1520) \to \Lambda \pi^- \pi^+$
3.6×10^4	7.2×10^4	5.2×10^5

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

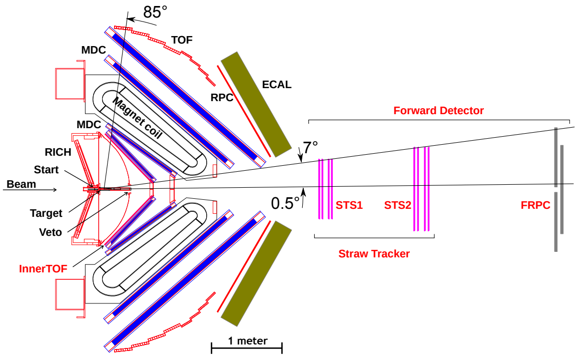
HADES at FAIR

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



HADES detector upgrades

High Acceptance Dielectron Spectrometer



Major HADES upgrades:

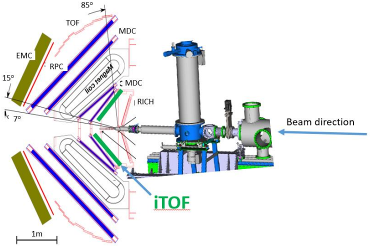
- RPC (2010)
- Pion Tracker (2014)
- ECAL (2017-2021)
- RICH (2018)
- Forward Detector (2021)
- iTOF (2021)
- START

- 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

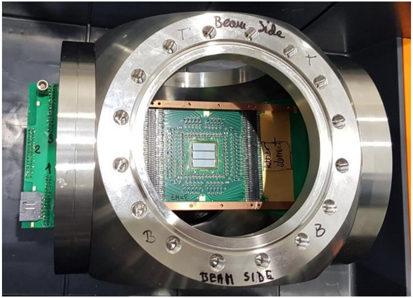
With the recent upgrades HADES is ready for new challenges

FEB21 - test beam time

- particle rates – 1×10^8 p/s
- beam energy – 3.5 GeV to 4.2 GeV
- test of various new elements in HADES:
  - T0 (START)
  - InnerTOF
  - STS
  - FRPC
  - New TRB3 readout for other systems
  - new trigger system (TriggerBox)



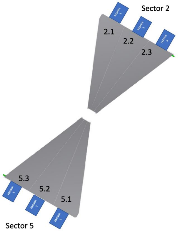
Low Gain Avalanche Detectors for the HADES reaction time (T) detector upgrade (Eur. Phys. J. A (2020) 56: 183)

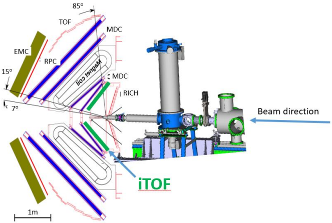


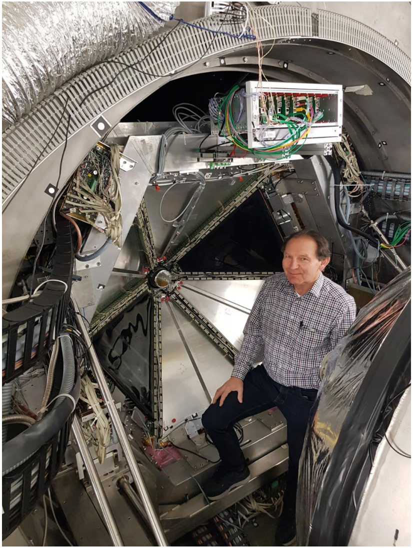
- timing < 100 ps
- PCB in the beam vacuum
- rate capability 10^8 p/s
- 2 cm x 2 cm, 96 channels
- pitch 387 µm

Inner TOF

- new trigger detector
- main goal – suppres empty events in HADES
- can also serve as a secondary T0

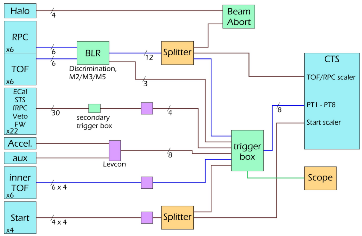


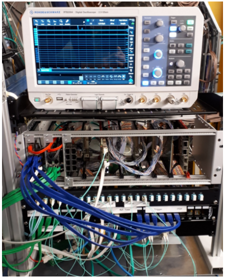




TriggerBox

- many new detectors, but central trigger not possible toextend
- new trigger unit: TriggerBox, old CTS just drives the detectors

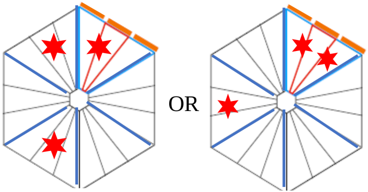


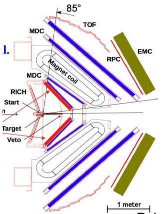


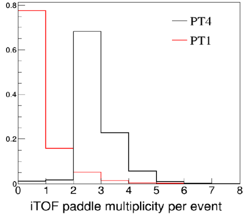
Trigger conditions for Feb21 beam

PT1: HADES META MULT >= 2

PT4: HADES META MULT && ITOF





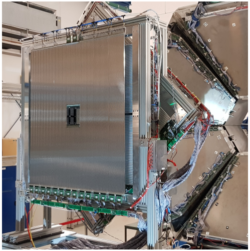


Forward Detector

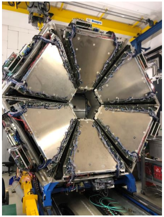
STS1

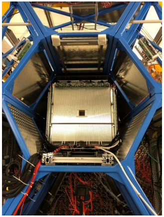
- FZ Juelich/IPN Orsay
- 704 straws
- PANDA-STS straws

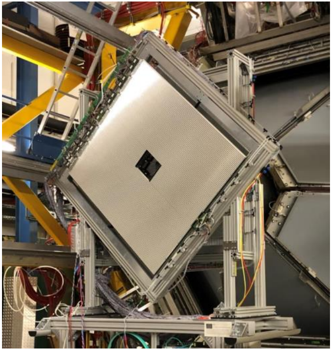
STS2

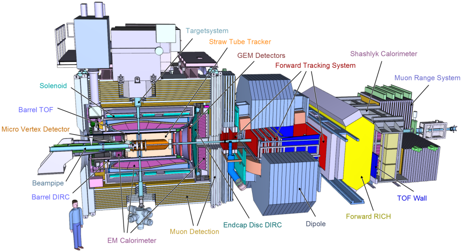


- UJ Kraków
- 1024 straws
- PANDA-FT straws





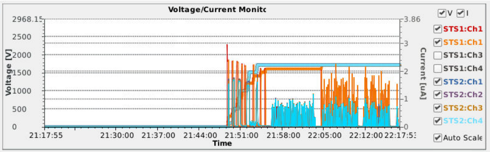




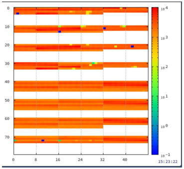
Also:

- INP FAS – gas system

Straw tracker

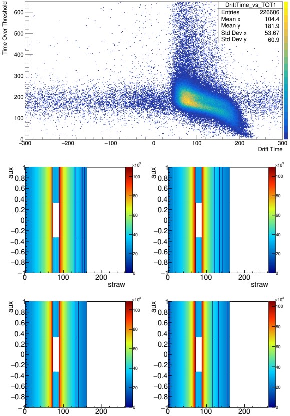


First beam spils in STS at HADES.

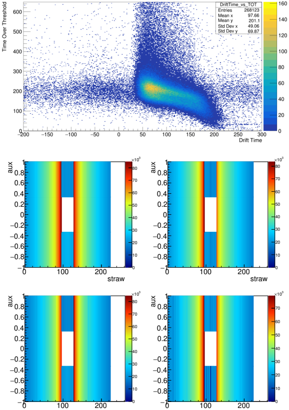


STS scaler – very uniform

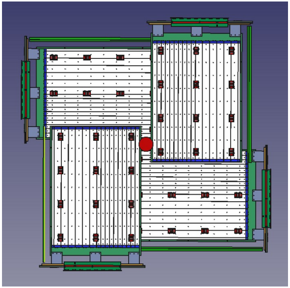
STS1

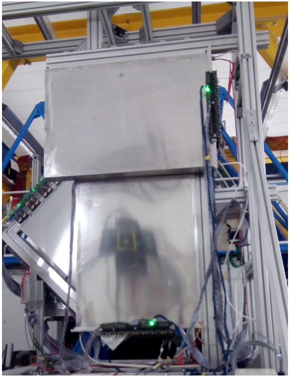


STS2



Forward RPC

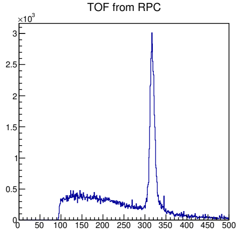


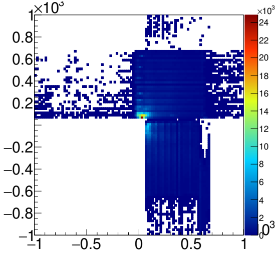


(Alberto Blanco, LIP Coimbra, Portugal)

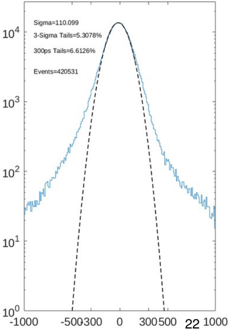
- NEULAND technology
- 4×32 readout strips
- 2 sectors installed
- efficiency: 85 %–90 %
- timing: 100 ps–120 ps

FRPC TOF

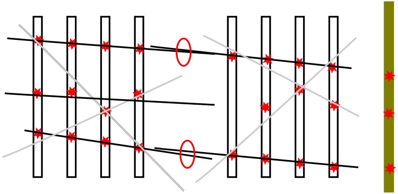


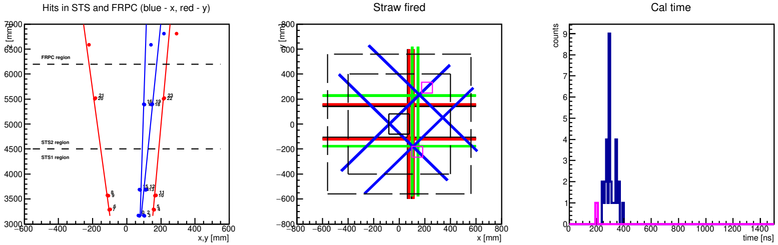


Time resolution



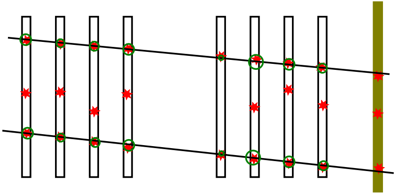
Tracking in Forward Detector

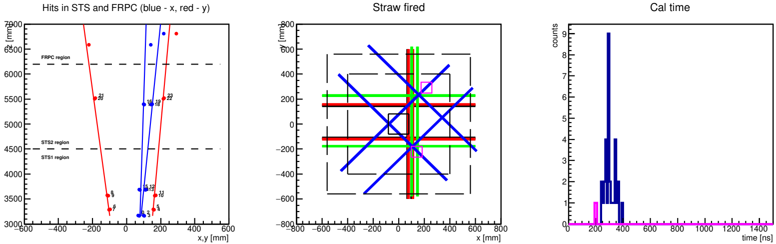




- LSM method (adaptation of CBM-MUCH tracking)
- LSM + COSY-TOF-like minimization

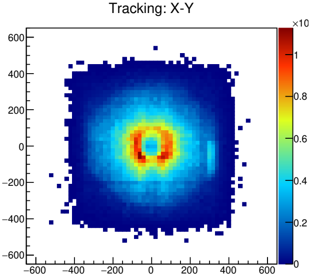
Tracking in Forward Detector

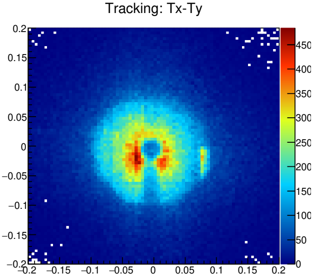


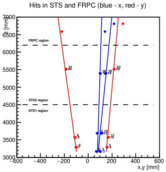


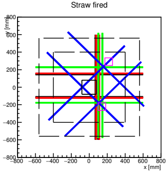
- LSM method (adaptation of CBM-MUCH tracking)
- LSM + COSY-TOF-like minimization

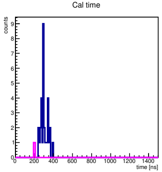
Tracking results











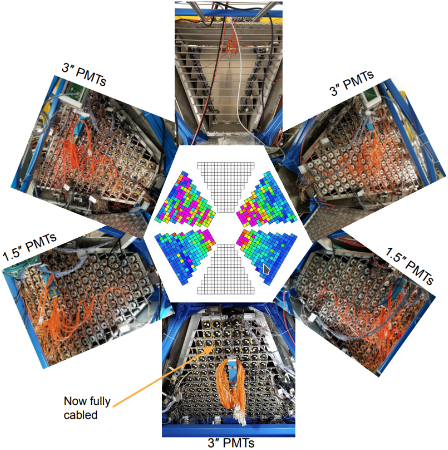
ECAL upgrade

ECAL detector status

- Sector no. 2,4,6 are newly installed and cabled, FEE and LASER is connected

  → **Now we have 5 ECAL sectors**

- Next steps: DAQ tests with LASER and cosmic muons runs in order to check FEE, look-up-tables, ...



- 2021/2022: Installation of the 6th sector (PMTs are ordered and in production)
- 2022: Production beamtimes
- 202?: Upgrade of sectors no. 3 & 5: 1.5" → 3" PMT

Summary and Outlook

- HADES has exciting physics program for p+p reactions at 4.5 GeV
- constantly undergo detector and infrastructure upgrades
- the Feb ’21 teast beam was succesfull - several new detector systems were tested
- the p+p production beam is scheduled for Feb ’22 (4 weeks)
- development of new analysis methods: NN, Kinematic Refit