Stockholms universitet

Investigating the Λ-Λ system: Insights into hyperonic interactions and neutron star cores

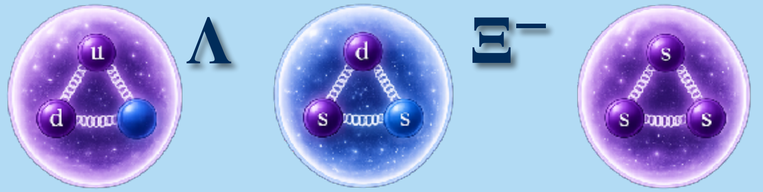
From HADES pp data to CBM at FAIR and neutron stars

Annual Swedish Nuclear Physicists and SFAIR Meeting 2026, Stockholm
October 28, 2026

G. Appagere
for PANDA@HADES and CBM collaborations

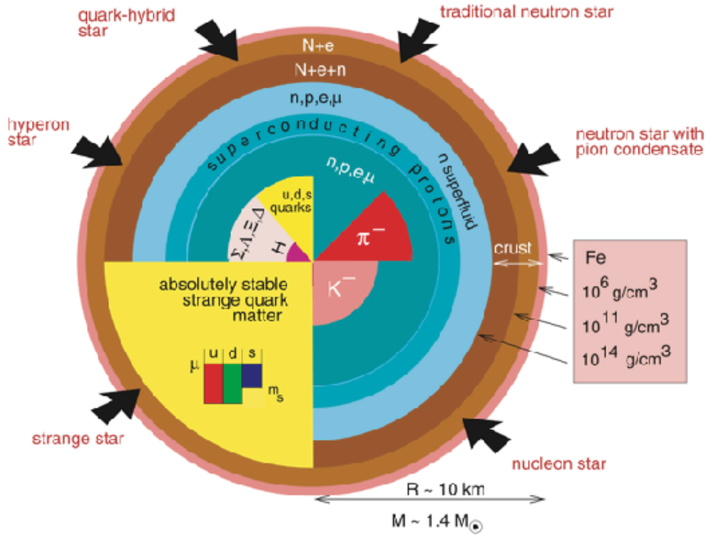
Neutron Stars and Λ-Λ Studies

Hyperons are Baryons with at least one strange quark in their composition

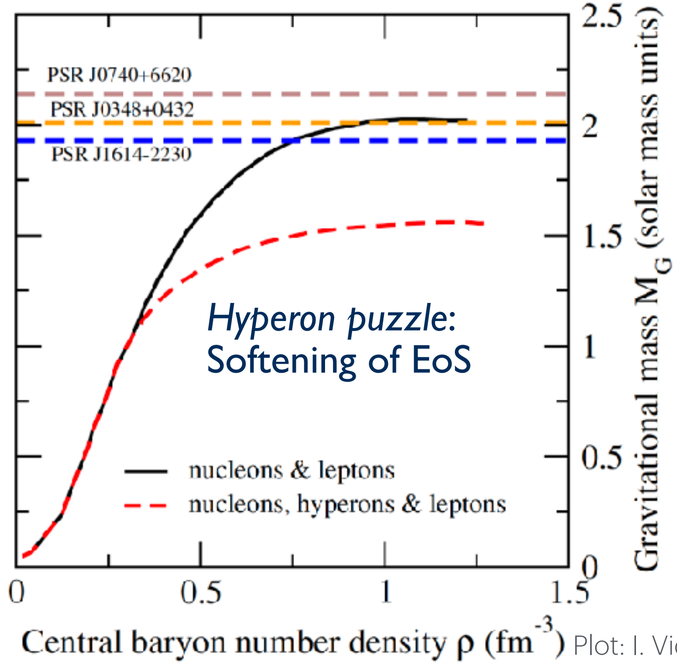


Conditions (energy, pressure, temperature) inside *neutron stars* are favourable for *strangeness* production: *Hyperonization*

[1]



[2]

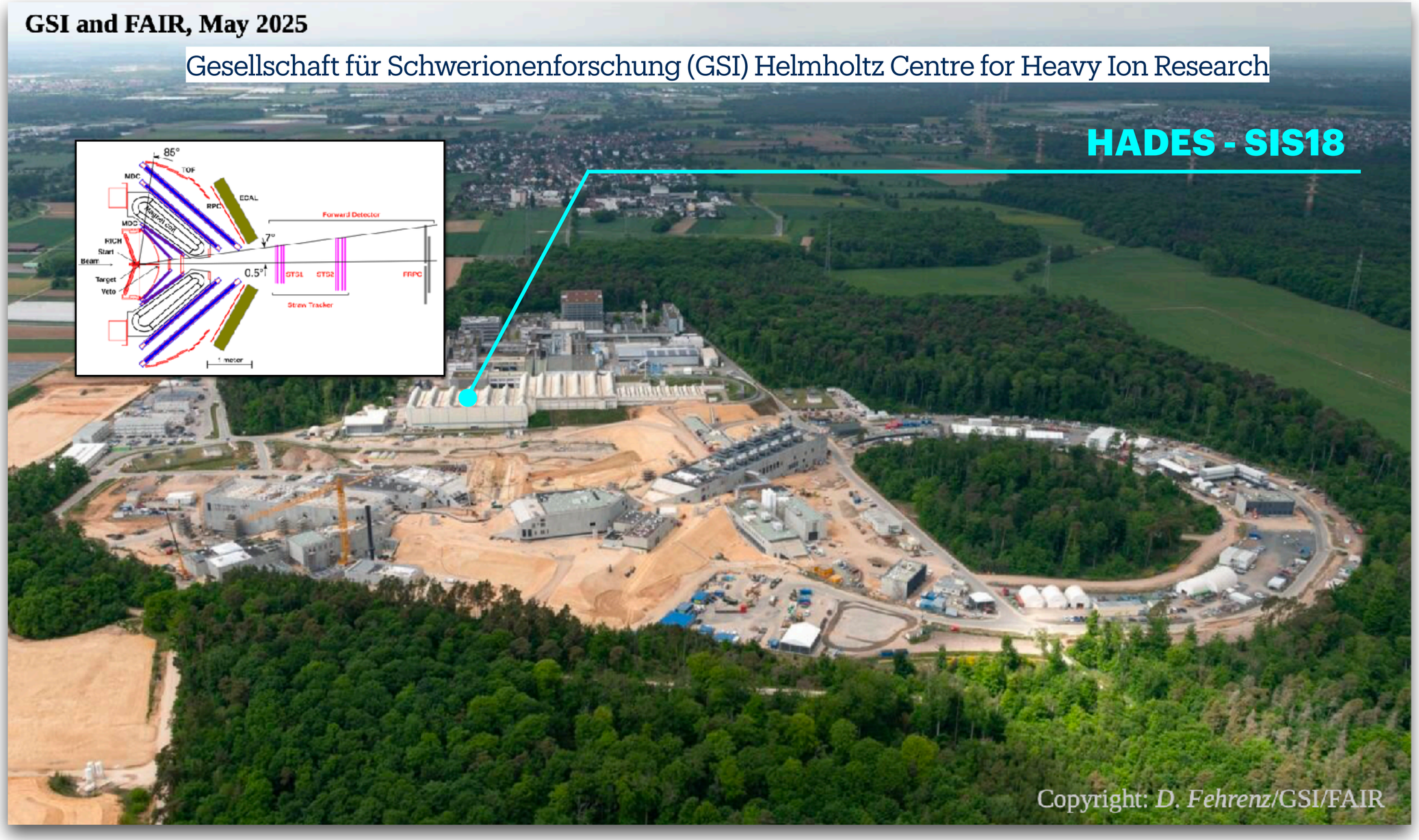


Plot: I. Vidana, Generic model with and without hyperons

Λ-Λ interaction studies at low relative momentum may help solve the Hyperon puzzle

[1] F. Weber *et al.*, arXiv:0705.2708 [astro-ph] (2007) [2] J. G. Messchendorp, F. Nerling (eds.) *et al.*, arXiv:2512.15986 [hep-ex] (2026)

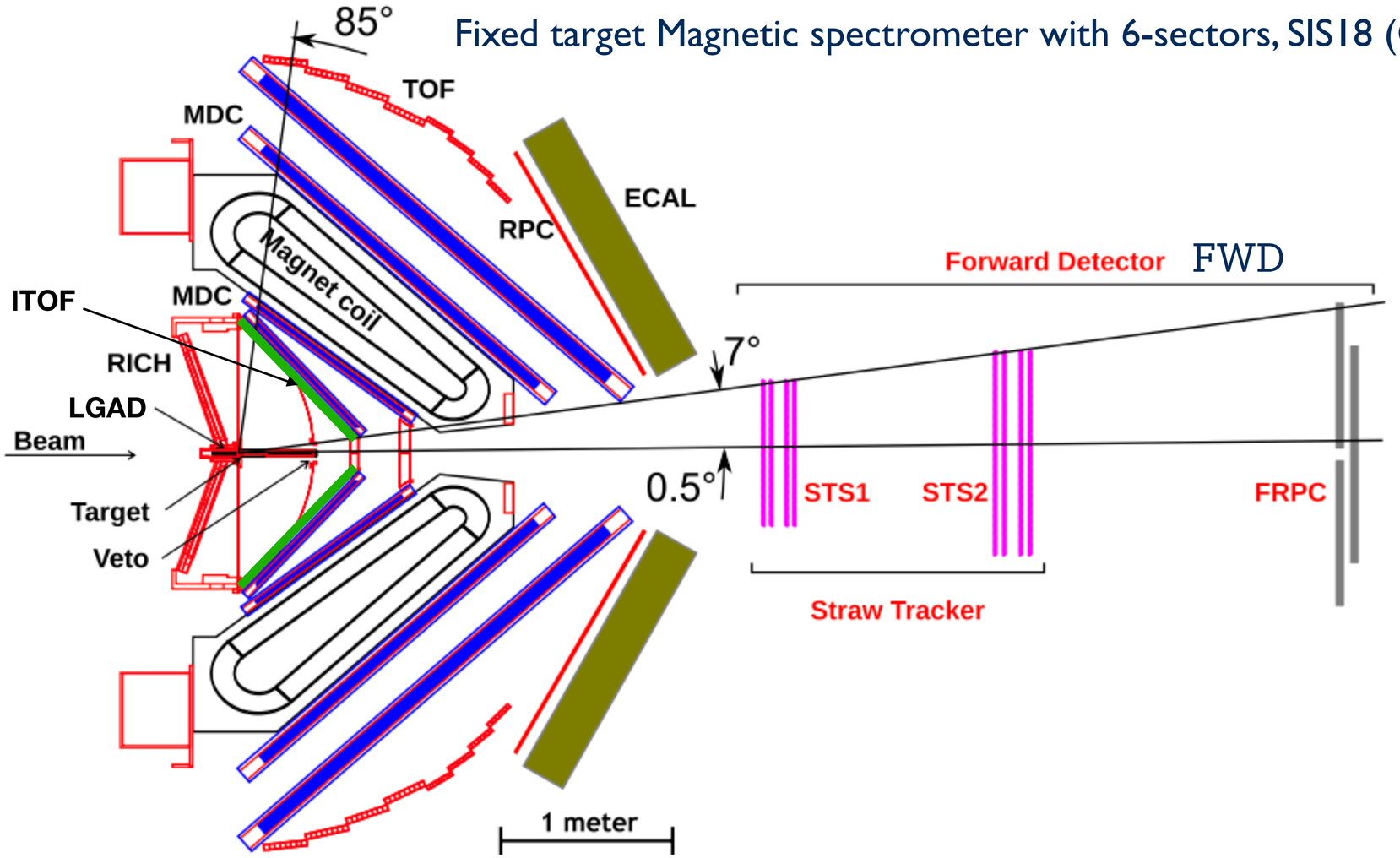
GSI and FAIR


GSI and FAIR, May 2025
Gesellschaft für Schwerionenforschung (GSI) Helmholtz Centre for Heavy Ion Research
HADES - SIS18
85°
TOF
MDC
RPC
ECAL
Forward Detector
MDC
RICH
Start
Beam
Target
Veto
7°
0.5°
GT31
GT32
FRPC
Straw Tracker
1 meter
Copyright: D. Fehrenz/GSI/FAIR

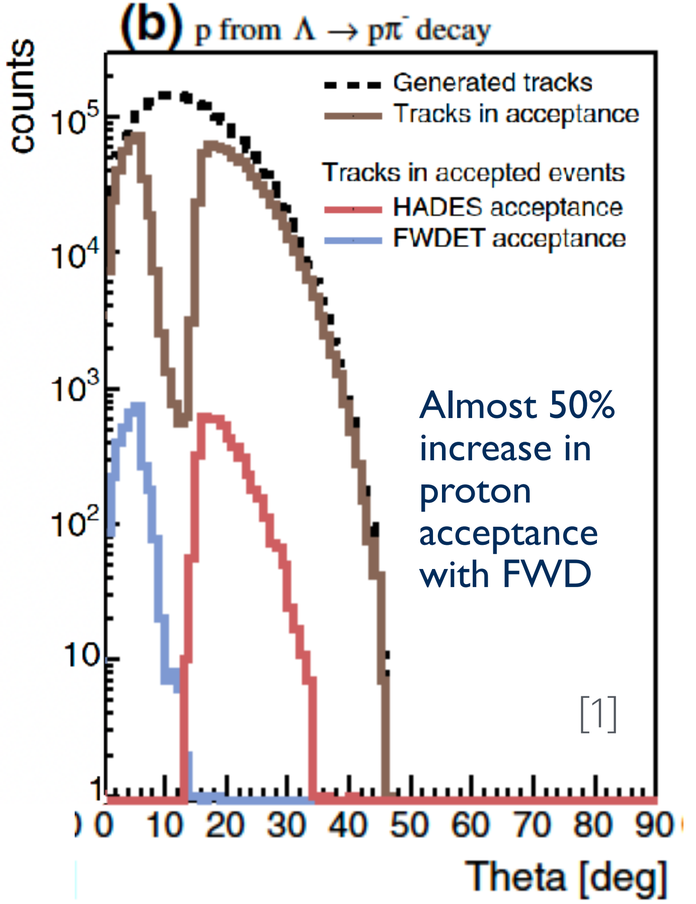
HADES (+ PANDA) detector

High **A**cceptance **D**i-**E**lectron **S**pectrometer

Fixed target Magnetic spectrometer with 6-sectors, SIS18 (GSI, Germany)

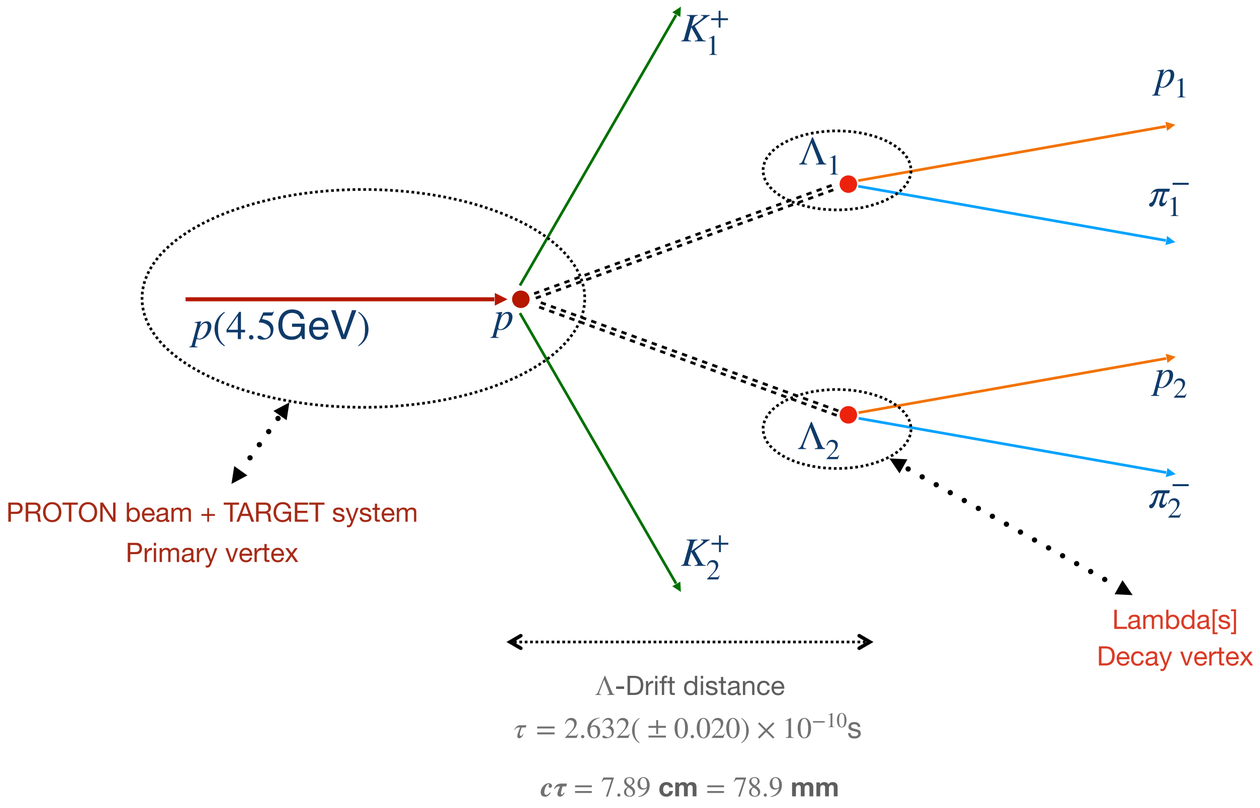


Cross-sectional sketch of the HADES spectrometer



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

The Λ-Λ reaction at HADES



If both the Λ pair is produced, and both decays are reconstructed.

cτ = 7.89 cm. The two decay vertices displaced from the production point and separate and from each other.

T = 4.5 GeV, √s = 3.46 GeV, only 0.24 GeV above threshold, so the Λ protons go forward.

Event selection conditions

Inclusive : $p(4.5)p \mapsto p\pi^-p\pi^- + X$

Semi-exclusive : $p(4.5)p \mapsto p\pi^-p\pi^- + K^+ + X$

Exclusive : $p(4.5)p \mapsto p\pi^-p\pi^- + K^+K^+$

This final state is what turns the hyperon puzzle into a measurement.

Analysis in a nutshell

28 days, ≈ 155 TB

L = 5.66 ± 0.26 pb^{-1}

S0 Particle Identification (PID) (MIN 4 Tracks)

- p, π^-, K^+, π^+ using relative-ToF method

S1 First-selection of the data

- Missing Mass selection with $pp \mapsto p\pi^-p\pi^- + X$: $M_X > 0$ MeV/c²
- To suppress Kapton Window tracks

S2 Lambda reconstruction and selection

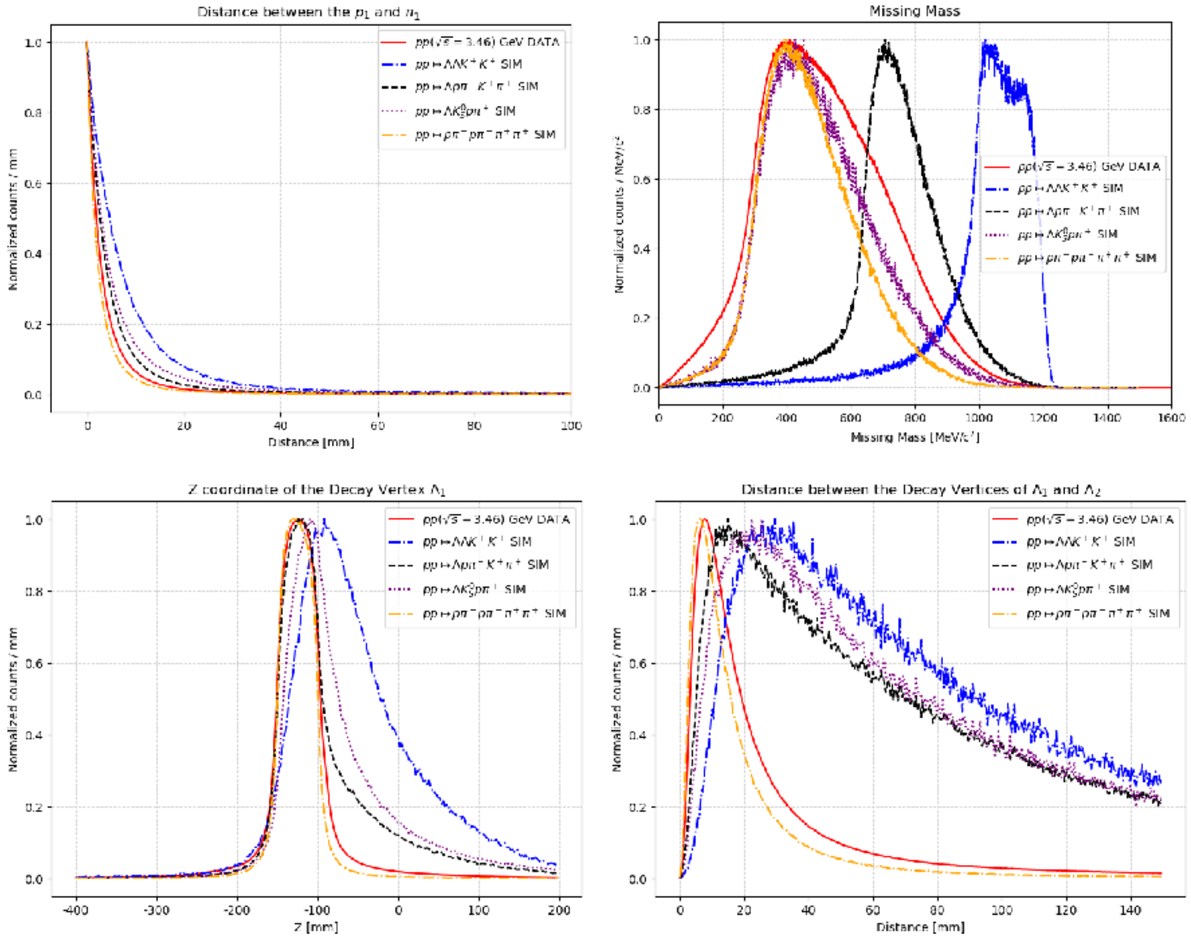
- $\Lambda\Lambda$ candidate selection with Physics cut-based
- Randomisation of Lambda candidate assignment as Λ_1 or Λ_2

S3 Optimising the cuts to suppress background

Optimal selection

MMX > 976 MeV/c², DCA < 40 mm, z(DV) > −100 mm, DDV > 10 mm

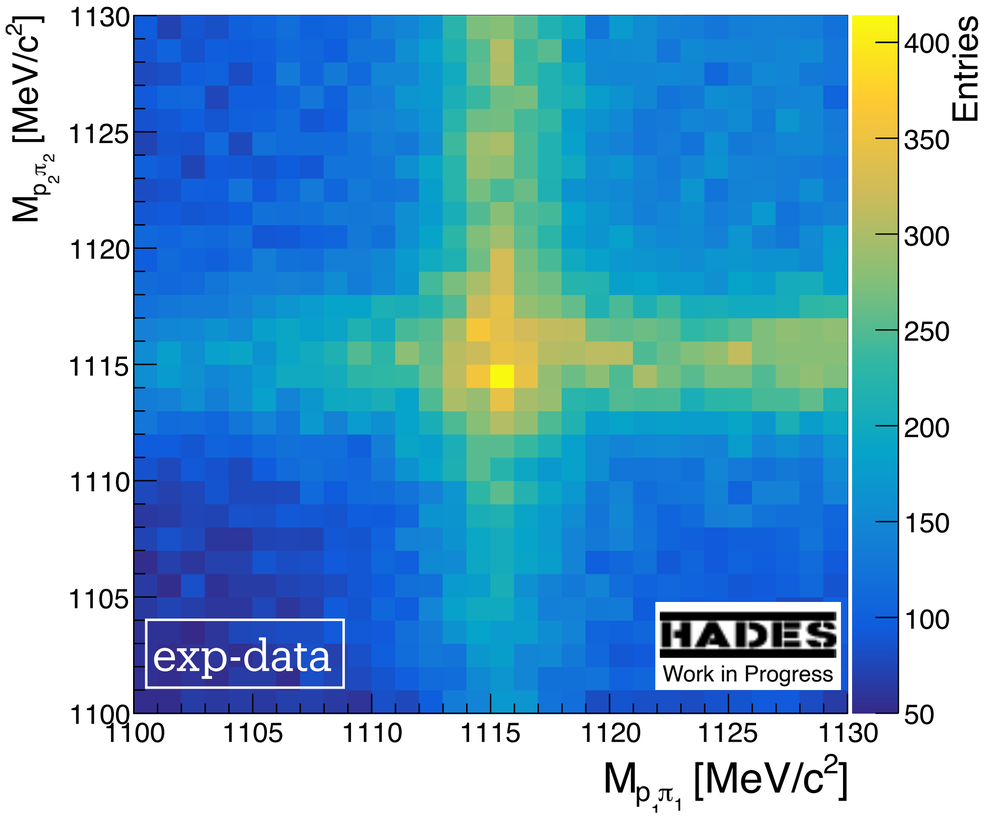
π^+ veto keeps 97 % of the signal



Signal $pp \mapsto \Lambda\Lambda K^+K^+$ (**blue, SIM**) against single-Λ and non-resonant backgrounds and data (**red**)

OLBG: $pp \mapsto \Lambda p\pi^-K^+\pi^+$ KSBG: $pp \mapsto \Lambda K^0_S p\pi^+$ NRBG: $pp \mapsto p\pi^-p\pi^-\pi^+\pi^+$

Λ-Λ signal at the optimal selection



Data: $M(p_1\pi_1^-)$ vs. $M(p_2\pi_2^-)$ after all selections

Optimal selection

MMX > 976 MeV/c², DCA < 40 mm,
z(DV) > −100 mm, DDV > 10 mm

Nominal method: SIM-based ML (binned)

– Binned Poisson likelihood of the 2D (m_1, m_2) histogram

– Λ-Λ and single-Λ shapes from symmetrised simulation; free polynomial non-resonant background

$$\mu(m_1, m_2) = N_{\Lambda\Lambda}\, f_{\Lambda\Lambda} + B\, f_{S\Lambda} + \sum_{k=0}^{3} C_k\, p_k(m_1, m_2)$$

Parameter	Fit value	Component
$N_{\Lambda\Lambda}$	60.4 ± 65.0	ΛΛ signal (simulation)
B	1403 ± 113	single-Λ: OLBG + KSBG (simulation)
C_0	1564 ± 159	non-resonant background:
C_1	75.0 ± 35.1	polynomials $p_k(m_1, m_2)$
C_2	-372 ± 88	
C_3	55.1 ± 25.5	
NLN = 1008.1 for NDF = 894		

⇒ N(ΛΛ) = 60 ± 65: negligible, near-zero

Λ-Λ cross section: HADES result

– No significant Λ-Λ signal ⇒ 95 % CL upper limit

– Six fit models span σ^{95} = 8.7–24.6 nb: the leading systematic

$$\sigma_{\Lambda\Lambda} = \frac{N_{\Lambda\Lambda}}{\mathcal{L}\,\epsilon_{AR}} = \frac{60.4 \pm 65.0}{5.66\,\mathrm{pb}^{-1} \times 0.120\,\%} = (8.9 \pm 9.6)\,\mathrm{nb}$$

$$\sigma^{95}_{\Lambda\Lambda} = \max(\sigma_{\Lambda\Lambda}, 0) + 1.645\,\sigma_{\mathrm{stat}} = 24.6\,\mathrm{nb}$$

Nominal 95 % CL (SIM-based ML, binned)
$\sigma^{95}_{\mathrm{nom}} = 24.6\,\mathbf{nb}$

Systematic uncertainty ($\delta\sigma^{95}$)			
Fit methods	PID	Cut var.	Luminosity
13.7 nb	6.7 nb	6.7 nb	1.1 nb

Quoted upper limit at 95 % CL (preliminary)
$\sigma^{95}_{\Lambda\Lambda} = (24.6 \pm 13.7_{fit} \pm 6.7_{PID} \pm 6.7_{cuts} \pm 1.1_{\mathcal{L}})\,\mathbf{nb}$
Combined (quadrature): $\boldsymbol{\sigma^{95}_{\Lambda\Lambda} = (24.6 \pm 16.7)\,nb}$

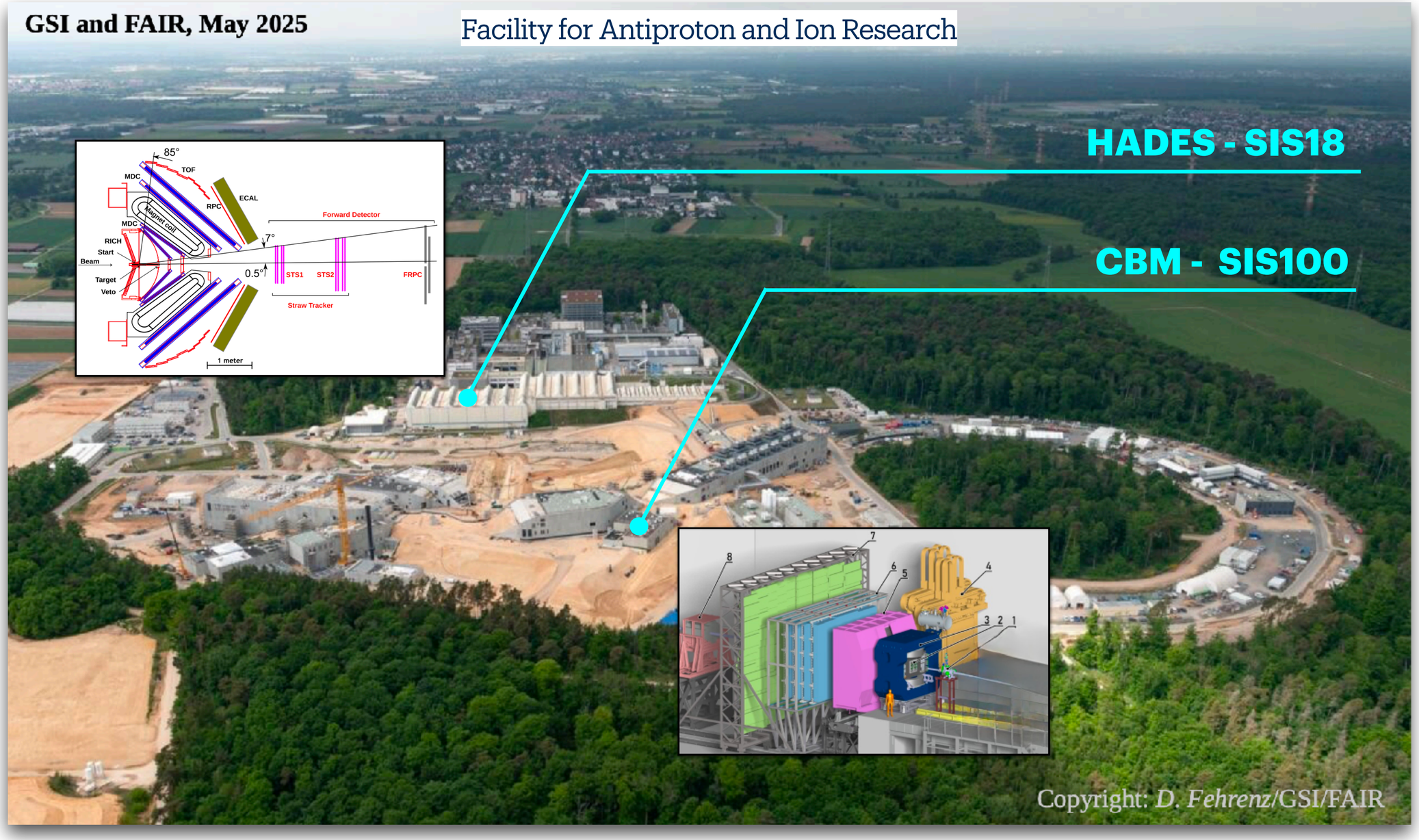
Where do the Λ decay protons go?

Class	Candidates	ϵ_{AR} [%]	$N_{\Lambda\Lambda}$	σ^{95} [nb]
HH	42	0.0009	31.8 ± 46.0	< 2210
HF	978	0.037	-5.6 ± 32.1	< 25.4
FF	1628	0.083	97.6 ± 45.3	< 36.8
All (nominal)	2648	0.120	60.4 ± 65.0	24.6

H: proton in HADES (18°–85°), F: proton in the FWD (0.5°–7°)

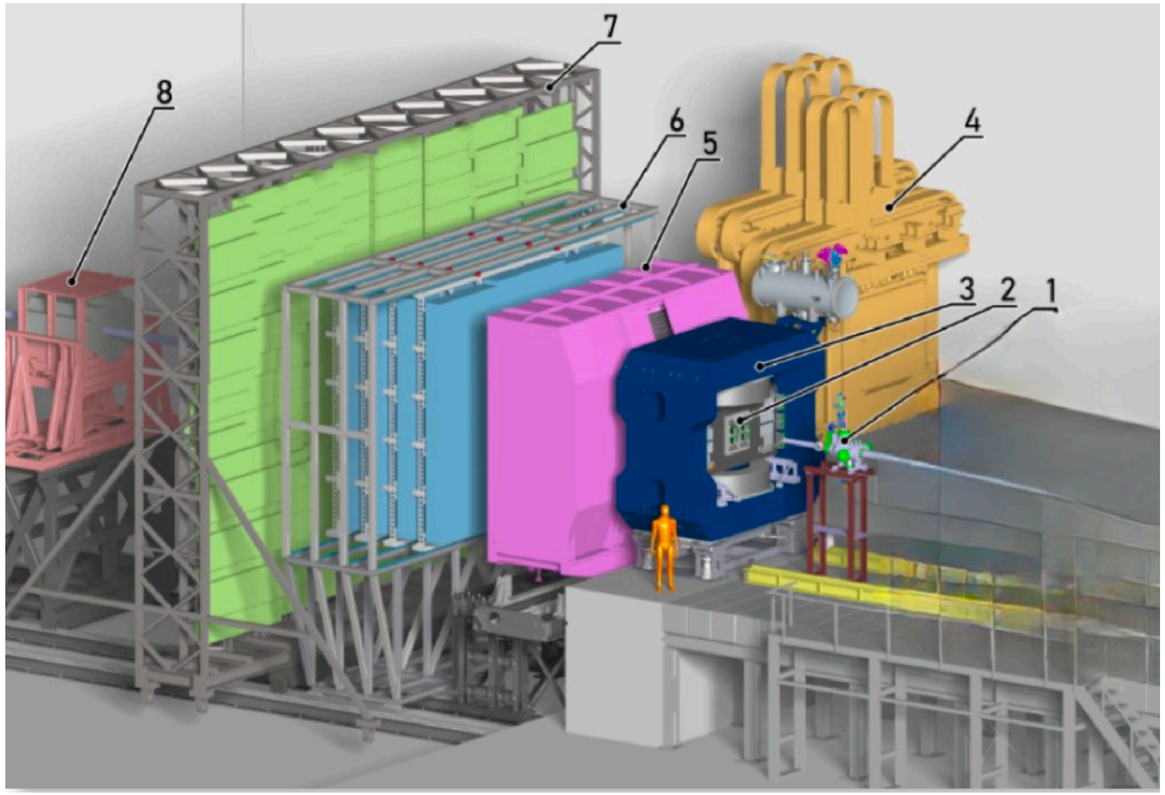
– HH has ε ≈ 10^{-5}: near threshold the Λ protons are boosted forward, 99 % of the efficiency relies on the FWD

FAIR: Looking Forward



Next step: CBM at FAIR (SIS100)

Compressed **B**aryonic **M**atter Experiment

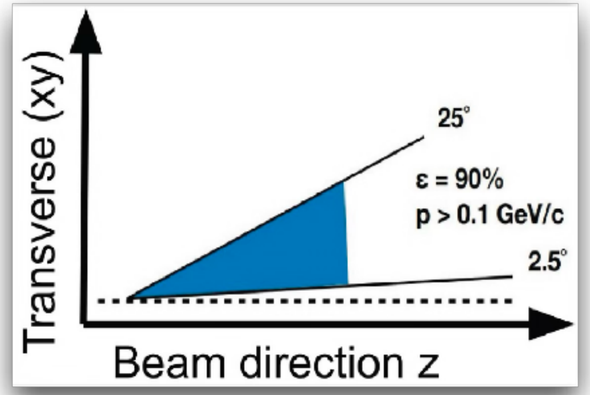


1. T0 detector
2. Superconducting dipole magnet
3. Silicon Tracking System / MVD
4. Muon chamber
5. RICH
6. Transition Radiation Detector
7. ToF detector
8. Forward Spectator Detector

– Fixed-target magnetic spectrometer for SIS100 energies (FAIR, Germany)

– Interaction rates 1–10 MHz with free-streaming readout

– Proton beams T ≈ 5–29 GeV; CH_2 or LH_2 target



Λ-Λ at CBM (simulation)

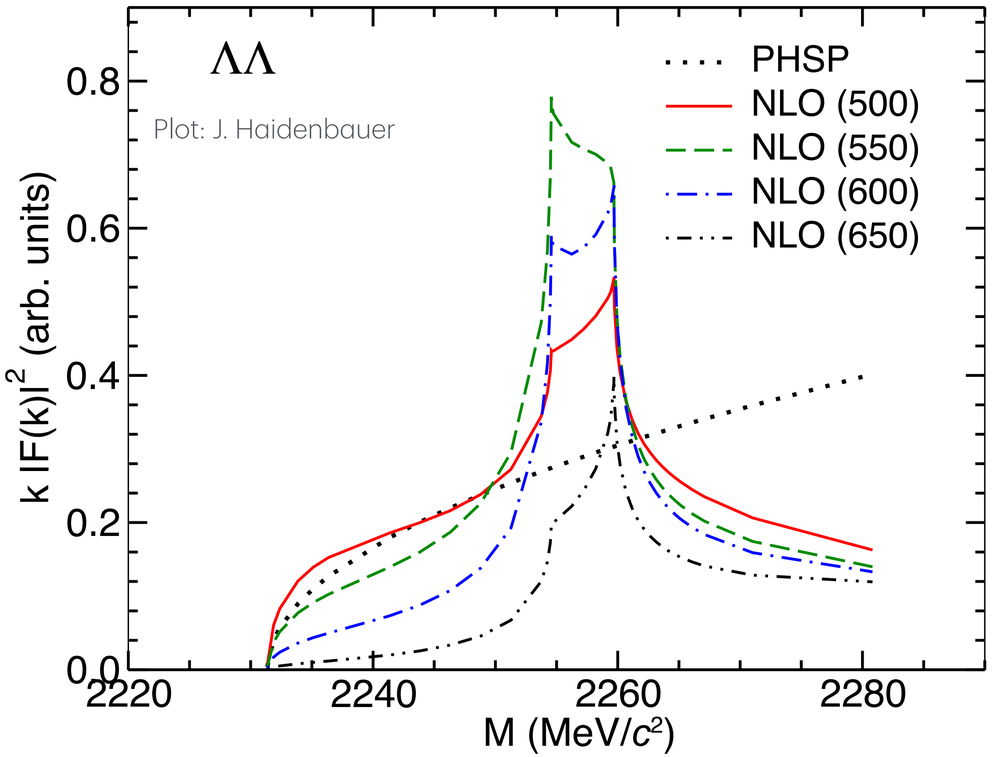
– Exclusive $pp \mapsto \Lambda\Lambda K^+K^+$ at T = 5 GeV: √s = 3.59 GeV, **0.37 GeV** above threshold

– Forward acceptance (2.5°–25°) catches the boosted Λ decay protons

– ≈ 20 % efficiency (HADES: 0.12 %) and σ(M) ≈ 6 MeV with a kinematic fit (Λ mass + 4C)

Picture: CBM Collaboration (GSI/FAIR). Response: W. Esmail et al., Comput. Softw. Big Sci. 8 (2024)

What the ΛΛ mass spectrum tells us



χEFT up to NLO for four cutoffs (500–650 MeV) vs. phase space (dotted) [arXiv:2512.15986]

$$p\cot\delta = -\frac{1}{a_{\Lambda\Lambda}} + \frac{r_e}{2}p^2 \qquad (a_{\Lambda\Lambda} < 0: \text{ attractive})$$

– No ΛΛ scattering experiment is possible: the final-state interaction in $pp \mapsto \Lambda\Lambda K^+K^+$ imprints the force on M(ΛΛ) near threshold

– The threshold rise fixes the scattering length a(ΛΛ) through a dispersion relation: no source function needed

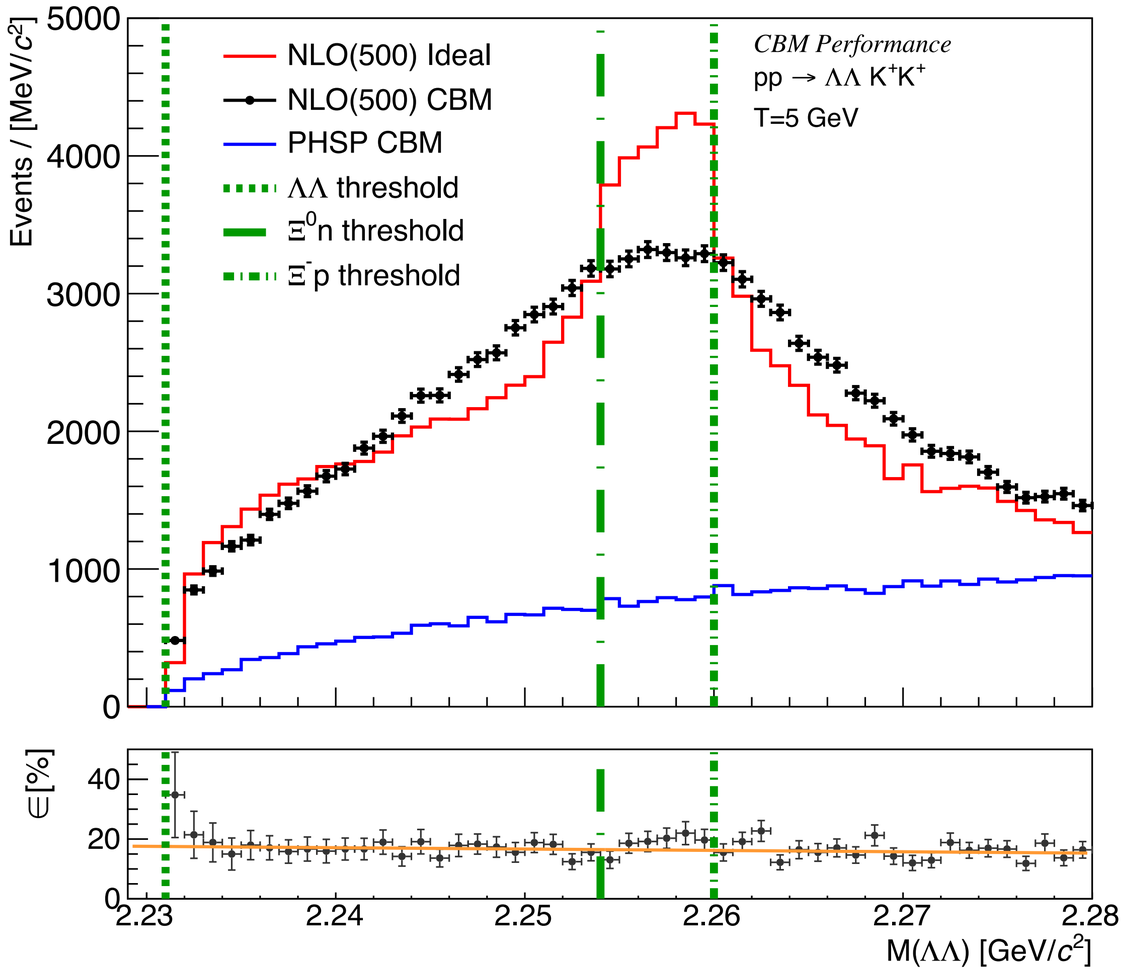
– The ΞN thresholds (2.254 / 2.260 GeV) add a structure sensitive to the ΛΛ–ΞN coupling

What we know today

Source	$a_{\Lambda\Lambda}$ [fm]
KEK-E522 (Gasparyan *et al.*)	-1.2 ± 0.6
χEFT NLO(550)	-0.61
χEFT LO(550)	-1.52
Femtoscopy (ALICE)	shallow attraction

A. Gasparyan et al., PRC 85 (2012) 015204; J. Haidenbauer et al., NPA 954 (2016) 273; ALICE, PLB 797 (2019) 134822

CBM feasibility, anchored by HADES



10 days at 1 MHz, 5 cm LH_2 target, assumed σ = 0.35 μb, NLO(500) amplitude [arXiv:2512.15986]

– ΞN structure survives σ(M) ≈ 6 MeV; the shape is clearly not phase space

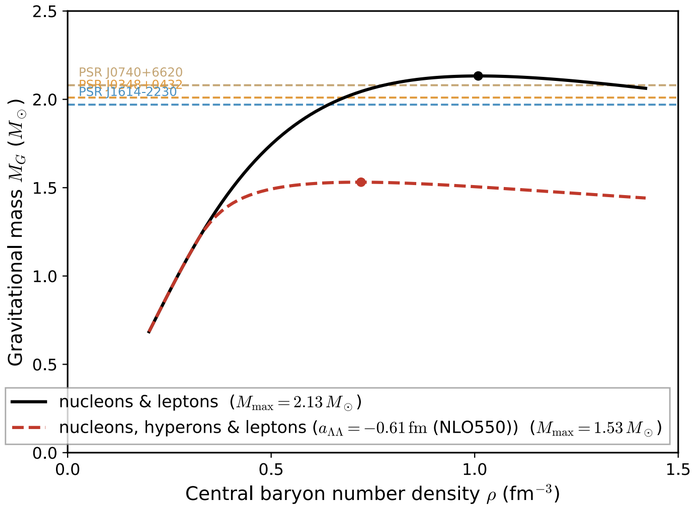
– The projection assumed 0.35 μb. HADES: $\sigma^{95} \leq 24.6$ nb at T = 4.5 GeV, ≈ 14× lower

– At the HADES limit the same spectrum needs ≈ 14 days at 10 MHz (≈ 140 days at 1 MHz); σ is expected to grow from 0.24 to 0.37 GeV excess energy

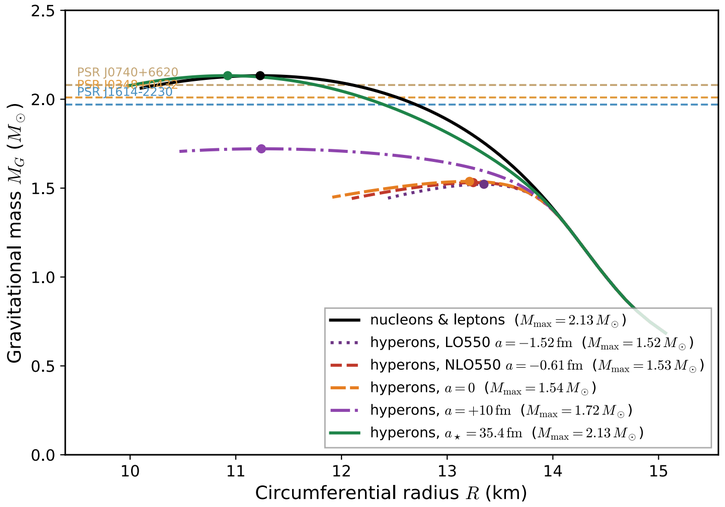
– Toy study (ideal resolution): $\sigma_a \approx 0.04$ fm with 10^6 events; separates NLO (−0.61 fm) from LO (−1.52 fm)

HADES turns the CBM rate from an estimate into a measured bound for beam-time planning

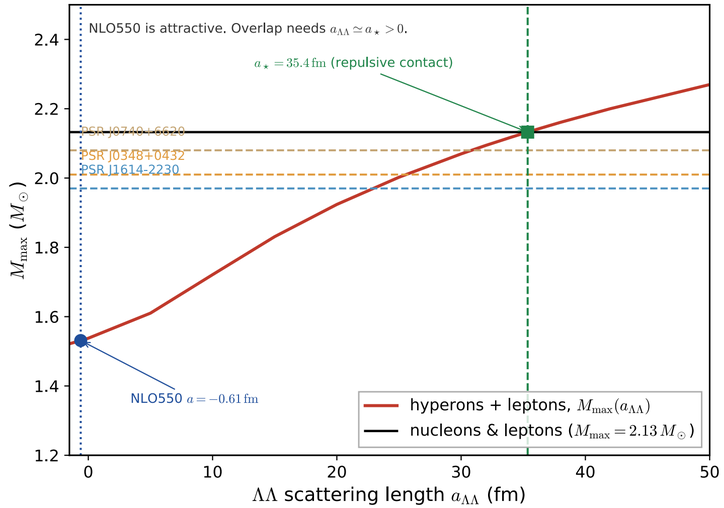
Implications for neutron stars



Mass vs. central density



Mass vs. radius



M_{max} vs. ΛΛ scattering length

– Λ onset at n ≈ 2n$_0$ softens the EoS: M_{max} 2.13 → 1.53 $M_\odot$, below the observed ≈ 2 $M_\odot$ pulsars ⇒ hyperon puzzle

– a(ΛΛ) enters the EoS through the $^1S_0$ contact pressure $P_{\Lambda\Lambda} = \dfrac{\pi\hbar^2}{m_\Lambda}\, a_{\Lambda\Lambda}\, n_\Lambda^2$

– Realistic |a(ΛΛ)| ≈ 1 fm moves M_{max} by only 0.01 M⊙. CBM separates NLO from LO ($\Delta a \approx 0.9$ fm ≫ $\sigma_a \approx 0.04$ fm), but 2 M⊙ also needs YN and YNN repulsion

EoS	$a_{\Lambda\Lambda}$ [fm]	$M_{\max}$ [$M_\odot$]
nucleons only	–	2.13
hyperons, LO550	−1.52	1.52
hyperons, NLO550	−0.61	1.53
hyperons	0	1.54
hyperons	+10	1.72
hyperons, $a_\star$	+35.4	2.13

Schematic piecewise-polytrope EoS + TOV (own calculation); a(ΛΛ): NLO550 −0.61 fm, LO550 −1.52 fm. Pulsars: J0740+6620, J0348+0432, J1614−2230.

Summary and Outlook

HADES

pp → ΛΛK^+K^+, 0.24 GeV above threshold

$\sigma^{95}(\Lambda\Lambda)$ = (24.6 ± 16.7) nb (preliminary)

CBM at FAIR

Exclusive M(ΛΛ): a(ΛΛ) from the threshold, plus the ΞN structure

≈ 14 days at 10 MHz at the HADES limit

Neutron stars

Hyperons soften the EoS: M_{max} 2.13 → 1.53 M⊙

a(ΛΛ) is needed; YN, YNN repulsion too

– HADES: Analysis Note for publication with the full methodology and systematics

– CBM: add resolution and efficiency to the a(ΛΛ) extraction; closure test with known a

– Neutron stars: replace the schematic polytrope by a microscopic EoS with measured YN, YY input