Investigating Proton-Proton Elastic Scattering with the Upgraded HADES Spectrometer

Gabriela Perez Andrade

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Donji Seget, Croatia

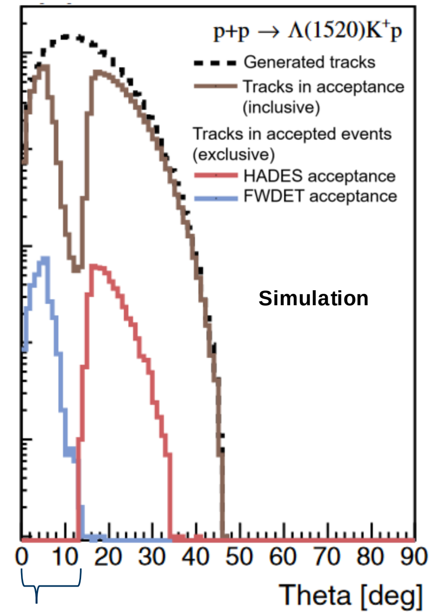
Outline

- HADES @FAIR Phase-0
- Proton-proton elastic scattering reaction event selection
- Time-integrated Luminosity
- Elastic scattering differential cross-section

HADES @FAIR Phase-0

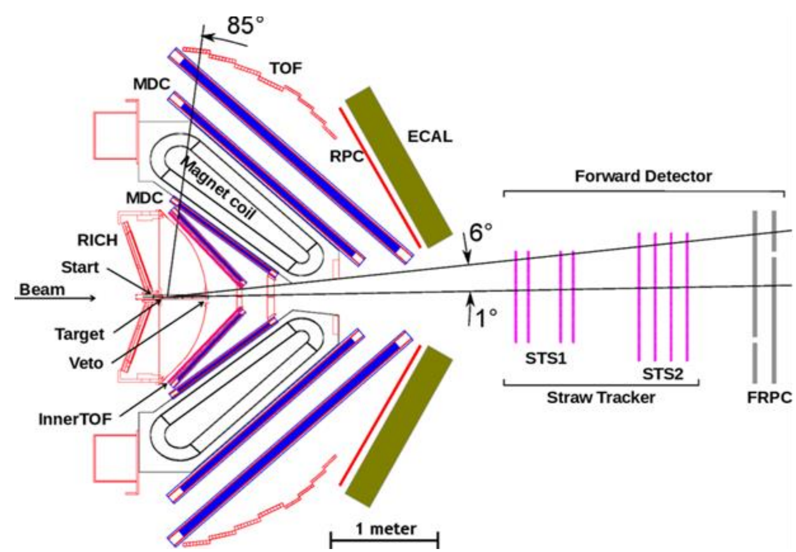
HADES **hyperon physics** program at SIS18 include (*):
- Hyperon electromagnetic decays
- Multi-strangeness production

Polar angle distribution of protons emitted from $\Lambda(1520)$ decay [1]



Forward Detector acceptance

The **Forward Detector** (FD)
- Installed as part of FAIR Phase-0 **upgrade:** essential for **hyperon** reconstruction
- Two Straw **Tracking** Stations (STS1/2)
- A forward Resistive Plate Chamber (fRPC)for **time-of-flight** measurements
- **Increases** the HADES **acceptance** to the region $1° < \theta < 6°$



HADES 2022 production run :
- Proton beam from SIS18 at E_{kin} = 4.5 GeV, p = 5.3 GeV/c
- LH_2 target

(*) E.g. Pattnaik, Kumar, Sumara, Władyszewska talks

[1] Adamczewski-Musch, J., et al. "Production and electromagnetic decay of hyperons: a feasibility study with HADES as a phase-0 experiment at FAIR." The European Physical Journal A 57.4 (2021): 1-21.

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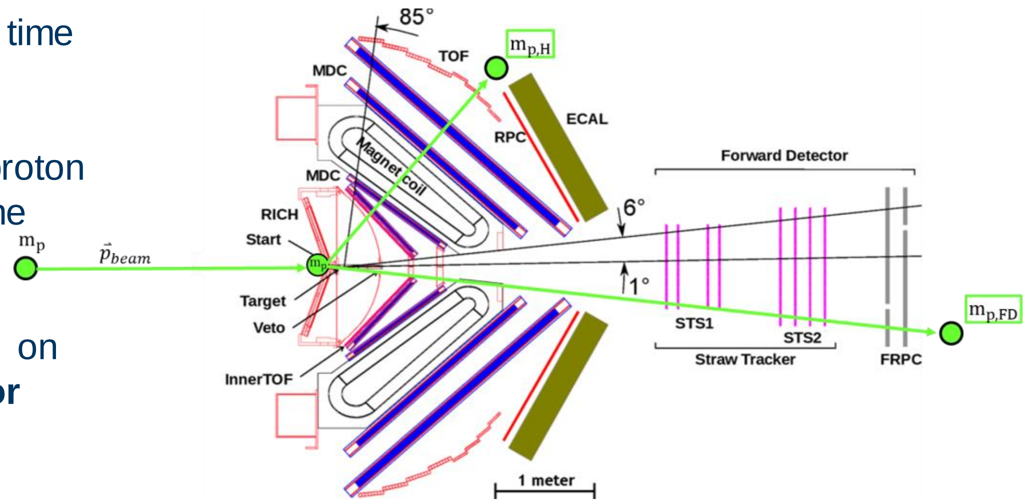
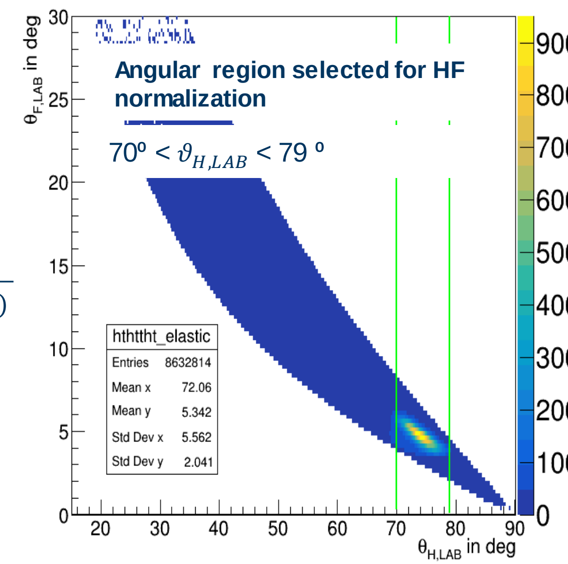
Proton-Proton Elastic Scattering

- Used to **calibrate** the FD and to determine the time **integrated luminosity** for the production run.
- The **HADES-FD (HF) selection** requires one proton detected in the **FD** ($1° < \vartheta_{FD} < 6°$) and one in the **main HADES** ($18° < \vartheta_{H} < 85°$).
- **Normalization** window ($70° < \vartheta_{H} < 79°$) based on **kinematics** of the reaction and overall **detector acceptance.**



HF event selection:

- PID graphical cut on β(p) for protons in main HADES acceptance
- $|\Delta p| = |p_{reco,H} - p_{el}| <$ 200MeV/c , where: $p_{el} = \frac{p_{beam}}{\cos\vartheta_{reco}(1+\tan^2\vartheta_{reco} \times \gamma^2_{CM})}$
- $|\tan\vartheta_{reco,H} \times \tan\vartheta_{reco,FD} - \frac{1}{\gamma^2_{CM}}| <$ 0.1, $\frac{1}{\gamma^2_{CM}}$ = 0.293
- $|\Delta\varphi - 180°| < 7°$, where $\Delta\varphi = |\varphi_H - \varphi_{FD}|$



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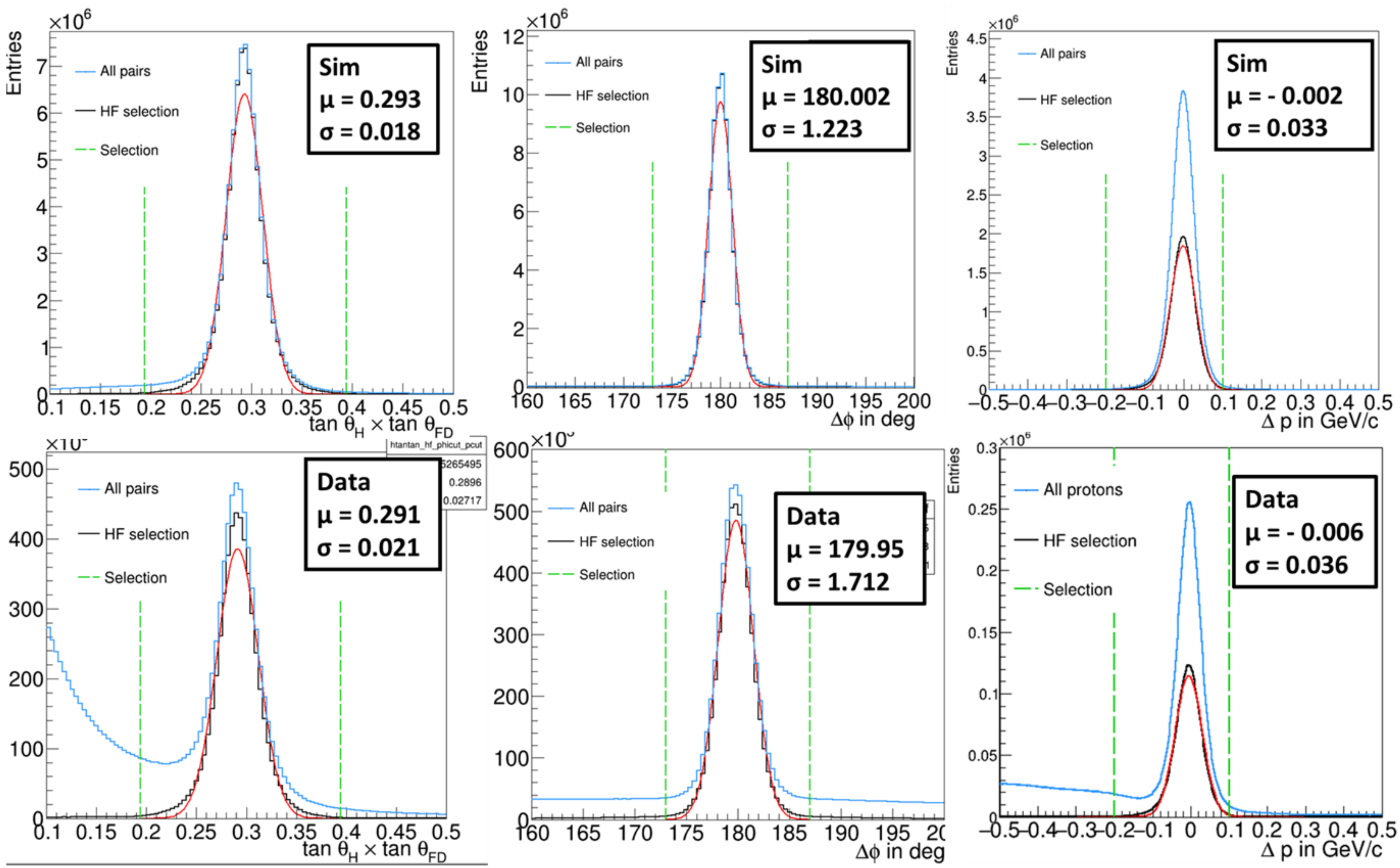
Proton-Proton Elastic Scattering Event Selection



- Negligible background after selection
- Distributions centered at nominal value show **good position alignment** between the **FD** system and **main HADES**

Time-integrated Luminosity ($\mathcal{L}$)

- The **cross section** (σ) of a measured reaction, e.g. hyperon decays, is determined by:

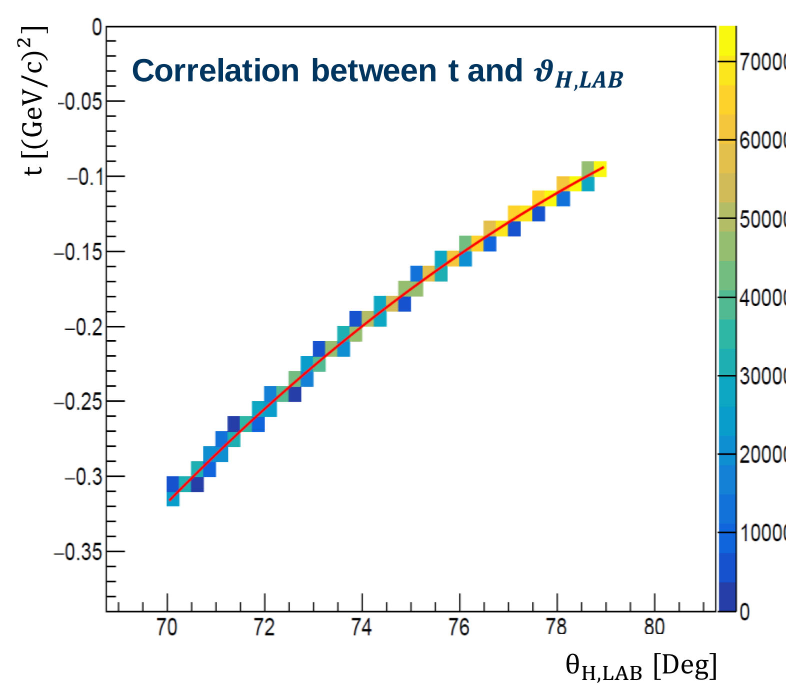
$$\sigma = \frac{N \times \epsilon}{\mathcal{L}}$$

N = Number of measured events
ϵ = Efficiency corrections
$\mathcal{L}$ = Time-integrated luminosity

- Number of p-p elastic (N_{el}) scattering events used to determine $\mathcal{L}$ achieved in the **HADES 2022 production** run:

$$\mathcal{L} = \frac{1}{\sigma_{el}} \int \frac{dN_{el} \times DS \times d\eta}{d\varepsilon} dt$$

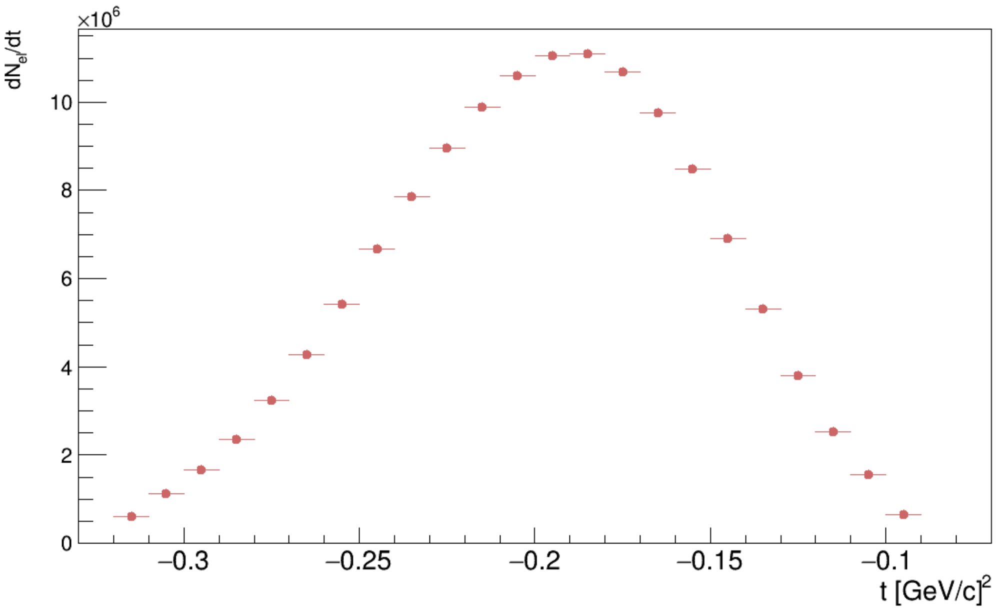
dt = **Squared four momentum** transferred
σ_{el} = Integrated **cross-section** interpolated from [2]
dN_{el} = Elastic scattering **yield**
DS = **64** = (Pre)-scaling factor
$d\eta$ = FD efficiency, **data vs simulation**
$d\varepsilon$ = **Reconstruction efficiency**



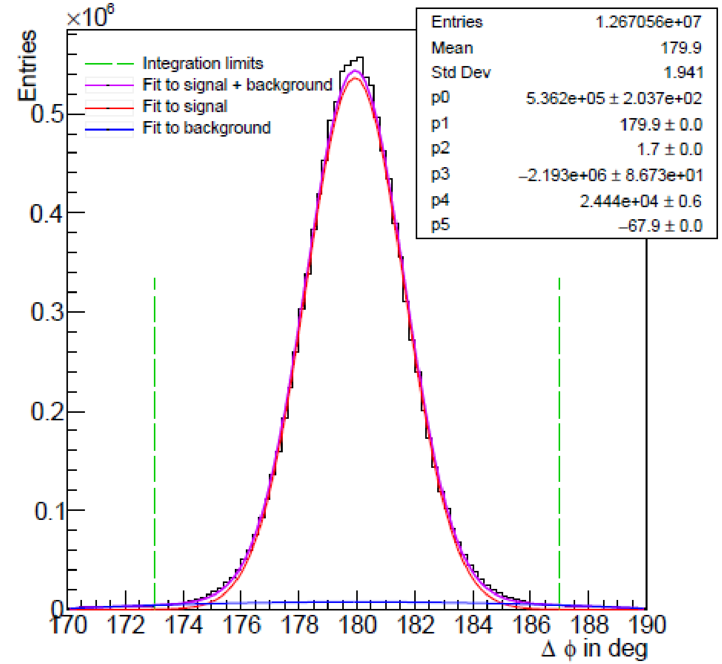
[2] I. Ambats et al., Nucl. Phys. D, 9(5), 1179

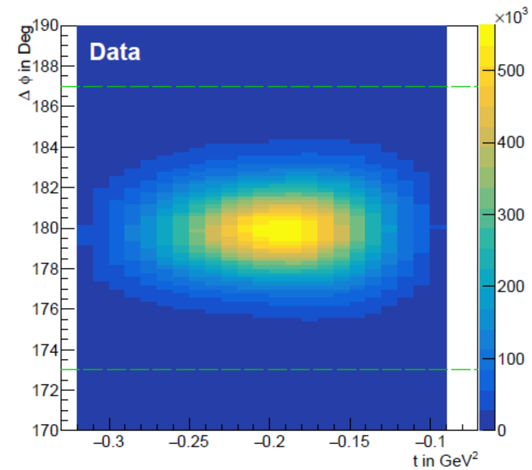
Elastic Protons Yield (N_{el})

- Obtained from the $\Delta\varphi$ **distribution** since it shows a negligible background after all selections.
- Bin by bin **integration** of $\Delta\varphi$ distribution within the **HF-selection** angular range.



Example of $\Delta\varphi$ distribution, single bin (DATA)

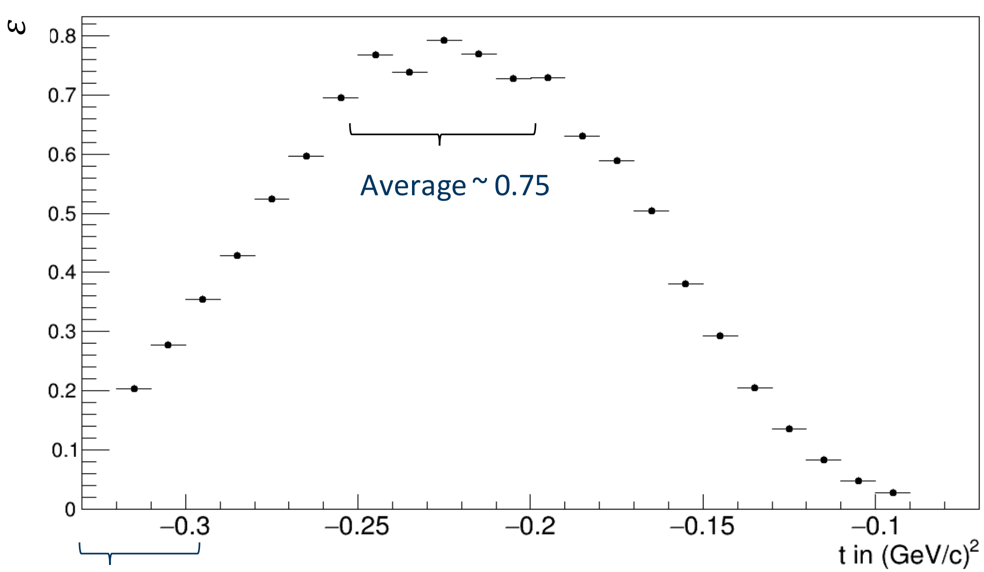




Efficiency Correction (ε)

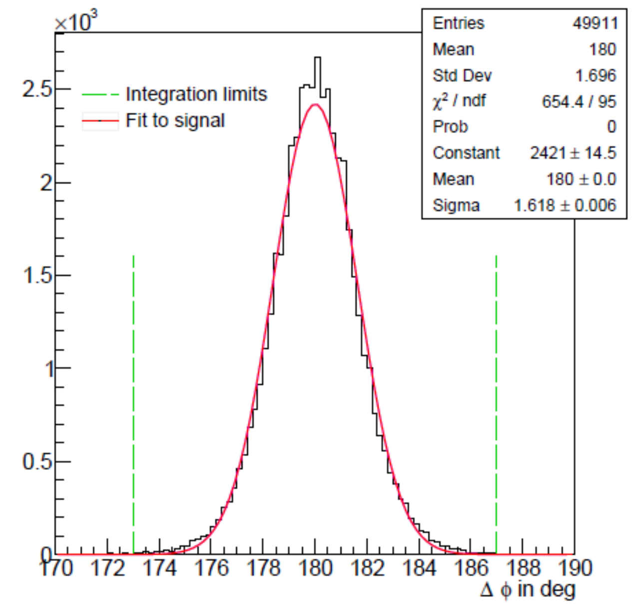
$$\varepsilon = \frac{N_{el,\,reco}}{N_{el,Total}} = \mathrm{A} \times \varepsilon_t \times \varepsilon_H \times \varepsilon_{H+FD} \times \varepsilon_{sel}$$

- Reconstruction efficiency from simulation, includes:
  - A = HADES Acceptance
  - ε_t = Trigger efficiency
  - ε_H = Single-H track reconstruction efficiency
  - ε_{H+FD} = FD track reconstruction efficiency under the condition that a H track was reconstructed
  - ε_{sel} = Efficiency after scattering selections



Low STS acceptance

Low HADES acceptance



Example of $\Delta\varphi$ distribution, single bin (SIM)

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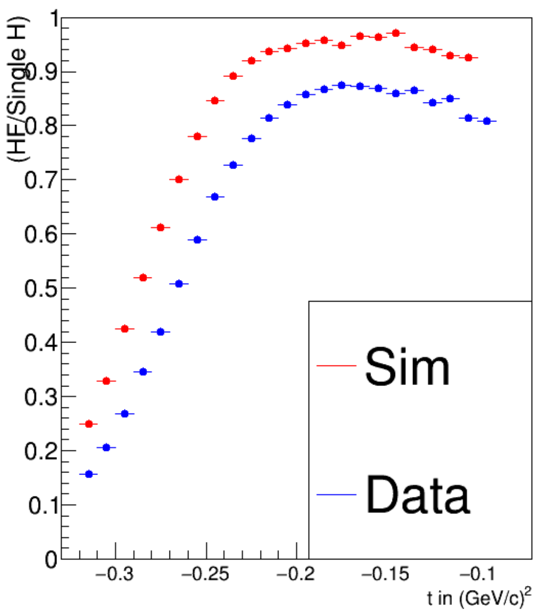
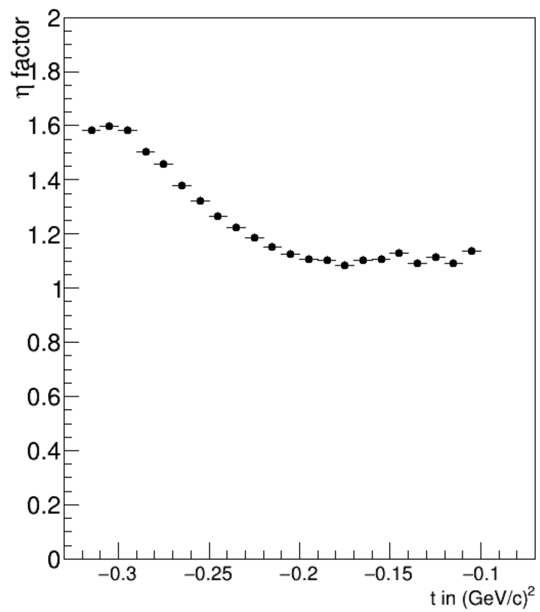
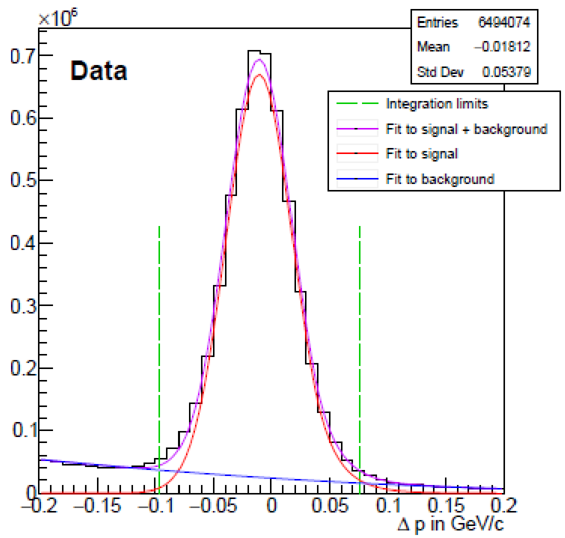
η-Correction Factor

$$\eta = \frac{(\Delta p\ HF{-}selection)/(\Delta p\ single{-}H\ selection)_{sim}}{(\Delta p\ HF{-}selection)/(\Delta p\ single{-}H\ selection)_{data}}$$

- Δp reco elastic = integral of **Δp distribution** after PID, $\Delta\varphi$ and $\tan\theta_1 \times \tan\theta_2$ cuts
- Δp total = integral of **Δp distribution** after PID (equivalent to Single-H selection)
- $\Delta p\ reco\ elastic\ /\Delta p\ total$ shows FD efficiency
- η compares efficiency between sim and data ⟶ Closer to 1 when efficiency in sim and data are the same







Example of Δp distribution, single bin

- Non-uniform background across t-range.

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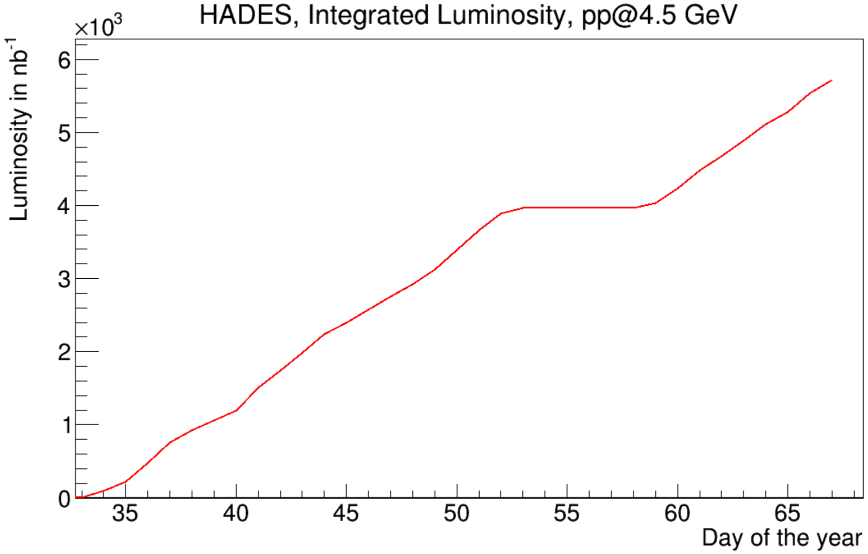
Time Integrated Luminosity ($\mathcal{L}$)

$$\mathcal{L} = \frac{1}{\sigma_{el}} \int \frac{dN_{el} \times DS \times d\eta}{d\varepsilon} dt$$

- **Normalization** range: $70^{o} < \vartheta_{H,LAB} < 79^{o}$ *or* $-0.318 < t < -0.093\ (\mathrm{GeV/c})^2$
- The yield of elastic scattering protons corrected by ε and η is given by: $dN = \dfrac{dN_{el} \times DS \times d\eta}{d\varepsilon}$
- The **interpolated** [2] cross section is: $\sigma_{el} = (4.69\ \pm 0.04)\ \mathrm{mb/GeV^2}$
- The **Integrated Luminosity** from the HF-selection (preliminary) is $\mathcal{L} = (5.86 \pm 0.09)\ pb^{-1}$



[2] I. Ambats et al., Nucl. Phys. D, 9(5), 1179

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Elastic Scattering Differential Cross-Section

- The proton-proton elastic scattering **differential cross-section** $\left(\frac{d\sigma_{el}}{dt}\right)$ is commonly written as**:**

$$\frac{d\sigma_{el}}{dt} = \frac{d\sigma_C}{dt} + \frac{d\sigma_n}{dt} + \frac{d\sigma_{int}}{dt}$$

Coulomb

Nuclear (hadronic)

Interference

The dominant contribution is determined by t

- For HADES measurements, the **nuclear** contribution **dominates**:

$$\frac{d\sigma_n}{dt} = \frac{\sigma_{tot}^2(1+\rho^2)}{16\pi(\hbar c)^2} e^{-B|t|}$$

, where:

B = nuclear slope parameter

$\rho = \frac{Re\{f_n(0)\}}{Im\{f_n(0)\}}$, f_n the nuclear component amplitude

σ_{tot} = total cross-section

Experimentally determined at different t ranges

- The differential cross-section in this t-region is well described by: $\frac{d\sigma_n}{dt} = Ae^{-B|t|}$

Where : $A = \left.\frac{d\sigma_n}{dt}\right|_{t=0}$ is called the **optical point**

B is the **nuclear slope** parameter

ρ is **not accessible** at this t-region

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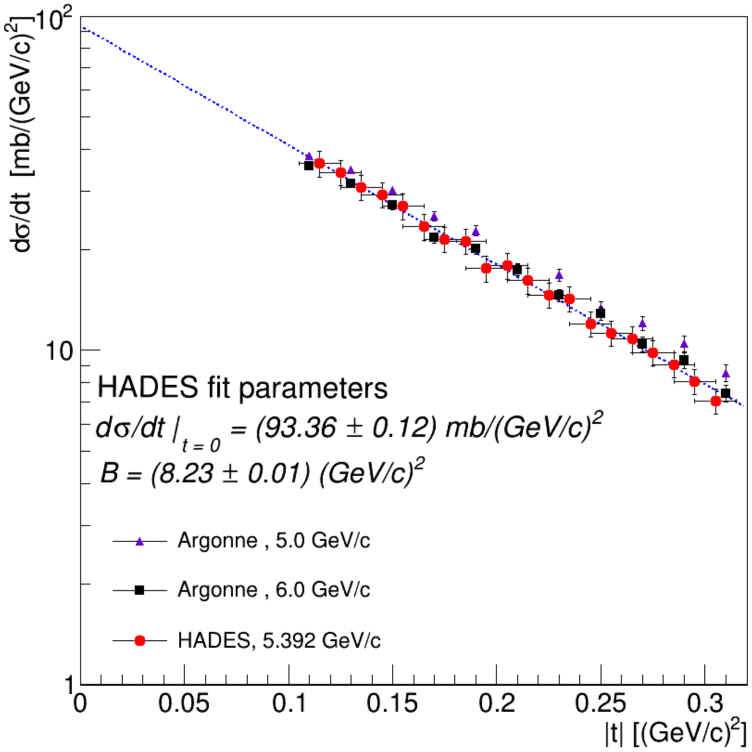
Elastic Scattering Differential Cross-Section

- The **differential cross-section** is obtained by **normalizing** the corrected number of elastic protons with $\mathcal{L}$ as: $\frac{d\sigma}{dt} = \frac{1}{\mathcal{L}} \frac{dN}{dt}$

- Parameters obtained **by fitting** the HADES data with $\frac{d\sigma_n}{dt} = \left.\frac{d\sigma_n}{dt}\right|_{t=0} e^{-B|t|}$



- The **differential cross-section** shape and **nuclear slope** obtained from **HADES** data at 5.3 GeV/c are in **good agreement** with existing data from other experiments.

- Figure shows the **extrapolation** of the cross-section to the optical point $\left.\frac{d\sigma_n}{dt}\right|_{t=0}$

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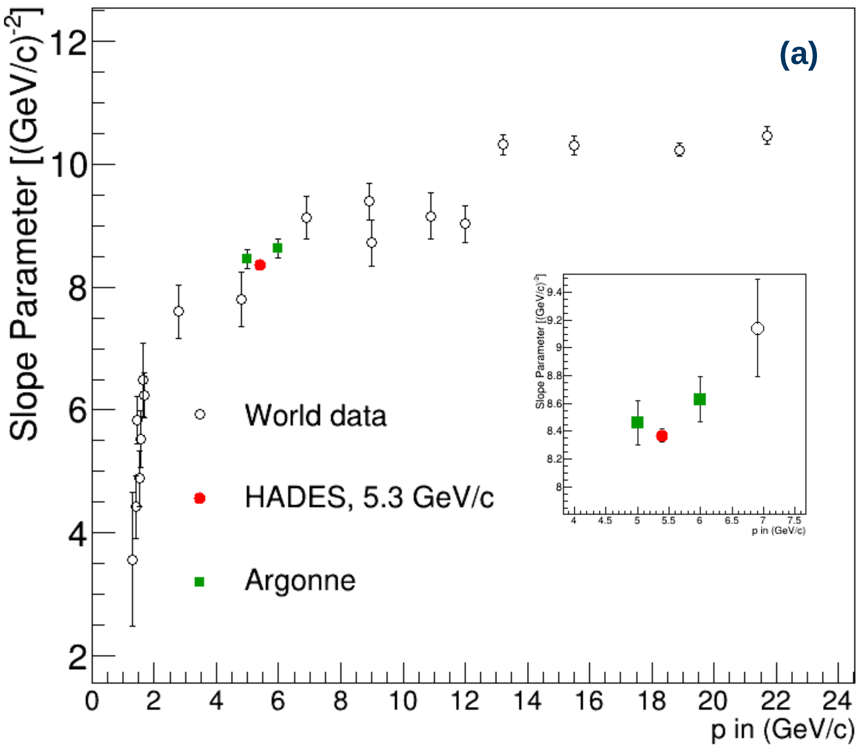
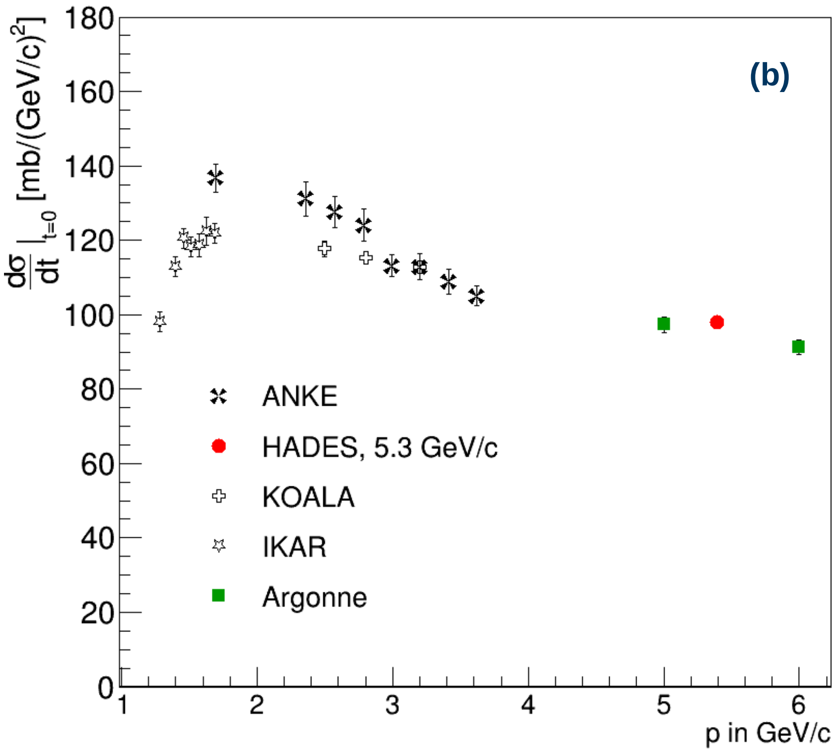
Optical Point and Nuclear Slope Parameter

Comparison with Other Experiments





- **Optical point,** has **dependence** on the **Argonne** data since it was used in the normalization ($\mathcal{L}$ determination).

- The **nuclear slope** parameter B only **depends** on the **HADES+FD performance** to measure elastic scattering events.

Figs. (a) and (b) adapted from Xu, H., *et al.* Physics Letters *B*, vol. 812, p. 136022 (2021).

Summary

- The **HADES** spectrometer **upgrade** for the **FAIR Phase-0** includes FD components, crucial for **hyperon reconstruction**

- The **proton-proton elastic scattering** event reconstruction:
  - Shows the **good alignment** between the **FD** system and the **main HADES**
  - Used to obtain the proton-proton elastic scattering **differential cross-section**

- The determined (preliminary) **integrated luminosity is**: $\mathcal{L} = (5.86 \pm 0.09)\ \mathrm{pb}^{-1}$

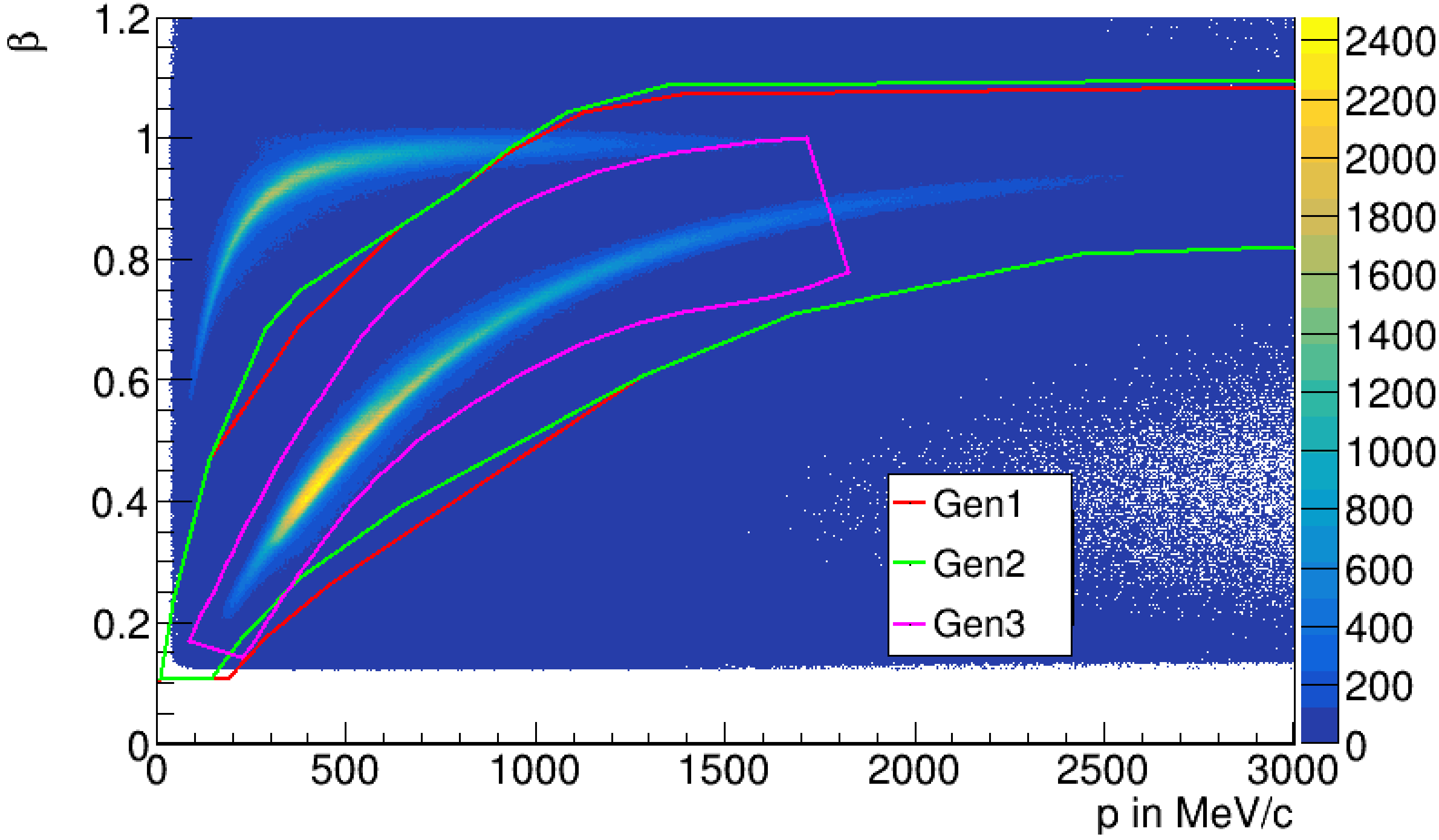
- The **differential cross-section** shape and nuclear slope obtained from **HADES** data at 5.3 GeV/c are in **good agreement** with existing data from other experiments

- Awaiting new interesting results from **hyperon** analyses

THANKS!!

Backup

Current PID based on p and β



Systematic uncertainties (preliminary)

Source	Uncertainty in % (4.5 GeV)
PID method	2.10
$\tan\theta_1 \times \tan\theta_2$	1.18
Δp fit	5.52
Normalization range	6.9
Total	**13.10**

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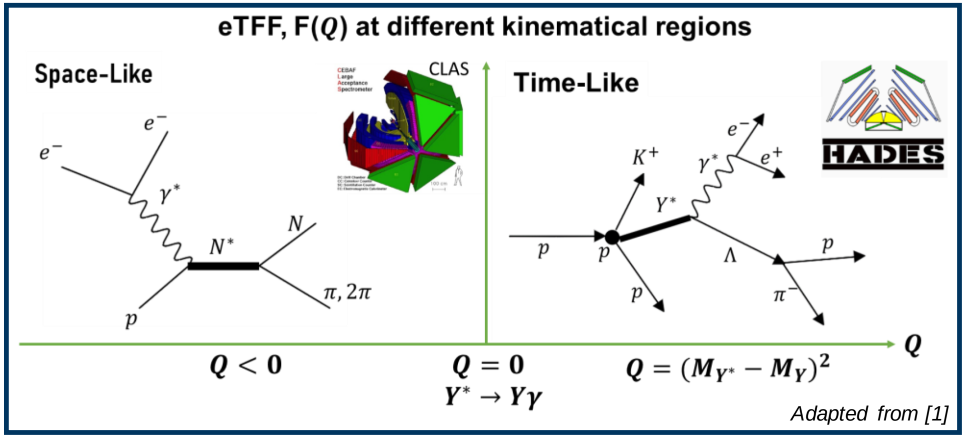
HADES hyperon physics program @FAIR PHASE-0

Hyperons are used as an experimental tool to probe the confinement domain (Λ_{QCD} ~ 200 MeV).



Hyperon Electromagnetic Decays:

- **Dalitz decays** $Y^* \to \Lambda e^+ e^-$:
  - Access electromagnetic Transition Form Factors (eTFF) at low t: **experimentally unexplored**
- **Radiative decays** $Y^* \to \Lambda\gamma$:
  - To differentiate between models [2]
  - **Sparse** experimental **results** available

HADES will provide pioneering information about baryon structure in the low Q-region.

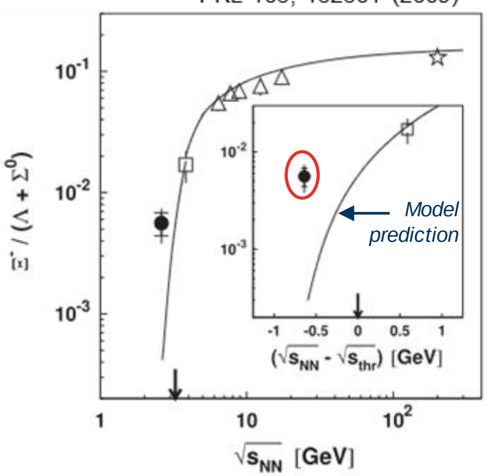
Double Strangeness Production:

- Ξ^- production: **Enhanced yield** seen in previous HADES measurements

HADES will provide pp references to quantify the strangeness enhancement in heavier systems

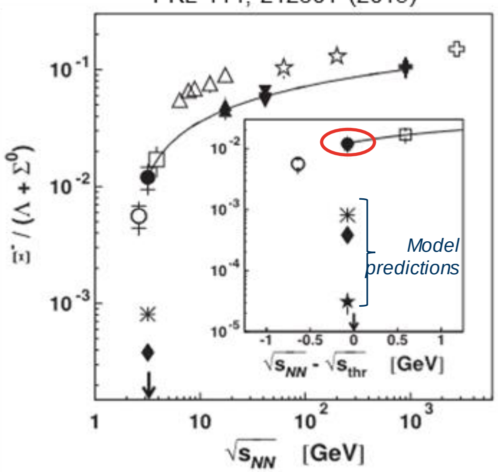
- Λ-Λ production/interaction in pp :
- Important for **neutron star core** studies [3,4]
- Complementary to upcoming PANDA studies of Λ-$\bar{\Lambda}$ in $\bar{p}p$

PRL 103, 132301 (2009)



*Filled black circle shows yield in **Ar + KCl** at 1.75 GeV by HADES Collaboration*

PRL 114, 212301 (2015)



*Filled black circle shows yield in **p + Nb** at 3.5 GeV by HADES Collaboration*

[1] B. Ramstein, AIP Conf. Proc. 1735, 080001 (2016) [HADES]
[2] E. Kaxiras, E.J. Moniz, M. Soyeur, Phys. Rev. D 32, 695 (1985)
[3] N.K. Glendenning, APJ 293, 470 (1985)
[4] Vidaña, I. (2022). *EPJ Web of Conferences* (Vol. 271, p. 09001). EDP Sciences.

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