S122@GSI: constraining symmetry energy at supra-saturation densities by means of HIC

Fabio Risitano

On behalf of the ASY-EOS collaboration

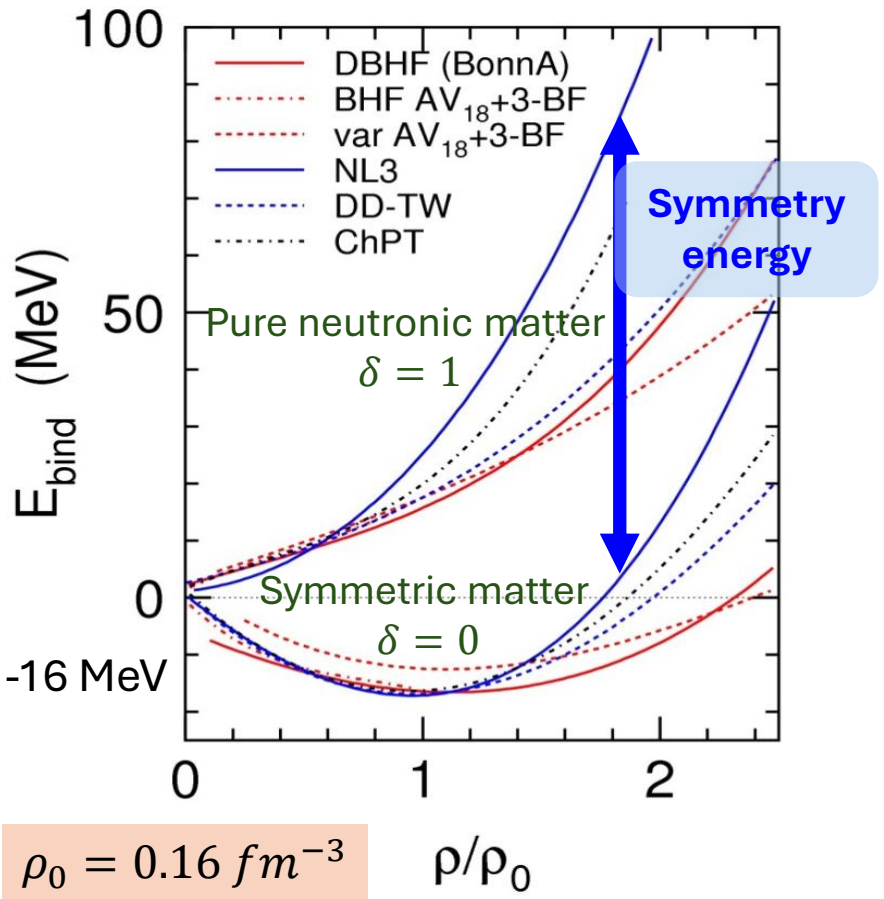
- *Centro Siciliano di Fisica Nucleare e Struttura della Materia (CSFNSM), Catania, Italy*
- *INFN Section of Catania, Catania, Italy*
- *Dipartimento MIFT, University of Messina, Messina, Italy*

EOS of asymmetric nuclear matter and neutron matter

Negligible

$$E(\rho,\delta) = E(\rho,\delta=0) + E_{sym}(\rho)\delta^2 + o(\delta^4) + \cdots$$

$$\delta = \frac{(\rho_n - \rho_p)}{\rho} = \frac{N-Z}{A}$$



$\rho_0 = 0.16\ fm^{-3}$

$$E_{sym}(\rho) = E(\rho,\delta=1) - E(\rho,\delta=0)$$

Curvature Parameter

$$K_{sym} \equiv 9\rho_0^2 \left.\frac{\partial^2 E_{sym}}{\partial \rho^2}\right|_{\rho=\rho_0}$$

$$E_{sym}(\rho) = E_{sym,0} + \frac{L}{3}\left(\frac{\rho-\rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2 + \cdots$$

Strength Parameter

$$S_0 \equiv E_{sym}(\rho=\rho_0)$$

Slope Parameter

$$L \equiv 3\rho_0 \left.\frac{\partial E_{sym}}{\partial \rho}\right|_{\rho=\rho_0}$$

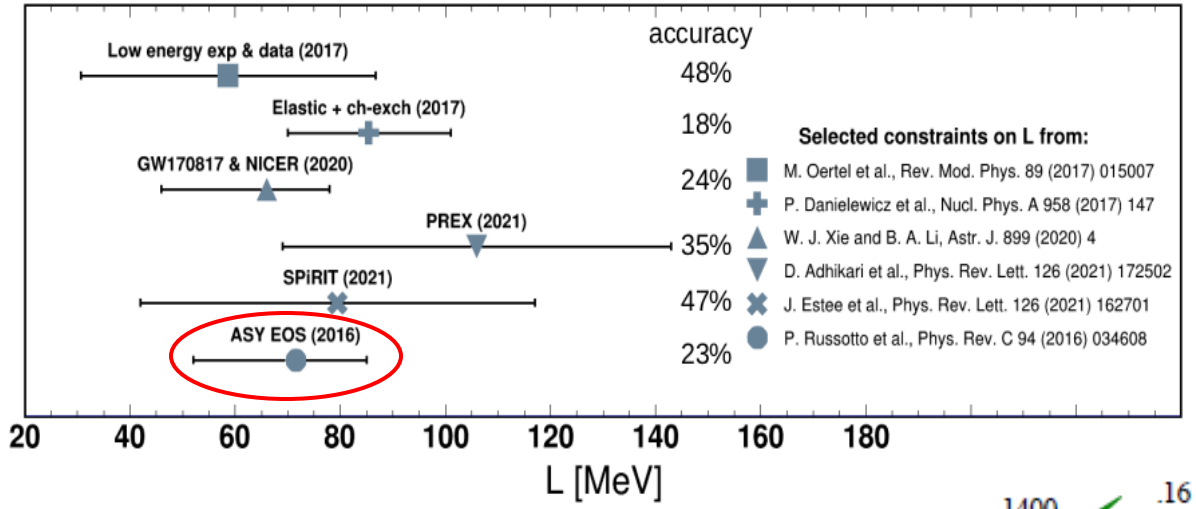
$$P_{sym}(\rho) = \rho_0^2 \frac{dE_{sym}}{d\rho} = \frac{\rho_0}{3} L$$

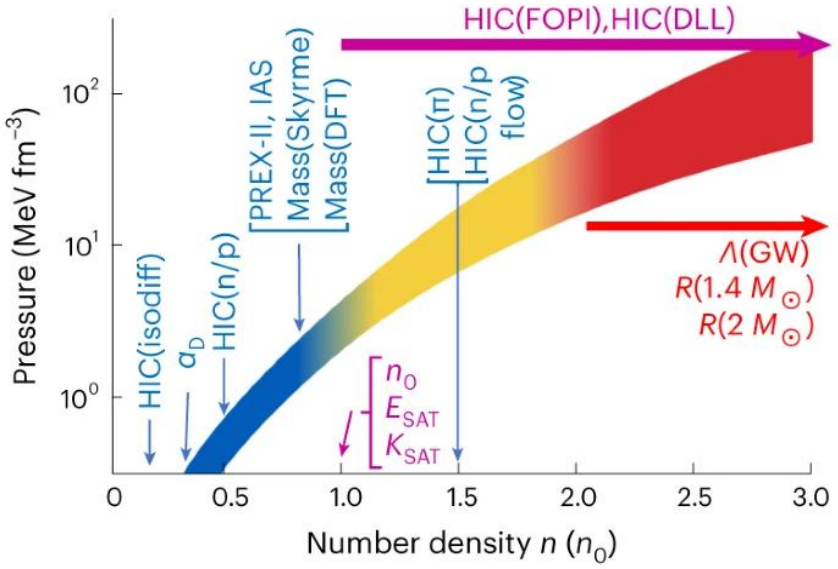
Fuchs and Wolter, EPJA 30 (2006)

Russotto P. et al., La Rivista del Nuovo Cimento 46, (2023) 1-70

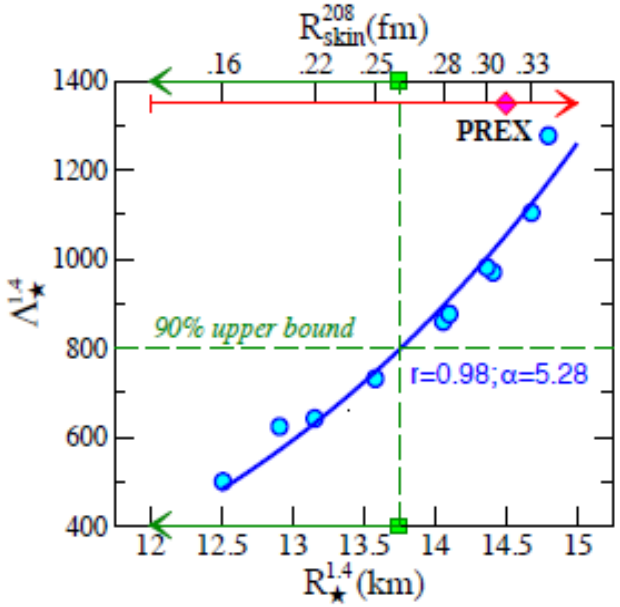
Investigate symmetry energy in experiments

Courtesy of J. Lukasik, NUSYM2024, Caen



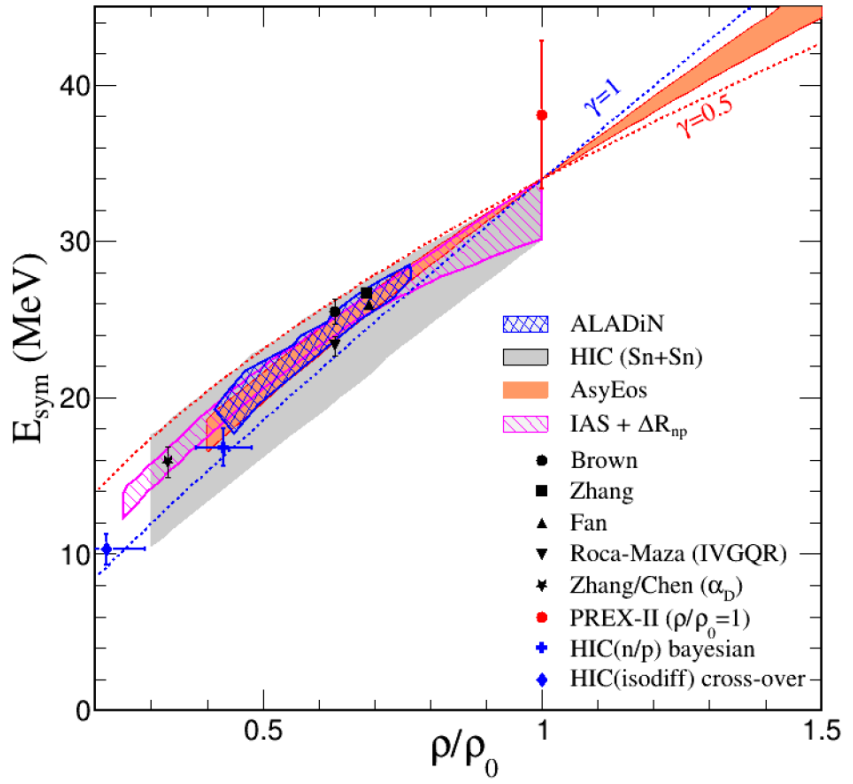


Chun Yuen Tsang et al., Nature Astronomy 8 328 (2024)



Fattoyev F.J., Piekarewicz J., Horowitz C.J., PRL 120, 172702 (2018)

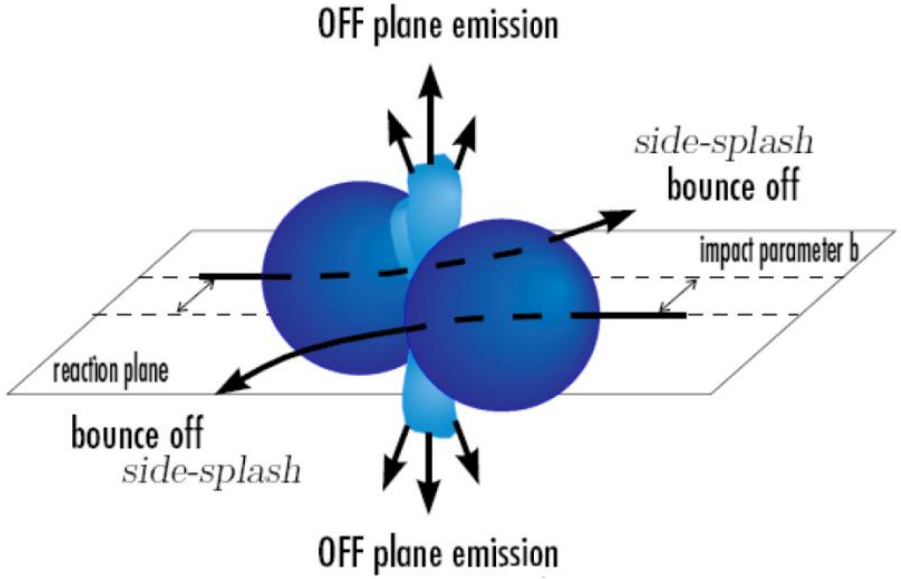
ASY-EOS I (2011)

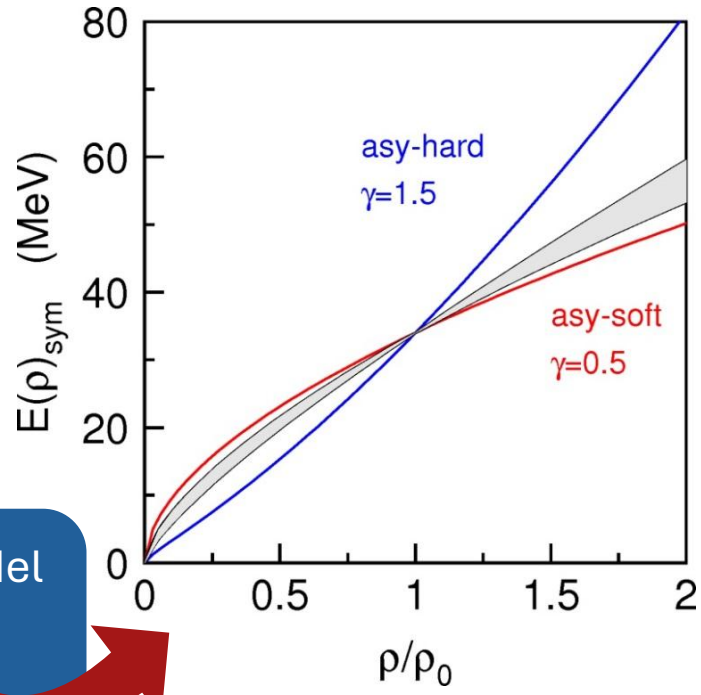


Russotto P. et al., La Rivista del Nuovo Cimento 46, (2023) 1-70

Symmetry energy at high densities: neutron/proton elliptic flow

$$\frac{dN}{d(\phi-\phi_R)}(y,p_t)=\frac{N_0}{2\pi}\left(1+2\sum_{n\geq 1}v_n\cos n(\phi-\phi_R)\right)$$

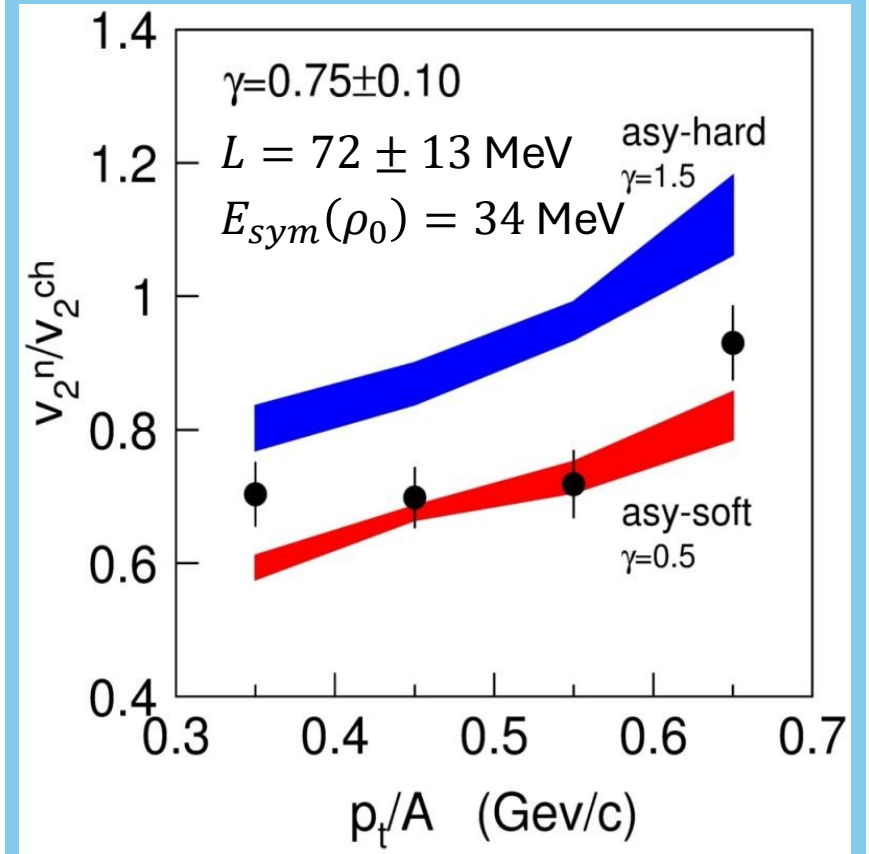




Parametrization for E_{sym} used in UrQMD model

$$E_{sym}=E_{sym}^{kin}+E_{sym}^{pot}=$$
$$12\ MeV\ (\rho/\rho_0)^{2/3}+22\ MeV\ (\rho/\rho_0)^{\gamma}$$

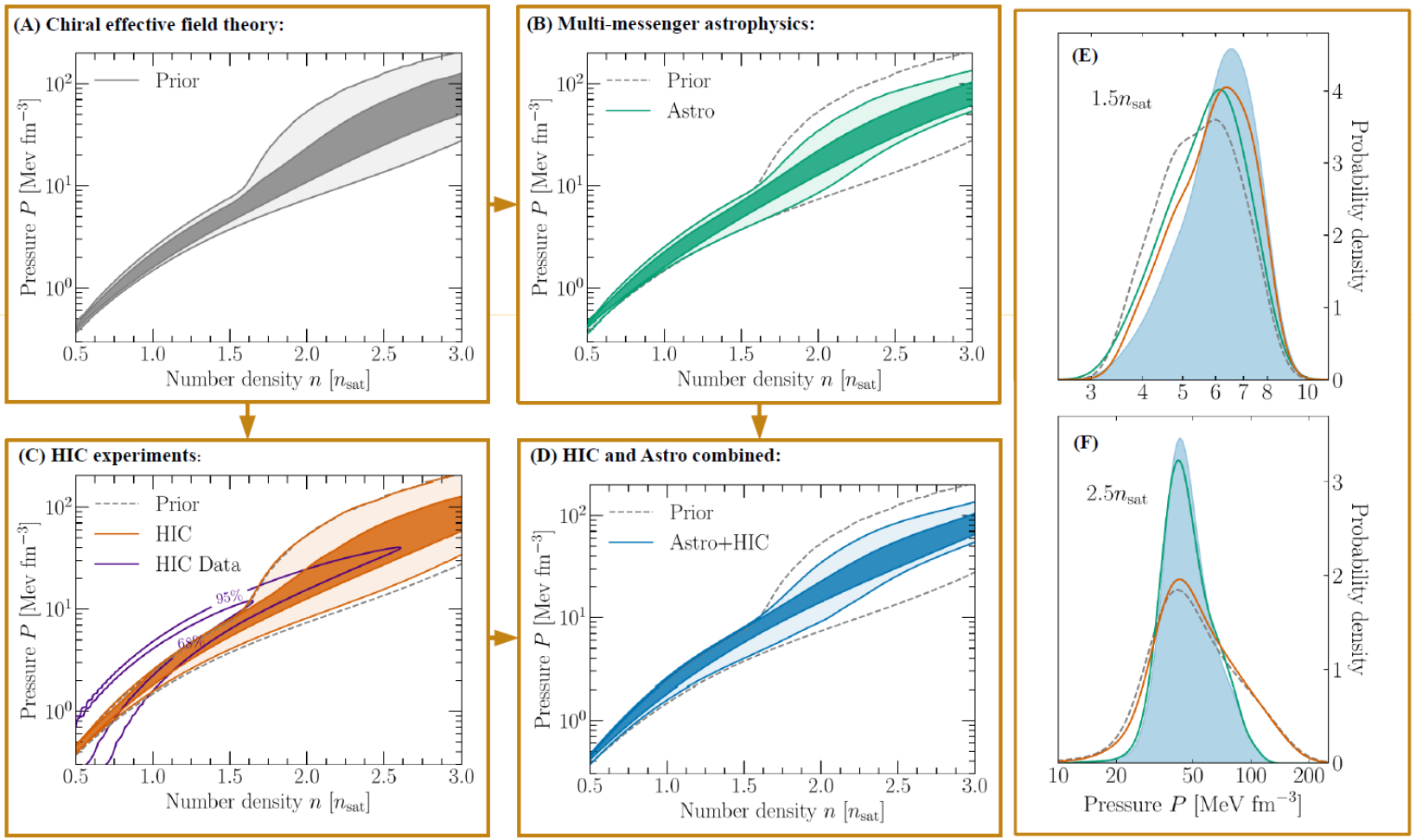
Elliptic flow from ASY-EOS I experiment (Au+Au@400 AMeV)



P. Russotto et al., PRC 94, 034608 (2016)

Constraining neutron matter EOS combining HIC and astrophysics

«HIC» = FOPI+ASYEOS+AGS
«Astro» = GW, NICER (pulsar X-ray hot spots)



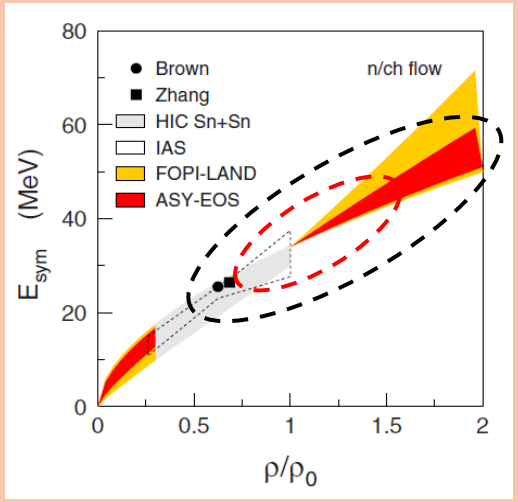
- HIC experiments probe EOS around 1–1.5 ρ_0 with high experimental sensitivity
- NICER measurement constrain independently giving similar observations
- Astrophysical observations dominate the current limit of EOS above $2\rho_0$

Extending HIC experiments toward higher densities is essential to bridge laboratory and astrophysical constraints

S. Huth et al., Nature 206 (2022) 276-280

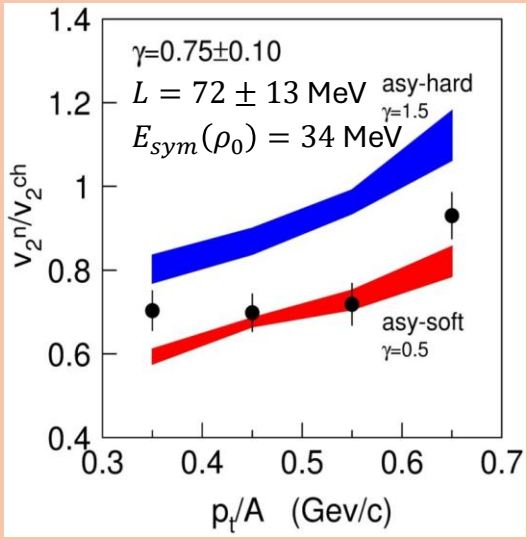
S122 (ASY-EOS II): advancing Symmetry Energy studies towards higher densities

P. Russotto et al., PRC 94, 034608 (2016)

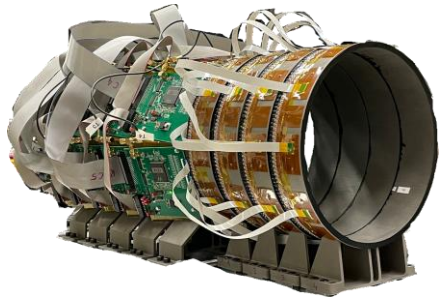


Density probed by the ASY-EOS I exp

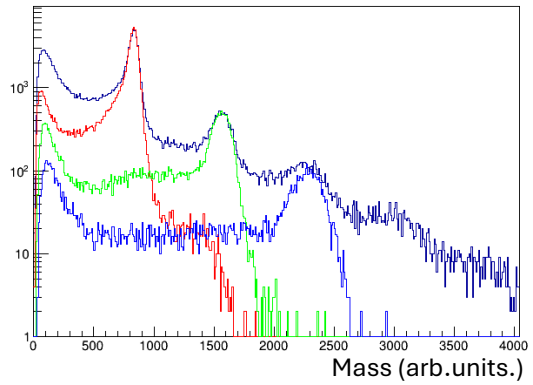
Density to be probed in the ASY-EOS II exp, most relevant for neutron star physics



Improved resolution



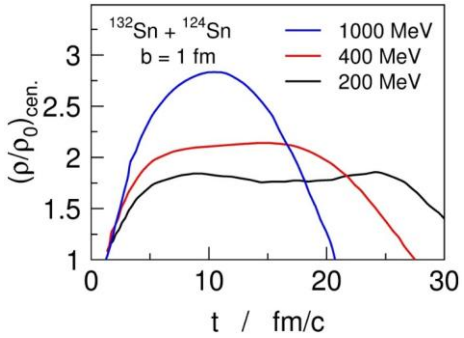
KRAB: new detector for reaction plane determination and on-beam centrality selection



NeuLAND: capability to resolve **p**, **d**, **t**

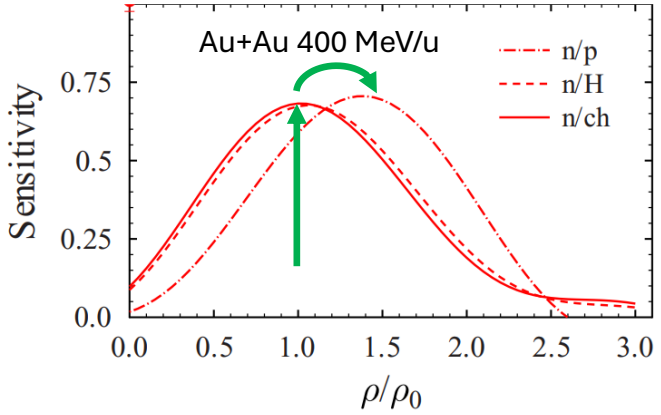
Higher densities

Li, Bao-An, NPA 708, 365 (2002)



Higher incident energies → higher densities reached (probed?)

P. Russotto et al., PRC 94, 034608 (2016)



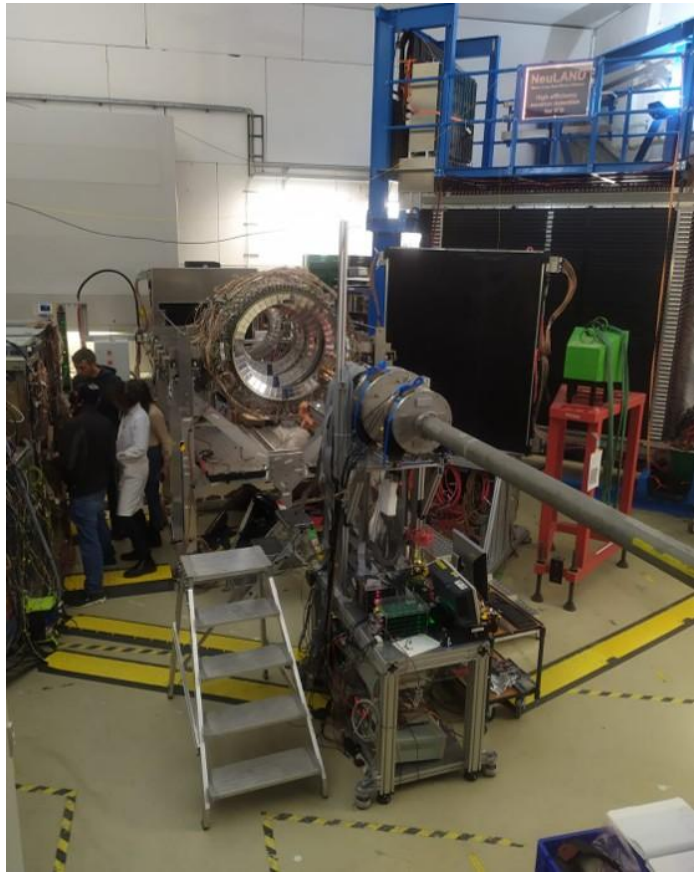
n/p observable → higher densities probed

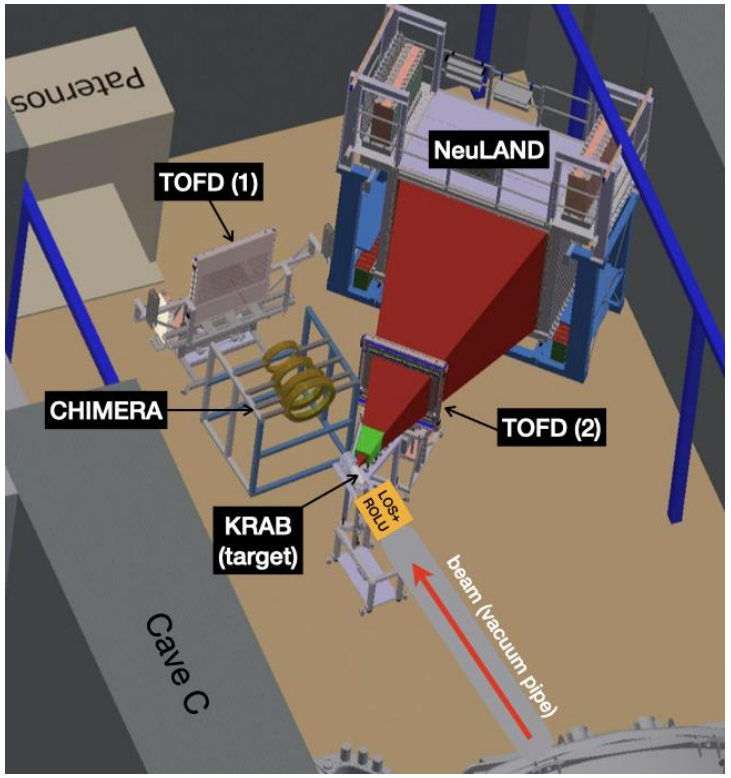
S122 (ASY-EOS II): advancing Symmetry Energy studies towards higher densities

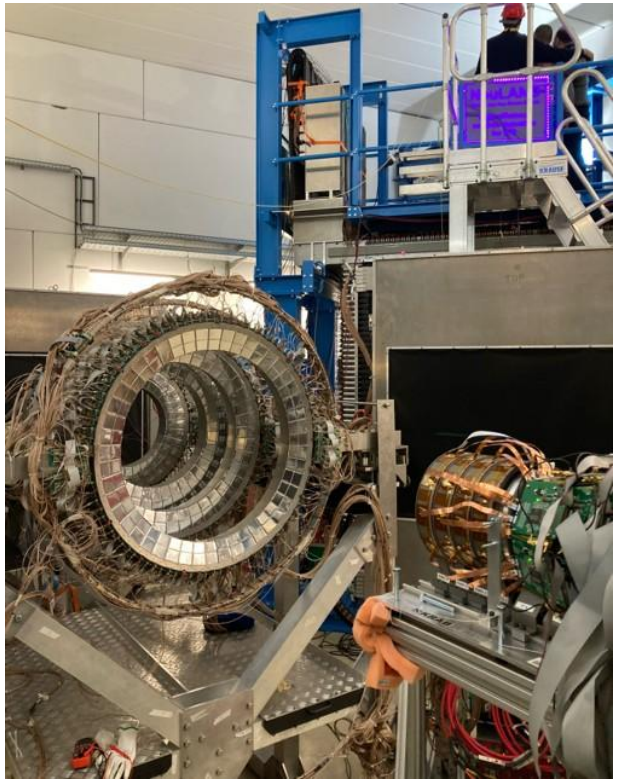
March 2025 measurements at GSI Darmstadt:

- Au+Au @ 280, 400, 600, 1000 AMeV.
- 10^5 pps, 2 weeks

Energy (AMeV)	Main motivation
280	highest sensitivity on K_{sym}
400	reference to ASY-EOS I, n/p tests higher densities than before
600	highest sensitivity on L, high-density tested
1000	Maximum energy (≈ density) where models agree on v2 sensitivity





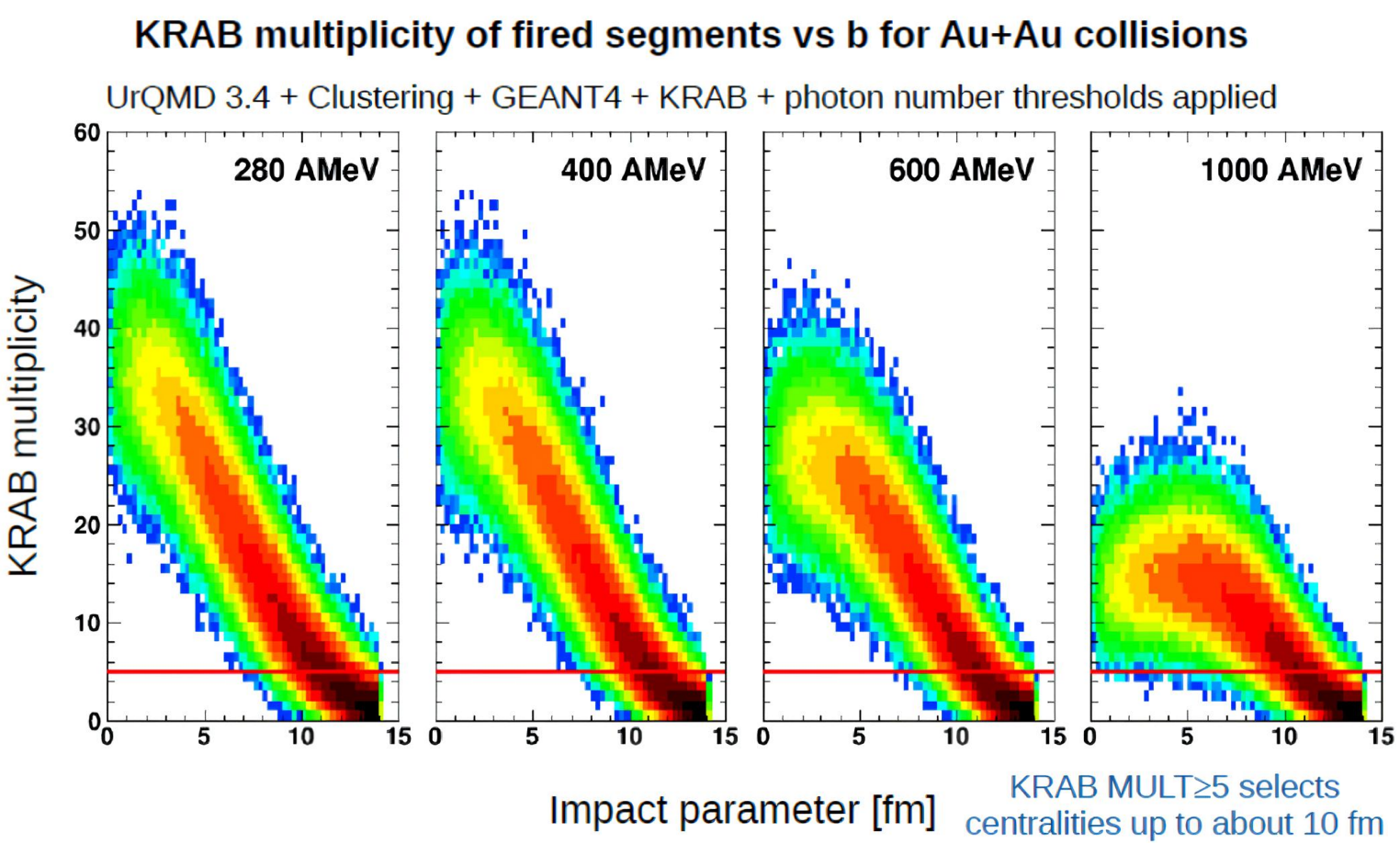


KRAB: multiplicity trigger, centrality and reaction plane detector

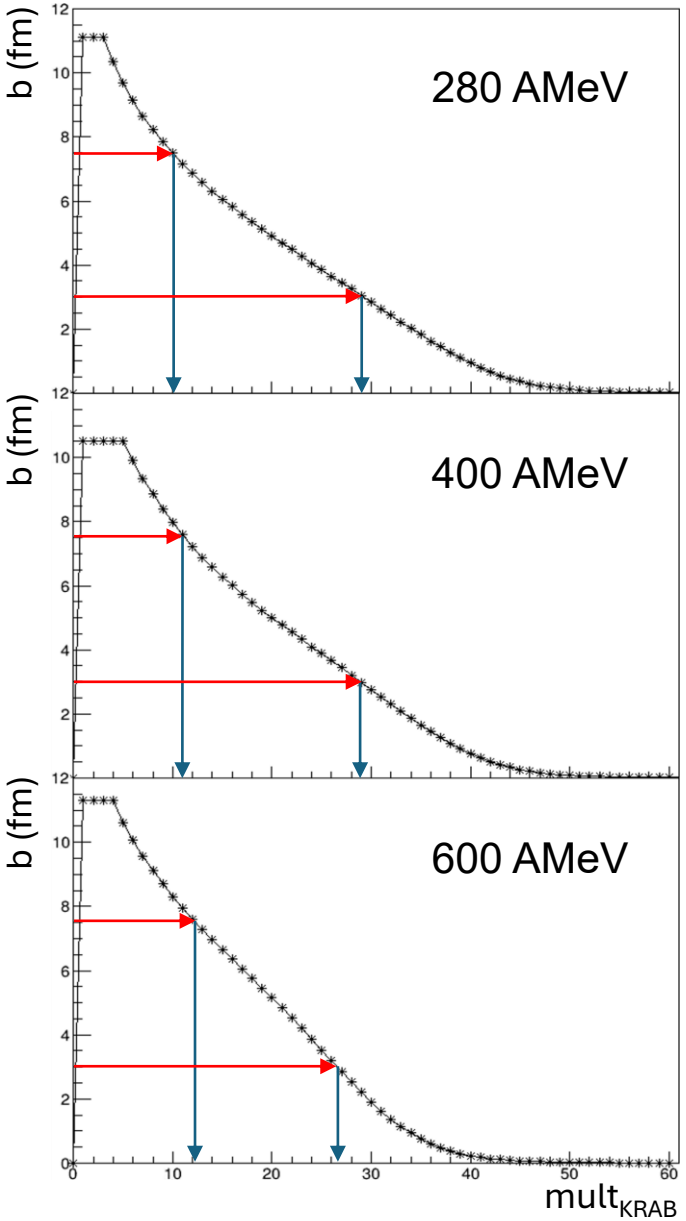
Beam direction

- 5 rings of 4×4 mm^2 segments of fast scintillating fibers, read out by 3×3 mm^2 SiPMs
- 4×160 segments in forward rings, 96 segments in backward ring
  - 736 total channels
- broad coverage from 30° to 165° (~87% geometric efficiency)
- ~5% multihit probability (for 1 AGeV Au+Au reaction)
- max radius 12 cm
- length ~43 cm, 3D printed

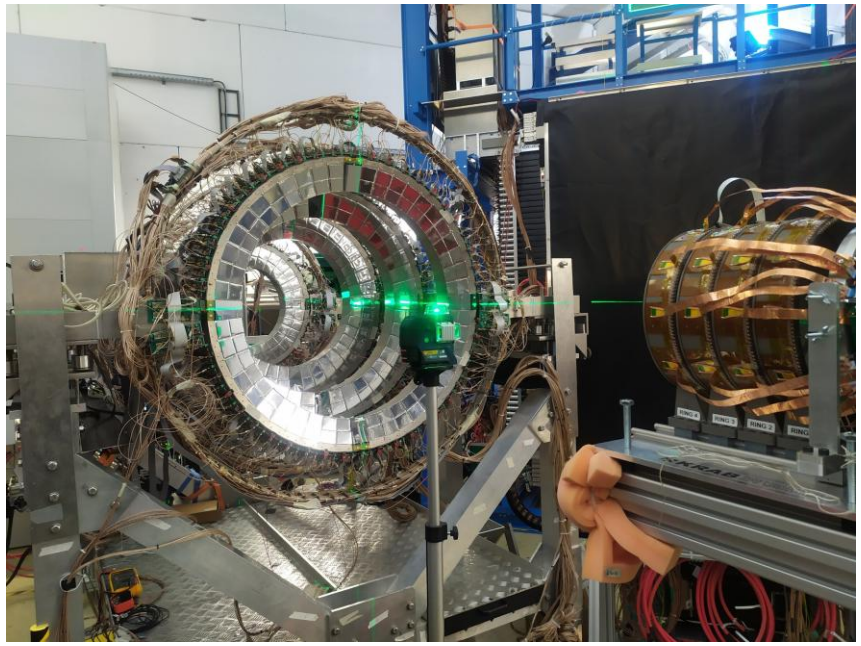
KRAB: impact parameter through multiplicity selection

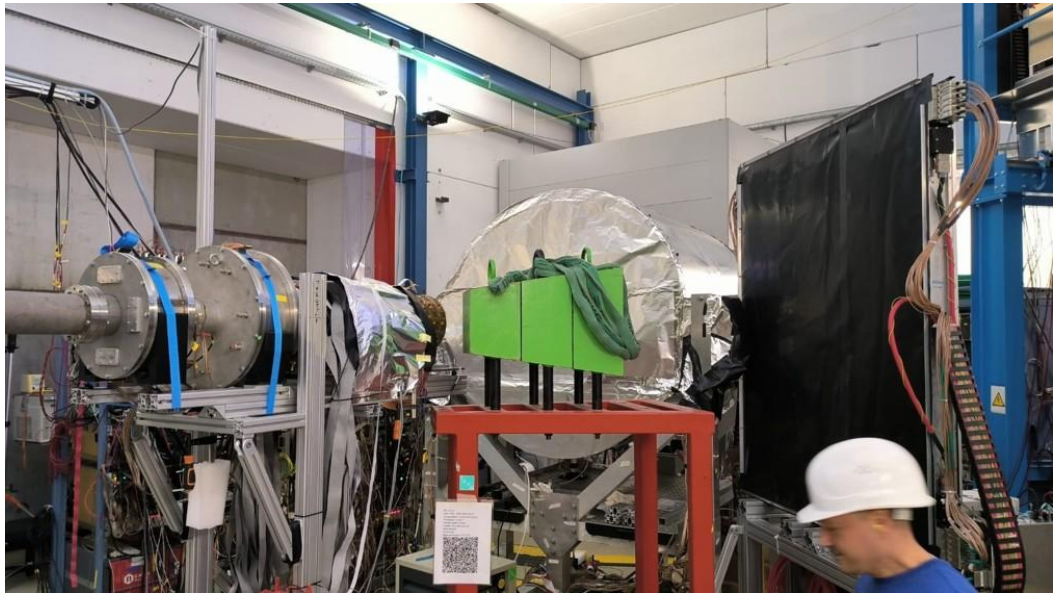


made by J. Łukasik



CHIMERA@GSI

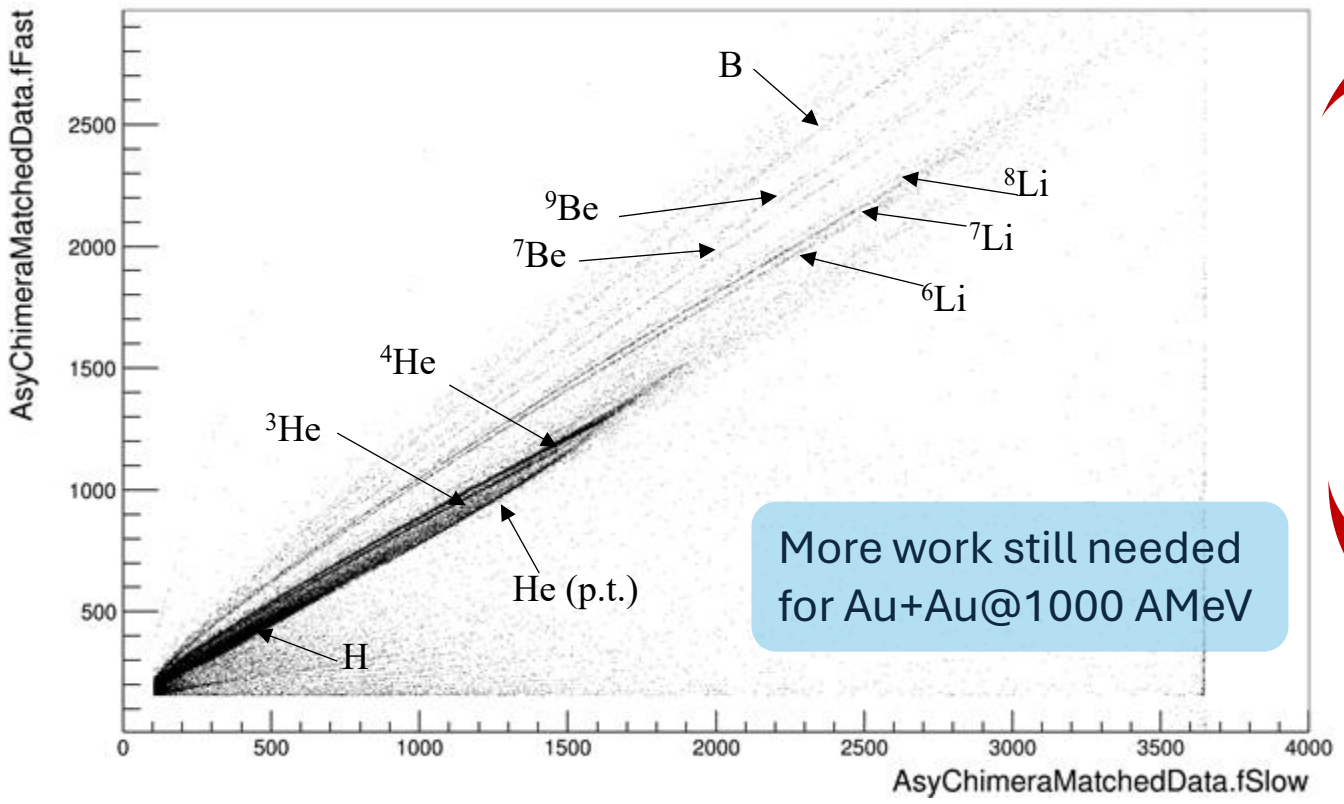




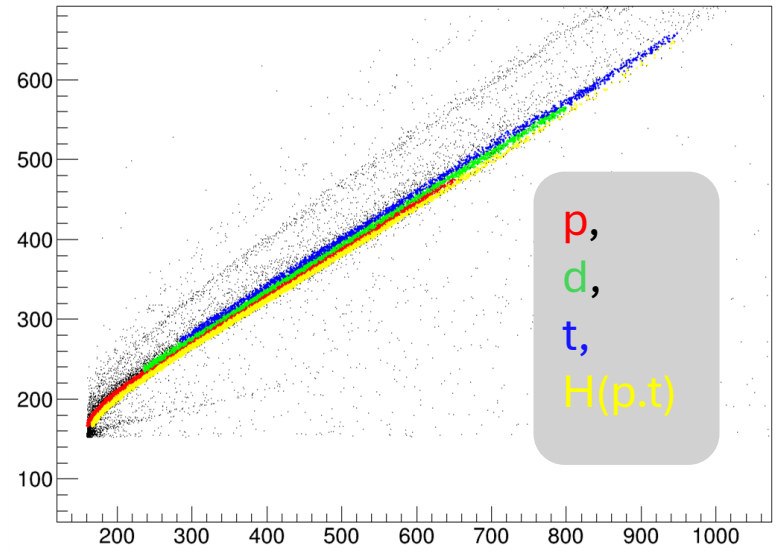
CHIMERA@GSI

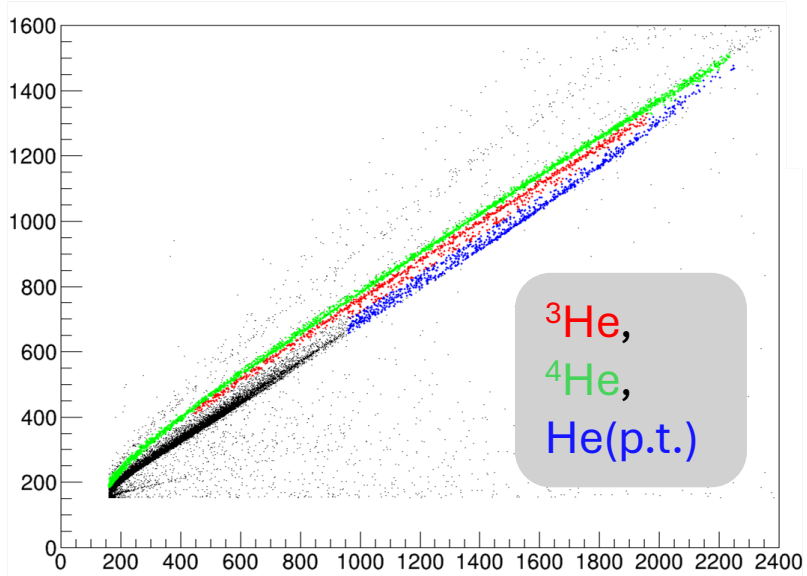
4 wheels (8 rings)
320 CsI(Tl) scintillators 12 cm thick
Polar angles $4.6° \leq \theta \leq 16°$

Identification plot of CsI(Tl) fast-slow signals at 400 AMeV

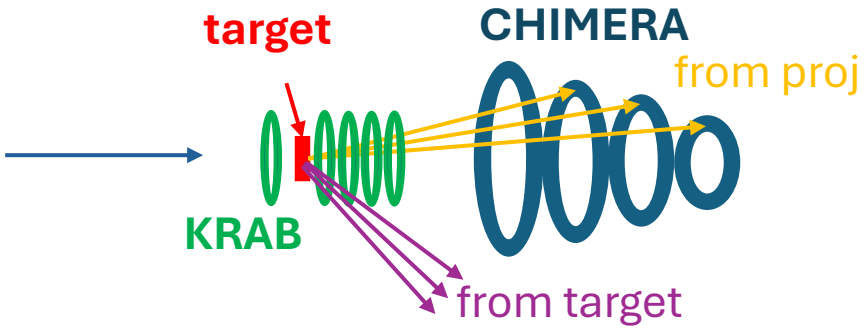


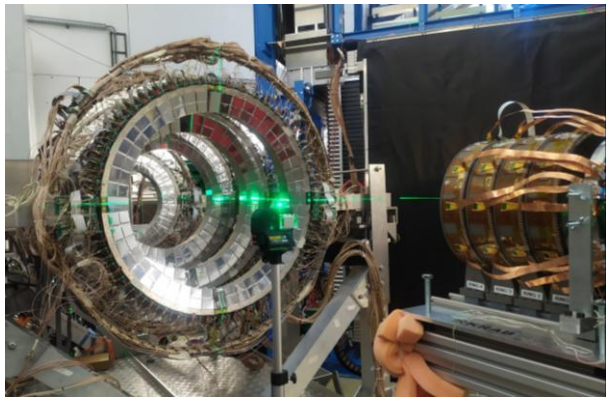
More work still needed for Au+Au@1000 AMeV



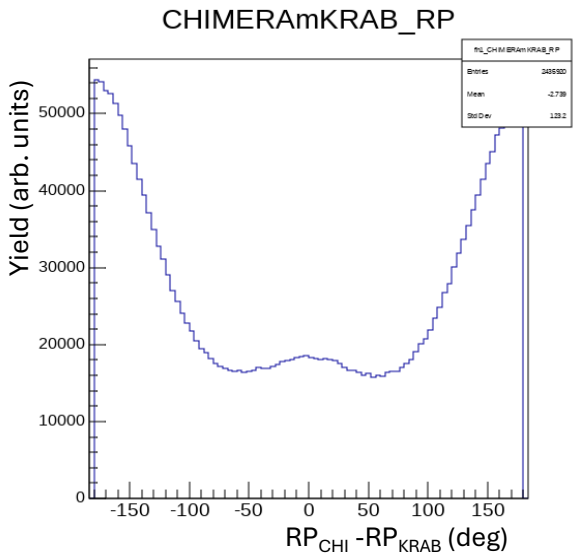


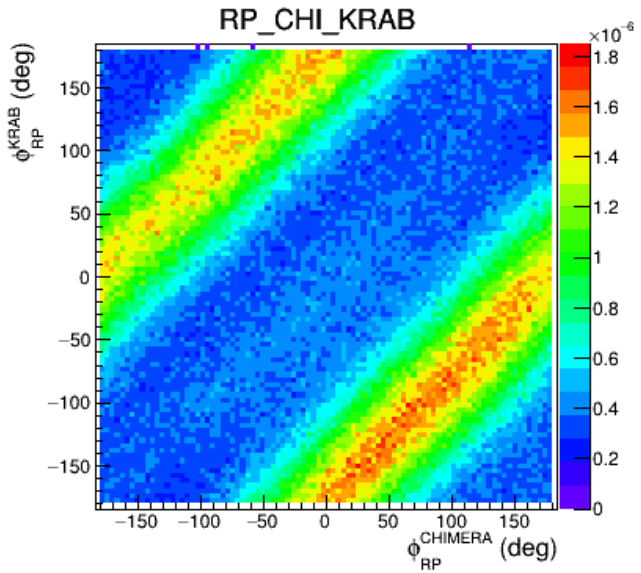
CHIMERA-KRAB correlations





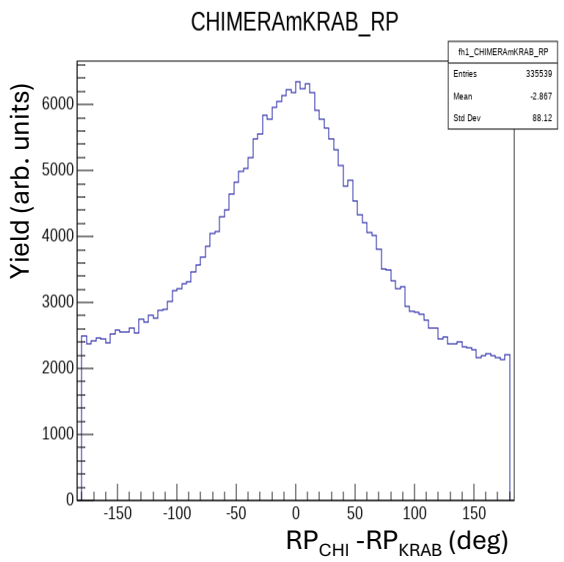
Au 400 AMeV + Au 2%

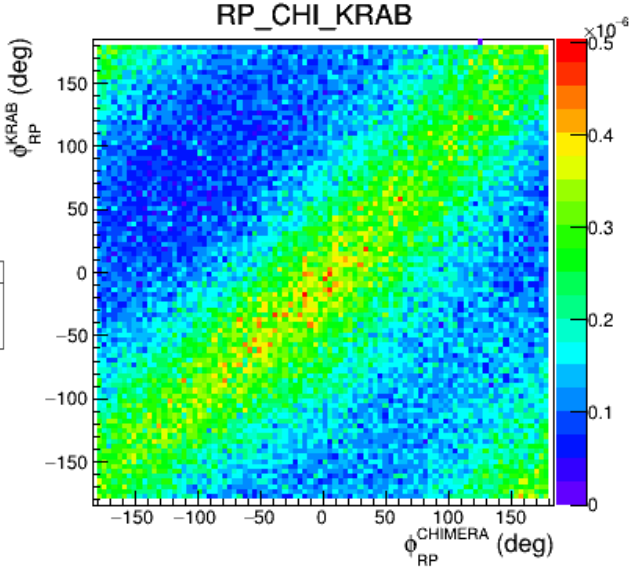




$\Delta\phi \approx 180°$

Au 400 AMeV + EMPTY target





$\Delta\phi \approx 0°$

CHIMERA-KRAB correlations: reaction plane determination

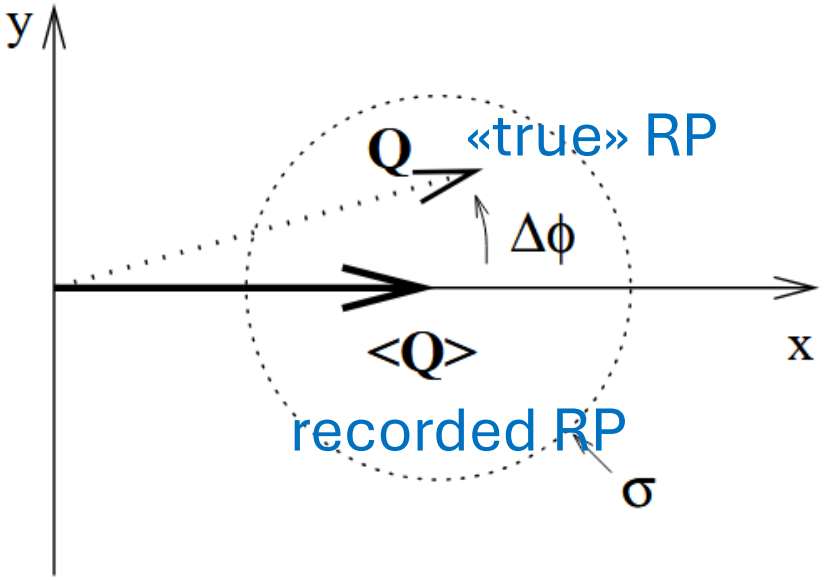
$$\frac{dN}{d\phi} = \frac{1}{2\pi}\left(1 + 2\sum_{n\geq 1} c_n \cos n\phi\right)$$

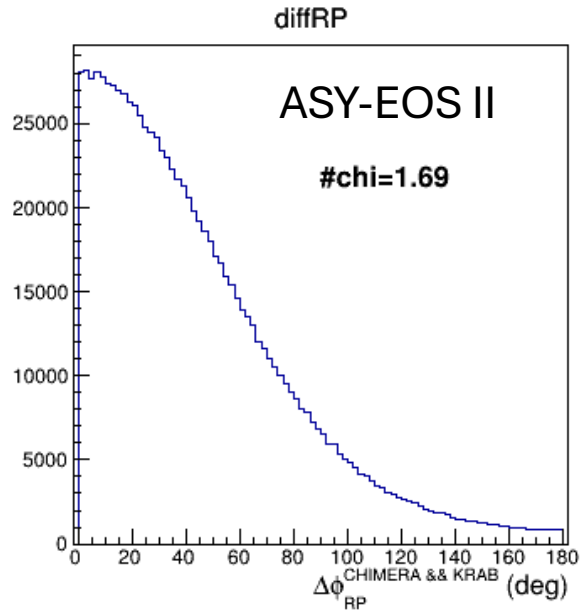
«true» flow

Attenuation coefficient

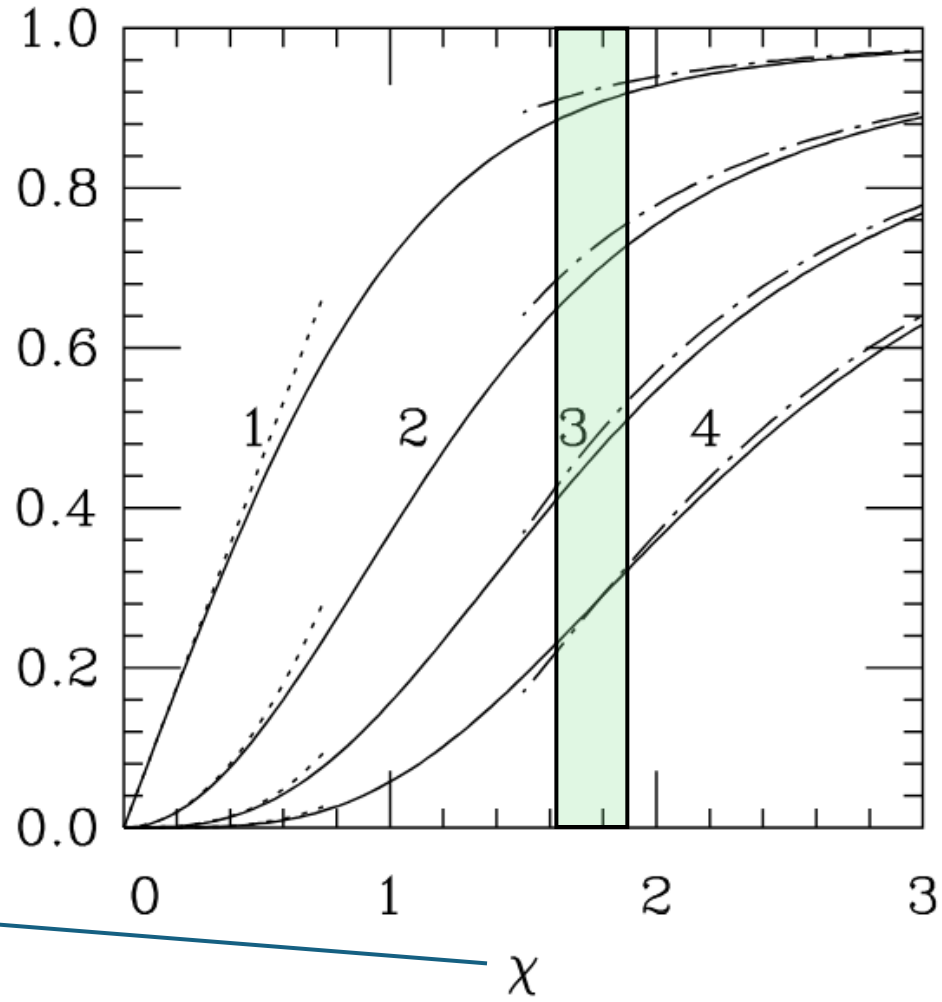
Measured flow

$$\langle \cos n\psi \rangle = \langle \cos n\phi \rangle \langle \cos n\Delta\phi \rangle$$





ASY-EOS I $\chi = 1.58$



Jean-Yves Ollitrault, arXiv:nucl-ex/9711003v2

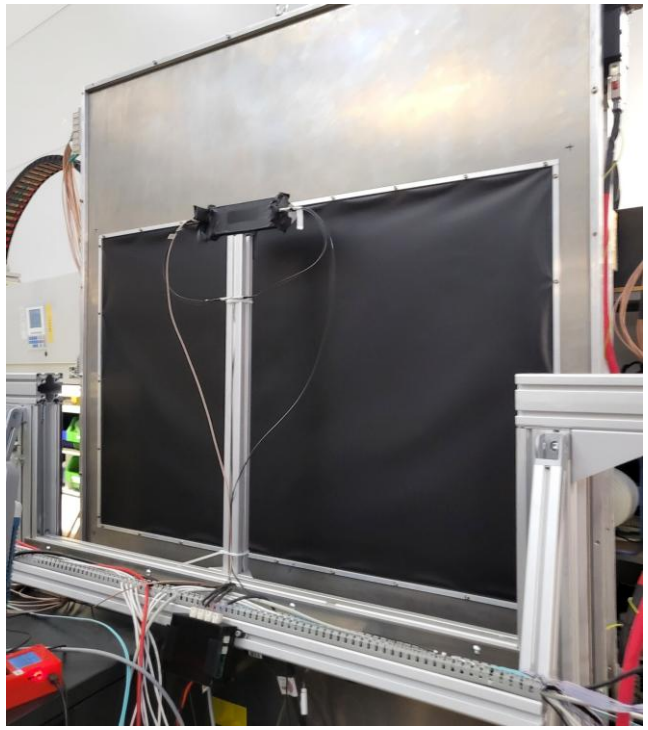
Forward TOFD: impact parameter (Z_{bound})

- 44 vertical plastic scintillating bars
  - Each readout by 2 photomultipliers
- Precise time-of-flight measurements
- Charge identification
- Position calibration

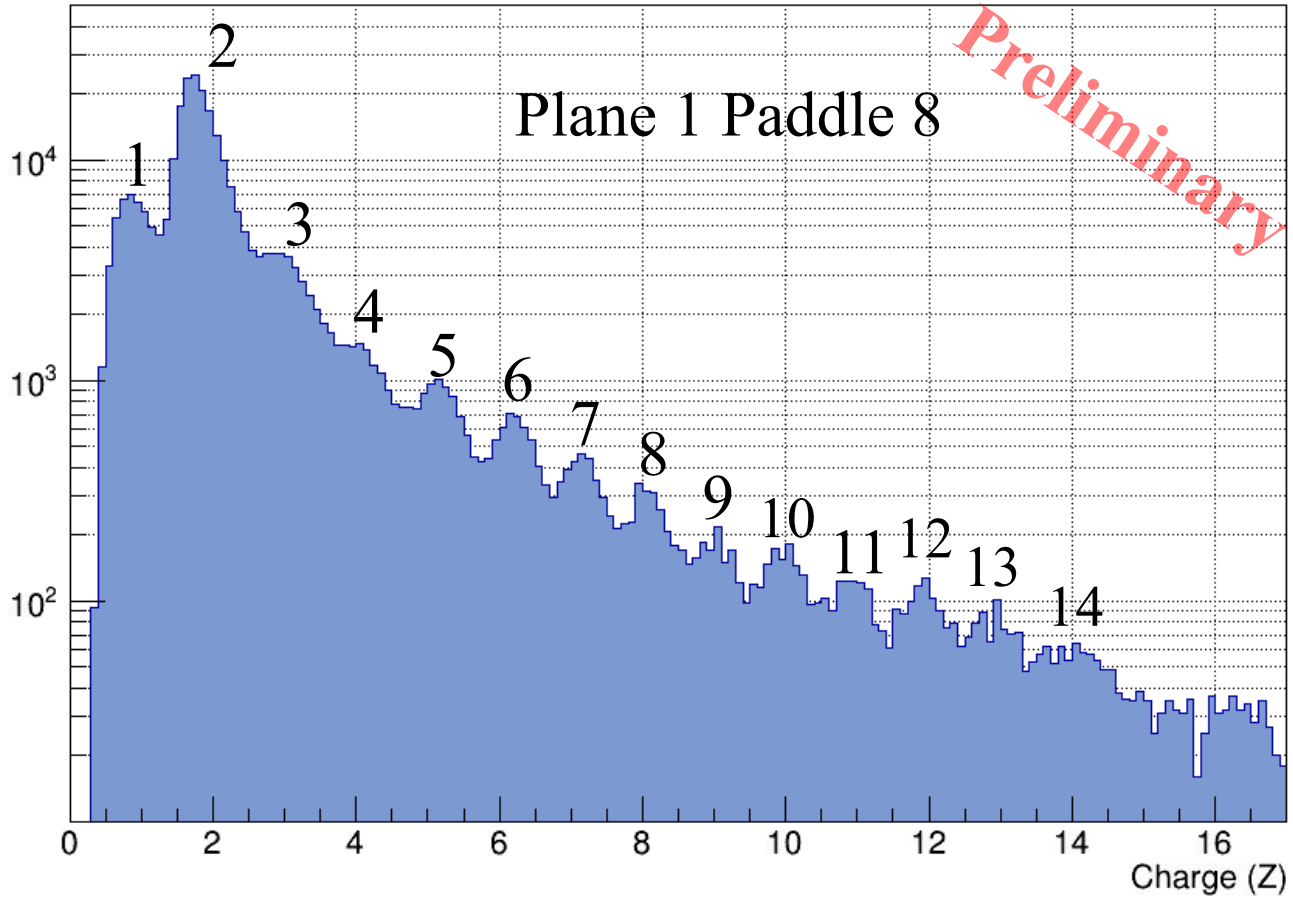
- Forward planes: charge, impact parameter
- 50° double plane: veto for charged particles for NeuLAND

$$Z_{Bound} = \sum_{i=1}^{M} Z_i \quad (\text{with } Z_i \geq 2)$$

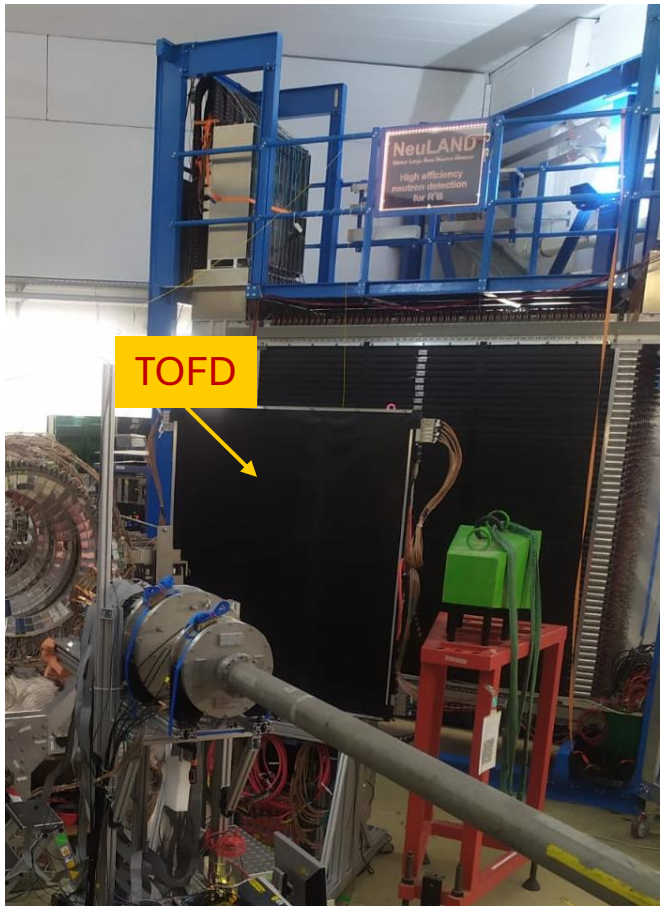
made by F.R.



Will be further improved with coincidence of plane 1-2 adjacent paddles

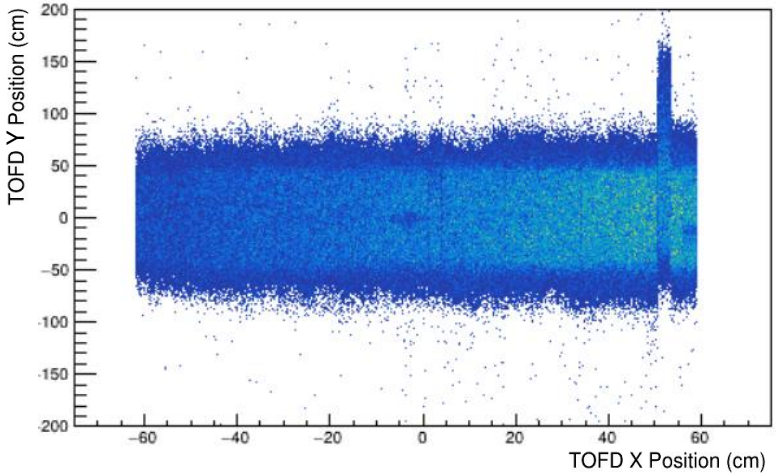


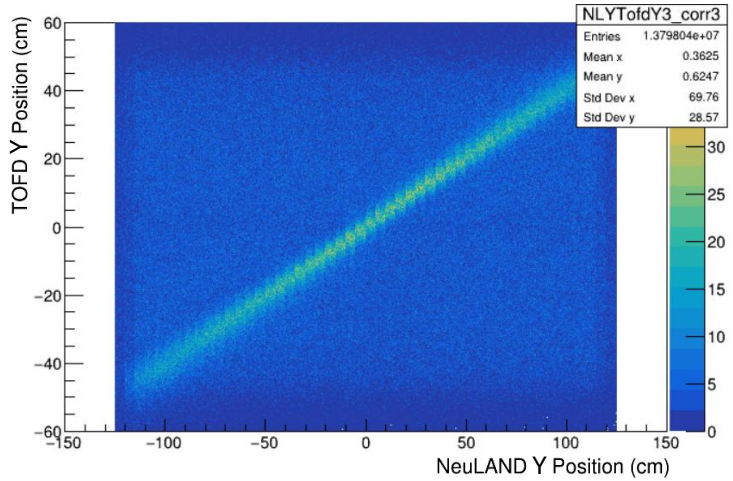
Veto TOFD for NeuLAND



made by E. Gambera and I. Gasparic

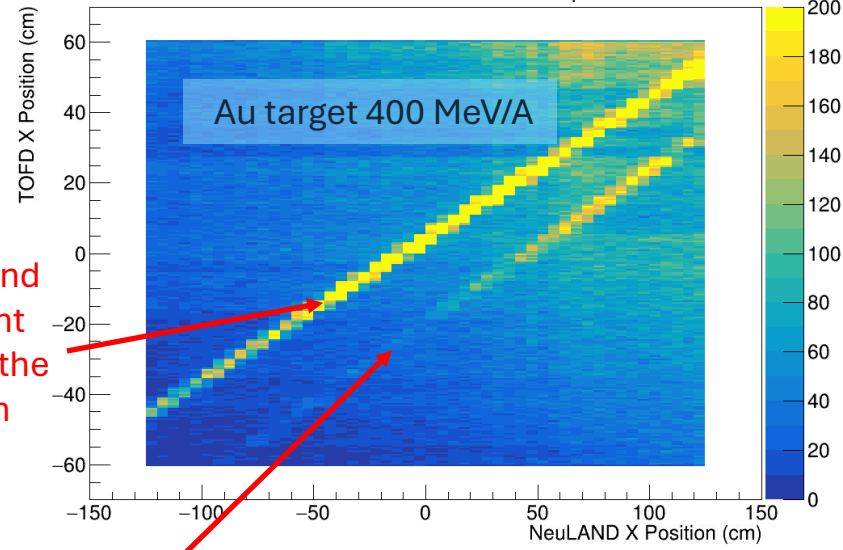
Y position calibration and correlation



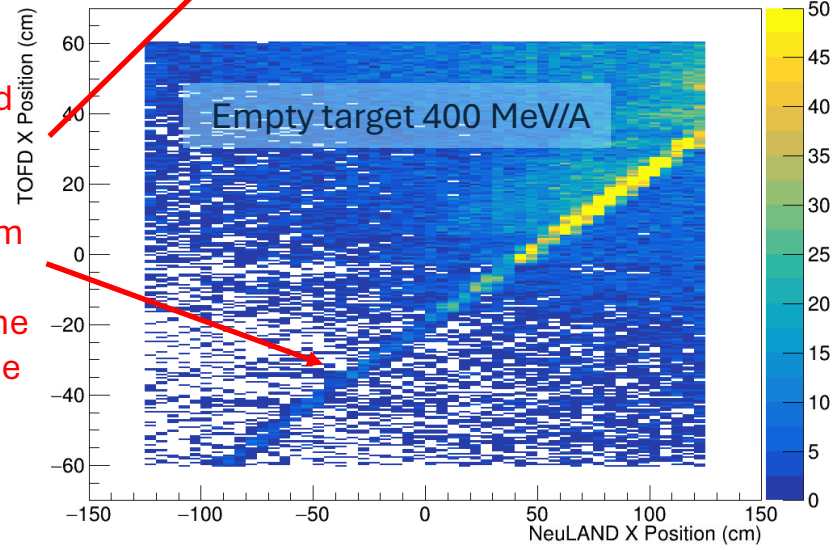


X position correlation

Neuland Plane 2 vs ToFD plane 4

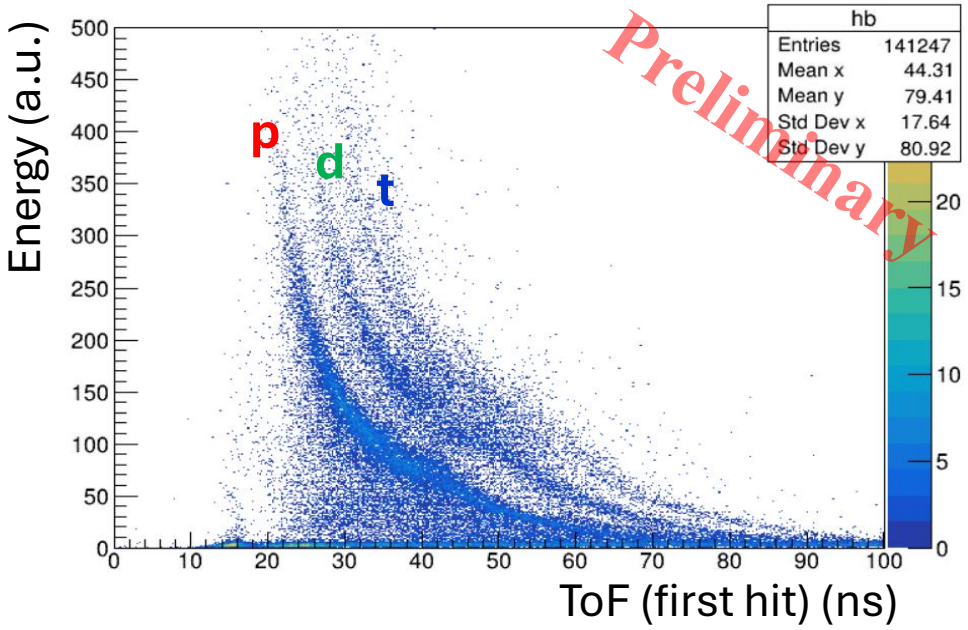


Protons and other light ions from the reaction target



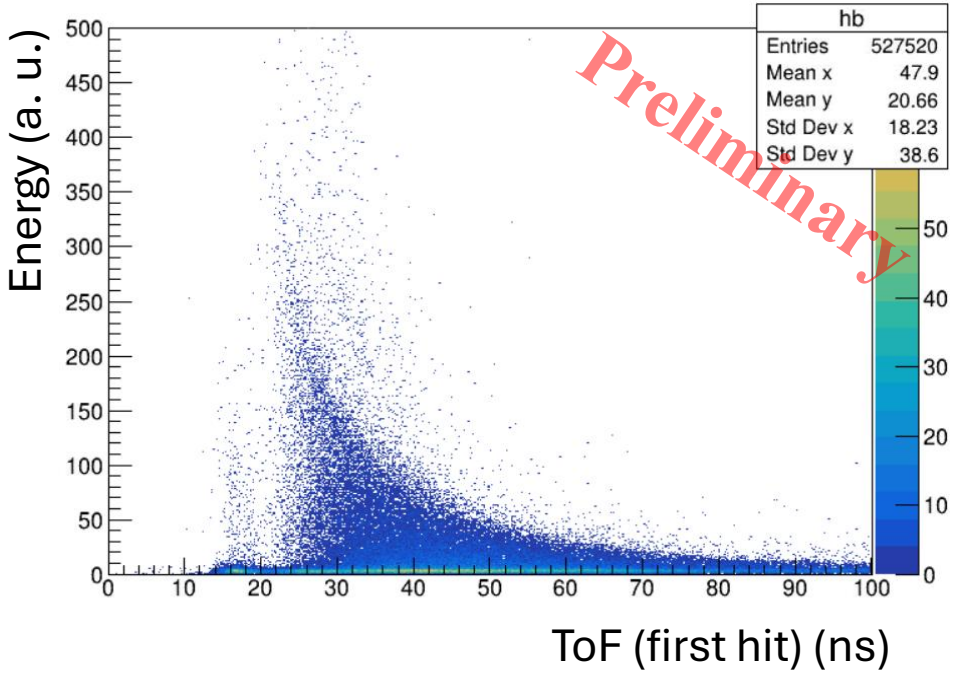
Protons and other light coming (mainly) from the exit window of the vacuum pipe

NeuLAND: n/p elliptic flows

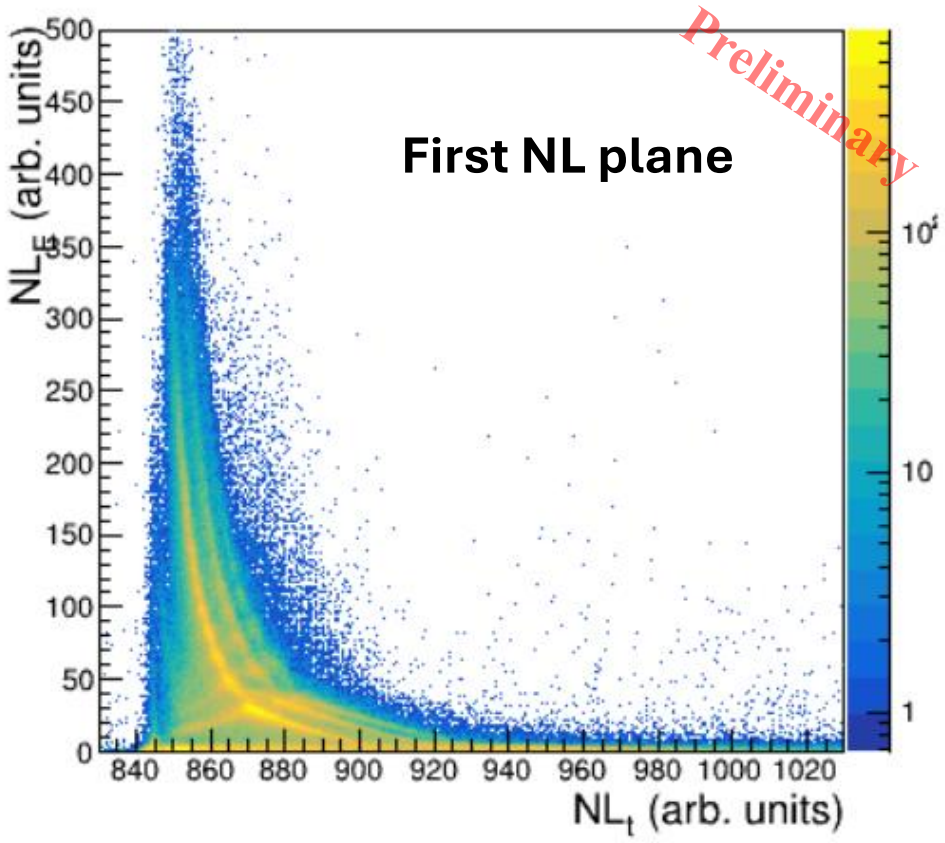


- Preliminary hit clusterizations and raw isotopic identification in Au+Au (280 MeV/A)
  - obtained using the NeuLAND first plane as «veto» detector.
- Charged particles (p, d, t) are well resolved.

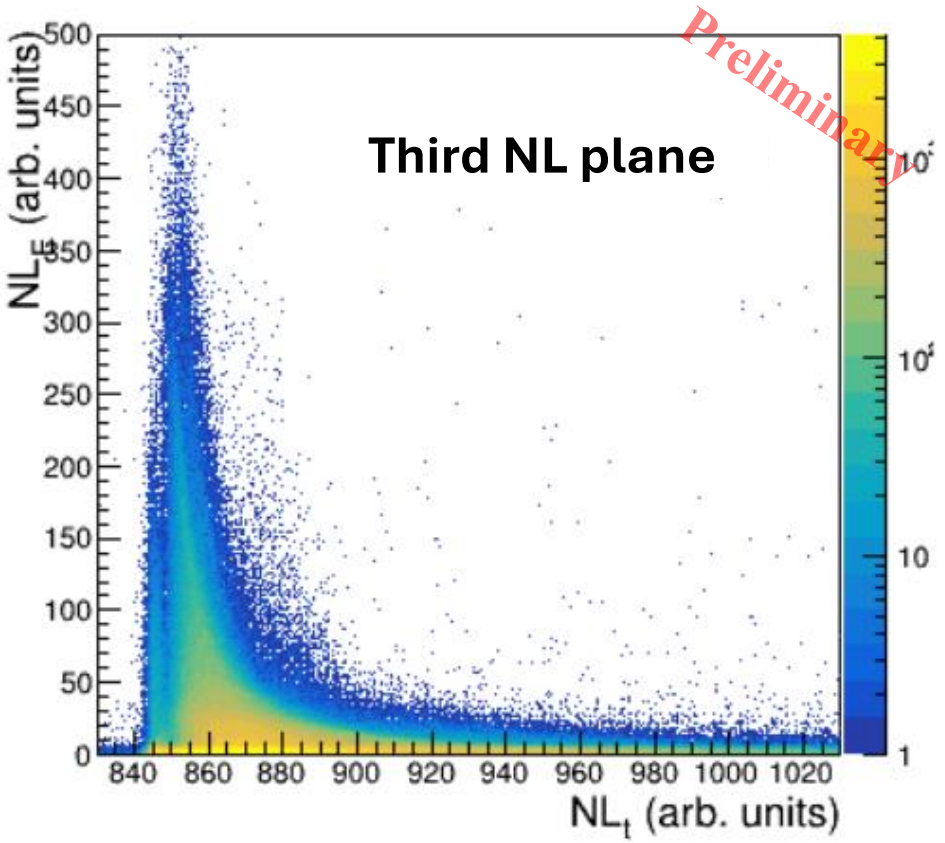
Raw **neutron** identification obtained using the complementary condition (no first plane fired)



NeuLAND: preliminary cluster analysis



Time-of-Flight vs cluster energy deposited on NeuLAND, in which the first hit of the “cluster” is in the first plane; p, d, t are clearly visible



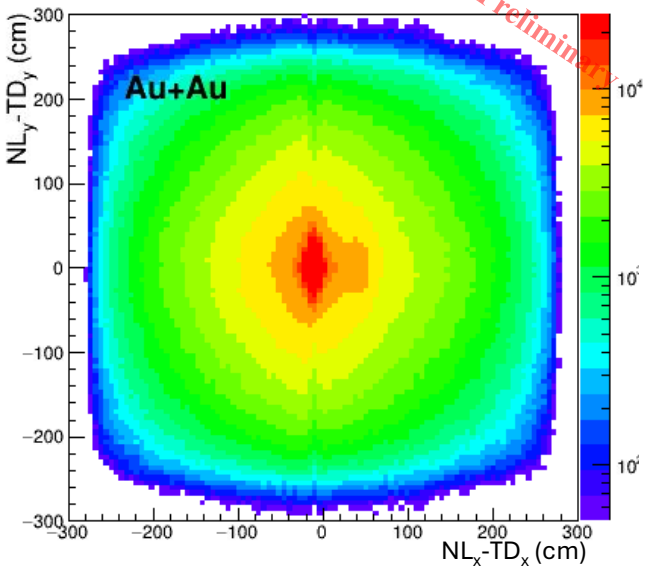
Time-of-Flight vs cluster energy deposited on NeuLAND, with the first hit of the “cluster” occurring in the third plane: n and γ rays

NeuLAND-Veto [Δx, Δy] position correlation

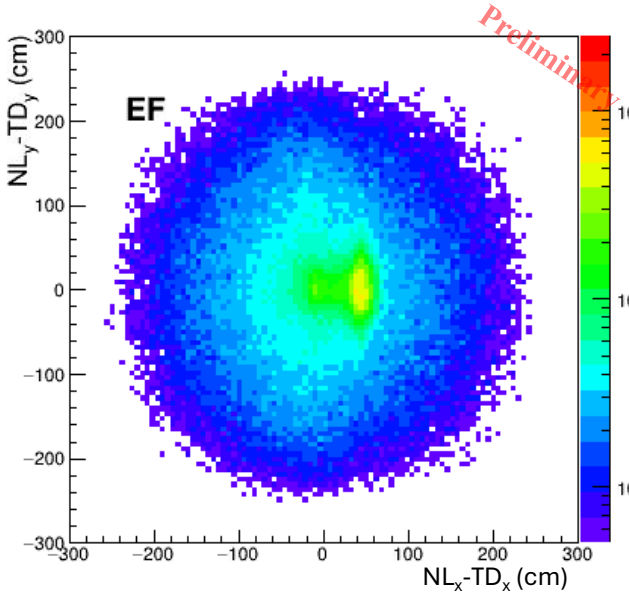
Horizontal Δx vs Vertical Δy position difference between NeuLAND and TOFD (veto) (normalized)

Quantify various sources of background for corrections of reaction plane and flow

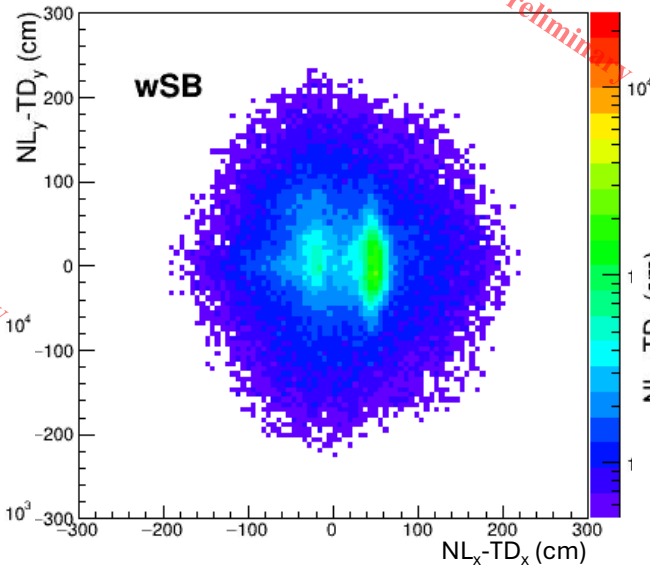
Au+Au@400 AMeV (physics run)



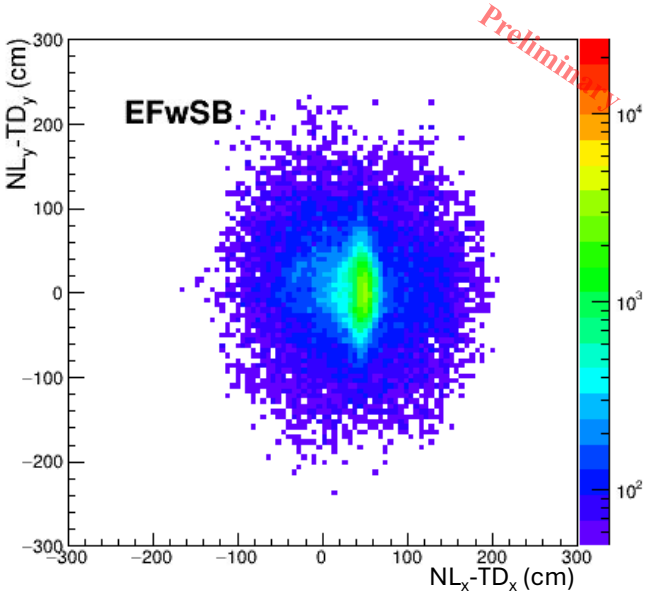
Au+EmptyFrame@ 400 AMeV



Au+Au@400 AMeV (w/ Shadow Bars)



Au+EF@400 AMeV (w/ Shadow Bars)



Conclusions

Experiment
- S122 completed (March 2025, ~16 days)
- Au+Au @ 280, 400, 600, 1000 AMeV
- Stable beam, high statistics

Analysis status
- CHIMERA & KRAB: advanced data reduction
- Reaction plane determination seems robust
- Preliminary impact parameter determination: (comparison with simulations needed)

Detector work
- ToFD calibration ongoing
- NeuLAND + veto refinement in progress
- Joint n/p flow extraction requires careful tuning

Next steps
- Optimizing data analysis ongoing
- Background evaluation and subtraction
- Setting up a theoretical taskforce (various transport models, TMEP)
- Consistent experiment–theory comparison

- This project has received funding from the European Union's Horizon Europe Research and Innovation programme under Grant Agreement No 101057511
- This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824093 (STRONG2020)

Thank you for your attention!

This was made possible by a large collaboration from many countries:

R³B – GSI (Germany)
CHIMERA (Italy)
IFJ-PAN Krakow (Poland)
INDRA-FAZIA (France-Italy)
MSU-FRIB (USA)
Texas A&M (USA)
GANIL (France)
RIKEN (Japan)

Spokespersons S122:

P. Russotto (INFN-LNS, Italy)
J. Łukasik (IFJ-PAN Krakow, Poland)
A. Le Fèvre (GSI Darmstadt, Germany)