Density Dependence of Symmetry Term from High Energy Experiments

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- Symmetry energy
- Observables and sensitivity (INDRA, FOPI)
- FOPI/LAND data (1993/2011)
- ASY-EOS Experiment (2011)
- Challenges and future directions

NuSYM13, East Lansing, 22-26.07.2013

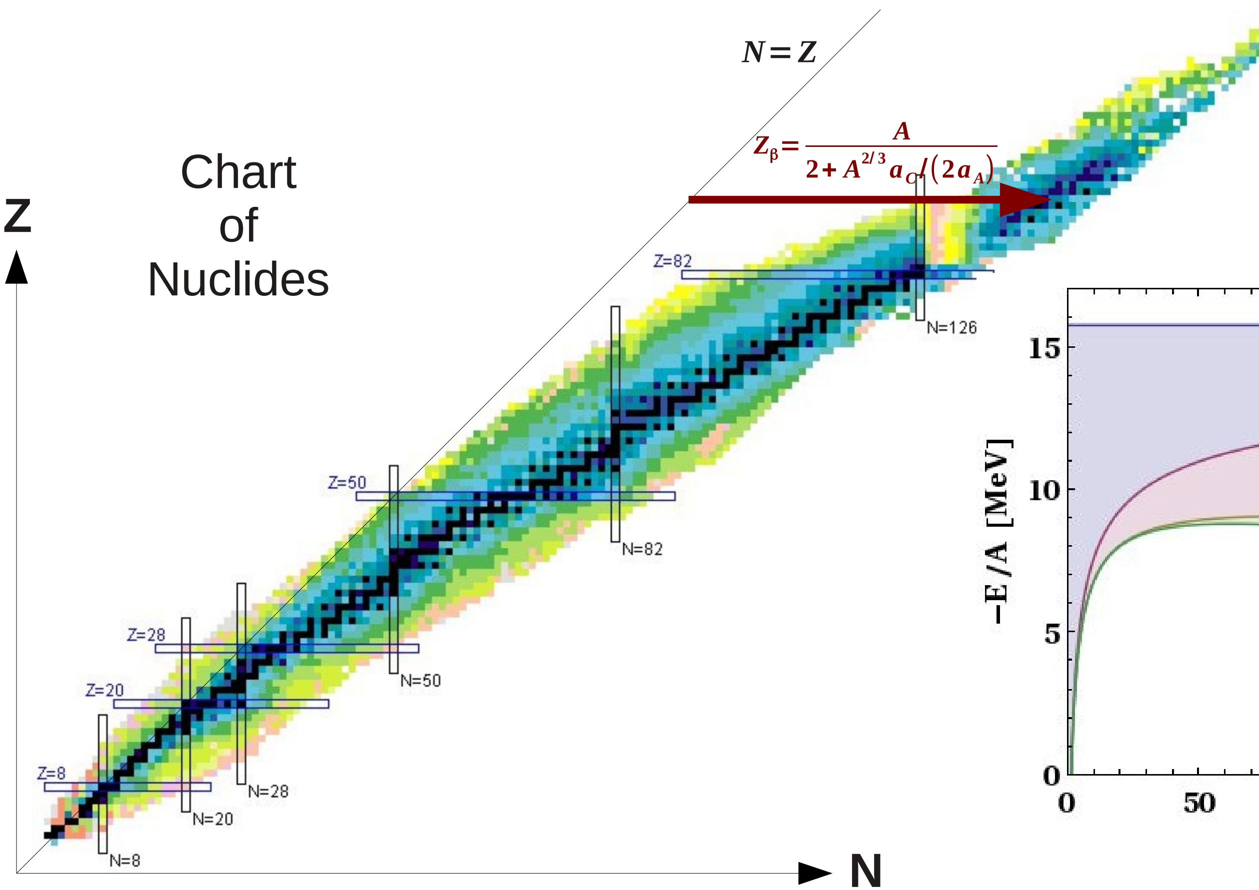
Symmetry Energy (nucleus)

$$\frac{E_B}{A} = \underbrace{-a_V}_{Volume} + \underbrace{a_S \frac{1}{A^{1/3}}}_{Surface} + \underbrace{a_C \frac{Z^2}{A^{4/3}}}_{Coulomb} \underbrace{+ a_A \left(\frac{N-Z}{A}\right)^2}_{Symmetry} \pm \underbrace{a_P \frac{1}{A^{3/2}}}_{Pairing}$$

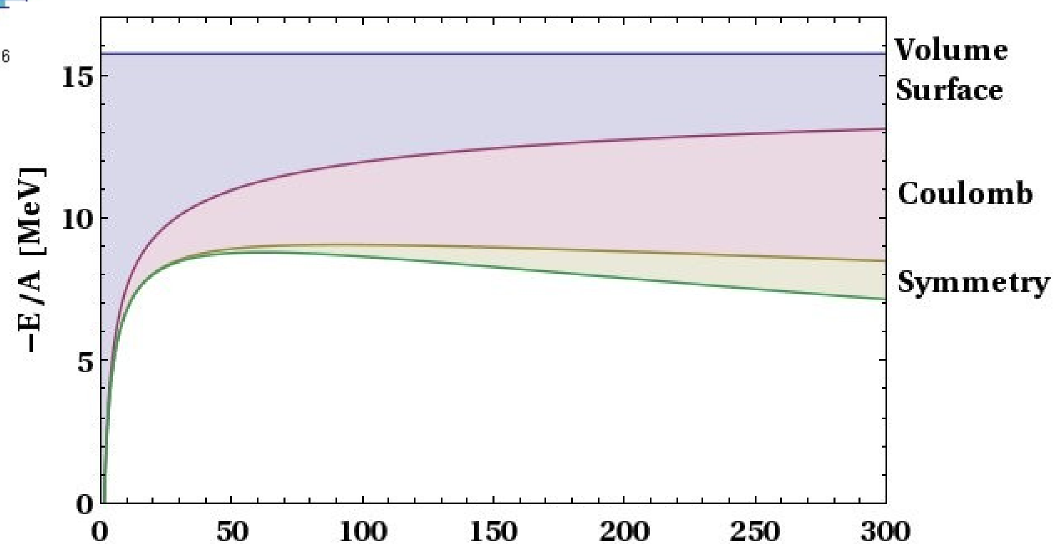
Binding Energy/Nucleon (semiempirical Bethe-Weizsäcker) acc. better than 1%

a_V=15.8	a_S=18.0	a_C=0.72	a_A=23.5	a_P=11.5|0	[MeV]

Chart of Nuclides



Contribution of:



β-stable isotopes

Symmetry Energy (nuclear matter)

$$\frac{E_B}{A} = \underbrace{-a_V}_{Volume} + \underbrace{a_S \frac{1}{A^{1/3}}}_{Surface} + \underbrace{a_C \frac{Z^2}{A^{4/3}}}_{Coulomb} \underbrace{+ a_A \left(\frac{N-Z}{A}\right)^2}_{Symmetry} \underbrace{\pm a_P \frac{1}{A^{3/2}}}_{Pairing}$$

Energy per nucleon in nuclear matter (EoS):

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

dominant symmetric matter (N=Z) term:

$$E(\rho,0) \approx -a_V + \frac{K}{18}\left(\frac{\rho-\rho_o}{\rho_o}\right)^2 + \cdots$$

symmetry term:

$$E_{sym}(\rho) \approx a_A^V + \frac{L}{3}\left(\frac{\rho-\rho_o}{\rho_o}\right) + \frac{K_{sym}}{18}\left(\frac{\rho-\rho_o}{\rho_o}\right)^2 + \cdots$$

ρ_n, ρ_p → neutron, proton densities

$\rho = \rho_n + \rho_p$ → nucleon density

$\delta = \frac{\rho_n - \rho_p}{\rho}$ → isospin asymmetry

$L = 3\rho_o \left.\frac{\partial E_{sym}}{\partial \rho}\right|_{\rho=\rho_o}$ → ~symmetry pressure

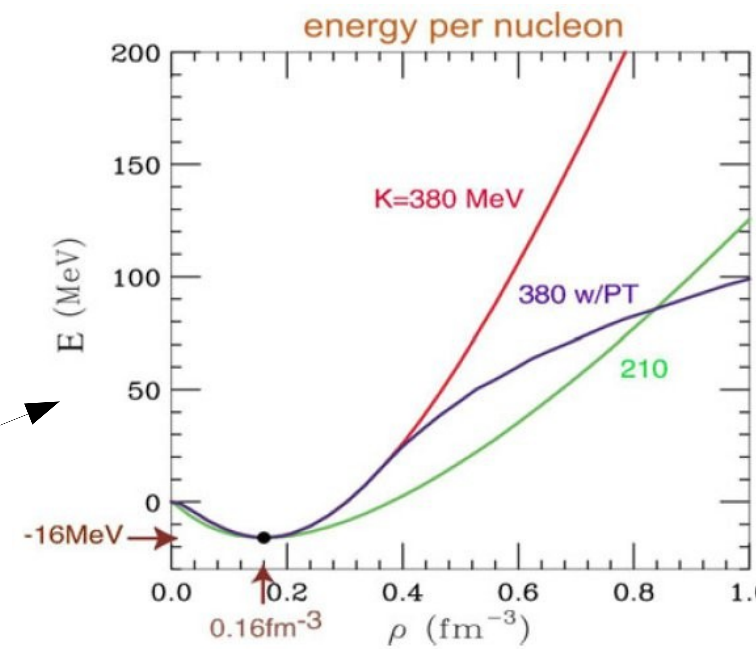
$K = 9\rho_o^2 \left.\frac{\partial^2 E}{\partial \rho^2}\right|_{\rho=\rho_o}$ → compressibility

$a_V \approx 15.8\, MeV$

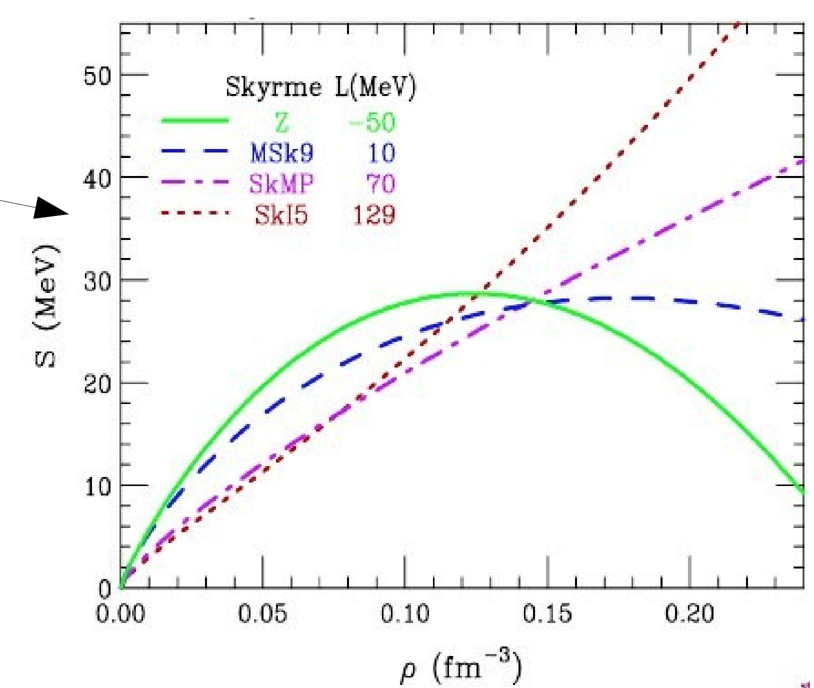
$a_A^V \approx 32.5^{(*)}\, MeV$

$\delta^2(^{208}\mathrm{Pb}) \simeq 0.04$

$\delta^2(^{271}\mathrm{Pb}) \simeq 0.16$

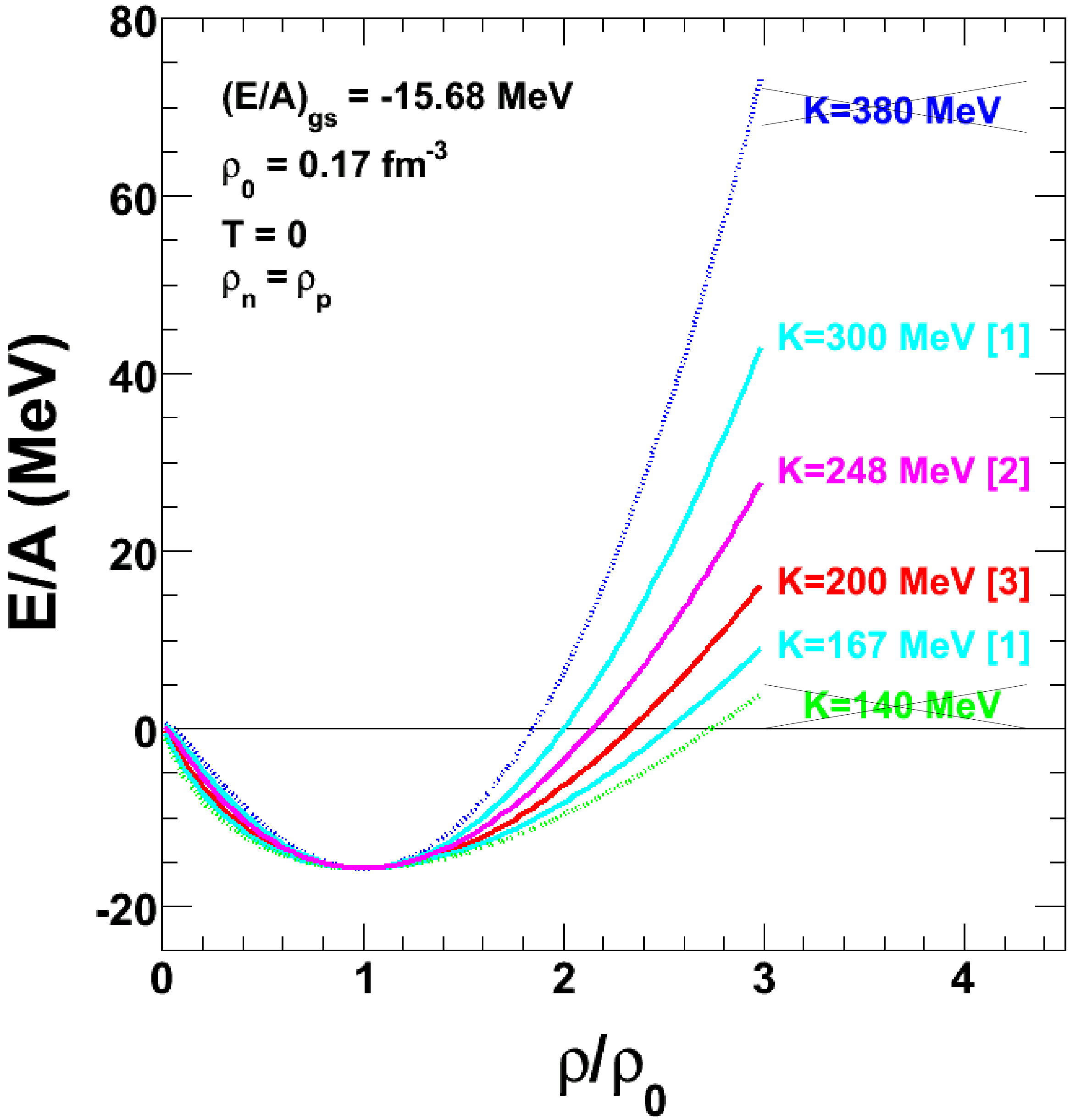


P. Danielewicz, arXiv:nucl-th/0512009



(*)P. Danielewicz, J. Lee, NPA 818(2009)36

Symmetric matter (δ=0)



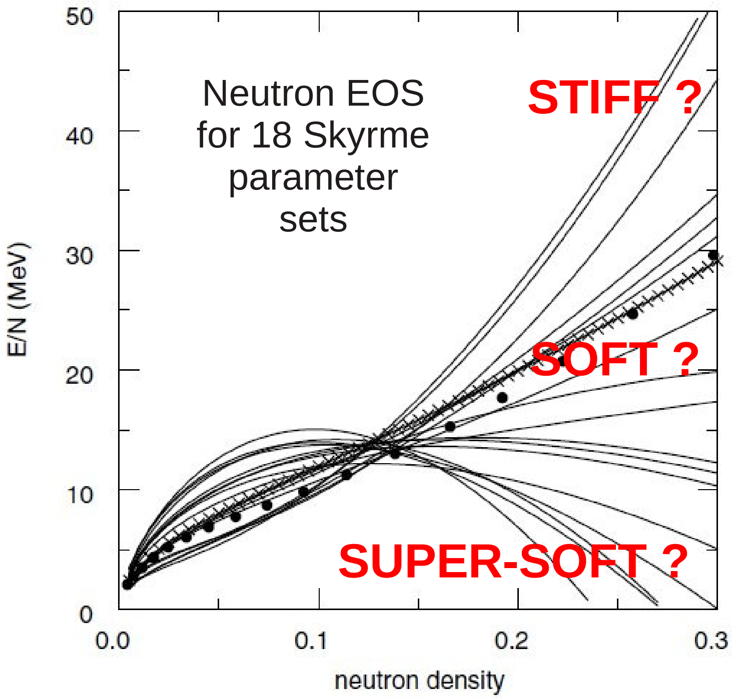
[1] Flow:
P. Danielewicz et al., Science 298 (02) 1592
BME: K = 167-300 MeV

[2] ISGMR:
J. Piekarewicz, PRC 69 (04) 041301
RMF: K=248 MeV
G. Colò et al.,PRC 70 (04) 024307
Skyrme HF: K=230 MeV

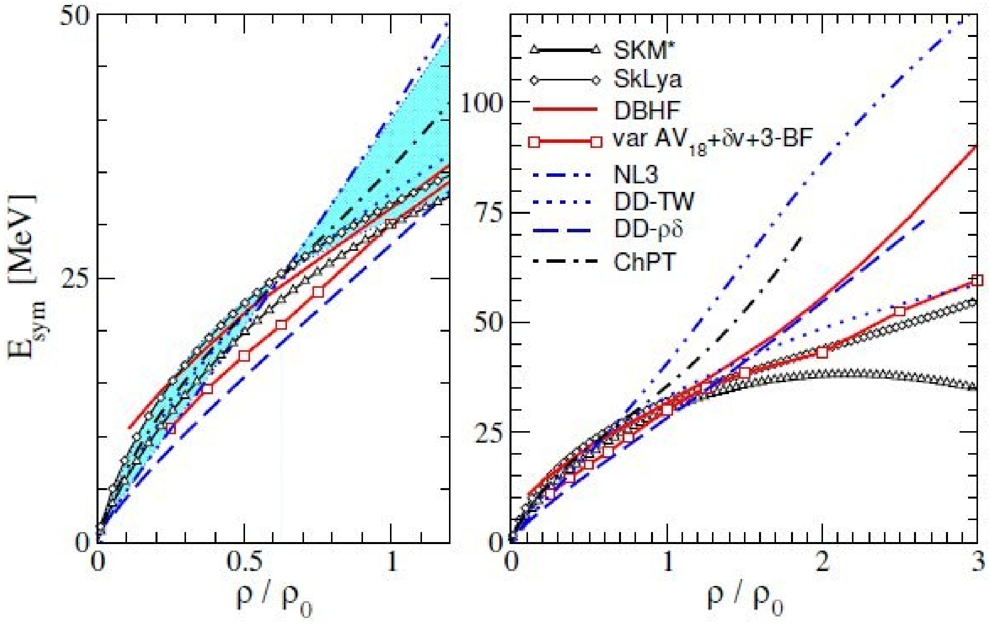
[3] Subtreshold K^+:
C. Sturm et al., PRL 86 (01) 39
Ch. Hartnack et al., PRL 96 (06) 012302
Flow:
W. Reisdorf (FOPI) arXiv:1307.4210 [nucl-ex]
IQMD: K=200 MeV

Model and data dependent values of K for isoscalar part
Still ~20-30% uncertainty

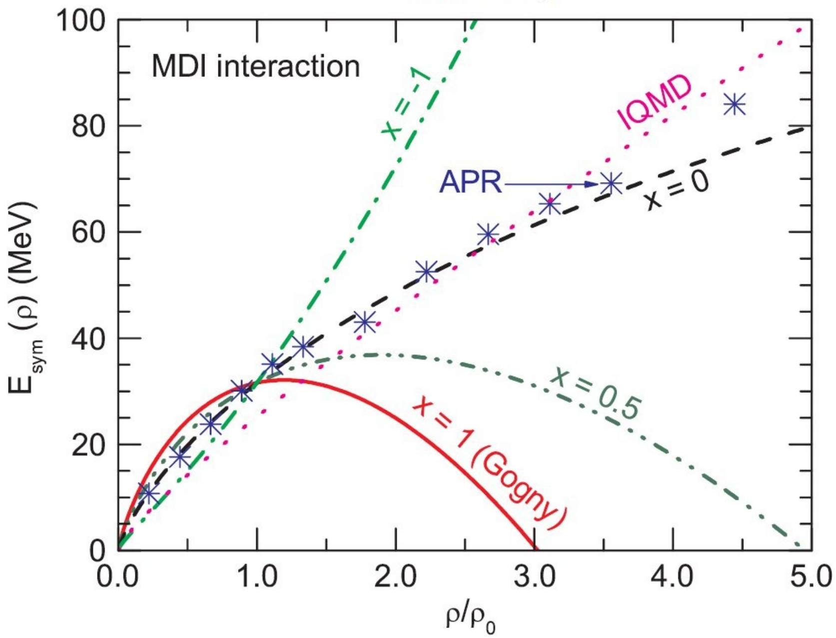
Symmetry term. Why so uncertain?



B. Alex Brown, PRL 85(2000)5296



C. Fuchs and H.H. Wolter, EPJA 30(2006)5



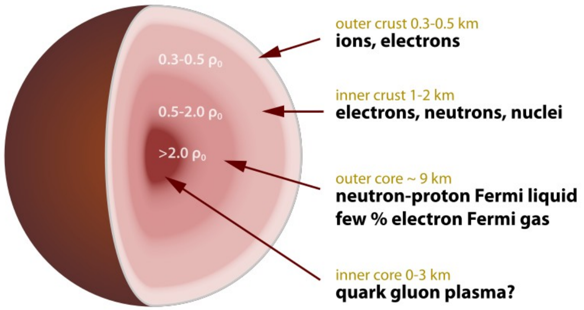
Z. Xiao et al., PRL 102(2009)062502

Symmetry energy uncertain at high density and modified by clustering at low density

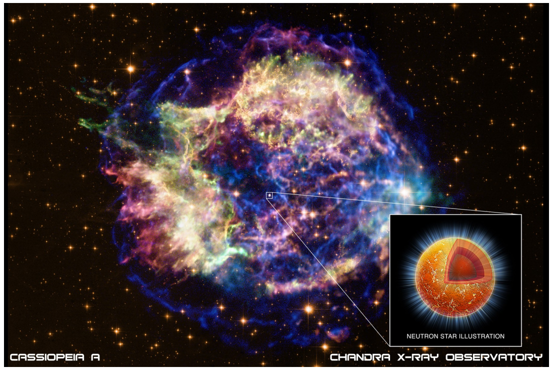
Phenomenological forces constrained around saturation and for nearly isospin-symmetric matter. Poor knowledge of effective forces in neutron-rich matter. Uncertainties in the nature of the three-neutron force. Uncertain extrapolations above the saturation density.

Why so important?

- Neutron star structure, composition, size, mass and cooling rate
- Supernova explosions

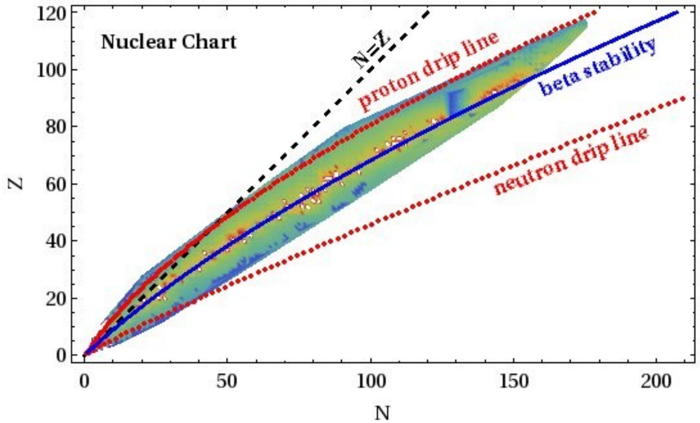


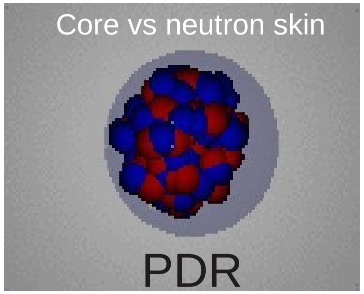
Robert Schulze (Wikipedia)



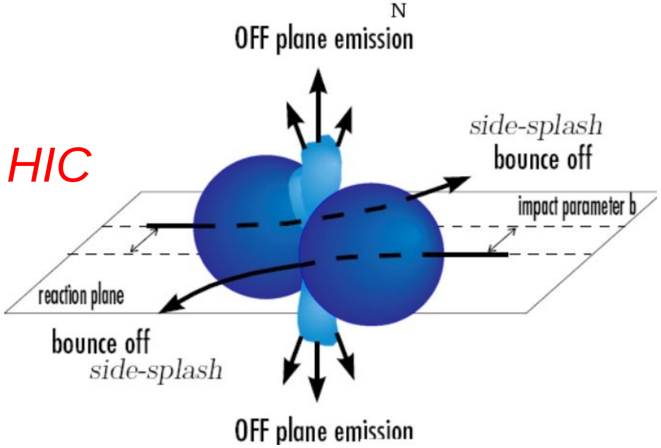
Cassiopeia A Supernova Remnant
(http://chandra.harvard.edu/photo/printgallery/2004/)

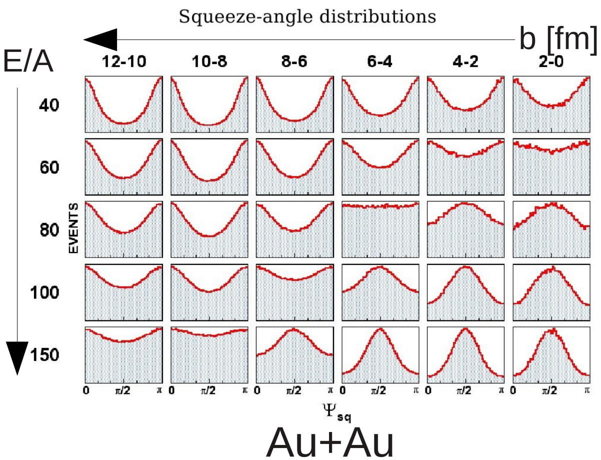
- Structure of the nucleus (masses, drip lines)
- Neutron skin thickness
- IvGDR
- Pygmy resonances
- Differences between IAS



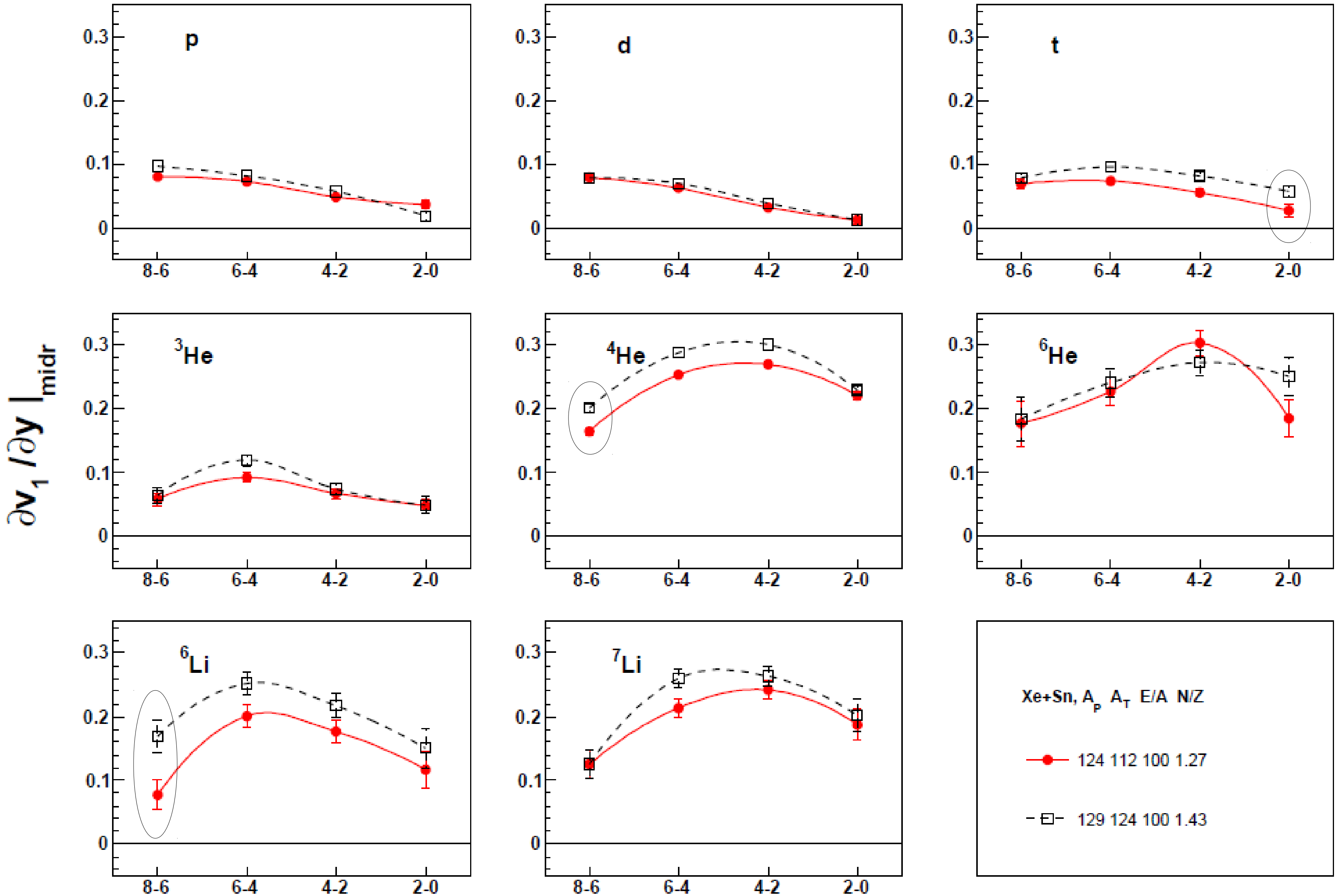


- *Flow patterns in HIC*
- *n/p, t/^{3}He, π^-/π^+, K^+/K^0 ratios in HIC*





INDRA@GSI: ^{124,129}Xe + ^{112,124}Sn @ 100 AMeV
slope of v1 at midrapidity

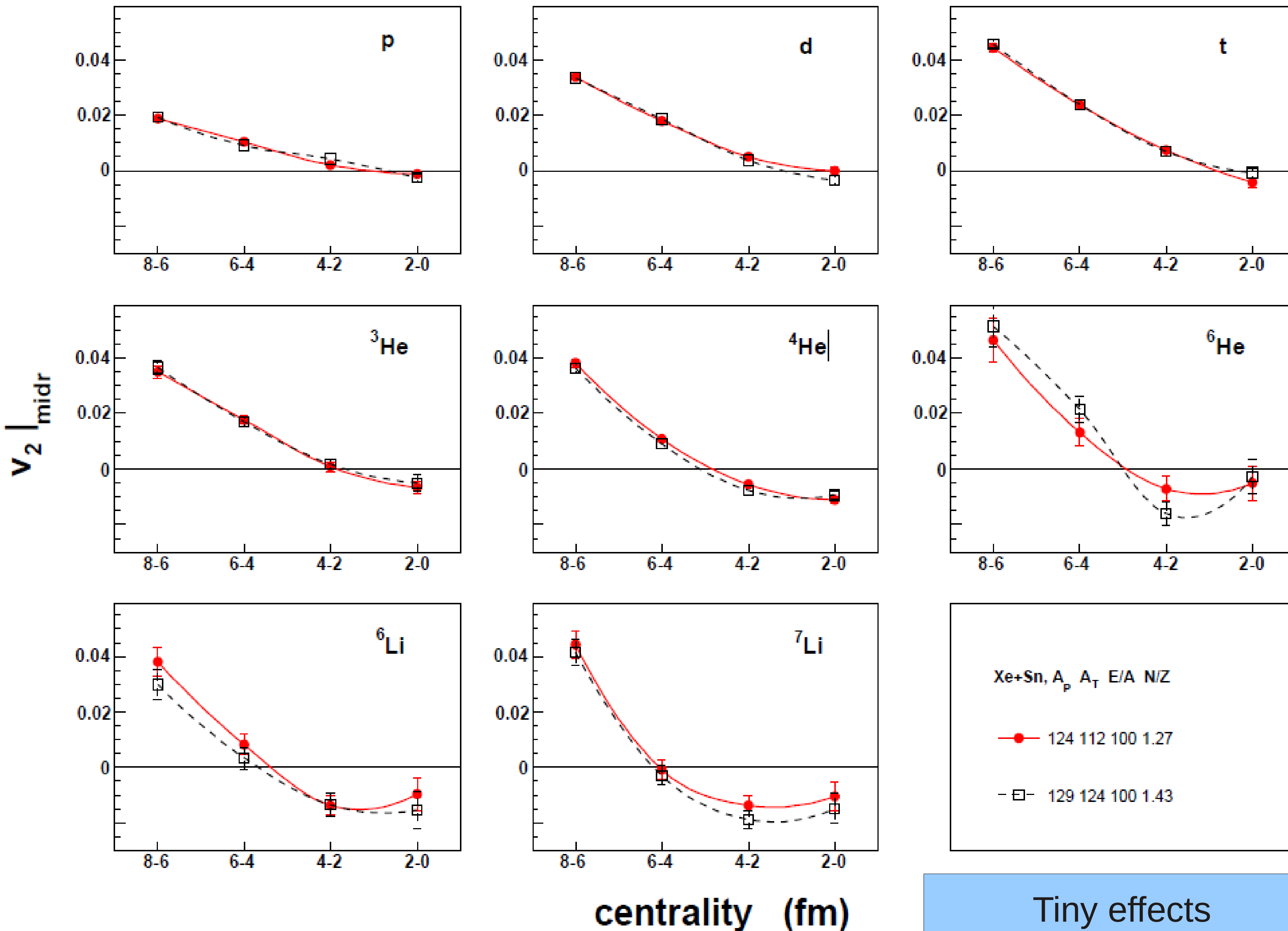


~7% total mass difference between the two systems

Tiny effects

J. Łukasik and W. Trautmann (INDRA-ALADIN), arXiv:0708.2821[nucl-ex]

INDRA@GSI: ^{124,129}Xe + ^{112,124}Sn @ 100 AMeV
v2 at midrapidity



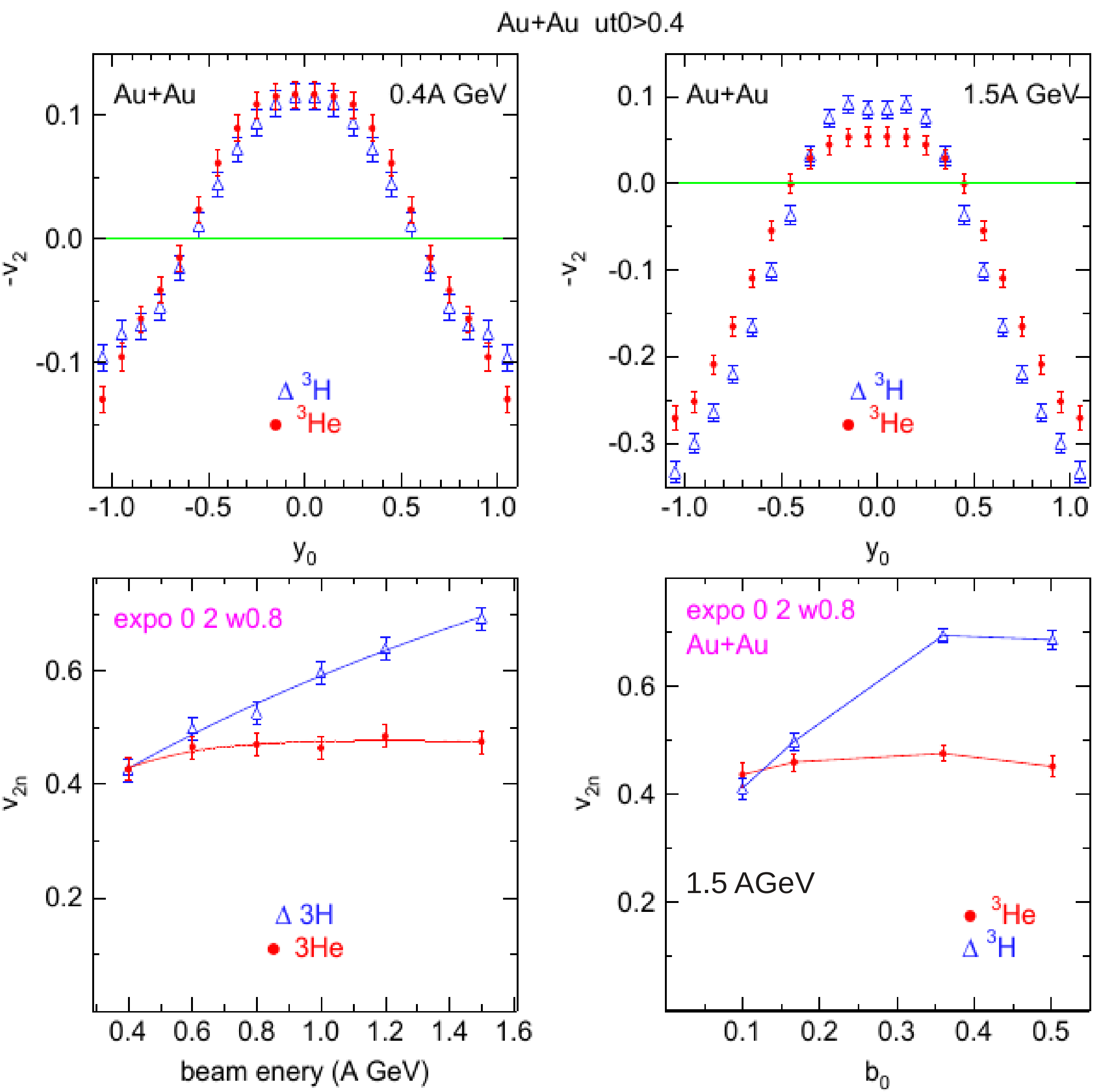
J. Łukasik and W. Trautmann(INDRA-ALADIN), arXiv:0708.2821[nucl-ex]

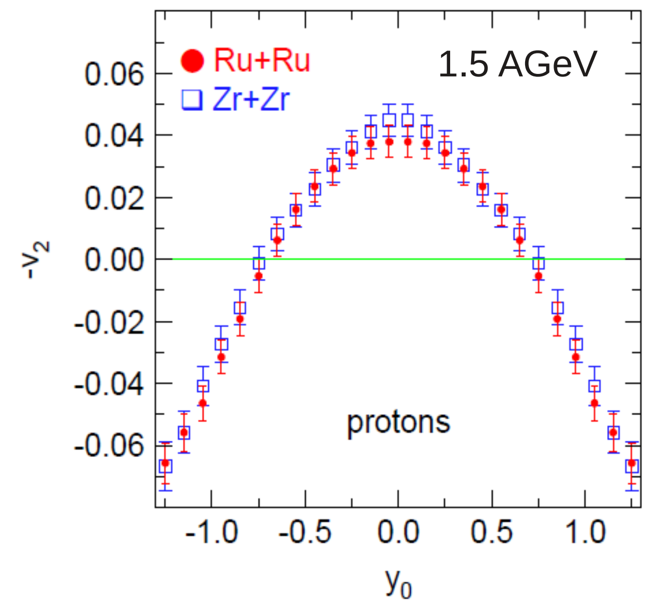
Tiny effects

FOPI

W. Reisdorf (FOPI) NPA 876(2012)1

W. Reisdorf (FOPI) arXiv:1307.4210 [nucl-ex]





Increasing sensitivity of cluster isospin probes with

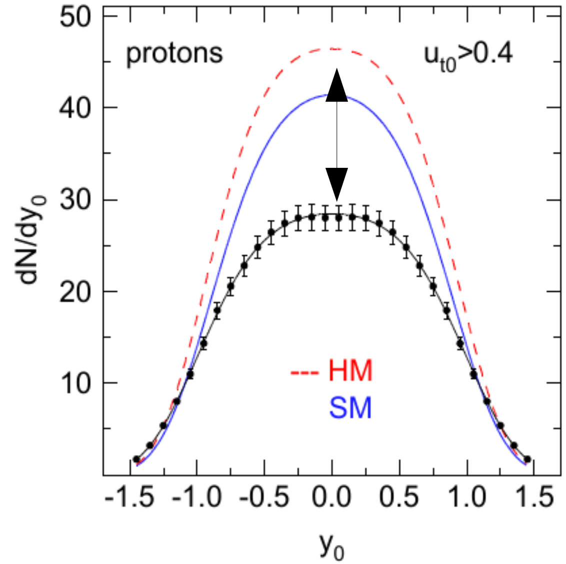
- beam energy
- impact parameter
- mass of the system
- mass of the probe

Reliable cluster production algorithms needed

v_{2n} parametrizes the whole v_2 rapidity distribution

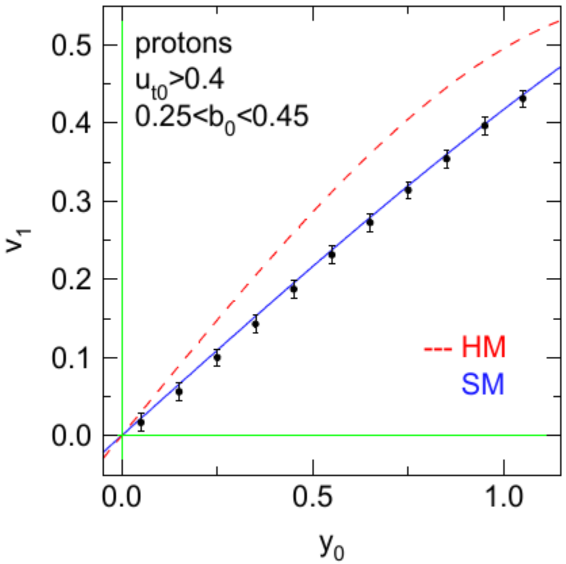
FOPI + IQMD

W. Reisdorf (FOPI) arXiv:1307.4210 [nucl-ex]



Au+Au @ 1 AGeV,
Scaled rapidity distribution

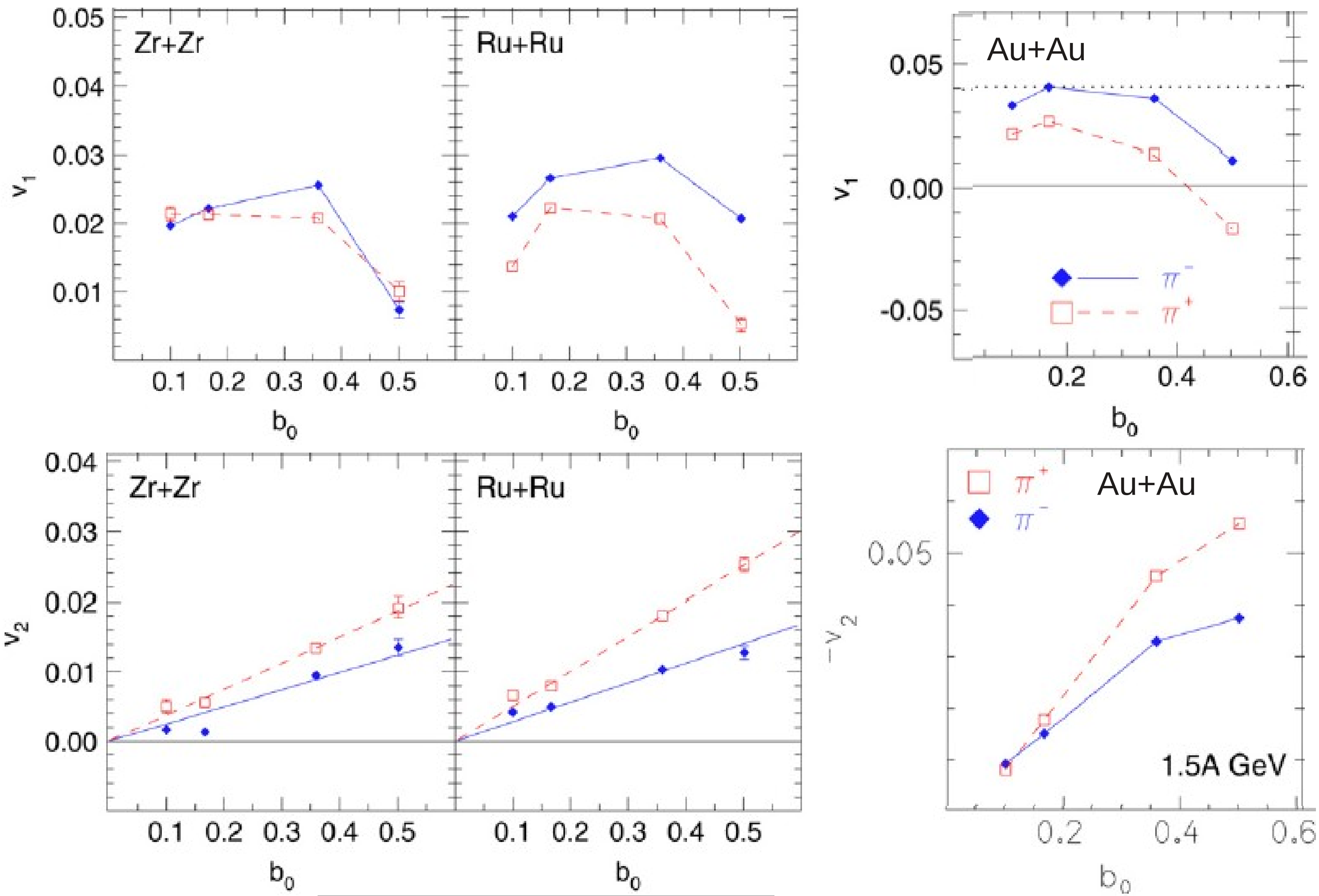
Reliable cluster production algorithms needed



Au+Au @ 1 AGeV,
v1 vs scaled rapidity

HM, SM – HARD and SOFT isoscalar EOS parametrizations with momentum dependence

Pion flows, FOPI, 1.5 AGeV

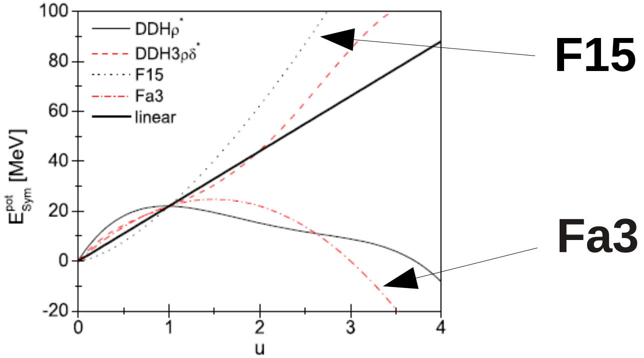


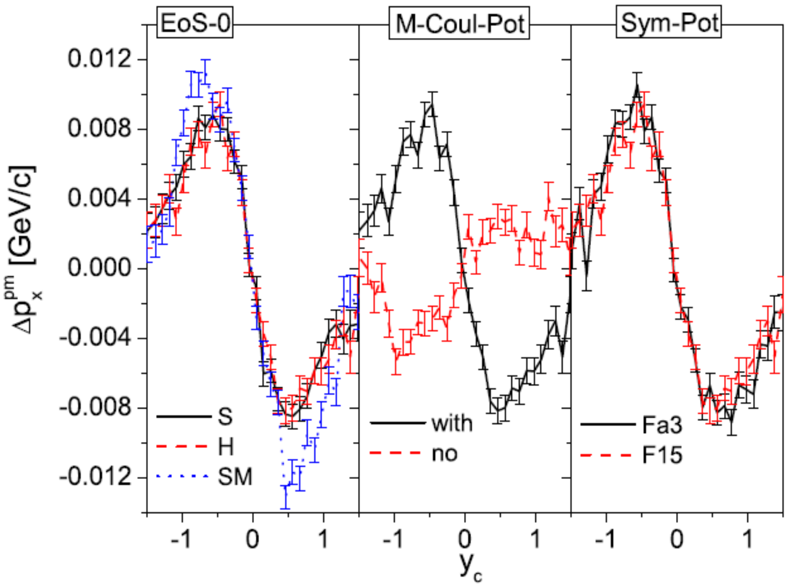
W. Reisdorf et al. FOPI, NPA 781(2007)459

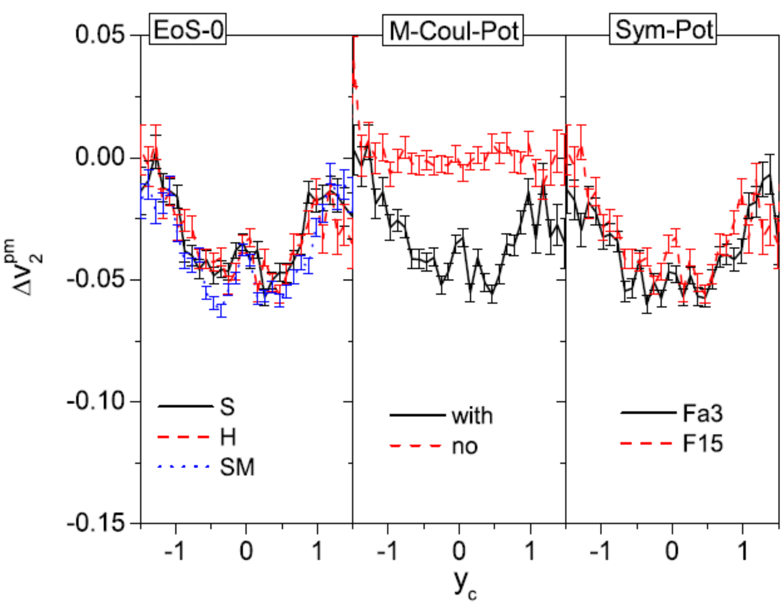
	N/Z	δ^2
$^{96}_{40}Zr$	1.40	0.028
$^{96}_{44}Ru$	1.18	0.007
$^{197}_{79}Au$	1.49	0.039

Coulomb + shadowing + Symmetry energy effects

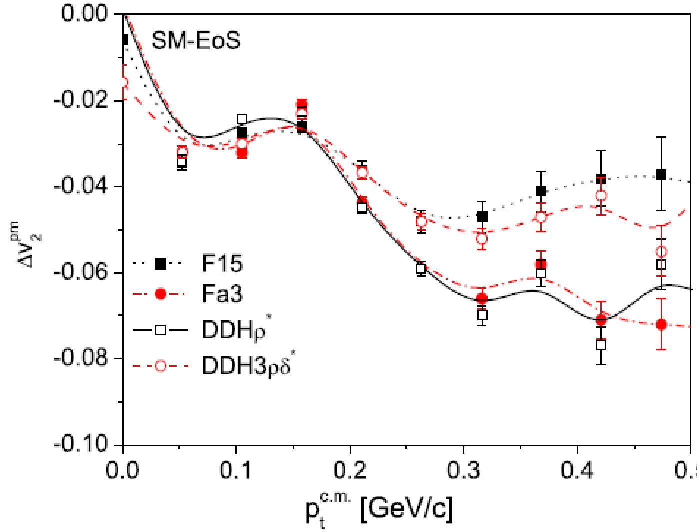
Q-F Li et al. JPG 32(2006) 151 (UrQMD): pion v1 and v2 depend weakly on Esym but are sensitive to the momentum dependence of the meanfield.
But, at high pT, v2 should discriminate between Esym



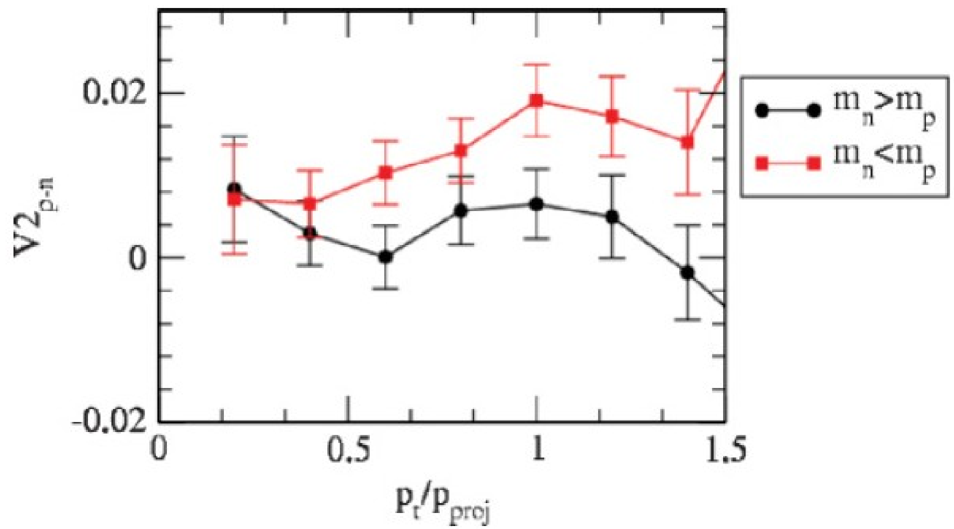




Q-F Li et al. JPG 32(2006) 151 (UrQMD)
208Pb +208 Pb reaction at Eb = 0.8 A GeV and b = 7–9 fm

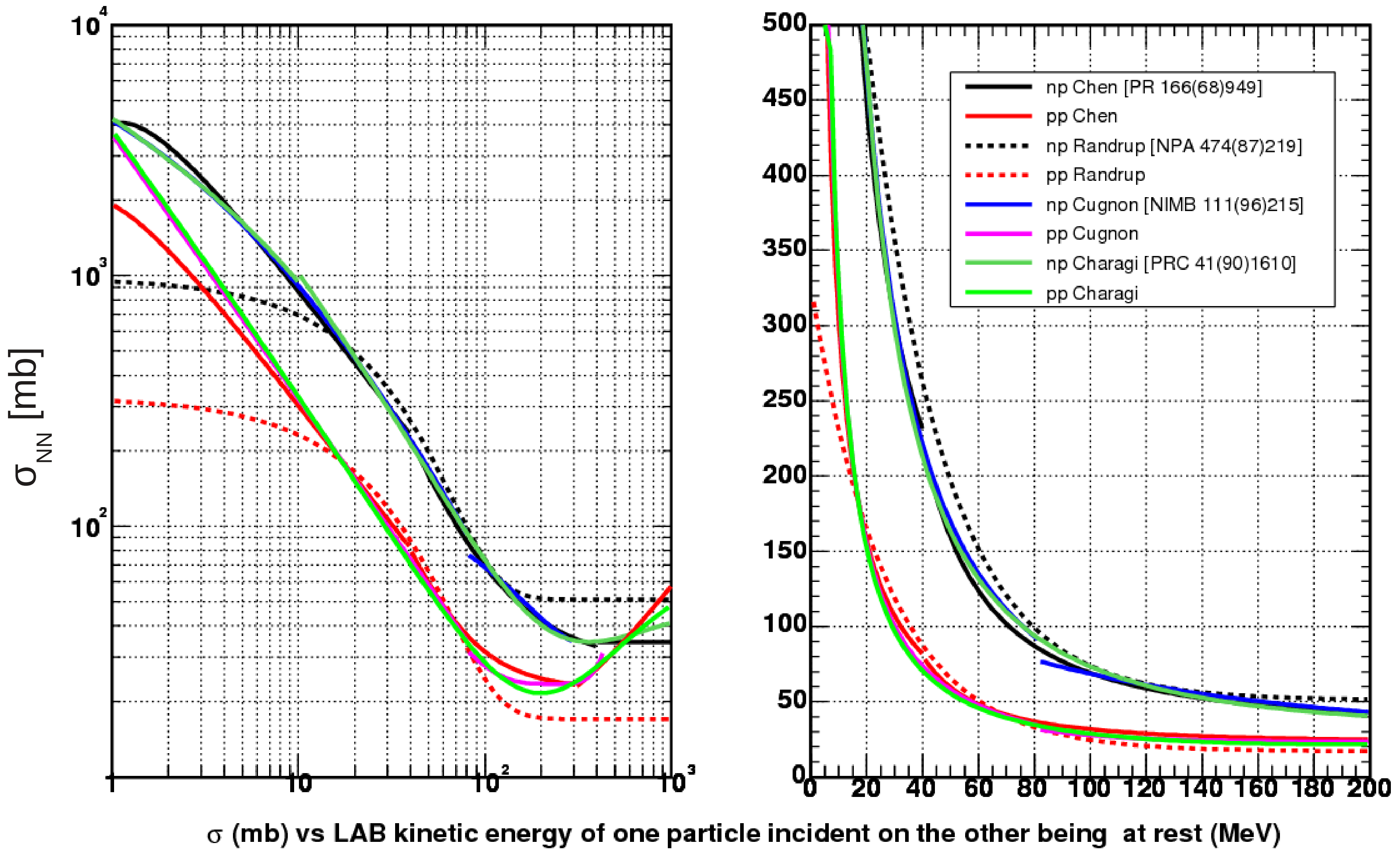


Giordano et al. PRC 81(2010)044611 (SMF)
Au+Au @ 400 AMeV, ASY-STIFF



It is possible that at high pT one may probe
the momentum dependence of the Esym
instead of its density dependence.
Some effects may be due to the σ_{NN} isospin dependence

Free σ_{np} and σ_{pp} as a function of energy



Reanalysis of FOPI/LAND Au+Au @ 400, 600, 800 AMeV

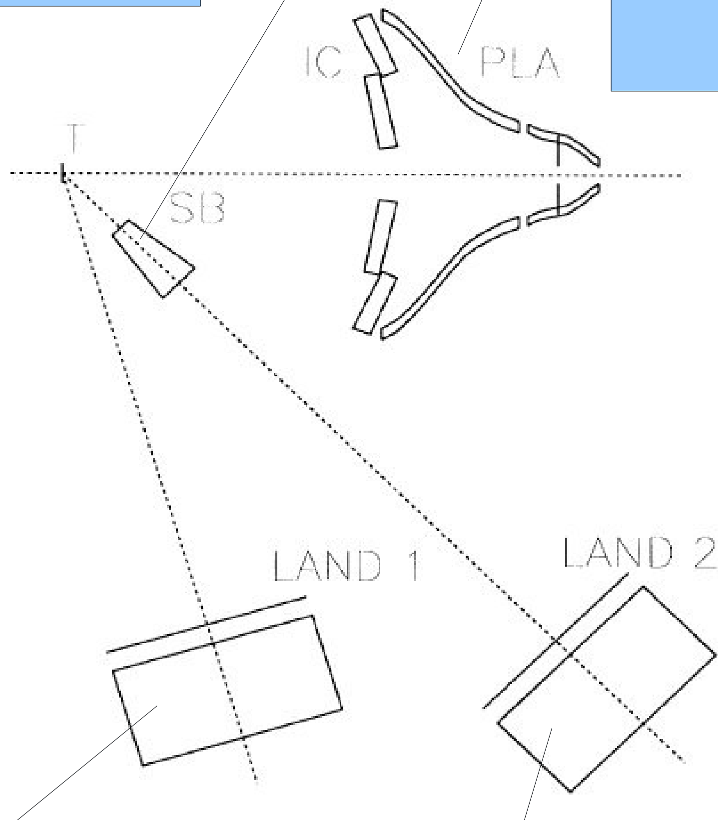
[Y. Leifels et al. PRL 71 (1993) 963]

Setup'93

„shadow bar”

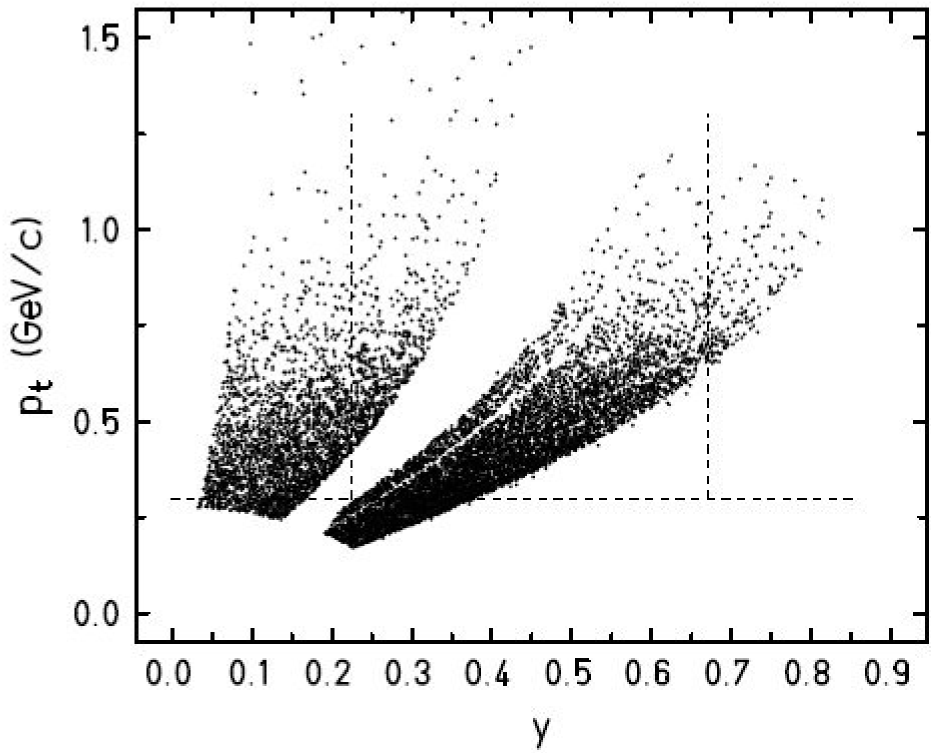
Plastic wall (1^o<θ<30^o)
Centrality &
Reaction plane

beam



LAND1 (61^o<θ<85^o)
Neutrons, Z=1

LAND2 (37^o<θ<53^o)
Neutrons, Z=1



Acceptance for neutrons
and cuts for analysis (dashed)

Reanalysis of FOPI/LAND Au+Au @ 400, 600, 800 AMeV

[Y. Leifels et al. PRL 71 (1993) 963] -> [P. Russotto et al. PLB 697 (2011) 471]

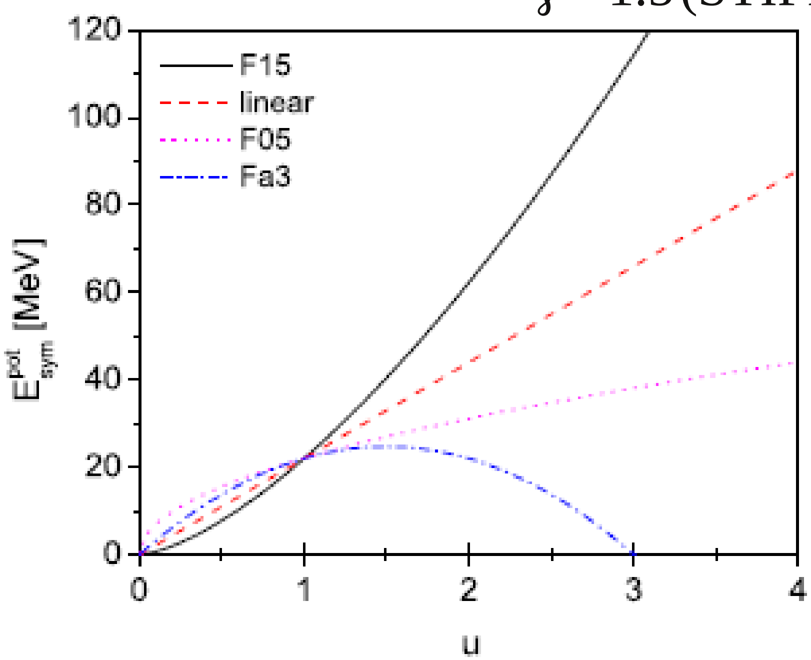
UrQMD, Q. Li, J.Phys. G 31(2005)1359

„Fermi-gas" parametrization of the symmetry term:

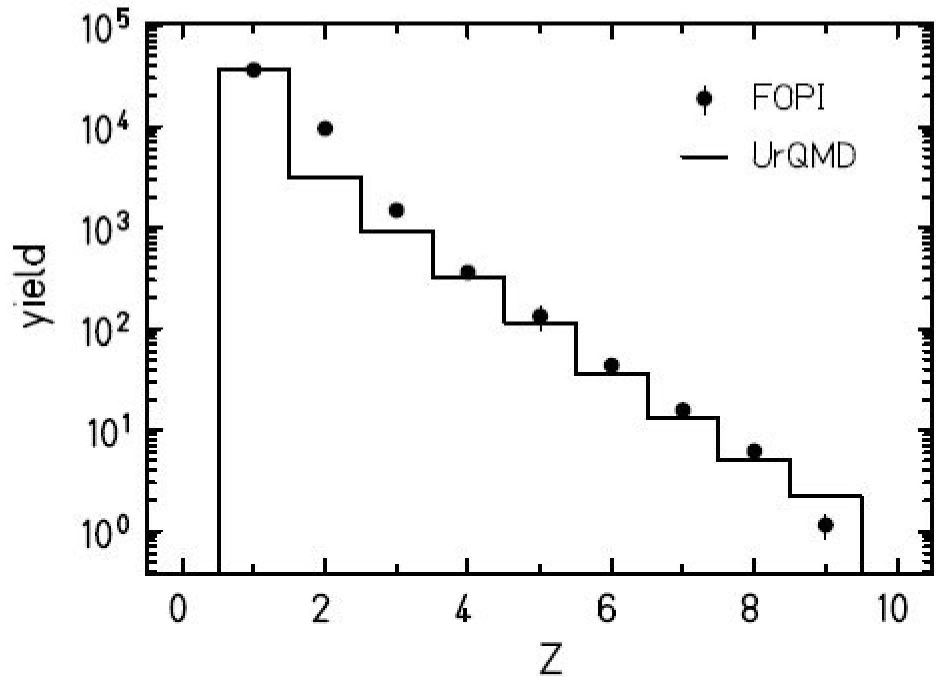
$$E_{sym} = E_{sym}^{pot} + E_{sym}^{kin} = 22\ \mathrm{MeV}\left(\frac{\rho}{\rho_o}\right)^{\gamma} + 12\ \mathrm{MeV}\left(\frac{\rho}{\rho_o}\right)^{2/3}$$

$\gamma = 1.5\,(\mathrm{STIFF})$

$\gamma = 0.5\,(\mathrm{SOFT})$



P. Russotto et al. PLB 697 (2011) 471
Data: W. Reisdorf, et al., NPA 612 (1997) 493
Central collisions, Au+Au @ 400 AMeV



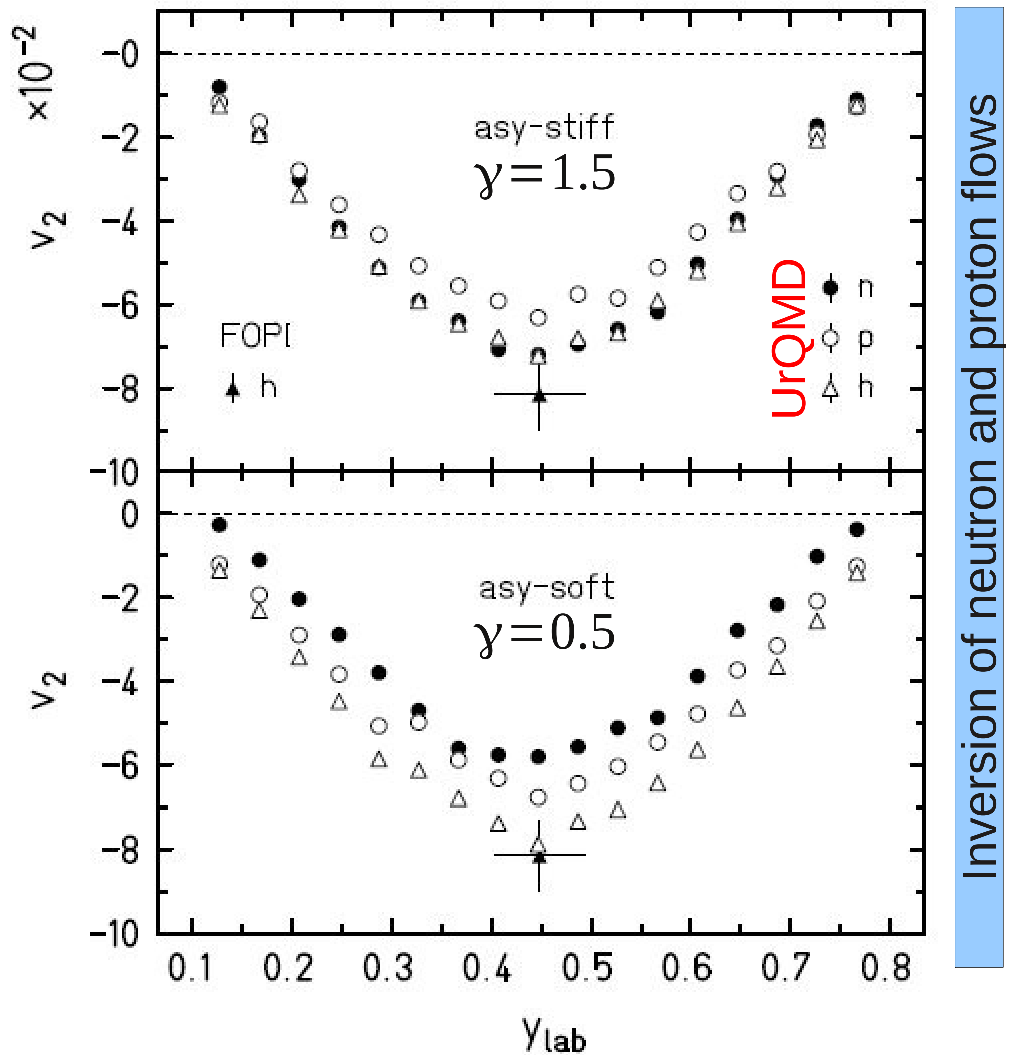
Fragment yields
(test of clustering procedure
with Δr=3 fm and Δp=275 MeV/c)
Normalization at Z=1

d,t,α underpredicted (x 2-3)

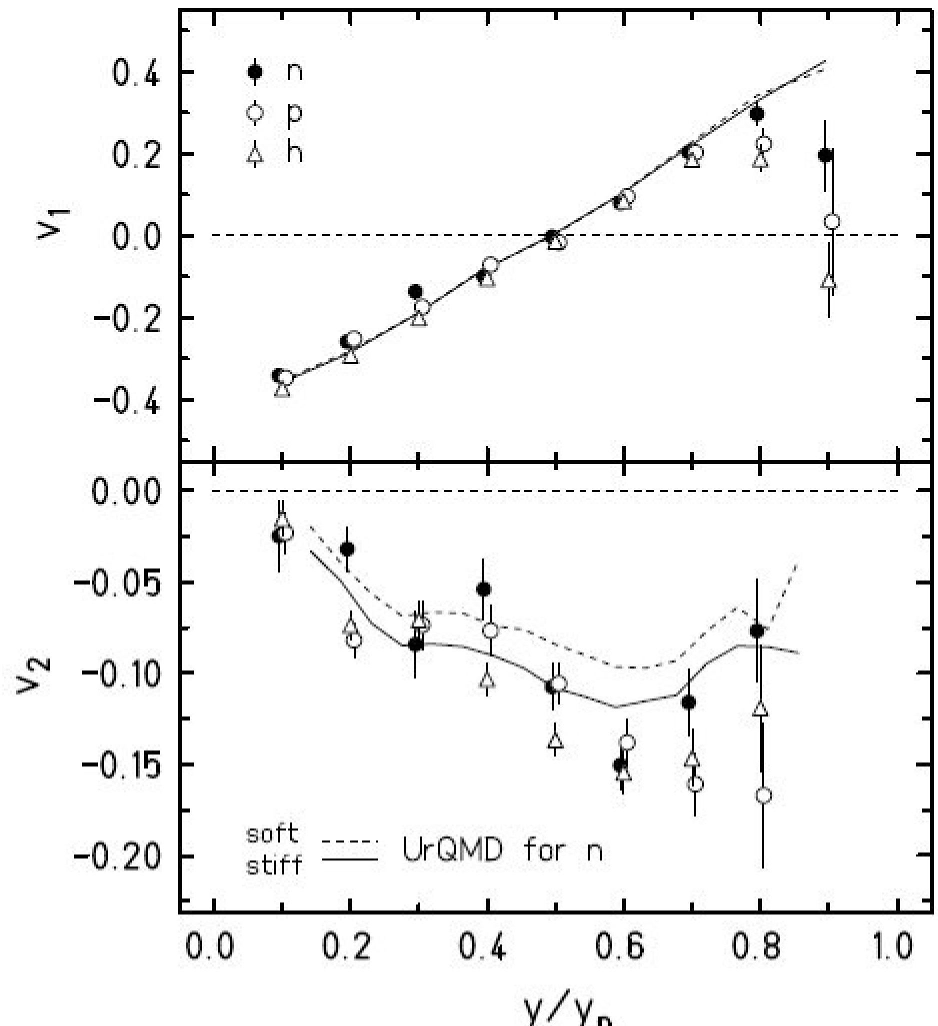
Reanalysis of FOPI/LAND Au+Au @ 400, 600, 800 AMeV

[P. Russotto et al. PLB 697 (2011) 471]

Elliptic flow (v_2)
400 AMeV, 5.5<b<7.5 fm

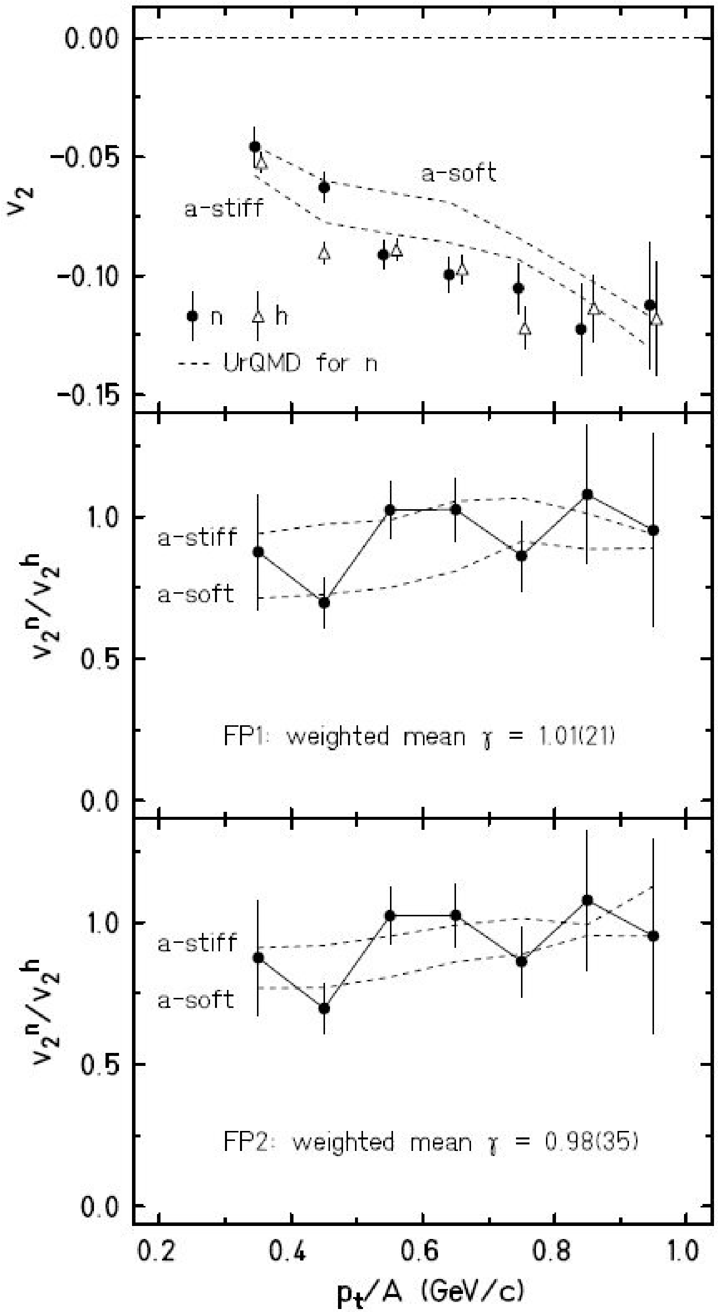


v_2 more sensitive than v_1



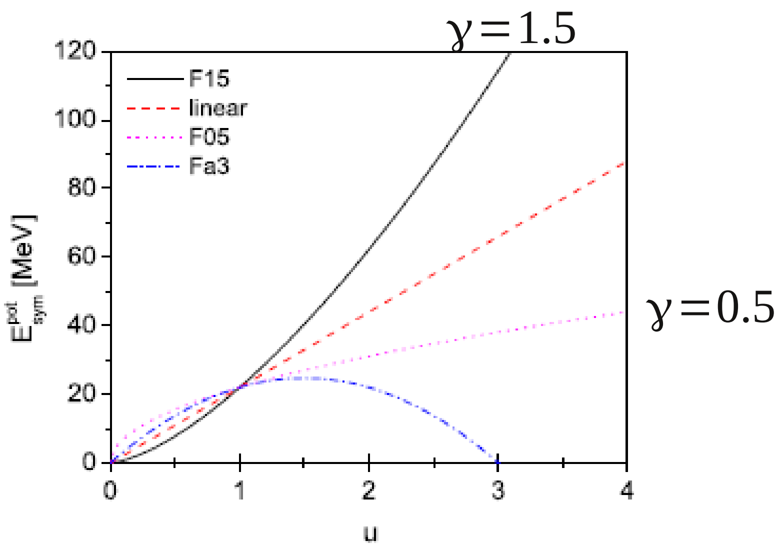
Reanalysis of FOPI/LAND Au+Au @ 400, 600, 800 AMeV

[P. Russotto et al. PLB 697 (2011) 471]



v_2^n / v_2^H ratio vs p_T sensitive to the symmetry term and not so much to the momentum dependence of the σ_{NN}

neutron/hydrogen
FP1: γ = 1.01 ± 0.21
FP2: γ = 0.98 ± 0.35
neutron/proton
FP1: γ = 0.99 ± 0.28
FP2: γ = 0.85 ± 0.47
adopted: γ = 0.9 ± 0.4

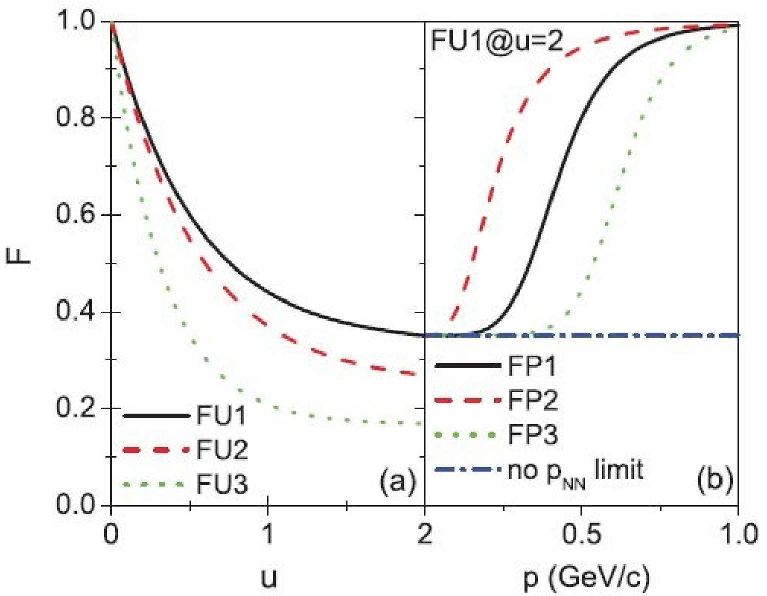


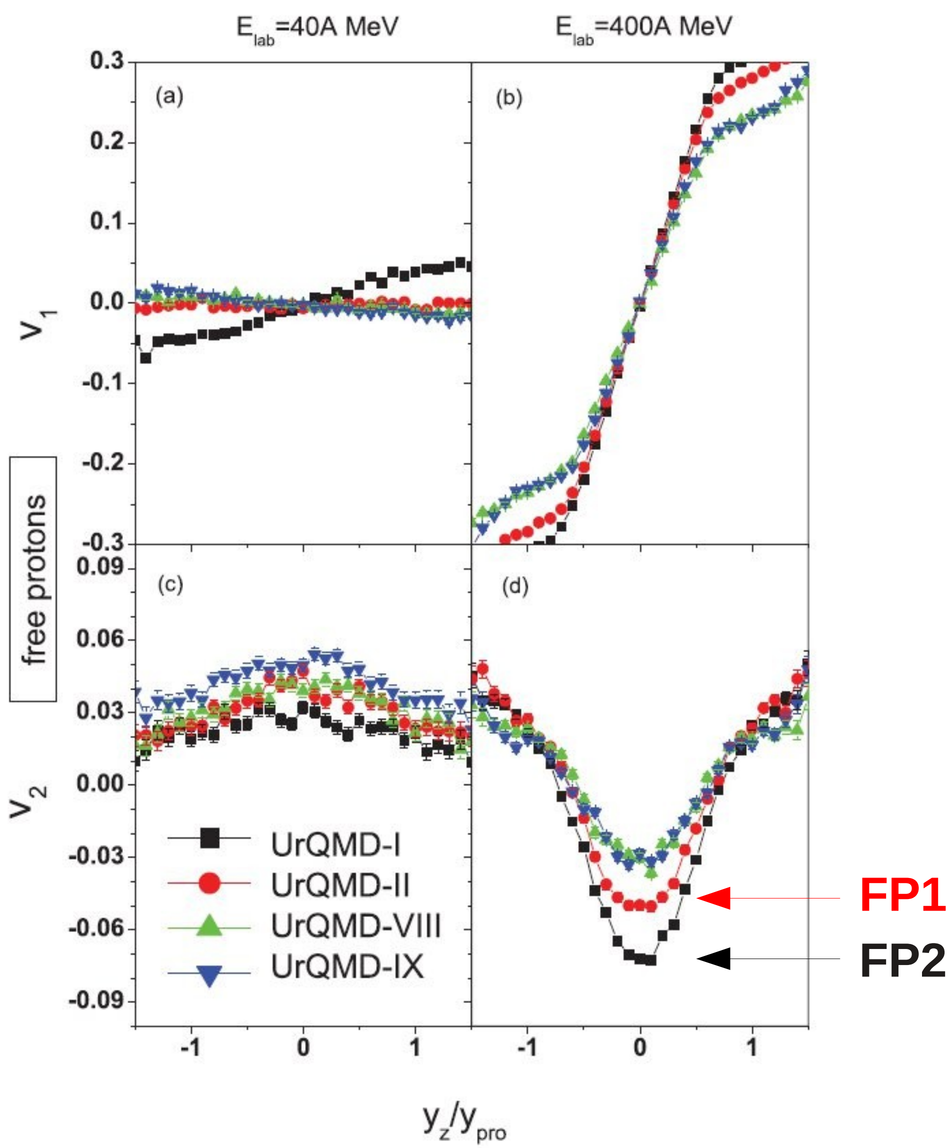
FP1, FP2: different parametrizations of the momentum dependence of the elastic nucleon-nucleon cross section
[Q. Li et al. PRC 83(2011)044617]

Medium correction factors to the elastic σ_{NN}

[UrQMD, Q. Li et al., PRC 83(2011)044616]

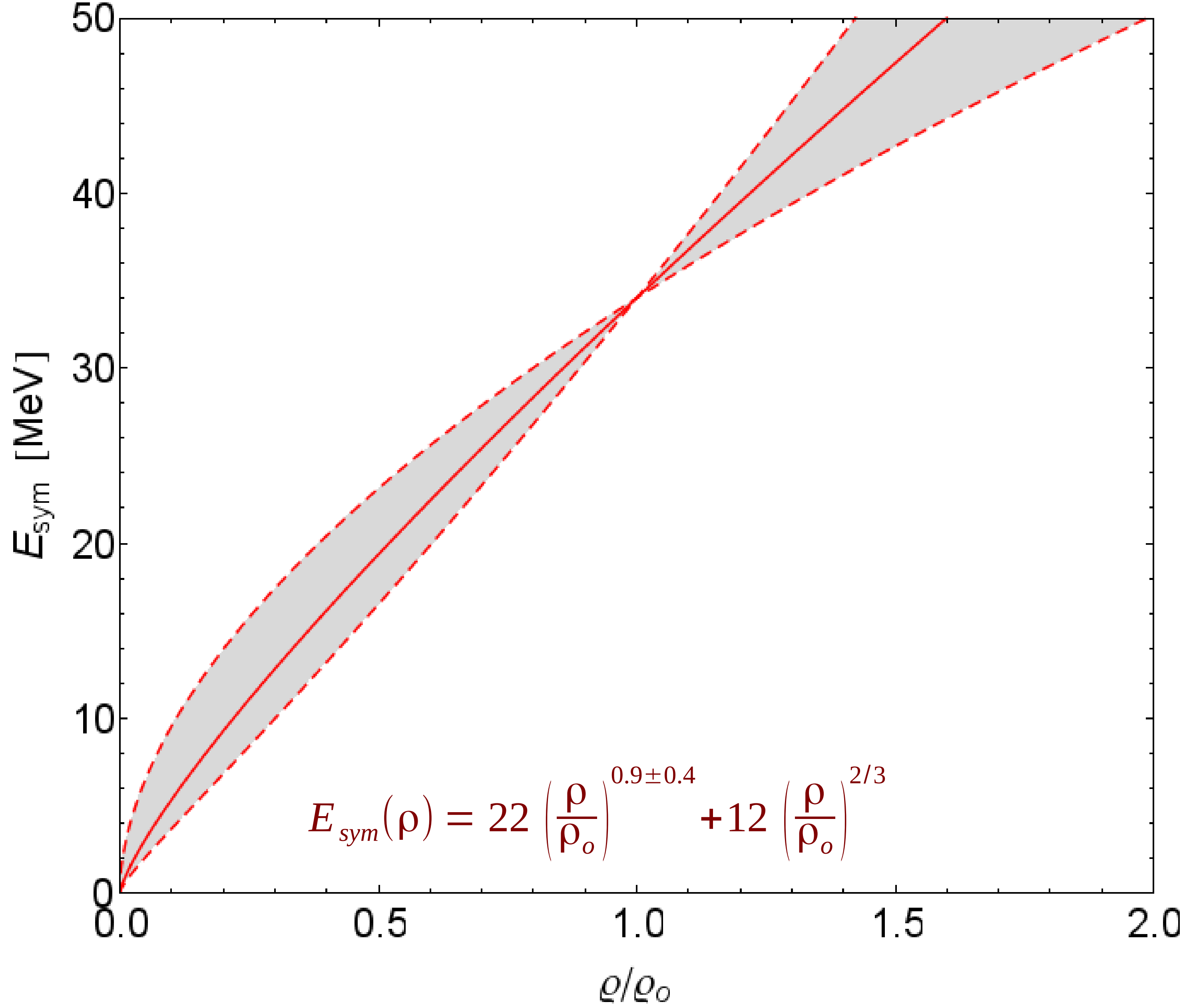
$$\sigma^*_{tot} = \sigma_{in} + \sigma^*_{el} = \sigma^{free}_{in} + F(\rho, p)\sigma^{free}_{el}$$





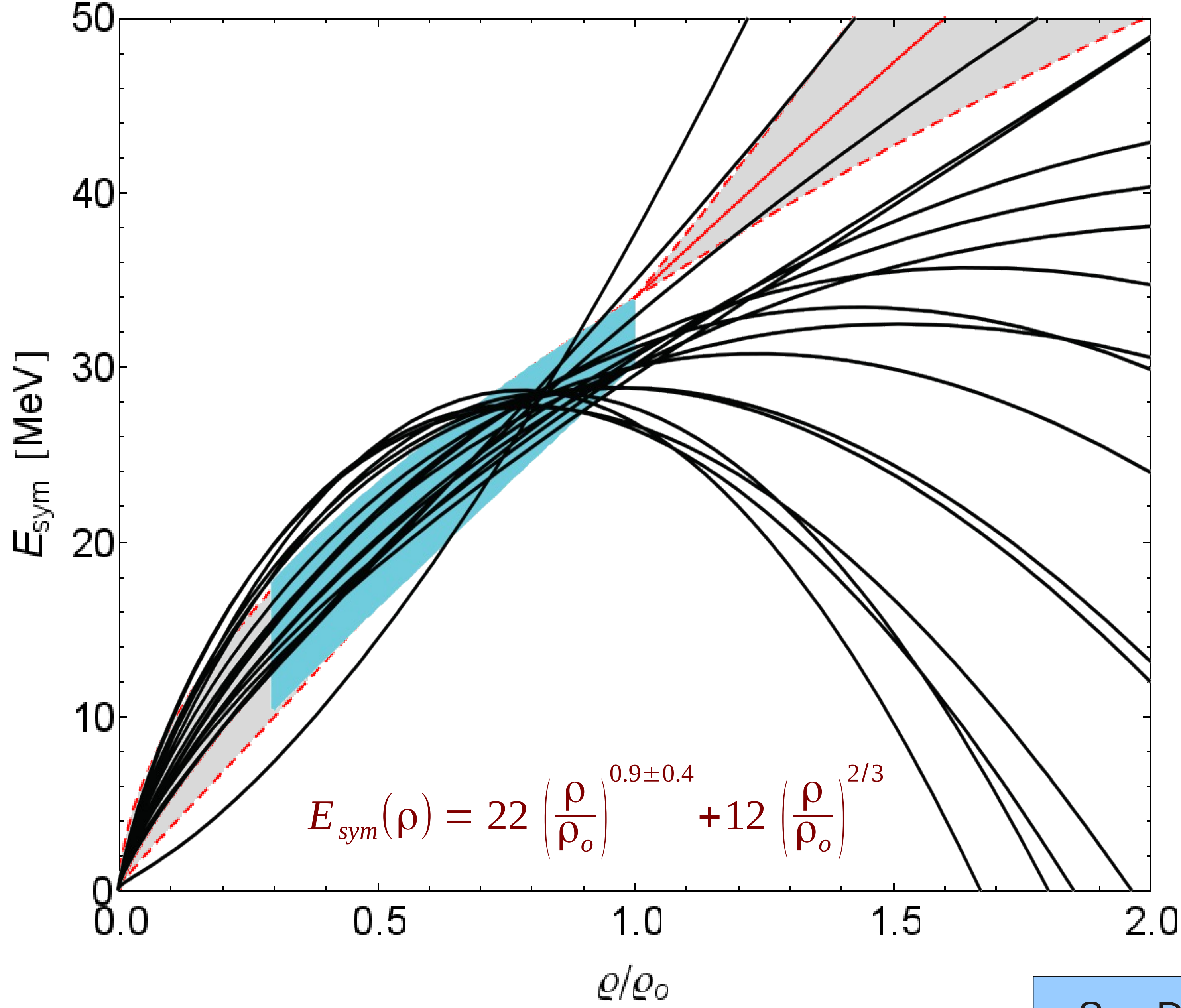
FP1 and FP2 differ by ≈ 40% in absolute v2 predictions

Esym from FOPI + UrQMD



P. Russotto et al. PLB 697 (2011) 471

Esym from FOPI + UrQMD + Tsang(2012)



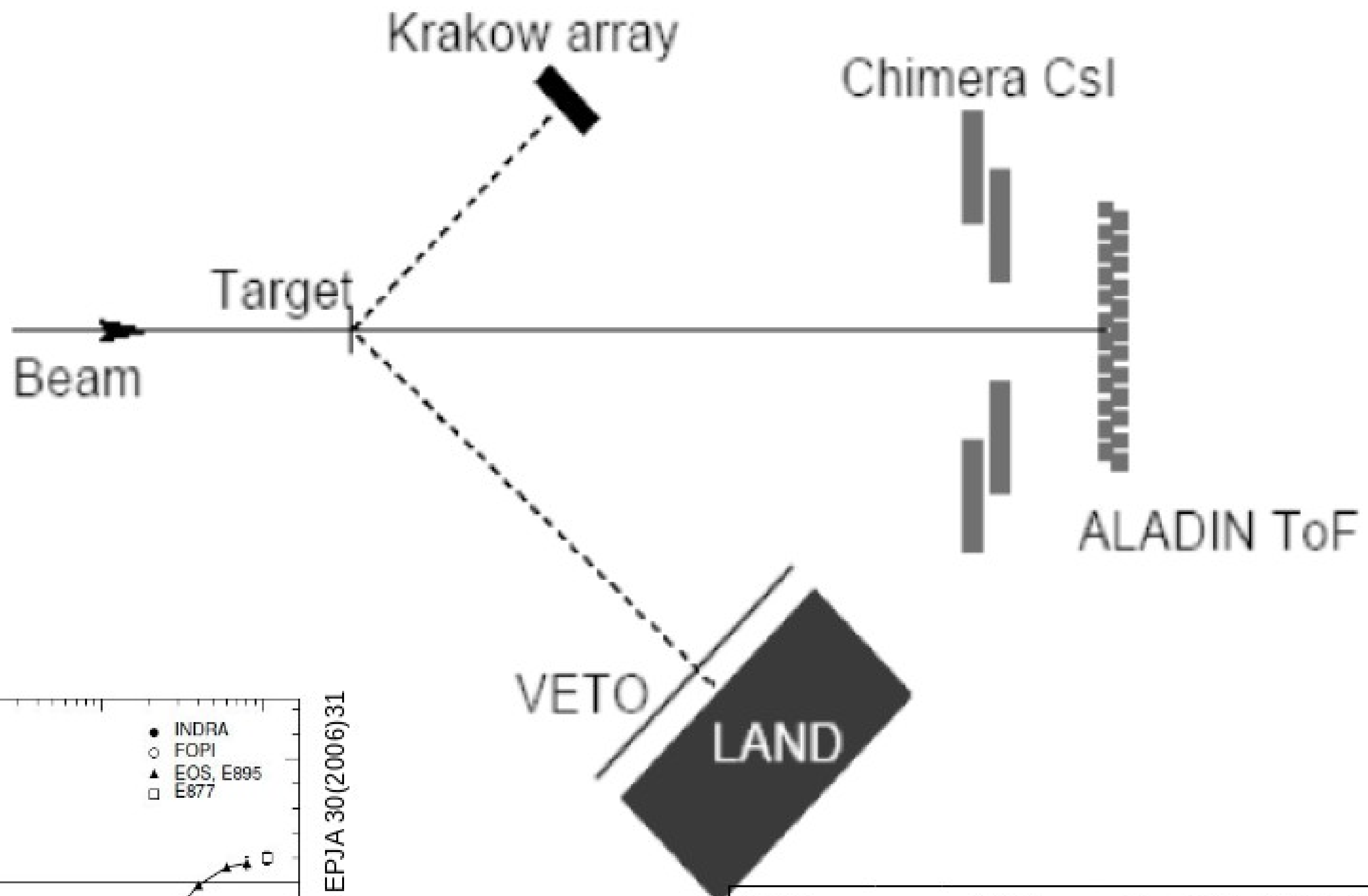
P. Russotto et al. PLB 697 (2011) 471
M.B. Tsang et al., PRC 86(2012)015803

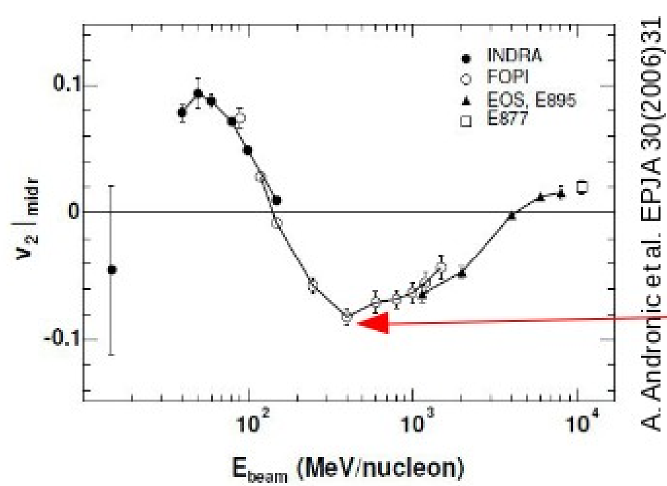
See D. Cozma

ASY-EOS experimental setup

May 2011

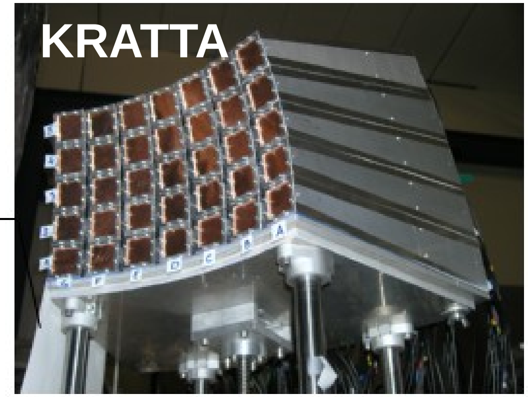
Setup from the proposal of 2009





^{197}**Au**	**+**	^{197}**Au**	**@ 400 AMeV**	**δ^2 = 0.039**
^{96}**Zr**	**+**	^{96}**Zr**	**@ 400 AMeV**	**δ^2 = 0.028**
^{96}**Ru**	**+**	^{96}**Ru**	**@ 400 AMeV**	**δ^2 = 0.007**

ASY-EOS setup

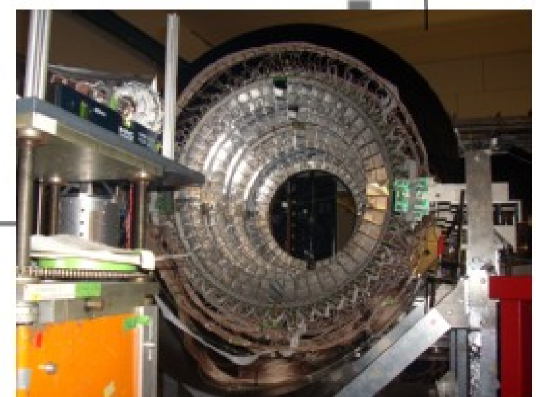


5x7 triple telescopes, 20°<θ<60°
Si-CsI-CsI
Midrapidity pdt +
Isotopes of Z<9

Krakow array

4 rings, 352 CsI(Tl), 7°<θ<20°
Centrality
&
Reaction plane

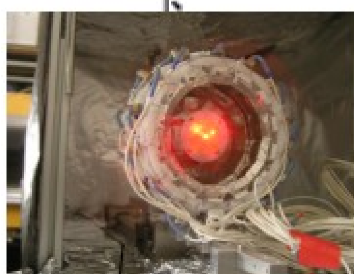
Chimera CsI



Start + ROLU

Target

Beam

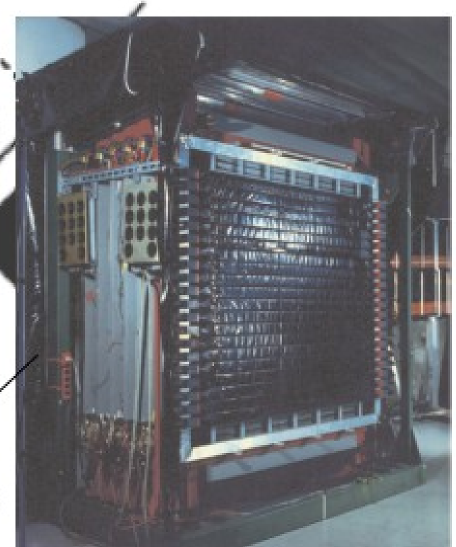


ALADIN ToF

μ-Ball + Halo

4 rings, θ>60°, CsI(Tl)
Discriminate target vs air interactions, remove halo, possibly centrality + rpl

SHADOW BAR

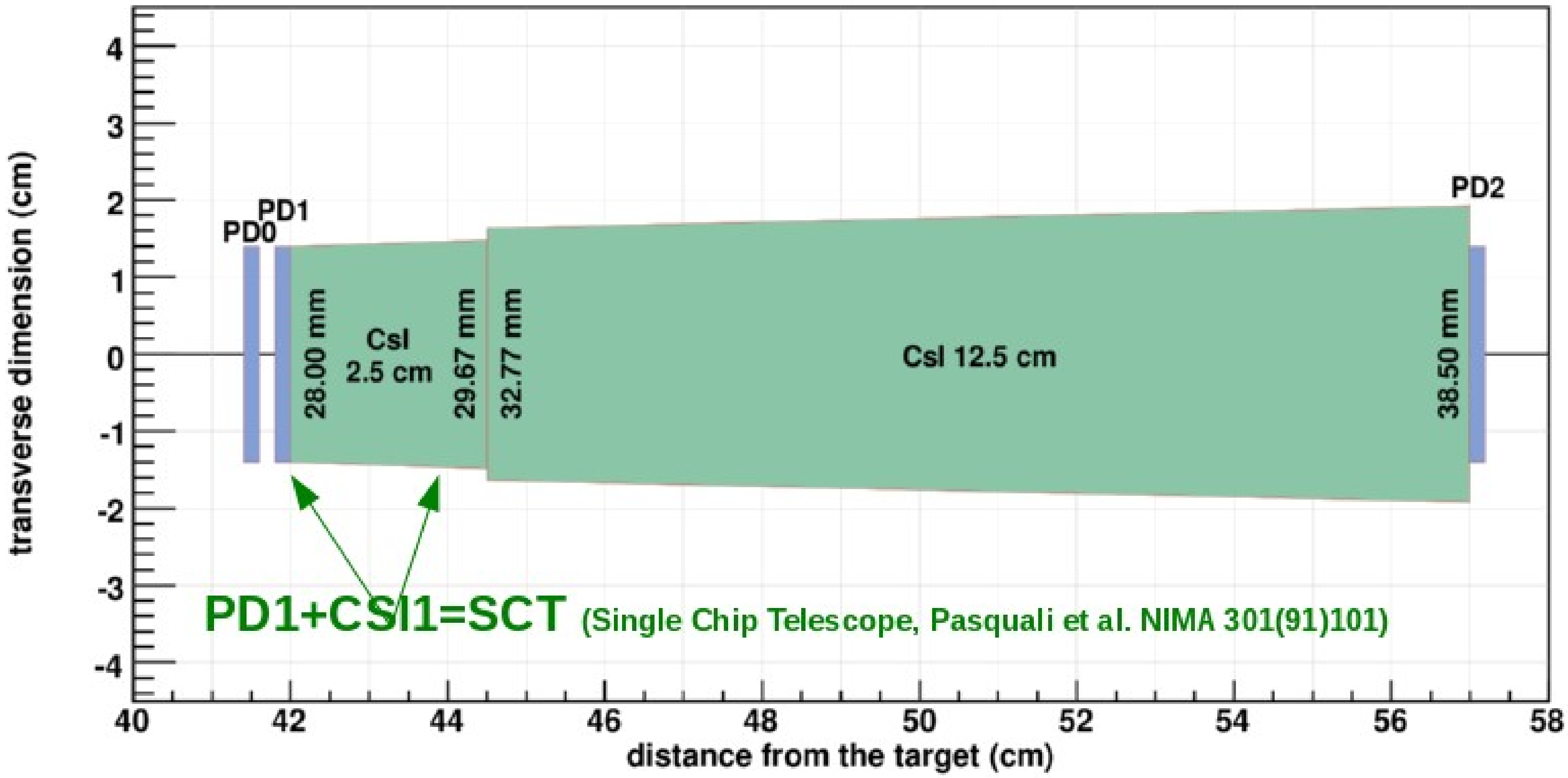


96 plastic bars
x-y positions, centrality, reaction plane, trigger

2x2x1 m^3 plastic/Fe sandwich
+ plastic veto wall
Midrapidity neutrons & Z=1

LAND+VETO

Active elements



Photodiodes: HAMAMATSU S5377-02

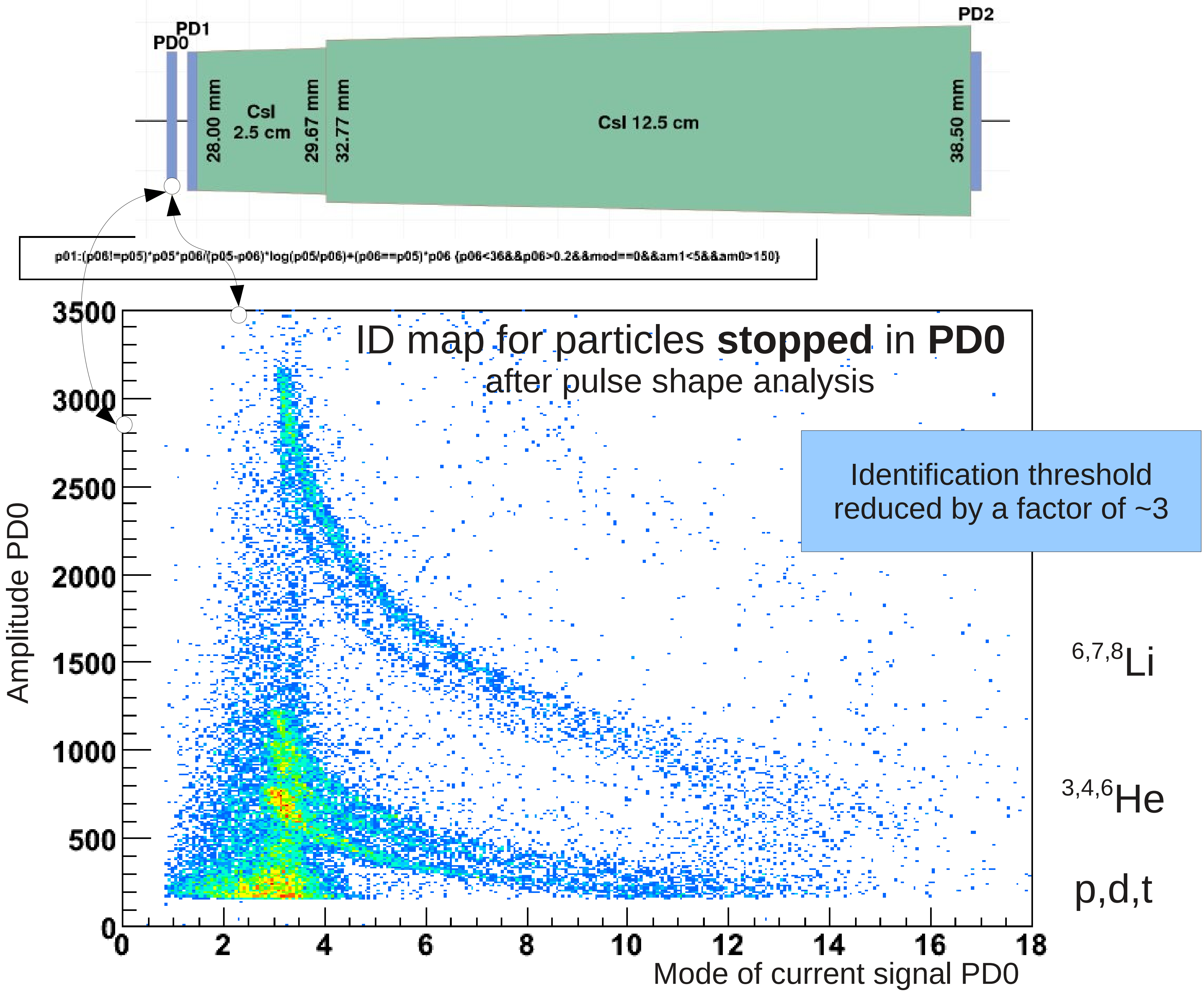
- Active Area: 28x28 mm^2
- Thickness: 500 ± 15 μm
- Orientation: (111)
- Dead Layers: 1.5 μm front, 20 μm rear
- Full Depletion: ~170 V
- Dark Current: 30 nA, (Max. 150 nA)
- Rise Time: 40 ns
- Capacitance: 200 pF

CsI(Tl): IMP-CAS, Lanzhou, China

- Tl concentration: 1500 ppm
- LO non-uniformity: <7%
- Shape: Truncated pyramids
- Tolerance: ± 0.1 mm

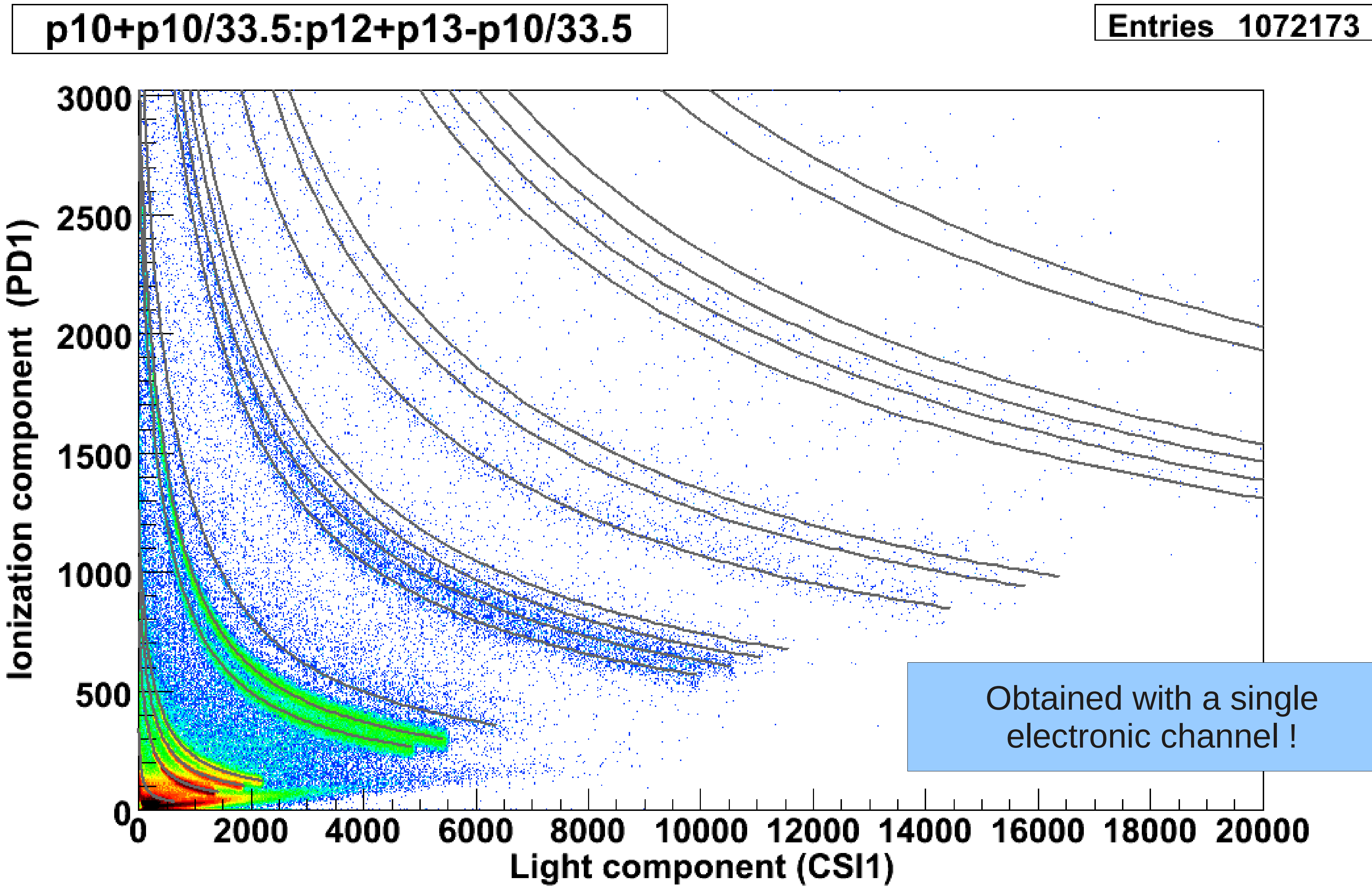
Wrapping: 3M Vikuiti™ ESR foil

- Reflectance: >98%
- Thickness: 65 μm


PD0
PD1
PD2
28.00 mm
CsI
2.5 cm
29.67 mm
32.77 mm
CsI 12.5 cm
38.50 mm
p01:(p06!=p05)*p05*p06/(p05-p06)*log(p05/p06)+(p06==p05)*p06 {p06<36&&p06>0.2&&mod==0&&am1<5&&am0>150}
ID map for particles **stopped** in **PD0**
after pulse shape analysis
Identification threshold reduced by a factor of ~3
Amplitude PD0
Mode of current signal PD0
6,7,8Li
3,4,6He
p,d,t

SCT decomposed (non-trivial)

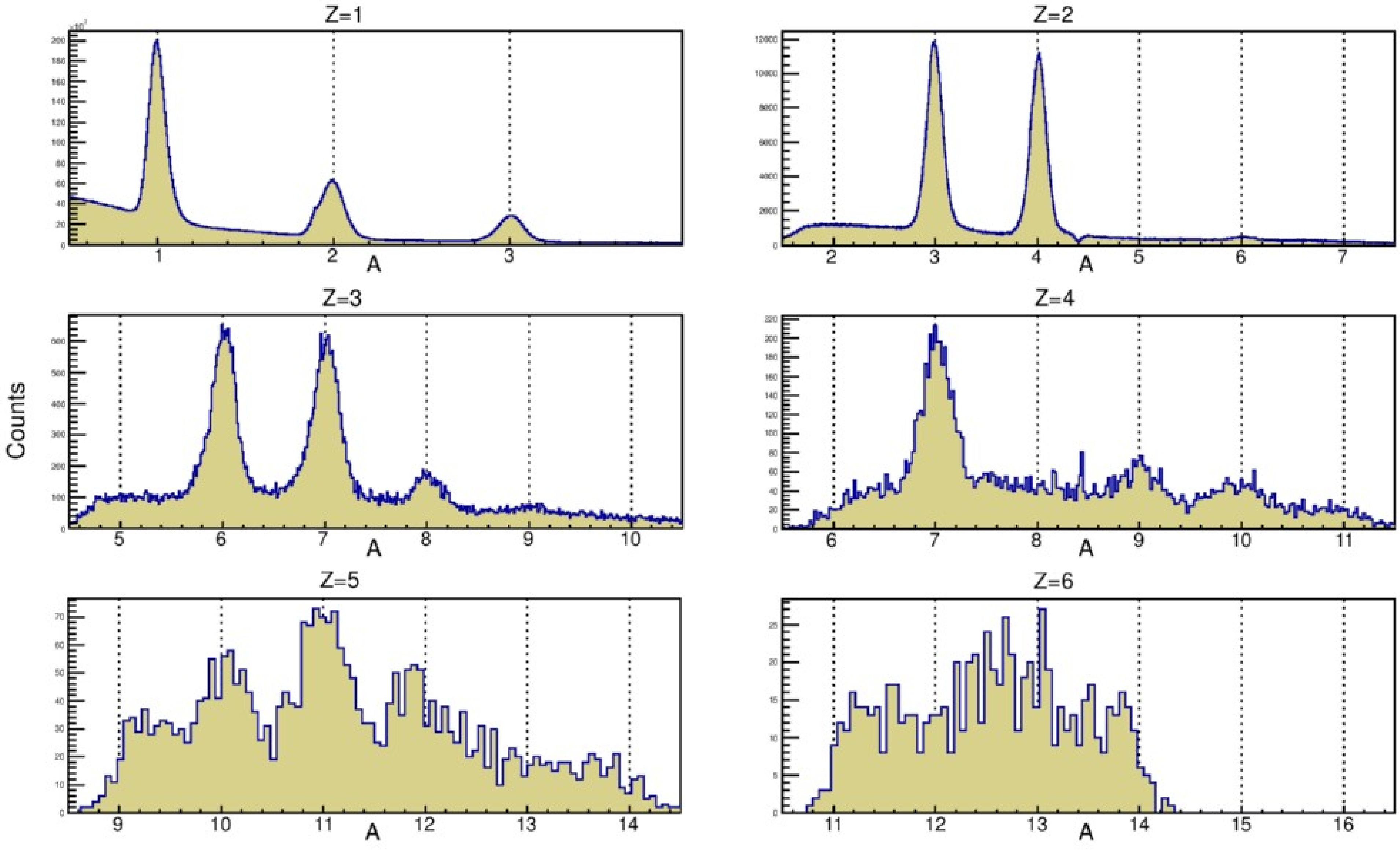
(lines from the ATIMA range-energy tables)



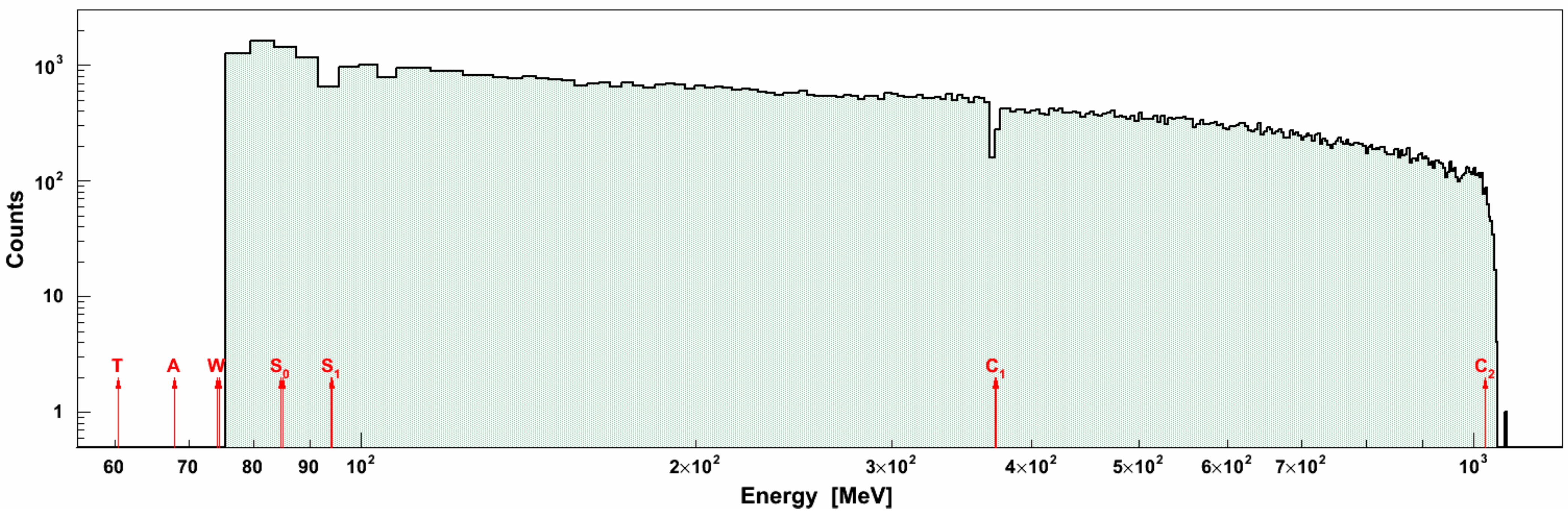
Obtained with a single electronic channel !

Mass distributions

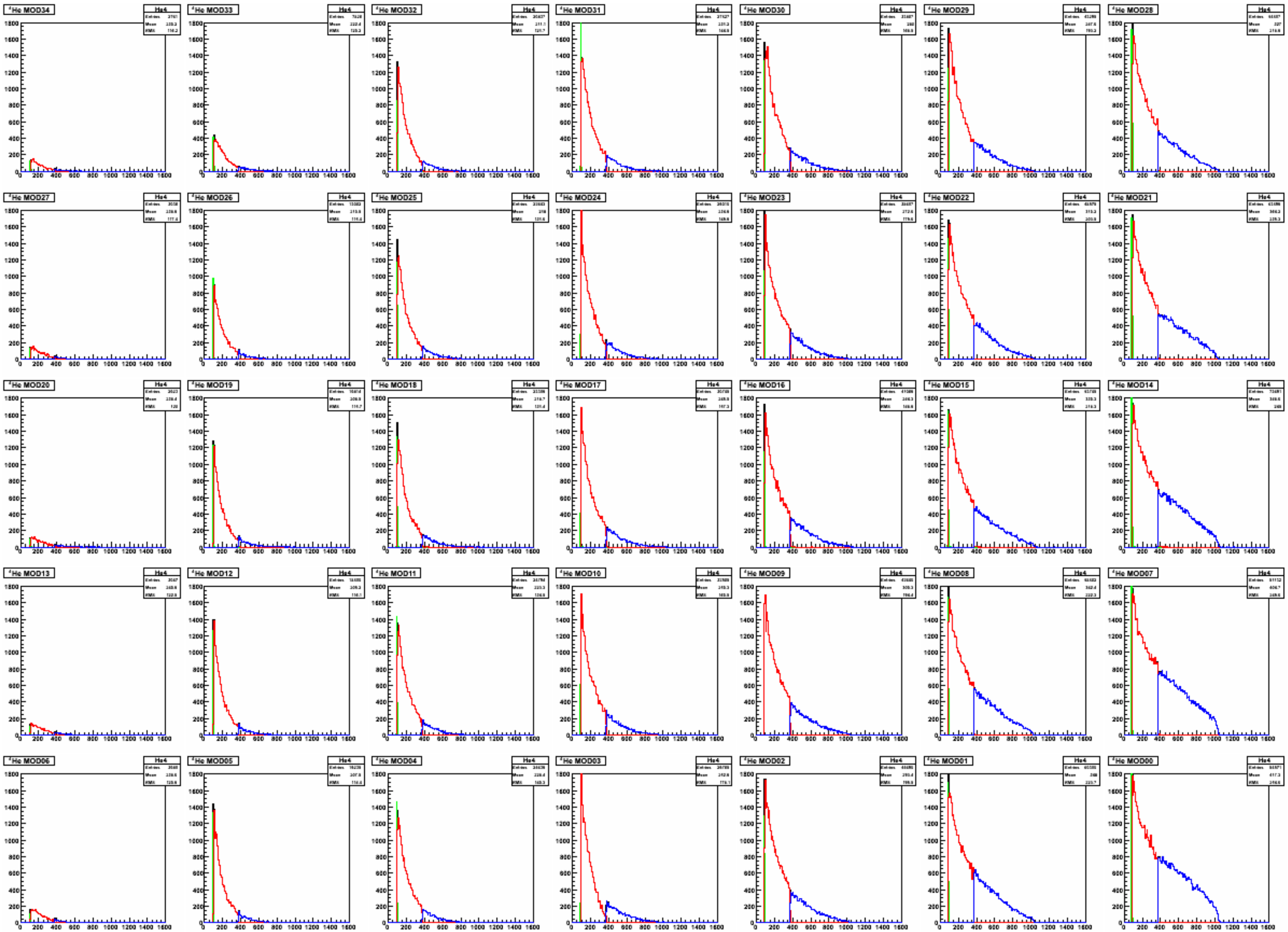
Au+Au @400 AMeV



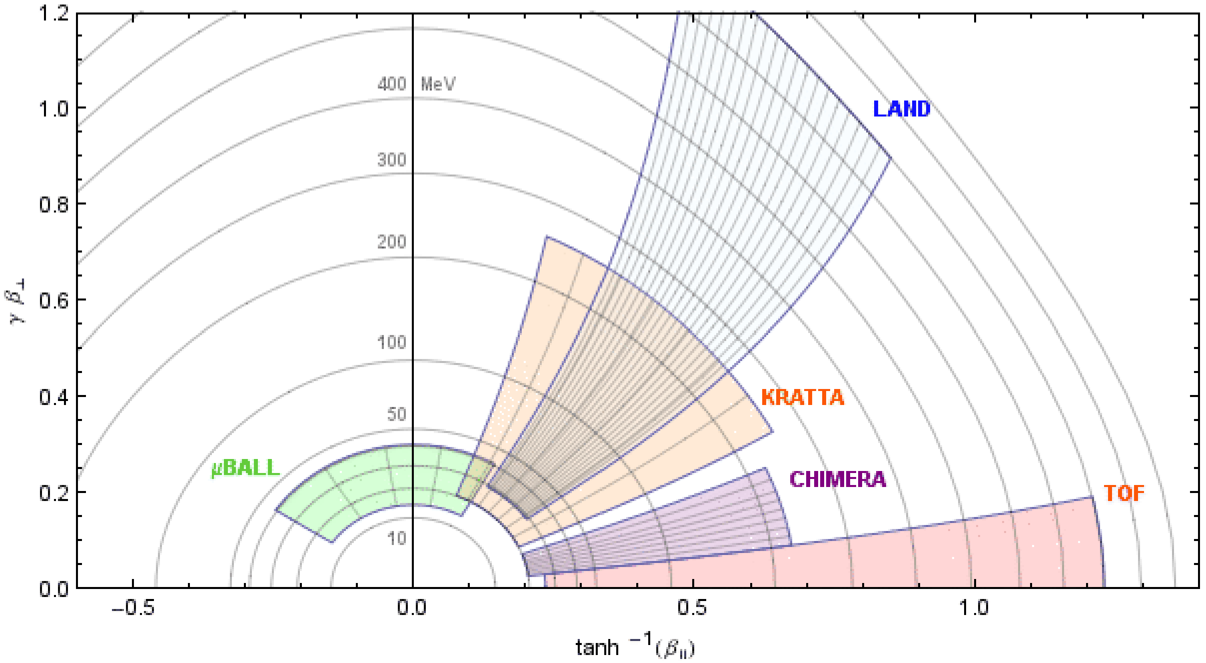
Alpha particle energy spectrum (MOD07) for Au+Au @400 AMeV
(log-log scale)



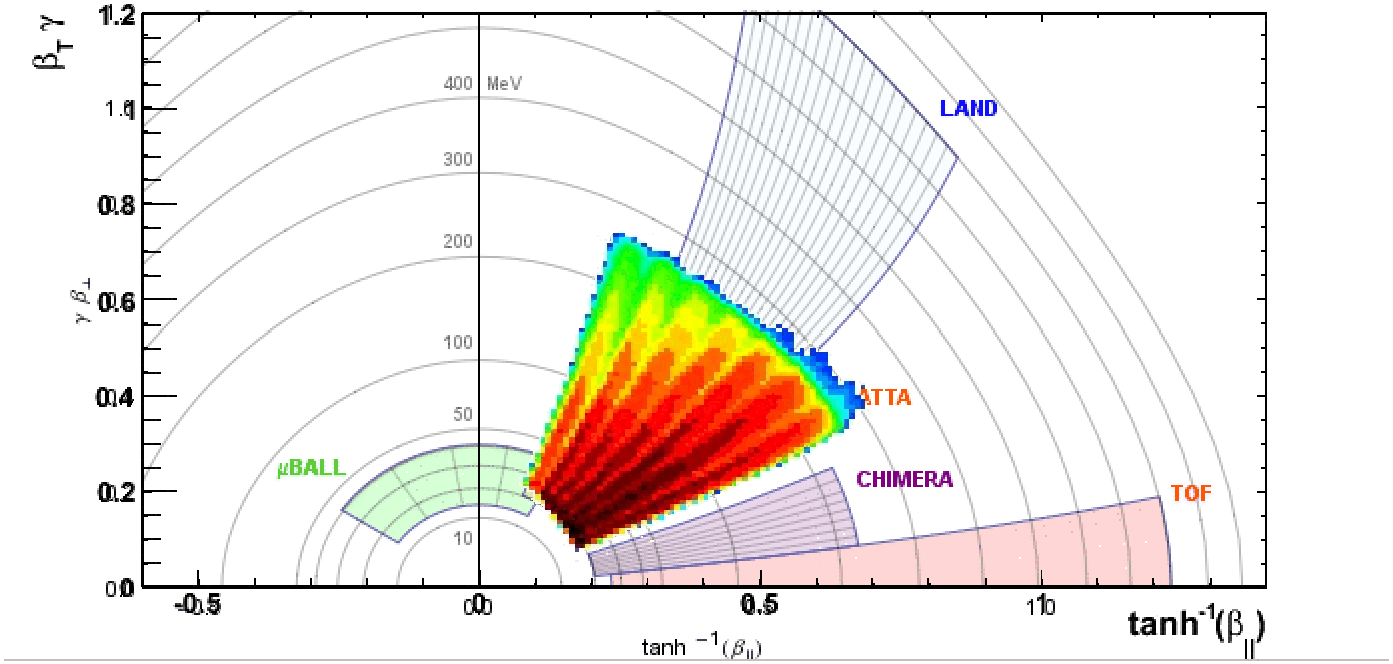
Alpha particles, all modules



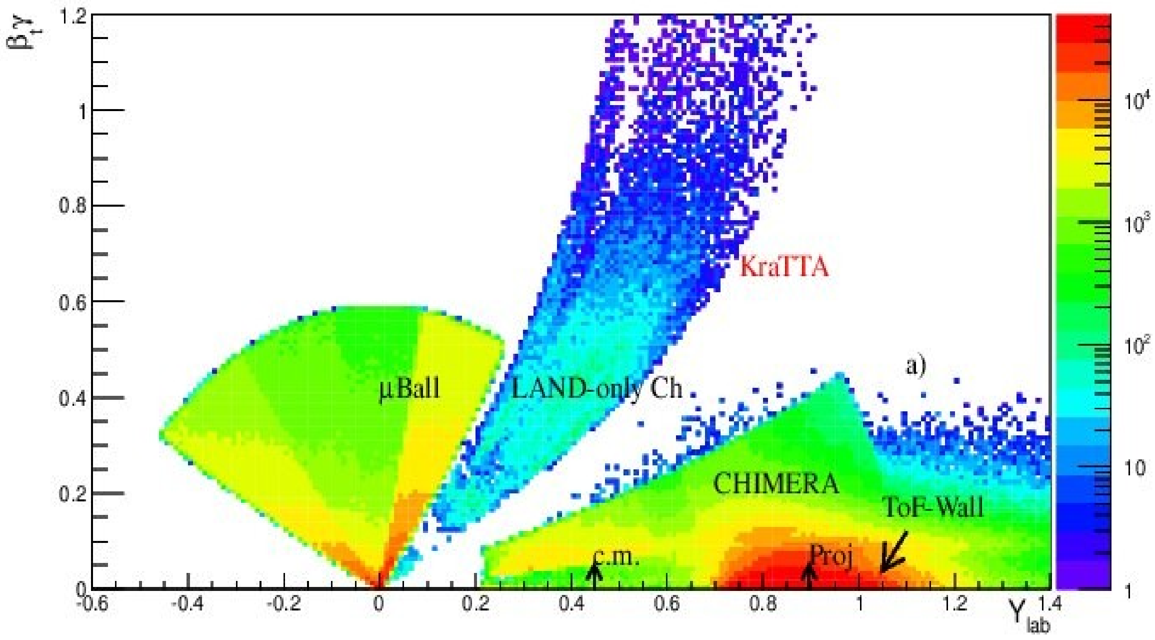
Acceptance of the setup (protons)



Acceptance of the setup (protons)

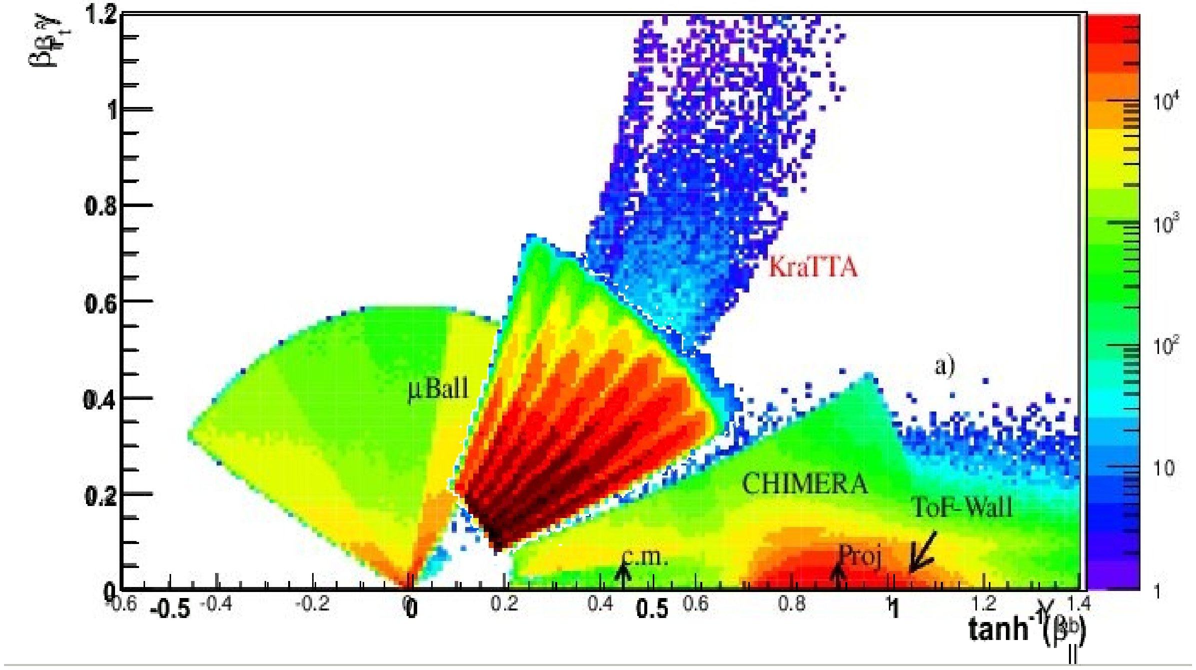


Acceptance of the setup (protons)



P. Russotto, INPC2013, Firenze, Italy 2-7.06.2013

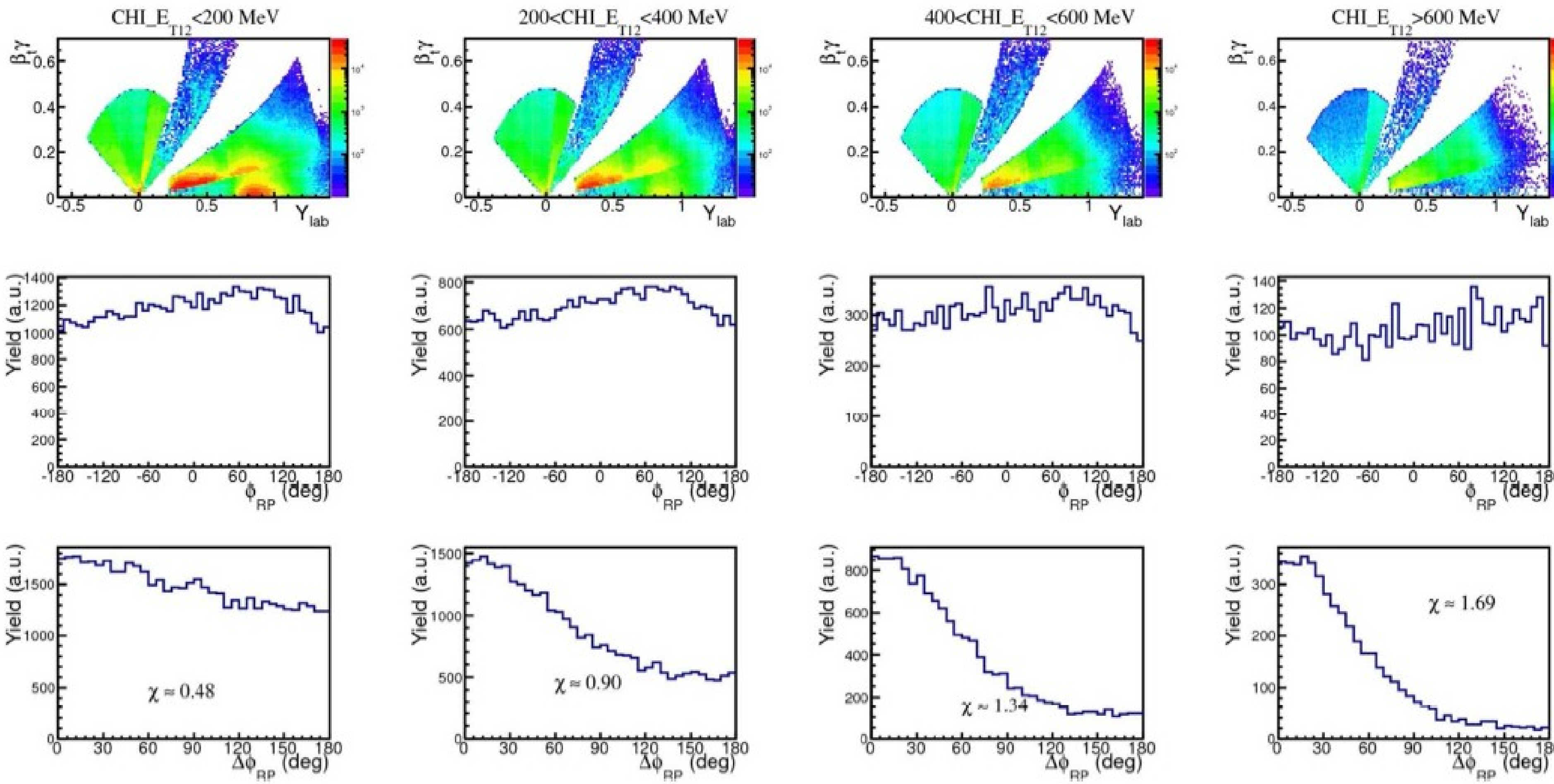
Acceptance of the setup (protons)



Centrality selection and Reaction plane orientation

Au+Au @ 400 AMeV

preliminary



$$\vec{Q} = \sum_{\nu=1}^{M} Z_\nu \hat{p}_t w_\nu \qquad w_\nu = \begin{cases} 1 & \text{for } Y_{c.m.} > 0.1 \\ 0 & \text{for } Y_{c.m.} < 0.1 \end{cases}$$

ad. from P. Danielewicz et al., PLB 1985

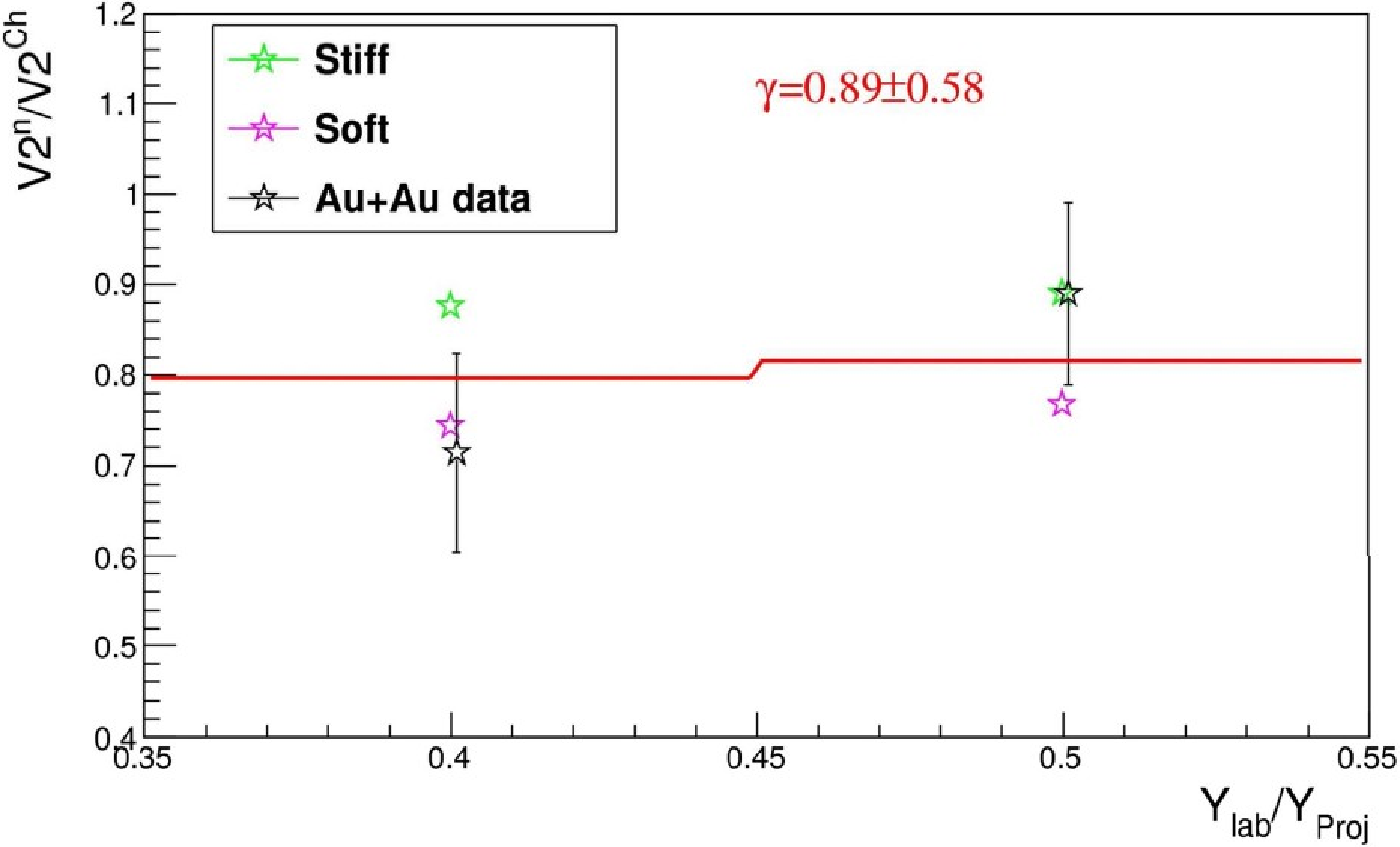
$Etrans_{12}$ (MeV)	χ~	<cos (2 ΔΦ) >~	ΔΦ (deg)~
<200	0.48	0.12	41
200-400	0.90	0.34	35
400-600	1.34	0.52	29
>600	1.69	0.66	24

J-Y Ollitrault arXiv:nucl-ex/9711003v2

Preliminary gamma extraction

Au+Au @ 400 AMeV

b< 7.5 fm

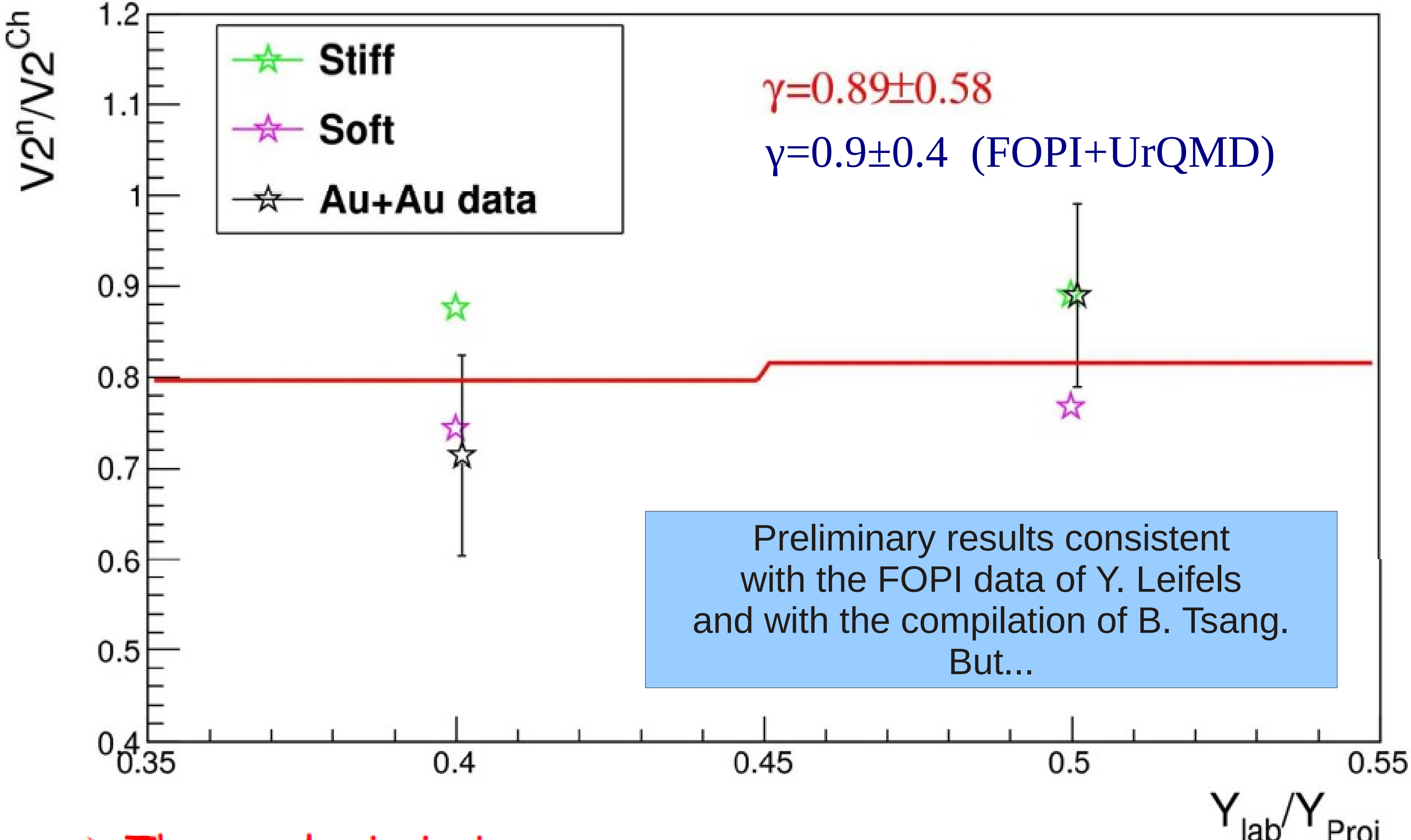


P. Russotto, INPC2013, Firenze, Italy 2-7.06.2013

Preliminary gamma extraction

Au+Au @ 400 AMeV

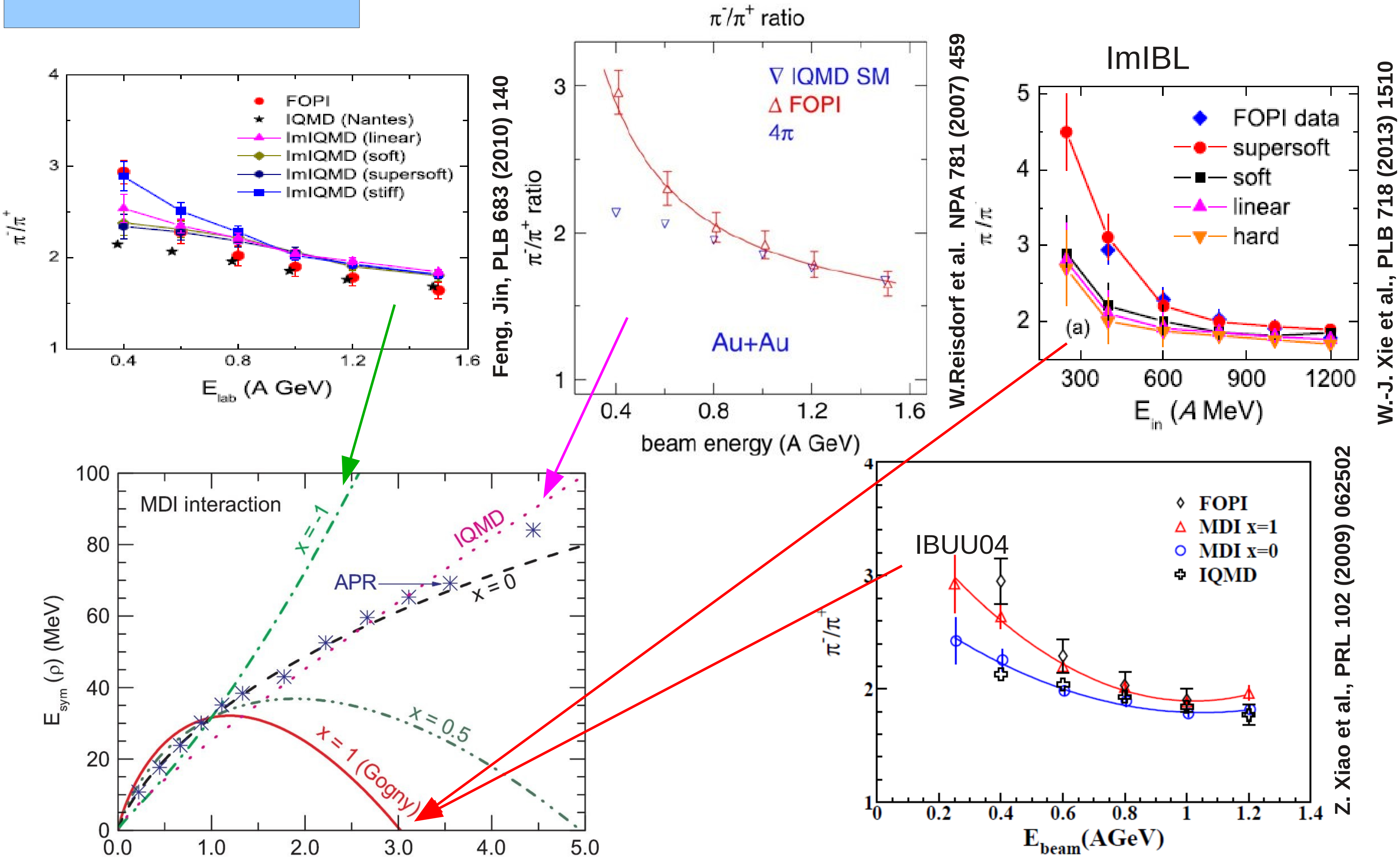
b< 7.5 fm



- The analysis is in progress...

$$\frac{\pi^-}{\pi^+} = \frac{5n^2 + np}{5p^2 + np} \approx \left(\frac{n}{p}\right)^2$$

Pion ratio puzzle (FOPI, Au+Au)



See also W-M..Guo et al. ArXiv:1306.4783v1 [nucl-th] for UrQMD vs IBUU04

Difficulties in measuring the $E_{sym}(\rho)$

Experiment

- Mixture of density, temperature and time dependent processes
- Detection of neutrons and protons simultaneously
- Tiny effects – high precision and statistics needed
- Observables minimizing the influence of the isoscalar part
- Correlations of many observables needed to disentangle competing effects
- Exotic beams, asymmetric systems (with larger δ)

Model

- In-medium cross sections, treatment of Δ resonance dynamics (π^-/π^+)
- Momentum dependence of the mean-field, effective masses
- Control the competition between the mean-field and collisions
- Realistic description of cluster formation (at least $t/^3He$)
- Ability to describe „hot" and „cold" observables. Often "hot" model observables are compared to "cold" experimental data.

What to measure?

- High energy tails (high p_T with high precision) of π^-/π^+, n/p, t/^{3}He, …,→ messengers of the high density first chance collisions, to resolve the influence of the competing effective mass splitting effect [Giordano et al.] and enhance sensitivity to the Esym [Q-F Li et al. JPG 32(2006) 151].
- Simultaneously π^-/π^+, n/p, t/^{3}He, … to constrain the Δ properties and dynamics.
- Observables minimizing the influence of isoscalar part of the EoS and of the in-medium cross sections (ratios [Russotto et al.], double-ratios, differences [Cozma et al.] of flow observables, differential flows [B-A.Li PRL 2002)].
- Two or more beam energies to account for the competing isospin dependence of the N-N cross sections and to vary the densities. Construct excitation functions, measure e.g. the balance energy of neutrons (low energy) [Guo et al. SCP 55(2012)252]
- Observable trends as a function of centrality, rapidity and p_T.
- High energies (E_{beam} >> 100 AMeV), heavy systems (A_{sys} > 100), non-central collisions, heavy clusters [W. Reisdorf (FOPI) arXiv:1307.4210 [nucl-ex]]

The ASY-EOS Collaboration

Co-Spokespersons: R.C. Lemmon[1]and P. Russotto[2]

Collaboration

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