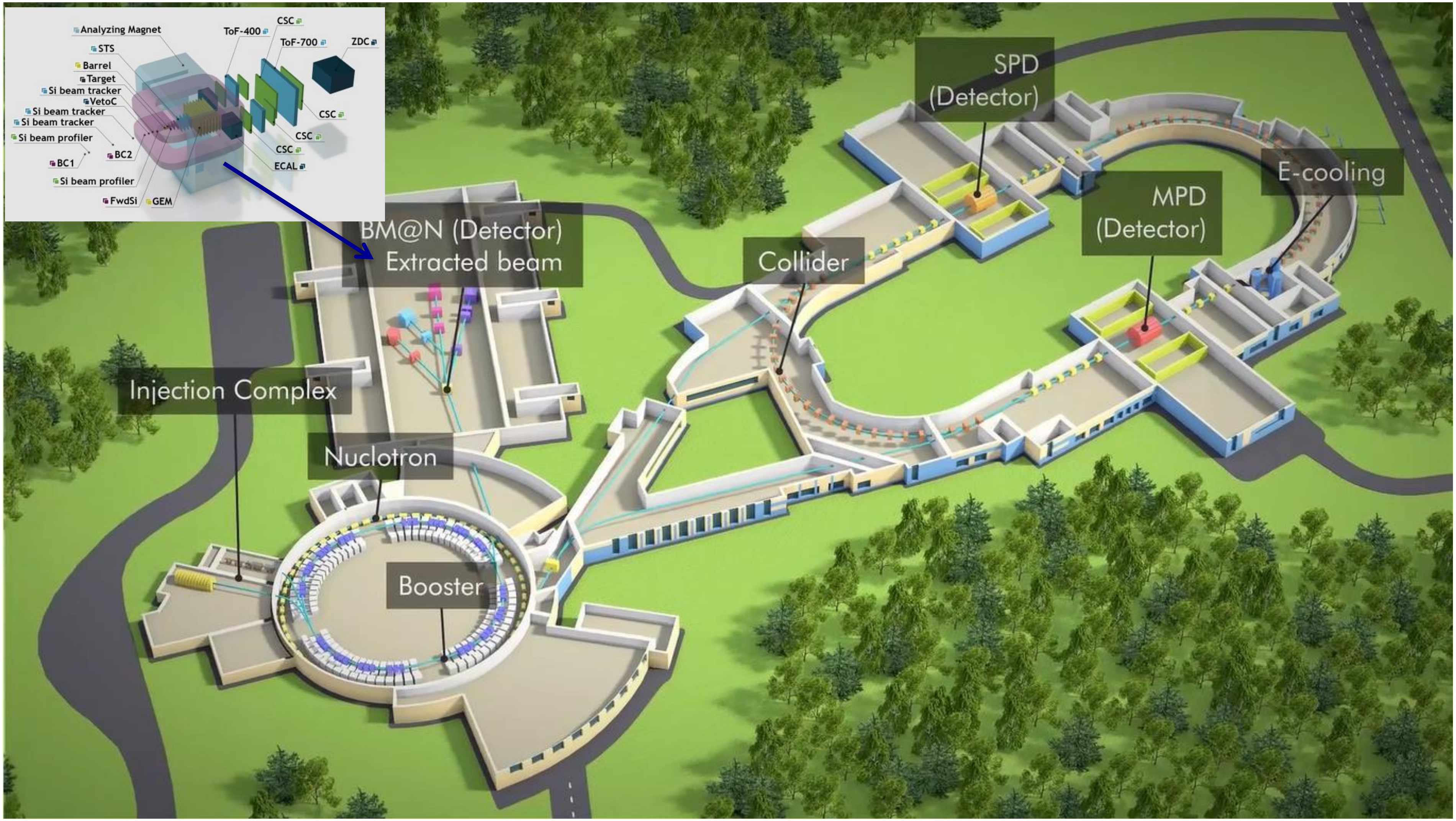
BM@N experiment: program, status and plans

M.Kapishin

NICA Heavy Ion Complex

BM@N: heavy ion energy 1-4 GeV/n, beams: p to Au, Intensity ~10^6 /s

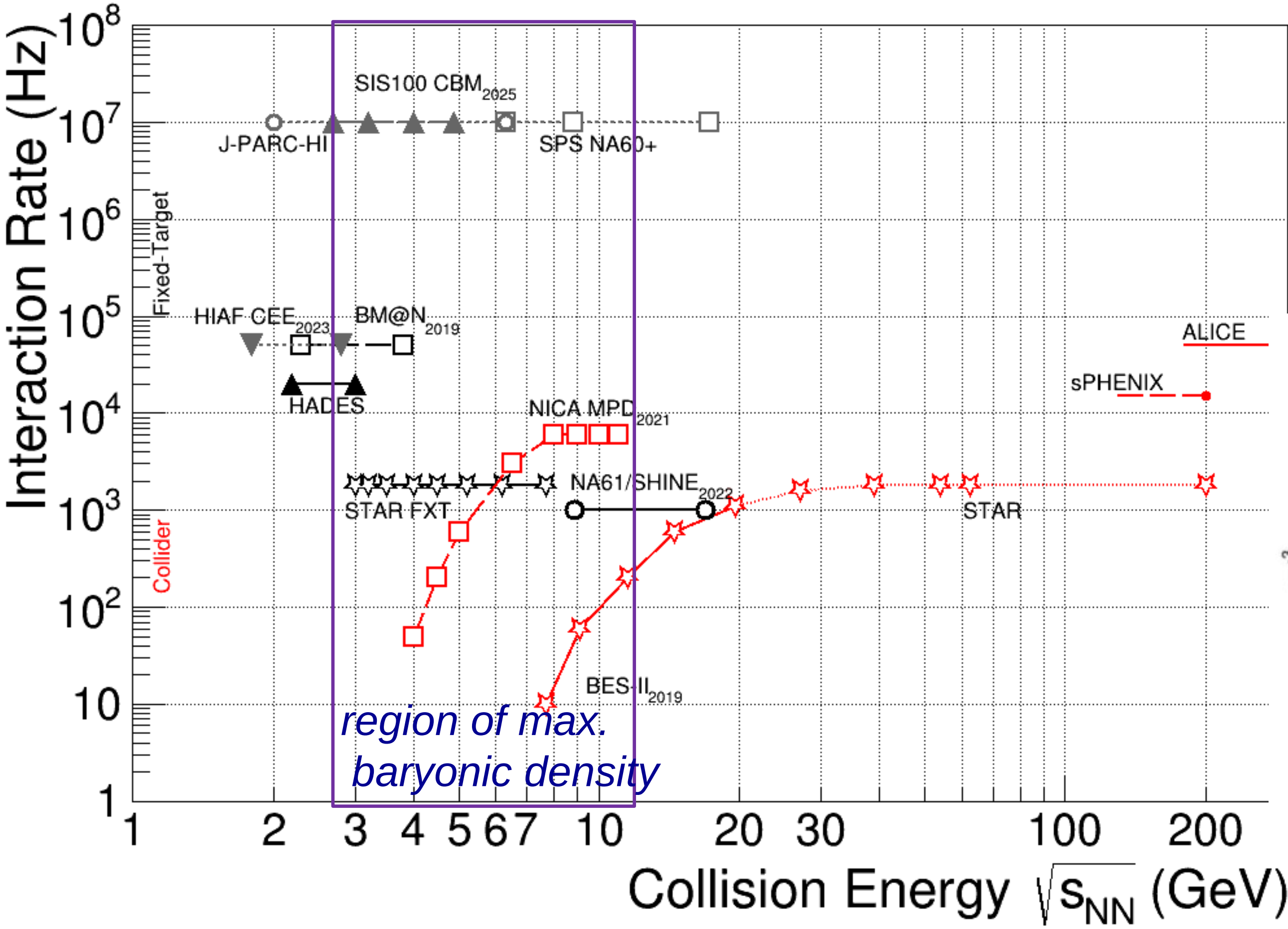


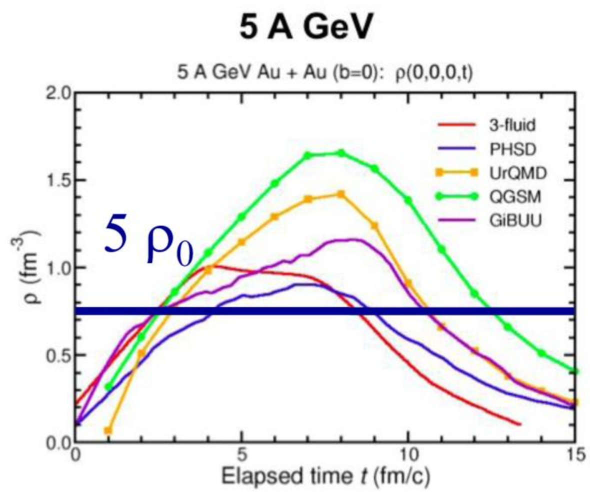
Baryonic Matter at Nuclotron (BM@N) Collaboration:

3 Countries, 10 Institutions, 188 participants

- ***University of Plovdiv, Bulgaria***
- ***St.Petersburg University***
- ***Joint Institute for Nuclear Research***
- ***Institute of Nuclear Research RAS, Moscow***
- ***Shanghai Institute of Nuclear and Applied Physics, CFS, China;***
- ***NRC Kurchatov Institute, Moscow***
- ***Moscow Engineer and Physics Institute***
- ***Skobeltsin Institute of Nuclear Physics, MSU, Russia***
- ***Moscow Institute of Physics and Technics***
- ***Lebedev Physics Institute of RAS, Moscow***

Heavy Ion Collision Experiments





BM@N: $\sqrt{s_{NN}}$= 2.3 - 3.3 GeV
MPD: $\sqrt{s_{NN}}$= 4 - 11 GeV

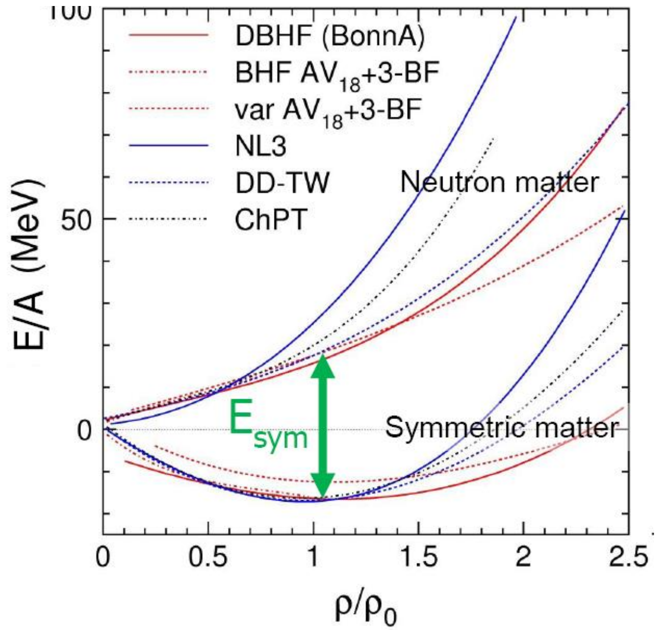
BM@N competitors:

HADES BES (SIS): Au+Au at $\sqrt{s_{NN}}$ = 2.42 GeV, Ag+Ag at $\sqrt{s_{NN}}$ = 2.42 GeV, 2.55 GeV.

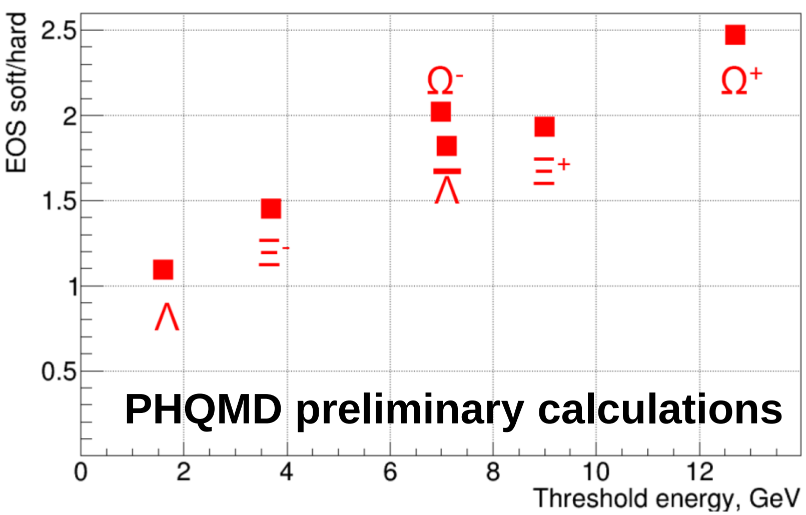
STAR BES (RHIC): Au+Au at $\sqrt{s_{NN}}$ = 3-200 GeV

EOS of symmetric and asymmetric nuclear matter

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



Hyperon yield in 4A GeV Au+Au:
soft EOS (K=240 MeV) / hard EOS (K=350) MeV



EOS: relation between density, pressure, temperature, energy and isospin asymmetry

$$E_A(\rho,\delta) = E_A(\rho,0)+E_{sym}(\rho)\cdot\delta^2$$

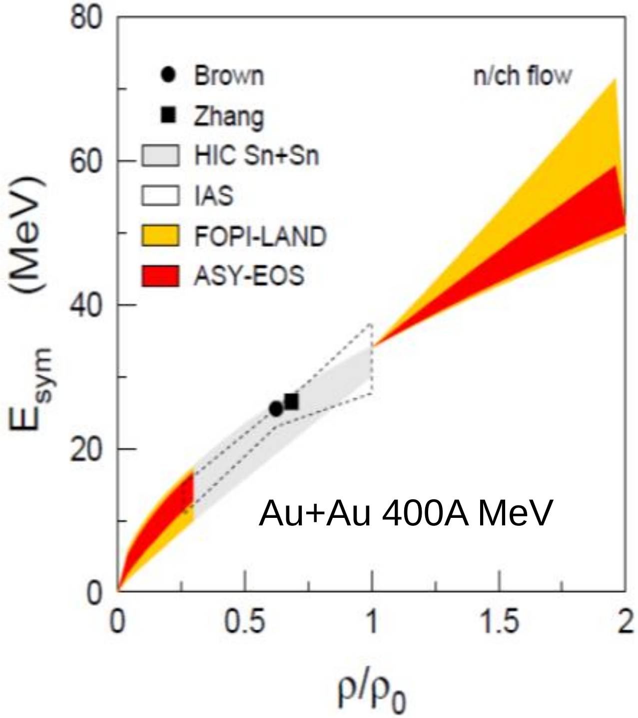
with $\delta = (\rho_n - \rho_p)/\rho$ $\quad E/A(\rho_o) = -16$ MeV

Curvature defined by nuclear incompressibility: $K = 9\rho^2\ \delta^2(E/A)/\delta\rho^2$

►Study symmetric matter EOS at ρ=3-5 ρ_0
→ elliptic flow of protons, mesons and hyperons
→ sub-threshold production of strange mesons and hyperons
→ extract K from data to model predictions
►Constrain symmetry energy E_{sym}
→ elliptic flow of neutrons vs protons
→ sub-threshold production of particles with opposite isospin

Nuclear matter equation-of-state up to 2 ρ_0

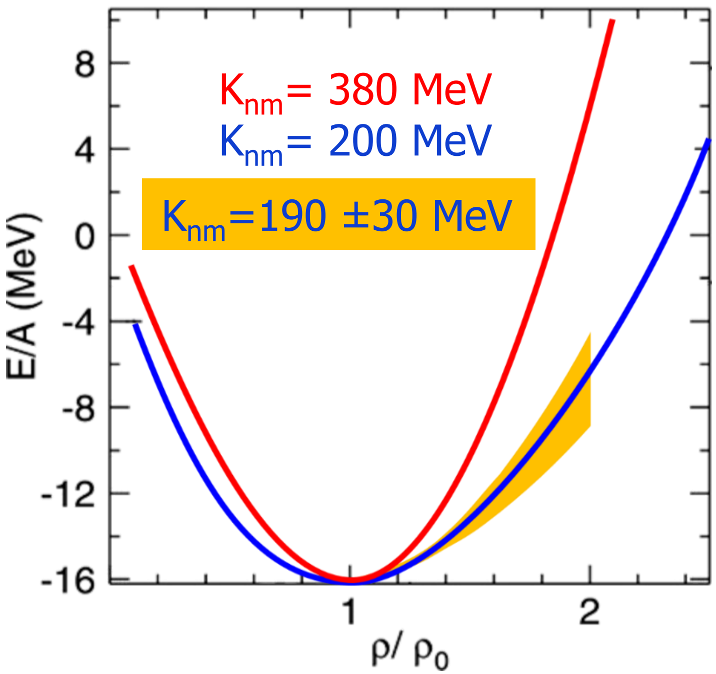
Symmetry energy



ASY-EOS: Elliptic flow of neutrons/charged particles

P. Russotto et al.,
Phys. Rev. C 94 (2016) 034608

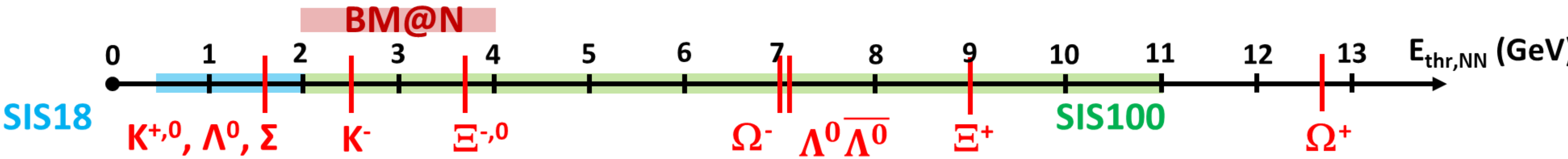
Symmetric matter



KaoS: Excitation function of kaon production in Au + Au collisions up to 1.5A GeV
C. Sturm et al., PRL 86 (2001) 39
C. Fuchs et al., PRL 86 (2001) 1974

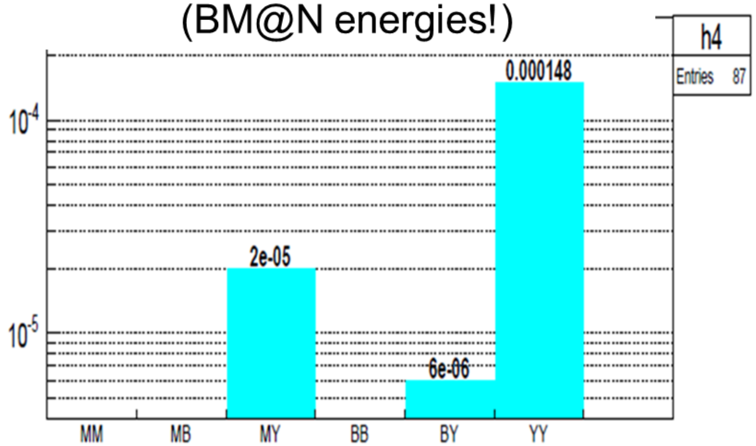
FOPI: Excitation function of elliptic flow of protons and light fragments in Au + Au collisions up to 1.5A GeV
A. Le Fevre et al., Nucl. Phys. A945 (2016) 112

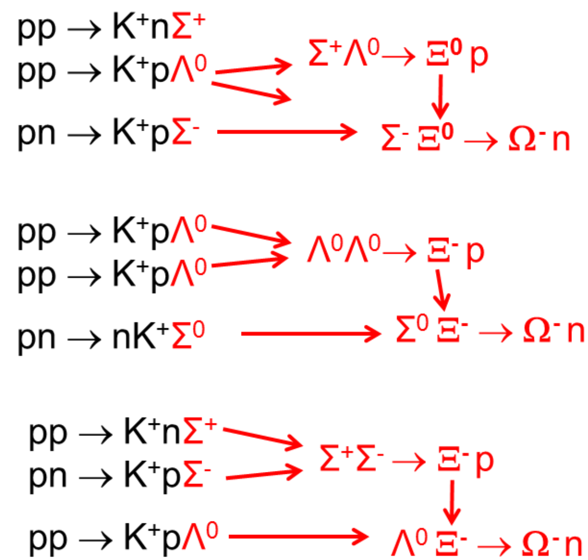
New probe of the high-density EOS: subthreshold production of multi-strange (anti-)hyperons via sequential collisions



Ω^- production in 4 A GeV Au+Au (BM@N energies!)

HYPQGSM calculations
K. Gudima et al.





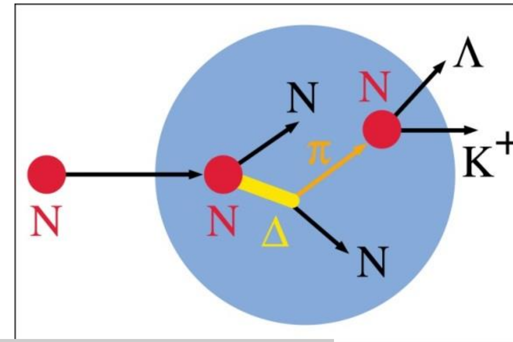
BM@N physics case and observables

The QCD matter equation-of-state at high densities

➢ particle production at (sub)threshold energies via multi-step processes

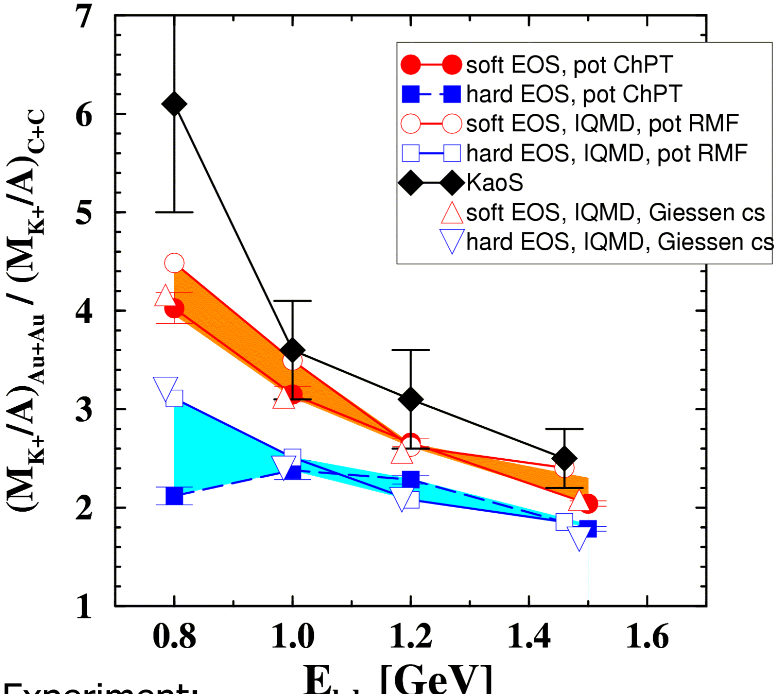
Example: subthreshold K^+ production at GSI

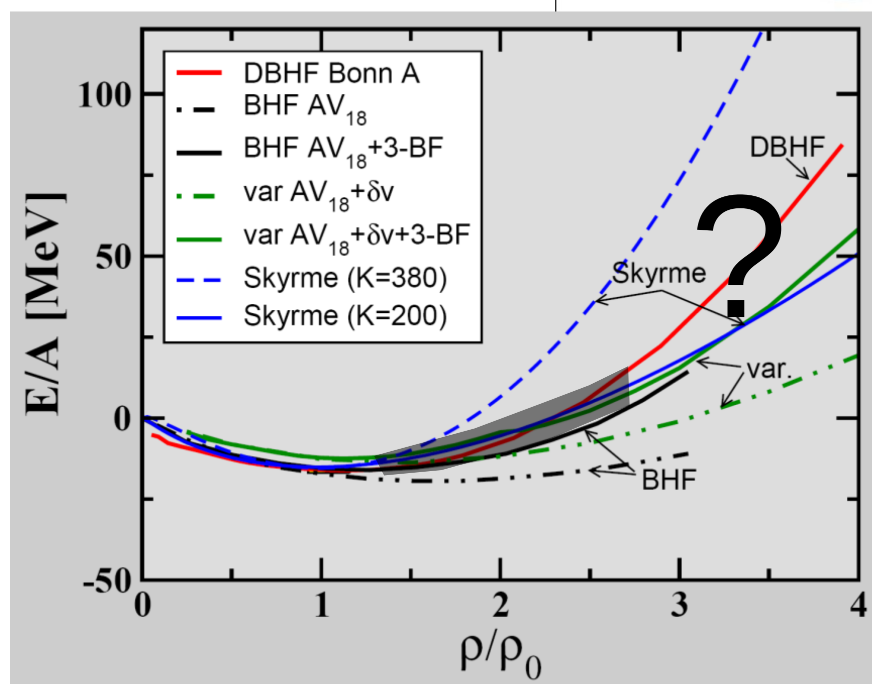
Idea: K^+ yield ∝ density ∝ compressibility



$pp \rightarrow K^+ \Lambda p$
$(E_{thres} = 1.6 \text{ GeV})$

K^+ from Au+Au/C+C

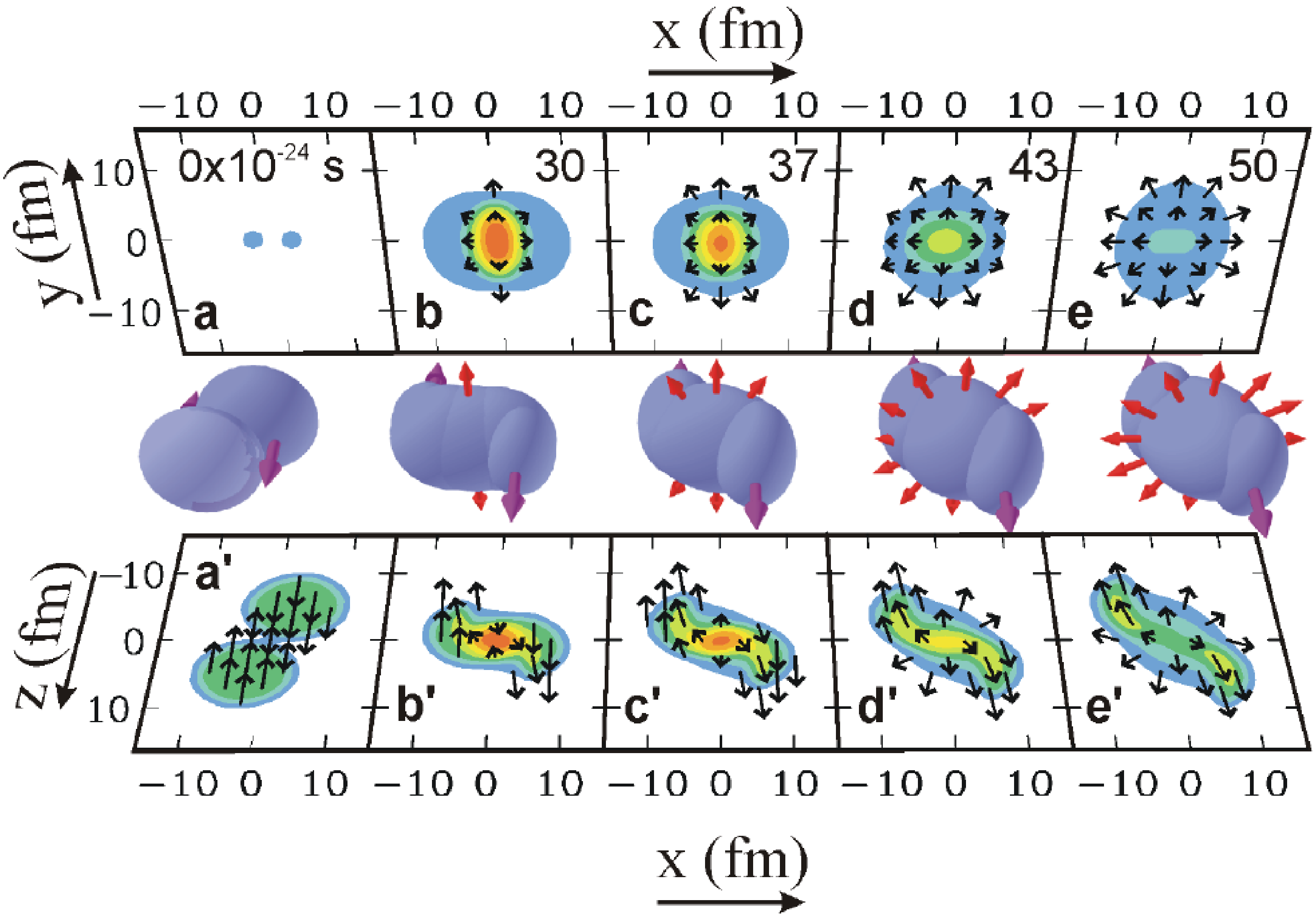




Experiment:
C. Sturm et al., (KaoS Collaboration)
PRL 86 (2001) 39

Theory: QMD: Ch. Fuchs et al., PRL86 (2001) 1974
IQMD Ch. Hartnack, J. Aichelin, J. Phys. G 28 (2002) 1649

Time (x axis) , transverse (y axis) and longitudinal (z axis) dynamics of Au+Au collision



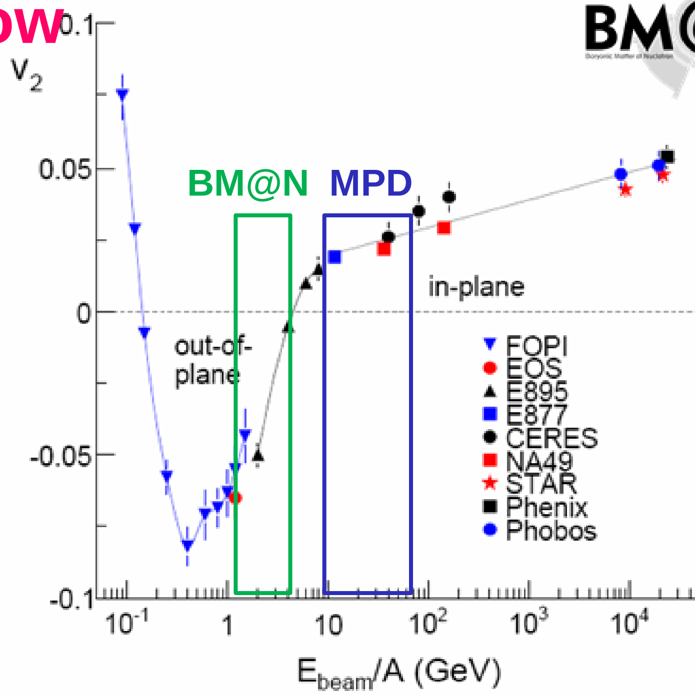
P. Danielewicz, R. Lacey, W.G. Lynch, Science 298 (2002) 1592

Study of EoS: Collective flow of identified particles

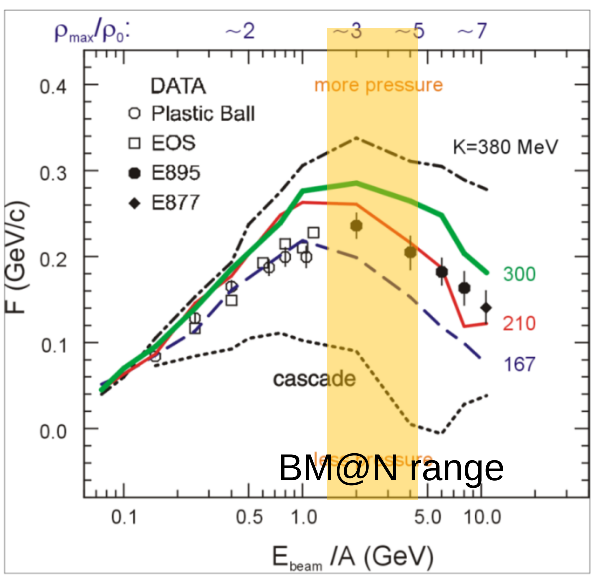
- collective flow of identified particles (π,K,p,Λ,Ξ,Ω,...) driven by the pressure gradient in the early fireball

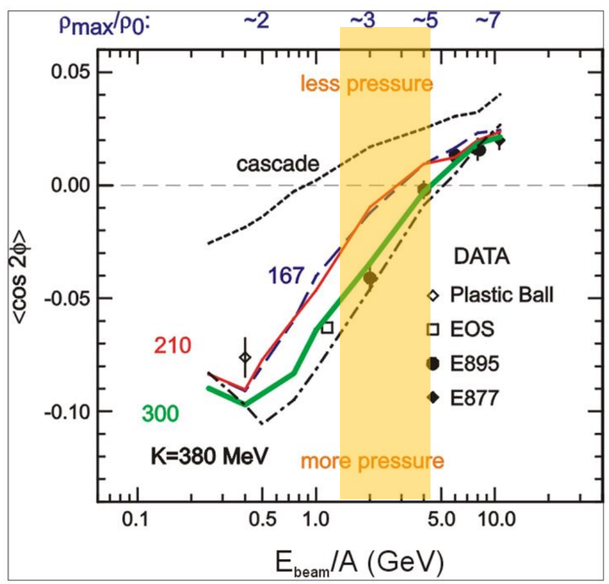
→ Nuclear incompressibility: $K = 9\rho^2\ \delta^2(E/A)/\delta\rho^2$

Azimuthal angle distribution:
$dN/d\varphi \propto (1 + 2v_1 \cos\varphi + 2v_2 \cos 2\varphi)$

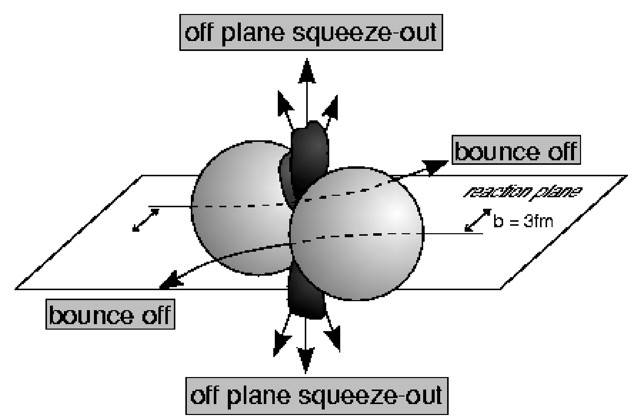


Proton flow in Au+Au collisions
in-plane flow ~ v_1 out-of-plane flow v_2



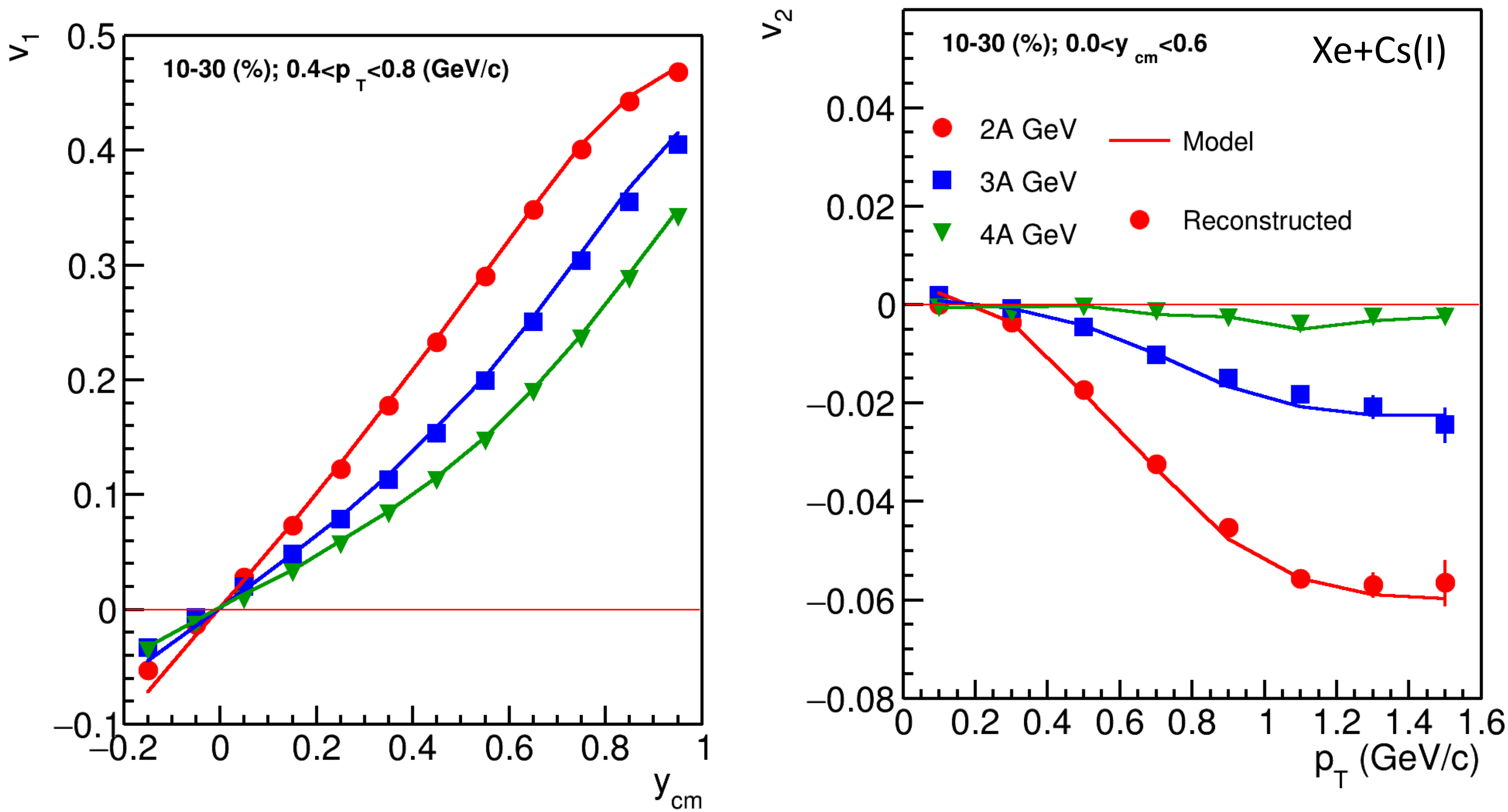


P. Danielewicz, R. Lacey, W.G. Lynch, Science 298 (2002) 1592



M.Kapishin **BM@N experiment**

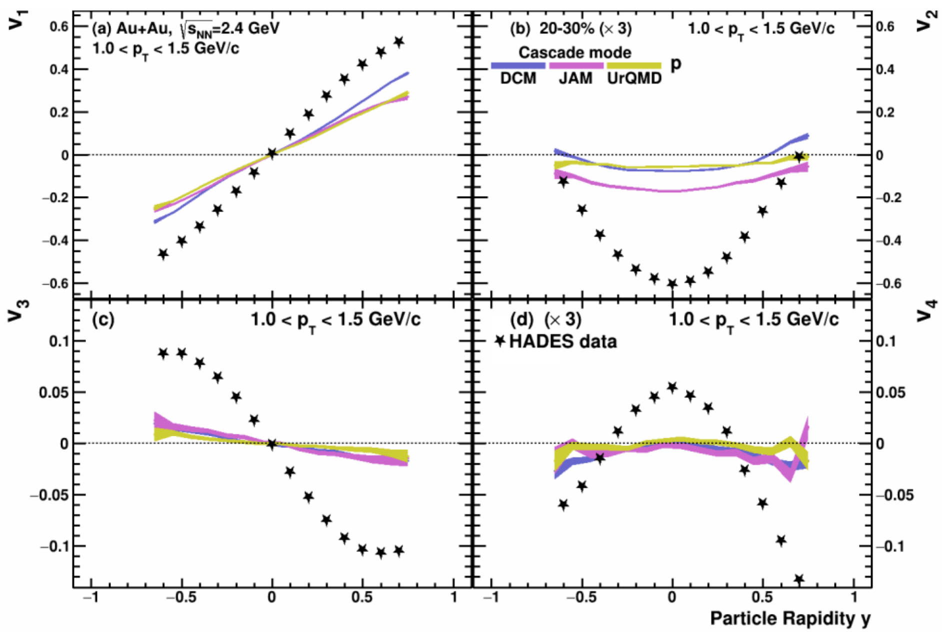
Directed and elliptic flow at BM@N

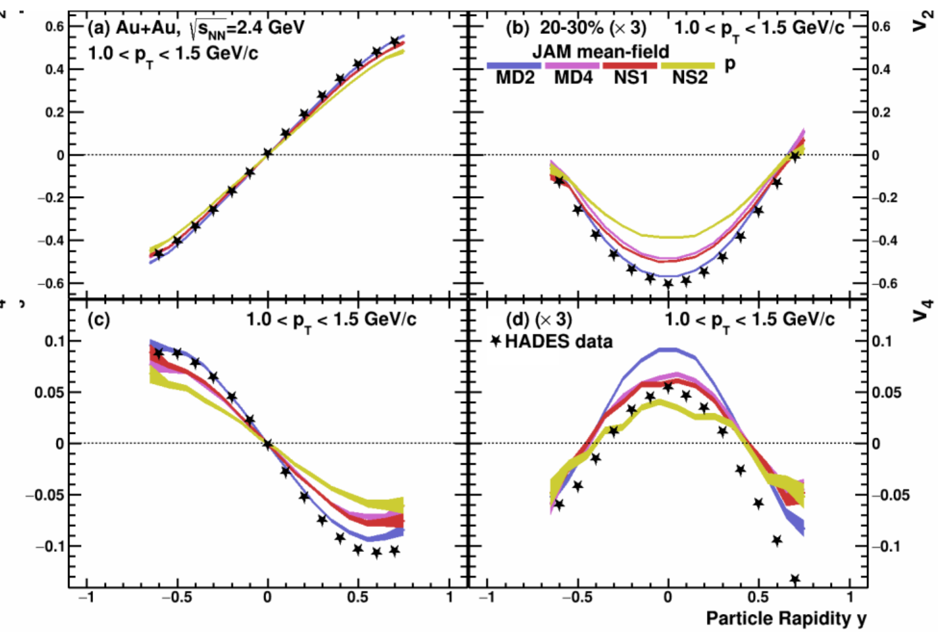


- Good agreement between reconstructed and model data
- Approximately 250-300M events are required to perform multi-differential measurements of v_n

$v_n(y)$ in Au+Au $\sqrt{s_{NN}}$=2.4 GeV: models vs. HADES data

Experimental data points:
Phys. Rev. Lett. **125** (2020) 262301

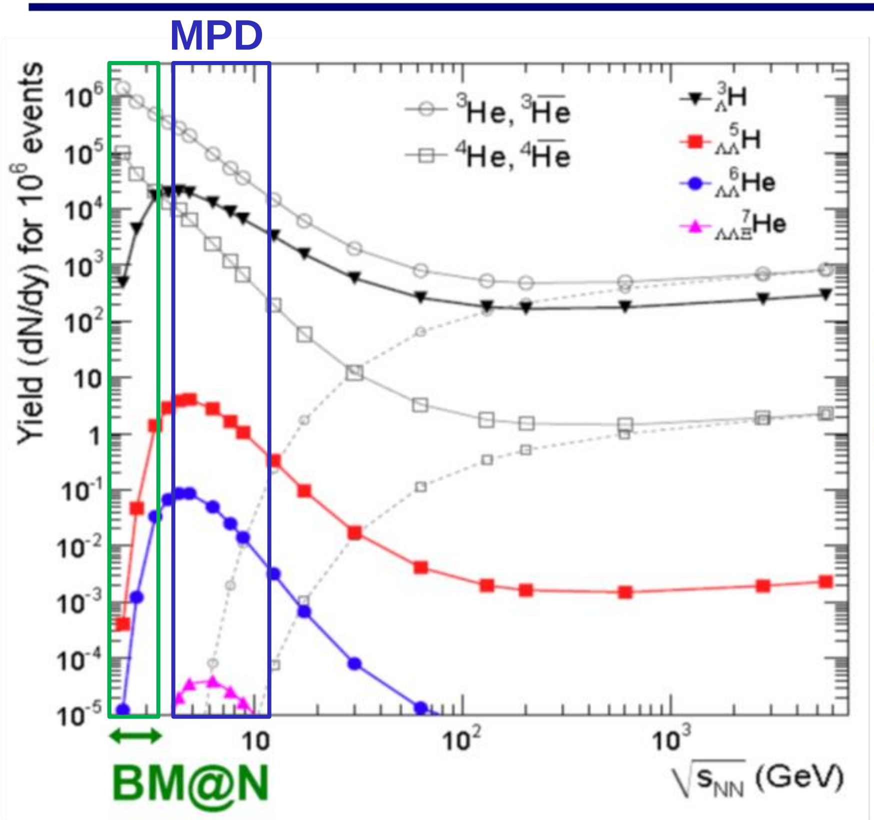


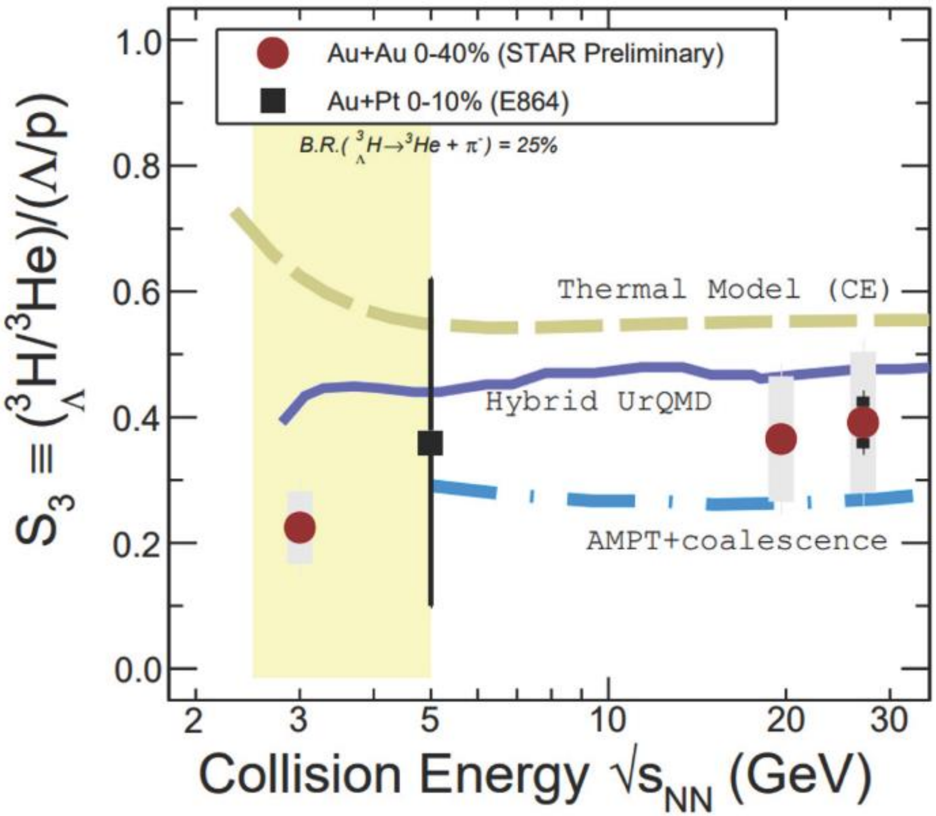


Cascade models fail to reproduce HADES experimental data

Reasonable agreement for $v_n(y)$
Higher harmonics are more sensitive to different EOS than v_1
More JAM results with different EOS are needed

Heavy-ions A+A: Hypernuclei production





- **In heavy-ion reactions:** production of hypernuclei through coalescence of Λ with light fragments enhanced at high baryon densities

- **Maximal yield** predicted for √s=4-5A GeV (stat. model) (interplay of Λ and light nuclei excitation function)

► **BM@N energy range is suited for search of hyper-nuclei**

Comparison HADES, STAR FxT, BM@N

	year	A+A	E_{kin} A GeV	# Events	Rare Observables		
					e^+e^-	Ξ^-, Ω^-	hypernuclei
HADES	2012	Au+Au	1.23	$7 \cdot 10^9$	✓	---	---
HADES	2019	Ag+Ag	1.58	$1.4 \cdot 10^{10}$	✓	---	800 $^3_\Lambda H$
STAR FxT	2018	Au+Au	2.9	$3 \cdot 10^8$	---	10^4 Ξ^-	10^4 $^3_\Lambda H$, $6 \cdot 10^3$ $^4_\Lambda H$,
STAR FxT	2021 planned	Au+Au	2.9	$2 \cdot 10^9$	---	$7 \cdot 10^4$ Ξ^-, Ω^- ?	$7 \cdot 10^4$ $^3_\Lambda H$, $4 \cdot 10^4$ $^4_\Lambda H$, $^5_\Lambda He$, $^7_\Lambda Li$, $^7_\Lambda He$, ?
BM@N	simulated	Au+Au	3.8	$2 \cdot 10^{10}$	---	$5 \cdot 10^6$ Ξ^- Expected: 10^5 Ω^- $3 \cdot 10^4$ anti-Λ $5 \cdot 10^2$ Ω^+	10^6 $^3_\Lambda H$, $^4_\Lambda H$, $^5_\Lambda He$, $^7_\Lambda Li$, $^7_\Lambda He$, Expected: 10^2 $^5_{\Lambda\Lambda} H$

Reaction rates: HADES ≈ 20 kHz, BM@N ≈ 20 kHz, STAR FxT ≈ 2 kHz
Energy Au beams: HADES: 0.2 - 1.25 A GeV, BM@N: 1.5 – 3.8 A GeV, STAR FxT: > 2.9 A GeV
Conclusion:
HADES and BM@N are complementary , no cascade hyperons (Ξ^-,Ω^-) at HADES
Statistics at BM@N ≈70 times higher (Ξ^-) than at STAR FxT

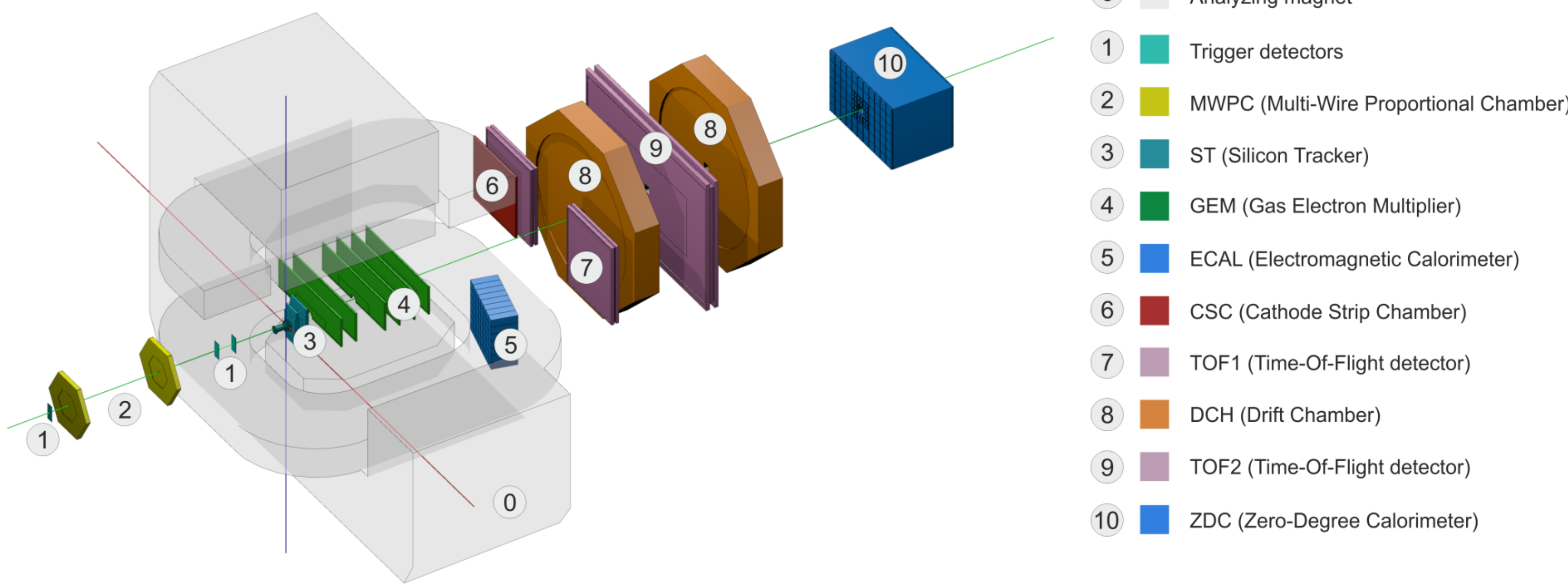
Heavy ion program goals and observables

1. BM@N energy range is very promising (EOS, symmetry energy, hypernuclei)
2. Sensitive probes have to be measured multi-differential (p_T, y) and as function of beam energy (2 – 4 GeV/u)

- EOS for high-density symmetric matter:
  - Collective flow of protons and light fragments in Au+Au collisions: Centrality, event plane, identification of fragments
  - Ξ^- (dss) and Ω^- (sss) hyperons: Yields, spectra, p_T vs. y from Au+Au and C+C collisions
- Symmetry energy at high baryon densities:
  - Particles with opposite isospin $I_3=\pm1$: Σ^{*+}(uus)/Σ^{*-}(dds)
  - Proton vs neutron collective flow (need highly granulated neutron detector)
- Λ-N and Λ-NN interactions
  - Hypernuclei: Yields, lifetimes, masses of $^{3}_{\Lambda}H$, $^{4}_{\Lambda}H$, $^{5}_{\Lambda}H$, $^{4}_{\Lambda}He$, $^{5}_{\Lambda}He$, …

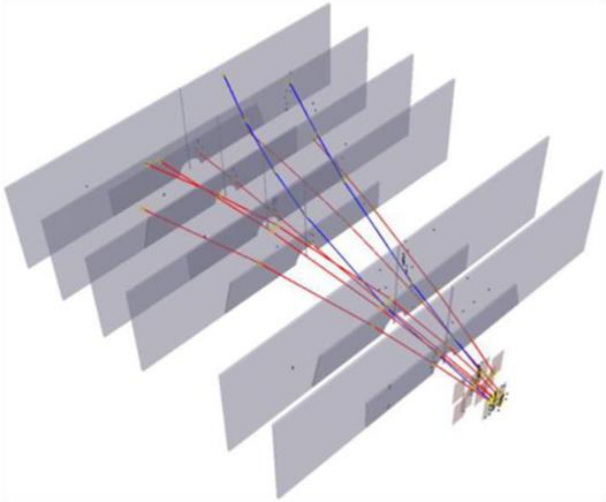
- Phase transition from hadronic to partonic matter:
  - Deconfinement: excitation function of Ξ^- (dss), Ω^- (sss) (EOS observables)
  - Transition to scaling of collective flow of mesons / hyperons with number of quarks (partonic matter)
  - Critical endpoint: higher order moments of the proton multiplicity distribution

BM@N setup in experimental run with 3.2 AGeV Ar beam, 2018

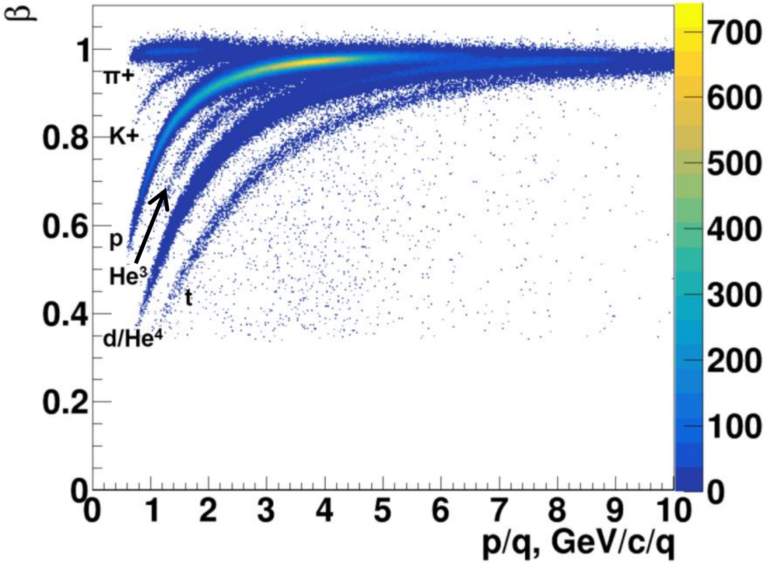


Tracking GEM detectors only in upper part of magnet

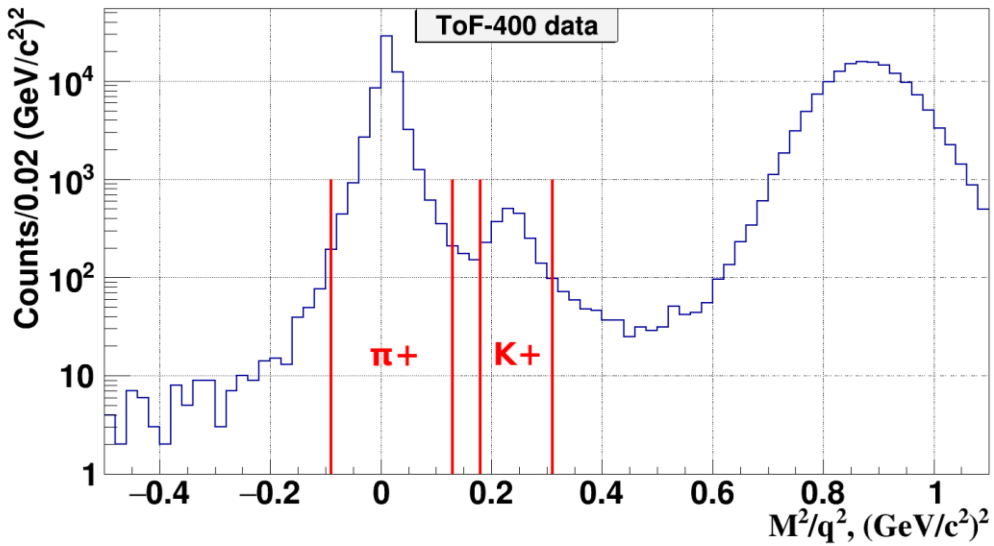
Ar beam , 3.2 AGeV , Ar + Al,Cu,Sn → X



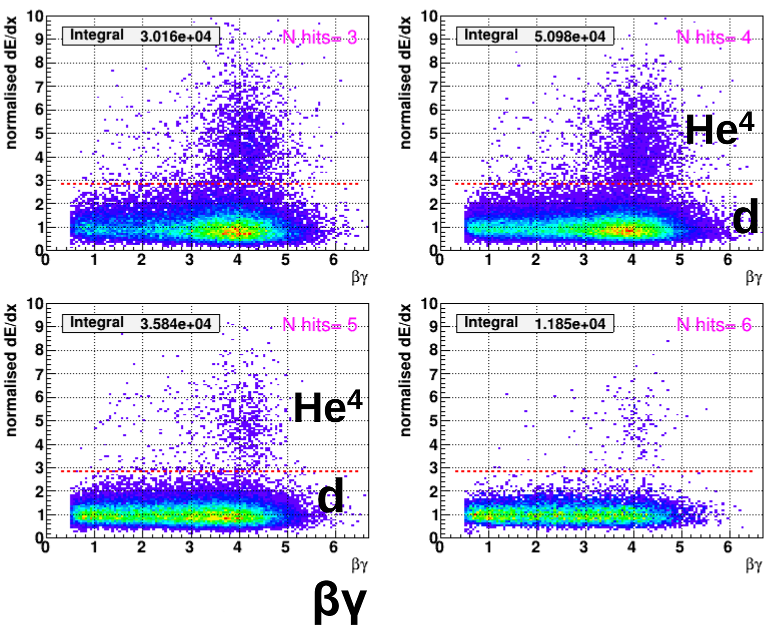
Identification of π+, K+, p, t, He3, d/He4

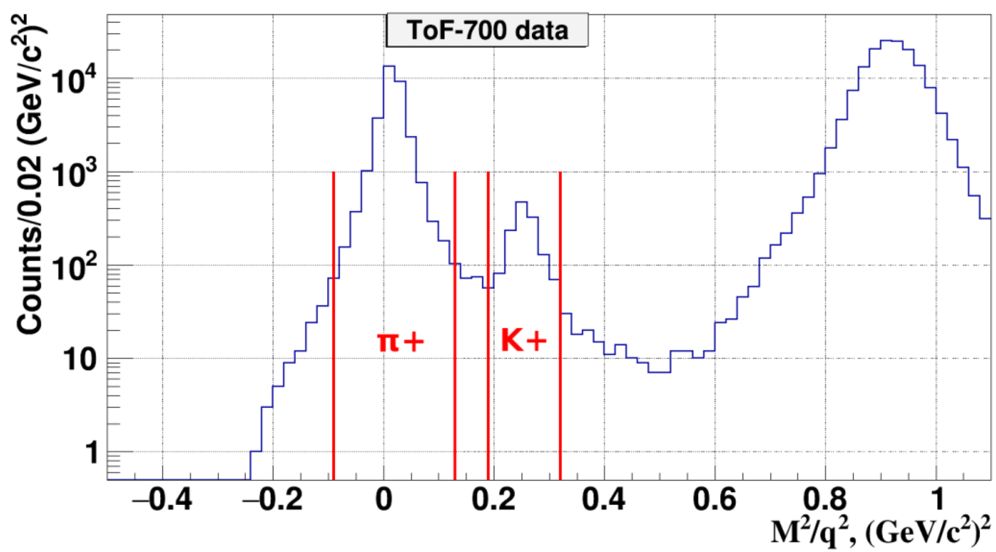


Ar beam , 3.2 AGeV , Ar + Al,Cu,Sn → X

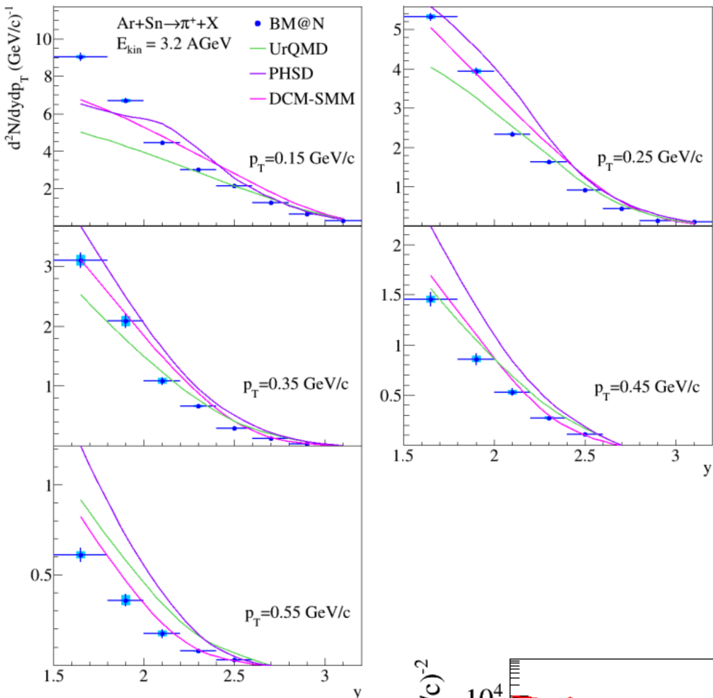


He⁴ / d separation by dE/dx in GEM detectors

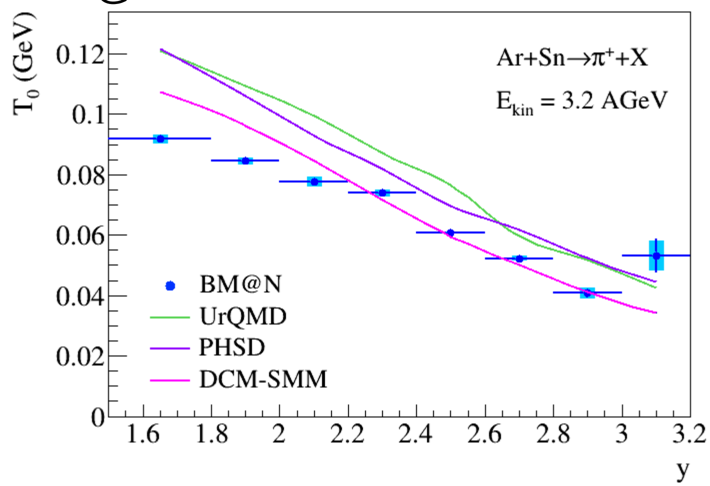


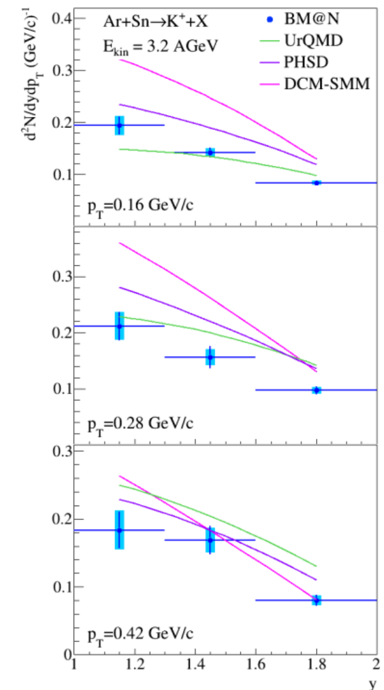


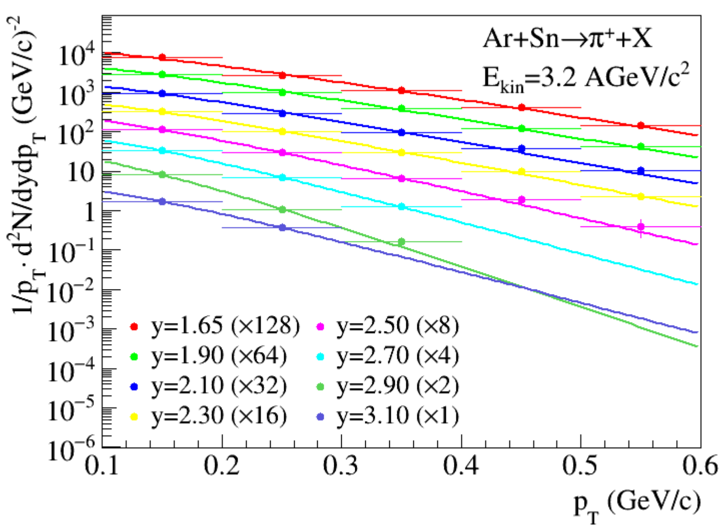
Production of π^+ and K^+ mesons in 3.2 AGeV argon-nucleus interactions at the Nuclotron

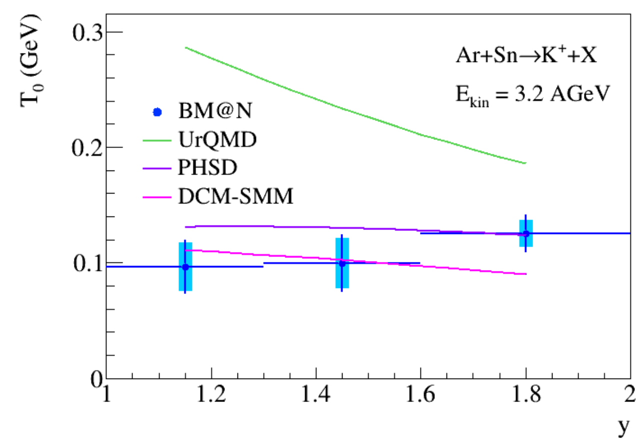


Draft of the paper in circulation at BM@N

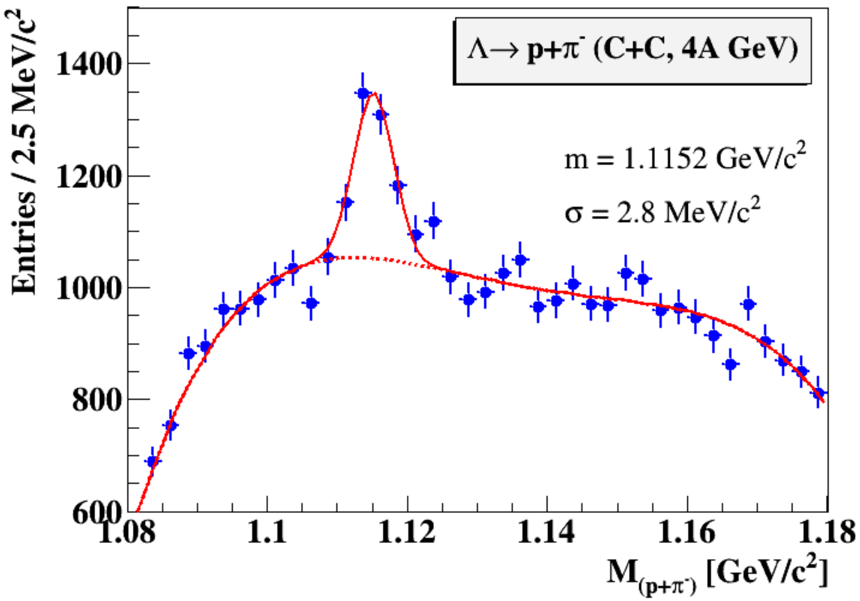


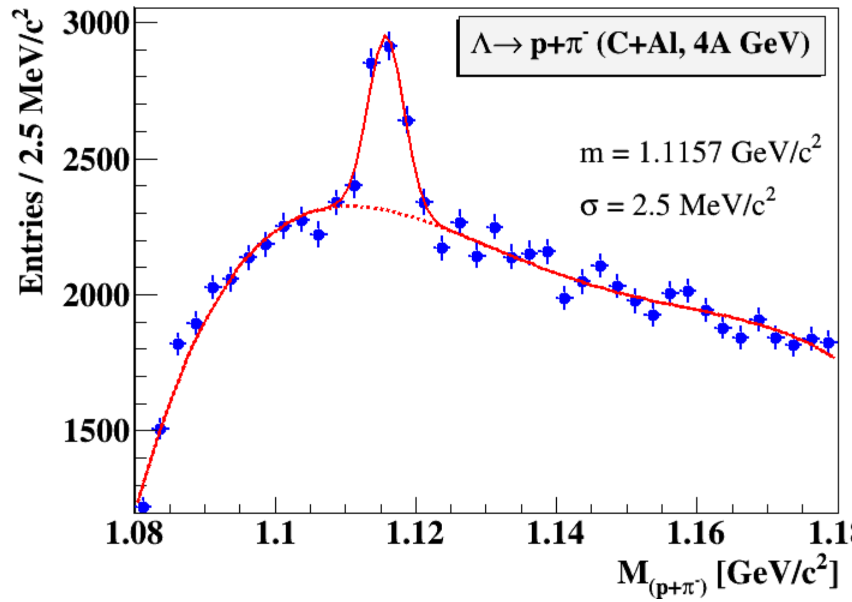


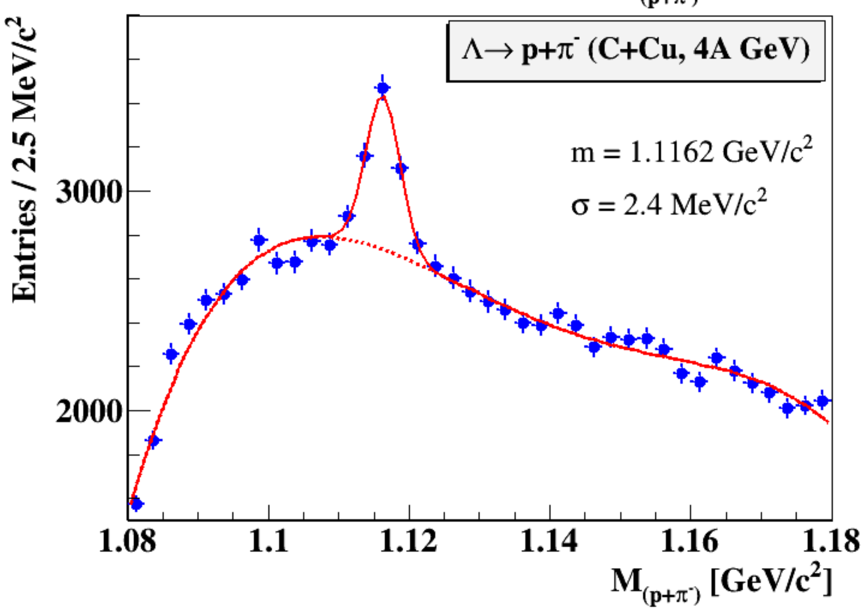




Λ hyperon signals in 4A GeV carbon-nucleus interactions



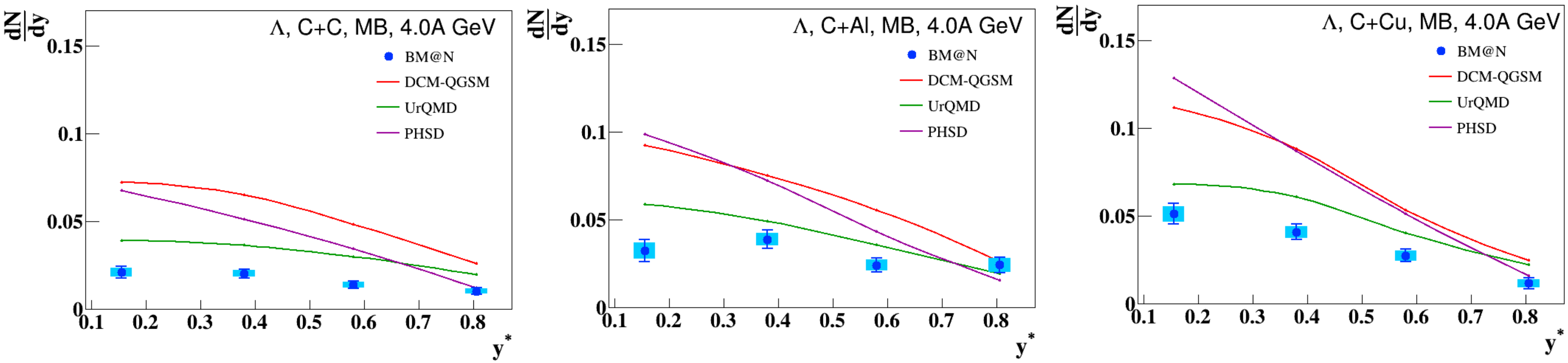




C beam 4 AGeV
C + C,Al,Cu → Λ + X minimum bias
Λ signal width 2.4 – 3 MeV

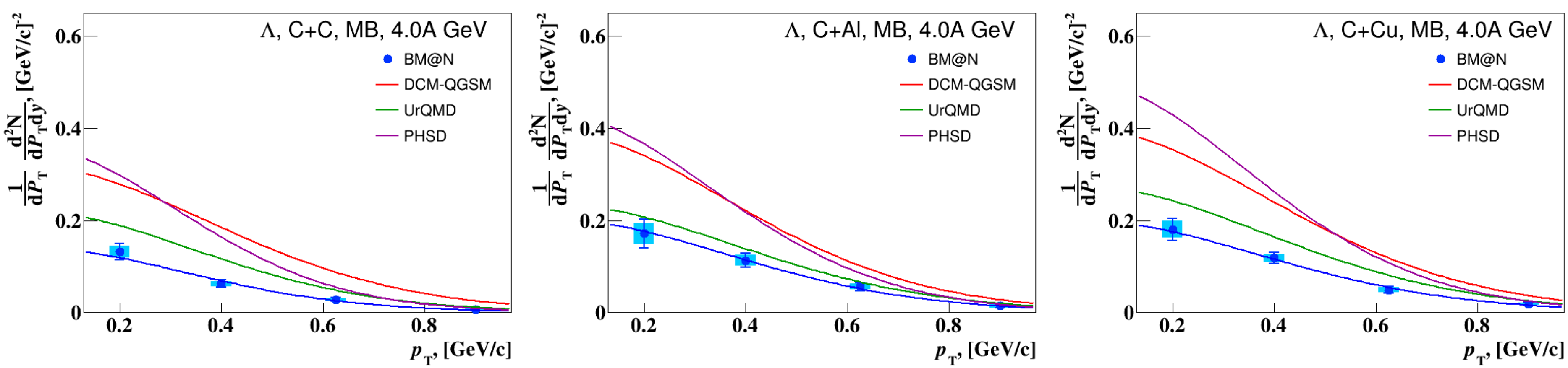
C+C: 4.6M triggers
C+Al: 5.3M triggers
C+Cu: 5.3M triggers

Λ hyperon yield in 4A GeV carbon- nucleus interactions



- **Yield of Λ in C+C, C+Al, C+ Cu minimum bias interactions in dependence on rapidity y* in c.m.s. transverse momentum p_T**
- **Comparison with predictions of DCM-QGSM, UrQMD , PHSD models**

$$1/p_T \cdot d^2N/dp_T dy = A \cdot exp(-(m_T - m_\Lambda)/T), \quad m_T = \sqrt{(m_\Lambda^2 + p_T^2)}$$



BM@N Experimental physics run in Xe beam with CsI target

BM@N: Estimated hyperon yields in Xe + Cs collisions

4 A GeV Xe+Cs collisions, multiplicities from PHSD model,
Beam intensity $2.5 \cdot 10^5$/s, DAQ rate $2.5 \cdot 10^3$/s, accelerator duty factor 0.25

$1.8 \cdot 10^9$ interactions
$1.8 \cdot 10^{11}$ beam ions

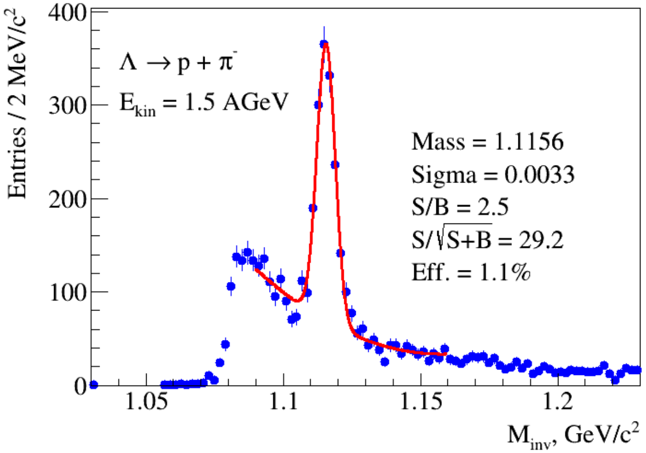
Particle	E_{thr}NN GeV	M b<10 fm	ε %	Yield/s b<10fm	Yield / 800 hours b<10 fm
Λ	1.6	1.5	2	150	$5 \cdot 10^7$
Ξ^-	3.7	$2.3 \cdot 10^{-2}$	0.5	0.55	$2 \cdot 10^5$
Ω^-	6.9	$2.6 \cdot 10^{-5}$	0.25	$3.2 \cdot 10^{-4}$	110
Anti-Λ	7.1	$1.5 \cdot 10^{-5}$	0.5	$3.7 \cdot 10^{-4}$	130

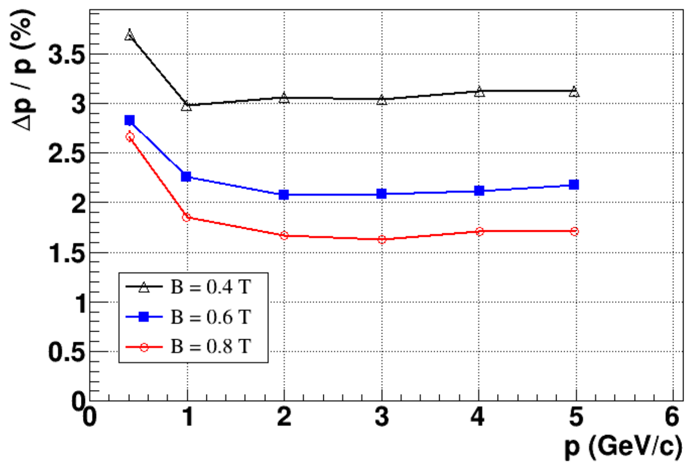
DCM-SMM
x 0.75
x 0.5

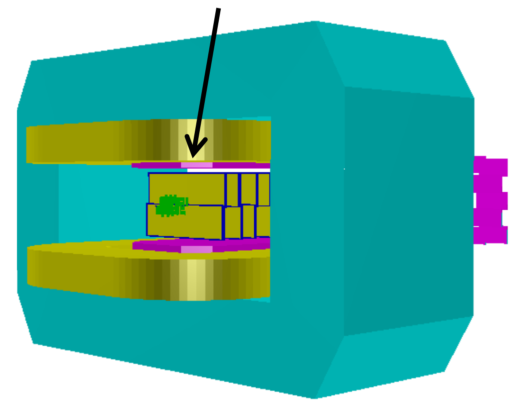
Xe + CsI run configuration of hybrid central tracker: 4 Forward Si + 7 GEM stations

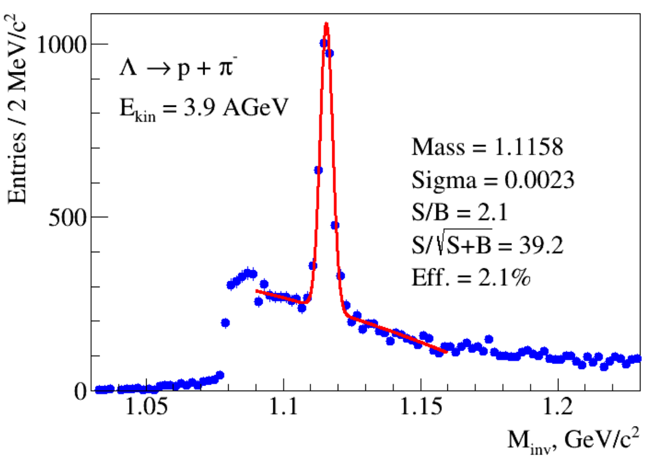
DCM-SMM model: Xe + Sn , T_0= 1.5 - 3.9 AGeV

4 Forward Si + 7 GEM

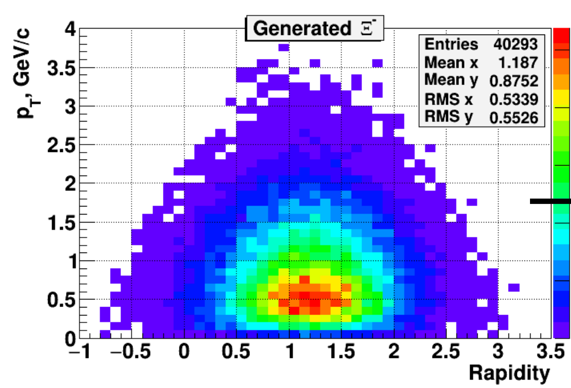


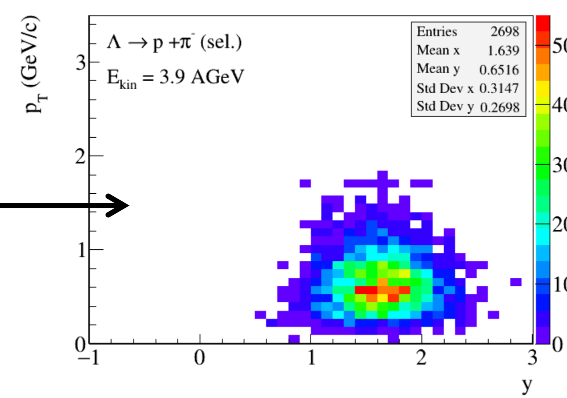






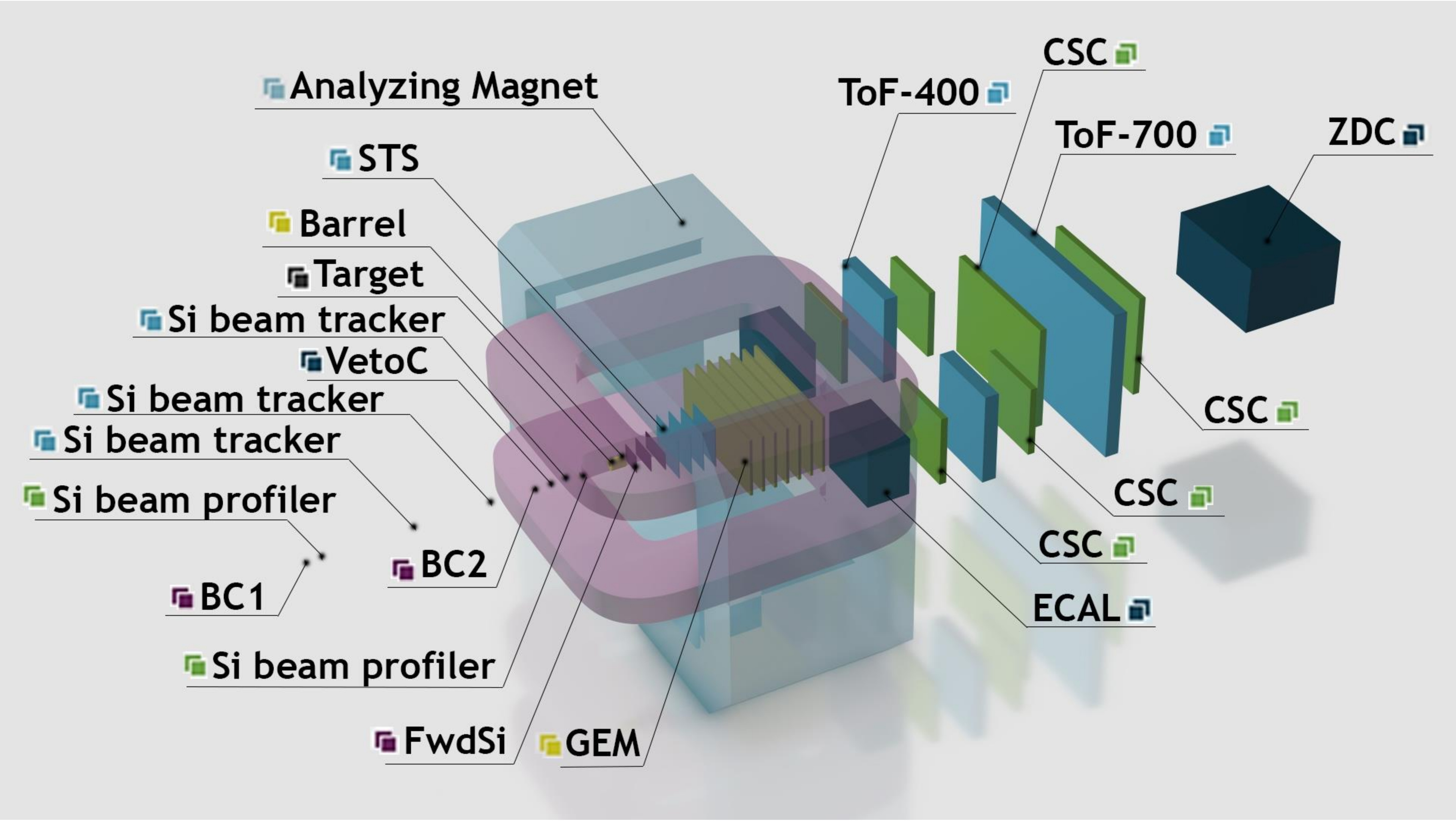
Phase space of reconstructed Λ





Laboratory system

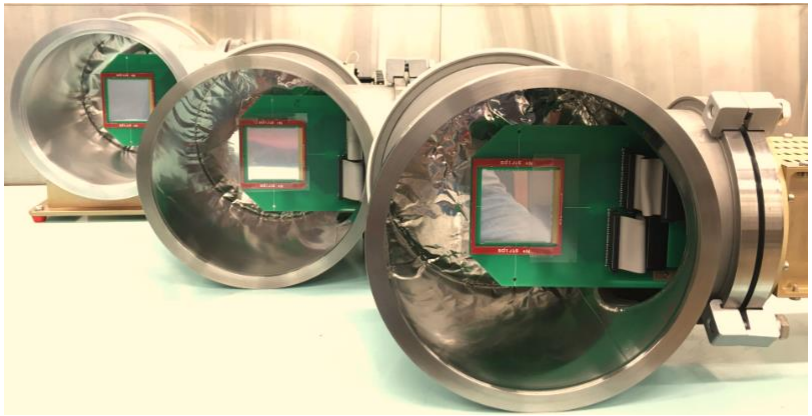
Configuration of BM@N detector for heavy ion program (without beampipe)



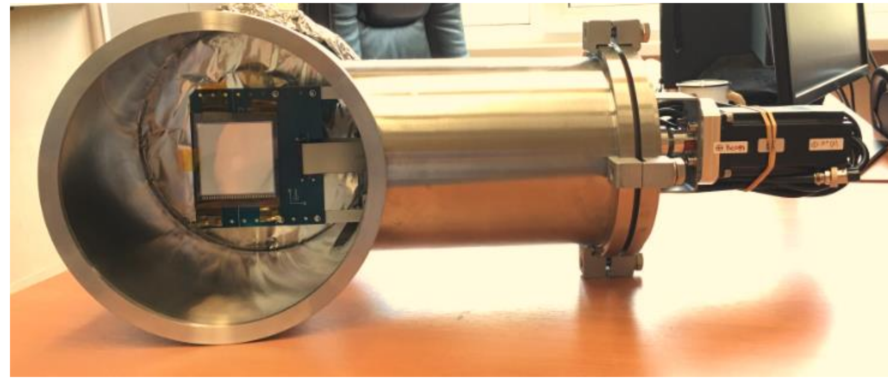
BM@N detector preparation for heavy ion run

FST group

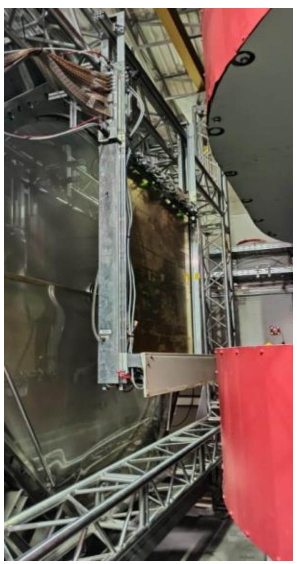
3 Silicon beam tracking detectors



Beam profile meter with Si detector and positioning mechanics



Outer tracker: Cathode Strip Chambers → 4 CSC of 106x106 cm2



Outer tracker group

Big CSC 220x145 cm2

Silicon beam tracking detector in SRC setup

INR RAS group

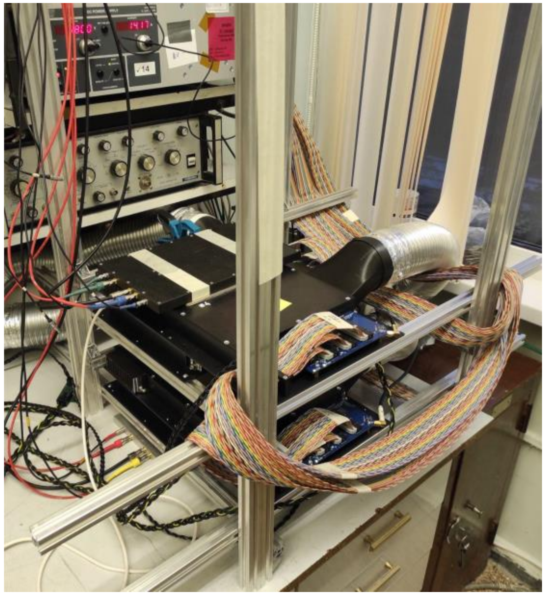
Forward hodoscope in front of FHCAL

BM@N experiment

Forward Silicon Tracker for heavy ion run

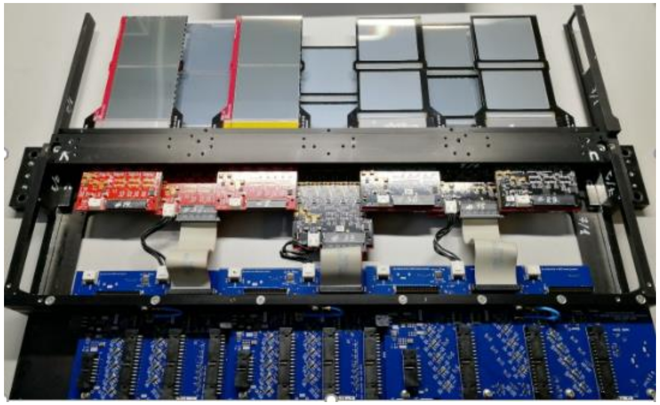
FST group

Setup for FST tests with cosmic rays

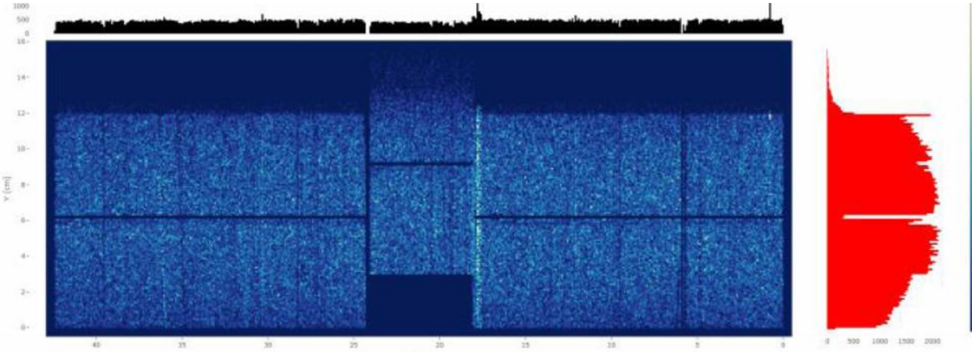


FST support mechanics

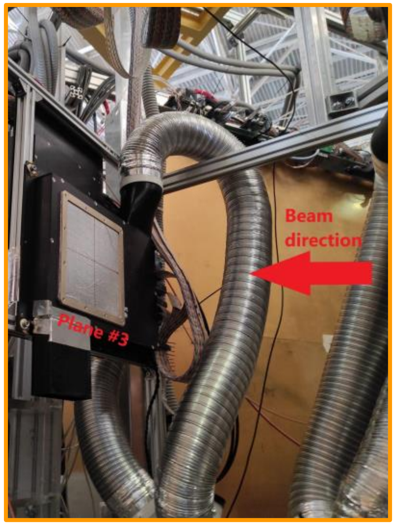
Assembled FST half station of 7 detectors



Cosmic ray X/Y profile of FST half station



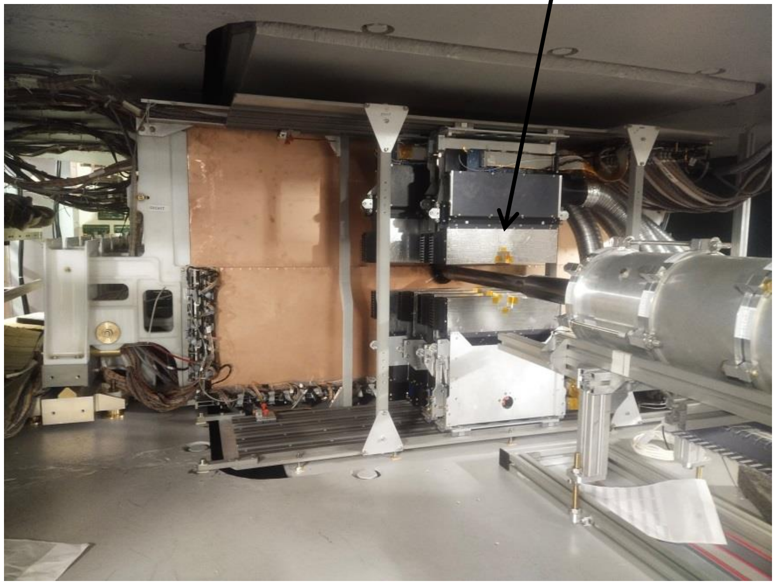
FST modules in SRC setup



►All 48 modules and 4 FST stations with 6, 10,14,18 modules are assembled, tested and installed

BM@N tracking detector installation for heavy ion run

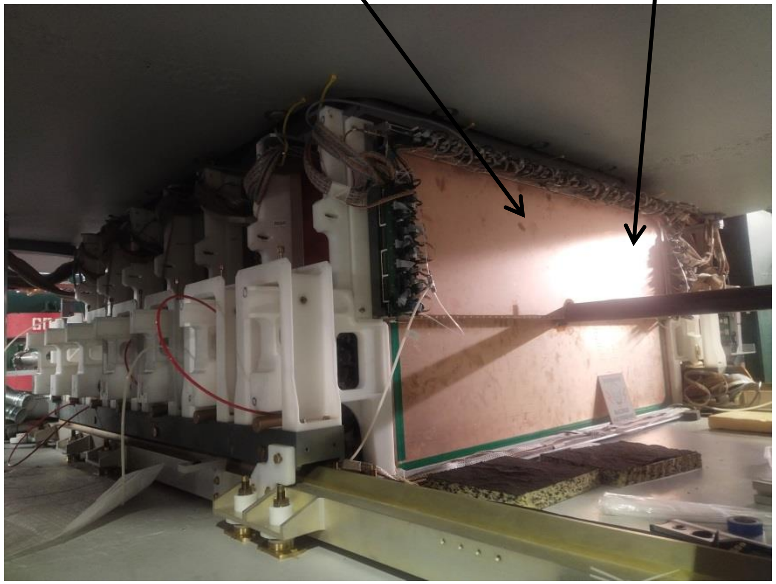
Forward Si tracker detectors in front of GEM detectors



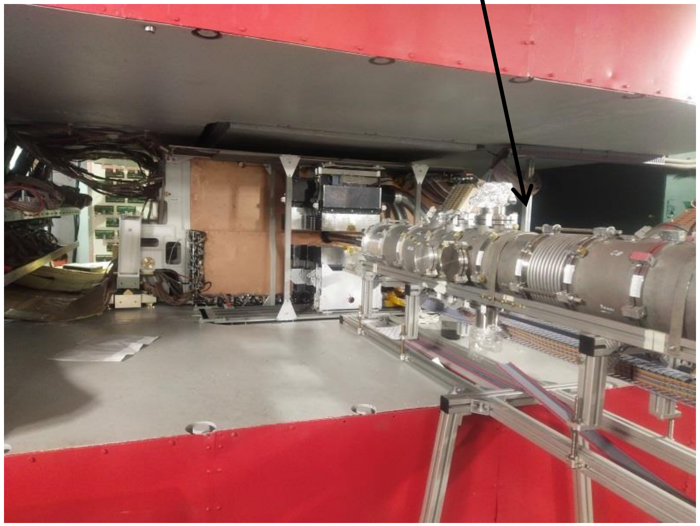
GEM, FST groups + engineer group

GEM detectors on positioning mechanics in magnet

Carbon vacuum beam pipe

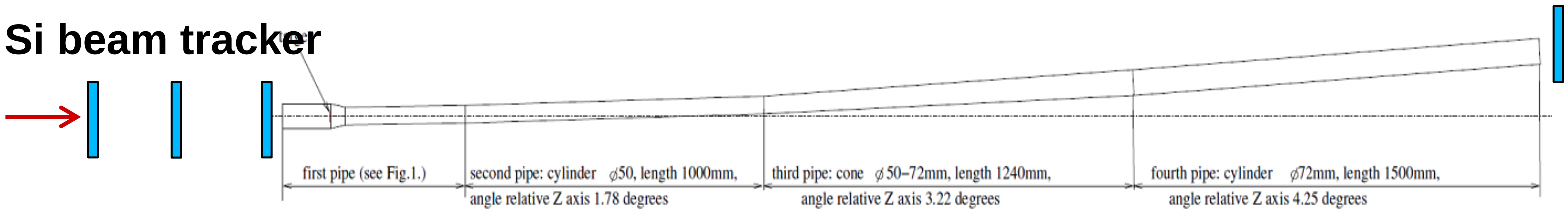


Vacuum boxes for beam detectors



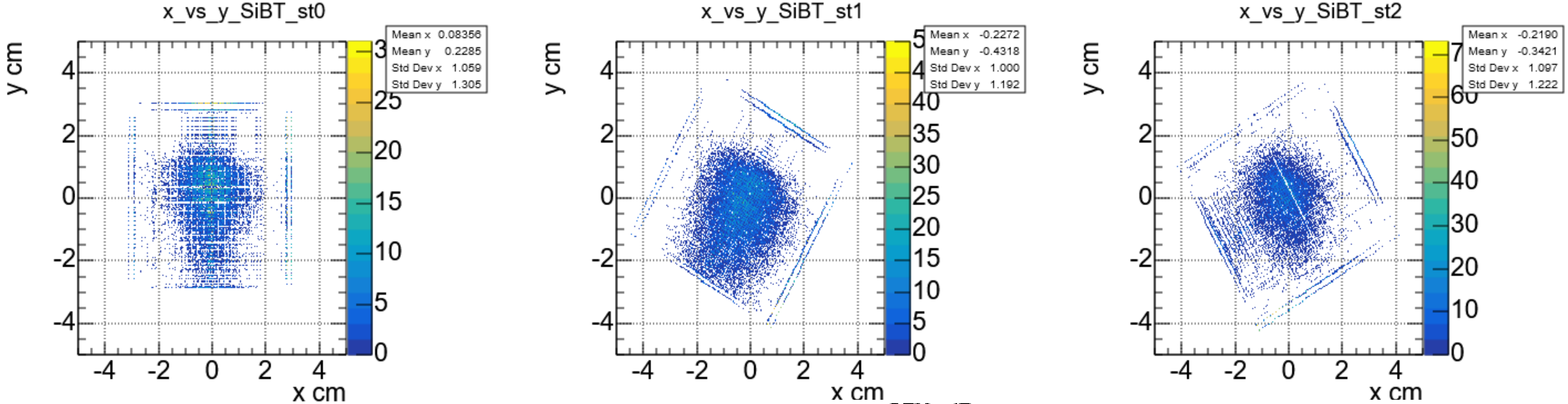
Experimental run in 3.85 AGeV Xe beam with CsI (2%) target

Si beam tracker



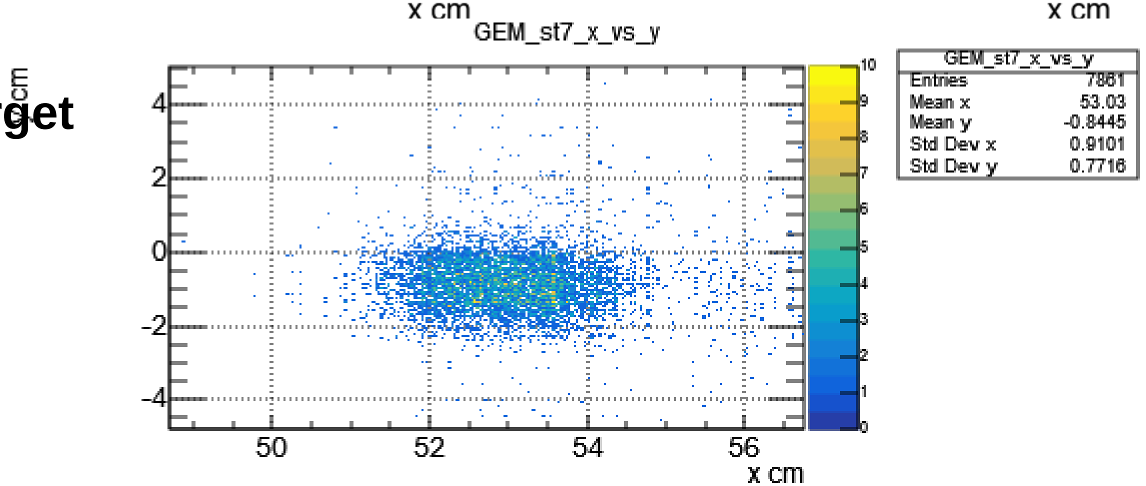
Small GEM as beam profile meter

First task of the Xe run → trace beam and monitor its profile in the end of the setup (try to find optimal trajectory to reduce background)

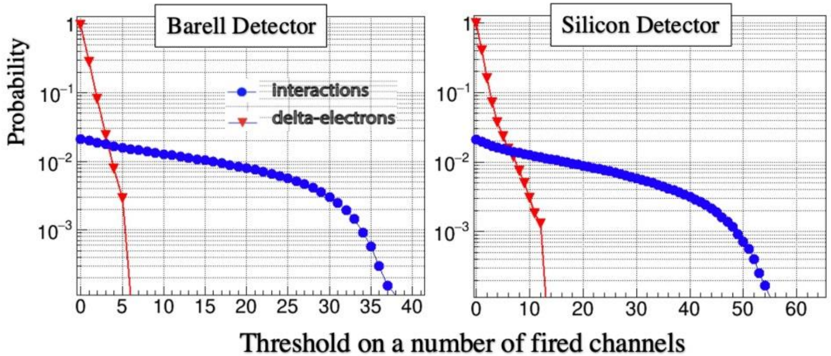


Measured beam spot at target

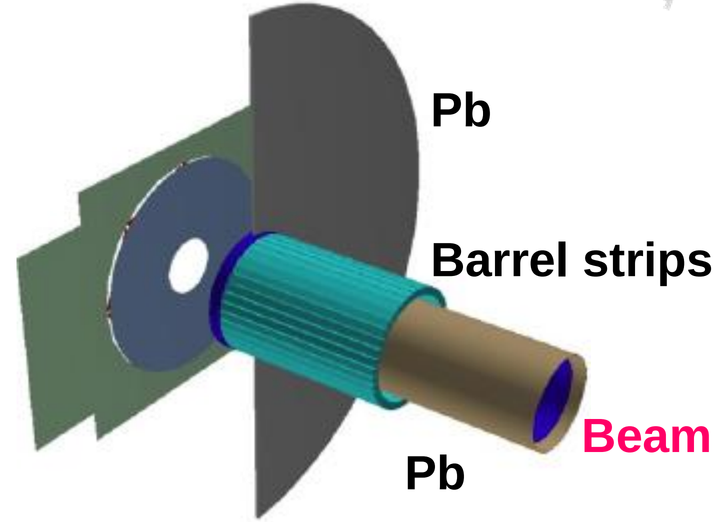
	Ar 2018	Xe 2022
σ_X =	5 mm	7 mm
σ_Y =	5 mm	7 mm



BM@N Trigger detectors



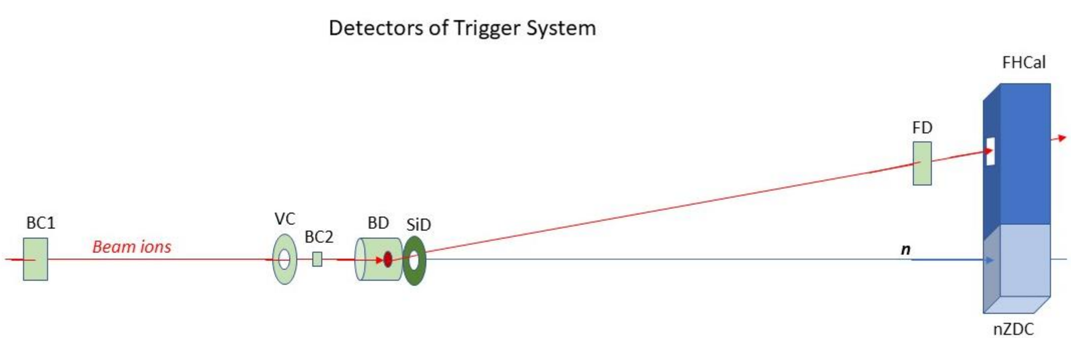
Trigger detectors in target area: multiplicity SiD and Barrel BD



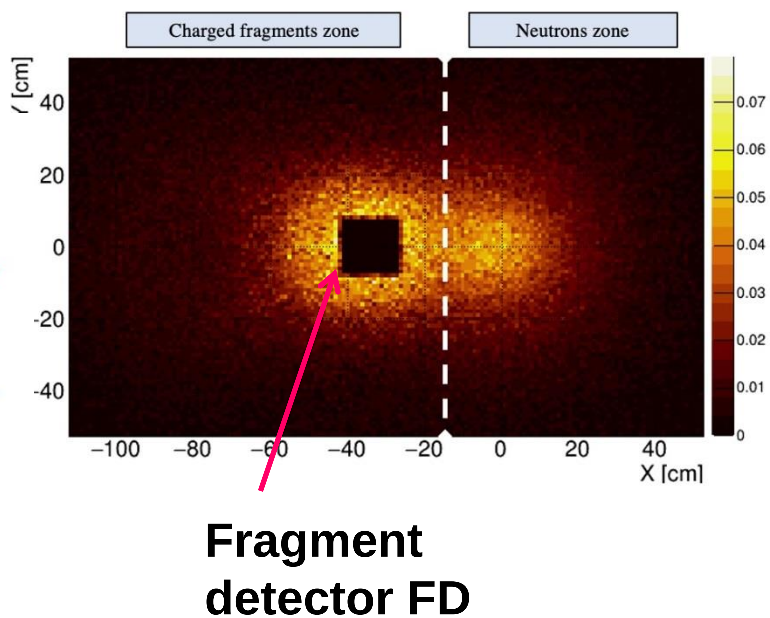
Variants of trigger logics **fraction**

Beam trigger:	BT = BC1 * BC2 * VC_{veto}	3 %
Min Bias trigger:	MBT = BT * FD Amp < thr	7 %
BD trigger:	CCT1 = BT * N(BD)>3	5 %

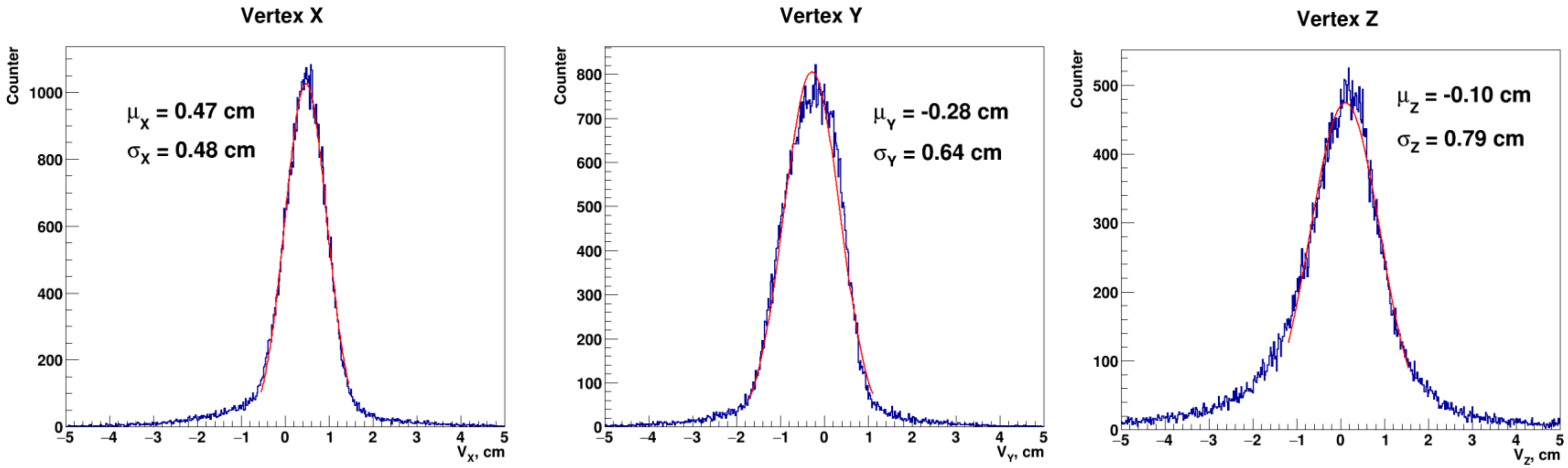
Combined trigger: CCT2 = MBT * CCT1 **main**



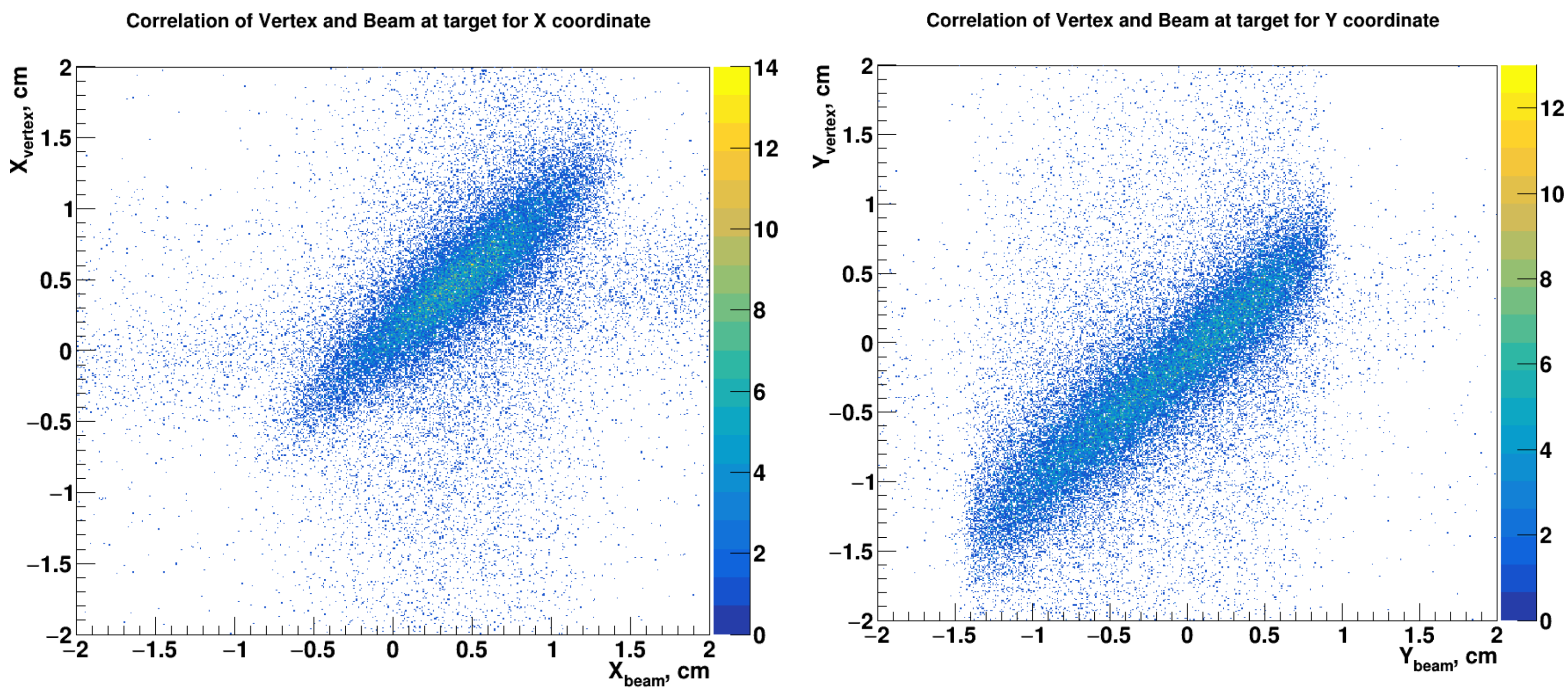
FHCAL rates



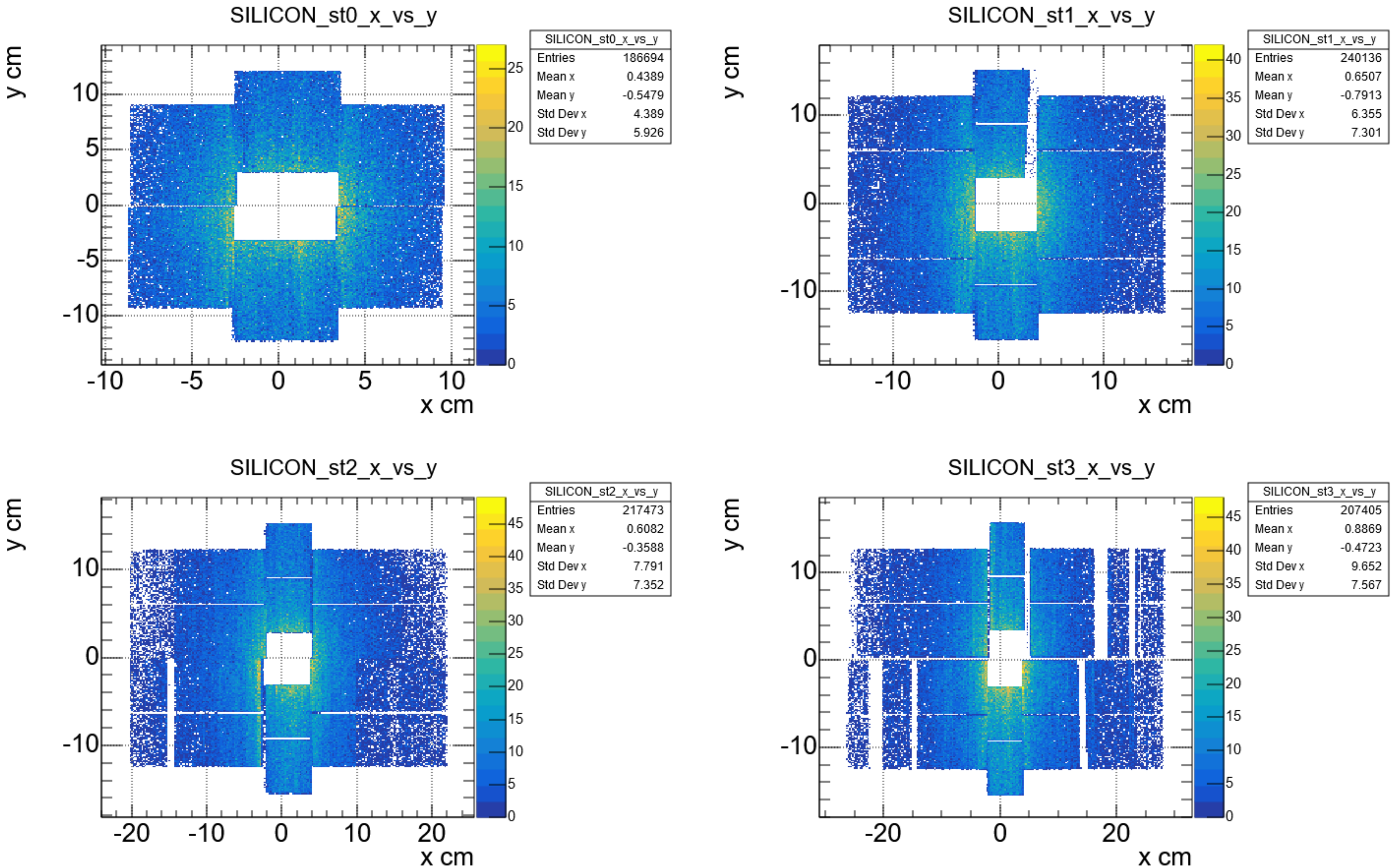
Vertex reconstruction



CsI (2%) target

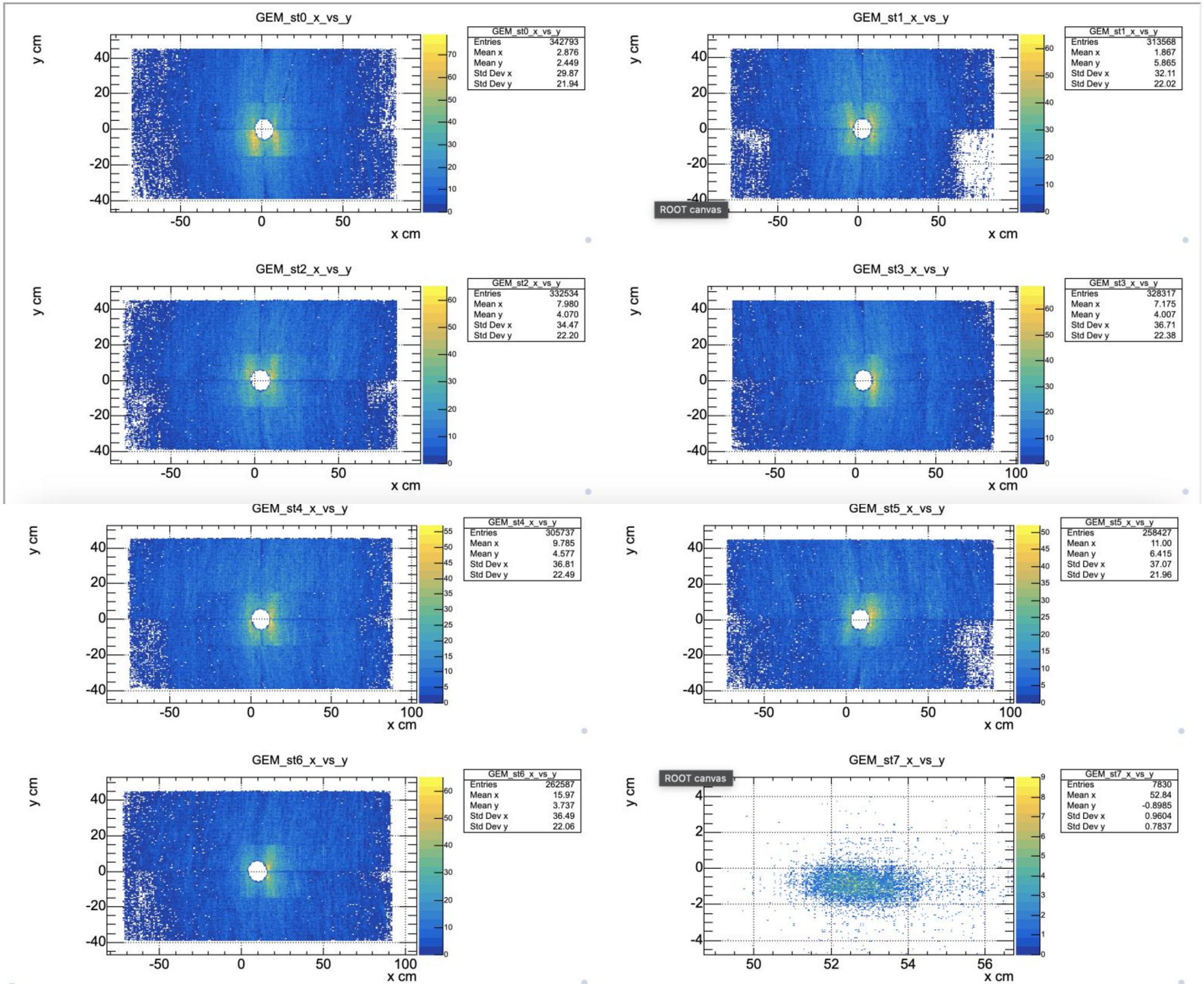


FST hit reconstruction: 4 Si stations



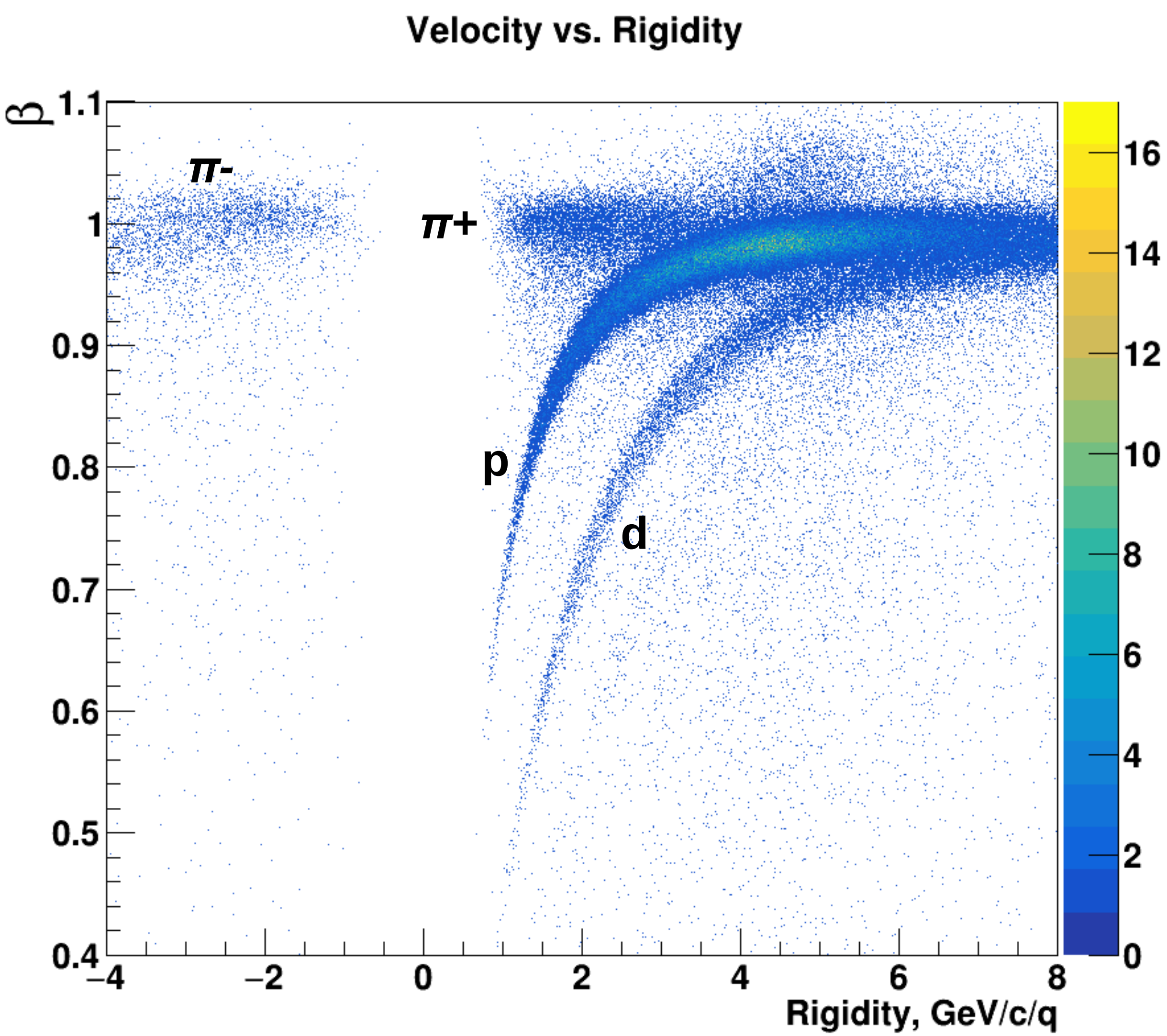
GEM hit reconstruction: 7 stations + small GEM profile meter

GEM Hits



Raw online data: ToF-700 π+, p, d identification

Without dedicated ToF calibration

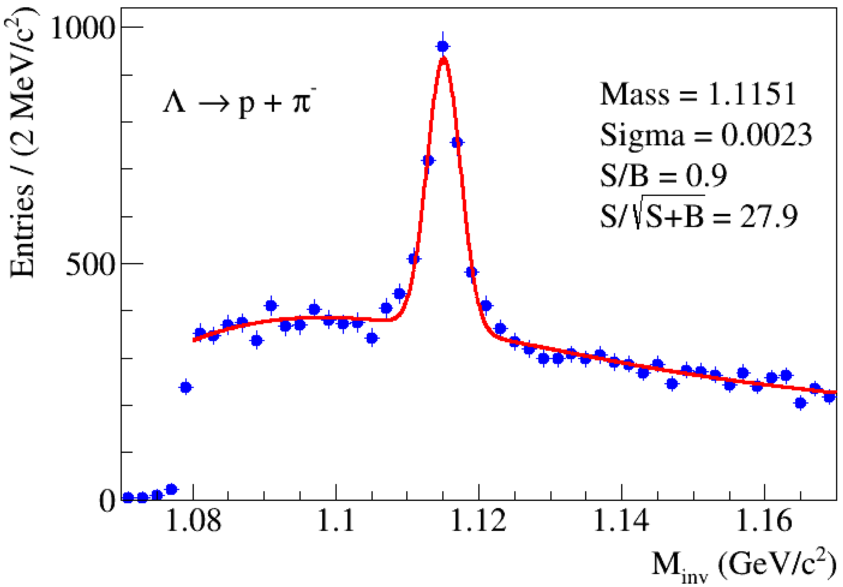


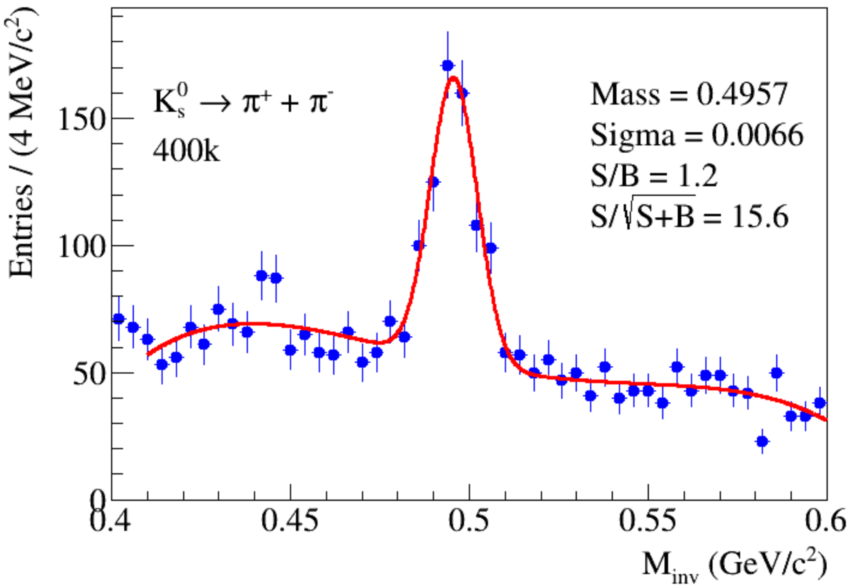
Raw data reconstruction: $\Lambda \rightarrow p\pi^-$ and $K^0_s \rightarrow \pi^+\pi^-$ signals

BM@N

Need dedicated alignment of silicon and GEM tracking detectors

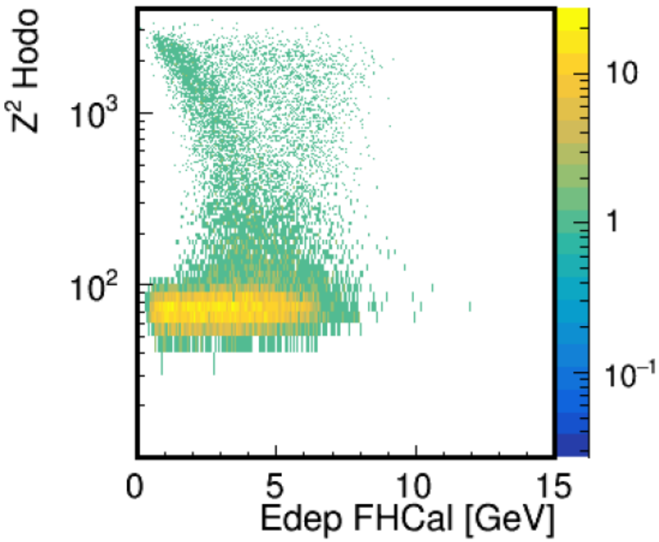
400k events





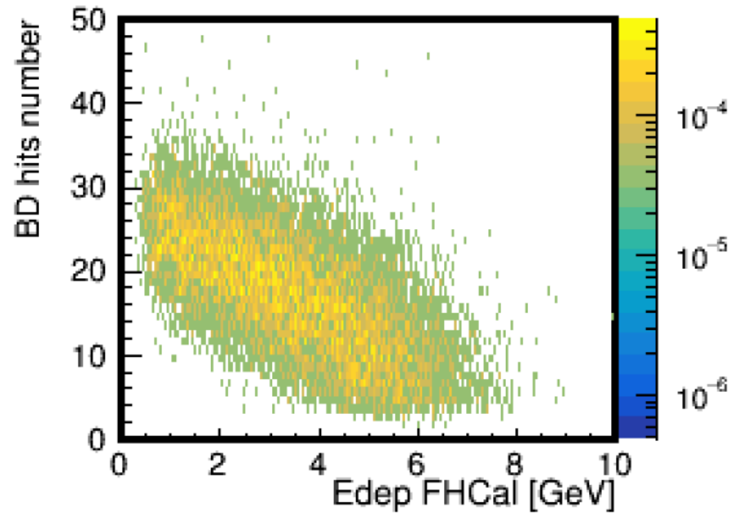
Centrality selection with Hodoscope and FHCal detectors

Min bias trigger



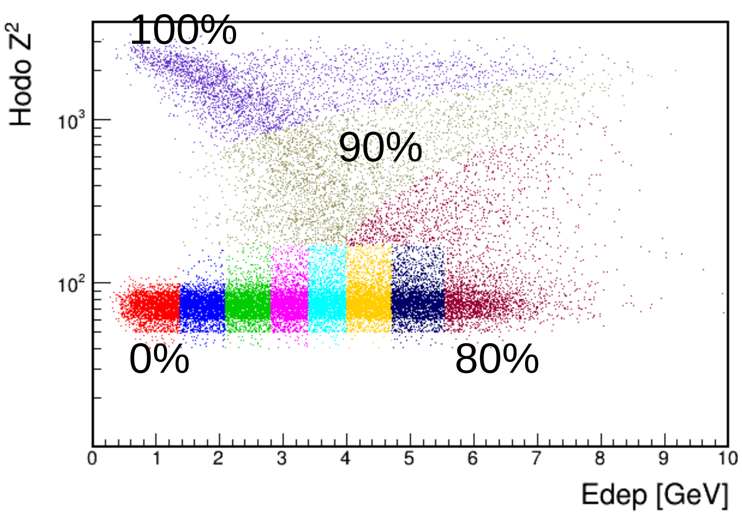
INR RAS group

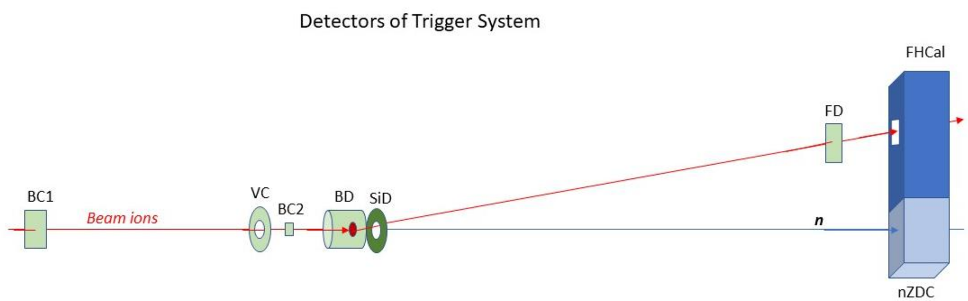
FHCAL: total energy
Fragment Hodoscope: Z^2
Barrel detector BD hits



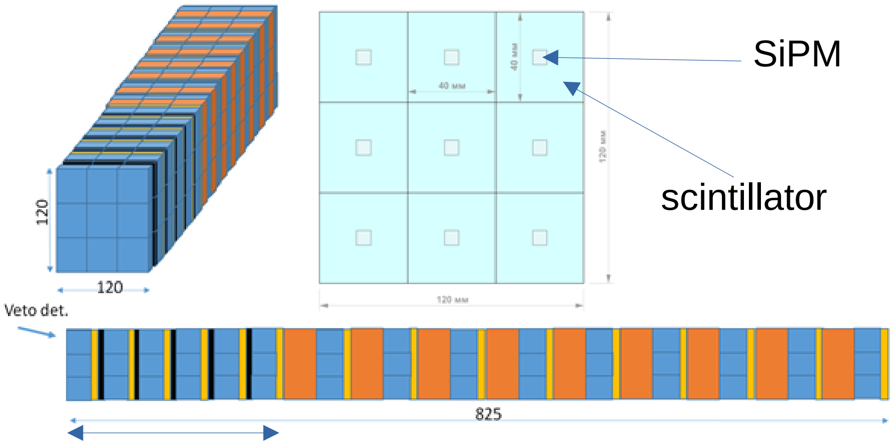
Color bins – 10% of number of events in each bin

CsI target, Z vertex cut (-1.5 < Z <1.5 cm), Ntr (vertex) >= 2 , single Xe ion



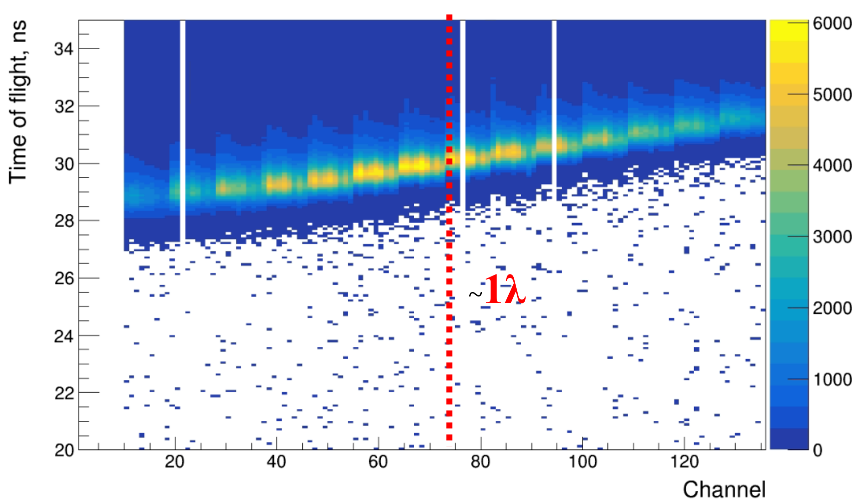


R&D High Granularity Neutron detector prototype

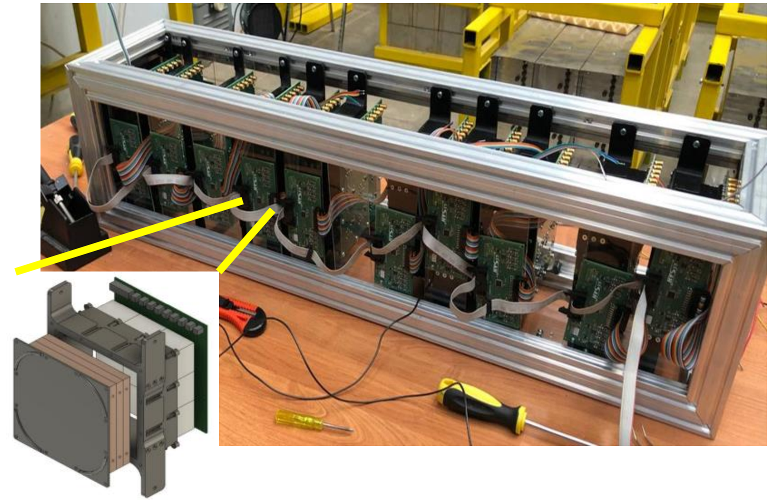


~12X_0

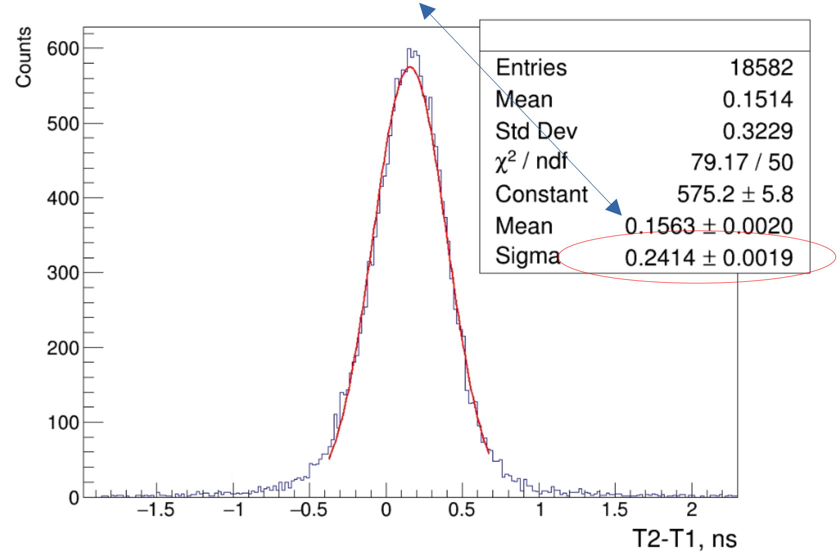
HGN prototype (15 layers, thickness > 2 λ_{int}):
1-st layer – VETO
2-6 layers – γ-detection part (Pb/Scint.)
7-15 layer – n-detection part (Cu/Scint.)



Prototype tested in Xe run



Time resolution between two nearest layers for neutron detection in the BM@N Run.
Single cell time resolution is better then 200ps



Trigger rates and DAQ capacity

3.8 AGeV: Spill ~2.2 s, cycle 12 s, up to 900k Xe ions per spill
3.0 AGeV: Spill ~3.5 s (up to 4 s), up to 1.3M ions per spill

♥ Spill nbr. 235164 16.01.2023 18:45:11

Event statistics, M

Detectors

BC1_low	1836957
BC1	765200
BC2	681683
VC	152651
NBD>L1	130762
NBD>H1	131236
NSiD>L2	0
NSiD>H2	0
FD	701453
nZDC	102589

Triggers

BT	576455
MBT	20761
CCT1	123806
CCT2	9912
NIT	492799

beam

triggers

fragments

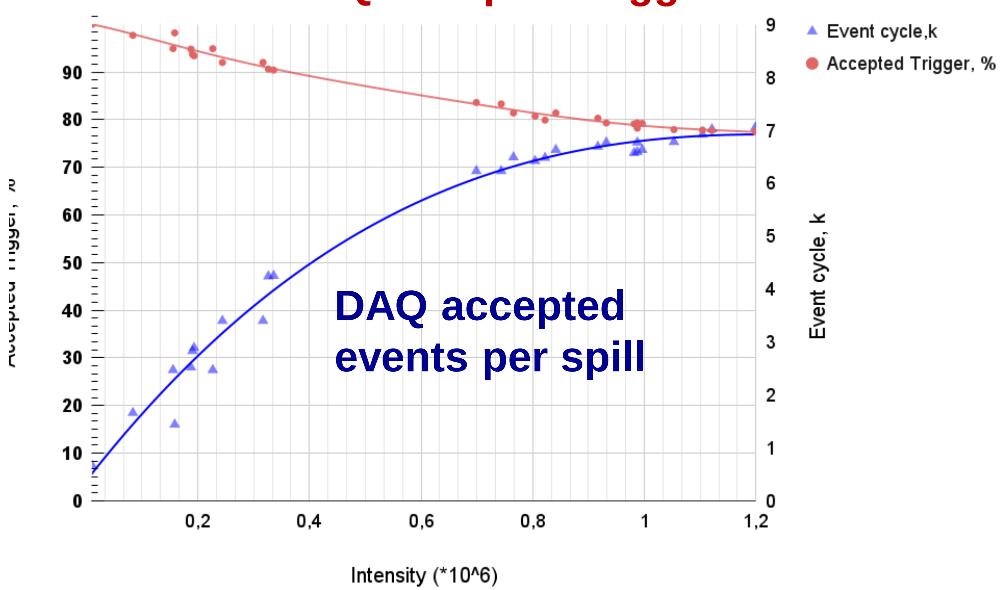
Ratios

BC1_low/BC1	2.40062
BC2/BC1	0.89086
VC/BC1	0.19949
FD/BC1	0.91669
NBD>L1/BC1	0.17089
NBD>H1/BC1	0.17151
NSiD>L1/BC1	0.00000
NSiD>L2/BC1	0.00000
nZDC/BC1	0.13407
BT/BC1	0.75334
MBT/BT	0.03601
CCT1/BT	0.21477
CCT2/BT	0.01719
NIT/BT	0.85488

Internal signals

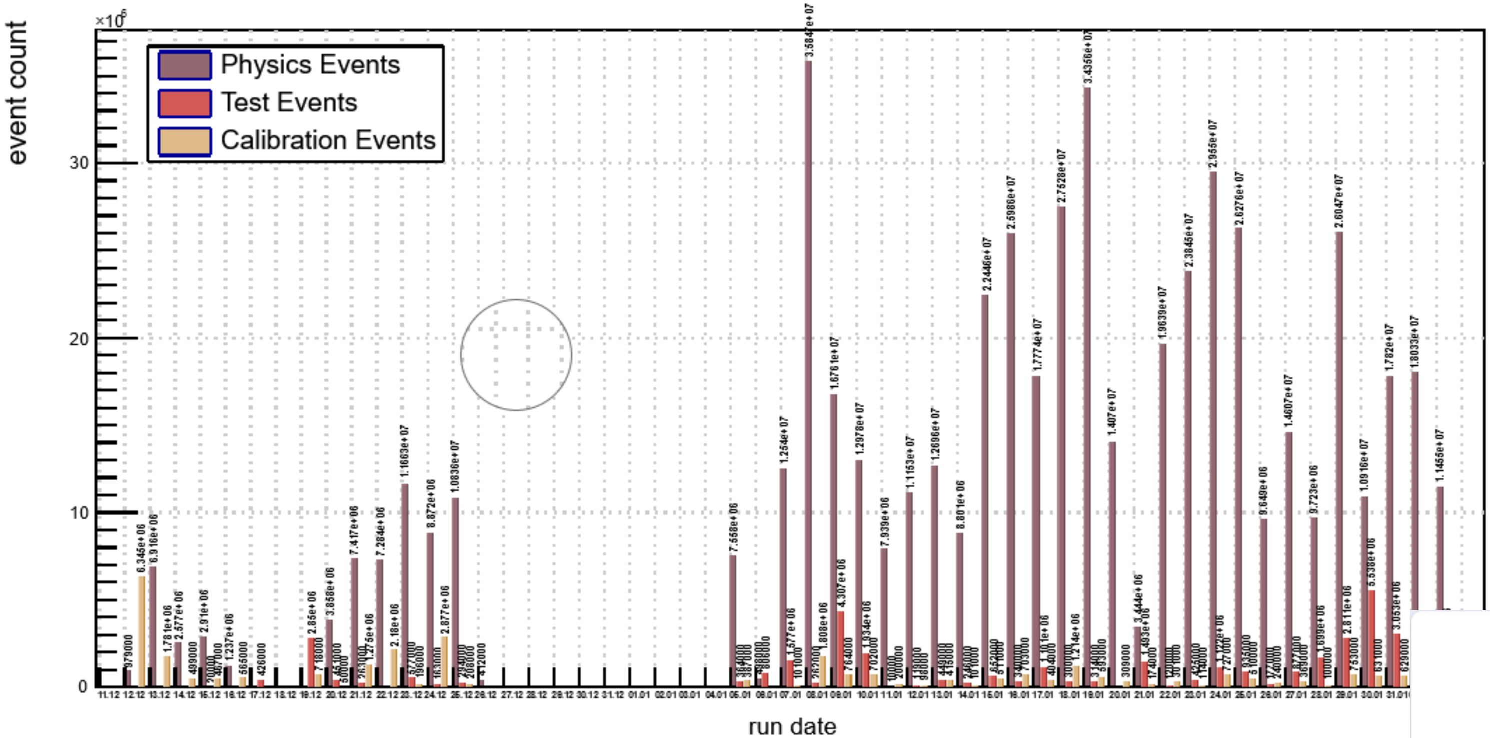
pCCT1	130882
pCCT2	130930
MBT1	20905
NIT1	492836
DAQ_Busy	0
BT*/DAQ_Busy	459879
pBT	668899

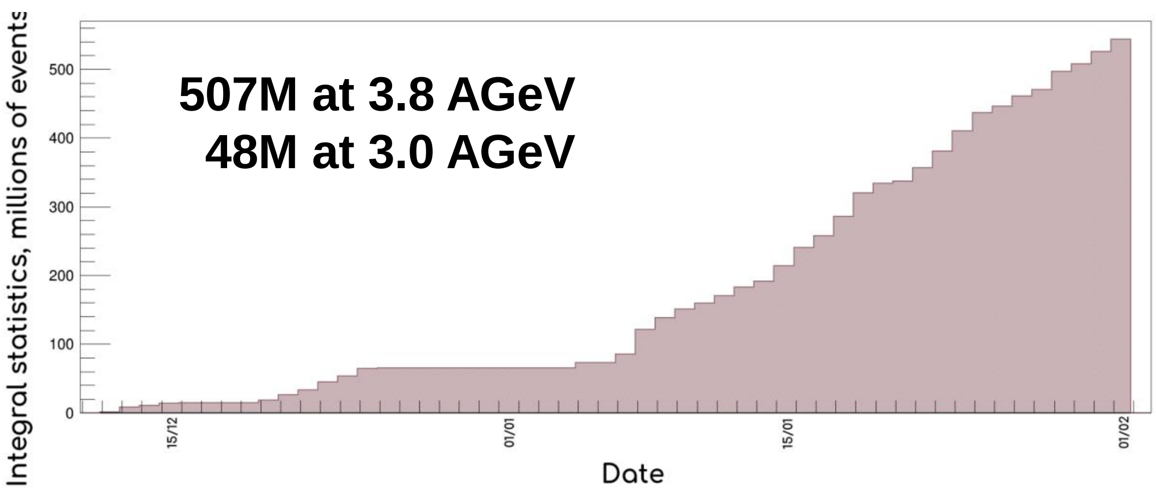
% of DAQ accepted triggers



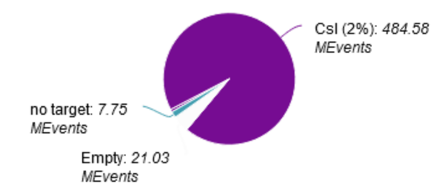
Statistics of recorded interactions

The information is current as of February 07 2023 23:59.

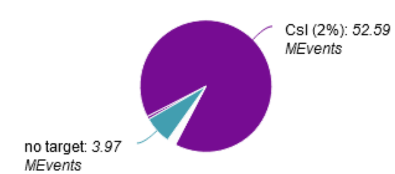




Beam Xe (E = 3.8 GeV/n)
Total: 516.80 MEvents



Beam Xe (E = 3 GeV/n)
Total: 58.26 MEvents



Beam parameters and setup at different stages of BM@N experiment

Year	2016	2017 spring	2018 spring	2023	2025 and later
Beam	d(↑)	C	Ar	Xe	Bi
Max.intensity / spill	0.5M	0.5M	0.5M	1M	1.5M
Trigger rate, spill	5k	5k	8k	10k	15k
Central tracker status	6 GEM half planes	6 GEM half planes	6 GEM half planes + 3 forward Si planes	7 GEM full planes + 4 forward Si planes	7 GEM full planes + forward Si + STS planes
Experimental status	technical run	technical run	technical run+physics	stage1 physics	stage2 physics

Статус и ближайшие планы

- В эксперименте BM@N течении 2014-2022 реализована конфигурация установки с полным аксептансом детекторов
- Проведены экспериментальные сеансы в пучках дейтронов, ядер углерода и аргона
- Выполнен анализ рождения Λ гиперонов в углерод-ядерных взаимодействиях при энергиях 4 и 4.5 АГэВ
- Подготовлена публикация по исследованию рождения π+ и K+ мезонов в аргон-ядерных взаимодействиях при энергии 3.2 АГэВ
- Проведен физический сеанс в пучке ядер ксенона с энергией 3.8 и 3 АГэВ на мишени CsI
- Ближайшие планы:

анализ рождения гиперонов, мезонов, легких ядерных фрагментов во взаимодействиях Xe+CsI;

определение классов центральности взаимодействий

анализ коллективных потоков протонов, пионов, легких ядерных фрагментов при энергии 3 АГэВ

поиск легких гиперядер $_{\Lambda}H^{3}$, $_{\Lambda}H^{4}$

→ Необходимы активные исследователи - анализаторы данных: опытные и молодые с перспективой защиты на данных, полученных в пучке ксенона

→ вклад НИИЯФ МГУ приветствуется

Планы по развитию и проведению физических сеансов

- В начале 2024 возможен физический сеанс в пучке ядер ксенона: скан по энергии пучка в диапазоне 2-3 АГэВ

→ та же конфигурация центрального трекера на основе кремниевых и GEM детекторов

→ полная замена внешних дрейфовых камер на катодные стриповые

- Физический сеанс в пучке ядер Bi возможен после 2024, зависит от реализации планов по коллайдеру NICA

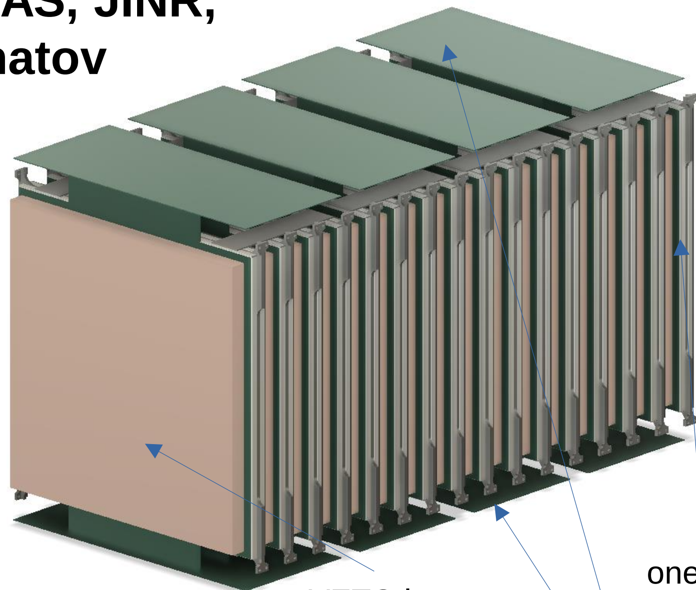
- Для готовности к эксперименту в пучке Bi необходимо дальнейшее развитие центрального трекера: инсталляция дополнительных станций кремниевых детекторов → вклад НИИЯФ МГУ необходим

- Планируется ввод в действие 3х координатного нейтронного детектора высокой гранулярности для измерения выходов и коллективных потоков нейтронов

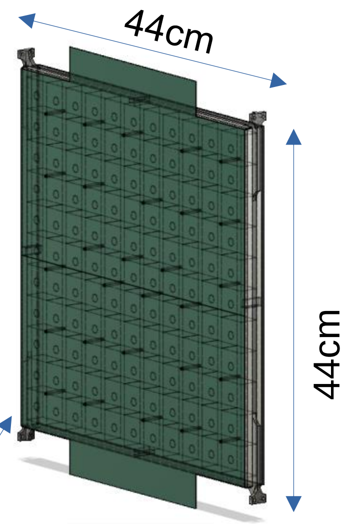
3D High Granularity Neutron detector

INR RAS, JINR, Kurchatov

→ plan to design and construct in 2023-2024

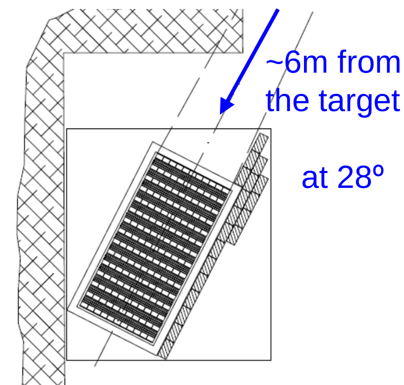


VETO layer



one layer containing 121 cells with individual SiPM read-out

FPGA based fast TDC read-out with additional ToT amplitude measurement

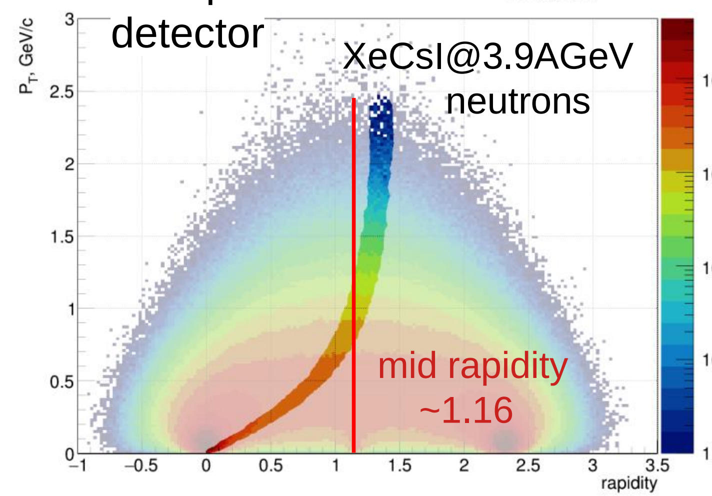


Position of HGN detector at BM@N

HGN detector parameters:

- 11 x 11 cells in one layer
- first layer works as VETO
- next layers: 3cm Cu + 2.5cm scintillator
- number of layers: 16 (~3 λ_{int})
- time resolution of one scint. cell ~ 100ps
- neutron detection efficiency: > 80% @ 1GeV

Acceptance of HGN detector



Thank you
for attention!

BM@N: Estimated hyperon yields in Au+Au collisions

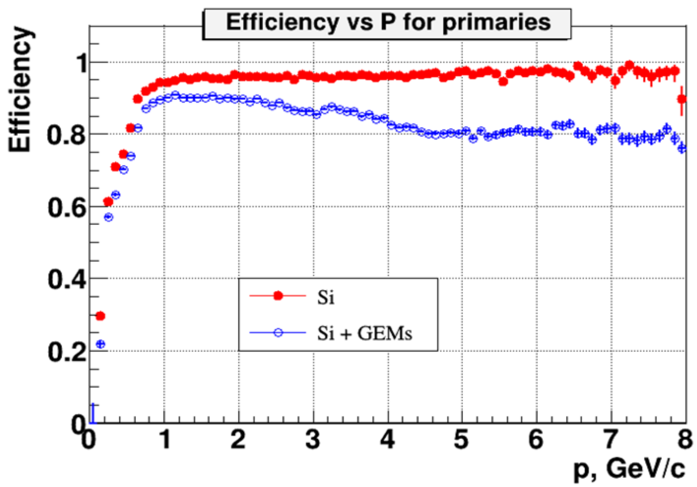
4 A GeV min. bias Au+Au collisions, multiplicities from statistical model,
Beam intensity $2.5 \cdot 10^5$/s , DAQ rate $2.5 \cdot 10^3$/s, accelerator duty factor 0.25

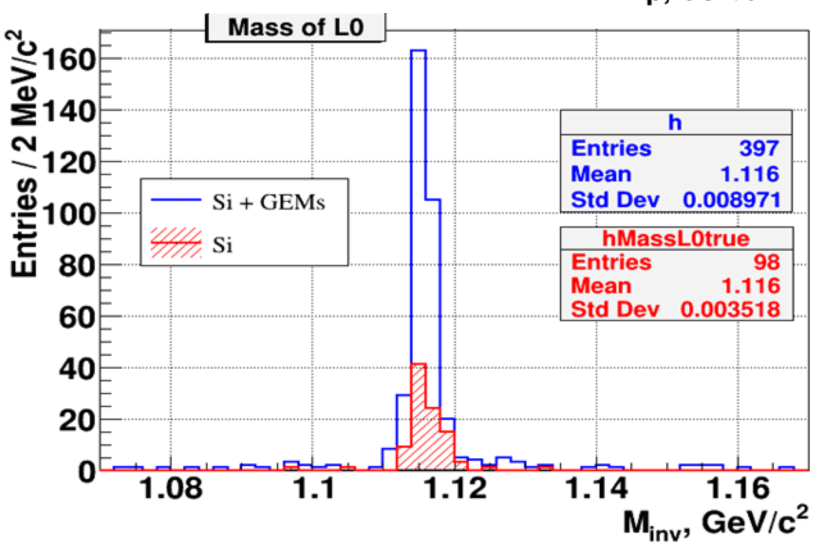
$1.8 \cdot 10^9$ interactions
$1.8 \cdot 10^{11}$ beam ions

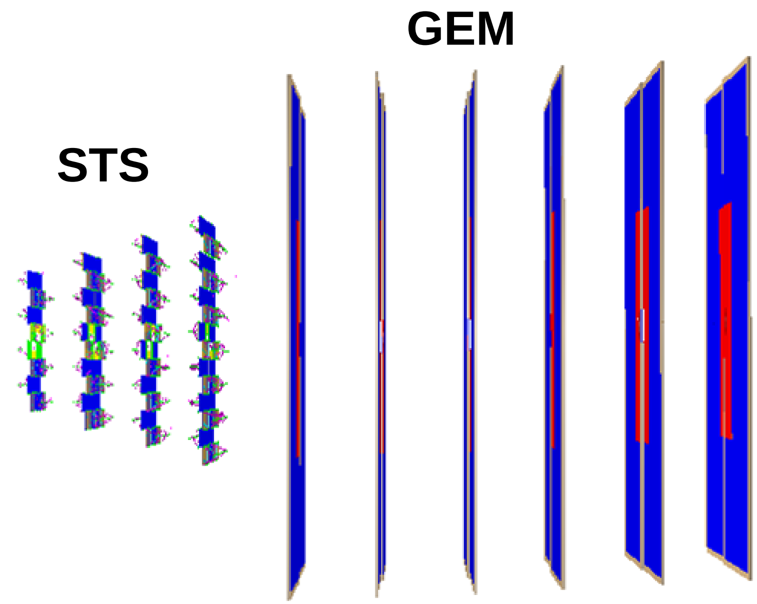
Particle	E_{thr}NN GeV	M central	M m.bias	ε %	Yield/s m. Bias	Yield / 800 hours m. Bias
Ξ^-	3.7	$1 \cdot 10^{-1}$	$2.5 \cdot 10^{-2}$	1	2.5	$4.5 \cdot 10^5$
Ω^-	6.9	$2 \cdot 10^{-3}$	$5 \cdot 10^{-4}$	1	$5 \cdot 10^{-2}$	$0.9 \cdot 10^4$
Anti-Λ	7.1	$2 \cdot 10^{-4}$	$5 \cdot 10^{-5}$	3	$1.5 \cdot 10^{-2}$	2700
Ξ^+	9.0	$6 \cdot 10^{-5}$	$1.5 \cdot 10^{-5}$	1	$1.5 \cdot 10^{-3}$	270
Ω^+	12.7	$1 \cdot 10^{-5}$	$2.5 \cdot 10^{-6}$	1	$2.5 \cdot 10^{-4}$	45
					${}_{\Lambda}^{3}H$	$0.9 \cdot 10^5$

Simulation of hybrid central tracker for heavy ion runs: STS +GEM

QGSM model, Au+Au, T_0 = 4 AGeV

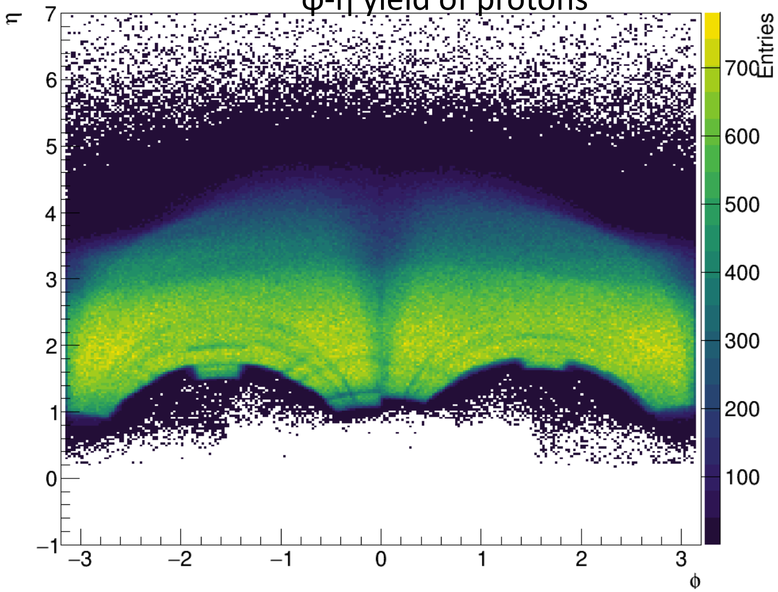




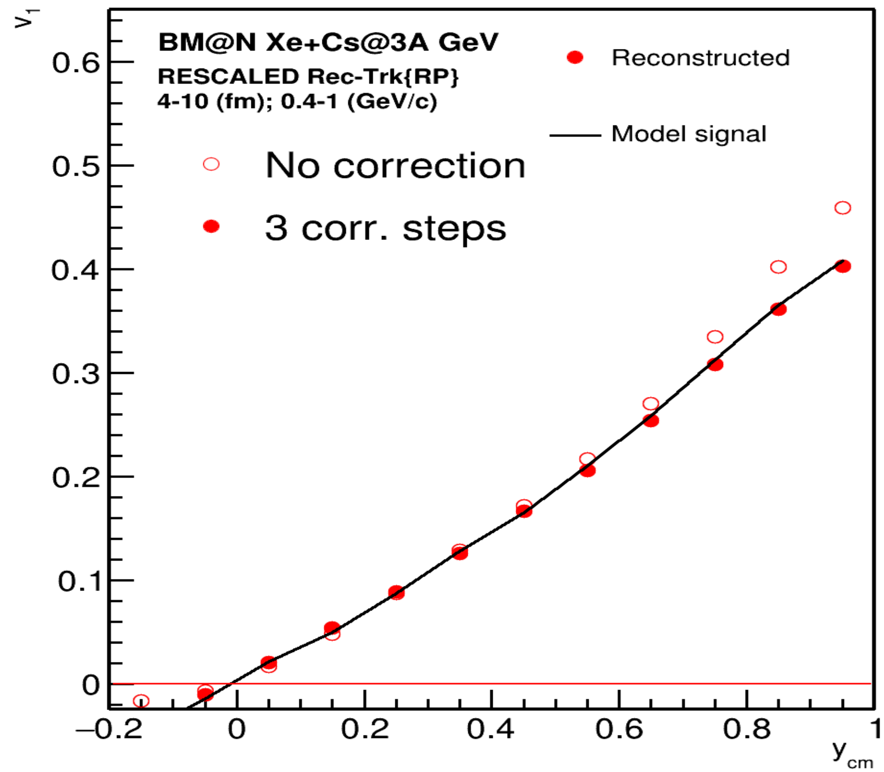


Hybrid STS + GEM tracker:
► 4 times increase in number of reconstructed Λ hyperons

Azimuthal acceptance of the BM@N experiment



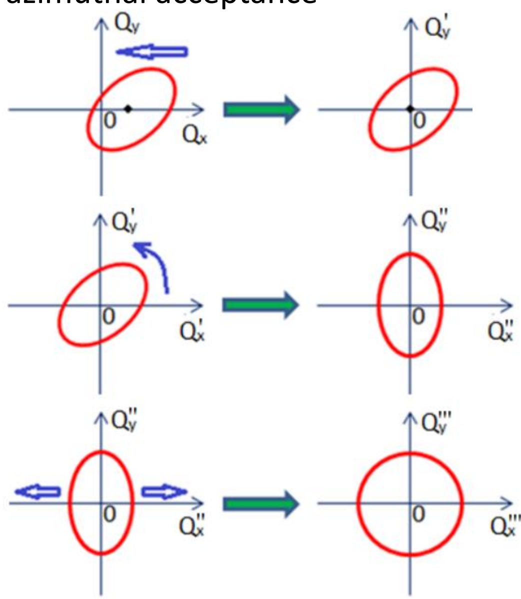
Corrections are based on method in:
I. Selyuzhenkov and S. Voloshin PRC77, 034904 (2008)



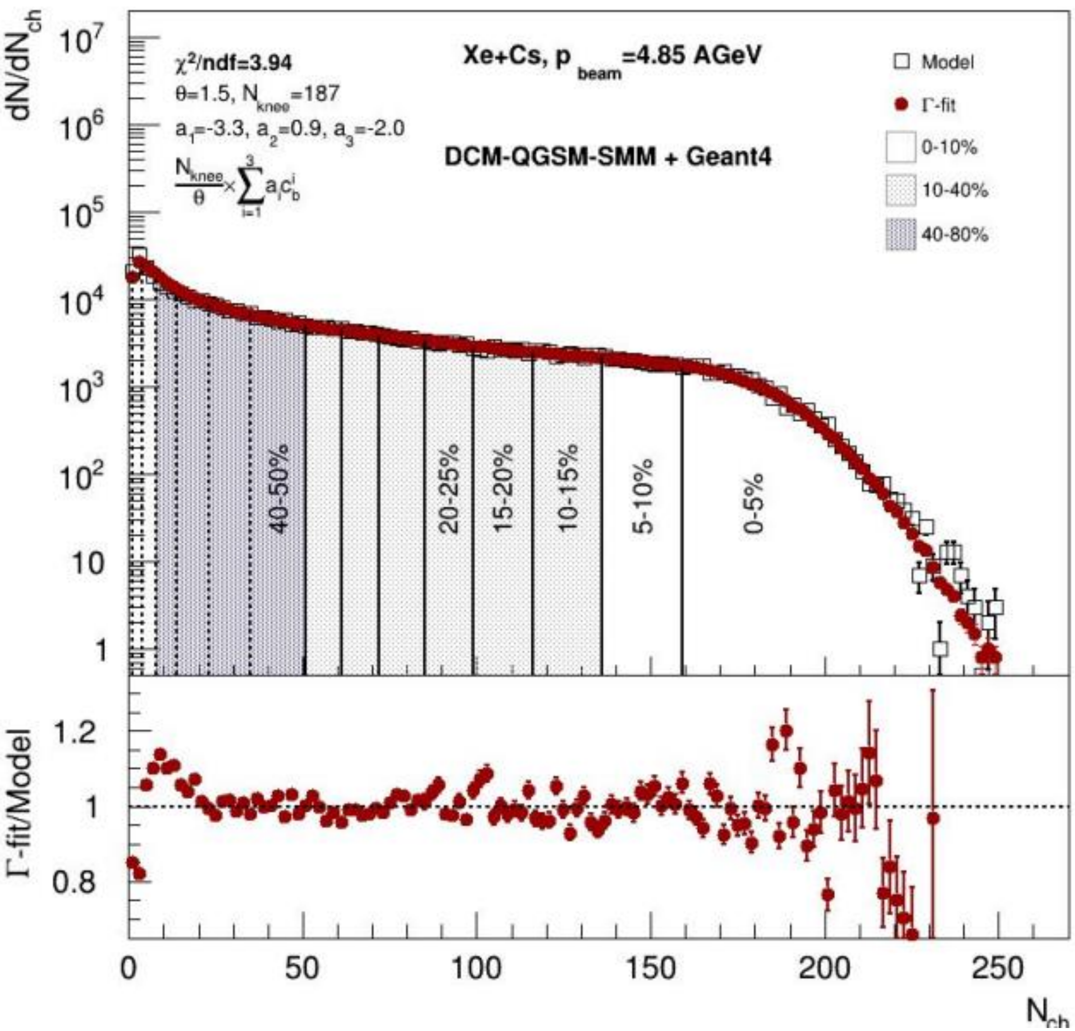
Better agreement after rescaling

Required corrections to reduce effects of non-uniform azimuthal acceptance

1. Recentering
2. Twist
3. Rescaling

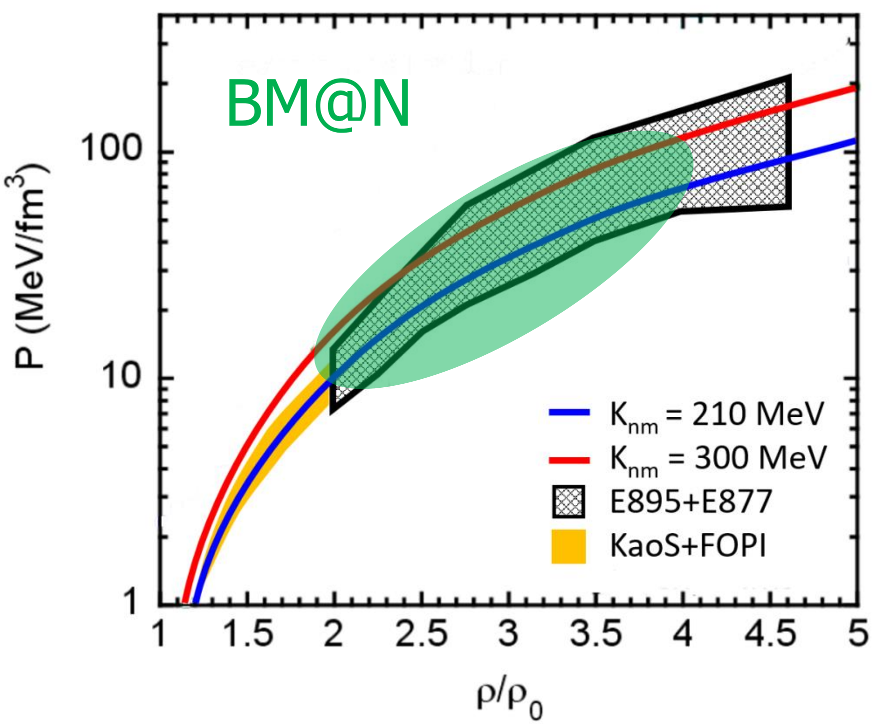


Centrality determination at BM@N



- Fit results are good both for MC-Glauber and Inverse Γ-fit methods
- Impact parameter distributions in centrality classes are well-reproduced

EOS of dense symmetric nuclear matter: The heavy-ion constraint



$P = \delta E/\delta V\,|_{T=const}$

$V = A/\rho$

$\delta V/\,\delta\rho = -\,A/\rho^2$

$P = \rho^2\ \delta(E/A)/\delta\rho\,|_{T=const}$

Grey area:

Data: transverse and elliptic proton flow (AGS)

E895: C. Pinkenburg et al., Phys. Rev. Lett. 83 (1999) 1295

E877: P. Braun-Munzinger et al., Nucl. Phys. A638 (1998) 3c

Theory:

P. Danielewicz, R. Lacey, W.G. Lynch, Science 298 (2002) 1592

Yellow area:

KaoS: Subthreshold K^+ production (GSI)

C. Sturm et al., Phys. Rev. Lett. 86 (2001) 39,

Theory: RQMD

Ch. Fuchs et al., Phys. Rev. Lett. 86 (2001) 1974

FOPI: Elliptic flow of protons and light fragments

A. Le Fevre et al., Nucl. Phys. A945 (2016) 112

BM@N →

collective flow, hyperon production