Towards the Heavy-Ion Program at J-PARC

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for J-PARC HI Collaboration

QM2014, Darmstadt

1. Introduction
2. Heavy ion acceleration scheme
3. Physics goals
4. Experimental design
5. Summary

Introduction

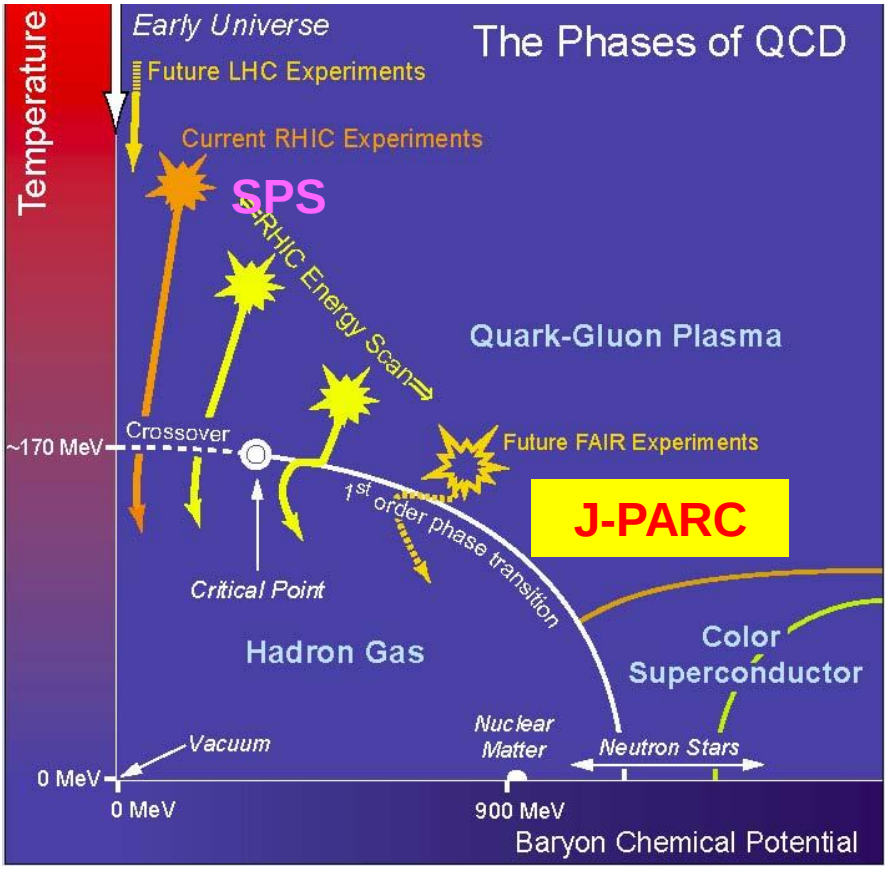
J-PARC will achieve designed beam power with proton beams in a few years

- 1MW at 3GeV
- 0.75MW at 30 GeV

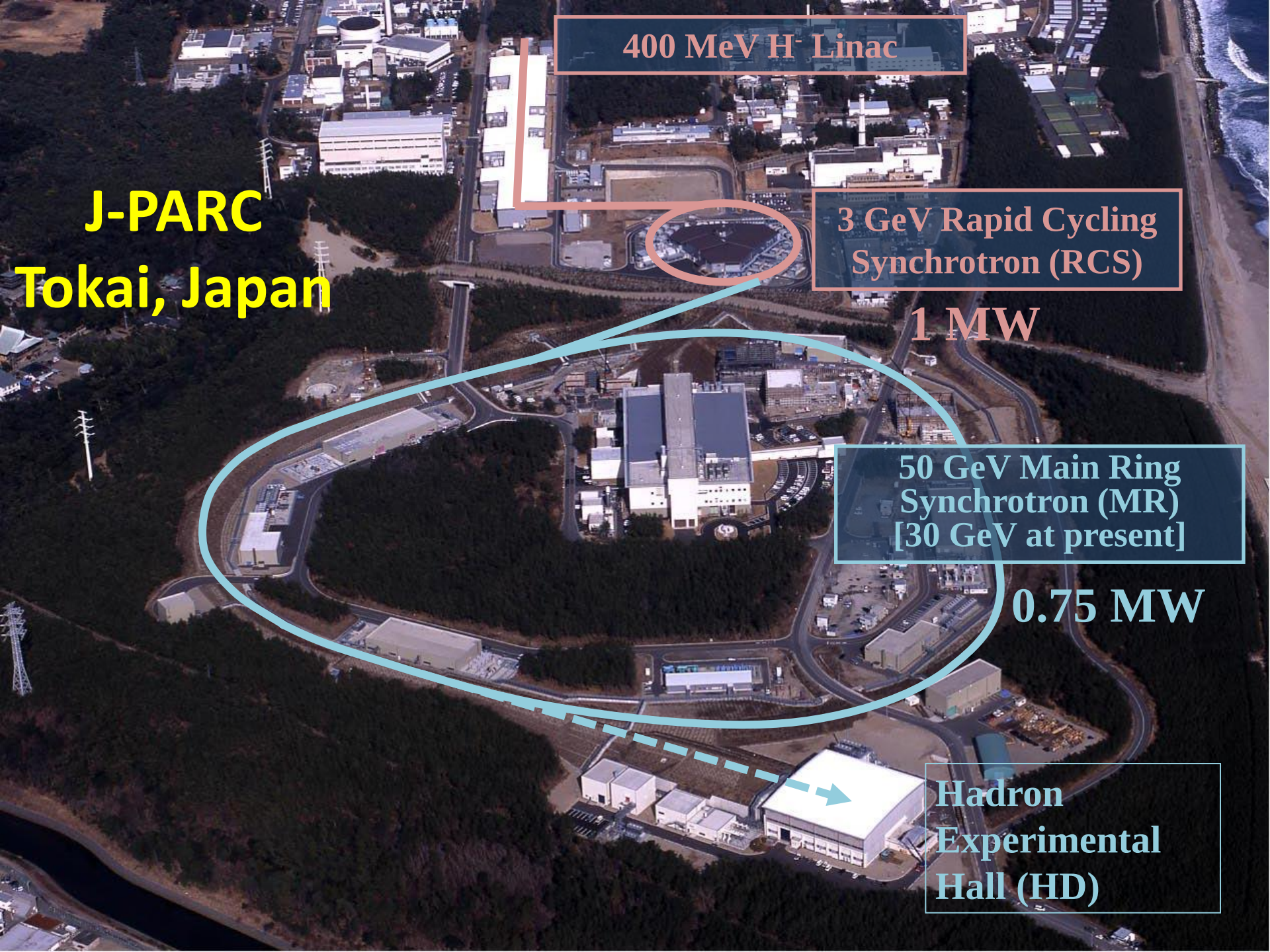
We started discussing experimental and accelerator schemes for heavy ion program at J-PARC

We aim at studies of QCD phase structures in high baryon density regime at J-PARC

- RHIC low energy scan, NICA, FAIR



Hadron Seminar @J-Parc Takao Sakaguchi


400 MeV H- Linac
J-PARC
Tokai, Japan
3 GeV Rapid Cycling Synchrotron (RCS)
1 MW
50 GeV Main Ring Synchrotron (MR) [30 GeV at present]
0.75 MW
Hadron Experimental Hall (HD)

Low and High energy programs

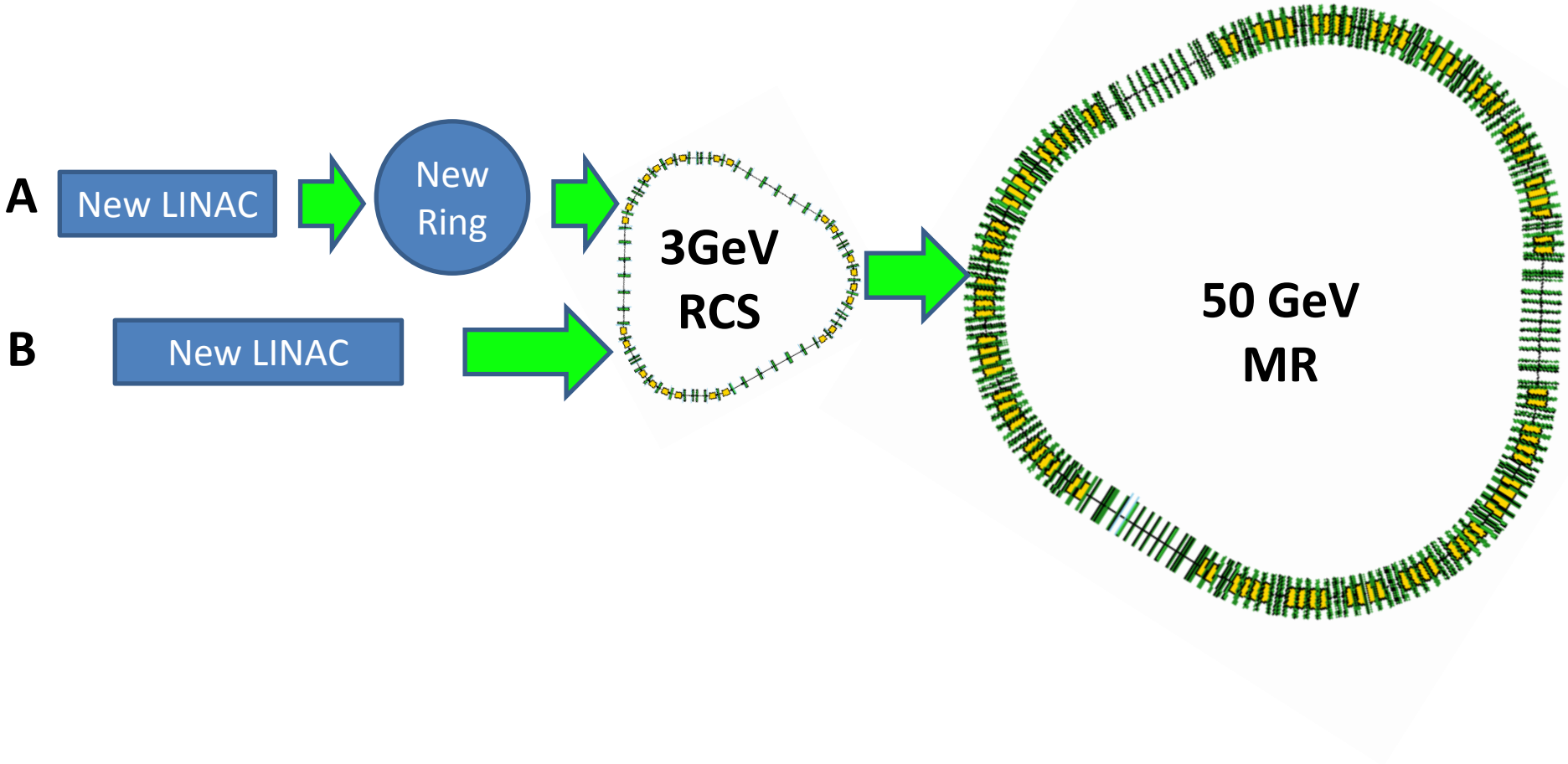
"Low energy" program (Linac) for unstable nuclei research

- Ion species
  - Ne, Ar, Fe, Ni, Kr, Xe,…,U
- Beam energy
  - 1 - 10 AMeV (U)
- Beam current
  - 10-30pμA
  - 10ms, 25Hz

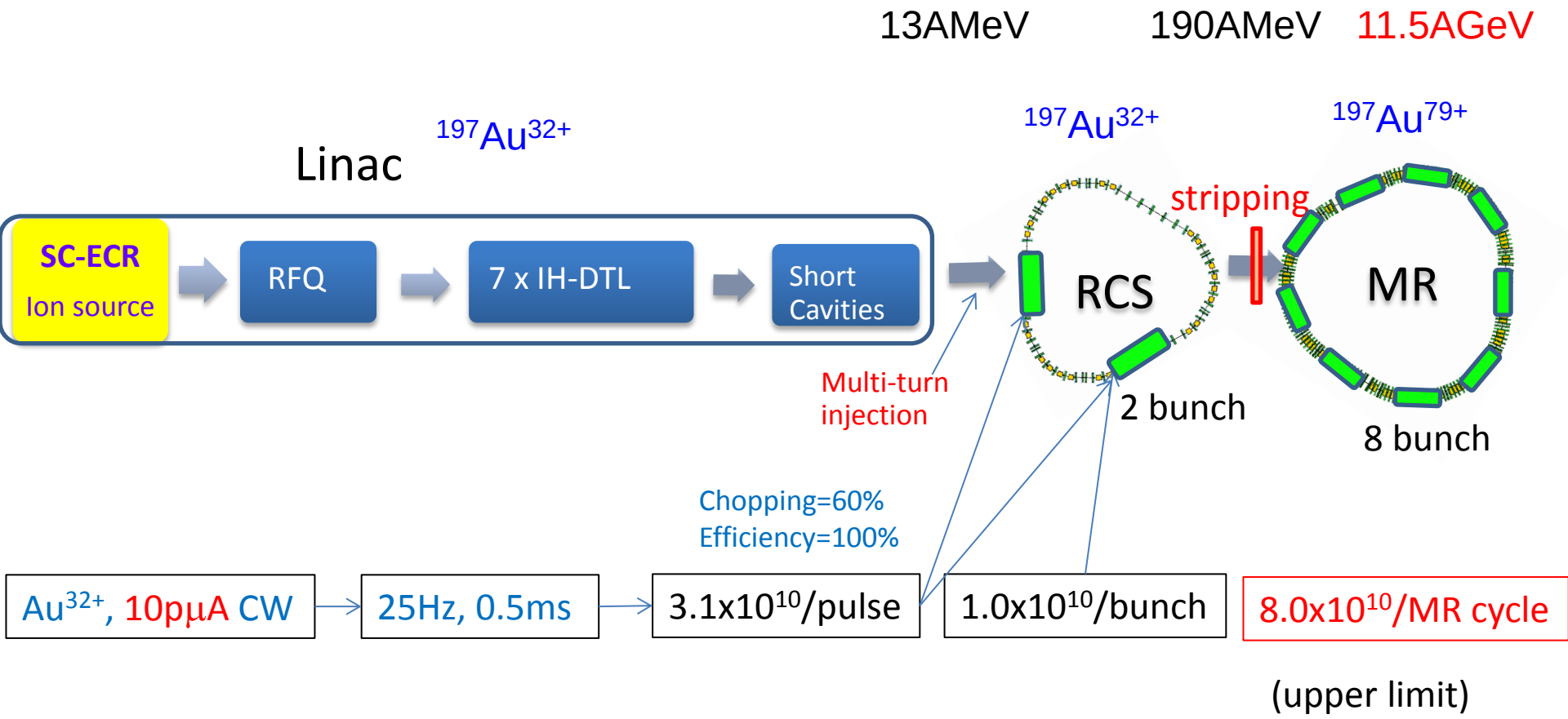
"High Enegy" Program (50 GeV MR)

- Ion species
  - p, Si, Cu, Au, U
    Au→U
  - Baryon density
    - $7.5\rho_0$ → $8.6\rho_0$ (JAM)
  - Duration at $\rho > 5\rho_0$
    - 4 → 7 fm/c
- Beam energy
  - 1 - 11.6 AGeV (U) ($\sqrt{s_{NN}} = 4.9\mathrm{GeV}$
  - Possibly 19 AGeV($\sqrt{s_{NN}} = 6.2\mathrm{GeV}$)
- Rate
  - 10^{10}-10^{11} ions per cycle (~a few sec)

Possible accelerator schemes



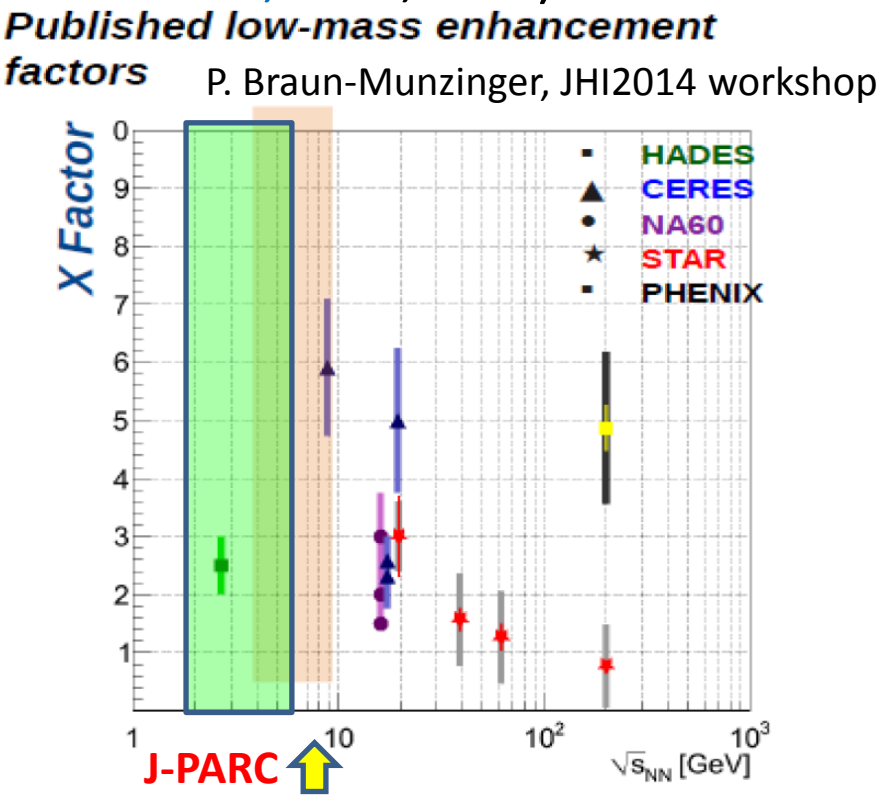
An example of acceleration scheme (with new HI Linac)



Y. Liu, J-PARC HI Meeting

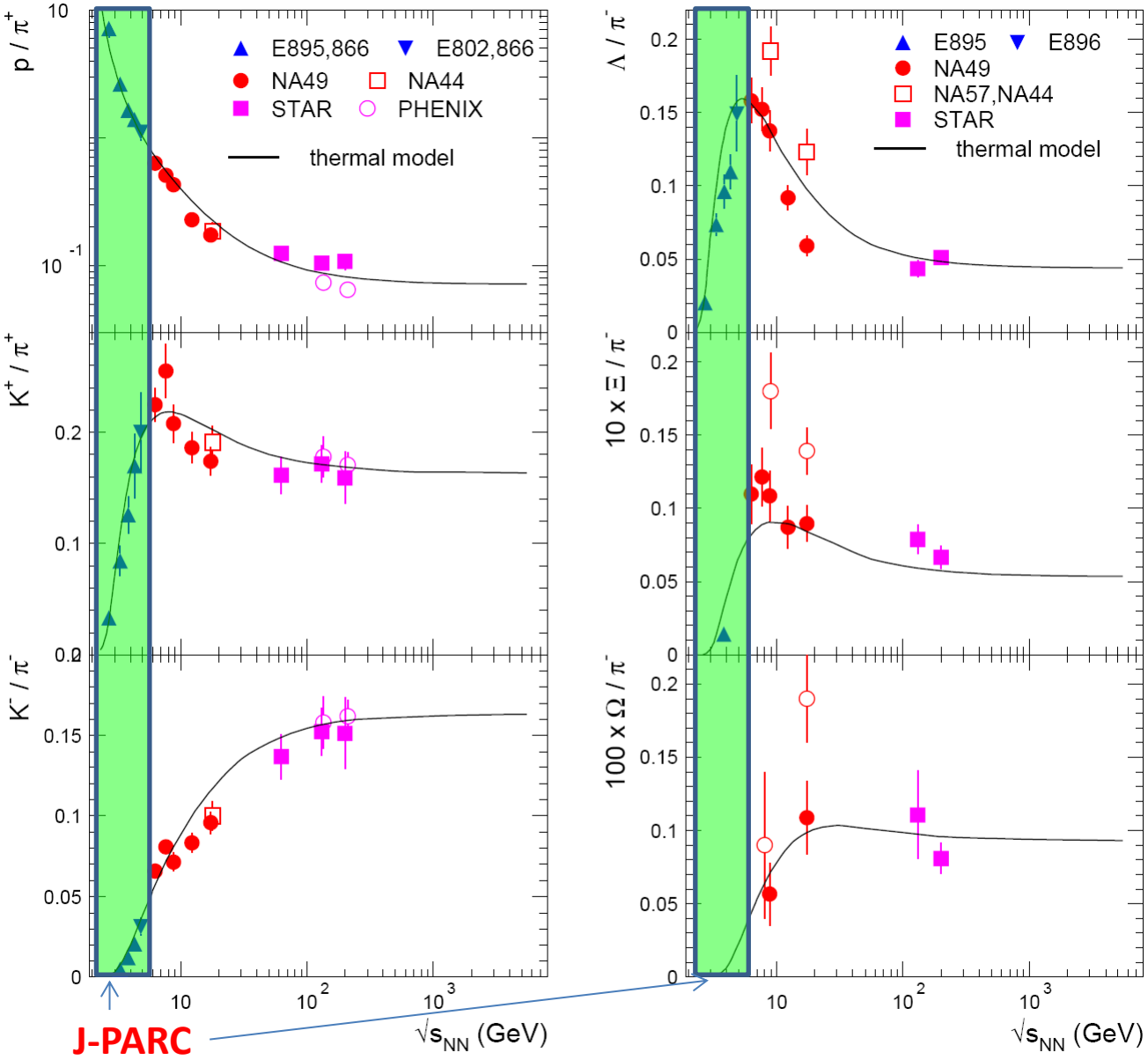
Physics goals

- Systematic and precise hadron measurements
  - Identified particle spectra (K/π,…)
  - Multi-strange baryons
  - Correlations (Event-by-event fluctuations, flow, HBT)
- Electrons and Muons
  - Di-lepton spectra of $\rho/\omega/\phi$
- Rare particles
  - Hypernuclei
  - Exotic hadrons
    - $\Lambda(1405)$
    - H-dibaryon
    - K^-pp
  - Charm
    - J/ψ, D
- Photons
  - Thermal photons from QGP



Maximum baryon density at freezeout (Randrup, PRC74(2006)047901)

Strange meson/baryons

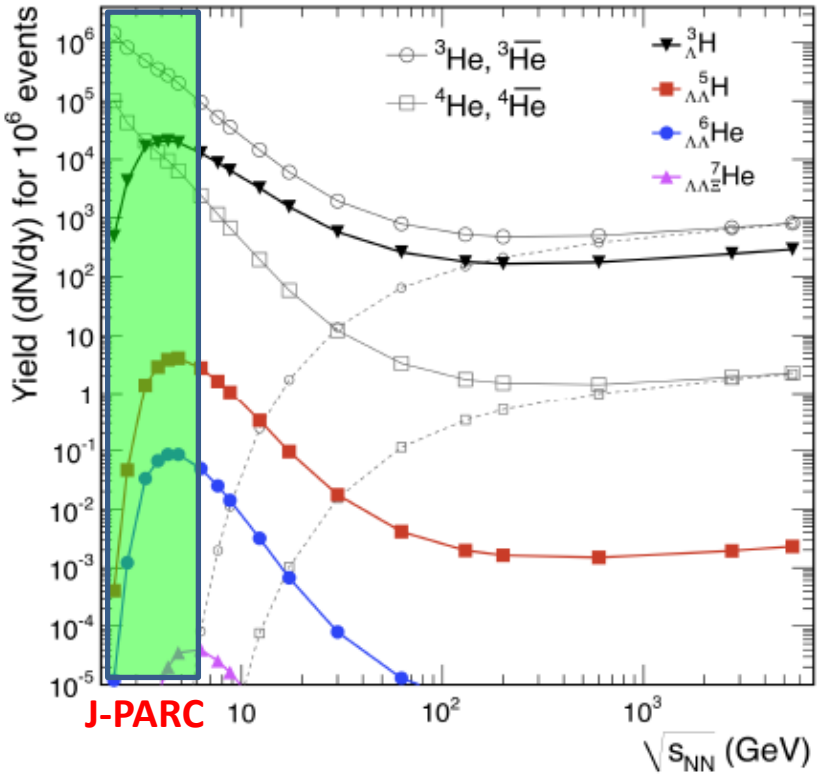


Strangeness enhancement at ~10GeV is connected to high baryon density via hyperons

Energy scan with high statistics

A. Andronic, et al, Nucl. Phys. A 837 (2010) 65

Hypernuclei



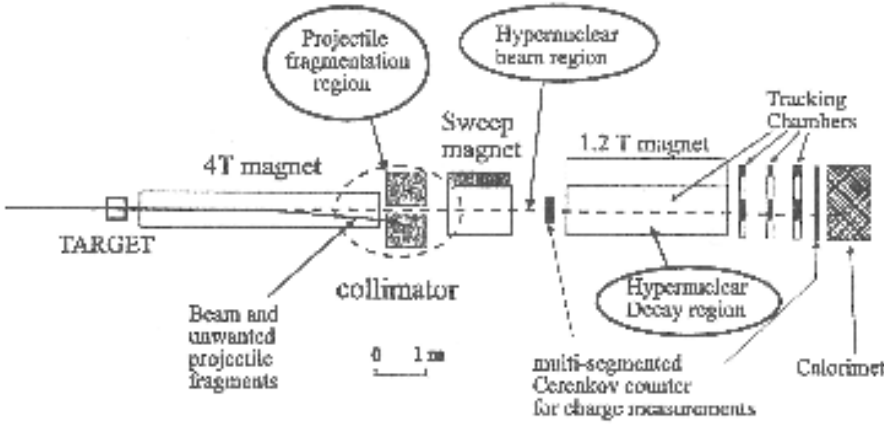
A. Andronic, PLB697 (2011) 203

Maximum yield at J-PARC

- coalescence of high-density baryons

Hypernuclei S=-3 in HI collisions

Closed geometry configuration for projectile region?

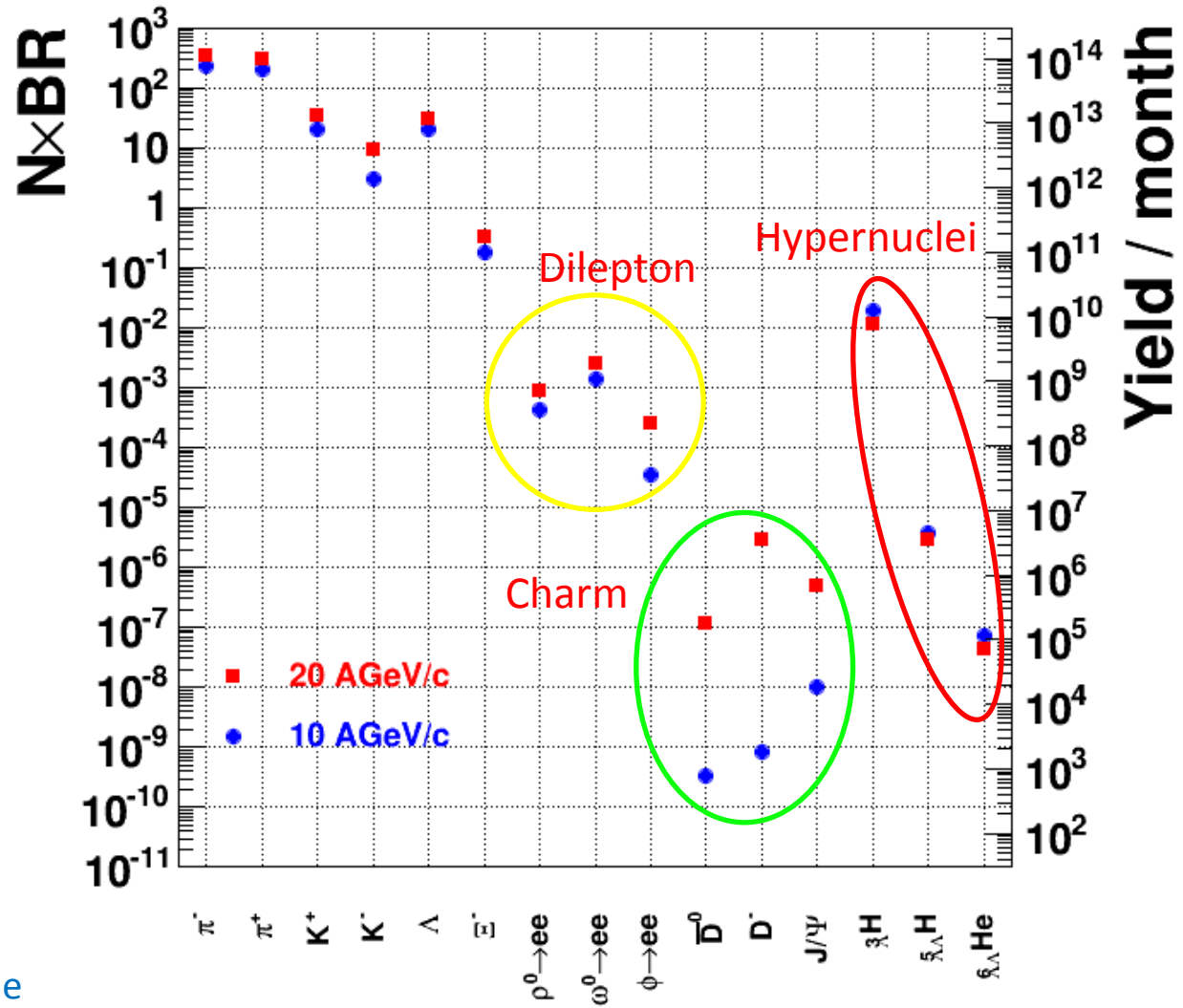


KEK Report 2000-11
Expression of Interest for Nuclear/Hadron Physics Experiments at the 50-GeV Proton Synchrotron

Particle production rates

Beam : 10^{11} Hz
0.1% target
→ Interaction rate 10^{8} Hz
Centrality trigger 0.1%
→ 100kHz
DAQ rate = 100kHz

In 1 month experiment:
$\rho,\omega,\phi \rightarrow ee$ 10^{8}-10^{9}
D,J/Ψ 10^{6} (20AGeV)
(10^{3} (10AGeV))
Hypernuclei 10^{5} -10^{10}



Ref: HSD calculations in FAIR Baseline Technical Report (Mar 2006)
A. Andronic, PLB697 (2011) 203

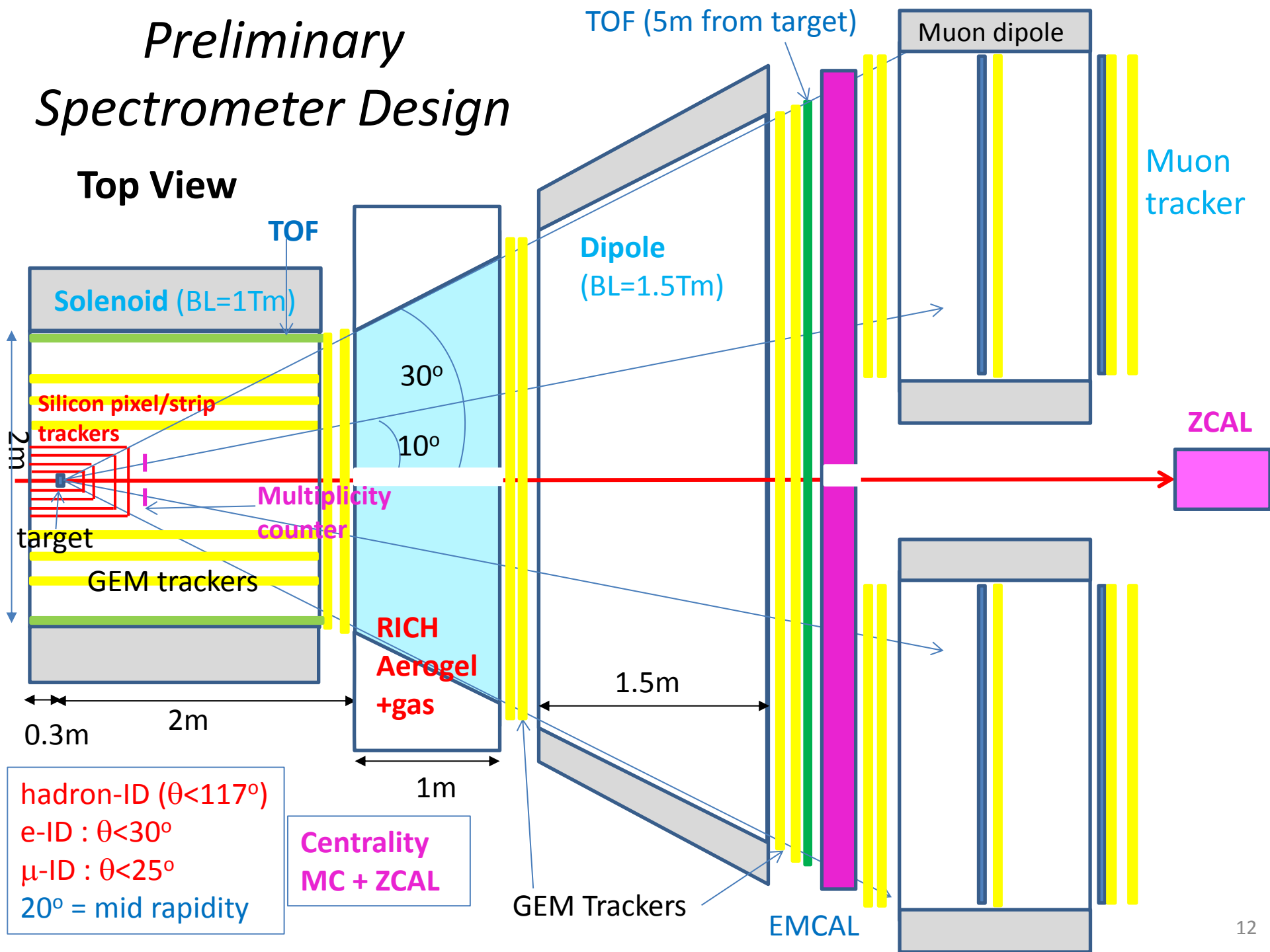
Experimental requirements

- High rate capability
  - Fast detectors
    - Silicon trackers, MPGD (e.g. GEM) trackers, …
  - Extremely fast DAQ
    - >= 100kHz
- High granularity

  Pixel size < 3x3mm^2

  (at 1m, θ<2deg, 10% occupancy)
- Large acceptance (~4π)
  - Multiplicity for e-b-e fluctuations
  - Backward physics (target fragment region)

Preliminary Spectrometer Design



Particle-ID methods

e–π separation

RICH (C_5F_{12})

p<3.4GeV/c (20mrad)

μ – π separation

- p<0.8 GeV/c

  TOF with 30ps (MRPD) in 5 m TOF
- p=0.8-1.5GeV/c

  RICH (Aerogel)
- p>1.5 GeV/c (20mrad)

  Fe absorbers + Trackers

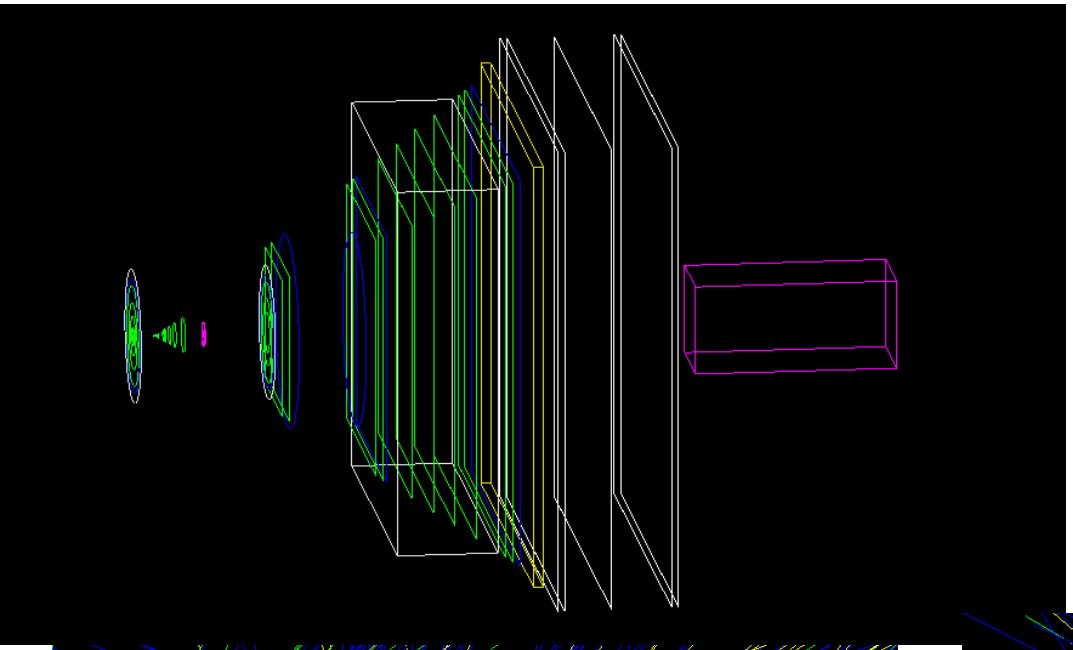
Dual radiator RICH (HERMES type)

EMCAL (e,γ ID)

$PbWO_4$

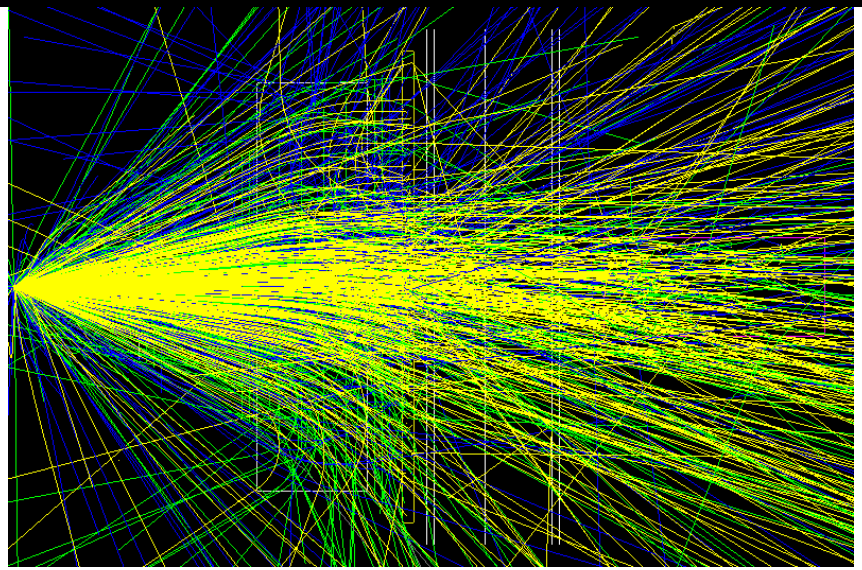
$15X_0$ (14cm)

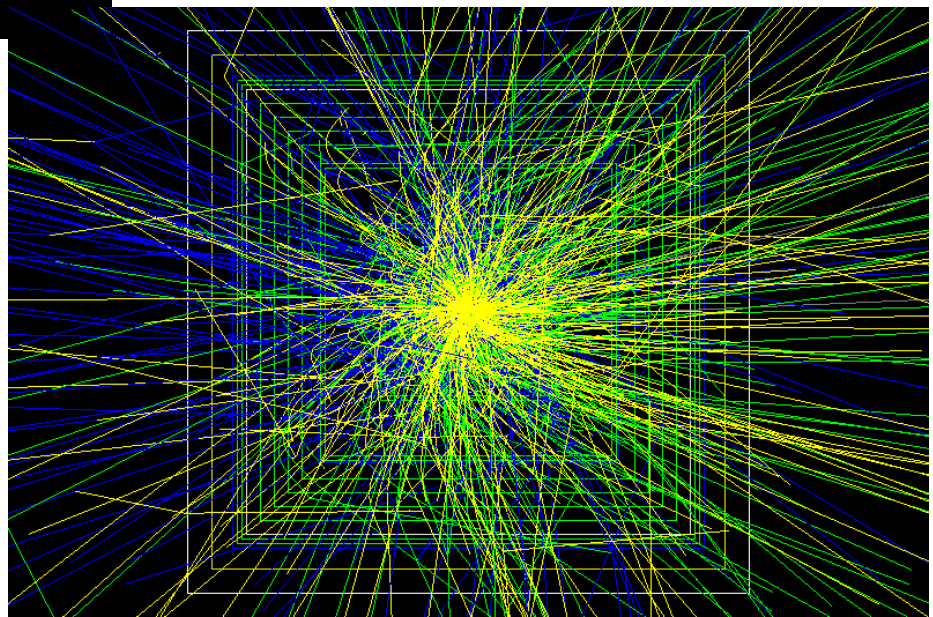
GEANT4 simulation



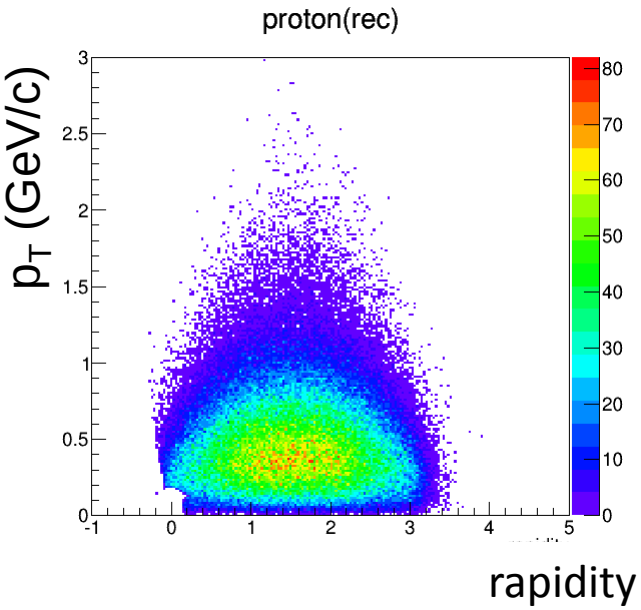
- JAM model

  U+U (10AGeV)
- Full physics processes

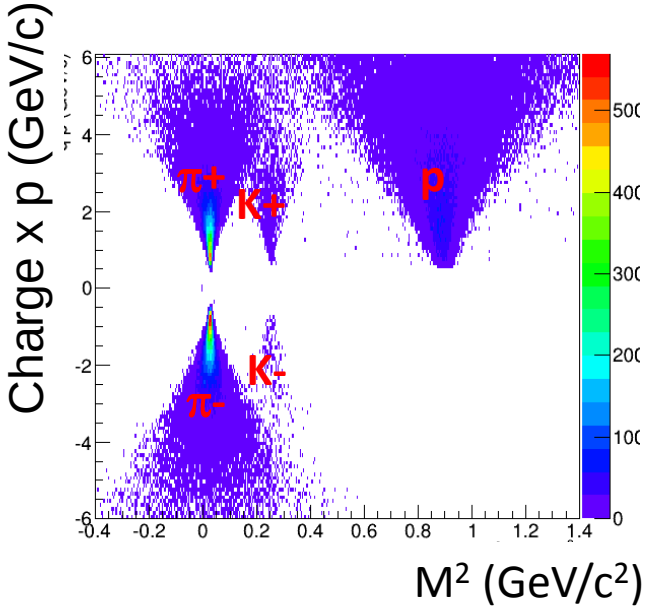




Simulation results (Preliminary)



Momentum vs m^2 (dipole spectrometer)



Acceptance

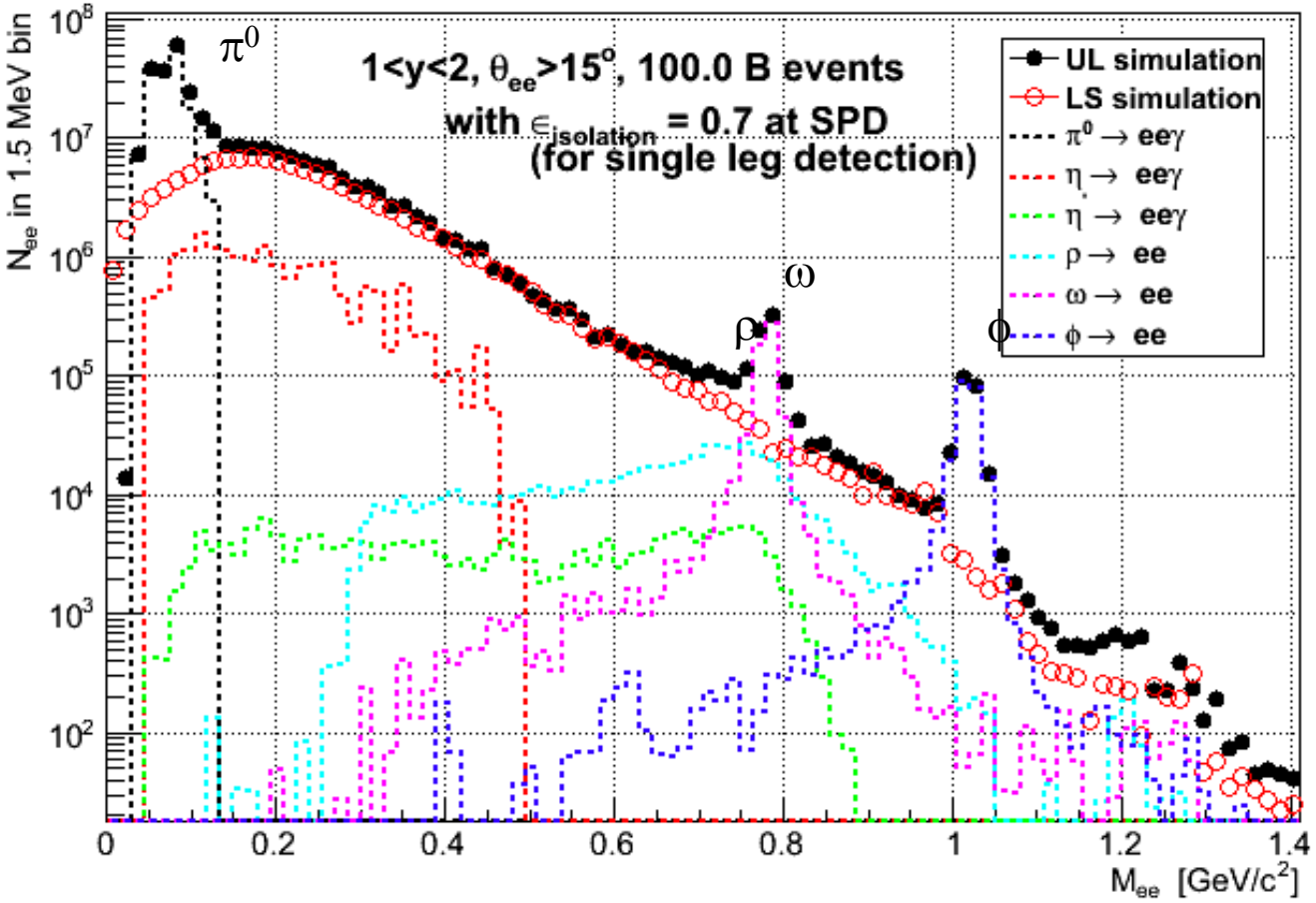
p	97.2%
K	91.7%
π	82.9%

TOF Resolution 50ps

Position resolution
Silicon trackers : 14-23μm
GEM trackers: 0.2-0.5mm

dp/p=1.3% (solenoid)
1% * p (GeV/c) (dipole)

Simulated di-electron spectrum (preliminary)



Calculations by T. Gunji and T. Sakaguchi

Based on pi0 spectra of JAM
Other hadrons mT-scaled
b<1fm (0.25% centrality)
Momentum resolution 2%
Electron efficiency 50%

No detector response

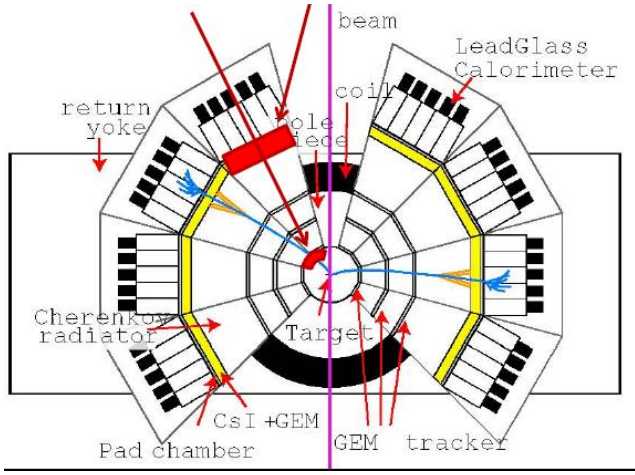
10^{11} events
⇔100k events/sec
x 1 month running

Summary

- A heavy ion program at J-PARC is under discussion
- Preliminary experimental setup has been designed
- Acceleration schemes are under design

Prospects

- Design of accelerators and experiments
  - A first complete design by Mar 2015 (White paper)
- Detector R & D
  - J-PARC E16 (electron/hadron in p+A)
    - J-PARC proton beams (10^{10} Hz)
    - Starting in 2016
- We wish international collaboration



J-PARC HI Collaboration

S. Nagamiya (JAEA/KEK/RIKEN)

H. Sako, K. Imai, K. Nishio, S. Sato (ASRC/JAEA)

H. Harada, P. K. Saha, M. Kinsho, J. Tamura, (J-PARC/JAEA)

K. Ozawa, Y. Liu (J-PARC/KEK)

T. Sakaguchi (BNL)

K. Shigaki (Hiroshima Univ.)

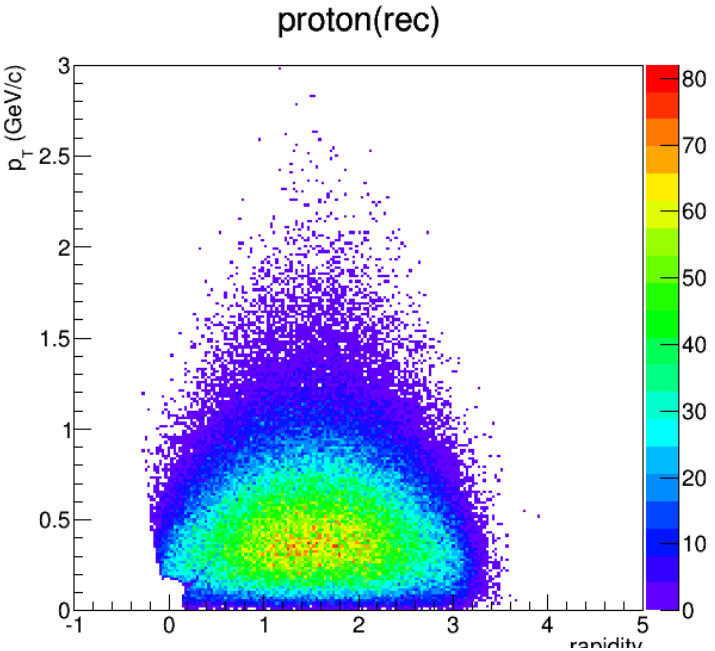
T. Chujo (Univ. of Tsukuba)

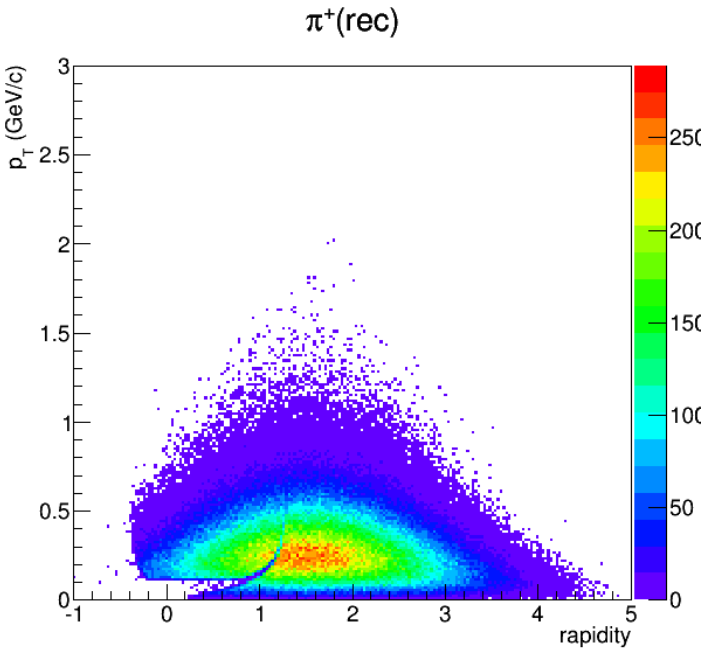
T. Gunji (CNS, Univ. of Tokyo)

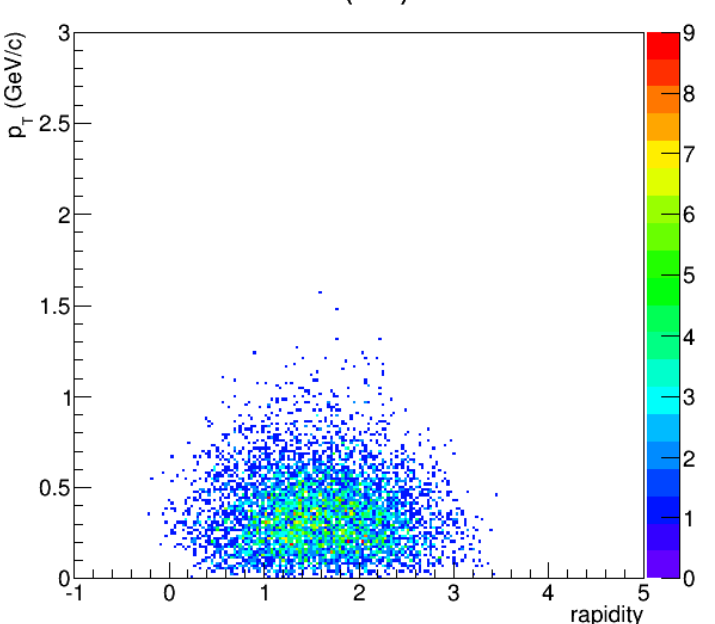
M. Kaneta (Tohoku Univ.)

Backup

U+U at 10 AGeV (Preliminary)







Acceptance

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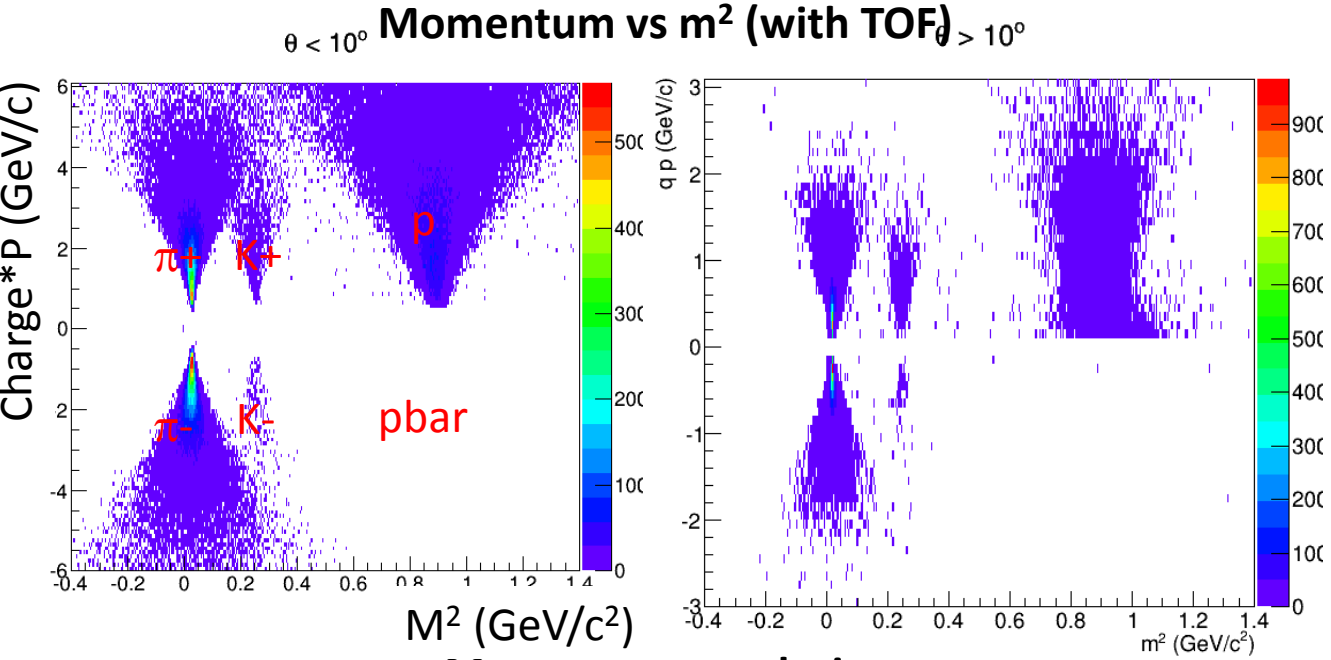
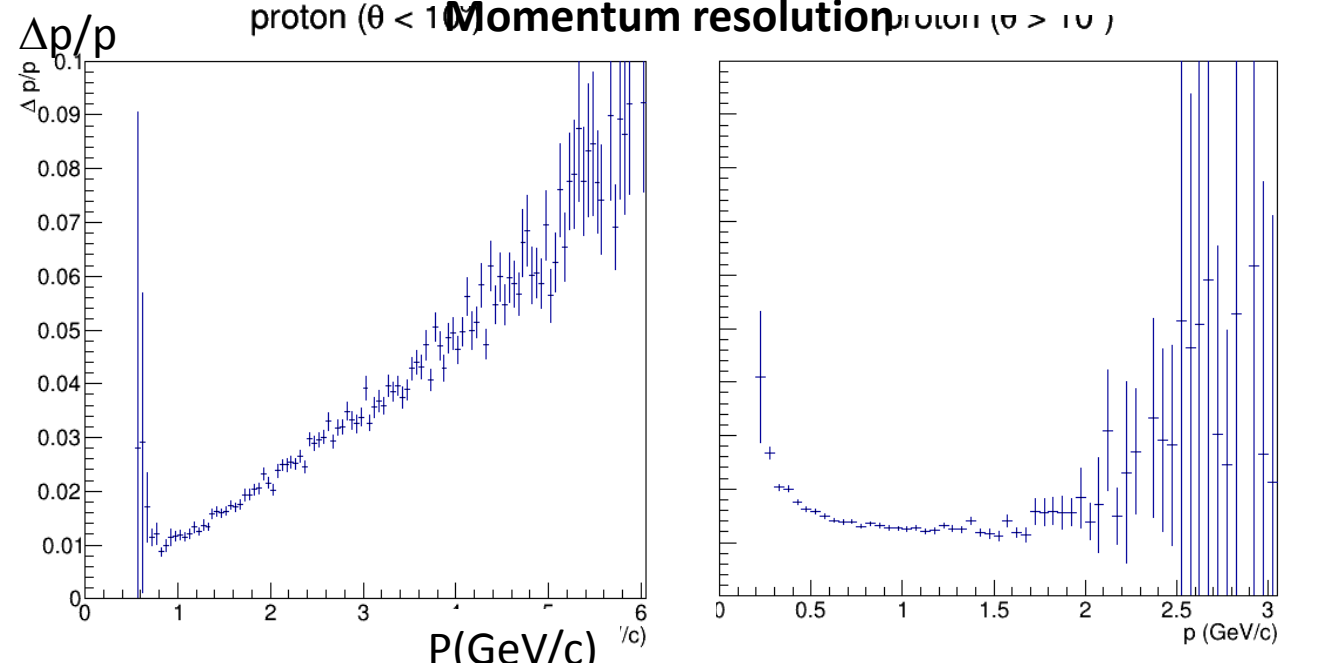
K	91.7%
π	82.9%

PID and momentum (Preliminary)



TOF Resolution 50ps

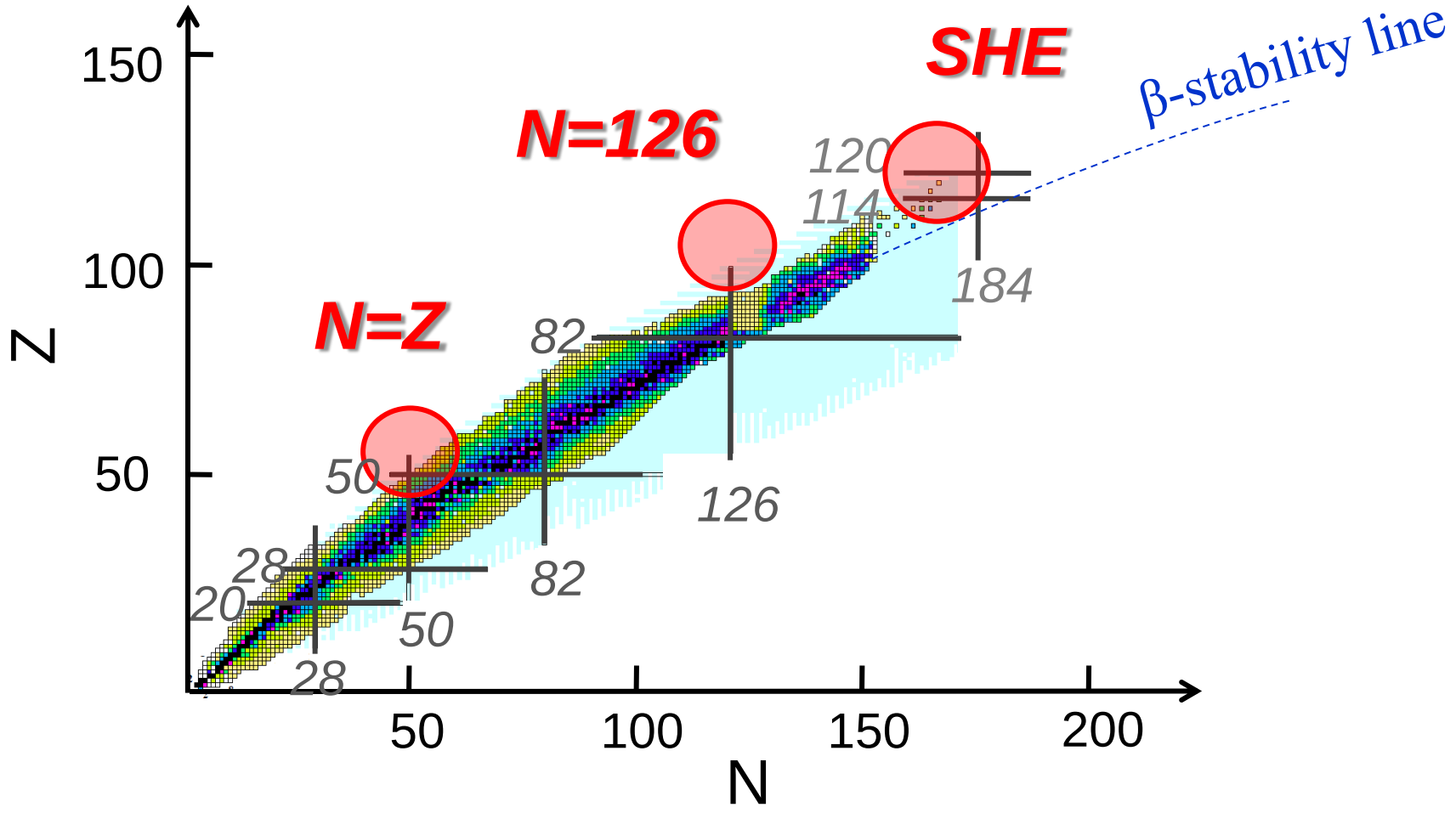
Position resolution
Silicon trackers : 14-23μm
GEM trackers: 0.2-0.5mm



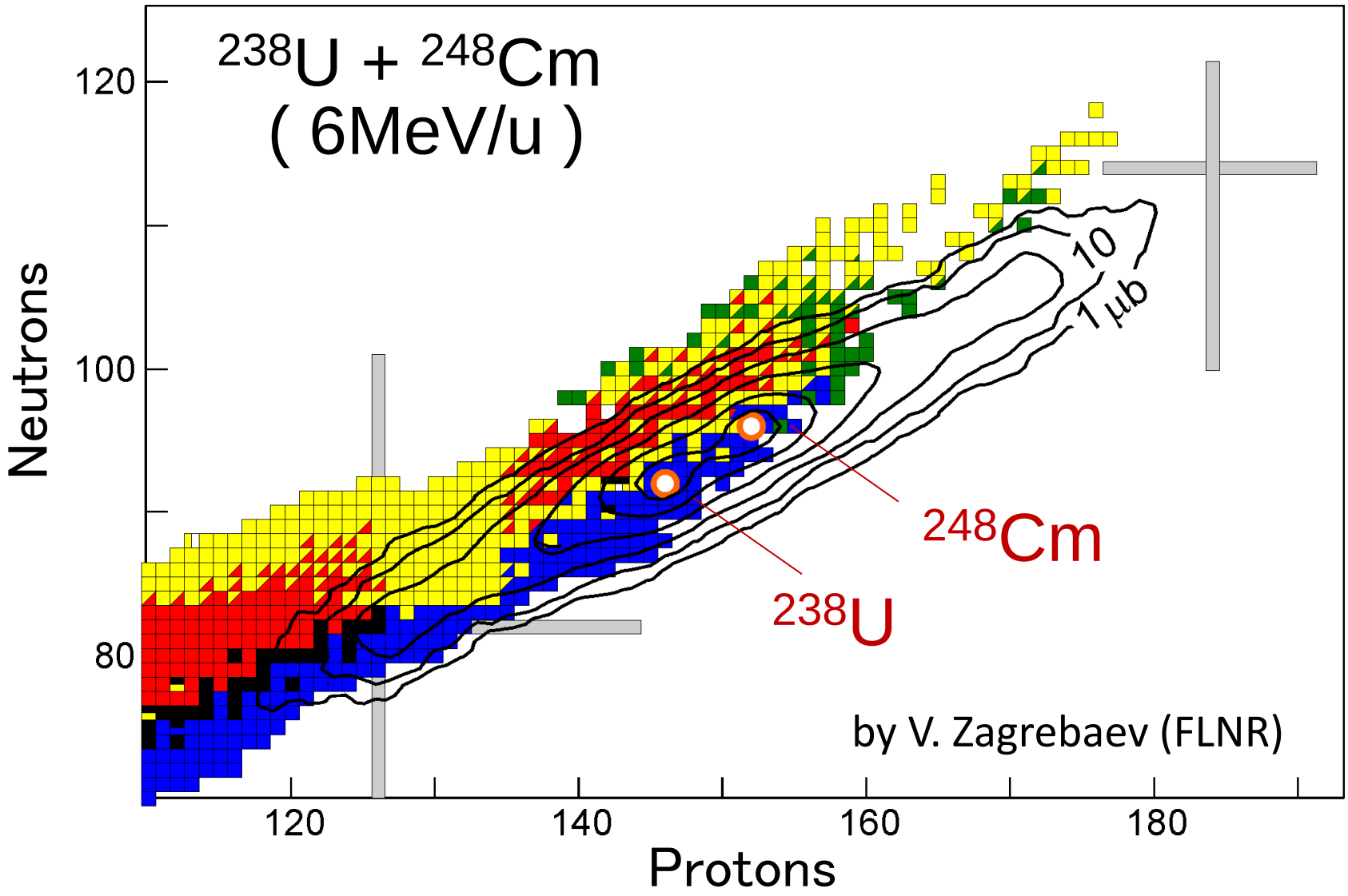
dp/p 1.3% (solenoid)
1%/GeV (dipole)

Three Extreme Region on Chart of Nuclei

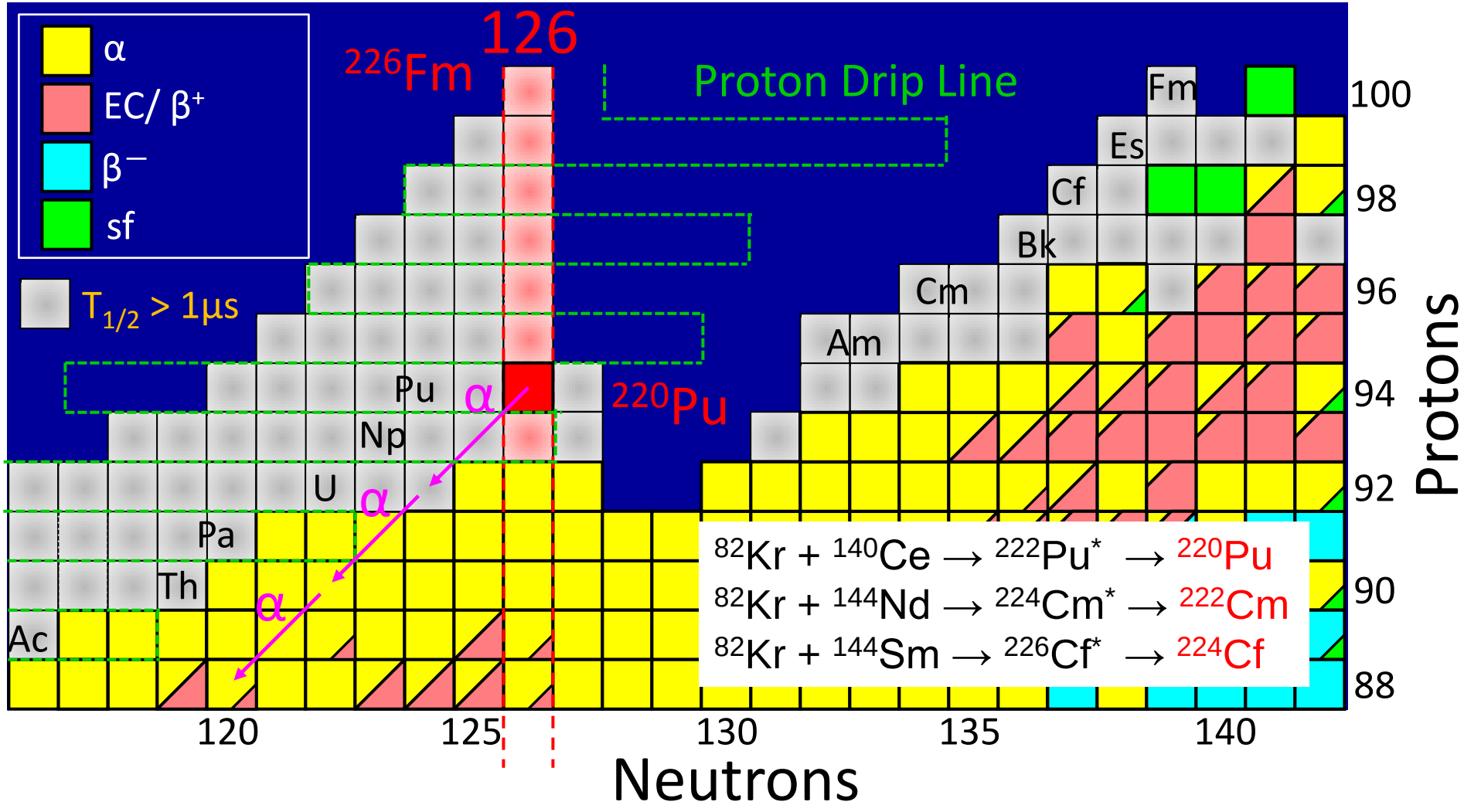
Search for Heaviest N=Z Nuclei (R. Grzywacz)
Search for Super-heavy Nuclei (S. Heinz)
Search for Heaviest N=126 Nuclei (K. Nishio)



Search for Super-Heavy Nuclei

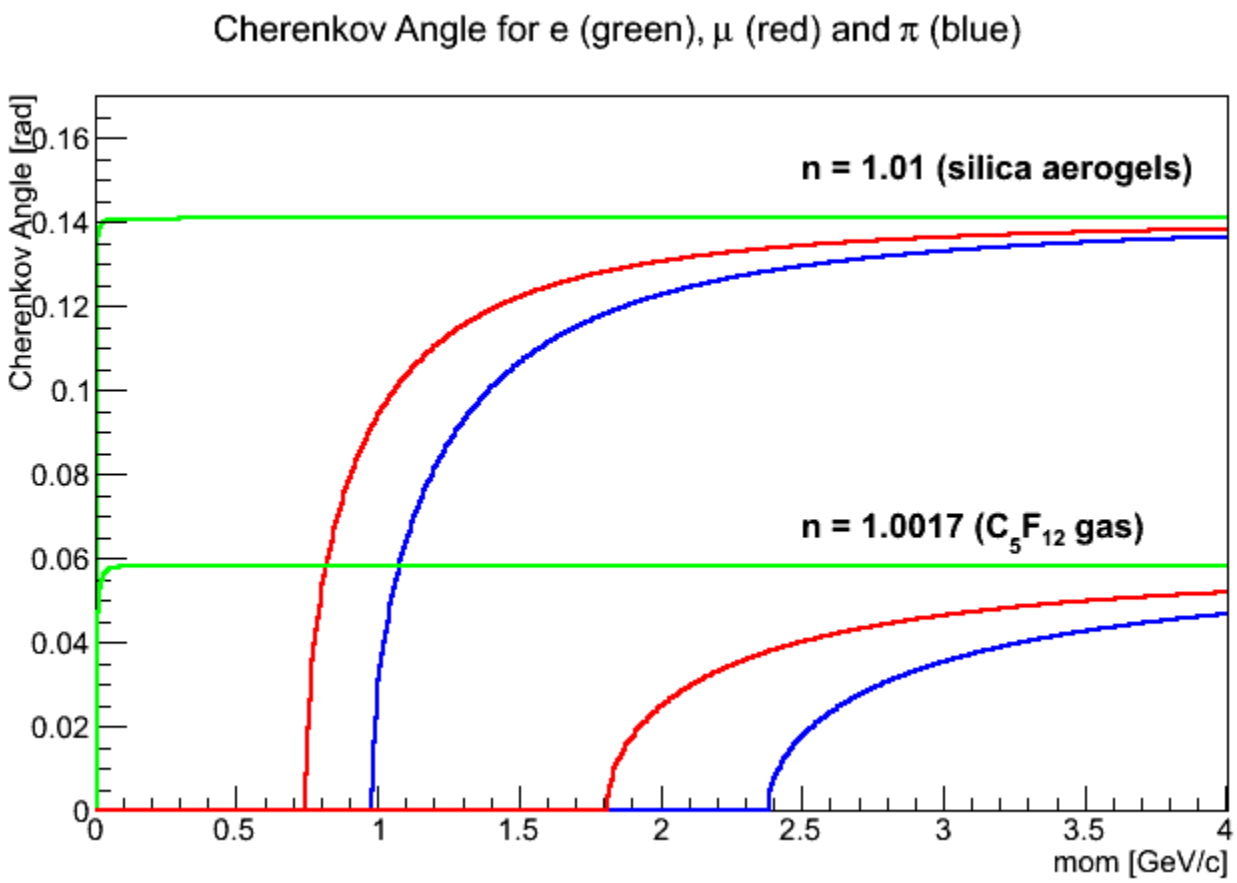


Search for Heaviest N=126 Nuclei



New Region Predicted by H. Koura, ASRC/JAEA

μ/π separation with RICH



P<0.8GeV/c

- TOF (MRPD)
- 3σ separation

σ_t=20ps , L=3m

0.8<p<1.5GeV/c
RICH(aerogel)

P>1.5 GeV/c
Fe absorbers
+trackers

Required pixel size at 10% occupancy
at 1m from the target

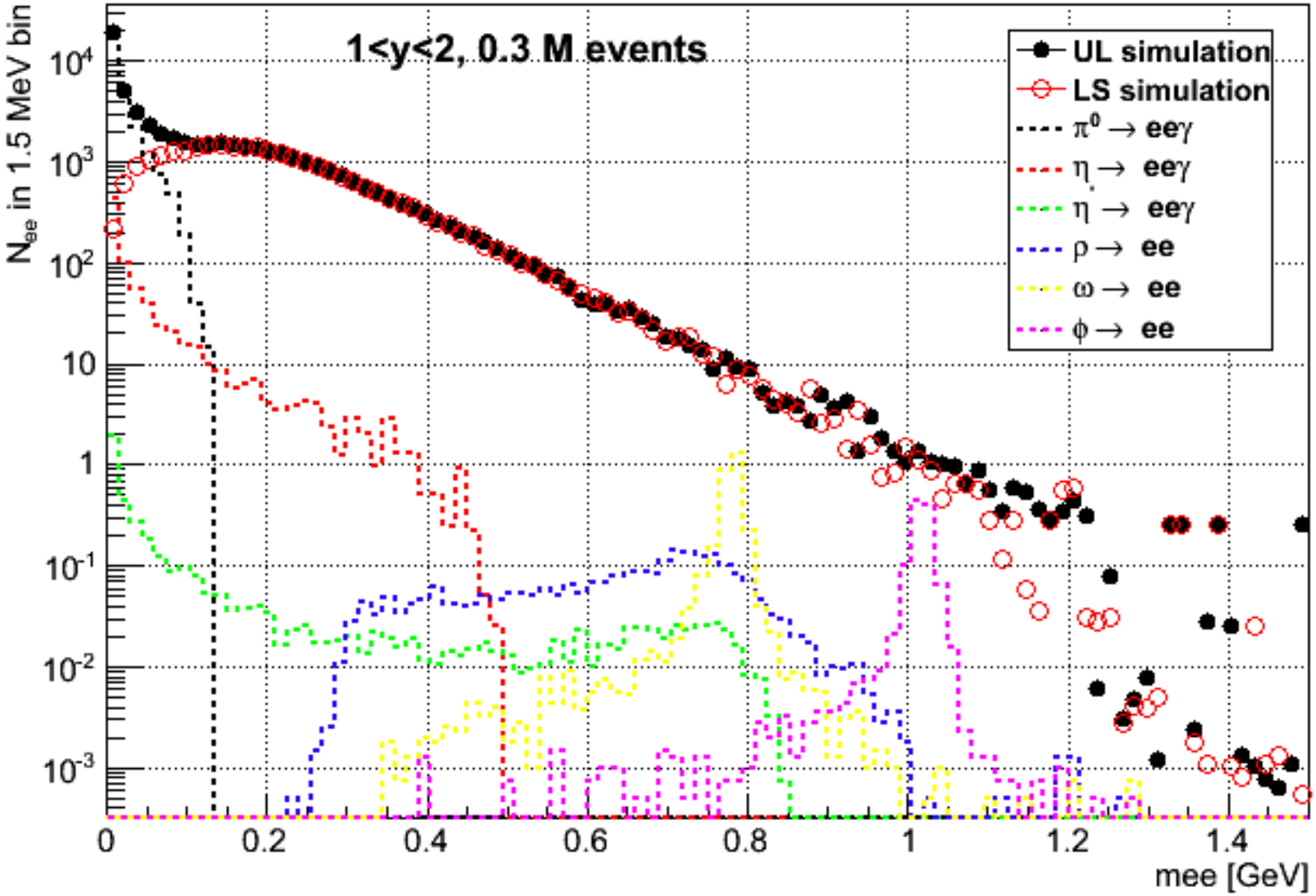
	1AGeV	5AGeV	10AGeV
θ<2deg	17x17mm^2	5x5mm^2	3x3mm^2
θ=10deg	18x18mm^2	7.5x7.5mm^2	6x6mm^2
θ=30deg	25x25mm^2	21x21mm^2	20x20mm^2

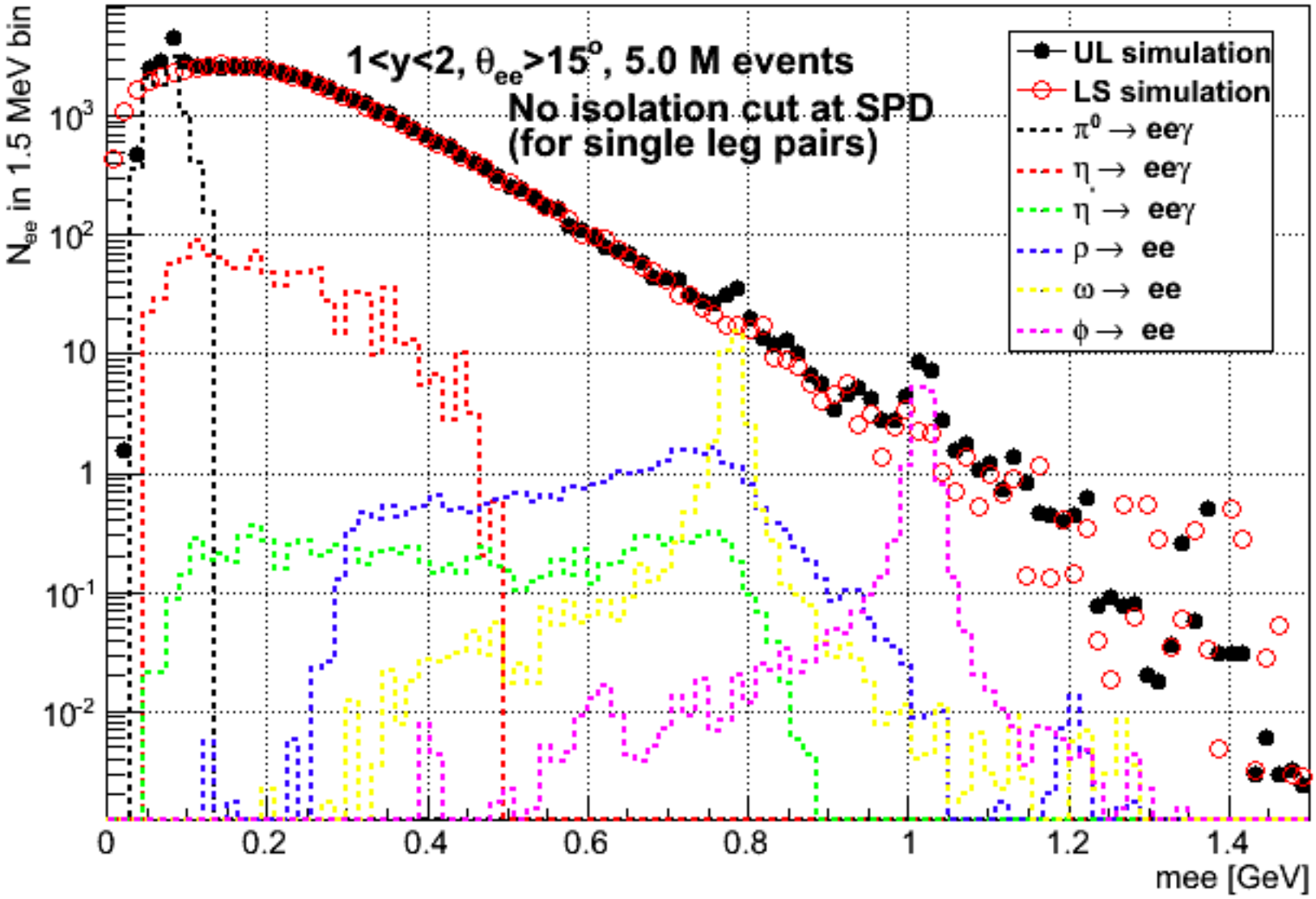
Heavy-ion programs in the world

Accelerator	Type	Beam energy (AGeV)	C.M. energy √s (AGeV)	Beam rate / Luminosity	Interaction rate (sec^{-1})	Year of experiment
Low energy RHIC (BNL)	Collider		8-62	10^{26} -$10^{27}cm^{-2}s^{-1}$ (√s=20AGeV)	600~6000 (√s=20AeV) (σ_{total}=6b)	2004-2010 2017-2018
NICA (JINR)	Collider		4-11	10^{27} $cm^{-2}s^{-1}$ (√s=9AGeV Au+Au)	~6000 (σ_{total}=6b)	2015- (BM@N) 2017- MPD
SIS-100 (FAIR)	Fixed target	2-11(Au)	**2-5**	**2x10^{10} cycle^{-1}** (2s cycle,U^{92+})	**10^{5}-10^{7}** (detector)	**2019-2024**
J-PARC	Fixed target	**0.1-12(U)**	**1.9-4.9**	**10^{10} -10^{11} cycle^{-1}**	**10^{7}-10^{8}** (0.1% target)	?

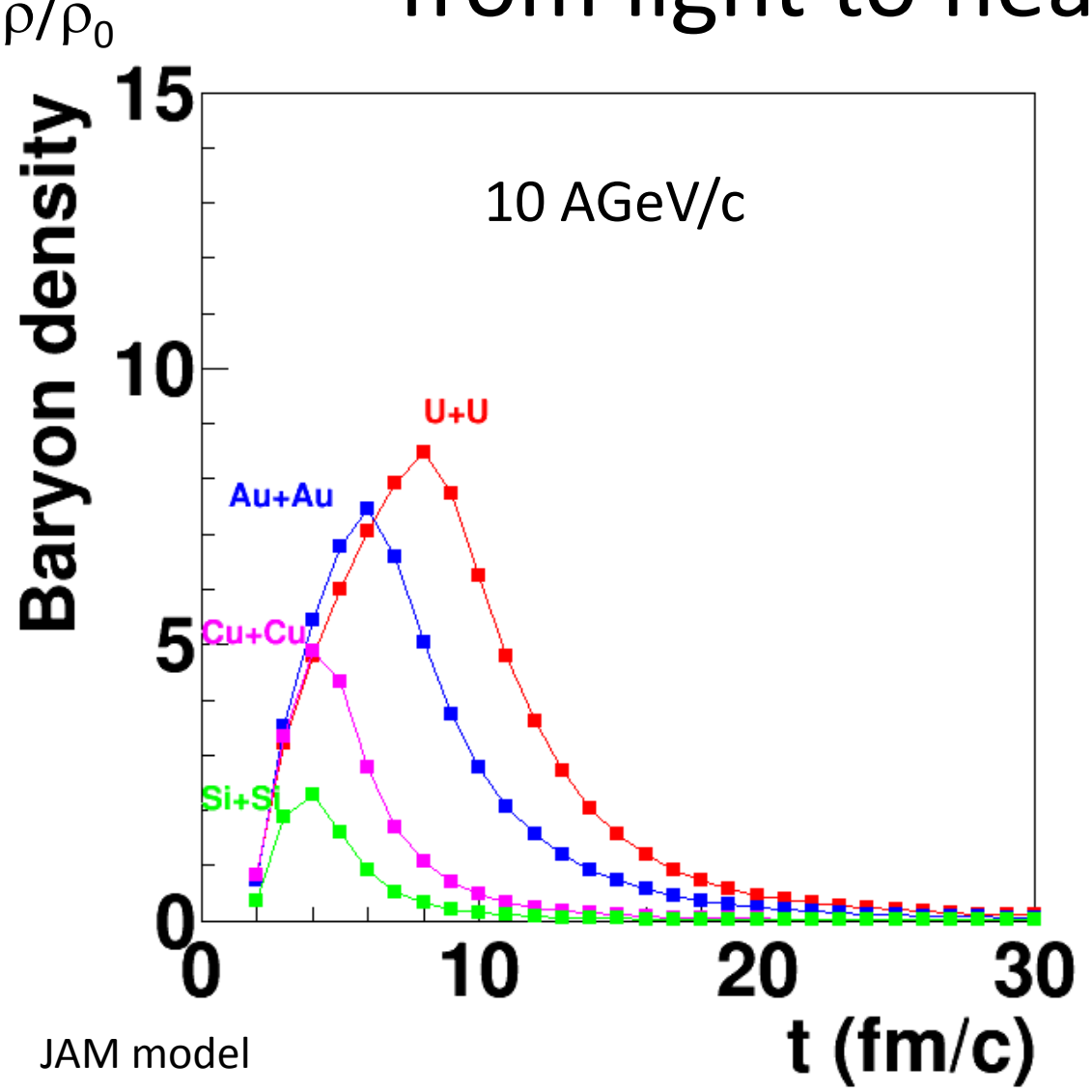
References

RHIC: A. Fedotov, LEReC Review, 2013
FAIR: FAIR Baseline Technical Review, C. Strum, INPC2013, Firenze, Italy; S. Seddiki, FAIRNESS-2013
NICA : A. Kovalenko, Joint US-CERN-Japan-Russia Accelerator School, Shizuoka, Japan, 2013


1<y<2, 0.3 M events
UL simulation
LS simulation
$\pi^0 \rightarrow ee\gamma$
$\eta \rightarrow ee\gamma$
$\eta' \rightarrow ee\gamma$
$\rho \rightarrow ee$
$\omega \rightarrow ee$
$\phi \rightarrow ee$
N_{ee} in 1.5 MeV bin
mee [GeV]


1<y<2, θee>15o, 5.0 M events
No isolation cut at SPD
(for single leg pairs)
UL simulation
LS simulation
π0 → eeγ
η → eeγ
η' → eeγ
ρ → ee
ω → ee
φ → ee
Nee in 1.5 MeV bin
mee [GeV]

Baryon density from light to heavy ions



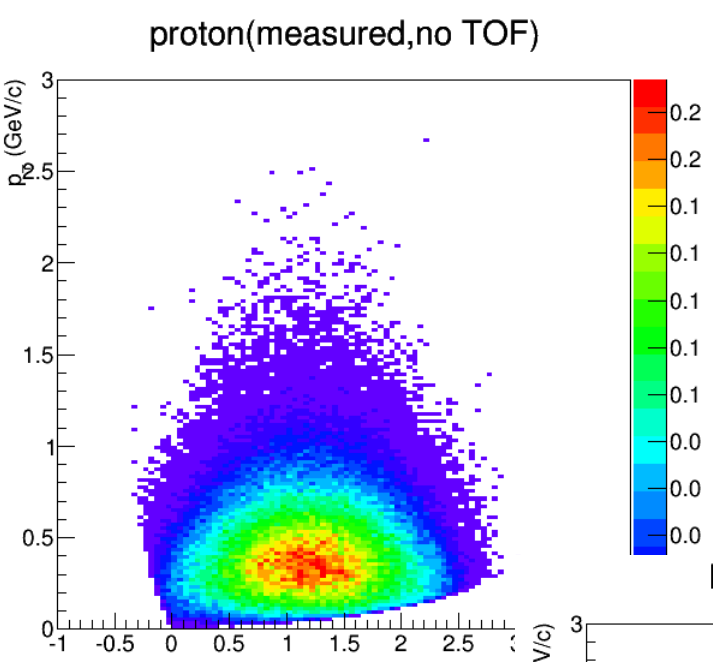
JAM model
Y. Nara, et al, Phys. Rev. C61,024901(1999)

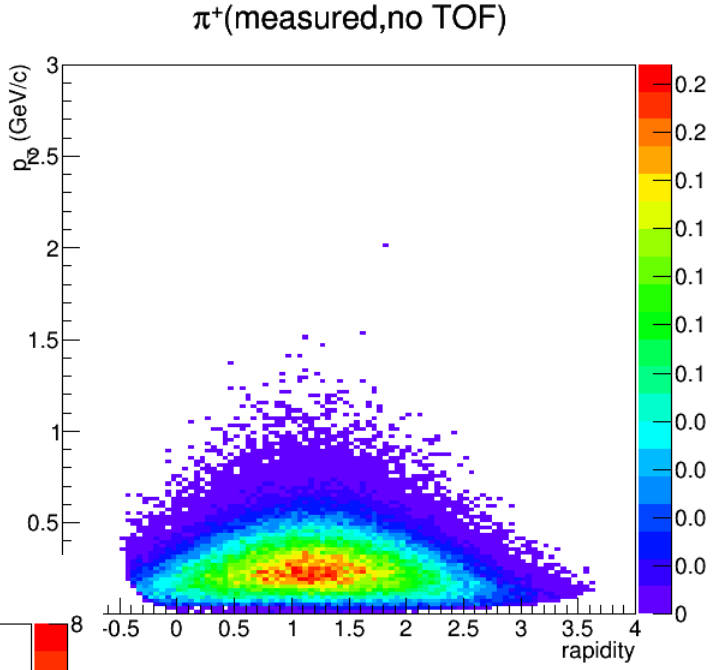
Au+Au→U+U

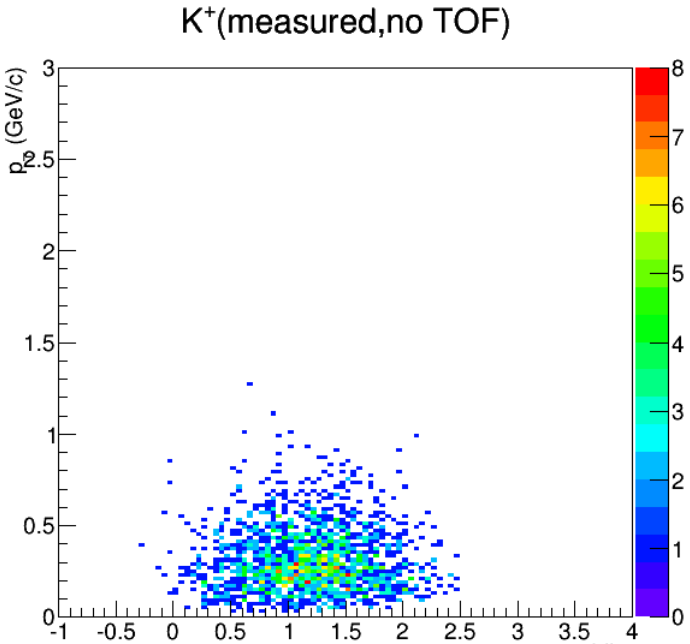
- Baryon density
  - $7.5\rho_0$ → $8.6\rho_0$
- Duration at $\rho>5\rho_0$
  - 4 → 7 fm/c

U beam is necessary at J-PARC!

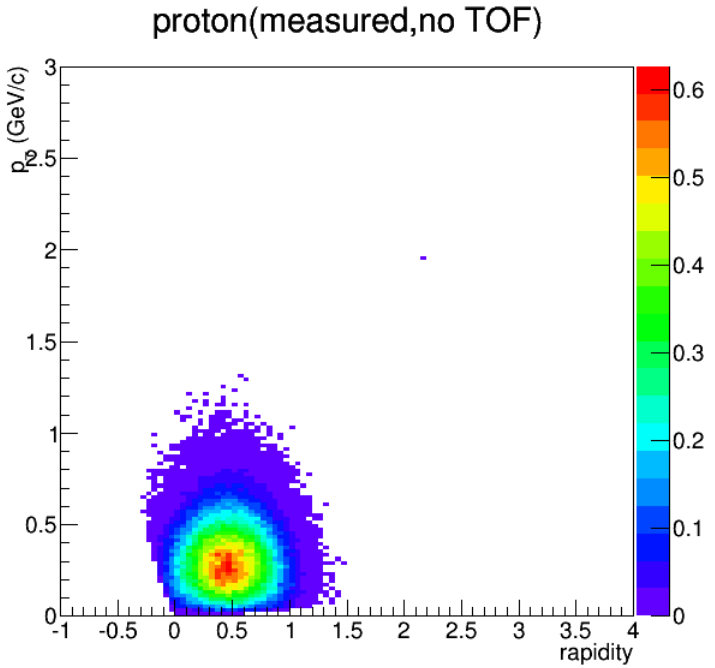
U+U at 5 AGeV/c

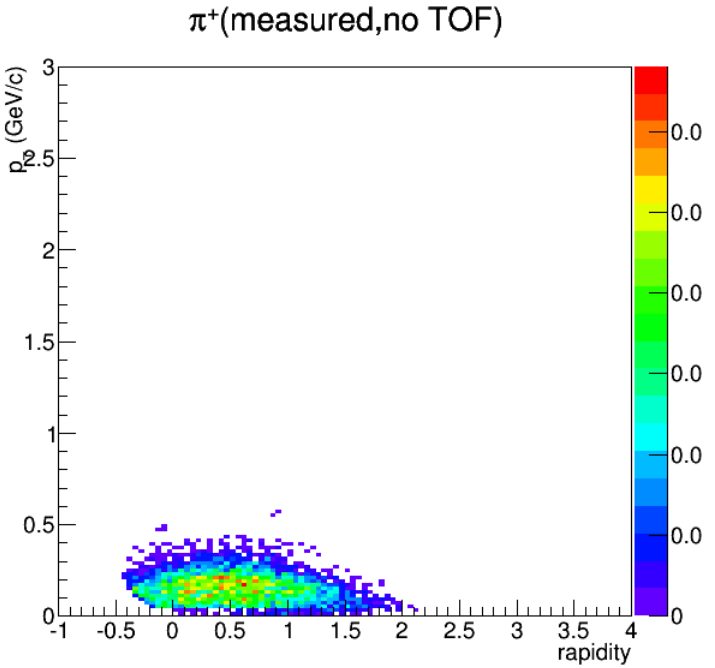

proton(measured,no TOF)
p_0 (GeV/c)

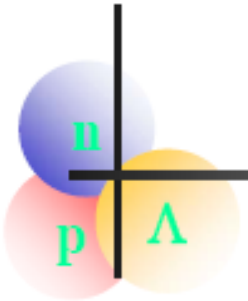

π⁺(measured,no TOF)
p_0 (GeV/c)
rapidity


K⁺(measured,no TOF)
p_0 (GeV/c)

U+U at 1 AGeV/c


proton(measured,no TOF)
p_T (GeV/c)
rapidity


π^+(measured,no TOF)
p_T (GeV/c)
rapidity



Why heavy ion for hypernuclei ? (1)

Advantage of heavy ion to K-beam

- S=-3 hypernuclei

  Only possible by HI collisions

- Double hypernuclei

  Fragments from Ξ-C,N,O atoms (Emulsion) $^{6}He_{\Lambda\Lambda}$, $^{10}Be_{\Lambda\Lambda}$

  $^{4}H_{\Lambda\Lambda}$, $^{5}H_{\Lambda\Lambda}$, $^{5}He_{\Lambda\Lambda}$ may be much more produced by HI

- Neutron/proton rich hypernuclei

  Light hypernuclei not produced by (γ,K+) (π-,K+),,,,

  nnnnΛ, $^{5}H_{\Lambda}$, $^{8}H_{\Lambda}$, $^{10}He_{\Lambda}$, $^{11}He_{\Lambda}$, $^{5}Li_{\Lambda}$, $^{12}Li_{\Lambda}$, $^{6}Be_{\Lambda}$,,,

See Presentation by Masashi Kaneta

Centrality Trigger

Narrow centrality cut taking advantage of high rate beams

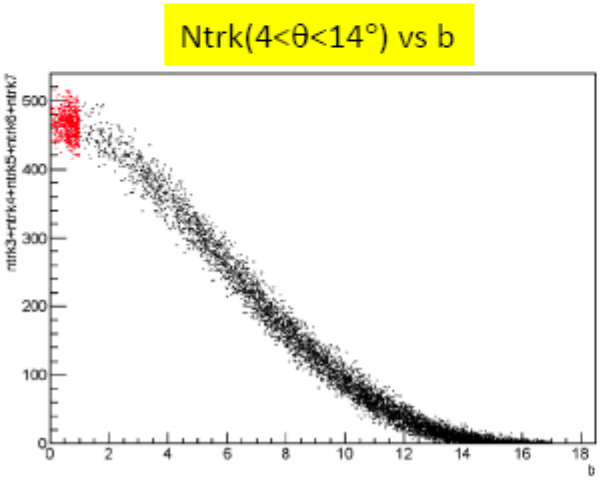
- Ultra-central
- Many narrow

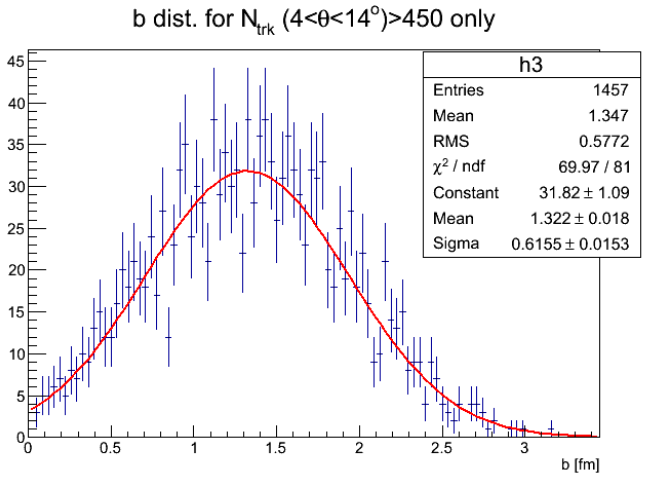
Centrality ranges

Triggering (E_{lab} = 10GeV case)

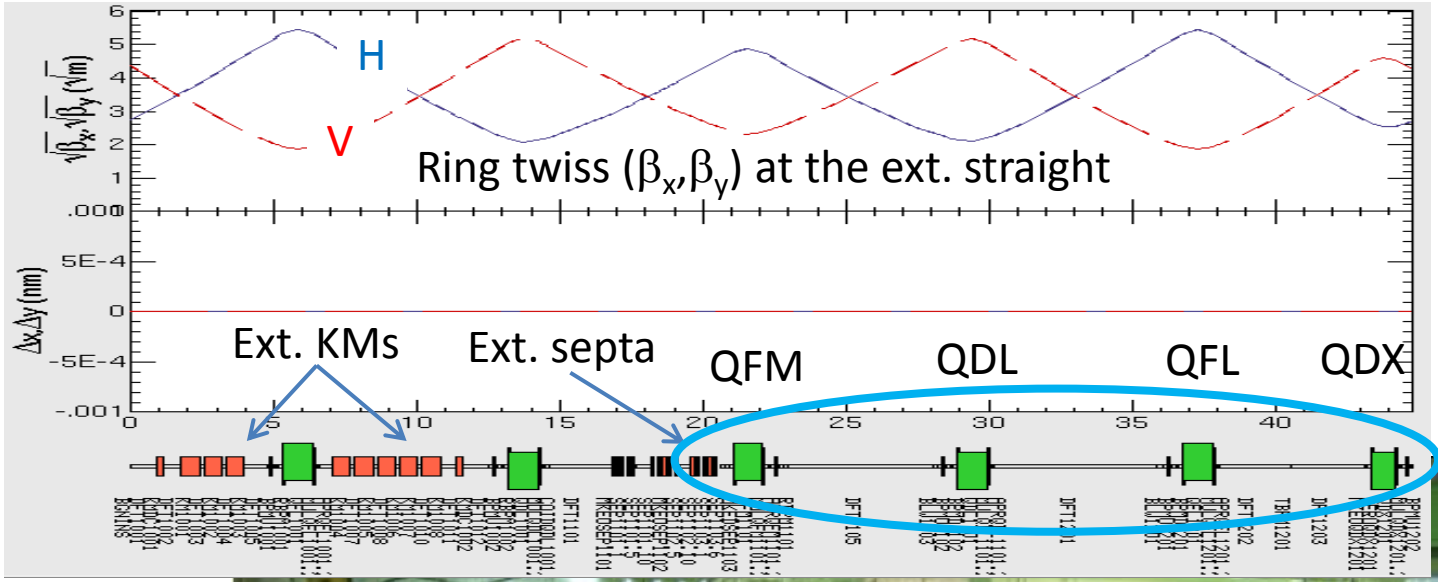
- We would like to see very central events
  - assuming b=17fm is maximum
  - b<1fm: ~0.25% central events (Marked as red points)
  - FYI, b<0.5fm → ~0.06%

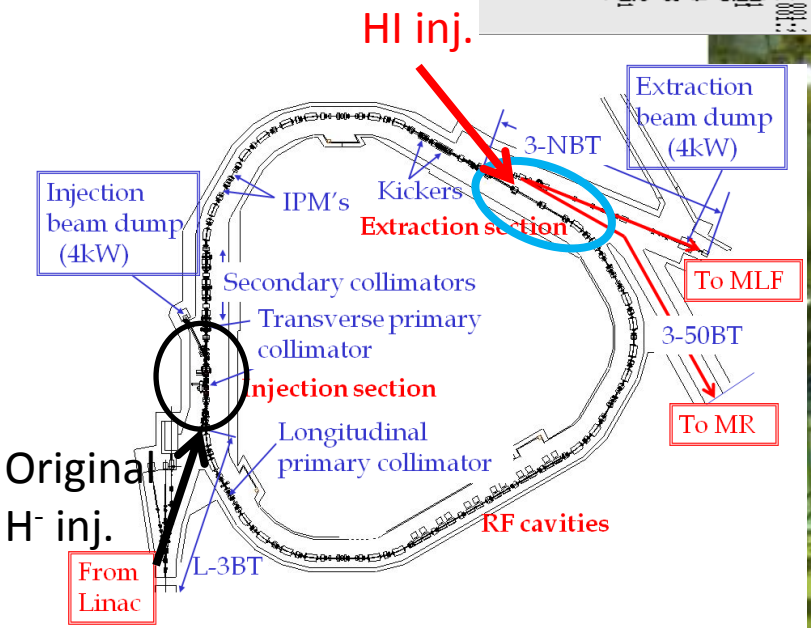
Impact parameter resolution ~0.62 fm





Injection system of RCS for Au beam

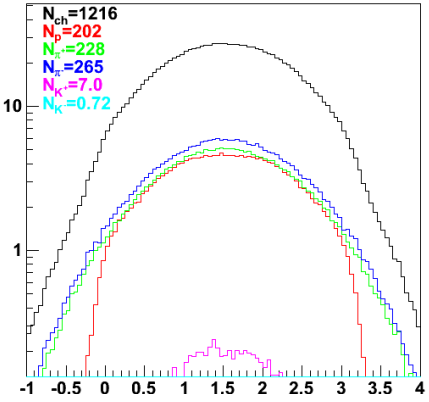


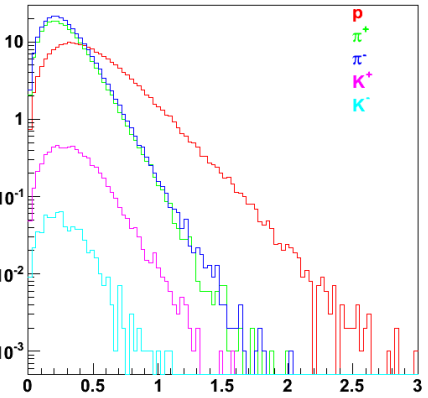


H. Harada

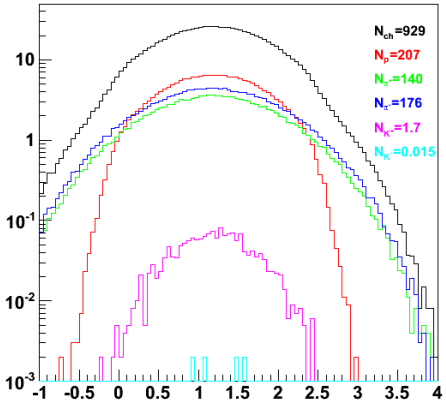
Rapidity and pt distributions

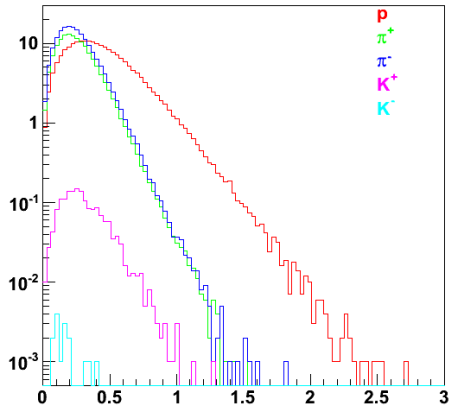
10AGeV/c



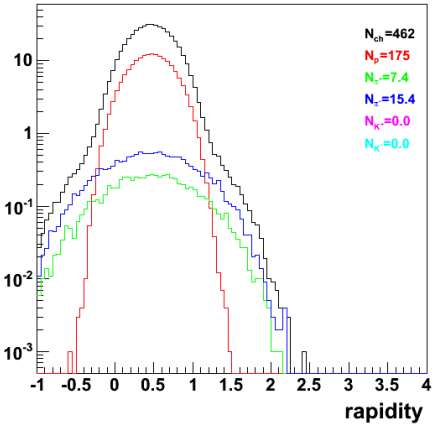


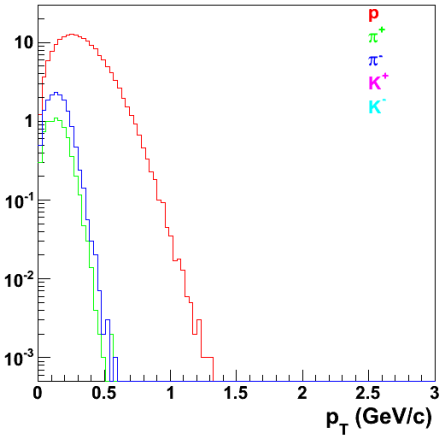
5AGeV/c





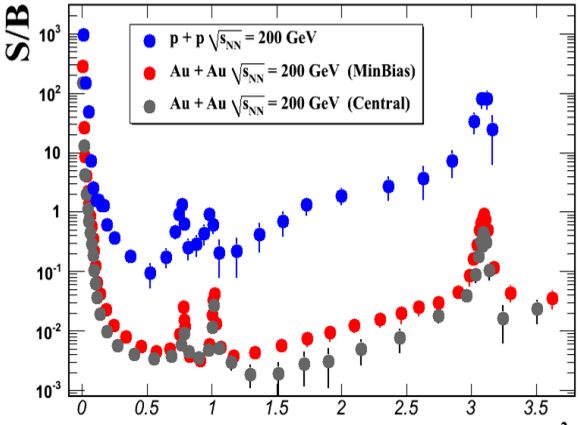
1AGeV/c

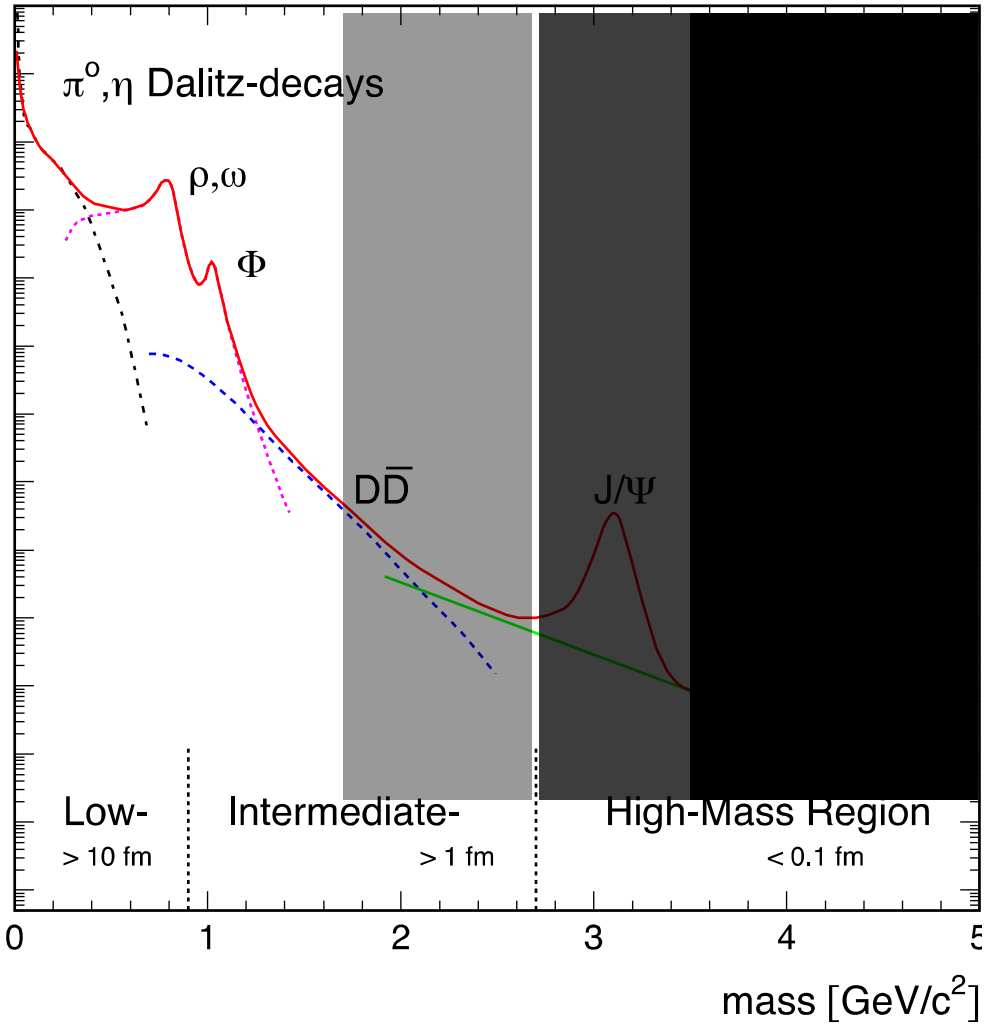




Dileptons at J-Parc energy

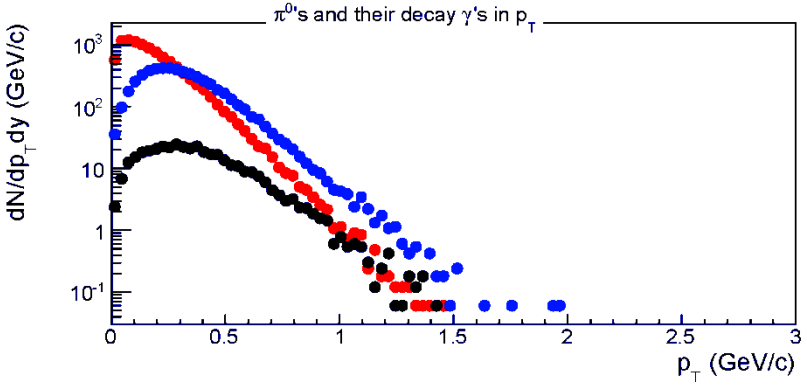
- Landscape for J-Parc
- Intermediate Mass Range
  - DDbar is very hard
  - QGP thermal radiation is on
- Low Mass Range
  - in-medium modification of vector mesons (link to chiral symmetry restoration)
  - Thermal radiation

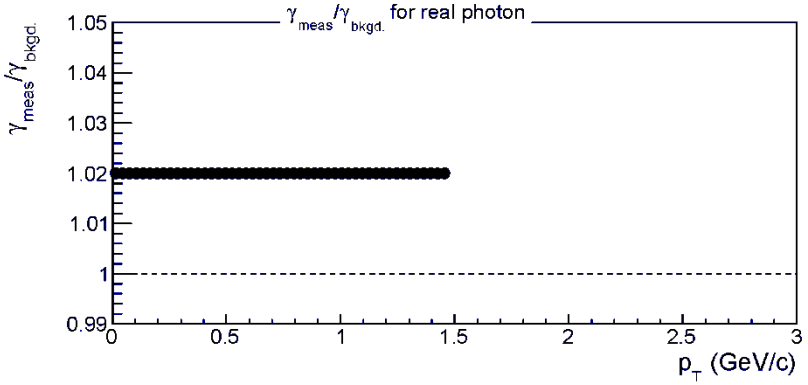


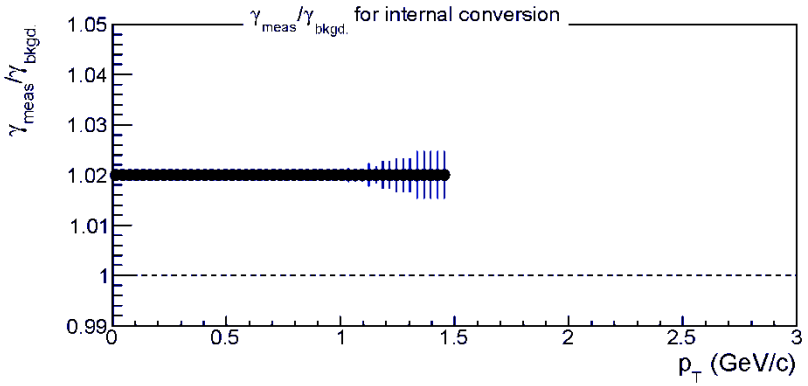


Photon feasibility study

- 0.1 T events 1<y<2, b<1fm
- Blue: pi0, Black: eta, Red: decay photons from pi0 and eta
- Direct photon signal is assumed to be 2% of background photons
- Statistical error only
- No hadron contamination, photon efficiency is taken into account.

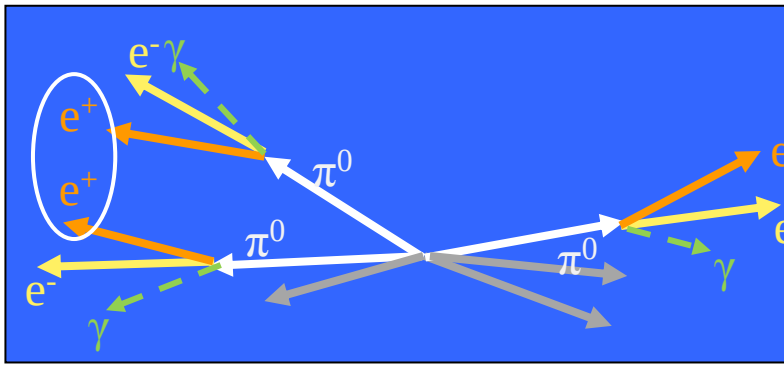






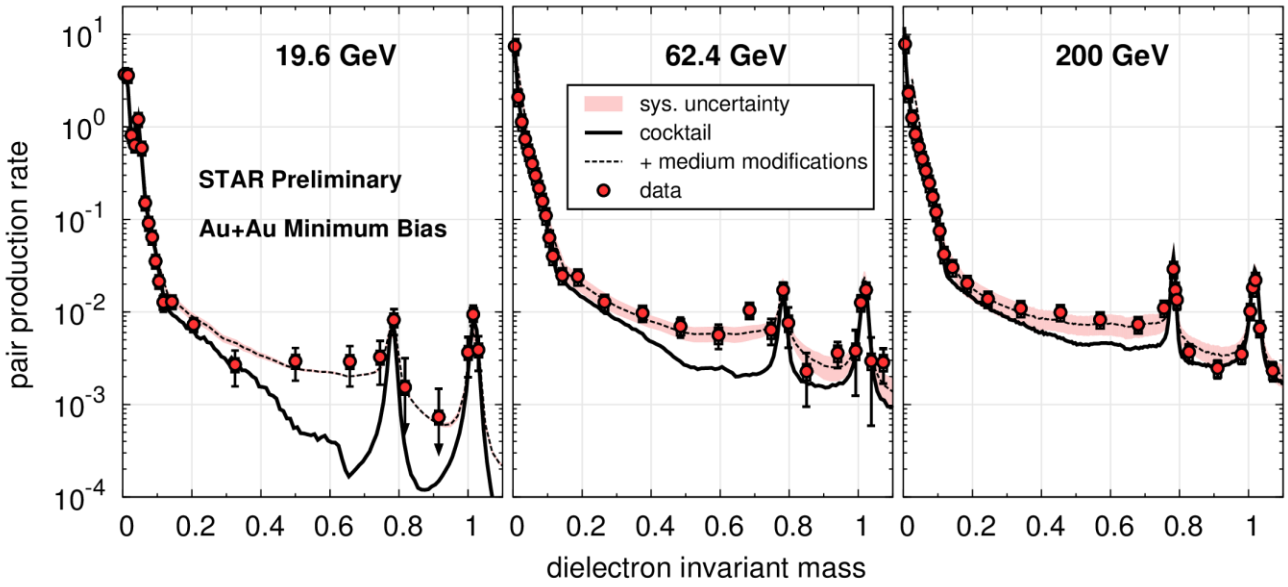
Electron feasibility study

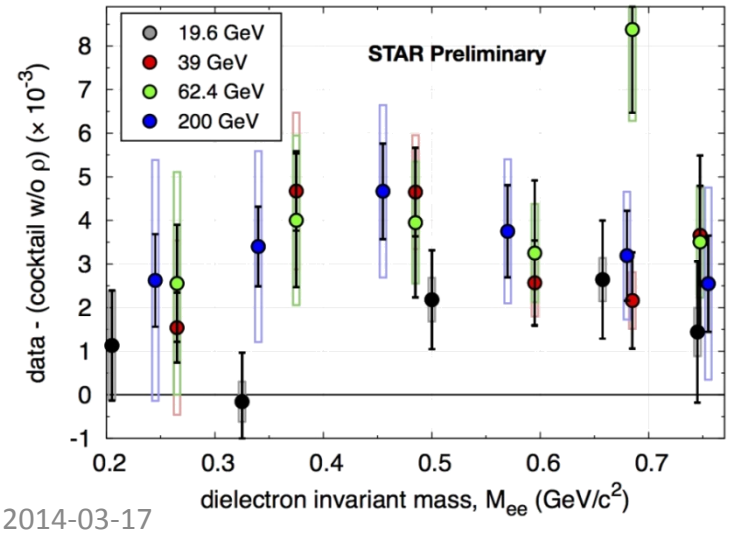
- Huge background is a problem
- Very small jet-originated background
  - No cross-pair
  - No charm contribution



- Base on pi0 spectra obtained from JAM event generator
  - Other hadrons mT-scaled
- 1<y<2 (in lab), b<1fm (0.25% centrality)
- 0.1T events (by one month running)

Beam Energy Scan of dielectrons

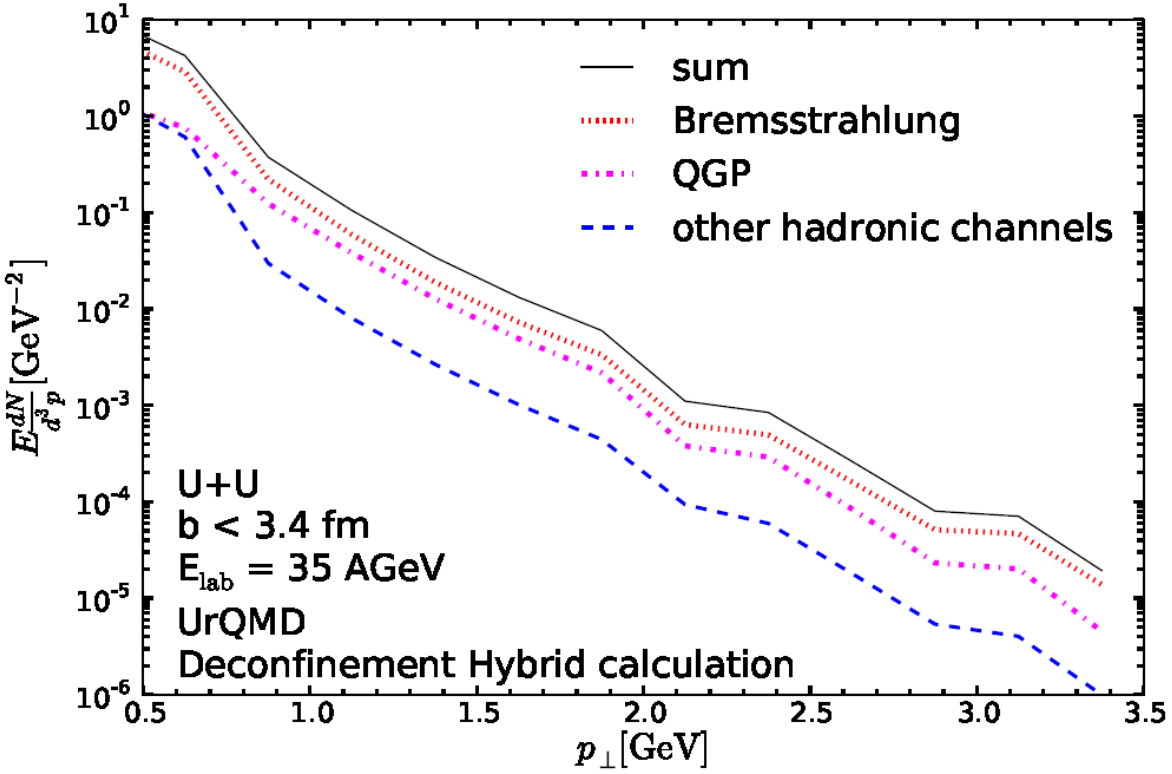




- LMR excess observed for all energies
- systematic measurement of excess
- Model calculations appear to provide robust description from RHIC down to SPS energies
- Measurements consistent with in-medium ρ broadening
  - expected to depend on total baryon density

Photon calculation

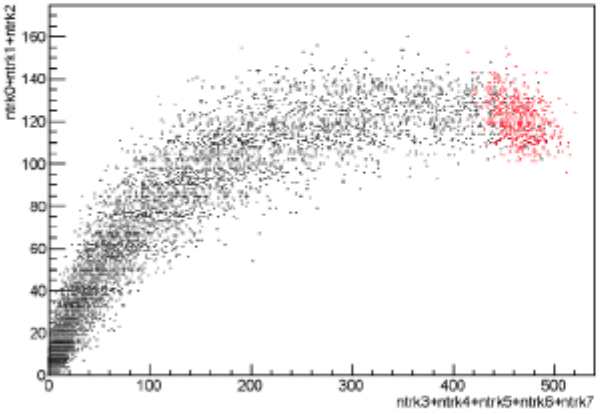
- Using UrQMD, low pT photons are calculated at FAIR energy
  - arxiv:1211.2401
  - Bremsstrahlung $\pi\pi \rightarrow \pi\pi\gamma$ is dominant
- Elliptic flow is estimated of the order of 1-2%



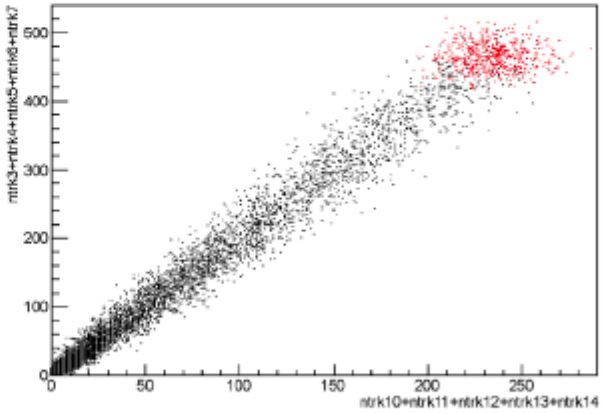
Centrality cut

- Correlating two Ntrks in different angle region
  - Possibility of higher selection power of very central events
  - Ntrk(0<θ<4°) vs Ntrk(4<θ<14°) looks good
  - Reds are b<1 events

Ntrk(0<θ<4°) vs Ntrk(4<θ<14°)



Ntrk(4<θ<14°) vs Ntrk(18<θ<28°)



Solenoid spectrometer

- Pixel size (<6x6mm^2 at 1m at θ>10^o)

B=2T

Layer	detector	R(cm)	Pixel size(ϕxz) (mm2)	thickness	material	L/X_0
1	SPD	1.5	0.05x0.4	0.3mm	Polyimide(286mm)	1.05e-3
2	SPD	3	0.05x0.4	0.3mm		1.05e-3
3	SSD	10	0.08x1	0.3mm		1.05e-3
4	SSD	14	0.08x1	0.3mm		1.05e-3
5	GEM TR	30	2x10	0.025mm 0.050mm 0.027mm	Kapton(286mm) Mylar(285mm) Cu(1.44mm)	2.32e-3
6	GEM TR	50	3x15			2.32e-3
7	GEM TR	75	5x20			2.32e-3
	He	75			He (568.192m)	1.30e-3
	TOF	85				
Total						1.25%

→ pTcut=0.26GeV/c

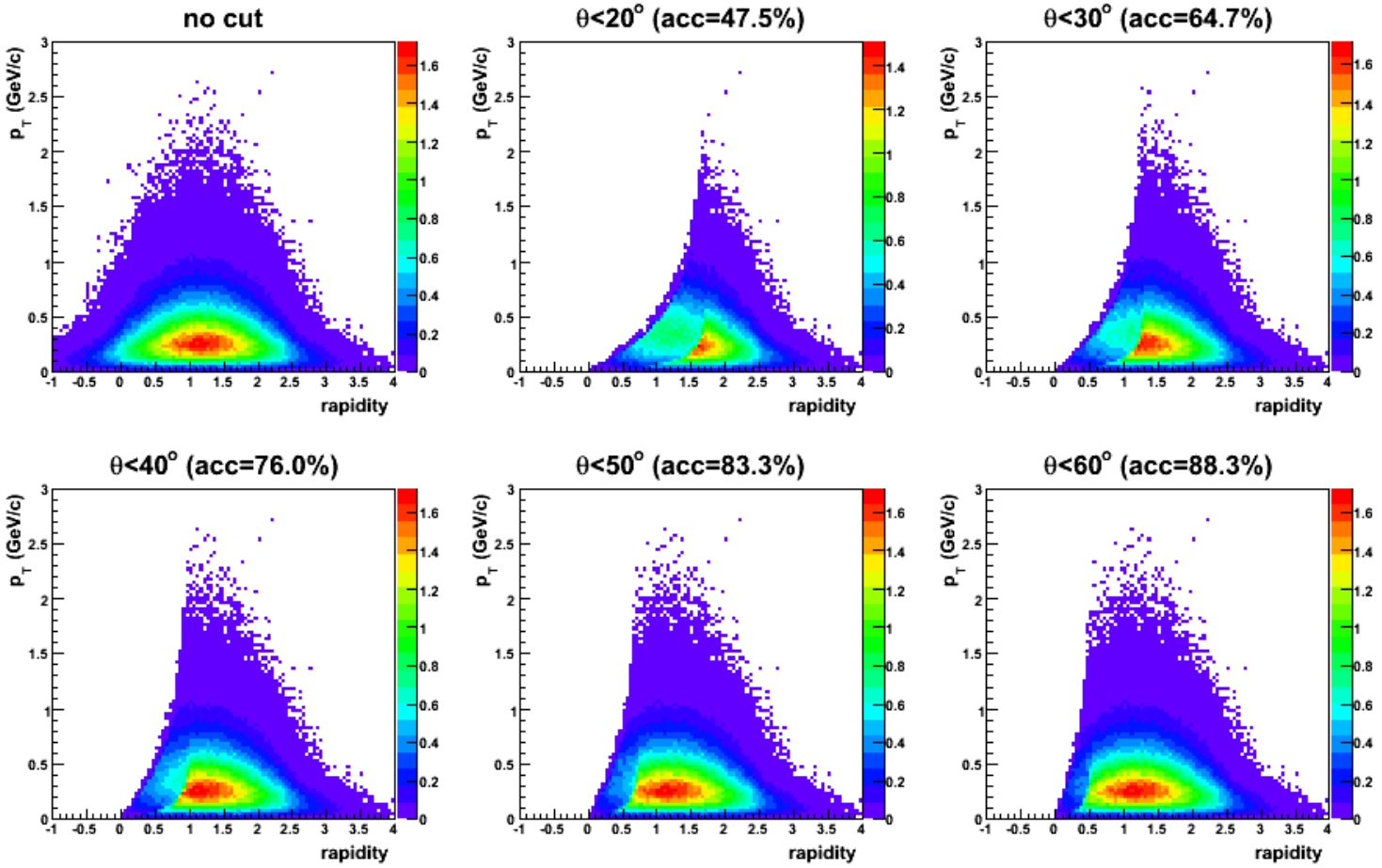
Dipole spectrometer (new)

- Pixel size (<6x6mm^2 at 1m at θ<10^o) B=2T

Layer	detector	Z(cm)	Pixel size(XxY) (mm2)	thickness	material	L/X_0
1	SPD	7.5	0.05x0.4	0.3mm	Polyimide(286mm)	1.05e-3
2	SPD	15	0.05x0.4	0.3mm		1.05e-3
3	SSD	32	0.08x1	0.3mm		1.05e-3
4	SSD	44.8	0.08x1	0.3mm		1.05e-3
5	GEM TR	180	2x10	0.025mm 0.100mm 0.027mm	Kapton(286mm) Mylar(285mm) Cu(14.35mm)	2.32e-3
6	GEM TR	190	3x15			2.32e-3
7	GEM TR	360	5x20			2.32e-3
8	GEM TR	370	5x20			2.32e-3
9	GEM TR	530				
	RICH	410				
	EMCAL	540				
	He	150			He(568.192mm)	2.64e-3

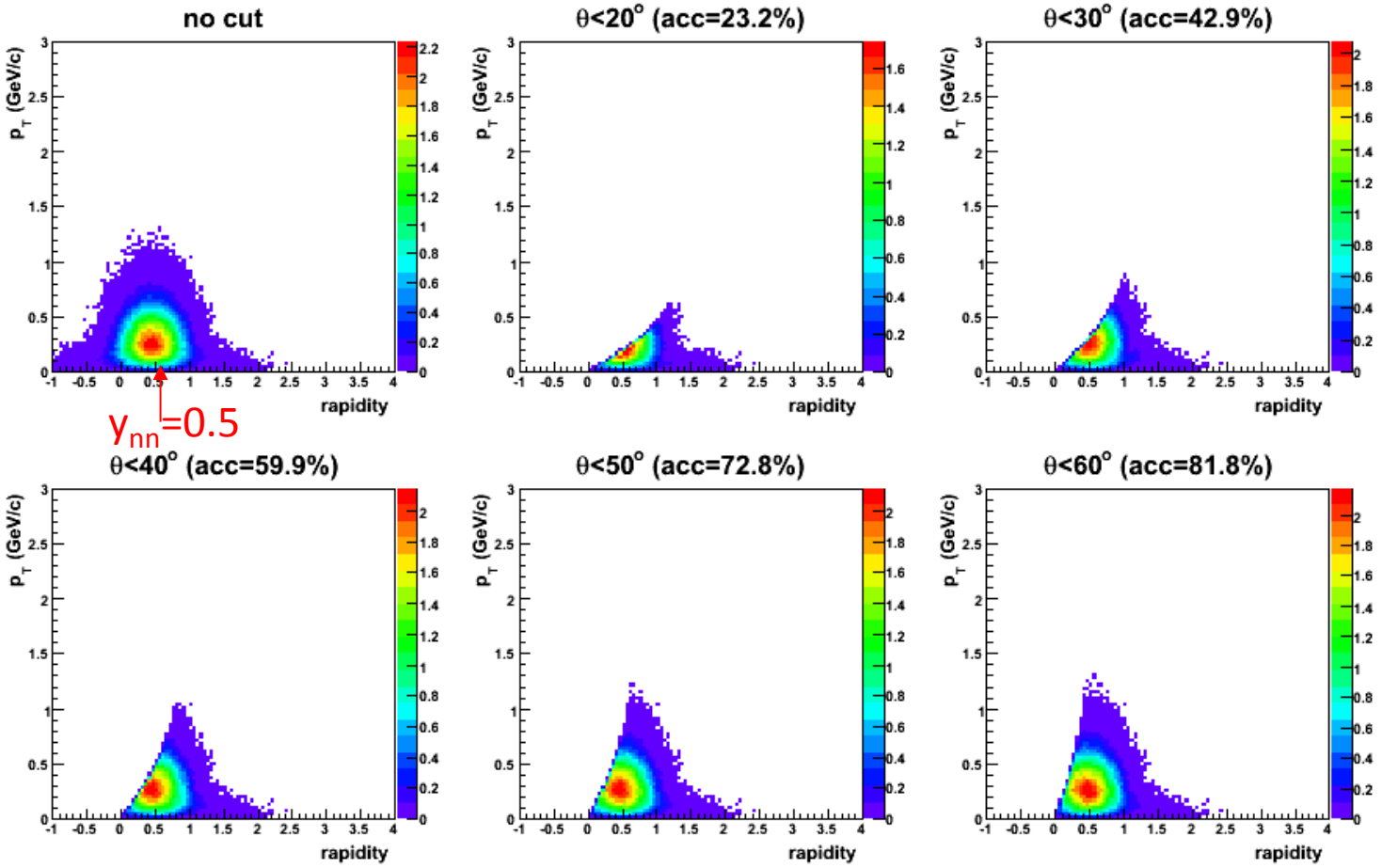
U+U at 5 AGeV/c

Mid-rapidity ~ 25 deg



U+U at 1 AGeV/c

Mid-rapidity ~ 30 deg



Summary of acceptance and pixel size

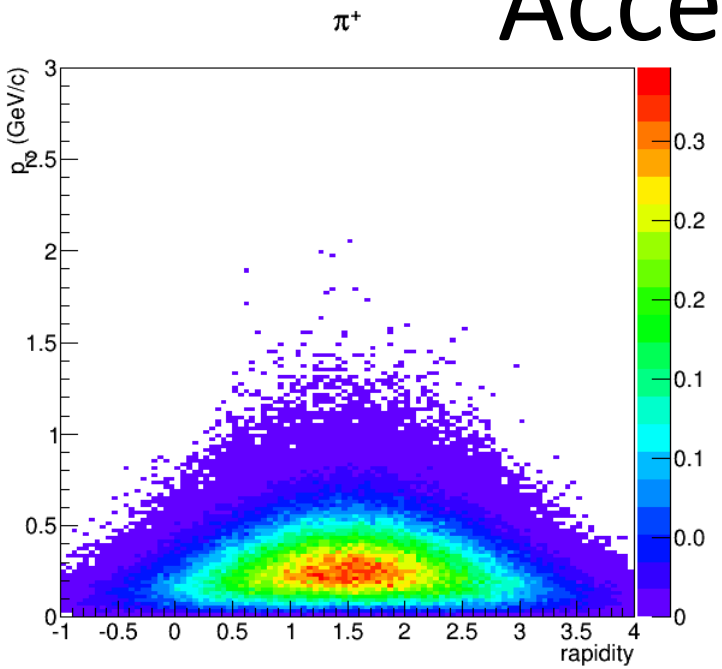
Acceptance

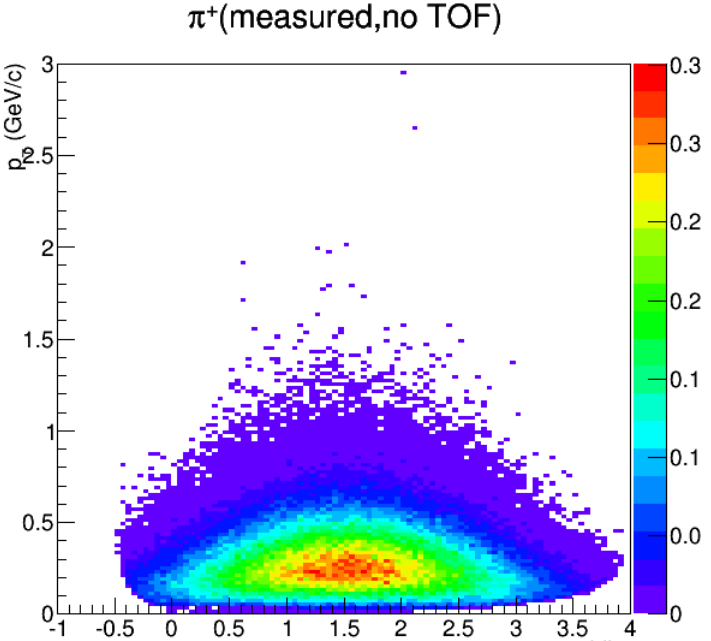
	1AGeV	5AGeV	10AGeV
θ<20deg	23.2%	47.5%	57.5%
θ<30deg	42.9%	64.7%	72.7%
θ<40deg	59.9%	76.0%	81.9%

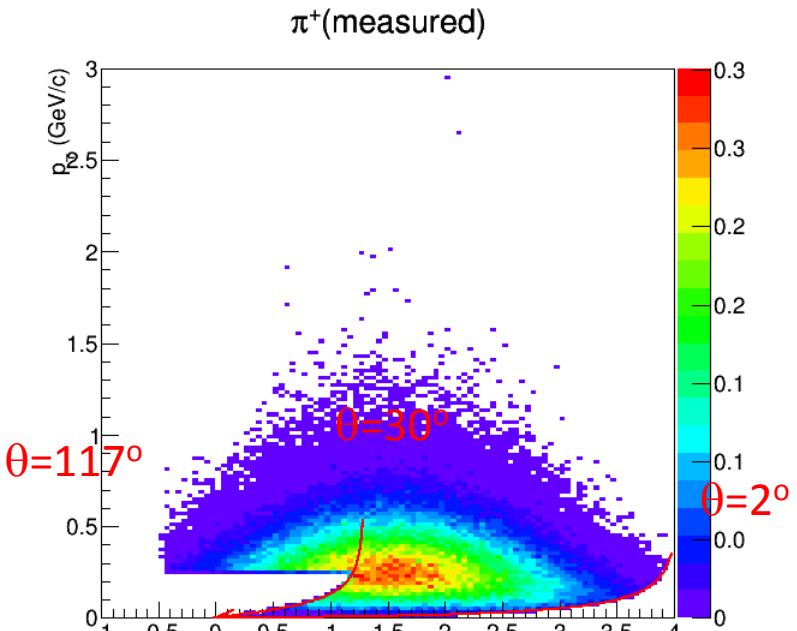
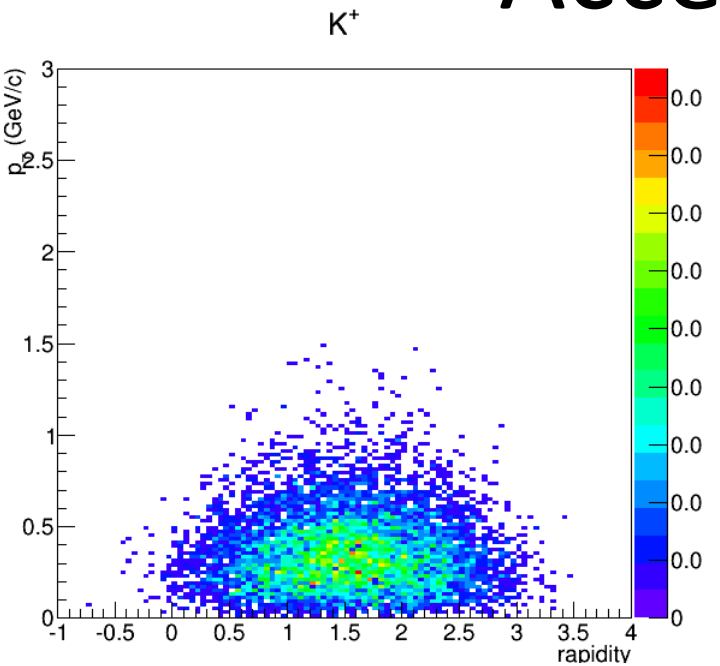
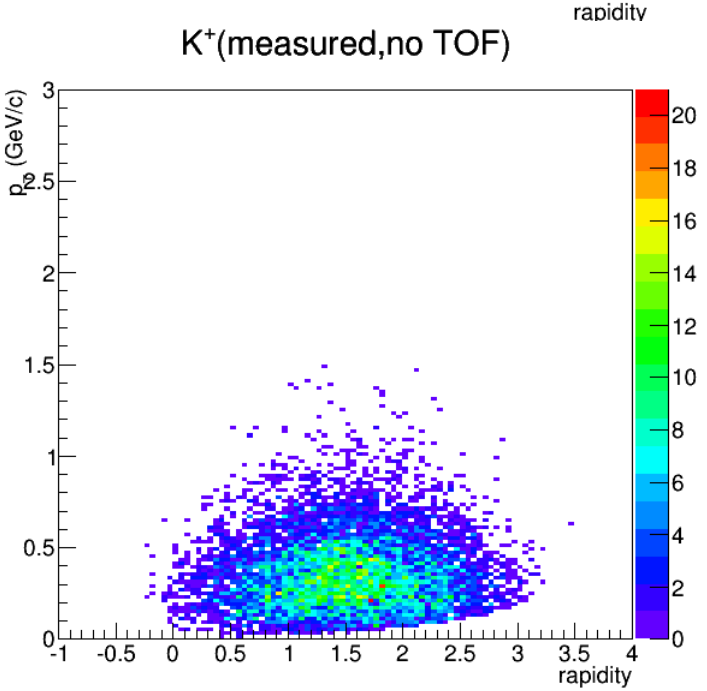
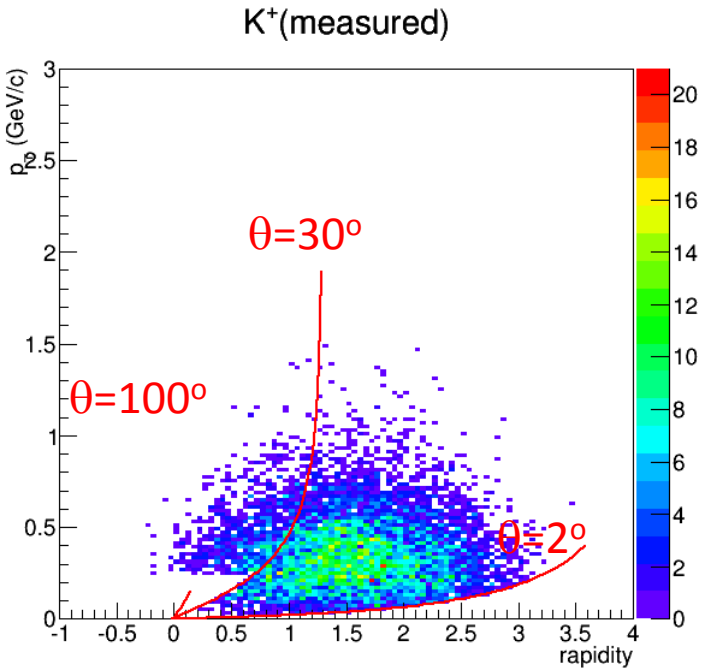
Required pixel size at 10% occupancy at 1m from the target

	1AGeV	5AGeV	10AGeV
θ<2deg	17x17mm^2	5x5mm^2	3x3mm^2
θ=10deg	18x18mm^2	7.5x7.5mm^2	6x6mm^2
θ=30deg	25x25mm^2	21x21mm^2	20x20mm^2

Acceptance(π^+)







Acceptance (K^+)