Future Heavy-ion Experiment at J-PARC

ASRC, JAEA
Hiroyuki Sako
for J-PARC HI Collaboration
J-PARC hadron workshop (5 Aug 2015)

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

J-PARC HI Collaboration

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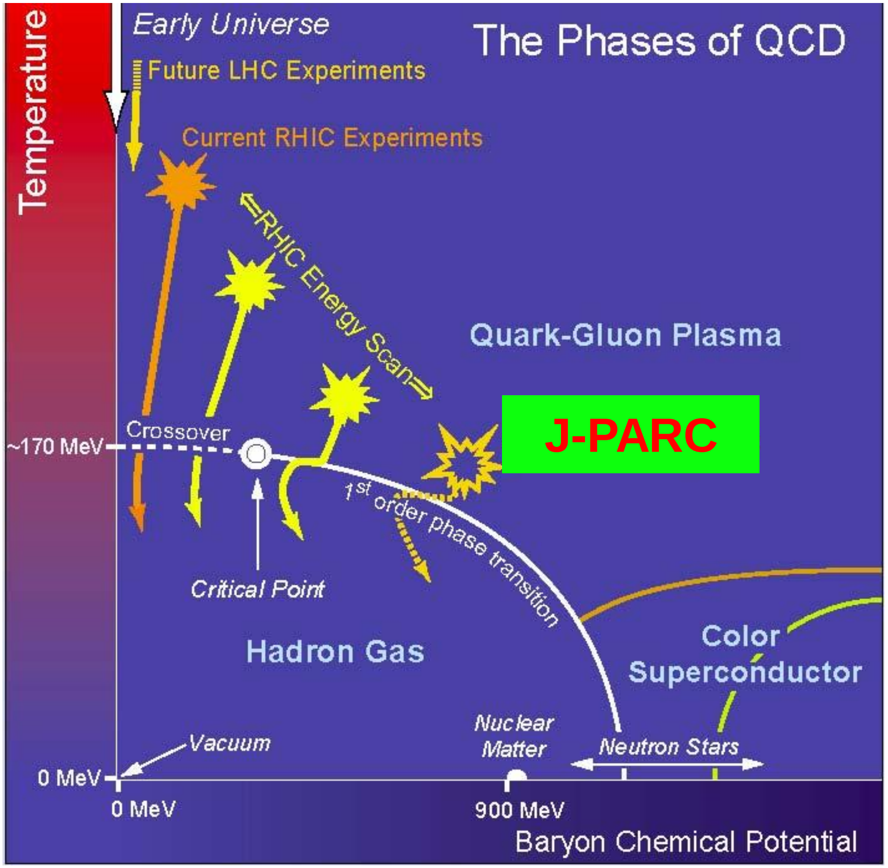
Introduction

In A+A collisions at RHIC and LHC, QGP has been discovered at high T and low ρ, but the phase transition is smooth cross over[1]

- High pt hadron suppression[2]
- Thermal photon radiation[3]

At J-PARC, we aim at studies of QCD phase structures (critical point and phase boundary) in high density regime (~neutron star)

- high statistics with world's highest intensity HI beams



[1] Y. Aoki et al, Nature 443 (2006) 675
[2] K. Adcox et al, PRL 89 (2002) 022301
[3] A. Adare et al, PRL 104 132301

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
RHIC Beam Energy Scan (BNL)	Collider		7.7-62	10^{26} -$10^{27}$$cm^{-2}s^{-1}$ (√s=20AGeV)	600~6000 (√s=20AeV) (σ_{total}=6b)	2004-2010 2018-2019 (e-cooling)
NICA (JINR)	Collider Fixed target	0.6-4.5	4-11 1.9-2.4	10^{27} $cm^{-2}s^{-1}$ (√s=9AGeV Au+Au)	~6000 (σ_{total}=6b)	2019- 2017-
FAIR SIS100 (CBM)	Fixed target	**2-11(Au)**	**2-4.7**	**1.5x10^{10} $cycle^{-1}$** (10s cycle,U^{92+})	**10^5-10^7** (detector)	**2021-2024**
J-PARC	Fixed target	**1-19(U)**	**1.9-6.2**	**10^{10} -10^{11} $cycle^{-1}$** (~6s cycle)	**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, C. Hoehne, CPOD2014

NICA : A. Kovalenko, Joint US-CERN-Japan-Russia Accelerator School, Shizuoka, Japan, 2013, A. Sorin, CPOD2014

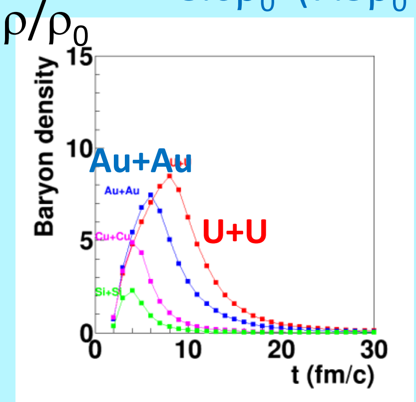
Low and High energy programs

"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
  - 10-30 pμA
  - 10ms, 25Hz

"High Enegy" Program (50 GeV MR)

- Ion species
  - p, Si, Ar, Cu, Xe, Au(Pb), U
  - Also light ions for hypernuclei
  - Maximum baryon density in U+U
    - $8.6\rho_0$ $(7.5\rho_0$ in Au+Au)



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

- Beam energy
  - 1 - 19 AGeV(U, $\sqrt{s_{NN}} = 2-6.2\text{GeV}$)
- Rate
  - 10^{10}-10^{11} ions per cycle (~a few sec)

Advantages/limitation of RCS/MR for HI beam

- Existing 3 GeV and 50 GeV synchrotrons
  HI injector and injection section in RCS are necessary

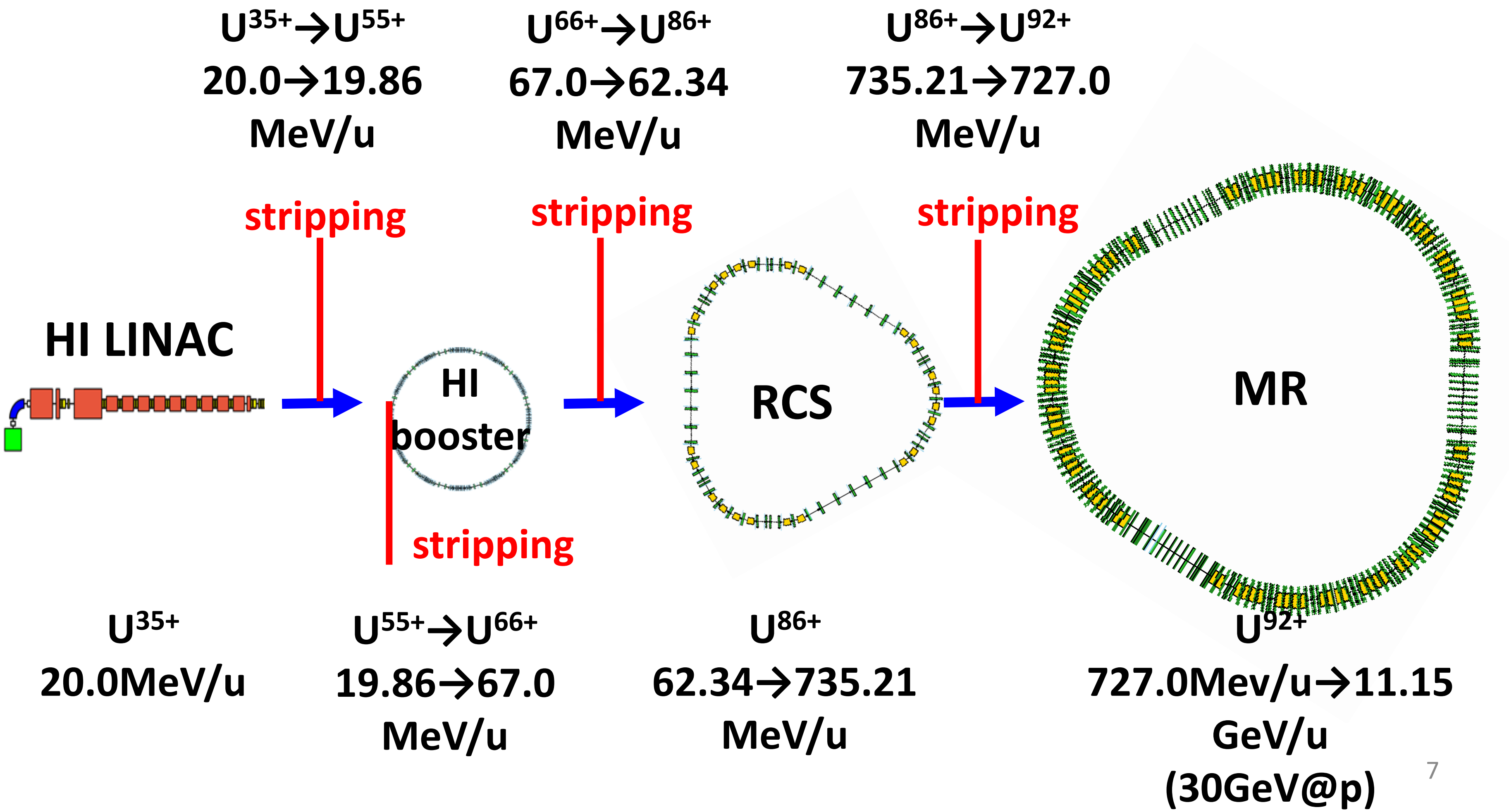
- Proven performance for high-intensity proton beam for RCS and MR
  - Slowly extracted proton beams
    2.5×10^{13}/cycle → 1.3×10^{14} /cycle (2017)

  Well understood accelerator performance
    Optics, lattice imperfections, acceleration, beam loss

- **Parallel RCS operations for MR(HI) and MLF(proton) are a must. (similarly to current operation)**
- Limited freedom in RCS for operation parameters (magnets, RF cavity…)

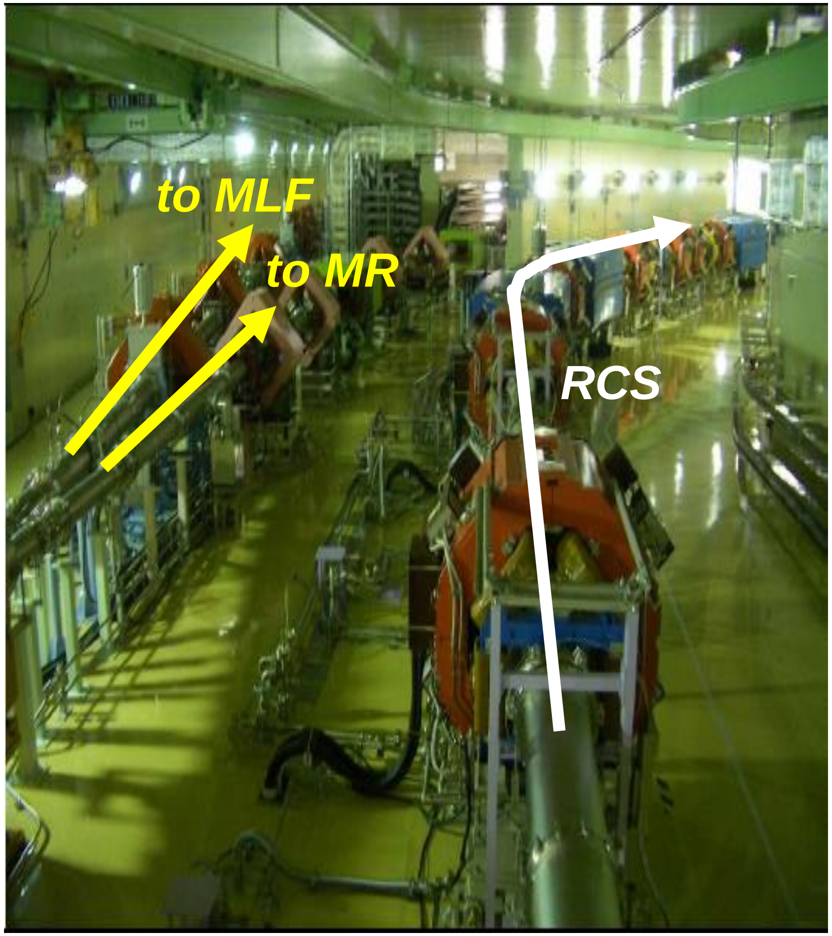
→ The injection booster is being designed to fit to RCS operations

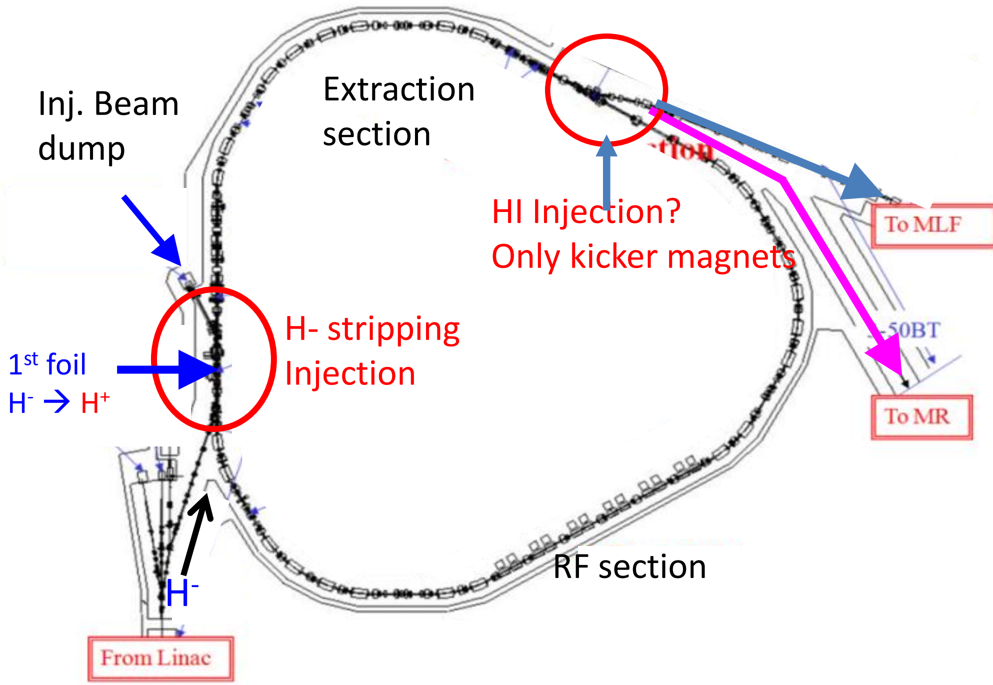
J-PARC HI Accelerator scheme
(H. Harada, J-PARC)



HI Injection to RCS

Candidate place:
End of extraction straight section

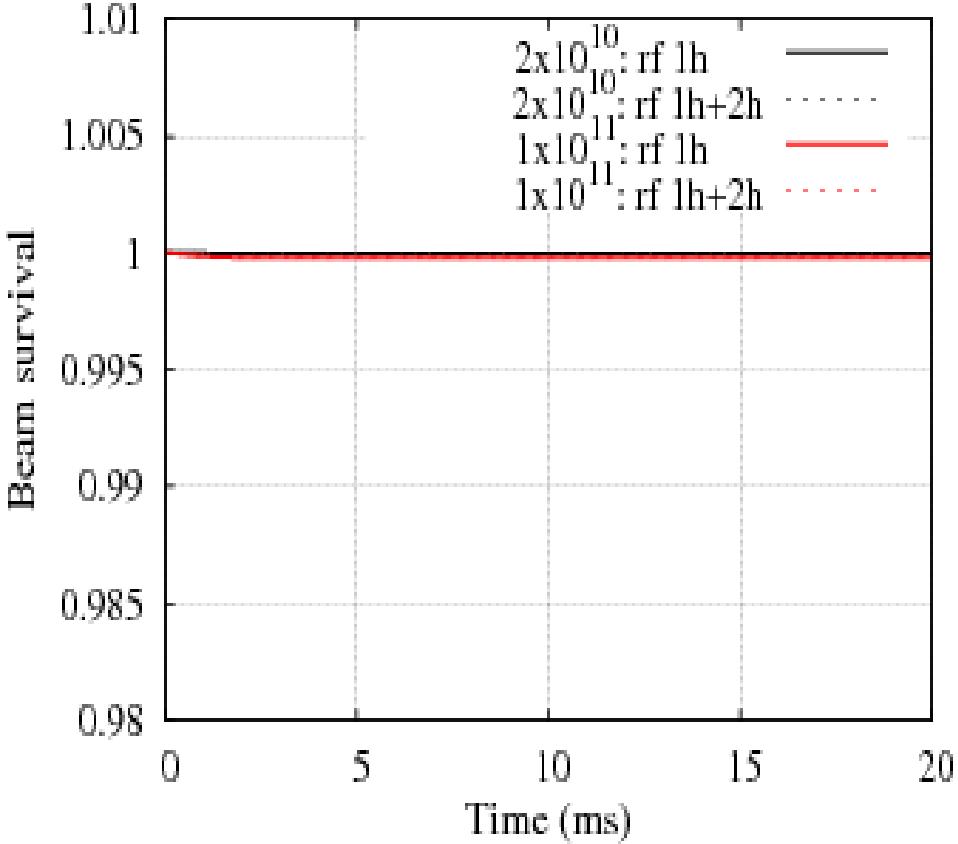




- Only injection kicker magnets are necessary in RCS in addition

Realistic simulation results: Beam survival (RCS)

2×10^{10} ~1×10^{11} ppb (P. K. Saha, J-PARC)



Same machine parameters as proton Beams (except for RF system)

Beam survival: > 99.97% even for 1×10^{11} ppb

Beam loss point: Collimator (100%)

[For 1 MW proton at present: ~99.8%, beam loss mainly due to foil scattering.]

Physics goals

- Dileptons (dielectron and dimuon)
  - ⟺ J-PARC E16 p+A
- Systematic and high statistics hadron measurements
  - Strange meson and baryons
  - Event-by-event fluctuations
  - Two particle correlations
    (YN, YY correlations in high baryon density)
  - flow (related to EOS?)
- Rare probes
  - Hypernuclei
  - Exotic hadrons
    - $\Lambda(1405)$
    - Dibaryon (H-dibaryon, ΩN, $\Delta\Delta$,…)
    - Kaonic nucleus (K^-pp,…)
  - Charm
    - J/ψ, D, charmed baryons
- Photons
  - Thermal photons from QGP

⟺ J-PARC π/K beams

Onset of QGP

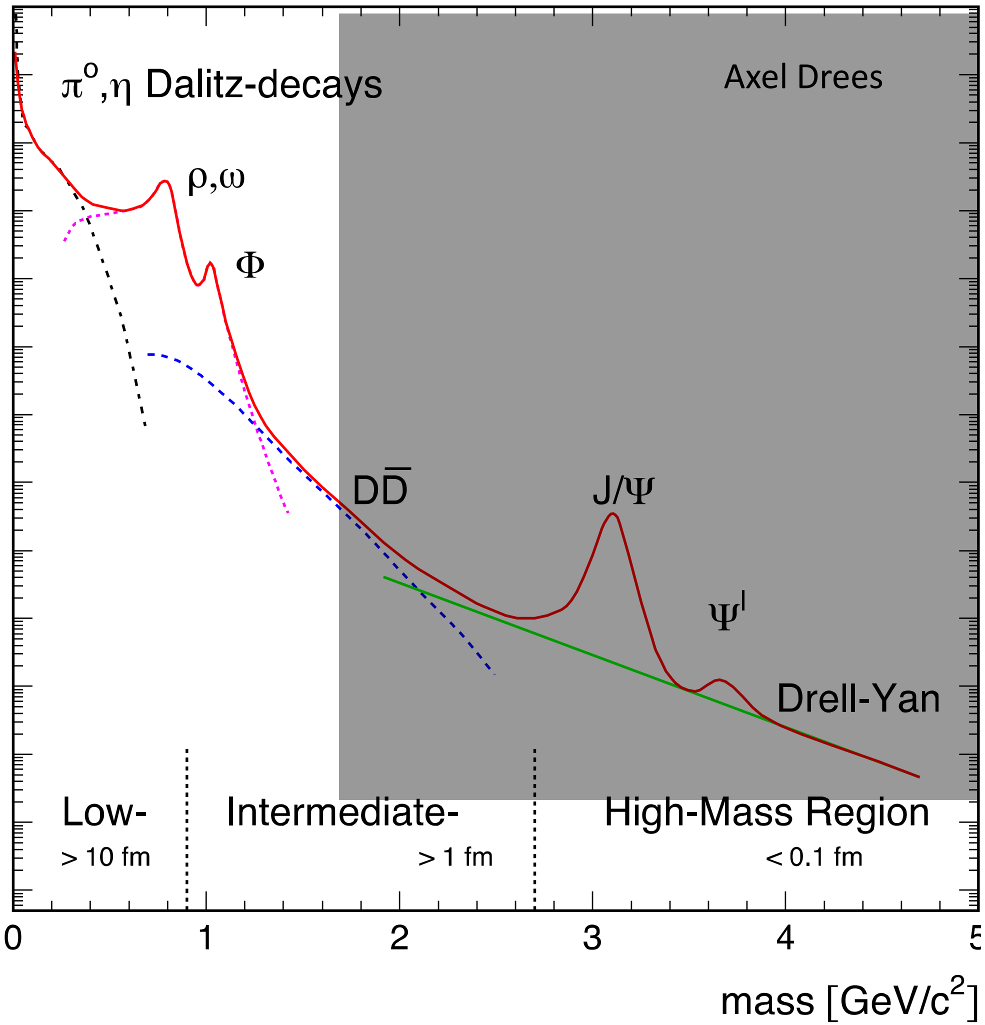
Search for critical point

Properties of Dense matter

Dileptons at J-PARC energy

Penetrating probes of dense matter

- Low Mass Range
  - in-medium modification of vector mesons (link to chiral symmetry restoration)
  - Thermal radiation
- Intermediate Mass Range
  - $D\bar{D}$ is suppressed
  - Sensitive to QGP thermal radiation?

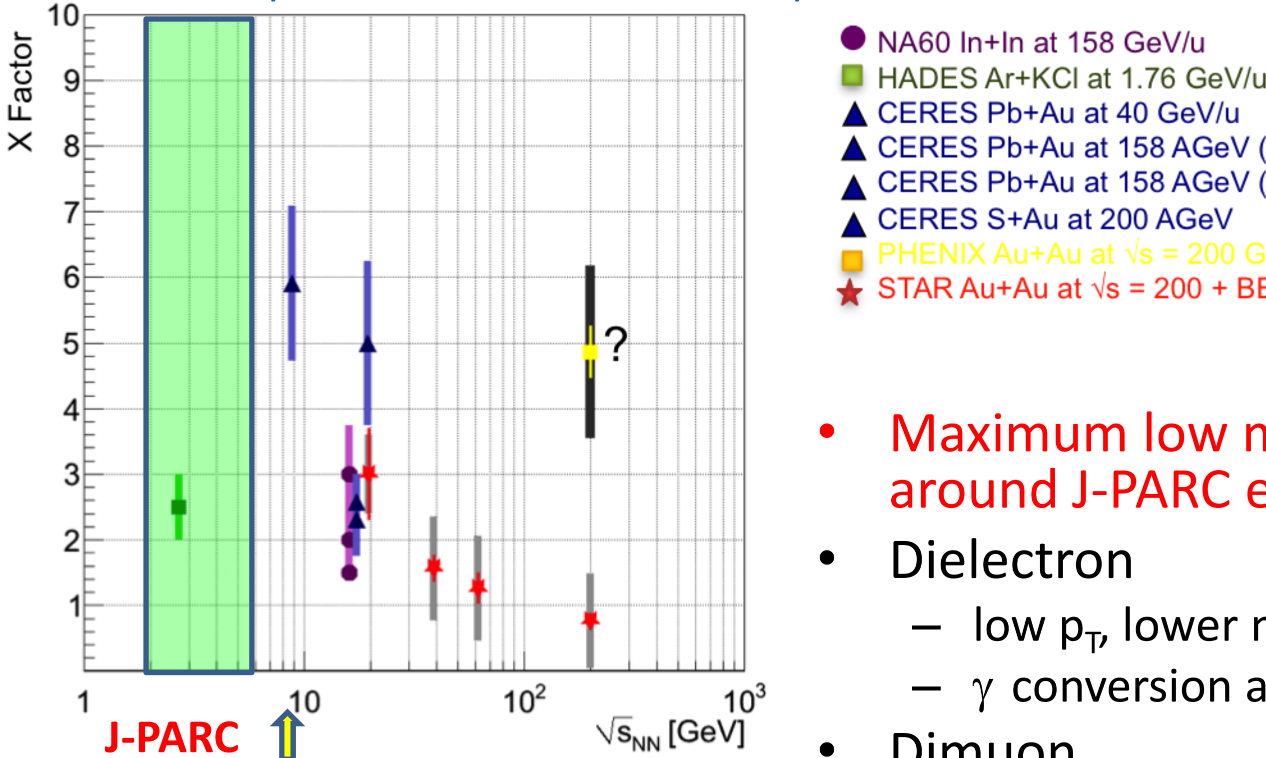


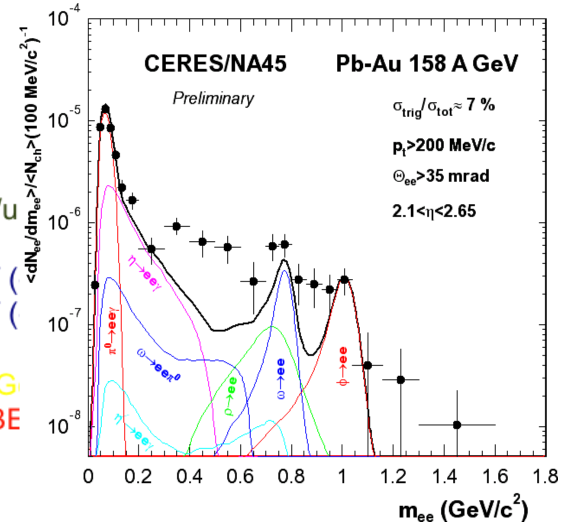
T. Sakaguchi, JHI2014

Low-mass dileptons

Low-mass dilepton enhancement factor

Measured / cocktail in m=0.2-0.8 GeV/c^2





Highest baryon density ~ 8GeV

(Randrup, PRC74(2006)047901)

T. Galatyuk, EM probes of Strongly Interacting Matter, ECT*, Trento 2007

$$\int dm_{ee} N(m_{ee}) {m_{ee}}^n$$

- Maximum low mass enhancement around J-PARC energies?
- Dielectron
  - low p_T, lower m
  - γ conversion at low m
- Dimuon
  - high p_T, higher m
  - π,K → μ decay background
  - Utilize highest beam intensity
- High statistics at J-PARC
  - Moment analysis→direct comparison to spectrum functions

Event-by-event fluctuations

Search for the critical point
and phase boundary
w/ 3rd and 4th-order fluctuations

Direct comparison to lattice-QCD may be possible

$S\sigma \cong \frac{\chi_B^3}{\chi_B^2}$

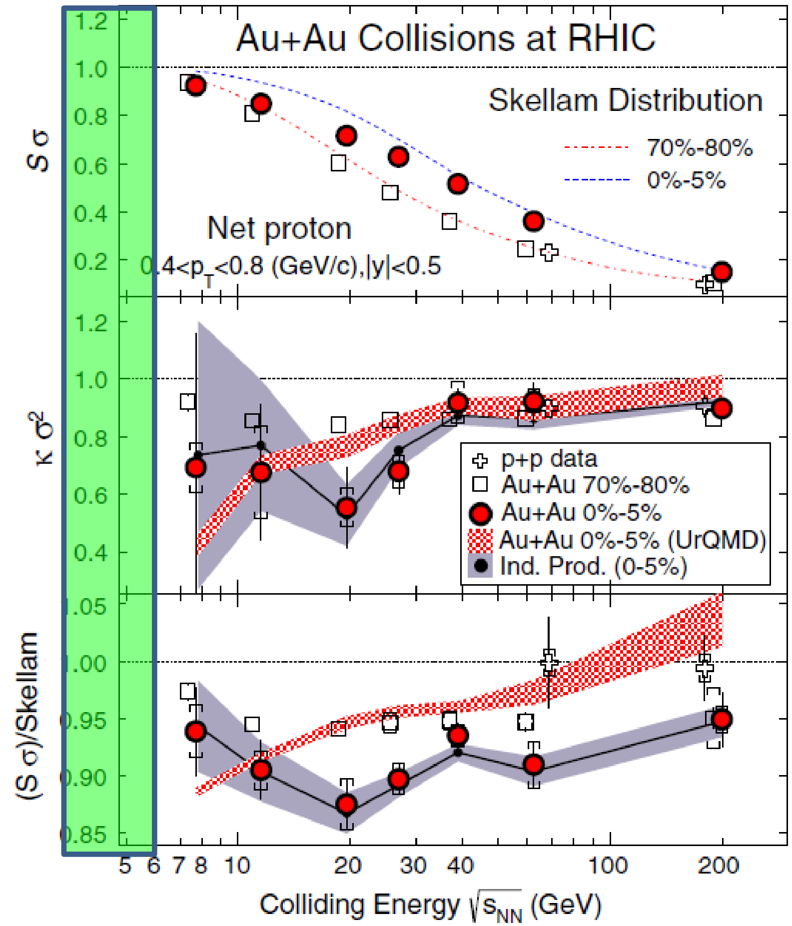
$\kappa\sigma^2 \cong \frac{\chi_B^4}{\chi_B^2}$

- Net-charge
- Net-proton
- Strangeness

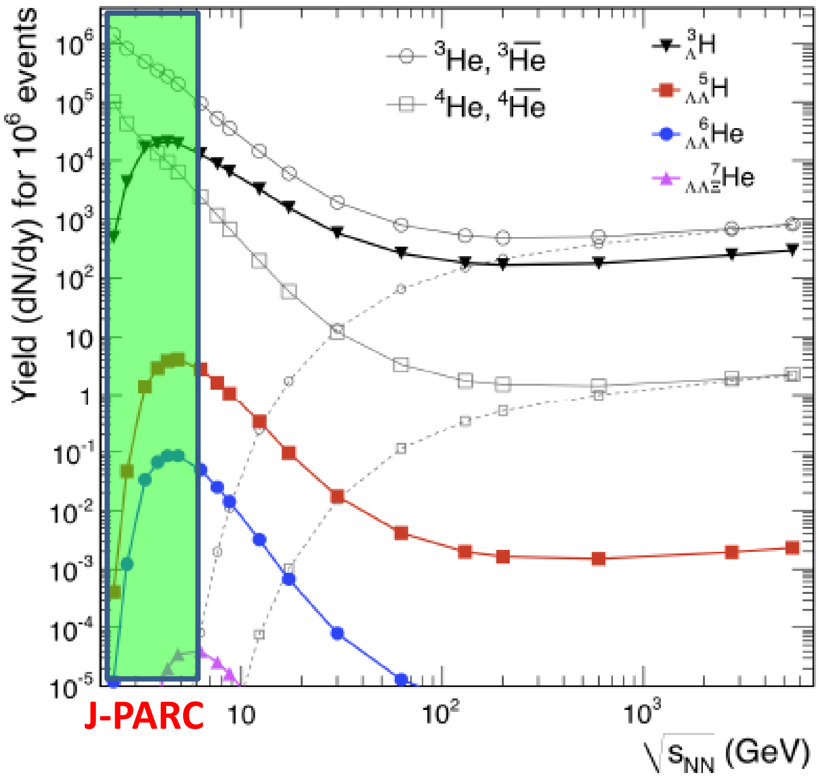
High statistics in J-PARC

Wide y-p_T acceptance required

STAR PRL112 (2014) 032302



Hypernuclei



A. Andronic, PLB697 (2011) 203

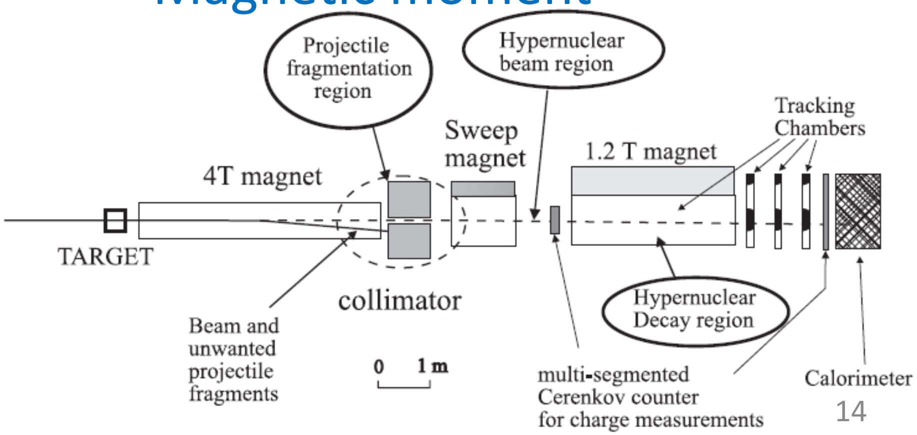
KEK Report 2000-11
Expression of Interest for Nuclear/Hadron Physics Experiments at the 50-GeV Proton Synchrotron

Maximum yield at J-PARC

- Coalescence of high-density baryons

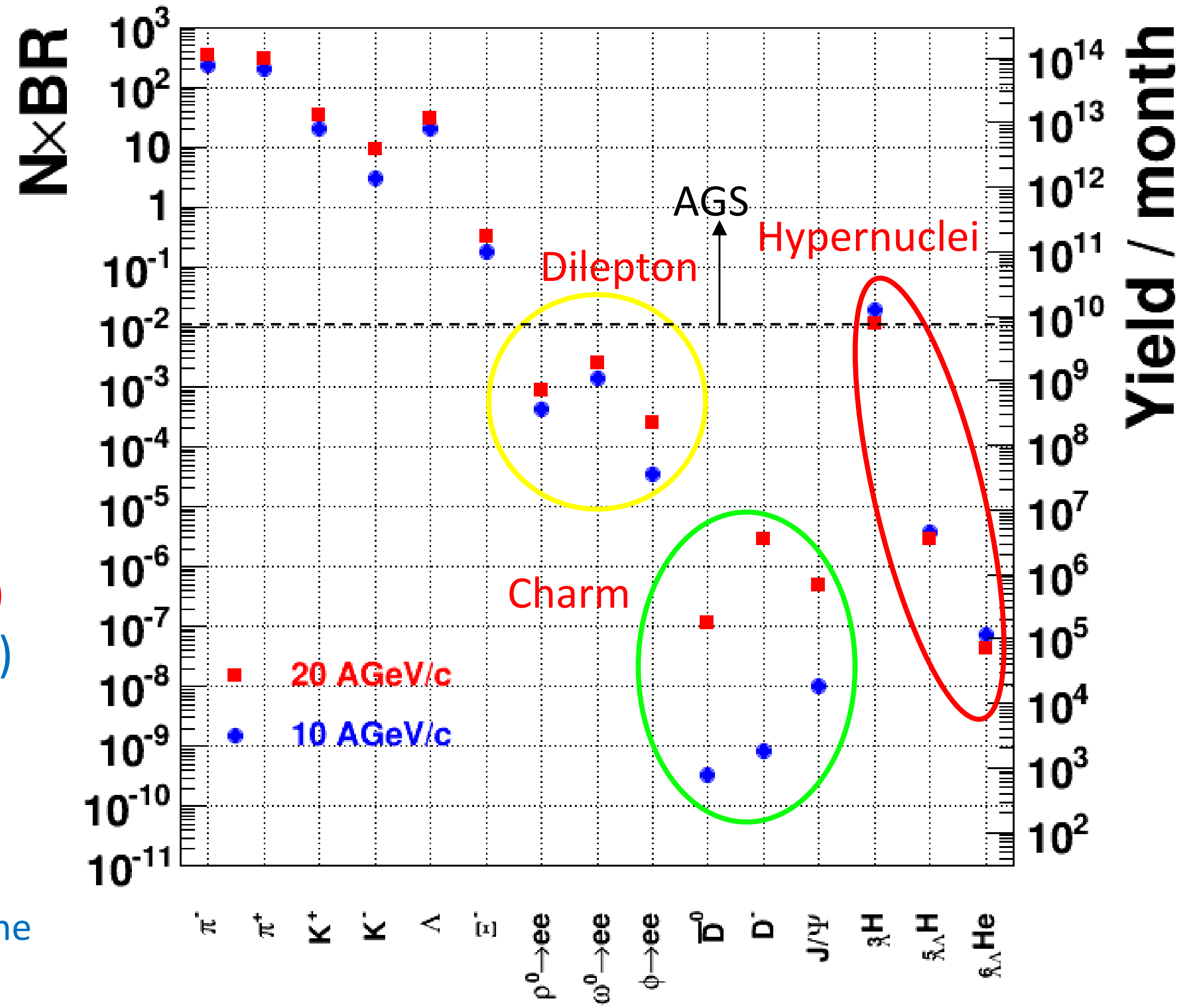
S=-3 Hypernuclei

- Precise secondary vertex reconstruction (mid rapidity)
- Closed geometry setup
  - Full intensity beam
  - Magnetic moment



Particle production rates

Beam : 10^{10} Hz
0.1% target
→ Interaction rate 10^{7} Hz
Centrality trigger 1%
→ DAQ rate = 100kHz



In 1 month experiment:
$\rho,\omega,\phi \rightarrow ee$ 10^{7}-10^{9}
D,J/Ψ 10^{5}-10^{6} (20AGeV)
(10^{3} -10^{4}(10AGeV))
Hypernuclei 10^{5} -10^{10}

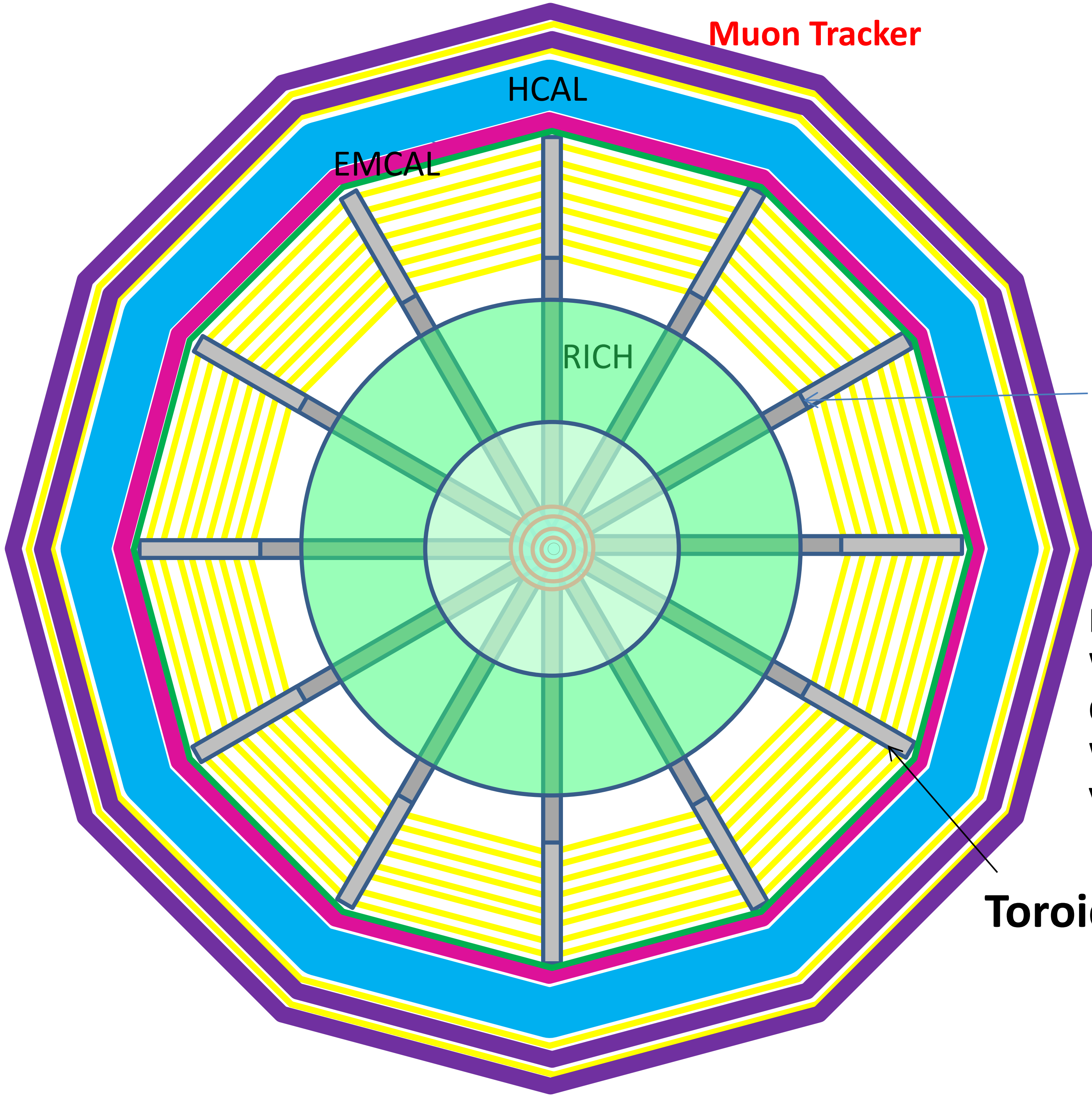
Ref: HSD calculations in FAIR Baseline Technical Report (Mar 2006)
A. Andronic, PLB697 (2011) 203

Experimental challenges

- High rate capability
  - Fast detectors
    - Silicon trackers, GEM trackers, …
  - Extremely fast DAQ → triggerless DAQ
    - >= 100kHz
- High granularity
  - Pixel size < $3x3mm^2$

  (at 1m from the target, θ<2deg, 10% occupancy)
- Large acceptance (~4π)
  - Coverage for low beam energies (CBM<30^o , beam energy>=8AGeV/c)
  - Maximum multiplicity for e-b-e fluctuations
  - Backward physics (target fragment region)
- Electron measurement
  - Field free region for RICH close to the target

➡ Toroidal magnet setup



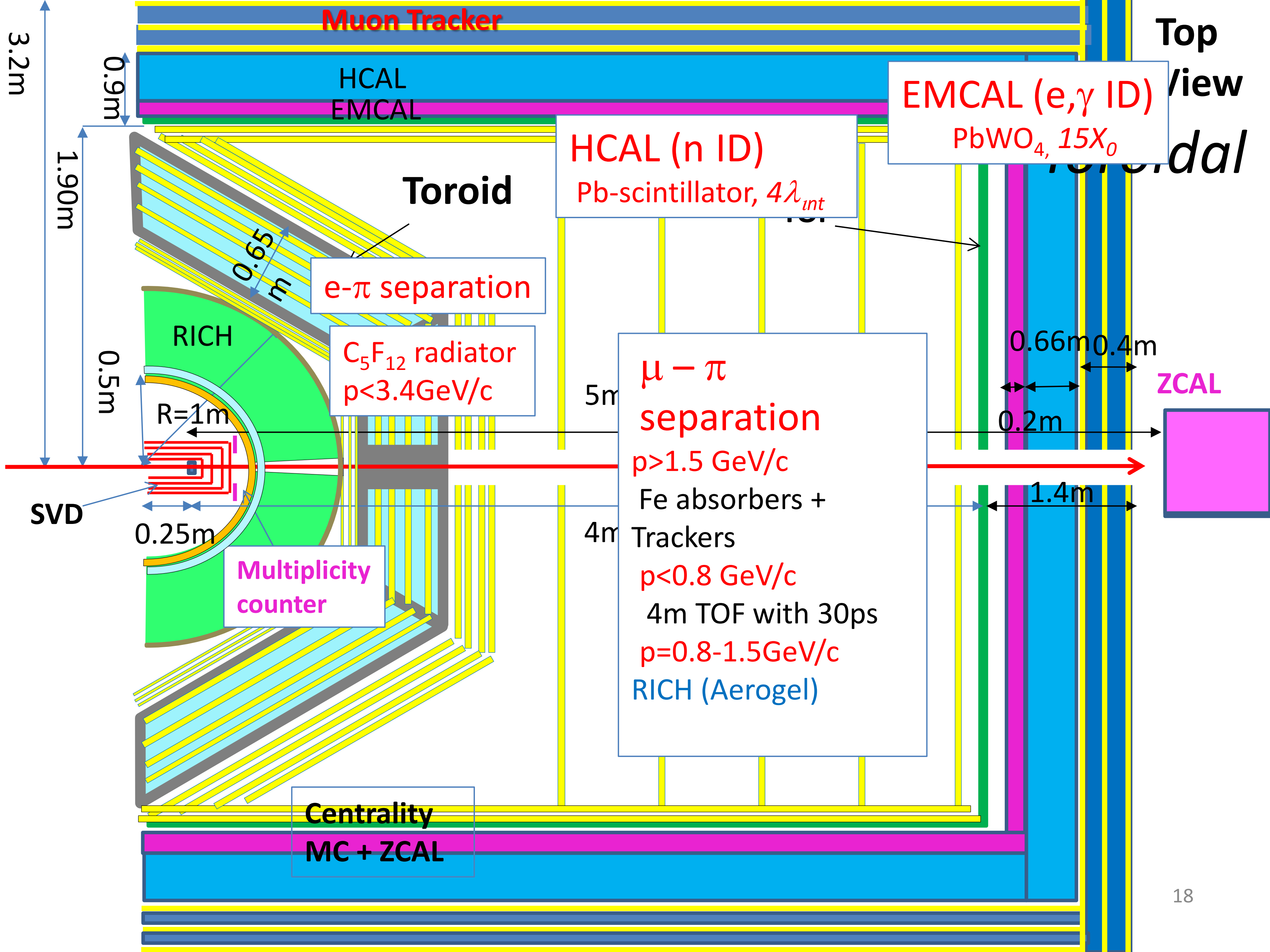
Beam View

Toroidal

Coils = insensitive area

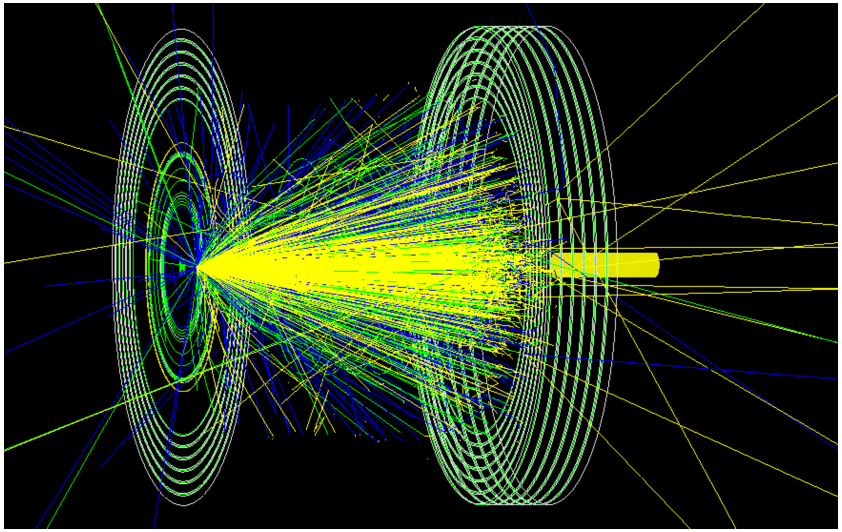
Better Bϕ uniformity
With larger number
Of coils
With 12 coils
Variations ~+-20%

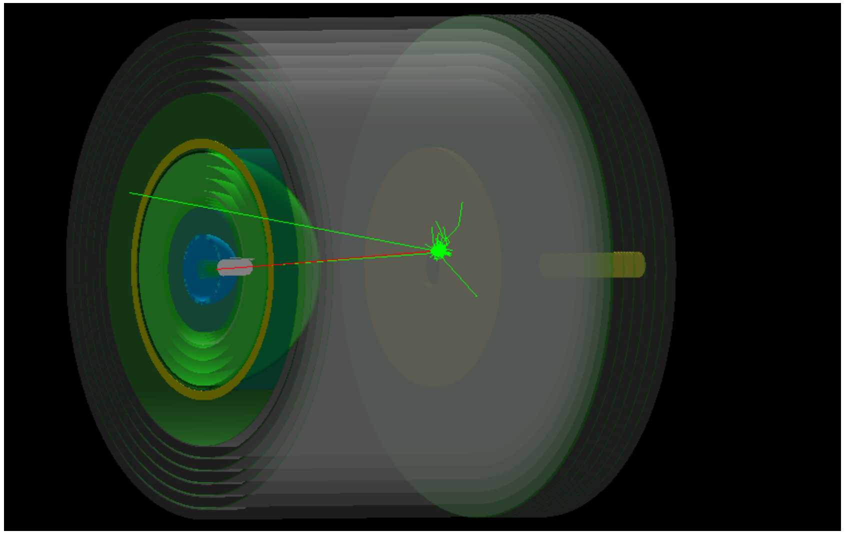
Toroid coils



Muon Tracker
HCAL
EMCAL
Top View
Toroidal
EMCAL (e,γ ID)
PbWO4, 15X0
HCAL (n ID)
Pb-scintillator, 4λint
Toroid
e-π separation
RICH
C5F12 radiator
p<3.4GeV/c
μ − π separation
p>1.5 GeV/c
Fe absorbers + Trackers
p<0.8 GeV/c
4m TOF with 30ps
p=0.8-1.5GeV/c
RICH (Aerogel)
Multiplicity counter
Centrality
MC + ZCAL
ZCAL
SVD
3.2m
0.9m
1.90m
0.5m
0.65 m
R=1m
0.25m
5m
4m
0.66m
0.4m
0.2m
1.4m

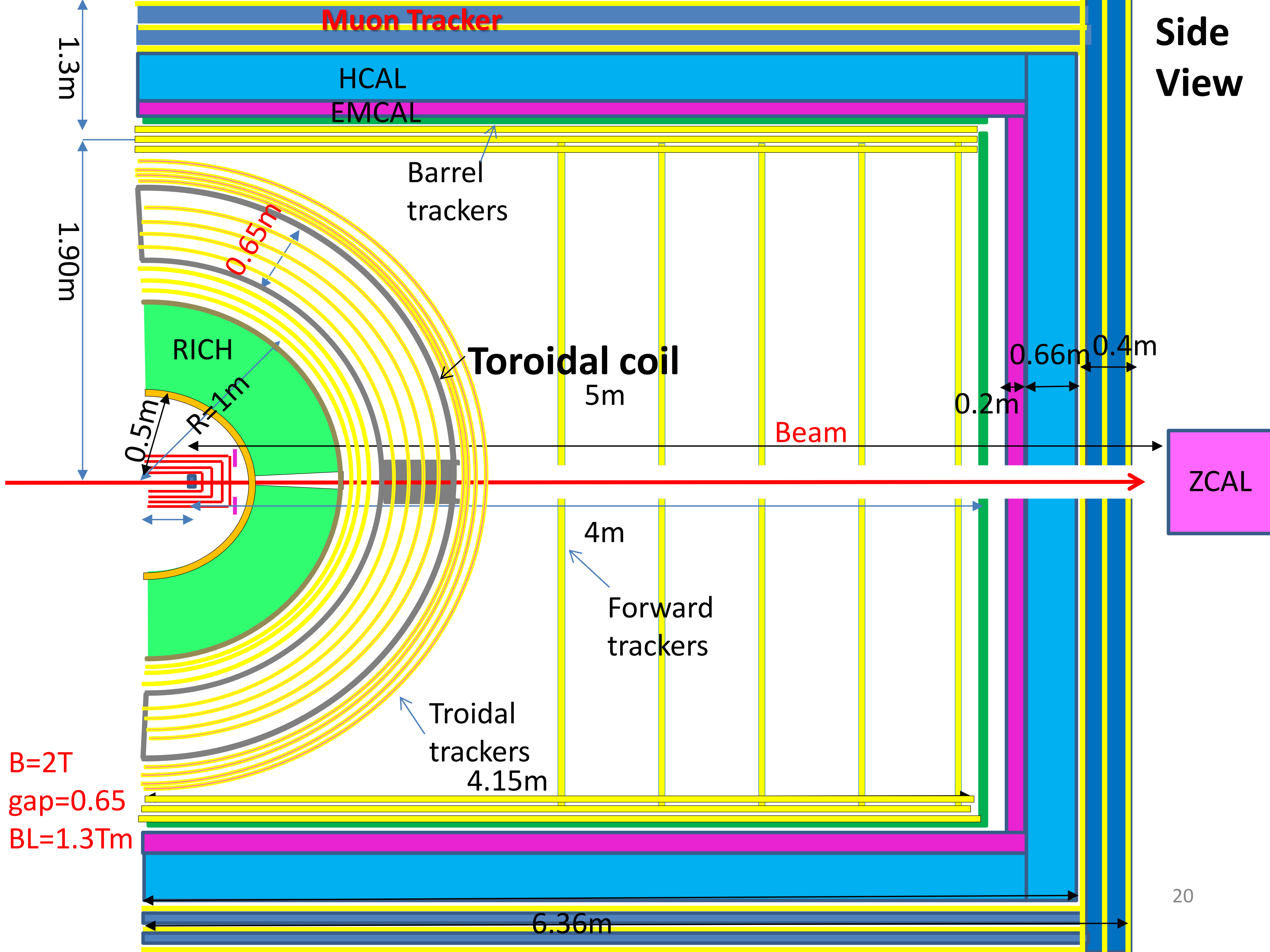
GEANT4 (Toroidal) setup



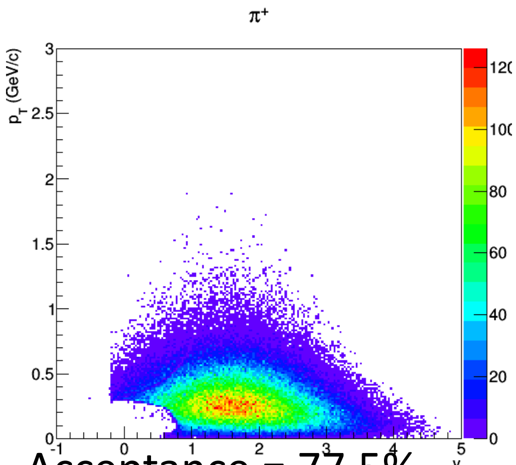


H. Sako, B.C. Kim

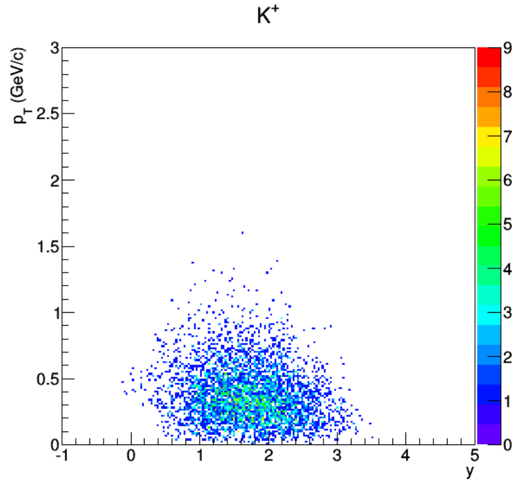
- U+U at 10AGeV/c with JAM
- For simplicity
  – Half-spherical toroidal shape
  – Uniform B_ϕ field
  – No dead area due to coils


Muon Tracker
Side View
1.3m
HCAL
EMCAL
Barrel trackers
1.90m
0.65m
RICH
Toroidal coil
R=1m
0.5m
5m
0.66m
0.4m
0.2m
Beam
ZCAL
4m
Forward trackers
Troidal trackers
4.15m
B=2T
gap=0.65
BL=1.3Tm
6.36m

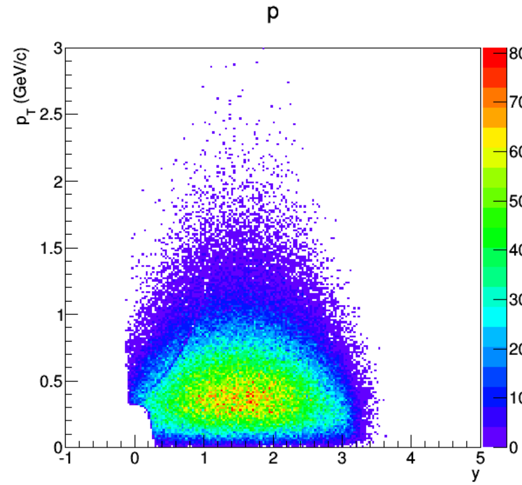
Acceptance



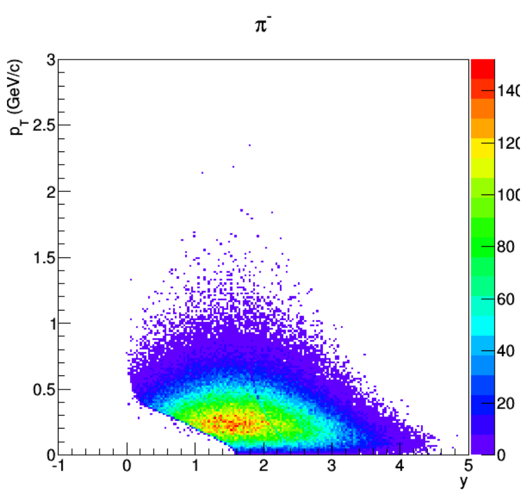
Acceptance = 77.5%



Acceptance = 64.2%



Acceptance = 95.0%

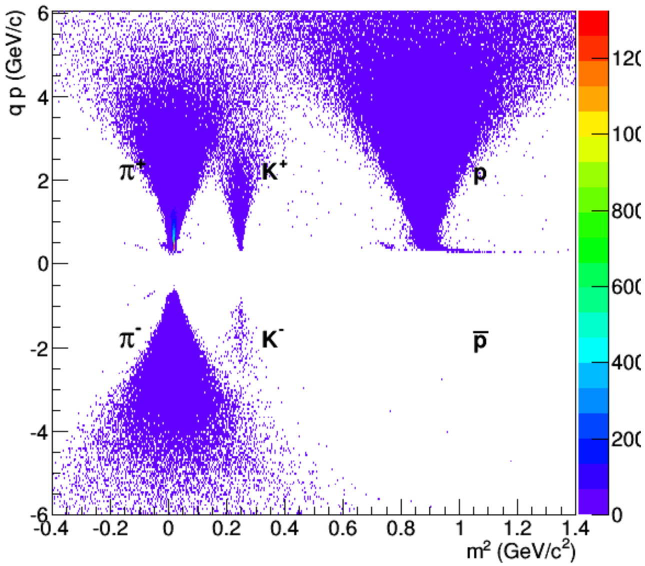


Acceptance = 70.9%

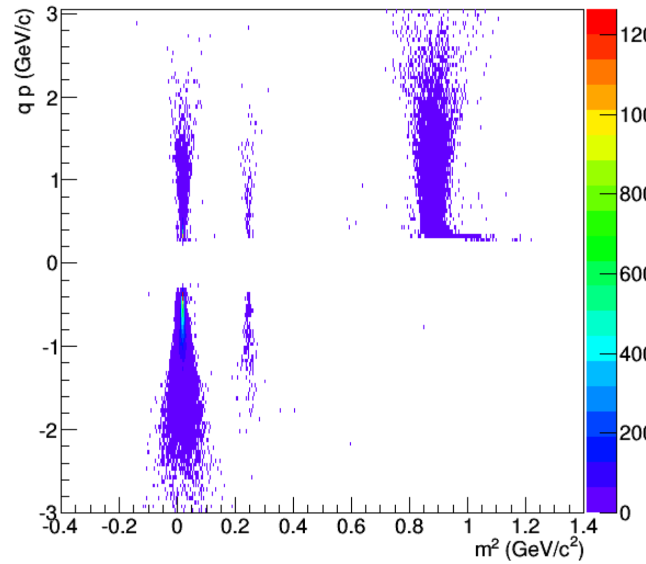
- TOF hits required

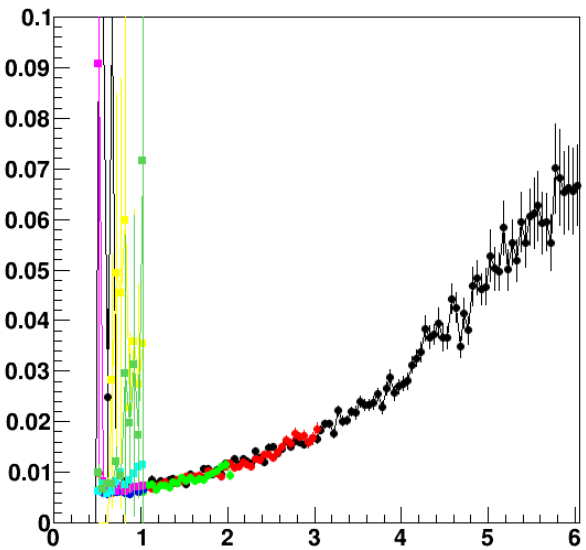
PID and momentum resolution

Forward



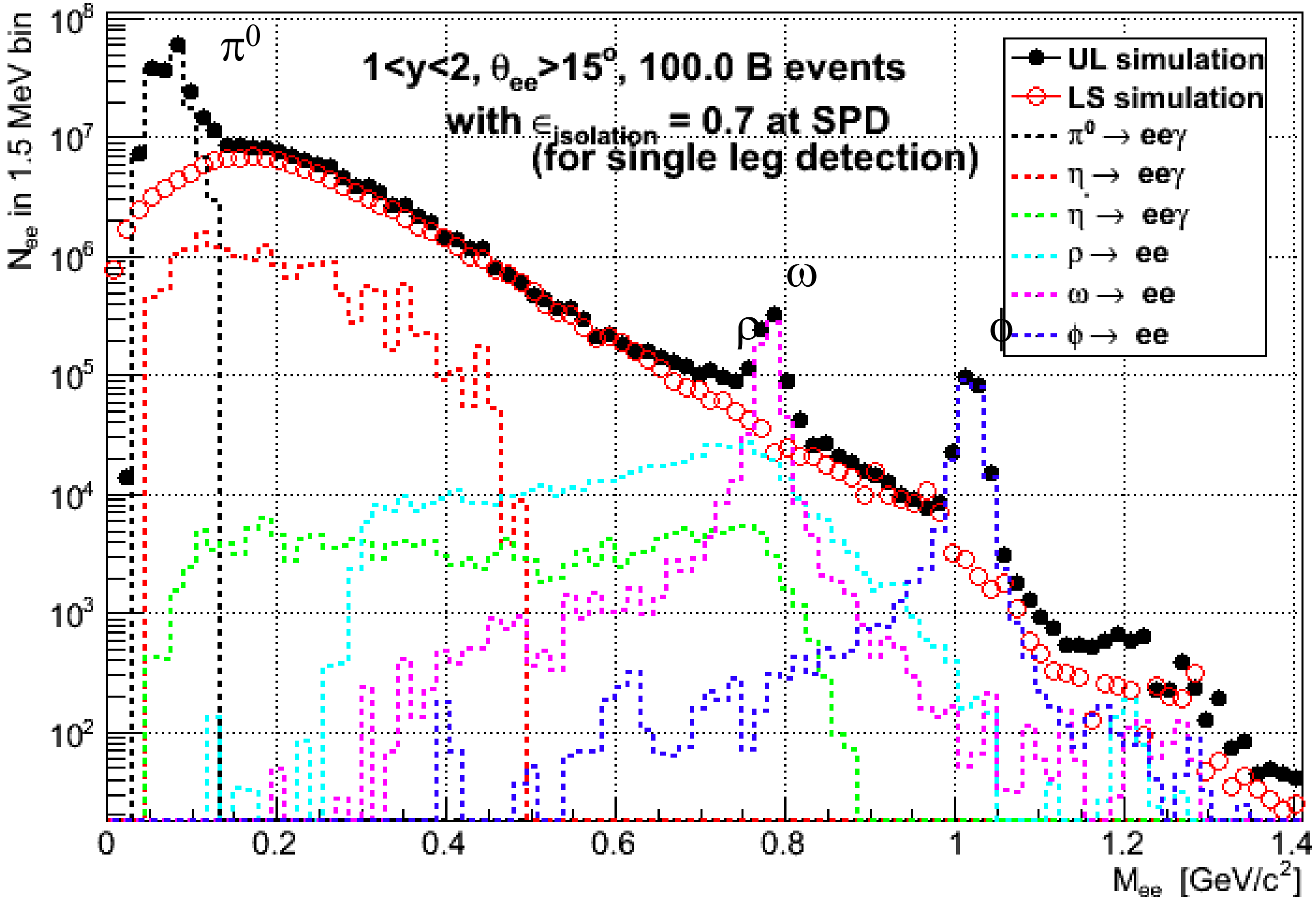
Barrel





- TOF resolution 50ps
- π/K separation 2.5GeV/c (2.5σ)
- Δp/p = 0.7% - 5% (0.5-5GeV/c)

Simulated di-electron spectrum (preliminary)



Calculations by T. Gunji and T. Sakaguchi

Based on π^0 spectra of JAM

Other hadrons m_T-scaled

b<1fm (0.25% centrality)

Momentum resolution 2%

Electron efficiency 50%

(No detector response)

10^{11} events

⇔100k events/s

x 1 month running

$\varepsilon_{isolation}$ = rejection efficiency of close opening angle Dalitz pair

Solenoid+Dipole setup

Summary

- A heavy-ion program at J-PARC is under design to study dense matter
  - Acceleration schemes with RCS and MR
  - Near-4π HI spectrometer with Toroidal to measure dileptons, hadrons, and photons

Prospects

- Design of accelerators and experiments
  - Detailed design for accelerators
  - Full simulation with RICH for dilepton spectrum
  - Design for the closed setup for hypernuclei
- R&D
  - MRPC-TOF (Tsukuba, JAEA, KEK) in E16 for hadron measurements
  - DAQ (JAEA,NIAS)

→A conceptual design report (white paper) in this year