Prospect of charmonium measurements with CBM experiment @ FAIR

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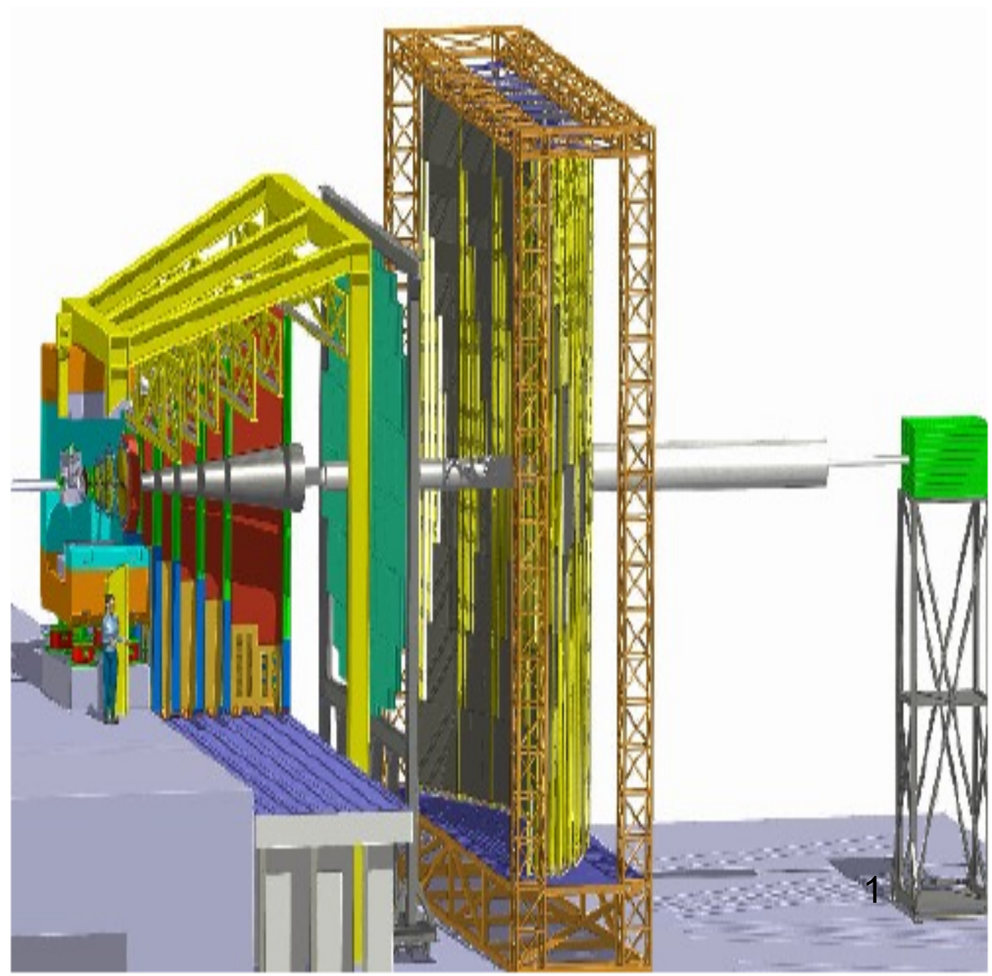
Outline:

- **Introduction**
- **Physics Motivation**
- **J/ψ phenomenology @ FAIR**
- **Reconstruction performance with MUCH**
- **Summary**

3rd Heavy Flavour Meet-2019,
March 18-20, 2019
IIT-Indore, Indore



Introduction

❖J/ψ suppression is classical signature of de-confinement in relativistic nuclear collisions

❖Color screening prevents resonance binding of cc-bar pairs inside the plasma (Matsui & Satz, PLB, 1986)

❖Experiment reveal considerable suppression present in p+A collisions due to presence of cold nuclear matter: *normal suppression/cold nuclear matter (CNM) suppression*

❖Baseline for A+A collisions, to identify the 'possible additional suppression patterns induced by plasma: *anomalous suppression*

❖Regeneration effects come into play at higher (RHIC, LHC) energies

❖The first measurement J/ψ production in heavy-ion collisions, in S+U collisions @ 200 A GeV by NA38 collaboration was compatible with suppression due to cold nuclear matter

❖ "Anomalous" suppression was first observed in Pb+Pb @158 A GeV by NA50 Collaboration at SPS

❖ No coherent theoretical interpretation: data can be explained by a variety of models with or without QGP effects

❖No anomalous suppression observed by the NA60 Collaboration In + In collisions @ 158 A

❖As of today, no data exists for J/ψ production in heavy-ion collisions below 158 A GeV

Lessons from SPS

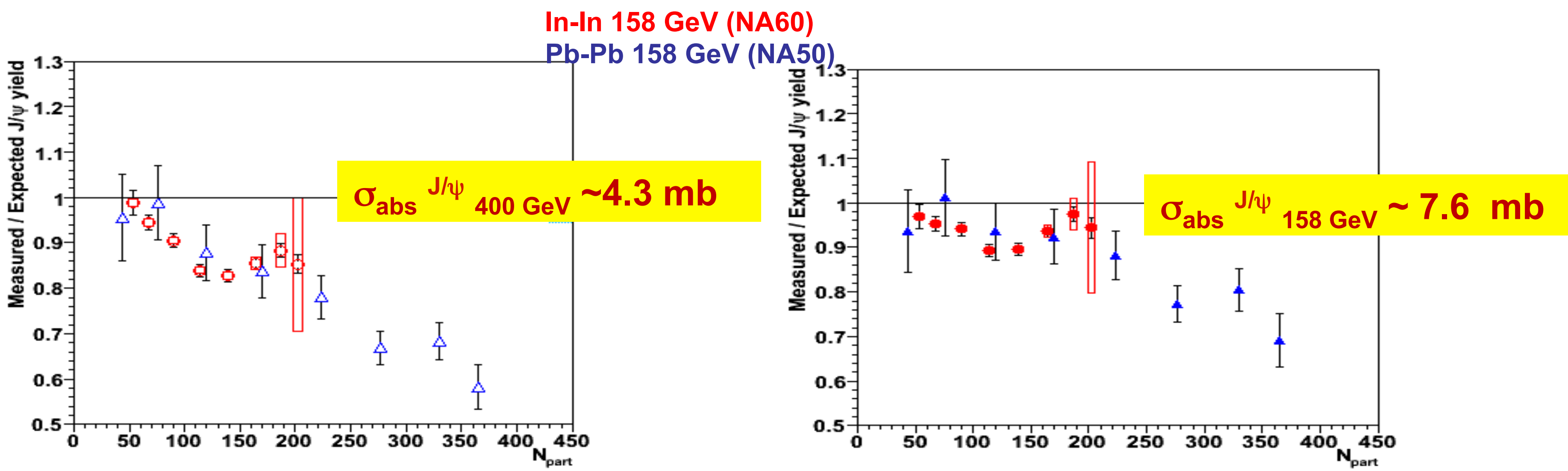
Nuclear dissociations are conventionally described by Glauber model with the "normal" suppression quantified by an effective absorption cross section σ_{abs} : S ~ $e^{-\rho\ \sigma abs\langle L\rangle}$

"Anomalous" J/ψ suppression was first observed in Pb+Pb collisions by NA50 Collaboration and later in In+In collisions by NA60 Collaboration @158 A GeV at SPS

First reference measurements for estimating the nuclear effects were taken from p+A collisions by NA50 @ 400 GeV ($\sigma_{abs}{}^{J/\psi}$ (400 GeV) ~ 4.3 mb)

Subsequent p+A measurements @ 158 GeV by NA60 revealed $\sigma_{abs}{}^{J/\psi}$ (158 GeV) ~ 7.6 mb

Smaller anomalous suppression with respect to the previous estimates !!



Comparison of p+A measurements in the same kinematic & energy domain of that of A+A collisions is absolutely necessary

Facility for Antiproton and Ion Research (FAIR)

FAIR Modularized Start Version (MSV) :

SIS-100: protons up to 30 GeV, heavy-ions up to 12 (15) A GeV

FAIR Phase -II

SIS-300: protons up to 90 GeV heavy-ions up to 35 (45) A GeV

Intensities:

protons: up to 10^{13}/s

heavy-ions: up to 10^{9}/s

Nucleus-nucleus collisions: **Compressed Baryonic Matter (CBM)**

Physics cases:

- baryonic matter at highest densities
- phase transitions and critical endpoint
- in-medium properties of hadrons

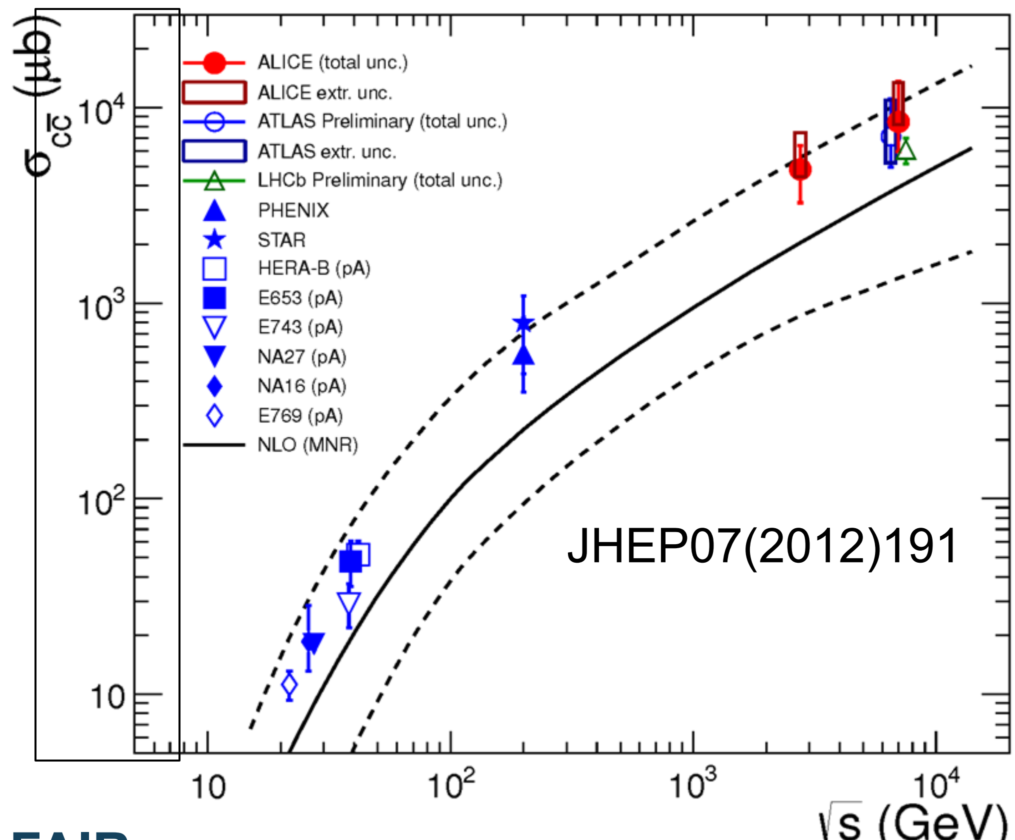
Charm production at FAIR and measuremnets with CBM

Cross sections and phase-space distributions of open and hidden charm in proton-nucleus collisions and nucleus-nucleus collisions.

Physics case

- Charm production at threshold energies
- Charm propagation in (dense) nuclear matter

No charm (hidden/open) data at FAIR energies



FAIR (SIS-100 + SIS-300)

Existing data for J/ψ production data close to threshold energies scenario

Expt.	p_{Lab} (GeV/c)	System	Channel	σ_{in} (nb)
CERN-PS	24	p-p	e^+e^-	0.56 +/-0.16
CERN-PS	24	p-C	e^+e^-	7.2+/-1.8
CERN-PS	24	p-W	e^+e^-	74+/-20
AGS	30	p-Be	e^+e^-	0.1
WA39	39	p-p	$\mu^+\mu^-$	1+/-0.5
IHEP	70	p-Be	$\mu^+\mu^-$	32+/-8

❖ Disperse data sets with proton beams

❖ Only measurement of inclusive cross sections (limited phase space, no differential measurements)

❖No detailed study of target mass dependence, difficult to extract cold nuclear matter effects

❖Absolutely no data on charmonium production in A-A collisions below top SPS energy (E_b = 158 AGeV)

J/ψ measurement at CBM-FAIR: Uniqueness & Challenges

Uniqueness:
•No data in heavy-ion sector below top SPS energies, exploratory measurements around threshold energies
•Multi-differential and high precision measurements

Opportunities @ SIS-100:
•Detailed measurement of charm production and propagation in cold matter with beams of proton and light nuclei (C, Ni, …)
•Test of pQCD inspired models at low energies
•Possibility to investigate sub-threshold production of charm with heavy-ion (Au) beams

Opportunities @ SIS-300:
•Production will be dominated by initial hard collisions, subsequent recombination effects is negligible
•Exact traces of the suppression pattern unlike higher energies
•Characterization of the dense baryonic medium

Challenges:
•Production cross sections are dramatically small
•Requires accelerators with unprecedentedly high beam intensities; with beam intensity for Au ions of 10^9/sec and 1 % λ_I peak event rate 10 MHz
• Detectors with high rate capabilities
• On-line event selection to reduce the raw data rate down to recordable

Highlights: charmonium physics @ FAIR SIS-100

For open charm @ FAIR see talk by M. Deveaux

J/ψ in p+A collisions up to beam energy 30 GeV:

Test of factorization and pQCD production
Hadronization models of resonance formation
Novel CNM efffcts: J/Psi-N interaction, in-medium mass shift

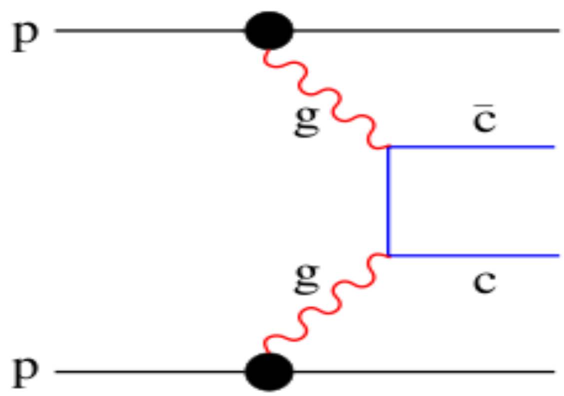
J/ψ in Ni+Ni collisions in 15 A GeV:

Dissociation in a hot hadronic medium,
Azimuthal anisotropy and (non)flow

J/ψ in 10 A GeV Au+Au collisions:

Pioneering measurement of sub-threshold production
Fermi motion vs. multiple collisions

J/ψ production in elementary collision: test of pQCD



At high energies, cc-bar production in elementary collisions described by pQCD

pQCD assumes factorization of the initial state (colliding hadrons)

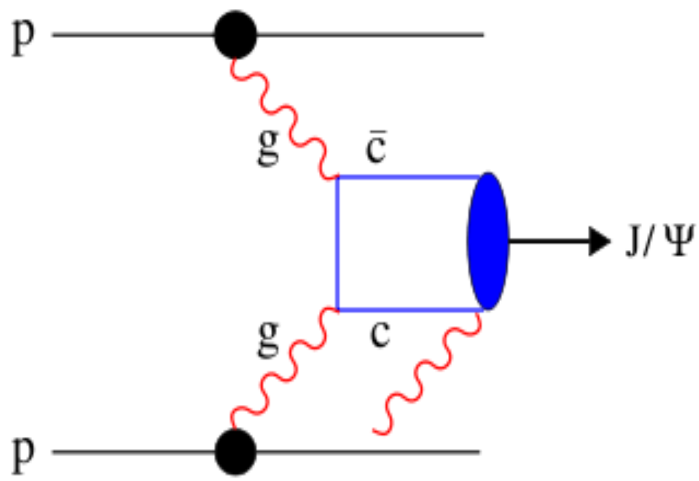
Break down of factorization at low energies

Alternative mechanisms based on scaling hypothesis proposed at near threshold energies (see for eg: P.P. Bhaduri and S. Gupta, PRC 88 (2013), 045205)

FAIIR SIS-100 is the facility to test perturbative production of charm

Measure J/ψ production in p+p (p+Be/C) collisions

J/ψ production in elementary collisions: test of color neutralization



Formation of resonance from evolving cc-bar pairs is a debated issue

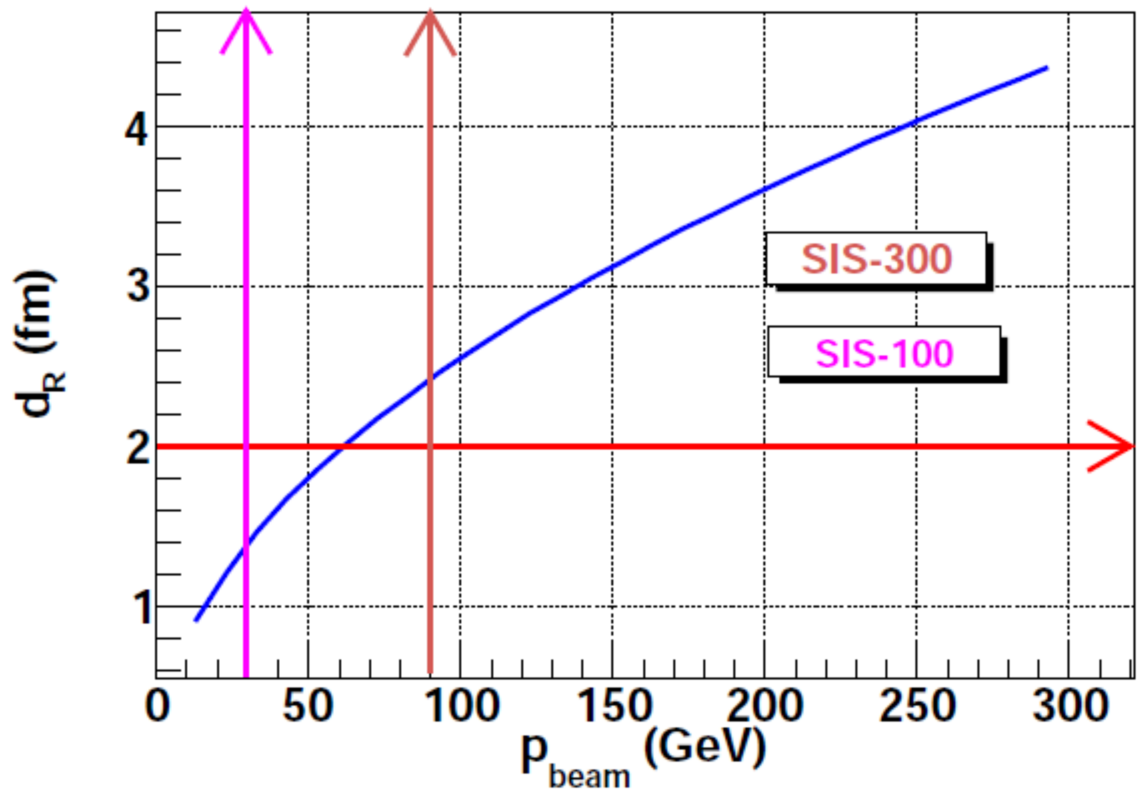
Many models in literature: Color Singlet model, NRQCD, Color Evaporation model

CEM: Total number of cc-bar pairs are conserved and distributed into different open charm and different charmonium states (~ 96 % open charm, ~1.2 % J/ψ, ~0.3 % ψ')

Fractions might be different at FAIR energies due to reduction in phase space

Requirement: To perform studies for different colliding systems (p+p/A)

J/ψ production in p+A collisions: resonance-nucleon interaction



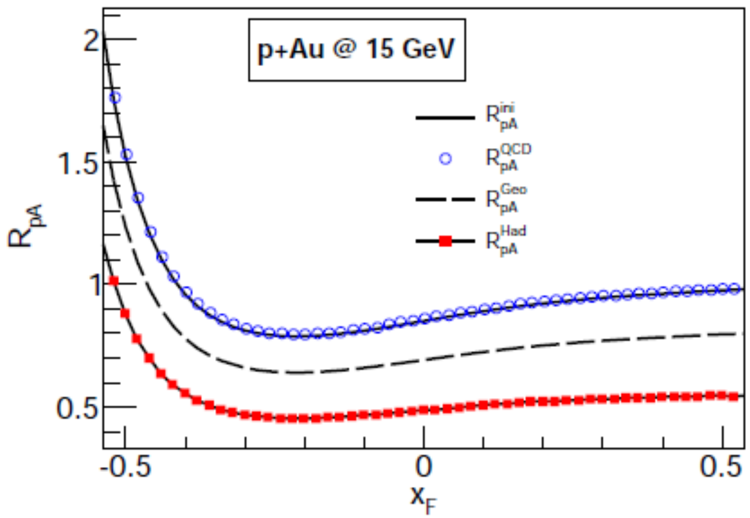
At FAIR, slow J/Psi mesons are produced, fully developed resonance state propagate through the nuclear matter

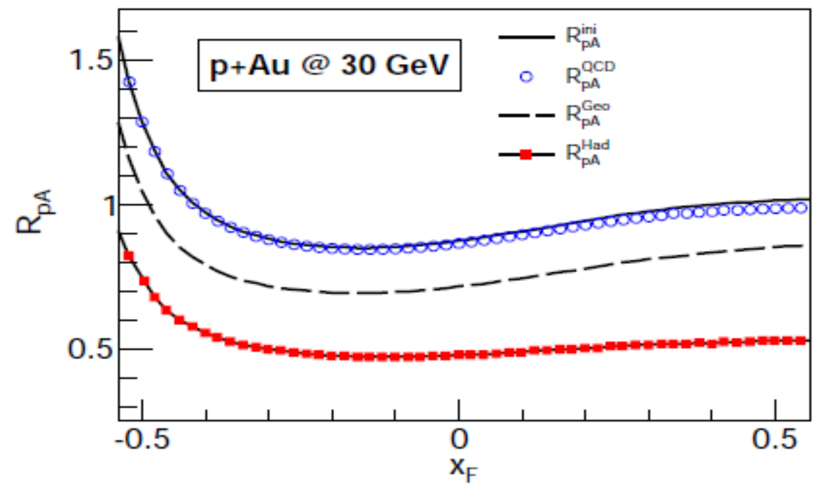
Golden opportunity to measure J/ψ-N interactions

Available world data not useful, measures cc-bar-N interaction

J/ψ transparency ratio for different dissociation scenarios

PPB, M. Deveaux, A. Toia, JPG 45 (2018) 055103





Charmonium-nucleon inelastic cross section is till an unsettled issue

Various different theoretical models, no experimental input so far

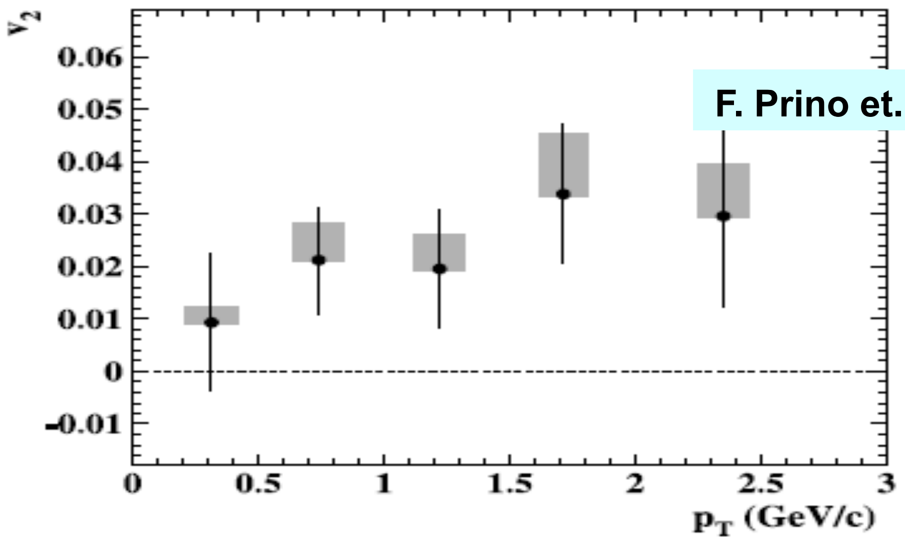
SIS-100 p+A collisions are most appropriate to address the issue

Measurements can be performed in the beam energy range 15 – 30 GeV

Slowest resonances @15 GeV, enhanced yield @ 30 GeV

An energy scan may help to reveal the beam energy dependence of dissociation

Can we detect J/ψ flow?



F. Prino et. al. , Eur. Phsy. J. C (2009), 61: 853

At SPS, J/ψ is not expected to thermalize with the medium, v_2 =0

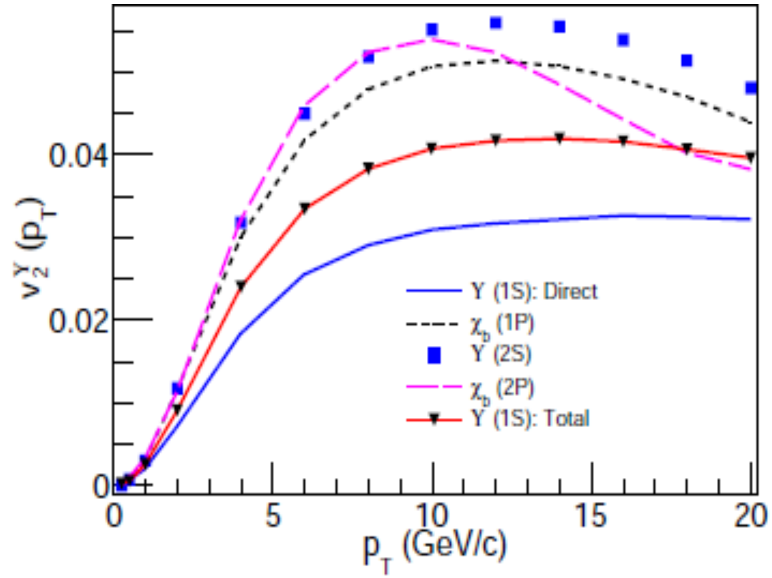
Data show non-zero v_2, in non-central Pb+Pb collisions at 158 A GeV

Path length dependent absorption: an-isotropic suppression of J/ψ in non-central collisions

Can we have similar effect at SIS100; non-central Ni+Ni collisions @ 15 A GeV?

Additional handle to constraint the hadronic dissociation; first measurement of non-flow

A complementary case study: Bottomonia flow @ LHC



See talk by A. Jaiswal

PPB, N. Norghini, A. Jaiswal, M. Strickland; arXiv:1809.06235

Bottomonia @ LHC are equivalent to charmonia @ FAIR:

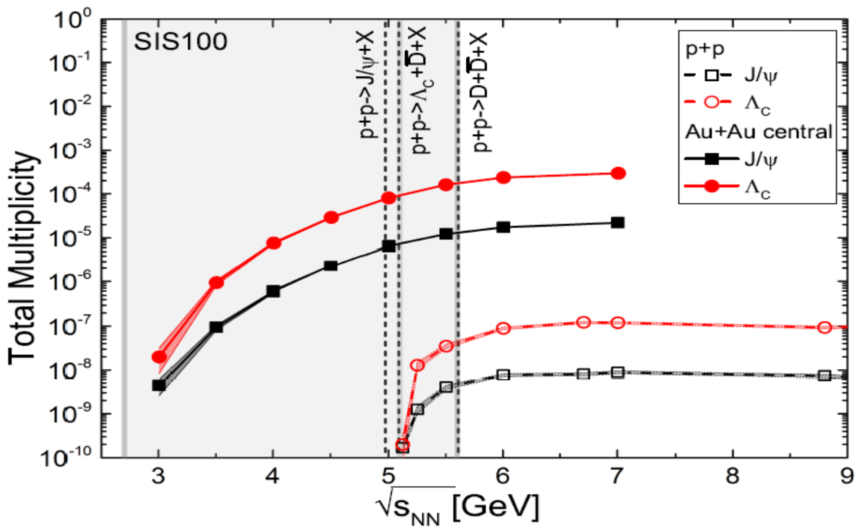
Production from initial hard scattering
No regeneration, negligible thermal production
No thermalization with the medium

However anisotropic fireball shape in non-central collisions may lead to:

Path length dependent absorption pattern
Anisotropic azimuth spectra
p_T dependent non zero v_2 ($\langle\cos(2\phi)\rangle$)

J/ψ production in the sub-threshold domain

J. Steinheimer, Phys. Rev. C 95, 014911 (2017)



Kinematic threshold for J/Psi production: E_b^{th} = 12. 5 GeV (p+p -> p +p +J/ψ)

J/ψ production in 10 A GeV Au+Au collisions via sequential multiple collisions and subsequent decay of heavy baryonic resonances (N* → N + J/ψ);

Negligible contribution due to Fermi motion

Increased production cross section; feasible detection

Summary (I) : Charmonium at FAIR SIS-100

❖J/ψ suppression has long been considered as a potential signature for QGP formation in nuclear collisions.

❖At FAIR energies the exact traces of the suppression pattern can be seen

❖However a very careful study is necessary to understand the cold nuclear effects can be realized at SIS100 p+A collisions

❖ Real size J/ψ mesons in SIS100 p+p/p+A collisions would help to study:

•*validity of pQCD production processes and hadronization models near threshold*
•*inelastic meson-nucleon interaction*
•*possible in-medium mass modifications*

❖In A+A collisions at SIS-100

•*First measurements of sub-threshold production in 10 GeV Au+Au collisions*
•*Hot medium effects in 15 GeV Ni+Ni colliisons*
•*Possibility of detecting azimuhtal anisotropy in non-central Ni+Ni collisions*

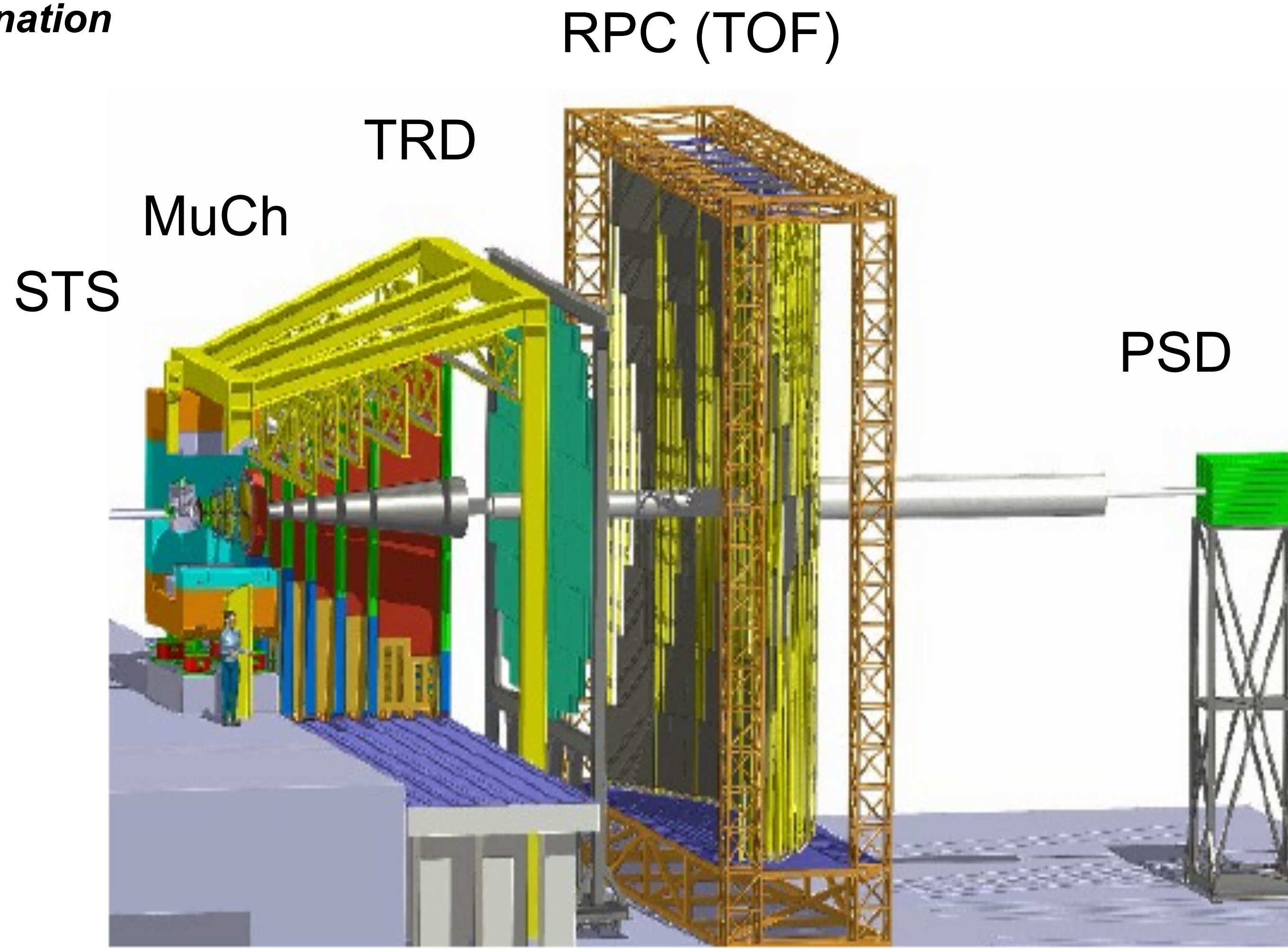
❖Hidden-to-open charm ratio might be useful to get rid of initial state effects

J/ψ detection via di-muon channel at CBM

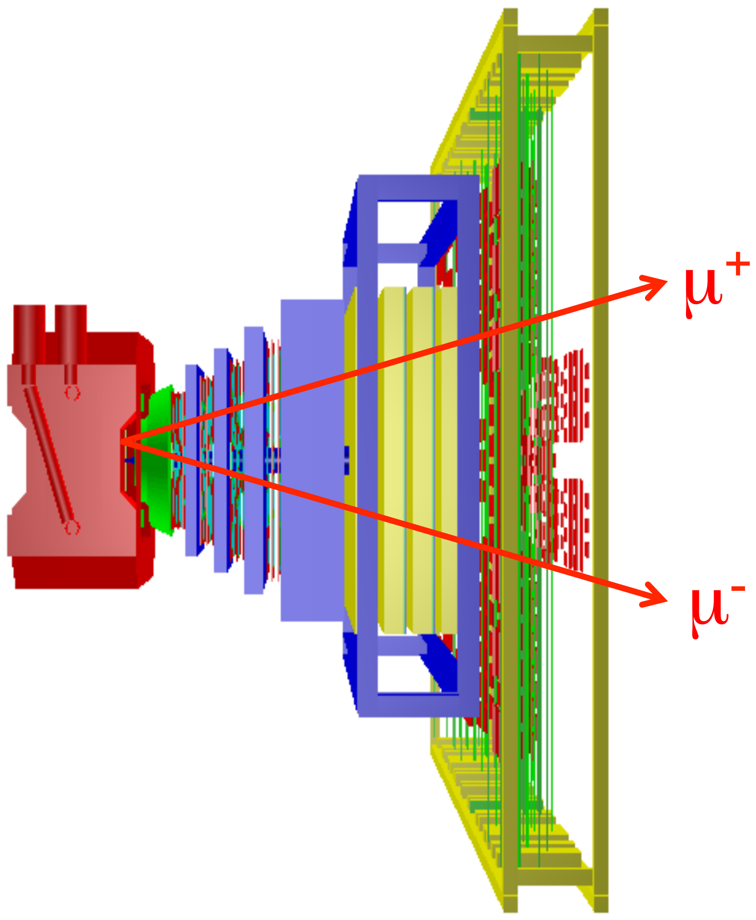
Simulation of MUon CHamber (MUCH) detector system

CBM setup with MUon CHamber (MUCH) subsystem

STS ***track, vertex and momentum reconstruction***
MUCH ***muon identification***
TRD ***global tracking***
RPC-ToF ***time-of-flight measurement***
PSD centrality determination



MUCH @ FAIR SIS100: J/ψ → μ+μ- reconstruction



Comprises of several detectors & segmented hadron absorbers made of graphite & iron

Total absorber is segmented & detectors are placed inside absorbers to facilitate tracking

Detectors are high resolution gas chambers with 3 mm Argon as active medium

Angular acceptance:

θ_{min}=5.7°: η_{max}= 3

θ_{max}=25° degree: η_{min}=1.44

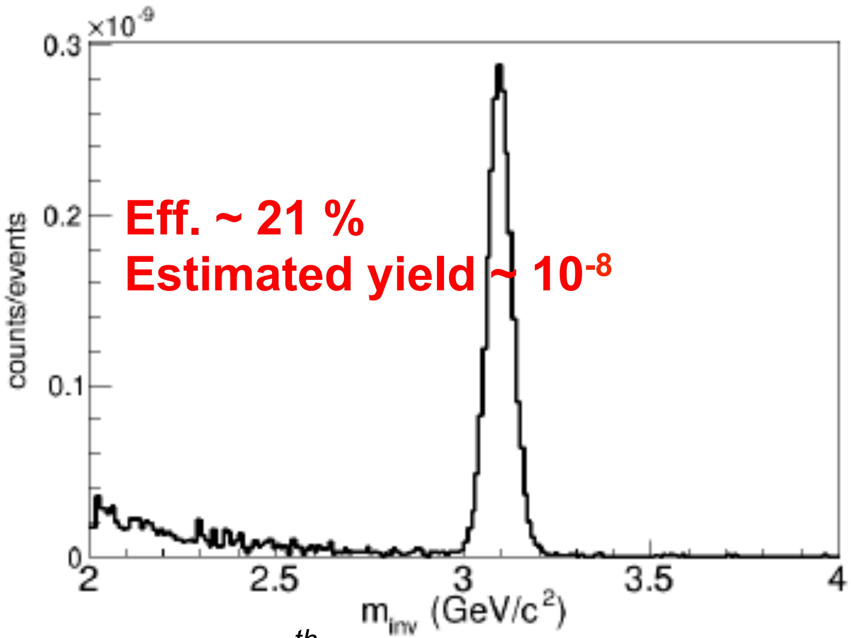
Simulation setup

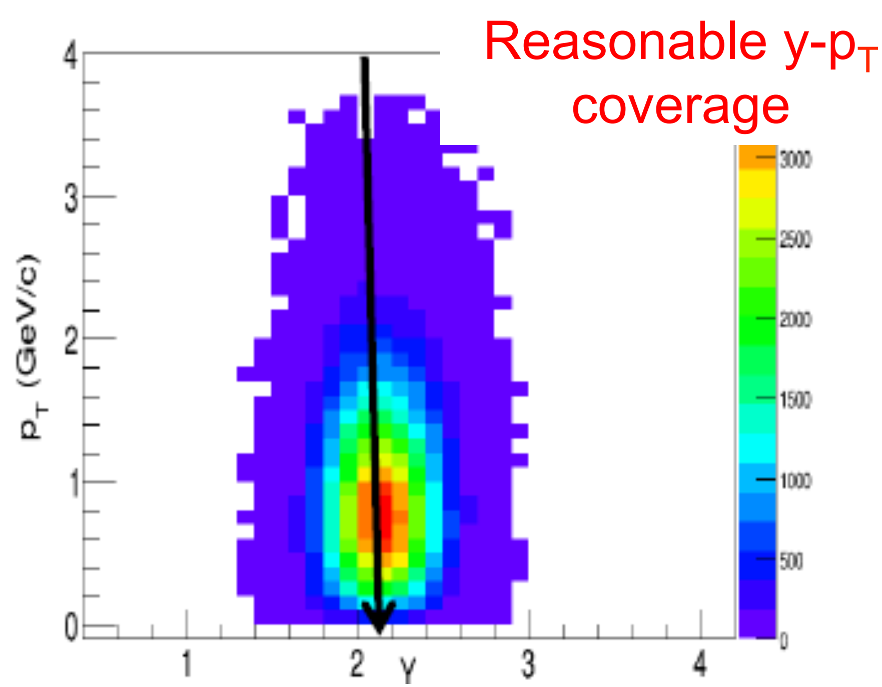
- background – UrQMD generator
- J/ψ:
  - yield from HSD generator/two component model
  - phase space distribution from PLUTO generator

Transport – cbmroot framework with GEANT3

Selection of reconstructed muon like track candidates based on associated hits and track χ^2 in each detector sub system involved

J/ψ reconstruction in 30 GeV p+A collisions

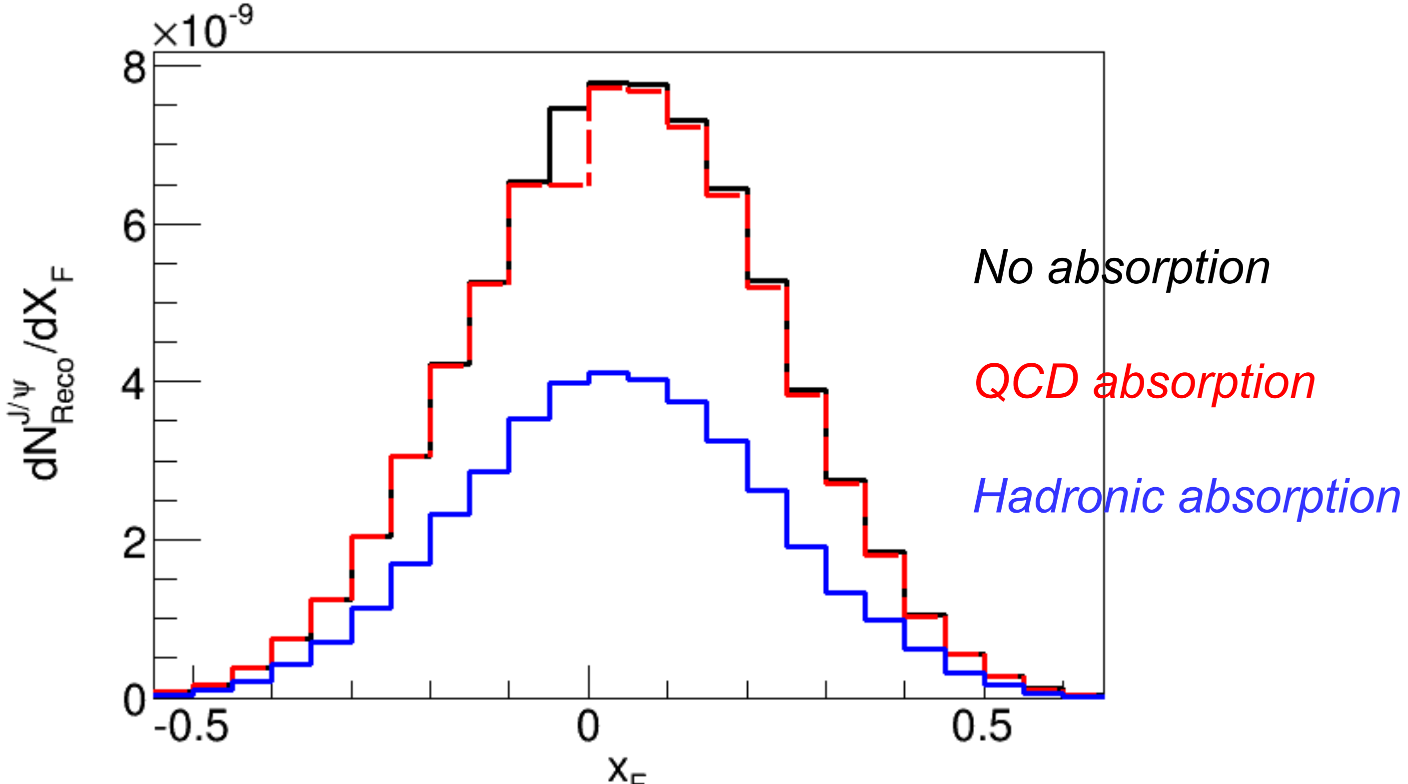




PPB, 28th CBM Collaboration meeting, September 2016, Tubingen, Germany

Reasonable coverage at mid-rapidity
Beam time requirement:
For a peak reaction rate of 10 MHz, 1 J/ψ per minute
1 week of data taking with highest rate would gather sufficient statistics

Differential distribution: Reconstructed J/ψ mesons



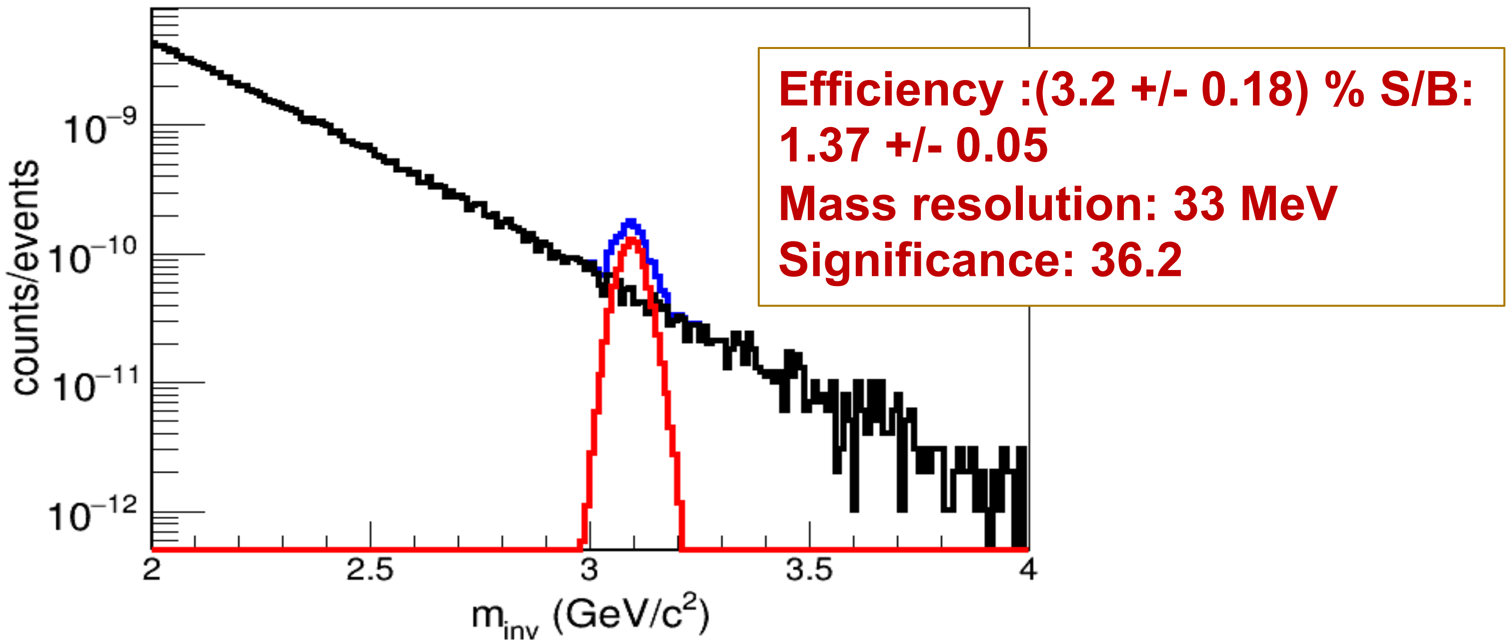
$$\frac{dN_{J/\psi}^{\mathrm{Reco}}}{dx_F} = \frac{dN_{J/\psi}^{in}}{dx_F} \times \varepsilon(x_F)$$

Reconstructed spectra reproduce the input distributions

Experimentally possible to distinguish between different absorptions scenarios in p+A collisions at FAIR SIS-100

One to a few weeks of data taking would provide sufficient statistics to look for the physics

J/ψ reconstruction in 15 A GeV central Ni+Ni collisions



PPB, 27th CBM Collaboration meeting, April , 2016, GSI, Germany

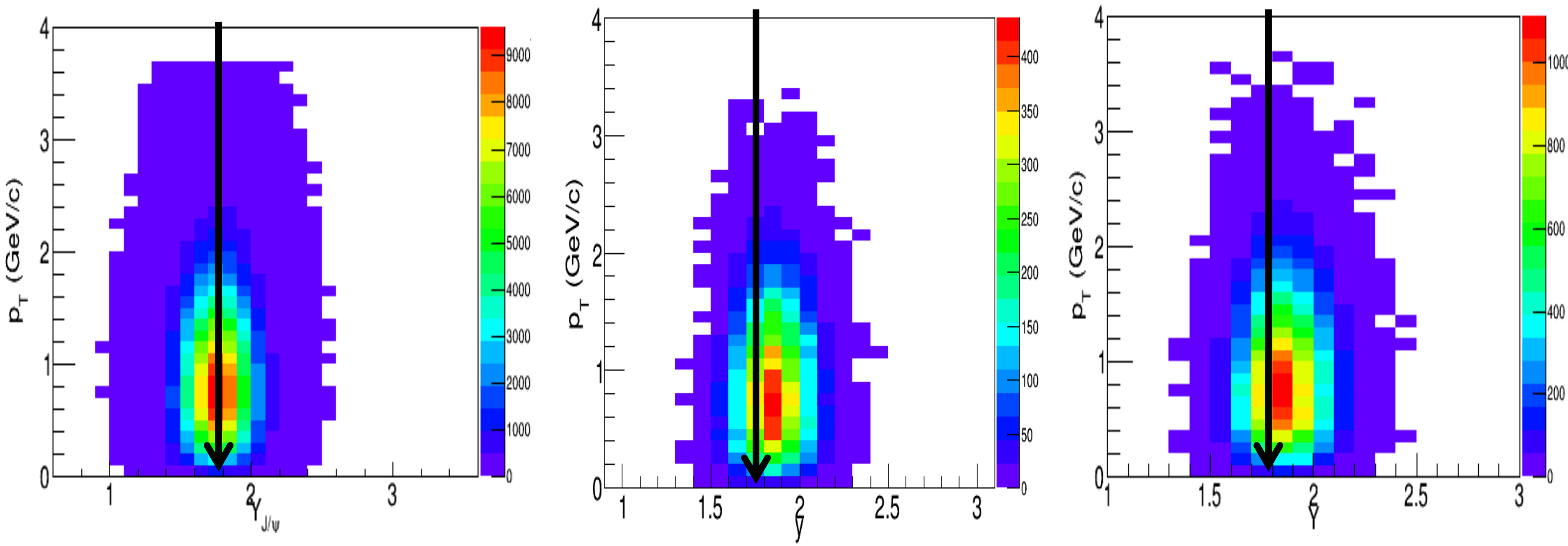
Feasible J/ψ detection in central Ni+Ni collisions

Need to perform the simulations with non-central collisions

Try to insert azimuthal anisotropy at the input level and look the effect the reconstruction

J/ψ Phase space (y, p_T) distributions: 15 A GeV Ni+Ni collisions

Input (Pluto) | Accepted (MC) | Reconstructed



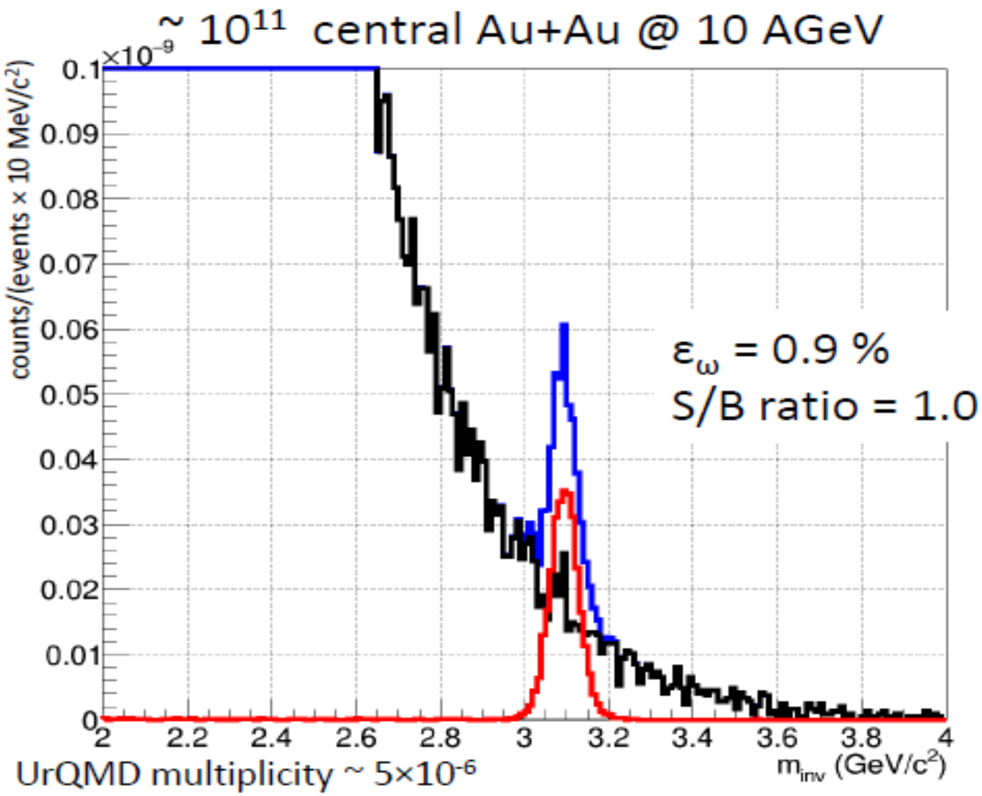
Accepted fraction: 19 %

Reconstructed: 3.2 %

Accepted : A MC track with:
7 STS points + 11 Much Points + 3 TRD points + 1 TOF point

Small shift in rapidity (Δy ~ 0.1) in forward direction due to absorbers

J/ψ reconstruction in 10 A GeV Au+Au collisions



A. Senger, International conference on matter at high baryon densities, Sikkim, India, 2016

Feasible detection, repeat simulations with more realistic detector set up
Simulations at different energies

Summary: Charmonium with CBM

- Performance study of the muon detection system with simulated signal and background yields for 30 GeV p+Au, 15 GeV Ni+Ni and 10 GeV Au+Au collisions in SIS-100 @ FAIR
- With the assumed charmonium yields, the measurements should be feasible with MUCH subsystem of CBM
- Measurement of open charm hadrons would be realized with an additional MVD detector
- The measurements require high interaction rate and fast detectors and electronis
- Online triggers are being designed to reduction of data volume to a recordable rate.
- The signal invariant mass has a Gaussian shape, thanks to low material budget of STS, and provides a better mass resolution compared to previous experiments

Summary and outlook

Charm(onium) physics at FAIR SIS100 offer many unique and unexplored questions to be addressed

Needs phenomenological as well as physics performance simulations

Preliminary simulations shows the feasibility of the muon set-up to facilitate these measurements

Requires realistic estimation of the yield and phase space distribution with foreseen beam intensities

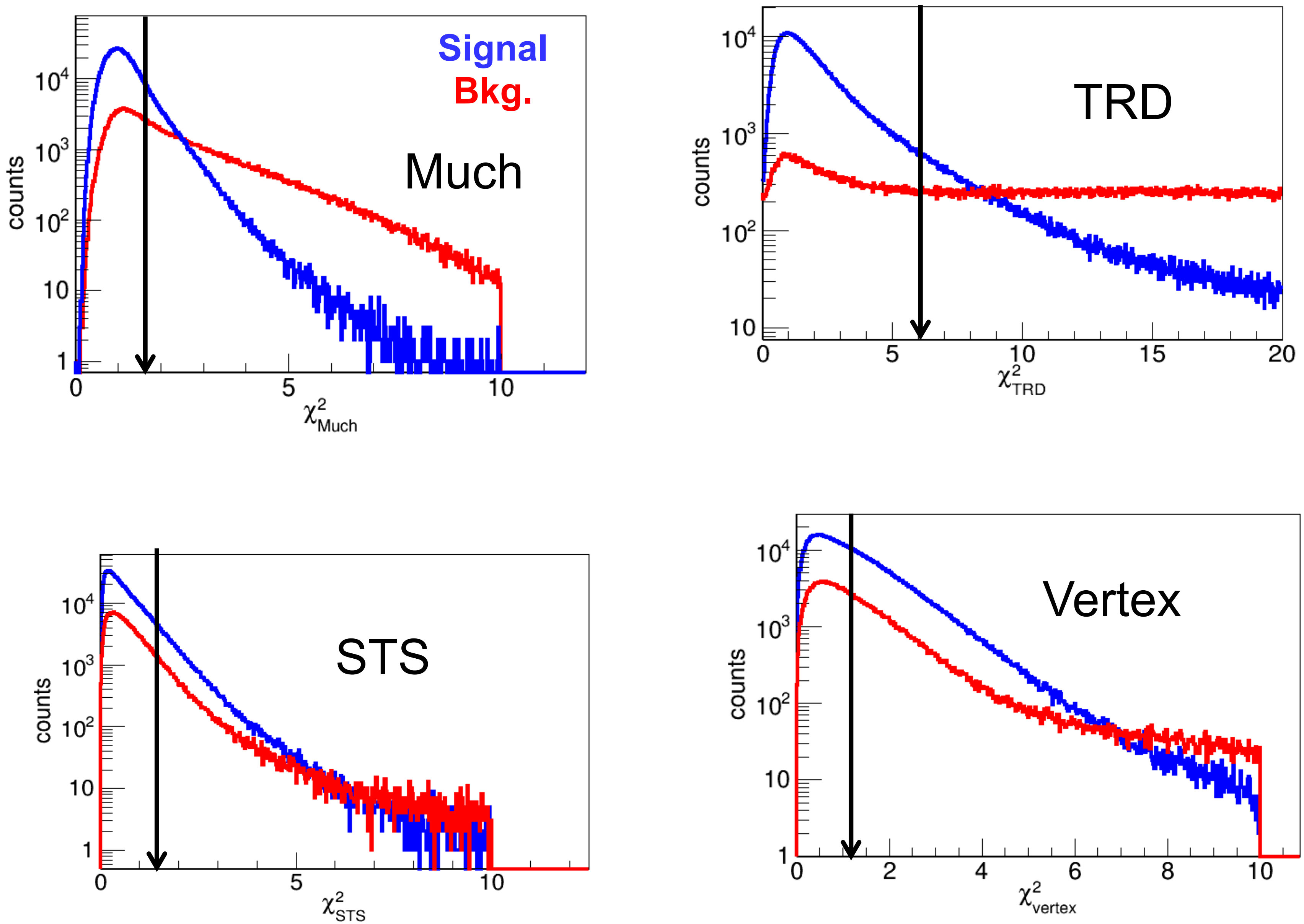
Plan to have extensive physics simulations with realistic set up and realistic rates

Look for other di-muon observables in LMR and HMR

Thank You

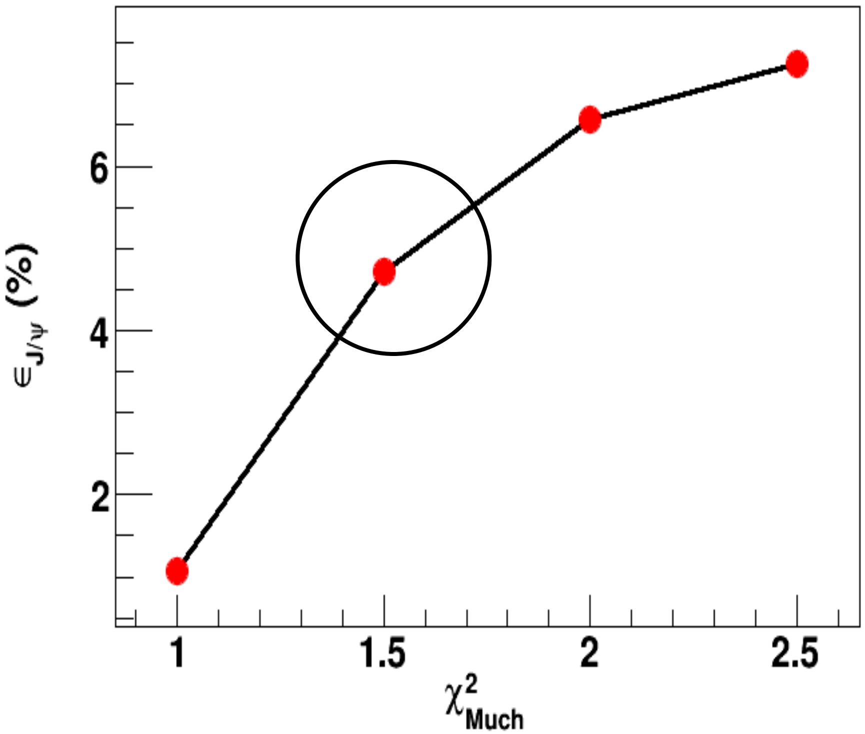
Back ups

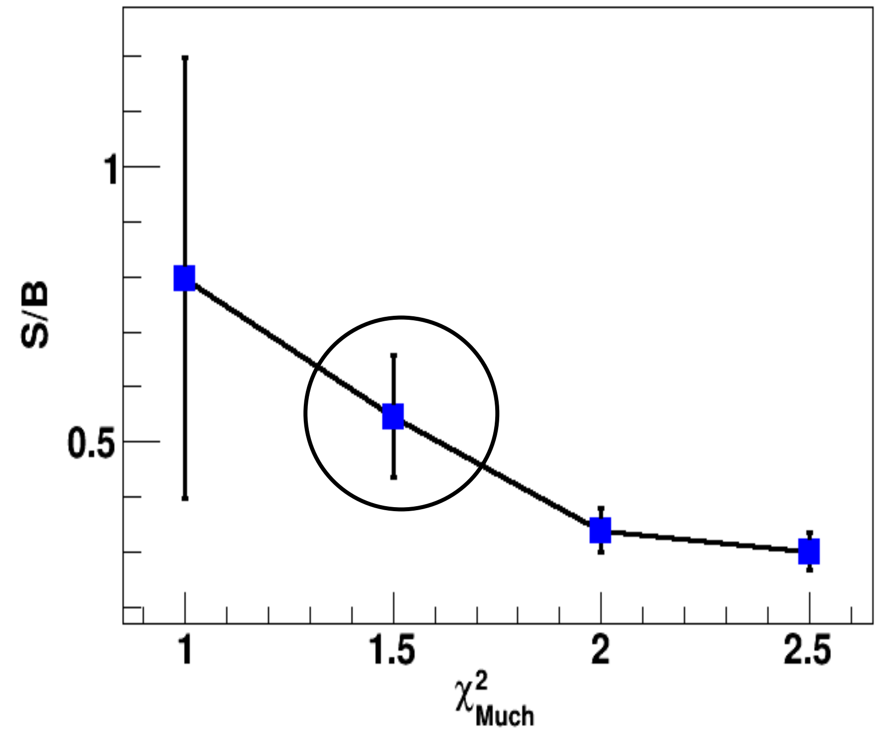
Quality of the reconstructed tracks: χ^2 distribution



Effect of track selection cut: χ^2_{Much}

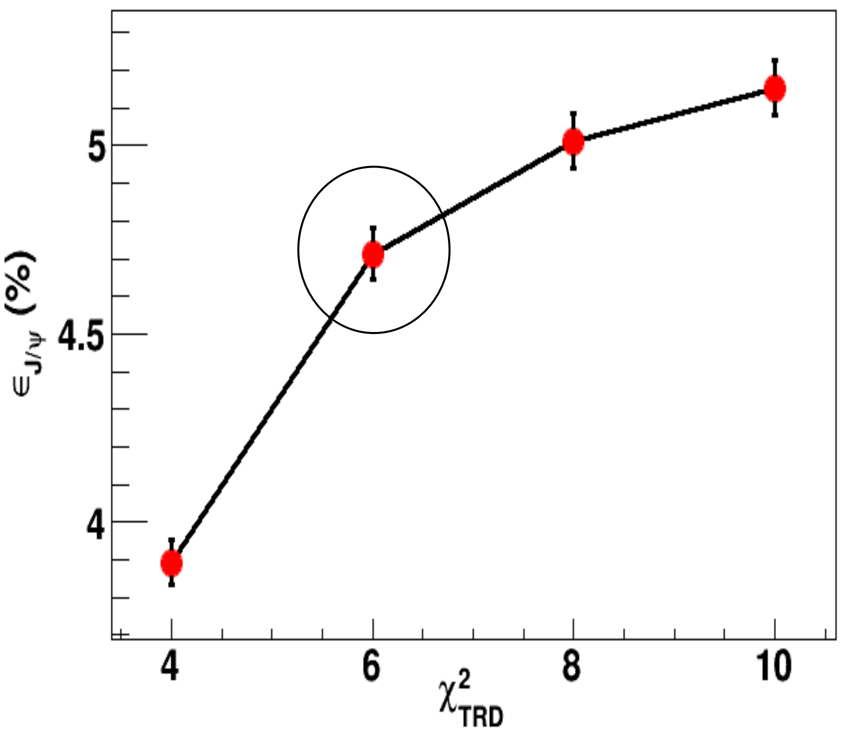
No. of STS hits > 6
No. of Much hits >10
No. of TRD (trigger) hits > 2
STS track χ^2 <=1.5
Vertex χ^2 < =2
TRD track χ^2 <=6

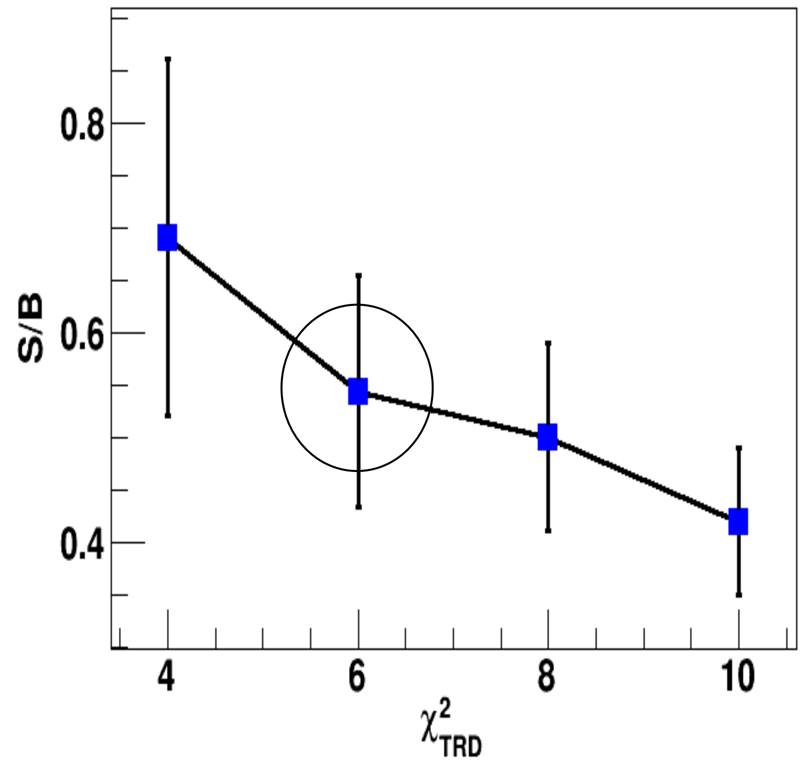




Effect of track selection cut: χ^2_{TRD}

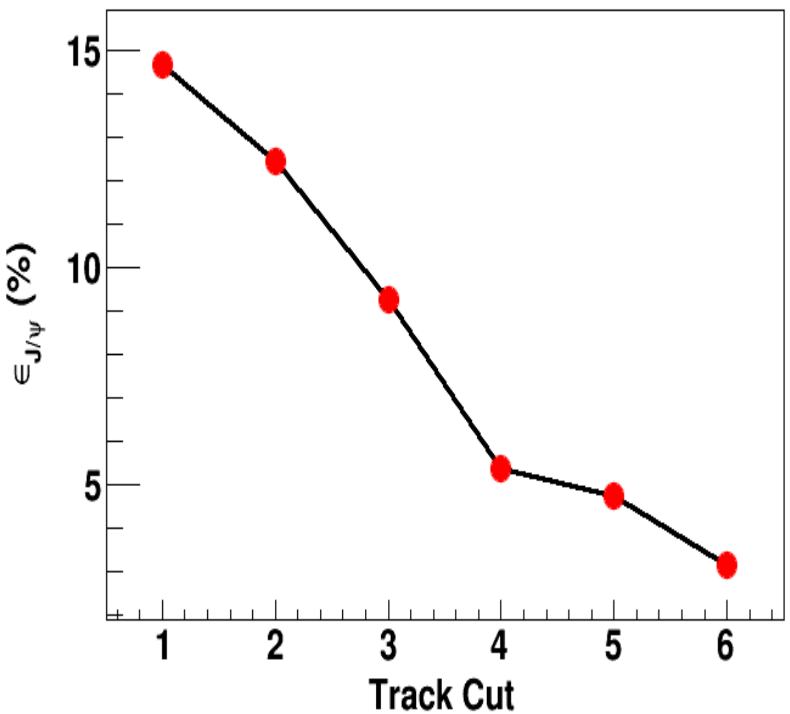
No. of STS hits > 6
No. of Much hits >10
No. of TRD (trigger) hits > 2
STS track χ^2 <=1.5
Vertex χ^2 < =2
TRD track χ^2 <=6

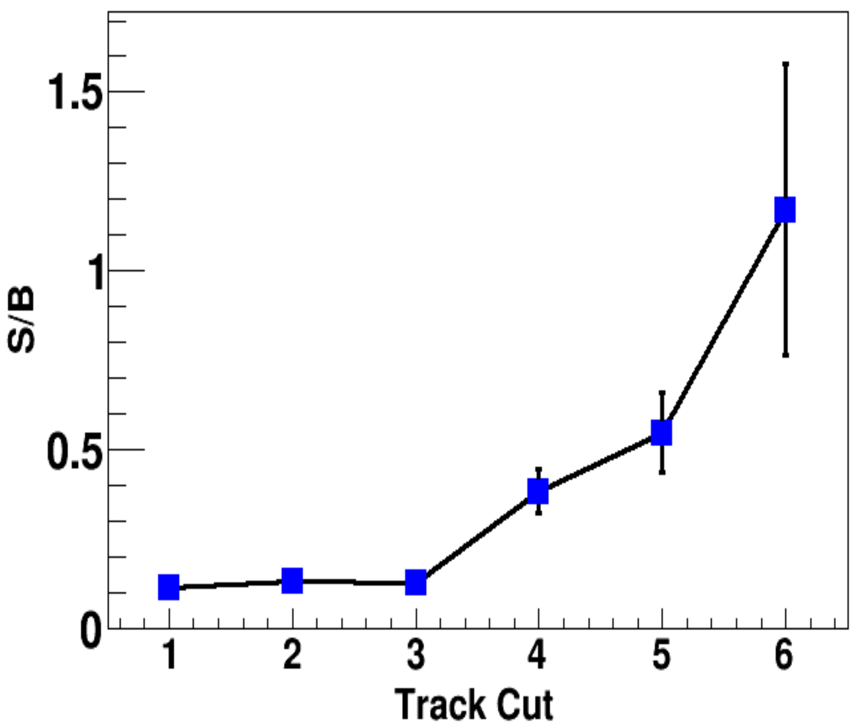




Sequential application of cuts

Cut 1: STS hits >6 + Much hits > 10 + TRD hits > 2
Cut 2: Cut 1 + χ^2_{STS} <= 1.5
Cut 3: Cut 2 + χ^2_{vertex} <=2
Cut 4 : Cut 3 + χ^2_{Much} <=1.5
Cut 5 : Cut 4 + χ^2_{TRD} <=6
Cut 6: Cut 5+ m^2_{TOF} <=0.6

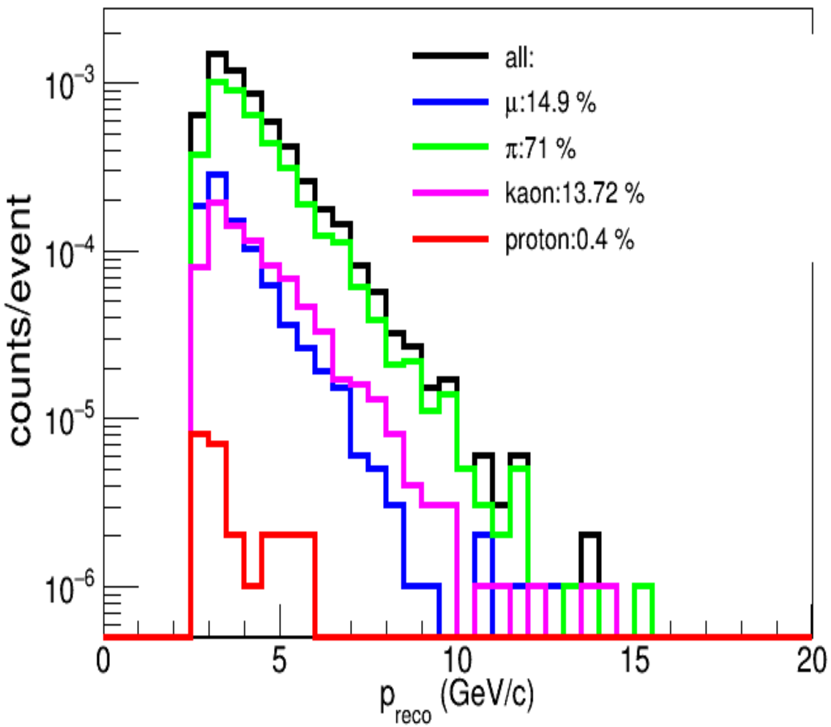




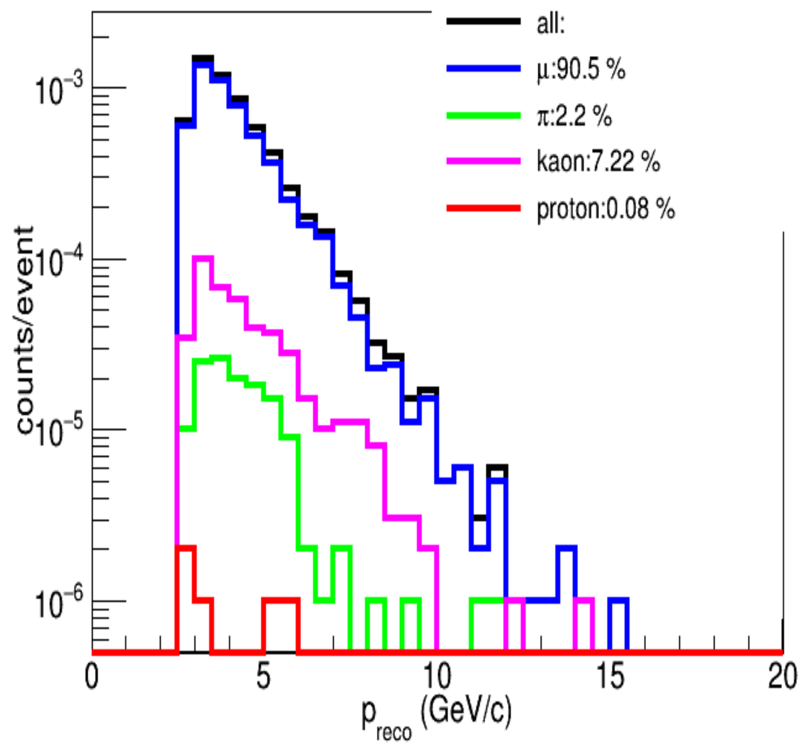
Composition of the background tracks

Selected tracks w/o TOF mass cut

MC Id from STS



MC Id from Much



Muon tracks @ Much from:

❖Pions decaying between STS & Much: ~ 69 %

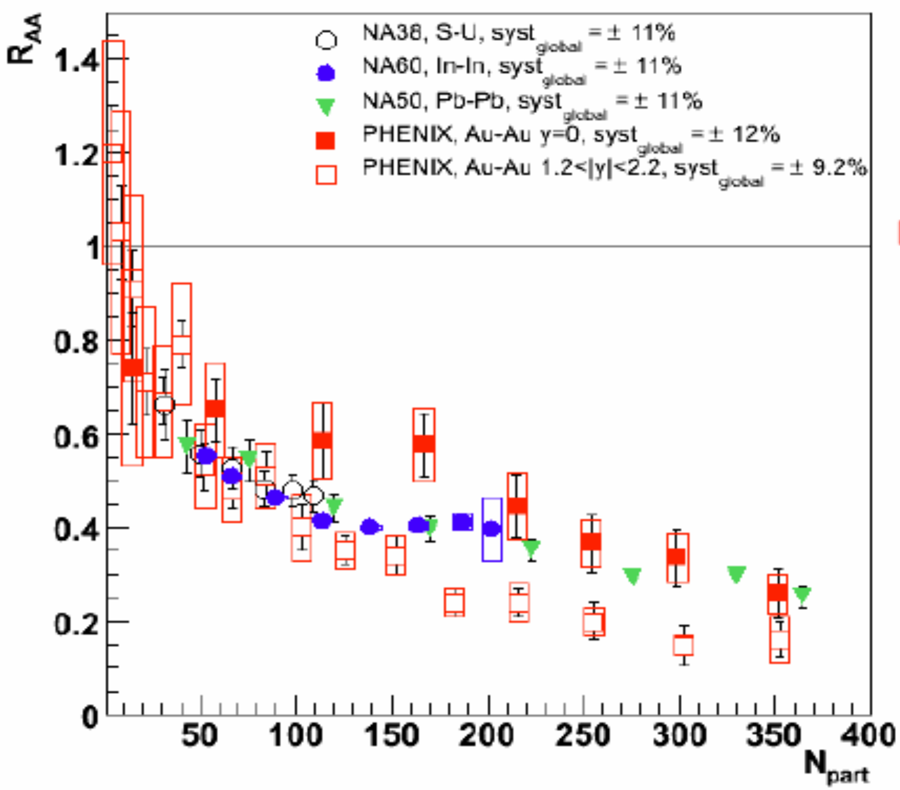
❖Kaons decaying between STS & Much :~ 7 %

❖Mismatch between proton (STS) & muon (Much) track: ~ 0.5 %

Lessons from SPS : II

Comparison SPS and RHIC

- R_{AA} comparison between SPS and RHIC



CAVEAT: at SPS no pp data taking @ 158GeV → need to build the reference extrapolating pA data to A=1

- The initial estimate of the pp reference was obtained from pA data at higher energy, 450 GeV, (and rescaled to 158GeV)
  → All R_{AA} looked similar!

- …but recently the pp reference was obtained directly from NA60 pA @ 158 GeV
  → the comparison looks different!

- pp reference is crucial to correctly interpret the results!

- …picture not yet clear!

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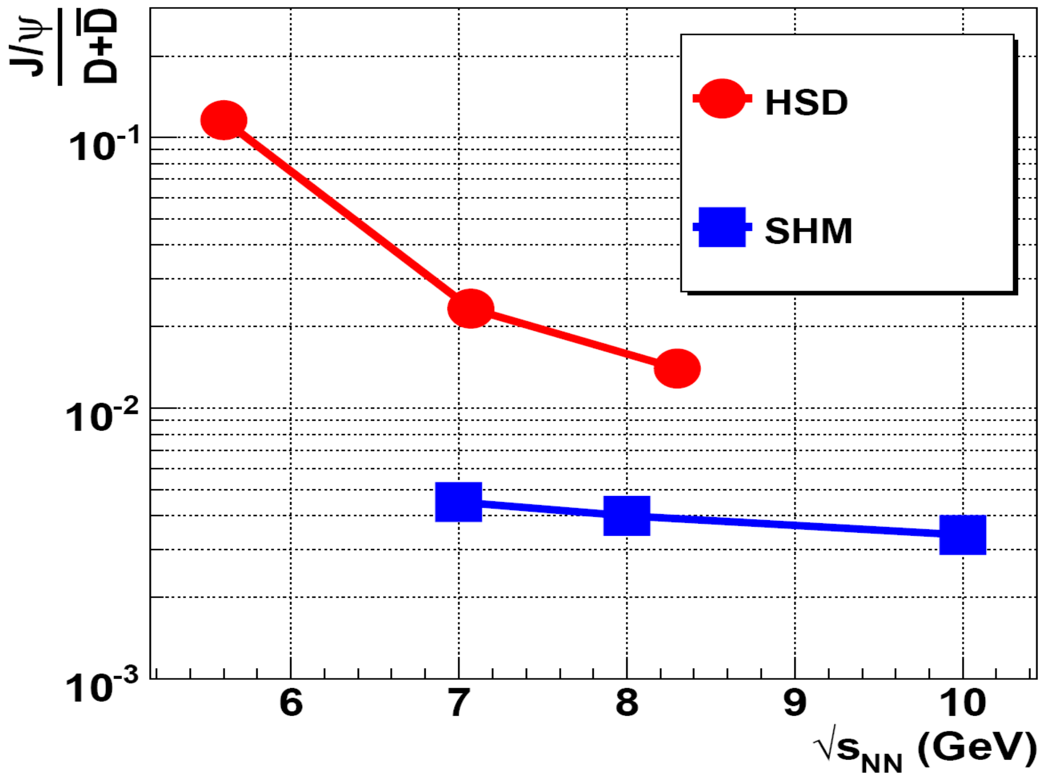
From R. Arnaldi's talk @ "Quarkonia in deconfined medium"

Hidden-to-open charm ratio



•SHM: assumes complete de-confinement (partonic scenario)

•HSD: purely hadronic medium

•Different production threshold owing to different production mechanisms

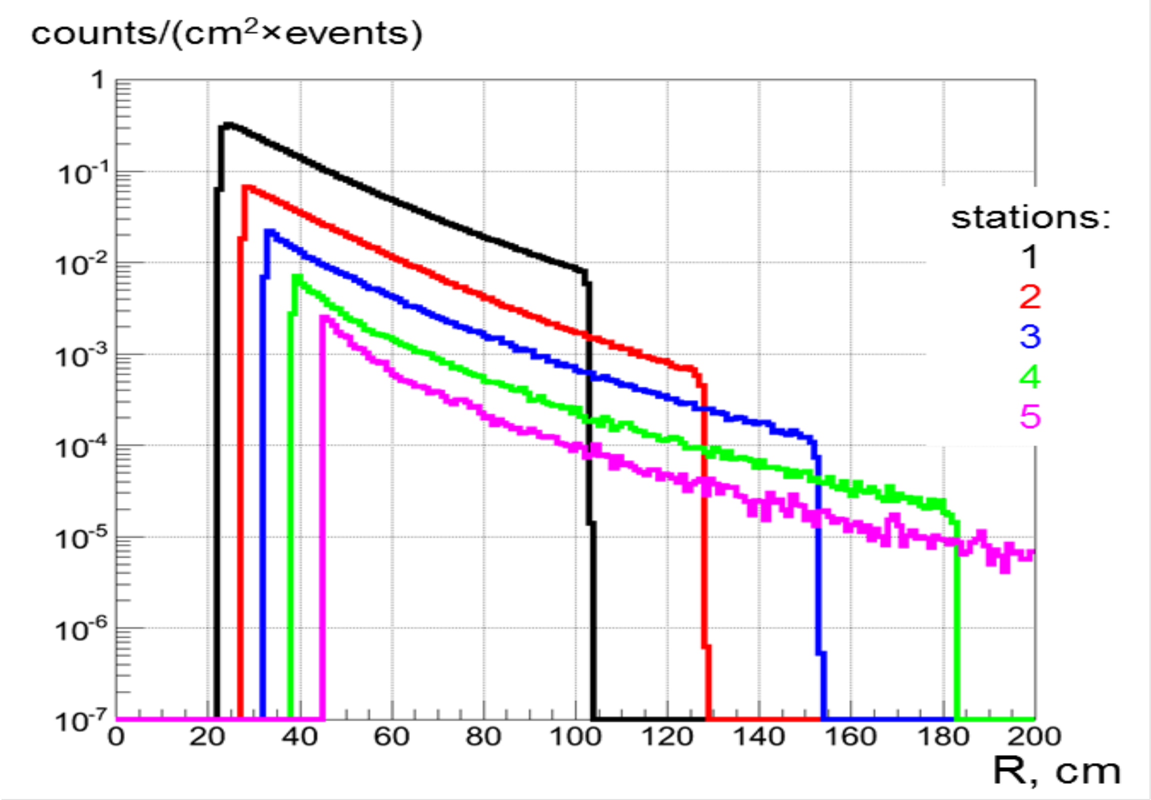
•Might help to probe the de-confinement transition

J/ψ Spectrum with other physical sources

Very small contribution from DY and open charm decays @ CBM energies

Composition of background tracks

Radial distribution of particle density in central Au + Au collisions @ 25 A GeV



- Distributions correspond to the average over the three layers
- Maximum near the beam pipe & falls as we go away from the centre
- Maxium particle rate @ MUCH at 1st station ~ 3 MHz
- For minimum bias collisions numbers will roughly be 25 % of the central values

Generation of signal muons in PLUTO

J/ψ mesons are produced from PLUTO event generator

PLUTO based on thermal fireball model; produced particles from a thermal source (generally energy sampling following relativistic Boltzmann distribution)

No explicit 4-momntum conservation in the reaction (NN collision)

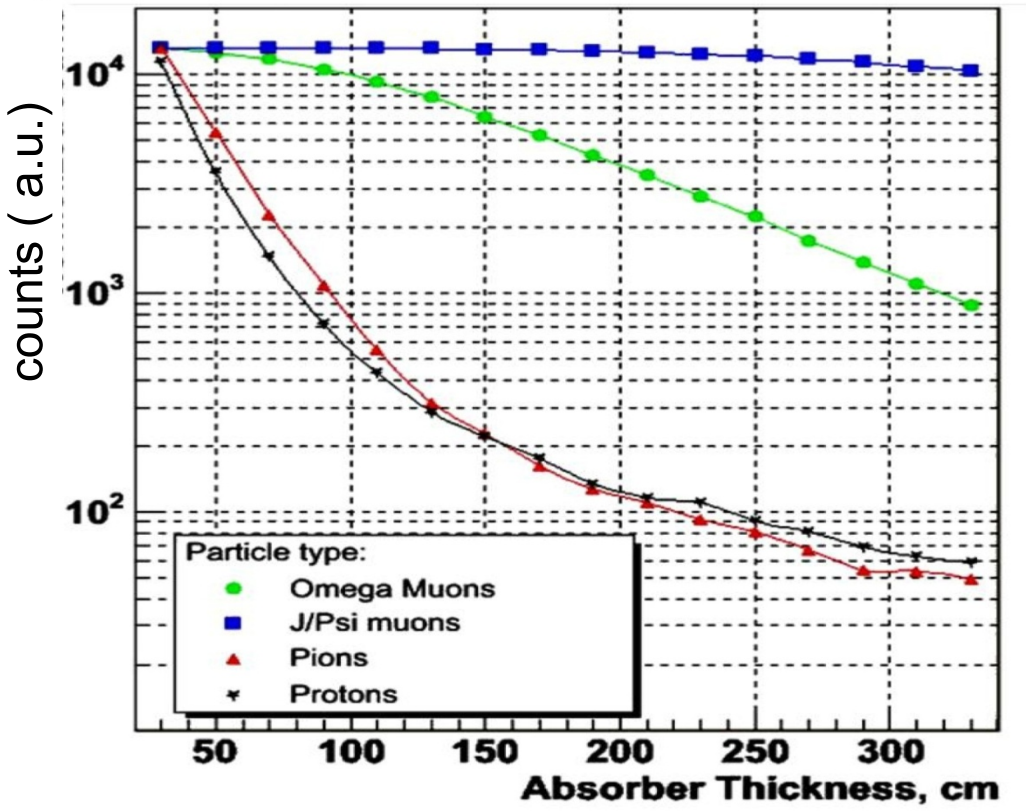
Tuning for CBM investigations:

- Thermal transverse distribution following $dN/dp_T \sim p_T \exp(-m_T/T_{eff})$ ($T_{eff} \sim T_{fo} + mv_r^2$)
- Gaussian rapidity distribution following $dN/dy_{cm} \sim \exp(-y_{cm}^2/2\sigma^2)$
- Generate azimuthal angles following uniform random distribution
- Input parameters: T_{fo} (= 170 MeV), sigma and v_r=0.0
- Generate 4-momentum of J/psi
- Decay isotropically into di-muons in the mother rest farme
- Boost the muons into the laboratory frame

Selection of absorber thickness

Muon measurements at FAIR energies: detector design considerations

Determination of effective absorber thickness

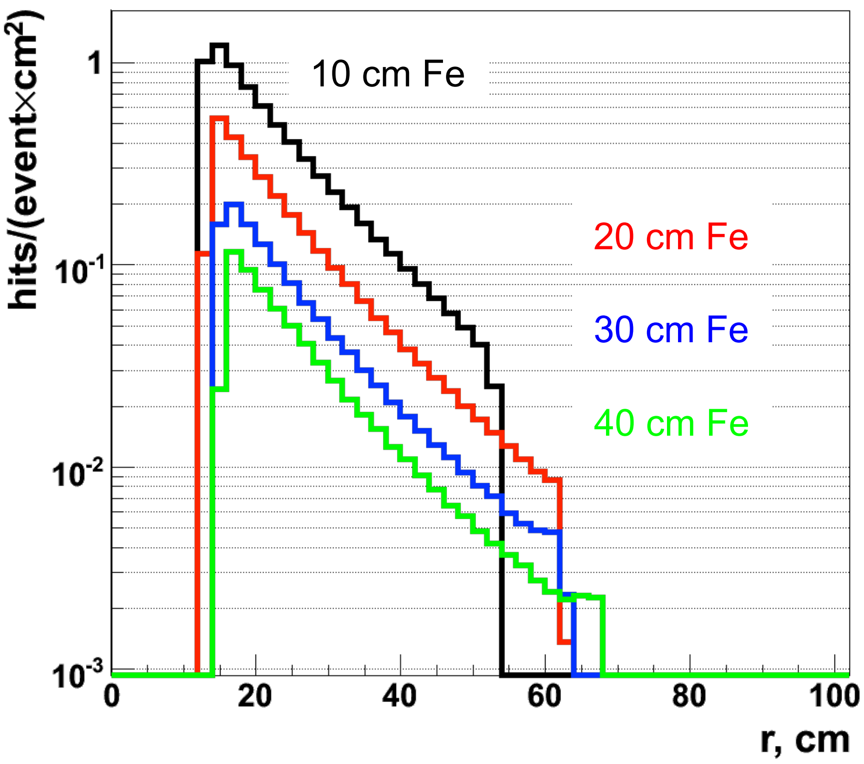


particle momenta:
Au+Au 25 A GeV
central collisions

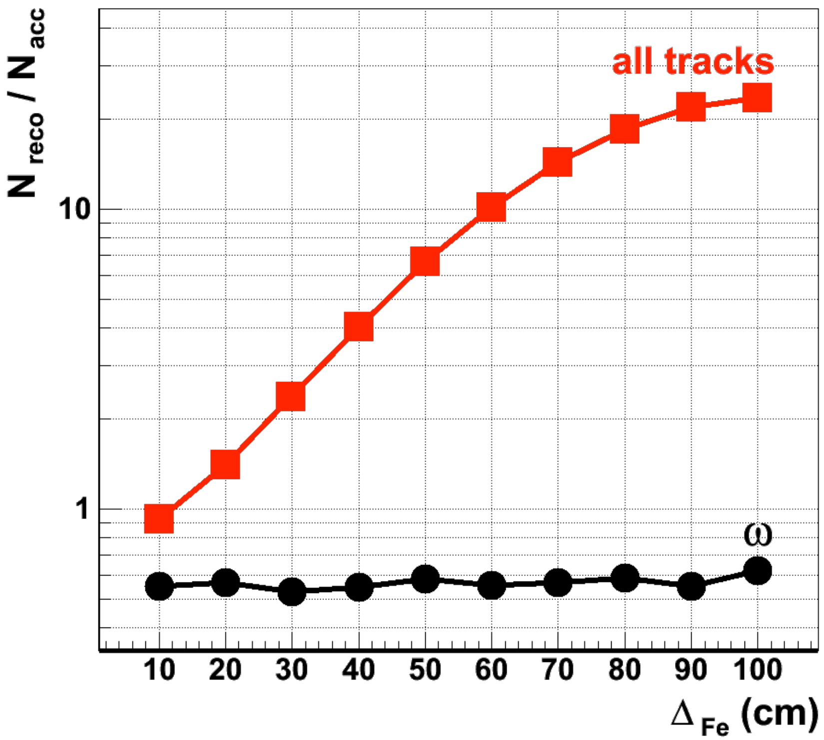
Absorber thickness versus track mismatches

Au+Au 25 A GeV central collisions

particle density after first absorber layer



mismatches

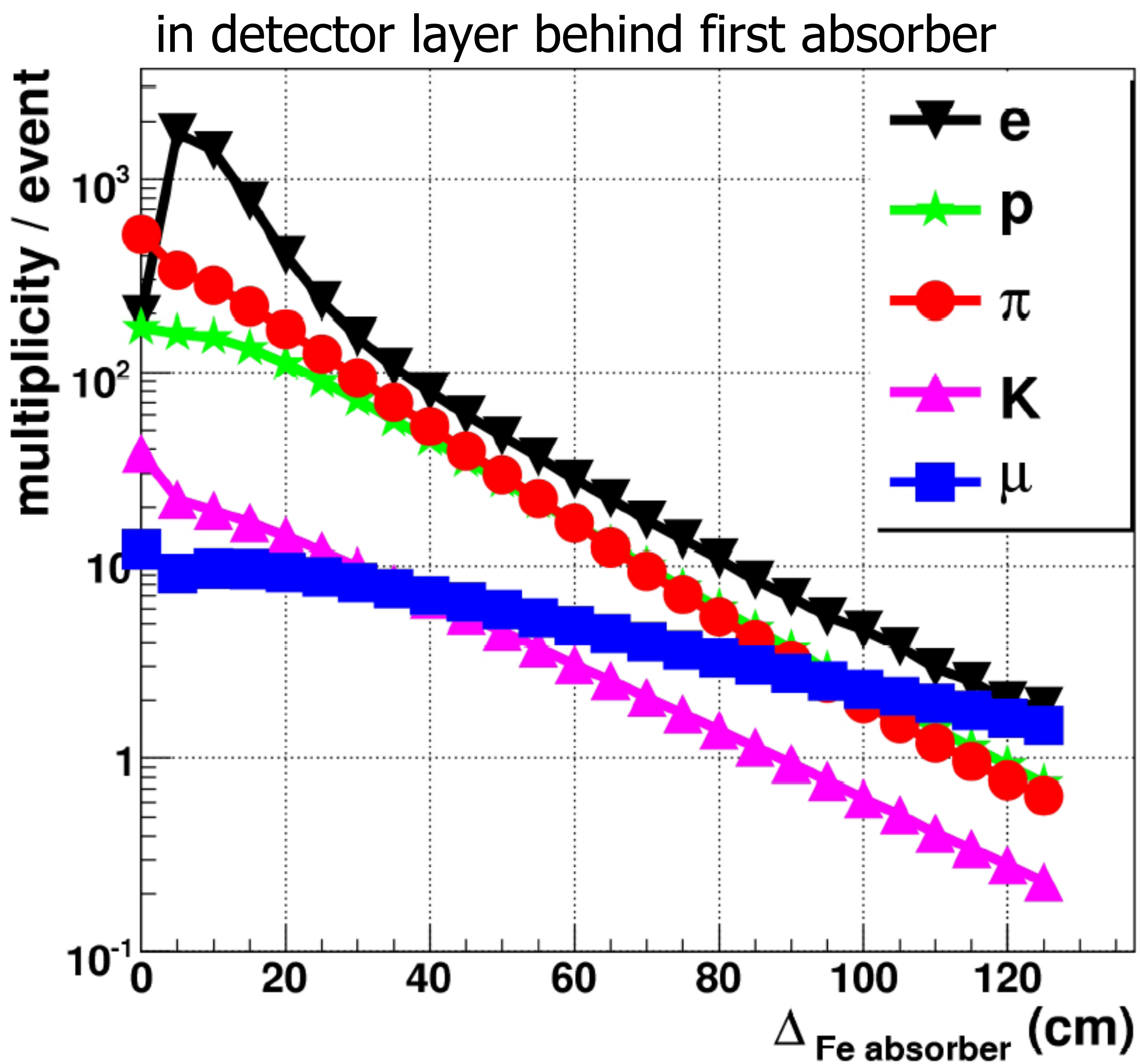


Smaller absorber thickness: too high particle density to handle

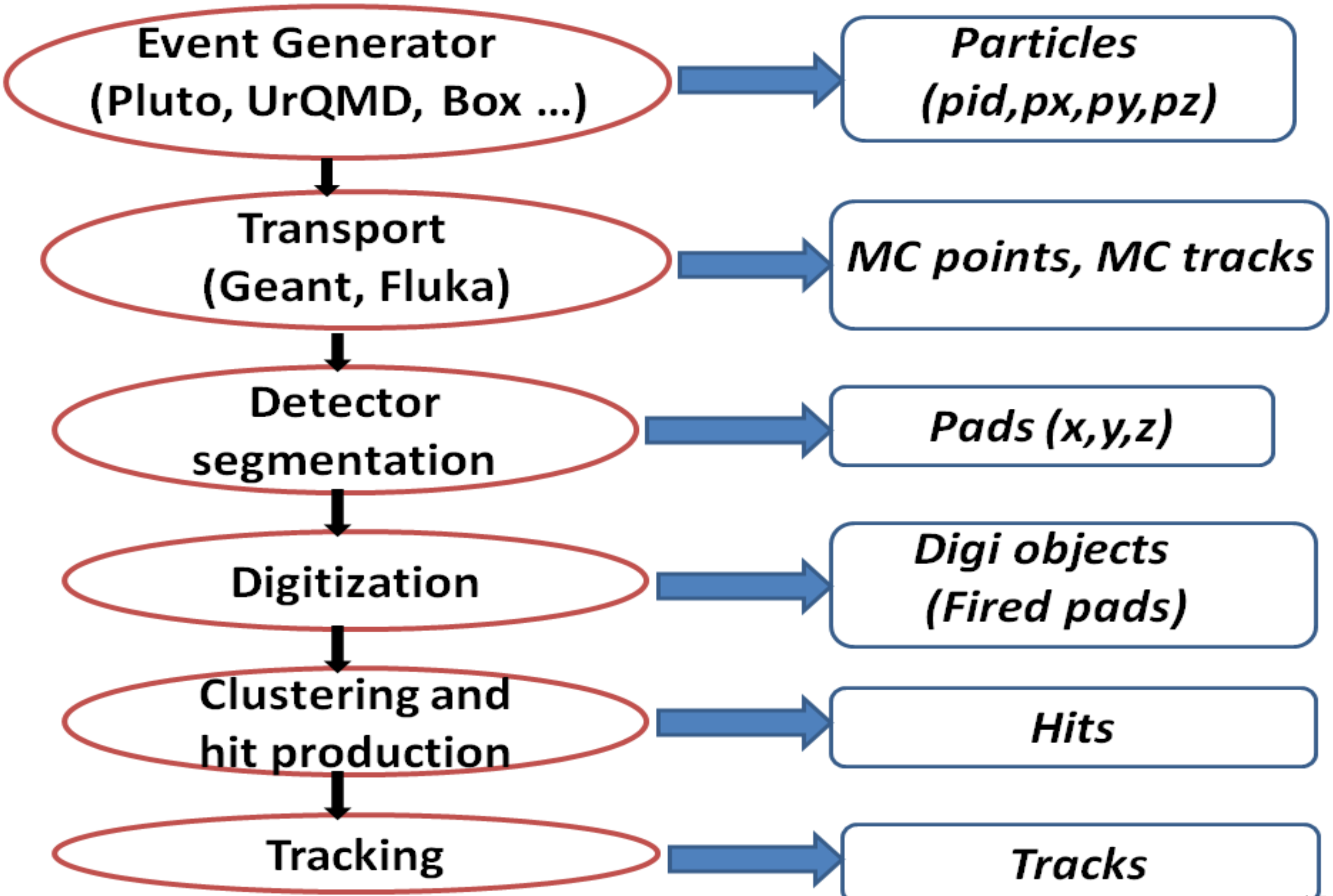
Larger absorber thickness: Large number of fake bkg tracks due to track mismatch

Particle multiplicity versus absorber thickness

Au+Au 25 A GeV central collisions

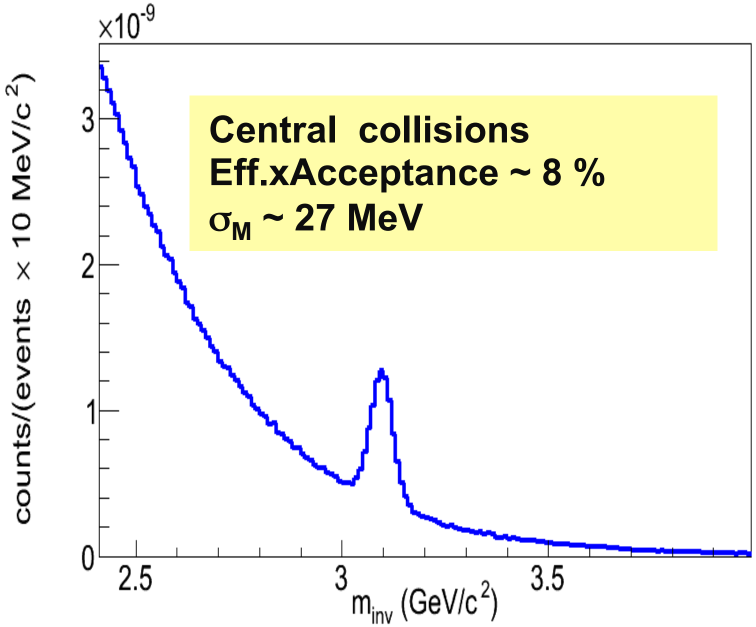


Basic ingredients of simulation: CBMROOT



Invariant mass spectra: SIS-300 Au+Au collisions @ 25 A GeV

Operation at maximum rate (10 MHz)
Trigger logic for online event selection



Clearly identified peak over the background: highly feasible detection

Background from Drell-Yan and semi-muonic open charm decays are negligibly small

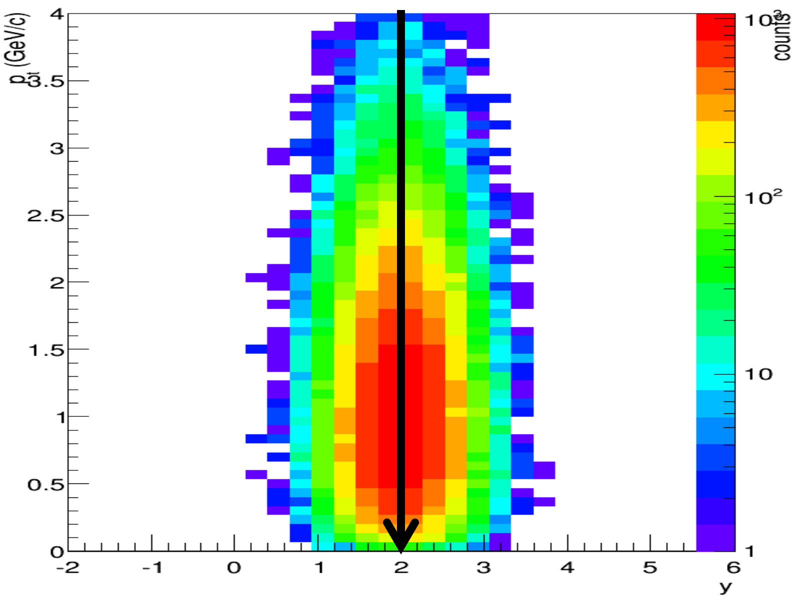
About factor of 4 better mass resolution (~ 100 MeV for 158 A GeV Pb+Pb collisions @ NA50)

Mass shape fitted with symmetric Gaussian

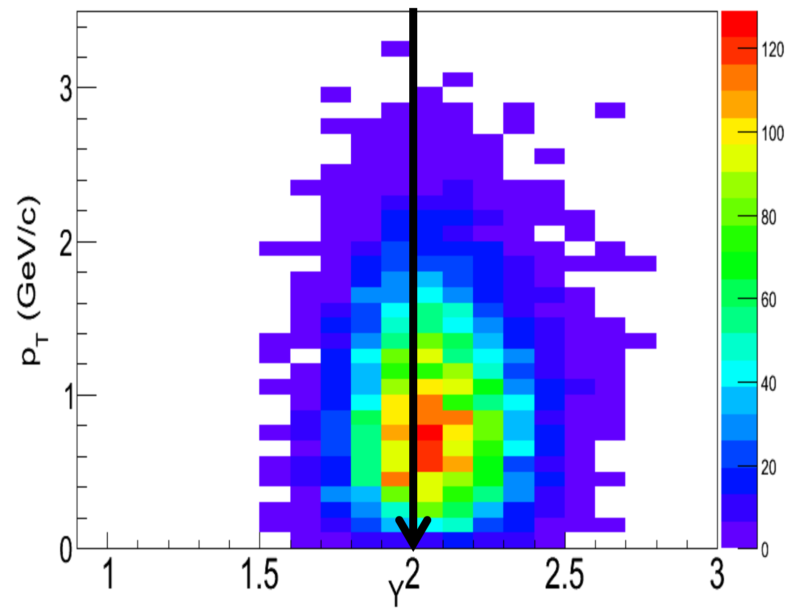
Improved S/B for central collisions

Acceptance (y-p_T) plots: SIS-300 25 A GeV Au + Au collisions

Pluto input



Reconstructed Central



y_{beam} ~ 3.99

MUCH has coverage for mid-rapidity

Beam time requirements: SIS-300

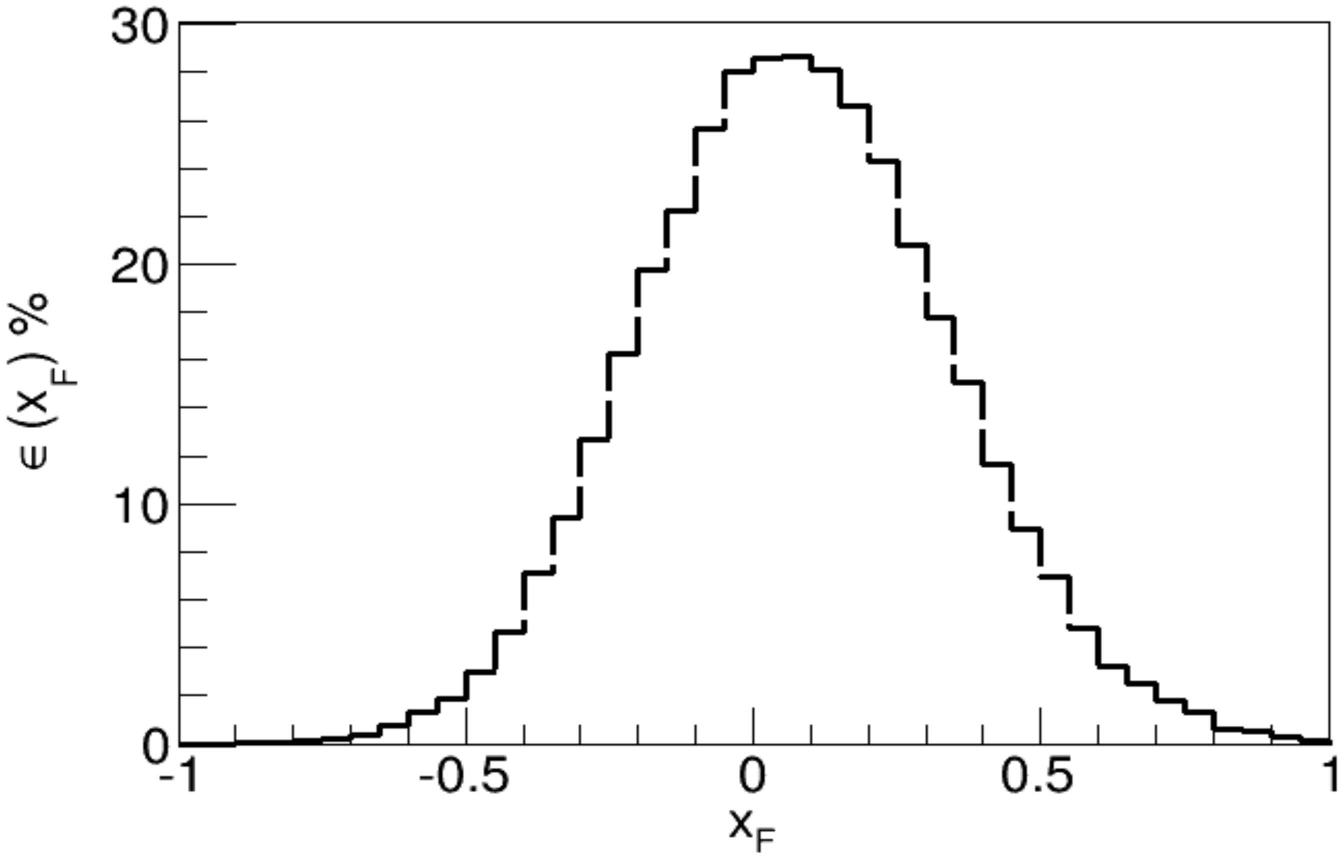
- Used J/ψ statistics (central collisions) = 8×10^5 J/ψ
  - Multiplicity (HSD) $=1.92\times10^{-5}$,
  - branching ratio = 0.06
  - Efficiency = 0.08

- Required central events
  $8\times10^5 /(1.92\times10^{-5}\times0.06\text{x}0.08) \approx 8.6\times10^{12}$

- Required minimum bias events $\approx 34.4\times10^{12}$

- Reaction rate 10^7 events/sec:
  34.4×10^5 sec ~ 35 days

Differential reconstruction efficiency

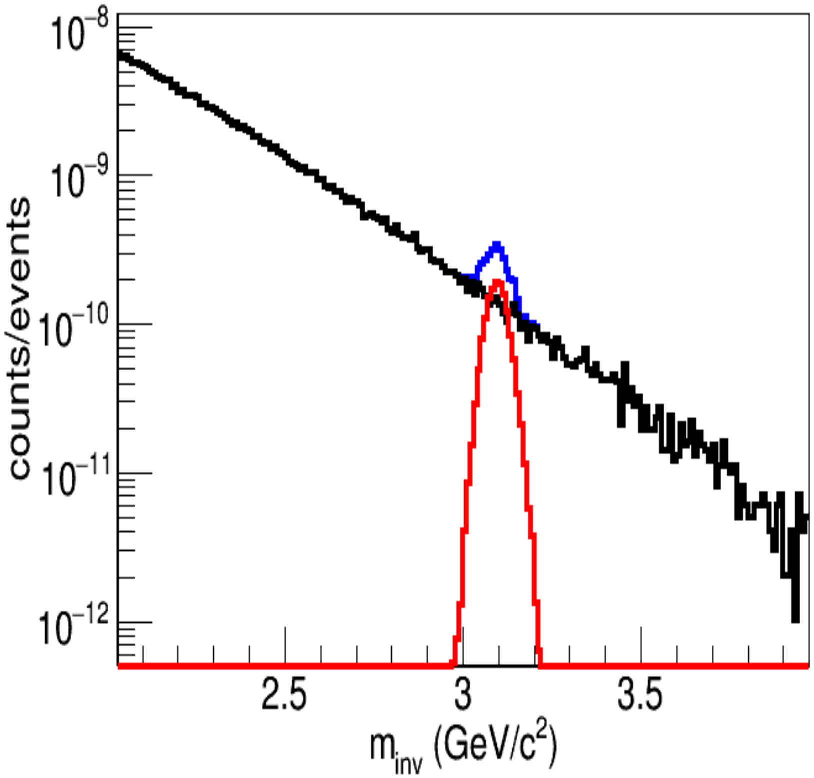


Reconstruction efficiency peaks at mid-rapidity

J/y reconstruction in 15 A GeV Ni+Ni collisions

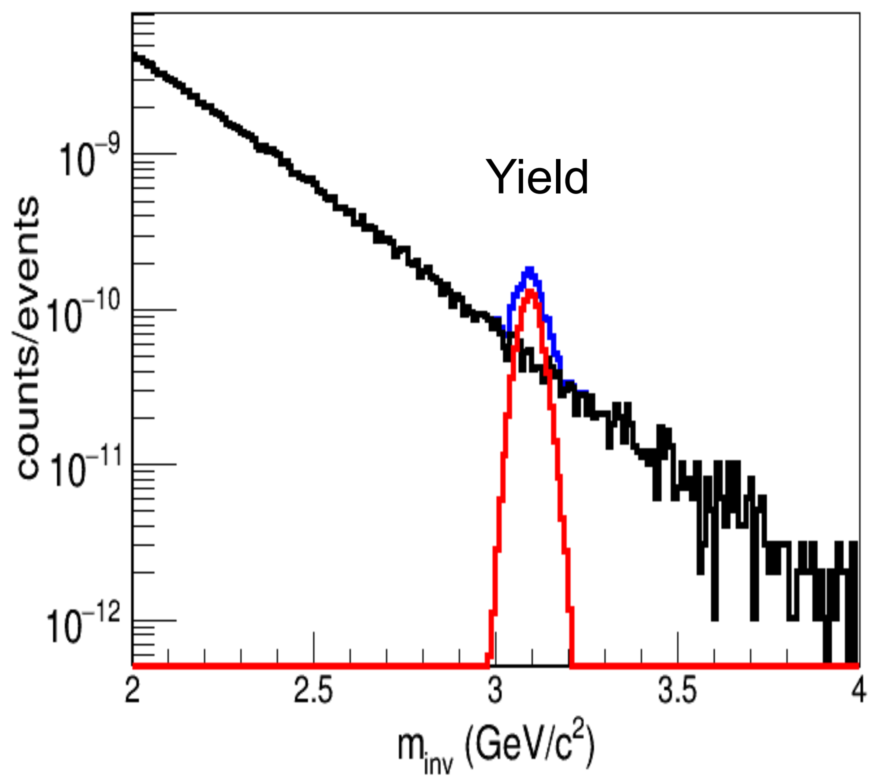
Tracks are selected with (i) > 6 STS hits (ii) > 11 MUCH hits (iii) > 2 TRD hits (trigger hits) (iv) vertex χ^2 < =2.0 (v) STS χ2 < =1.5 (vi) Much χ2 <= 1.5 (vii) TRD χ2 <=6 (viii) m^2_{TOF} <=6 hits

w/o TOF mass cut



Efficiency : 4.8 +/- 0.22 %
S/B: 0.72 +/- 0.22
Mass resolution 32.4 MeV (~ 1.04 %)
Significance: 32

With TOF mass cut



Efficiency : 3.2 +/- 0.18
S/B: 1.37 +/- 0.05
Mass resolution: 33 MeV
Significance: 36.2