Performance studies for the future flow measurements in heavy-ion collisions

Petr Parfenov (MEPhI)

Arkadiy Taranenko (MEPhI)

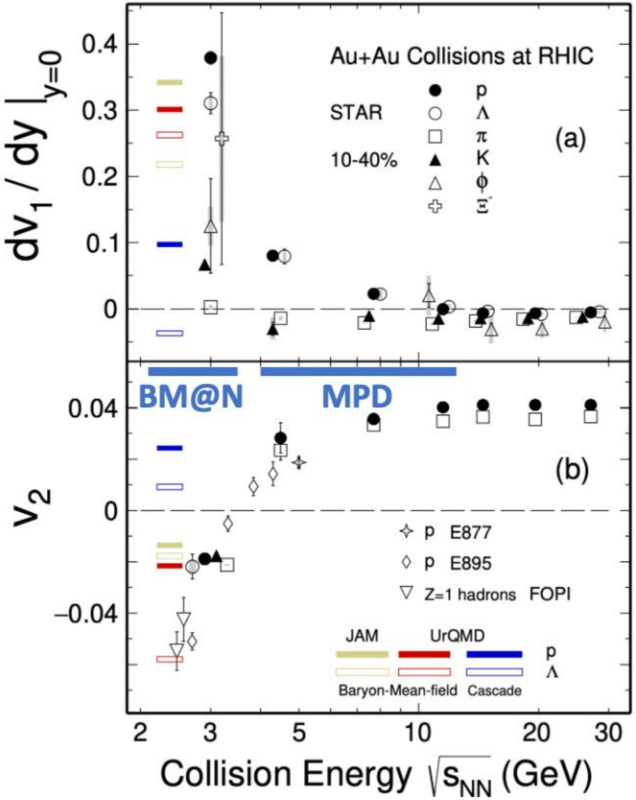
Ilya Selyuzhenkov (GSI, MEPhI)

8th Collaboration Meeting of the BM@N experiment at the NICA facility

3-8 October 2021

Anisotropic flow in Au+Au collisions at $\sqrt{s_{NN}}$= 2-4 GeV

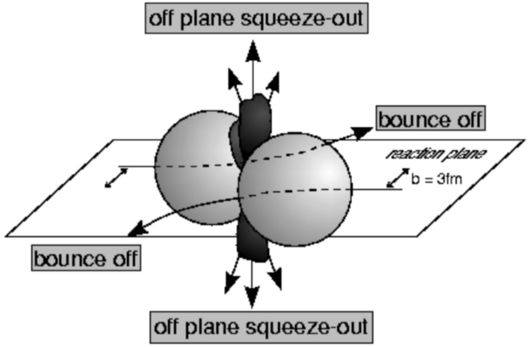
STAR Collaboration nucl-ex/2108.00908



$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1} v_n \cos[n(\phi - \Psi_{RP})]$$

$$v_n = \langle \cos[n(\phi - \Psi_{RP})] \rangle$$

$v_1 > 0$ $v_2 < 0$



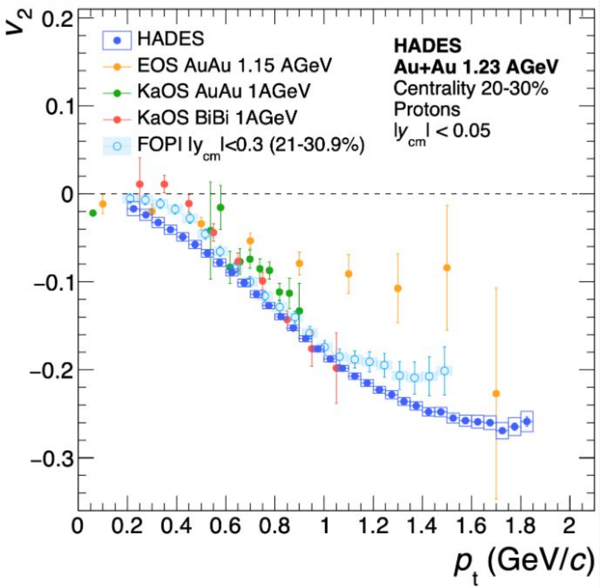
BM@N: $\sqrt{s_{NN}}$=2.3-3.3 GeV

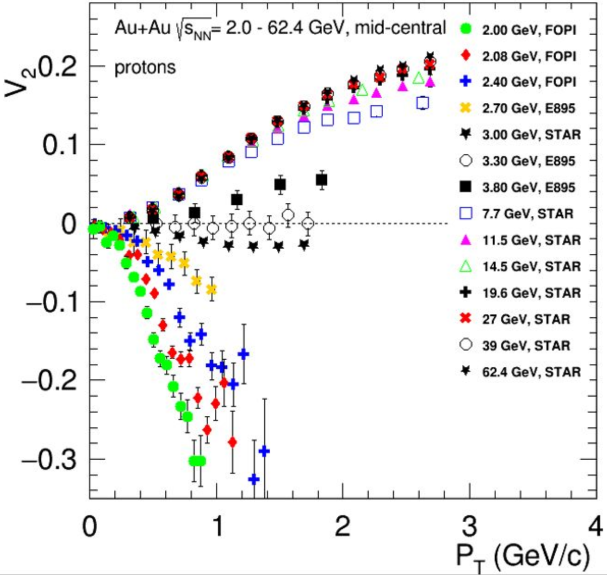
Strong energy dependence of dv_1/dy and v_2 at $\sqrt{s_{NN}}$ = 2-4 GeV
out-of-plane to in-plane v_2 at $\sqrt{s_{NN}}$ ~ 3.3 GeV

Anisotropic flow at BM@N energies is a delicate balance between

I. pressure development early in the reaction zone
II. Shadowing by spectators due to long passage time

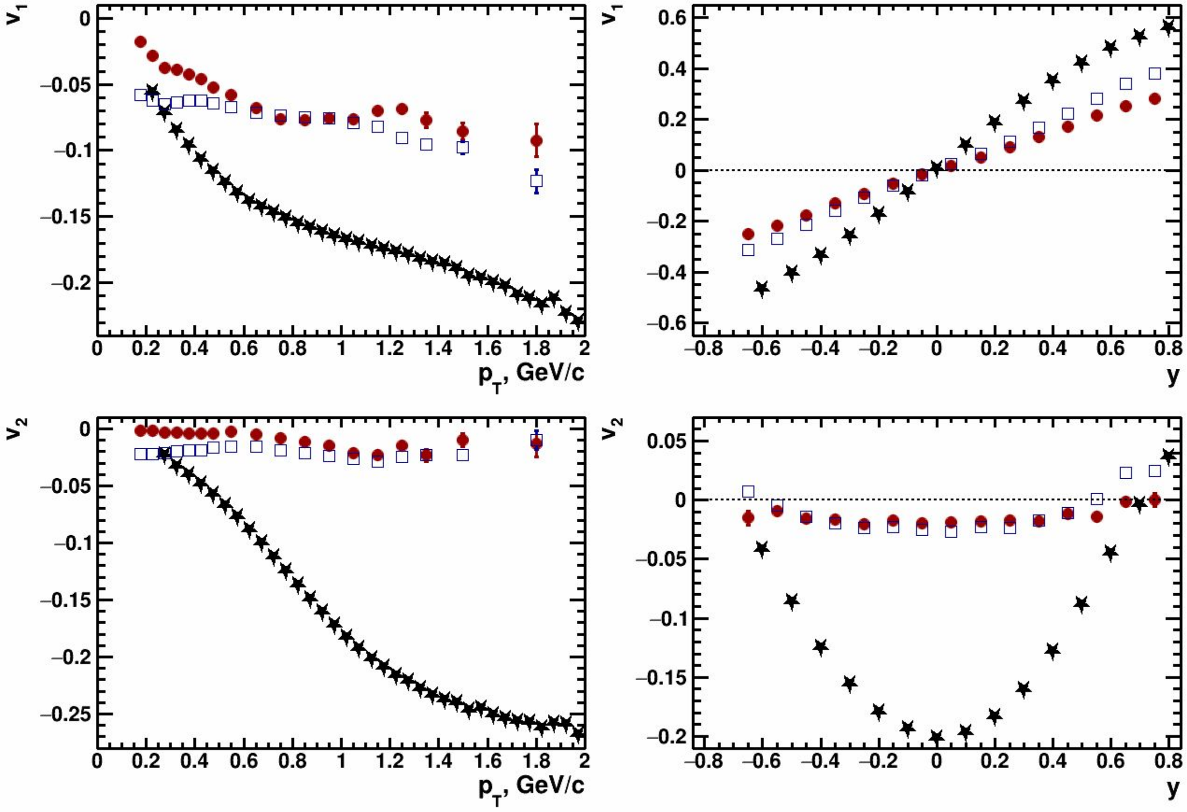
Why do we need new flow measurements with BM@N?





- Lack of differential flow measurements at $\sqrt{s_{NN}}$=2.3-3.3 GeV
- Difference between results from different experiments (e.g. FOPI vs. HADES) is the main source of existing systematic errors in v_n measurements
- Future BM@N data for $\sqrt{s_{NN}}$=2.3-3.3 GeV) will provide detailed and robust v_n measurements

$v_{1,2}(p_T,y)$ of protons in Au+Au $\sqrt{s_{NN}}$=2.4 GeV: model vs. HADES data



Au+Au, 20-30% **(6<b<9 fm)**

- ☐ **DCM-QGSM-SMM**
- ● **UrQMD cascade mode**
- ★ **HADES data**

HADES data from: Phys. Rev. Lett. **125** (2020) 262301

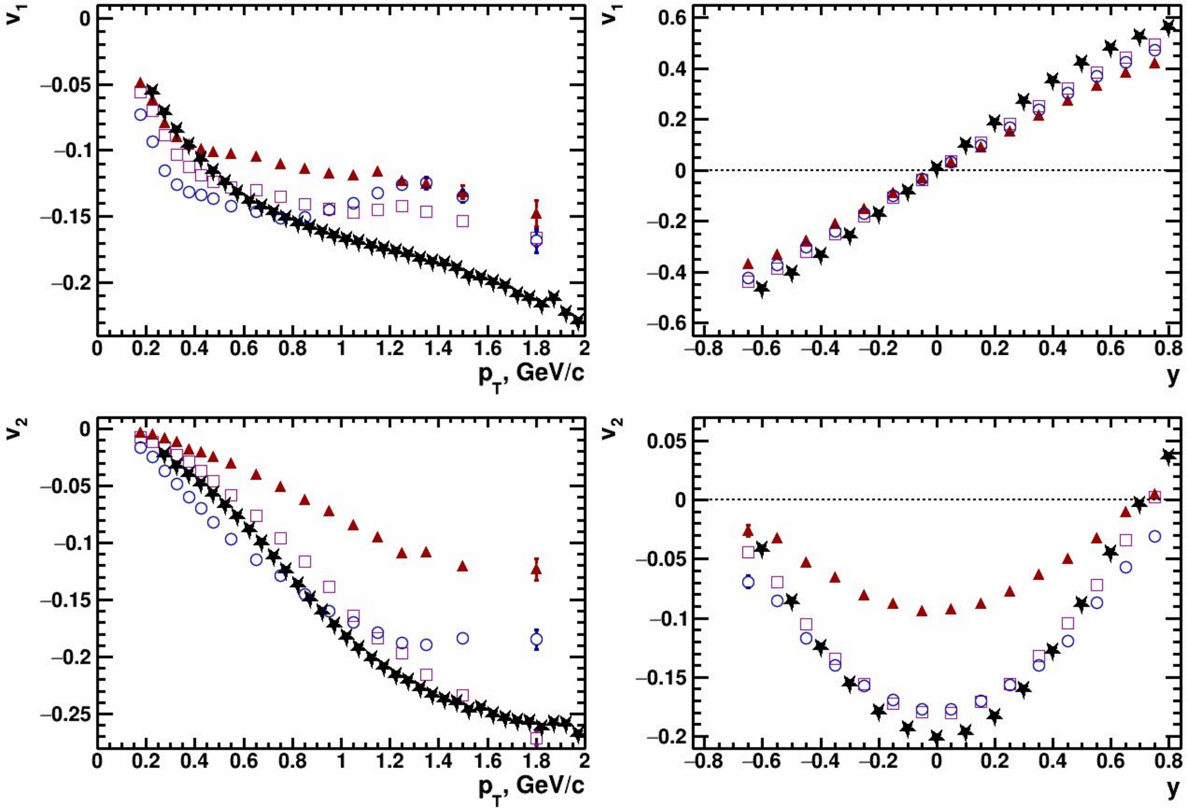
Kinematic cuts:

$v_1(p_T)$: -0.25 < y < -0.15
$v_2(p_T)$: -0.05 < y < 0.05
$v_{1,2}(y)$: 1.0 < p_T < 1.5 GeV/c

$-0.79 < \eta < 0.96$ (HADES acceptance)

Cascade models are not a good choice for BM@N energy region

$v_{1,2}(p_T,y)$ of protons in Au+Au $\sqrt{s_{NN}}$=2.4 GeV: model vs. HADES data



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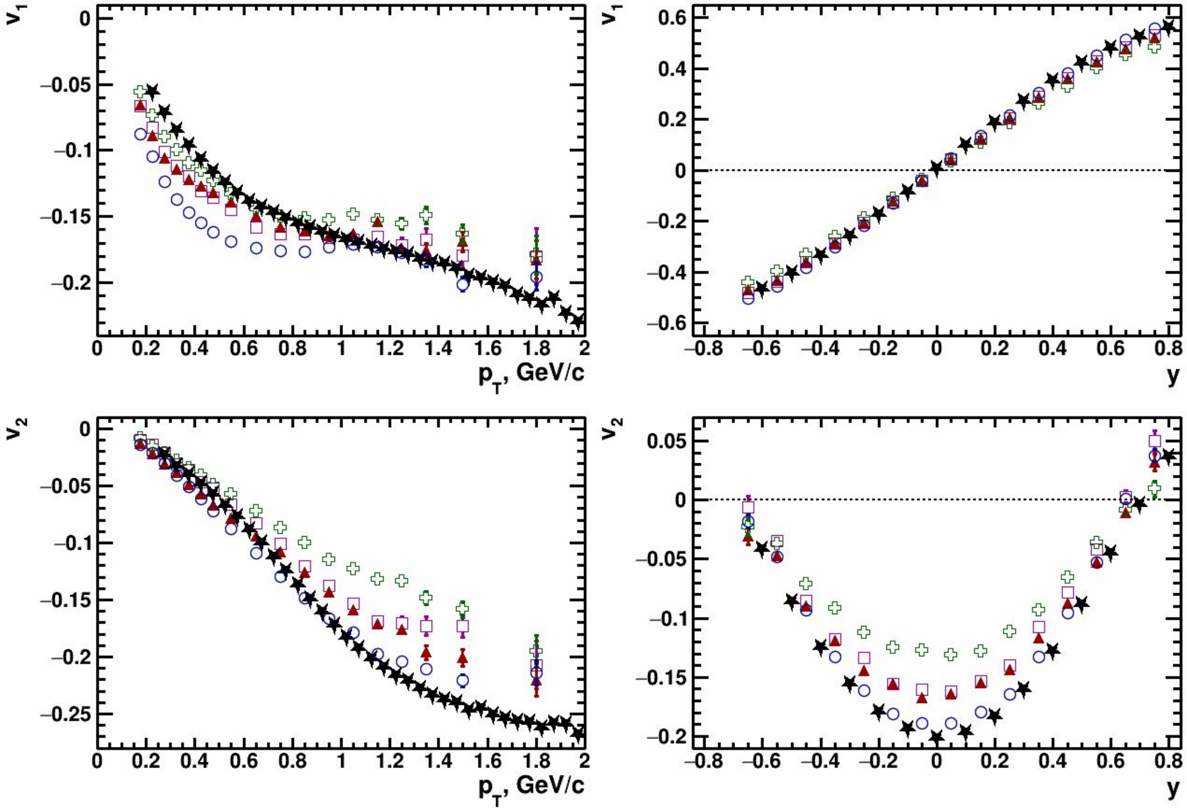
Better description of HADES data with mean-field and hard EoS

$v_{1,2}(p_T,y)$ in Au+Au $\sqrt{s_{NN}}$=2.4 GeV: model vs. HADES data



JAM, Au+Au, 20-30% (6<b<9 fm)

- ○ **MD3, K=380 MeV**
- □ **MD2, K=210 MeV**
- ▲ **NS1, K=380 MeV**
- ✚ **NS2, K=210 MeV**
- ★ **HADES data**

K - nuclear incompressibility

HADES data from: Phys. Rev. Lett. **125** (2020) 262301

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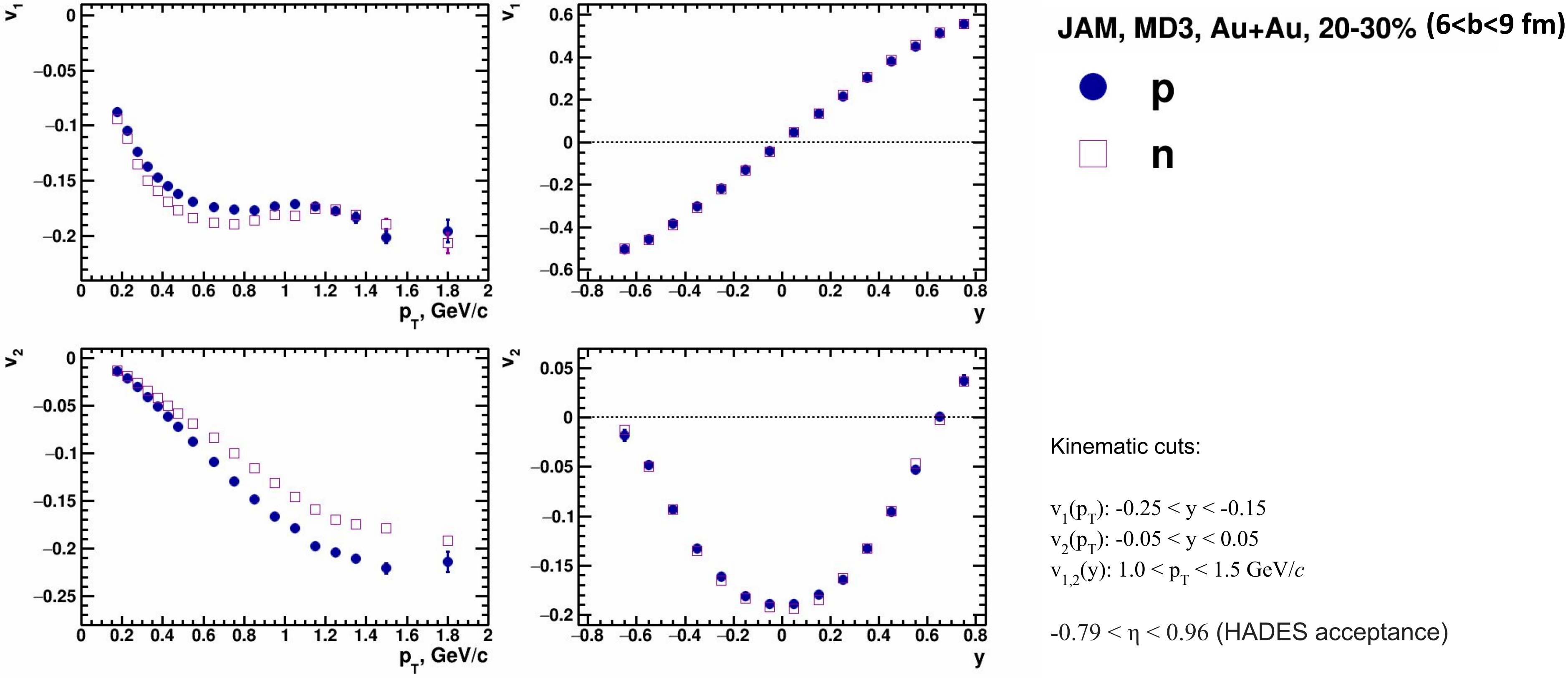
Dependences of v_1&v_2 on p_T and v_2 on rapidity are very sensitive to the details of the EoS

$v_{1,2}(p_T,y)$ in Au+Au $\sqrt{s_{NN}}$=2.4 GeV: protons vs. neutrons



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Different p_T dependence of v_2 for protons and neutrons

Simulation setup

System ^{131}Xe - ^{119}Sn

$\sqrt{s_{NN}}$ = 3.296 GeV

p_{beam} = 4.76 GeV/c

$y_{beam} = y_{CM} = y_{proj} / 2 = 1.163$

N_{events} = 90K

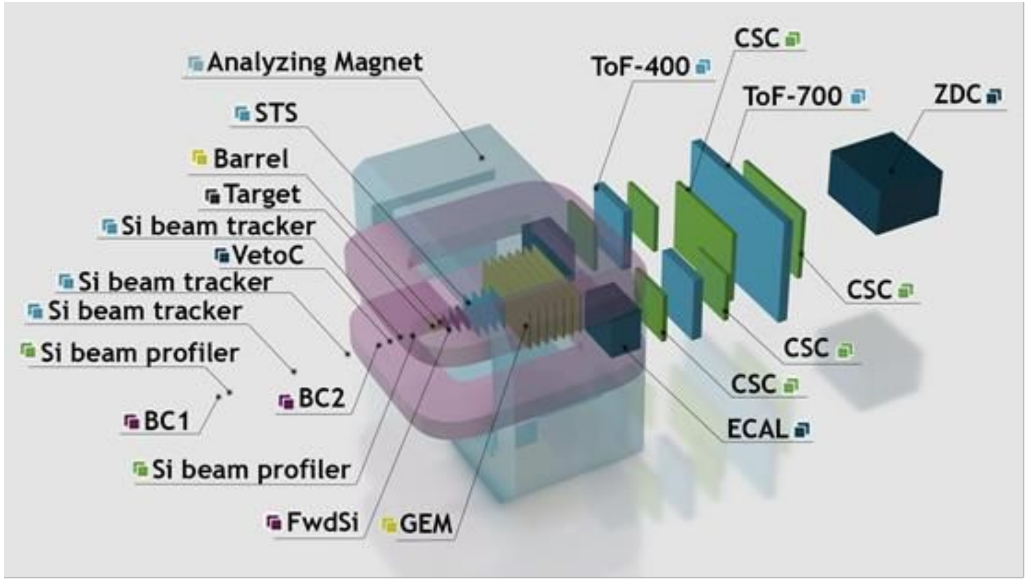
Model: DCM-QGSM-SMM

(version from Genis Musulmanbekov)

Simulation: GEANT4

Reconstruction:

- Tracking system (cluster finder)
- TOF (hit producer)
- FHCal (digitizer)
- ...

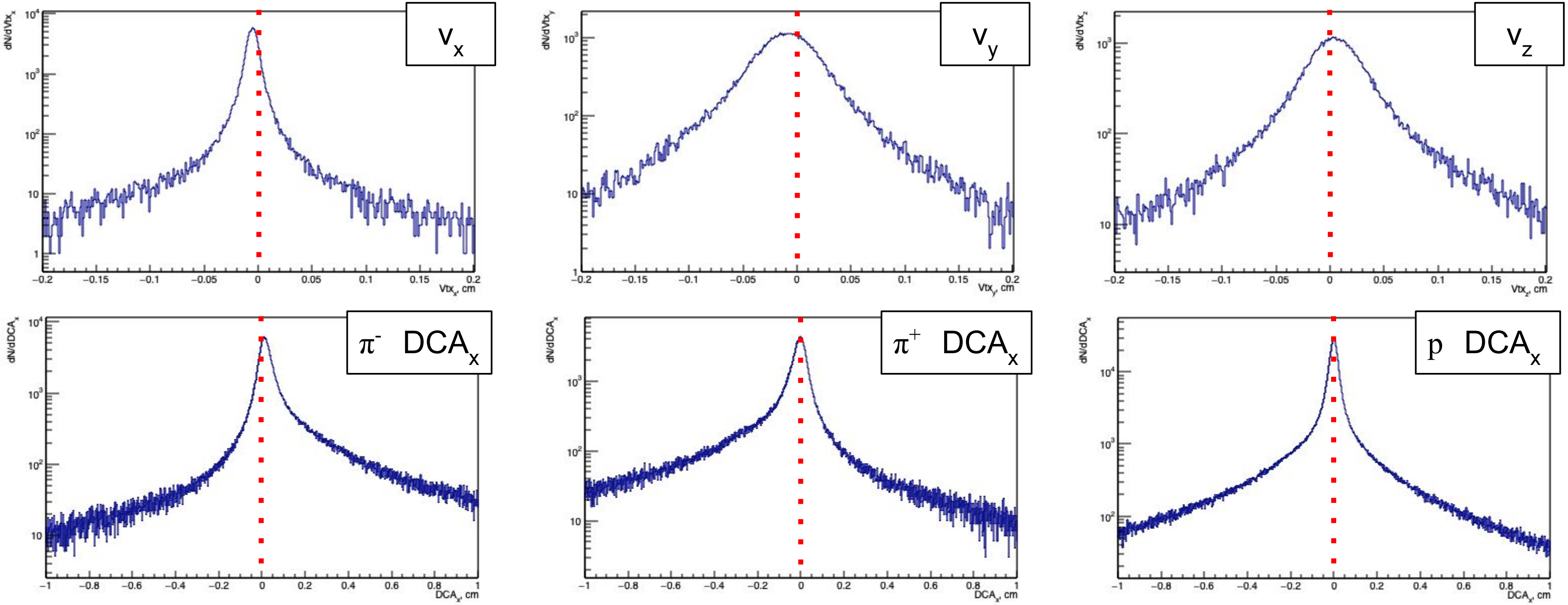


BMNROOT: bmnroot-digi branch from 2 August 2021

TOF400 geometry: create_rootgeom_TOF400_RUN8.C

FHCal digitizer: code from zdc_dev branch

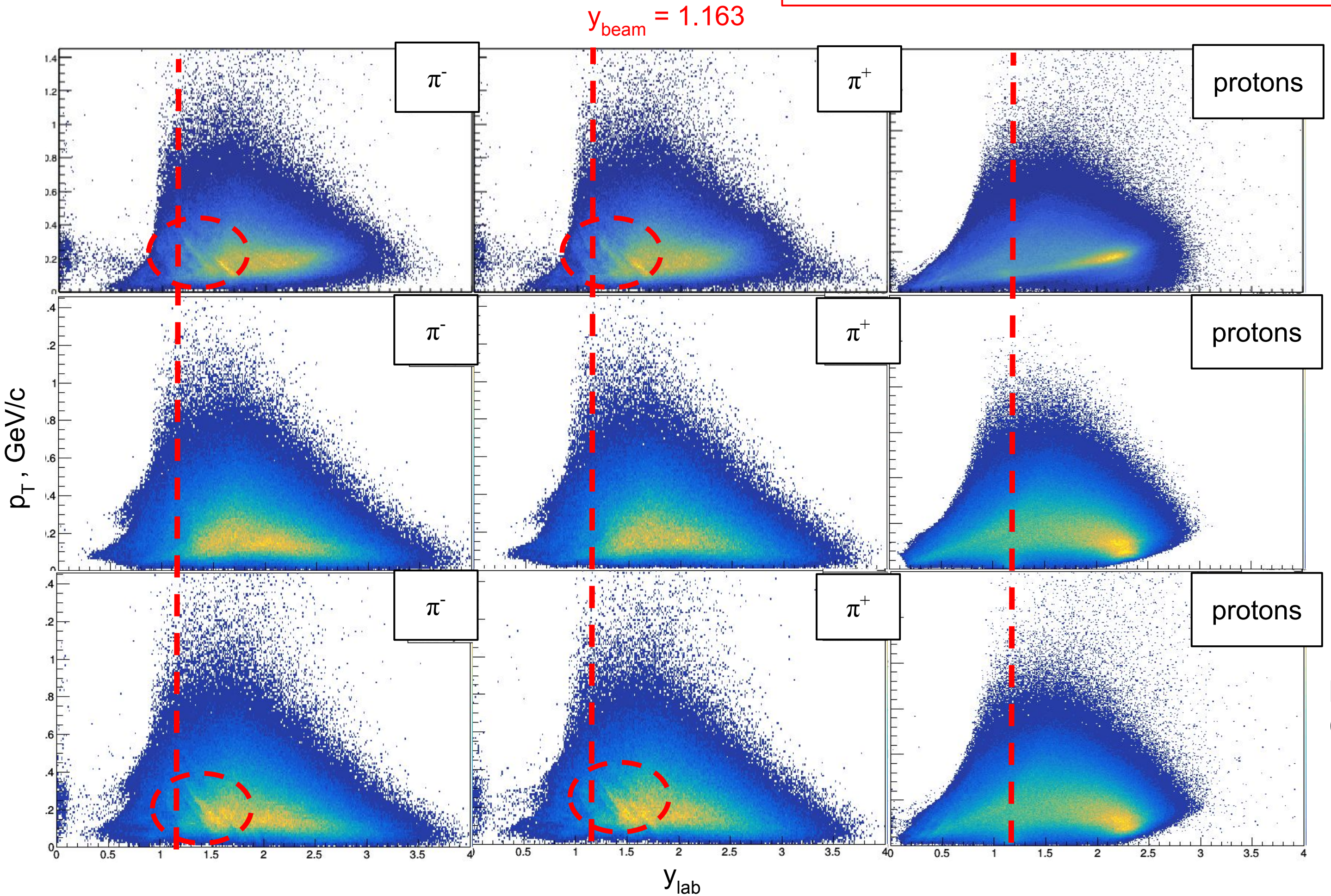
Reconstructed vertex position and DCA



Asymmetry in reconstructed vertex position: bias of the magnetic field in tracking?
Asymmetry in DCA of π^- and π^+: use only protons for collision vertex reconstruction?

Acceptance: tracking only

Extrapolation according to the particle mass is important
zig-zag structures for reco-track of pions



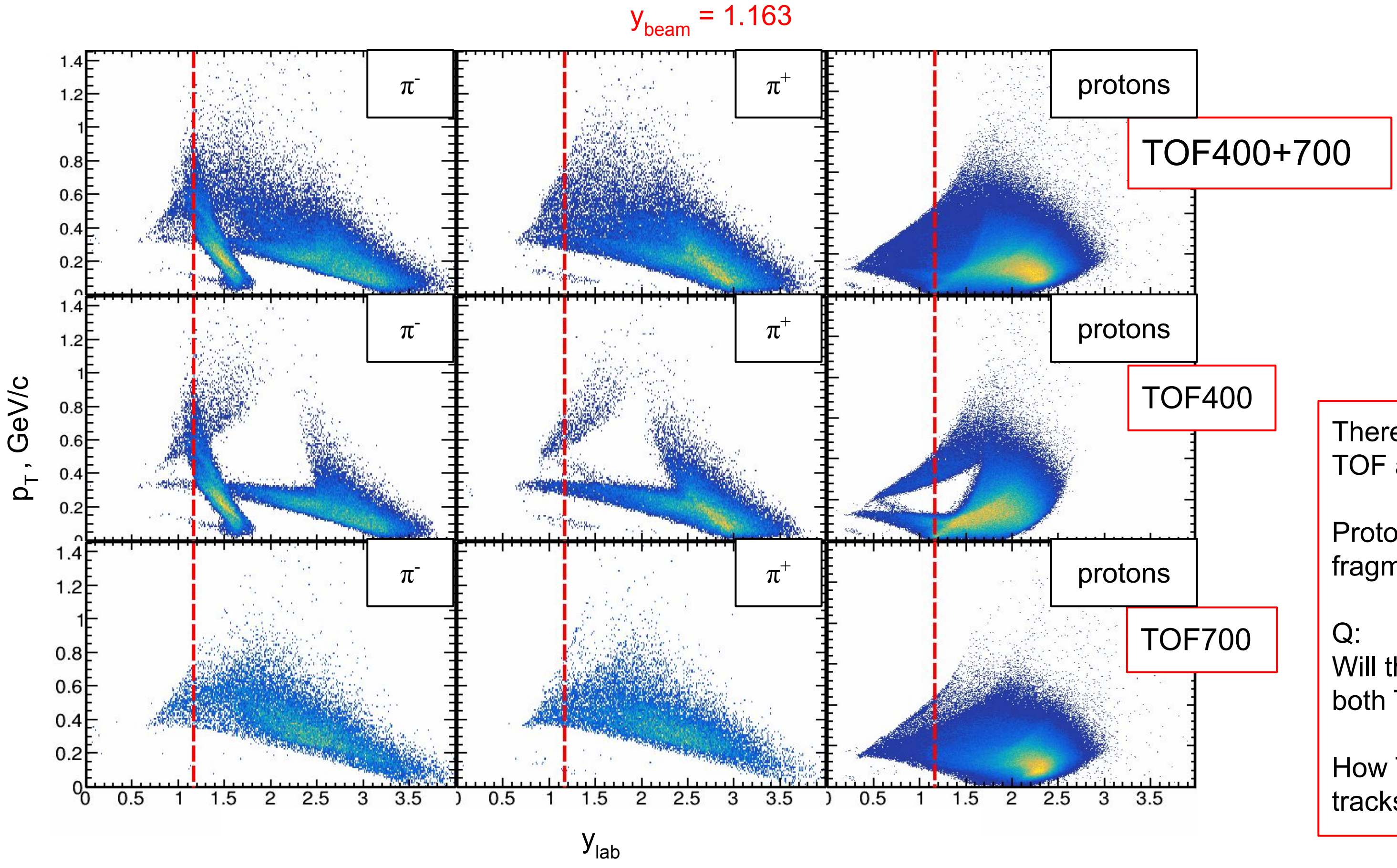
Momentum at 1st track hit

Momentum at Z=0 from MC tracks

Momentum at Z=0 using PDG (extrapolated reco tracks)

Acceptance: tracking + TOF PID

Momentum extrapolated to z=0 using PDG;
Require matched TOF hit



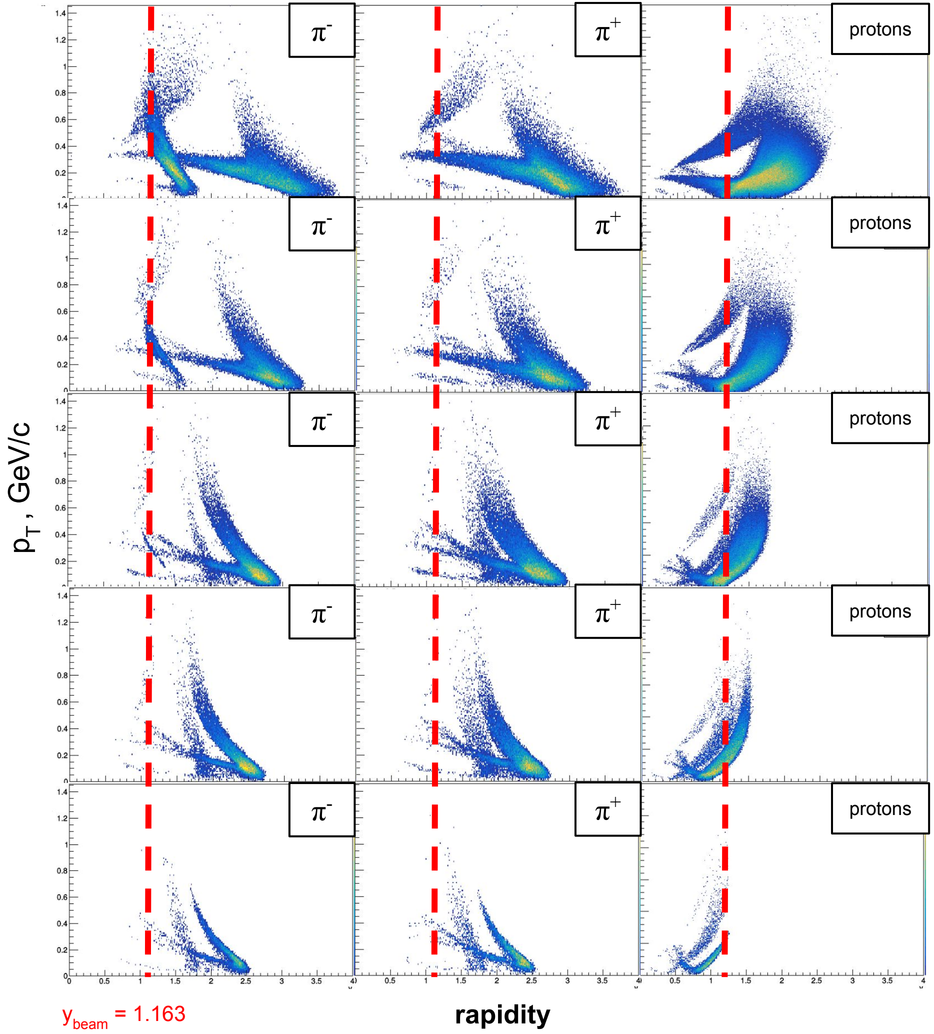
There are no pions at midrapidity in TOF acceptance

Proton acceptance is very fragmented

Q:
Will there be track matching with both TOF400 and TOF700 hits?

How TOF hit is associated for the tracks that have hits in both TOFs?

TOF400 (RUN8) acceptance study



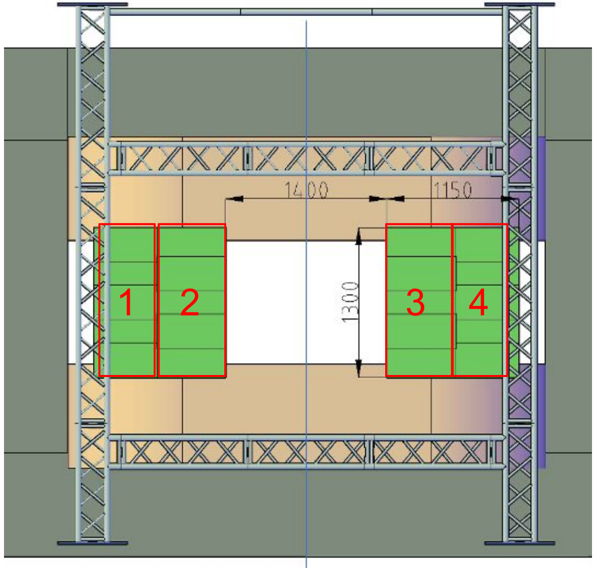
S1

S2

S3

S4

S5

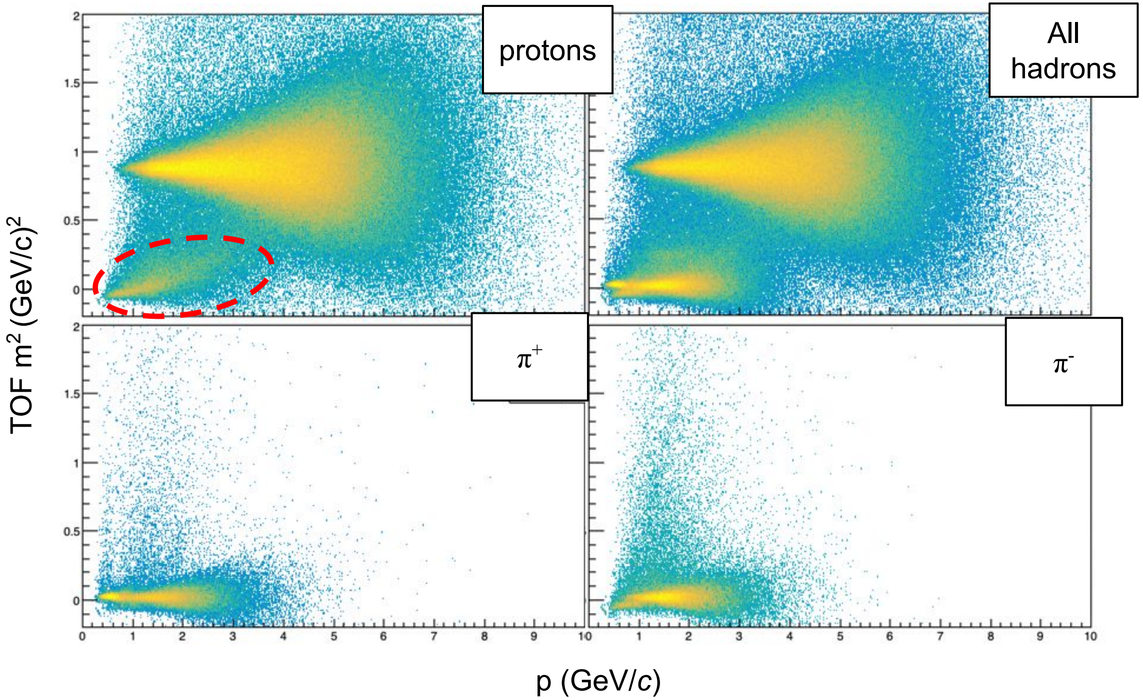


Tested setups prepared using create_rootgeom_TOF400_RUN8.C

TOF400	Box1	Box2	Box3	Box4
S1	-150	-95	95	150
S2	-200	-145	145	200
S3	-250	-195	195	250
S4	-300	-245	245	300
S5	-350	-295	295	350

TOF400 acceptance needs to be optimized!

Particle identification with TOF400 + TOF700

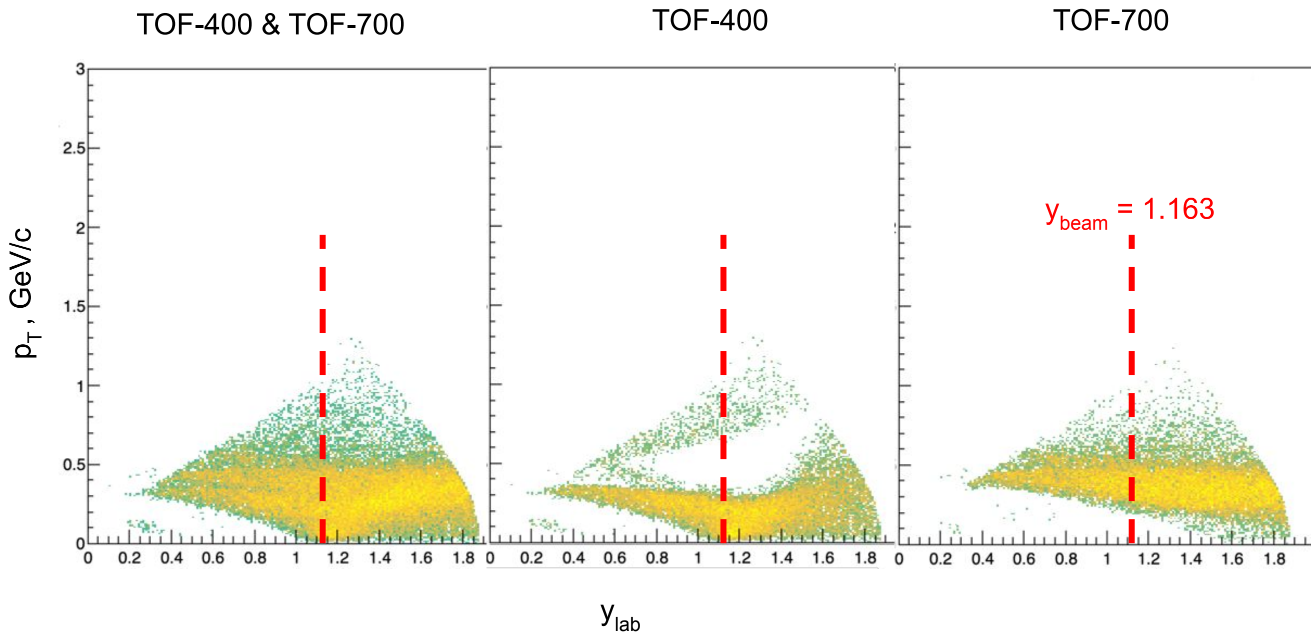


Currently BmnTofMatching allows only matching of tracks with a hit from either TOF-400 or TOF-700, but not in both

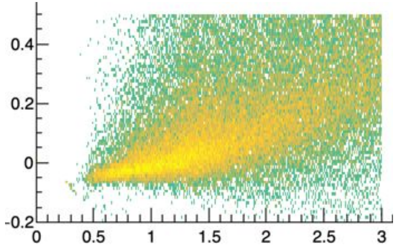
Q: can this be fixed?

Observe mismatch for protons when proton’s track is matched pion’s TOF hit

Particle identification: a closer look at the mismatched protons



Additional cuts for protons:
$0 < p < 3$ GeV/c
$m^2 < 0.5$ (GeV/c²)²

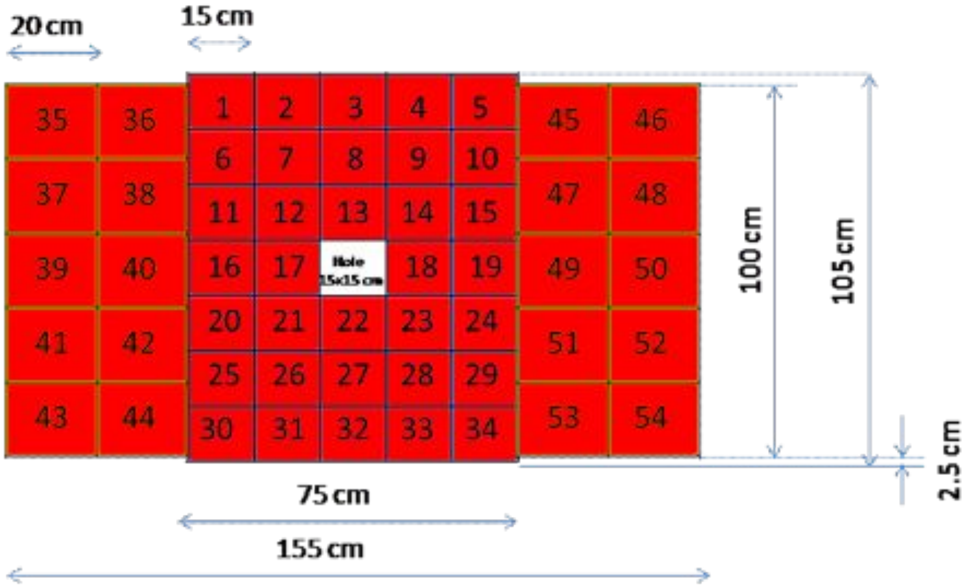


What can be done to improve the track to TOF hit matching?

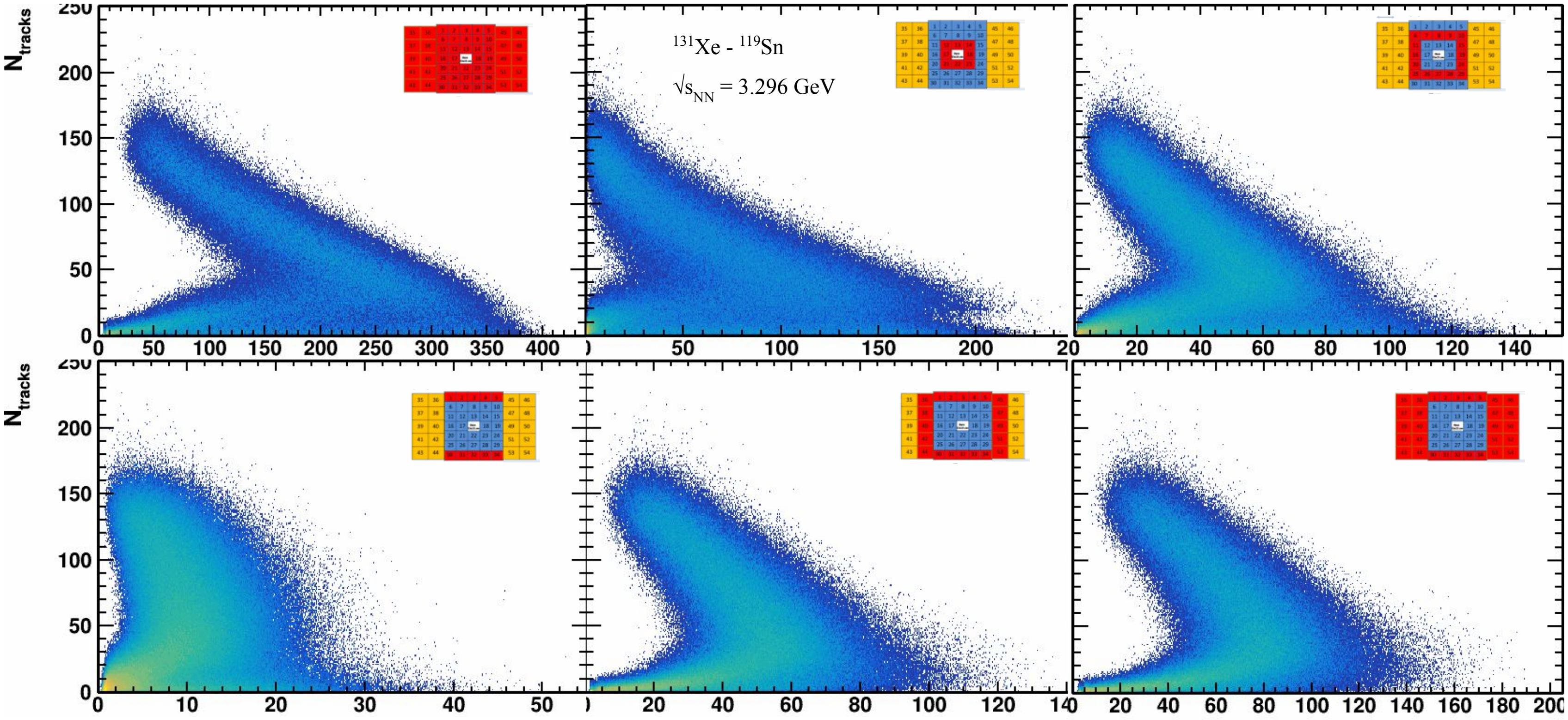
FHCal studies

Geometry file: zdc_oldnames_CBM_20mods_NICA_34mods_54mods_hole_Zpos_878.1cm_Xshift_49.50cm_Yshift_0.0cm_rotationY_0.0deg_v1.root (FHCal shifted on X axis by 49.5 cm)

FHCal digitizer provided by S. Morozov was used (link)

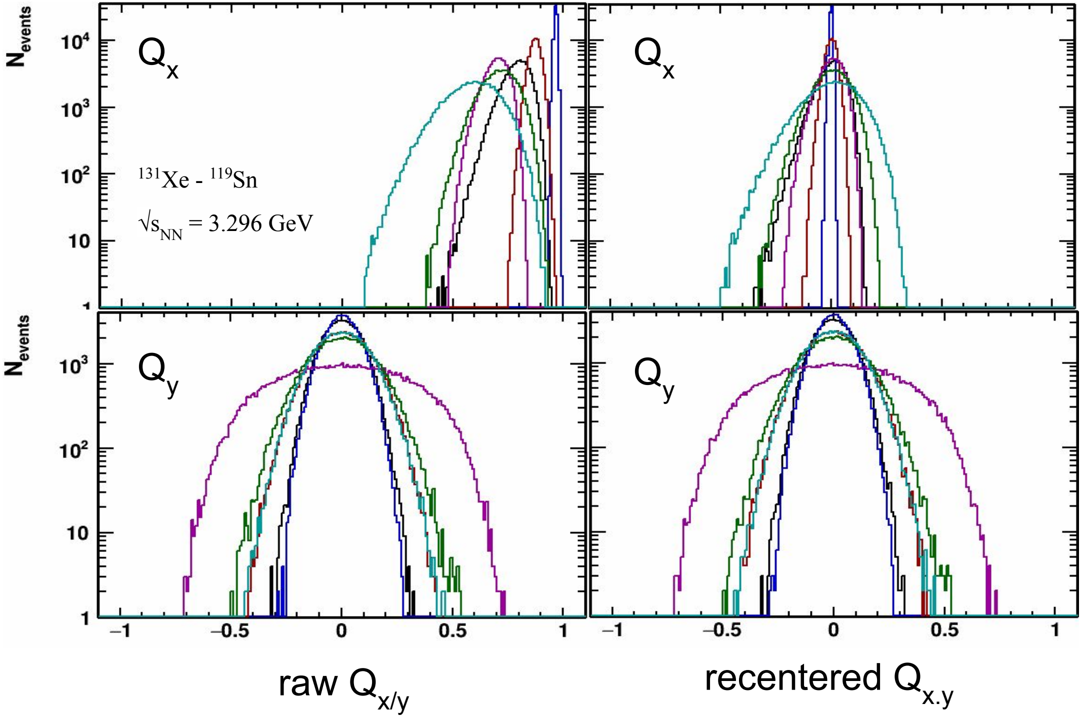


Multiplicity in tracking system vs. E_{dep} in FHCal

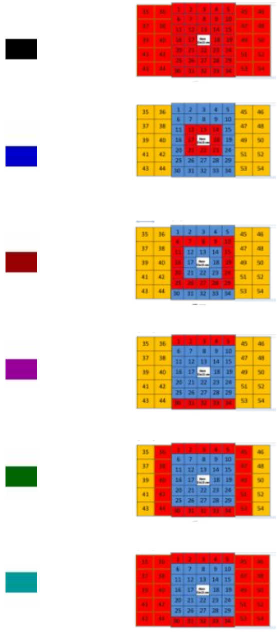


Energy sum in FHCal subevents

Q-vector distributions for mid-central collisions (b = 5-6 fm)



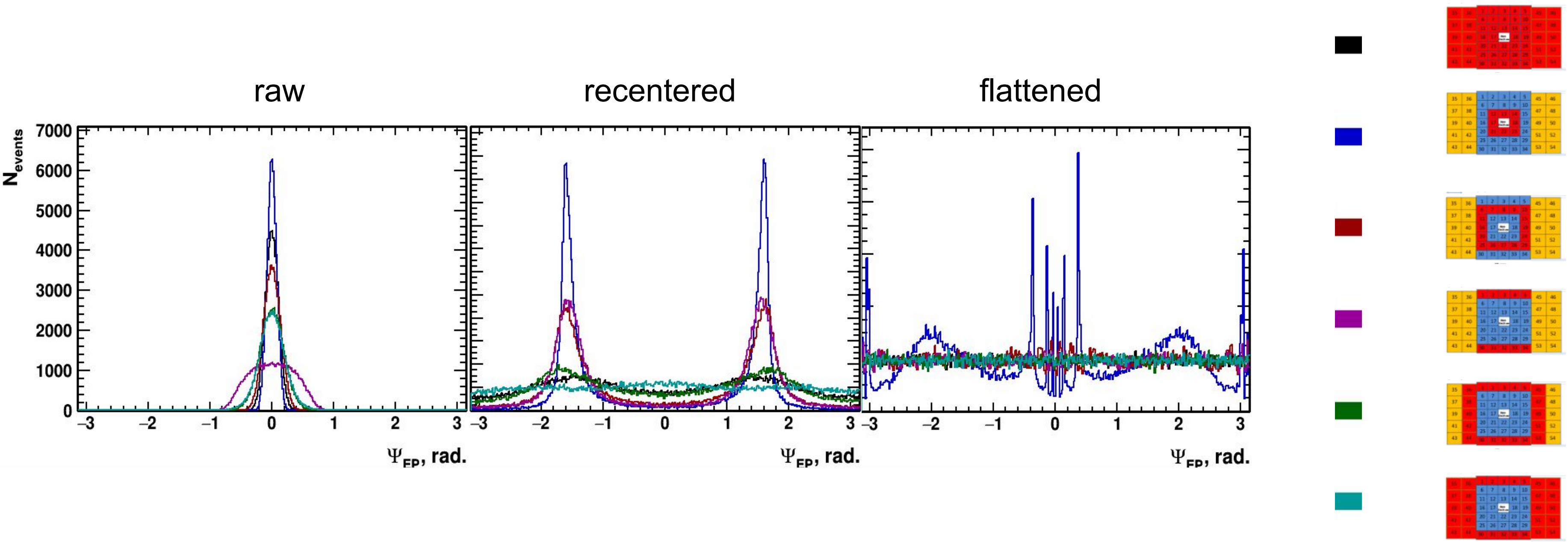
$$Q_1 = \sum_{k=0}^{M} E_{dep} e^{i\varphi_k} = \begin{cases} \sum\limits_{k=0}^{M} E_{dep} \cos\varphi \\ \sum\limits_{k=0}^{M} E_{dep} \sin\varphi \end{cases}$$



Strong effect (shifts) of Q_x due to the field of dipole magnet

Event plane distributions for mid-central collisions (b = 5-6 fm)

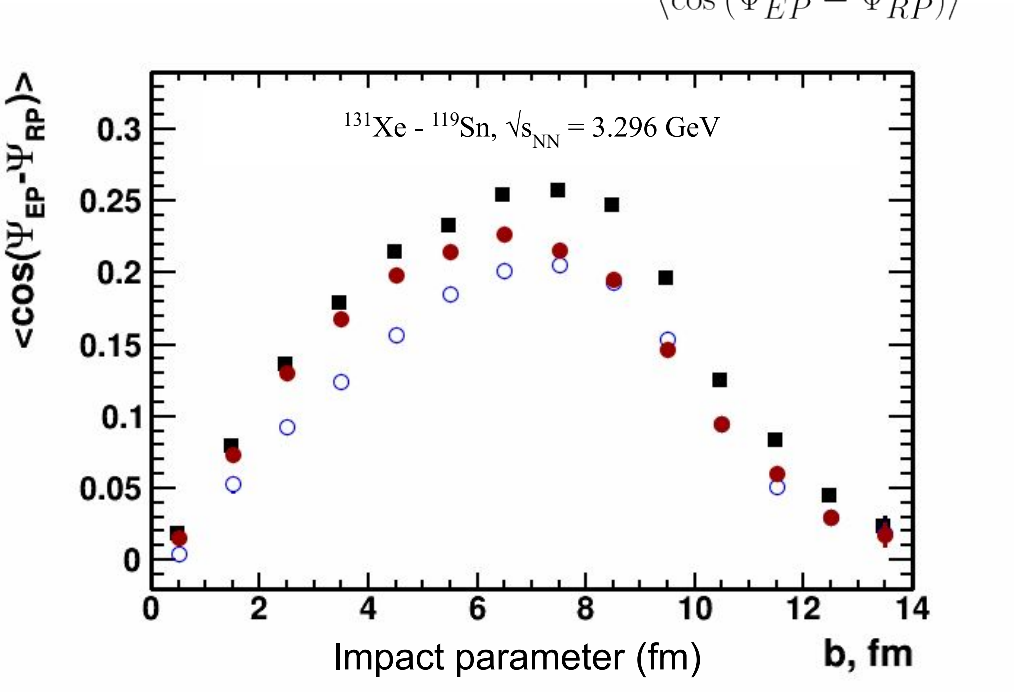
$$\Psi_{EP} = \tan^{-1}\left(\frac{Q_{1y}}{Q_{1x}}\right)$$

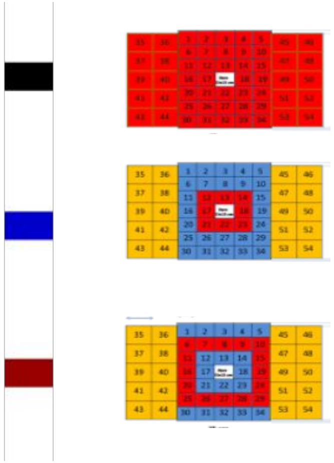


Further investigation of acceptance corrections is needed

1^{st} order event plane resolution correction factor

Observable for directed flow: $$v_1 = \frac{\langle \cos(\varphi - \Psi_{EP}) \rangle}{\langle \cos(\Psi_{EP} - \Psi_{RP}) \rangle}$$





Summary

Anisotropic flow at BM@N energy range:

- Cascade models fail to reproduce v_n and the models with incorporated mean-field theory with different EoS are required
- There's a difference between $v_2(p_T)$ of protons and neutrons

Xe+Sn data with BM@N GEANT4 simulation and CA-tracking reconstruction:

- Asymmetry in reconstructed vertex position and DCA of pions
- Currently, there's a mismatching for protons where the proton track is associated with the pion hit in TOF400 / TOF700
- TOF400 acceptance should be optimized to improve acceptance of pions and protons, especially near mid-rapidity region
- Event plane determination using FHCal is implemented, corrections for the non-uniform acceptance should be further investigated

Backup

JAM microscopic model (ver. 1.90597)

NN collisions are simulated by:

- √sNN < 4 GeV: resonance production
- 4 < √sNN < 50 GeV: soft string excitations
- √sNN > 10 GeV: minijet production

RQMD with relativistic mean-field theory (non-linear σ-ωmodel) implemented in JAM model

Different EOS were used:

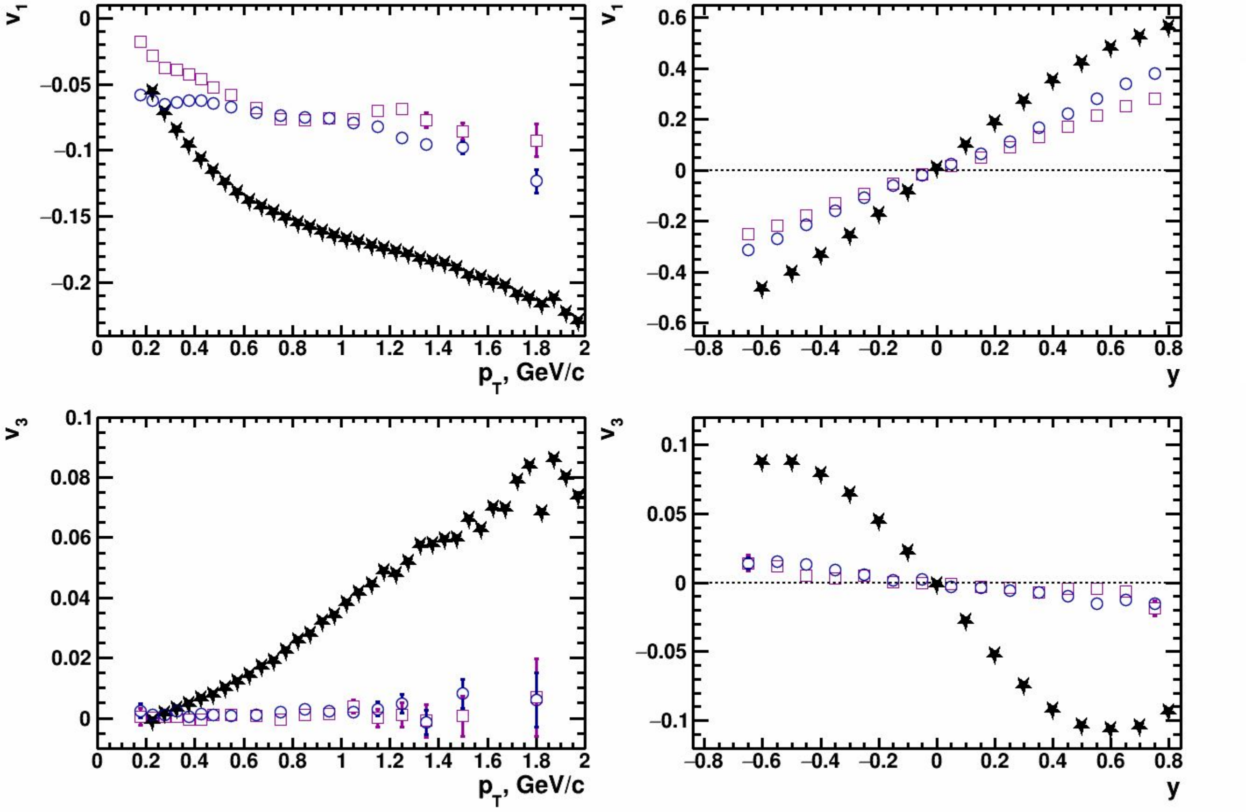
•**MD3** (momentum-dependent potential): K=380 MeV, m*/m=0.65, Uopt(∞)=37

•**MD2** (momentum-dependent potential): K=210 MeV, m^∗/m=0.83, Uopt(∞)=67

•**NS1** (standard potential): K=380 MeV, m*/m=0.83

•**NS2** (standard potential): K=210 MeV, m*/m=0.83

$v_{1,3}(p_T,y)$ in Au+Au $\sqrt{s_{NN}}$=2.4 GeV: model vs. HADES data



Au+Au, 20-30% **(6<b<9 fm)**

○ **DCM-QGSM-SMM**

□ **UrQMD cascade**

★ **HADES data**

Experimental data points were taken from:

Phys. Rev. Lett. **125** (2020) 262301

Kinematic cuts:

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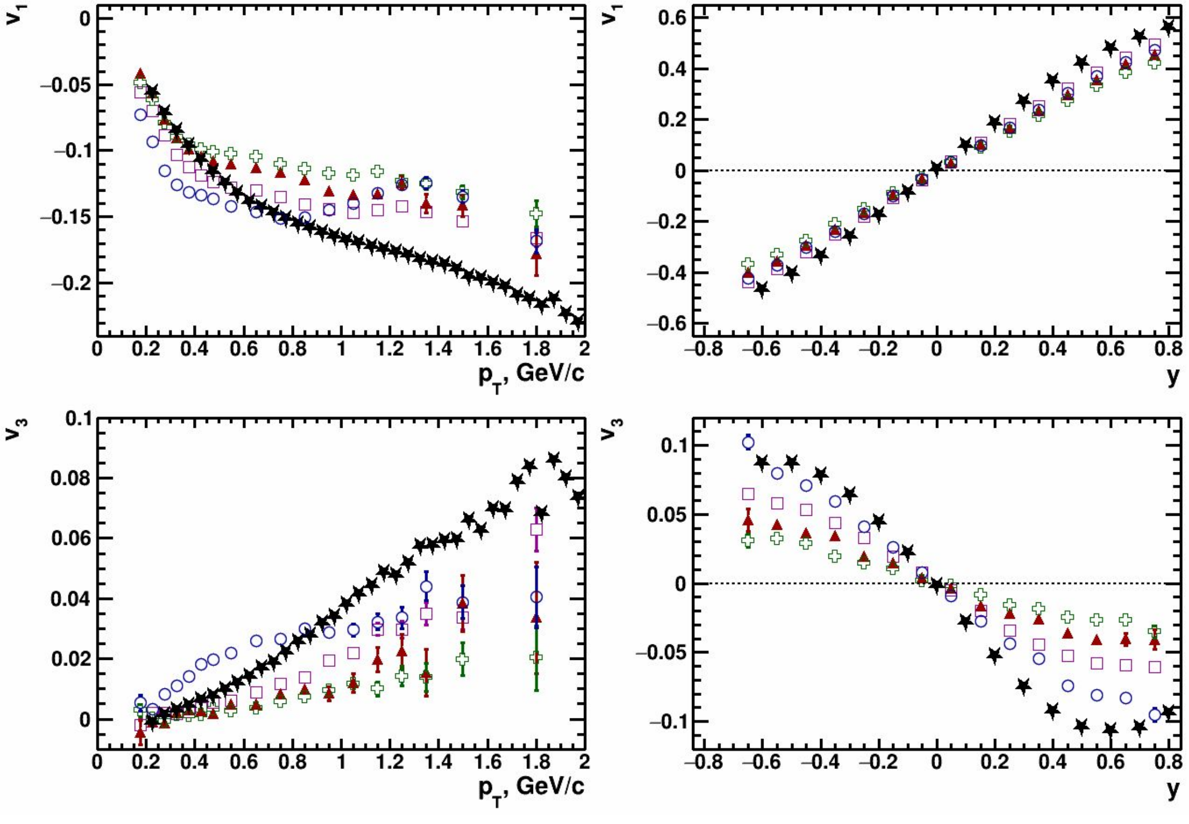

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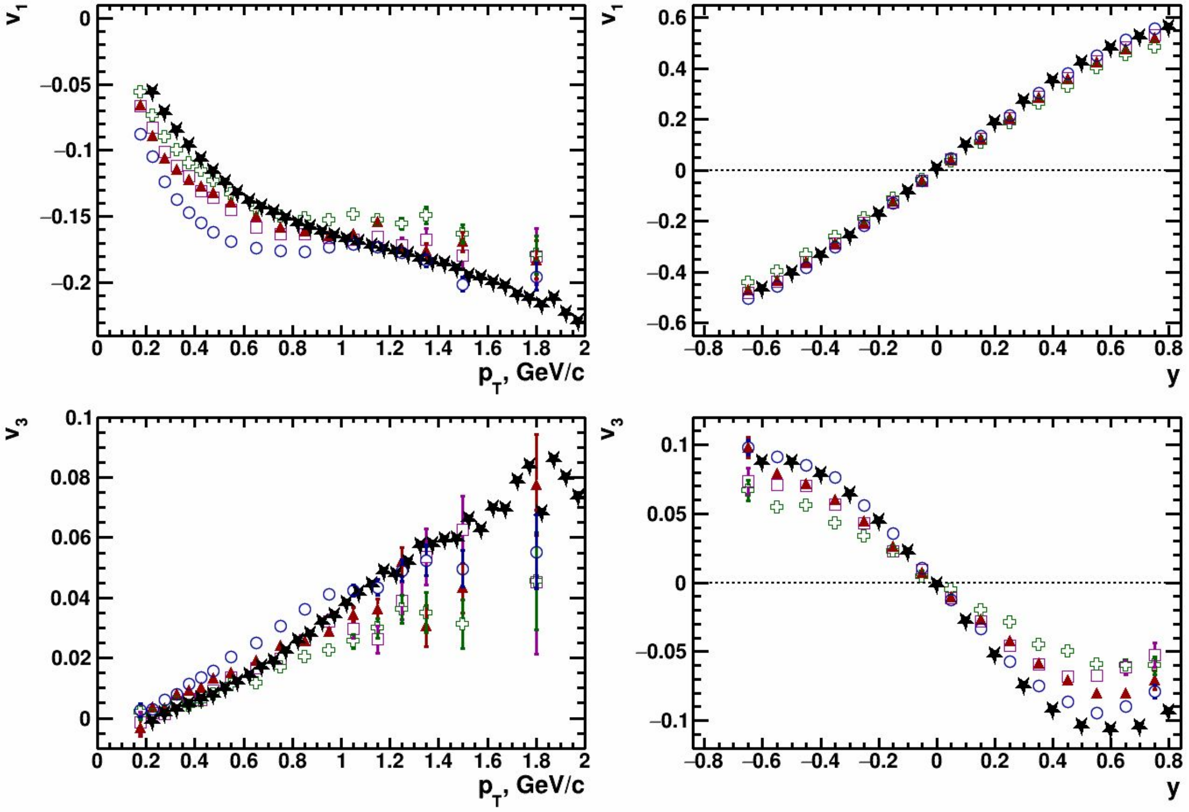

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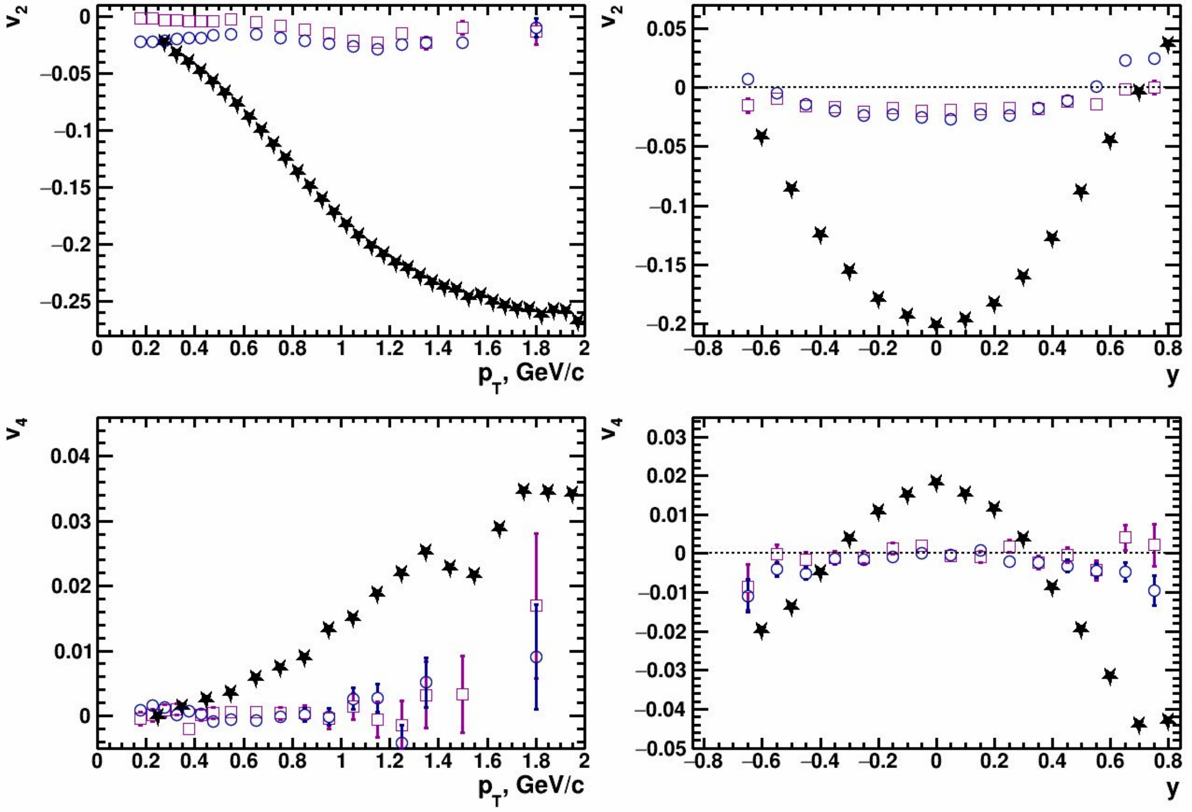
$v_{2,4}(p_T,y)$ in Au+Au $\sqrt{s_{NN}}$=2.4 GeV: model vs. HADES data



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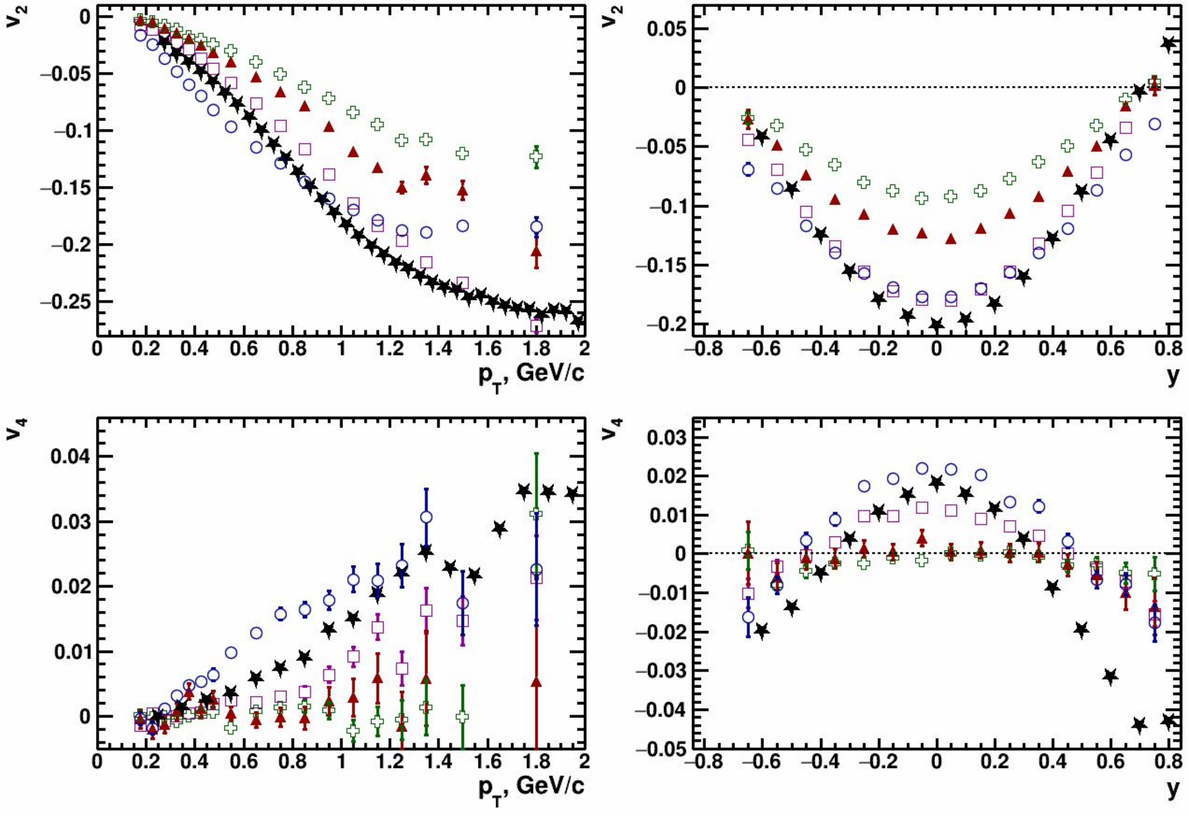
$v_{2,4}(p_T,y)$ in Au+Au $\sqrt{s_{NN}}$=2.4 GeV: model vs. HADES data



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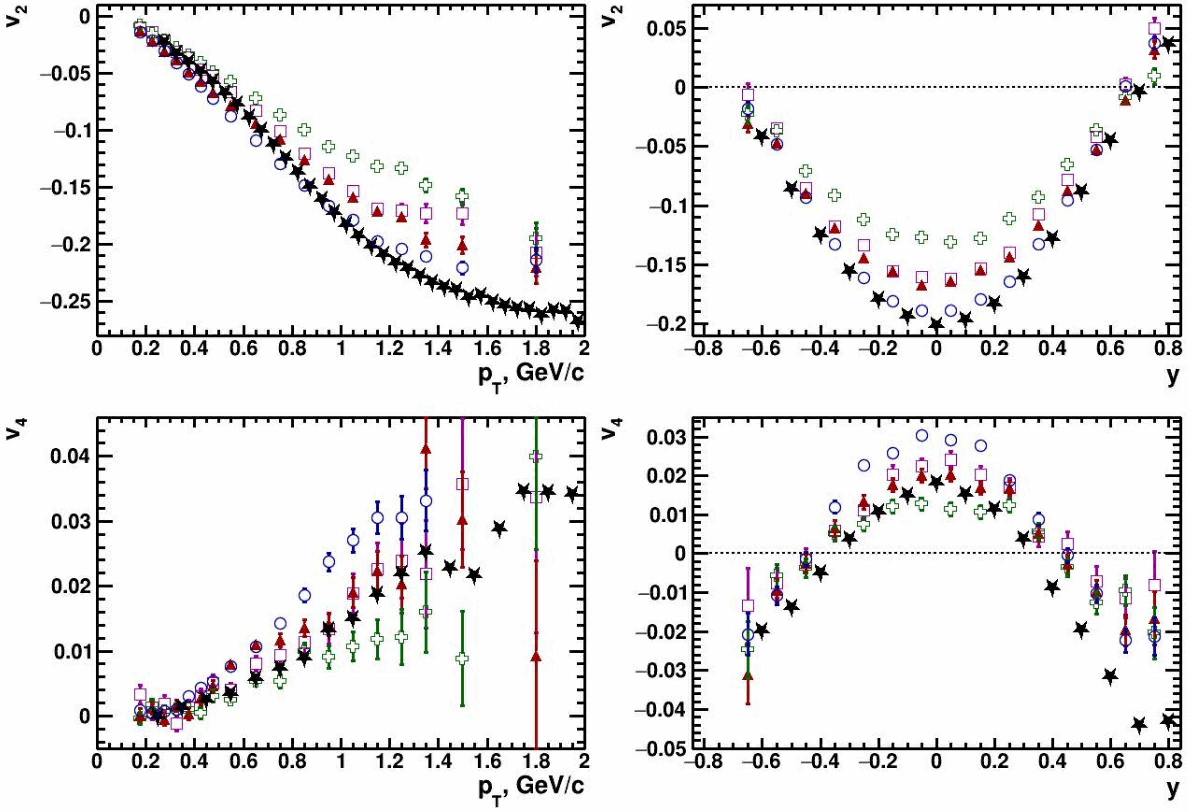
$v_{2,4}(p_T,y)$ in Au+Au $\sqrt{s_{NN}}$=2.4 GeV: model vs. HADES data



JAM, Au+Au, 20-30% (6<b<9 fm)

- ○ **MD3**
- □ **MD2**
- ▲ **NS1**
- ✚ **NS2**
- ★ **HADES data**

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Phys. Rev. Lett. **125** (2020) 262301

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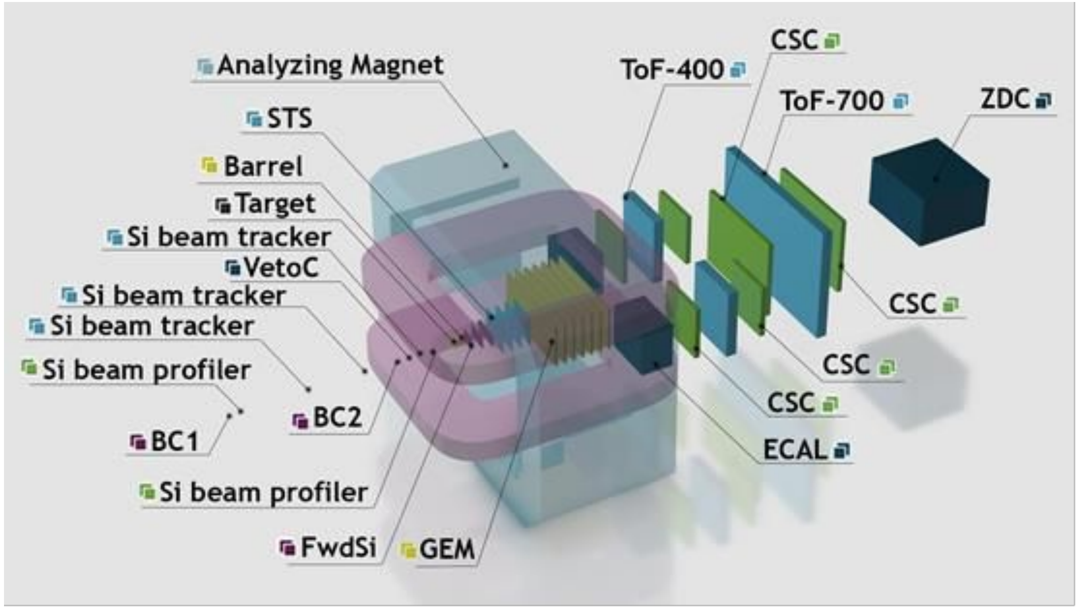
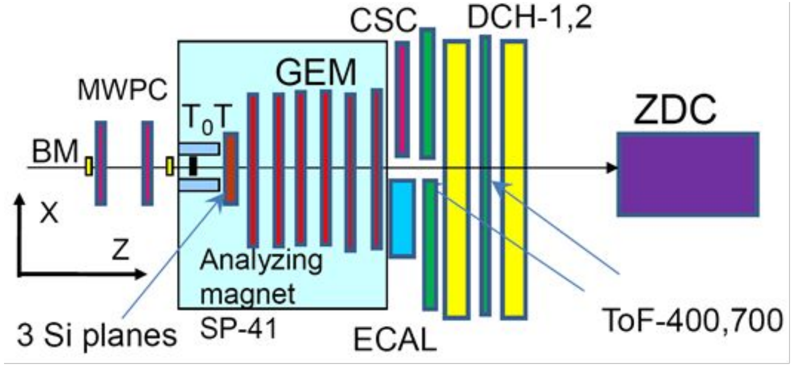
Overview of the BM@N subsystems relevant for charged hadron flow analysis

BMN setup overview



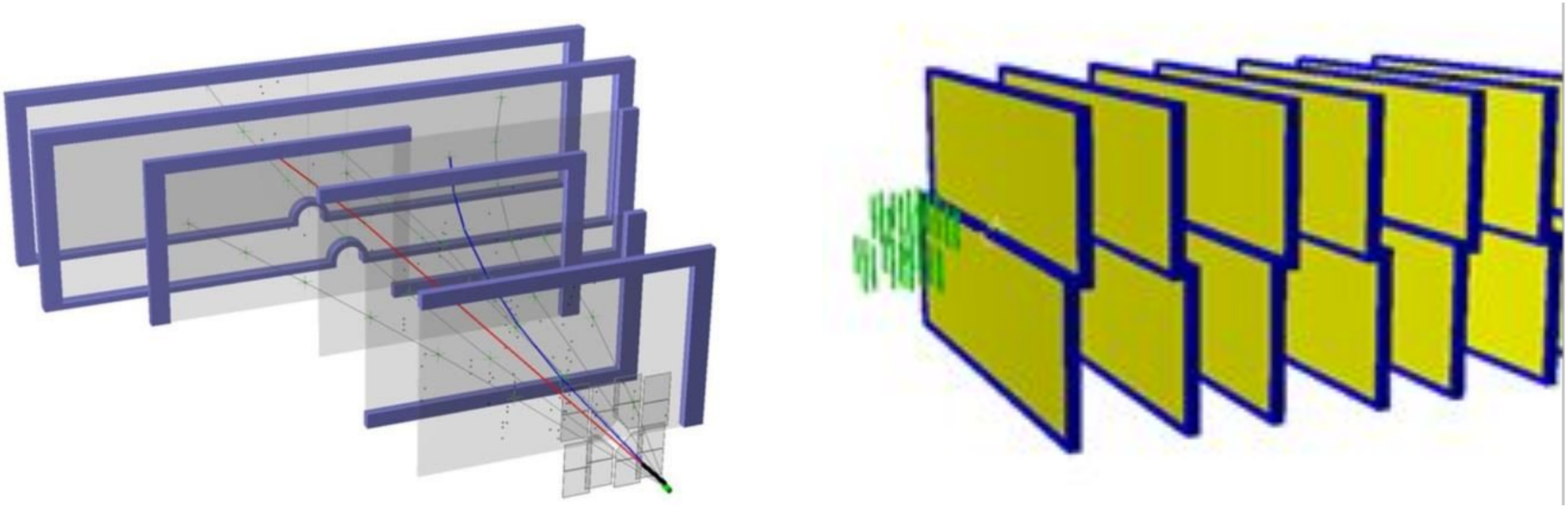


Q: Do we have all planned detectors in the simulations?

Which are still missing?

Hybrid tracking system

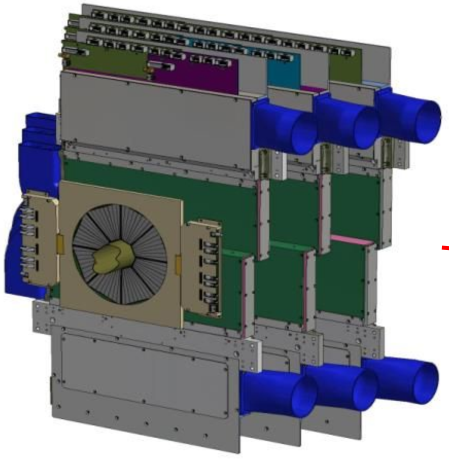
based on 3 front silicon FwdSi planes and 7 GEM planes

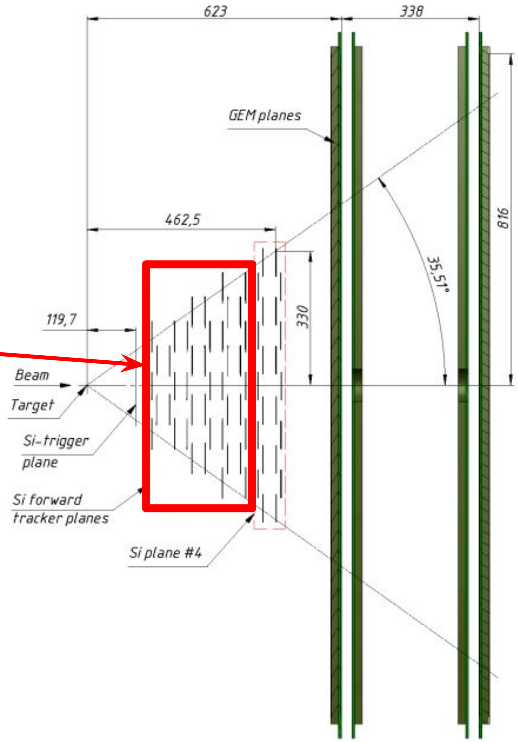


Q: How CA tracker was optimized for BM@N?
When it will be integrated into the BMNROOT version,
which will be used for real data analysis?

Tracking system: FwdSi

consist of three planes, each made up of two halfs



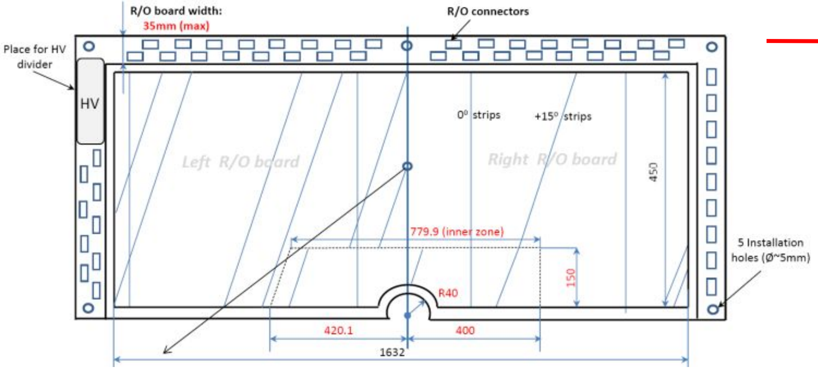


- A module of the FwdSi silicon detector consists of two double-sided DSSD silicon detectors that are wired from strip to strip
- Sensitive volume of the detector is 63x63x0.3 mm^3.
- Step for the p+ (n+) side is 95 (103) µm.
- Stereo angle between stripes is 2.5 degrees, the number of stripes on each side is 640

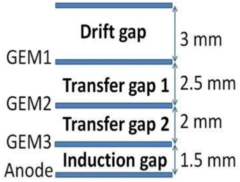
Is this is the design (3 FwdSi planes) planned to be used in 2022 data taking, any changes foreseen?

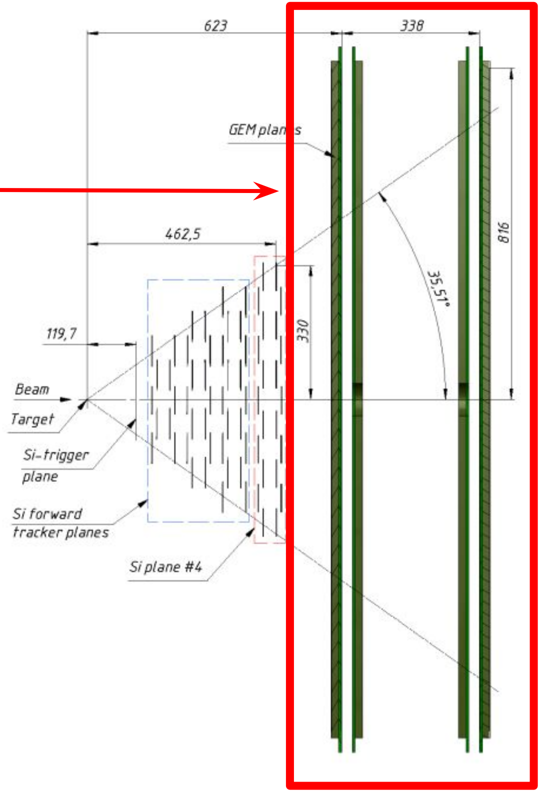
Tracking system: GEM

The measuring 2D readout plane of the GEM detector is 1632 × 450 mm^2



schematic view of the transverse structure of a triple GEM detector





- Signal is read in two coordinates by a set of parallel metal strips on the anode readout board.
- Vertical inclination angles of the lower layer strips (X coordinate) and upper layer strips (X (or Y) coordinate) ares 0 and 15 degrees.
- Strip’s width along the X and X direction is 0.68 and 0.16 μm.
- Strip pitch for both layers is 800 μm.
- Groups of 128 strips are connected to the ASIC inputs via a connector on the read plane.

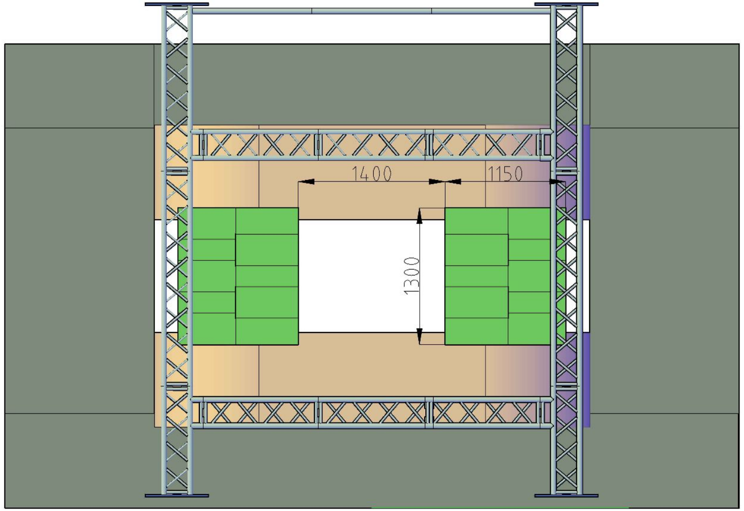
Is this is the design (7 GEM planes) planned to be used in 2022 data taking, any changes foreseen?

Time of Flight: TOF-400 & TOF-700

Time resolution of the ToF system 80–100 ps

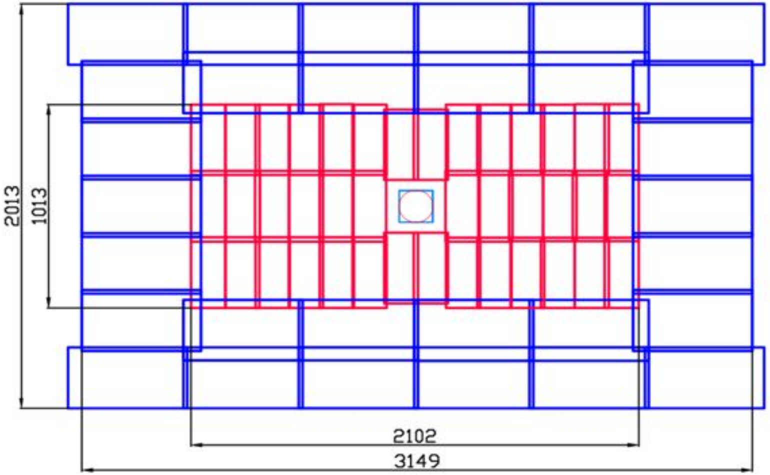
Schematic view of the (5+5) mRPCs TOF-400 wall
and its position behind the analyzing magnet

@ 4m from the target



Placement of 40 "warm" and 18 "cold" mRPCs
on the plane of the TOF-700 wall

@ 7m from the target



Is this is the design (TOF-400+700) planned to be used in 2022 data taking, any changes foreseen?

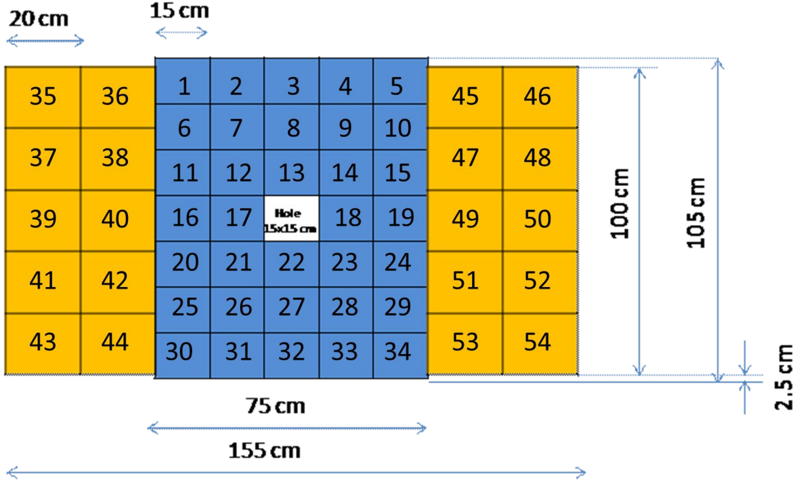
FHCAL calorimeter

FHCal Calorimeter is located at a distance of 9 m from the target and consists of 54 individual modules in the transverse plane

Outer part: 20 modules with transverse dimensions 20 × 20 cm^2

Inner part: 34 modules with transverse dimensions 15 × 15 cm^2

beam hole in the center with a transverse dimension of 15 x 15 cm^2



Is this is the design (FHCAL module layout) planned to be used in 2022 data taking, any changes foreseen?

Simulation: geometry configurations

Subsystem	**Geometry file**	**comments**
Cave	Cave.geo	
Pipe	none	
Target	Target_0cm.geo	Single event in (0,0,0)
Magnet	magnet_modified.root	Field = 0.81 T
Tracking system	sigems2021.root	3 Fwd Si + 7 GEM plates
TOF400	TOF400_RUN8.root	5 + 5 mRPC
TOF700	tof700_run7.root	40 “warm” + 18 “cold” mRPC
BD	none	
Ecal	ECAL_v3_run7_pos4.root	Placed after GEM plates
ZDC	zdc_oldnames_CBM_20mods_NICA_34mods_54mods_hole_Zpos_878.1cm_Xshift_49.50cm_Yshift_0.0cm_rotationY_0.0deg_v1.root	34 modules 15x15 cm^2 + 20 modules 20x20 cm^2

Q: Is it possible to include the target material (thickness) into simulations?

Simulated output structure

Simulated (sim)

C++ Class	Name
FairMCEventHeader	MCEventHeader
TClonesArray(CbmMCTrack)	**MCTrack**
TClonesArray(CbmStsPoint)	StsPoint
TClonesArray(BmnTOF1Point)	TOF400Point
TClonesArray(BmnTOFPoint)	TOF700Point
TClonesArray(BmnZdcPoint)	MCEventHeader

Note:
sim information is stored in a separate files from reco
Both set of files are needed for simulation studies

Both (reco & sim) trees are called “bmndata”:
Q: use different names to avoid confusion?

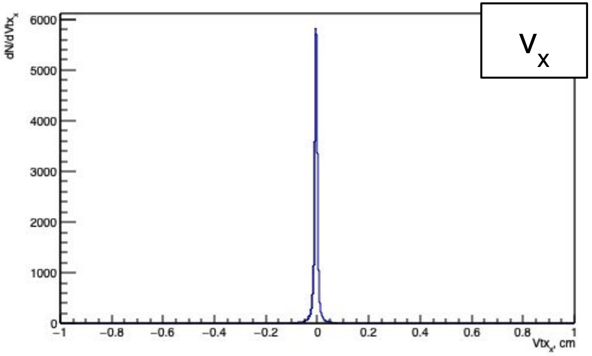
Reconstructed (reco)

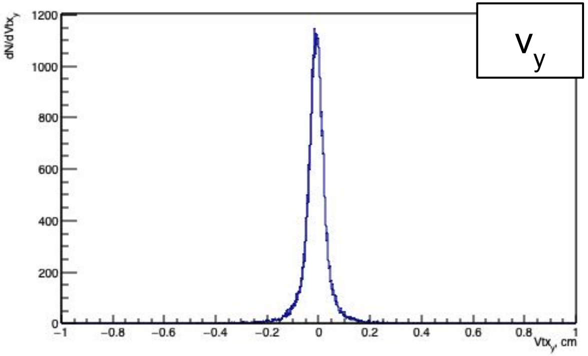
C++ Class	Name
FairEventHeader	EventHeader
CbmVertex	**PrimaryVertex**
BmnZDCEventData	**ZDCEventData**
TClonesArray(CbmStsDigi)	StsDigi
TClonesArray(CbmStsDigiMatch)	StsDigiMatch
TClonesArray(CbmStsCluster)	StsCluster
TClonesArray(CbmStsCluster)	StsClusterCand
TClonesArray(CbmStsHit)	StsHit
TClonesArray(CbmStsTrack)	**StsTrack**
TClonesArray(CbmStsTrackMatch)	**StsTrackMatch**
TClonesArray(BmnTofHit)	BmnTof400Hit
TClonesArray(BmnTofHit)	BmnTof700Hit
TClonesArray(BmnTofMatch)	**TofMatch**
TClonesArray(BmnZDCDigit)	ZDC

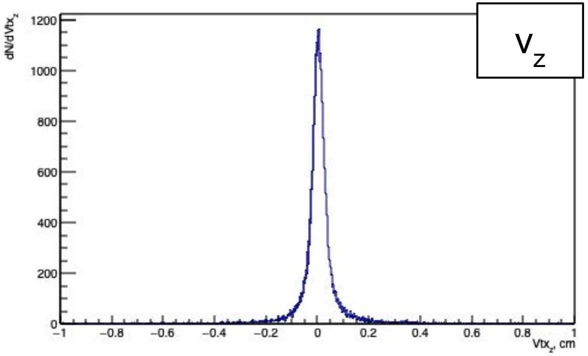
Performance plots from simulations

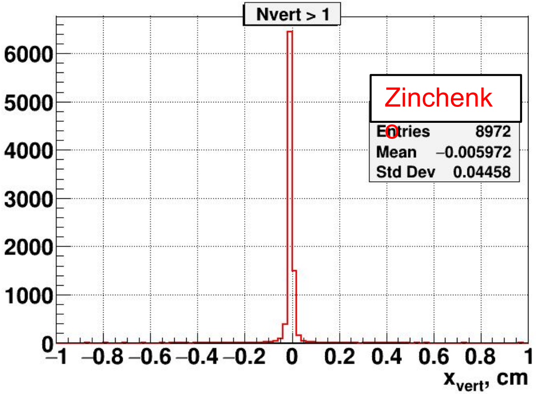
- Reconstructed vertex position
- Distance of closest approach (DCA)
- Number of track hits for Fwd-Si and GEM tracks
- track multiplicity vs. FHCal energy
- STS track extrapolation (π^-, π^+, protons)
- TOF matching
- p_T-y acceptance:
    - Tracking
    - TOF400 + Tracking
    - TOF700 + Tracking

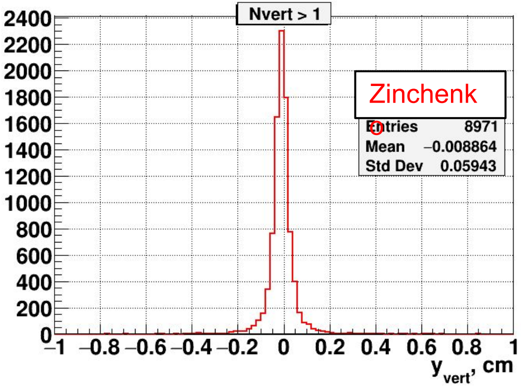
Reconstructed vertex: comparison with A. Zinchenko

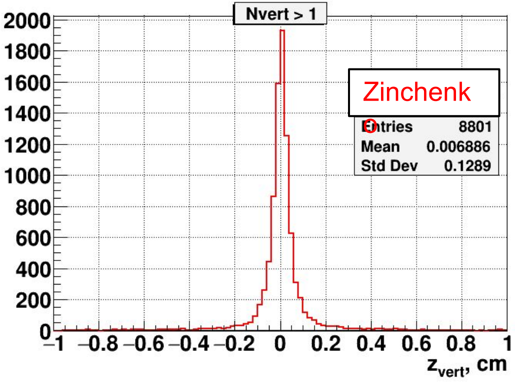






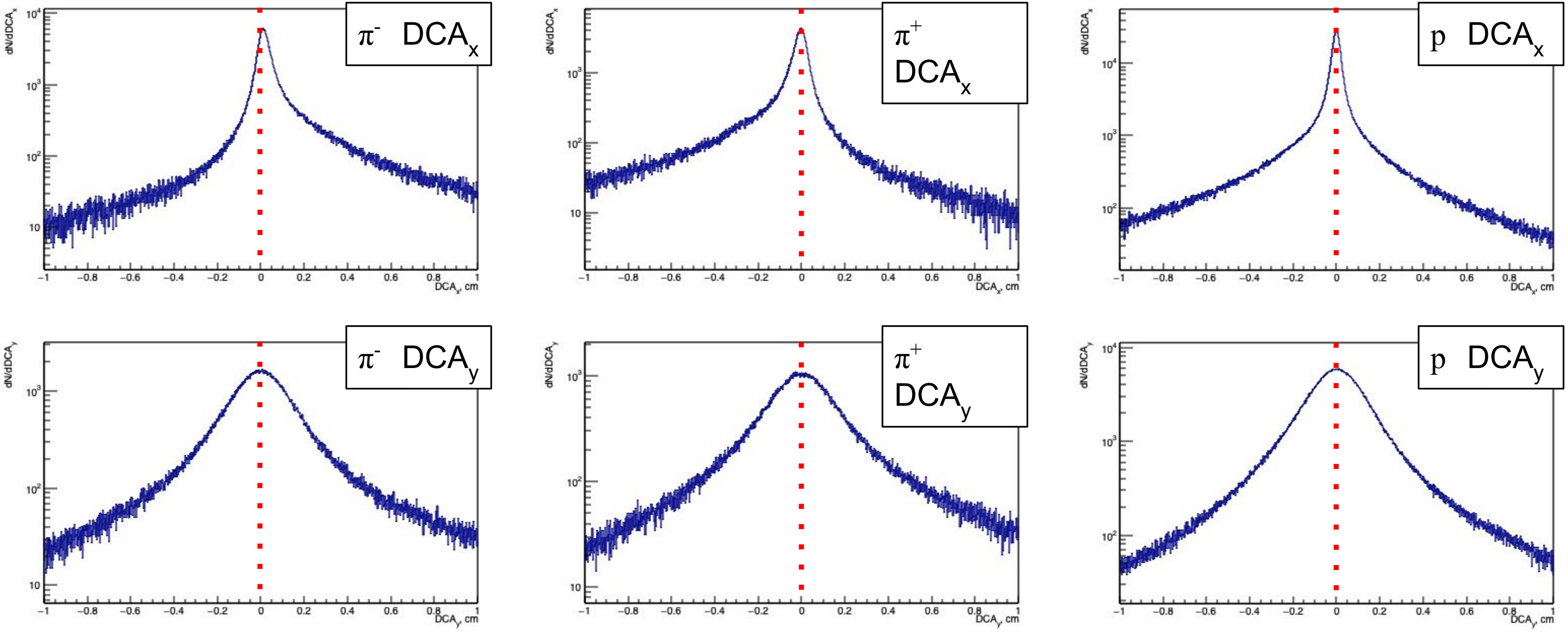






Consistent results

Distance of closest approach (DCA): primary π^+, π^+ and protons

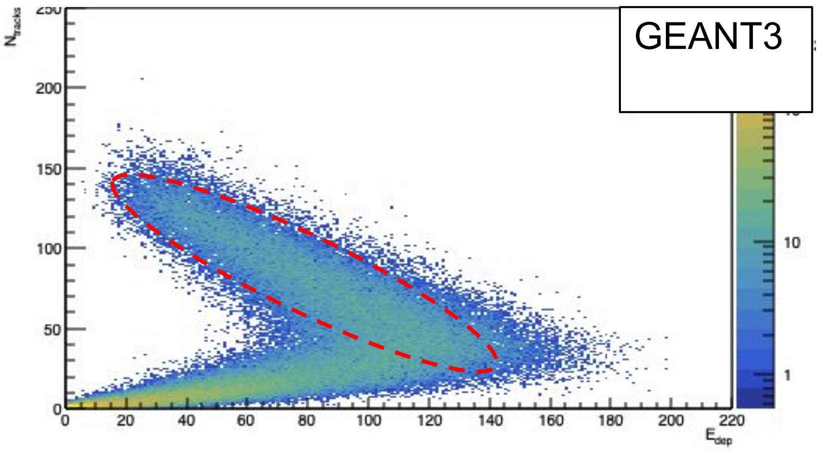


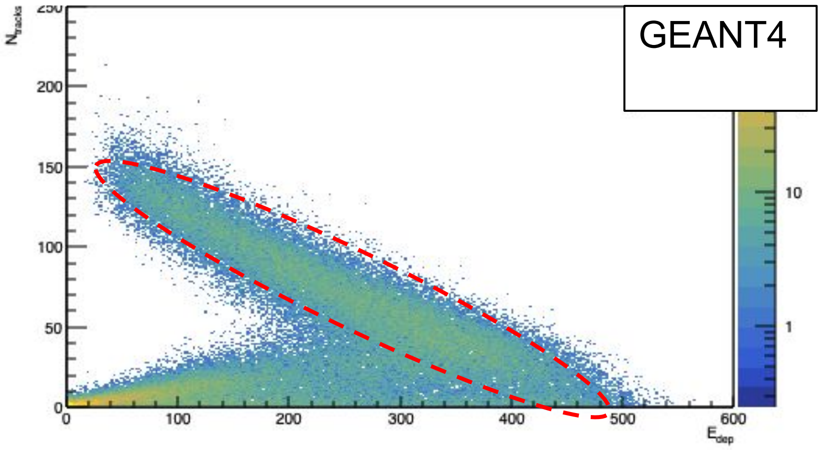
DCA$_x$ and DCA$_y$ are calculated at the reconstructed vertex position (DCA$_z$ = 0)

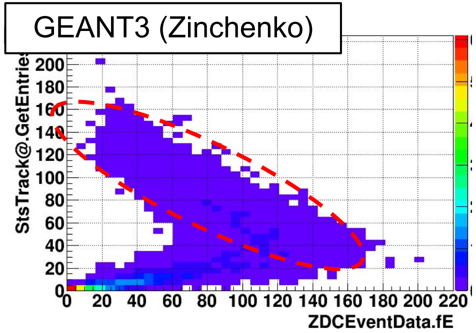
Q: Why π^- and π^+ DCA$_x$ are asymmetric, while protons are symmetric?

Use only protons for collision vertex reconstruction?

Track multiplicity vs. FHCal energy

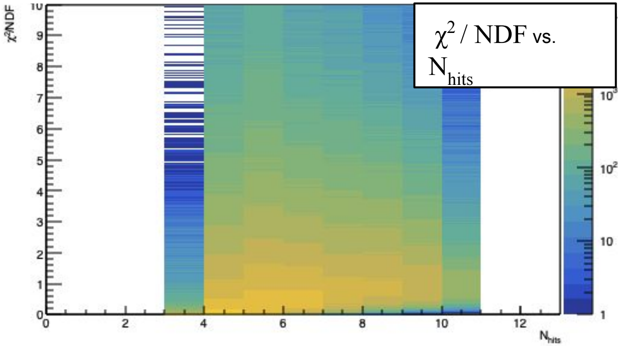


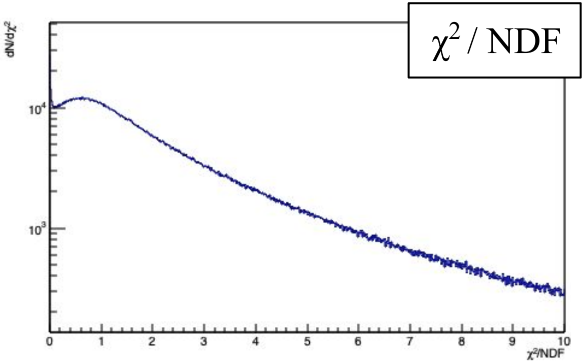


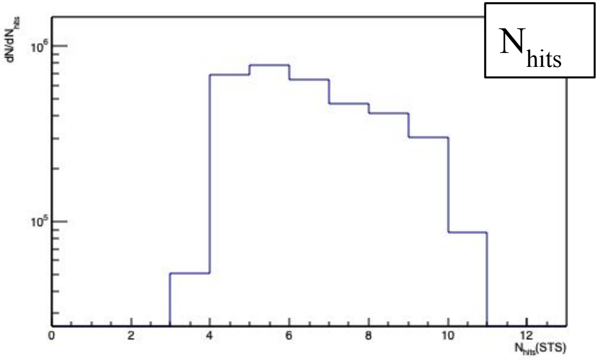


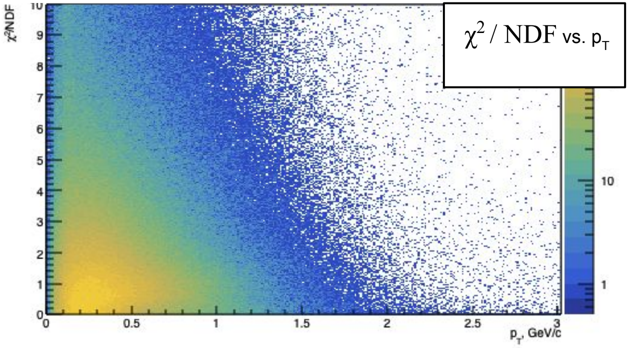
GEANT4 should be used to model the loss of
the projectile spectator fragment in the beam hole of the FHCAL

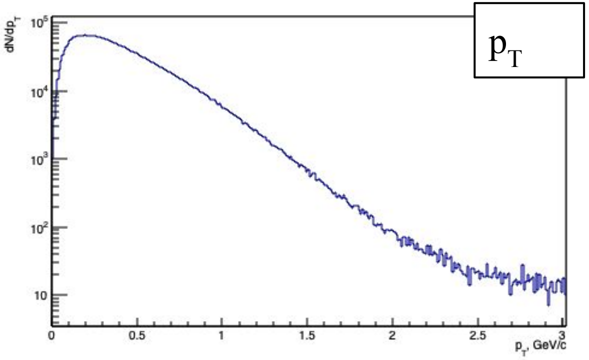
Number of track hits for Fwd-Si and GEM tracks


χ^2 / NDF vs. N_{hits}


χ^2 / NDF

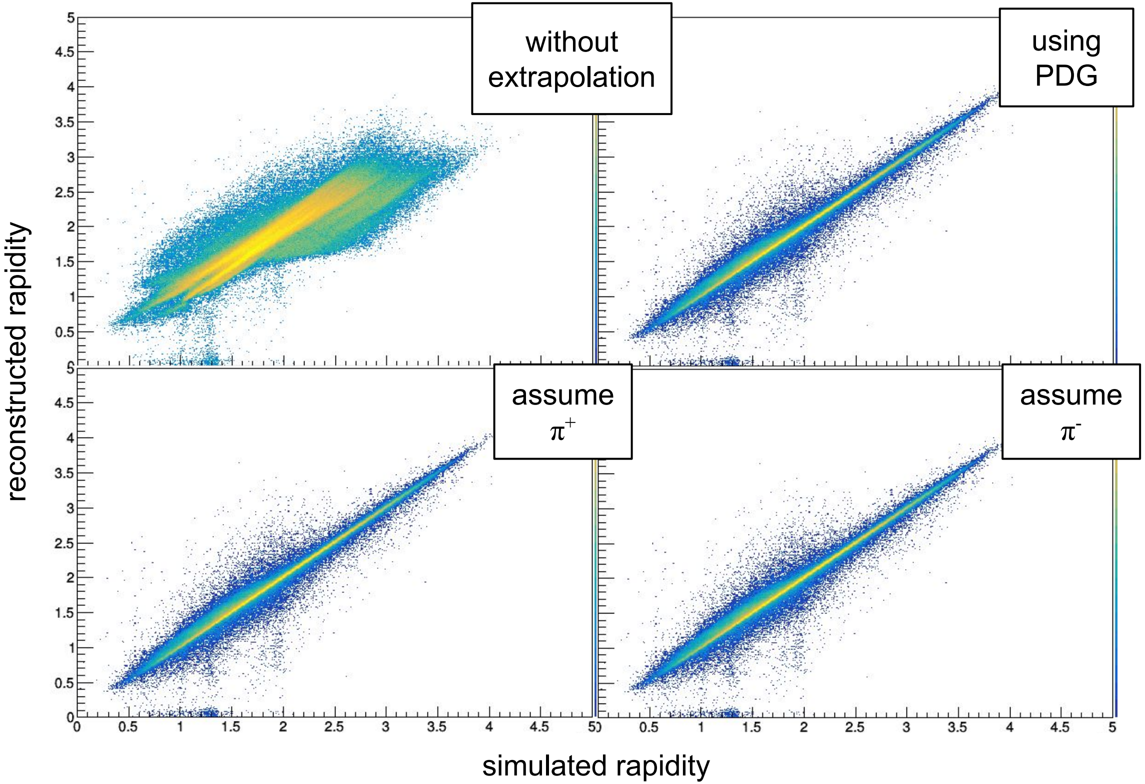

N_{hits}


χ^2 / NDF vs. p_T


p_T

Q: Is it possible to store the N_{hits} for FwdSi and GEM separately?

Track extrapolation to vertex (π^-)



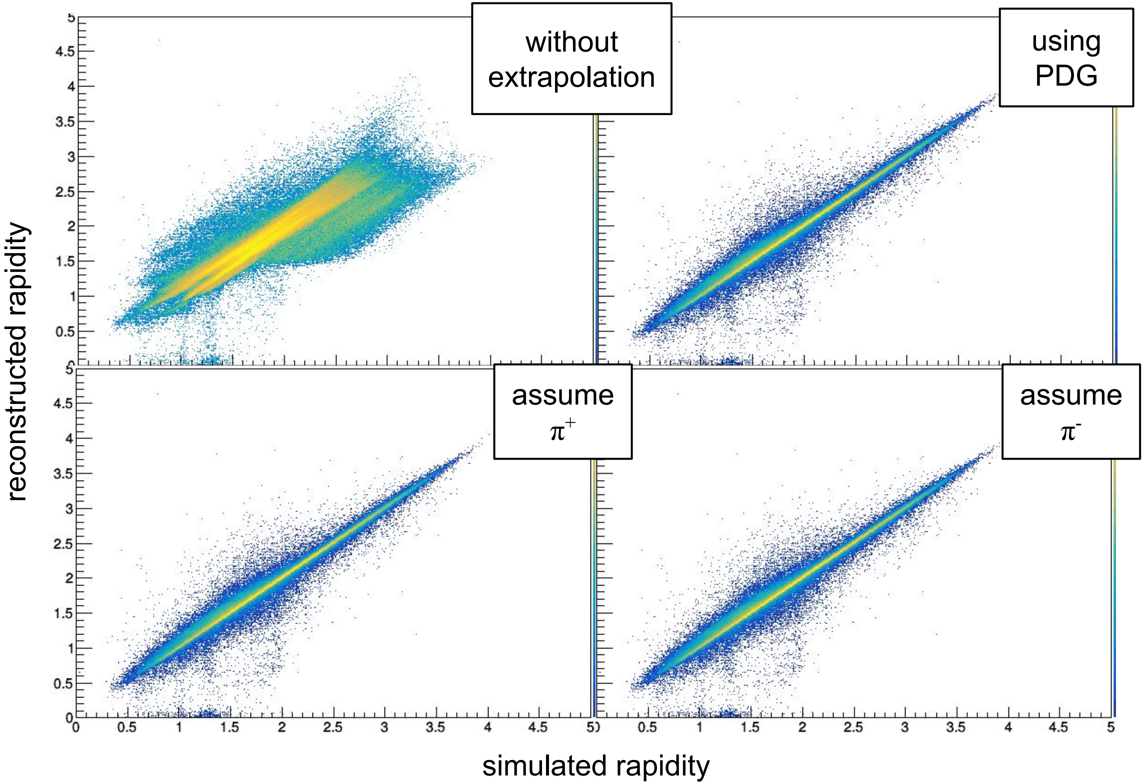
No extrapolation
information from the reconstructed track

PDG
extrapolation using pdg code

assume π^+ or π^-
extrapolation assuming the track is a pion

Using pion mass for extrapolation of the π^- tracks gives consistent result

Track extrapolation to vertex (π^+)



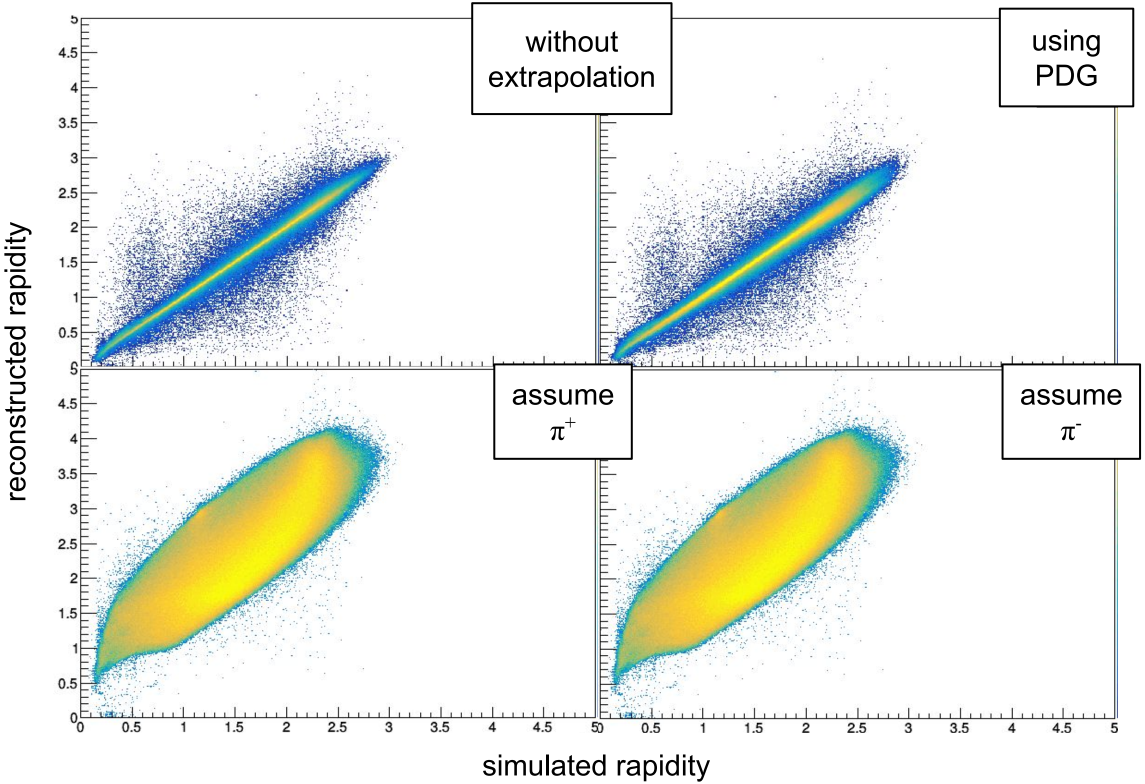
No extrapolation
information from the reconstructed track

PDG
extrapolation using pdg code

assume π^+ or π^-
extrapolation assuming the track is a pion

Using pion mass for extrapolation of the π^+ tracks gives consistent result

Track extrapolation to vertex (protons)



No extrapolation

information from the reconstructed track

PDG

extrapolation using pdg code

assume π^+ or π^-

extrapolation assuming the track is a pion

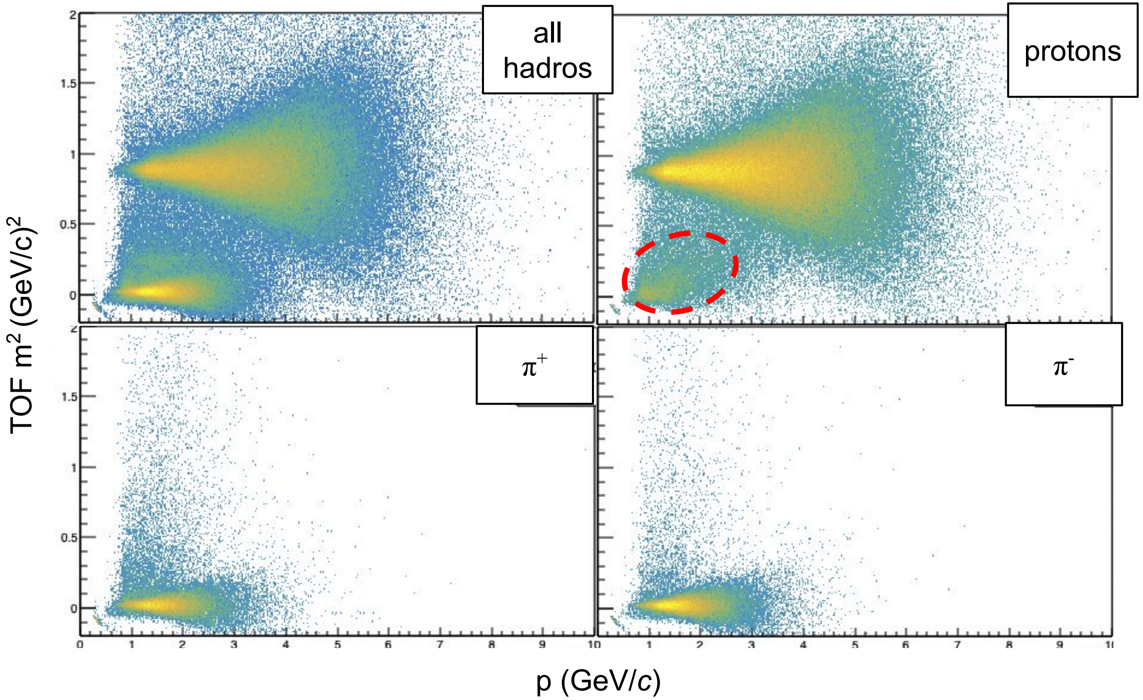
Assuming pion mass for extrapolation of the protons tracks gives wrong result

To compare with simulated tracks the reconstructed tracks have to be extrapolated to the primary collision vertex position (currently $z = 0$)

Q:

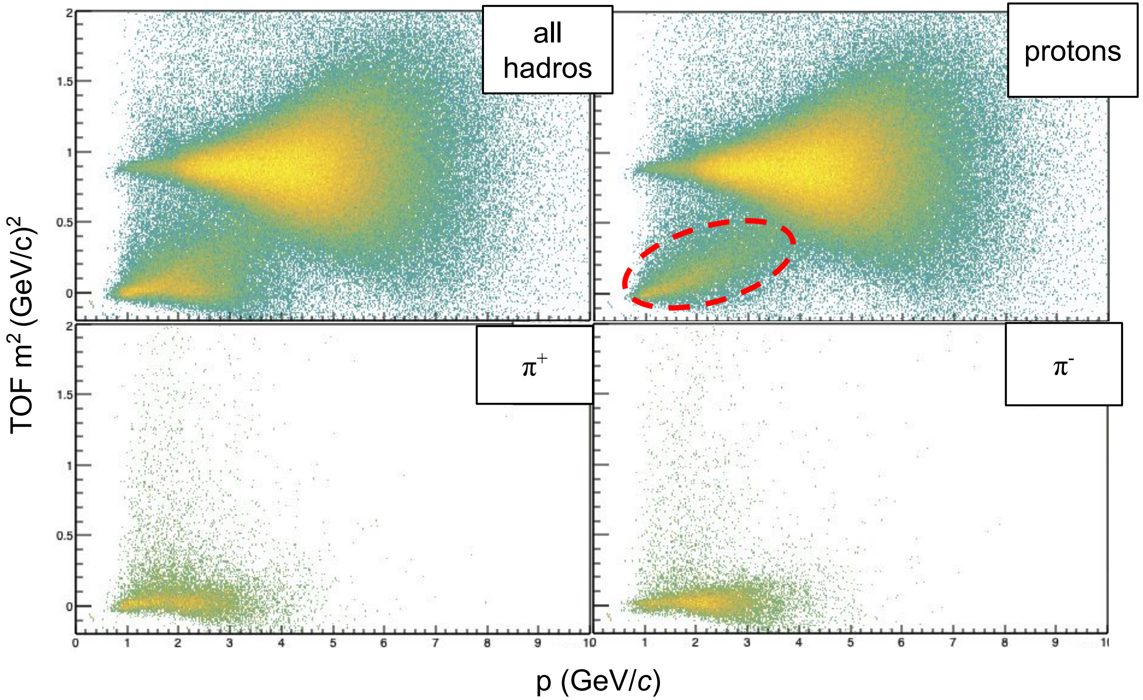
Can a common Getter() be added to the BMNROOT to perform this extrapolation?

Particle identification with TOF-400



Q: Mismatch is present in TOF-400

Particle identification with TOF700



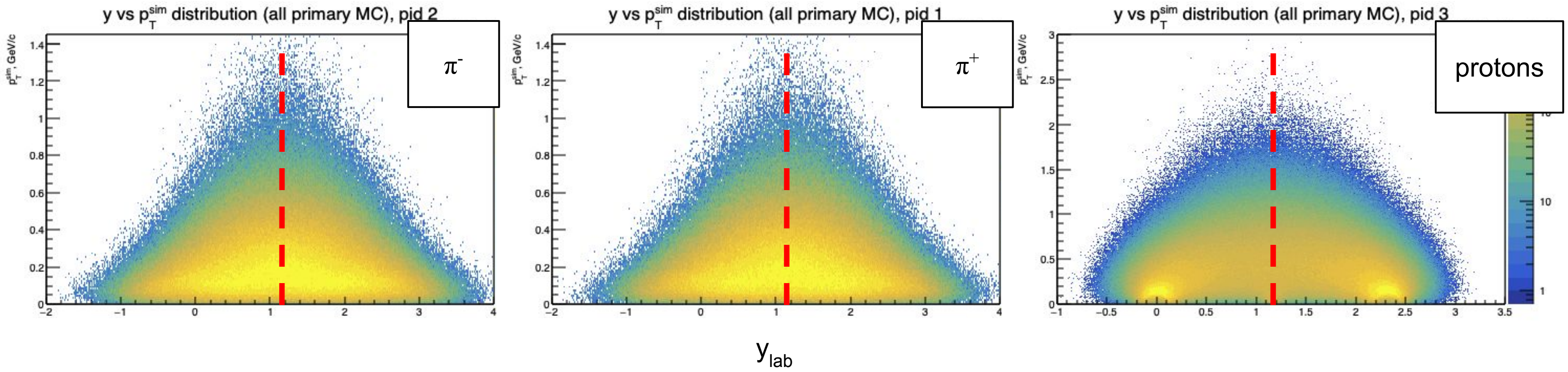
Q: More mismatch is present in TOF-700 strong non-flat dependence with momentum

Q: What can be done to improve the track to TOF hit matching?

How the current algorithm is implemented? Is the matching radius of 10 cm a rough estimation that needs to be optimized in the future?

Acceptance: true MC

y_{beam} = 1.163

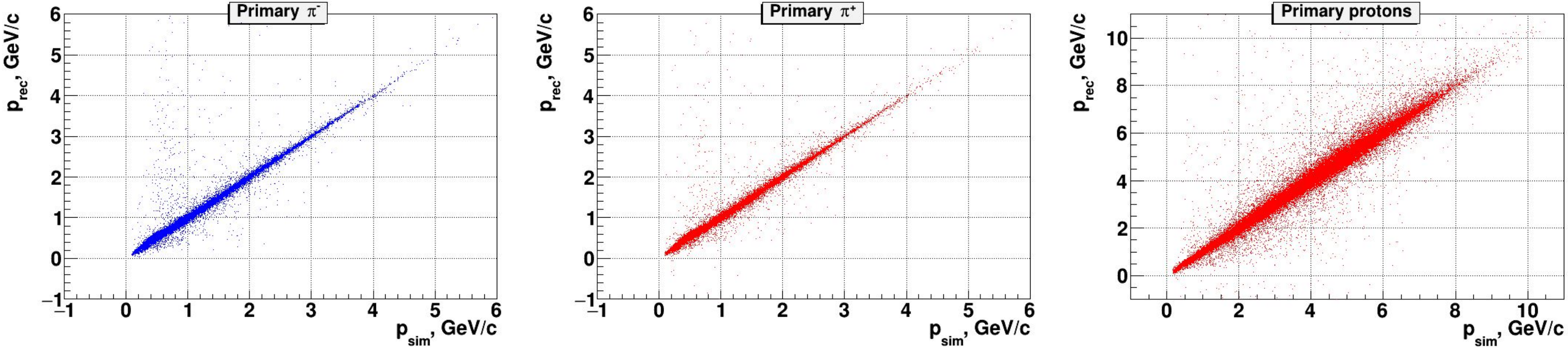

y vs p_T^{sim} distribution (all primary MC), pid 2

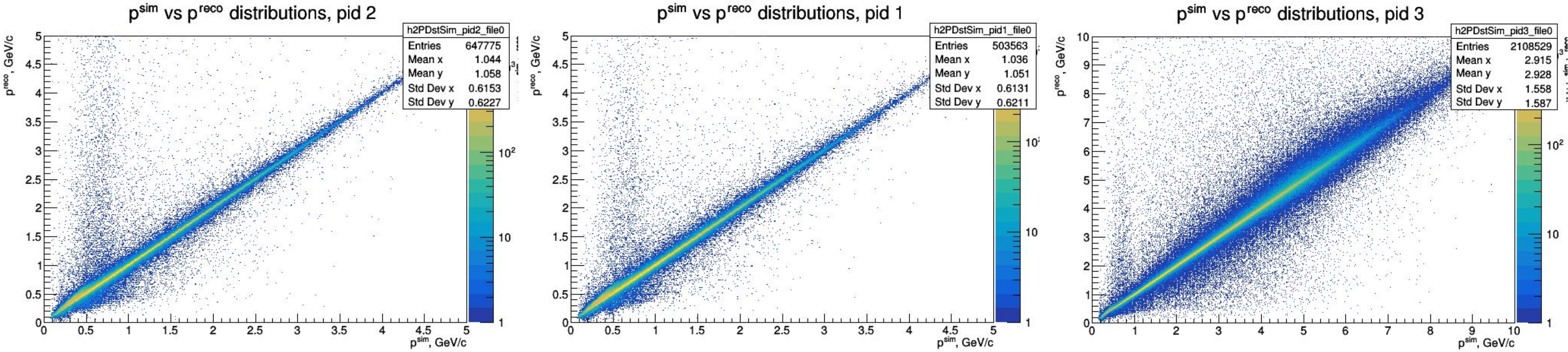
y vs p_T^{sim} distribution (all primary MC), pid 1

y vs p_T^{sim} distribution (all primary MC), pid 3

Simulated vs reconstructed: Momentum

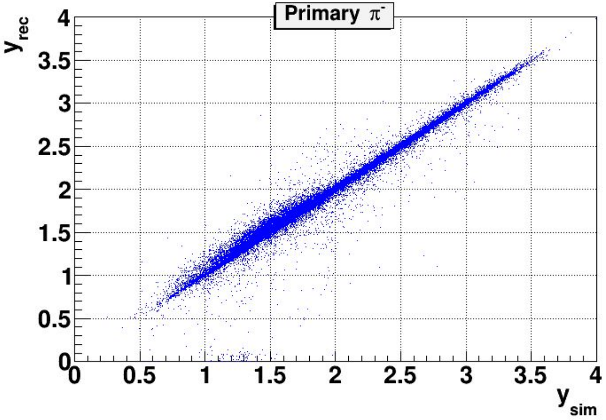
Zinchenko’s plots

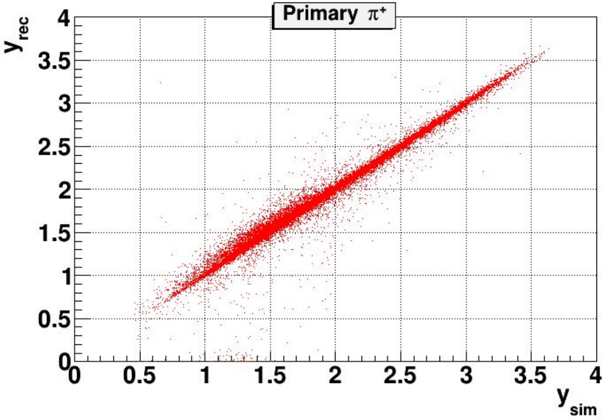


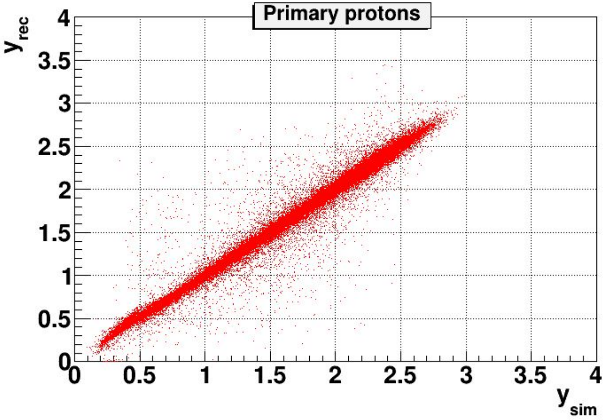


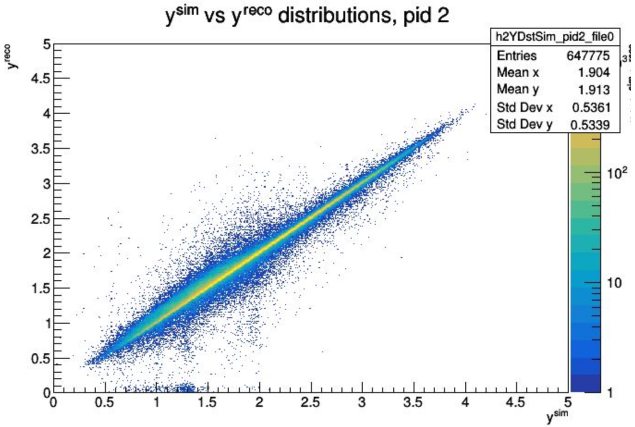
Simulated vs reconstructed: Rapidity

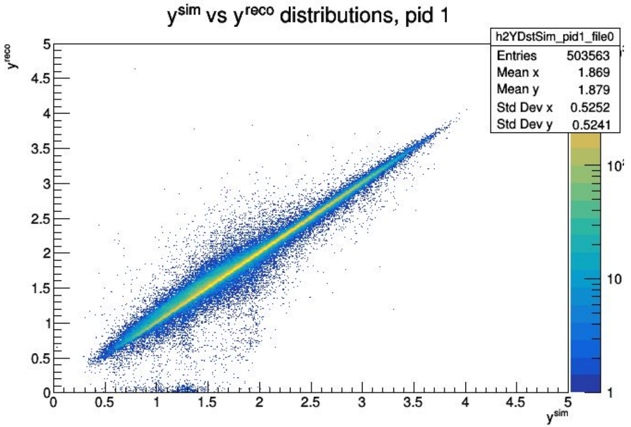
Zinchenko's plots

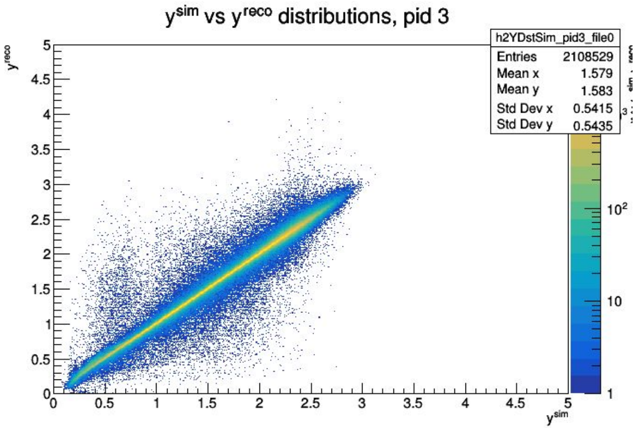






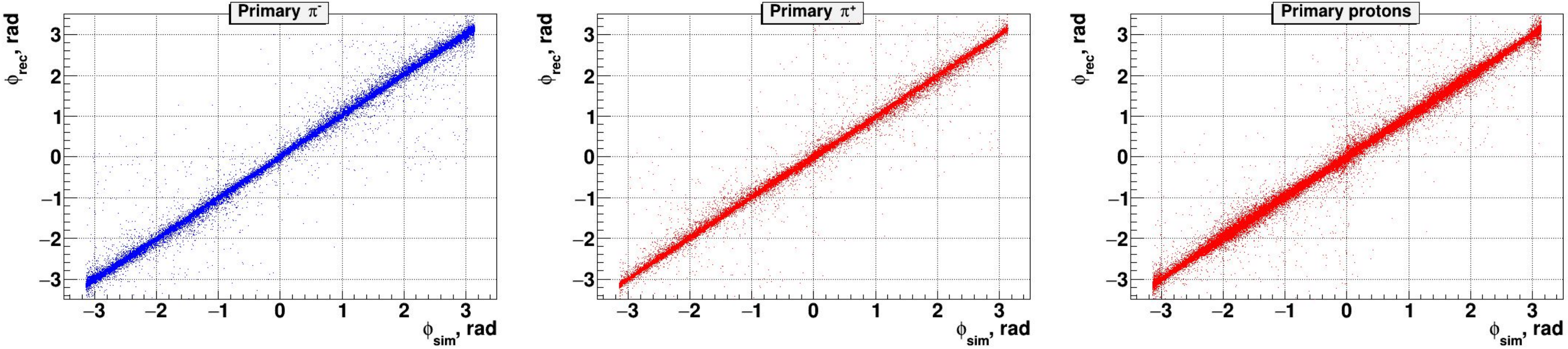


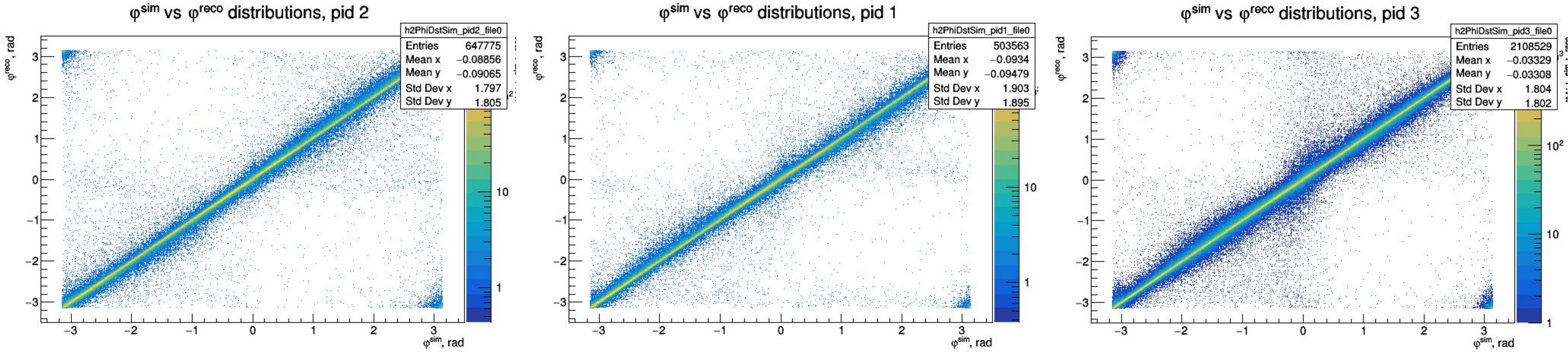




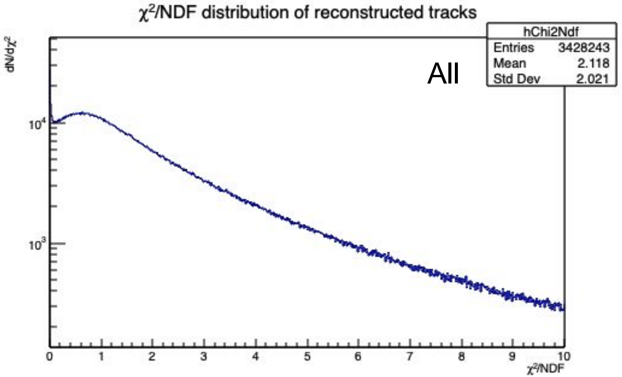
Simulated vs reconstructed: Azimuthal angle

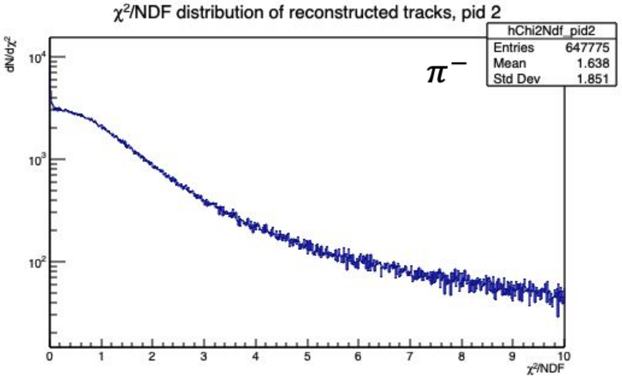
Zinchenko's plots

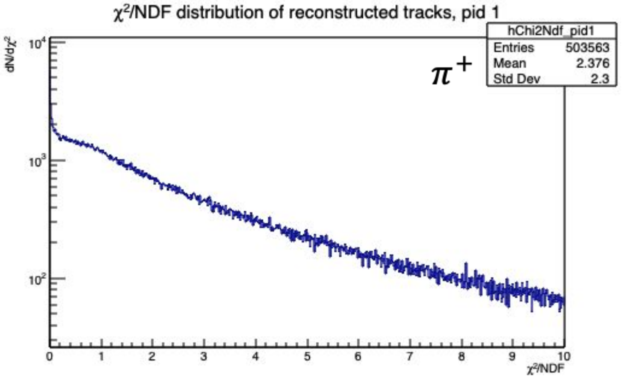


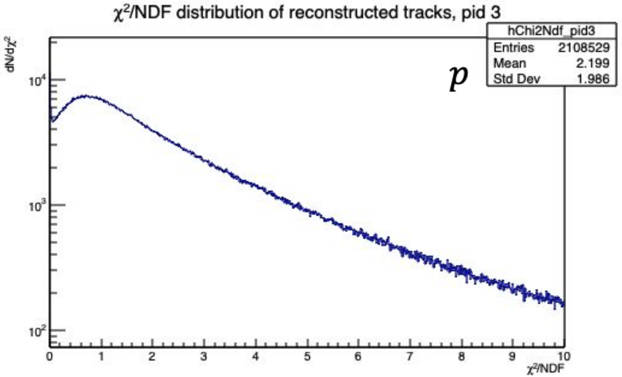


Track quality parameters I

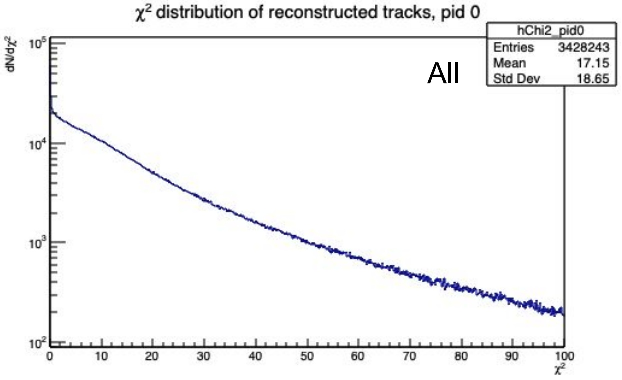


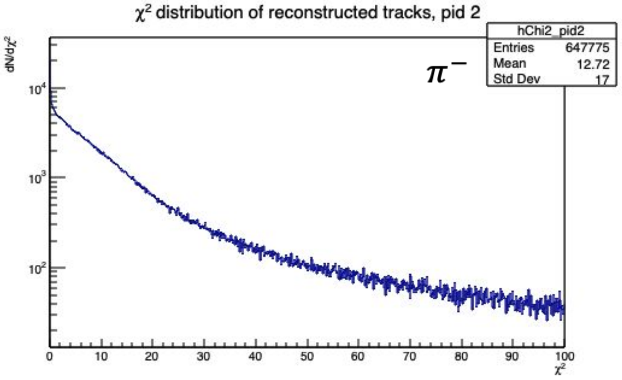


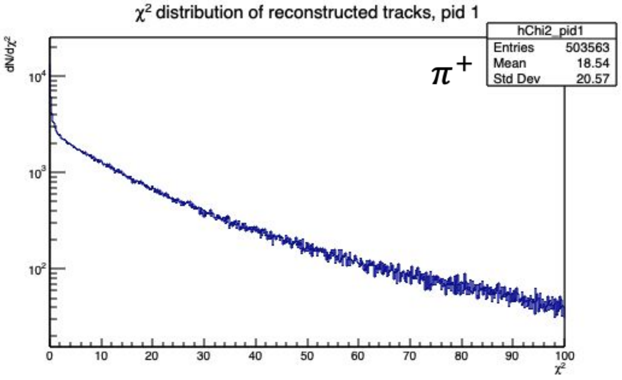


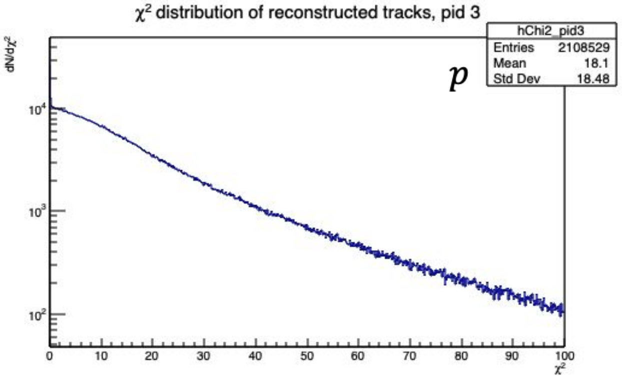


Track quality parameters II


χ^2 distribution of reconstructed tracks, pid 0


χ^2 distribution of reconstructed tracks, pid 2


χ^2 distribution of reconstructed tracks, pid 1


χ^2 distribution of reconstructed tracks, pid 3

Track quality parameters III