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Los Alamos NATIONAL LABORATORY EST. 1943

CFNS Workshop 2020
Opportunities with Heavy Flavor at the EIC

EIC Silicon Tracking in the Forward Direction and Physics Studies

Cheuk-Ping Wong
On Behalf of LANL EIC team

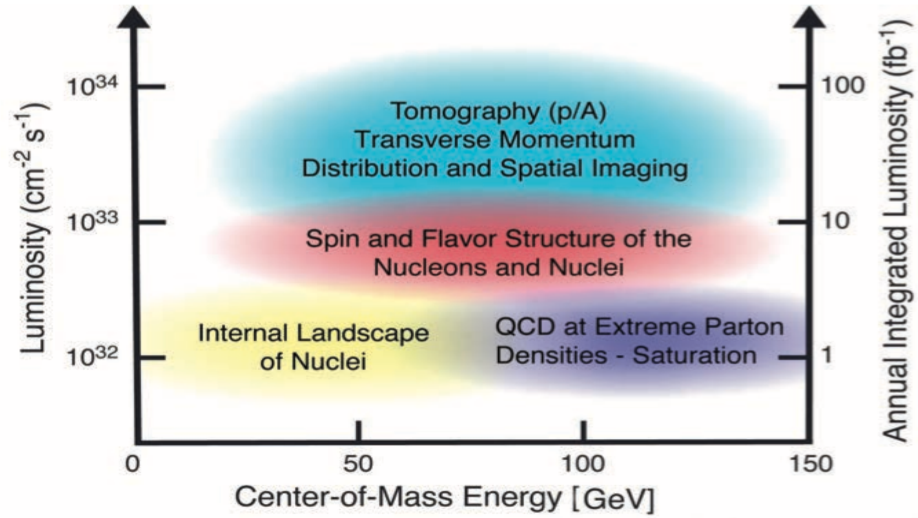
11-06-2020

Outline

- Motivation:
  Propose a forward silicon tracker (FST) to measure heavy flavor and jet in EIC
- A forward silicon trackers:
  - Detector design and material budgets
  - Detector performance
- Physics Studies with detector response:
  - Heavy Flavor R_{eA}
  - Jet substructure study using jet angularity
- Summary and outlook

The Finest Microscope: Electron-Ion Collider

Solving fundamental physics problems in a wide x_{BJ} and Q^2 kinematic region with high luminosity and c.m. energy



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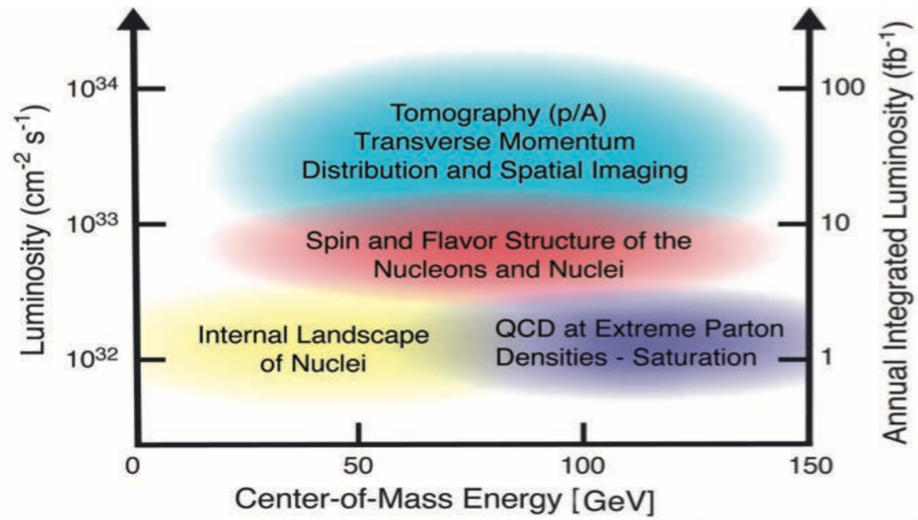
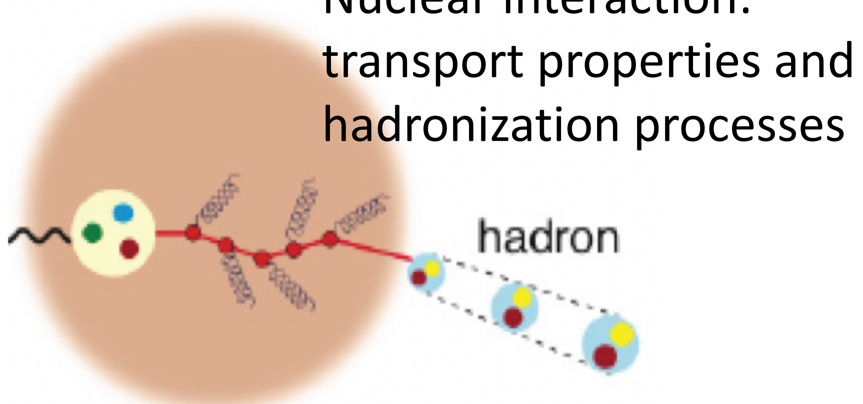


Nuclear interaction: transport properties and hadronization processes



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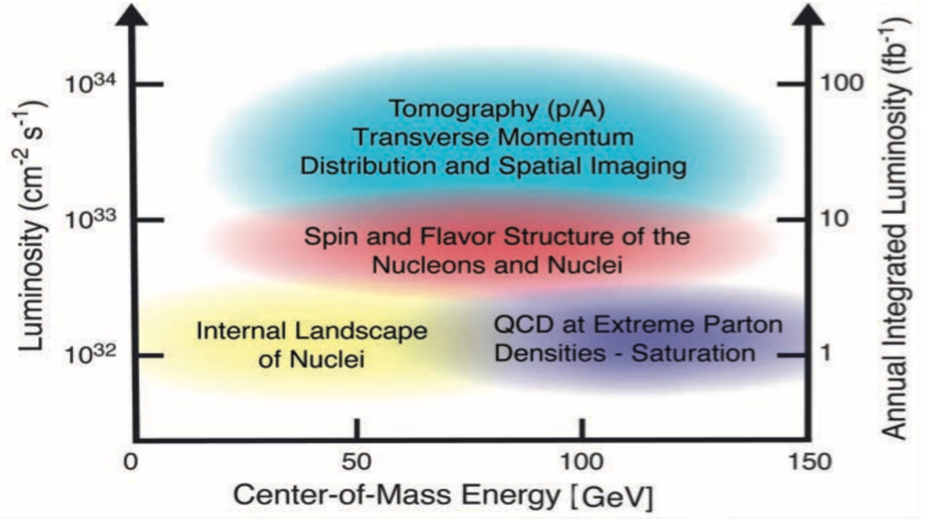

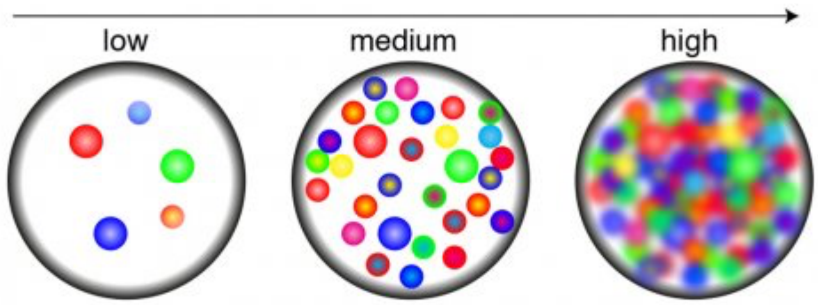

Gluon saturation at high energy

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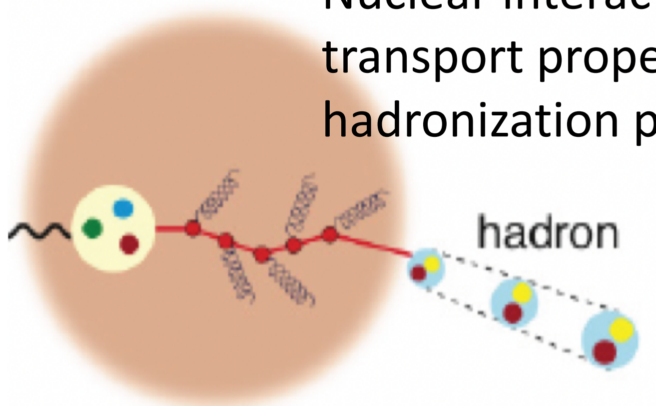

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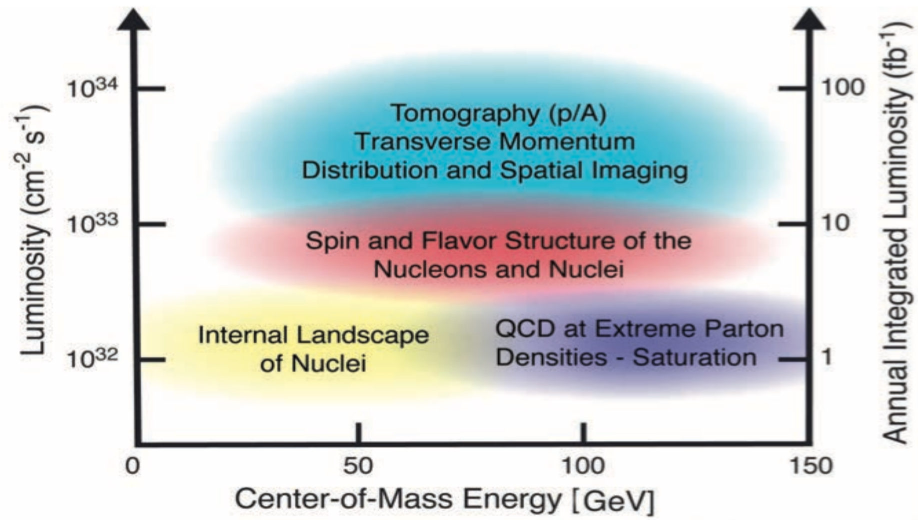

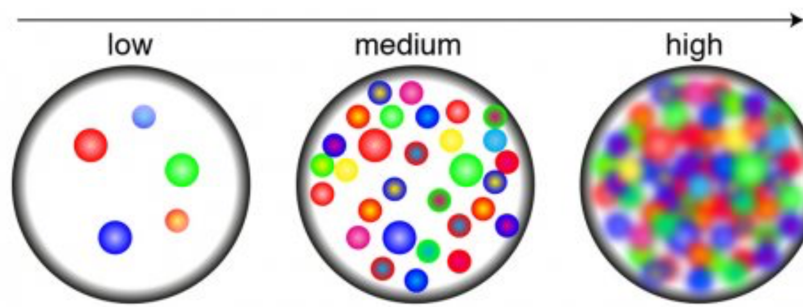

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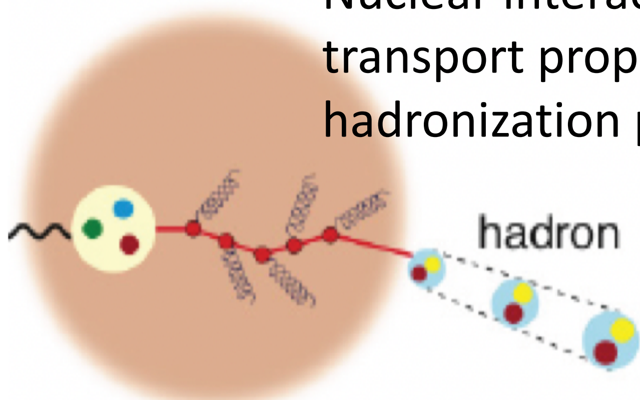
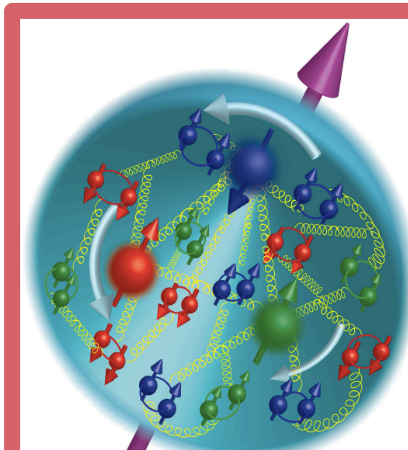
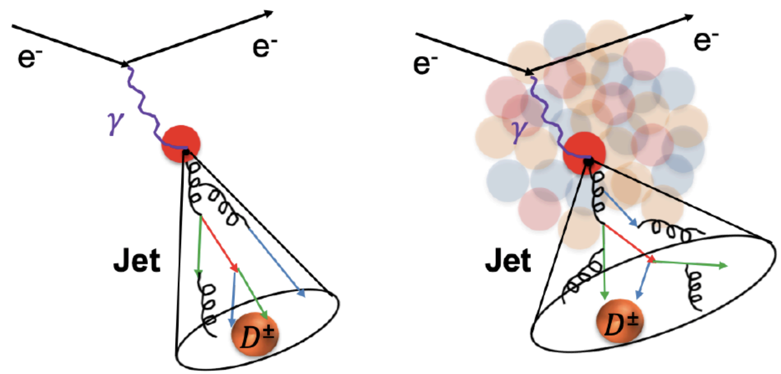




Nucleon/nuclei tomography in flavor, spin, momentum and spatial space

Heavy Flavor and Jet Measurements

$e^- + \mathrm{p} \rightarrow e^- + jet(D^{\pm}) + X$ $e^- + \mathrm{Au} \rightarrow e^- + jet(D^{\pm}) + X$



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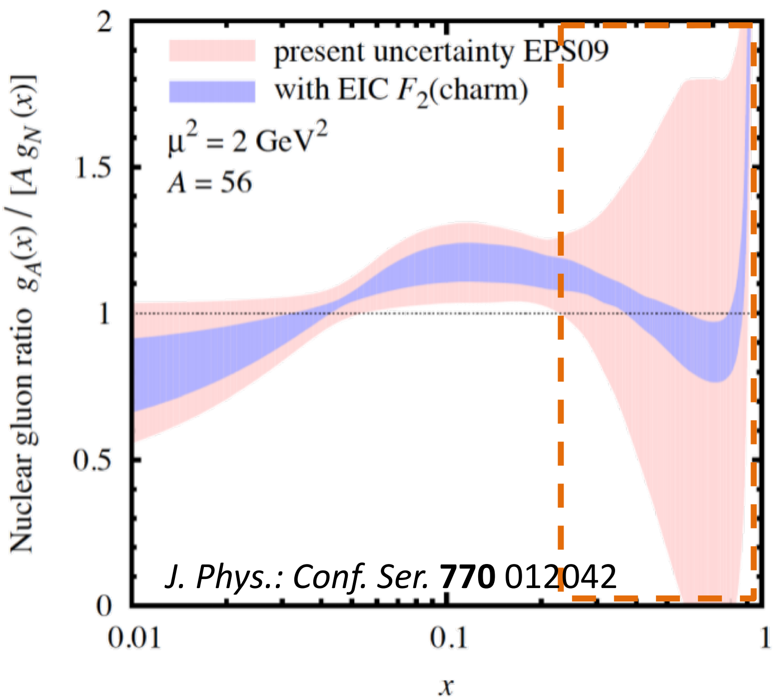
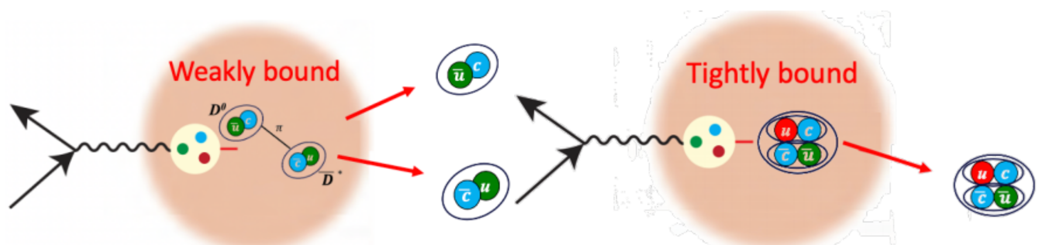


J. Phys.: Conf. Ser. **770** 012042

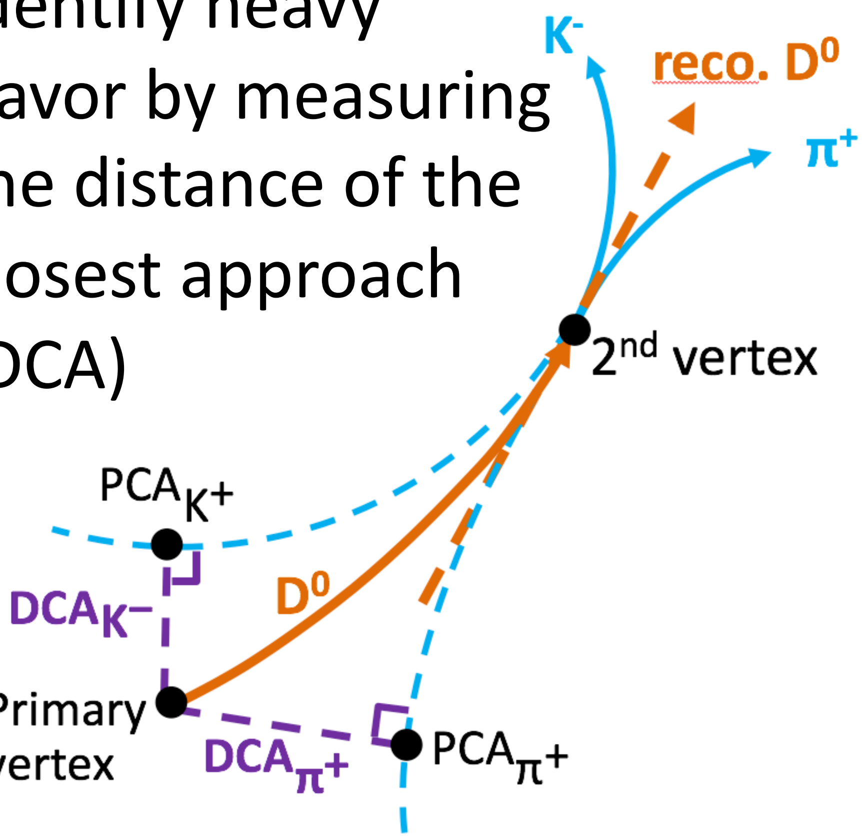
Heavy flavor & jet physics

- Obtain the initial state nPDF and Constrains the nPDF at large x
- Final state fragmentation and hadronization process
- Gluon Sivers function
- Exploration of exotic hadrons, e.g. X(3872)



Heavy Flavor Identification

Identify heavy flavor by measuring the distance of the closest approach (DCA)



$$DCA_{2D} = (\overrightarrow{pca} - \overrightarrow{vtx}) \cdot (\overrightarrow{p_T} \times \hat{z})$$

Heavy flavor mass and decay length

Particle	Mass (GeV/c²)	$c\tau$ decay length
$D^{\pm}$	1.869	312 micron
D^0	1.864	123 micron
$B^{\pm}$	5.279	491 micron
B^0	5.280	456 micron

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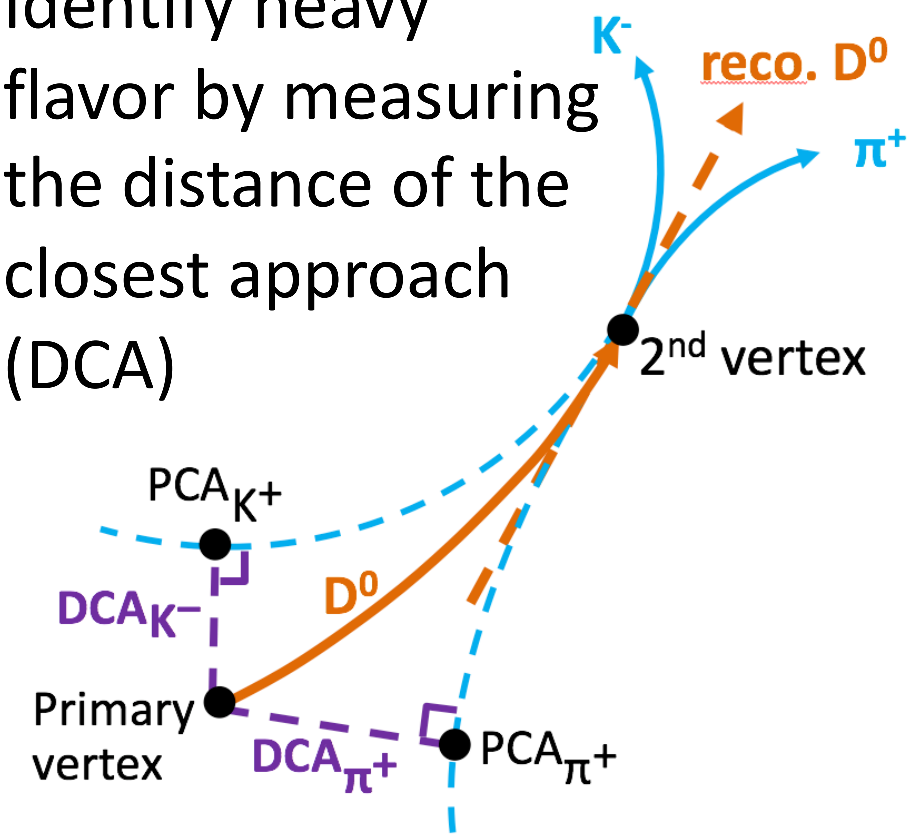

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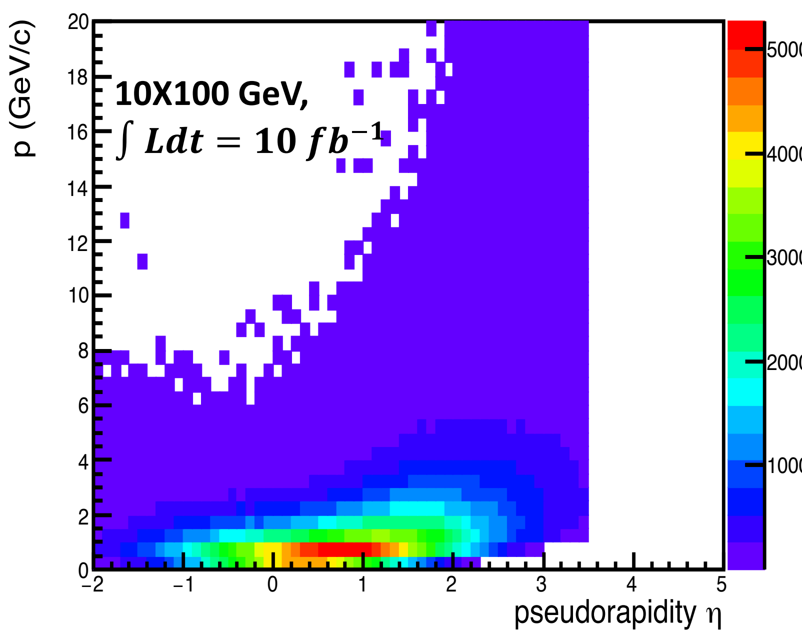
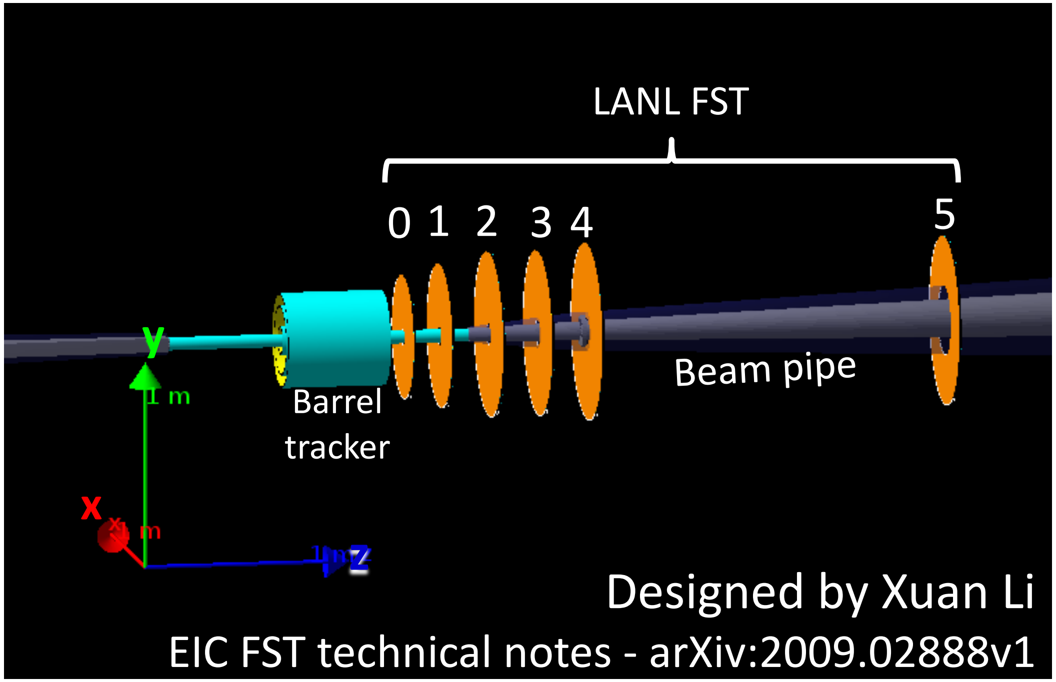
Reconstructed D daughter p VS η



Most of the decay products of heavy flavors are within $-2 < \eta < 3.5$ and $p < 10$ GeV

EIC FST Setup in Fun4All



FST Setup

Plane	z (cm)	r_{in} (cm)	r_{out} (cm)	Pixel pitch (um)	Silicon thickness (um)
0	35	4	25	20	50
1	62.3	4.5	42	20	50
2	90	5.2	43	20	50
3	115	6	44	36.4	100
4	125	6.5	45	36.4	100
5	300	15	45	36.4	100

Barrel Tracker Setup

Layer	Half length (cm)	r (cm)	Pixel pitch (um)	Silicon thickness (um)
0	20	3.64	20	50
1	20	4.81	20	50
2	25	5.98	20	50
3	25	16	36.4	100
4	25	22	36.4	100

Silicon sensor options

	Pixel pitch	Silicon thickness	Integration time
LGAD/AC-LGAD	100µm	<300µm (<1% X_0)	300-500ps
MALTA	36.4µm	100µm (<0.5% X_0)	5ns
ITS-3 type	20µm	50µm	100ns ?

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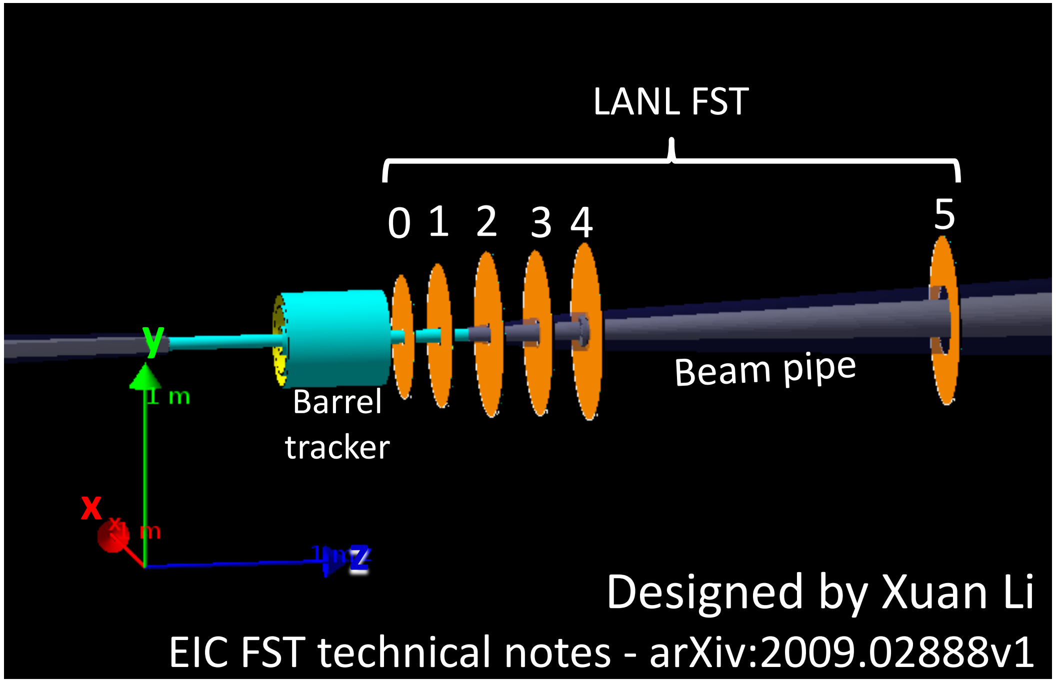

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ITS-3 type (planes 0–2)　MALTA (planes 3–5)

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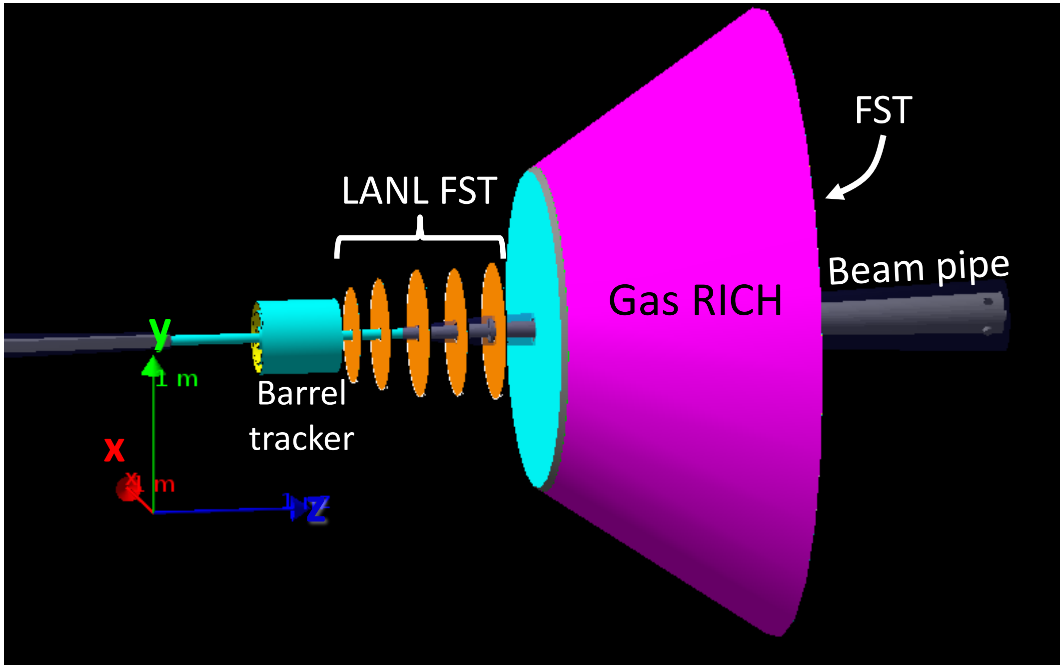
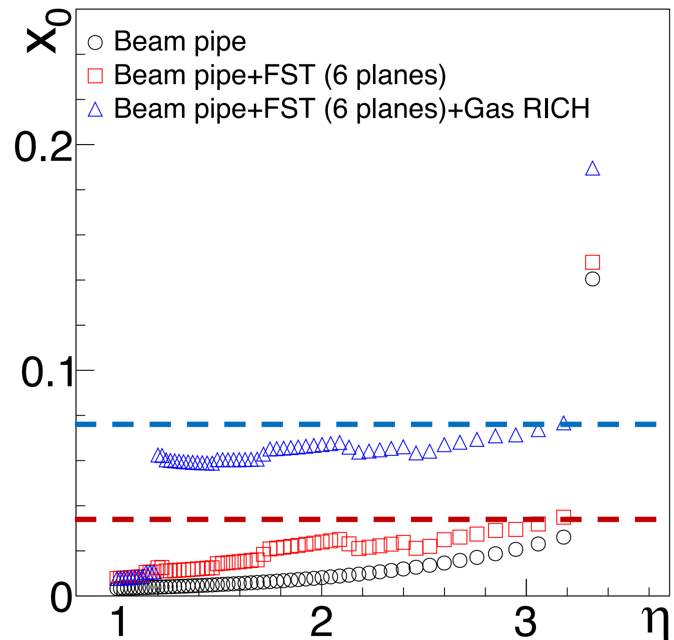
With the use of both sensor technologies, the FST can give good spatial and timing resolutions

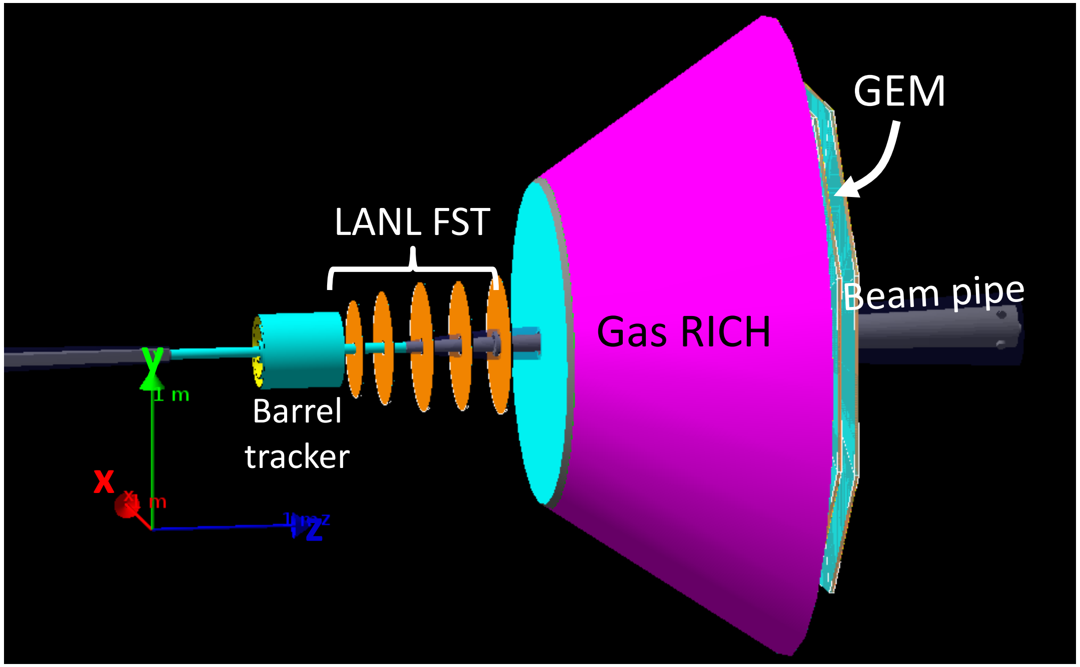
Material Budget: FST(6 planes)+RICH

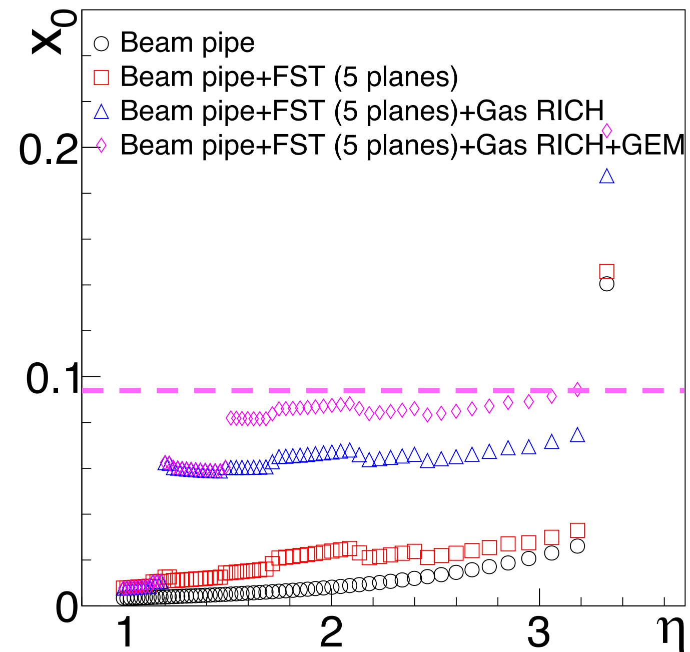




- Mockup Gas RICH by LBNL with dual radiators: aerogel and C_2F_6 gas
- Total material budget (blue) is <8% at $\eta < 3.3$

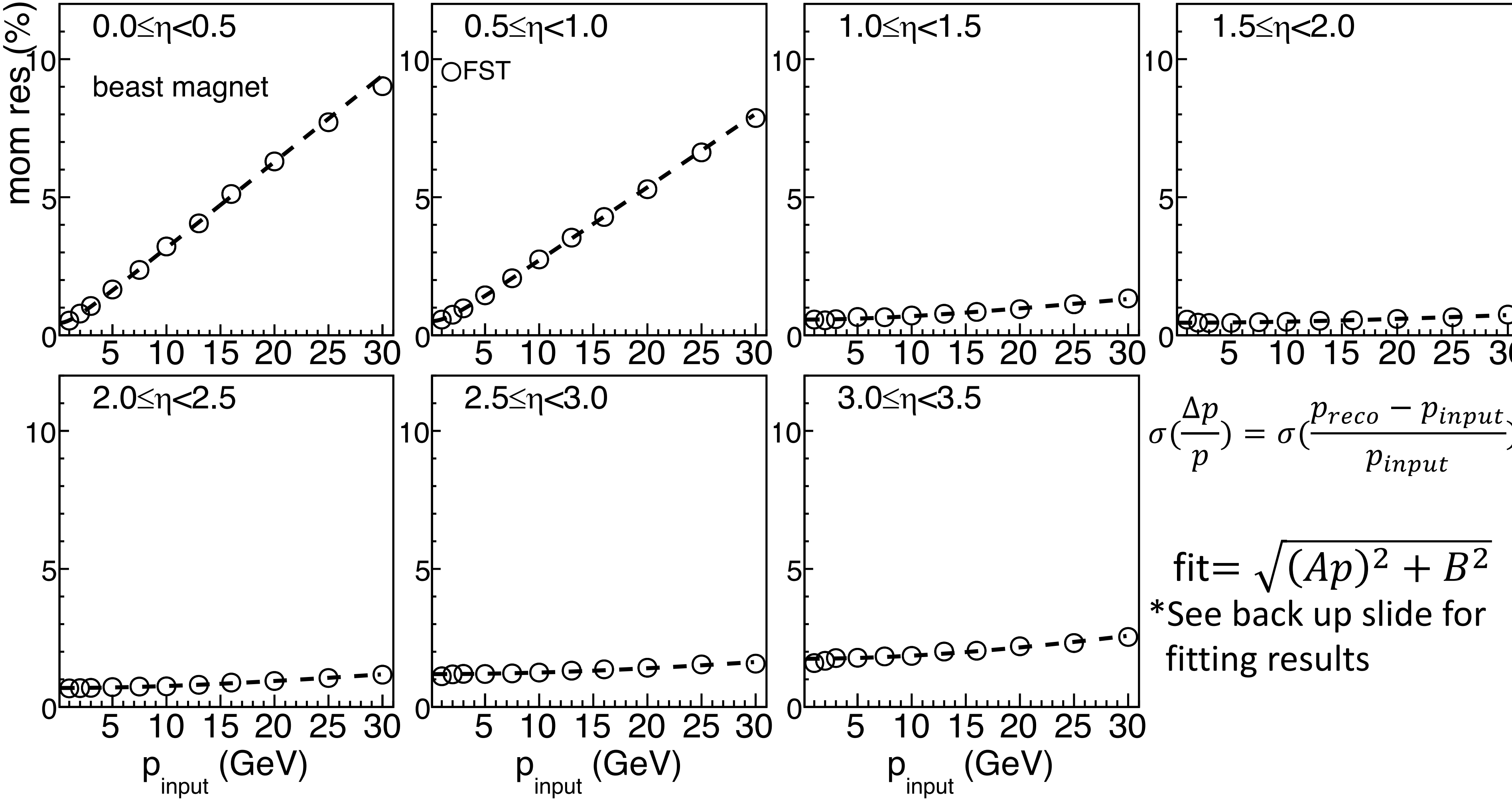
Material Budget: FST(5 planes)+RICH+GEM





- Replacing the last plane (z=300cm) of FST by a GEM tracker could be a cost-effective option
- Mockup GEM tracker: 3-plane / methane / $1.5 < \eta < 3.5$
- Total material budget (magenta) is ~10% at $\eta < 3.3$, and <8% at $\eta < 1.5$

Momentum Resolution of Tracking System with BeAST Magnet



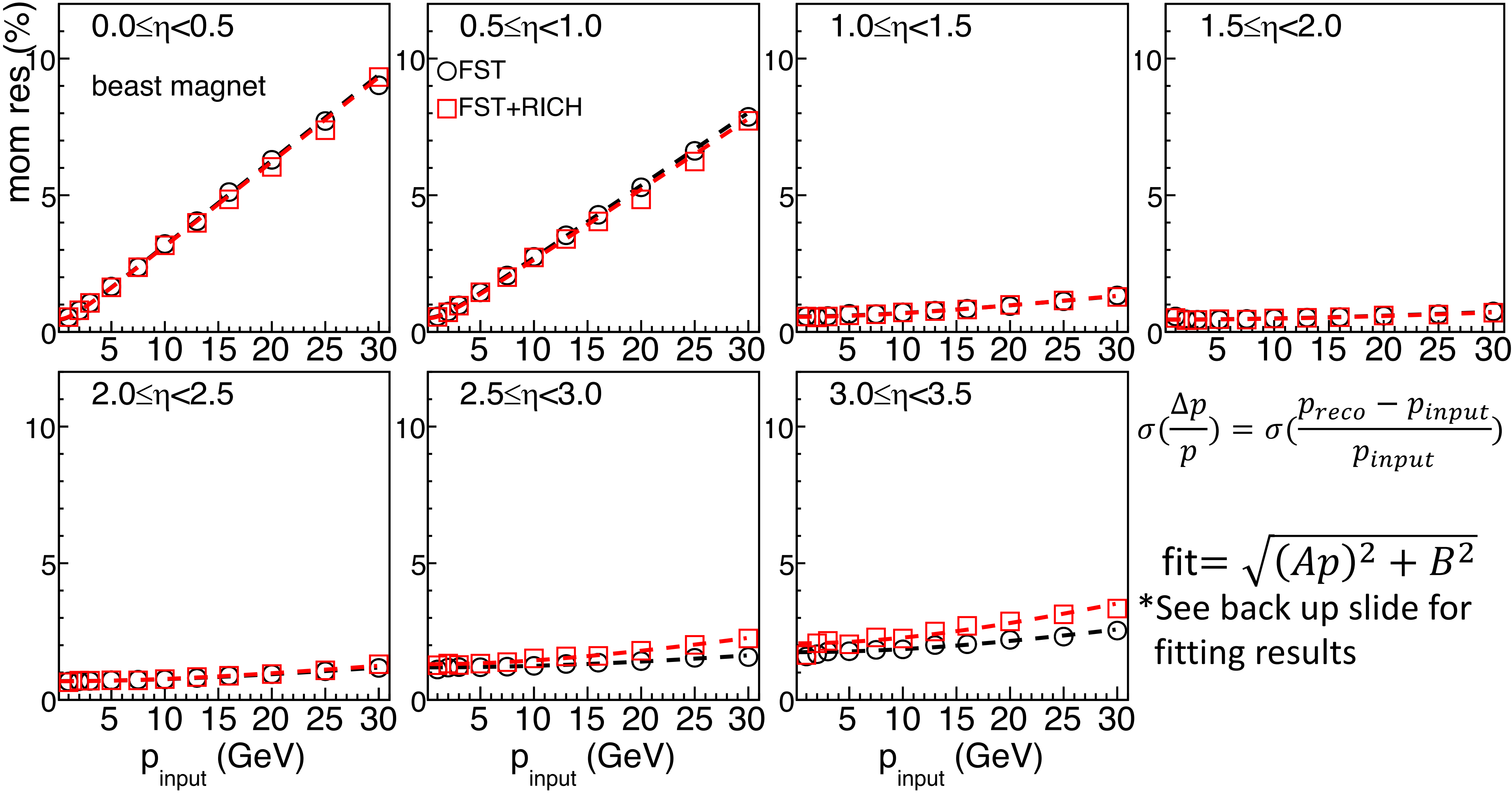
$$\sigma(\frac{\Delta p}{p}) = \sigma(\frac{p_{reco} - p_{input}}{p_{input}})$$

fit= $\sqrt{(Ap)^2 + B^2}$

*See back up slide for fitting results

- $\eta < 1$: mom res <10% / $\eta > 1$: mom res <4%

Momentum Resolution of Tracking System with BeAST Magnet



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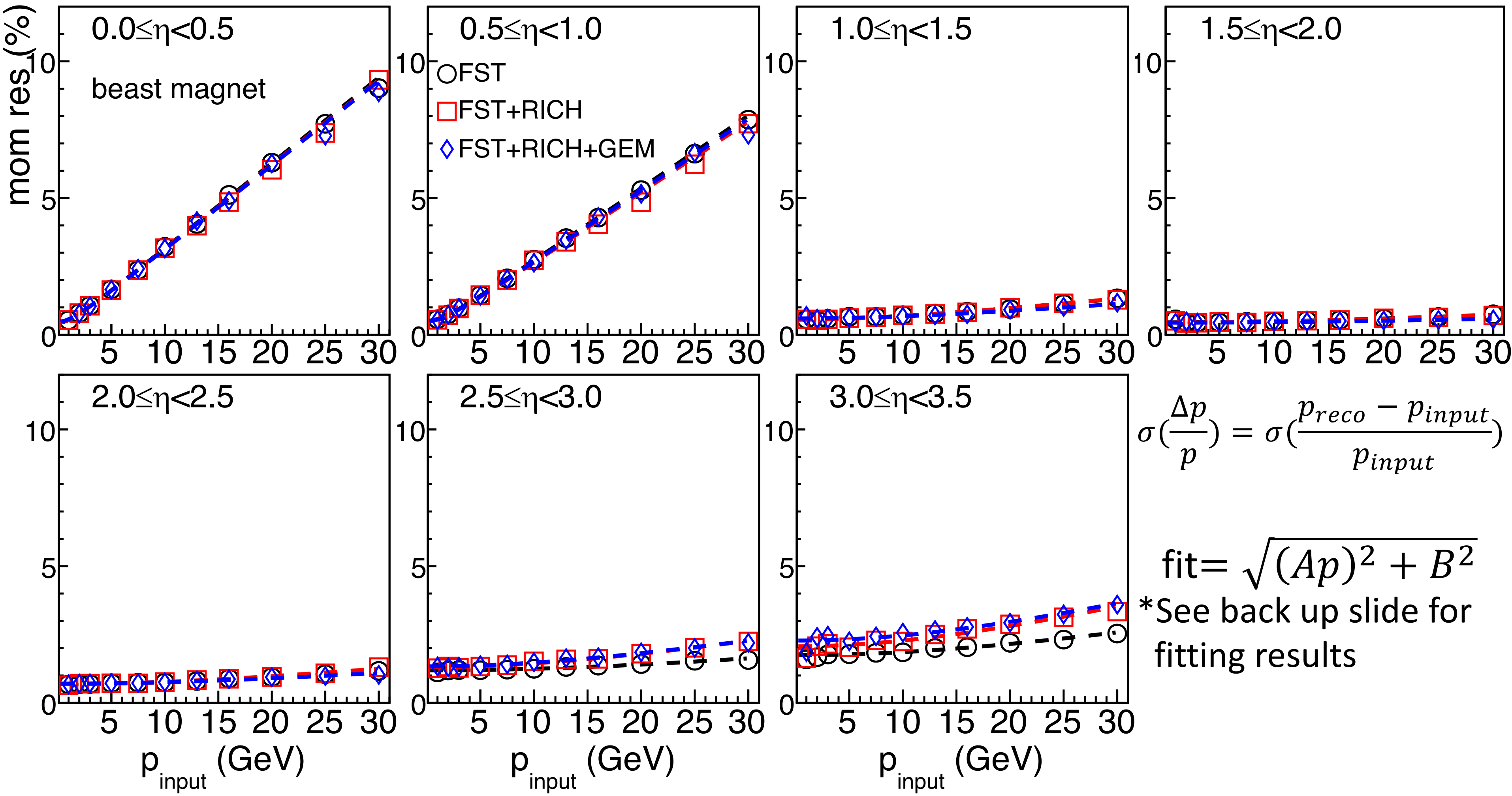
- The Gas RICH worsen the mom res by ~1% at $\eta > 2.5$

Momentum Resolution of Tracking System with BeAST Magnet



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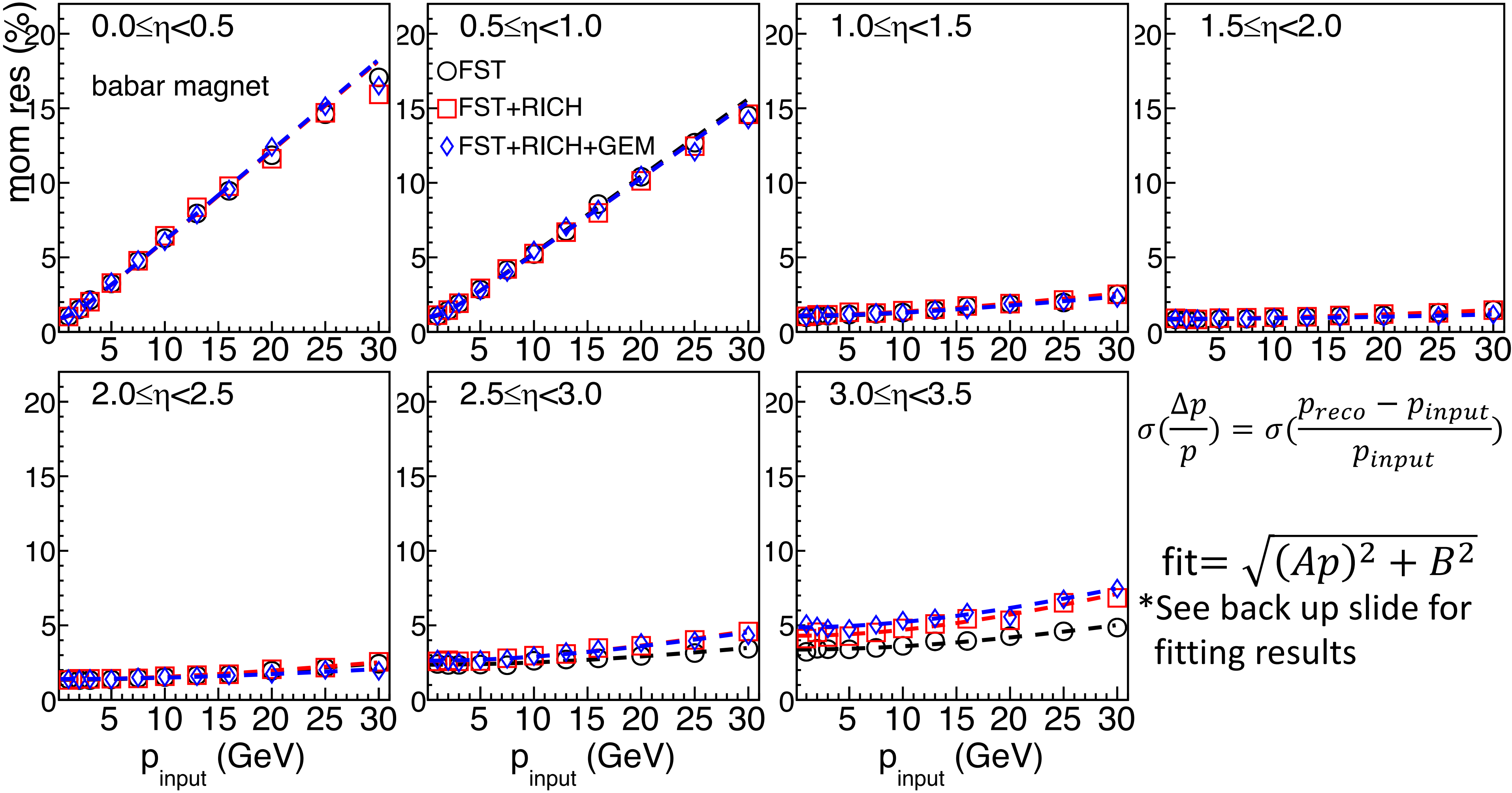
- $\eta < 1$: mom res <10% / $\eta > 1$: mom res <4%
- The Gas RICH worsen the mom res by ~1% at $\eta > 2.5$
- The mom res with the use of GEM agrees with the results without GEM

Momentum Resolution of Tracking System with Babar Magnet



$$\sigma\left(\frac{\Delta p}{p}\right) = \sigma\left(\frac{p_{reco} - p_{input}}{p_{input}}\right)$$

fit= $\sqrt{(Ap)^2 + B^2}$

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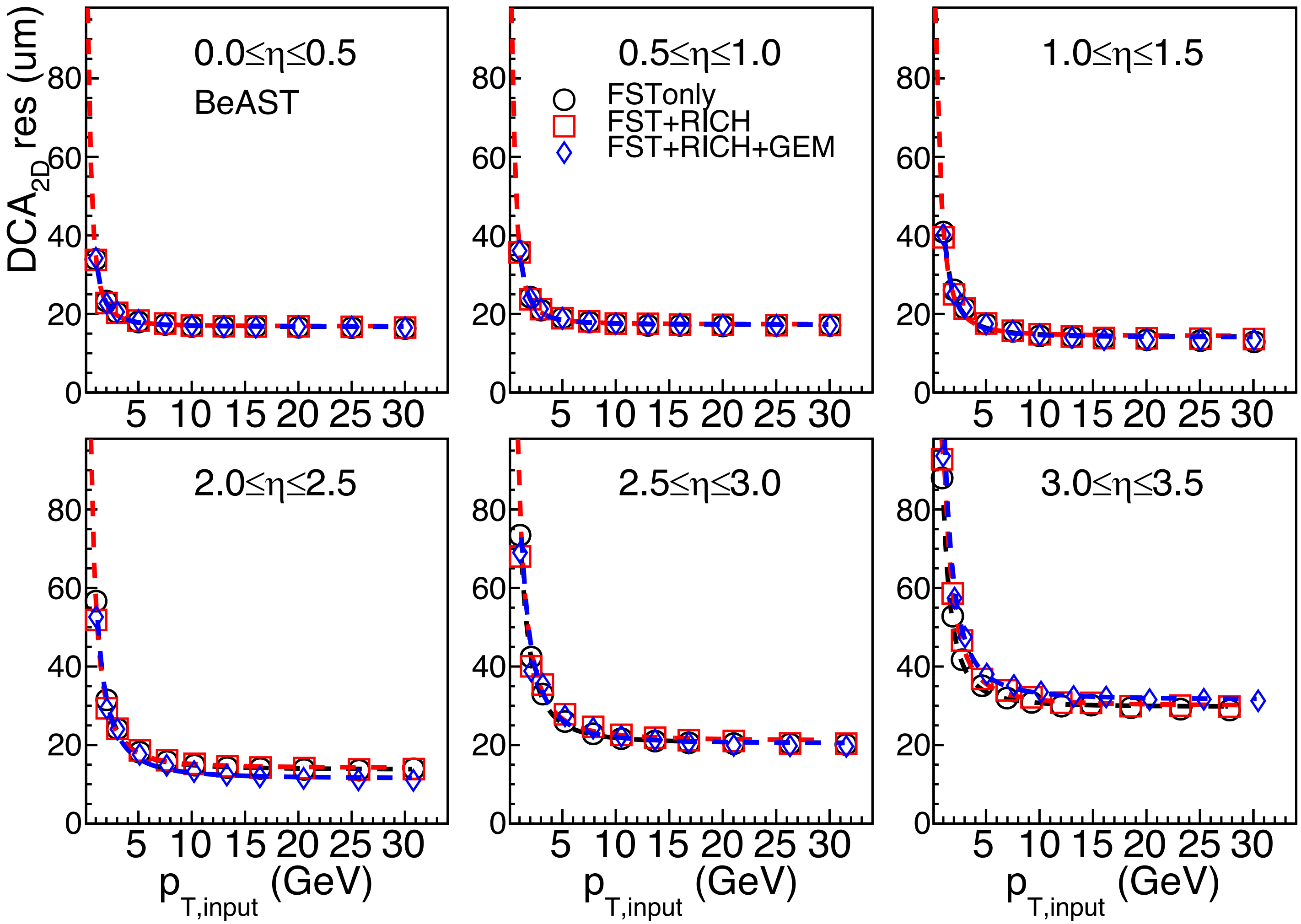
- $\eta < 1$: mom res <18%
- $\eta > 1$: mom res <9%

DCA_{2D} Resolution of Tracking System with BeAST Magnet



$\sigma(DCA_{2D})$

$$\text{fit} = \sqrt{\left(\frac{A}{p_T}\right)^2 + B^2}$$

*See back up slide for fitting results

- $\eta < 2$: DCA_{2D} res <50um / $\eta > 2$: DCA_{2D} res <110um
- Similar results with the use of the Babar magnet

Heavy Flavor Reconstruction w/ Detector Response

The full analysis framework includes the event generation (PYTHIA), detector response in GEANT4 simulation, beam remnant & QCD background, and hadron reconstruction algorithm

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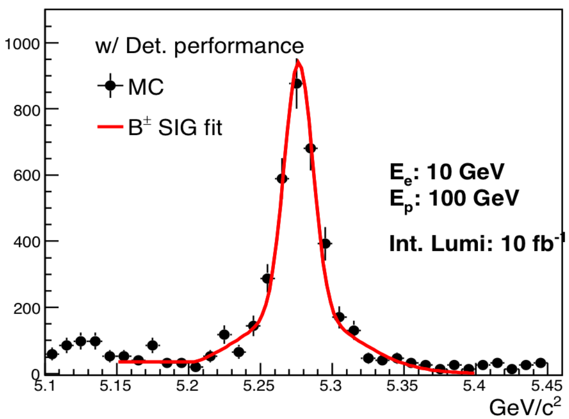
arXiv:2009.02888

- 10 x 100 GeV e-p collisions
- $\int \mathrm{Ldt} = 10\mathrm{fb}^{-1}$
- $-2 < \eta < 3.5$
- 20-35 μm primary vertex resolution depends on the track multiplicity
- Const. 95% $K/\pi/p$ separation
- DCA cut on tracks

Reconstructed B meson



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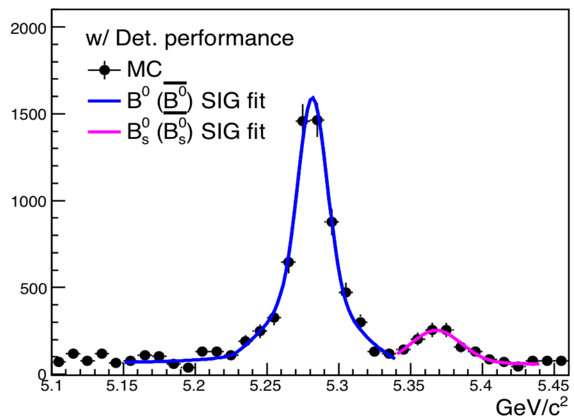
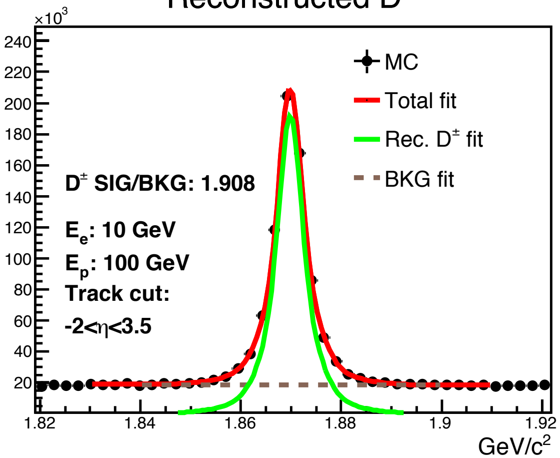
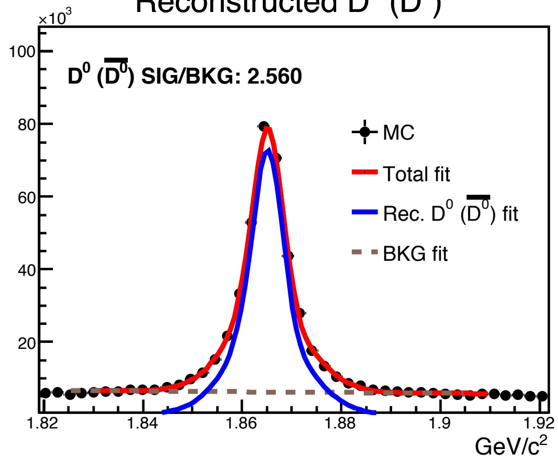


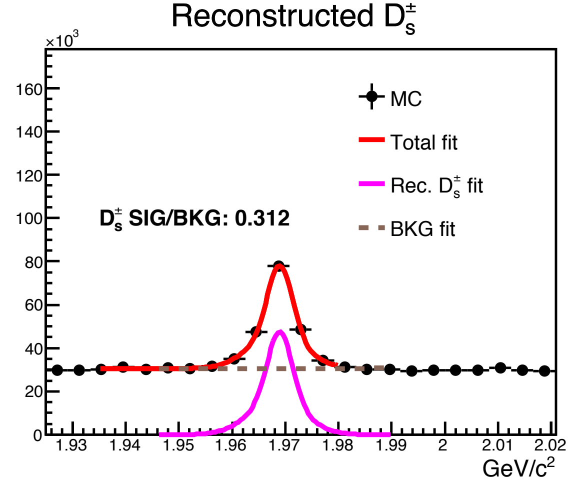
Reconstructed D±



Reconstructed D^0 ($\overline{D^0}$)



Reconstructed $D_s^\pm$



Meson R_{eA} Projections

$$R_{eA} = \frac{\text{e+A}}{\text{scaled}\cdot\text{e+p}} = \frac{N_{eA}}{\langle N_{coll}\rangle N_{ep}}$$

- $R_{eA}=1$: No nuclear medium effect. e+A is simply a scaled-up system of e+p
- $R_{eA}<1$: suppression in e+A
- $R_{eA}>1$: enhancement in e+A

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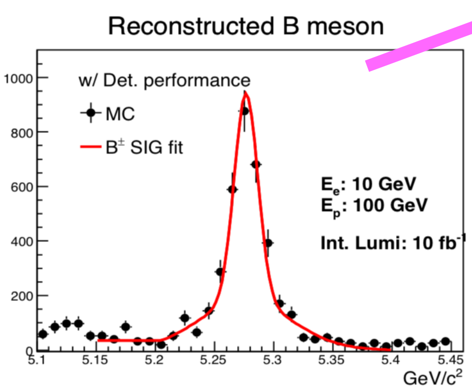
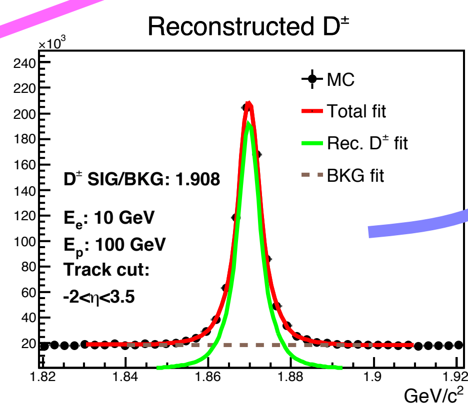
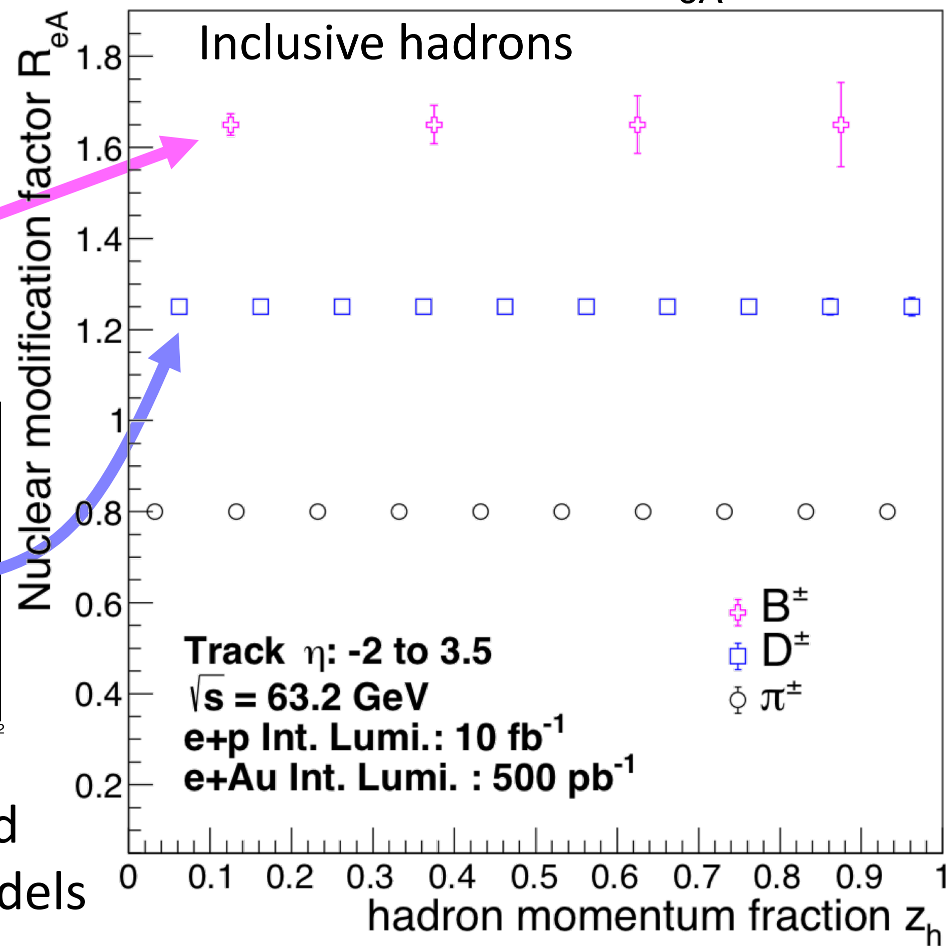




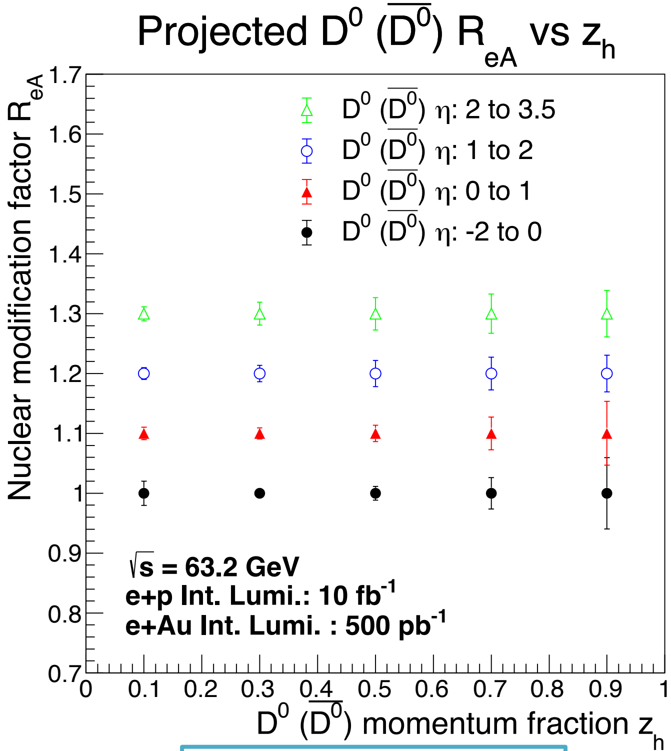
Projected hadron R_{eA} vs z_h



The statistical precision of reconstructed hadrons can help separate different models of the nuclear modifications on the hadronization process

arXiv:2009.02888

Pseudorapidity Dependent Reco. D^0 R_{eA} Projections



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Heavy flavor measurements at the EIC will enhance the sensitivity of the nuclear transport properties and discrimination power in pseudorapidity study

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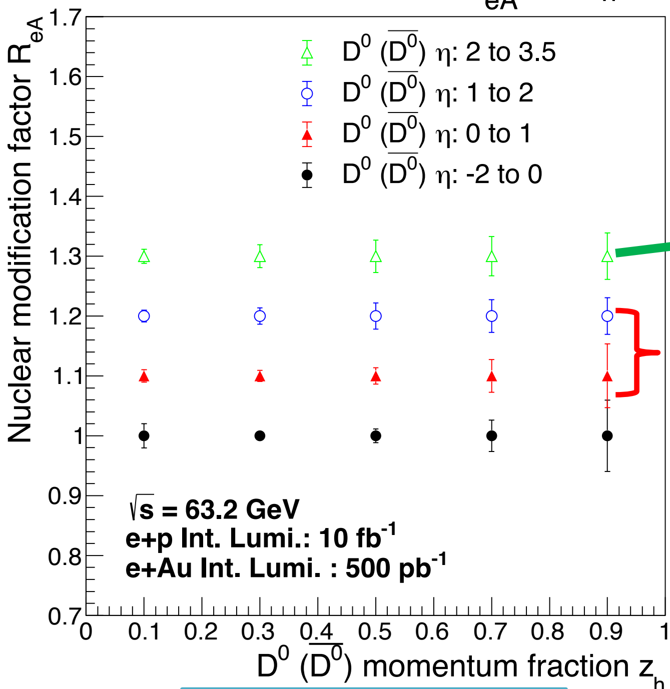

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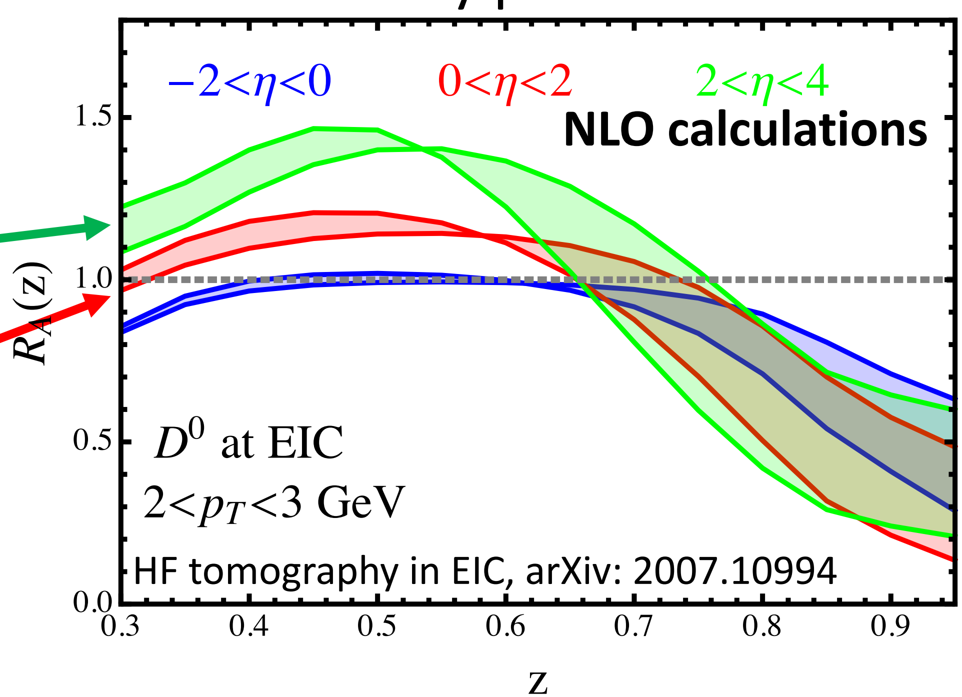
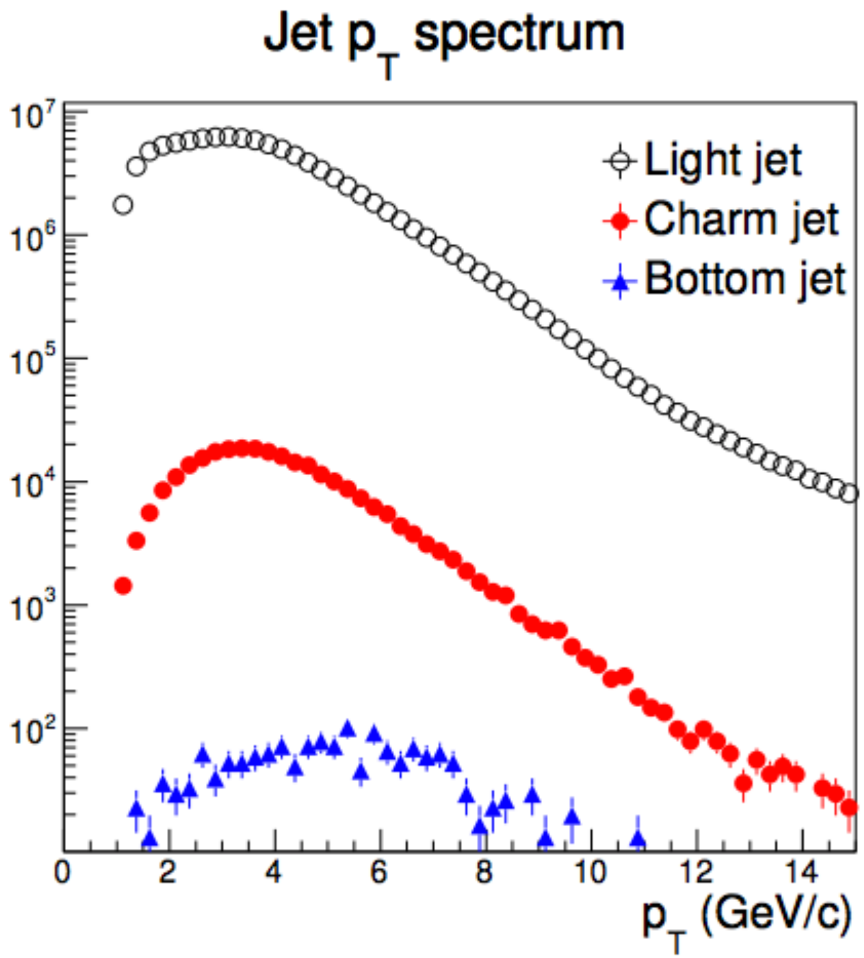


Heavy flavor measurements at the EIC will enhance the sensitivity of the nuclear transport properties and discrimination power in pseudorapidity study

→ Constraint theory predictions

Inclusive Jet Studies



arXiv:2009.02888v1

- Jet algorithm: Anti-k_T with R=0.8
- Tag jets:
  - ≥ 1 heavy flavor inside the jet cone: heavy flavor jets
  - otherwise: light flavor jet
- Reconstruction efficiency will be applied in jet yield in future study

Jet Substructure for Different Flavor Jets

A new probe to explore the hadronization origin and process:

Jet angularity $\tau_a \equiv \tau_a^{pp} \equiv \frac{1}{p_T} \sum_{i \in J} p_T^i \left(\Delta \mathcal{R}_{iJ}\right)^{2-a}$

JHEP 1804 (2018) 110

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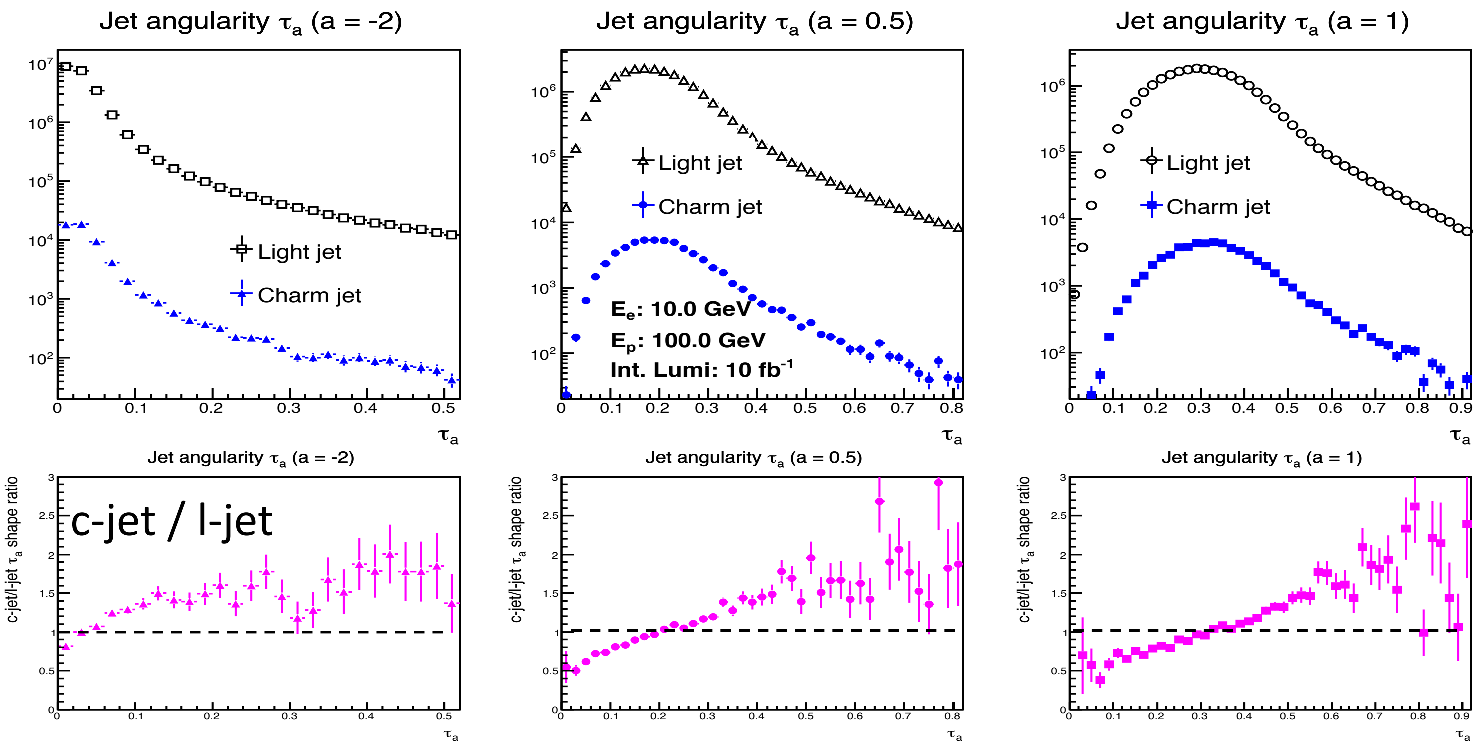

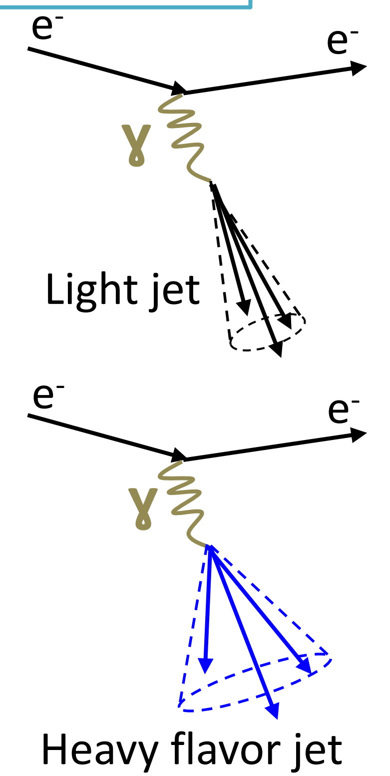

Charm jets become broader compared to light jets with increasing $\boldsymbol{a}$

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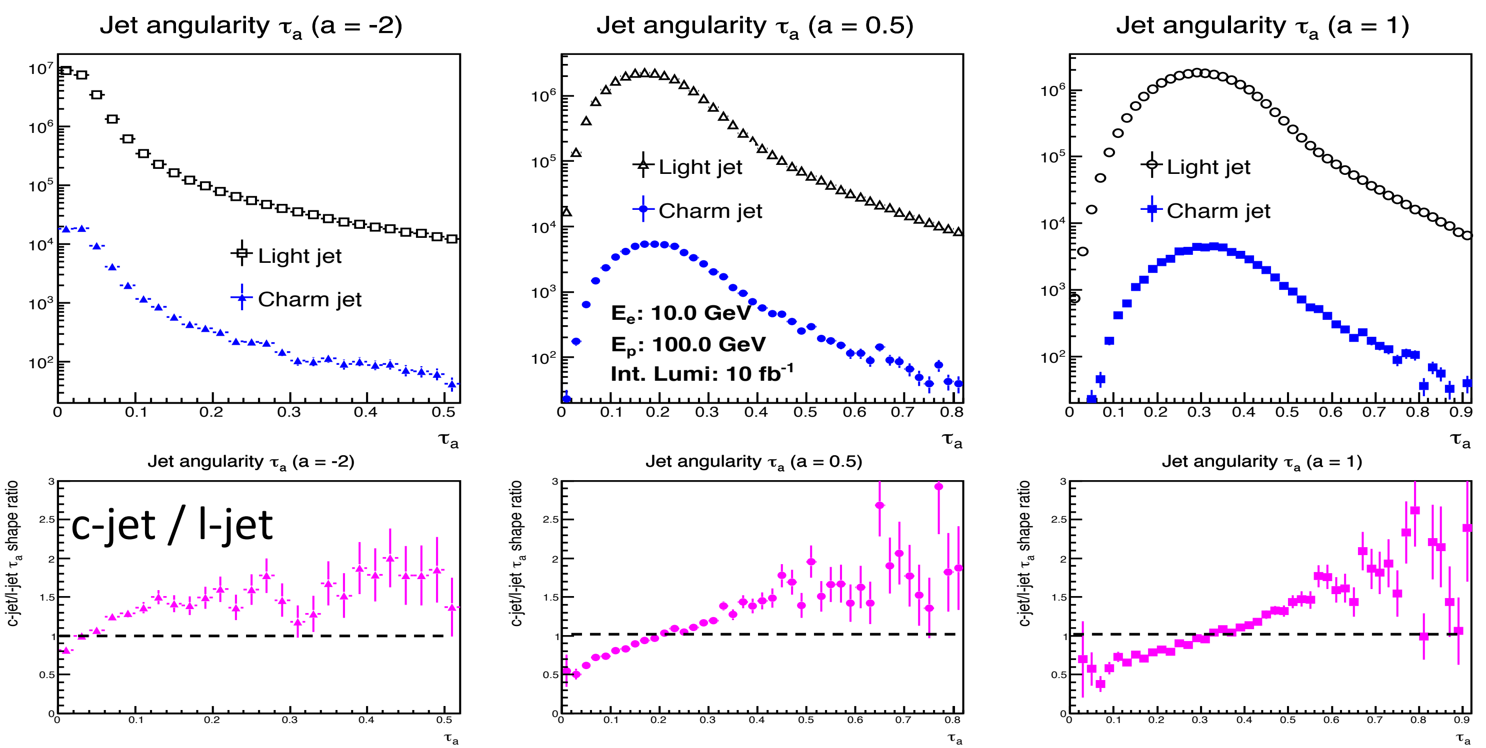

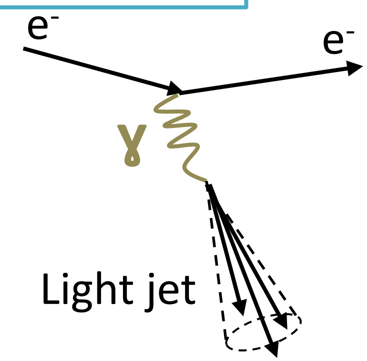

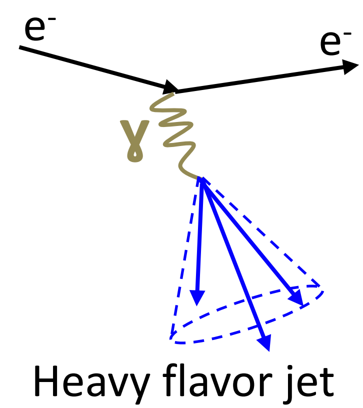

- Distinguish quark and gluon jets
- Study quark/gluon recombination into final hadrons with different masses
- Study the impact of nuclear medium effects in e+A collisions

Summary

Heavy flavor and jet measurements are crucial to study EIC physics

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- A 5/6-plane forward silicon detector is proposed for heavy flavor and jet measurements in the EIC
  - Detector performances, which are studied from extensive simulations, are included in physics studies

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- A 5/6-plane forward silicon detector is proposed for heavy flavor and jet measurements in the EIC
  - Detector performances, which are studied from extensive simulations, are included in physics studies
- Physics studies of heavy flavor R_{eA} and jet angularity
  - Help constraint theoretical predictions
  - Distinguish quark/gluon jets and nuclear medium effect in e+A collisions

EIC FST technical notes - arXiv:2009.02888v1

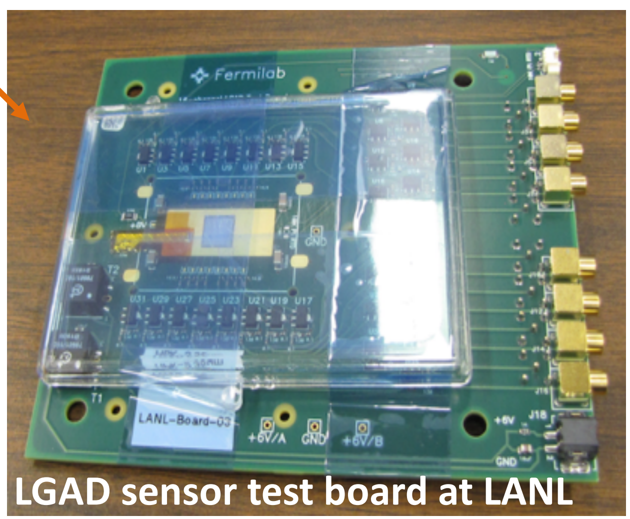
Outlook

Detector R&D work underway

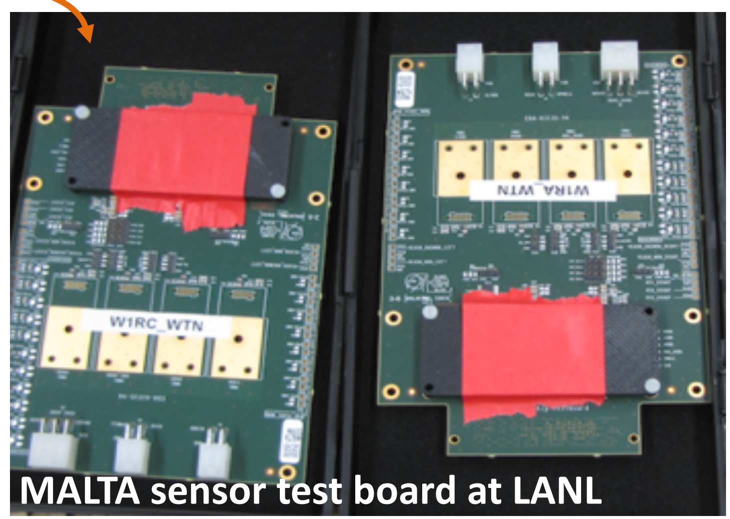
- Bench test for the LGAD & MALTA received
- FST prototype development and beam test

Silicon sensor options

	Pixel pitch	Silicon thickness	Integration time
LGAD/AC-LGAD	100µm	<300µm (<1% X_0)	300-500ps
MALTA	36.4µm	100µm (<0.5% X_0)	5ns
ITS-3 type	20µm	50µm	100ns ?



LGAD sensor test board at LANL

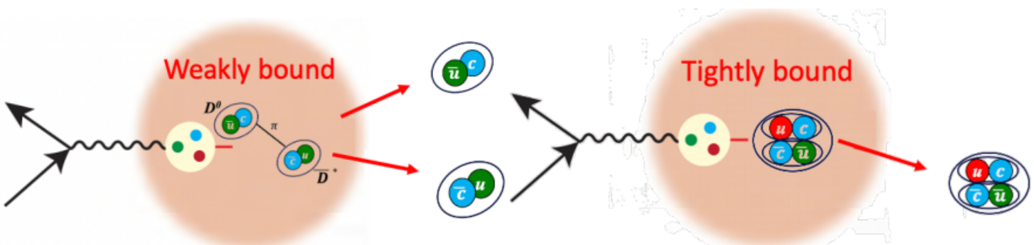


MALTA sensor test board at LANL

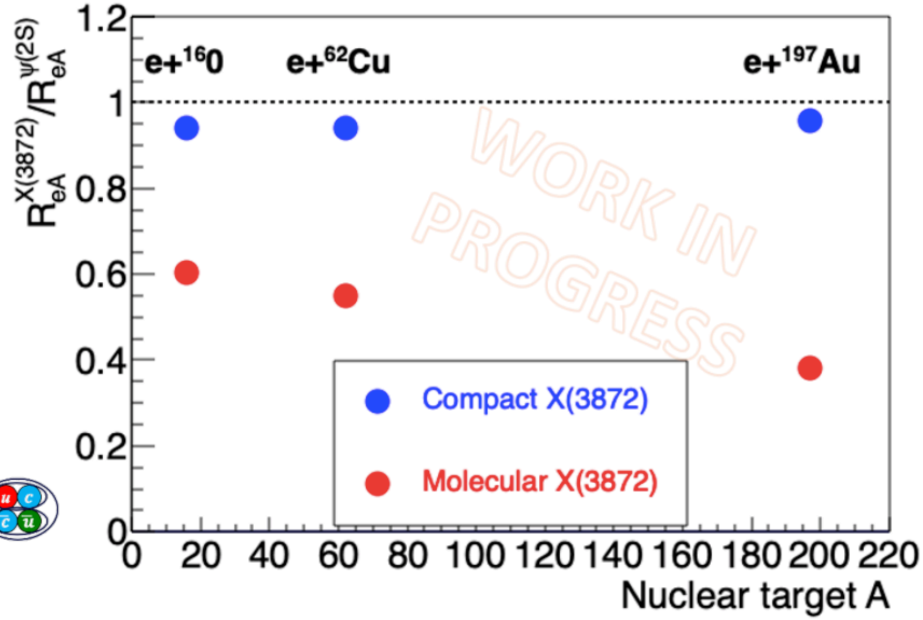
Outlook

Physics Study

- Continue heavy flavor and jet studies with updated detector response
- Exotic heavy flavor studies



Relative modification of X(3872)/ $\psi(2S)$ projection at $\sqrt{s}$ = 63.2GeV

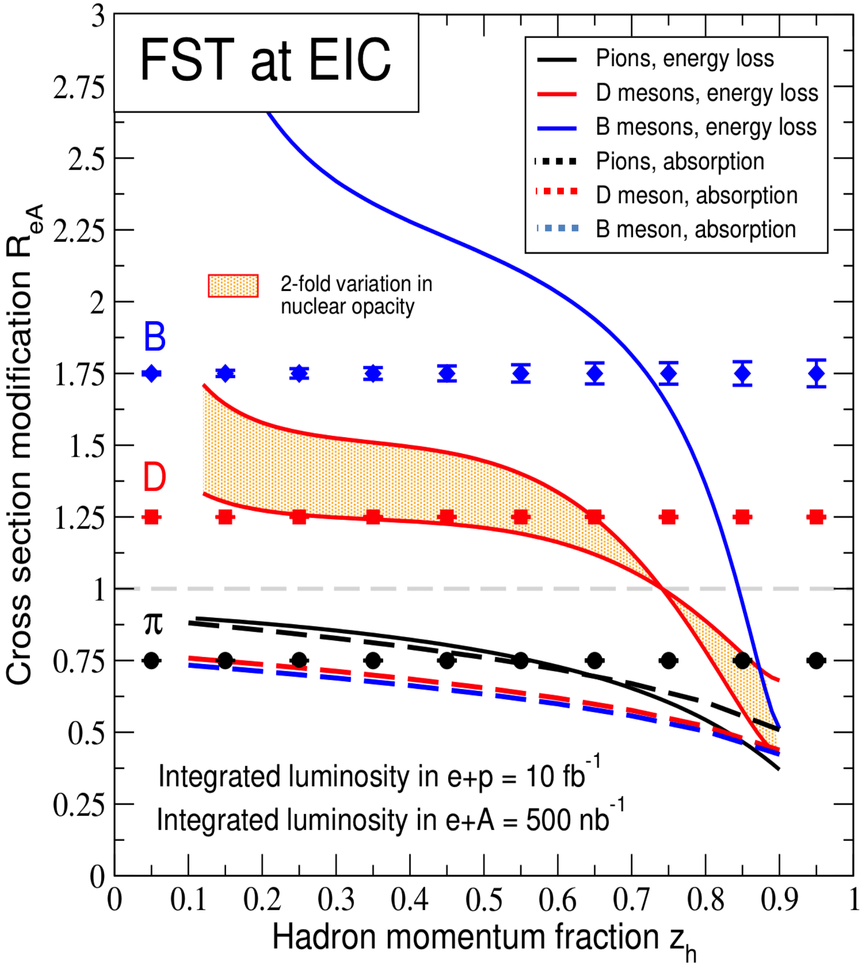


arXiv:2009.02888v1

Back Up

Key to EIC Physics: Heavy Flavor

EPJ Web of Conferences 235, 04002 (2020)



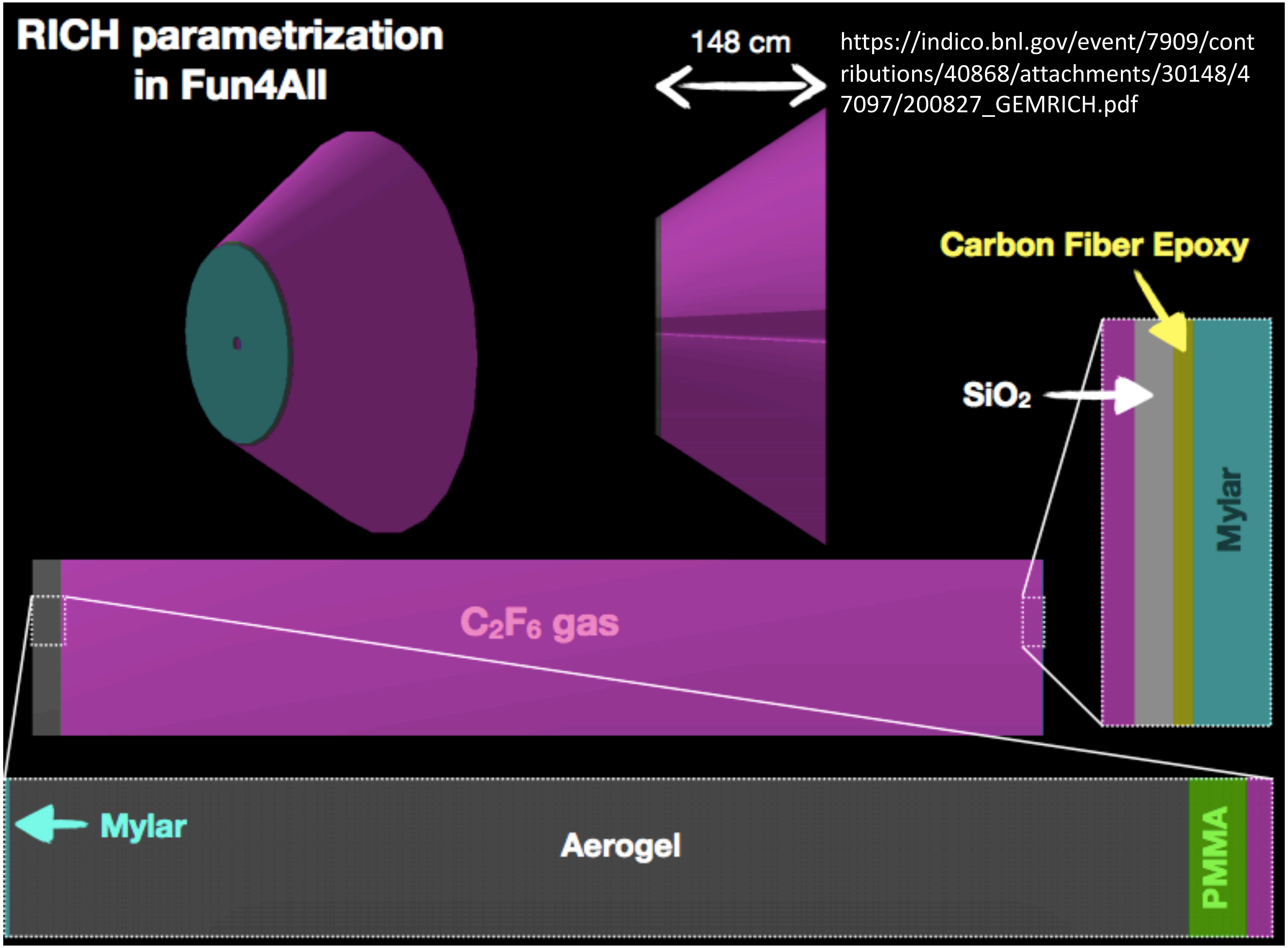
Projected stat. uncertainties at event generation level and include evaluated sampling efficiencies

- Competing models of nuclear modification in DIS reactions with nuclei (e.g HERMES data)
  - — Energy loss of partons, hadronization **outside** the nuclear matter
  - .... Hadronization **inside** nuclear matter
- Heavy mesons have very different fragmentation functions and formation times compared to light mesons
- Easy to discriminate between larger suppression for D/B mesons (in-medium hadronization) and strong/intermediate z enhancement (E-loss)
- **Enhanced sensitivity to the transport properties of nuclei**

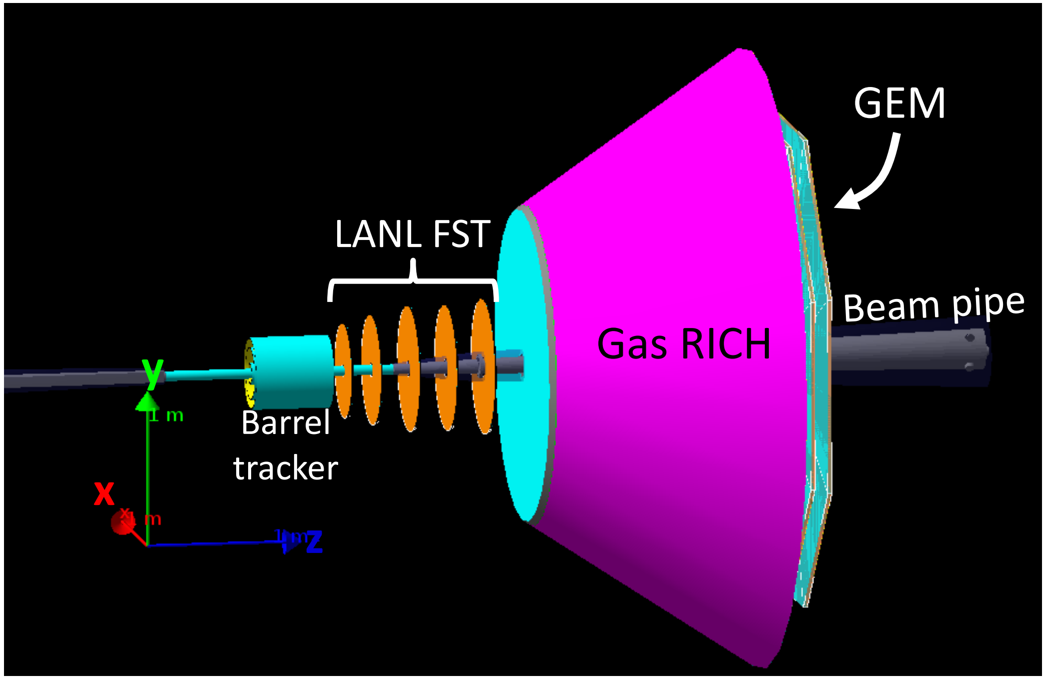
Simulation Setup

- Fun4All Simulation: Geant based simulation package developed by PHENIX collaboration at BNL
- Both **BeAST** (max. 3T) and **Babar** (max. 1.4T) magnets are tested
- Event configuration:
  - **single (10) π-** per event for momentum (vertex) reconstruction
  - Vertex (0,0,0)
    - 20um smearing in x and y direction for track reconstruction
    - no smearing for vertex reconstruction
  - 7.5M events in each p (p_T) bin
- Track configuration:
  - p (p_T): **1-30 GeV**
  - Pseudorapdity: **0-3.5** w.r.t. to the beam pipe
  - Hit efficiency at 95%
  - Pseudorapidity correction for ion beam angle

Gas RICH Setup in Fun4All

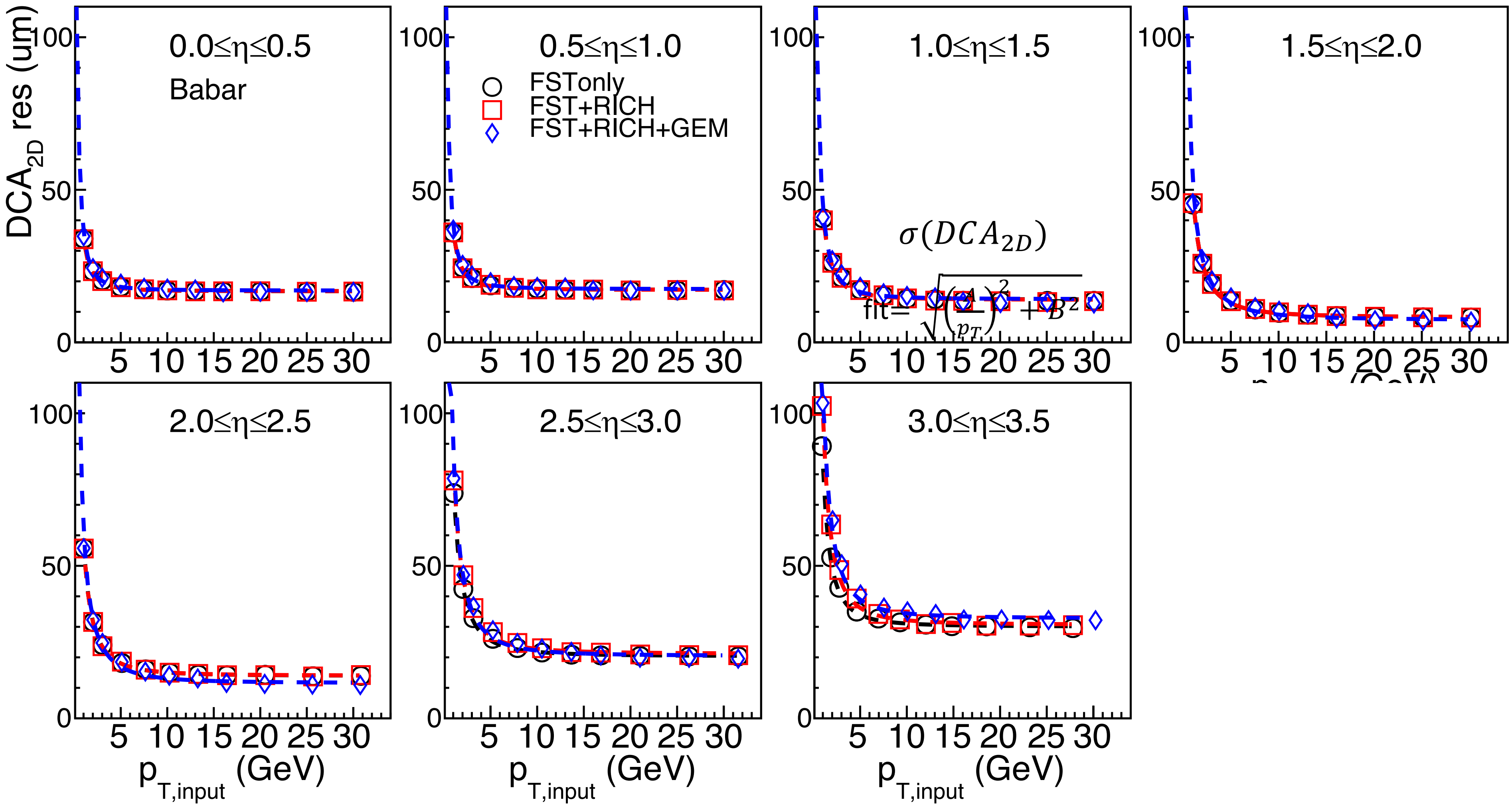


GEM Tracker Setup in Fun4All



Plane	z (cm)	η_{min}	η_{max}	r res (um)	ϕ res (um)	Gas
0	300	1.5	3.5	100	70	methane
1	310	1.5	3.5	100	70	methane
2	320	1.5	3.5	100	70	methane

DCA_{2D} Resolution of Tracking System with Babar Magnet



Fitting Parameters of Momentum Resolution

$$\frac{\Delta p}{p}(p) = \sqrt{(Ap)^2 + B^2}$$

η	B field	FST (6 planes)		FST (6 planes) + RICH		FST (5 planes) + RICH + GEM	
		A (%/GeV)	B (%)	A (%/GeV)	B (%)	A (%/GeV)	B (%)
0.0–0.5	BeAST	0.313	0.440	0.310	0.457	-0.309	0.475
	Babar	0.608	0.880	0.605	0.892	0.608	0.915
0.5–1.0	BeAST	0.267	0.510	0.259	0.494	0.263	0.494
	Babar	0.520	0.971	0.513	1.035	0.513	1.010
1.0–1.5	BeAST	0.039	0.568	0.040	0.551	0.032	0.597
	Babar	0.076	1.039	0.077	1.120	0.070	1.088
1.5–2.0	BeAST	0.019	0.454	0.018	0.448	0.013	0.445
	Babar	0.039	0.839	0.039	0.882	0.026	0.876
2.0–2.5	BeAST	0.032	0.687	0.035	0.682	0.028	0.704
	Babar	0.068	1.346	0.070	1.374	0.051	1.402
2.5–3.0	BeAST	0.037	1.190	0.062	1.306	0.062	1.336
	Babar	0.086	2.362	0.127	2.607	0.123	2.629
3.0–3.5	BeAST	0.063	1.746	0.095	2.069	0.095	2.278
	Babar	0.124	3.378	0.189	4.305	0.189	4.868

- BeAST vs Babar: Fitting parameters with the use of Babar magnet are about double of the use of BeAST magnet
- $\boldsymbol{\eta < 2.5}$: Comparable values between different detector systems
- $\boldsymbol{\eta > 2.5}$: Fitting parameters increases with the more integrated detector systems

Fitting Parameters of DCA_{2D} Resolution

$$DCA(p_T) = \sqrt{\left(\frac{A}{p_T}\right)^2 + B^2}$$

η	B field	FST (6 planes)		FST (6 planes) + RICH		FST (5 planes) + RICH + GEM	
		A (μm·GeV)	B (μm)	A (μm·GeV)	B (μm)	A (μm·GeV)	B (μm)
0.0–0.5	BeAST	30.73	16.71	30.17	16.86	30.84	16.78
	Babar	30.80	16.74	30.56	16.75	32.55	16.97
0.5–1.0	BeAST	32.80	17.22	32.14	17.37	32.83	17.28
	Babar	32.98	17.22	32.99	17.21	34.76	17.46
1.0–1.5	BeAST	41.54	14.19	39.47	14.39	40.73	14.06
	Babar	41.40	14.01	40.92	13.93	42.62	14.15
1.5–2.0	BeAST	49.57	8.24	48.49	8.43	51.56	7.36
	Babar	49.20	8.18	49.30	8.21	53.72	7.32
2.0–2.5	BeAST	57.87	13.73	54.79	14.16	59.58	11.48
	Babar	57.21	13.91	57.00	13.97	61.83	11.54
2.5–3.0	BeAST	76.78	20.42	81.63	21.13	83.90	20.35
	Babar	77.10	20.37	84.77	21.15	86.97	20.45
3.0–3.5	BeAST	77.79	29.71	95.90	30.01	104.95	31.55
	Babar	78.50	30.08	96.37	30.68	105.17	32.77

- BeAST vs Babar: comparable fitting parameters
- $\eta < 2.5$: Comparable values between different detector systems
- $\eta > 2.5$: Fitting parameters increases with the more integrated detector systems