From sPHENIX to EIC

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Los Alamos National Laboratory
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APCTP Workshop on the Physics of Electron Ion Collider

Open Questions in Cold-QCD …

- from 2022 US NP LRP QCD Town Hall Meeting (X. Ji)

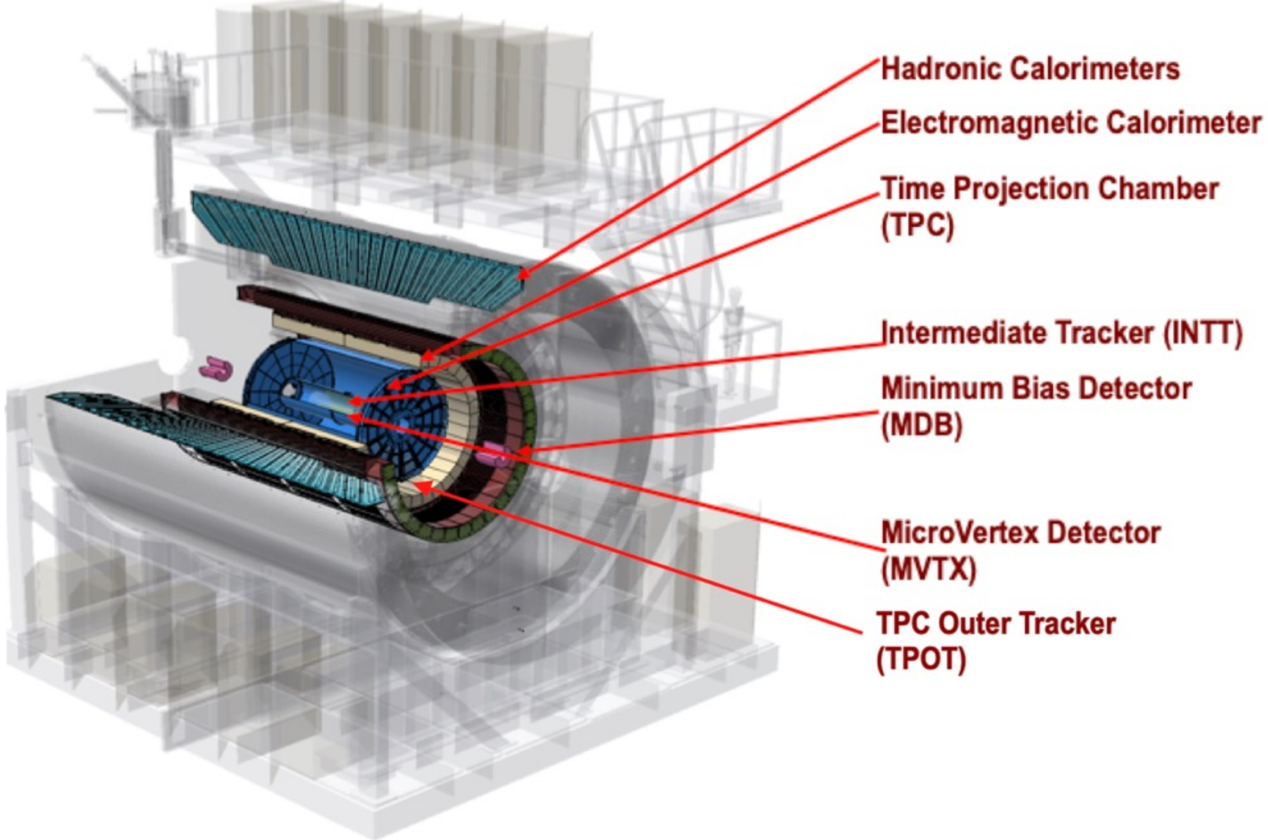
1. How does QCD (non-pert. QFT) work?
2. ***Can confinement be proven and experimentally tested in cold QCD?***
3. What do existence and non-existence of exotics states tell us about properties of QCD?
4. Why is the proton's spin not 17/2?
5. ***What is the role of gluon in hadron structure, in hadron masses in particular?***
6. ***How to understand the universality & saturation properties of nucleon/nucleus wave function at small-x and to test it in exp?***
7. ***How does hadronization happen?***
8. What is the phase diagram of nuclear matter as function of density and isospin?
9. Can a quantum computer help in solving QCD?
10. ….

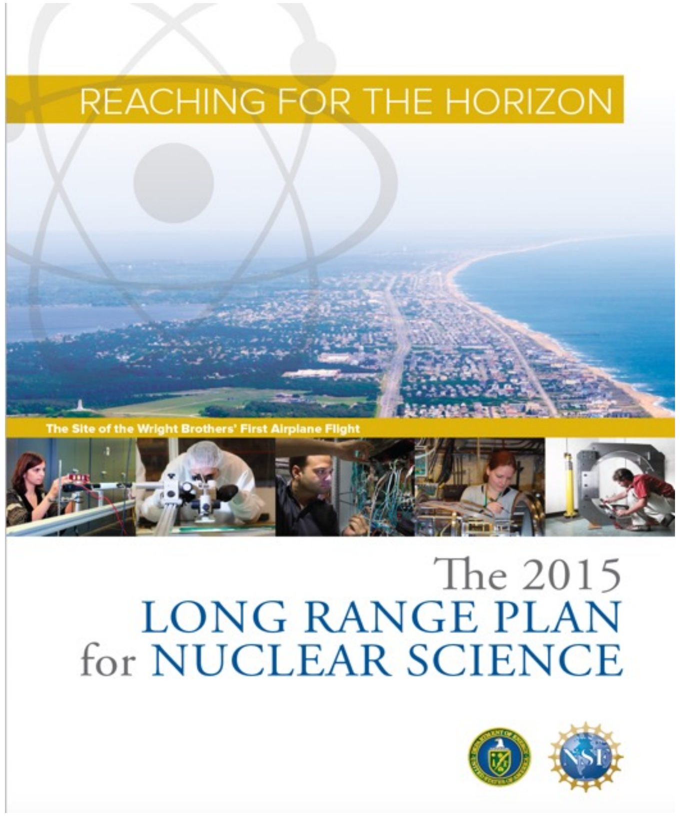
=> Study heavy quark production and hadronization in sPHENIX/HI and EIC

Outline

- sPHENIX HF physics in pp, pA and AA collisions
- HF physics with EIC
- sPHENIX and EIC R&D collaboration opportunities
    - sPHENIX MVTX pixel detector and HF physics
    - SRO and AI-based HF “Trigger” for sPHENIX and EIC
    - Forward/backward Si-detector for HF at EIC

sPHENIX Experiment at RHIC

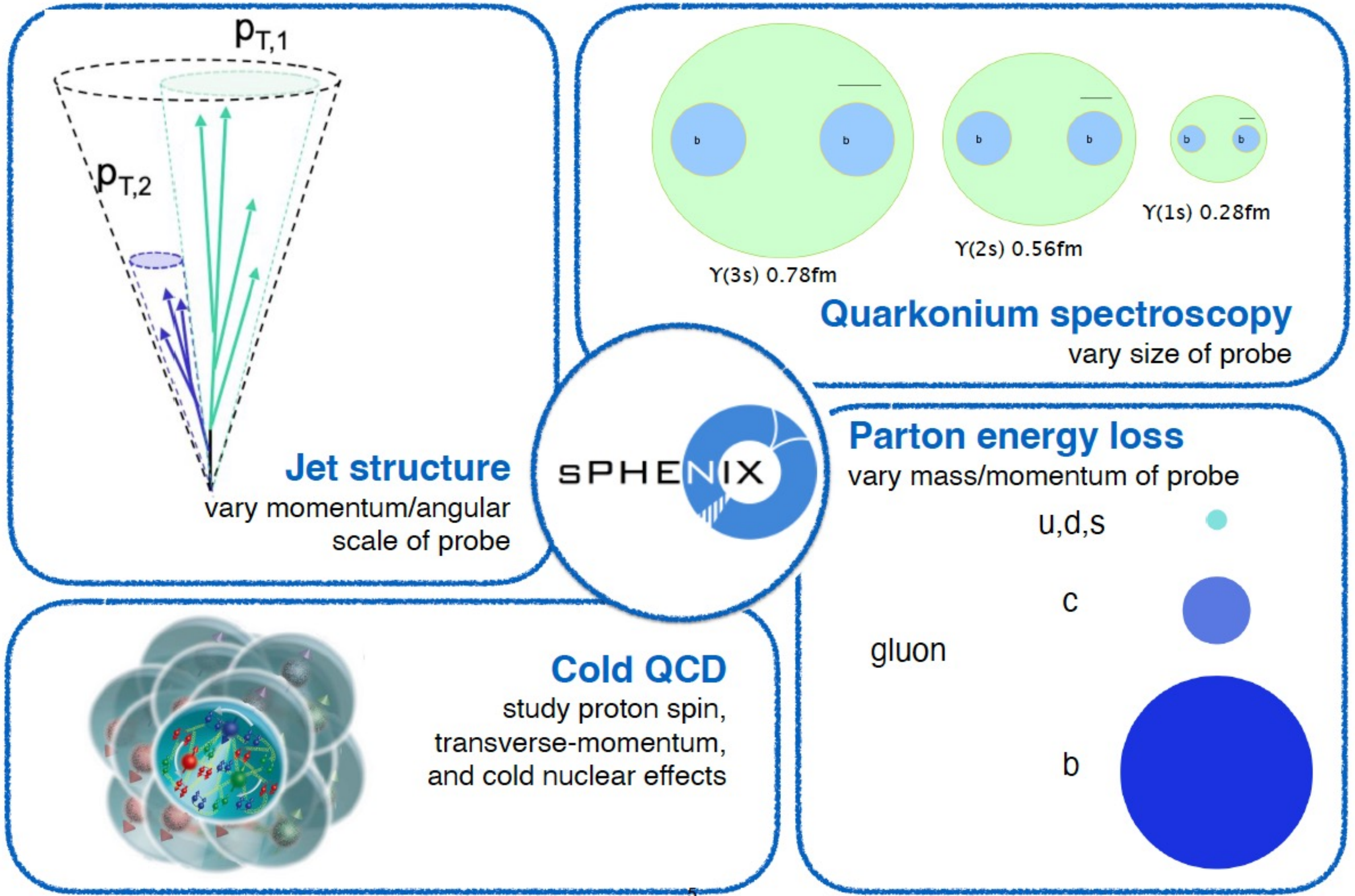




<u>2015 NSAC Long Range Plan for Nuclear Science: sPHENIX Experiment at RHIC</u>

- Probe the inner workings of QGP by resolving its properties at shorter and shorter length scales
- Complementary to LHC experiments to study relativistic heavy-ion collisions

sPHENIX Physics Pillars

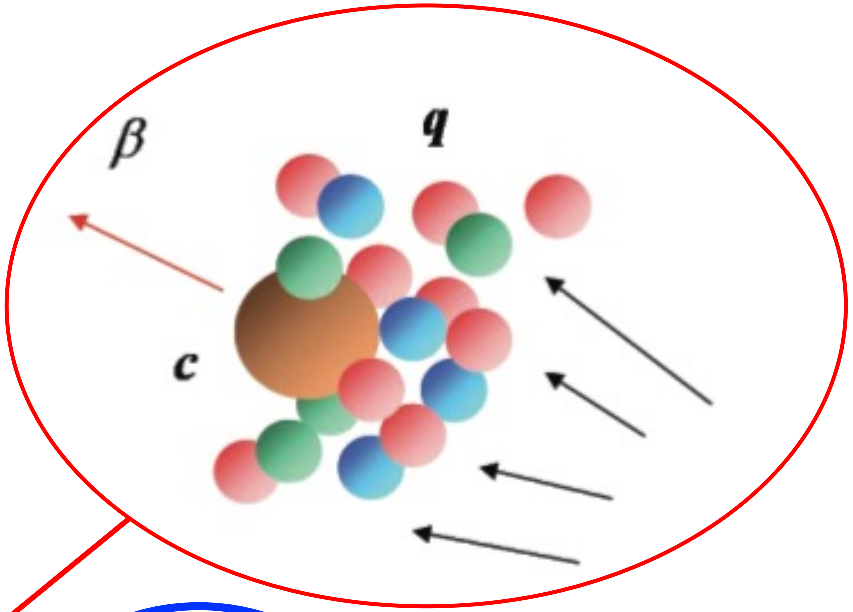


Heavy Quark (HQ) to Probe QGP

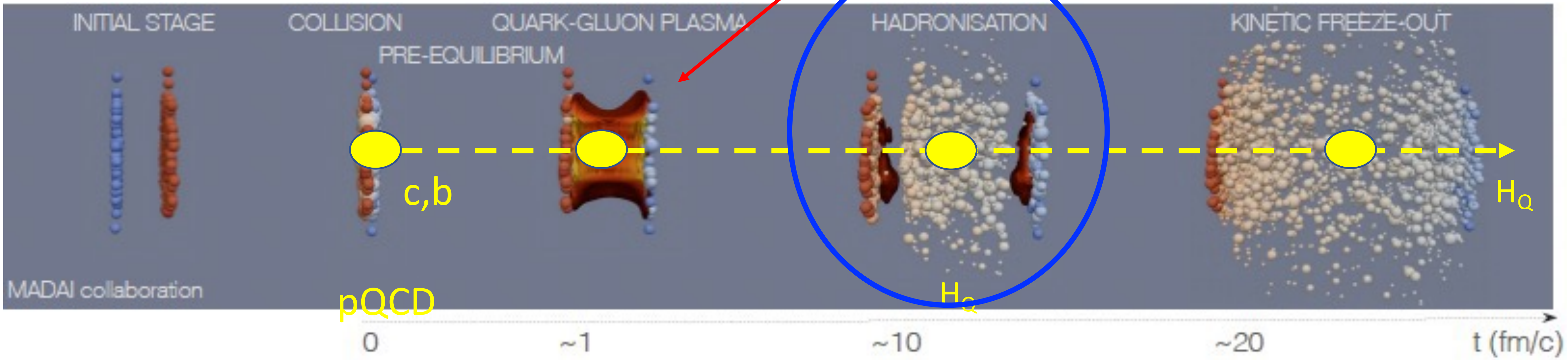
- **Quark diffusion in QGP**
  - ➢Flow, medium interactions

- **Quark energy loss in QGP**
  - ➢Collisional vs radiative
  - ➢Mass dependence

Most of current focus



Understanding hadronization is important!



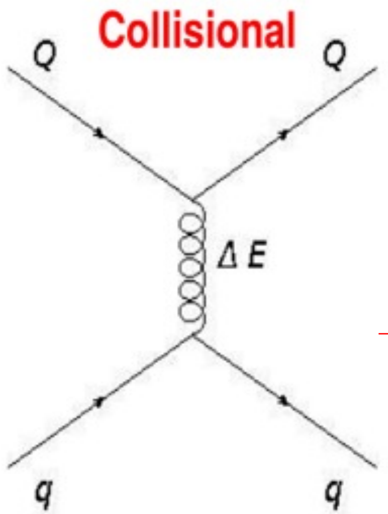
Role of Mass in Heavy Quark Energy Loss

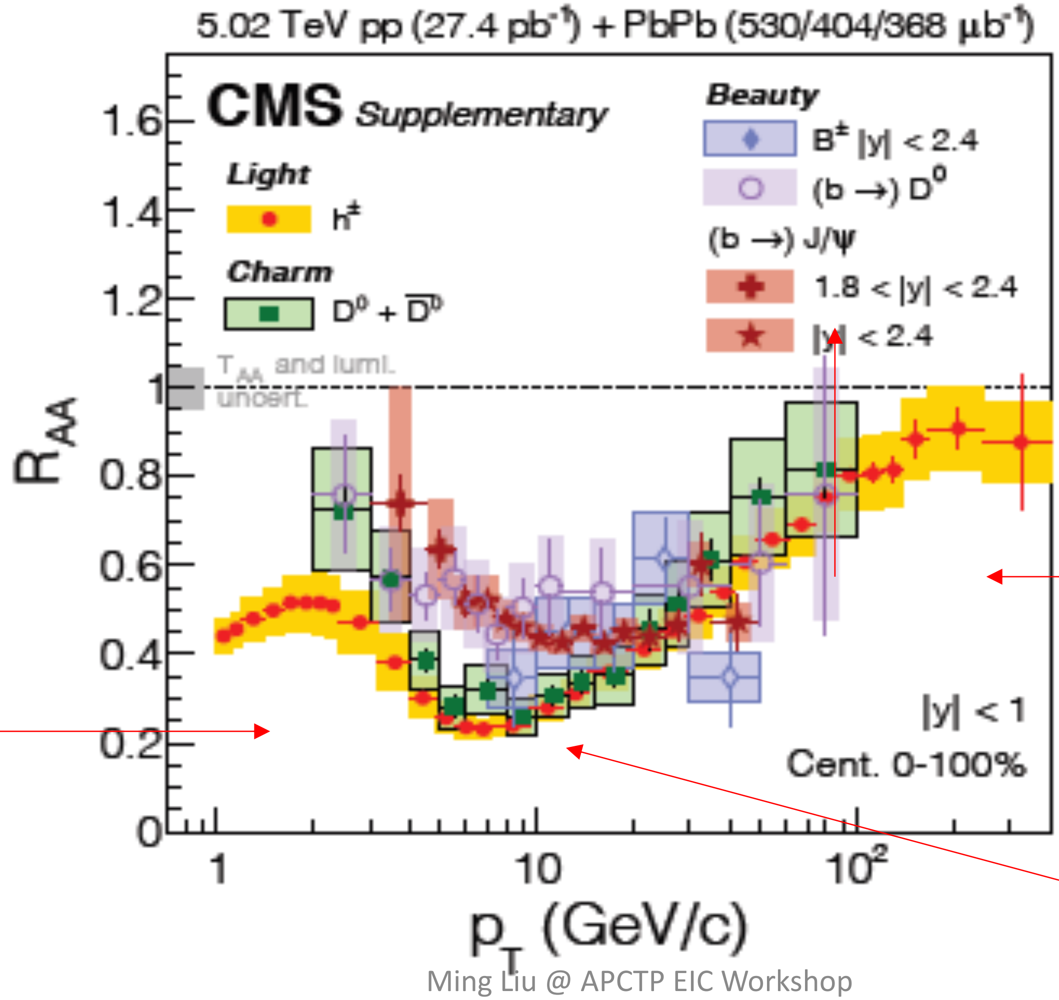
- A beautiful but over simplified picture

HI provides very reach measurements about HF hadronization

Low pT:

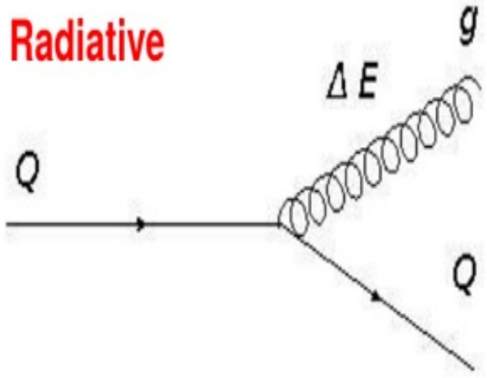
- Strong mass-dependence
- Diffusion





High pT:

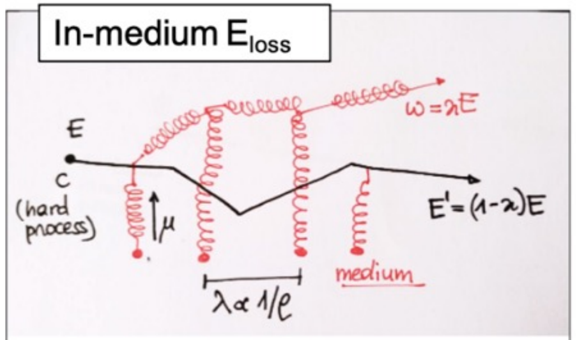
- Weak mass-dependence
- Energy loss



Mass effect at intermediate pT

$$\frac{dn_g}{dx\,dk_T^2} = \frac{2\alpha_s(k_T^2)}{3\pi\,x}\,\frac{k_T^2[1+(1-x)^2]}{[k_T^2+x^2m_q^2]^2}$$

HF Suppression and Flow – early Challenge



Baier-Dokshitzer-Mueller-Peigné-Schiff, Nucl. Phys. B. 483 (1997) 291

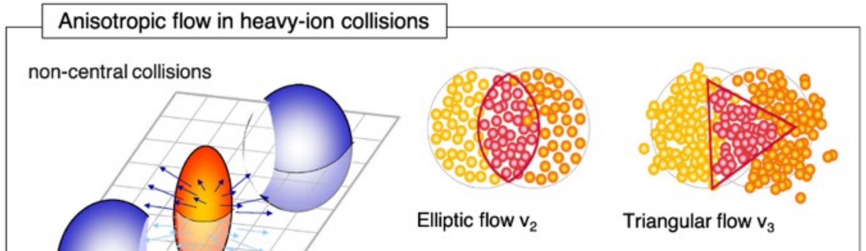
$$\langle \Delta E \rangle \propto \alpha_s C_r \hat{q} L^2$$

$$\hat{q} = \frac{\mu^2}{\lambda}$$

Average transverse momentum transfer

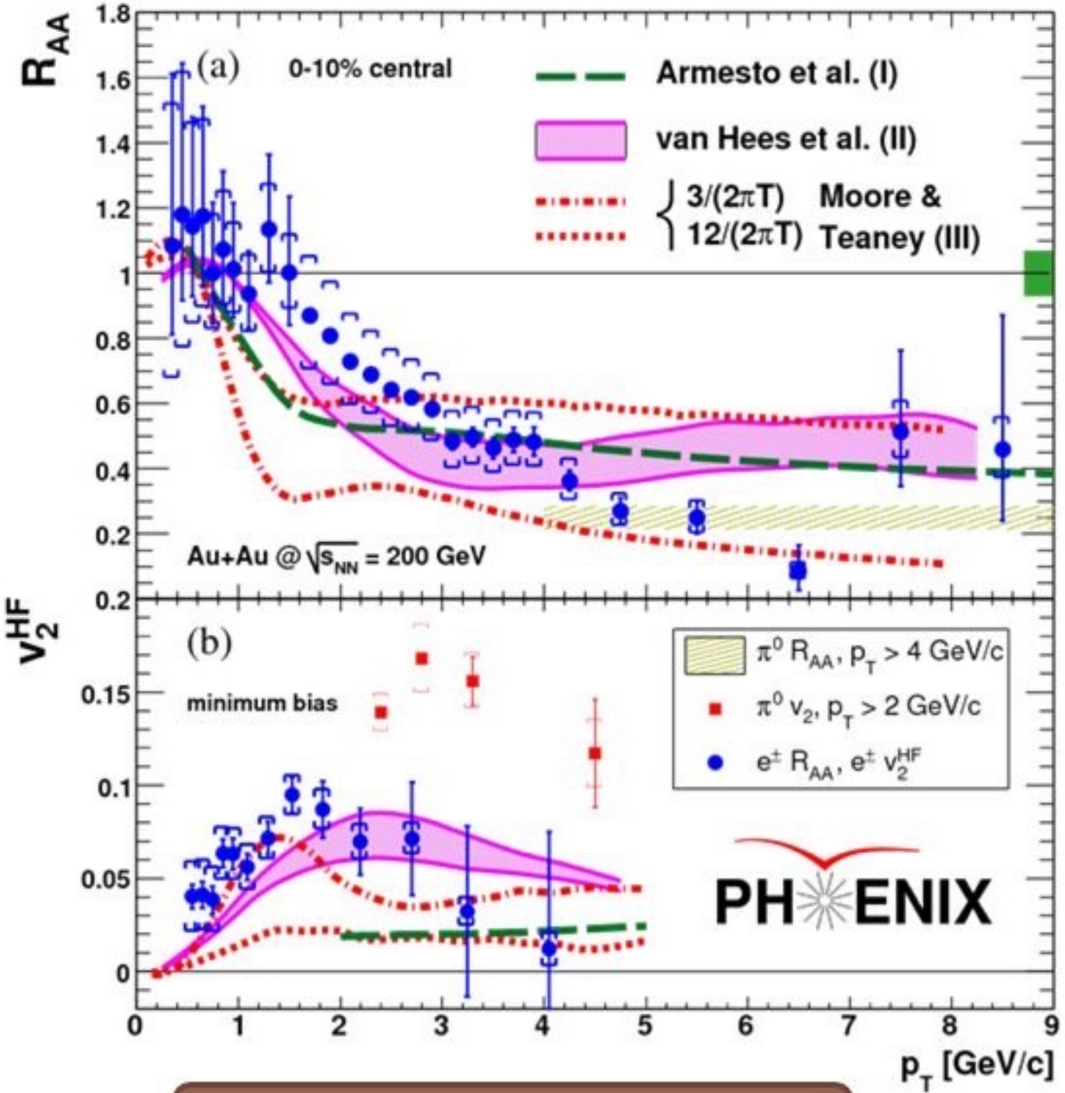
Mean free path ~1/density

Energy loss



$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\varphi - \Psi_n)]$$

HQ flow

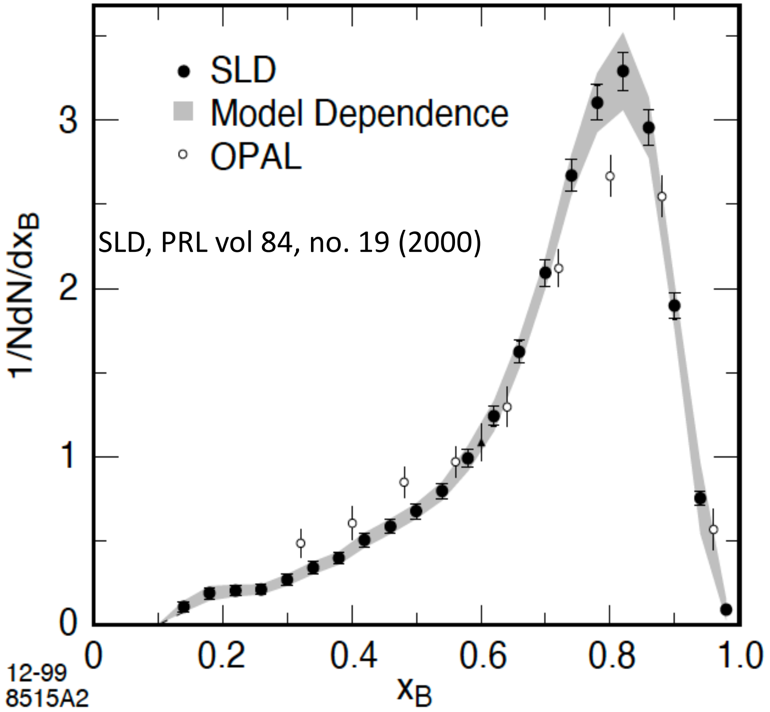


PHENIX, PRL98 (2007) 172301

Experimentally we measure hadrons, not quarks …

- hadronization to connect observables with QGP parameters and more

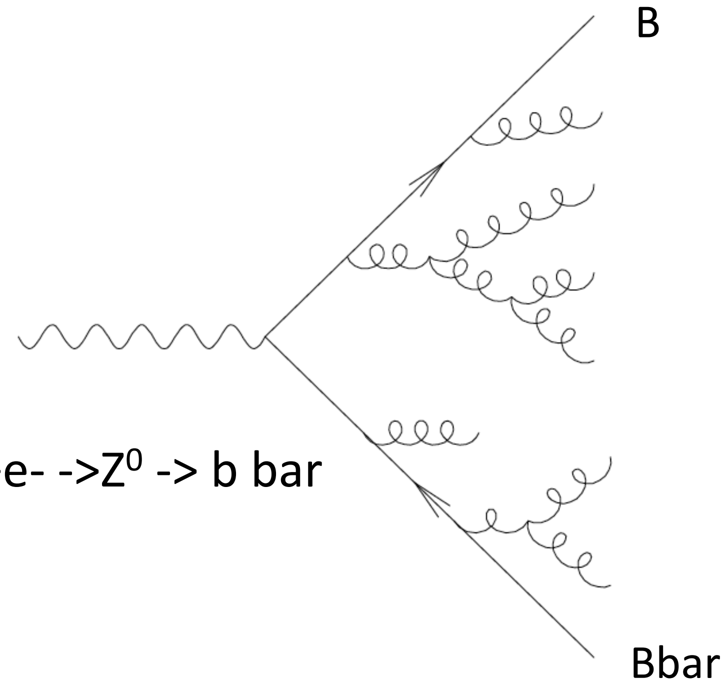
HQ FF assumed universal in all pT in most models until recently (~2018)



A good approximation at high energy e+e-/ep:

- Independent fragmentation in vacuum
- Universal FF

$$x_B = E_B/E_{\text{beam}}$$



e+e- ->Z^0 -> b bar

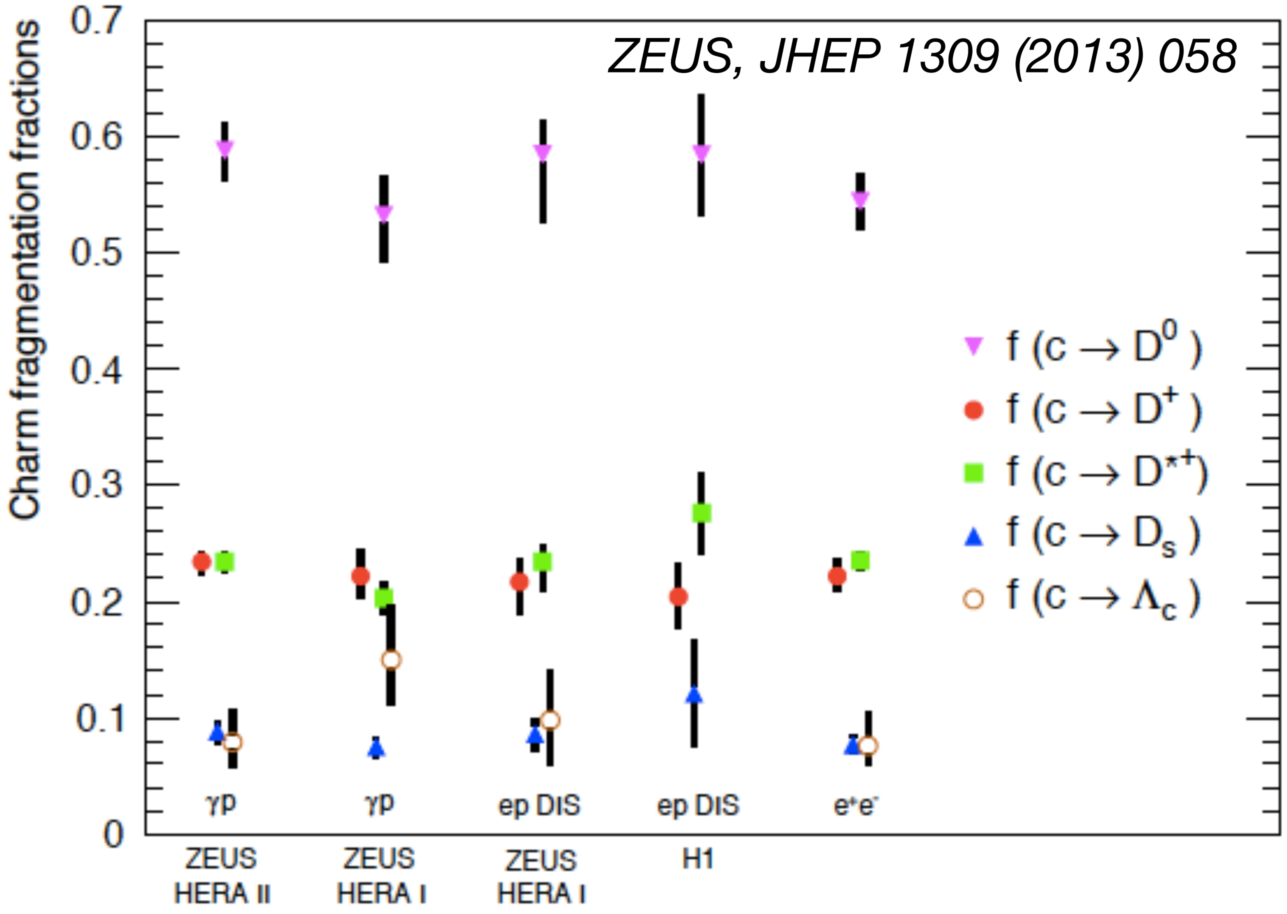
Data: Charm Photoproduction in e^+e^- and ep

- **FF seems "Universal"**

$$2\sigma_{c\bar{c}} = D^0 + D^+ + D_s^+ + \Lambda_c^+ \quad + \text{c.c.}$$

60.8% 24.0% 8.0% 6.2%

Lisovyi, et. al. EPJ C 76 (2016) 397



Recent LHC and RHIC HF precision data:

- Breakdown of the "Universality of HQ FF" in hadroproduction at "low pT"

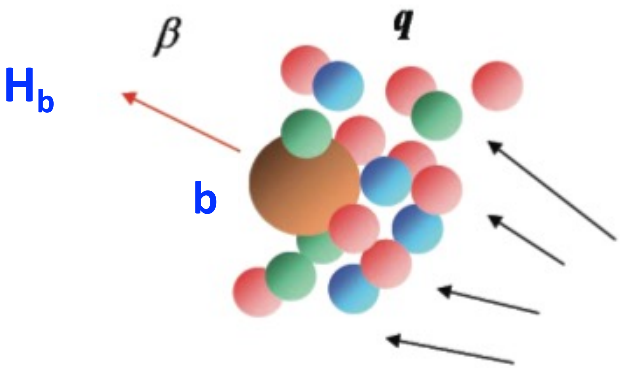
Heavy Quark Hadroproduction in p+p

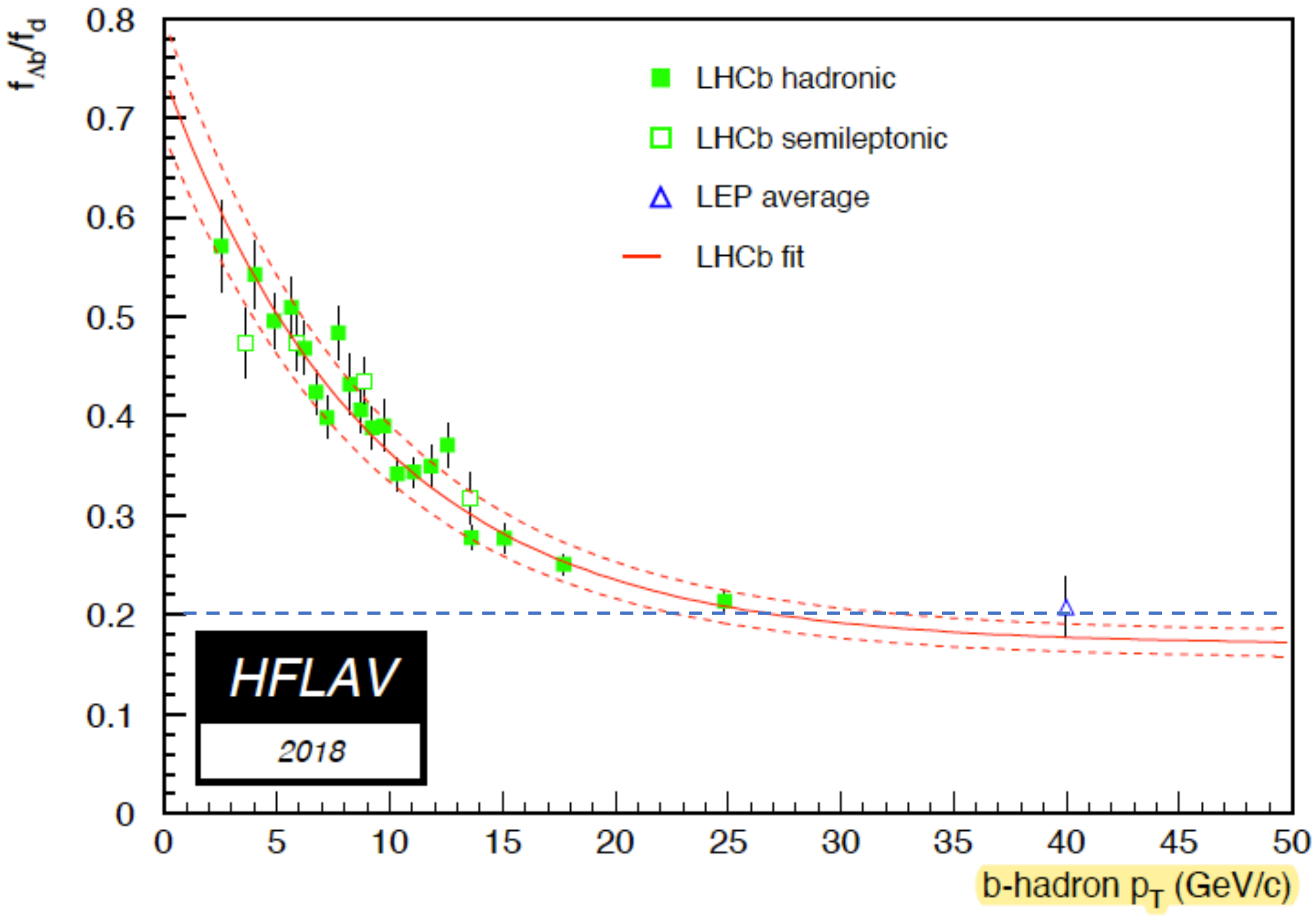
- Break down of the factorization/universality of FF at "low pT"

$\frac{f_{\Lambda_b}}{f_{B_d}}$ vs pT

- **Final state interactions with nuclear medium modifies b-quark hadronization**

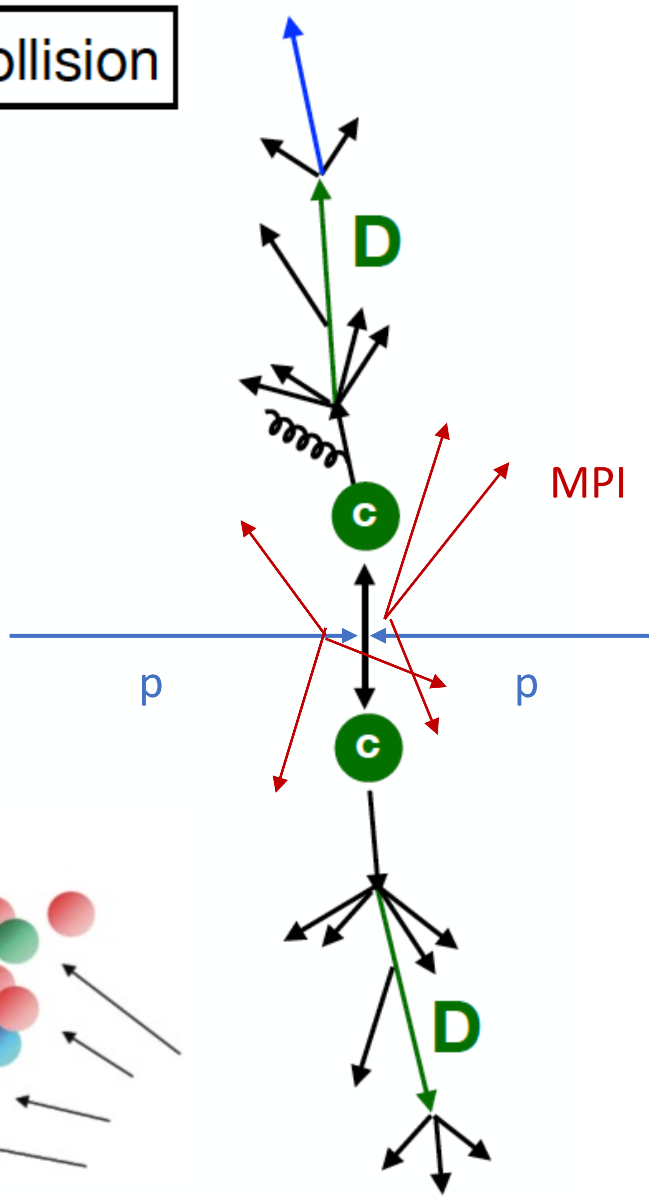
Significant at low pT ~<20 GeV (~5x M_b)

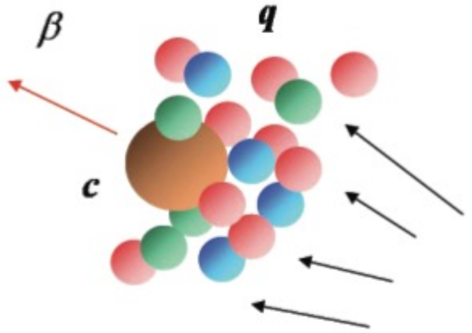




HQ Production in p+p at RHIC

- **One-pair of Q-Qbar produced from one hard-scattering**
  - ➢Double-charm possible but rare
  - ➢Multi-parton interactions important (MPI)
- **Final state interaction (FSI) matters**
  - ➢"Independent fragmentation", like in vacuum, at very high pT
  - ➢Coalescence and interactions with nuclear media important at low pT, mostly local?
    - ❑Hadronization time scale expected very short





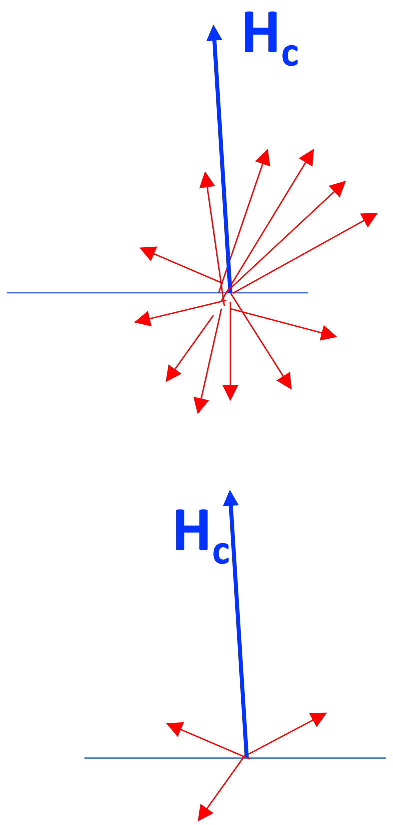
Multiplicity Dependence: Baryon/Meson Ratio in p+p

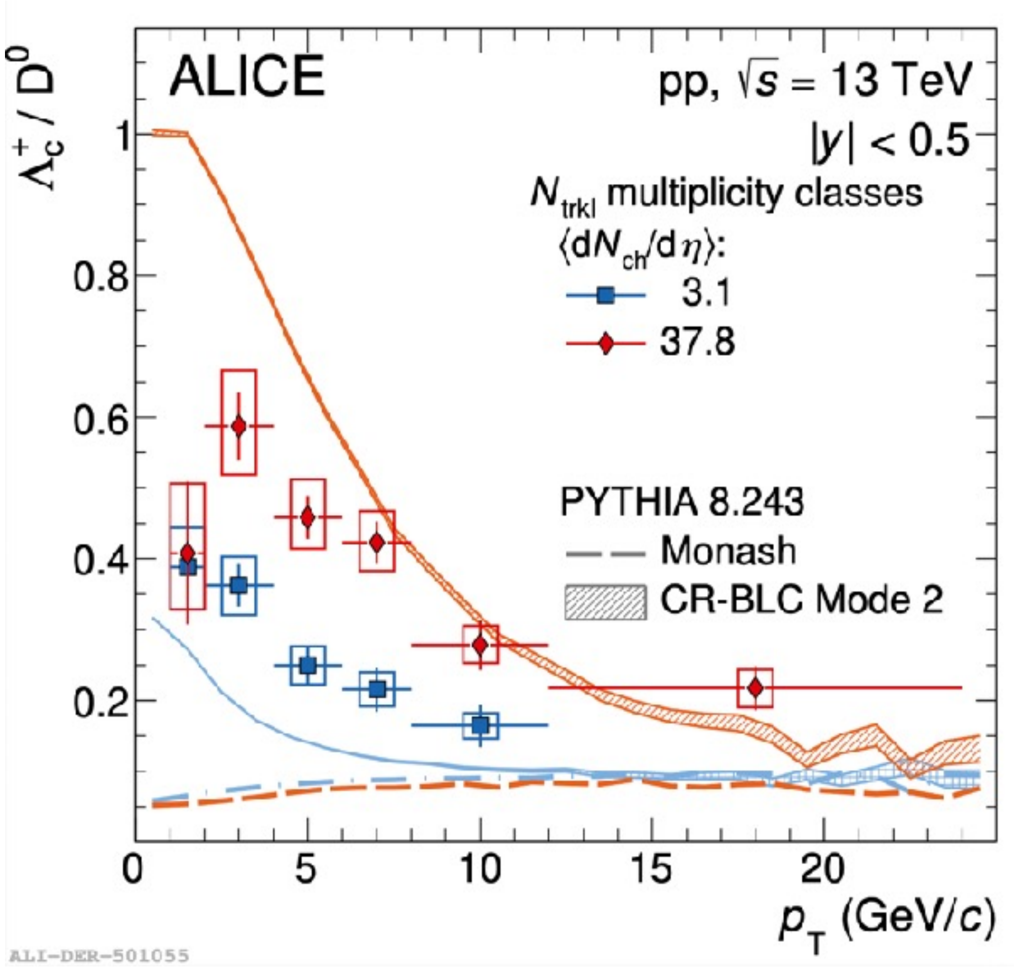
– MPI and FSI Important

- **Strong enhancement vs event multiplicity**
  - ➢ Default PYTHIA significantly underestimate data
- **With MPI and color reconnection PYTHIA agrees better with data**

Given the small proton size, clear evidence of short hadronization time in p+p collisions, ~ 1fm

- *Strong consequence on HI data interpretation*
- *Local or long-range correlation?*

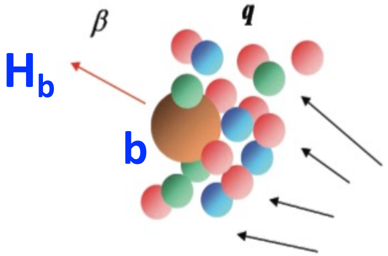


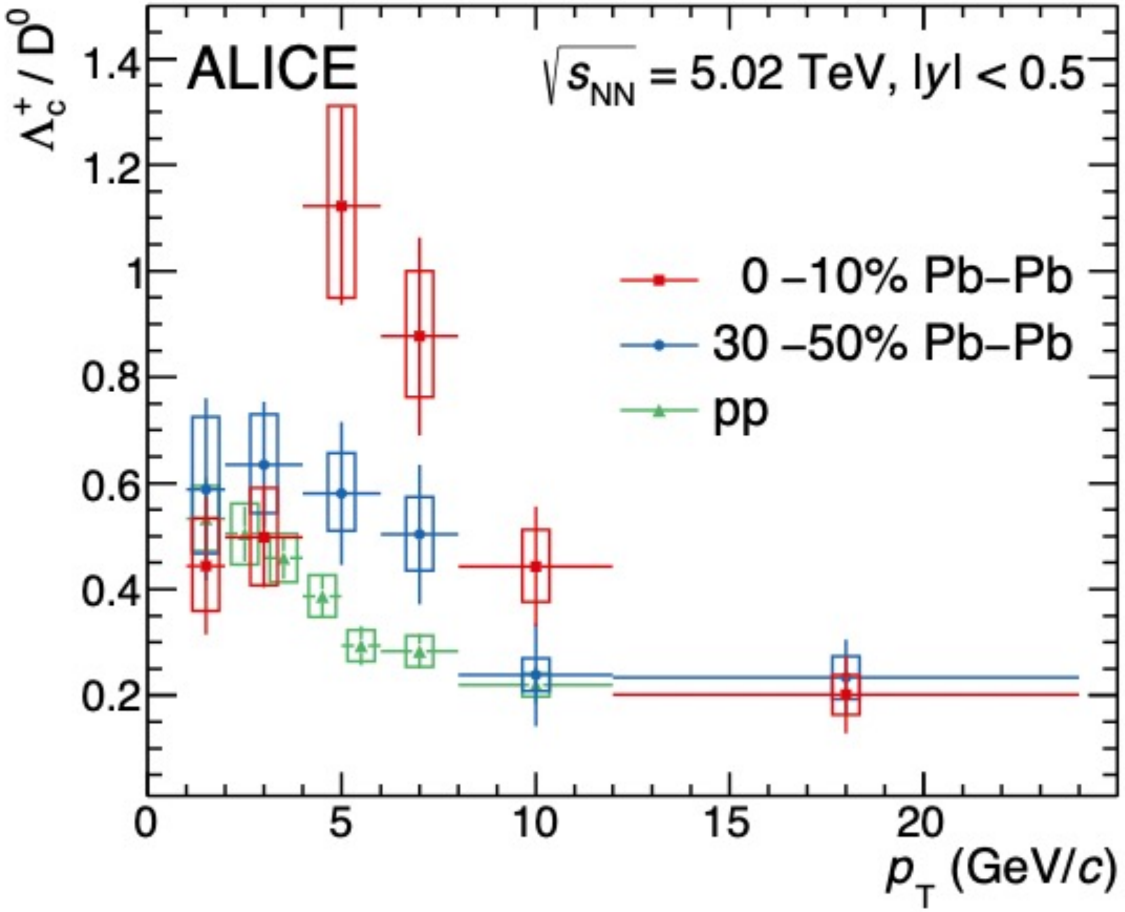


HF in AA Collisions

– broad dynamic range, new challenges and opportunity

- **Charm-quark pair yield: pQCD**
  - ➢Same per nucleon pair
- **Enhancement in AA at low pT**
  - ➢FSI important, centrality
  - ➢Models with fragmentation and coalescence agree with data better
  - ➢Strangeness enhancement



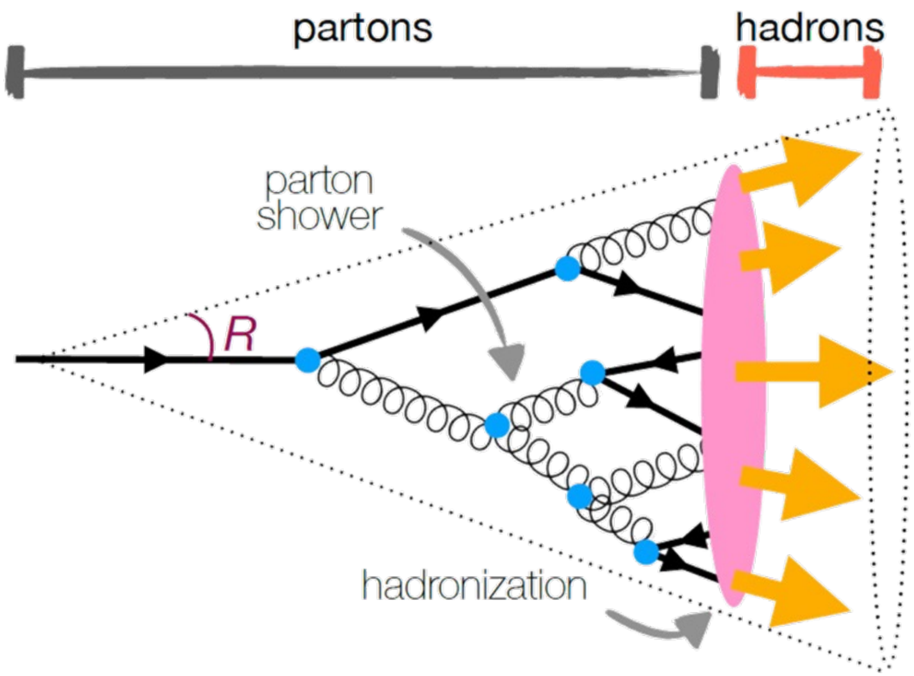


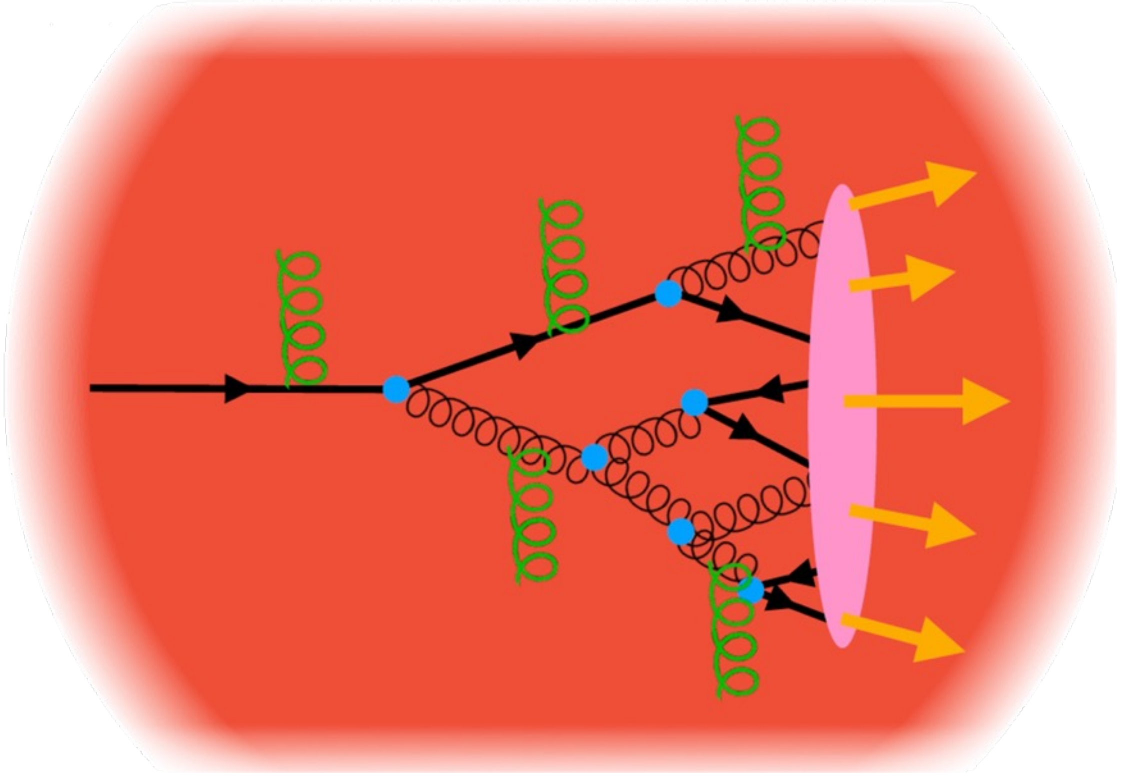
More precision data needed to better understand HQ hadronization

HQ Hadronization at "high pT" in pp and AA
- mostly follows pQCD

pp

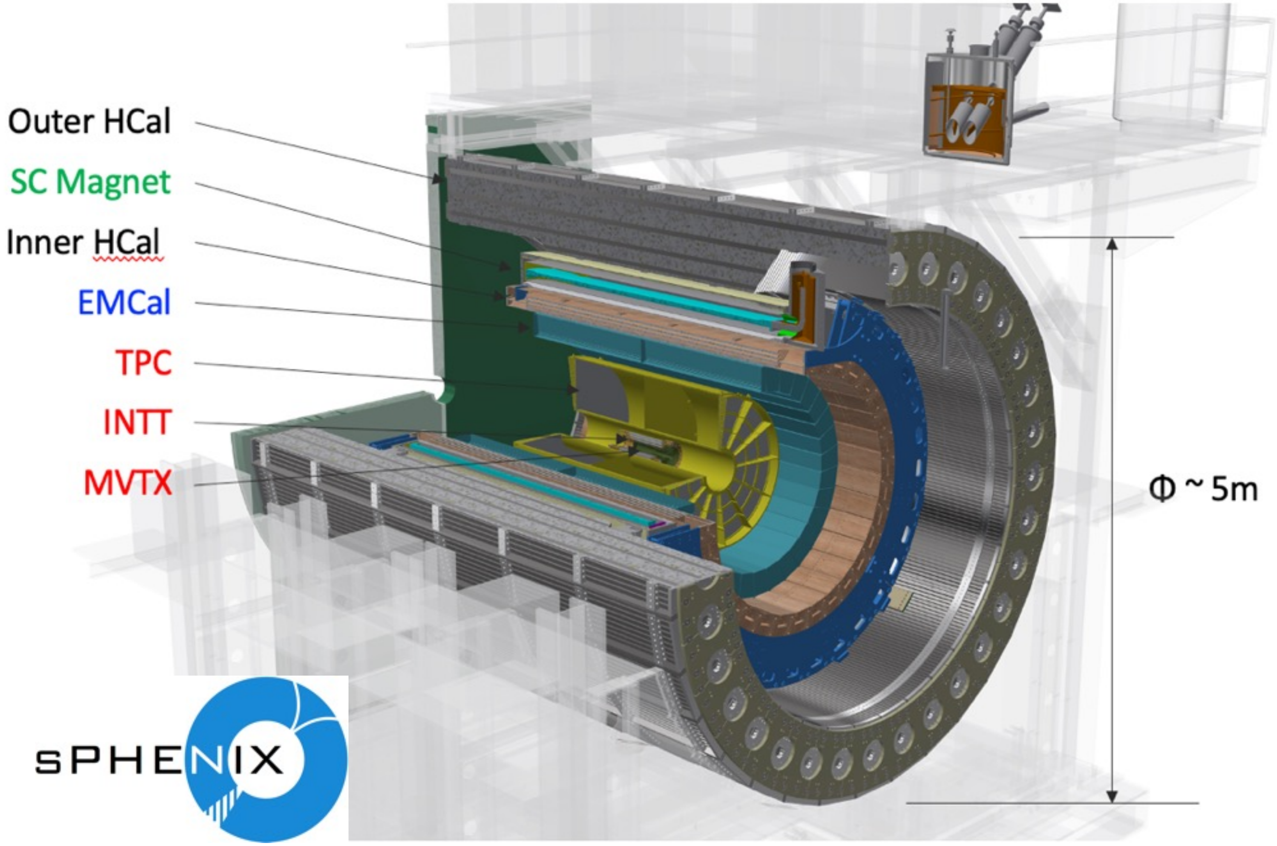
AA





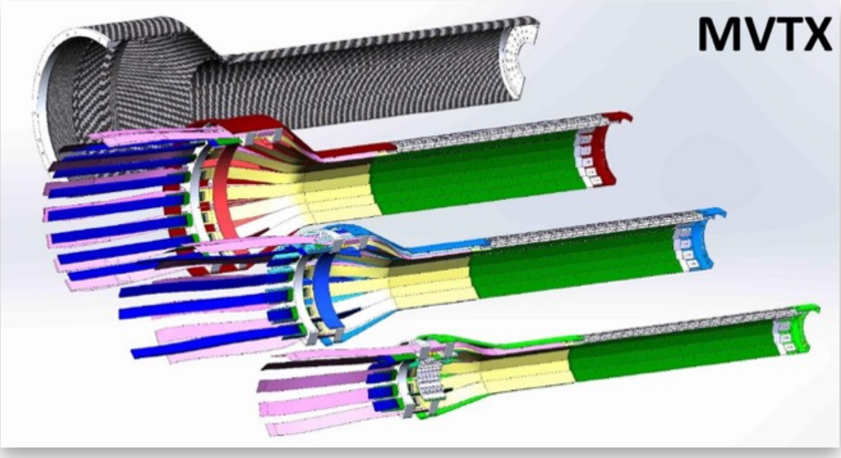
A Great New Opportunity at RHIC
- sPHENIX: 2023-2025

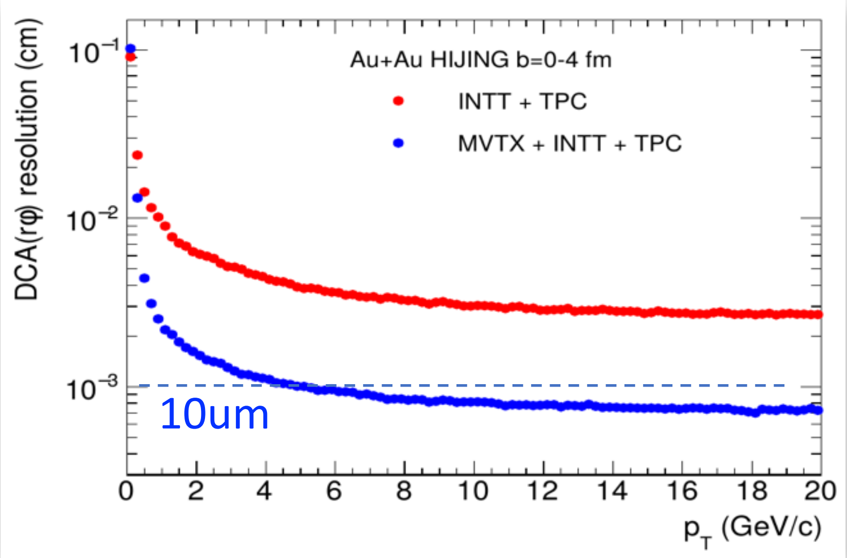
- **Open HF jet in AuAu**
  - ➢Beauty jets
  - ➢Charm jets
  - ➢J/Psi jets
- **Open HF hadrons**
- **Quarkonia**
  - ➢Charm – many <c-cbar> in central AuAu
    - ❖J/Psi : strong coalescence
  - ➢Beauty – single <b-bbar> in central AuAu
    - ❖Upsilon: no coalescence



Open HF Tagging with MVTX

- Monolithic-active-pixel-sensor based VerTeX detector

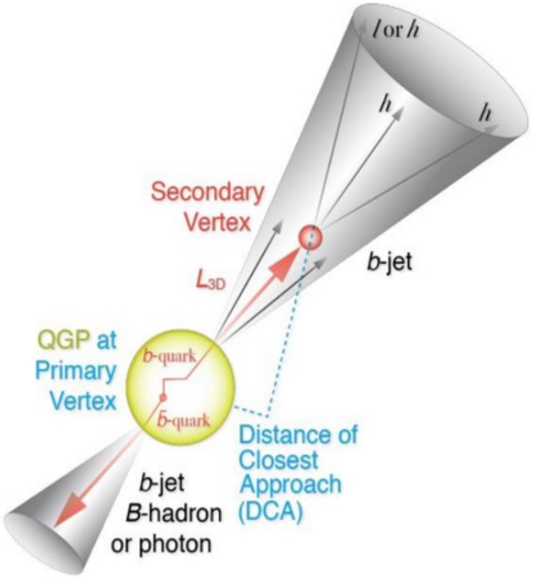


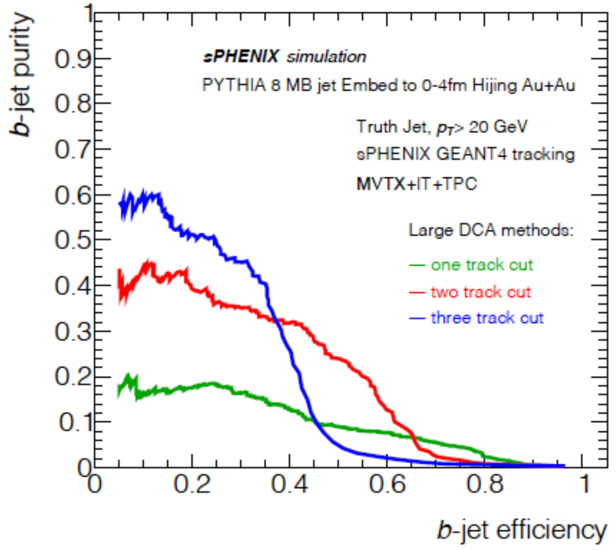


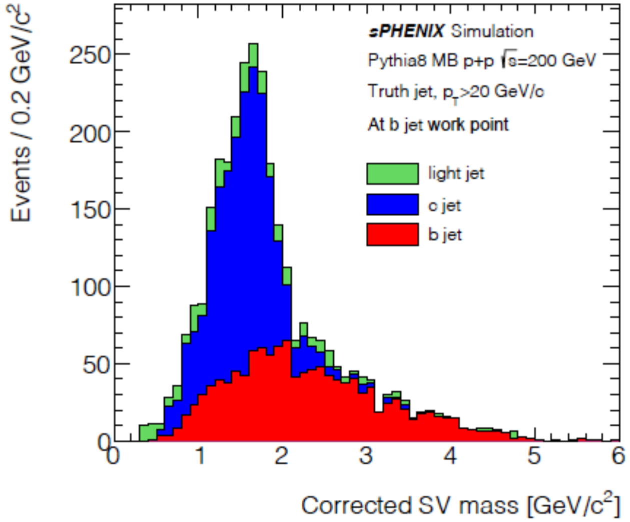
MVTX key parameters: (ALPIDE, ITS-2)

- pixel size: **27um x 29 um**
- ultra-thin stave: **0.35%X_0**
- Integration time: **~5us**

- Multi-tracks w/ large DCA
- 2nd vertex mass
- Exclusive hadron reconstruction





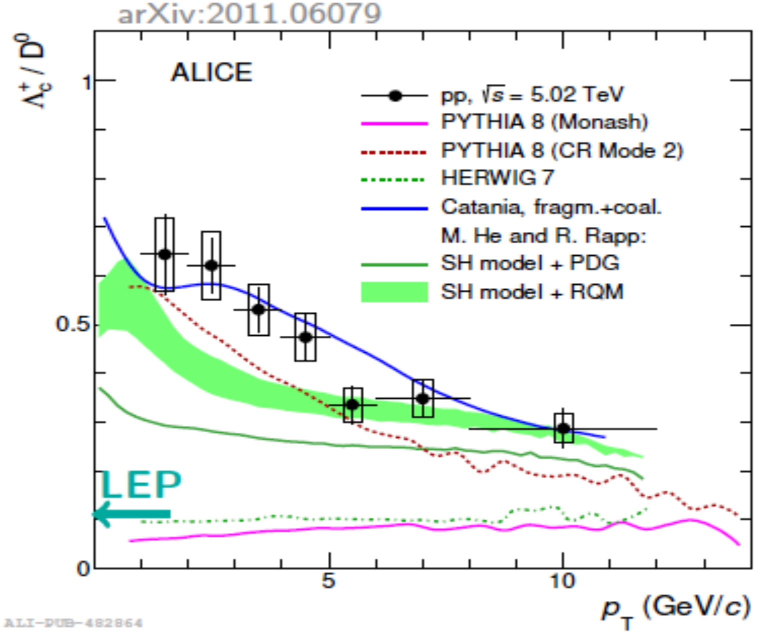


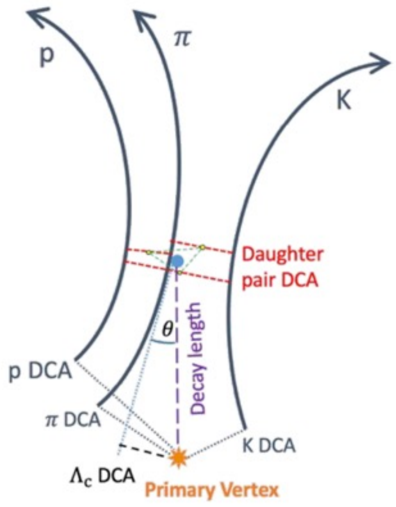
From Quark to Hadron in QGP

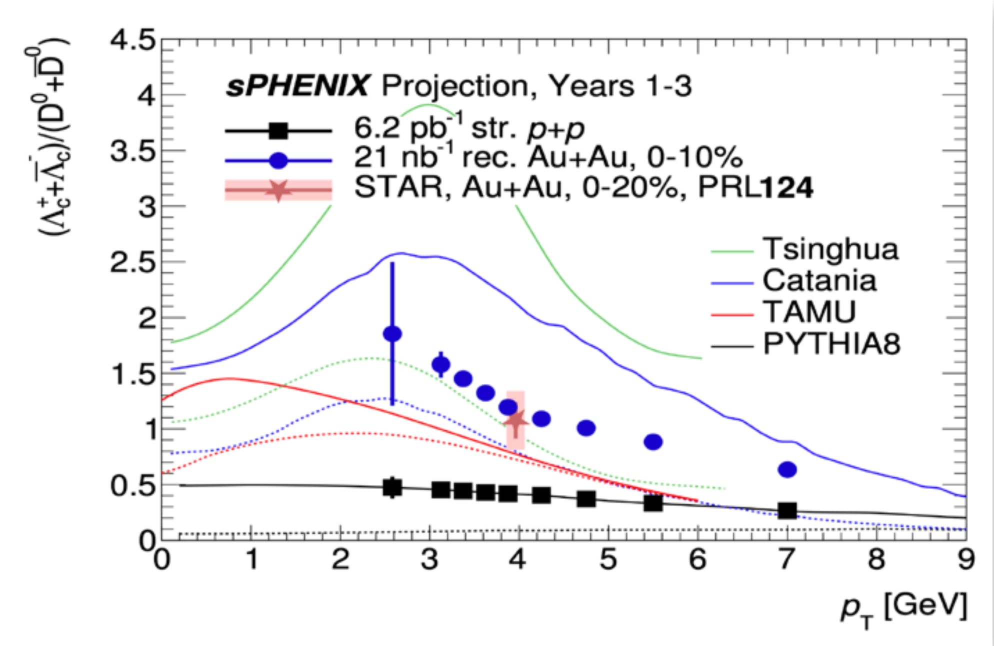
- Critical to understand the hadronization process

- **Hadron production strongly affected by the QCD environment**
  - ➢ Non-perturbative process important at low pT, coalescence etc.
  - ➢ Strong multiplicity dependence observed in p+p, pA and AA … @RHIC and LHC
  - ➢ Study the breakdown of pQCD factorization at low pT …
- **High precision measurements of HF meson and baryons in sPHENIX**

Clear pT dependence observed: e+e- vs pp

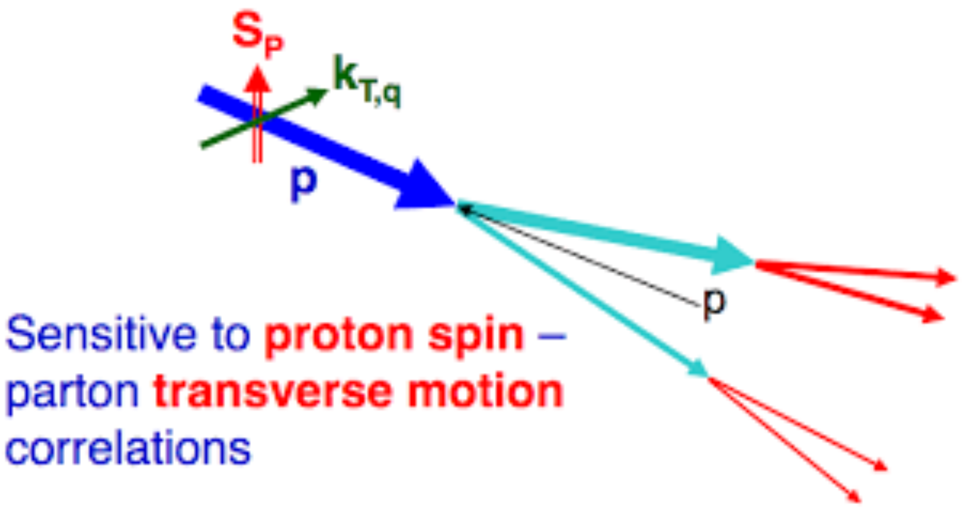


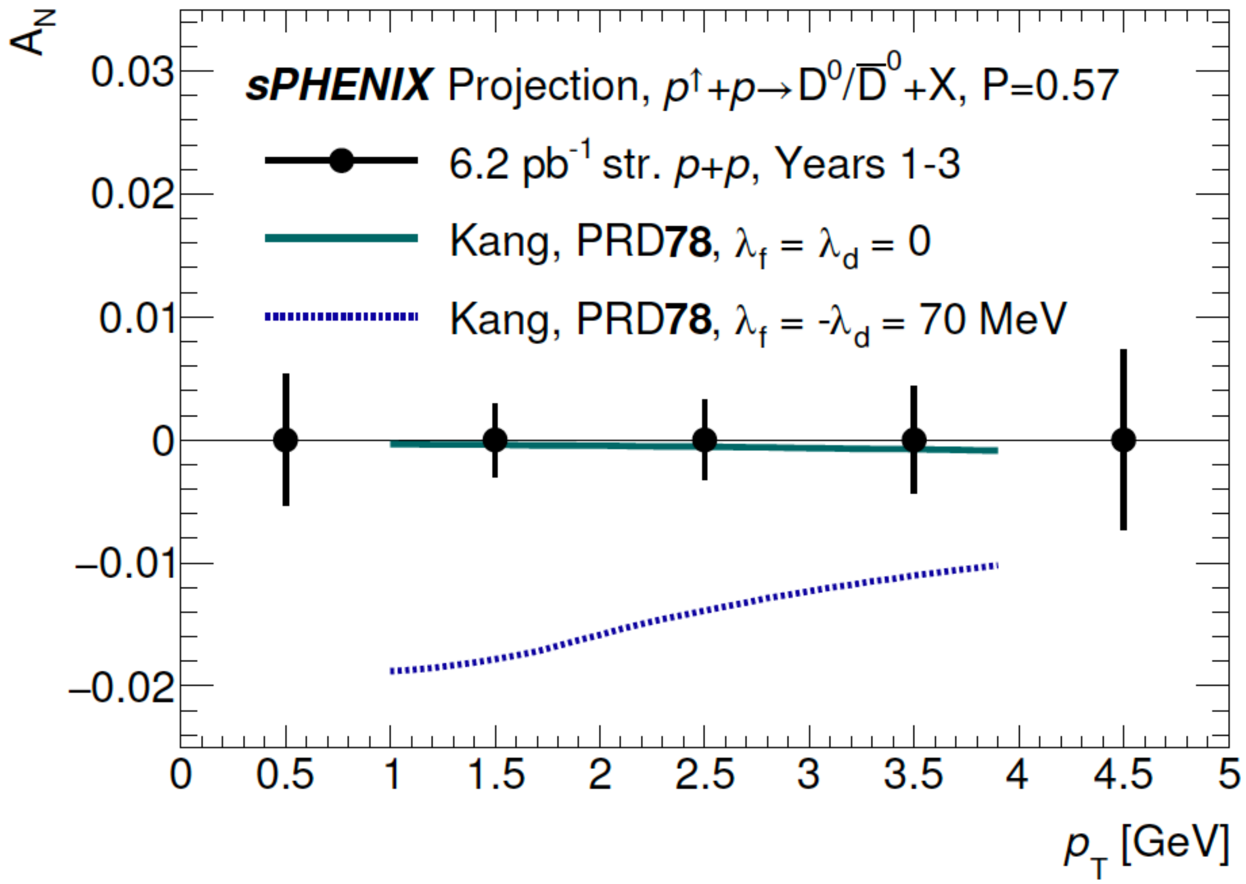




Gluon TMD Physics in Transversely Polarized p+p/Au

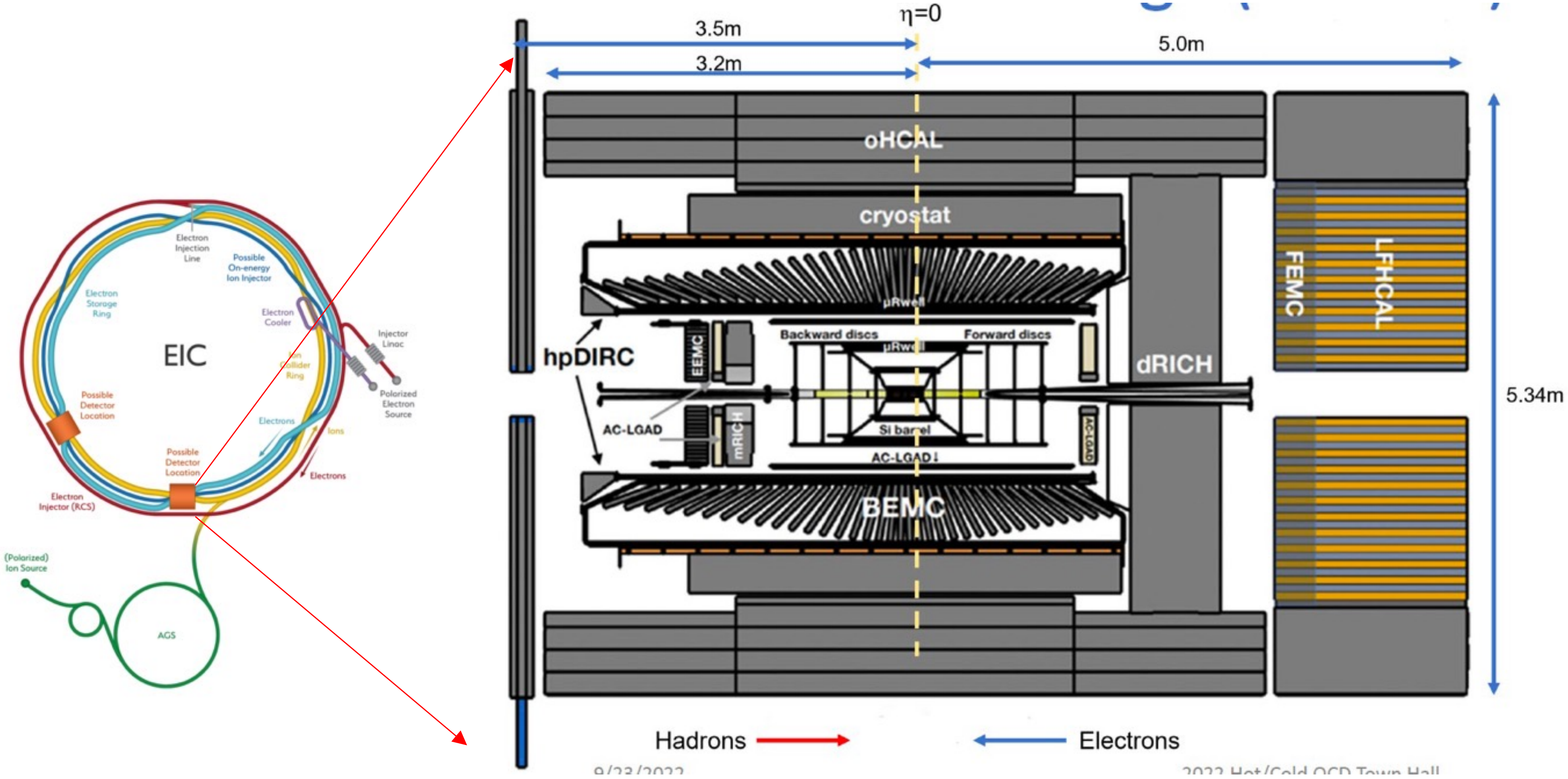
- Sivers asymmetry of charm





The Electron-Ion Collider

- High luminosity: $> \sim 100 fb^{-1}$/year
- Highly polarized beams
- Broad kinematic range coverage: $\sqrt{s} = 20 - 140$ GeV
- 3D tomography of nucleon and nuclei and more



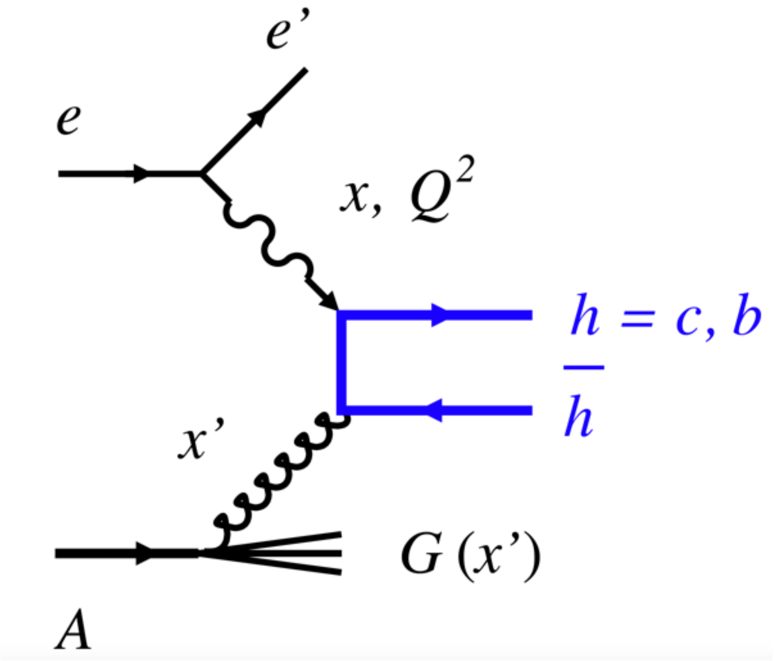
Current ePIC Reference Design

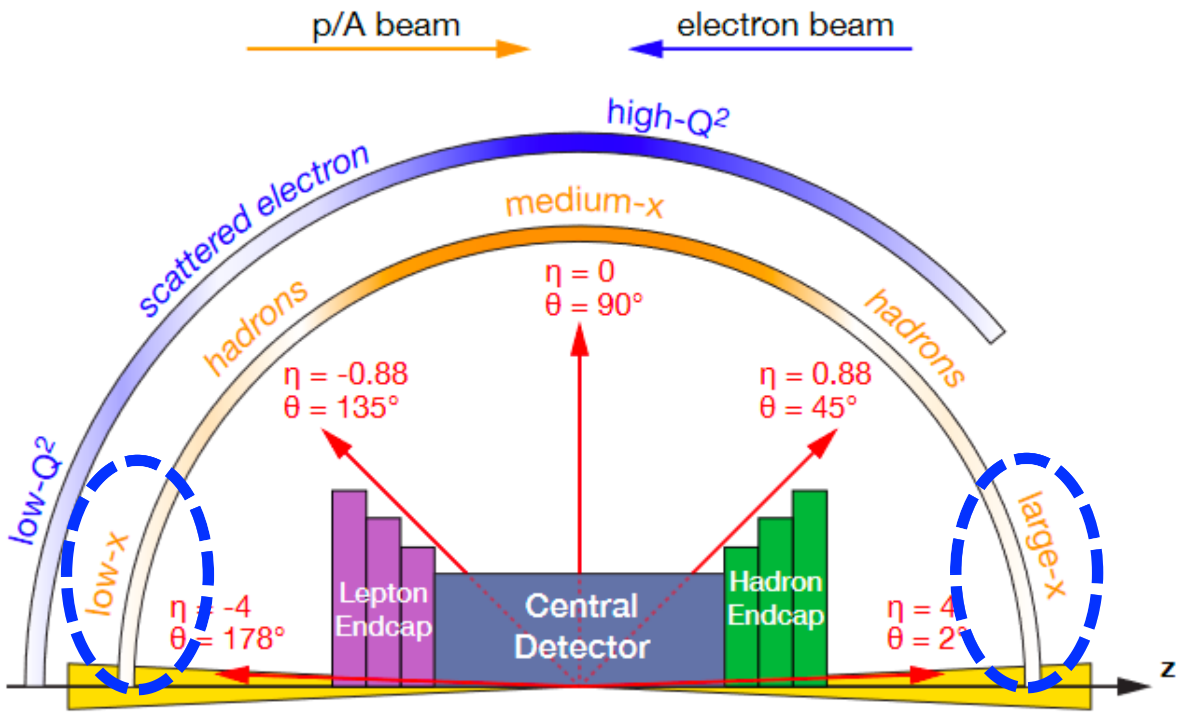
Tracking:
- New 1.7T solenoid
- Si MAPS Tracker
- MPGDs (μRWELL/μMegas)

PID:
- hpDIRC
- mRICH/pfRICH
- dRICH
- AC-LGAD (~30ps TOF)

Calorimetry:
- SciGlass/Imaging Barrel EMCal
- PbWO4 EMCal in backward direction
- Finely segmented EMCal +HCal in forward direction
- Outer HCal (sPHENIX re-use)

Heavy Quark Production at EIC

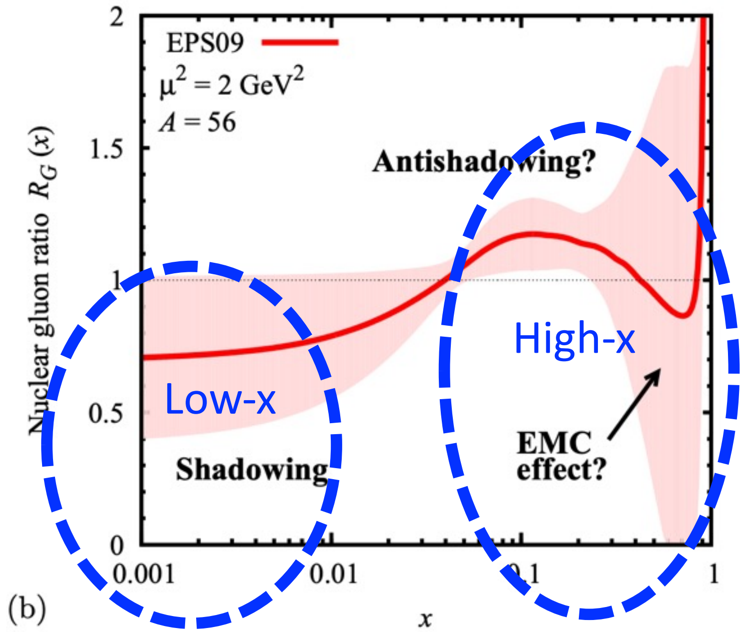




Dipole Nucleus Cross Section: $\sigma_A^{q\bar{q}}(x, r^2) \sim \frac{\pi^2}{3}\alpha_S r^2 x G_A(x, 10/r^2)$

- At the EIC, for ep at $\sqrt{s} = 100$ GeV: $\sigma_{c\bar{c}}^{Inc} \sim 100\, nb$ and $\sigma_{b\bar{b}}^{Inc} \sim 10\, nb$
- The luminosity at the EIC $> \sim 10\, fb^{-1}$/year

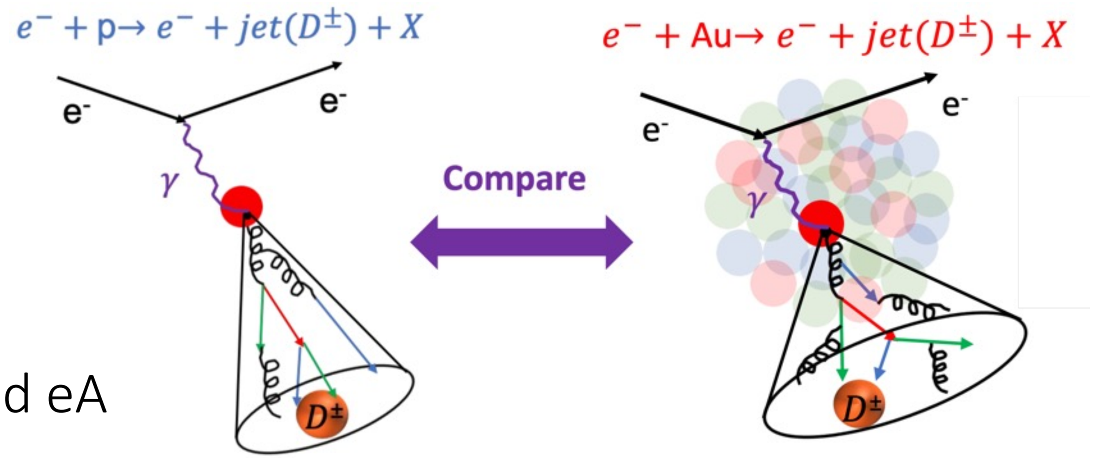
Heavy Flavor Physics at the EIC



$$R_G(x) = G_A(x)/G_N(x)$$

Quark-Gluon Structure of Nuclei

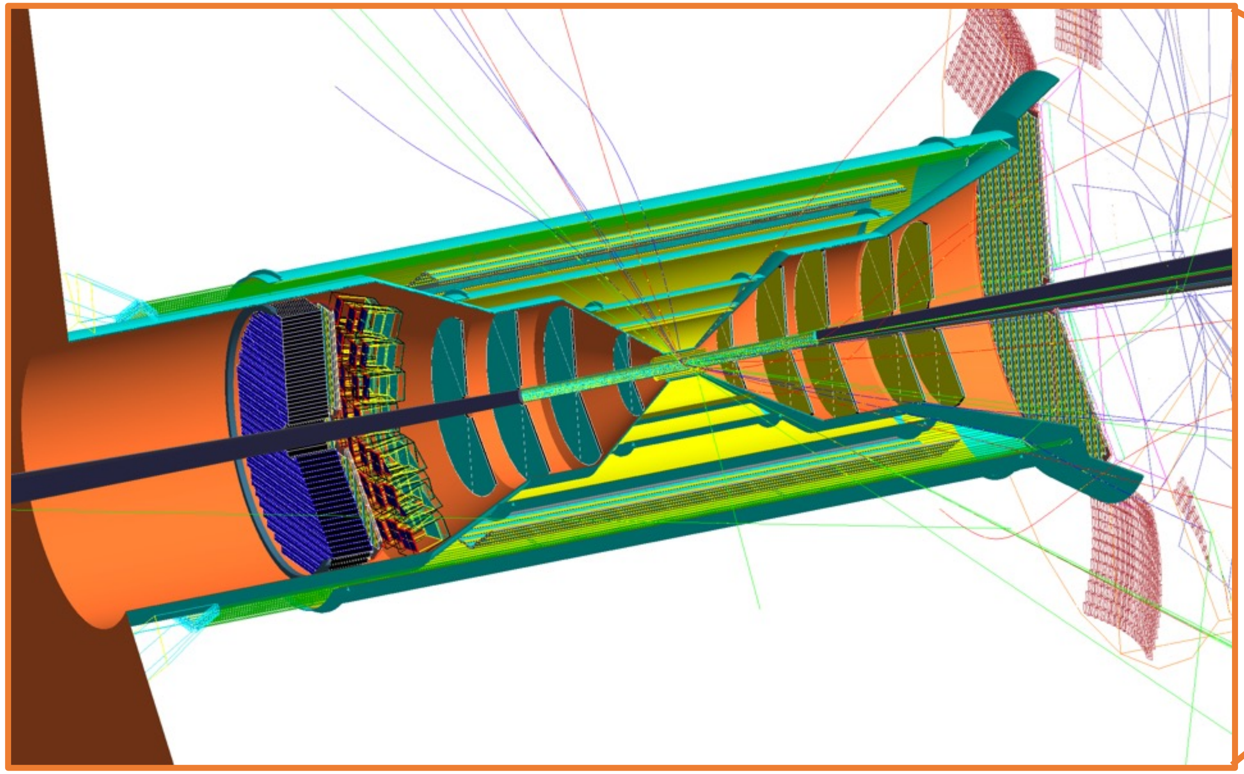
- Powerful observable complement to inclusive DIS measurements
- Clean probe: sensitive to gluon dynamics
- Probe gluon saturation regime
- Understand nuclear gluon shadowing effect
- Extract the Sivers Function with polarized DIS

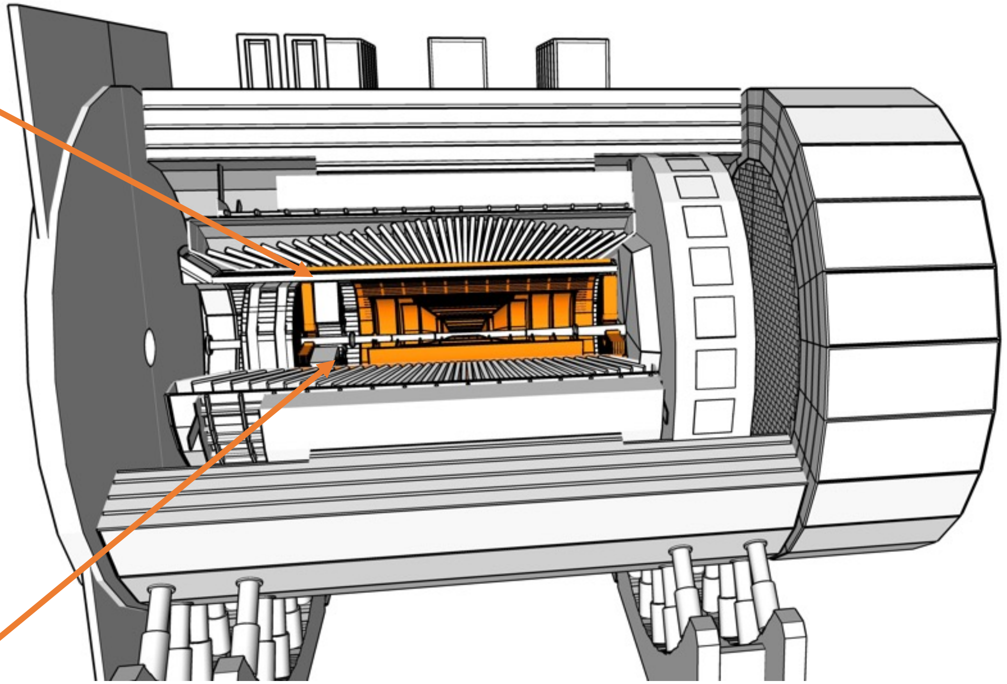


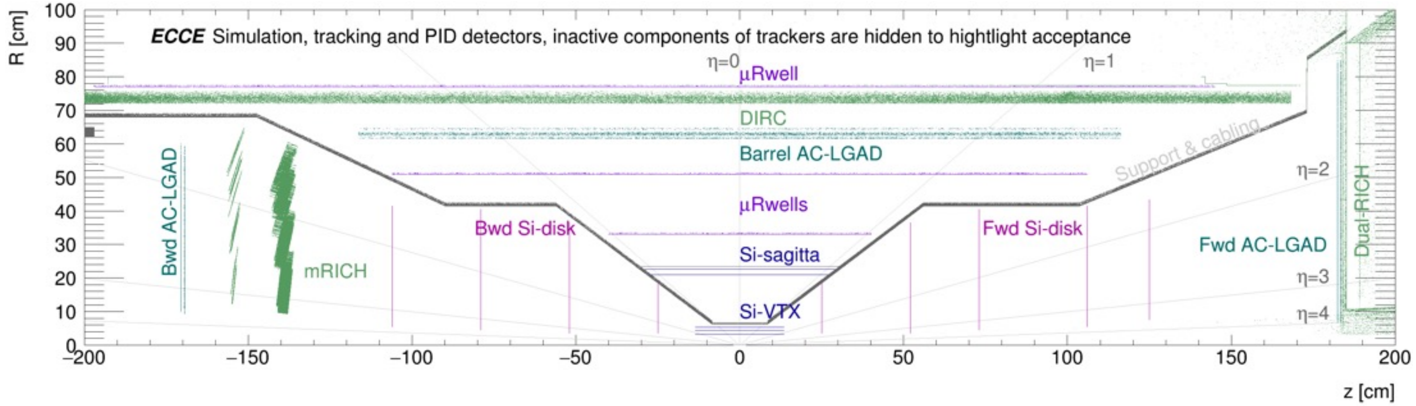
Parton Propagation and Hadronization

- Heavy quark interaction in cold nuclear medium
- Hadronization modification
- Test QCD factorization breaking in ep and eA

Forward/Backward and Barrel Silicon Trackers







ECCE Reference Design
arXiv:2209.02580

Opportunities for Collaboration

- **sPHENIX HF physics program**
  - ➢ MVTX detector work and lessons learned
    - ❖ Design, operation & calibration
  - ➢ HF physics analyses
    - ❖ Hadronization
    - ❖ Gluon TMD
  - ➢ HF AI-ML trigger R&D
    - ❖ Streaming readout and AI-trigger
- **EIC HF physics program**
  - ➢ MAPS silicon detector R&D
    - ❖ ITS2, ITS3 and more
    - ❖ Forward/Backward regions
  - ➢ HF physics R&D
    - ❖ Gluon TMD, polarization and saturation
    - ❖ HF hadronization, ep and eA

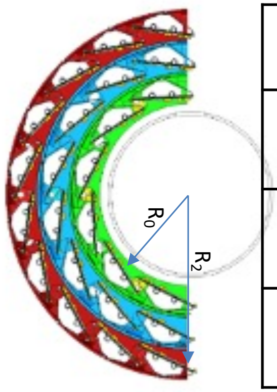
ITS-2 technology

- great experience Korean groups

ITS-2/3-like technology

MVTX: Lessons Learned and More
- from conceptual design to realization

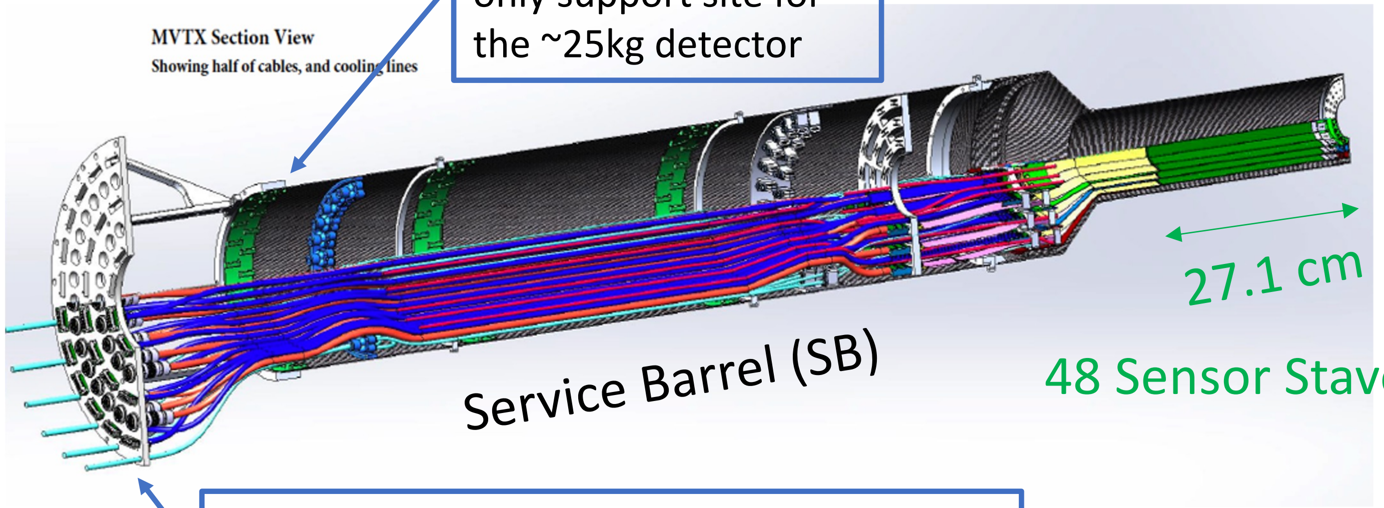
- **Sensor production & QA**
  - ➢ Korean groups played major role, cost effectiveness high quality work
- **Sensor support services**
  - ➢ Major challenges in mechanical & electrical



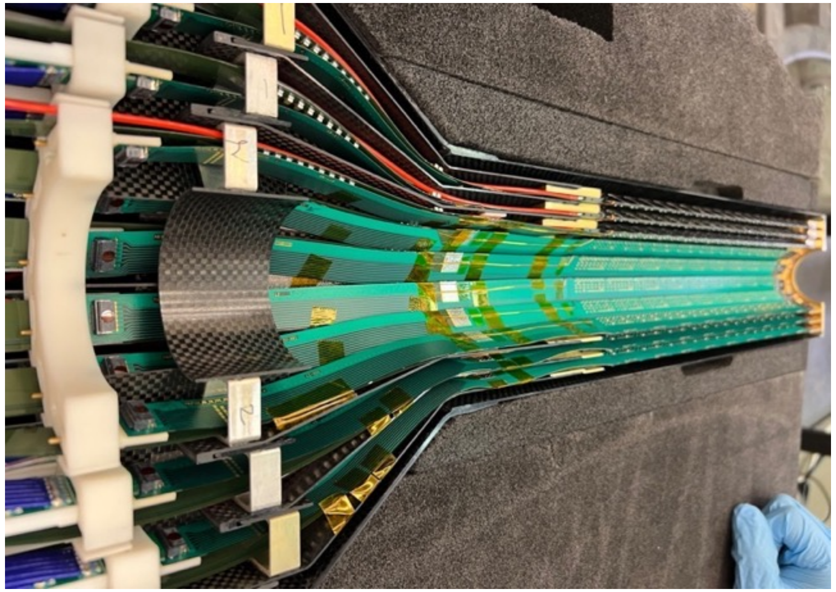
3 layers with full azimuth coverage

R (mm)	min	mid	max
Layer 0	24.61	25.23	27.93
Layer 1	31.98	33.35	36.25
Layer 2	39.93	41.48	44.26

Cantilivered:
only support site for the ~25kg detector



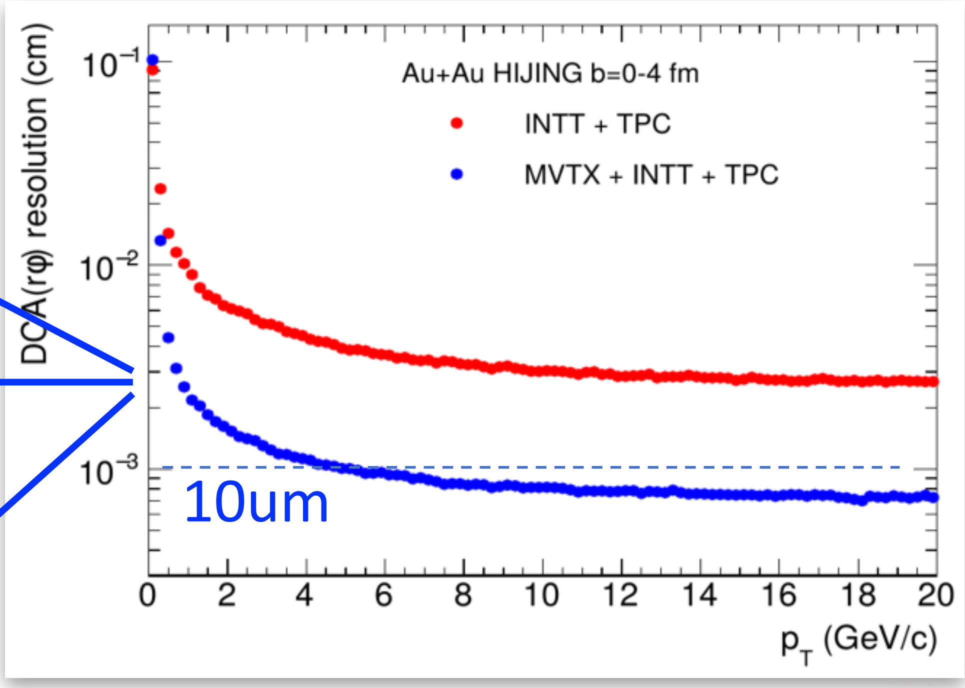
PP3: connected to all services
- high-speed signal, power and cooling



sPHENIX MVTX Challenges and Opportunities:

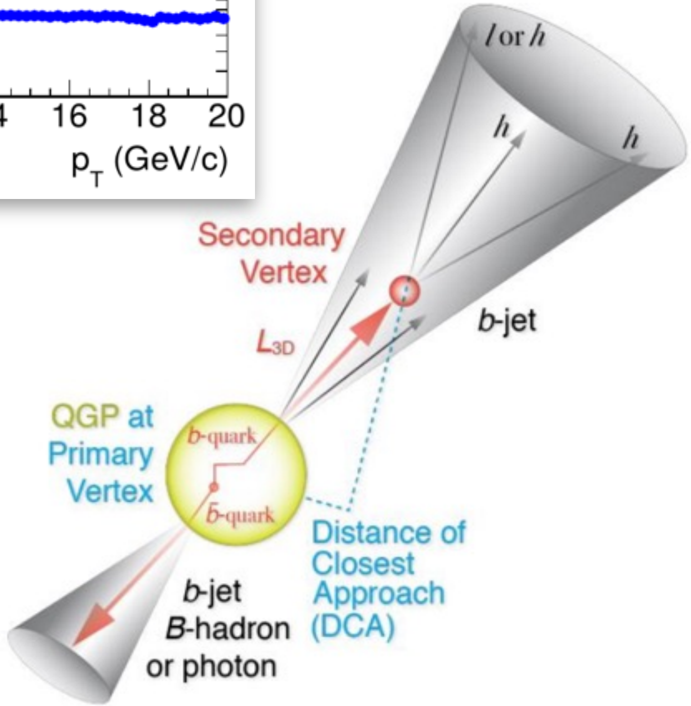
Hardware/Software/Physics

- **Data quality control**
  - ➢ Detector calibration and alignment
  - ➢ Thresholds, noise and cluster size
- **Detector simulation and analysis**
  - ➢ Software implementation
    - ❖ Stave and sensor geometry
    - ❖ Hit simulation, clustering
  - ➢ MVTX (+ INTT) internal alignment with data
    - ❖ Primary vertex finding, tracking, DCA
- **Tracking simulation and analysis**
  - ➢ Tracklet seeding
  - ➢ 2nd vertex finding
- **HF physics analysis**
  - ➢ Inclusive HF Jet tagging
  - ➢ Charm and beauty hadron tagging
  - ➢ Correlations



Precision detector alignment critical

Applicable to EIC HF detector and physics analysis



MVTX Alignment with AI Approach (**Regression fit**)

The idea - align MVTX detector geometry sens by sensor with reconstructed good tracks

- Chip: 512[R] x 1024[C] pixels
- 9 chips per stave
- 48 staves total

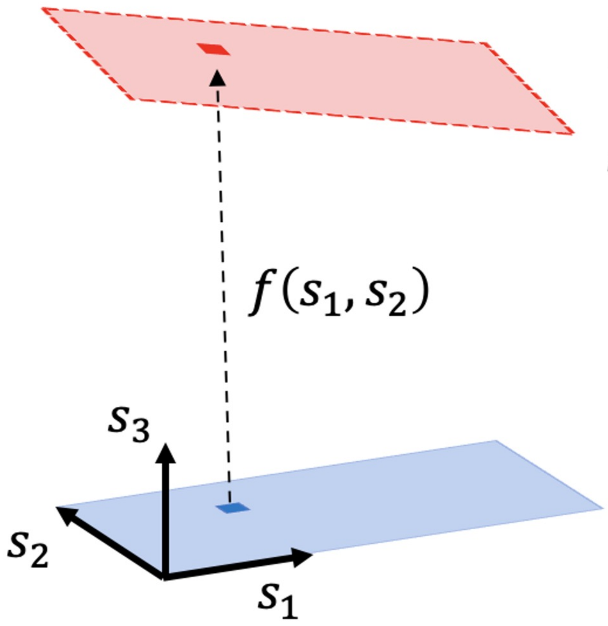
Staves per layer: 12/16/20

AI/NN:

- find correction factors for each sensor (**translation/rotation/shear/expansion/c raction**)

Yonsei, Hanyang, Inha, Pusan groups …

Alignment in the sensor coordinate



Deformed Sensor Position

$$s' = s + f(s_1, s_2)$$
$$= (s_1, s_2, 0) + \boxed{(\Delta s_1, \Delta s_2, \Delta s_3)}$$

Correction Function

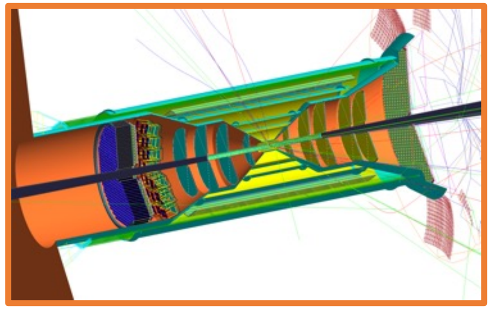
Reconstructed Sensor Position
$s = (s_1, s_2, 0)$

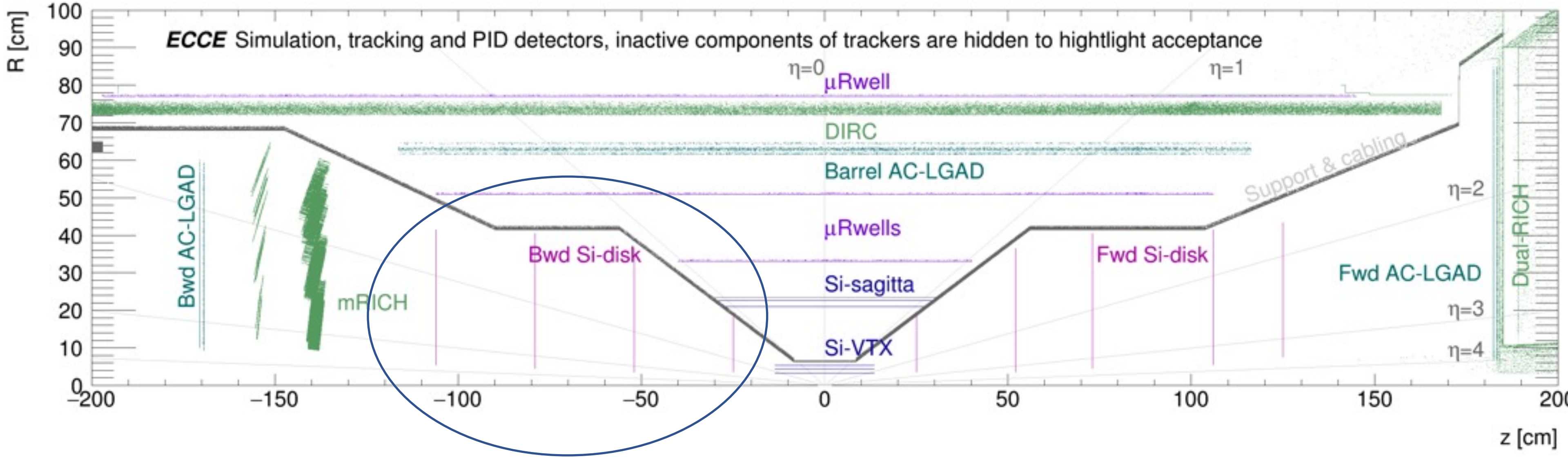
s_1 : column direction, parallel to z axis
s_2 : row direction
s_3 : normal to sensor

Silicon Detector R&D for EIC

- **MAPS**
  - ➢ITS2 ALPIDE sensor applications
  - ➢ITS3-like
- **Central barrel: ITS-3 and ITS-2 like applications**
- **Forward/Backward silicon detector design challenge**
  - ➢Large area low mass forward disks, R ~ 50cm

Youngil's talk





New Opportunity for AI/ML Applications

- HF trigger challenge in p+p

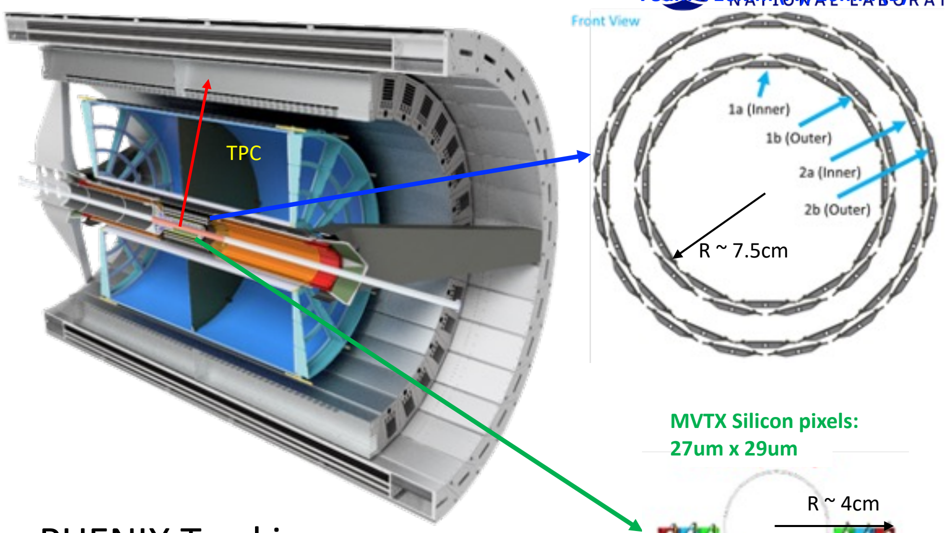
sPHENIX experiment at RHIC

- Very high p+p collision rate: ~3MHz
  - Rare Beauty production rate: ~150Hz (or 0.005% of collisions)
- Limited DAQ bandwidth
  - 15 kHz (or 0.5% of p+p collisions)
- No effective conventional triggers available
- Streaming readout (SRO) -> huge data volume, high cost

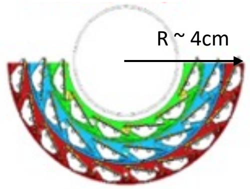
Our approach:

Develop effective HF triggers for p+p with SRO and AI

- Streaming readout key detectors for high efficiency
- ML-trained algorithm for HF event selection
- AI-based beam/detector monitoring and autonomous feedback & control



MVTX Silicon pixels:
27um x 29um

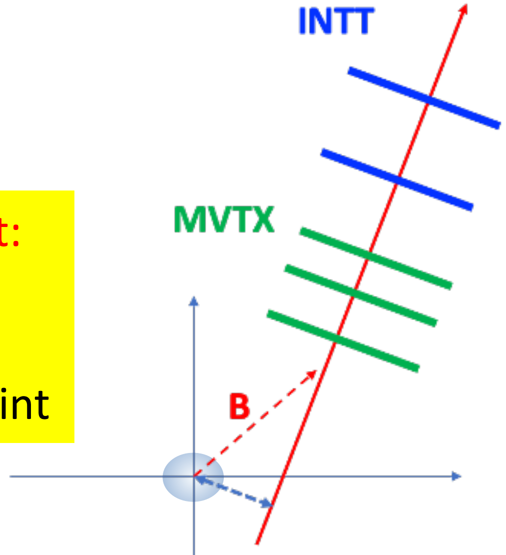


sPHENIX Tracking:

- MVTX + INTT(fast)
- TPC(slow)

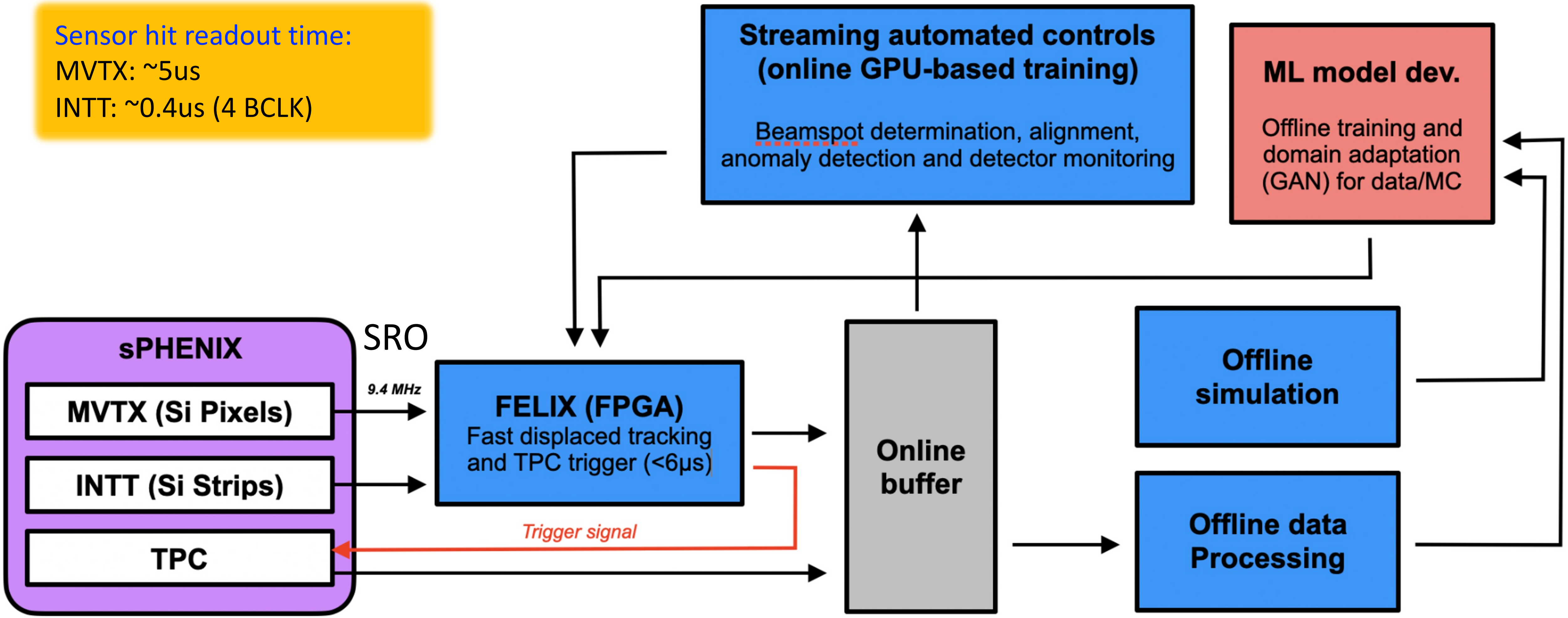
Identify B-hadron event:

- Topology of B decay, with large DCA
- Monitor collision point



HF AI Trigger: sPHENIX as a Test Ground

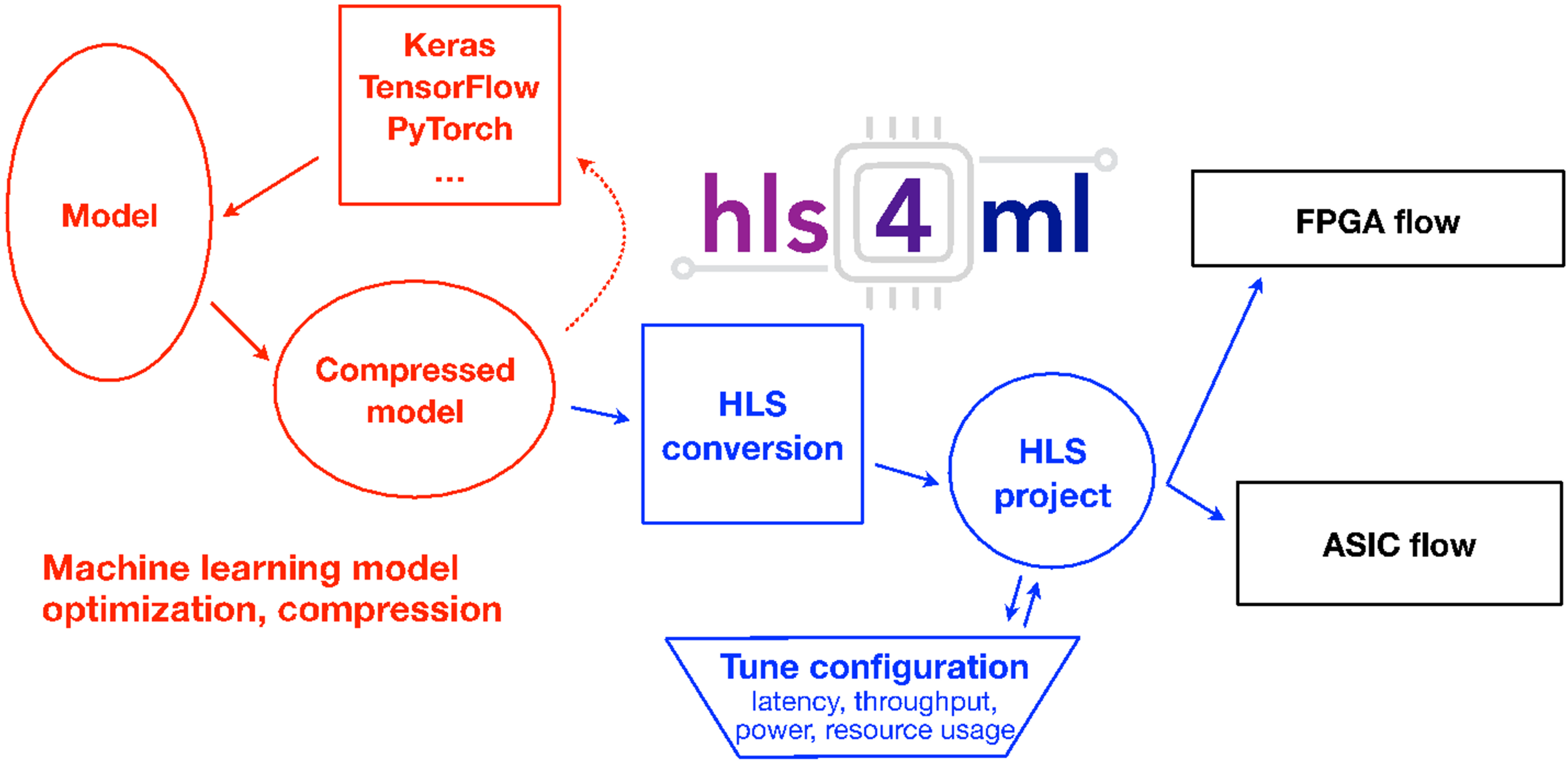
Sensor hit readout time:
MVTX: ~5us
INTT: ~0.4us (4 BCLK)



sPHENIX DAQ & Trigger integration challenge

Translating Models into FPGA Firmware

- Algorithms must have low latency and resource usage
- hls4ml translates NN algorithms into high level synthesis
- Also generates IP cores for easy implementation



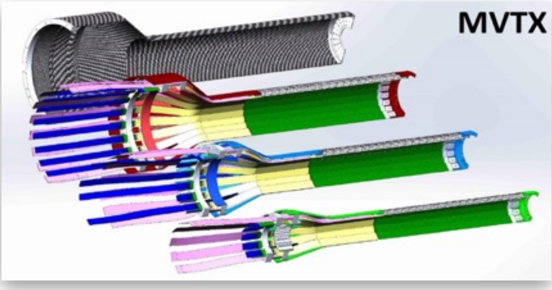
Red – typical ML algorithm development stages, Python/C++

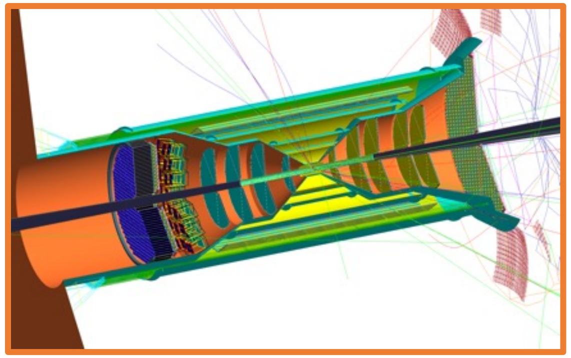
Blue – HLS conversion to FPGA IP

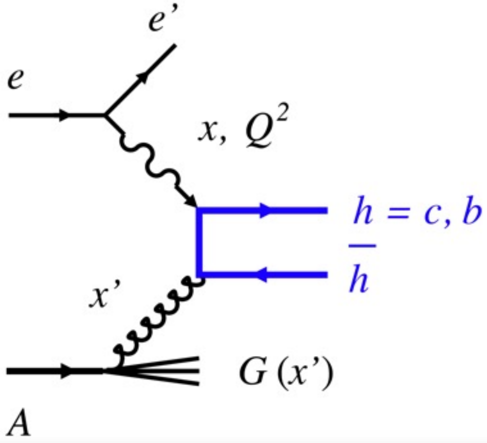
Black – typical implementation onto chips

Summary

- **sPHENIX HF program**
  - Hadronization
  - Gluon TMD
  - MVTX experience for EIC R&D
- **EIC future**
  - Silicon detector R&D
  - Physics exploration
- **Great opportunity in coming years**
  - Silicon detector R&D
  - SRO, AI-ML application for sPHENIX and EIC
  - HF physics and more







Backup

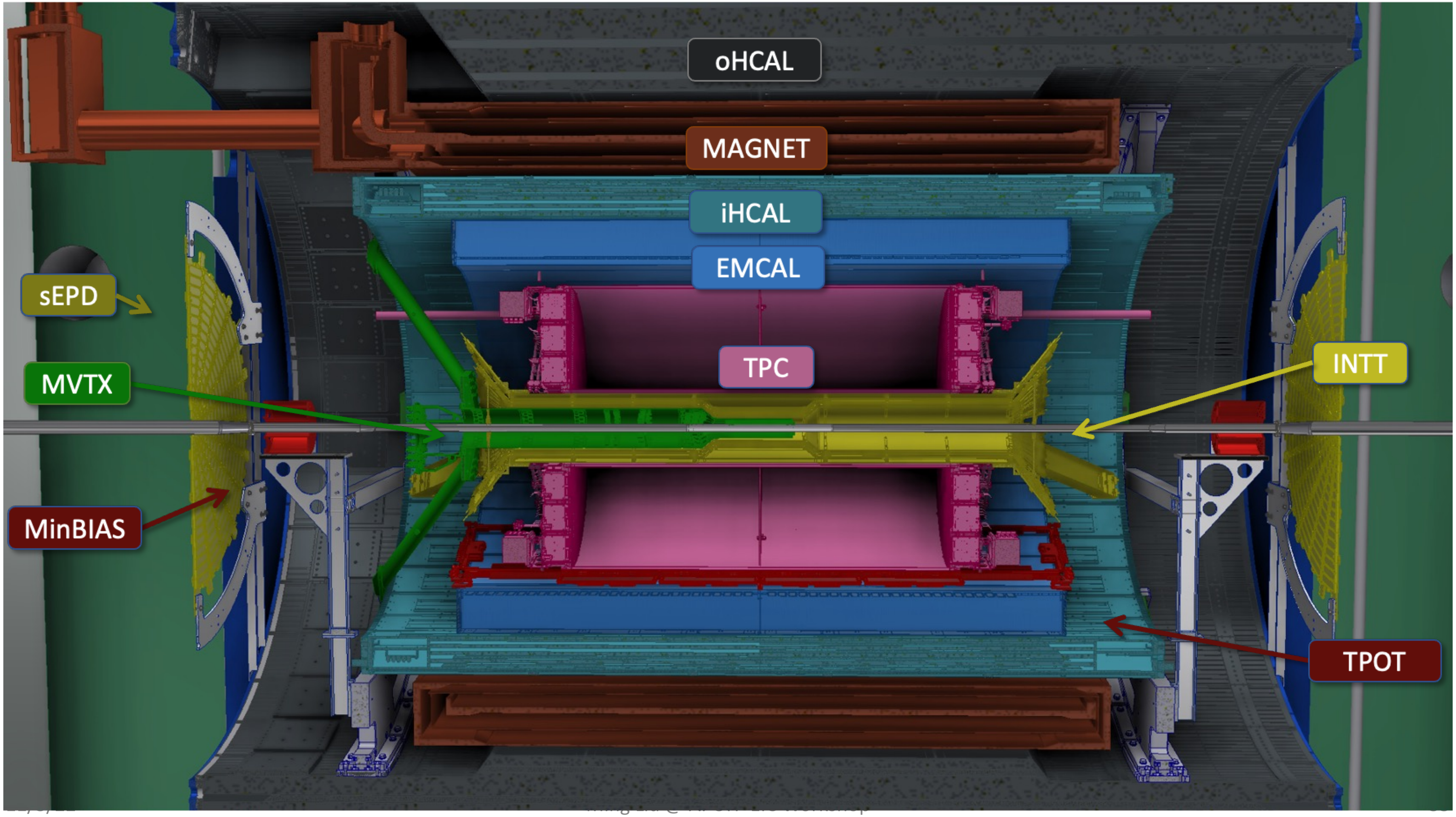
sPHENIX Run Plan

Year	Species	$\sqrt{s_{NN}}$ [GeV]	Cryo Weeks	Physics Weeks	Rec. Lum. $\lvert z\rvert$ <10 cm	Samp. Lum. $\lvert z\rvert$ <10 cm
2023	Au+Au	200	24 (28)	9 (13)	3.7 (5.7) nb^{-1}	4.5 (6.9) nb^{-1}
2024	$p^{\uparrow}p^{\uparrow}$	200	24 (28)	12 (16)	0.3 (0.4) pb^{-1} [5 kHz] 4.5 (6.2) pb^{-1} [10%-*str*]	45 (62) pb^{-1}
2024	$p^{\uparrow}$+Au	200	–	5	0.003 pb^{-1} [5 kHz] 0.01 pb^{-1} [10%-*str*]	0.11 pb^{-1}
2025	Au+Au	200	24 (28)	20.5 (24.5)	13 (15) nb^{-1}	21 (25) nb^{-1}

sPHENIX Beam Use Proposal
endorsed by the BNL NPP
(Nuclear and Particle Physics)
PAC (Physics Advisory Committee)

- Extensive **3-year** data taking starting in around 6 months
  - **Year-1**: commissioning and first physics in Au+Au
  - **Year-2**: p+p and p+Au runs for heavy-ion reference and cold QCD physics
  - **Year-3**: very large Au+Au dataset (141B events in total)

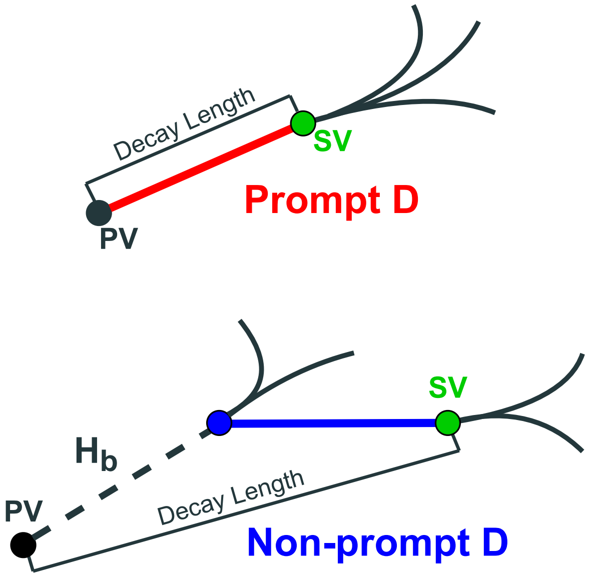
sPHENIX Detectors



Work in Progress: from Full Monte Carlo Simulations

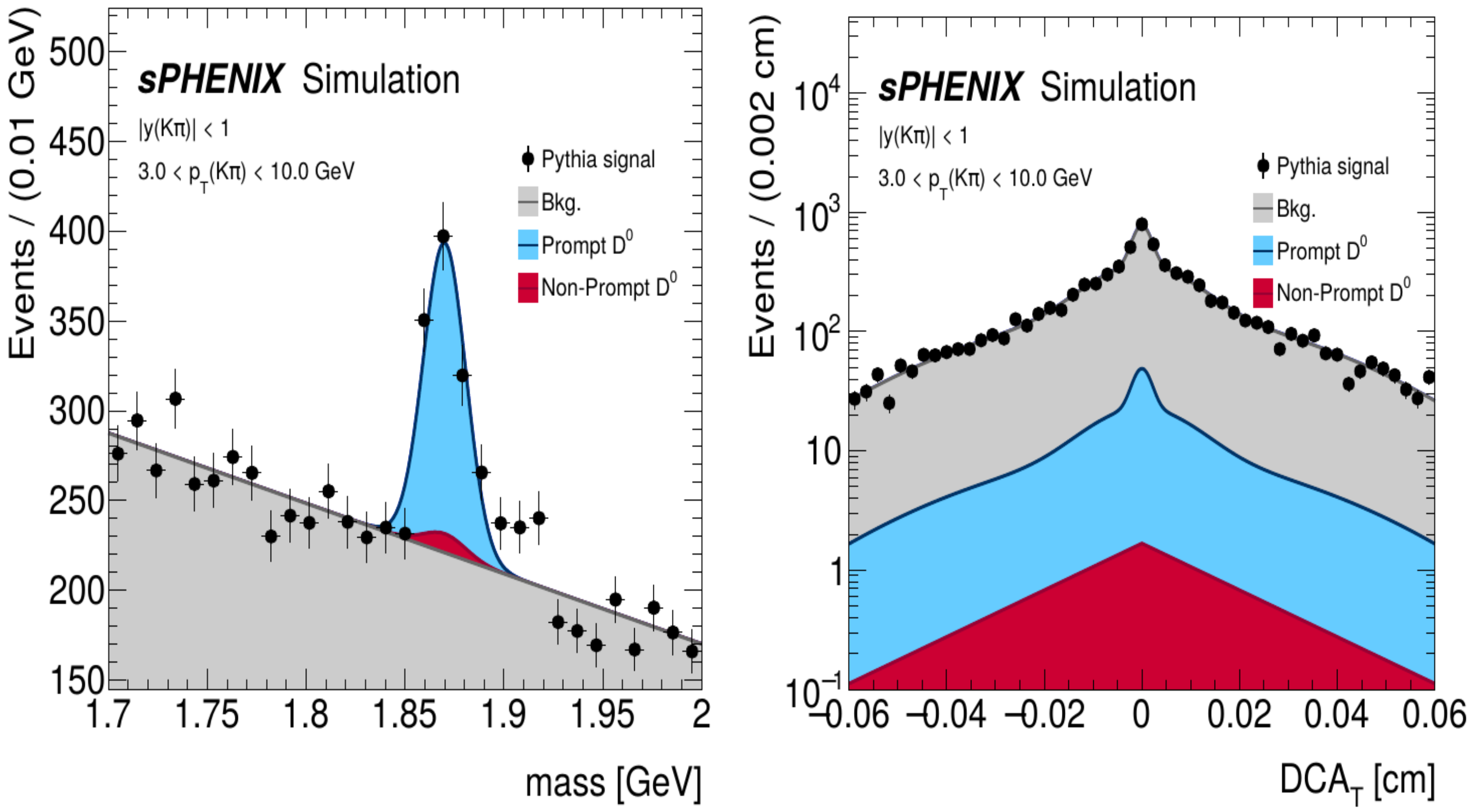
PYTHIA 8 p+p with full detector GEANT sim + reco

$$p + p \to D^0 + X \to (K^- \pi^+) + X$$

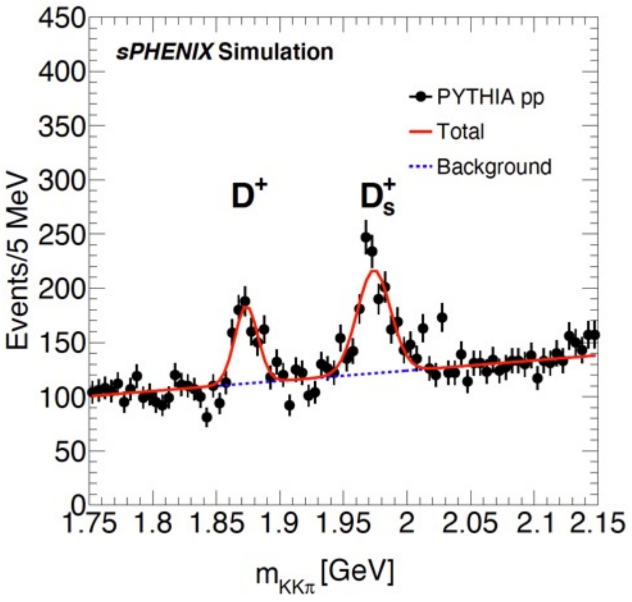


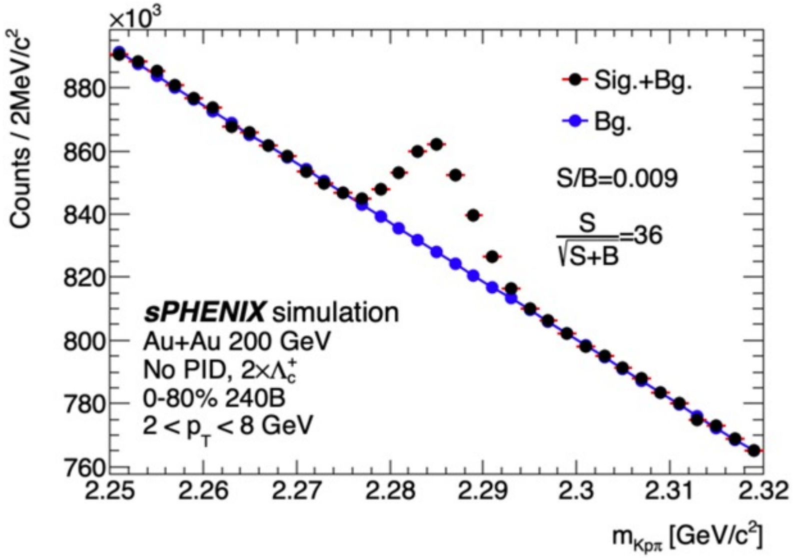
$$p + p \to H_b + X \to (D^0 + X') + X$$

KFParticle package implemented for exclusive HF hadron reconstruction

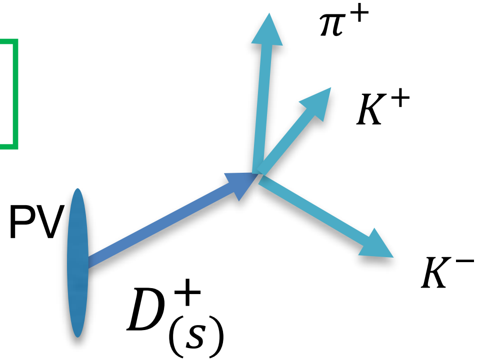


Charm Hadronization: D_s^+/D^+ and Λ_c^+/D^0 Ratios

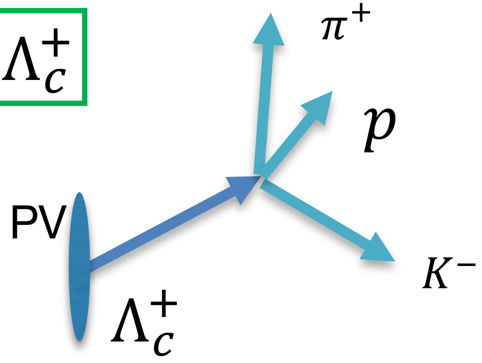




Prompt $D_{(s)}^+$

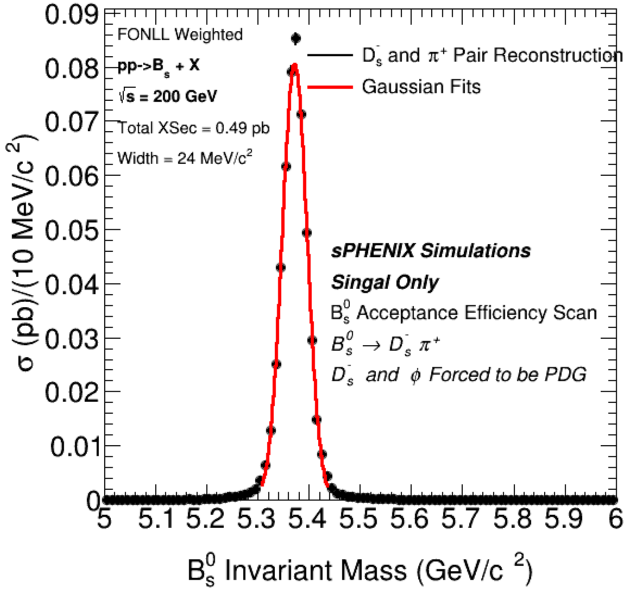


Prompt Λ_c^+

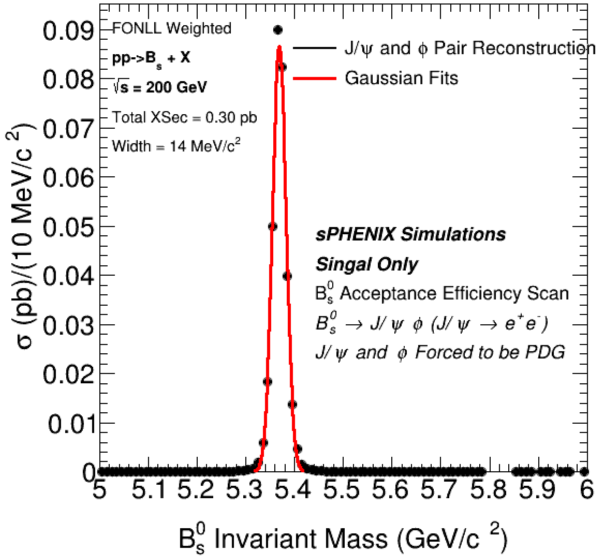


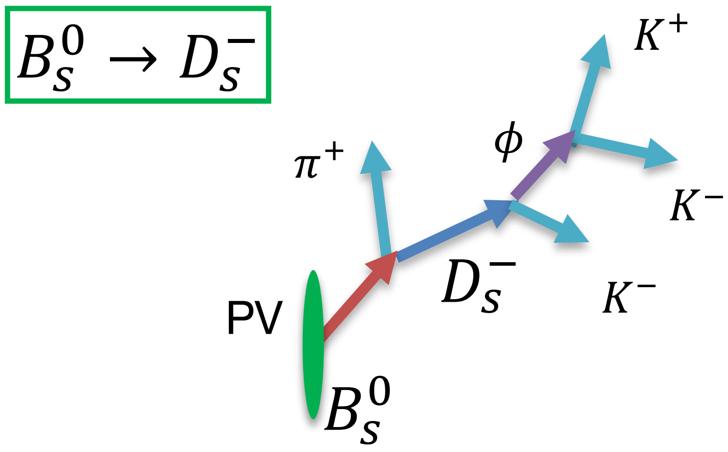
- High precision measurement thanks to streaming readout data taking and tracking
- Understand charm hadronization mechanism via the measurements of D_s^+/D^+ and Λ_c^+/D^0

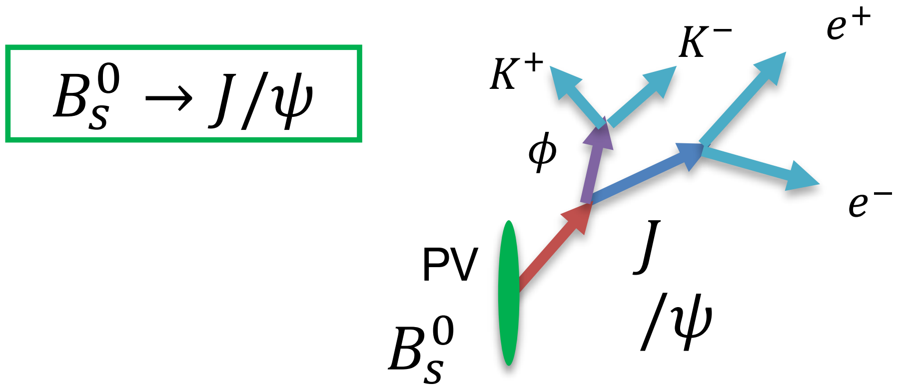
Physics – Fully Reco'd Bs



- **Test QCD factorization theorem at RHIC energy in the beauty sector**
- Study beauty quark hadronization mechanism with B_s^0/B^+ ratio, strangeness enhancement in HI
- Exotic-hadron like complex 4-prong decays
- FONLL weighted B_s^0 in GEANT simulation for signal only prediction
- First observation of fully reconstructed B-meson in nuclear collisions at RHIC

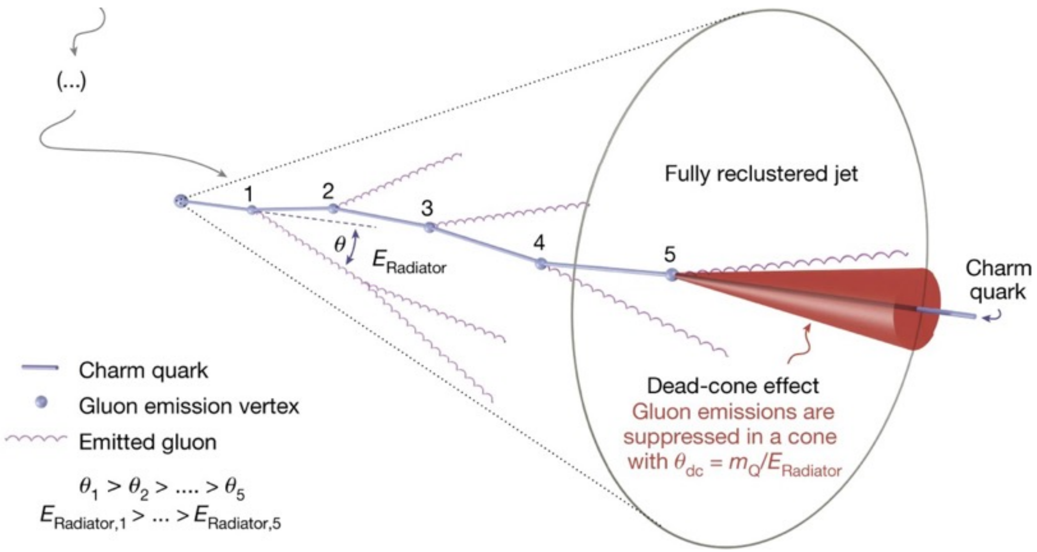


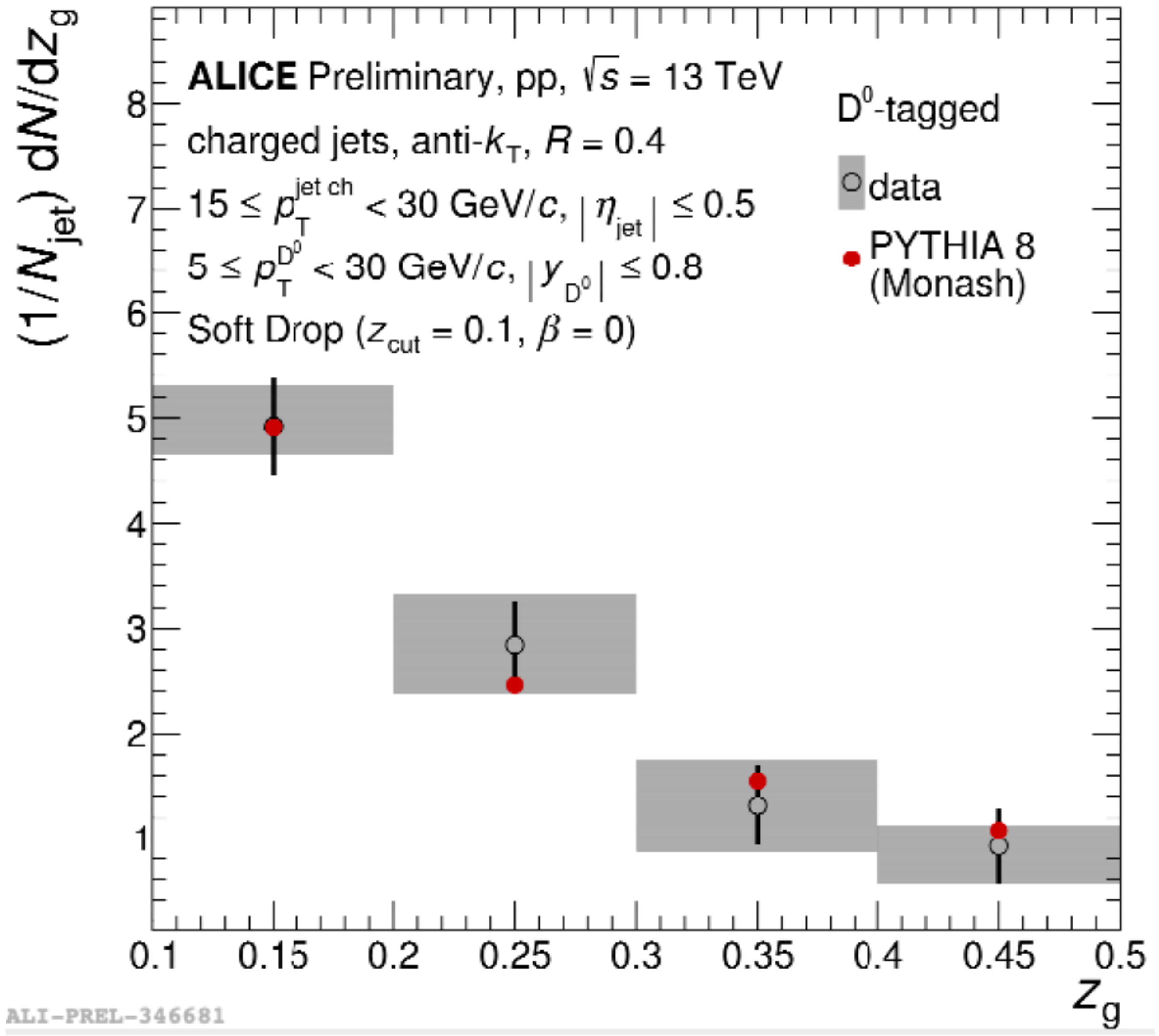




D^0-Jets in pp
- jet substructure

$$Z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$$





J/Psi-Jets in pp
- flat distribution?

- **Quite different from expectation**
- **J/Psi production mechanisms**
  - ➢ CEM
  - ➢ NRQCD
  - ➢ Jet fragmentation
  - ➢ …