A tale told by hard probes in high energy nuclear collisions

from PHENIX to sPHENIX and on toward the EIC

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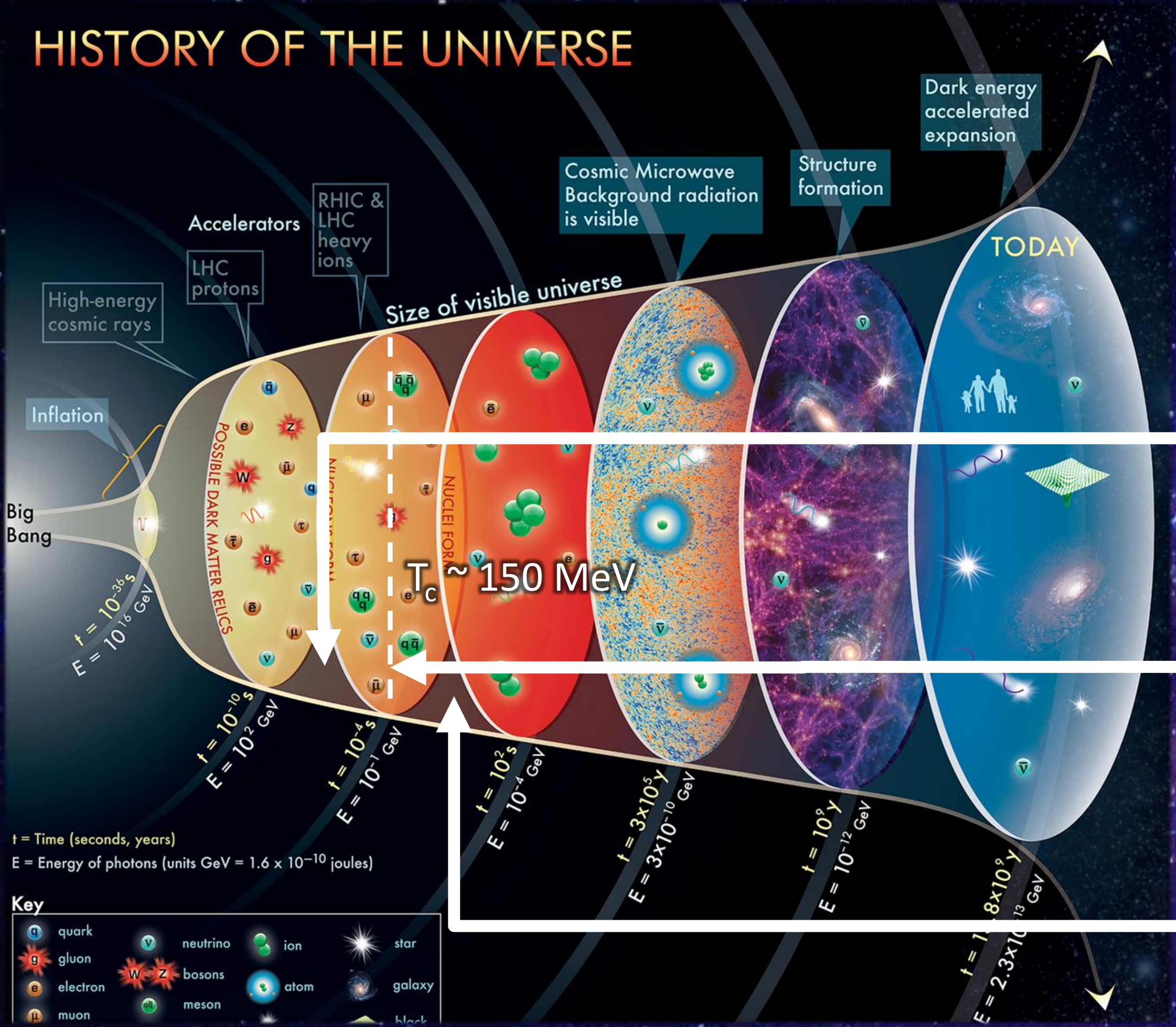
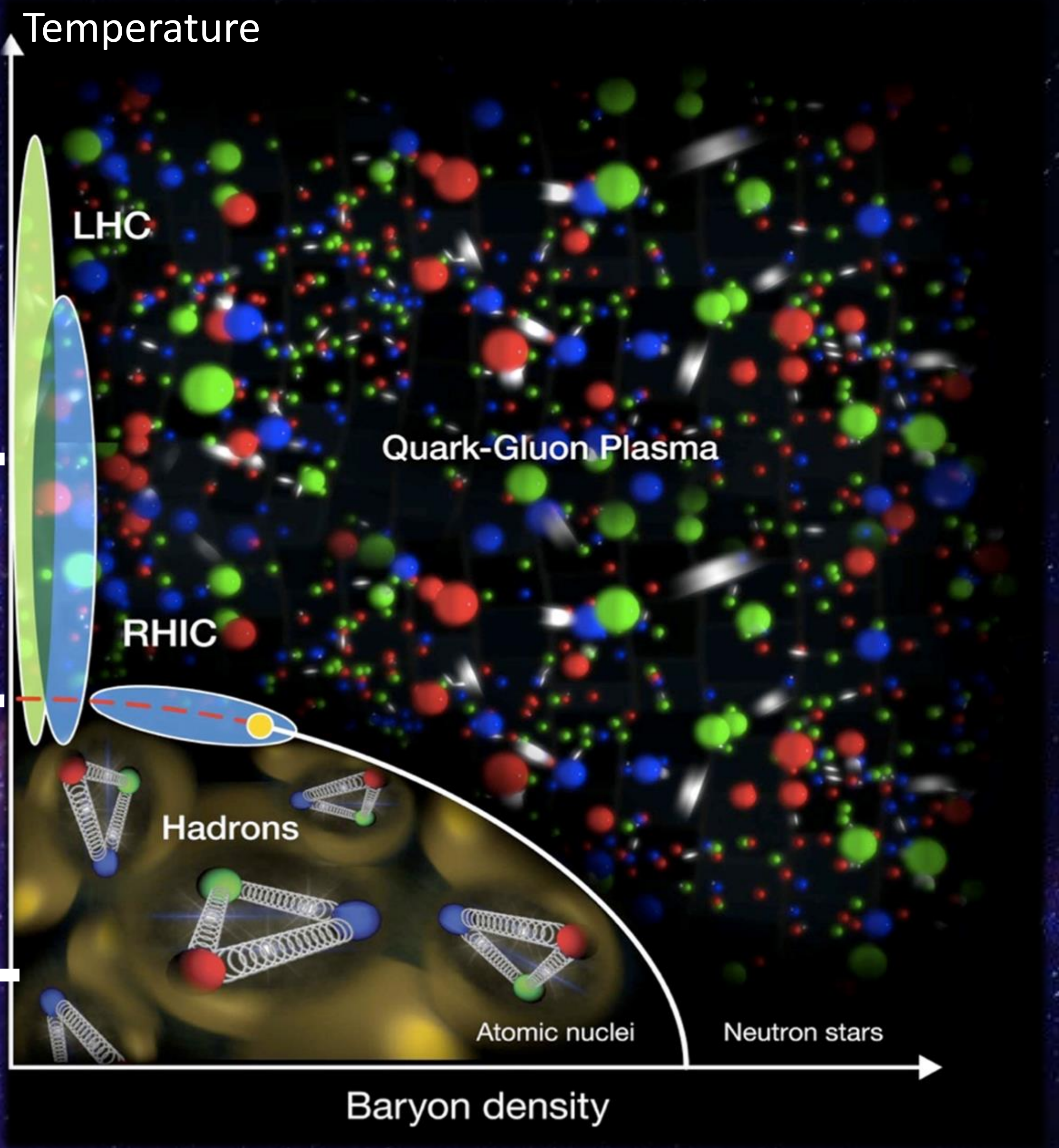
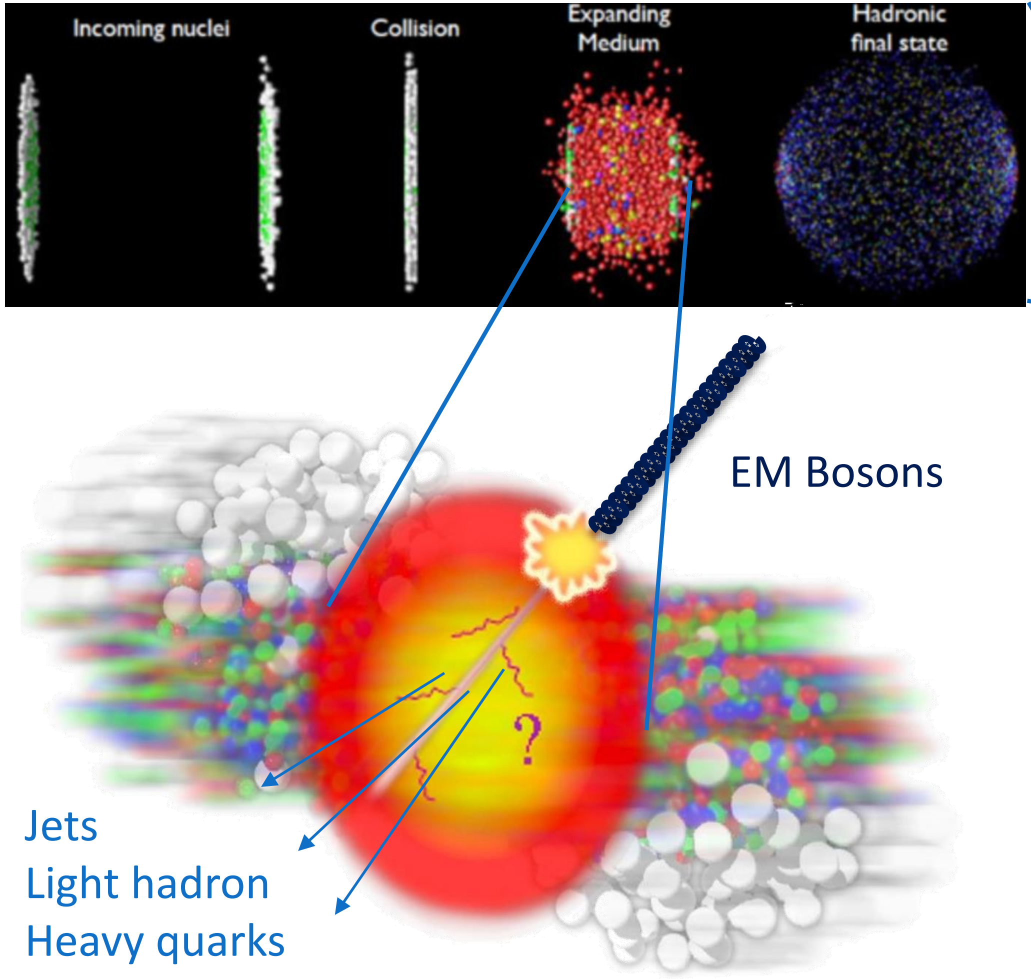

HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Cosmic Microwave Background radiation is visible
Structure formation
Accelerators
RHIC & LHC heavy ions
LHC protons
High-energy cosmic rays
Size of visible universe
TODAY
Inflation
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEI FORM
T_c ~ 150 MeV
$t = 10^{-36}$ s
$E = 10^{16}$ GeV
$t = 10^{-10}$ s
$E = 10^{2}$ GeV
$t = 10^{-4}$ s
$E = 10^{-1}$ GeV
$t = 10^{2}$ s
$E = 10^{-4}$ GeV
$t = 3x10^{5}$ y
$E = 3x10^{-10}$ GeV
$t = 10^{9}$ y
$E = 10^{-12}$ GeV
t = Time (seconds, years)
E = Energy of photons (units GeV = 1.6 x 10^{-10} joules)
Key
quark
gluon
electron
muon
neutrino
bosons
meson
ion
atom
star
galaxy

Temperature
LHC
RHIC
Quark-Gluon Plasma
Hadrons
Atomic nuclei
Neutron stars
Baryon density

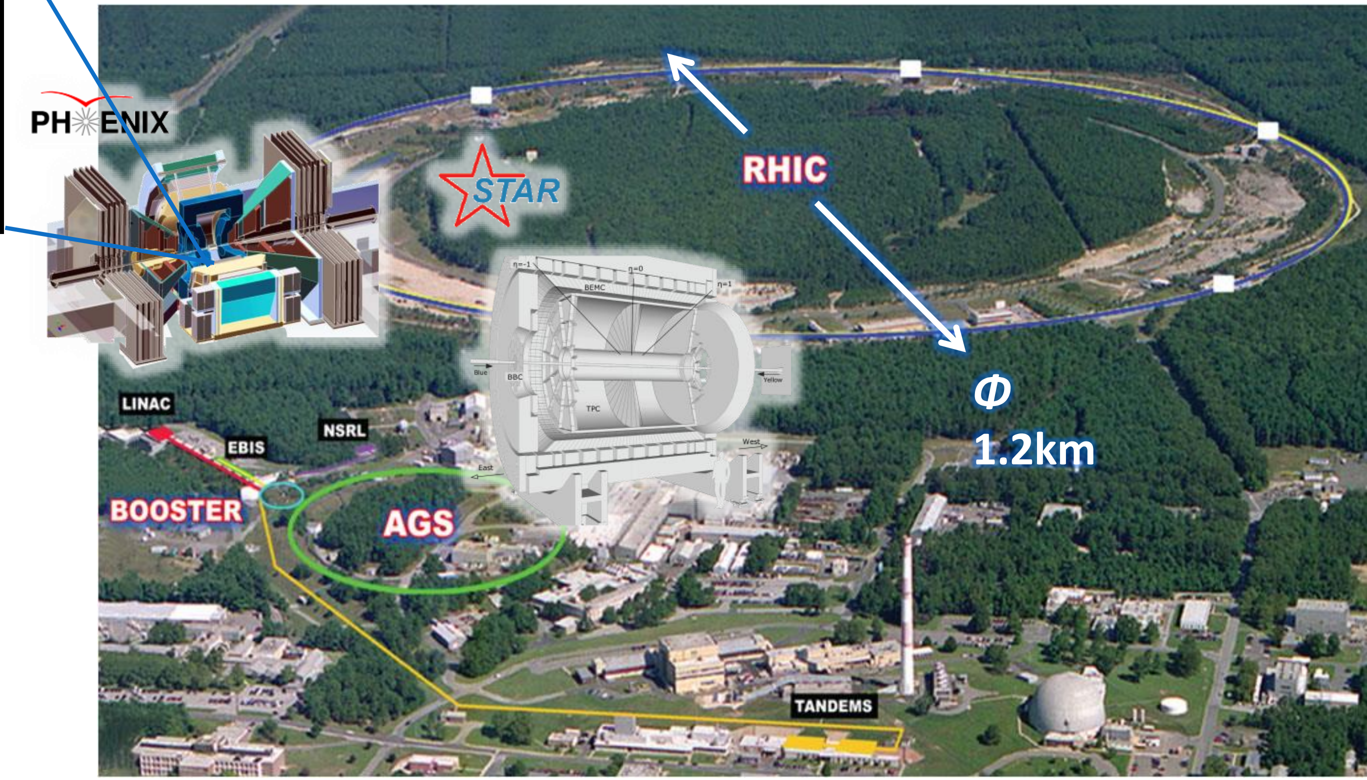
Hard probes in p/A+p/A collisions



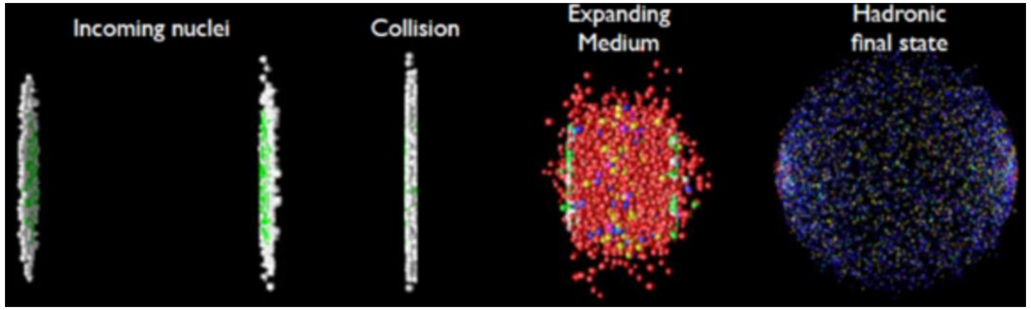
EM Bosons

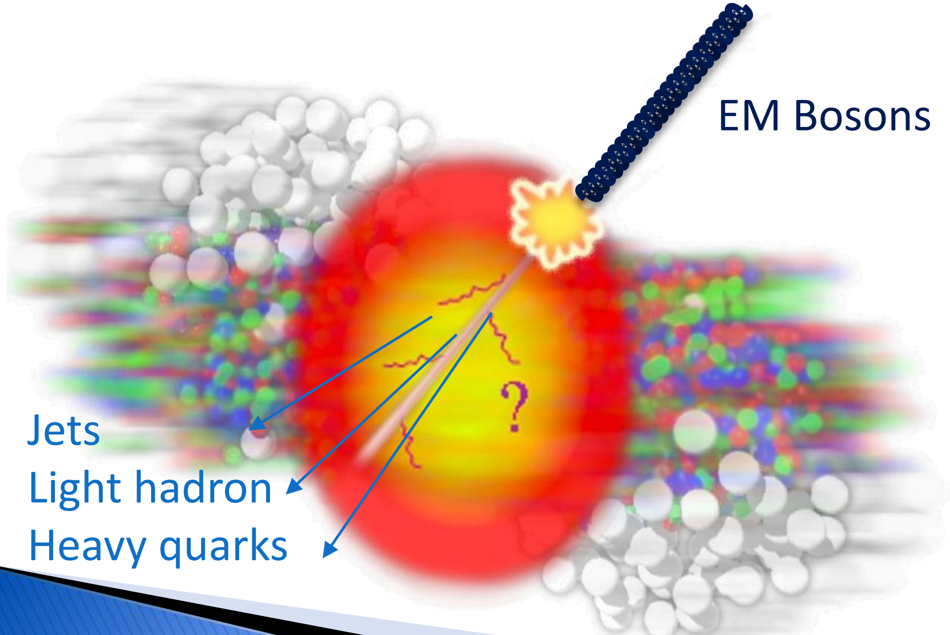
Jets
Light hadron
Heavy quarks
$(m, p_T \gg T_{QGP}, \Lambda_{QCD})$

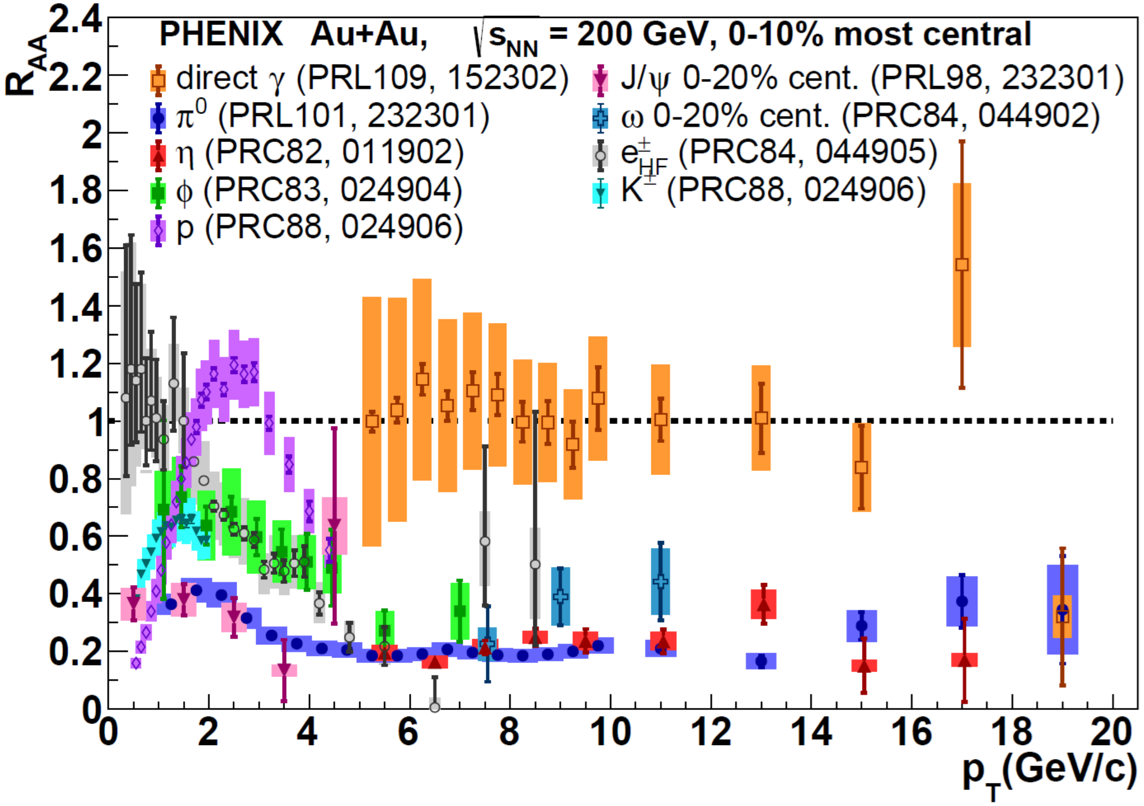
RHIC @ last decade



Hard probes in p/A+p/A collisions



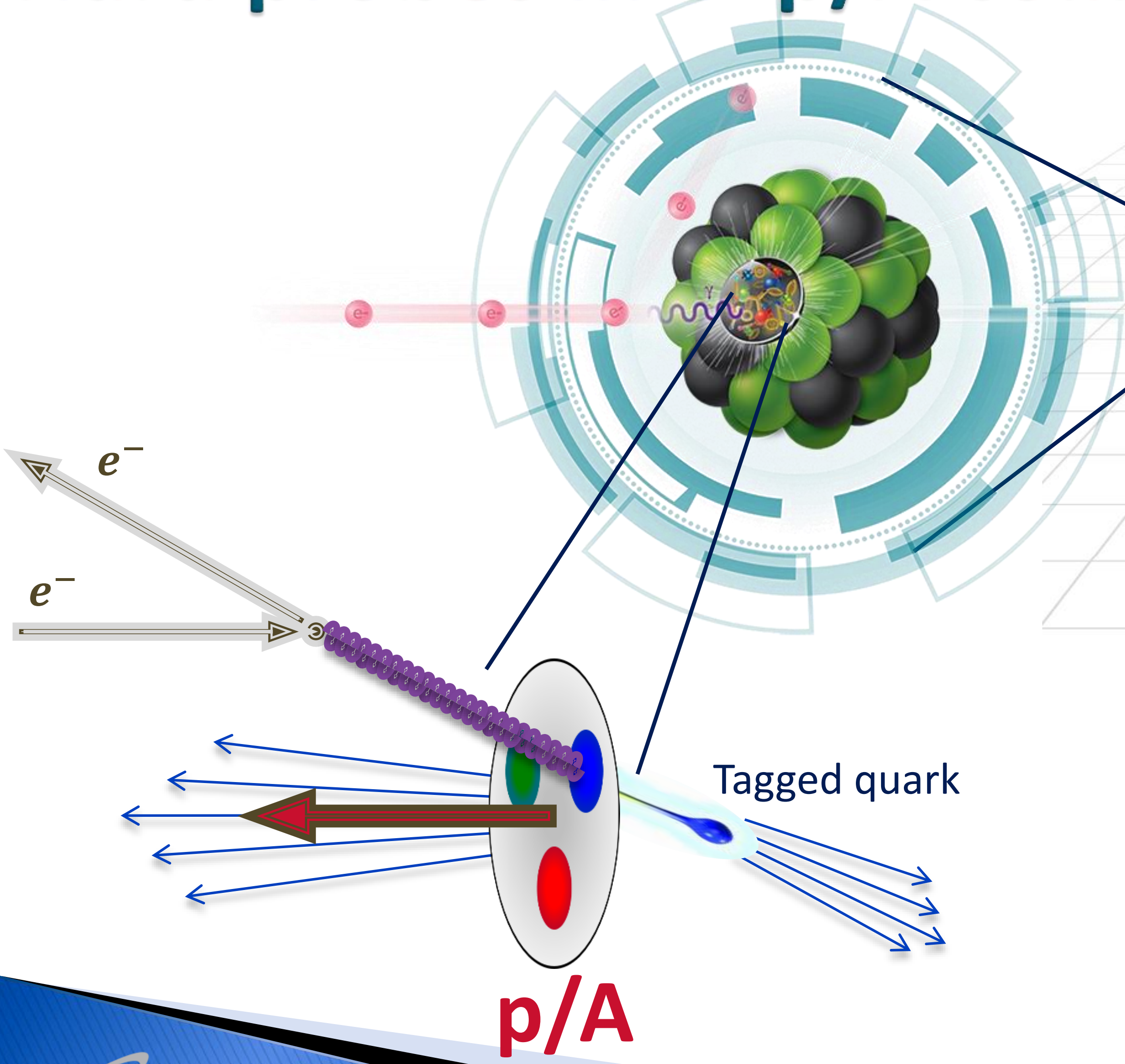


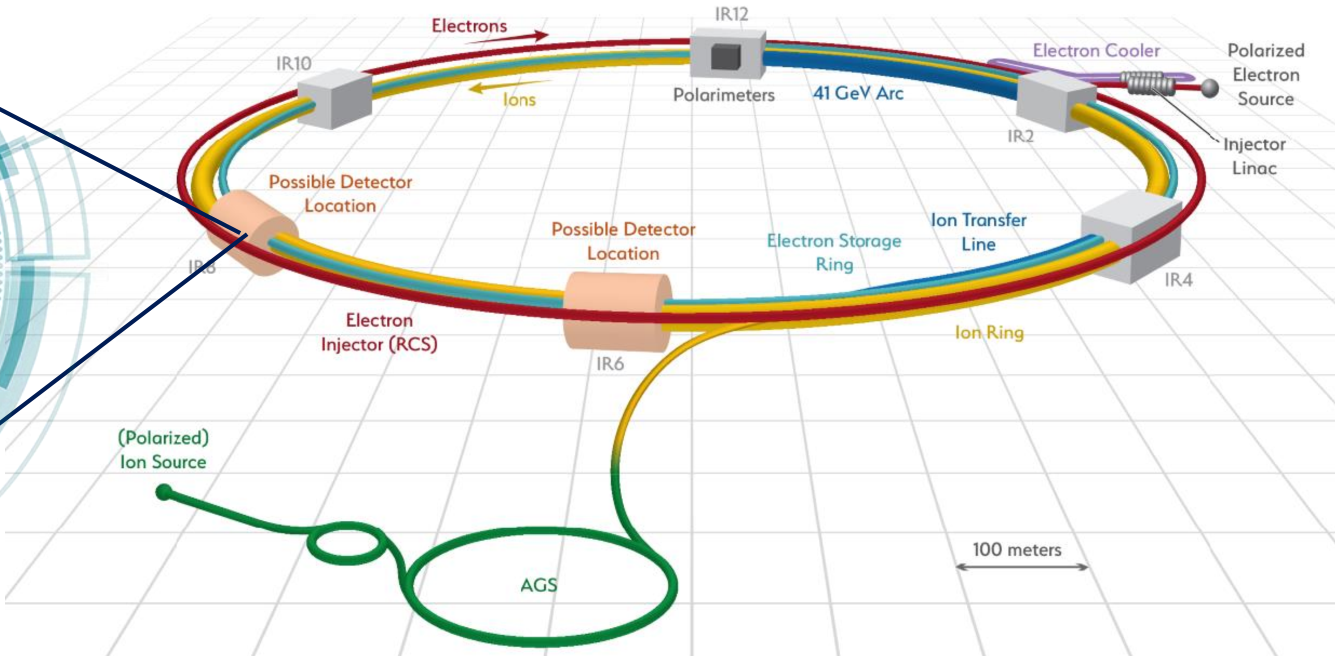


+ wealth body of results from RHIC and LHC

→ extract Parton Transport Parameter, $\hat{q} = \frac{\sqrt{\mu^2}}{\lambda}$ ← Momentum transfer ← mean free path

Hard probes in e+p/A collisions

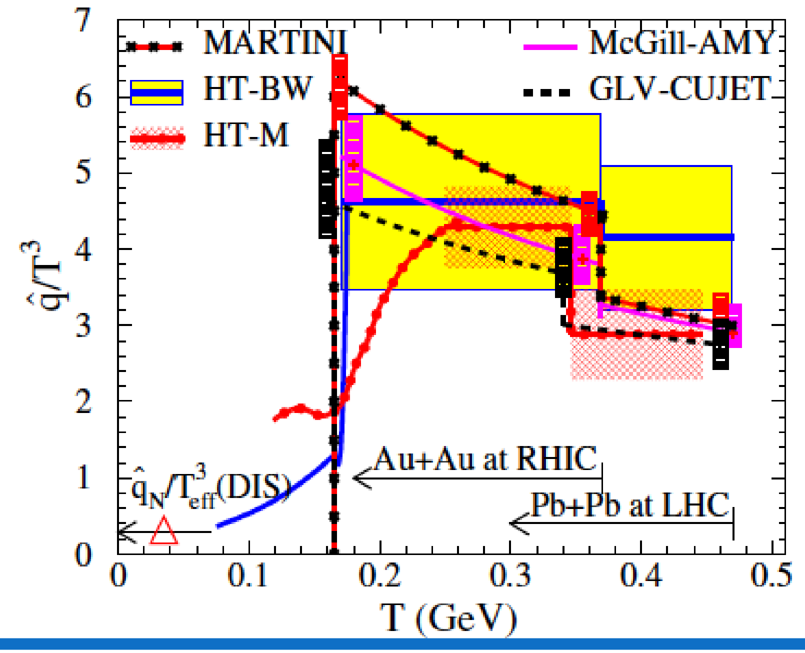




Jan 2020 DOE announces

- EIC CD-0 (Mission need)
- BNL will be the host of the EIC

JET Collaboration PRC90, 014909 (2014)



Parton transport parameter, $\hat{q}$ =

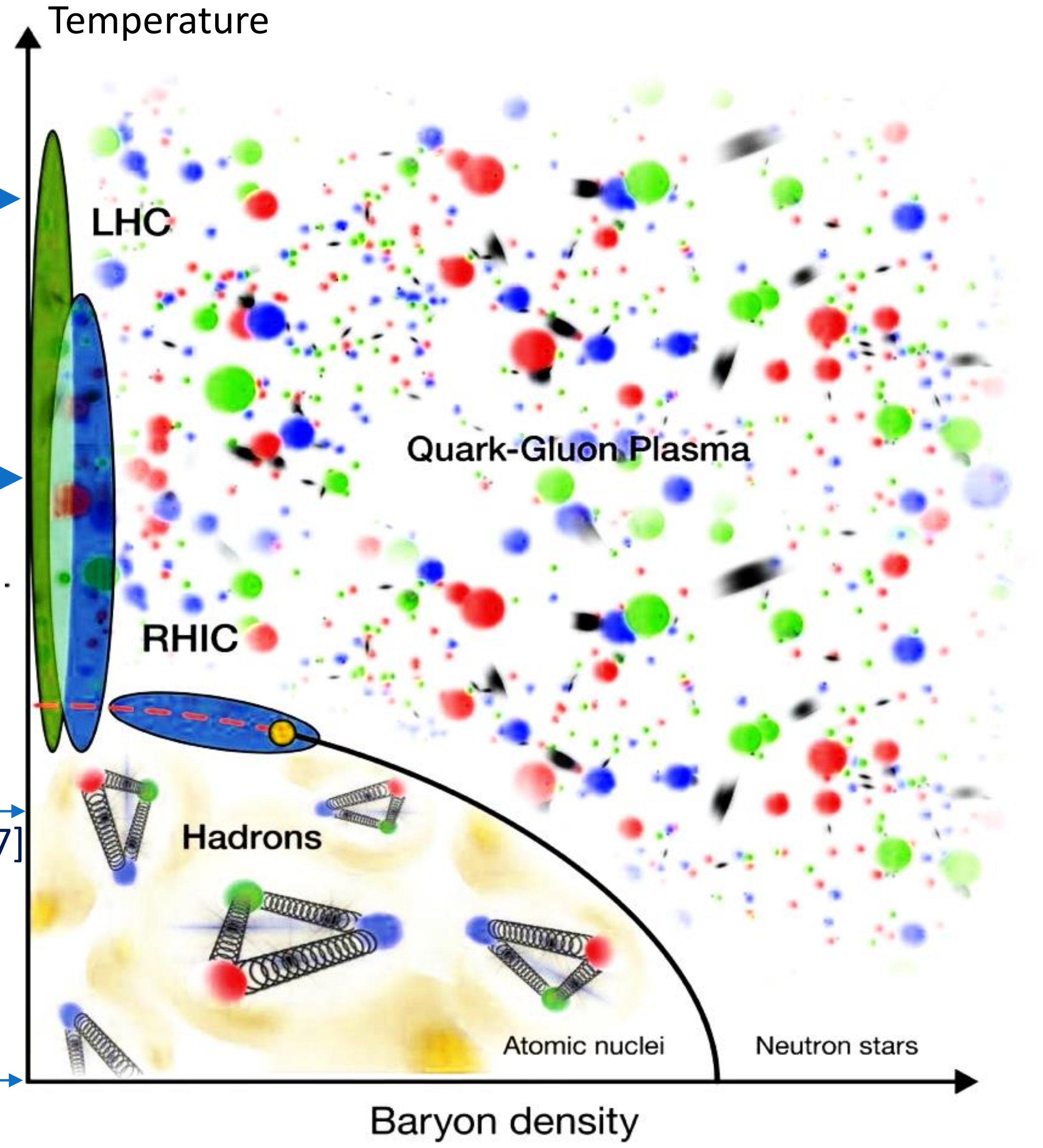
1.9 +/- 0.7 GeV²/fm

1.2 +/-0.3 GeV²/fm

~0.38 GeV²/fm

[arXiv: 1910.07027]

~0.02 GeV²/fm



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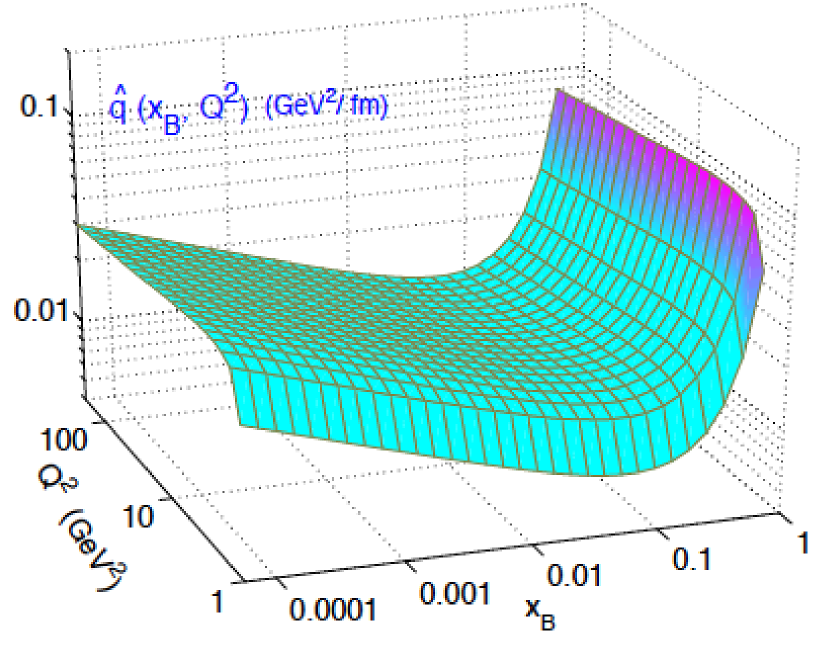
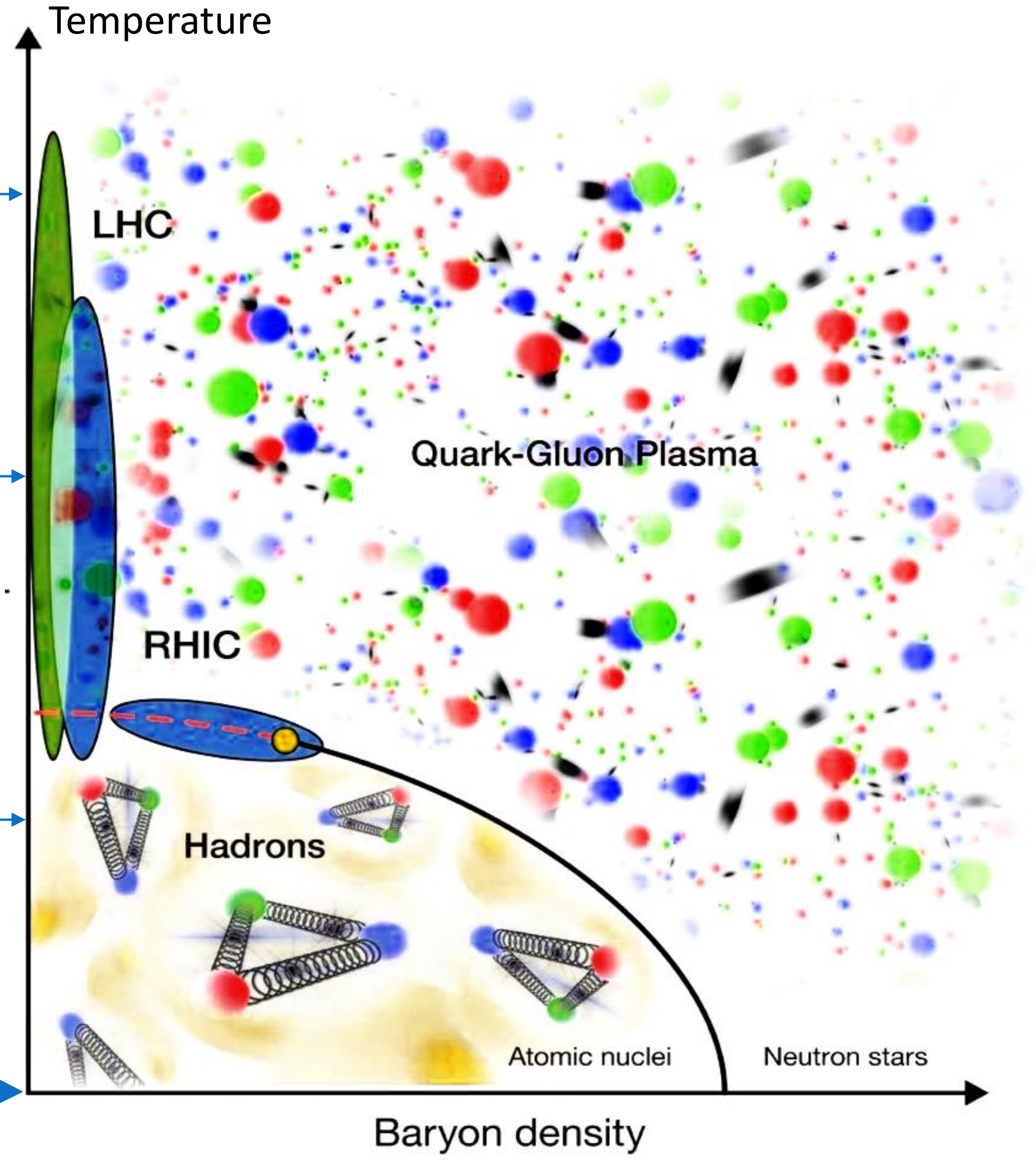
[arXiv: 1910.07027]

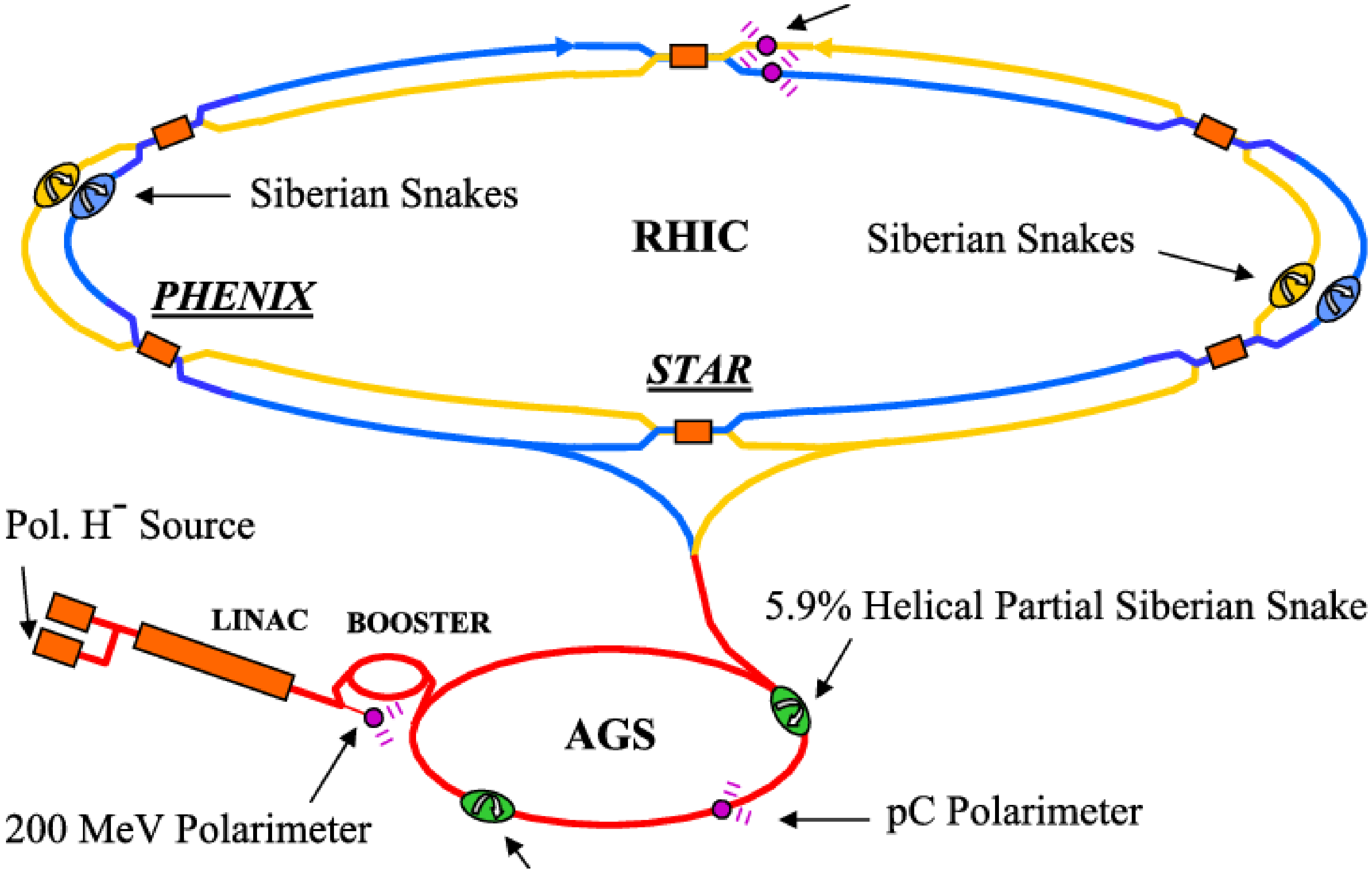
~0.02 GeV^2/fm

P. Ru et. al, arXiv:1907.11808





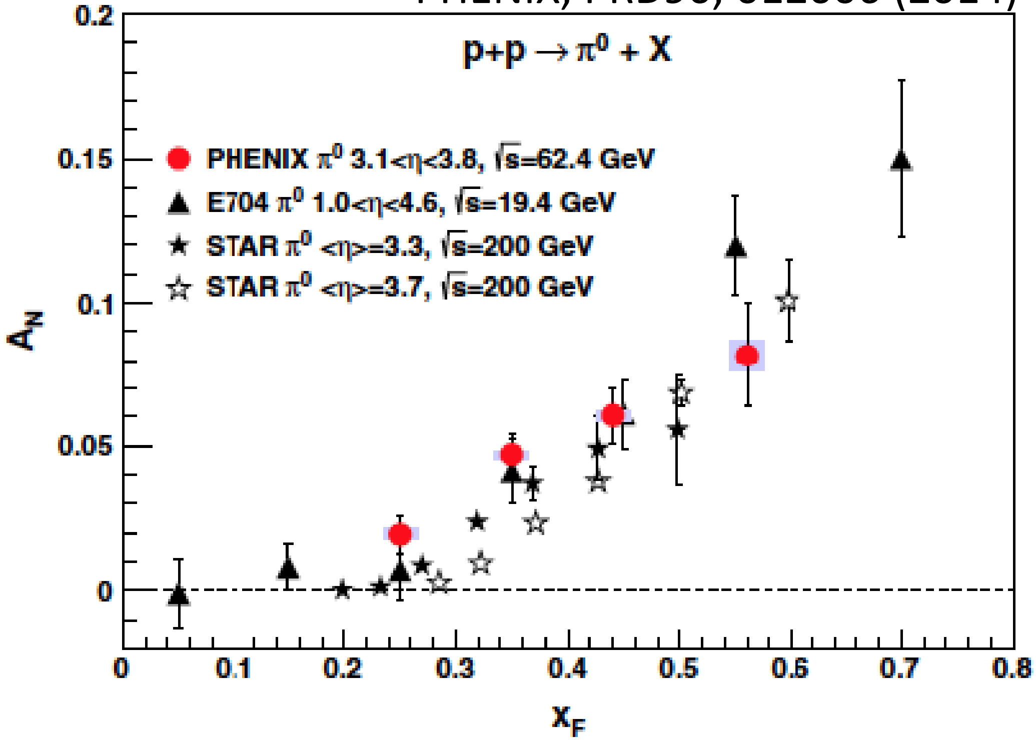
RHIC : world only spin polarized $p + p/A$ collider



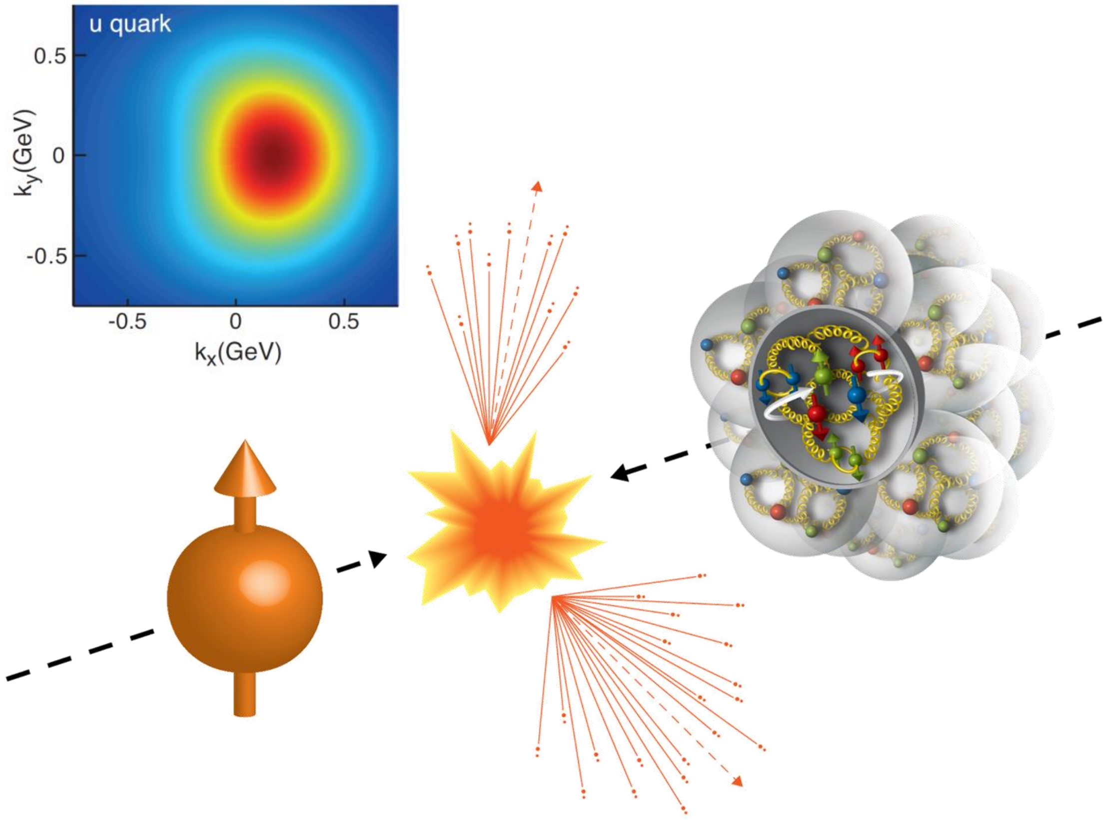
Single spin asymmetry, how about nuclear target?

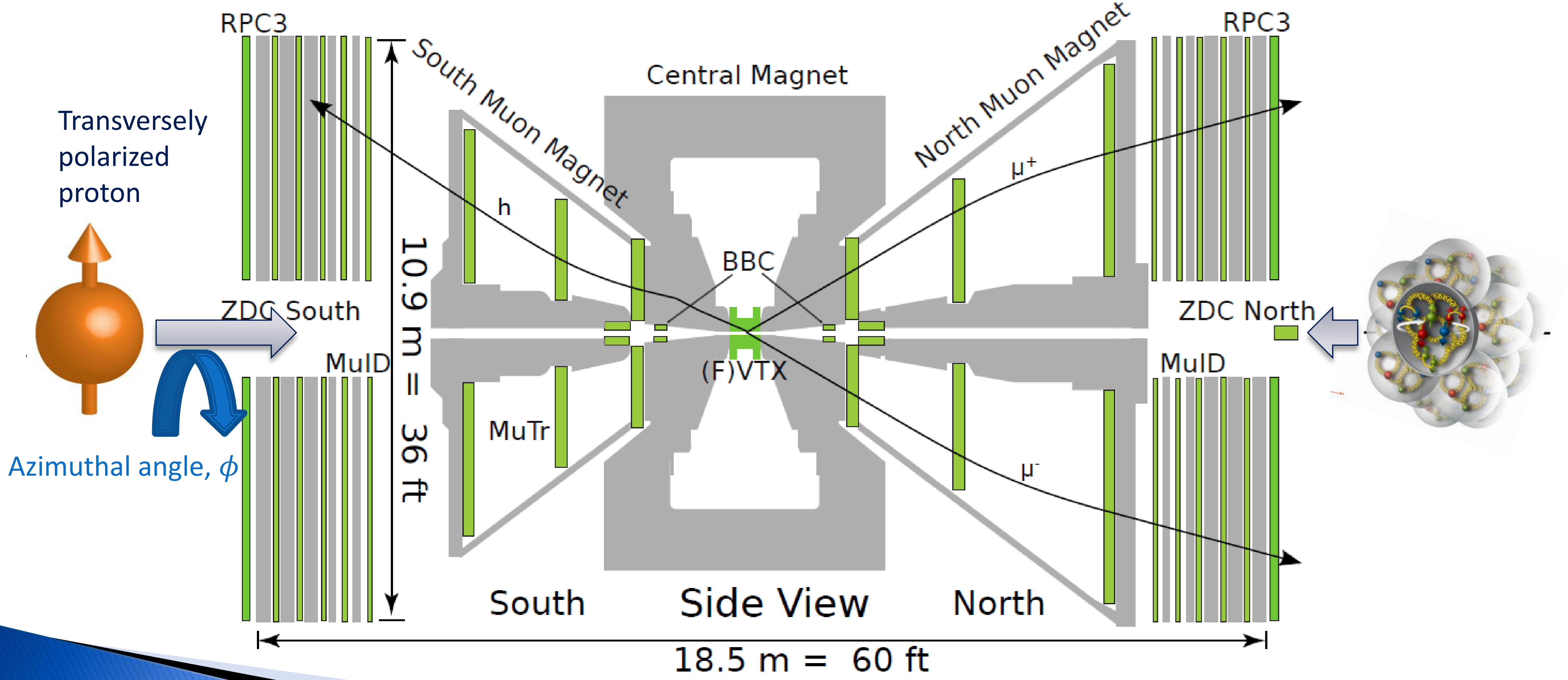
A_N: Transverse spin asymmetry, $O(100\ MeV/c)$ k_T shift in the transverse momentum relative to the transverse spin
A_N in $p + A$: potentially sensitive to parton interaction of nuclear matter as decorrelation of spin and k_T

PHENIX, PRD90, 012006 (2014)



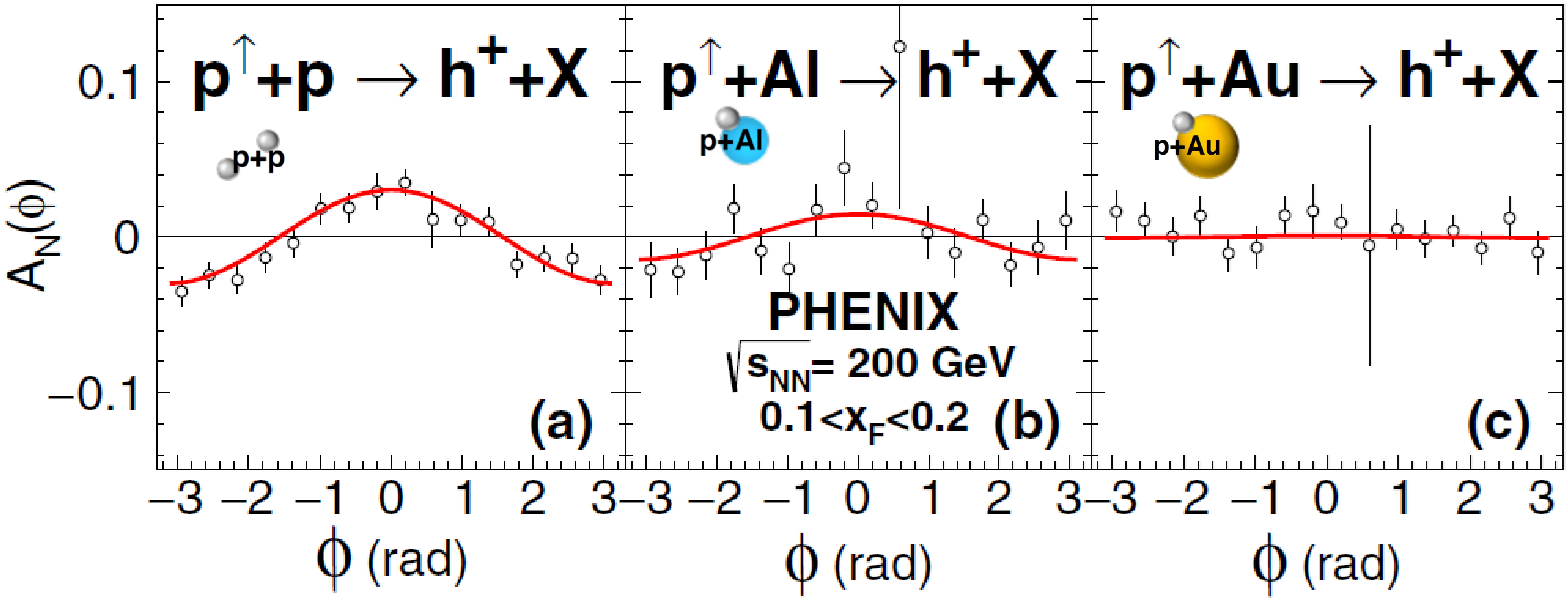
Longitudinal momentum/beam momentum




Transversely
polarized
proton
Azimuthal angle, ϕ
RPC3
South Muon Magnet
Central Magnet
North Muon Magnet
RPC3
h
BBC
μ^+
ZDC South
ZDC North
MuID
MuID
(F)VTX
MuTr
μ^-
10.9 m = 36 ft
South
Side View
North
18.5 m = 60 ft

The nuclear dependence is visible!

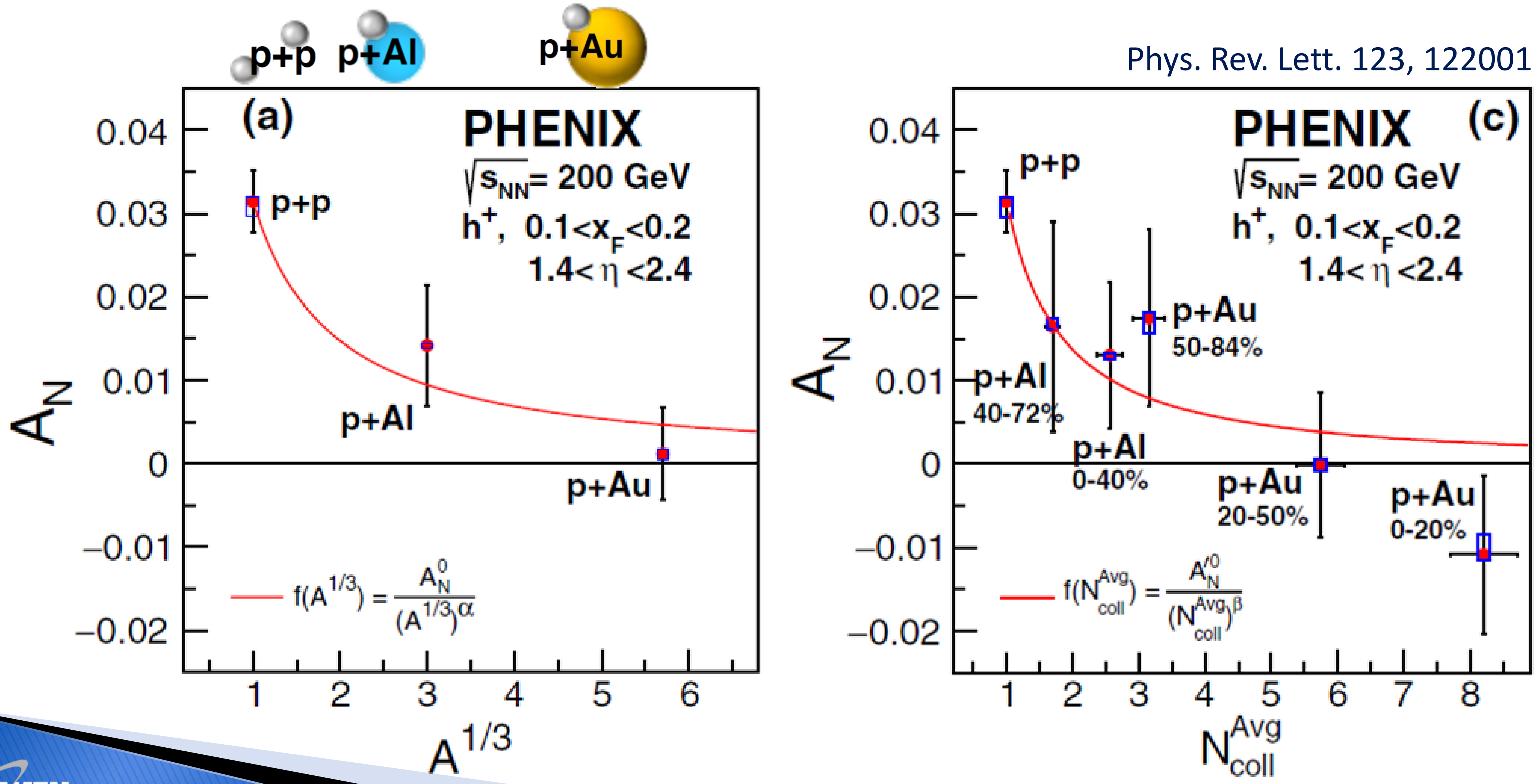
PHENIX, Phys. Rev. Lett. 123, 122001



Azimuth angle

Data show significant nuclear dependence of A_N

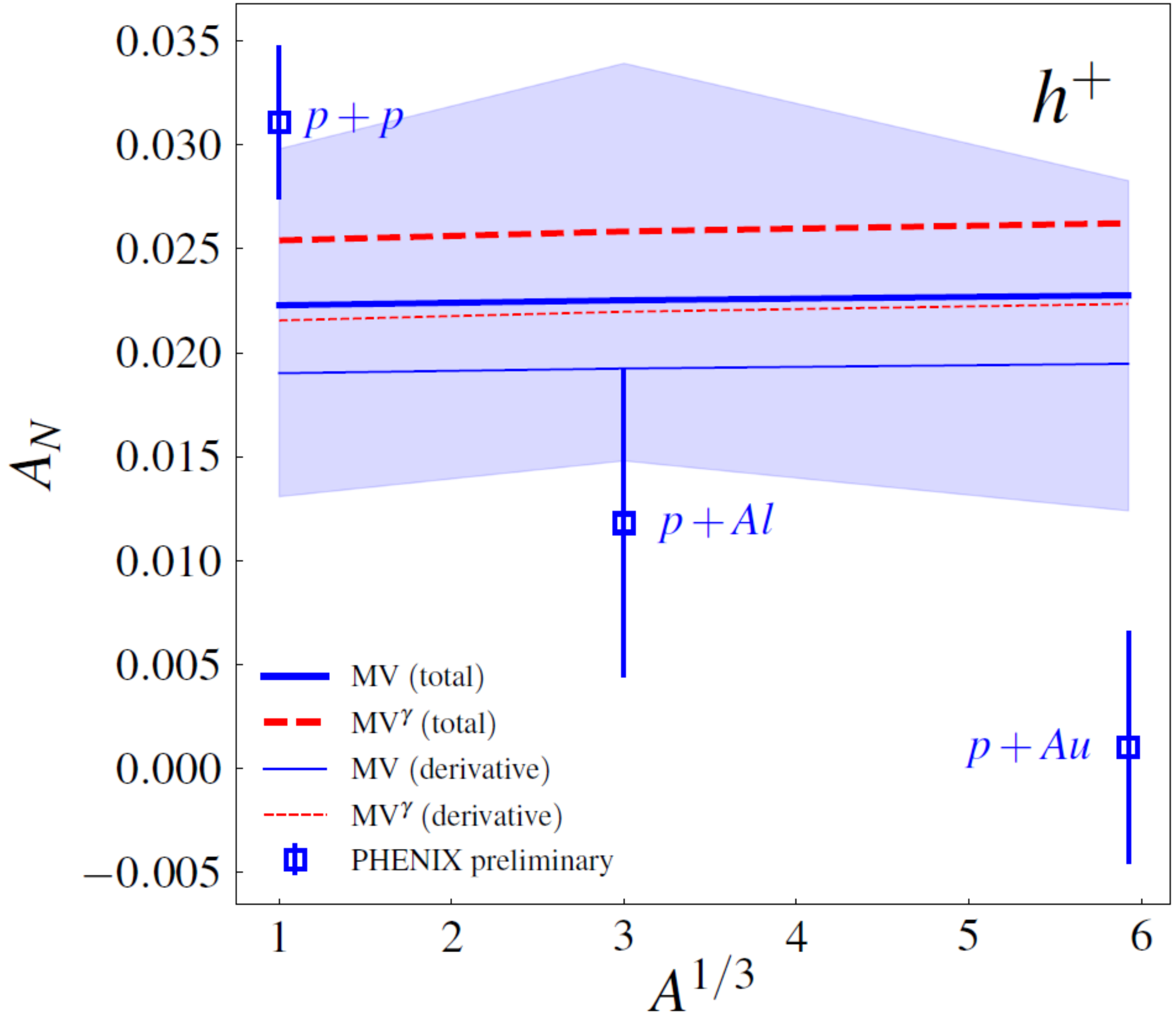
Phys. Rev. Lett. 123, 122001



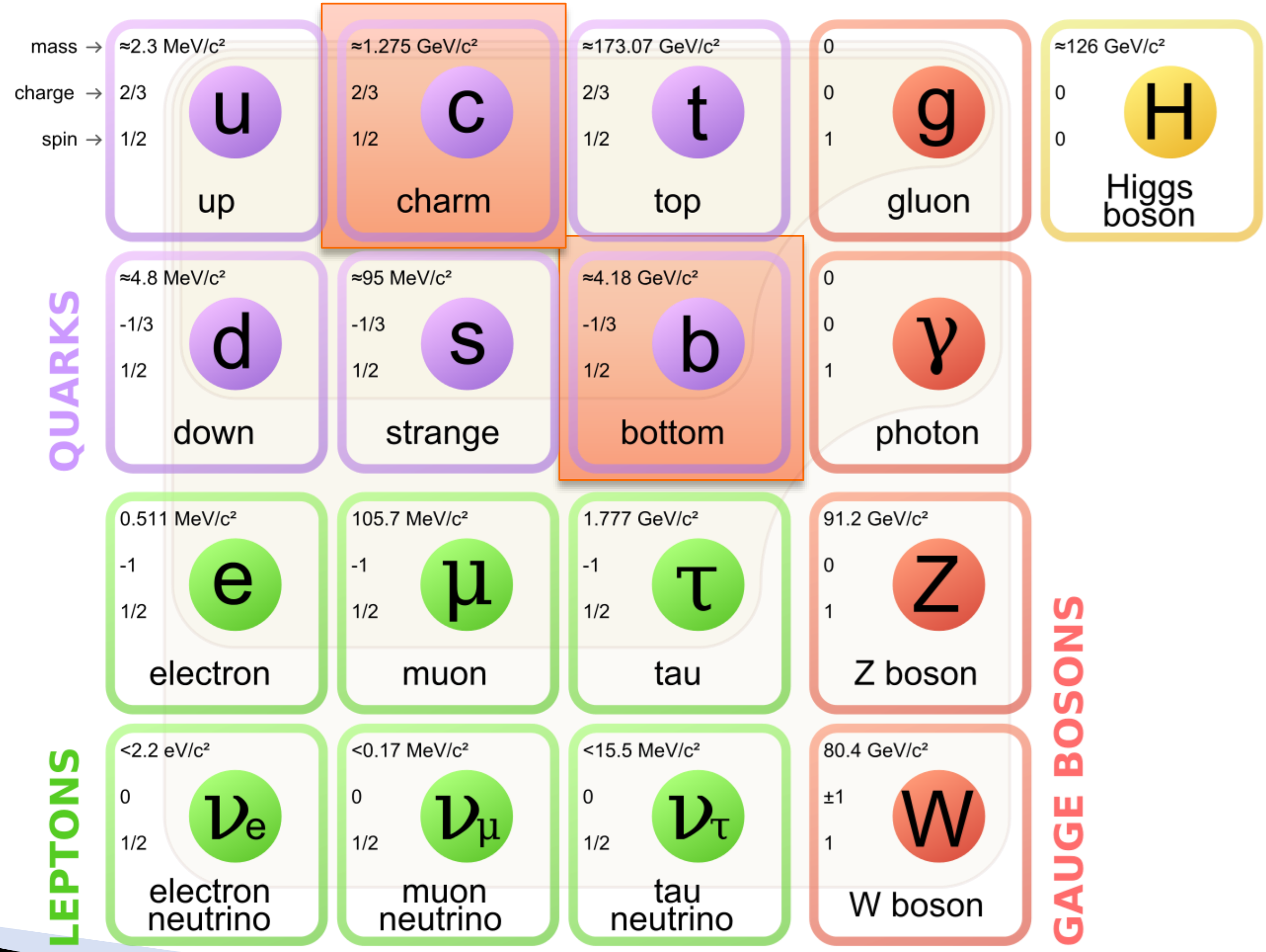
Discussion and interpretation

- This is a surprising finding
  - Hatta's group calculated nuclear AN in gluon saturation model, which suggested much weaker nuclear dependence
  - Meanwhile, our momentum scale is much higher than saturation scale suggest new effect come into play
- Scattering of hard probe on cold/hot nuclear matter? Link with the transport of hard probe?

S.Benic and Y.Hatta, PRD99, 094012

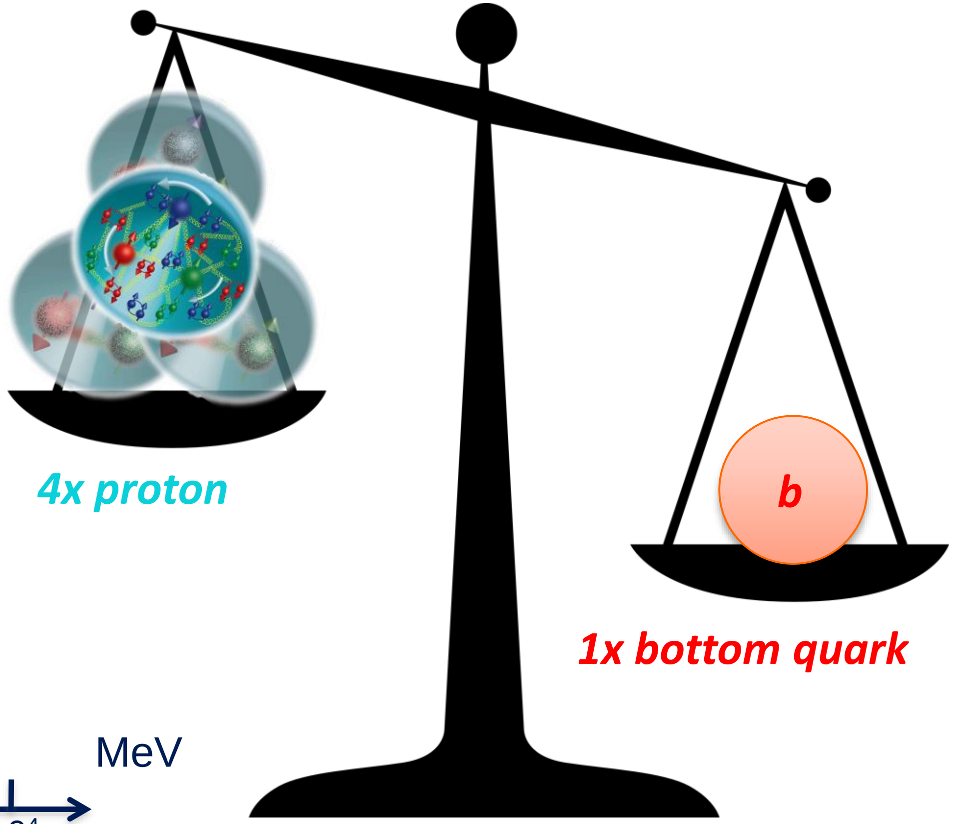


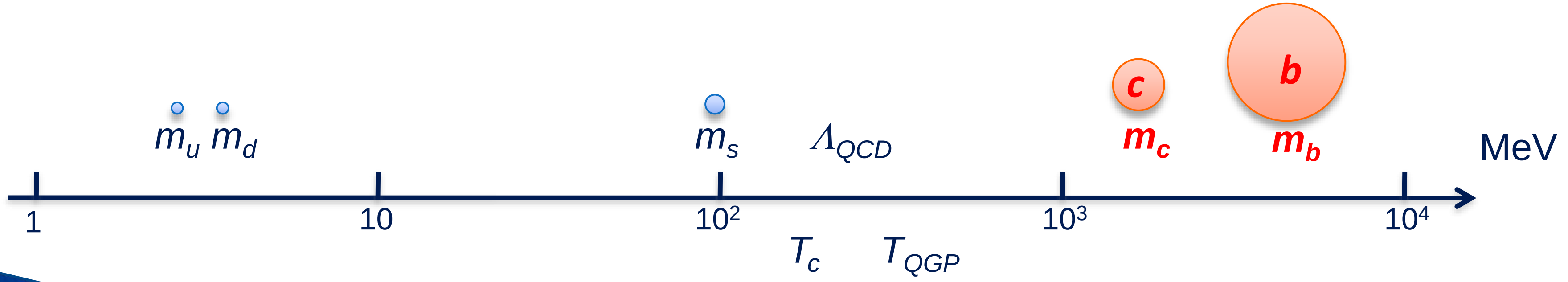
Heavy flavor : a rarer hard probe with unique prop.



Why heavy quark?

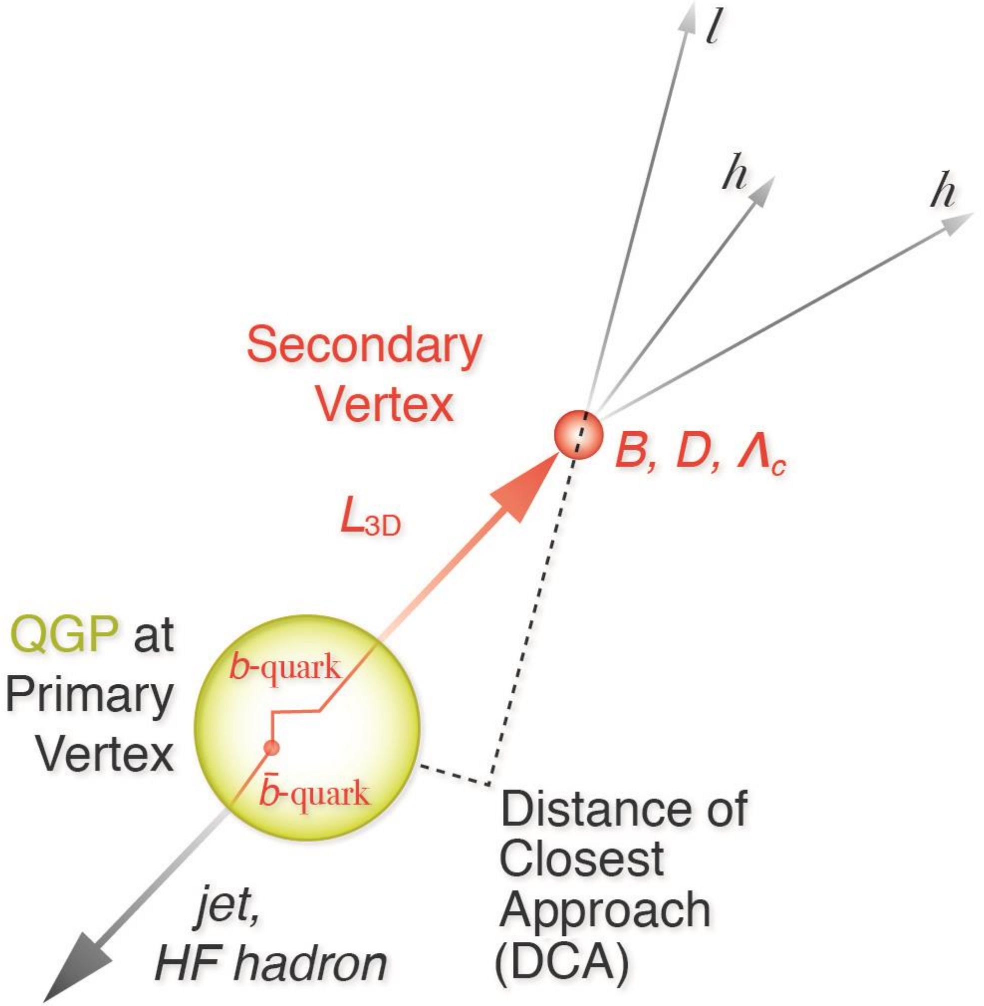
- Produced via hard collision
- Probing the initial gluon field
- Experience full evolution of collision
- Measure the diffusion
- Differentially sensitive to collisional energy loss
- Keep identity during hadronization



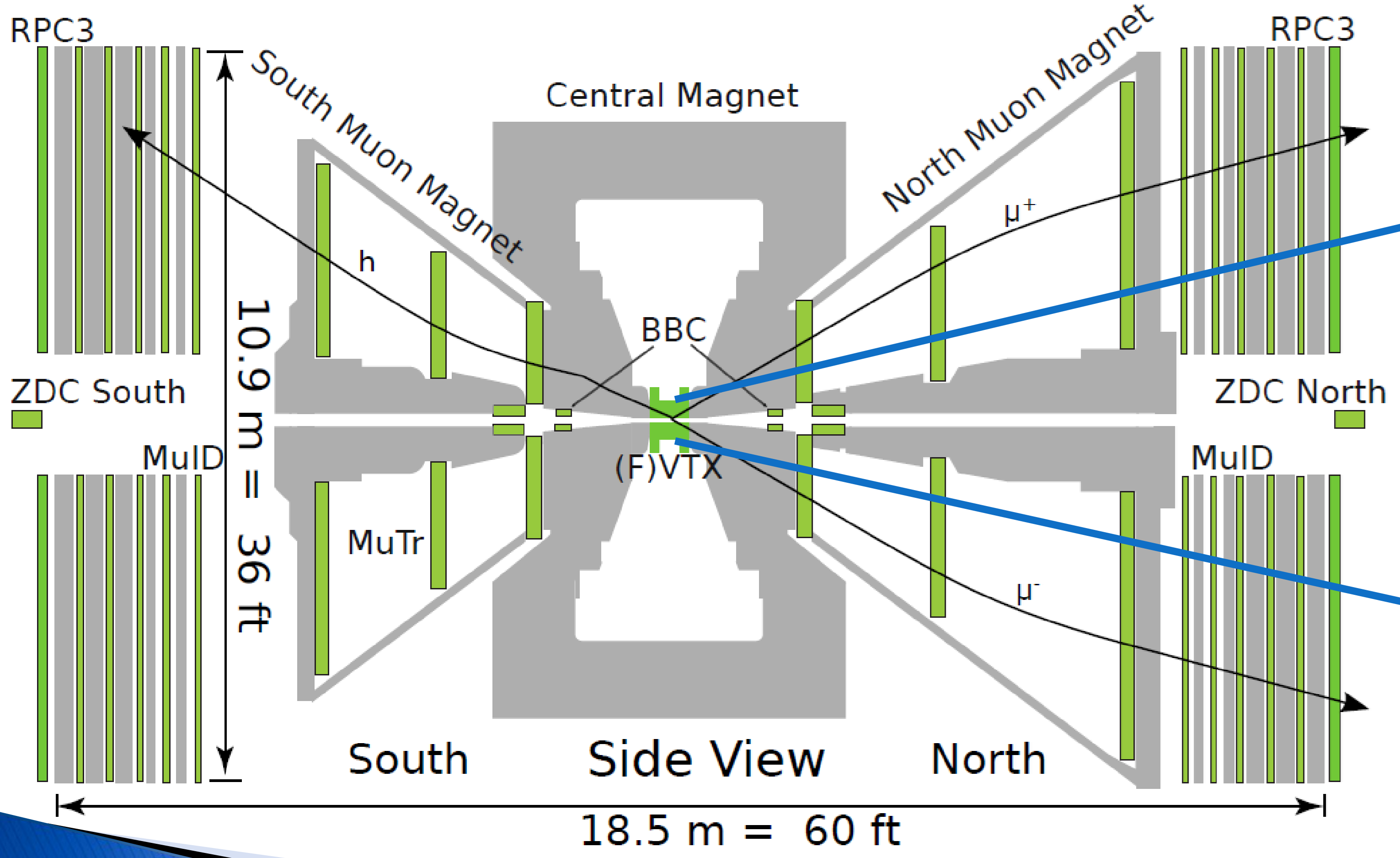


Heavy flavor detection in nuclear collisions

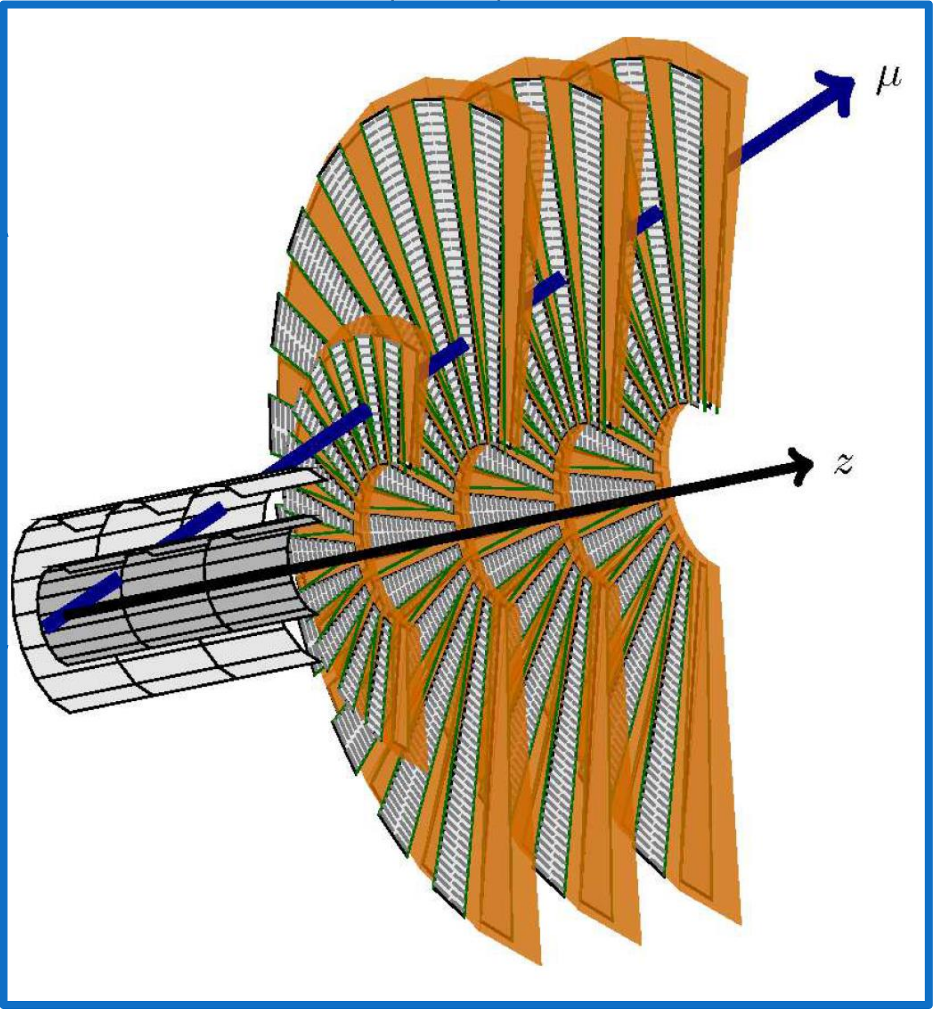
- Open HF hadron usually weak decay to multiple leptonic/hadron final states
- Finite life time → typical decay vertex ~ $O(100\mu m)$ from primary vertex
- Require high resolution vertex tracker and high rate capability → Driving detector design

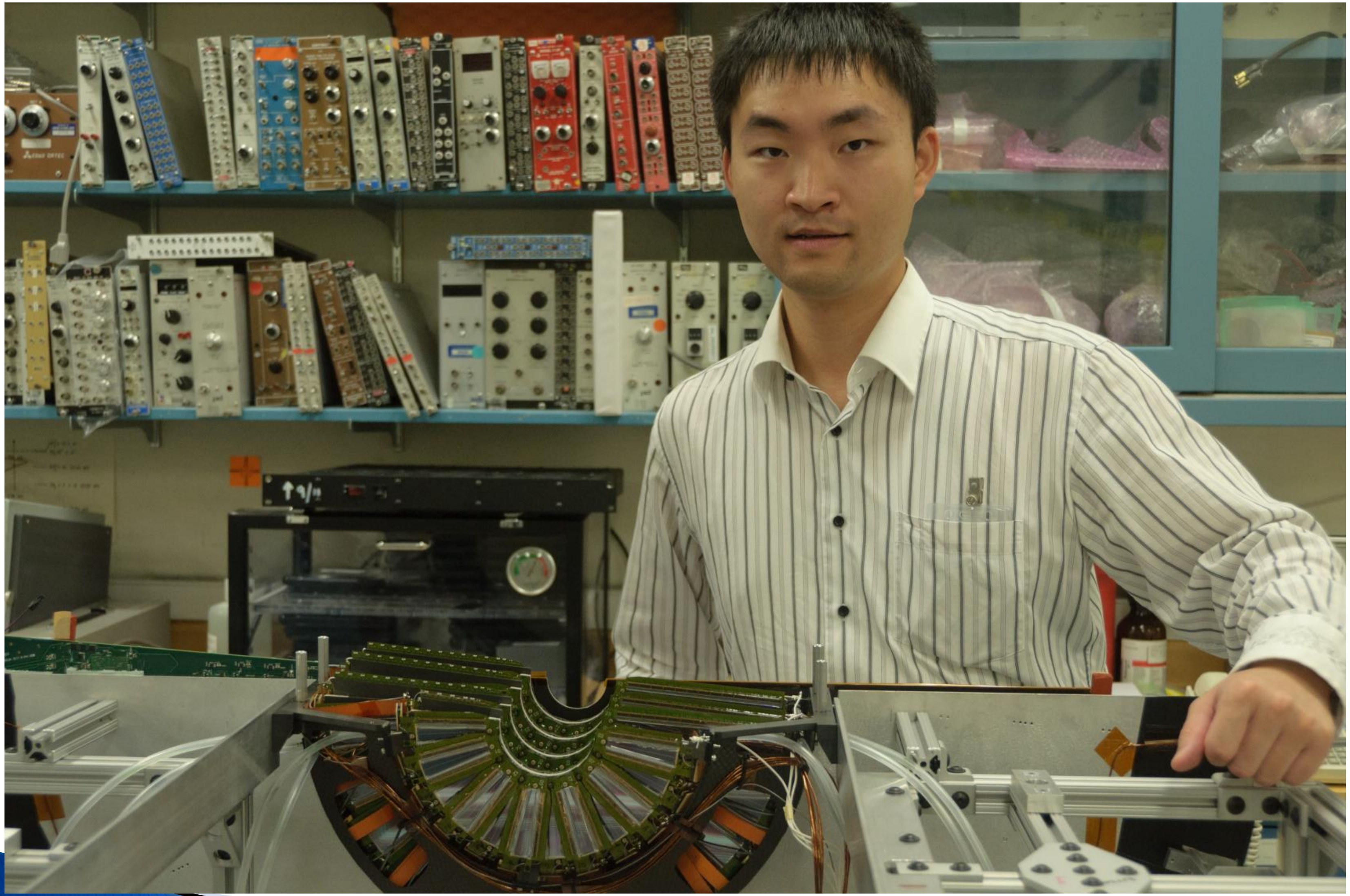


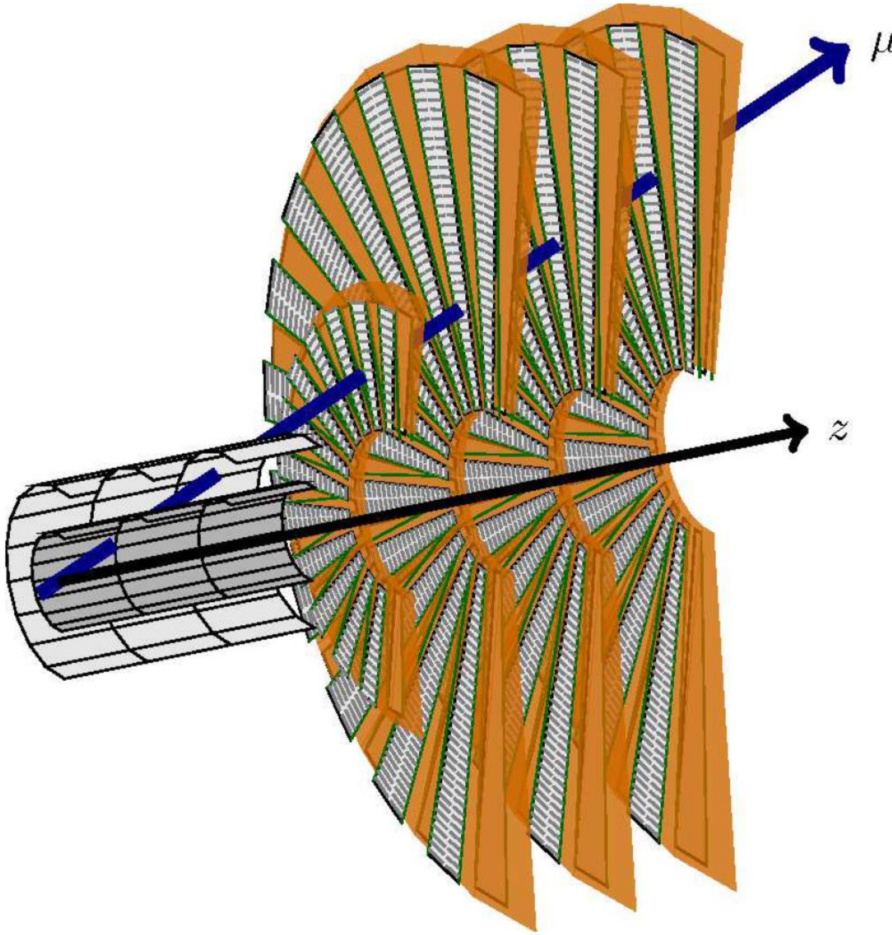
Forward silicon tracker at PHENIX



PHENIX, NIM. A755 (2014) 44-61



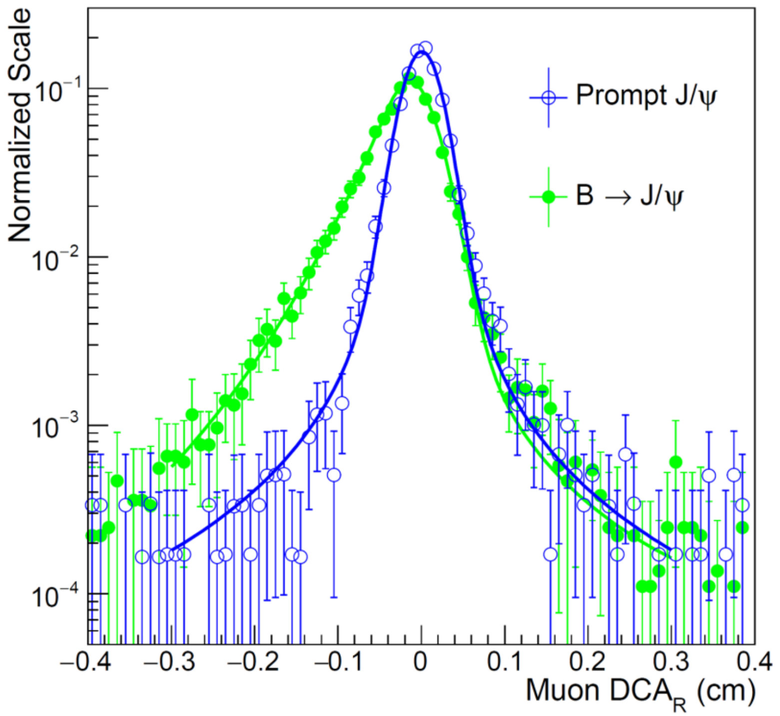




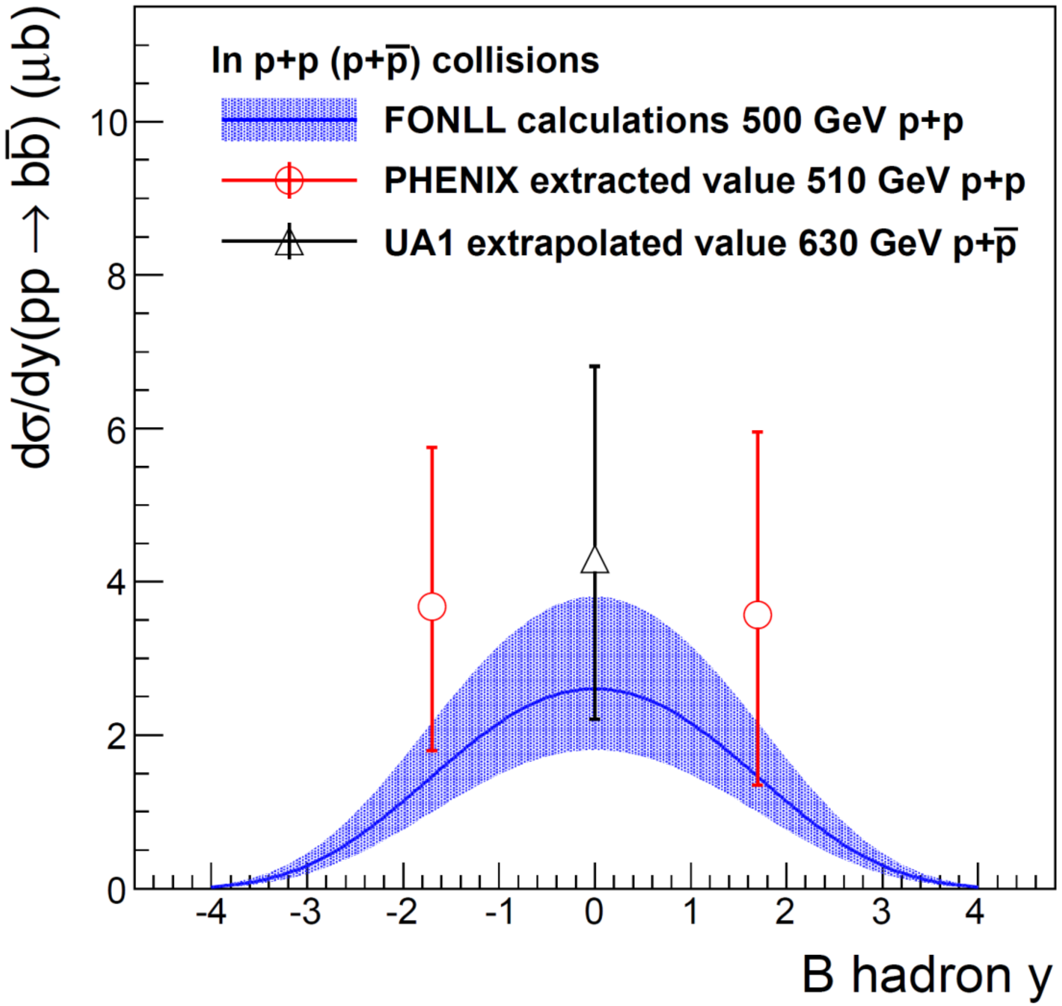
μ
z

Heavy quarks are produced via hard collision
→ cross section is calculable in perturbative theories

$B \to J/\Psi \to \mu^+ \mu^-$

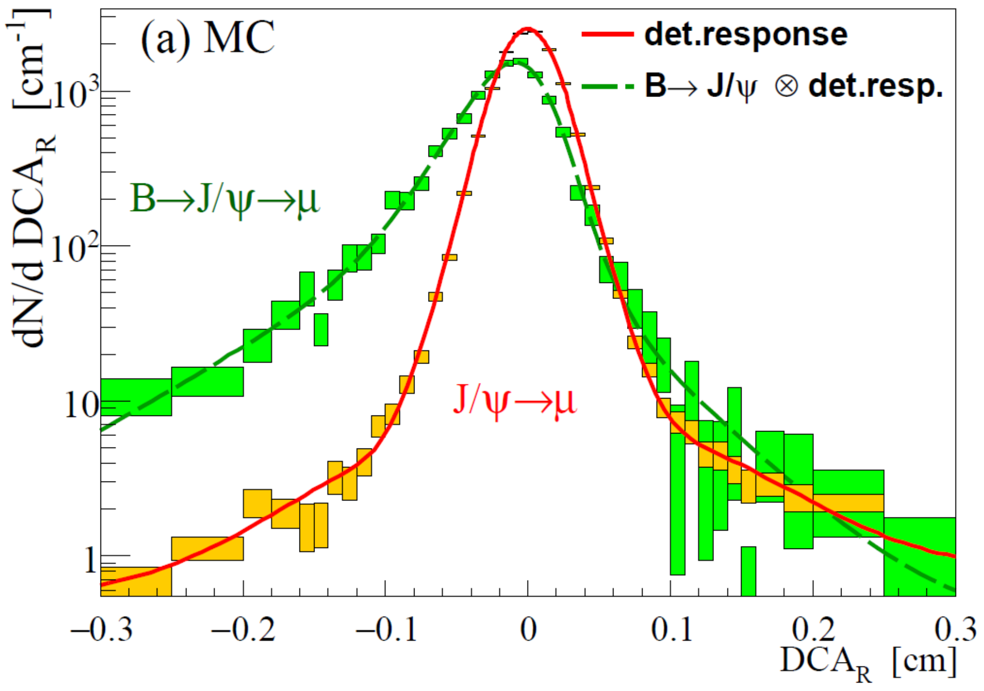


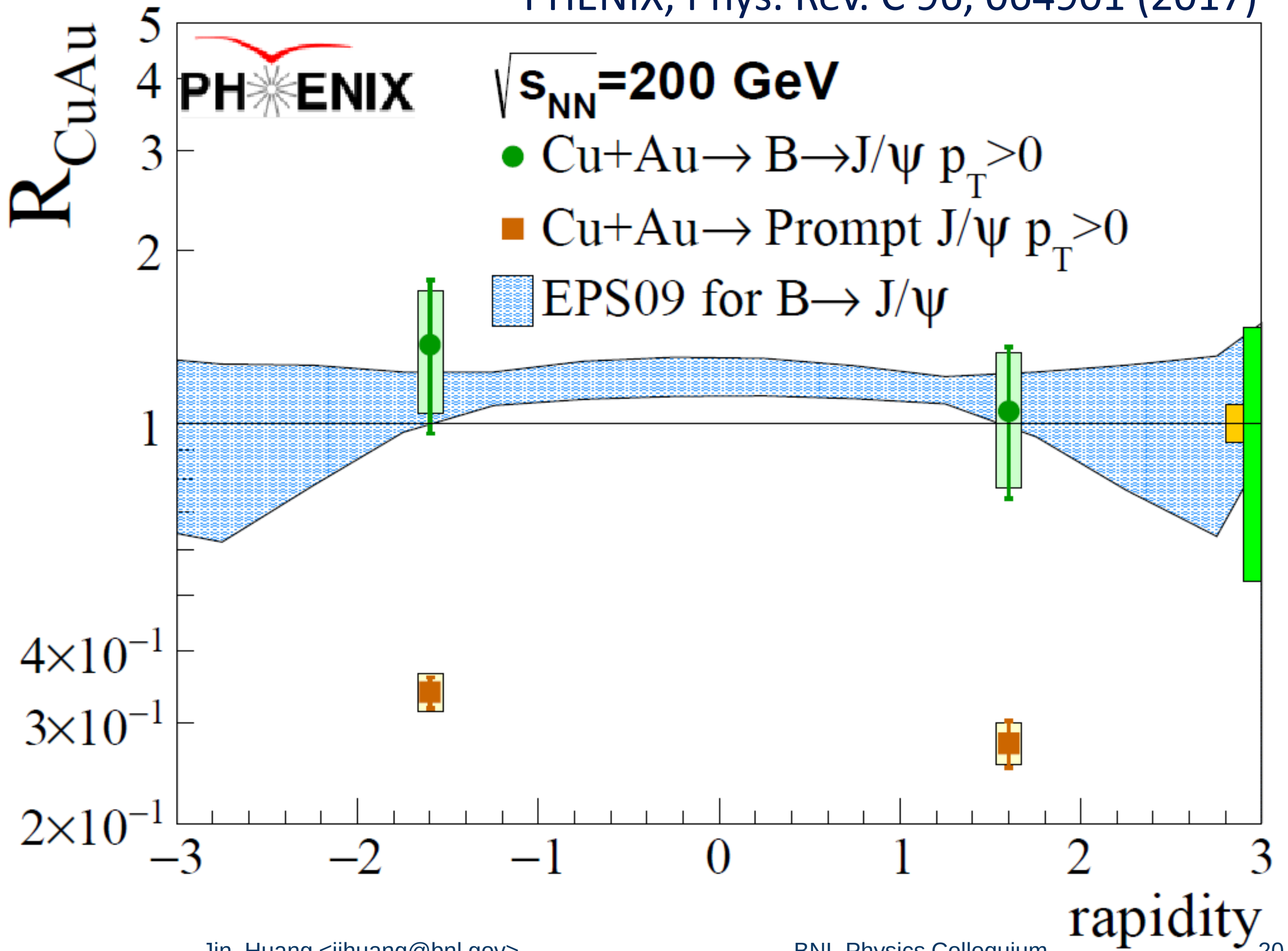
PHENIX, Phys. Rev. D 95, 092002 (2017)



Heavy quark production trace back to the initial gluon field in nuclei

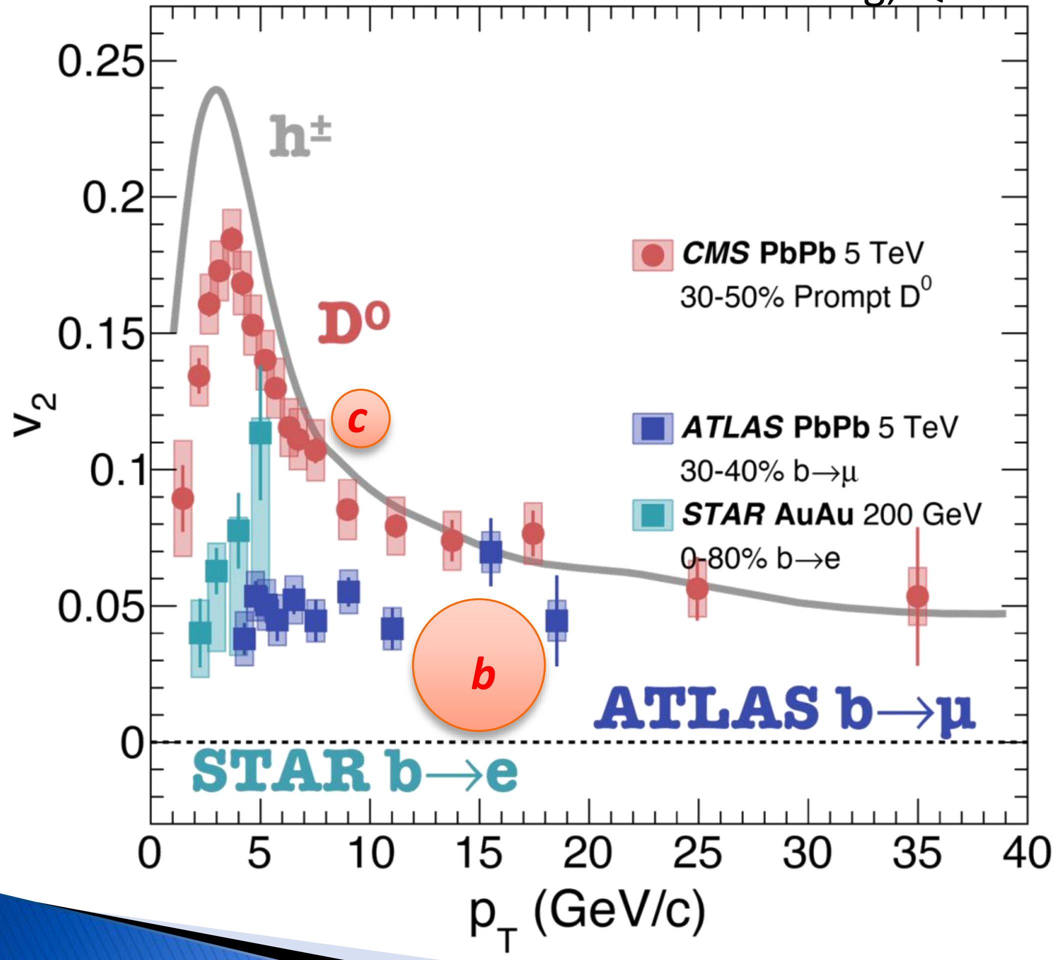
PHENIX, Phys. Rev. C 96, 064901 (2017)



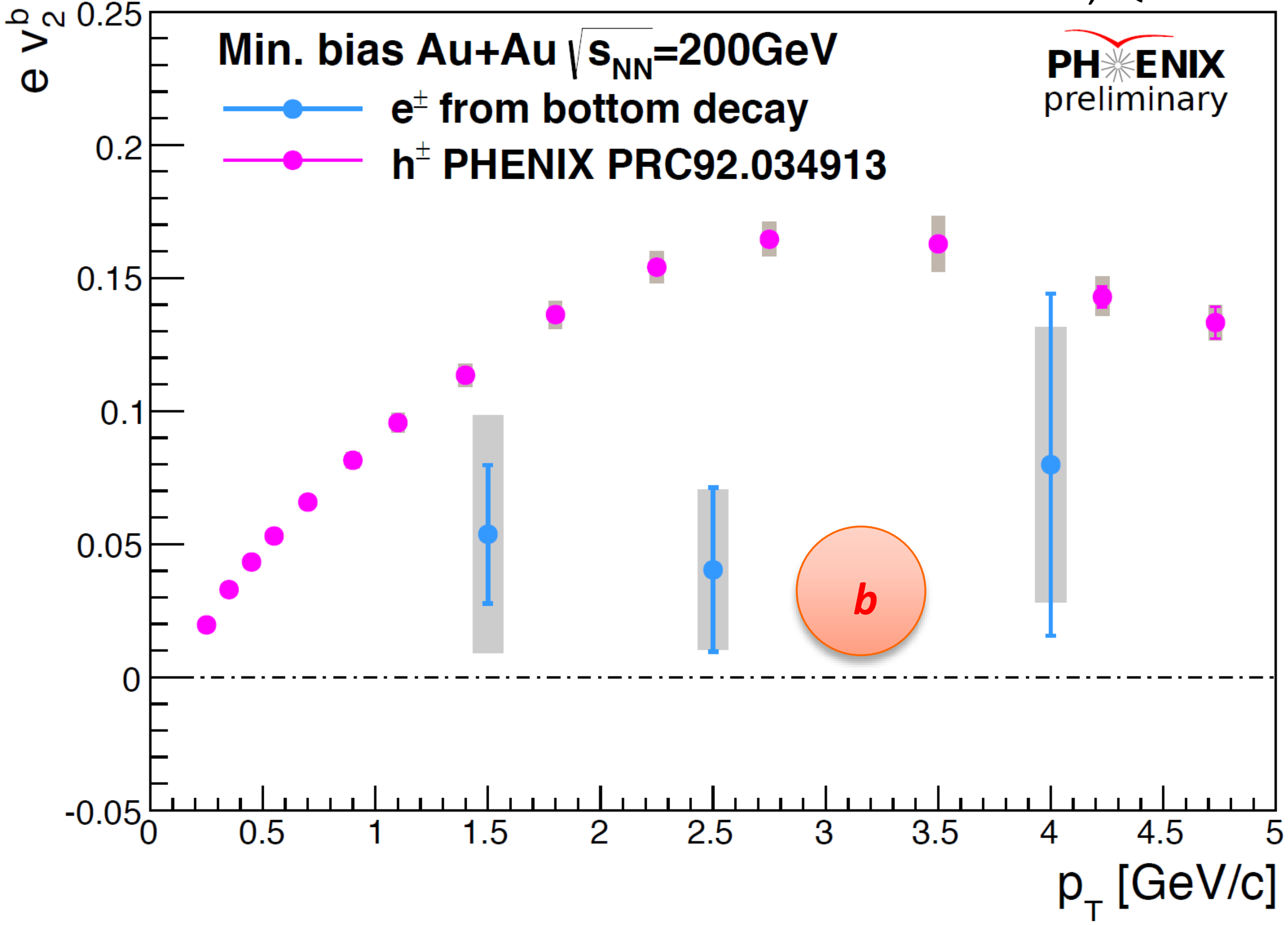


Bottom shows mass effect, while RHIC data is scarce

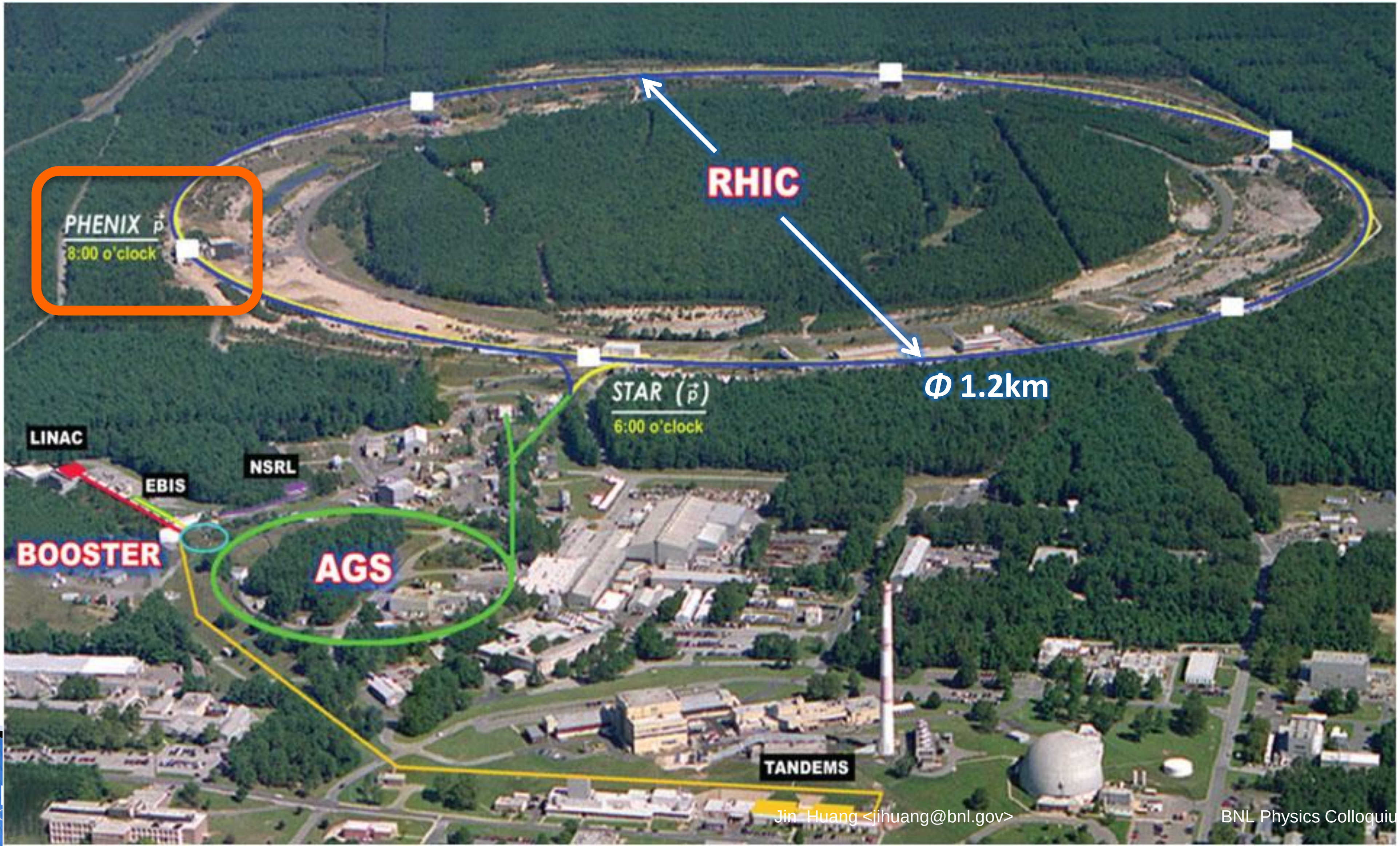
J. Wang, QM19

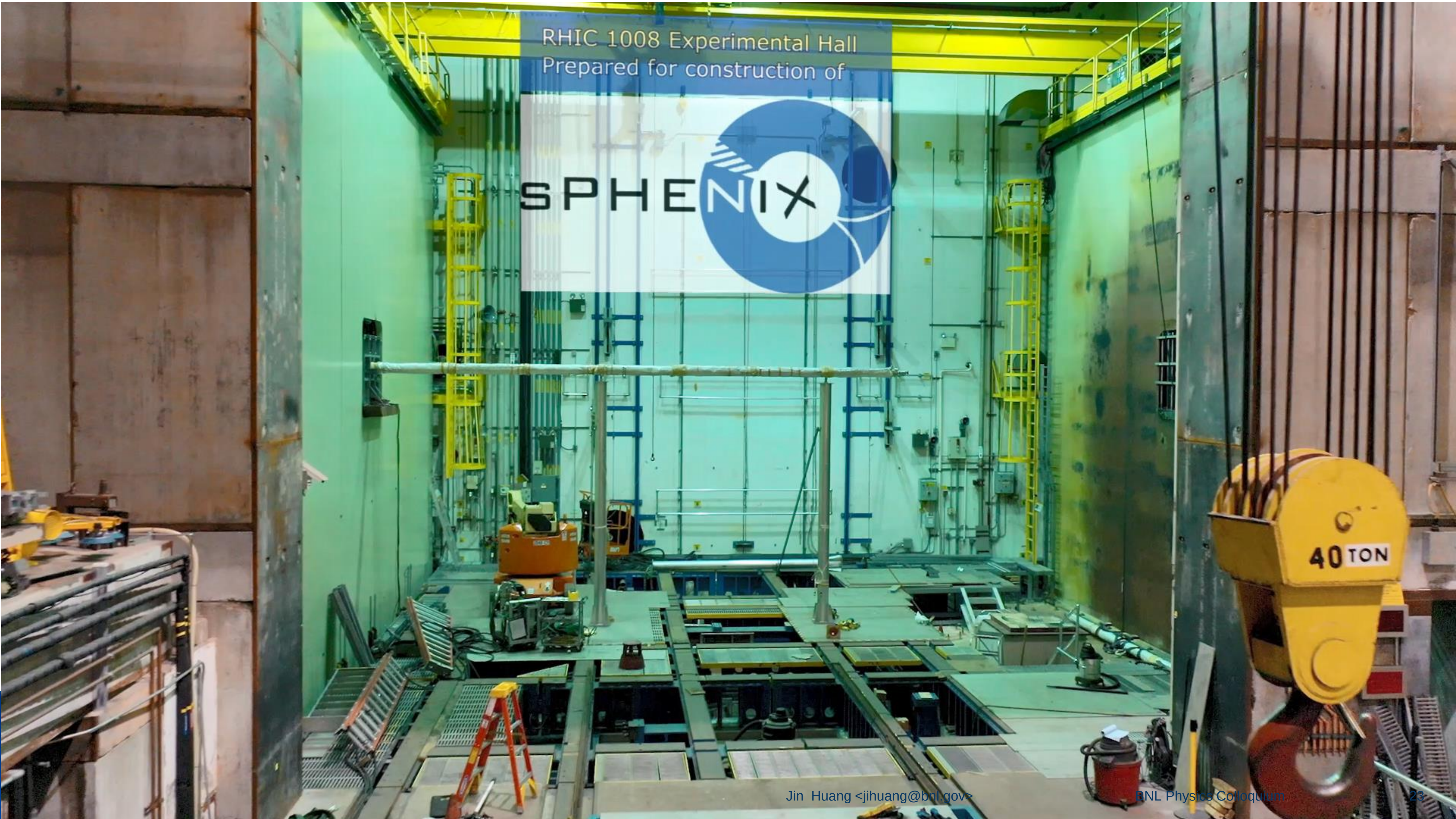


T. Todoroki, QM19

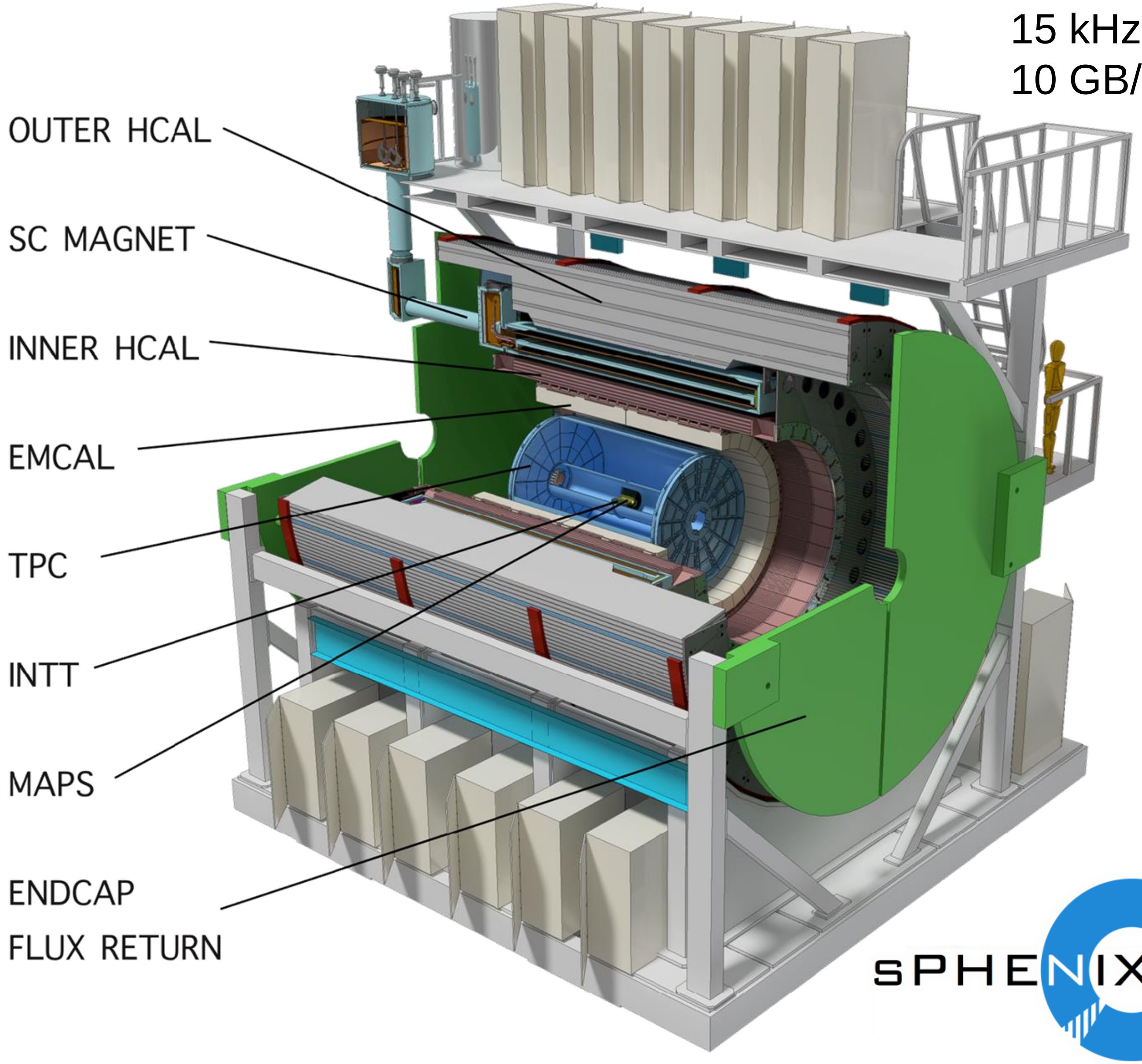


Relativistic Heavy Ion Collider (RHIC)
View from this room + 2000 ft




RHIC 1008 Experimental Hall
Prepared for construction of
SPHENIX
40 TON

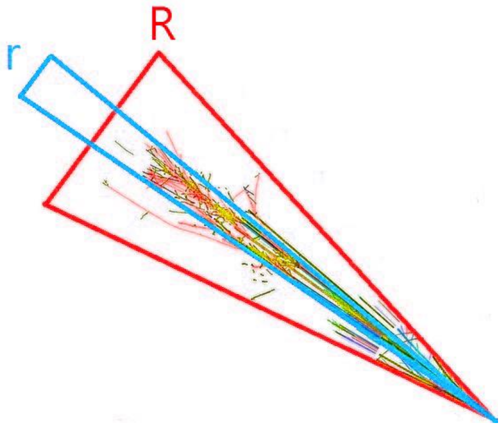
15 kHz MB trigger
10 GB/s data logging



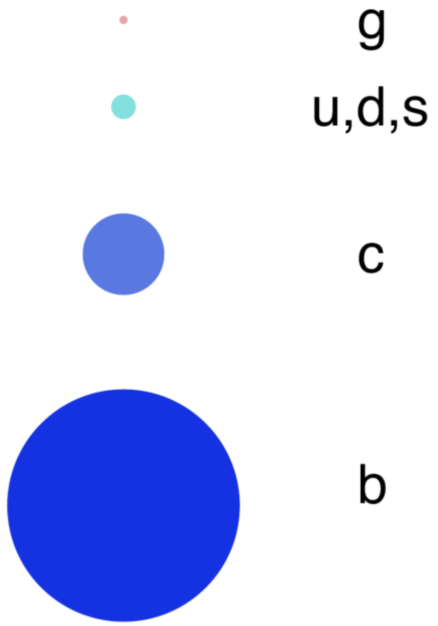
sPHENIX Detector

Core physics programs

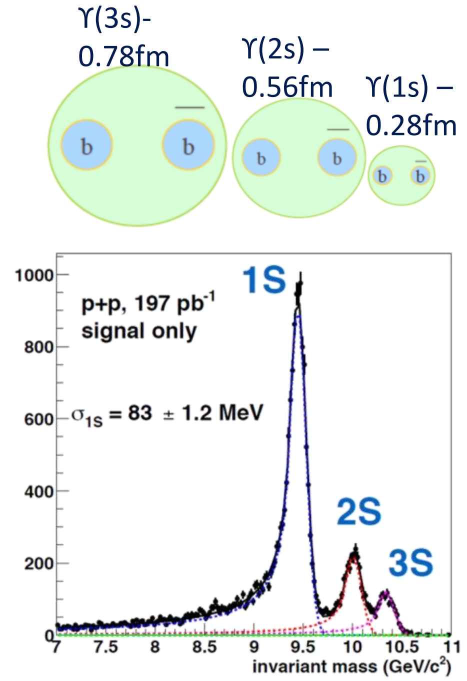
Jet cor. & substructure
Vary momentum/angular size of probe



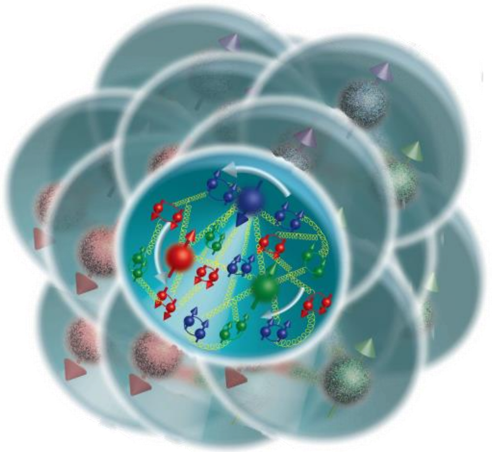
Parton energy loss
Vary mass/momentum of probe



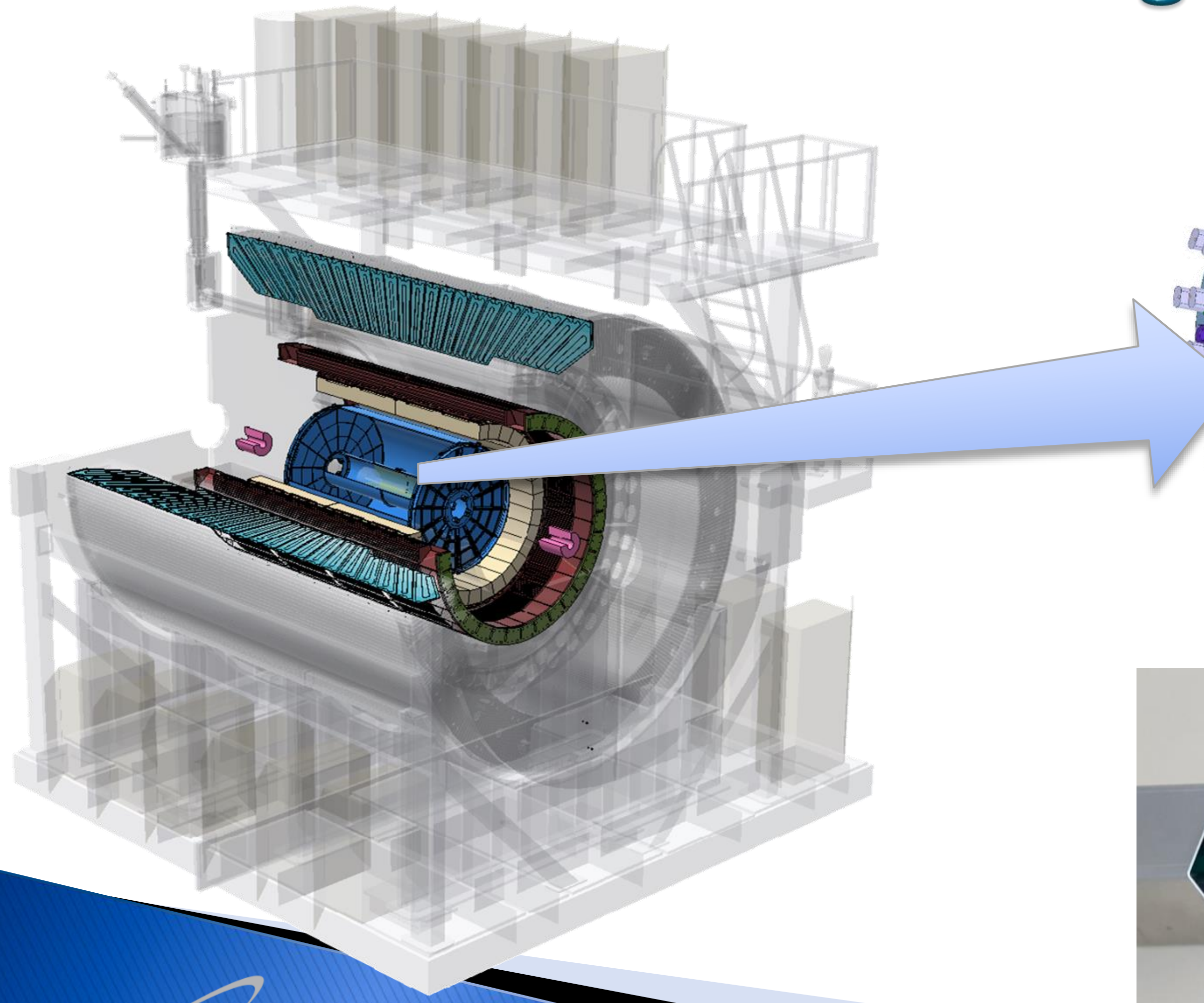
Upsilon spectroscopy
Vary size of the probe

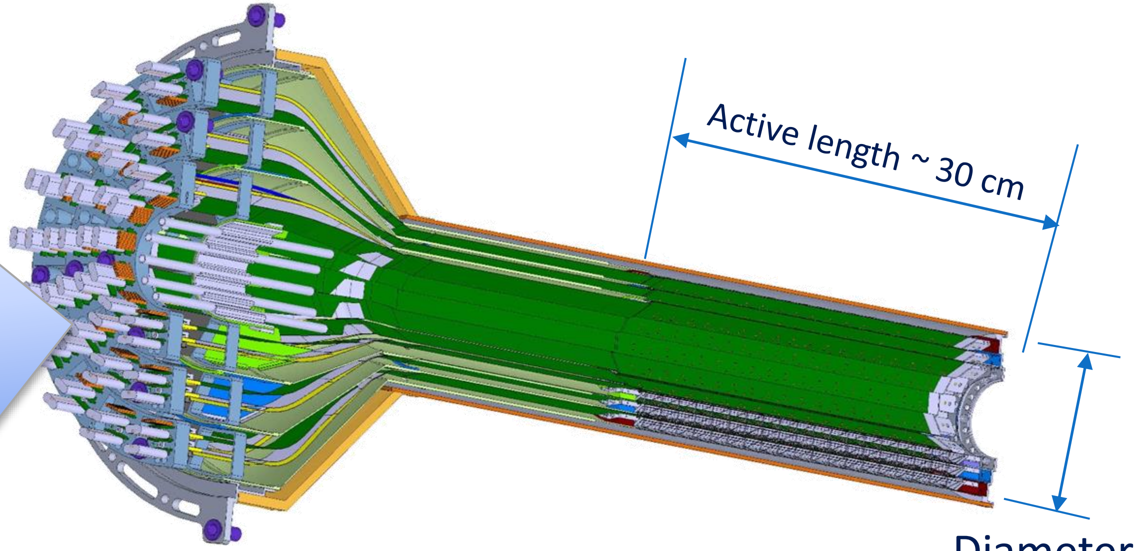


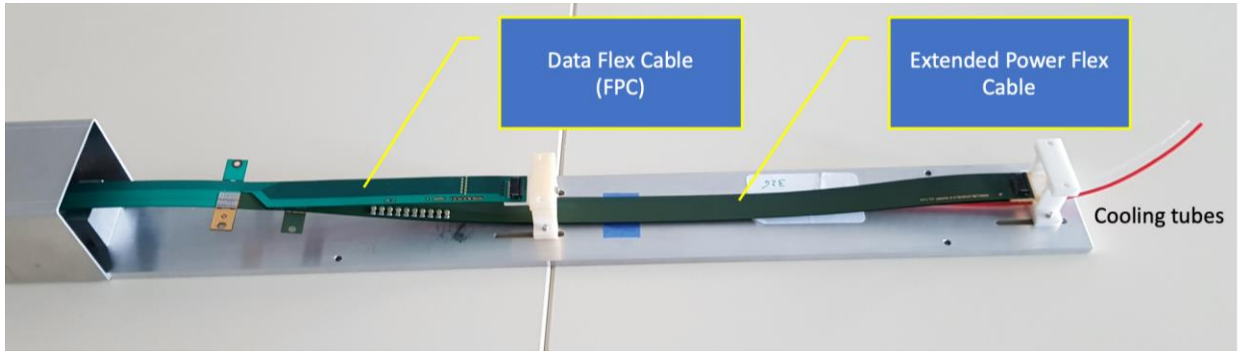
Cold QCD
Vary temperature of QCD matter



Hunting heavy flavor:
High precision vertex tracker

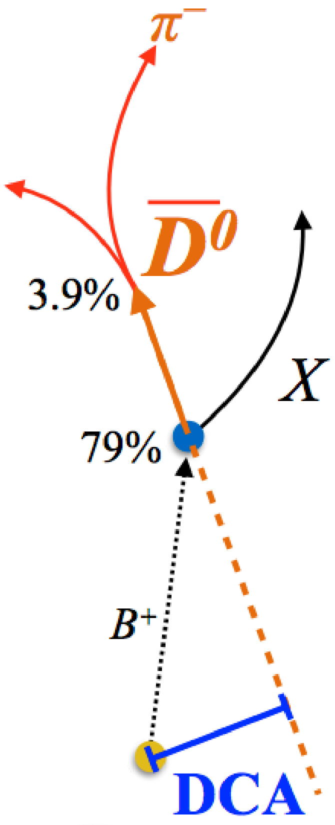






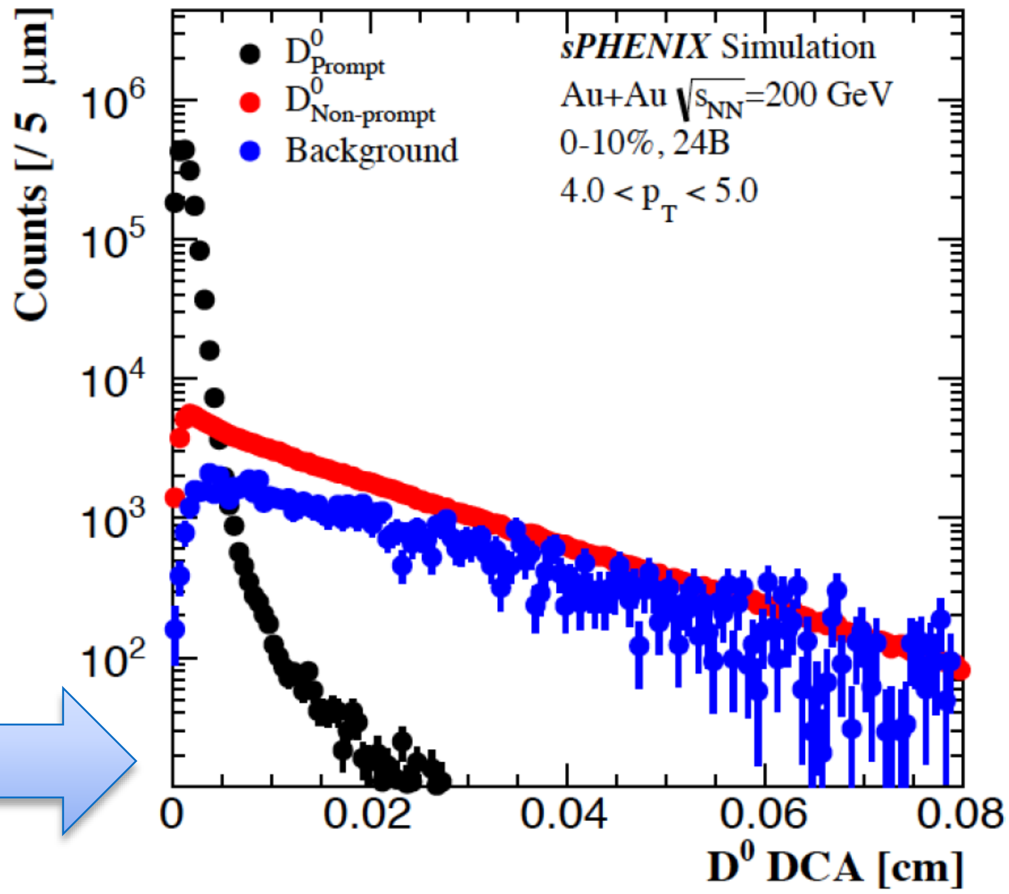
Cleanly separate open bottom meson via DCA

$$B \rightarrow \overline{D}^0 + X$$

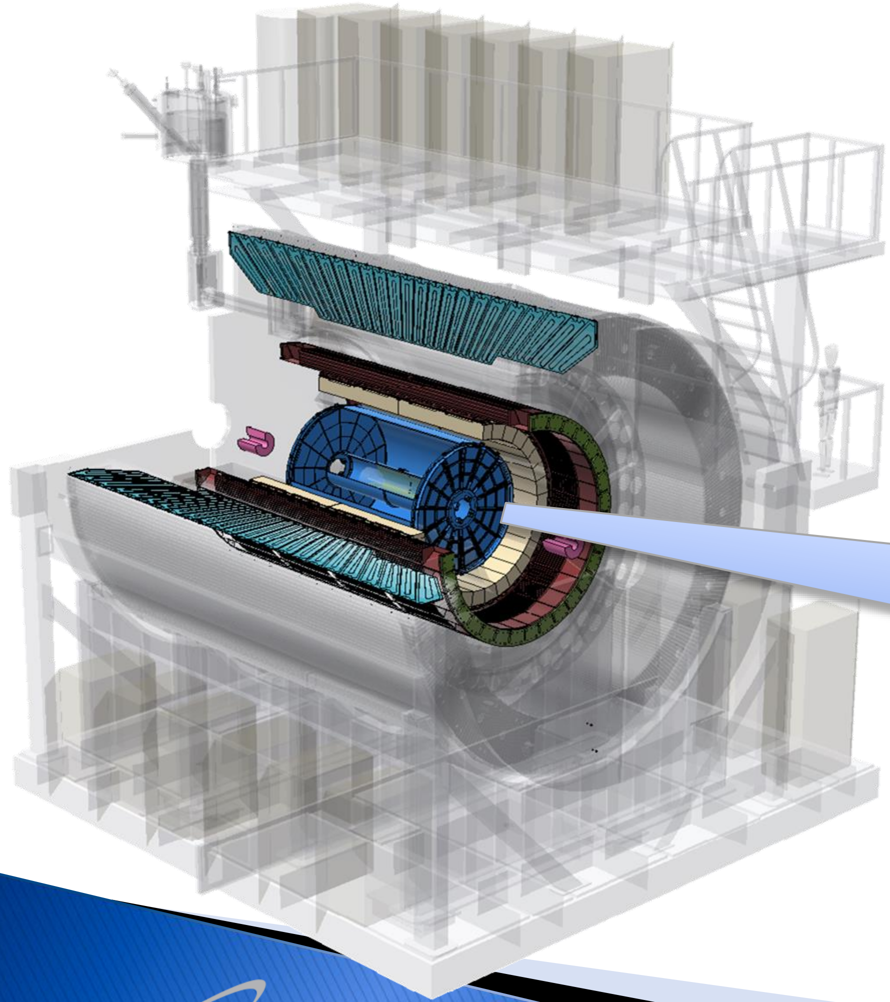


(Distance of closest approach)

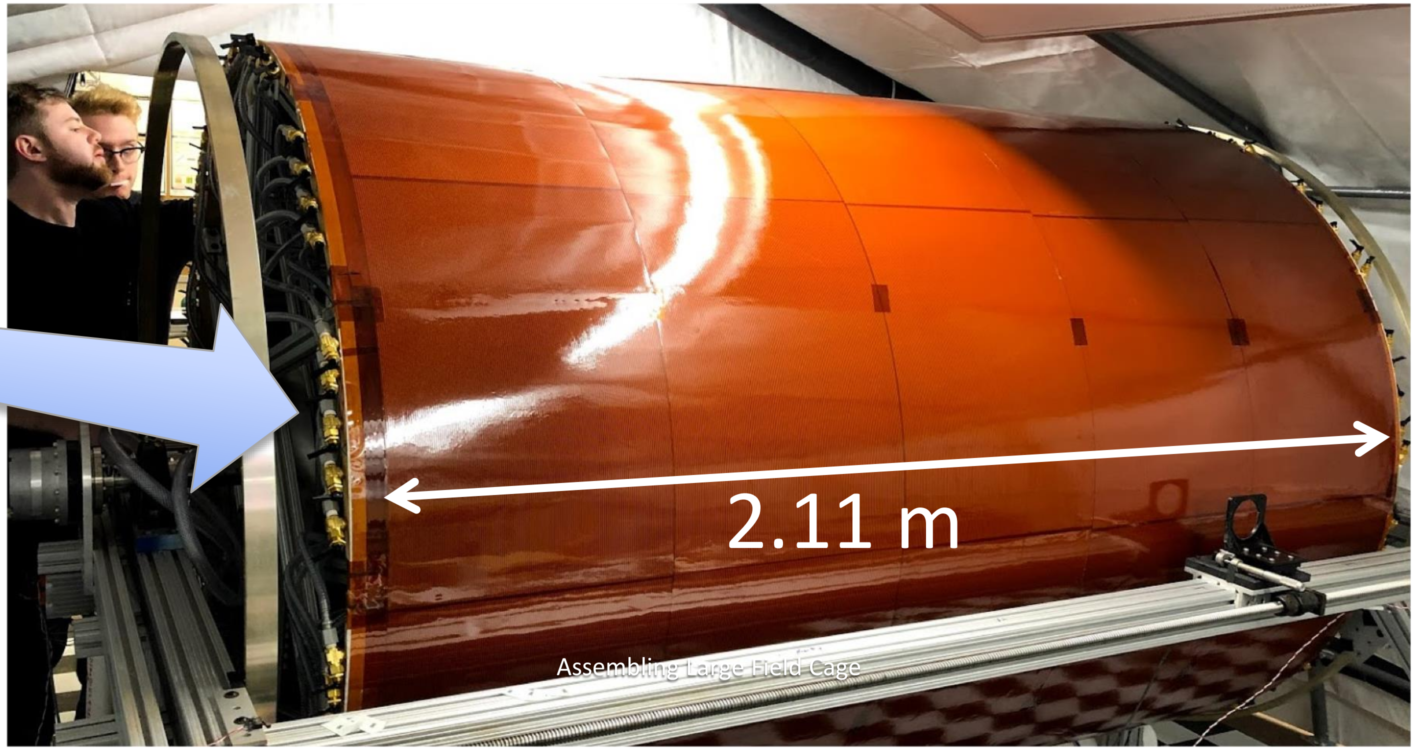
Prompt and non-prompt D-meson



Hunting heavy flavor: High rate capability



Compact next generation TPC with streaming readout

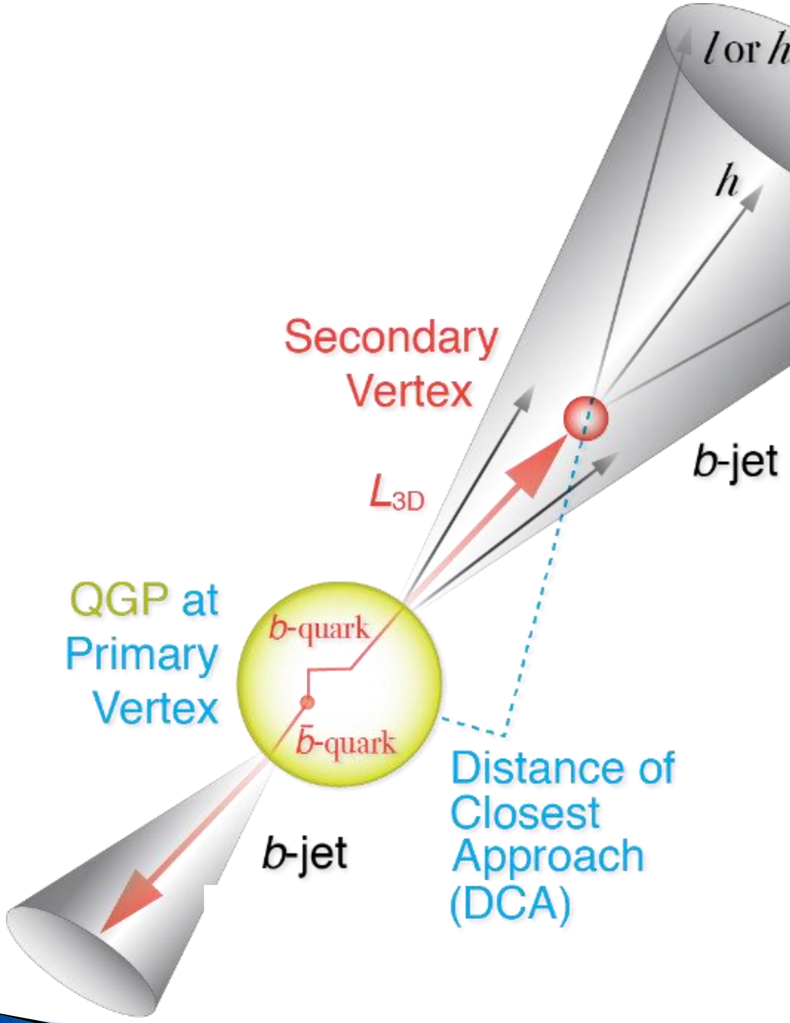


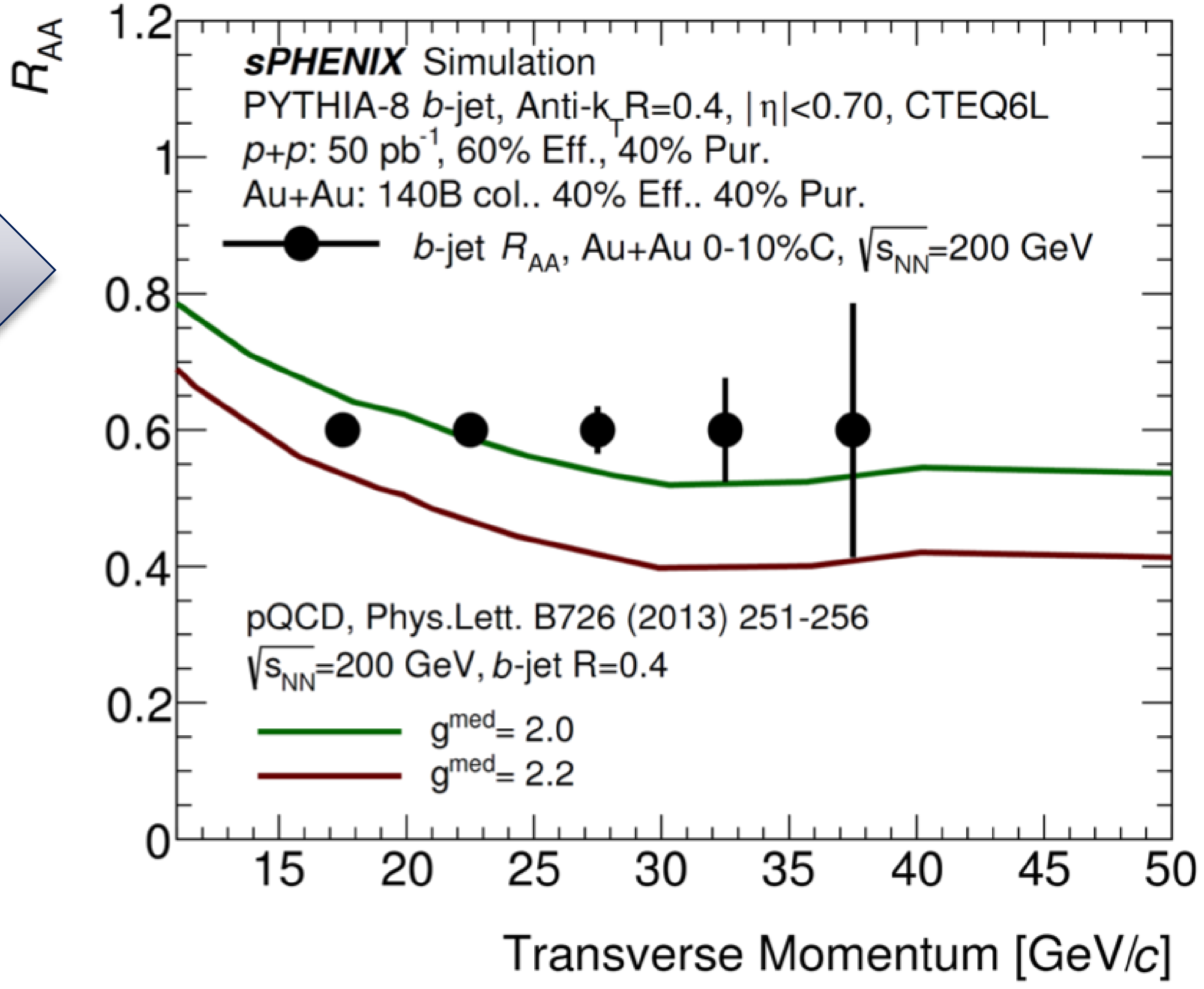
Broadening kinematic coverage with calorimetry

sPHENIX EMCal sector 0

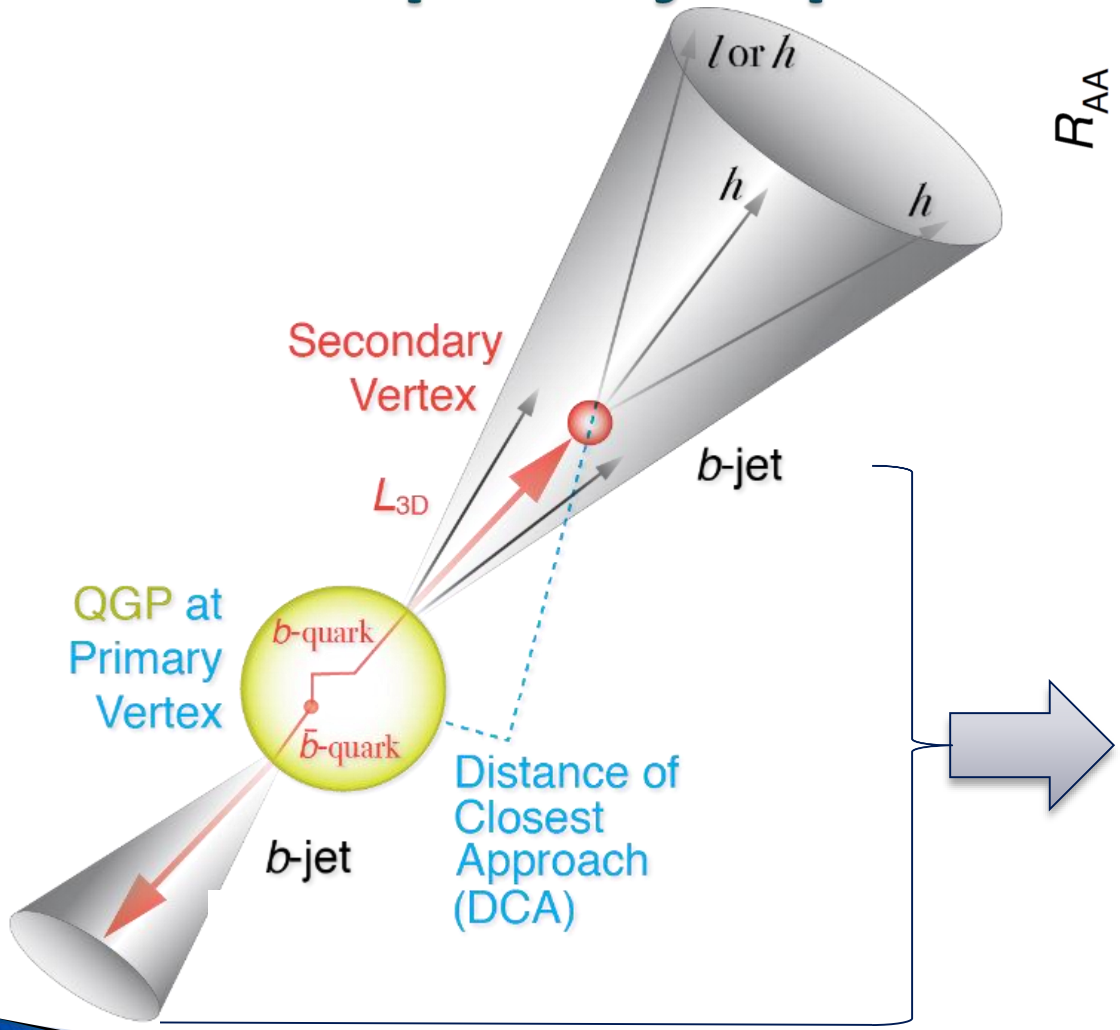
sPHENIX outer HCal sectors

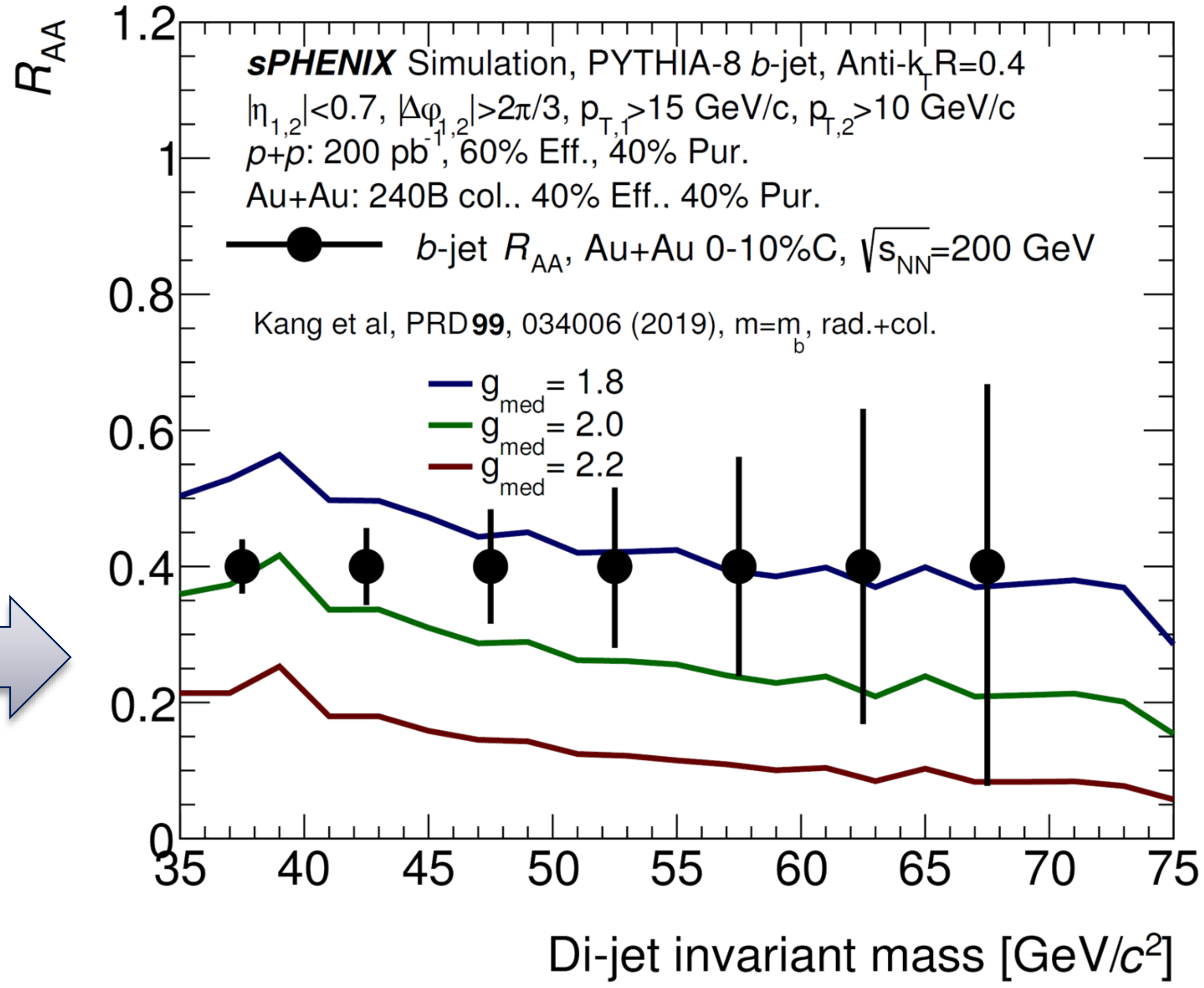
sPHENIX bottom quark jet





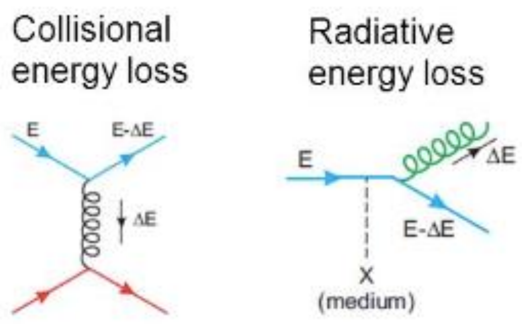
Bottom quark jet pairs → Enhanced sensitivity





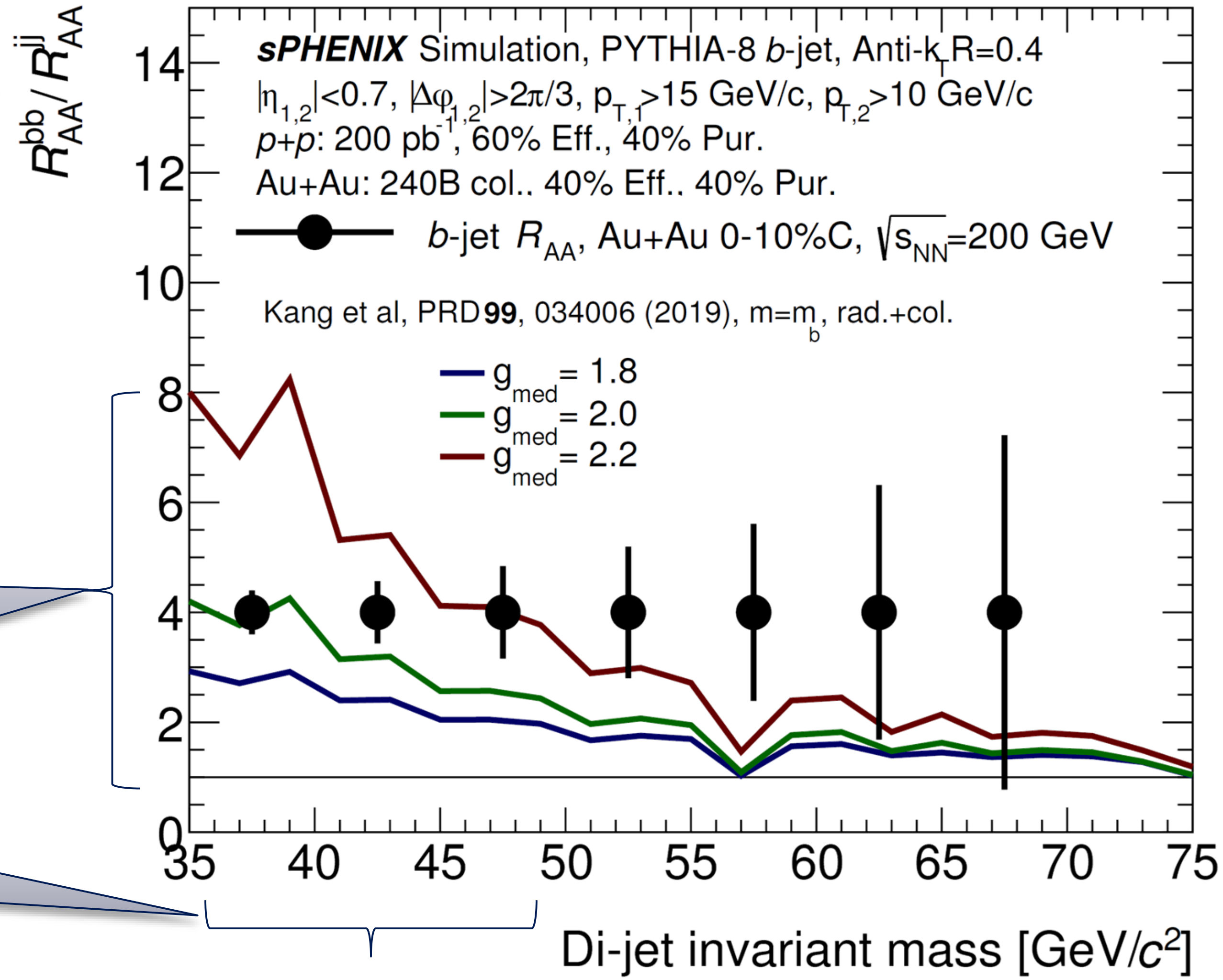
b-jet vs light jet → differentiating energy loss mech.

b/light ratio on RAA
Partial exp. systematic uncert. cancelation



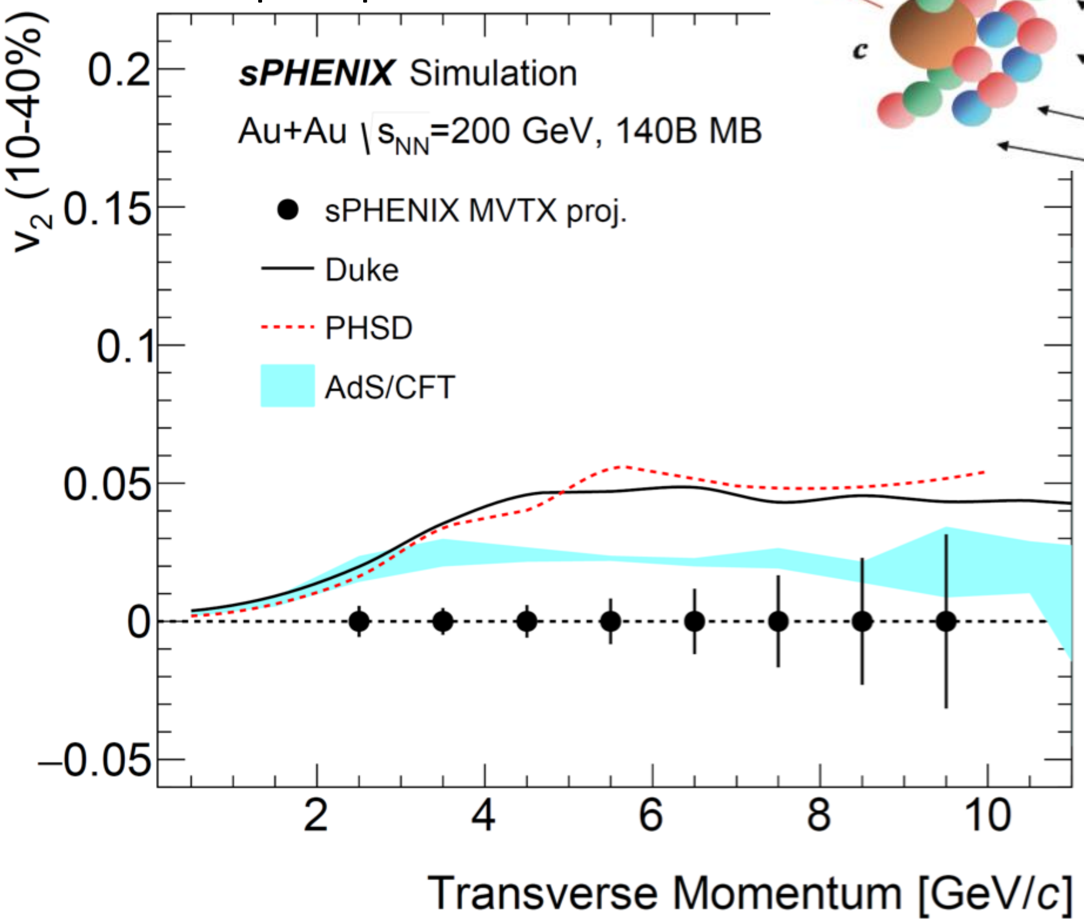
1-8 times mass effect!
x2 effect vs 10% variation on g_{med}!

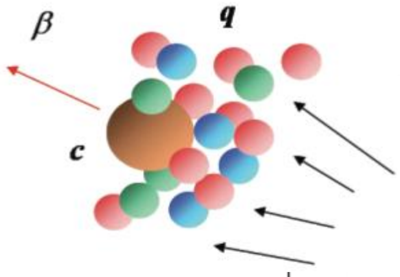
Unique region in the RHIC kine.
@ max sensitivity to mass eff.



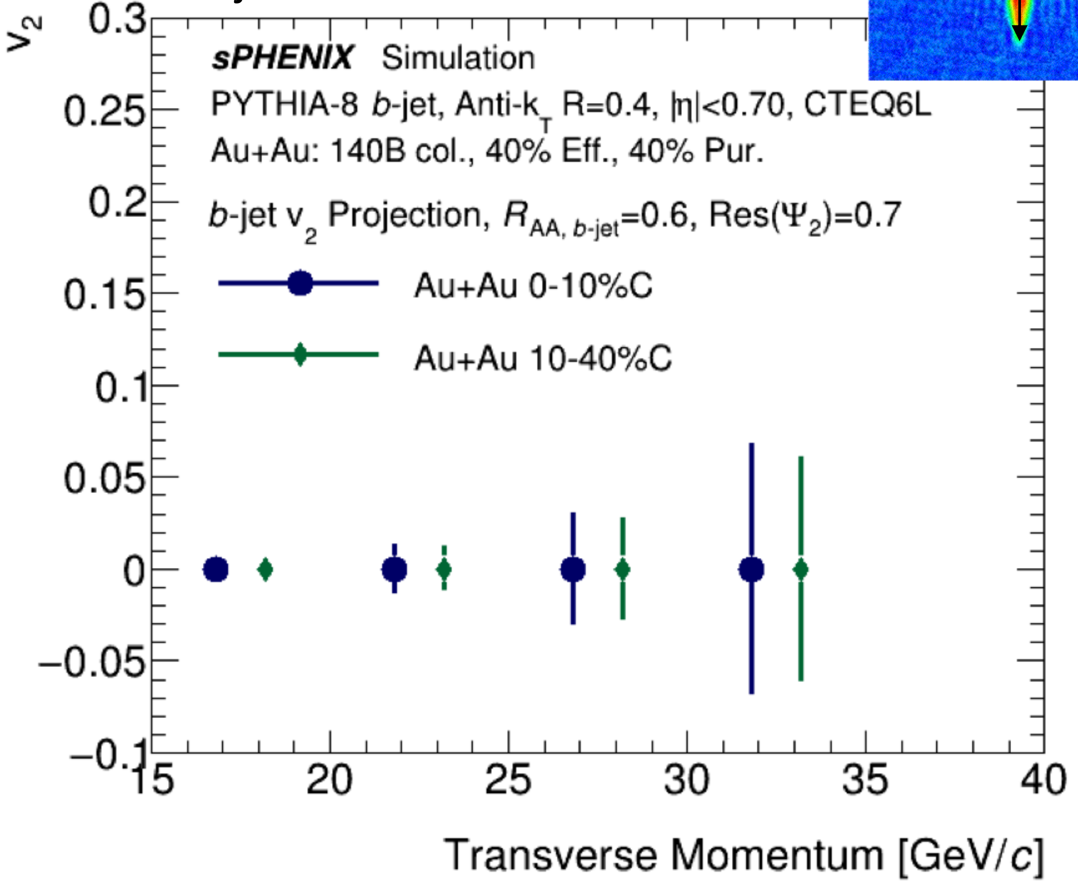
Flow signature
→ diffusion, pathlength dependence energy loss

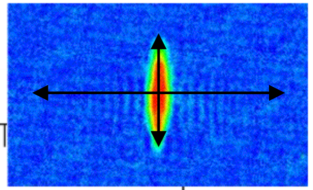
Non-prompt D^0 meson





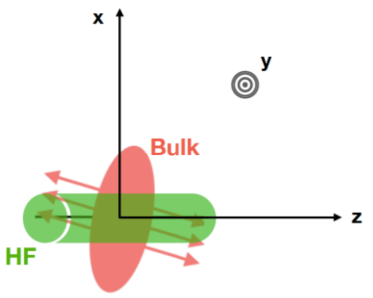
b-jet



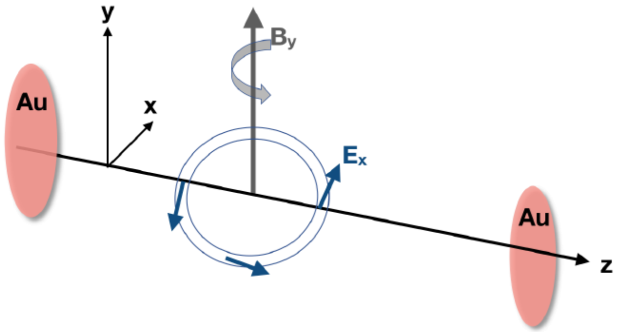


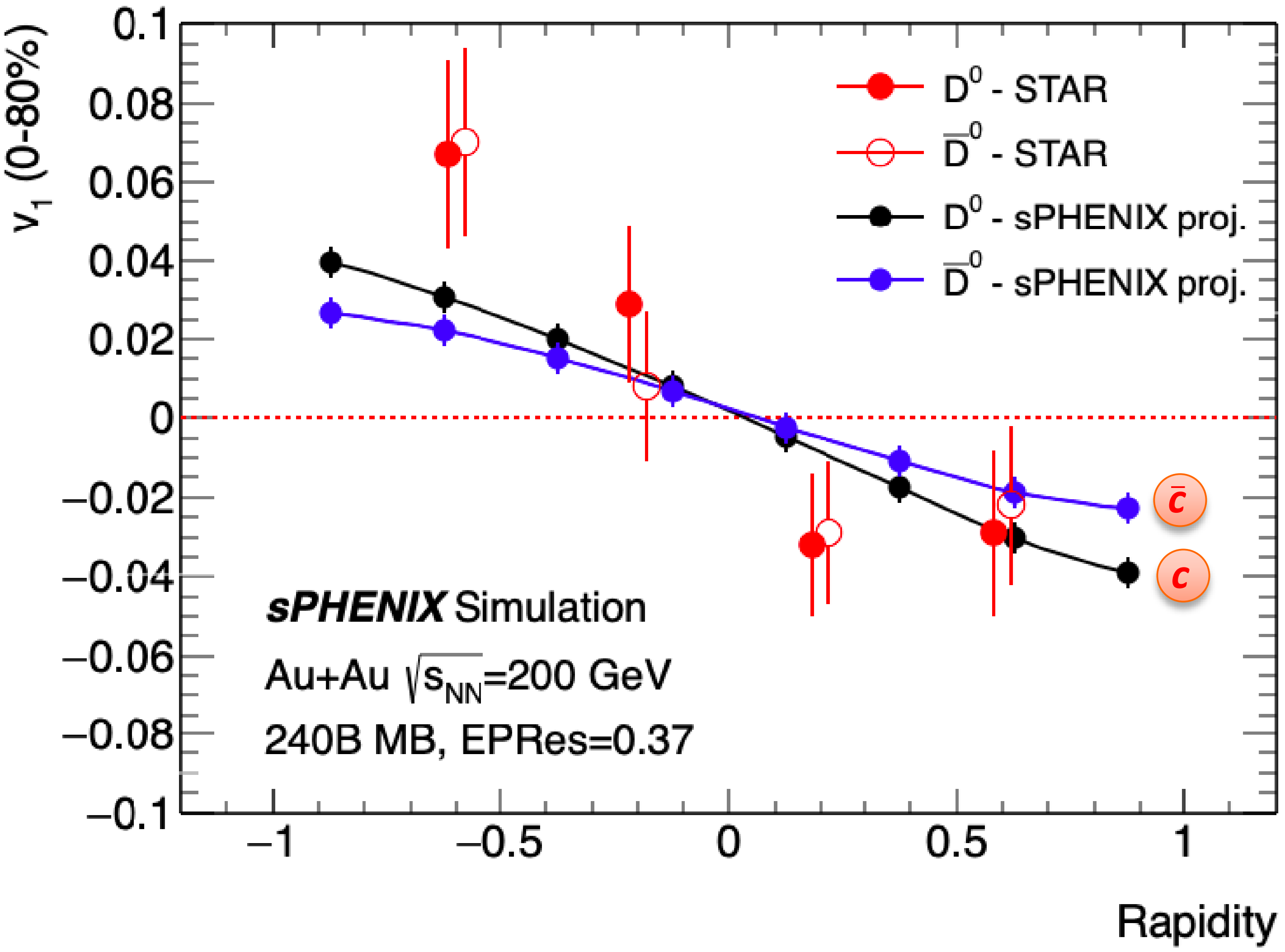
Charm v_1 (via prompt D_0)→ initial geom. & *B*-field

- v_1: Geometry tilt of QGP source

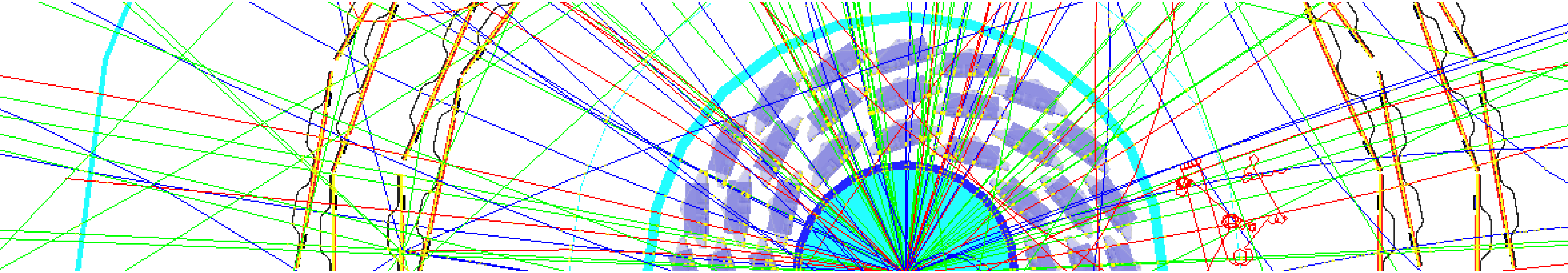


- Δv_1: Initial magnetic field



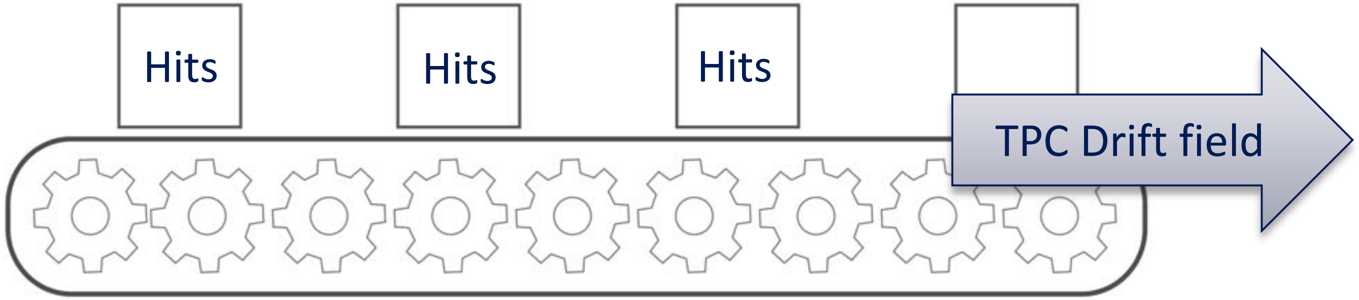


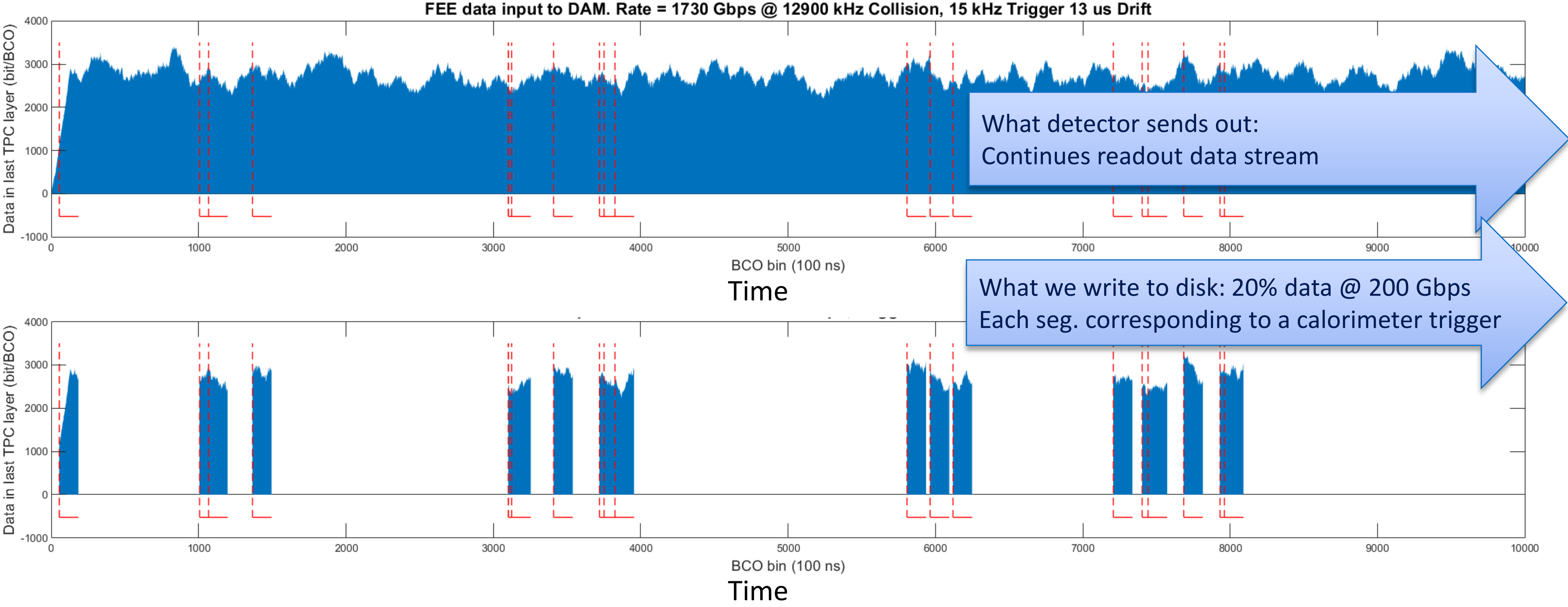
Challenge in $p + p$ collisions for heavy flavor hadrons



- They are rare processes (1 in 10k collisions w/ a D^0 hadron detectable)
- In a traditional triggered experiment:
  Difficult to trigger for hadronic decay of low p_T heavy flavor hadron
  - Nonetheless, if one would like to try:
    sPHENIX ML open data https://github.com/sPHENIX-Collaboration/HFMLTrigger

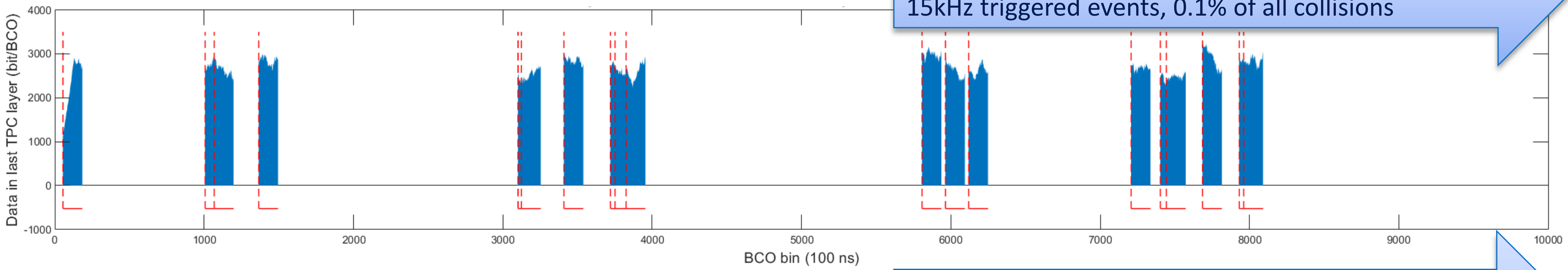
TPC data stream in sPHENIX triggered DAQ





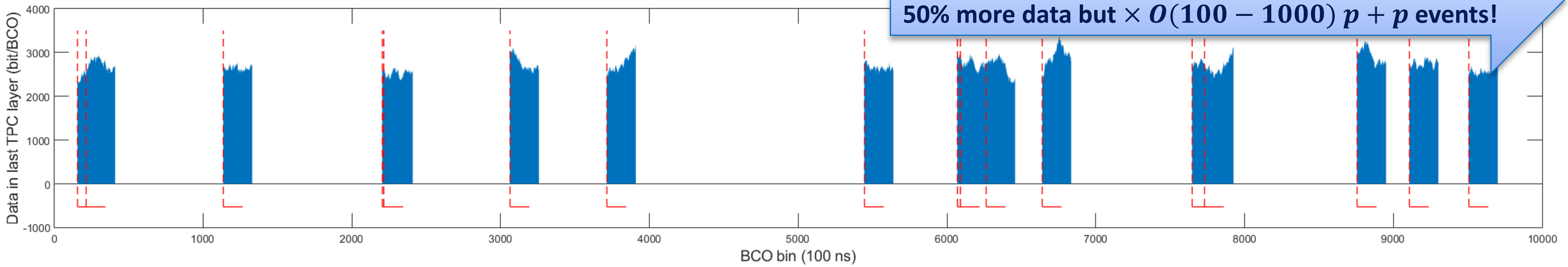
Extending streaming time window, a partial triggerless DAQ
→ × $O(100)$ gain in statistics!

What we write to disk, 200 Gbps
15kHz triggered events, 0.1% of all collisions



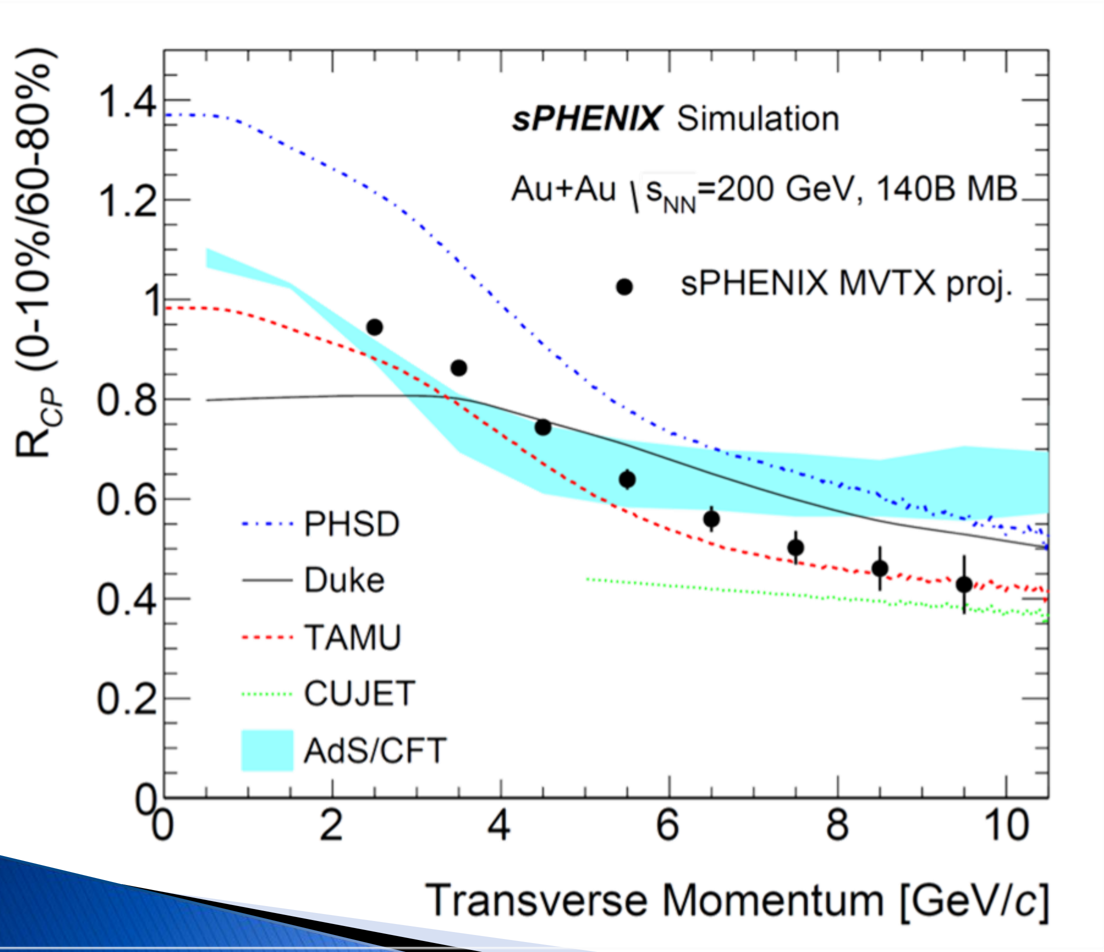
Time

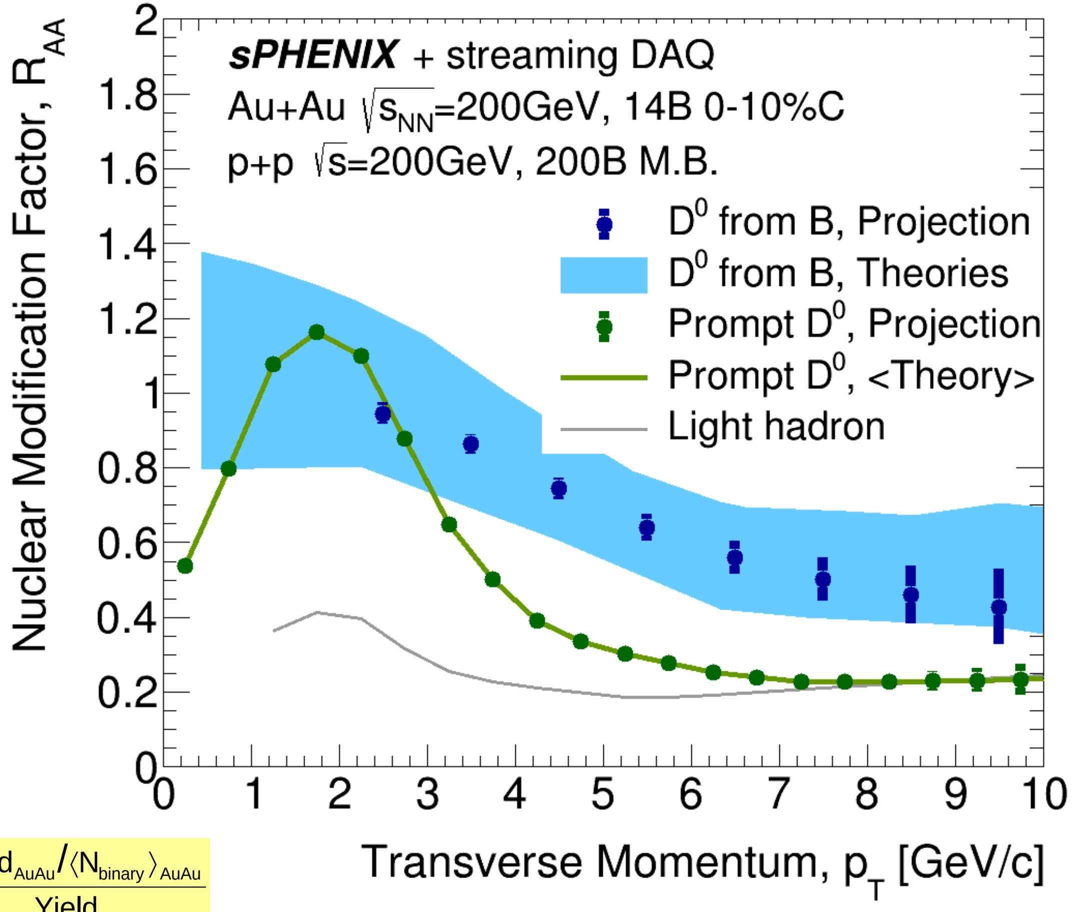
+ Streaming 10% of all collisions, 300Gbps
50% more data but × $O(100-1000)$ $p+p$ events!



Time

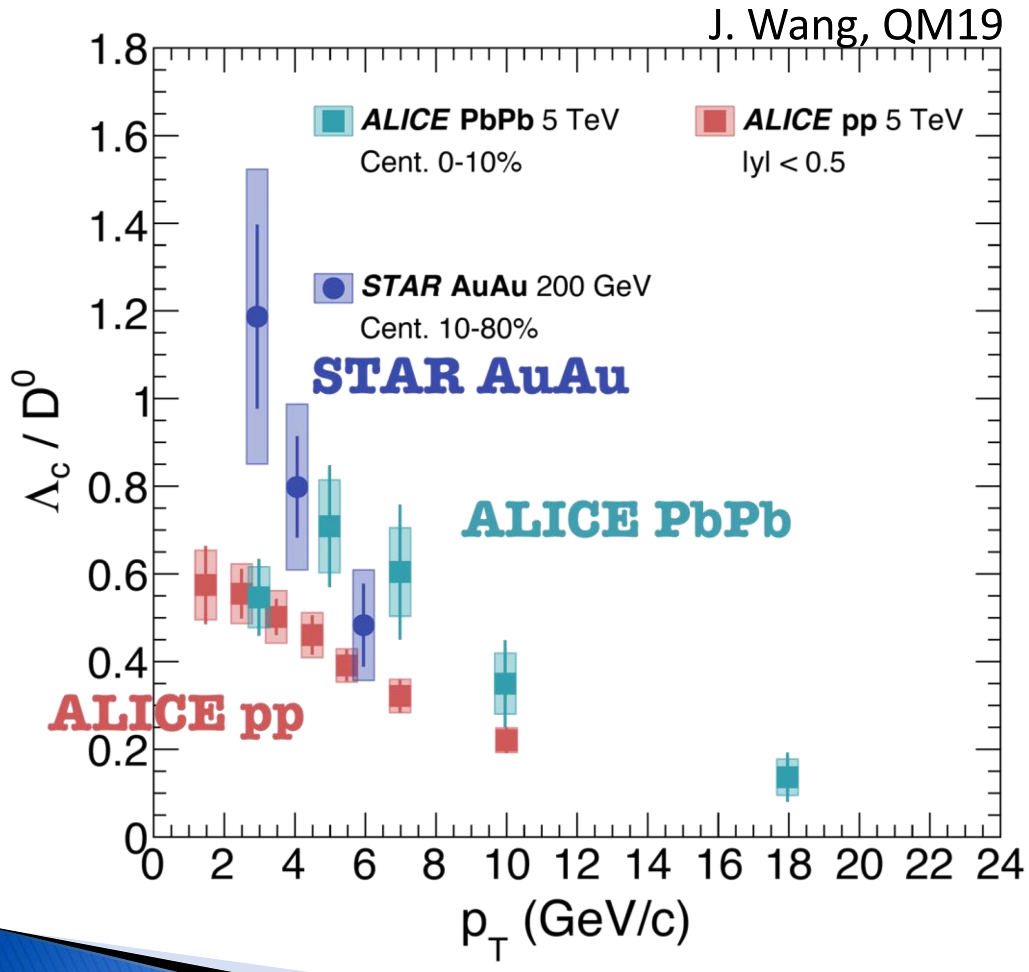
Physics gain of sPHENIX streaming DAQ: Recovering heavy flavor meson baseline

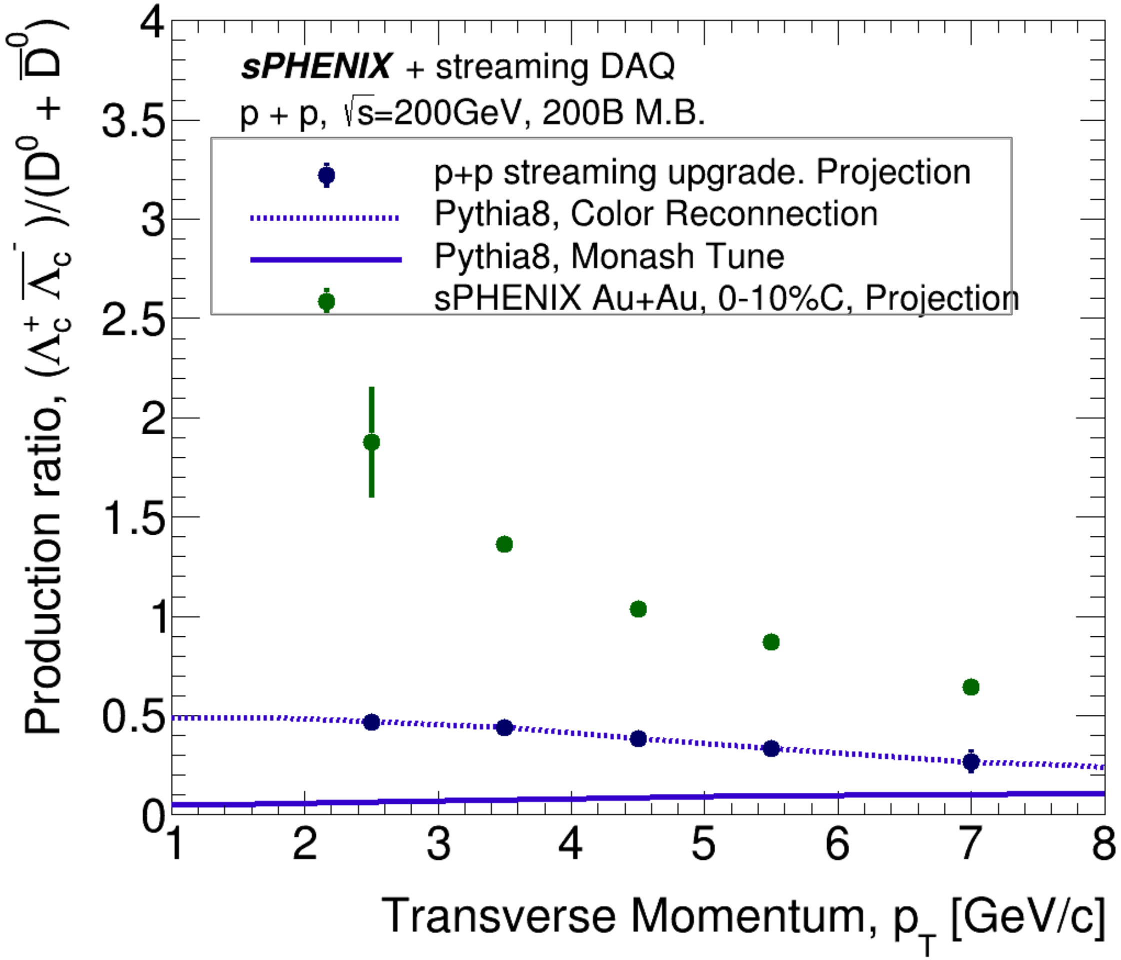




$$R_{AA} = \frac{Yield_{AuAu} / \langle N_{binary} \rangle_{AuAu}}{Yield_{pp}}$$

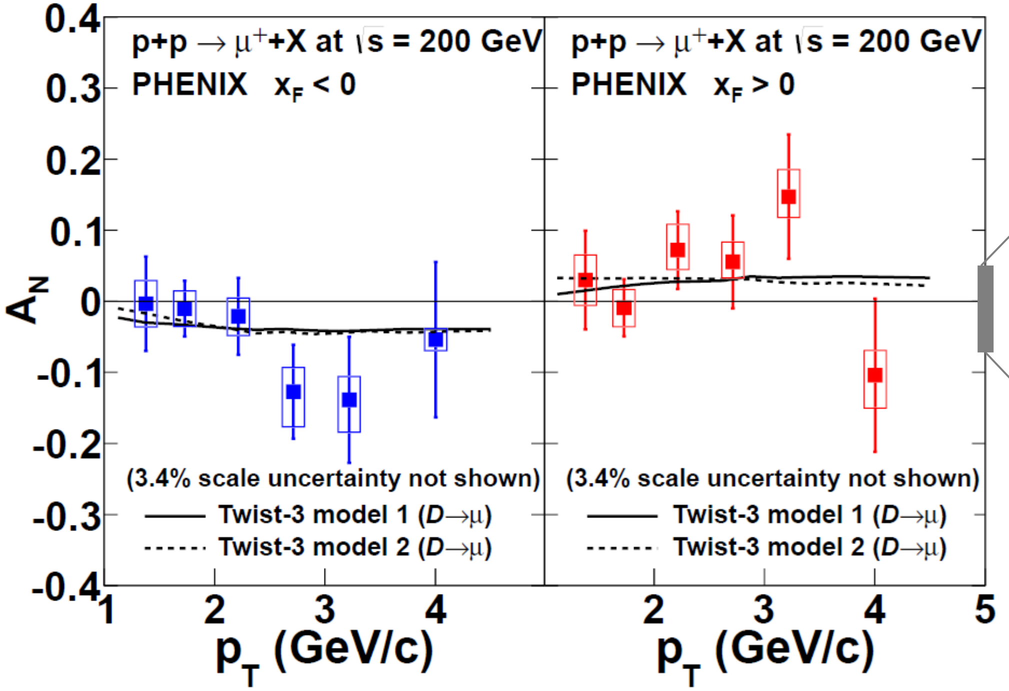
Physics gain of sPHENIX streaming DAQ: Baseline for Λ_c and charm hadronization



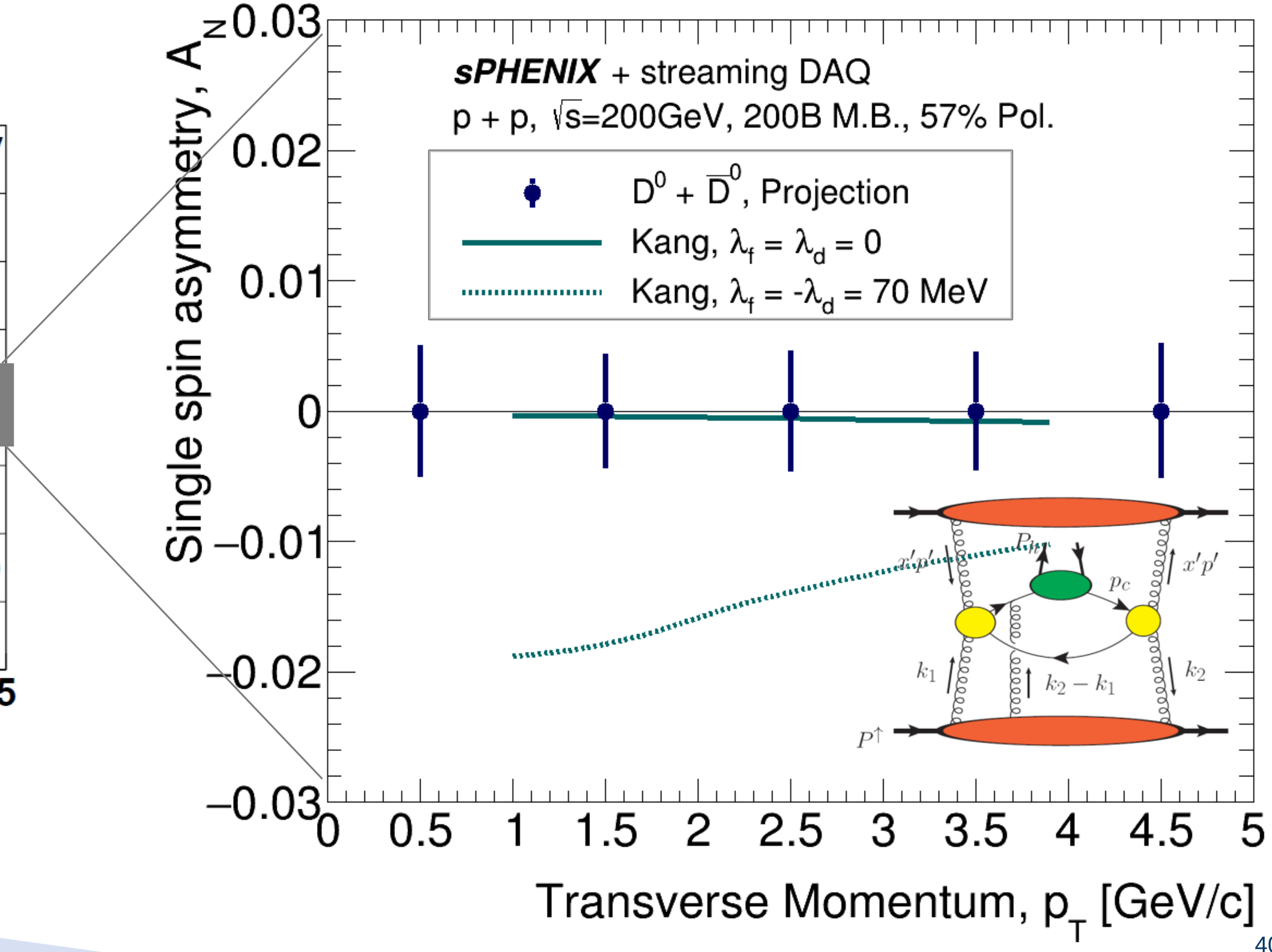


Physics gain of sPHENIX streaming DAQ: Gluon dynamic via heavy flavor asymmetry, A_N

- 200Billion M.B. $\vec{p} + \vec{p}$ data record w/o trigger bias for future data mining
- e.g. D^0 A_N → Tri-gluon correlation

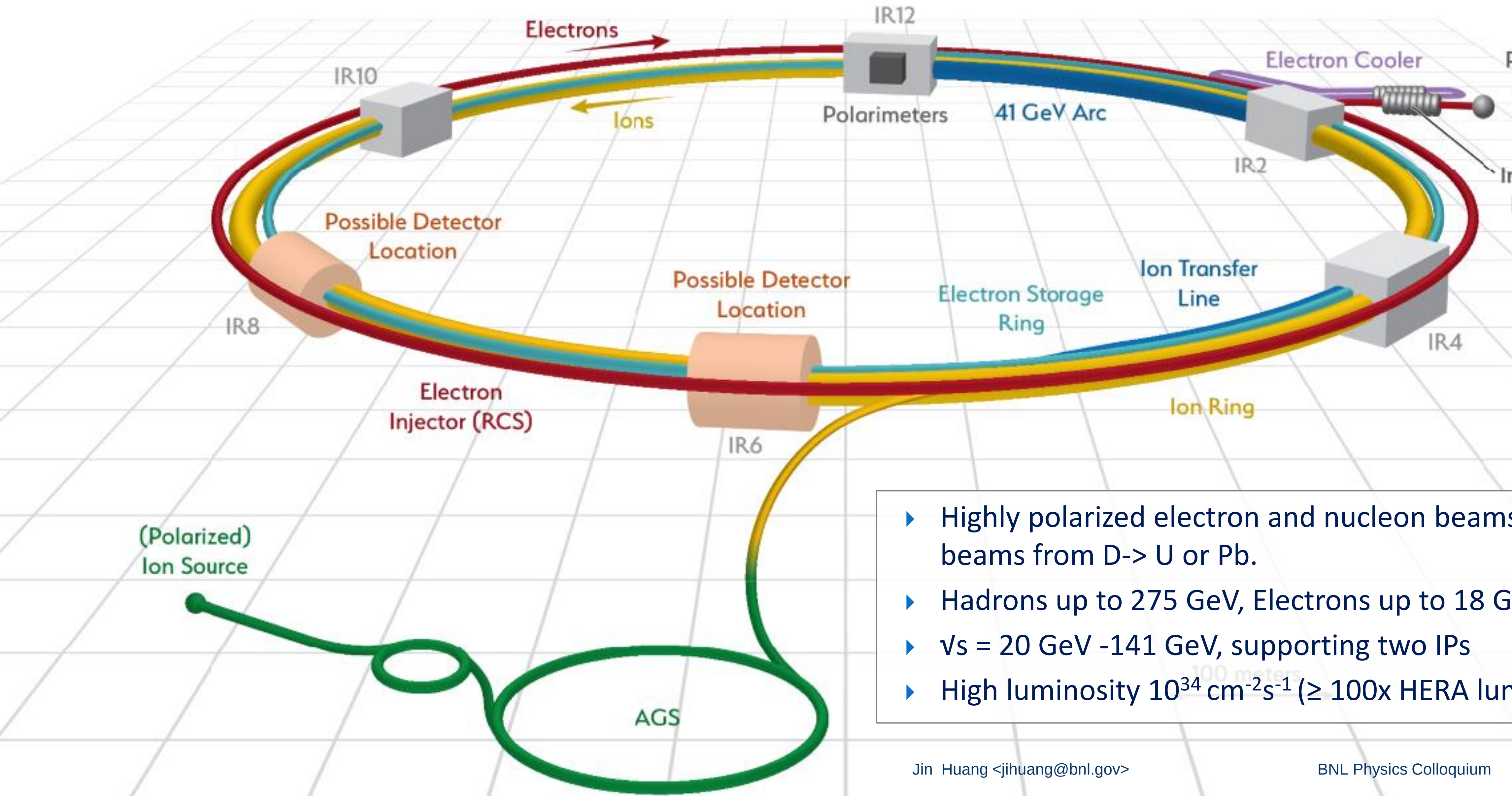


PHENIX, PhysRevD.95.112001



RHIC transition to the EIC

eRHIC pre-CDR, EIC design study
https://wiki.bnl.gov/eic/upload/EIC.Design.Study.pdf

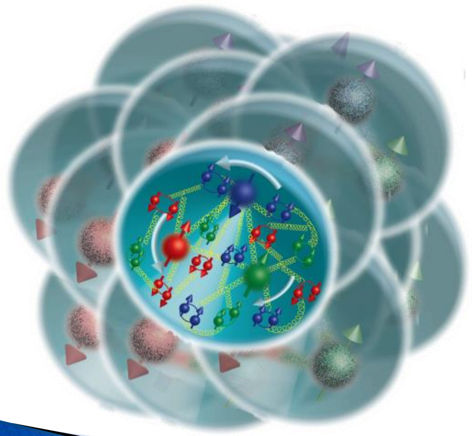


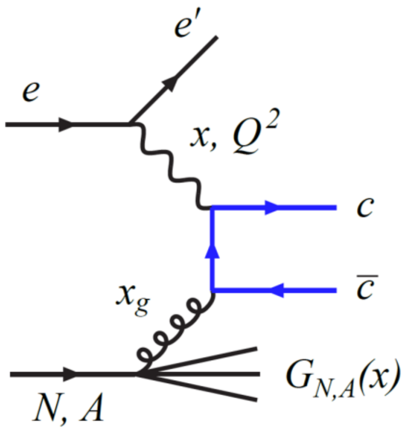
- Highly polarized electron and nucleon beams, Ion beams from D-> U or Pb.
- Hadrons up to 275 GeV, Electrons up to 18 GeV .
- $\sqrt{s}$ = 20 GeV -141 GeV, supporting two IPs
- High luminosity 10^{34} $cm^{-2}s^{-1}$ (≥ 100x HERA luminosity)

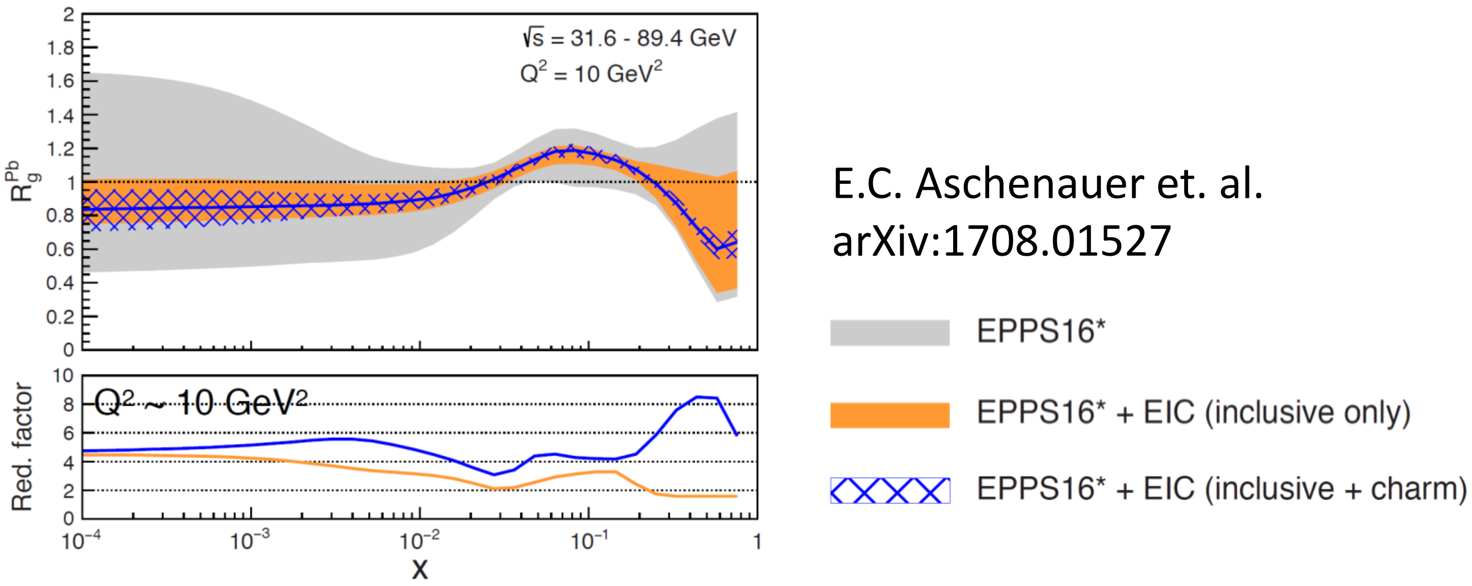
EIC physics at a glance

[EIC white paper, EIC assessment by NAS]

- How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon? How does the mass of the nucleon arise?
- How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei?
- Many EIC physics process are trigger-able with traditional DAQ, e.g. HF in $e + A$







E.C. Aschenauer et. al. arXiv:1708.01527

Physics Opportunities w/ streaming DAQ @ EIC

- Full statistics
- Systematics control w/o hardware trigger bias
- Diverse events topologies @ EIC for future analysis
  - For example, flow signature search in $e + p/A$ over broad Q^2

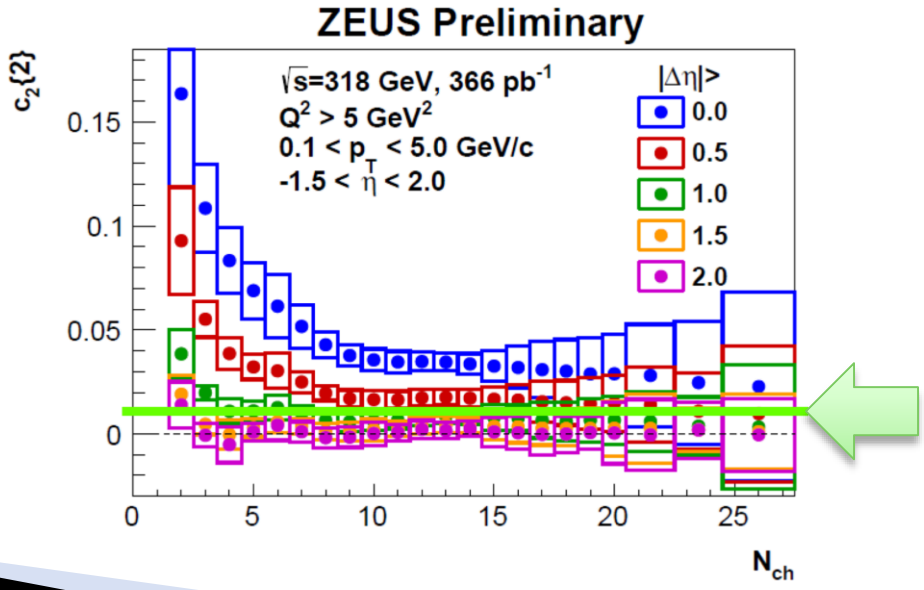


Figure & quoting from Baty/ZEUS IS2019

- $c_2\{2\} < 0.01$ at $N_{ch} = 15$
- implies $v_2 < 0.1$
- Room for small v2 signal
- Need more statistics

EIC: unique collider
→ unique real-time system challenges

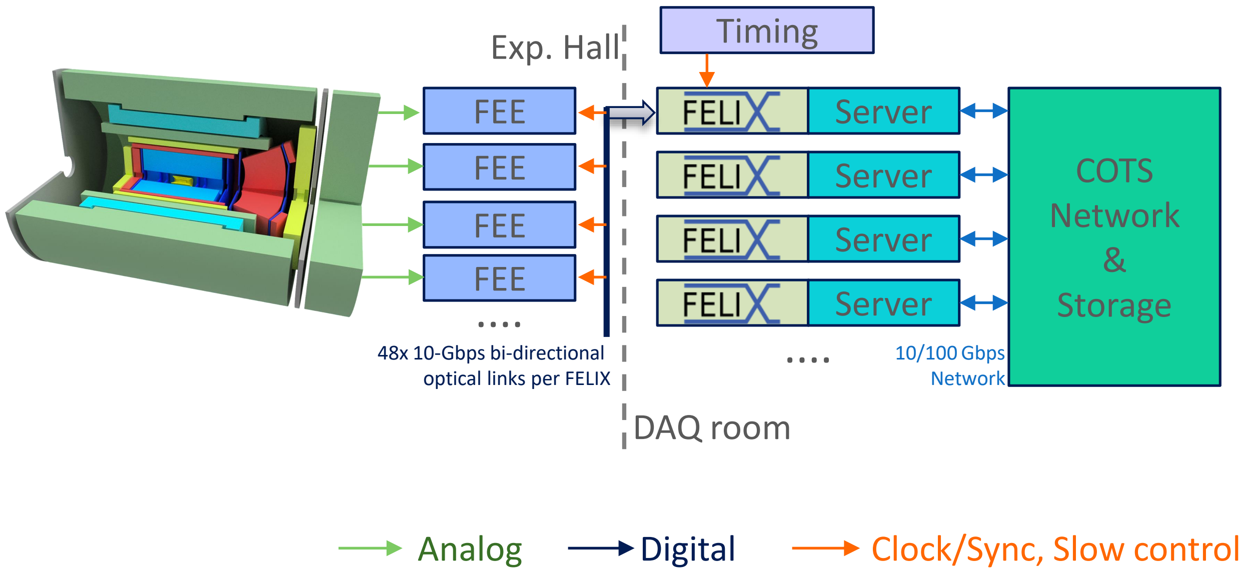
	EIC	RHIC	LHC → HL-LHC
Collision species	$\vec{e}+\vec{p}, \vec{e}+A$	$\vec{p}+\vec{p}/A, A+A$	$p+p/A, A+A$
Top x-N C.M. energy	140 GeV	510 GeV	13 TeV
Bunch spacing	10 ns	100 ns	25 ns
Peak x-N luminosity	10^{34} cm^{-2} s^{-1}	10^{32} cm^{-2} s^{-1}	$10^{34} \to 10^{35}$ cm^{-2} s^{-1}
x-N cross section	**50 μb**	**40 mb**	**80 mb**
Top collision rate	500 kHz	10 MHz	1-6 GHz
$dN_{ch}/d\eta$ in p+p/e+p	0.1-Few	~3	~6
Charged particle rate	**4M N_{ch}/s**	**60M N_{ch}/s**	**30G+ N_{ch}/s**

- EIC luminosity is high, but collision cross section is small ($\propto \alpha_{EM}^2$) → low collision rate
- But events are precious and have diverse topology → hard to trigger on all process
- Background and systematic control is crucial → avoiding a trigger bias

Strategy for an EIC real-time system

LDRD 19-028

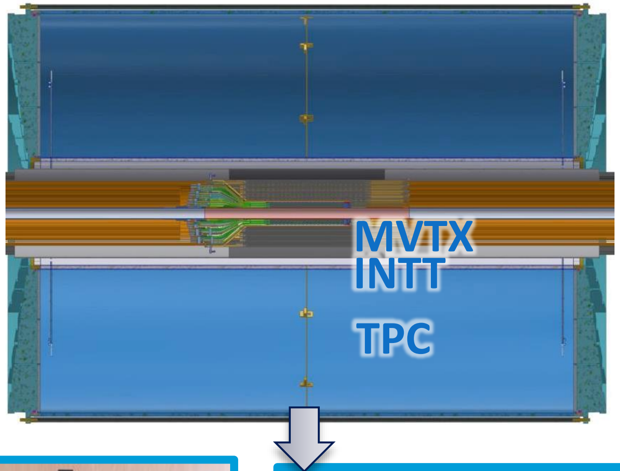
- For the signal data rate from EIC (100 Gbps), we can aim for filtering-out and streaming all collision in raw data without a hardware-based global triggering
- **New DAQ paradigm: streaming and triggerless DAQ**
  - Full streaming readout front-end (buffer length : μs)
  - → DAQ interface to commodity computing (e.g. ATLAS/sPHENIX FELIX)
  - → Disk/tape storage of streaming time-framed zero-suppressed raw data (buffer length : s)
  - → Collision event tagging in offline production (latency : days)

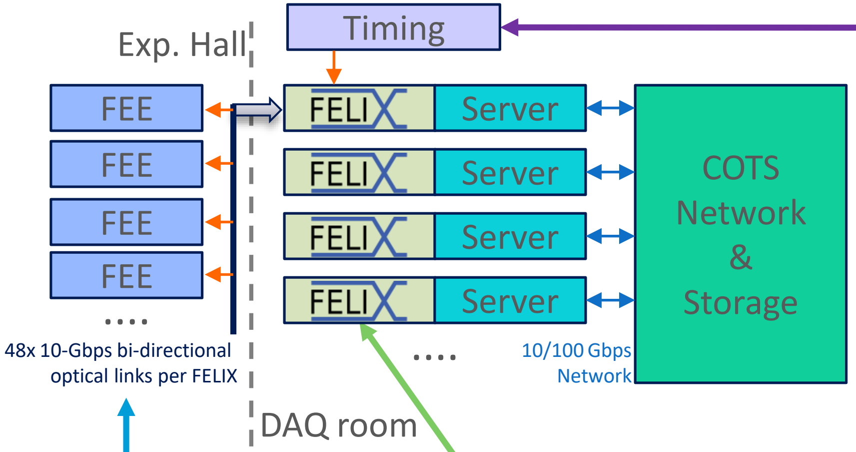


Streaming readout at BNL and towards EIC

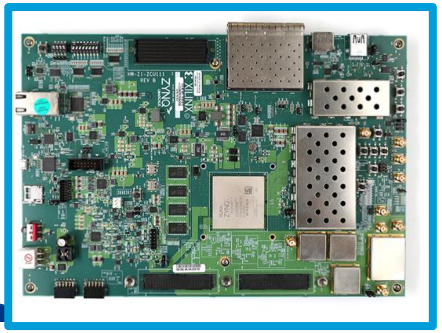
- Interdisciplinary BNL development: PHENIX, STAR, ATLAS, Instrumentation, CAD, NSLS II
- EIC application supported by LDRD 19-028
- Large scale application in sPHENIX and CBM, in eval for DUNE, PUMA, nEXO

Precision timing digitizer
DRS4GlO (SBIR/LDRD)

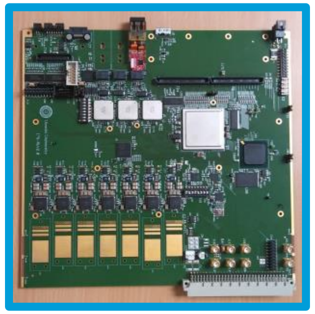




Global Timing Module (NSLS II/sPHENIX)



Generic stream digitizer
RFSoC ZCU111 (LDRD)



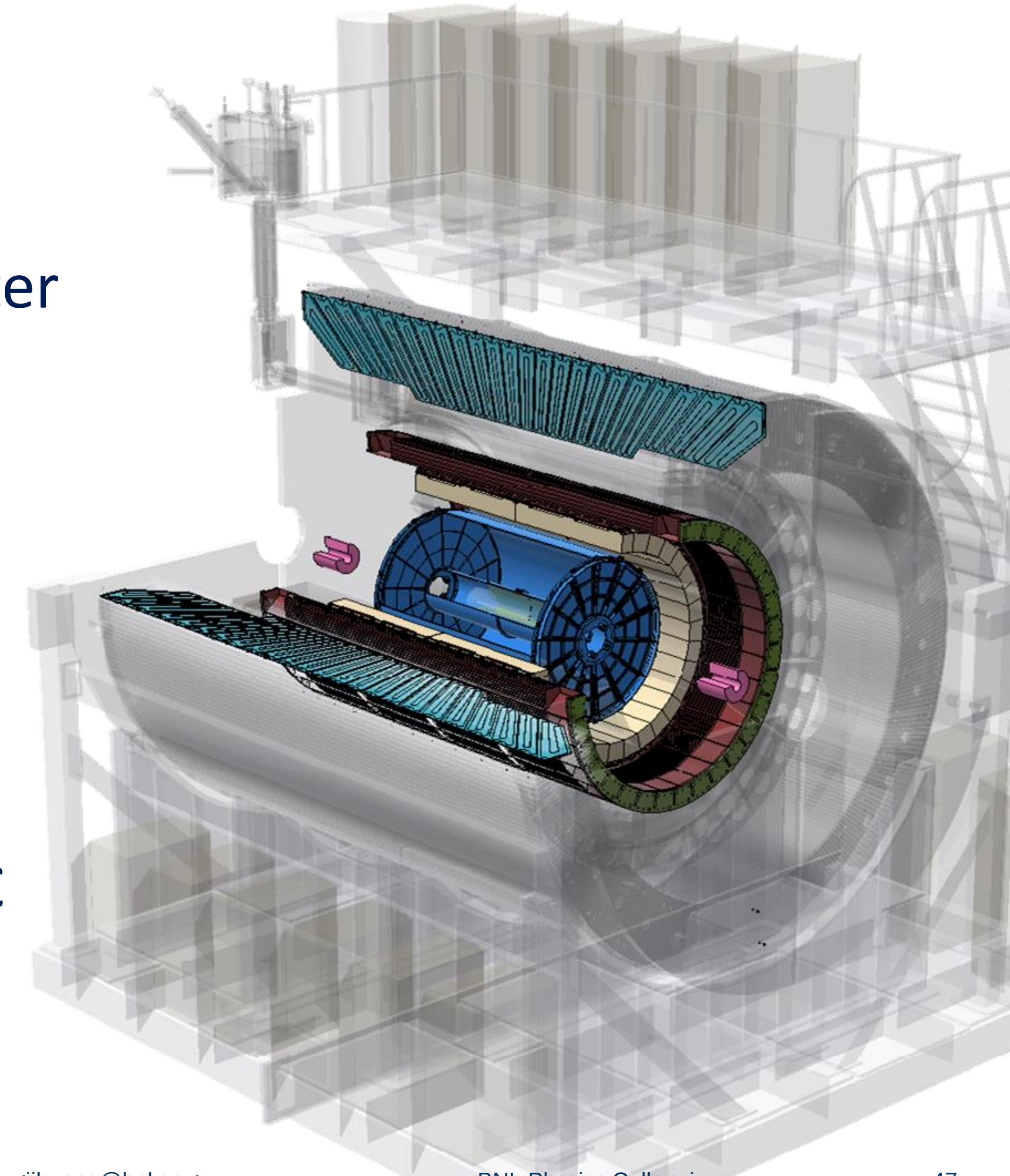
MVTX RU, 200M ch INTT ROC, 400k ch
ALPIDE (ALICE/sPHENIX), FPHX (PHENIX)

TPC FEE, 160k ch
SAMPA (ALICE/sPHENIX)

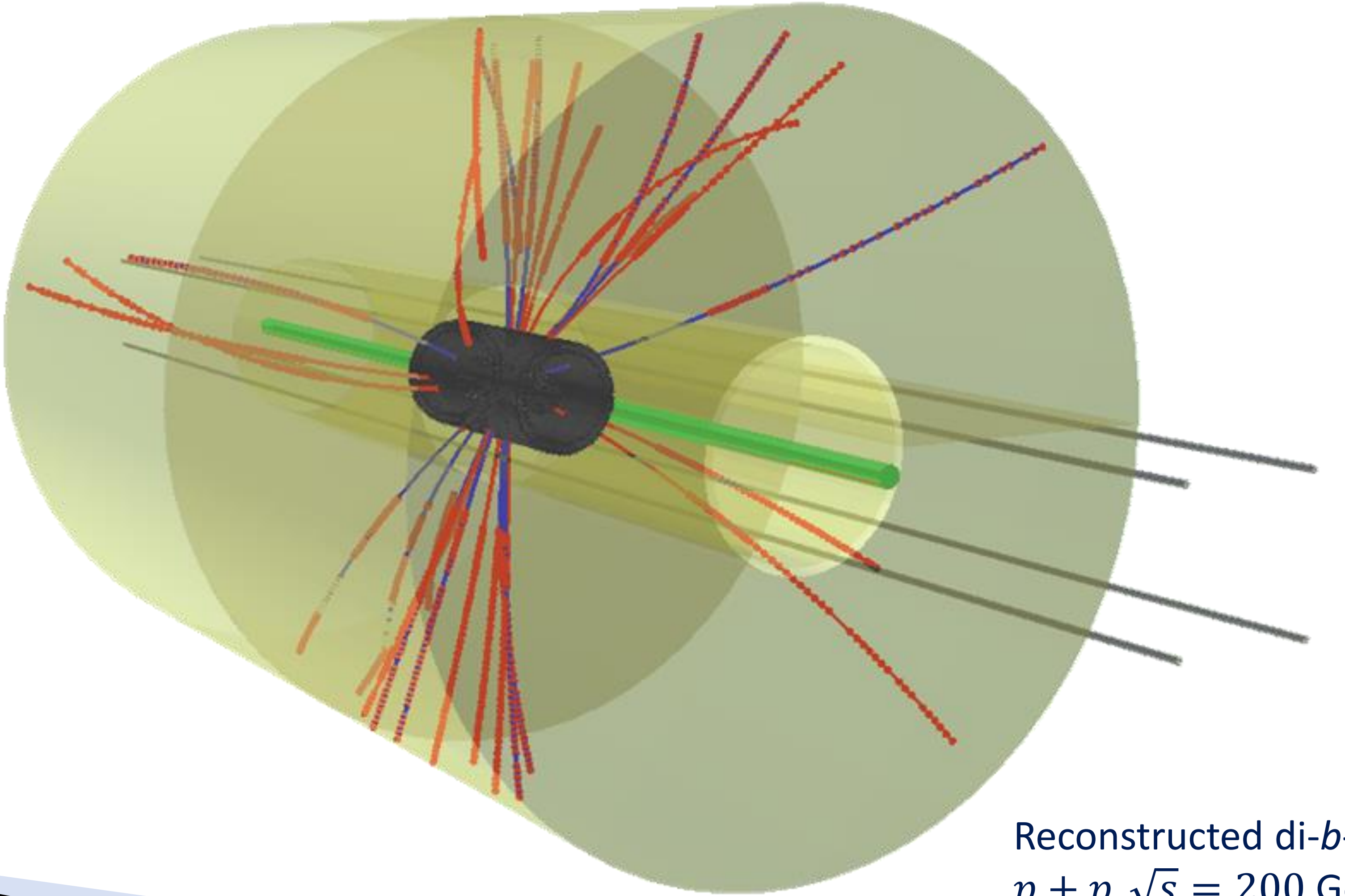
BNL-712 / FELIX v2 x48 (ATLAS/sPHENIX)

Summary

- A tale of connections between hot and cold QCD studies, in physics pursuit of QCD matter and in next-gen instrumentation
- Novel use of spin tools to study hard probe transport in cold nuclear matter
- sPHENIX is being constructed to bring precision bottom observables to RHIC
- Streaming detectors and triggerless DAQ promise to transform both sPHENIX and EIC experiments with unique physics gains



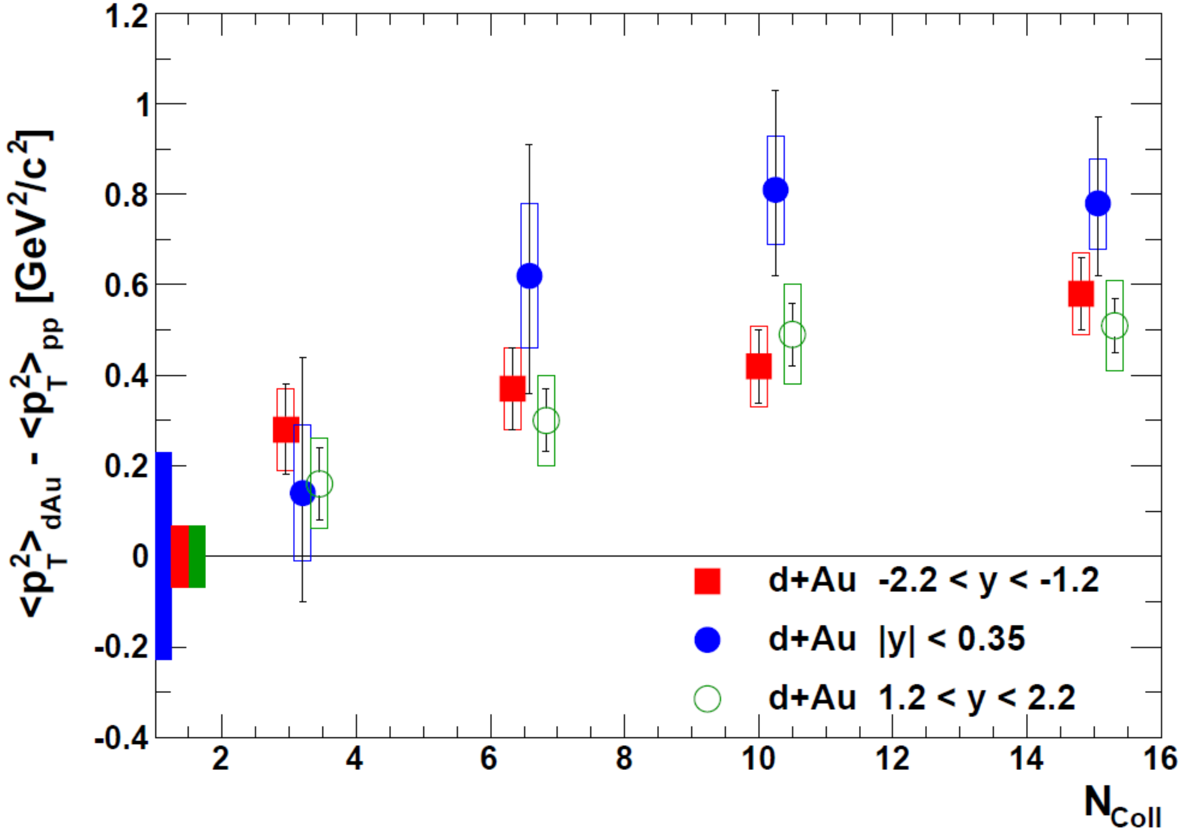
Thank you and take care!

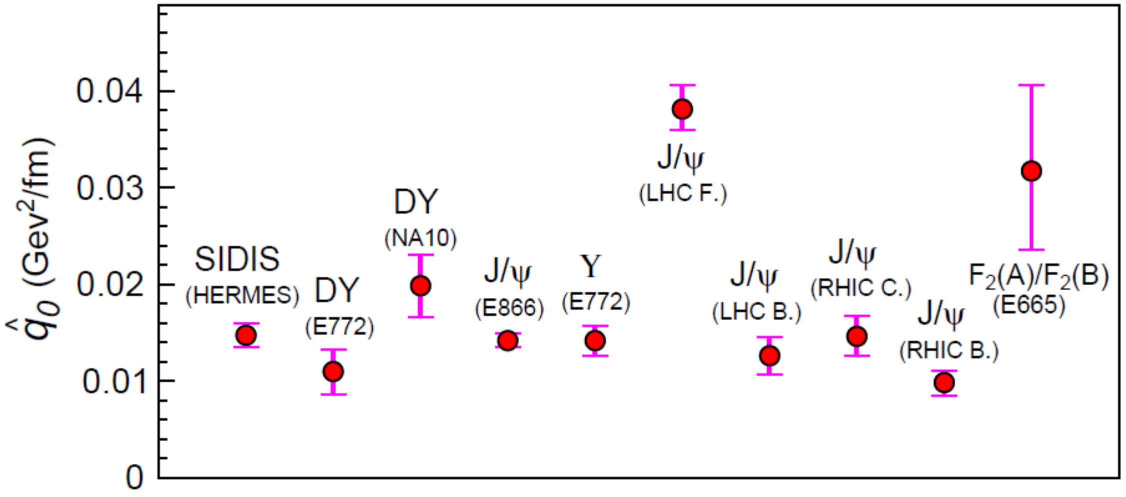


Reconstructed di-b-jet in sPHENIX tracker
$p + p, \sqrt{s} = 200$ GeV

Extra information

PHENIX, Phys. Rev. C 87, 034904 (2013)

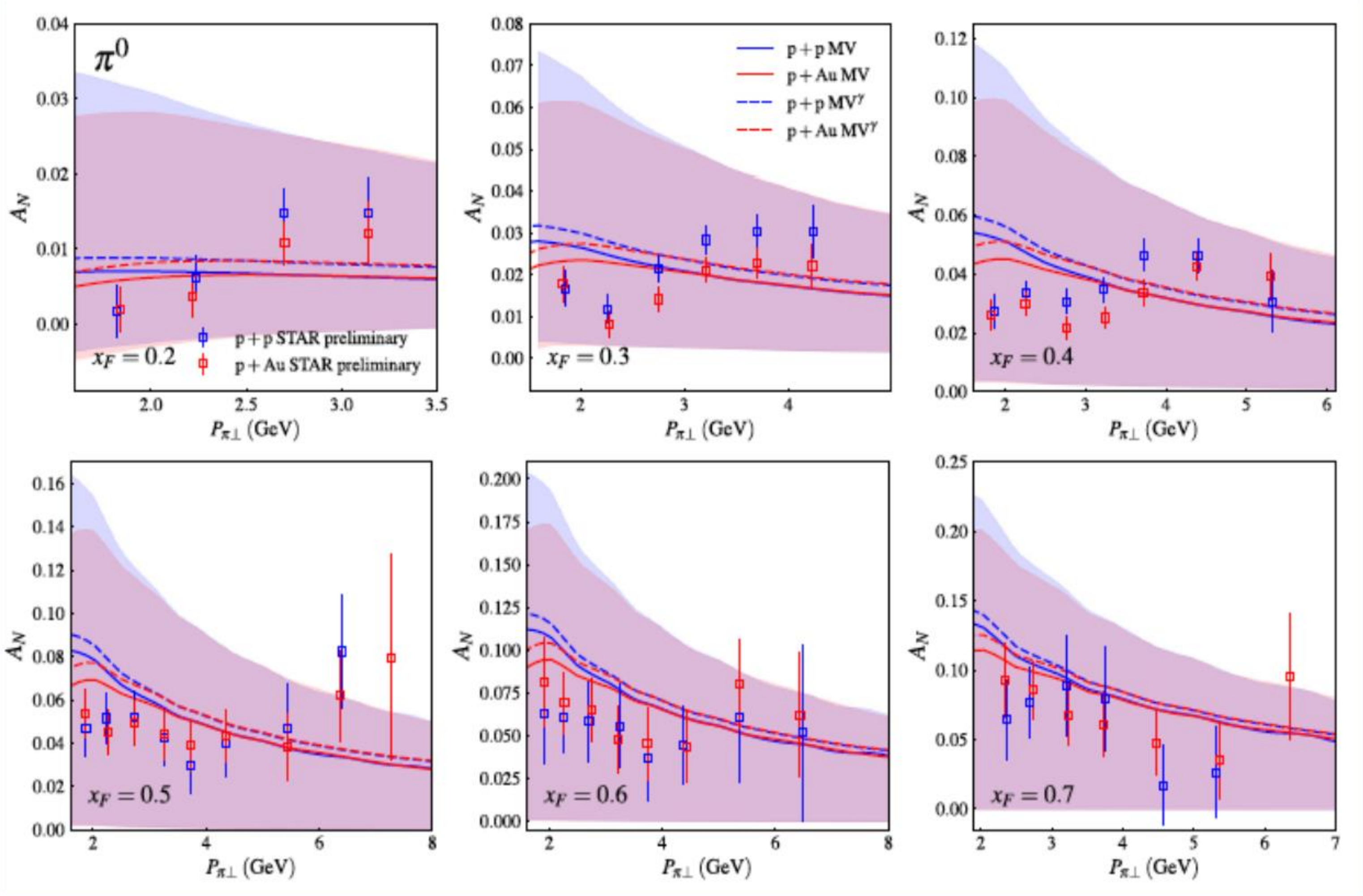




PHENIX STAR comparison

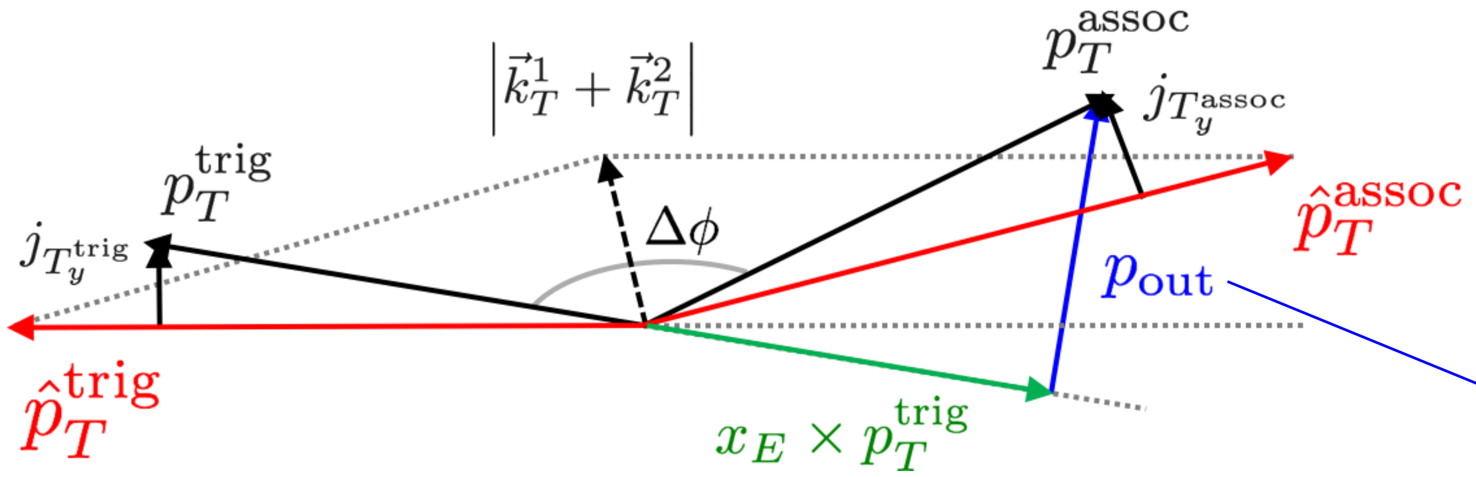
S.Benic and Y.Hatta, PRD99, 094012, STAR preliminary

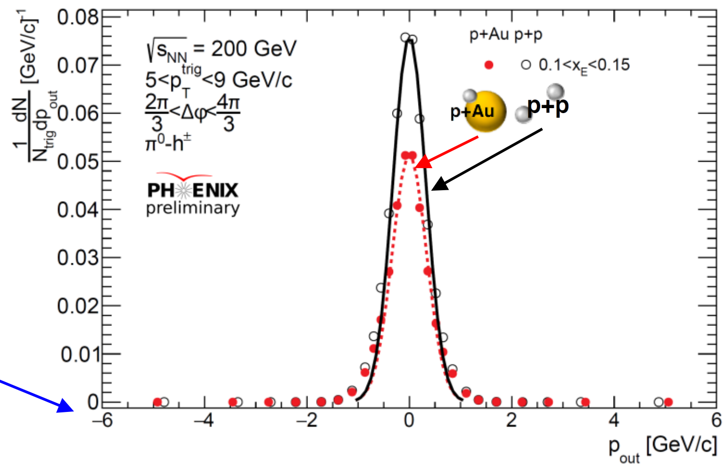
PHENIX (Preliminary)	STAR (Preliminary)
h+	$\pi 0$
$1.4<\eta<2.4$	$2.6<\eta<4.0$
$0.1<x_F<0.2$	$0.2<x_F<0.7$
$1.8<p_T<7$	$1.5<p_T<7$
A_N suppressed	A_N (almost) not modified



Dihadron correlation for

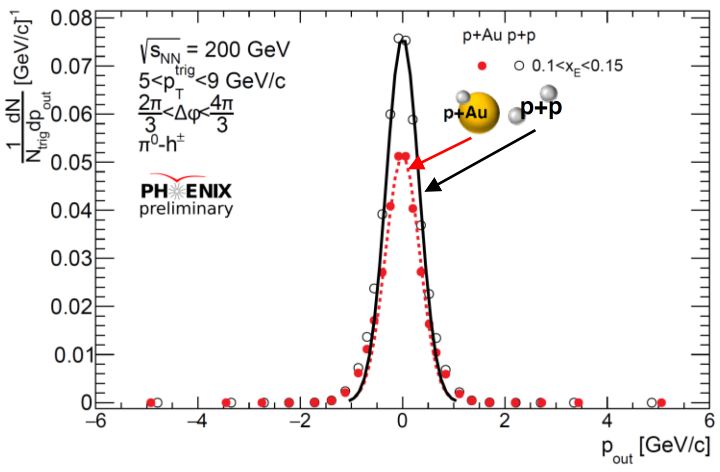
- Dihadron p_{out} More direct observing multiple scattering of quark in nuclear matter



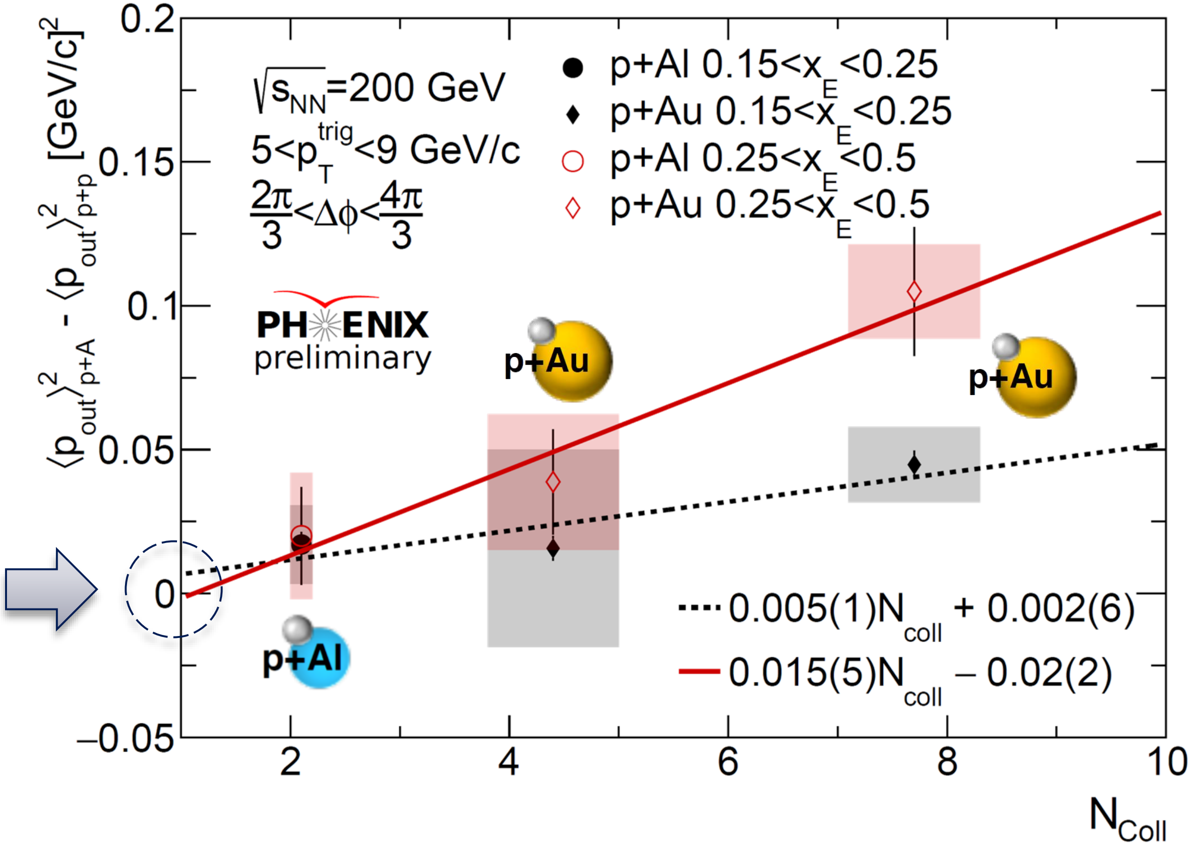


PHENIX, Phys.Rev. D98 (2018) no.7, 072004, Phys.Rev. C99 (2019) no.4, 044912

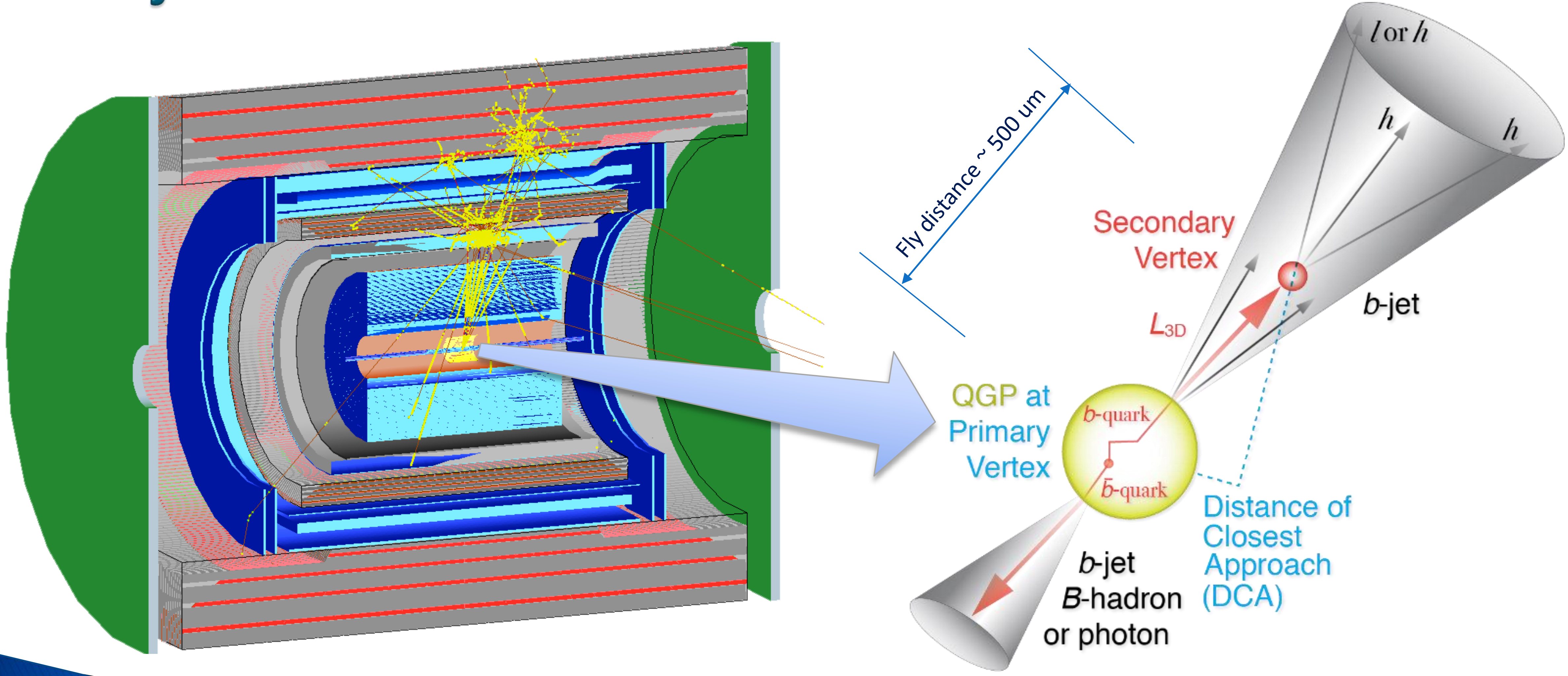
Data consistent with linear broadening



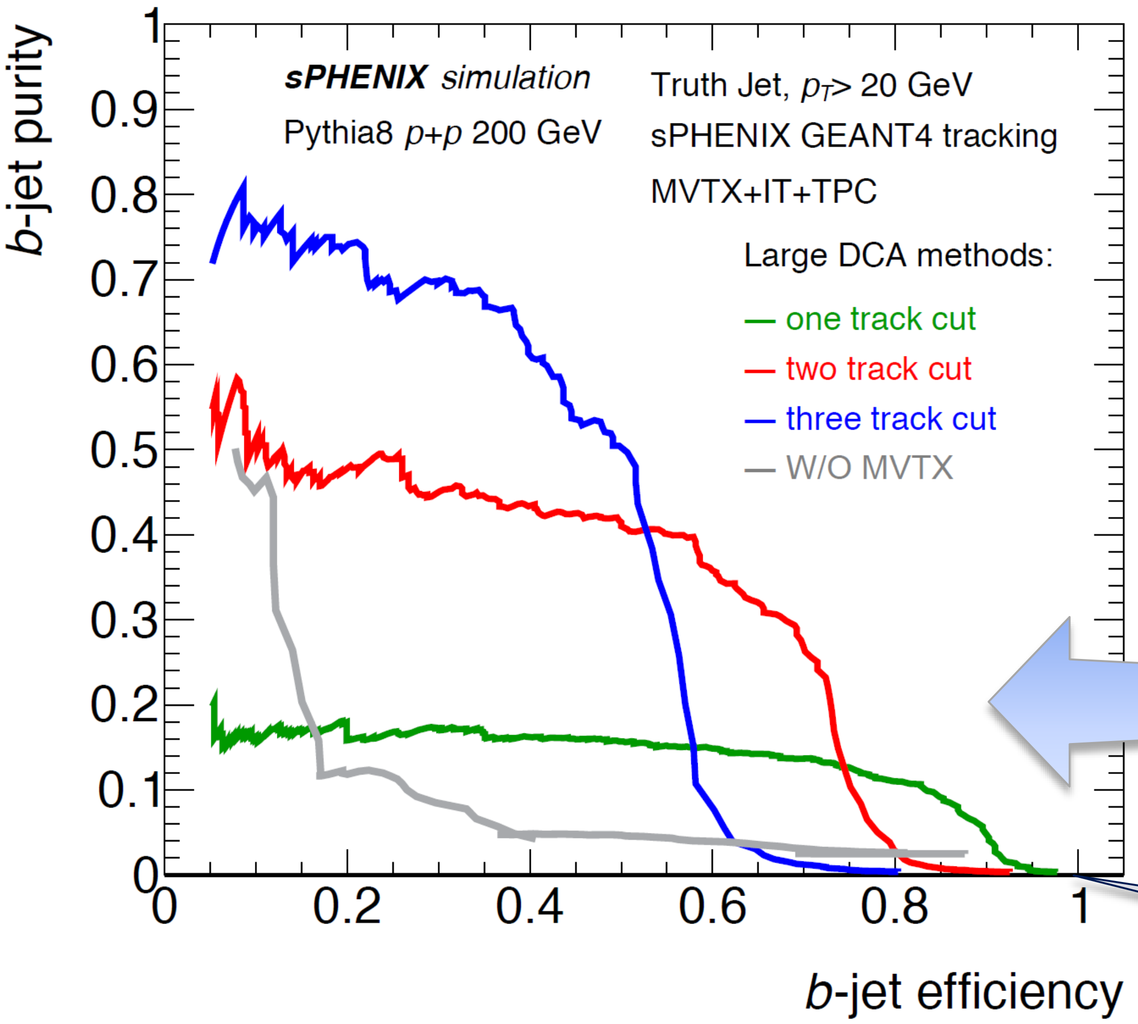
$p + A$ of $N_{coll} = 1$ also consistent with $p + p$

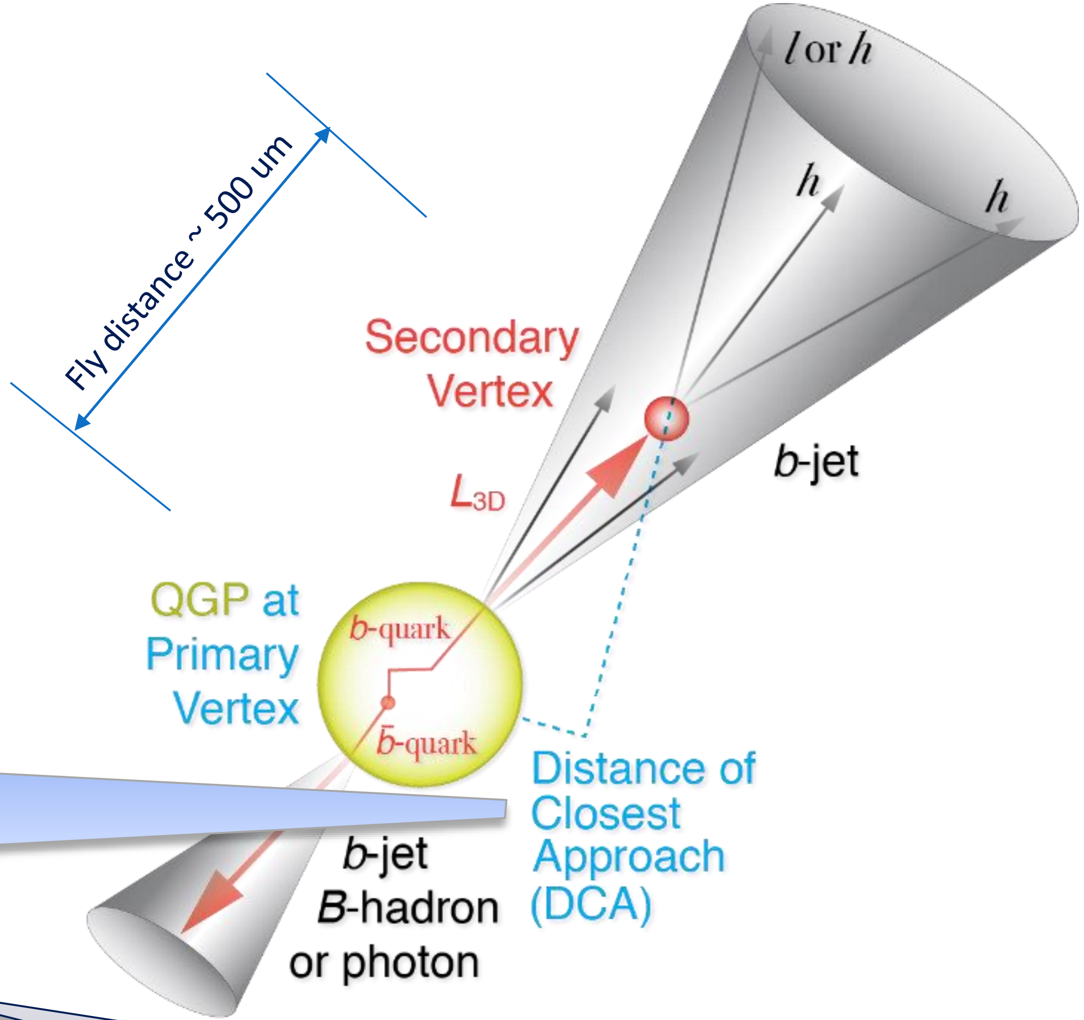


b-jet detection



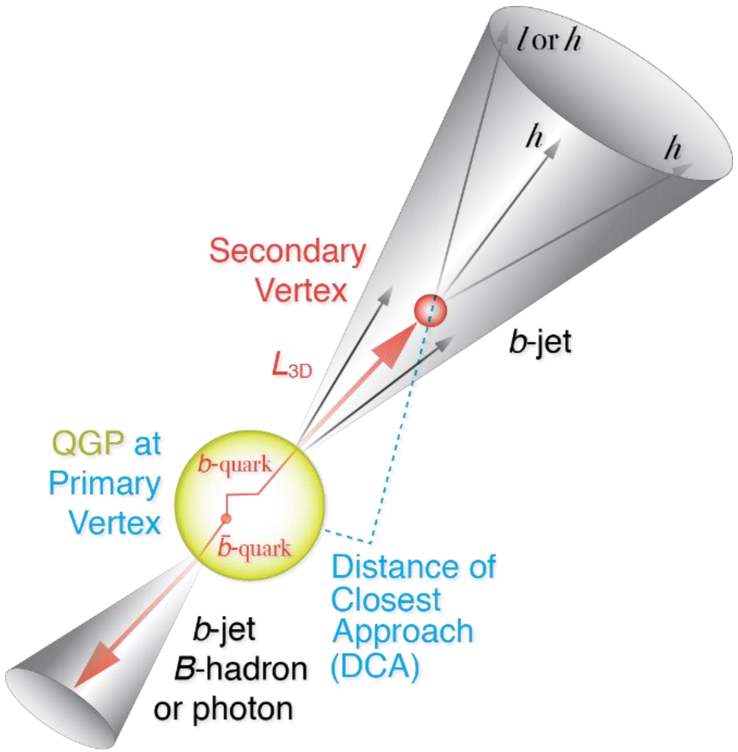
b-jet detection





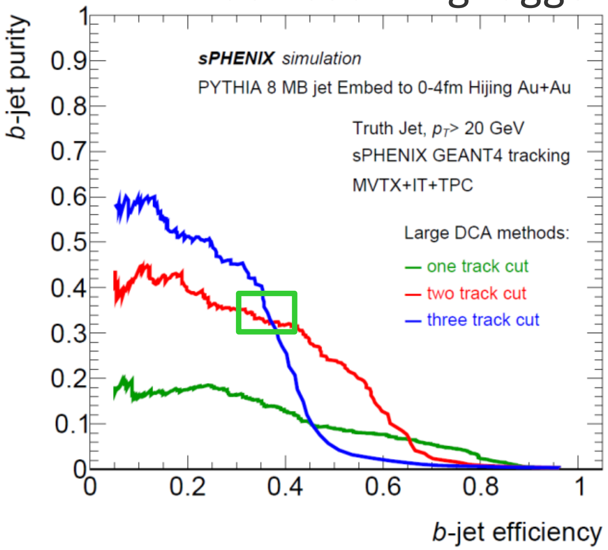
Natural abundance < 1%

b-jet tagging @ sPHENIX

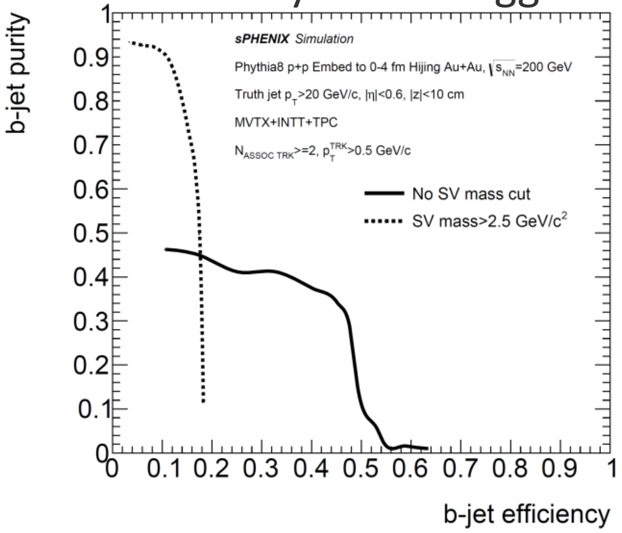


- Demonstrate b-jet capability: tagging algorithms evaluated using full detector HI simulation
- Reaching a promising working point in central Au+Au collisions

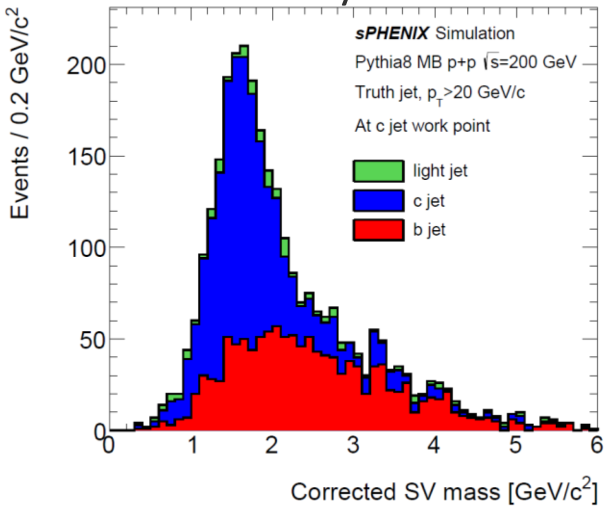
Track-counting tagger



Secondary-vertex tagger

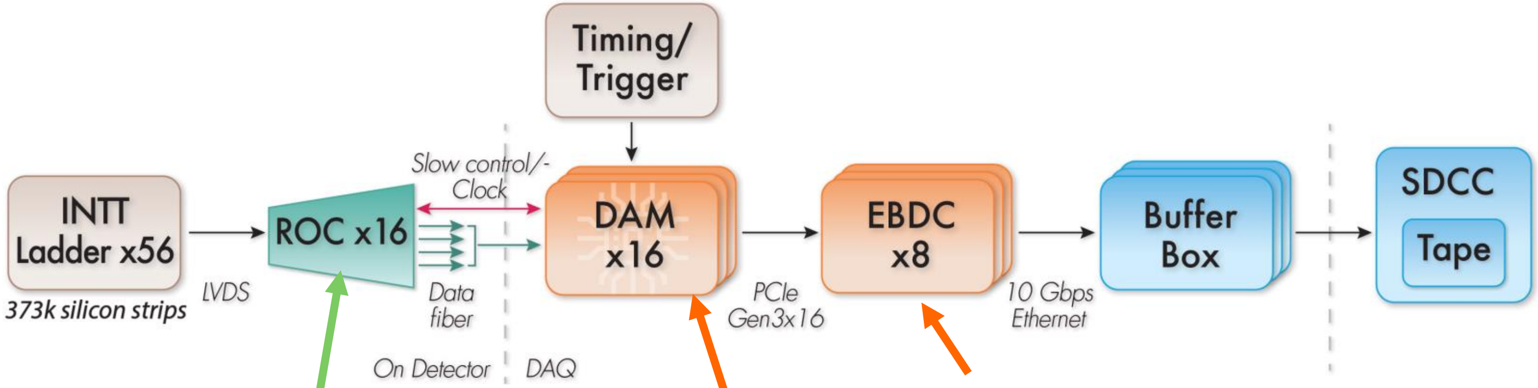


Secondary-vertex mass

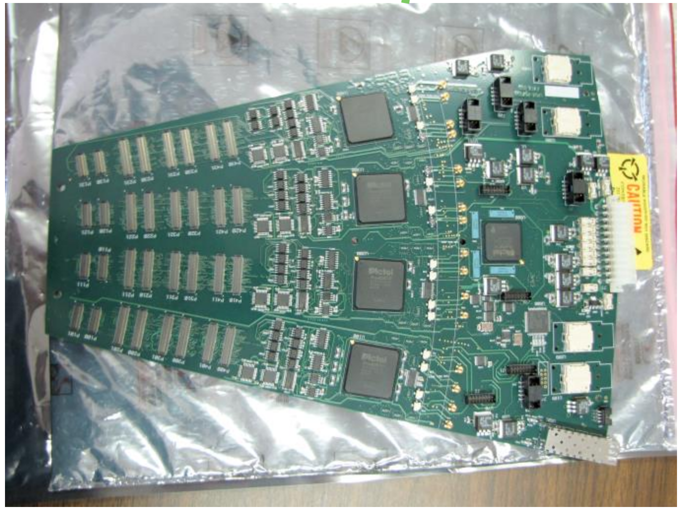


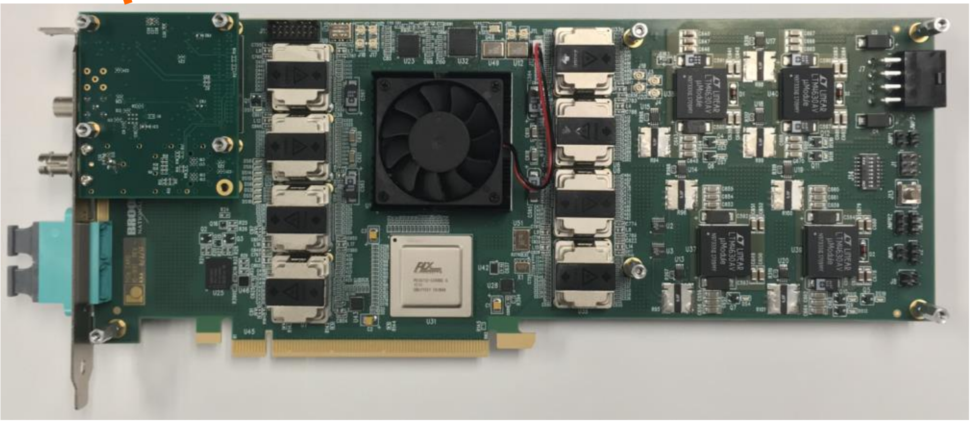
CMS work-point, Phys. Rev. Lett. 113, 132301 (2014)

Then it may looks like this

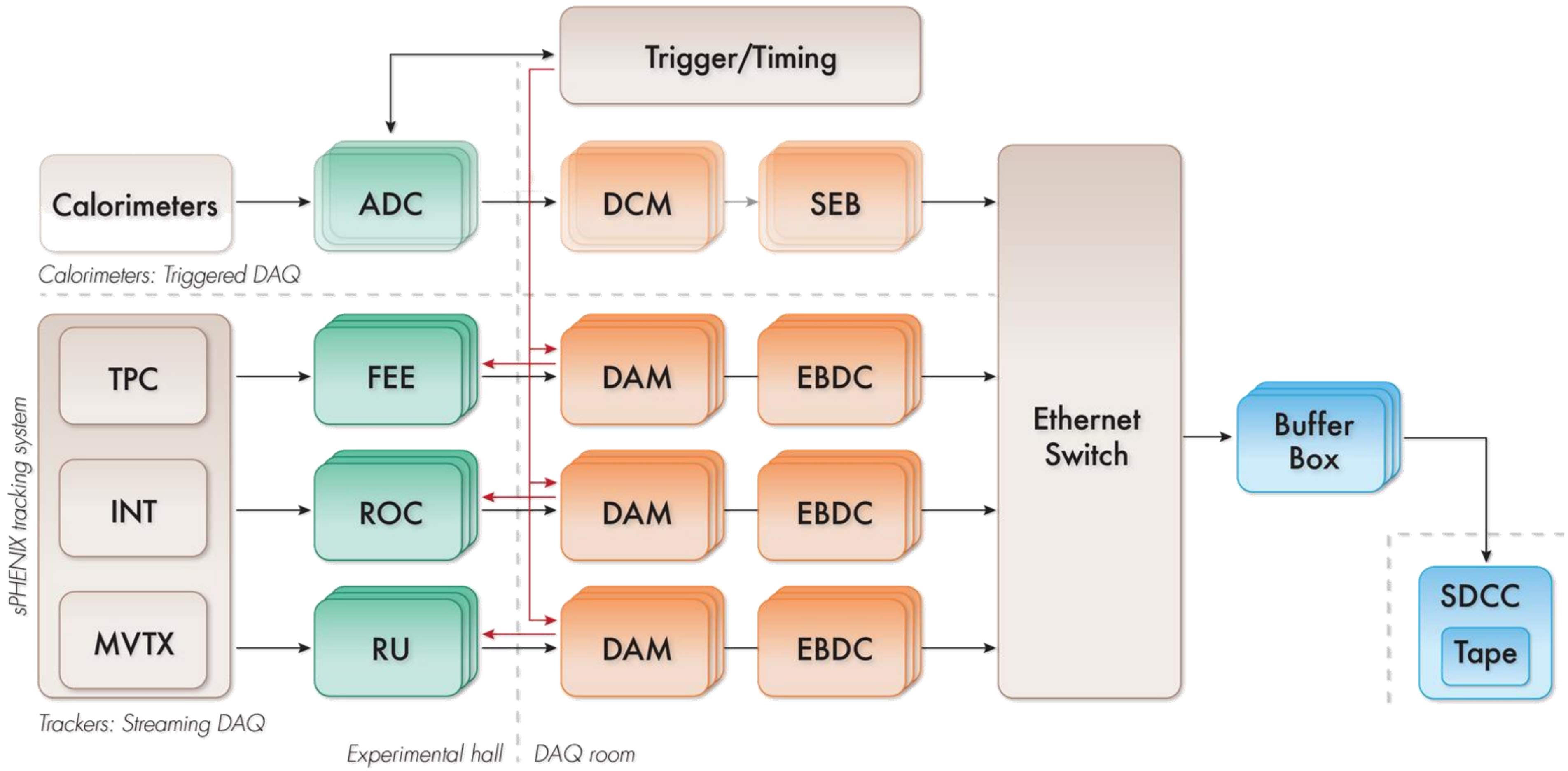


Relatively low-load commodity server
@ ~0.1 Gbps << TPC





→ Streaming DAQ for sPHENIX trackers



See also DAQ talk, M. Purschke

Observables → x500 improvement

		Year-2 in current setup	Year -2 w/ Streaming tracker	Year -2+4 w/ Streaming tracker
M.B. $p+p$	Data recorded	1k Hz M.B. trigger with 2×10^{-4} of M.B. collisions triggered	10% M.B. events streaming recorded	
	Statistics	0.4 Billion M.B. events 0.01 pb^{-1} recorded	200 Billion M.B. events 5 pb^{-1} recorded	800 Billion M.B. events 20 pb^{-1} recorded
Physics reach	$B \to D^0 \to \pi K$	250 events	120k events	500k events
			Reference in R_{AA} for B→D^0	
	$D^0 \to \pi K$ pair	250 events	120k events.	500k events
			Diffusion of c-quarks in angular space	
	$\Lambda_c \to \pi K p$	500 events	250k events.	1M events
			Charm hadronization in p+p; reference for $\mathrm{A+A}$	
	Prompt D^0→πK	75k events	40 Million events.	150 Million events
			Pinging down tri-gluon correlation via single spin asymmetry	

A conservative working point