sPHENIX Jet Physics

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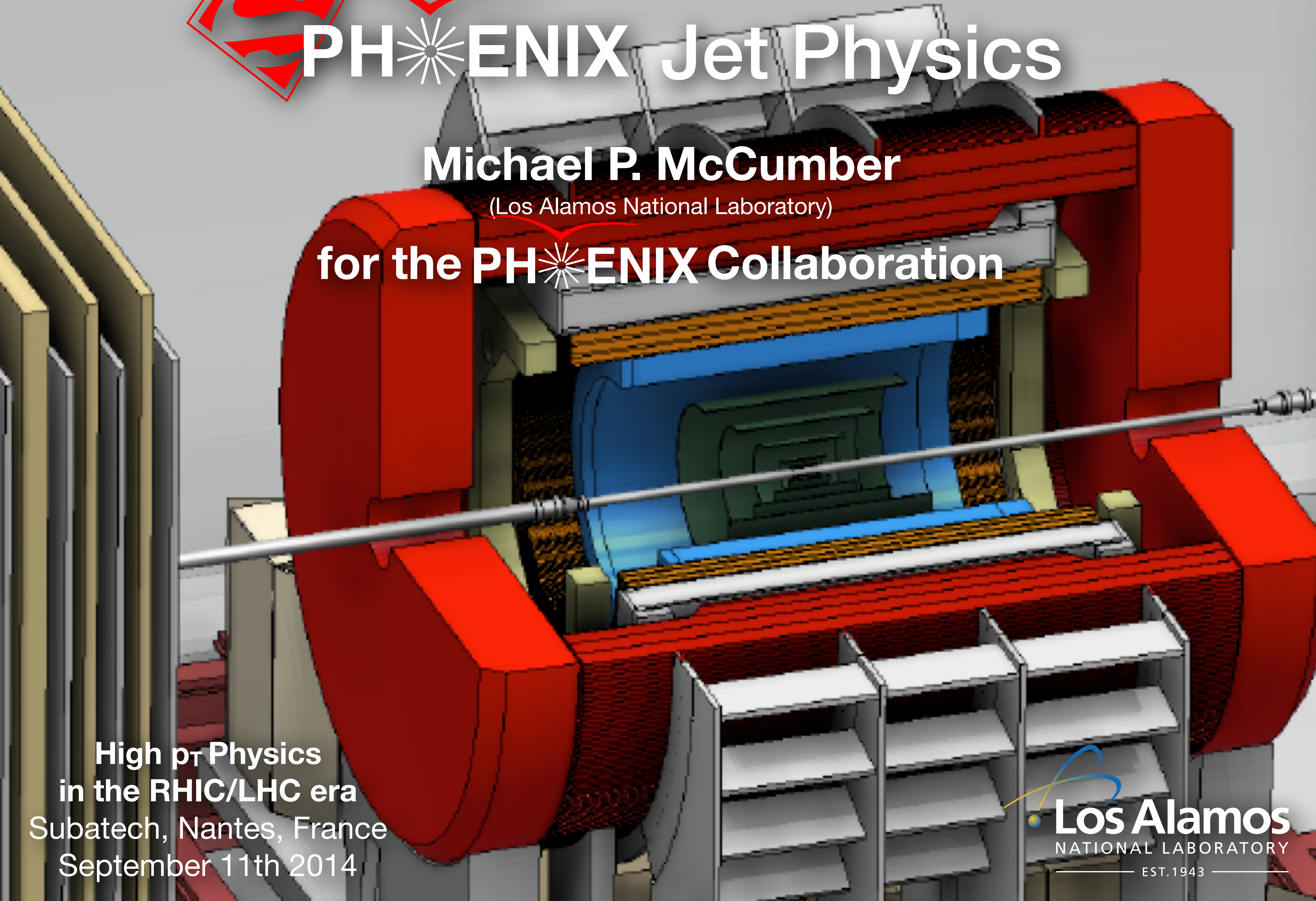
(Los Alamos National Laboratory)
for the PHENIX Collaboration



High p_T Physics
in the RHIC/LHC era
Subatech, Nantes, France
September 11th 2014

Los Alamos
NATIONAL LABORATORY
EST. 1943

the mission for today…

(1) **Physics case** for a jet detector at RHIC (sPHENIX)
and the key measurement observables

Are jet measurements interesting at RHIC?
Can jets be well-measured at RHIC?

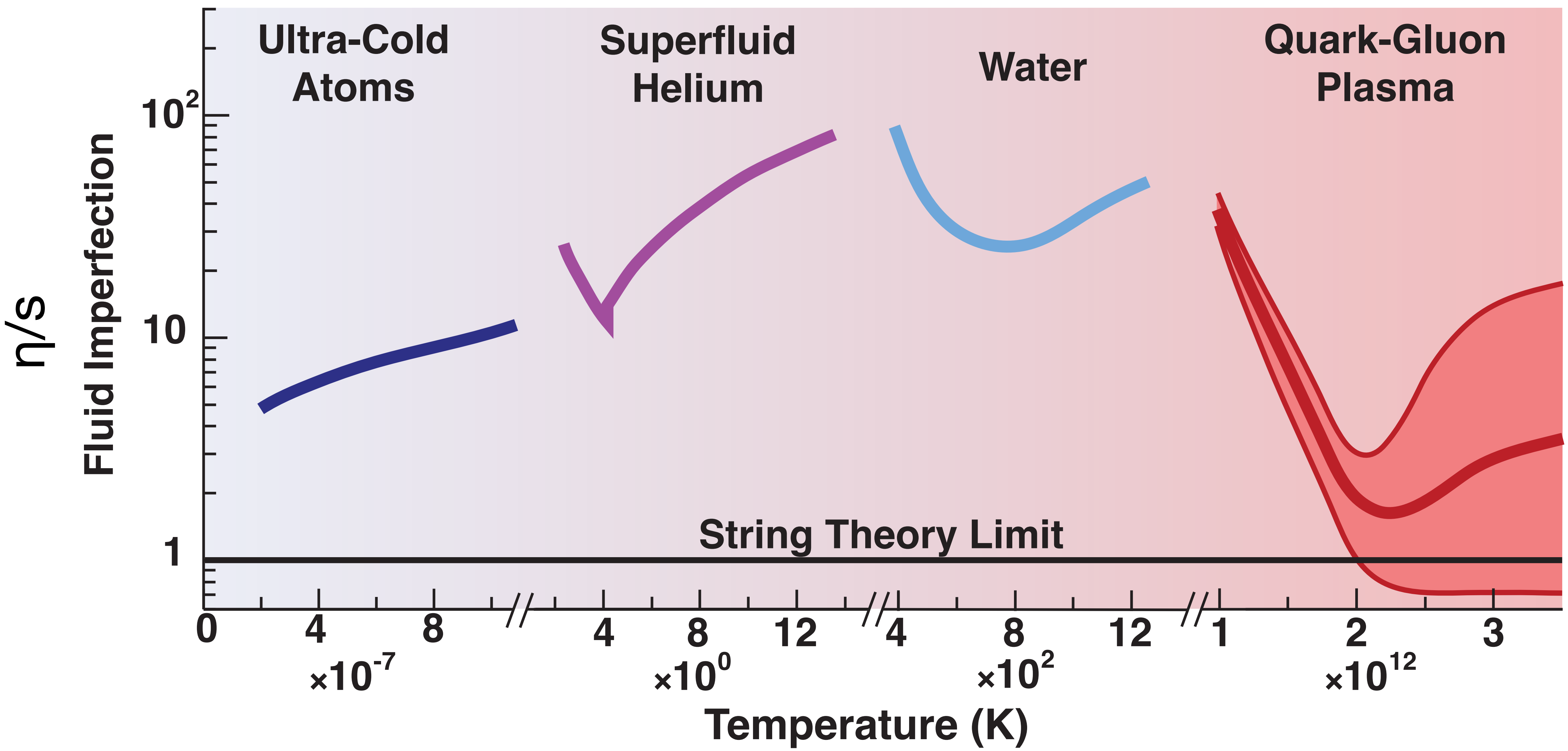
(2) The **detector configuration** to fit these observables

Can a detector be built to make these measurements?

Briefly: Planned **operations** and additional **opportunities**

Does the jet program align with our other goals as a community?

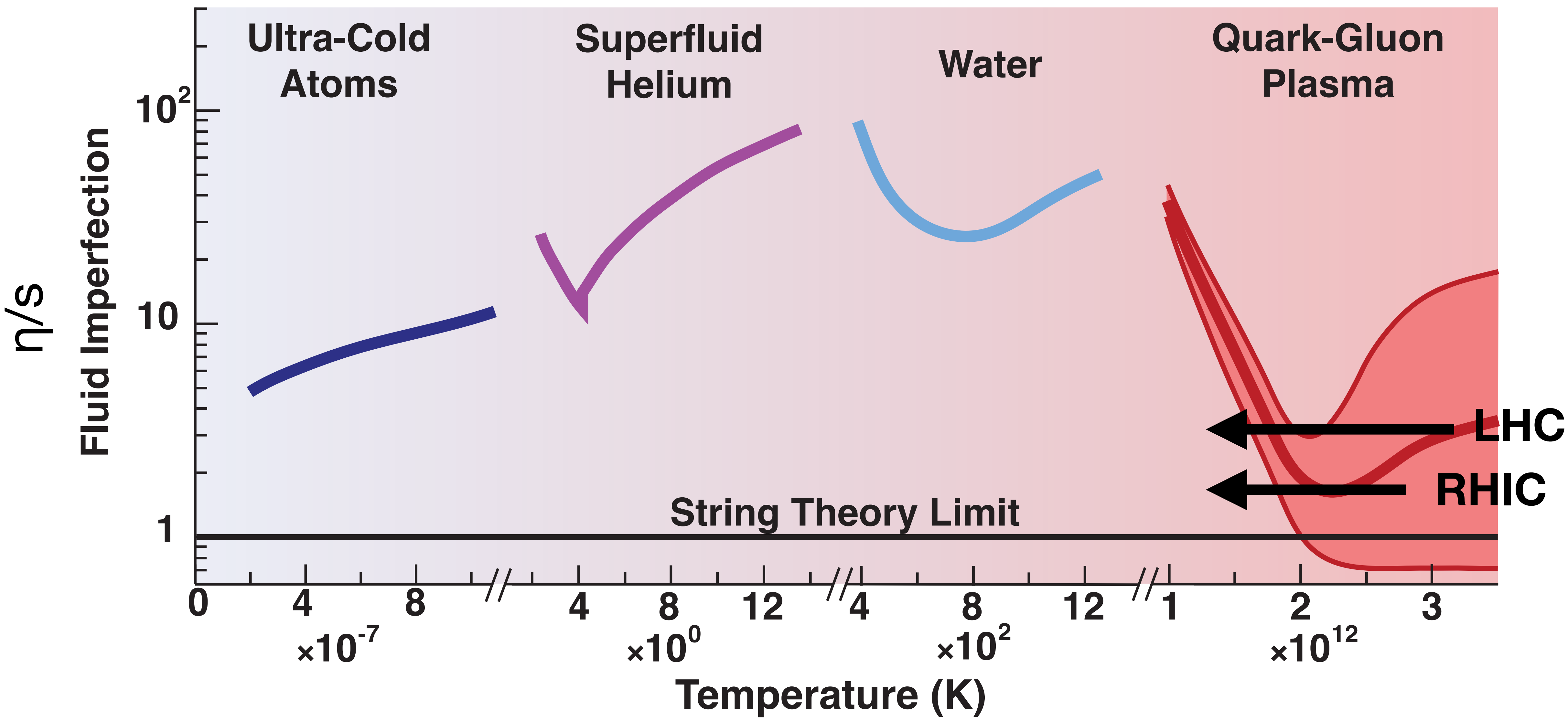
Viscosity near Phase Transitions



Many systems have minimum shear viscosity to entropy density near phase transformation

Quark-Gluon Plasma is not yet well constrained on this question

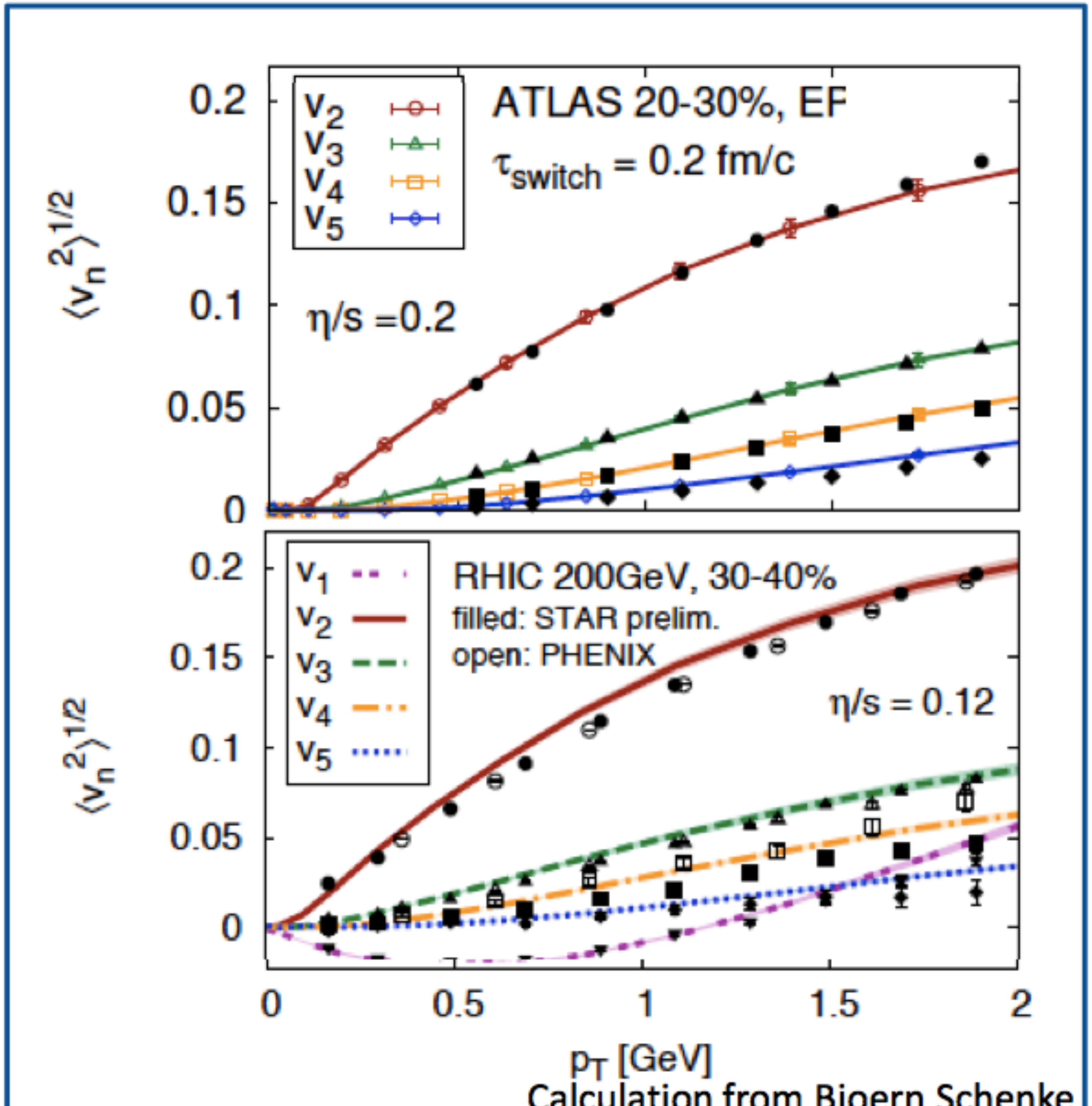
Viscosity near Phase Transitions



Many systems have minimum shear viscosity to entropy density near phase transformation

Quark-Gluon Plasma is not yet well constrained on this question

Indications of Viscosity Differences



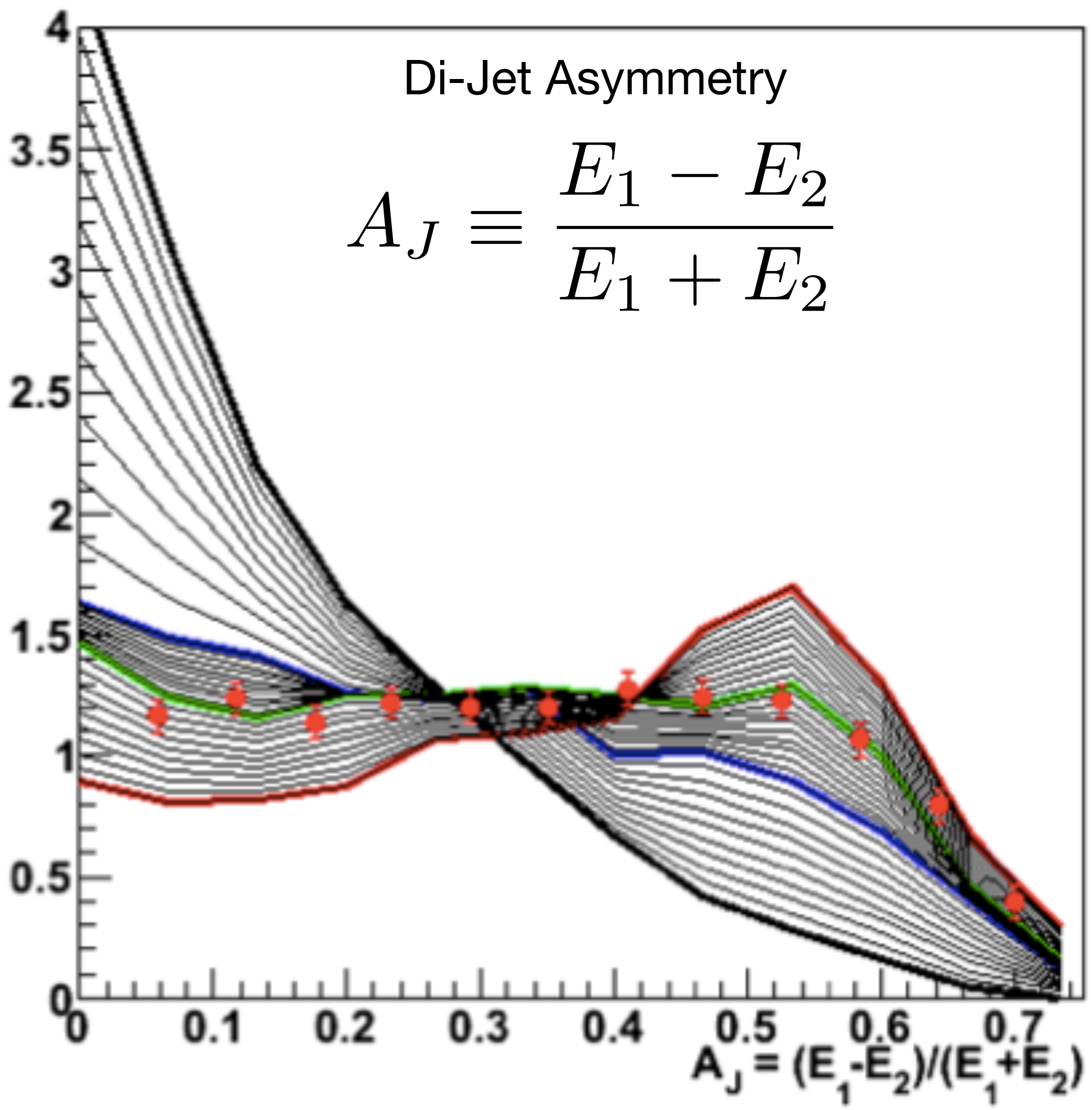
from the soft sector:

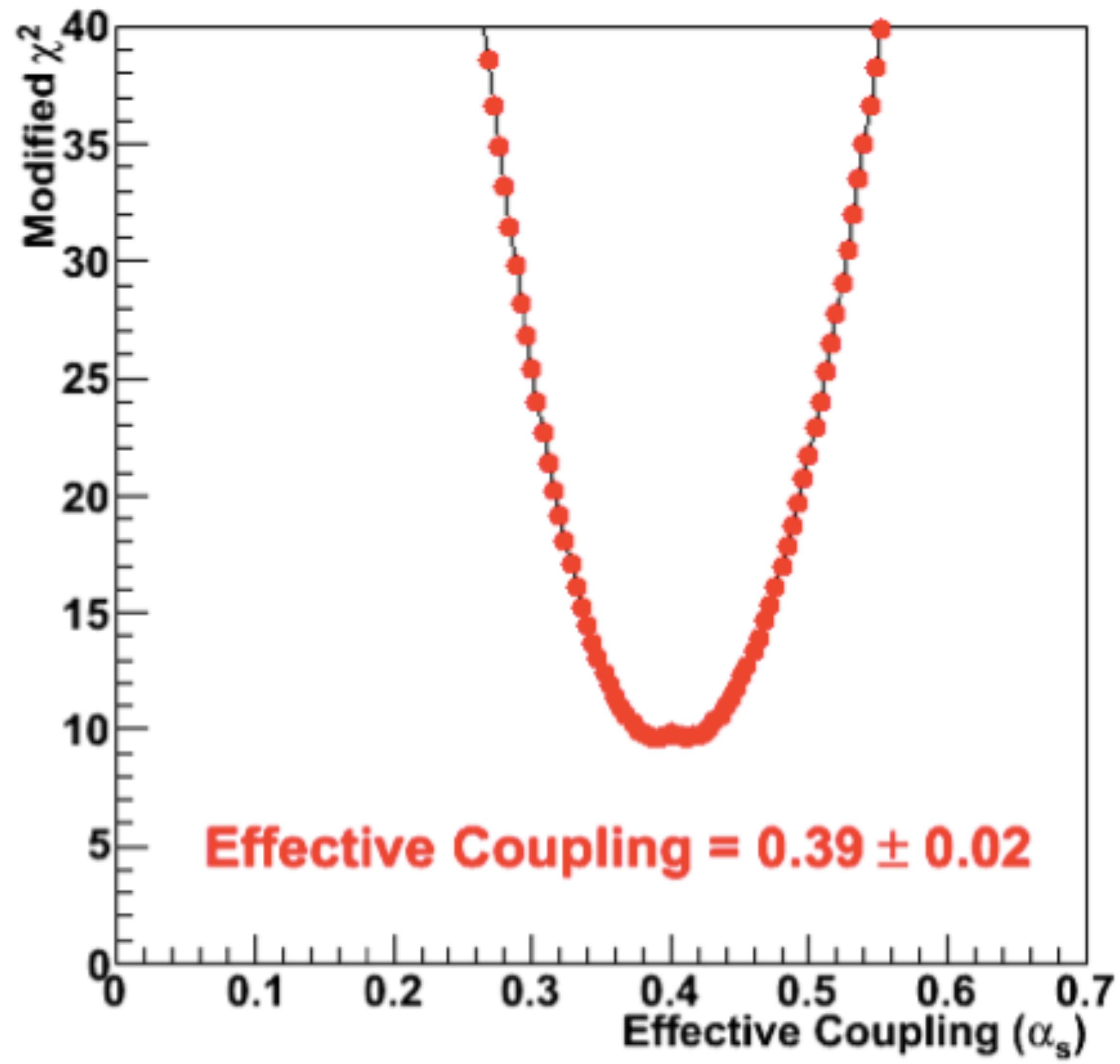
There are indications now that the shear viscosity to entropy is smaller at RHIC

How might these changes appear in the hard sector?

Information on Medium Properties

Using Coleman-Smith's dijet asymmetry the effective coupling is varied, how well can our projected measurement for 35 GeV jets with R = 0.3 constrain this parameter.

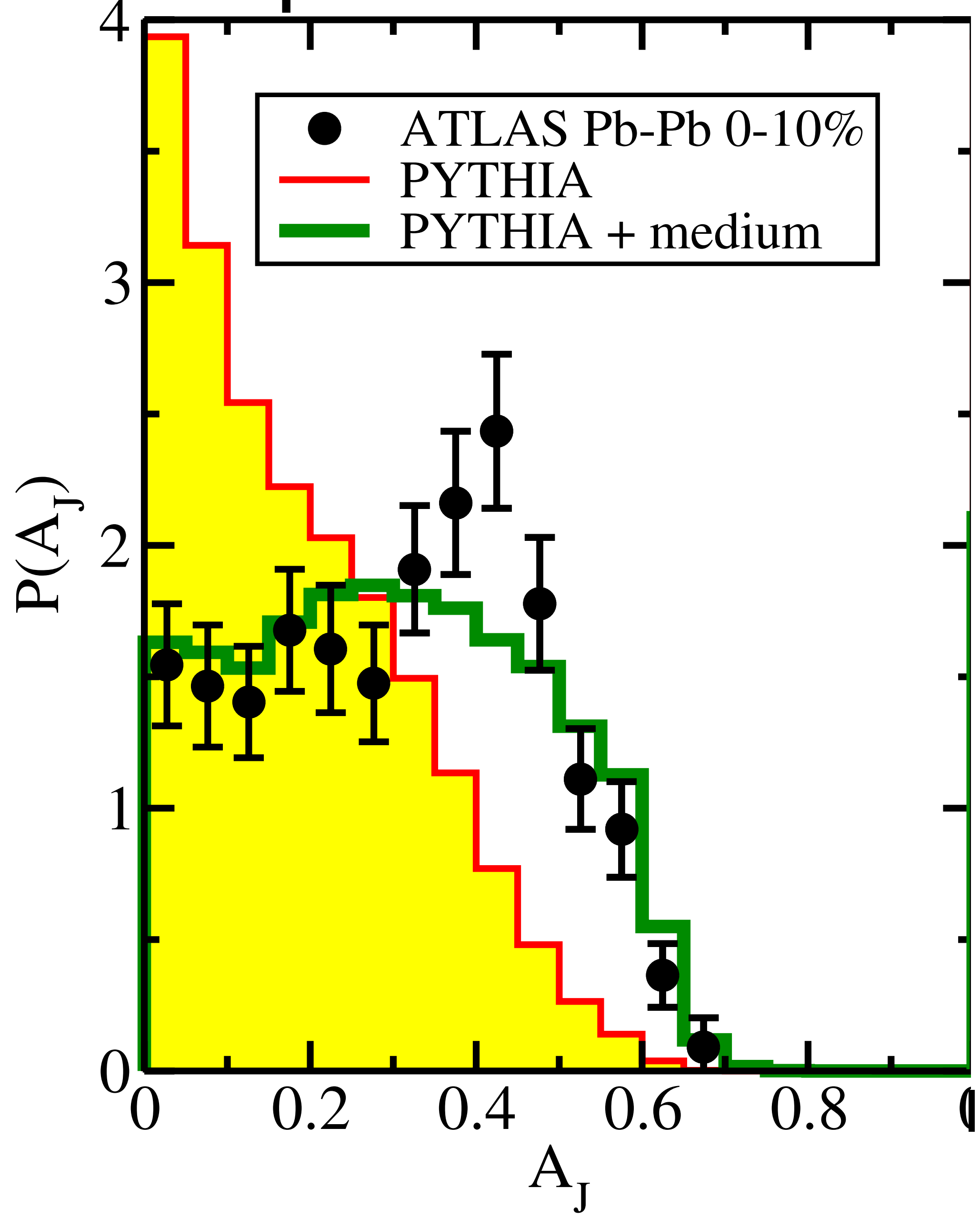




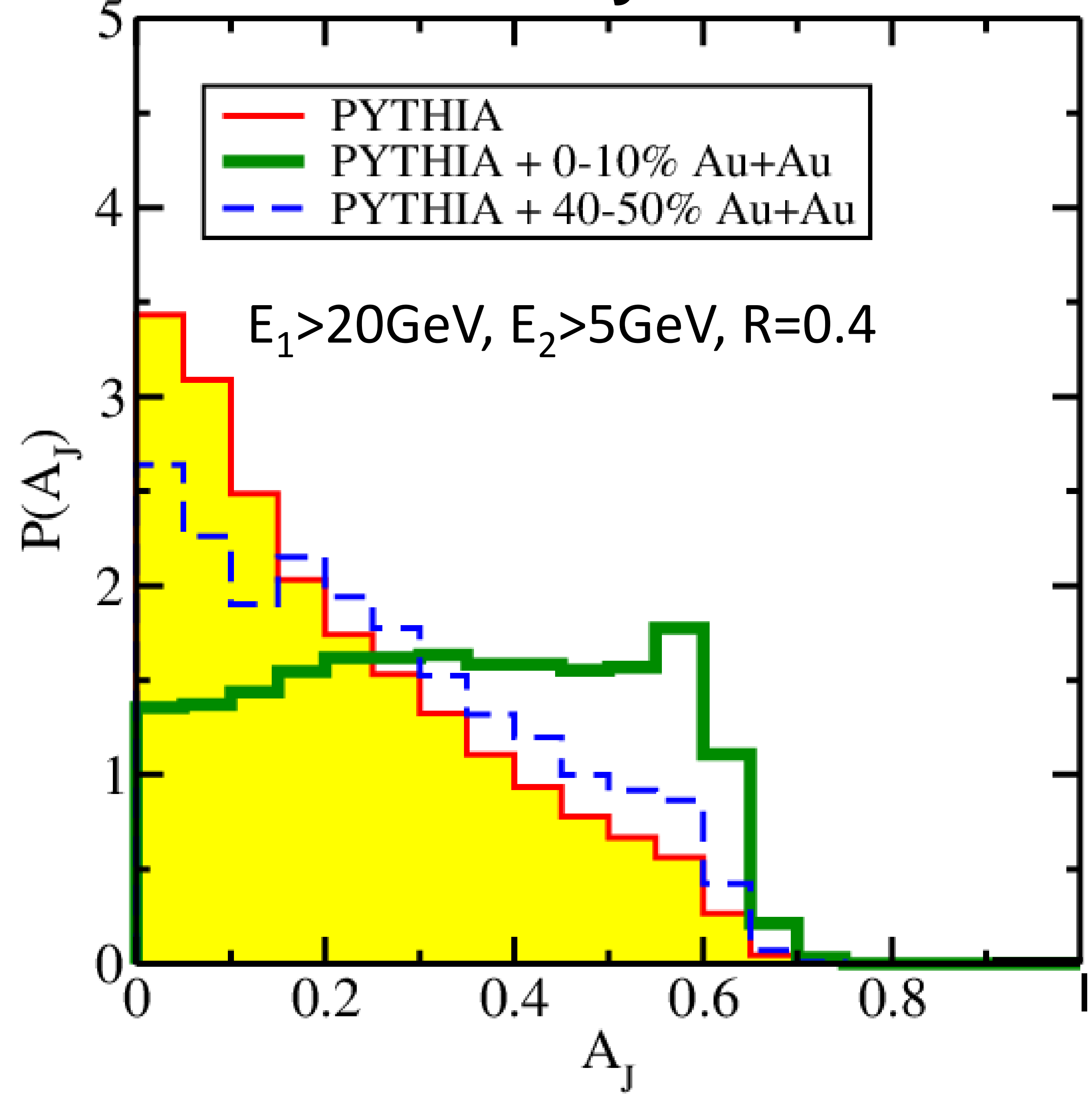
Of course, many observables need to be included since there is more than one unknown. The key is over-constraining the problem

Interaction of jet with medium

Comparison to LHC data

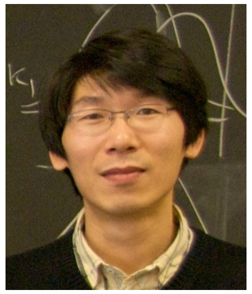


Distribution of AJ at RHIC energies

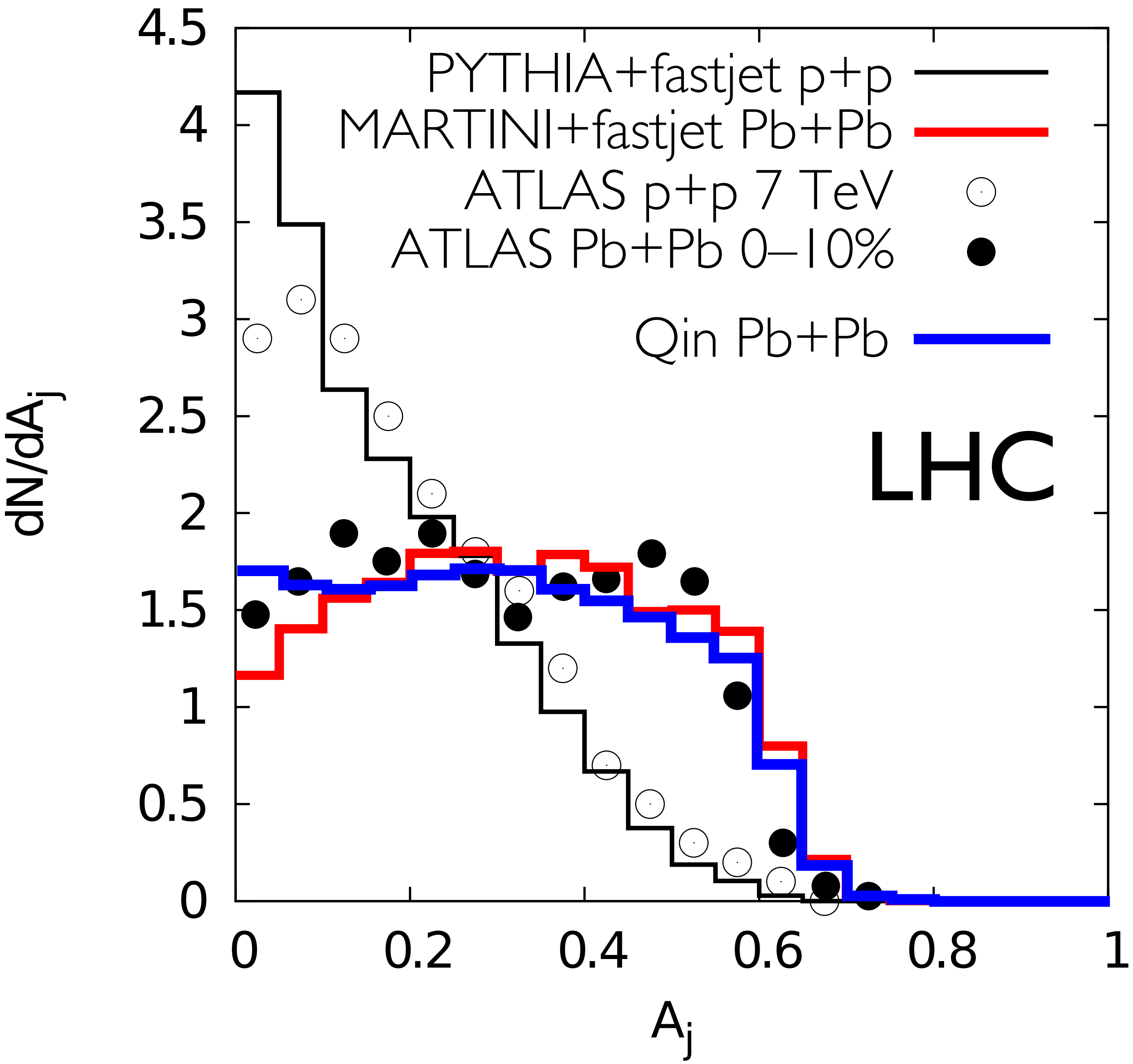


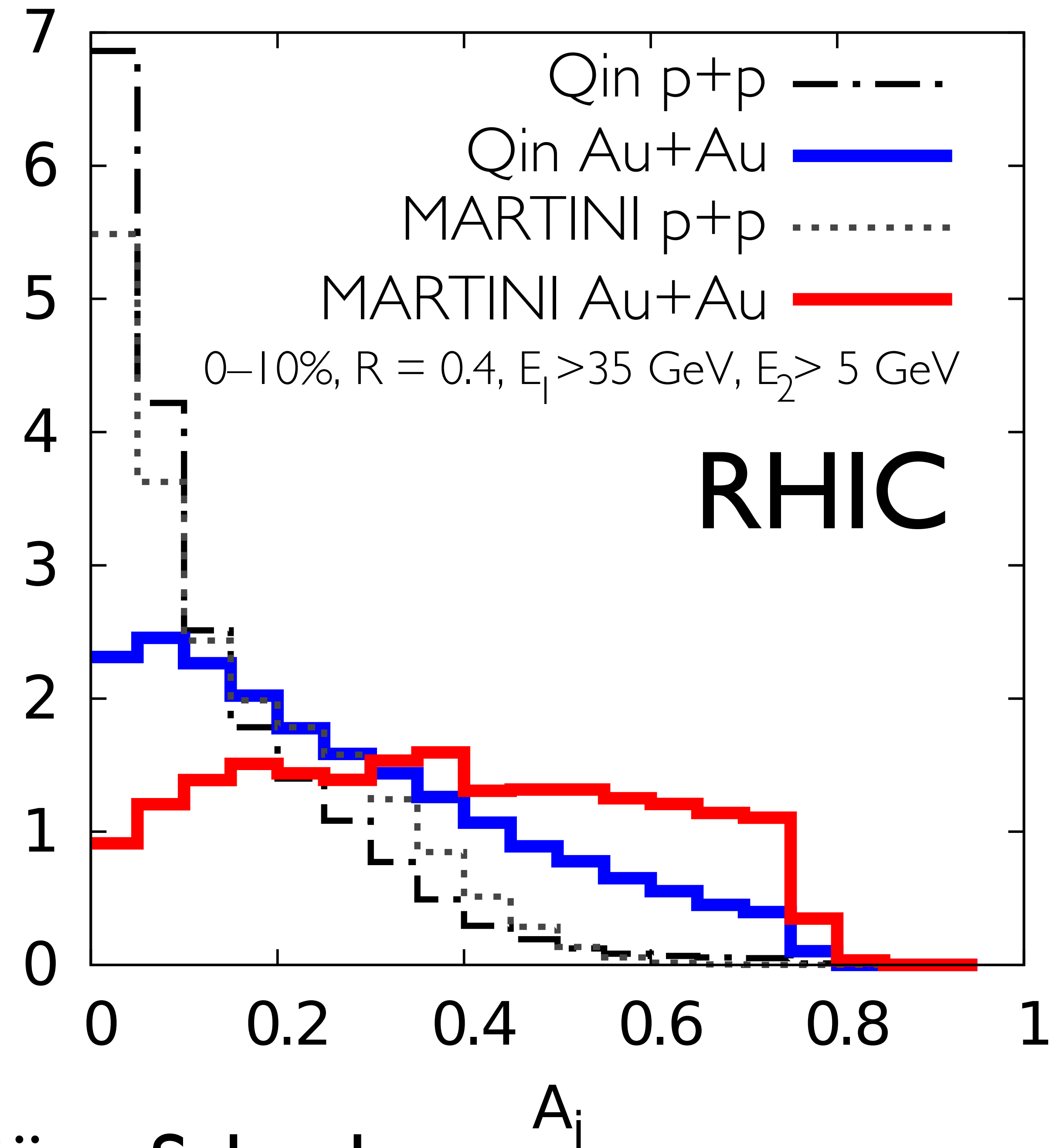
Guang-You Qin, Berndt Muller

PRL 106, 162302 (2011)



Same at LHC, different at RHIC





MARTINI: Björn Schenke

Differences to Explore at RHIC

Temperature dependence of the QGP by **beam energy** variation

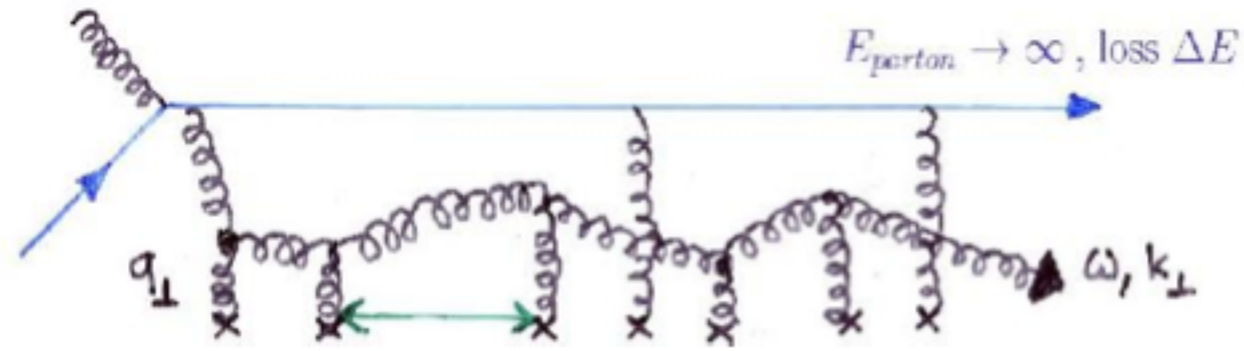
Time dependence of the QGP by virtuality variation (**hard process Q^2**)

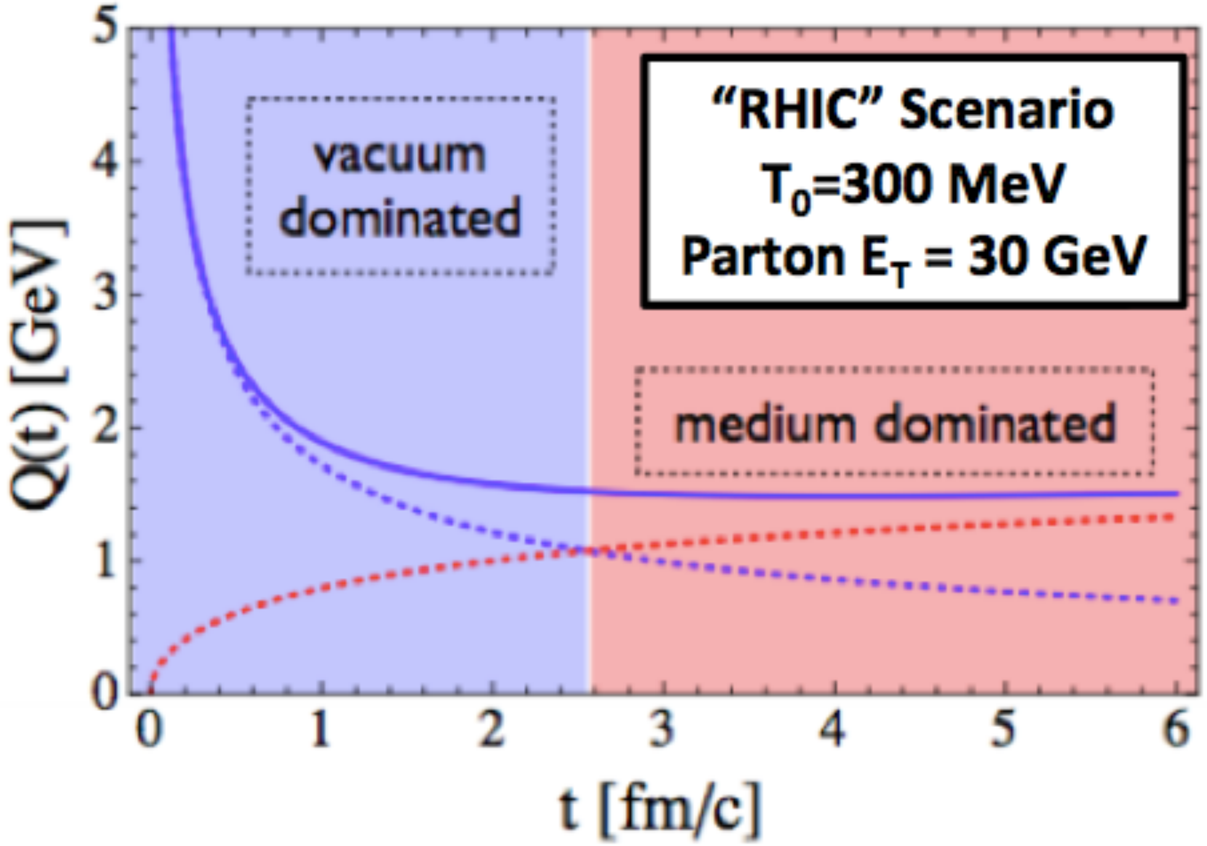
Length scale within the QGP by interaction hardness (**interaction Q^2**)

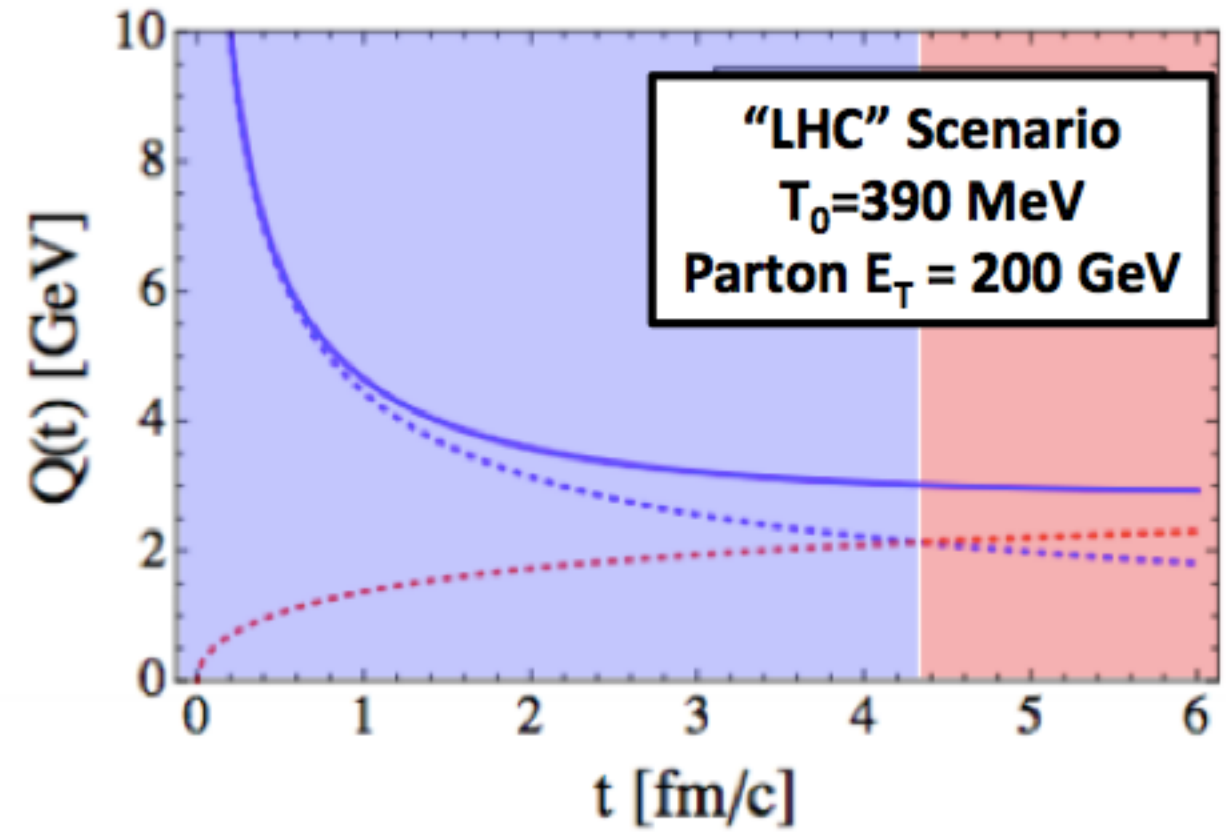
Virtuality Evolution

$\cdots\cdots\; Q^2_{vac}(t) = \dfrac{E}{2t}$ $\qquad\cdots\cdots\; Q^2_{med}(t) = \int \hat{q}(t)\,dt$

$—— \; Q^2(t) = Q^2_{vac}(t) + Q^2_{med}(t)$







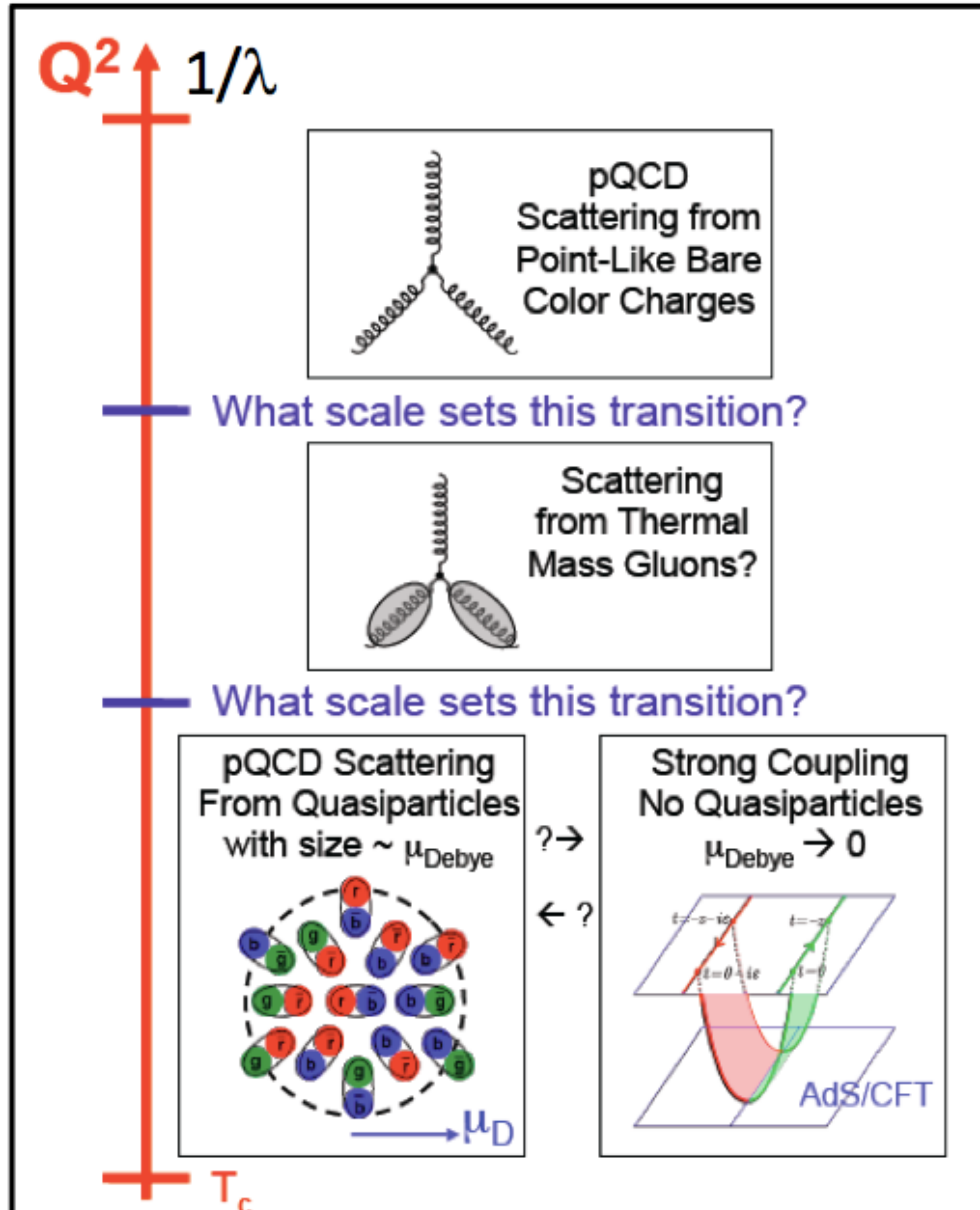
the vacuum contribution to the parton virtuality to fall below the in-medium contribution in the pQCD scenario. This effect is due to the collinear splitting in pQCD, which reduces the parton energy only gradually and thus leads to an increase in time dilation as the virtuality drops. This means that the very energetic parton hardly notices the medium for the first 3 – 4 fm of its path length. On the other hand, in the AdS/CFT scenario, parton energy and virtuality

B. Muller. Nucl.Phys., A855:74–82, 2011

Length scales of interactions with QGP

Do the highest energy jets at LHC see point-like color charges?

Do the lowest energy jets at RHIC scatter from coherent fields or only excite sound waves?



W. Horowitz

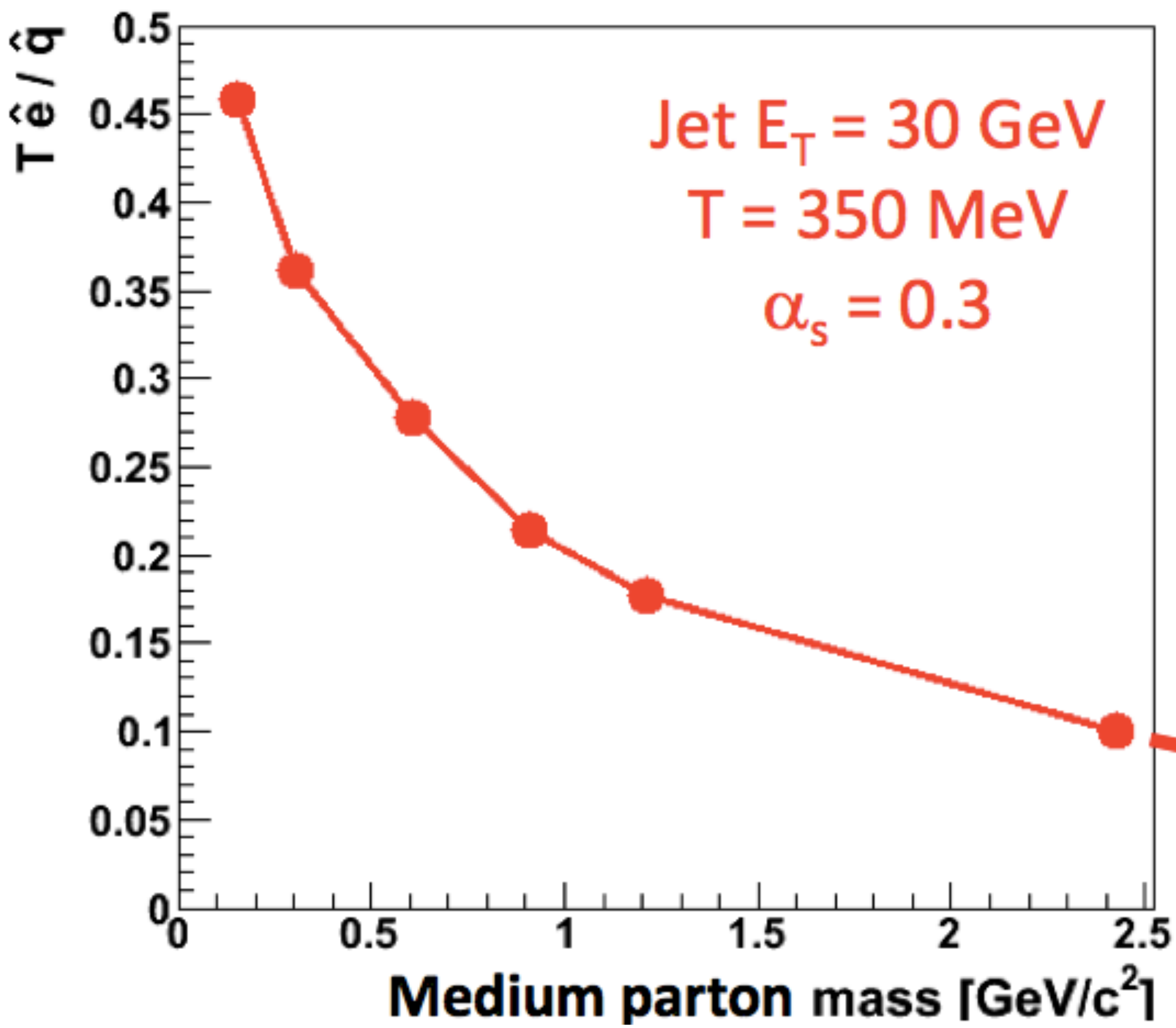
QGP Constituent Mass Dependence

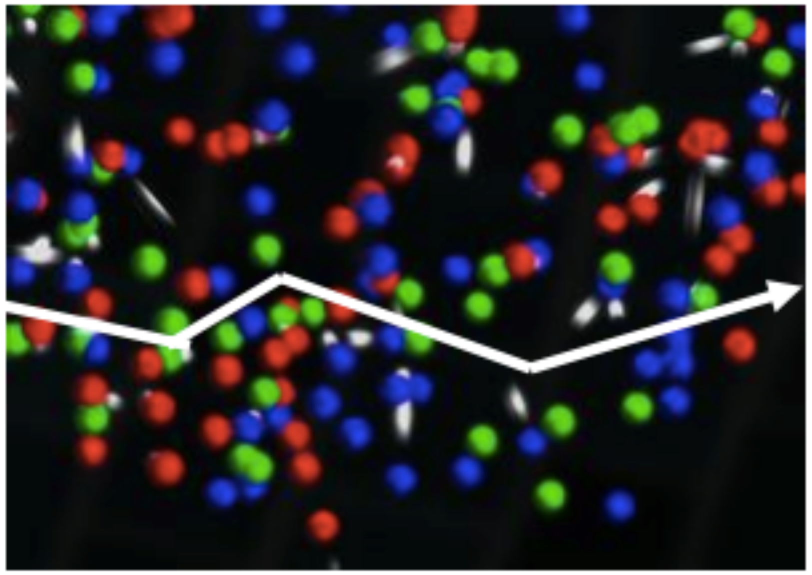
C. E. Coleman-Smith* and B. Müller
Department of Physics, Duke University, Durham, NC 27708-0305

http://arxiv.org/abs/arXiv:1209.3328

qhat → scattering of leading parton → radiation e-loss

ehat → energy transferred to the QGP medium



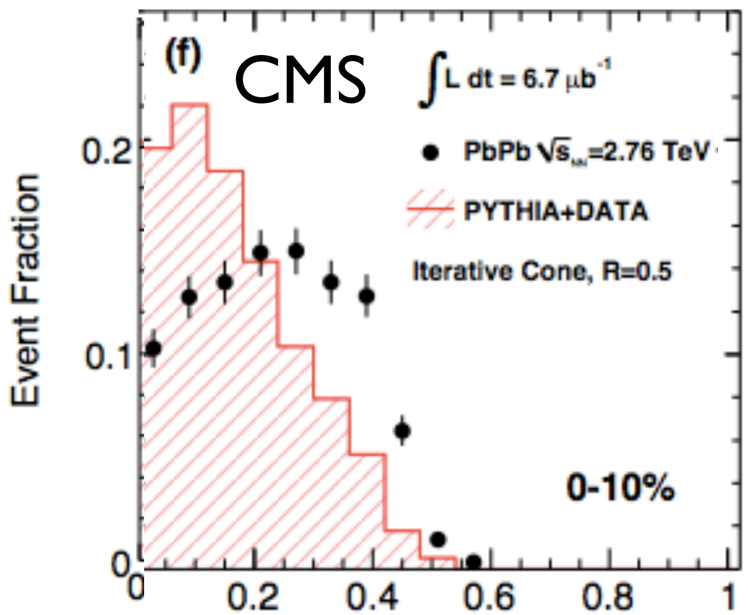


Limit of infinitely massive scattering centers yields all radiative e-loss.

sPHENIX Observables

A comprehensive program of many observables will be needed.

- Single jets, direct photons: $\mathbf{R_{AA}}$, v_N
- Intra-jet hadron correlations (longitudinal and radial modifications)
- Jet-jet, photon-jet correlation: I_{AA}, $\mathbf{A_J}$
- Jet-hadron correlations (global response)
- Heavy flavor jets
- Separated Upsilon States



$$A_J \equiv \frac{E_1 - E_2}{E_1 + E_2}$$

How well could jets be measured at RHIC?

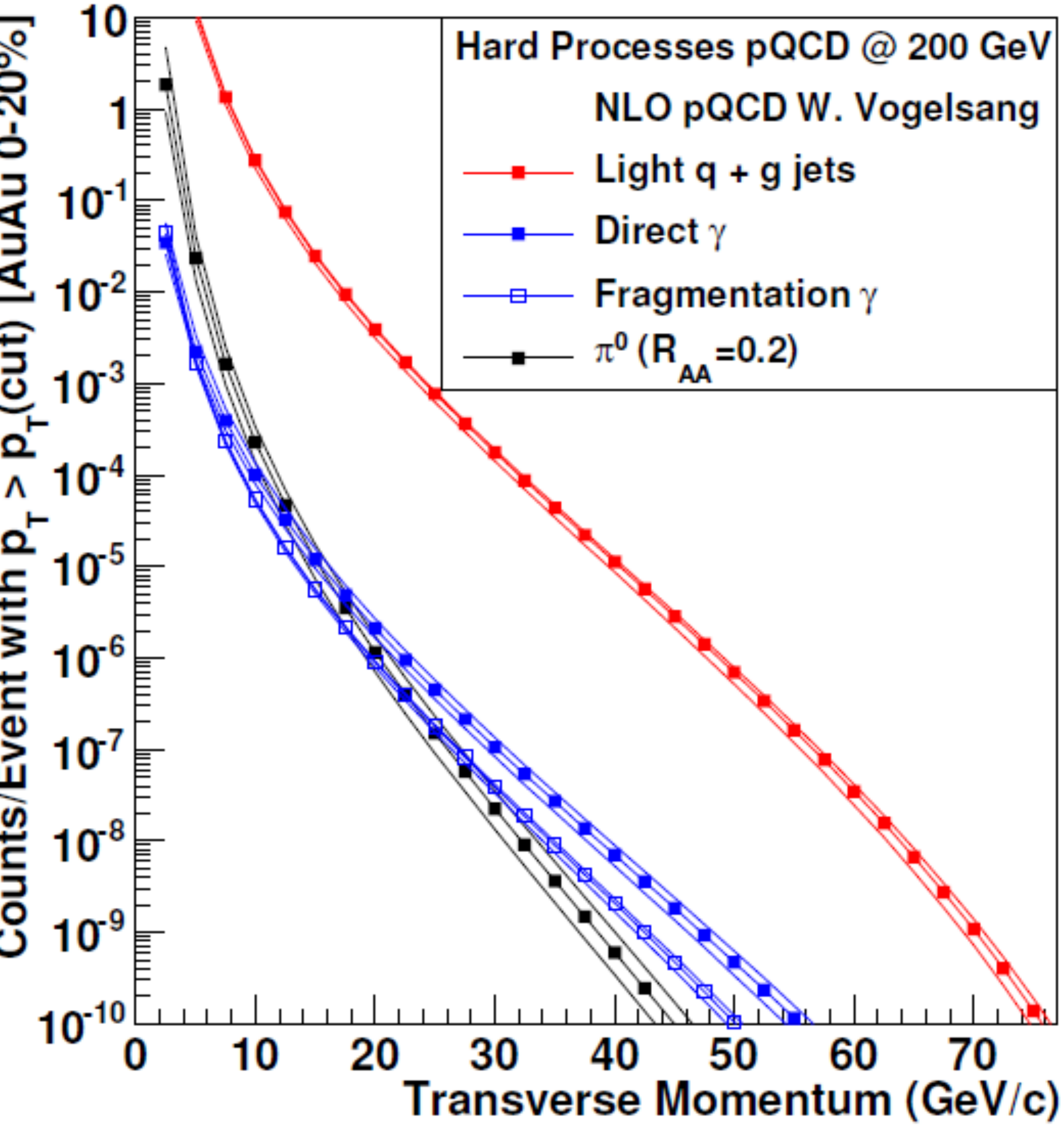
An ideal detector, even sPHENIX, would encounter these 3 issues:

(1) Rate: How quickly does hard production drop at RHIC?

(2) Resolution: How well can we measure real jets?

(3) Contamination: How are the jet measurements impacted by background fluctuations masquerading as jets--fakes?

Rates: jets, di-jets, γ-jets



Events: 50 billion collected, 200 billion sampled

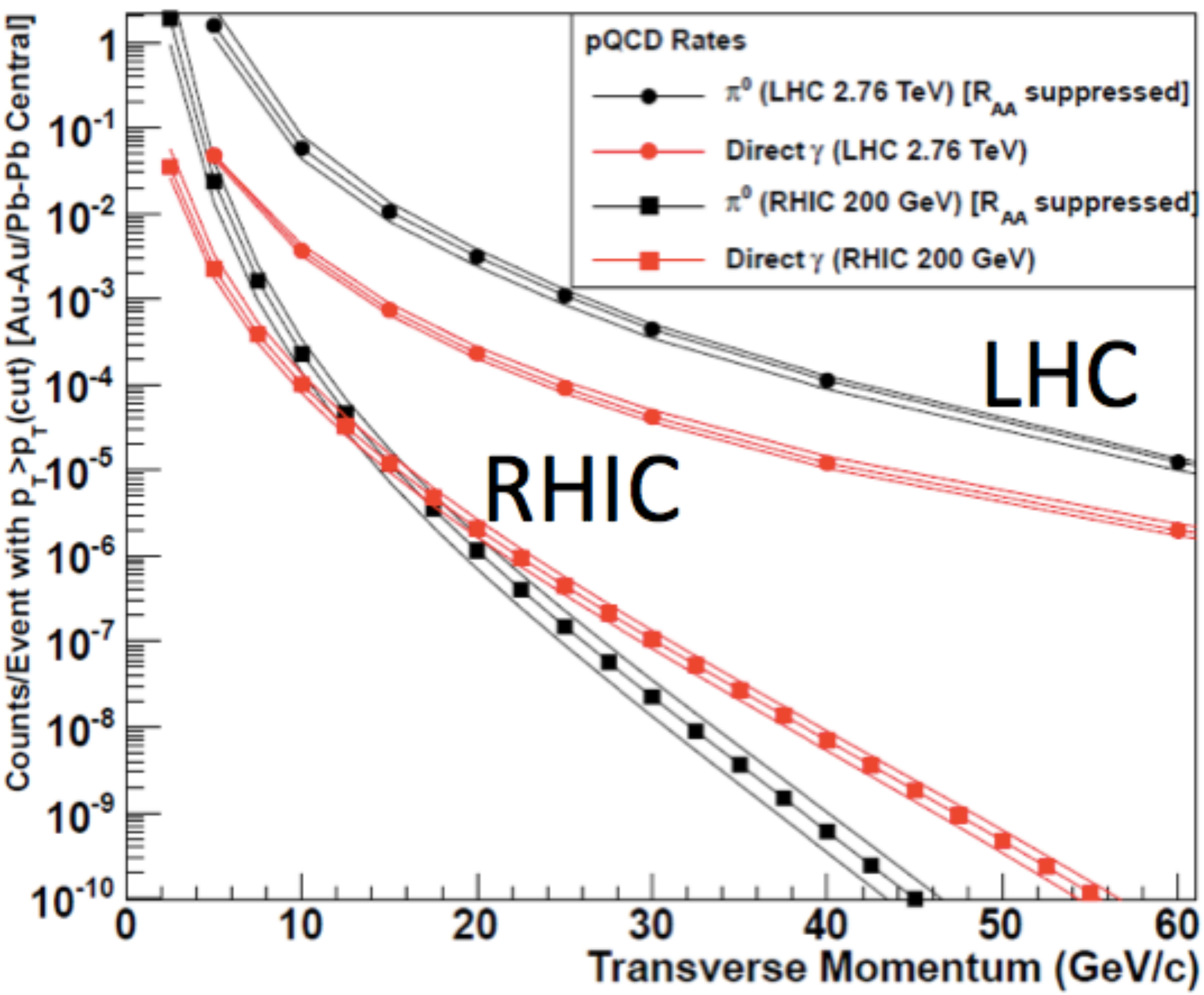
$-1 < \eta < 1$	Au+Au (central 20%)	p+p	d+Au
>20GeV	10^7 jets 10^4 photons	10^6 jets 10^3 photons	10^7 jets 10^4 photons
>30GeV	10^6 jets 10^3 photons	10^5 jets 10^2 photons	10^6 jets 10^3 photons
>40GeV	10^5 jets	10^4 jets	10^5 jets
>50GeV	10^4 jets	10^3 jets	10^4 jets

Rates based on full stochastic cooling, but no additional accelerator upgrades

Huge rates allow differential measurements with geometry (v_2, v_3, A+B, U+U, …) & precise control measurements (p(d)+Au & p+p). ~80% as dijets!

Direct γ Signal-to-Background

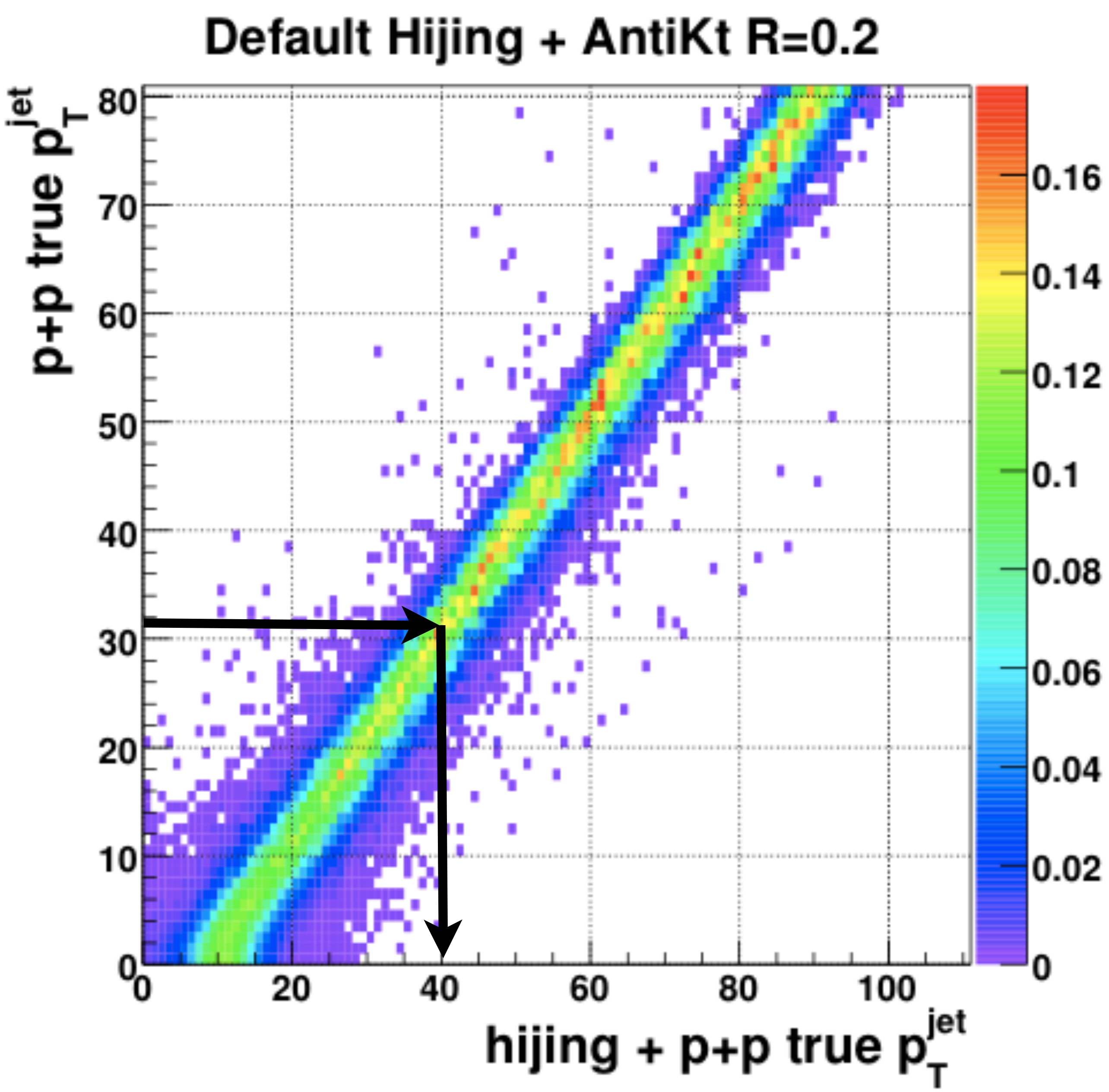
sPHENIX has excellent direct photon capabilities

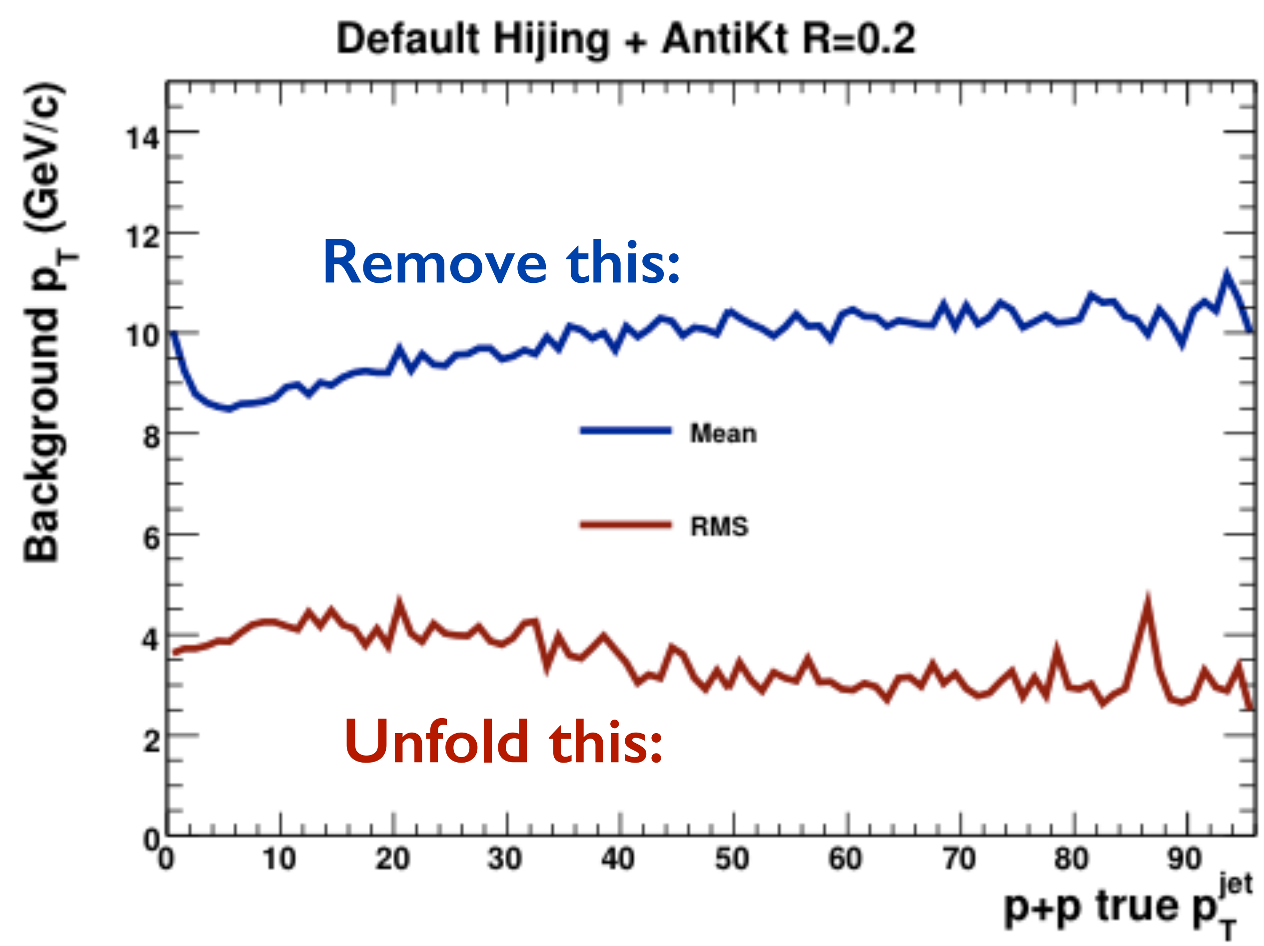


In Au+Au central collisions for $p_T > 20$ GeV, direct photons dominate S/B > 3

Simple isolation cuts with full calorimetry give additional handle and enable p+p and p+A comparison measurements

Resolution: Underlying Event Impact





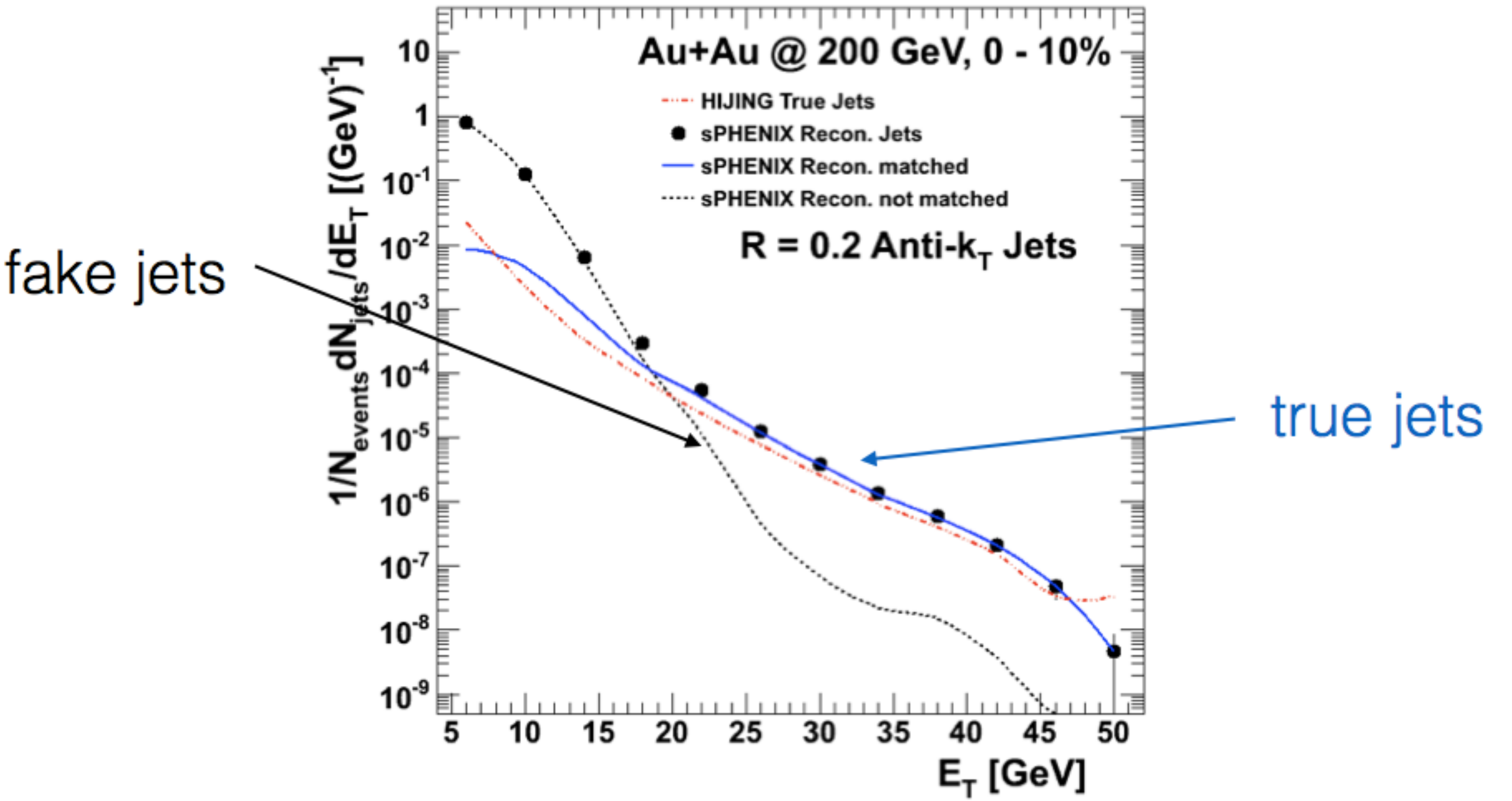
A 30 GeV embedded jet picks up ~10 GeV from the background to become a 40 GeV reconstructed jet

Subtract: ~10 GeV/c per jet
Unfold: ~3.5 GeV/c of smearing

~7 GeV/c of smearing at R=0.4
Comparable to HCAL resolution

More on jet subtraction:
PRC 86, 024908 (2012)

Contamination: Fake Jet Rates

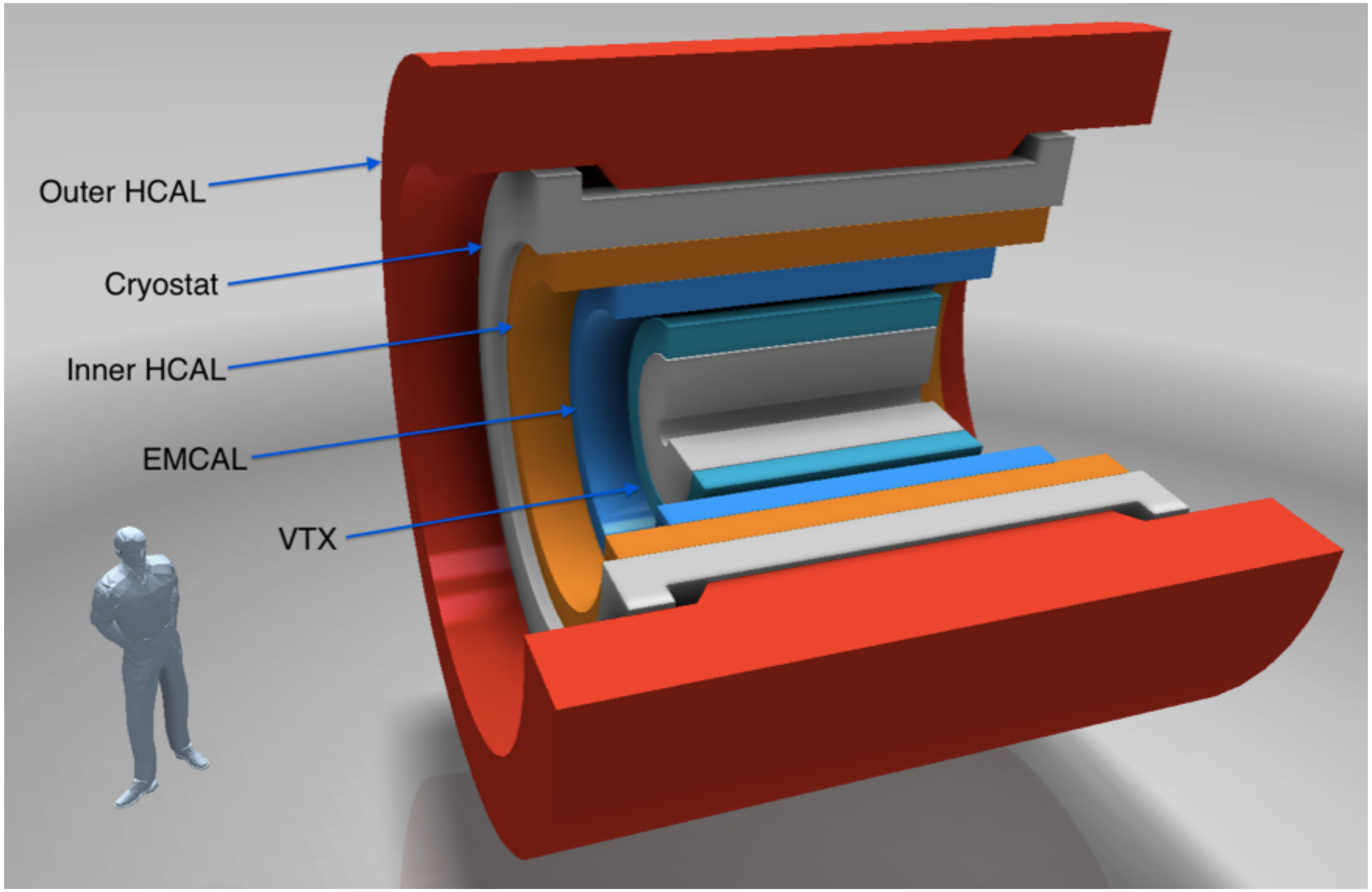


for R=0.2 jets, > 20 GeV real jets dominate in HIJING

for R=0.4 jets, > 35 GeV

enables broad coverage without jet fragmentation bias

sPHENIX detector



BaBar Magnet 1.5 T

Coverage |η| < 1.1

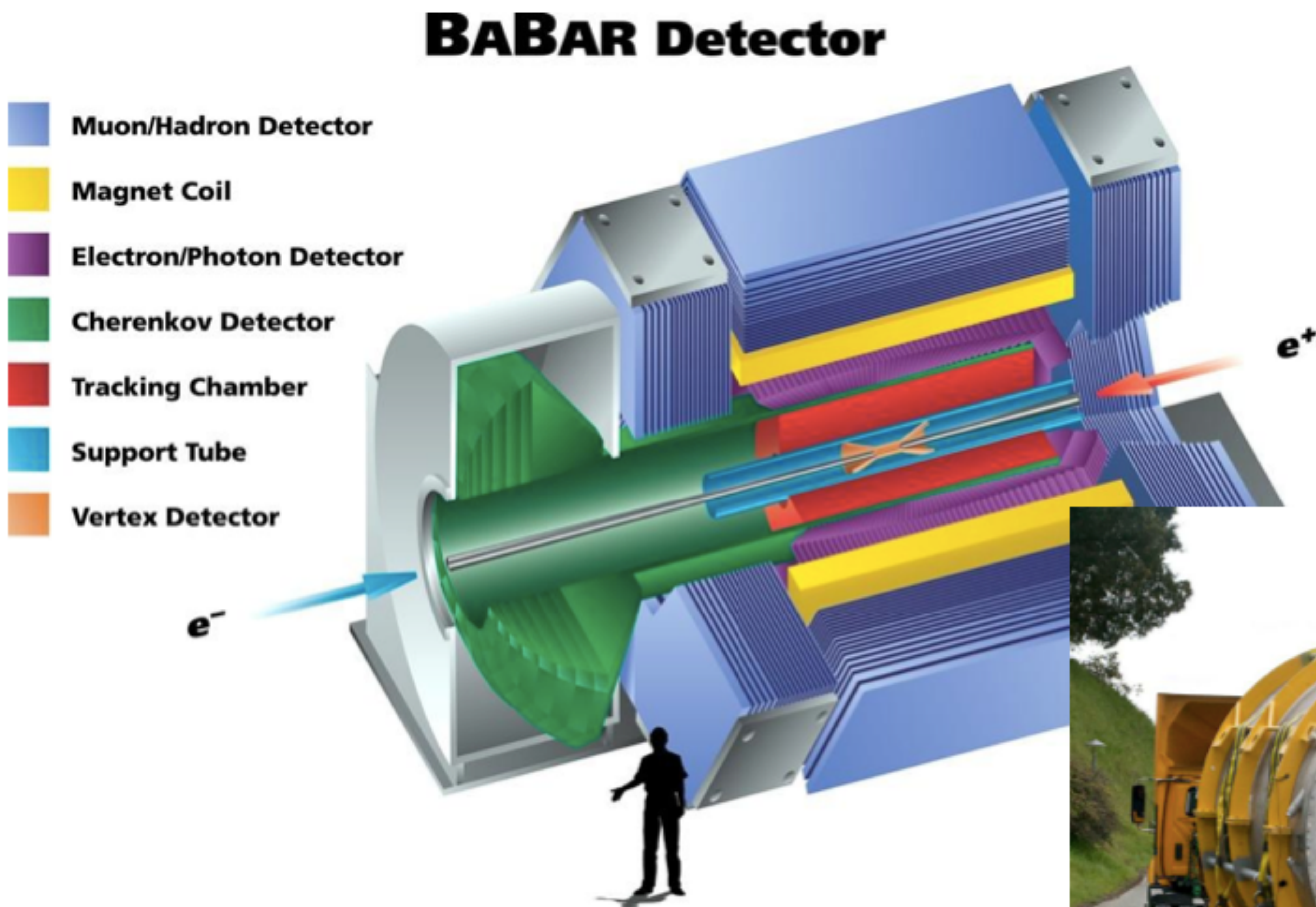
All silicon tracking
Heavy flavor tagging

SPACAL EmCal
12%/sqrt(E) resolution

Two longitudinal segments of HCal
5 interaction lengths

Common Silicon Photomultiplier readout for Calorimeters
Full clock speed digitizers, digital information for triggering
High data acquisition rate capability ~ 10 kHz

Acquisition of the BaBar Magnet



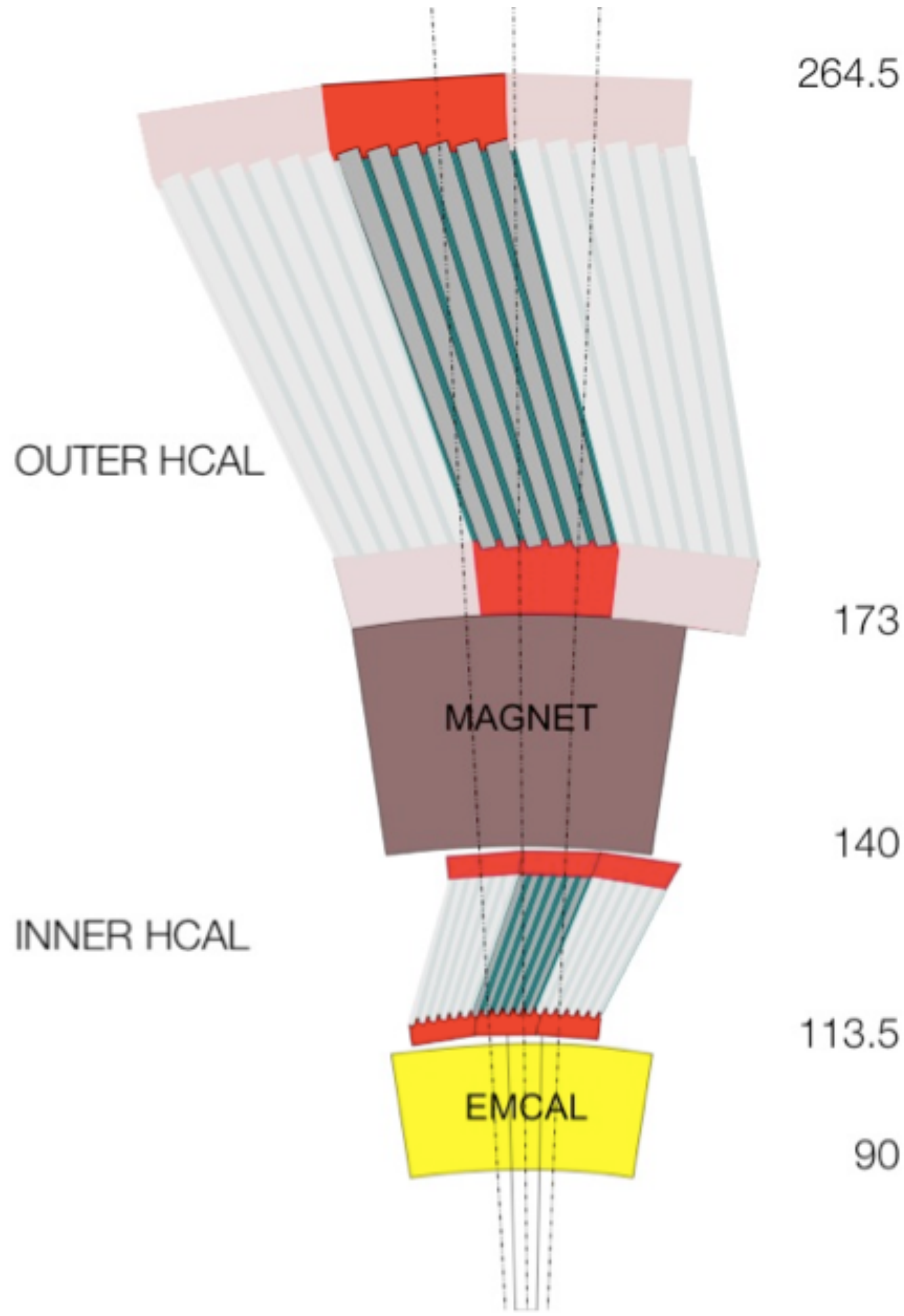
ITEM NO. (b)	DESCRIPTION (Include noun name, FSC Group and Class, Condition Code and if available, National Stock Number) (c)	UNIT (d)	QUANTITY (e)	ACQUISITION COST UNIT (f)	ACQUISITION COST TOTAL (g)
	Administrative Transfer				
1	BaBar Solenoid and Components Date of Mfr: 1996 (See attached list)	ea	1	12,000,000.00	$ 12,000,000.00
				Total Acquisition Cost	$ 12,000,000.00

sPHENIX Calorimeters

- EMCAL ≈$18X_0$≈$1\lambda_I$
- Inner HCAL ≈$1\lambda_I$
- Magnet ≈$1X_0$
- Outer HCAL ≈$4\lambda_I$

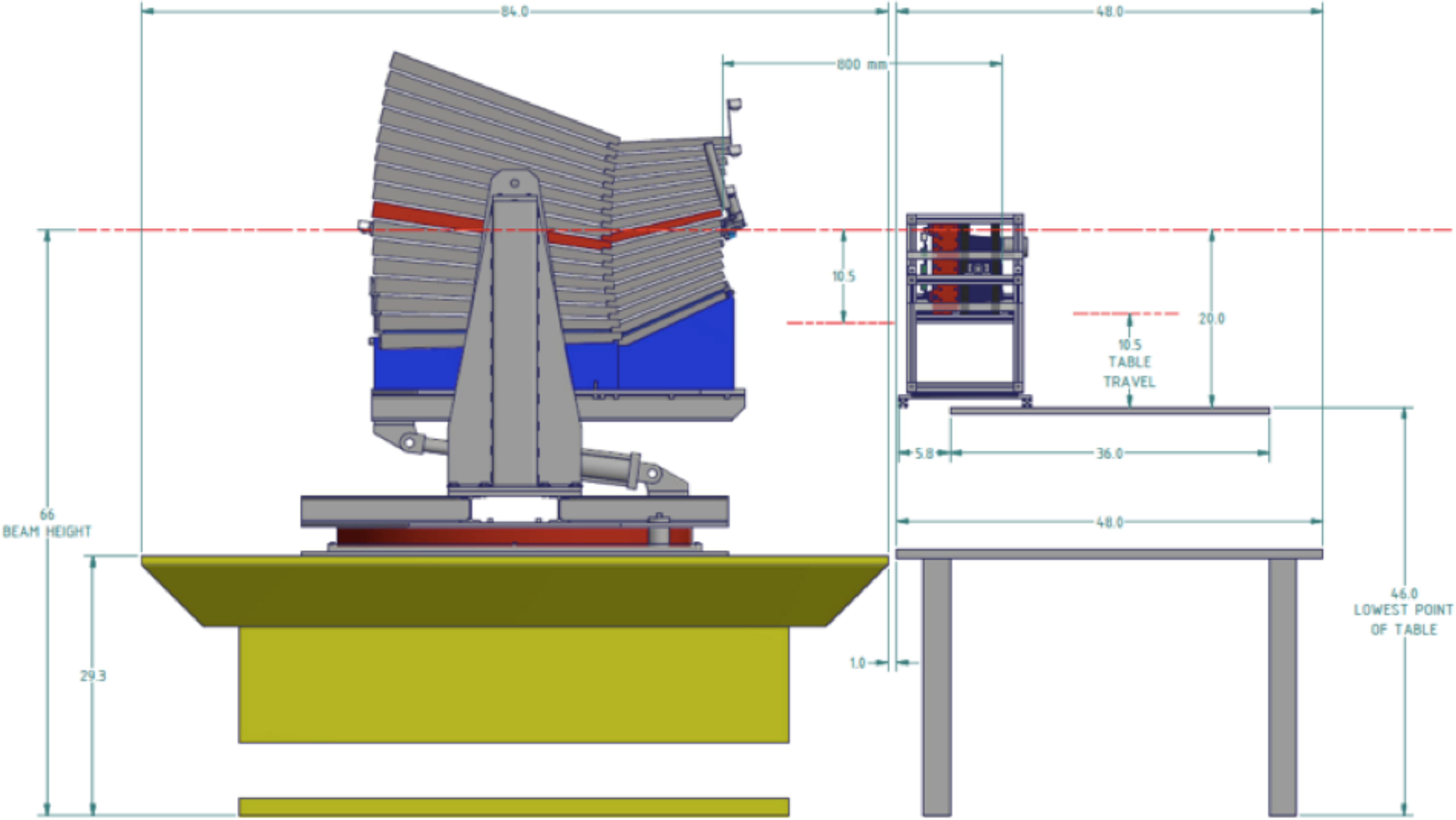
HCal 5λ deep (plus EMCal 1λ deep) leads to few percent energy leakage for hadrons above 50 GeV; comparable to other contributions to energy resolution constant term.

Key difference with calorimeters for much higher energy jets.



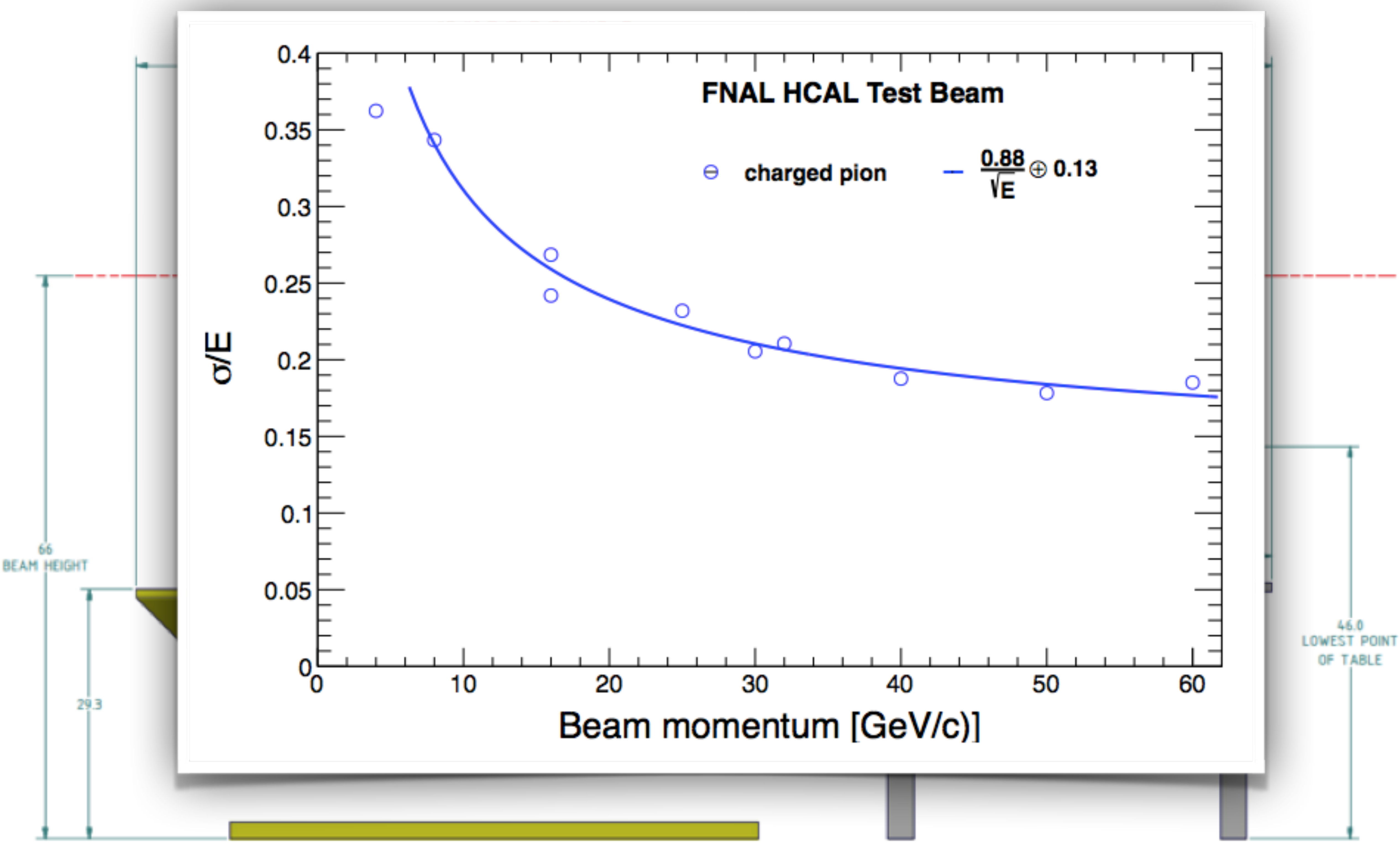
FNAL Test Beam Exp T-1044

HCAL prototype



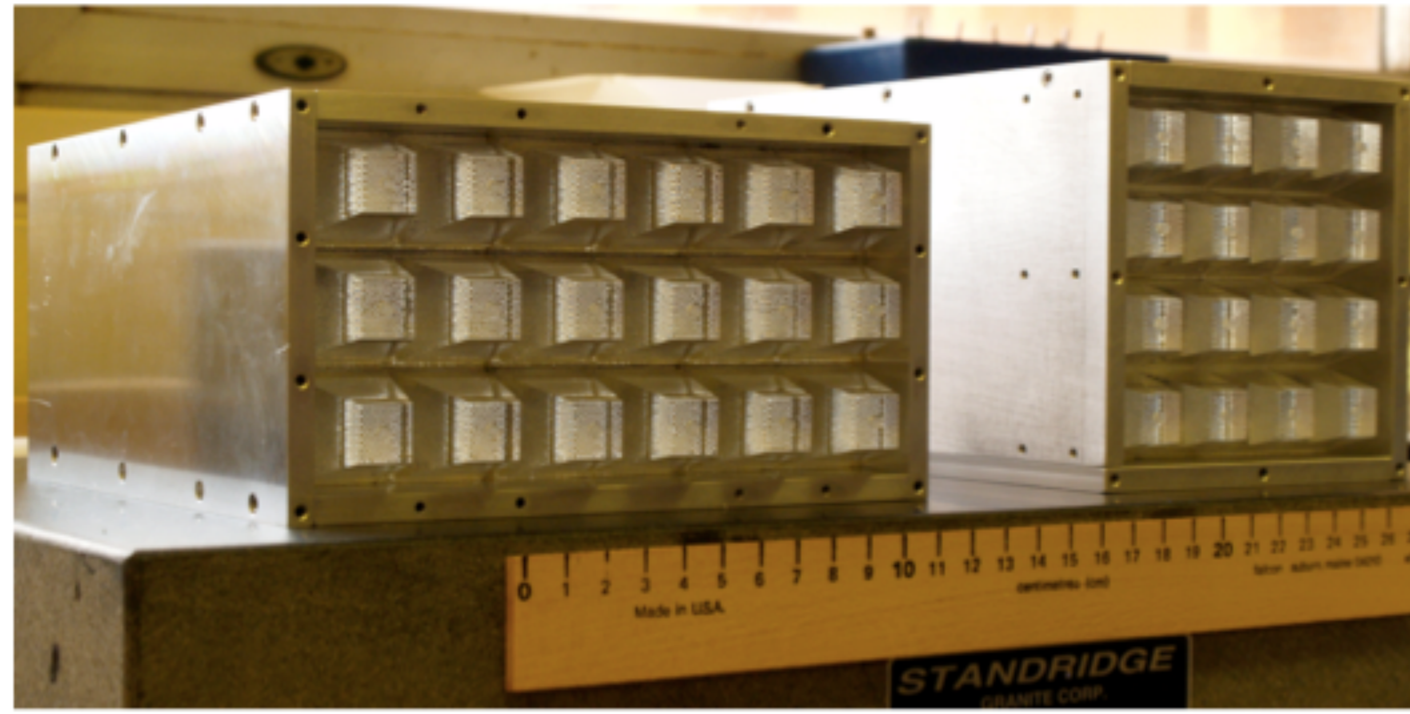
FNAL Test Beam Exp T-1044

HCAL

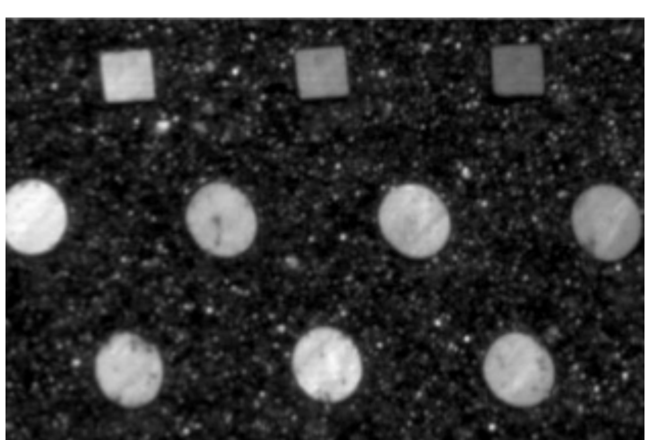


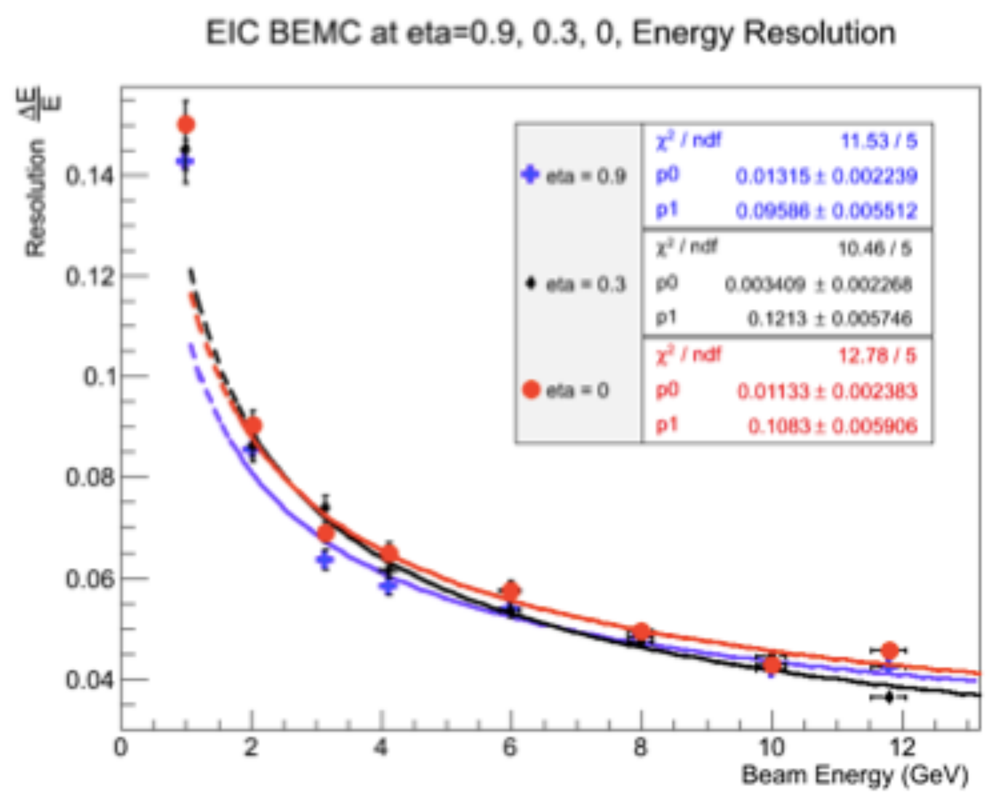
EMCAL SPACAL Option

- 18 X_0 deep
- 2.3 cm R_M ≈ cell size
- 256x96 = 24,576 channels
- Sampling fraction ≈ 2%
- Resolution ≈ 12%/√E
- ≈ 500 pe/GeV



SPACAL prototypes (Tsai)

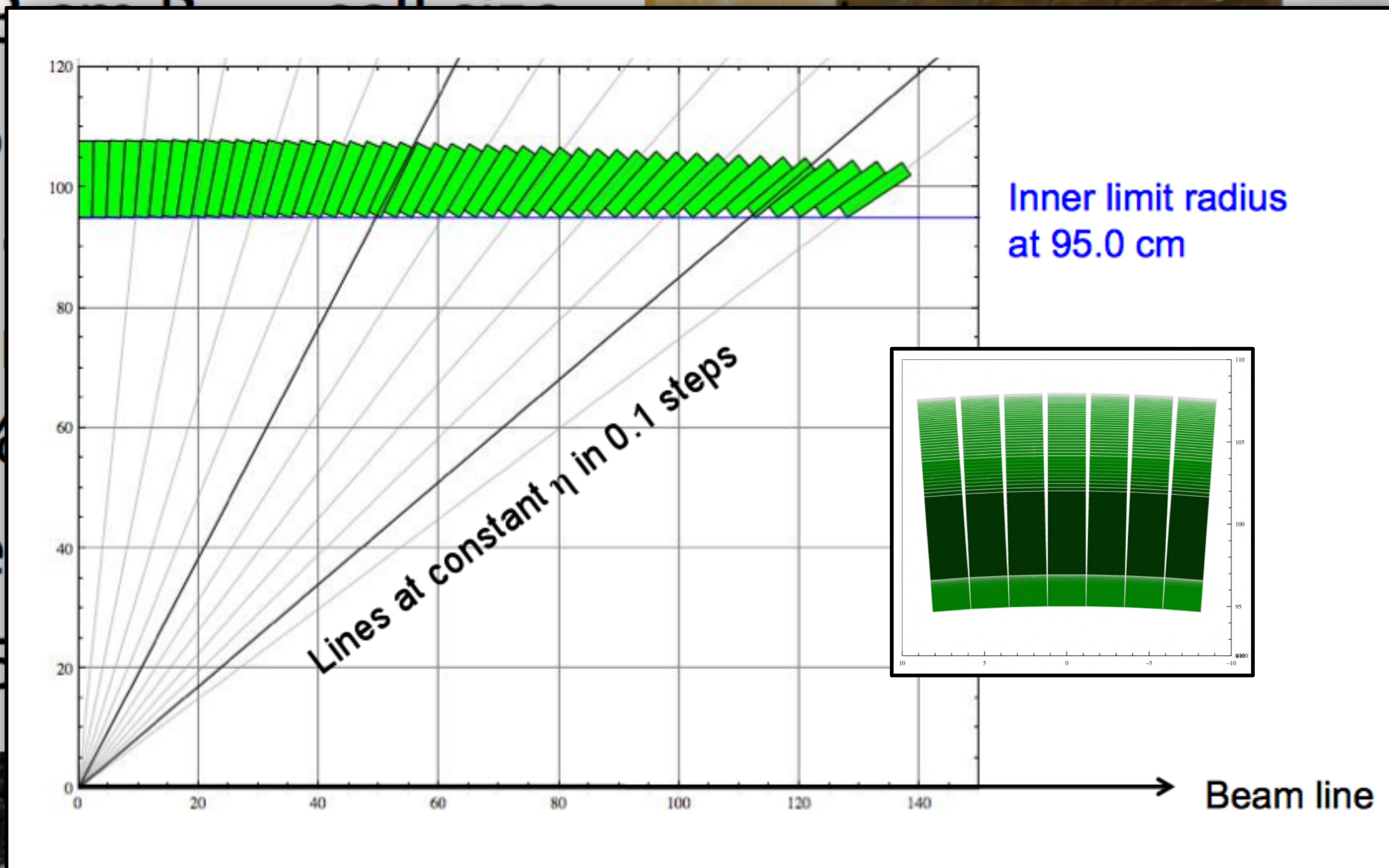


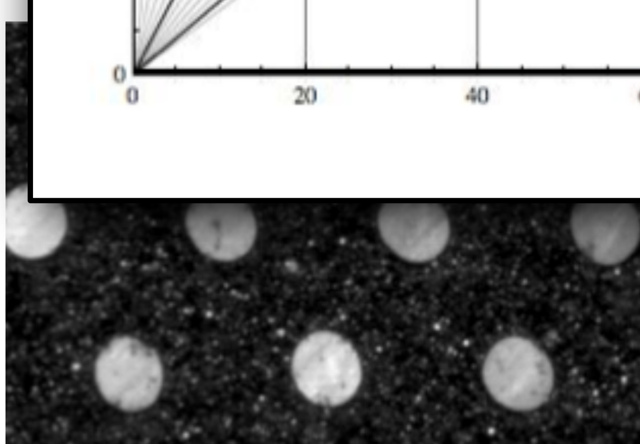


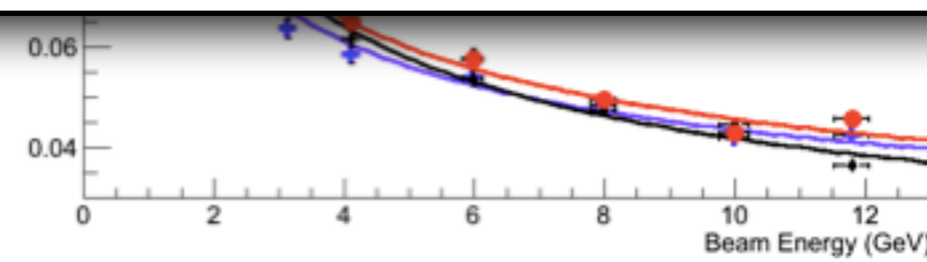
FNAL T-1018 results

EMCAL SPACAL Option

- 18 X_0 deep
- 2.3
- 25 ch
- Sa 2%
- Re
- ≈ 5

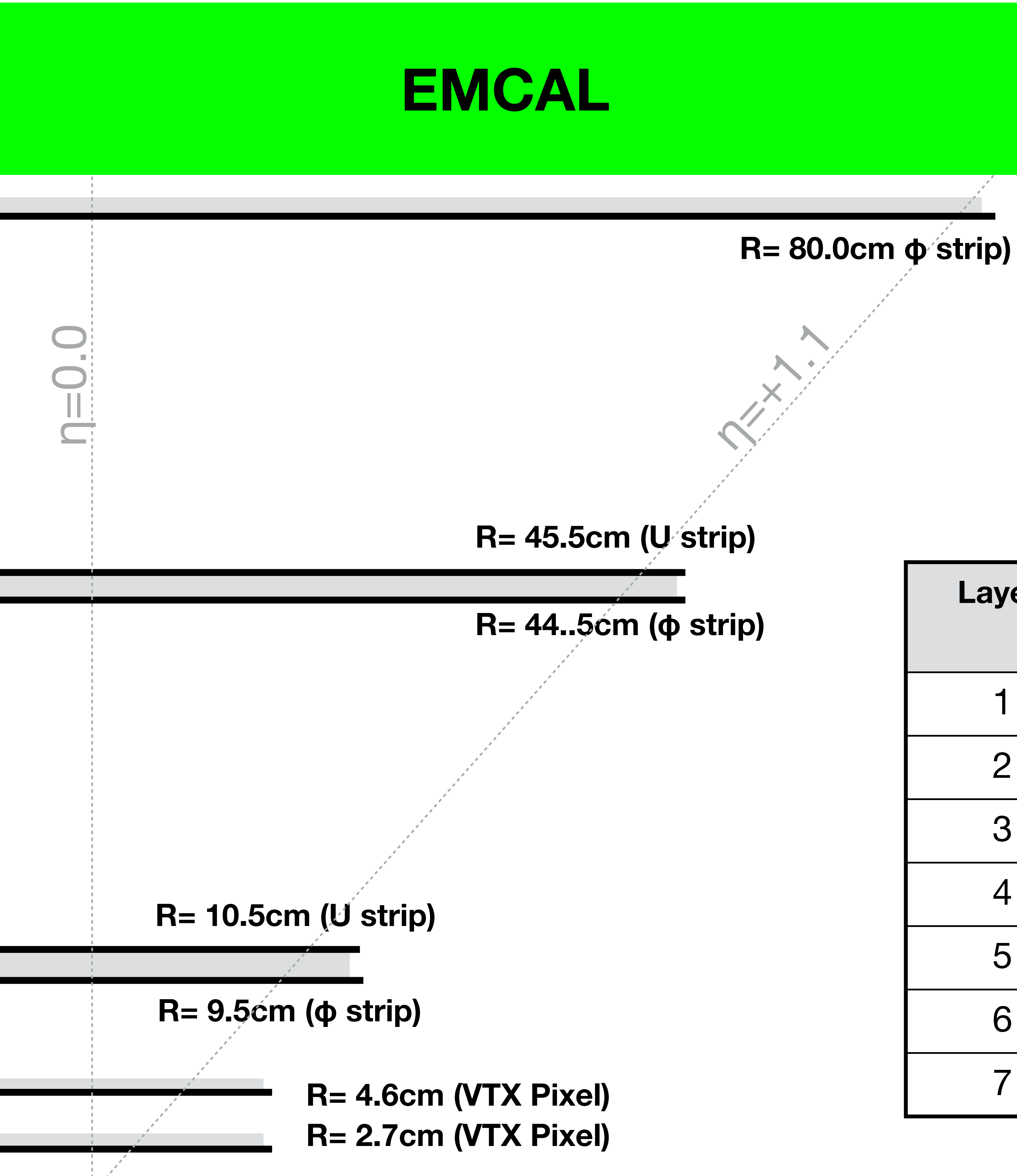






AL T-1018
results

Silicon Tracking Layers

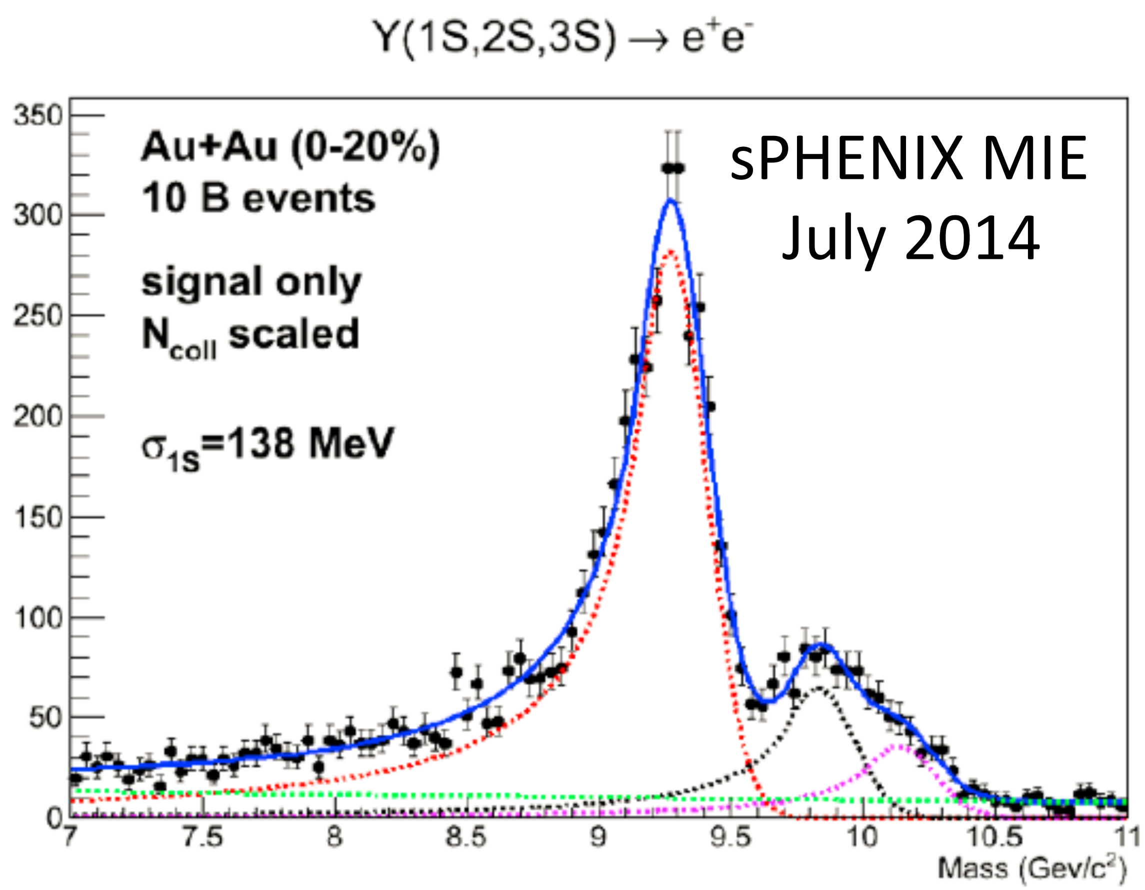


Extended radial reach for **improved resolution**

Shared support for outer tracking momentum and pattern recognition layers for **material budgeting**

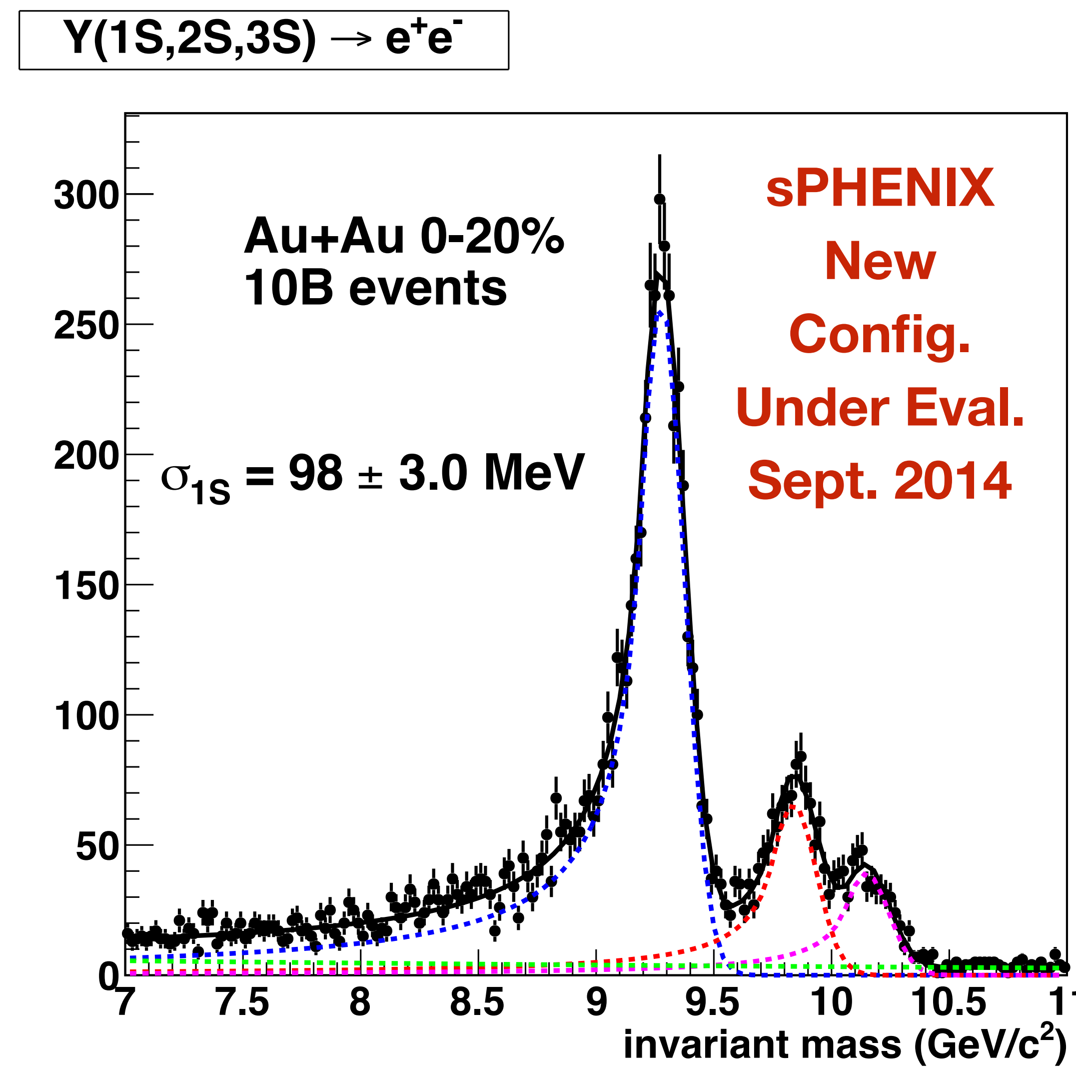
Layer	ϕ pitch (um)	z pitch (mm)	Thickness (%)
1	50	0.425	1.3
2	50	0.425	1.3
3	60	8	2.7
4	*240*	*2*	
5	60	8	2.0
6	*240*	*2*	
7	60	8	2.0

Tracking Optimization I



Mass resolution and expected counts (without backgrounds) from sPHENIX Proposal

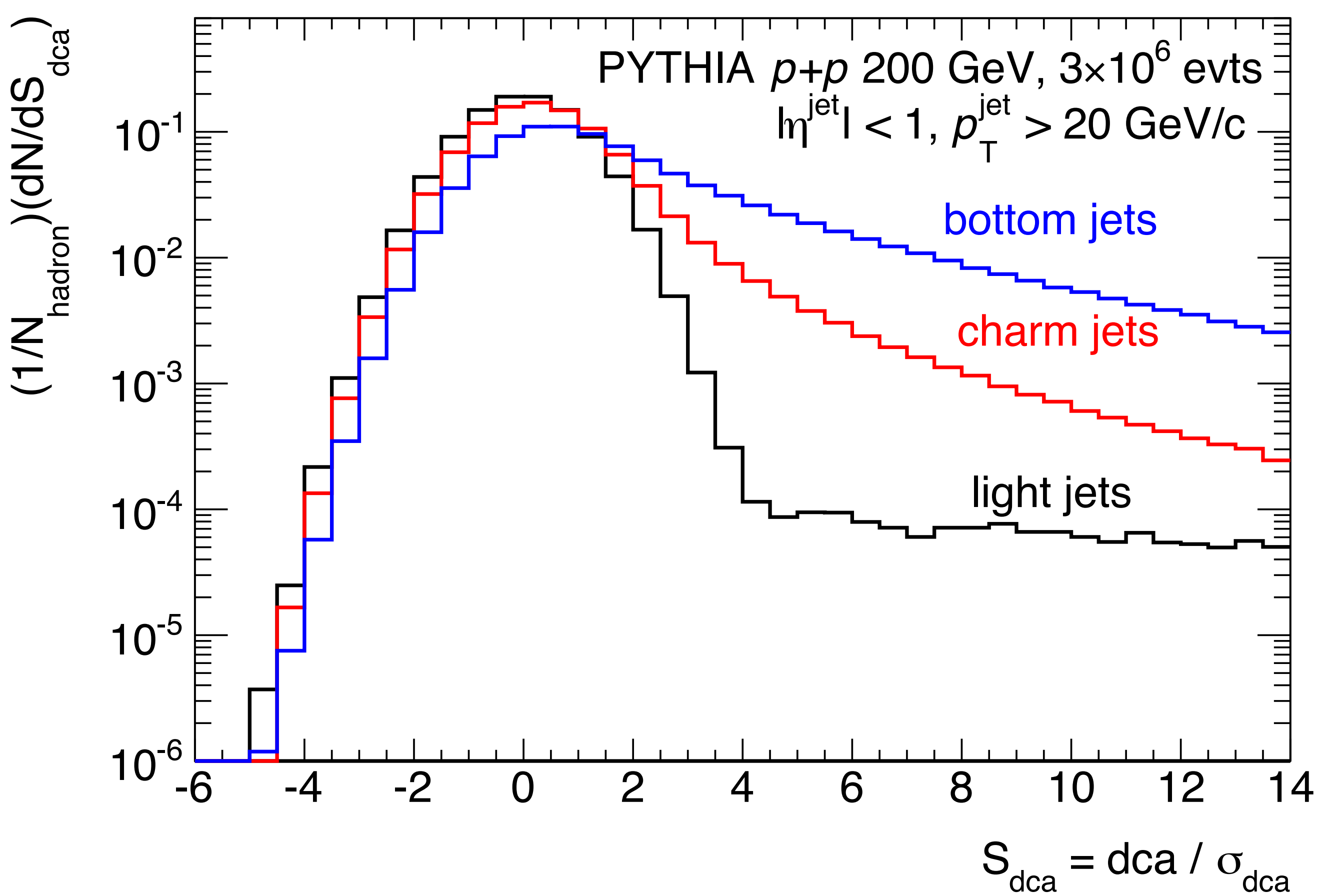
Received suggestion at physics review to further optimize tracking and evaluate performance/cost tradeoff

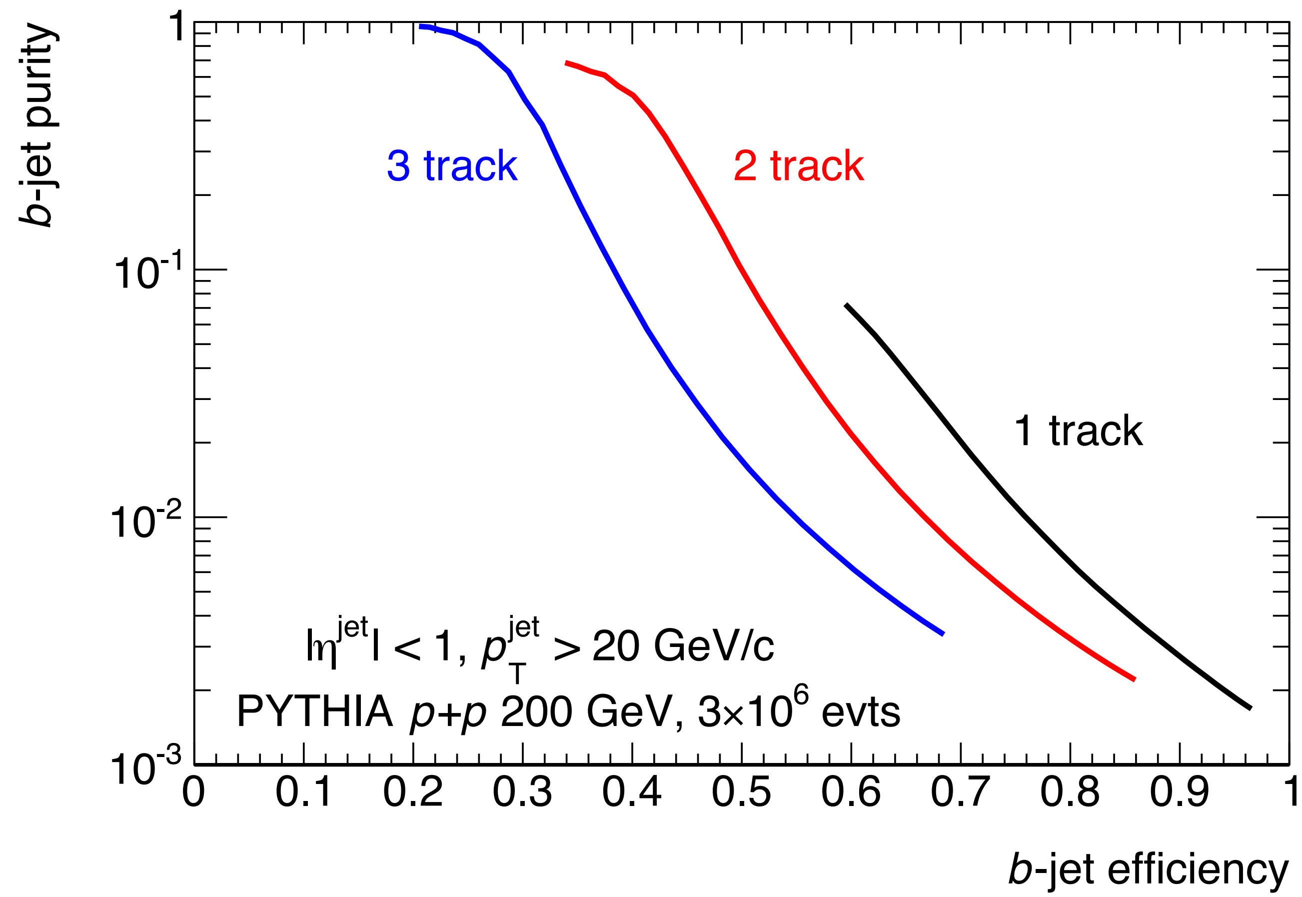


Revised design improve mass resolution

Figure of merit to preserve as we further revise the design

Tracking Optimization II





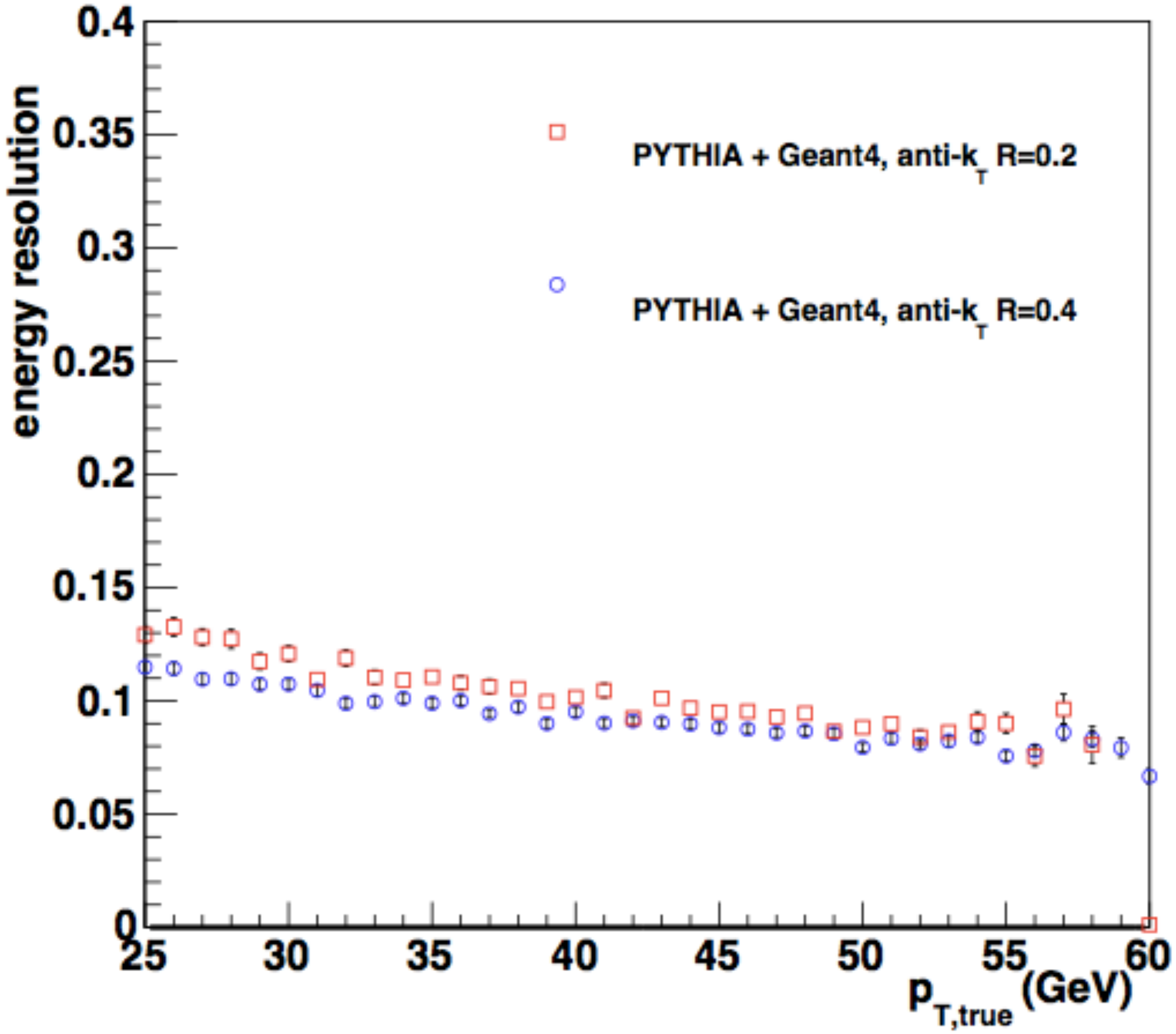
sPHENIX has explored b-jet tagging through requiring tracks in the jet with **a large 2-D distance of closest approach** (d.c.a) to the primary vertex

Fast simulation using parameterized detector responses (inc. vertex resolution of 70 μm)

Reasonable efficiency vs purities can be achieved.

Preserve as design criteria during follow-up GEANT4 studies

Jet Performance: p+p



R=0.2: 65%/√E

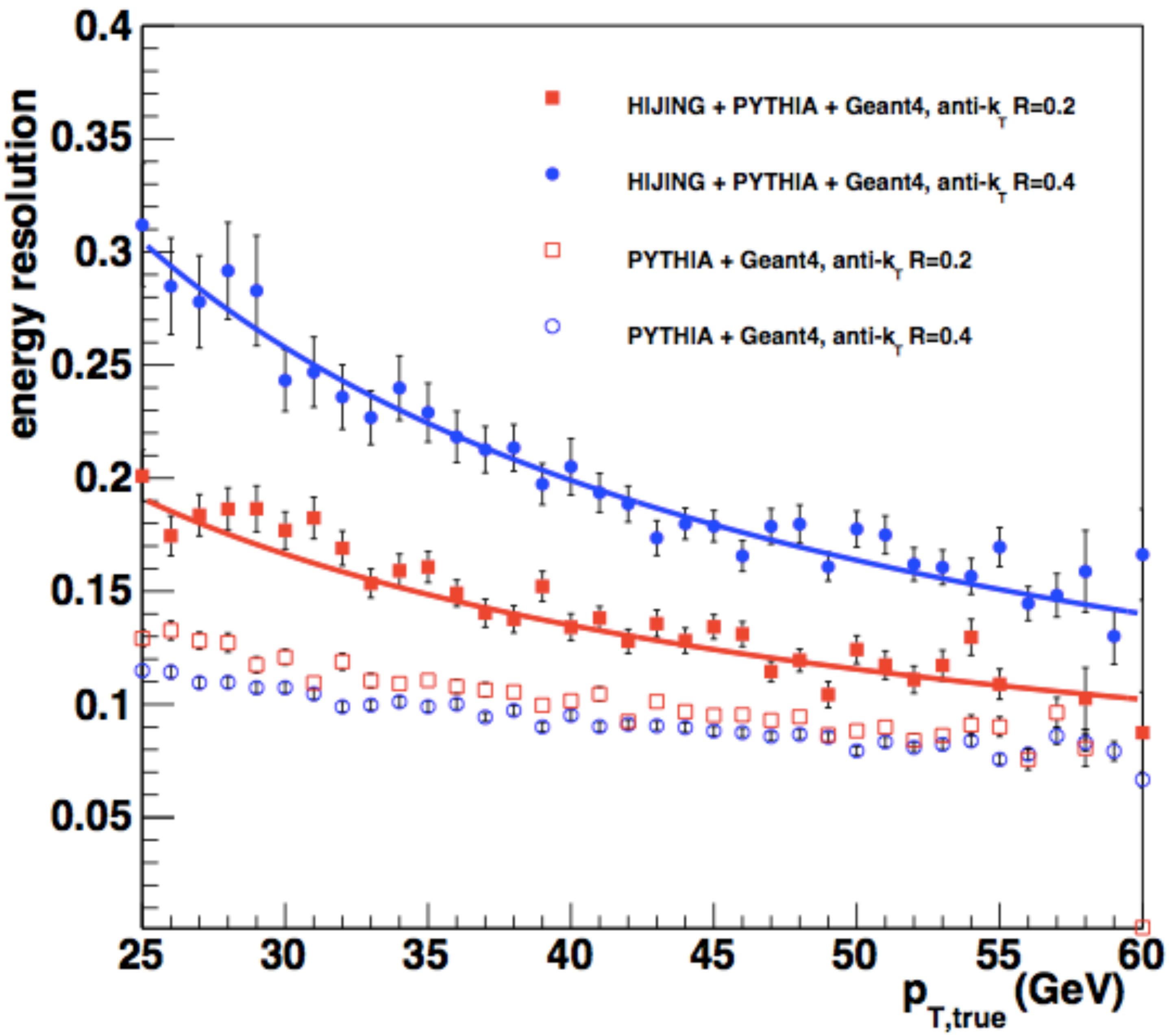
R=0.4: 60%/√E

both small constant term

these resolutions are substantially better than the required resolution, driven by very good HCal resolution

Jet Performance: A+A

PYTHIA events embedded into central HIJING events

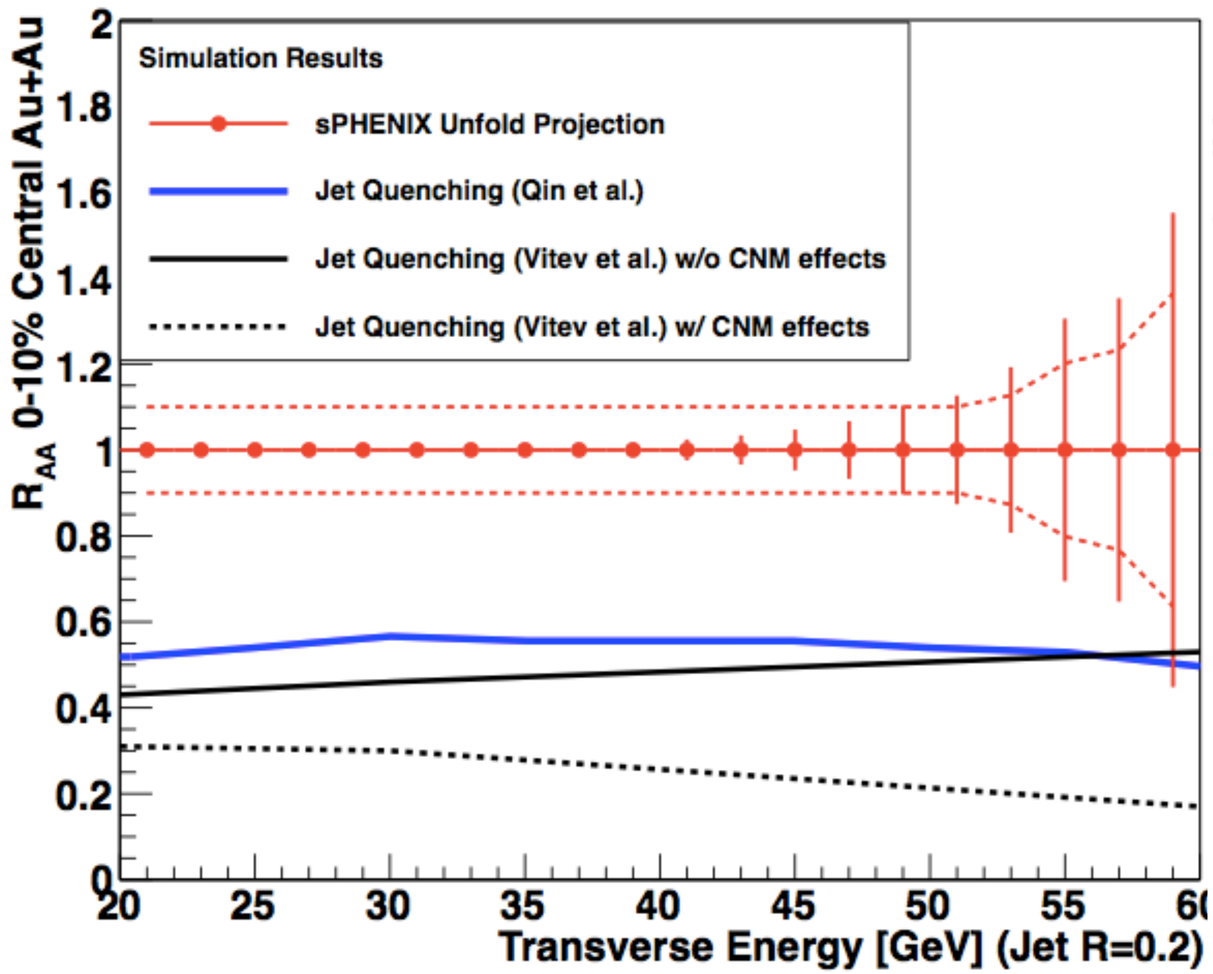


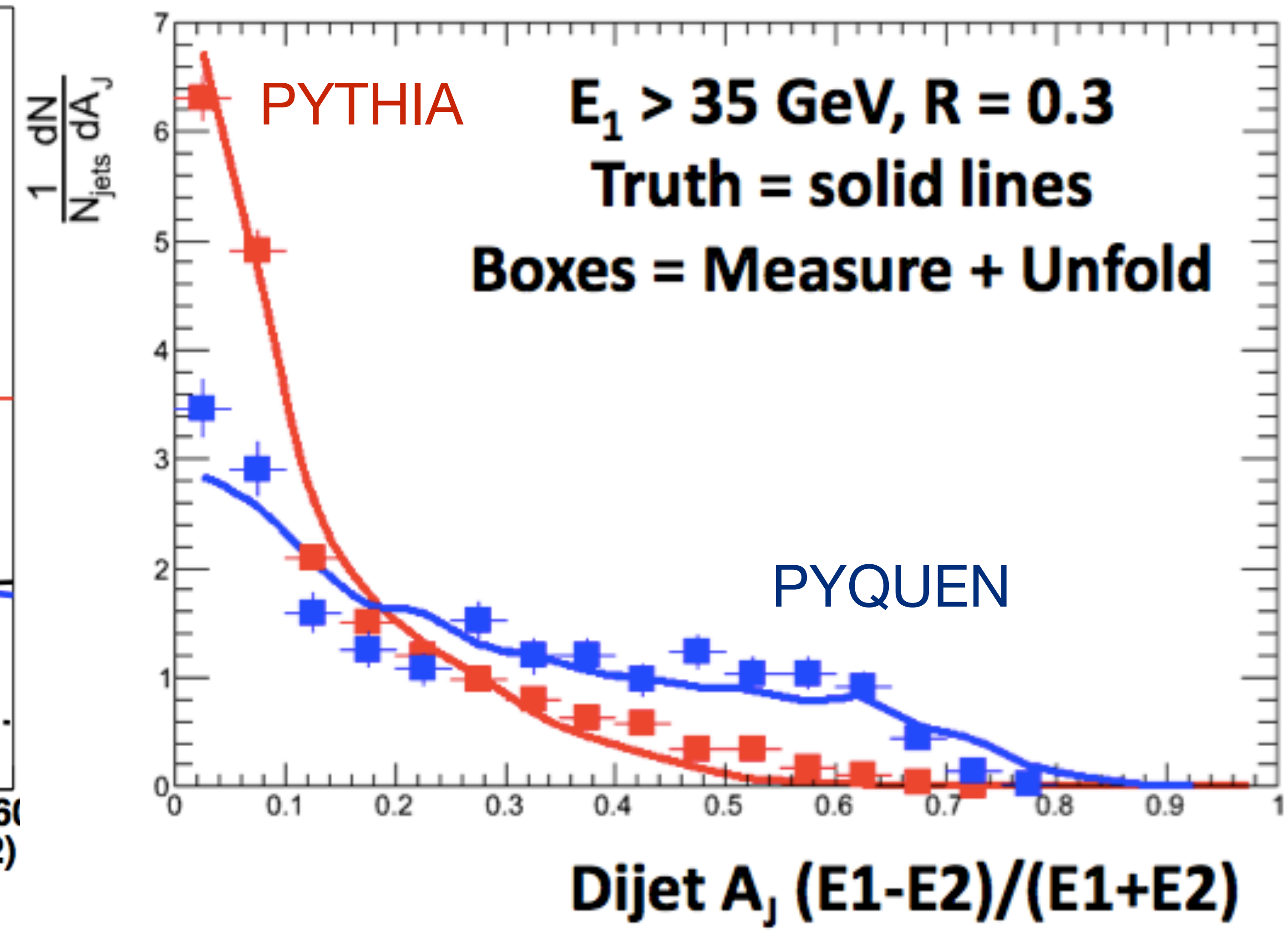
lines: p+p resolution ⊕ UE smearing

7 GeV for R = 0.4

3.5 GeV for R = 0.2

Projected jet R_{AA} and A_J



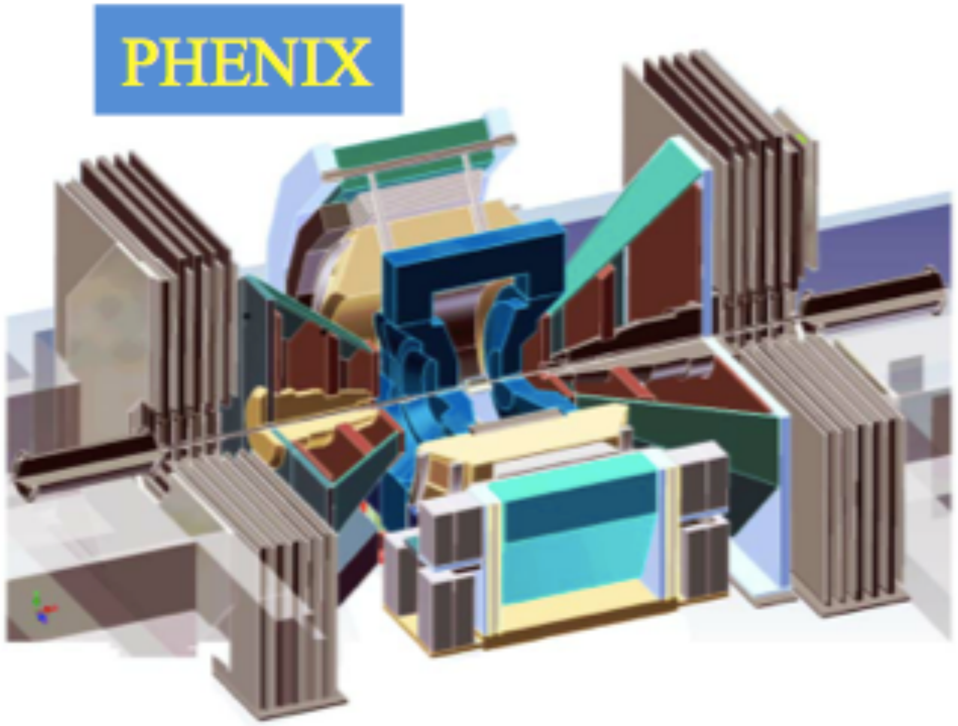


High precision out to 50 GeV/c

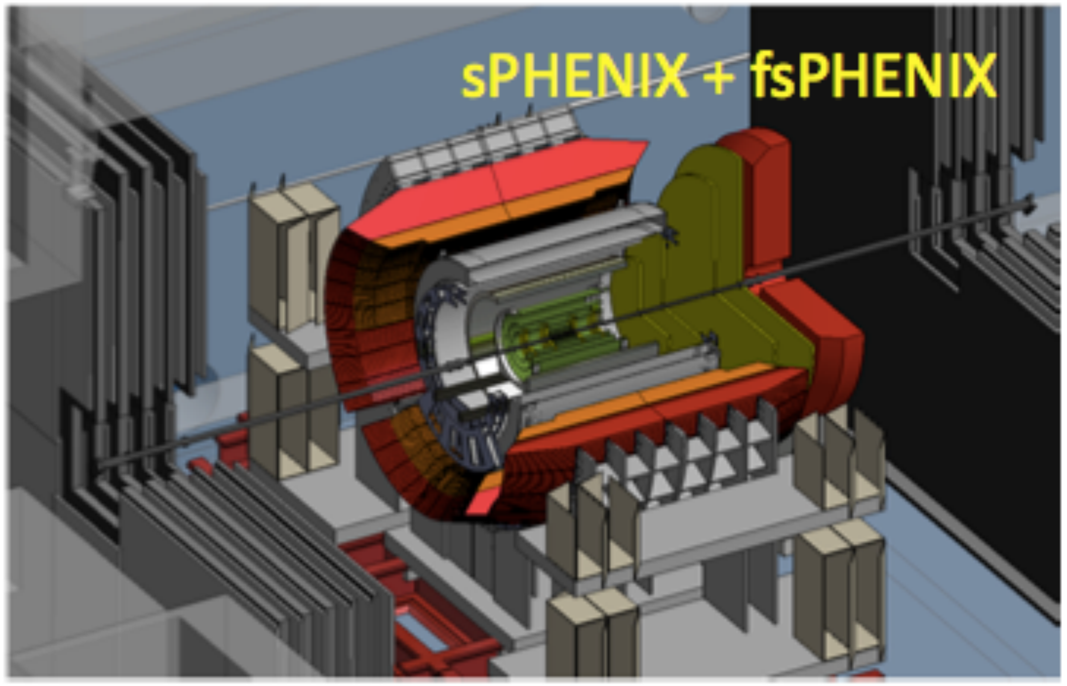
Easily resolvable A_J modification

Unfolding of detector resolutions under-control

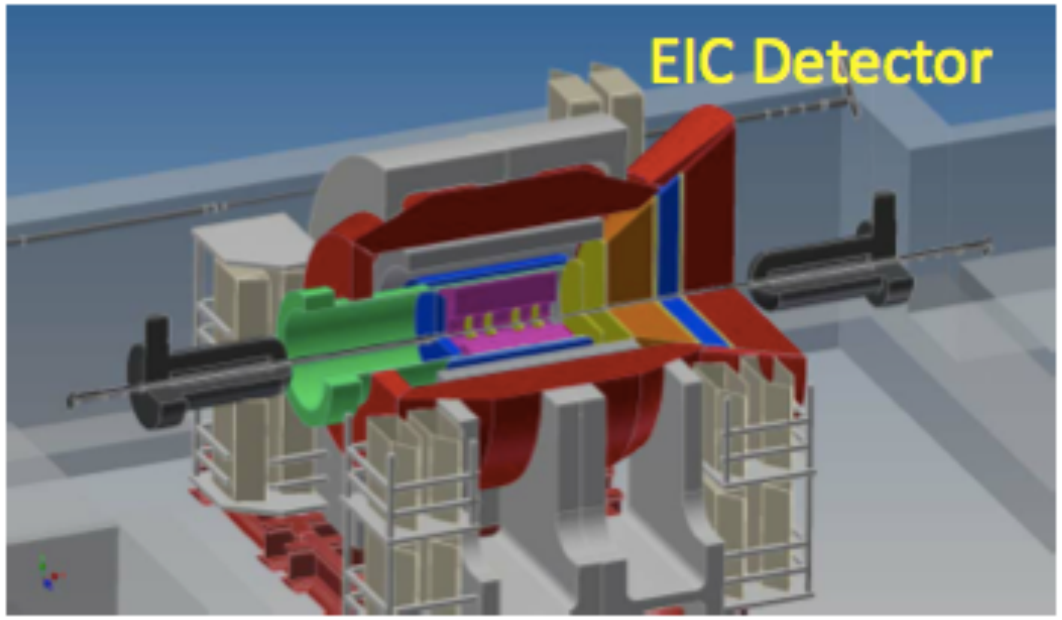
sPHENIX evolution



~2021-22



~2025



sPHENIX evolution
into an EIC detector

Summary

(1) Physics case for a jet detector at RHIC
and the key measurement observables

Are jet measurements interesting at RHIC? ***YES!***
Can jets be well-measured at RHIC? ***YES!***

(2) The detector configuration to fit these observables

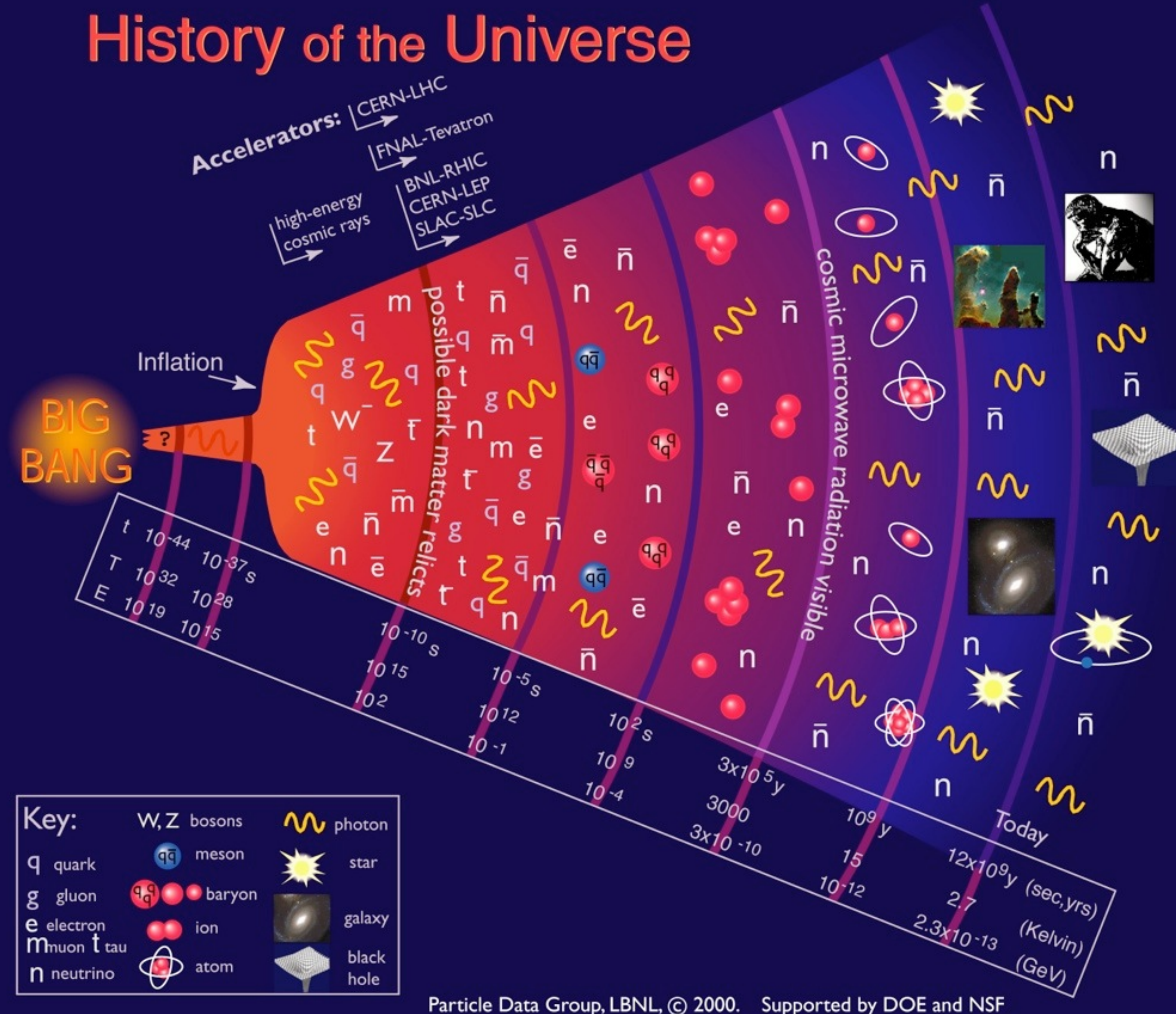
Can a detector be built to make these measurements? ***YES!***

(3) Planned operations and additional opportunities

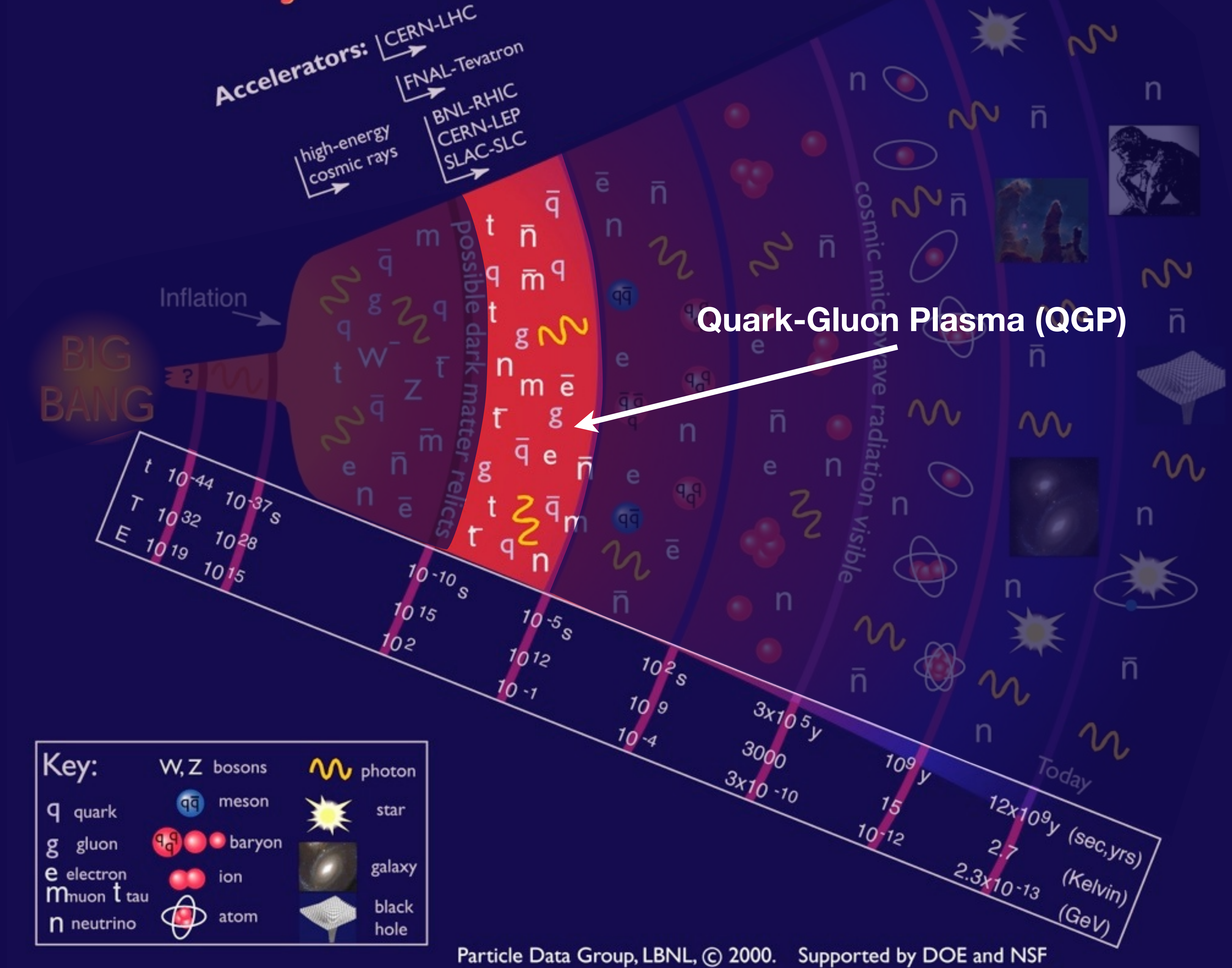
Does the jet program align with our other
goals as a nuclear physics community? ***YES!***

Backup Slides

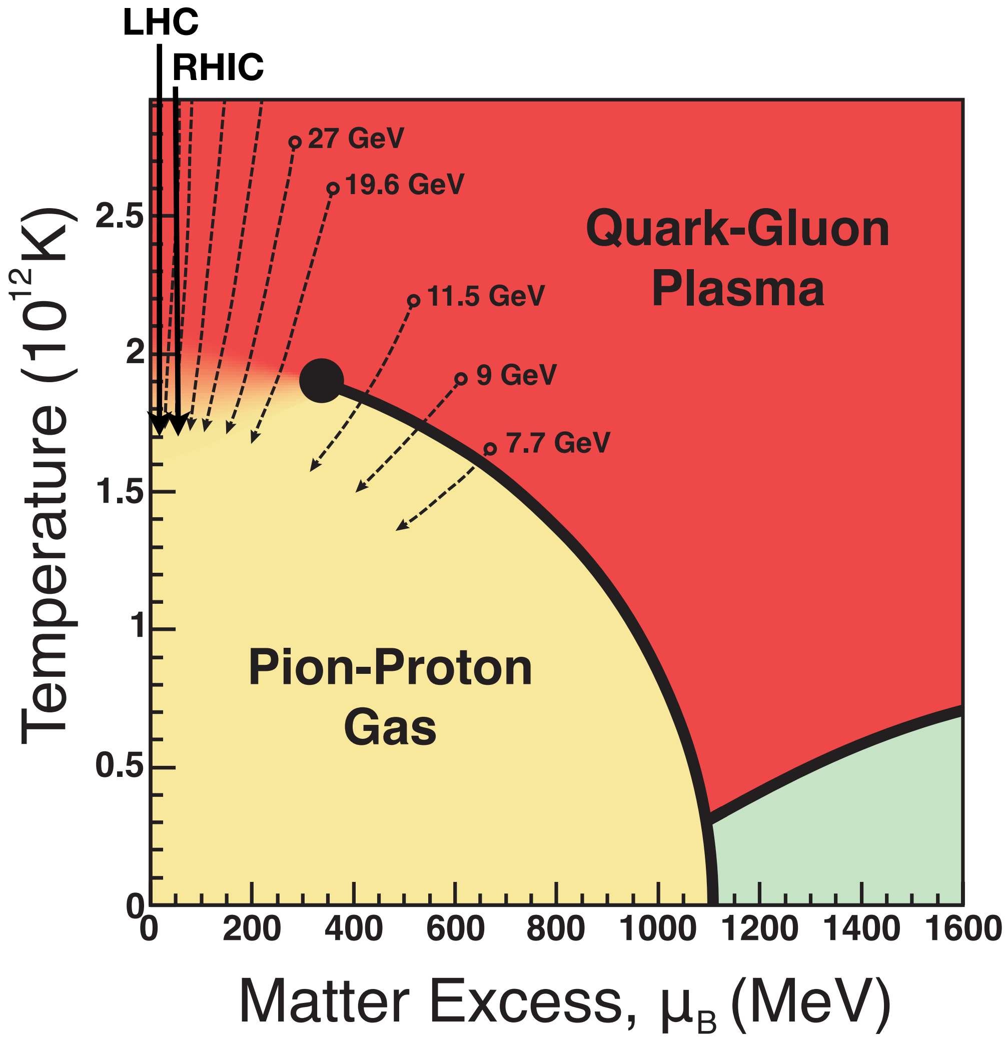
Physics	Detectors	Requirements	
Full jet reconstruction	EMCal	$\sigma/E < 20\%/\sqrt{E}$	sPHENIX
	HCal	$\sigma/E < 100\%/\sqrt{E}$	
		$\Delta\eta \times \Delta\phi \sim 0.1 \times 0.1$	
		uniform within $\|\eta\| < 1$	
Direct γ, $p_T > 10\,\mathrm{GeV}/c$	EMCal	$\sigma/E \simeq 15\%/\sqrt{E}$	sPHENIX
		$\Delta\eta \times \Delta\phi \sim 0.03 \times 0.03$	
Jet-hadron	VTX 4 layers	tracking $p_T < 4\,\mathrm{GeV}/c$	Current PHENIX
	Solenoidal field		sPHENIX
High-z FFs	Jets as above	EMCal and HCal	sPHENIX
	Tracking	$\Delta p/p \simeq 2\%$	Future Option
Tagged HF jets	Jets as above	EMCal and HCal	sPHENIX
	DCA capability	Current PHENIX VTX	Current PHENIX
	Tracking	$\Delta p/p \simeq 2\%$	Future Option
Heavy quarkonia	Electron ID		
	EMCal	$\sigma/E \simeq 15\%/\sqrt{E}$	sPHENIX
		$\Delta\eta \times \Delta\phi \sim 0.03 \times 0.03$	
Separation of Υ states	Preshower	e/π rejection	Future Option
		fine segmentation	
	Tracking	$B = 2T$	sPHENIX
		$\Delta p/p \simeq 2\%$	Future Option
π^0 to $p_T = 40\,\mathrm{GeV}/c$	EMCal	$\sigma/E \simeq 15\%/\sqrt{E}$	sPHENIX
		$\Delta\eta \times \Delta\phi \sim 0.03 \times 0.03$	
	Preshower	2γ separation	Future Option
		fine segmentation	


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s
T 10 32 10 28
E 10 19 10 15
10 -10 s
10 15
10 2
10 -5 s
10 12
10 -1
10 2 s
10 9
10 -4
3x10 5 y
3000
3x10 -10
10 9 y
15
10 -12
Today
12x10 9 y (sec,yrs)
2.7 (Kelvin)
2.3x10 -13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W,Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

History of the Universe



Heavy Ion Collisions

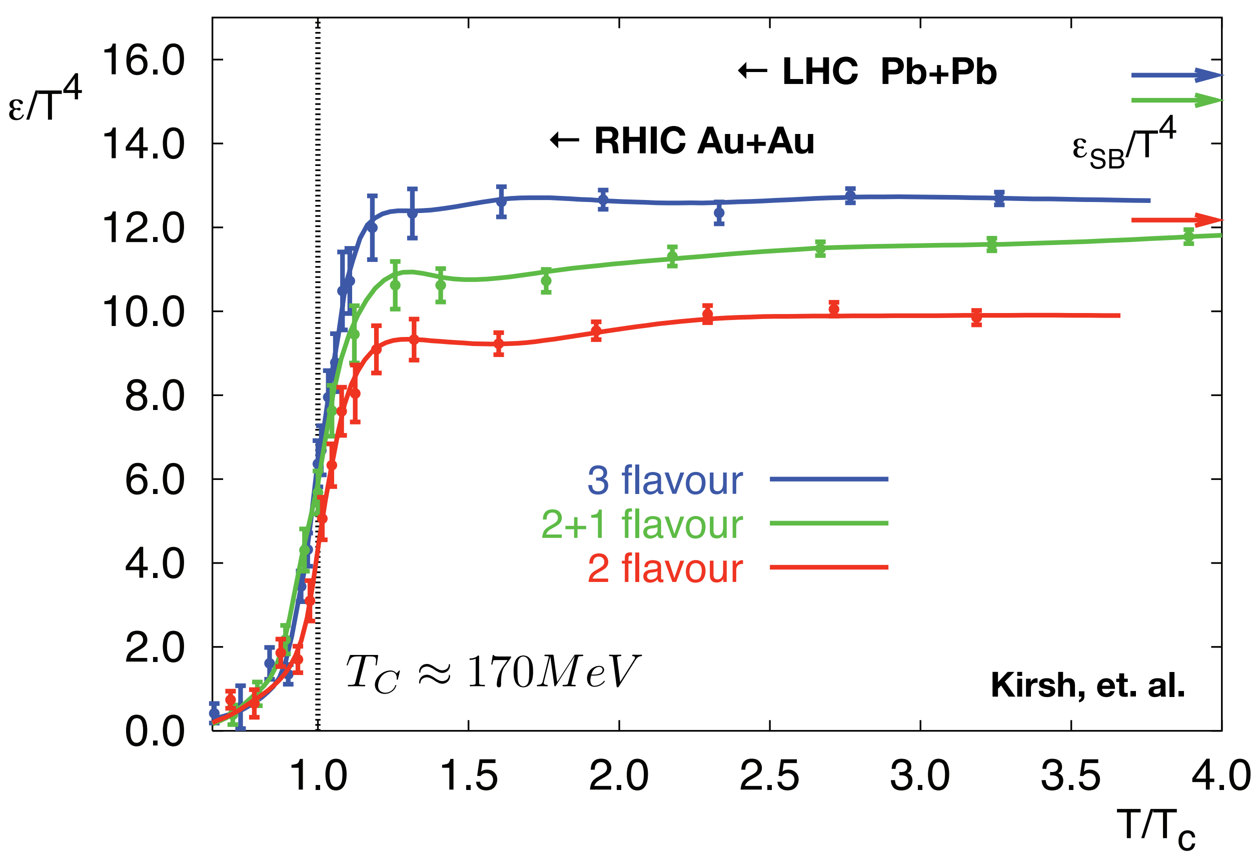


QCD Phase Diagram

Quark-gluon plasma above a few 10^{12} K

Reachable by collider facilities

Critical point being sought



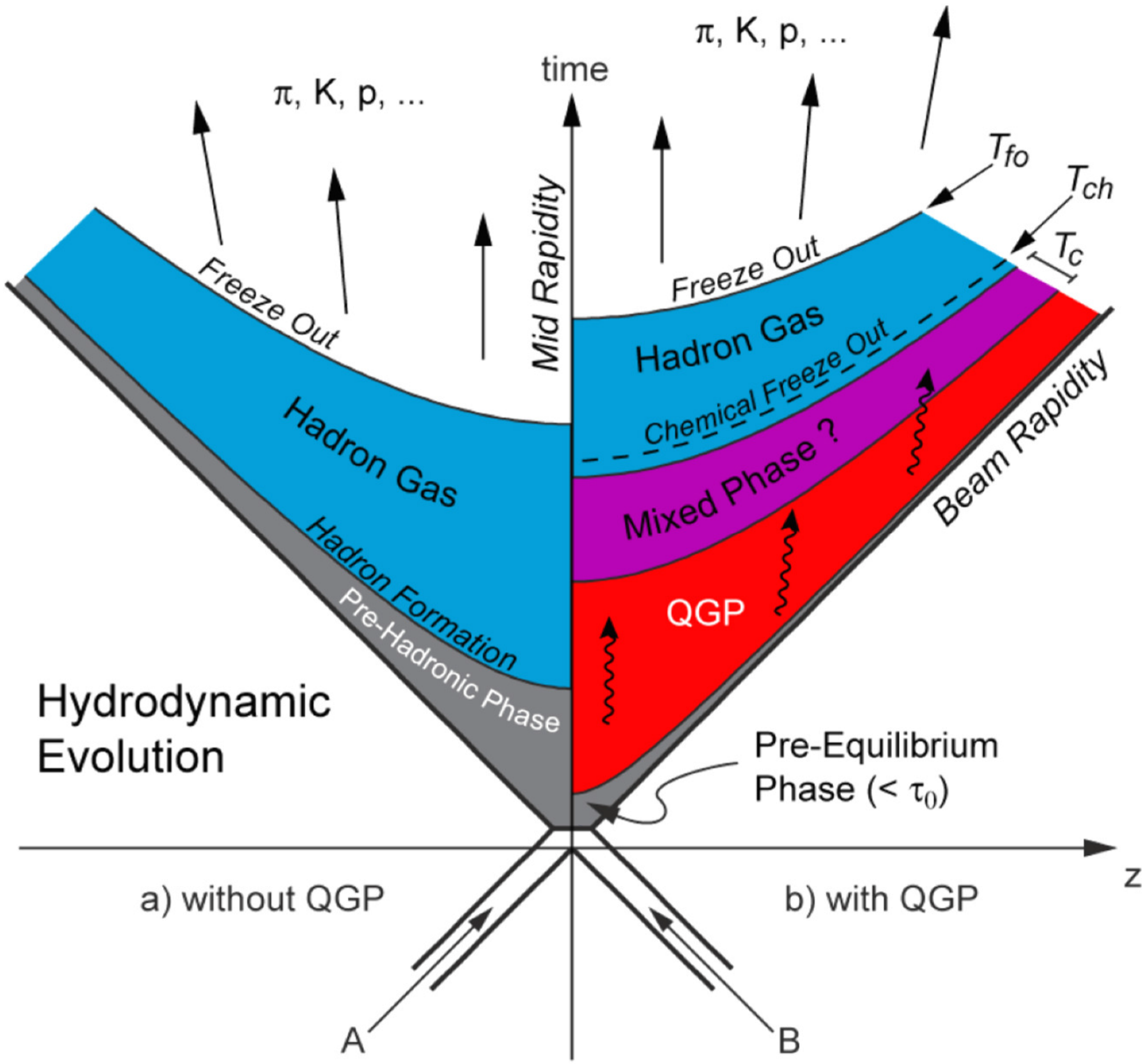
Lattice QCD Calculations

Energy density indicates partonic degrees of freedom open at $T_c \approx 170$ MeV

Ideal gas of quarks and gluons at arbitrarily large T

(Data) Strongly-coupled fluid near T_C

Space-Time Evolution



Kinetic Freeze Out (~10-15 fm/c)

Chemical Freeze Out (~7 fm/c)

Hadron Gas

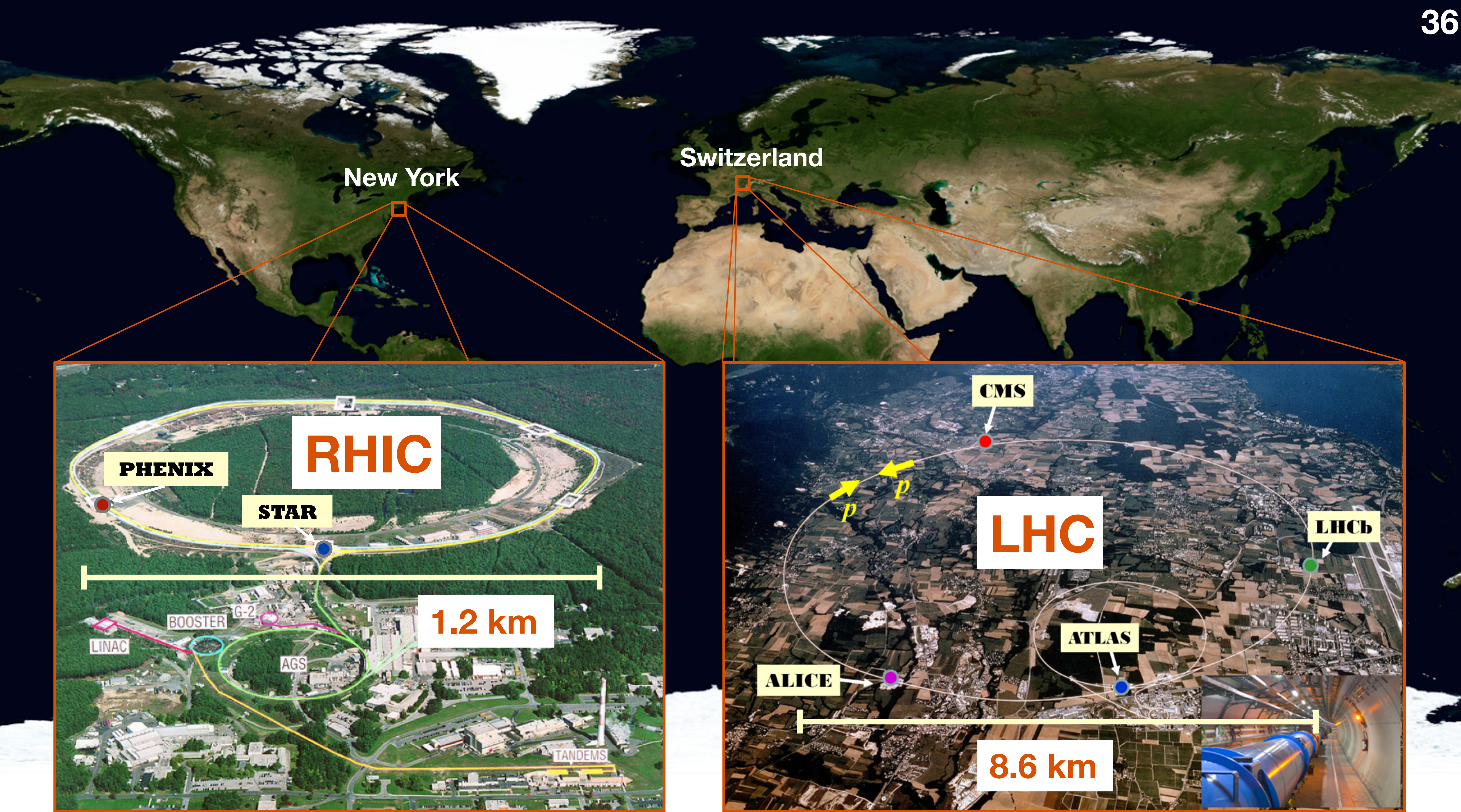
Phase Transition (~4 fm/c)

QGP

Thermalization (~0.6 fm/c)

Nuclear Crossing (~0.1 fm/c)

***values for RHIC at 200 GeV**



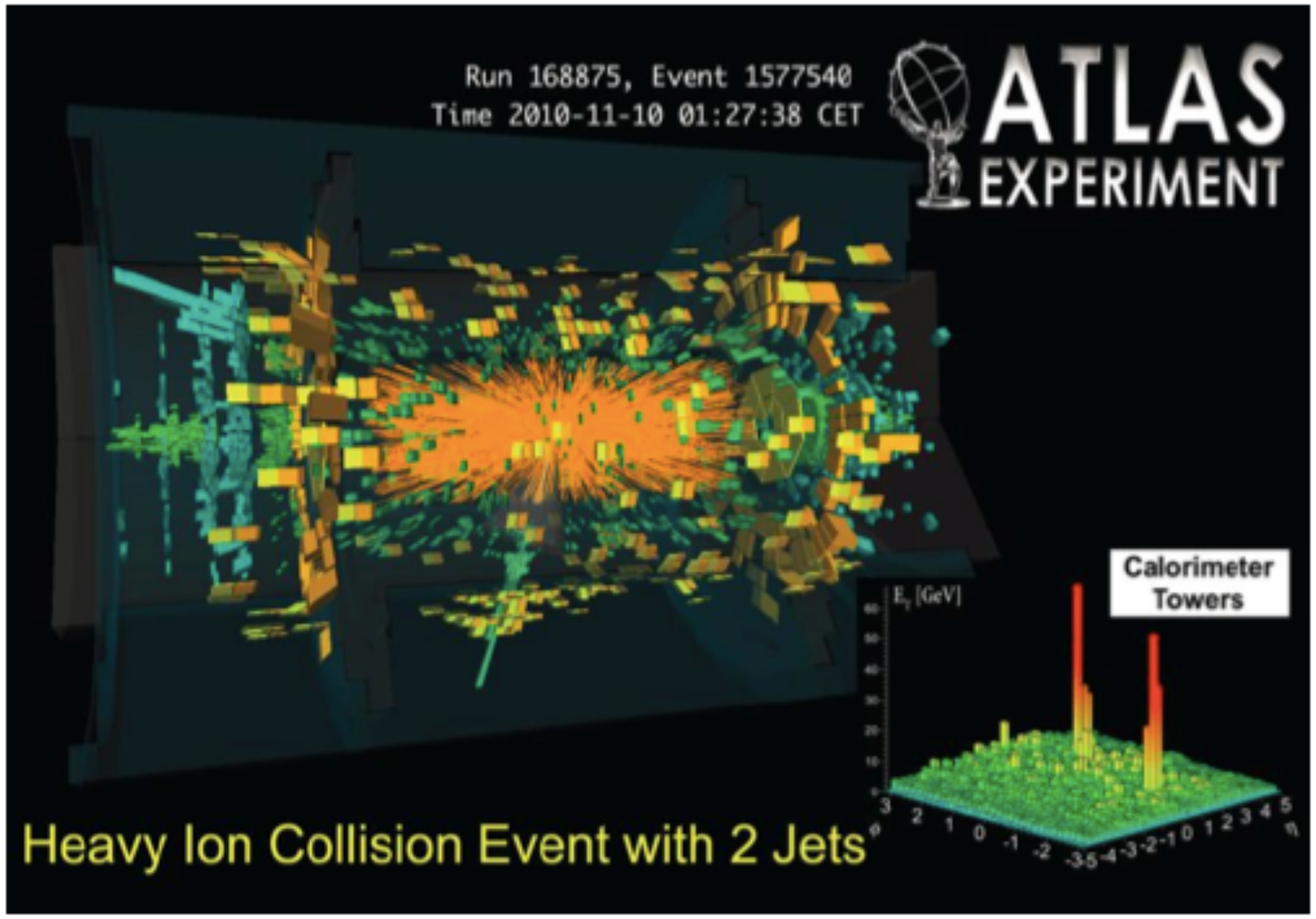
beam	energy (GeV)
$\vec{p}+\vec{p}$	62 - 510
(d,He^3)+Au	200
Cu+Cu	22 - 200
Cu+Au	200
Au+Au	7 - 200
U+U	193

beam	energy (GeV)
p+p	7000-8000
p+Pb	5020
Pb+Pb	2760

Hadronic Calorimetry

ATLAS and CMS heavy ion jet observables come from calorimeter measurements

Ability to try different methods (supplementing with tracking) is also an advantage

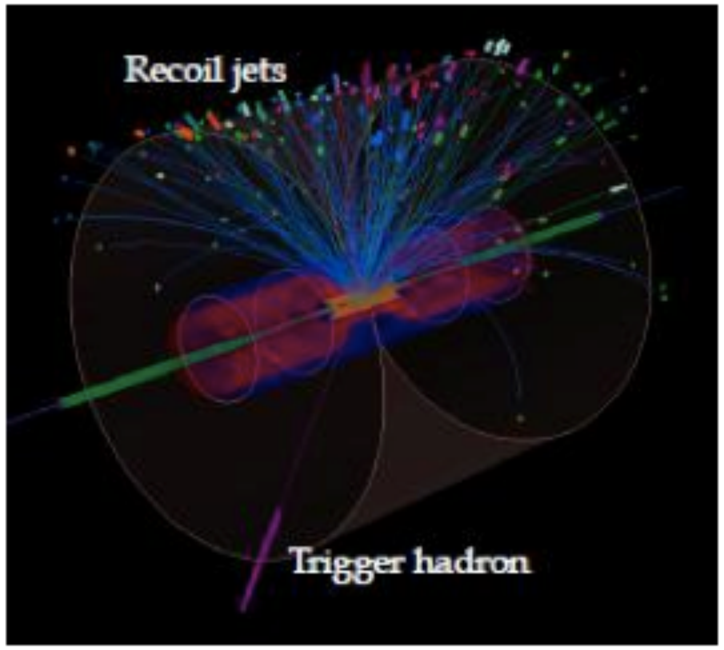


Critical to have EMCal + HCAL with continuous coverage (no gaps, spokes, holes) with large acceptance to see both jets and γ-jet and at very high rate. Then add in tracking information as key additional handle for systematic studies

Also, when measuring fragmentation functions, hadron p_T and jet energy measures are independent

Very useful for triggering in p+p, p+A without jet bias

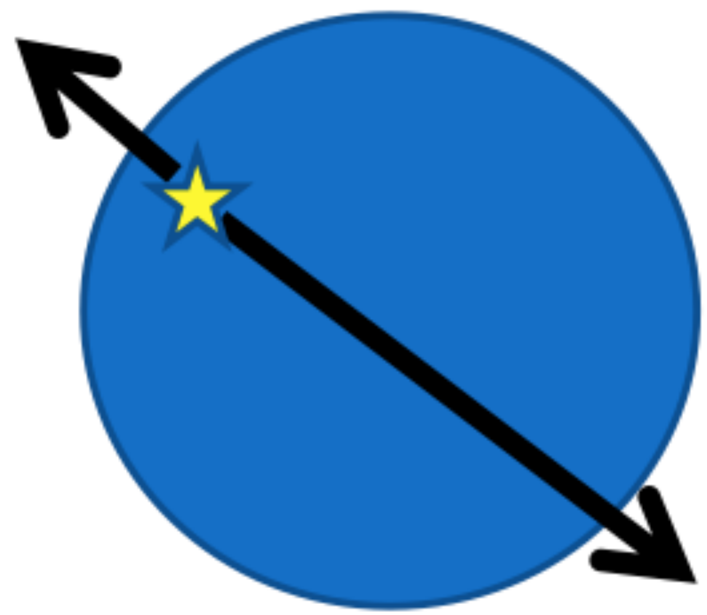
STAR Jet Program



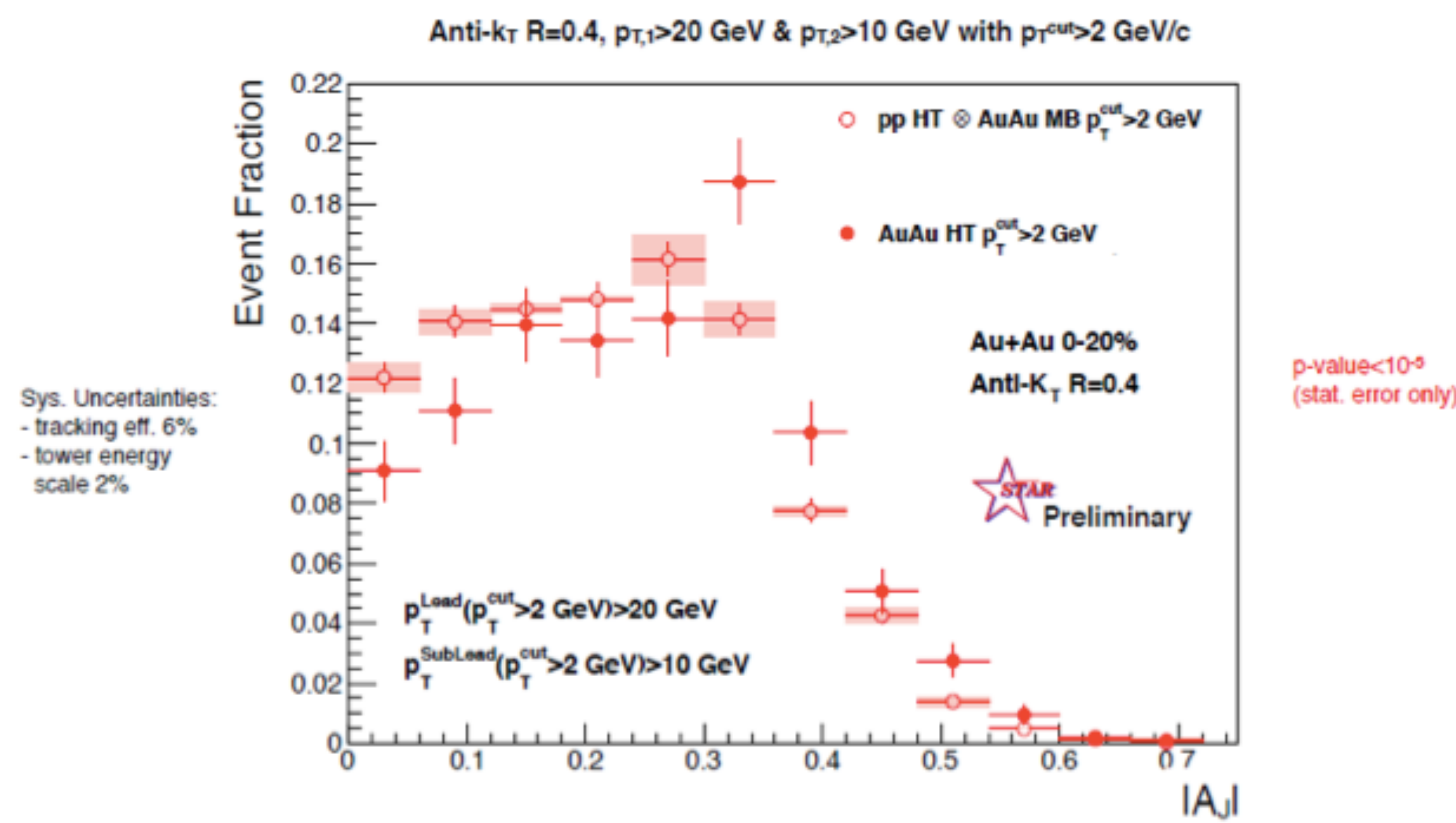
Very good jet capabilities
Large acceptance, tracking + EMCal

Exciting recent results from QM2014
Trigger on jet > 20 GeV requiring online trigger of > 5.4 GeV in one EMCal tower and all p_T > 2 GeV

Expect Surface Bias on Trigger
And Long Path on Opposite Side

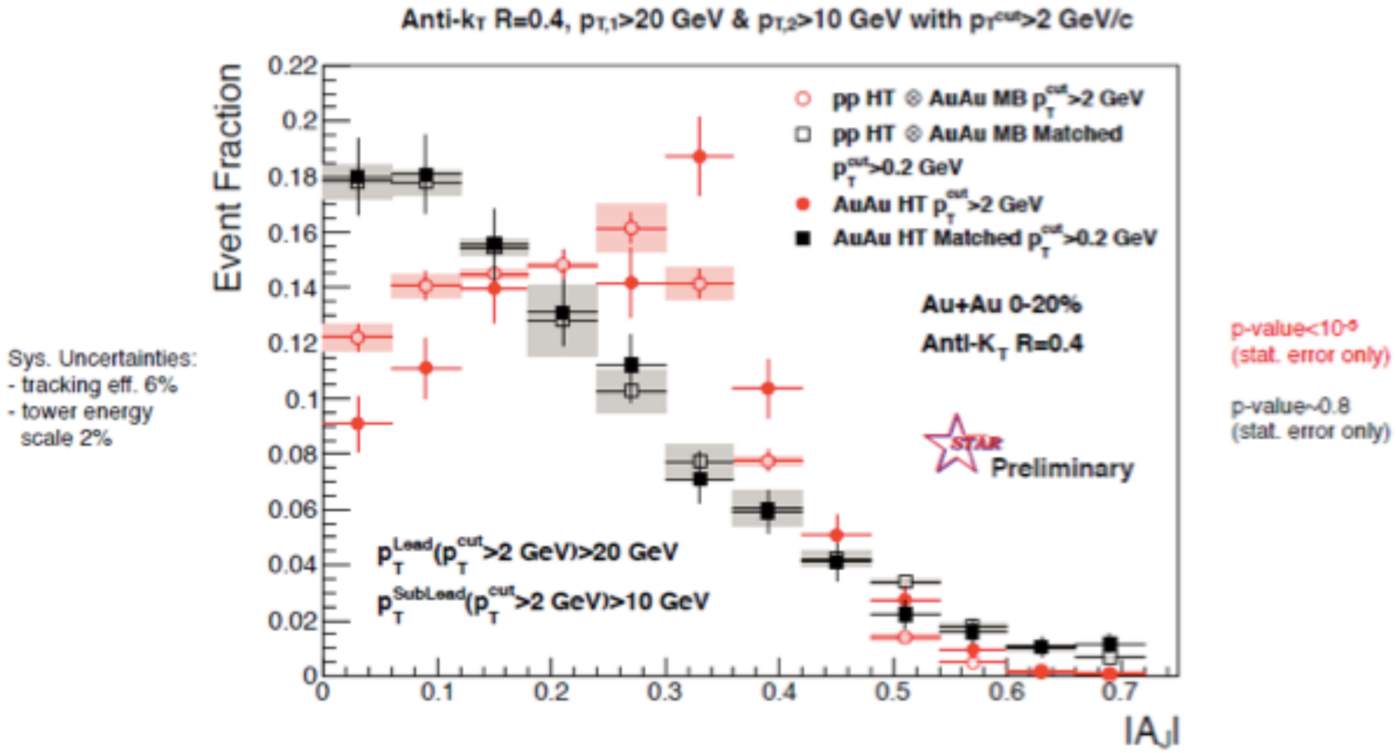


However, only modest suppression of balanced jets



Au+Au di-jets more imbalanced than p+p for p_T^{cut}>2 GeV/c

STAR Jet Program II



Au+Au di-jets more imbalanced than p+p for p_T^{cut}>2 GeV/c

Au+Au A_J ~ p+p A_J for matched di-jets (R=0.4)

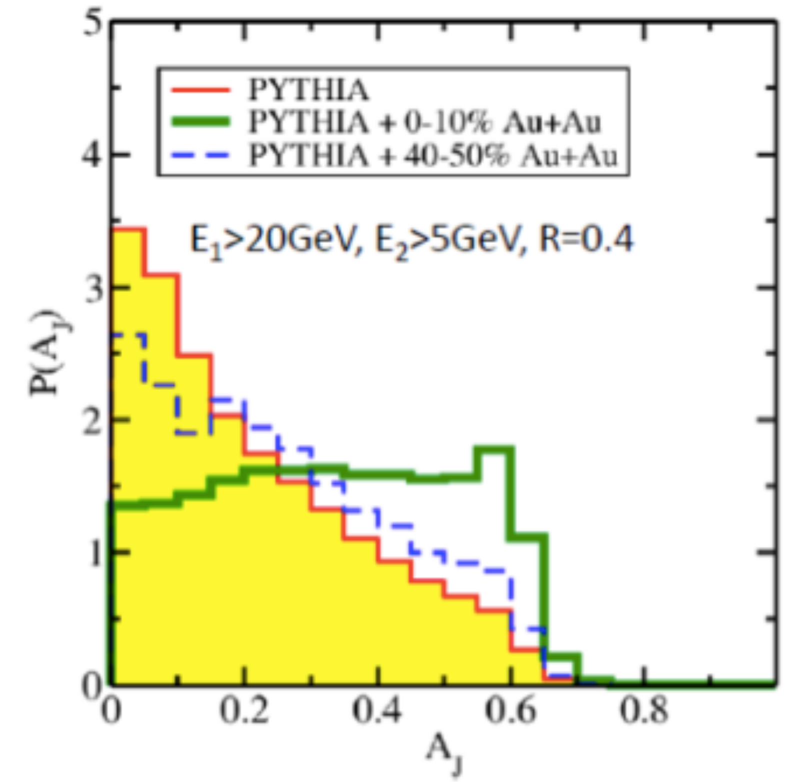
Now re-run jet algorithm with all particles around originally found jets

Dijet asymmetry identical in pp and AA!

Very different result from theory expectations and LHC results.

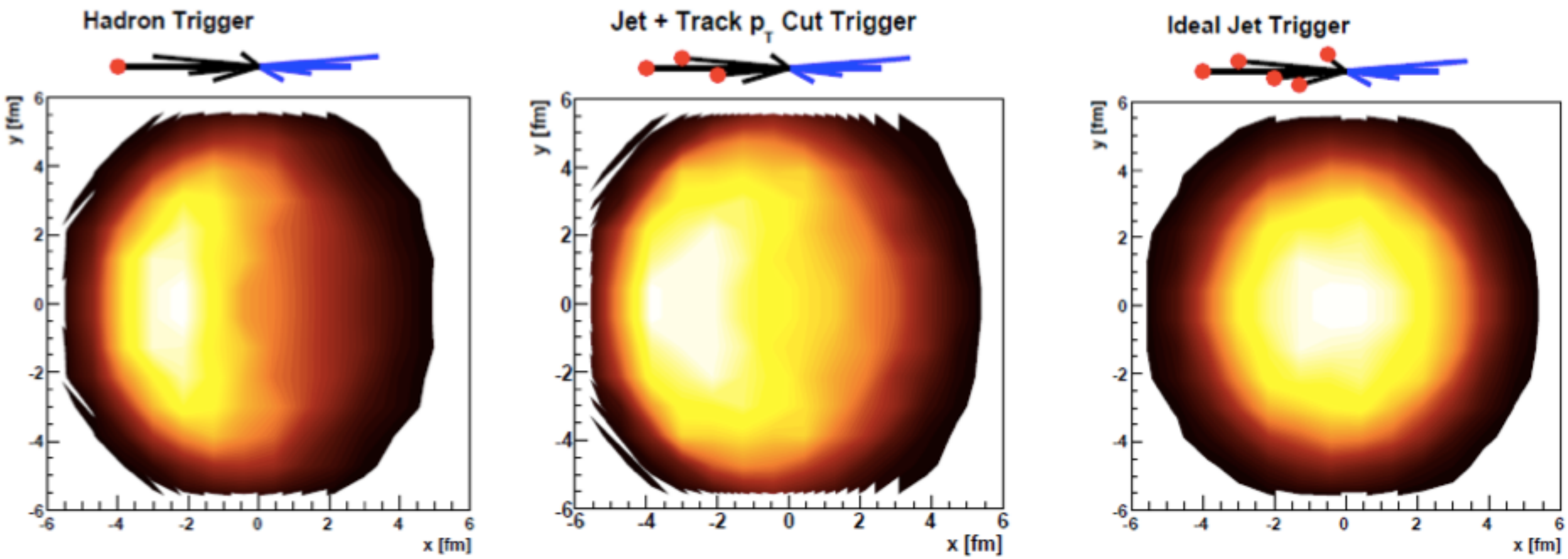
If full jet energy recovered, real unbiased FF measurements available to sPHENIX.

Biased di-jet case may select particular geometry.
Perhaps biased towards both jets tangential.



Surface Bias Engineering

Thorsten Renk has explored the ability to engineer the surface and energy loss bias to gain more information. Works particularly well at RHIC due to steeply falling jet spectrum.

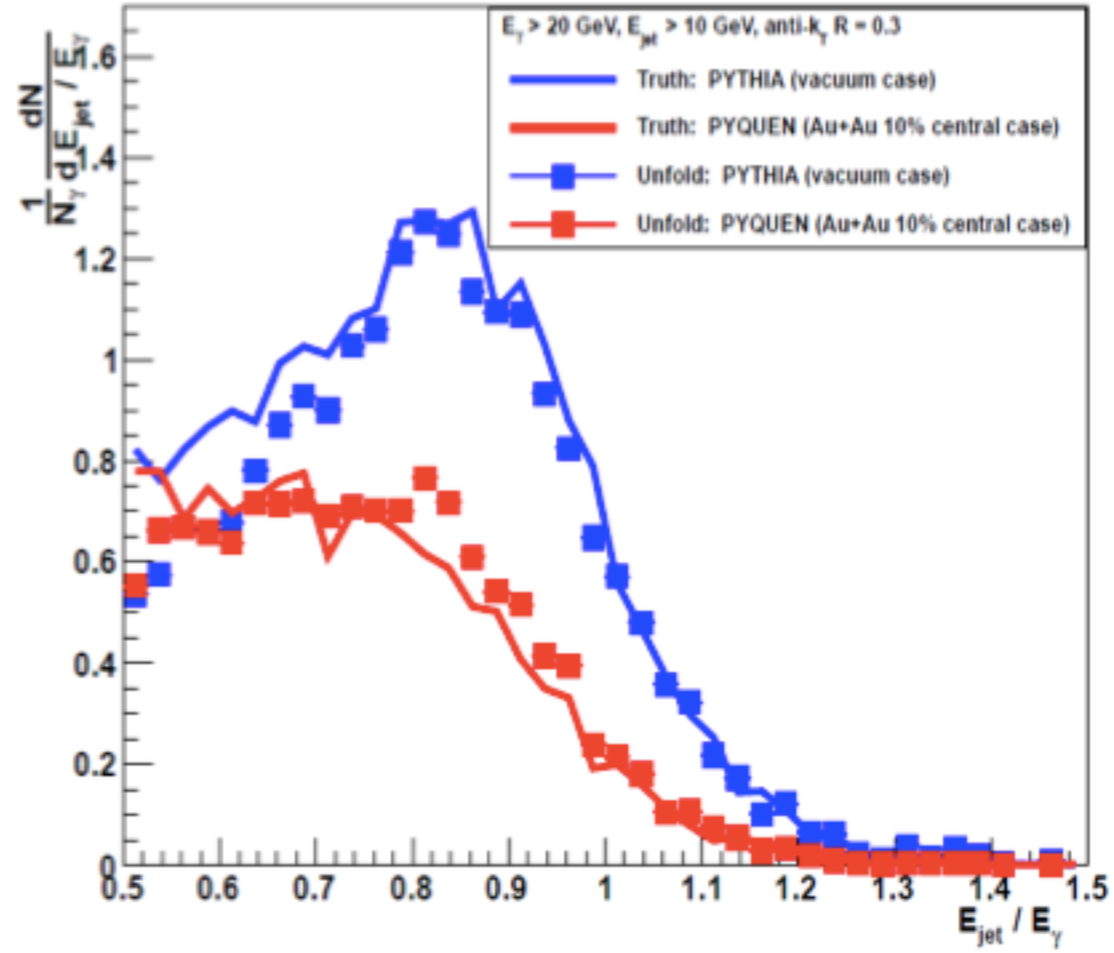


PHENIX

STAR

sPHENIX

γ-jet Observables



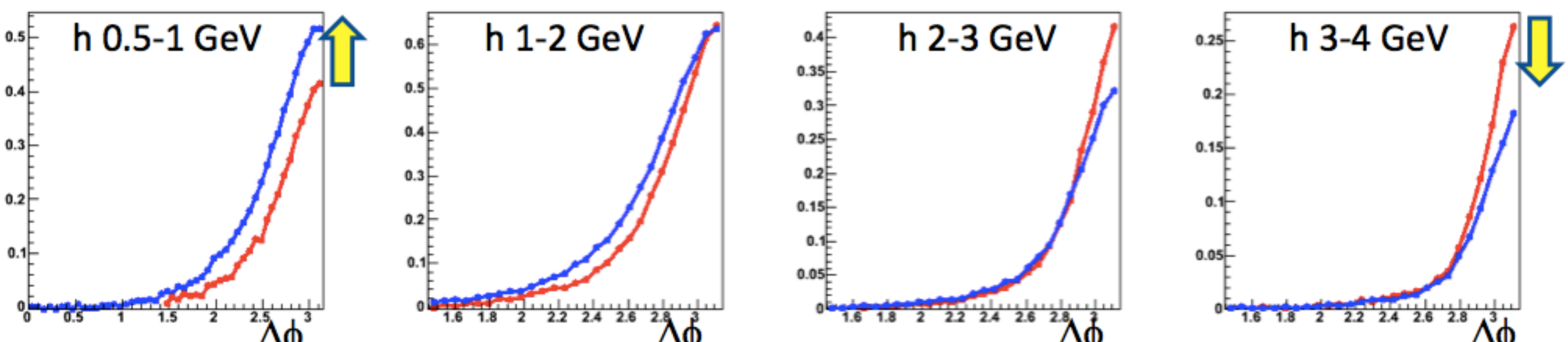
For p_T > 15 GeV, direct photons dominate at RHIC

Direct γ – jet correlations

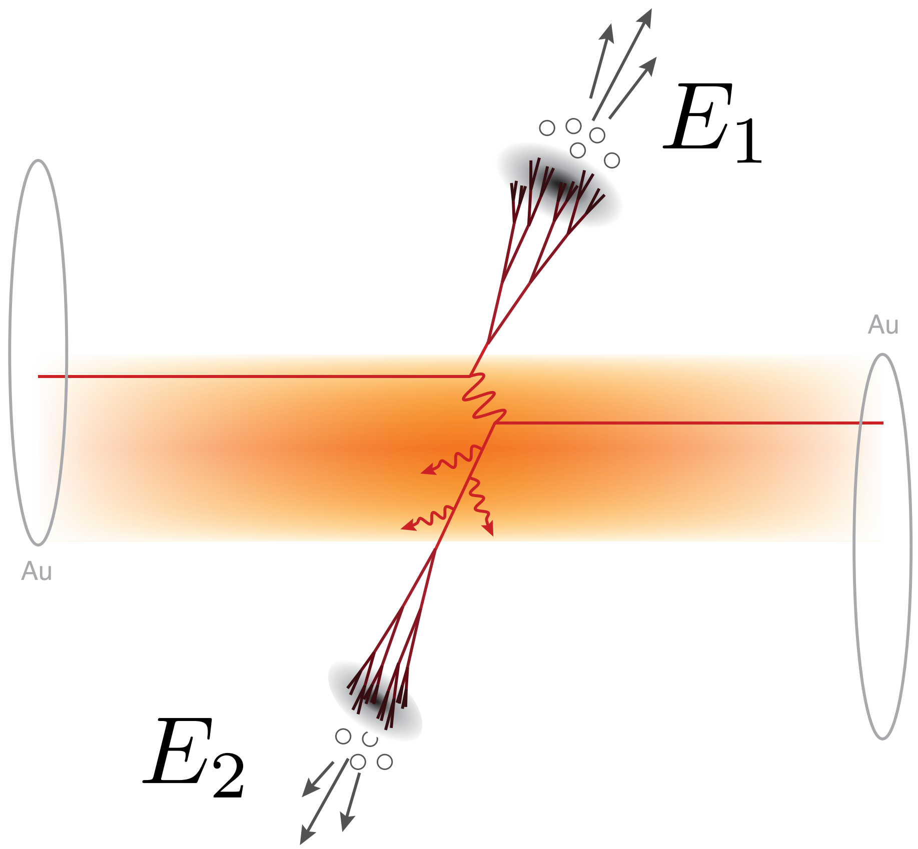
- PYTHIA (vacuum)
- PYQUEN (quenching)

γ– hadron correlations

Track where the energy goes (transverse and longitudinal)!



Reconstructed Jets and A_J

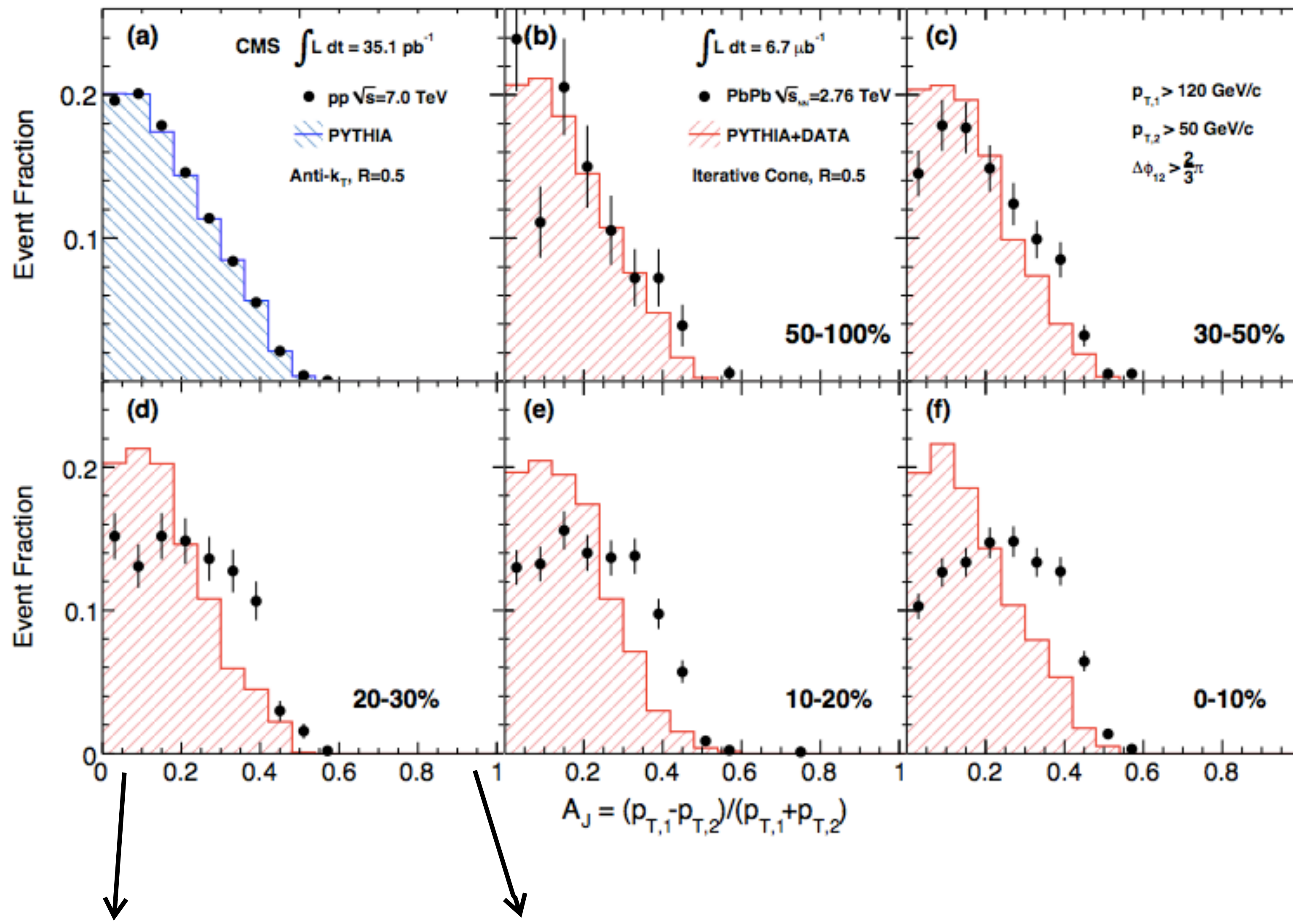


require: $E_1 > E_2$

$$A_J \equiv \frac{E_1 - E_2}{E_1 + E_2}$$

Large modification in central collisions

CMS, arXiv:1102.1957



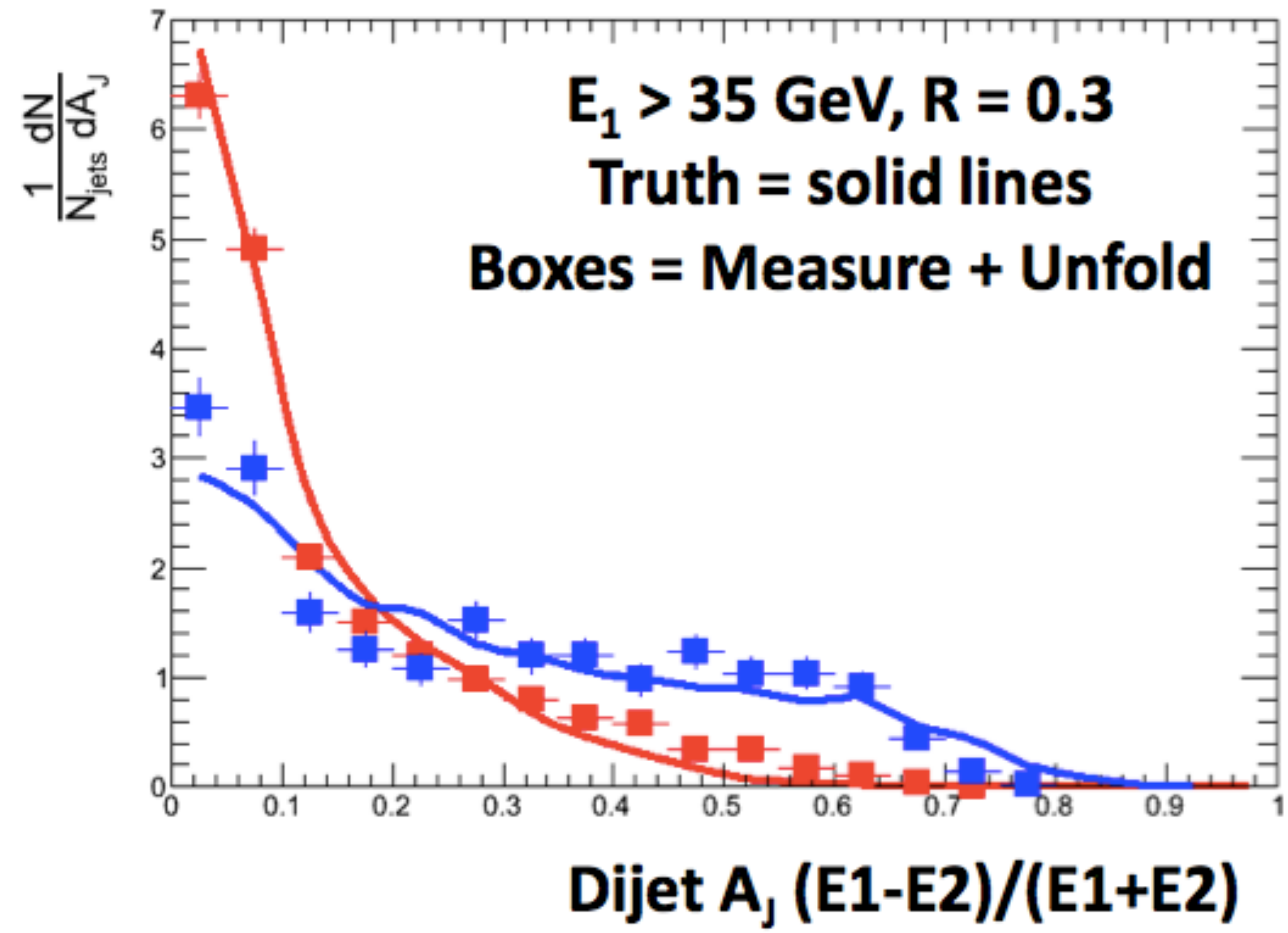
$E_1 \approx E_2$ $\quad$ $E_1 >> E_2$

Jet-jet Asymmetries

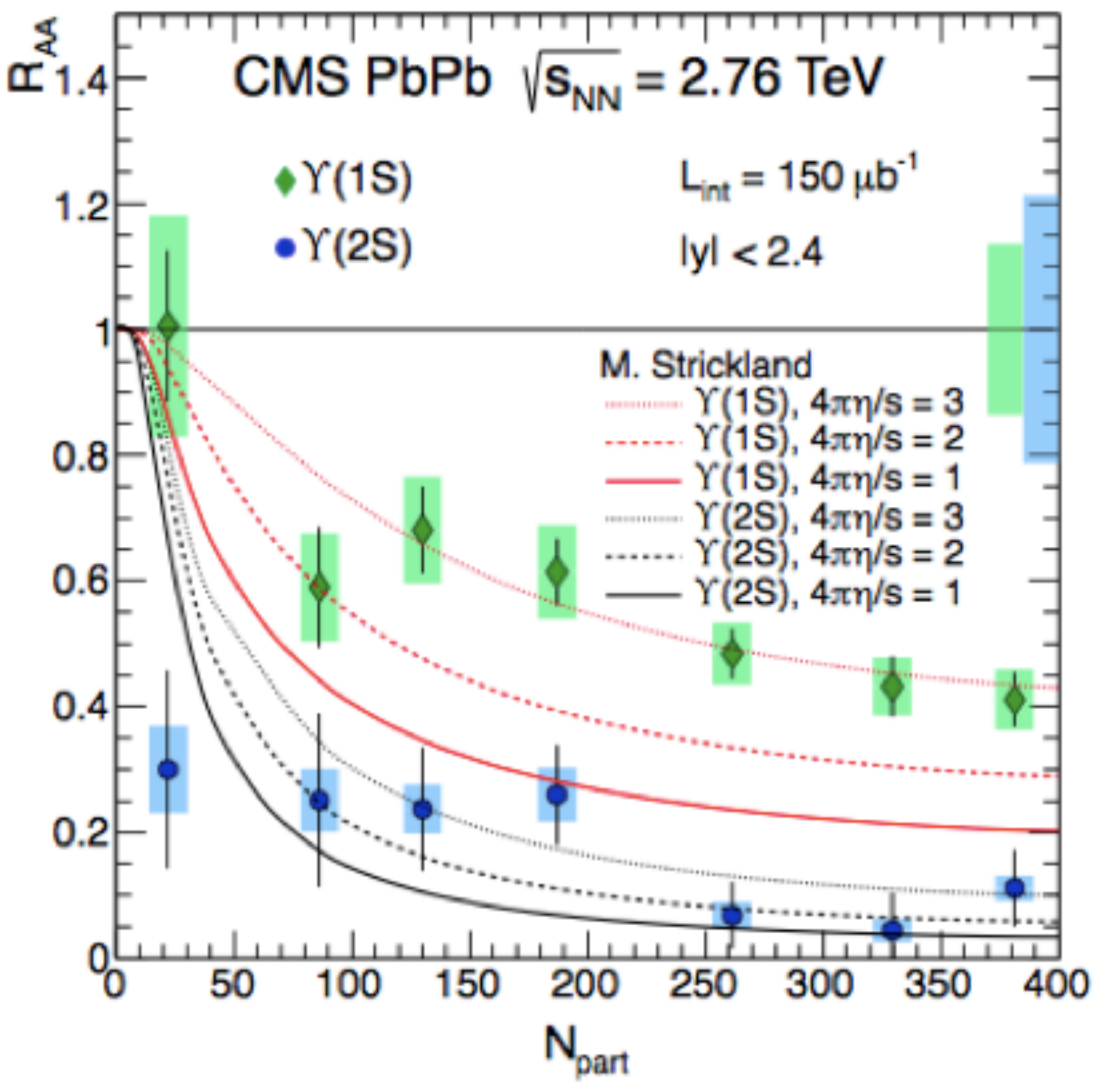
- PYTHIA (vacuum case)
- PYQUEN (quenched case)

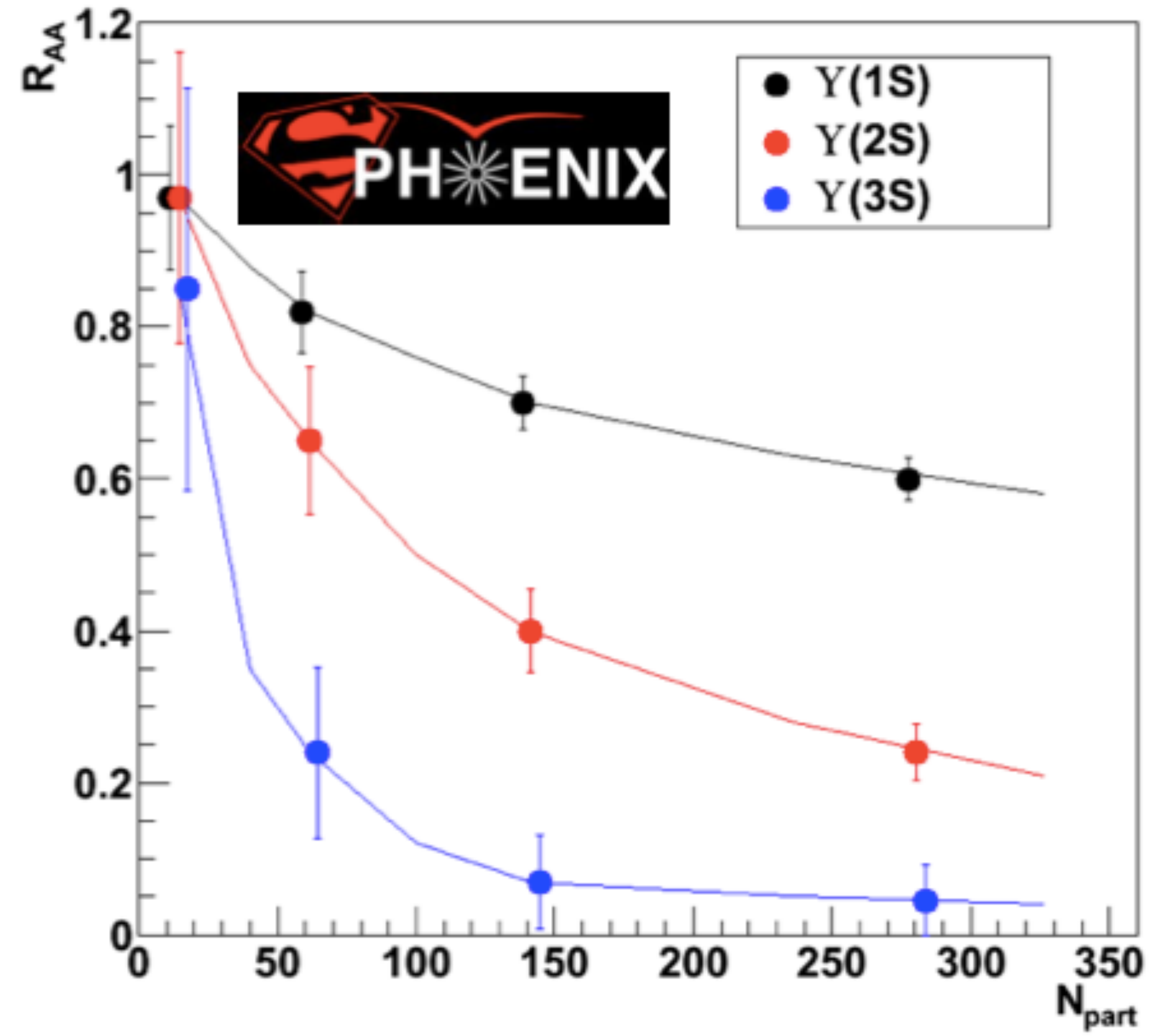
Full jets + HIJING background + detector resolution + FastJet + underlying event subtraction

Very easily discriminated (large effect)



sPHENIX Upsilon Measurements





Extremely exciting LHC Upsilon results

Key to map out temperature dependence in A+A combined with p+p and p+A with good statistics

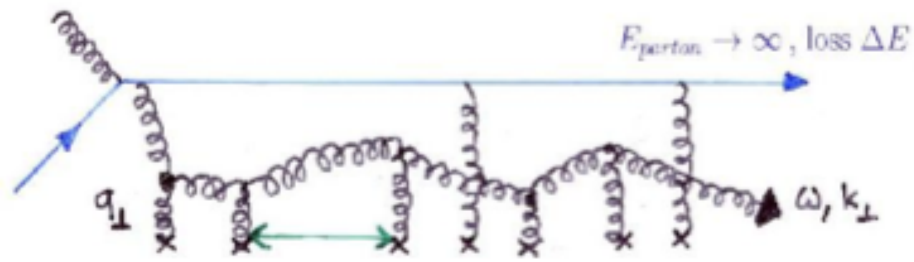
Relationship to Hard Sector Physics

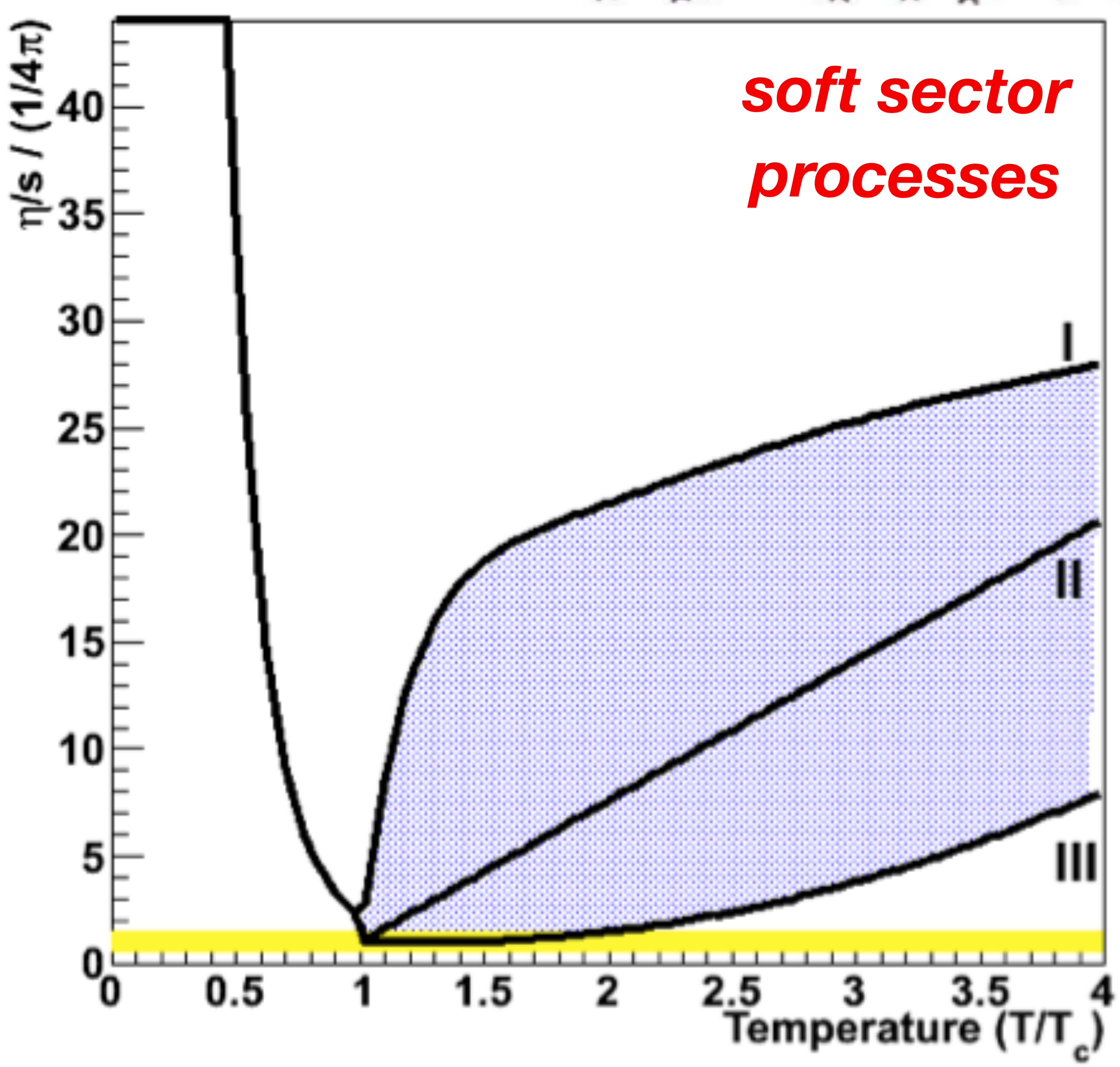
smaller viscosity ⇒ larger coupling ⇒ larger interaction with jets

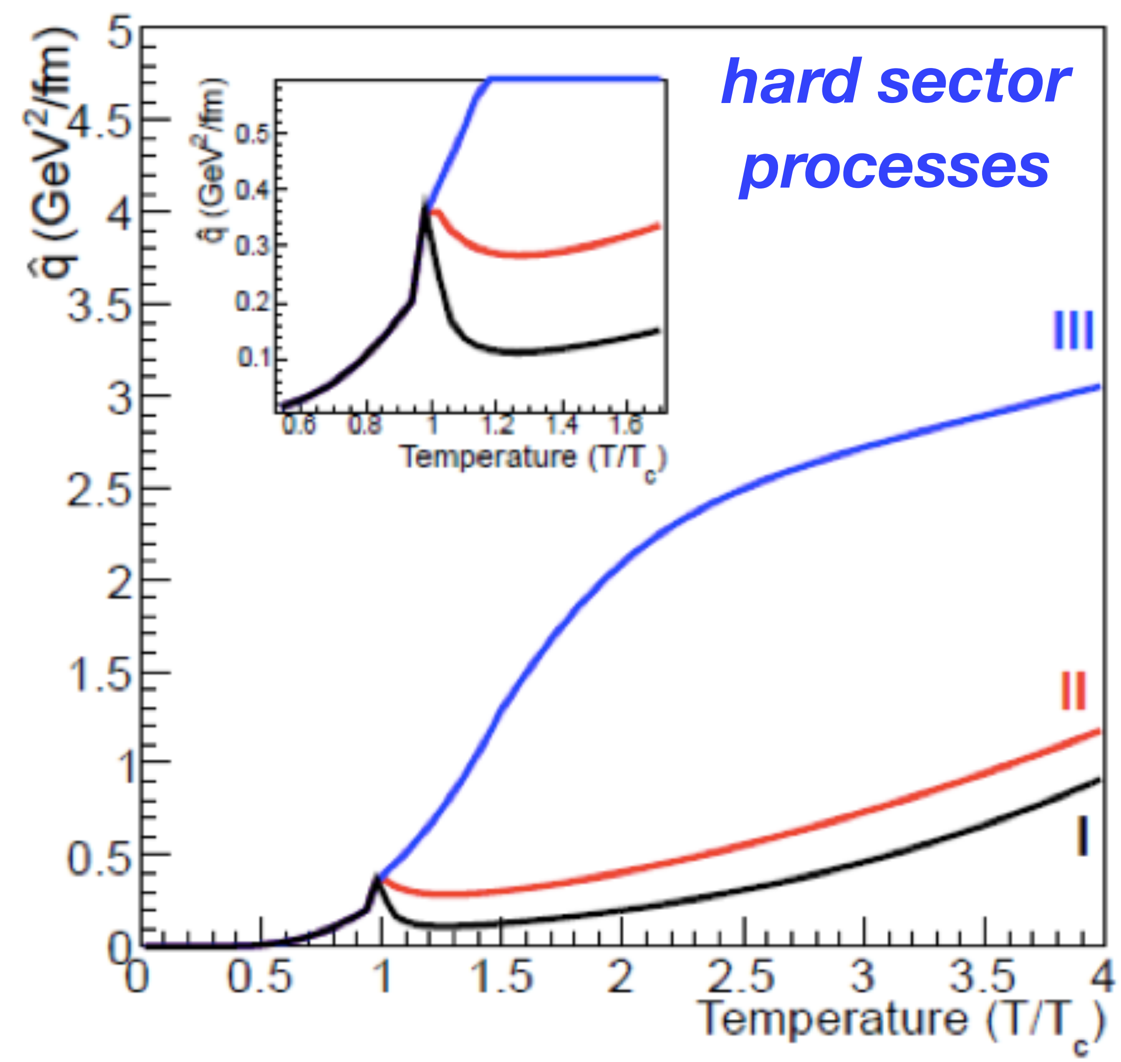
"Small Shear Viscosity Implies Strong Jet Quenching"

A. Majumder, B. Muller, X.N. Wang, PRL (2007).

$$\hat{q} \stackrel{?}{=} \frac{1.25T^3}{\eta / s}$$



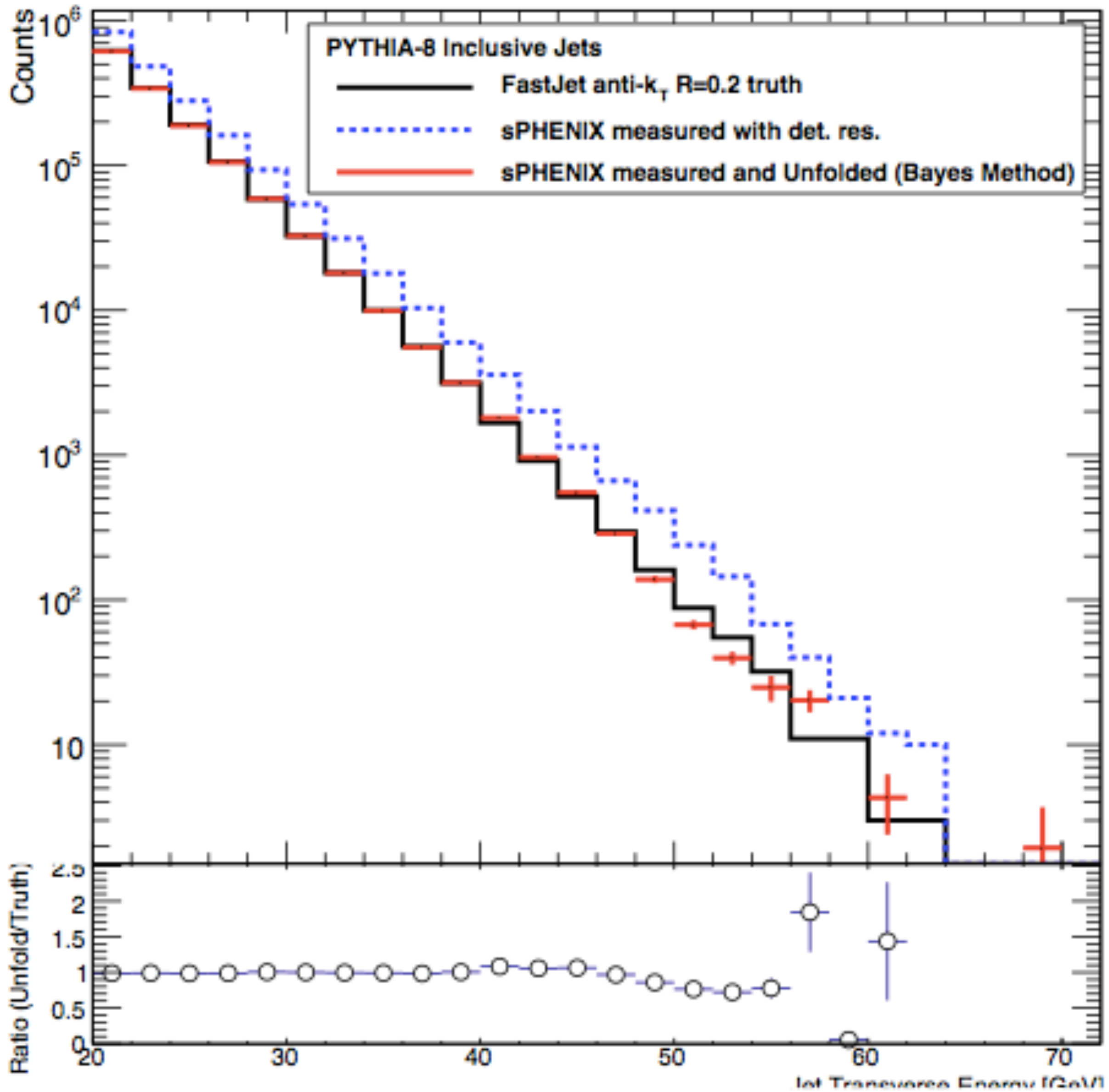




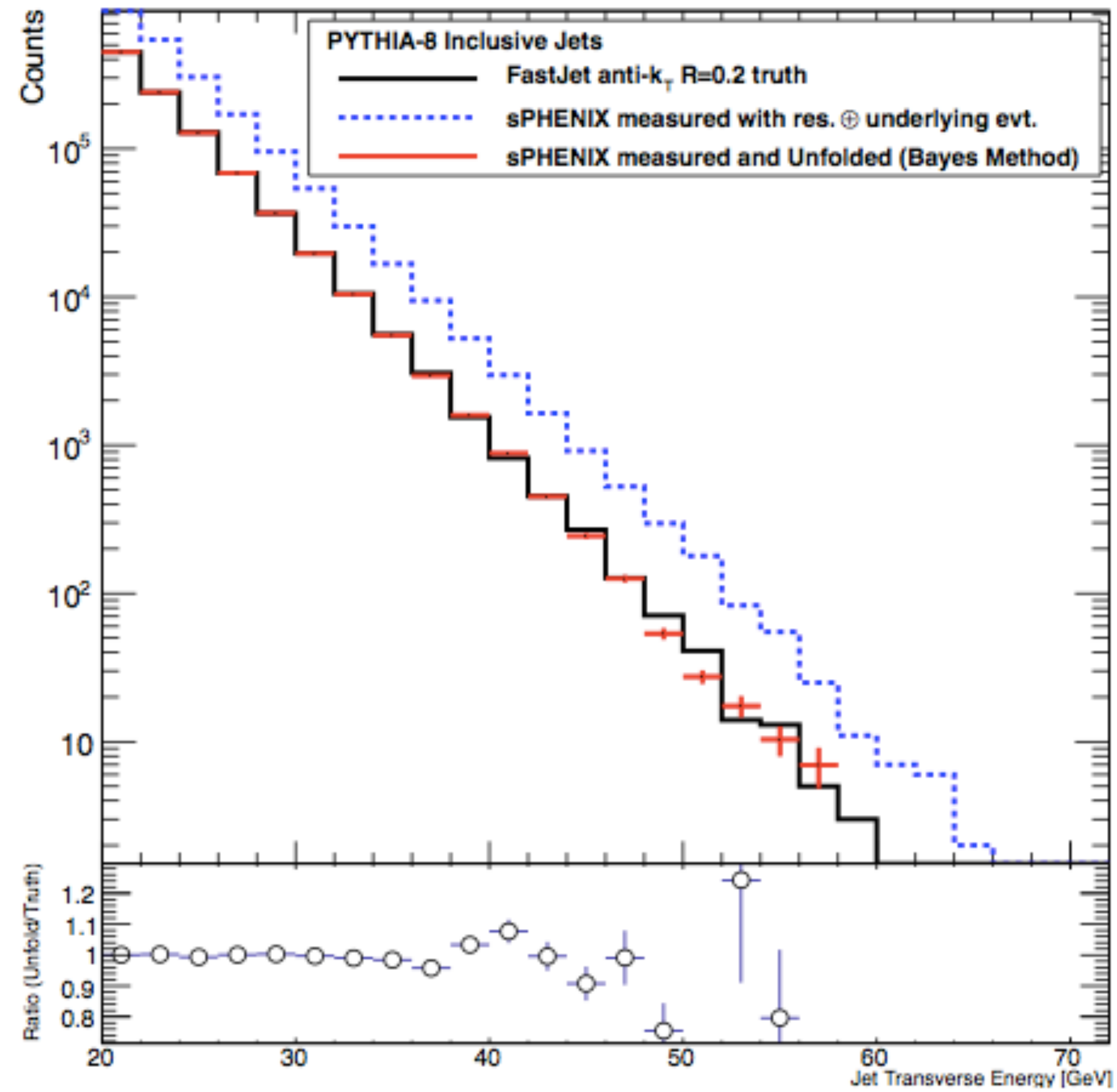
<u>Key is independently measuring both sides of this equation</u>

Jet Spectra Projections

p+p



central Au+Au



resolution **shifts** exponential spectra out in p_T

red shows **unfolded** result which **agrees with truth**

Resolution: Background Subtraction

PHYSICAL REVIEW C **86**, 024908 (2012)

Method for separating jets and the underlying event in heavy ion collisions at the BNL Relativistic Heavy Ion Collider

J. A. Hanks,[1] A. M. Sickles,[2] B. A. Cole,[3] A. Franz,[2] M. P. McCumber,[4] D. P. Morrison,[2] J. L. Nagle,[4] C. H. Pinkenburg,[2] B. Sahlmueller,[1] P. Steinberg,[2] M. von Steinkirch,[1] and M. Stone[4]
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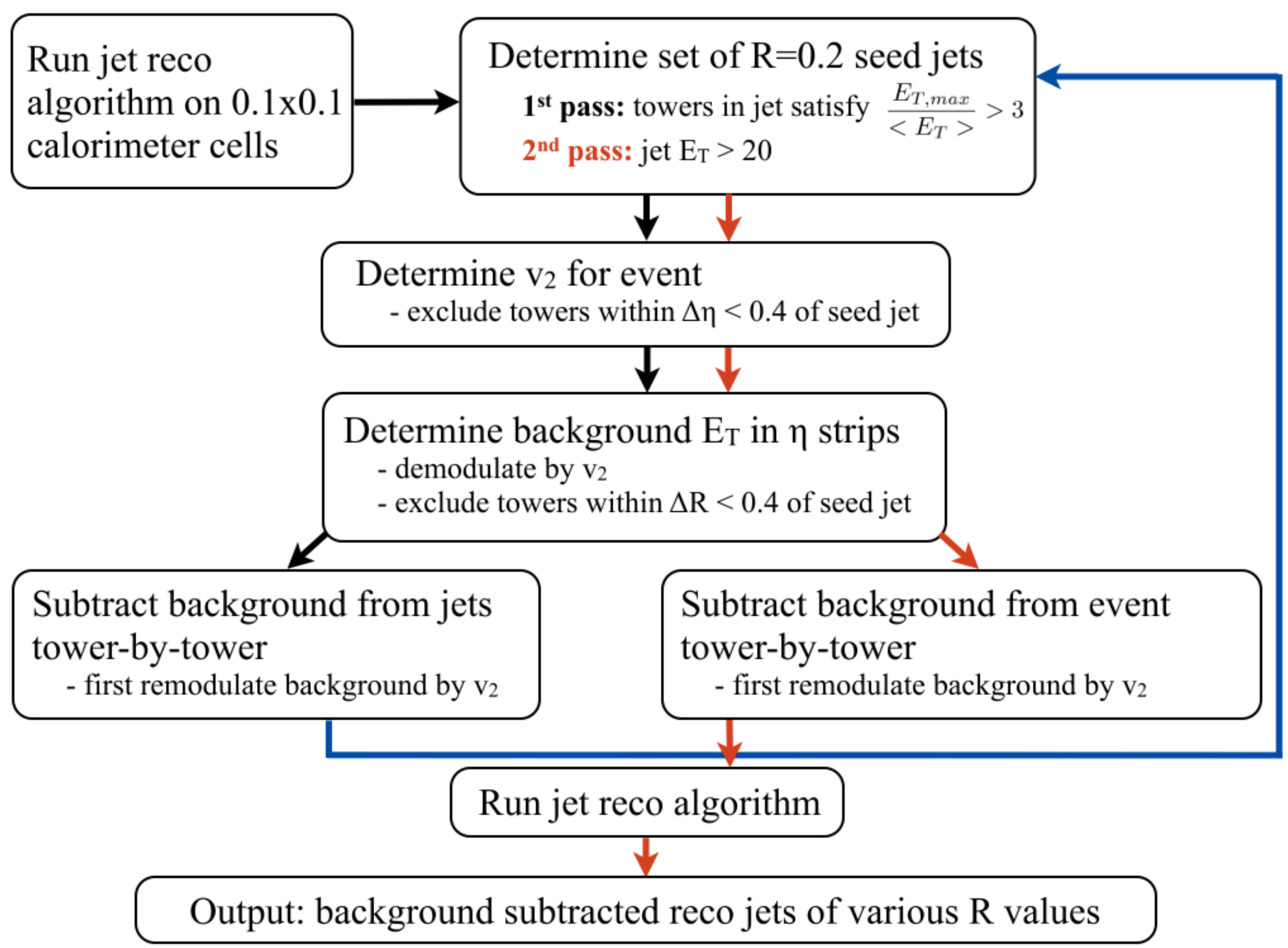
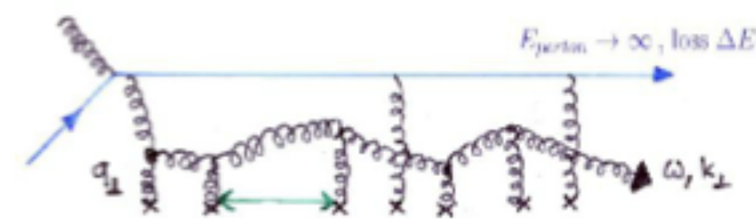
[4]*University of Colorado, Boulder, Colorado 80309, USA*
(Received 6 April 2012; published 10 August 2012)



Probing the QGP across Length Scales

To address these questions, need to probe the QGP at different length scales and particularly in the region of strongest coupling (RHIC)

Hard Scattered Partons Traversing the QGP
(Jets, Dijets, γ-Jet, Fragmentation, Medium Response)
length scale set by initial energy, coherent energy lost
20-50 GeV (0.01-0.004 fm), 1-5 GeV (0.2-0.05 fm)



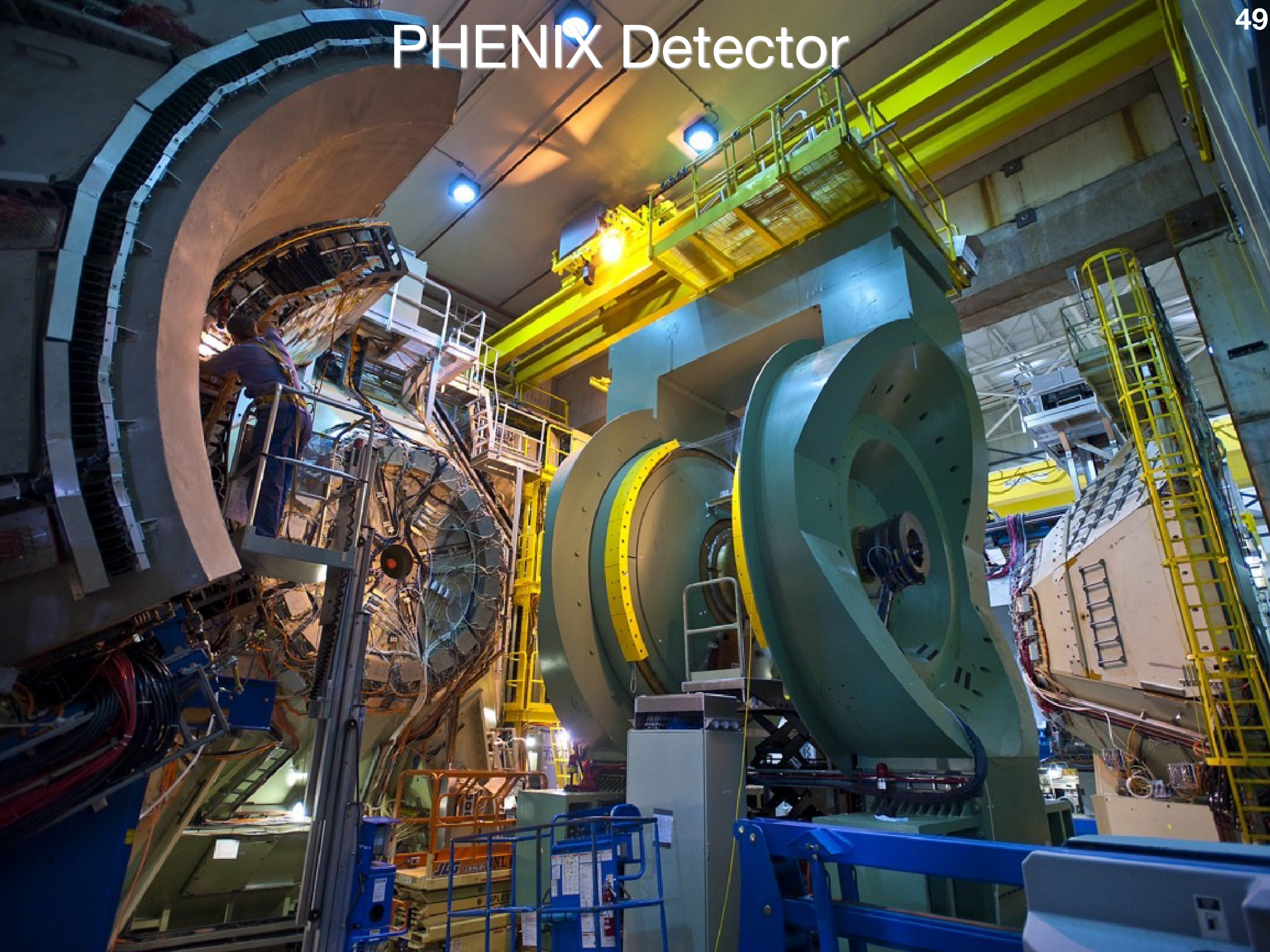
Beauty Quarkonia
length scale set by size of state (ϒ(1s,2s,3s) ~ 0.28, 0.56, 0.78 fm)

<u>Post-QM Meeting (Mont Sainte Odile)</u>

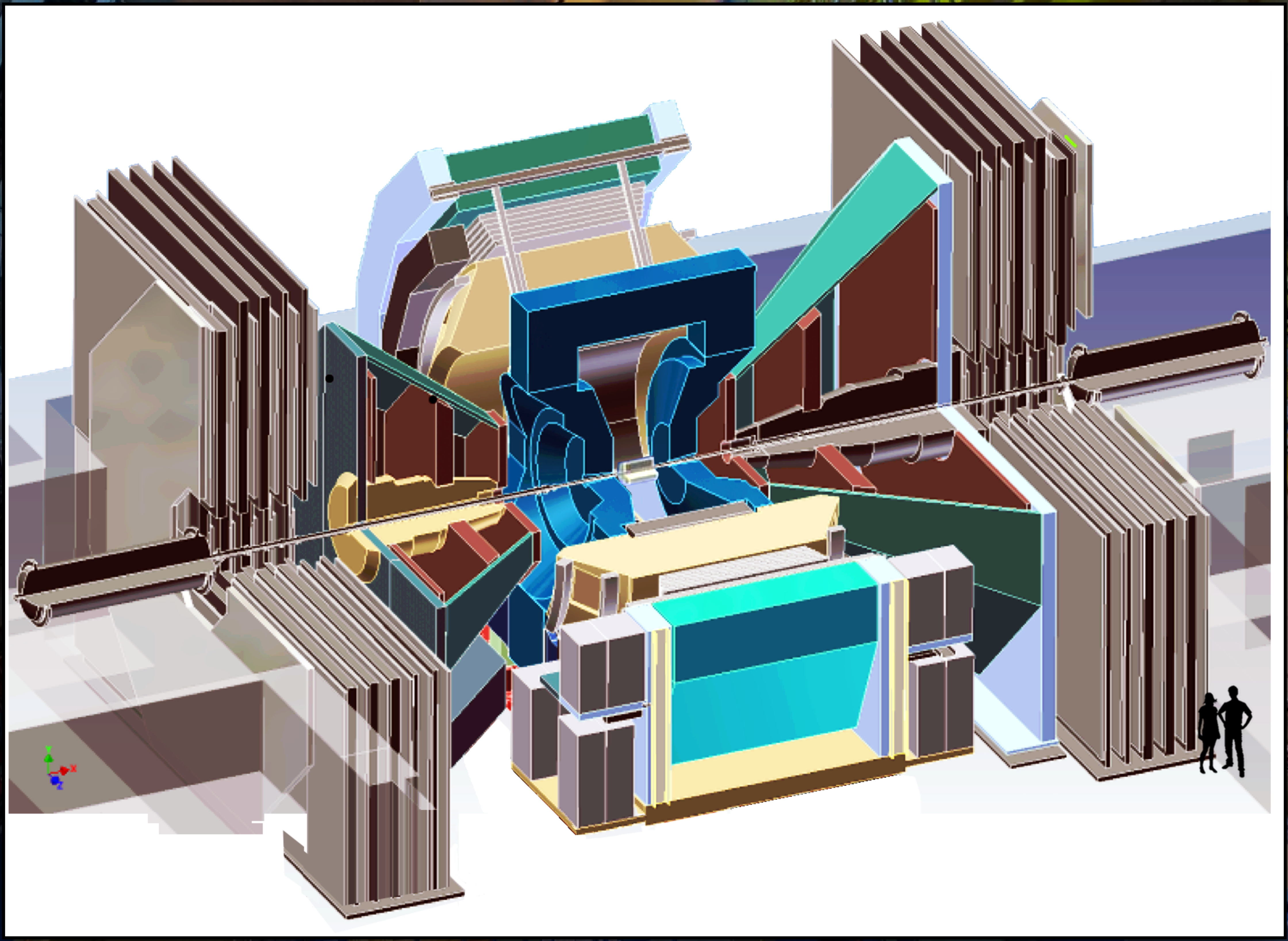
Krishna referred to this as microscopy of the QGP

Critical to push jets to lower energy, looking for hard radiation to understand what is being scattered from?

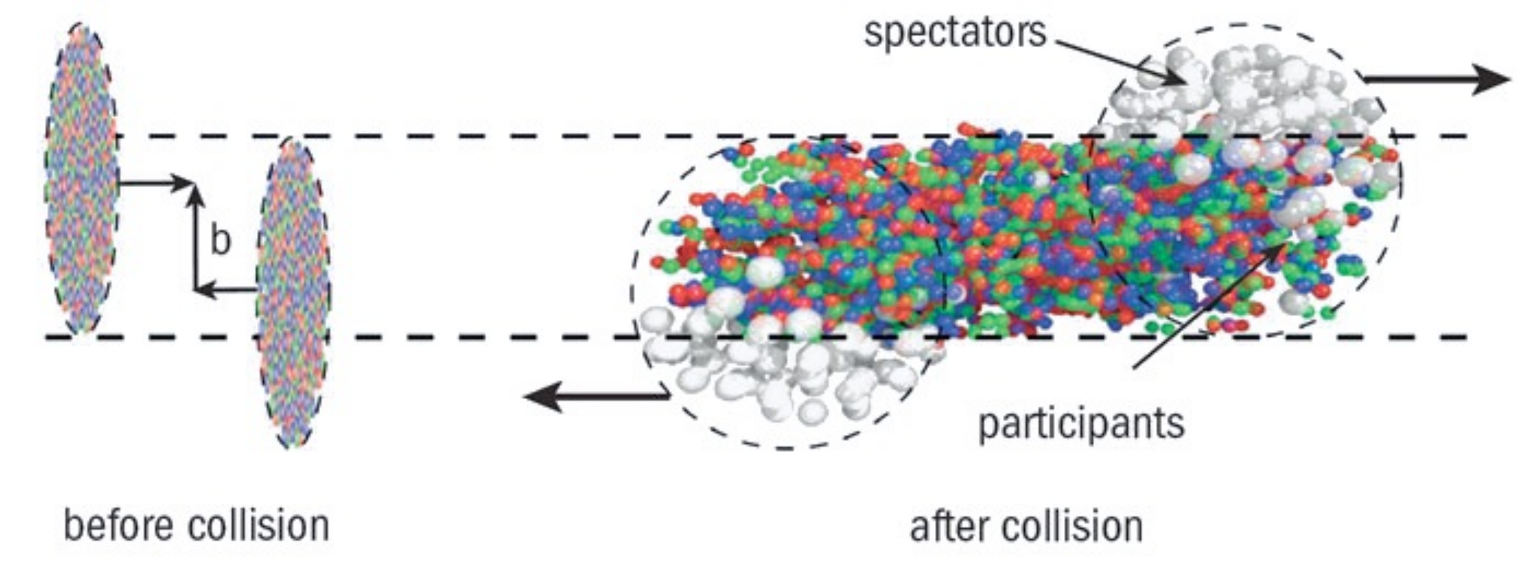
PHENIX Detector



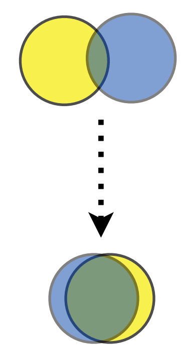
PHENIX Detector



Event Geometry Controls



Impact parameter studied via **centrality** selection



Large impact parameter
→ peripheral events, ≲100%

Small impact parameter
→ central events, ≳0%

Measured at large pseudorapidity

Tool: Glauber Monte Carlo simulation

Simple geometric description of A+A

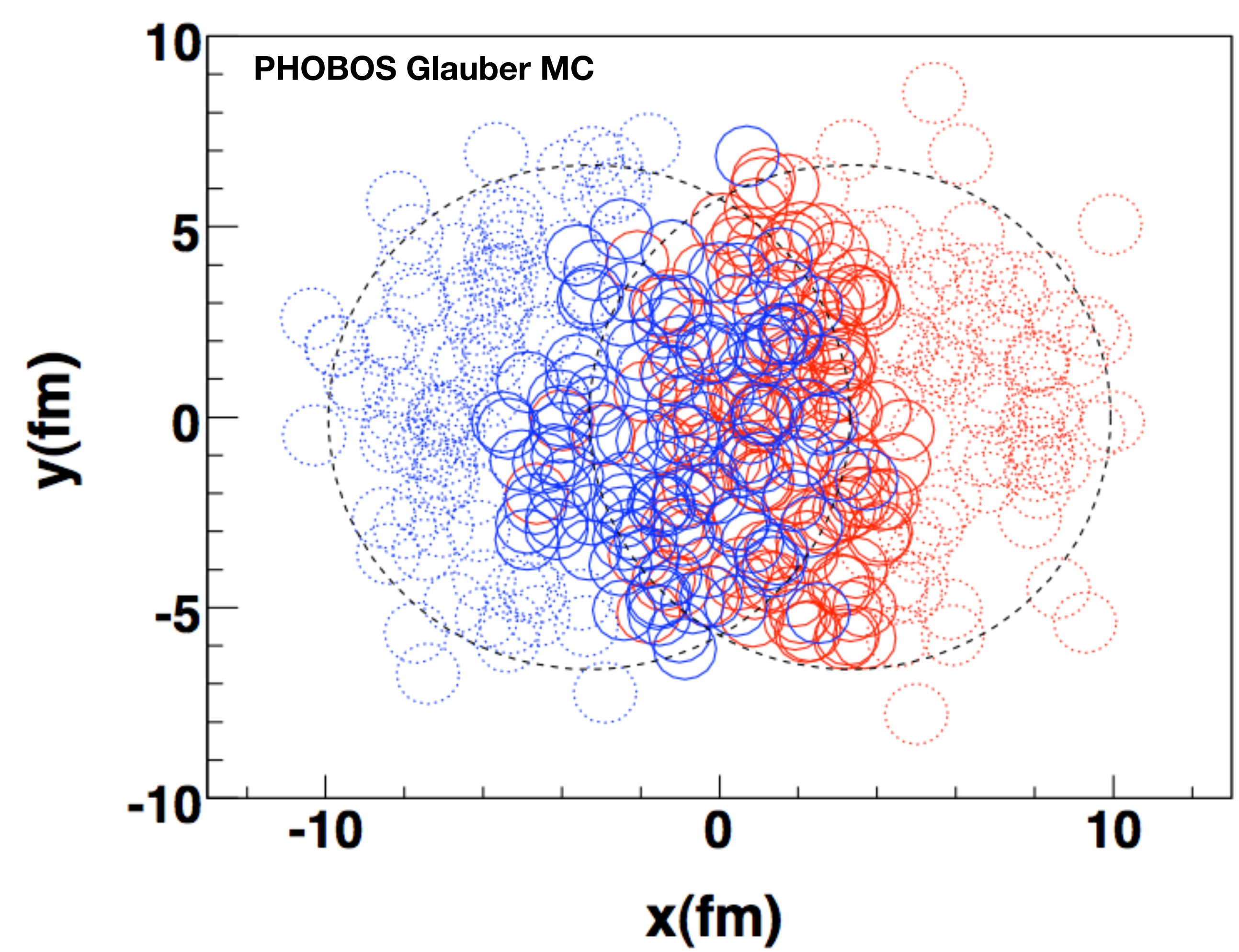
Includes statistical fluctuations

Number of Participating Nucleons, N_{part}

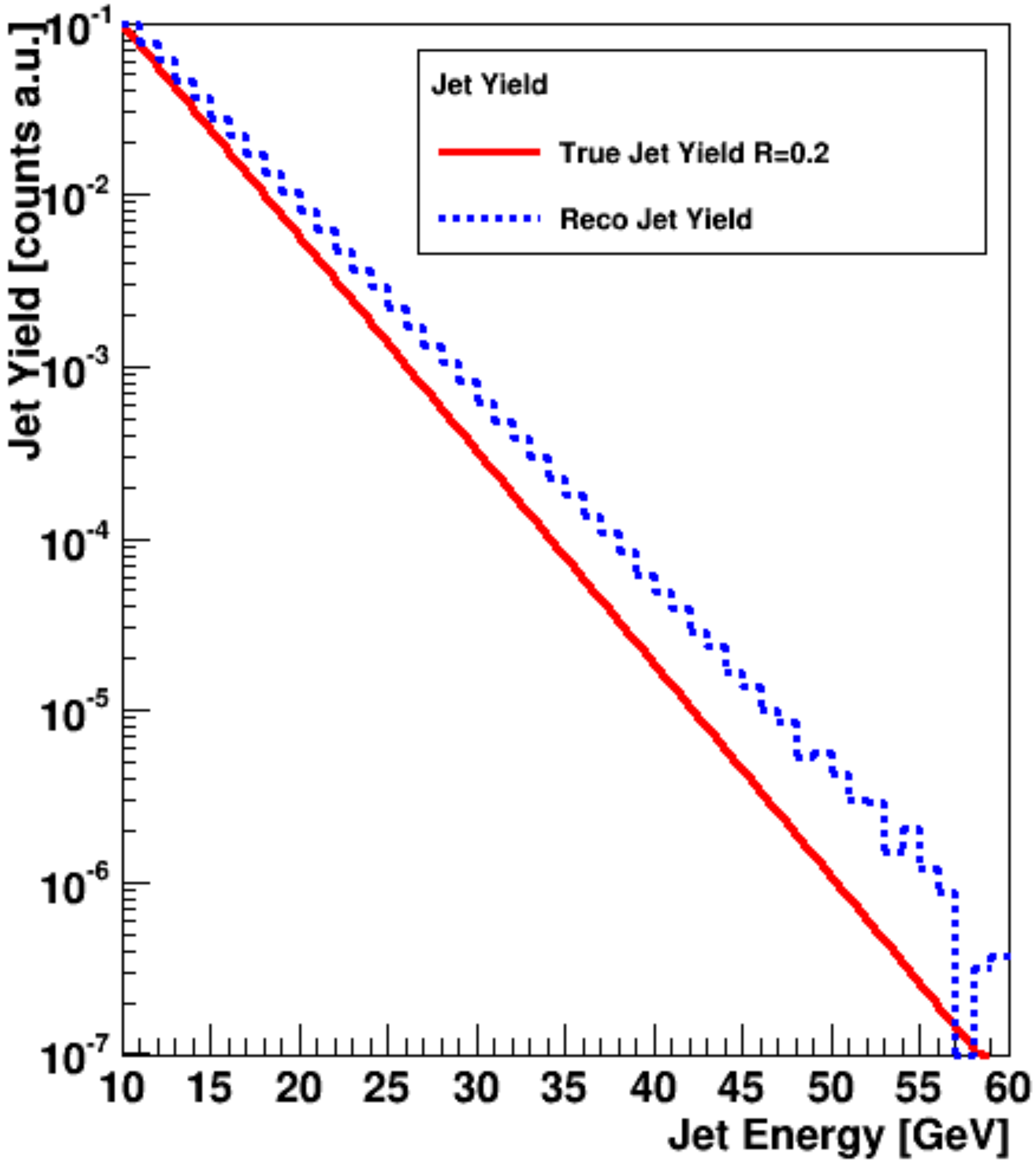
~ system size

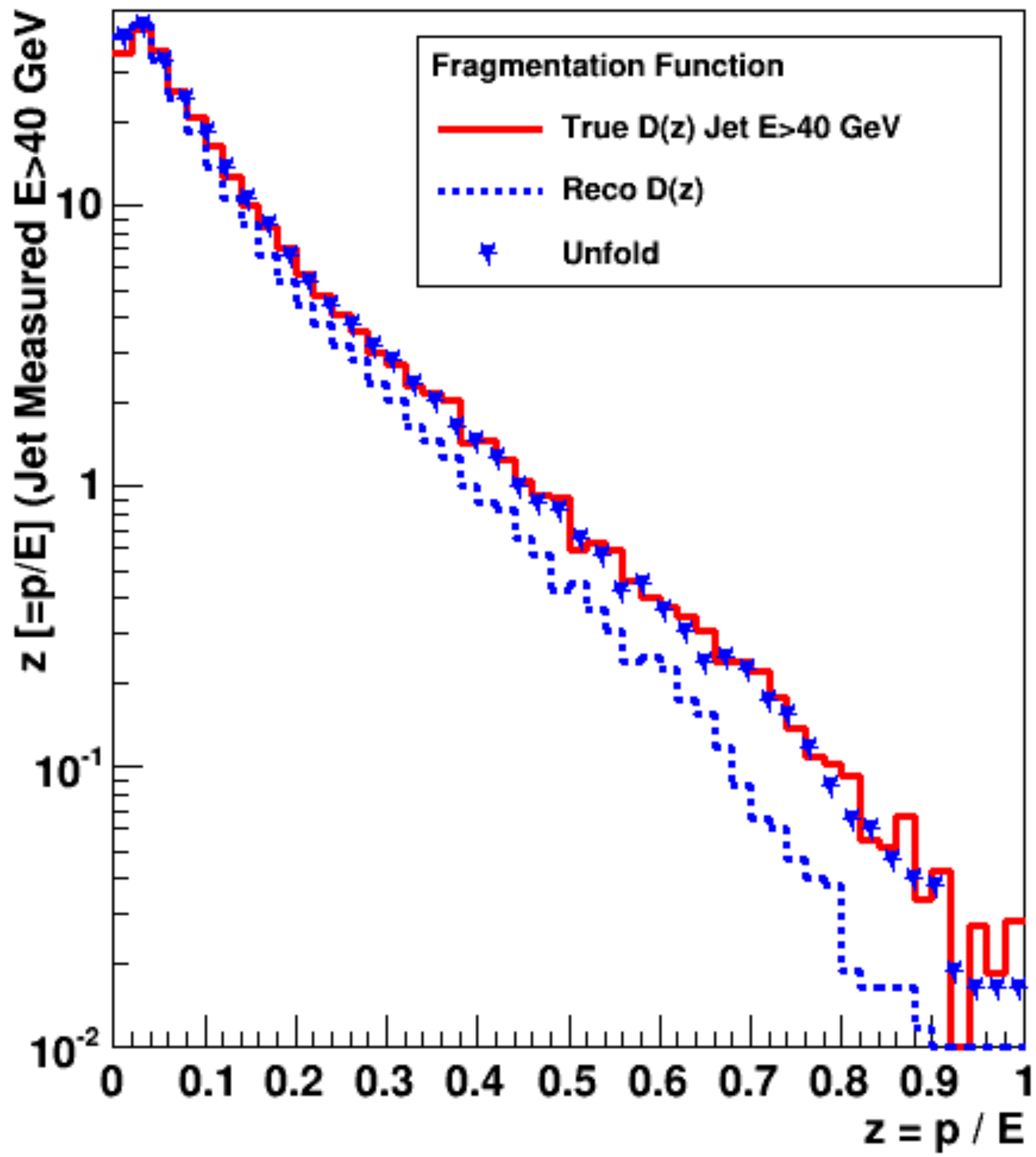
Number of Binary Scatterings, N_{coll}

~ hard process cross-section

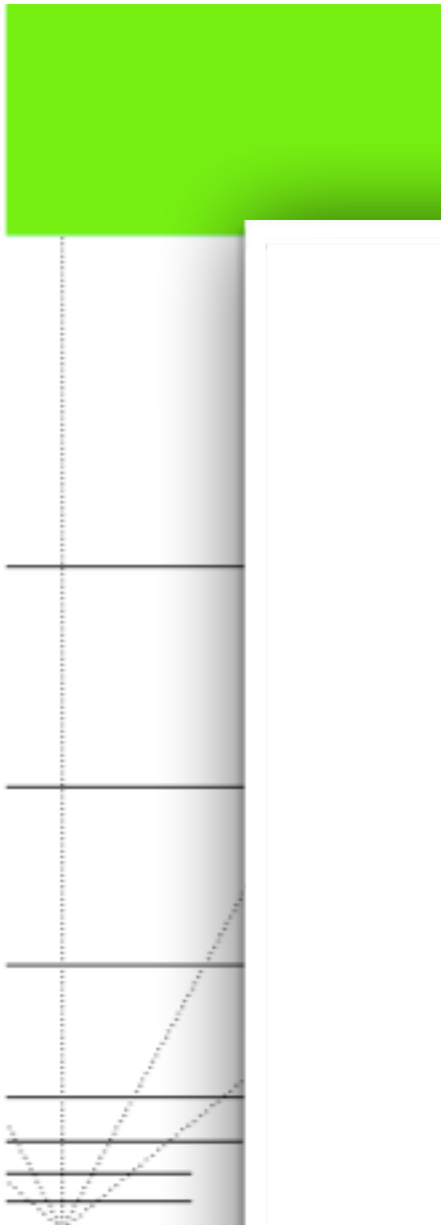


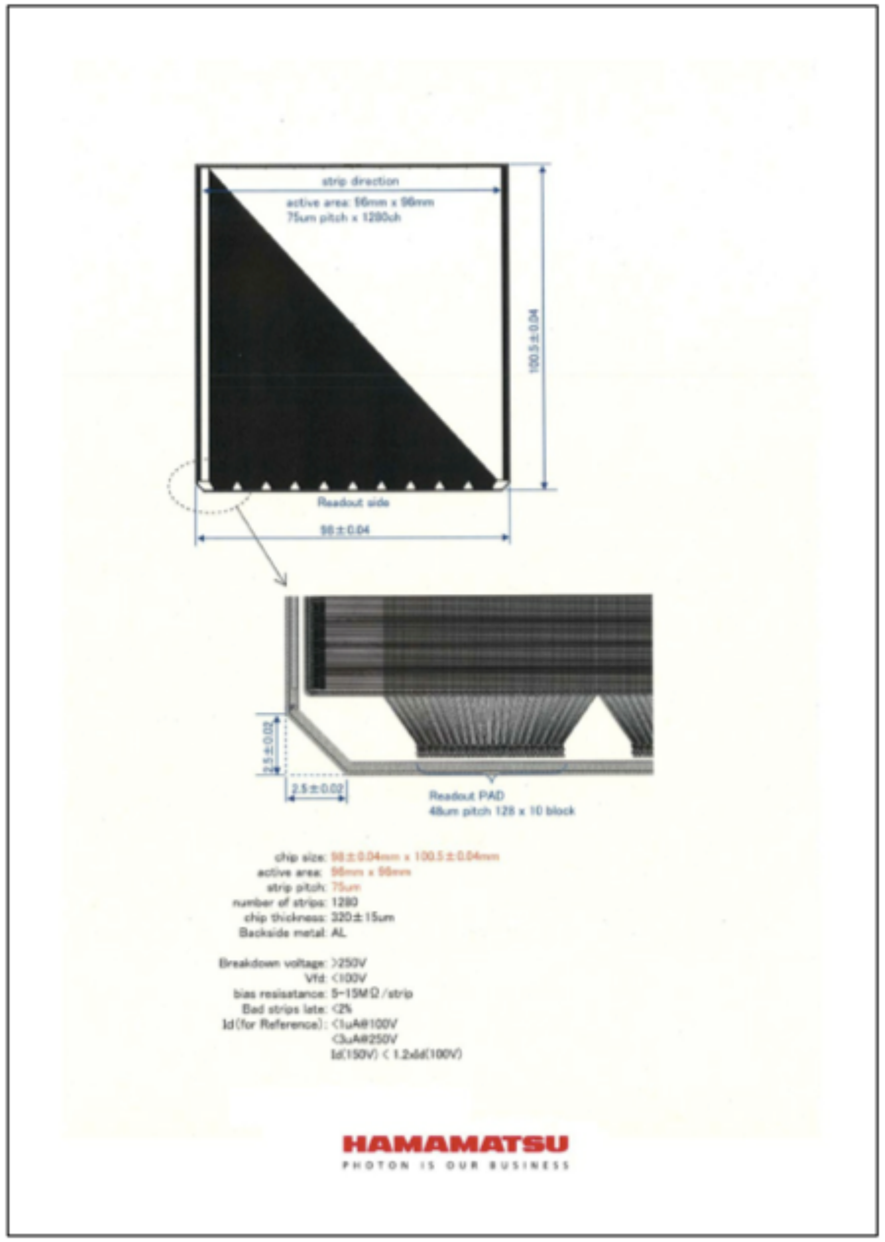
Longitudinal Unfolding





Extended Silicon Tracking Layers





- 75 µ pitch
- 96 mm sensor

= 6.0m²

= 2.7m²

= 0.96m²

ngle layer)

eeded

ncy

uAu

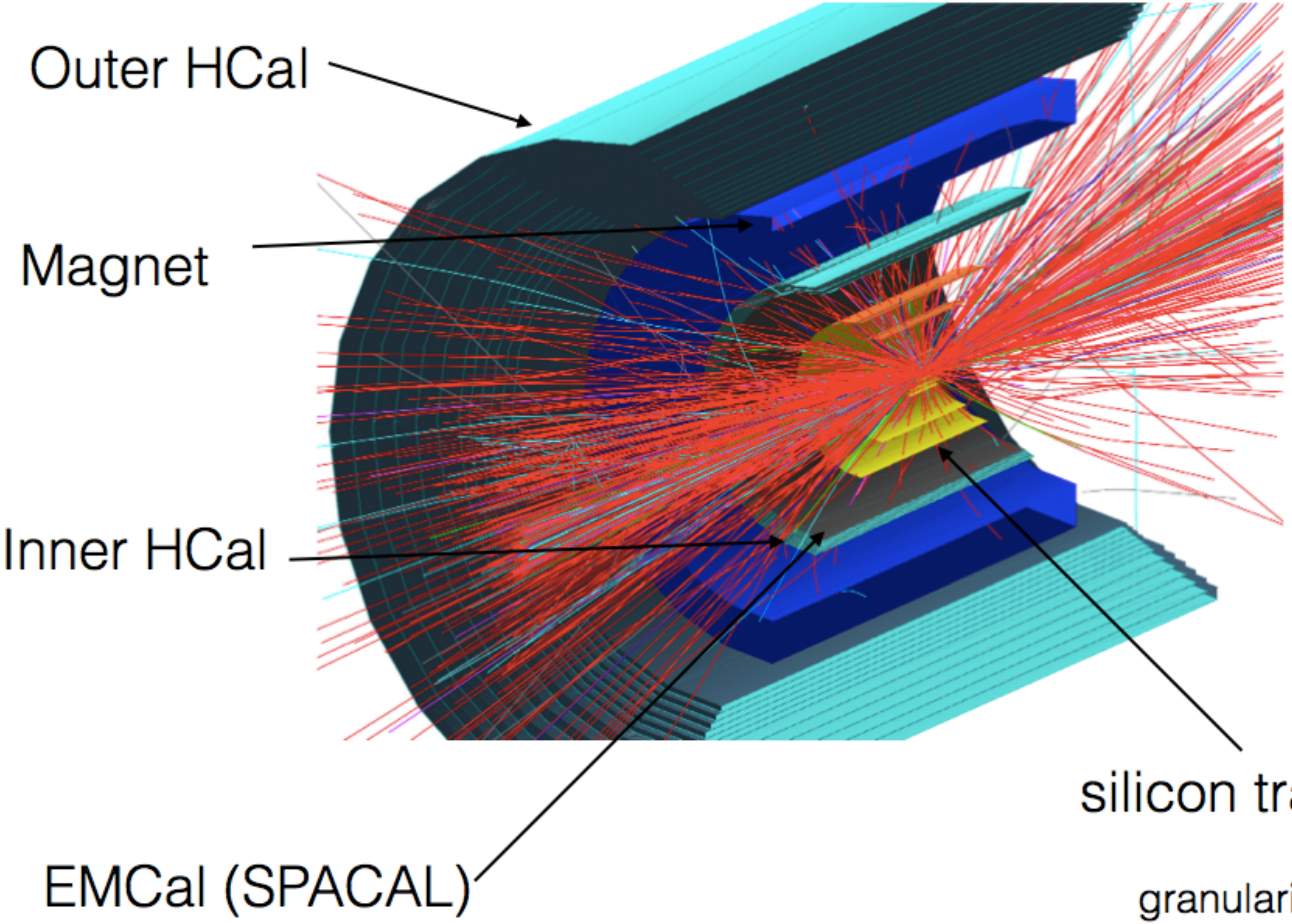
B3: R

B4: R

B5: R=60cm 16 sensors/ladder 40 ladders 640SM 0.35%

Total 1038 SMs 10.4K SVX4s 1.33M ch

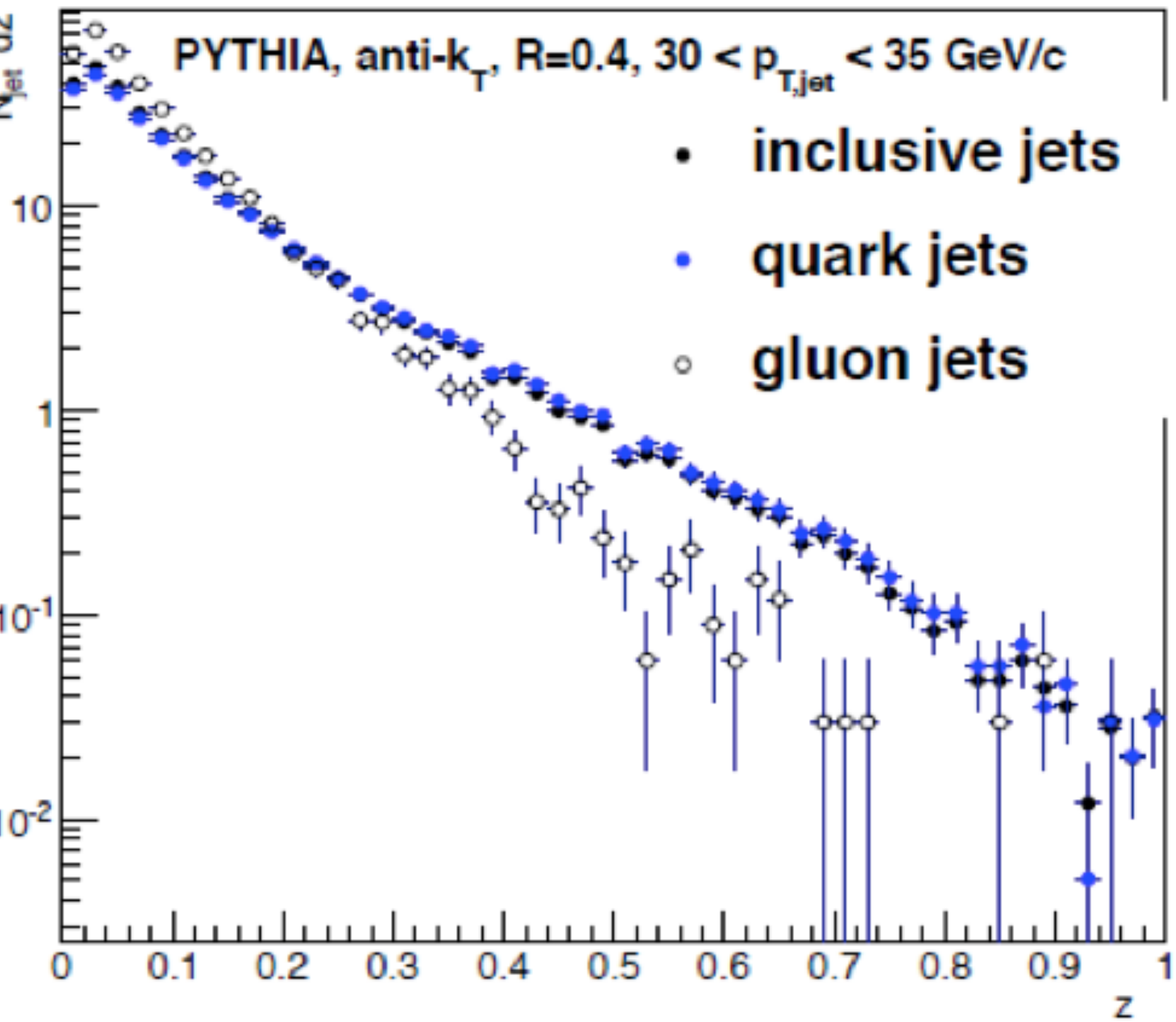
sPHENIX in GEANT4

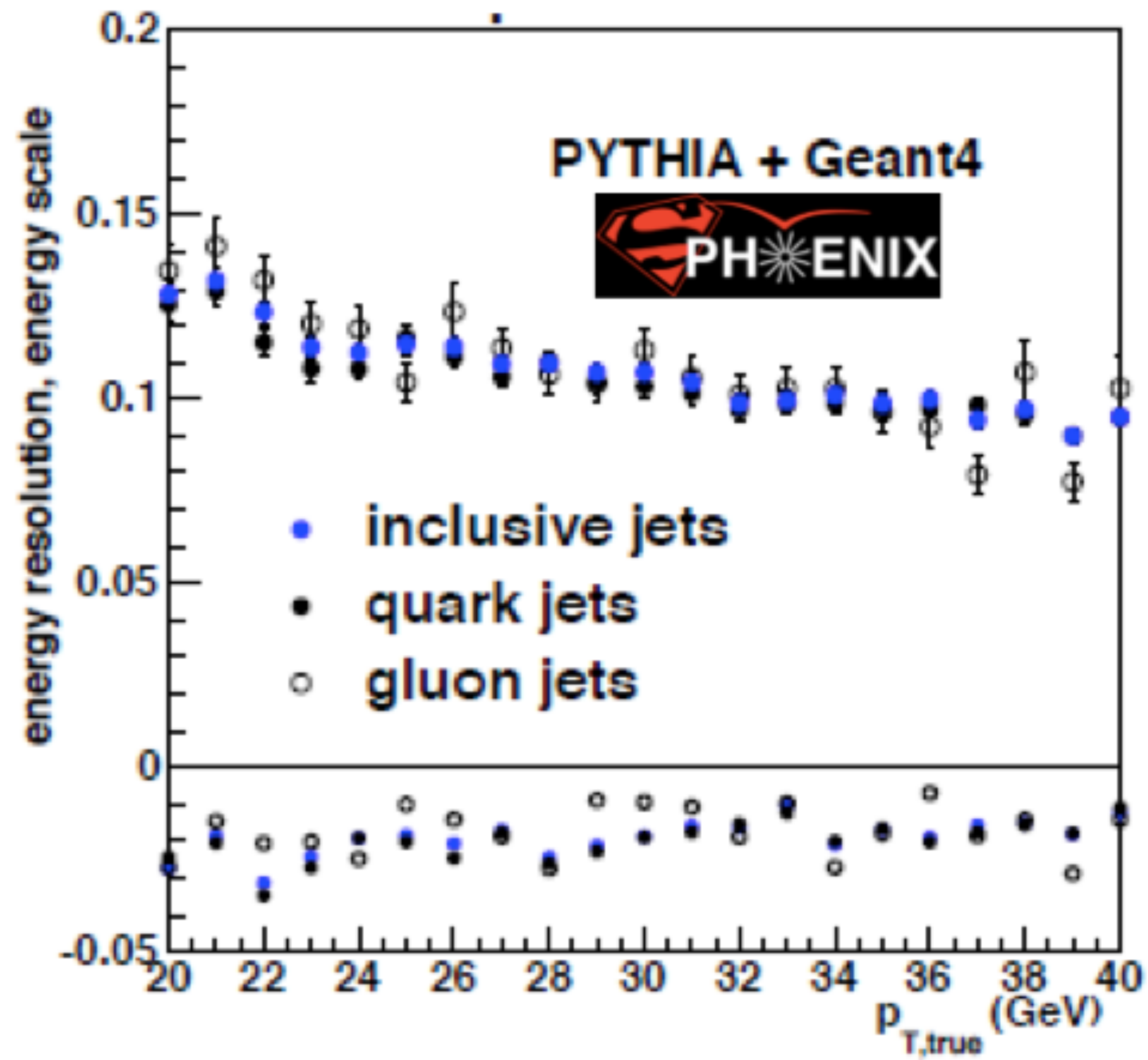


granularity in η x Φ
HCal (both) = 0.1 x 0.1
EMCal = 0.024 x 0.024

Flavor Dependence

Quark and Gluons have very different fragmentation functions



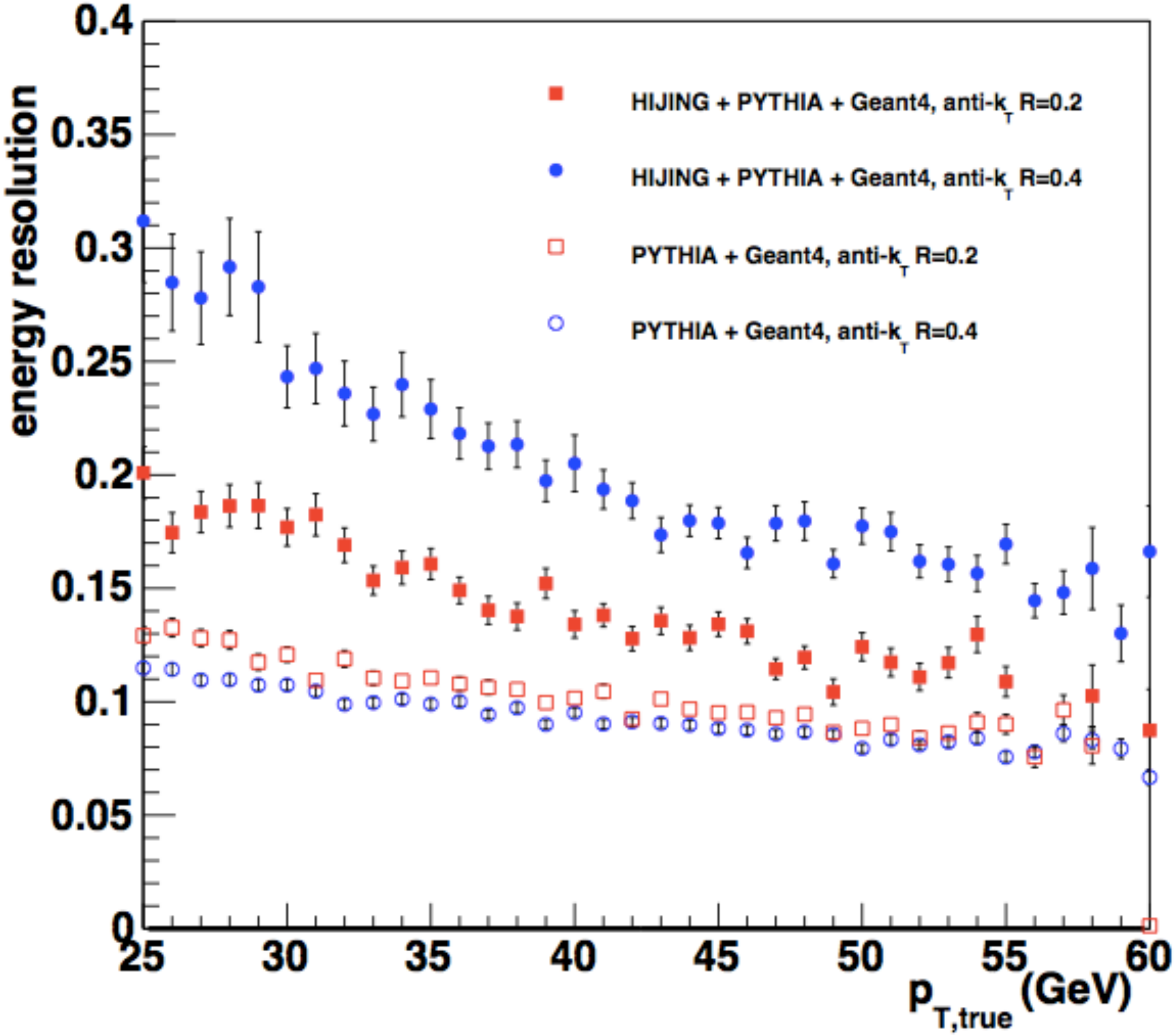


sPHENIX calorimetric measurement gives the same energy scale and resolution.

Critical for extracting longitudinal redistribution of energy.

Jet Performance: A+A

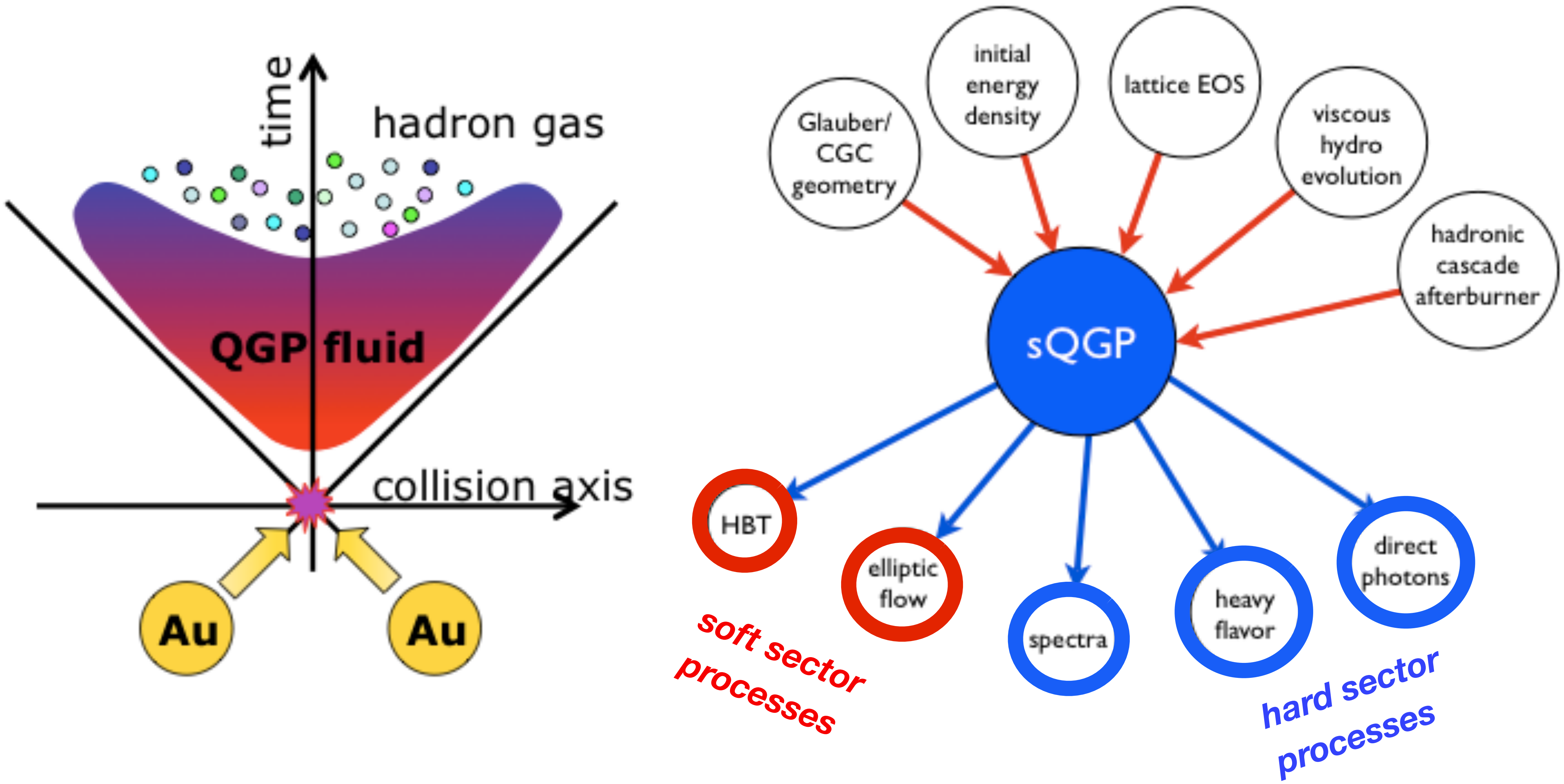
PYTHIA events embedded into central HIJING events



underlying event determines jet performance in AA

4x larger area for R=0.4 jets →larger effect of underlying event, degrades resolution

Strongly Coupled (s)QGP Paradigm



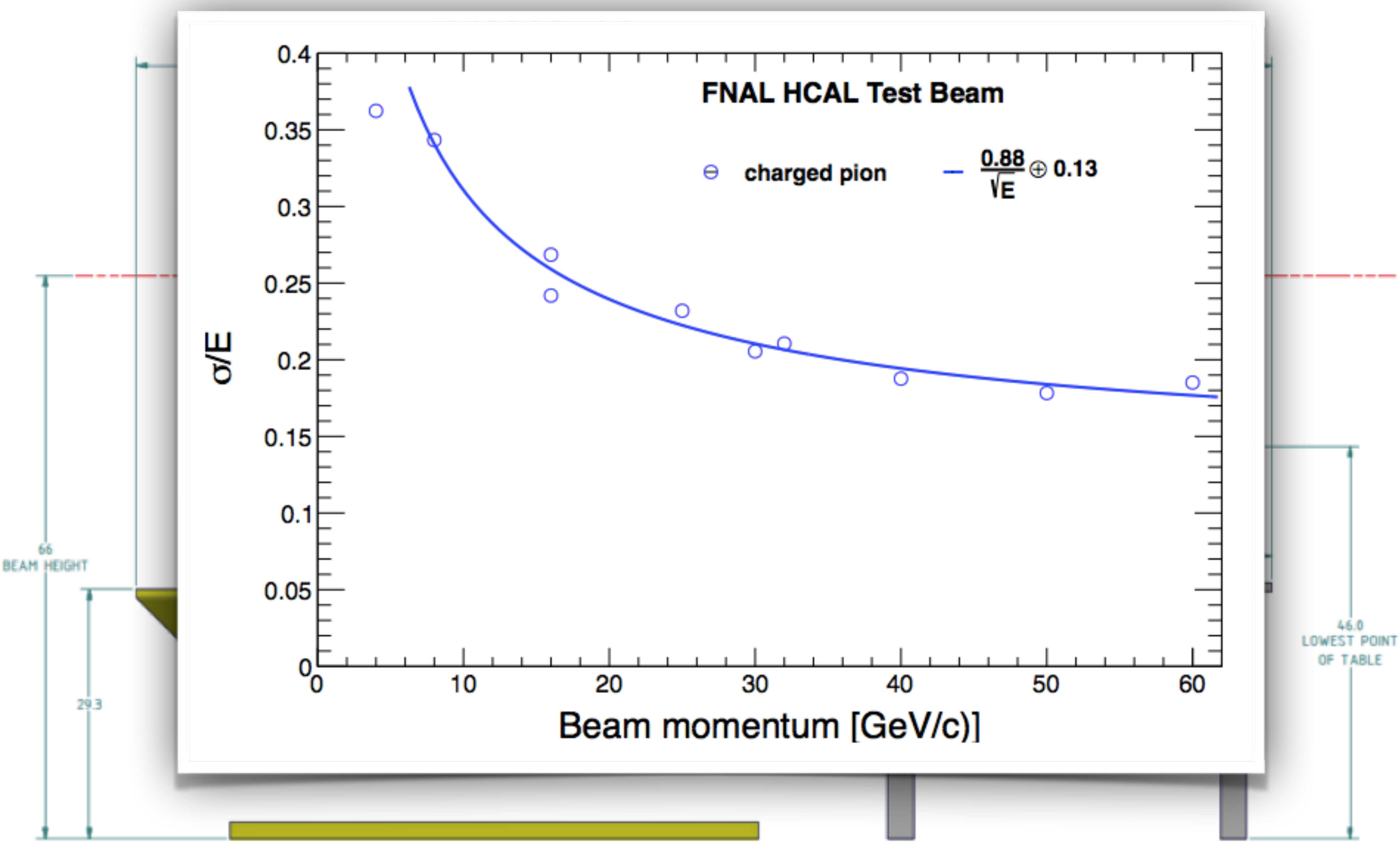
small-viscosity hydrodynamic evolution of QGP implies a strong-coupling and is at the heart of a "*standard model*" for heavy ion collisions

but is missing a comprehensive examination from the hard sector:

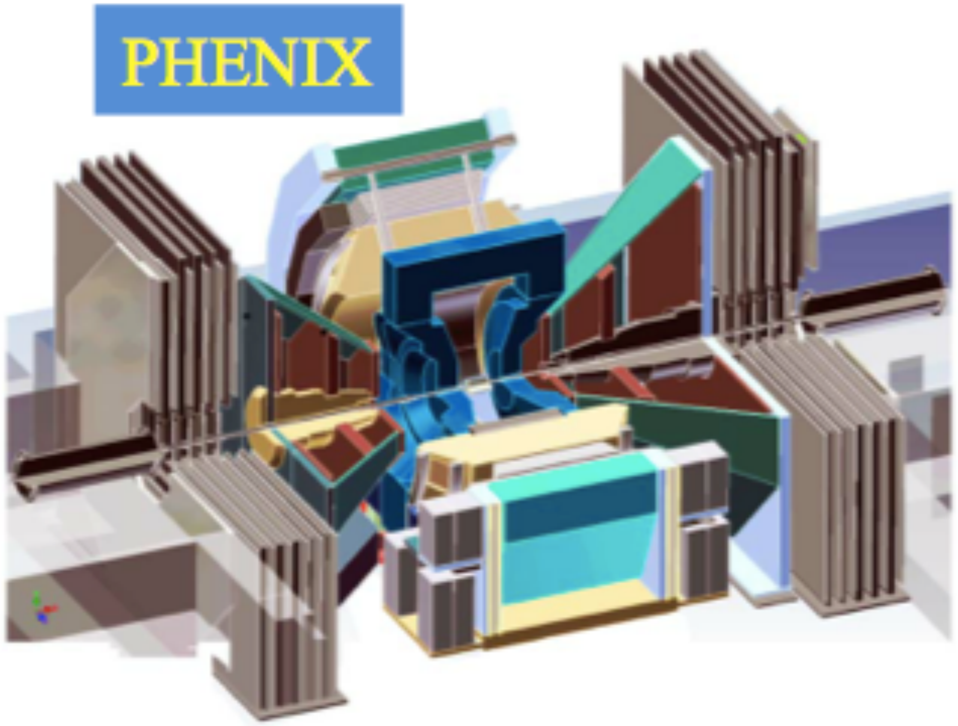
parton energy loss and *quarkonia suppression*

FNAL Test Beam Exp T-1044

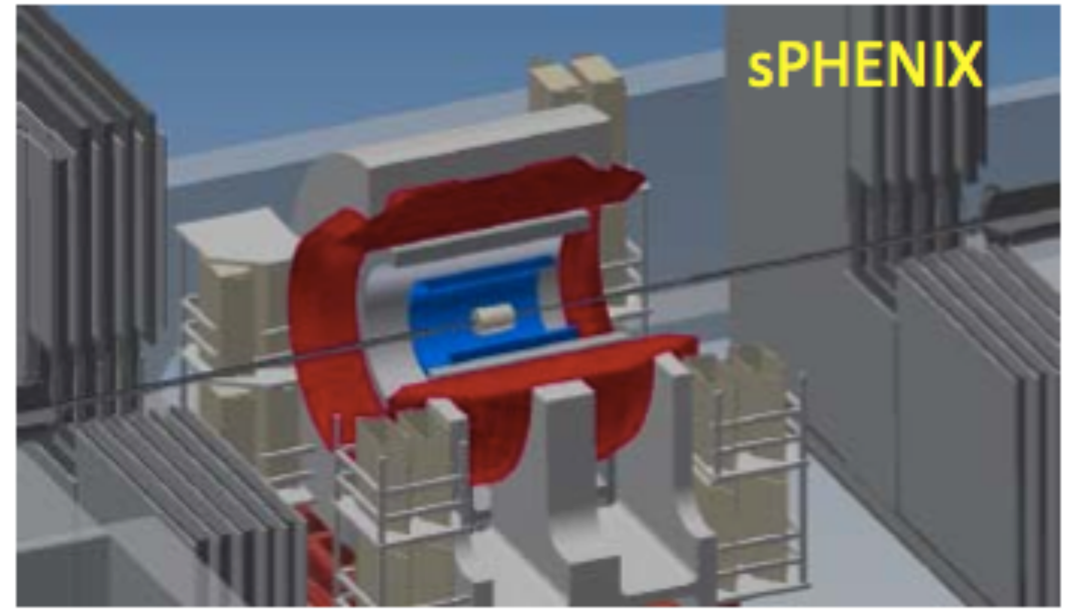
HCAL



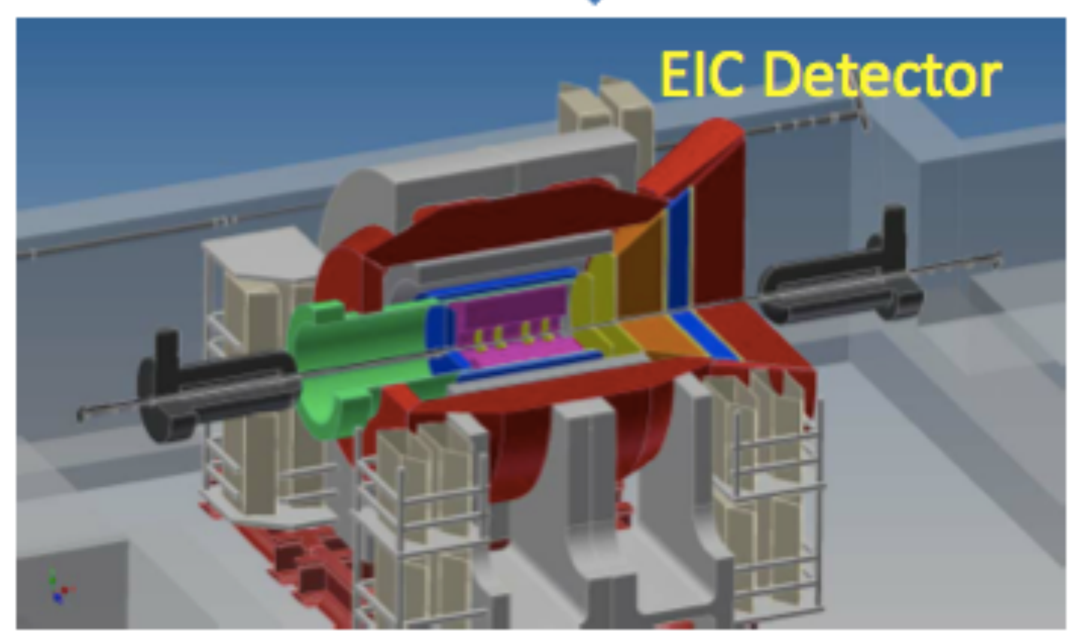
sPHENIX evolution



~2021-22



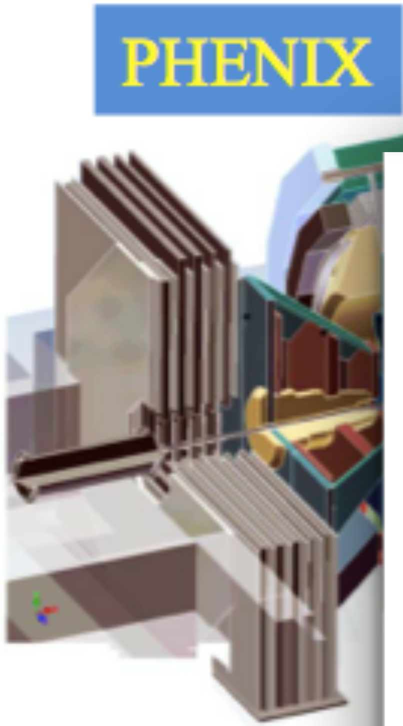
~2025

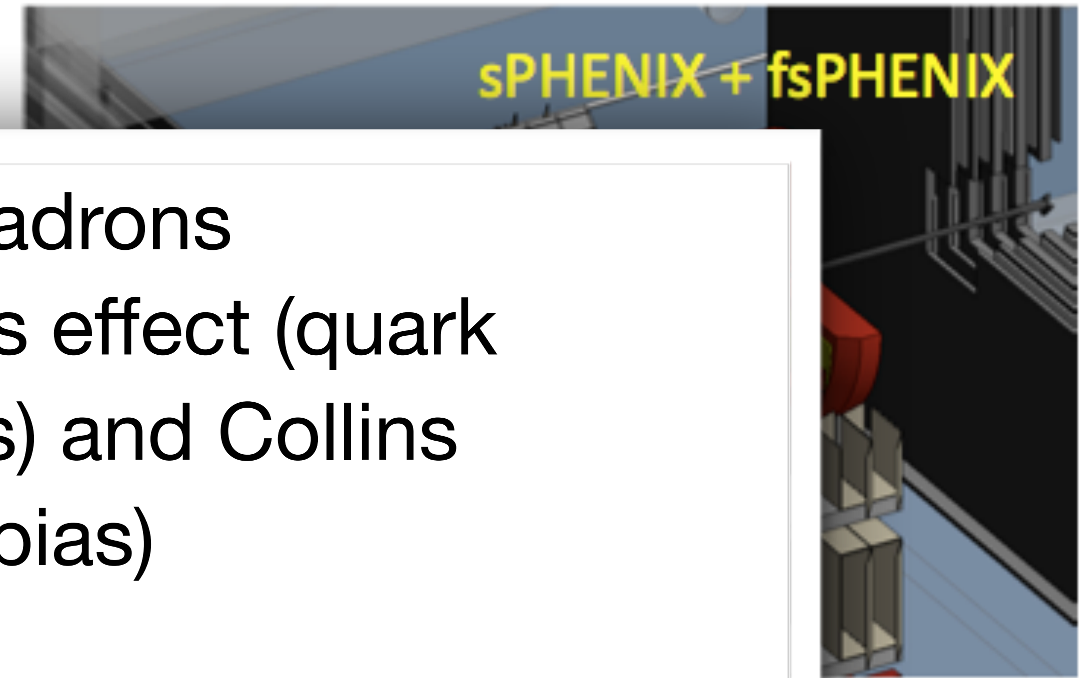


Evolve sPHENIX (pp and HI detector) to an EIC Detector (ep and eA detector):

- To utilize e and p (A) beams at eRHIC with *e*-energy up to 15 GeV and *p*(*A*)-energy up to 250 GeV (100 GeV/n)
- *e*, *p*, He^3 polarized
- Stage-1 luminosity ~10^{33} cm^{-2} s^{-1} (~$1fb^{-1}$ /month)

sPHENIX evolution





- Forward jets + charged hadrons

  clear separation of Sivers effect (quark distribution left-right bias) and Collins (fragmentation left-right bias)

  isolate Sivers effect contributions from up- and down-quark

- Forward muons

  Drell-Yan SSA process dependence

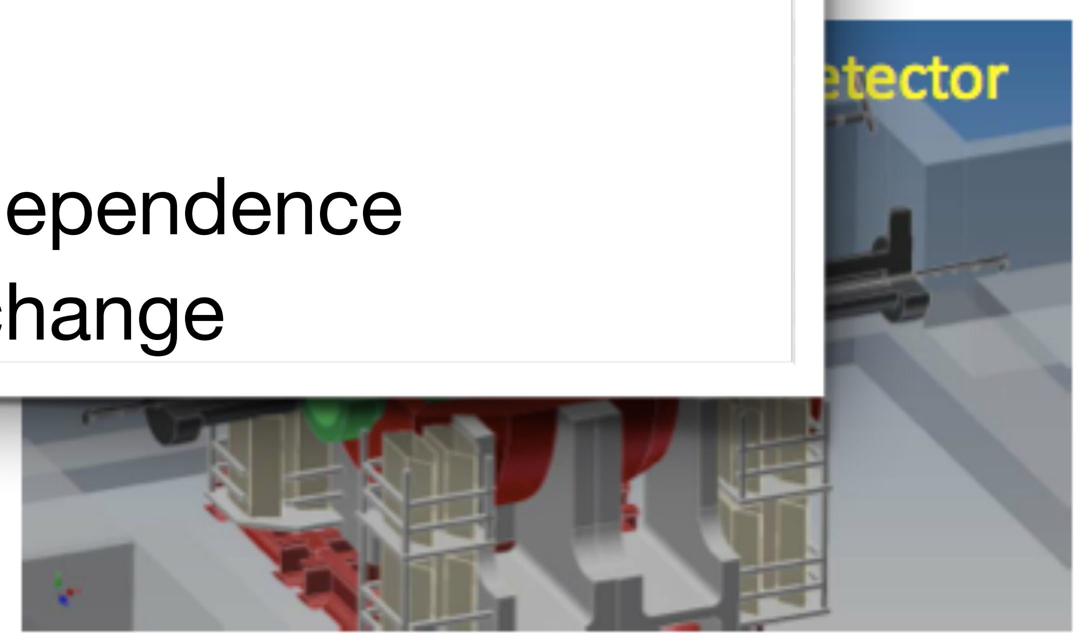
  Sivers distribution sign change

25

Evolve sPHE

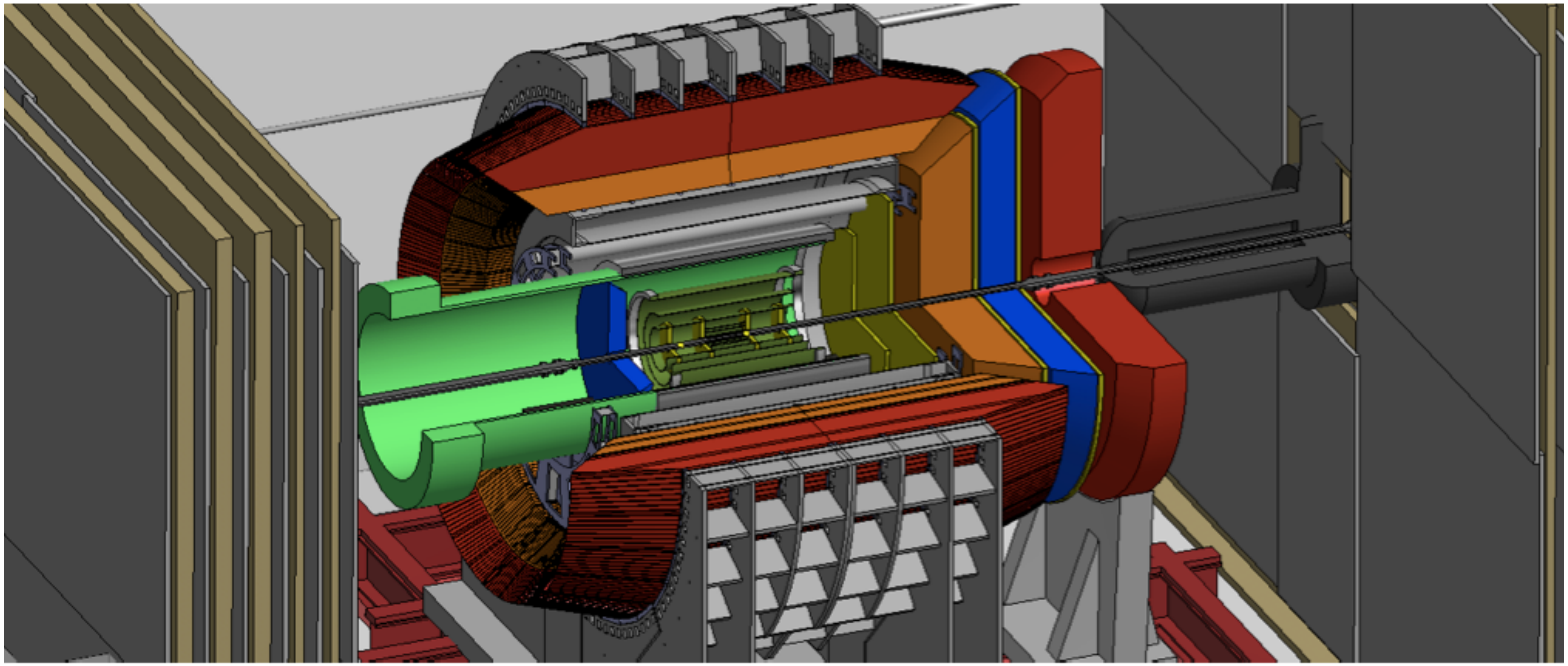
EIC Detector

- To utili with e energ
- *e*, *p*, *He*³ polarized
- Stage-1 luminosity ~10^{33} cm^{-2} s^{-1} (~$1fb^{-1}$ /month)



sPHENIX transforms into an EIC detector

Built around the BaBar Magnet and sPHENIX Calorimetry



- BaBar magnet has extra coil density near the ends – with proper flux return shaping, provides good analyzing power at very forward angles
- sPHENIX EMCal meets EIC detector specifications
- sPHENIX HCal doubles as requires flux return

sPHENIX run plan

Two years of physics running 2021 and 2022 with 30-cryo week runs

20 weeks Au+Au @ 200 GeV
10+ weeks p+p @ 200 GeV [comparable baseline statistics]
10+ weeks p+Au @ 200 GeV [comparable baseline/new physics stats]

sPHENIX maintains very high PHENIX DAQ rate – nominal 8 kHz
sPHENIX maintains fast detector capability – no pile up problems

If we just record Au+Au minimum bias events (no trigger bias), in 20 weeks with current RHIC performance and PHENIX livetime, we record **50 billion events within $|z| < 10$ cm** [optimal for silicon tracking]

Note this is not sampled, but recorded. Full range of differential measurements and centralities with no trigger biases.

BNL Proposed 10-year Plan

Years	Beam Species and Energies	Science Goals	New Systems Commissioned
2014	15 GeV Au+Au 200 GeV Au+Au	Heavy flavor flow, energy loss, thermalization, etc. Quarkonium studies QCD critical point search	Electron lenses 56 MHz SRF STAR HFT STAR MTD
2015-16	p+p at 200 GeV p+Au, d+Au, ^{3}He+Au at 200 GeV High statistics Au+Au	Extract $\eta/s(T)$ + constrain initial quantum fluctuations More heavy flavor studies Sphaleron tests Transverse spin physics	PHENIX MPC-EX Coherent e-cooling test
2017	No Run		Low energy e-cooling upgrade
2018-19	5-20 GeV Au+Au (BES-2)	Search for QCD critical point and onset of deconfinement	STAR ITPC upgrade Partial commissioning of sPHENIX (in 2019)
2020	No Run		Complete sPHENIX installation STAR forward upgrades
2021-22	Long 200 GeV Au+Au with upgraded detectors p+p, p/d+Au at 200 GeV	Jet, di-jet, γ-jet probes of parton transport and energy loss mechanism Color screening for different quarkonia	sPHENIX
2023-24	No Runs		Transition to eRHIC