# PHENIX *Physics* & **Plans**


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(Los Alamos National Laboratory)

**for the PHENIX Collaboration**


**RHIC & AGS Users Meeting**

Upton, NY

June 17 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?*

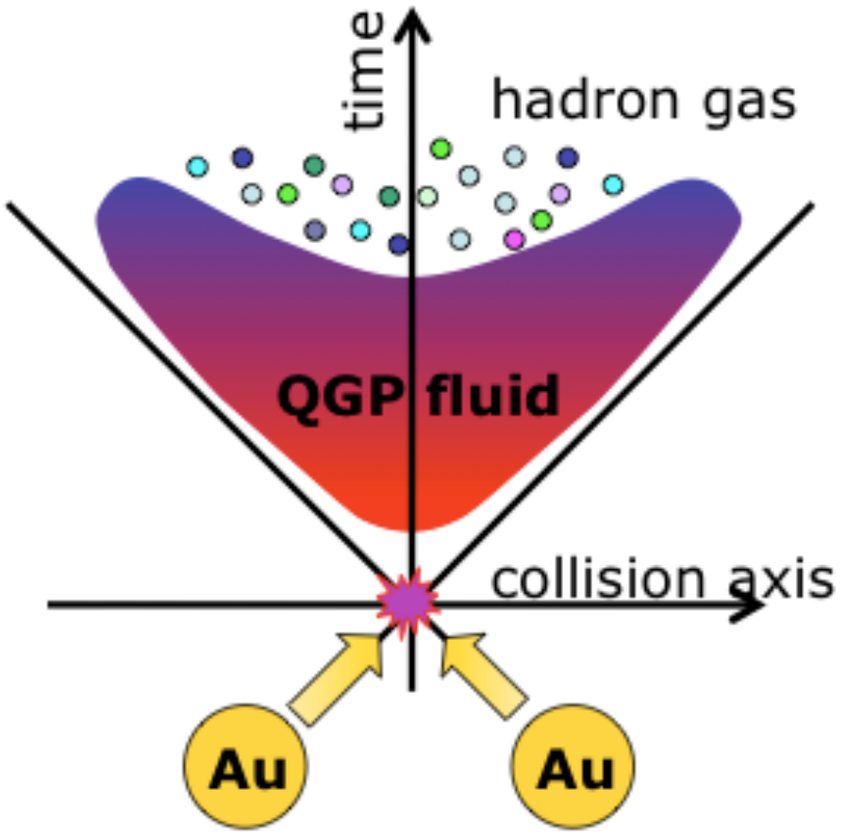
(2) The **detector configuration** to fit these observables

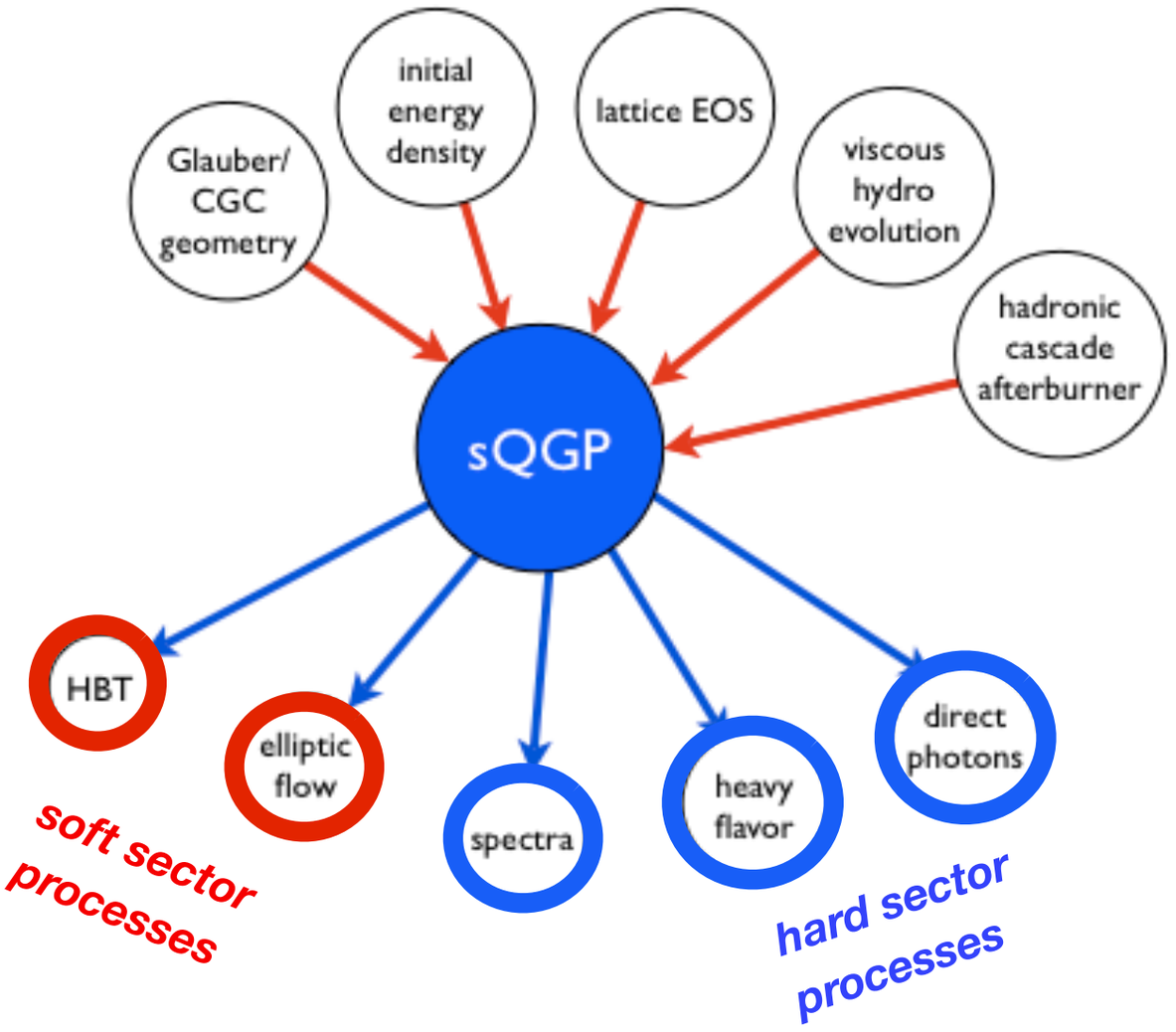
*Can a detector be built to make these measurements?*

(3) Planned **operations** and additional **opportunities**

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

# Strongly Coupled (s)QGP Paradigm



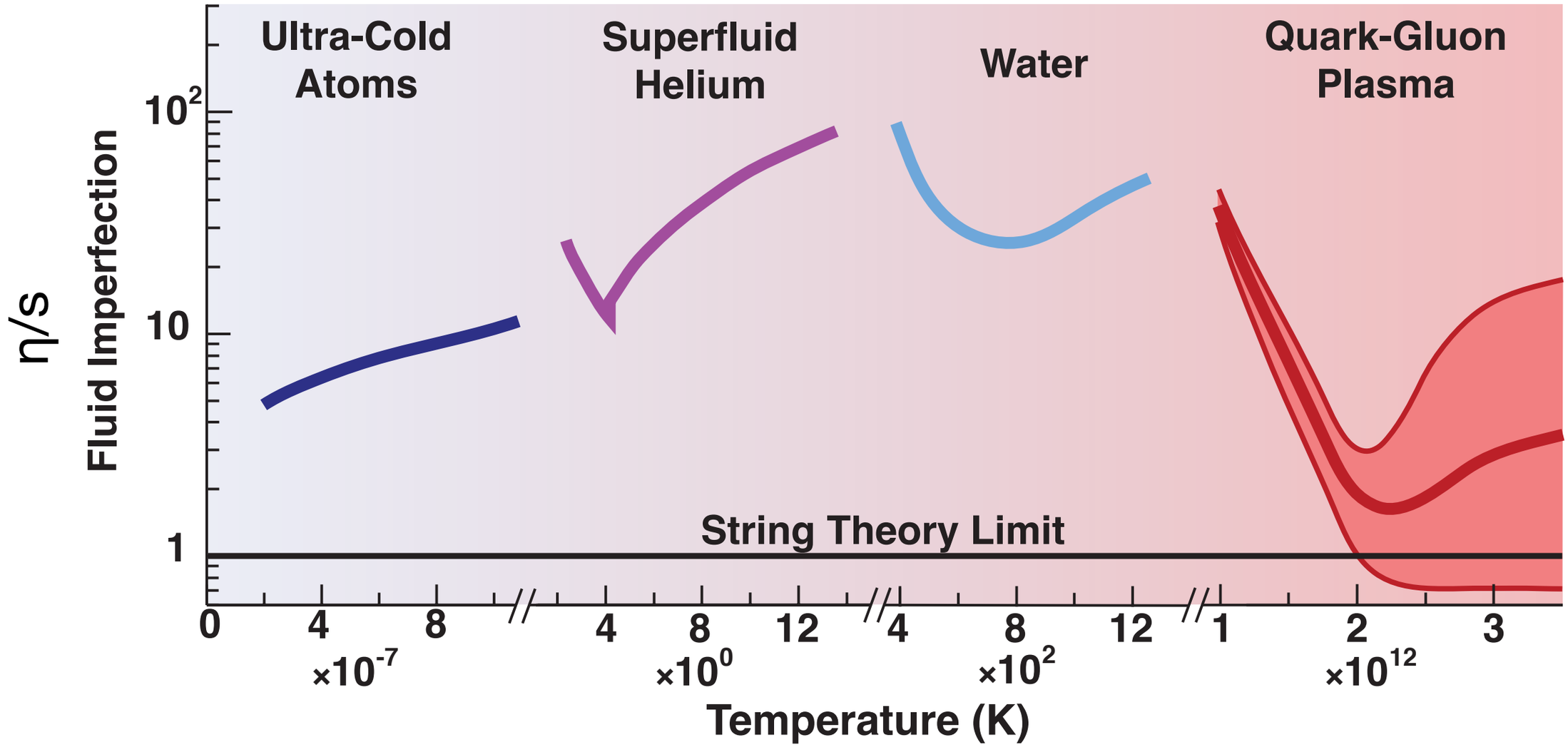




small-viscosity hydrodynamic evolution of QGP implies a strong-coupling and is at the heart of a "*standard model*" for heavy ion collisions

but is missing a comprehensive examination from the hard sector:

***parton energy loss*** and *quarkonia suppression*

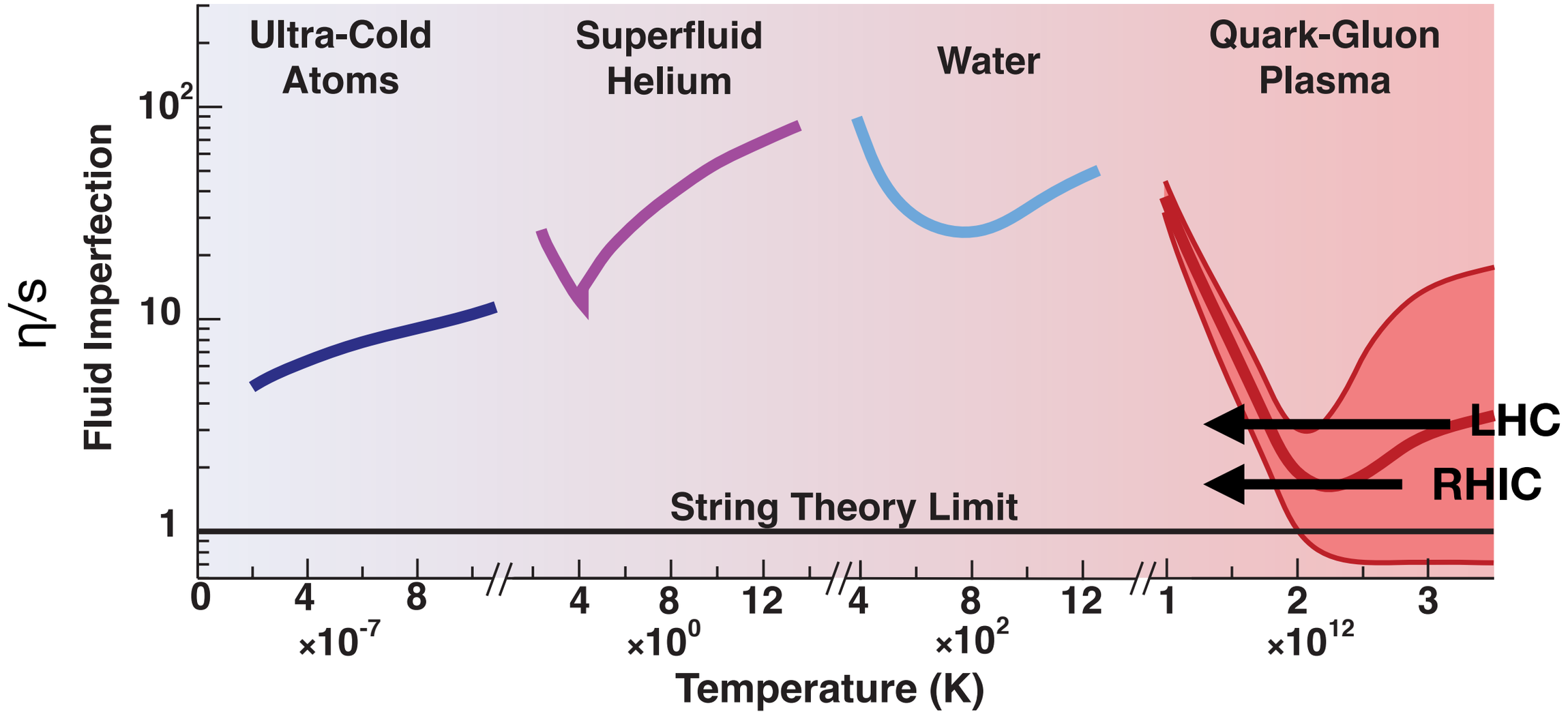
# Viscosity near Phase Transitions




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

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

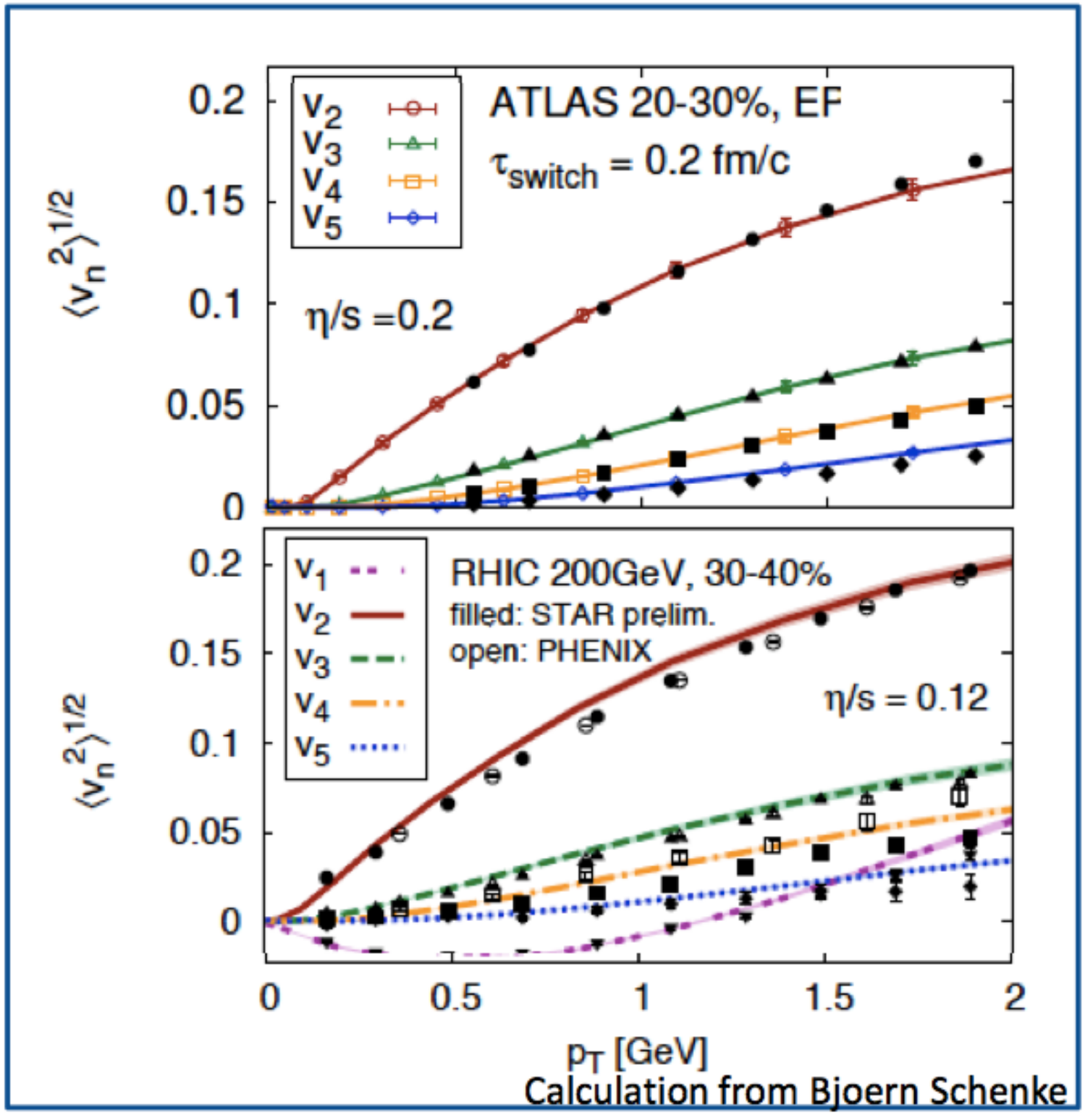
# Viscosity near Phase Transitions




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?

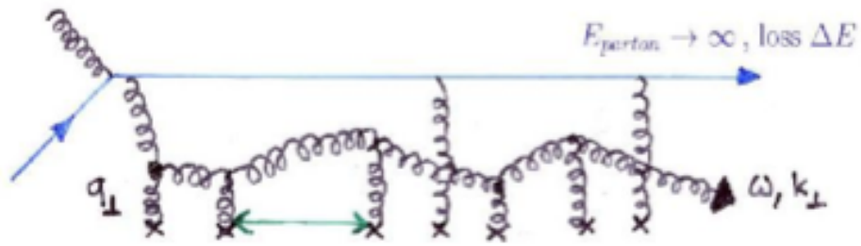
# Relationship to Hard Sector Physics

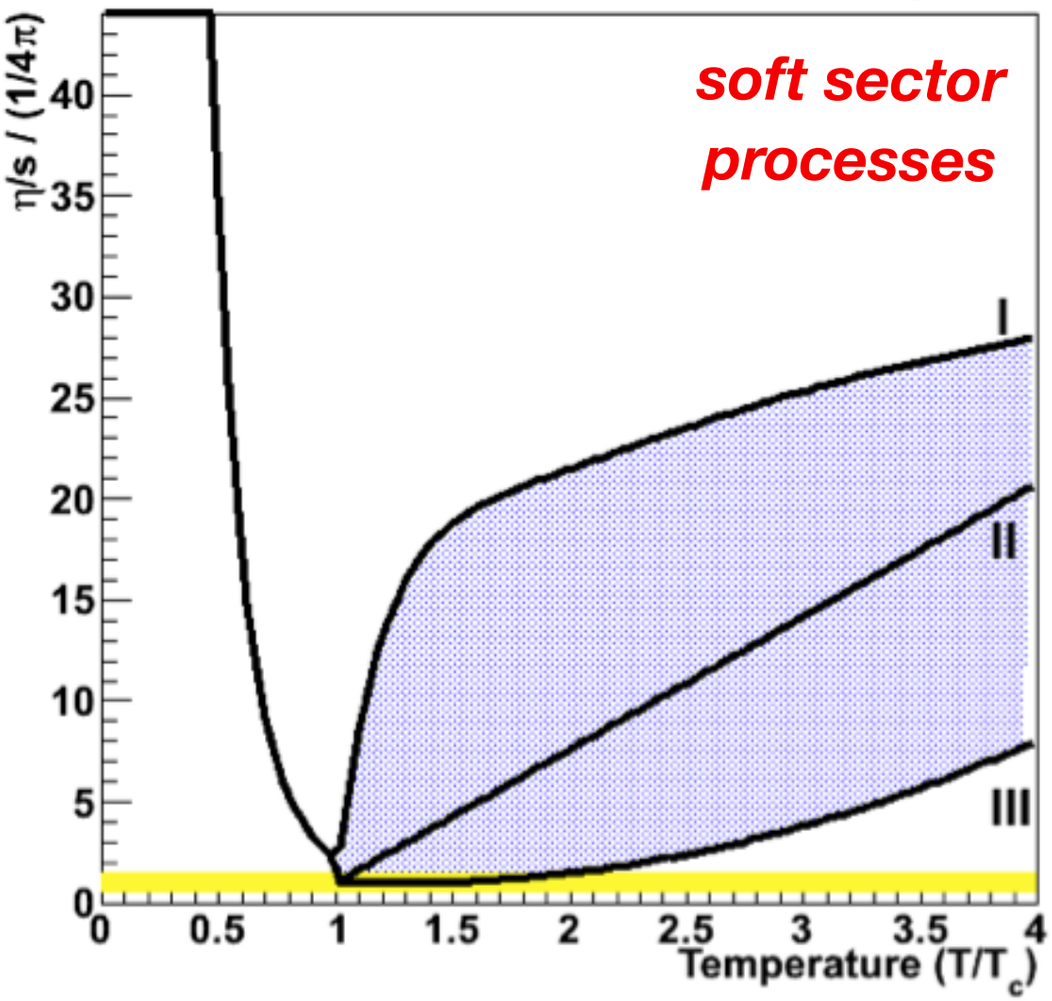
smaller viscosity ⇒ larger coupling ⇒ larger interaction with jets

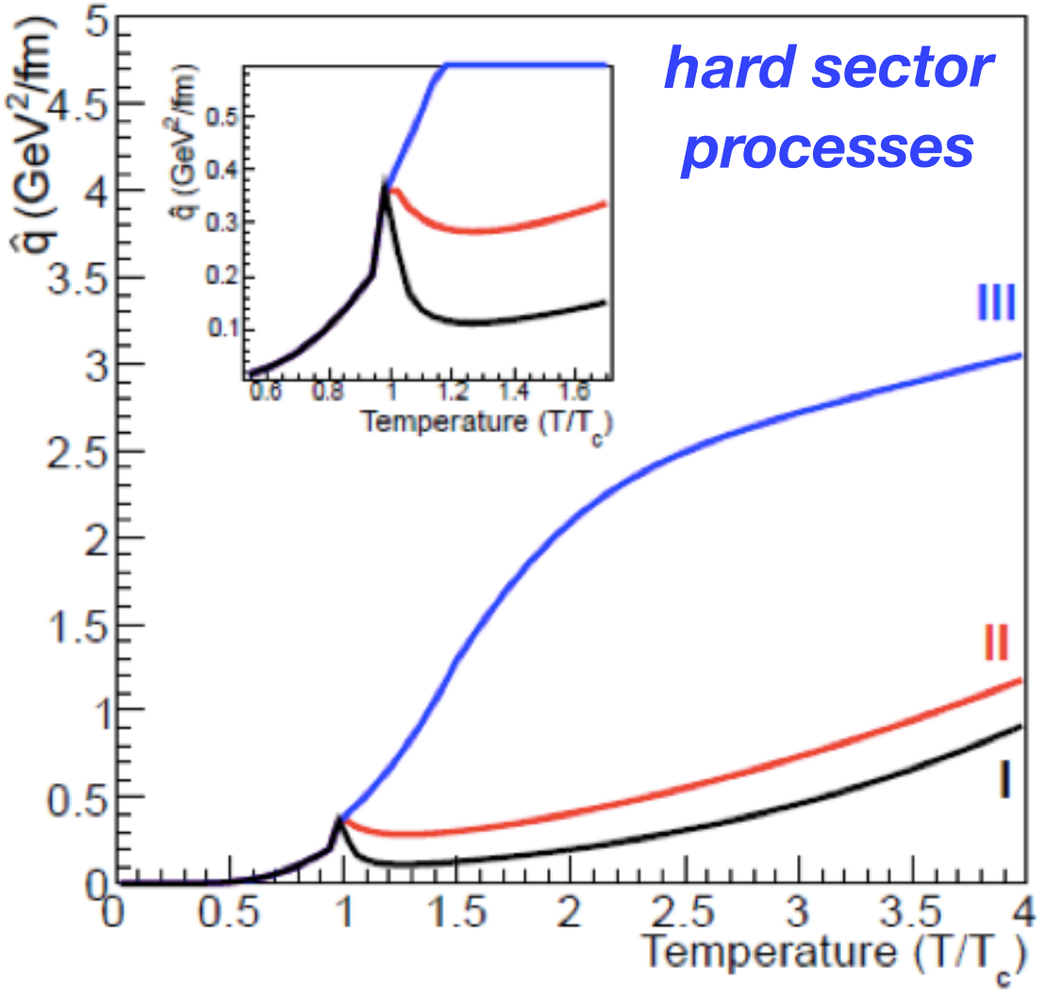
"Small Shear Viscosity Implies Strong Jet Quenching"

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

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




Key is independently measuring both sides of this equation

# Critical Knobs to Explore

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

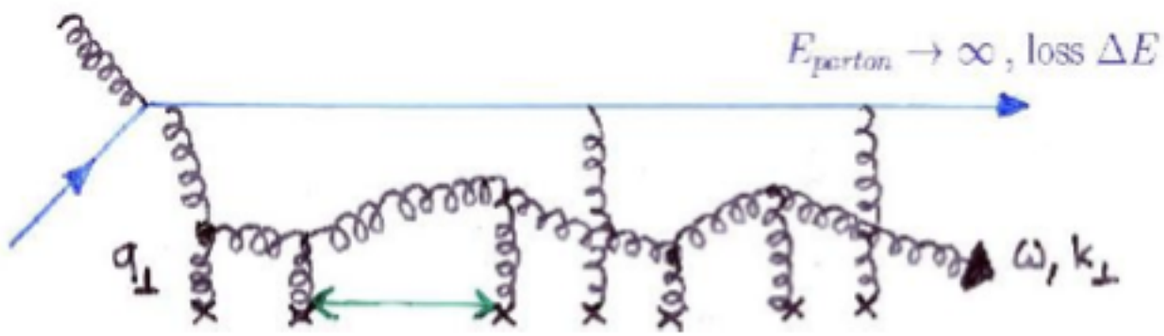
Time dependence of the QGP by virtuality variation (**hard process $Q^2$**)

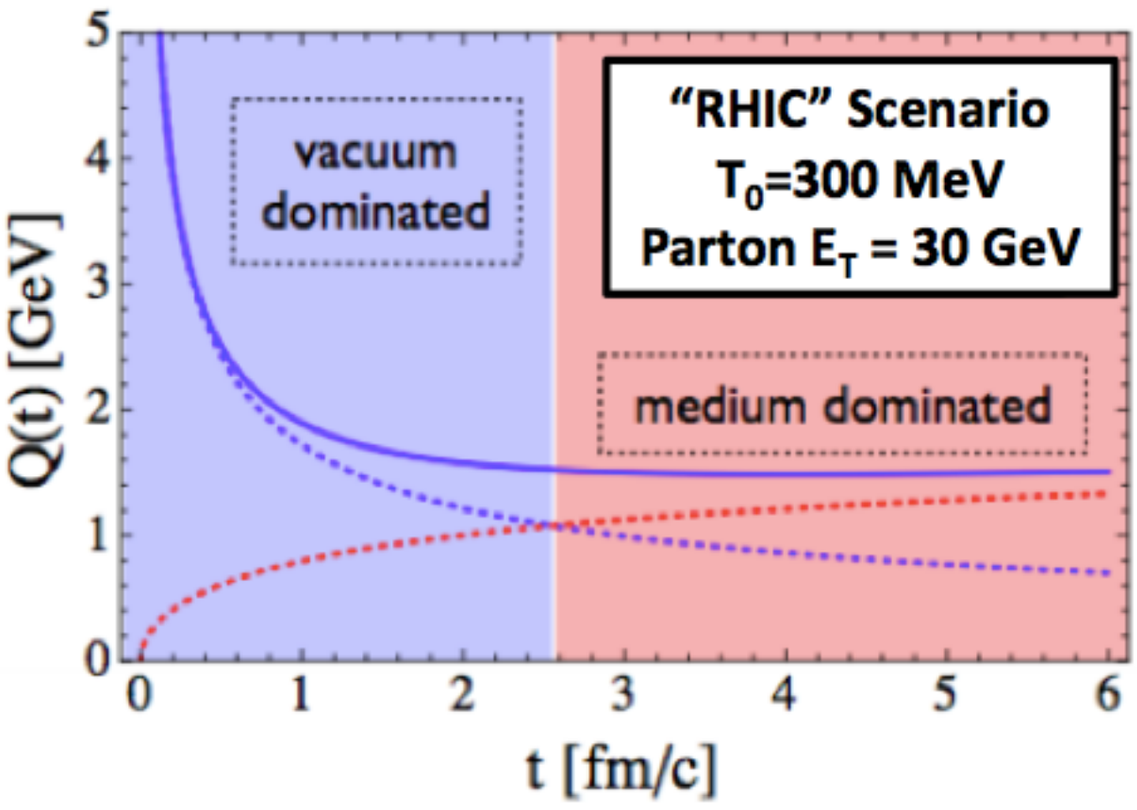
Length scale within the QGP by interaction hardness (**interaction $Q^2$**)

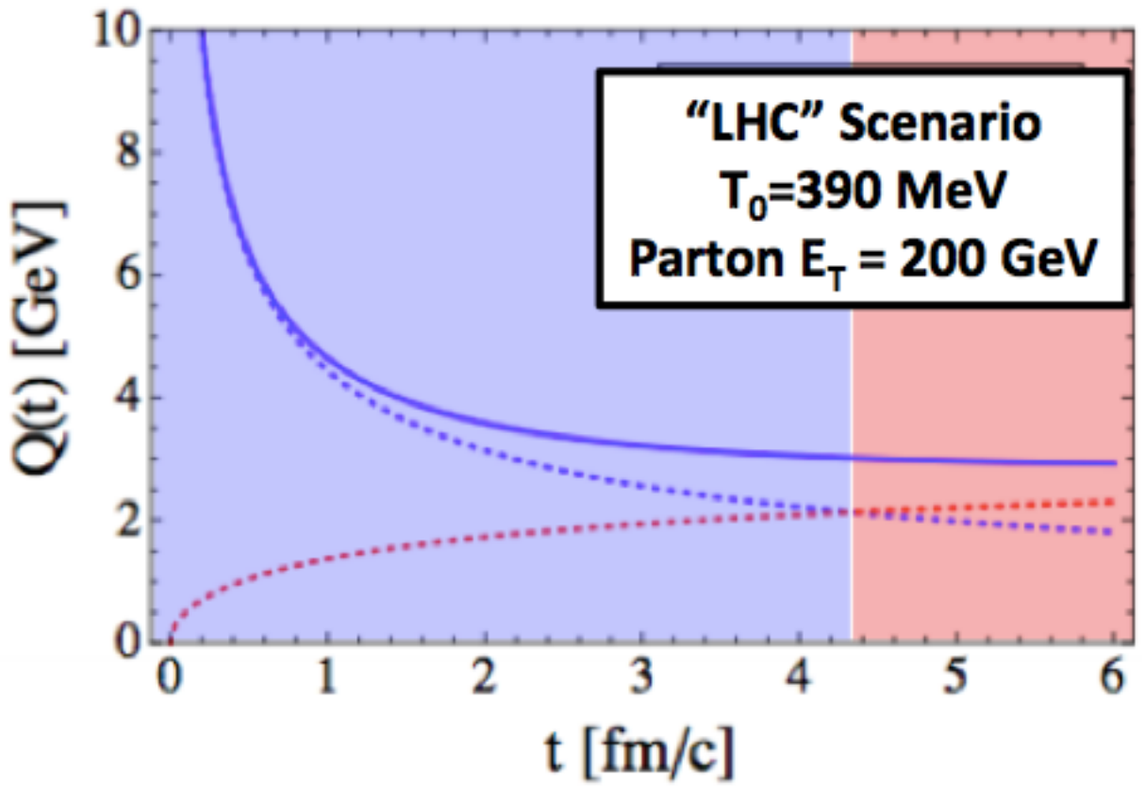
# Virtuality Evolution

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

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



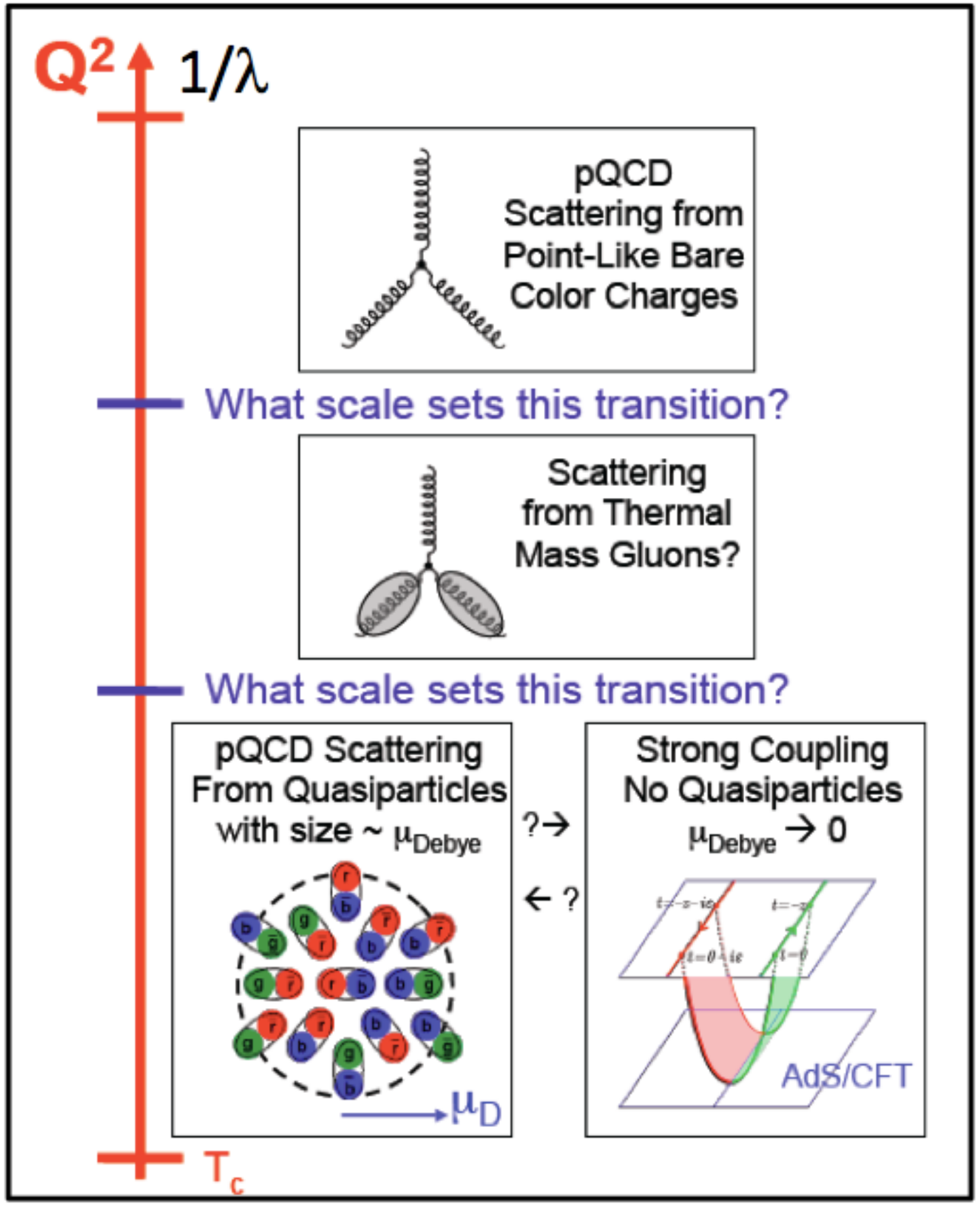

the vacuum contribution to the parton virtuality to fall below the in-medium contribution in the pQCD scenario. This effect is due to the collinear splitting in pQCD, which reduces the parton energy only gradually and thus leads to an increase in time dilation as the virtuality drops. This means that 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

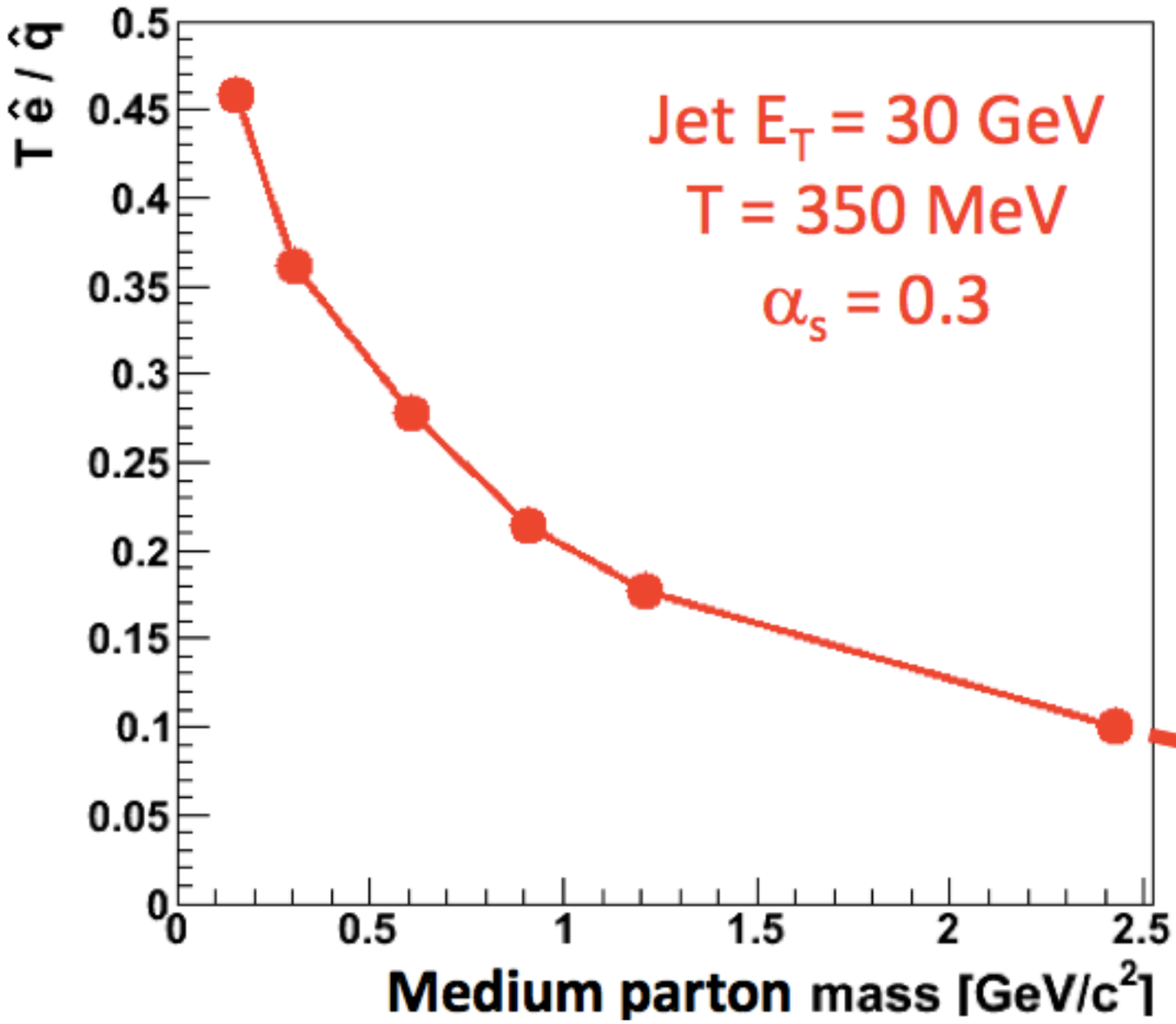
# QGP Constituent Mass Dependence

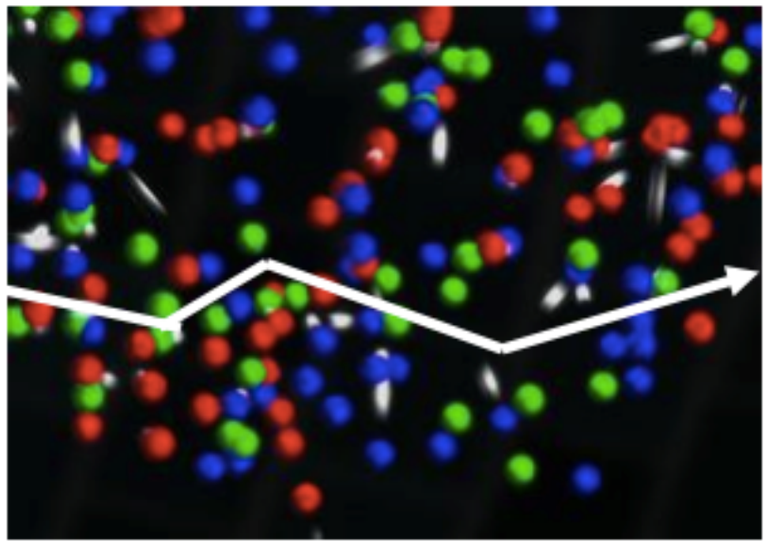
C. E. Coleman-Smith* and B. Müller
*Department of Physics, Duke University, Durham, NC 27708-0305*

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

qhat → scattering of leading parton → radiation e-loss

ehat → energy transferred to the QGP medium



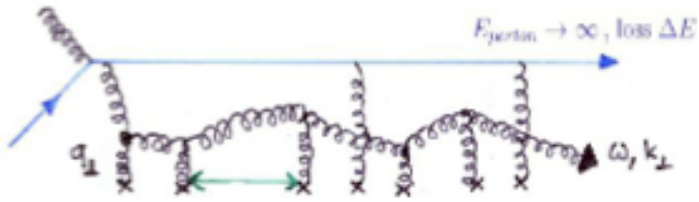



Limit of infinitely massive scattering centers yields all radiative e-loss.

# 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)

Post-QM Meeting (Mont Sainte Odile)

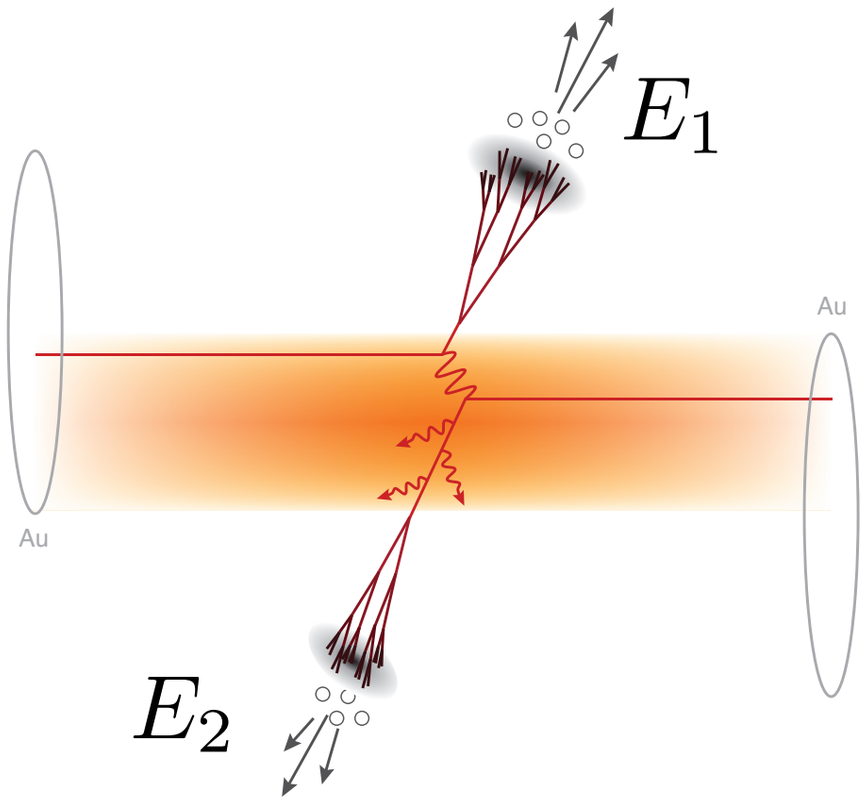
Krishna referred to this as microscopy of the QGP

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

# *sPHENIX Observables and Contraints*

- Single jets, direct photons: $R_{AA}$, $v_N$
- 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
- Compatibility with future EIC detector

# Reconstructed Jets and $A_J$

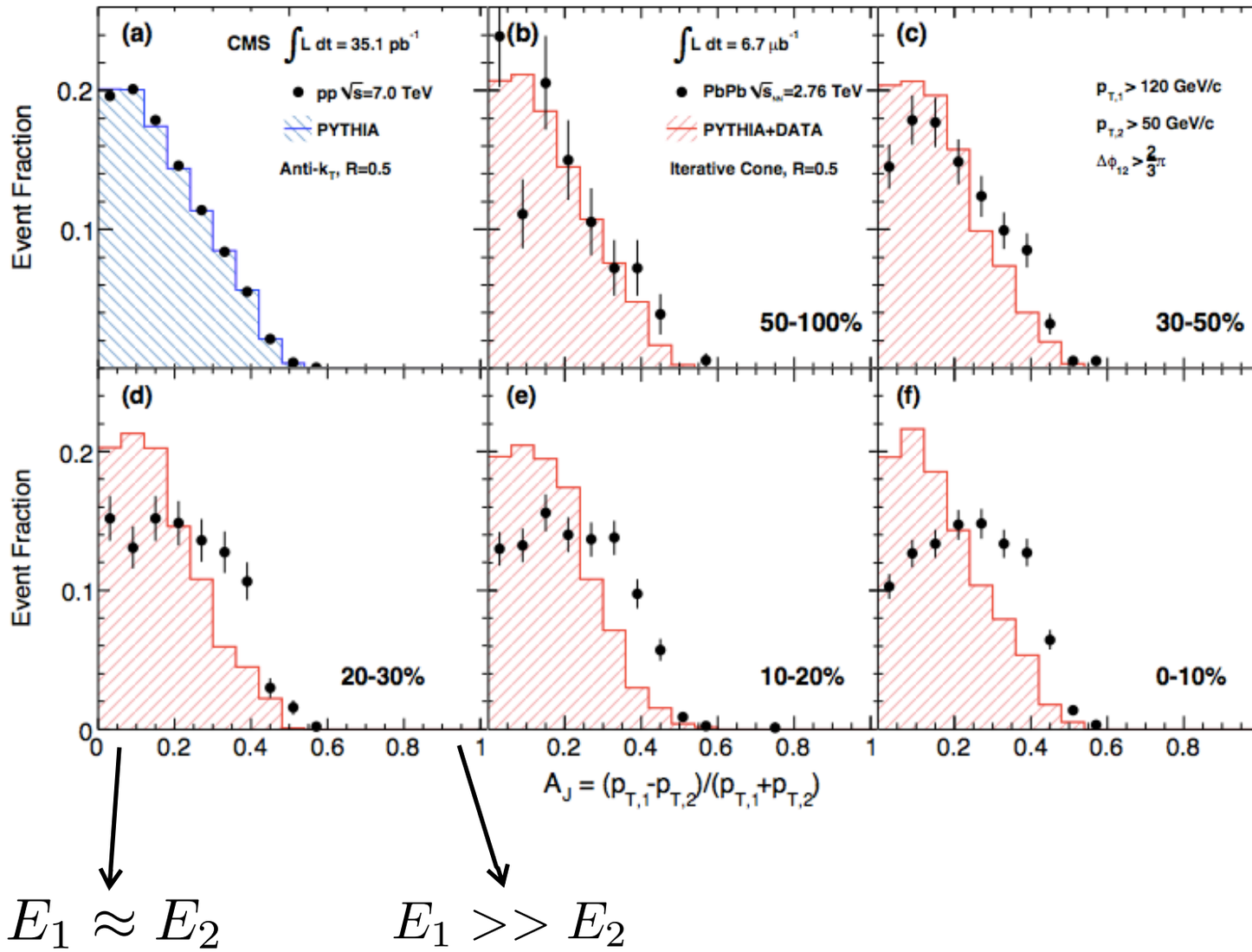



require: $E_1 > E_2$

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

Large modification in central collisions

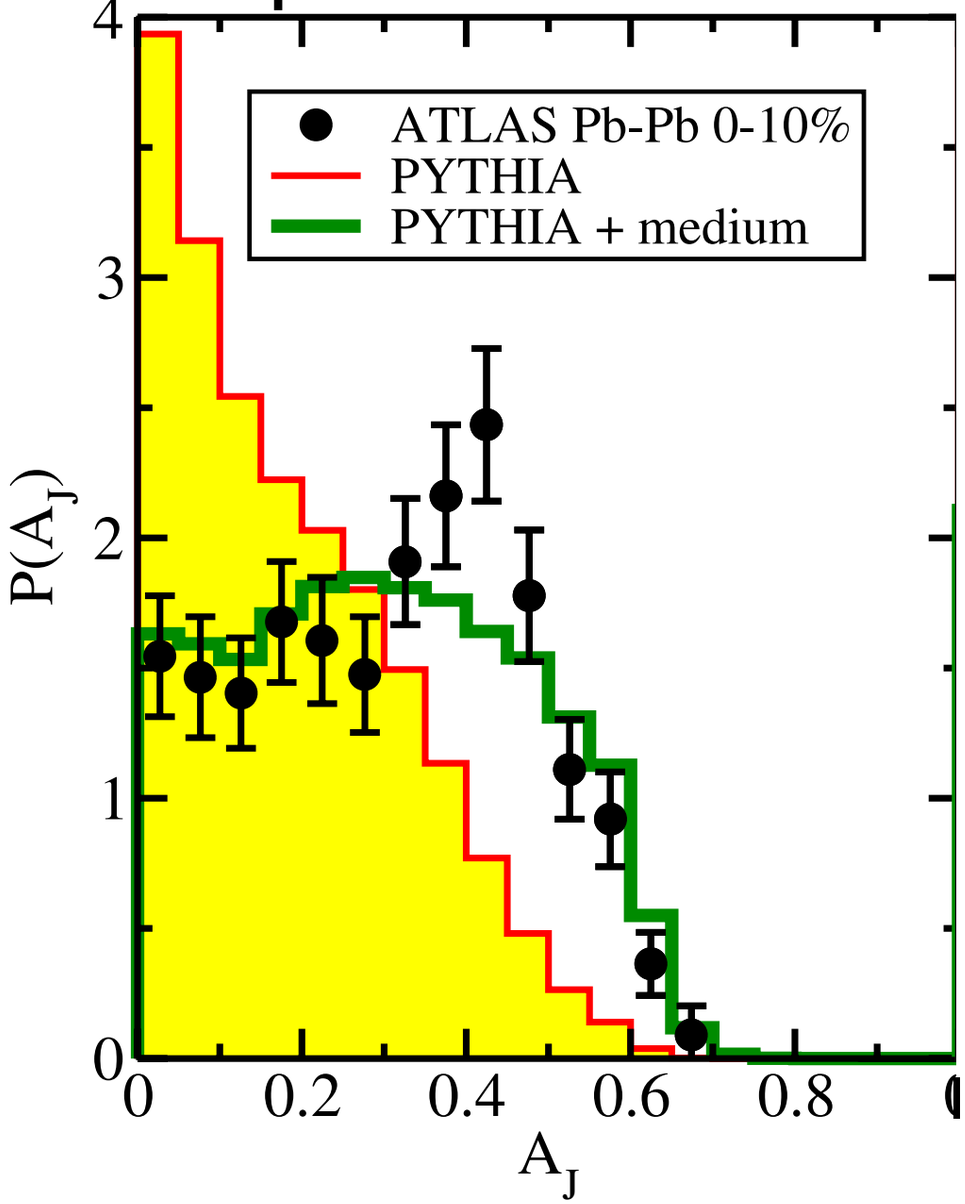
CMS, arXiv:1102.1957



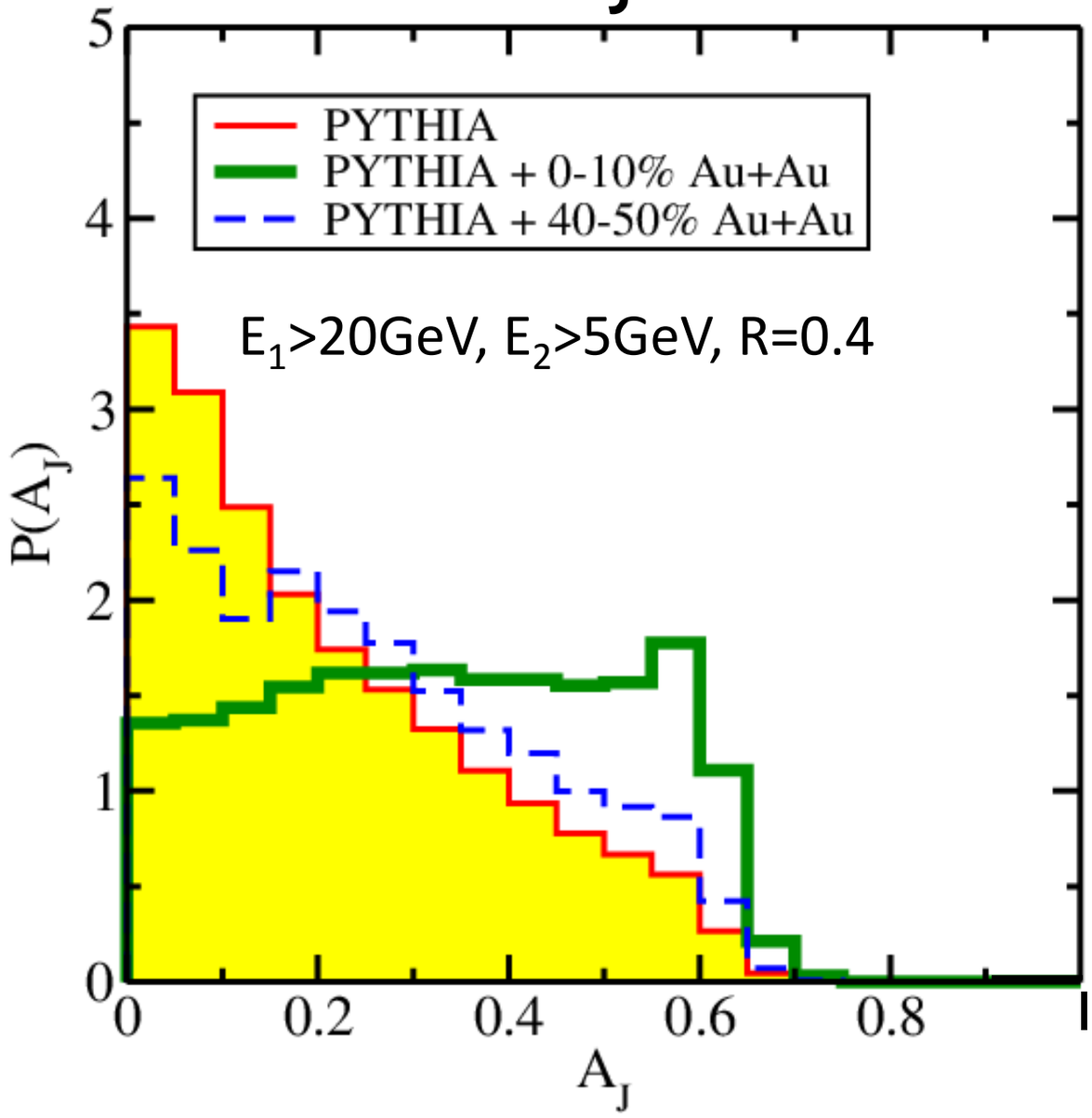

$E_1 \approx E_2$ $E_1 >> E_2$

# Interaction of jet with medium

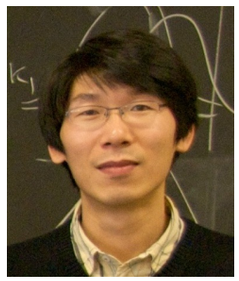
## Comparison to LHC data



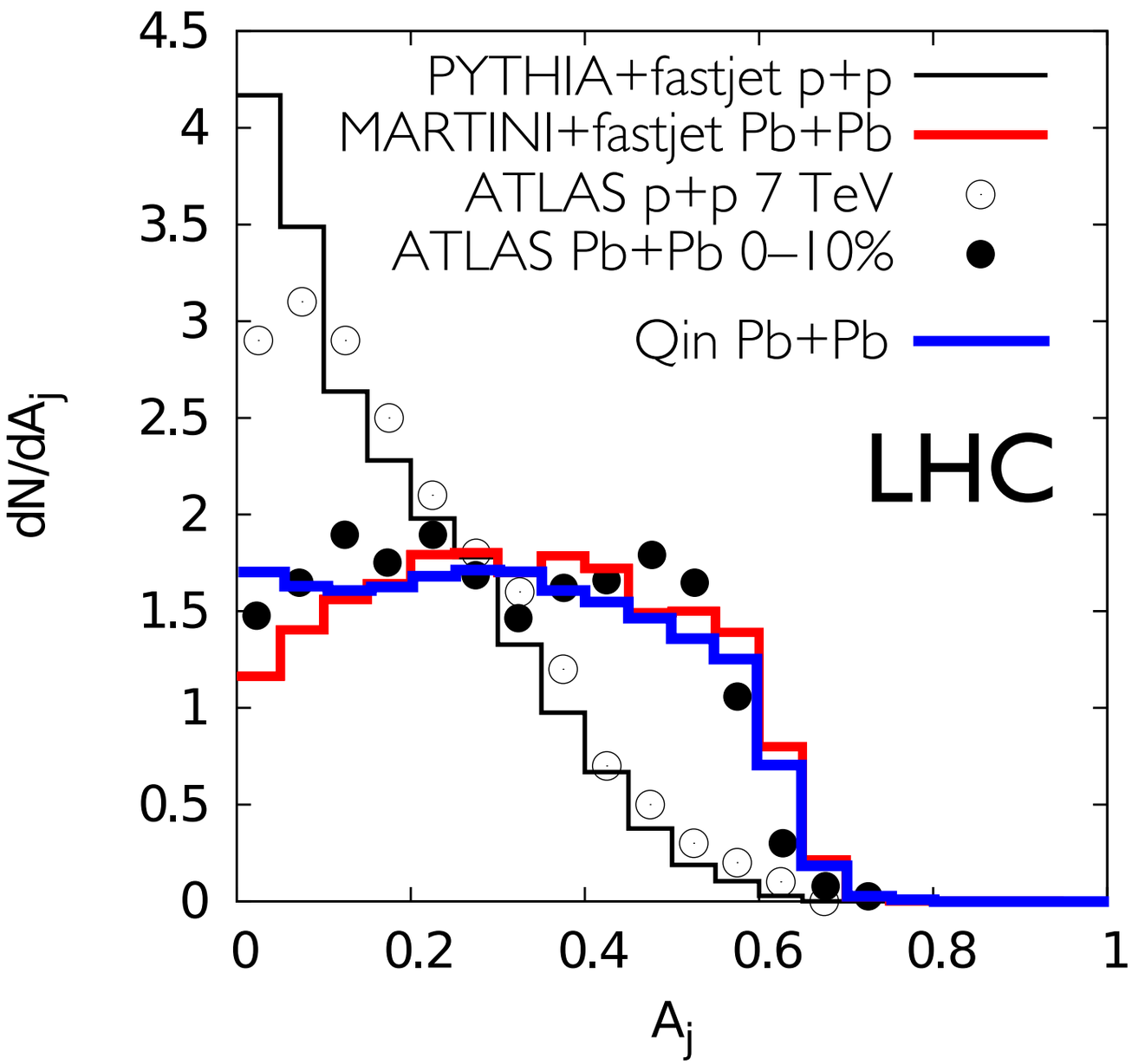

## Distribution of AJ at RHIC energies

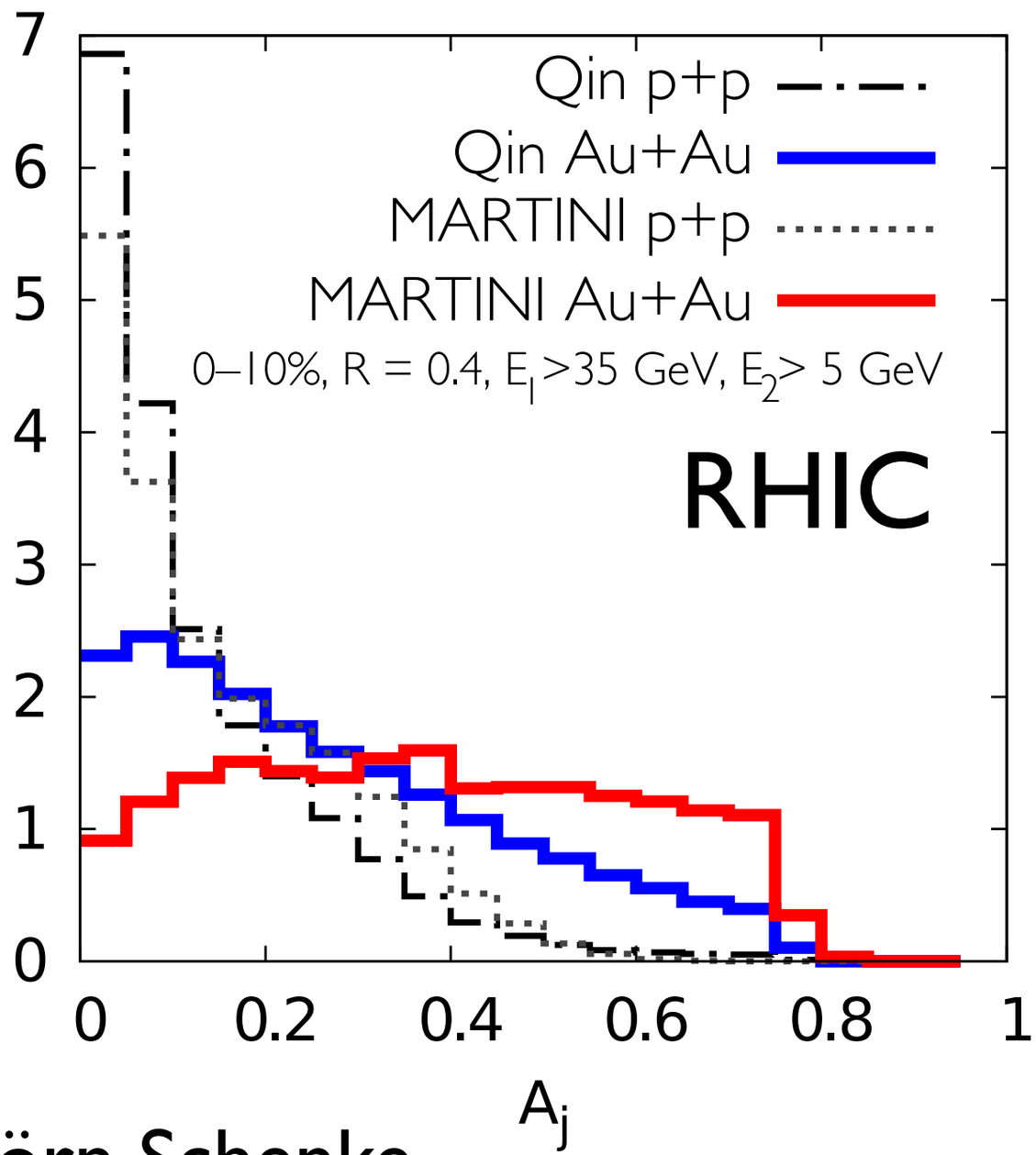



Guang-You Qin, Berndt Muller
PRL 106, 162302 (2011)



# Same at LHC, different at RHIC

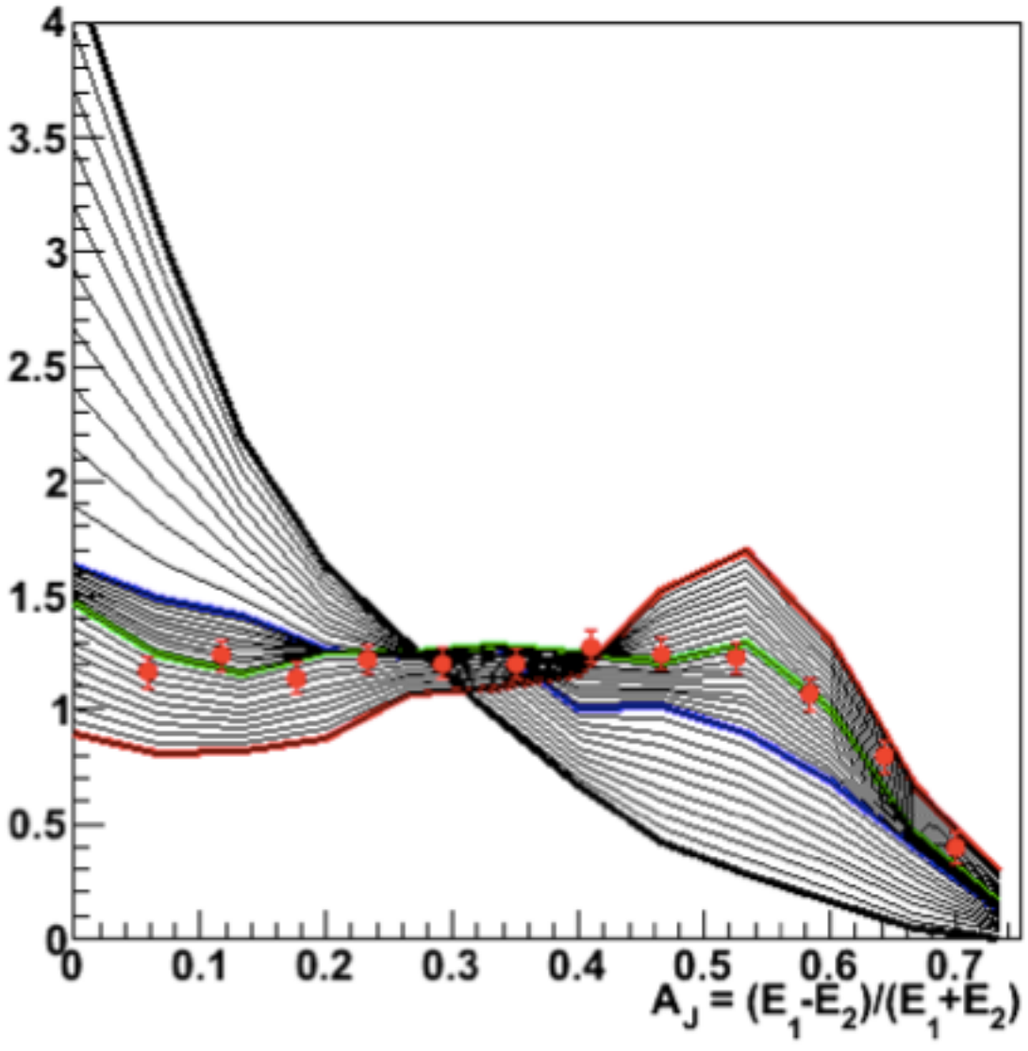


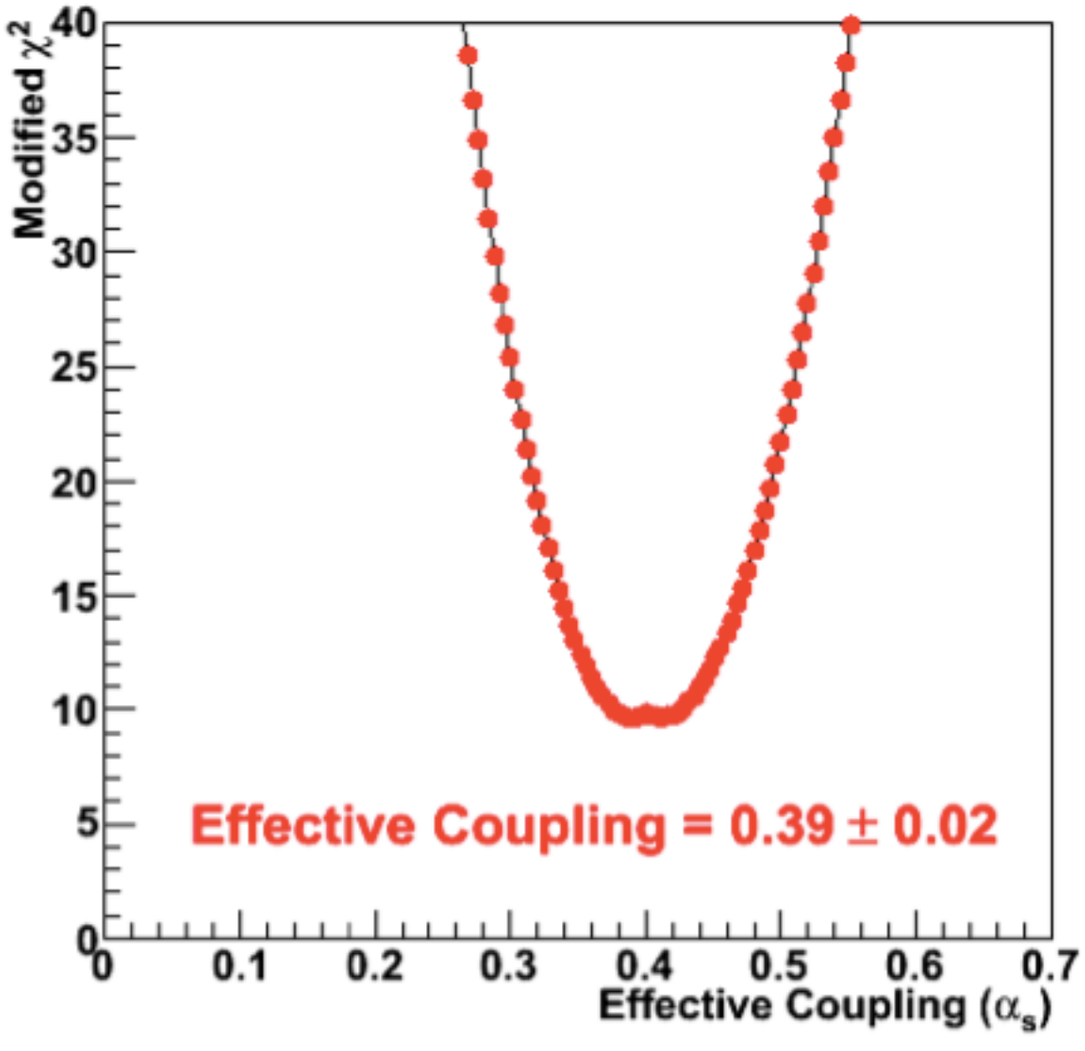




MARTINI: Björn Schenke

# Extracting 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

# *How well could jets be measured at RHIC?*



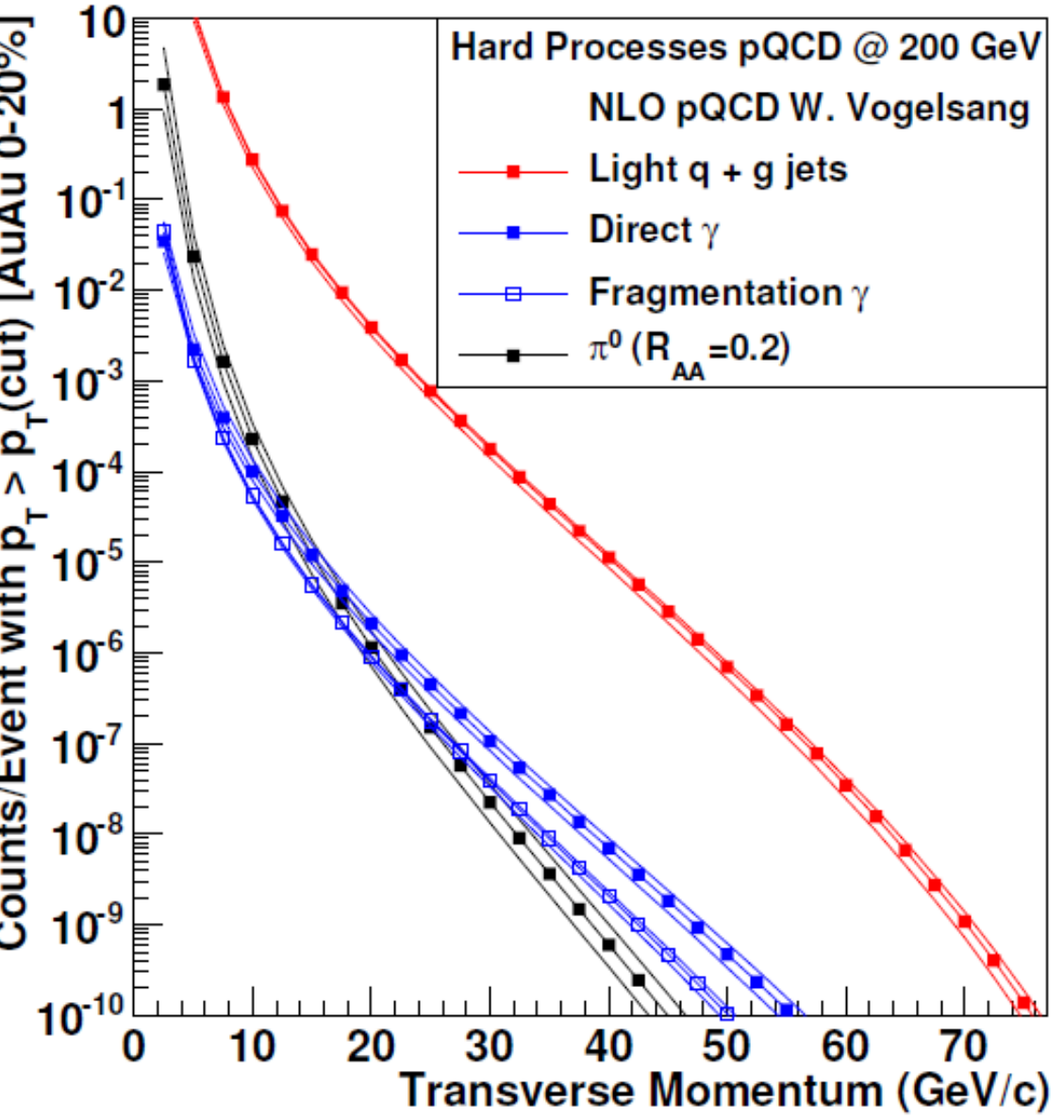
An ideal detector, even sPHENIX, would encounter these 3 issues:

**(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




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

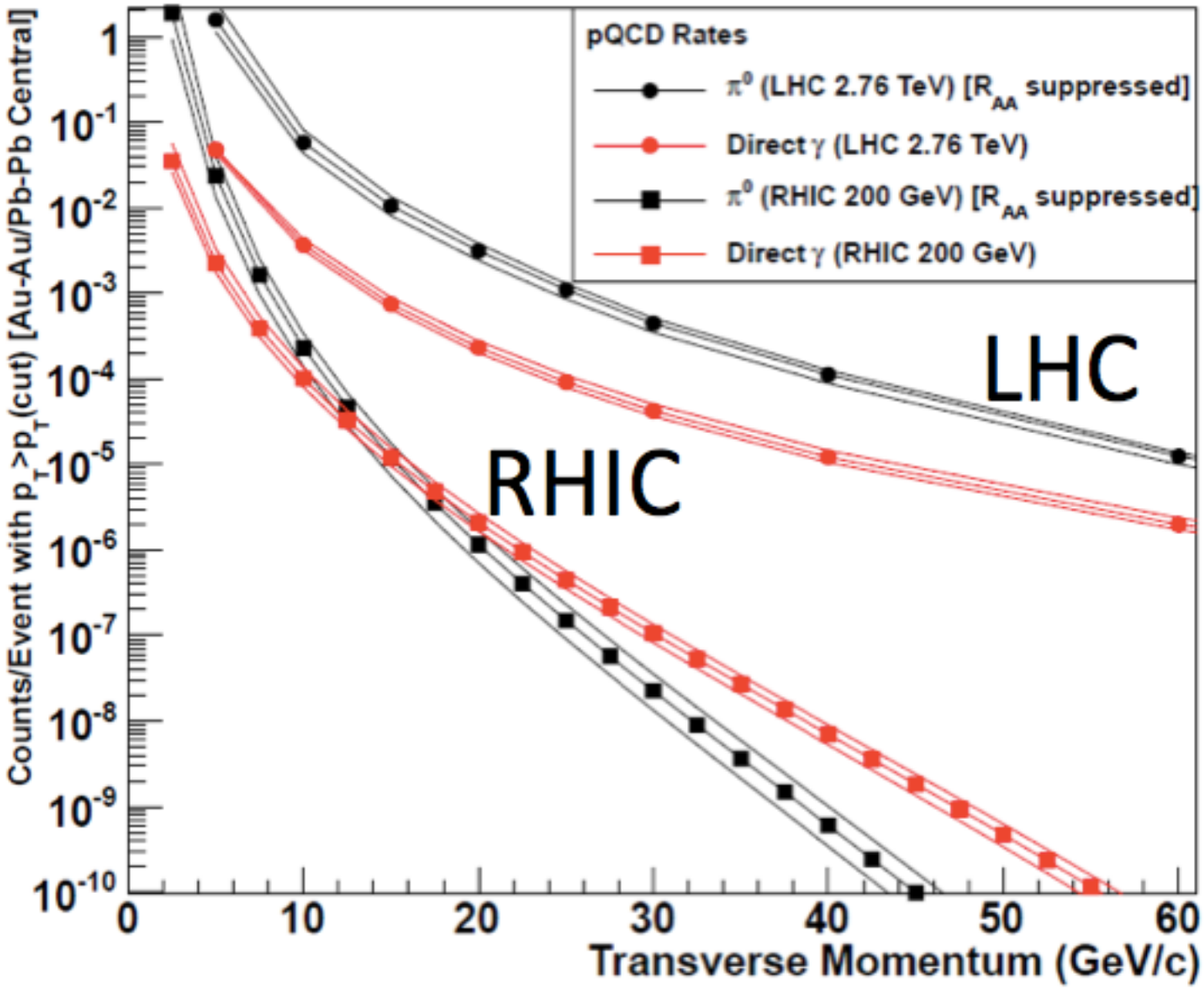
Events: 50 billion collected, 200 billion sampled

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

**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

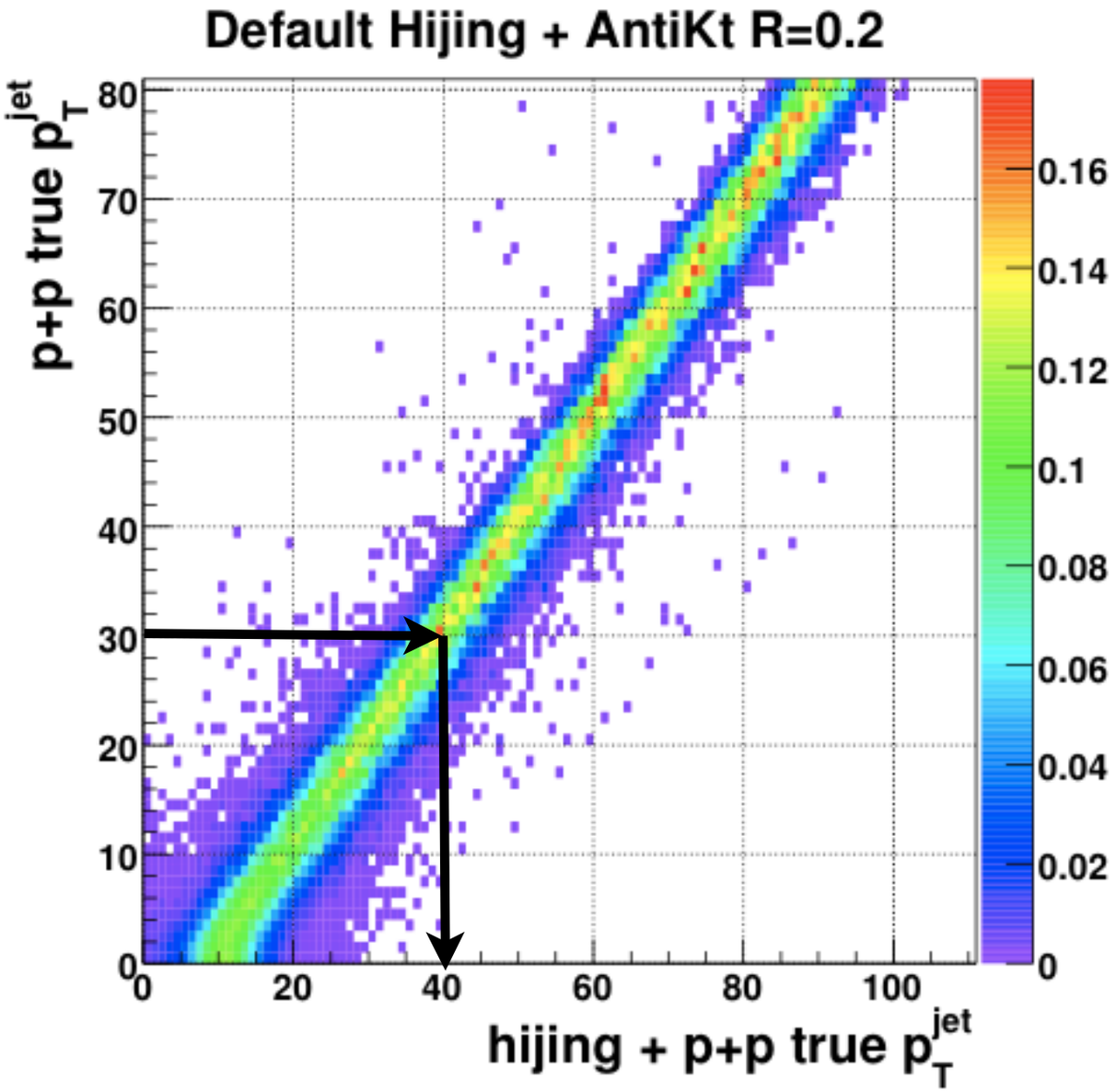
## sPHENIX has excellent direct photon capabilities

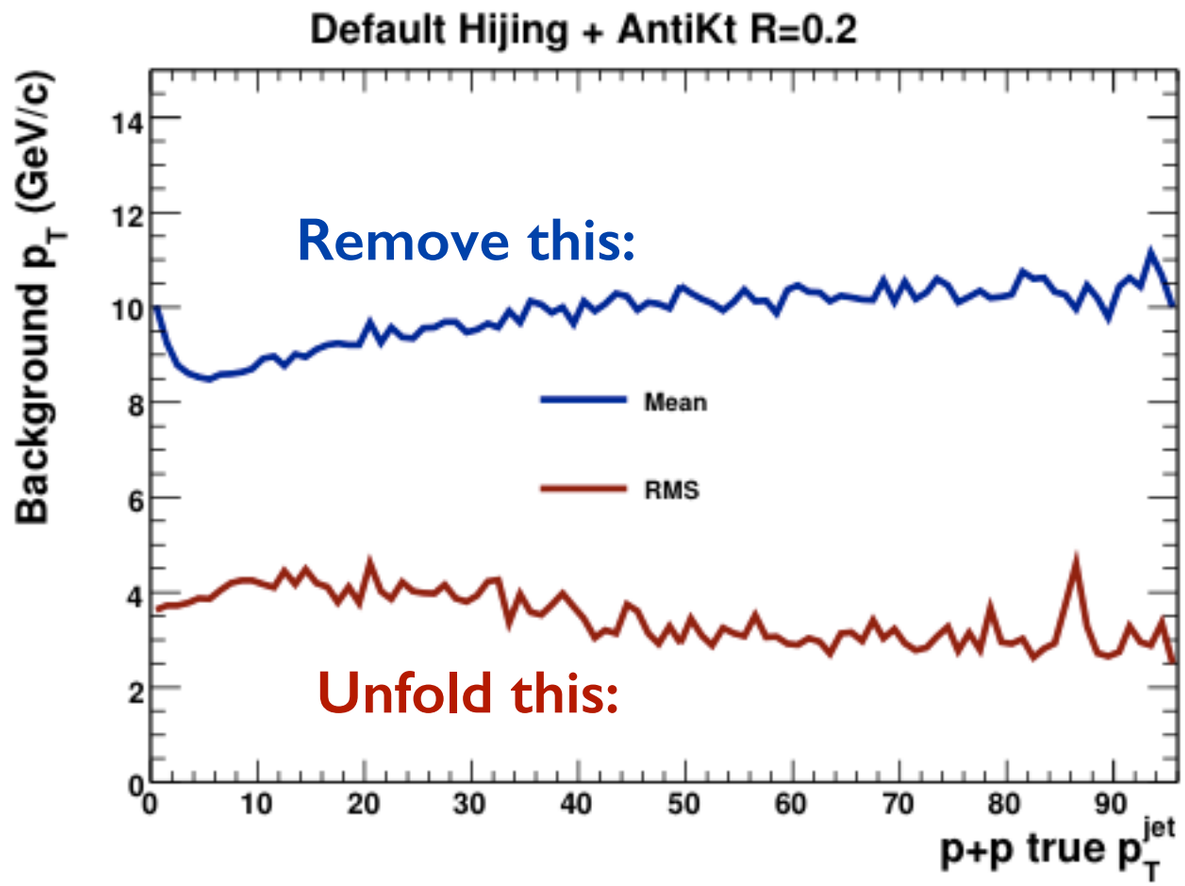



In Au+Au central collisions for $p_T > 20$ GeV, direct photons dominate S/B > 3

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

# 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]

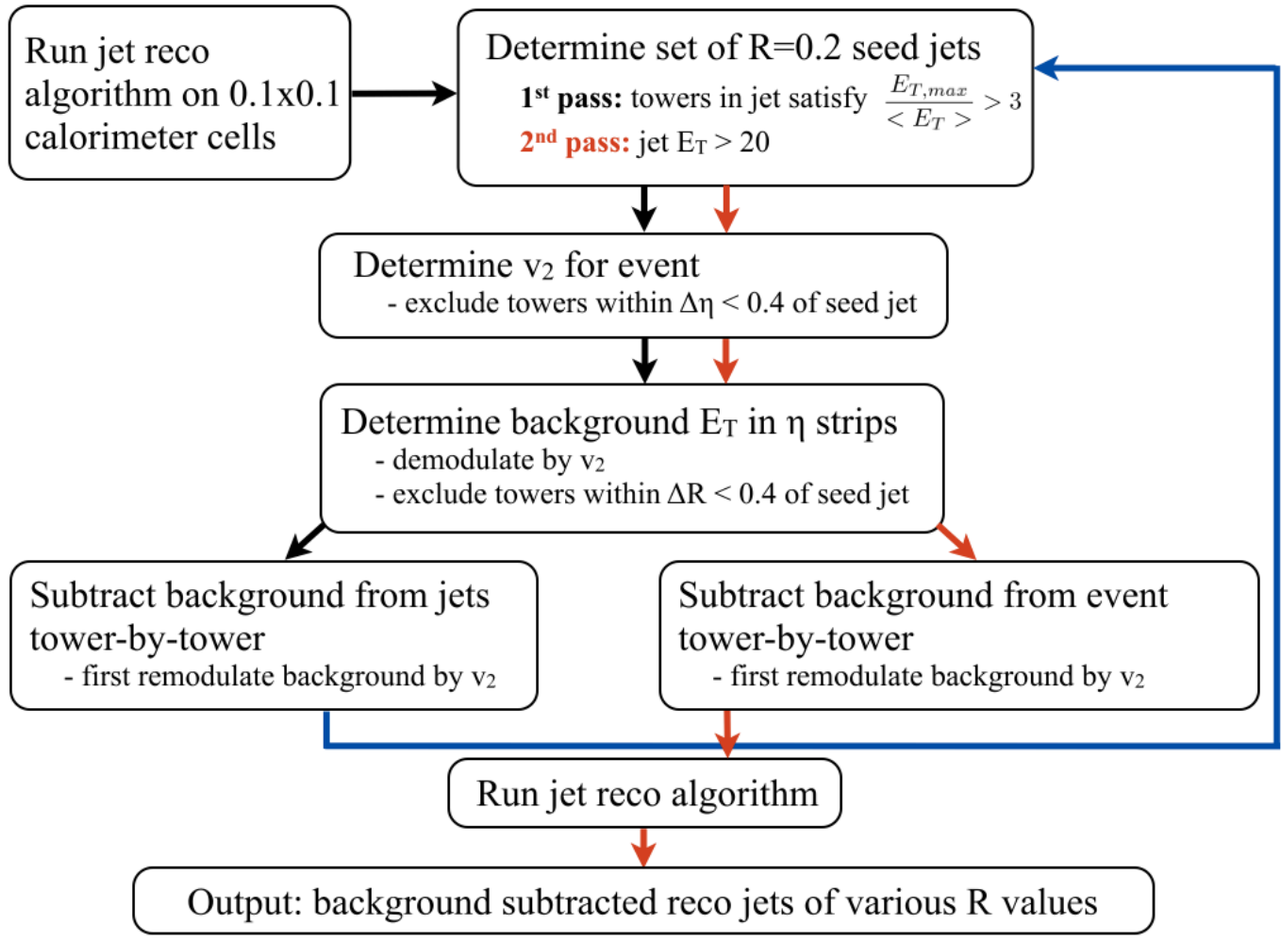
[1]*Department of Physics and Astronomy, Stony Brook University, SUNY, Stony Brook, New York 11794-3400, USA*

[2]*Physics Department, Brookhaven National Laboratory, Upton, New York 11973-5000, USA*

[3]*Columbia University, New York, New York 10027, USA and Nevis Laboratories, Irvington, New York 10533, USA*

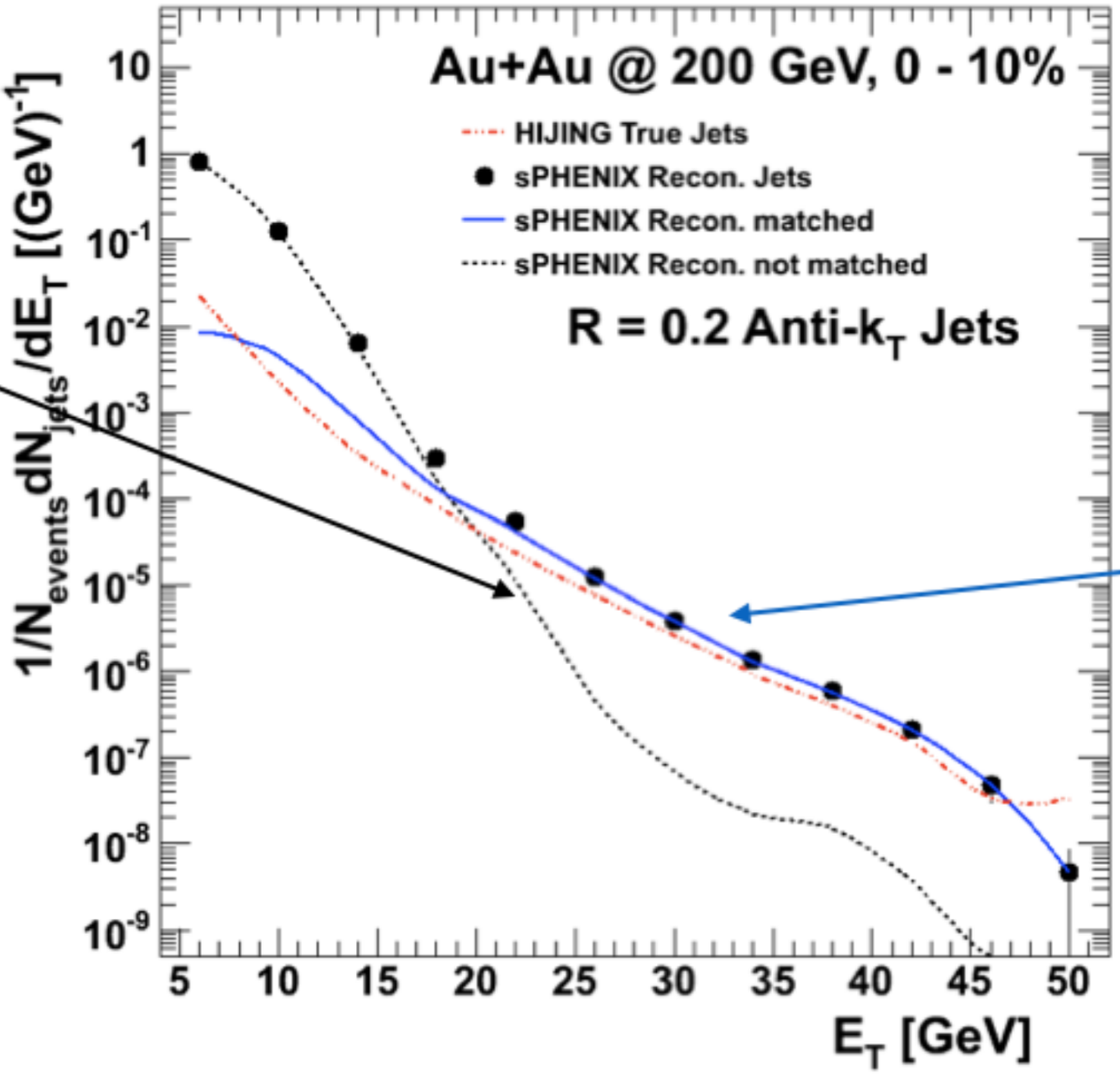
[4]*University of Colorado, Boulder, Colorado 80309, USA*

(Received 6 April 2012; published 10 August 2012)



# Contamination: Fake Jet Rates

fake jets



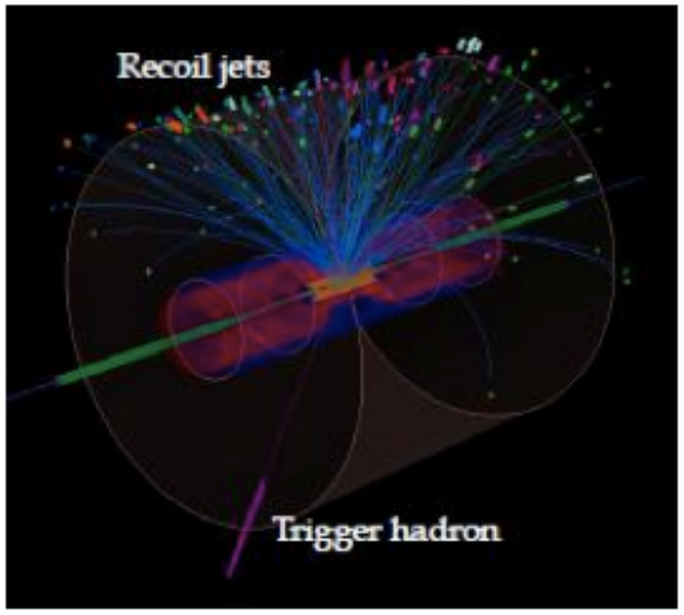

true jets

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**

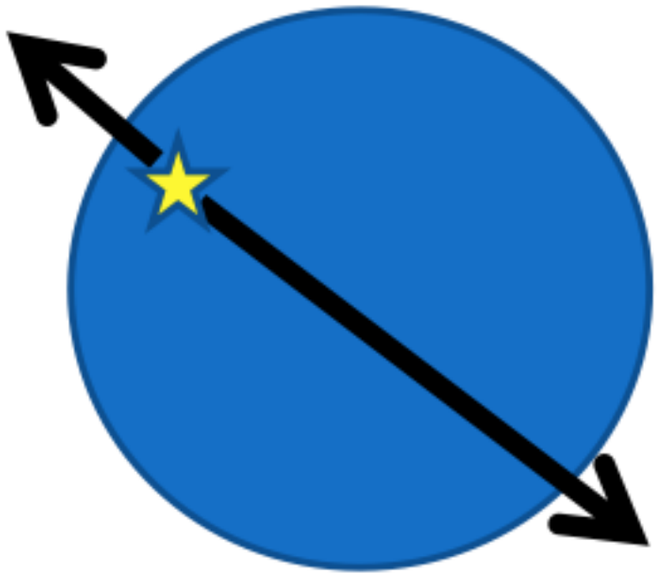
# STAR Jet Program



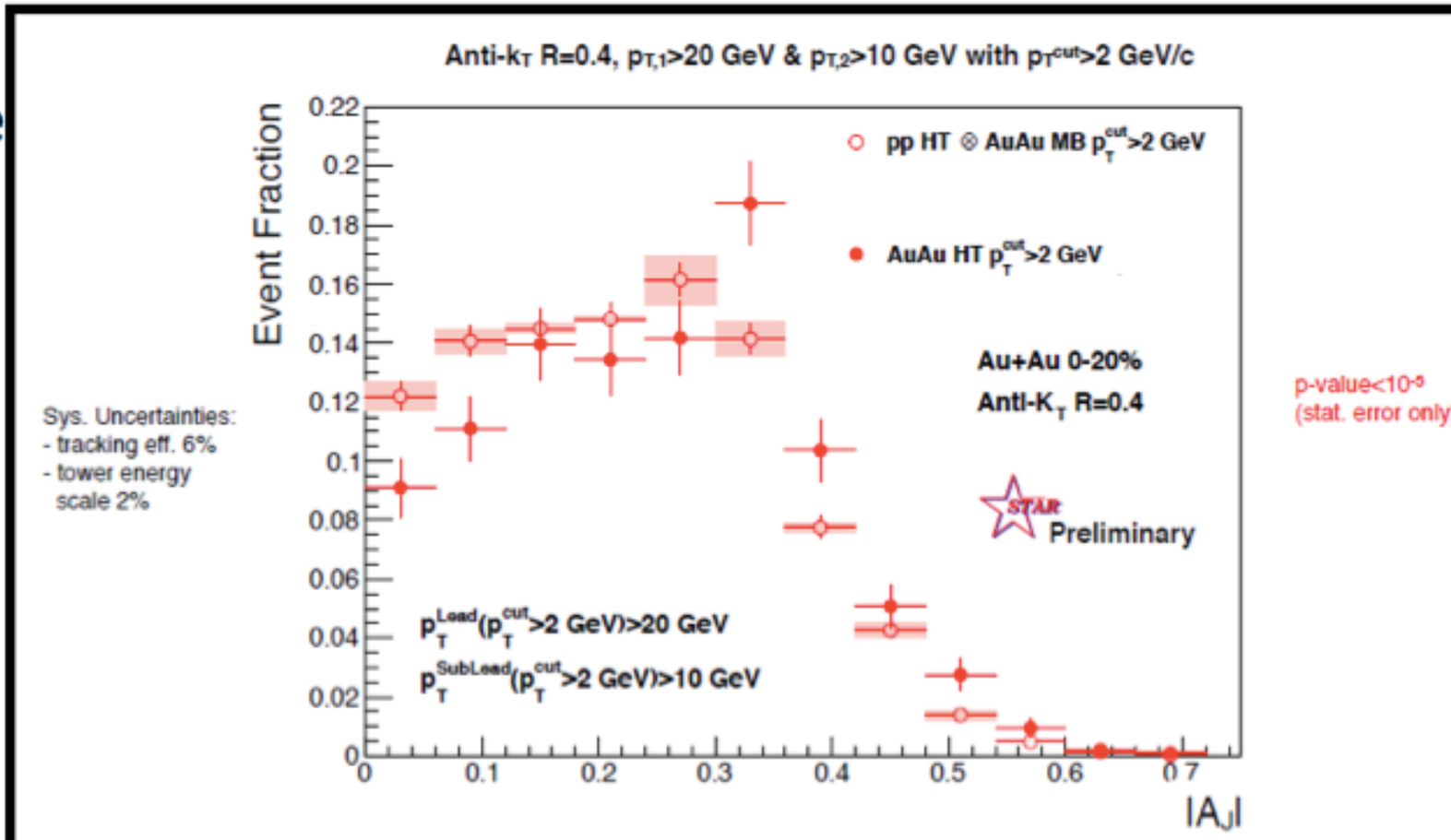

Very good jet capabilities
Large acceptance, tracking + EMCal

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

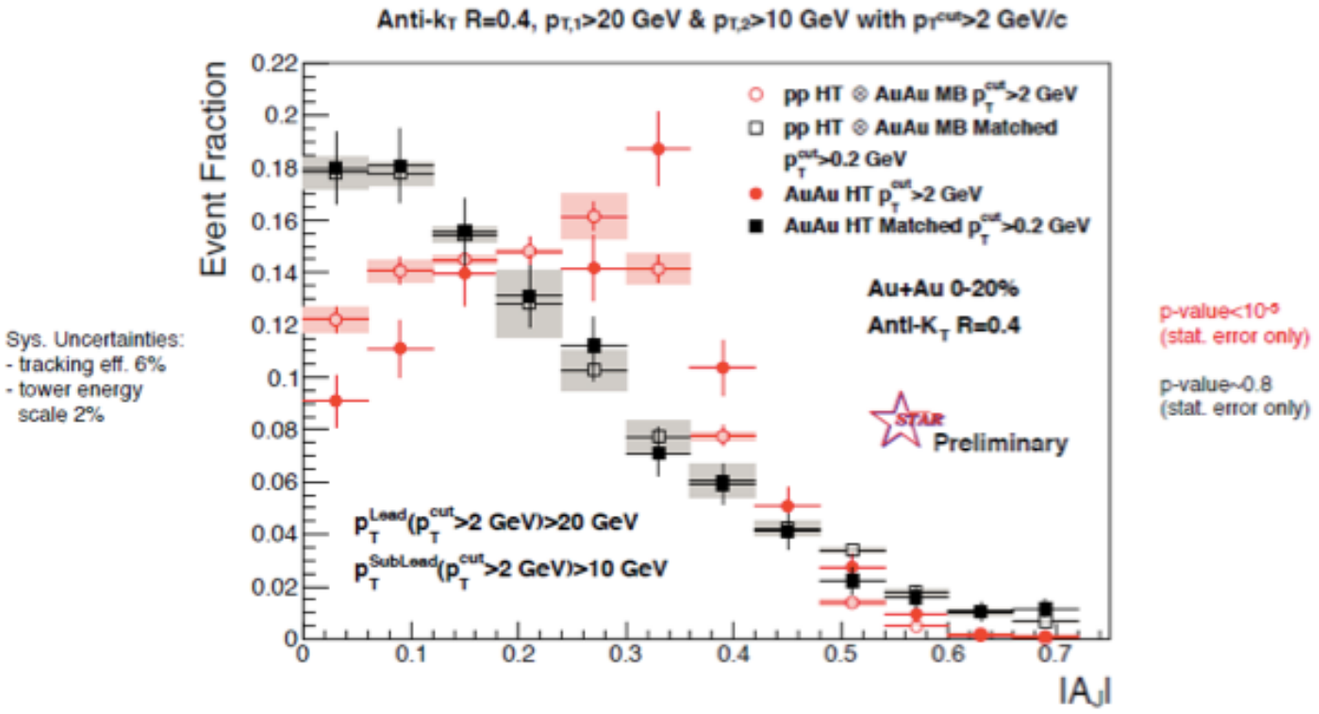


However, only modest suppression of balanced jets




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

# STAR Jet Program II




Sys. Uncertainties:
- tracking eff. 6%
- tower energy scale 2%

p-value<$10^{-9}$ (stat. error only)

p-value~0.8 (stat. error only)

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

Dijet asymmetry identical in pp and AA!

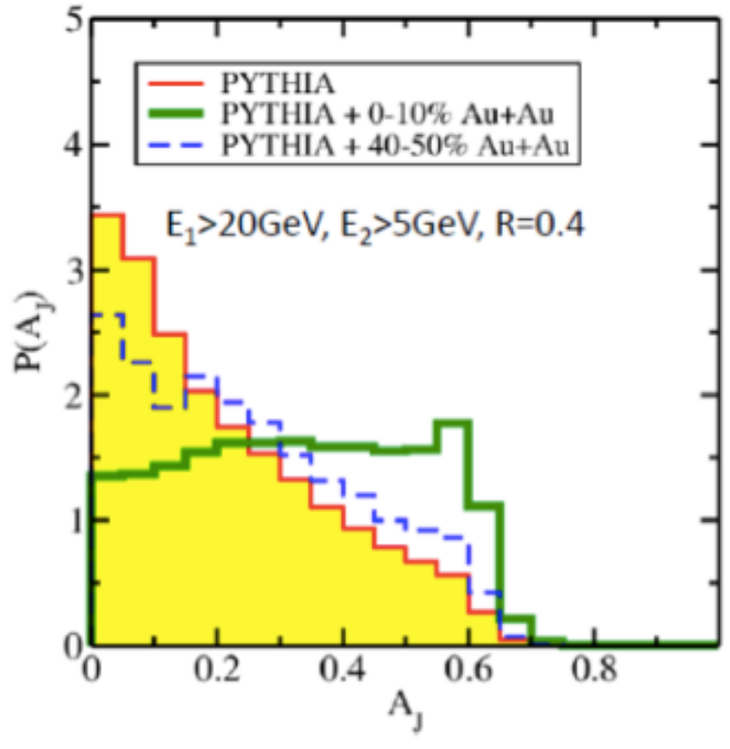
**Au+Au di-jets more imbalanced than p+p for $p_T^{cut}$>2 GeV/c**

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

Very different result from theory expectations and LHC results.

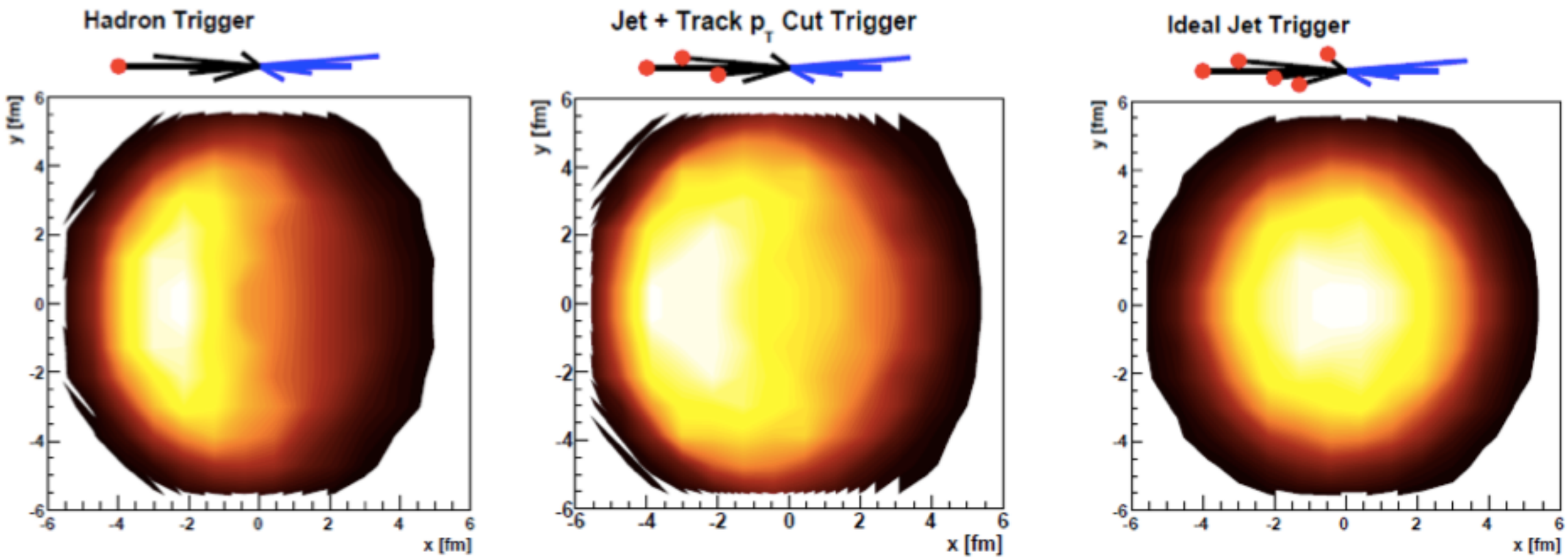
If full jet energy recovered, real unbiased FF measurements available to sPHENIX.

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.

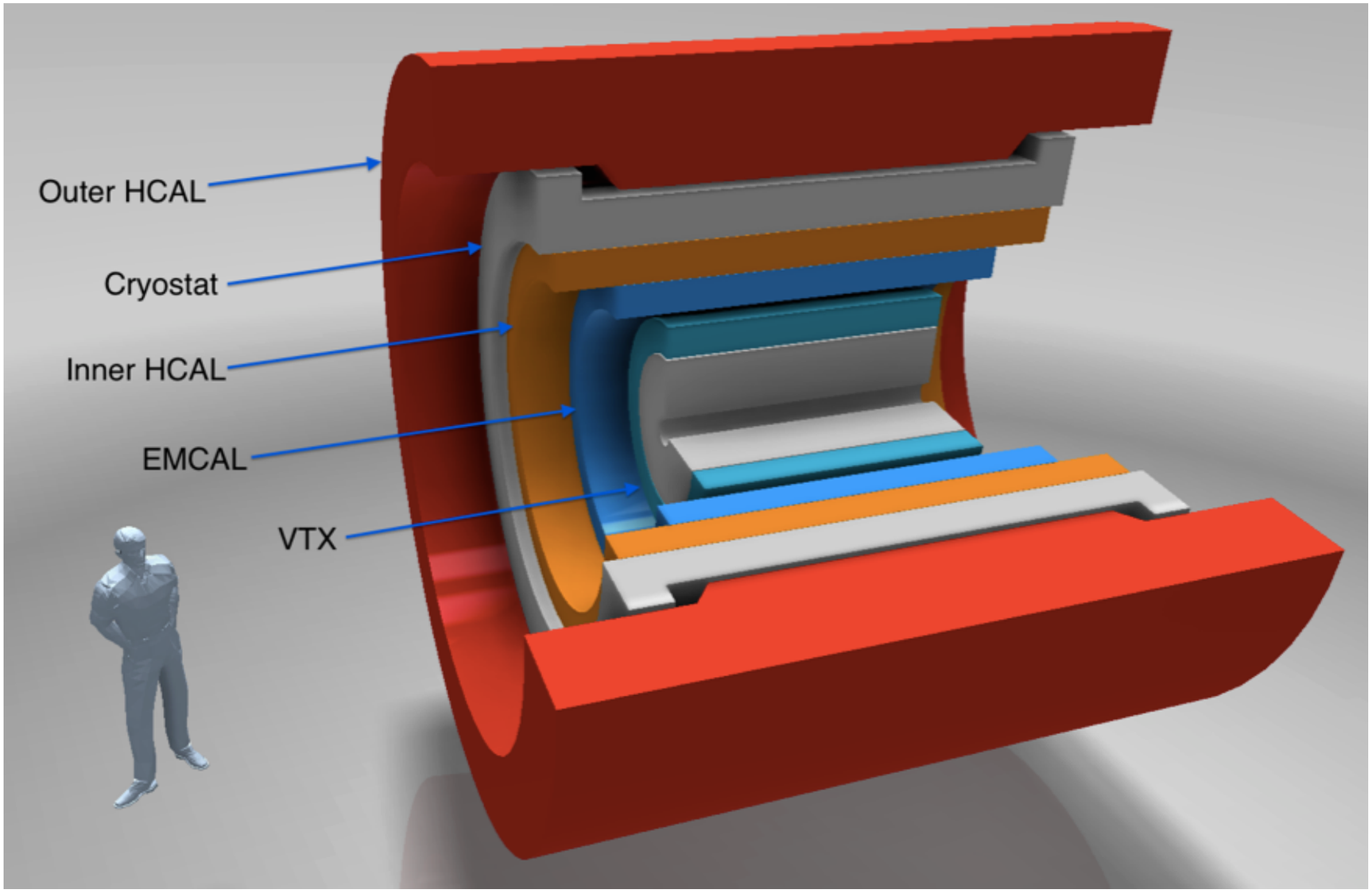



**PHENIX**

**STAR**

**sPHENIX**

# sPHENIX detector




BaBar Magnet 1.5 T

Coverage $|\eta| < 1.1$

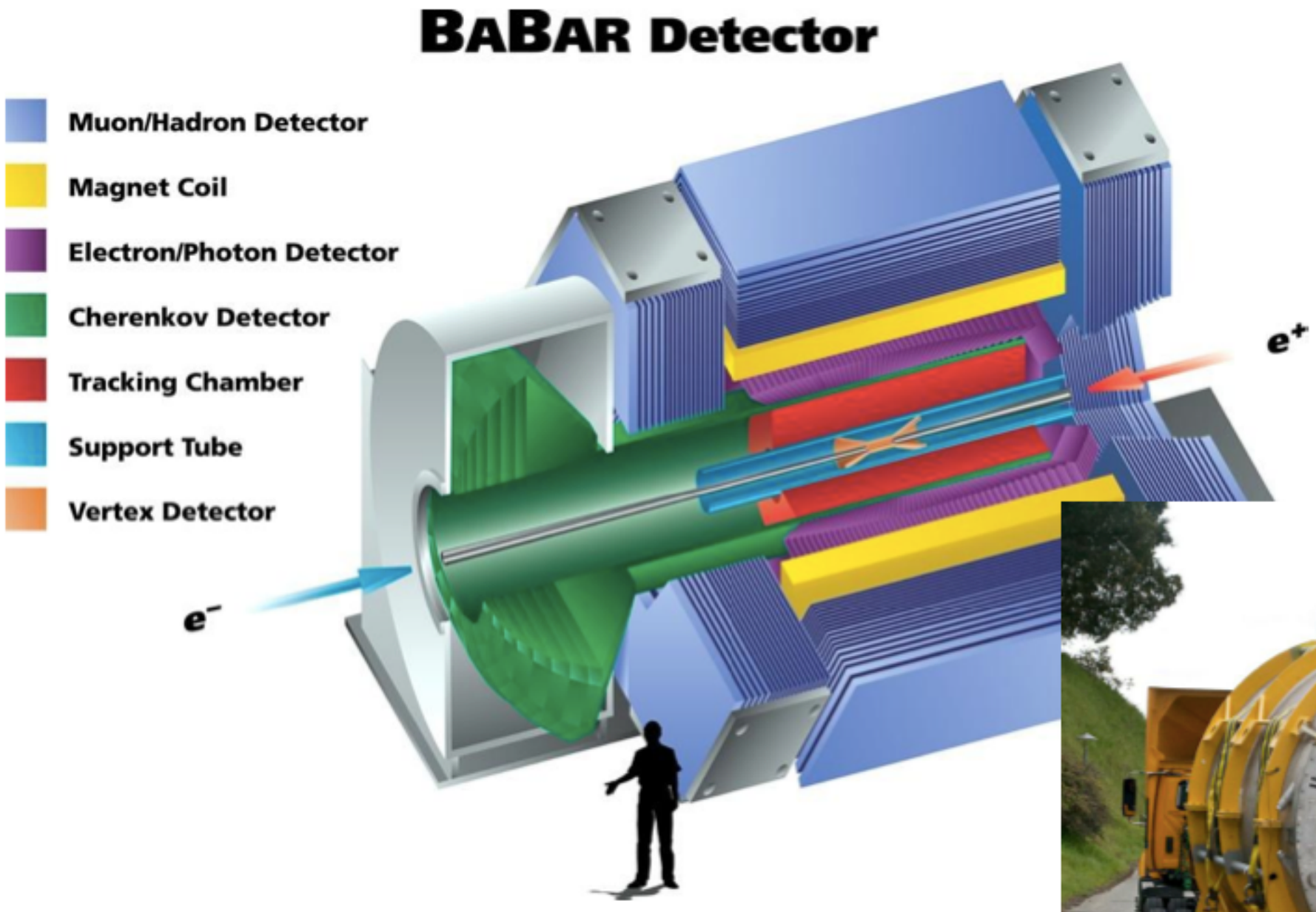
All silicon tracking
Heavy flavor tagging

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

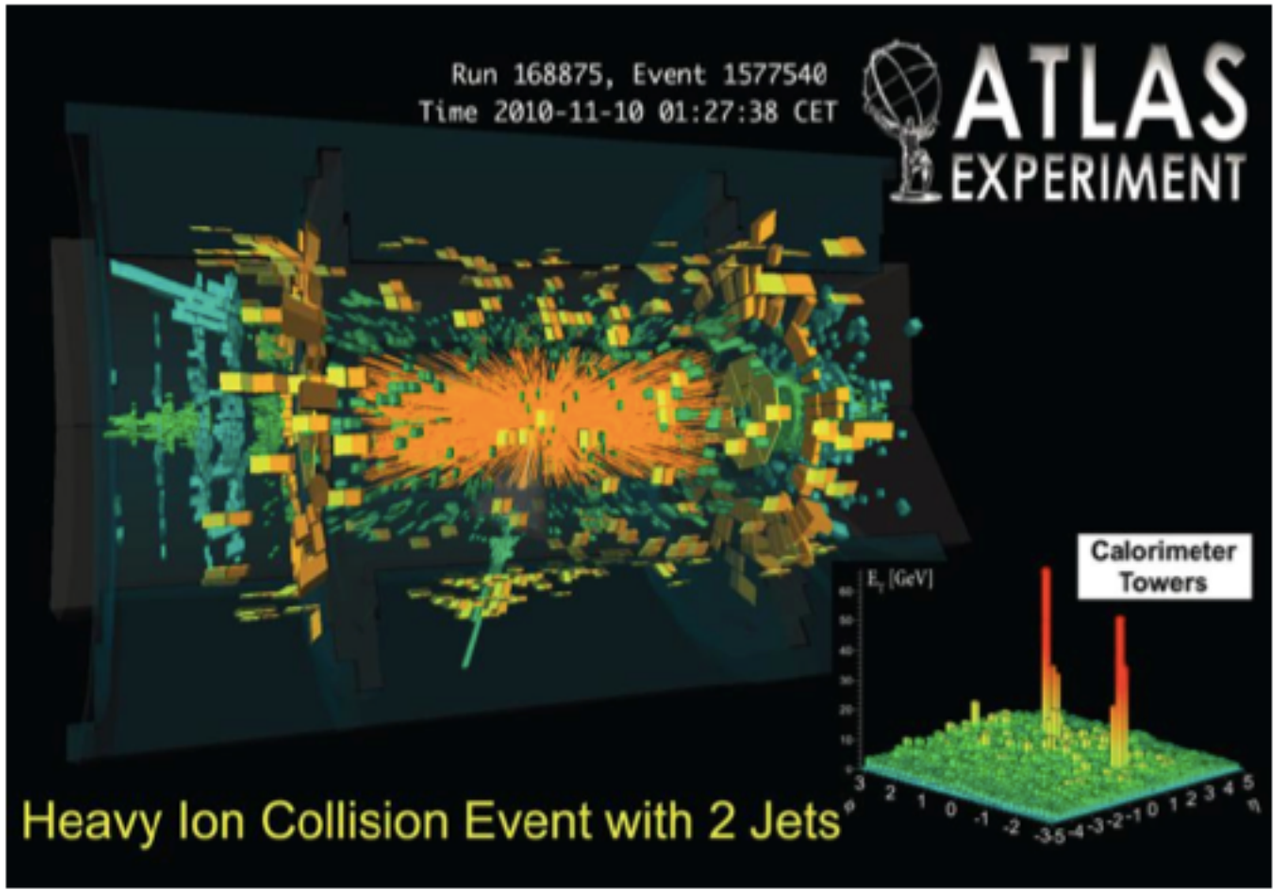



| ITEM NO. (b) | DESCRIPTION (Include noun name, FSC Group and Class, Condition Code and if available, National Stock Number) (c) | UNIT (d) | QUANTITY (e) | ACQUISITION COST UNIT (f) | ACQUISITION COST TOTAL (g) |
|---|---|---|---|---|---|
| | Administrative Transfer | | | | |
| 1 | BaBar Solenoid and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

# 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 $\gamma$-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

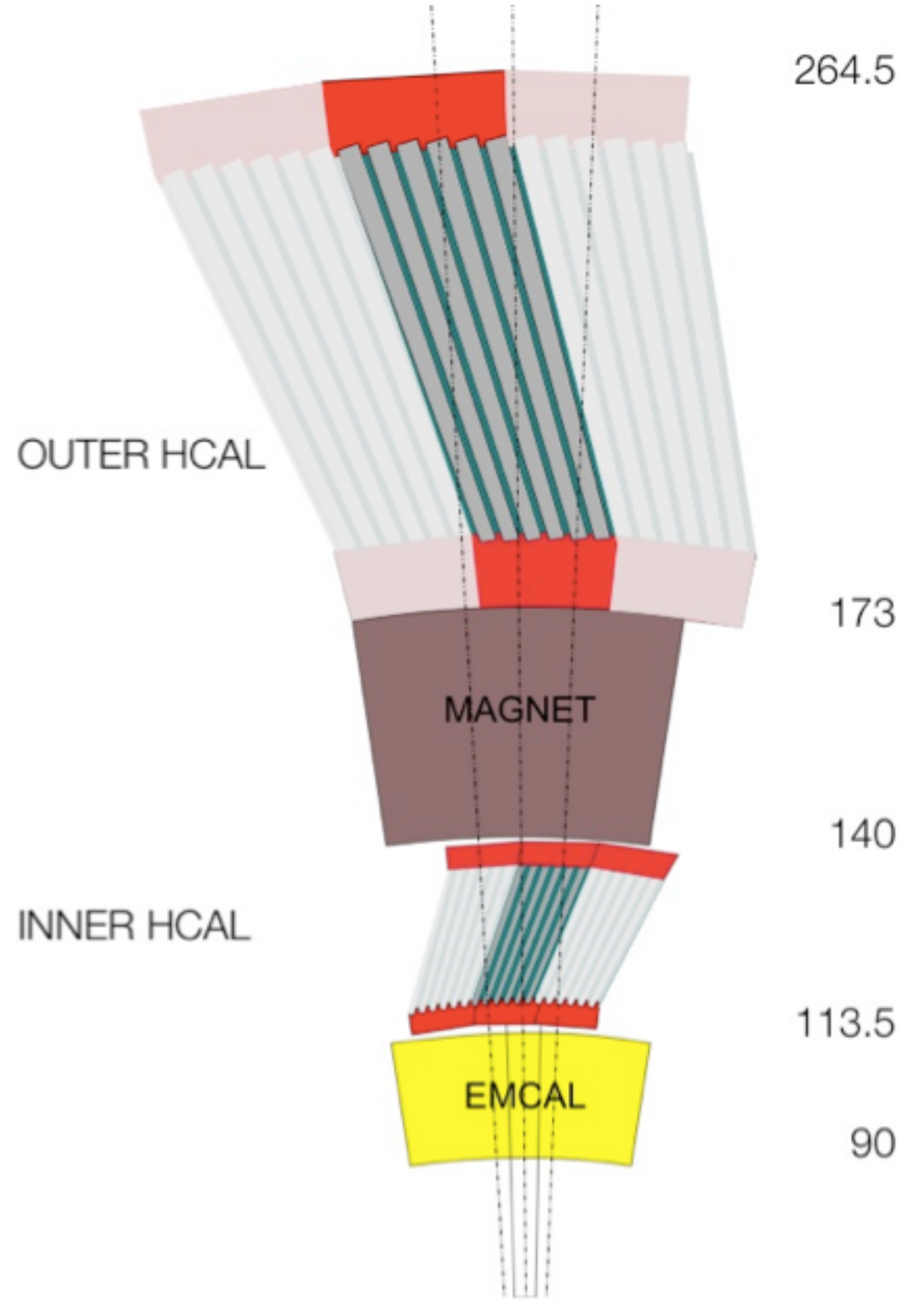
Very useful for triggering in p+p, p+A without jet bias

# sPHENIX Calorimeters

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

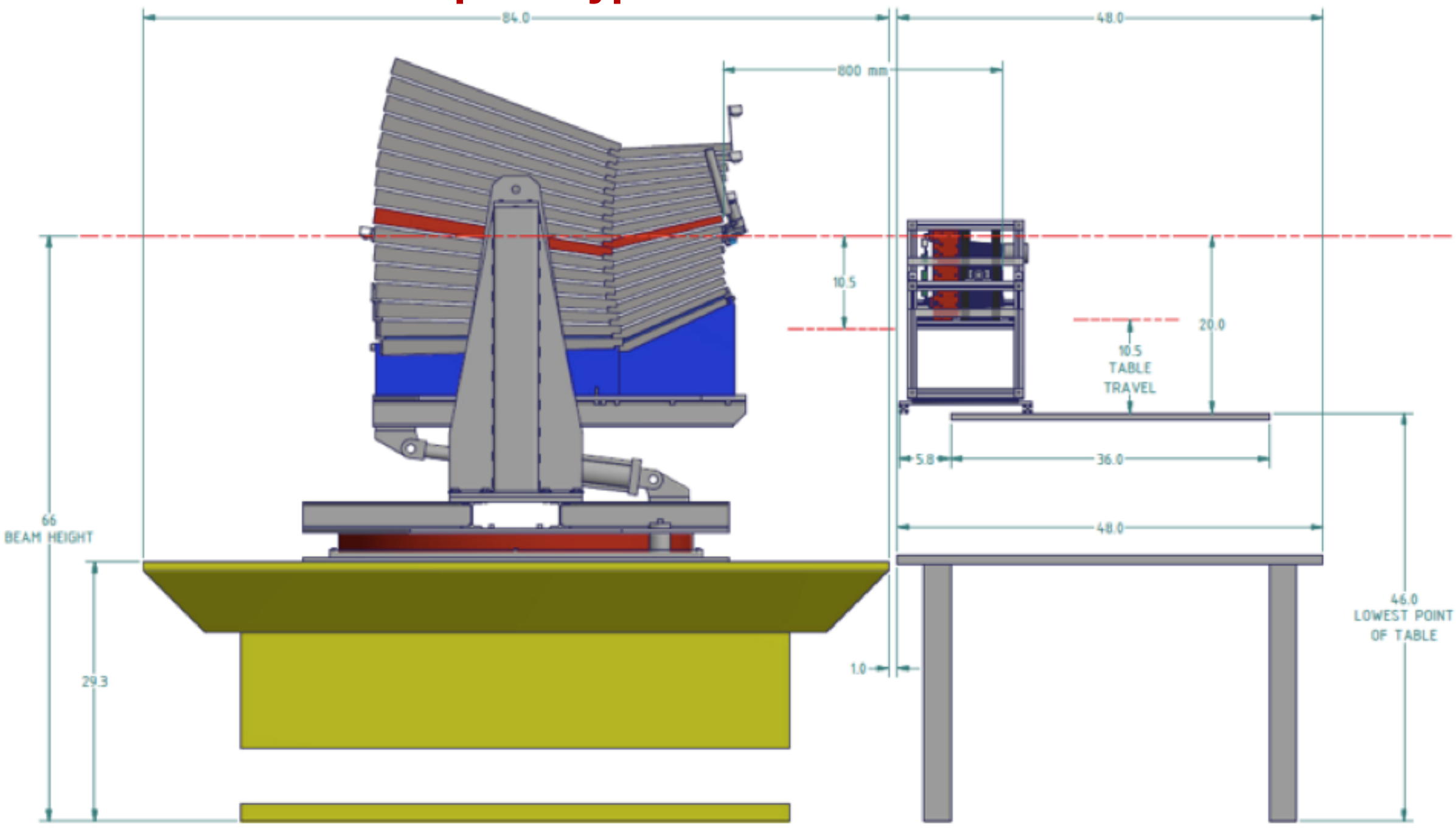
HCal 5λ deep (plus EMCal 1λ deep) leads to few percent energy leakage for hadrons above 50 GeV; comparable to other contributions to energy resolution constant term.

Key difference with calorimeters for much higher energy jets.



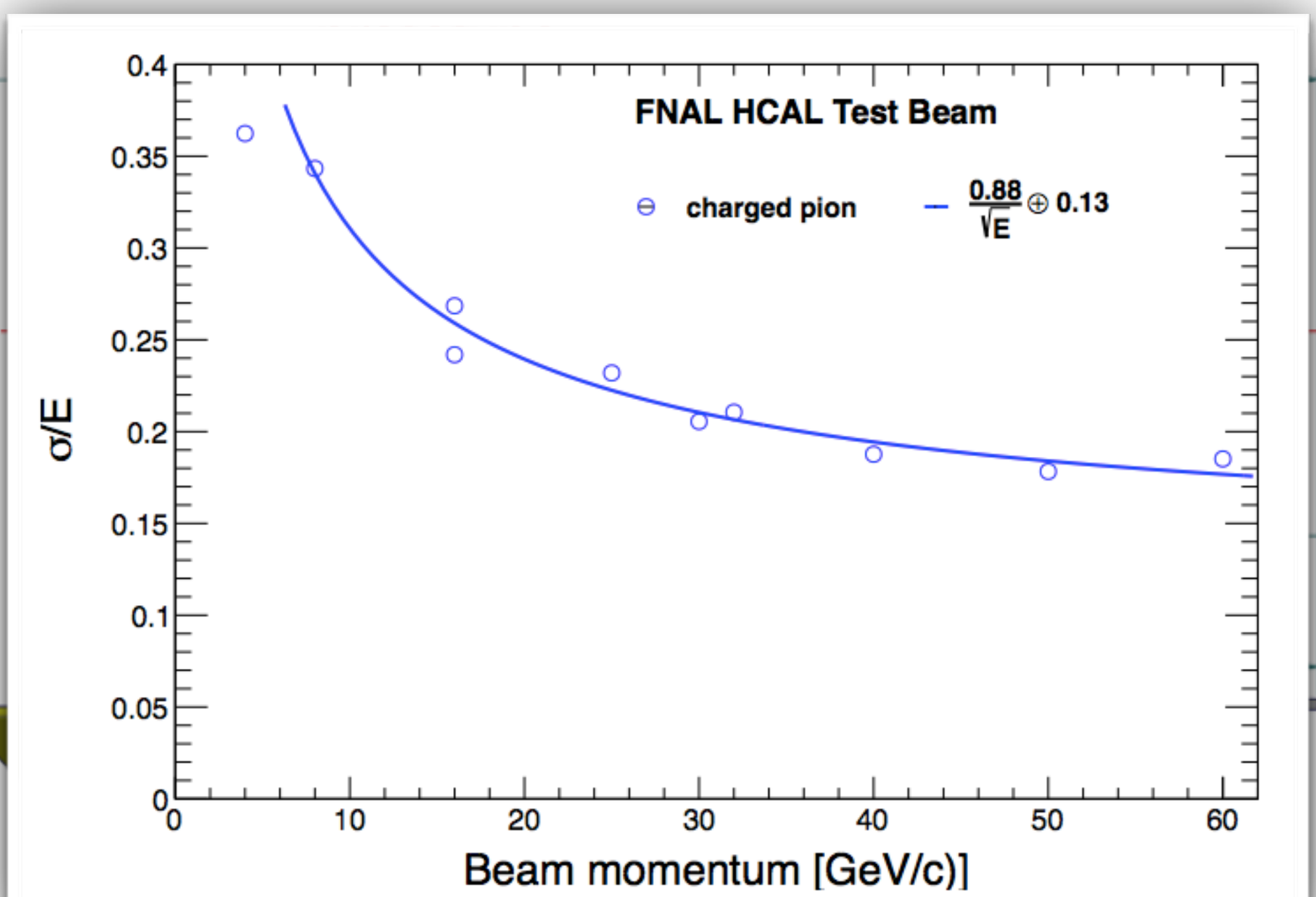
# FNAL Test Beam Exp T-1044

**HCAL prototype**



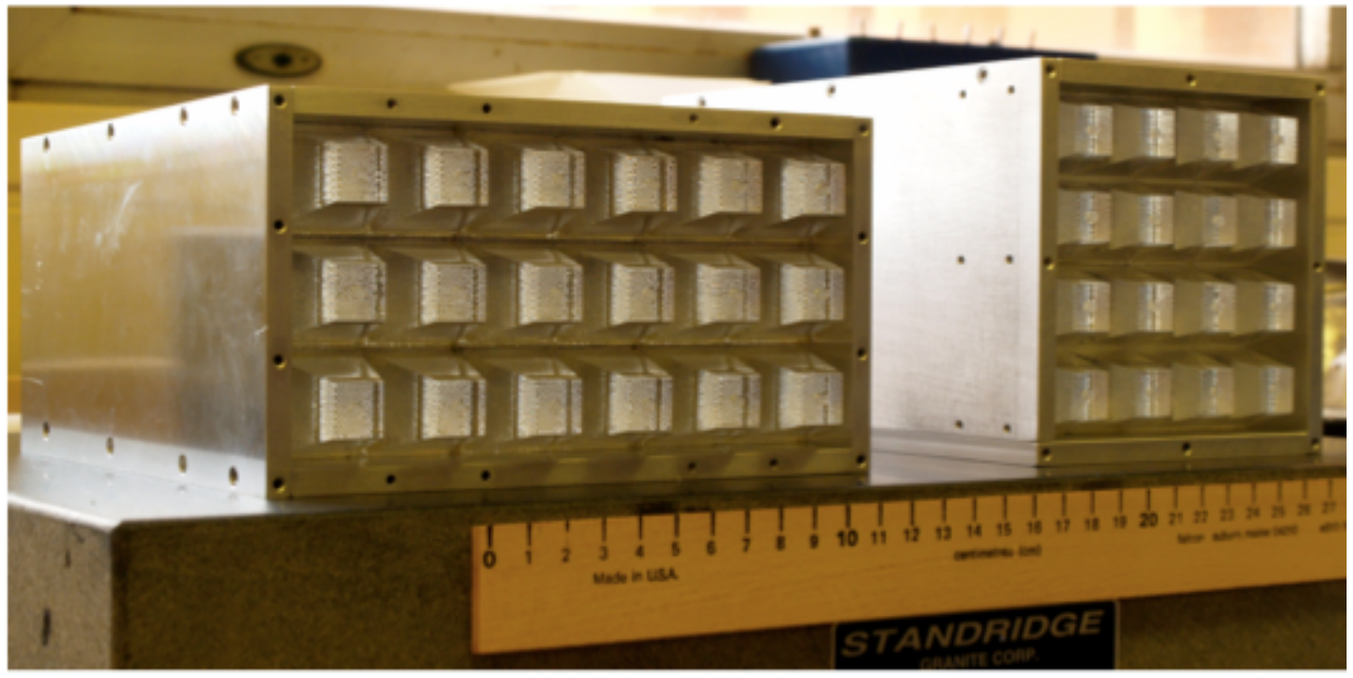
# FNAL Test Beam Exp T-1044

## HCAL

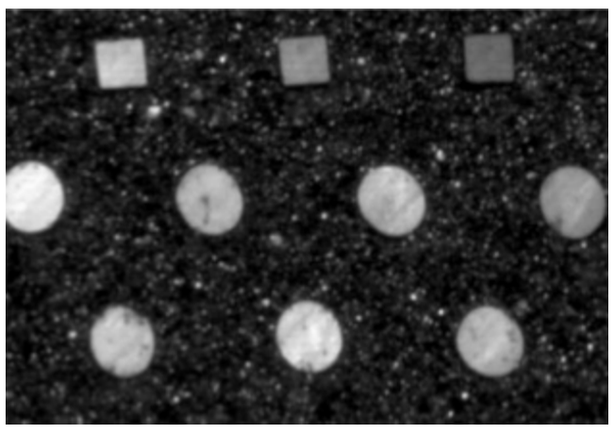


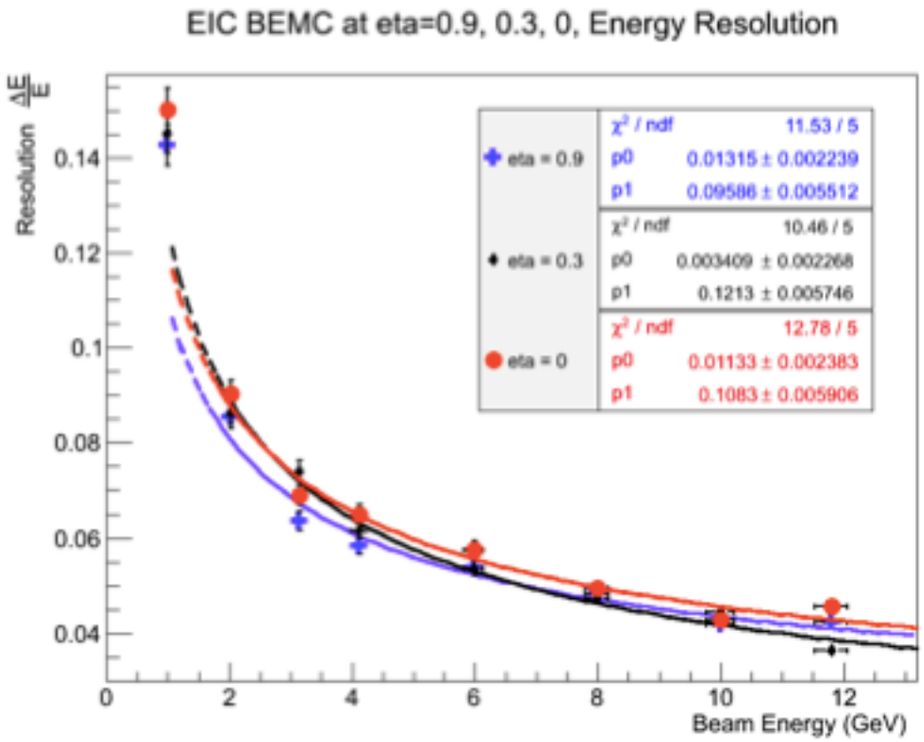
# EMCAL SPACAL Option

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



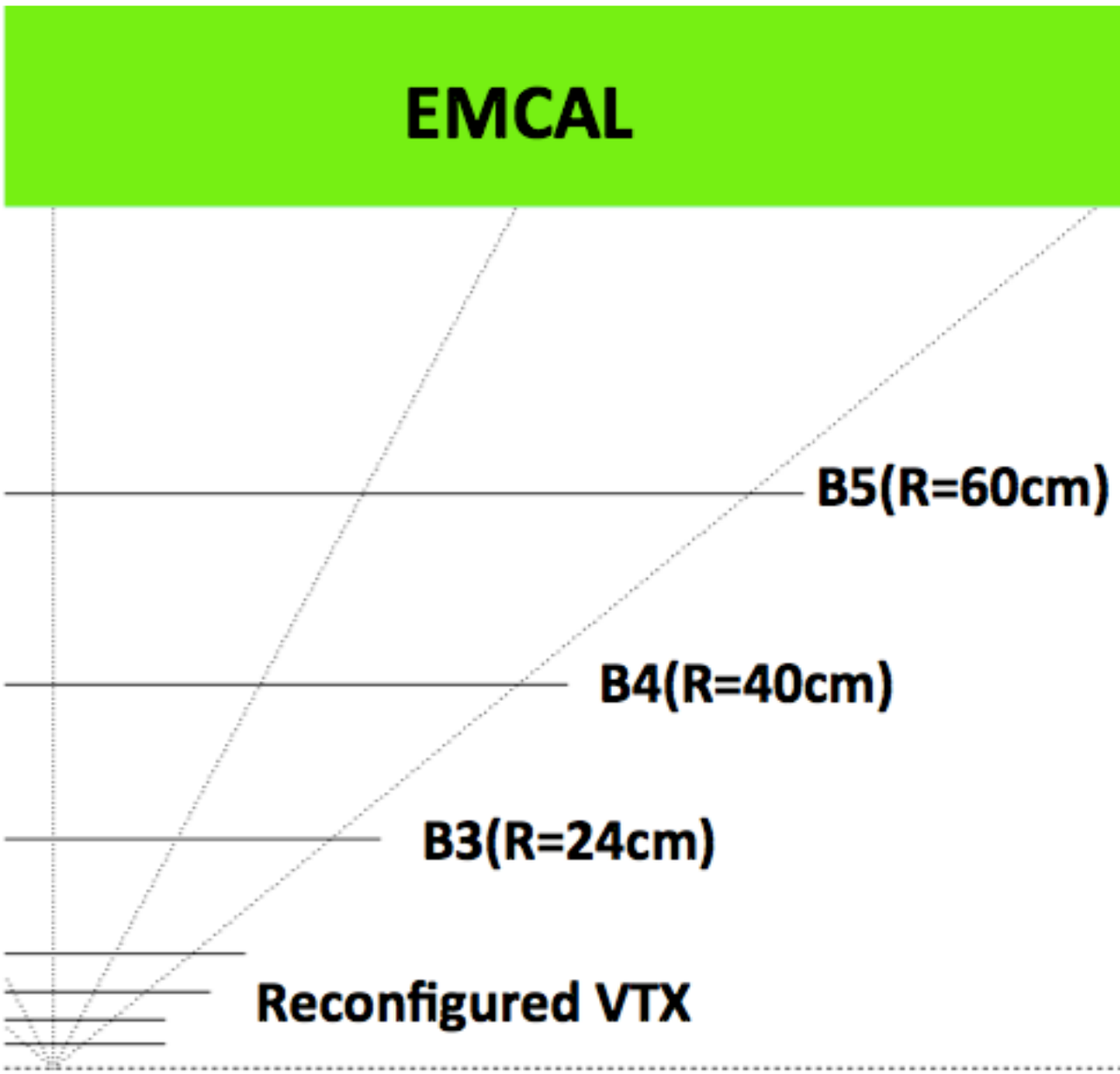

SPACAL prototypes (Tsai)






FNAL T-1018 results

# Extended Silicon Tracking Layers




To cover $|\eta|<1.1$

R=60 cm zmax = 80cm Area = 6.0m$^2$

R=40 cm zmax = 53cm Area = 2.7m$^2$

R=24 cm zmax = 32cm Area = 0.96m$^2$

Total Area: 9.7 m$^2$ of silicon (single layer)

*About 1000 10x10cm sensors needed*

strip occupancy in central AuAu

B3: R=24cm 7 sensors/ladder 16 ladders 112SM 2%

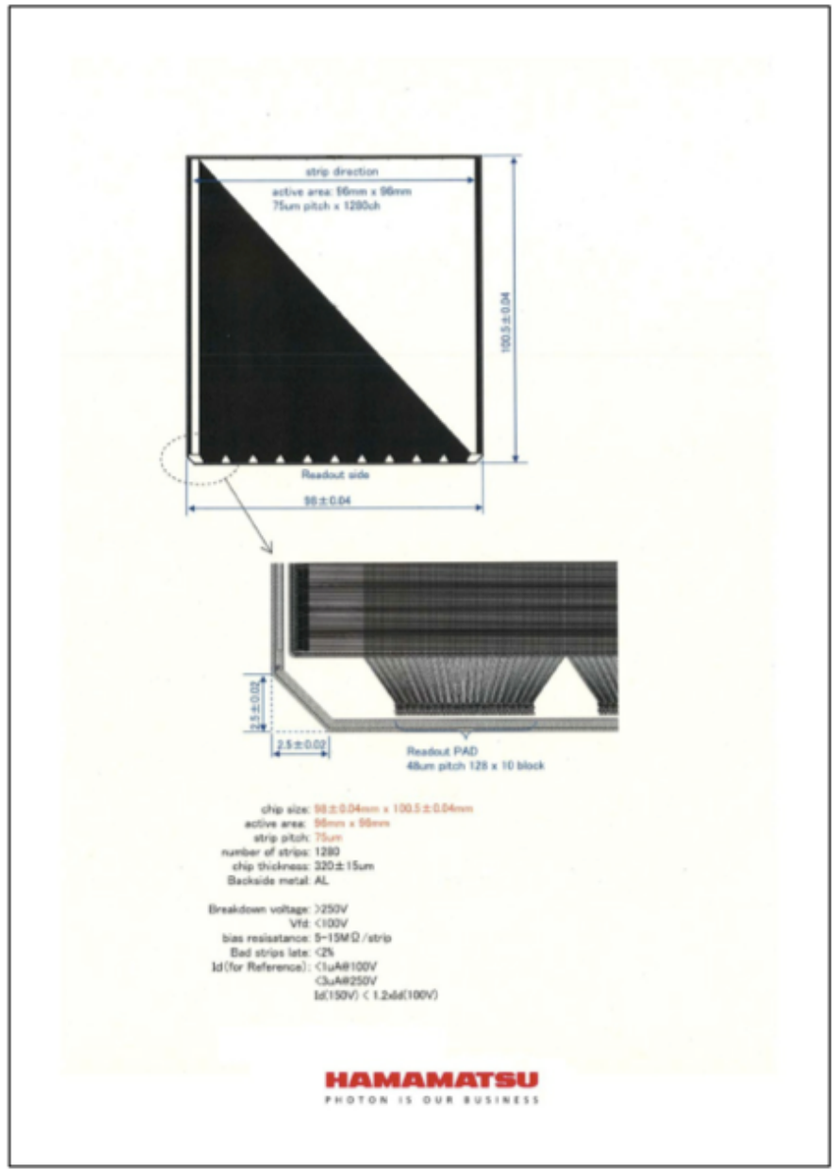
B4: R=40cm 11 sensors/ladder 26 ladders 286SM 0.74%

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

**Total 1038 SMs 10.4K SVX4s 1.33M ch**

# Extended Silicon Tracking Layers

## EMCAL




- 75 μ pitch
- 96 mm sensor

= 6.0m²
= 2.7m²
= 0.96m²
ngle layer)

eeded

ncy
uAu

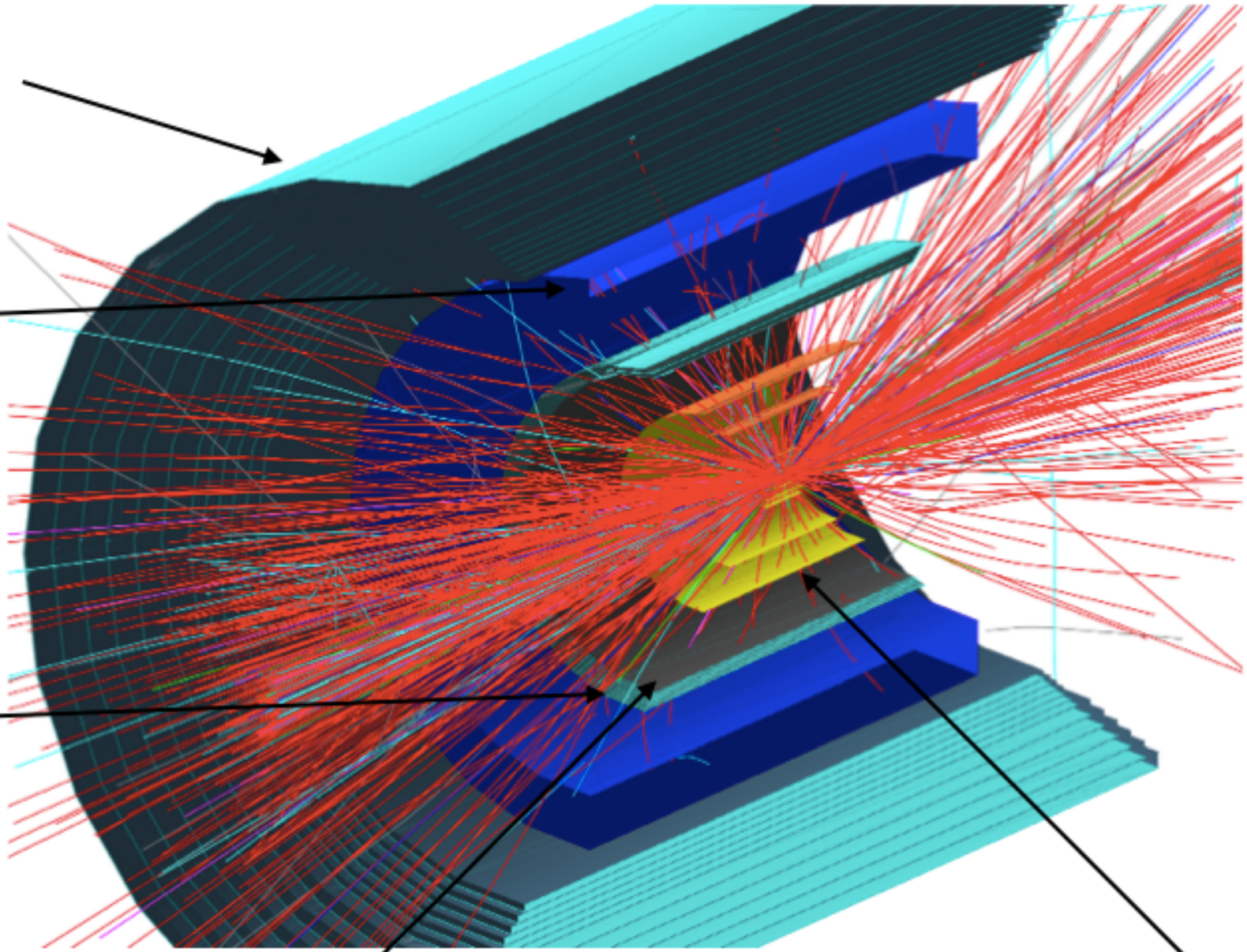
B3: R

B4: R

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

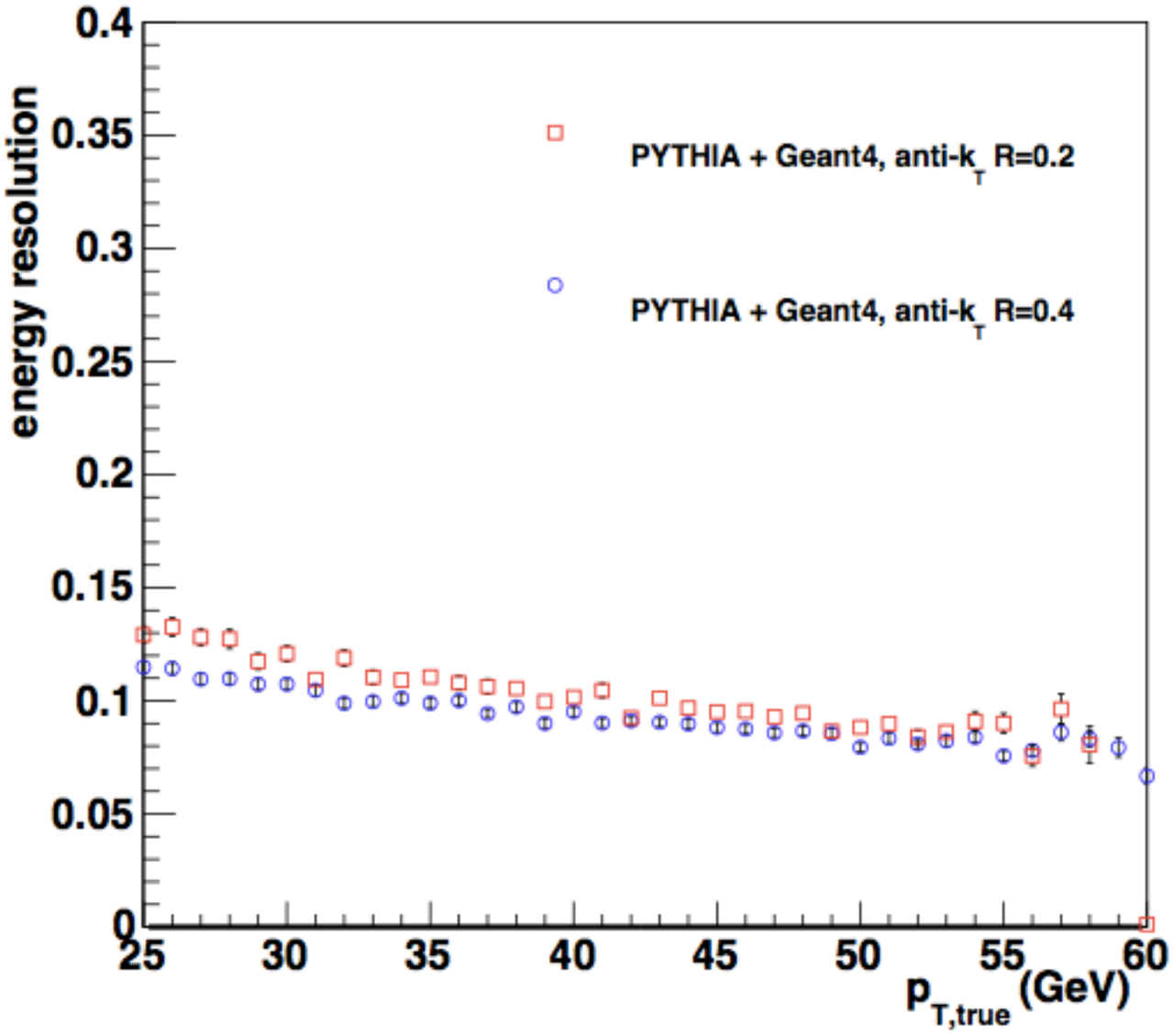
**Total 1038 SMs 10.4K SVX4s 1.33M ch**

# sPHENIX in GEANT4




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

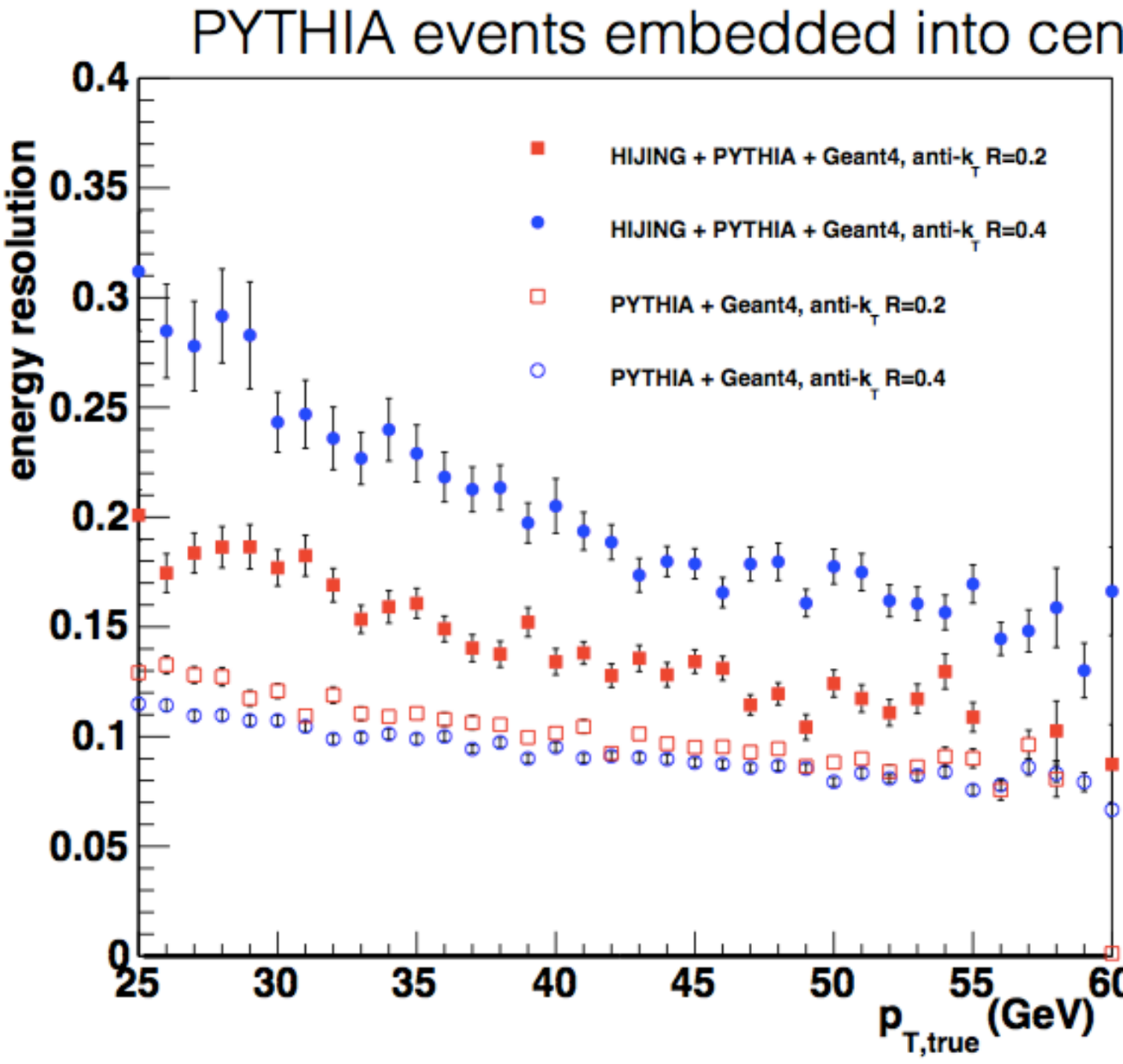
# Jet Performance: p+p




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

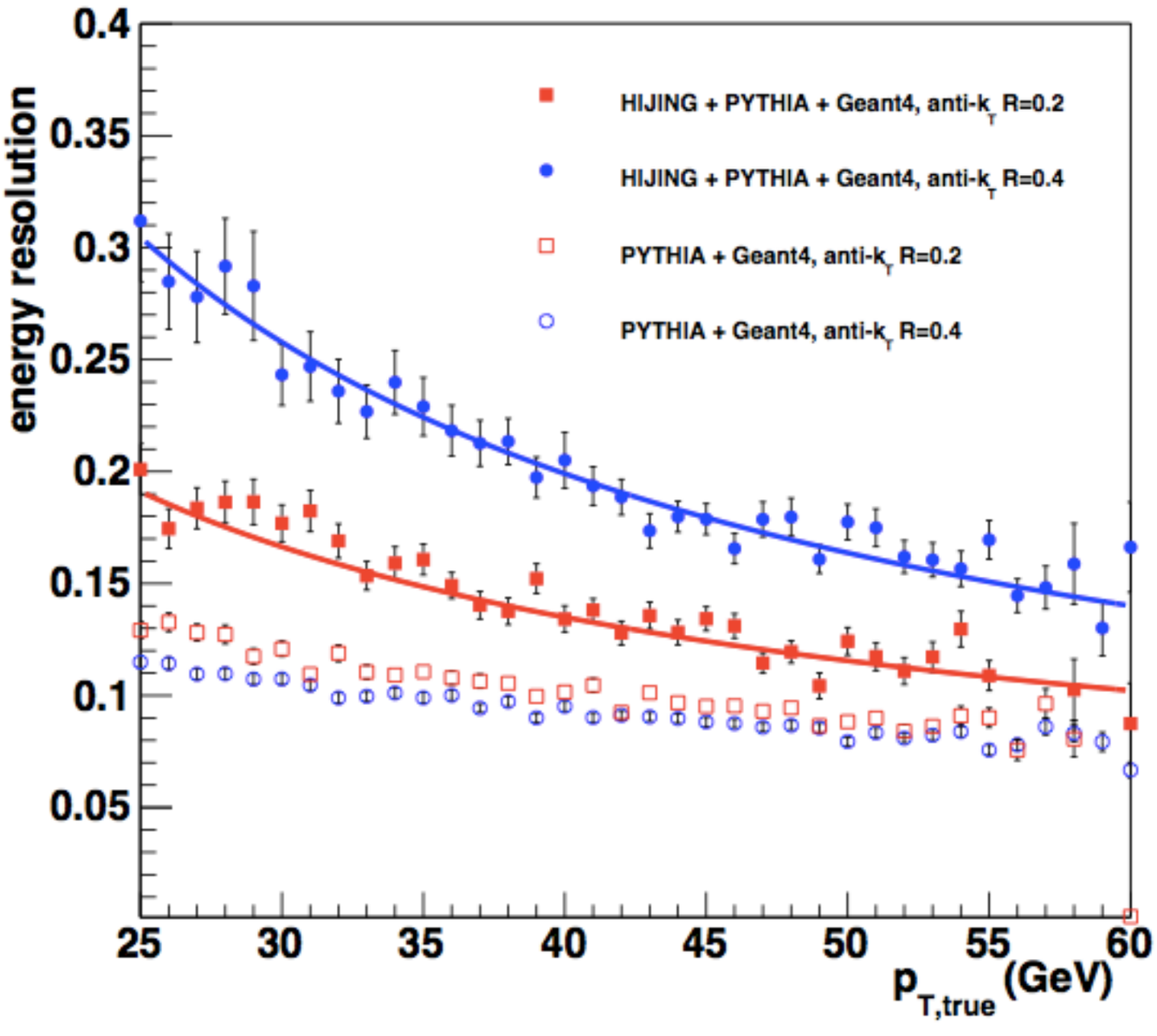



underlying event determines jet performance in AA

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

# Jet Performance: A+A

PYTHIA events embedded into central HIJING events




lines: p+p resolution ⊕ UE smearing

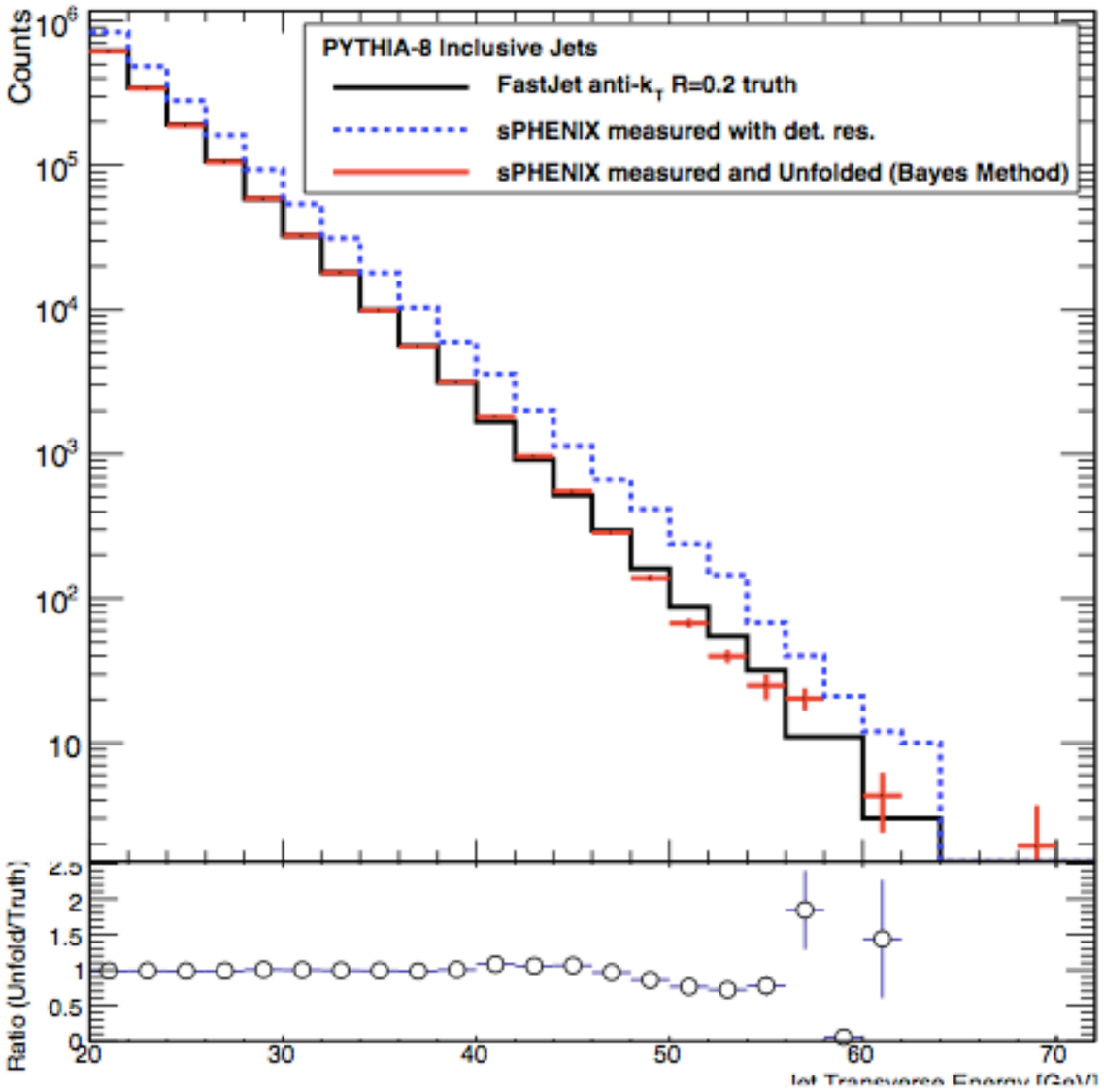
7 GeV for R = 0.4

3.5 GeV for R = 0.2

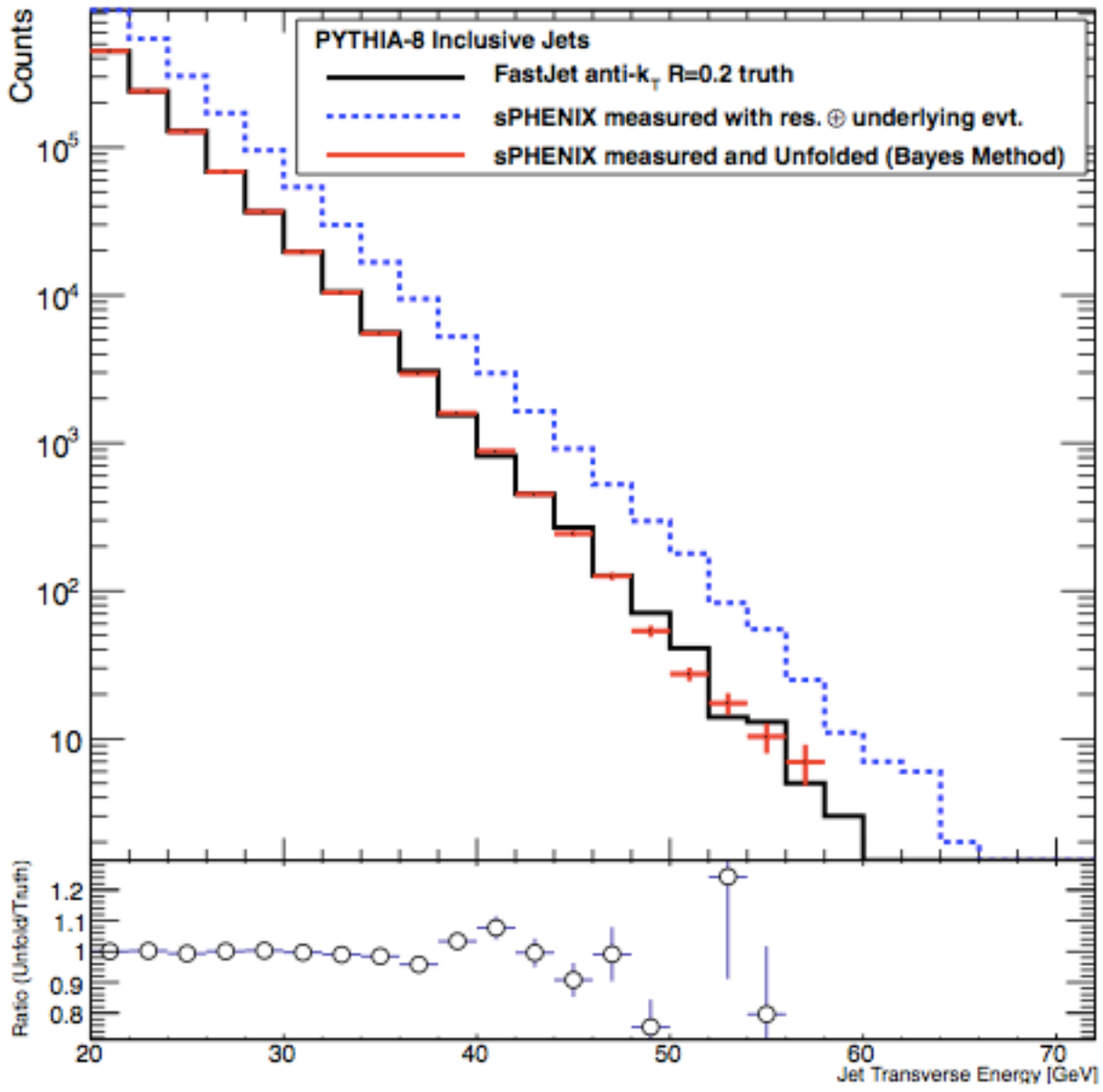
**effect dominated by intrinsic background fluctuations, not detector**

# Jet Spectra Projections

p+p




central Au+Au

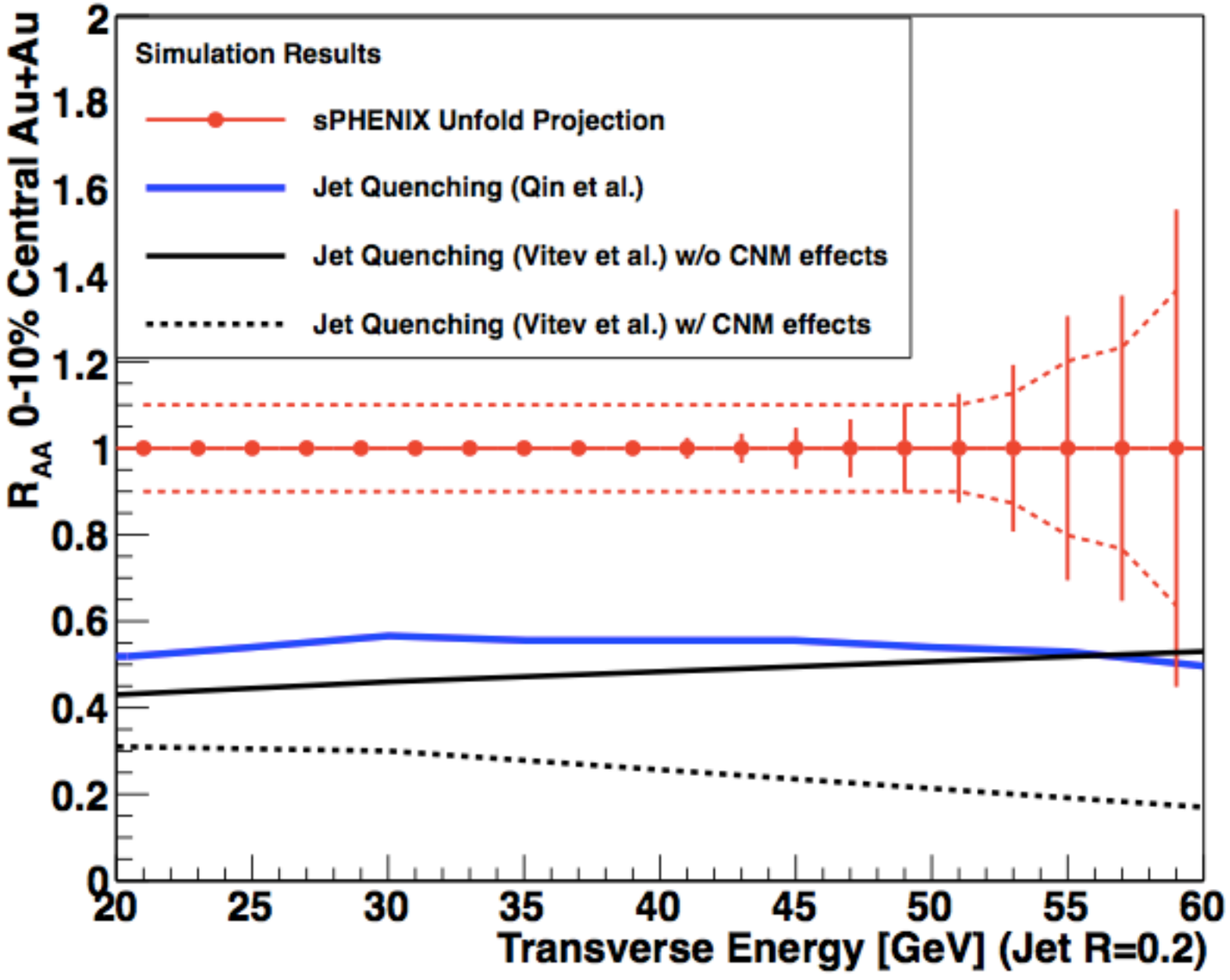



resolution **shifts** exponential spectra out in $p_T$

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

# Projected jet $R_{AA}$

50B events




high precision to ~ 50 GeV

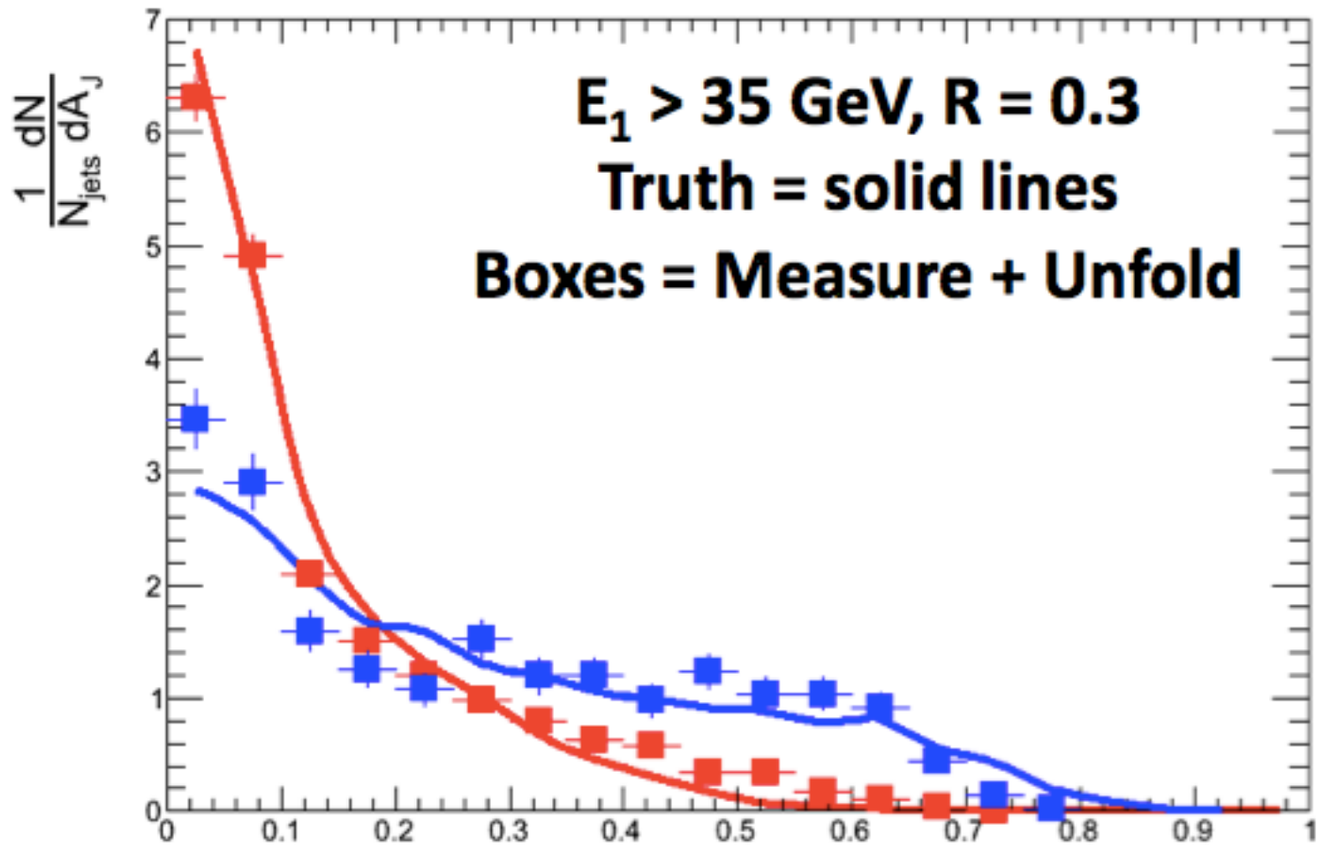
systematics estimated based on unfolding for jet energy resolution

# Jet-jet Asymmetries

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

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

***Very easily discriminated (large effect)***




Using core calorimeter energy cuts and also hybrid tracking methods one can also reproduce the STAR biased dijet result, again scanning the range of surface bias engineering

# 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

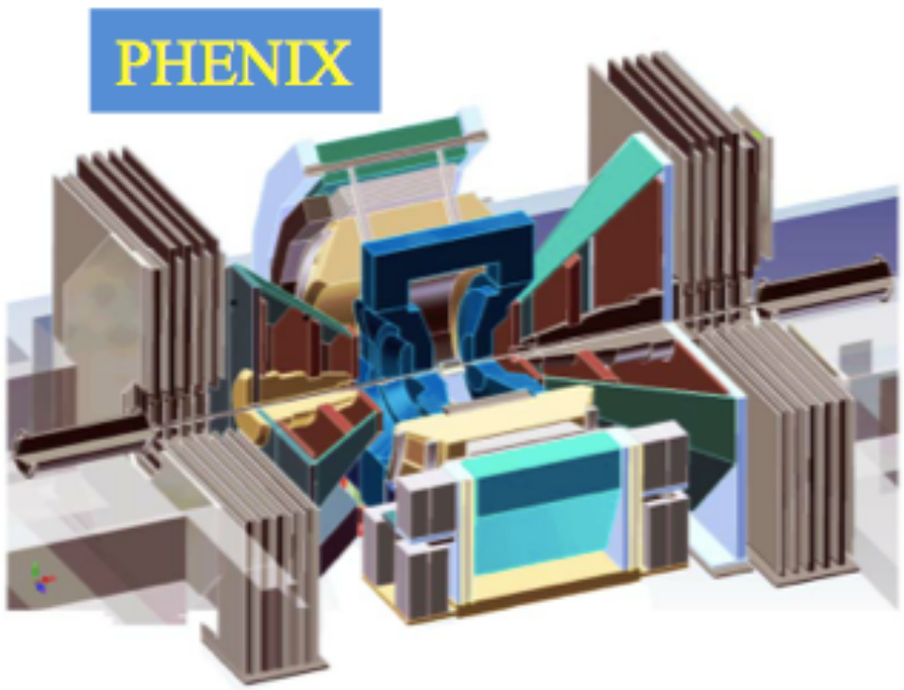
If we just record Au+Au minimum bias events (no trigger bias), in 20 weeks with current RHIC performance and PHENIX livetime, we record **50 billion events within |z| < 10 cm** [optimal for silicon tracking]

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

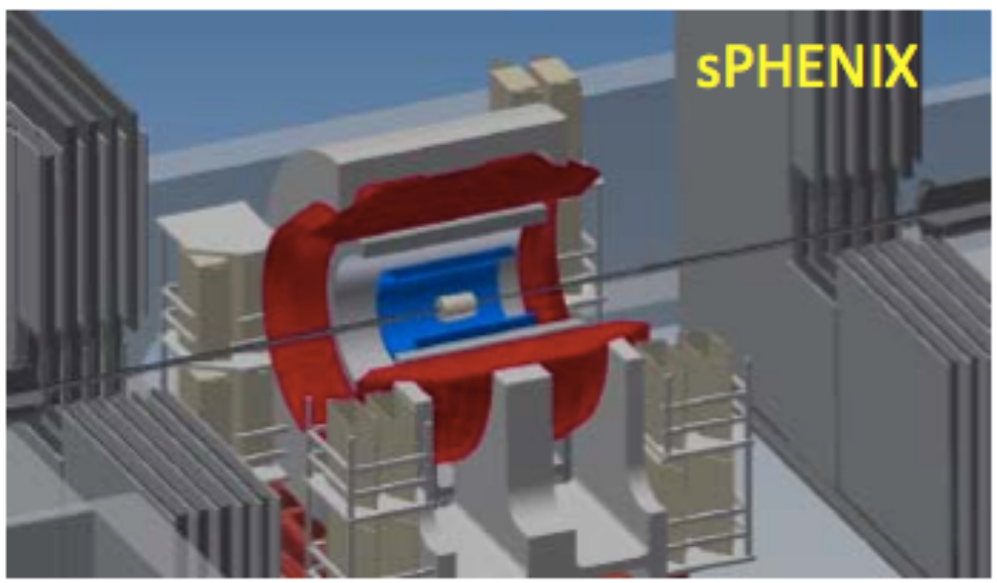
# BNL Proposed 10-year Plan

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

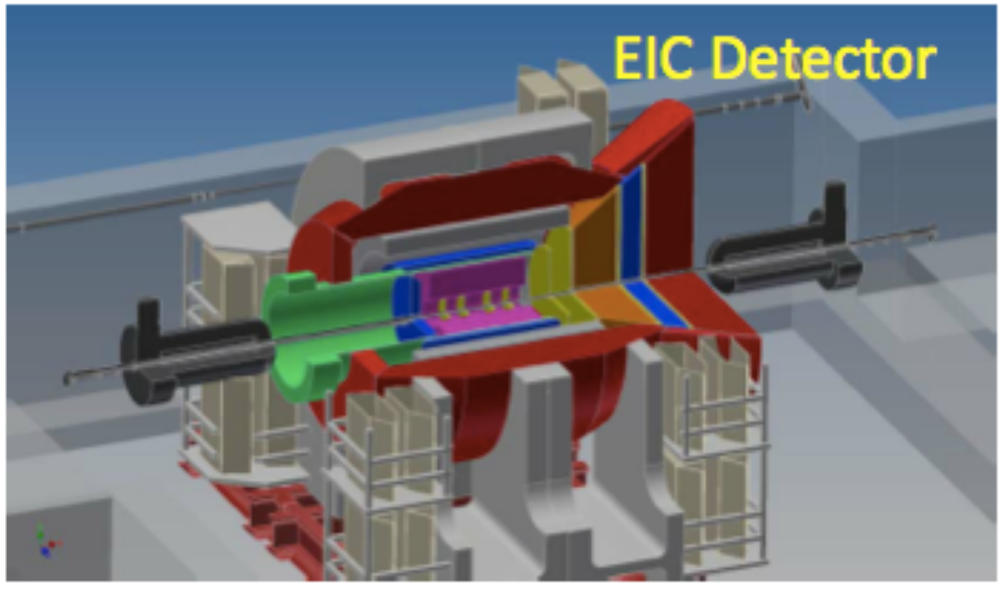
# sPHENIX evolution




~2021-22



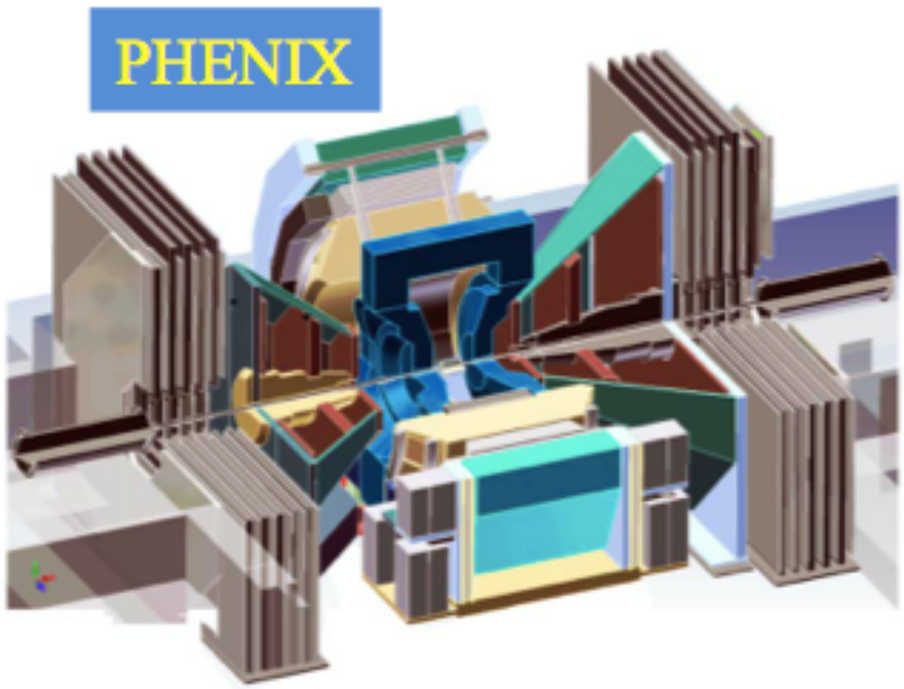

~2025



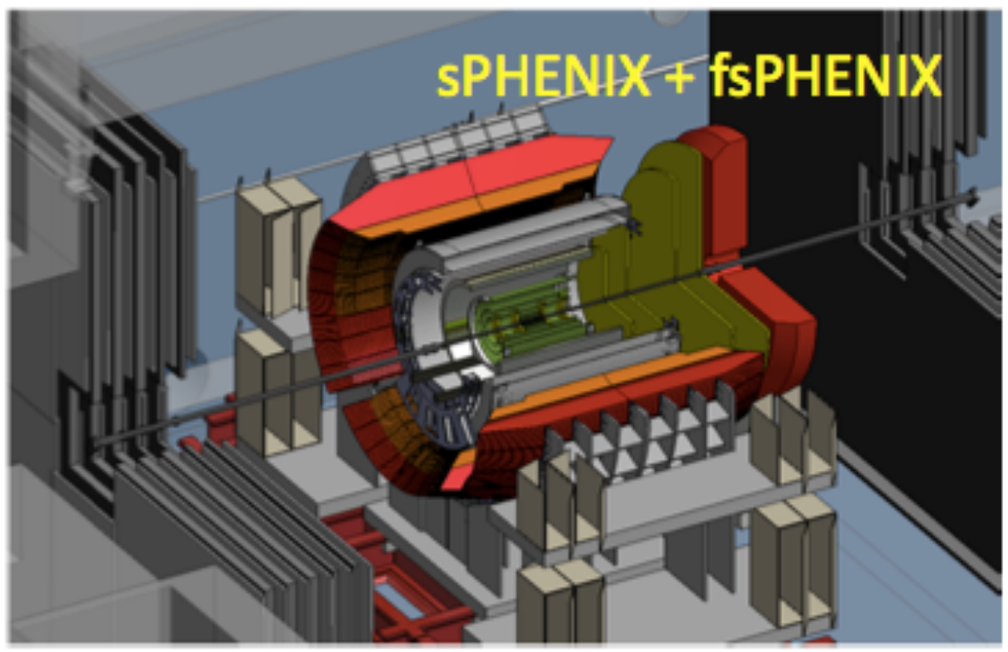

## Evolve sPHENIX (pp and HI detector) to an EIC Detector (ep and eA detector):

- 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 ~$10^{33}$ $cm^{-2}$ $s^{-1}$ (~1$fb^{-1}$ /month)

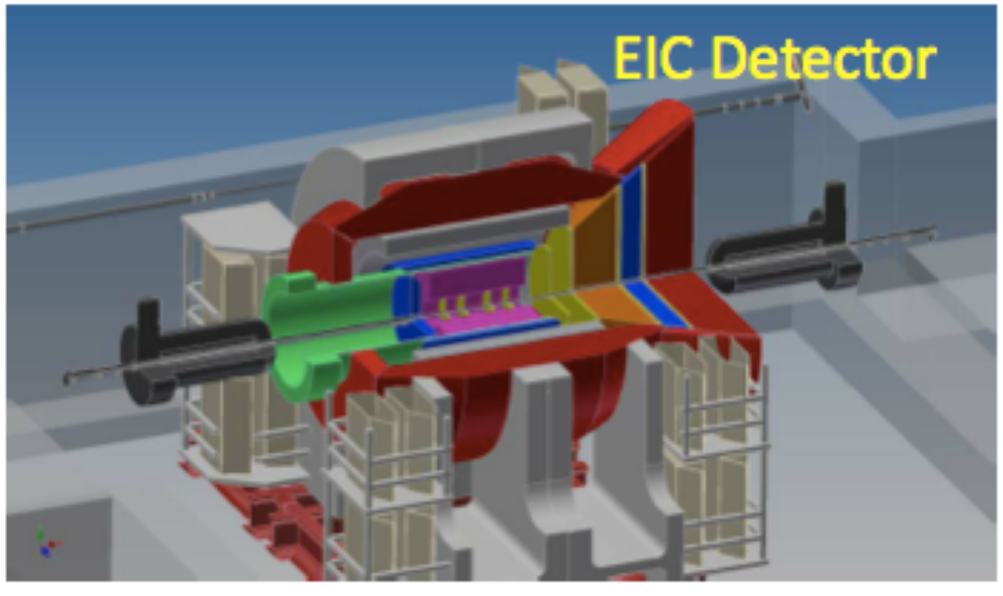
# sPHENIX evolution




~2021-22




~2025

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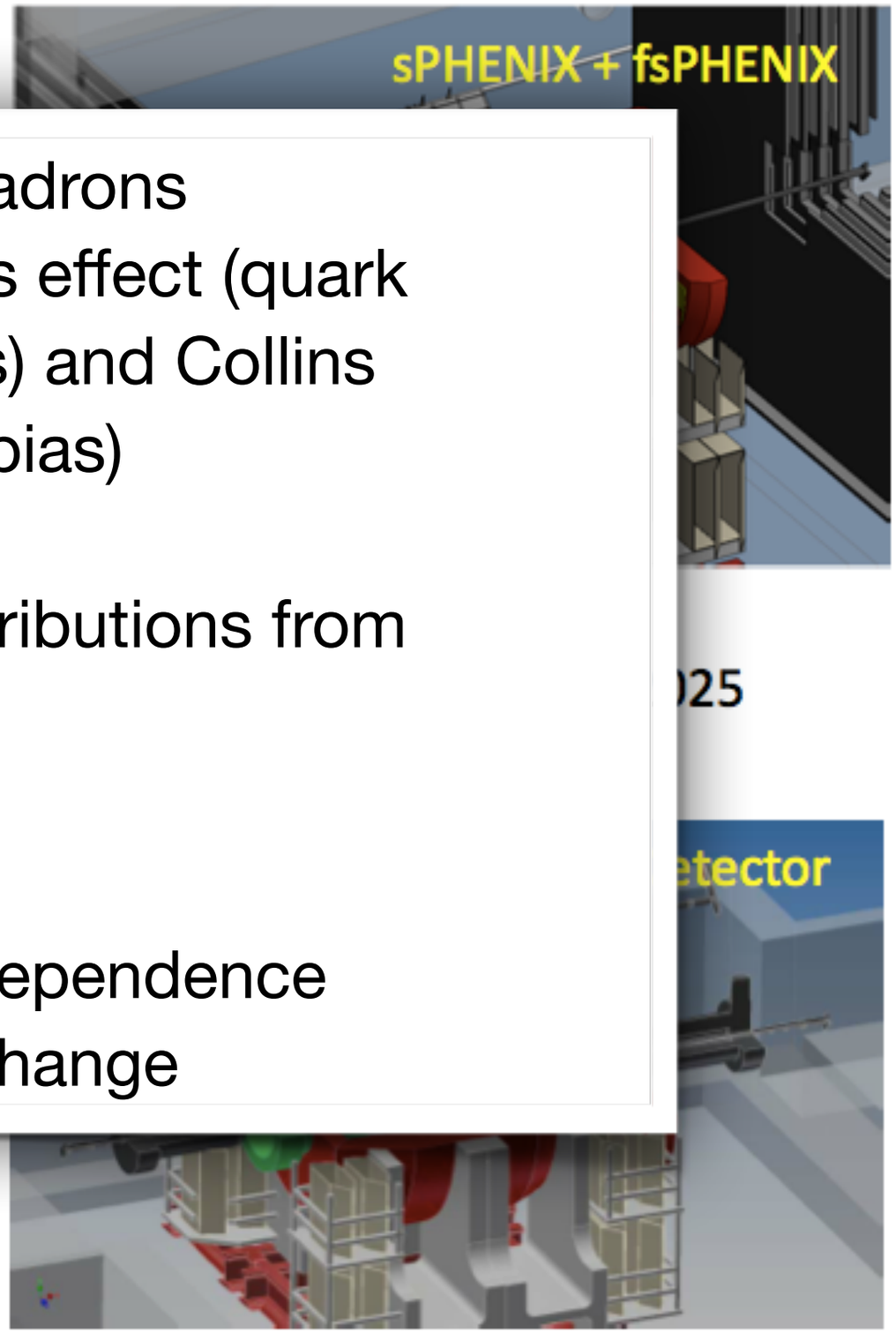
# sPHENIX evolution




- 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

Evolve sPHE
EIC Detector

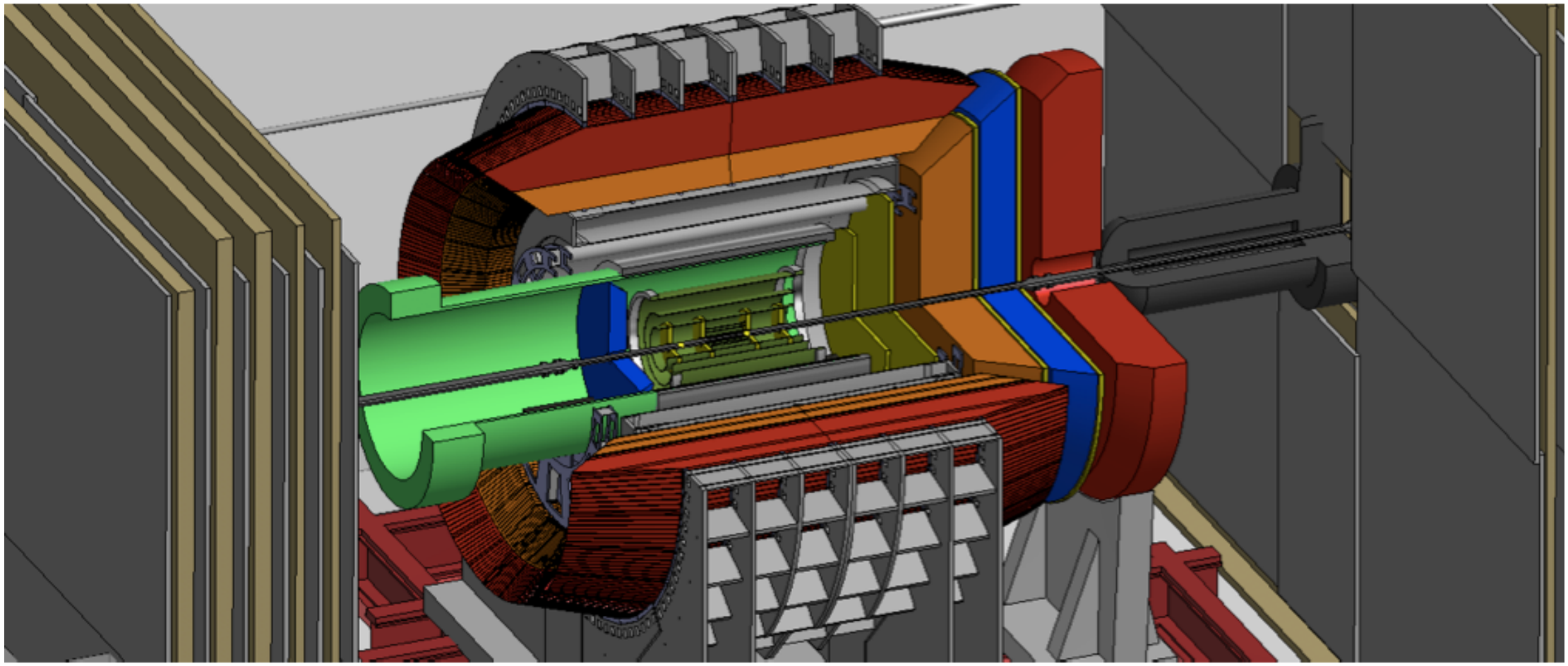
- To utili
  with e-
  energy
- *e*, *p*, $He^3$ polarized
- Stage-1 luminosity ~$10^{33}$ $cm^{-2}$ $s^{-1}$ (~1$fb^{-1}$ /month)

)25

etector

# 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

**see talk by Jin Huang this afternoon in the Nucleon Structure session for full details on forward sPHENIX and 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!***

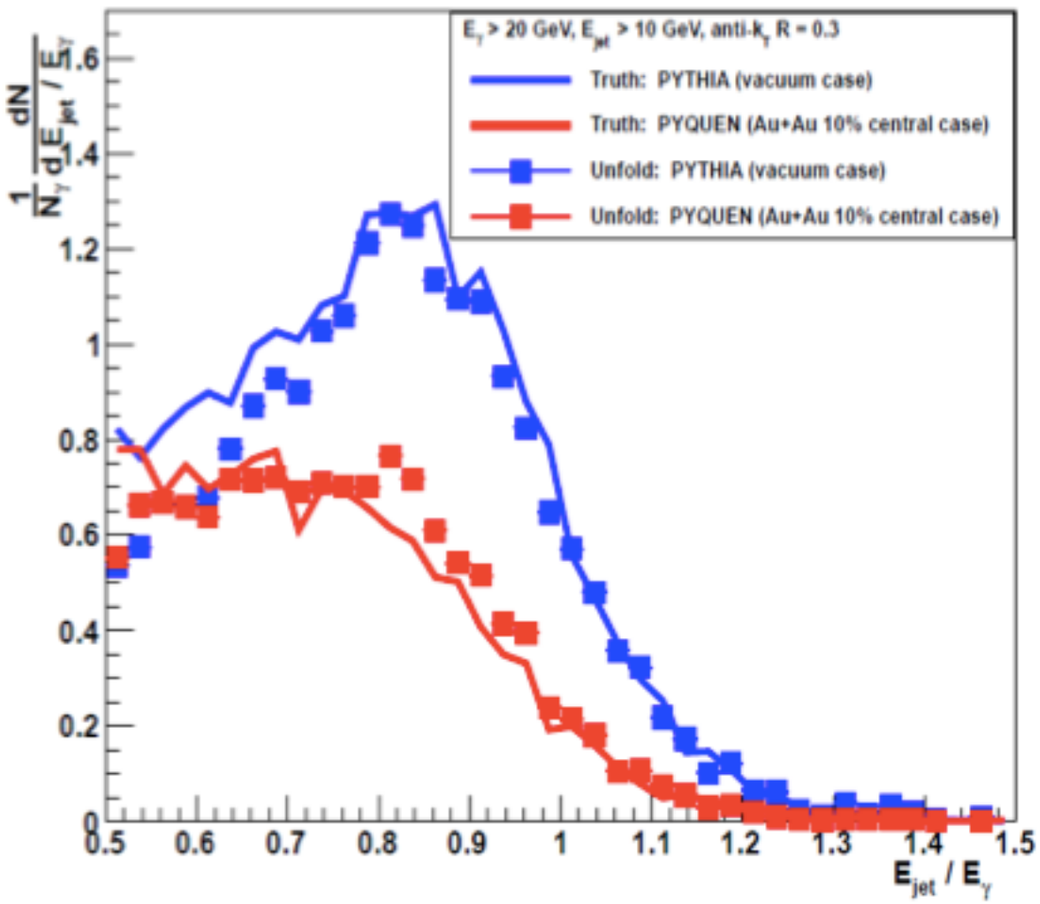
(3) Planned operations and additional opportunities

*Does the jet program align with our other goals as a 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 $\lvert\eta\rvert < 1$ | |
| Direct $\gamma$, $p_T > 10\,\mathrm{GeV/c}$ | 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 | | |
| Separation of Y states | EMCal | $\sigma/E \simeq 15\%/\sqrt{E}$ | sPHENIX |
| | | $\Delta\eta \times \Delta\phi \sim 0.03 \times 0.03$ | |
| | Preshower | $e/\pi$ rejection | Future Option |
| | | fine segmentation | |
| | Tracking | $B = 2T$ | sPHENIX |
| | | $\Delta p/p \simeq 2\%$ | Future Option |
| $\pi^0$ 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 | $2\gamma$ separation | Future Option |
| | | fine segmentation | |

# γ-jet Observables




For $p_T$ > 15 GeV, direct photons dominate at RHIC

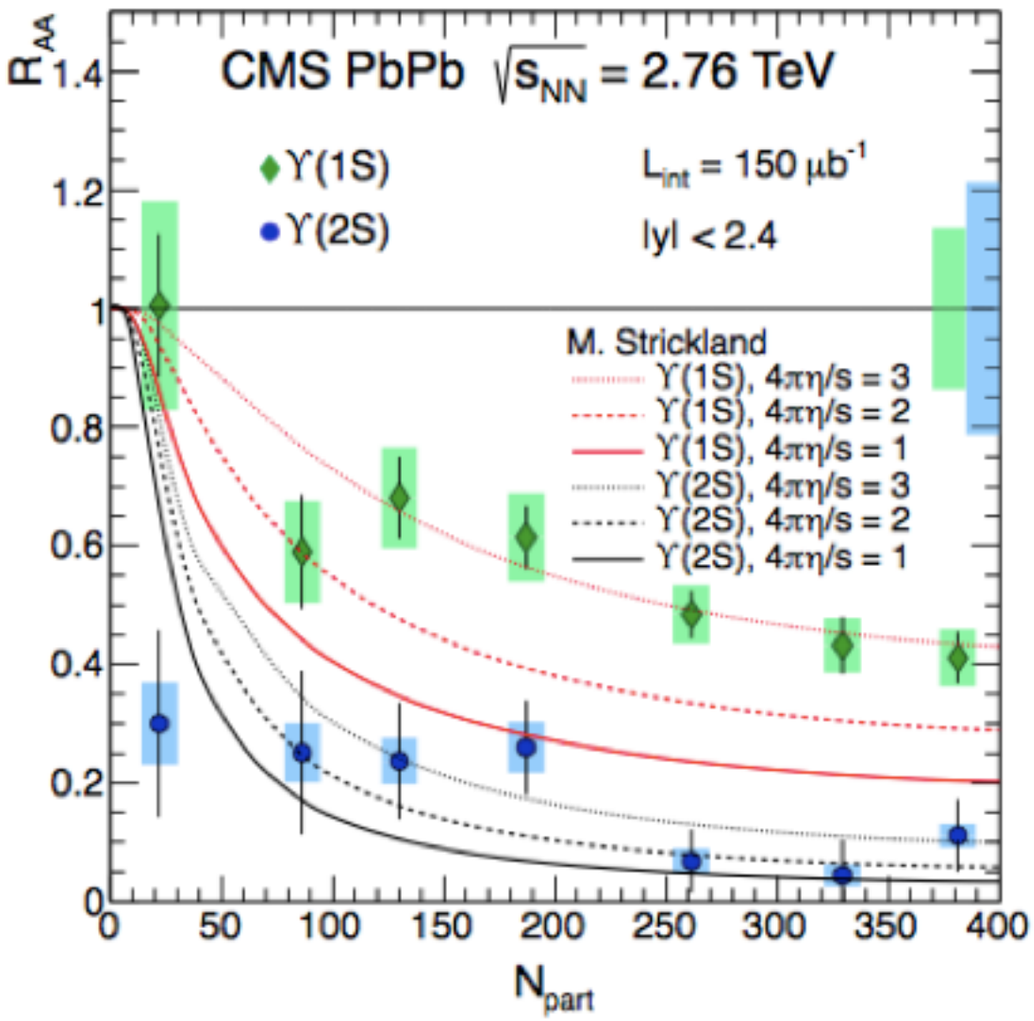
Direct γ – jet correlations

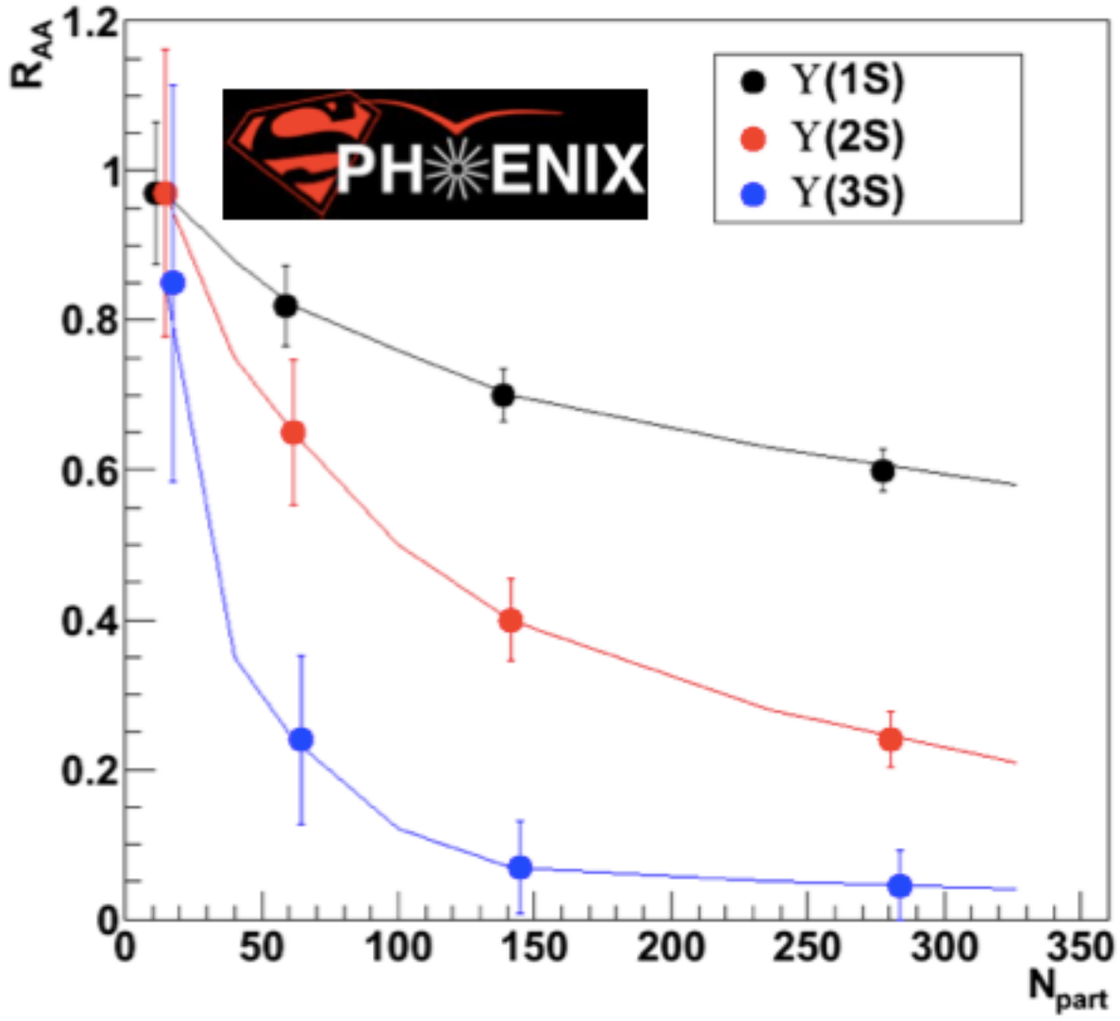
- **PYTHIA (vacuum)**
- **PYQUEN (quenching)**

γ– hadron correlations

Track where the energy goes (transverse and longitudinal)!

# sPHENIX Upsilon Measurements

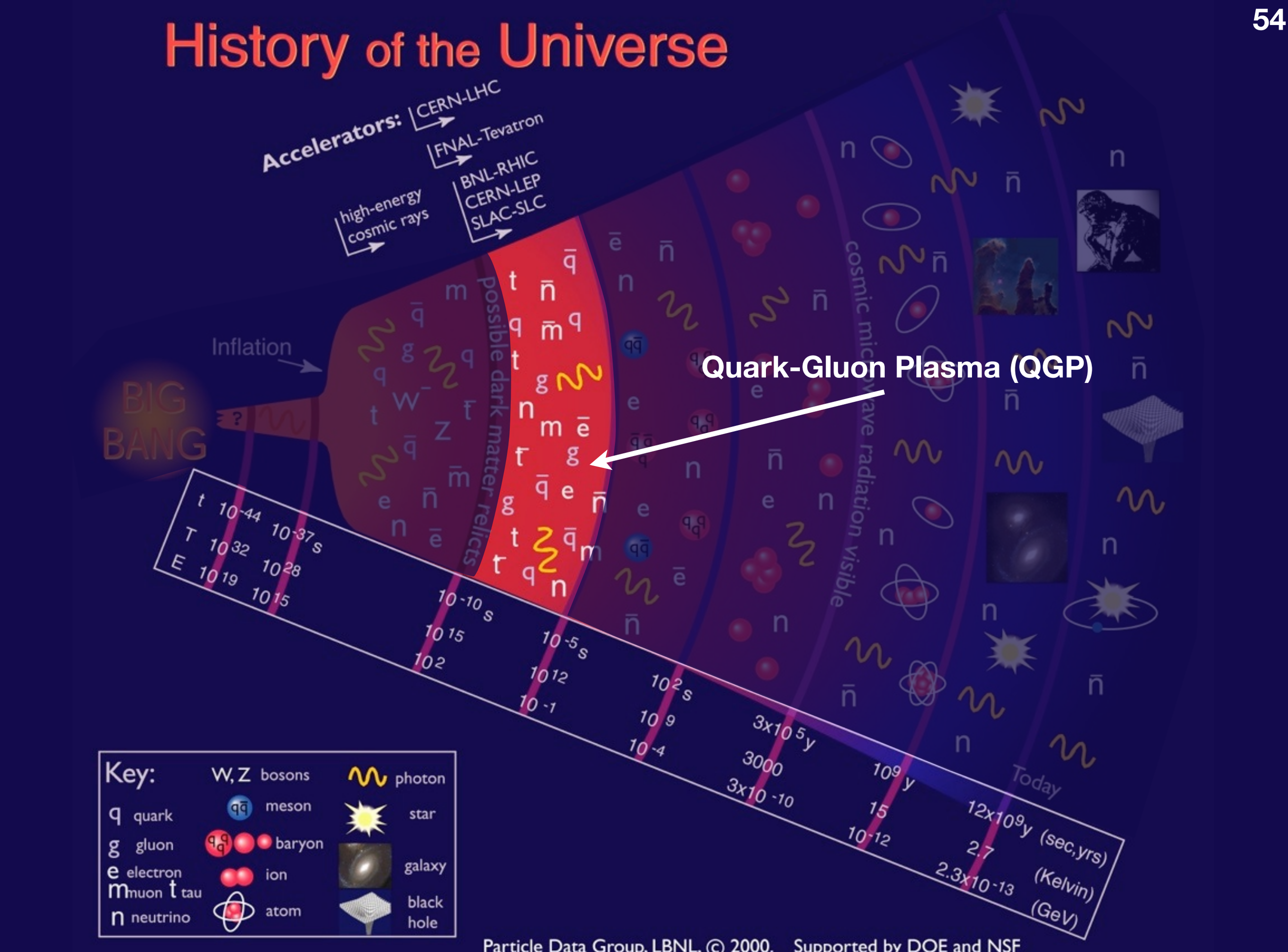



Extremely exciting LHC Upsilon results

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

# History of the Universe




Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

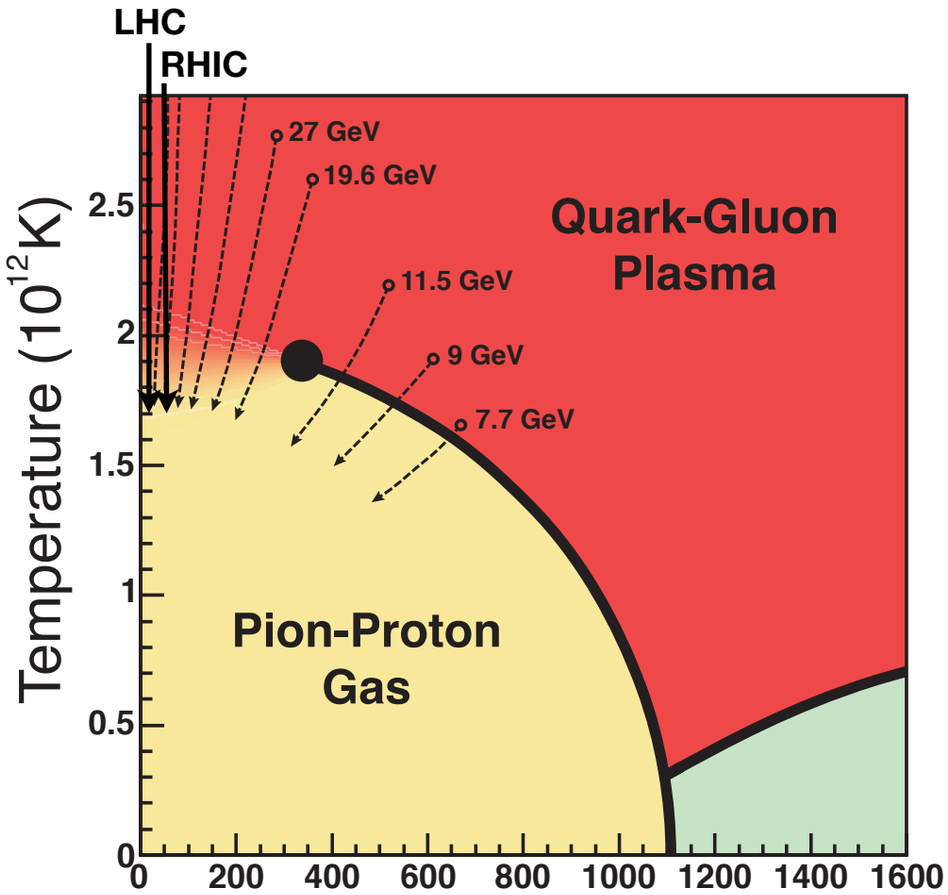
# Heavy Ion Collisions

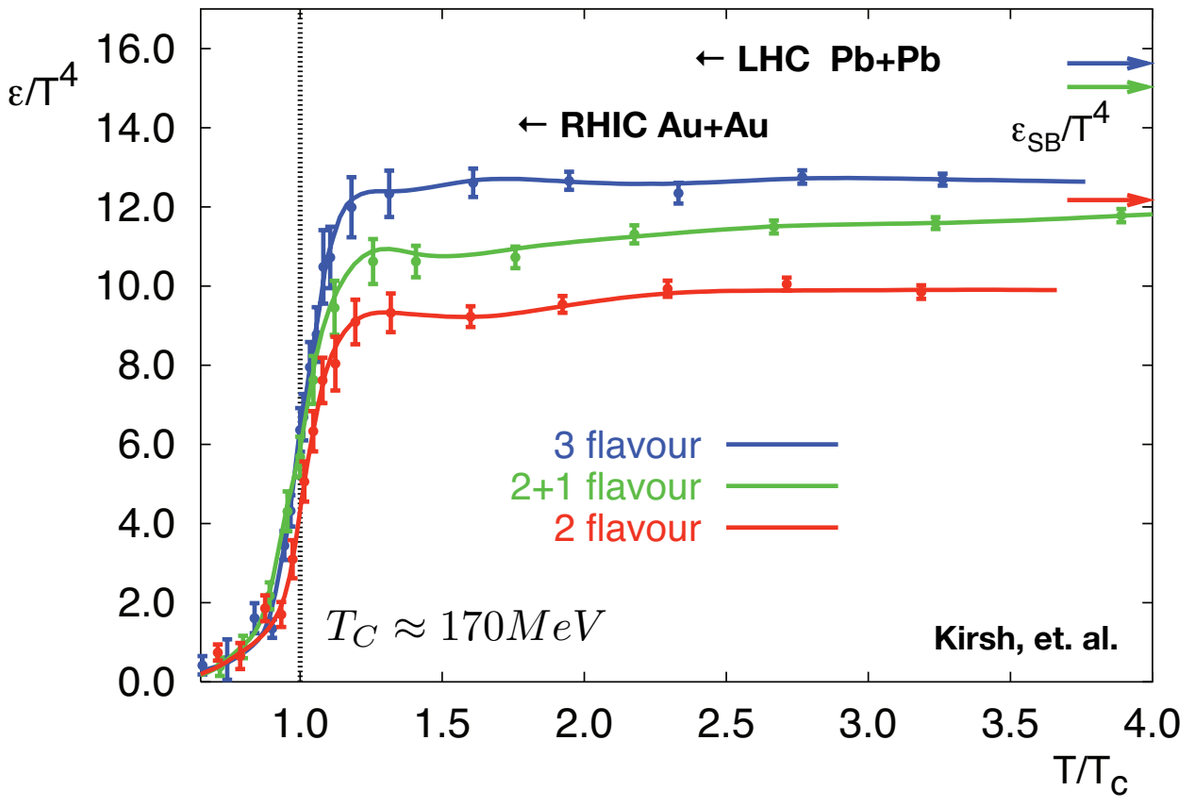
## QCD Phase Diagram

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

Reachable by collider facilities

Critical point being sought



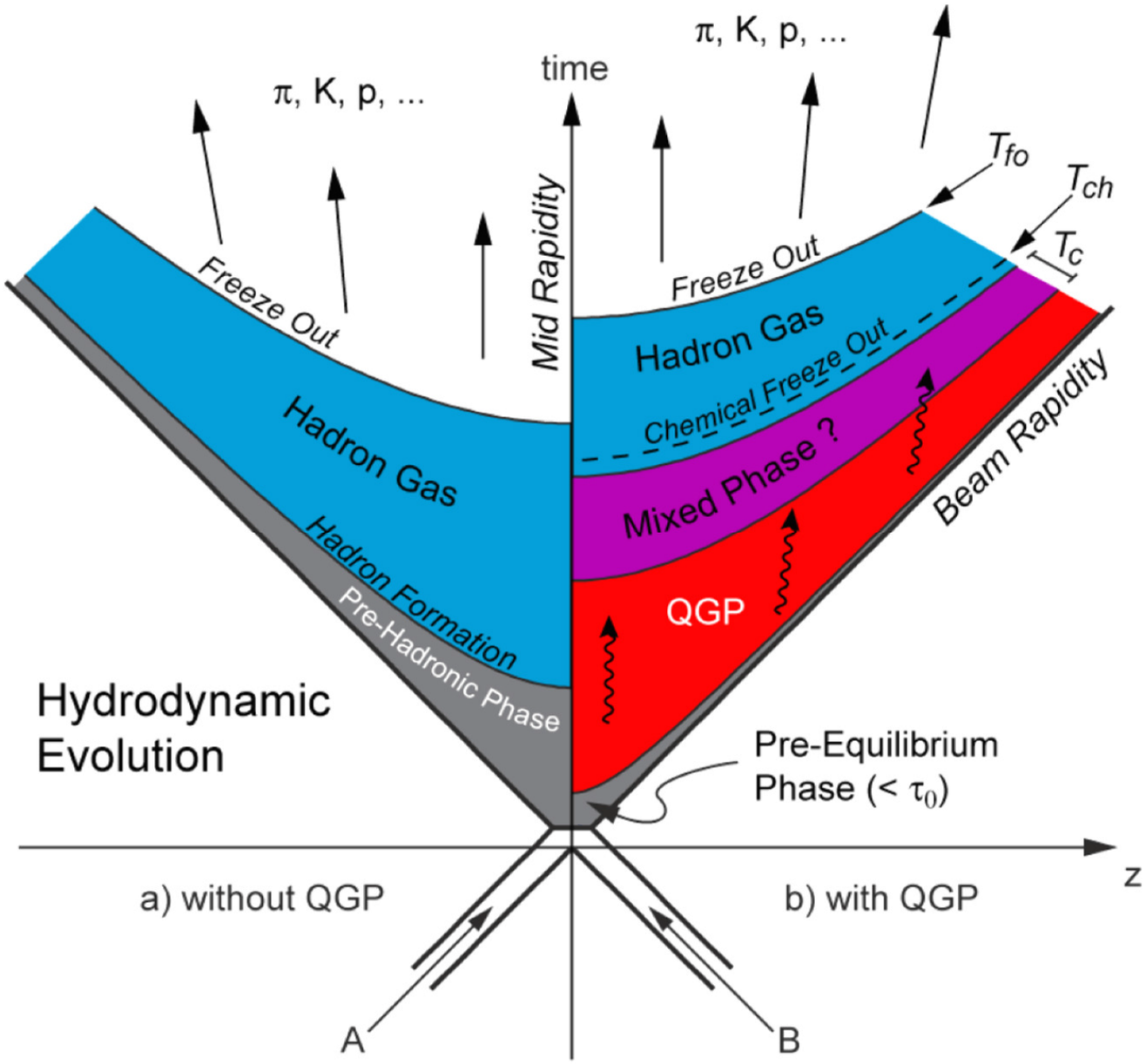

## Lattice QCD Calculations

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***

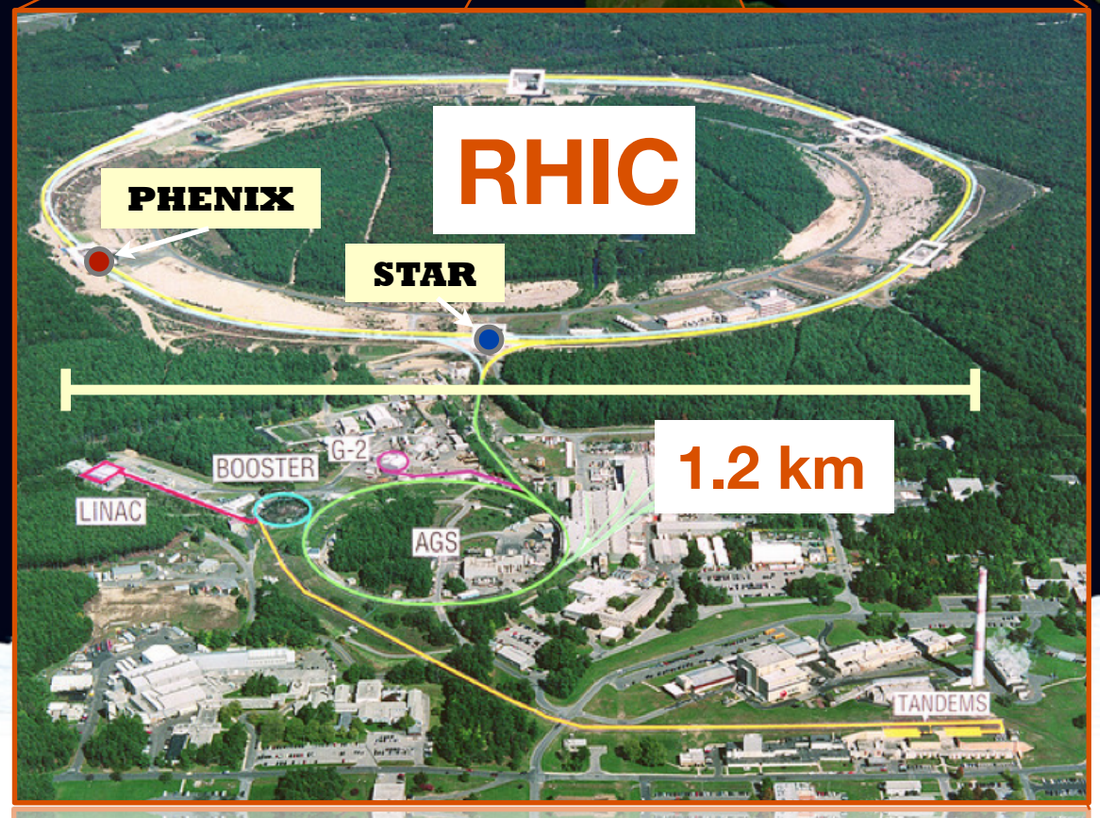
**Thermalization (~0.6 fm/c)**

**Nuclear Crossing (~0.1 fm/c)**

***values for RHIC at 200 GeV**

New York

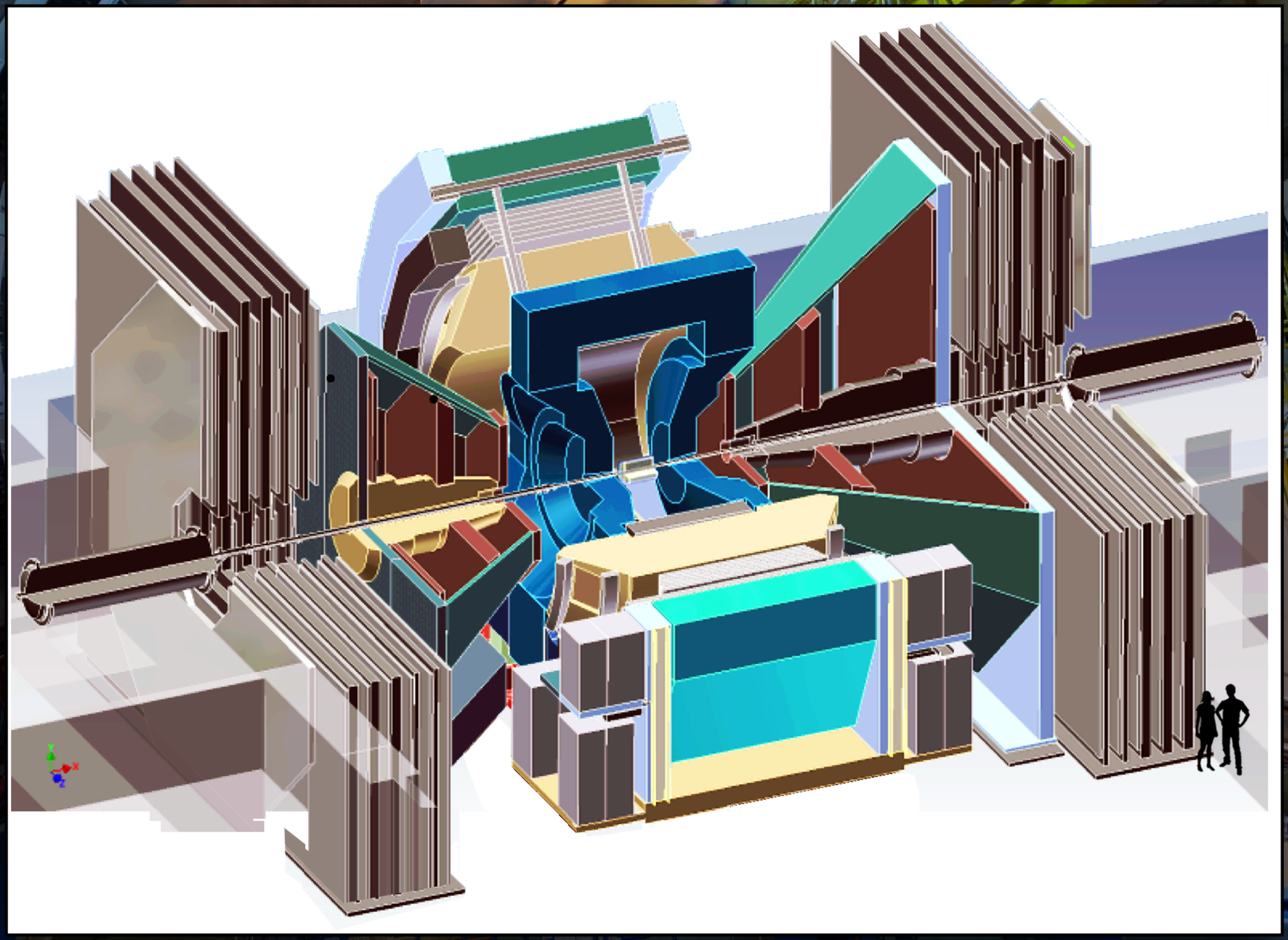
Switzerland



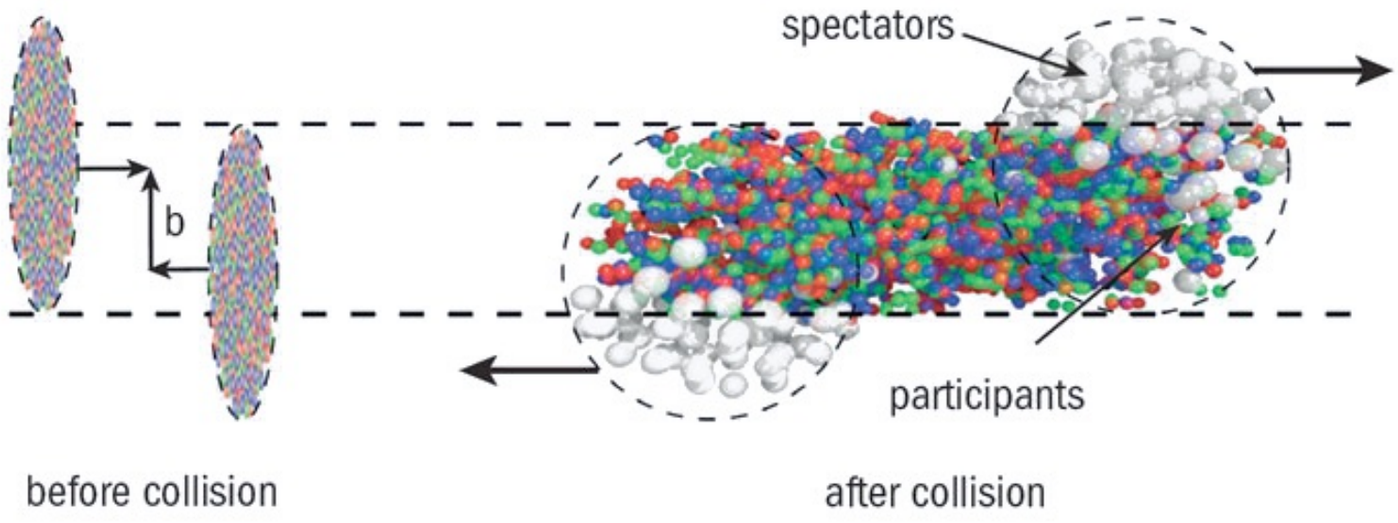

| beam | energy (GeV) |
|---|---|
| $\vec{p}+\vec{p}$ | 62 - 510 |
| (d,$He^3$)+Au | 200 |
| Cu+Cu | 22 - 200 |
| Cu+Au | 200 |
| Au+Au | 7 - 200 |
| U+U | 193 |

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

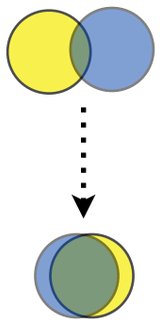
# PHENIX Detector



# Event Geometry Controls




Impact parameter studied via **centrality** selection



Large impact parameter
→ peripheral events, ≲100%

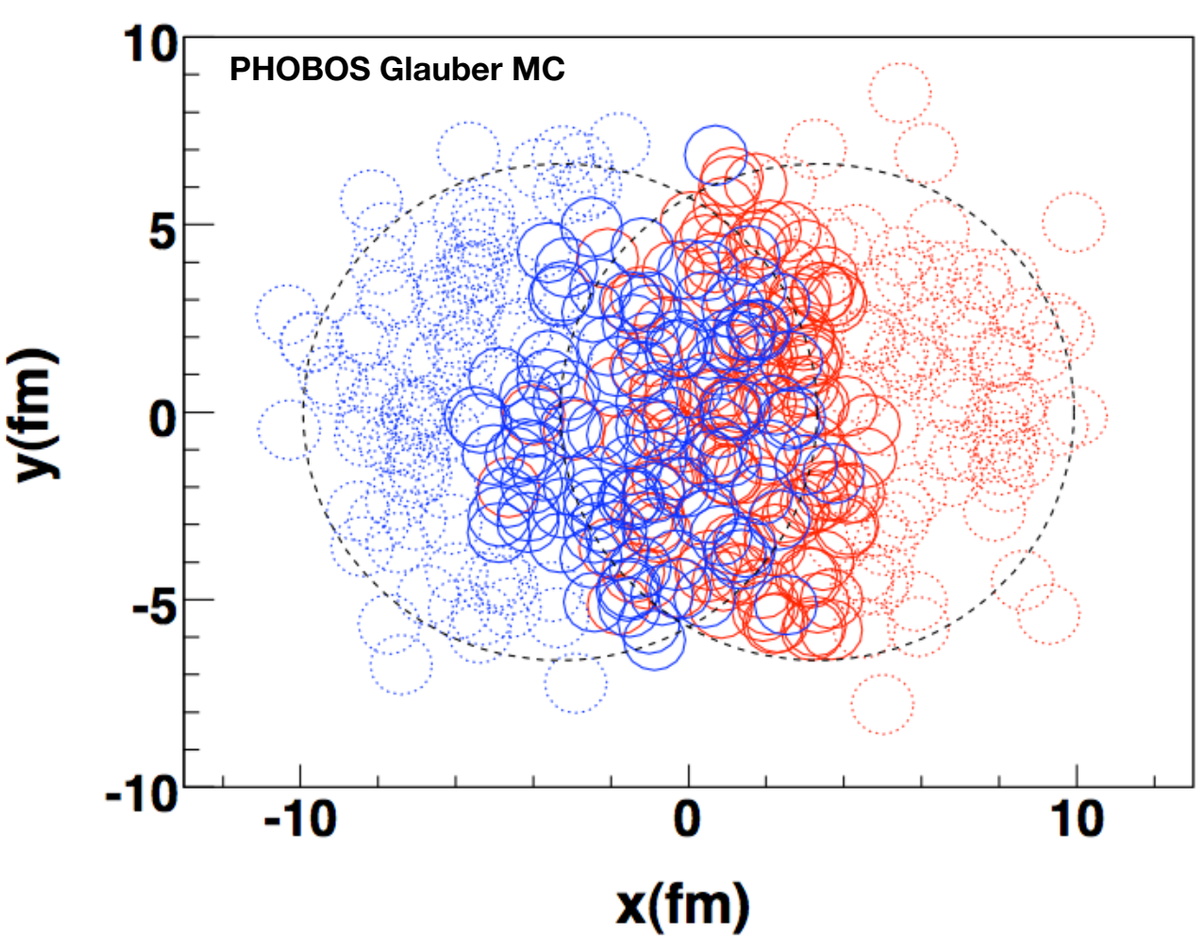
Small impact parameter
→ central events, ≳0%

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