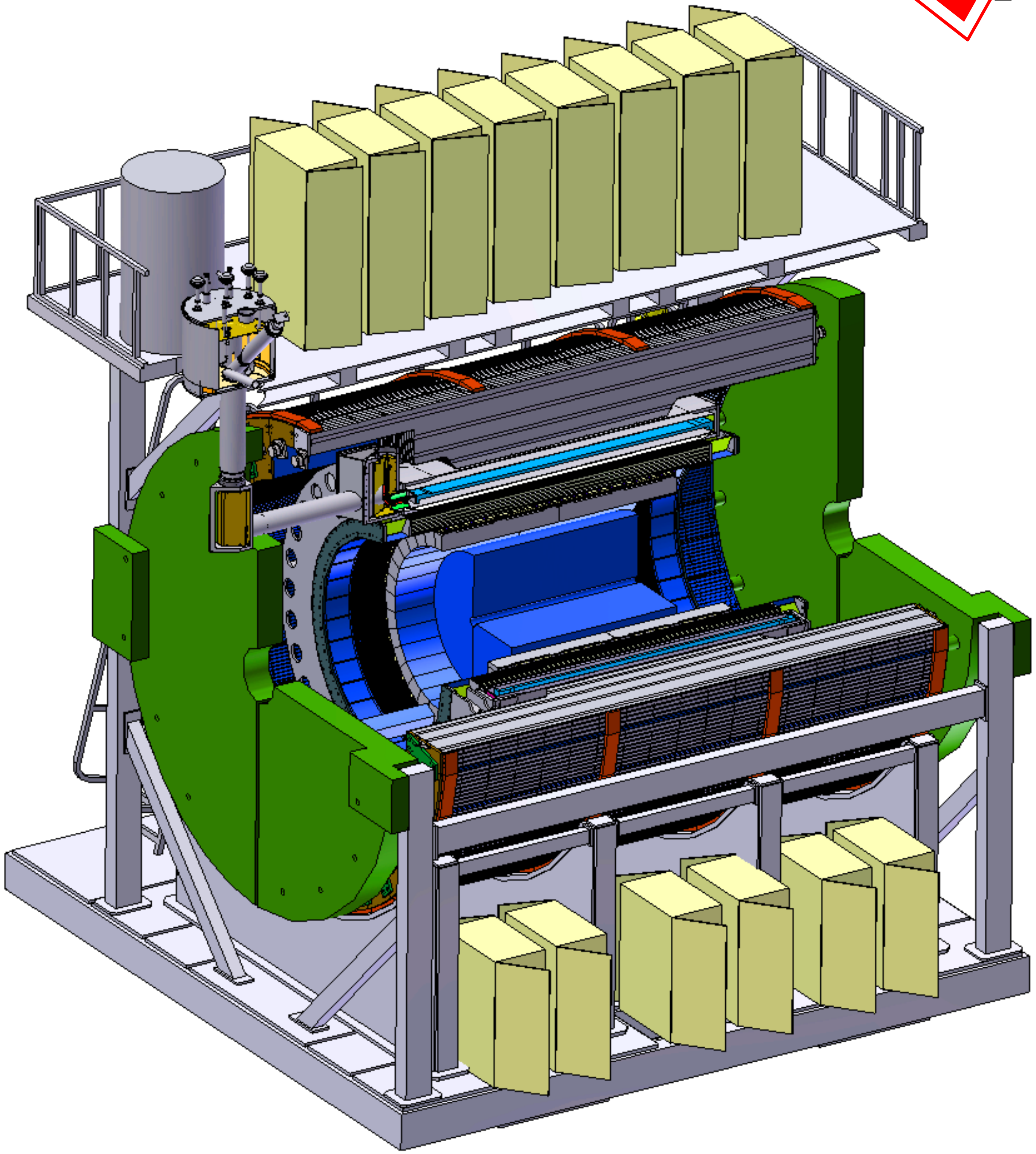
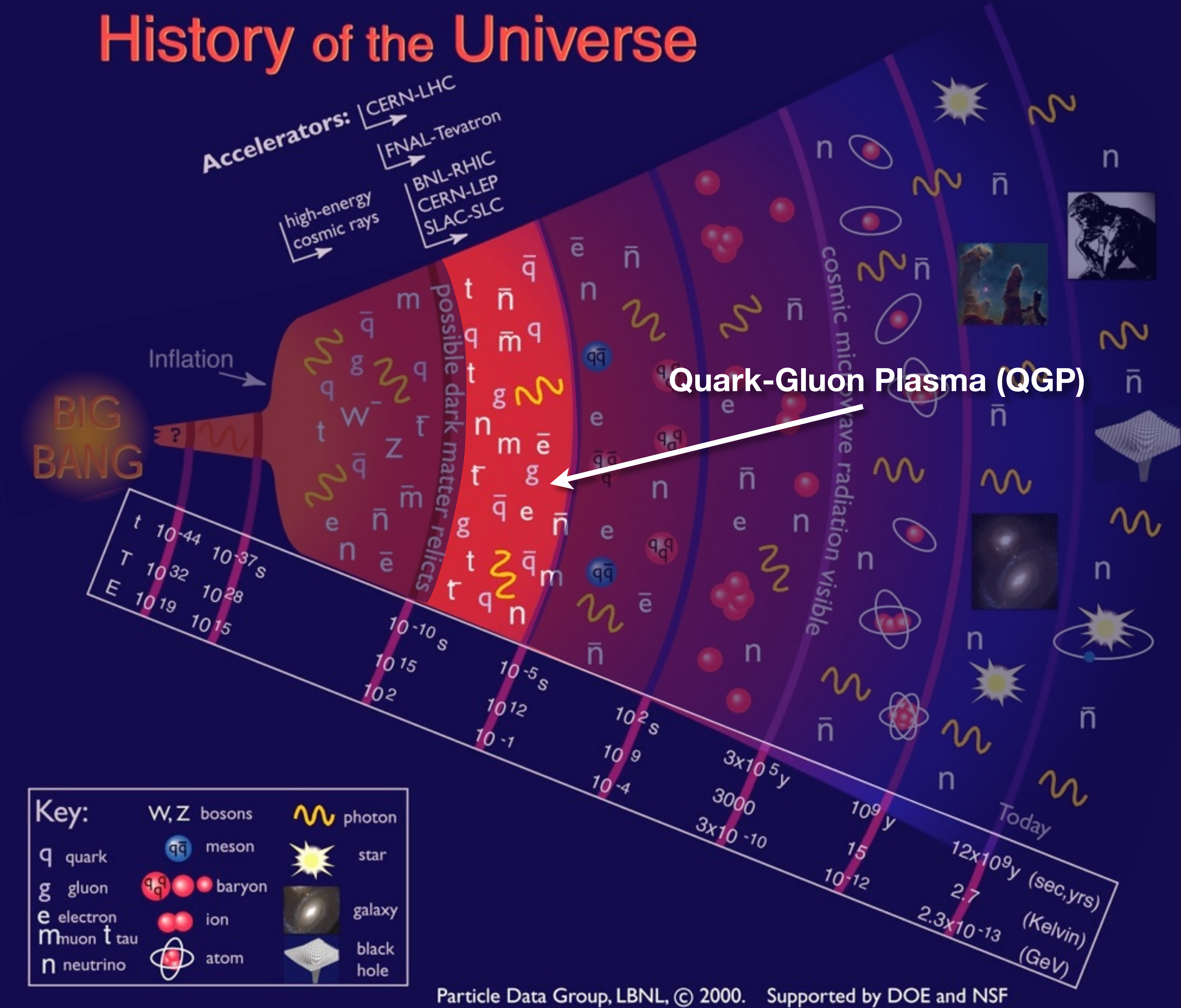
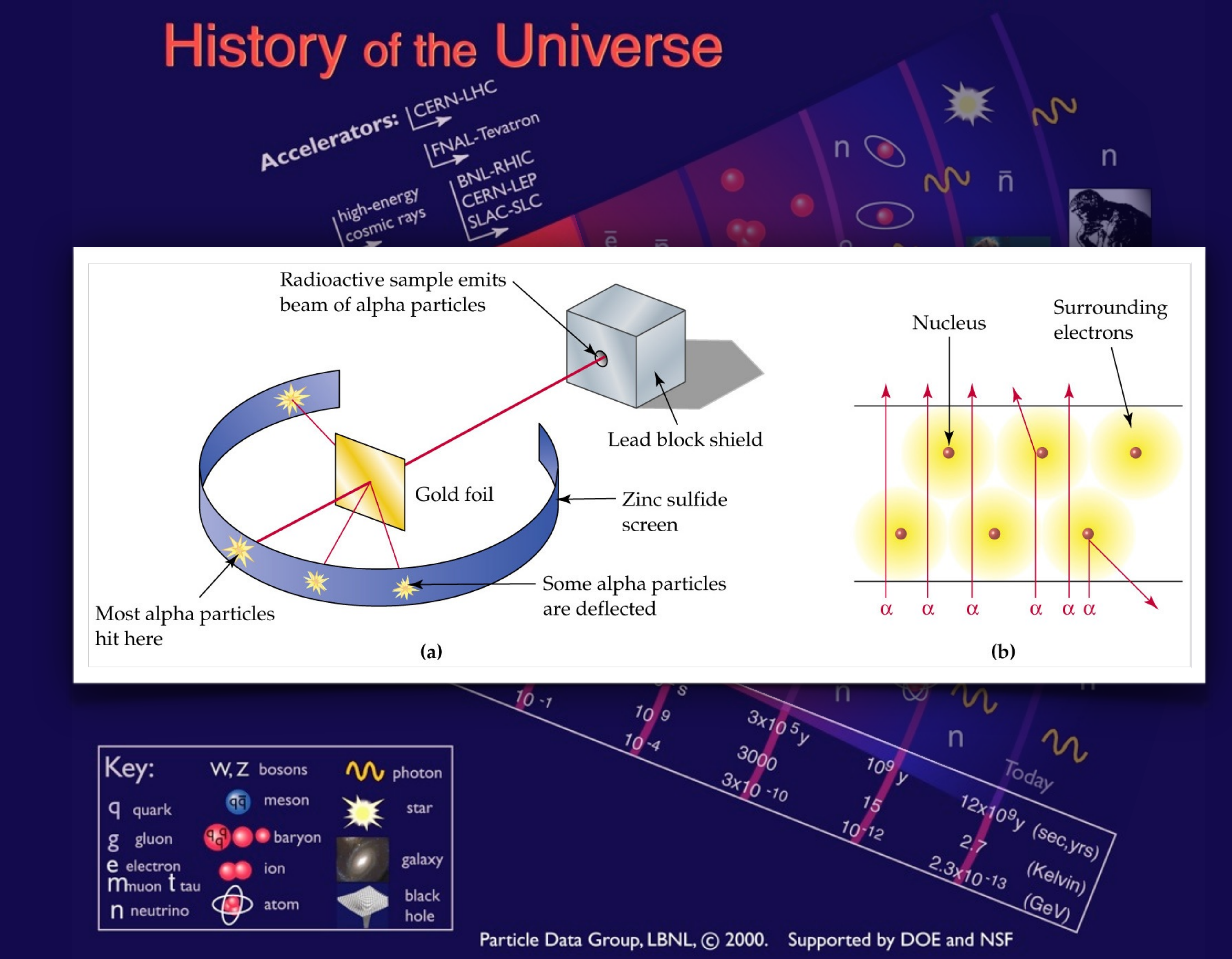
Future b-jet Measurements with sPHENIX



Michael P. McCumber
(Los Alamos National Laboratory)
for the PHENIX Collaboration

RHIC & AGS Users' Meeting
BNL, New York, USA
June 10th 2015


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
Quark-Gluon Plasma (QGP)
t 10-44 10-37 s 10-10 s 10-5 s 10 2 s 3x10 5 y 10 9 y 12x10 9 y (sec,yrs)
T 10 32 10 28 10 15 10 12 10 9 3000 15 2.7 (Kelvin)
E 10 19 10 15 10 2 10 -1 10 -4 3x10 -10 10 -12 2.3x10 -13 (GeV)
Today
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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10 -1
10 9
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3x10 5 y
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10 9 y
15
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Key:
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W, Z bosons
meson
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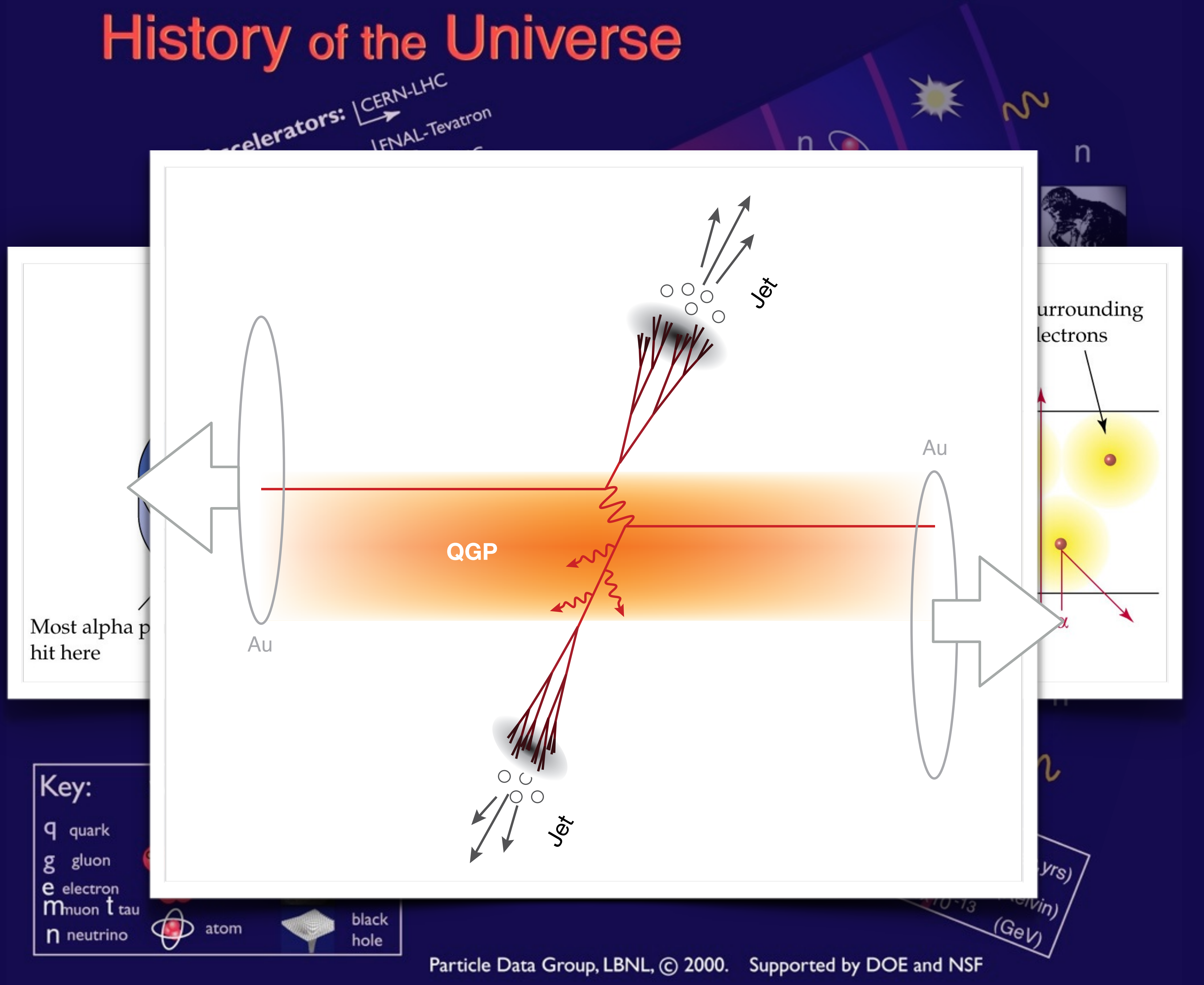
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000.
Supported by DOE and NSF
Radioactive sample emits beam of alpha particles
Lead block shield
Gold foil
Zinc sulfide screen
Some alpha particles are deflected
Most alpha particles hit here
(a)
Nucleus
Surrounding electrons
α α α α α α
(b)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CERN-LHC
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Jet
Jet
Au
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Key:
q quark
g gluon
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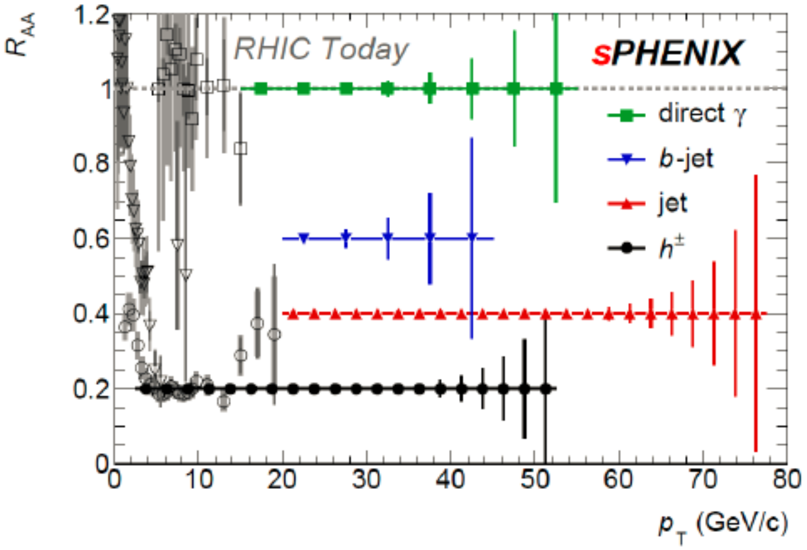
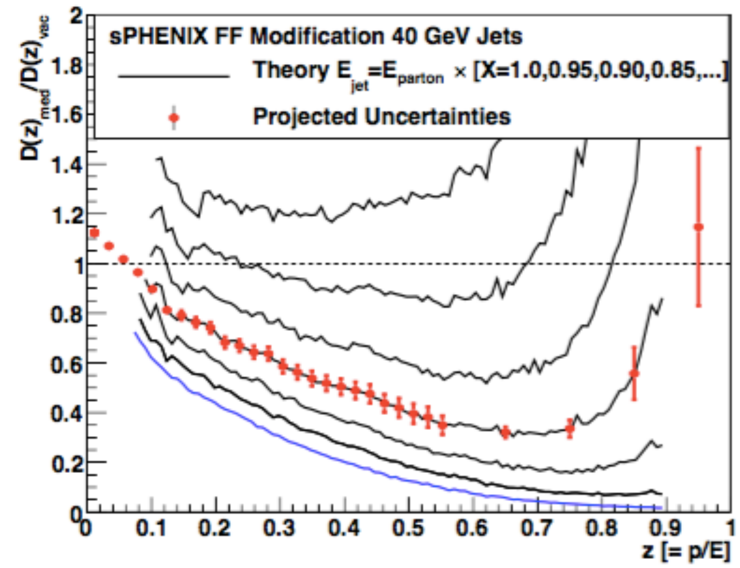
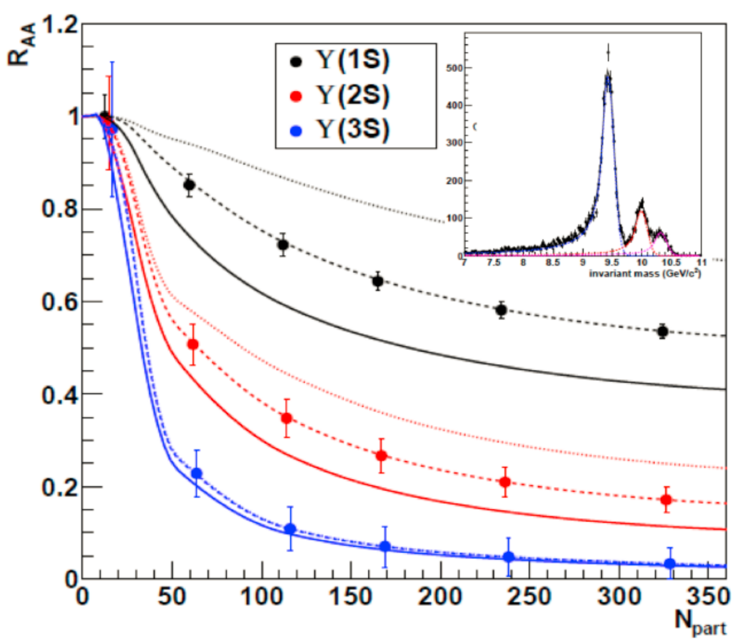
m muon t tau
n neutrino
atom
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

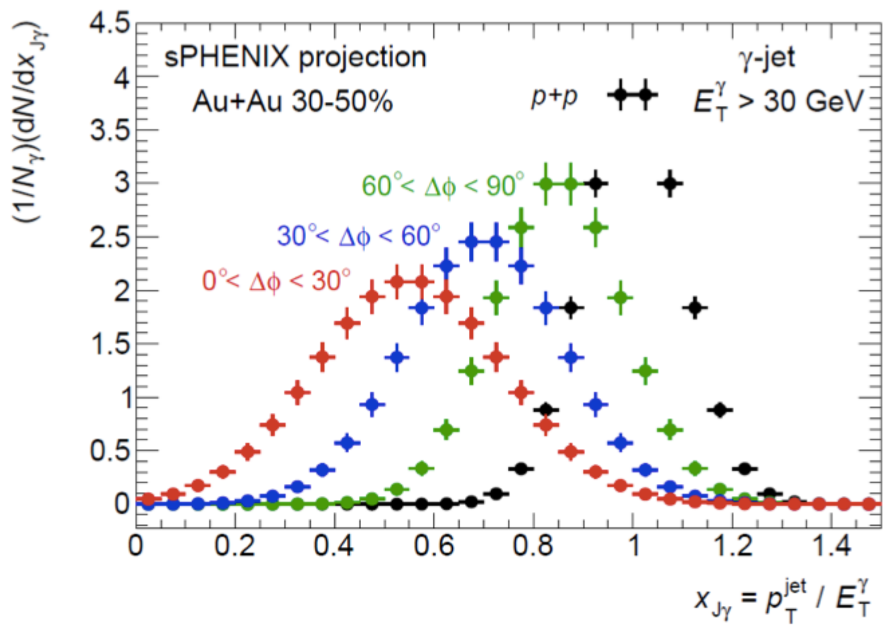
sPHENIX proposal

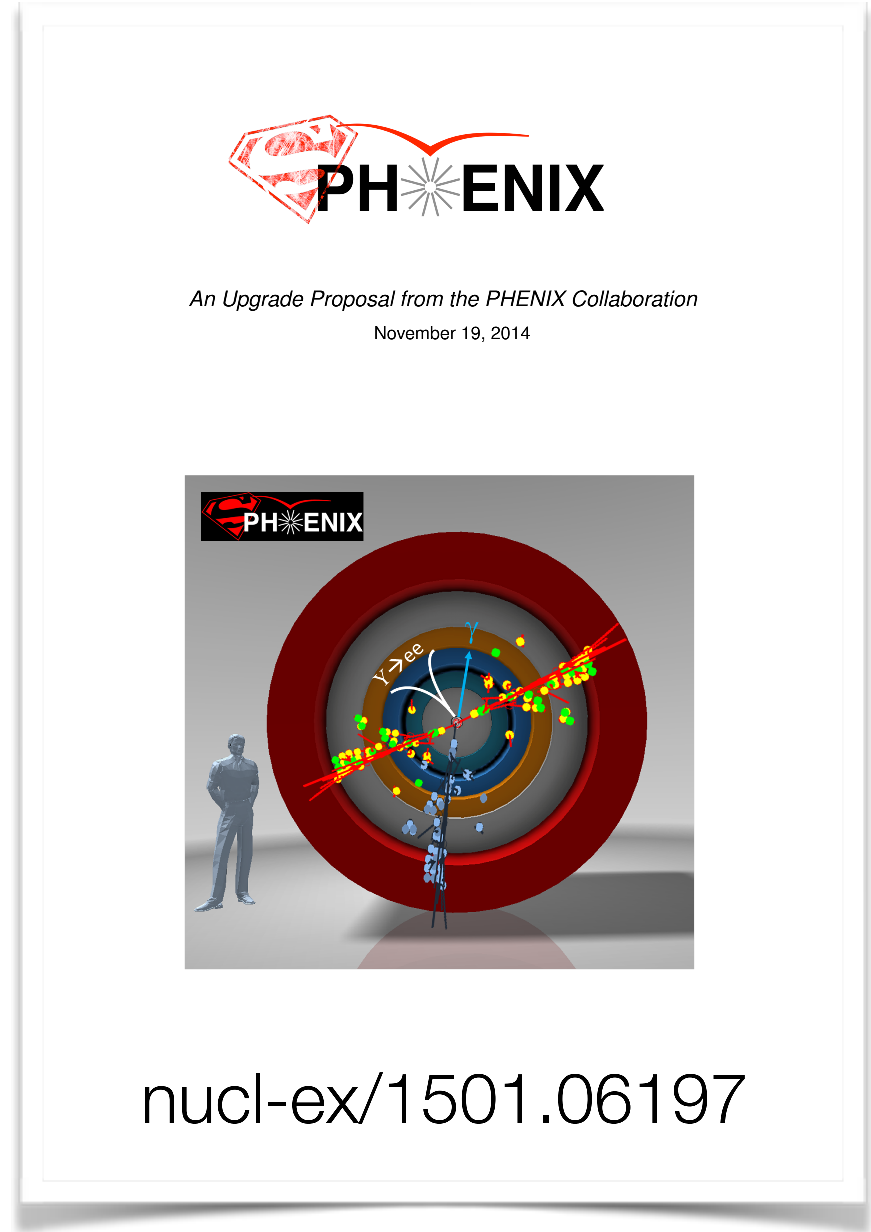
Jets and Upsilons…











Goal: study of QGP structure over a range of length scales and temperatures with **hard-scattered probes**

Additional sPHENIX topics this week:
see D. Morrison's talk: Thursday, Plenary I

Updates include:

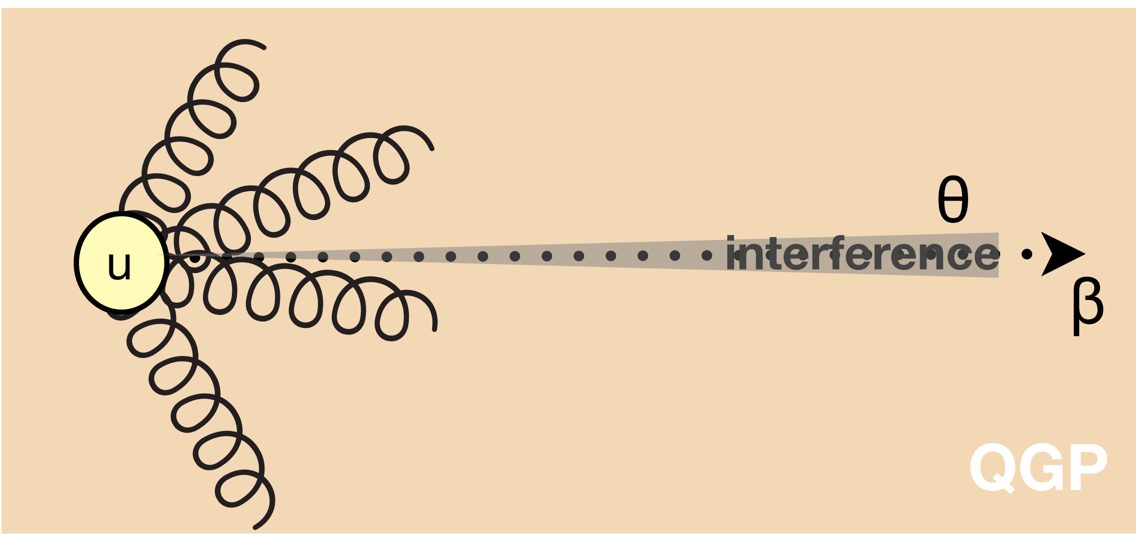
- jet trigger estimates
- **b-tagged jets**
- updated luminosity proj.
- jet+X observables
- tracking performance
- etc…

Bottom Quark Jets, b-jets

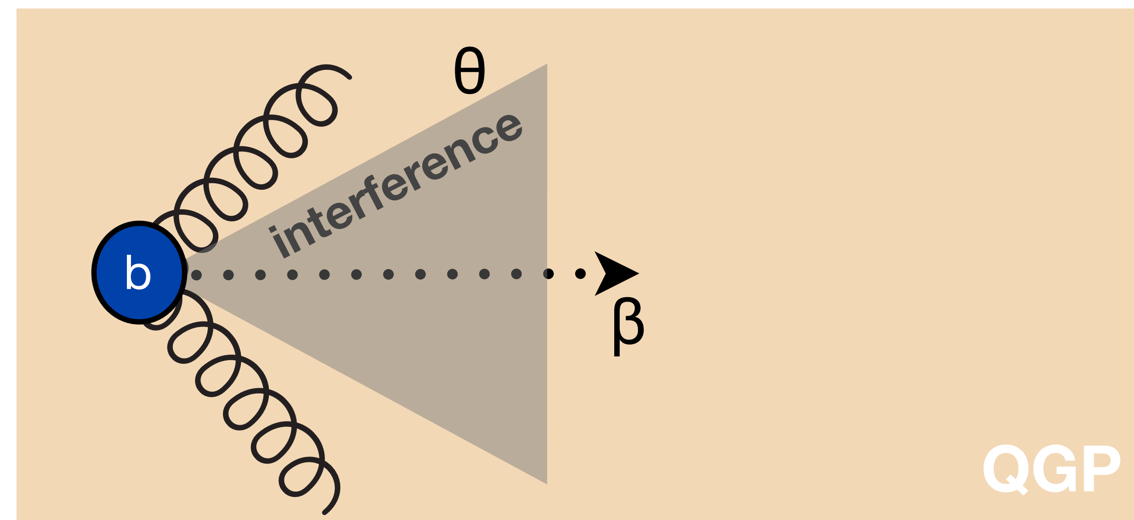
Why Bottom Quarks? They're heavy!, 4.2 GeV/c^2

- competition between **gluon radiation** and **collisional energy loss**
- **"Dead cone effect"** on gluon radiation (proposed Dokshitzer & Kharzeev, 2001)
- More sensitive to collisions with constituents within the plasma

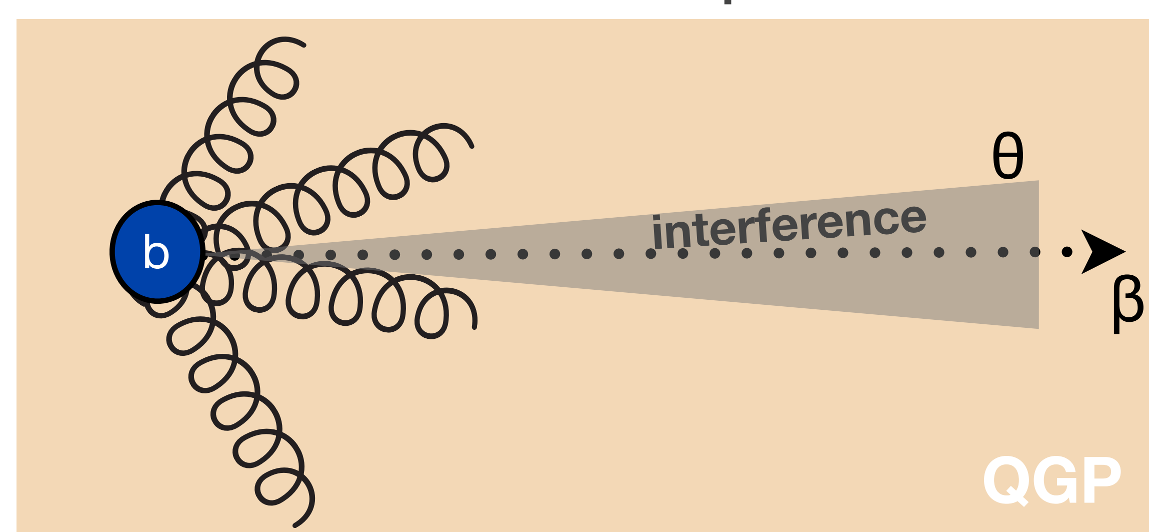
light up quark



slower bottom quarks



faster bottom quarks



mass-ordering of energy loss:
(expectation)

$$\Delta E_g > \Delta E_{u,d} > \Delta E_c > \Delta E_b$$

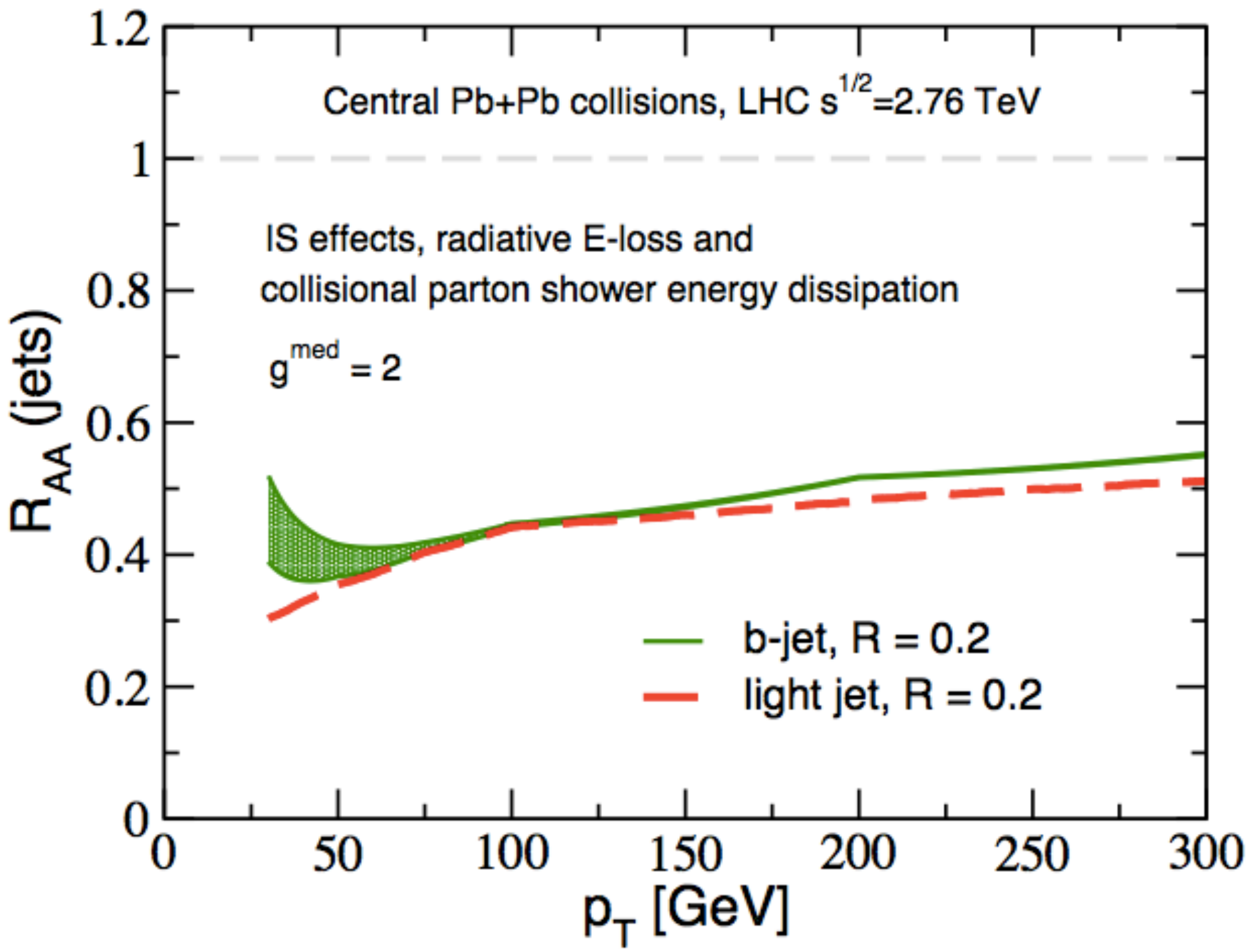
b-jets Calculations

B-jet Suppression Features:

High p_T b-jets behave very much like light jets

Low p_T jets most impacted by bottom mass

Huang, Kang, Vitev: hep-ph/1306.0909



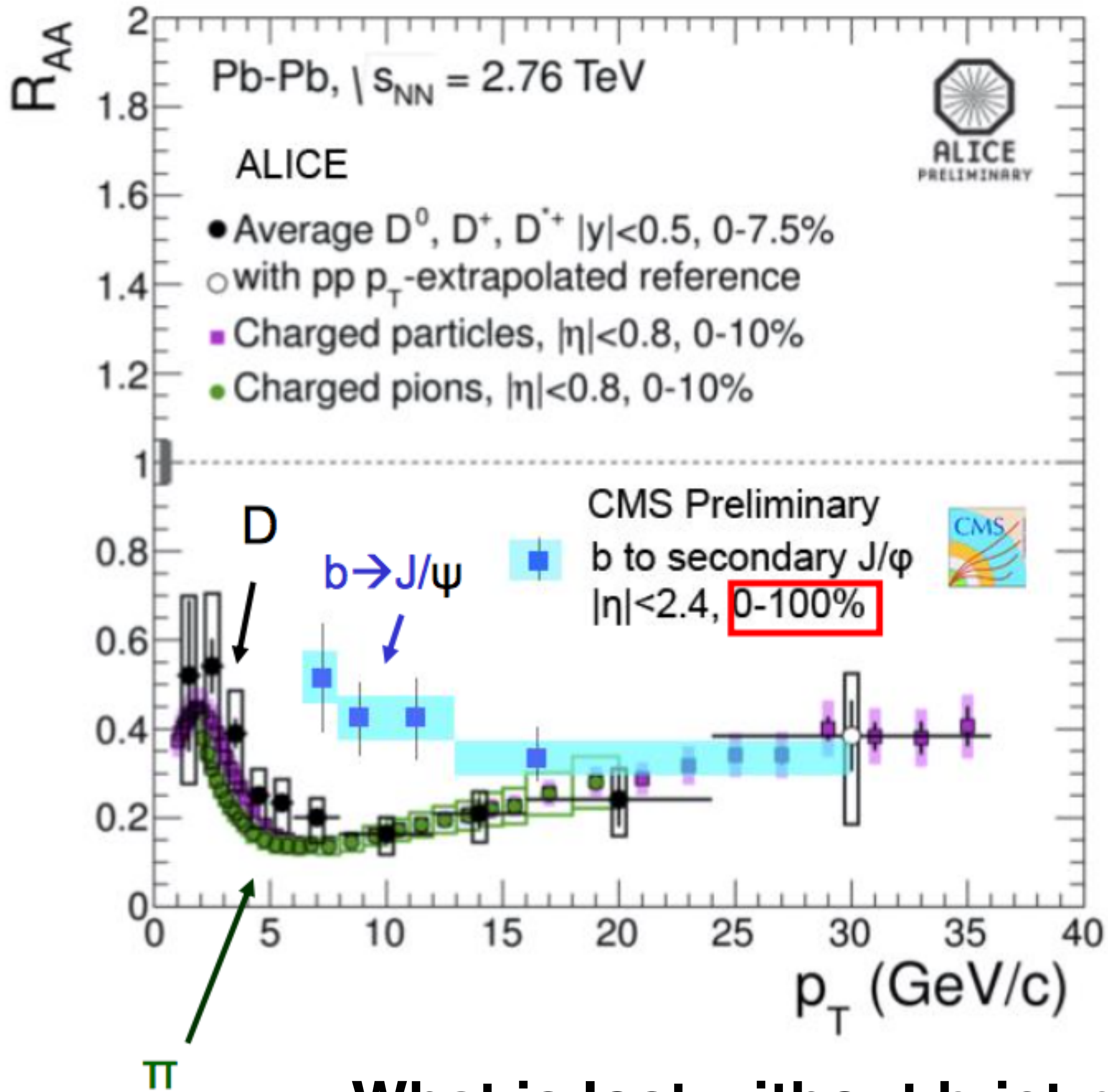
Needs from experiment:

b-jet measurements ≲ 75 GeV/c

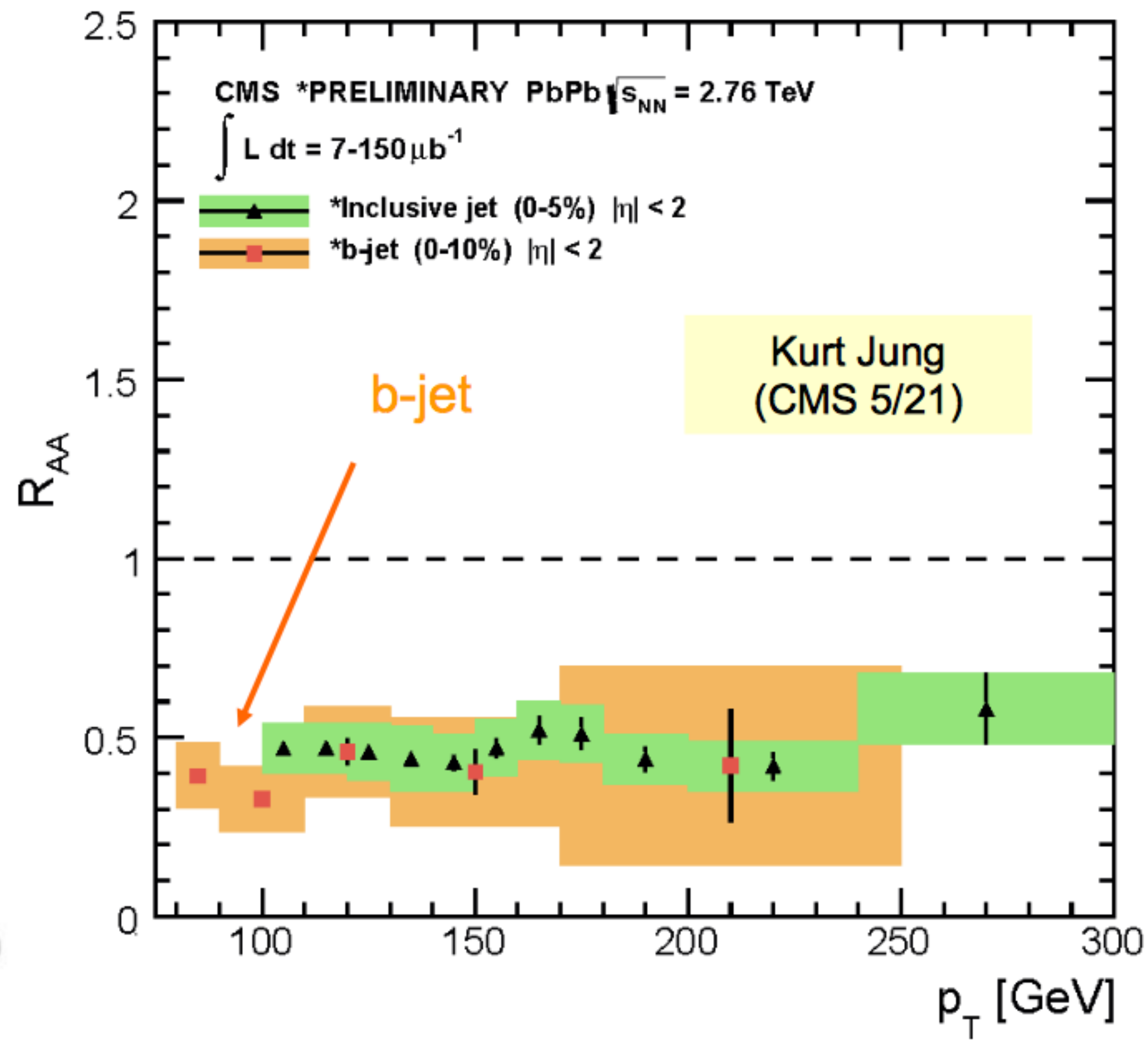
Large cone sizes preferred

LHC Bottom in Pb+Pb

smaller pT : hints of mass-ordering



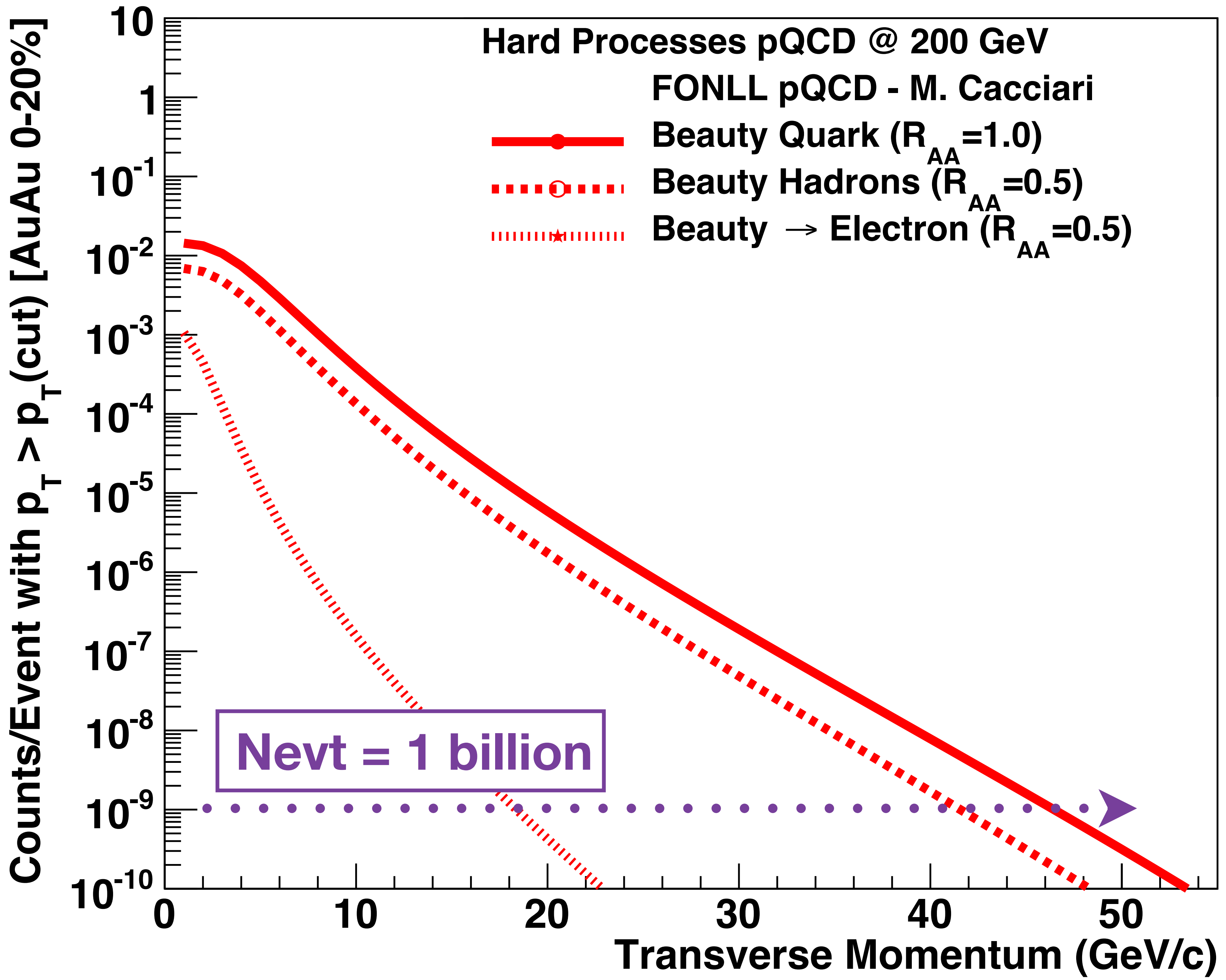
large pT : no indications



What is lost without b-jet measurements also at RHIC?

lowest b-jet momentum jets (~10 GeV/c), different part of QGP evolution
uncertainty on energy loss description
broad impact on understanding light quark and gluon jet measurements

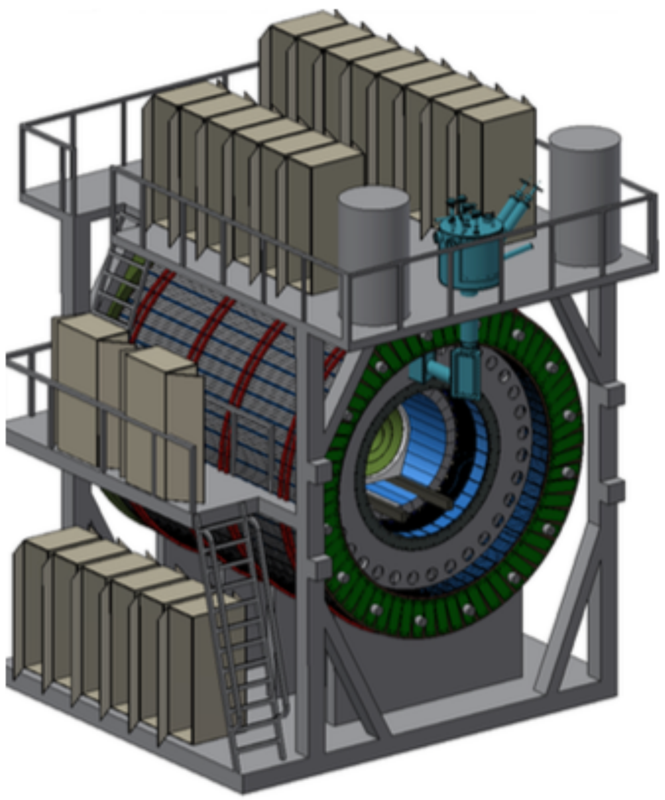
Bottom Jet Rates at RHIC

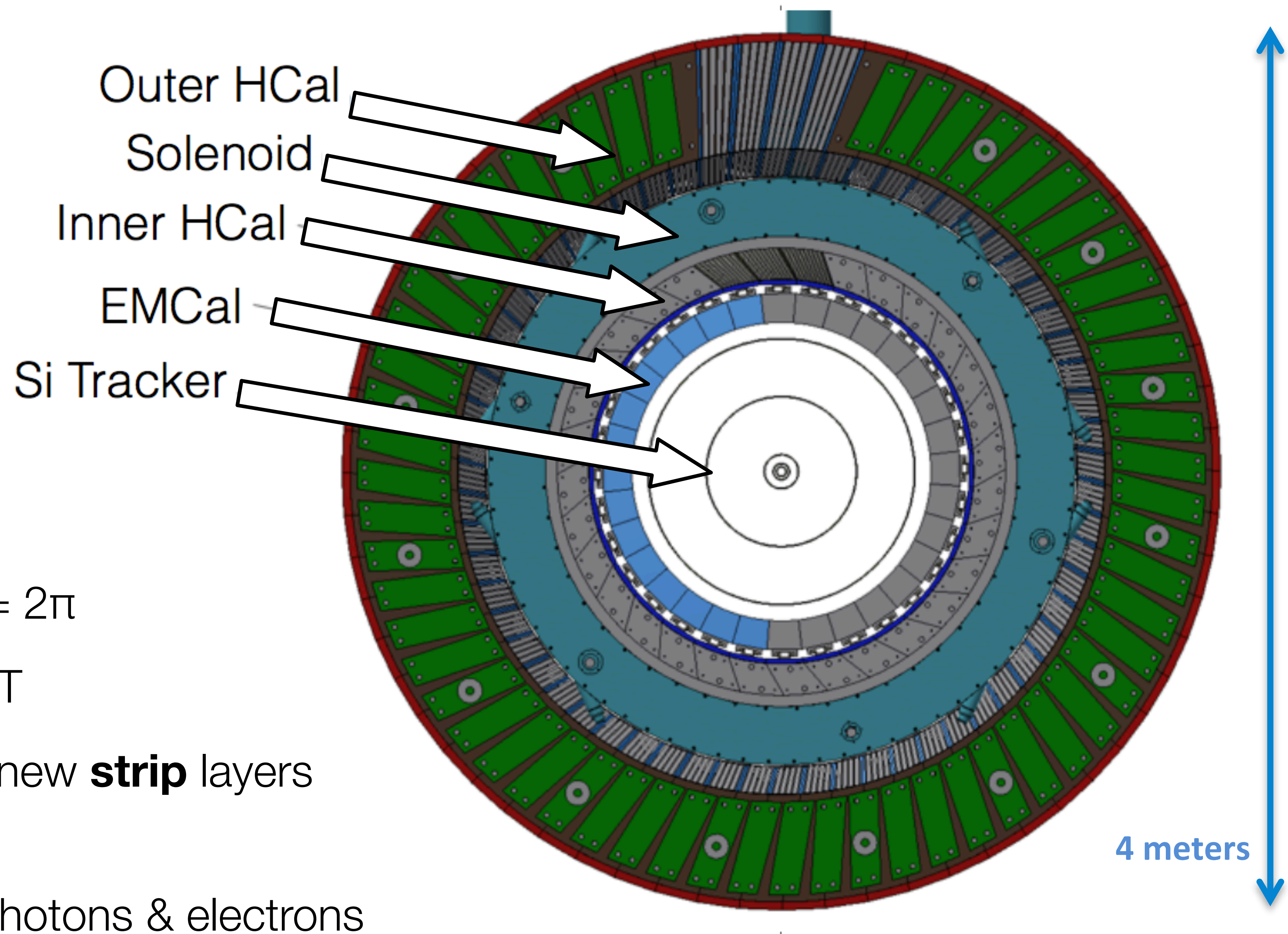


C-AD projections: **0.1 trillion MB** Au+Au events with |z| < 10 cm

Large b-jet samples with a suitable high rate detector!

sPHENIX Detector Design





Conceptual Design:

- $-1.1 < \eta < +1.1$, $\Delta\phi = 2\pi$
- **BaBar magnet**, 1.5 T
- reconfigured **pixel** + new **strip** layers for charged particles
- **EMCal** to measure photons & electrons
- **Inner+Outer HCal** to complete jet measurement
- High rate DAQ, 15 kHz

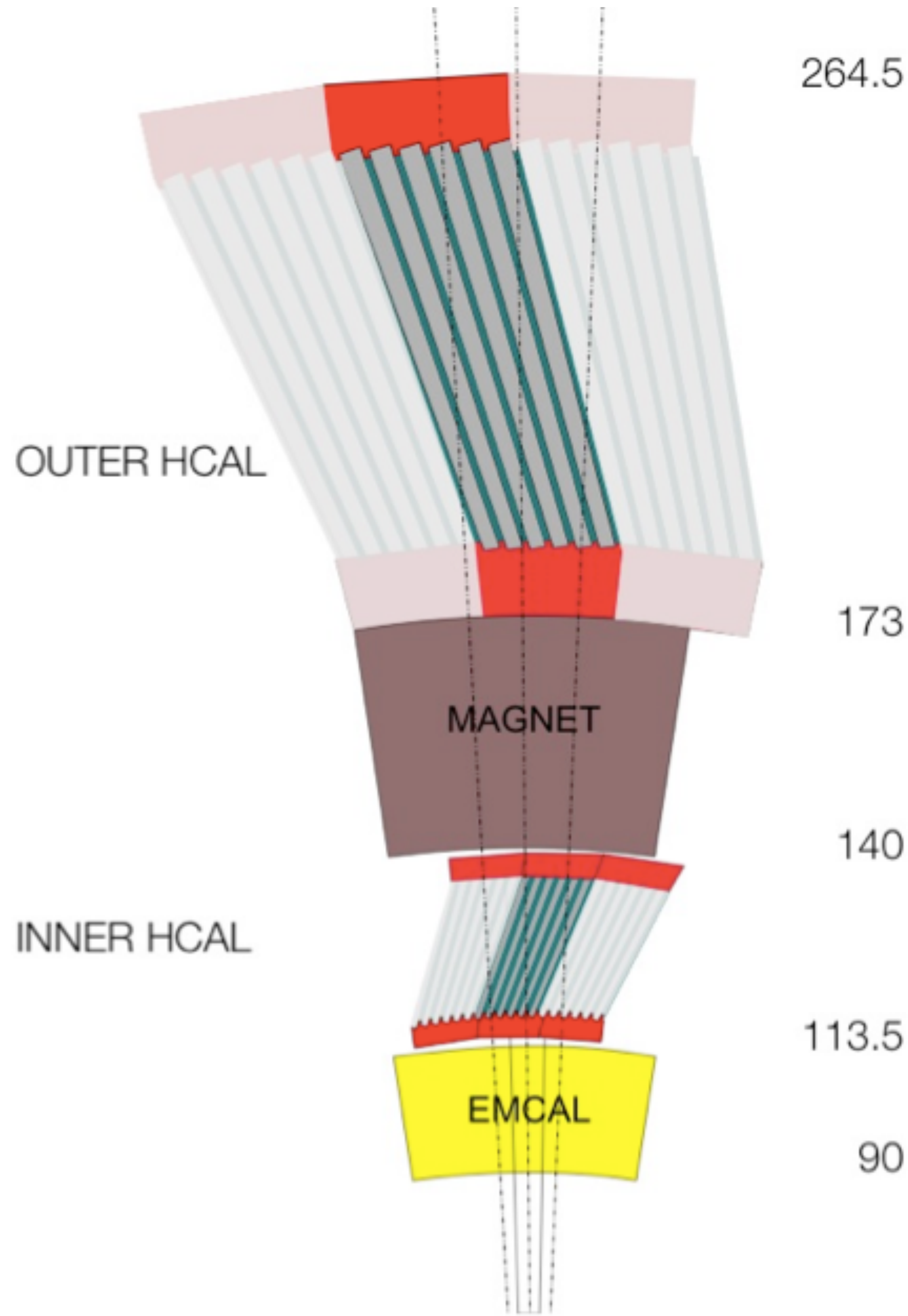
sPHENIX Calorimeters

Total = 6λ

- 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.

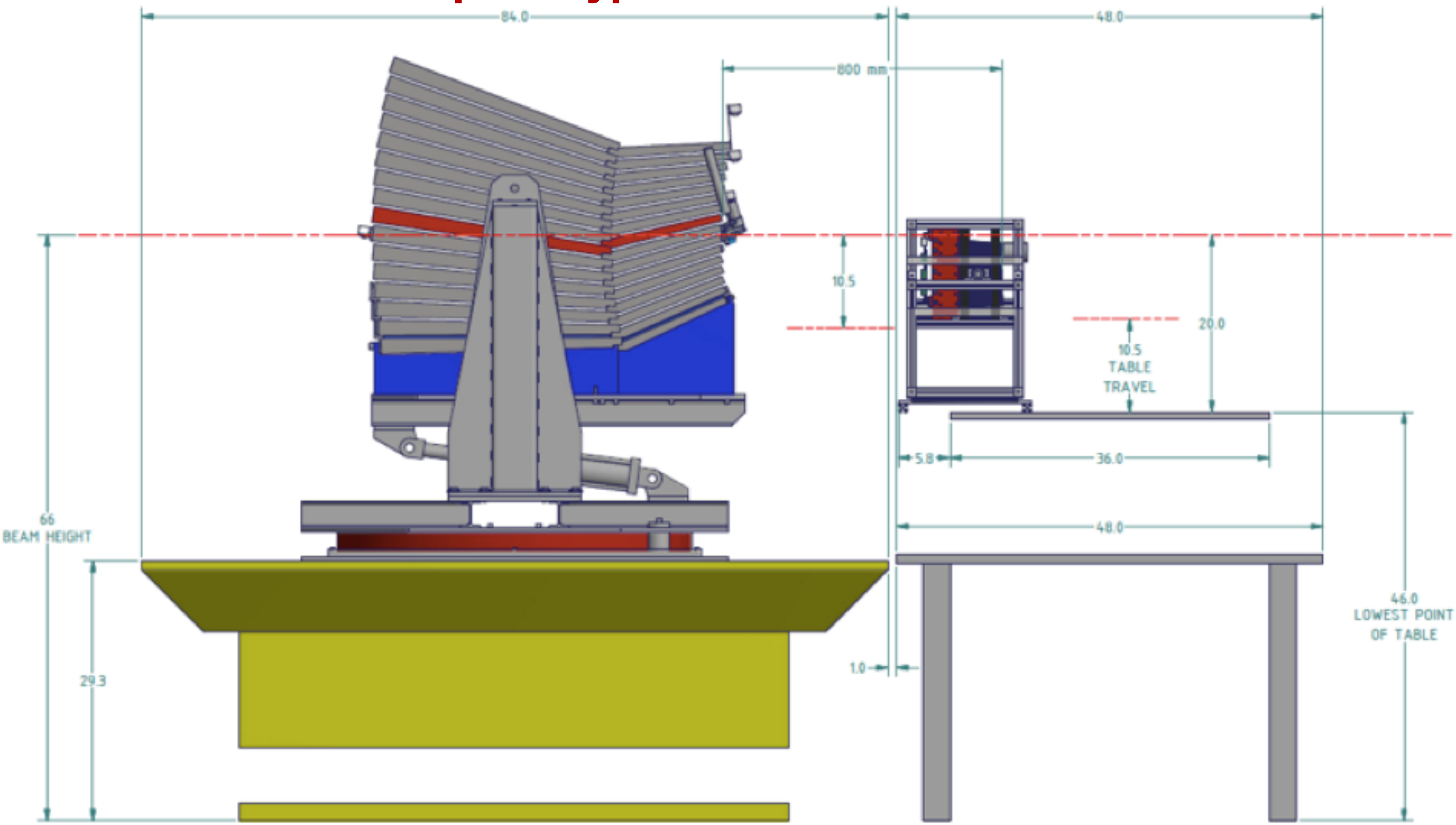
Key difference with calorimeters for much higher energy jets.



p+p jet energy resolution ~ 65% / sqrt(E)

FNAL Test Beam Exp T-1044

HCAL prototype



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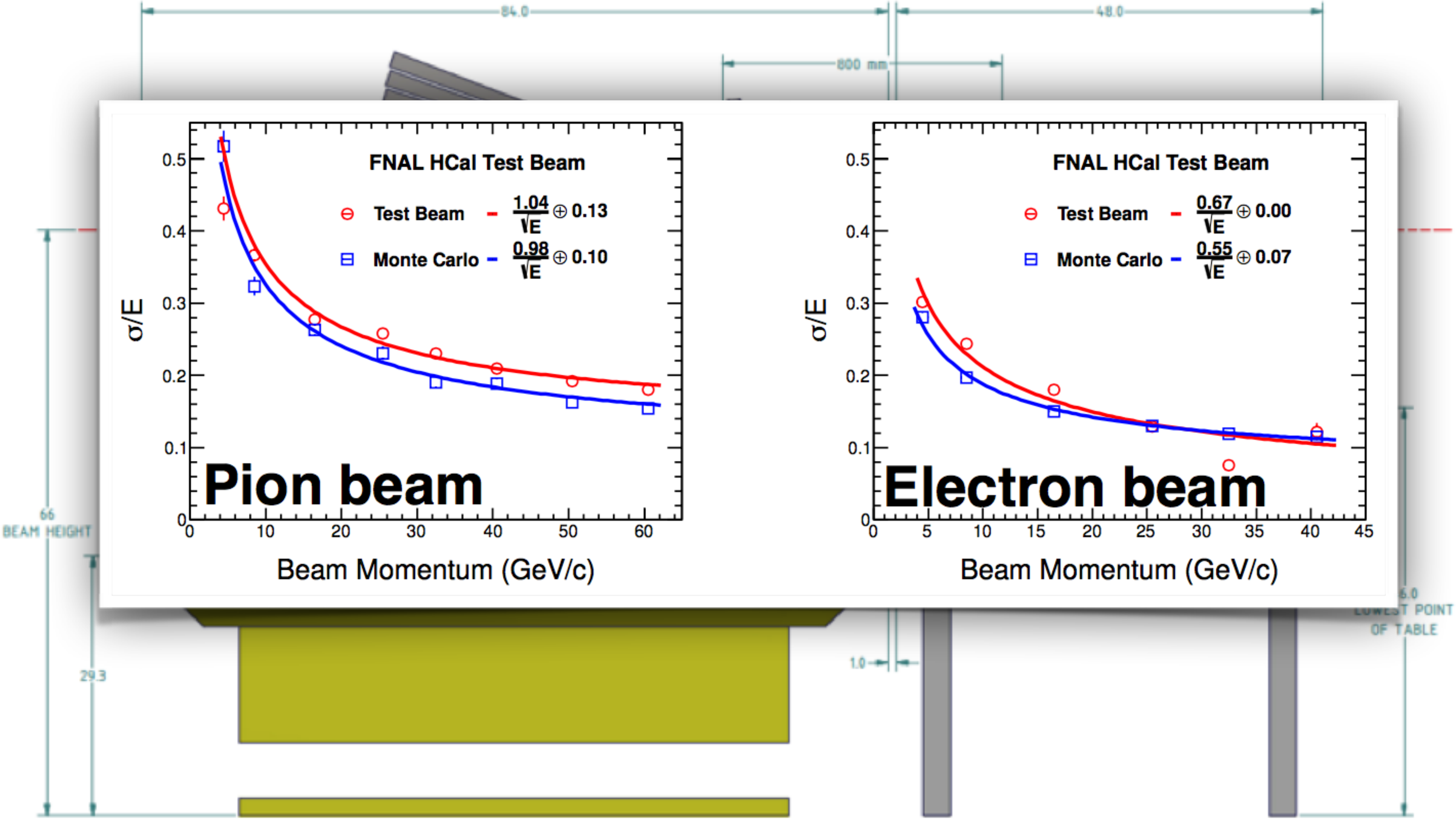
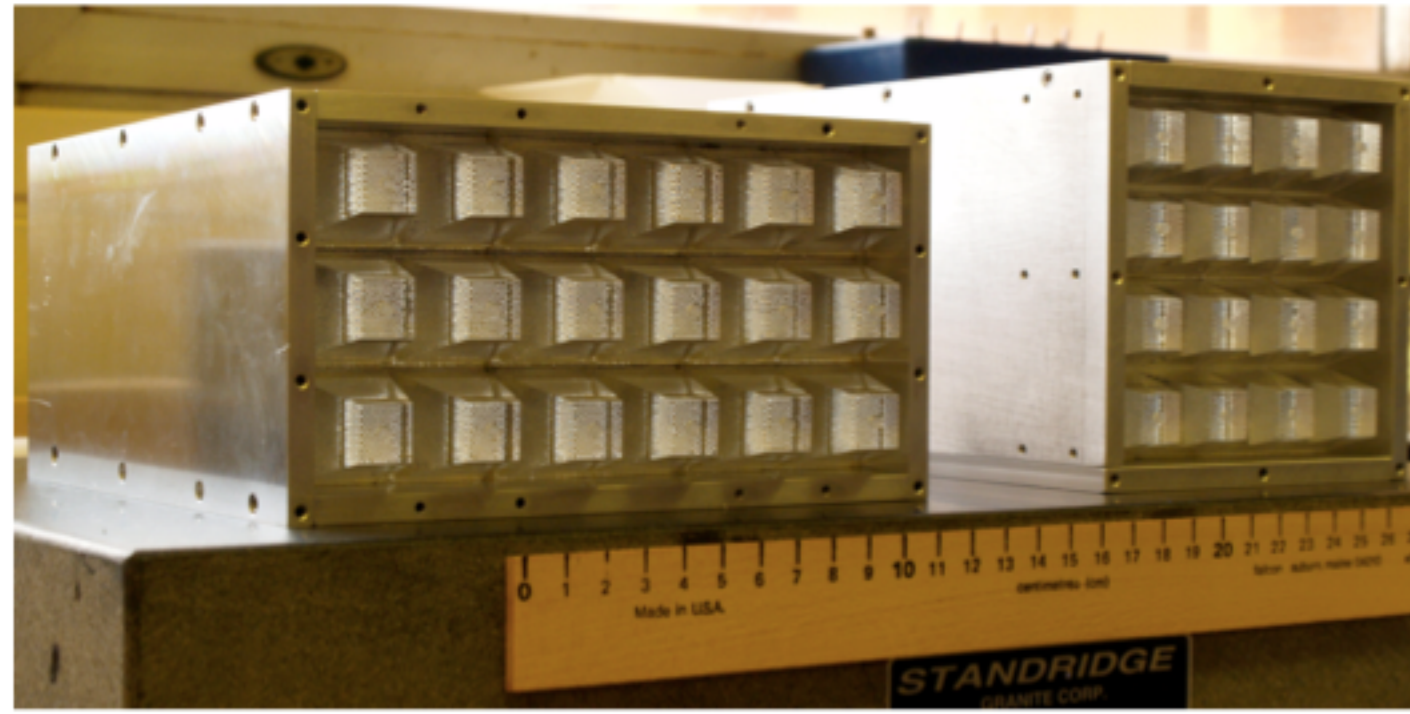
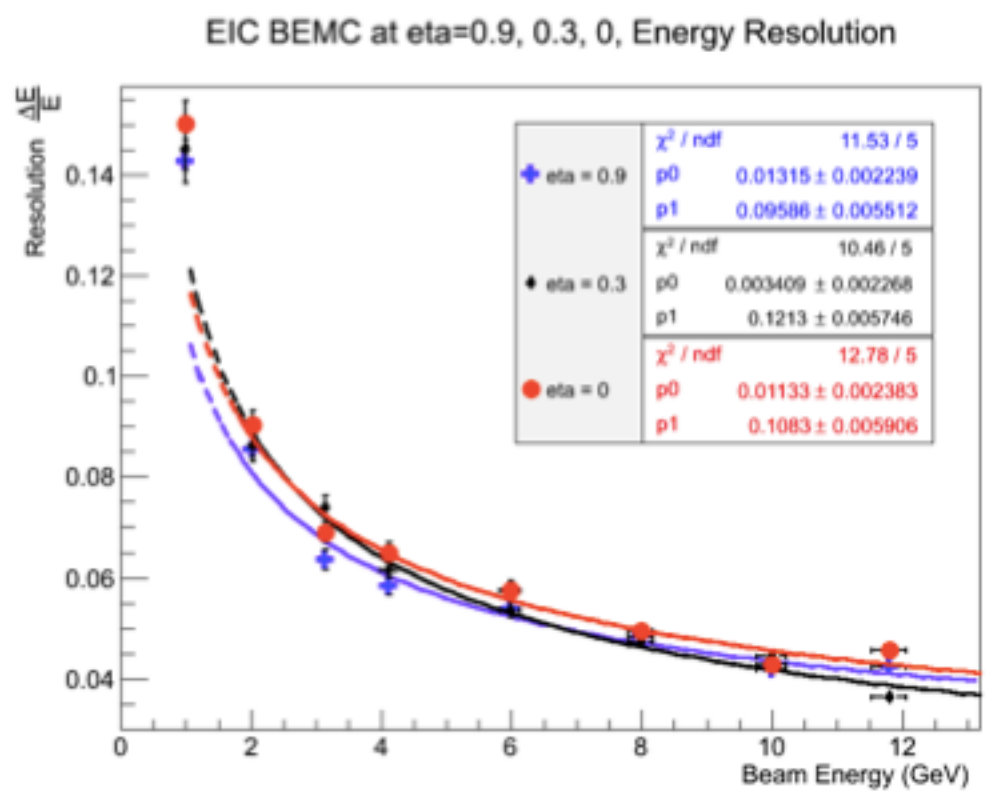


EMCAL SPACAL Design

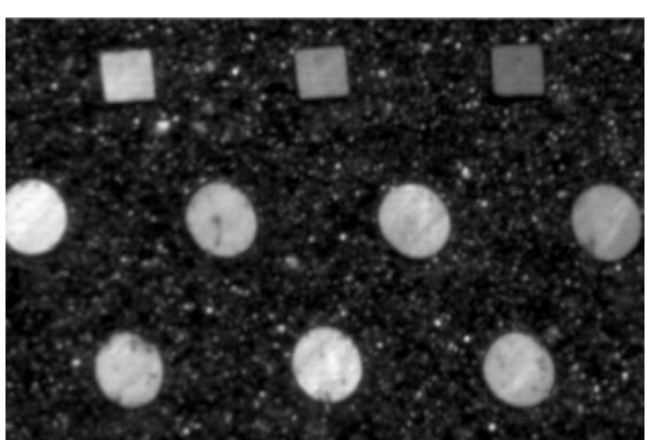
- 18 X_0 deep
- 2.3 cm R_M ≈ cell size
- 256x96 = 24,576 channels
- Sampling fraction ≈ 2%
- Resolution ≈ 12%/√E
- ≈ 500 pe/GeV



SPACAL prototypes (Tsai)

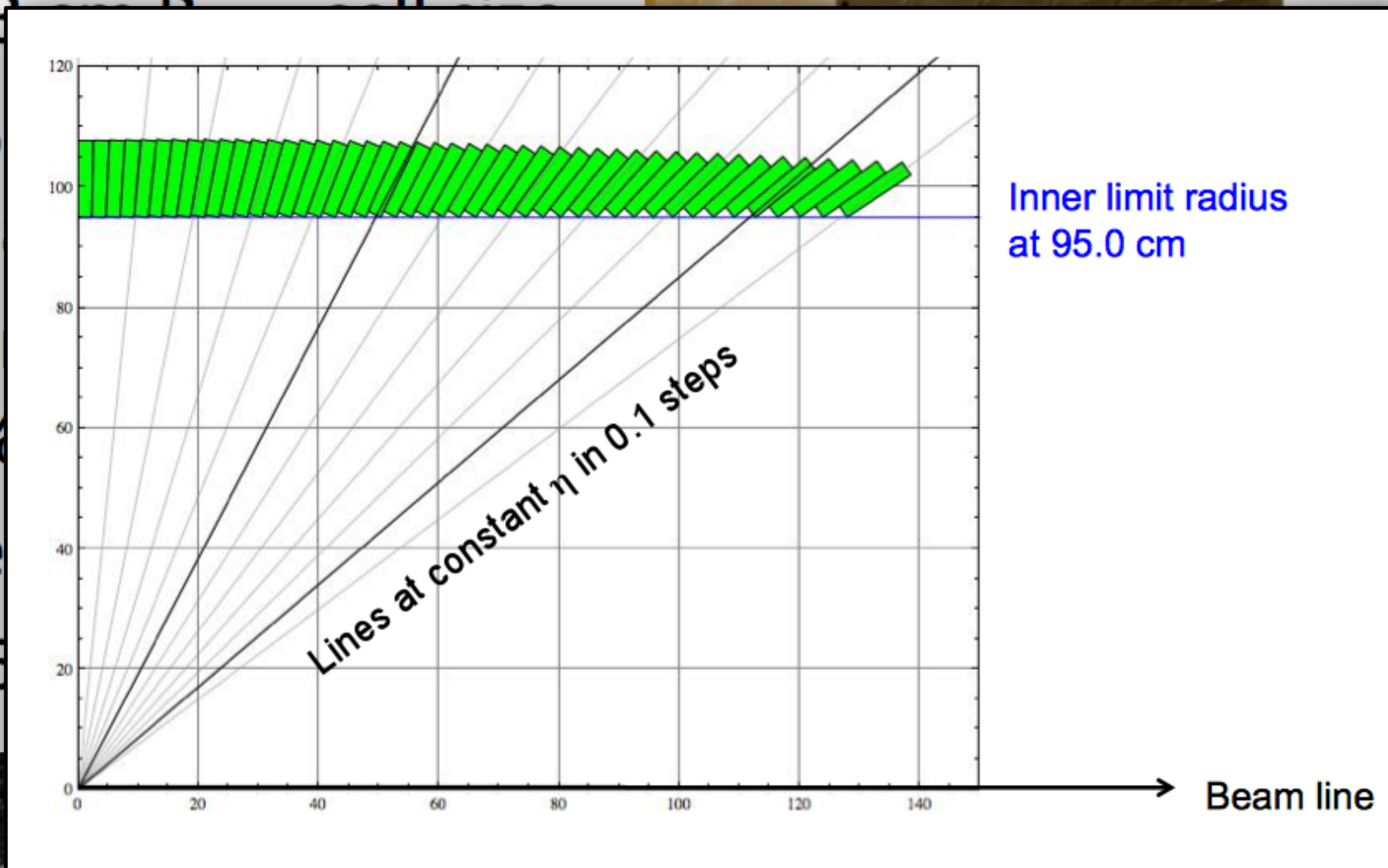


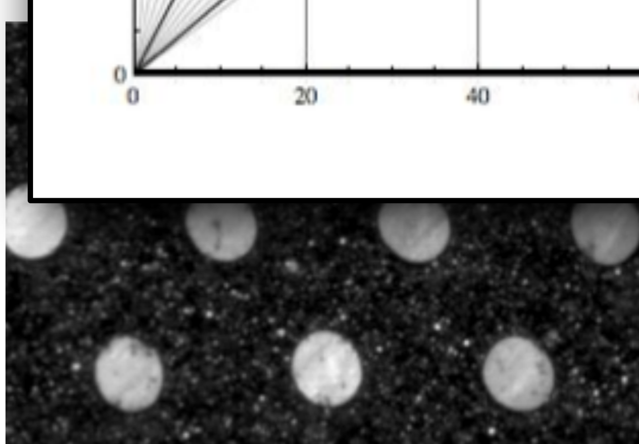
FNAL T-1018 results



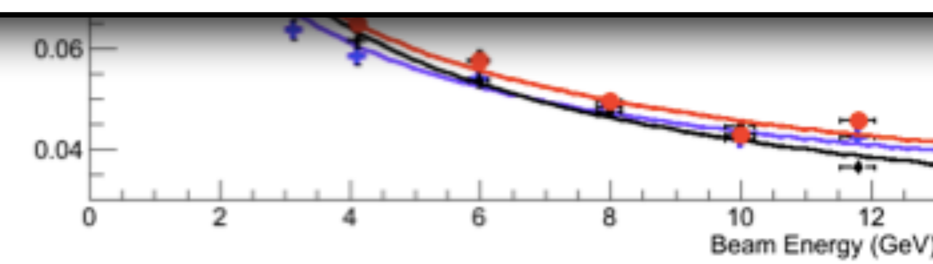
EMCAL SPACAL Design

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

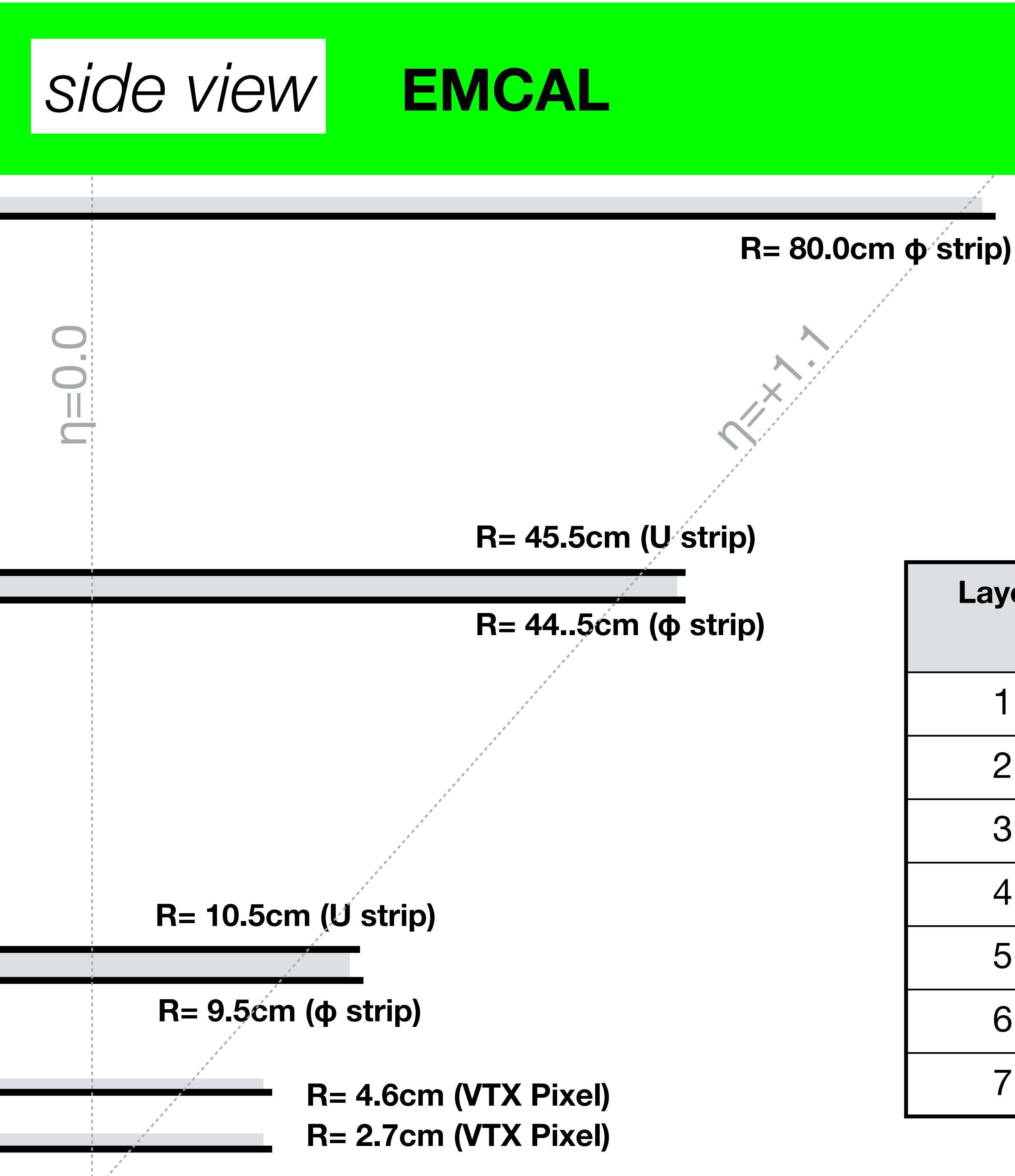




AL T-1018
results



Silicon Tracking Layers



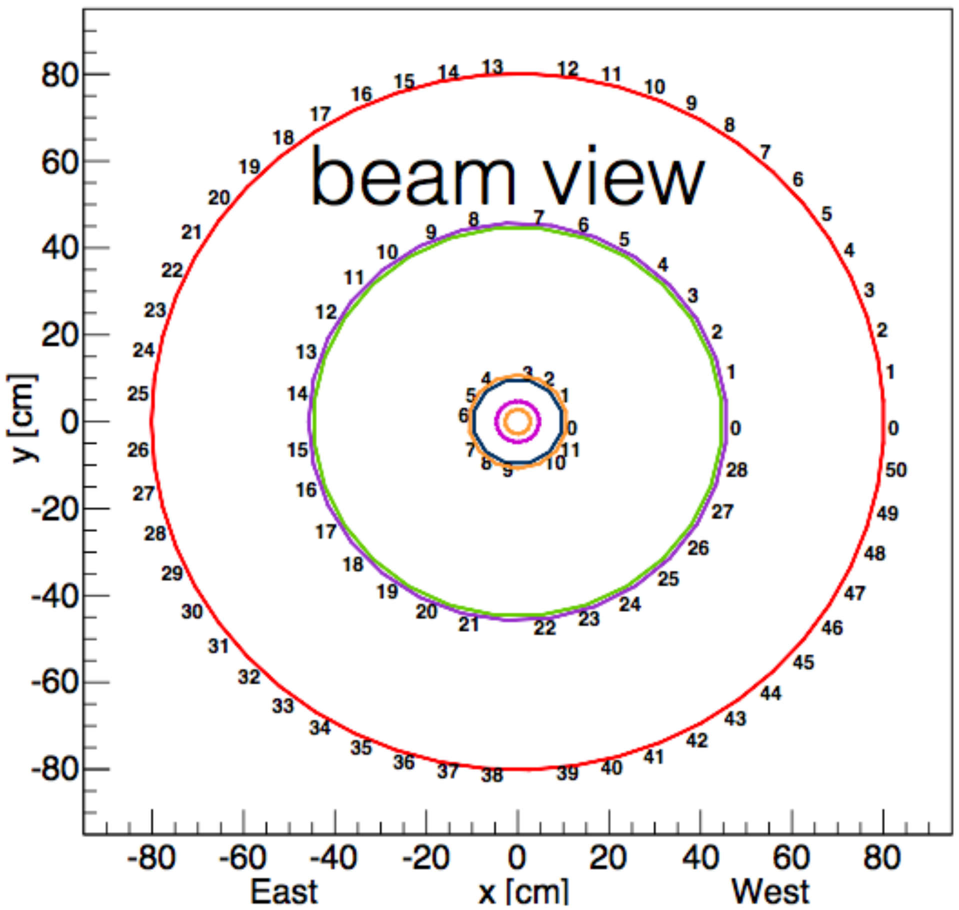
sPHENIX conceptual design

Extended radial reach for **improved resolution**

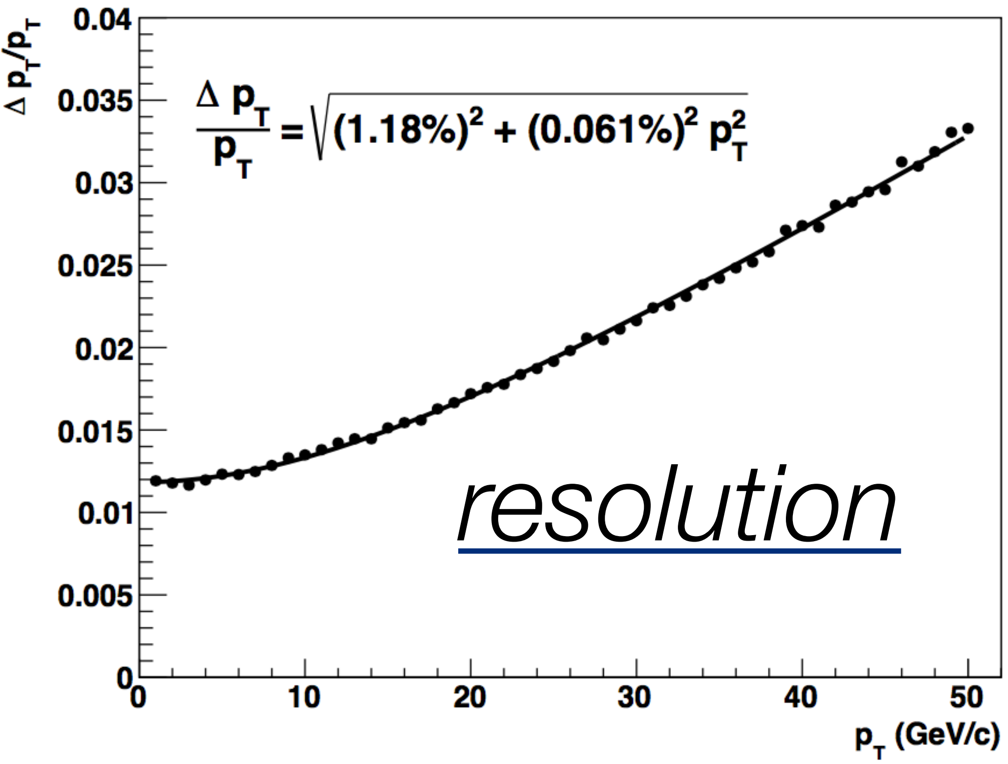
Outer layers minimize **material budget**

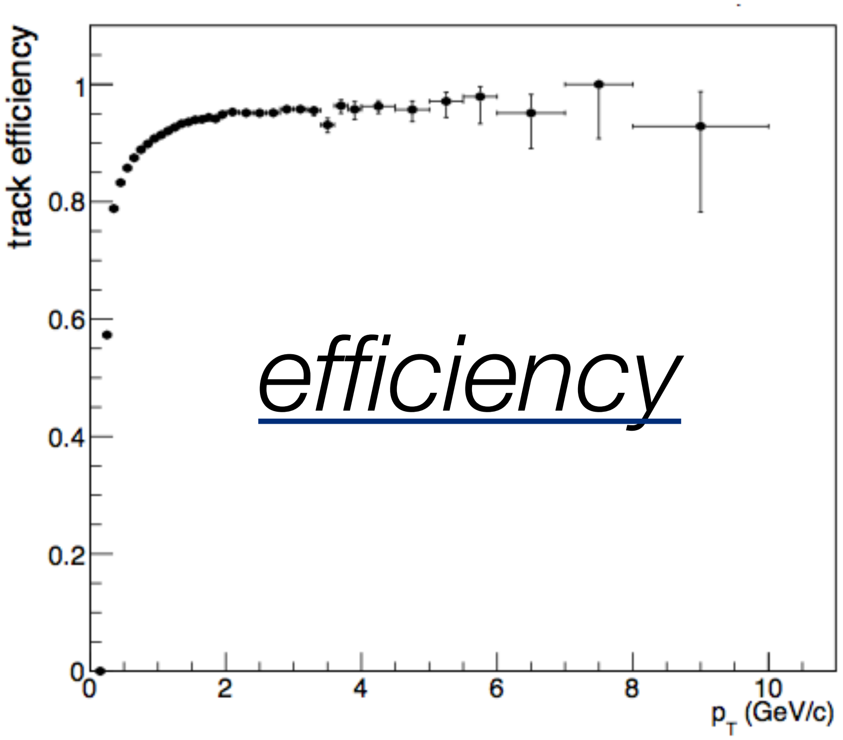
Layer	ϕ pitch (um)	z pitch (mm)	Thickness (%)
1	50	0.425	1.3
2	50	0.425	1.3
3	60	8	2.7
4	*240*	*2*	
5	60	8	2.0
6	*240*	*2*	
7	60	8	2.0

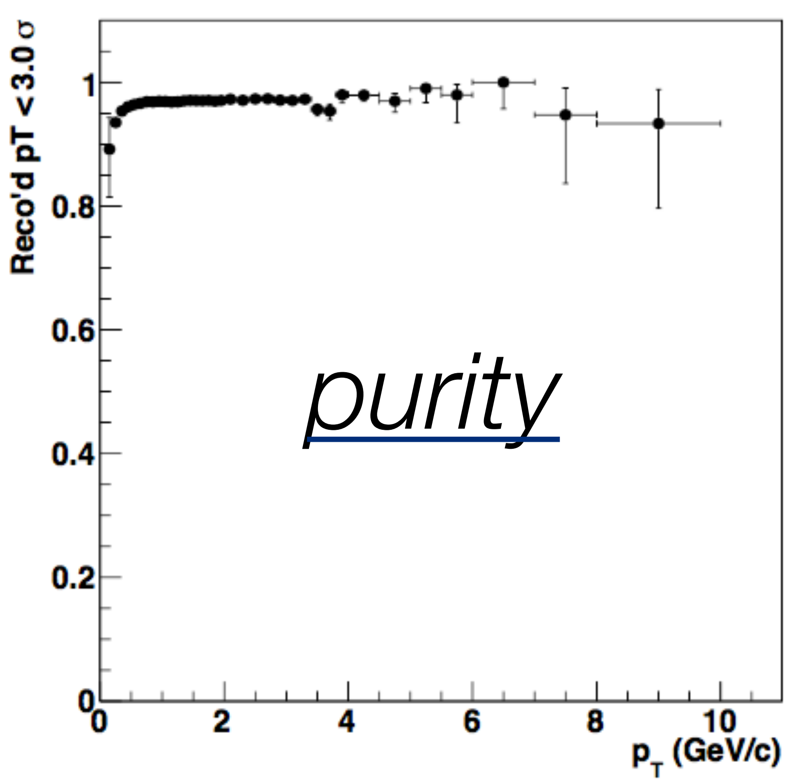
Tracking Performance Target



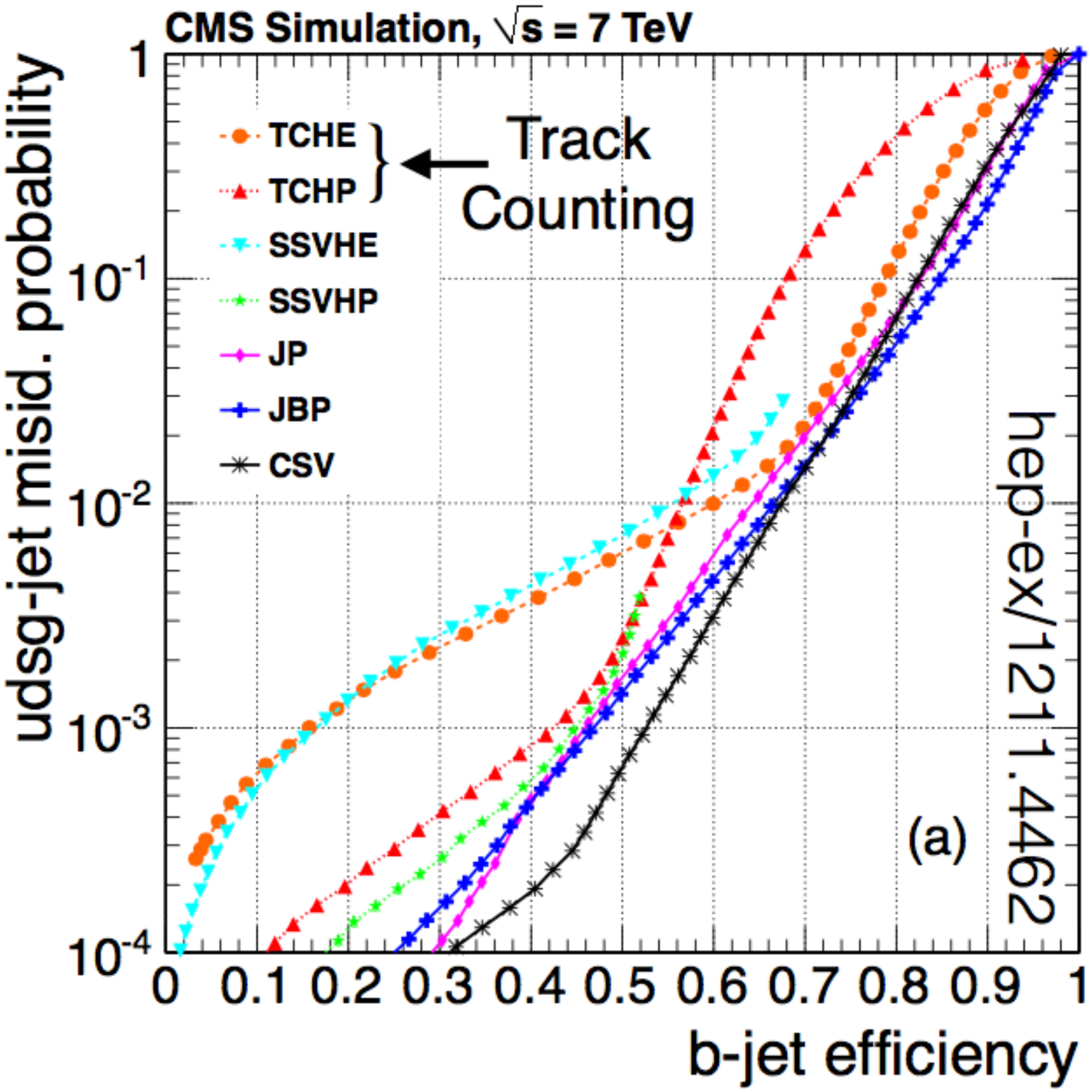
- performance estimates from GEANT4
- optimized to give Upsilon mass resolution of < 100 MeV/c²
- robust behavior in high multiplicity environments (central Au+Au)







Bottom Jet Tagging Overview



Experimental b-jet tagging relatively new to heavy ions

- adapting techniques from HEP

b-jet tagging relies on B hadron properties:

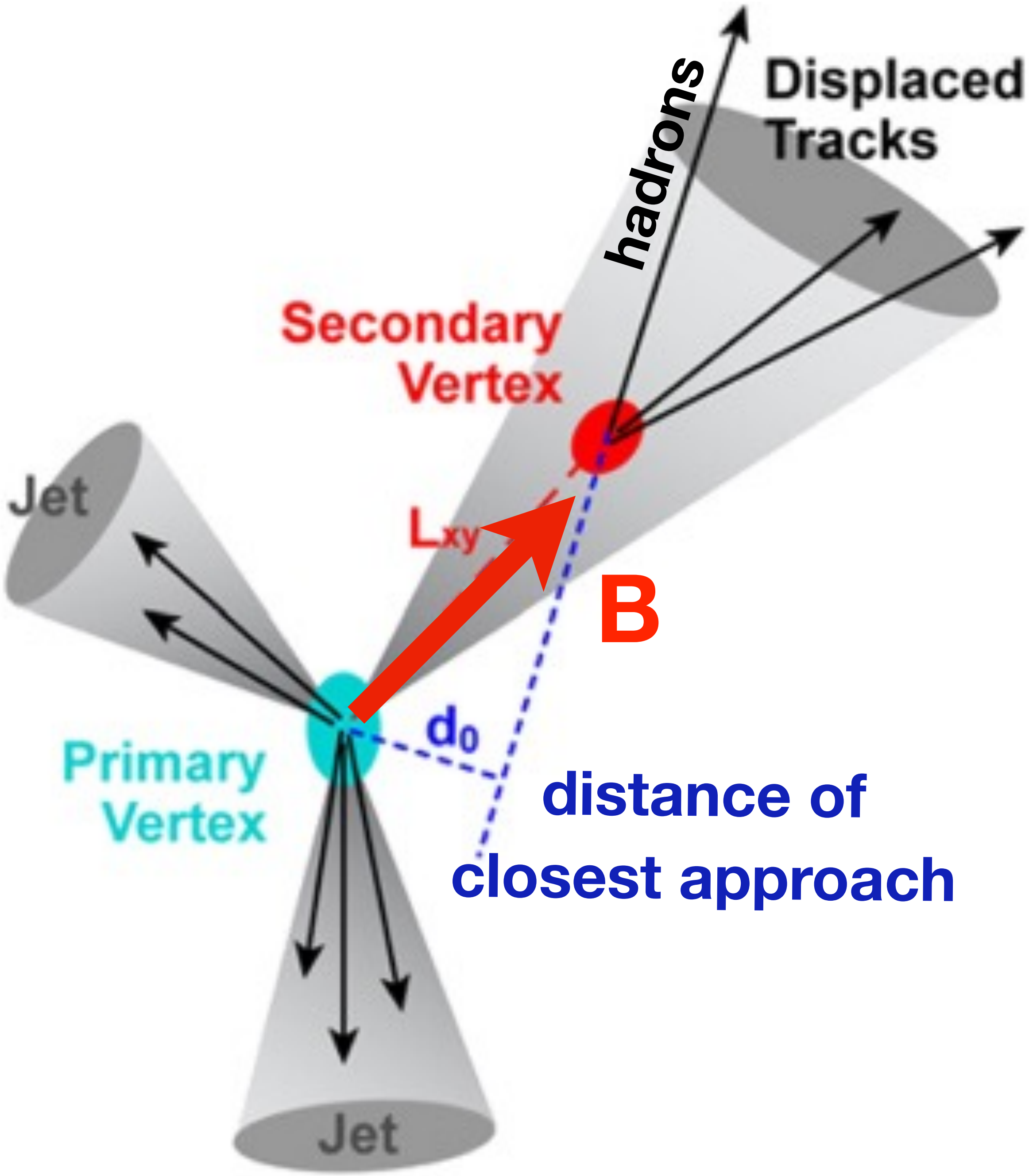
- long lifetimes
- displaced, high mass vertex
- large decay multiplicities

Modern algorithms employ multiple handles

Differing remaining contamination from charm

Common Feature: trade-off between **b-jet purity** and **b-jet efficiency**

Bottom Quark Jet Identification



Goal: reject light jets,
keep b-jets with high efficiency

"TrackCounting" algorithm
(e.g. ATLAS-CONF-2010-091):

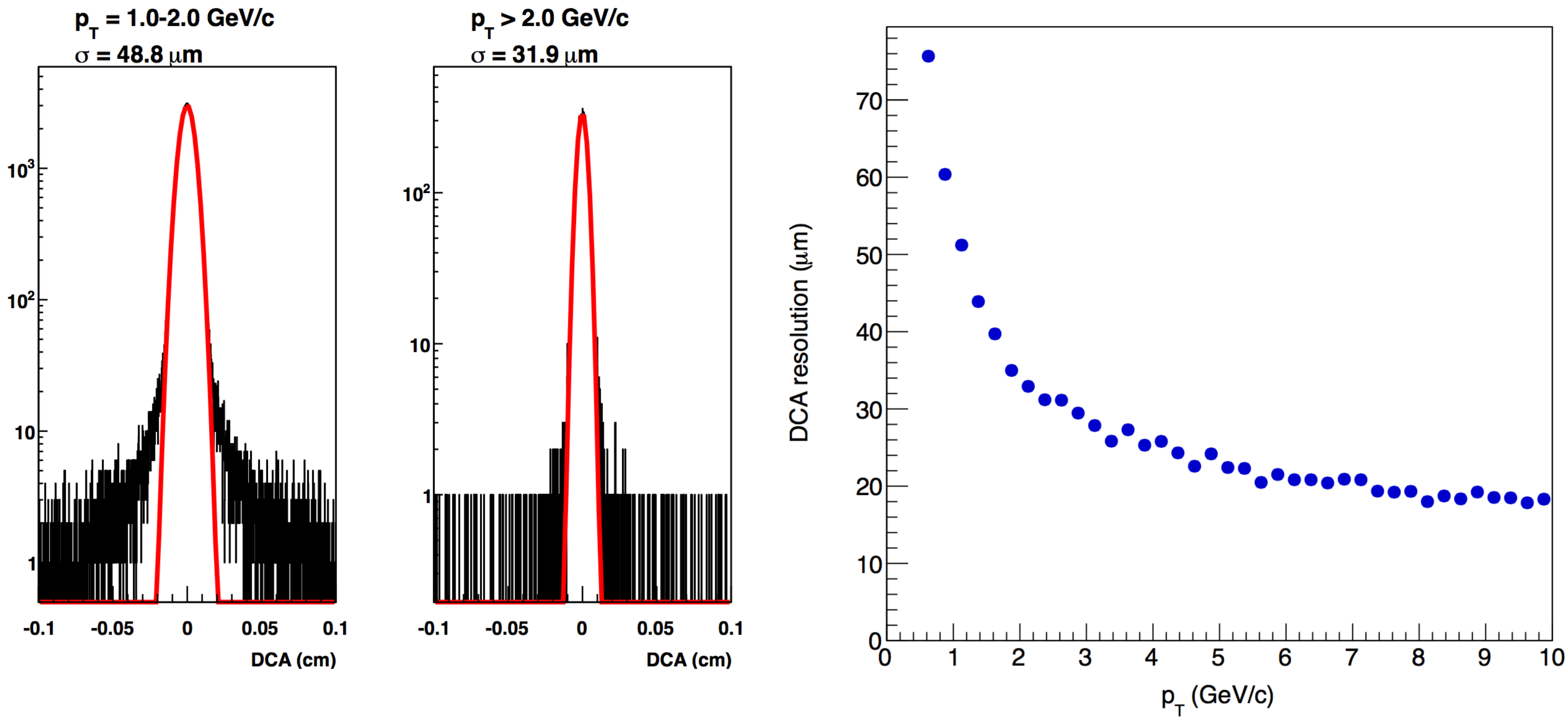
requires one or more tracks with a **non-zero DCA with respect to the primary vertex**

depends on the tracking performance

Other methods: secondary vertex reconstruction are promising, but we've started with this straight-forward approach

DCA Resolutions

Charged hadron distance-of-closest approach (DCA) in central Au+Au events



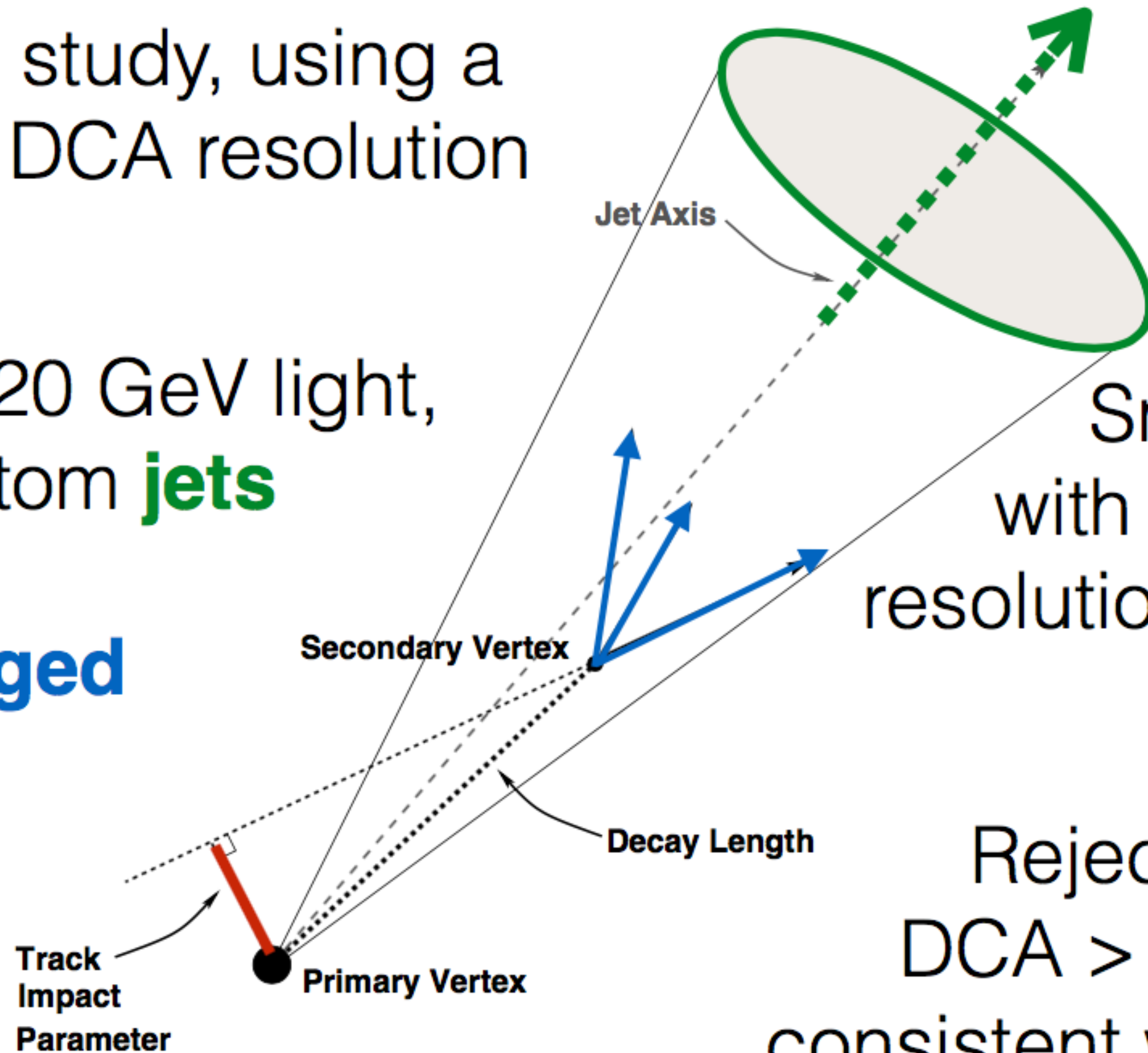
- cτ for D decay: 123 μm, for **B decay: 457 μm**
- Good 2D DCA resolution a design requirement for b-jet identification

TrackCounting Algorithm

Fast simulation study, using a parameterized DCA resolution

Generate $p_T > 20$ GeV light, charm and bottom **jets**

Consider **charged hadrons** with $p_T > 0.5$ GeV in the **jet** cone



Calculate true signed **DCA**

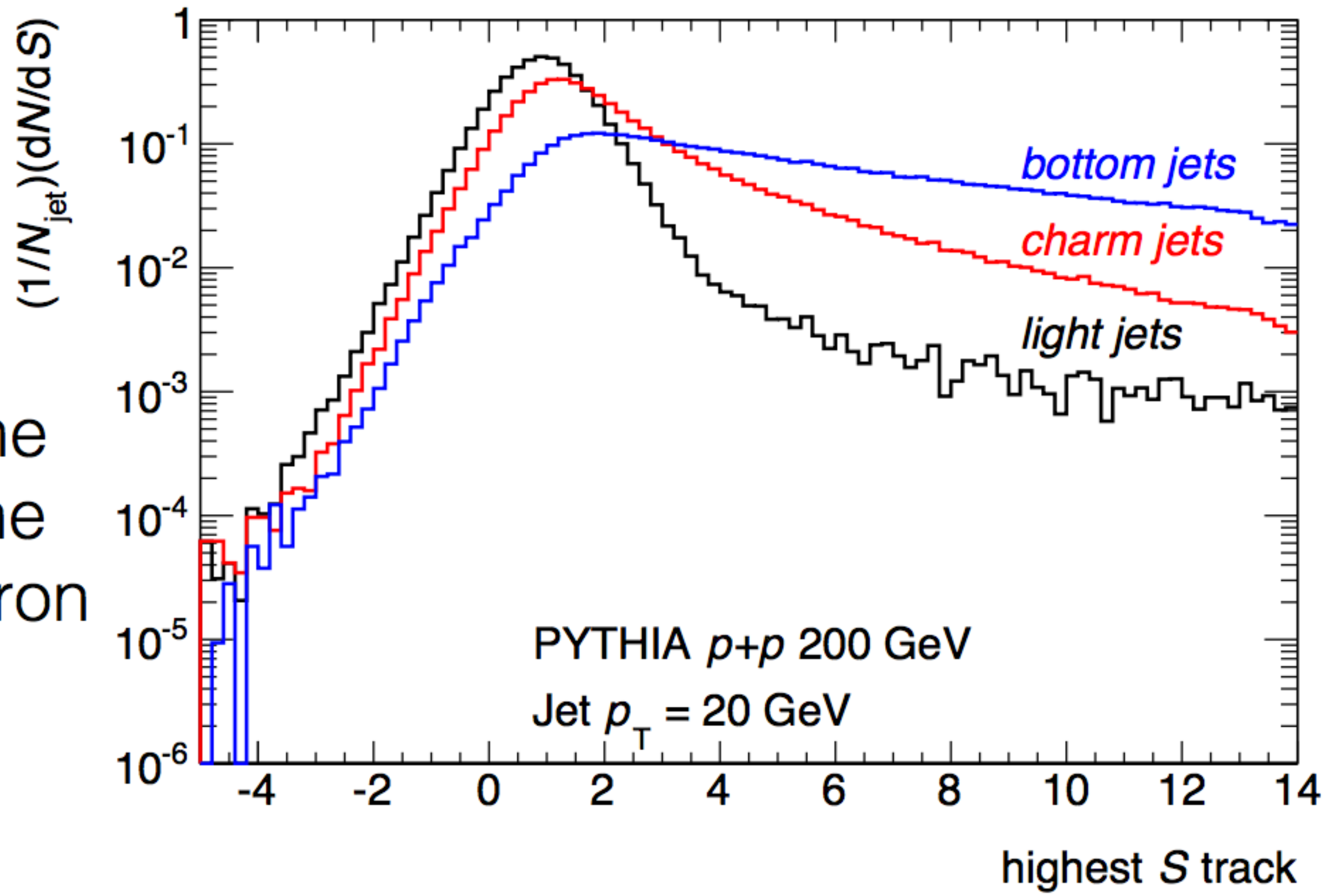
Smear true **DCA** with parameterized resolution derived from GEANT4

Reject hadrons with DCA > 1 mm or those consistent with $V^0 \to h^\pm h^\pm$

Sort remaining hadrons by their signed <u>*DCA significance*</u> S_{DCA} = **DCA** / σ_{DCA}

Leading DCA Significance

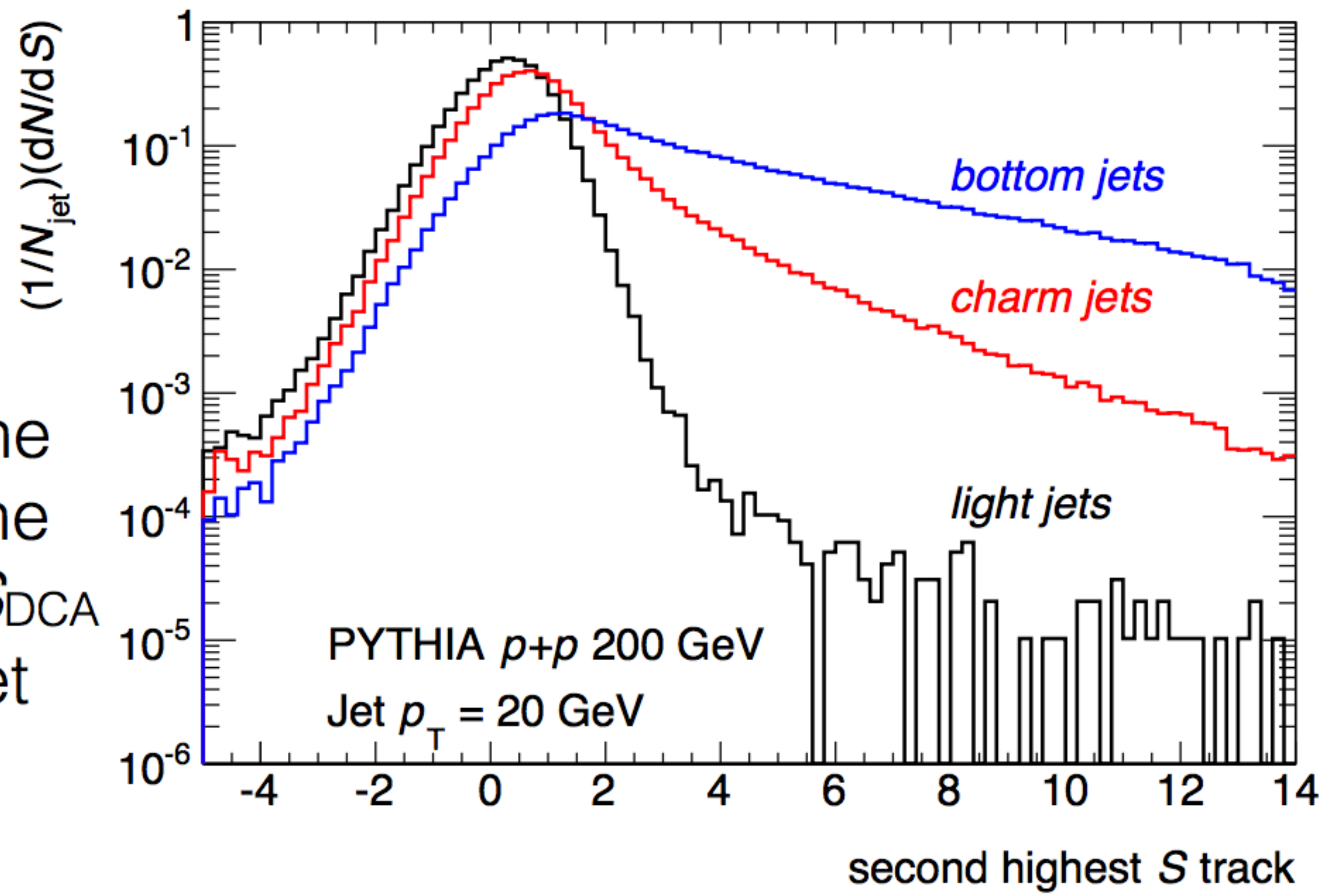
Distribution of the S_{DCA} value for the *highest*-S_{DCA} hadron in the jet



- High-S_{DCA} in **charm**/**bottom** jets from displaced vertices
- High-S_{DCA} tail in **light** jets from tails in DCA resolution and Σ/Ξ decays (cannot be removed with two-track mass analysis)

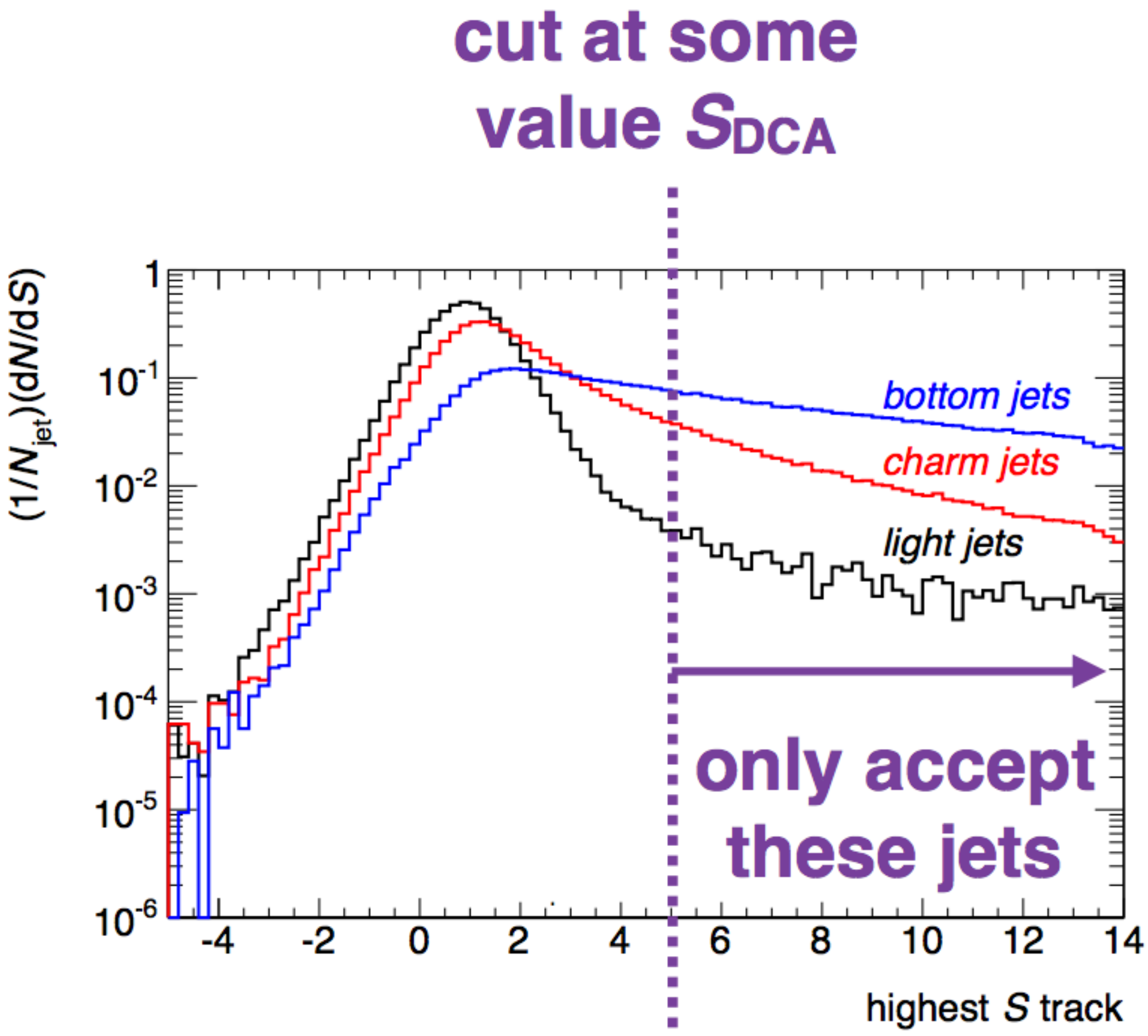
Sub-leading DCA Significance

Distribution of the S_{DCA} value for the <u>*second highest*</u>-S_{DCA} hadron in the jet



- Asking for a *second* track with high S_{DCA} cuts down on the **light** jet background
- **Charm** and **bottom** jets retain large-S_{DCA} tails

B-jet ID in p+p

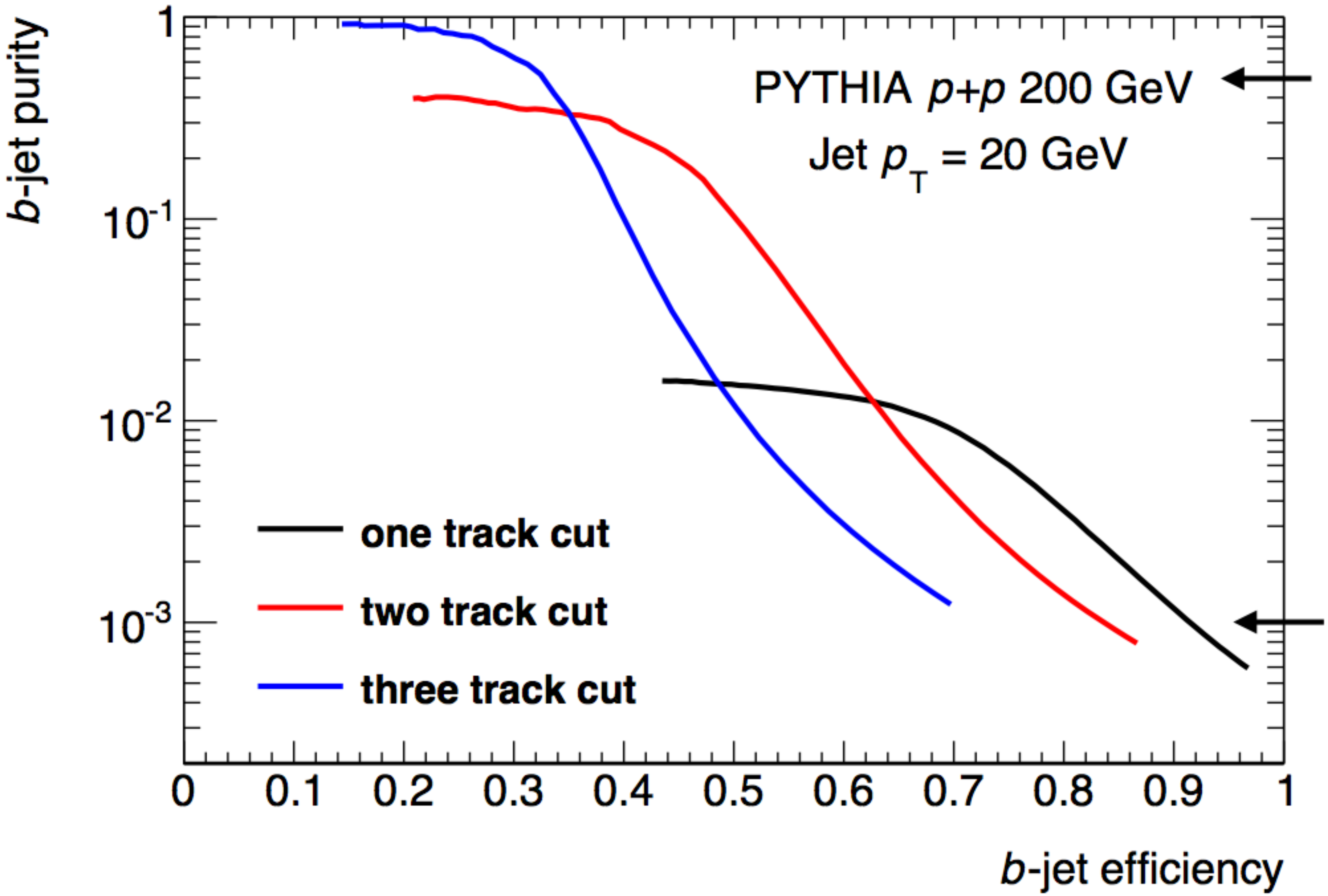


Calculate **efficiency** for light, charm and bottom jets

Calculate **purity** of *b*-jets after cuts as $P = N_b / (N_b + N_c + N_l)$

Vary S_{DCA} cut value to trade off ***b*-jet efficiency** vs. ***b*-jet purity**

b-jet Performance in p+p



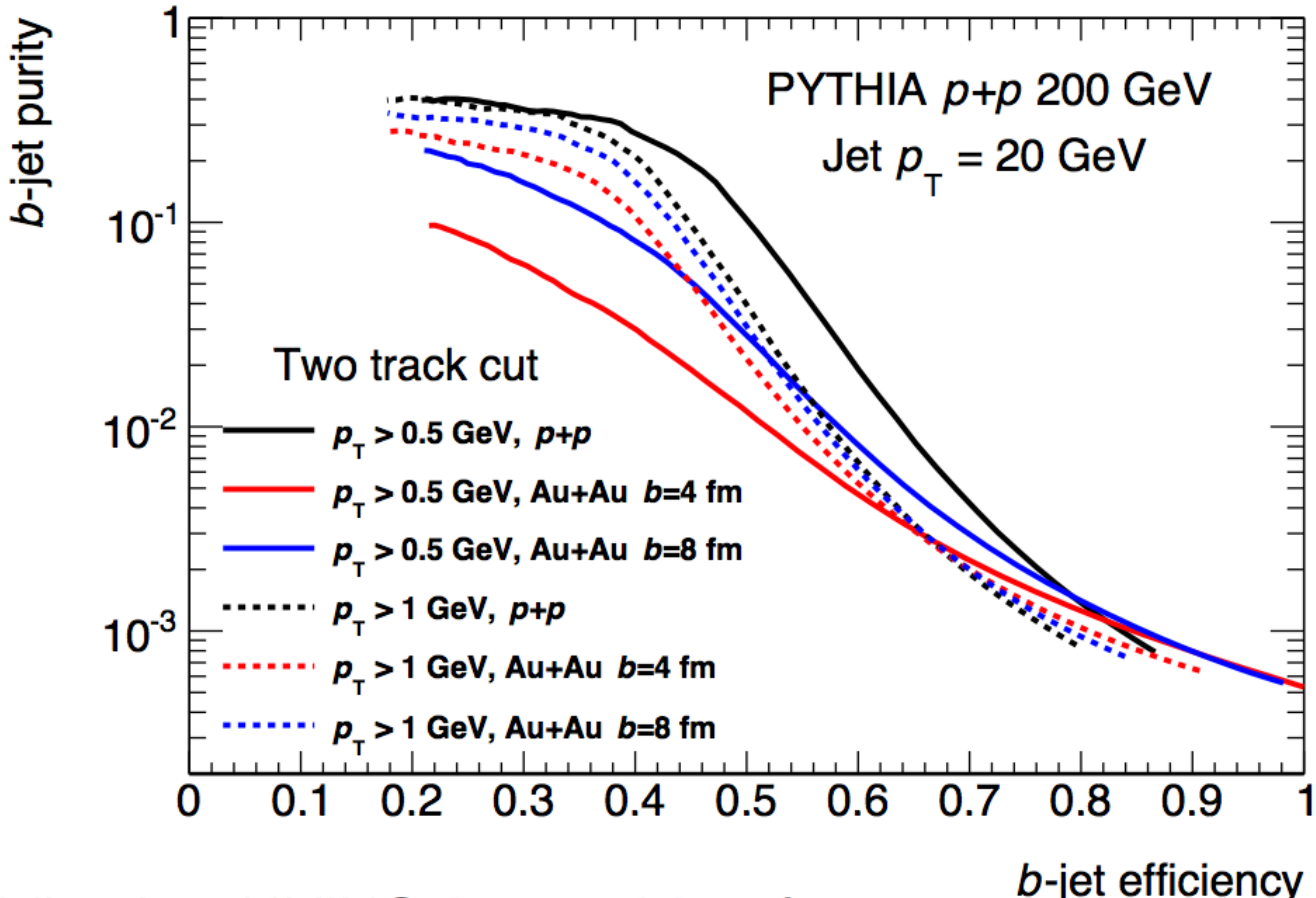
Purity ~ 0.5 is achievable at reasonable efficiency!

Purity <10^{-3} before any cuts!

P vs. **E** curves for requiring **1**, **2** or **3** tracks with S_{DCA} above some minimum value

Heavy Ion Backgrounds

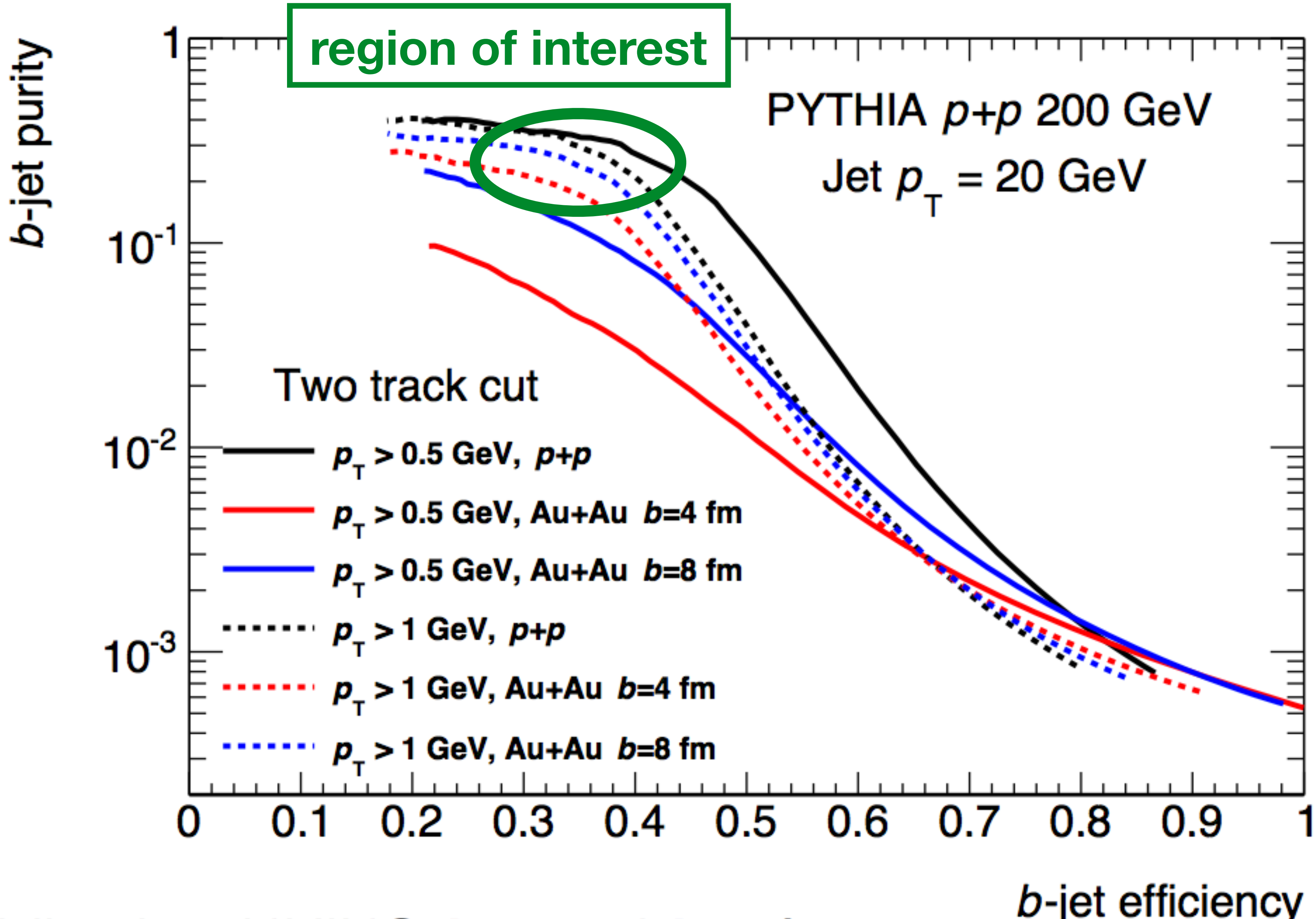
how does the performance depend on *environment multiplicity?*



- P vs. E after embedding into HIJING ***b*=4** and ***b*=8** fm events
  - ➡ ultimately, large MB dataset will allow us to study this in real data
- Requiring only a few or low-p_T tracks leads to large UE-susceptibility
  - ➡ resilient behavior when, for example, requiring two > 1 GeV tracks

Heavy Ion Backgrounds

how does the performance depend on *environment multiplicity?*



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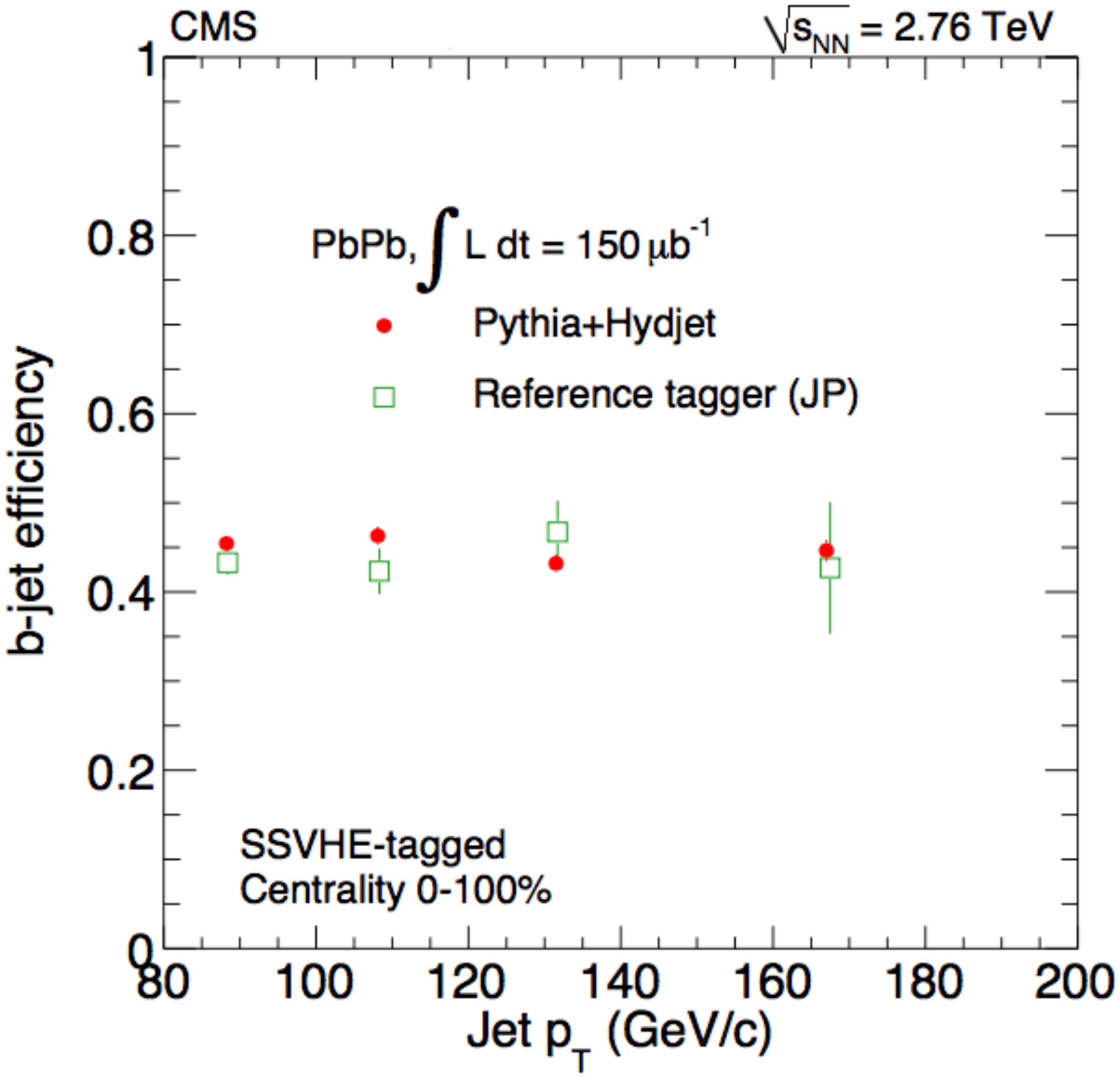
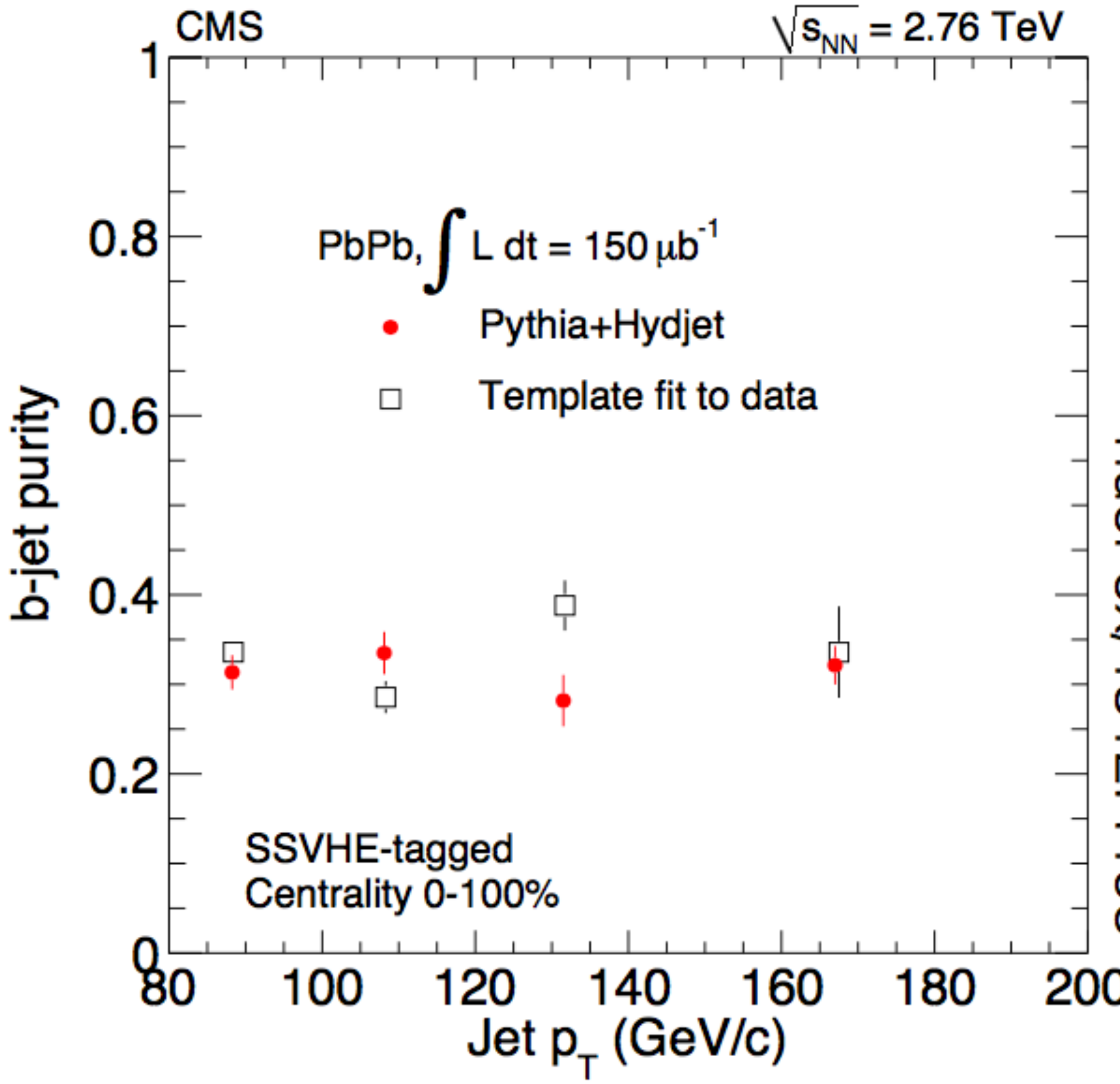
LHC Comparison





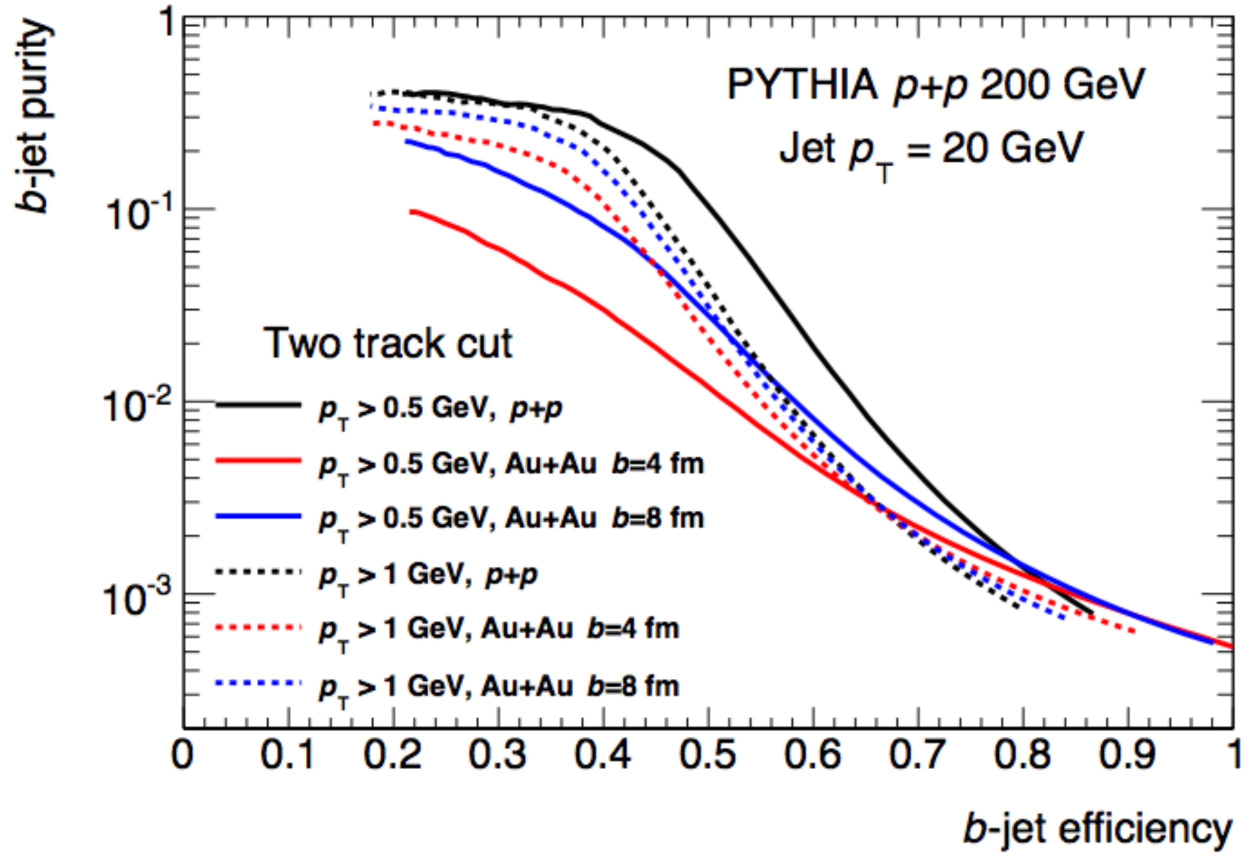
nucl-ex/1312.4198

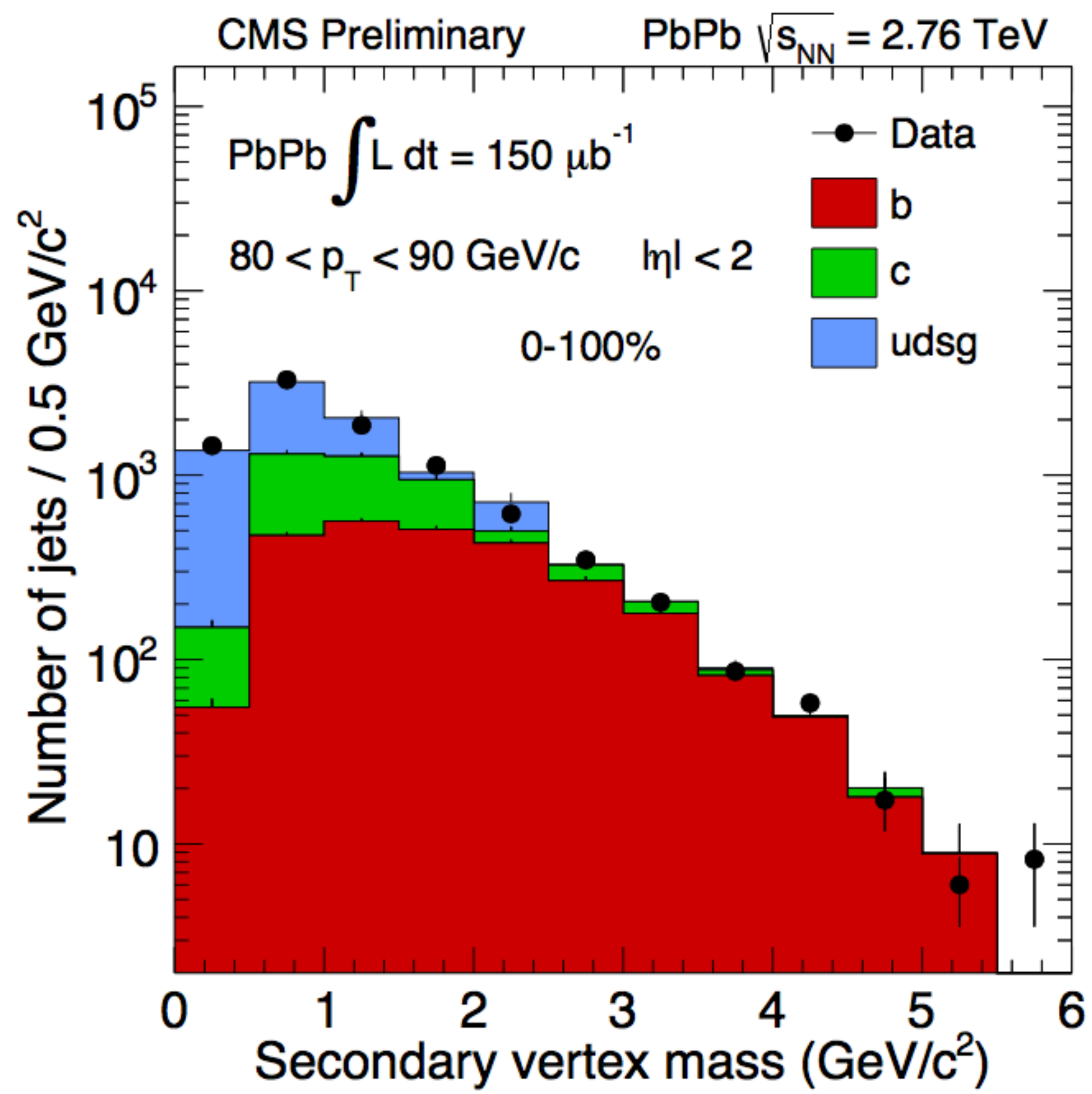
CMS Pb+Pb *b*-jet spectrum: *≈45% Efficiency* and *≈35% Purity*

➡ resulting *15-20% uncertainty in R_{AA}*, dominated by *b*-tagging uncertainty

➡ comparable to that achievable with TrackCounting

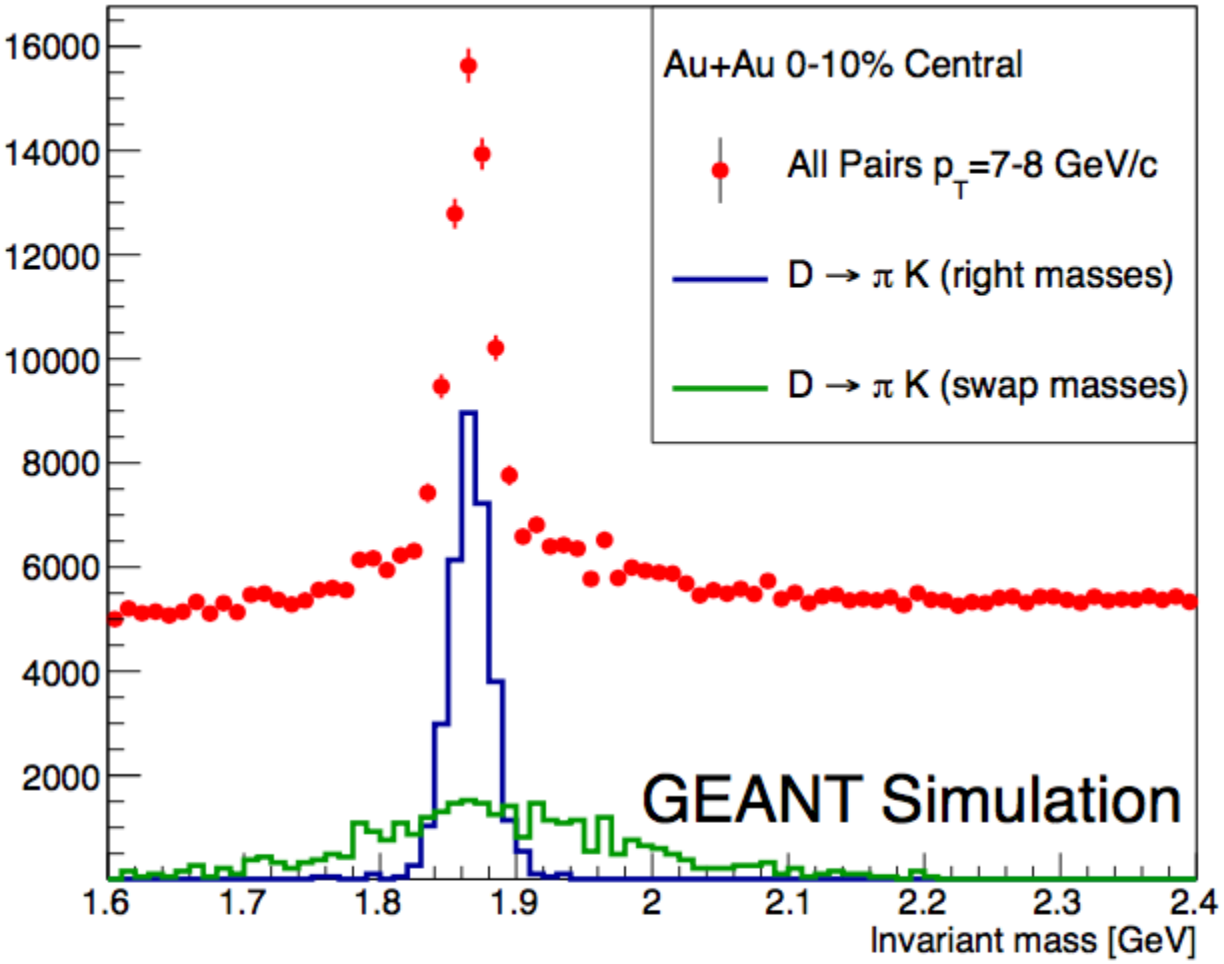
Further Development

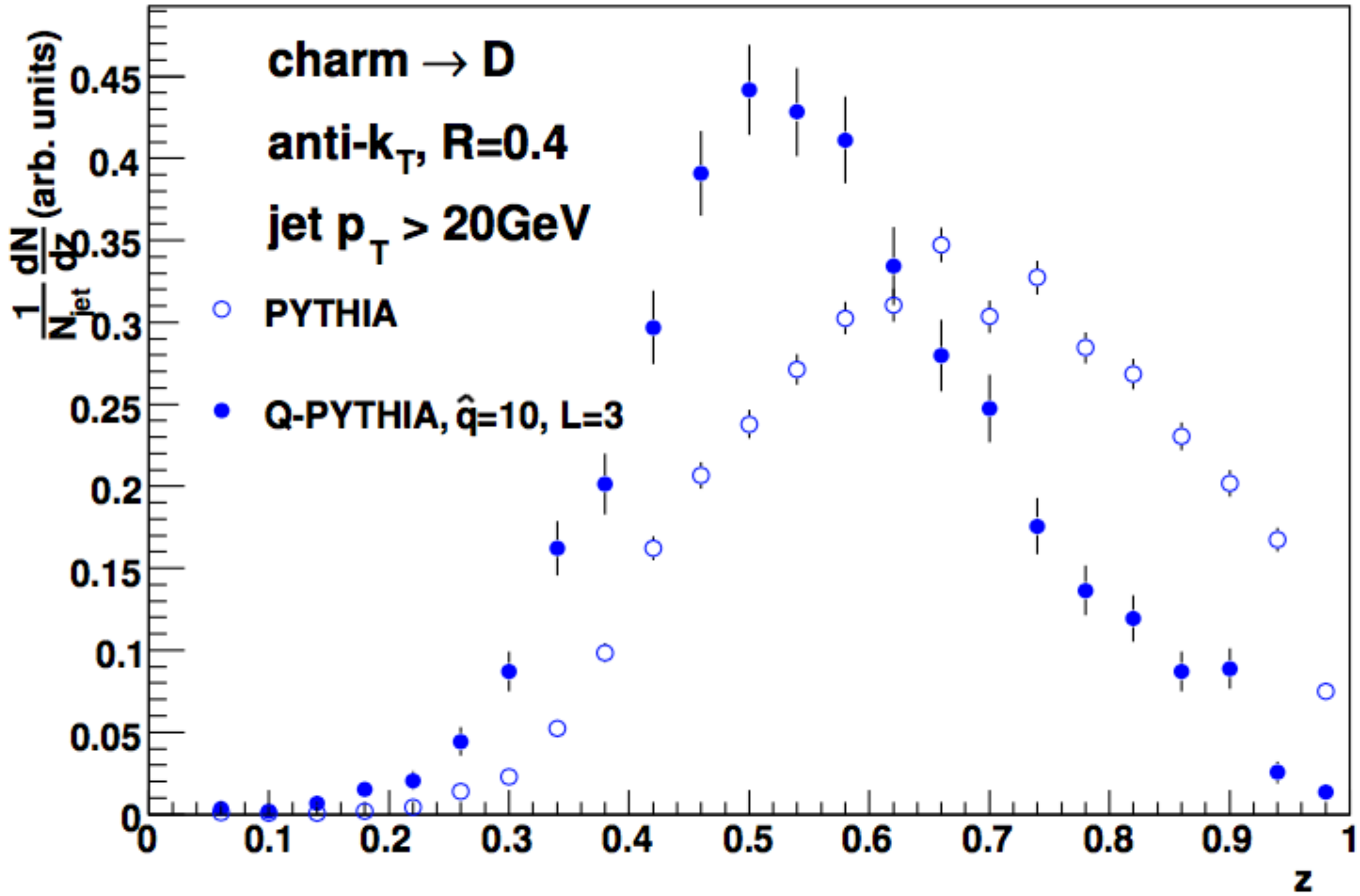




- These results indicate that selecting *b*-jets with good discrimination is achievable at RHIC
  - ➡ high efficiency (for good statistics)
  - ➡ high purity (to control systematics on extracted *b*-jet fraction)
- Other approaches would be explored in a full experimental program: soft lepton tagging, secondary vertex reconstruction

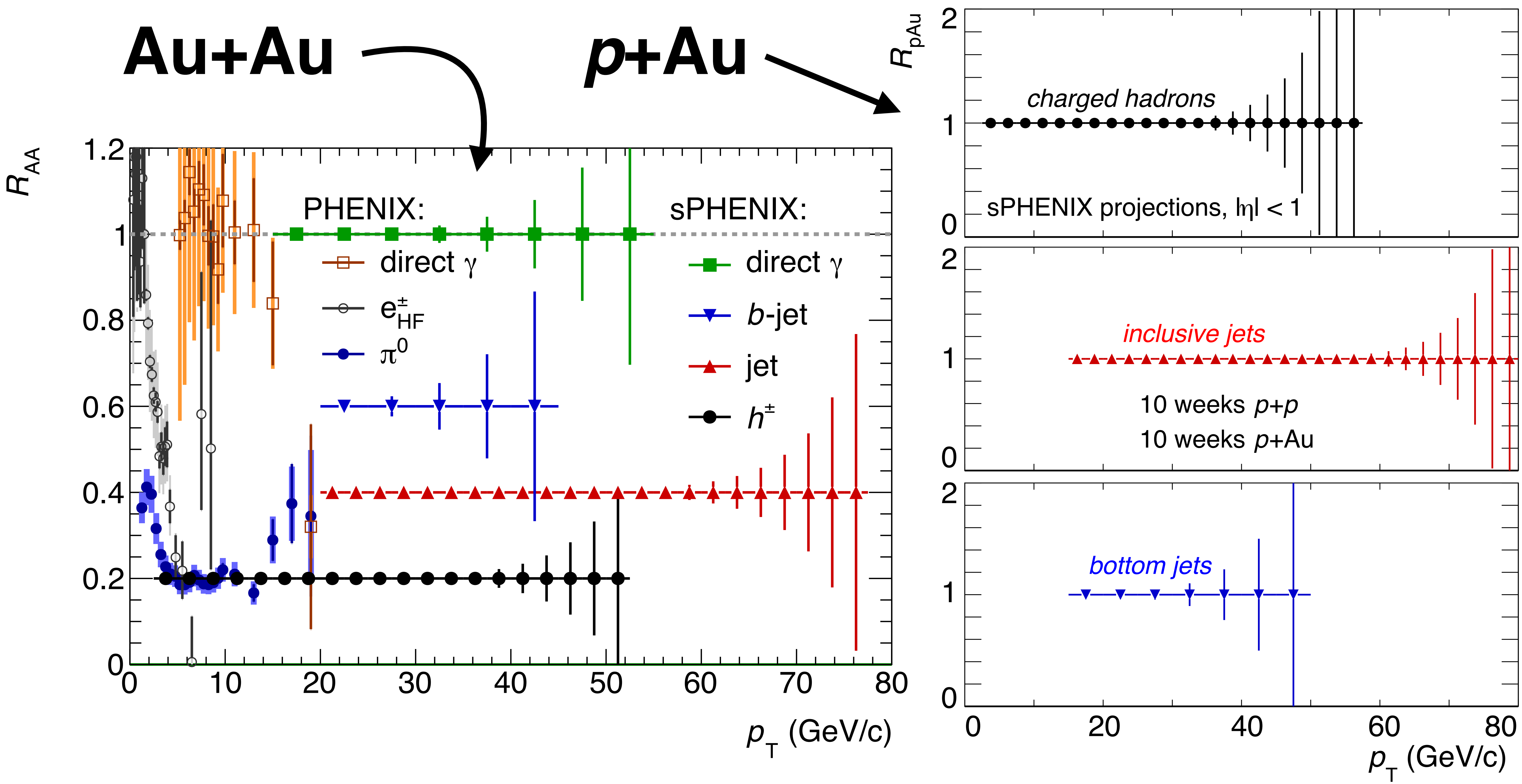
Charm Identification





- The requirement of a secondary vertex allows us to reconstruct D mesons without particle ID
  - ➡ high signal/background ratio for mesons at intermediate *z*, *even in central Au+Au events!*
- Important capability for calculations of modified fragmentation to heavy flavor hadrons

b-jets at RHIC

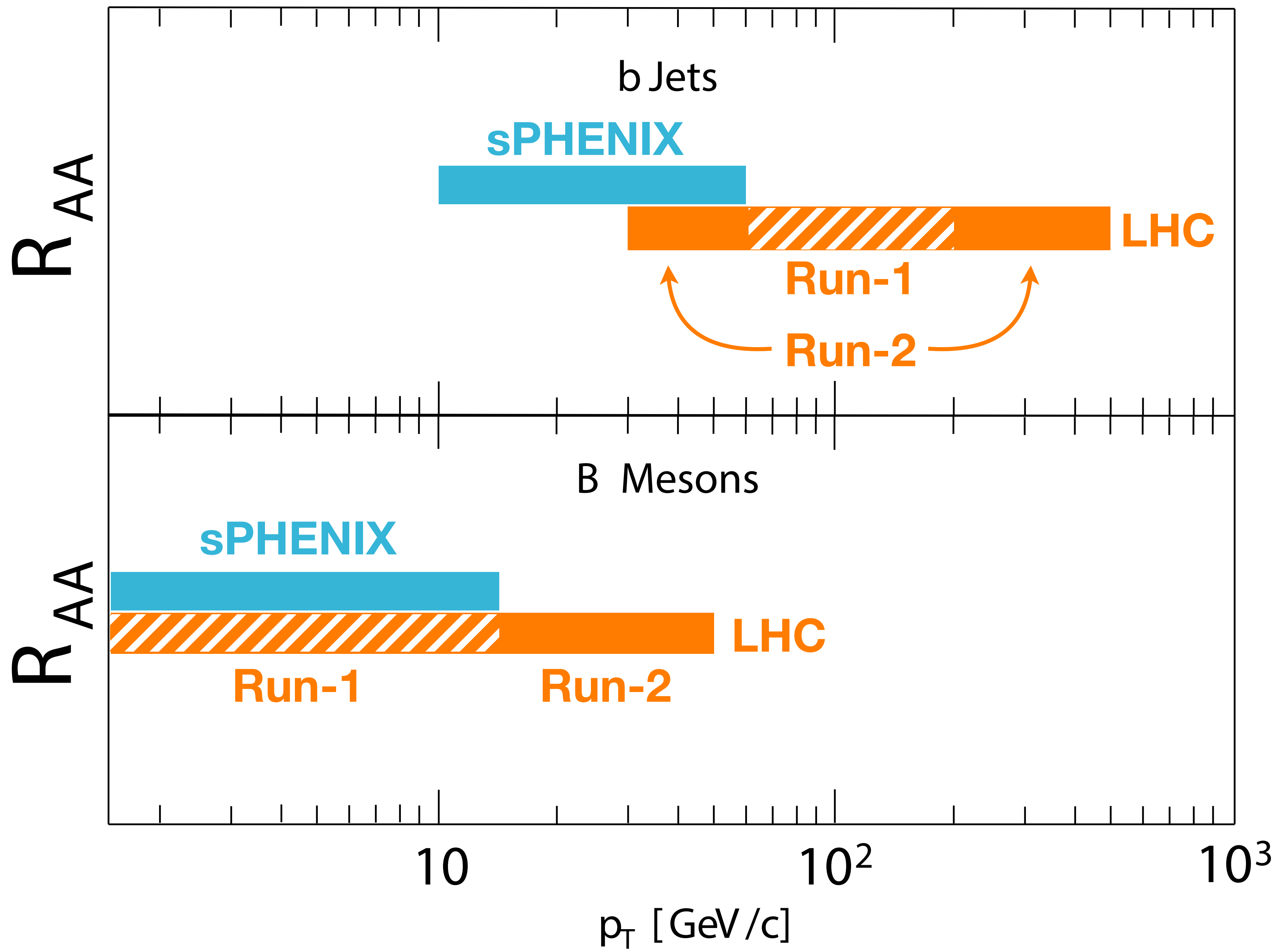


Statistical projections for the *b*-jet R_{AA} and R_{pA}

- assuming 50% tagging-efficiency

sPHENIX and the LHC

Crucial extension to low p_T for jets at sPHENIX



Completion lowest p_T with meson reconstructions

Highly complementary to LHC program

Summary

- b-jets at RHIC will provide crucial information on the ***inner working of the QGP*** and explore ***a different regime*** than the LHC
- current projections yield ***a large, unbiased sample of heavy flavor jets*** during two years of sPHENIX data-taking
- b-jets are identified through the selection of charged tracks with ***large impact parameter to the primary vertex***
- studies show that a ***high efficiency and purity*** are simultaneously achievable
- further improvements will be possible with additional refinements (e.g. secondary vertexing)

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 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	

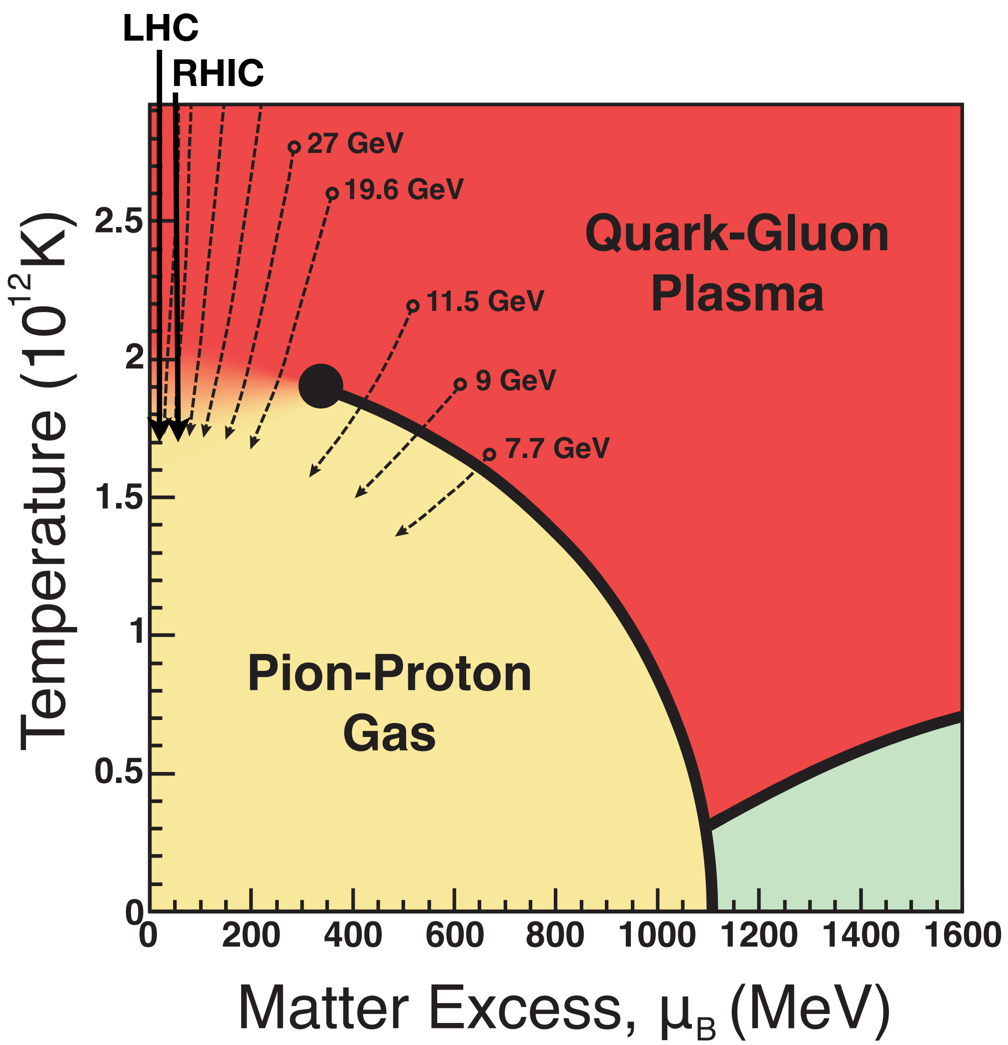
Heavy Ion Collisions

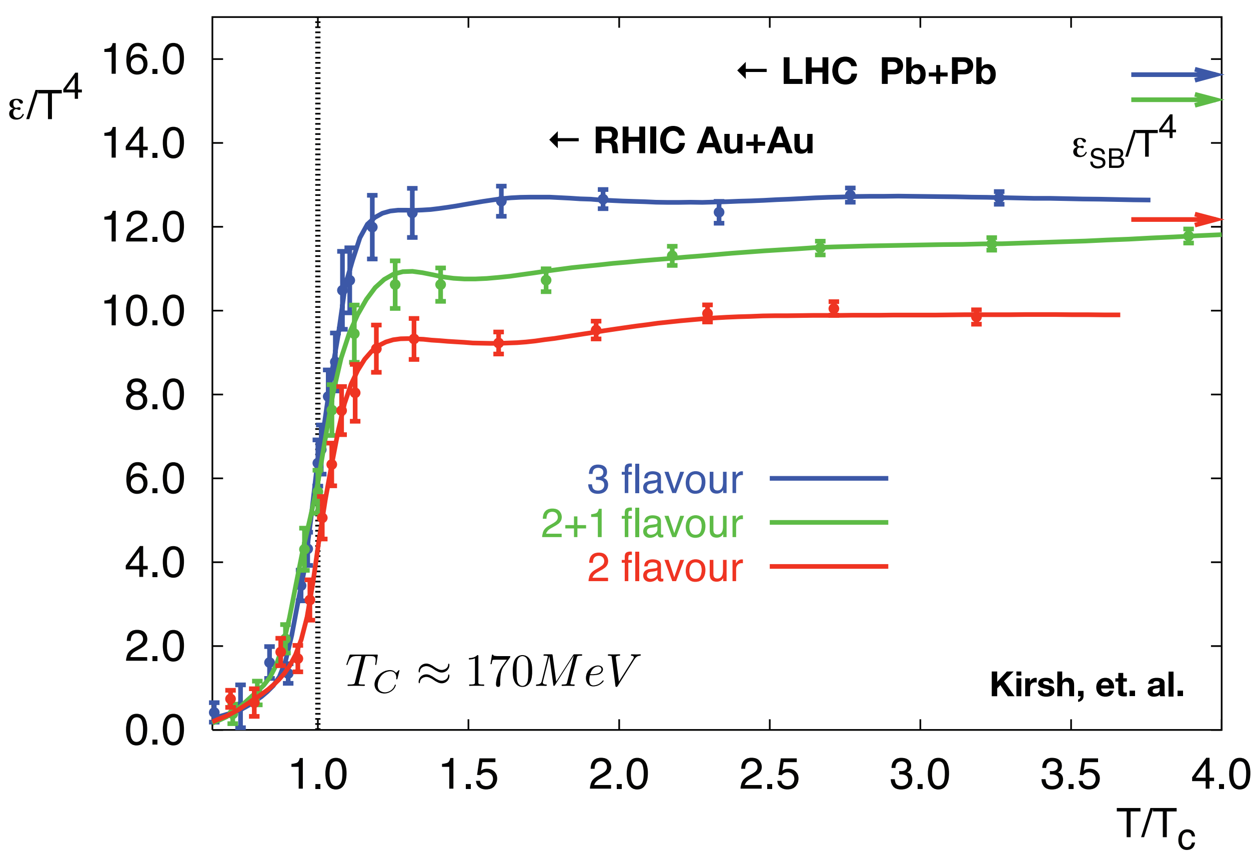
QCD Phase Diagram

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

Reachable by collider facilities

Critical point being sought





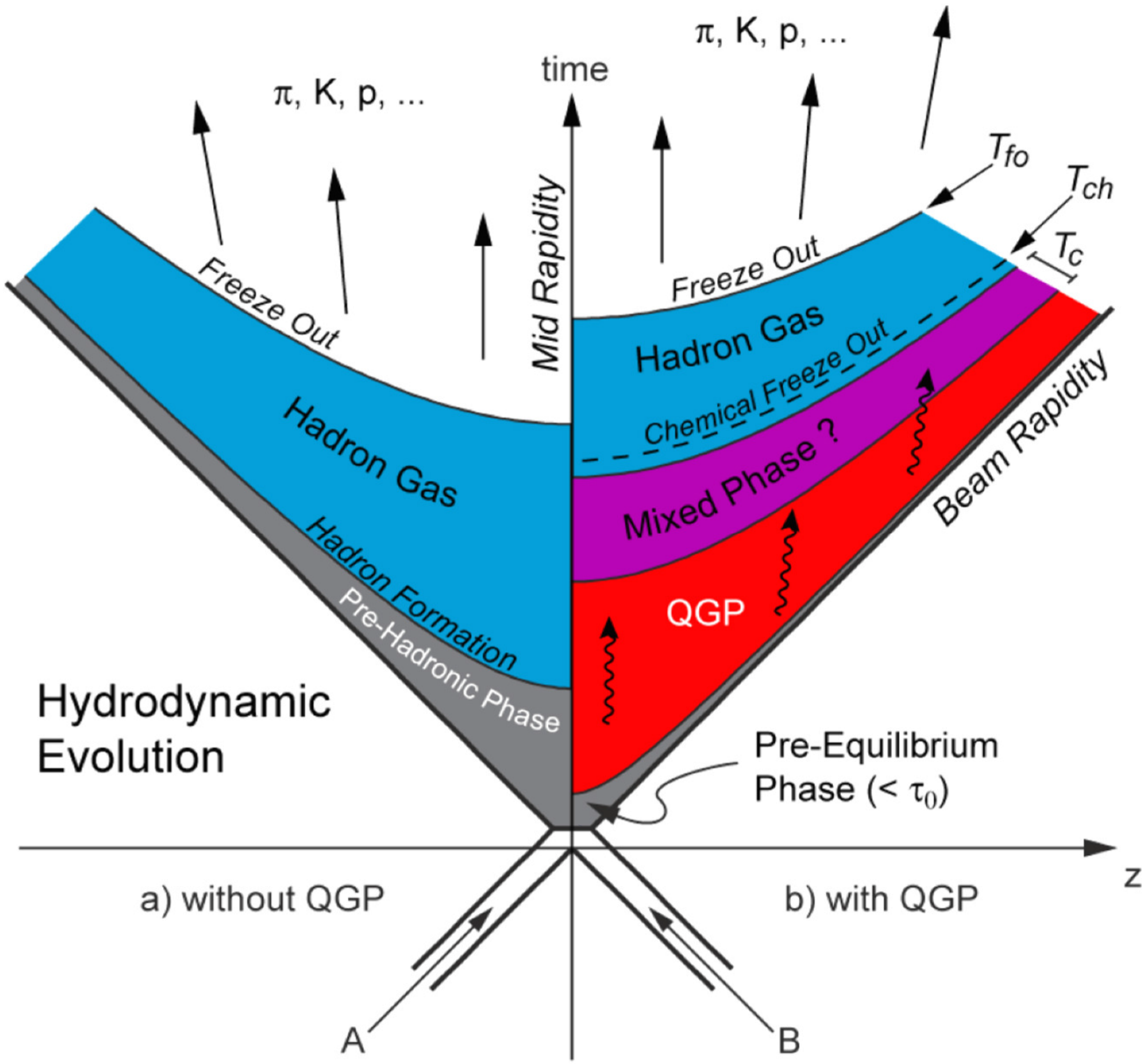
Lattice QCD Calculations

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)

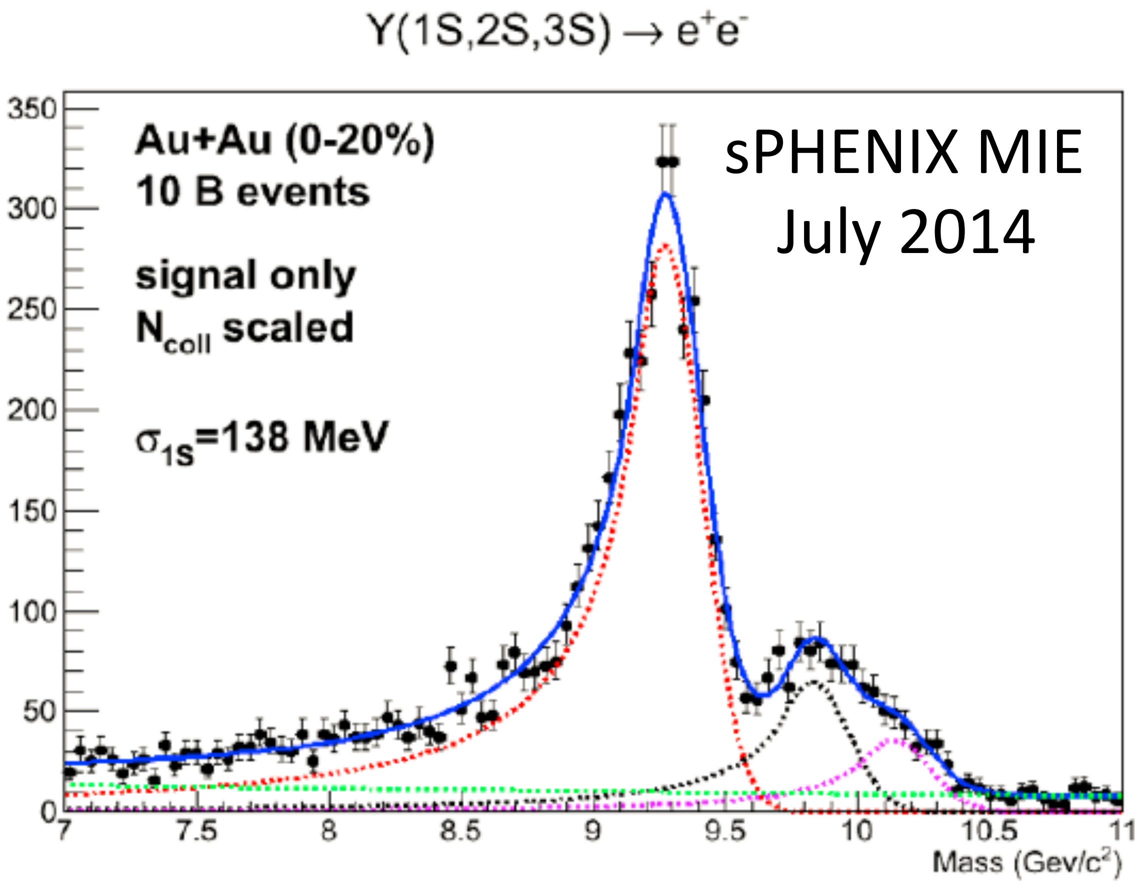
QGP

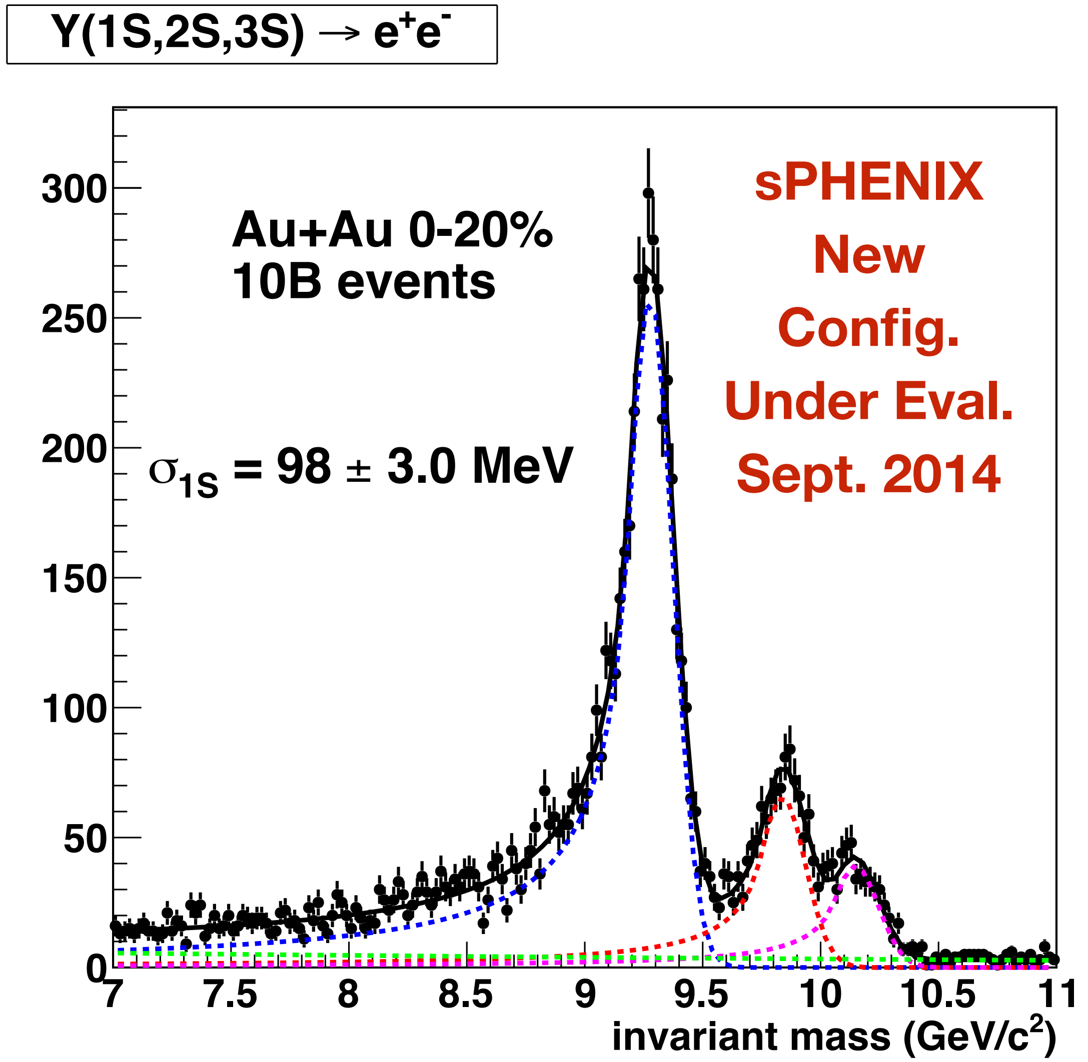
Thermalization (~0.6 fm/c)

Nuclear Crossing (~0.1 fm/c)

***values for RHIC at 200 GeV**

Tracking Optimization I





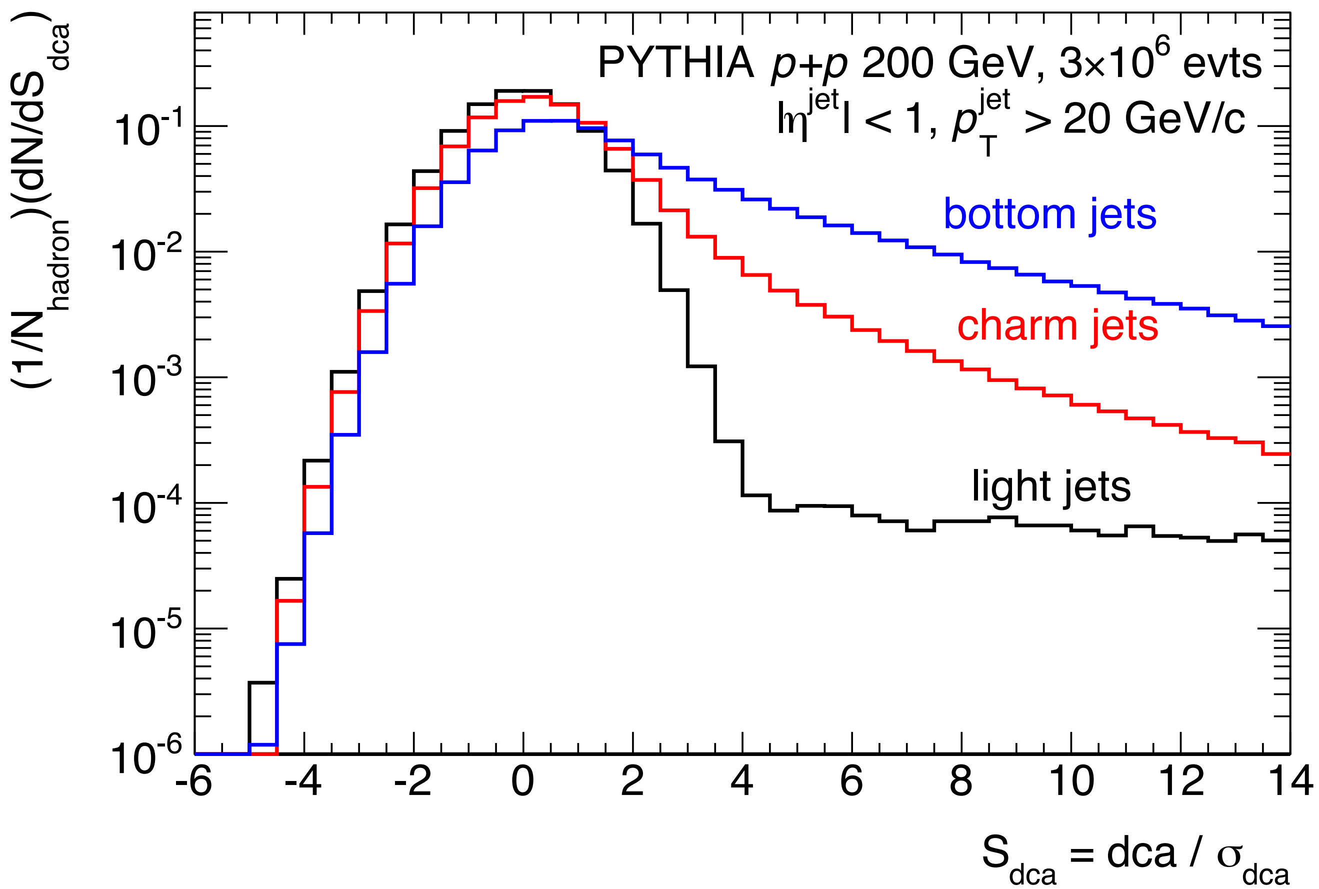
Mass resolution and expected counts (without backgrounds) from sPHENIX Proposal

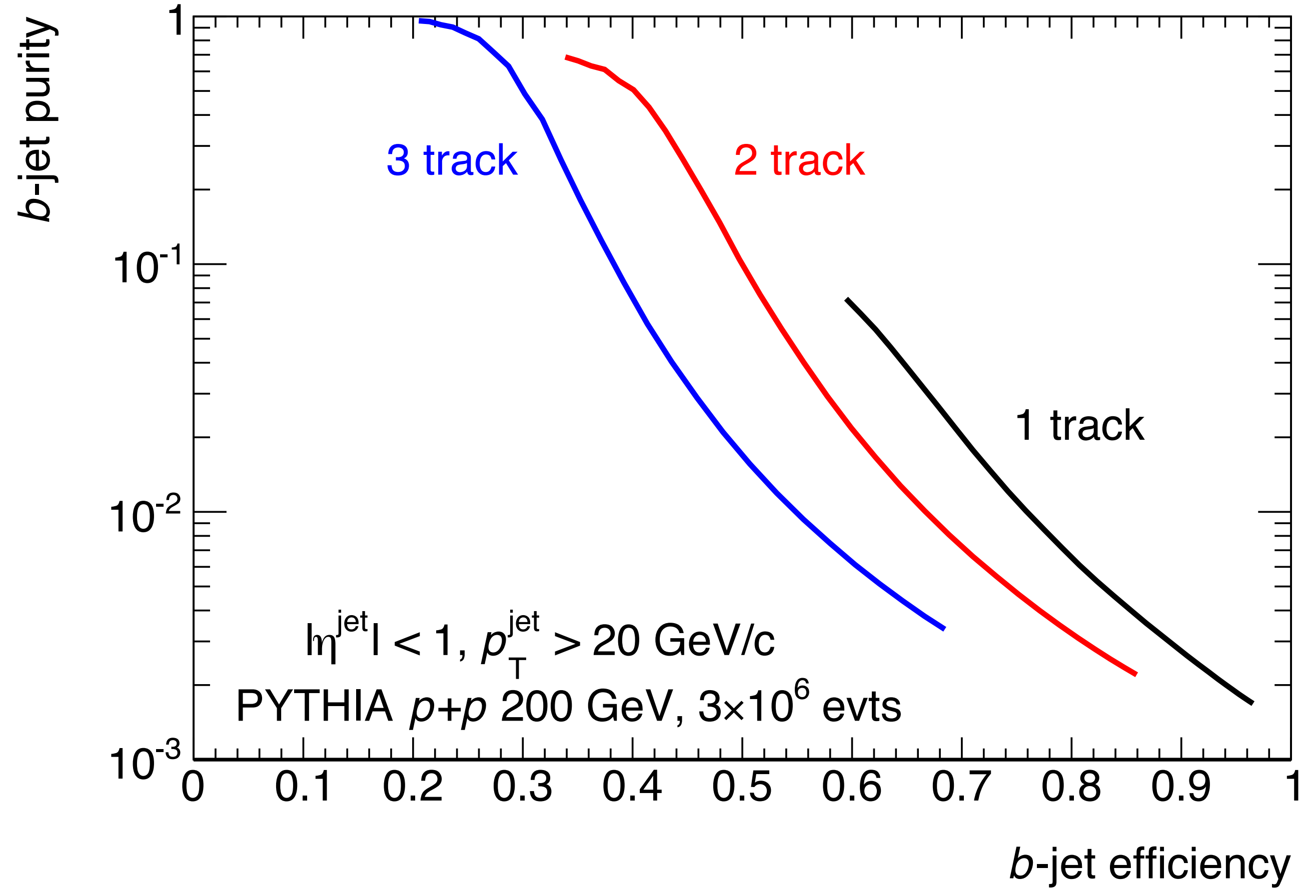
Received suggestion at physics review to further optimize tracking and evaluate performance/cost tradeoff

Revised design improve mass resolution

Figure of merit to preserve as we further revise the design

Tracking Optimization II





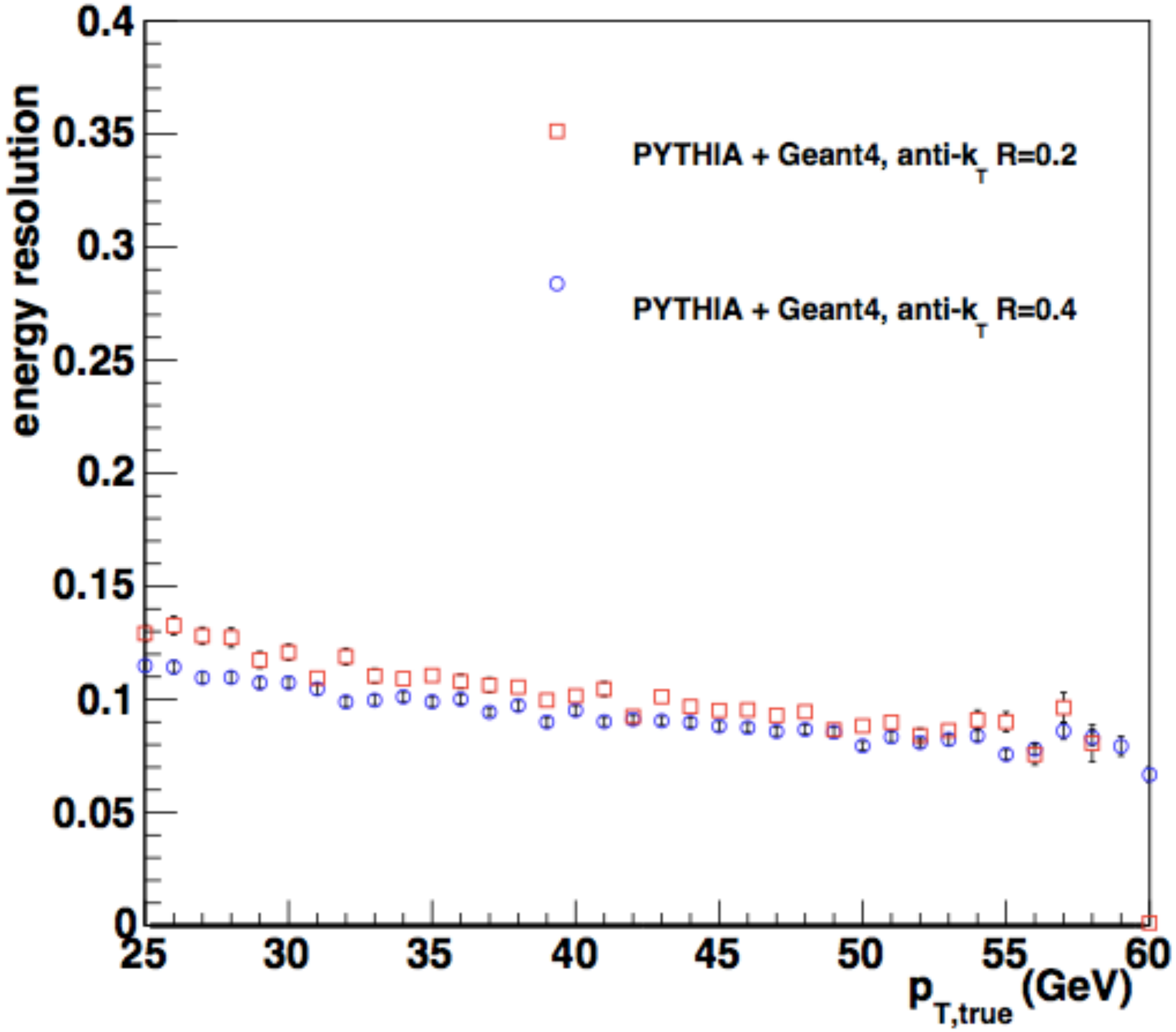
sPHENIX has explored b-jet tagging through requiring tracks in the jet with **a large 2-D distance of closest approach** (d.c.a) to the primary vertex

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

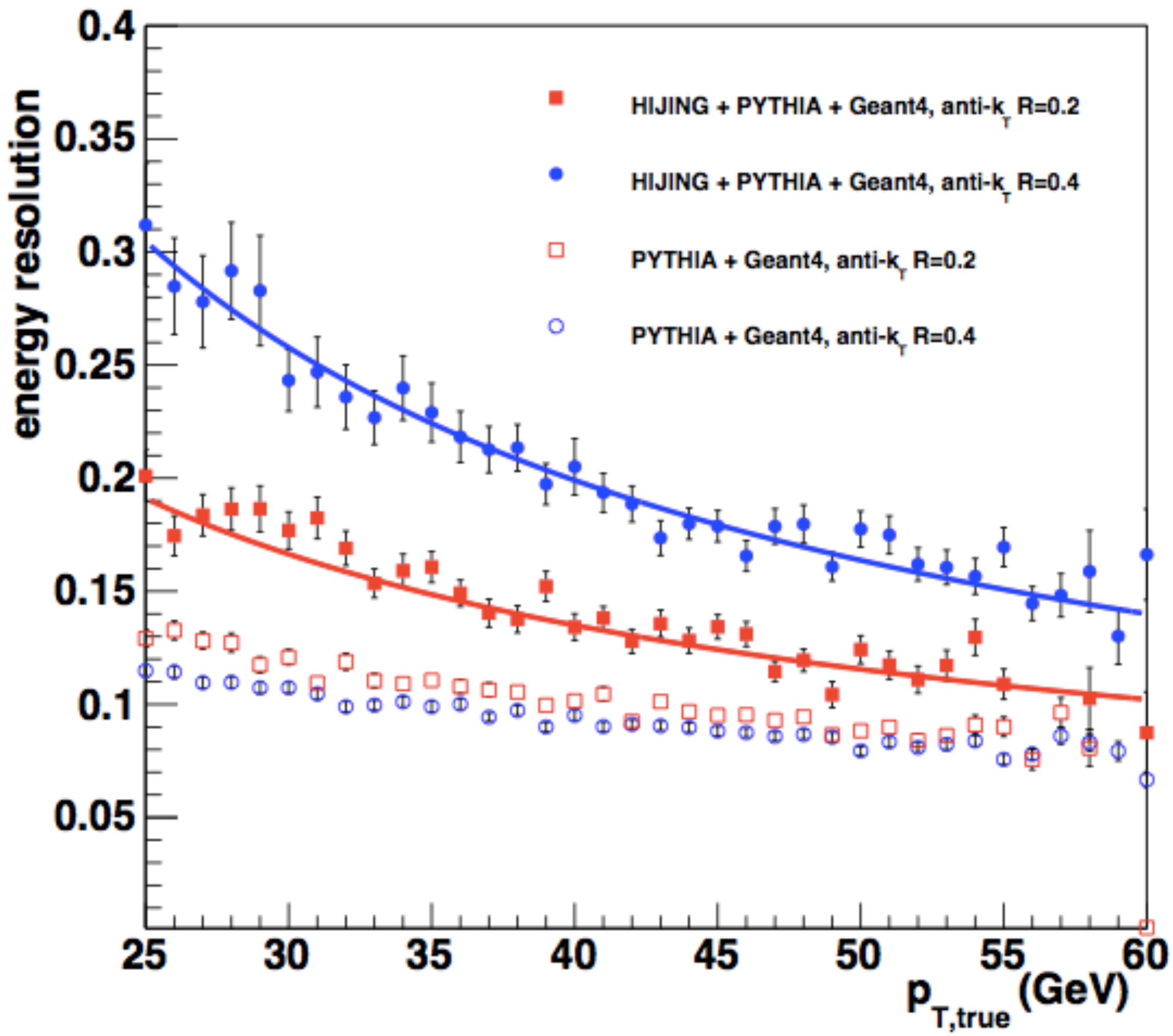


R=0.2: 65%/√E
R=0.4: 60%/√E
both small constant term

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

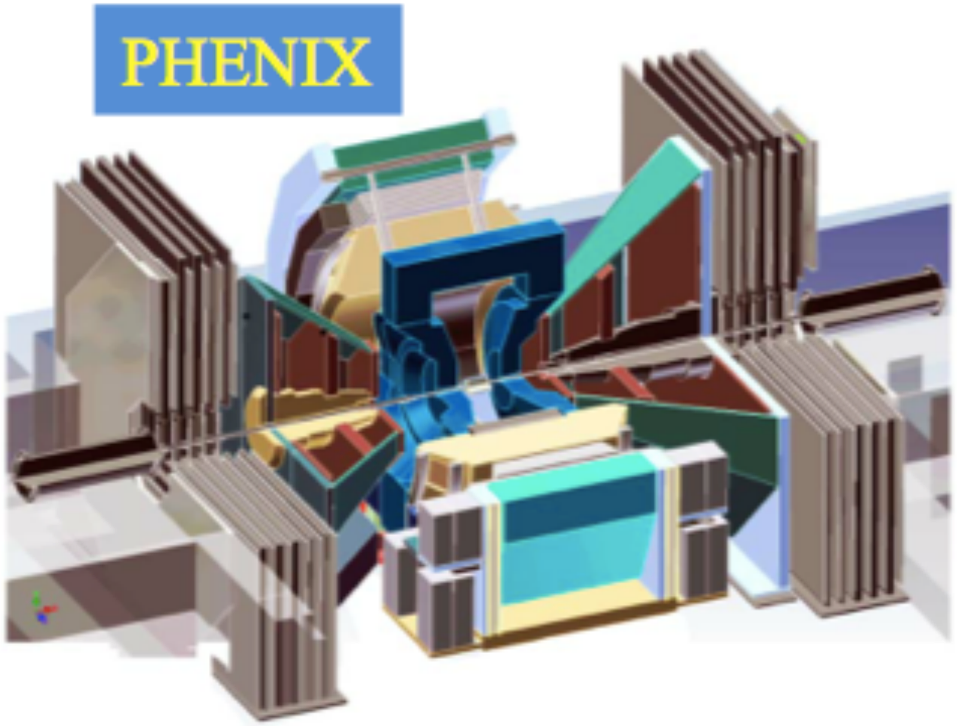


lines: p+p resolution ⊕ UE smearing

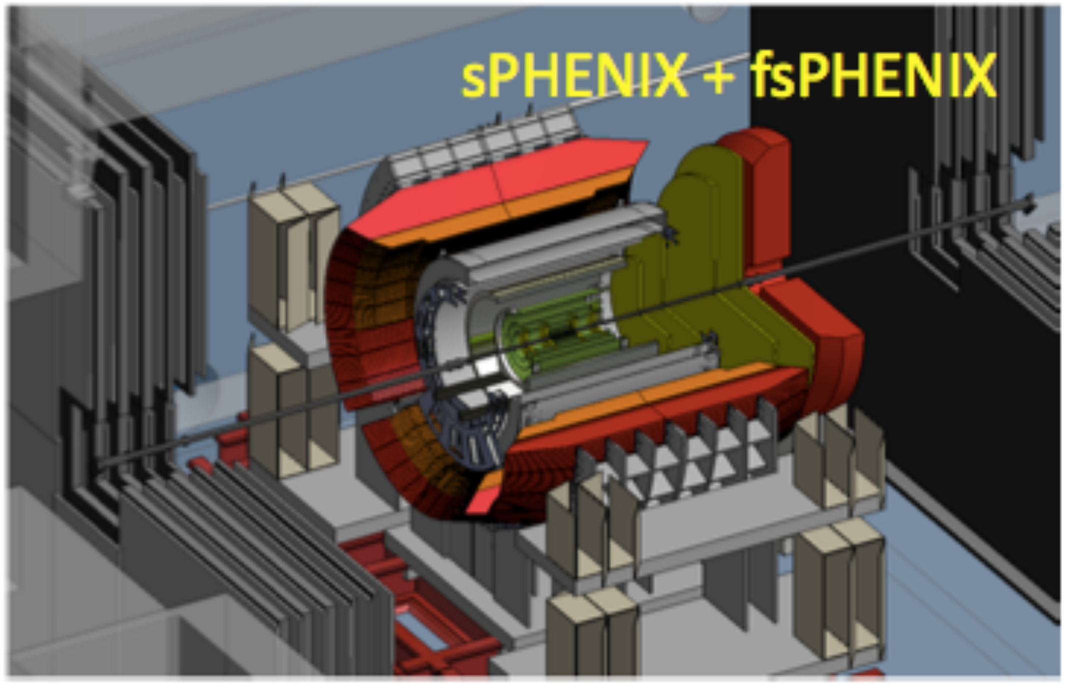
7 GeV for R = 0.4

3.5 GeV for R = 0.2

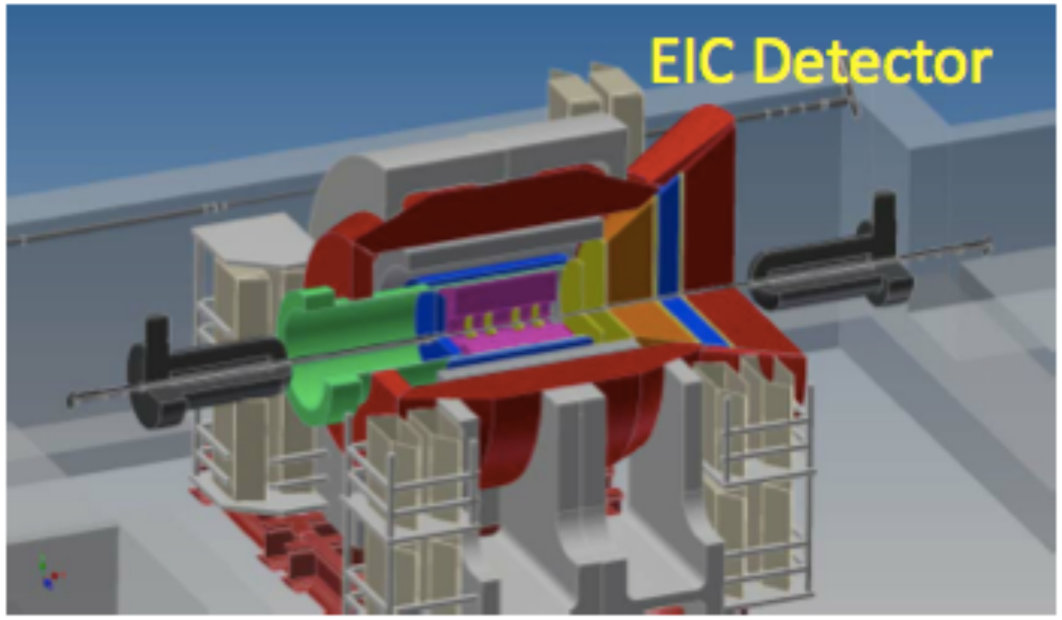
sPHENIX evolution



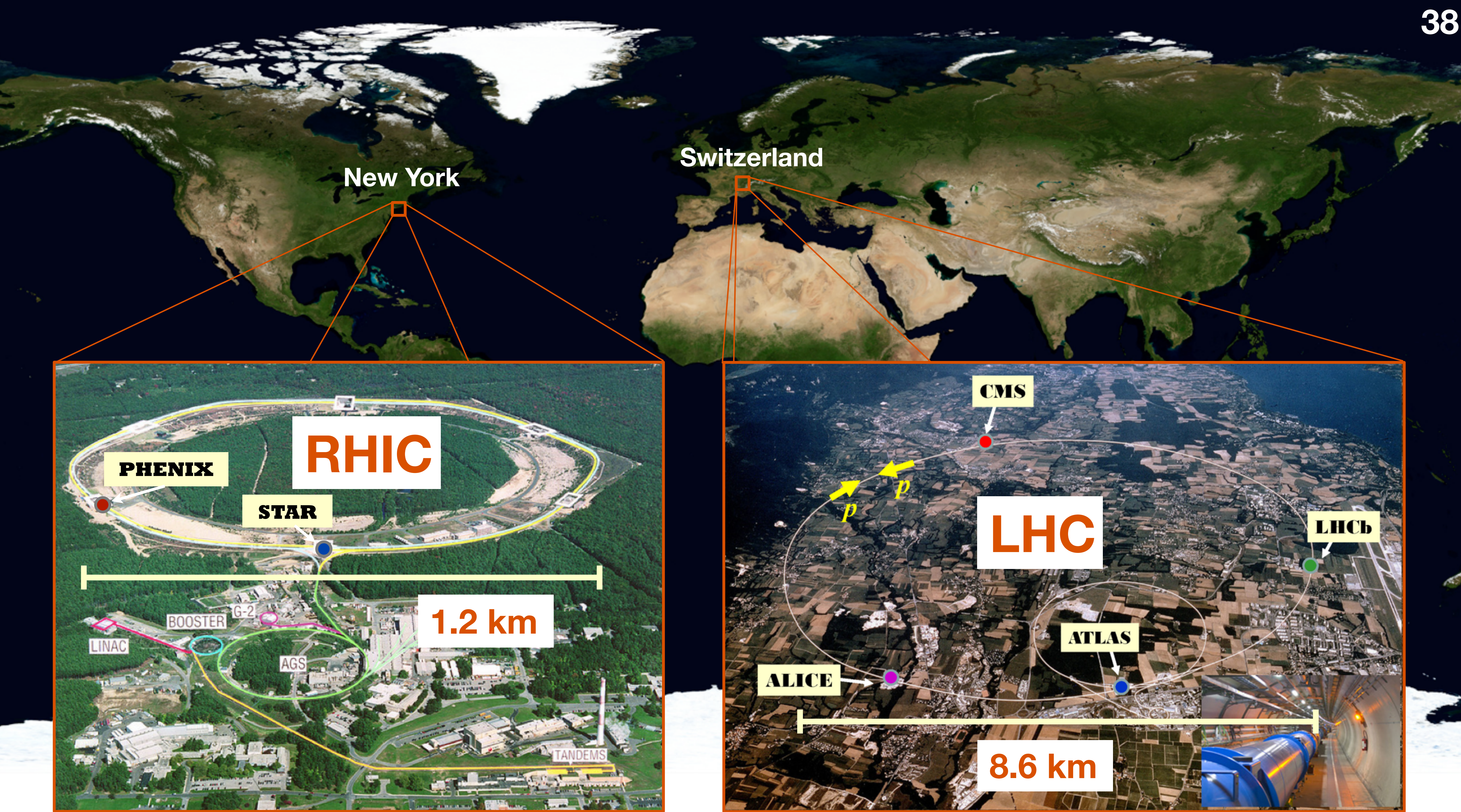
~2021-22



~2025



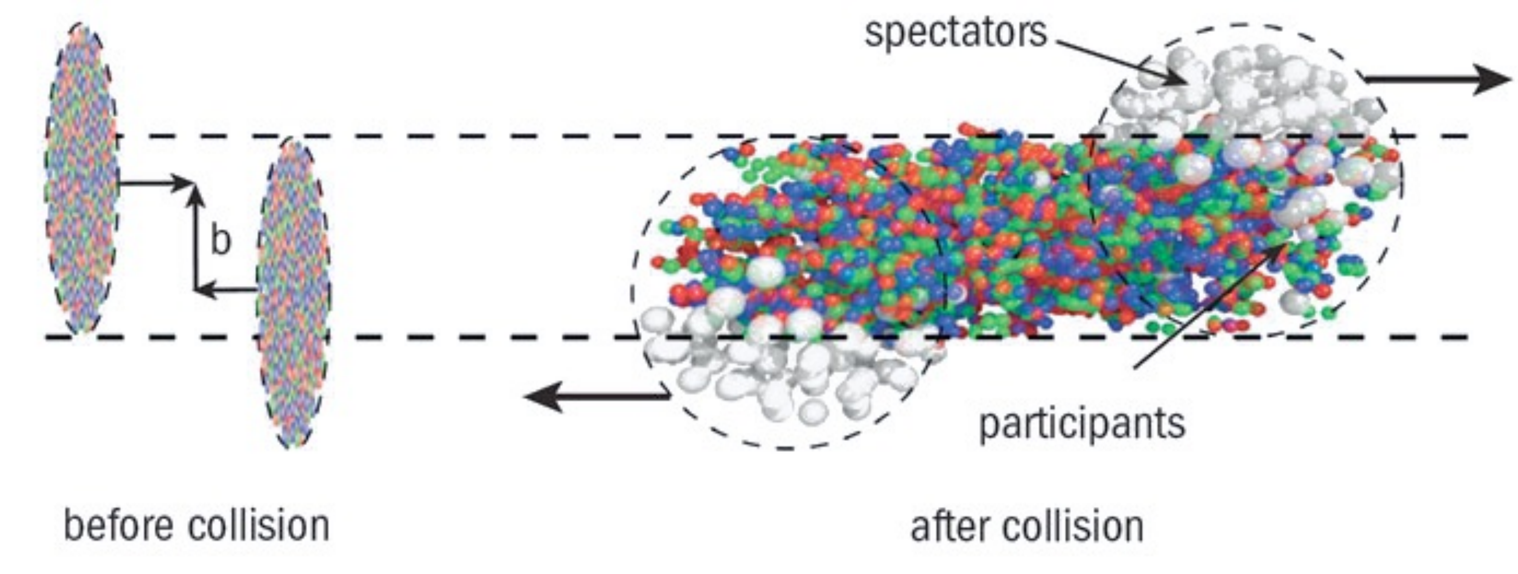
sPHENIX evolution
into an EIC detector



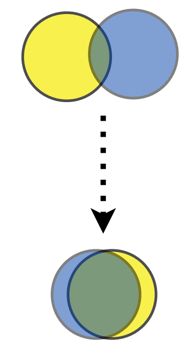
beam	energy (GeV)
$\vec{p}+\vec{p}$	62 - 510
$(\vec{p},d,He^3)+(Al,Au)$	200
Cu+Cu	22 - 200
Cu+Au	200
Au+Au	7 - 200
U+U	193

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

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

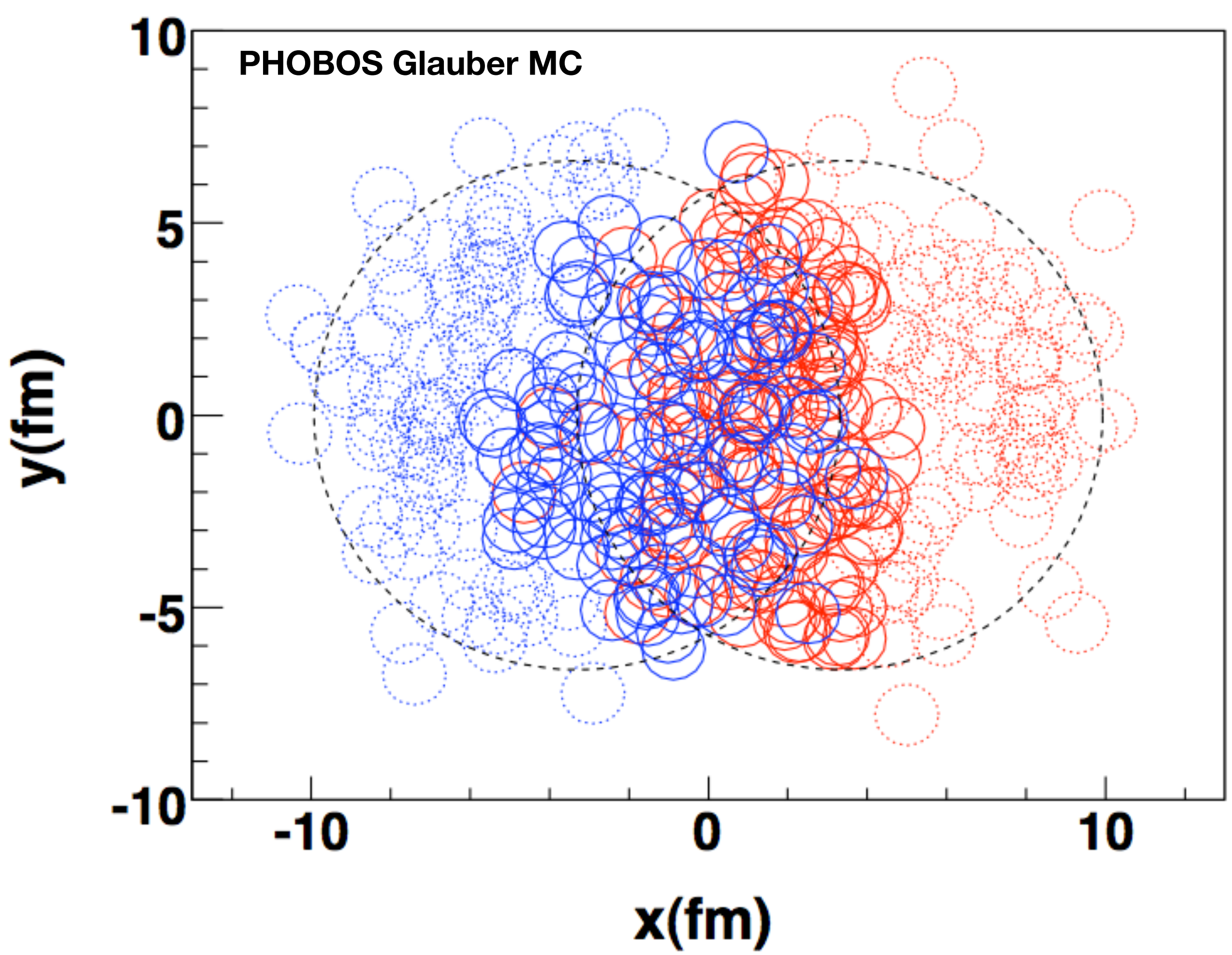
Tool: Glauber Monte Carlo simulation

Simple geometric description of A+A

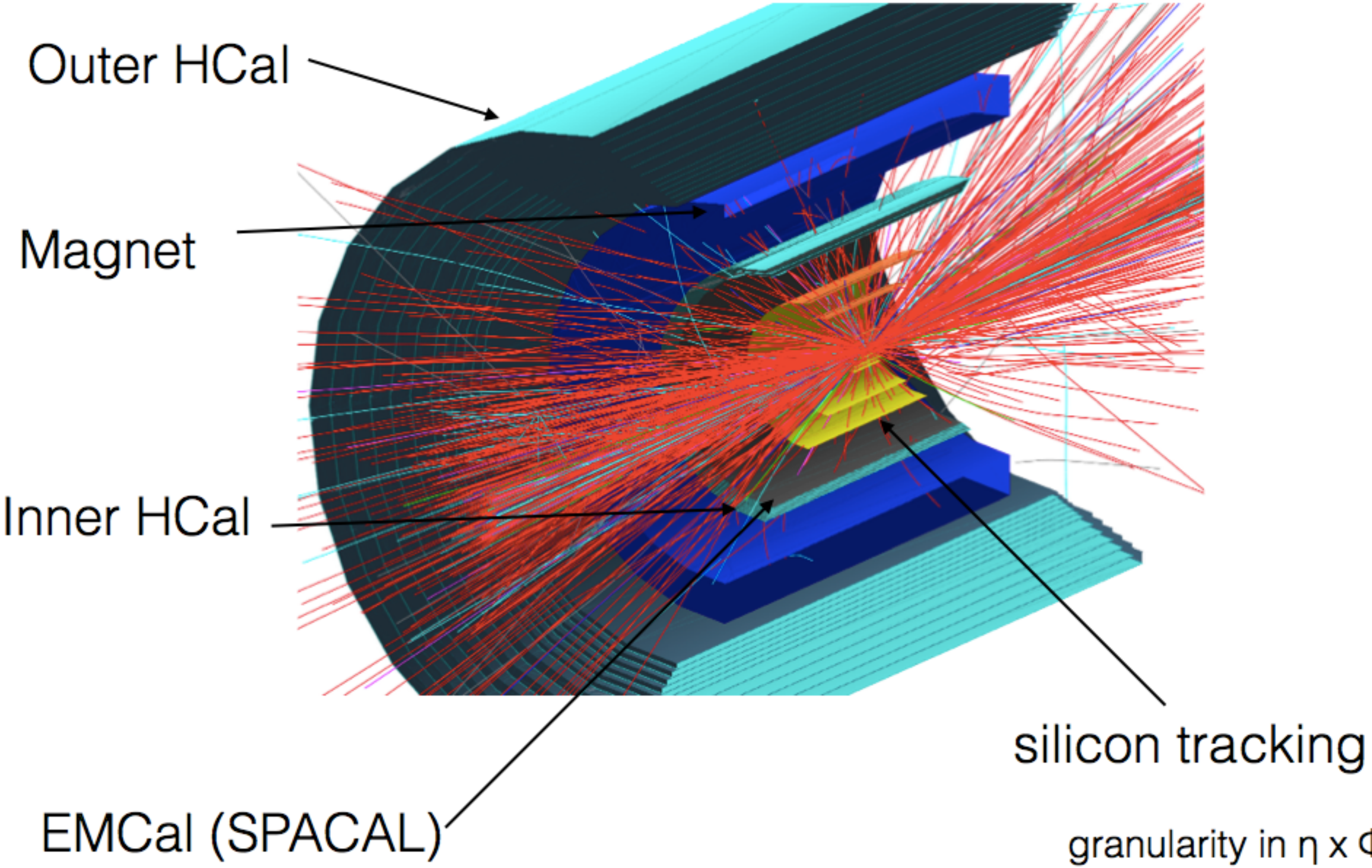
Includes statistical fluctuations

Number of Participating Nucleons, N_{part}
~ system size

Number of Binary Scatterings, N_{coll}
~ hard process cross-section



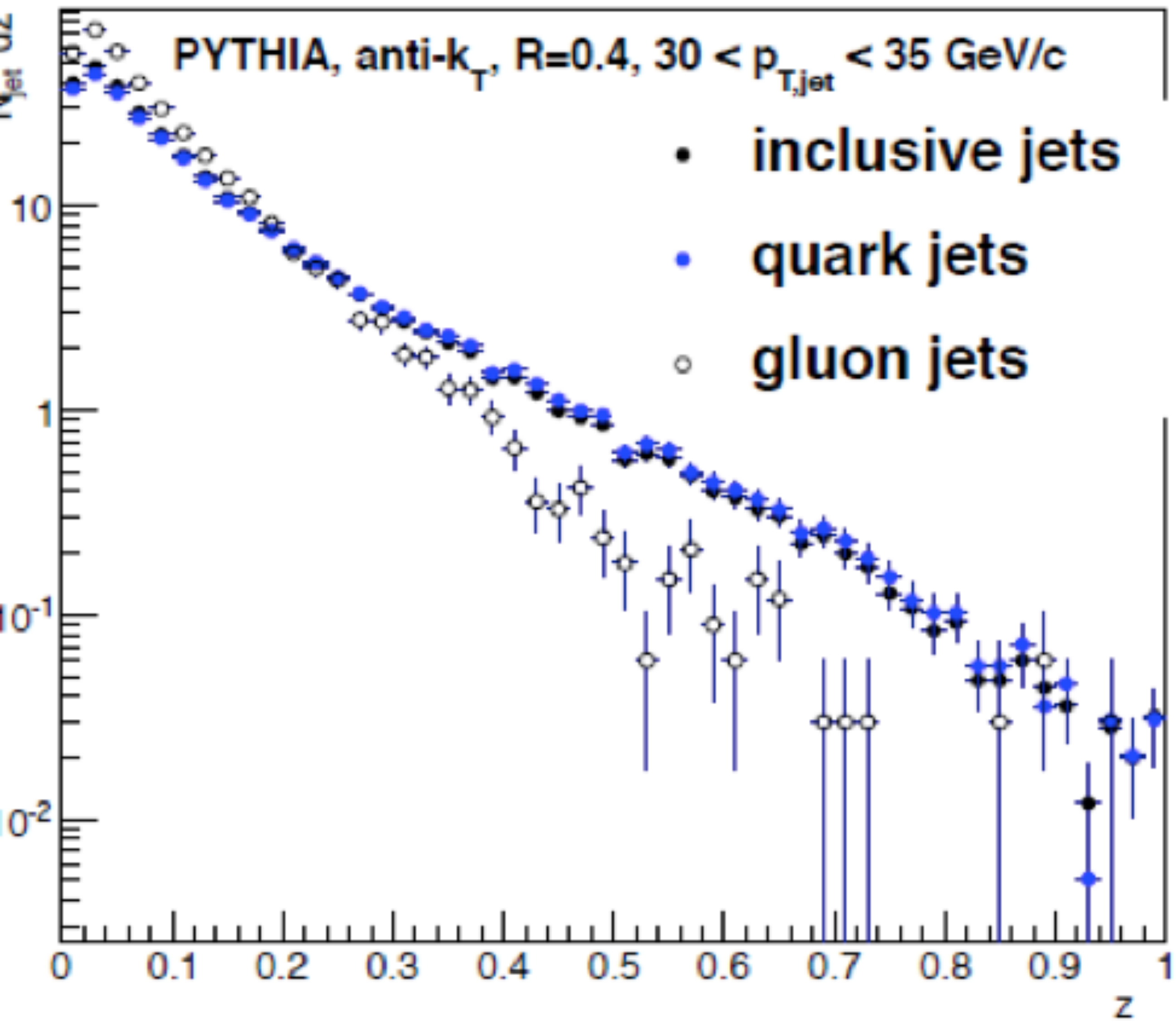
sPHENIX in GEANT4

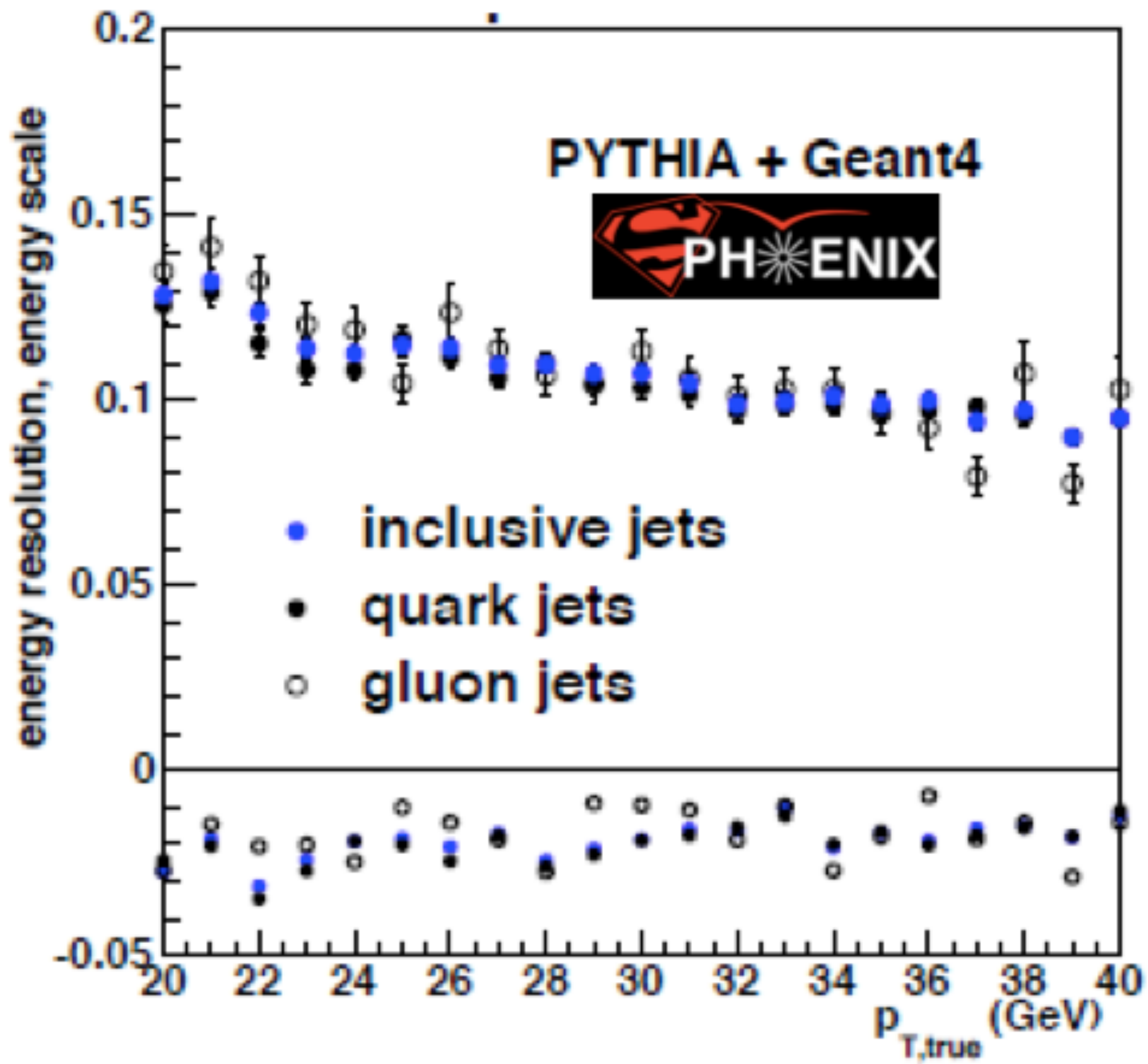


granularity in η x Φ
HCal (both) = 0.1 x 0.1
EMCal = 0.024 x 0.024

Flavor Dependence

Quark and Gluons have very different fragmentation functions

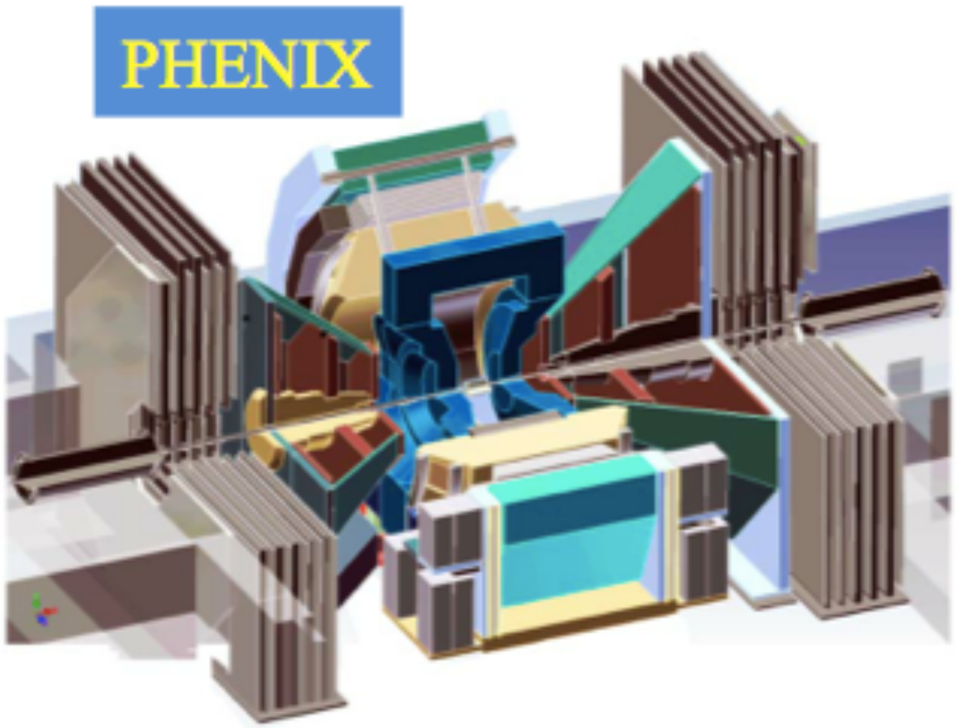




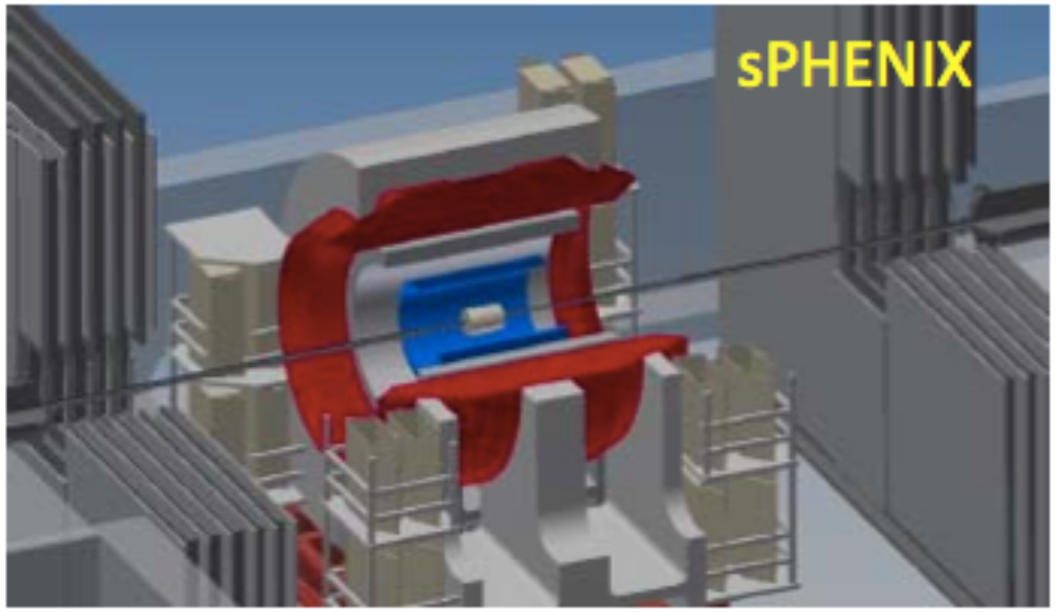
sPHENIX calorimetric measurement gives the same energy scale and resolution.

Critical for extracting longitudinal redistribution of energy.

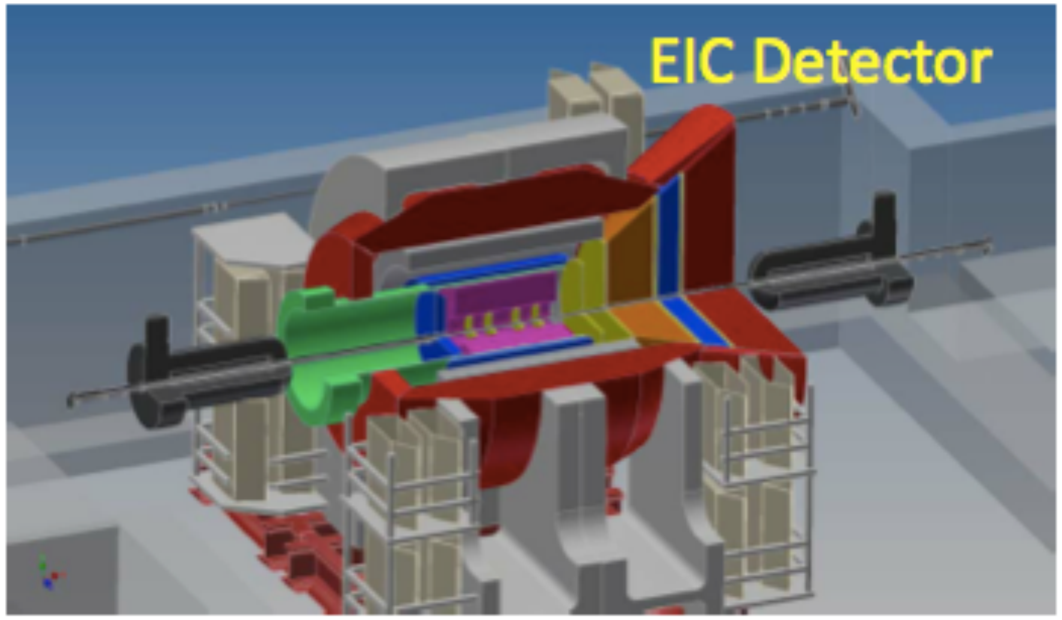
sPHENIX evolution



~2021-22



~2025

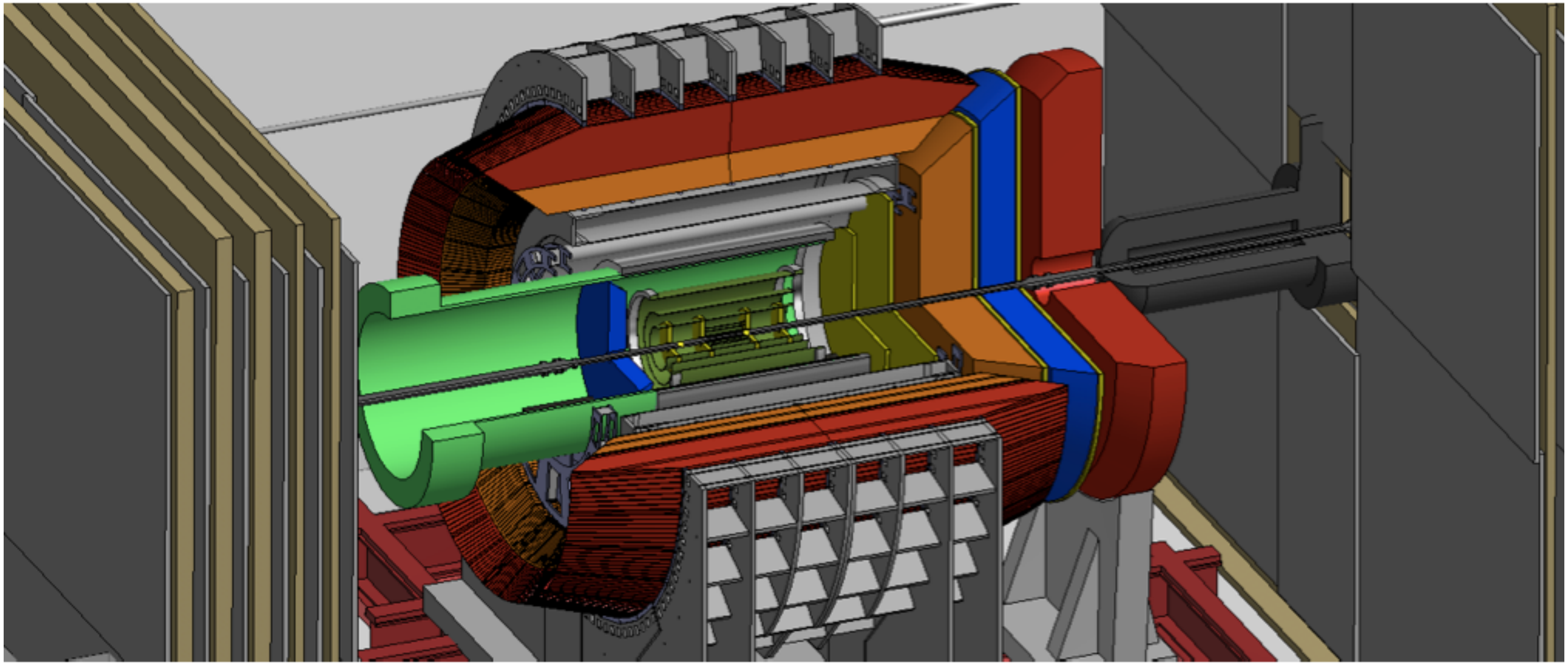


Evolve sPHENIX (pp and HI detector) to an EIC Detector (ep and eA detector):

- ➢ 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 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

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