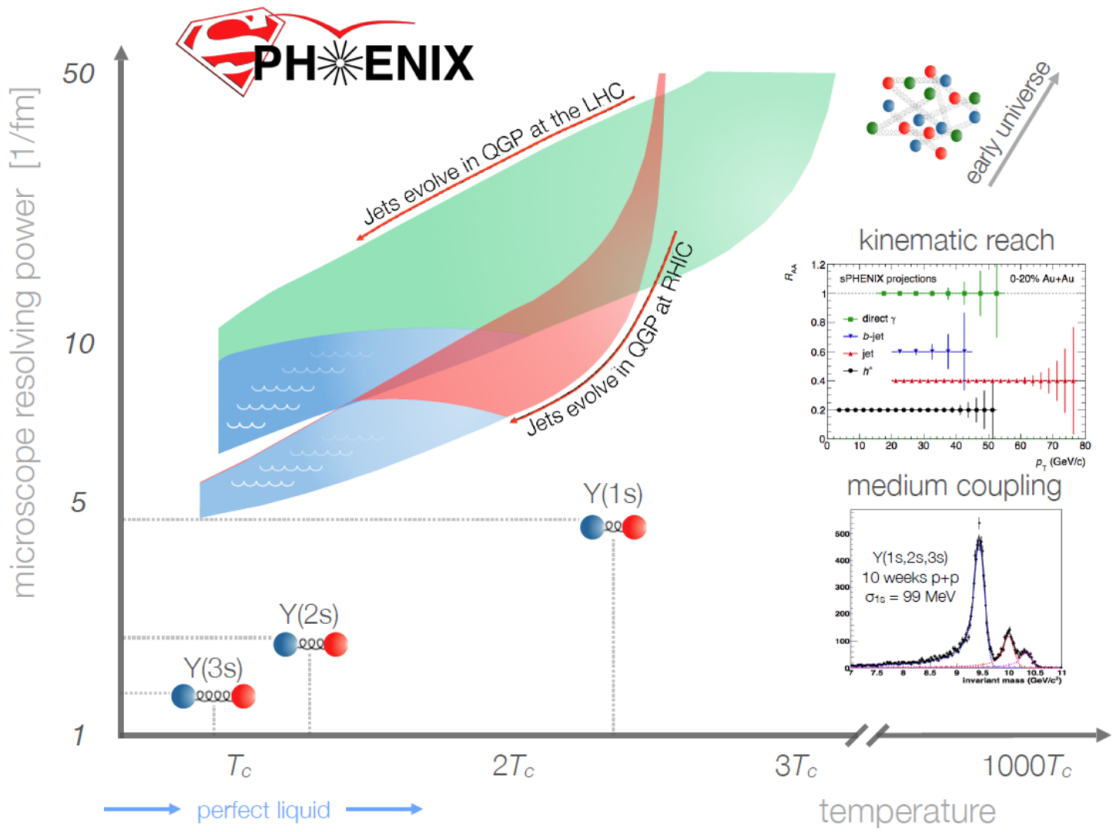
Heavy Flavor and Quarkonia Prospects in sPHENIX

Outline • Physics Case • sPHENIX News • Performance studies • Summary

Jin Huang (BNL)

for sPHENIX collaboration

sPHENIX Physics Program



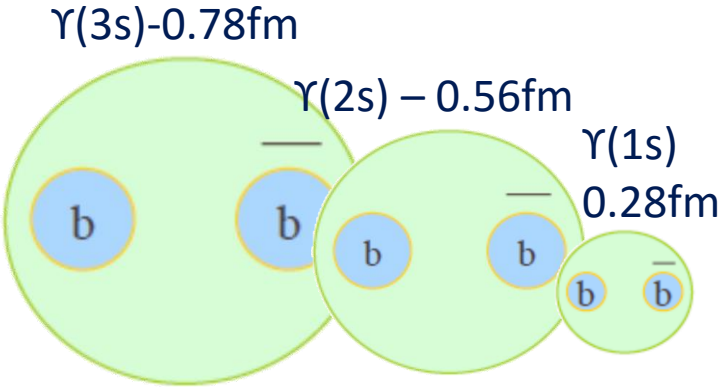
- Detailed inspection of QGP near T_c using probes over a broad range of scales with observables of
  - Jet (inclusive, di-jets, γ-jet)
  - Heavy flavor-tagged jets
  - Separated ϒ(1s), ϒ(2s), ϒ(3s)
- Forward program in development (spin, CNM) and foundation to an EIC detector

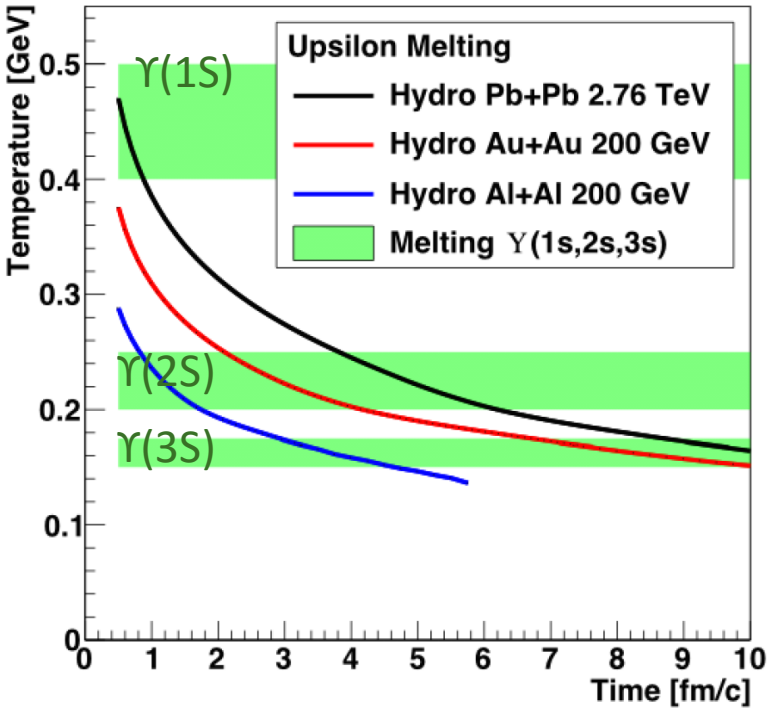
sPHENIX talks in AUM 2016:

- Tue/Spin: Physics Opportunities with Forward Instrumentation in sPHENIX - John Lajoie
- Wed/Jets: Jet measurements with sPHENIX - Sarah Campbell
- Thu/Plenary Session I: sPHENIX - Megan Connors

Three-states-separated Upsilon measurement at sPHENIX

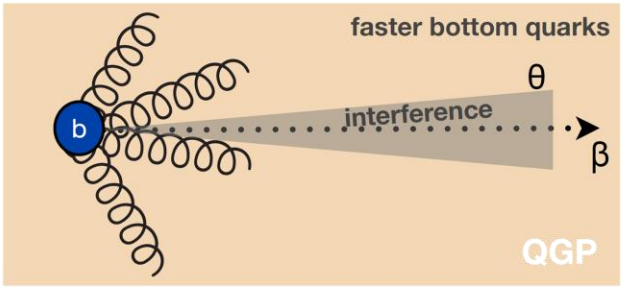
- Upsilons @ RHIC serves as an excellent thermometer around T_c
  - Heavier quark, cleaner theoretical treatment, lower regeneration and CNM eff.
  - Three states of Upsilon mesons are sensitive to very different distance and binding strength
- Lower bottom production rate at RHIC leads to much smaller coalescence for ϒ-production, clean access to color screening and CNM eff.
- Study of coalescence by compare separated- ϒ(2S)-state in comparison to J/ψ yield
- STAR/MTD detector, fully operational in Run14, will first extract 3-states yield at RHIC through fitting (see *Yang's* talk). sPHENIX will provide much better resolution of three states and x7 acceptance

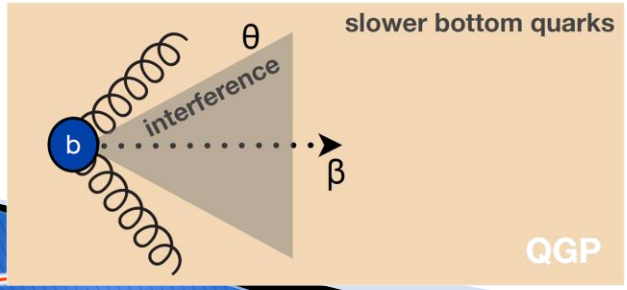


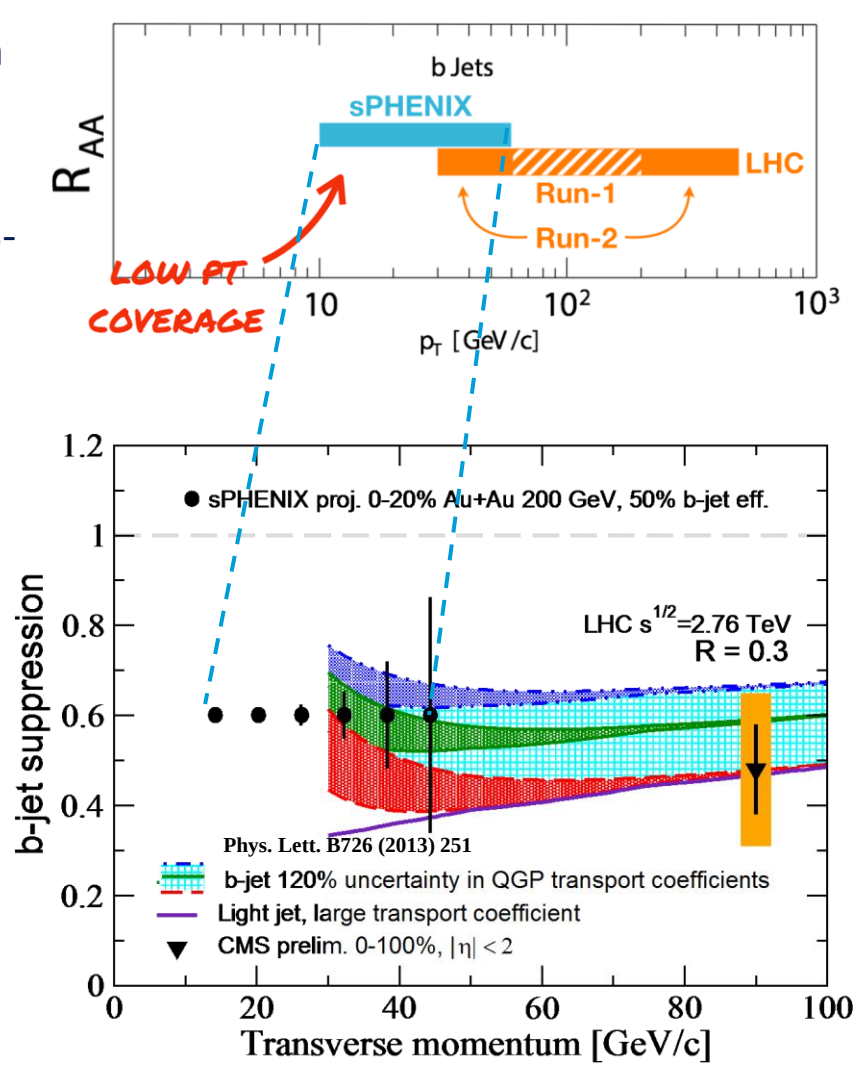


B-tagged jets in sPHENIX

- Heavy quarks traversing the quark-gluon plasma are an excellent test of our understanding of the mechanisms of parton energy loss.
- New tool to study @ RHIC via sPHENIX B-tagged jets
- Allow lower p_T reach, that is sensitive to constraint transporation models

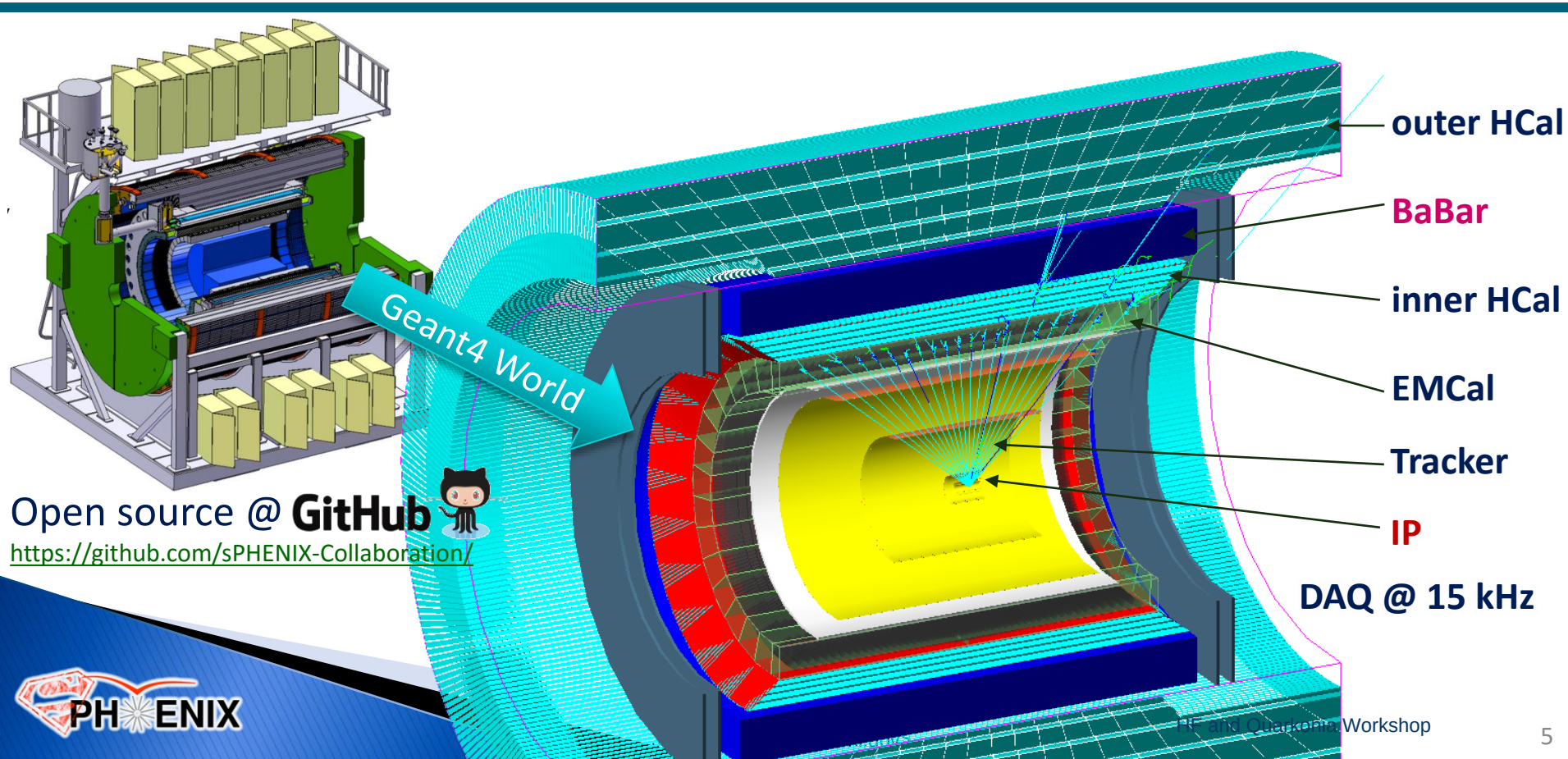






sPHENIX detector in CAD and Geant4

- Tracker: vertex tracker + outer tracker with few options (ref: MAPS inner + gateless TPC)
- EM calorimeter (EMCal) : 18 X_0 SPACAL
- Inner hadron calorimeter (inner HCal) : ~1 λ_0 SS-Scint. sampling
- BaBar coil and cryostat: B_0 = 1.4 T 1.4 X_0 Coil & Cryostat
- Outer hadron calorimeter (outer HCal) : ~4 λ_0 SS-Scint. sampling



Open source @ GitHub
https://github.com/sPHENIX-Collaboration/

Project News from last User Meeting

- June 2015: Call for new collaboration
- Nov 2015: Cost schedule review
- Dec 2015: First collaboration meetings
- Early 2016: Formation of topical groups
- Apr 2016: Calorimetry beam test
- Series of sPHENIX work-fest on calorimeters, forward opportunities, MAPS tracker, HF-jet

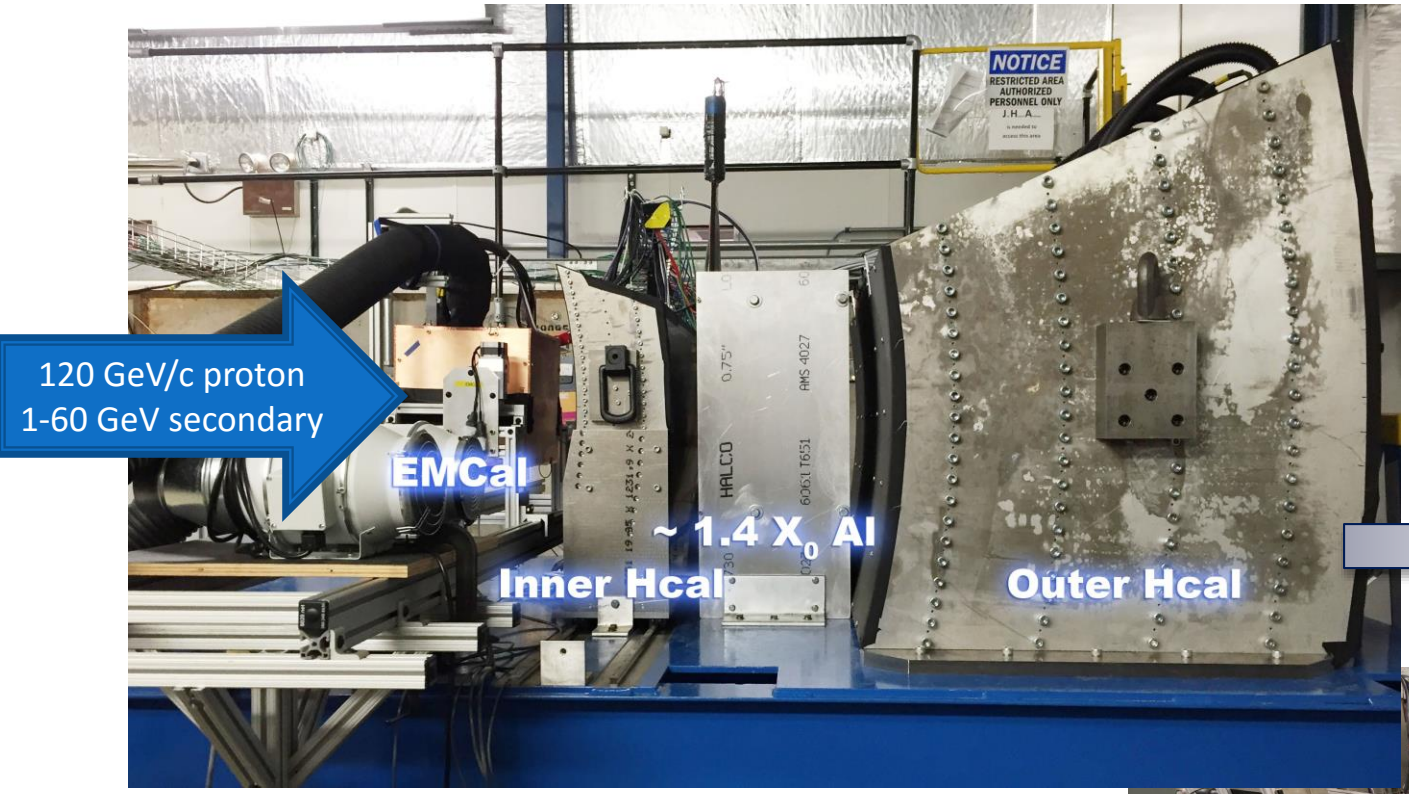
MAPS workfest

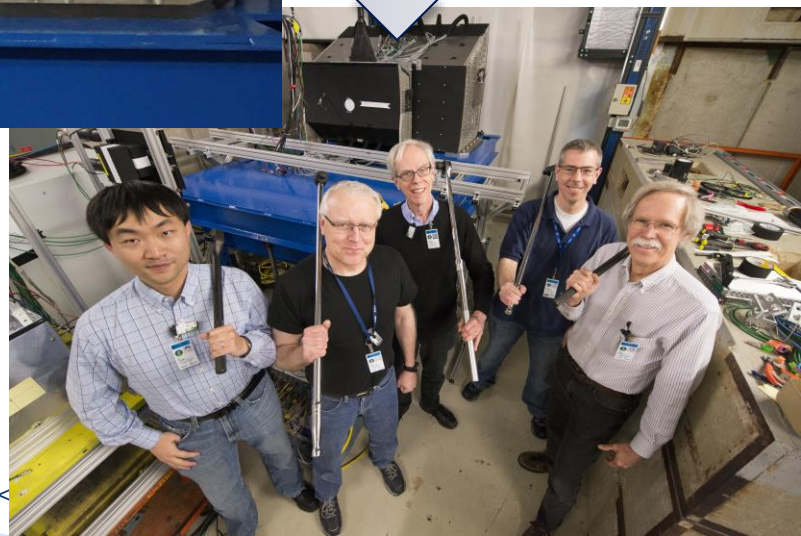
HF-jet workfest

Forward workfest

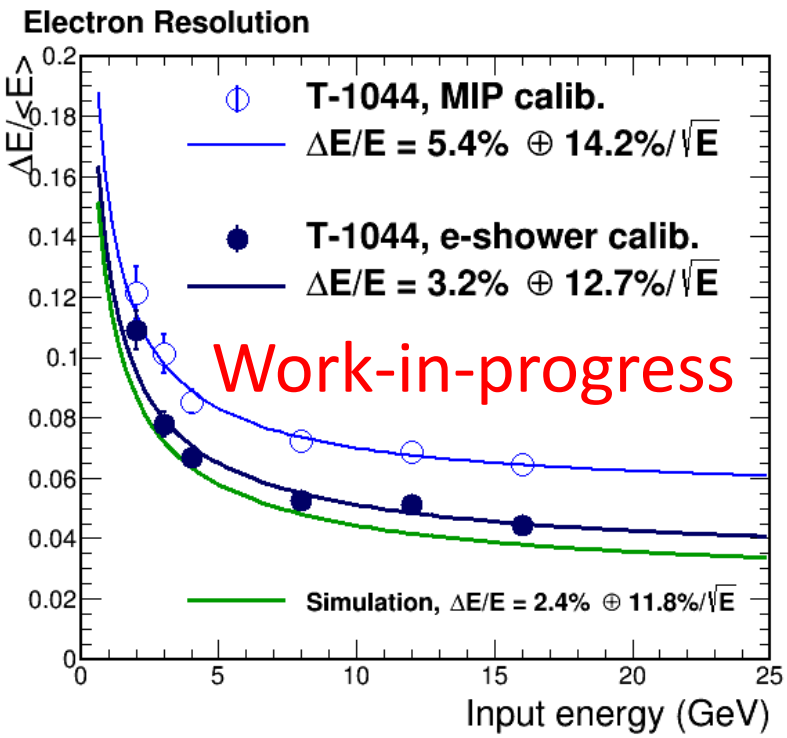
Dec 2015 Collaboration Meeting

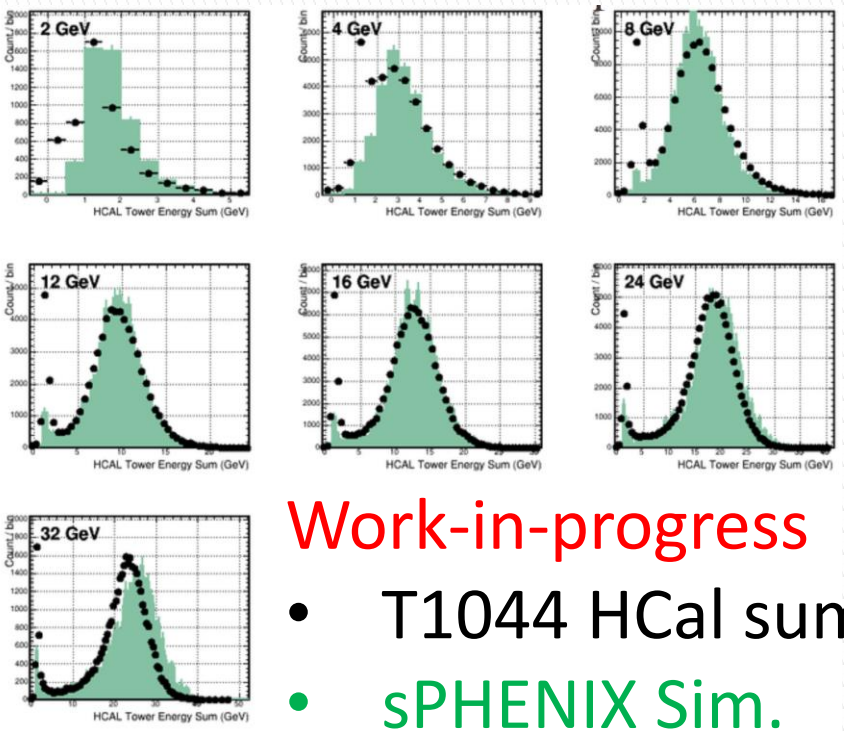
sPHENIX news – Beam Test





sPHENIX news – Beam Test Preliminary results





Work-in-progress

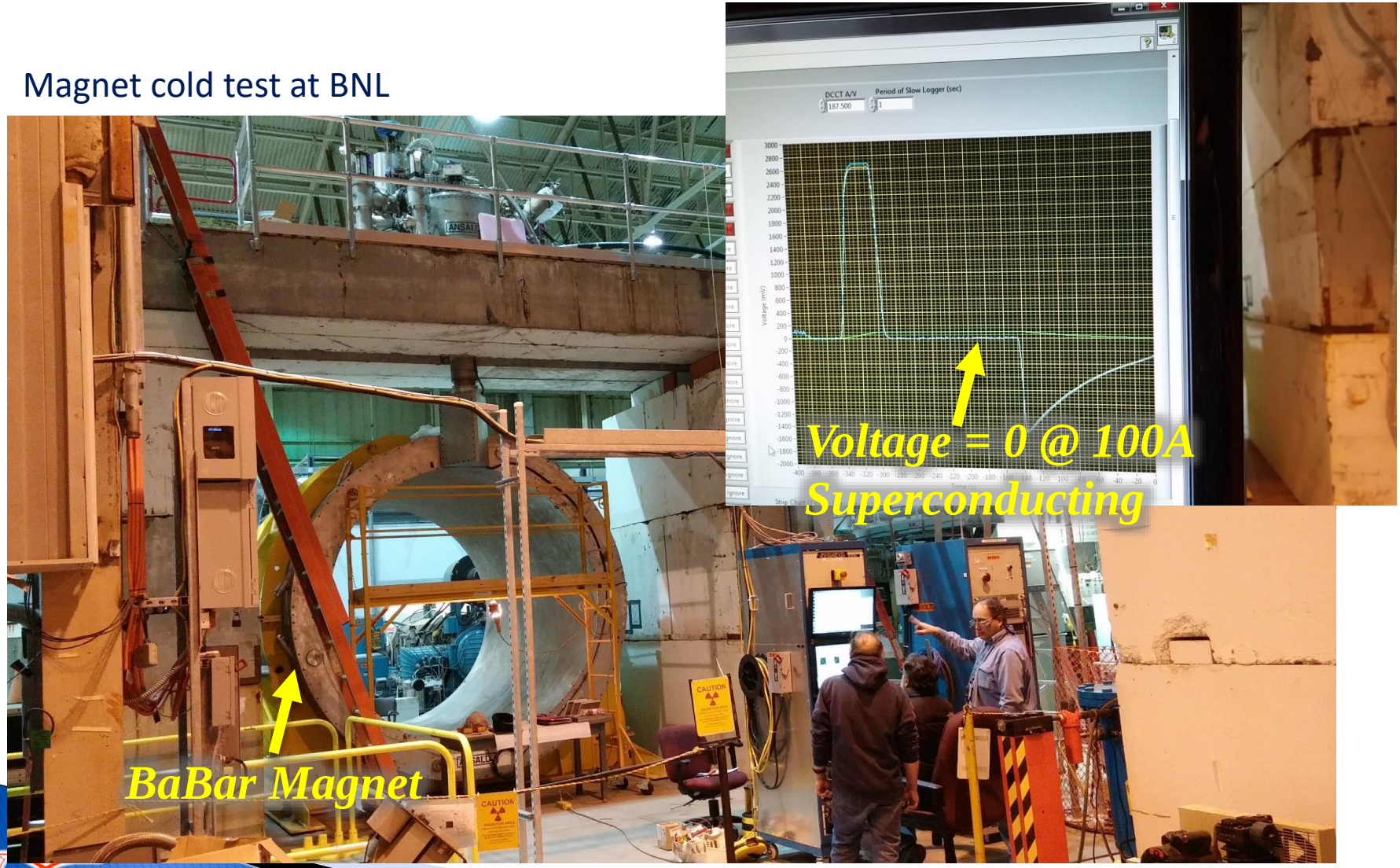
- T1044 HCal sum
- sPHENIX Sim.

EMCal energy resolution

Inner + Outer HCal line shape

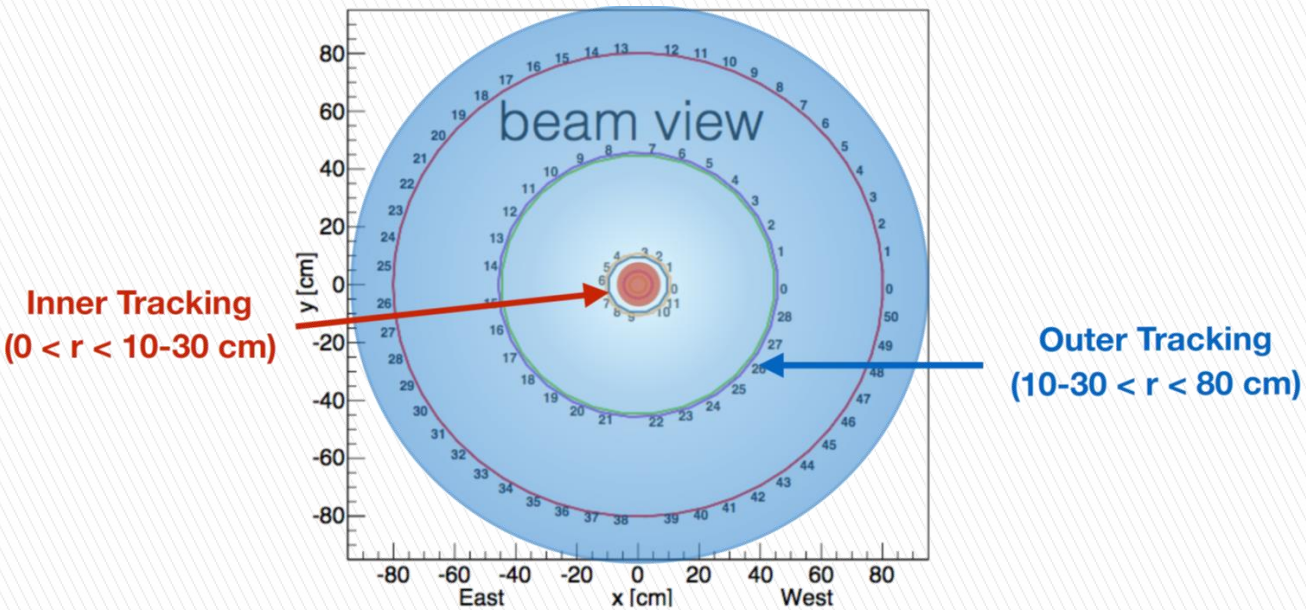
sPHENIX news – Magnet test @ BNL

Magnet cold test at BNL



Tracking options under study

Down-selection expected tracking review later 2016



Inner Tracker

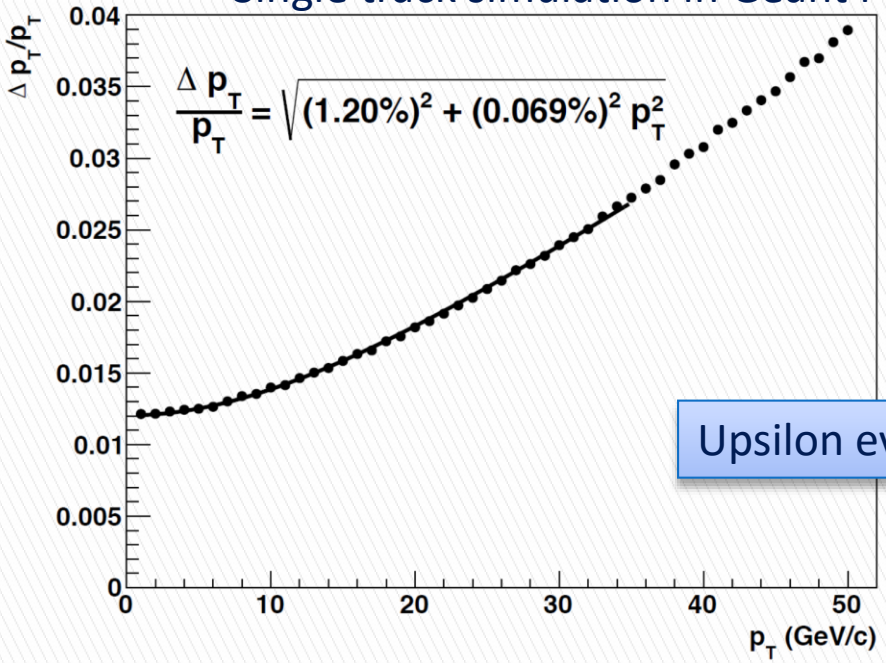
- Goals:
  - Precision DCA
  - Primary/secondary vertex finding
  - Assist Pattern recognition
- Options studied/studying
  - [Reference] 2/3 MAPS layers based on ALICE stave R&D
  - Restacking PHENIX vertex detector

Outer Tracker

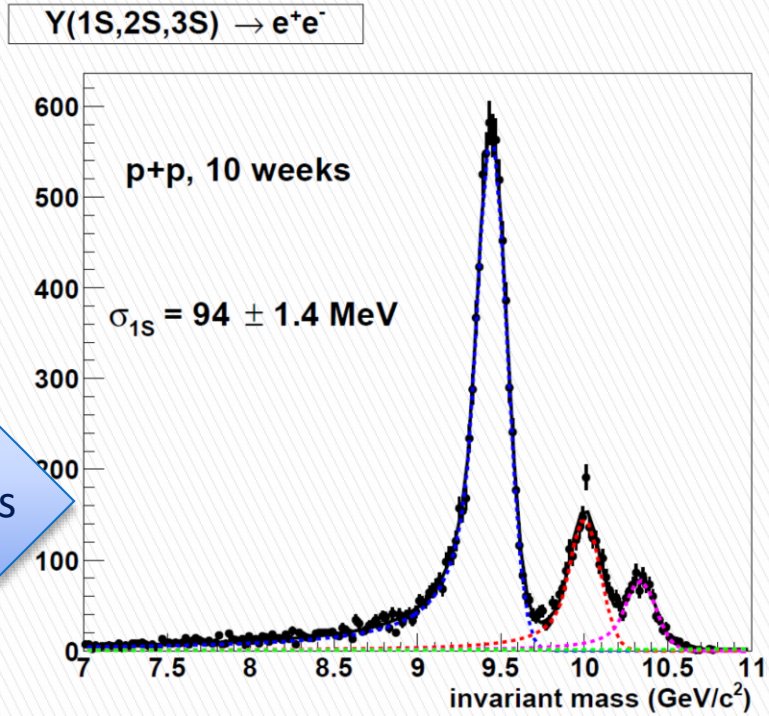
- Goals:
  - Momentum measurement
  - Pattern recognition
- Options studied/studying
  - [Reference] gateless TPC
  - Silicon strip tracker
  - MAPS tracker

Tracking : momentum resolution

Single track simulation in Geant4



Upsilon events



Single track performance (Silicon tracking option)

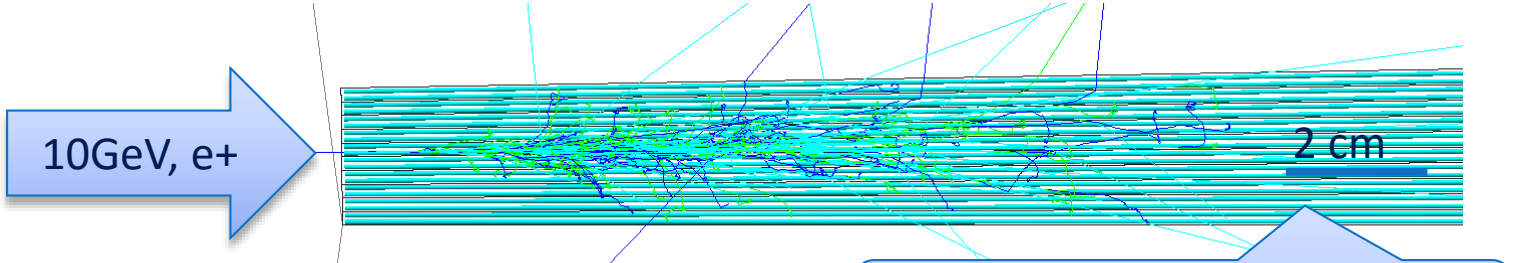
Invariant mass for e^+e^- pairs (Silicon tracking option)

TPC option is under study. Preliminary result indicates better performance in Upsilon mass resolution

Electron ID: EM Calorimeter

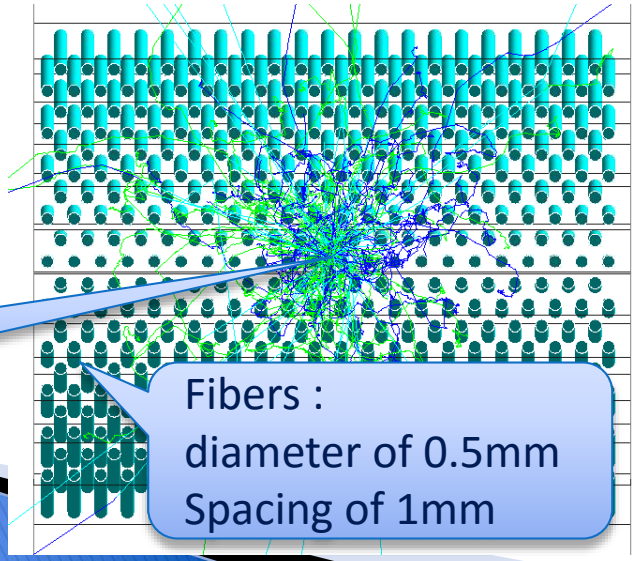
- Electron ID using a compact EMCal with assistance from inner HCal
- Scintillation fiber-W powder sampling calorimeter (SPACAL) used in reference design and first developed by UCLA. $dE/E < 15\%/\sqrt{E}$
  R_M~2 cm, X_0~0.7 cm, critical for background reduction in AA collisions
- Reference design covers full azimuthal and $|\eta|<1.1$ in sPHENIX

Side view



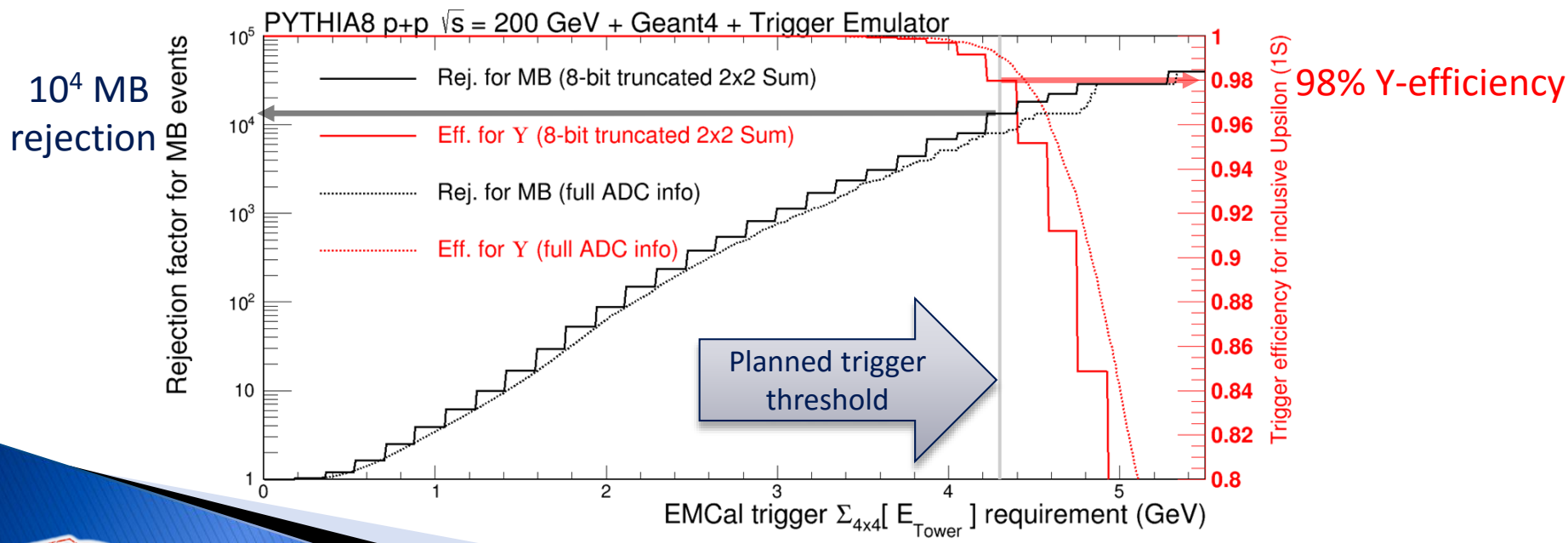
Particle view

1 cm



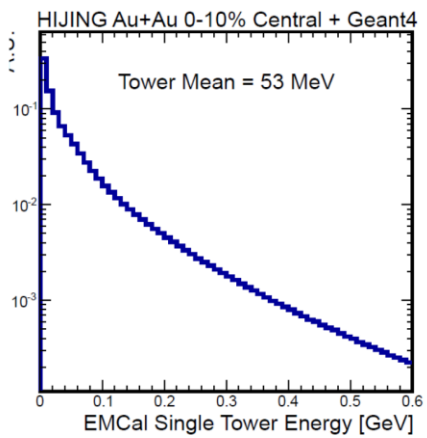
Trigger Performance

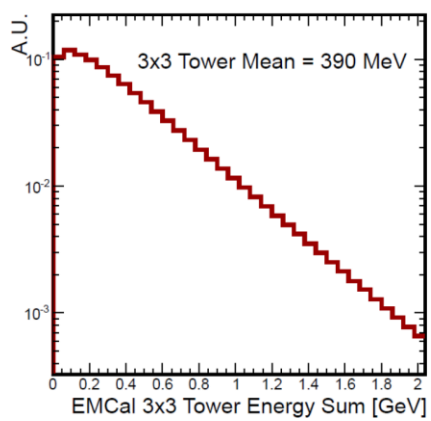
- Most challenging is trigger in pp for rare Upsilon signal
  - Simulated in trigger emulator with truncated ADC bits
  - > 5000:1 rejection with 98% Upsilon efficiency, fit Upsilon in the sPHENIX DAQ bandwidth (15 kHz)
- Jets trigger via calorimeter patch-sum too

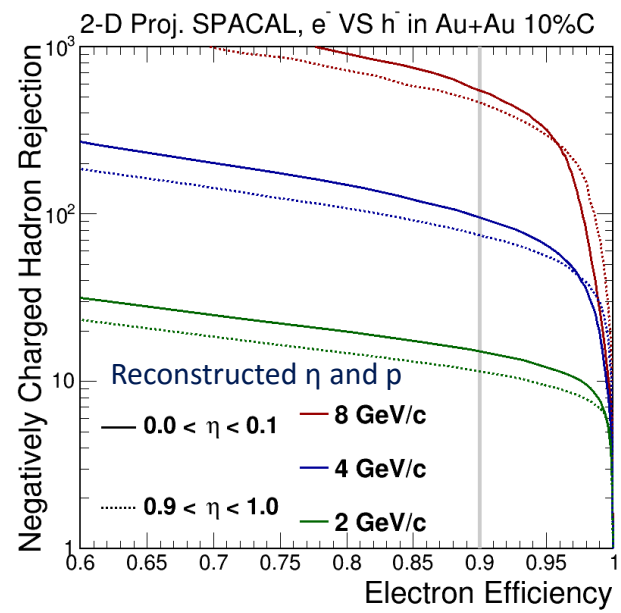


Electron ID: HIJING event in Geant4

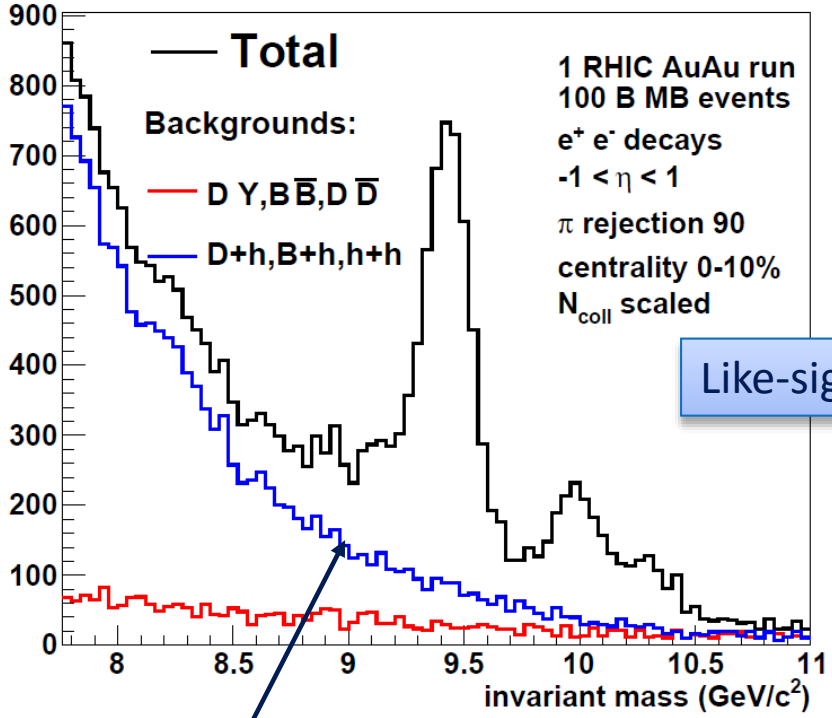
- Large scale HIJING+Geant4 simulation performed with detailed implementation of calorimeters
  22M scintillation fibers with thousands of particle showers in each Geant4 event
- Event background distribution in Central AuAu, showing background for electron ID under control thanks to the high density EM calorimeter.



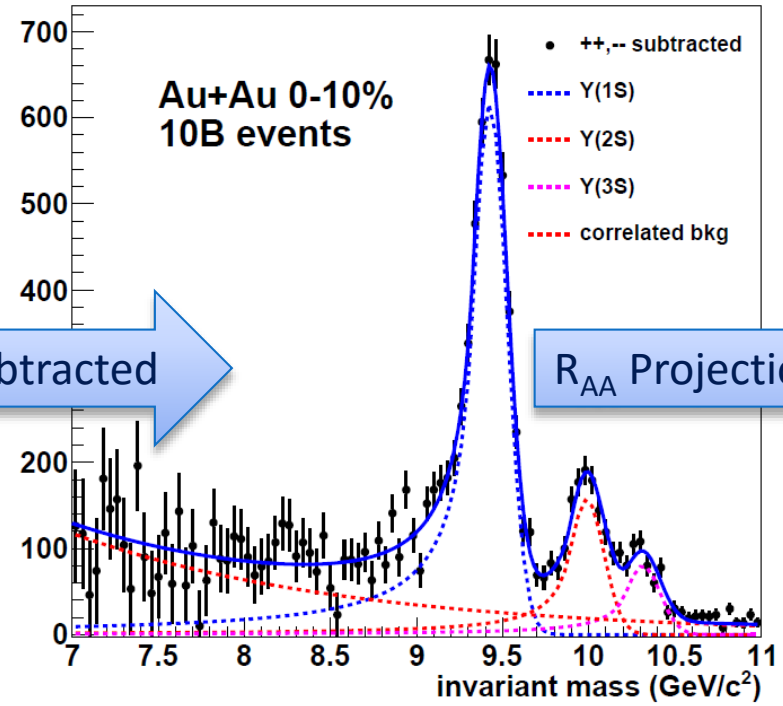




Electron ID: Performance in identified e^+e^- pairs



Like-sign subtracted

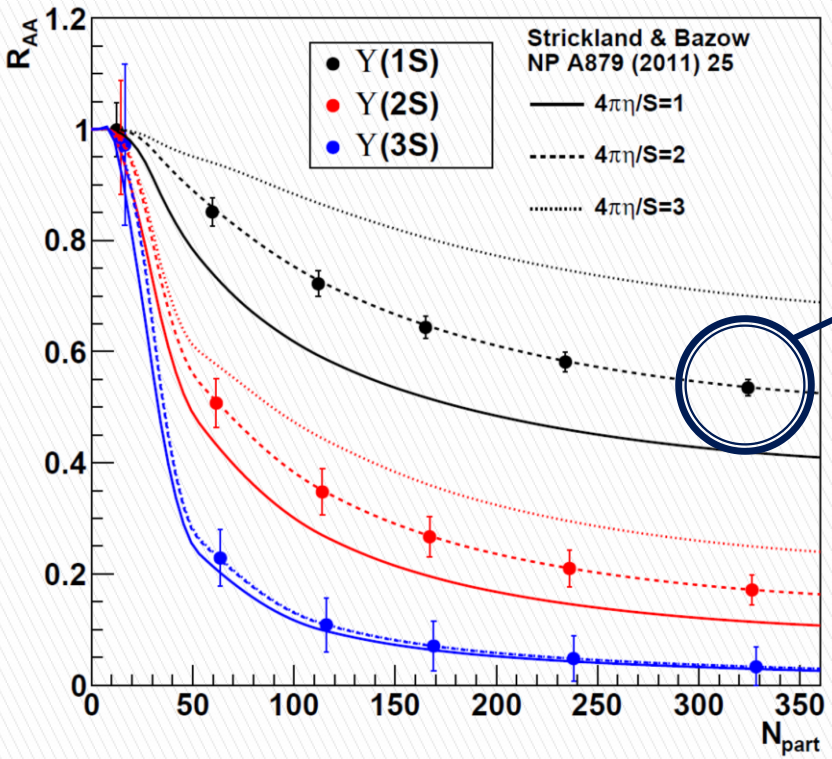


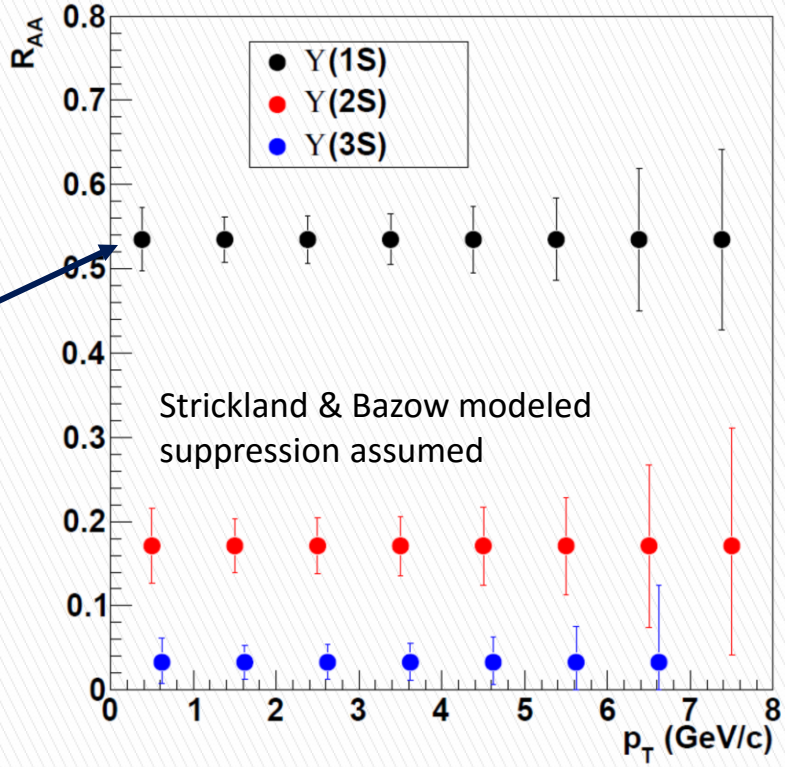
R_{AA} Projections

Background of mis-identified hadron

Differential Suppression in Au+Au

Stringent constraint to theoretical models over different length scales at RHIC energy





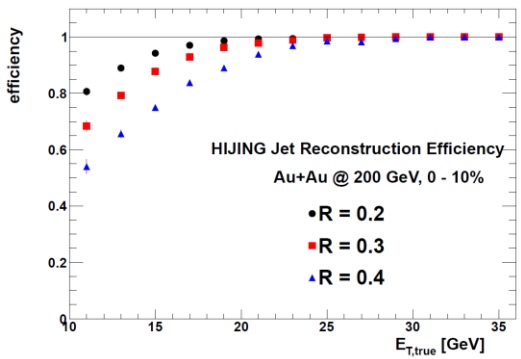
Centrality dependency

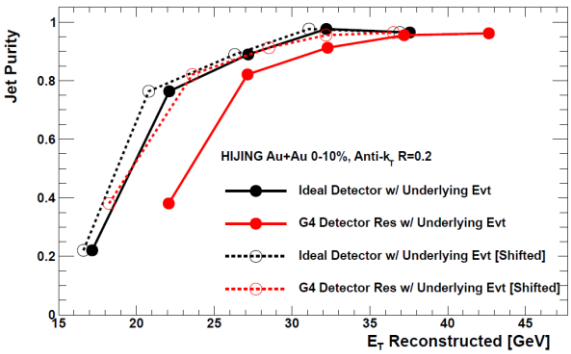
pT dependency

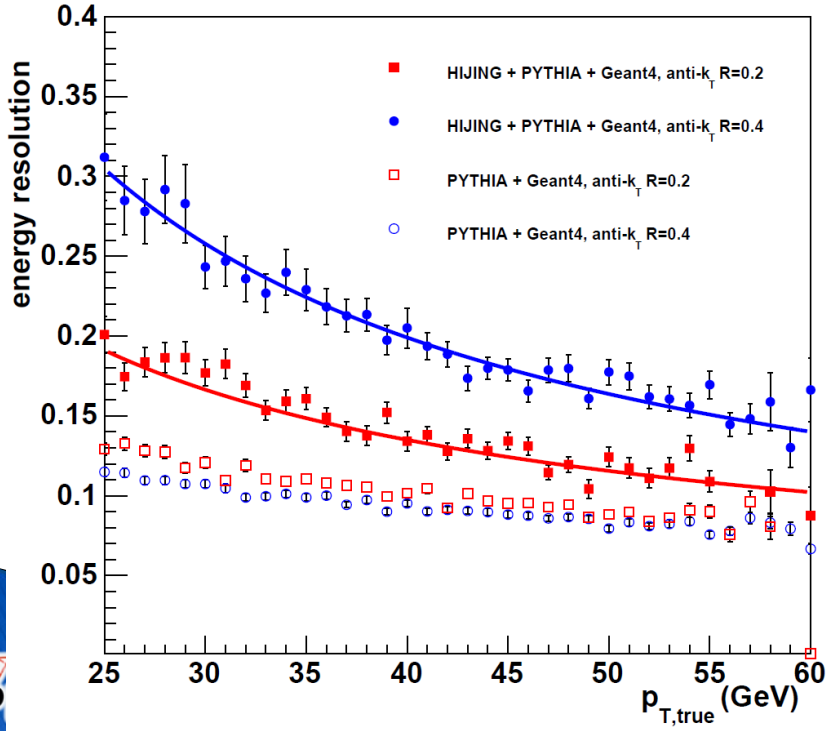
sPHENIX Jets in sPHENIX

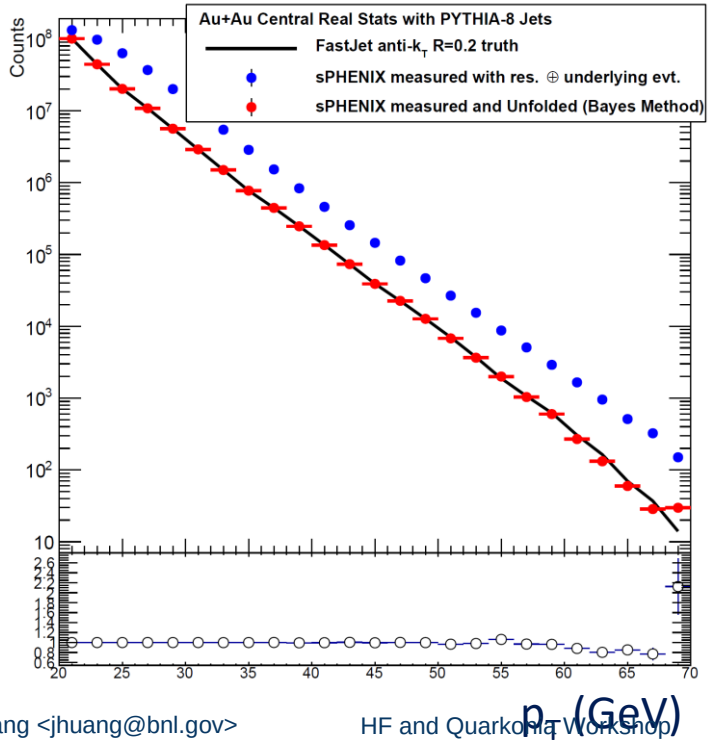
More: Wed/Jets workshop Jet measurements with sPHENIX - Sarah Campbell

- Algorithm developed based on ATLAS and CMS heavy ion experience
- Good efficiency and purity
- Resolution/tails fit for unfolding jet spectrum
- Updates as detector design/performance evolves



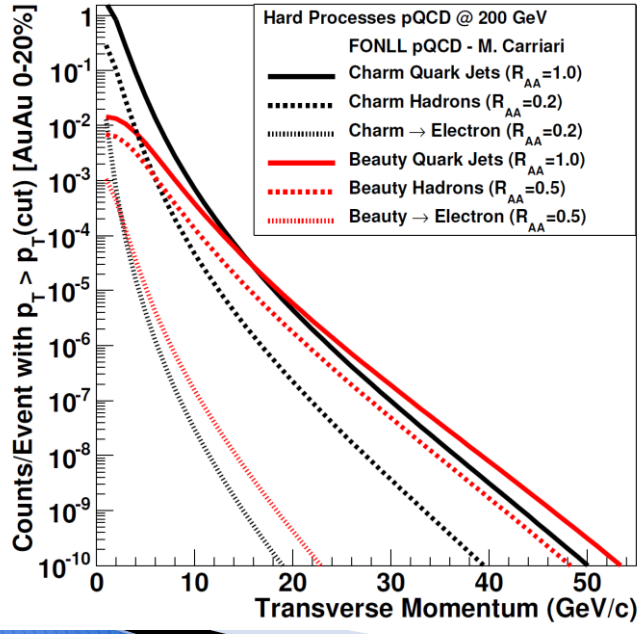


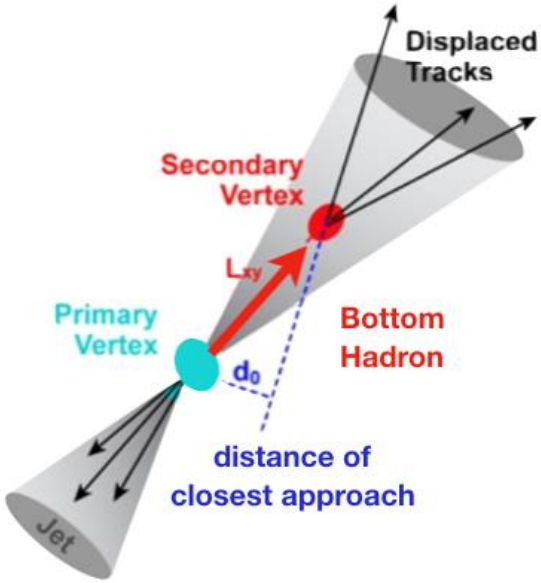




Tagging B-jets in sPHENIX

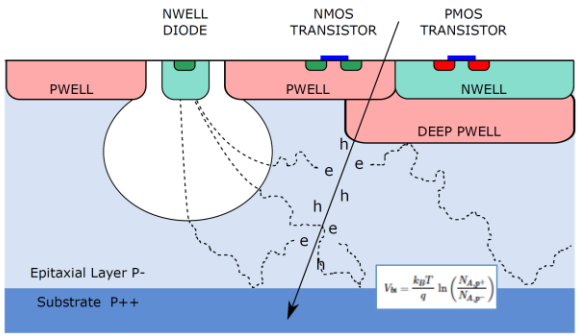
- In short length scale, sPHENIX utilize jet as precision probe
- HF-tagged jet, in particular B-jet provide additional nob of parton-mass relative to jet energy, powerful in differentiating energy-loss mechanism and transpiration models
- Tagging of B-jet, based on life time and decay features



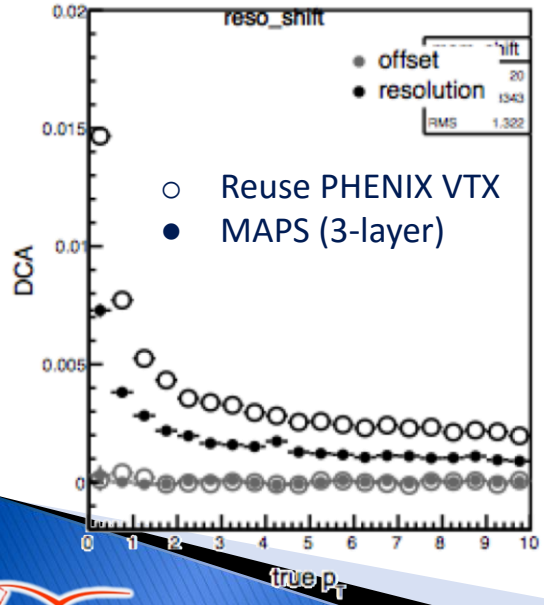


Inner tracker performance

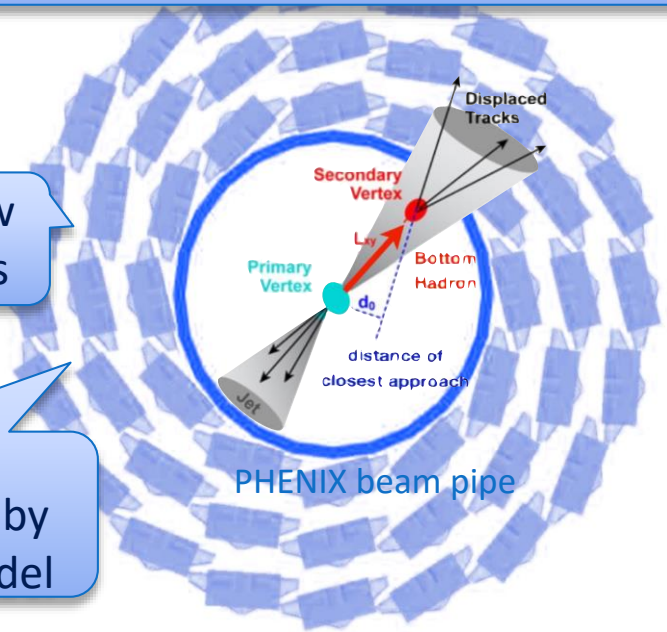
- Inner track is key element in b-jet tagging
- Reference inner tracker use MAPS staves of ALICE design, stacked in sPHENIX acceptance
- Expect larger acceptance, higher precision and efficiency compare to restacked PHENIX vertex tracker



ALICE MAPS stave in sPHENIX simulation
Study on-going

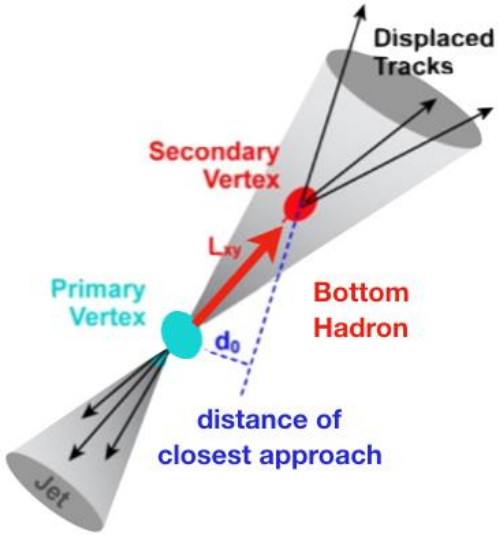


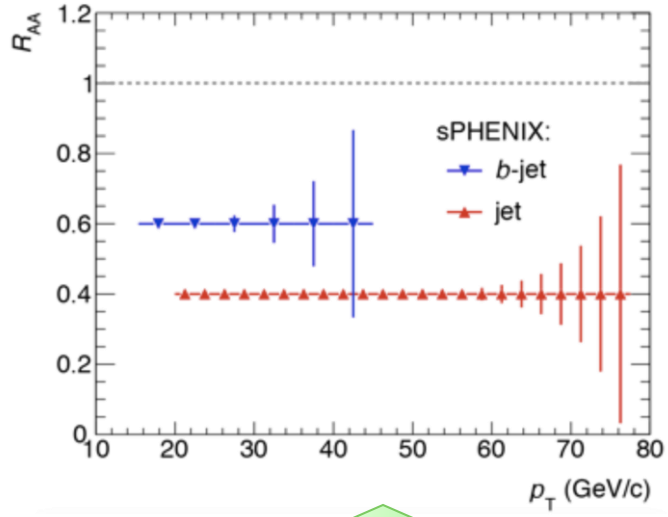
Stave layout follow sPHENIX demands



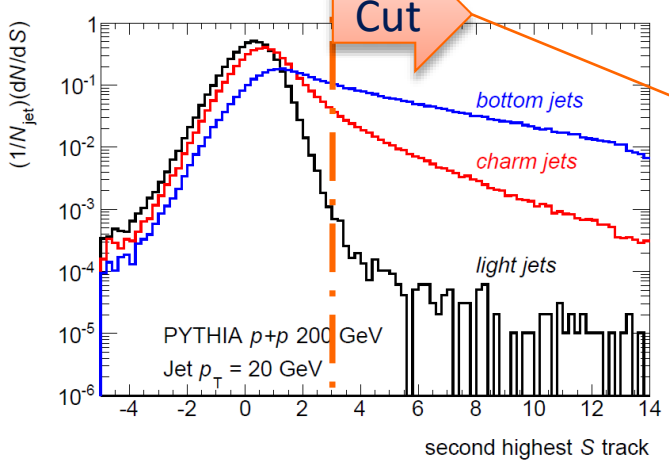
Stave geometry simulated in details by importing ALICE model

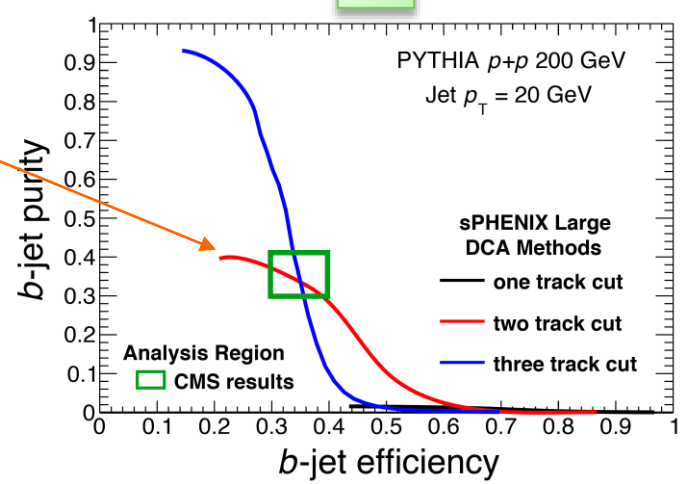
B-jets tagger in sPHENIX based on high-DCA track counting





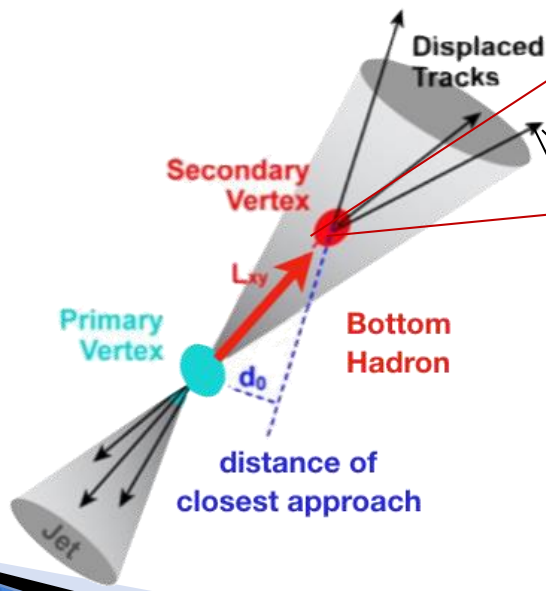
Cut

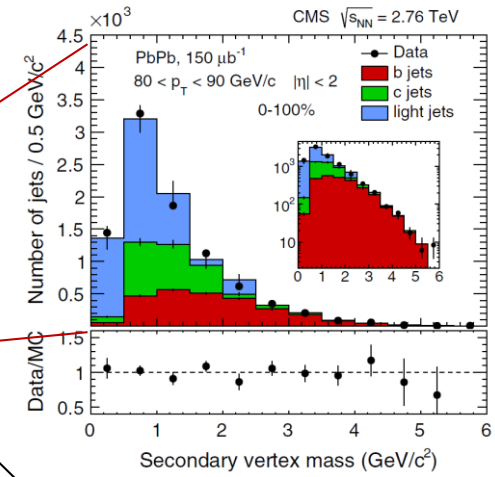


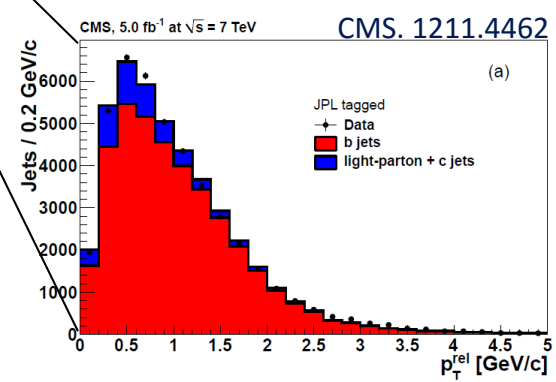


In-developing B-jets tagger in sPHENIX

- Identify B-jets via the higher-inv-mass secondary decay vertex
  - Implementing general purpose Kalman filter and vertex finder to systematically study in sPHENIX
- Cross checking B-jet tagging efficiency by analyzing electron inside jet cone
  - Orthogonal to life-time based tagger, does suffer from branching ratio of electron decay
  - Suppress gluon-splitting contributions







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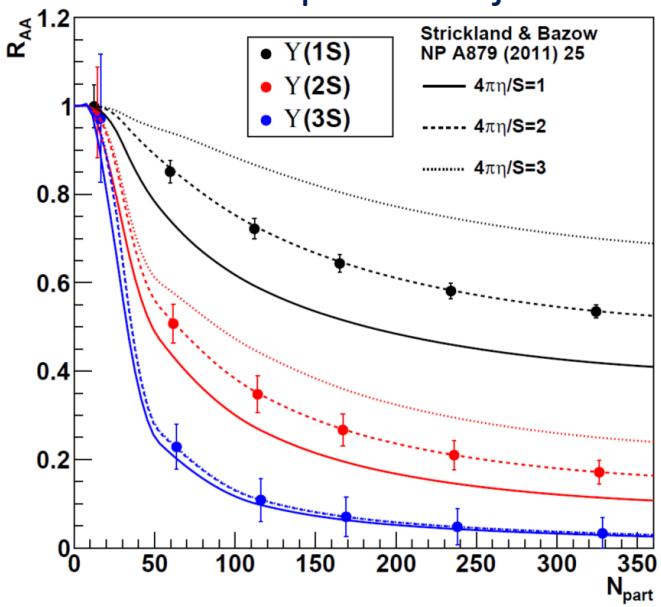
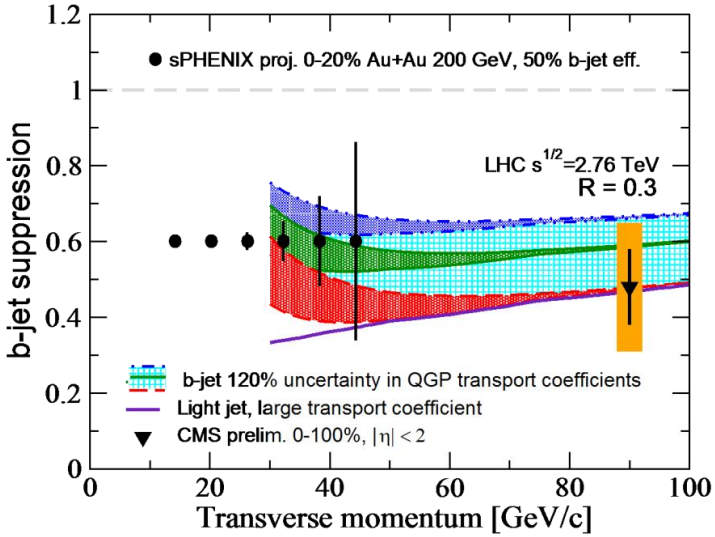
Summary

- sPHENIX - inspection of QGP near T_c using probes over a broad range of scales
- B-tagged jets – transportation of heavy quark in QGP
- High precision Upsilon spectroscopy – long distance probe over three very different length
- Abundant opportunities to contribute and open for suggestions
  - E.g. D→πK, B→J/ψ, J/ψ@High p_T, etc.

sPHENIX Upsilon Projection



sPHENIX B-tagged Jet Projection



Extra information

Internal discussion: talk info

- Session: Heavy Flavor and Quarkonia
- Date, Time: Tuesday, June 7, 2016, 04:00-04:30
- Length: 30min, expected talk 25min
- Related talks
  - Tue/HF workshop: PHENIX/STAR/LHC results talk
  - Tue/Spin: Physics Opportunities with Forward Instrumentation in sPHENIX - John Lajoie
  - Wed/Jets: Jet measurements with sPHENIX - Sarah Campbell
  - Thu/Plenary Session I: sPHENIX - Megan Connors

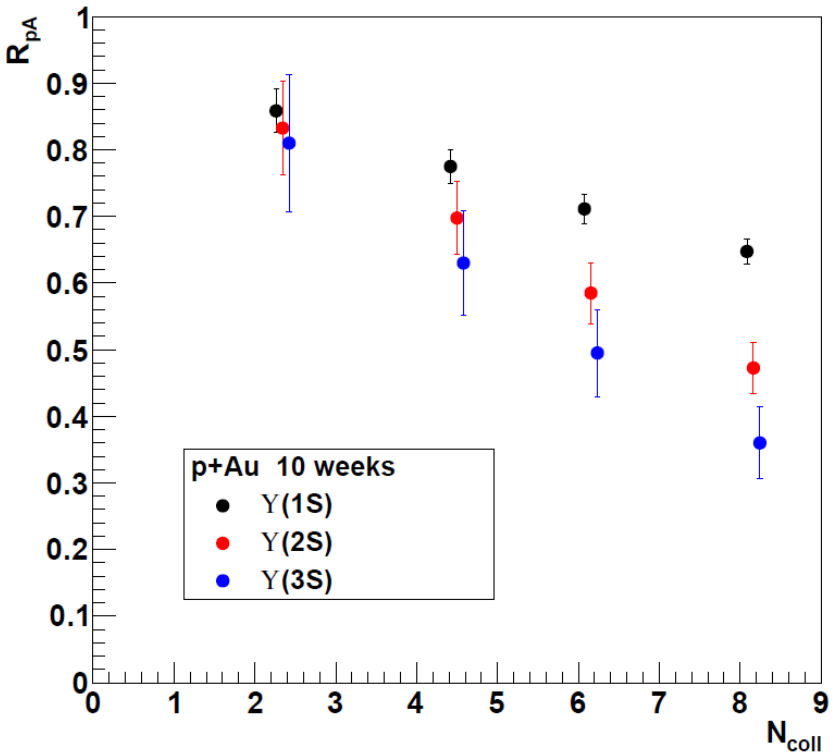
Proposed Running Time

- Baseline sPHENIX program consists of
  - 1 year of commissioning run and 2 years of production
  - 22 week of Au+Au running, 100B MB event recorded
  - 10 week of p+p and p+A each, EMCal trigger used
- Projected yield with detection efficiency applied summarized below

Species	$\int \mathbf{L\,dt}(\lvert\mathbf{Z}\rvert < \mathbf{10cm})$	Events	$\langle N_{coll} \rangle$	eID eff.	Υ(1S)	Υ(2S)	Υ(3S)
$p+p$	175 pb^{-1}	7350 B	1	0.9	8770	2205	1155
Au+Au (MB)		100 B	240.4	0.57	16240	4080	2140
Au+Au (0–10%)		10 B	962	0.49	5625	1415	740
p+Au (MB)	960 nb^{-1}	1680 B	4.3	0.84	6560	1650	860
p+Au (0–20%)		336 B	8.2	0.8	2360	592	311

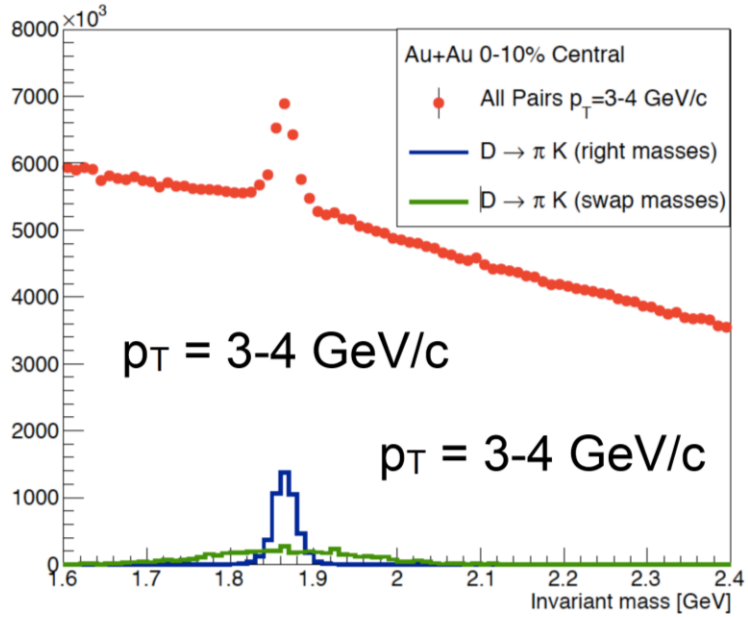
(Before suppression)

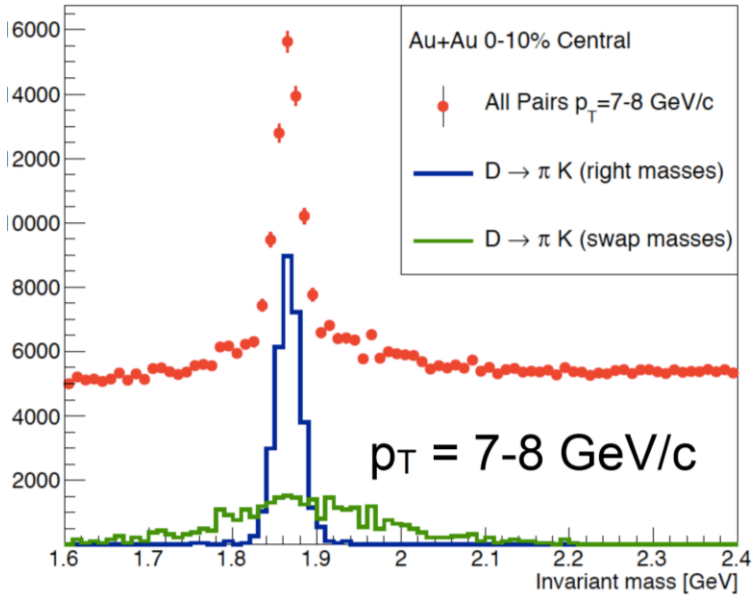
Differential Suppression in p+Au



- Baseline for understanding Au+Au collisions
  + access to Quark energy loss, final state effect, medium effect
- Large pT coverage and 2-unit of rapidity dependency investigates the initial state PDF and energy loss
- At lower binding energy, ϒ(2s), ϒ(3s) tests suppression mechanism in pA in complimentary to LHC and ψ' channels

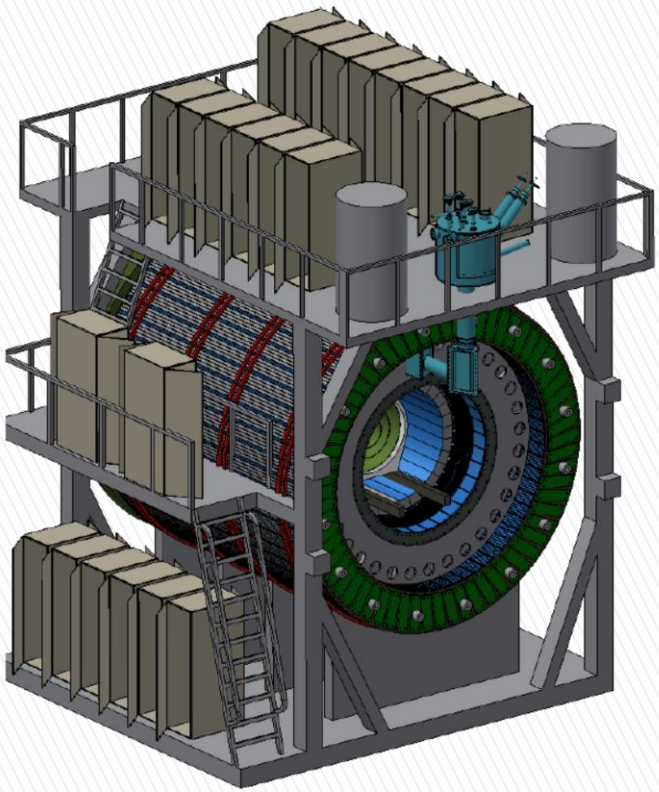
D meson

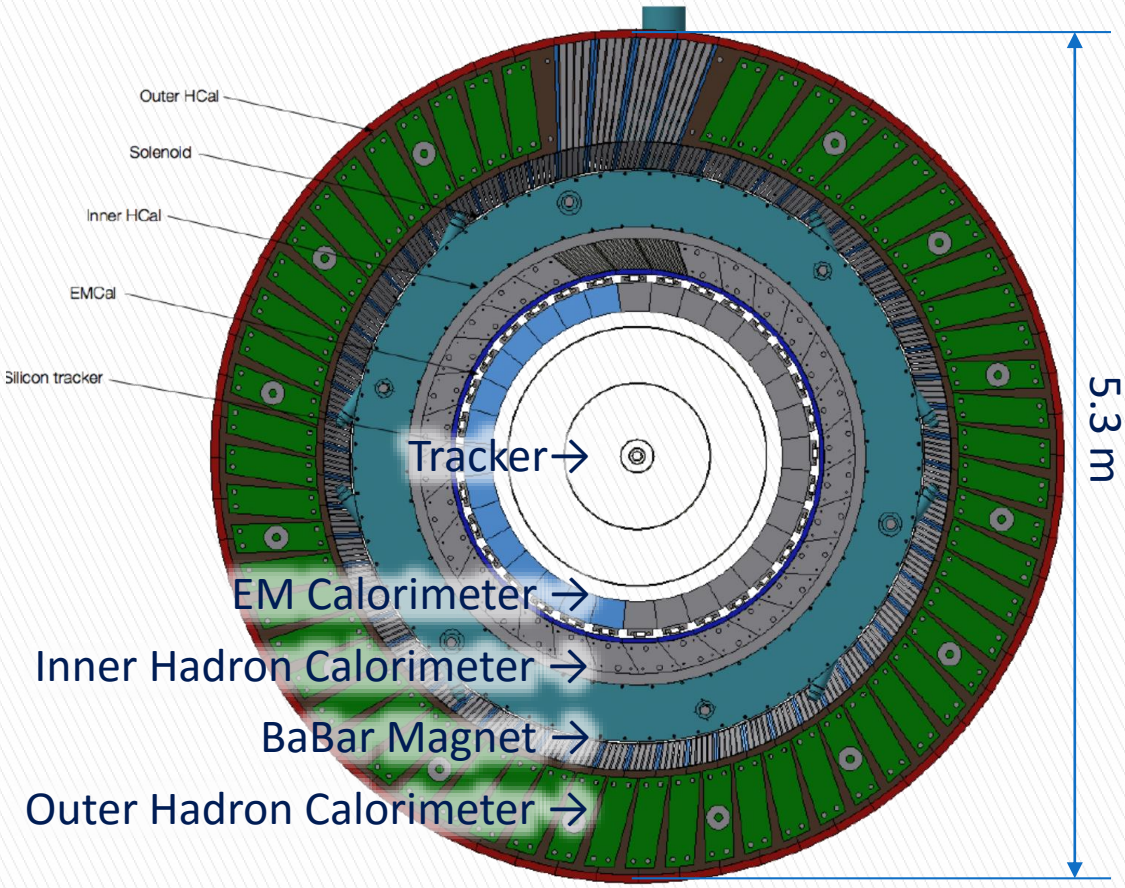

Au+Au 0-10% Central
All Pairs p_T=3-4 GeV/c
D → π K (right masses)
D → π K (swap masses)
p_T = 3-4 GeV/c
p_T = 3-4 GeV/c
Invariant mass [GeV]


Au+Au 0-10% Central
All Pairs p_T=7-8 GeV/c
D → π K (right masses)
D → π K (swap masses)
p_T = 7-8 GeV/c
Invariant mass [GeV]

sPHENIX experiment

See more: Plenary Talk M. Corners



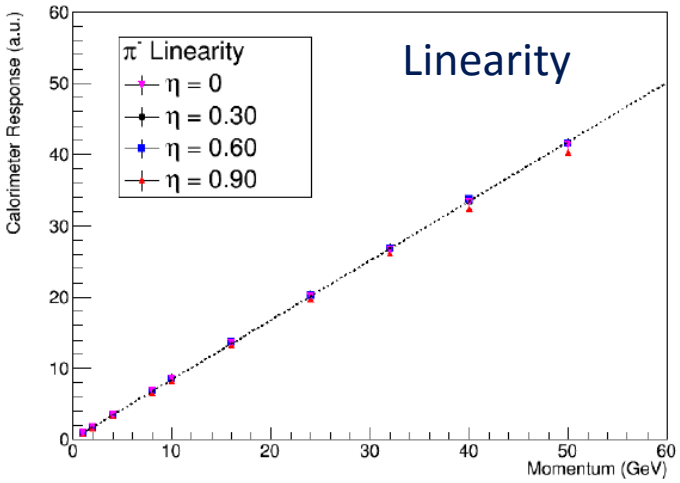


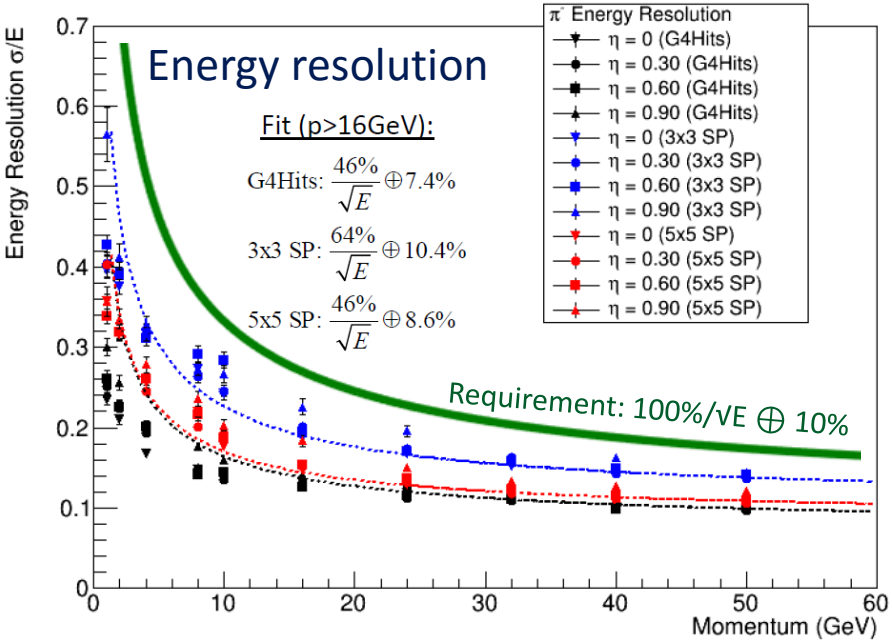
Detailed CAD model

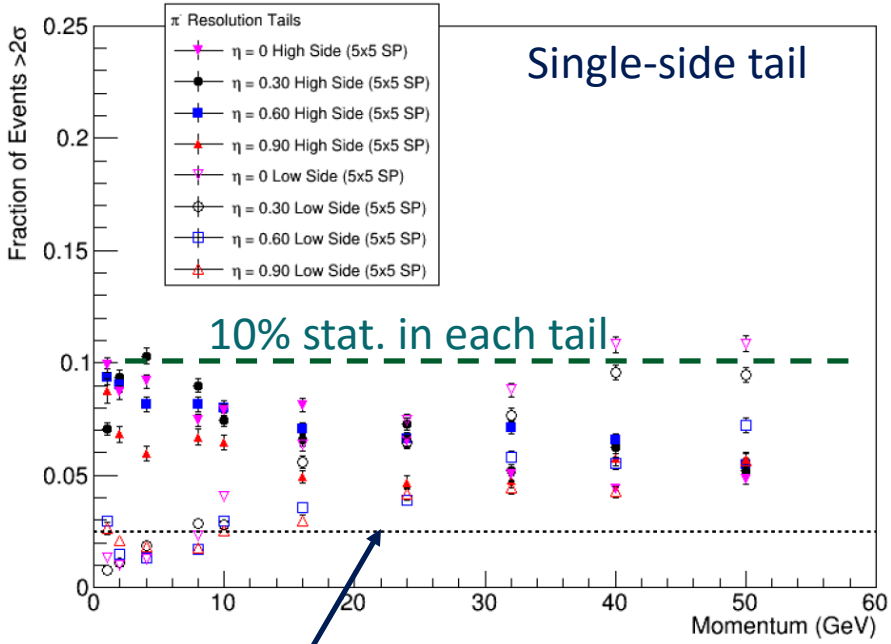
Beam view

Performance : Single Hadron showers

- Single pion shower studied with clusters of digitized towers (3x3 and 5x5 clusters), which is compared with ideal sum of Geant4 hit in scintillator (label G4Hits)
- Energy resolution satisfied design goal. Tails <= 10%
- Refinement underway: time cut-off and light collection variations

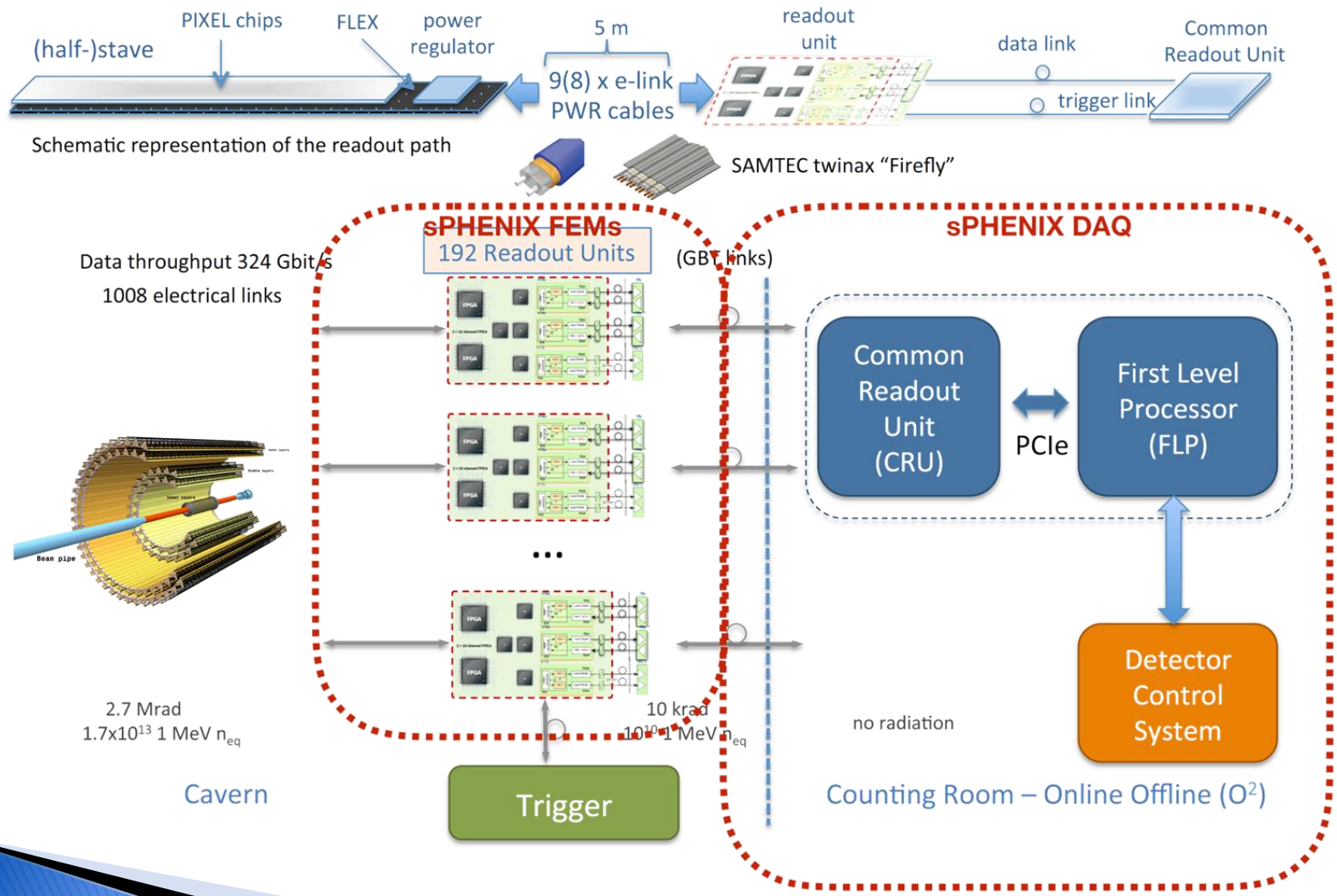






2.5% stat. in tails as expected from Gauss shape

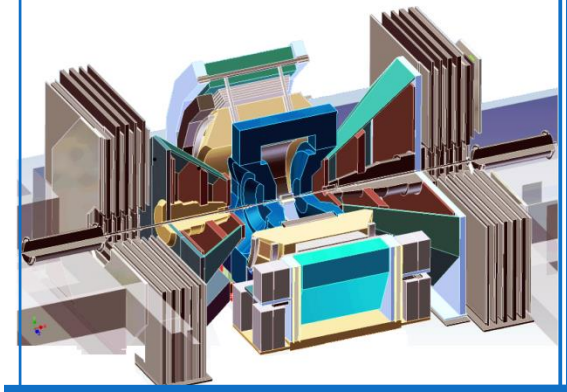
MAPS readout

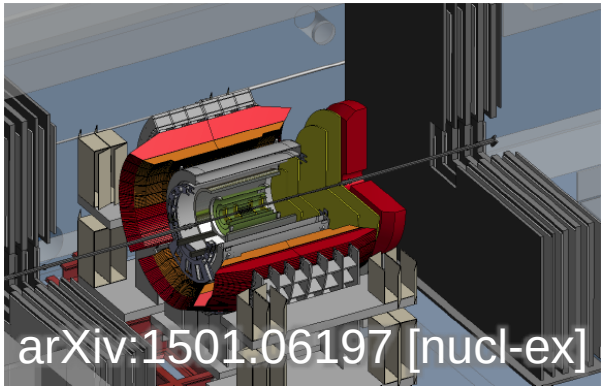


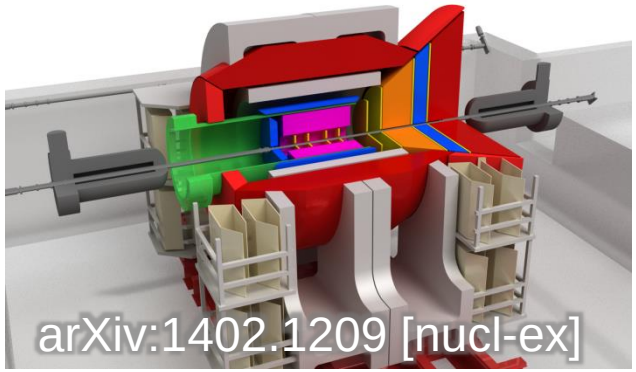
Overview of PHENIX Long-term Upgrades

Documented: http://www.phenix.bnl.gov/plans.html

Current PHENIX	*s*PHENIX (+fsPHENIX)	An EIC detector
14y+ operation 100+M$ investment 140+ published papers to date WWND Talks: Dion, Brooks, Bazilevsky, Sharma, Stankus, Todoroki Last run in this form 2016	Comprehensive central upgrade base on BaBar magnet fsPHENIX : forward tracking, Hcal and muon ID WWND talk: Huang, Perepelitsa	Path of PHENIX upgrade leads to a capable EIC detector Large coverage of tracking, calorimetry and PID Open for new collaboration/new ideas Ref: arXiv:1406.2980 [hep-ex]







~2000 | 2017→2020 | ~2025 | Time

RHIC: A+A, spin-polarized p+p, spin-polarized p+A → eRHIC: e+p, e+A

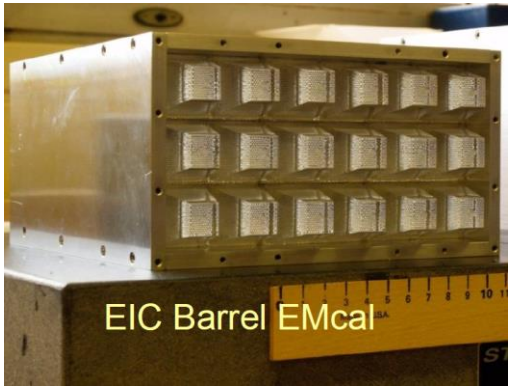
Verification of Simulation: EMCal

Verification of EMCal simulation using eRD1 2014 data VS sim using sPHENIX Geant4

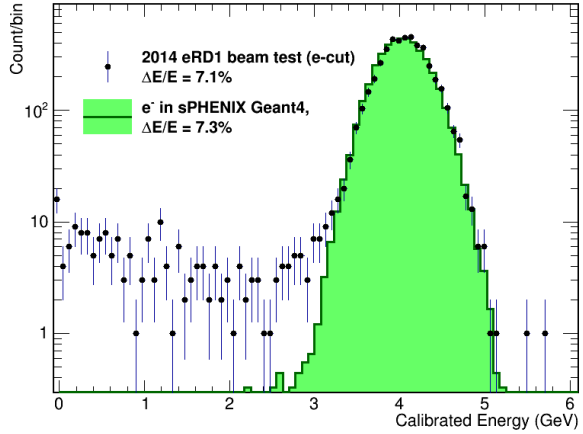
Need this excessive with sPHENIX config, better quantification of hadron tail/tunnel effect

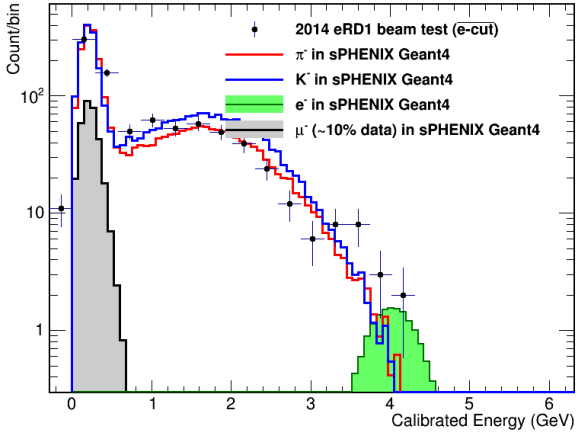
eRD1 2014 test beam (UCLA)

- 1D projective tower in 3x6 block
- slightly different fiber with double cladding

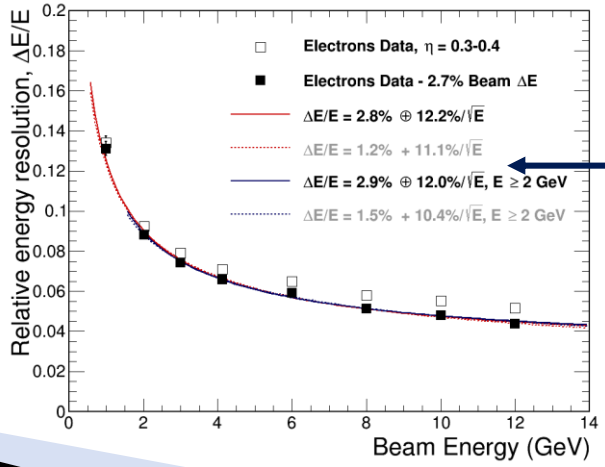


Beam test data reproduced in simulation (4GeV shown, more in pre-CDR)

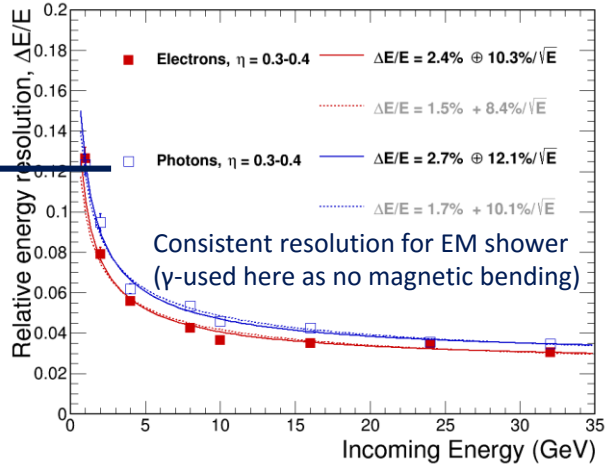




Energy resolution: eRD1 test beam



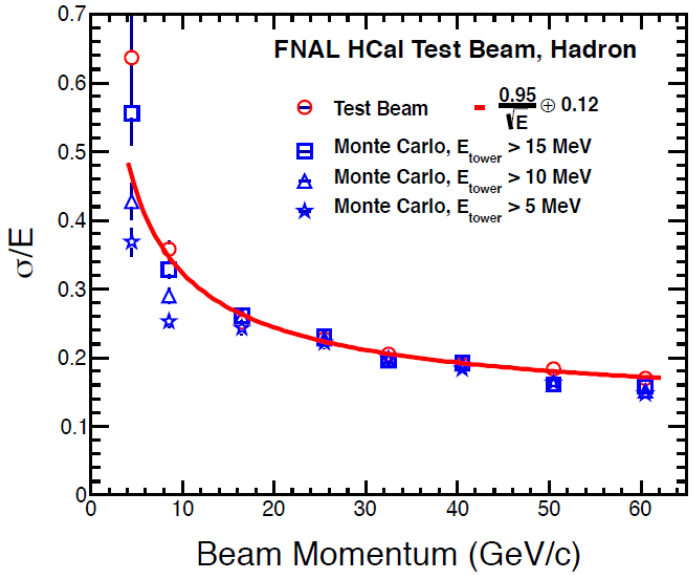
sPHENIX full SPACAL

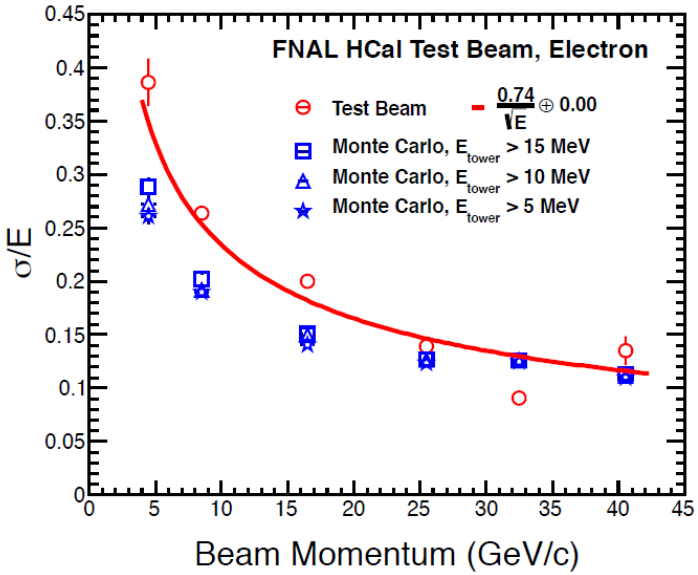


Consistent resolution for EM shower (γ-used here as no magnetic bending)

Verification of Simulation: HCal

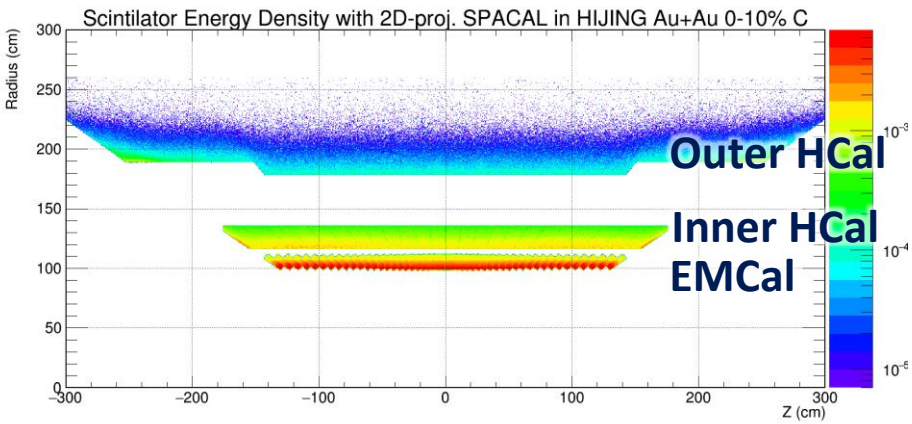
- HCal Simulation tested against Apr 2014 sPHENIX Fermi-lab test beam (HCals alone, v1-design)
- Reasonably reproduced resolution
- New test beam Apr 2016 with full calorimeter system planned (EMCal + Inner Hcal + magnet gap + Outer HCal). Effort on-going with GSU group

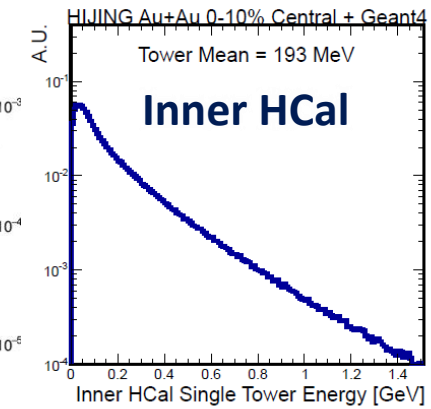


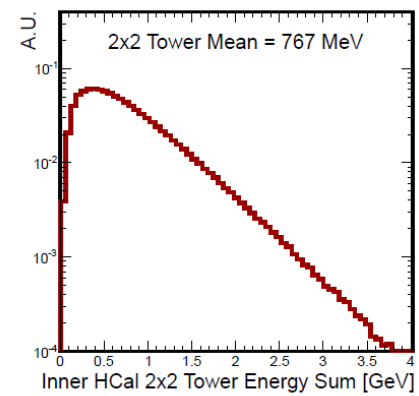


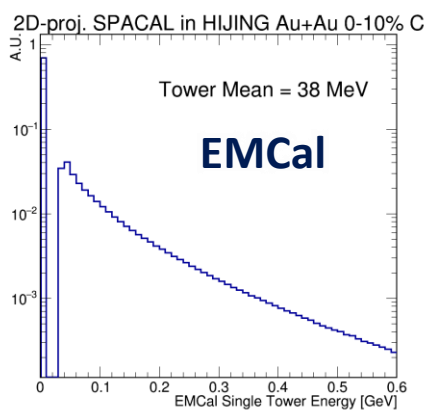
Occupancy in central Au+Au

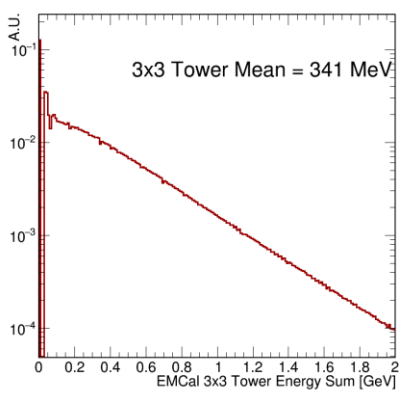
- sPHENIX are designed to handle large background environment of central AuAu collisions
- Such background is simulated with HIJING → full detector in Geant4 → full analysis chain
- Folded into electron ID and jet projections via embedding

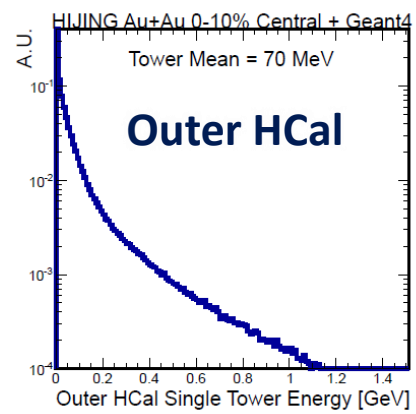


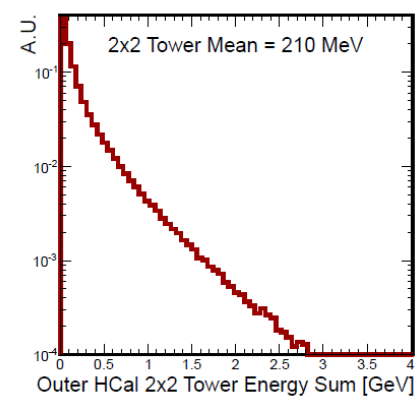






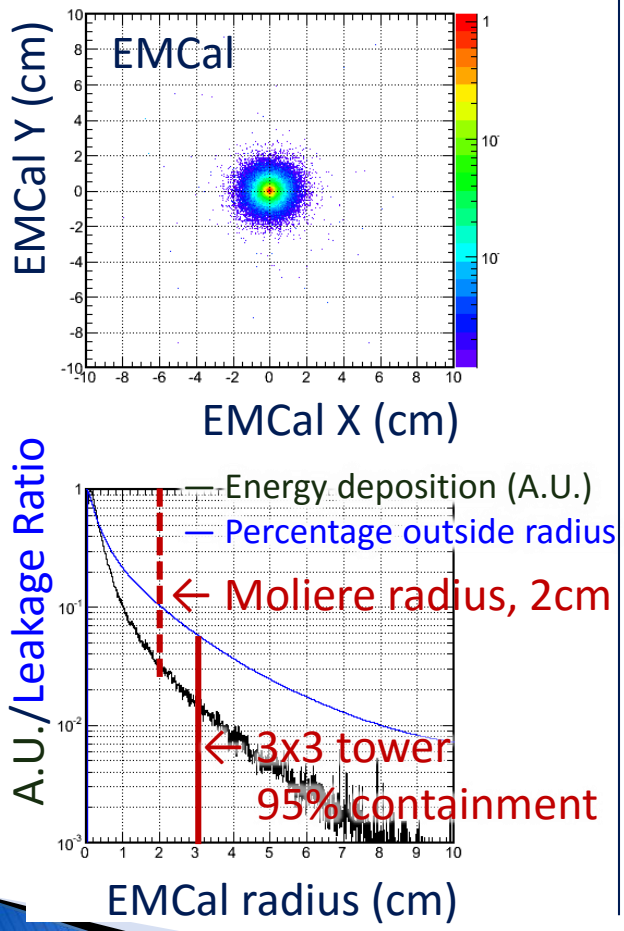




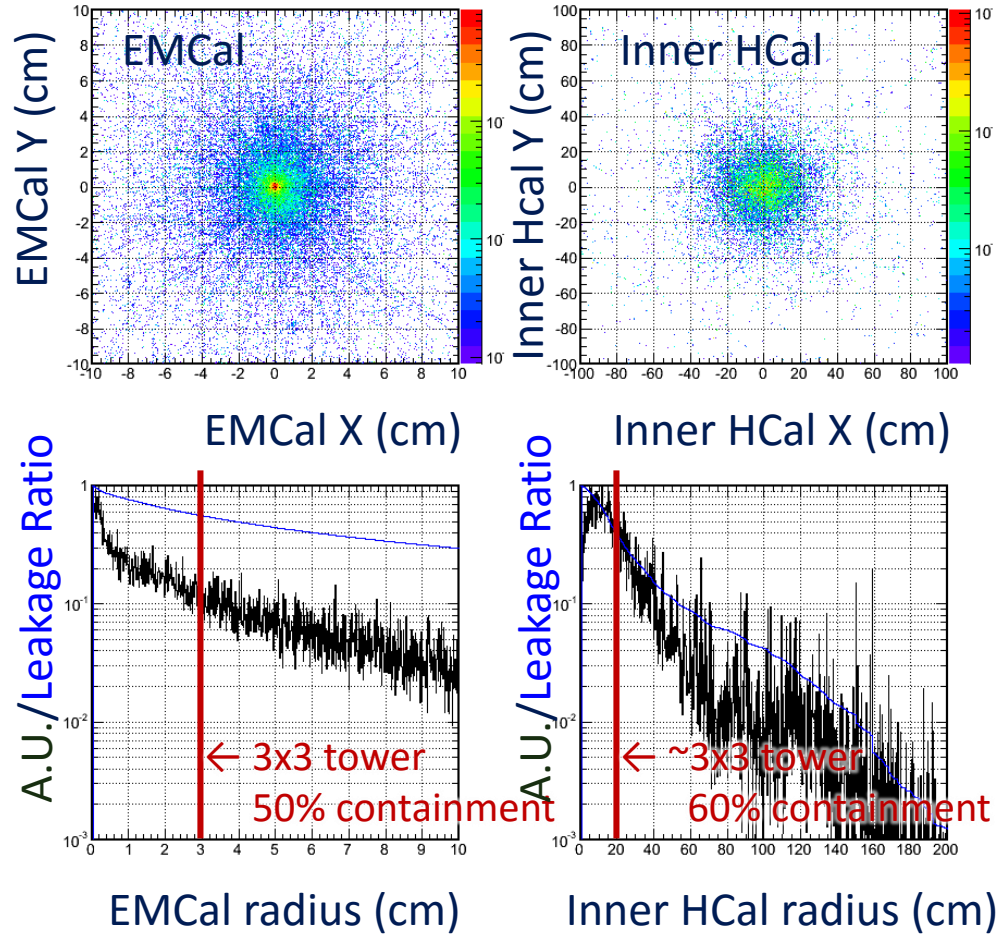


Performance : Single EM showers

4 GeV Electrons



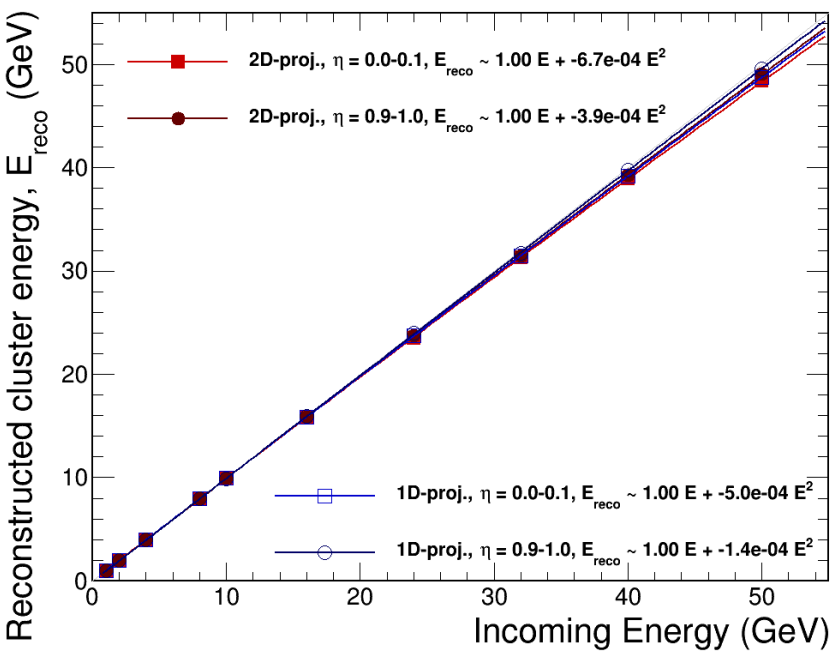
4 GeV Pions, that **passed E/p electron-ID cut**

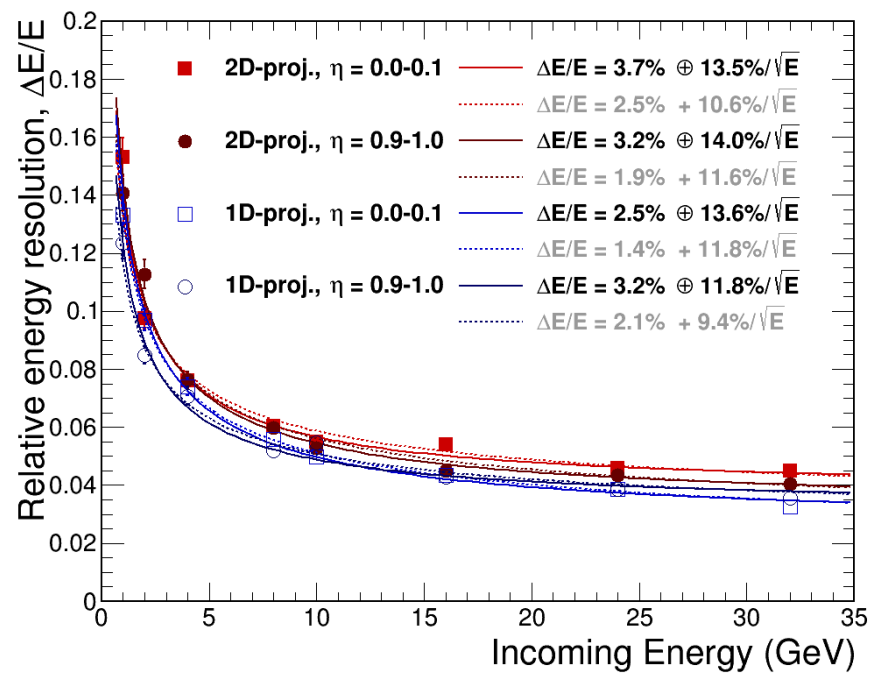


Performance : Single EM showers

- dE/E < 14%/sqrt(E)+4% for photon (fit sPHENIX γ-jet goal)
- dE/E < 12%/sqrt(E) for electrons (fit EIC electron kine. goal)
- Linearity is reasonable

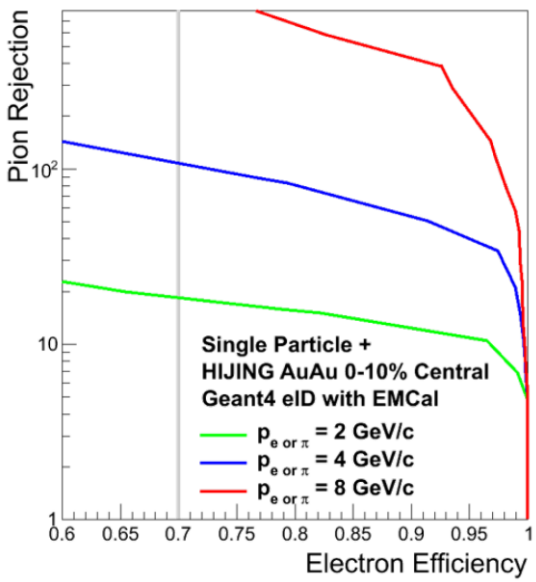
sPHENIX full detector single photon simulation

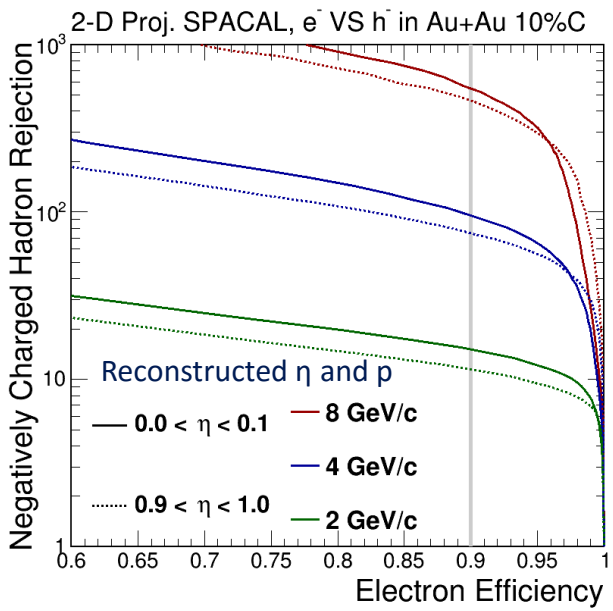


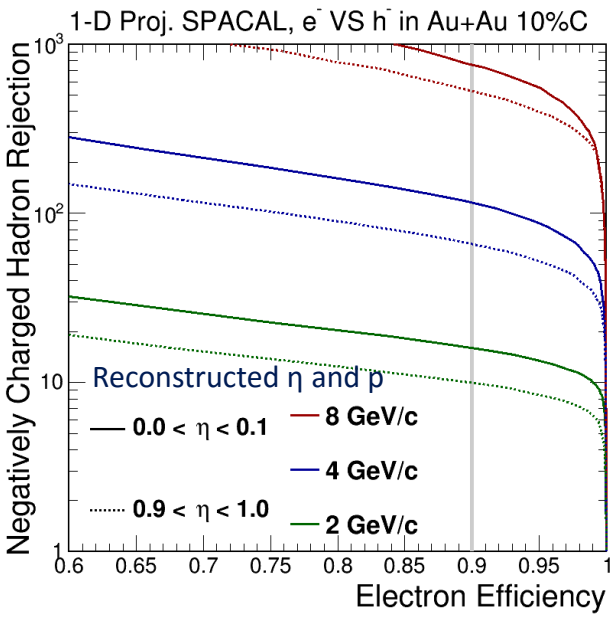


Performance : electron-ID in Au+Au

Updated and more detailed simulation show good safety margin on electron-ID performance on top of the baseline design (as required to reach Upsilon program physics goal)







Baseline performance, design goals

- Sum all scintillator energy
- 1D SPACAL material with hits grouped into 2D SPACAL towers

2D projective SPACAL

- Updated studies (Preliminary)
- Sum all hadron taking account of hadron ratio
- Full digitization (w/ Birk corrections)
- Full tracking with silicon opt.
- Fully implemented 2D SPACAL (tower/support structure)

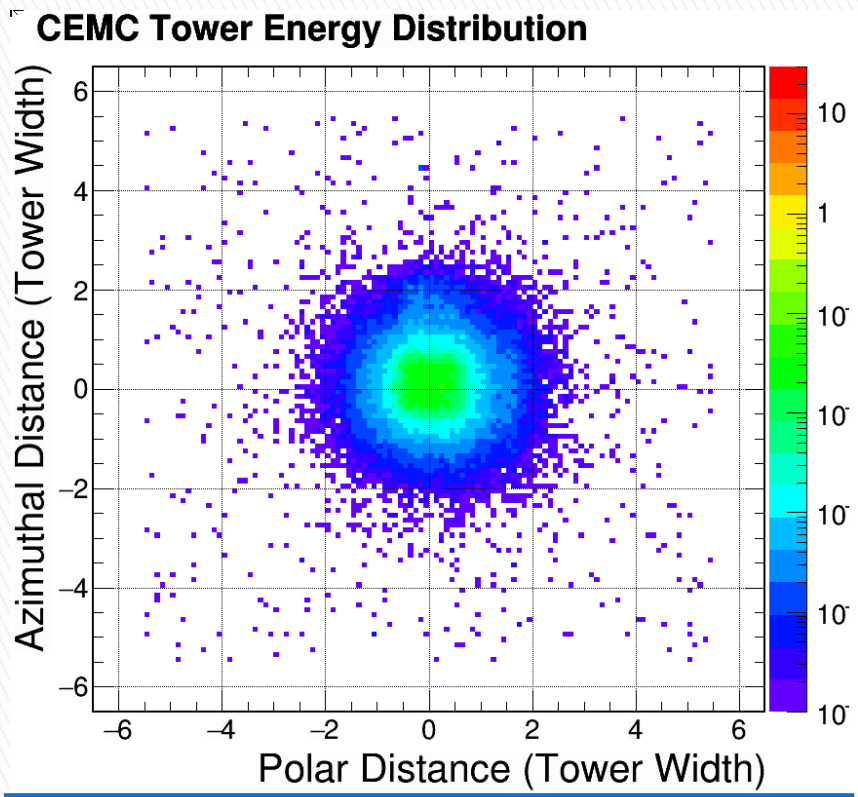
1D projective SPACAL

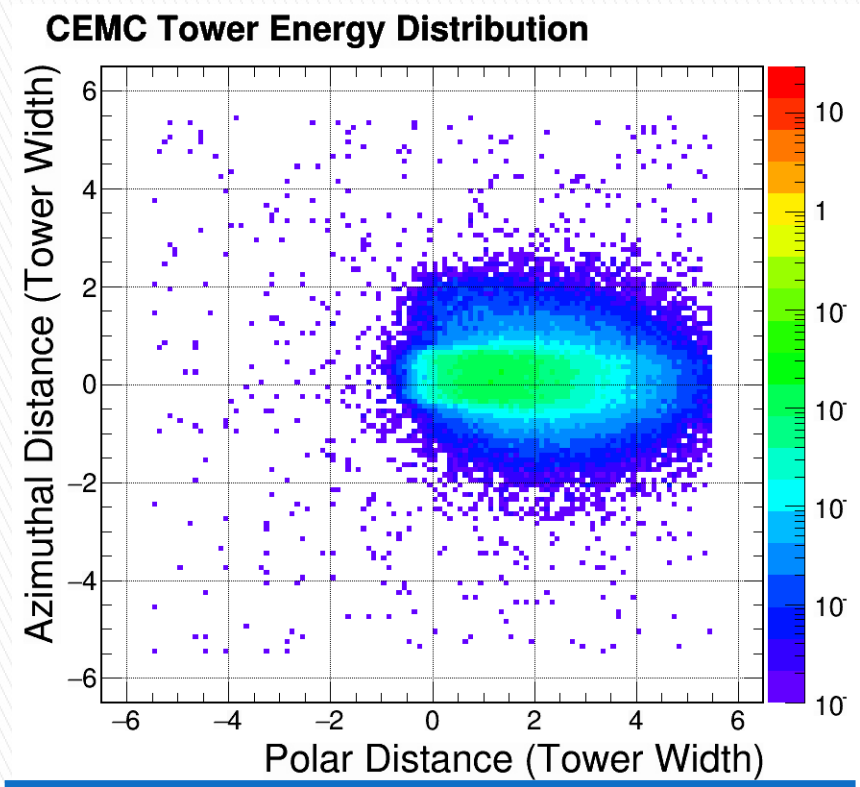
- Updated studies (Preliminary)
- Sum all hadron taking account of hadron ratio
- Full digitization (w/ Birk corrections)
- Full tracking with silicon opt.
- Ideally towering (no-tower boarder, no enclosure structure)

Other considerations in projectivity

- Safety factor to deliver Upsilon physics
- Pi-0 ID and calibration (just starting)
- Soft-lepton tagging in jets (need study)

Single e- 8 GeV shower in 1D/2D proj. SPACAL @ eta=0.9-1.0

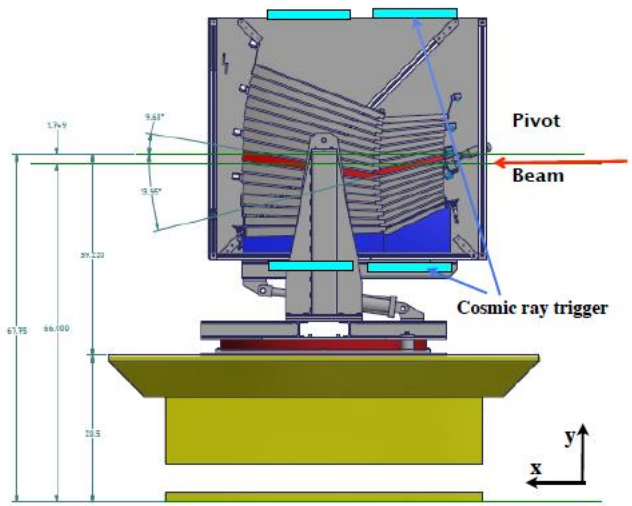


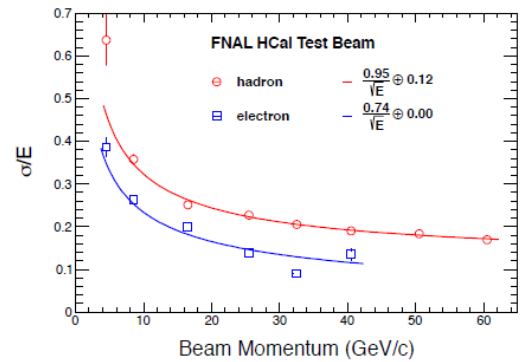


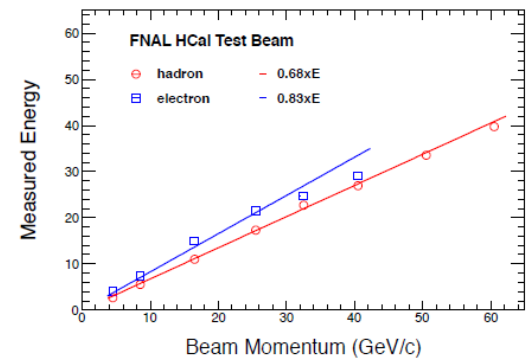
2D projective SPCAL
Average cluster ~8 towers

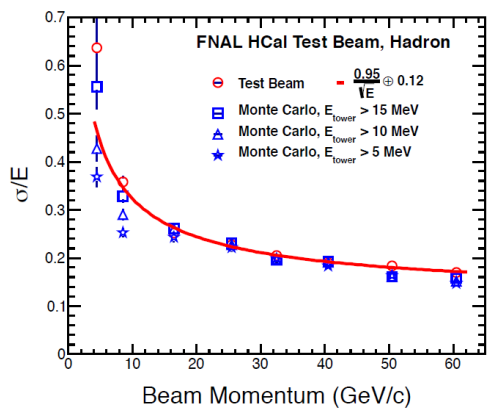
1D projective SPCAL
Average cluster ~12+ towers

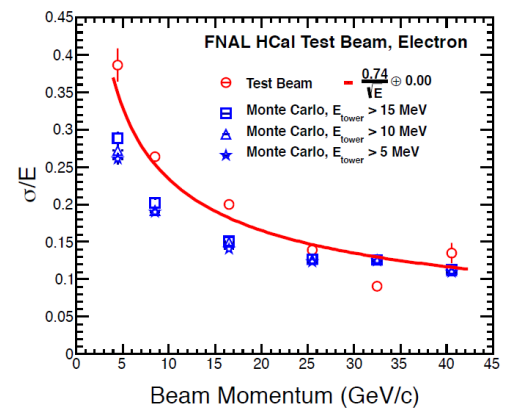
Hcal Test beam 2014 FNAL

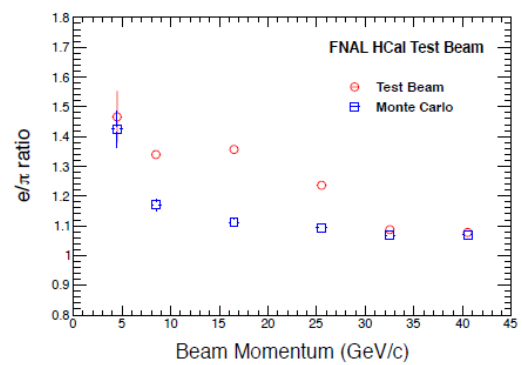












Energy resolution inspections

Simulated on SPACAL without VTX and in full magnetic field

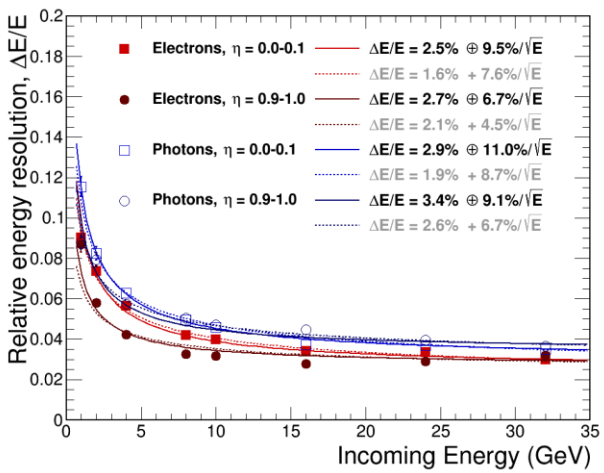
- 1GeV electron is bended by 0.45 rad → performance ~ photon w/ eta of 0.45 and view higher SF.
- **For EIC, Resolution ~< 12%/√E for electrons after magnetic field bending**
- **For sPHENIX, Resolution ~< 14%/√E for direct photons**

Sampling fluctuation
- 11%/√E for γ
- 9.5%/√E for e^- w/ B

+ readout / clustering
- 13.2%/√E for γ
- 11.9%/√E for e^- w/ B

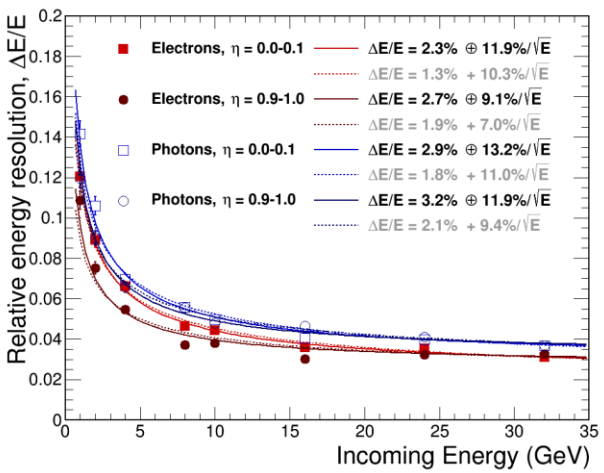
+ 2D SPACAL
- 13.8%/√E for γ
- 12.2%/√E for e^- w/ B

+ Silicon detector
- 13.5%/√E for γ



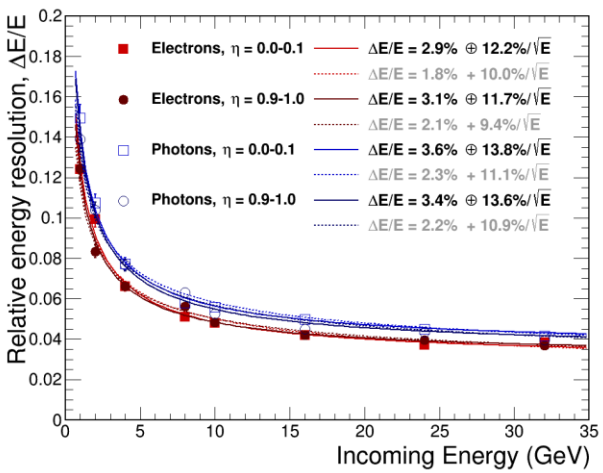
1D SPACAL, No SVX, Sum all tower

No photo-electron fluctuation/pedestal noise



1D SPACAL, No SVX,

Pedestal noise (2ADC), photon fluctuation (500e/GeV)

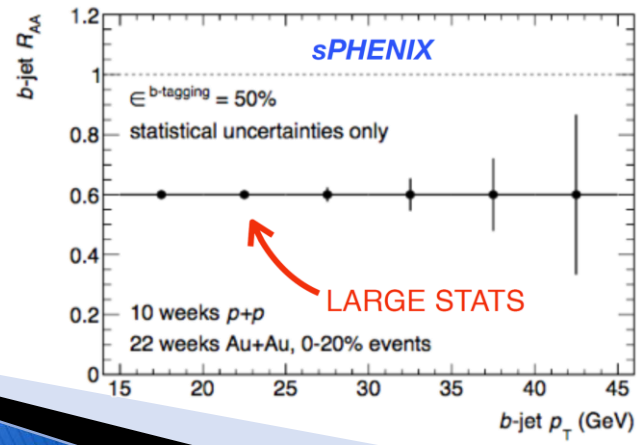


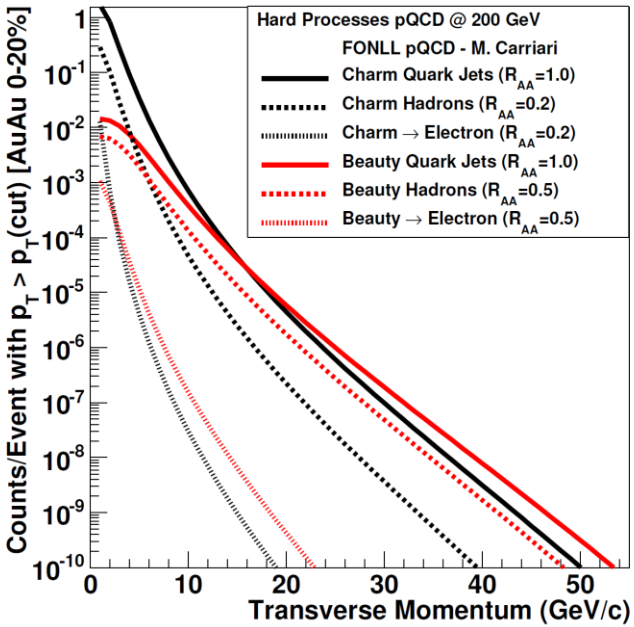
2D SPACAL, No SVX,

Pedestal noise (2ADC), photon fluctuation (500e/GeV)

B-jet tagging – Decay lepton tagging

- None-photonic lepton has been a successful tool in studying heavy quark behavior in QGP
- Given a jet detected, lepton tagging in or near the jet cone could enhance HF jet fraction due to larger fraction of B(->d)->e decay than h->e decays.
  - Benefit:
    - Not necessarily require a DCA capability. No additional sPHENIX detector required
    - (Largely) orthogonal to and cross check life-time-based B tagging: e.g. DCA-track-counting and Secondary vertex mass methods
  - Cost: B->e branching ratio (~20%), electron identification efficiency, (b-tagging efficiency)
- Challenge:
  - Exploring possibility @ RHIC energy
  - Signal/background ratio and
  - Optimization both in $j_{T,e}$ and DCA_e
  - Statistics

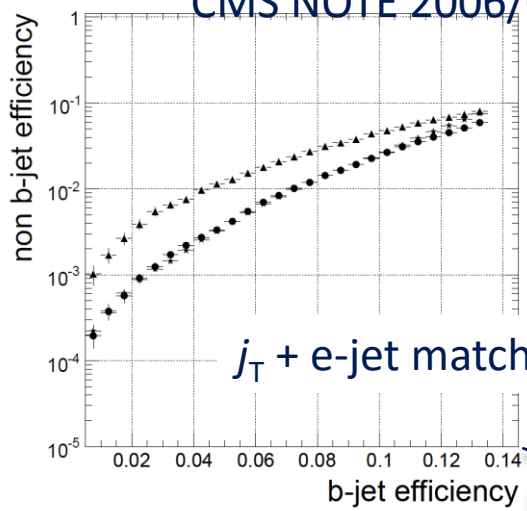




Decay lepton tagging
- CMS studies (muon tagging)

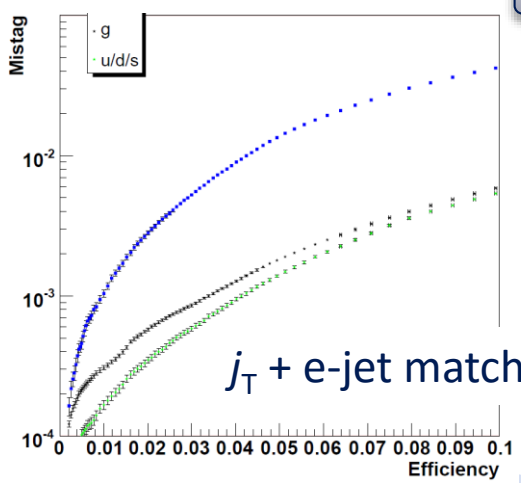
Rejection VS tagging eff.

CMS NOTE 2006/043



j_T + e-jet matching + DCA_e

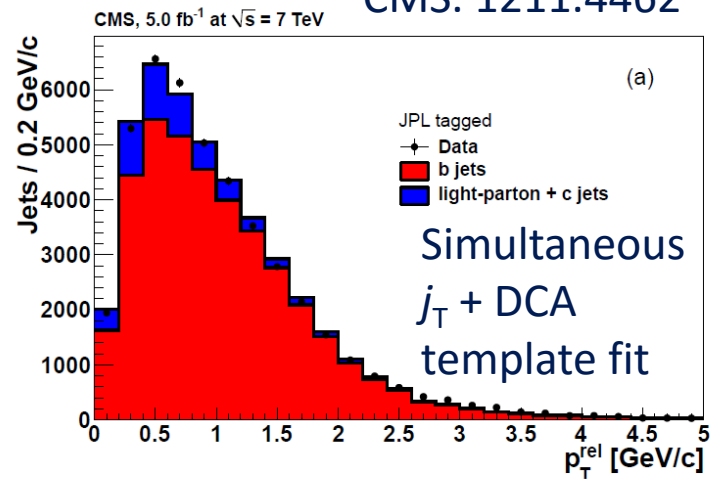
Suffer of B->μ BR



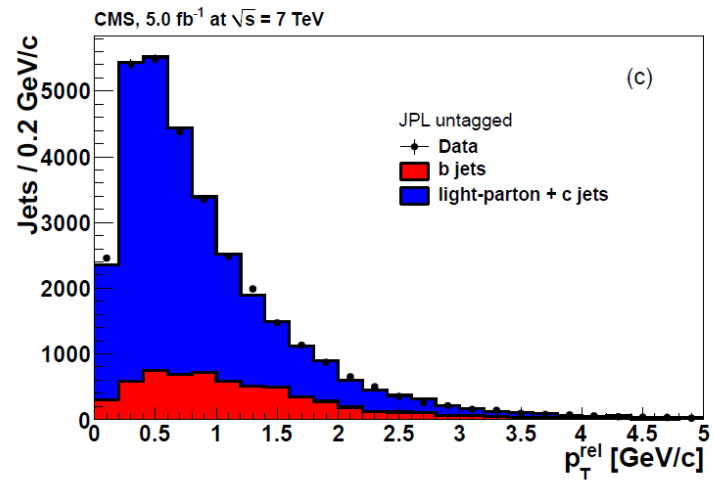
j_T + e-jet matching ~~no DCA~~$_e$

As cross check to JP/L method

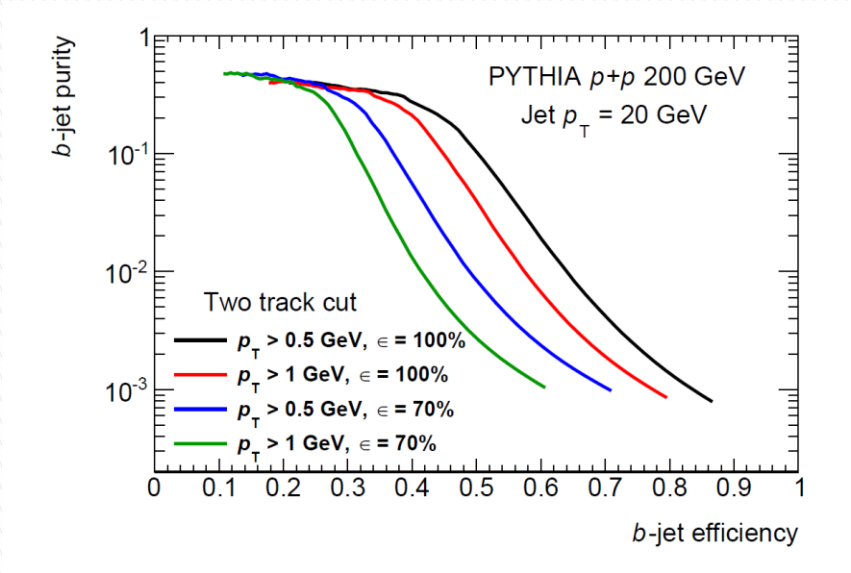
CMS. 1211.4462

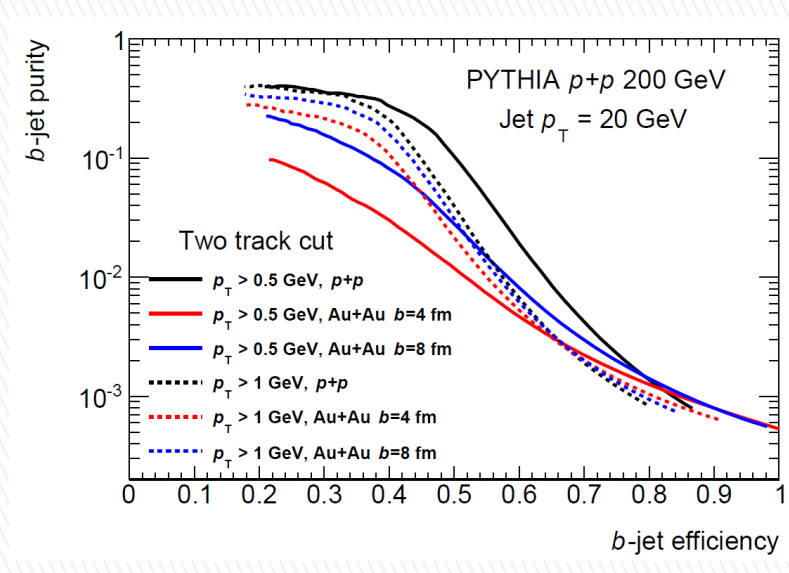


Simultaneous j_T + DCA template fit



B-tagging VS track efficiency [1501.06197]





Tracking efficiency dependence

Occupancy dependence