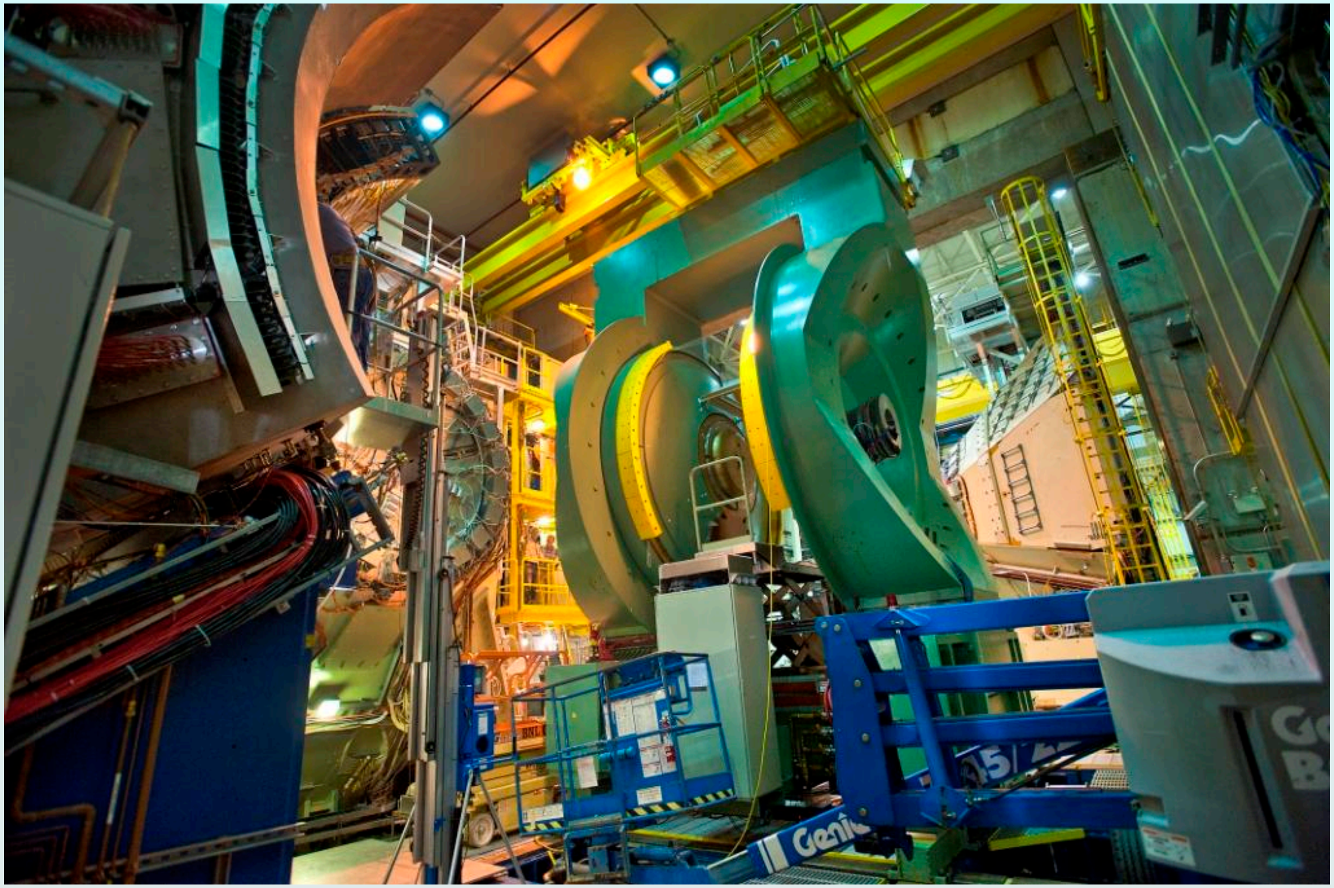
PHENIX Upgrade Overview



Barbara Jacak,
Stony Brook

Oct. 20, 2011

RIKEN workshop on Future Directions in High Energy QCD

Decadal Plan: http://www.phenix.bnl.gov/phenix/WWW/docs/decadal/2010/phenix_decadal10_full_refs.pdf

PHENIX: Take data +analyze + upgrade

Central Arm Tracking
- Drift Chamber
- Pad Chambers
- Time Expansion Cha

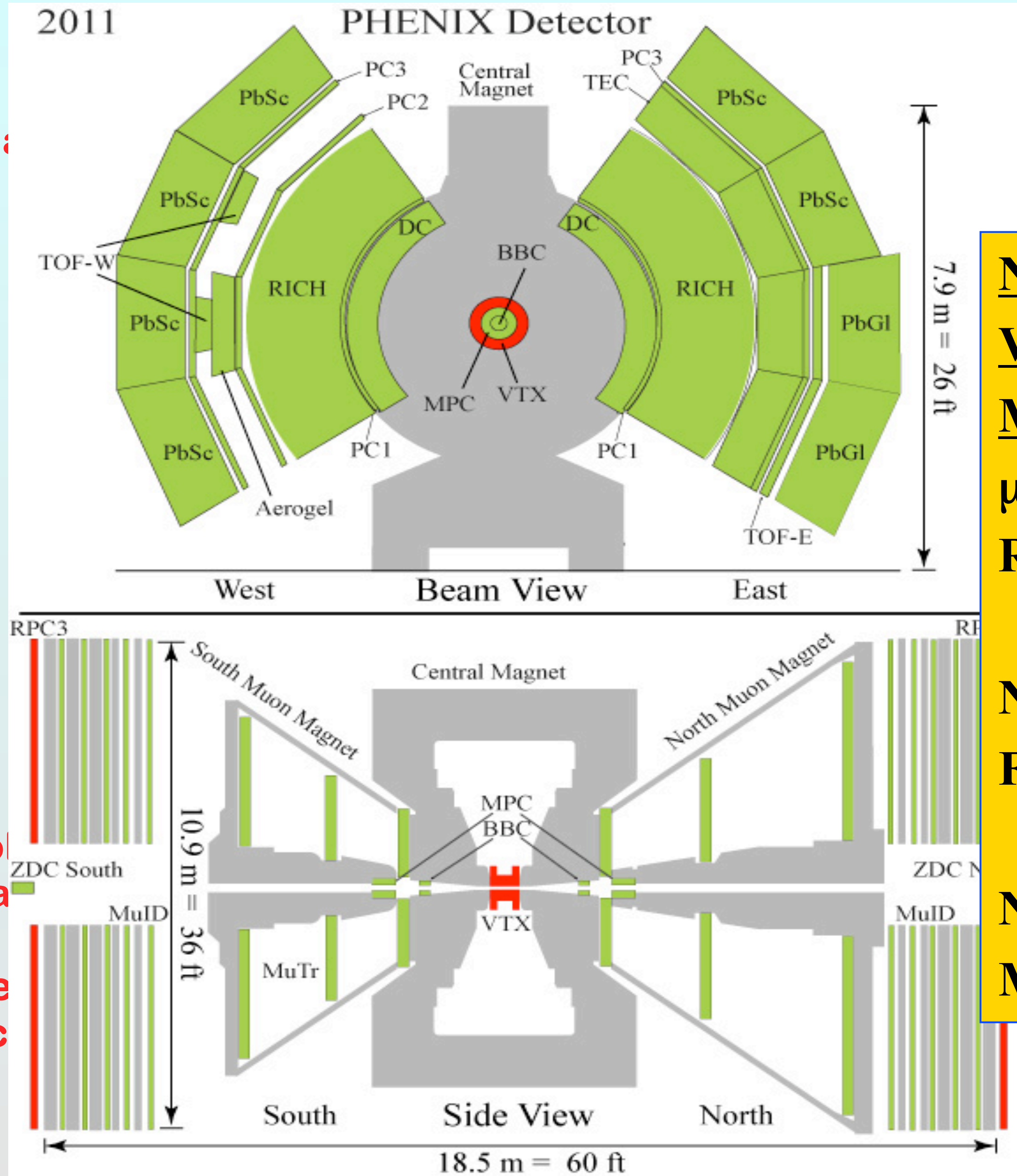
Muon Arm Tracking
- Muon Tracker

Calorimetry
- PbGl
- PbSc
- MPC

Particle Id
- Muon Identifier
- RICH, HBD
- TOF E & W
- Aerogel
- TEC

Global Detectors
- BBC
- ZDC/SMD Local Pol
- Forward Hadron Ca
- RXNP

DAQ and Trigger Syste
Online Calib. & Produc



New in 2011:
VTX
Muon Trigger:
μTr FEE
RPC station 3

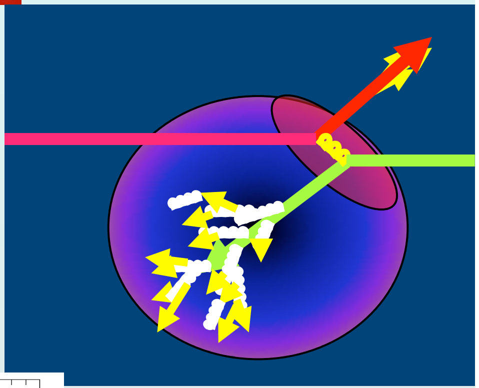
New in 2012:
FVTX

New in ~2014:
MPC-EX

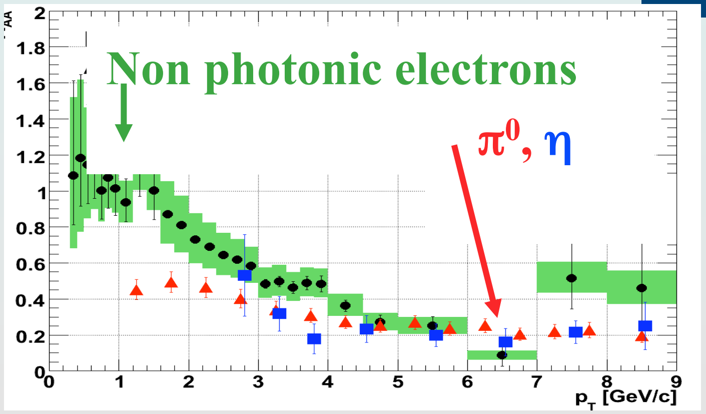
We find

- Collective flow with low viscosity/ entropy ratio: *"perfect liquid"*
  How low? Strong coupling…

- Opacity very high
  Effectively stops quarks & gluons
  How and why? Strong coupling…



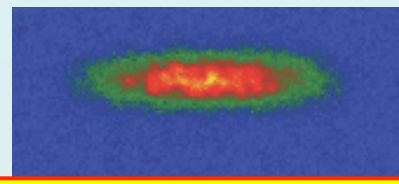
- Even heavy quarks lose energy & flow
  Not expected from radiative energy loss
  -> strong coupling
  High mass scatterers

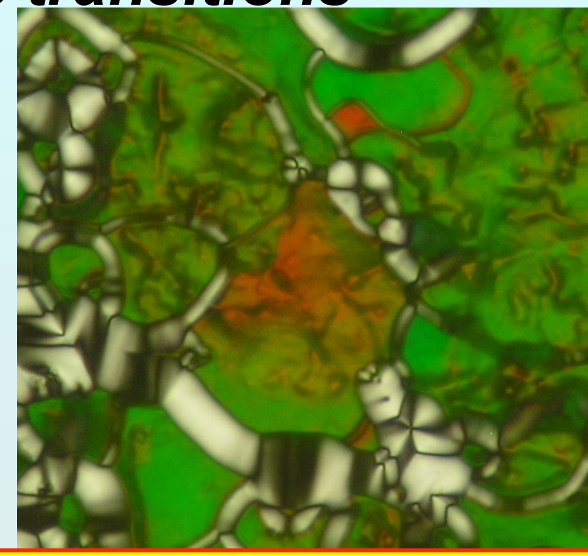


Many types of strongly coupled matter

Quark gluon plasma is like other systems with strong coupling - all flow and exhibit phase transitions

Cold atoms: coldest & hottest matter on earth are alike!





Dusty plasmas &

In all these cases have a competition:

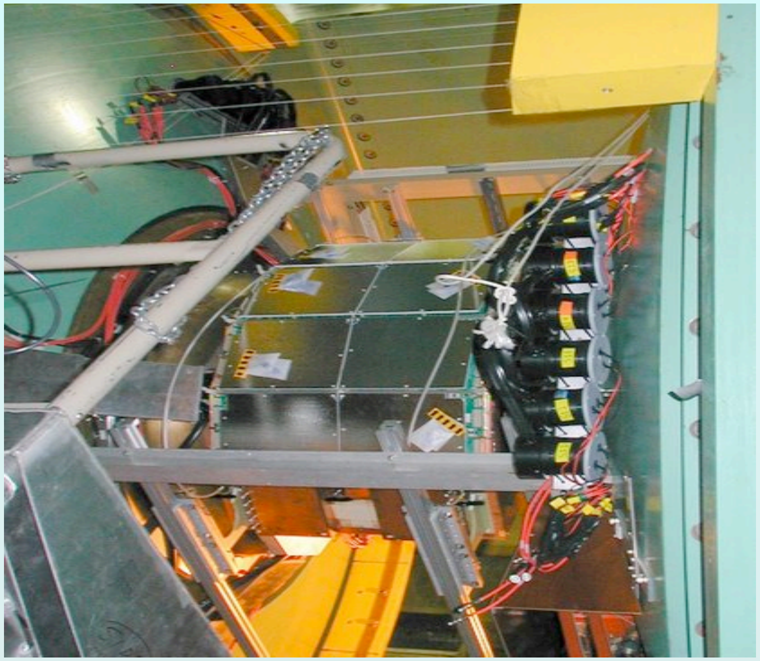
Attractive forces ⇔ repulsive force or kinetic energy

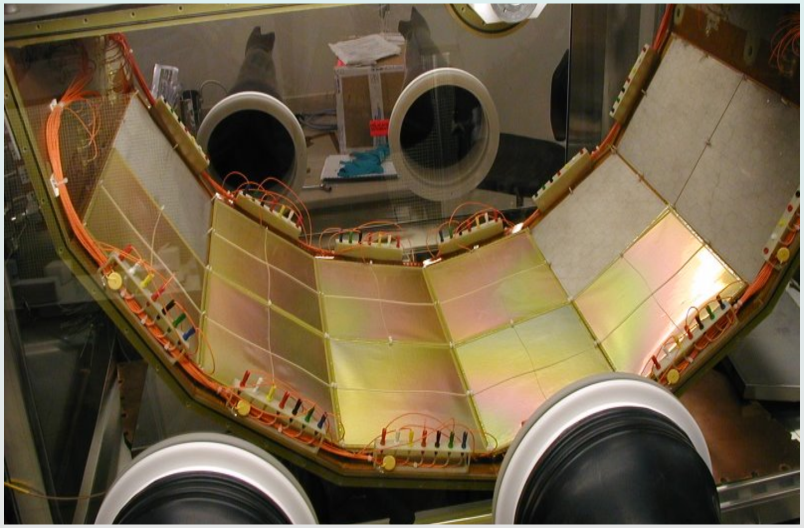
Result: many-body interactions; quasiparticles exist?

QCD offers: known Lagrangian, well-defined short-range interaction w/o non-relativistic approximation, theoretical tools to understand complex data

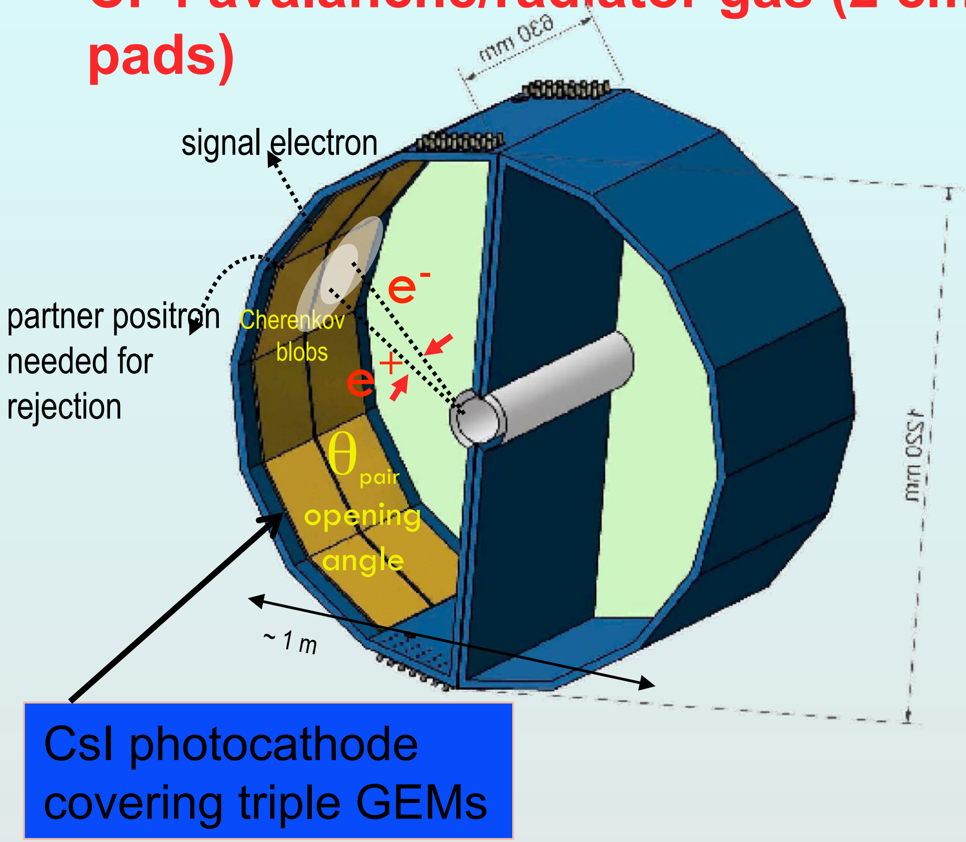
Upgrades in the next few years (used to be called "mid-term upgrades"

2010: Hadron Blind Detector





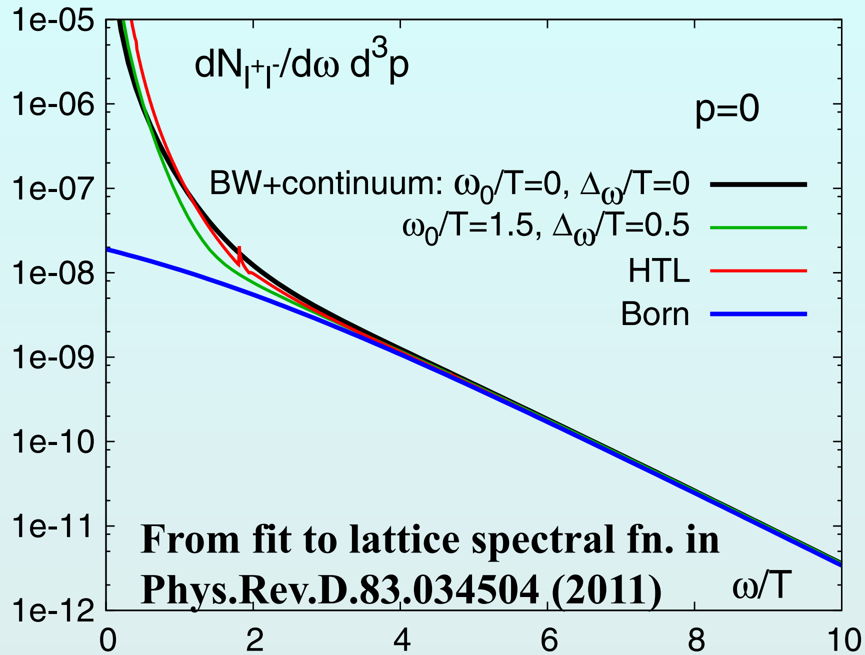
Windowless Cerenkov detector with CF4 avalanche/radiator gas (2 cm pads)



Removes Dalitz & conversion pairs (small opening angle)

Calculate EM correlator with lattice QCD

➔ non-perturbative thermal dilepton rates at low mass

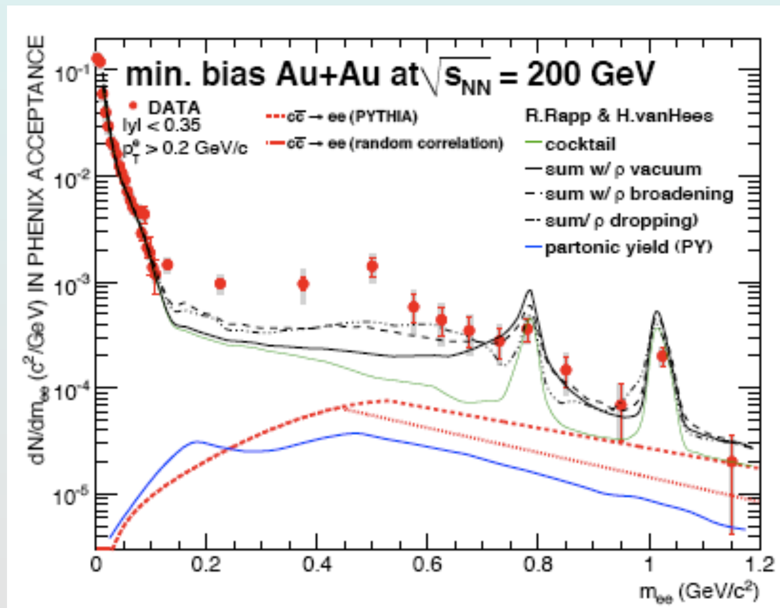


- For small energy, ω/T<(1-2) spectral function ≠ free form
- For ω/T ≃ 1 thermal dilepton rate ~ order of magnitude > leading order Born rate
- for ω/T>~(2 – 4) the spectral function is close to the free

✓ *we see an excess*

Is it non-perturbative?

Is it pre-equilibrium?



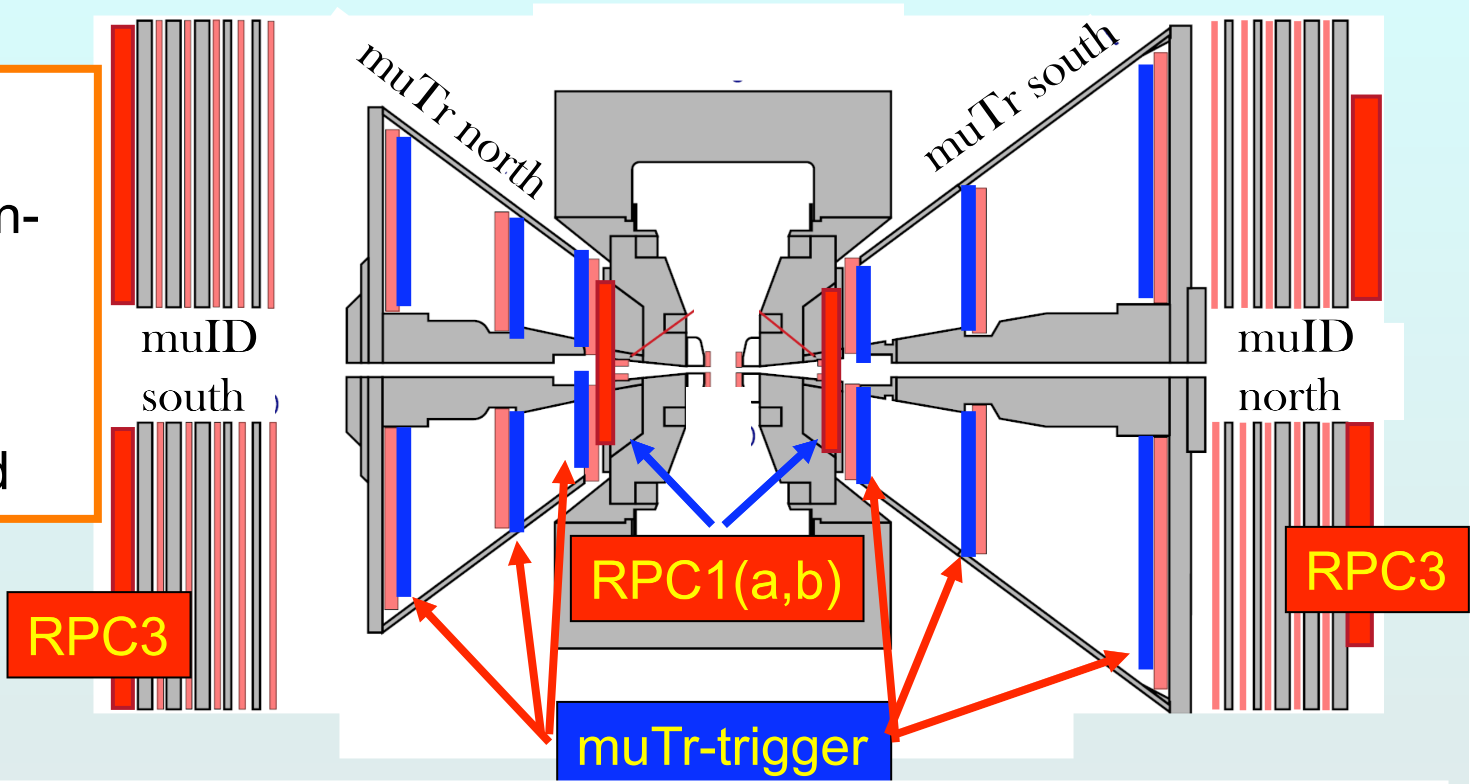
PRC81, 034911 (2010)

Muon Trigger Upgrade

Trigger idea:

Reject low momentum muons

Cut out-of-time beam background



Upgrade:

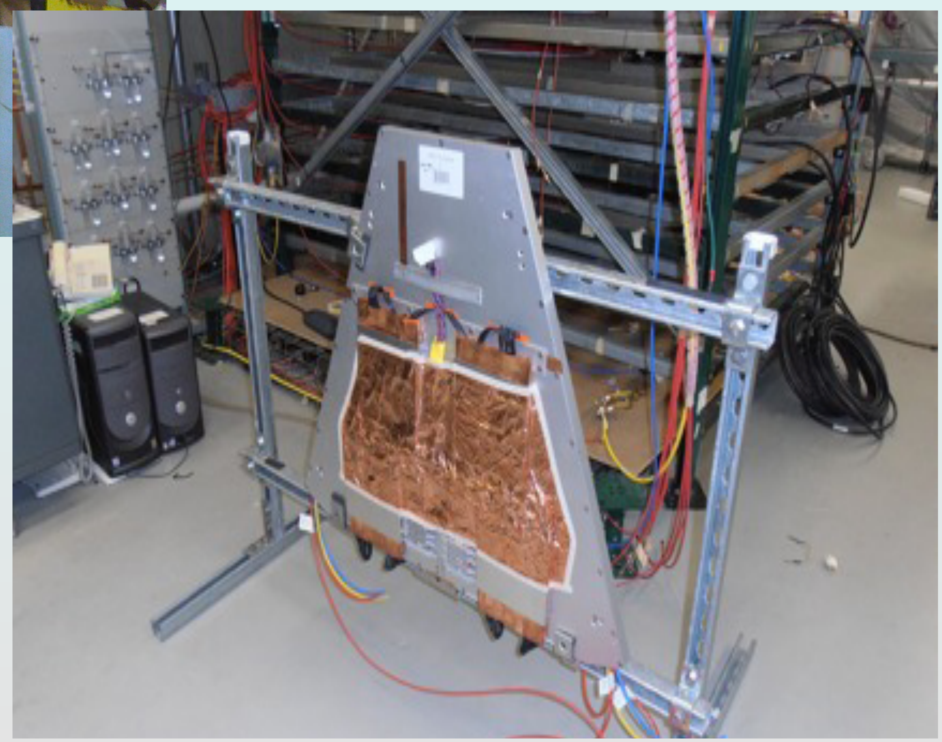
o muTr trigger electronics: muTr 1-3 ➔ send tracking info to level-1 trigger

o RPC stations: RPC 1+3 ➔ tracking + timing info to level-1 trigger

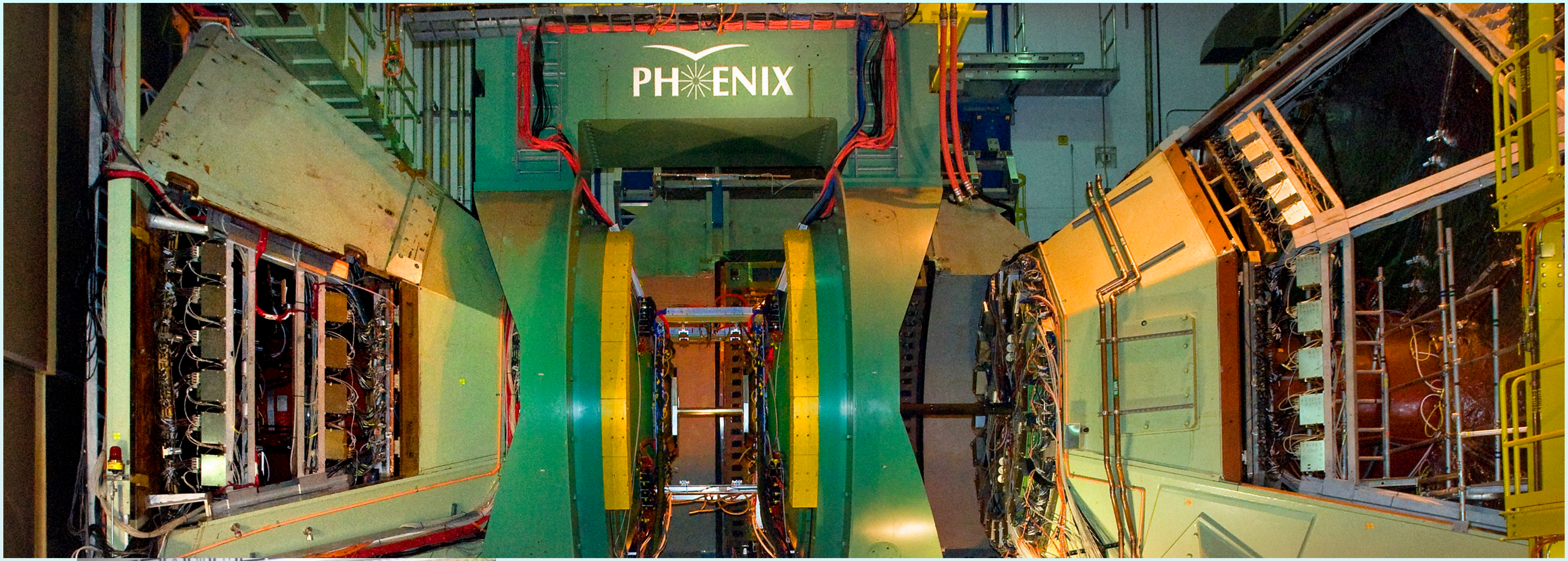
Status

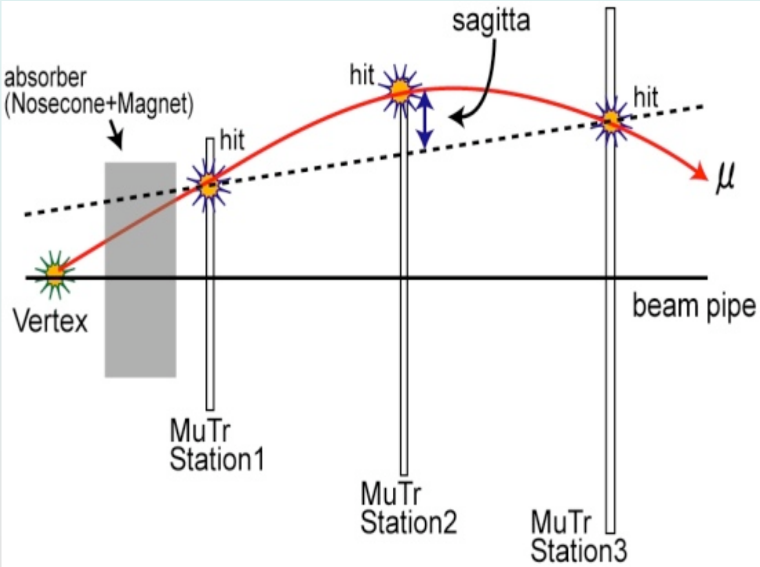
RPC3 N and S
took data in 2011

RPC1N in place
RPC1S installation is
underway



Muon tracker trigger in place for 2011

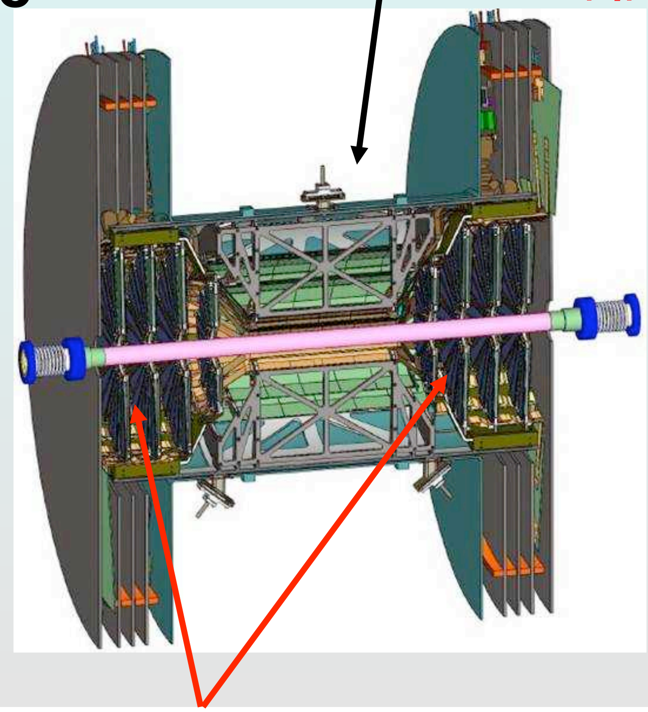




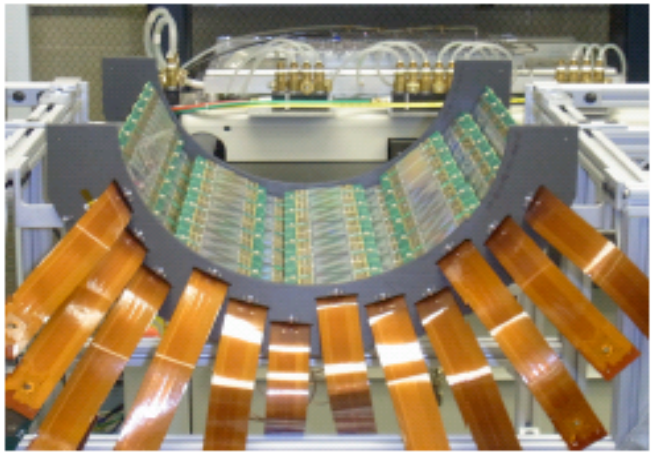
Next step to understand QGP

- c quarks lose energy and flow!
  Do *b* quarks (M_b ~ 4.2 GeV/c^2) flow too?
  What does *b* tell about interaction with plasma?
- Add silicon detectors around beam pipe VTX & FVTX
  Tag displaced vertex to separate
  c,b; reconstruct D & B mesons
- + accelerator luminosity upgrade
  ➔ for better statistics

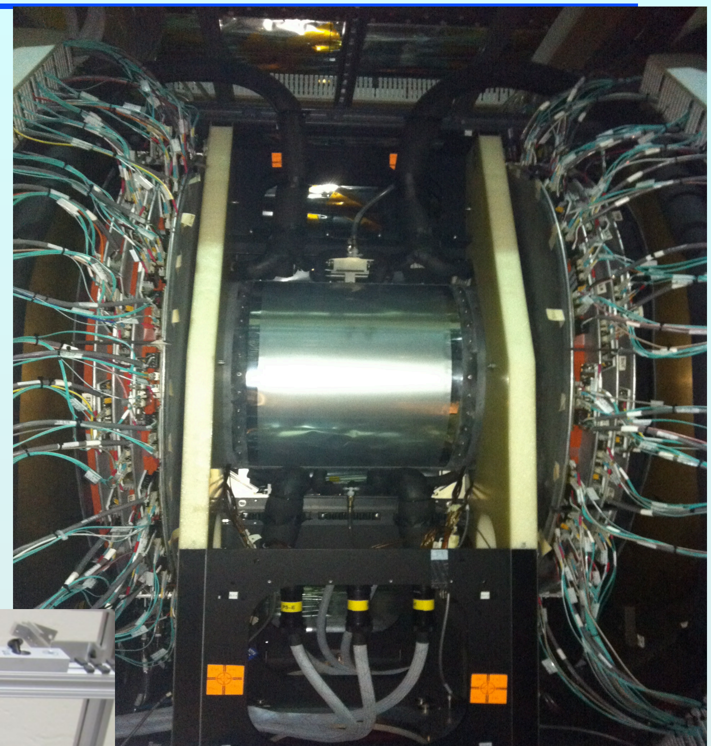
VTX barrel $|\eta|<1.2$

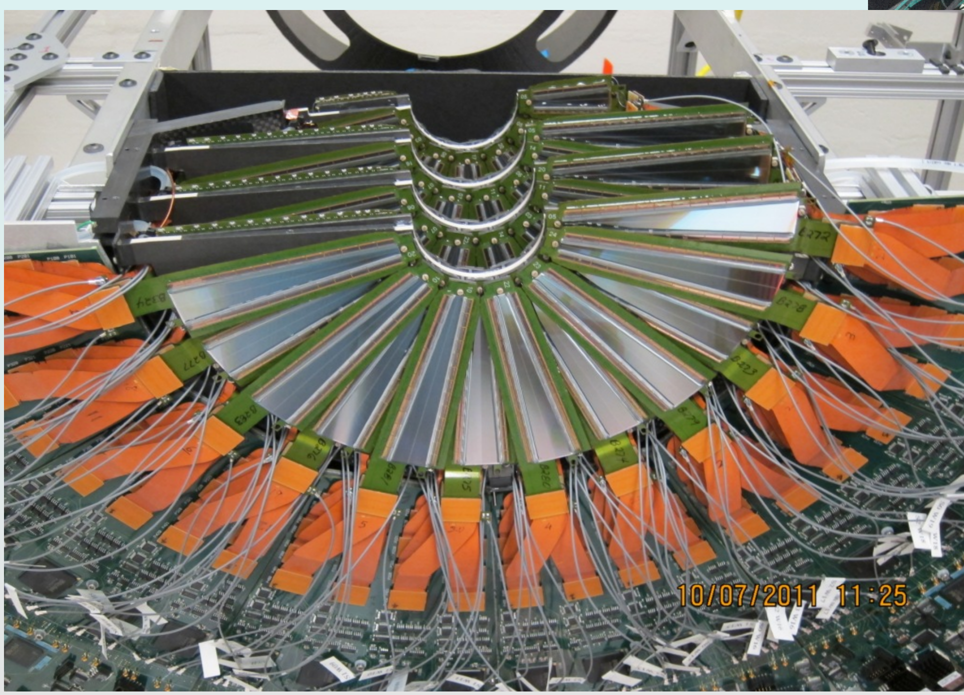


VTX in Run-11, FVTX for Run-12



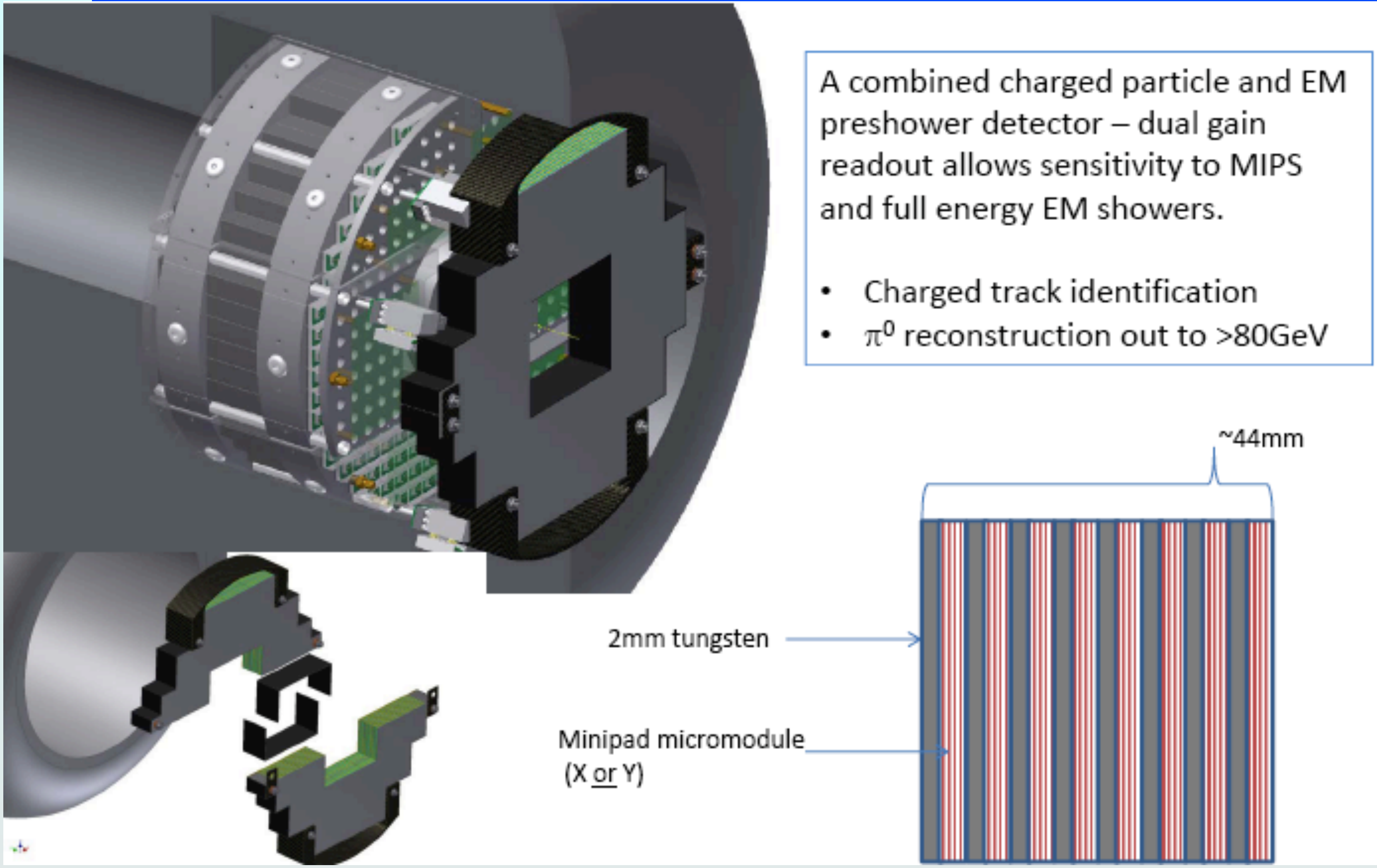
VTX Stripixel Layer 4





FVTX will go into enclosure in ~1 month

MPC-EX: future of pp and d+A is forward



Preshower detector for muon piston calorimeter

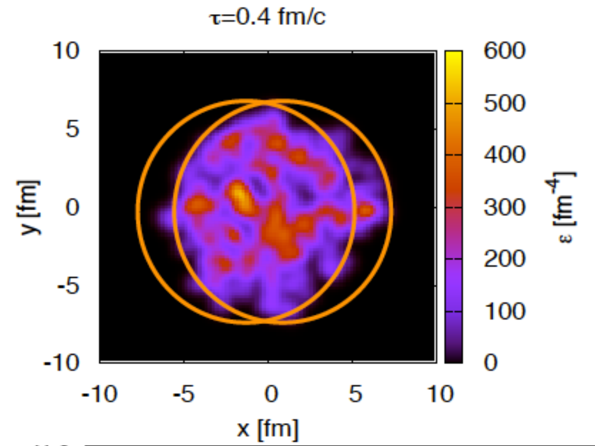
γ/π^0 separation: γ_{dir} in d+Au; Collins in jets for p+p$_\perp$

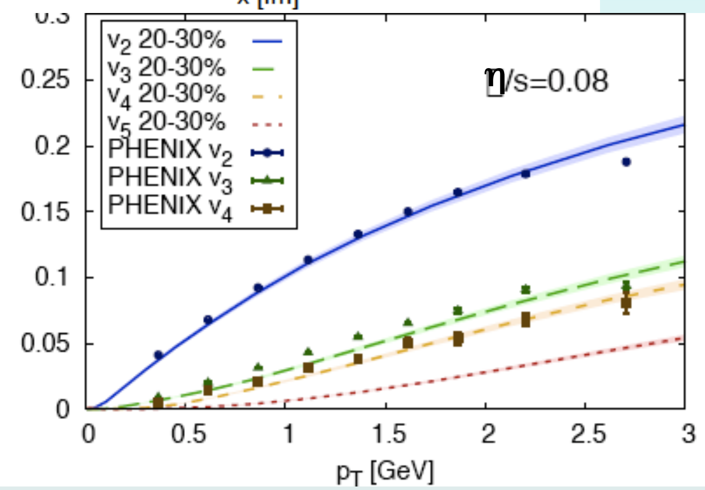
proposal being completed now

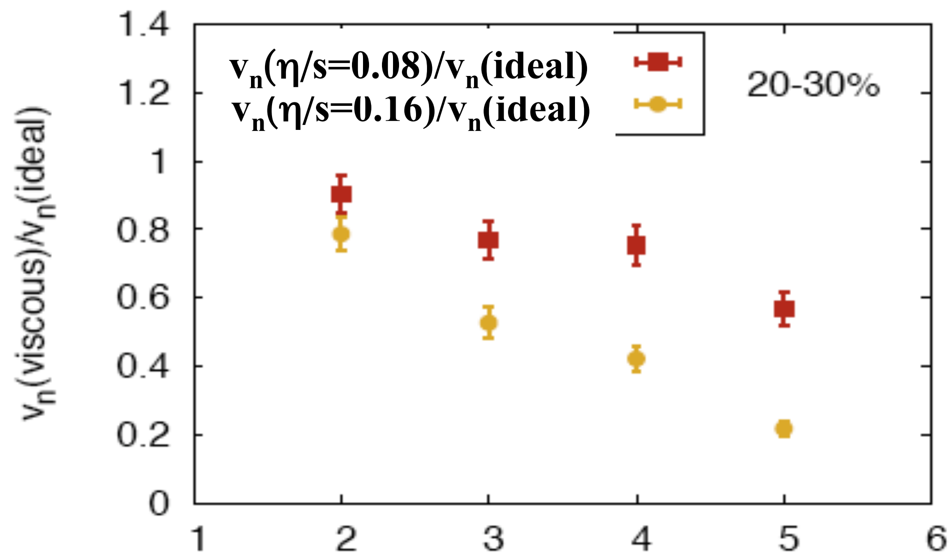
In the medium term ~2017-2022

address entirely new questions raised by results from RHIC and LHC

Quantify the viscosity







Schenke: arXiv:1109.6289

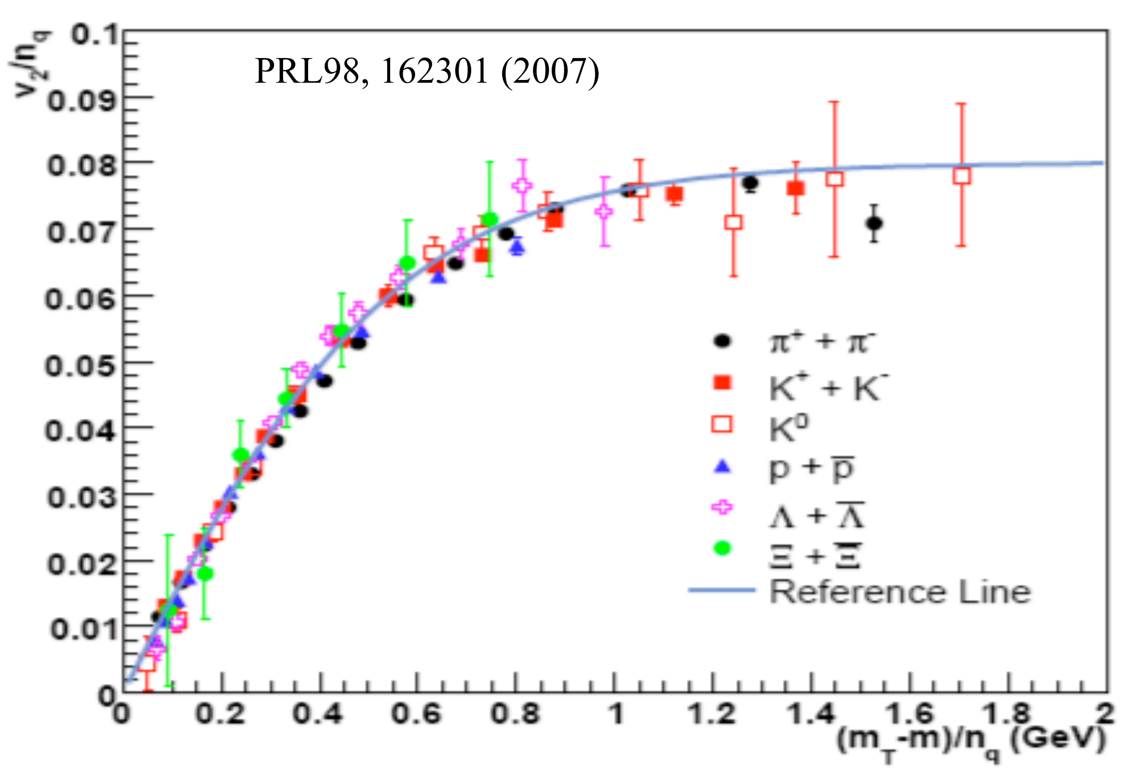
✓ Viscosity/entropy ratio near quantum bound 1/(4π)

➔Low viscosity/entropy → very good momentum transport

∴ strong coupling

- *At what scales is the coupling strong?*
- *What are the initial conditions?*

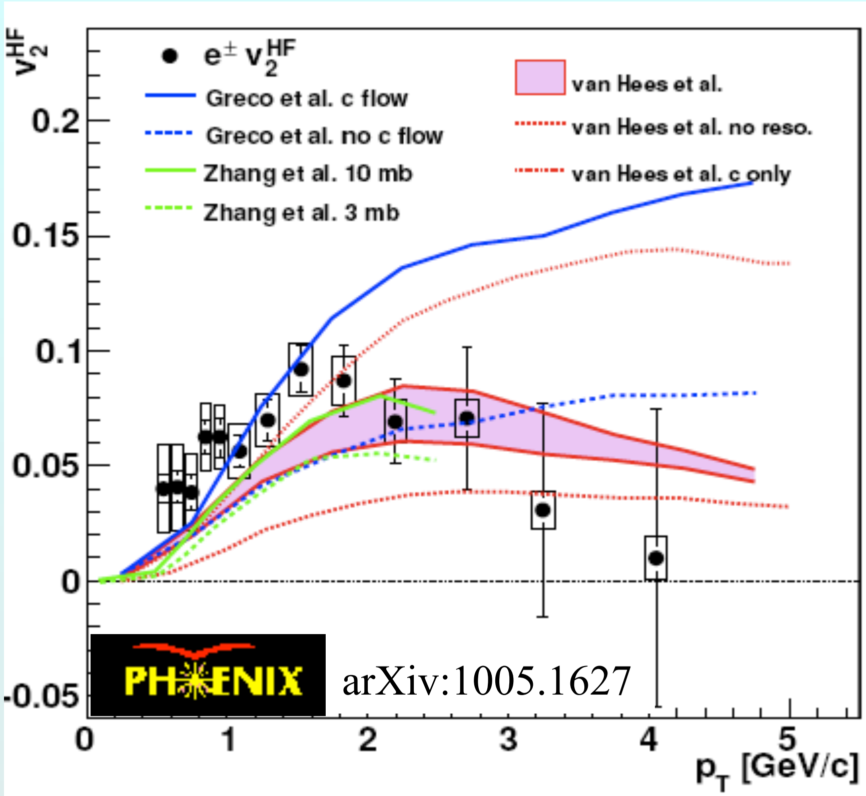
Collective flow scales with # of valence quarks

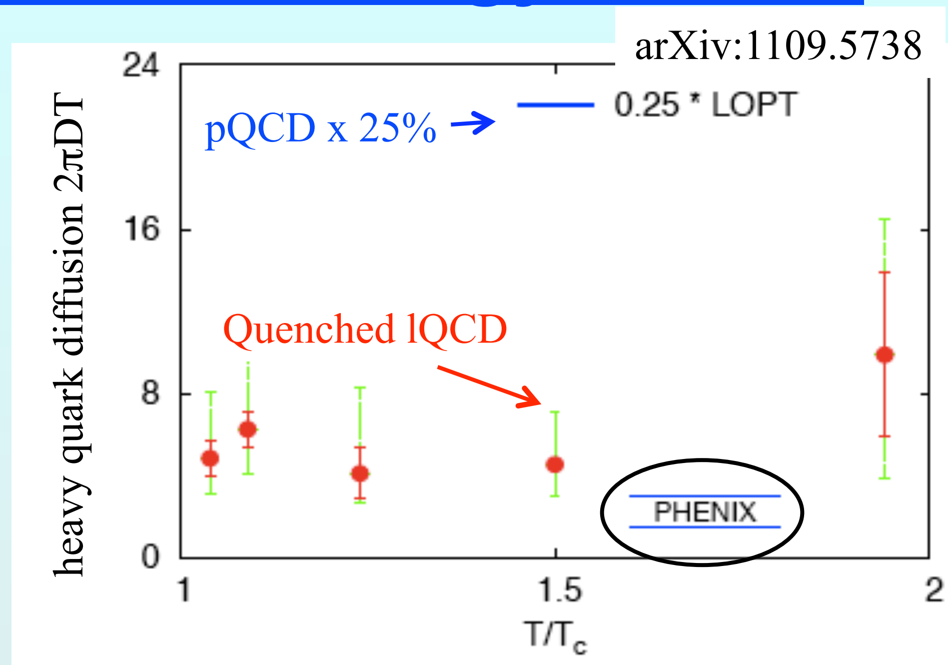


- ✓ As predicted by hydrodynamics
- ✓ Data requires thermalization in < 1 fm/c

- *How can equilibration be achieved so rapidly?*
- *Are there quasiparticles in the quark gluon plasma? If so, when and what are they?*

Even heavy quarks lose energy & flow!

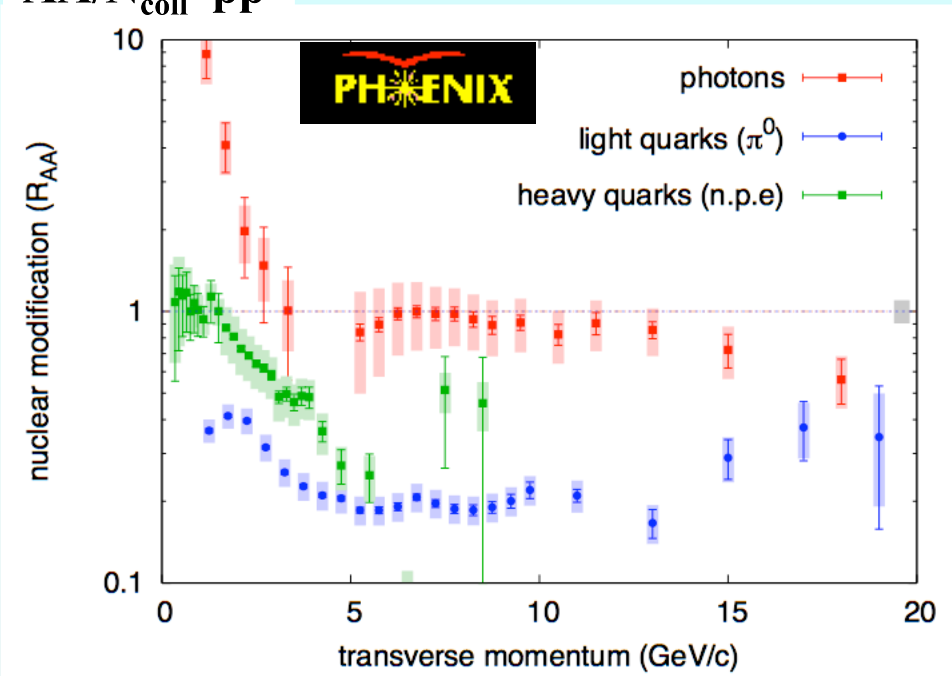


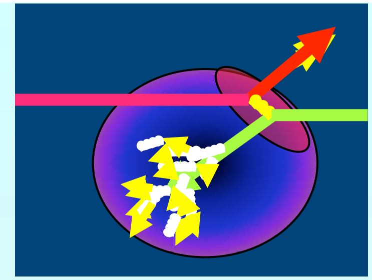


- *At what scales (distance, E, M) is the coupling strong?*
- *What is the parton-plasma interaction?*
  Is there a plasma response?
- *Are there quasiparticles?*

Plasma is very opaque

AA/N$_{coll}$*pp





✓ *Colored particles suffer large energy loss*

✓*opaque up to high p_T*

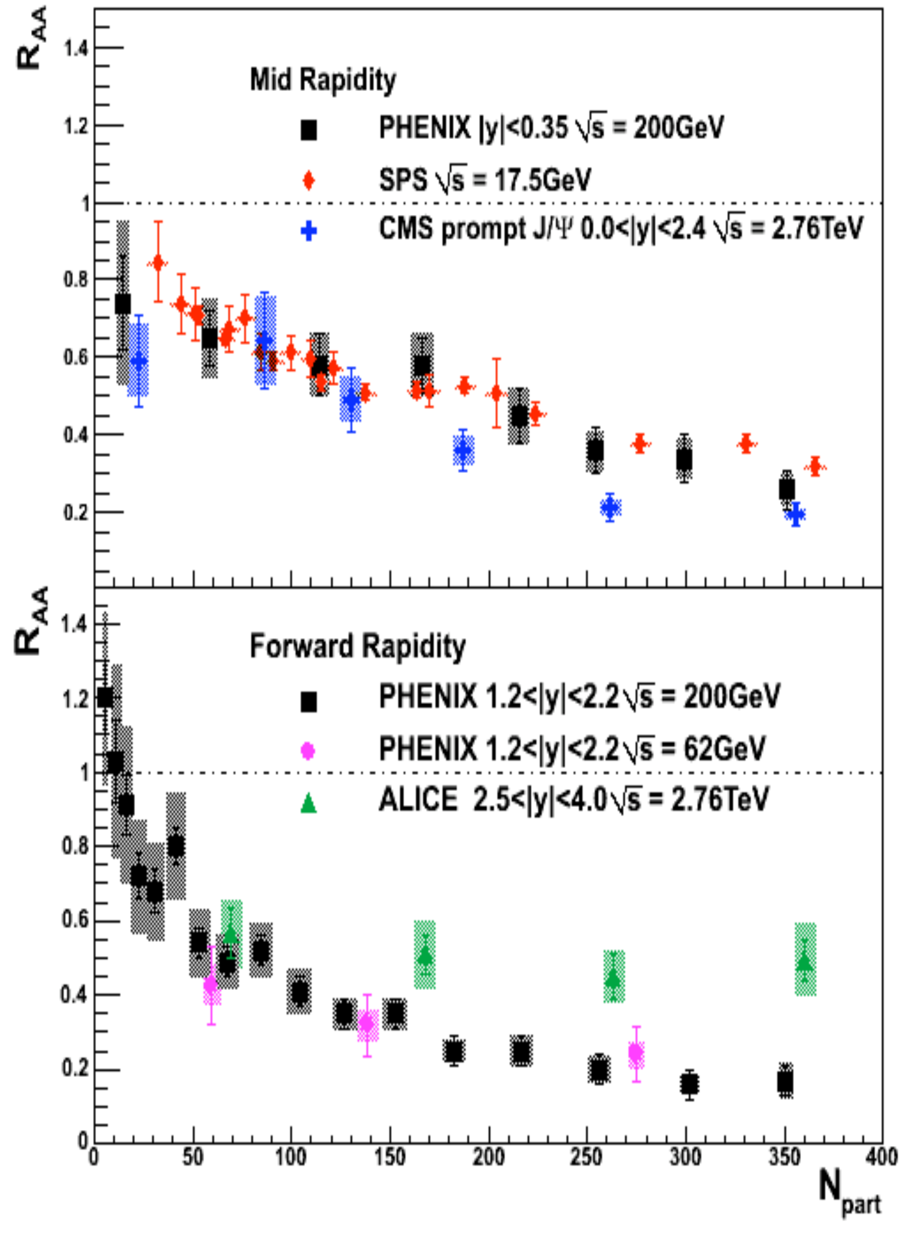
A challenge for pQCD (g radiation dominated)

Radiation + collisional energy loss?

- ***At what scales (distance, E, M) is coupling strong?***
- ***What mechanisms for parton-plasma interactions? For plasma response?***

AA/N_{coll}*pp

J/ψ: color screening in QGP?



✓ No obvious suppression pattern with ε, T!

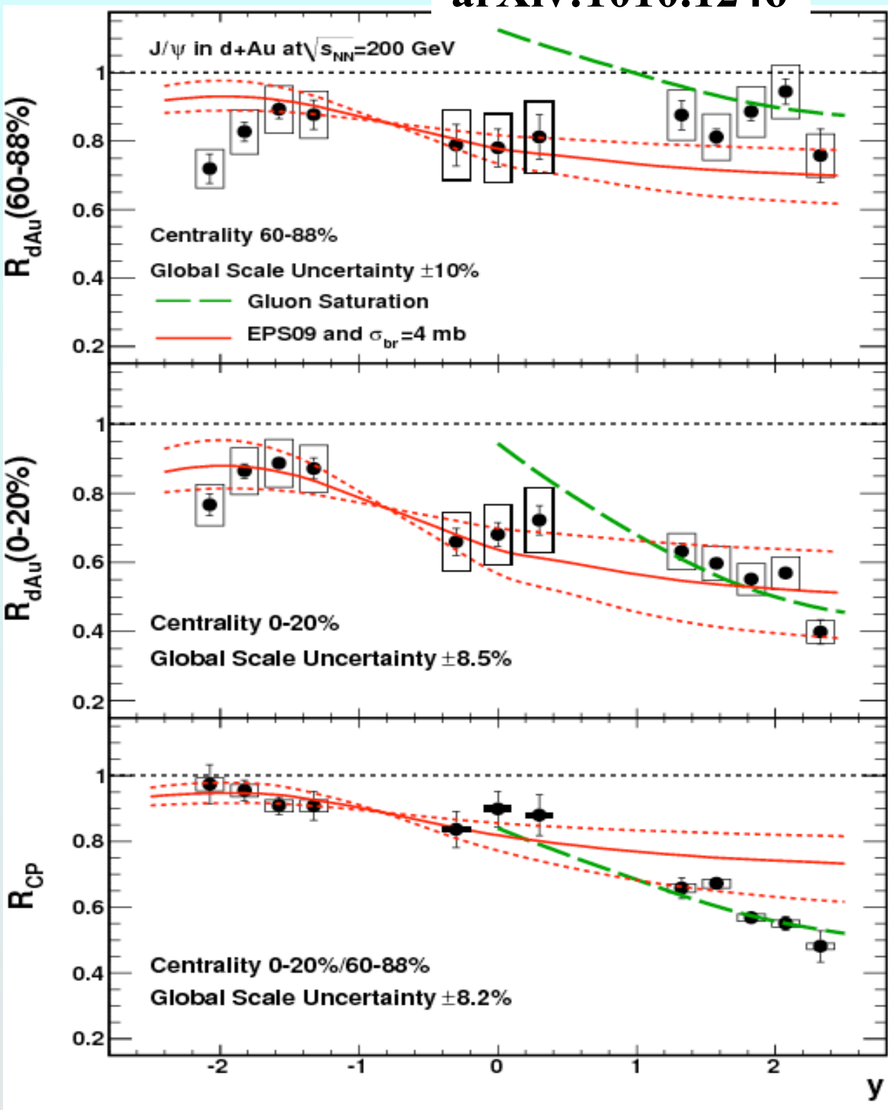
✓ Final state recombination plays a √s dependent role

● **To understand color screening: study as a function of √s, p_T, r_{onium}**

● NB: need d+Au data to disentangle cold matter effects in initial state

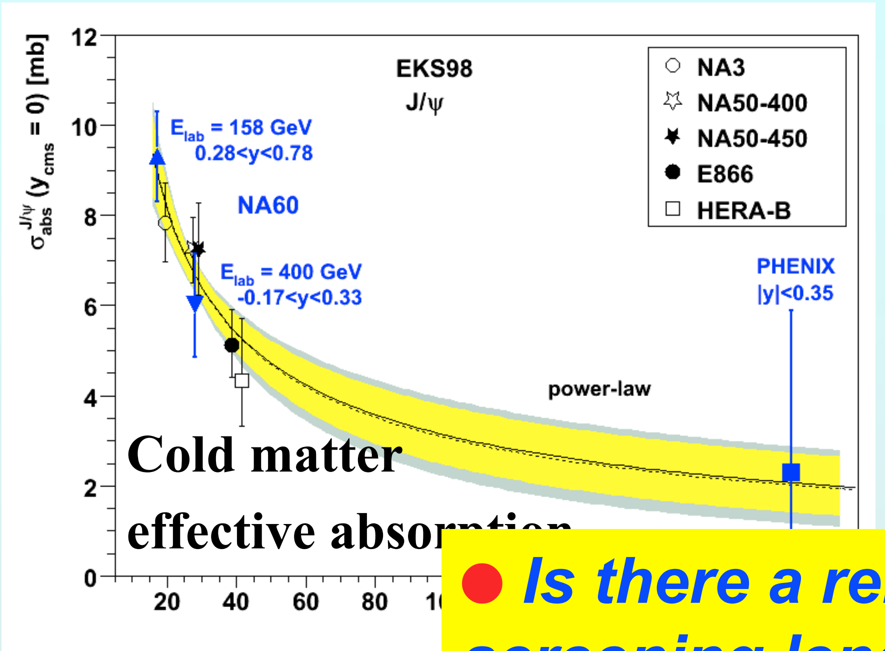
Suppression pattern ingredients

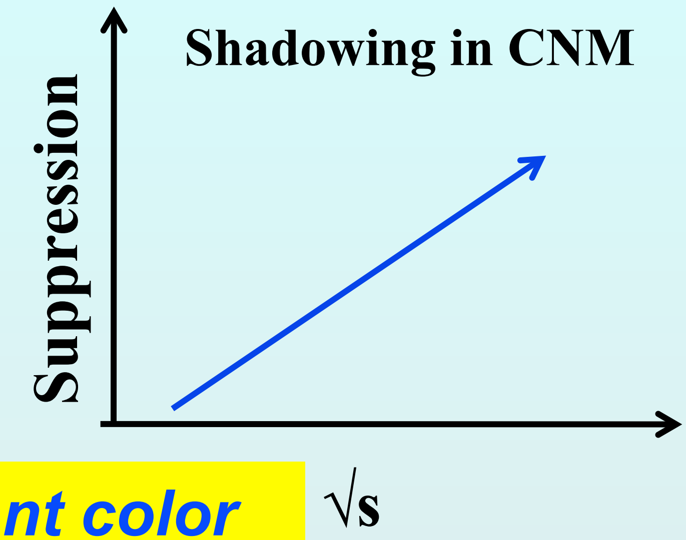
arXiv:1010.1246



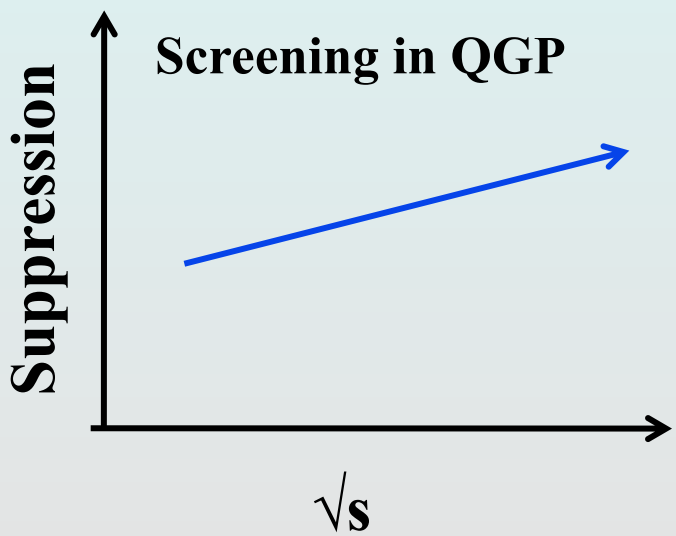
- Color screening
- Initial state effects
  - Shadowing or saturation of incoming gluon distribution
  - Initial state energy loss
  - (calibrate with p+A or d+A)
- Final state effects
  - Breakup of quarkonia due to co-moving hadrons
  - Coalescence of q and qbar at hadronization
  - (calibrate with A, centrality dependence)

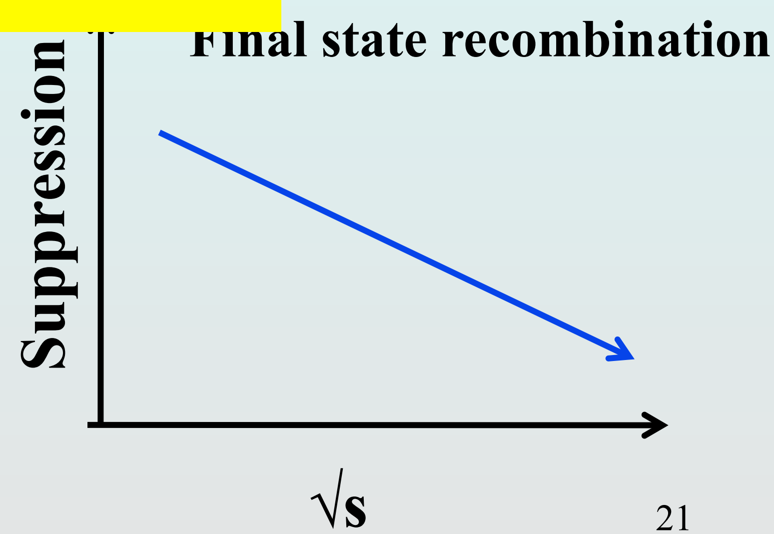
√s dependence of suppression effects





- ***Is there a relevant color screening length?***

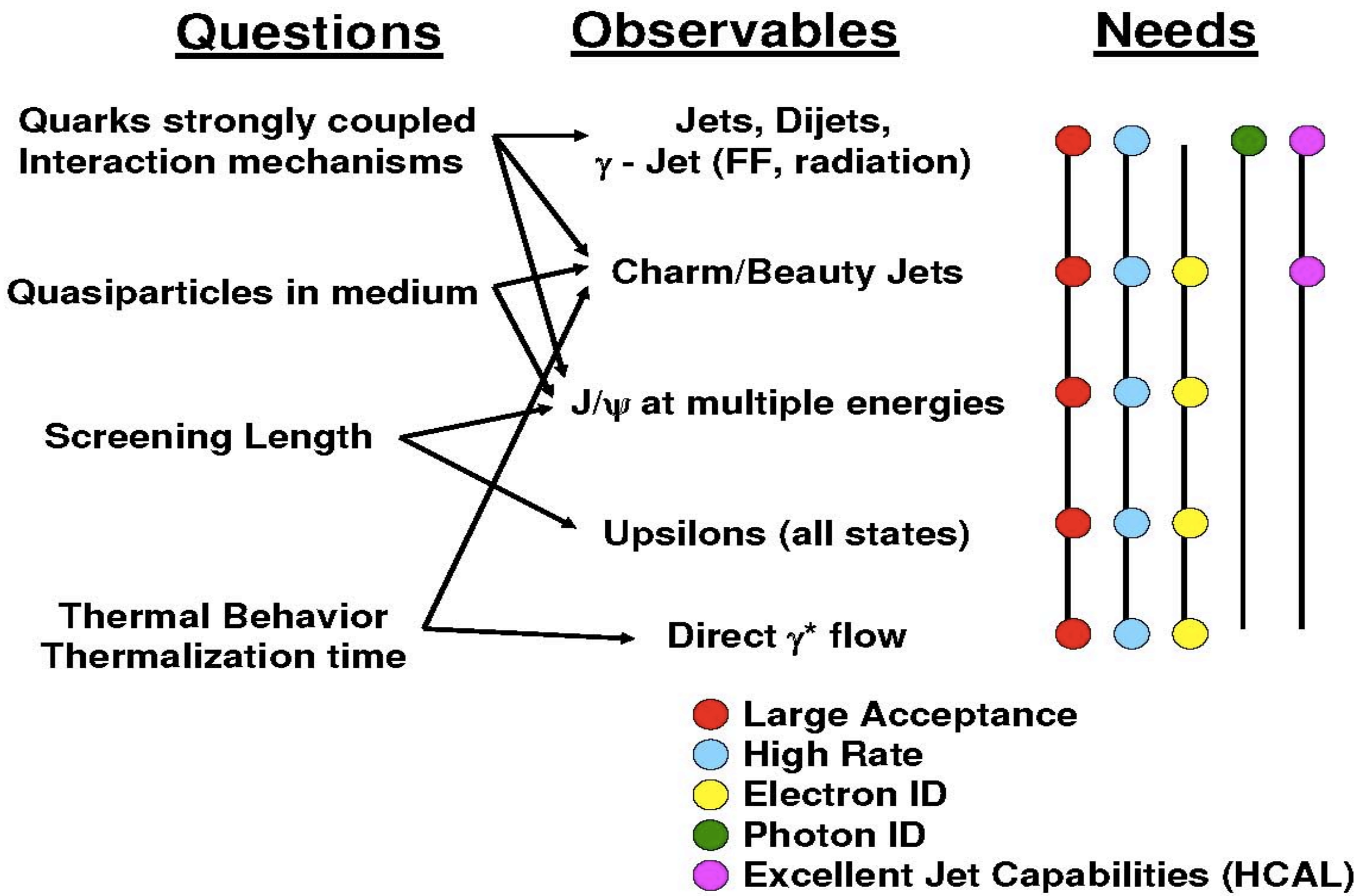




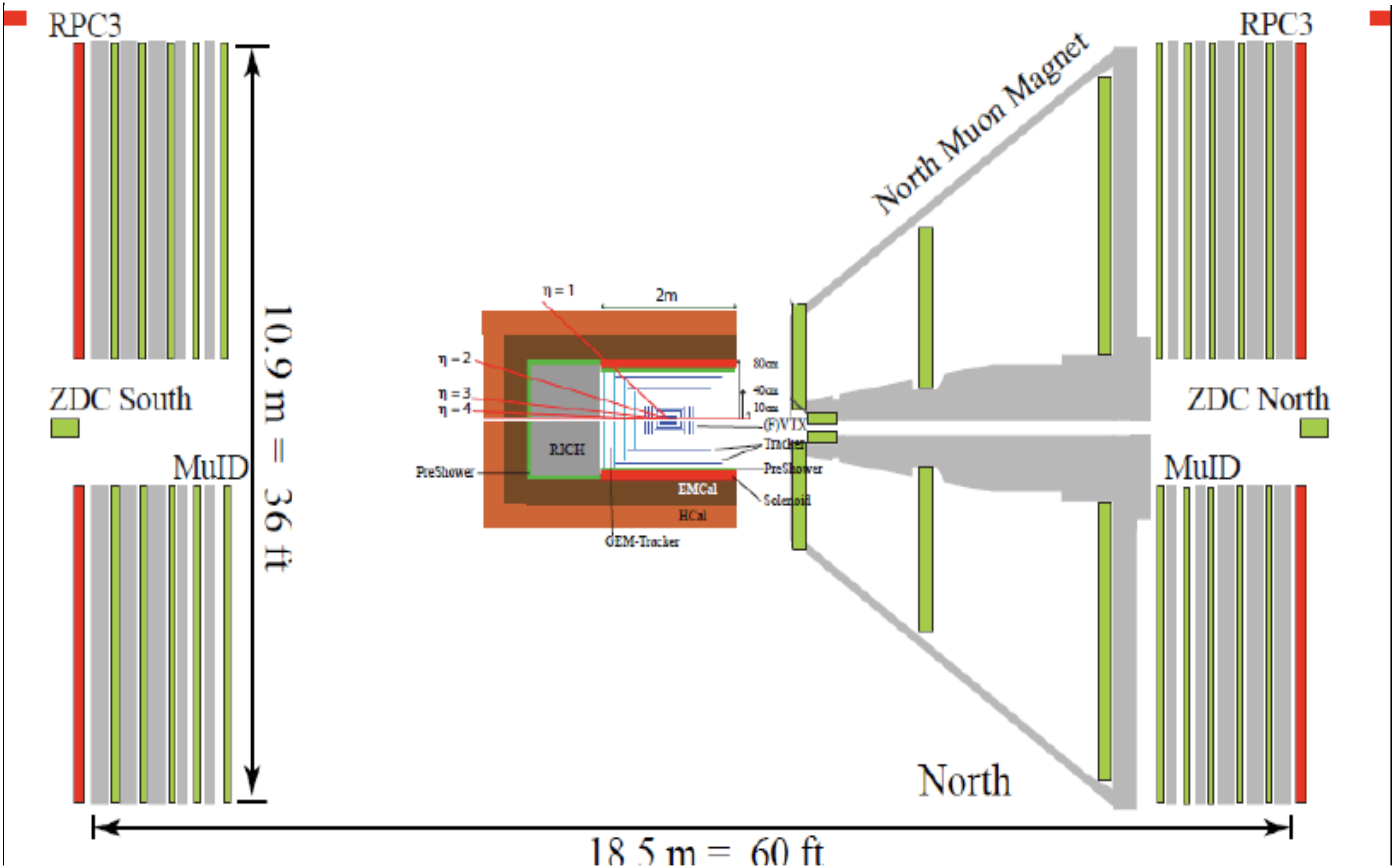
New questions from RHIC & LHC data!

1. At what scales is the coupling strong?
2. What is the mechanism for quark/gluon-plasma interactions? Plasma response? Is collisional energy loss significant?
3. Are there quasiparticles in the quark gluon plasma? If so, when and what are they?
4. Is there a relevant (color) screening length?
5. How is thermalization achieved so rapidly?
6. Are there novel symmetry properties?
7. Nature of QCD matter at low T but high ρ? (i.e. what is the initial state?)

To answer: PHENIX Decadal Plan

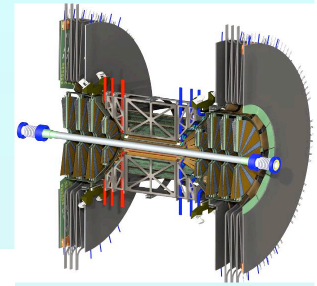


Upgrade PHENIX to answer the questions

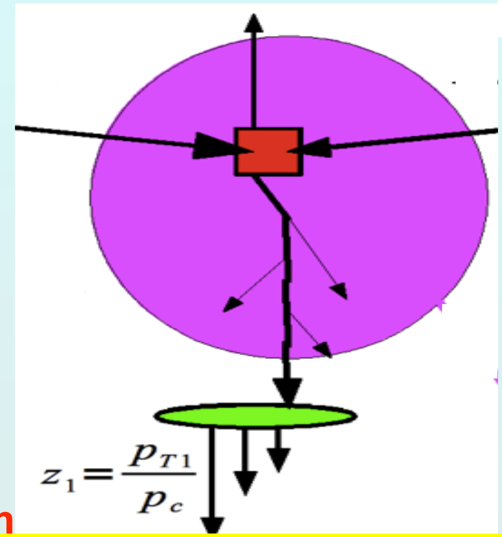


Compact, hermetic, EM + hadron calorimetry

Use RHIC's key capabilities*



- **Coupling scale & quasiparticle search**
  charm hard(not thermal) probe @ RHIC
  c vs. b in QGP
- **parton-plasma interaction**
  Jets ≤ 50 GeV, γ-jet
  E_{jet}, ℓ, q_{mass}, angle dep. of dE/dx
  Jet virtuality ~ medium scale
- **Screening length**
  study as function of $\sqrt{s}$, p_T, r_{onium}
- **Thermalization mechanism**
  γ_{dir} yield, spectra & flow
- **QCD in cold, dense (initial) state**
  y dependence in d+Au
  Gluon saturation scale?
  EIC



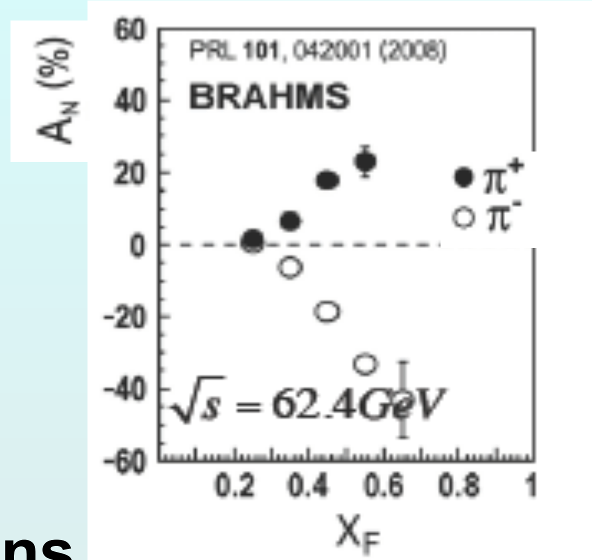
Au+Au
Cu+Au
U+U

Luminosity x10 at RHIC
Large acceptance
➔rare probe scan:
$50<\sqrt{s}<200$ GeV
➔ asymmetric systems

*In the era of P

Forward spectrometer: transverse spin

- Quarks have transverse motion inside proton (uncertainty principle demands it…)
- Large A_N observed
  pQCD predicts scaling: $$A_N \approx \frac{m_q \alpha_S}{p_T}$$
- Other sources can give $A_N \neq 0$



s. $$x_F = \frac{2p_L}{\sqrt{s}}$$

- Initial state: (Sivers) spin-p correlations
  intrinsic p_T inside nucleon
- Final state: (Collins) p_T inside jet
  + initial & final state interactions

NB: these say interactions among partons in a nucleus are not so simple!

Guessing What Might Be Doable for sPHENIX

1) Regardless of the detailed measurements to be made in the future, there was general agreement that **PHENIX needs a substantial increase in acceptance** to remain competitive

- ***BNL+DOE request sPHENIX 1st upgrade proposal***
  - ***Request is due July 2012***
  - ***We should ask for ≤ $20M***
  - ***We must identify physics goals for 2017***

2)

3)

4)

- ***Construction of full sPHENIX will be staged***

- ***BNL encourages PHENIX to identify international contributions of detectors.***
  - ***We should include these in our physics plan for 2017!***

5)

simply complementarity to the LHC heavy-ion program and experiments.

6) It is also vital that an upgrade of this magnitude **be compatible with future PHENIX upgrades that would be considered for the eRHIC era.**

A first cost guesstimate

Carry over from existing PHENIX:

- VTX and FVTX
- EMCal in Forward Arm and perhaps barrel
- DAQ
- Infrastructure (LV, HV, Safety systems…)

What is new:

- 2-3T solenoid (R = 60-100 cm)
- Preshower detector
- Barrel EMCal (maybe new)

} $20M

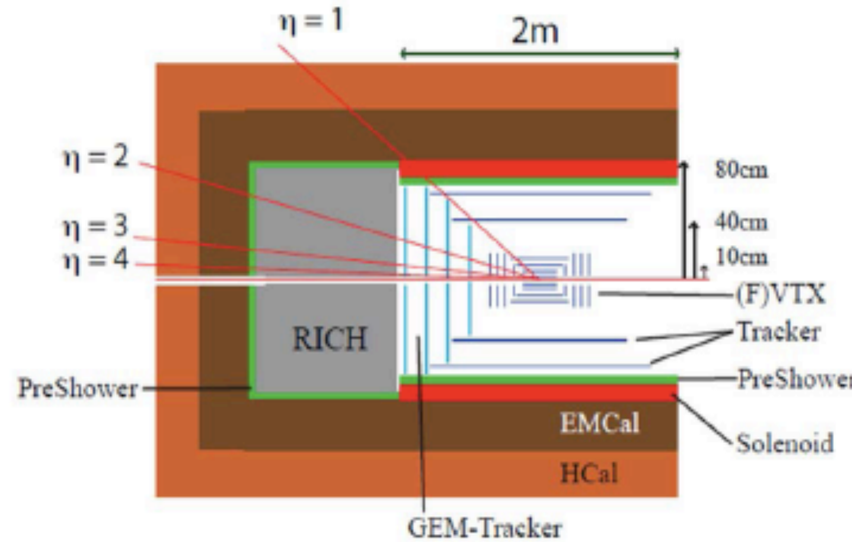
- Hadronic Calorimetry } $8-10M
- Additional tracking layers of Si at ~ 40cm } $5-7M
- Forward Arm with RICH and GEM tracker } $10M

Other

- Forward magnet
- Forward HCAL
- Barrel trking layer ~60cm

} $10-15M

All cost estimate include overhead and contingency

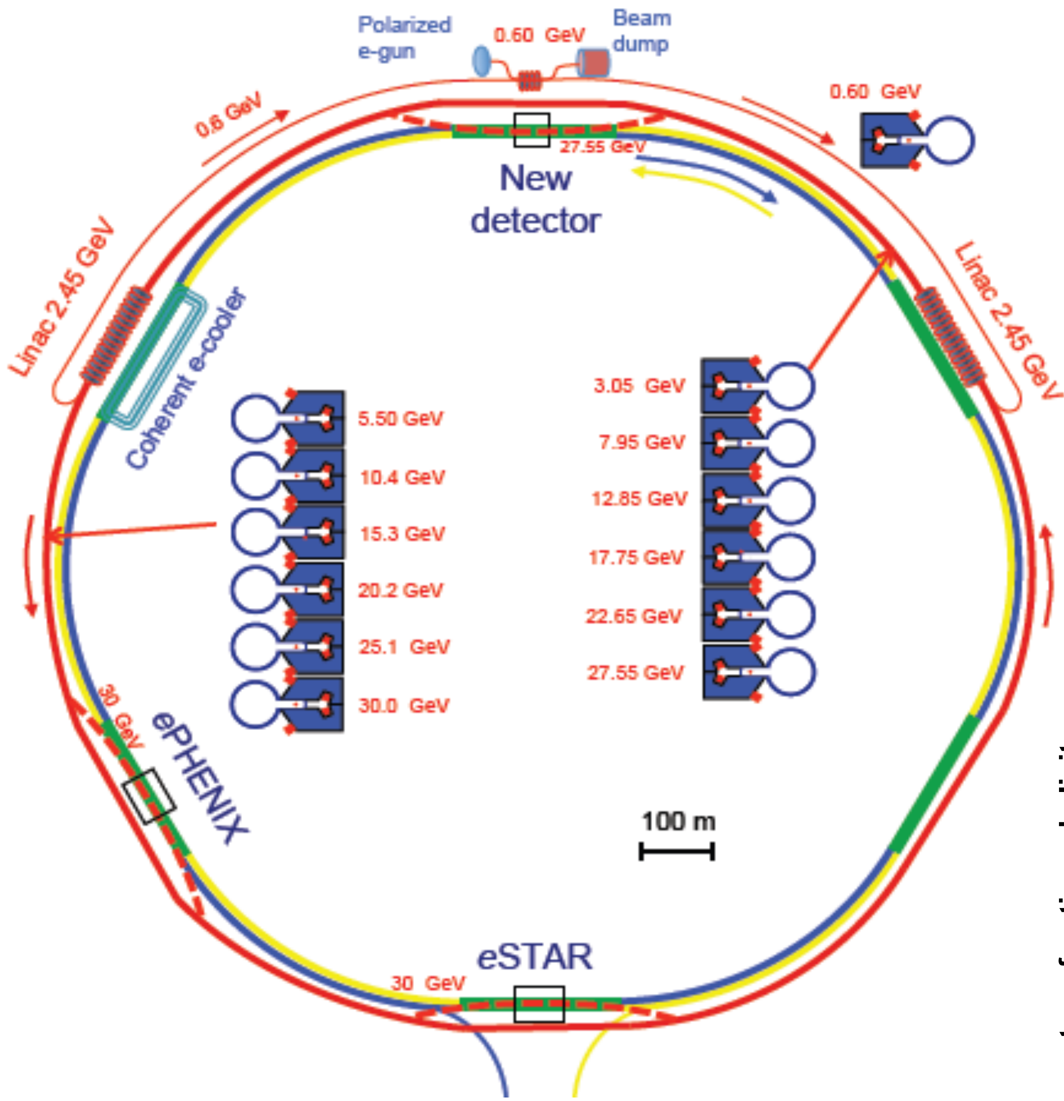


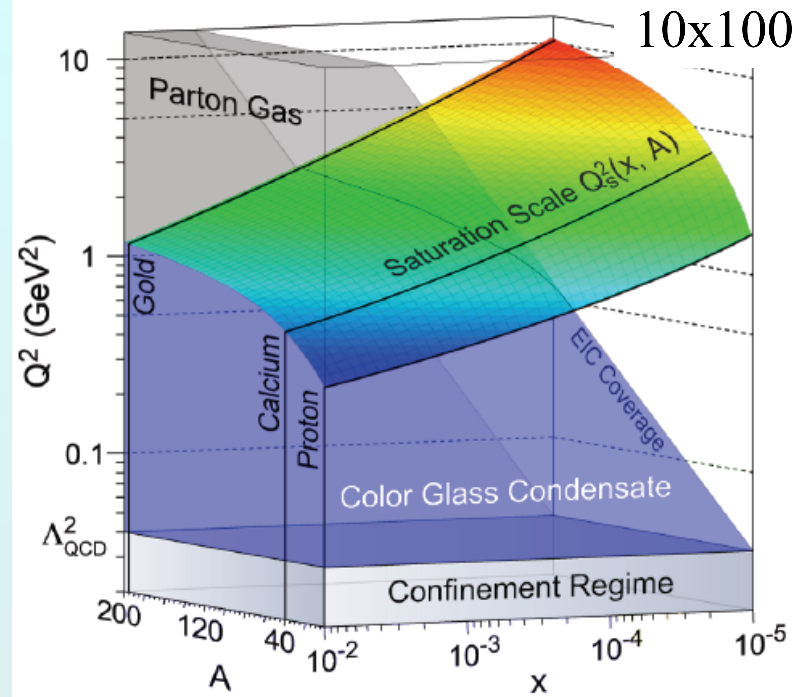
Can be built incrementally

Total Project Cost $53-62M

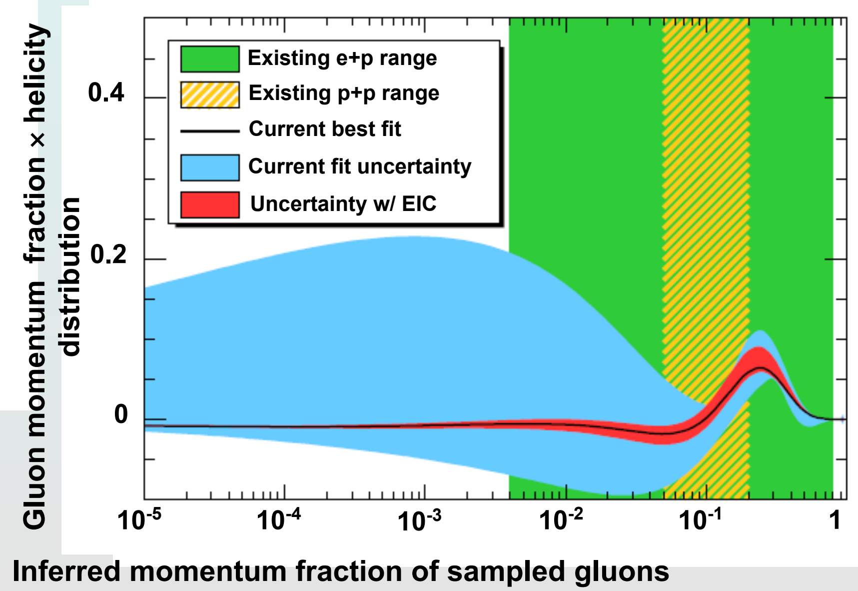
- Approx ½ replacement cost of existing $130M PHENIX detector
- DOE contribution estimated to be 60% of total $32-44M
- Forward detector is key for eRHIC physics (part of eRHIC project?)

> 2012: Electron-ion collider; $\vec{e}$-p collider



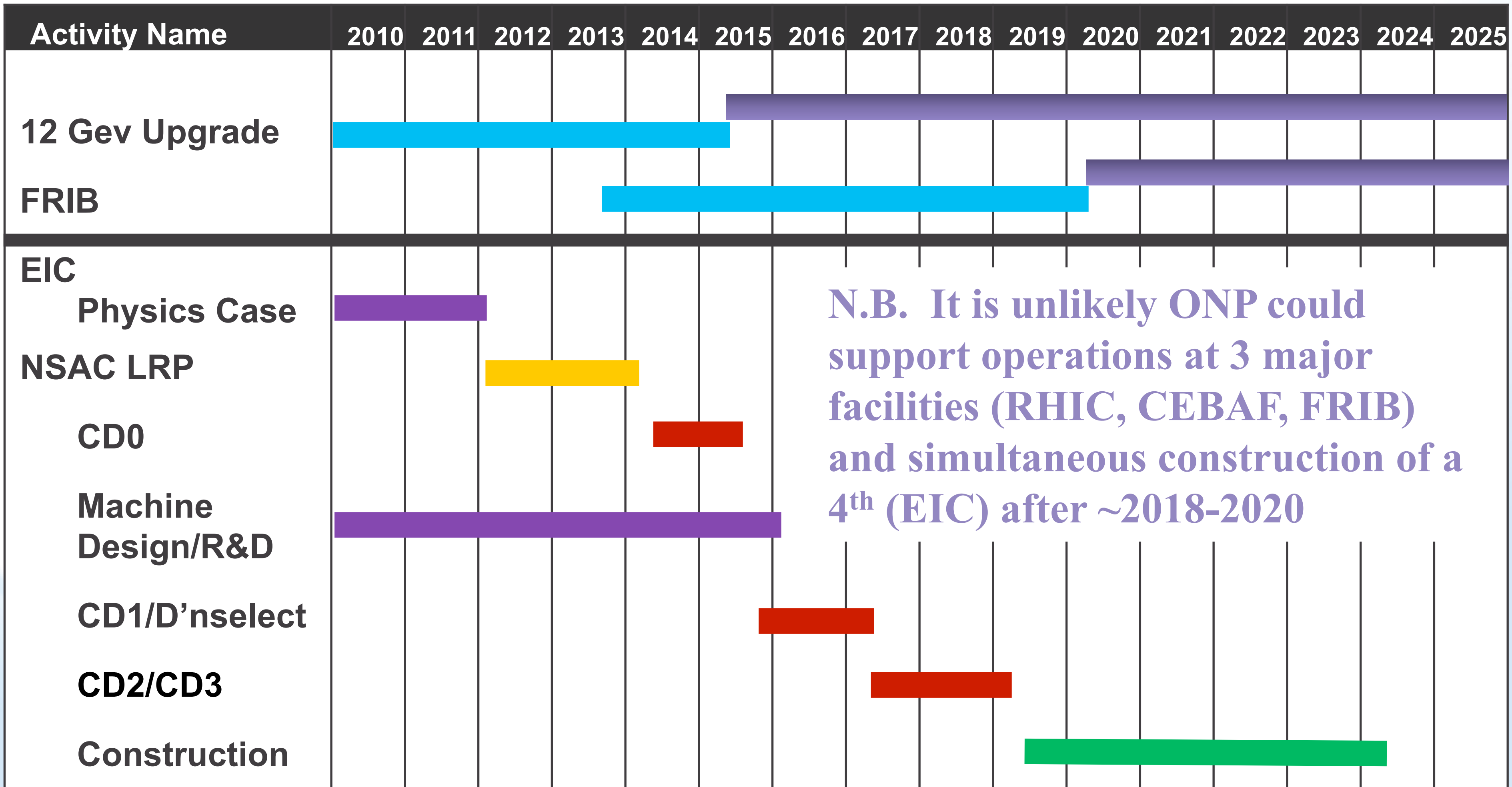


$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta g + L_g$$



Potential EIC Timeline from Hugh Montgomery (INT Workshop, Sept. 2010)

EIC Realization Imagined



sPHENIX → ePHENIX will require

- Hadron PID in barrel region
- Excellent electron ID and thin tracking forward
  - For higher luminosity/energy replace N muon arm
    - not required for day-1 EIC operations
- Thinner tracker in barrel region
  - Minimize electron's multiple scattering
  - NB: by then, the VTX will be ~10 years old

- ***Staged upgrades!***

Some things to consider

- ***Size***

  Decadal Plan concept too small for barrel PID

  Probably need another ~50cm
- ***Schedule***

  Must replace central magnet in first step!

  is it wise to reuse and old magnet???

  HCAL + EMCAL fundamentally new at RHIC

  include in DOE proposal?!

  Barrel intermediate tracker from RIKEN for 2016/17
- ***Pre-shower necessary for 2016/17***

  good candidate for Japan HI groups

  Synergy with ALICE forward calorimeter upgrade
- ***NSF*** has funded W trigger upgrades

  Request forward tracker/RICH from NSF?
- ***Electron ID*** requirements under study; $\Upsilon \rightarrow \mu\mu$?

PHENIX future is hot & very cool & exciting

- **Near-term (2011-2016)** Stochastic cooling ➔ 4 x 10^{27}; Cu+Au

  New microvertex detectors for heavy quark probes

  Quantify properties of near-perfect fluid QGP (v_n)

  Quantify features of the QCD phase diagram

  Pin down sea quark spin

- **Medium-term (2017-2022) Upgraded detectors**

  Upgrade PHENIX: compact, large acceptance jet, quarkonia, photon detector

  Attack the list of new QGP questions

  Study parton transverse spin in polarized p+p

- **Long-term (≥ 2023) Electron-Ion Collider**

  Add ~5 GeV (upgradable to 30 GeV) electron Energy Recovery Linac inside RHIC tunnel

  e+A, $\vec{e}$+$\vec{p}$ (^{3}He) for GPDs, Δg, gluonic cold matter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- **Backup**

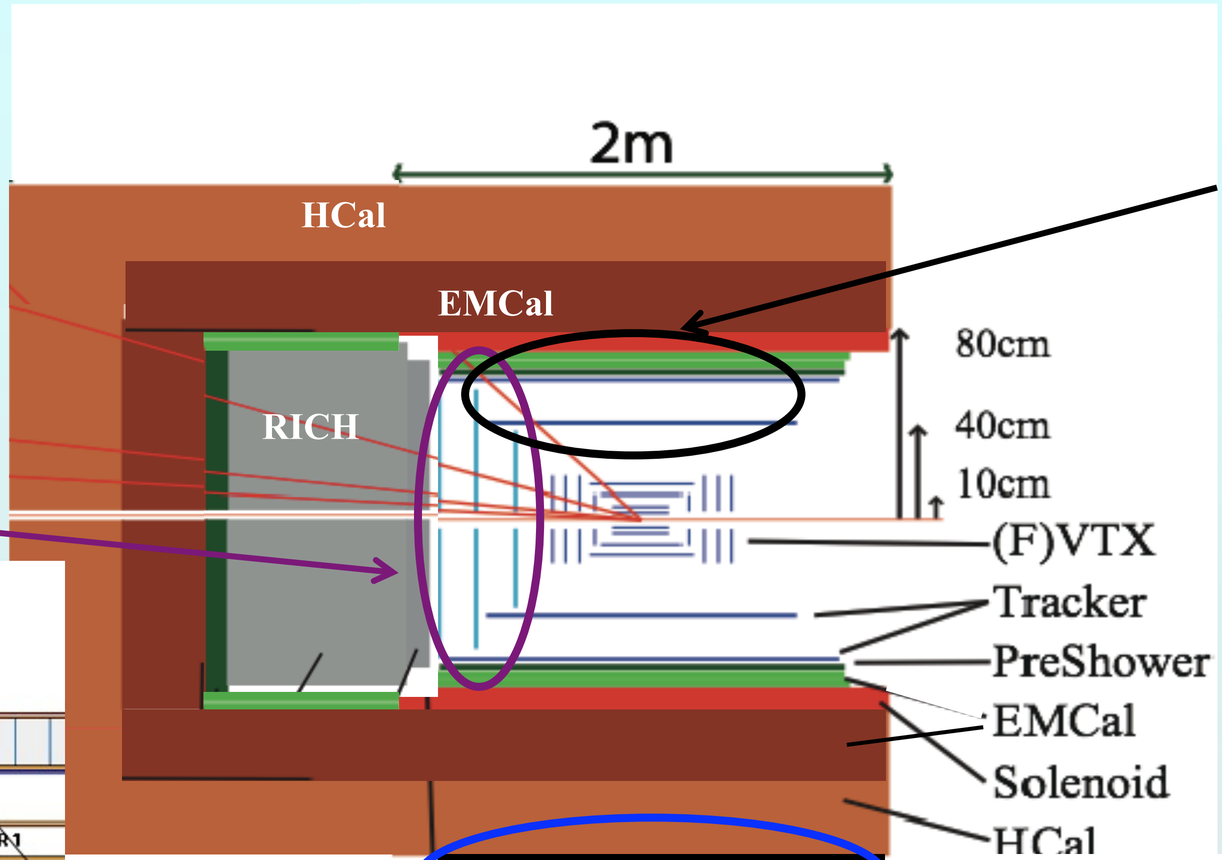
Why is RHIC Essential to Pursuit of This Science?
(Steve Vigdor, BNL Associate Director)

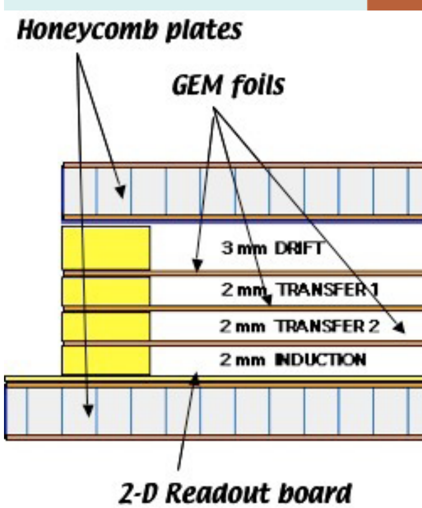
- **Spans energy "sweet spot" where deconfinement transition to QGP appears to set in, permitting study of early universe matter above & below transition**
  - ***Can't be done at LHC, where injection energy is well above top RHIC E***
- **Flexibility in colliding beam species, incl. asymmetric collisions (e.g., Cu + Au) and highly deformed nuclei (e.g., U+U), permits systematic unraveling of effects of impact parameter, spatial anisotropy and asymmetry, path length through QGP, geometry fluctuations and magnetic field**
  - ***2-in-1 magnet design ⇒ asymmetric collisions very challenging at LHC***
- **In combination with LHC, provides very large energy lever arm for some observables, to constrain models, e.g., of parton E loss and color screening**
- **Detectors best suited to measure thermal photon and di-lepton spectra**
- **RHIC is world's only polarized proton collider, yielding unique spin program**
  - ***Polarized pp extraordinarily difficult technically at LHC energies***
- **Provides cost-effective path to future polarized EIC identified in 2007 NP Long Range Plan as highest priority next-generation facility for study of QCD in matter**
- **Maintains critical collider R&D capabilities in U.S. (where RHIC will be only operating collider beginning in FY12)**

Some interesting technology

Si + cylindrical GEM tracker for pattern recognition?

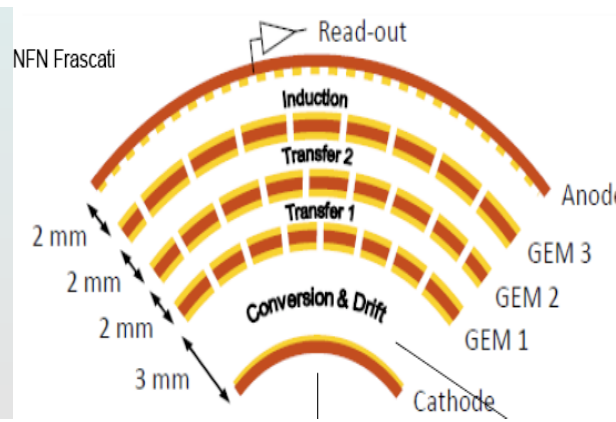
Thin GEM tracker



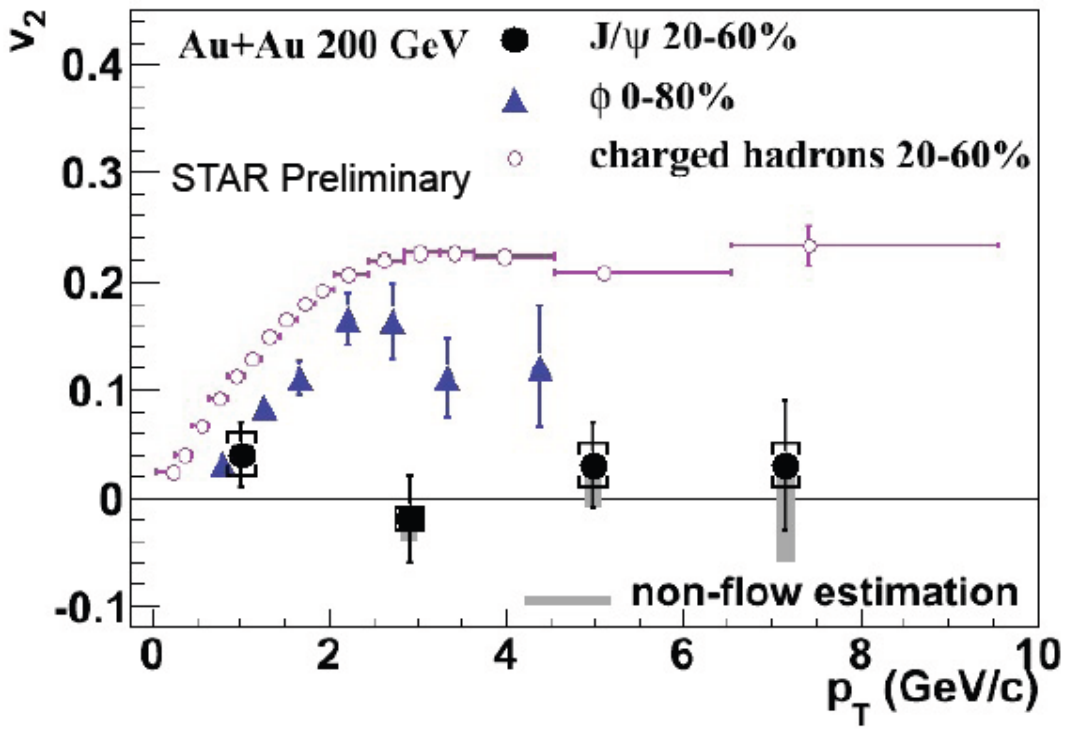


e.g. Compass, but with 3-d readout

layer of RPCs outside HCAL for Y -> μ+μ−?



Effect of final state $c\bar{c}$ coalescence?



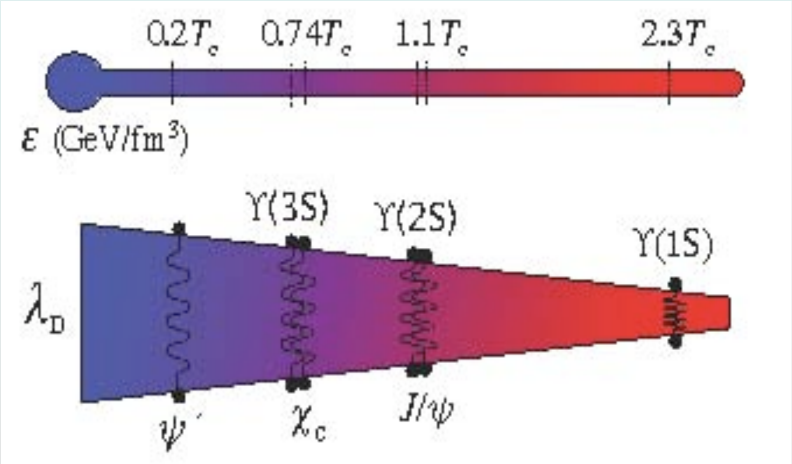
Open charm flows but J/ψ does not

➔c-cbar coalescence @ RHIC is not large

Correlations remain in QGP due to strong coupling?

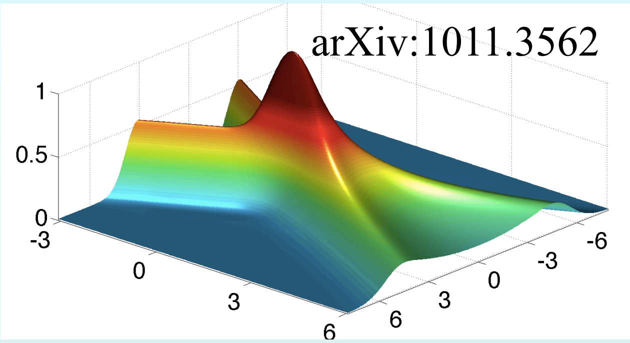
Need Υ 1S, 2S, 3S

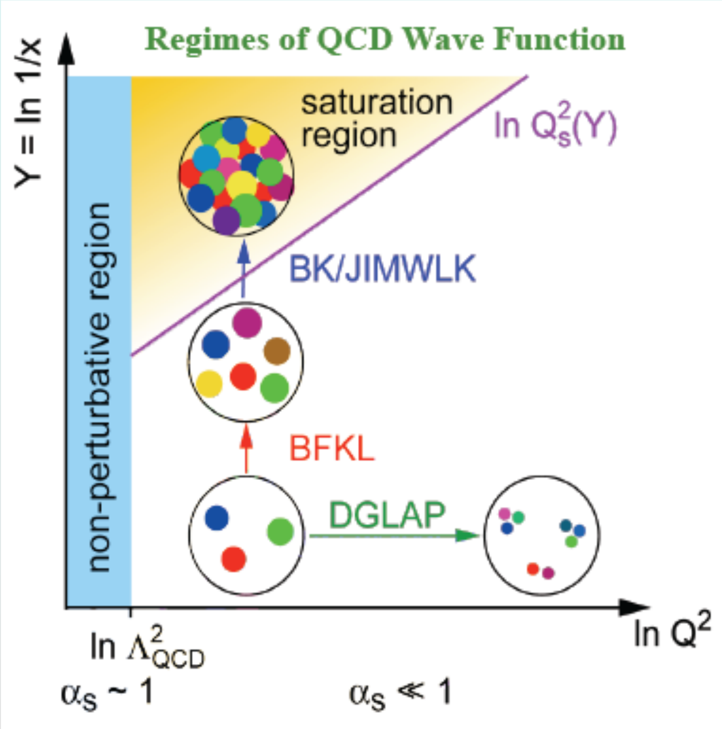
- *Is there a relevant color screening length?*



Rapid thermalization?

- Parton cascade is simply not fast enough
- A number of cool, inventive ideas
  Plasma instabilities?
  v. strong coupling (holographic)
    -> hydro valid after 3 sheet thicknesses!
  Shatter a color glass condensate?

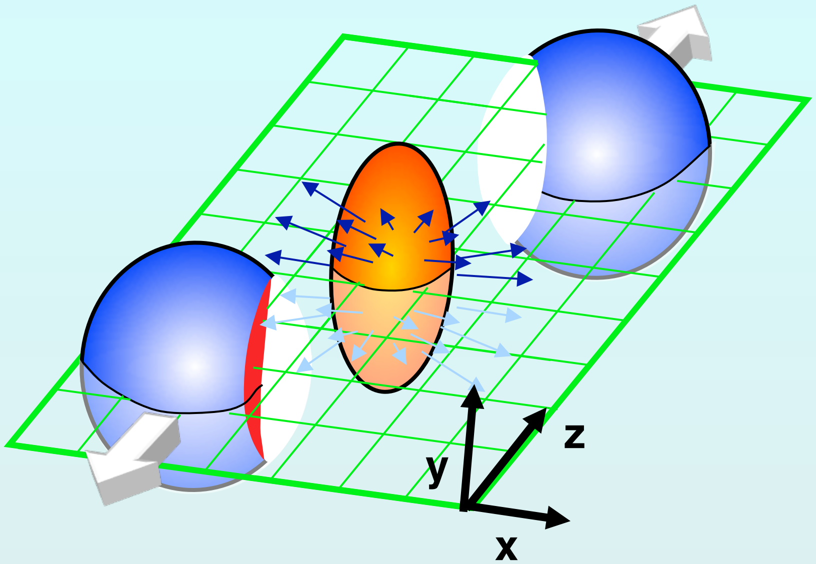




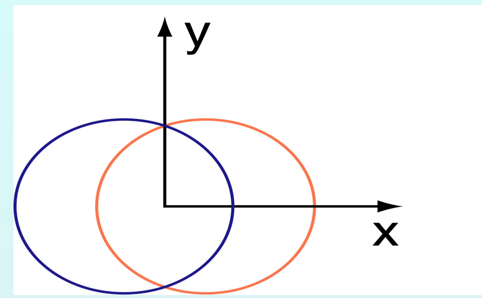
- A paucity of predicted experimental observables
  Needs more theory work

- Understanding the initial state (cold gluonic matter) is key

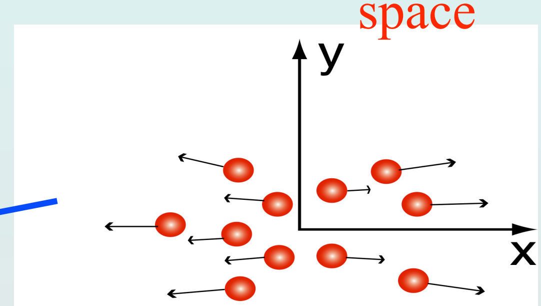
Measuring collective flow: start with v_2

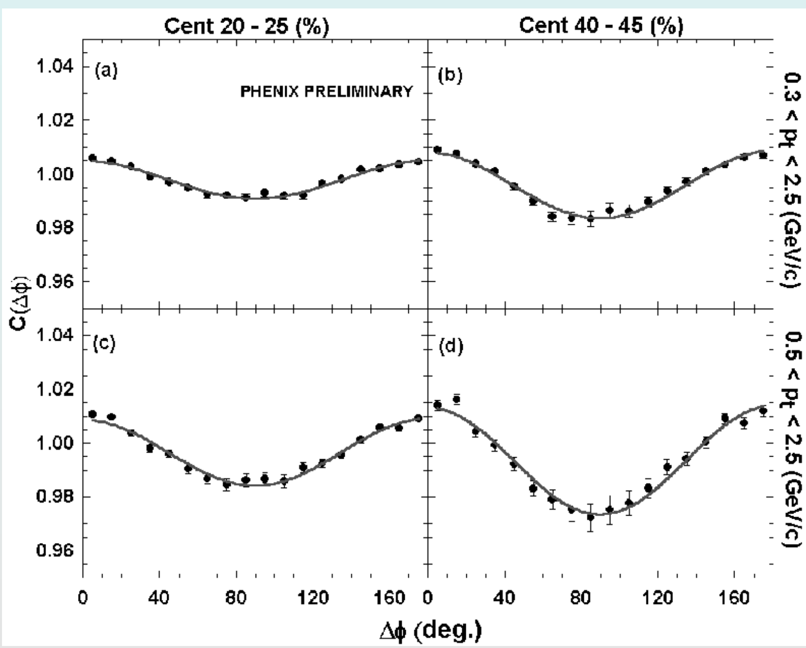


Almond shape overlap region in coordinate space



momentum space

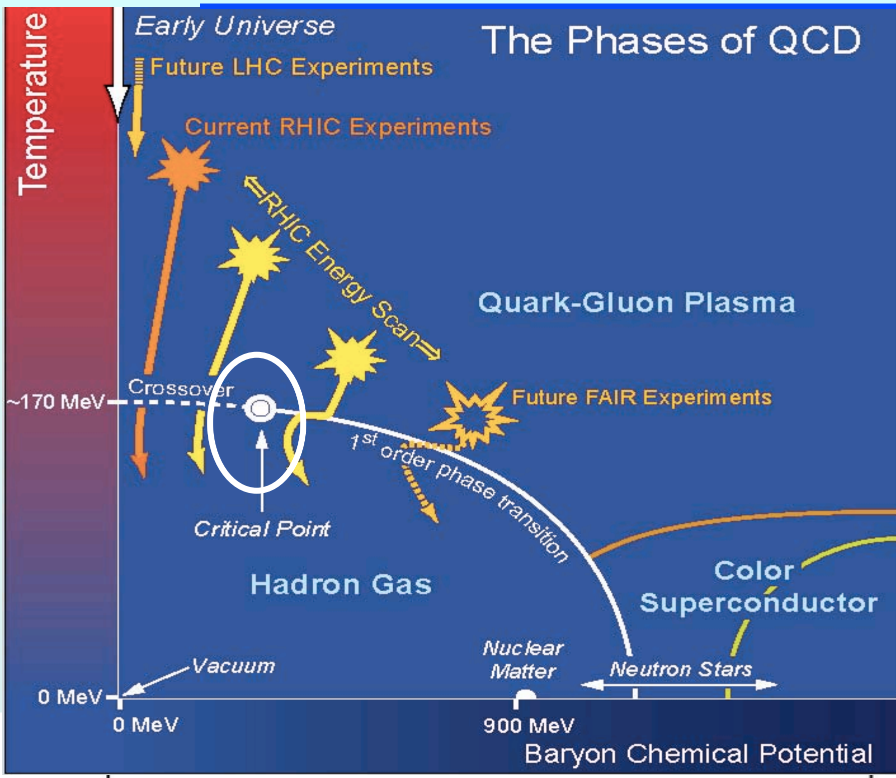


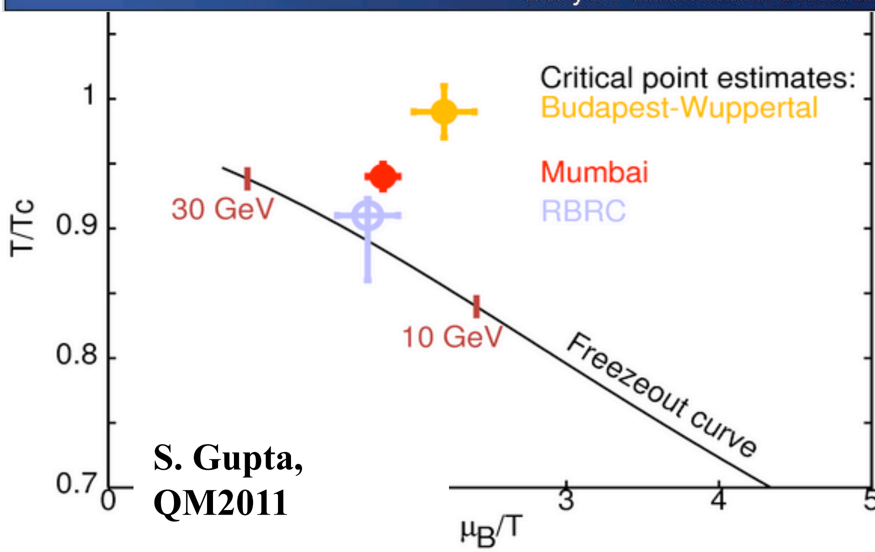


$dN/d\phi \sim 1 + 2\, v_2(p_T) \cos(2\phi) + \ldots$

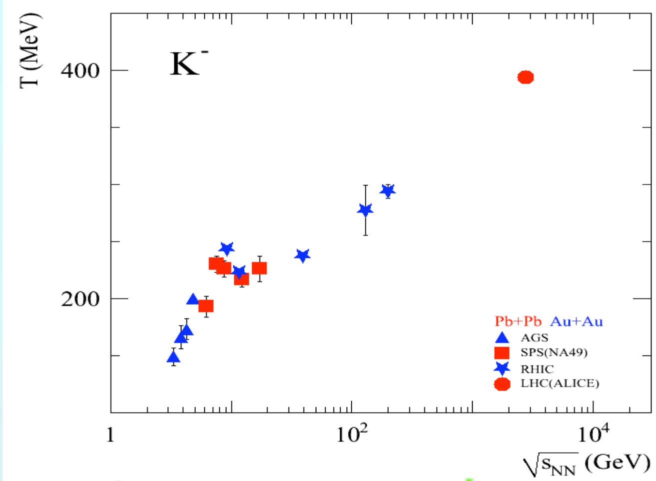
"elliptic flow"

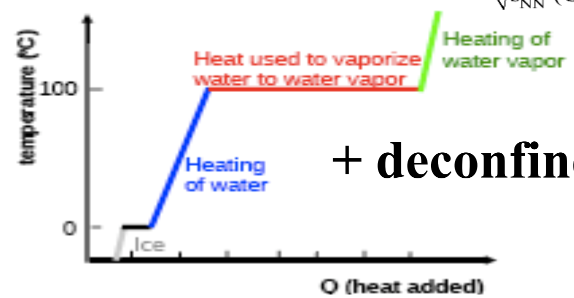
Can we locate the QCD critical point?



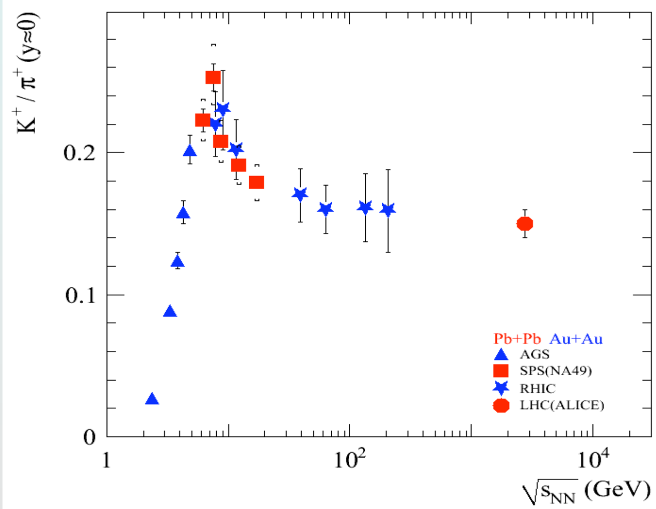


S. Gupta,
QM2011





+ deconfinement onset



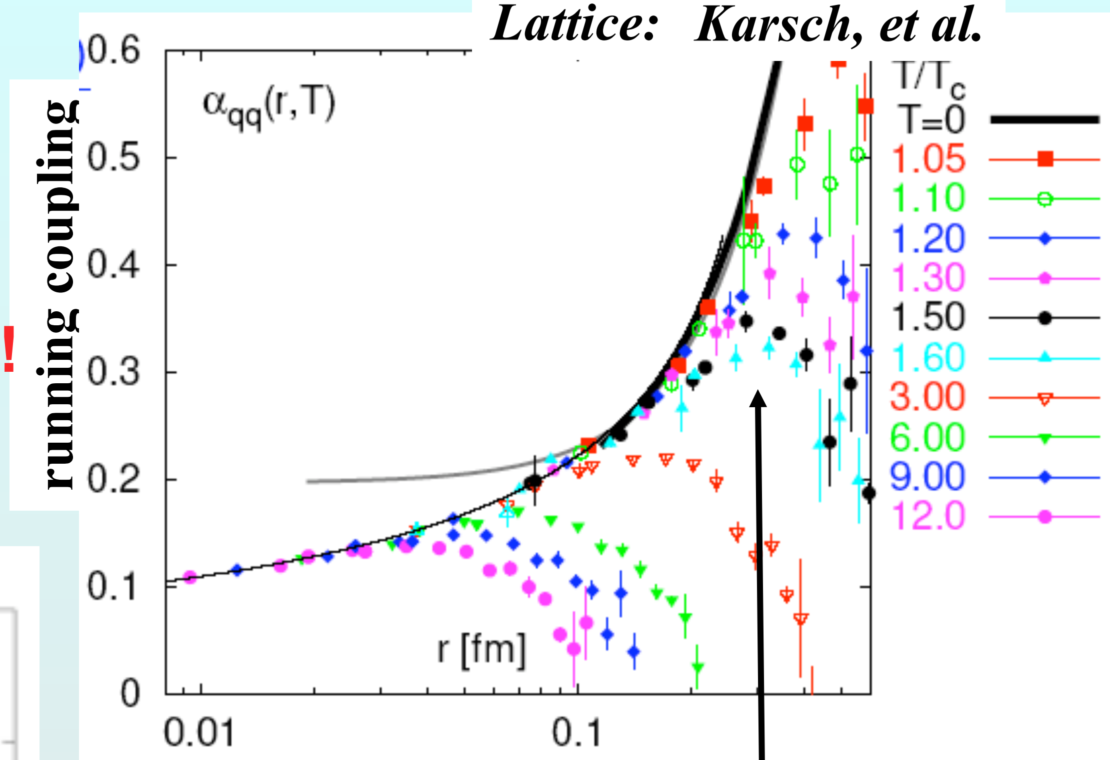
Early hard probe insights from LHC

- **Quarkonia energy dependence not understood!**
  Need charmonium and bottonium states at >1 √s at RHIC
  + guidance from lattice QCD!
- **Jet results from LHC very surprising!**
  Steep path length dependence of energy loss
  also suggested by PHENIX high p_T v_2; AdS/CFT is right?
  Unmodified fragmentation function of reconstructed jets
  looks different at RHIC, depends on "jet" definition?
  Lost energy goes to low p_T particles at large angle
  is dissipation slower at RHIC? Due to medium or probe?
  Little modification of di-jet angular correlation
  appears to be similar at RHIC
- Need full, calorimetric reconstruction of jets in wide y range at RHIC to disentangle probe effects/medium effects/ initial state

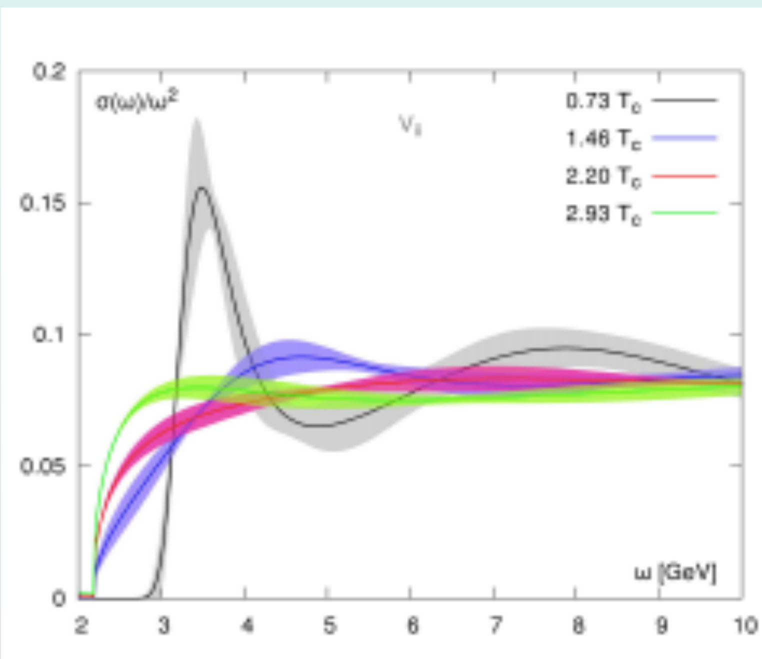
Is there a relevant screening length?

- **Strongly coupled matter: few particles in Debye sphere - decreases screening!**

Lattice: Karsch, et al.



coupling drops off for r > 0.3 fm



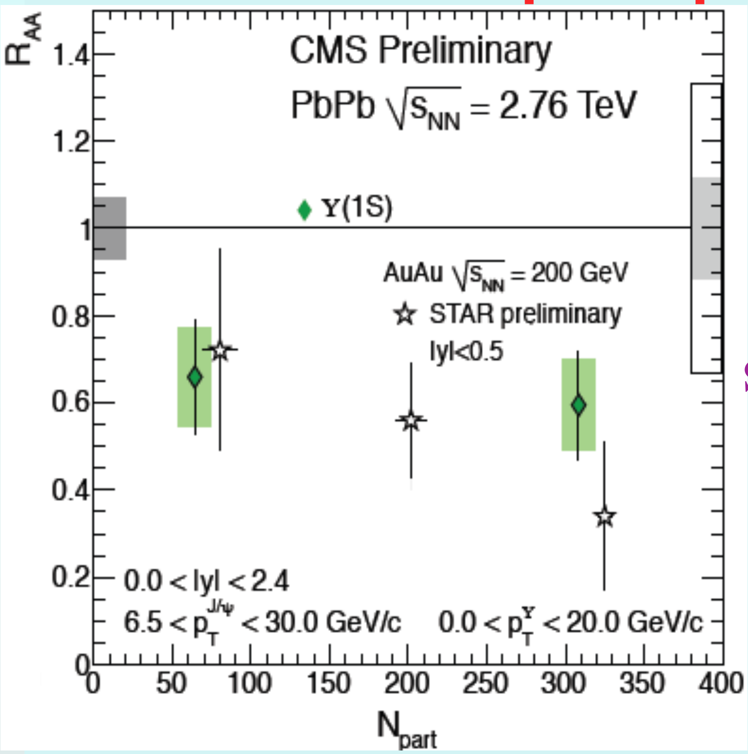
Ding, et al. arXiV: 1107.0311

LQCD spectral functions show correlation remaining at $T>T_c$
Partial screening?

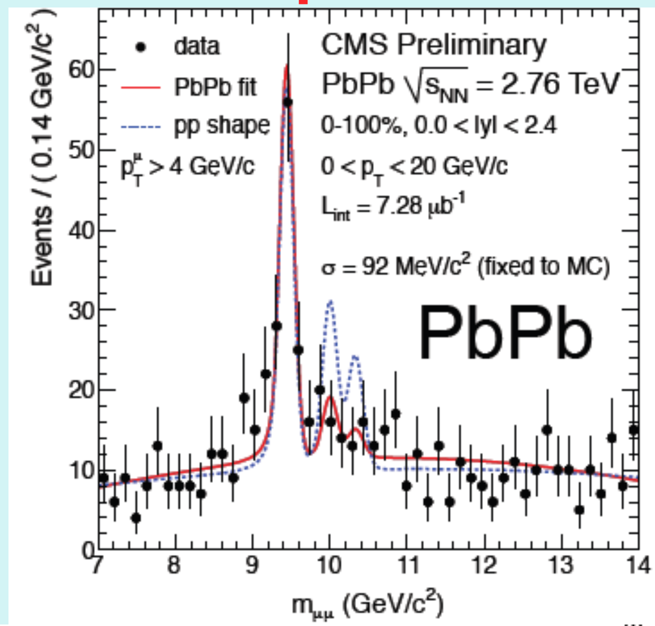
Need to understand quantitatively!

- Coalescence *could* be important at LHC

  More c-cbar pairs produced. Use b-bar to probe…



Υ (2S,3S) suppressed



$$\frac{\Upsilon(2S+3S)/\Upsilon(1S)|_{PbPb}}{\Upsilon(2S+3S)/\Upsilon(1S)|_{pp}} = 0.31^{+0.19}_{-0.15} \pm 0.03$$

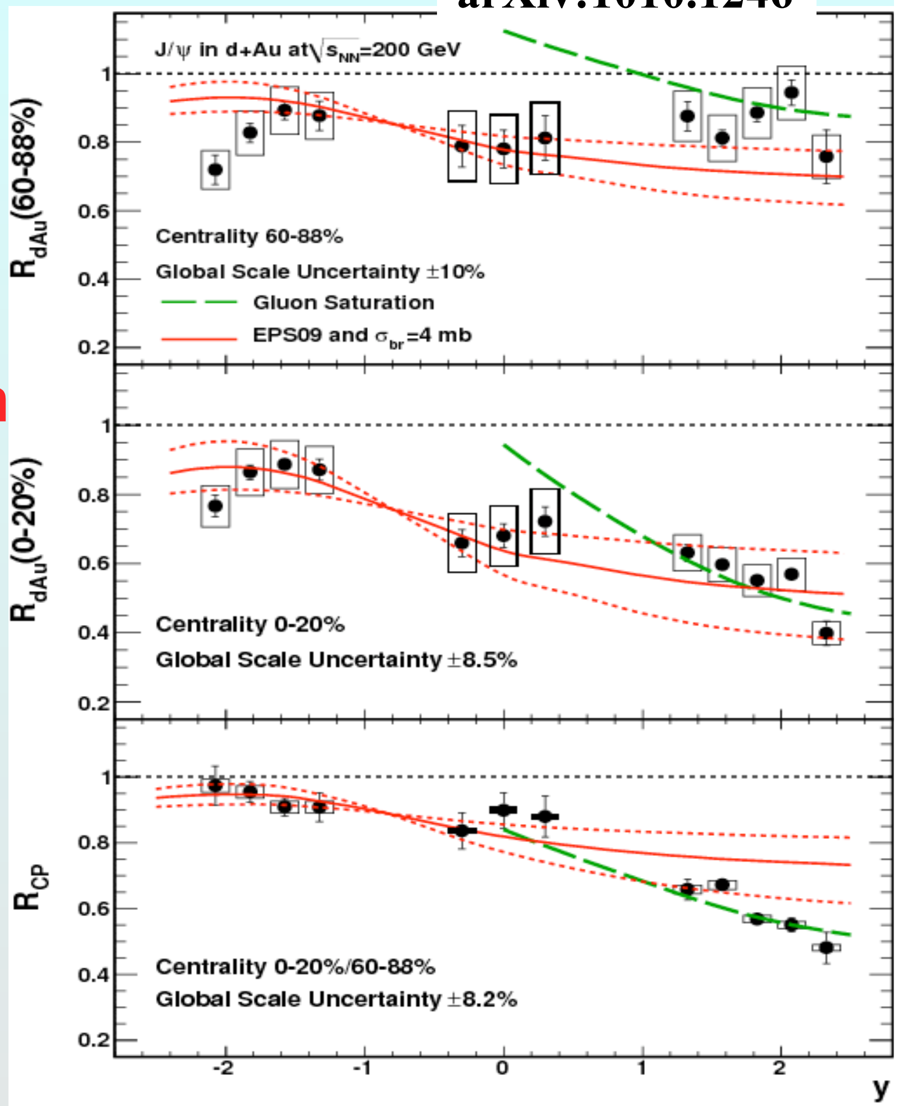
- Does partial screening preserve correlations, enhancing likelihood of final state coalescence?
- arXiV:1010.2735 (Aarts, et al): Υ unchanged to 2.09T_c

  χ_b modified @ 1-1.5T_c, then free. Need Υ states at RHIC!

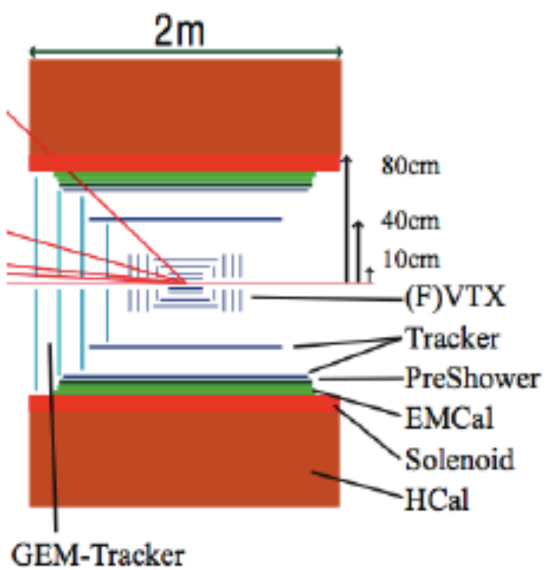
Suppression pattern ingredients

- Color screening
- Initial state effects
  - Shadowing or saturation of incoming gluon distribution
  - Initial state energy loss
  - (calibrate with p+A or d+A)
- Final state effects
  - Breakup of quarkonia due to co-moving hadrons
  - Coalescence of q and qbar at hadronization
  - (calibrate with A, centrality dependence)

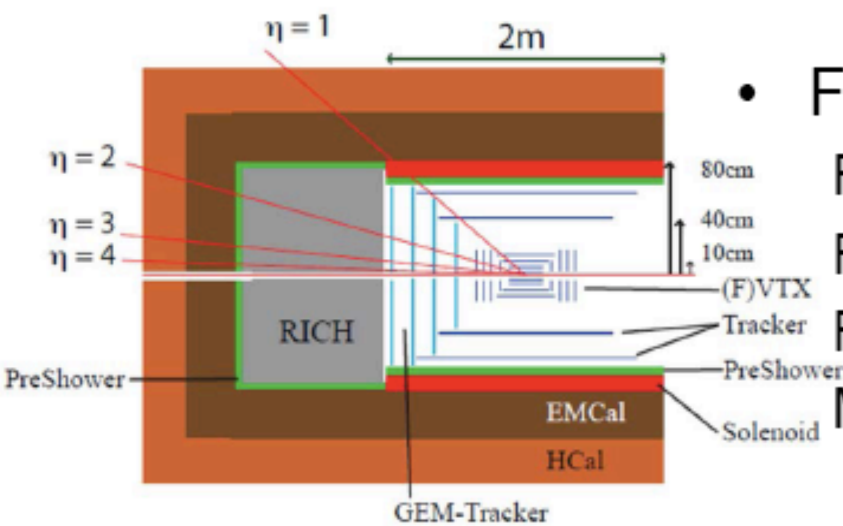
arXiv:1010.1246



Staging



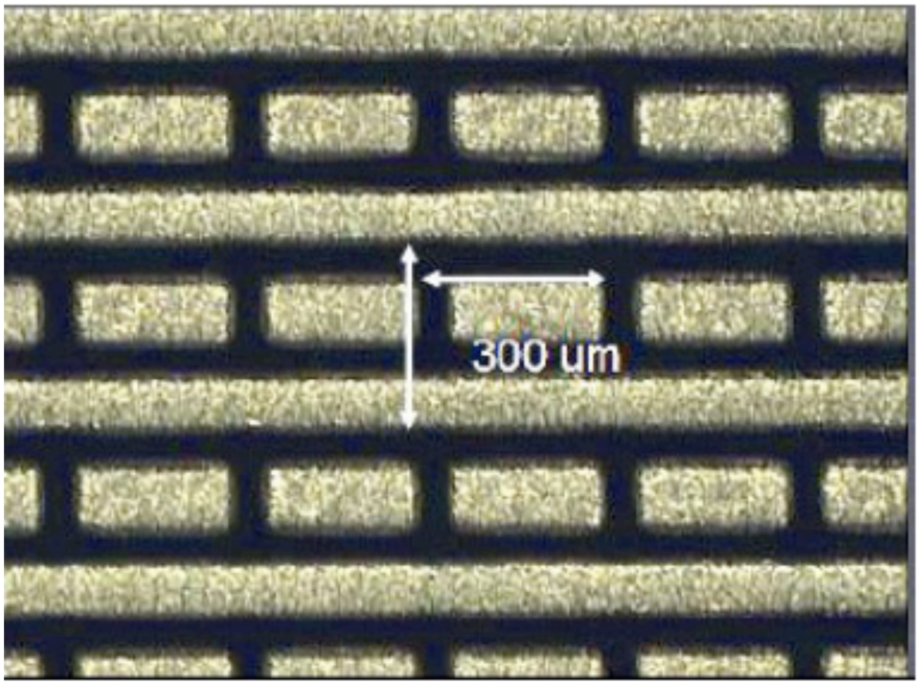
- Mid-rapidity detector
  - Additional (Si) tracking — *High stat. charm* 5-7 M
  - Solenoid
  - pre-shower
  - EMCal — *Direct γ, π^0 Quarkonia* 20 M
  - Hcal — *Jets* 8-10M



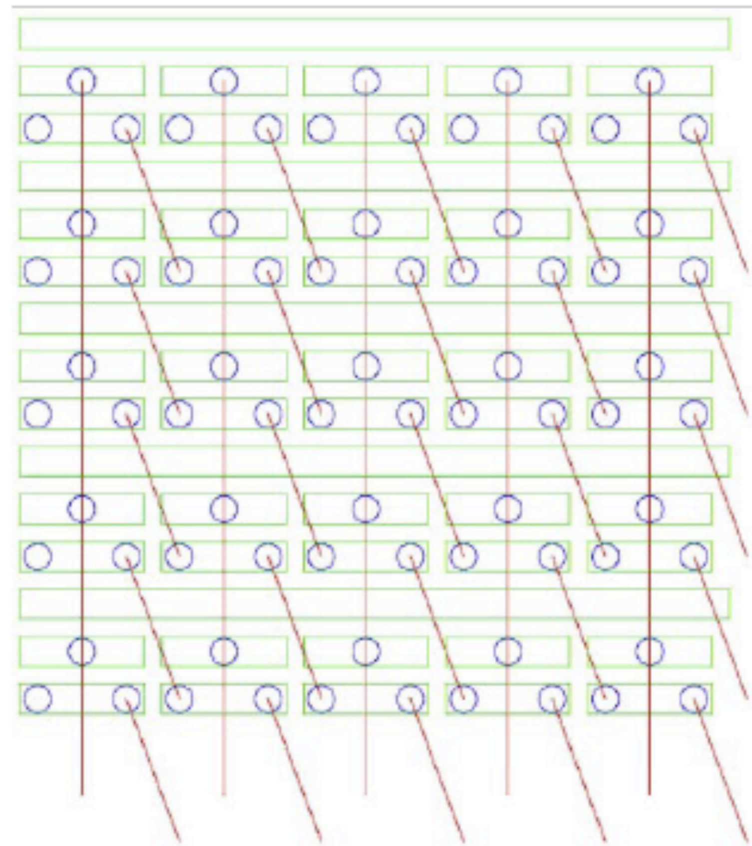
- Forward Detector
  - RICH and GEM tracker — *CNM, eRHIC* 10M
  - Forward magnet
  - Forward Hcal
  - More barrel tracker — *Saturation QGP @ Fwd eRHIC* 10-15M

e/sPHENIX Forward Tracker

R. Majka, Yale Univ.

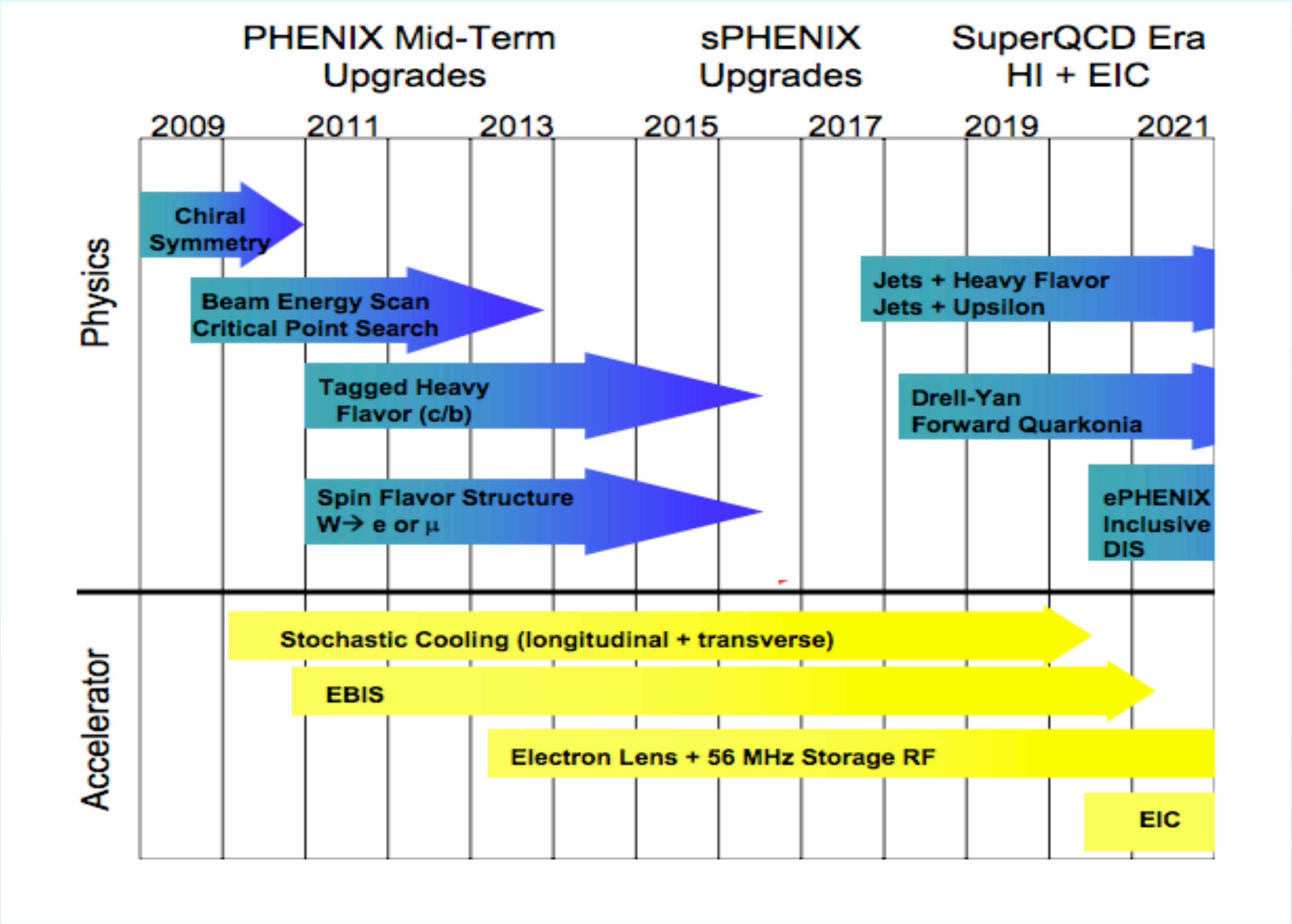


Outline of strips and pads on side facing GEM
Via pads on back side
Paths of routing traces on back side



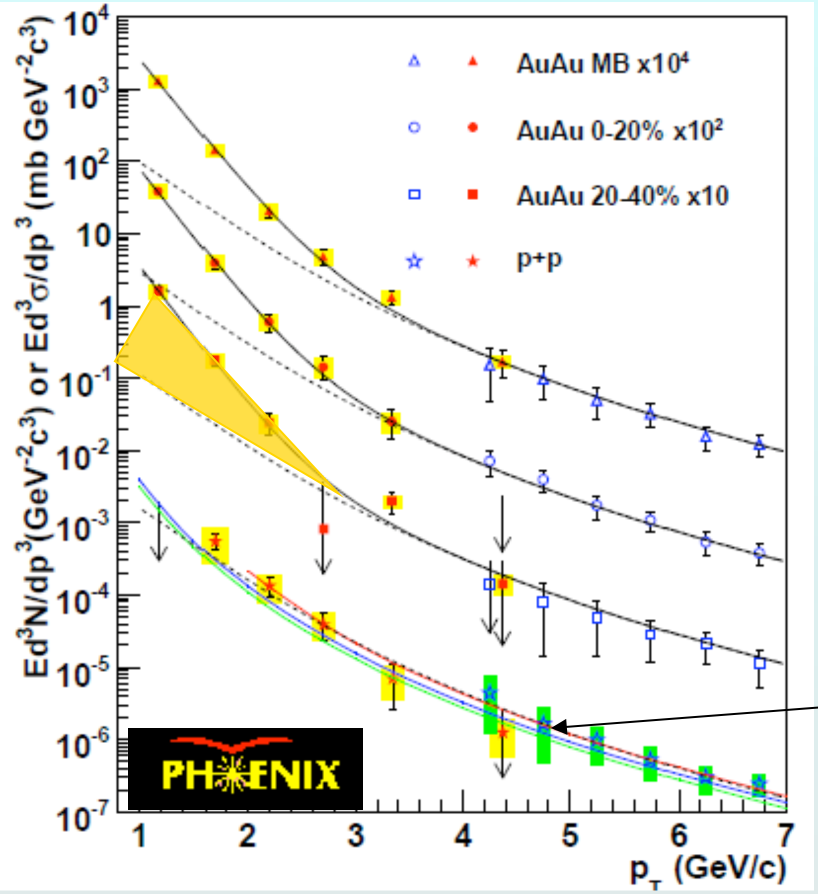
3D readout for higher track multiplicity capability

Upgrades schedule

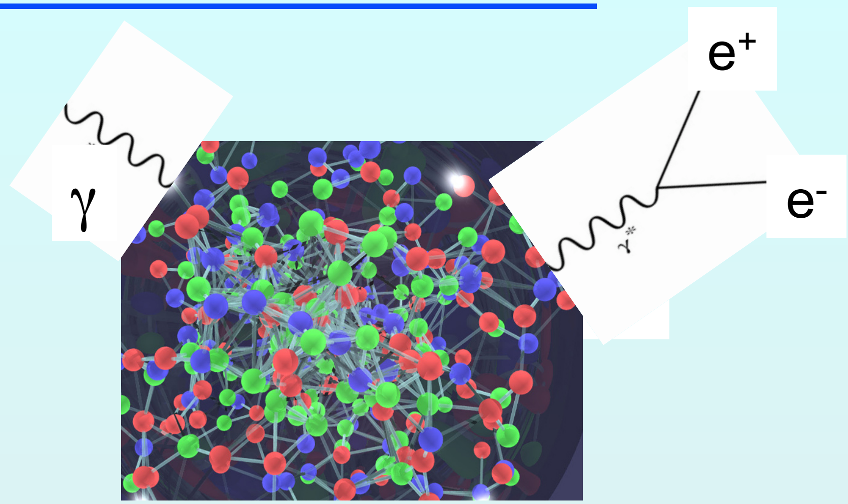


Exciting new physics opportunities in the coming decade!

Thermal radiation



PRL104, 132301 (2010)

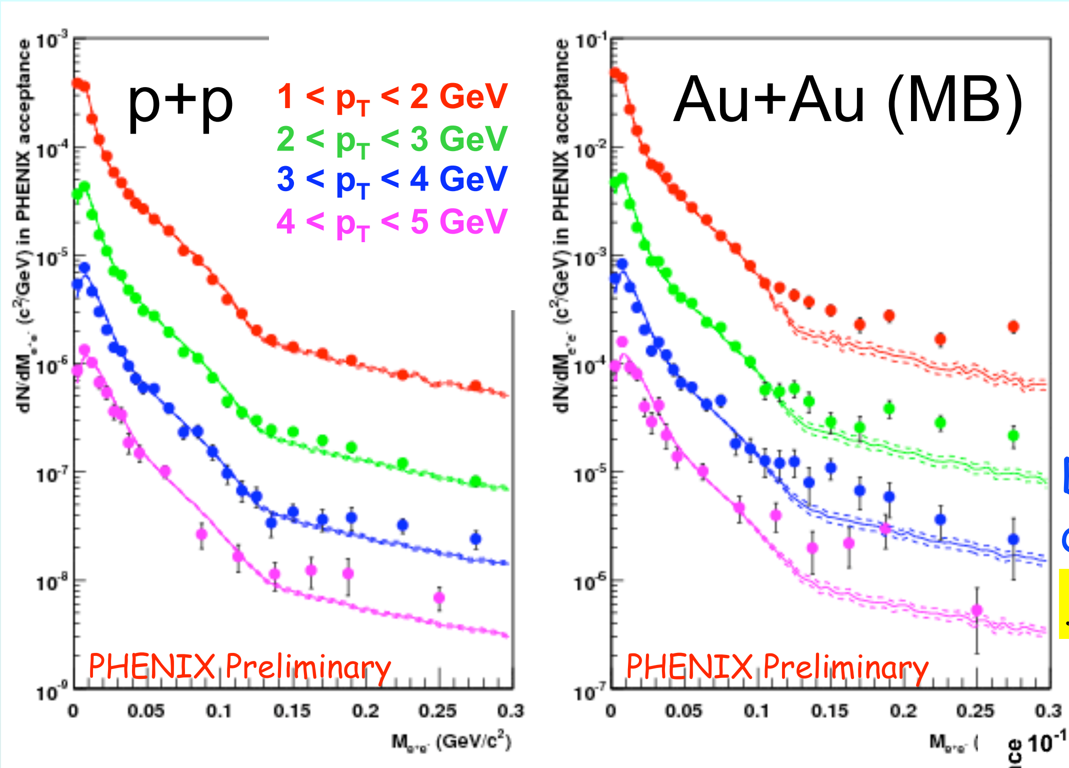


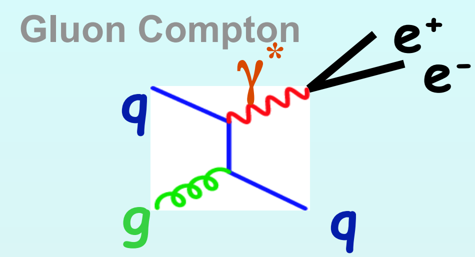
Low mass, high p_T e^+e^- → nearly real photons

pQCD γ spectrum (Compton scattering @ NLO) agrees with p+p data

Large enhancement above p+p in the thermal region

Dileptons at low mass and high p_T



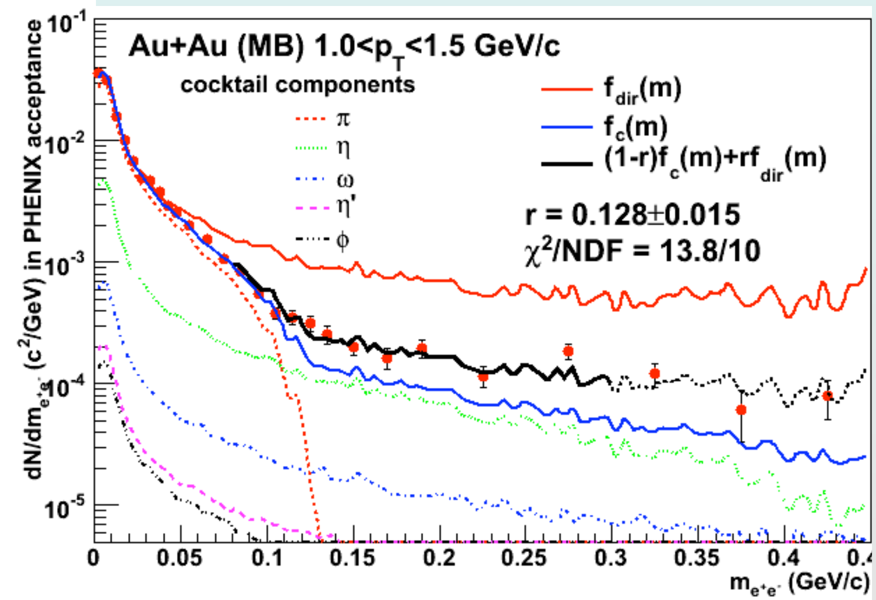


Direct γ^*/Inclusive γ^* determined by fitting each p_T bin

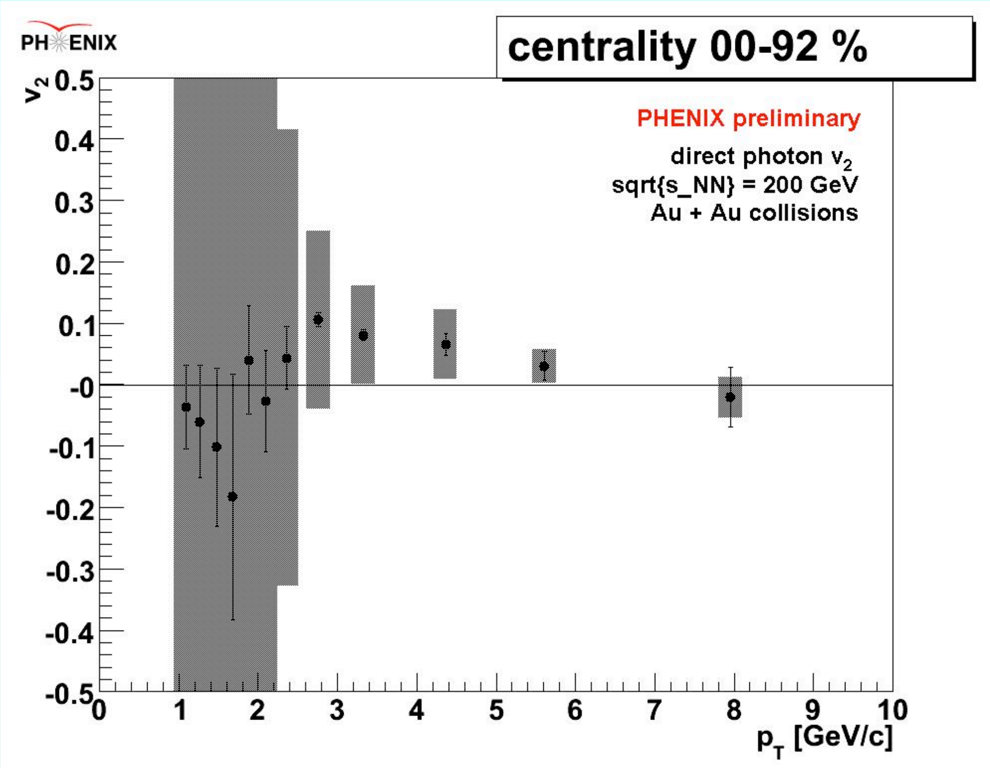
$$f_{data}(M_{ee}) = (1-r)\cdot f_{cocktail}(M_{ee}) + r\cdot f_{direct}(M_{ee})$$

r : direct γ^*/inclusive γ^*

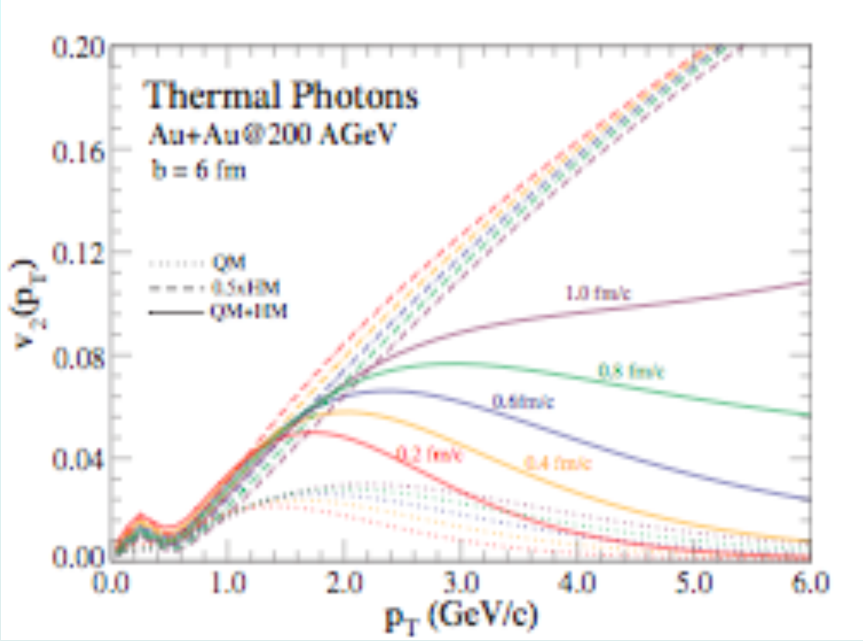
- m<2π only Dalitz contributions
  - p+p: no enhancement
  - Au+Au: large enhancement at low p_T
- A *real* γ source → *virtual* γ with v. low mass
- We assume internal conversion of direct photon → extract the fraction of direct photon



Pre-equilibrium flow prior to τ_0?



Chatterjee, Srivastava & Heinz
PhysRevC79, 021901,'09

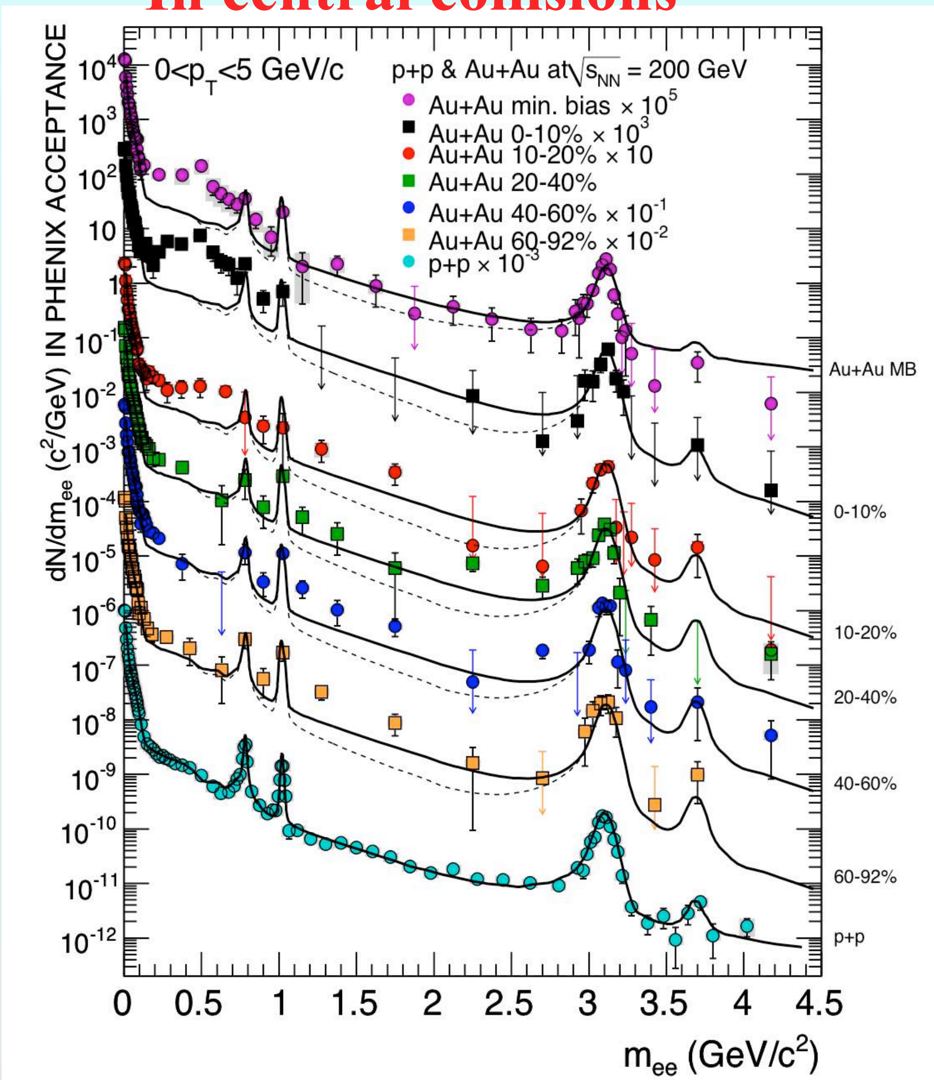


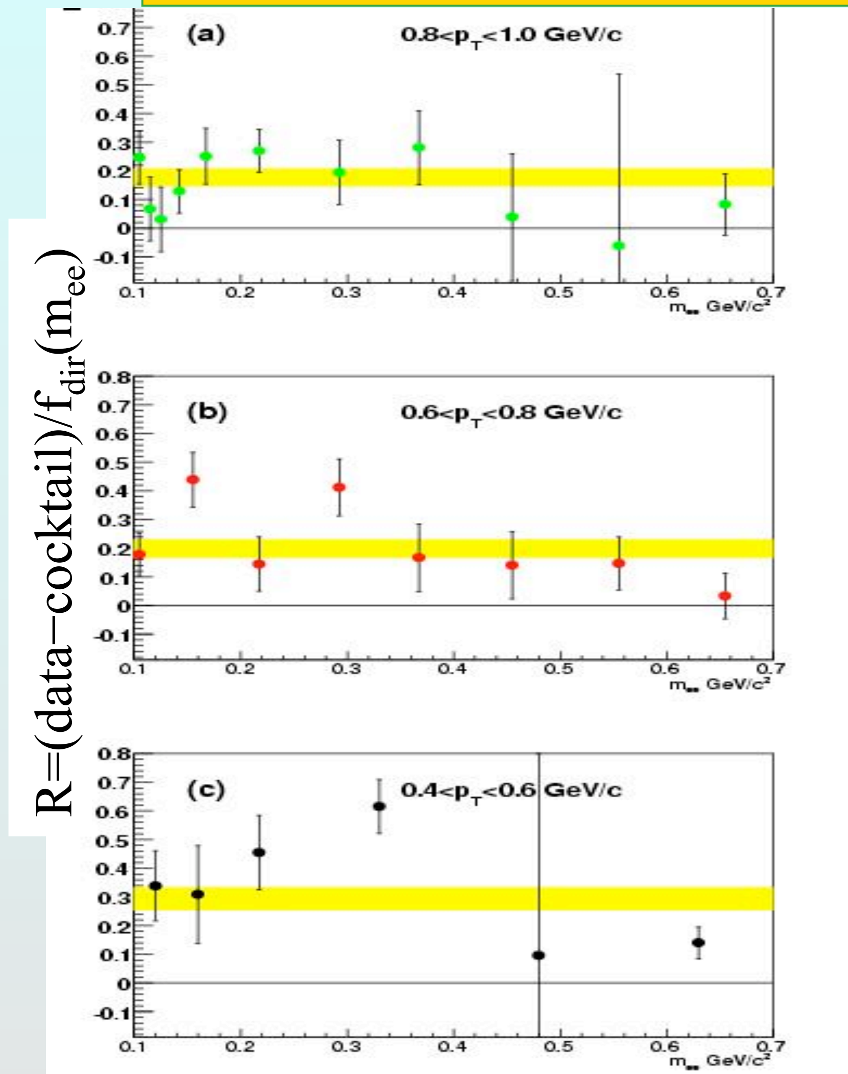
- Do the direct photons flow?
- First step: compare to hydro *after* equilibration
  Experiment homework: smaller errors $2<p_T<4$ GeV/c
  Theory homework - pre-equilibrium v_2 magnitude?

low mass di-electron excess

Run-4 *PRC81, 034911 (2010)*

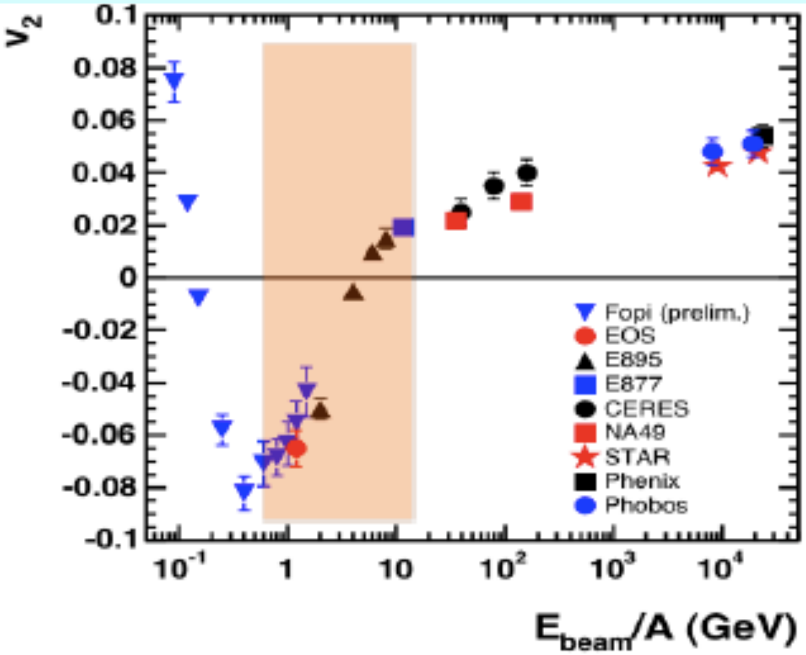
In central collisions



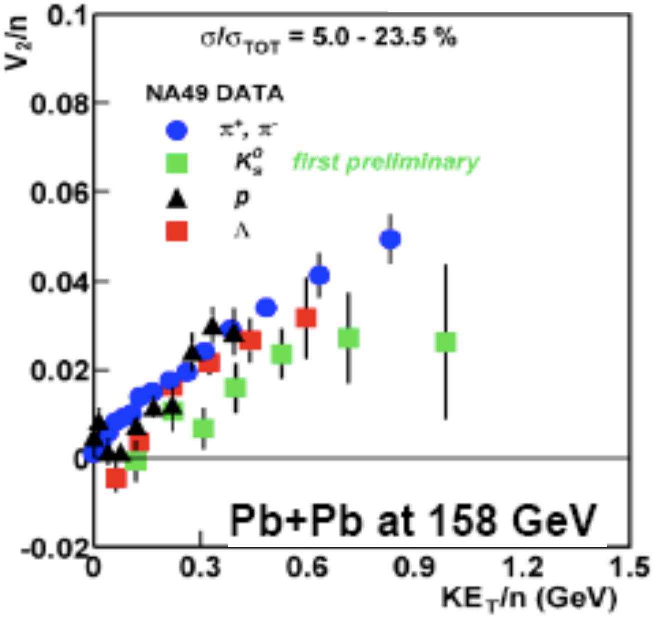


and low p_T

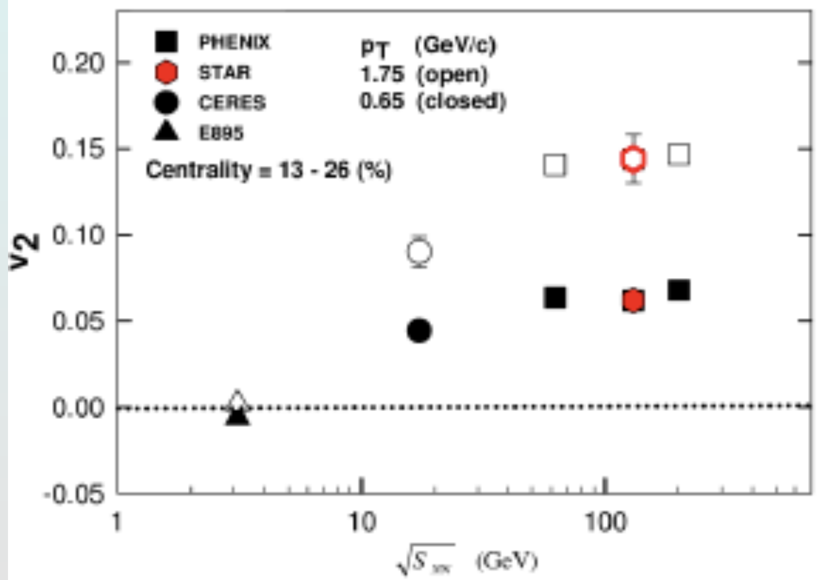
√s dependence



M. Mitrovski



Phys. Rev. Lett. 94, 232302 (2005)



Quark number Scaling works at √s = 62

@ 17 GeV?

Properties of hot QCD matter?

- **thermodynamic (equilibrium)**
  T, P, ρ
  Equation Of State (relation btwn T, P, V, energy density)
  v_{sound}, static screening length

- **transport properties (non-equilibrium)***
  particle number, energy, momentum, charge
  diffusion sound viscosity conductivity

In plasma: interactions among charges of multiple particles
charge is spread, screened in characteristic (Debye) length, λ_D
also the case for strong, rather than EM force

***measuring these is new for nuclear/particle physics!**

Nature is nasty to us: does a time integral…

Small viscosity/entropy is surprising

Viscosity: inability to transport momentum & sustain a wave

low viscosity → absorbs particles & transports disturbances

Viscosity/entropy near 1/4π limit from quantum mechanics!

∴ liquid at RHIC is "perfect"

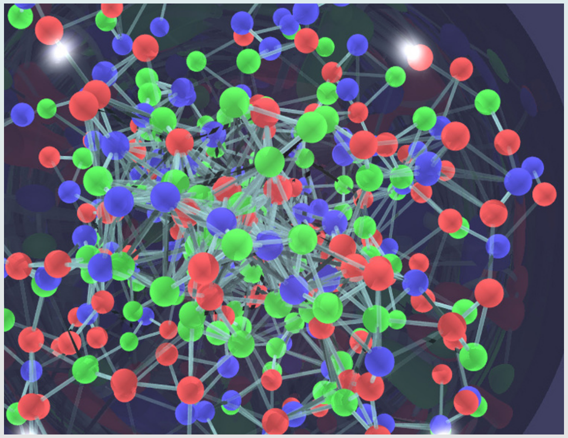
Example: milk. Liquids with higher viscosities will not splash as high when poured at the same velocity.

Good momentum transport: neighboring fluid elements "talk" to each other

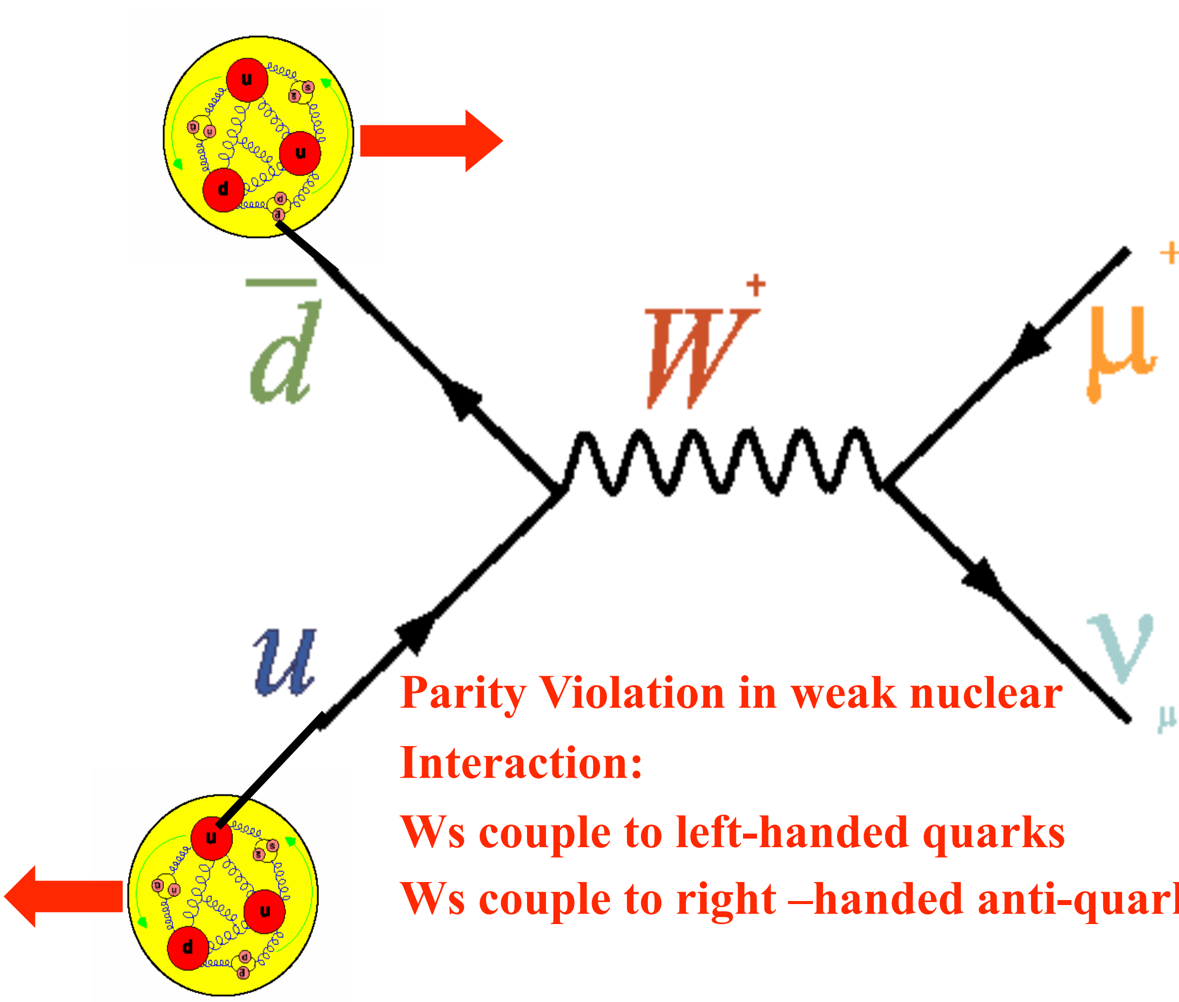
→ QGP is strongly coupled

Should affect opacity :

e.g. q,g collide with "clumps" of gluons, not individuals



Isolate Sea Quark Contributions to Spin



Parity Violation in weak nuclear Interaction:

Ws couple to left-handed quarks

Ws couple to right –handed anti-quarks

Proton Structure:

(1) u-quarks have their spin (mostly) aligned with the proton spin.

(2) d-quarks have their spin (mostly) anti-aligend with the proton spin.

To probe anti-d-quark:

(1) need right handed anti-d-quark

(2) need proton p and spin parallel

. Turns off u-contribution

. anti-d quark comes from polarized proton