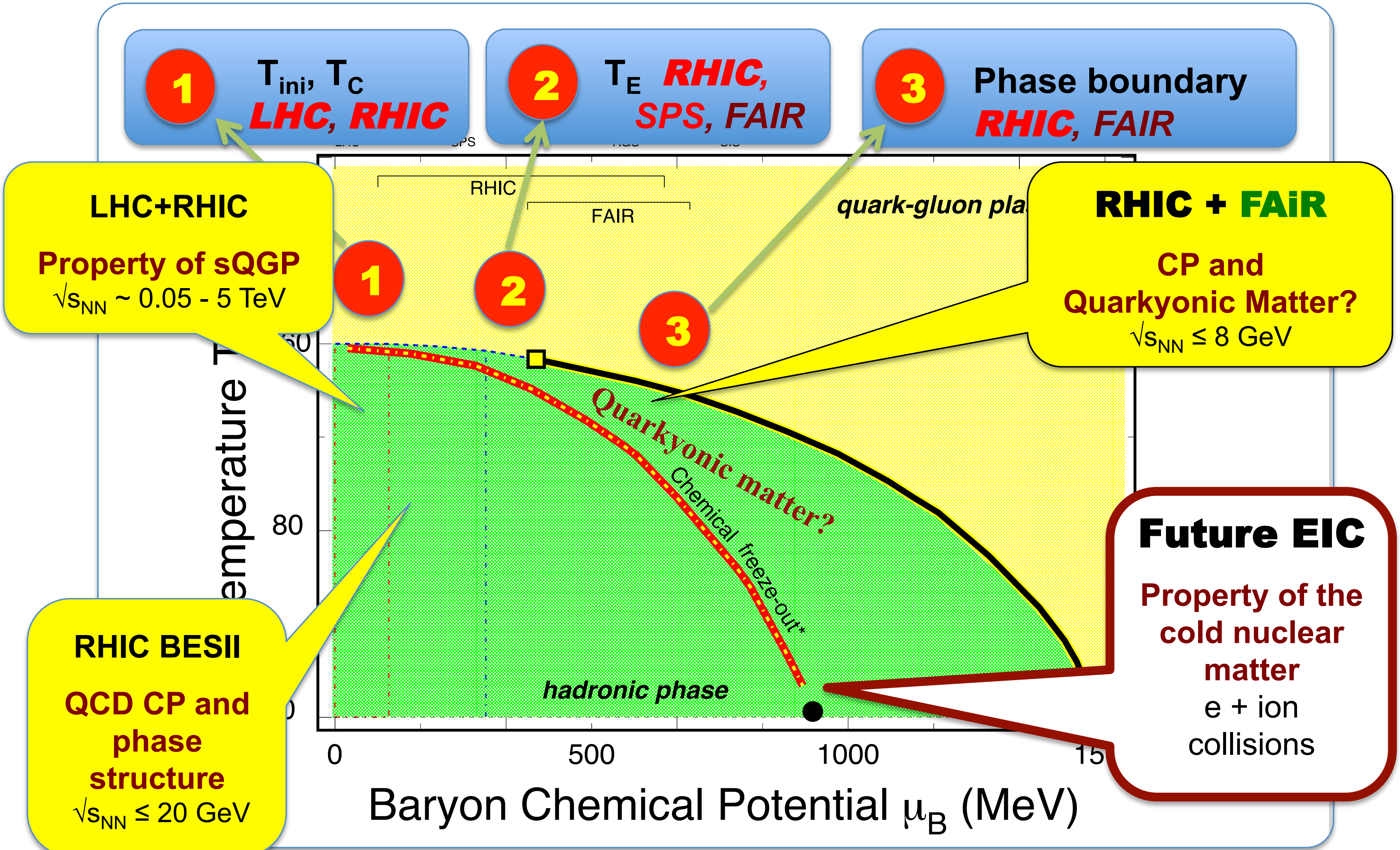
*Exploring **QCD Emergent Properties** via high-energy collisions*

Study the QCD Phase Structure at High Baryon Density

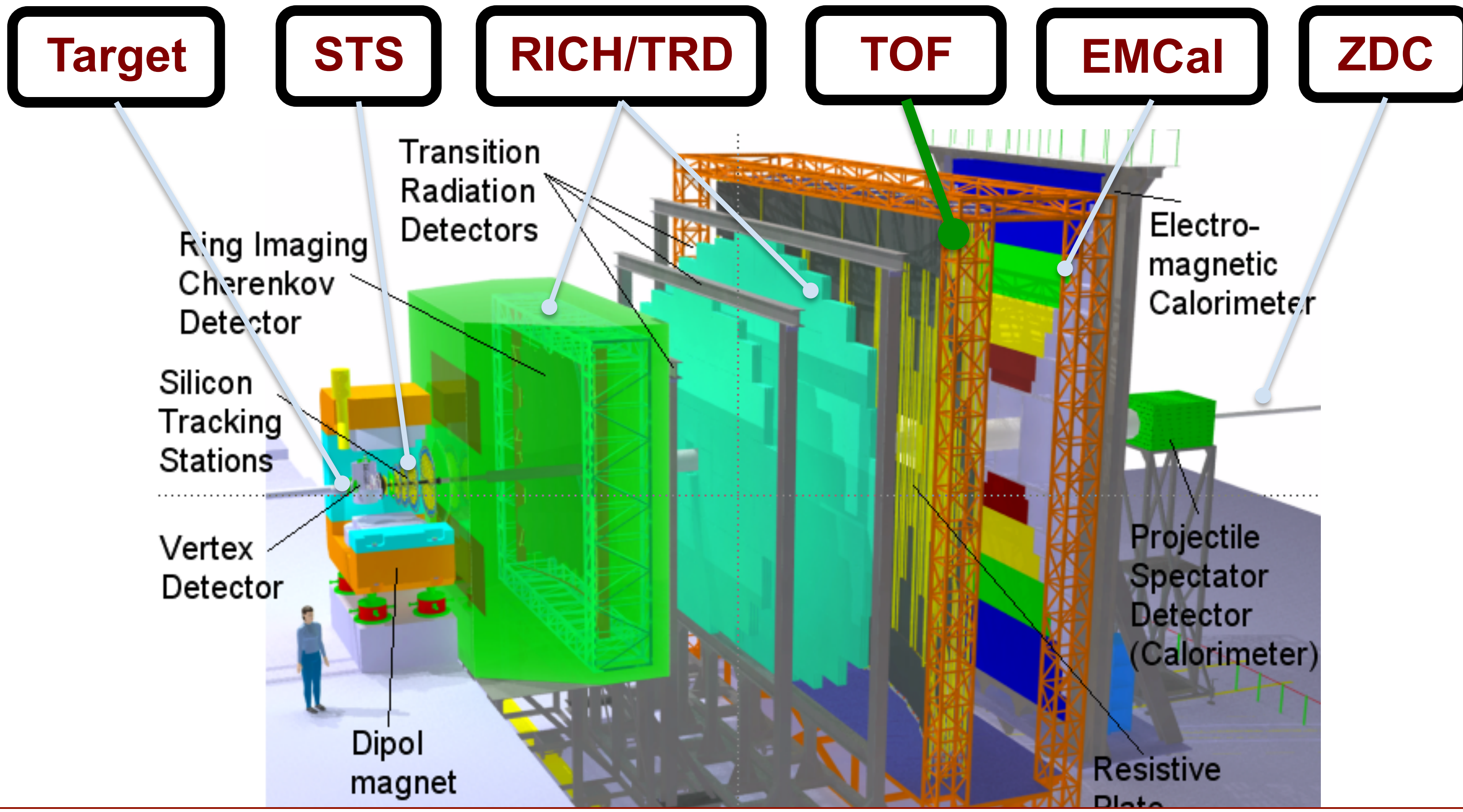
Nu Xu (LBNL)

"If one does not know which harbor to go to, there is no favorable wind."

Exploring QCD Phase Structure



The CBM Experiment



FAIR: the highest intensity accelerator complex in the 21st century

Precision measurements at high baryon density region for:

(i) dileptons (***e, μ***); (ii) high order baryon correlations; (iii) flavor productions (***s, c***)

Be Part of CBM!

CBM Experiment at FAIR:

1) Next generation fixed-target high rate experiment
2) $\sqrt{s_{NN}}$ = **2 – 5** (– 8) GeV (450 ≤ μ_B ≤ 700 MeV)
3) 2019: FAIR accelerator / CBM experiment commissioning
4) Natural continuation of RHIC BESII towards higher net-baryon density region. Key physics topics are:
   - CP and phase boundary: *confirm RHIC BESII findings*
   - Quarkyonic matter (?)
   - Chiral properties and more …

"FAIR will start its operation in the year of 2019. US scientists should take advantage of unique opportunities provided by FAIR, as they have at the LHC and at other facilities in the world. Especially, for understanding of the QCD phase diagram, studies at the high baryon density region, within CBM's reach, are required. The US should undertake timely investment in that program."

Quantifying the Properties of QCD Matter with Relativistic Heavy Ion Collisions
(white paper available)

2008 Long-Range Plan

The major discoveries in the first five years at RHIC must be followed by a broad, ***quantitative*** *study of the fundamental properties of the quark-gluon plasma. This can be accomplished through a 10-fold increase in collision rate, detector upgrades, and advances in theory. The RHIC II luminosity upgrade, using beam cooling, enables measurements using uniquely sensitive probes of the plasma such as energetic jets. and rare bound states of heavy quarks. The detector upgrades make important new types of measurements possible while extending significantly the physics reach of the experiments.* ***Achieving a quantitative understanding of the quark-gluon plasma also requires new investments in modeling of heavy-ion collisions, in analytic approaches, and in large-scale computing.***

Quantitative Properties

1a. Eq. of State ($\mu=0$)

1b. Eq. of State ($\mu\neq0$)

2. Chemical make-up
3. Chiral symmetry restoration
4. Heavy resonances
5. Viscosity
6. Diffusion
7. Jet-Energy Loss
8. Saturation

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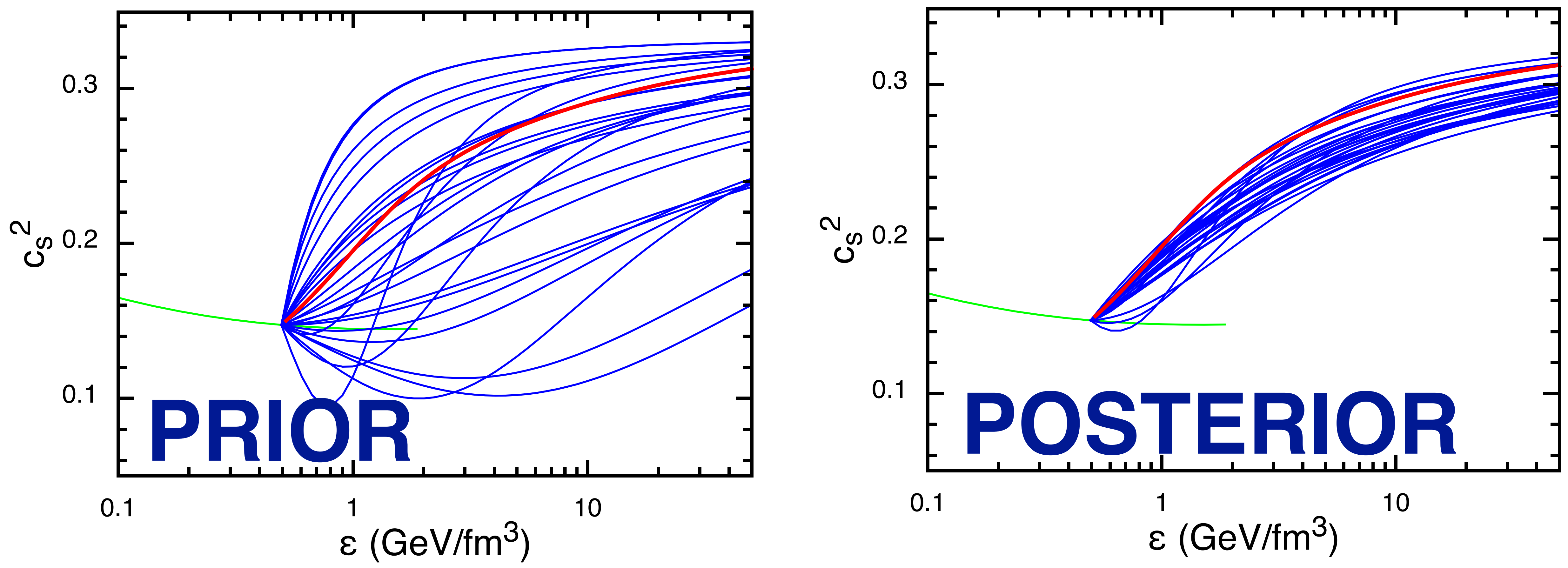
Progress

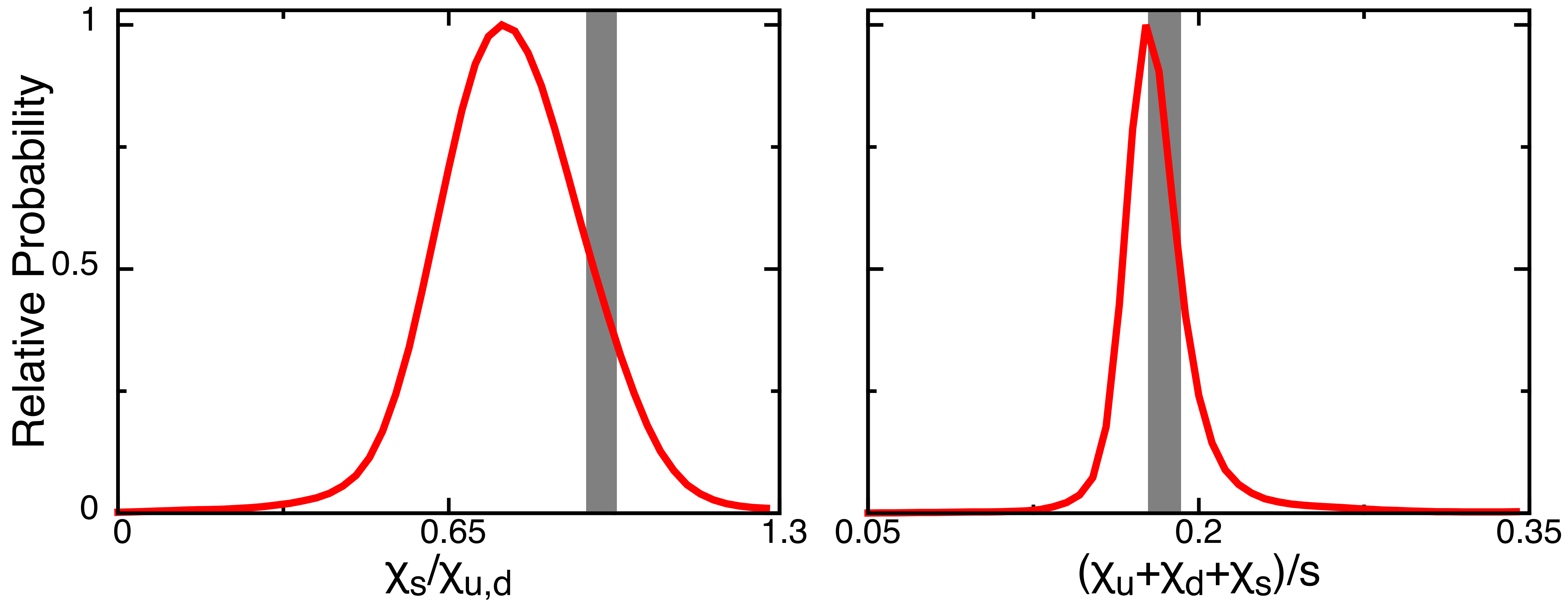
STRATEGY

- Collect Data
  - Express uncertainties
- Parameterize Models (perhaps dozens)
  - Initial state + hydro + cascade …
- Compare models to data
  - Use model emulator
  - ~1000 samplings of parameter space
  - Determine likelihood
- Results can:
  A. Determine parameters with uncertainties
  B. Provide validated foundation for studies
  C. State whether collisions created matter with same properties as lattice

Eq. of State from Spectra/V2/HBT vs. Lattice (speed of sound)



QGP Charge Fluctuations from Charge Balance Functions vs. Lattice



FUTURE

Quantitative Properties

1a. Eq. of State ($\mu=0$)*
1b. Eq. of State ($\mu\neq0$)*
2. Chemical make-up*
3. Chiral symmetry restoration*
4. Heavy resonances*
5. Viscosity*
6. Diffusion*
7. Jet-Energy Loss*
8. Saturation*
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*** Ripe for quantitative approach**

NEEDS

- **Better Understanding of Current Data**
- **More Detailed Experimental Analysis**
- **New Data (BES)**
- **Improved Modeling**
  - **3D Hydro**
  - **Initial state**
  - **Diffusion**
  - **Description of transition region**
  - **Overlaying jets/heavy flavors onto 3D evolution**
  - **....**
- **Computational Resources**
  - **Statistics to compare to data x 1000**
- **Collaboration, Cooperation, Coordination**
  - **Theory-Theory, Theory-Exp, Exp-Exp**

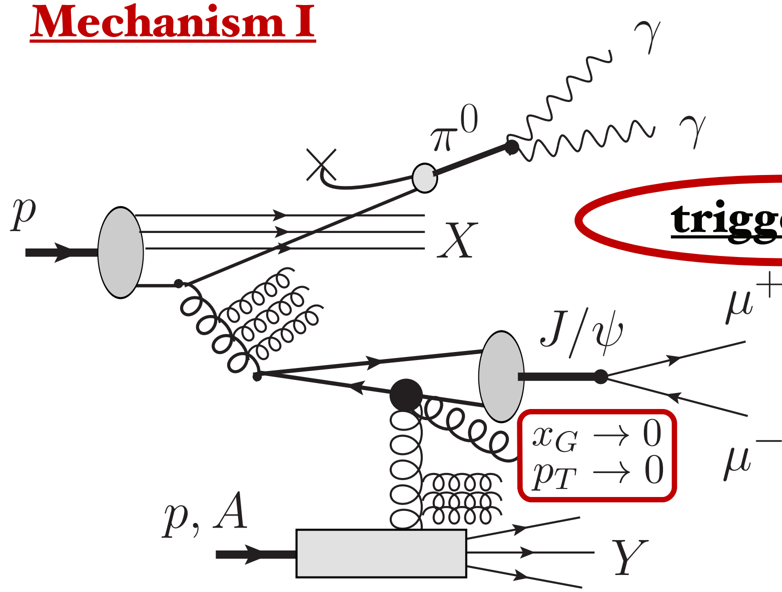
Forward-central pion-quarkonia correlations at RHIC

- ✓ **Quarkonia production in pp/pA, as well as high pT forward particle production in pA, traditionally are very important probes for QCD dynamics in hard and soft regimes.**
  e.g. QCD factorisation, gluon resummations, higher order PT and non-PT effects, CGC etc

- ✓ **J/psi puzzle: highly uncertain production and evolution in hot environment**
  What is the dominating QCD mechanism and role of the medium? why R_{pA} is close to one?

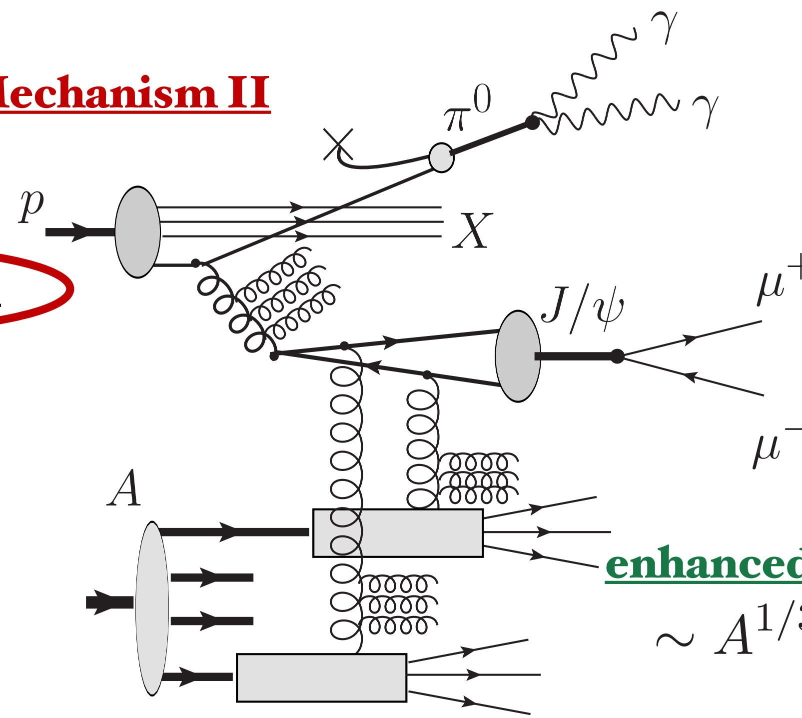
- ✓ **In order to address these issues, we propose a new measurement:**
  central J/psi or Upsilon production in association with forward leading pion

Mechanism I



triggerable!

Mechanism II



enhanced as $\sim A^{1/3}$

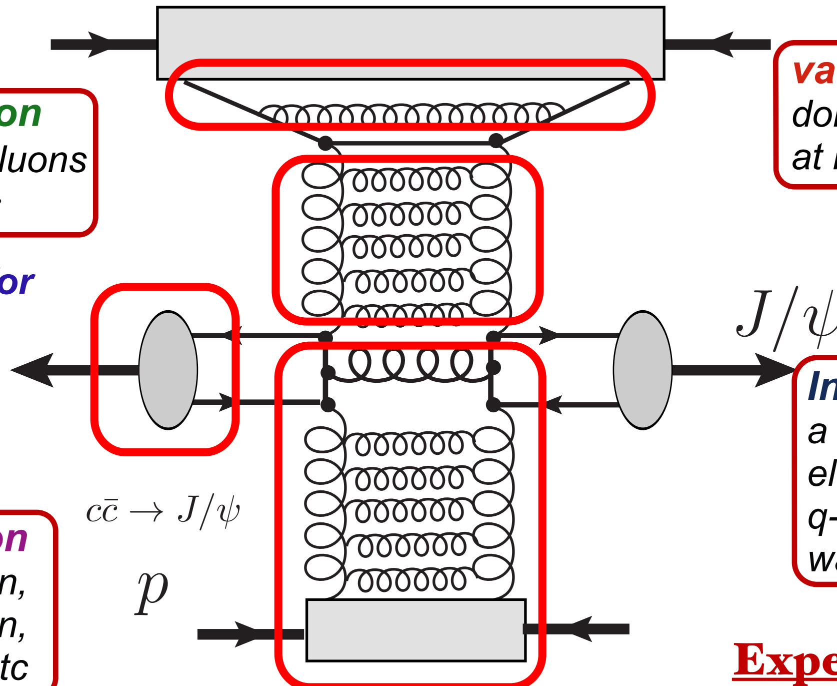
Strategy and expectations

Mueller graph:

BFKL Pomeron
resummed low-x gluons
$\sim \alpha_s(\mu) \ln x$

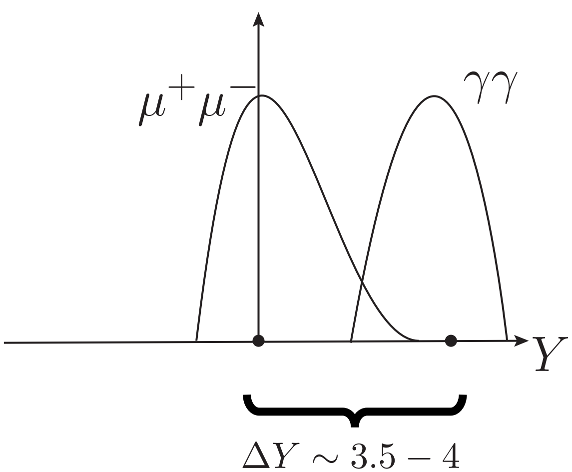
Pomeron *becomes* ***important for a large rapidity difference*** *between pion and quarkonium, but* ***less important for harder scale and lower energy***

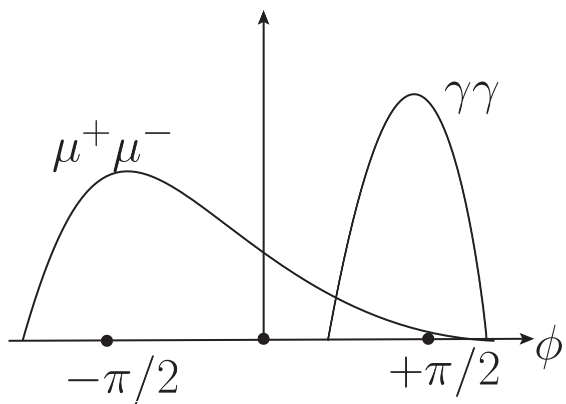
J/psi wave function
accounts for suppression, energy loss, polarisation, non-PT effects, etc



valence quark PDF
dominates the Reggeon at large x ~ 1

In the dipole approach:
a superposition of universal elastic dipole amplitudes times q->qG, G->ccbar and c->cG wave functions





Expectations:

- ✓ nearly back-to-back azimuthal correlation broadened by soft gluon emissions etc
- ✓ background due to Drell-Yan is is strongly reduced due to a harder pion p_T spectrum
- ✓ uncertainties are cancelled in R_{pA}
- ✓ improved test of quarkonia production mechanisms

Future prospects and needs

- **Future prospects:**
  Both PHENIX and STAR experiments are (or will be in near future) well equipped to measure forward-central correlations both in pp and pA.

- **Needs:**
  Strong “Theory-Experiment” co-operation is needed to test the importance of such pQCD aspects as BFKL evolution, QCD factorisation, proton structure at low x, quarkonia production mechanisms, polarisation effects, CNM effects (such as J/psi suppression, rescattering, melting, energy loss etc).

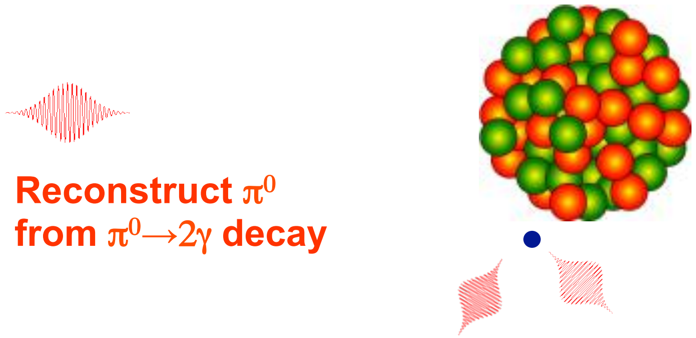
- **Physics goals:**
  The proposed measurement provides a good way to reduce backgrounds and uncertainties in studies of quarkonia production in pp/pA and thus allows to test higher order effects in pQCD at RHIC and disentangle them from e.g. CGC and other multi-particle effects.

Michal Sumbera (NPI ASCR) in collaboration with:
R.Pasechnik (Lund U./NPI ASCR) and J. Nemchik (IEP, Kosice)

Neutron Skin Thickness via Coherent Pion Photoproduction

Photon probe ✓
Interaction well understood

Reconstruct π^0 from $\pi^0 \to 2\gamma$ decay

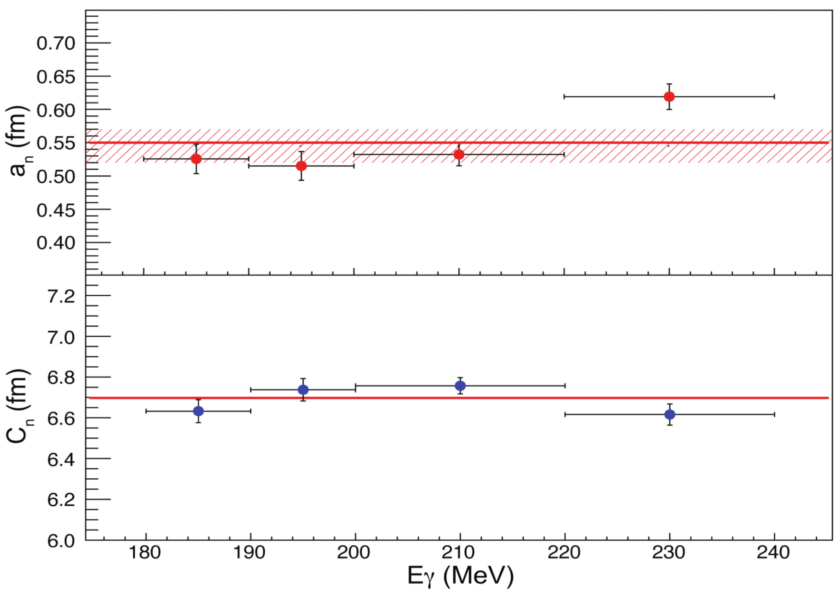


π^0 meson – produced with ~equal probability on protons *AND* neutrons.

- Angular distribution of π^0 → PWIA contains the matter form factor

$$d\sigma/d\Omega(\text{PWIA}) = (s/m_N^2)\, A^2\, (q_\pi^*/2k_\gamma)\, F_2(E_\gamma^*,\theta_\pi^*)^2\, |F_m(q)|^2 \sin^2\theta_\pi^*$$

- π^0 final state interactions - use latest complex optical potentials tuned to π-A scattering data. Corrections modest at low pion momenta



$$a_n = 0.55 \pm 0.01(stat.)\,^{+0.02}_{-0.03}(sys.)$$

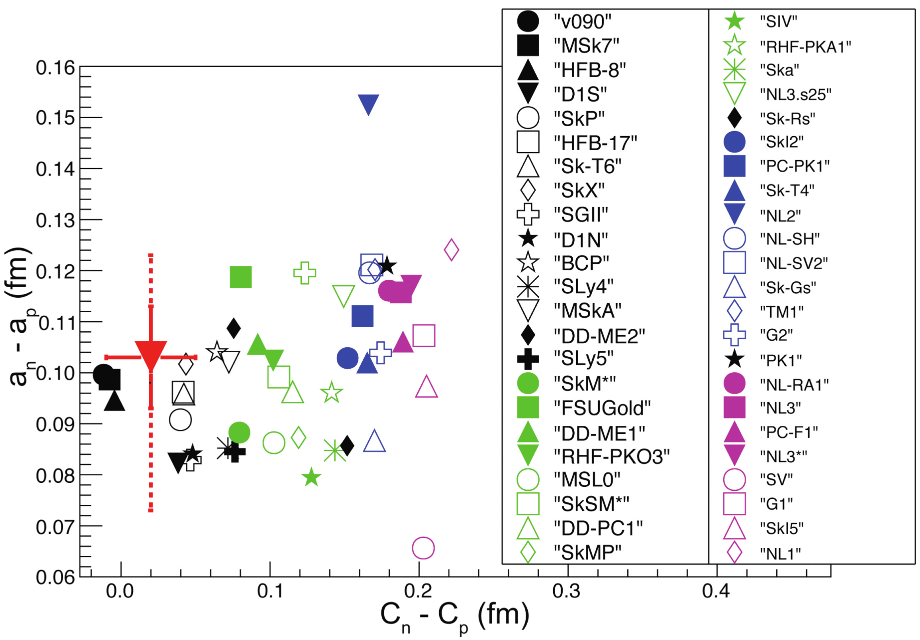
$$c_n = 6.70 \pm 0.03(stat.)\text{fm}$$

$$\Delta r_{np} = 0.15 \pm 0.03(stat.)\,^{+0.01}_{-0.03}(sys.)$$

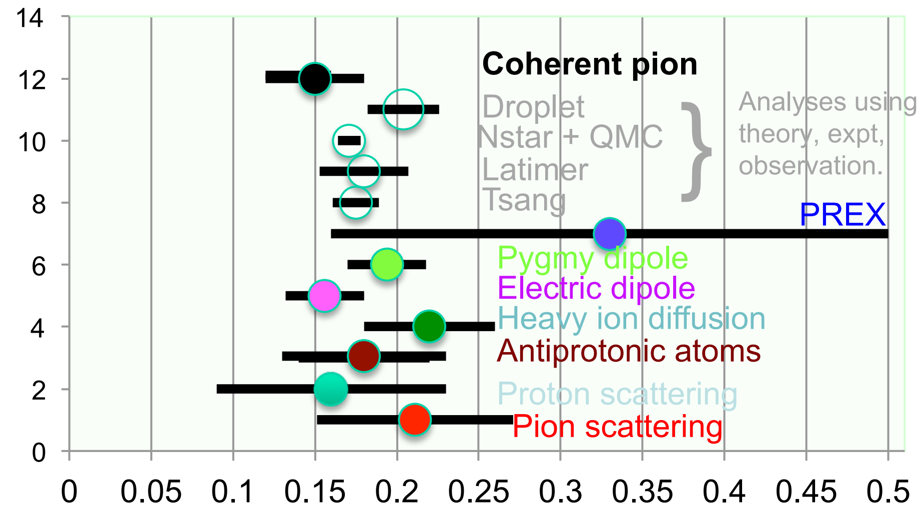
The extracted skin properties

- Systematics:
  - i) Normalization parameter within ±5% of unity for all bins
  - ii) E_γ dependences – a_n high E_γ bin 3.5σ away from average
  - iii) Vary yield fitting procedure
  - iv) 10% variation relative p,n amplitudes in the model (mainly affects diffuseness)
  - v) Different fit ranges

Comparison with theory



Results agree with previous measurements



Work in Progress: Data under analysis for ^{116}Sn, ^{120}Sn, ^{124}Sn & ^{56}Ni

Future Plans for ^{48}Ca, ^{40}Ca and Xenon isotopic chain

Needs: Availability of Isotopically Separated Targets