Improving our Understanding of Hadronization Through p+p, d+Au, and Au+Au Measurements at PHENIX

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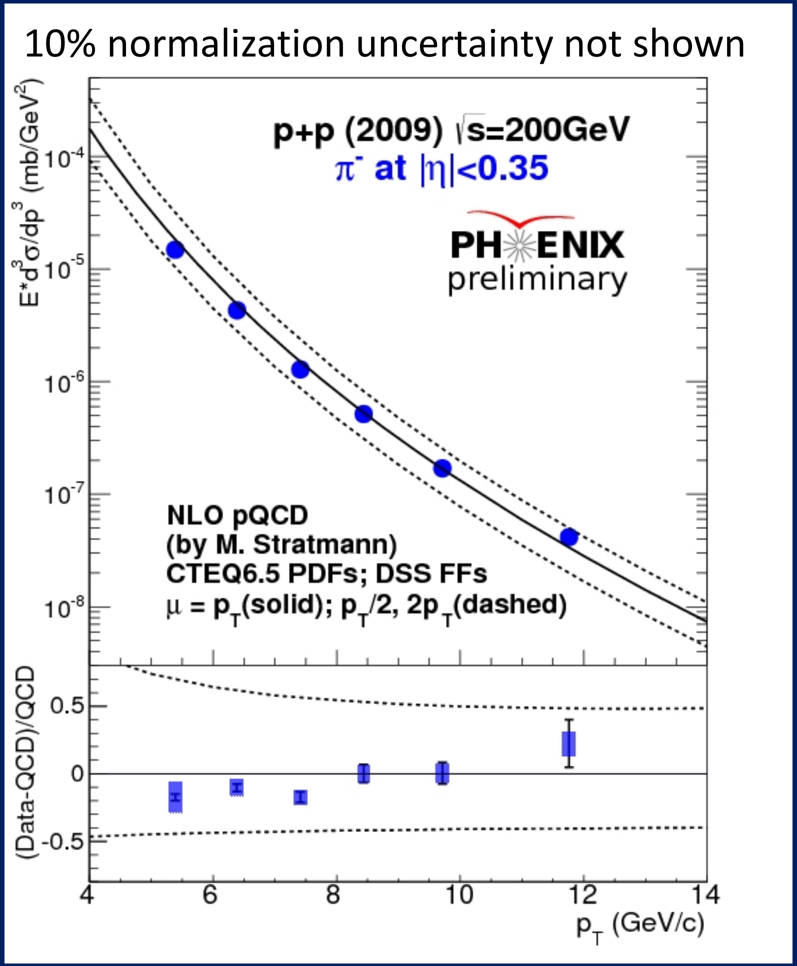
Indiana-Illinois Workshop on Fragmentation Functions
December 13, 2013

How can we use hadronic collision data to help us understand more about partons turning into hadrons from . . .

I. Hard scattering and "traditional" fragmentation

p+p cross sections: Charged pions, 200 GeV



- Charge-separated pion cross sections $5 < p_T < 14$ GeV
- Consistent with NLO pQCD calculations using DSS FFs, within (large) scale uncertainty
- Data themselves have 10% normalization uncertainty
- Use as input in future fits—how best to incorporate?

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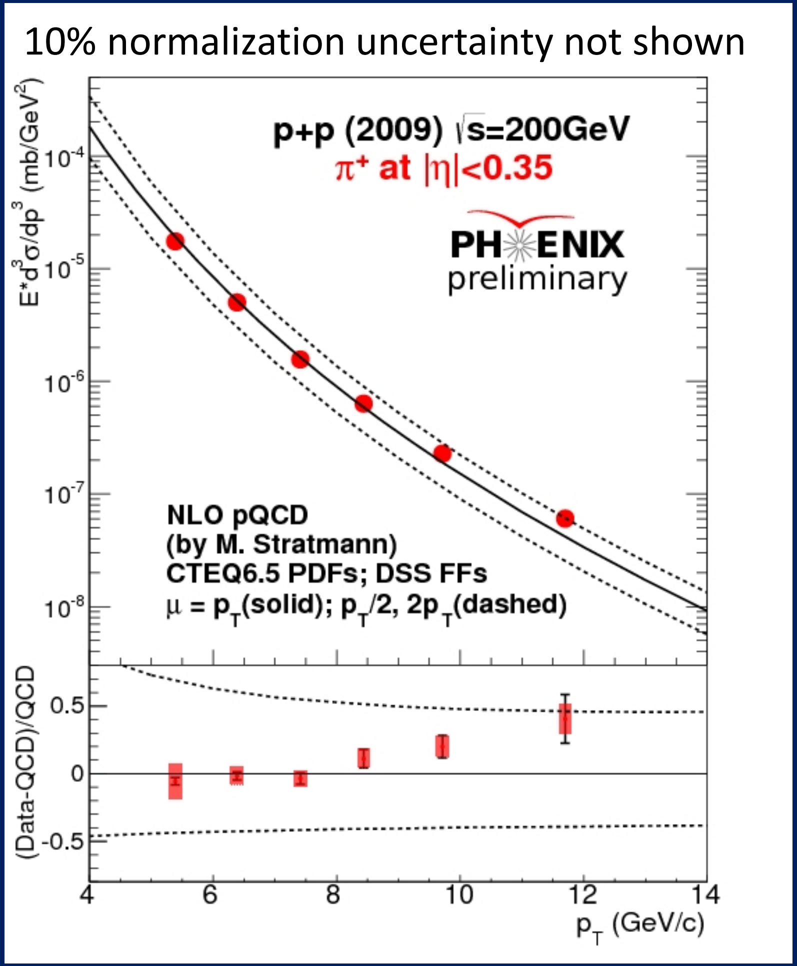

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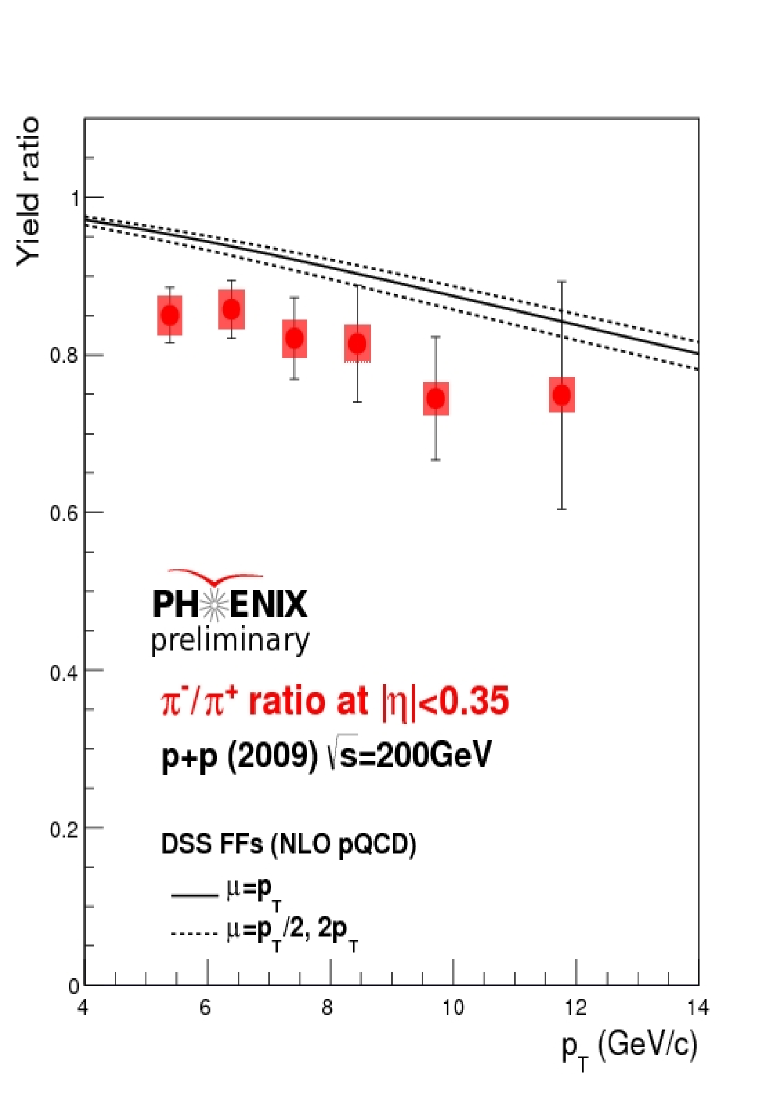
Charged pion ratio, 200 GeV p+p



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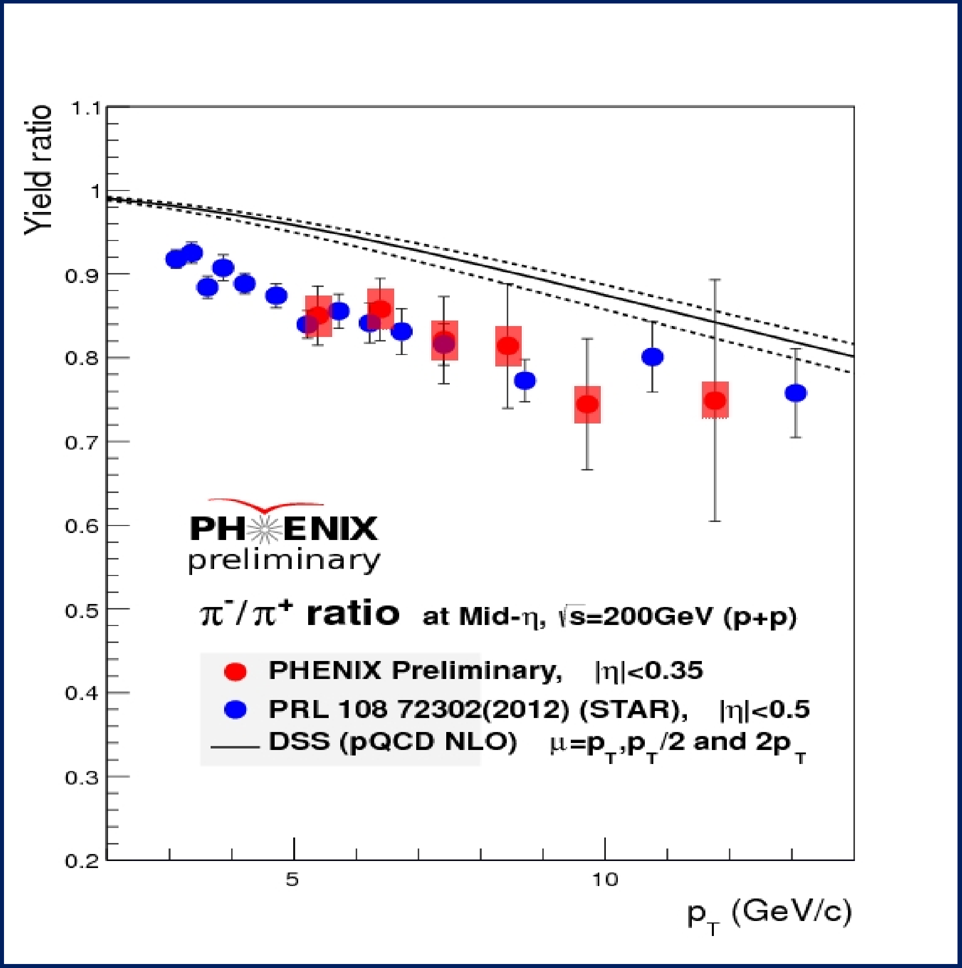

- Measured π-/π+ *ratio* significantly below NLO calculation in lower range of p_T
  - Data: 10% normalization uncertainties on cross sections cancel *completely*
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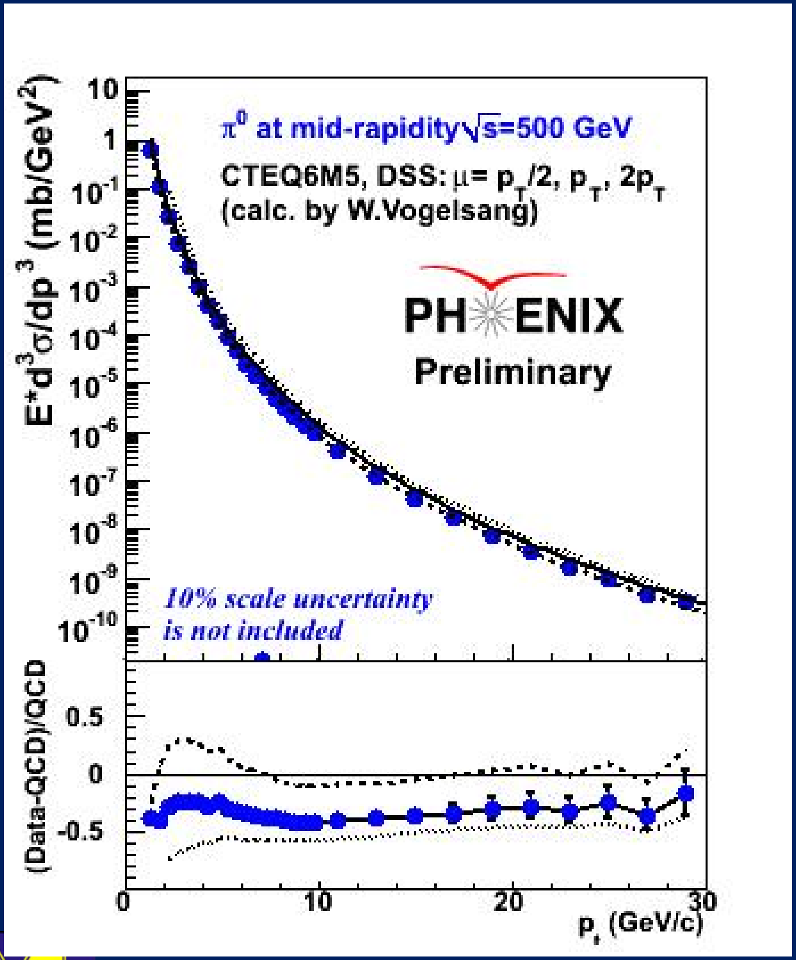
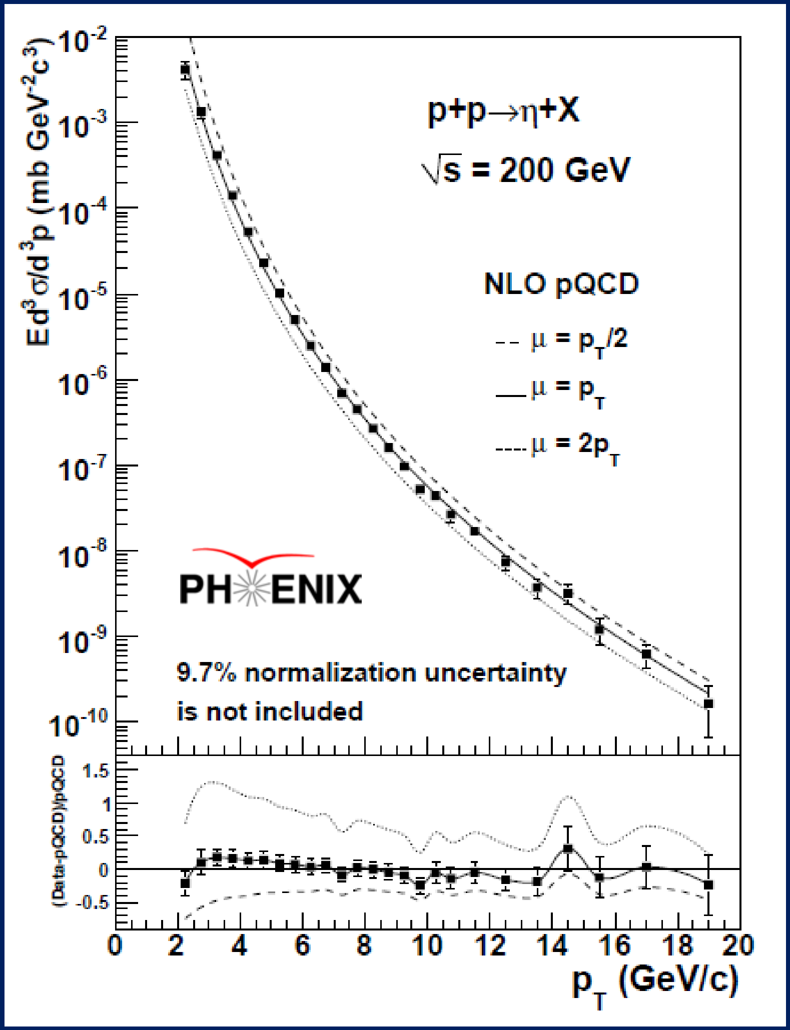
- PHENIX ratio consistent with STAR points, which lie many sigma below NLO calculation out to ~10 GeV
- More powerful to fit ratio directly in the future?

Scale uncertainty remains large for single-particle cross sections even for $\sqrt{s}$ =500 GeV and p_T up to 30 GeV



- "Good" agreement with NLO, but still only within ~20-50%
- Measured π-/π+ ratio at 200 GeV within ~15% of NLO calculation, but less "good" because of greatly reduced scale uncertainties
  - Evidently other uncertainties relevant
- What are the most appropriate uncertainties to use in each case?

Eta mesons in 200 GeV p+p



PRD83, 032001 (2011)

- Cross section data used in FF fit

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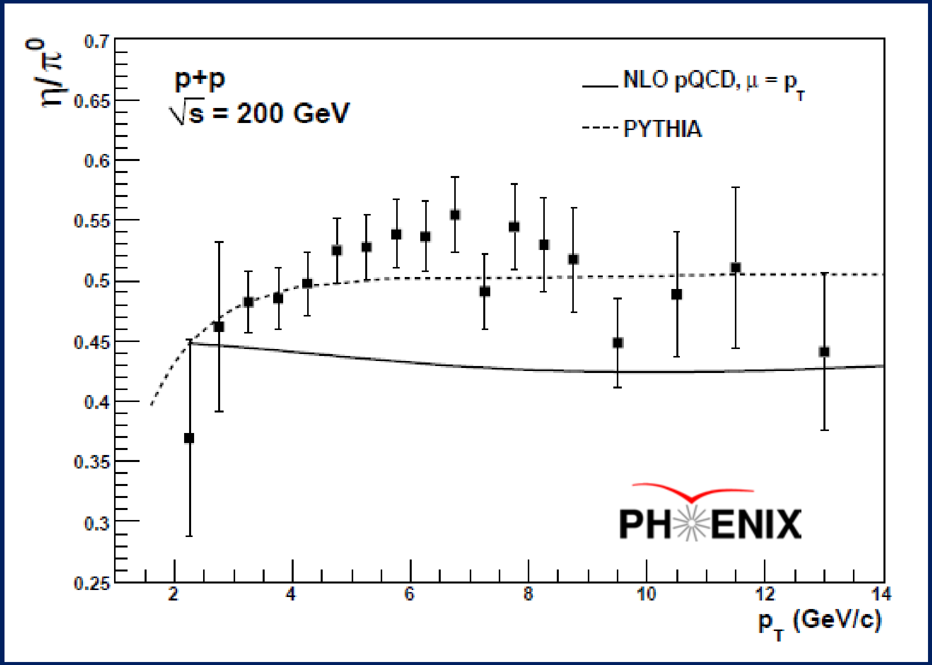

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- In this particular case, PHENIX eta data and (earlier but consistent) π^0 data were used in the respective FF fits, but in π^0 fit, PHENIX data normalization scaled within uncertainty in one direction, and in eta fit, scaled in other direction

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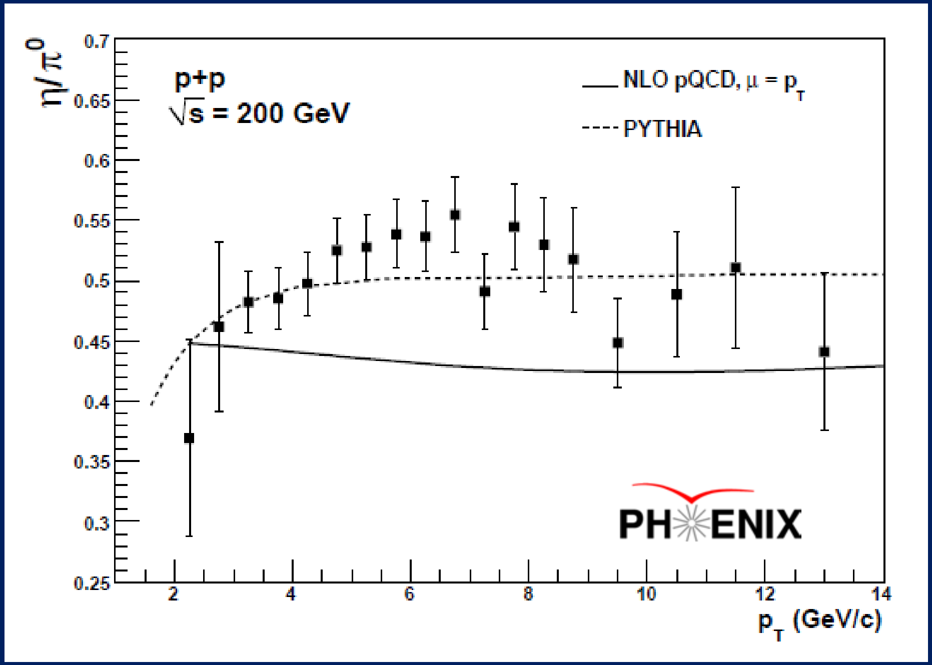

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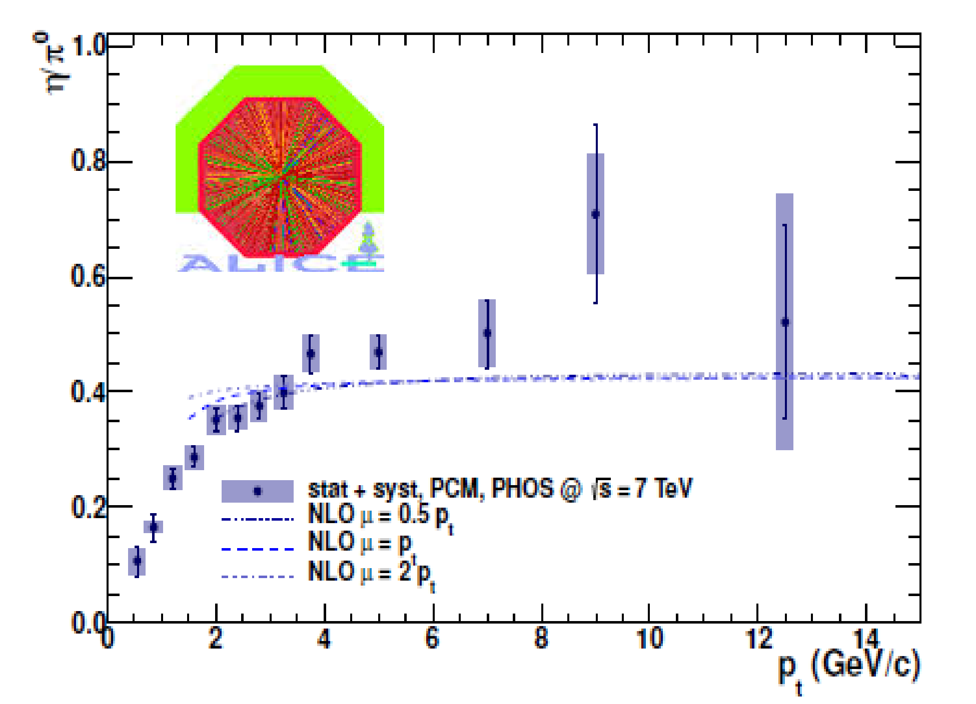
- Fitting ratio directly would automatically take into account the 100% correlated normalization uncertainties

PRD83, 032001 (2011)

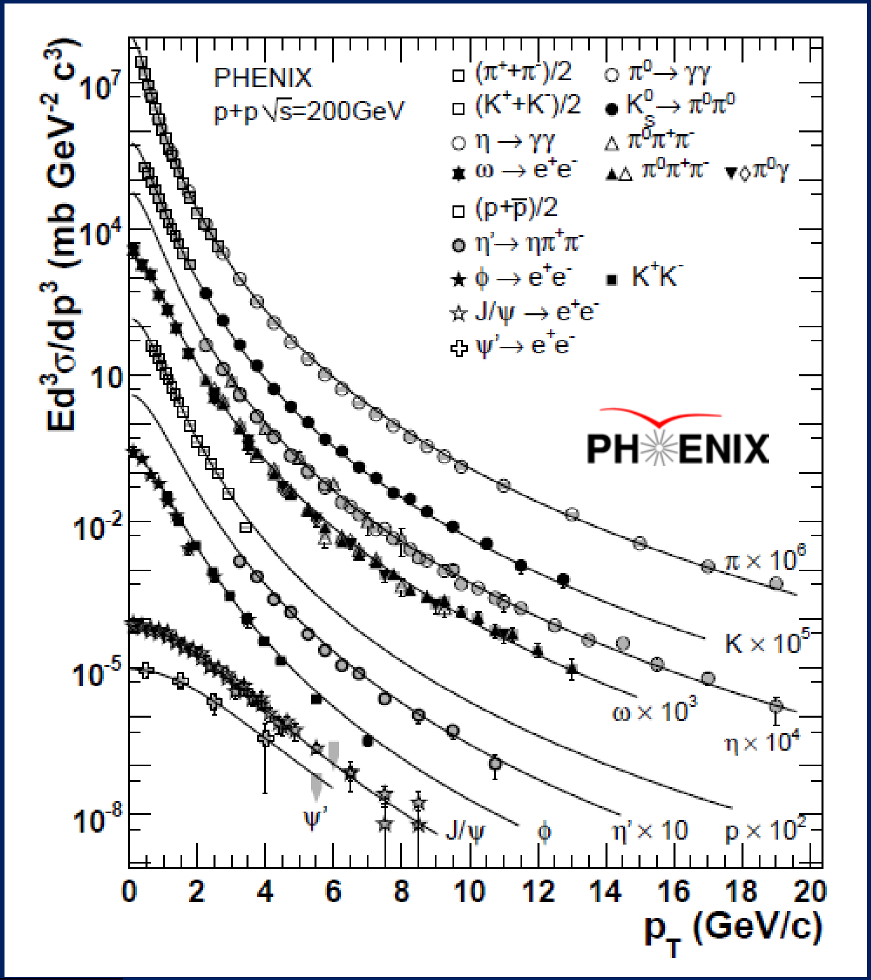
ALICE η/π^0 ratio, p+p at 7 TeV



PLB717, 152 (2012)

- Same p_T range as PHENIX data
- Calculated ratio again below data
- Scale uncertainty on NLO calculation shown

Eventually even more global global fits?



PRD83, 052004 (2011)

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  - Will constrain relative normalizations well!

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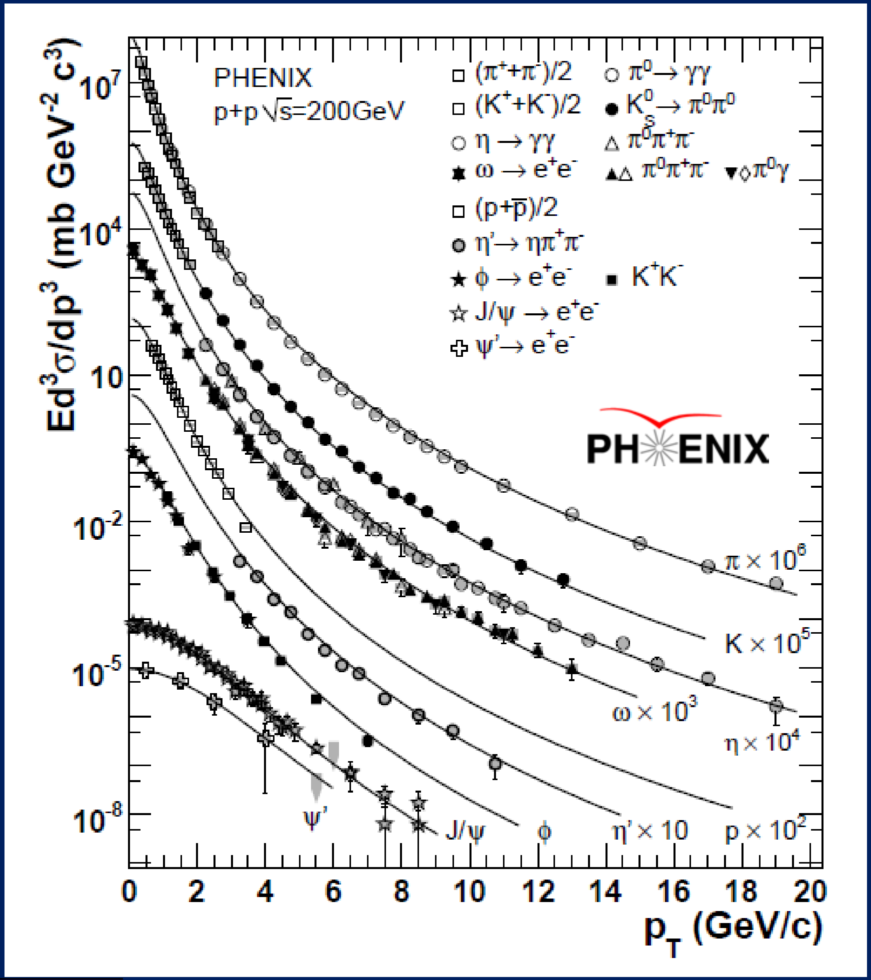

PRD83, 052004 (2011)

- Perform FF parameterizations for even more particles simultaneously?
  - Will constrain relative normalizations well!
- Can we learn by comparing similar mass states? E.g. about gluon FFs?
  - Is a gluon any more or less likely to fragment into a kaon vs. an eta? Eta’ vs. phi? Proton?

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- FFs can be thought of as conditional probabilities: given a particular flavor parton, the FF tells you the probability it'll fragment into a particular final-state hadron (as a function of z)

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- But in a sense they're parameterized the other way around: in all the data that are fit, you're given a particular final-state hadron

- At some point, performing simultaneous fits with enough final-state hadrons included, could you potentially constrain sum of probabilities for each flavor parton to be (nearly) 1?
  - E.g. better constraints for lambda FFs—uds valence quarks
    - Given an observed lambda, you might expect that it was equally likely to have fragmented from a u, d, or s
    - *But* given a u, d, or s quark, you might expect u and d to go to lighter states "most" of the time—if we know approximately how often, can we in turn better constrain the s → lambda FF?

How can we use hadronic collision data to help us understand more about partons turning into hadrons from . . .

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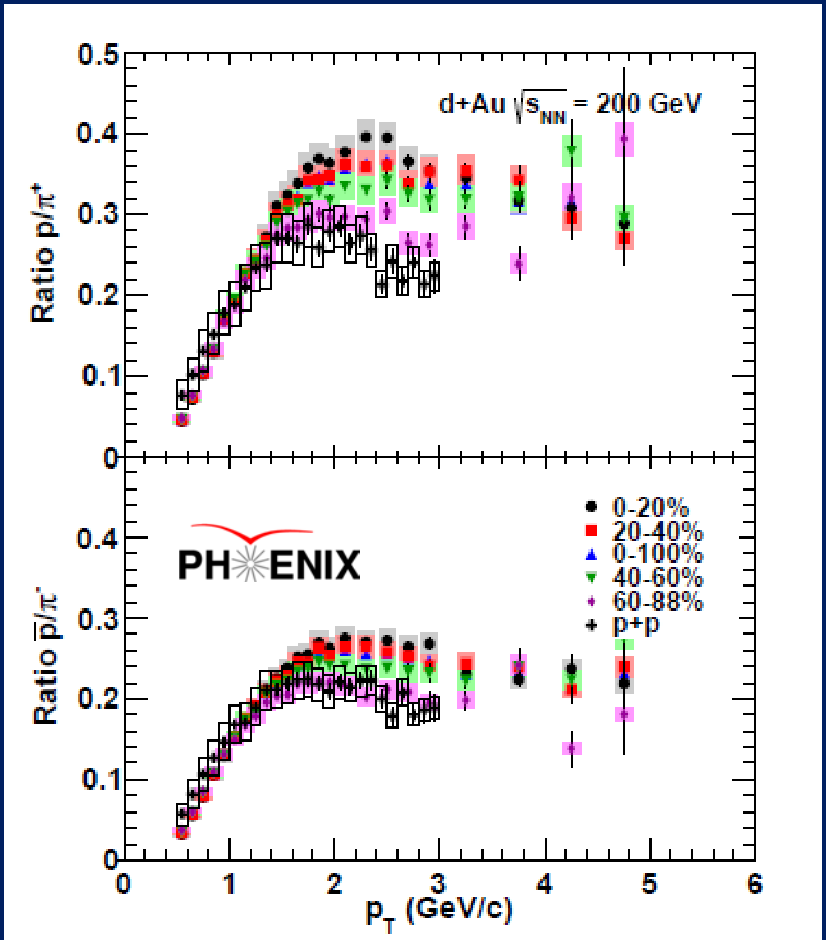
2. ***A denser partonic environment and partonic recombination(?)***

Centrality-dependent baryon enhancement in d+Au compared to p+p



- Precision d+Au data for identified charged hadrons in bins of centrality
- New hadron production mechanism enabled by presence of additional partons/ nucleons
  - Parton recombination?

PRC88, 024906 (2013)

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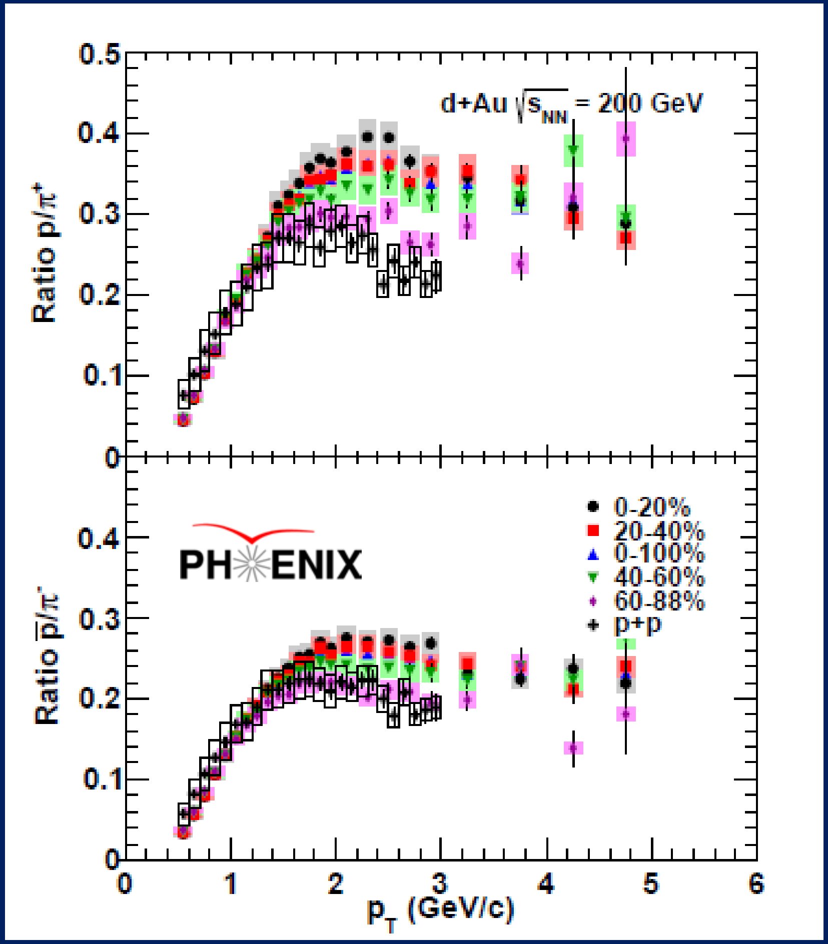

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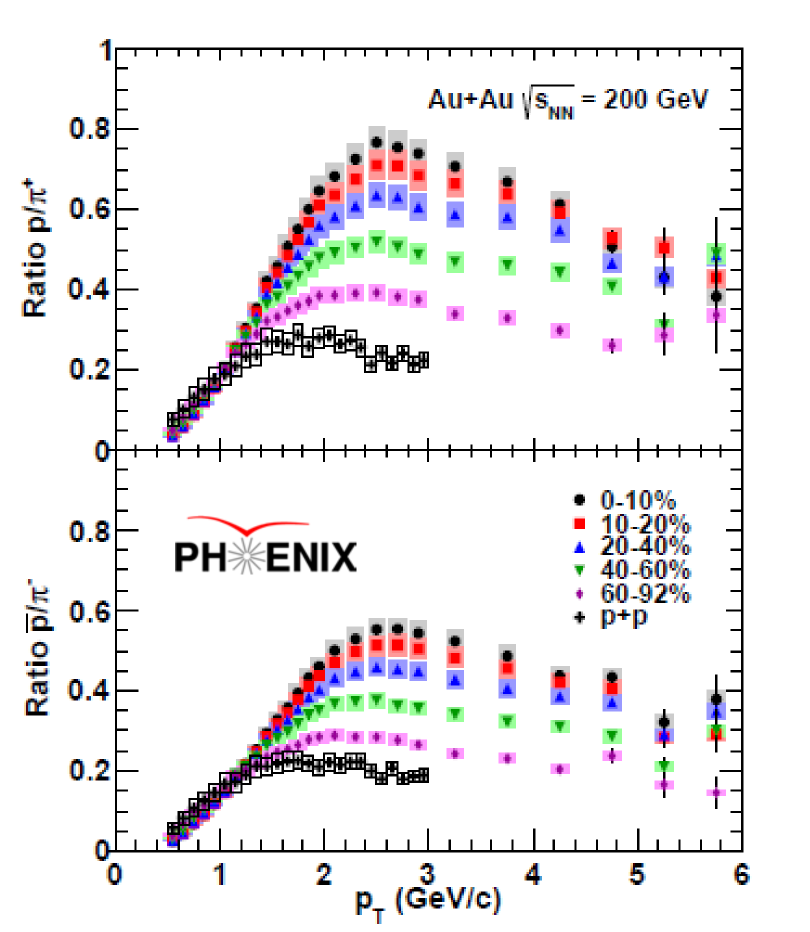

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- New hadron production mechanism enabled by presence of additional partons/ nucleons
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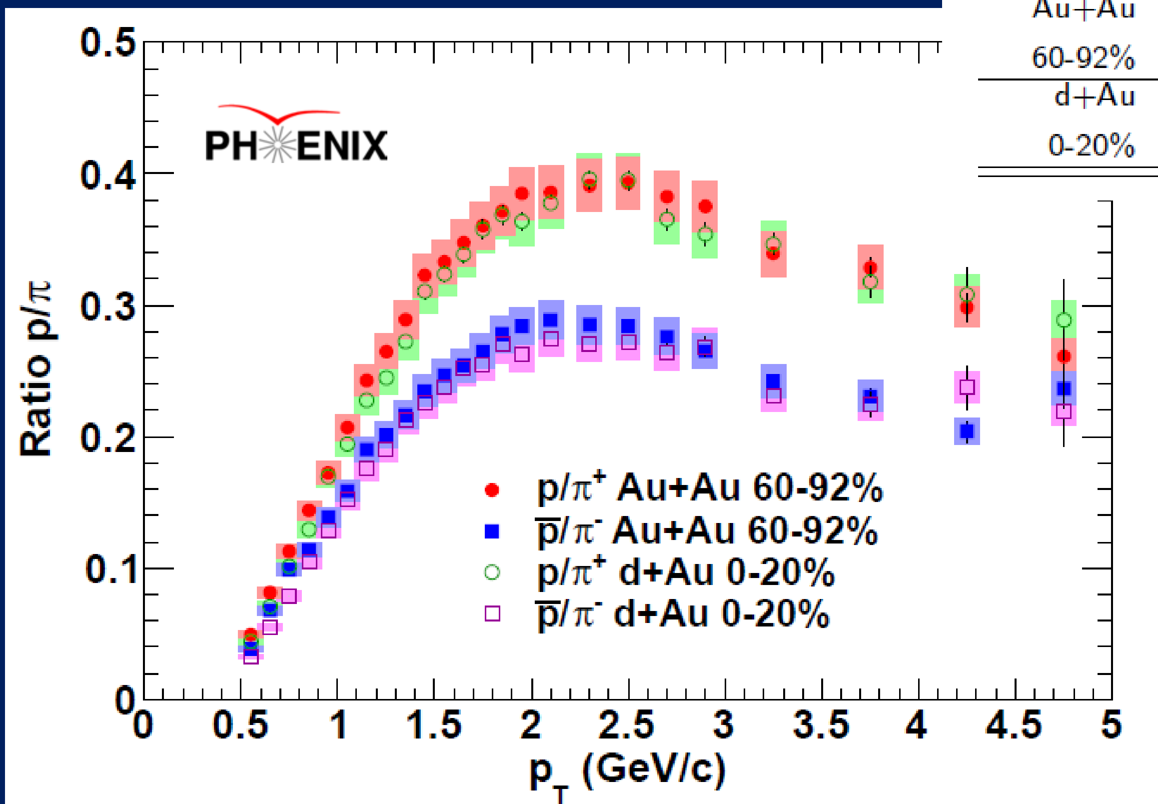
- Strong centrality dependence despite small range of N_{part} and N_{coll} values in d+Au
- Well-known centrality-dependent baryon enhancement in Au+Au

Comparing central d+Au with peripheral Au+Au

Centrality	$\langle N_{coll} \rangle$	$\langle N_{part} \rangle$
Au+Au 60-92%	14.8 ± 3.0	14.7 ± 2.9
d+Au 0-20%	15.1 ± 1.0	15.3 ± 0.8

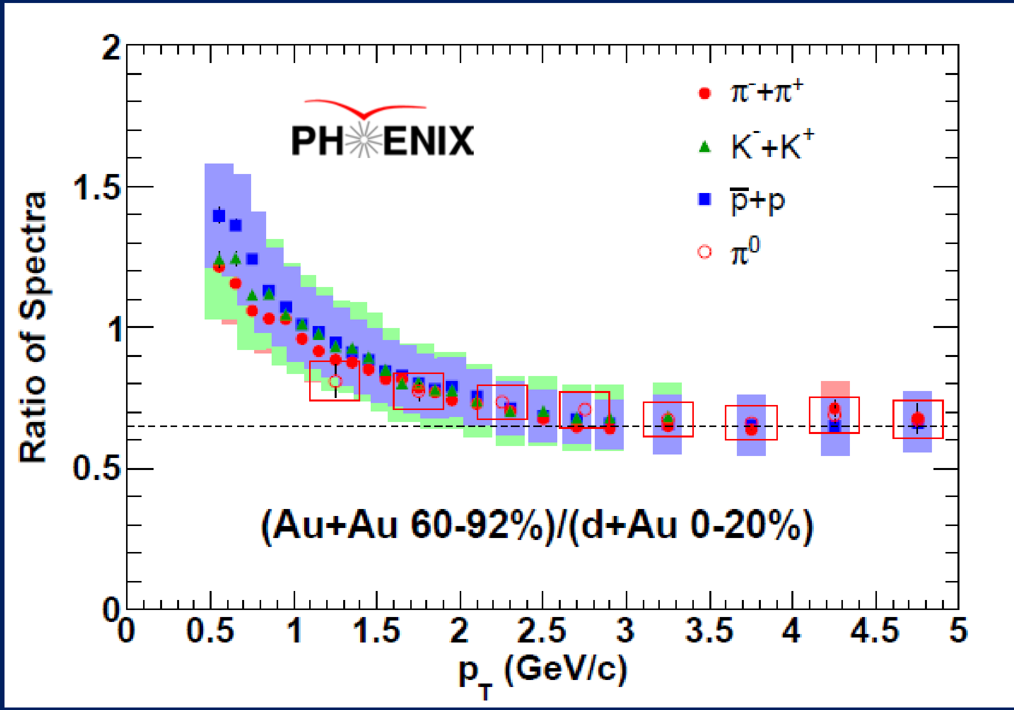


PRC88, 024906 (2013)

Both shape and magnitude identical!

Suggests common mechanism(s) for baryon production in the two systems

Comparing central d+Au with peripheral Au+Au



PRC88, 024906 (2013)   *No scaling applied*

- Direct ratio of spectra is flat above 2.5 GeV and species independent
  - Baryon enhancement is *quantitatively* the same
  - Ratio significantly less than unity—suggests energy loss for all species in peripheral Au+Au

How can we use hadronic collision data to help us understand more about partons turning into hadrons from . . .

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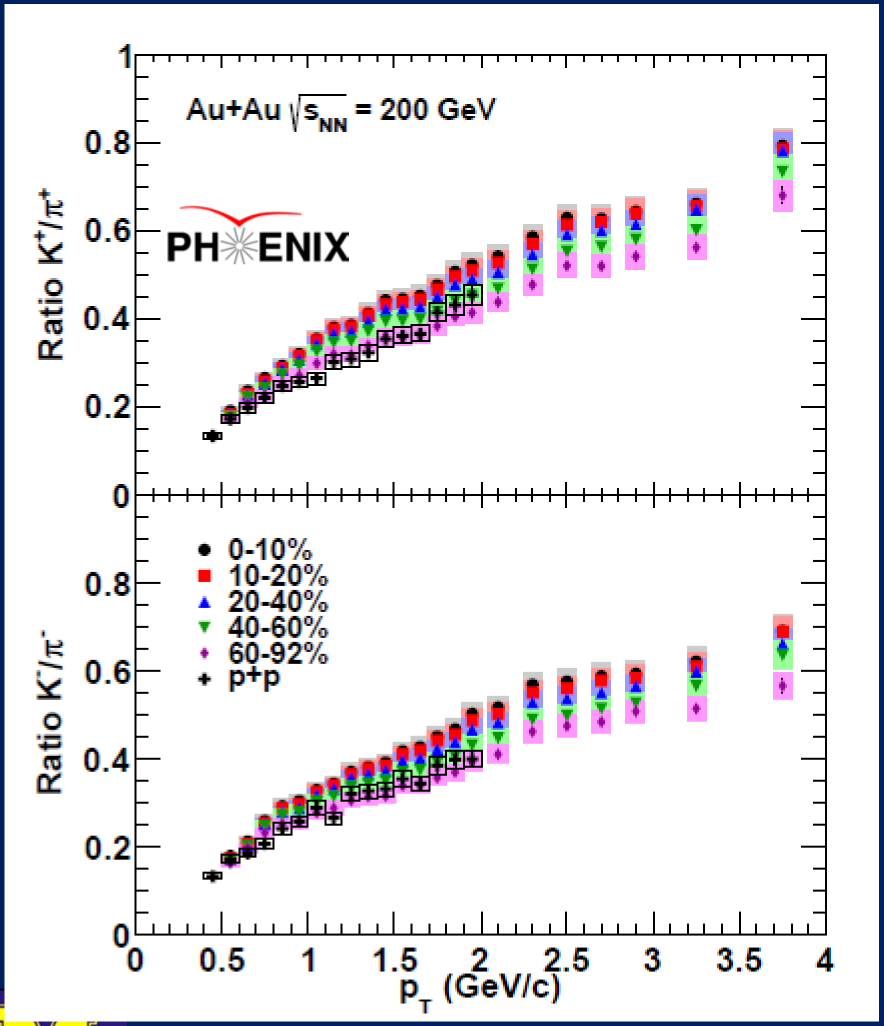
II. ***A denser partonic environment and partonic recombination(?)***

III. ***A thermalized, deconfined environment***

Enhancement of strange meson production in central Au+Au



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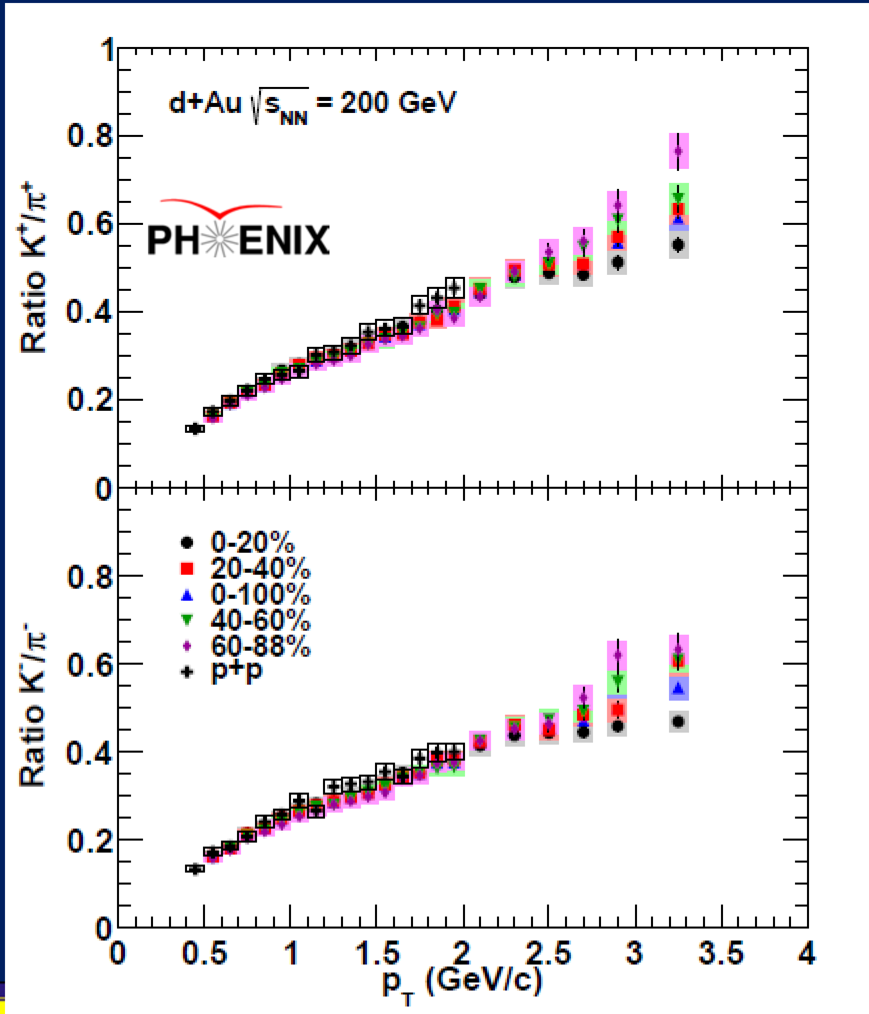
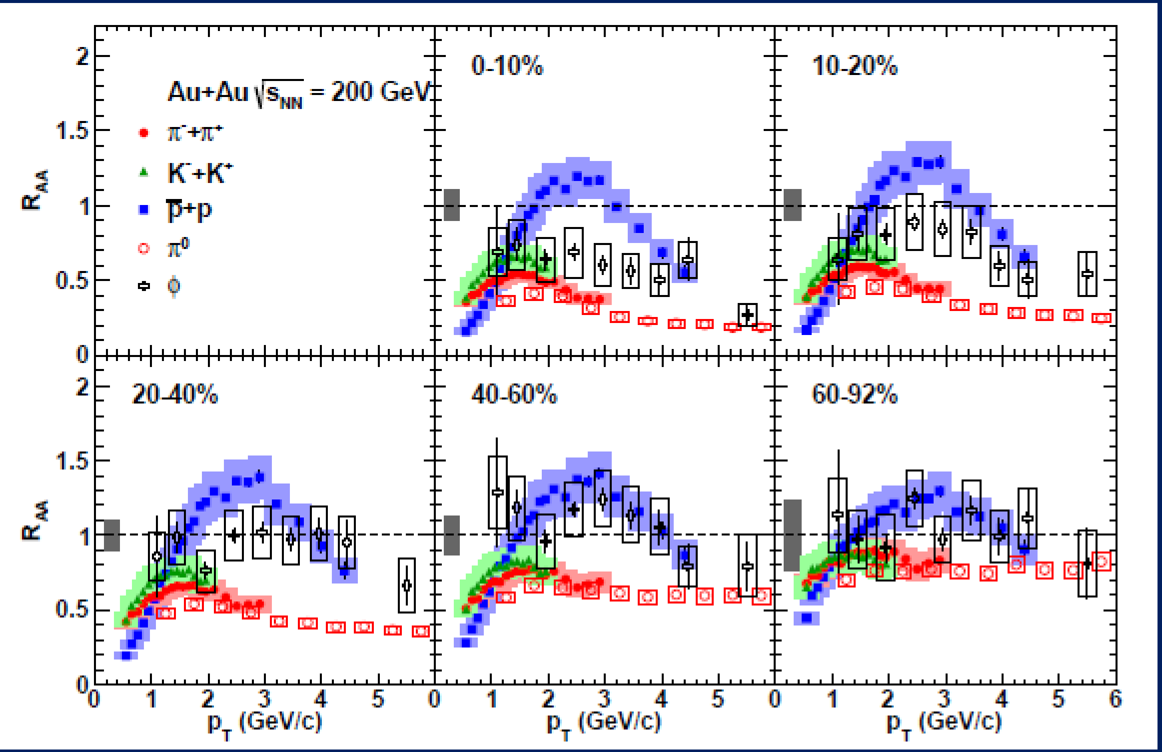


- K/π ratio higher in more central Au+Au than p+p, increases with centrality
- K/π ratio in d+Au same as p+p for all centralities

Strange meson production in Au+Au



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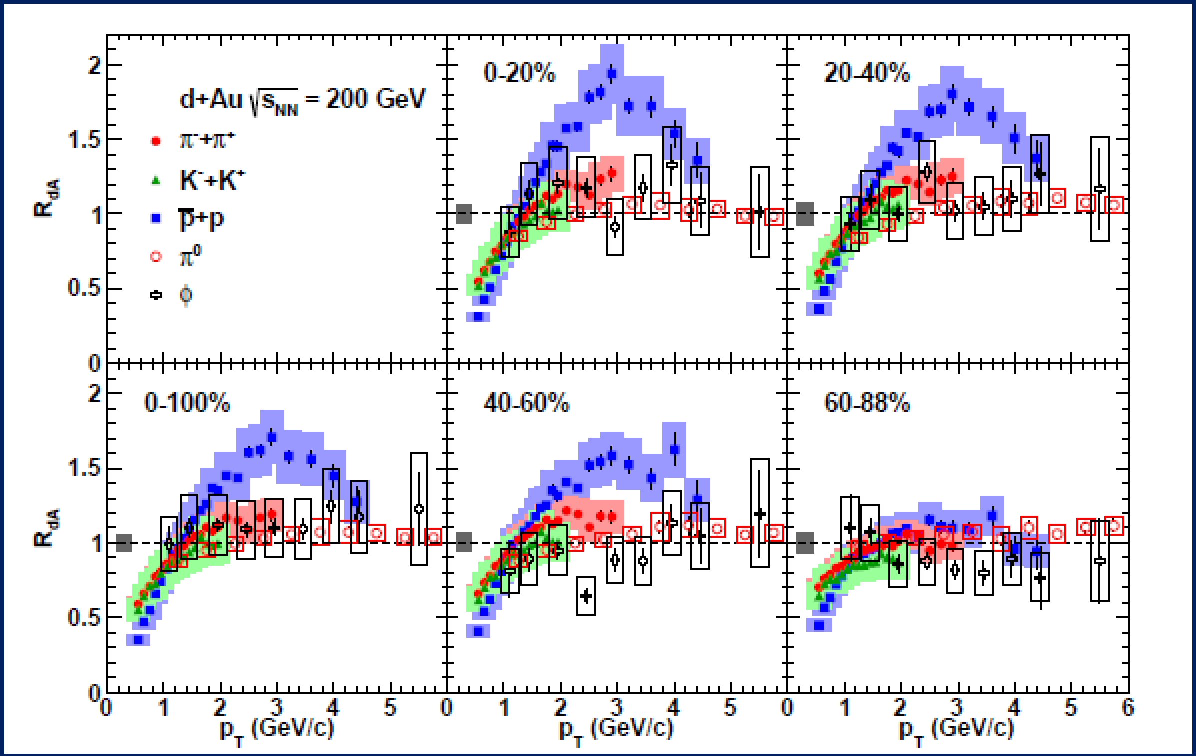
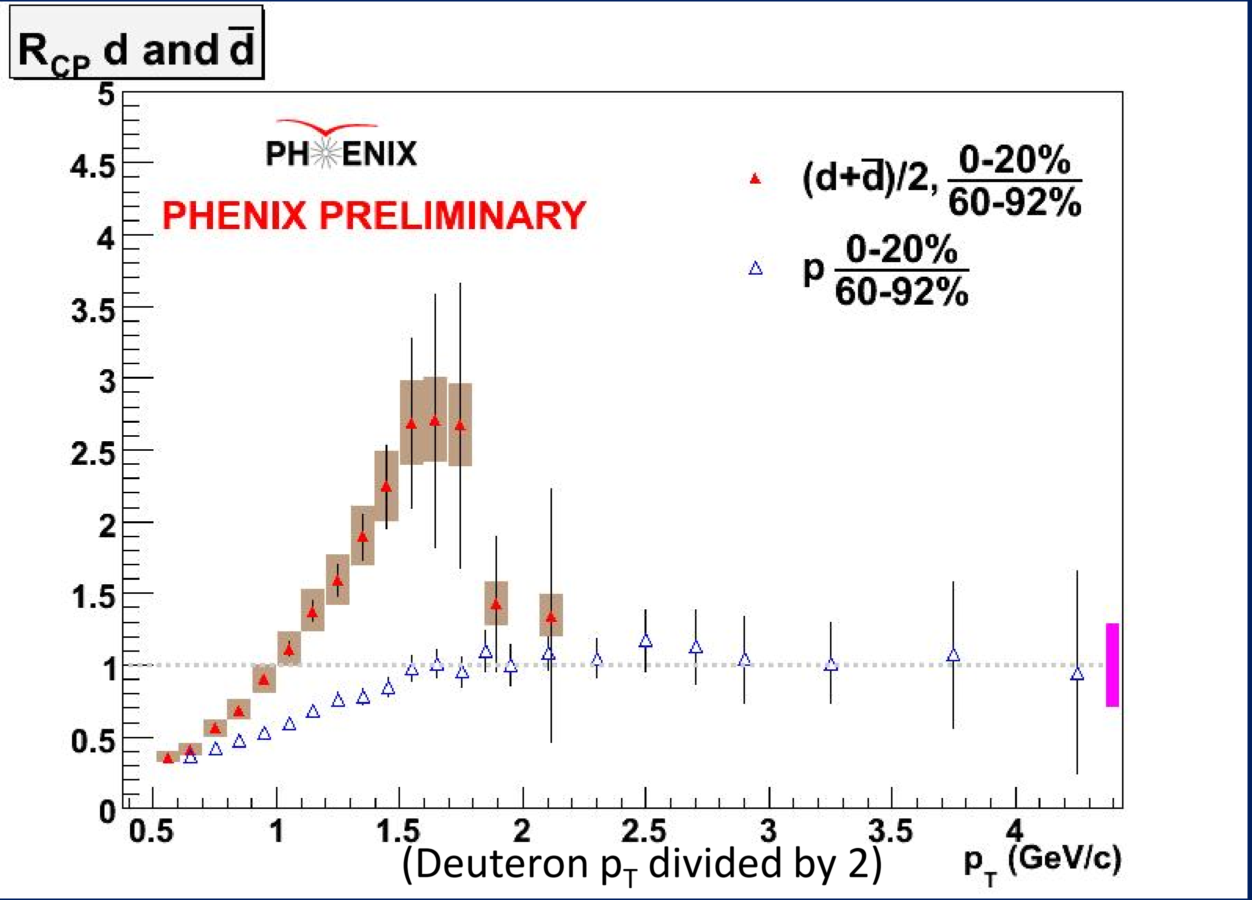


- In Au+Au, kaon and pion most separated in central events
- Phi seems to stay between kaon and proton
- In d+Au, charged pions and kaons consistent with each other, and phi exhibits minimal modification
- Suggests additional strange meson production mechanism in central Au+Au compared to d+Au or p+p

How can we use hadronic collision data to help us understand more about partons turning into hadrons from . . .

I. Hard scattering and “traditional” fragmentation
II. A denser partonic environment and partonic recombination(?)
III. A thermalized, deconfined environment
IV. Bound states of hadronic bound states: nucleon coalescence(?)

Bound states of hadronic bound states: Creating nuclei!



(Deuteron p_T divided by 2)

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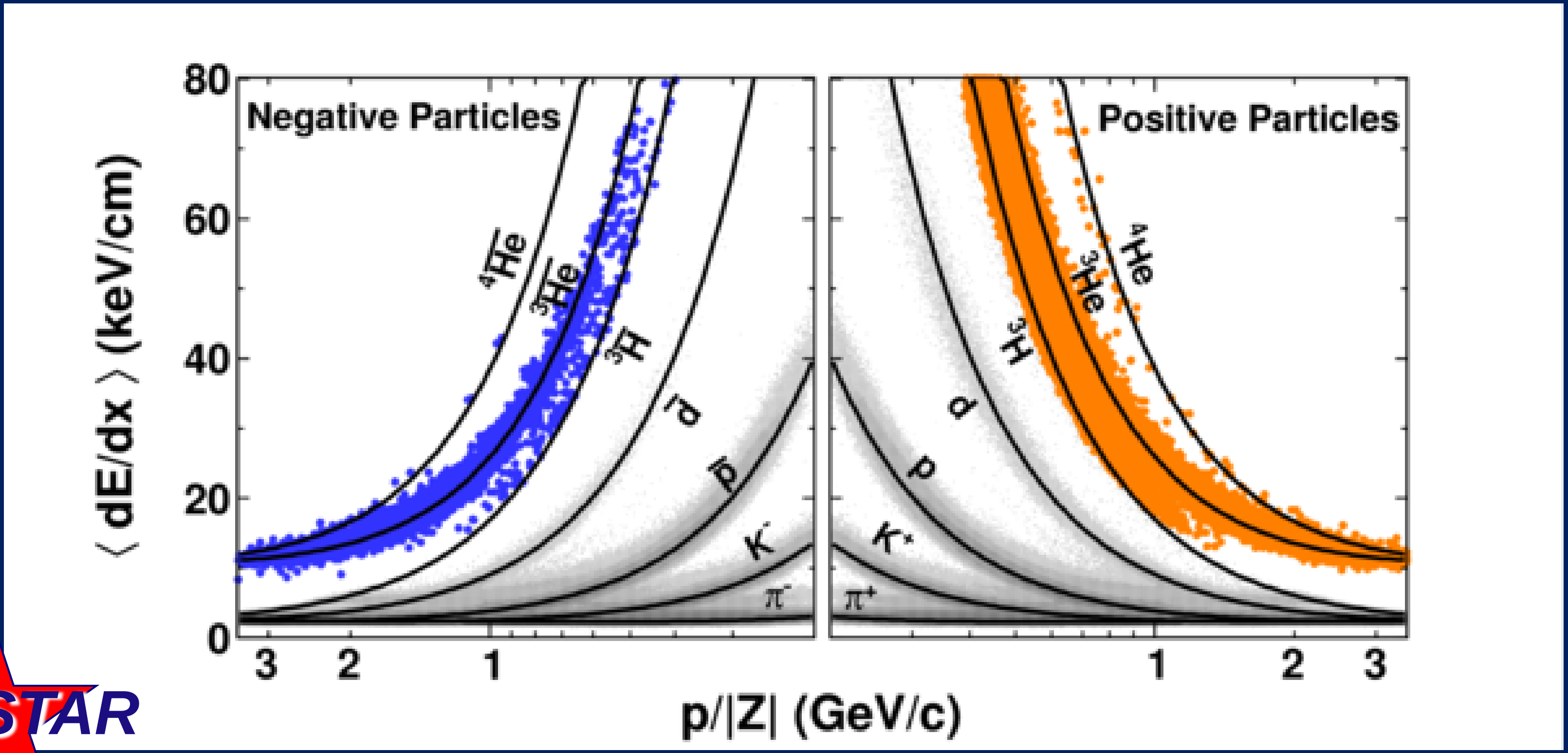

Nature 473, 353 (2011)

Bound states of hadronic bound states: Creating nuclei, and building up the world…

- Heavy ion collisions let us create nuclei—and antinuclei!—up to ^{4}He
  - Big Bang Nucleosynthesis in the lab . . .
  - Building up the antiworld as well . . .

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- Heavy ion collisions let us create nuclei—and antinuclei!—up to ^{4}He
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- Do we understand enough by now about QCD bound states—and nucleons specifically—to start to think more about going from first principles to the “van der Waals” forces that bind color-neutral nucleons into nuclei??
  - What are the differences between production of nuclei in relativistic heavy ion collisions and low-energy nucleon capture experiments??

100 years from now: Nuclear gecko tape???

Van der Waals force

From Wikipedia, the free encyclopedia

This article **may be too technical for most readers to understand**. Please help improve this article to make it understandable to non-experts, without removing the technical details. The talk page may contain suggestions. *(January 2013)*

In physical chemistry, the **van der Waals' force** (or **van der Waals' interaction**), named after Dutch scientist Johannes Diderik van der Waals, is the sum of the attractive or repulsive forces between molecules (or between parts of the same molecule) other than those due to covalent bonds, the hydrogen bonds, or the electrostatic interaction of ions with one another or with neutral molecules or charged molecules.[1] The term includes:

- force between two permanent dipoles (Keesom force)
- force between a permanent dipole and a corresponding induced dipole (Debye force)
- force between two instantaneously induced dipoles (London dispersion force).

It is also sometimes used loosely as a synonym for the

Geckos can stick to walls and ceilings because of Van der Waals forces; see the section below.

100 years from now: Nuclear gecko tape???

5 science breakthroughs in 2012

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Gecko tape

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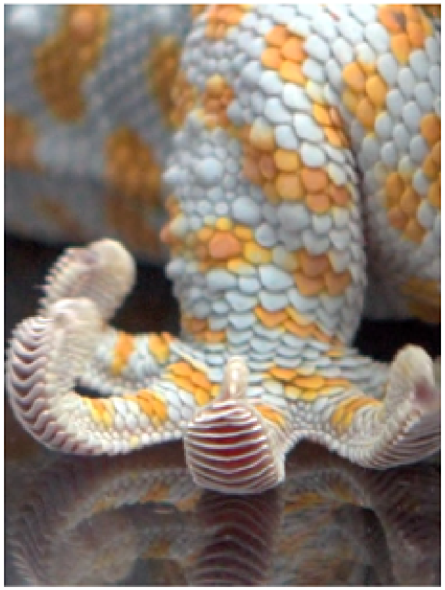

The natural world is one of the most reliable resources for tech inspiration. DARPA (Defense Advanced Research Projects Agency), the Pentagon's research arm, is well aware of this. Just last year, it rolled out a new version of a hummingbird-shaped spy drone that can even perch on windowsills to collect information.

But long before the general consumer can purchase his or her own mechanical avian espionage unit, civilians should be able to buy a product inspired by the footpad of a Gecko. The product, called Geckskin, is a super-strong adhesive. Geckskin was discovered by a team of scientists at the University of Massachusetts and, like other major biomimicry projects, it was funded by DARPA.

Unlike other DARPA projects, Geckskin could have more immediate uses for your everyday non-spy. For example, an index-card-size piece of Geckskin should support up to 700 pounds. That's enough might to secure large-screen televisions to a wall without damaging it or leaving residue after it's removed.

Final remarks

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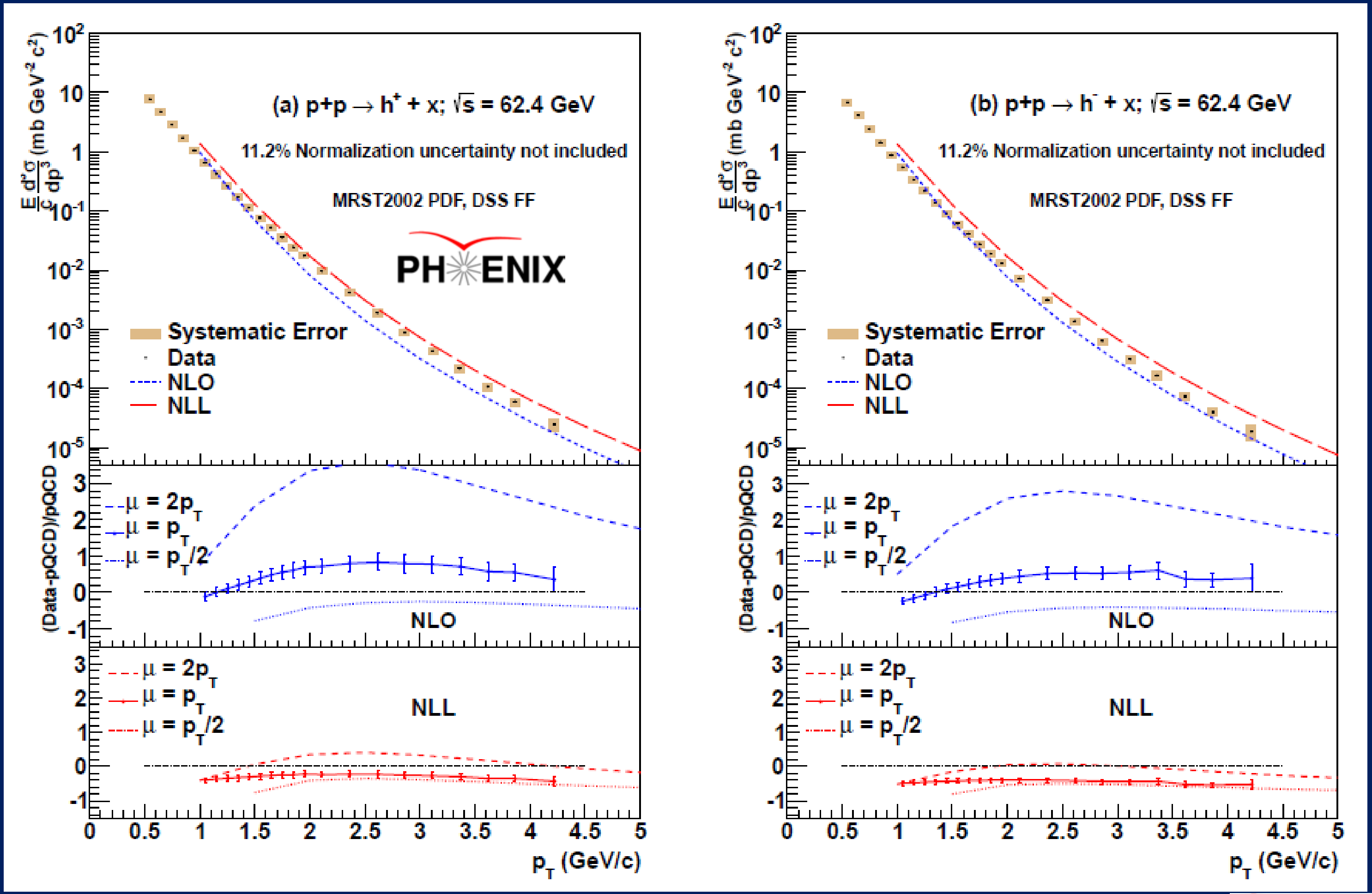
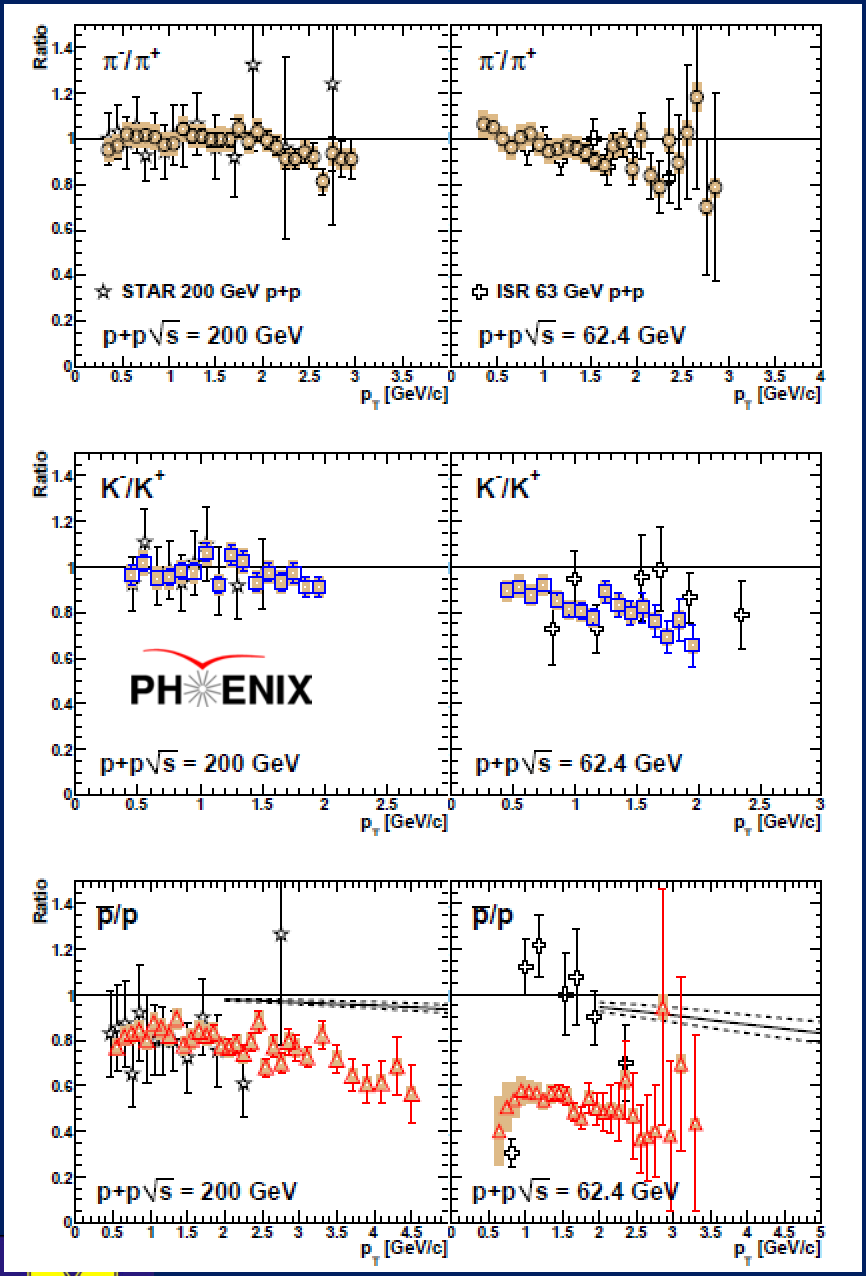
- Look forward to lots of progress in next ~5 years!

Extra

Charge-separated hadrons in 62.4 GeV p+p: Reining in scale uncertainties with NLL resummation

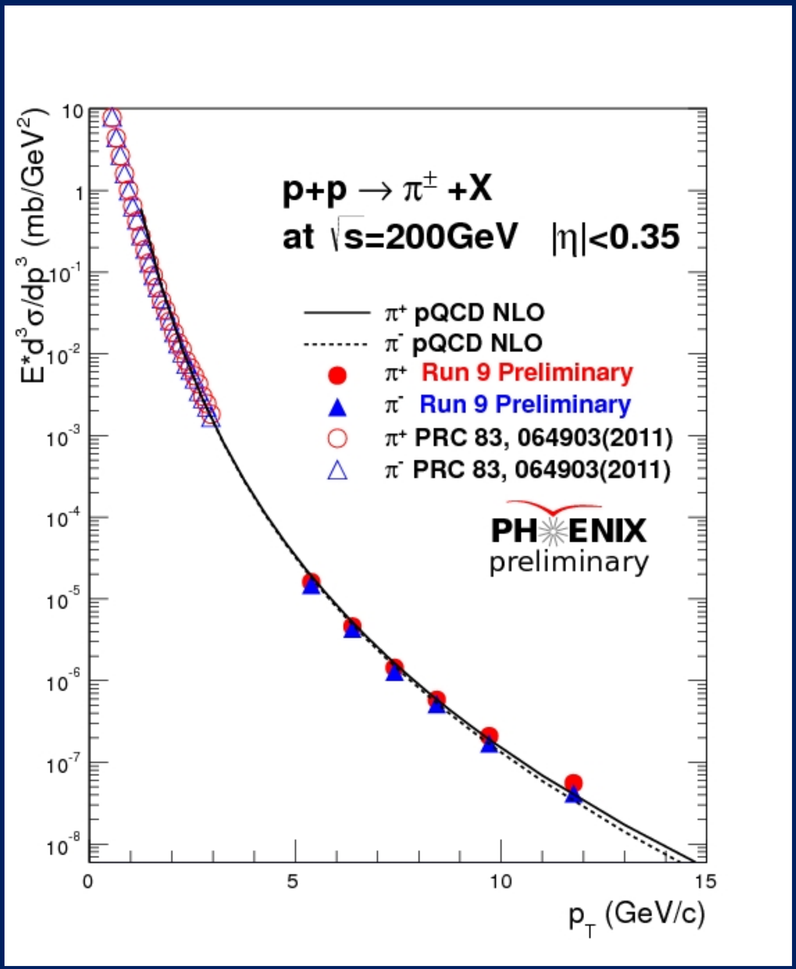


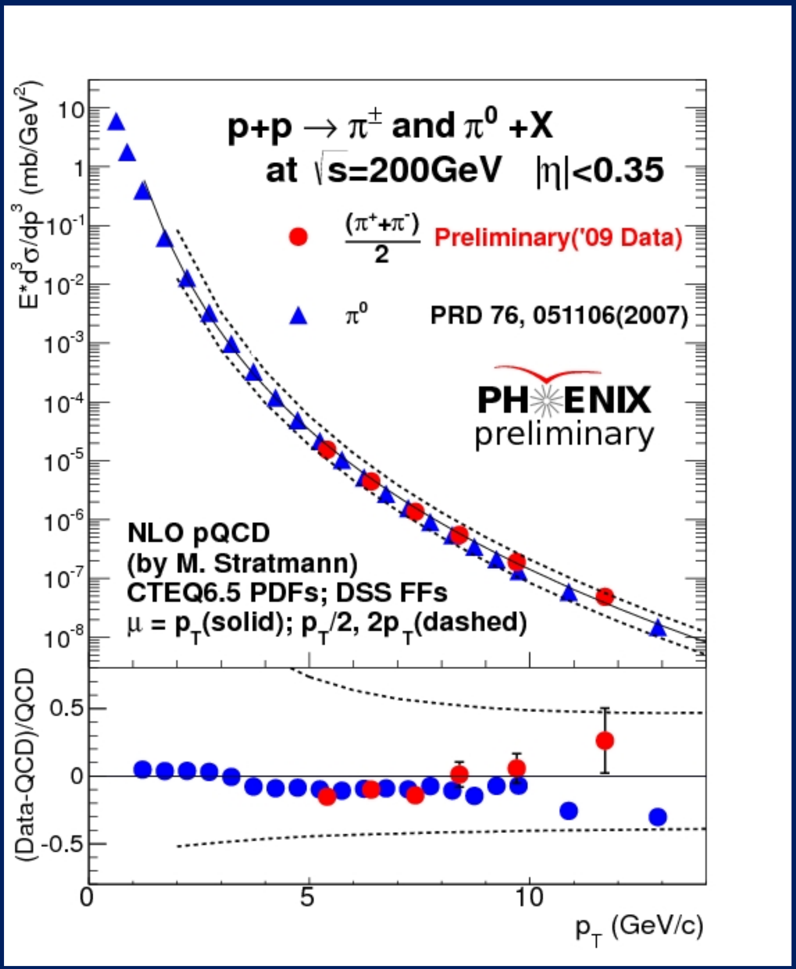


- π, K, p charge ratios in 200 and 62.4 GeV p+p
- For antiproton-to-proton ratio, comparison shown to NLO calculations using DSS FFs

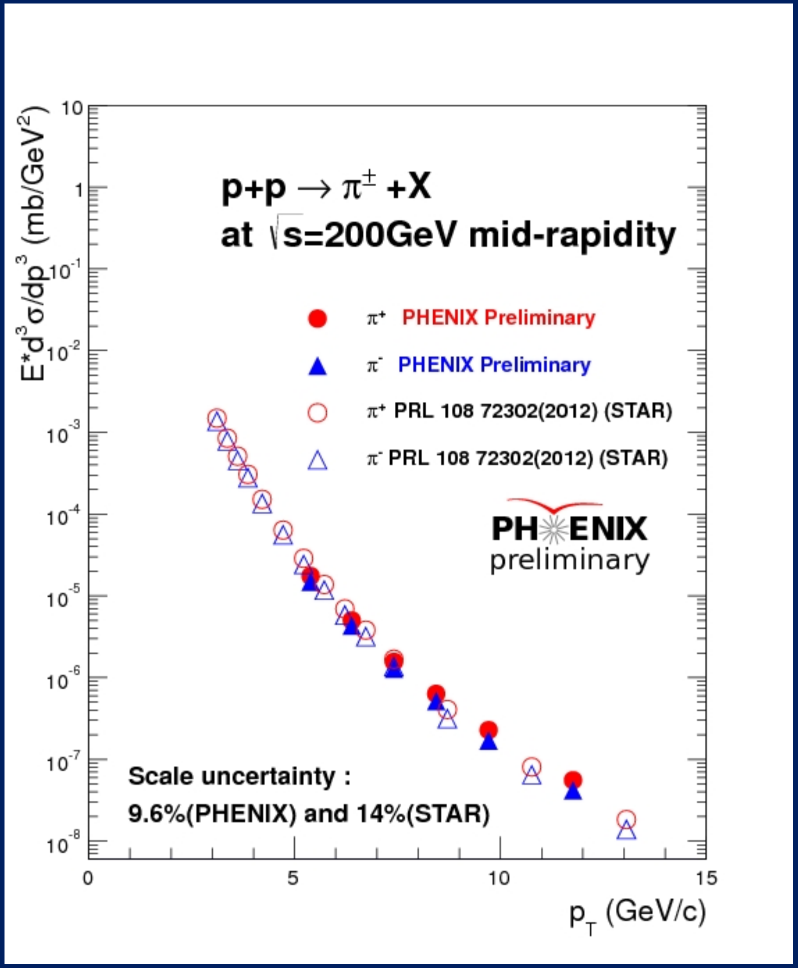
PRC83, 064903 (2011)

PHENIX pions, 200 GeV p+p



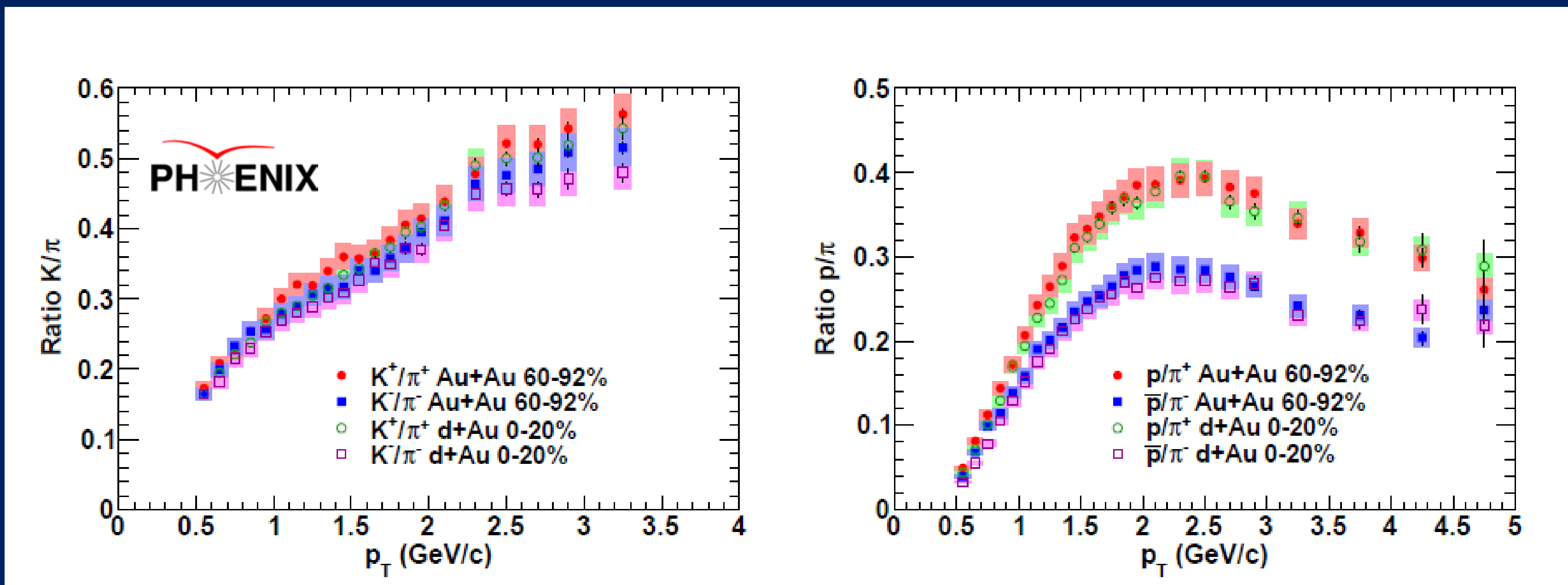


Charged pions at PHENIX and STAR



Comparing central d+Au with peripheral Au+Au

PRC88, 024906 (2013)



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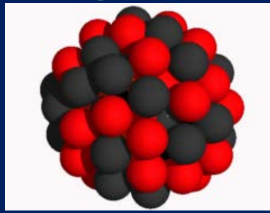
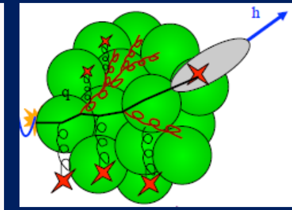
Both shape and magnitude identical!

Electron-Ion Collider

- A facility to bring this new era of quantitative QCD to maturity!
- *How can QCD matter be described in terms of the quark and gluon d.o.f. in the field theory?*
- *How does a colored quark or gluon become a colorless object?*

- Study in detail
  - "Simple" QCD bound states: Nucleons
  - Collections of QCD bound states: Nuclei
  - Hadronization