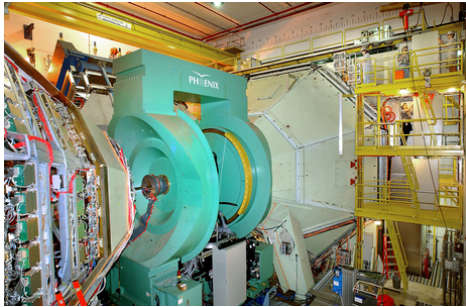


Overview of recent PHENIX results



ZIMÁNYI SCHOOL 2025

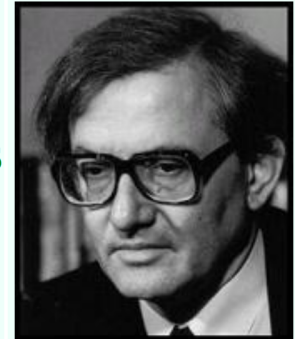


I. Csók: Lightning over Balaton

25th ZIMÁNYI SCHOOL
WINTER WORKSHOP
ON HEAVY ION PHYSICS

December 1-5, 2025

Budapest, Hungary



József Zimányi (1931 - 2006)

Márton Nagy

Zimányi School 2025

Dec 5, 2025



ELTE
EÖTVÖS LORÁND
TUDOMÁNYEGYETEM

(Very short) introduction: RHIC & PHENIX past → present & future...

„Discovery phase” of QGP research → precision measurements

Results: classic → somewhat recent → recent → to come...

Direct photons ($p+p$, Au+Au, d+Au)

Light flavor hadrons

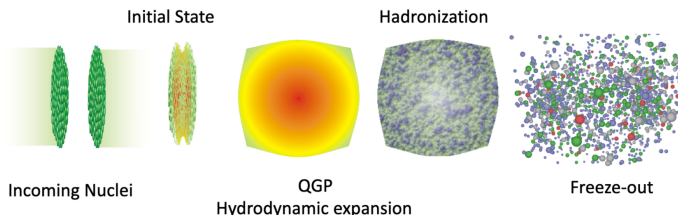
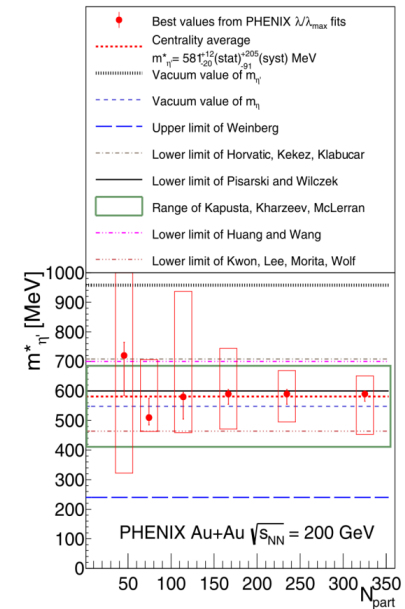
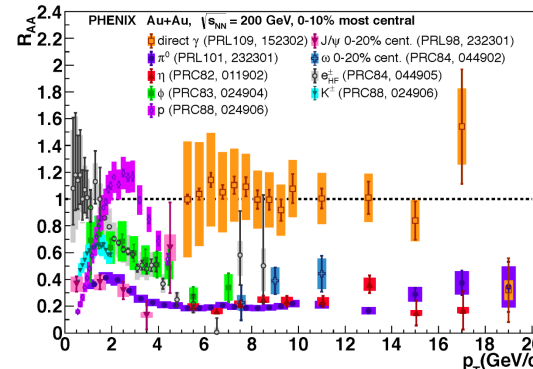
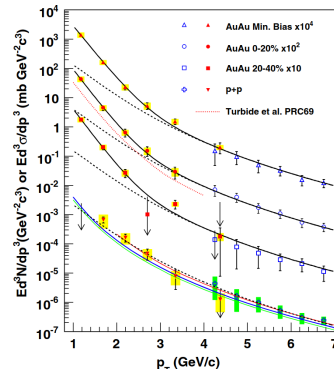
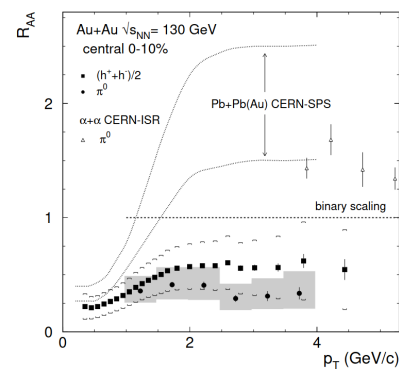
Heavy flavor (from electrons) Au+Au, p+p

Other p+p results

Bose-Einstein correlations

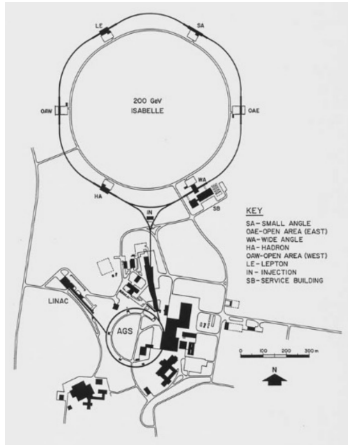
DAP (Data & Analysis Preservation)

→ Expect more!!



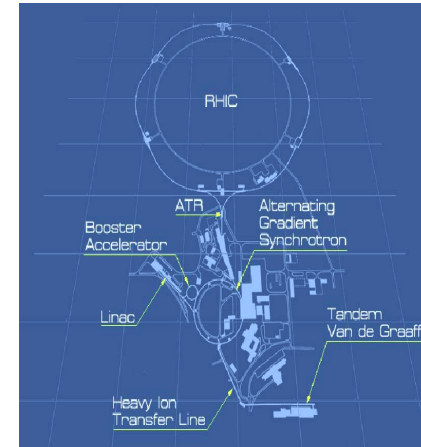
1971: Accelerator plans at BNL: ISABELLE (200+200 GeV) → CBA

CBA proposal



→

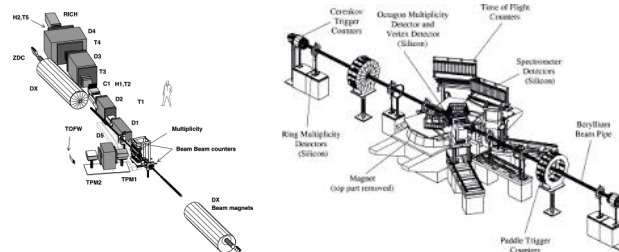
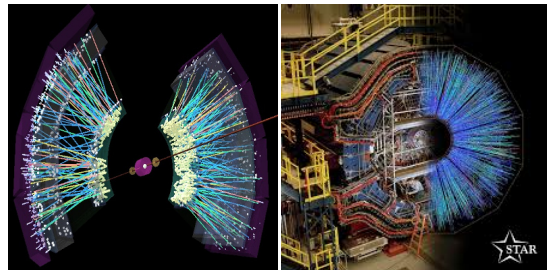
RHIC today



1983: CBA (terminated) → RHIC in LRP for NP

2000: RHIC start-up:

- 4 experiments (**PHENIX**, STAR, BRAHMS, PHOBOS)



PHENIX & STAR: two large detectors; \$30M+, for decades:

STAR: data taking from 2000-present

PHENIX: data taking 2000-2016; successor: sPHENIX

PHENIX charge:

Highest luminosity; rare processes, excellent PID

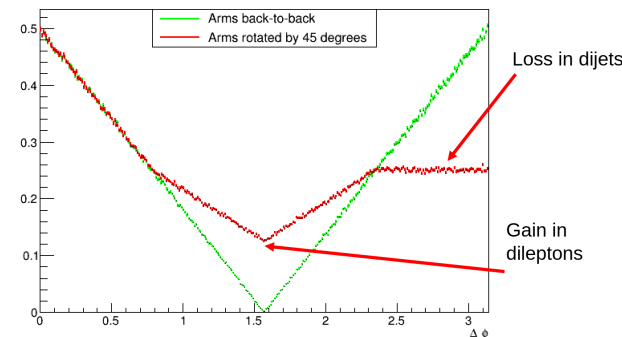
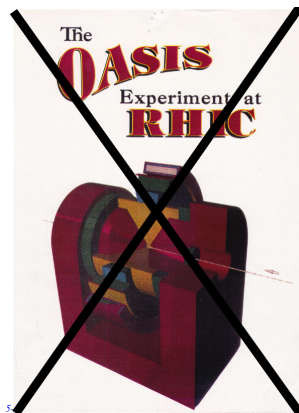
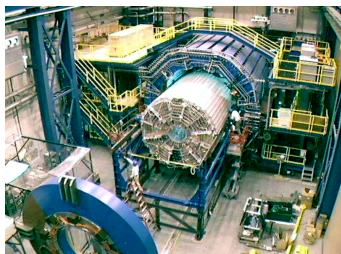
- Sacrifice acceptance: $2 \times 90^\circ$, $|y| < 0.35$

PHENIX

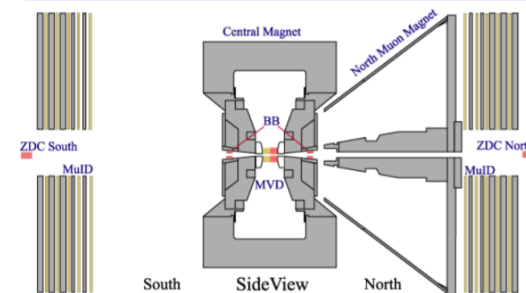
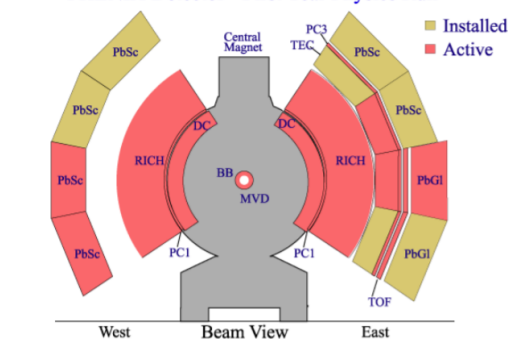
Photons, **H**adrons, **E**lectrons, **M**uons

Pioneering **H**igh **E**nergy **N**uclear Interaction **eX**periment

- Reborn from ashes...



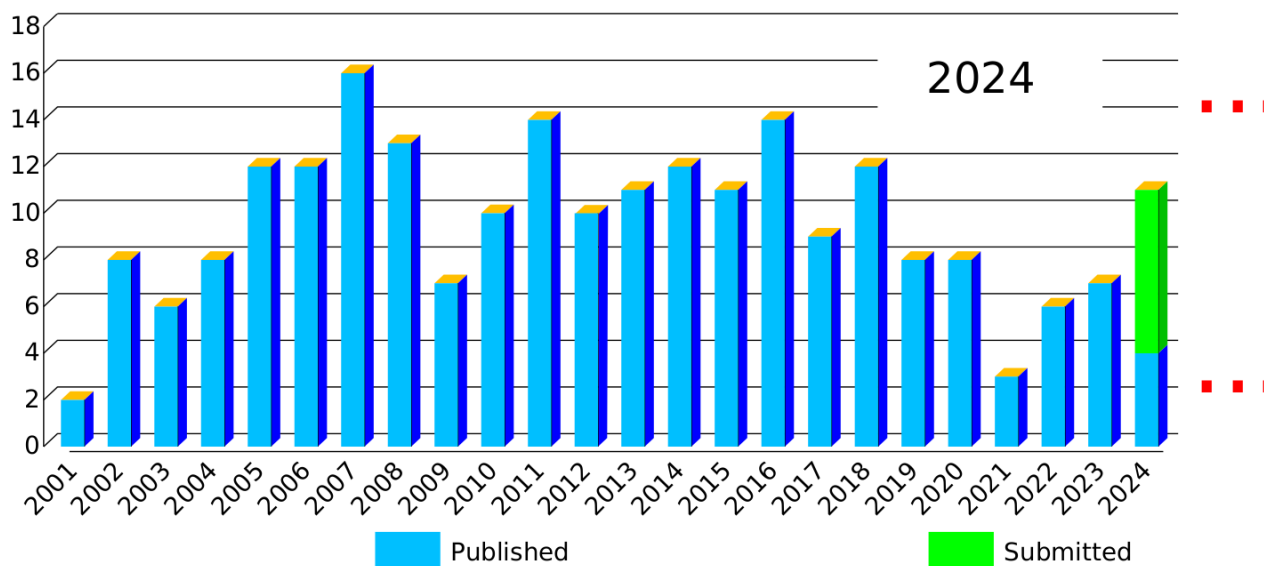
PHENIX Detector - First Year Physics Run



„Milestone”s:

- new phenomenon (jet quenching, R_{AA})
- new form of matter (jet quenching not initial state effect)
- liquid (v_2)
- quarks d.o.f. (v_2 scaling of different species)
- η/s (v_2/v_4 etc.): perfect fluid
- initial temperature (direct γ s)
- ...

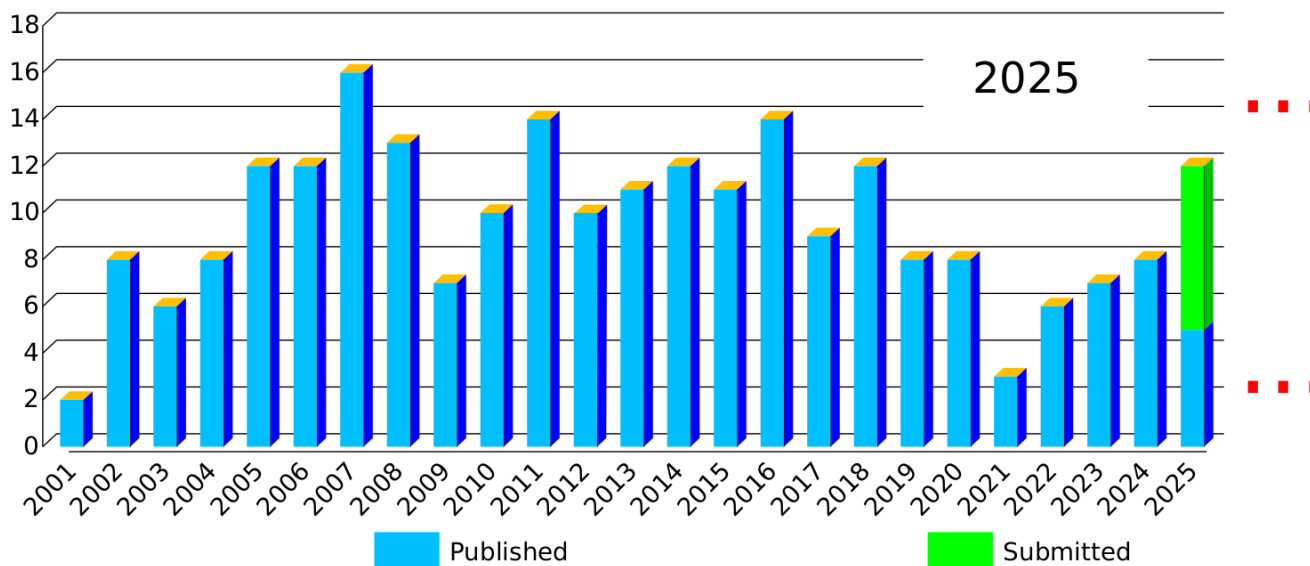
Data taking until 2016; data analysis: ever since, new results are abounding!



„Milestone”s:

- new phenomenon (jet quenching, R_{AA})
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- ...

Data taking until 2016; data analysis: ever since, new results are abounding!



RHIC: versatile collider

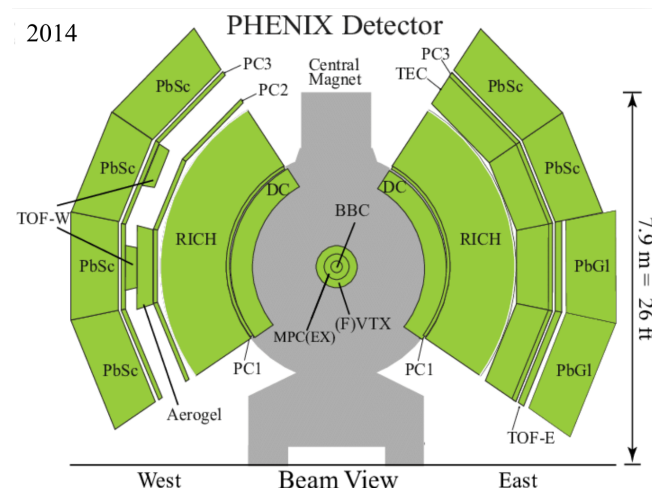
PHENIX data:

many different energies, species...



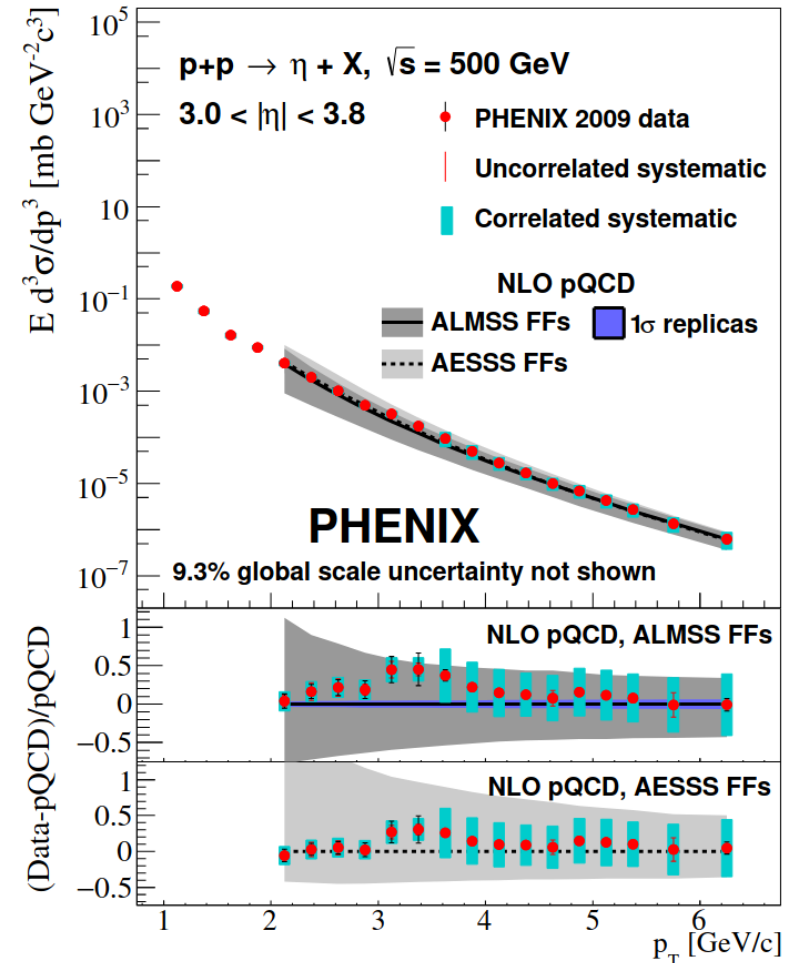
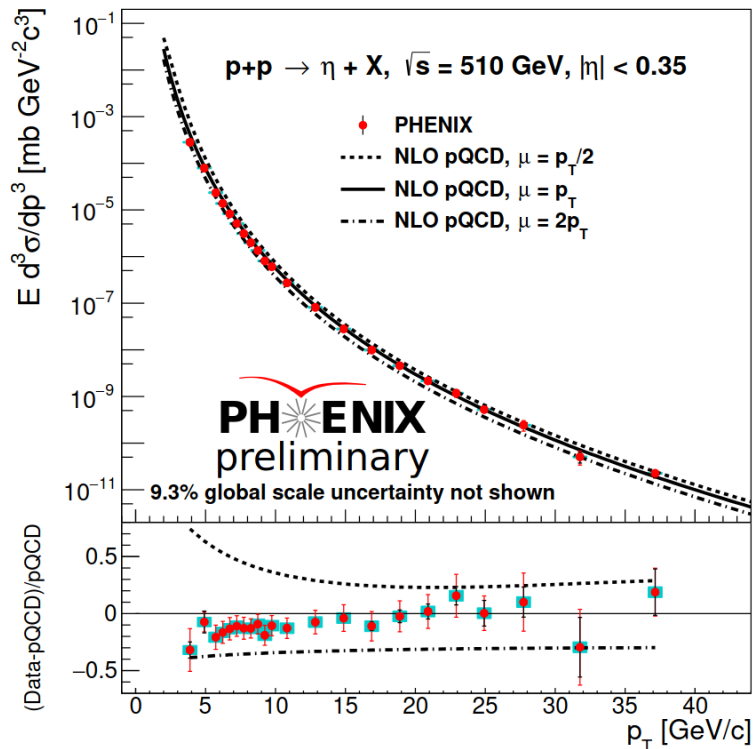
$\sqrt{s_{NN}}$ [GeV]	p+p	p+Al	p+Au	d+Au	$^3\text{He}+\text{Au}$	Cu+Cu	Cu+Au	Au+Au	U+U
510	✓								
500	✓								
200	✓	✓	✓	✓	✓	✓	✓	✓	
193									✓
62.4	✓			✓		✓		✓	
39				✓				✓	
27								✓	
19.3								✓	
14.5								✓	
7.7								✓	

Some new results follow...



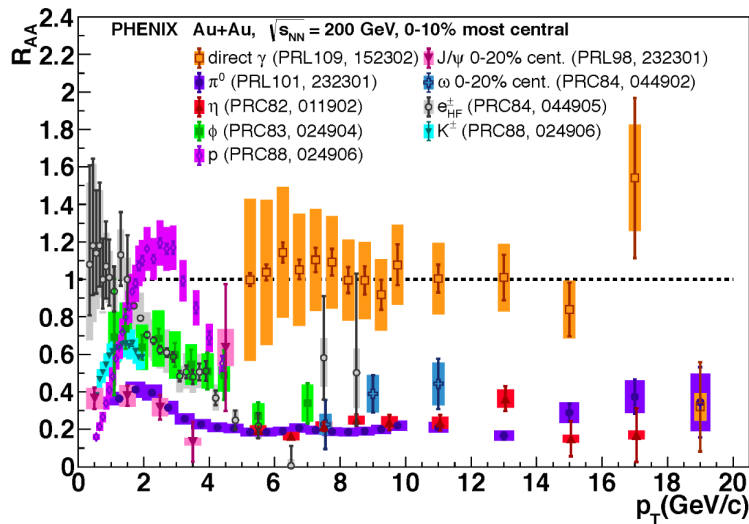
New result in p+p collisions @ 510 GeV

- Simultaneous measurement at mid-rapidity and at forward rapidity
- Constraining global fit for Fragmentation Functions



Nuclear modification factors:

- a key component in establishing presence of new form of matter
- direct photons: follow Glauber scaling; not suppressed in Au+Au

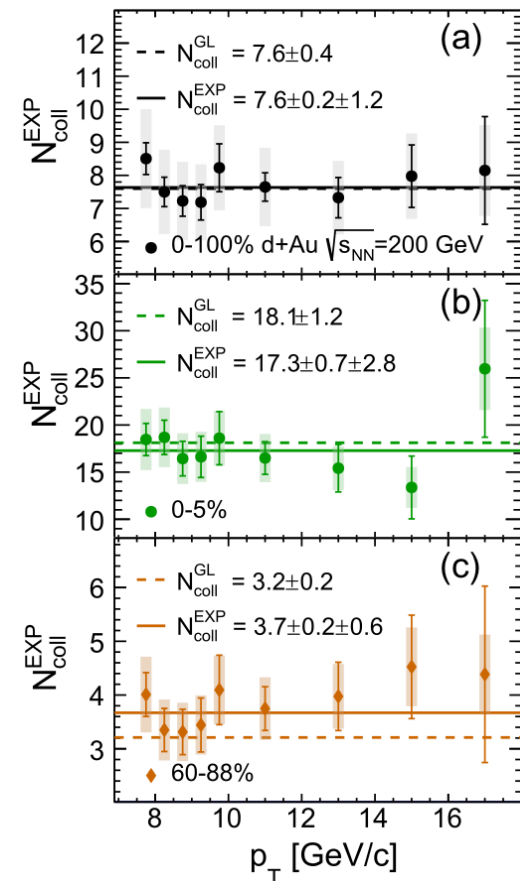
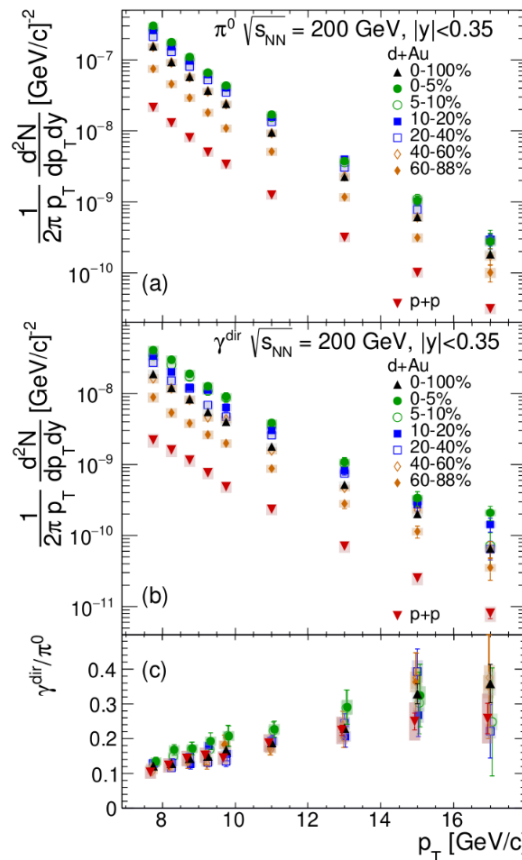


Observation \rightarrow paradigm!

Direct photons: „standard candles”
centrality vs. event activity
(forward yield)

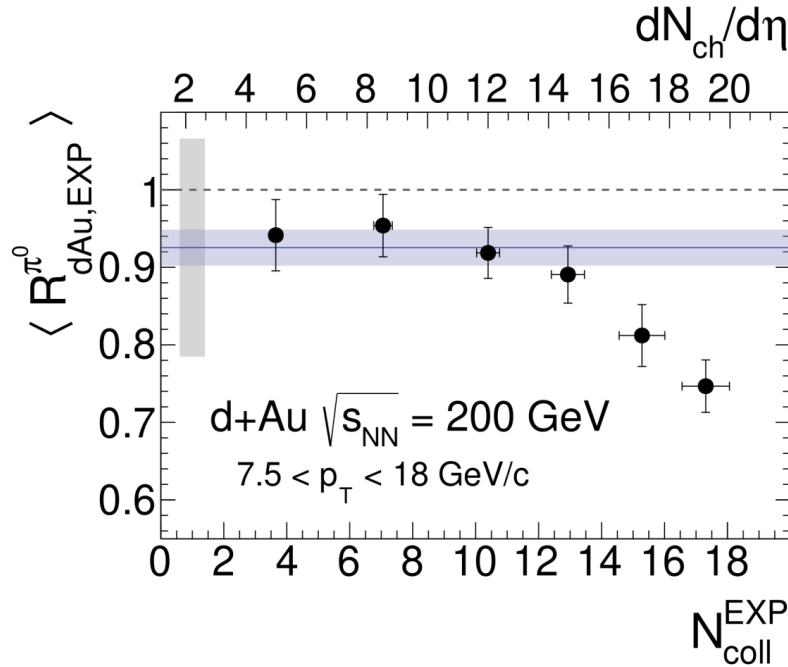
\rightarrow Bias in Glauber modeling for

„peripheral” events \rightarrow caused previously observed enhancement



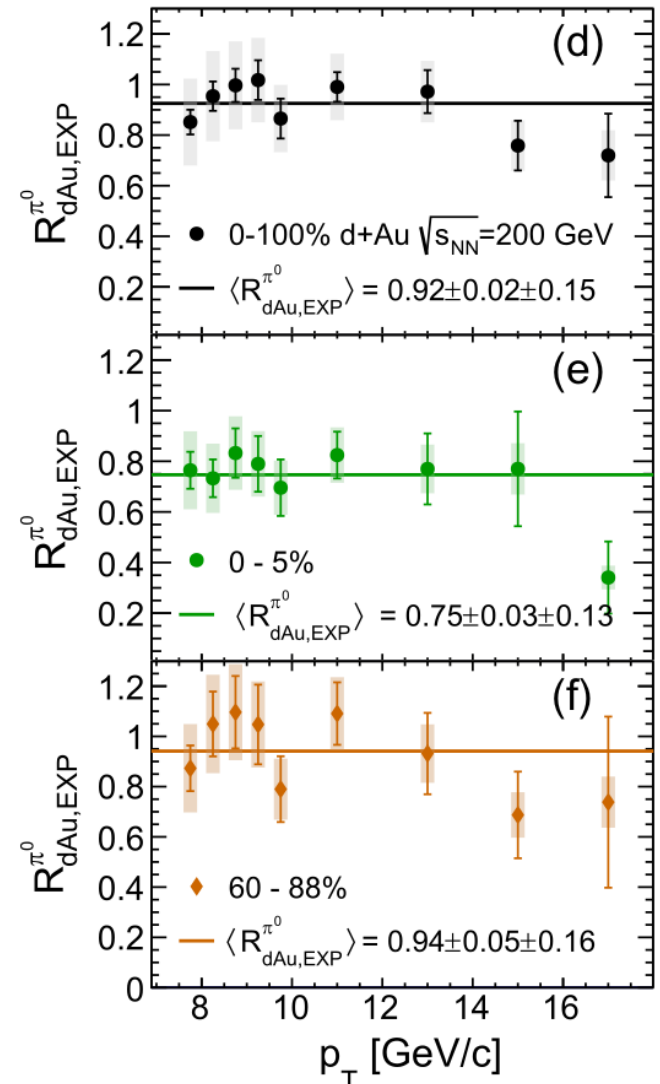
d+Au π^0 suppression vs. event characterization based on direct γ s:

- still suppression in most central
- consistent with no nuclear effects in peripheral



PRL 134, 022302 (2025)

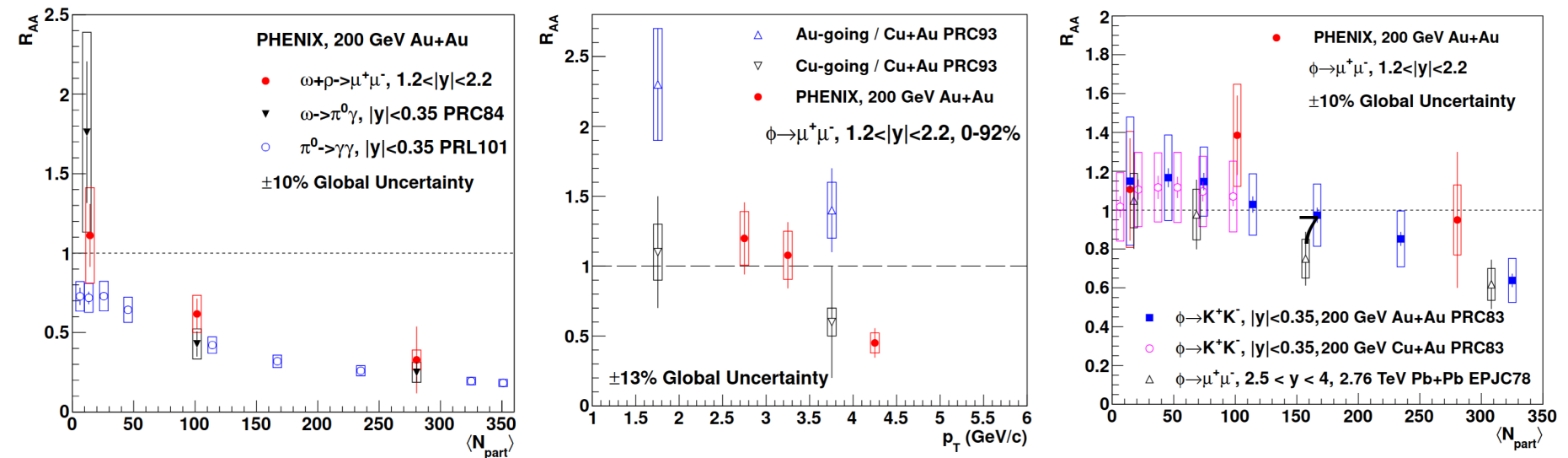
Further studies on system size, collision species...
($^3\text{He}+\text{Au}$, p+Au...)



Vector meson measurements

- $\omega + \rho$, ϕ meson measurement using $\mu^+\mu^-$ decay channel (at forward rapidity; per PHENIX capabilities...)
- $\omega + \rho$ suppression observed; consistent with midrapidity & π^0 ; π^0 suppression slightly higher
suppression of $\omega + \rho$ similar to ω : suppression of ρ also
- ϕ meson: hint at enhancement in mid-central collisions (different from ALICE measurements)

arXiv:2507.04463



p+p collisions @ RHIC - goals:

- Baseline for Au+Au collision measurements
- Parton Distribution Functions

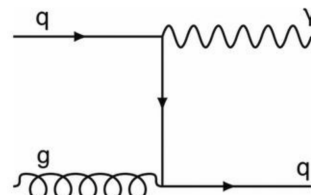
Spin dependent PDFs: "spin puzzle"

valence quark spin vs. hadron spin...

- collisions @ 200 GeV: π^0 , γ , ...
- collisions @ 500/510 GeV: ... + W, Z

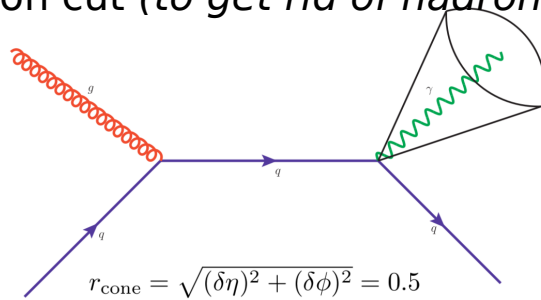
New result: direct photons @ 510 GeV

Quark-gluon Compton process:
main source of direct photons in
p+p above $p_T > 5$ GeV; sensitive
to polarized gluon distribution



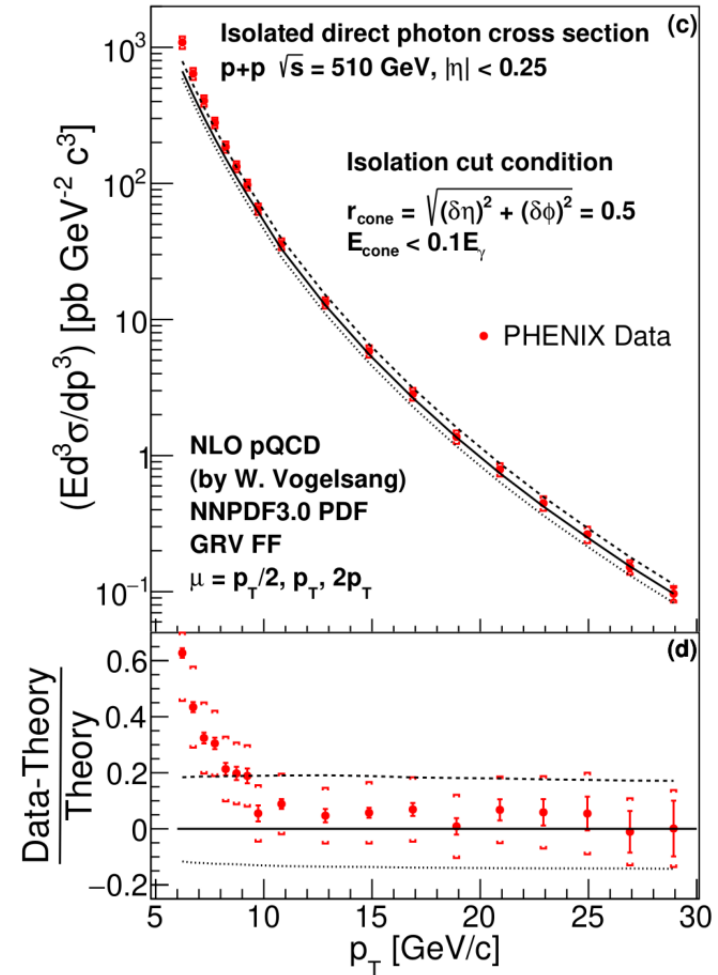
Experimentally:

isolation cut (to get rid of hadron (mainly π^0) decays)



Isolation cut requirement:

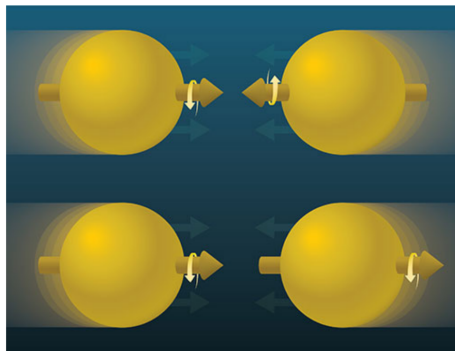
$$\sum E_{\text{neutral}} + \sum E_{\text{charged}} < 0.1 E_\gamma$$



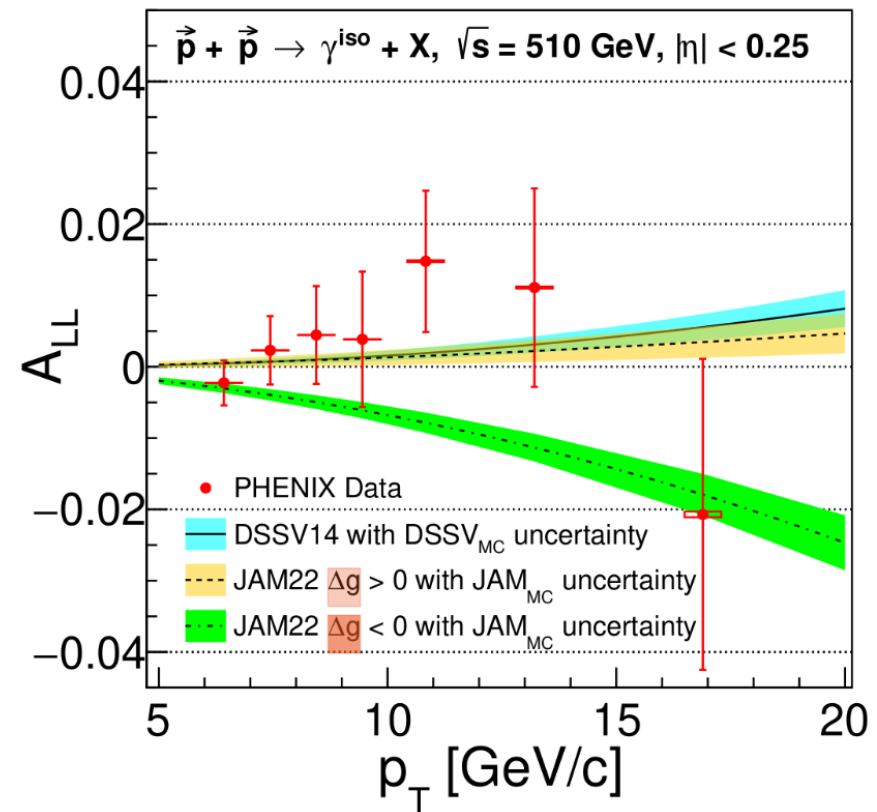
Spin dependent PDFs:

- Gluon spin contribution to proton spin (in perturbative regime):
direct photons: „golden channel”

PHENIX data are consistent with the **positive gluon-spin contributions** and strongly disfavor the negative gluon-spin scenario, that the previously published data were unable to resolve.



$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}}$$



Prompt (i.e. from initial hard scattering) **vs. non-prompt** (i.e. thermal) **photons**:

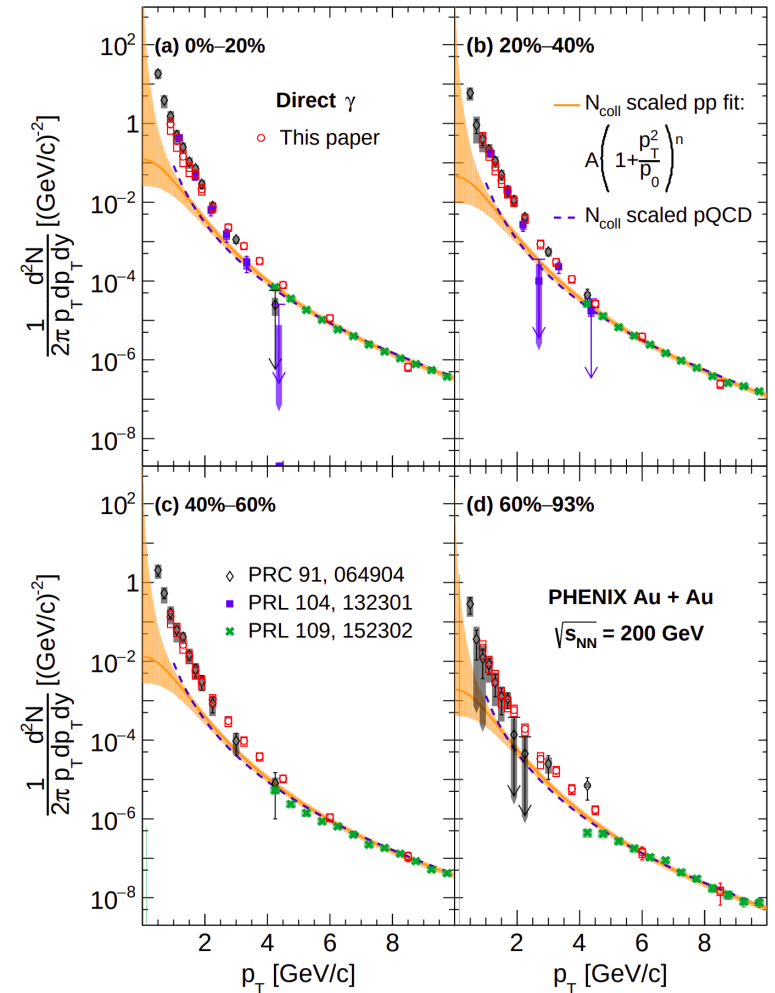
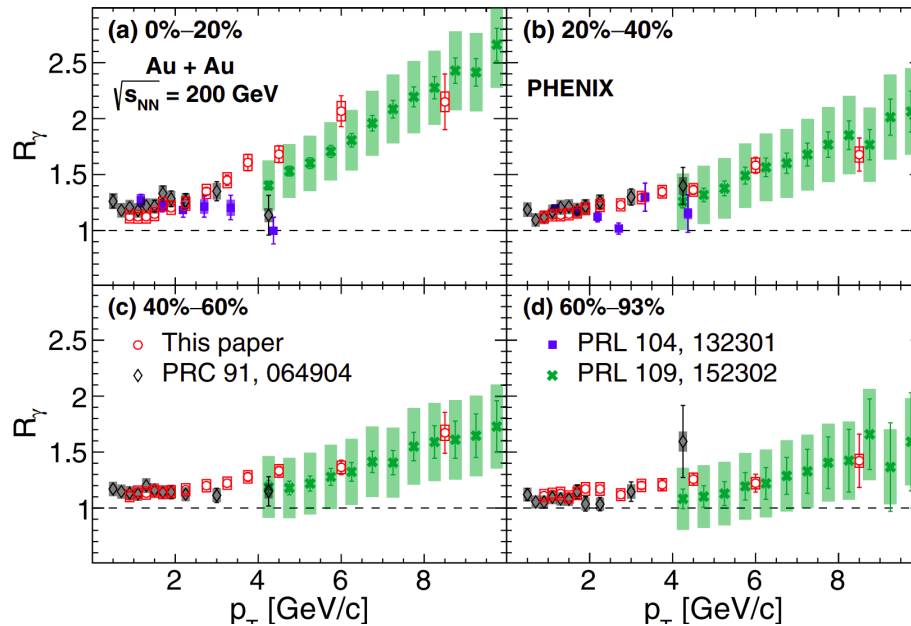
- Subtracted N_{coll} -scaled p+p yield (=prompt) from Au+Au direct photon yield

Internal PRL 104 132301

External HBD PRL 91 064904

Calorimeter PRL 109 152302

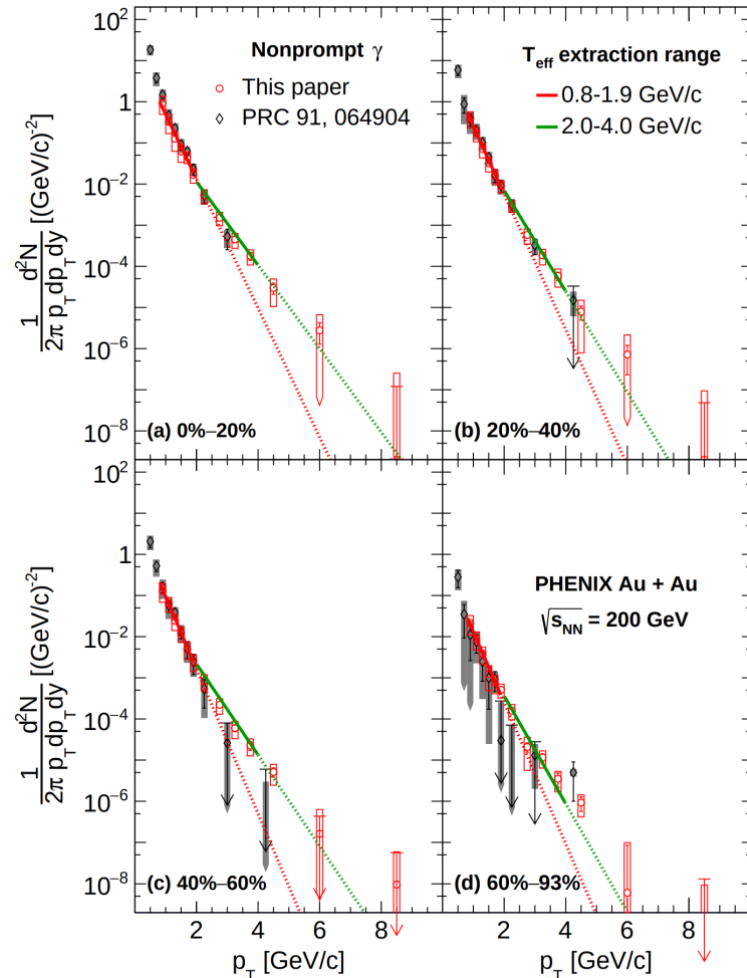
External VTX PRC 109, 044912



Nonprompt direct photon spectra determined for each 10% centrality bin

Fitted by exponential functions in the p_T ranges $\rightarrow T_{\text{eff}}$

no dedependence on centrality (8 bins!)



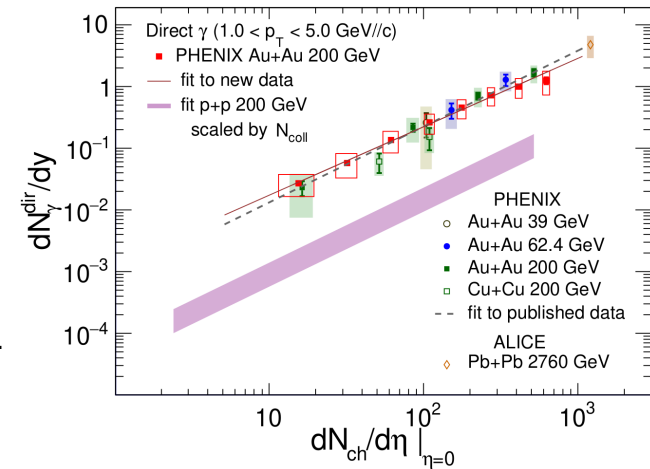
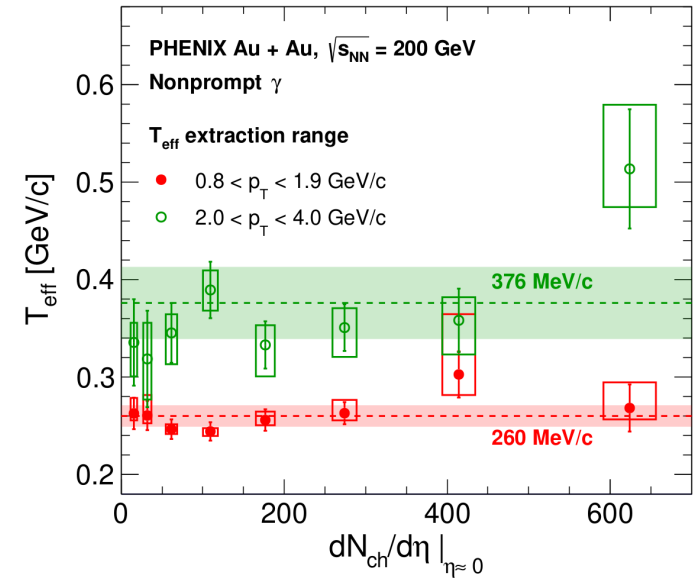
T_{eff} varies w/ p_T

Integrated yield

($1 < p_T < 5$ GeV/c):

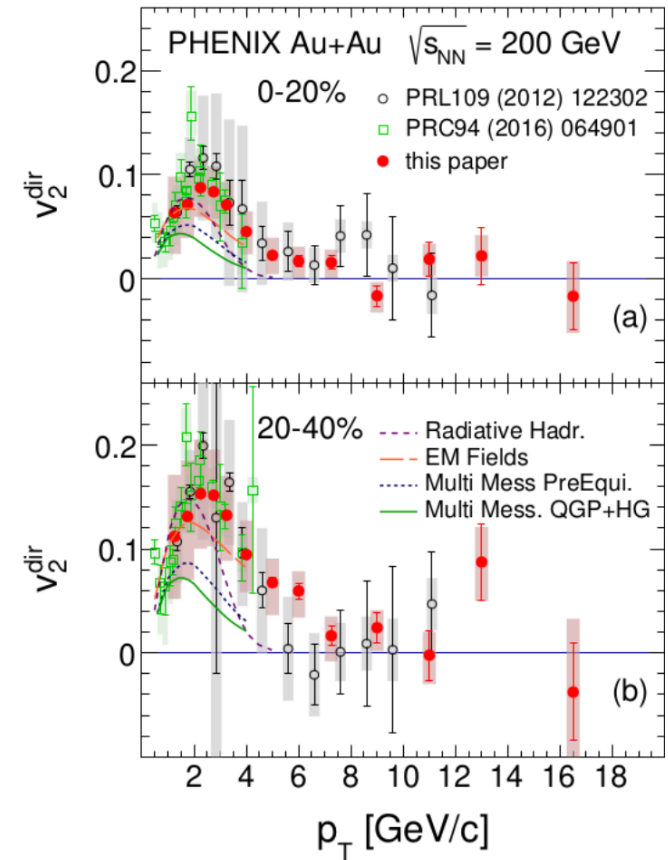
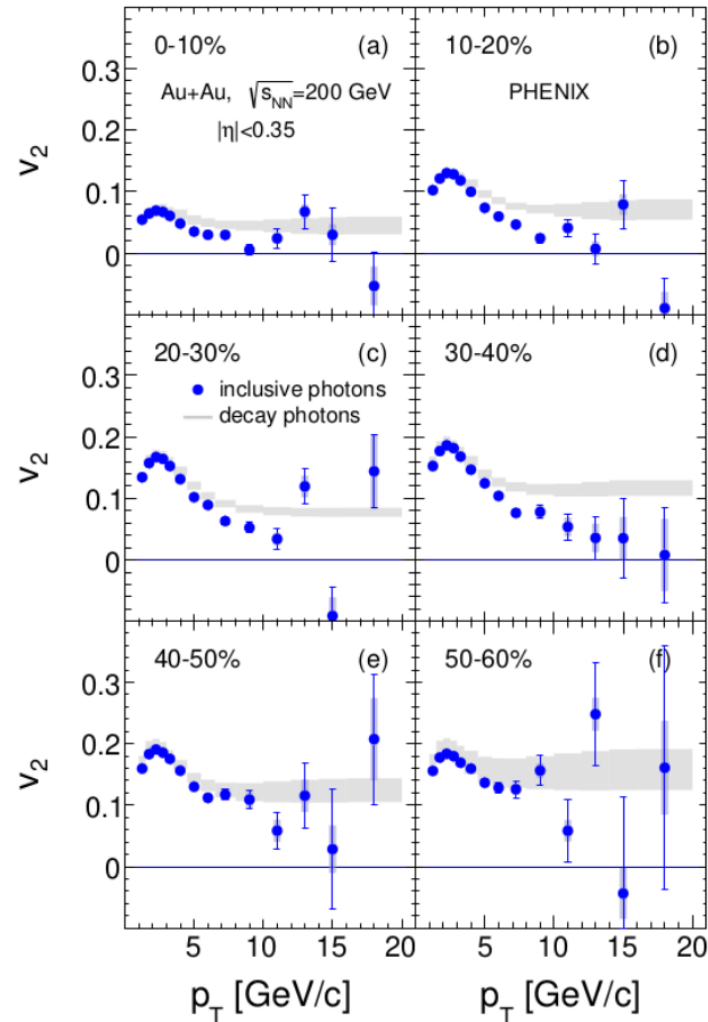
\rightarrow scaling with
multiplicity only!
(different sys-
tem sizes!)

\rightarrow Exponent: $\alpha = 1.11$
surprisingly small



Direct photon puzzle: observed large yields: require early production; observed v_2 (comparable to hadrons) requires late formation

New measurement: 2504.02955



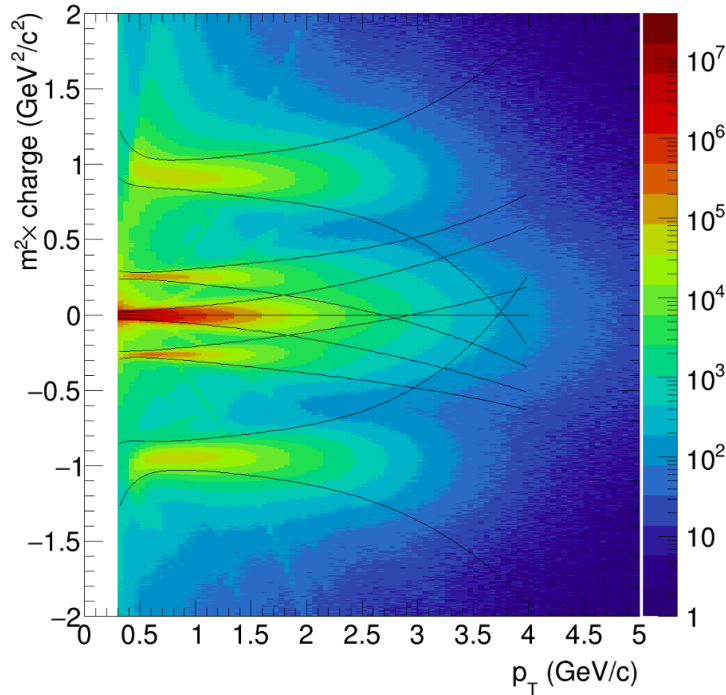
Many possible scenarios:

- radiative hadronization
- effects of EM field
- pre-equilibrium v_2

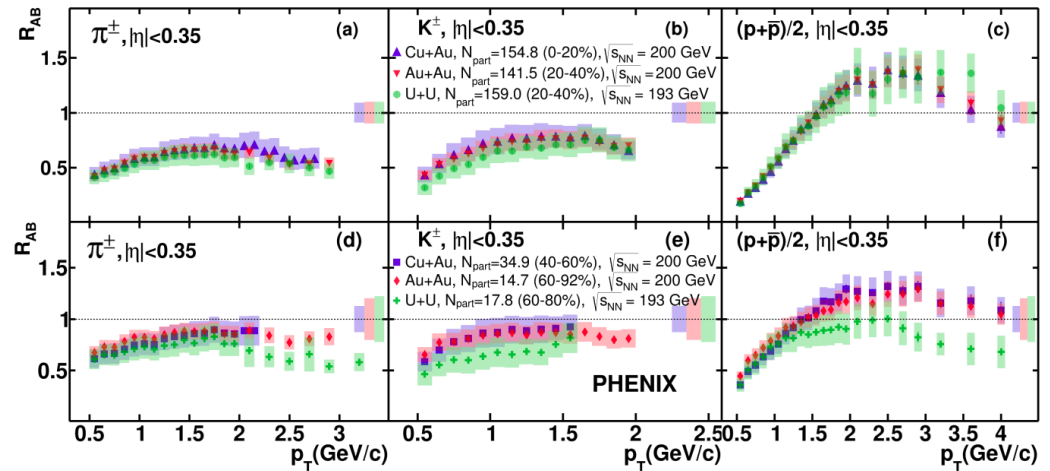
Measured particle yields (π , K, p), ratios (K/π , p/π), nuclear modification factors (R_{AB})

→ freeze-out temperature T_0 & transverse flow $\langle u_t \rangle$ vs. N_{part}

p+Al, ^3He +Au, Cu+Au, (200 GeV), U+U (193 GeV)

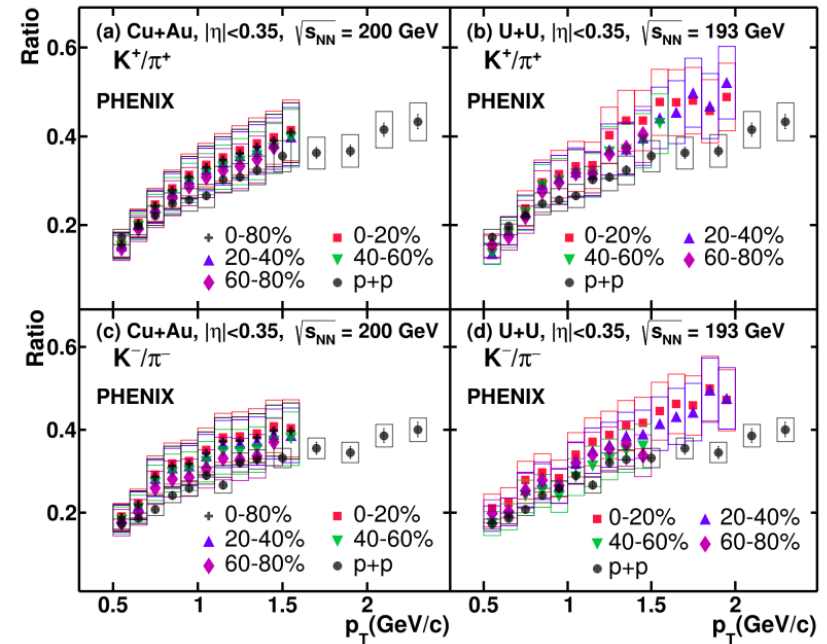
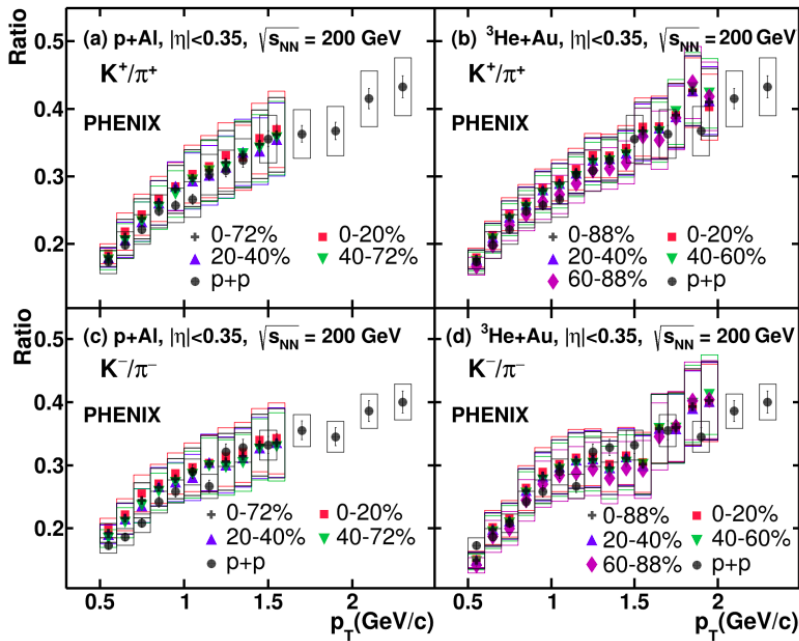


Identified charged hadron production does not depend on the geometry and collision species, but rather on the N_{part} values

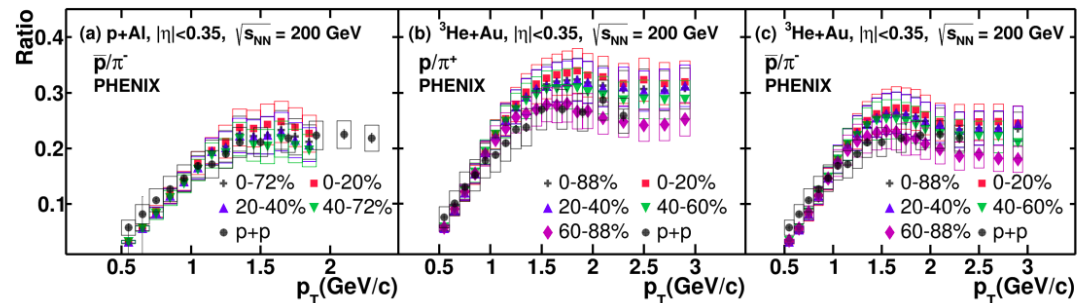


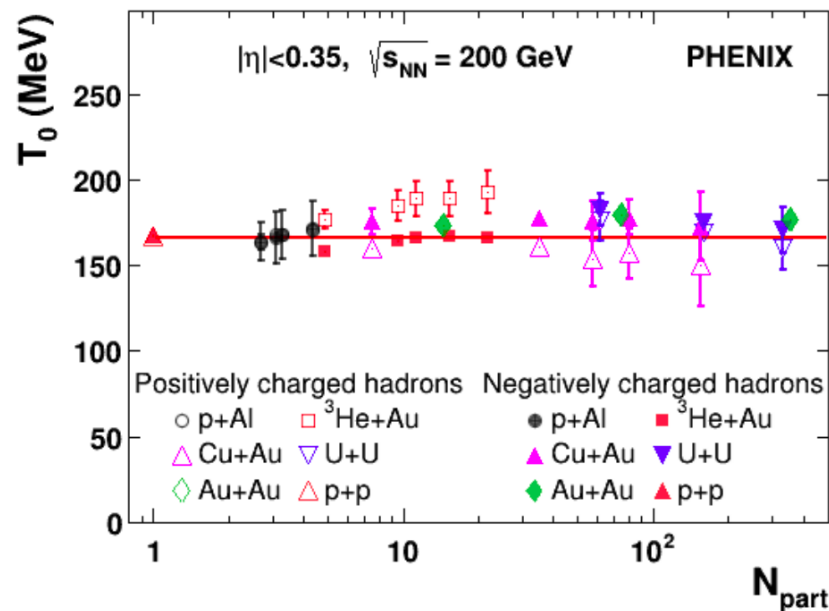
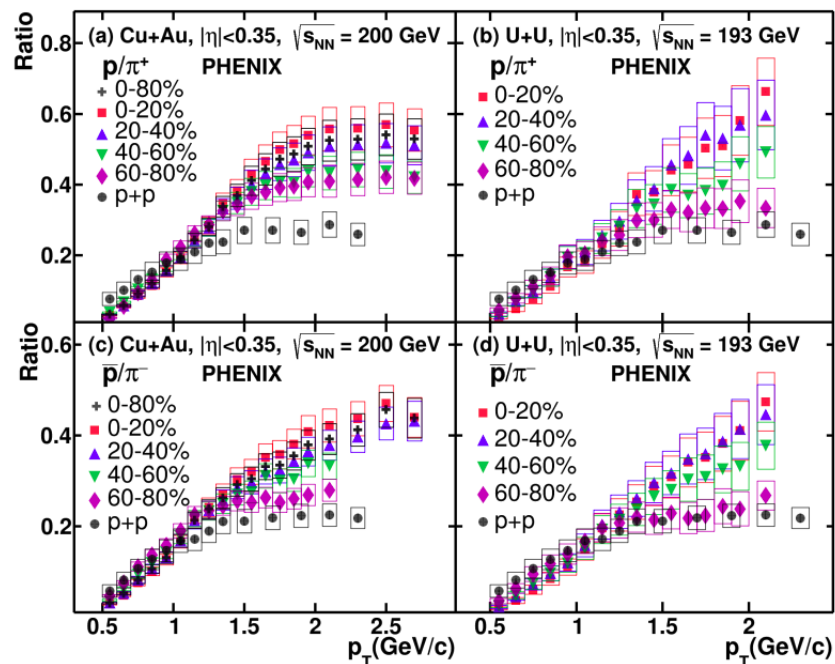
PRC 109 (2024) 5, 054910

K/π : in small systems, consistent with p+p; in large systems: strangeness enhancement



p/π : small to large systems: \rightarrow 2 times p+p values (baryon-to-meson enhancement)
strong centrality dependence



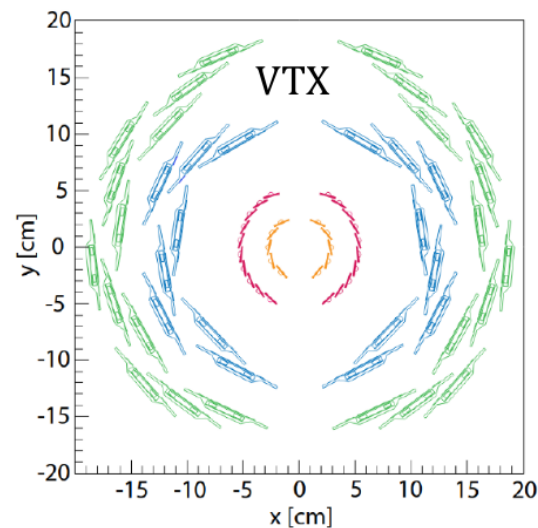
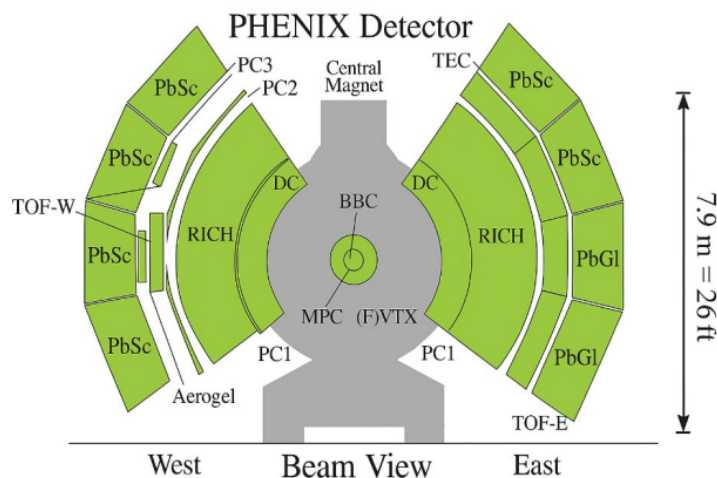
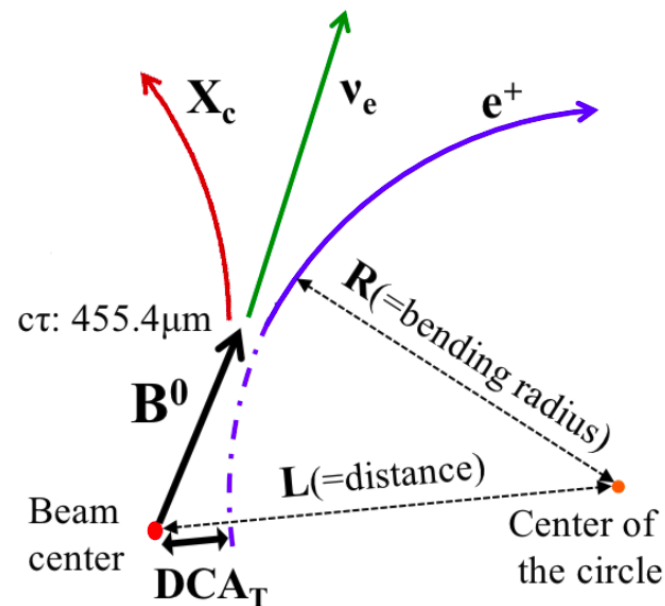
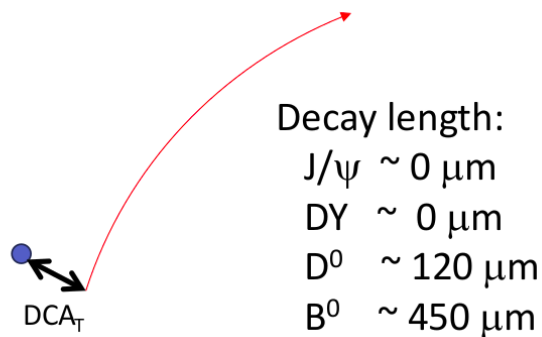


T_0 approx. independent of N_{part}
(in different geometries!);
 $\langle u_t \rangle$ scales linearly

Since 2011/2012: precision vertexing (VTX/FVTX)

Largest Au+Au & p+p datasets: 2014/2016 & 2015

Main goal: charm & bottom separation (via e^+/e^-),
based on DCA requirement



→ PRC 109, 044907 (2024)

Significant suppression at high p_T for both charm & bottom for all centralities

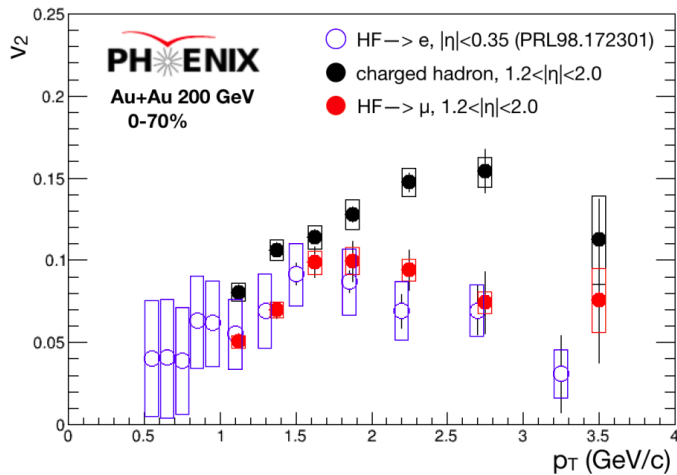
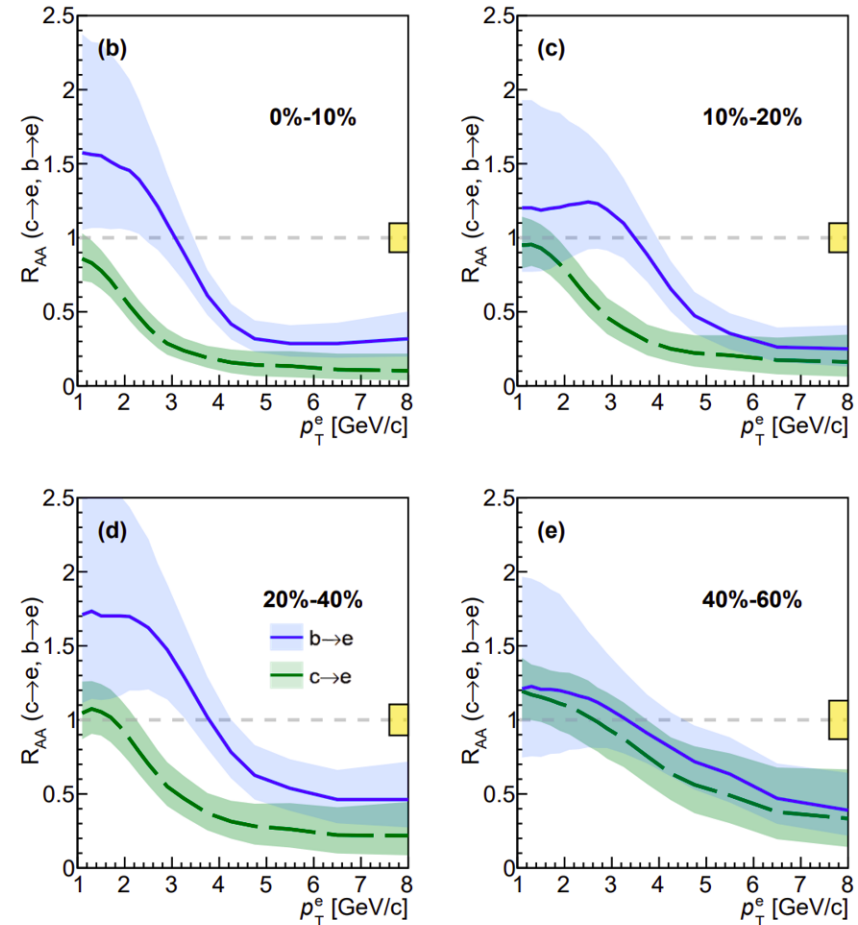
Charm electrons show a stronger suppression than bottom electrons for $2 < p_T < 5$ GeV/c from 0 to 40%.

In 40-60%, bottom and charm are similar

→ arXiv:2409.12715:

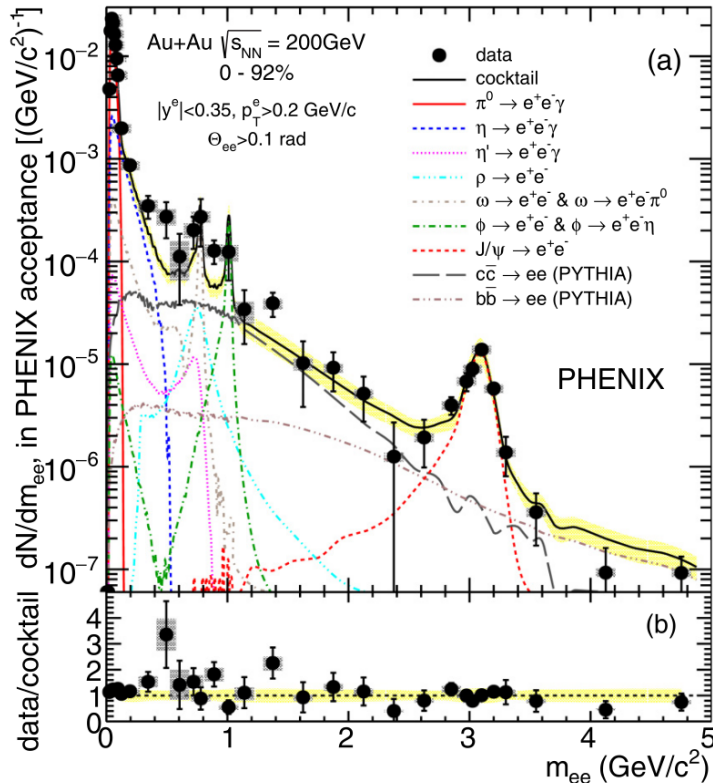
Significant heavy flavor v_2 at forward rapidity

However, smaller than light hadrons: less medium interaction of c/b



Dilepton measurements:

- Sensitive to initial state (penetrating probes)
- Previous measurements (using the Hadron Blind Detector):
some enhancement at low m_{inv} ; were unable to resolve thermal vs. hadronic

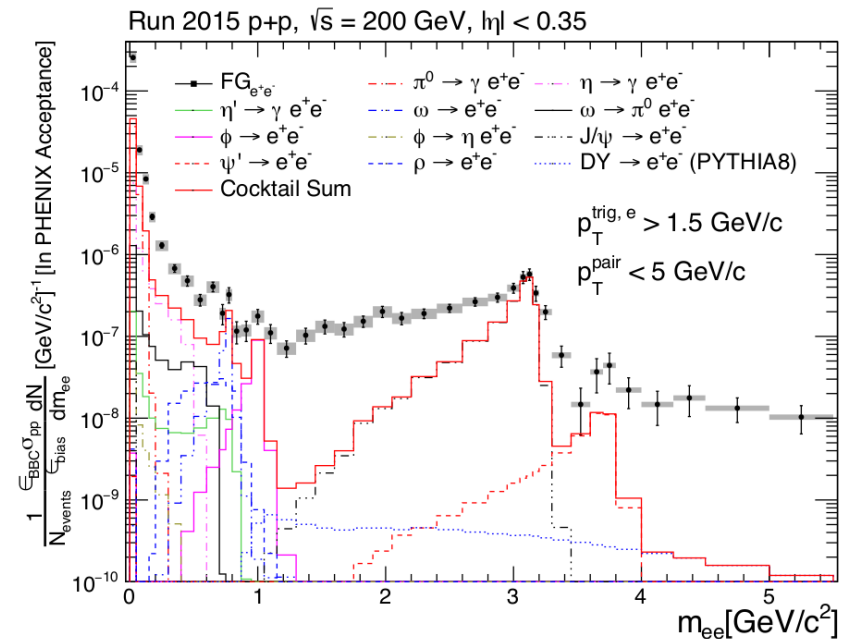


PRC 93, 014904 (2016)

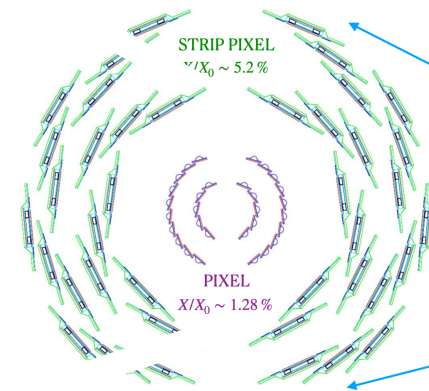
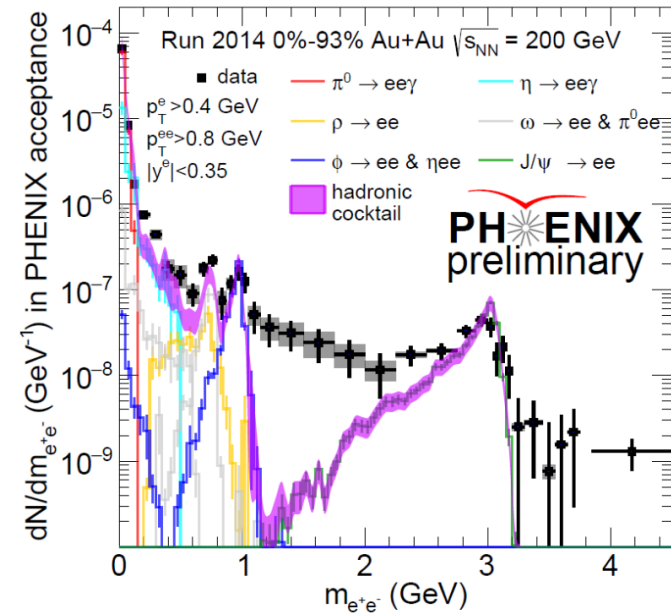
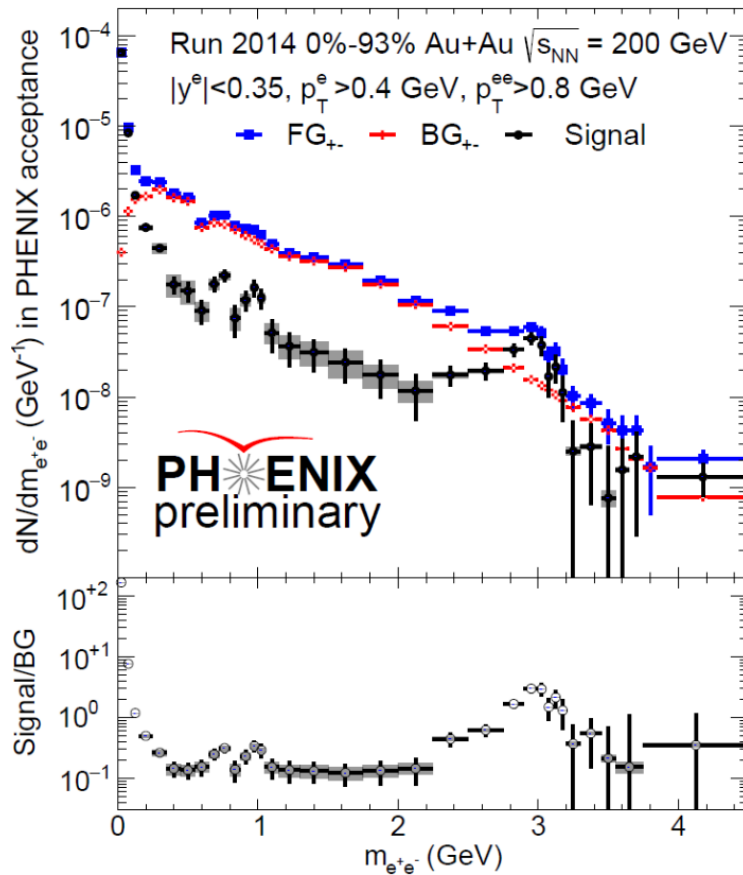
New methodology:

- Use VTX detector to disentangle thermal vs. heavy flavor decay dielectrons

Proof of principle: p+p collisions

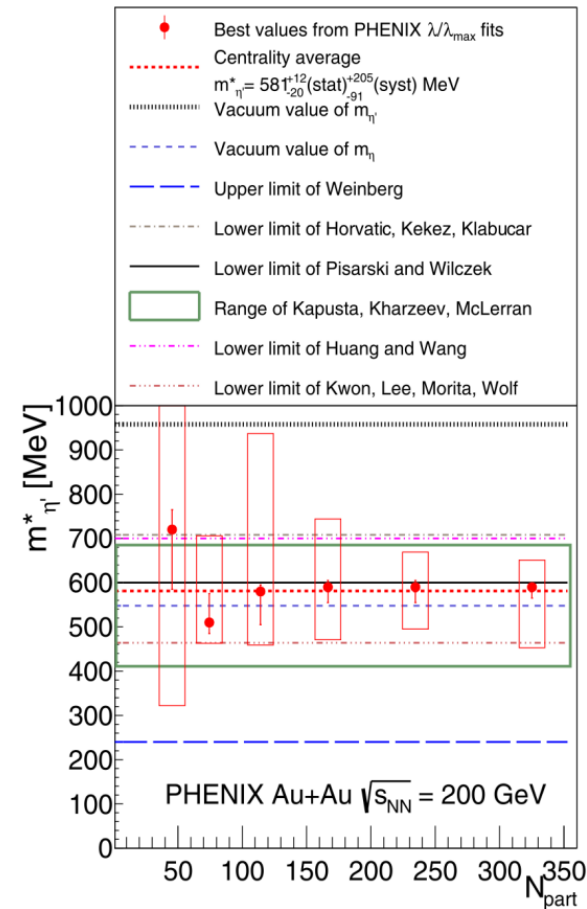
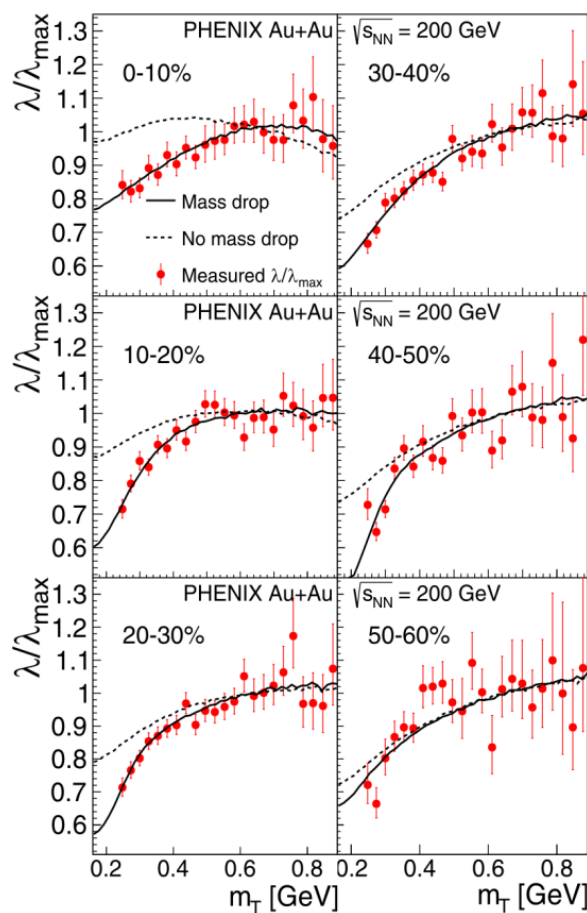
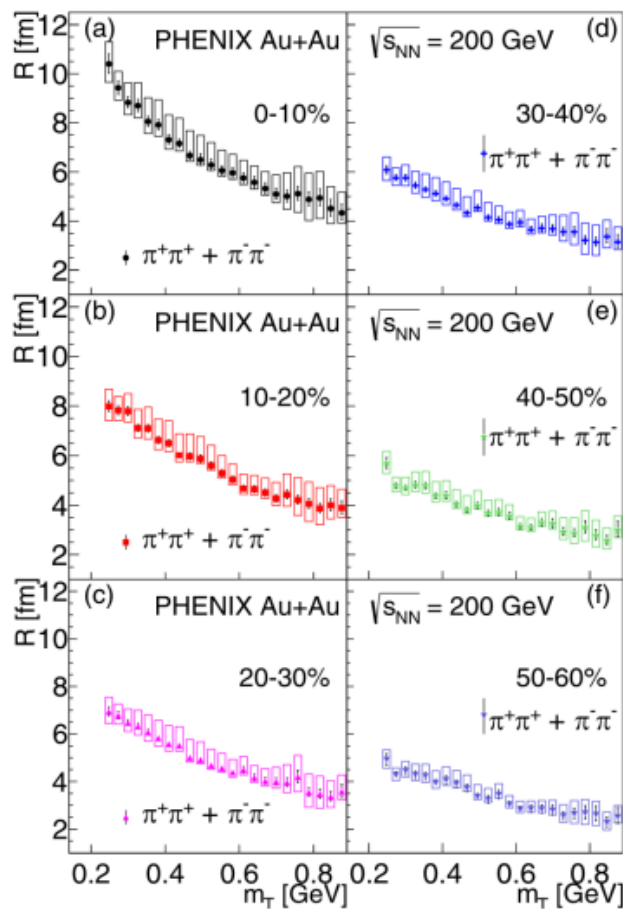


Clear separation of c+b decay electrons & thermal radiation



Lévy HBT measurements for pions:

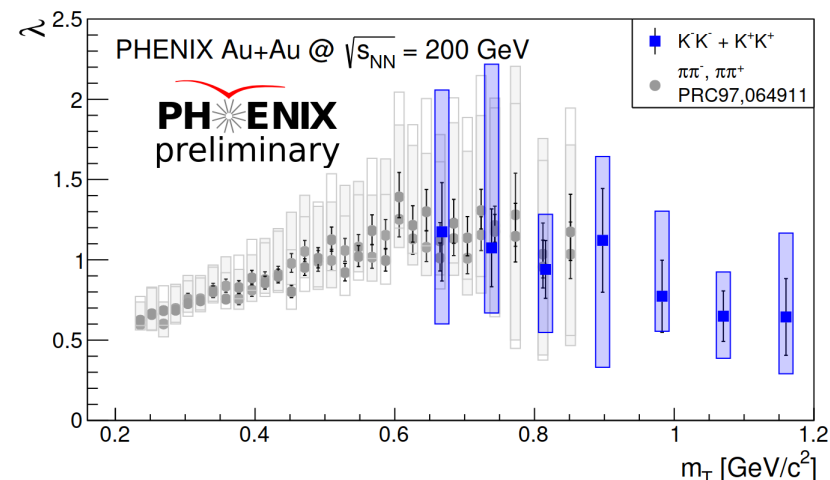
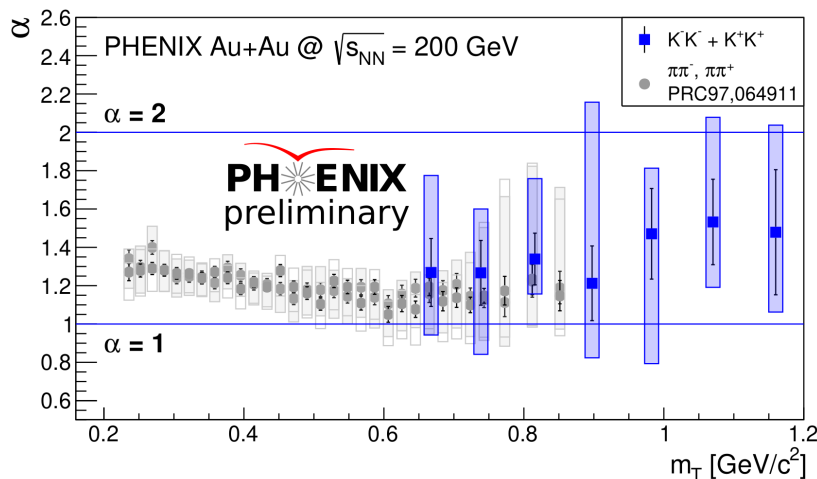
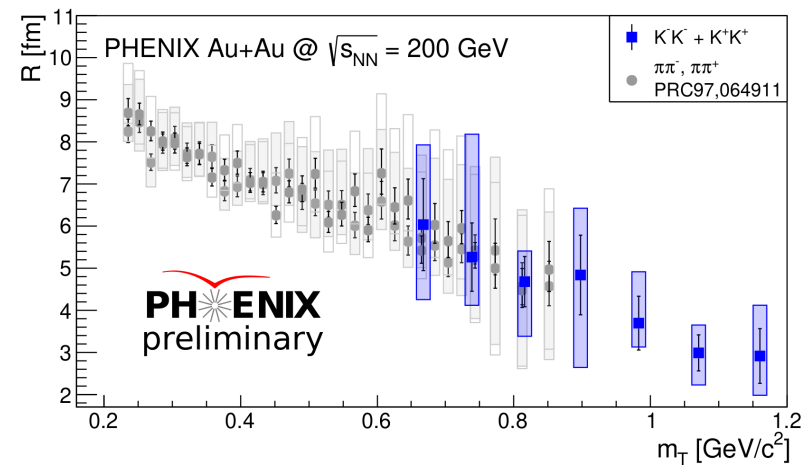
- Centrality dependent Lévy parameters (PRC 2024, 110 (2024) 6; Editor's Choice!)
- Consistent with & hinting at η' mass reduction (according to core-halo model)
→ presence of hadronic matter with chiral $U_A(1)$ symmetry restoration



Lévy HBT measurements for kaons:

- Kaons: different scattering cross sections; would be interesting to see a dependence on particle species...

→ Pinning down origin of Lévy distributed source functions



PHENIX

- Just as the mythological bird, was reborn from the ashes
- Took data for 16 years; fair share in QGP discovery
- Many analyses still in the pipeline...

Data & Analysis Preservation

- HEPData: data tables for (almost) all published papers
- Zenodo: >700 documents (including theses since 2016)
- Analysis Notes: began publishing ANs in support of publications; just finished first physics paper (PRL 86 (2001) 3500)
- REANA: toolkit to archive analysis methodology
Example: π^0 & direct γ analysis chain implemented (even: „tested”...)

Standing strong - 9 years later!

RHIC data: unique, PHENIX: unique in itself...

Thanks for your attention!

