Stony Brook University

PHENIX

Photon measurements in proton and nucleus collisions at PHENIX

Norbert Novitzky for PHENIX collaboration

Stony Brook University

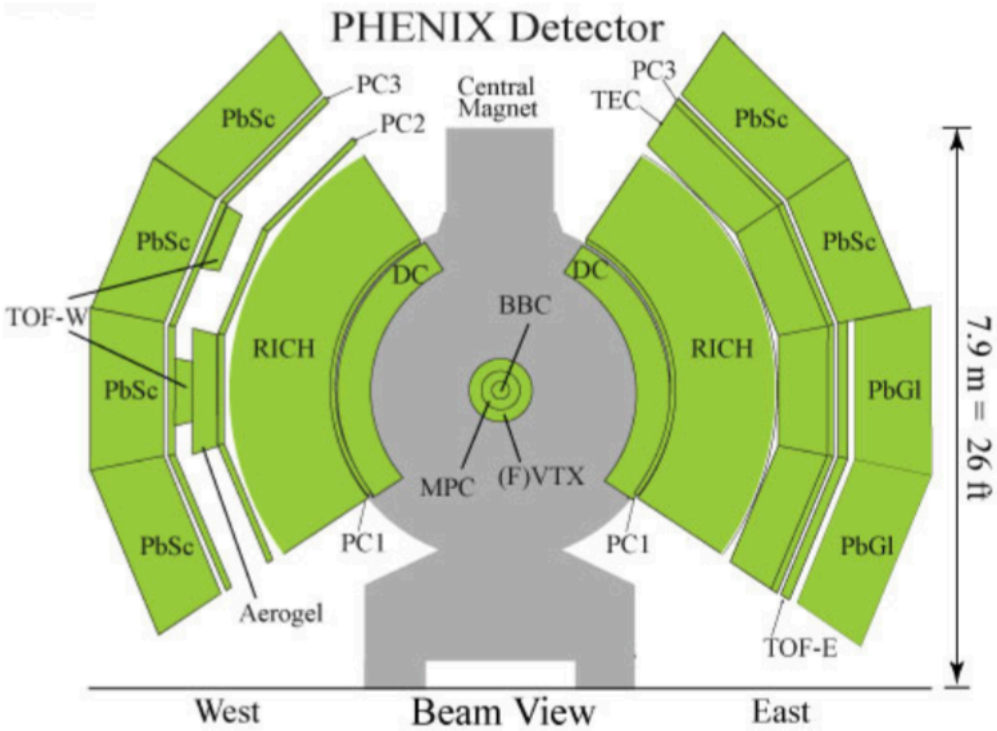
PHENIX detector

Central Arm, $|\eta| < 0.35$:

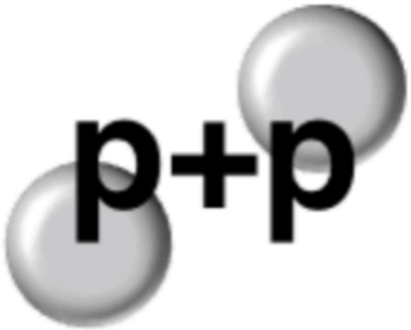
- **Tracking:**
  - Drift Chambers (DC)
    $\delta p/p = 0.7\ \% + 1.1\% p$
  - Pad Chambers (PC)
    $\sigma = \pm 1.7$ mm

- **Electromagnetic Calorimeter:**
  - 2 PbGl: 0.8 % + 5.9 %/√E
  - 6 PbSc: 2.1 % + 8.1 %/√E

- **Particle Identification:**
  - RICH – $e^{\pm}$
  - TOF East and TOF West:
    - $\sigma_T \cong 100$ps
    - π/K $p_T < 2.5$ GeV/c
    - K/p $p_T < 4.0$ GeV/c
  - EMCal timing:
    - $\sigma_T \cong 600$ps



Acceptance: $-0.35 < \eta < 0.35$, $\Delta\varphi$ – 2 x 90°

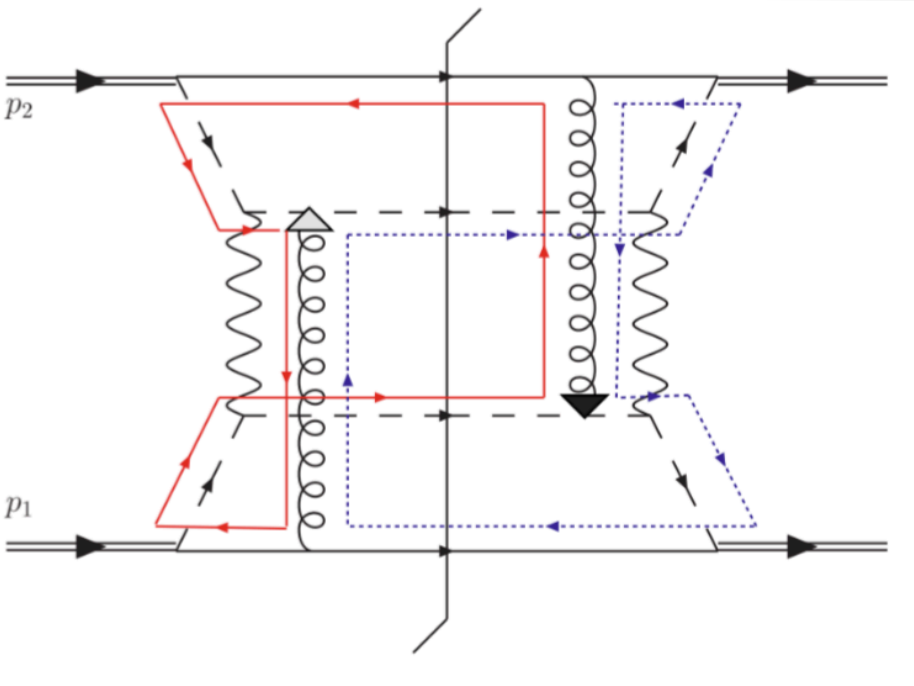


$$\sqrt{s} = 510 \text{ GeV}$$

Non-Abelian Gauge Theory

- Factorization breaking predicted in a transverse-momentum-dependent (TMD) framework in dihadron production (Phys. Rev. D 81,094006 (2010))

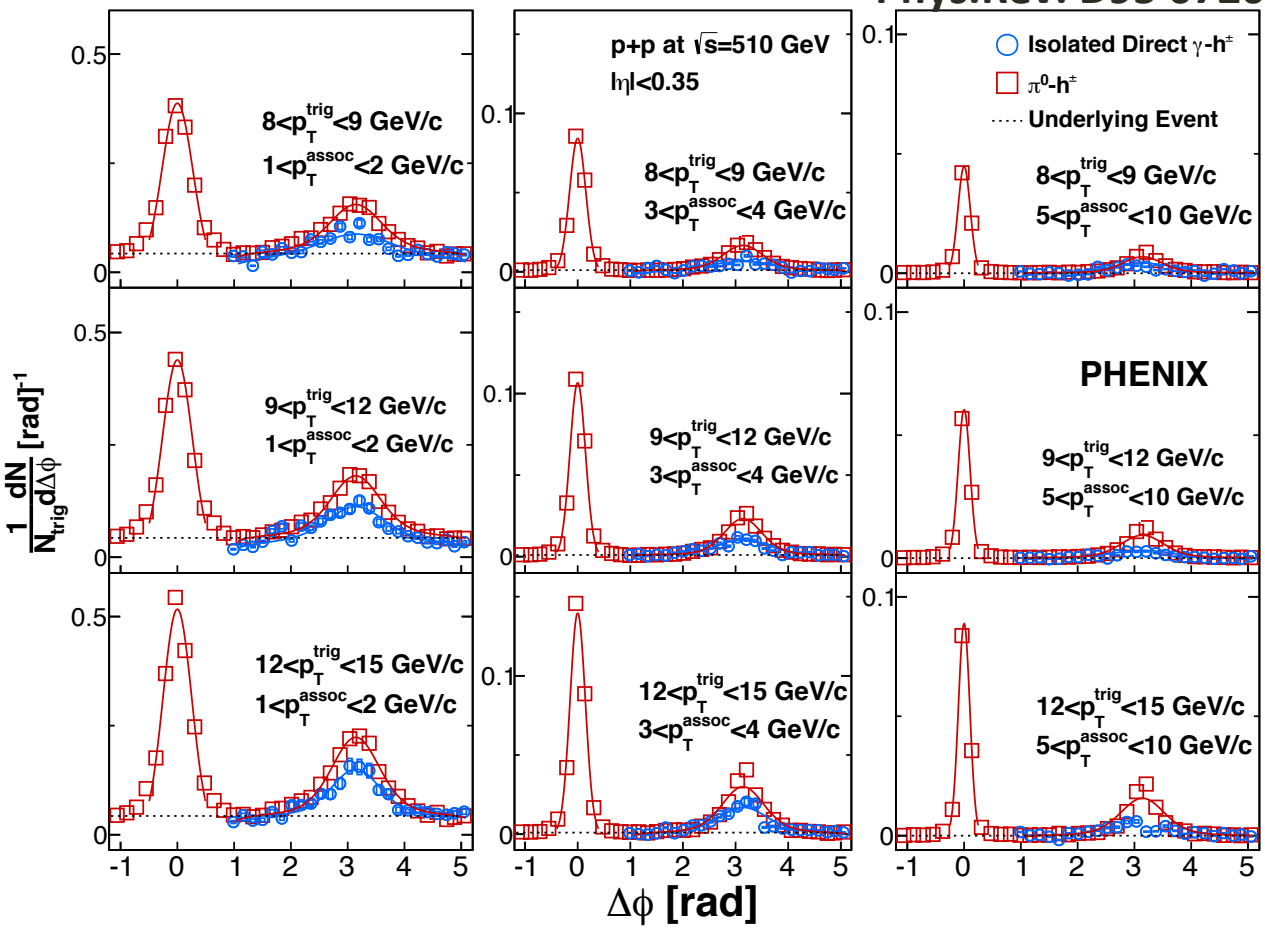
- Back-to-back two particle angular correlations give sensitivity to initial- and final-state transverse momentum $\mathbf{k_T}$ and $\mathbf{j_T}$



- >=2 gluon exchanged with the proton remnants predicts the breakdown

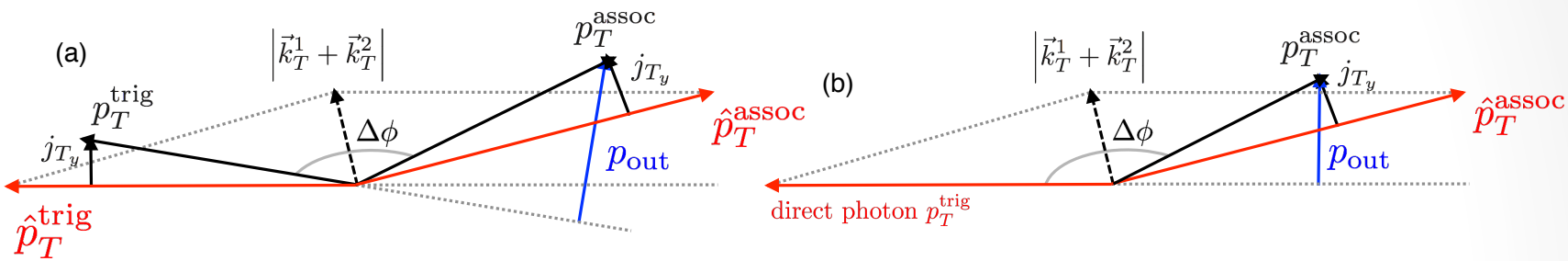
Correlation function

Phys.Rev. D95 072002 (2017)



π^0-h$^\pm$ and direct γ-h$^\pm$ correlation function in order to probe the factorization breaking

Correlation Function



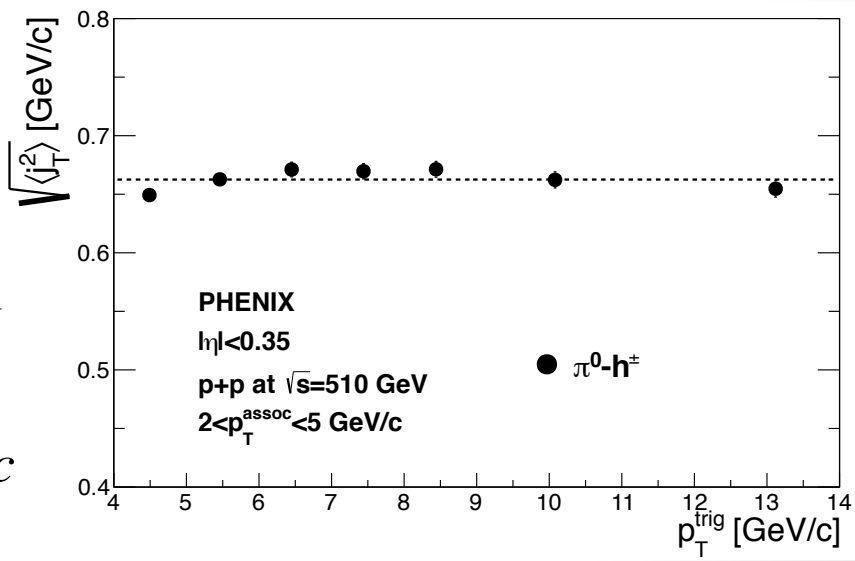
Out-of-plane momentum component:

$$p_{out} = p_T^{assoc} \cdot \sin(\Delta\phi)$$

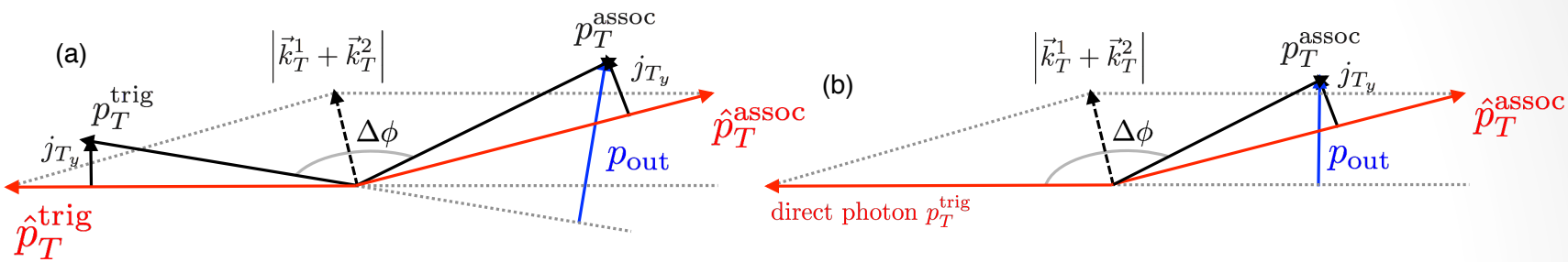
Extracting the $\mathbf{j_T}$ from near side:

$$\sqrt{\langle j_T^2 \rangle} = \sqrt{2\langle j_{T_y}^2 \rangle} \cong \sqrt{2}\,\frac{p_T^{trig}\, p_T^{assoc}}{\sqrt{p_T^{trig^2} + p_T^{assoc^2}}}\,\sigma_N$$

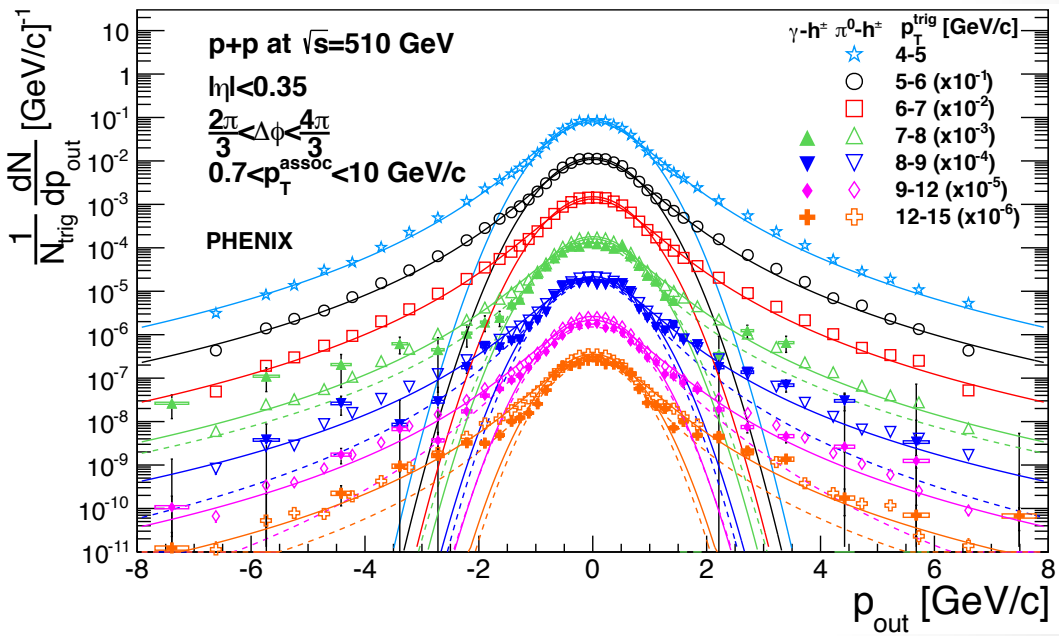
$$\sqrt{\langle j_T^2 \rangle} = 0.662 \pm 0.003 \pm 0.012\ GeV/c$$



Correlation Function



- Measure p_{out} non-perturbative momentum widths as a function of p^{trig}_T
- Perturbative TMD evolution, which comes directly from the generalized TMD QCD factorization theorem, predicts increasing non-perturbative momentum **widths** with hard scale of interaction



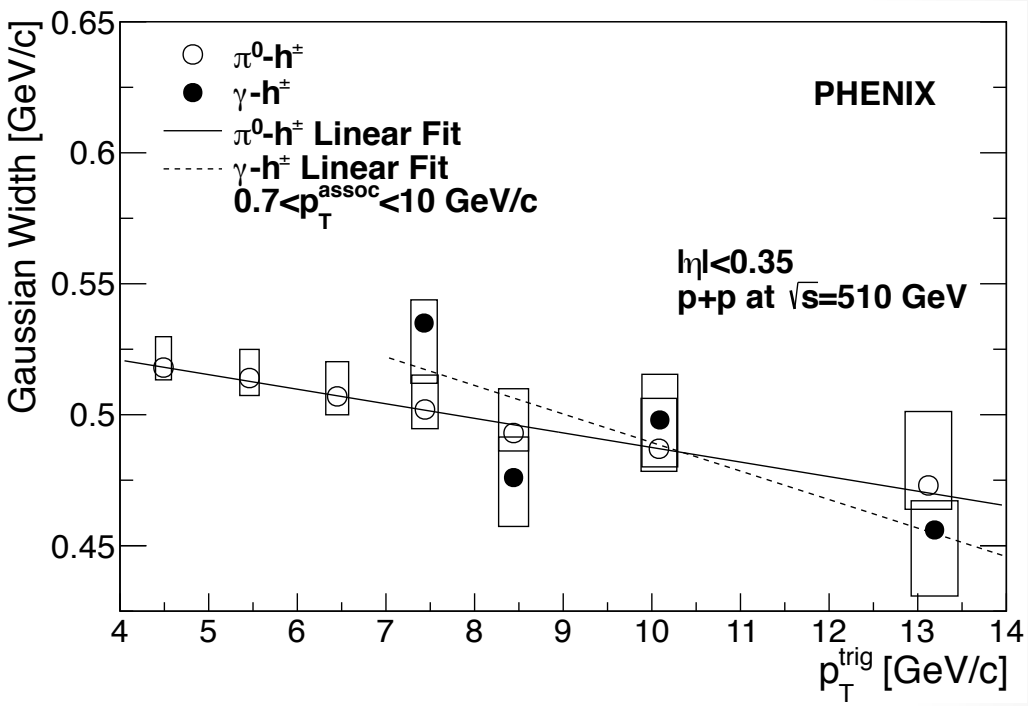
Gaussian and Kaplan fits on the data

Gaussian widths of p_{out}

The Gaussian widths of the p_{out} distribution are decreasing with p_T - Opposite of the prediction from TMD factorization

Sensitive to only nonperturbative k_T and j_T in the nearly back to back region

Phys.Rev. D95 072002 (2017)

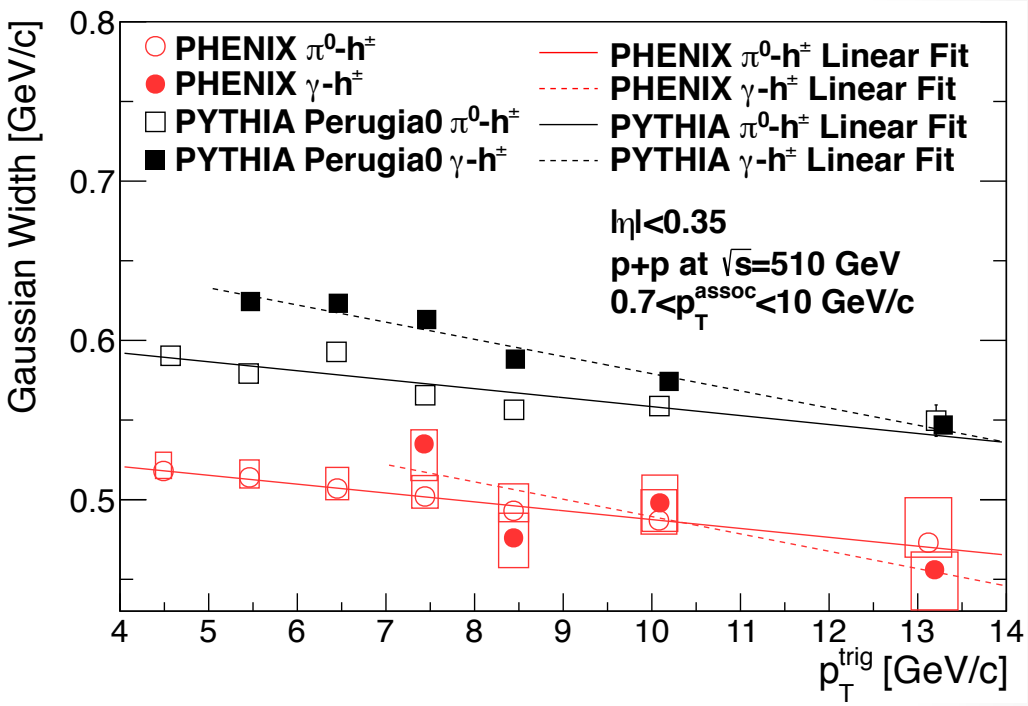


Comparison with PYTHIA

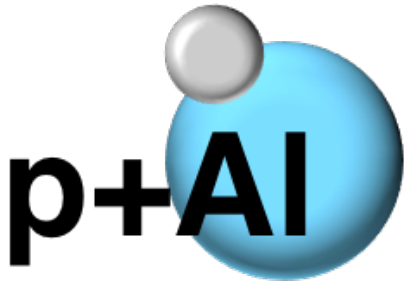
The Gaussian widths of the p_{out} distribution are decreasing with p_T - Opposite of the prediction from TMD factorization

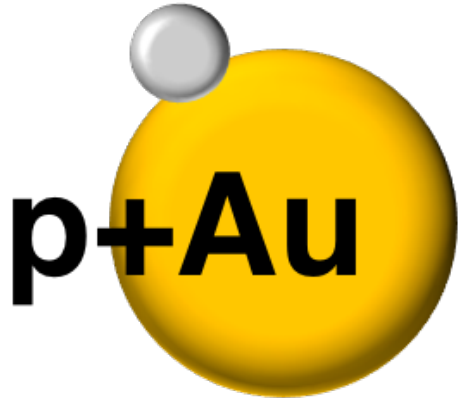
Sensitive to only nonperturbative k_T and j_T in the nearly back to back region

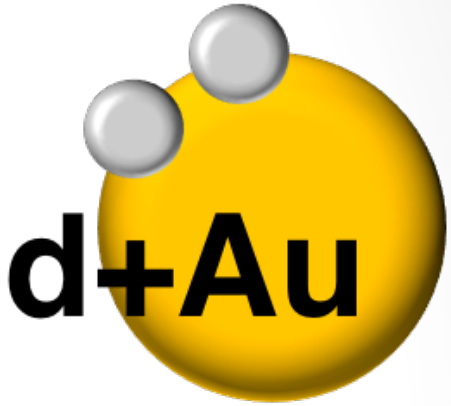
Phys.Rev. D95 072002 (2017)

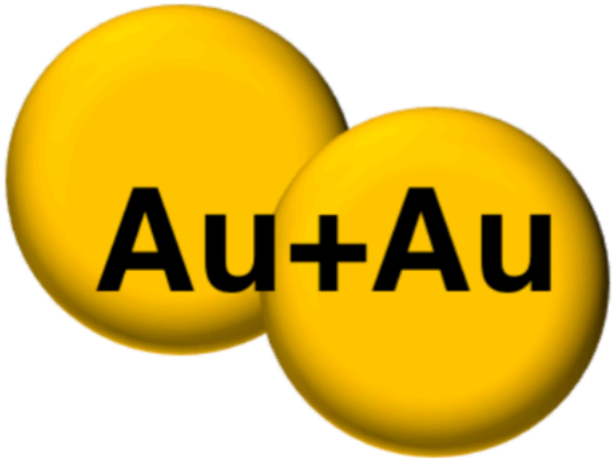


PYTHIA reproduces the decreasing trend, but the magnitude is off by 10-15%









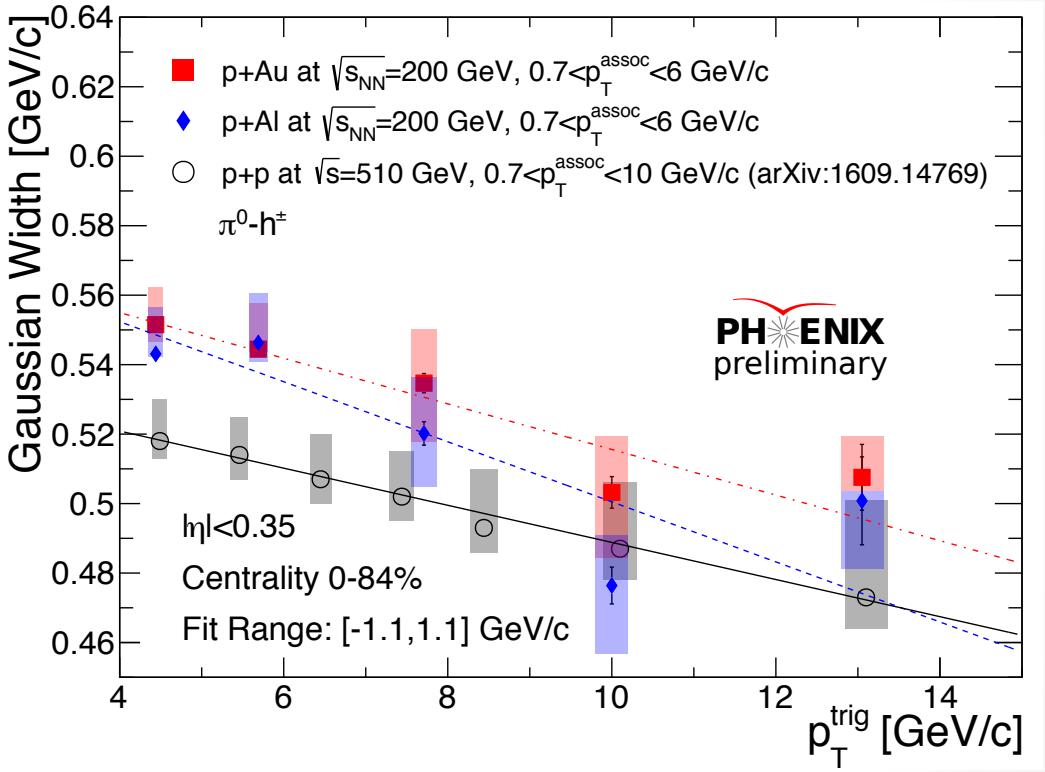
$$\sqrt{s_{NN}} = 200 \text{ GeV}$$

Gaussian widths of p_{out} in p+Au

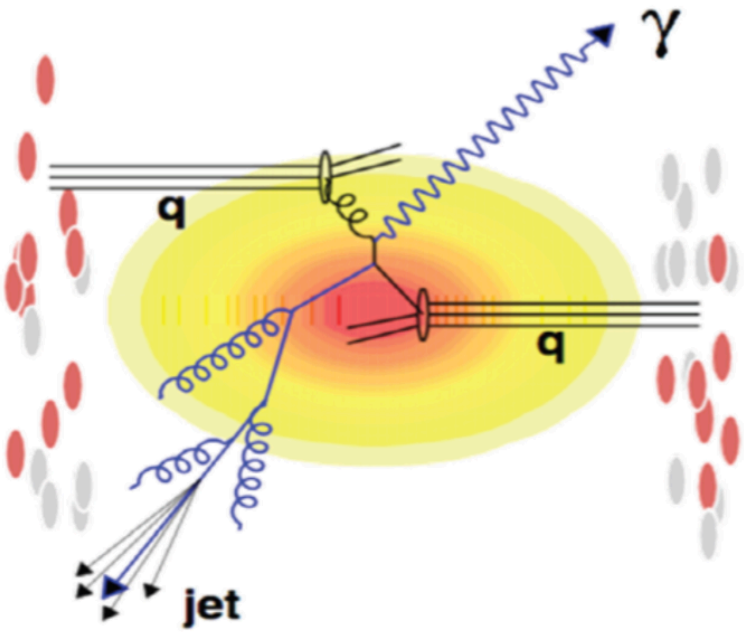
We can search for similar factorization breaking effects in p+A

Additional nuclear effects may increase the measured width of the p_{out}

Hint to have a larger p_T dependency in p+A collisions



Frag. Study in nucleus collisions



The direct photon energy is a good measurement of the outgoing parton energy:

$$z_T = p_T^h / p_T^{jet}$$

We can define a quantity:

$$\xi = \ln(1/z_T) = \ln(p_T^\gamma / p_T^h)$$

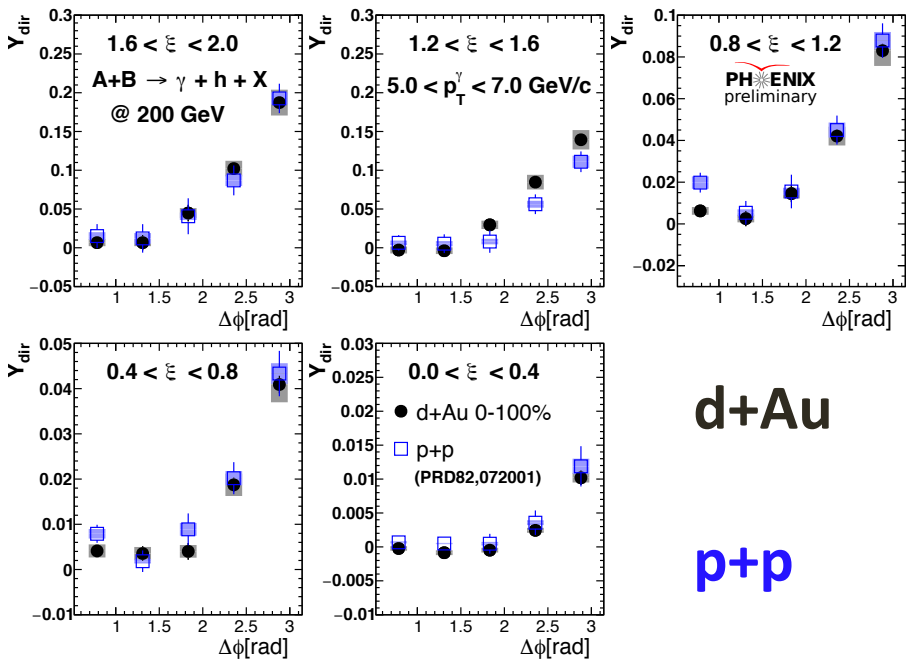
The fragmentation function can be written in form:

$$D_q(\xi) = 1 / N_{evt} dN(\xi) / d\xi$$

The modification of the fragmentation function is quantified as

$$D_{AA} / D_{pp} \approx Y_{AA} / Y_{pp} = I_{AA}$$

Frag. Study in nucleus collisions



d+Au

p+p

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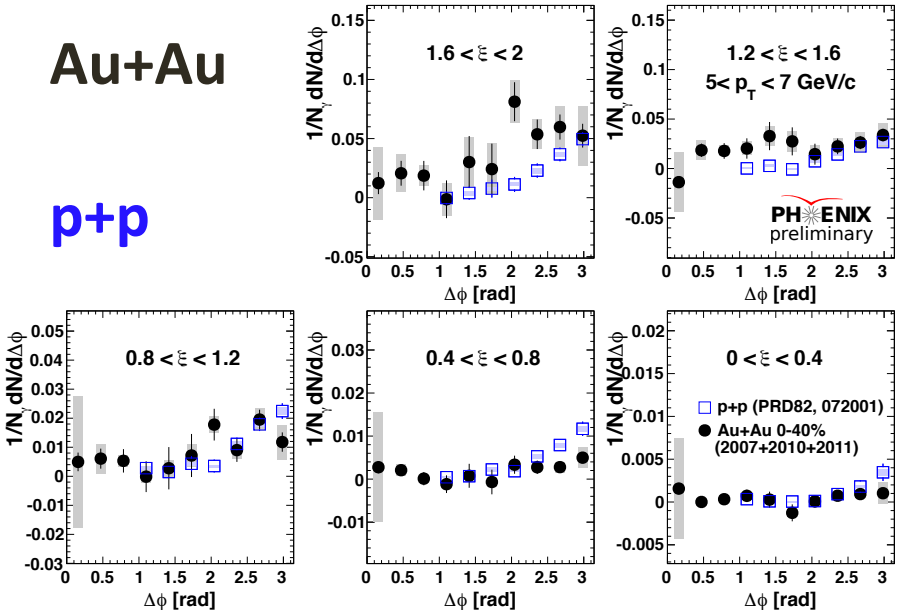
Frag. Study in nucleus collisions

Au+Au

p+p



The direct photon energy is a good measurement of the outgoing parton energy:

$$z_T = p_T^h / p_T^{jet}$$

We can define a quantity ($p_T^\gamma = p_T^{jet}$)

$$\xi = \ln(1/z_T) = \ln(p_T^\gamma / p_T^h)$$

The fragmentation function can be written in form:

$$D_q(\xi) = 1/N_{evt} dN(\xi)/d\xi$$

The modification of the fragmentation function is quantified as

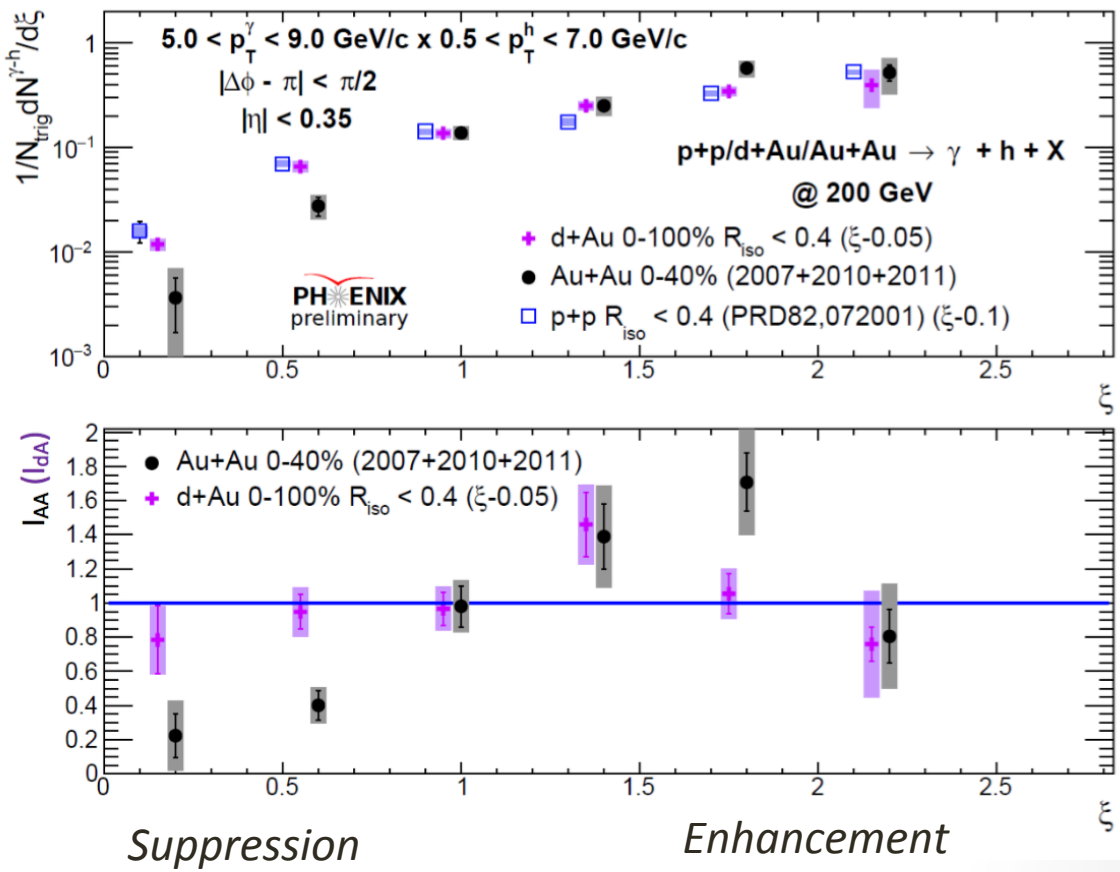
$$D_{AA}/D_{pp} \approx Y_{AA}/Y_{pp} = I_{AA}$$

Fragmentation modification

No visible modification in d+Au compared to p+p collisions

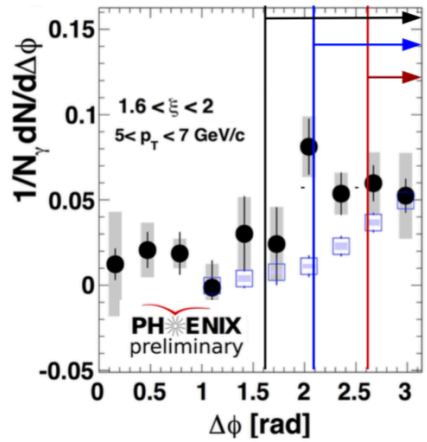
Modification in the Au+Au collisions.

Transition from suppression to enhancement around $\xi \sim 1$



$$\xi = \ln(1/z_T) = \ln(p_T^\gamma / p_T^h)$$

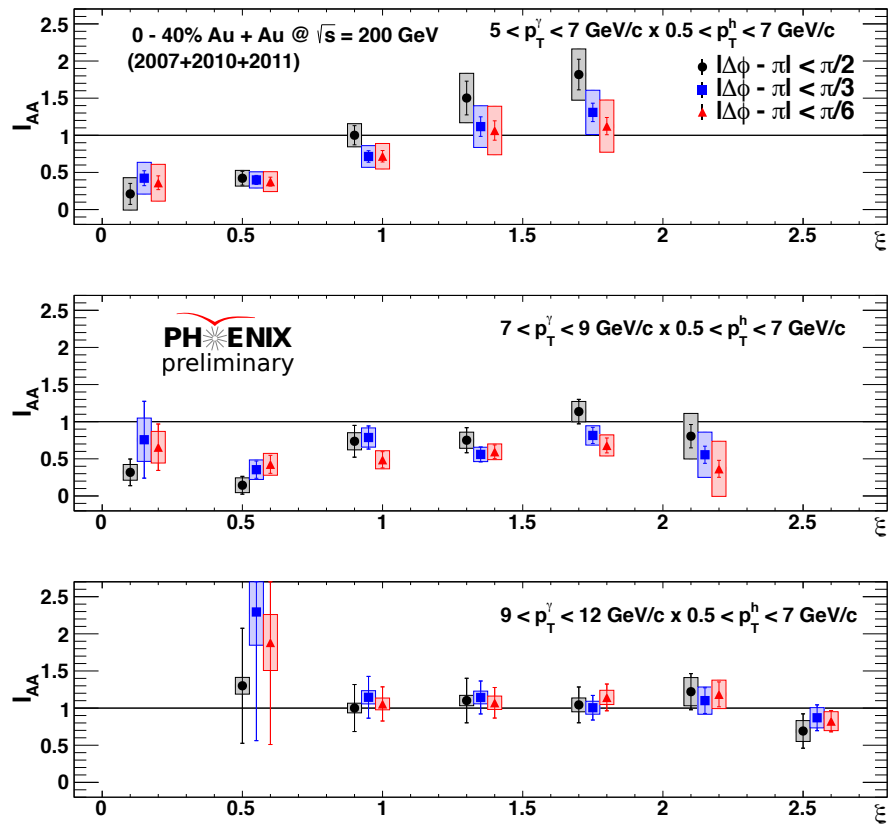
Fragmentation modification



Integrating the away side correlation function in different intervals to study the medium effect on the away side jet fragmentation.

The enhancement is more visible when integrating the full away side jet.

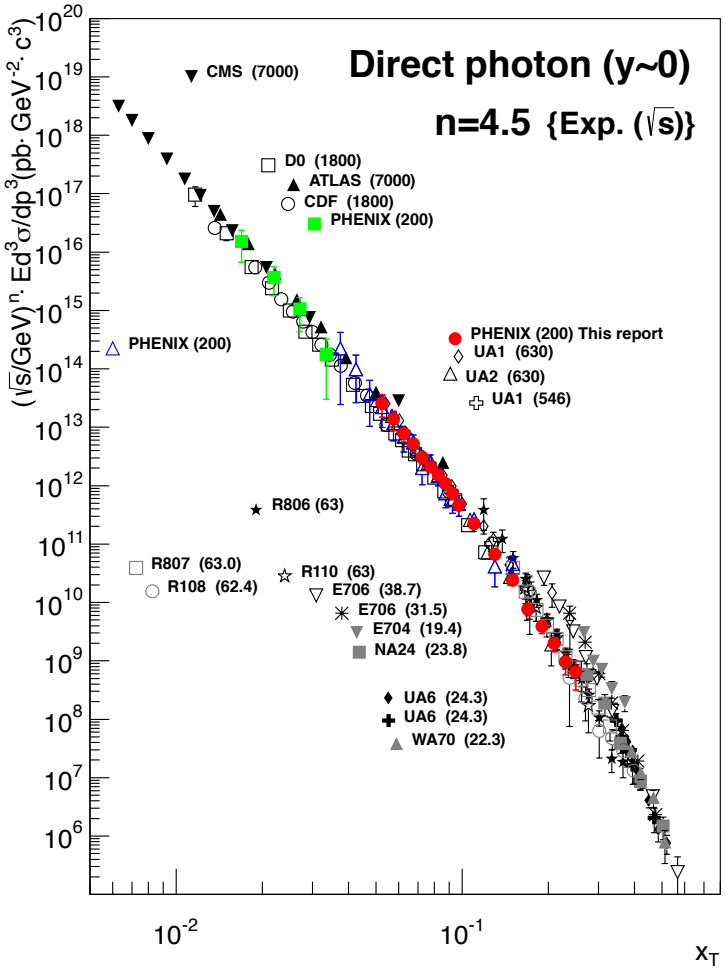
Harder jets seems to have no visible modifications



p_T trig

Direct photons spectrum in p+p

PhysRevD 86 072008

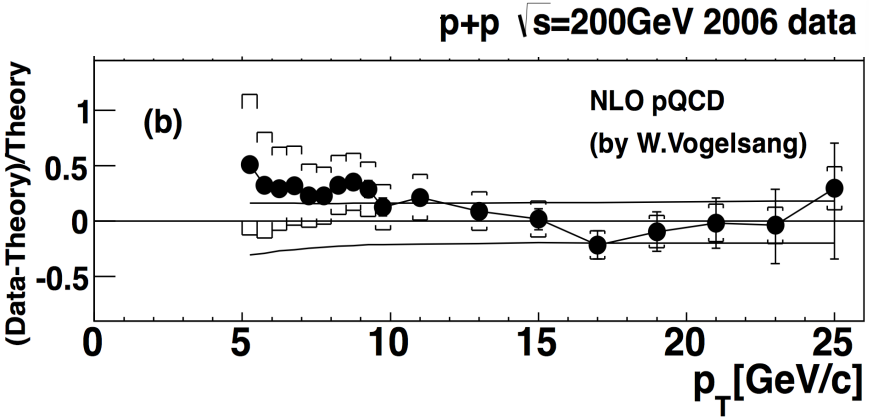


The invariant cross of direct photon production in p+p collisions (from 20 GeV to 7 TeV) factorizes in dimensional and dimensionless parts, as

$$E\frac{d^3\sigma}{dp^3} = \frac{1}{\sqrt{s}^{\,n_{eff}(x_T,\sqrt{s})}} G(x_T)$$

PRD 11, 1199 (1975).

- holds for any scale-free theory.
- n_{eff} = 4 LO, n_{eff} > 4 for NLO



PhysRevD 86 072008

Direct photons spectra in Au+Au

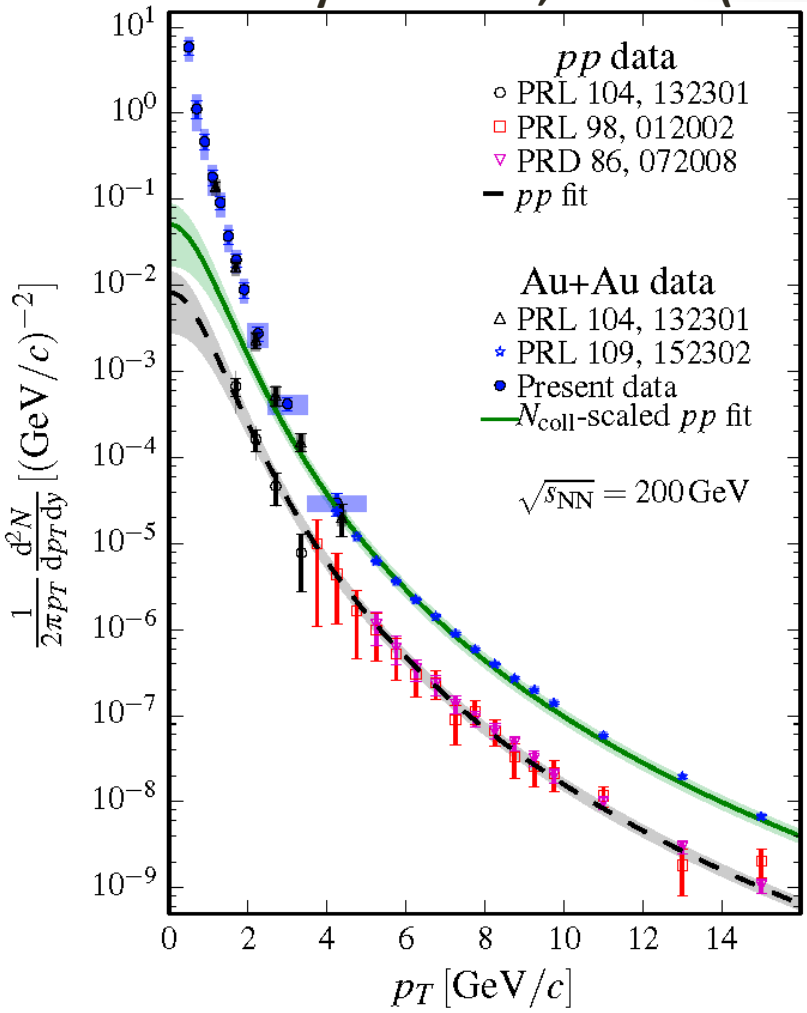
The spectrum in p+p collisions is described with an empirical function

Comparison to Au+Au collisions, the scaled fit function from p+p collisions:

- Described the $p_T > 5$ GeV/c
- $p_T < 4$ GeV/c shows large deviation

The inverse slope of the enhancement could carry information about the temperature.

Phys.Rev. C91, 064904 (2015)



Three different measurements are very consistent in their overlap regions

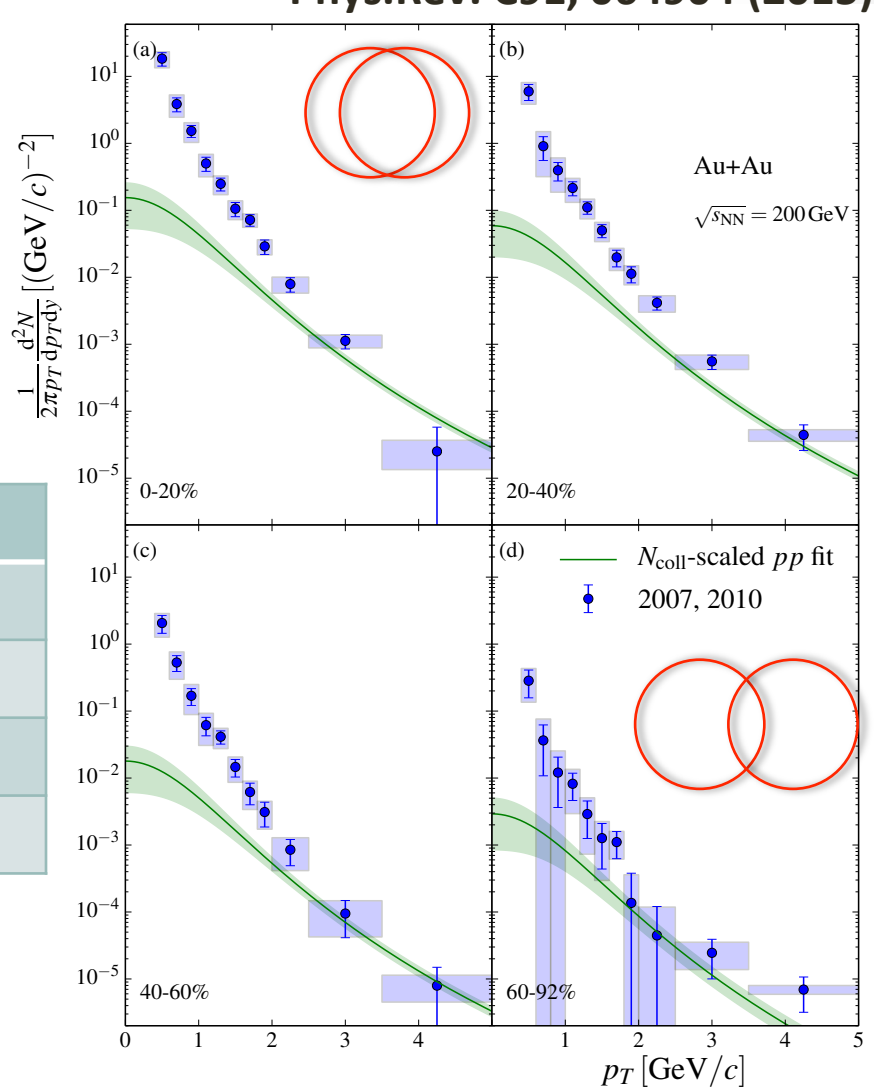
Direct photon spectra in Au+Au

Phys.Rev. C91, 064904 (2015)

Thermal yield of the photons can be extracted

The inverse slope shows no significant dependence on the size of the medium

Centrality	Inv. Slope [MeV/c]
0-20%	239 ± 25 ± 7
20-40%	260 ± 33 ± 8
40-60%	225 ± 28 ± 6
60-92%	238 ± 50 ± 6



This is not the temperature, rather the space-time integrated yield

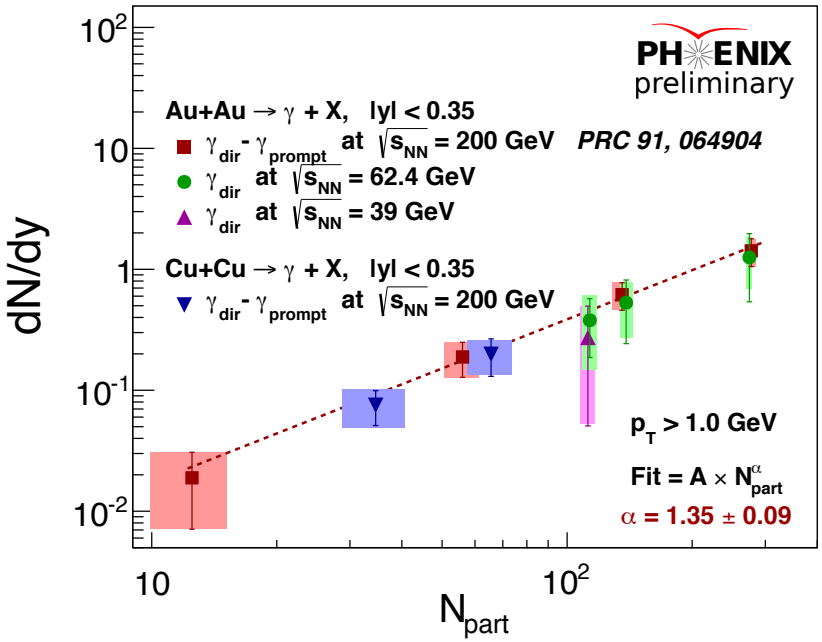
Thermal yield vs volume

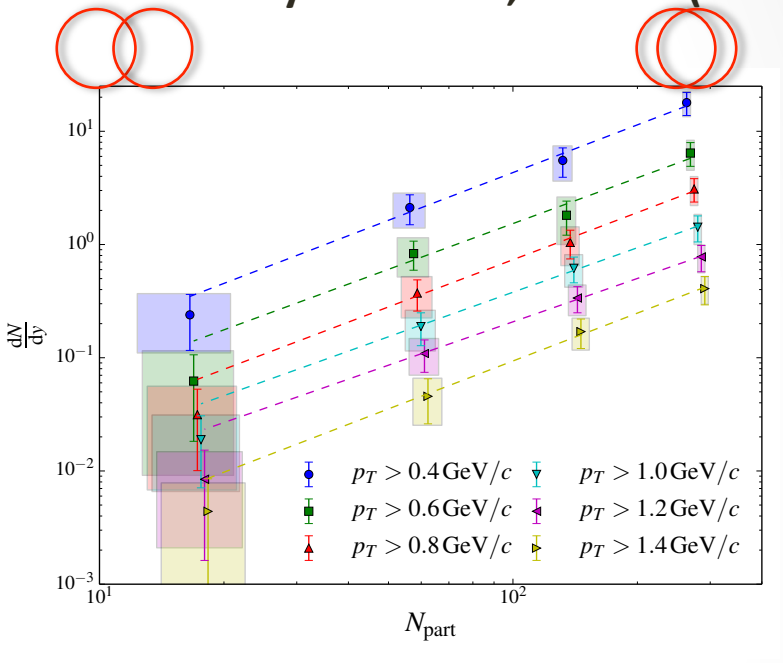
Phys.Rev. C91, 064904 (2015)

The thermal yield depends on the medium size:

$$dN/dy = A \cdot N_{part}^{\alpha}$$

α = 1.38 ± 0.03 ± 0.07, does not depend on the p_T limit of the integral





Integrated yield is consistent in various systems and energies:

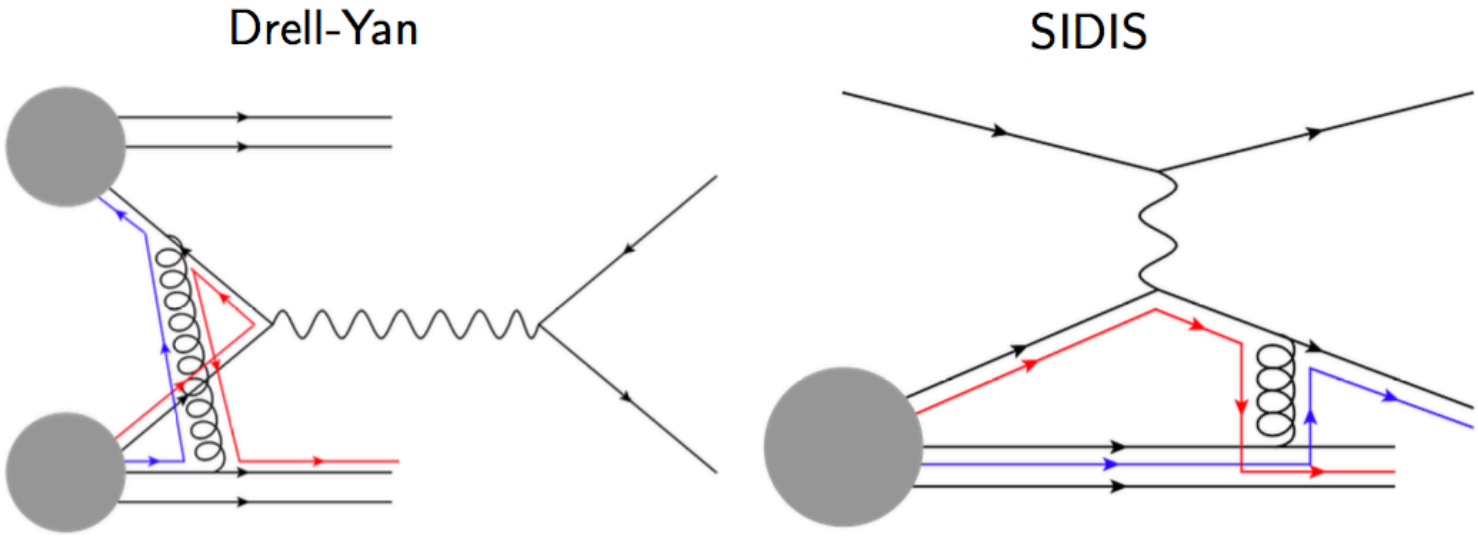
- Au+Au at 39, 62.4 and 200 GeV
- Cu+Cu at 200 GeV

Summary

- p_{out} measurement
  - p+p at $\sqrt{s}$ = 510 GeV first measurement probing the predicted factorization breaking (PRD 81,094006)
  - p+Au and p+Al at $\sqrt{s_{NN}}$ = 200 GeV show similar or stronger effect on the factorization breaking
- Fragmentation function:
  - d+Au at $\sqrt{s_{NN}}$ = 200 GeV no fragmentation modification compared to p+p collisions
  - Au+Au at $\sqrt{s_{NN}}$ = 200 GeV shows strong modification of fragmentation function
- Spectra:
  - Au+Au at $\sqrt{s_{NN}}$ = 200 GeV shows large enhancement to p+p at low-p_T
  - The excess yield depends on N_{part}^{α}, where $\alpha \sim 1.38$.

Backups

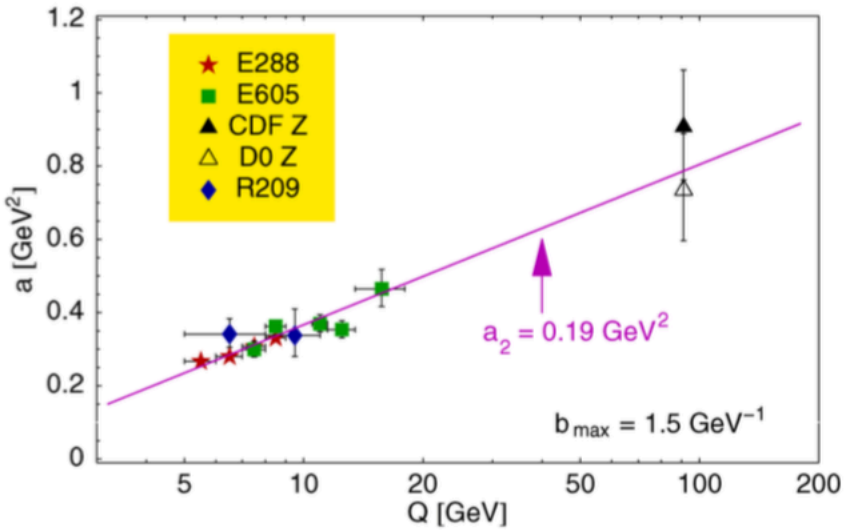
Universality and Factorization in TMD's



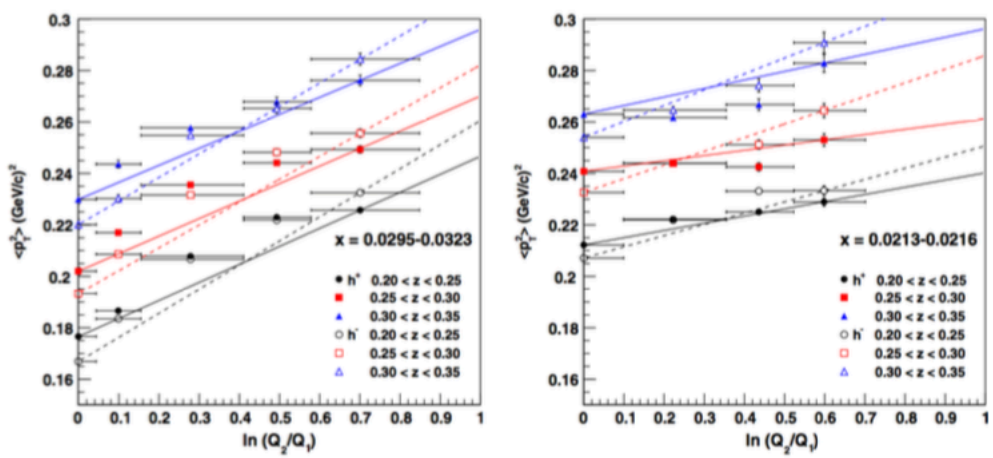
- Sign change in Sivers TMD PDF predicted due to initial-state vs. final-state gluon exchange with proton remnants between DY and SIDIS: modified universality!
- What about p+p → h_1h_2 where both initial- and final-state interactions are possible?

Colin-Soper-Sterman (CSS)

Phys. Lett. B 633, 710 (2006) (DY/Z)



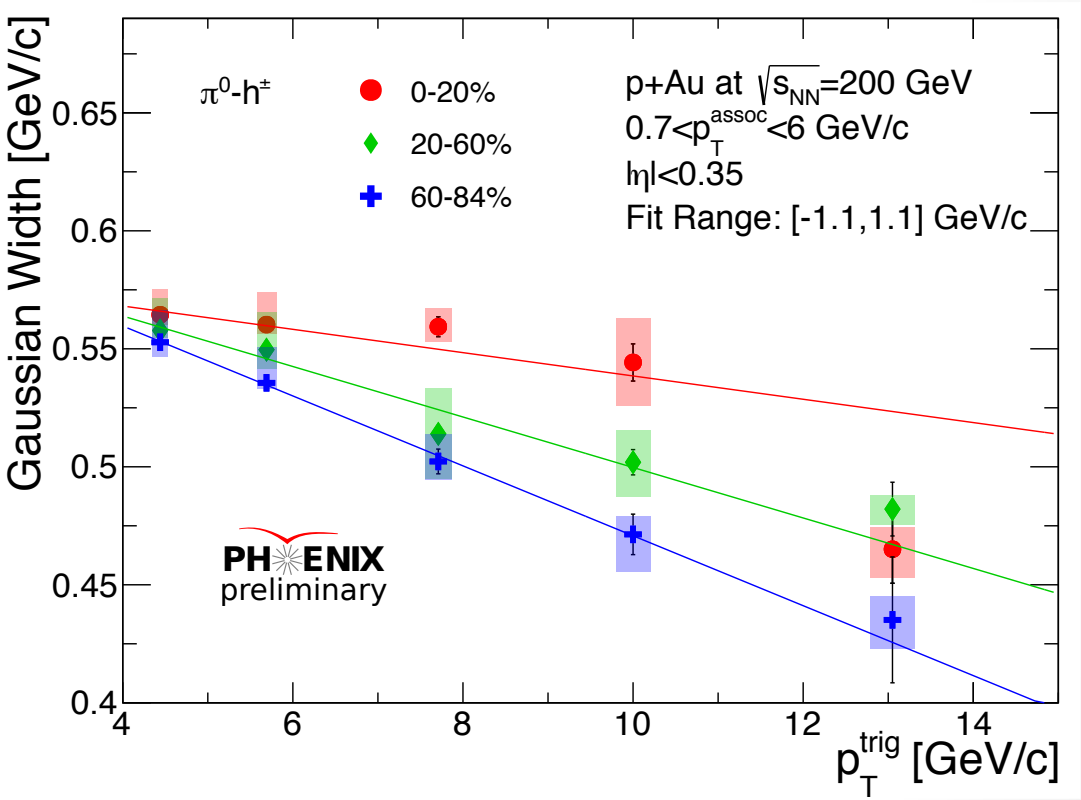
- Expectation from CSS evolution is that any momentum width sensitive to nonperturbative k_T grows with the hard scale
  - Broadening due to increased phase space for hard gluon radiation
    - Note that the CSS evolution equation comes directly out of the derivation for TMD factorization
    - Phenomenological studies have shown that DY/Z and SIDIS follow this expectation



Phys. Rev. D 89, 094002 (2014) (SIDIS)

p_{out} in p+A centralities

Surprising centrality dependency of the gaussian widths in p+Au

Are there some centrality dependence of nuclear effects: k_T broadening, multiple scattering, flow, etc.

Interpretations are still ongoing