Recent PHENIX results probing gluon dynamics in p+p and highly asymmetric nuclear collisions

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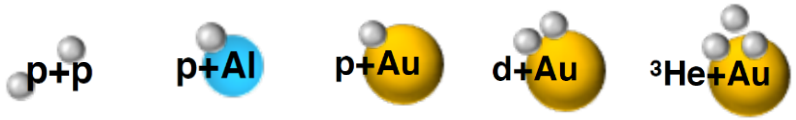
For PHENIX Collaboration

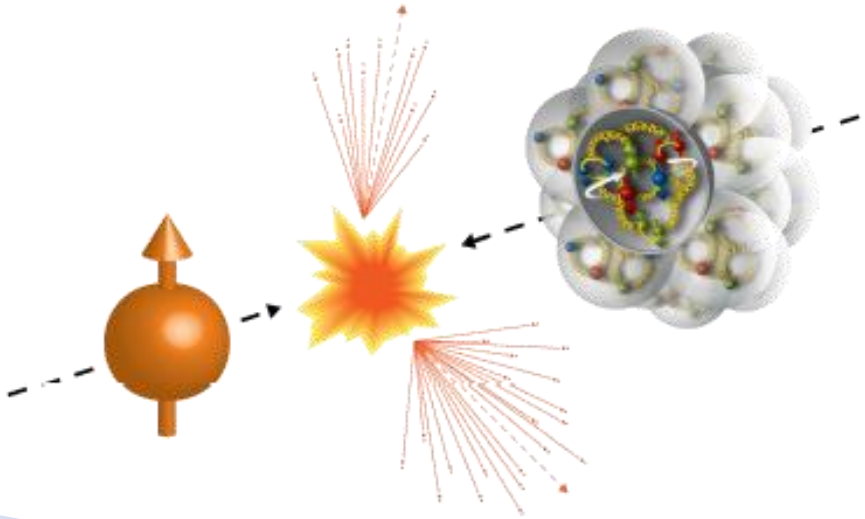
PHENIX

Gluon dynamics in hadron collisions

- Dynamics of gluon fields play important roles in hadron collisions and can be accessed via multiple probes, that includes (not limited to) heavy flavor, hadron production, di-hadron correlation
- Highly asymmetric collision also allow tune up the gluon densities in a controlled manner



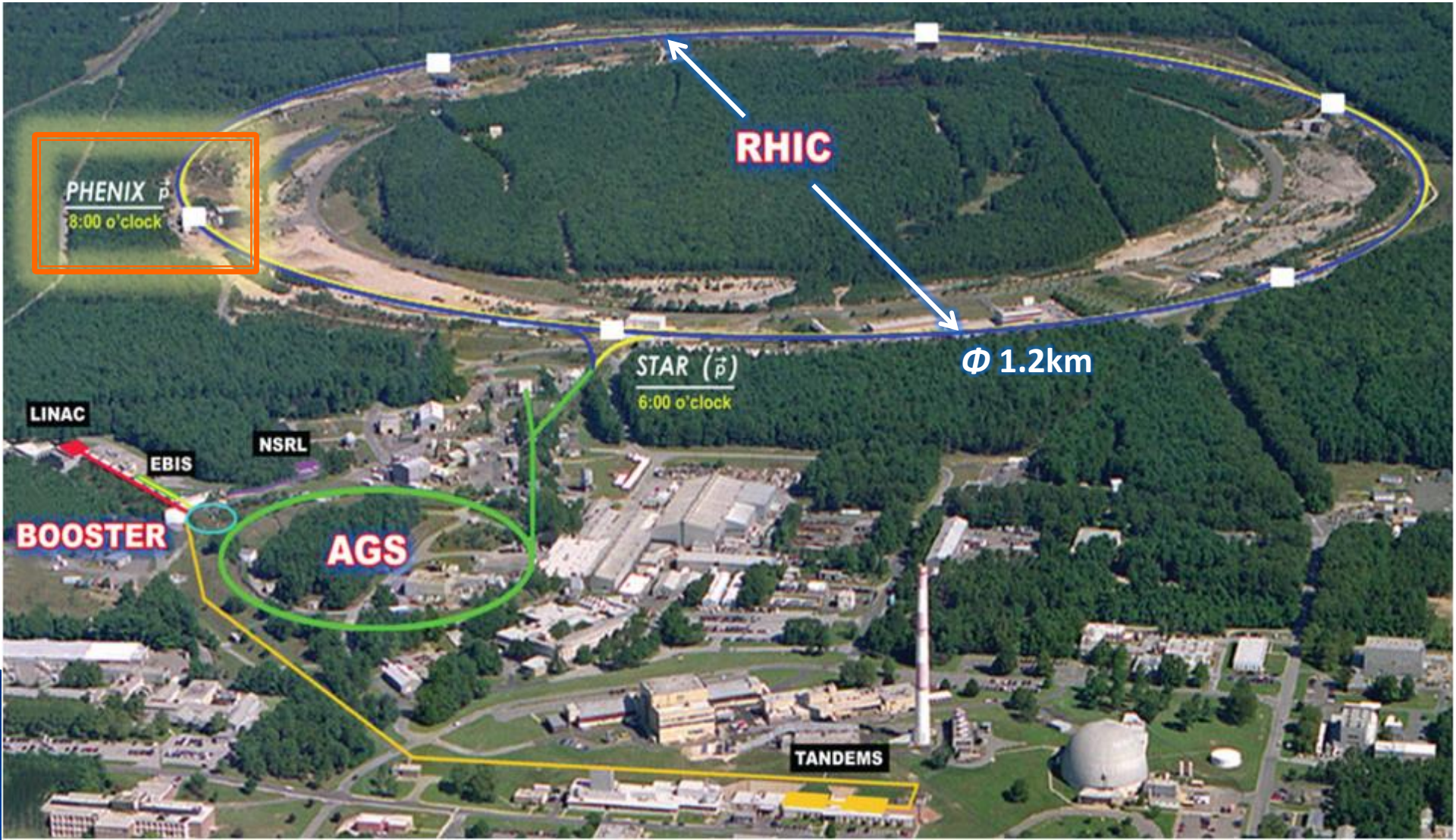
- Correlation with initial proton spin : unique handle



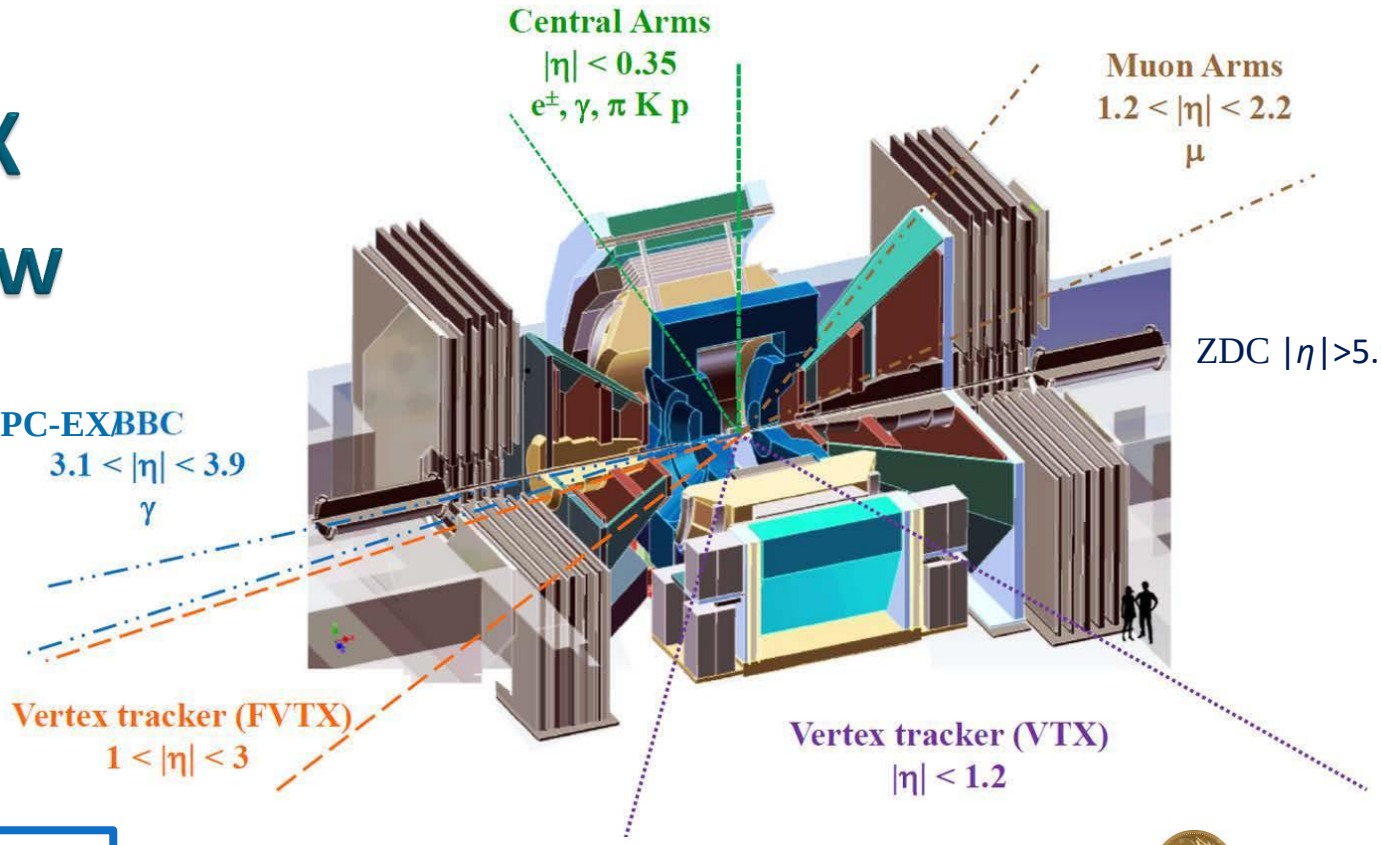
Relativistic Heavy Ion Collider, NY, USA

The most versatile hadron collider in the world

World's first and only spin-polarized proton collider



PHENIX Overview



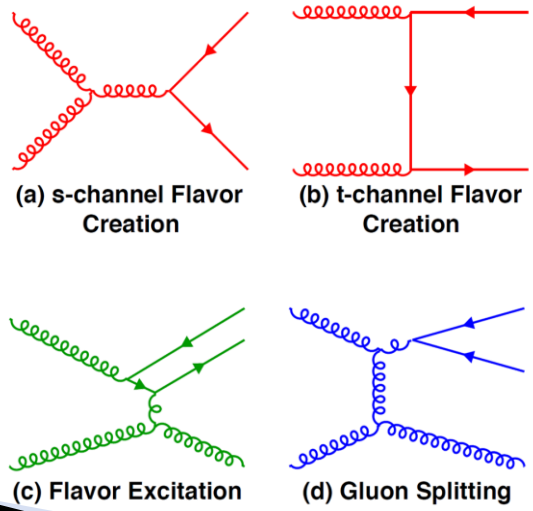
√s [GeV]	p+p	p+Al	p+Au	d+Au	³He+Au	Cu+Cu	Cu+Au	Au+Au	U+U
510	●								
200	●	●	●	●	●	✓	✓	●	✓
130								✓	
62.4	✓			●		✓		✓	
39				●				✓	
27								✓	
20				●		✓		✓	
14.5								✓	
7.7								✓	

- Multiple golden data sets (●), from decades of hard work
- Highlighting four sets of recent results in this talk
  1. p+p → HF and DY
  2. p+Au, d+Au, ³He+Au → hadron modification
  3. p+p, p+Al, p+Au → di-hadron correlation
  4. p+p, p+Al, p+Au → hadron asymmetry

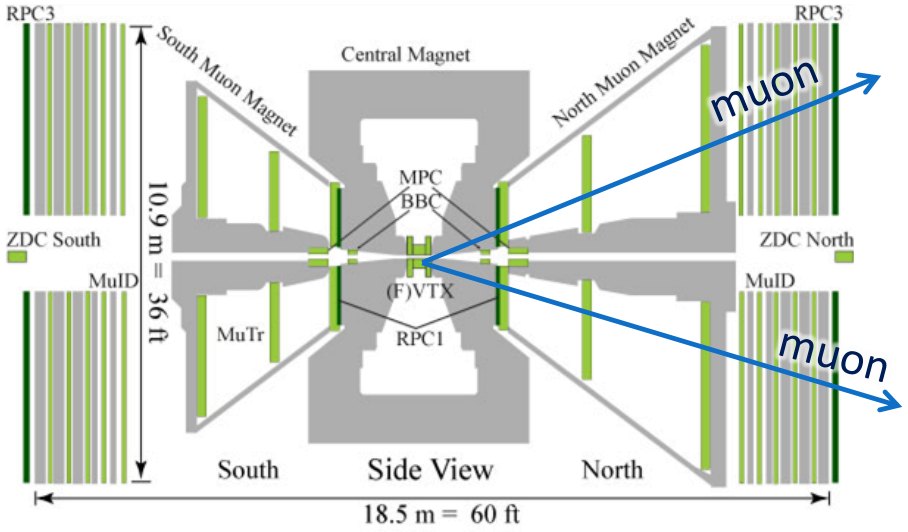
Heavy flavor measurement via di-muons

- Heavy flavor (HF) production in hadron collision provide a clean probe on parton interactions that originates from gluons
- Calculable by pQCD
- New measurement from PHENIX extract HF by decomposition di-muon production in the forward direction via fits on inv. mass-p_T spectrums

$g + g \rightarrow Q\bar{Q}$ channels

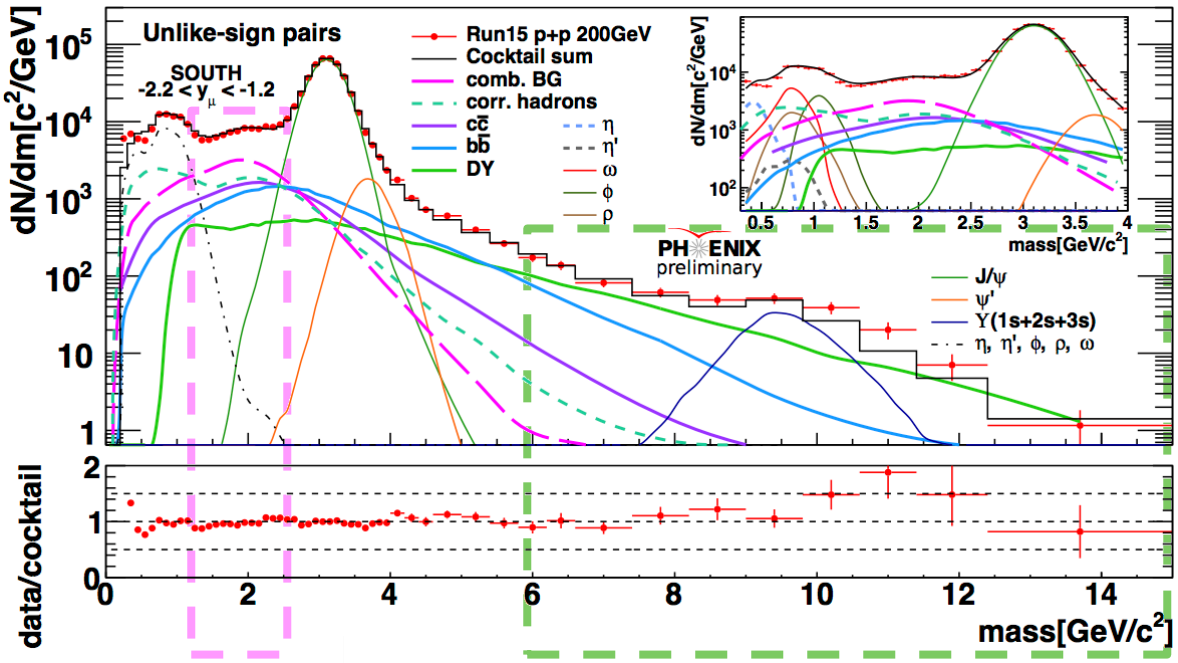


$p + p \rightarrow Q\bar{Q} \rightarrow \mu^{\pm}\mu^{\pm}$ in PHENIX experiment

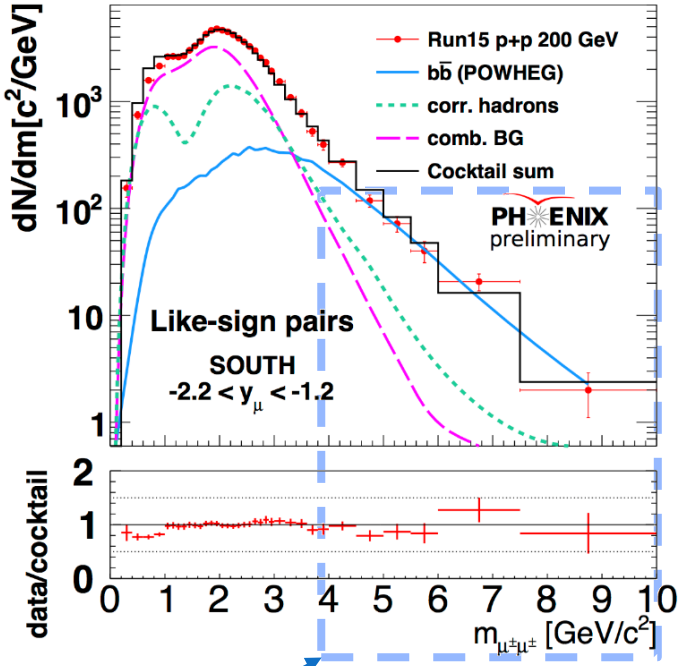


Decomposing di-muon cocktail

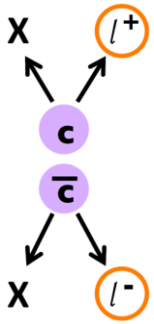
Opposite charge-sign di-muon pairs

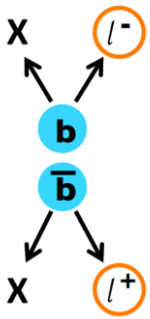


Same charge-sign di-muon pairs

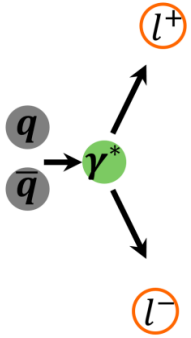


Charm highest S/B

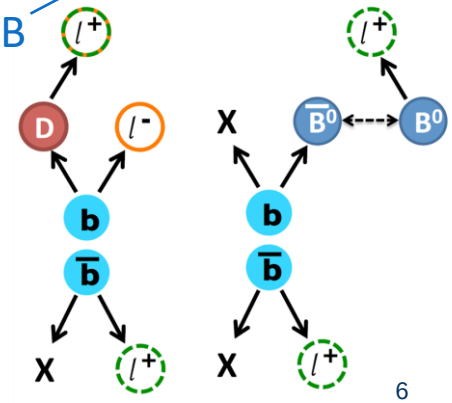




DY highest S/B

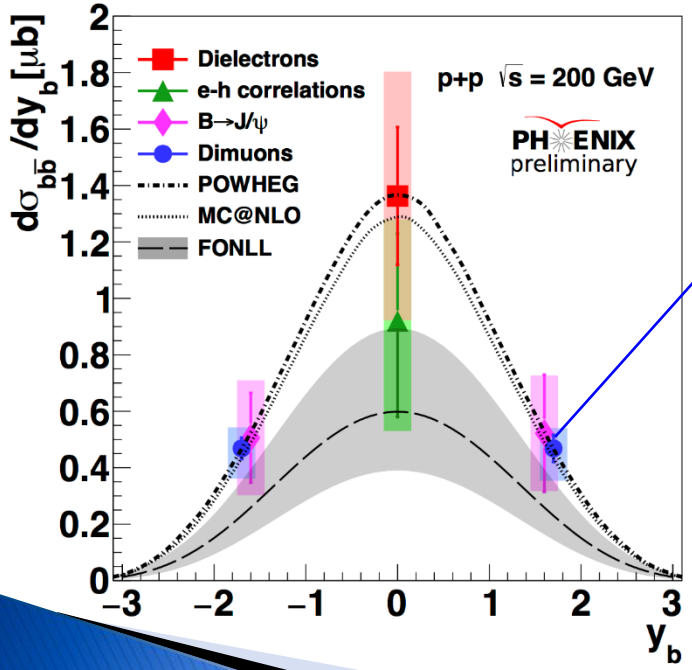


Bottom highest S/B



Extract bottom cross section

- Extract bottom cross section via fitting of mass-p_T distributions
- Measured Cross section about 2x from central FONLL value
- Stay tuned: results coming for 510 GeV *p*+*p* and 200 GeV *p*+A collisions too



DIS 2018,

$b\bar{b} \rightarrow \mu^{\pm}\mu^{\pm}$, 1.2 < |y| < 2.2, this analysis

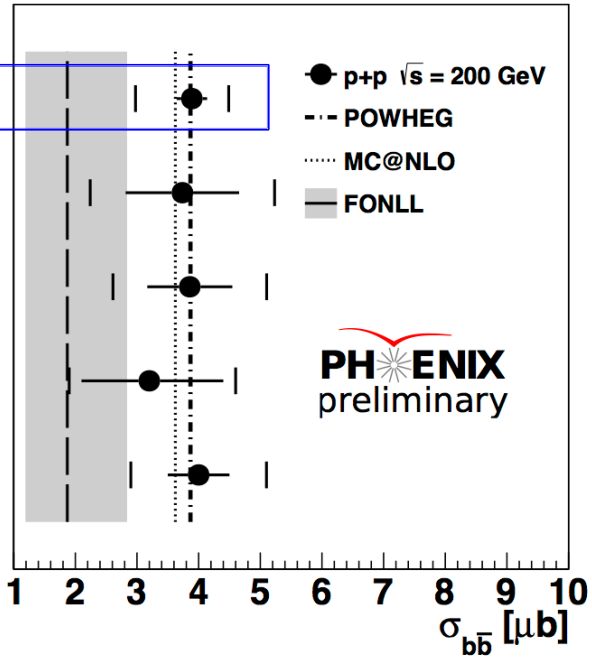
DIS 2017, PHENIX *PRC* 96, 064901

PHENIX *arXiv:1702.01085*

$b\bar{b} \rightarrow e^{+}e^{-}$, |y| < 0.35
PHENIX *PRC 96, 024907*

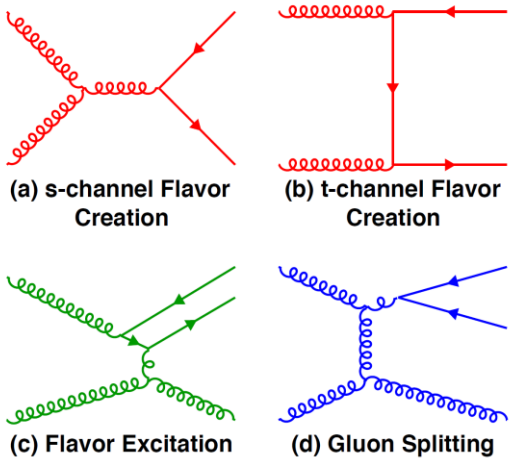
e-h correlations, |y| < 0.35
PHENIX *PRL 103, 082002*

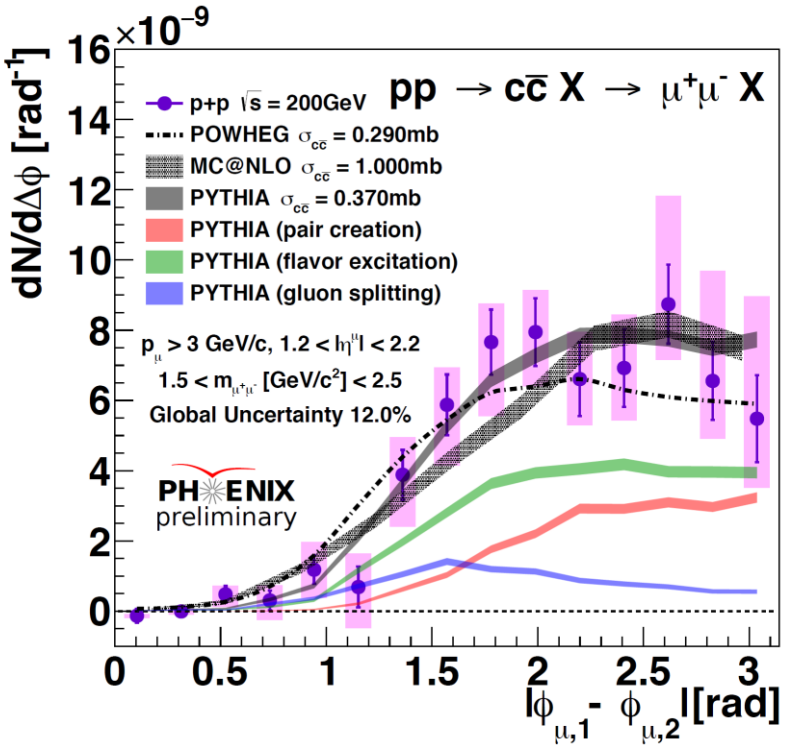
$b \rightarrow e$, |y| < 1
STAR *PRD 83, 052006*

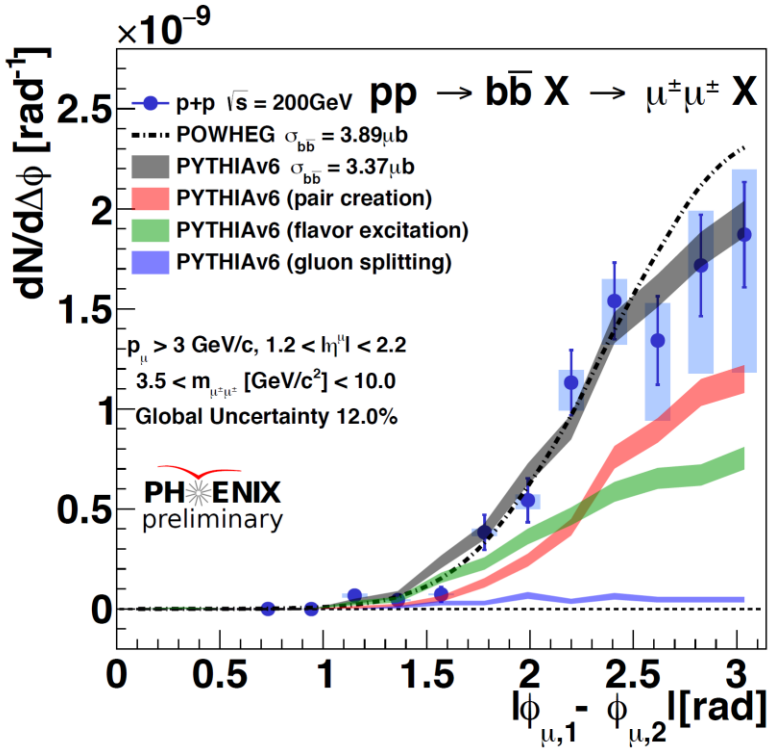


Angular corrections

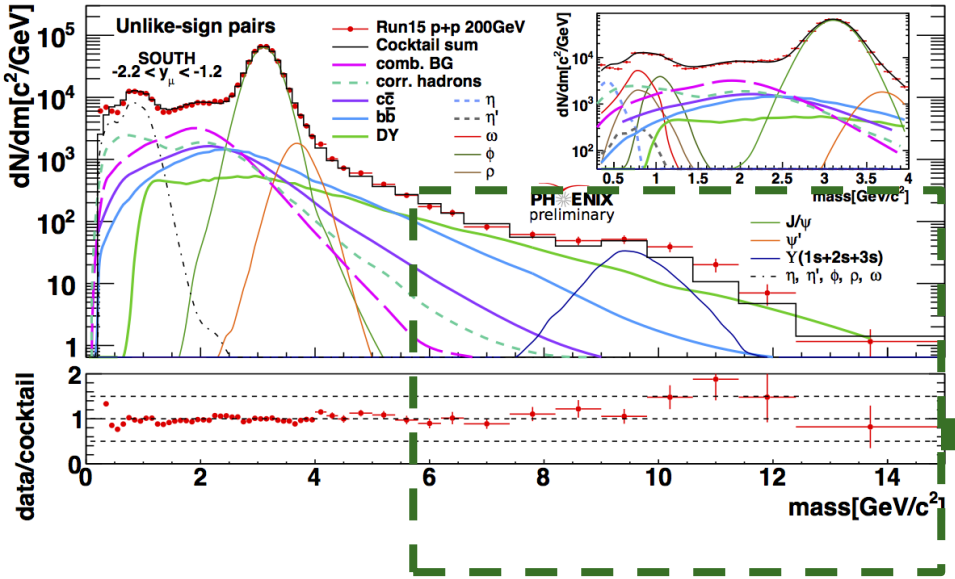
- Decay muons' azimuthal angle → parent heavy quark
- Azimuthal angular correlation sensitive to HF production channels in LO and NLO gluon interactions
- Qualitatively described by Pythia and NLO event generators

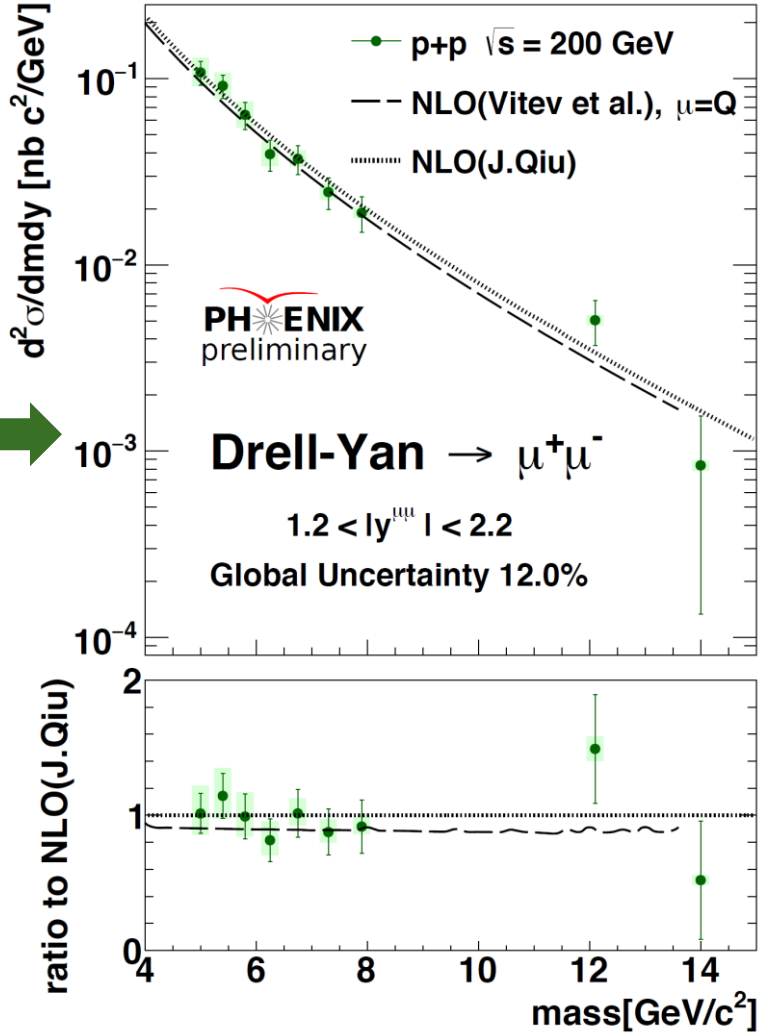




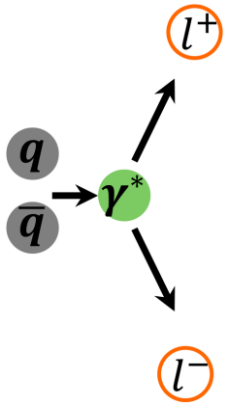


Drell-Yan cross section



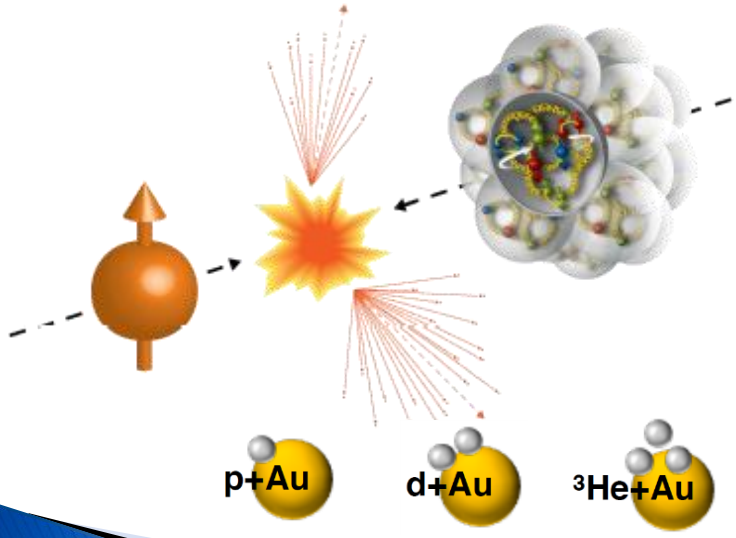


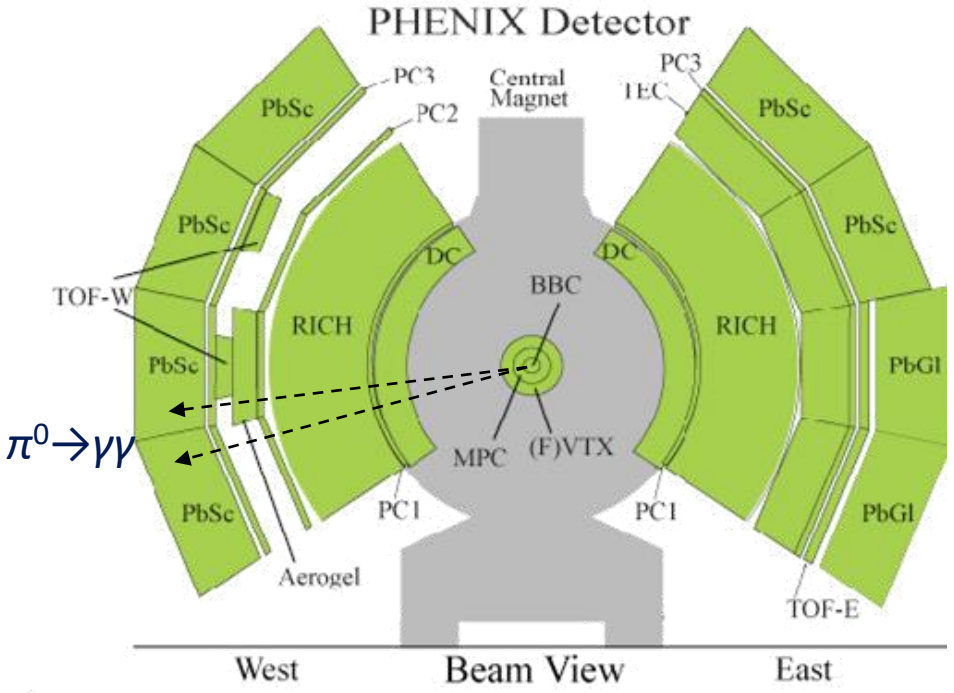
- Drell-Yan process is sensitive to anti-quark distribution in proton
- Drell-Yan cross section consistent with NLO calculations



Hadron production in *p*+A collisions

- Hadron production in the PHENIX central rapidity is dominated by *g*+*g*/*g*+*q* interaction and described by NLO calculation for *p*+*p* collisions [10.1103/PhysRevD.76.051106, arXiv:1501.01220]
- Modification of hadron production in highly asymmetric collision system gives access to nuclear PDF

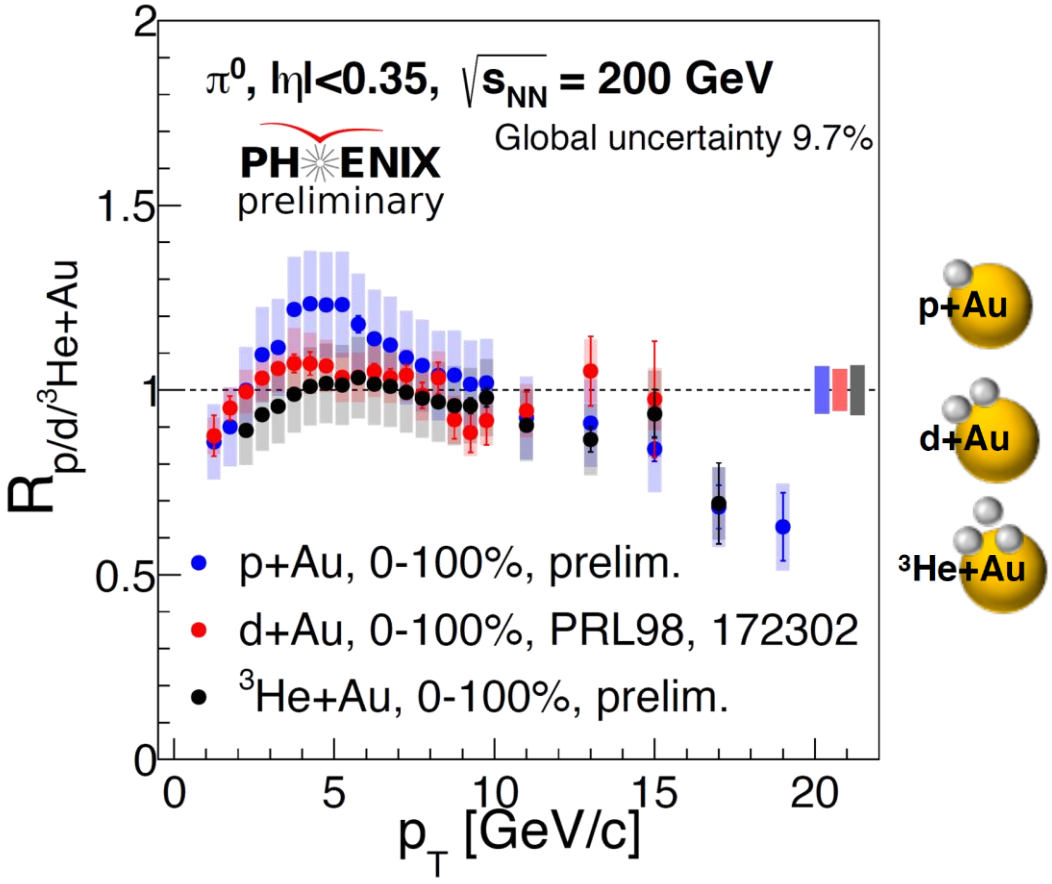




π^0 production in asymmetric collisions

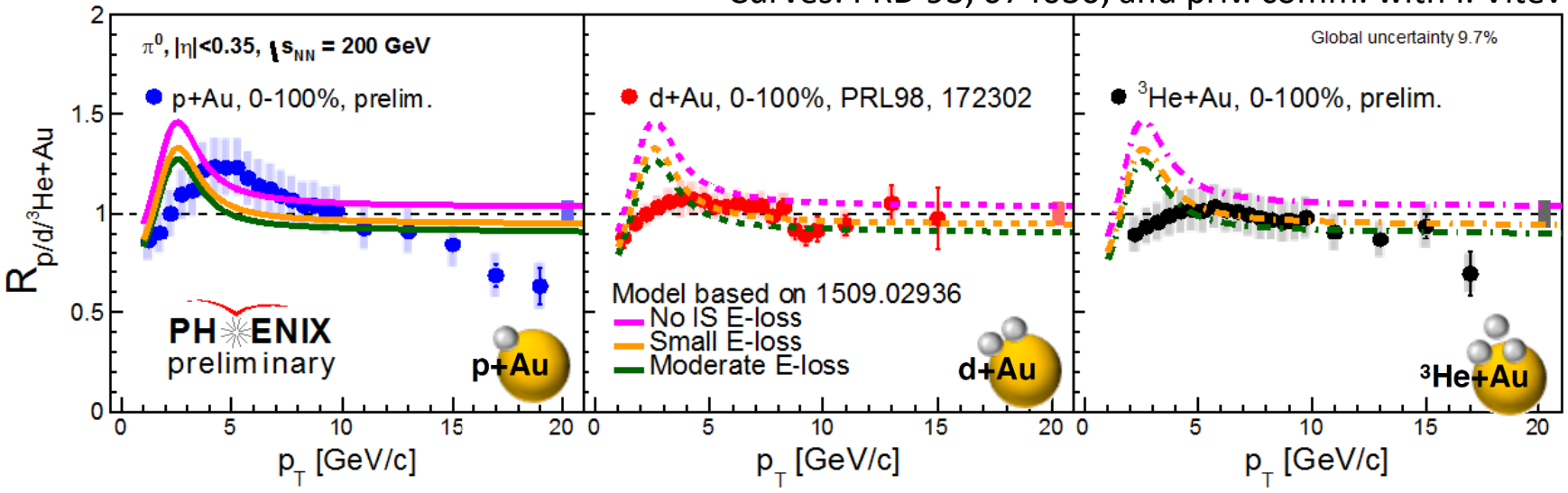
- Enhancement around p_T~5GeV/c
- The enhancement is system size dependent :

$R_{p+Au} > R_{d+Au} > R^{3}_{He+Au}$



Source of the enhancement

Curves: PRD 93, 074030, and priv. comm. with I. Vitev

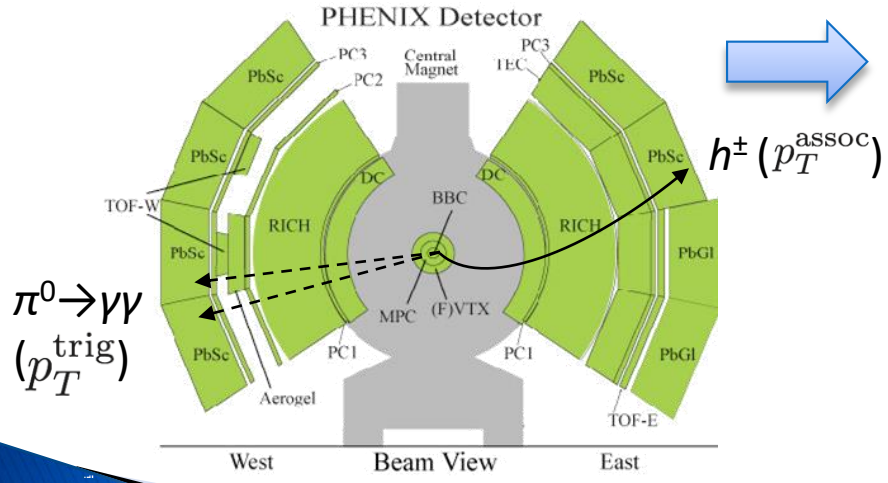


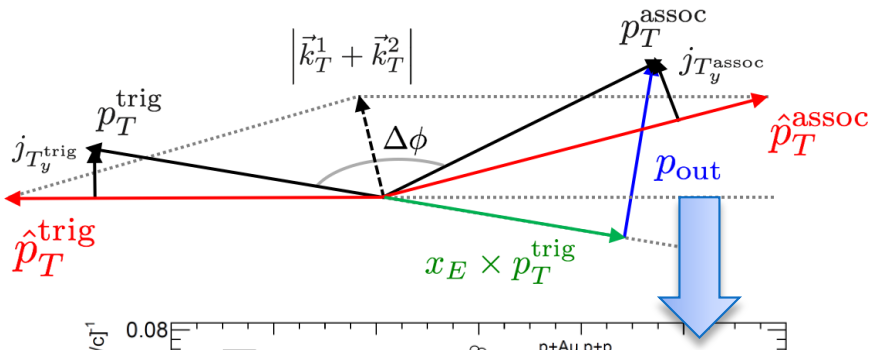
- Comparing with models of cold nuclear energy loss
  - Different loss scenario are comparable to data high p_T
  - Collision system dependent is not described and location of low p_T peak is shifted
  - Insights from theoretical interpretation welcomed

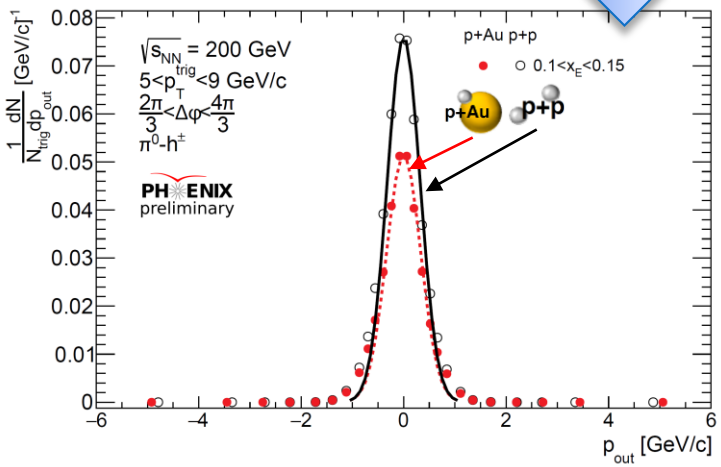
- Meanwhile, further exploring additional handles revealing interactions between hard parton probes and nuclear matter
  - 2-h correlation and transverse spin asymmetry

New handle 1: 2-p correlation

- p_{out}: Transverse momentum correlation of two particles that is perpendicular to the trigger p_T
- Gauss-core width of p_{out} sensitive nonperturbative effects
  - Much smaller (σ~0.5 GeV/*c*) than scales of p_T and is sensitive to minute changes
- Comparing *p*+A to *p*+*p*: probes interaction of parton in nuclear matter
  - e.g. soft gluon exchange and radiative energy loss

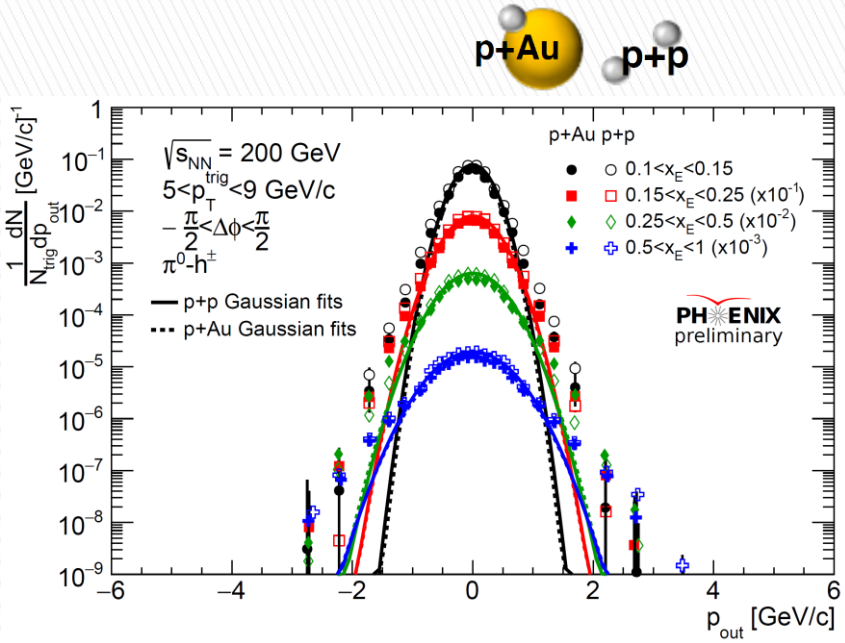


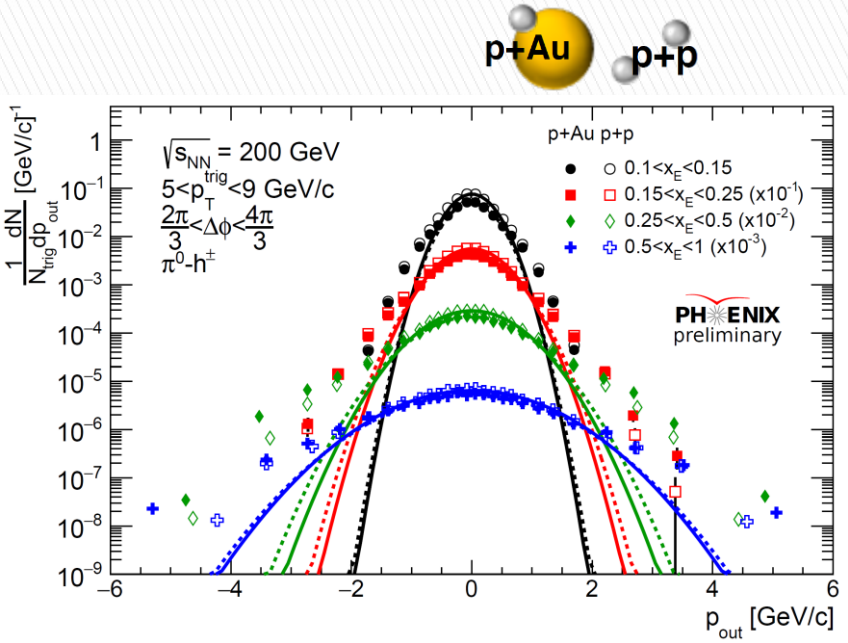




p_{out} fit method see DOI: 10.1103/PhysRevD.95.072002

Near side and away side correlations





Near side correlation:

Sensitive to modification of fragmentation

Away side correlation:

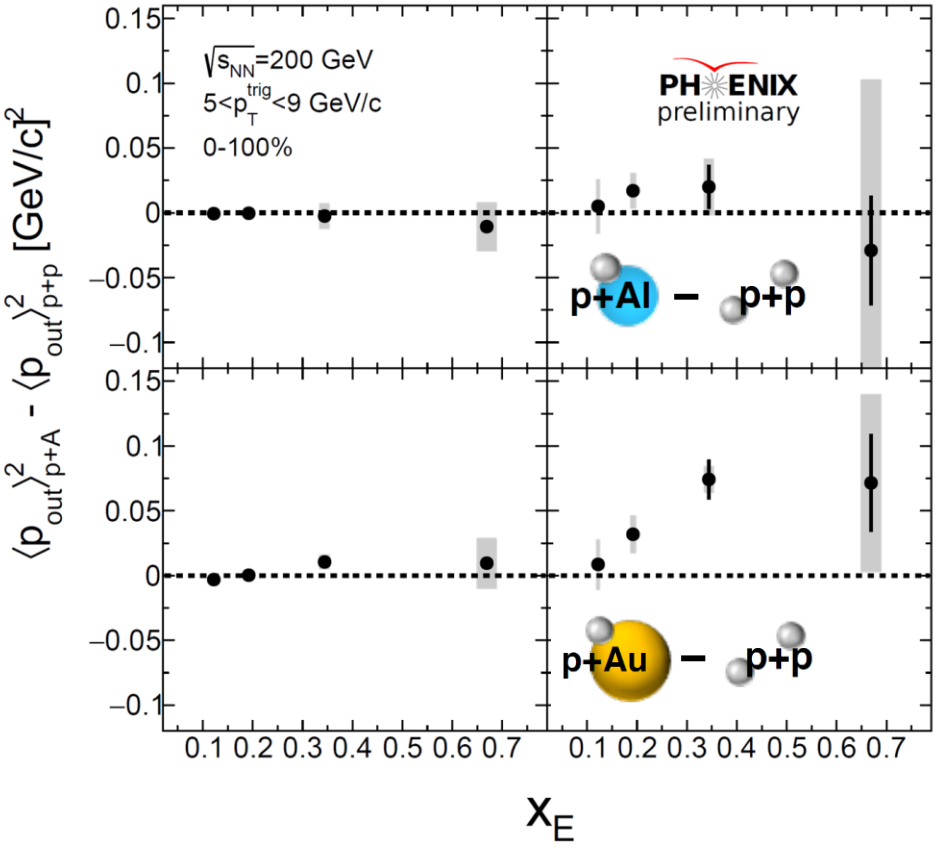
Sensitive to initial k_T, initial radiation and modification to fragmentations

p_{out} Gauss-core difference in pp and pA

- Observed away-side broadening of Gauss-core of p_{out}, but *not* for near side modification
- Suggest parton-nuclear interaction that leads to the broadening
- Consistent with picture that fragmentation outside nuclear and is not strongly modified in *p*+A collisions

Near side $-\frac{\pi}{2}<\Delta\phi<\frac{\pi}{2}$

Away side $\frac{2\pi}{3}<\Delta\phi<\frac{4\pi}{3}$

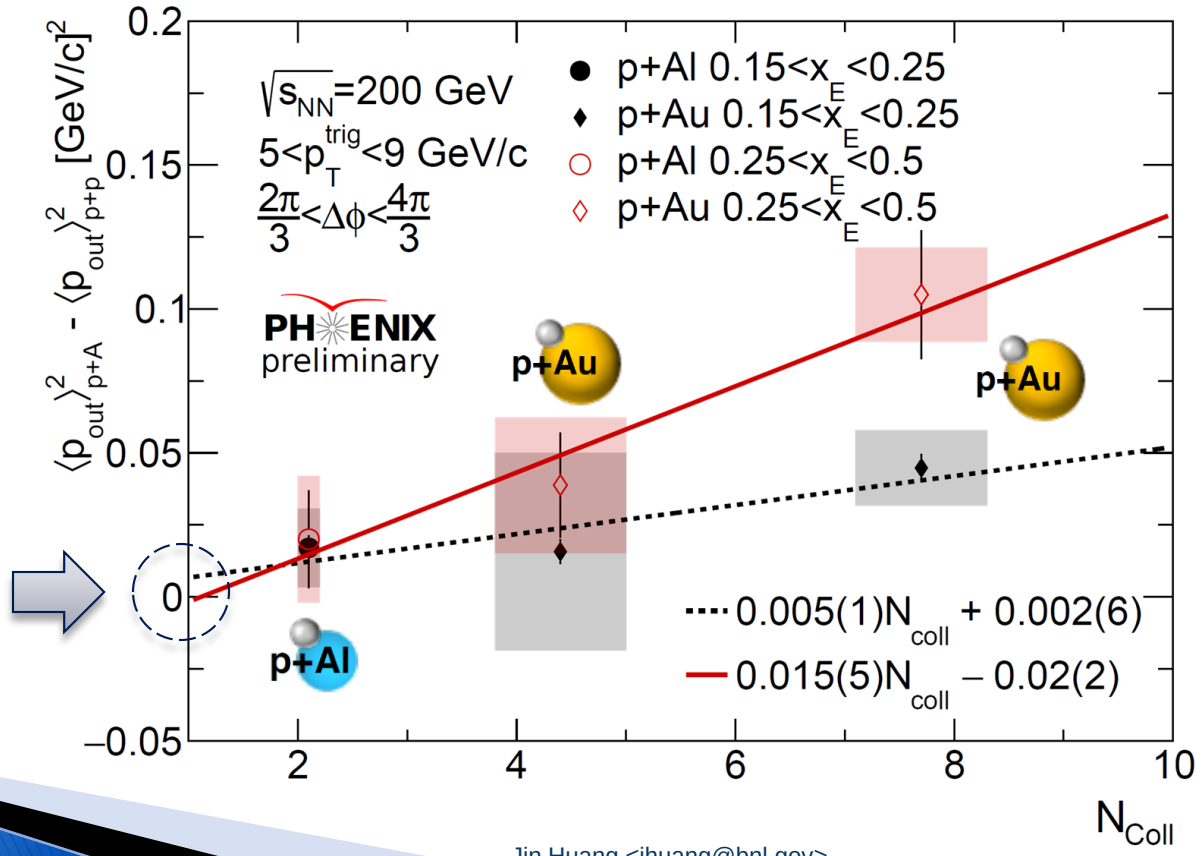


p_{out} Gauss-core difference vs N_{coll}

- Further correlate the away-side broadening vs path length of parton in nuclear matter, approximated by N_{coll}
- Broadening of the Gauss-core of p_{out} lines up in linear dependence of N_{coll}

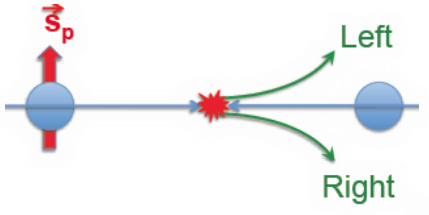
Centrality and N_{coll} in p+A collisions: PRC 90,034902

p+A of N_{coll}=1 also consistent with p+p

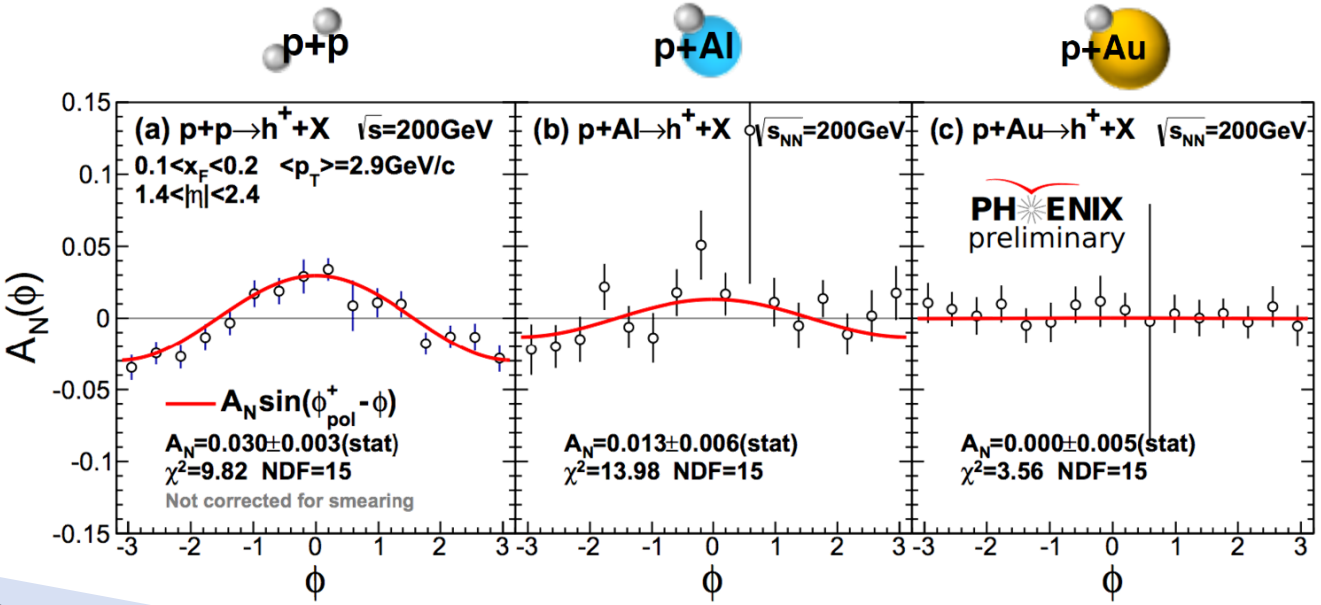


New handle 2: Transverse spin asymmetry

- Hadron production is correlated with in coming proton transverse spin: observed as sine-modulation of transverse spin asymmetry, A_N
  - One way to generate A_N is interference of parton through color field (Sivers effect)
- When parton traverse nuclear matter, A_N may be modified
  - Sensitive to gluon exchange and small change of parton p_T that is ⊥ to spin direction
  - Suppress to A_N presumably proportional to $1/A^{1/3}$ or 1/(path length) in nuclear matter
    [10.1103/PhysRevD.84.034019, 10.1103/PhysRevD.86.034028, 10.1103/PhysRevD.95.014008]

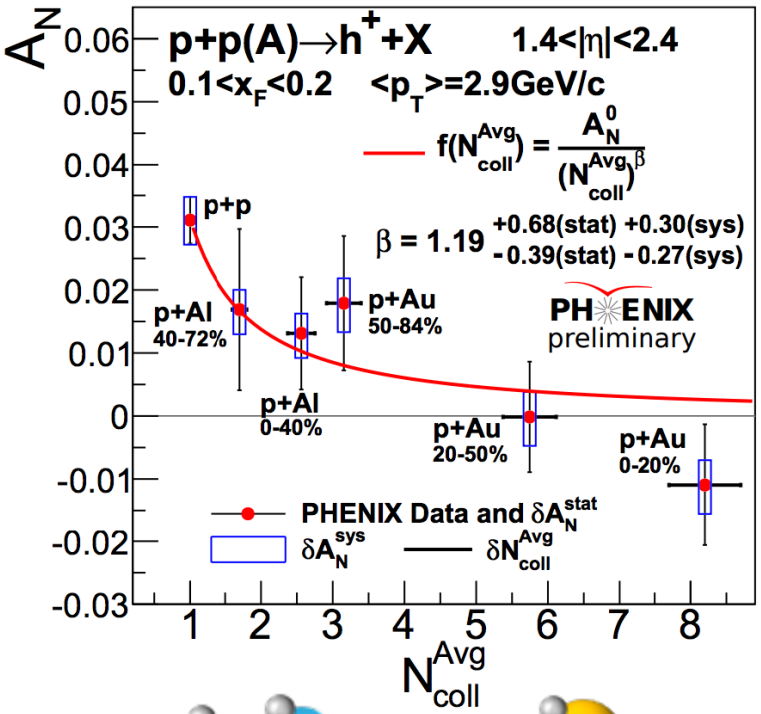


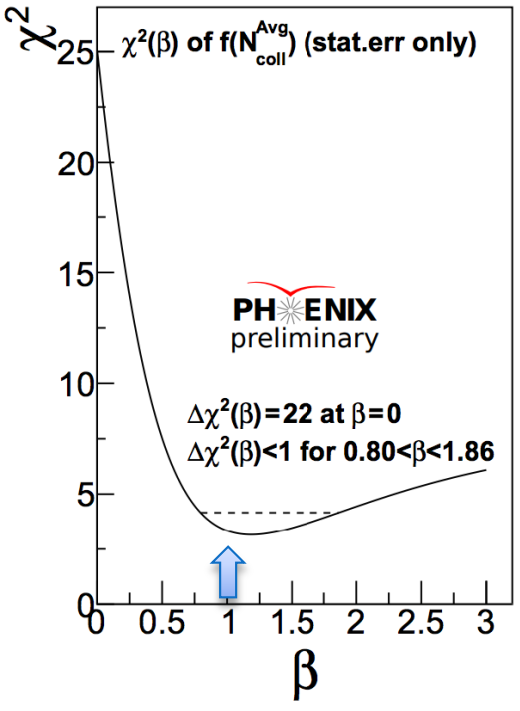
Details see Apr 17
WG Spin: Jeongsu Bok
(New result for DIS18)

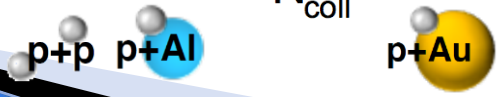


A_N vs effective path length in nuclei

- Data is consistent with A_N suppression of 1/<path length>, which is approximated by $1/N_{Coll}$
- Strongly *reject* the scenario of *no* nuclear modification of A_N



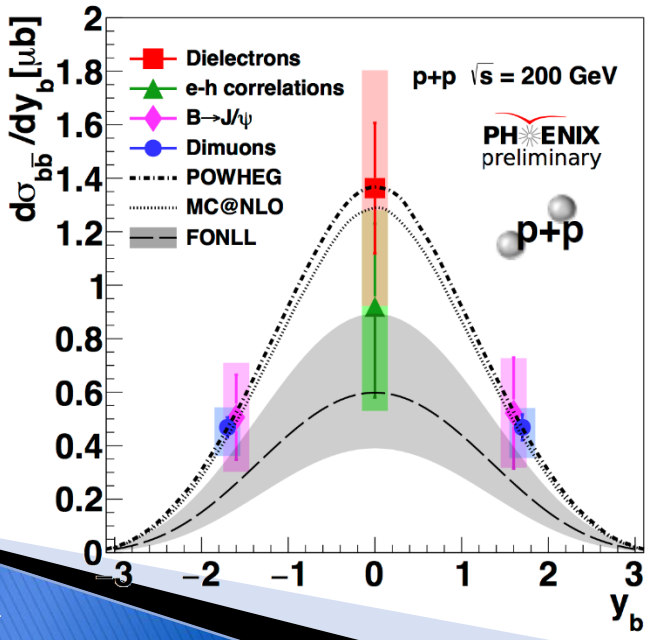


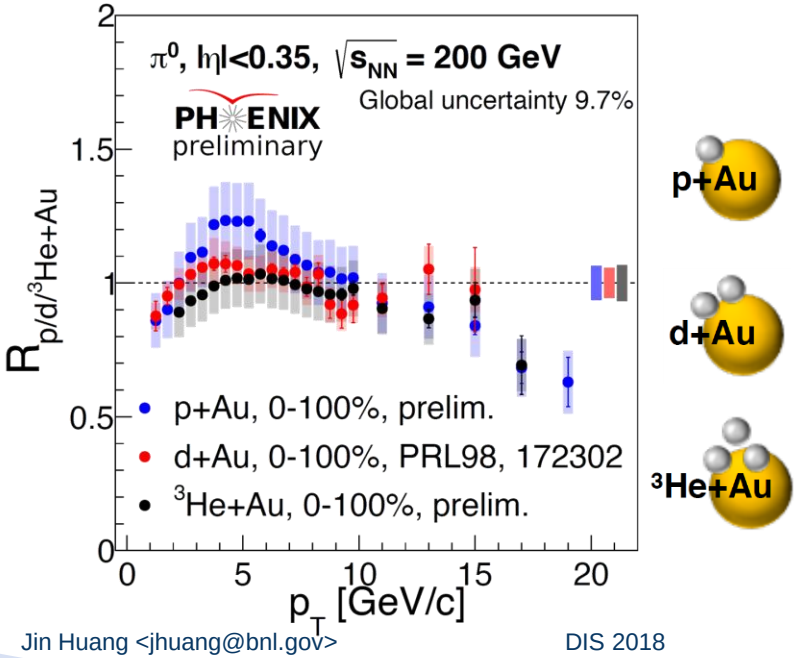


Details see Apr 17 WG Spin: Jeongsu Bok

Summary 1: HF and π^0 production

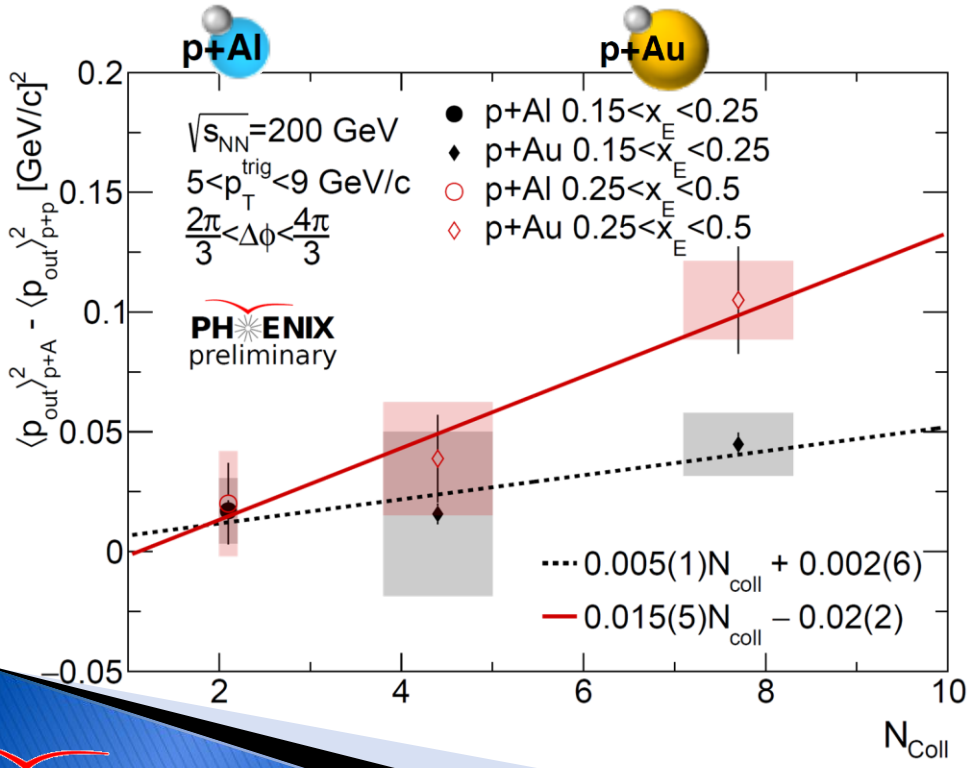
- Measurement of HF production via di-muon production in p+p collisions
  - Favor 2x *b*-cross section of FONLL central cross section
  - Azimuthal correlation described by Pythia and NLO generators
- π^0 production in highly asymmetric *p*/^{3}He+A collusions:
  - Constraints nPDF. Hints energy loss of in cold nuclear mater.
  - Observed ordering of enhancement with system dependence

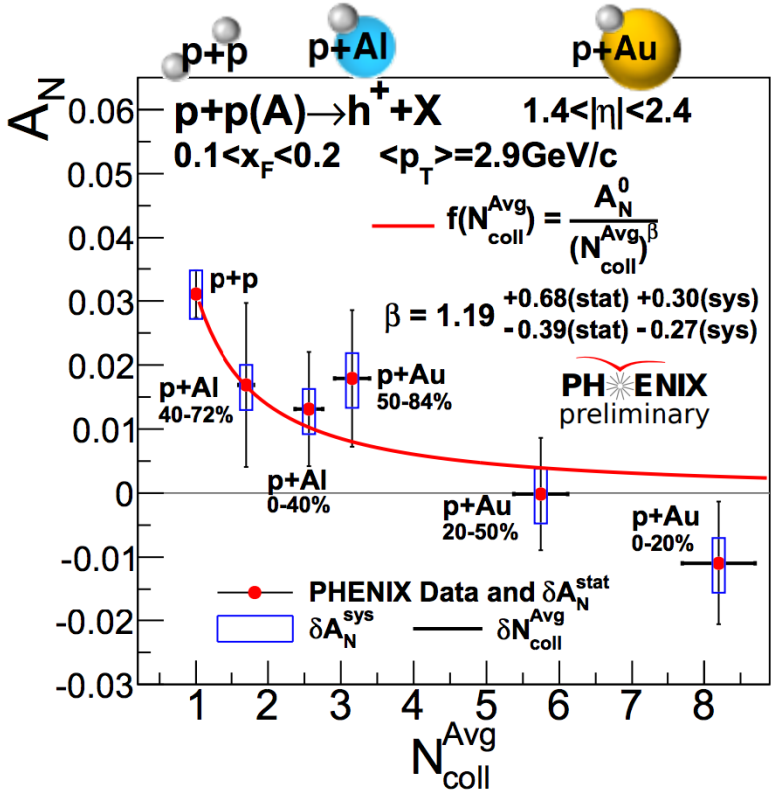




Summary 2: new handles

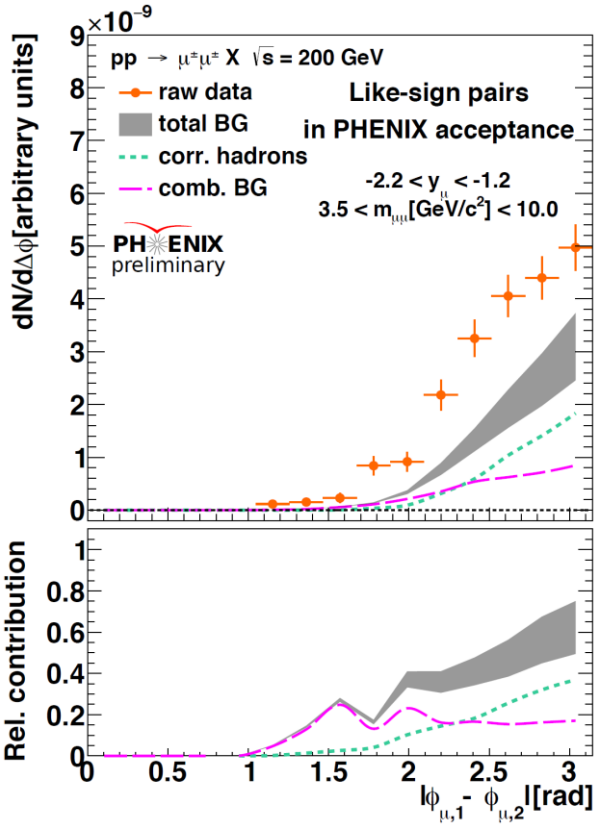
- Additional handles on parton interaction of gluon field in *p*+A collisions:
  - 2-particle correlation (p_{out} width) and transverse-spin asymmetry (A_N)
- Data lines up as function of path-length in nuclear, approximated by N_{coll}
- Stay tuned: final results and more explorations on gluon dynamics to come from PHENIX!

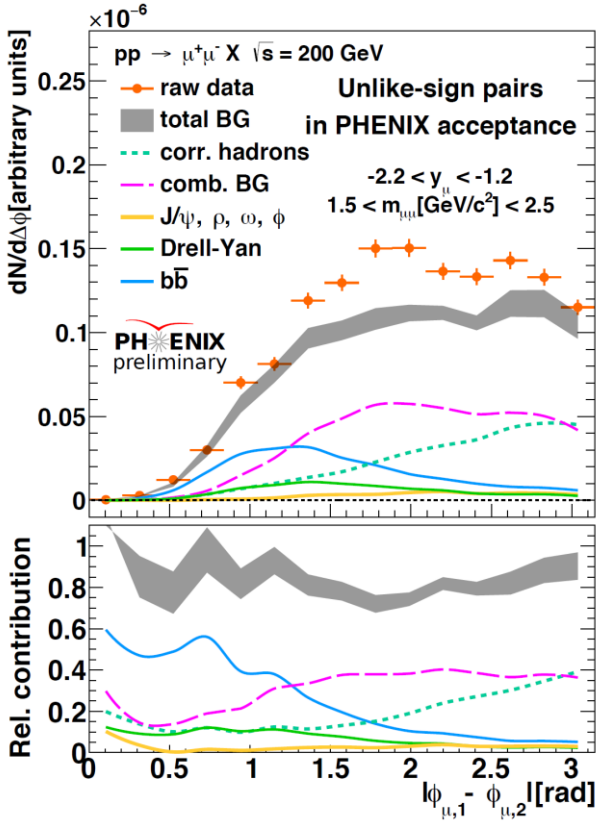




Extra Infomation

S/B for di-muon azimuthal angular correction

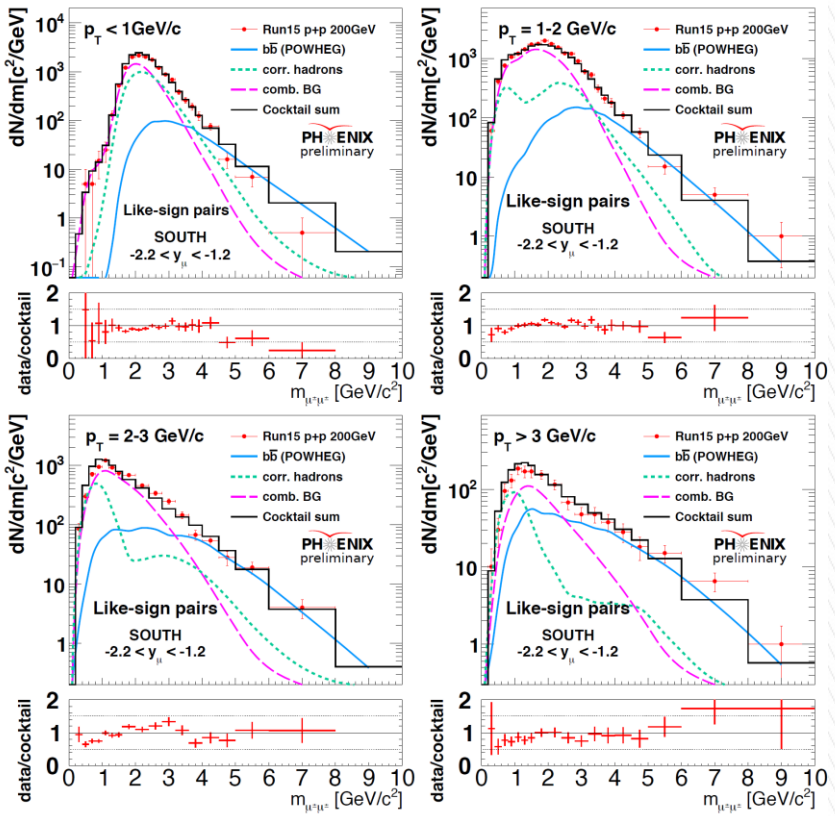


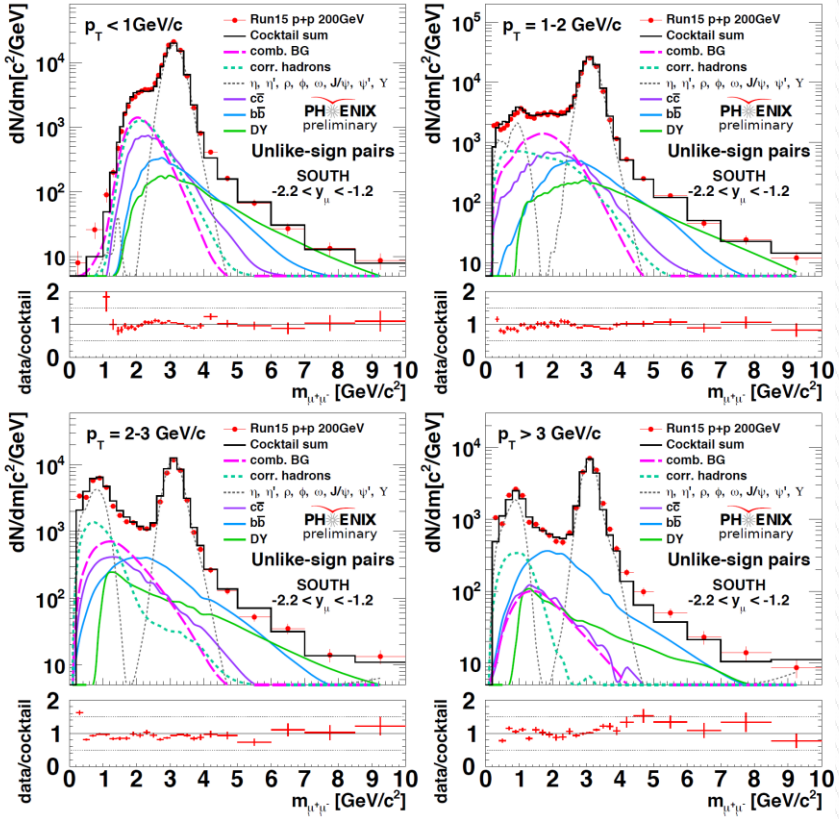


Bottom region

Charm region

Mass-pT fits

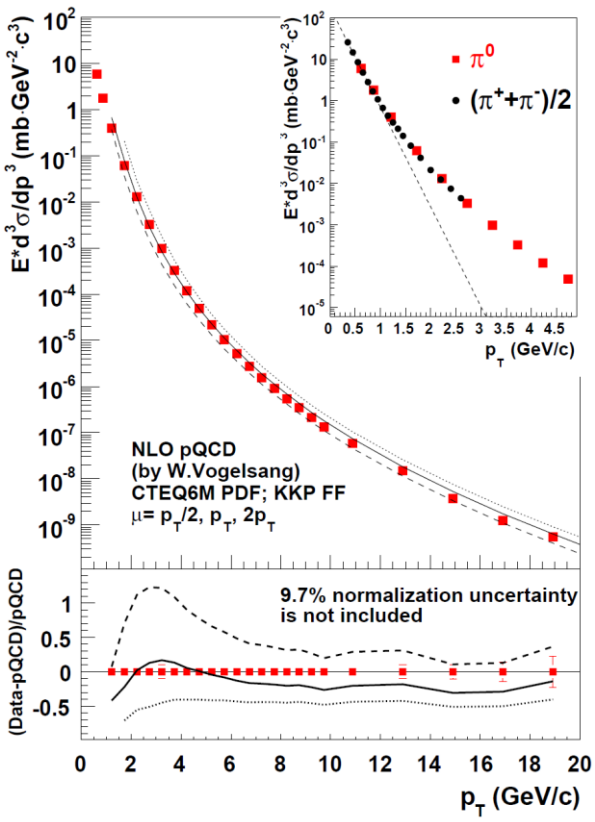


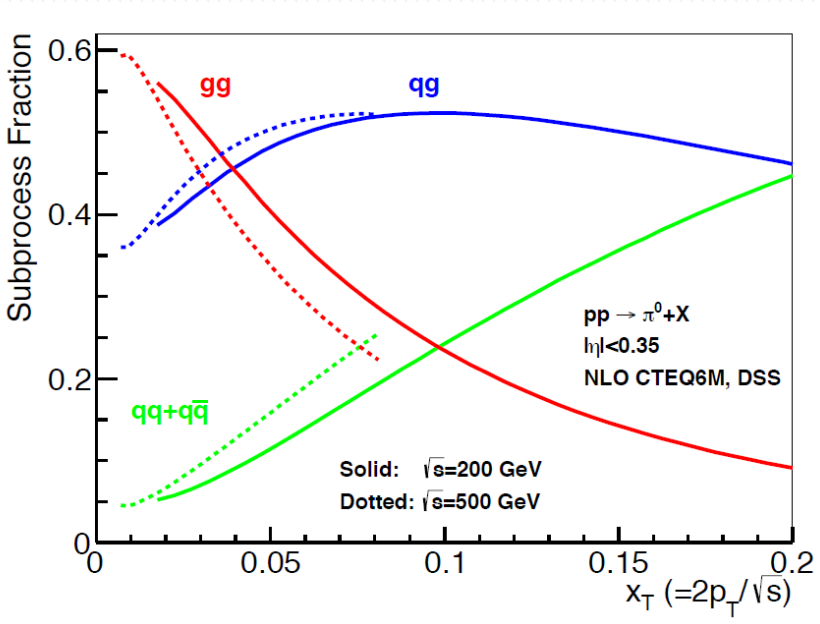


Same sign

Opposite sign

Pion production in |eta|<0.35



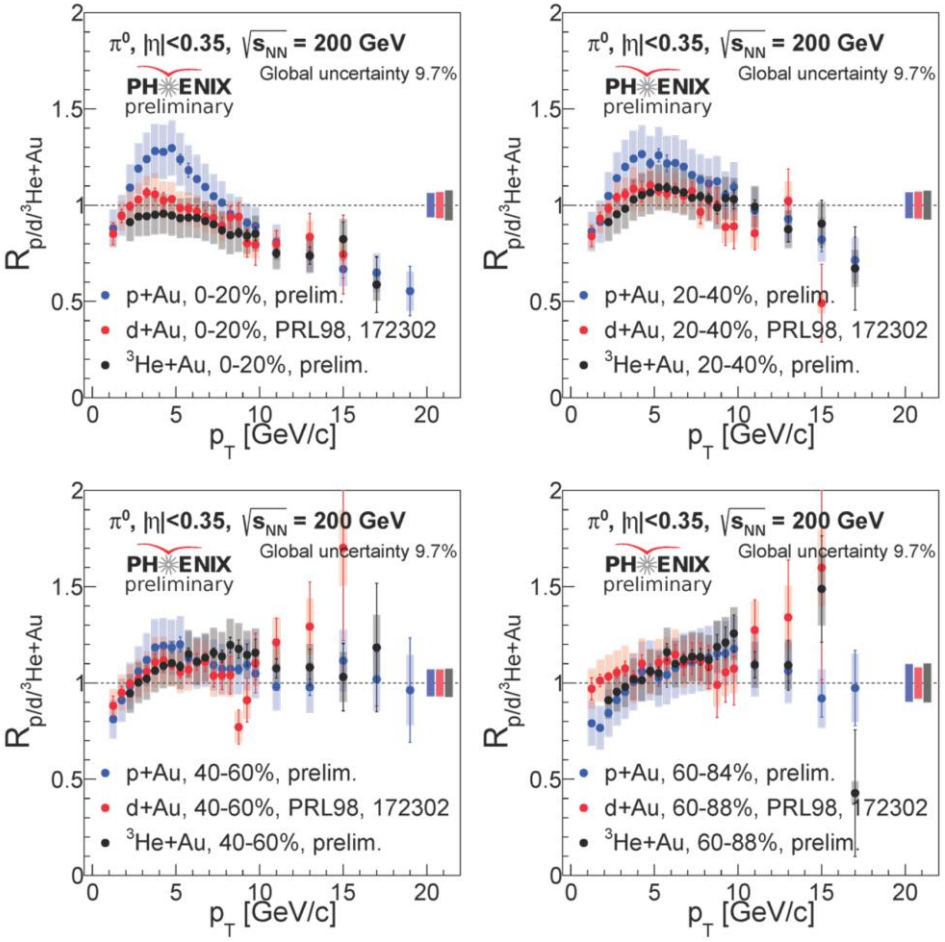


Cross section

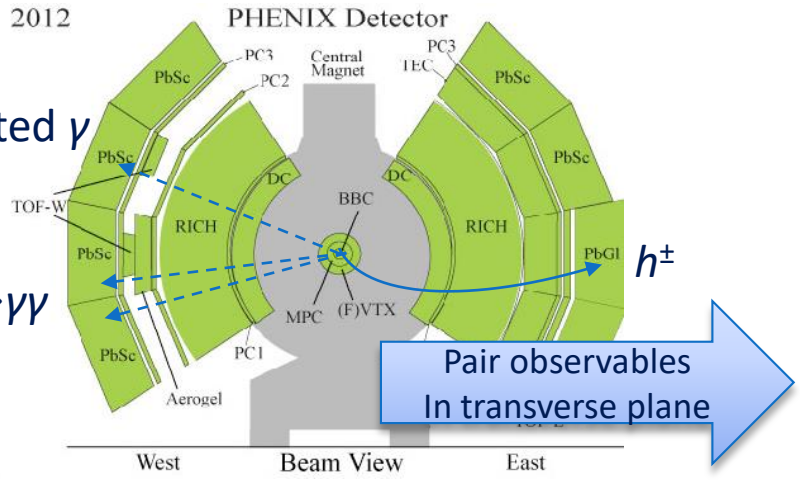
Production channels

Centrality dependence on π^0

- ***p*+Au results show large centrality dependence**
- ***d*+Au results agree with *p*+Au at high-p_T**
- **^{3}He+Au results agree with *p*+Au and *d*+Au at high-p_T**
- **At moderate p_T an ordering is seen as a function of systems**



p_out in p+p collisions



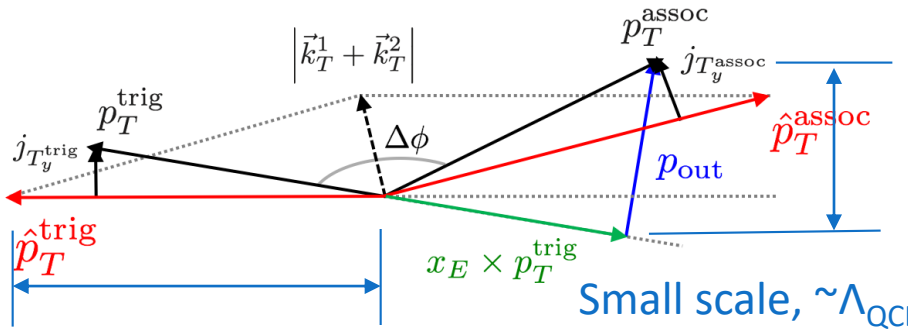
Isolated γ

$\pi^0 \rightarrow \gamma\gamma$

$h^{\pm}$

Pair observables
In transverse plane

Di-hadron production



Small scale, ~Λ_{QCD}

Large scale, ~Q^2

Histogram p_{out}

Relation with energy loss per unit length
DOI: 10.1016/j.physletb.2017.05.090

$$\langle \hat{q}L \rangle /2 = \left[\frac{\hat{x}_h}{\langle z_t \rangle}\right]^2 \left[\frac{\langle p_{\text{out}}^2 \rangle_{AA} - \langle p_{\text{out}}^2 \rangle_{pp}}{x_h^2}\right]$$

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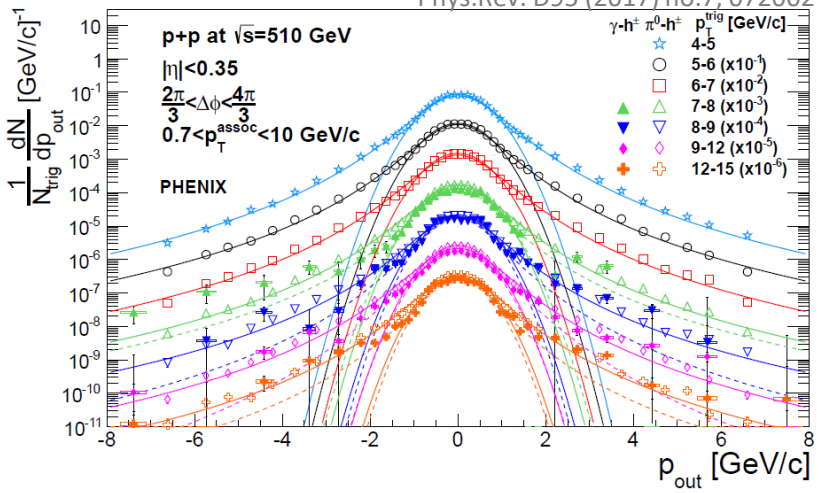
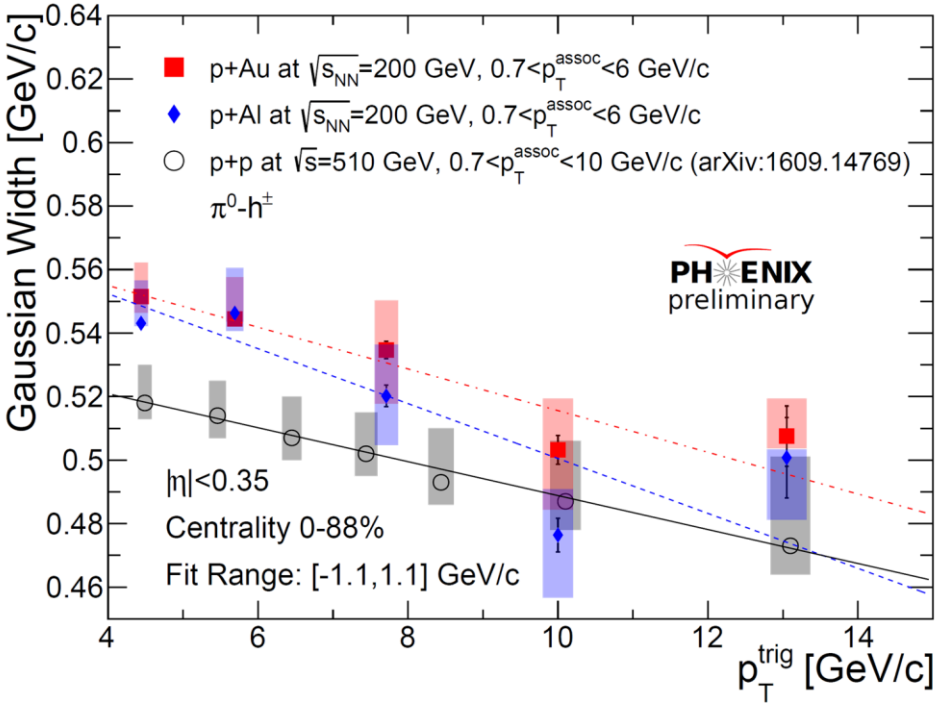
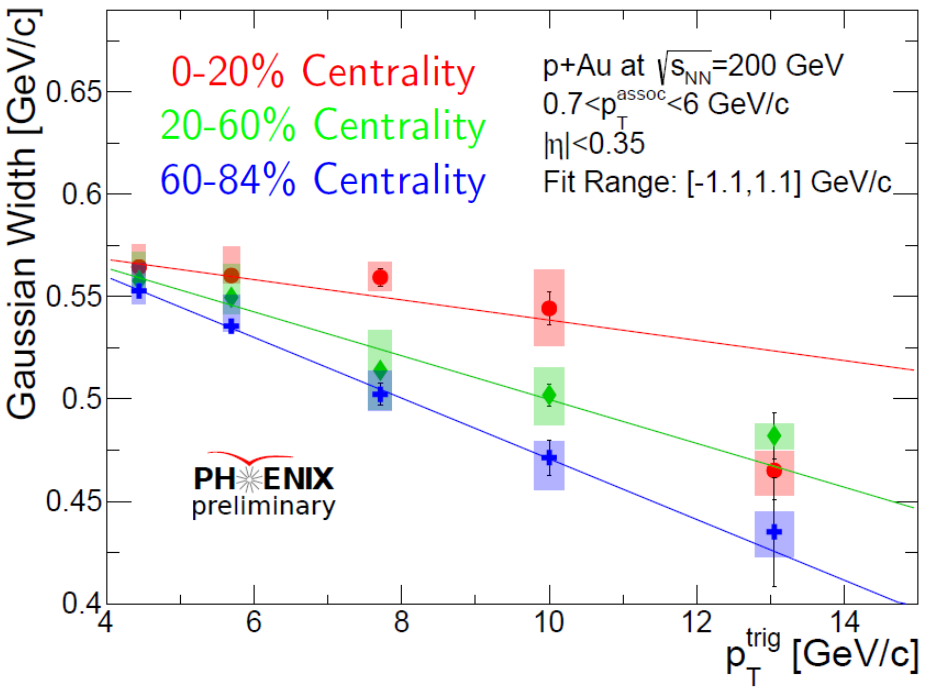


p_out in p + A→π^0 + h (+ X)





- Wider Gauss core for p_{out} in p+A collisions: multiple scattering in A?
- Stronger p_T^{trig} dependence in peripheral p+Au: Ideas for interpretation?

See also: H. Ge (Tue), M. Skoby (Tue)

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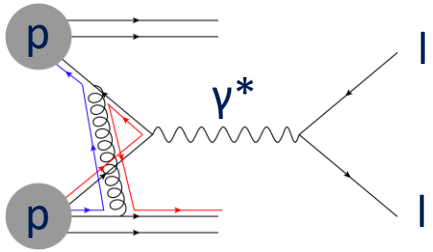
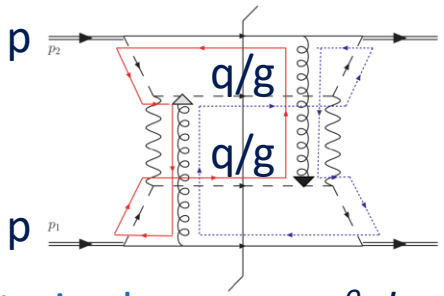
Access the Non-Abelian nature of gluon field





Example of TMD-factorized process:
DY in Pythia simulation
Positive width against scale (M)
As expected in CSS evolution

Non-TMD-factorized process: π^0+h, γ+h
Data and Pythia simulation:
Both show negative width slope against scale (p_T^{trig})
Opposite to CSS indicate impact from color flow

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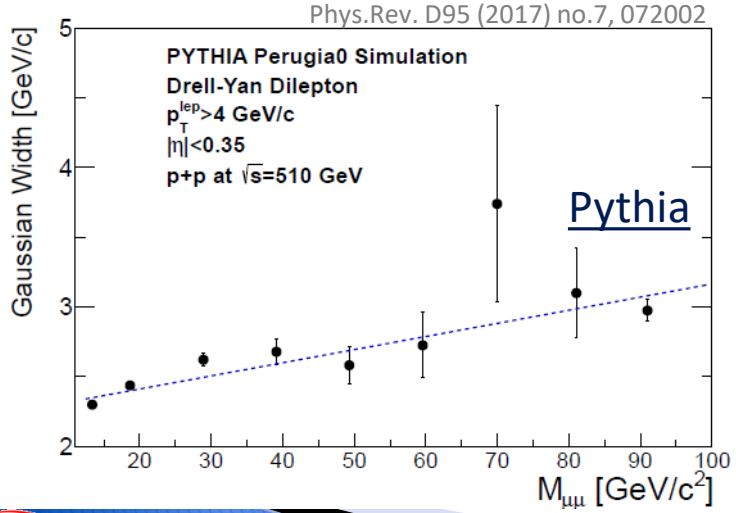
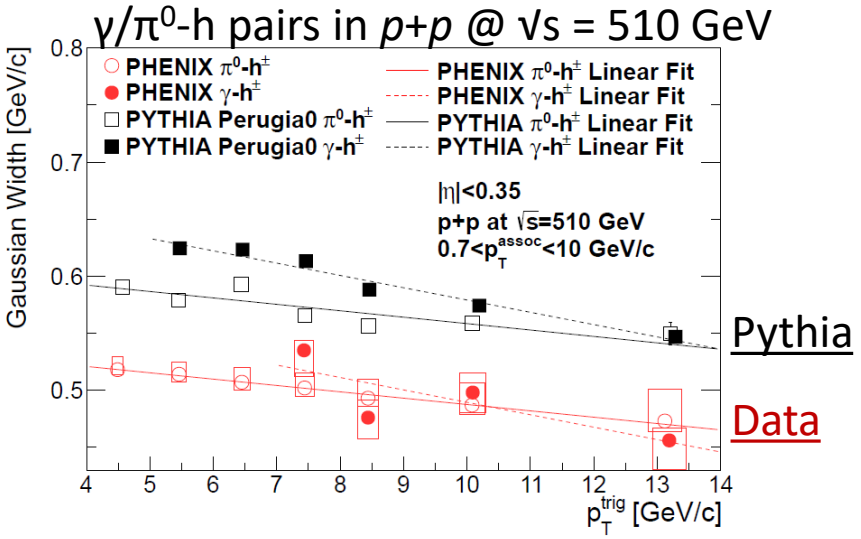
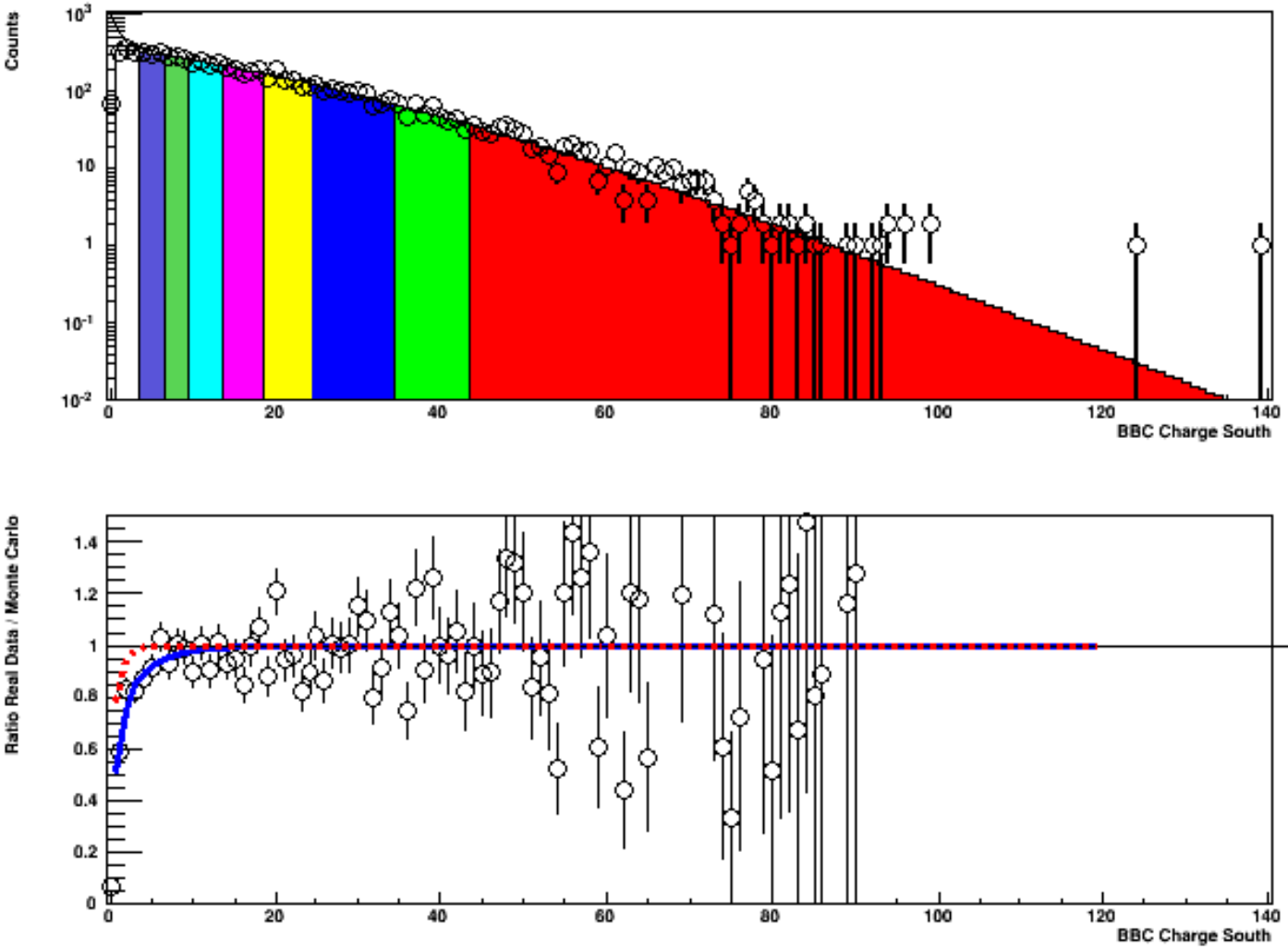




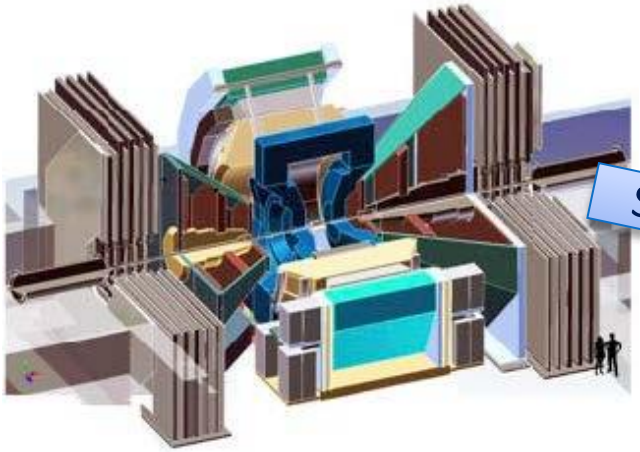
See also: H. Ge (Tue), M. Skoby (Tue)

Centrality p+Au



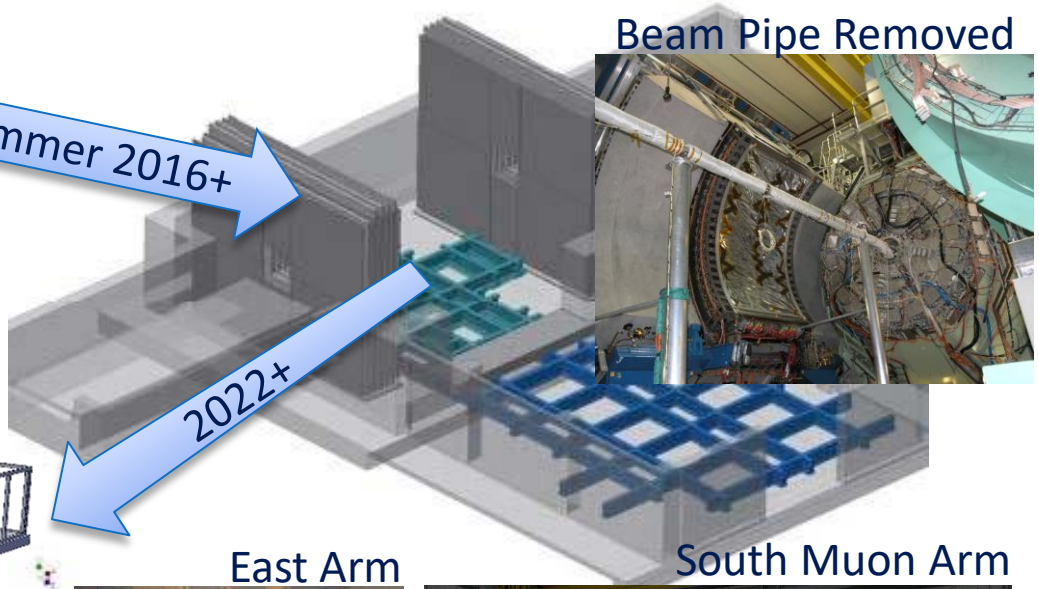
PHENIX hall is being upgraded to sPHENIX

- Many detector preserved, reused in future exp.
- Thanks to the removal and repurposing crew!

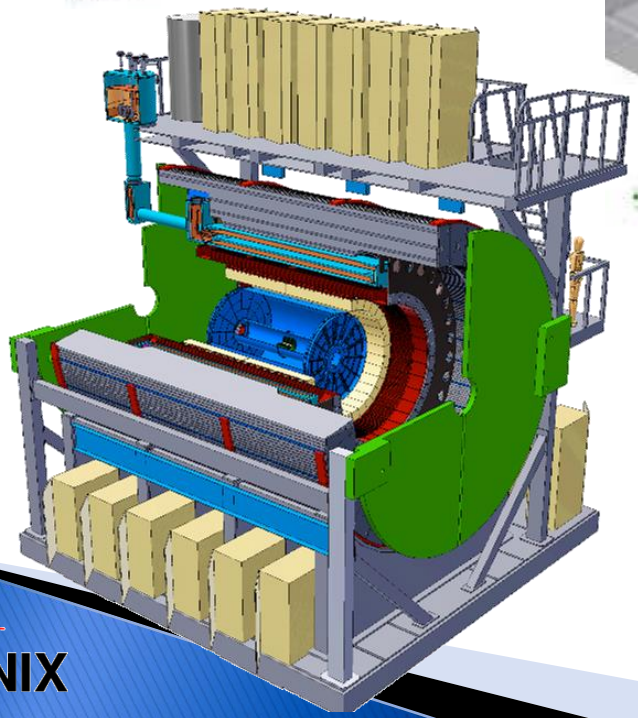


Summer 2016+

Beam Pipe Removed



2022+



East Arm

South Muon Arm