Forward Physics Opportunities at RHIC

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Outline

- Cold QCD interests
- Heavy ion perspectives
- Upgrades for 2021+

2+1 Dimensional Imaging of Proton

Why pp and pA for Cold QCD before EIC?

Complementarity

Two concepts lay the foundation of QCD

factorization & universality

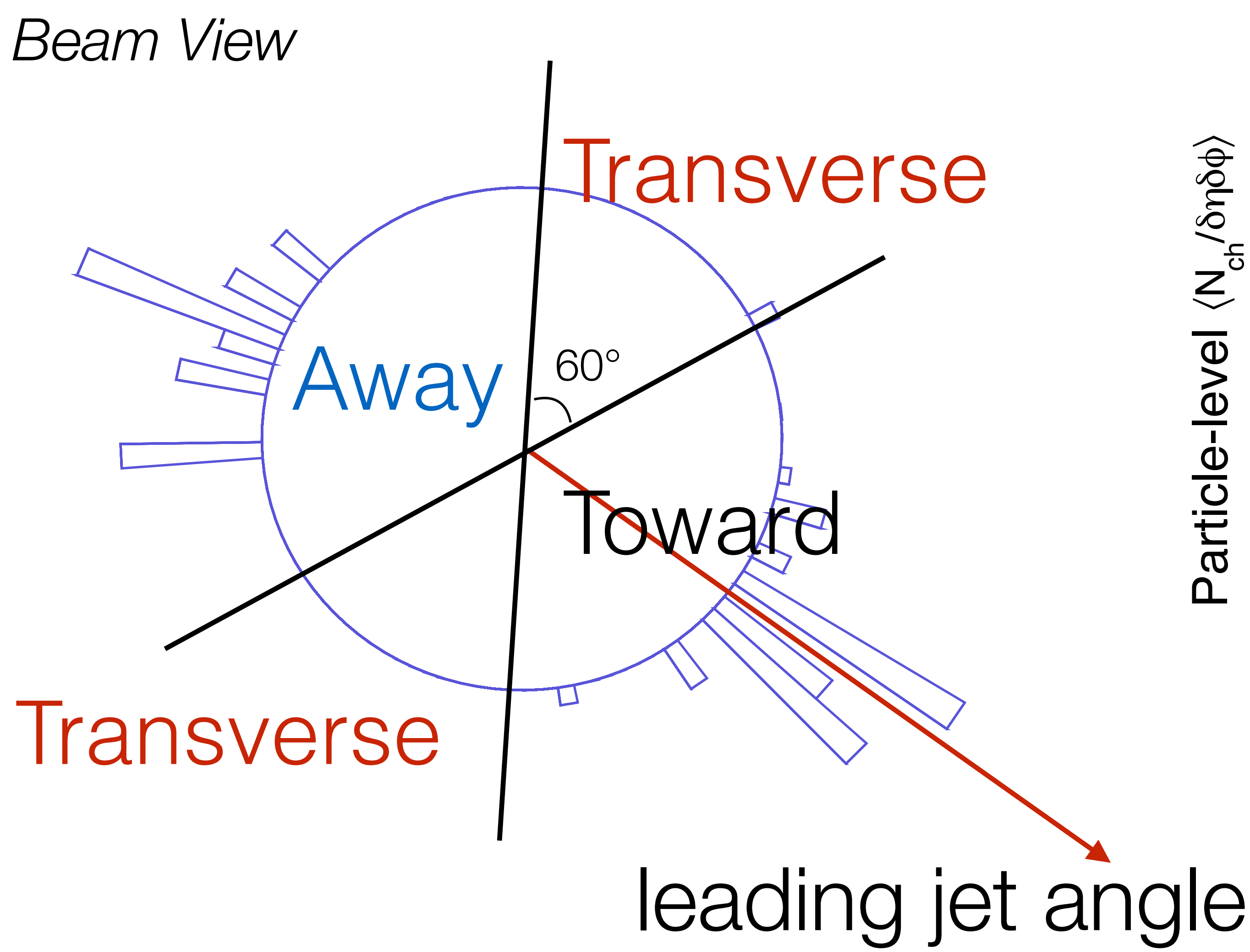
To tests these concepts and separate interaction dependent phenomena from intrinsic nuclear properties

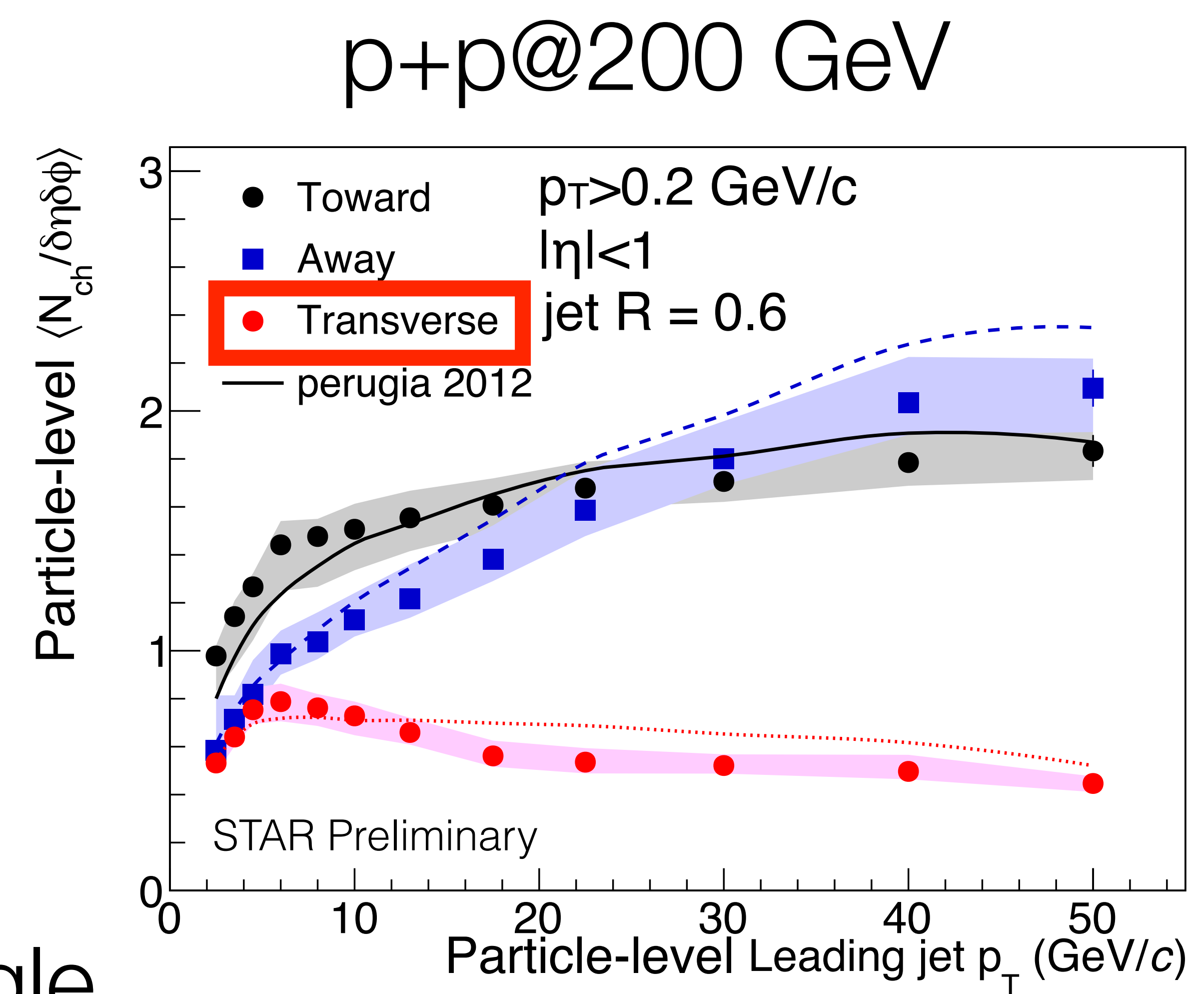
different **complementary** probes are critical

Probes: high precision data from ep, pp, e+e-

credit: E.C. Aschenauer

Jet Underlying Event at Mid-rapidity



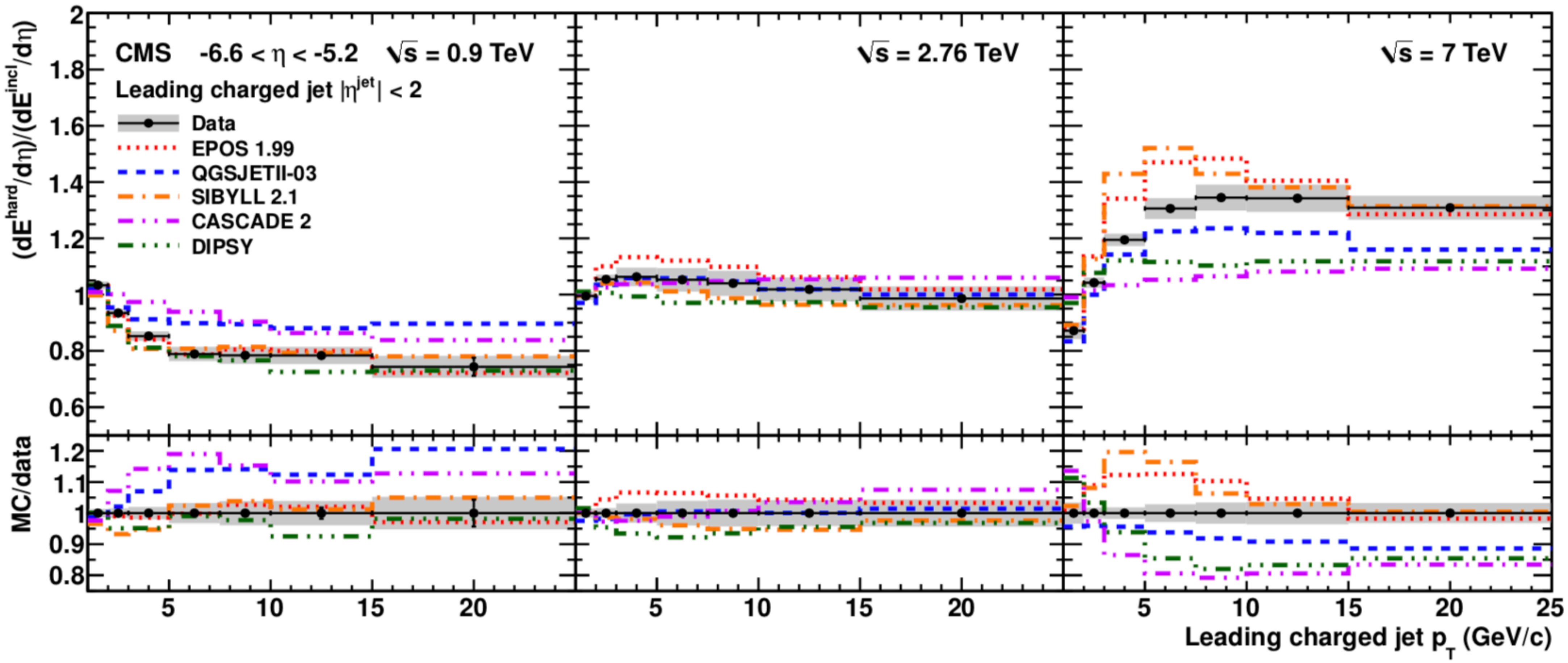


- Multi-parton interaction, initial/final state radiation, color reconnection with beam remnant..
- Involve multiple scales; No formal factorization theorems

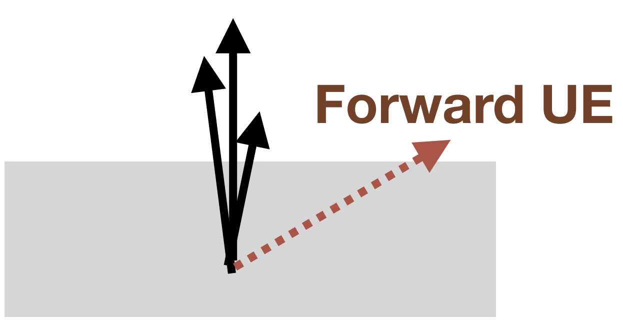
Forward UE with Mid-rapidity jet

CMS, JHEP04(2013)072

Collision energy



Mid-rapidity jet

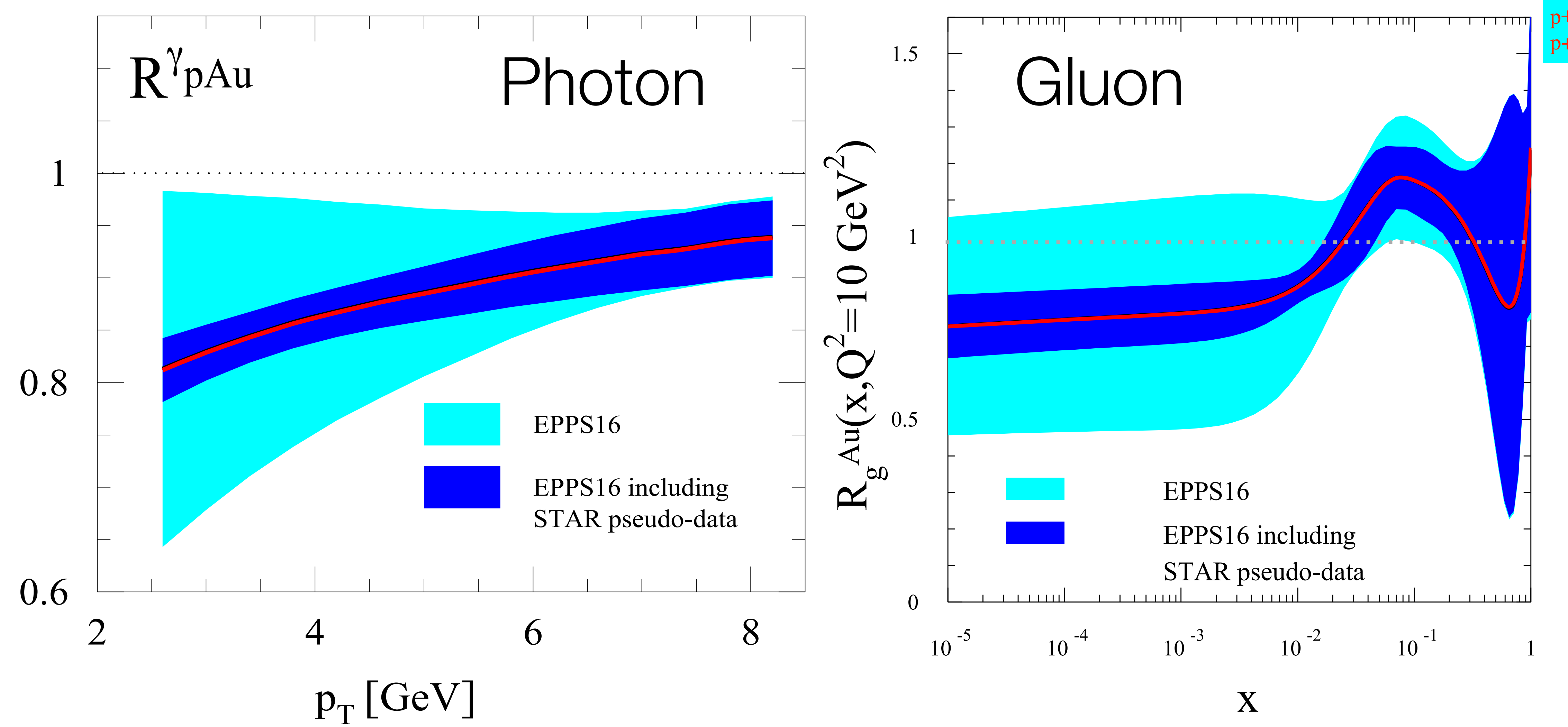


- Energy dependence: kinematic effects?

➡ RHIC energy?

Nuclear Parton Distribution Function (nPDF)

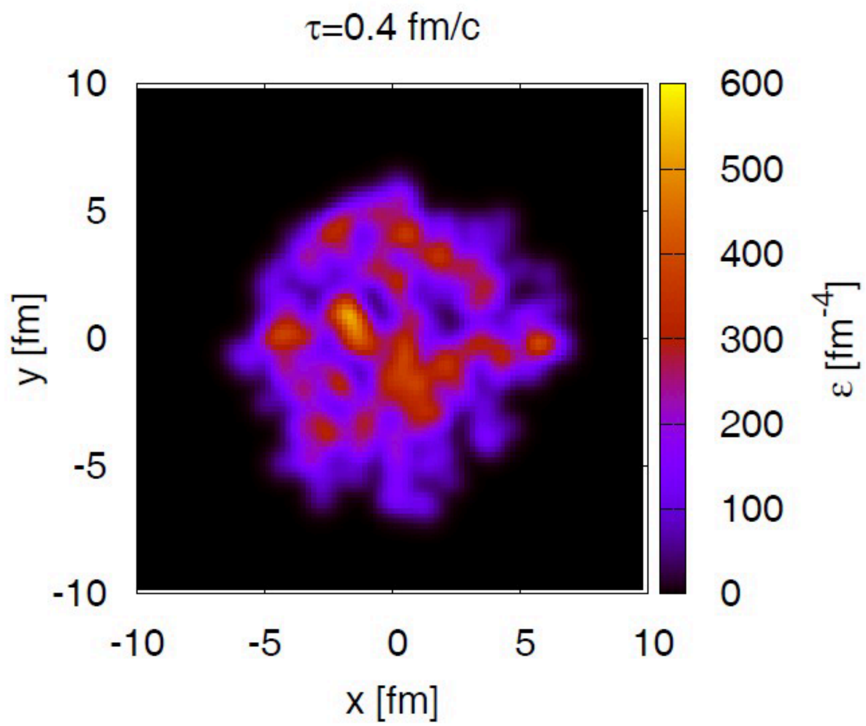
Error estimation with
p+Au@200 GeV 1.8 pb^{-1}
p+p@200 GeV 300 pb-1



- Reveal gluon distribution in nucleus
- Set baseline of cold matter effect for HIC

Toward Mapping 3D Initial State in A+A

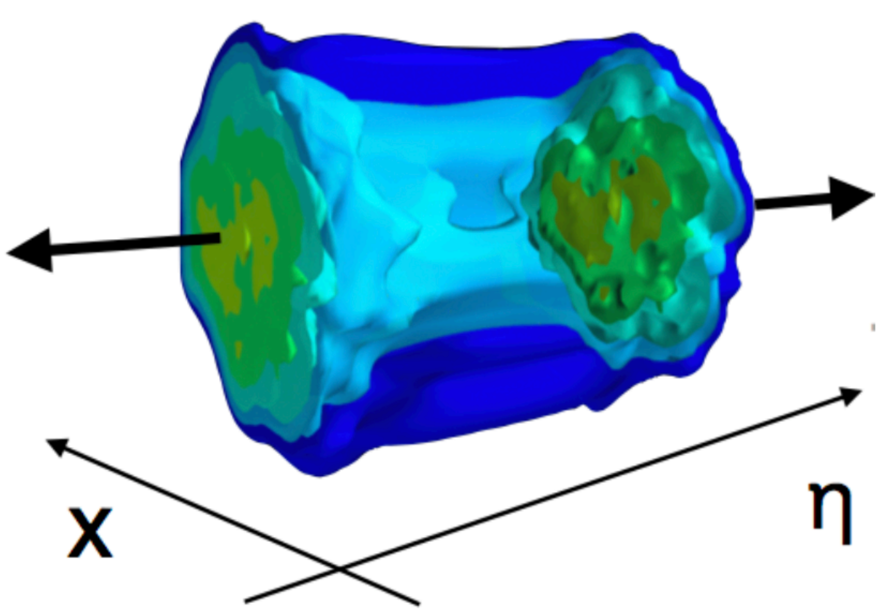
2D



credit: B. Schenke

Initial fluctuation in the transversal plane at mid-rapidity well studied, but very little knew in the longitudinal direction

3D

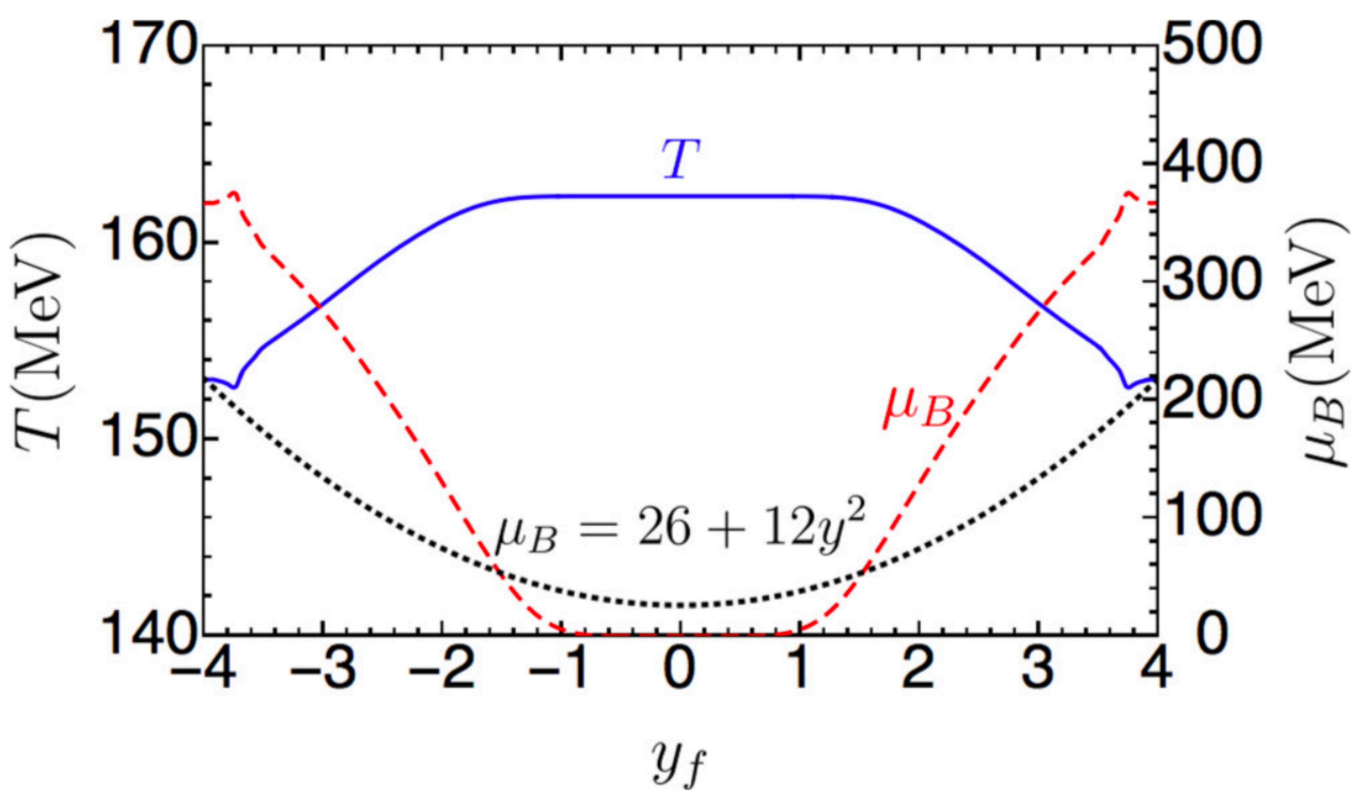


Studying **forward rapidity** to constrain longitudinal structure of initial conditions

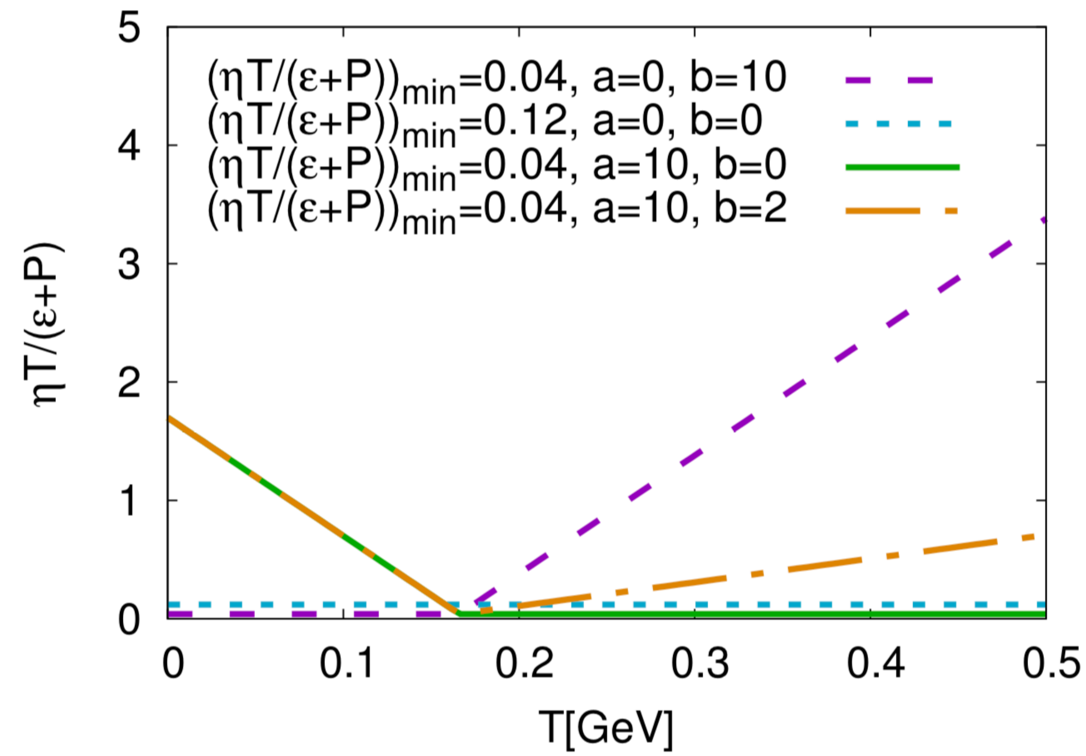
- **perfect fluidity**
- **most vortical**
- **opaque to color object**

Moving forward to constrain the shear viscosity of QCD matter

M.Li, C. Shen, PRC **98**, 064908 (2018)



G. Denicol, A. Monnai, B. Schenke, PRL 116, 212301 (2016)

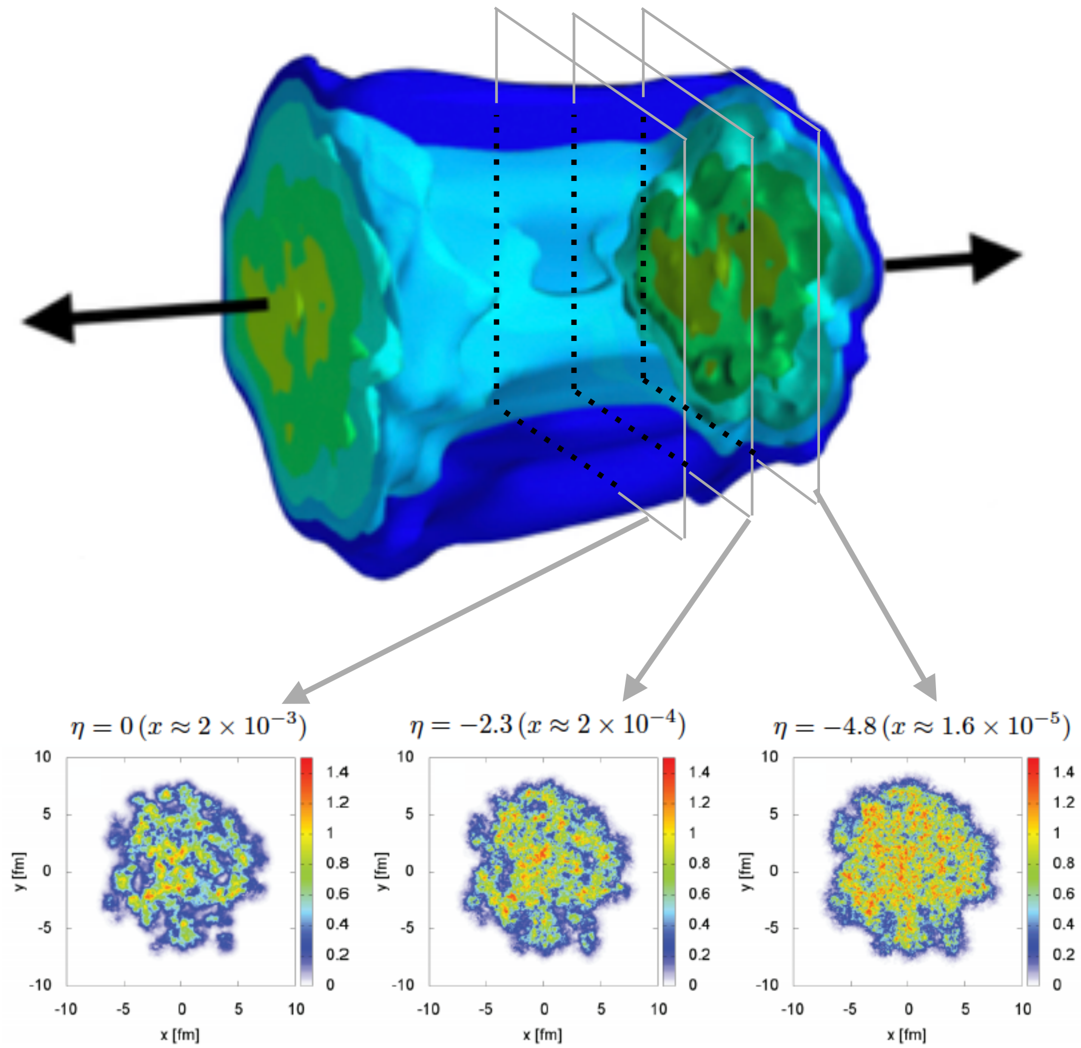


T (and μ_B!) profiles vary longitudinally

(alternative exp. approach to map QCD phase diagram)

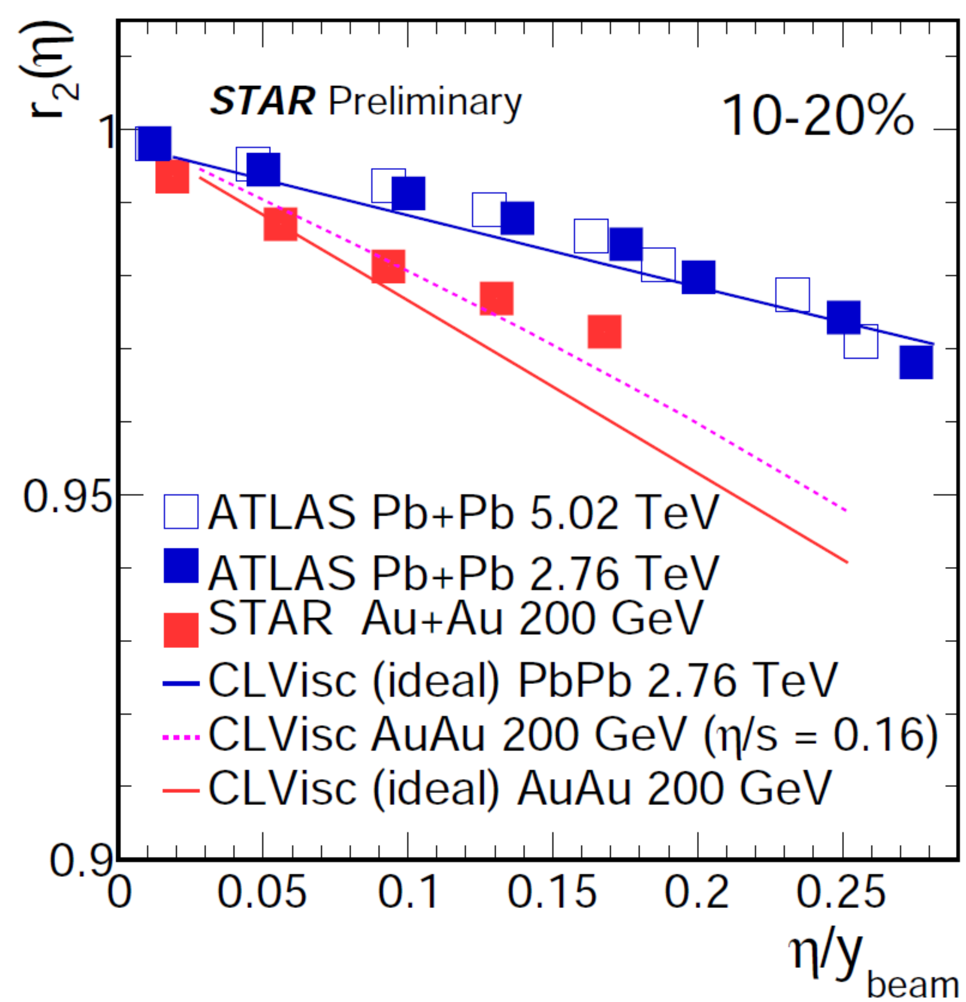
η**/s(T)** can be constrained by $\mathbf{v_n(\eta)}$

Longitudinal Fluctuation by EP de-correlation



Initial density profile is not boost-invariant:

- Fluctuating length of string
- Fluctuation of forward and backward going participants
- Fluctuating strength of string



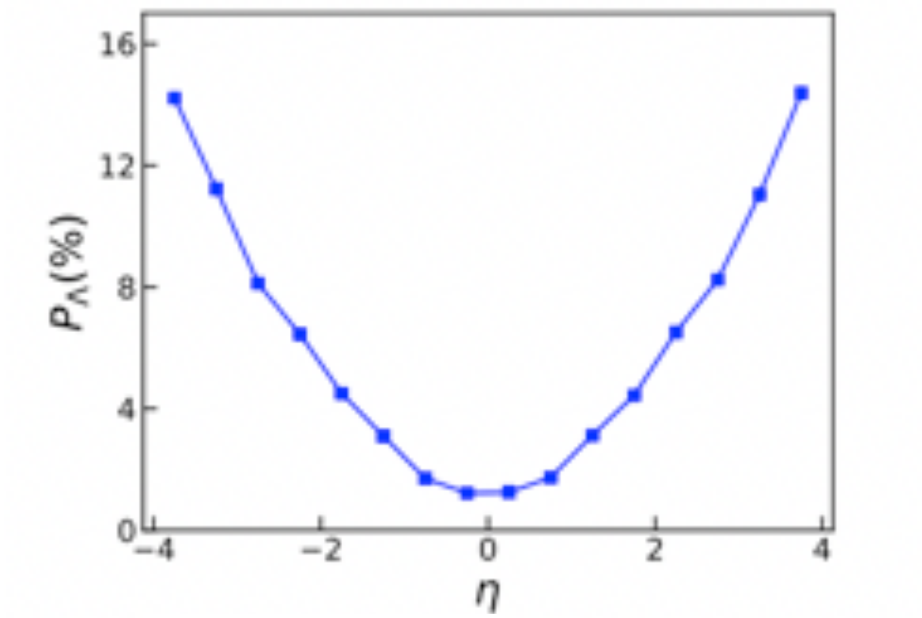
Event Plane de-correlation:

$$r_n \equiv \frac{\langle \vec{V}_n(-\eta^a)\vec{V}_n^*(\eta^b)\rangle}{\langle \vec{V}_n(\eta^a)\vec{V}_n^*(\eta^b)\rangle} \sim \langle \cos n[\Psi_n(\eta^a) - \Psi_n(-\eta^a)]\rangle$$

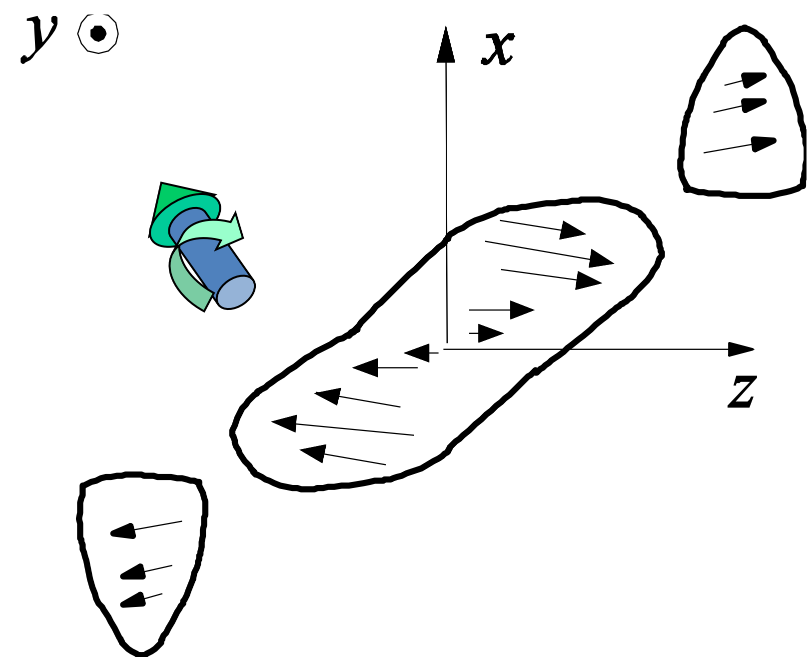
$$Vn = v_n e^{in\Psi n}$$

ATLAS Collaboration, EPJC (2018) 78:142
L. Pang et al, Eur. Phys. J. A 52 (2016) 97
L. Pang et al, arXiv: 1802.04449
STAR, QM18

Global Polarization vs Rapidity

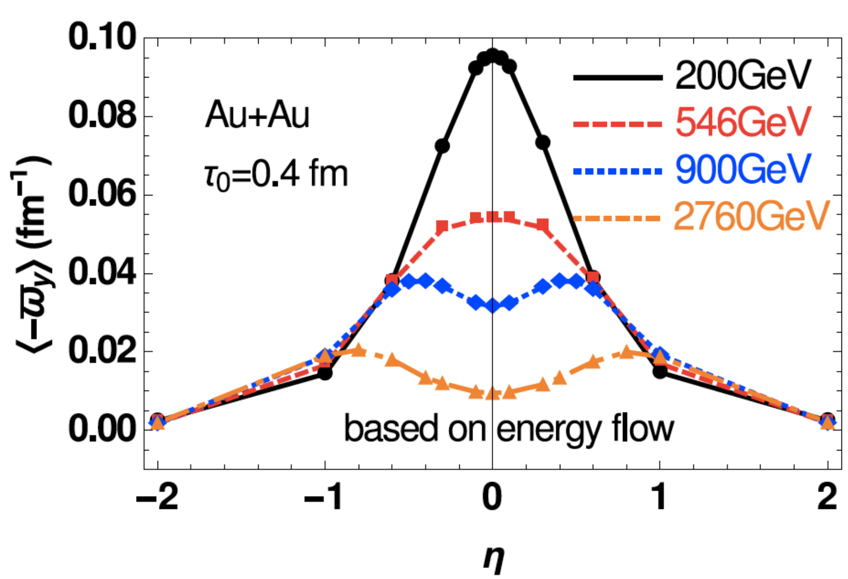


Hydrodynamic calculations:
Li,Pang,Wang&Xia, PRC 96 (2017) 054908; (private comm.)
F. Beccattini et al. EPJC 75(2015)406; arXiv:1501.04468



STAR, *Nature* **548**, 62–65

Liang & Wang, PRL 94 (05) 102301
Liang & Wang, PLB 629(05)20
Gao et al, PRC 77 (08) 044902
Yang, et al arXiv:1711.06008
…



HIJING with energy flow:
Deng&Huang, PRC 93 (2016) 064907
Ko, et al., arXiv:1706.09467

- Most vortical fluid (ω/T ~ 0.001)
- Measured through Λ polarization
- Forward discriminates models

Forward Jets in HIC

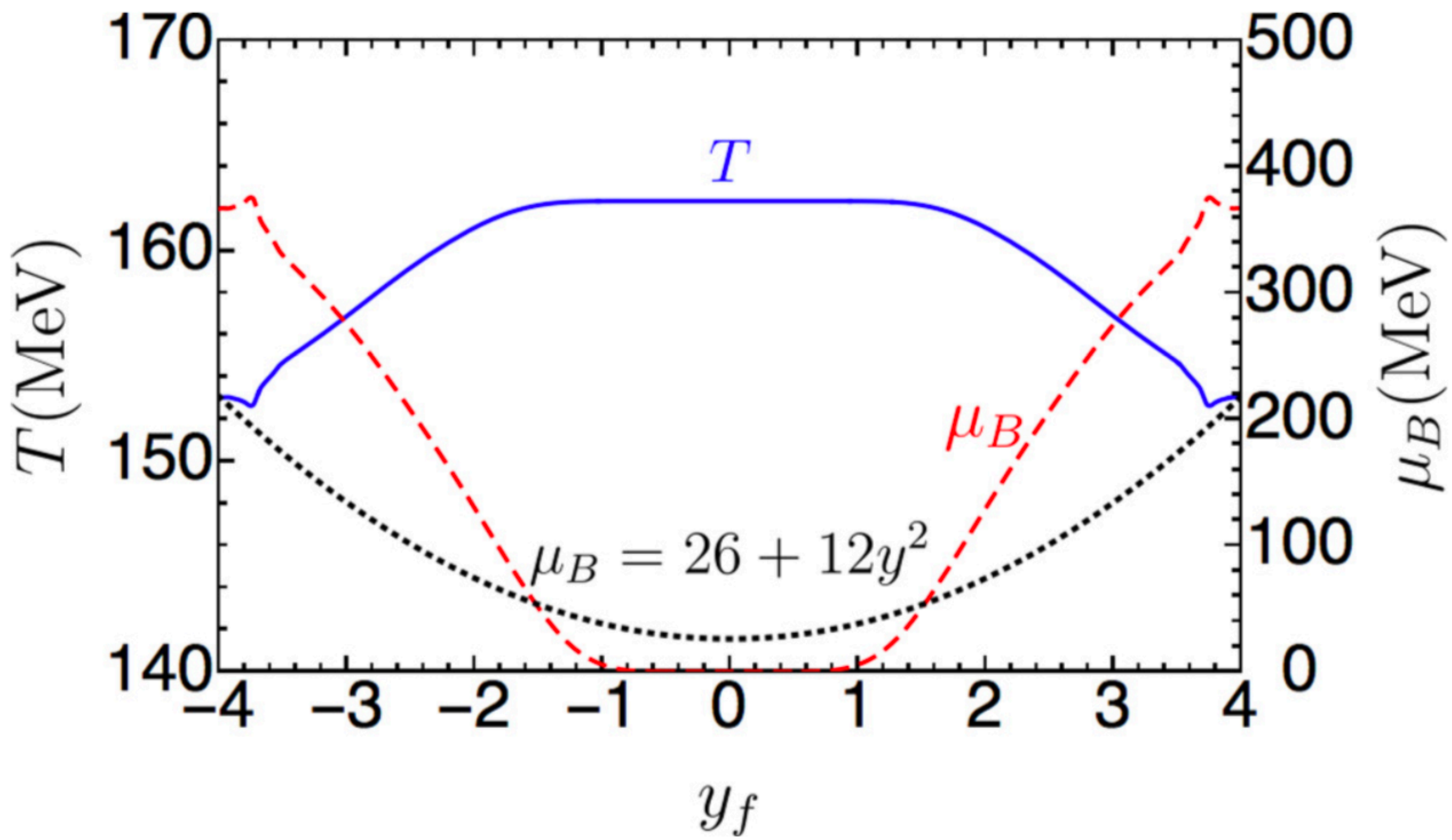
Varying

- Medium profiles
- Parton mixture
- Spectra slope
- Jet shape/sub-structure

w/o the need to compare across different $\sqrt{s}$ and experiments

Medium Profiles

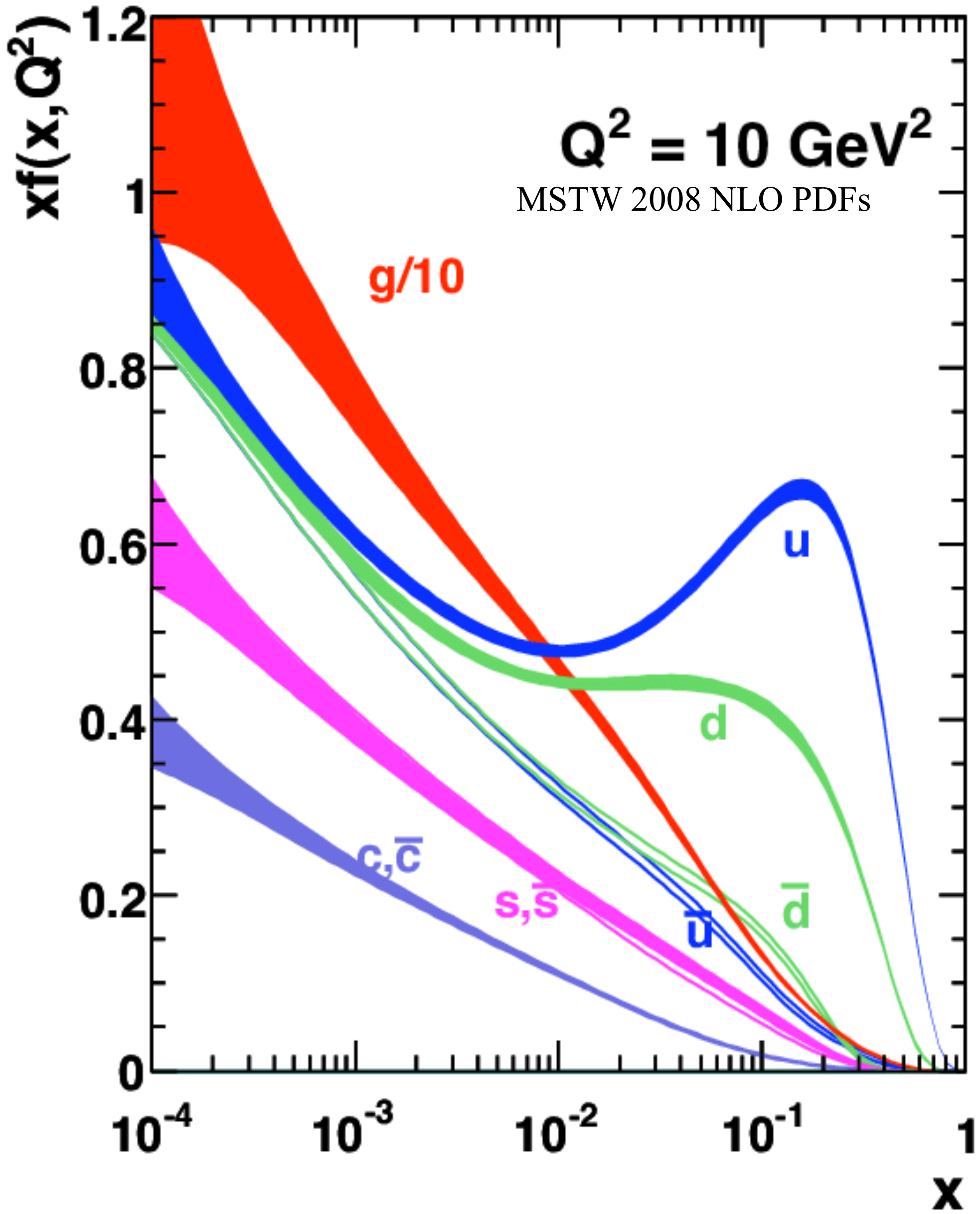
M.Li, C. Shen, PRC **98**, 064908 (2018)



Forward region: lower T, higher μ_B

Parton Mixture

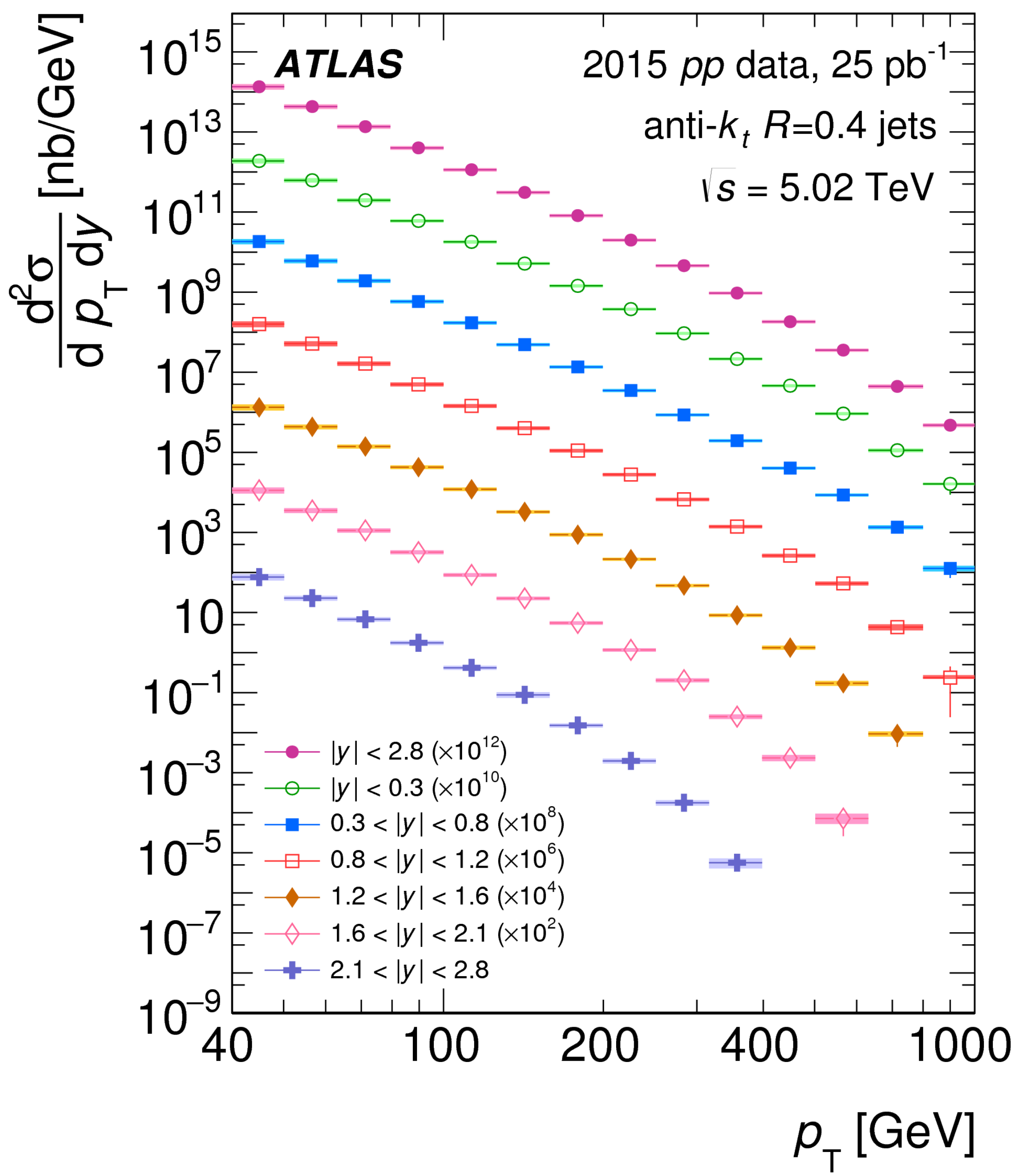
Martin *et al*., EPJC63 (2009) 189



Higher gluon density

Spectra Slope

ATLAS, PLB 790 (2019) 108–128



mid-rapidity

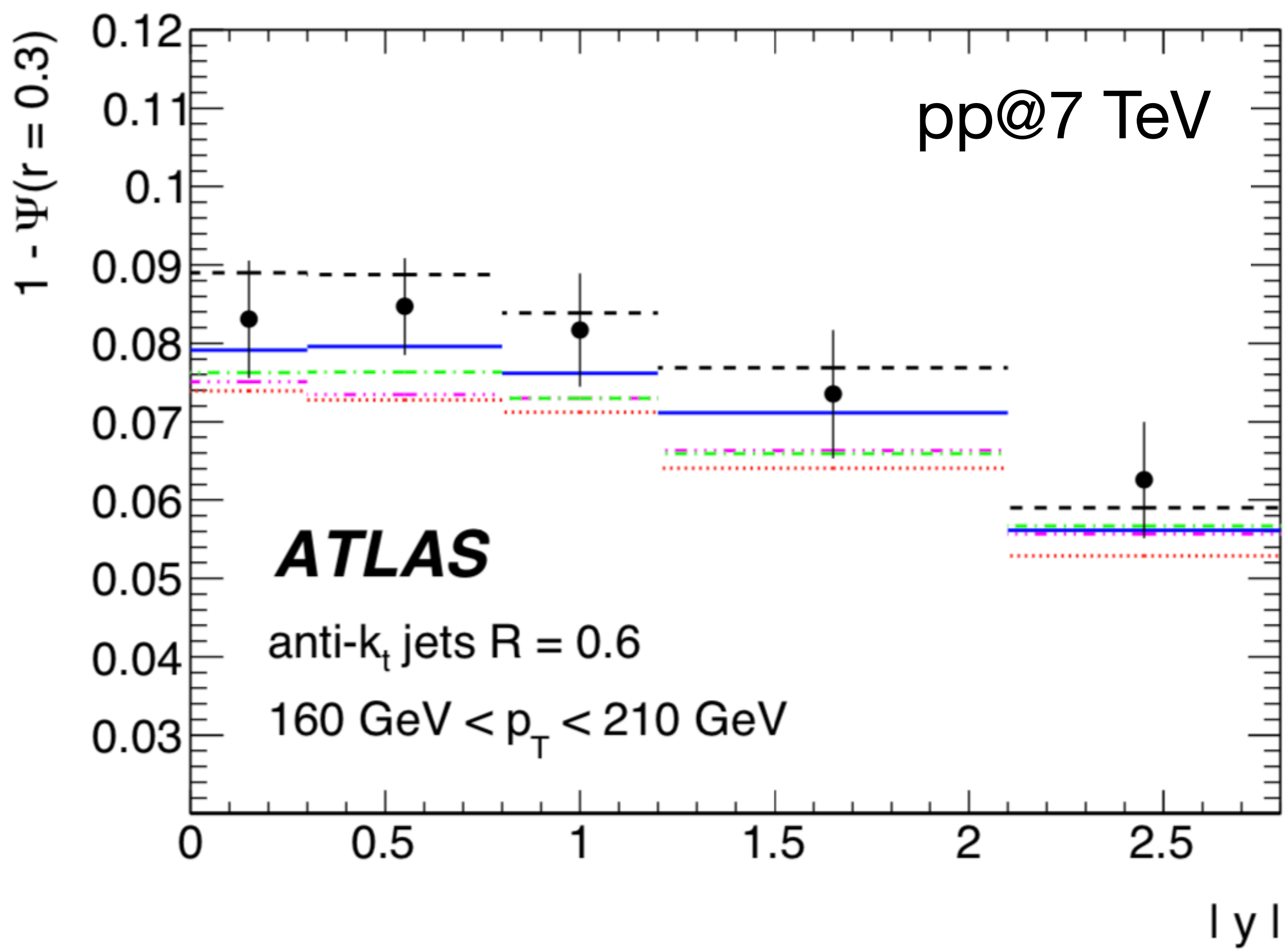
forward

Steeper falling

Jet Shape/Sub-structure

$$\Psi(r) = \frac{1}{N^{\rm jet}} \sum_{\rm jets} \frac{p_T(0,r)}{p_T(0,R)},\ 0 \le r \le R$$

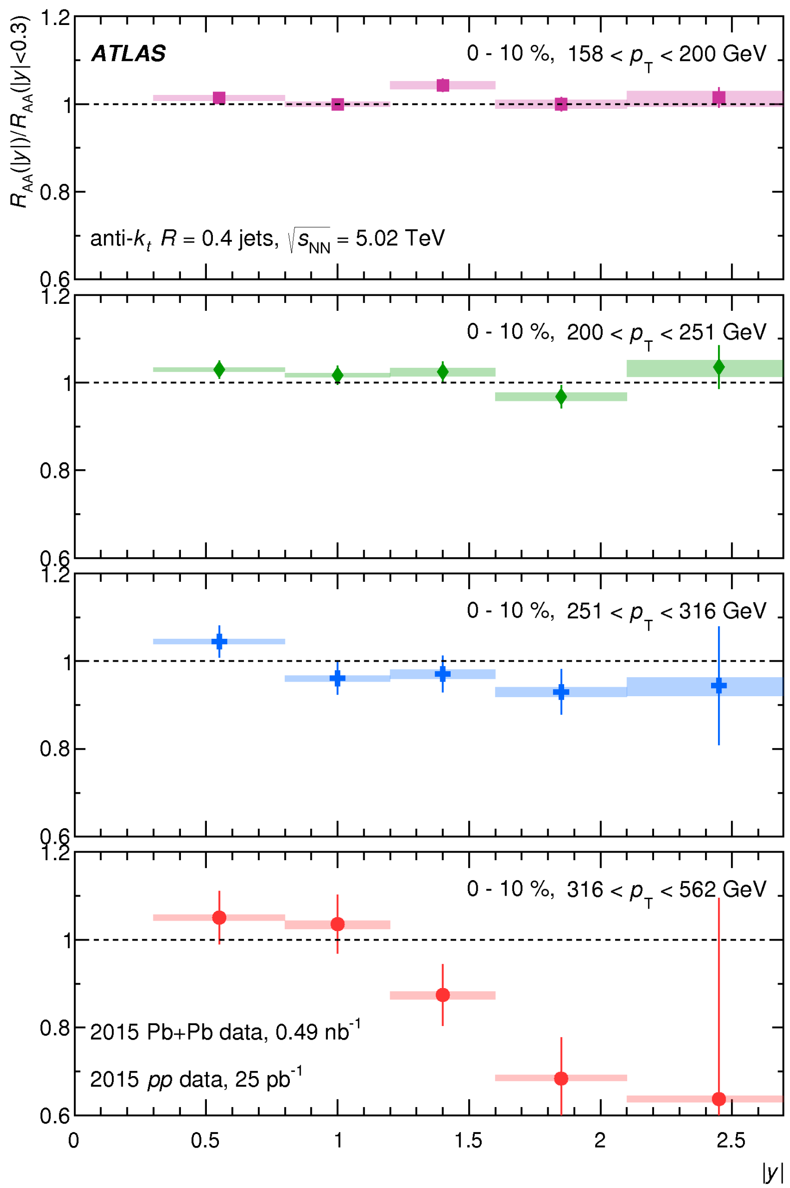
ATLAS, PRD.83.052003



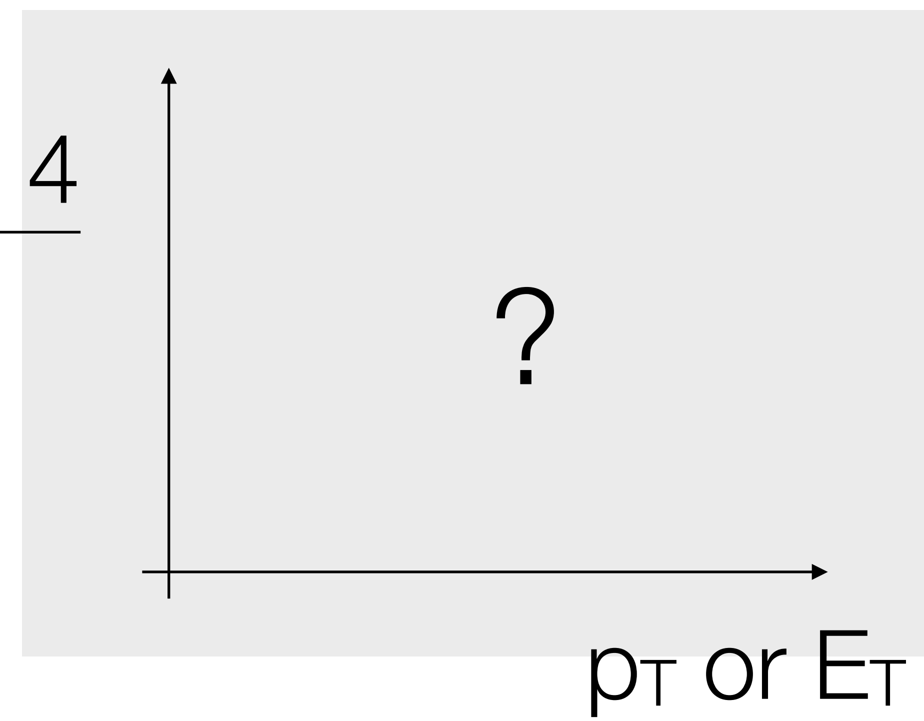
Slighter narrower

Explore Medium Profiles with Forward Jets

ATLAS, PLB 790 (2019) 108–128



$$\frac{2.5 < \eta < 4}{|\eta| < 1}$$



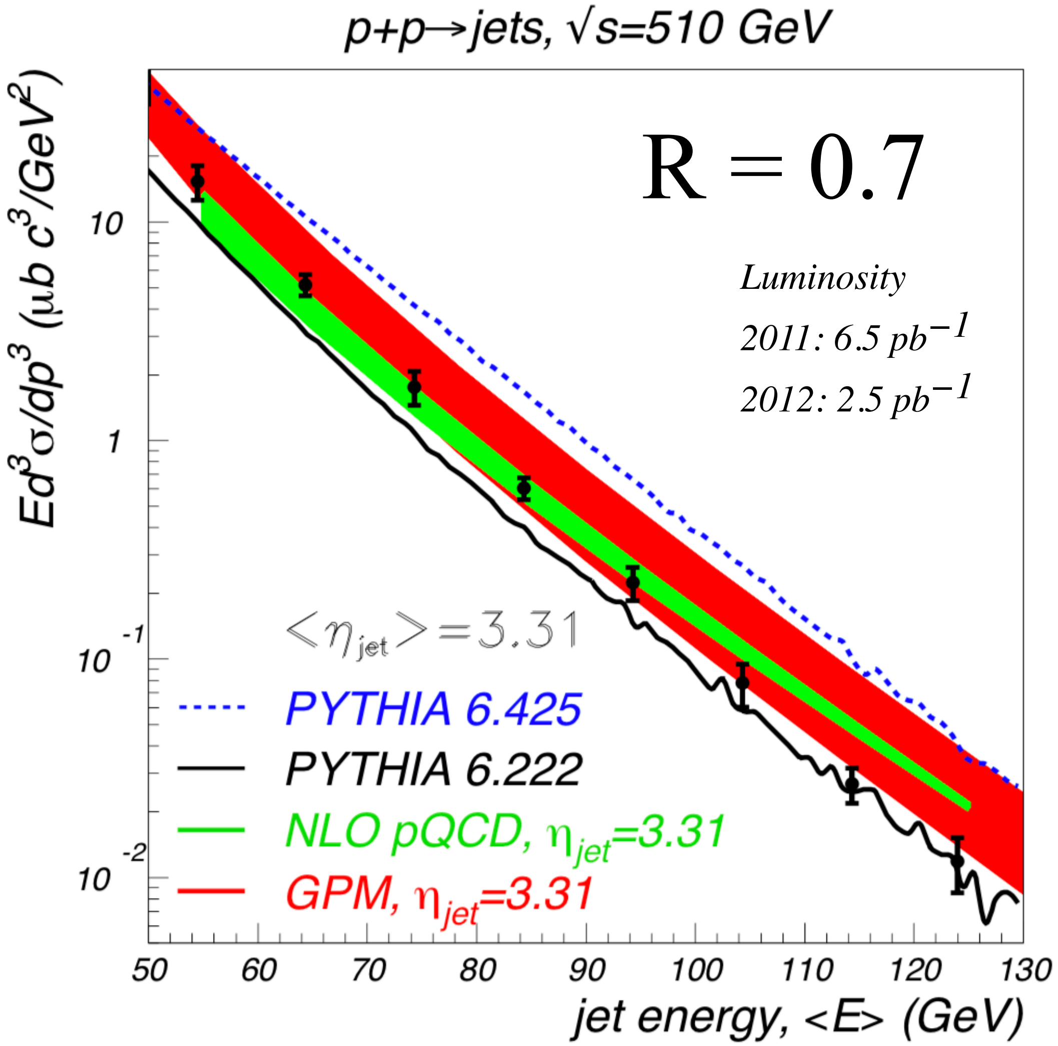
At RHIC?

At LHC:
More suppression at forward for high p_T

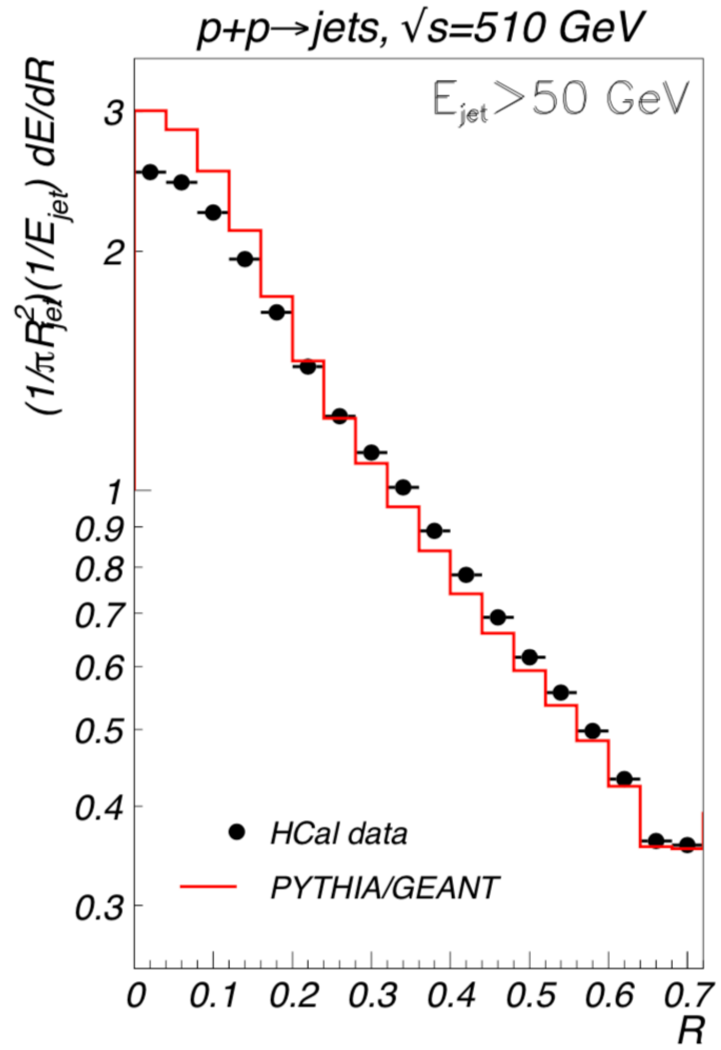
Forward Jet in pp@500 GeV

A_N DY, PLB 2015 10 001

jet cross section



jet shape



Good jet statistics at forward $(2.4 < \eta < 4.0)$

What will Come

Proposed RHIC runs (one version):

2021	$p^{\uparrow}p$@510	1.1 fb^{-1}
2021	$\vec{p}\vec{p}$@510	1.1 fb^{-1}
2023	$p^{\uparrow}p$@200	300 pb^{-1}
2023	$p^{\uparrow}Au$@200	1.8 pb^{-1}
2023	$p^{\uparrow}Al$@200	12.6 pb^{-1}
2024/2025	AuAu@200	1B MB

Forward Program

Objective:

unique program addressing several fundamental questions in QCD

-> essential to

- the mission of the RHIC physics program in cold and hot QCD
- fully realize the scientific promise of the EIC
  - lay the groundwork, scientifically & by refining exp. requirements
  - detector technologies under real conditions

Scientific goals:

p+p:

3-dim. imaging of the proton in momentum and spatial coordinates

p+A

Nature of initial state and hadronization in nuclear collisions

Onset and A-dependence of saturation

A+A

Longitudinal medium characterization

Flow + vorticity + jet

Forward Upgrade: fSTAR

https://drupal.star.bnl.gov/STAR/system/files/Proposal.ForwardUpgrade.Nov_.2018.Review.pdf

Requirements:

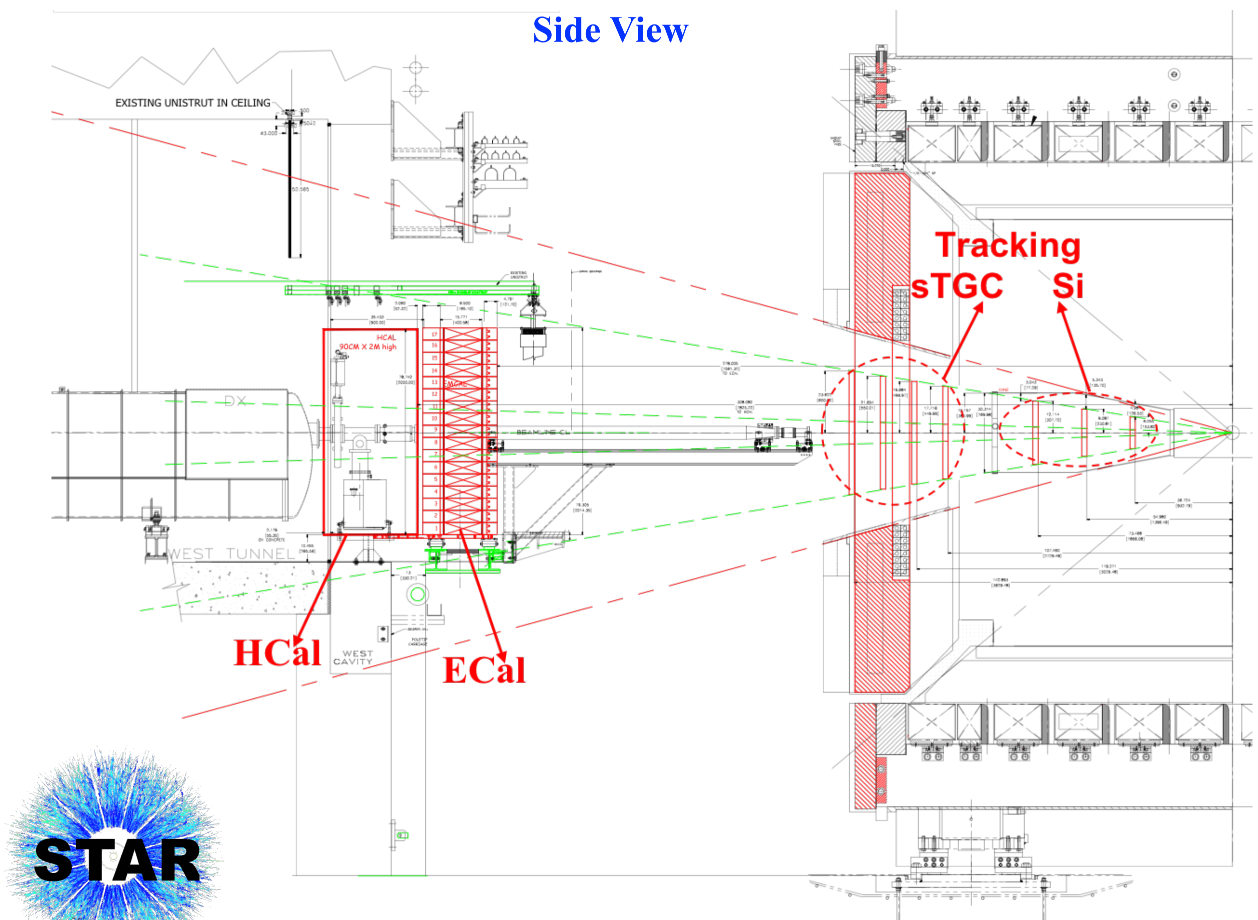
measure jets, photons, electrons, charged particles

STAR forward upgrade:

Coverage: $2.5 < \eta < 4$

Calorimetry:
Electromagnetic and Hadronic

Tracking:
Silicon detectors and
small-strip Thin Gap Chambers (sTGC)



Detector	pp and pA	AA
ECal	~10%/√E	~20%/√E
HCal	~50%/√E+10%	---
Tracking	charge separation photon suppression	$0.2<p_T<2$ GeV/c with 20-30% $1/p_T$

Forward Upgrade: fSTAR

Requirements:
measure jets, photons, electrons, charged particles

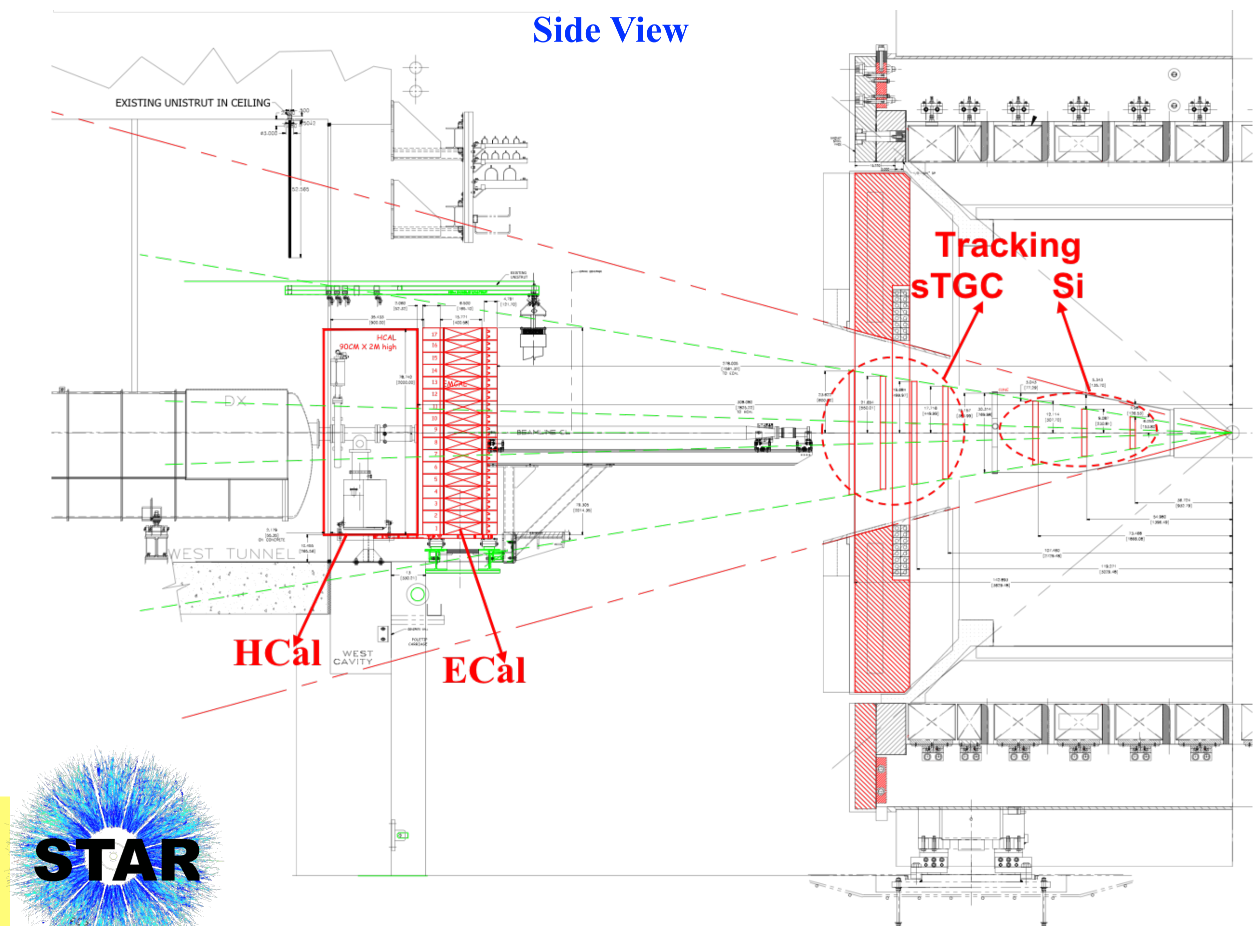
STAR forward upgrade:
Coverage: $2.5 < \eta < 4$

Calorimetry:
Electromagnetic and Hadronic

Tracking:
Silicon detectors and
small-strip Thin Gap Chambers (sTGC)

SDU contributes to

https://drupal.star.bnl.gov/STAR/system/files/Proposal.ForwardUpgrade.Nov_.2018.Review.pdf



Detector	pp and pA	AA
ECal	~10%/√E	~20%/√E
HCal	~50%/√E+10%	---
Tracking	charge separation photon suppression	$0.2<p_T<2$ GeV/c with 20-30% $1/p_T$

Forward Upgrade: fsPHENIX

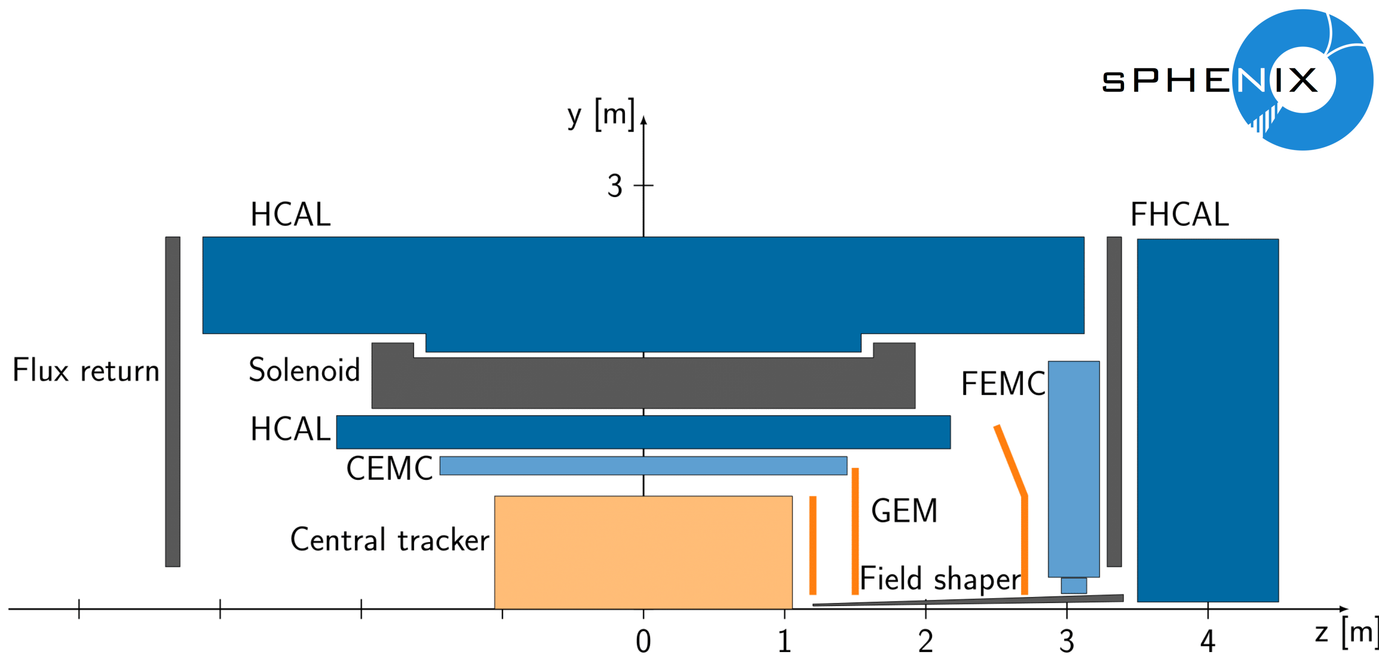
sPHENIX forward design:
Coverage: 1.2 < η < 4

Default choice

Calorimetry*:
Electromagnetic (PbSc + $PbWO_4$)
Hadronic (PbSc with SiPMs)

Tracking*:
Gas electron multiplier (GEM)

https://www.sphenix.bnl.gov/web/system/files/sPH-cQCD-2017-001_draft_2017_06_02.pdf



Tracking: $dp/p < 10\%$ for $0 < p < 30$ GeV/c
ECal: $\sigma_E/E \sim 8\%/E\ (GeV)$ PbSc
$\sigma_E/E \sim 12\%/E\ (GeV)$ $PbWO_4$
Hcal: $70\%/E(GeV)$

* default choice

Summary

The Forward program at RHIC is

- A tale of initial state: nucleon to nuclei
- 3-D imaging of HIC with flow + vorticity + jet + …
- A portal to EIC

Detector upgrades Now - 2021 for running in 2021-2025

SHANDONG UNIVERSITY

Thanks to E. A. Aschenauer, H. Caine, G. Y. Qin, L. Ruan, Q. Xu for their inputs!

Join Us to work on:

Detector upgrade

Forward simulation

HIC & Spin physics ..

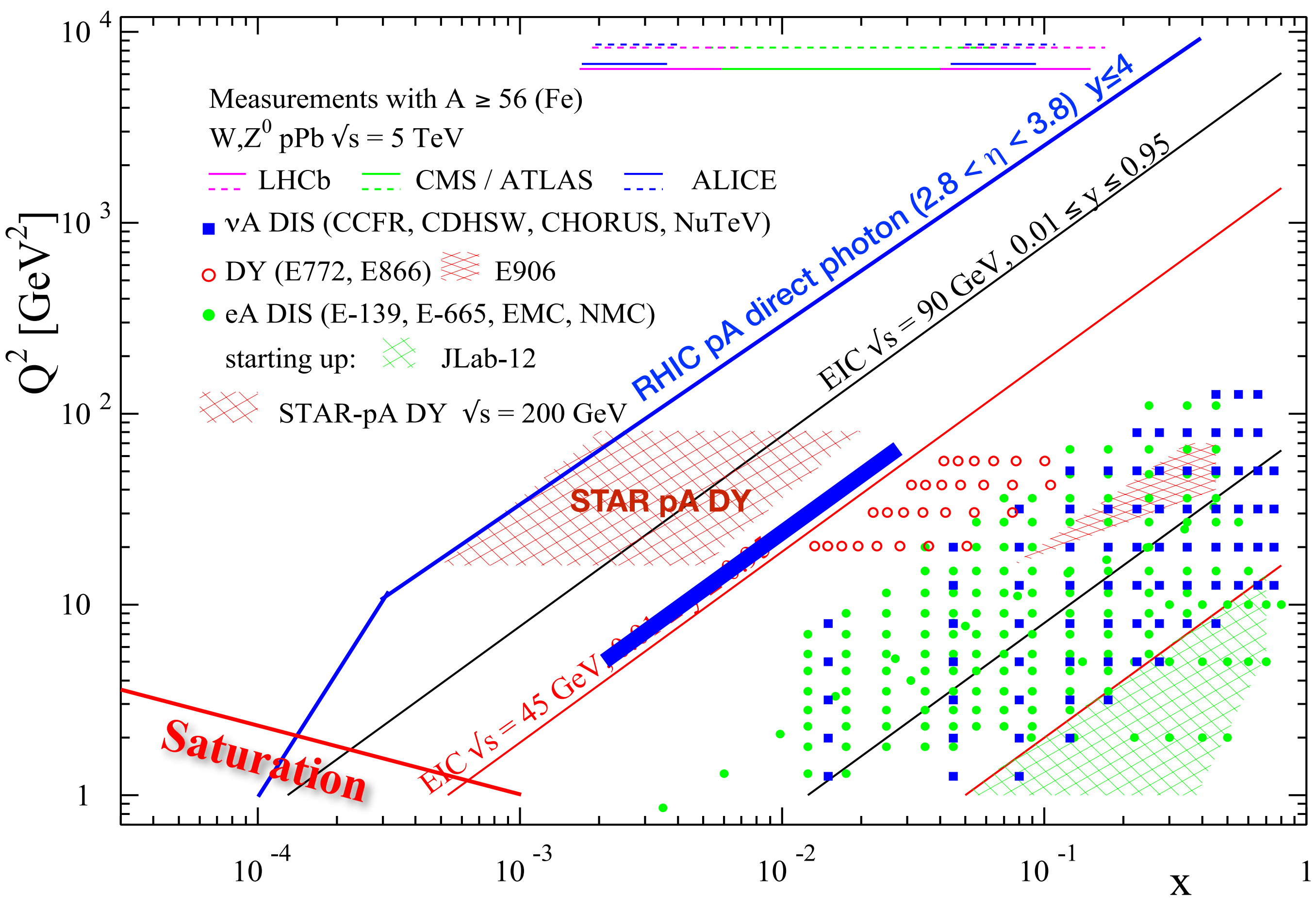
Shandong University
Qingdao Campus

We're hiring:

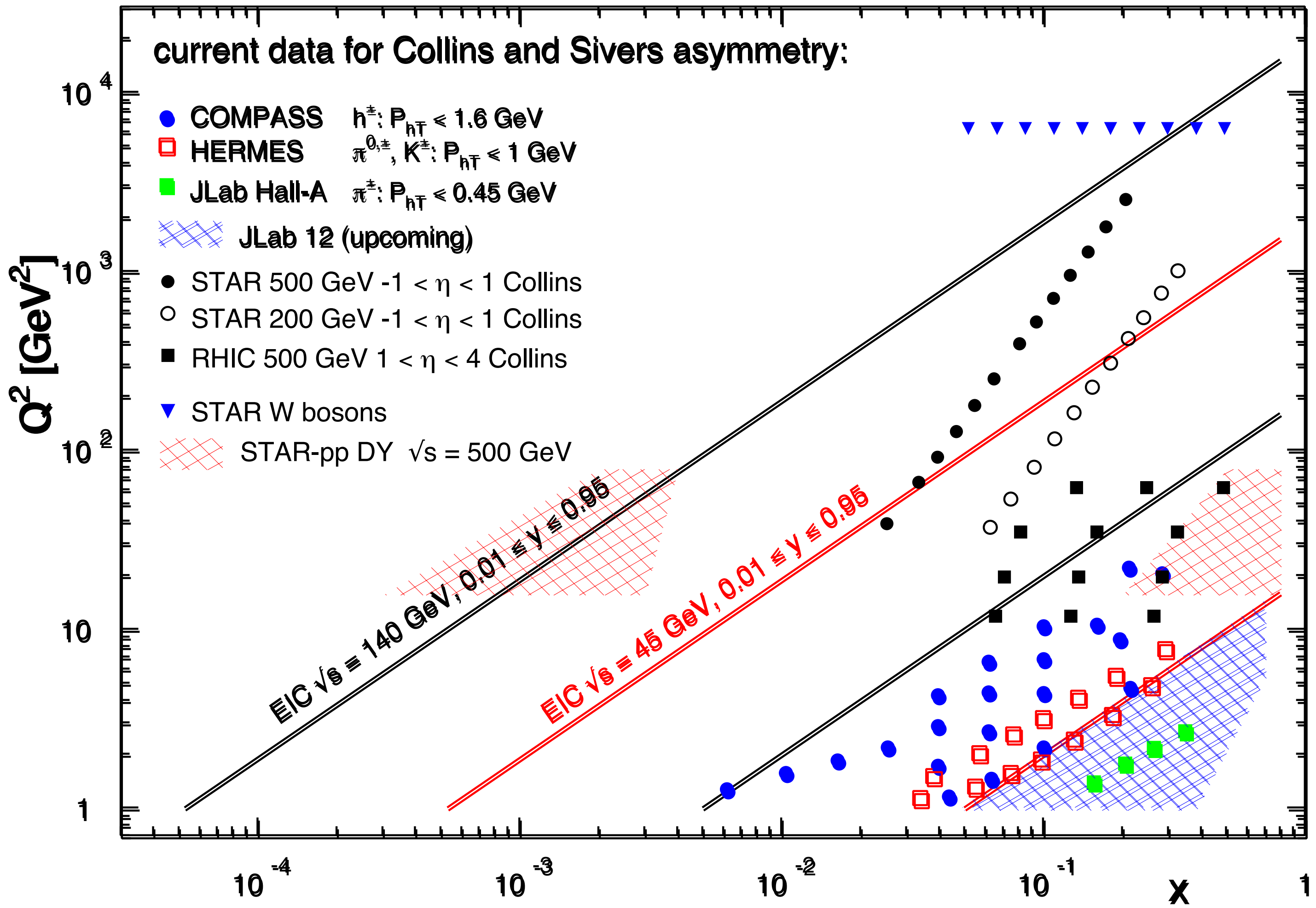
Postdocs, graduates, ..

More info: li.yi@sdu.edu.cn

pA@RHIC: unique kinematics



TMDs at RHIC



Till today TMDs came only from fixed target data —> high x @ low Q^2

need to establish concept at high Q^2 and wide range in x

polarized pp at RHIC

RHIC unique kinematics: from low to high x at high Q^2

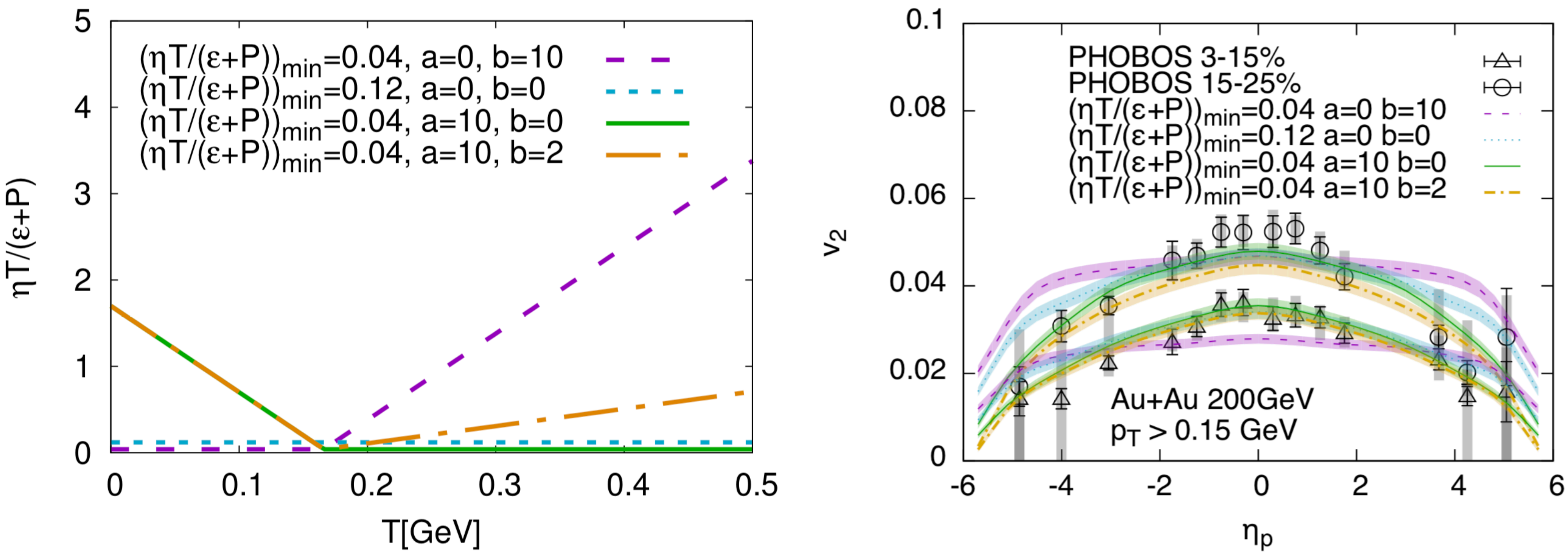
only way to access gluon TMDs before an EIC

			Clear signatures for Saturation	Dihadrons, γ-jet, h-jet, diffraction	ECal+Hcal+Tracking
2023 to 2025	p↑Al @ 200	12.6 pb^{-1} 8 weeks	A-dependence of nPDF, A-dependence for Saturation	R_{pAl}: direct photons and DY Dihadrons, γ-jet, h-jet, diffraction	Forward instrum. ECal+HCal+Tracking
	AuAu @ 200	1 Billion Minbias Events	Longitudinal de-correlation	$C_n(\Delta\eta)$ and $r_n(\eta_a,\eta_b)$	Forward instrum. ECal+HCal or Tracking
			η/s(T) and ζ/s(T)	$V_{n\Delta}(\eta)$	Forward instrum. Tracking
			Mixed flow Harmonics	$C_{m,n,m+n}$	Forward instrum. ECal+HCal or Tracking
			Rapidity dependence of Hyperon Polarization	$P_H(\eta)$	Forward instrum. Tracking
			Ridge	$dN/d(\Delta\eta)d(\Delta\phi)$ & $V_{n\Delta}$	Forward instrum. ECal+HCal or Tracking
2021	p↑p @ 510	1.1 fb^{-1} 10 weeks	TMDs at low and high x	A_{UT} for Collins observables, i.e. hadron in jet modulations at $\eta > 1$	Forward instrum. ECal+HCal+Tracking
2021	$\vec{p}\vec{p}$@ 510	1.1 fb^{-1} 10 weeks	$\Delta g(x)$ at small x	A_{LL} for jets, di-jets, h/γ-jets at $\eta > 1$	Forward instrum. ECal+HCal

	Year	√s (GeV)	Delivered Luminosity	Scientific Goals	Observable	Required Upgrade
In parallel with sPHENIX running	2024	p↑p @ 200	300 pb^{-1} 8 weeks	Subprocess driving the large A_N at high x_F and η	A_N for charged hadrons and flavor enhanced jets	Forward instrum. ECal+HCal+Tracking
	2024	p↑Au @ 200	1.8 pb^{-1} 8 weeks	What is the nature of the initial state and hadronization in nuclear collisions Clear signatures for Saturation	R_{pAu} direct photons and DY Dihadrons, γ-jet, h-jet, diffraction	Forward instrum. ECal+HCal+Tracking
		p↑Al @ 200	12.6 pb^{-1} 8 weeks	A-dependence of nPDF, A-dependence for Saturation	R_{pAl}: direct photons and DY Dihadrons, γ-jet, h-jet, diffraction	Forward instrum. ECal+HCal+Tracking
Potential future running	2021/22	p↑p @ 510	1.1 fb^{-1} 10 weeks	TMDs at low and high x	A_{UT} for Collins observables, i.e. hadron in jet modulations at $\eta > 1$	Forward instrum. ECal+HCal+Tracking
	2021/22	$\vec{p}\vec{p}$@ 510	1.1 fb^{-1} 10 weeks	$\Delta g(x)$ at small x	A_{LL} for jets, di-jets, h/γ-jets at $\eta > 1$	Forward instrum. ECal+HCal

Moving forward to constrain the shear viscosity of QCD matter

G. Denicol, A. Monnai, B. Schenke, PRL 116, 212301 (2016)



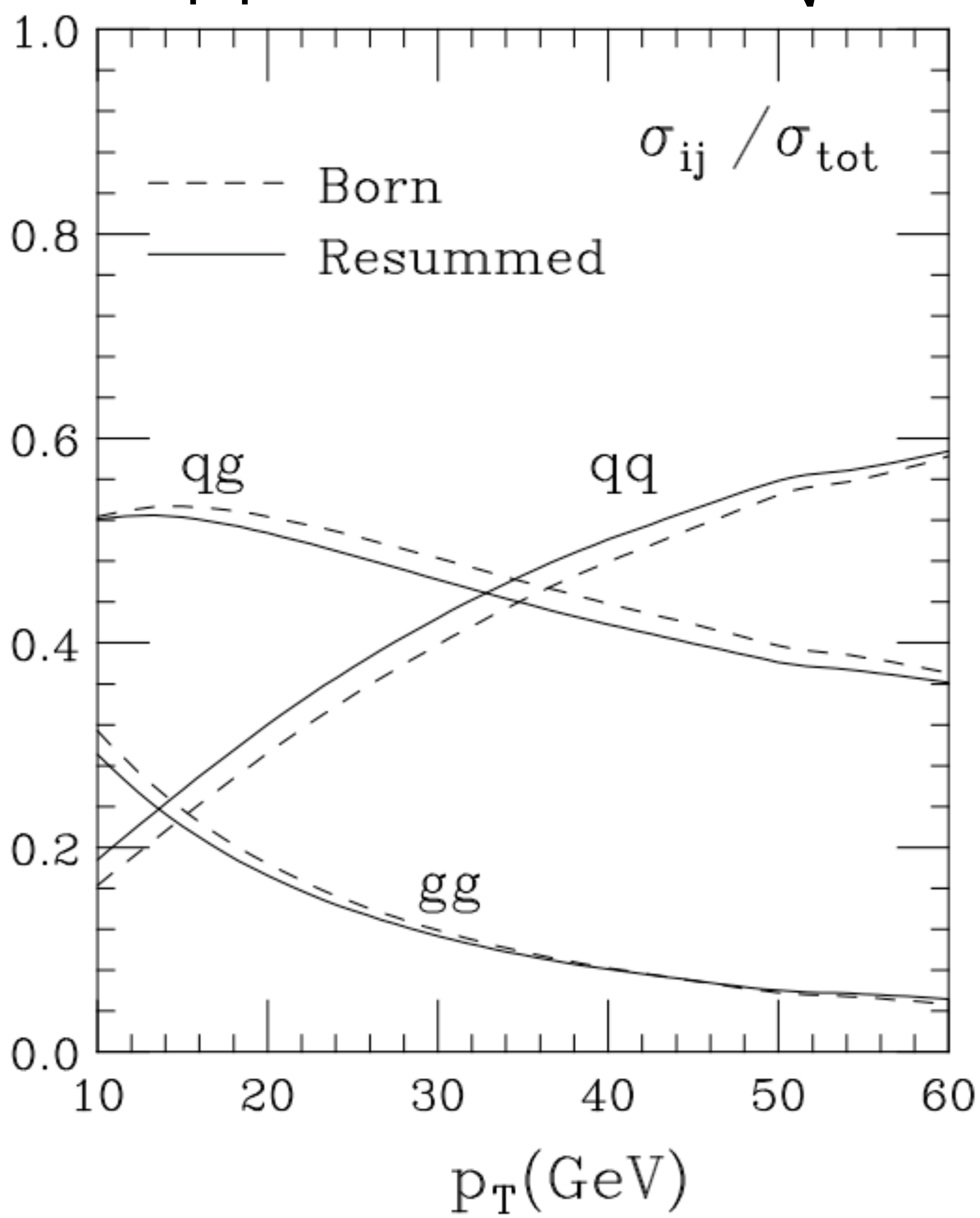
✳ *need to remove nonflow*

Medium T (and μ_B) profiles vary in the longitudinal direction

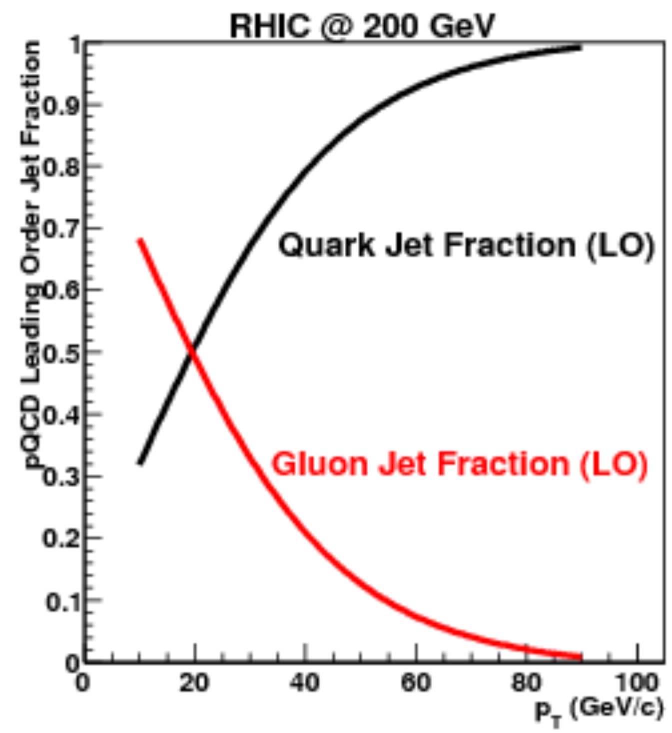
η/s(T) can be constrained by $v_n(\eta)$

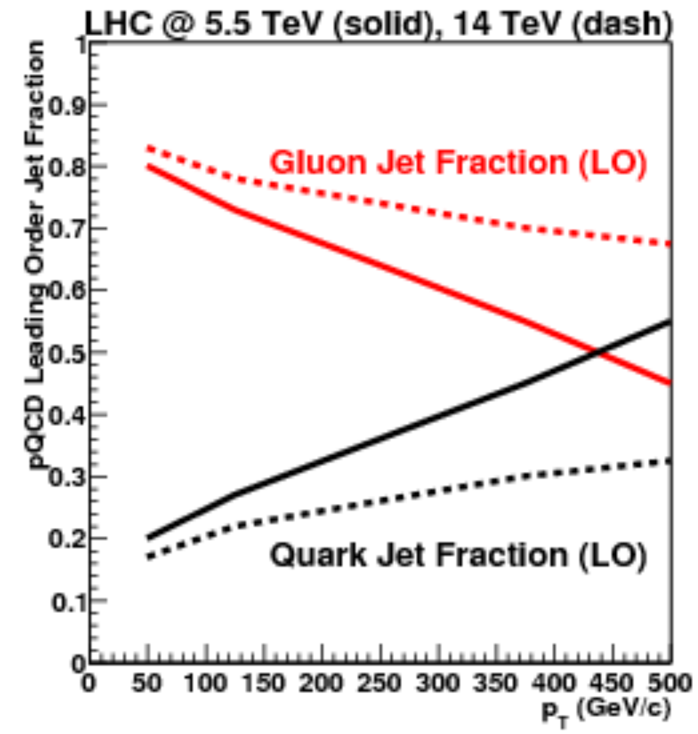
√sNN	ybeam
200GeV	5.36
2.76TeV	7.99
5.02TeV	8.59
7TeV	9.61

pp collisions at $\sqrt{S}$ = 200 GeV and R = 0.4

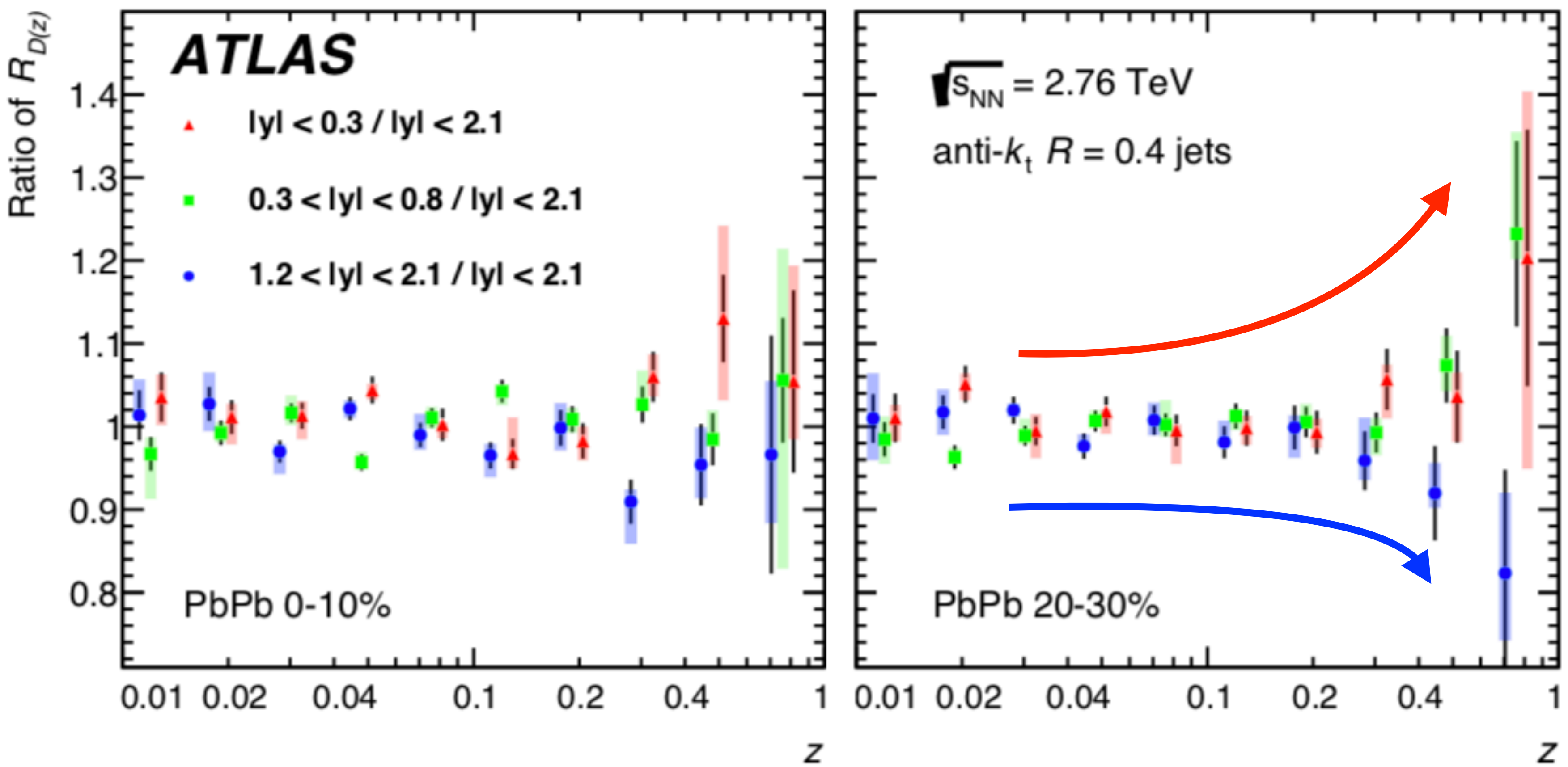


D. Florian and W. Vogelsang, Phys. Rev. D **76**, 074031

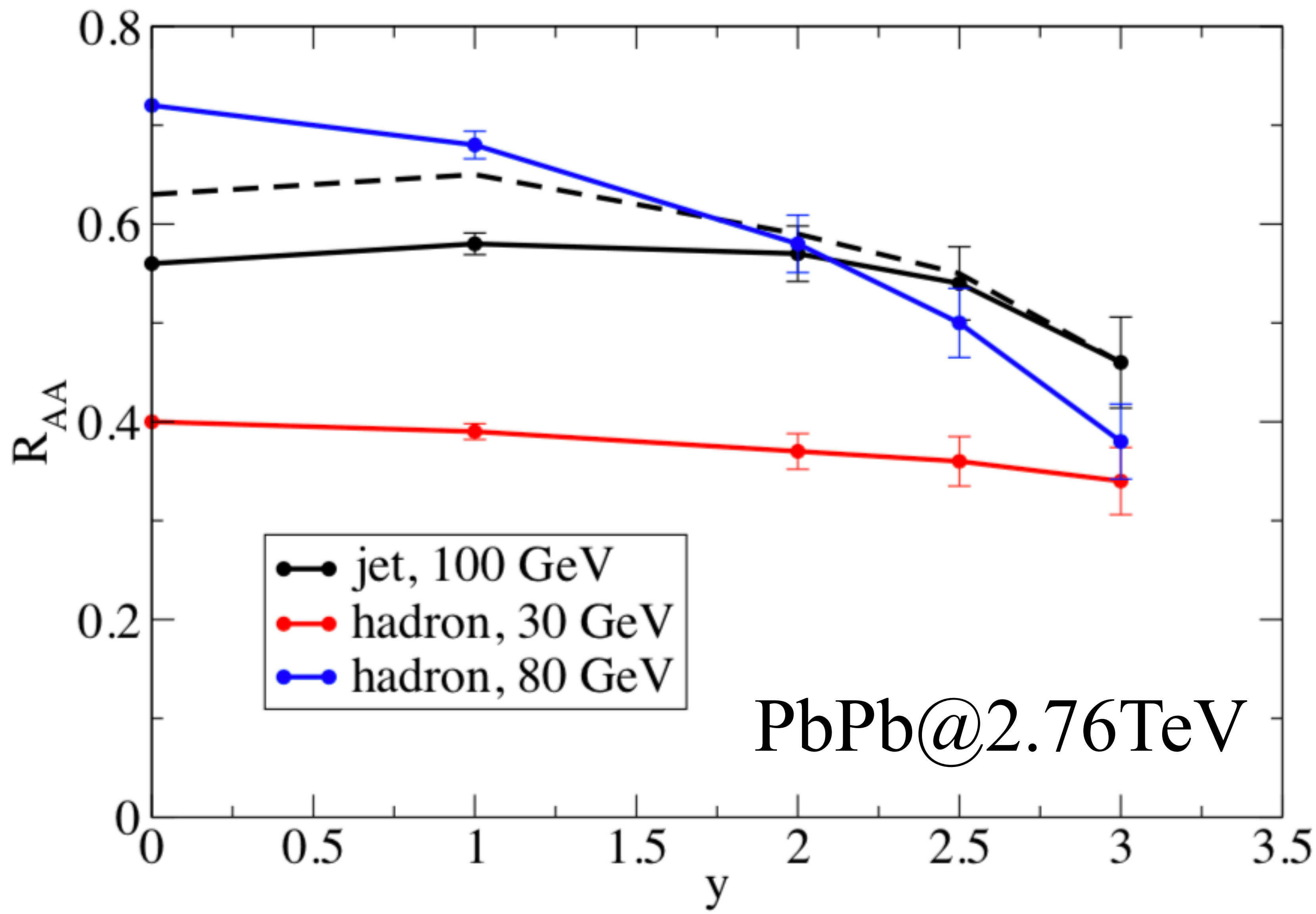




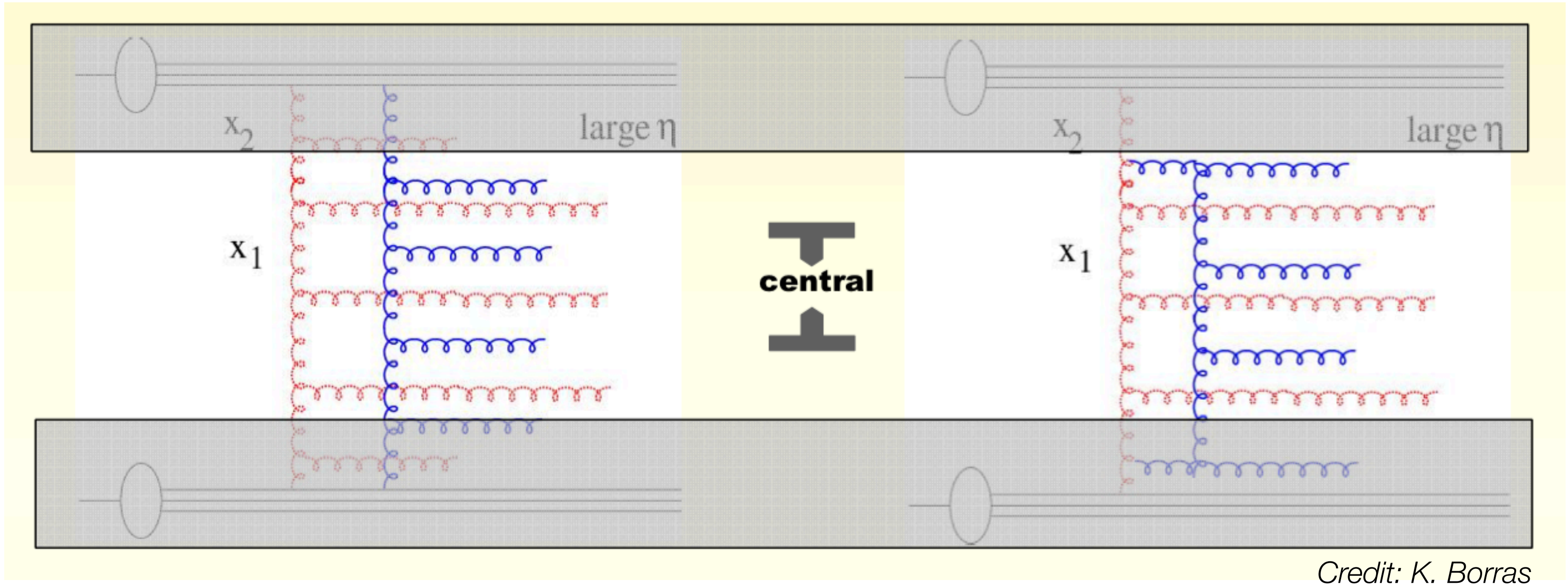
PHENIX, arXiv:1501.06197



ATLAS, arXiv:1702.00674v2



T. Renk, 1406.6784



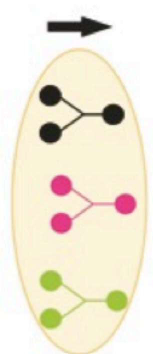
Credit: K. Borras

Central region does not distinguish between processes.

Saturation vs shadowing

Both relate to the same concept: # of gluons in the wave function of a nucleus at small-x is reduced wrt the simple addition of the gluon field of constituent nucleons

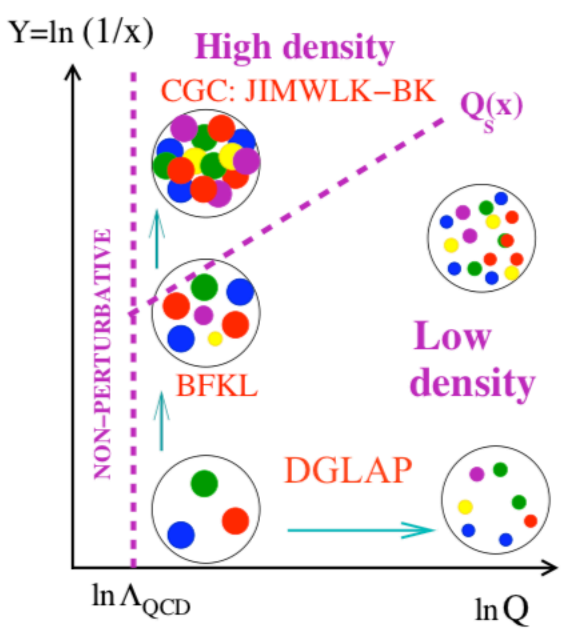
Saturation: Dynamical description via gluon self-interactions that tame the growth of gluon densities towards small-x



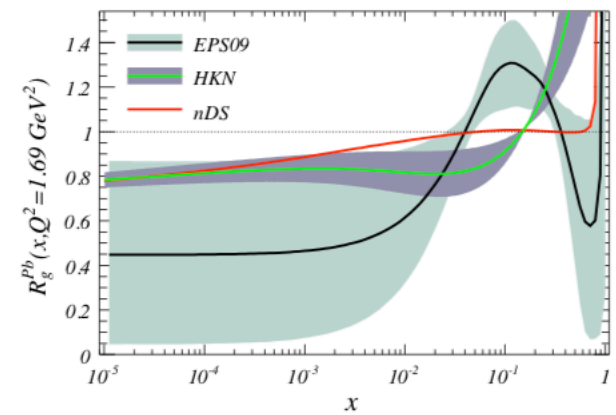
"BK-JIMWLK":

$$\frac{\partial \phi(\mathbf{x}, \mathbf{k_t})}{\partial \ln(\mathbf{x_0}/\mathbf{x})} \approx \mathcal{K} \otimes \phi(\mathbf{x}, \mathbf{k_t}) - \phi(\mathbf{x}, \mathbf{k_t})^2$$

radiation recombination



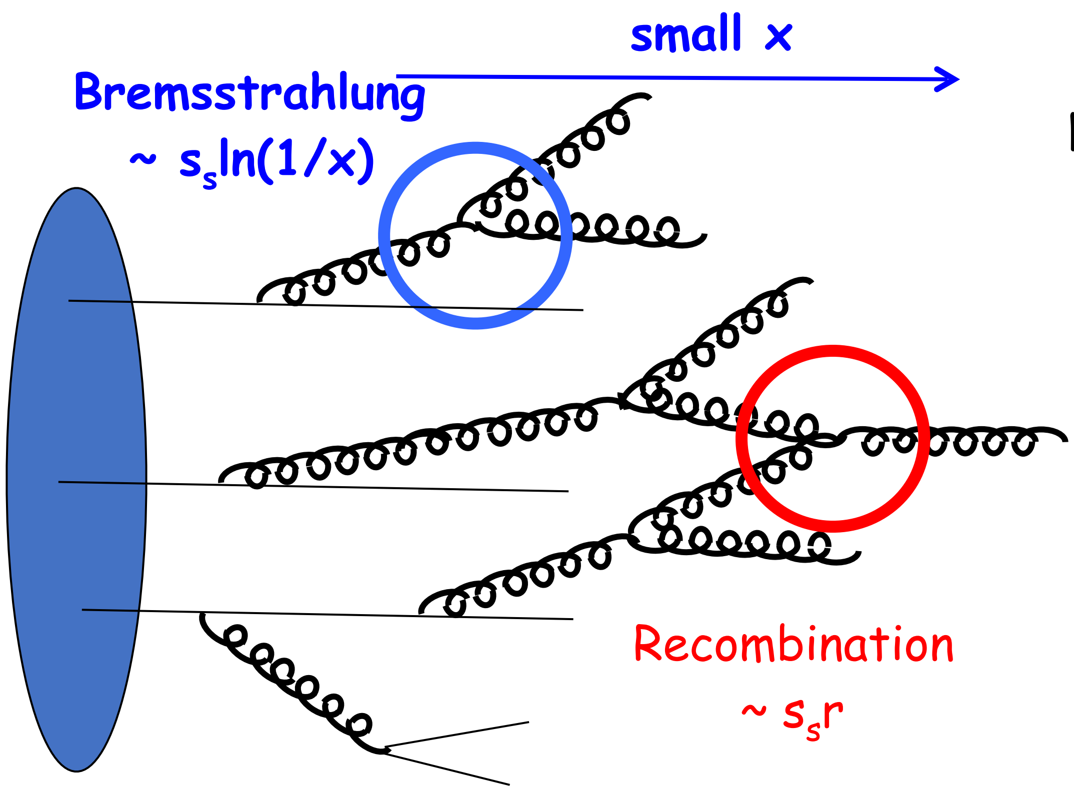
• Nuclear shadowing: Empiric parametrization fitted to data. Q2-depencende assumed to be described by DGLAP evolution.



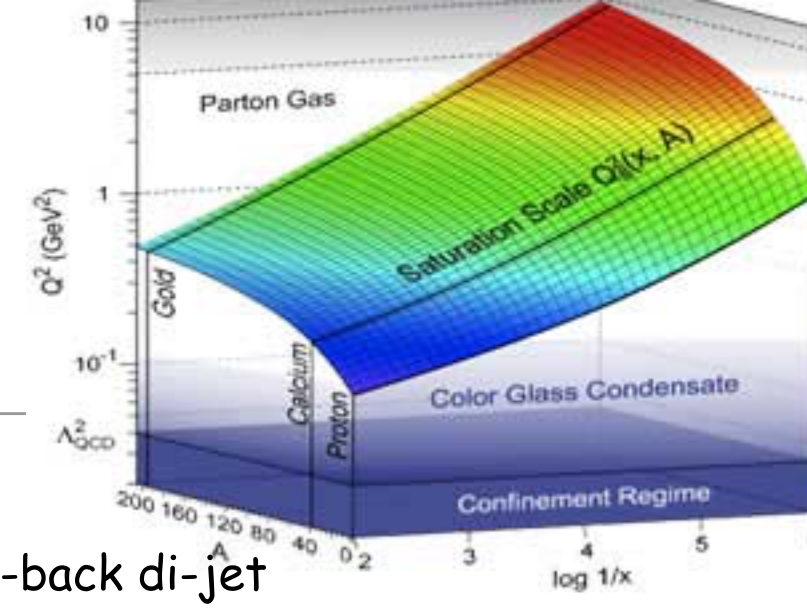
• Also models 'a la' Gribov-Glauber

J. L Albacete

Gluon Density in Nuclei

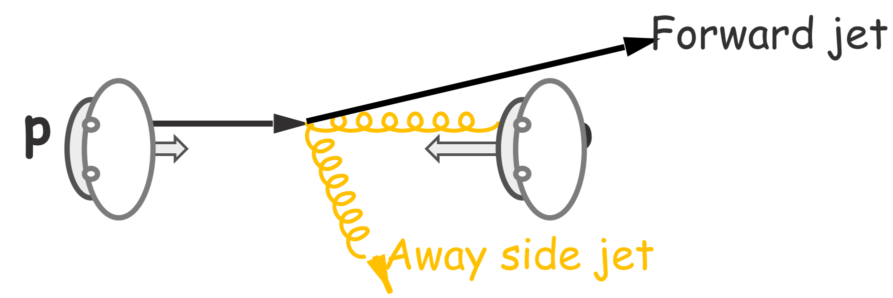


credit: E.C. Aschenauer



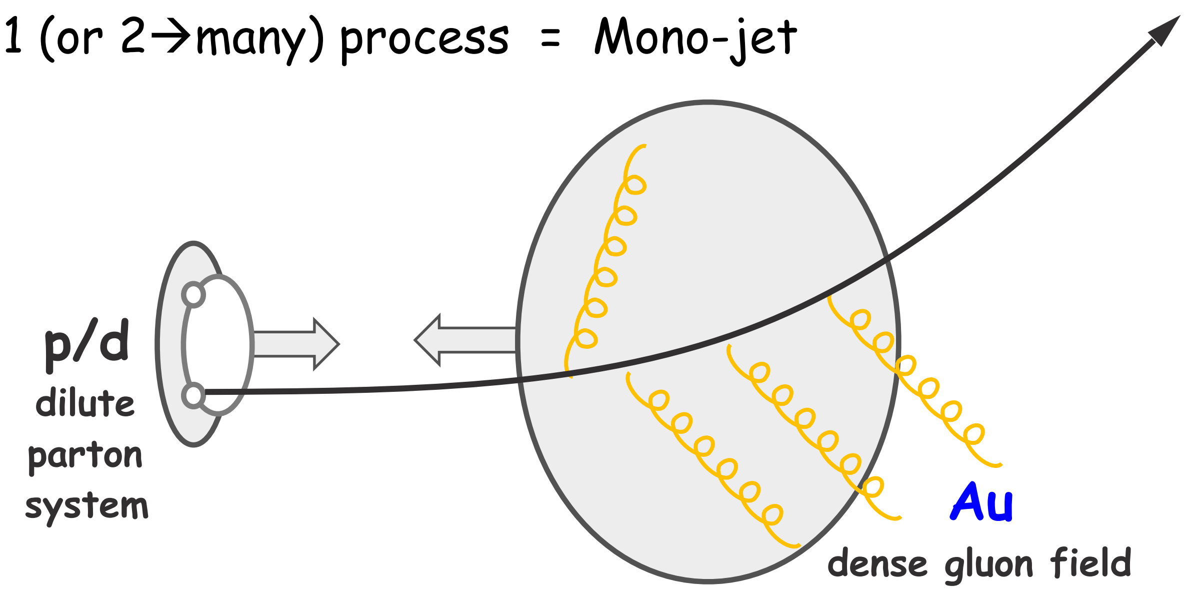
$Q_s^2 \sim (A/x)^{1/3}$

pQCD 2→2 process = back-to-back di-jet



With high gluon density

2→1 (or 2→many) process = Mono-jet

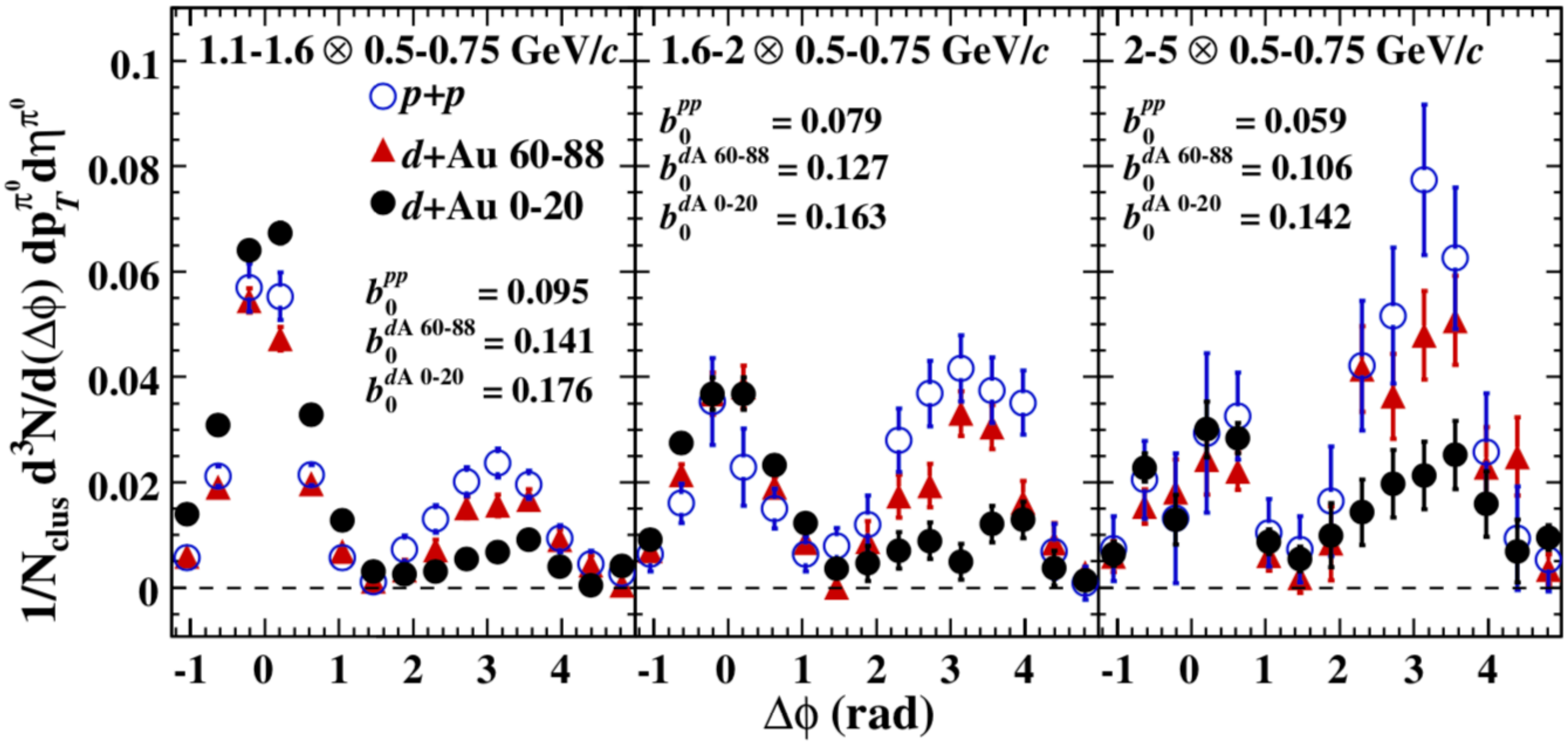


d+Au collisions:

CGC predicts suppression of back-to-back correlation

Saturation Physics

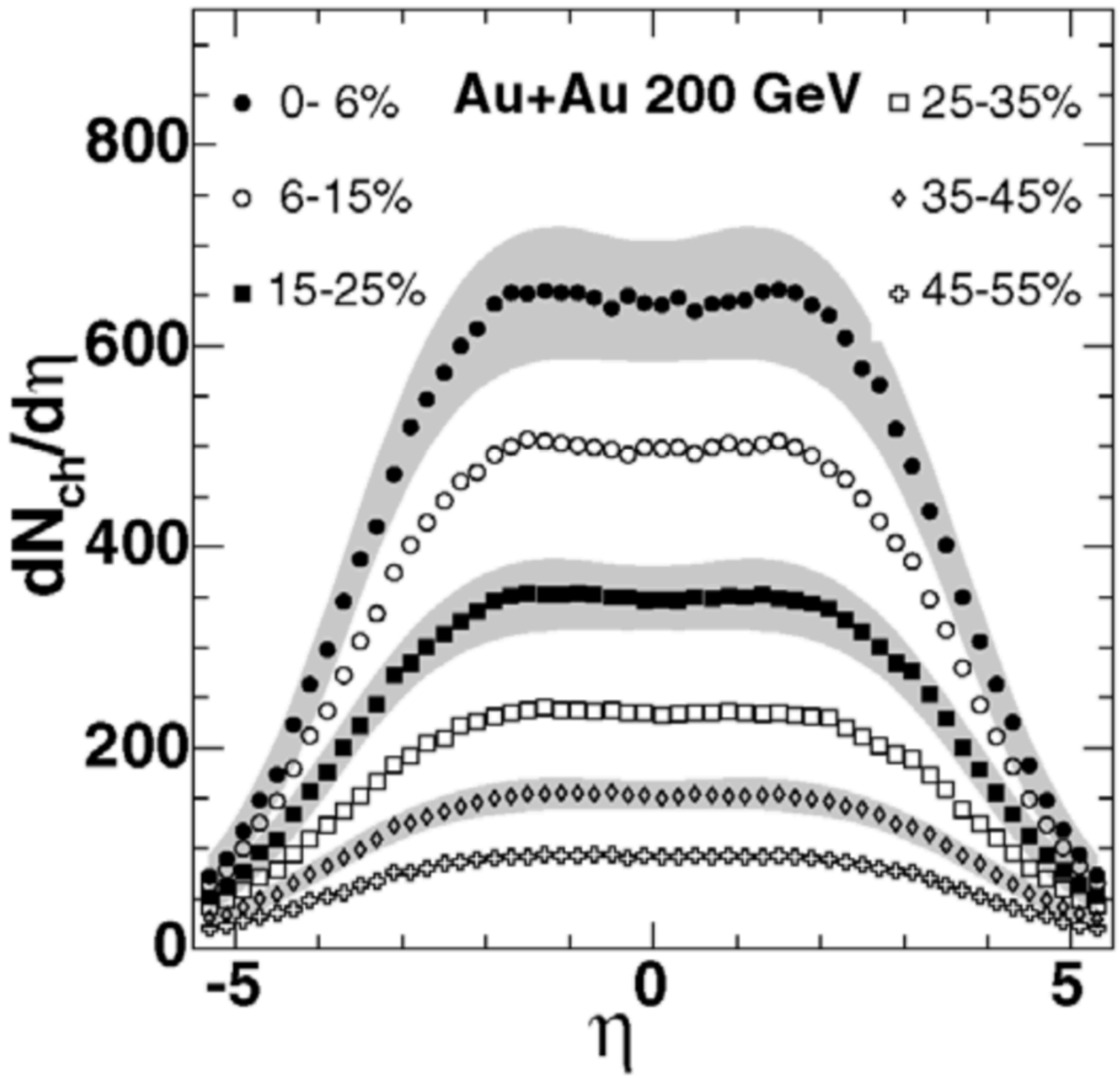
PHENIX, Phys. Rev. Lett. 107, 172301 (2011)



Suppressed away-side: consistent with CGC expectation

Alternative explanation: double interaction in deuteron;

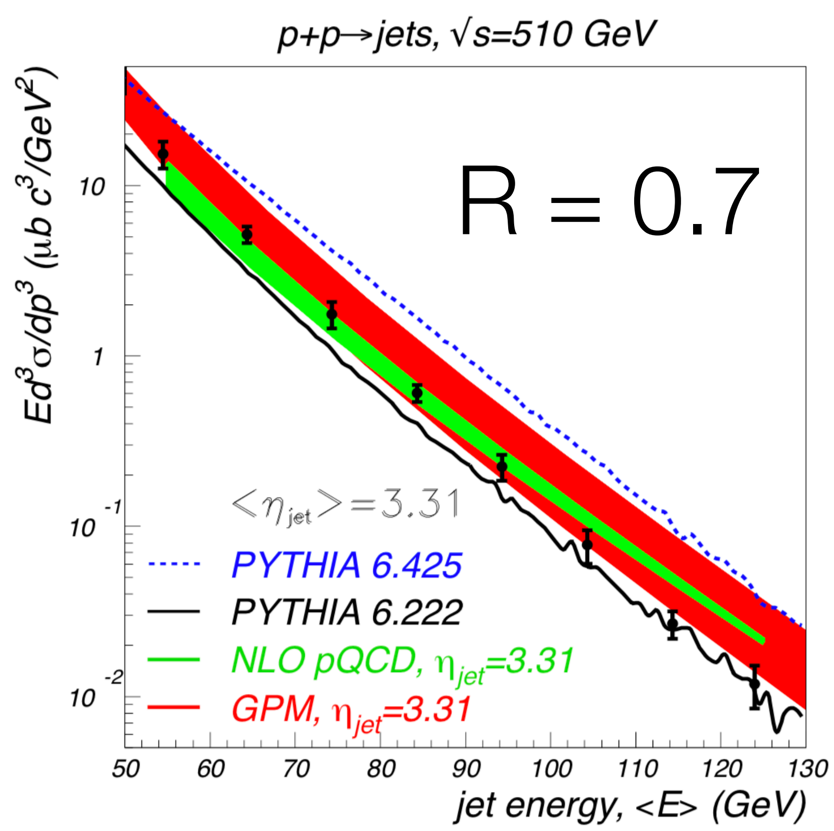
—> p+Au instead of d+Au



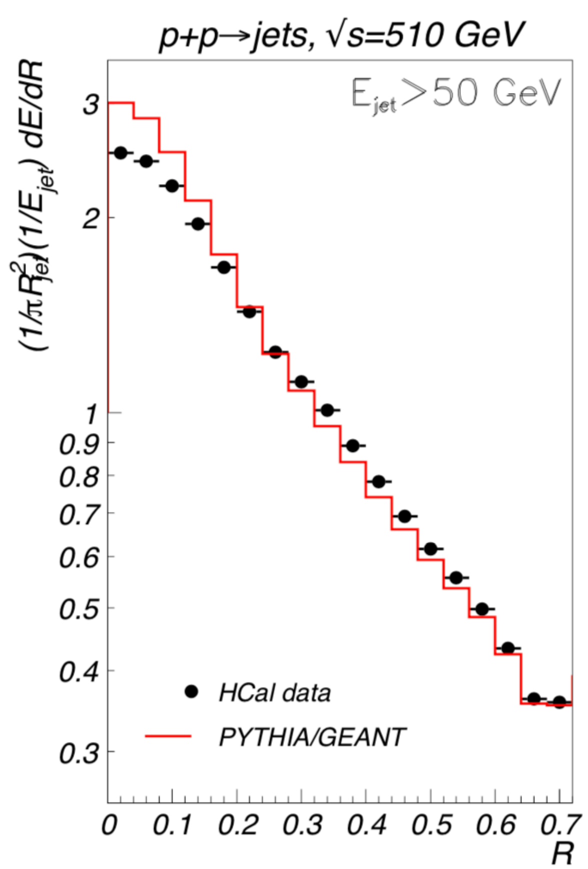
PHOBOS, White paper, NPA 757 (2005) 28–101

Forward Jet at RHIC Energy (pp@500 GeV)

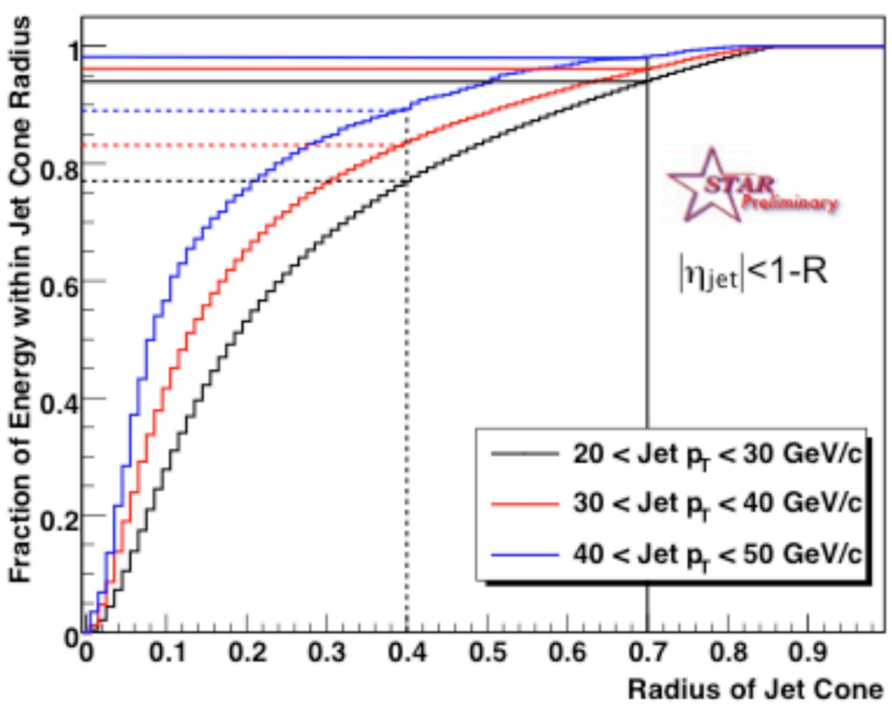
cross section



jet shape



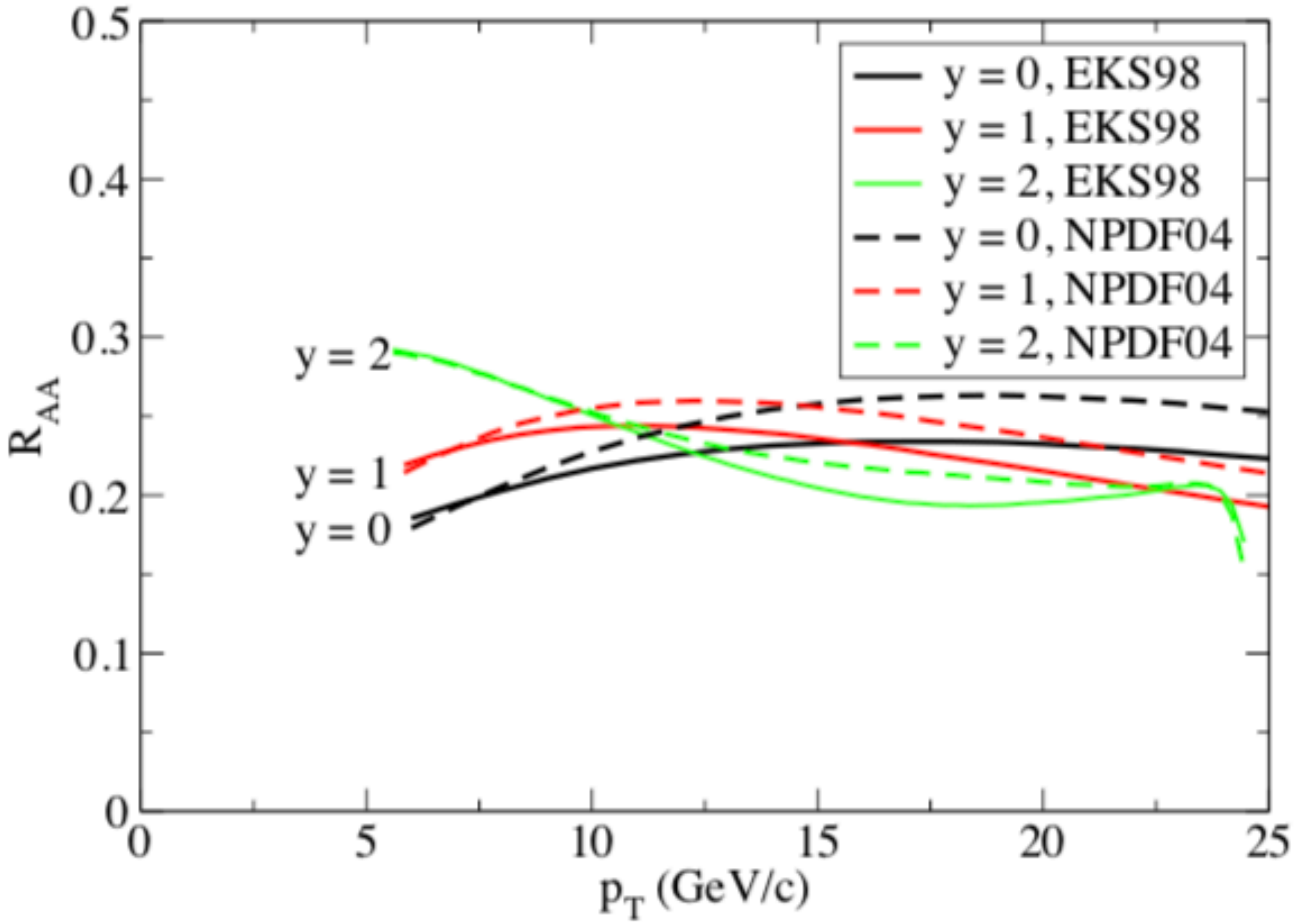
jet shape
(mid-rapidity 200 GeV)



A_NDY Collaboration

arXiv:1304.1454v2

physletb.2015.10.001



GY. Qin, et al, PhysRevC.76.064907