Some Physics of Small Collision Systems

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New Trends in HEP 2024 Green Village, Romania

Introduction

does QGP/flow appear in small collision systems?

- PID Spectrum TCM for *p-p, p*-Pb
- centrality determination for *p*-Pb
- nuclear modification in *p*-Pb
- strangeness enhancement in *p-p, p*-Pb
- *p-p* two-particle correlations
- the Ridge – measurement and origins

TCM for (Multi)strange Spectra

kaons, Lambdas, Cascades and Omegas

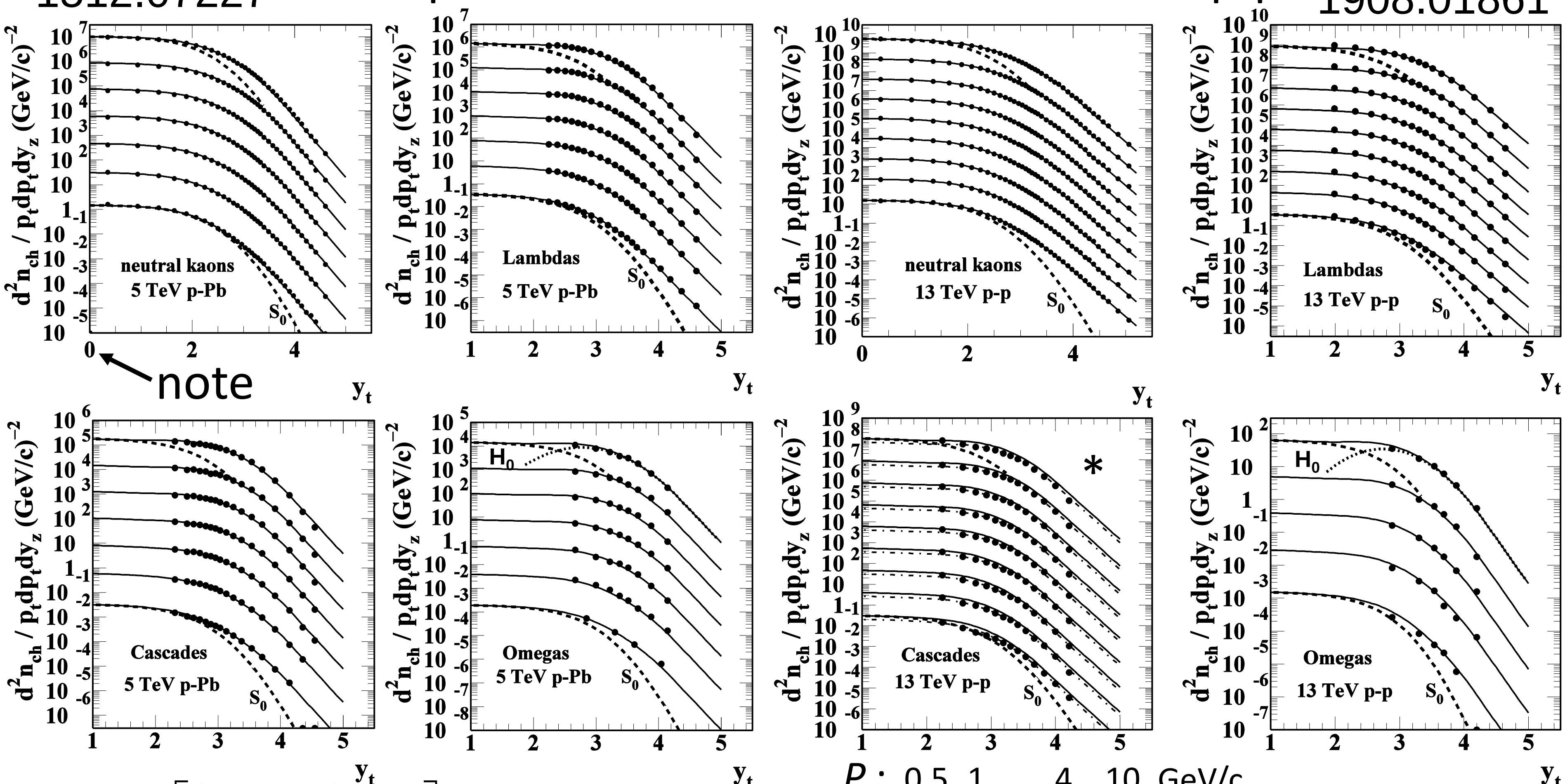
ALICE
1307.6796
1512.07227

5 TeV p-Pb

densities on p_t^2

13 TeV p-p

ALICE
1908.01861



P_t: 0.5 1 4 10 GeV/c

$$y_{t\pi} = \ln\left[\left(m_{t\pi} + p_t\right)/m_\pi\right]$$

2303.14299

p-Pb Centrality – I

A = 1801.05862

spectrum TCM

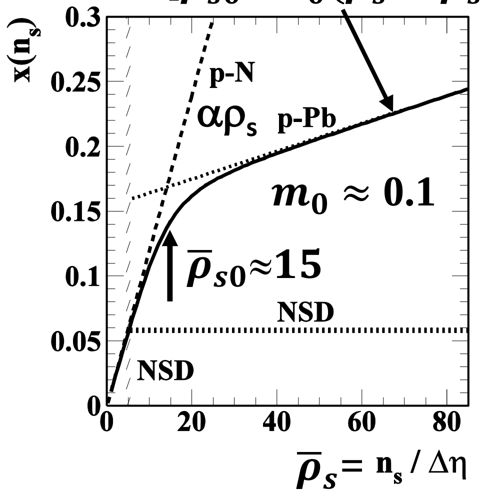
nonPID for A-B collisions

$$\bar{\rho}_0(p_t, n_s) = \underbrace{\boxed{\frac{N_{part}}{2}\bar{\rho}_{sNN}}}_{\bar{\rho}_s}\hat{S}_0(p_t) + \underbrace{\boxed{N_{bin}\bar{\rho}_{hNN}}}_{\bar{\rho}_h}\hat{H}_0(p_t)$$

$$\bar{\rho}_{hNN} \approx \alpha\bar{\rho}_{sNN}^2 \Rightarrow x(n_s) \approx \alpha\,\bar{\rho}_{sNN}$$

↓

exclusivity



$\bar{\rho}_{s0}, m_0$ **only params**

mean p_t

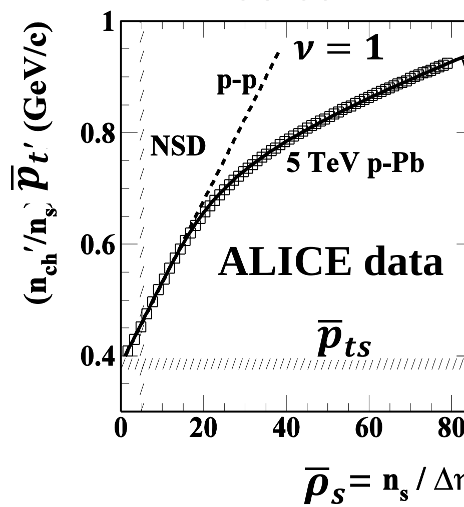
$$\bar{P}_t = \underbrace{\boxed{\frac{N_{part}}{2}n_{sNN}}}_{n_s}\bar{p}_{ts} + \underbrace{\boxed{N_{bin}n_{hNN}}}_{n_h}\bar{p}_{th}$$

$$\frac{\bar{P}_t}{\boxed{n_s}} = \bar{p}_{ts} + \underline{x(n_s)\nu(n_s)}\bar{p}_{th}$$

n_h / n_s

→

1708.09412



***p*-Pb TCM**

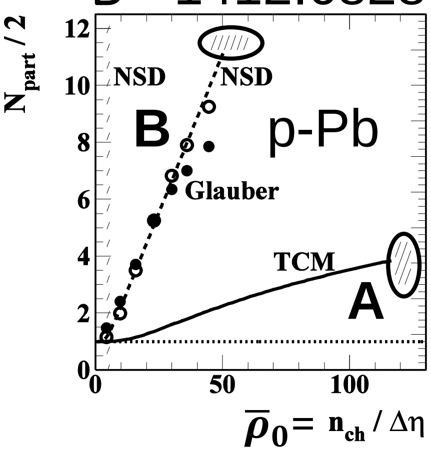
for p-Pb

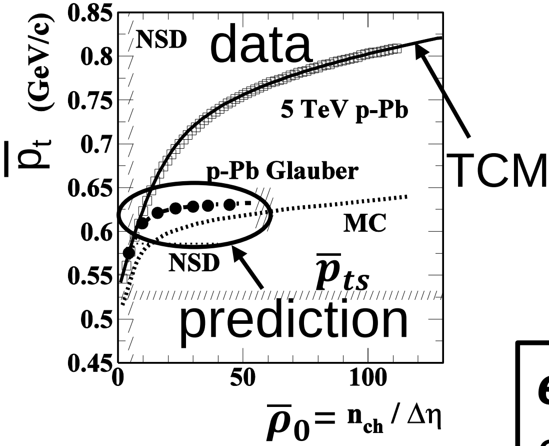
$$N_{part}/2 = \alpha\,\bar{\rho}_s\,/\,x(n_s) \quad N_{part} = N_{bin} + 1 \quad \nu \equiv 2N_{bin}/N_{part} \leq 2$$

$N_{part} \propto \bar{\rho}_0$

p-Pb Centrality – II

B =1412.6828



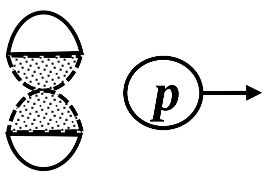


p-Pb Glauber based on the eikonal approximation greatly overestimates N_{part}

1801.06579

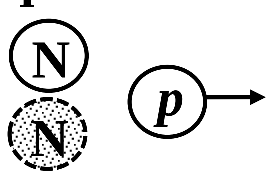
exclusivity – projectile nucleon can collide with only one target nucleon at a time, where “a time” is consistent with a nucleon diameter

classical



eikonal approximation

quantum

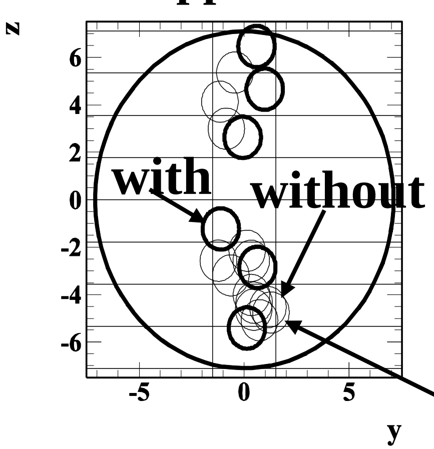


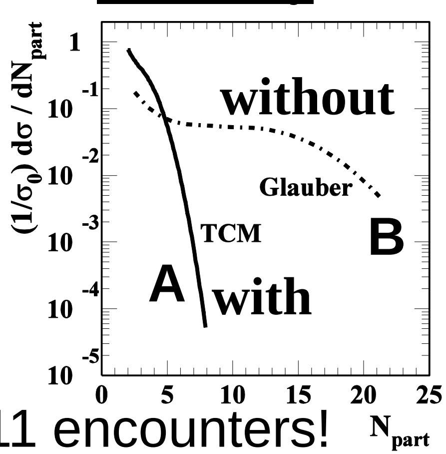
noneikonal <u>exclusivity</u>

exclusivity: $\bar{\rho}_{hNN} \approx \alpha \bar{\rho}_{sNN}^2$

100% overlap

classical Glauber: $\bar{\rho}_{hNN} \propto \bar{\rho}_{sNN}^{4/3}$





11 encounters!

p-Pb Glauber Monte Carlo <u>with</u> *exclusivity* imposed provides N_{part} estimates consistent with data

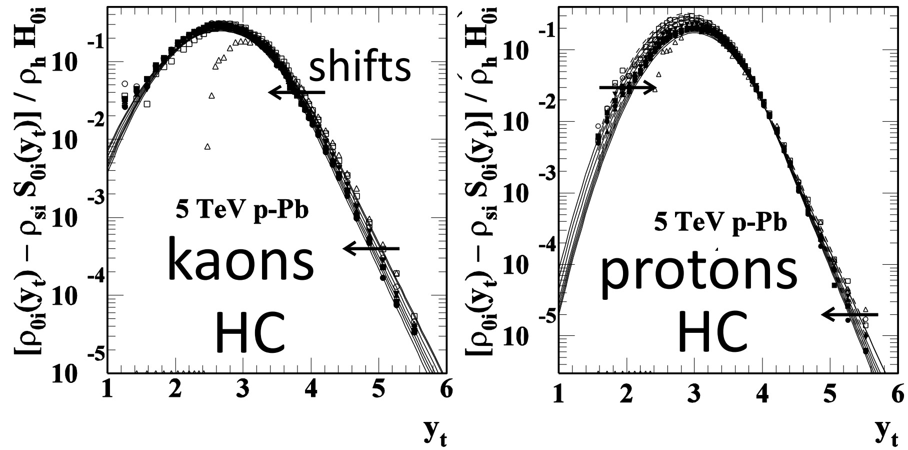
Nuclear Modification Factors (NMFs) – I

is jet production modified?

hard components at right carry *all available spectrum information* about *p*-Pb jets

TCM describes spectra within statistical uncertainties

variable TCM



arrow trends for *increasing* centrality

mesons vs baryons

NMF convention: $\mathbf{R}_{pPb} = \dfrac{\bar{\rho}_{0pPb}(p_t, n_s)}{N_{bin} * \bar{\rho}_{0pp}(p_t)}$

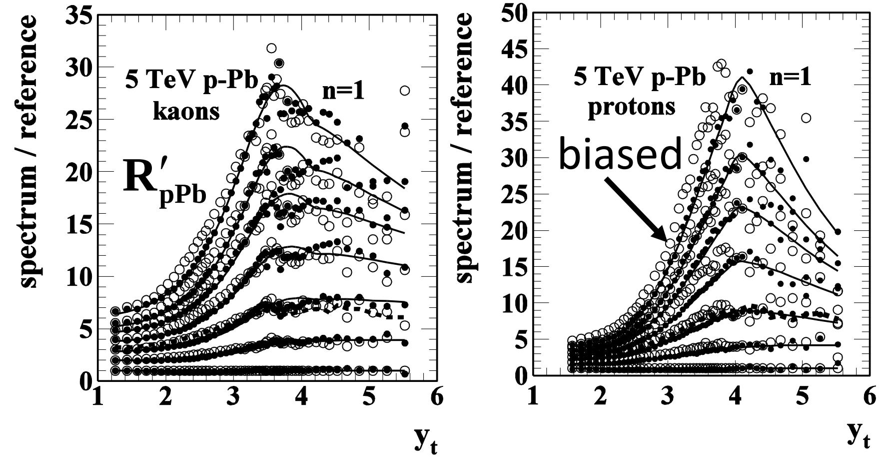
but what is N_{bin}?

unrescaled spectrum ratio

$$R'_{p\text{Pb}} = \frac{z_{si}(n_s)\bar{\rho}_s \hat{S}_{0i}(p_t) + z_{hi}(n_s)\bar{\rho}_h \hat{H}_{0ip\text{Pb}}(p_t, n_s)}{z_{sipp}\bar{\rho}_{spp}\hat{S}_{0i}(p_t) + z_{hipp}\bar{\rho}_{hpp}\hat{H}_{0ipp}(p_t)}$$

the devil is in the details

solid dots: data/TCM n=7



solid curves: TCM/TCM n=7

Nuclear Modification Factors – II

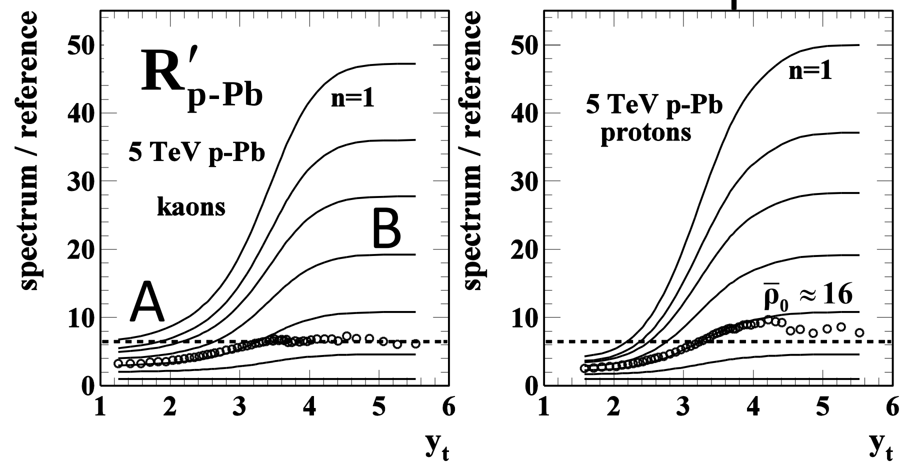
2304.02170

$$R'_{p\mathrm{Pb}} \;=$$

$$\text{A} \rightarrow \frac{z_{si}(n_s)(N_{part}/2)\bar{\rho}_{sNN}\hat{S}_{0ipPb}(p_t)}{z_{sipp}\bar{\rho}_{spp}\hat{S}_{0ipp}(p_t)} \quad \boxed{\text{for low } p_t}$$

$$\text{B} \rightarrow \frac{z_{hi}(n_s)N_{bin}\bar{\rho}_{hNN}\hat{H}_{0ipPb}(p_t, n_s)}{z_{hipp}\bar{\rho}_{hpp}\hat{H}_{0ipp}(p_t)} \quad \boxed{\text{for high } p_t,}$$

TCM with fixed hard component

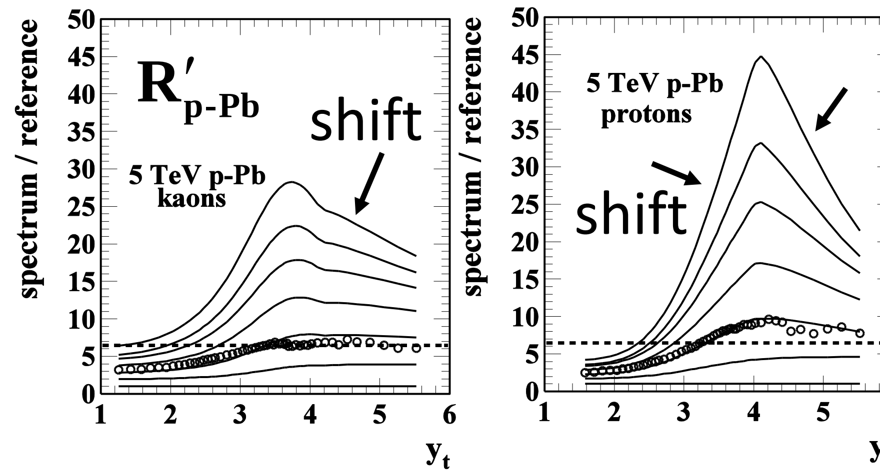


H_0: *large ratio variations* arise from *small* HC shifts

$$\bar{\rho}_{hNN} = \alpha \bar{\rho}_{sNN}^2 \qquad \nu = 2N_{bin} / N_{part} \leq 2$$

opposing shifts for protons lead to sharp peaks near $y_t = 4$

unbiased data ⇔ TCM



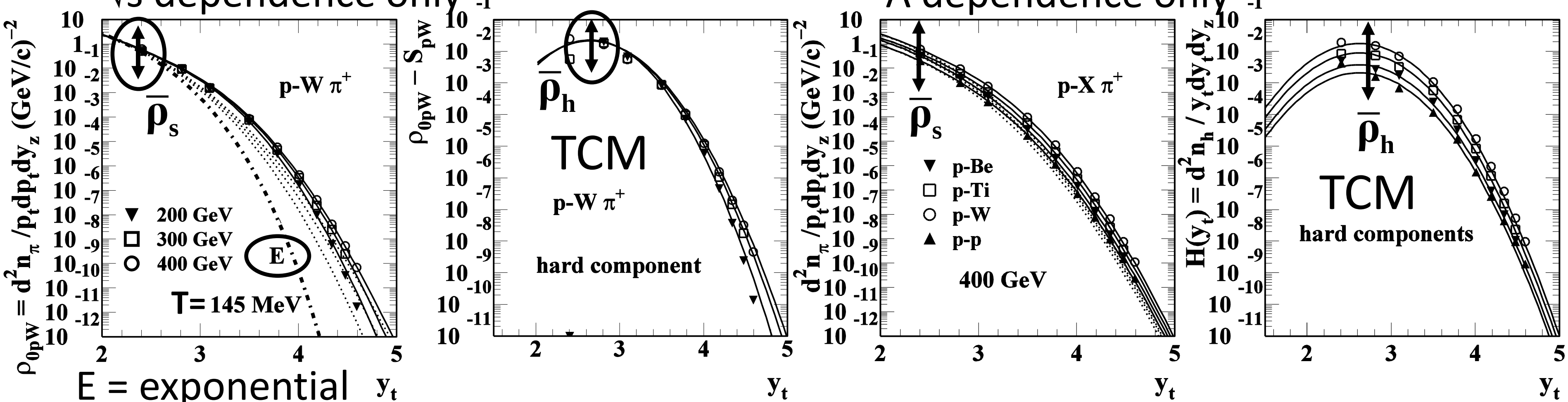
$R_{p\text{-}Pb}$ as defined is uninterpretable

Chicago-Princeton Spectra and Cronin

PRD 11, 3105 (1974) What is the Cronin effect? PRD 19, 764 (1979)

$\sqrt{s}$ dependence only

A dependence only



Cronin ≡ jet physics

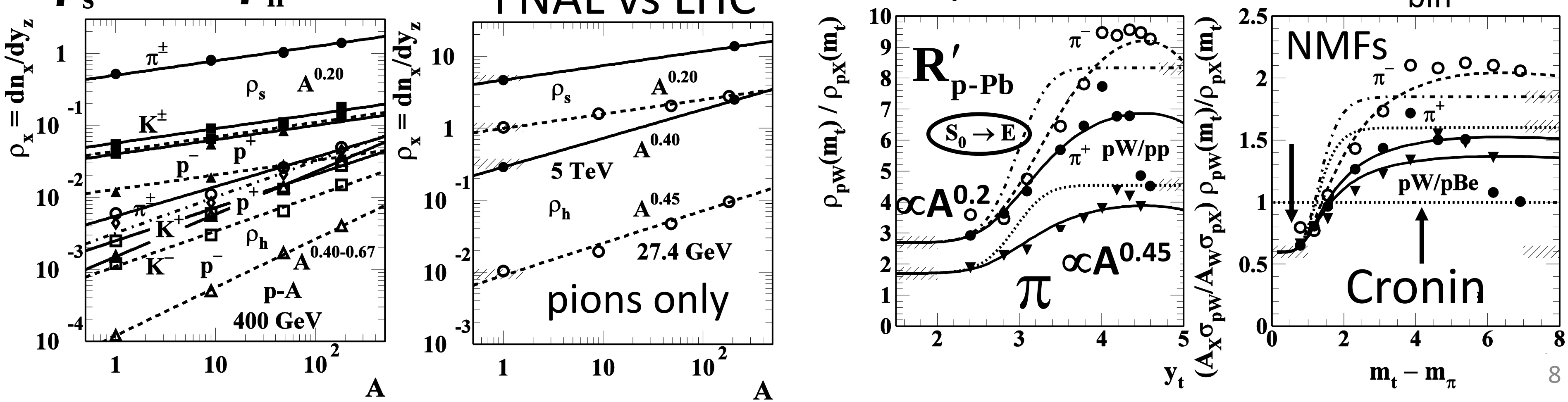
$\bar{\rho}_s \propto A^{0.2}$ $\bar{\rho}_h \propto A^{0.40\text{-}67}$

$\bar{\rho}_{hNN} \approx \alpha \bar{\rho}_{sNN}^2$

FNAL vs LHC

A/B ratios

assume $N_{bin} \sim A^{1/3}$



Strangeness Enhancement – I

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hadron species i $\quad \bar{\rho}_{0i}(p_t, n_s) = \bar{\rho}_{si}\,\hat{S}_{0i}(p_t) + \bar{\rho}_{hi}\,\hat{H}_{0i}(p_t, n_s)$ **soft + hard**

$$\bar{\rho}_{si} = z_{si}(n_s)\bar{\rho}_s \qquad \bar{\rho}_{hi} = z_{hi}(n_s)\bar{\rho}_h$$

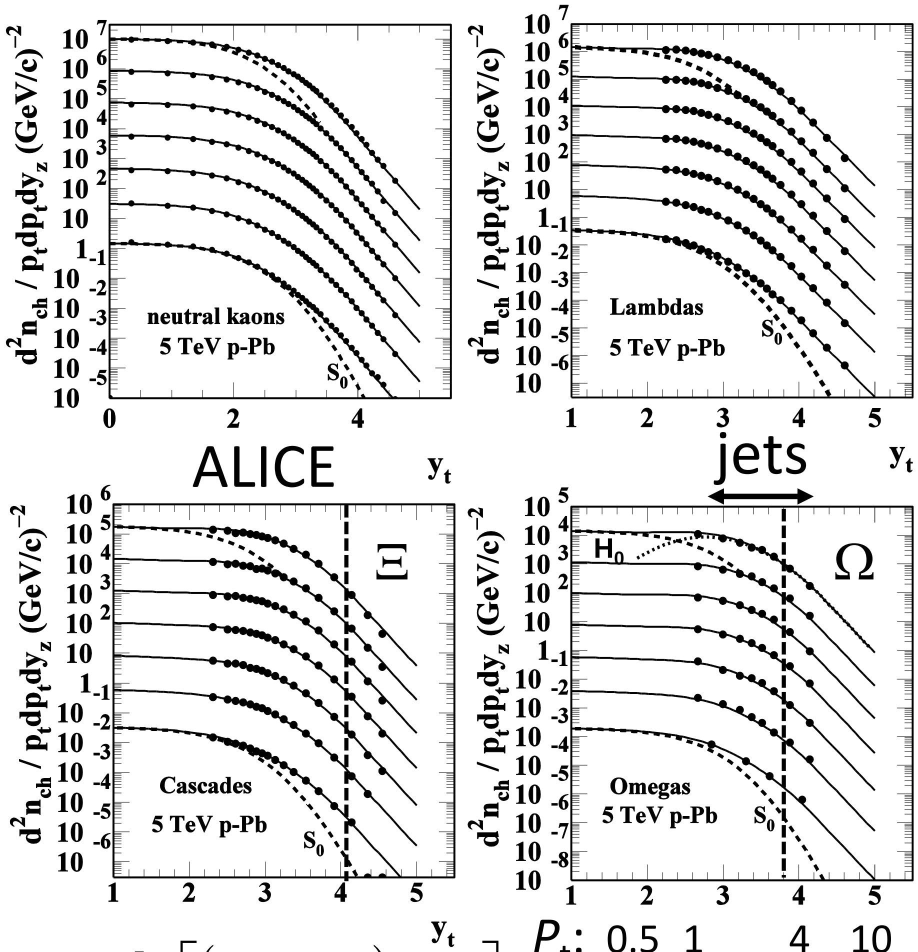
$$\bar{\rho}_{0i} = z_{0i}\,\bar{\rho}_0 = z_{si}\,\bar{\rho}_s + z_{hi}\,\bar{\rho}_h$$

$$z_{si}(n_s) = z^*_{0i}\frac{1 + x(n_s)\nu(n_S)}{1 + \tilde{z}_i(n_s)x(n_s)\nu(n_S)}$$

intercept

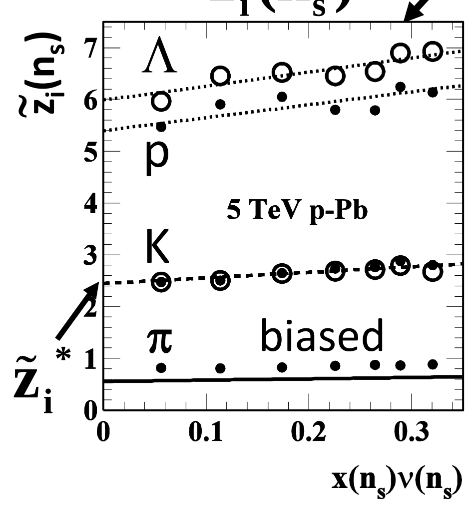
measured

$$\tilde{z}_i(n_s) = z_{hi}(n_s)/z_{si}(n_s)$$

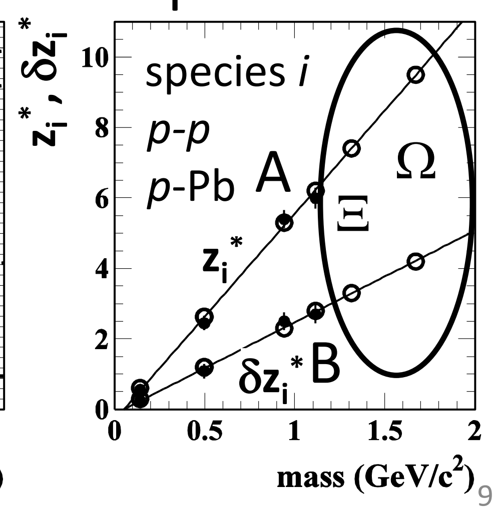


$$y_{t\pi} = \ln[(m_{t\pi} + p_t)/m_\pi]$$

$\tilde{z}_i(n_s)$



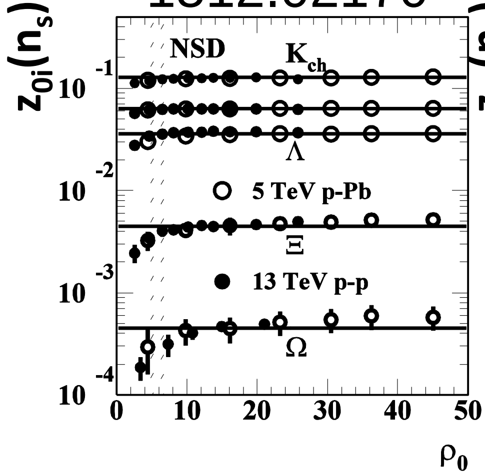
prediction



Strangeness Enhancement – II

ALICE

1512.02170



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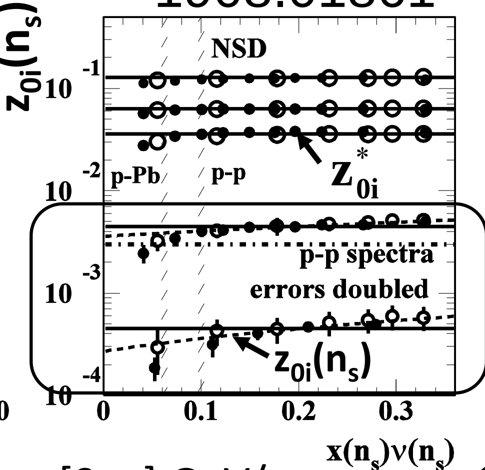
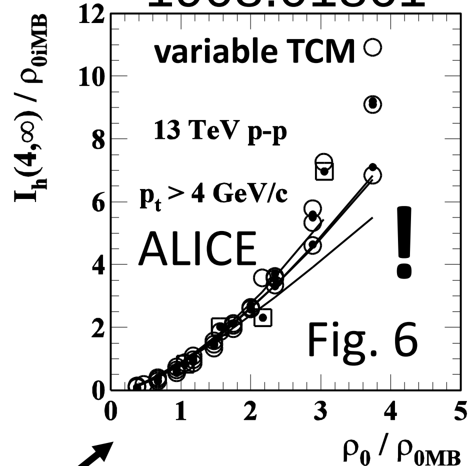
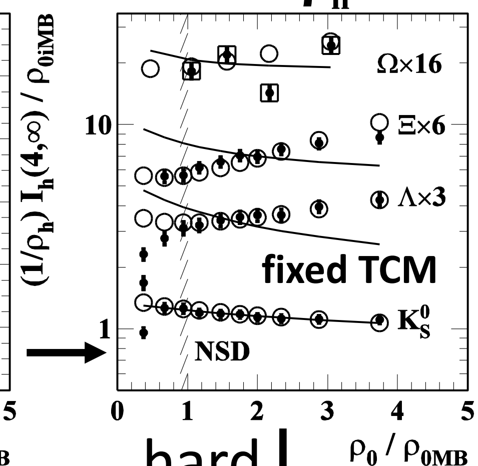


[0,∞] GeV/c

1908.01861



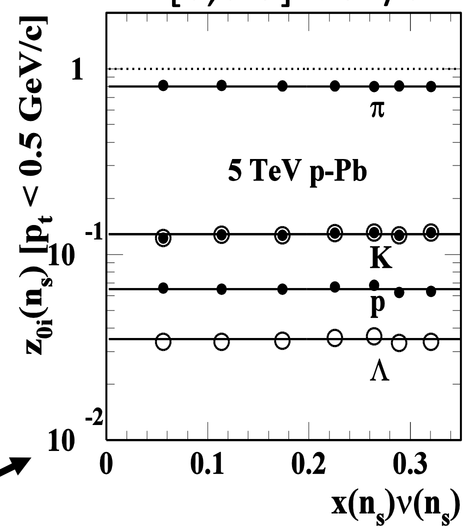
$\div \bar{\rho}_h$



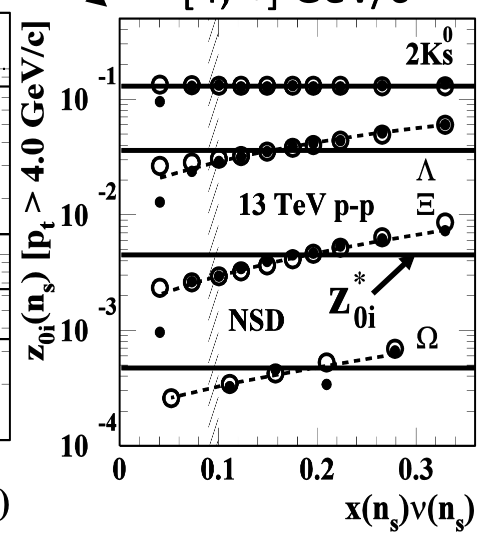
hard

?

[0,0.5] GeV/c



[4,∞] GeV/c



TCM: $I_h(a,b) \propto z_{hi}(n_s)\bar{\rho}_h \times \int_a^b p_t dp_t \hat{H}_{0i}(p_t, n_s)$

?

$$z_{hi}(n_s) = z_{0i}(n_s) \frac{\tilde{z}_i(1 + x(n_s)\nu(n_S))}{1 + \tilde{z}_i(n_s) x(n_s)\nu(n_S)}$$

$$z_{0i}(n_s) \sim \frac{1 + \tilde{z}x\nu}{1 + x\nu} I_s(0, 0.5) / \bar{\rho}_s$$

soft

z_{0i} variation ↔ jets

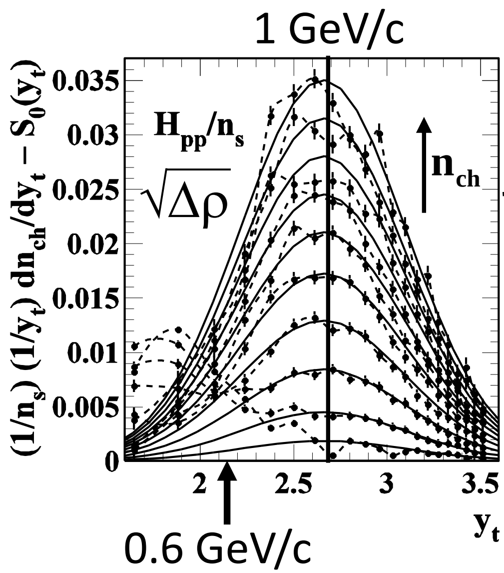
p-p Two-particle Correlations – 2005

200 GeV p-p

p_t spectrum
hard component

2003

PRD 74, 032006 (2006)

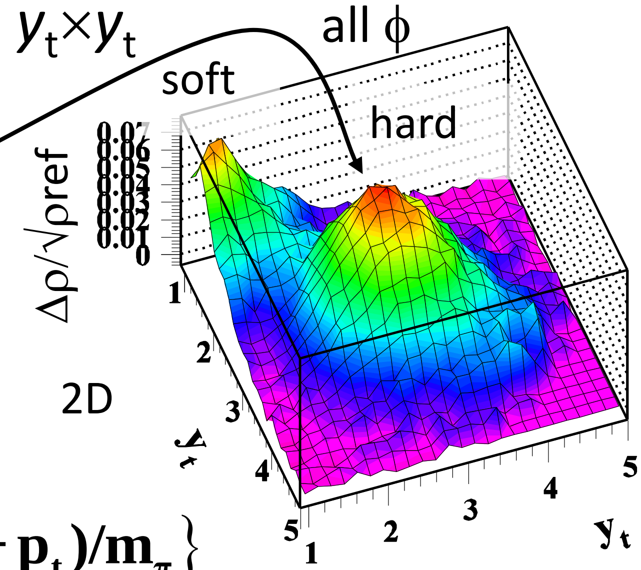


JETS

1D

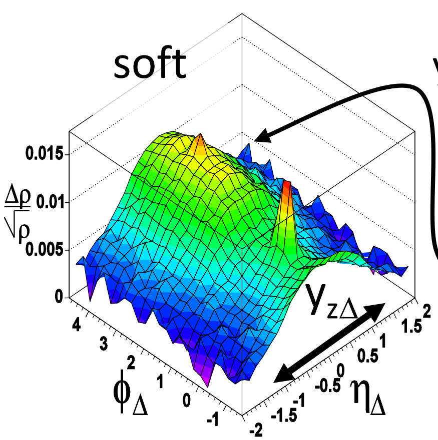
parton
fragments

2D

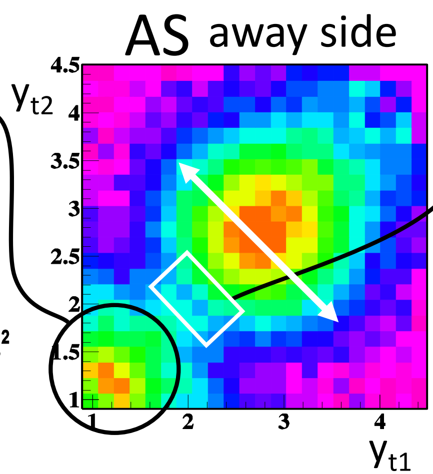


$$y_t \equiv \ln\{(m_t + p_t)/m_\pi\}$$

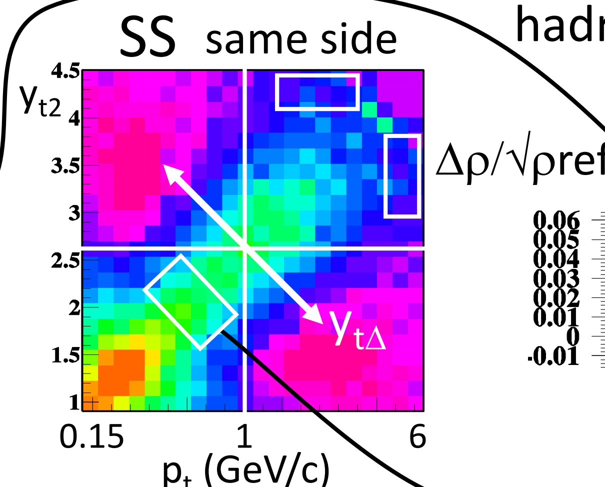
minimum-bias:
no trigger condition



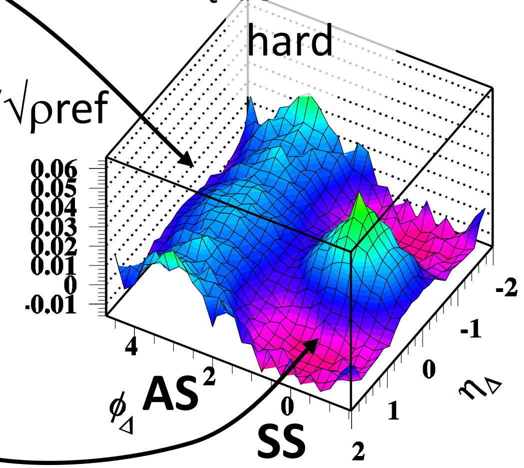
proton fragments



jet recoil + k_t



hadron $p_t \approx 0.6$ GeV/c



gluon fragments

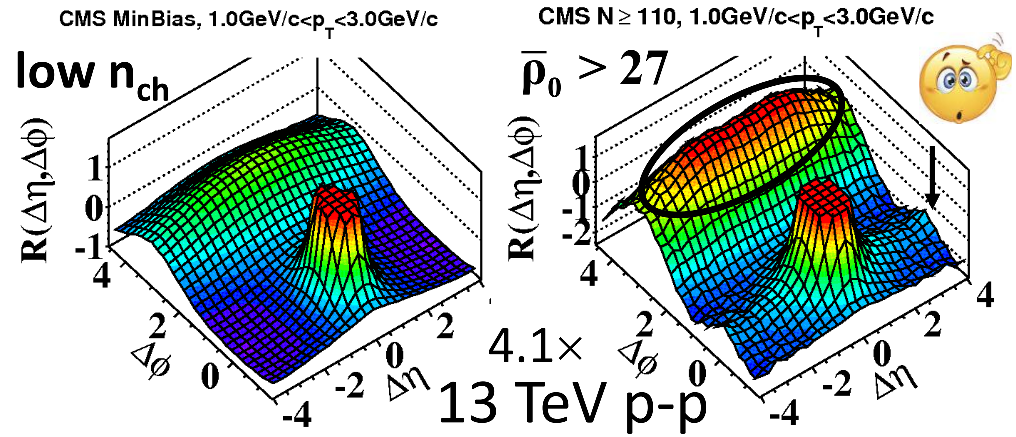
The Ridge – I

2010

The CMS "ridge" is viewed as evidence for "collectivity," indicating a flowing medium

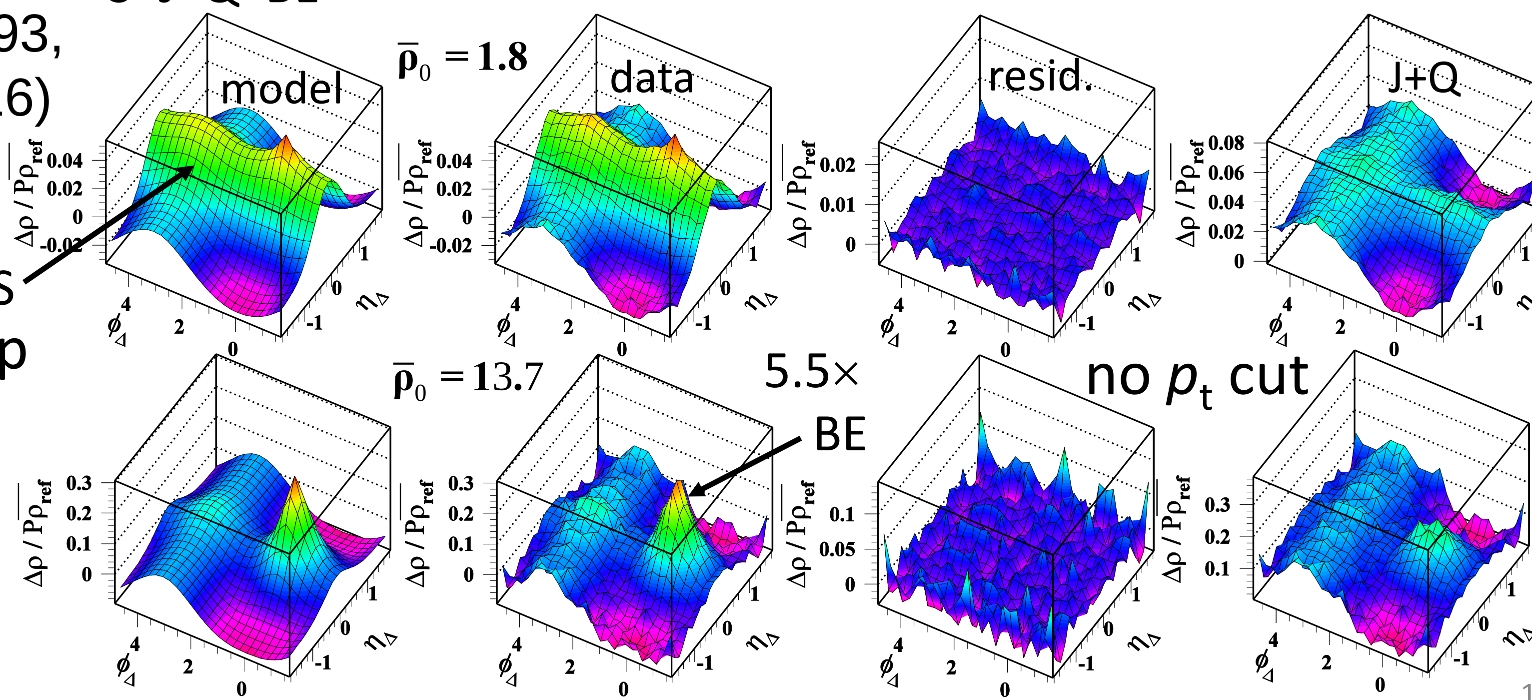
Analysis of lower-energy p-p data provides greater detail

p_t>1 GeV/c $\bar{\rho}_{0NSD} \approx 6.5$



S+J+Q+BE

Phys Rev D 93, 014031 (2016)



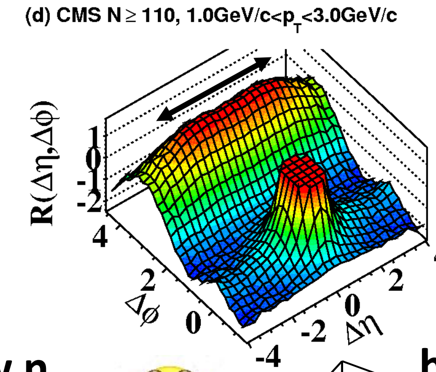
200 GeV p-p

$\bar{\rho}_{0NSD} \approx 2.5$

1512.01599

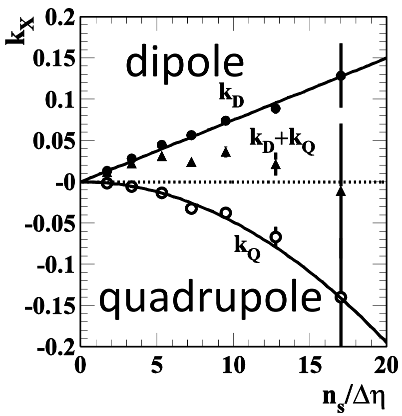
The Ridge – II

the "ridge" is a manifestation of
a cylindrical quadrupole component

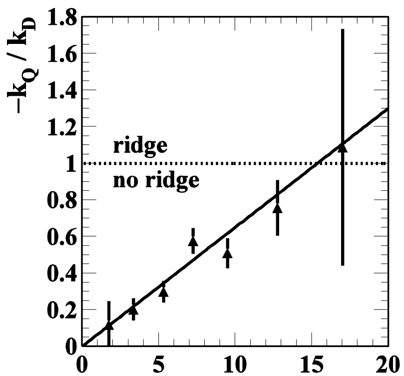


no p_t cut

SS curvatures

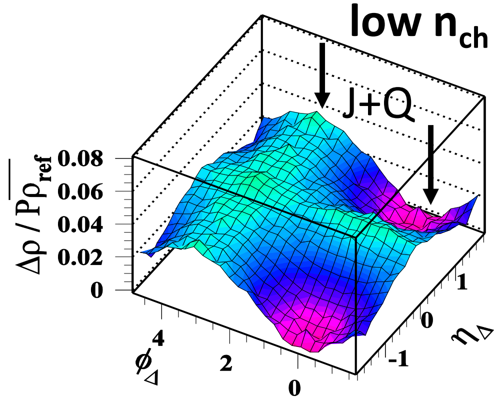


curvature ratio

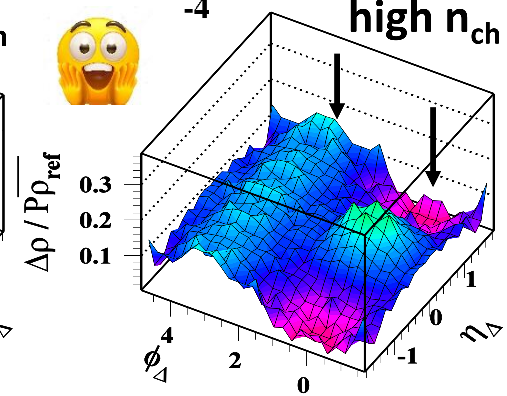


$\bar{\rho}_s = n_s/\Delta\eta$

low n_{ch}



high n_{ch}



$\bar{\rho}_{hNN} \approx \alpha \bar{\rho}_{sNN}^2$

jets plus quadrupole

jets $\propto \bar{\rho}_s^2$

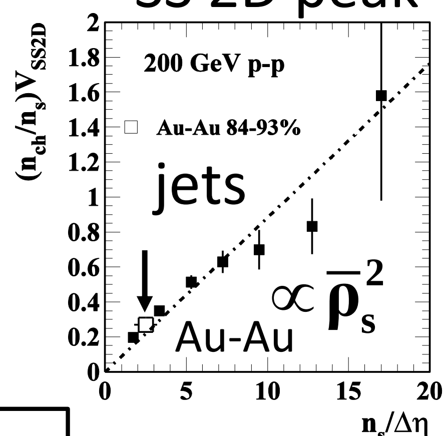
two-gluon R_x

cyl. quad $\propto \bar{\rho}_s^3$

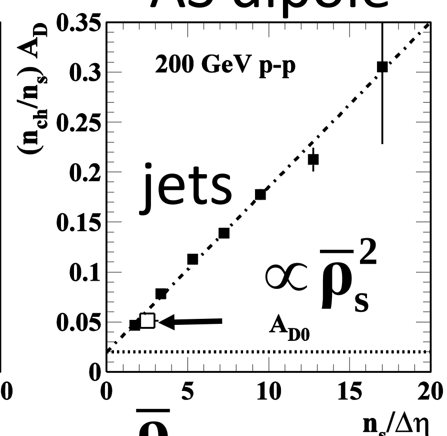
three-gluon R_x

no flowing medium

SS 2D peak

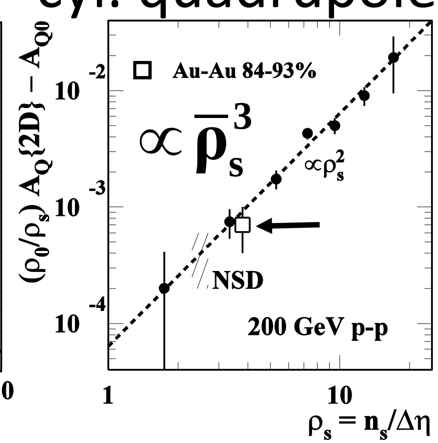


AS dipole



$\bar{\rho}_s$

cyl. quadrupole



all azimuth structure explained

Summary

- *p*-Pb centrality *requires N-N* exclusivity
- Small shifts in hard-component (jet) widths?
  (a) conventional NMFs are uninterpretable
  (b) apparent strangeness enhancement is not
- *p-p* two-particle correlations are complex
- the “ridge” is actually a cylindrical quadrupole
  – likely from a three-gluon direct interaction

no evidence for QGP/flow in small systems