Harmonic jet tomography at RHIC+LHC

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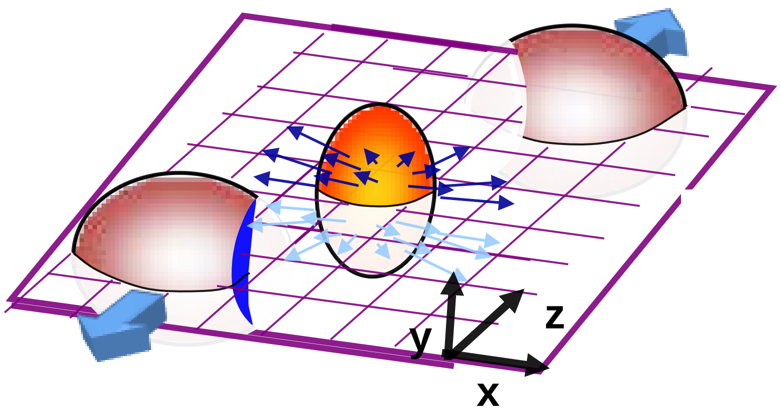
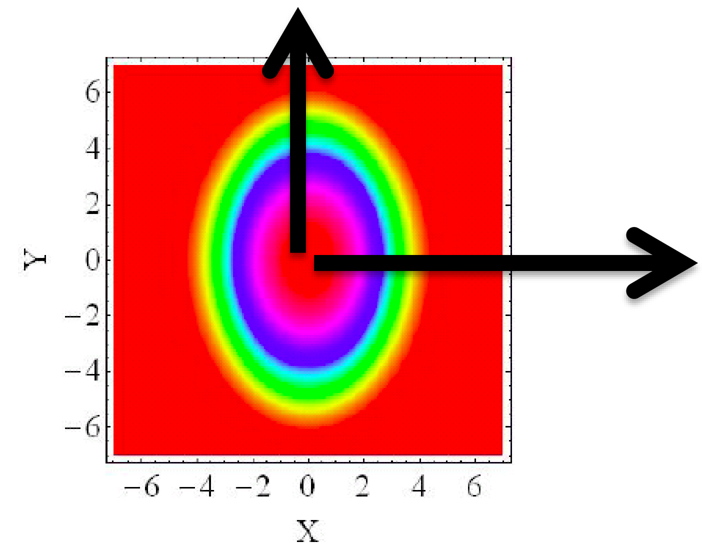
*PLB **713,** 35 (2012)*
*arXiv:**1208.6361**, **1210.1245**.*

Outline

- Jet tomography: geometry and fluctuations; different jet energy loss models
- High-pt Vn at different centralities from RHIC to LHC
- Hard-soft correlation
- P-Pb case
- Conclusion and outlook

Jet tomography: geometry

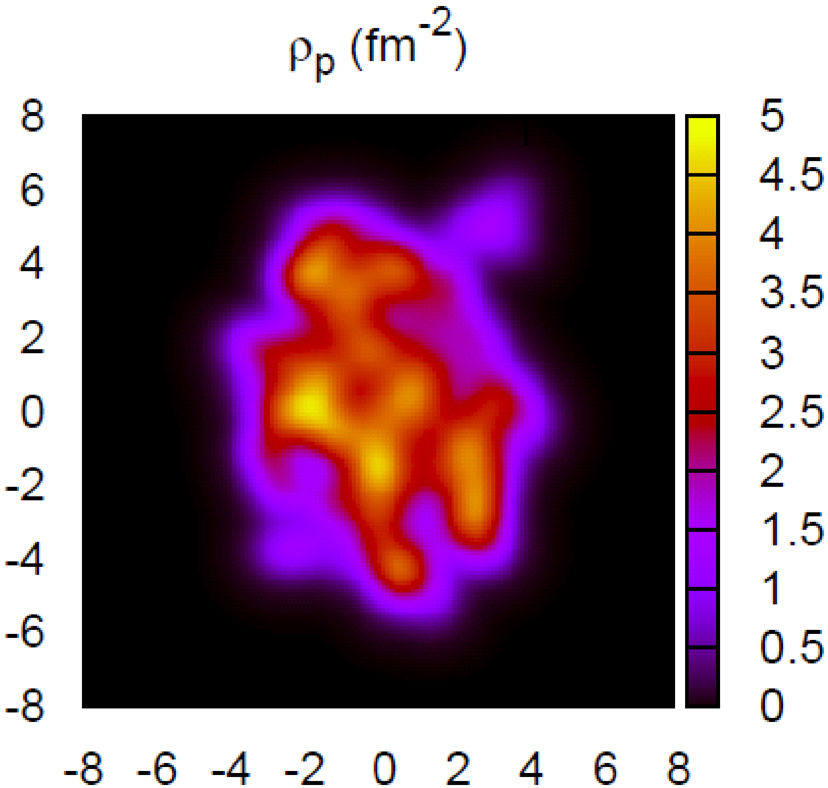




$$\frac{dN^h}{d\phi} \sim R_{AA}(\phi) \sim 1 + 2v_2 \cos[2(\phi - \Psi_R)]$$

Can V2 be understood in a consistent picture <u>from</u> RHIC <u>to</u> LHC?

Jet tomography: **High pt Vn!**



Initial state, and jet production fluctuations

Glauber model

$$R_{AA}(\phi) \sim 1 + 2\sum_n v_n \cos[n(\phi - \Psi_n^J)]$$

- **Consistent picture and more information!**
- **Hard-soft correlation.**

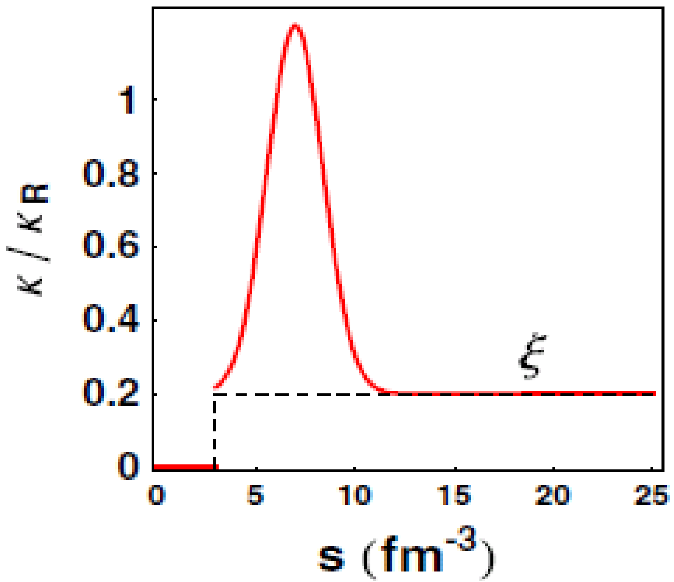
Jet energy loss

- Length dependence?
- Density dependence?

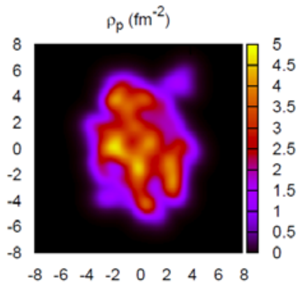
*J. Liao and E. Shuryak, PRL **102**, 202302 (2009)*

$$\Delta E = -E\,\kappa[s(l)] \times s(l) \times l^m \times \Delta l$$

- NTcE model: m=1.
  (Nontrivial matter near Tc)
- L^2 model: m=1, κ const.
  (pQCD)
- L^3 model: m=2, κ const.
  (AdS/QCD)



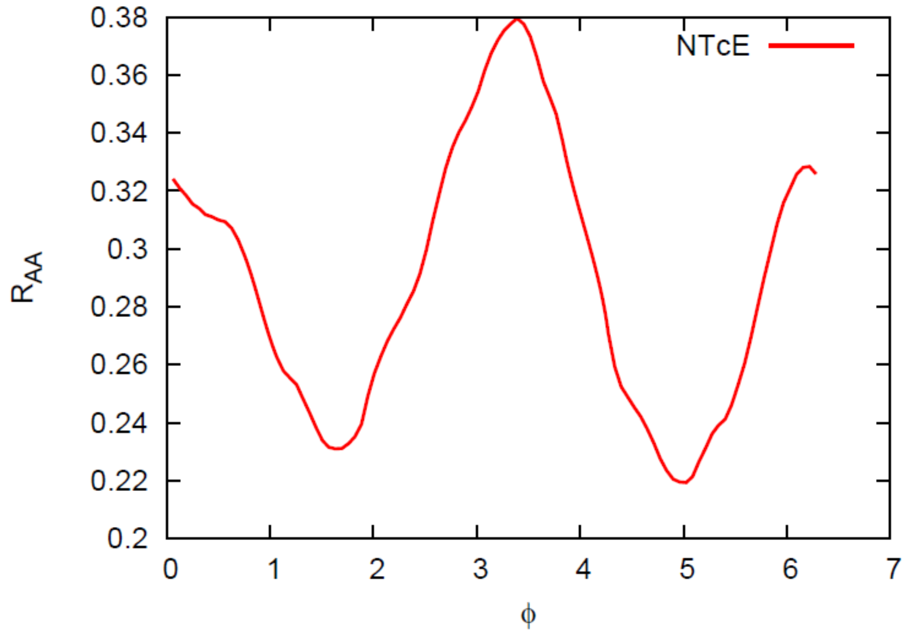
*Barbara Betz et.al., PRC **84**, 024913 (2011)*
*W.A. Horowitz and M. Gyulassy, NPA **872**, 265 (2011)*



MC: one event

$$g_{pp}(p_t) \propto \frac{1}{p_t^n}$$

$$E_f = E_i \times f_{\vec{P}} \qquad R_{AA} = < (f_{\vec{P}})^{n-2} >_{\vec{P}}$$

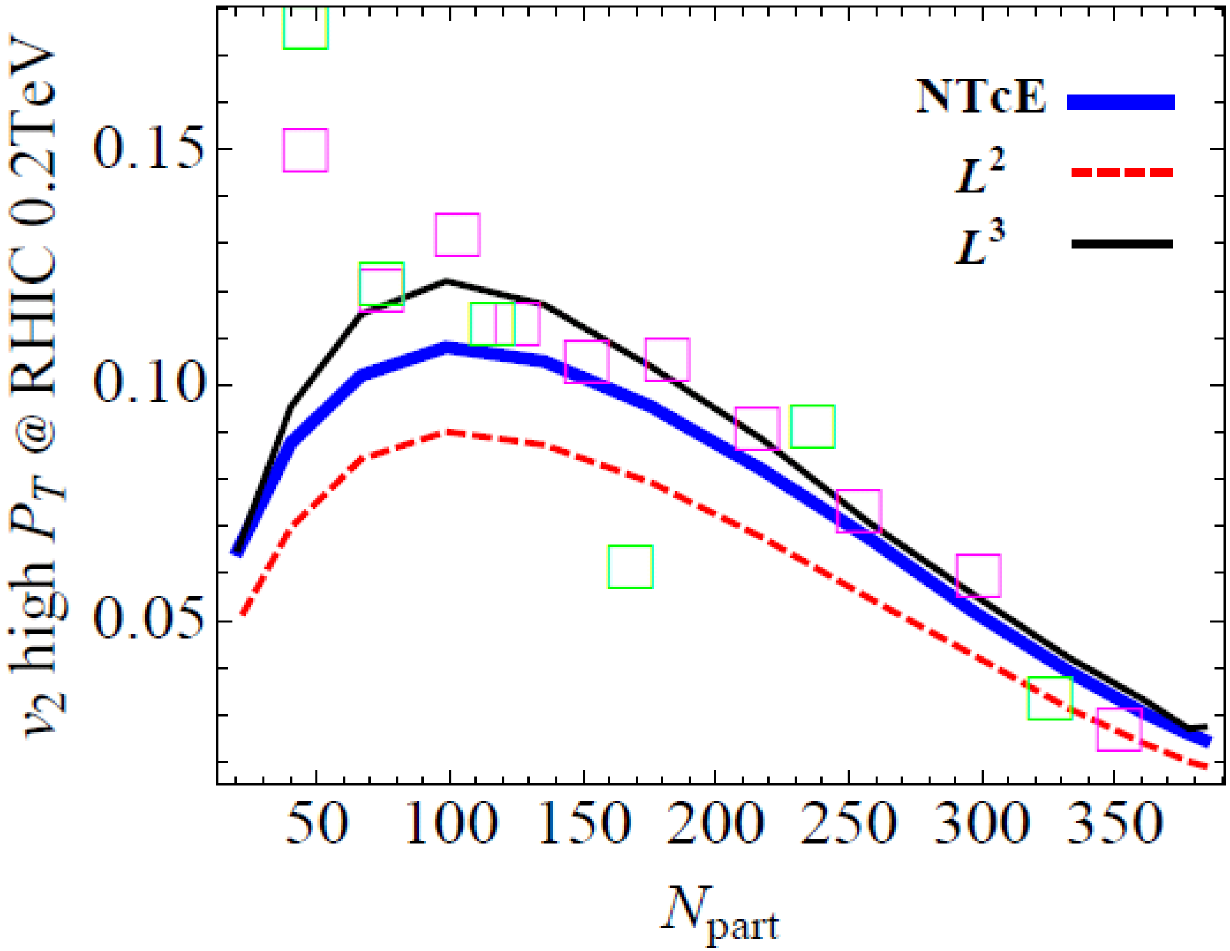


Sum over all the jet spots and jet paths

n= 8.1 (200 GeV), n=6.0 (2.76 TeV)

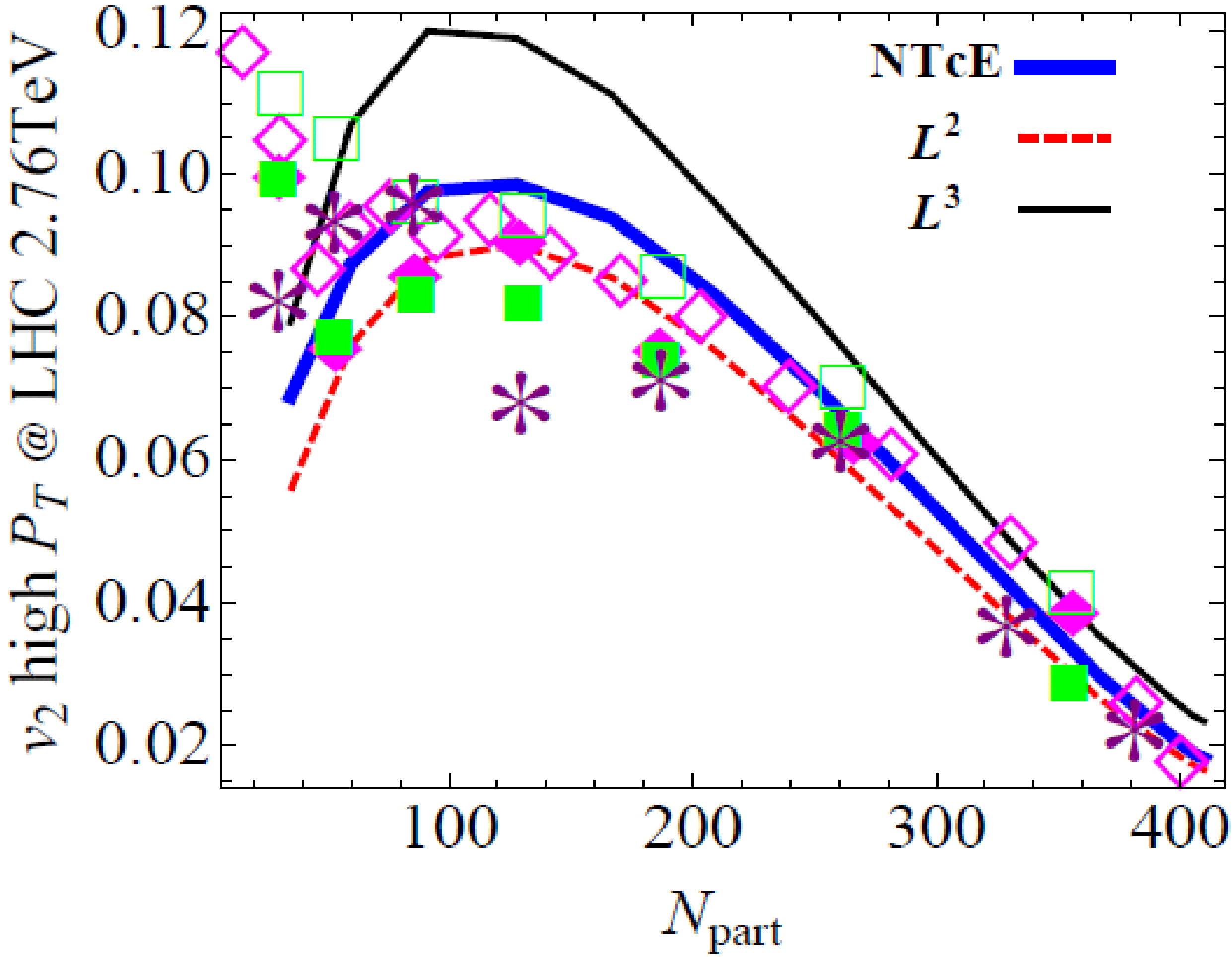
$$R_{AA}(\phi) \sim 1 + 2\sum_n v_n \cos[n(\phi - \Psi_n^J)]$$

Results: V2, RHIC 200 GeV



*PHENIX, Pt: 6--9 GeV and > 9 GeV, PRL **105**, 142301 (2010).*

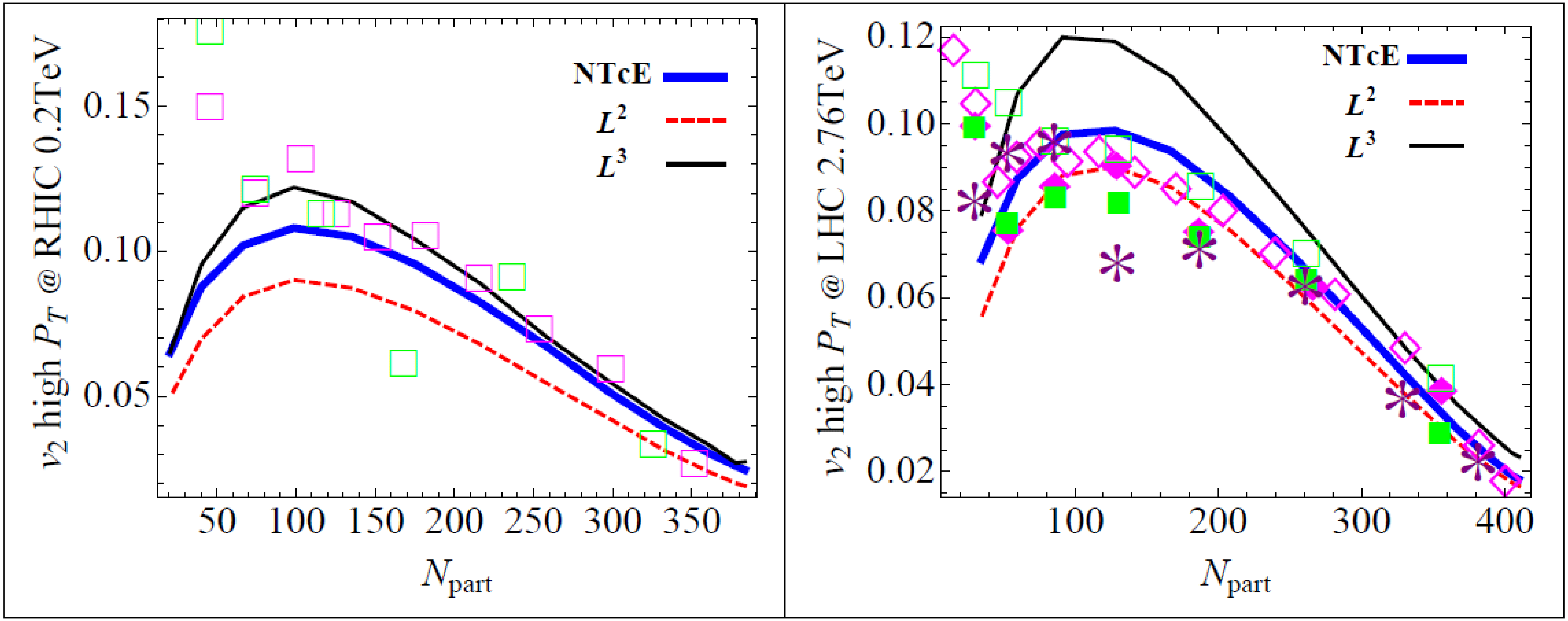
Results: V2, LHC 2.76 TeV

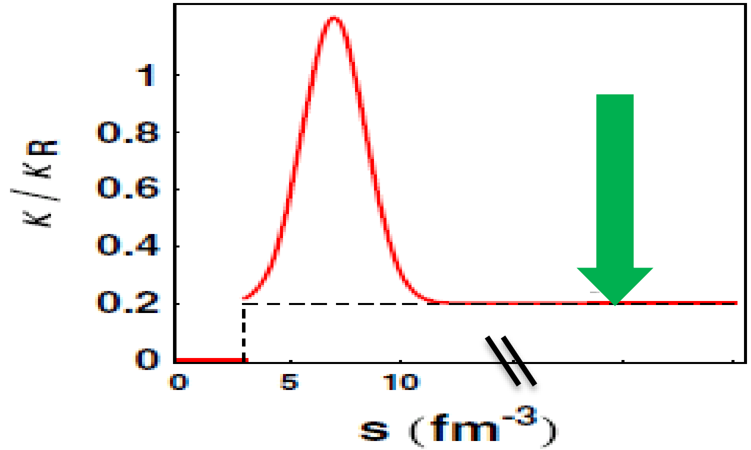


ATLAS, CMS, and ALICE, Pt: ~10--20 GeV,

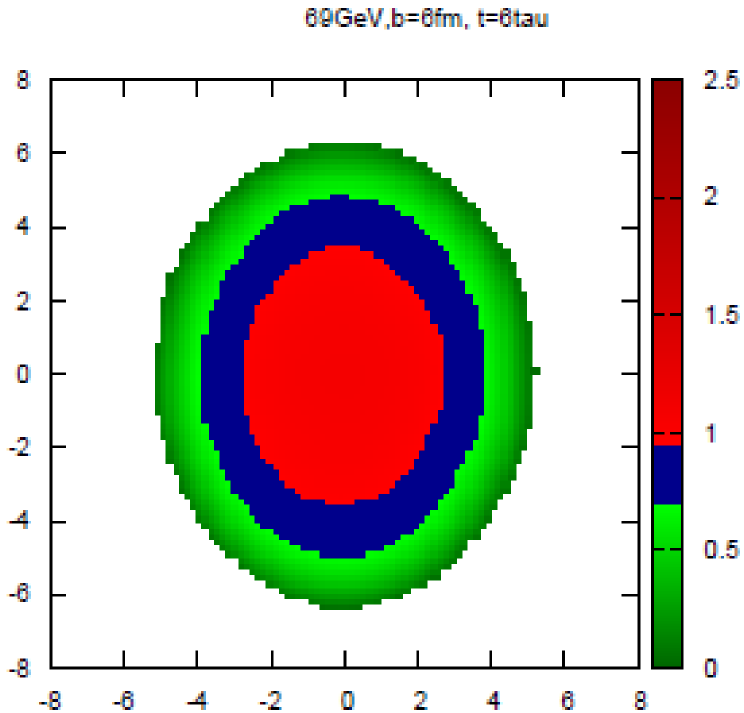
*arXiv:1205.5761, 1204.1850, PLB **707**, 330 (2012)*

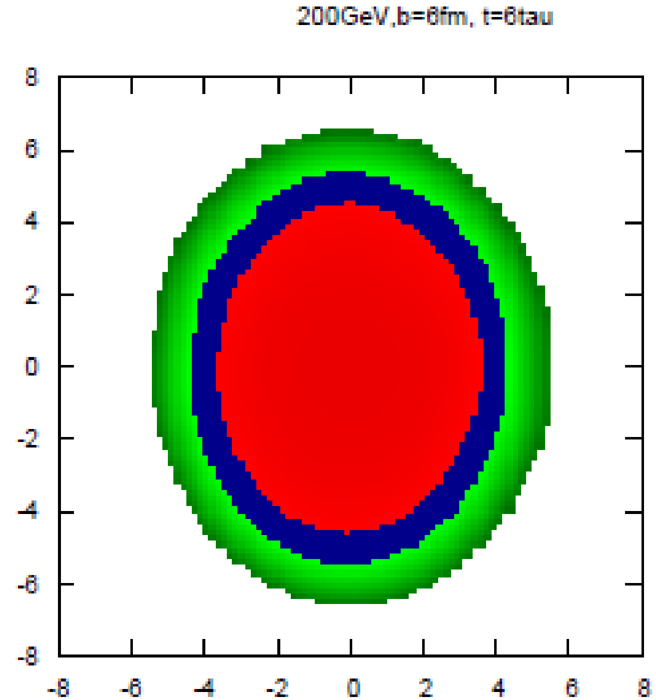
From RHIC to LHC



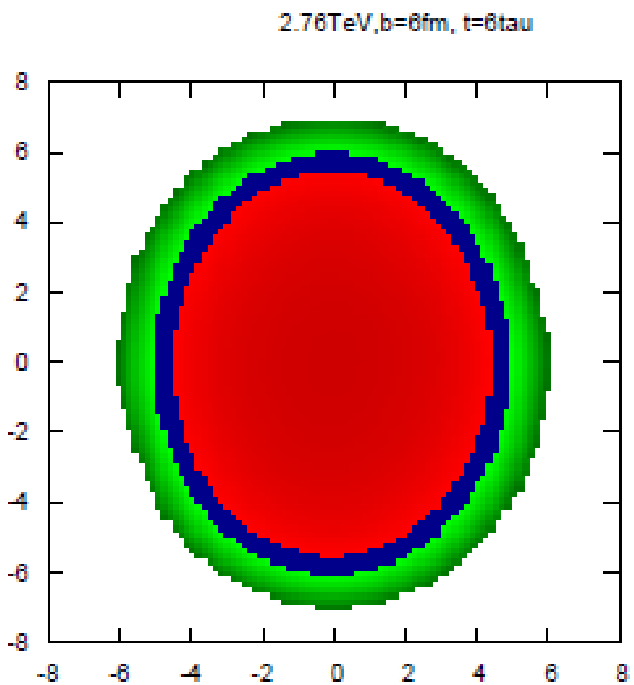


X.Z. and J. Liao, arXiv:1208.6361

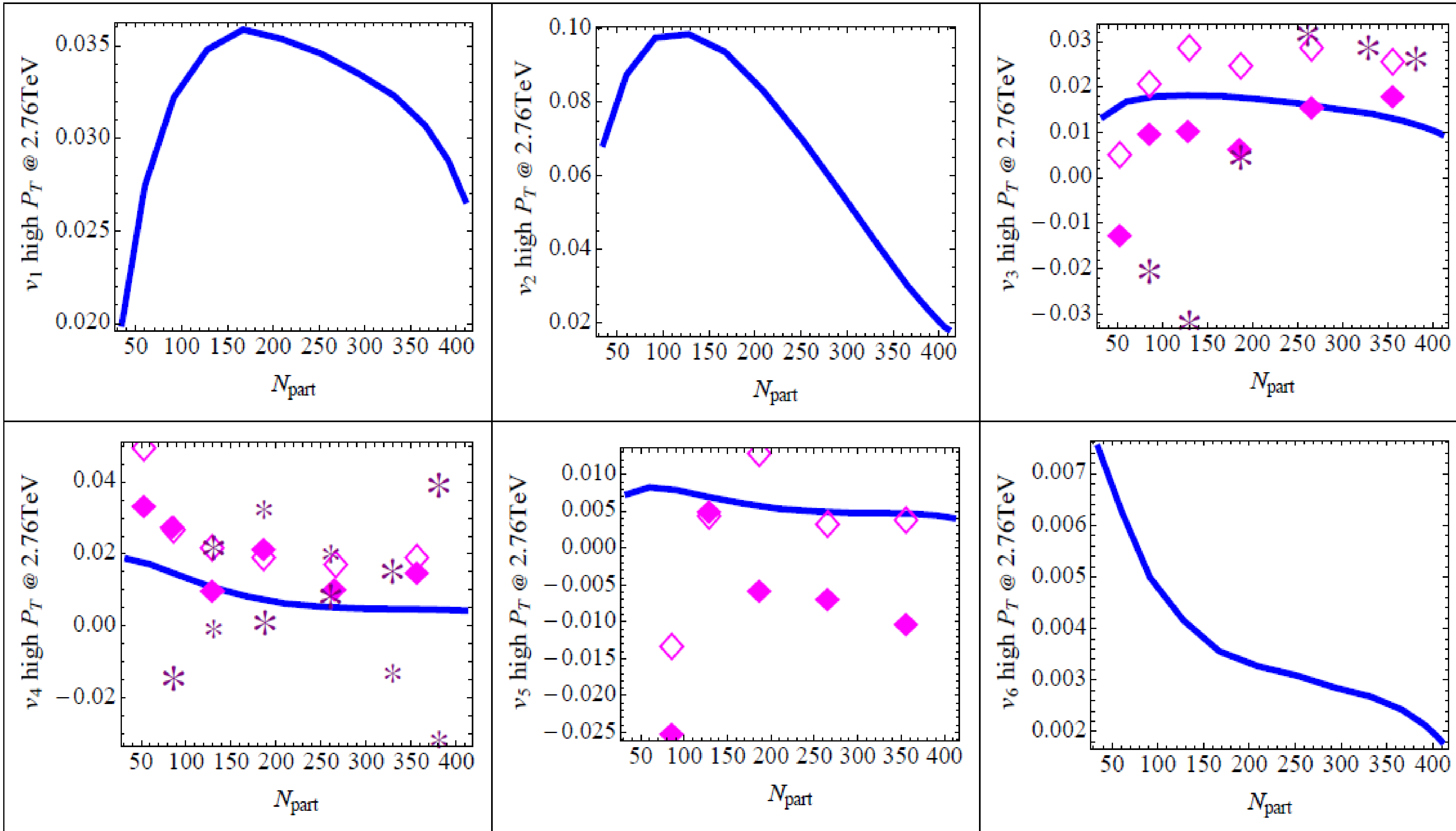




Entropy density

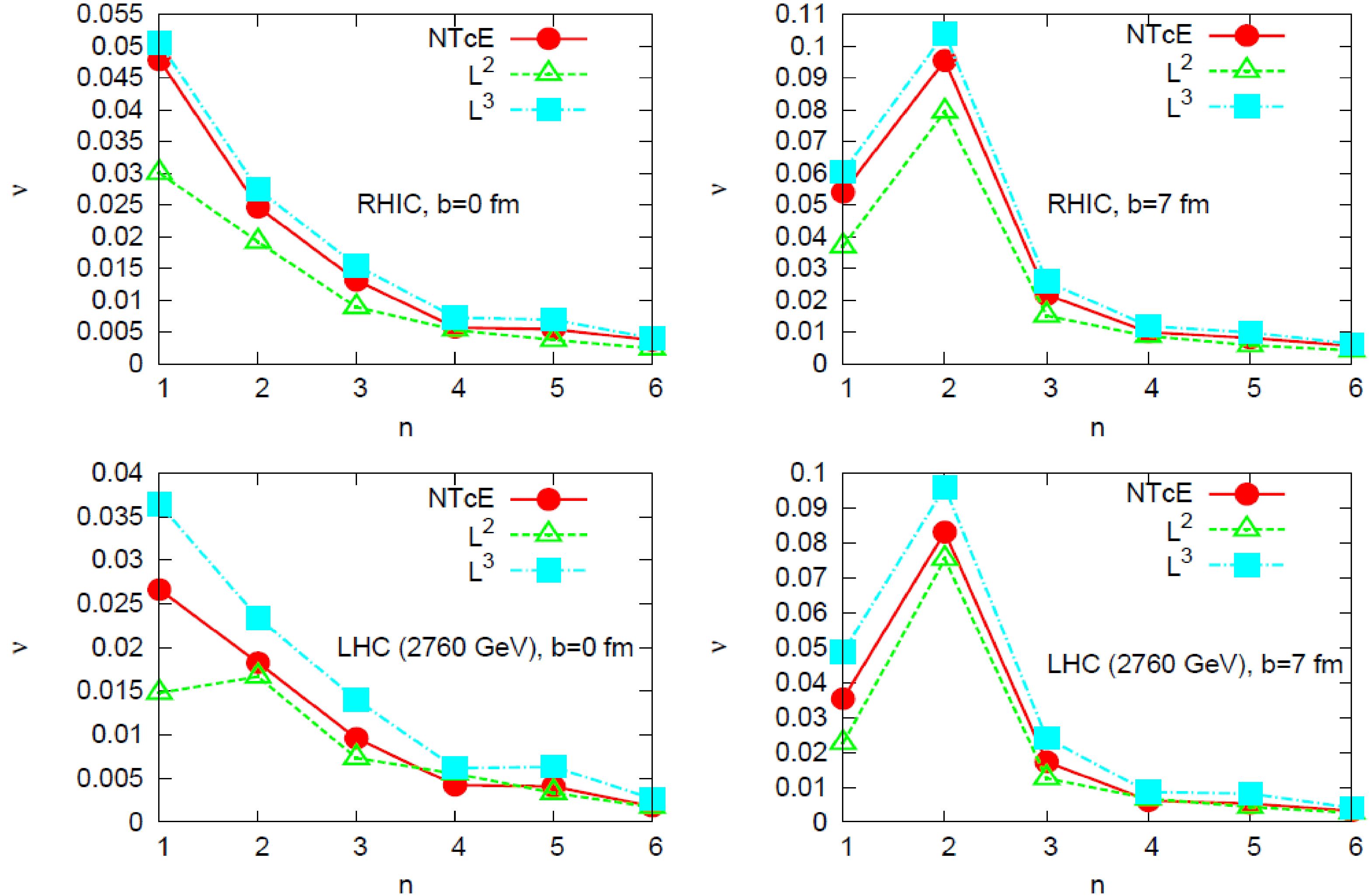


Results: Vn, LHC 2.76 TeV



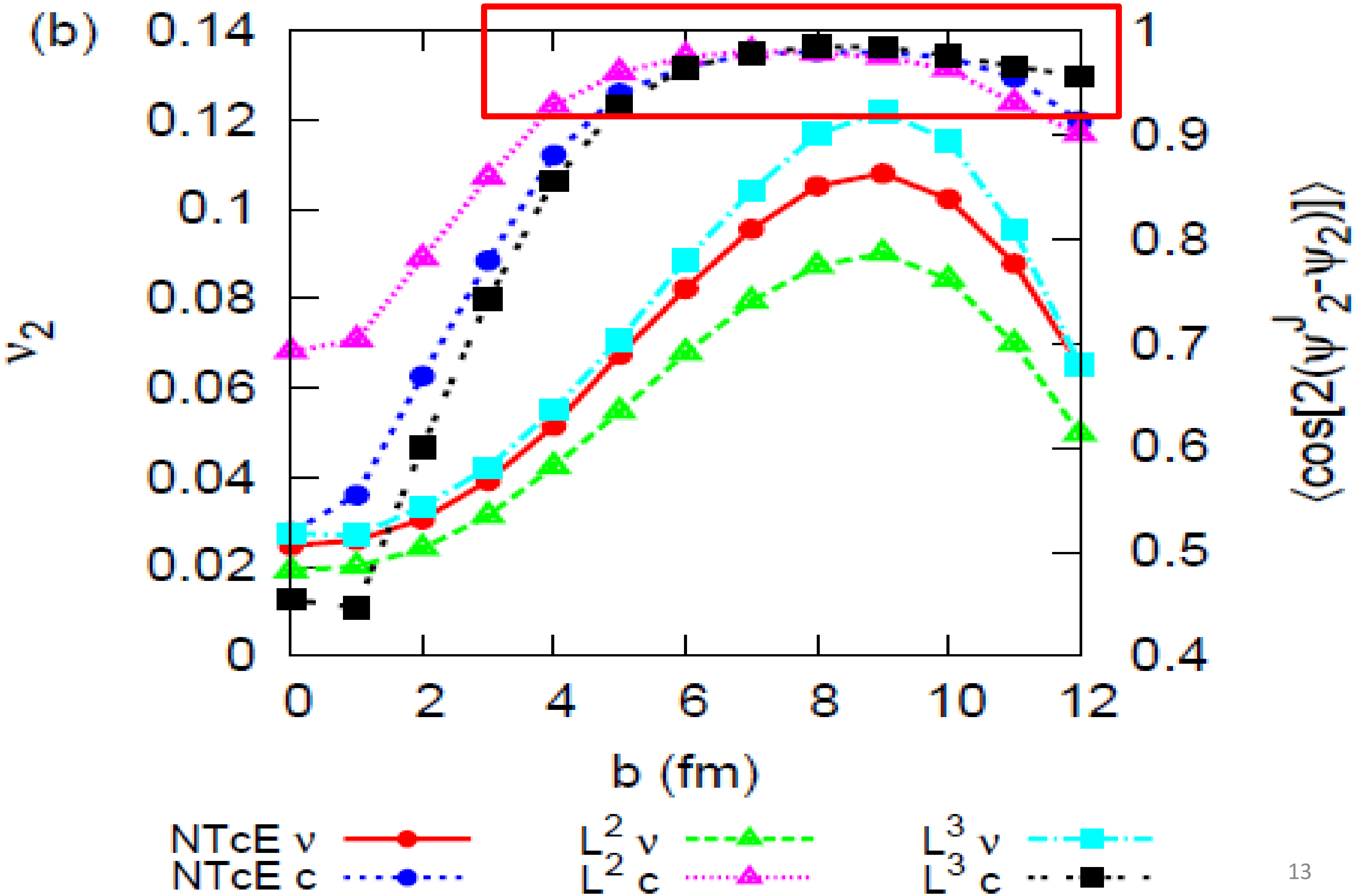
Based on NTcE model

Some details: Vn spectrum

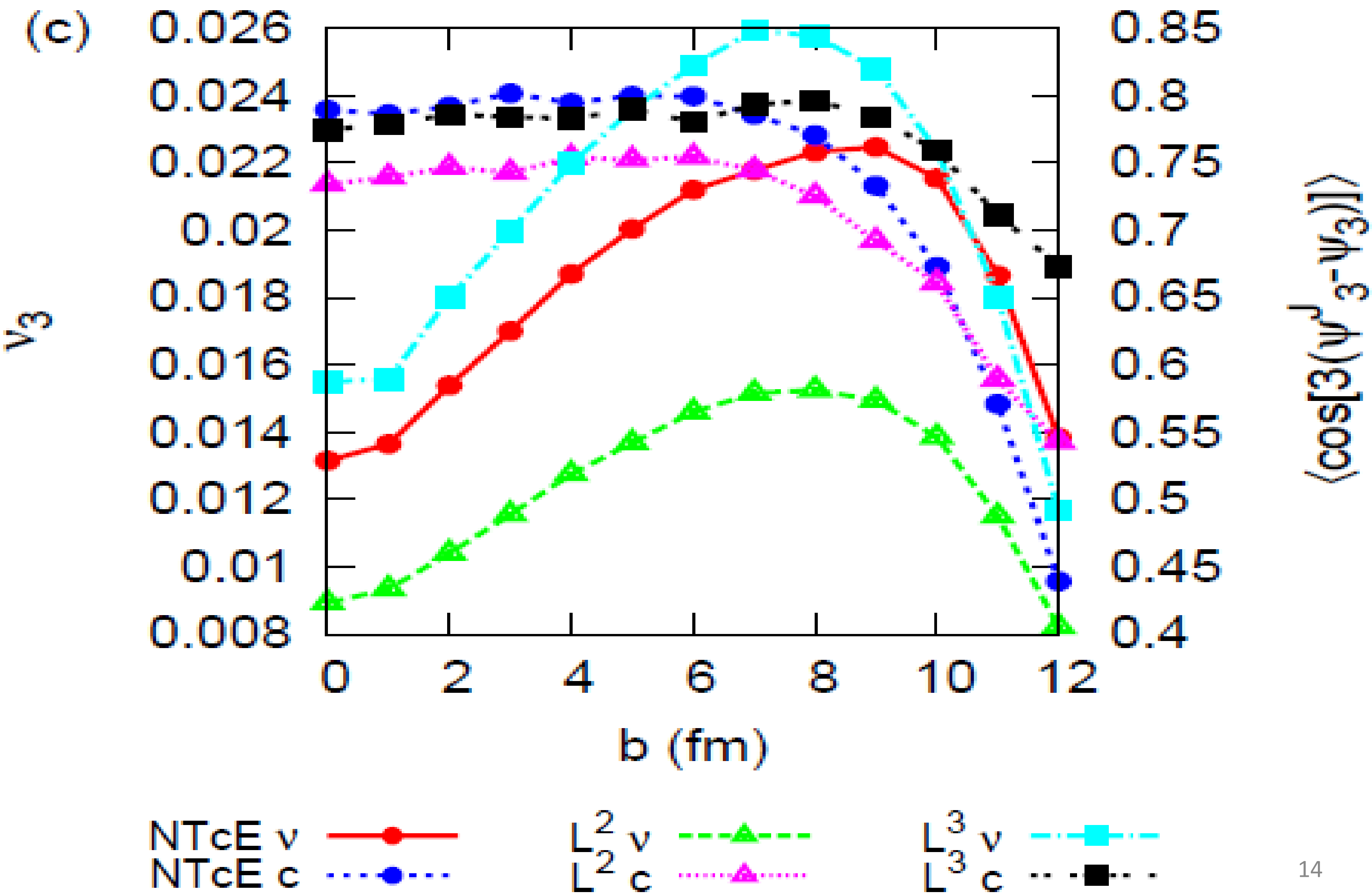


X.Z. and J. Liao, arXiv:1210.1245

Some details: angle dispersion

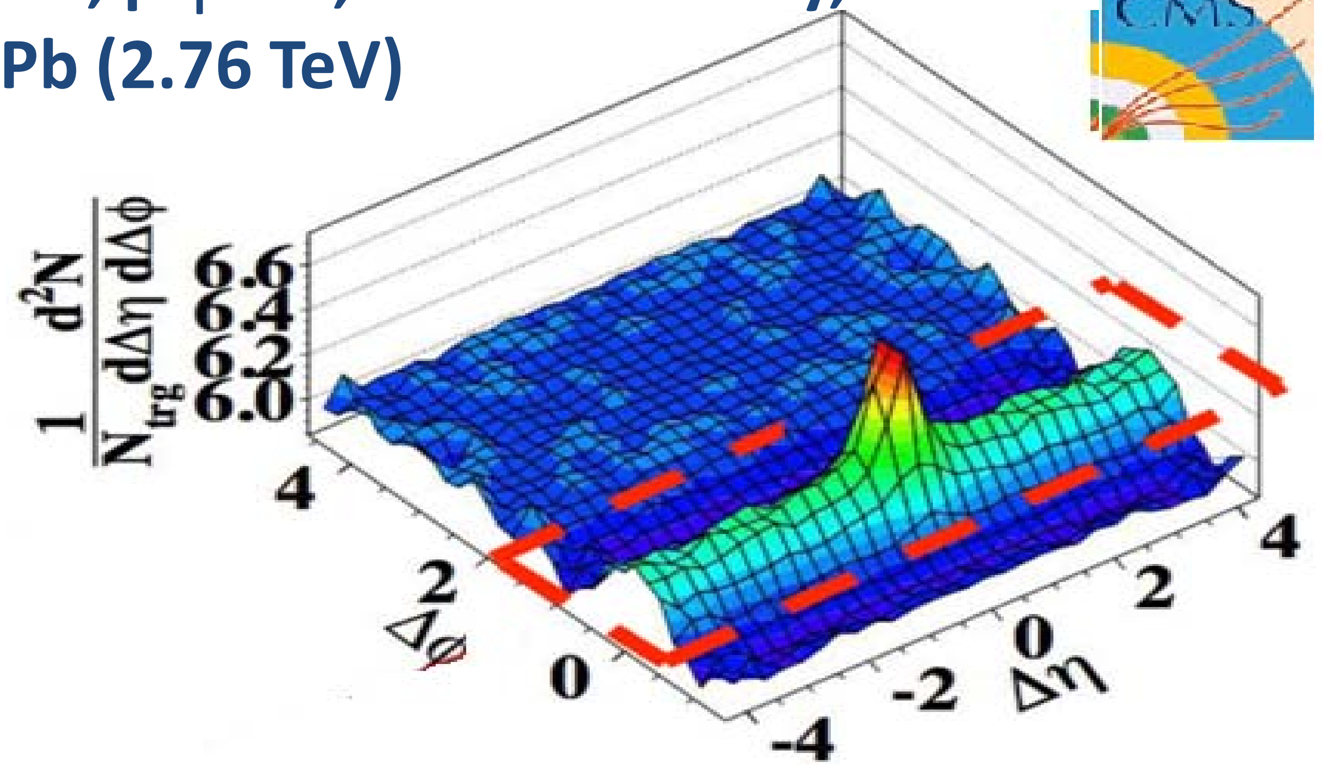


Some details: angle dispersion



Hard-soft Correlation

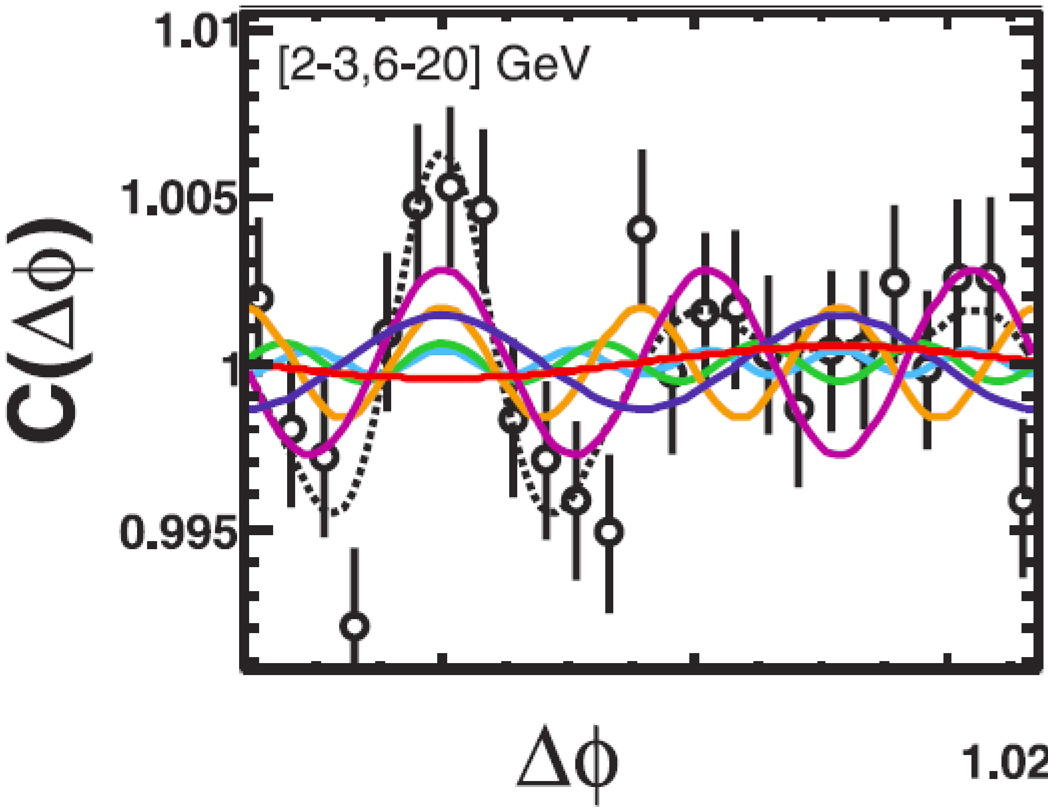
p^t_T 4-6, p^a_T 2-4, 0-5% centrality, Pb-Pb (2.76 TeV)



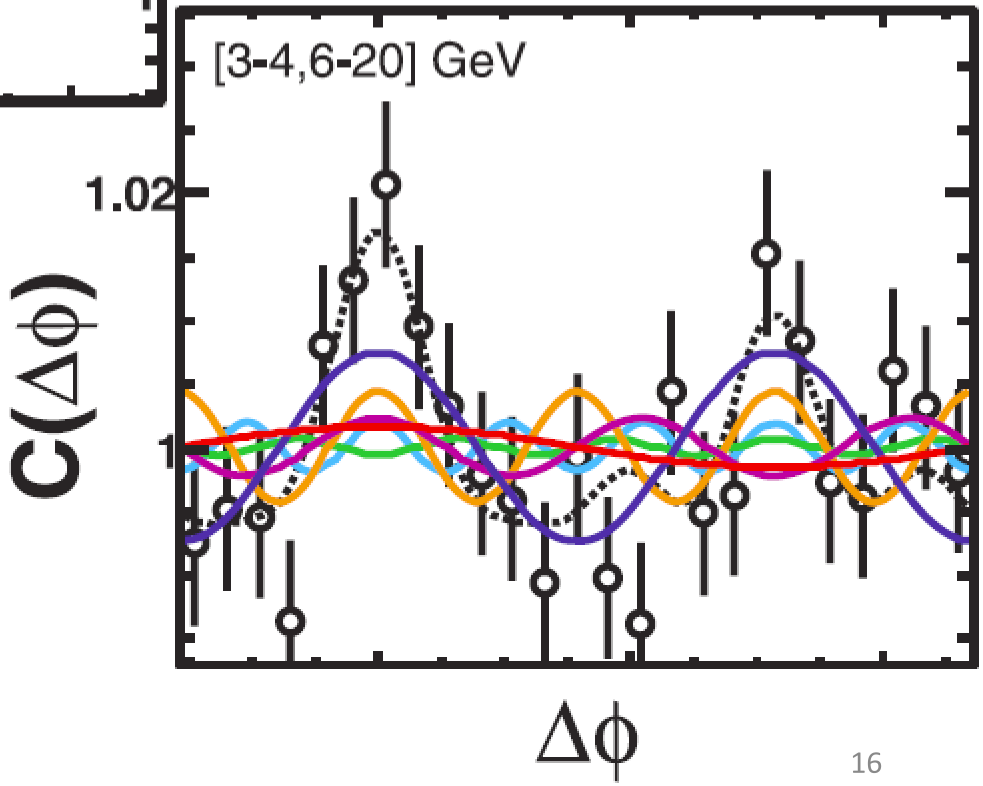
Elliptic flow not subtracted

Hard-ridge phenomena

From Olga Evdokimov's talk at NNPSS2011



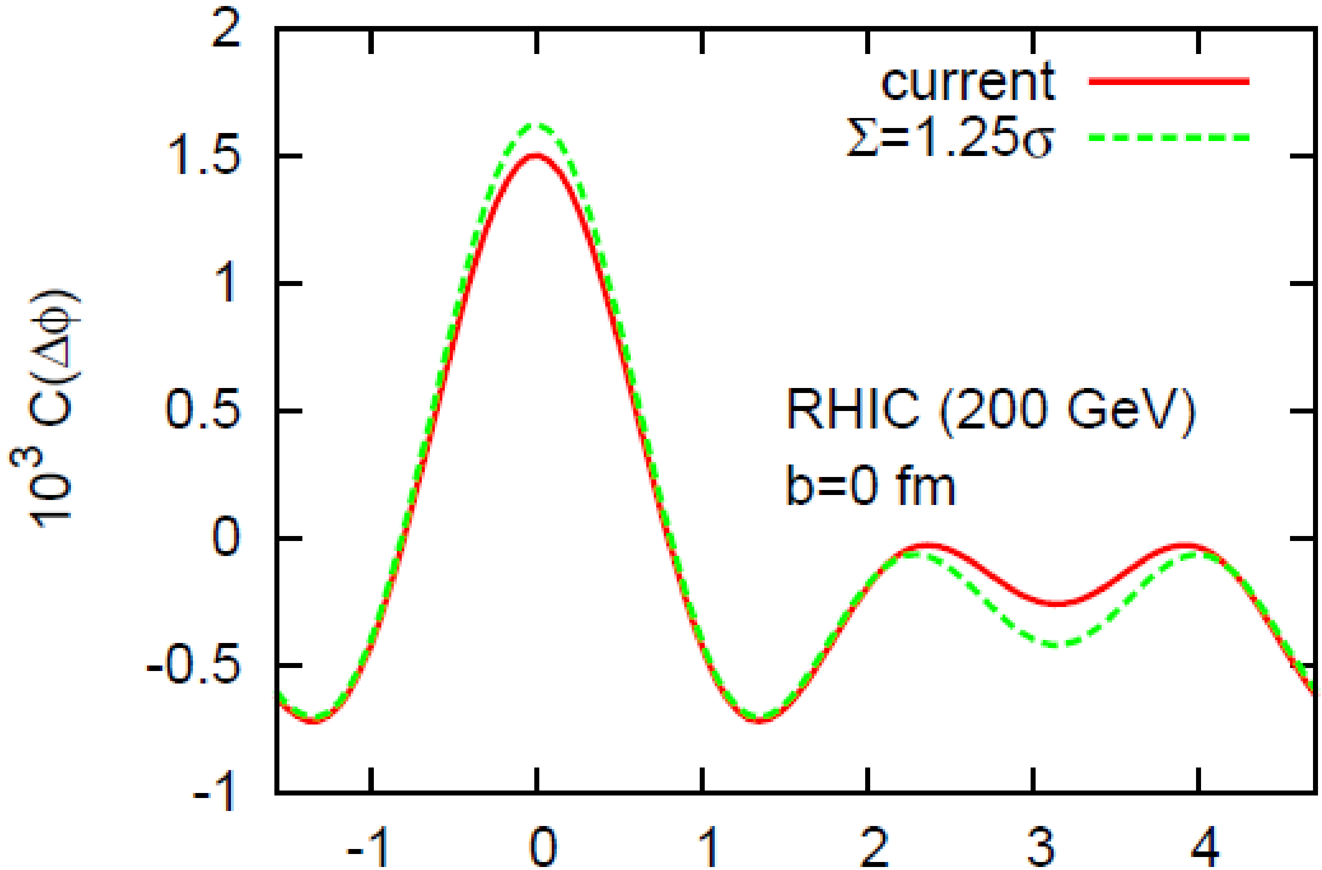
ATLAS,
*PRC **86**, 014907 (2012)*



0-1% centrality,

$2 < |\Delta\eta| < 5$

Hard-soft Correlation



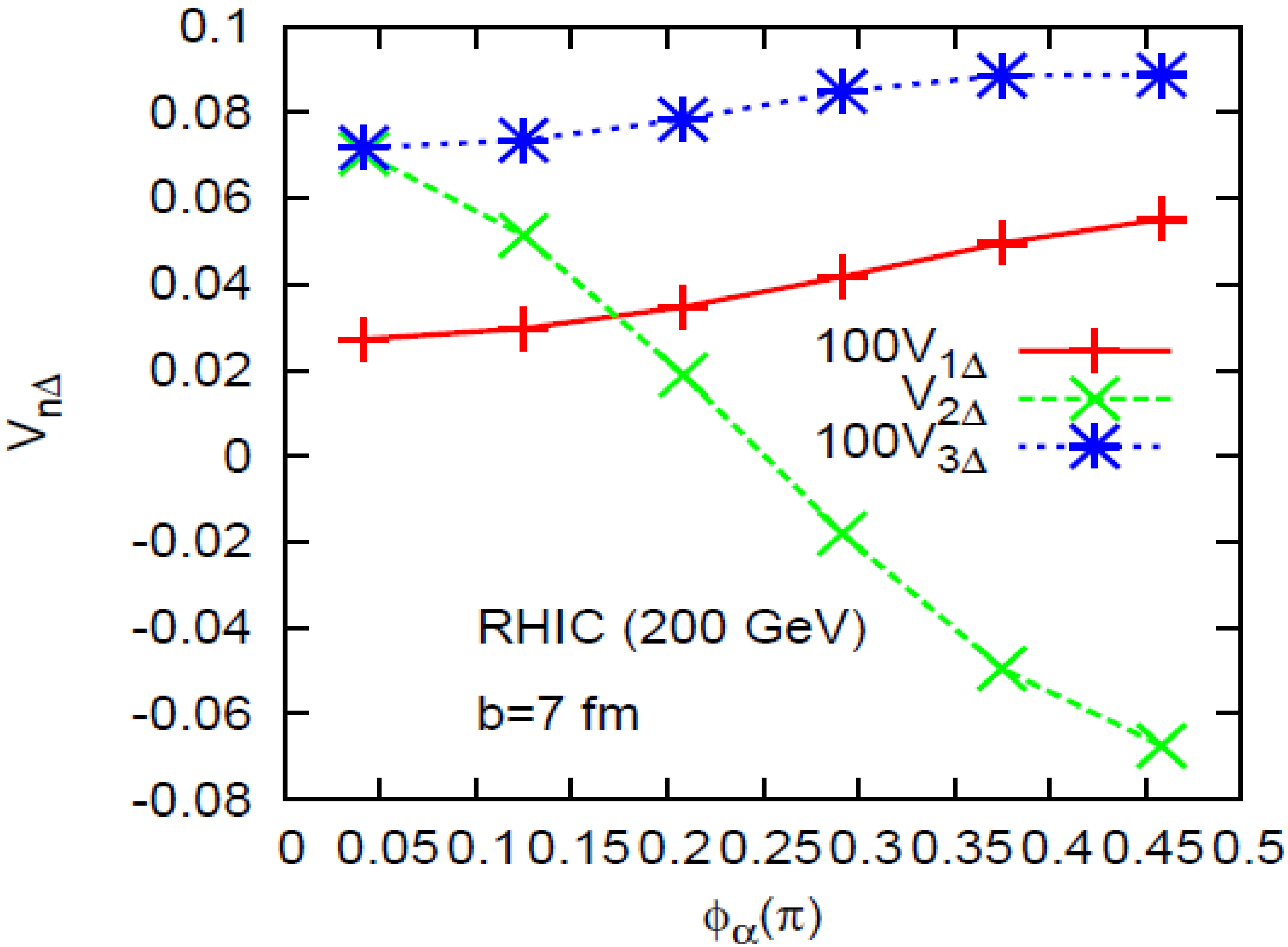
$$\frac{dN^s}{d\phi^s} \sim 1 + 2\sum_n \nu_n^s \cos[n(\phi^s - \psi_n^S)] \; ,$$

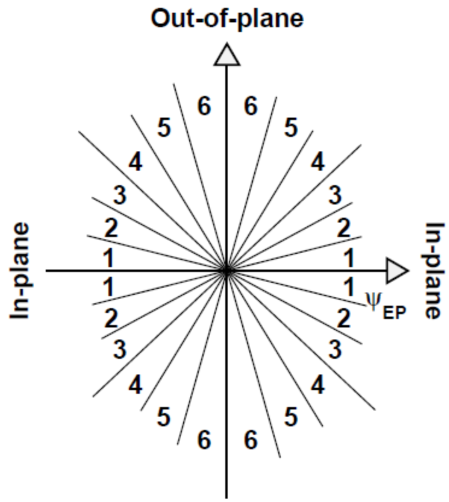
$$\frac{dN^h}{d\phi^h} \sim 1 + 2\sum_m \nu_m^h \cos[m(\phi^h - \psi_m^J)]$$

$$< \frac{dN^{hard}}{dyd\phi_1} \frac{dN^{soft}}{dyd\phi_2} > \sim 1 + \sum_{n=1,2,3,\ldots} 2 < v_n^h v_n^s > \cos(n\Delta\phi)$$

*X.Z. and J. Liao, PLB **713,** 35 (2012).*

Hard-soft Correlation



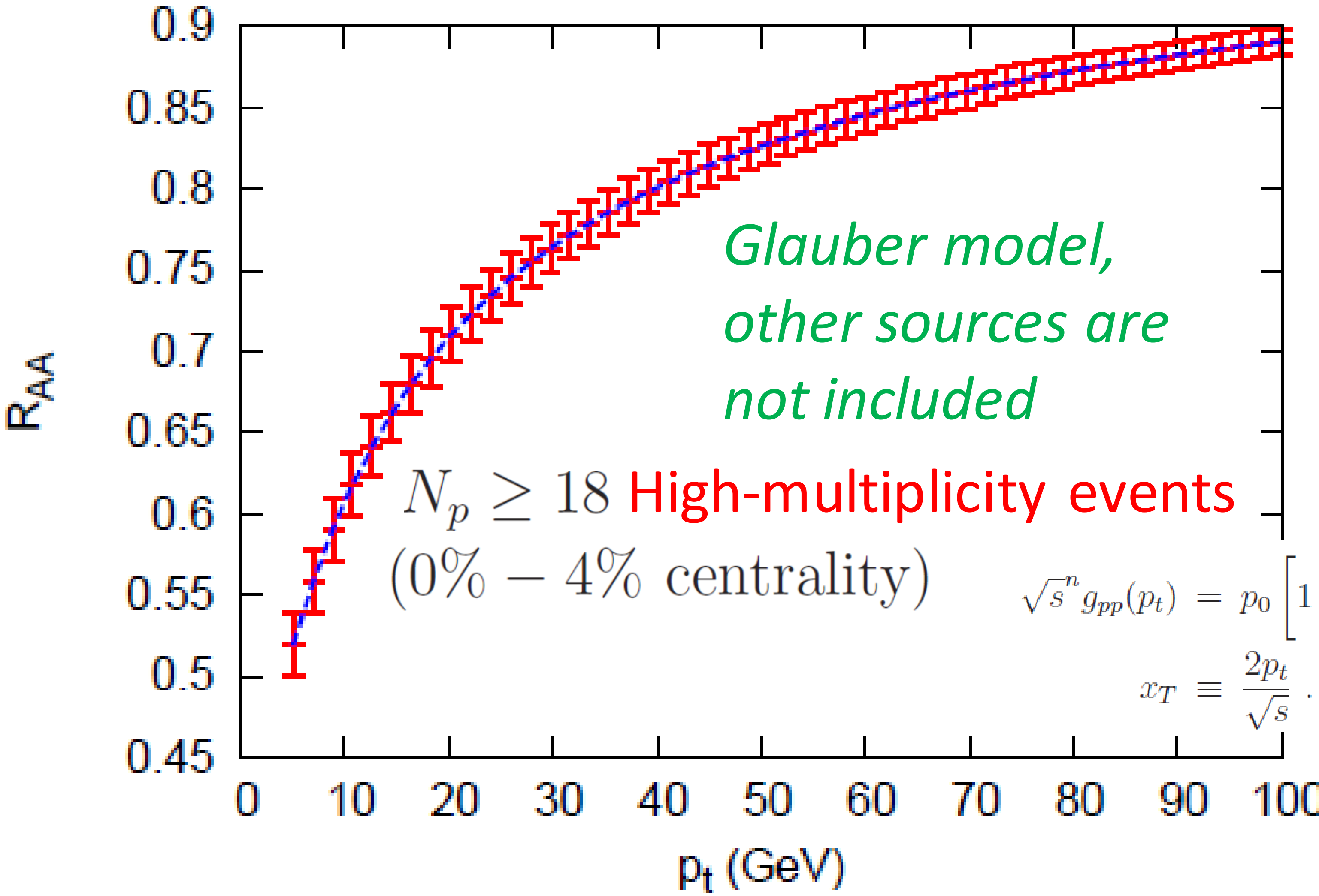


RHIC, arXiv:1010.0690 M. Luzum, ***PLB*** *696, 499 (2011)*

$$C(\Delta\phi) \equiv 2 \times \left[\sum_n V_{n\Delta}\cos(n\Delta\phi)\right]$$

X.Z. and J. Liao, arXiv:1210.1245

P-Pb case (5.02 TeV): a try

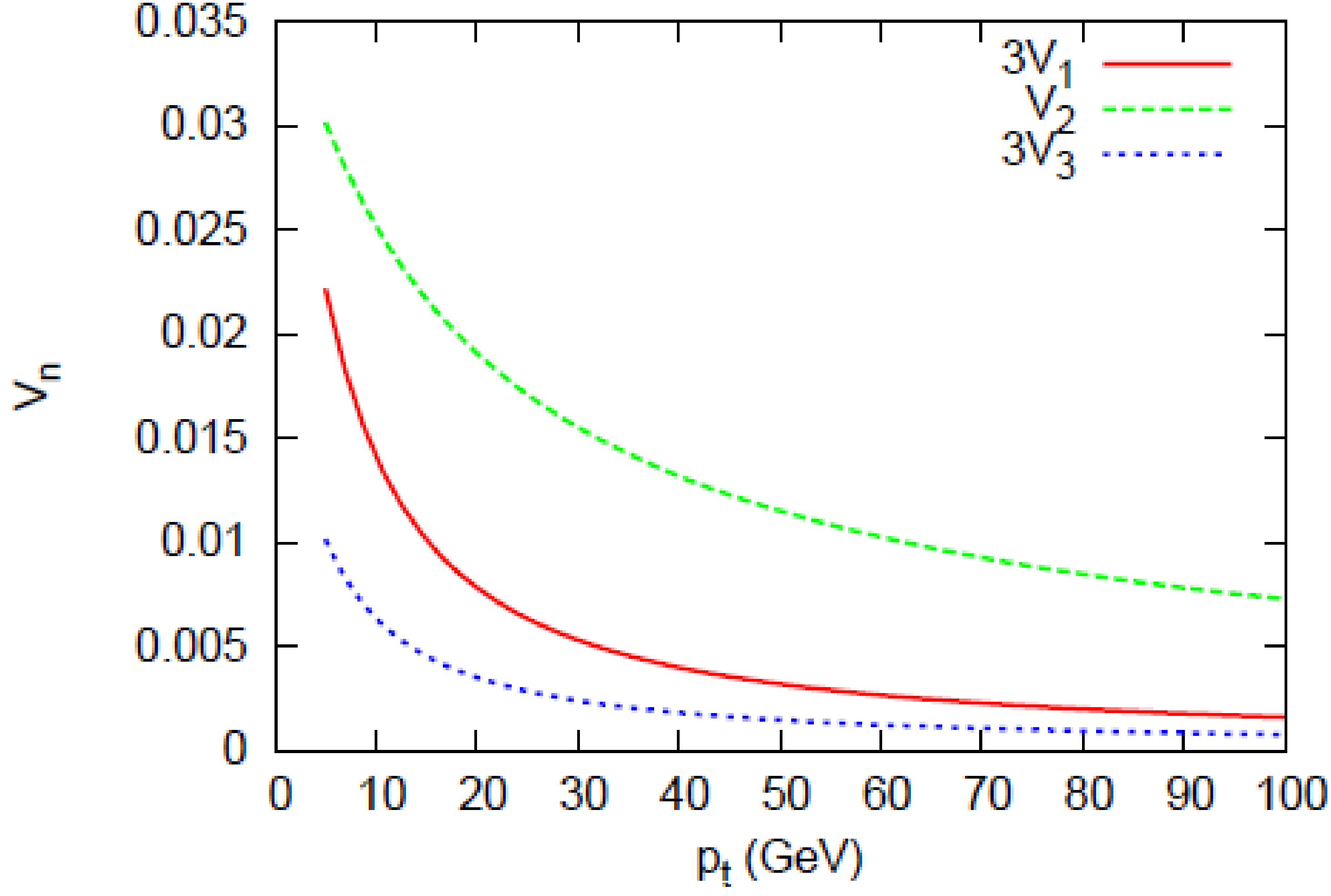


$$\sqrt{s}^n g_{pp}(p_t) = p_0 \left[1 + \frac{x_T}{p_1}\right]^{p_2}$$

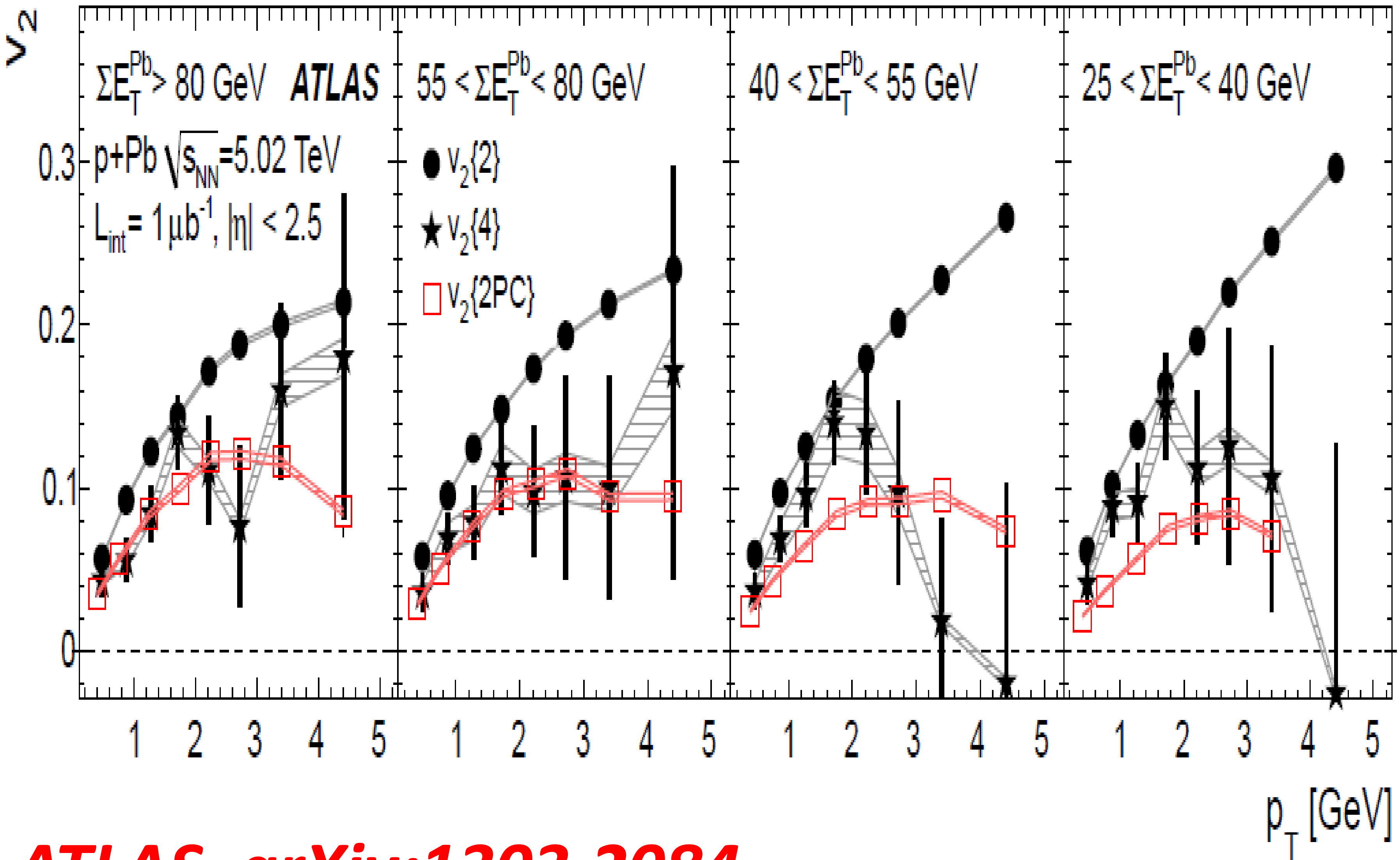
$$x_T \equiv \frac{2p_t}{\sqrt{s}} \,.$$

*Piotr Bozek, PRC **85**, 014911 (2012).*

P-Pb case (5.02 TeV): a try

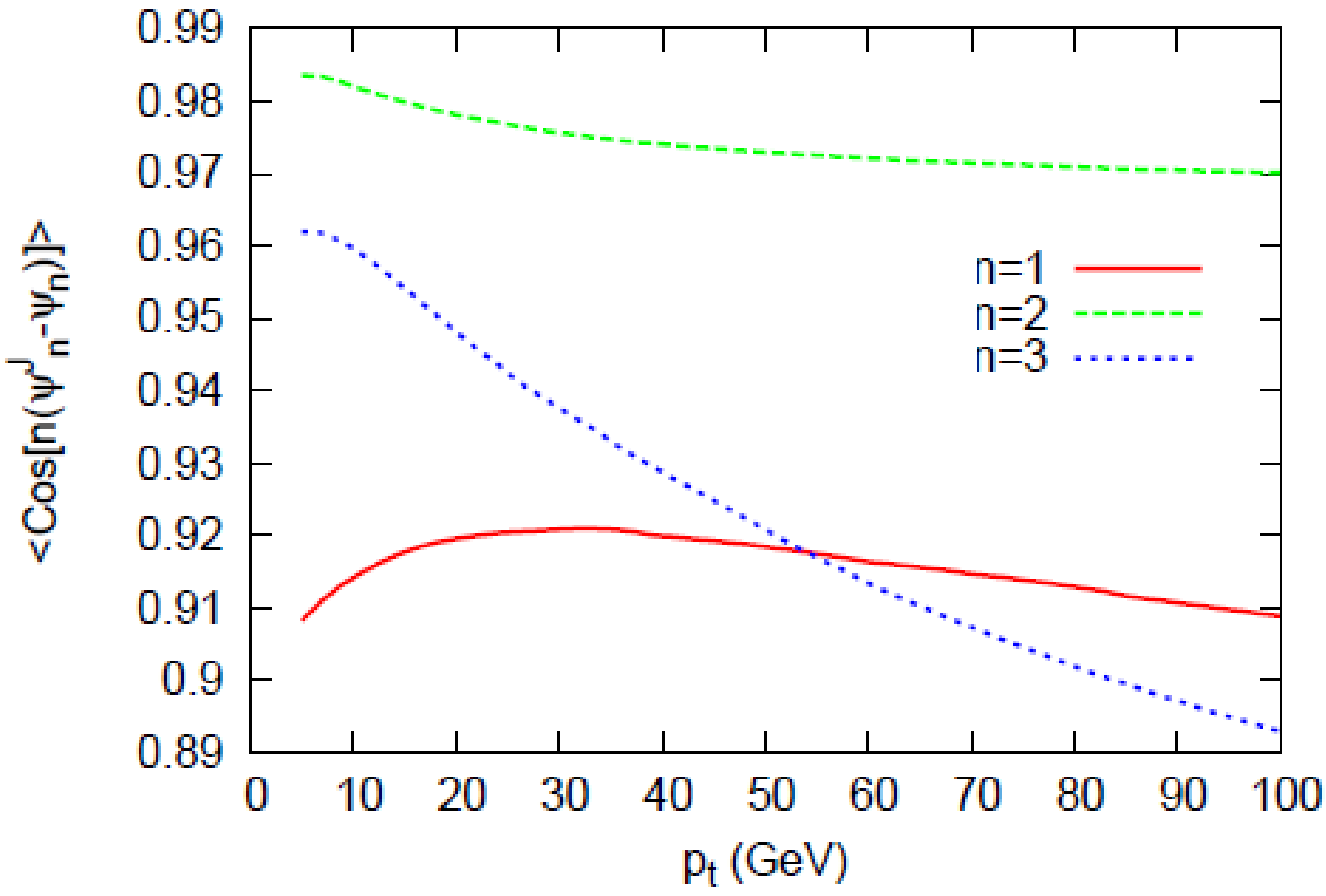


Final state interaction?



ATLAS, arXiv:1303.2084

P-Pb case (5.02 TeV): a try



Angle dispersion

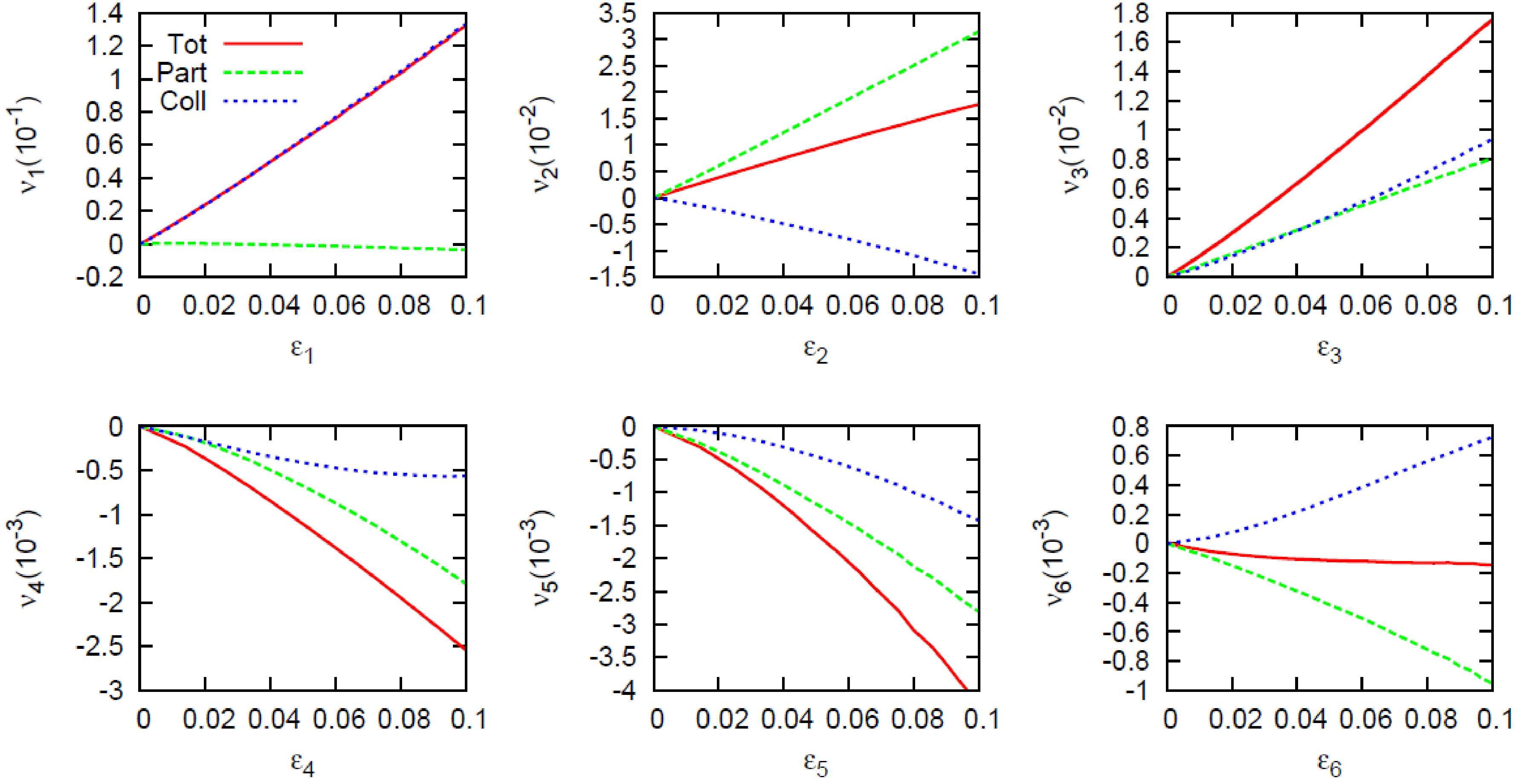
Conclusion and outlook

- NTcE explains well the **centrality-dependence** of high-pt V2 from RHIC 200 GeV to LHC 2.76 TeV (Vn?)
- Need more and better data on high-pt Vn
- Vn contribute to hard-soft correlation
- High-pt Raa and anisotropy are explored for high multiplicity P-Pb events, data are needed
- Realistic matter evolution is needed (in progress)
- Connection between NTcE and QCD needs to be explored

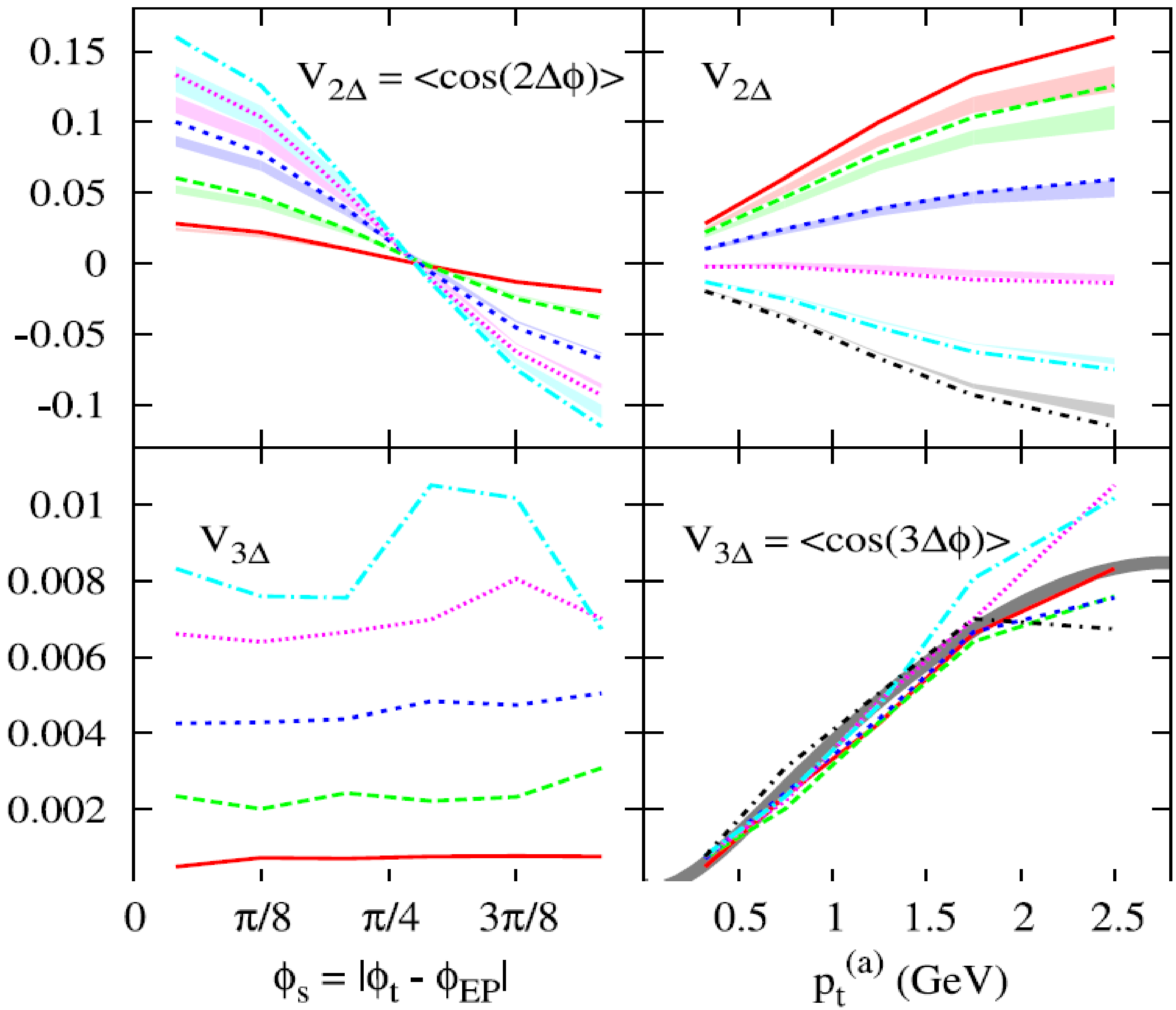
Back up

Jet response at b=0 fm

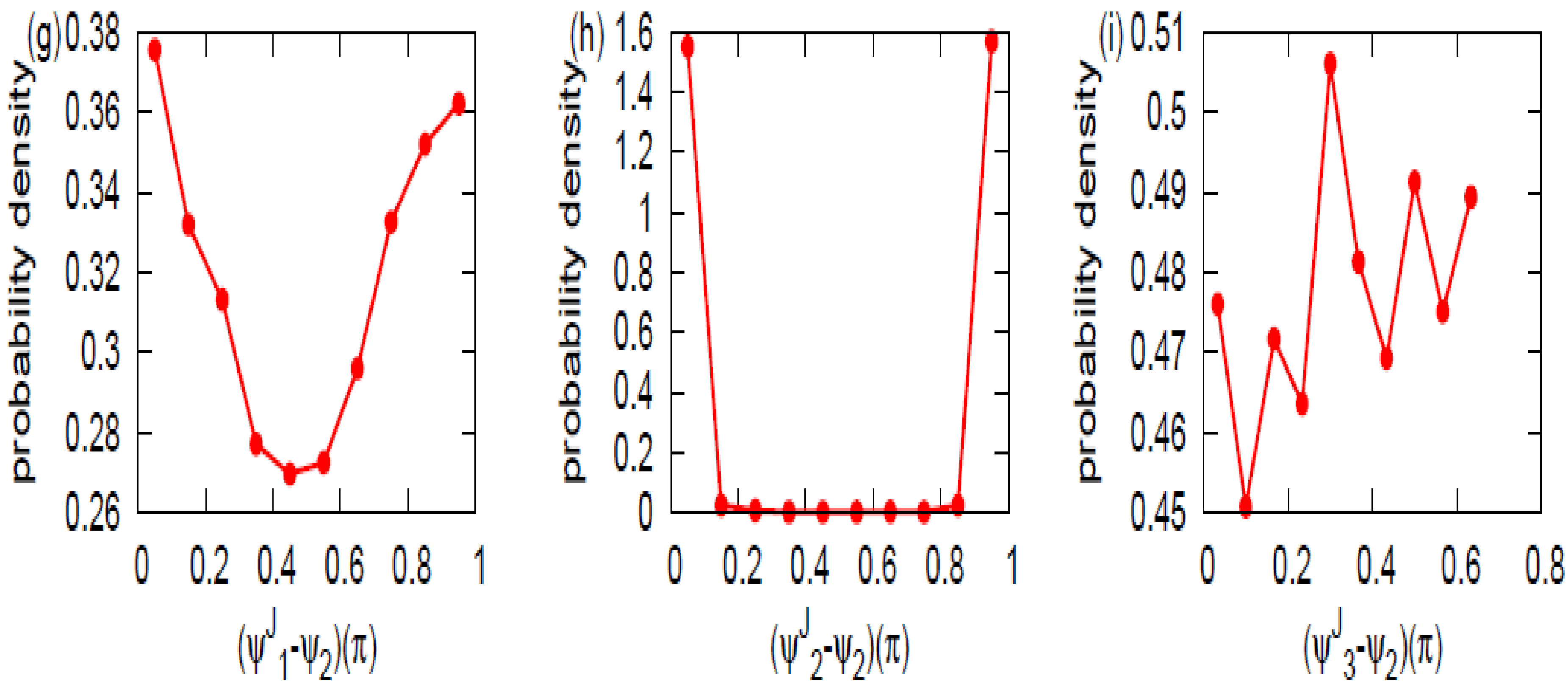
Simple estimate



X.Z. and J. Liao, 2012



*M. Luzum, **PLB** 696, 499 (2011)*



RHIC (200 GeV), b=7 fm

Weak-coupling pQCD (Baier et al.):

$$\hat{q}_{pQCD} = \frac{8\varsigma(3)}{\pi} \alpha_S^2 N_{color}^2 T^3 \sim 0.94 \frac{GeV^2}{fm} \text{ at } T = 300 \text{ MeV}$$

Strong-coupling *N*=4 SYM (Liu, Rajagopal and Wiedemann):

$$\hat{q}_{AdS/CFT} = \frac{\pi^{\frac{3}{2}} \Gamma\left(\frac{3}{4}\right)}{\Gamma\left(\frac{5}{4}\right)} \sqrt{\alpha_{SYM} N_{color}} T^3 \sim 4.5 \frac{GeV^2}{fm} \text{ at } T = 300 \text{ MeV}$$

From P. Jacob’s NNPSS2011 lecture

Jet tomography: pt dependence

$$dE = -E^{\delta}\,\kappa[s(l)]\,l^m\,dl$$

P-P effective spectrum index is energy dependent.

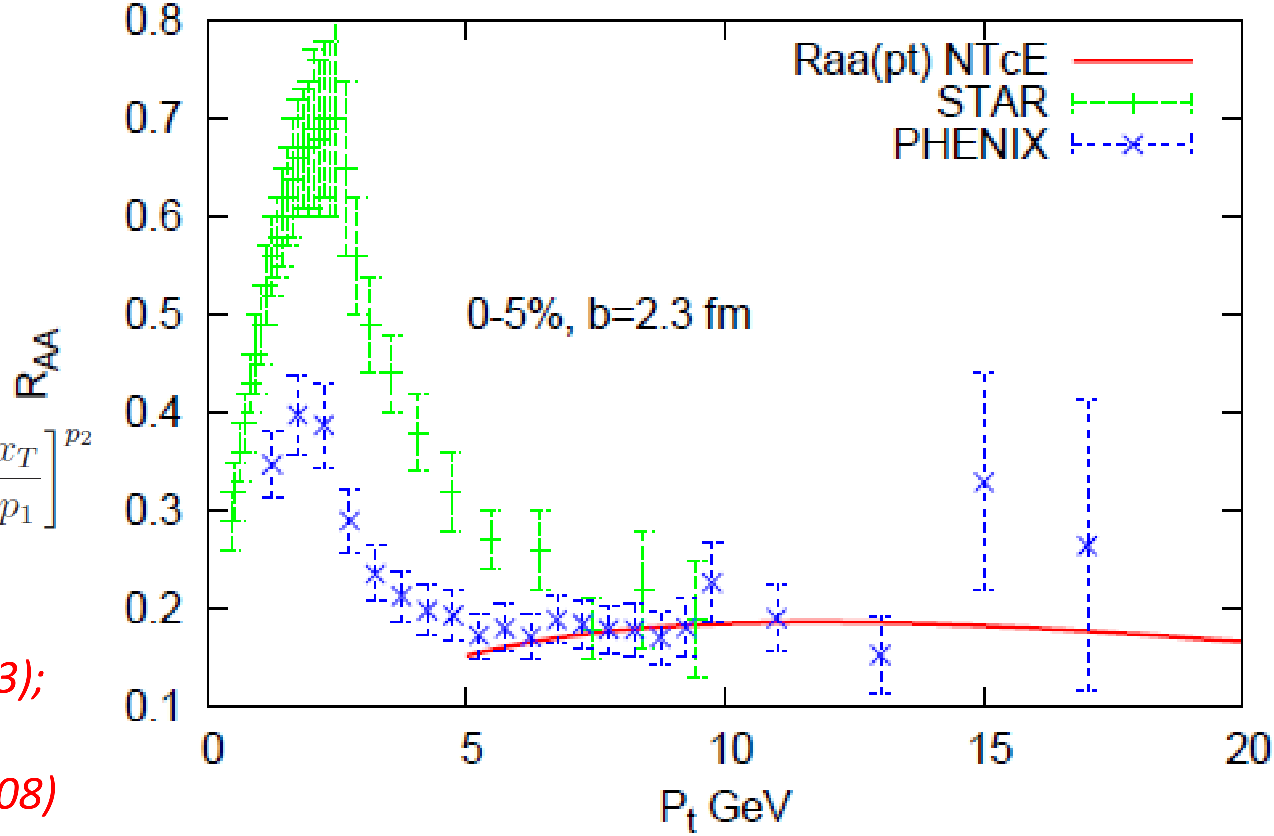
*W. A. Horowitz and M. Gyulassy, NPA **872**, 265 (2011).*

Two para. fitted to central Raa

$$\sqrt{s}^{\,n} g_{pp}(p_t) \;=\; p_0\left[1+\frac{x_T}{p_1}\right]^{p_2}$$

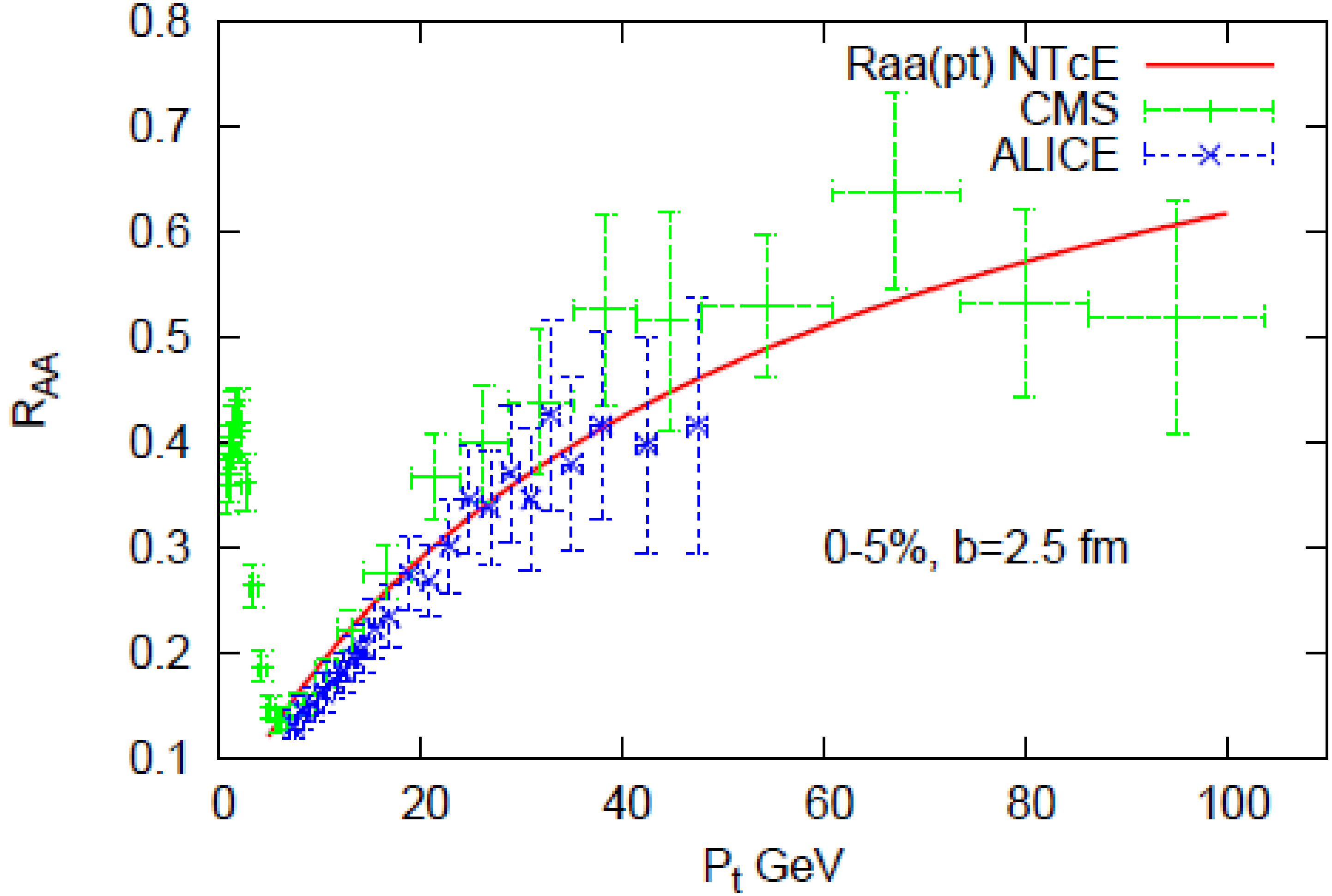
$$x_T \;\equiv\; \frac{2p_t}{\sqrt{s}}\,.$$

STAR, PRL 91, 172302 (2003); PHENIX, PRL 101, 232301 (2008)

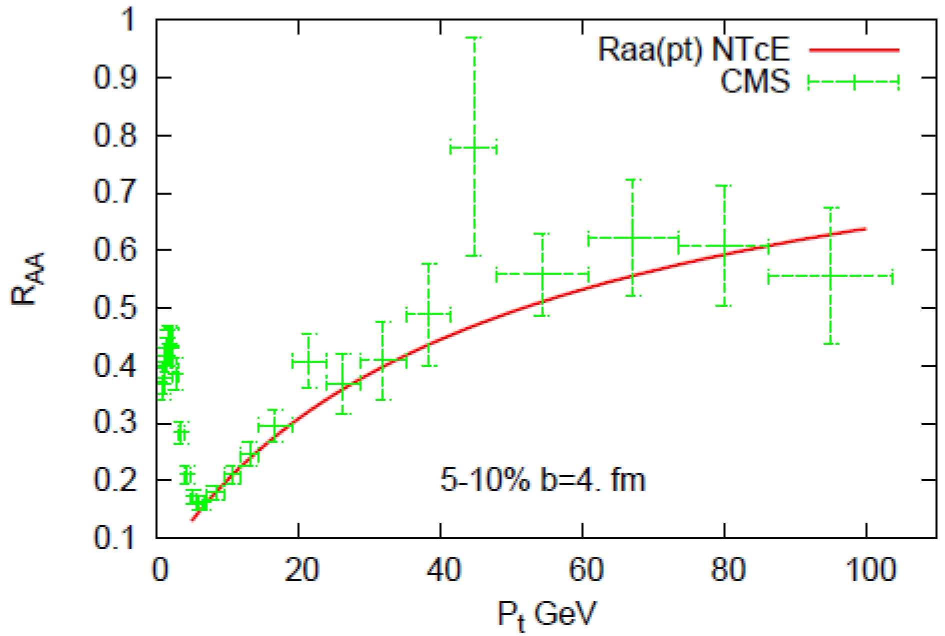


Jet tomography: pt dependence

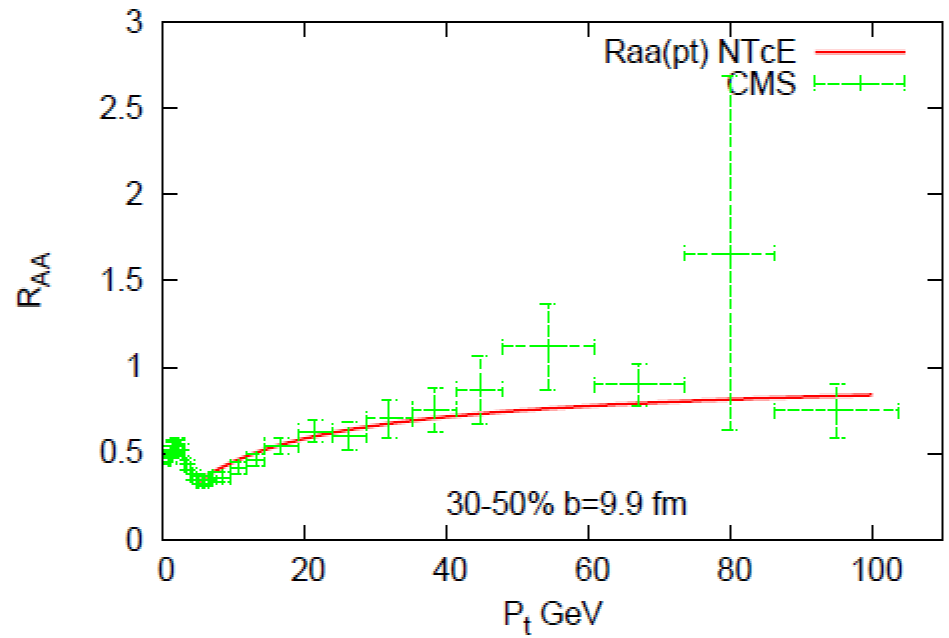
P-P spectrum: QCD scaling formula.



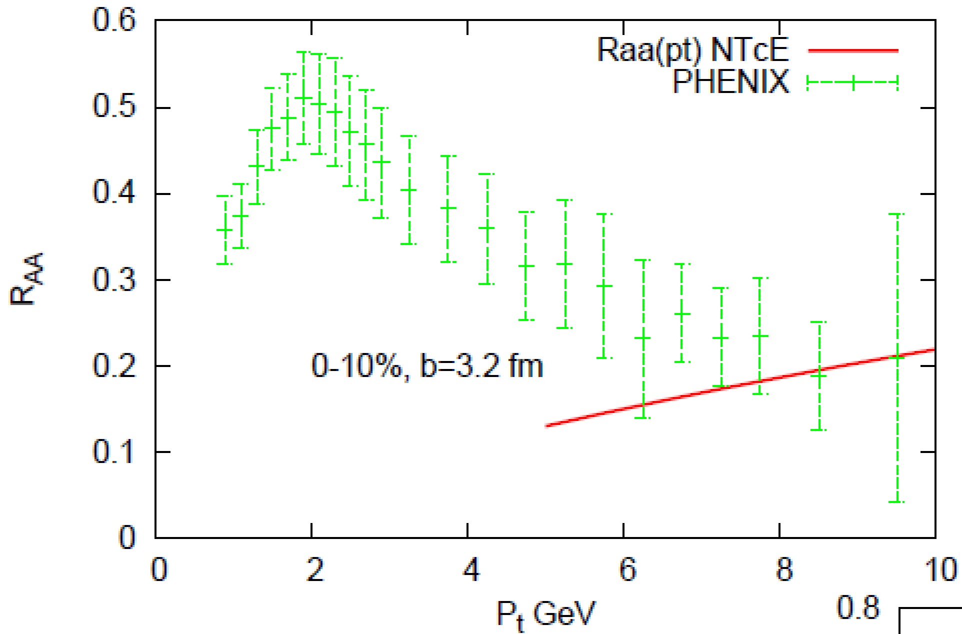
*CMS, Eur. Phys. J. C **72**, 1945 (2012); ALICE, arXiv:1208.2711*



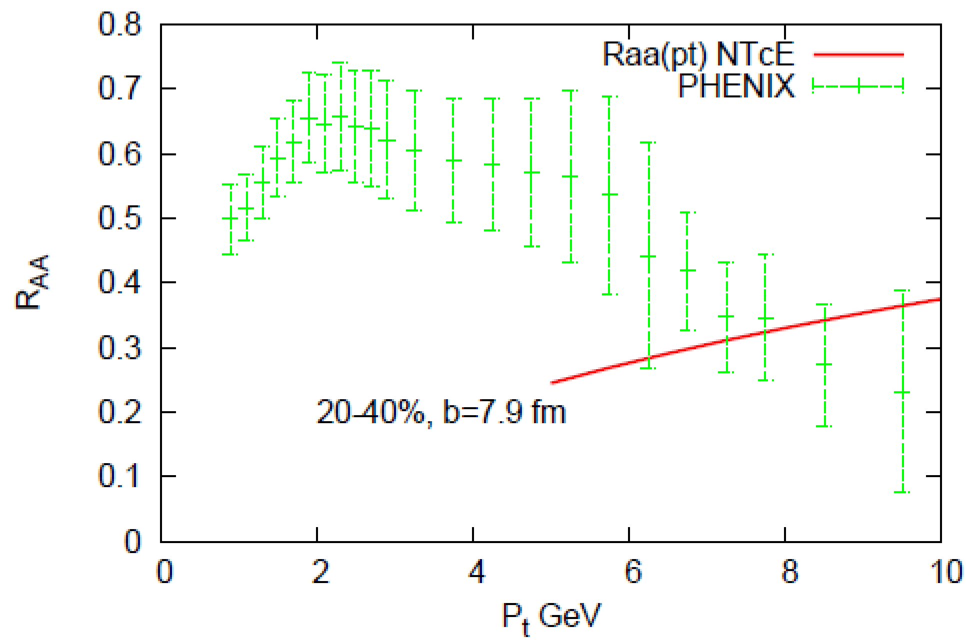
Raa(pt) NTcE
CMS
5-10% b=4. fm
R_{AA}
P_t GeV



Raa(pt) NTcE
CMS
30-50% b=9.9 fm
R_{AA}
P_t GeV

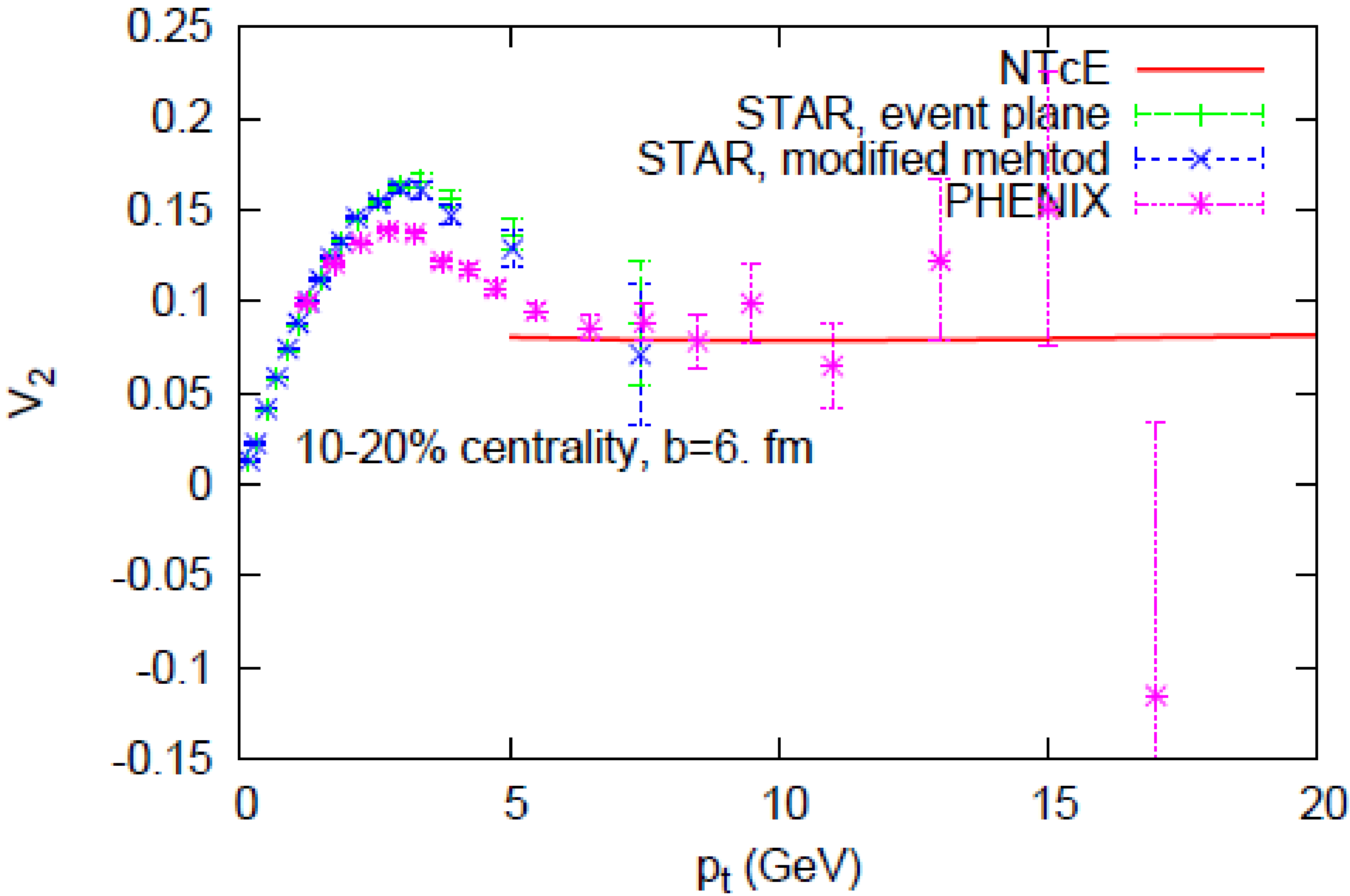


Raa(pt) NTcE
PHENIX
0-10%, b=3.2 fm
R_{AA}
P_t GeV
0
0.1
0.2
0.3
0.4
0.5
0.6
0
2
4
6
8
10



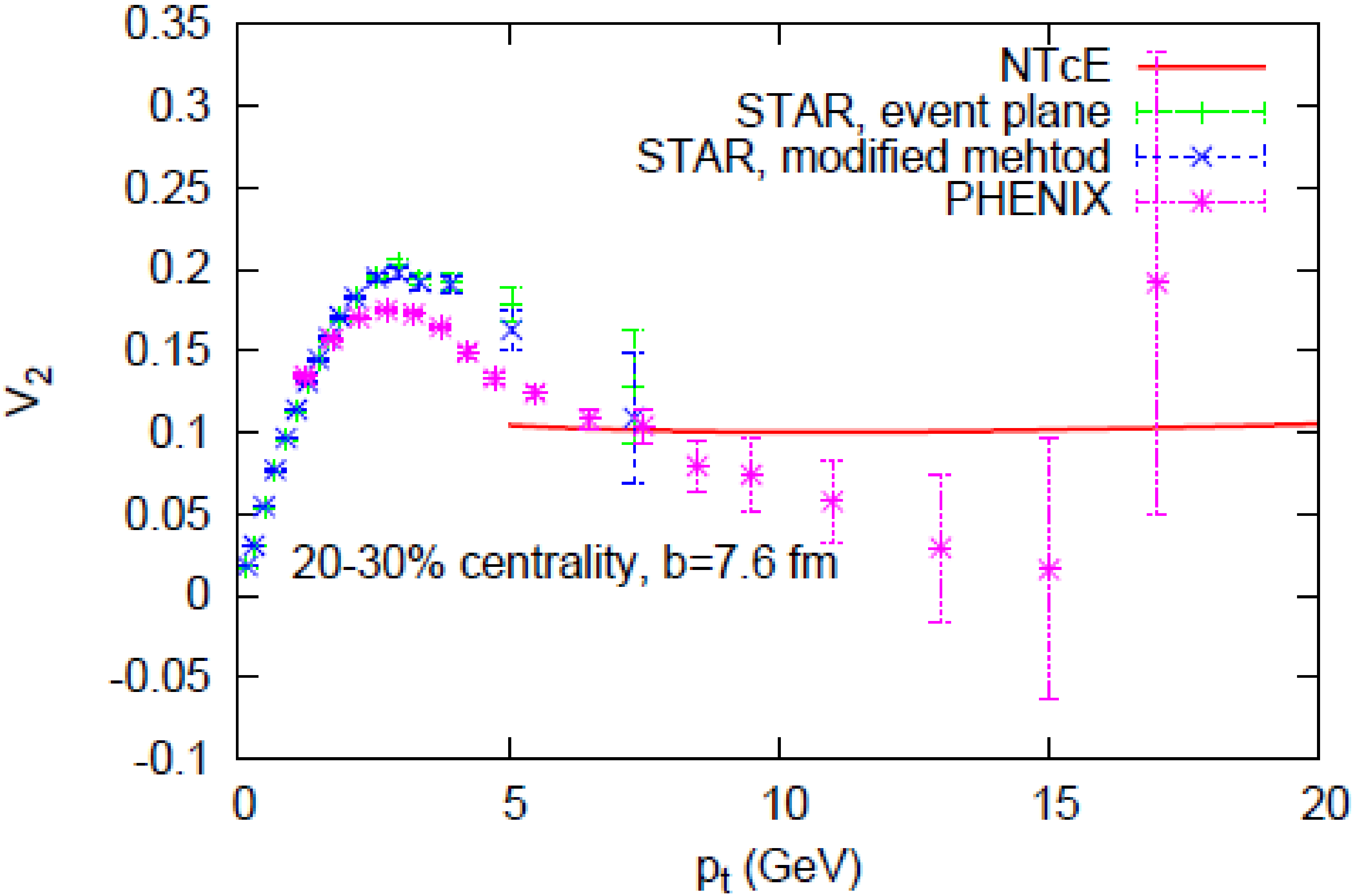
Raa(pt) NTcE
PHENIX
20-40%, b=7.9 fm
R_{AA}
P_t GeV
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0
2
4
6
8
10

Jet tomography: pt dependence

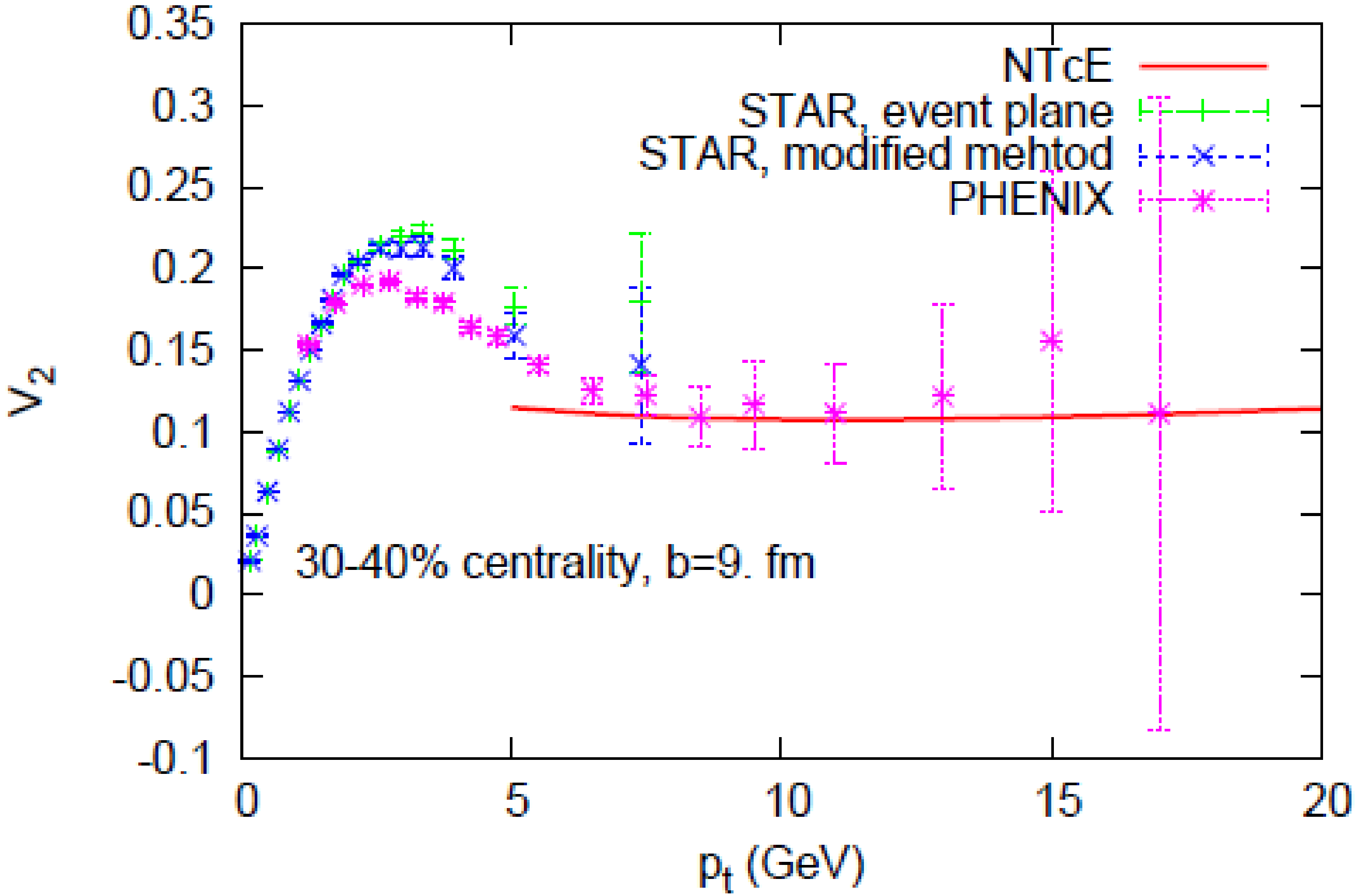


*STAR, PRC **72**, 014904 (2005); PHENIX, PRL **105**, 142301 (2010).*

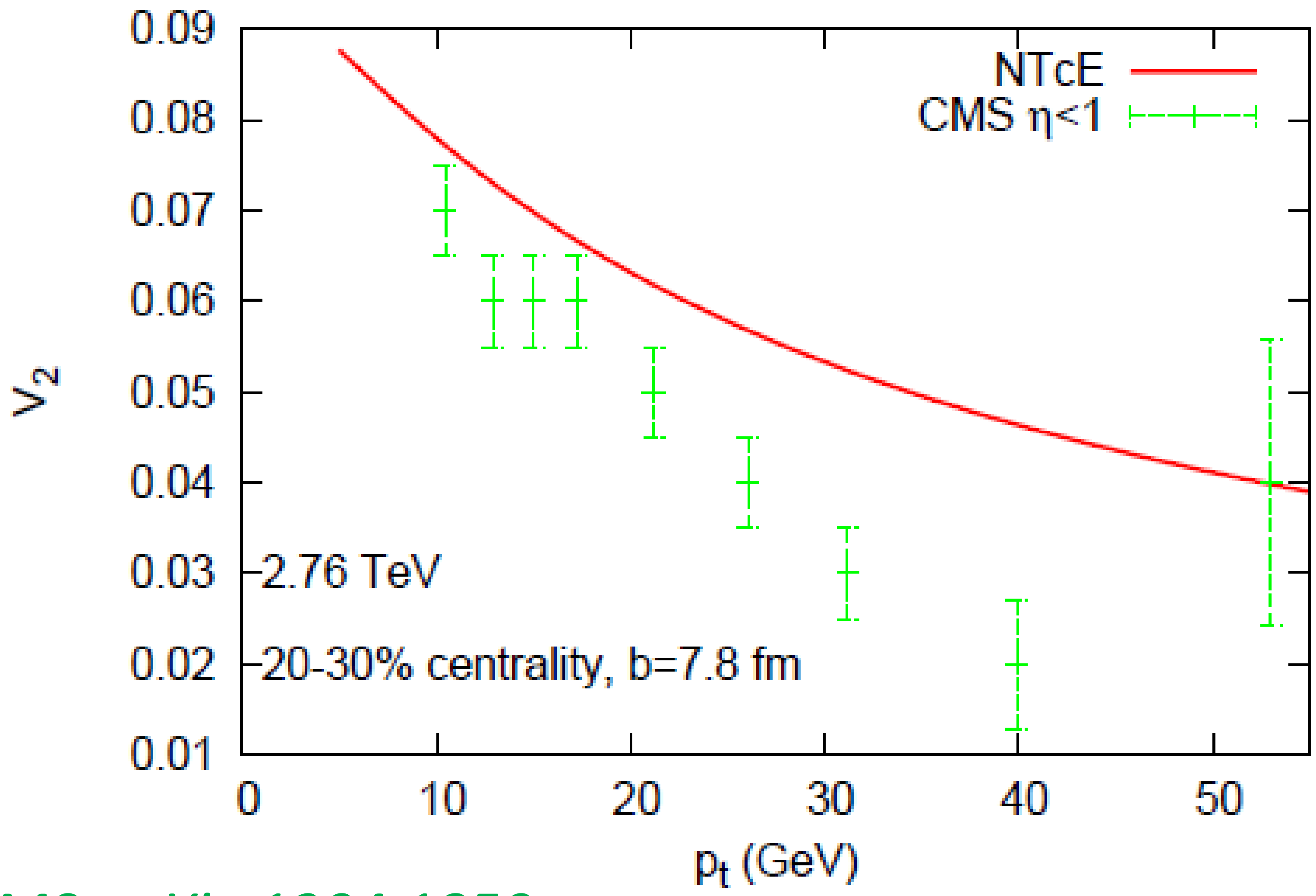
Jet tomography: pt dependence



Jet tomography: pt dependence

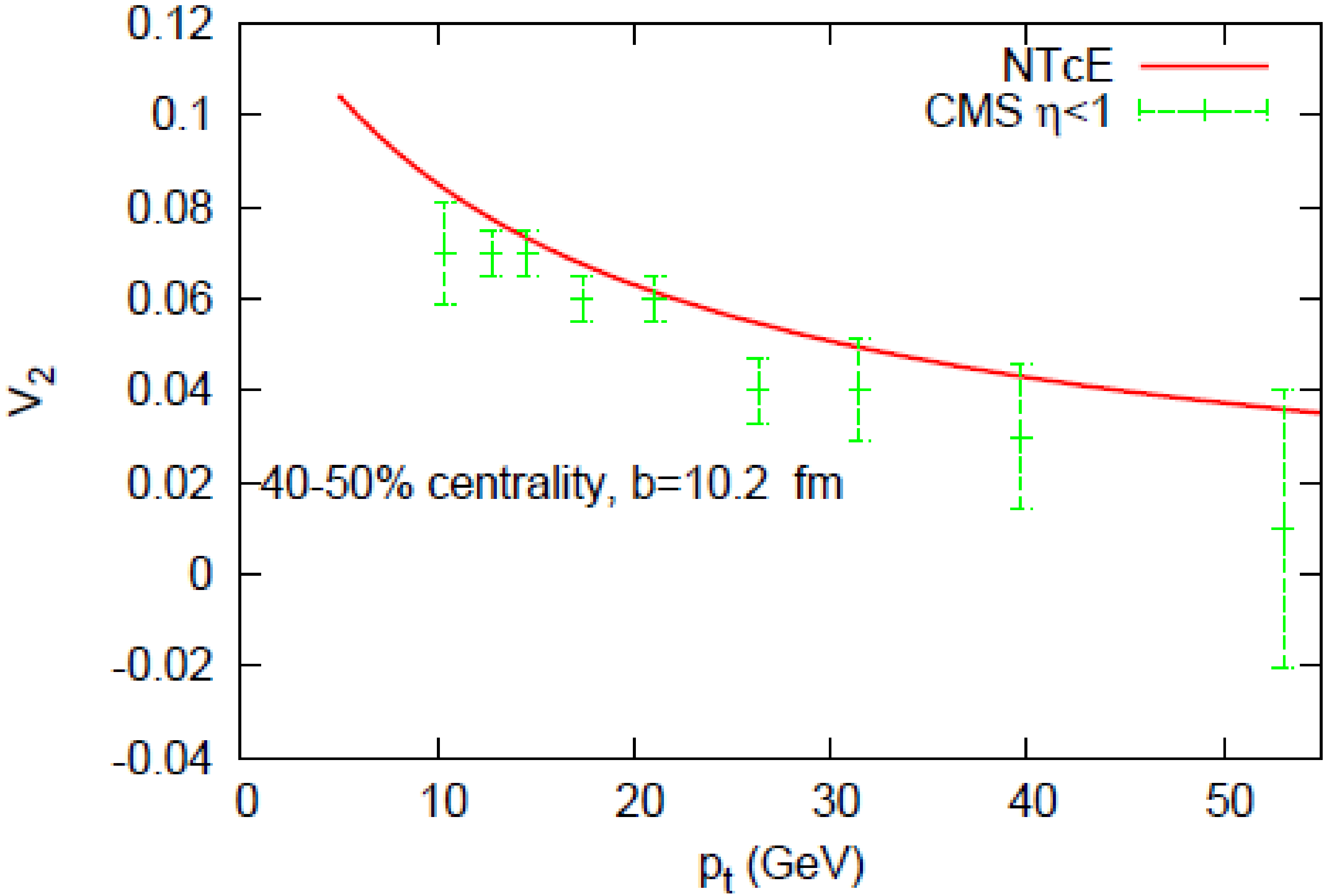


Jet tomography: pt dependence

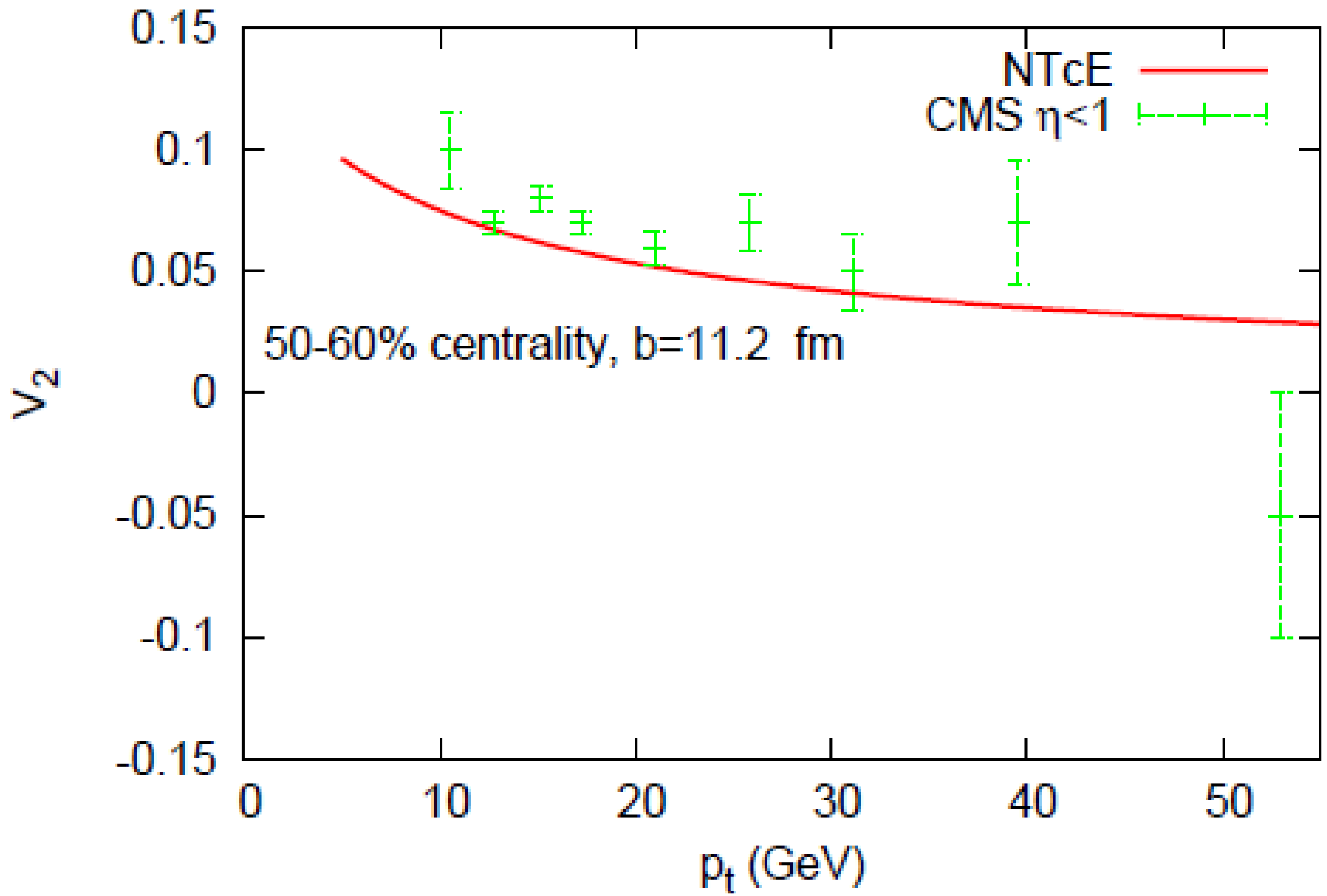


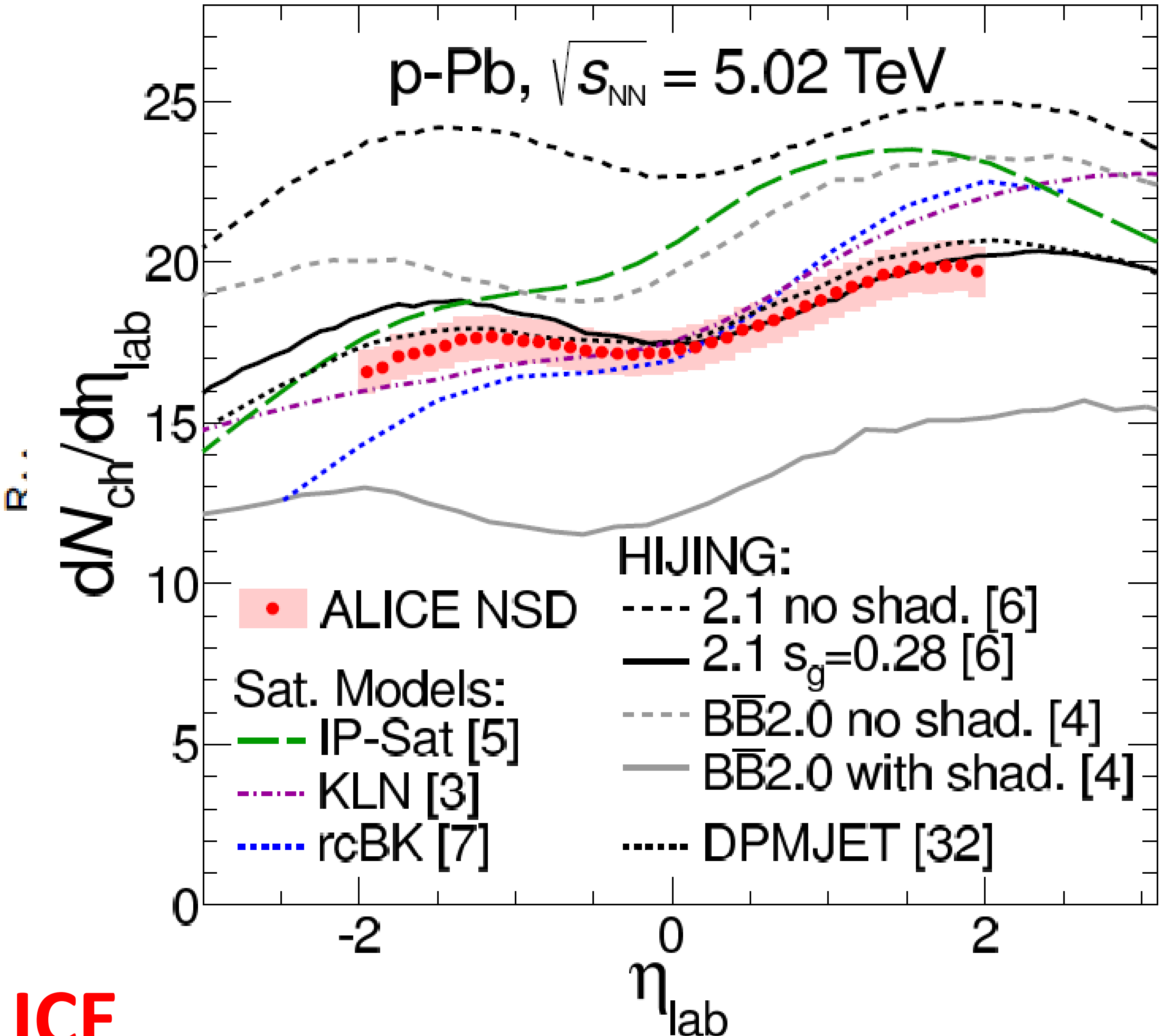
CMS, arXiv:1204.1850

Jet tomography: pt dependence



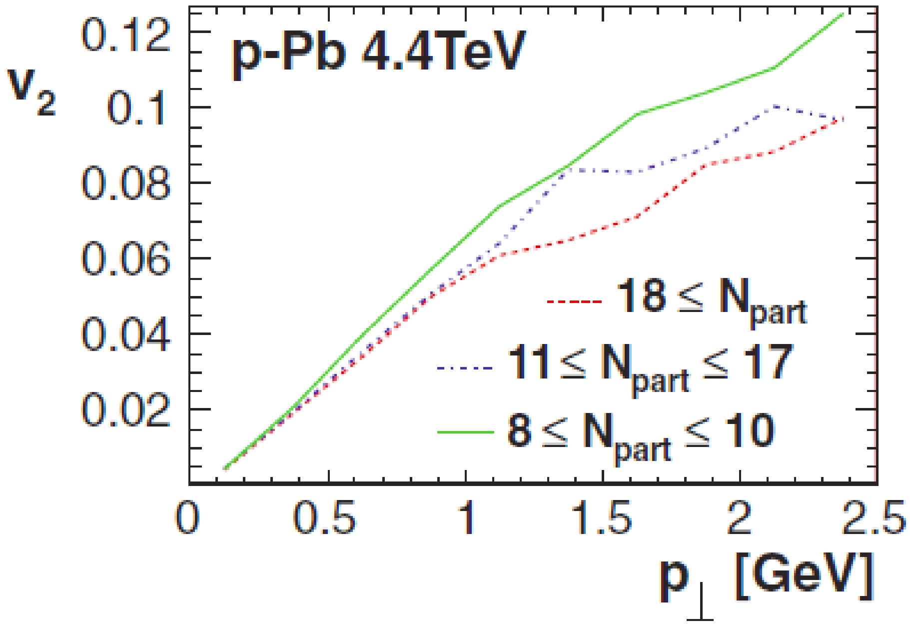
Jet tomography: pt dependence

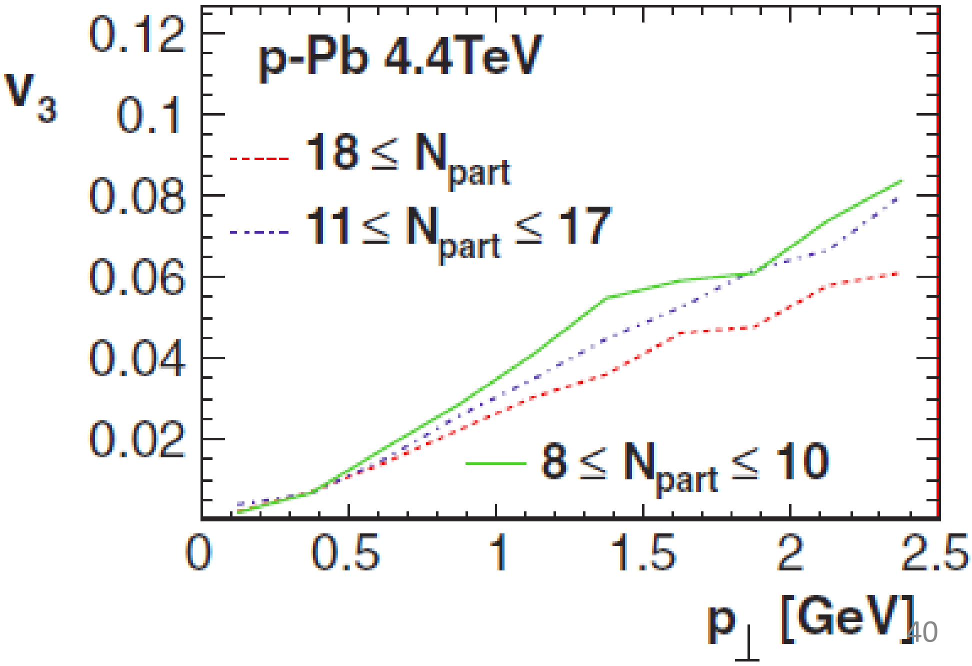




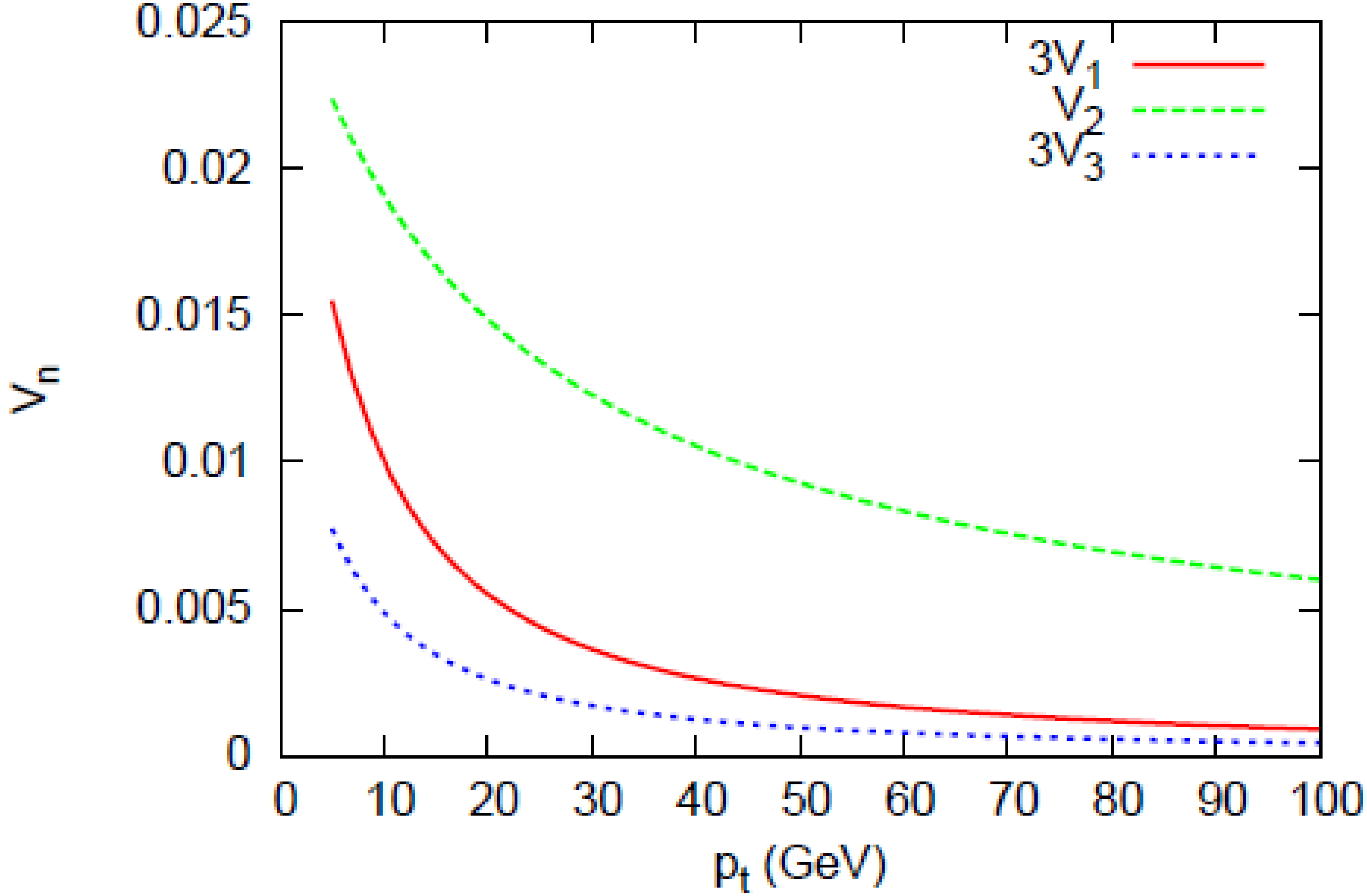
p-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV
$dN_{ch}/d\eta_{lab}$
η_{lab}
ALICE NSD
Sat. Models:
IP-Sat [5]
KLN [3]
rcBK [7]
HIJING:
2.1 no shad. [6]
2.1 s_g=0.28 [6]
$B\overline{B}$2.0 no shad. [4]
$B\overline{B}$2.0 with shad. [4]
DPMJET [32]

ALICE


p-Pb 4.4TeV
v_2
0.12
0.1
0.08
0.06
0.04
0.02
$18 \leq N_{part}$
$11 \leq N_{part} \leq 17$
$8 \leq N_{part} \leq 10$
0
0.5
1
1.5
2
2.5
$p_\perp$ [GeV]


p-Pb 4.4TeV
v_3
0.12
0.1
0.08
0.06
0.04
0.02
$18 \leq N_{part}$
$11 \leq N_{part} \leq 17$
$8 \leq N_{part} \leq 10$
0
0.5
1
1.5
2
2.5
$p_\perp$ [GeV]

Smaller profile



Smaller profile