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USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Predictions for the LHC: an Overview

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CERN Theory Institute, May-June 2007

Heavy Ion Collisions at the LHC - Last Call for Predictions

organized by *N.A., N. Borghini, S. Jeon and U.A. Wiedemann*,

arXiv:0711.0974 (93/170/82 contributions/authors/institutes).

Contents:

A. The bulk:

- A.1. Multiplicities.
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- A.4. Correlations at low p_T.

B. Hard and EM probes:

- B.1. High-p_T observables and jets.
- B.2. Heavy quarks and quarkonium.
- B.3. Leptonic probes and photons.

Only predictions for PbPb.

See also Borghini and Wiedemann, arXiv:0707.0654.

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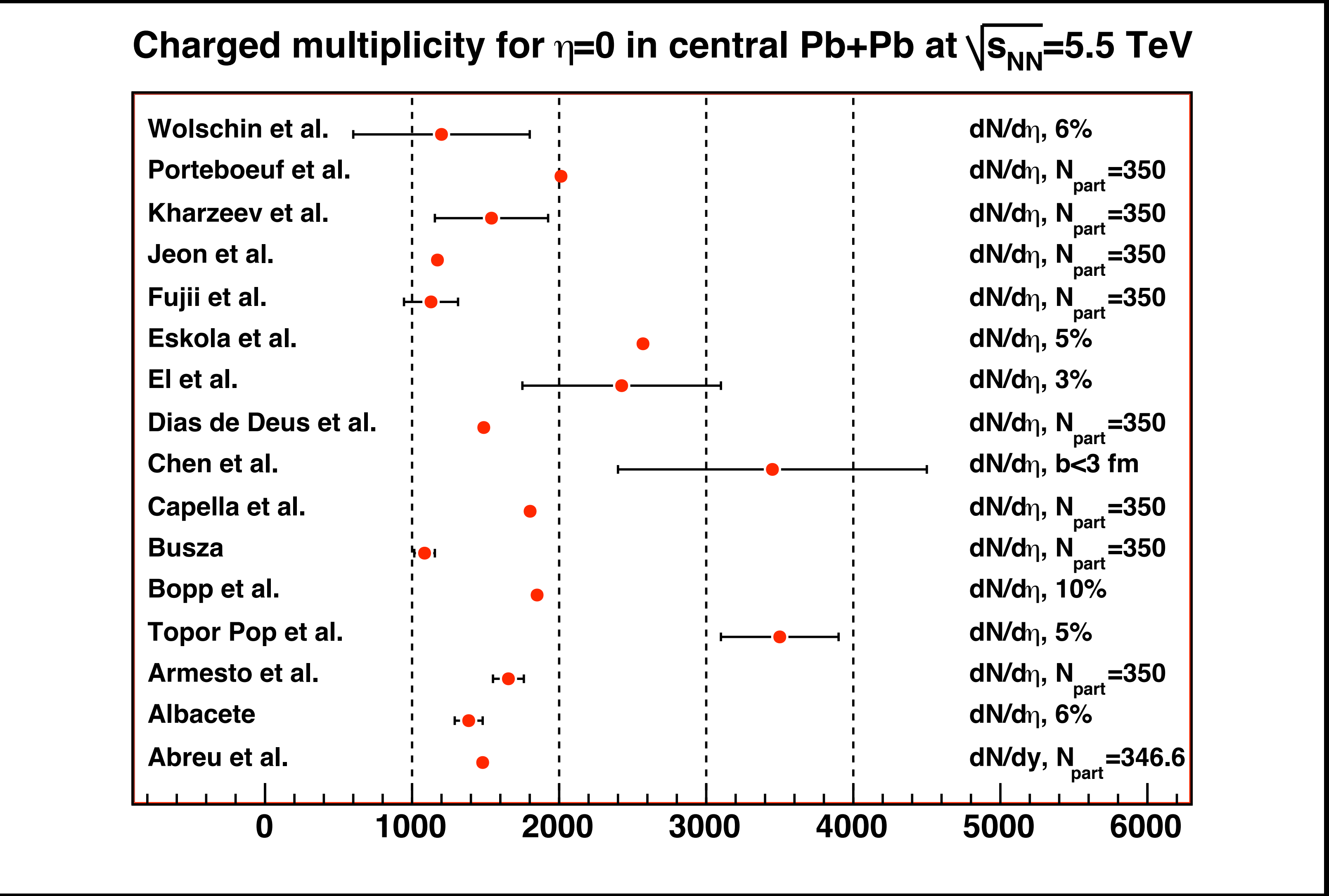
➪ Remark: I assume that a RHIC- (and possibly SPS-) tested model can be reliably extrapolated to the LHC. The huge lever arm in energy will eventually falsify some of them.

Only predictions for PbPb.

See also Borghini and Wiedemann, arXiv:0707.0654.

A.1. Multiplicities (I):



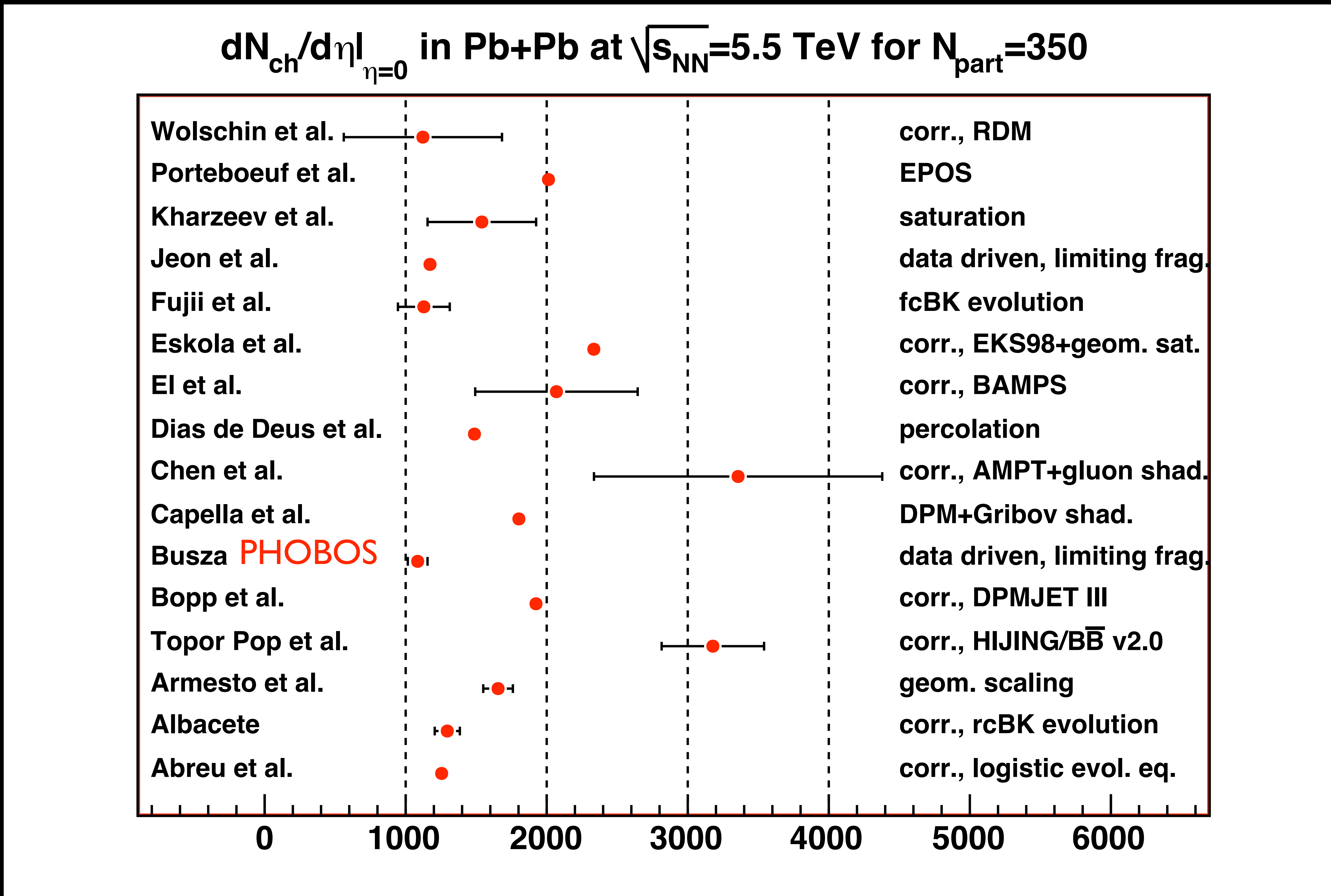
1st-day observable, key input in almost all other predictions.

To unify the discussion, I 'rescale' to $dN_{ch}/d\eta|_{\eta=0}$ for N_{part}=350 using a Monte Carlo (Amelin et al., EPJC22(2001)149):

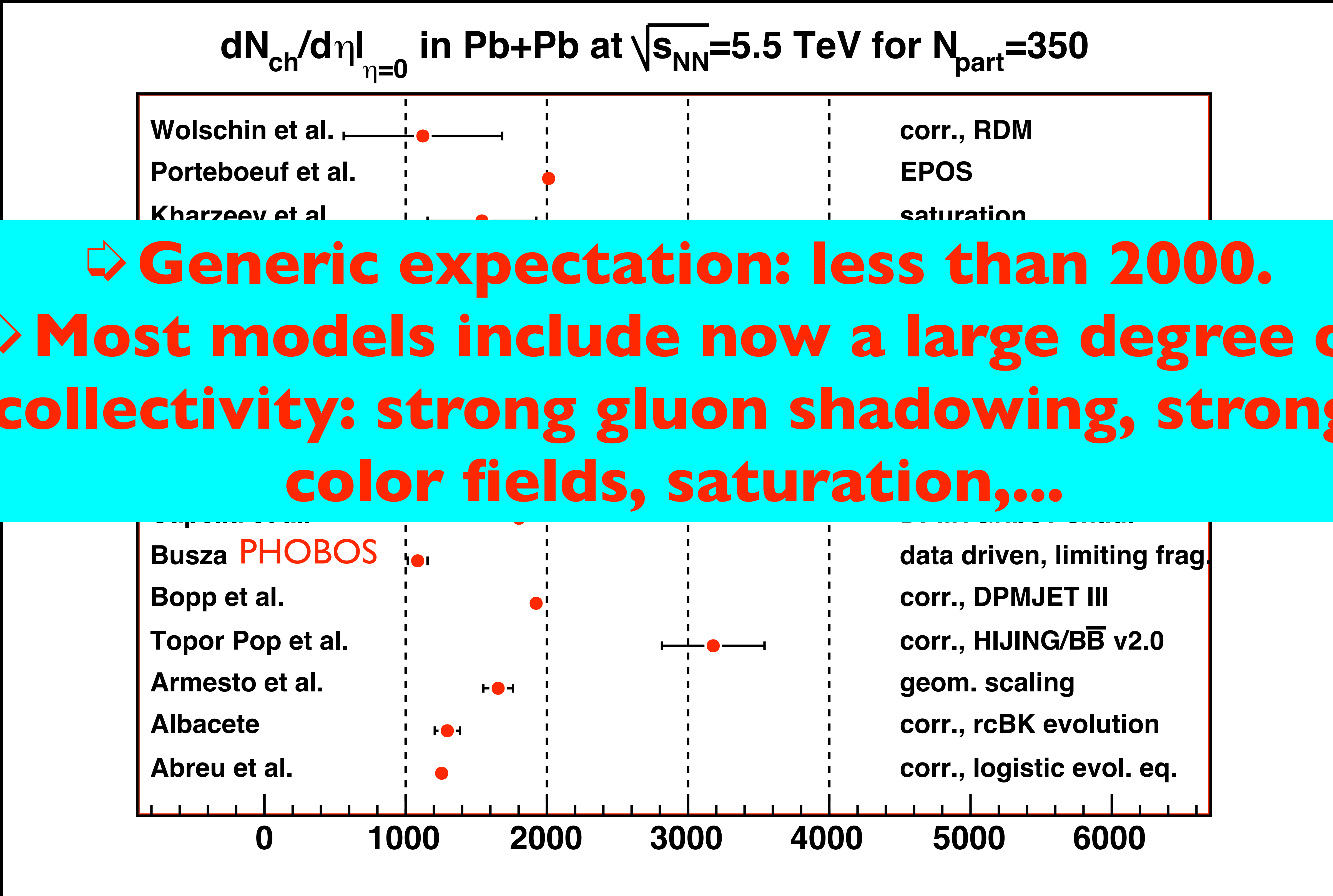
%	<b> (fm)	$\langle N_{part} \rangle$	$\langle N_{coll} \rangle$	$dN_{ch}/dy\|_{y=0}$	$dN_{ch}/d\eta\|_{\eta=0}$
0-3	1.9	390	1584	3149	2633
0-5	2.4	375	1490	2956	2472
0-6	2.7	367	1447	2872	2402
0-7.5	3.0	357	1390	2759	2306
0-8.5	3.1	350	1354	2686	2245
0-9	3.2	347	1336	2649	2214
0-10	3.4	340	1303	2583	2159

Predictions for the LHC: an Overview: A. The bulk

A.1. Multiplicities (II):



A.1. Multiplicities (II):

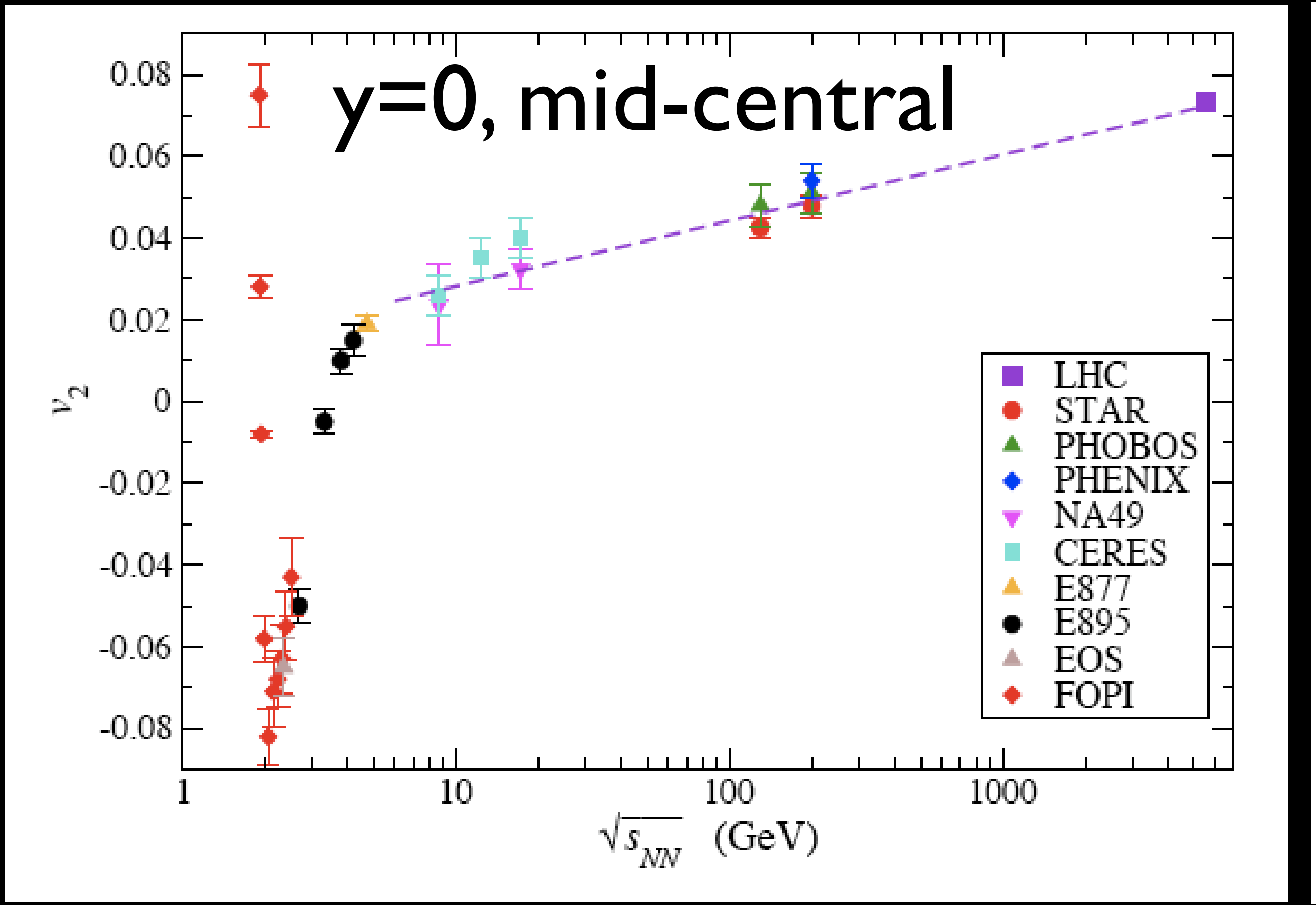


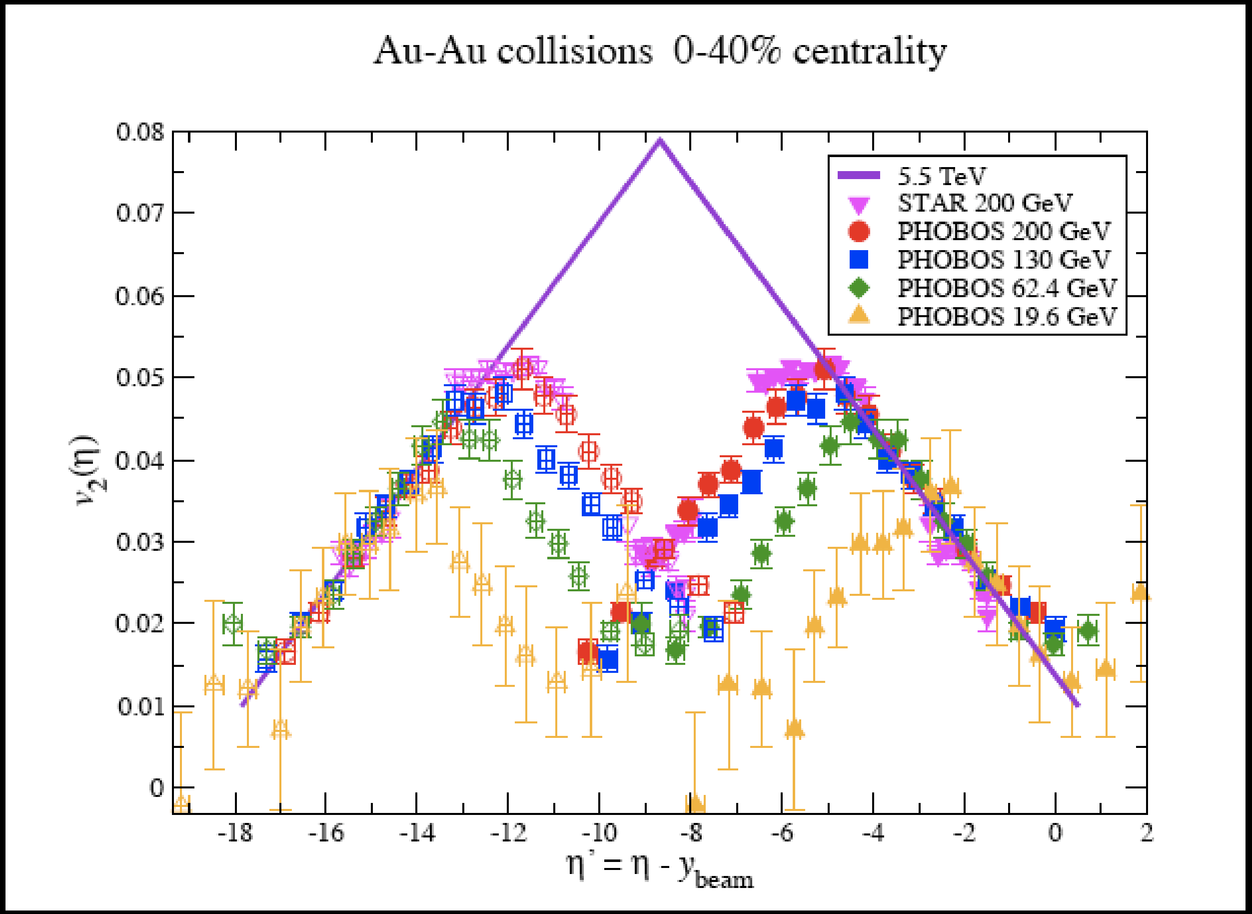
⇨ Generic expectation: less than 2000.

⇨ Most models include now a large degree of collectivity: strong gluon shadowing, strong color fields, saturation,...

A.2. Azimuthal asymmetries: v_2

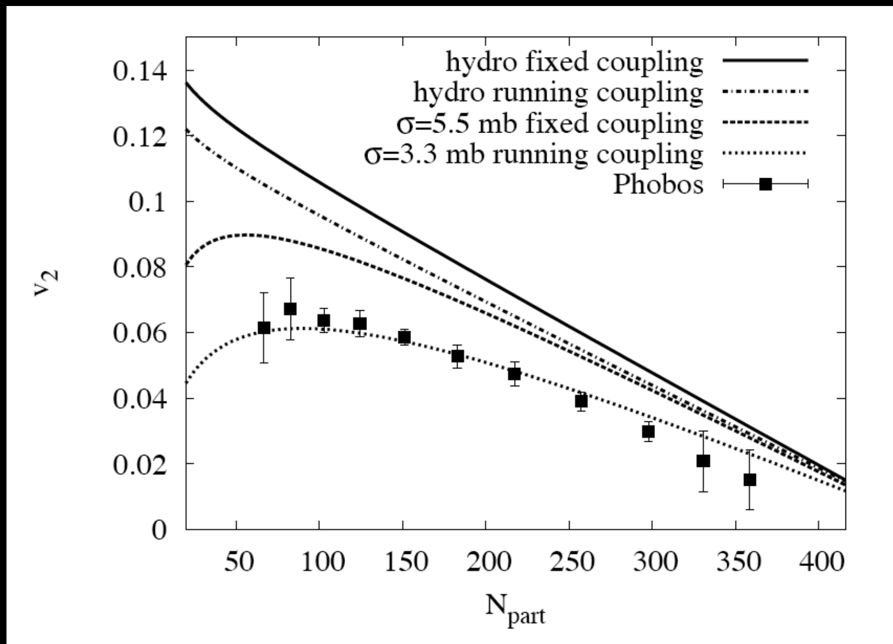
p_T-integrated v_2 is expected to increase from RHIC to the LHC: origin? Hydro predictions do not coincide with naive extrapolations.



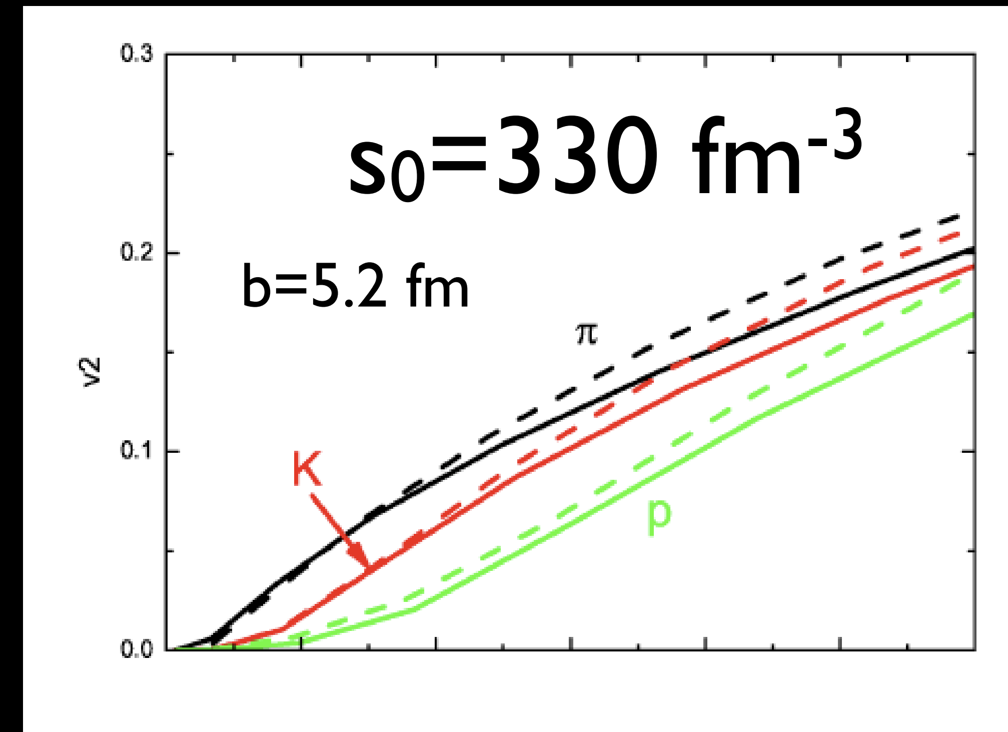


From BW.

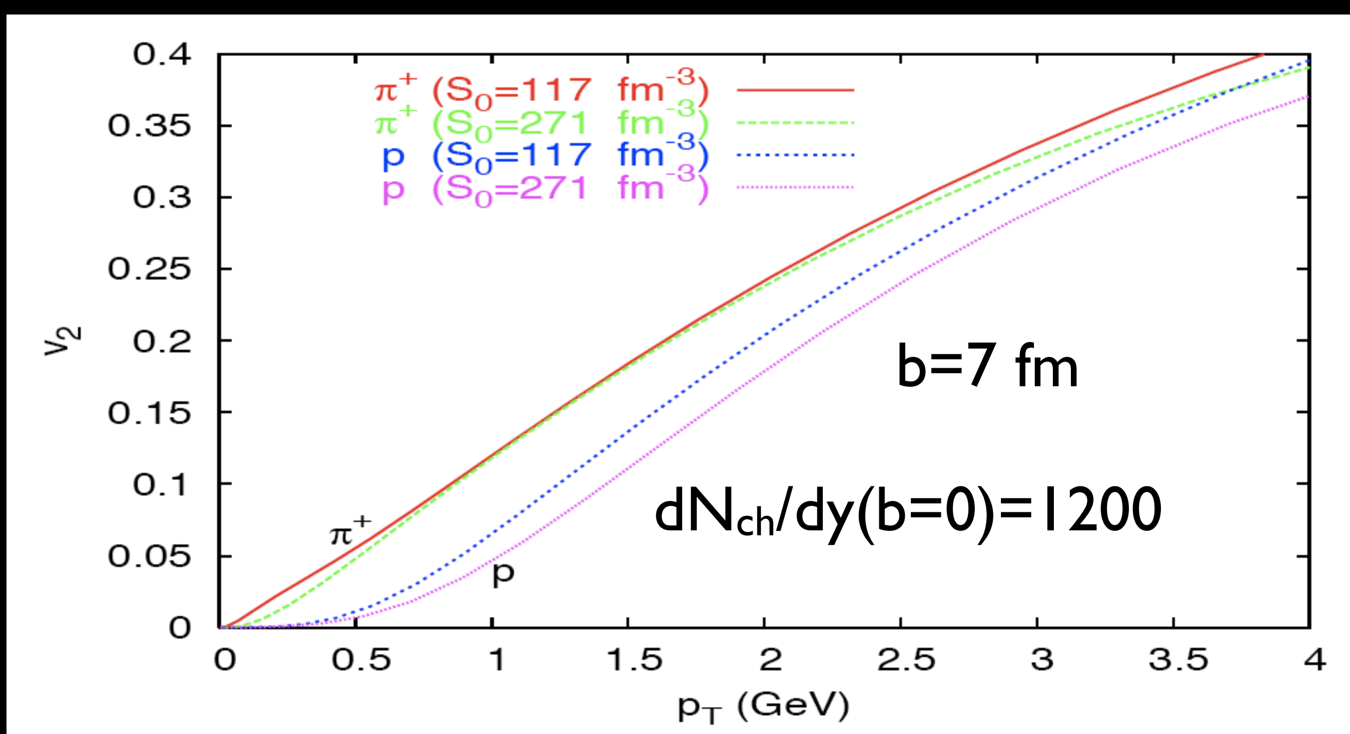
A.2. Azimuthal asymmetries: v_2 in hydro



Drescher et al., smaller deviation from ideal hydro limit than at RHIC.

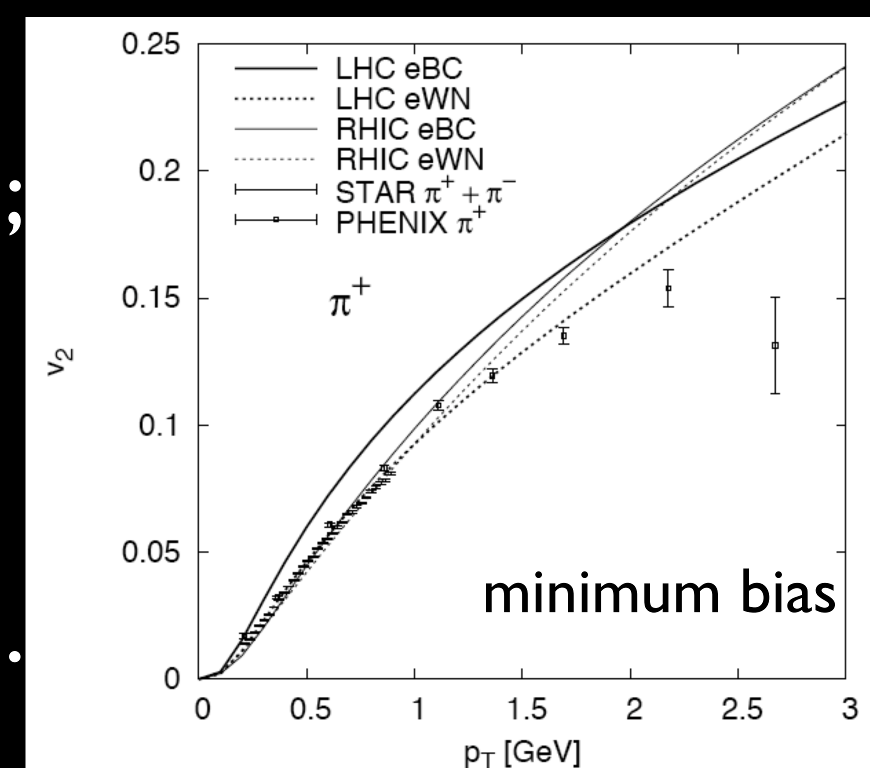


Bluhm et al., QPM EOS, results < RHIC at low p_T.



Kestin et al.

Eskola et al.; hydro valid for $p_T<4$ GeV (also Arleo et al.).



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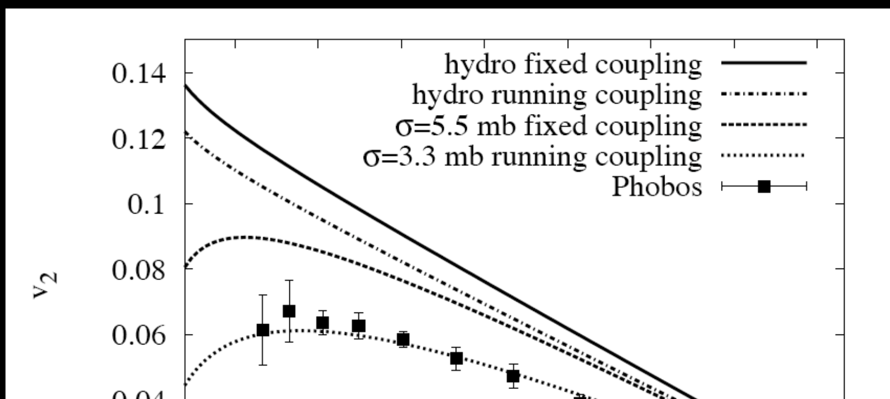

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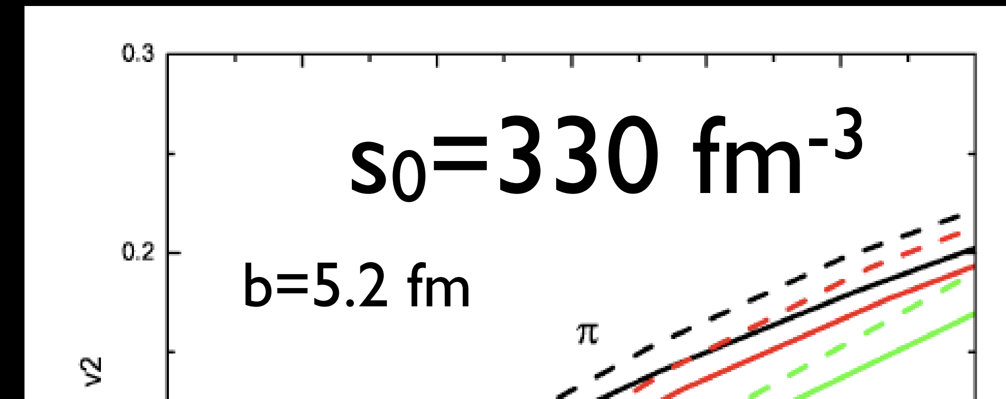
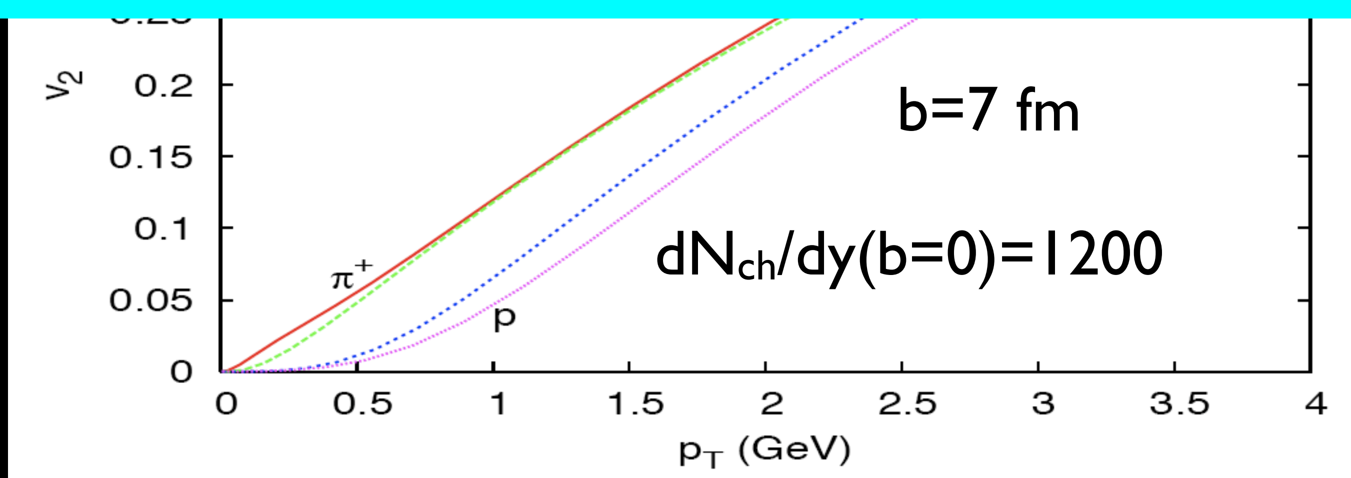


⇨ Generic expectation: v_2 similar or slightly decreasing at low p_T.

⇨ A strong decrease would probably signal an increase in η/s, but initial conditions have to be settled.



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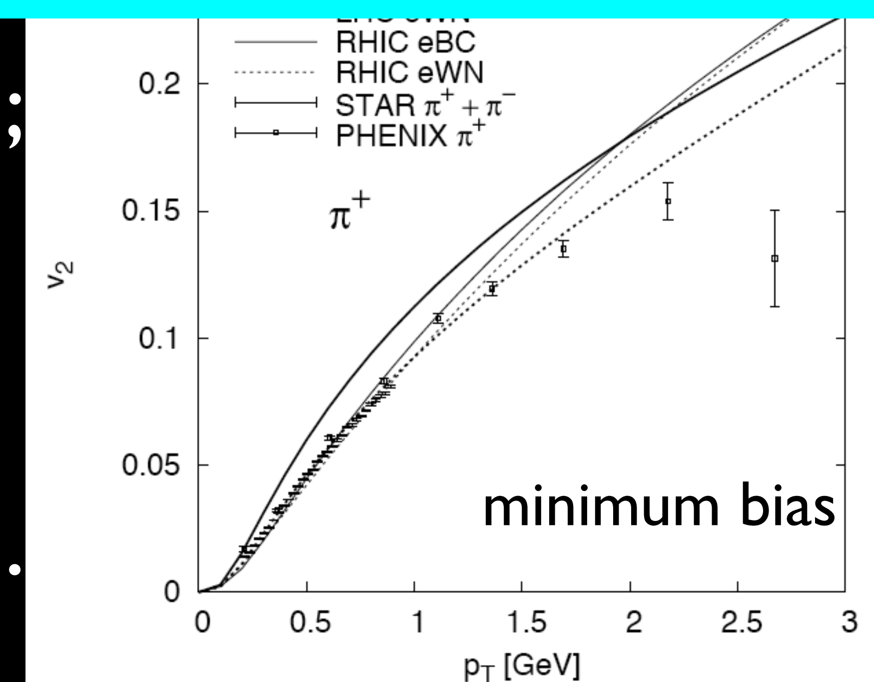
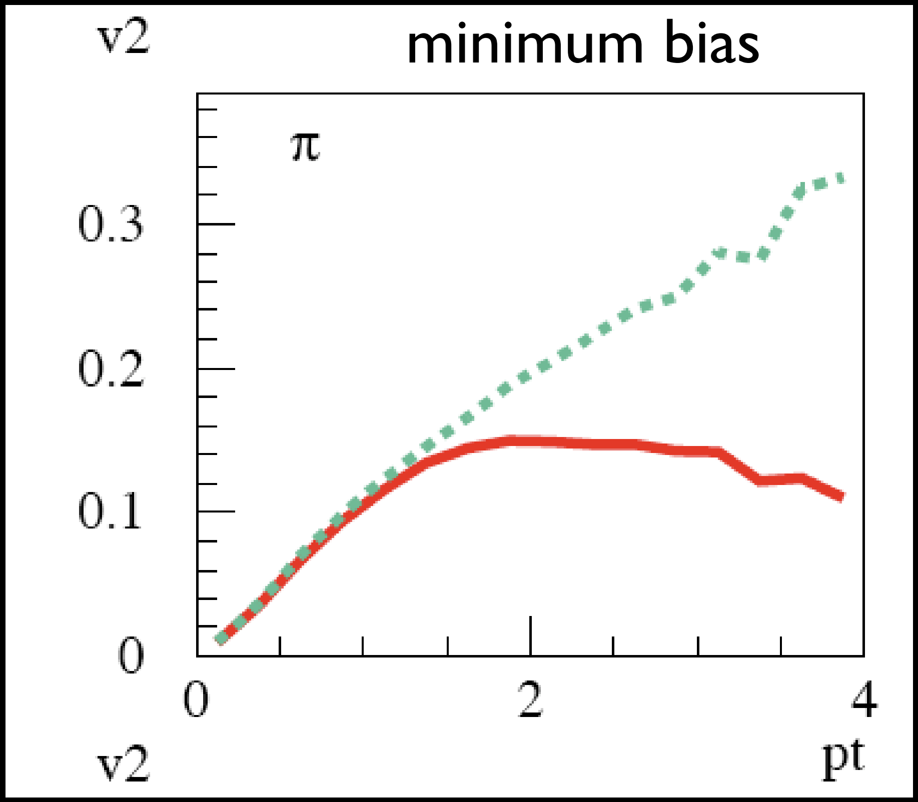
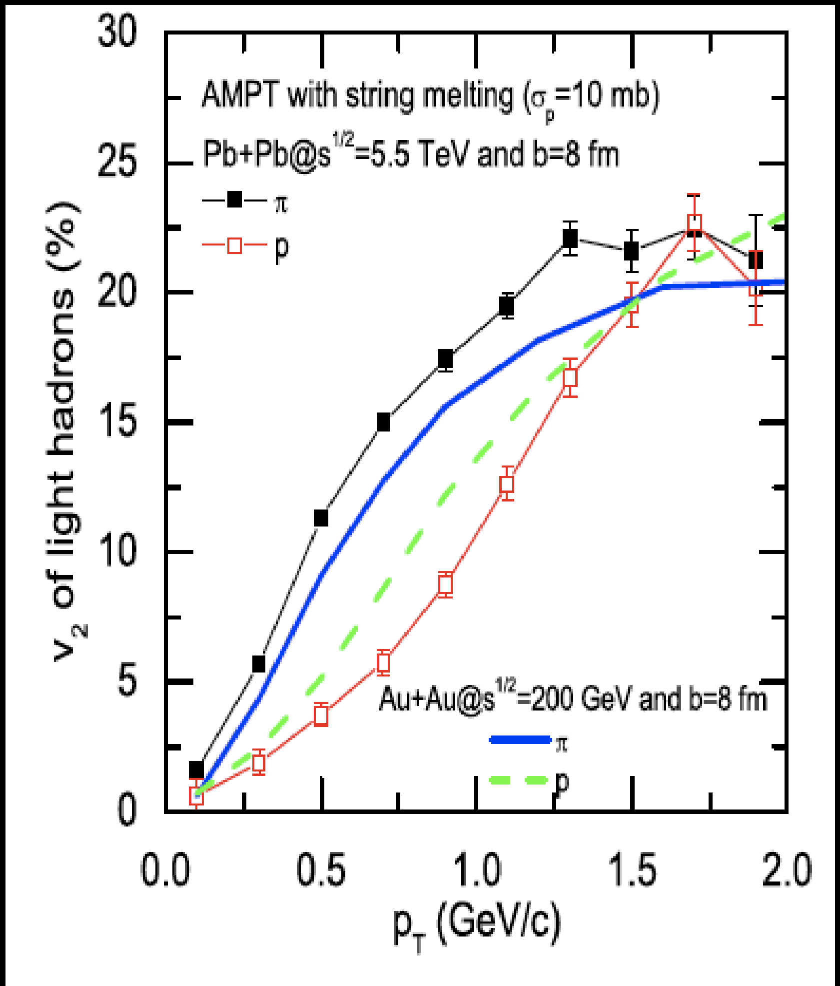


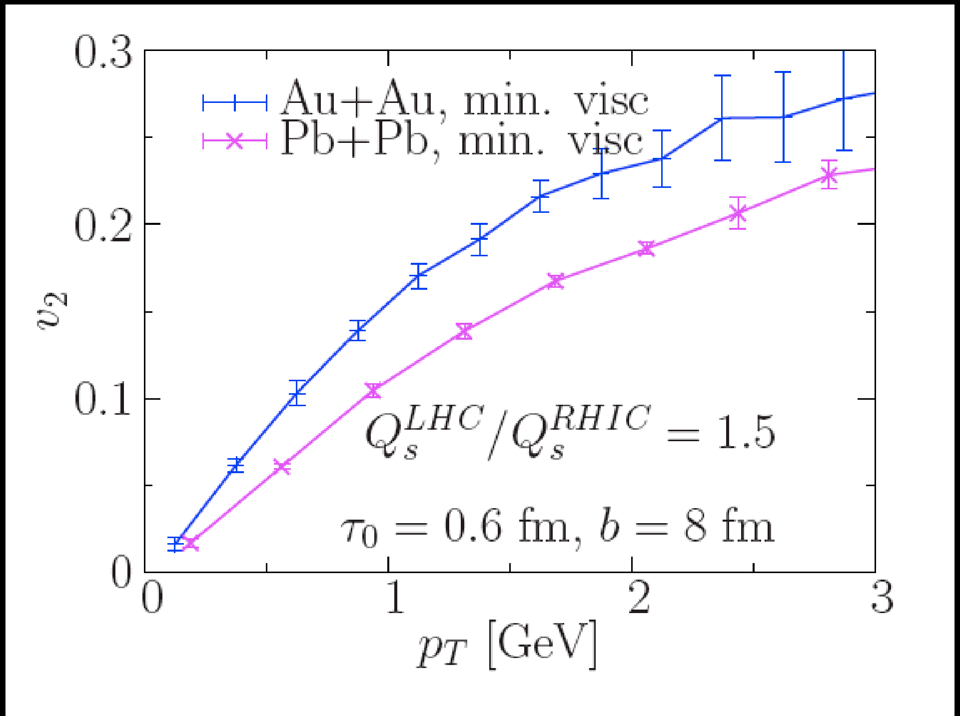
A.2. Azimuthal asymmetries: v_2 in others



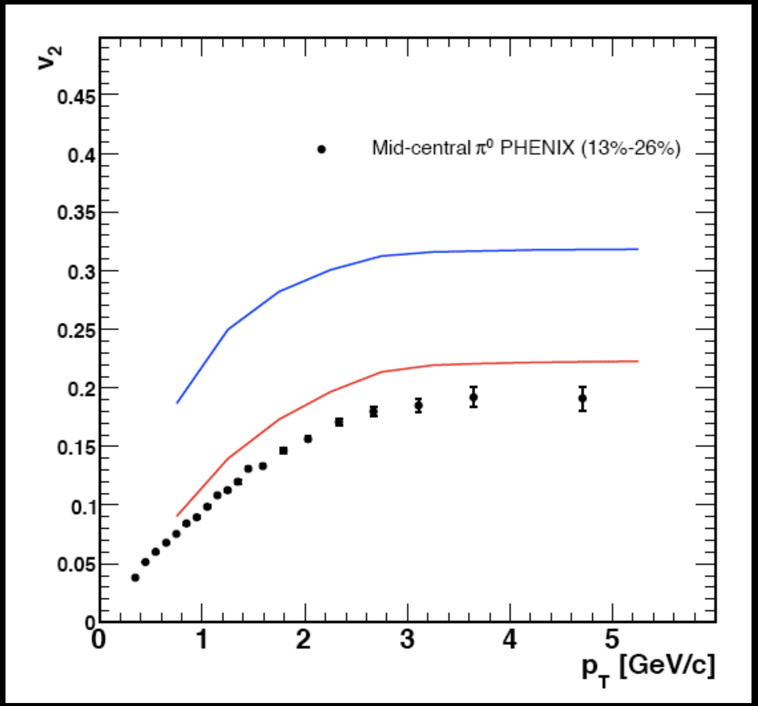
Porteboeuf et al., EPOS, hydro core, v_2~RHIC.

Chen et al., AMPT, parton + hadron transport.





Molnar, MPC parton cascade, fixed η/s=0.08.



Capella et al., comovers.

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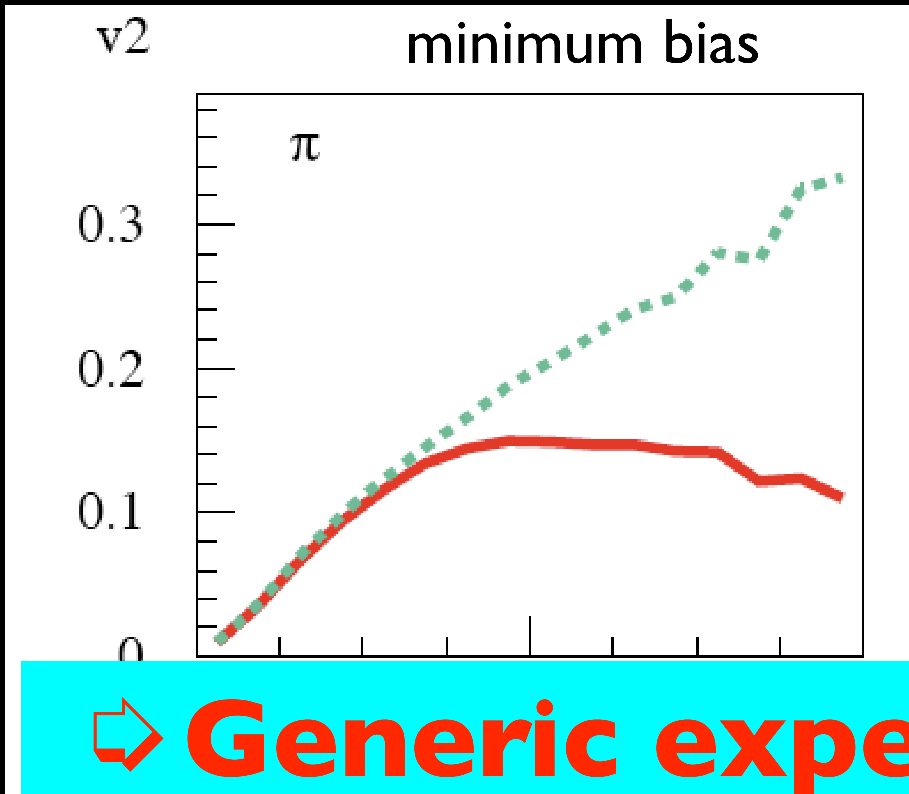

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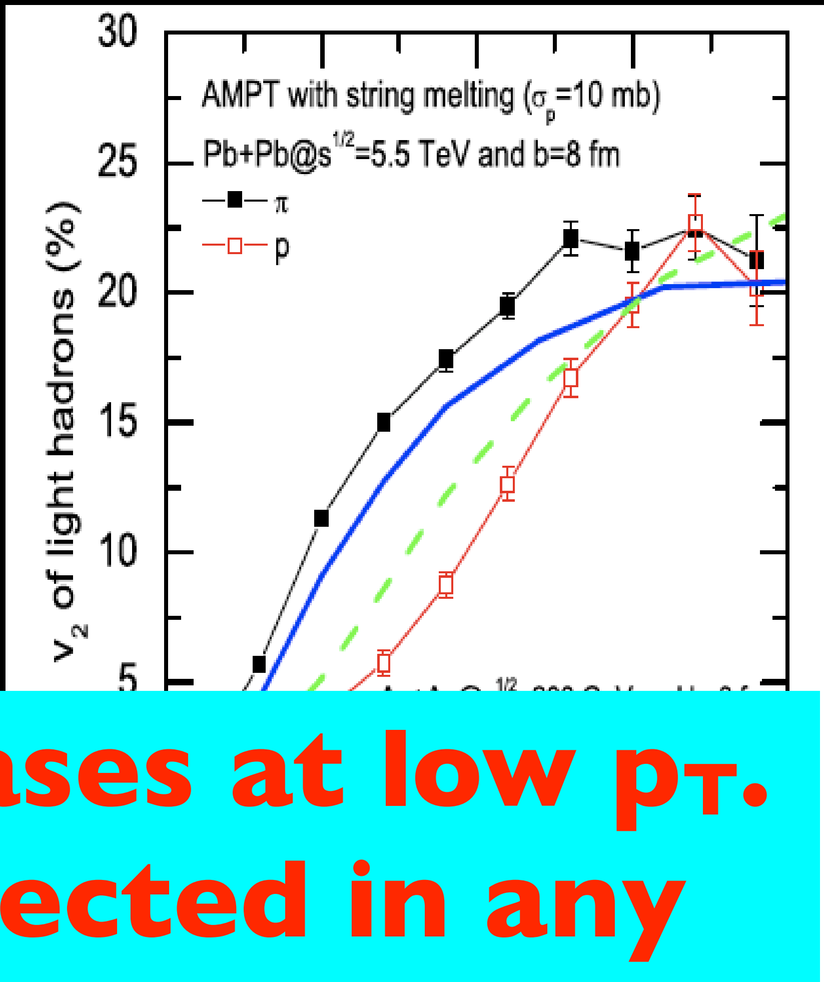
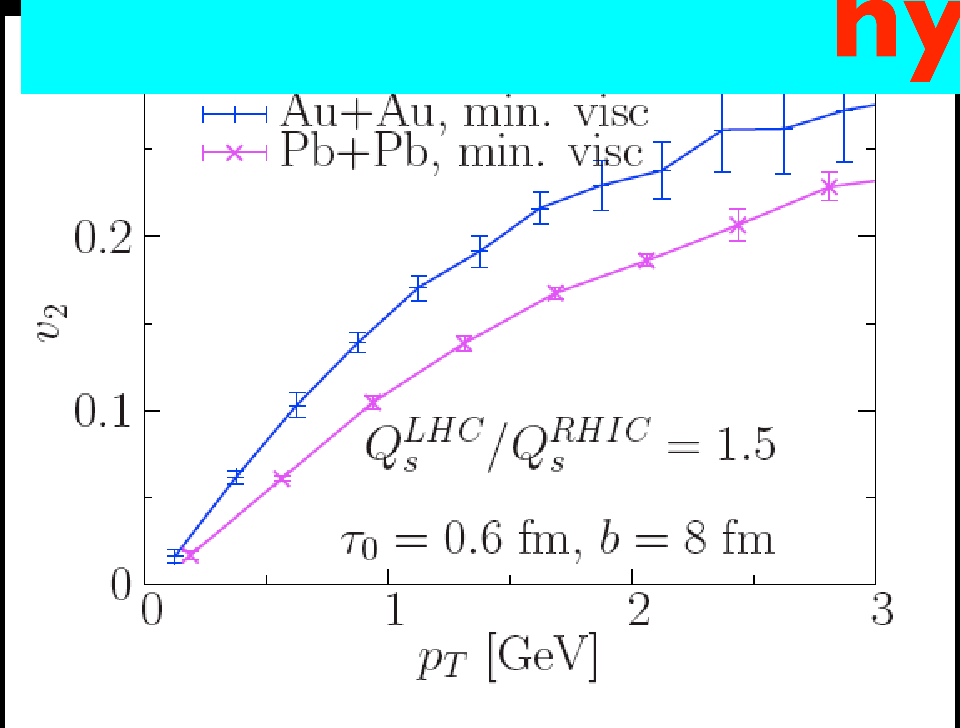


⇨ Generic expectation: v_2 increases at low p_T.
⇨ A strong increase is not expected in any hydro description.



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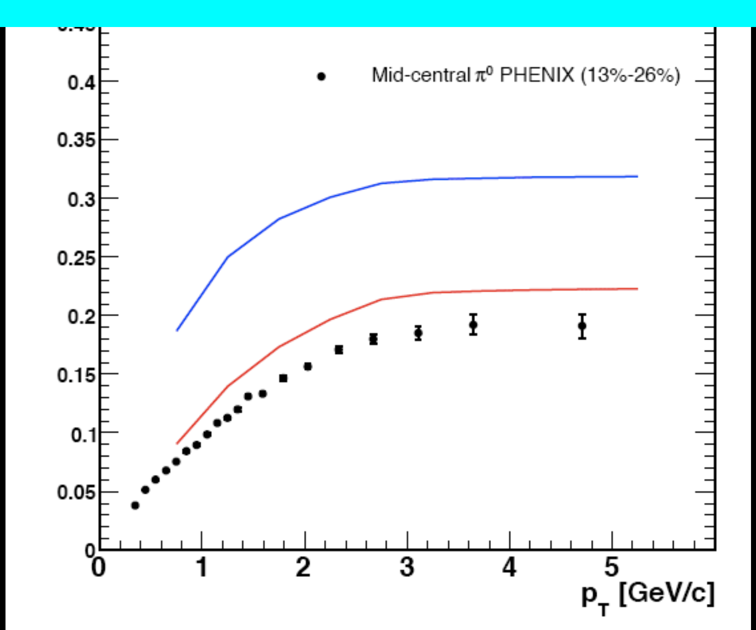


Capella et al., comovers.

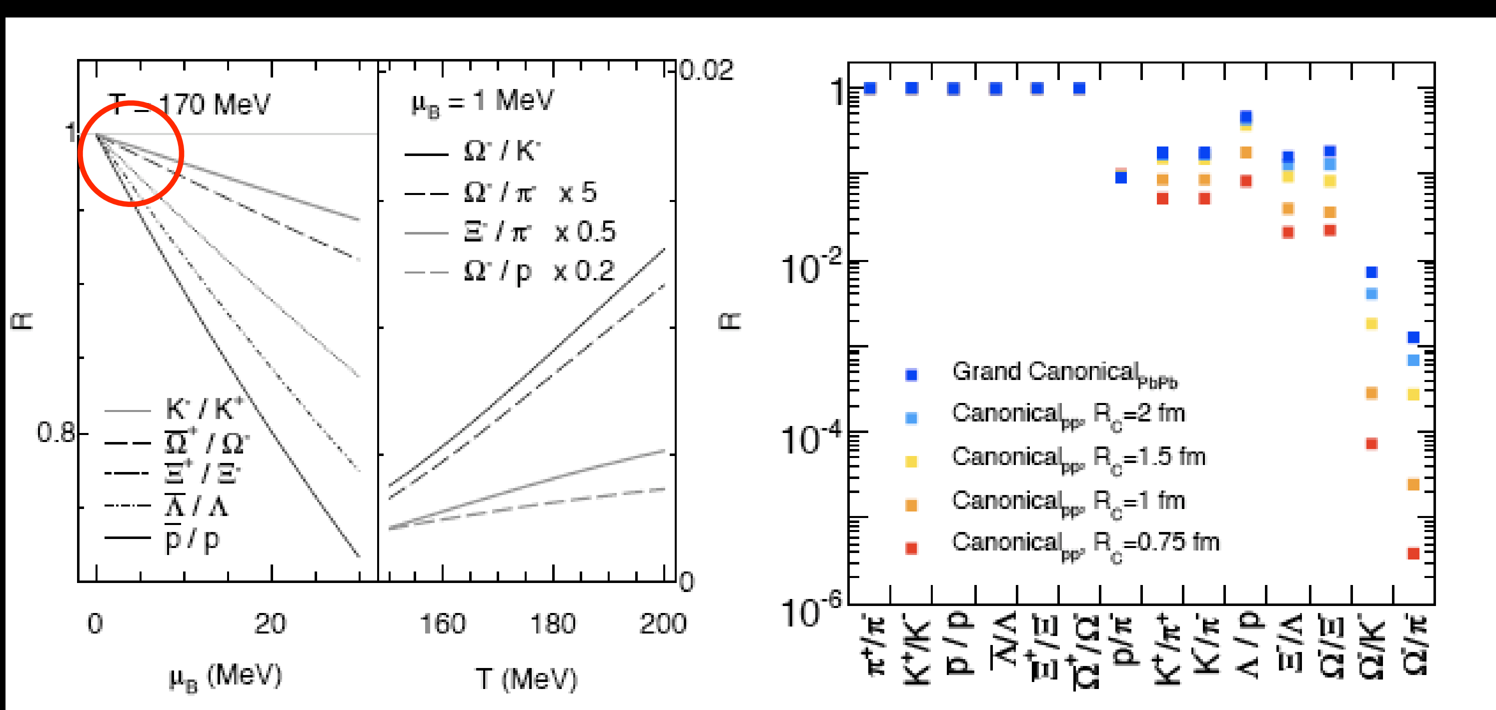
A.3. Hadr. flavor observ.: statistical

π^-/π^+	K^-/K^+	$\bar{p}/p$	$\bar{\Lambda}/\Lambda$	$\bar{\Xi}/\Xi$	$\bar{\Omega}/\Omega$
1.001(0)	0.993(4)	$0.948^{-0.013}_{+0.008}$	$0.997^{-0.011}_{+0.004}$	$1.005^{-0.007}_{+0.001}$	1.013(4)

Andronic et al., equilibrium values for μ_b=0.8 MeV, T=161 MeV.

T[MeV]	140*	140*	162*
dV/dy[fm^3]	2036	4187	6200*
dS/dy	7517	15262	18021
dh_{ch}/dy	1150*	2351	2430
dh_{ch}^{vis}/dy	1351	2797*	2797
$1000 \cdot (\lambda_{q,s}-1)$	5.6*, 2.1	5.6*, 2.1	5.6*, 2.0
$\mu_{B,S}$[MeV]	2.4, 0.5	2.3, 0.5	2.7, 0.6
$\gamma_{q,s}$	1.62, 2.42	1.6*, 2.6	1*, 1*
s/S	0.034*	0.037*	0.025
E/b	420*	428	408
E/TS	1.02	1.05	0.86
P/E	0.165	0.164	0.162
E/V[MeV/fm^3]	530	538	400
P[MeV]	87	88	65
p	25/45	49/95	66/104
$b-\bar{b}$	2.6	5.3	6.1
$(b+\bar{b})/h^-$	0.335	0.345	0.363
$0.1 \cdot \pi^\pm$	49/67	99/126	103/126
$K^\pm$	94	207	175
ϕ	14	33	23
Λ	19/28	41/62	37/50
Ξ^-	4	9.5	5.8
Ω^-	0.82	2.08	0.98

Kraus et al., (grand-)canonical, T and R_c may be determined.



Rafelski et al., non-equilibrium scenarios; non-strange resonances reduced.

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Andronic et al., equilibrium values for

T[MeV]	140*	140*	162*
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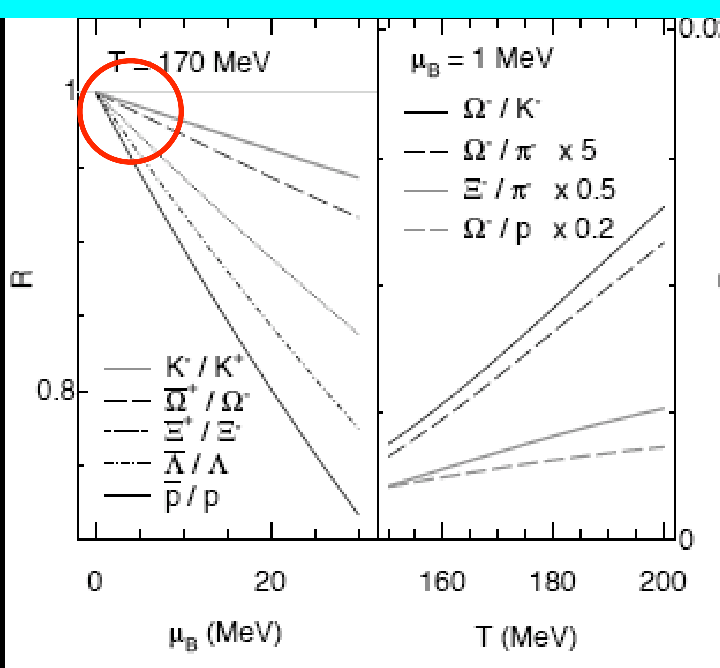
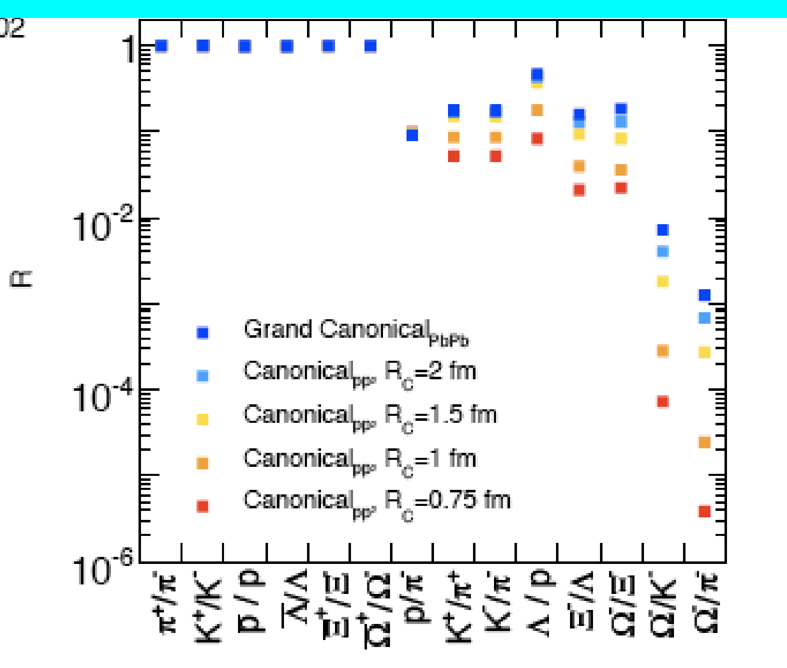
$dh^{\rm vis}_{\rm ch}/dy$	1351	2797*	2797
$1000\cdot(\lambda_{q,s}-1)$	5.6*, 2.1	5.6*, 2.1	5.6*, 2.0

⇨ Different statistical scenarios may be distinguished.

⇨ This becomes of great importance for open charm and charmonium: different scenarios lead to marked differences in production.





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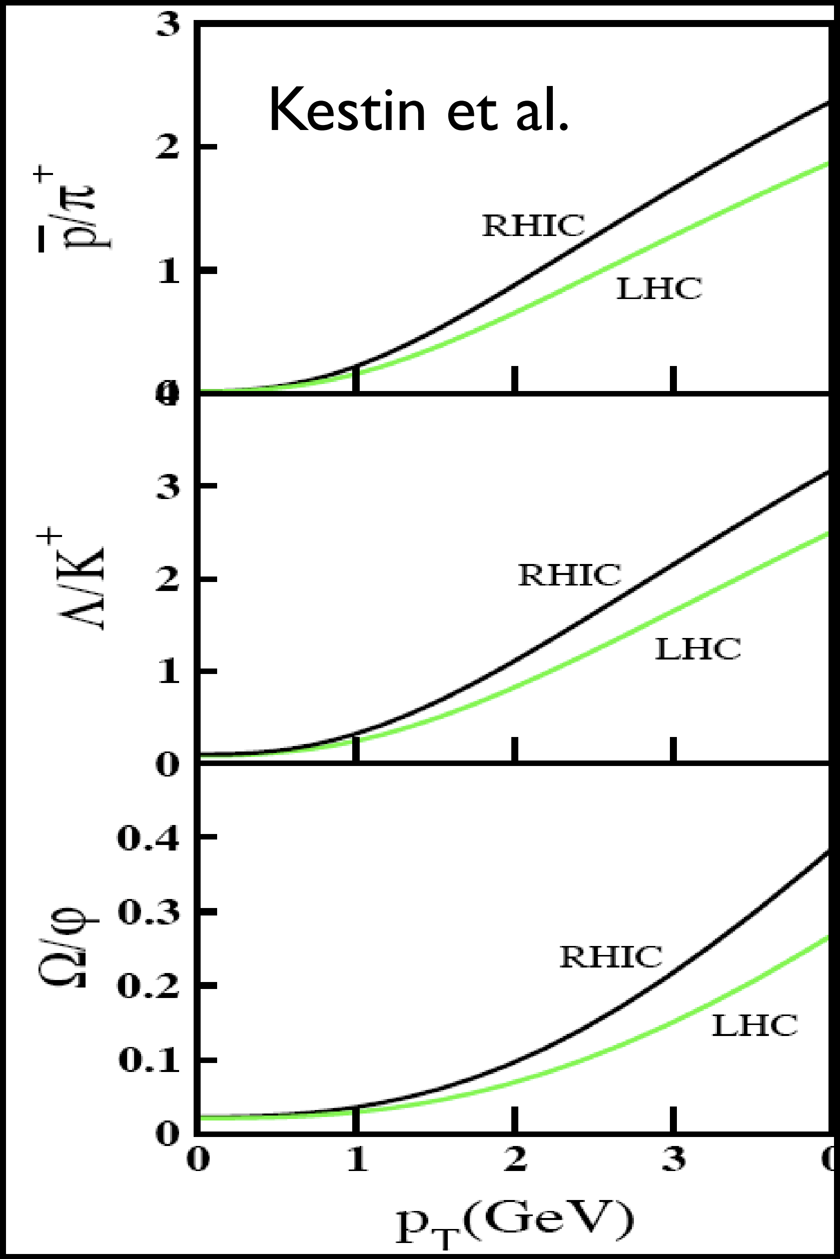
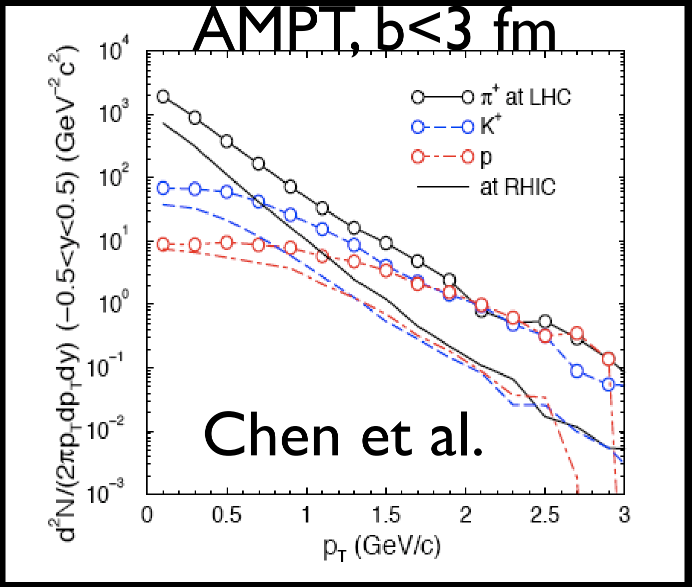
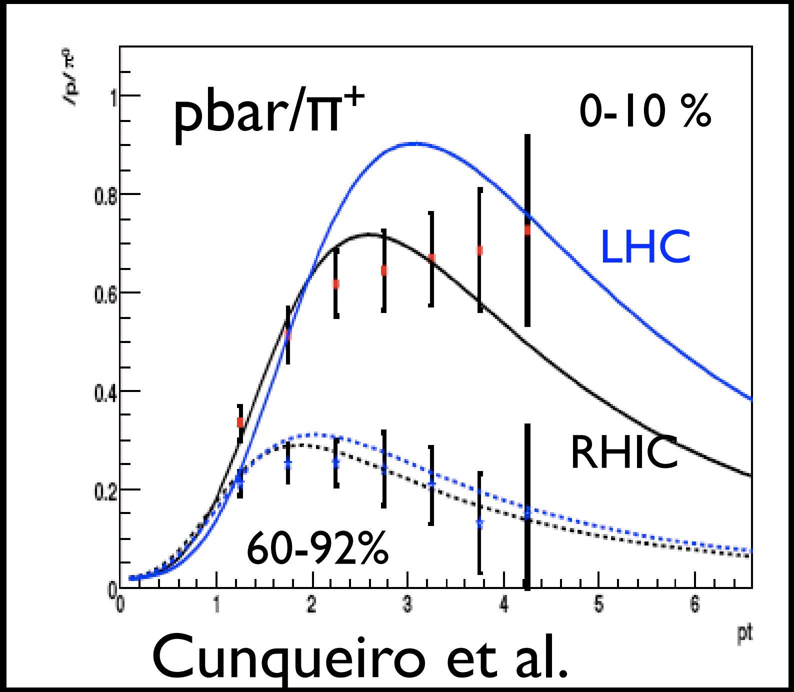
A.3. Hadr. flavor observ.: baryons at low p_T

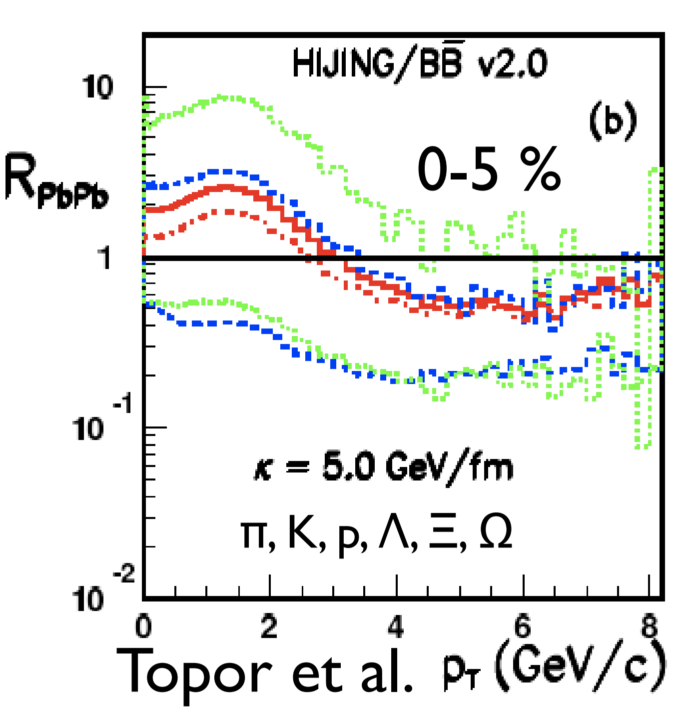
p-pbar<4 at η=0 (BJ: Topor Pop et al., Bopp et al.; hydro: Eskola et al.; EPOS: Porteboeuf et al., RDM: Wolschin et al.).



Hydro and recombination predict larger baryon/meson ratios than models with higher string tension; the latter predicts Cronin for protons.







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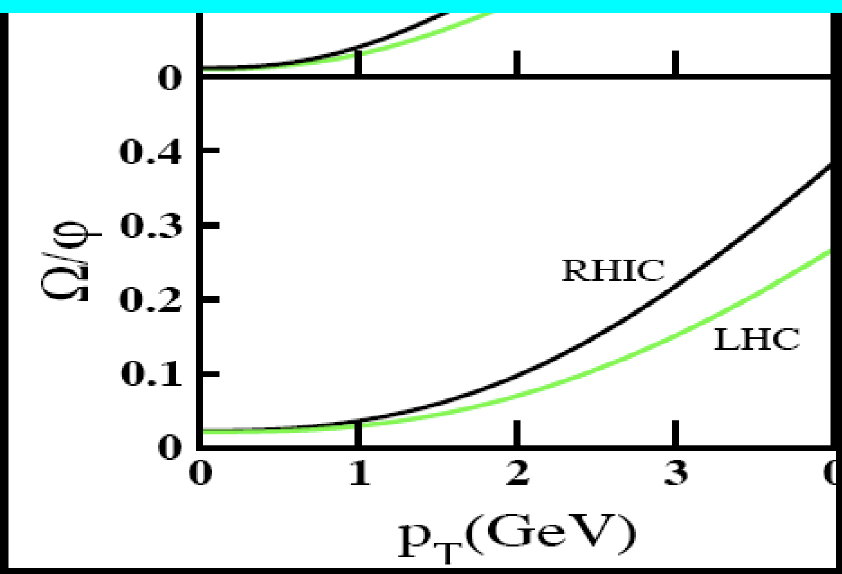
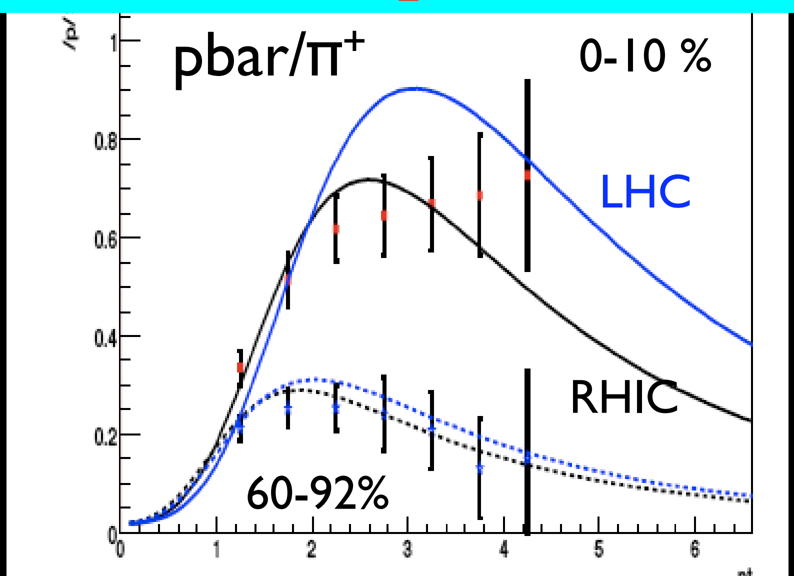
p-pbar<4 at η=0 (BJ: Topor Pop et al., Bopp et al.; hydro: Eskola et al.; EPOS: Porteboeuf et al., RDM: Wolschin et al.).

➪ Cronin effect for protons will strongly constrain models.

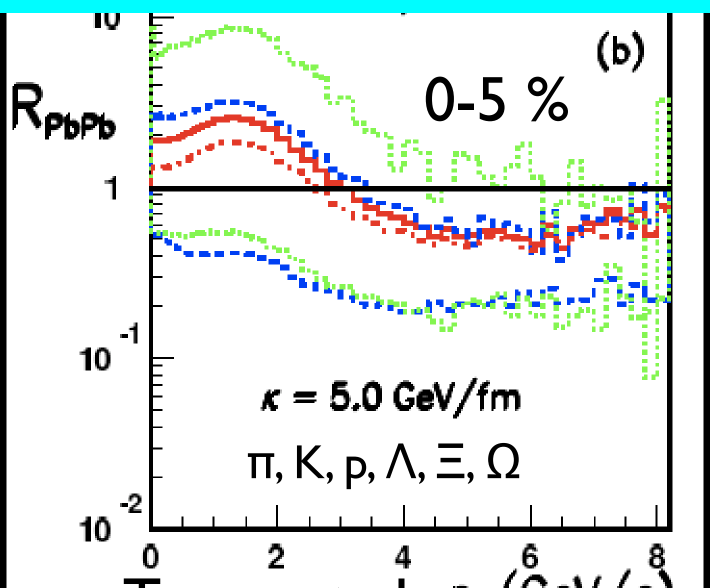
➪ Ratios will further clarify the hadronization mechanism.

➪ A large b-bbar at η=0 would be a real surprise.



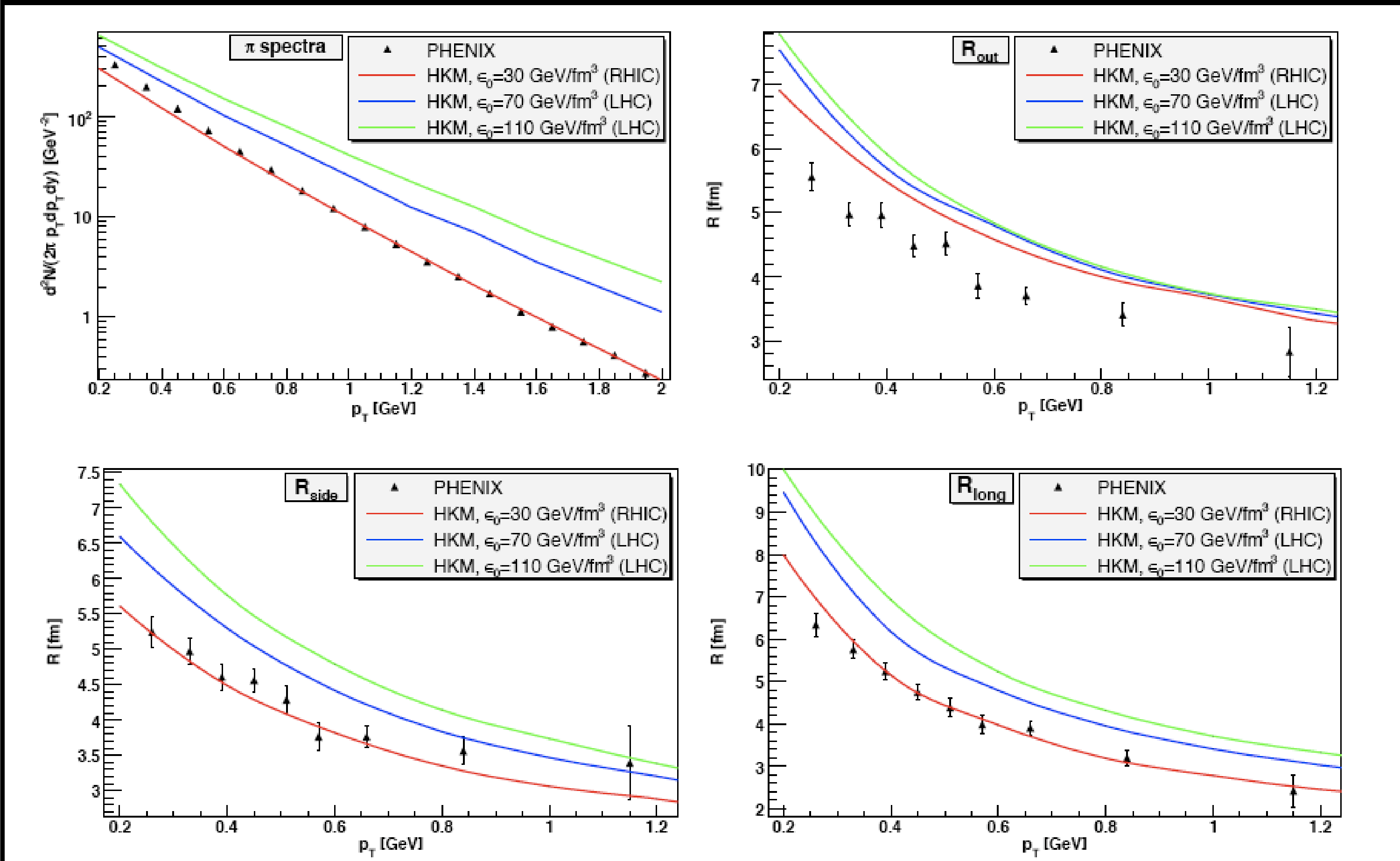


Cunqueiro et al.



Topor et al.

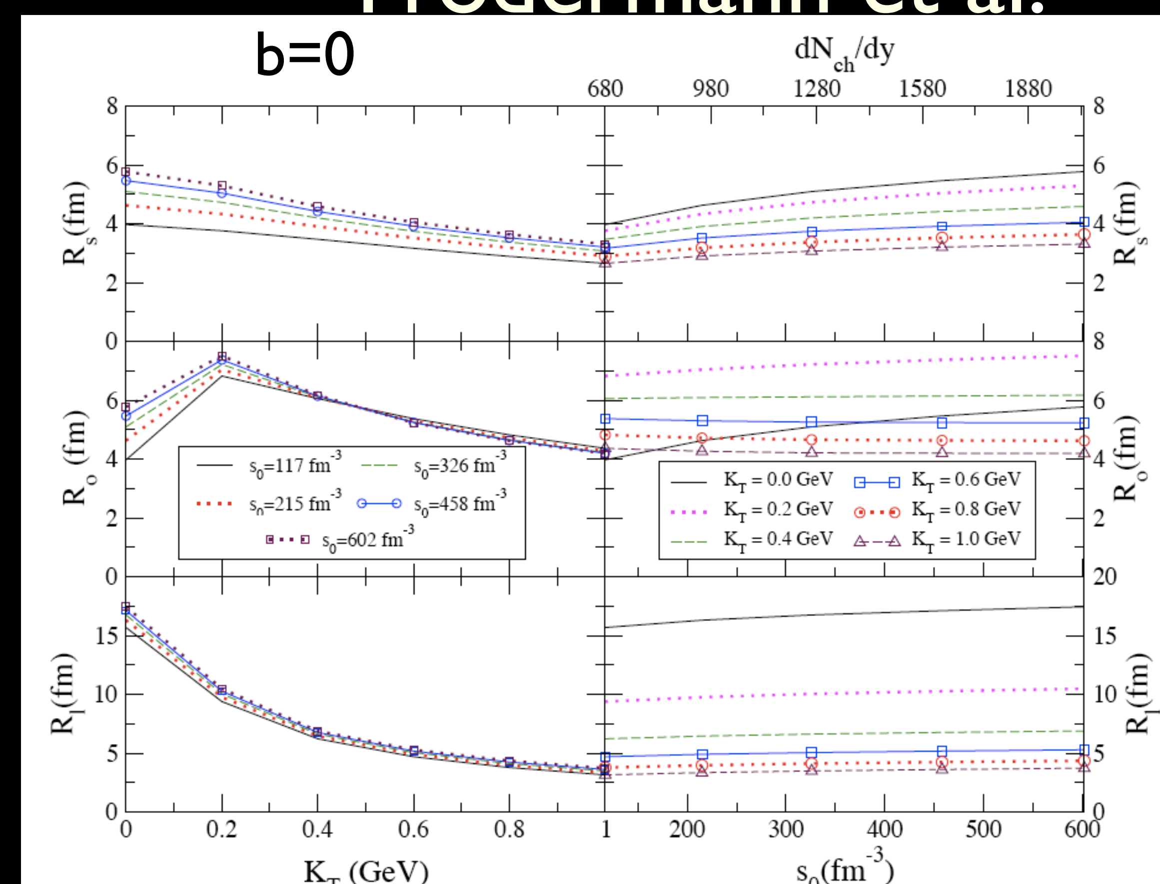
A.4. Correlations at low p_T: HBT



Sinyukov et al., HKM; also Karpenko et al., FASTMC.

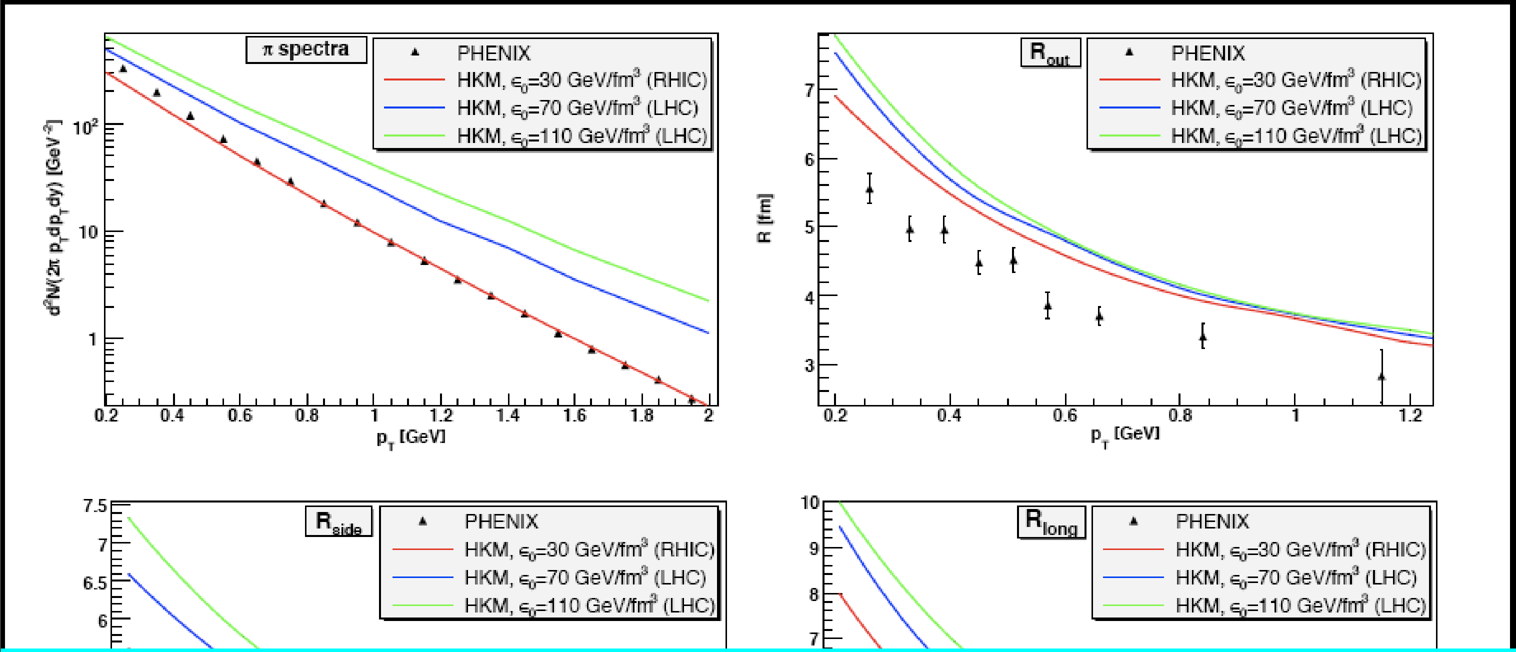
Hydro: same problems as at RHIC - R_{out} (k_T), R_{side}(k_T), R_{out}>> R_{side}; out- → in-plane shape.

Frodermann et al.



RHIC/LHC for π's	Chen et al., AMPT, b=0, 0.3<k_T<1.5	Chojnacki et al., 0712.0947, hydro+stat., b=1 fm, k_T=0.3 GeV
R_{out}	3.60/4.23	5.4/6.0-6.5
R_{side}	3.52/4.70	4.3/5.3-6.3
R_{long}	3.23/4.86	6.1/7.6-8.6

A.4. Correlations at low p_T: HBT



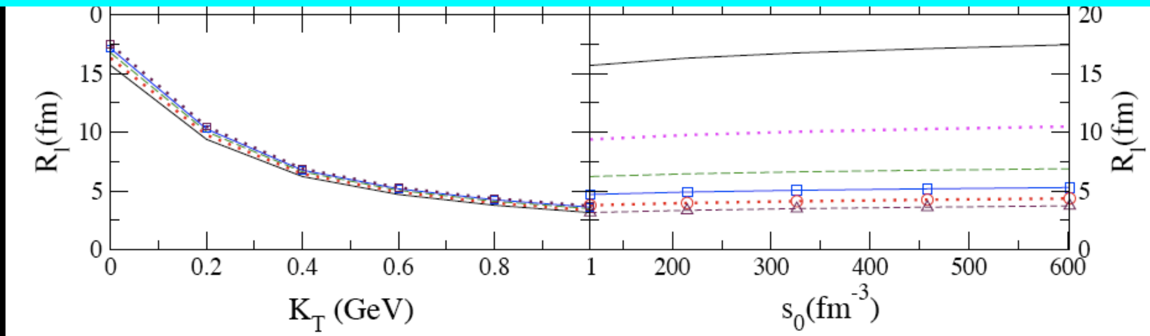
Hydro: same problems as at RHIC - R_{out} (k_T), R_{side}(k_T), R_{out}>> R_{side}; out- → in-plane shape.

➪ R's increase from RHIC to the LHC in all models.

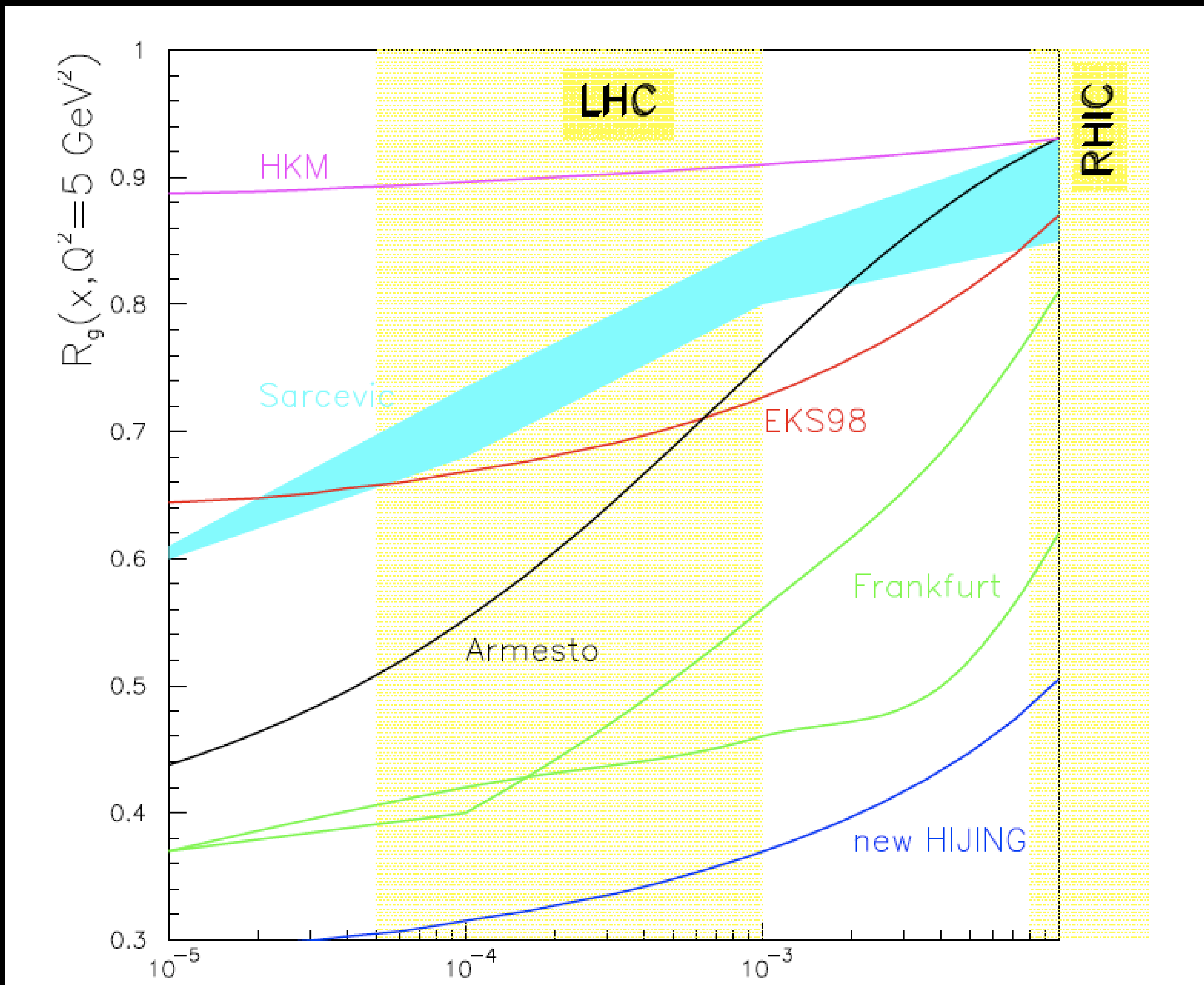
➪ But the predictive power is limited by the problems at RHIC.

➪ Dissipative effects on HBT are not well understood yet.

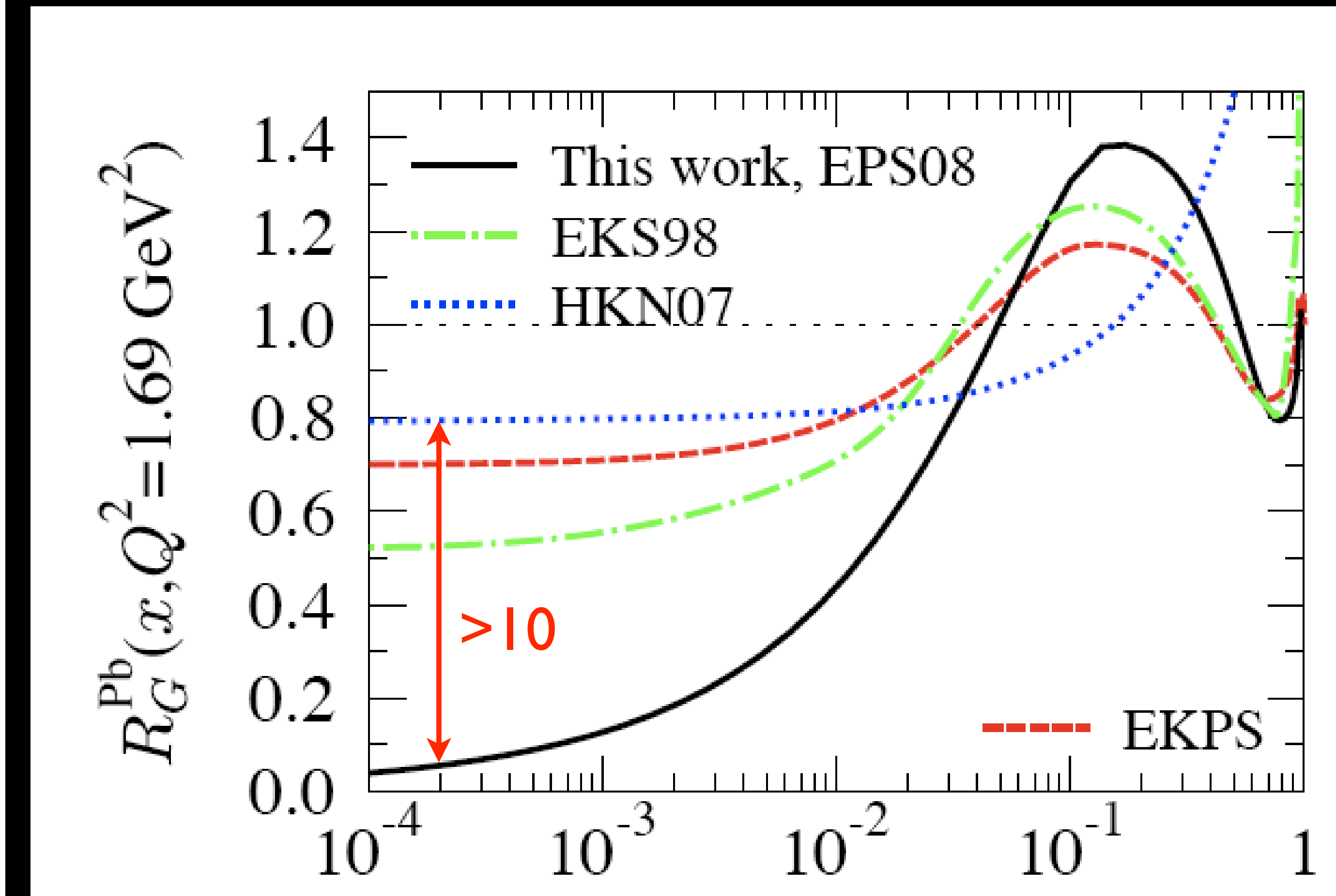
R_{out}	3.60/4.23	5.4/6.0-6.5
R_{side}	3.52/4.70	4.3/5.3-6.3
R_{long}	3.23/4.86	6.1/7.6-8.6



B. Hard probes: benchmark



Yellow Report on Hard Probes, 2004



Eskola et al., 0802.0139

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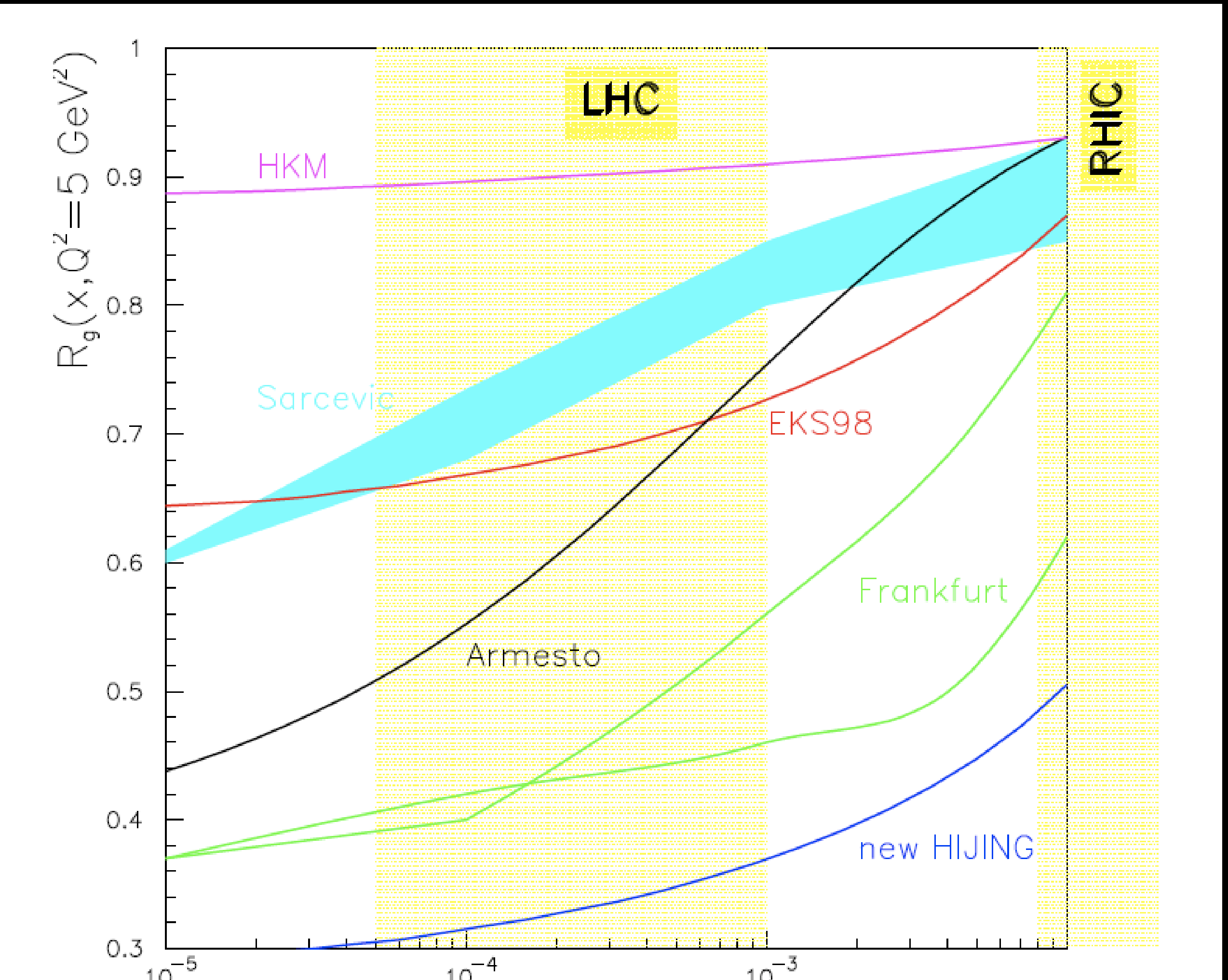

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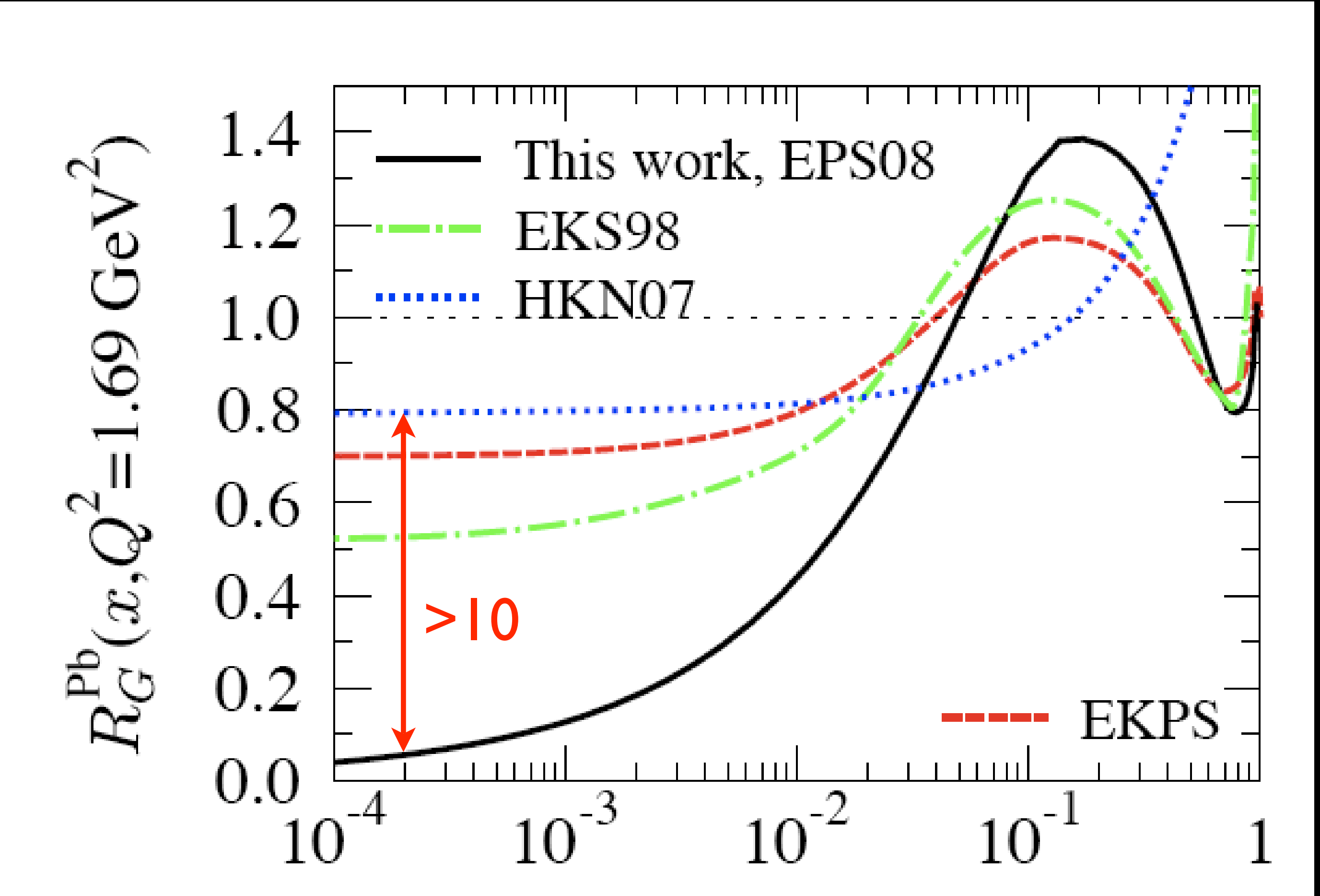
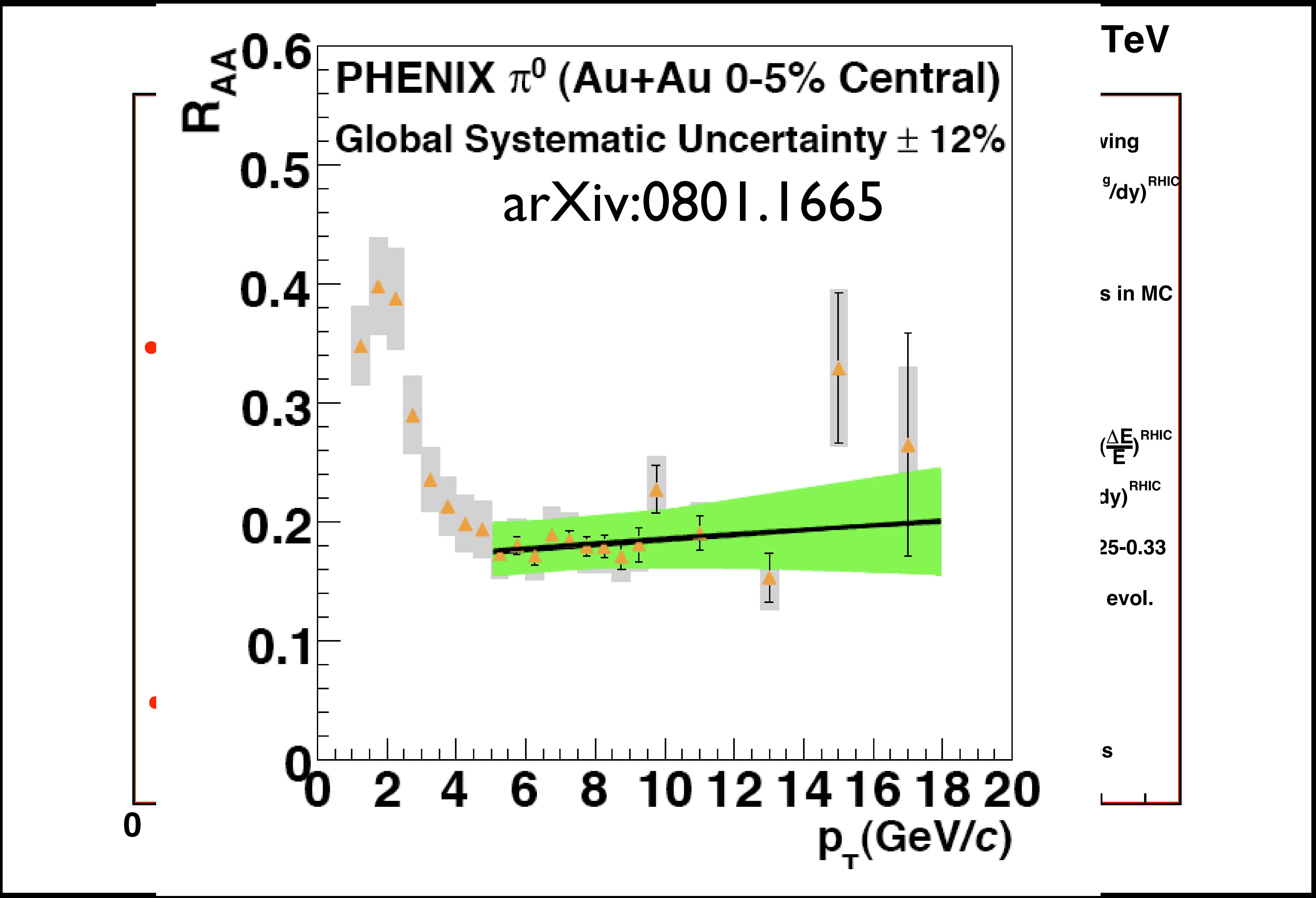


Eskola et al., 0802.0139

➪ To avoid this uncertainty within the LHC frame, an accurate control of the benchmark will be required (as it was at RHIC).

B.1. High-p_T observ.: R_{AA} for light flavors



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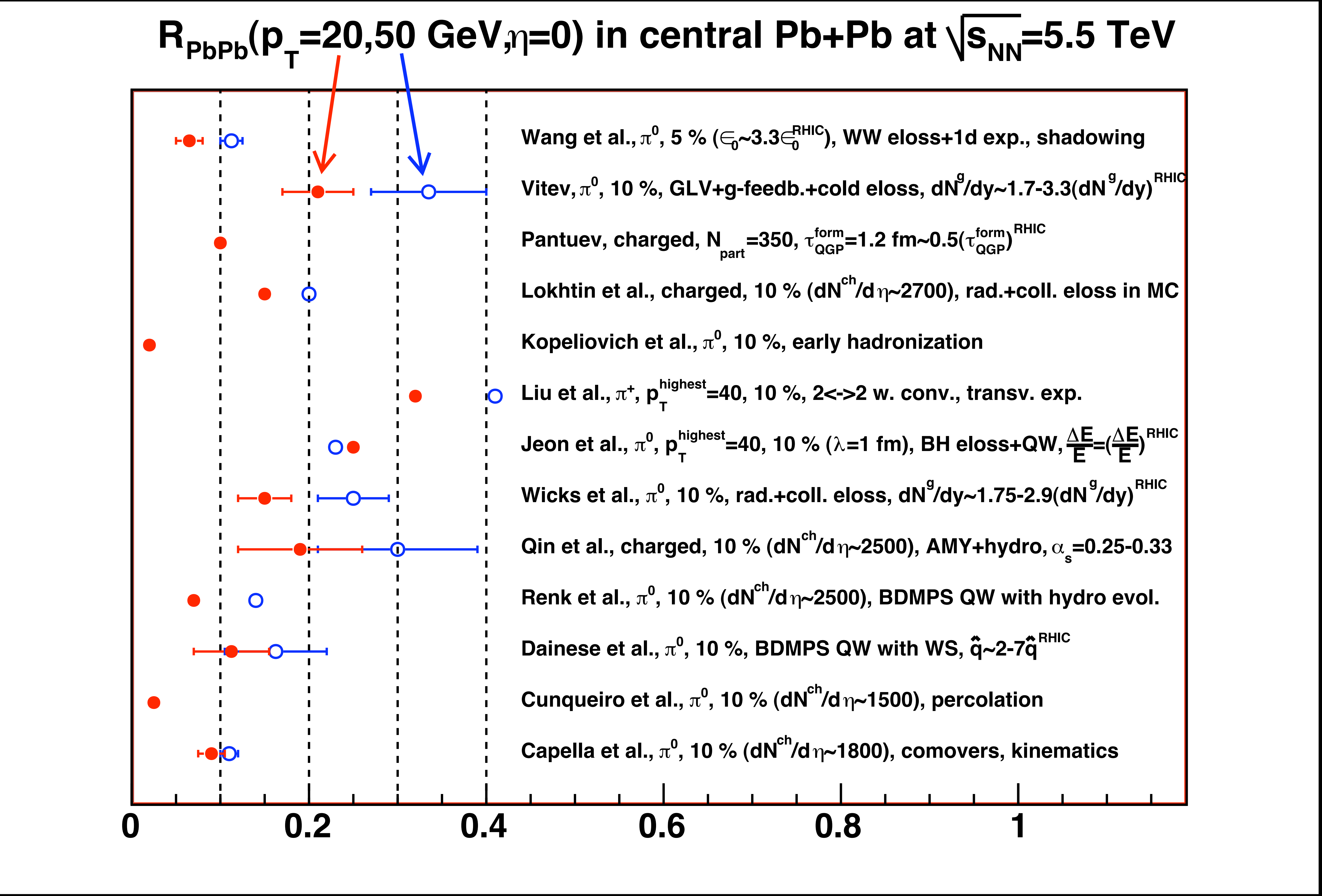

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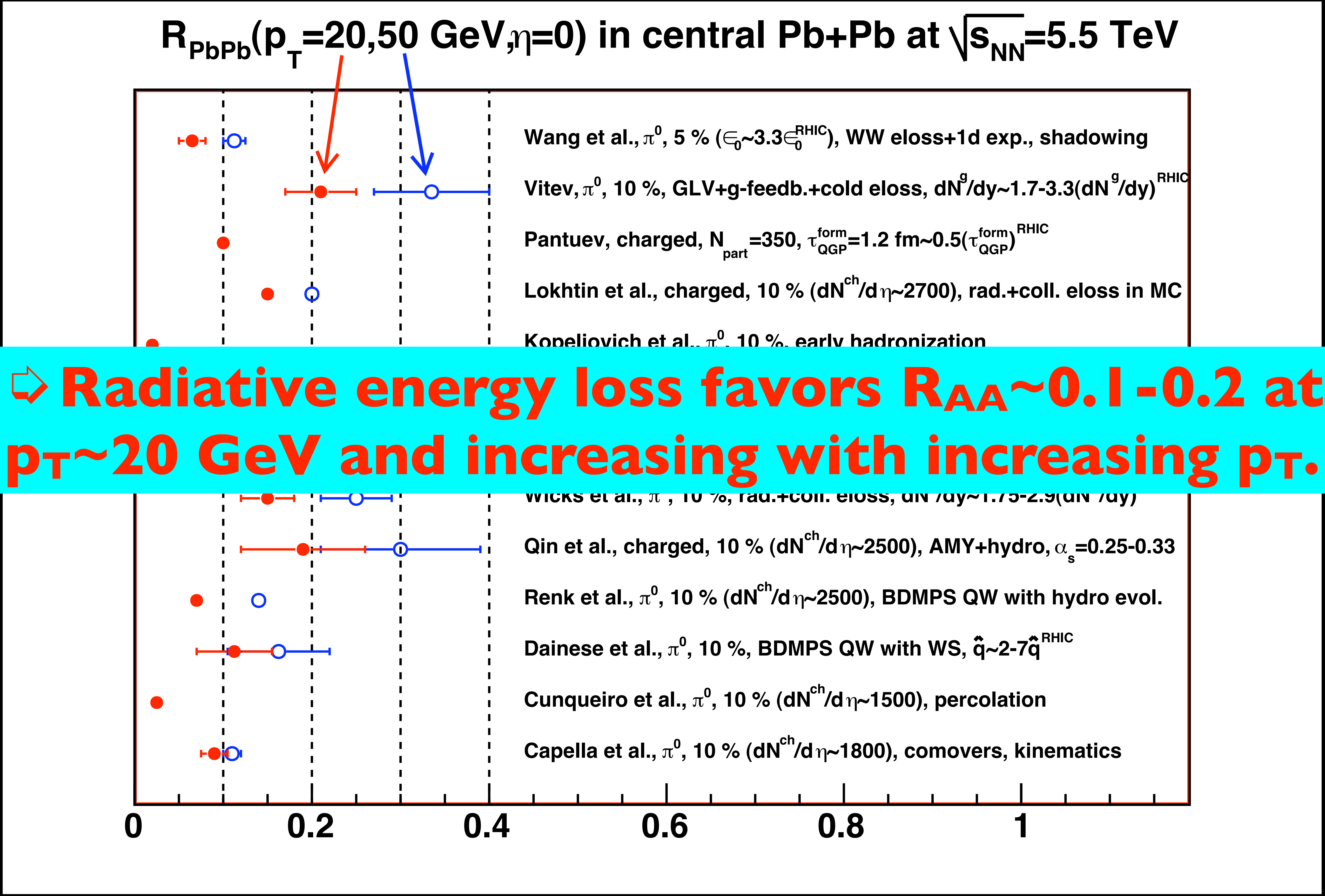
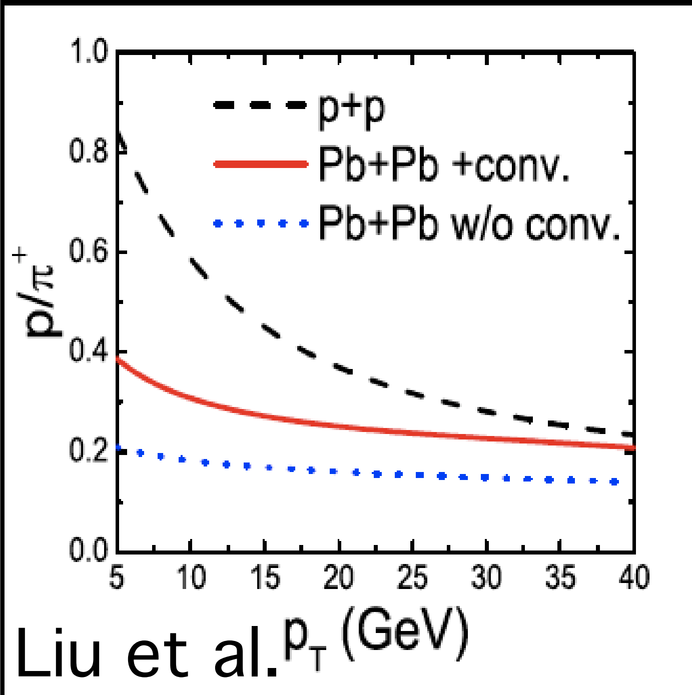
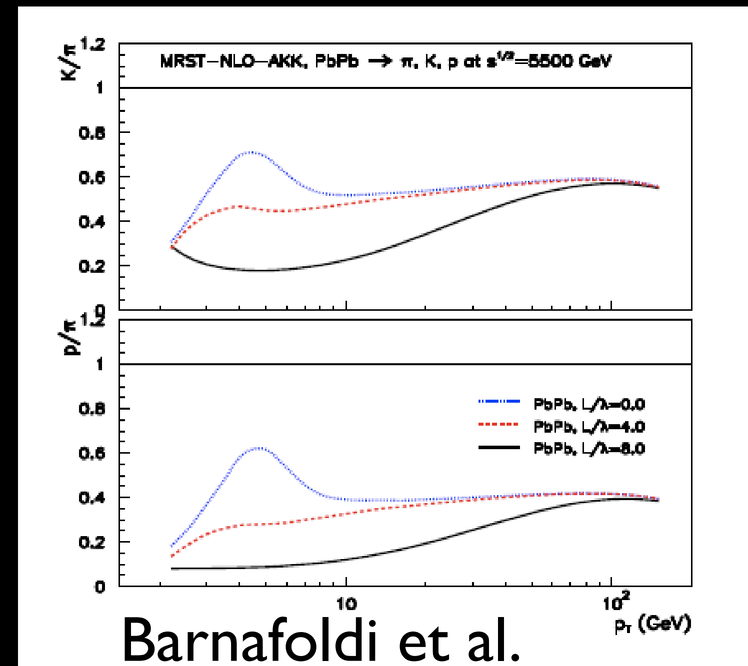


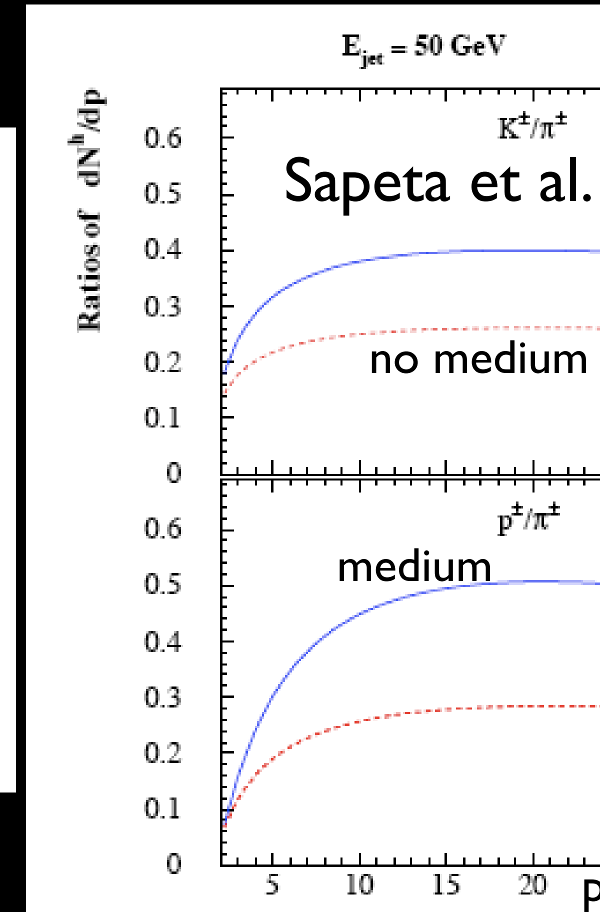
⇨ Radiative energy loss favors R_{AA}~0.1-0.2 at p_T~20 GeV and increasing with increasing p_T.

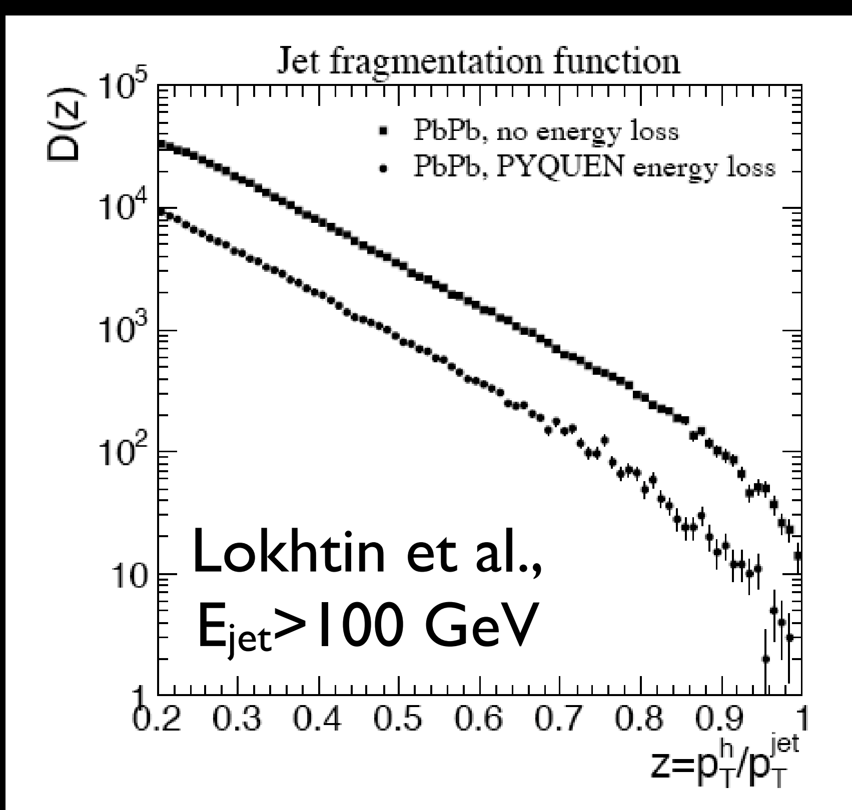
B.1. High-p_T observ.: hadrochemistry and FF



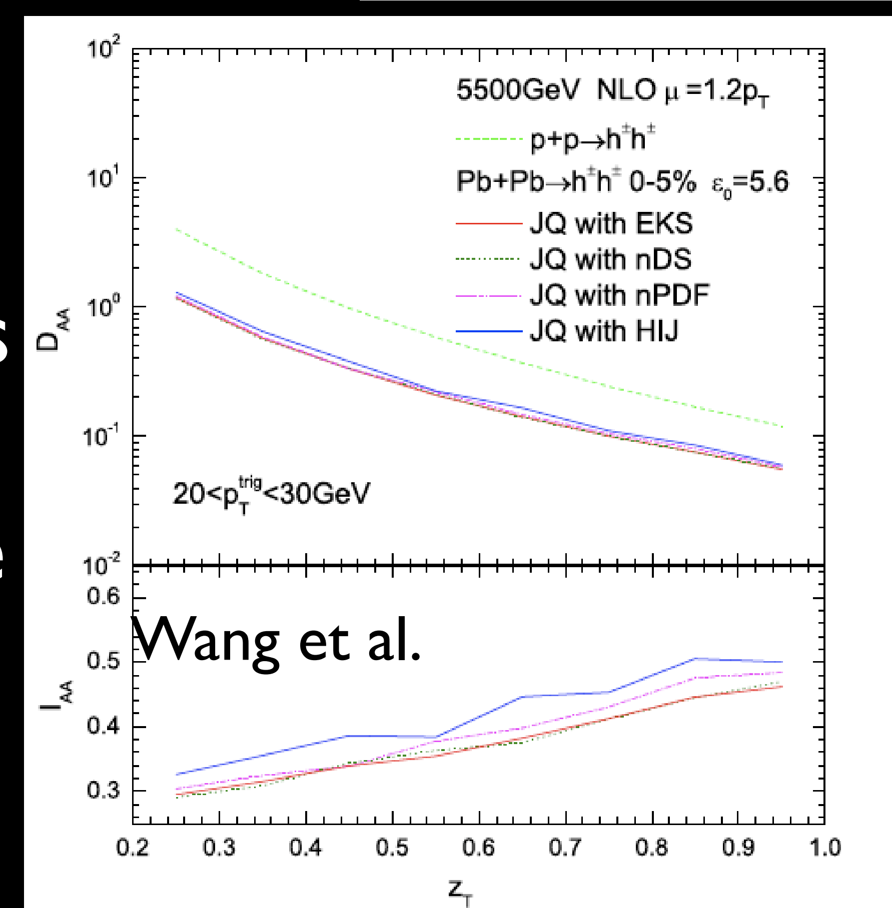
Modification of hadrochemistry due to elastic +conversions, rad. eloss or modified jet radiation.



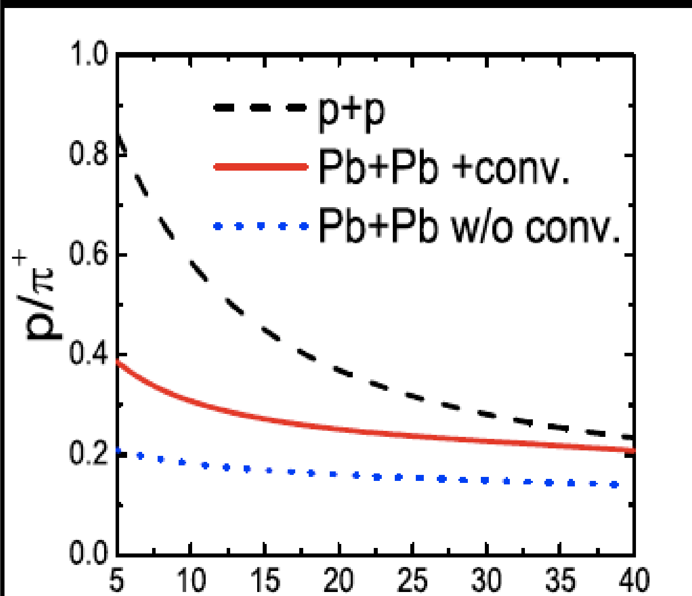




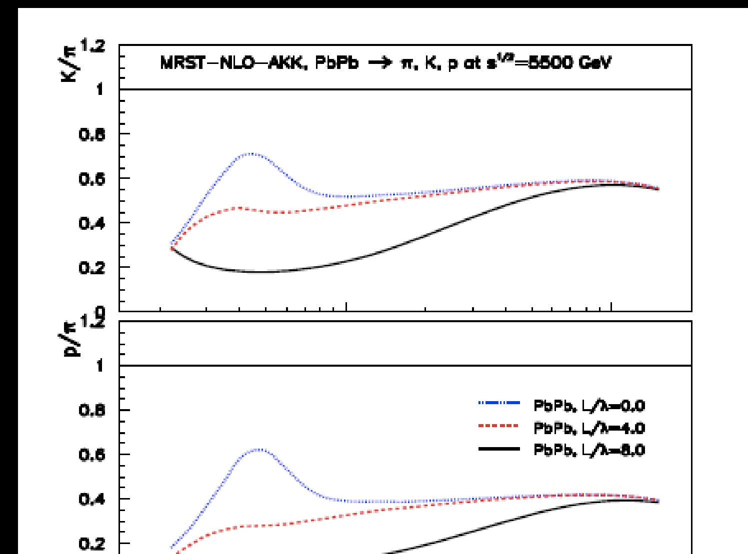
Modified fragmentation functions, both for jets (elastic+radiative in PYQUEN) and for the hadron-triggered case (WW rad. model).

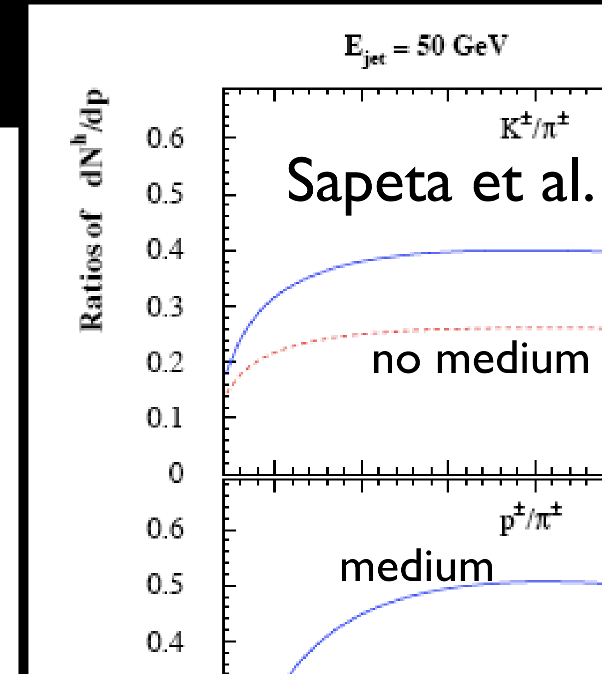


B.1. High-p_T observ.: hadrochemistry and FF

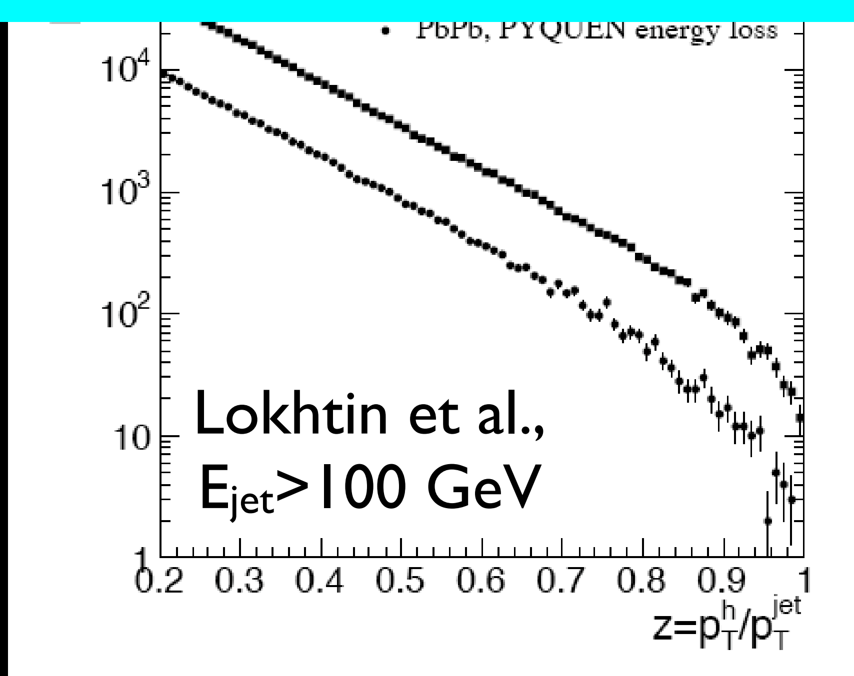


Modification of hadrochemistry due to elastic +conversions, rad. eloss or modified jet

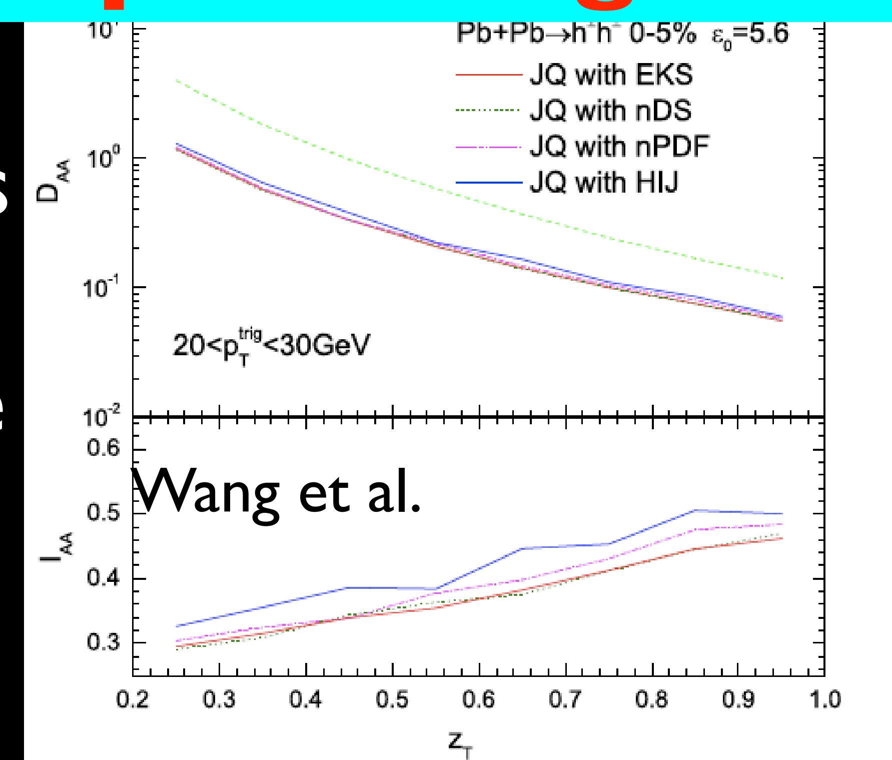




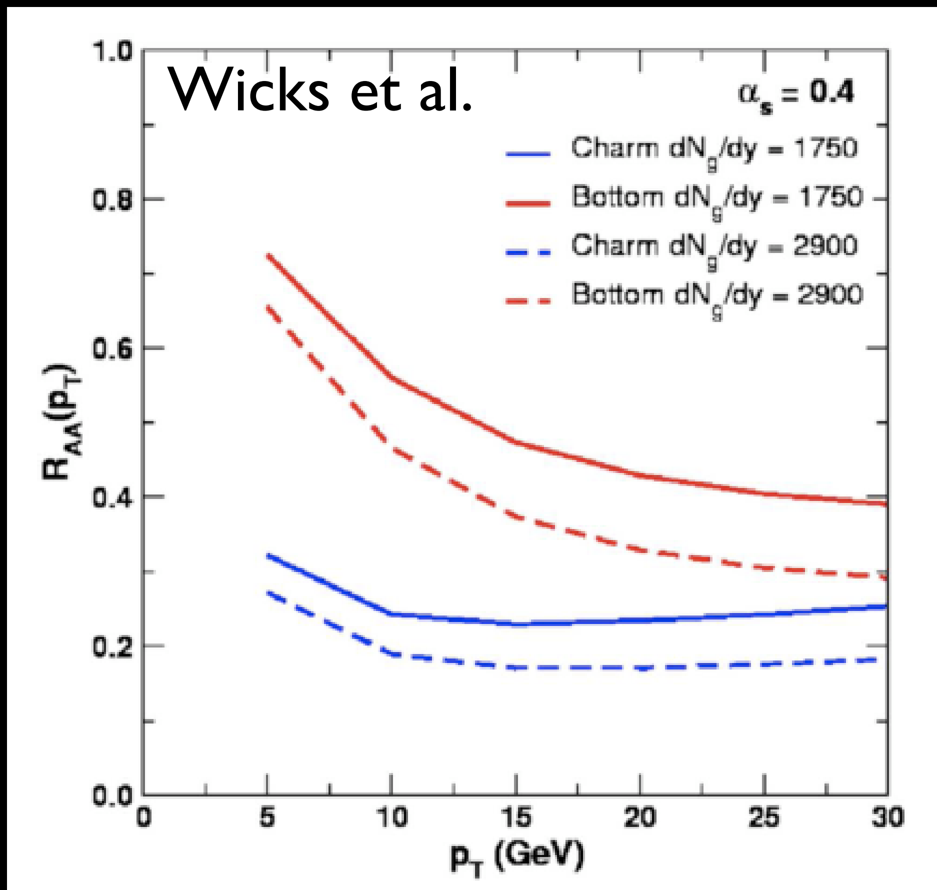
⇨ **Chemical composition and more differential observables will be key to establish the mechanism underlying jet quenching.**

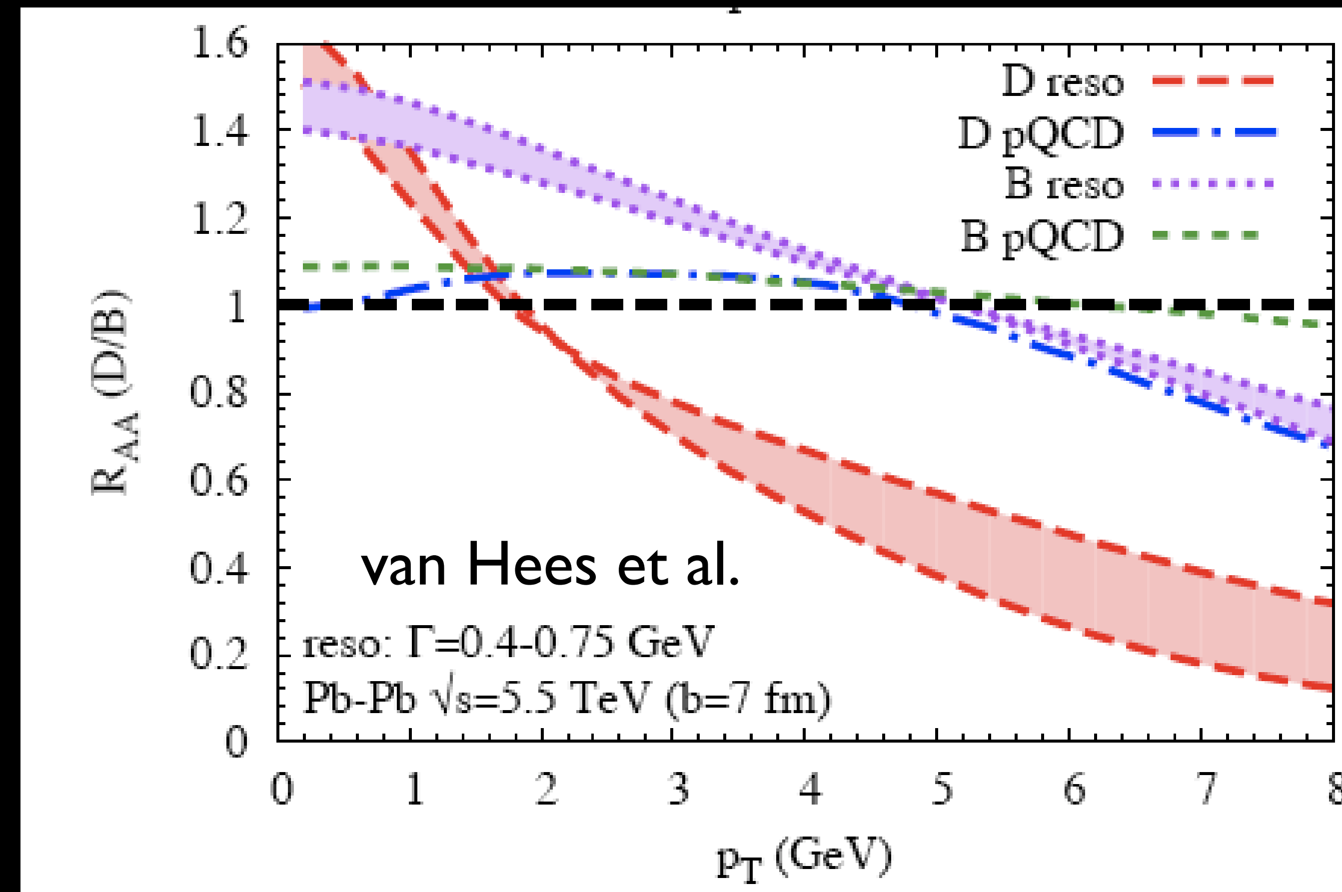


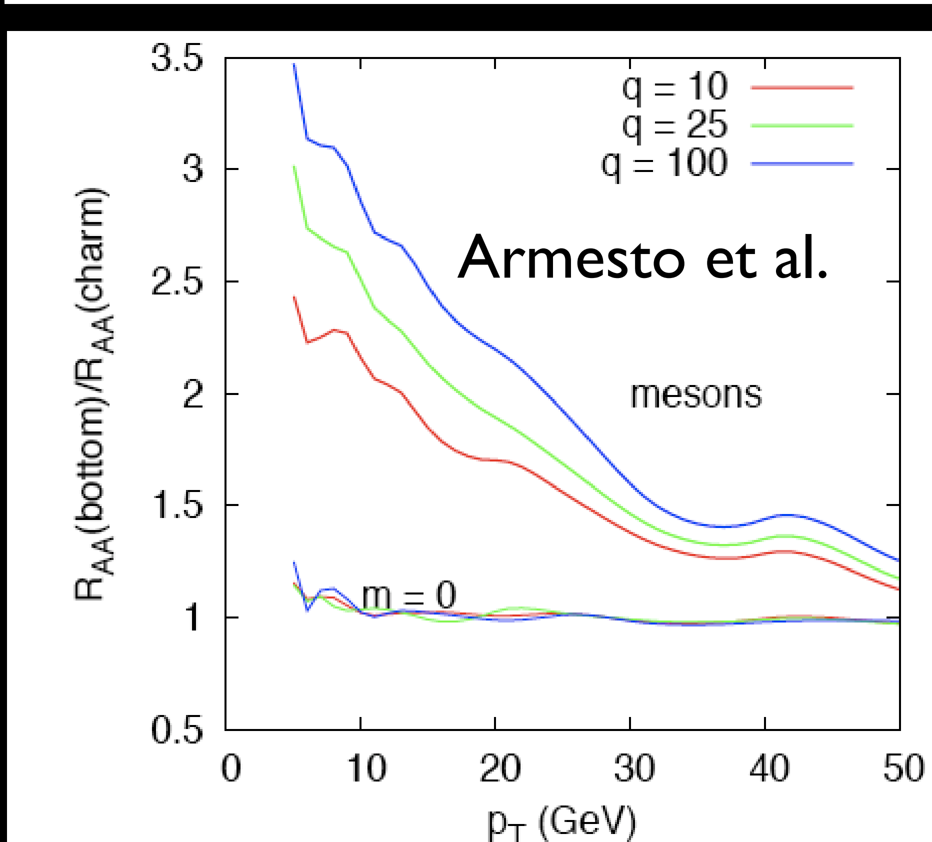
fragmentation functions, both for jets (elastic+radiative in PYQUEN) and for the hadron-triggered case (WW rad. model).



B.2. HQ and quarkonium: R_{AA} for heavy

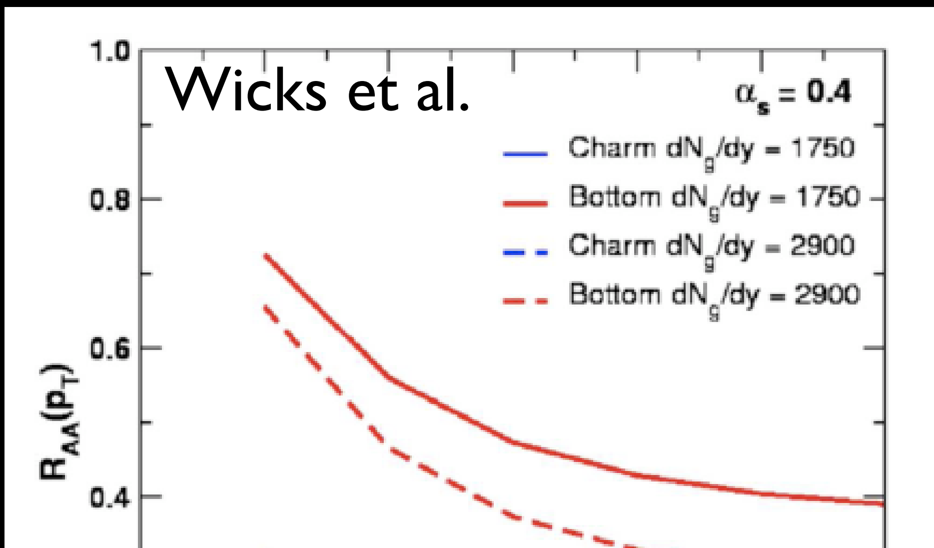


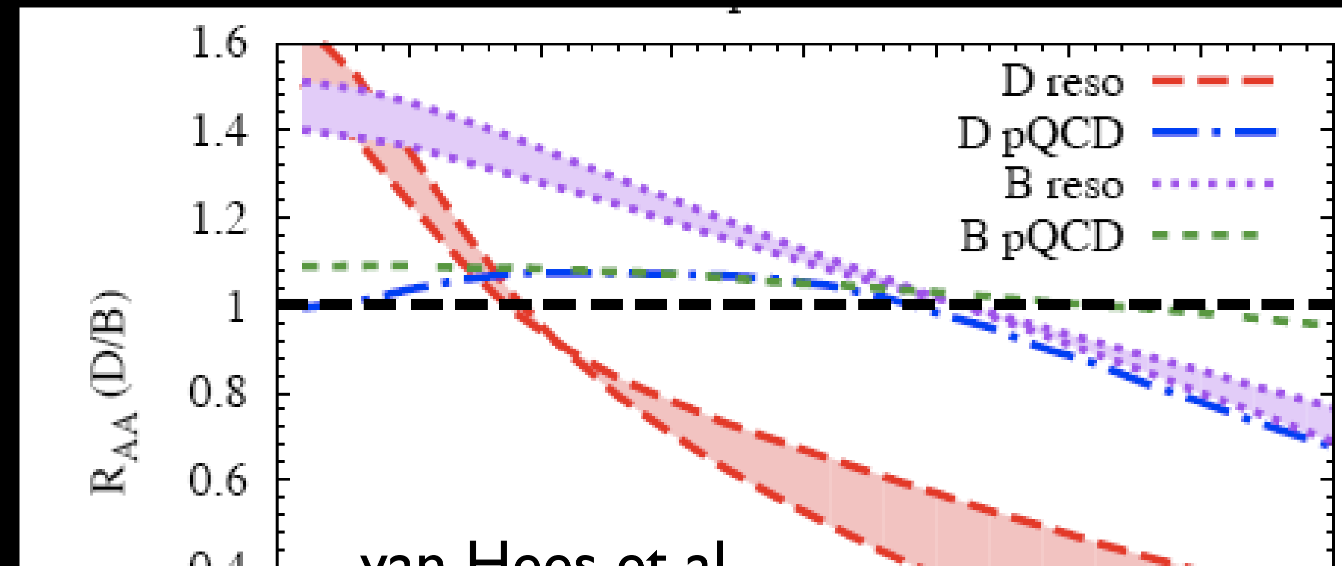




pQCD-based models valid for hadronization outside the medium, so for high p_T (see also Vitev).
Double ratios B/D are sensitive to mass effects until quite high p_T and offer possibilities to discriminate models for HQ jet quenching (Horowitz et al.).

B.2. HQ and quarkonium: R_{AA} for heavy

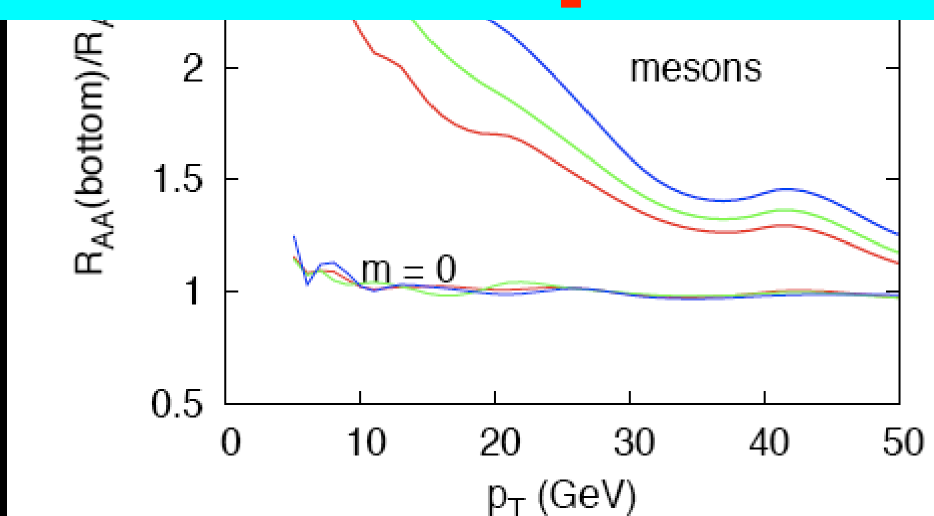




⇨ LHC will provide R_{AA} for both leptons and mesons.

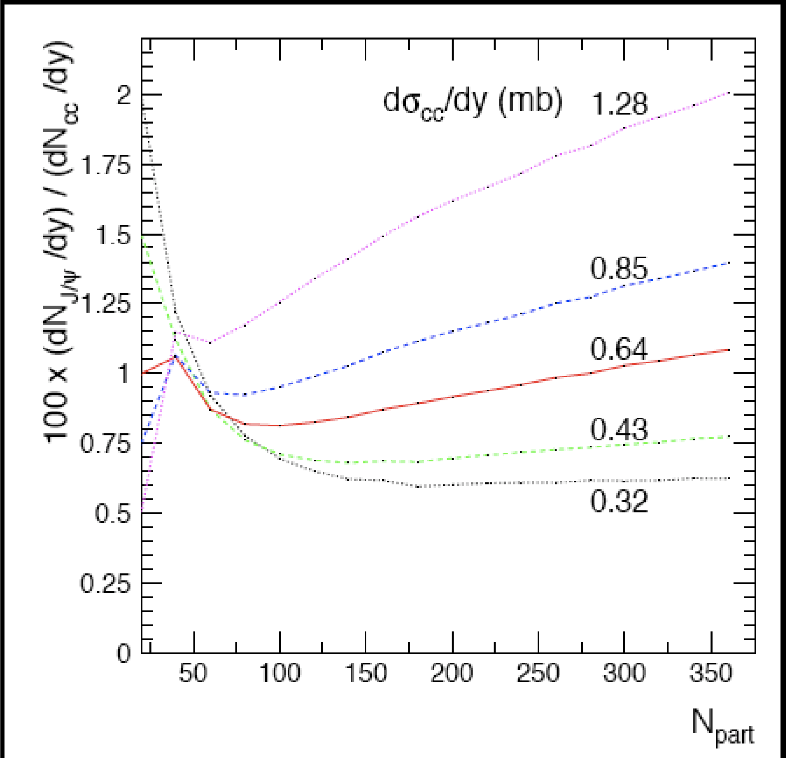
⇨ Double ratios will become available.

⇨ This will clarify the mechanism for HQ jet quenching and hadronization.

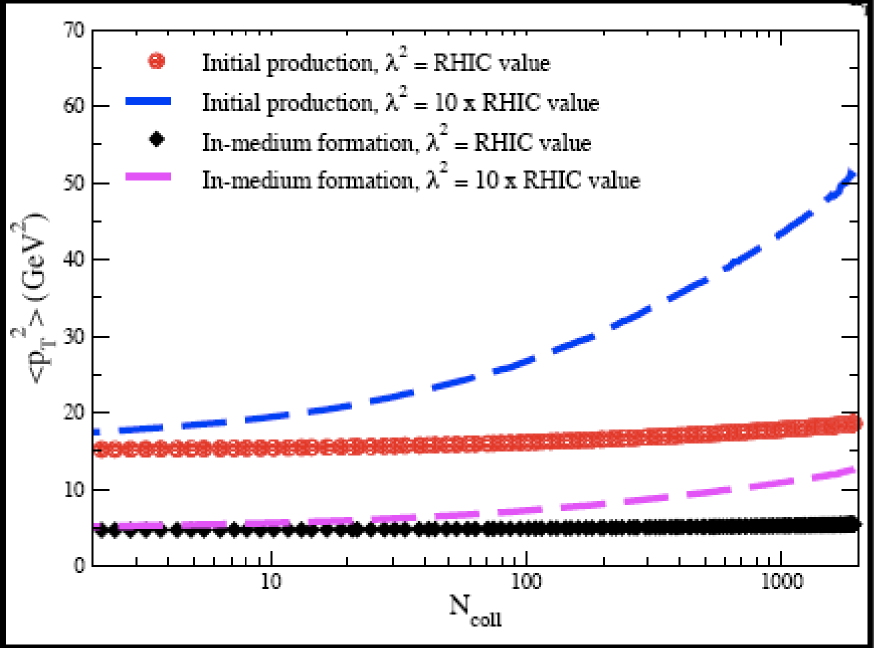


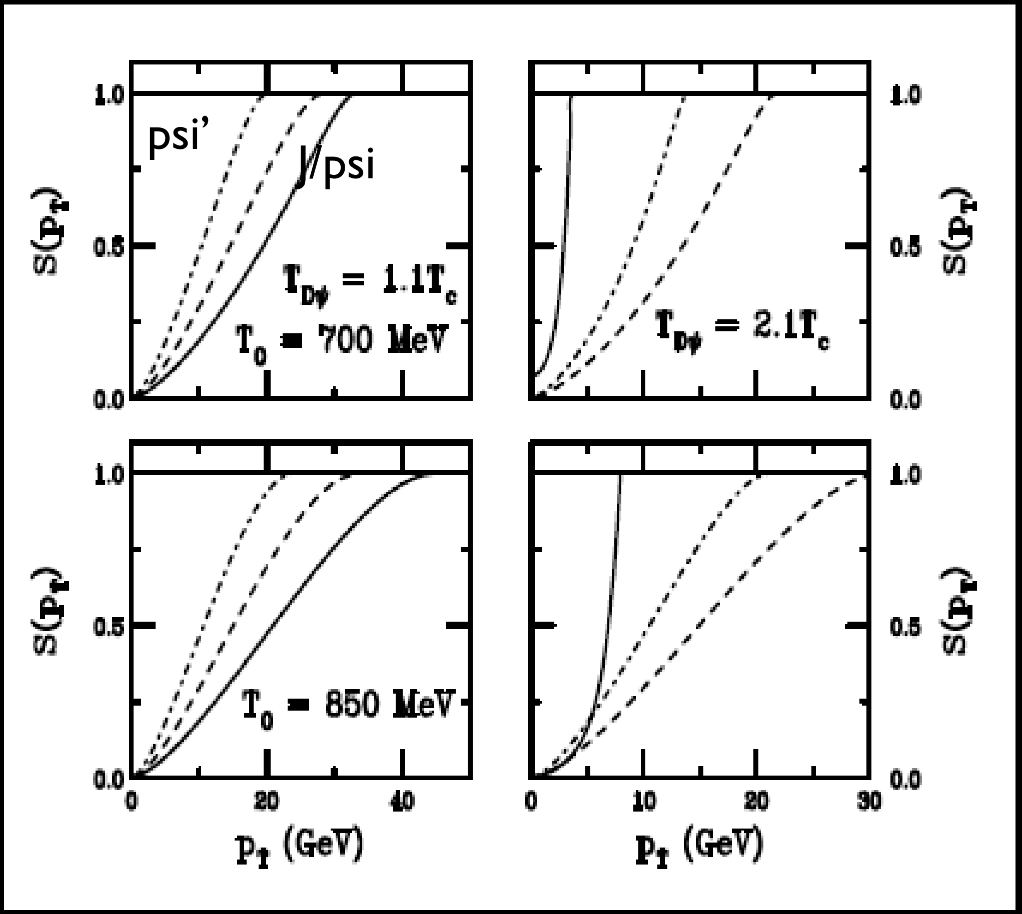
Double ratios B/D are sensitive to mass effects until quite high p_T and offer possibilities to discriminate models for HQ jet quenching (Horowitz et al.).

B.2. HQ and quarkonium: quarkonia suppr.

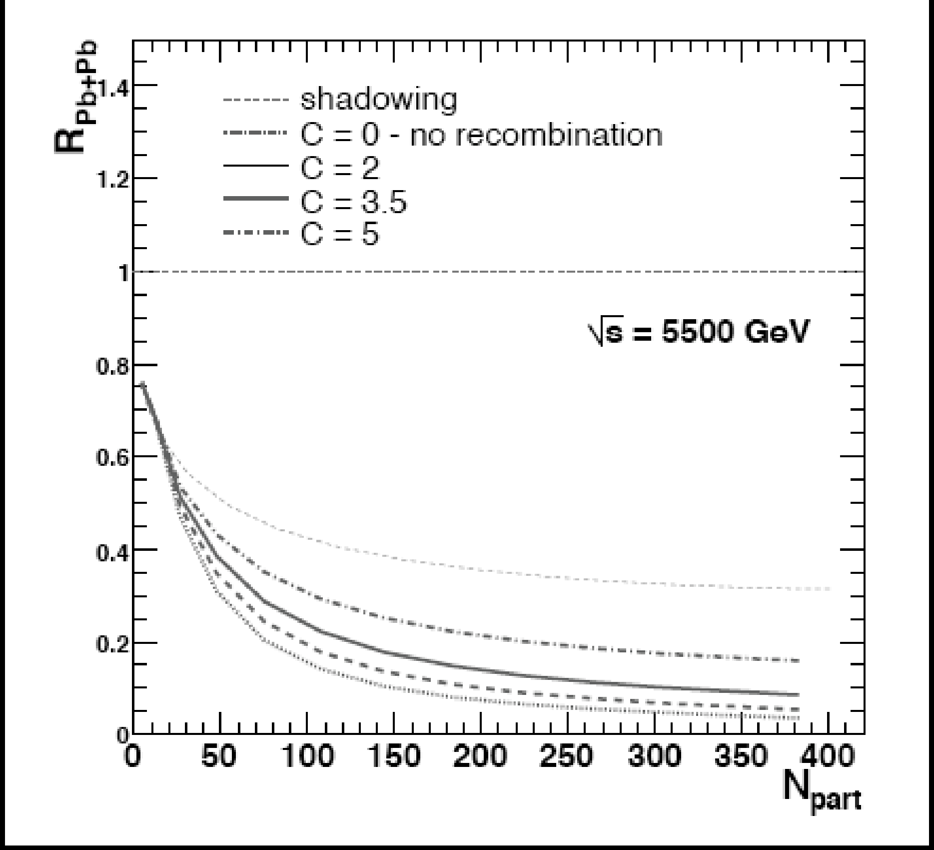


Andronic et al.: dependence on charm cross section; Thews et al.: pT-broadening to verify recombination, with uncertainties from cold matter effects (Kang et al.).



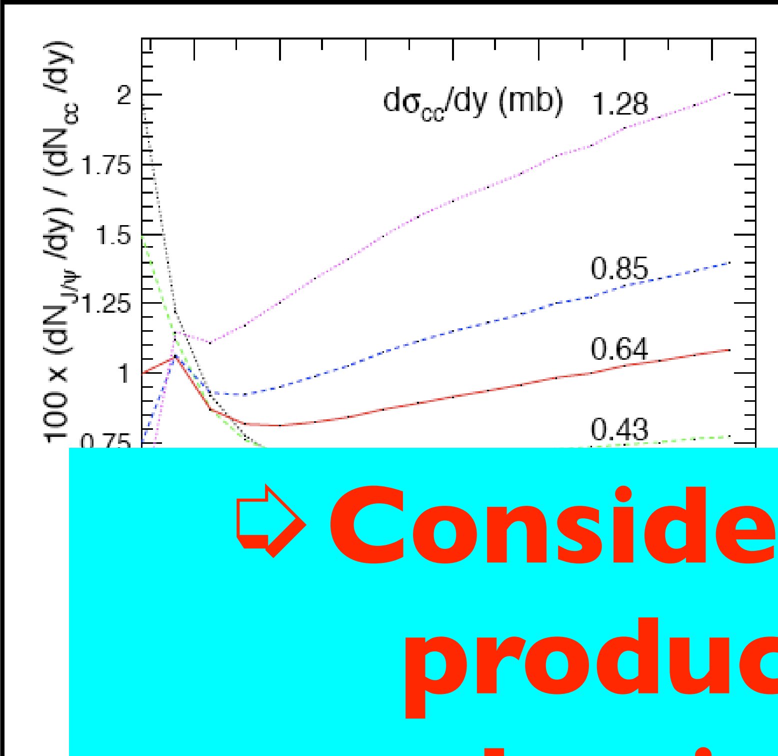


Vogt: pT-dependent screening, no regeneration; H. Liu et al., suppression at larger pT.

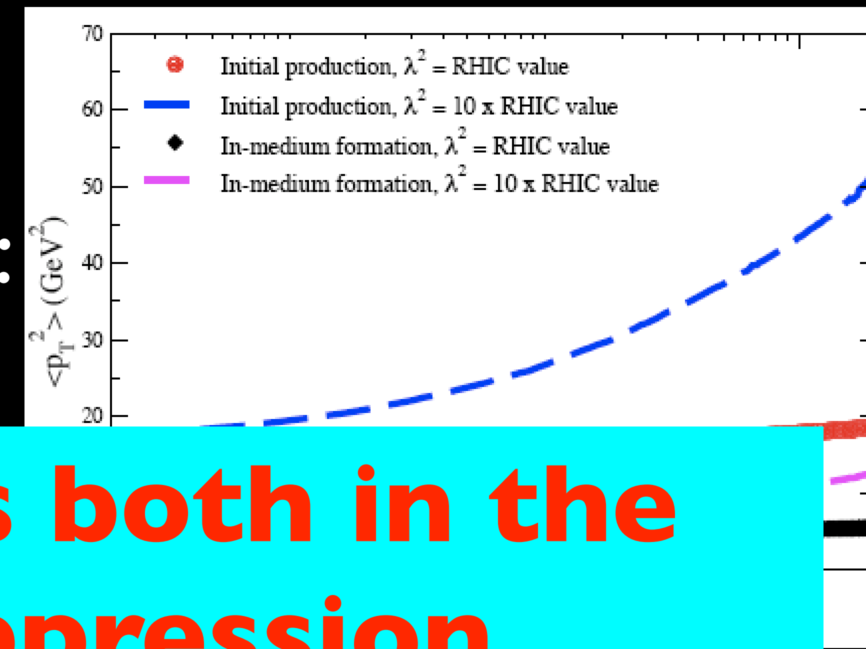


Capella et al., 0712.4331, comovers+reco.

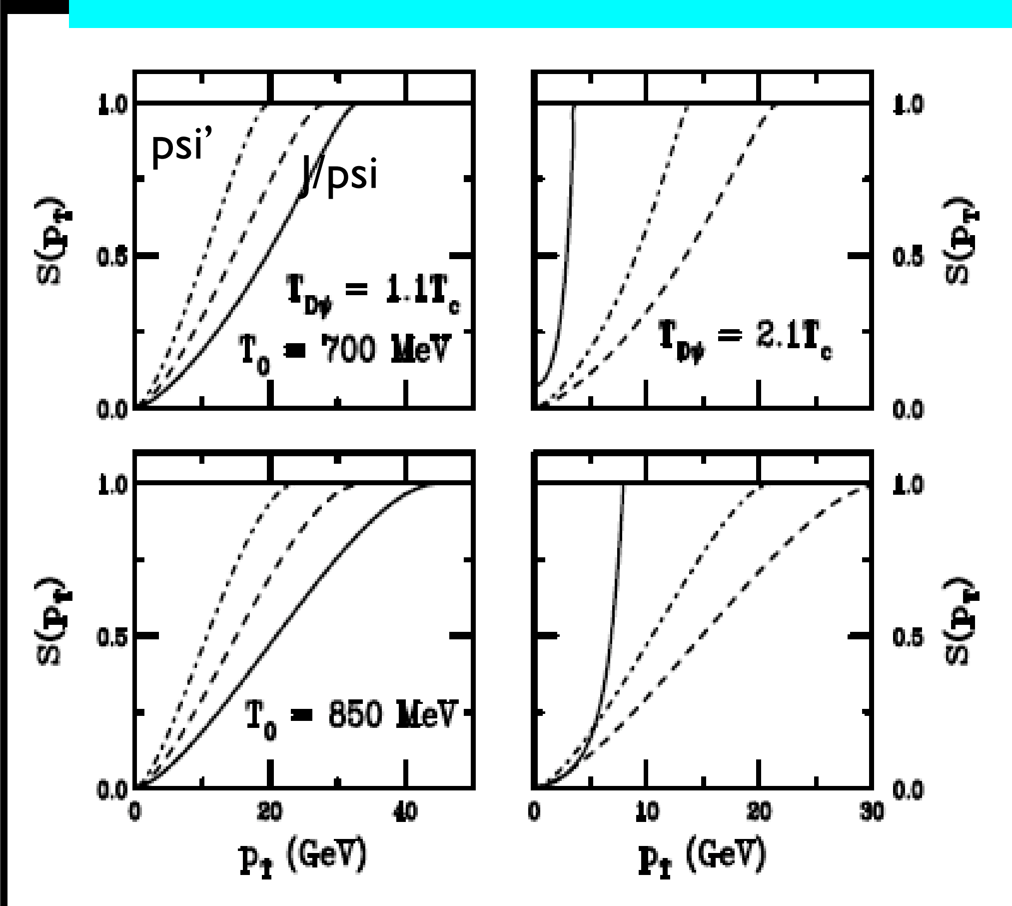
B.2. HQ and quarkonium: quarkonia suppr.



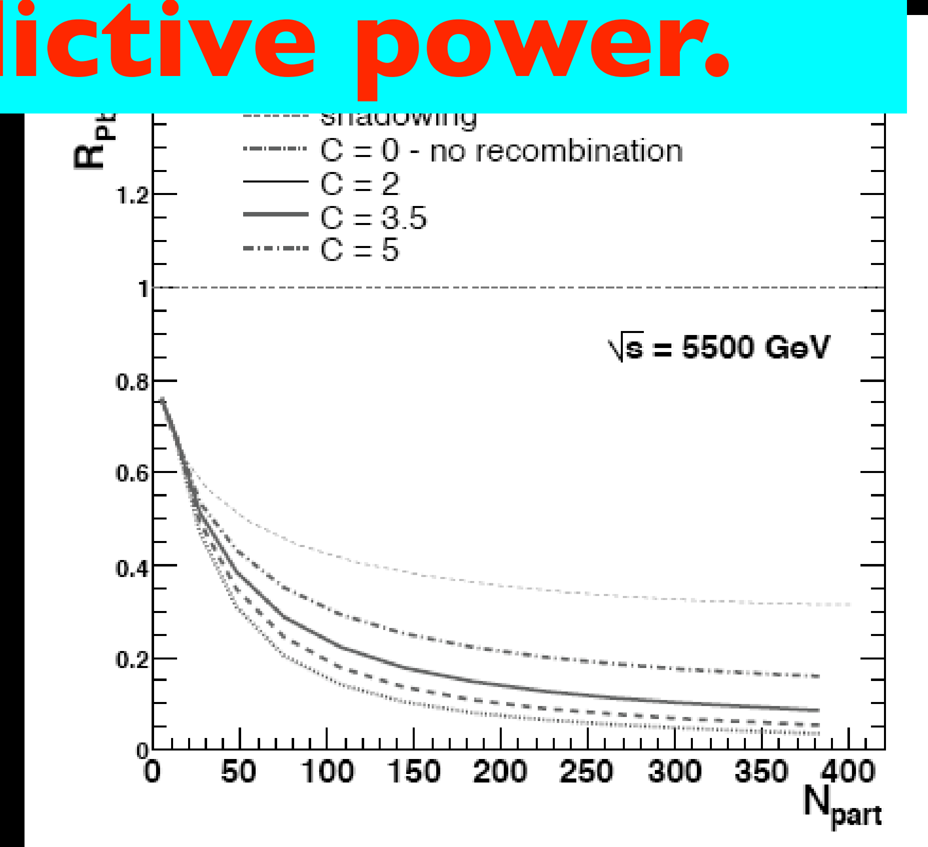
Andronic et al.: dependence on charm cross section; Thews et al.: p_T-broadening to verify



➪ Considerable uncertainties both in the production and in the suppression mechanisms limit our predictive power.

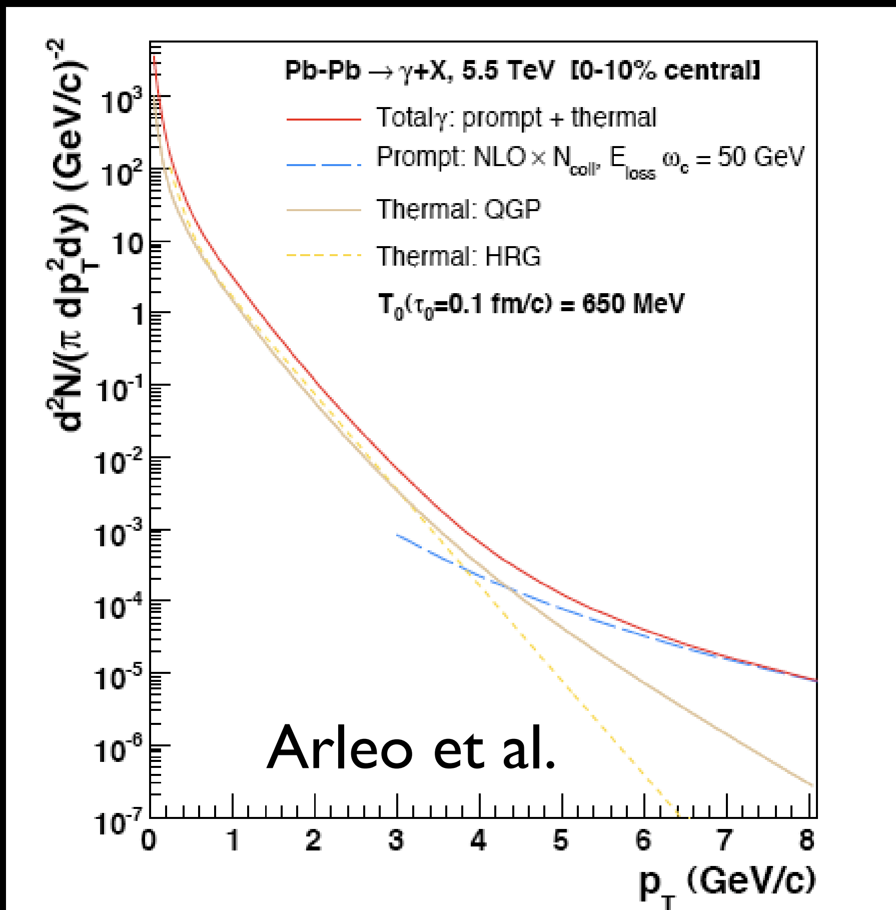


Vogt: p_T-dependent screening, no regeneration; H. Liu et al., suppression at larger p_T.



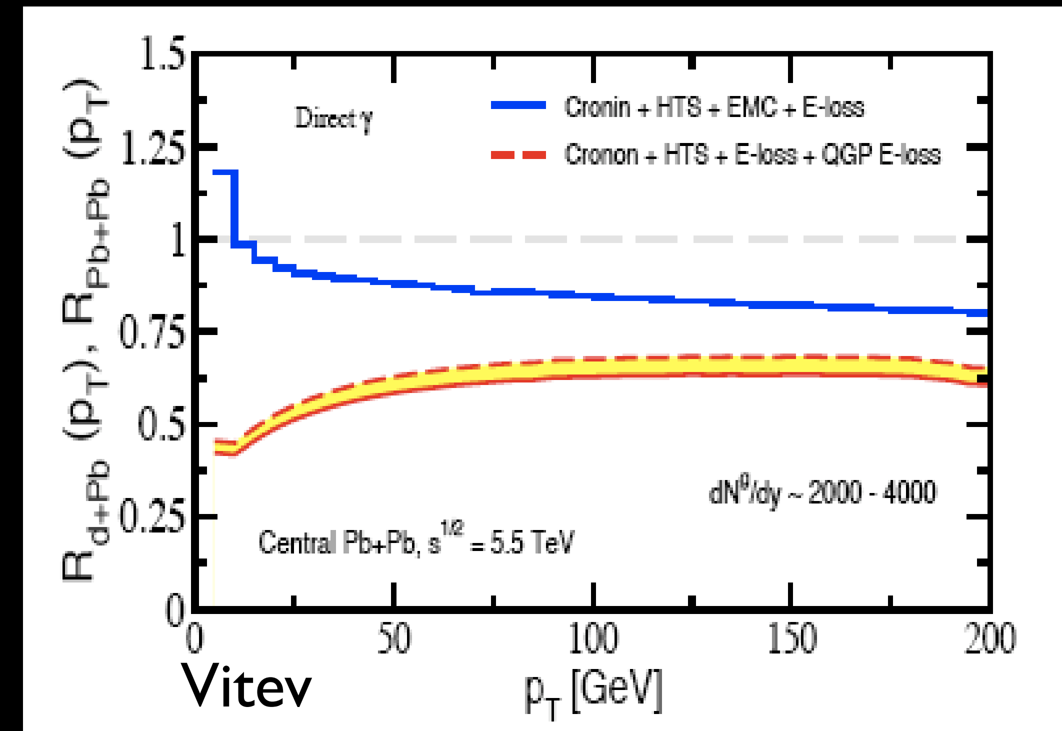
Capella et al., 0712.4331, comovers+reco.

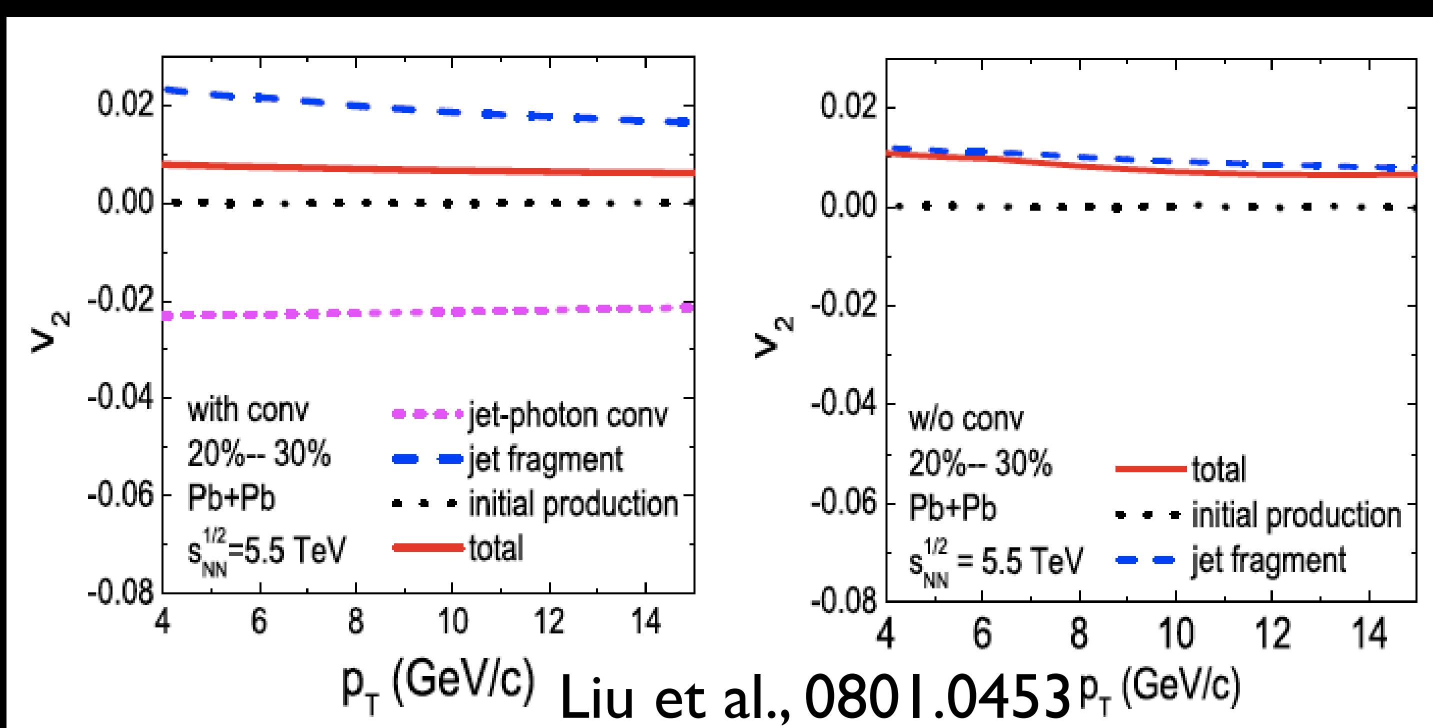
B.3. Leptonic probes and photons: photons

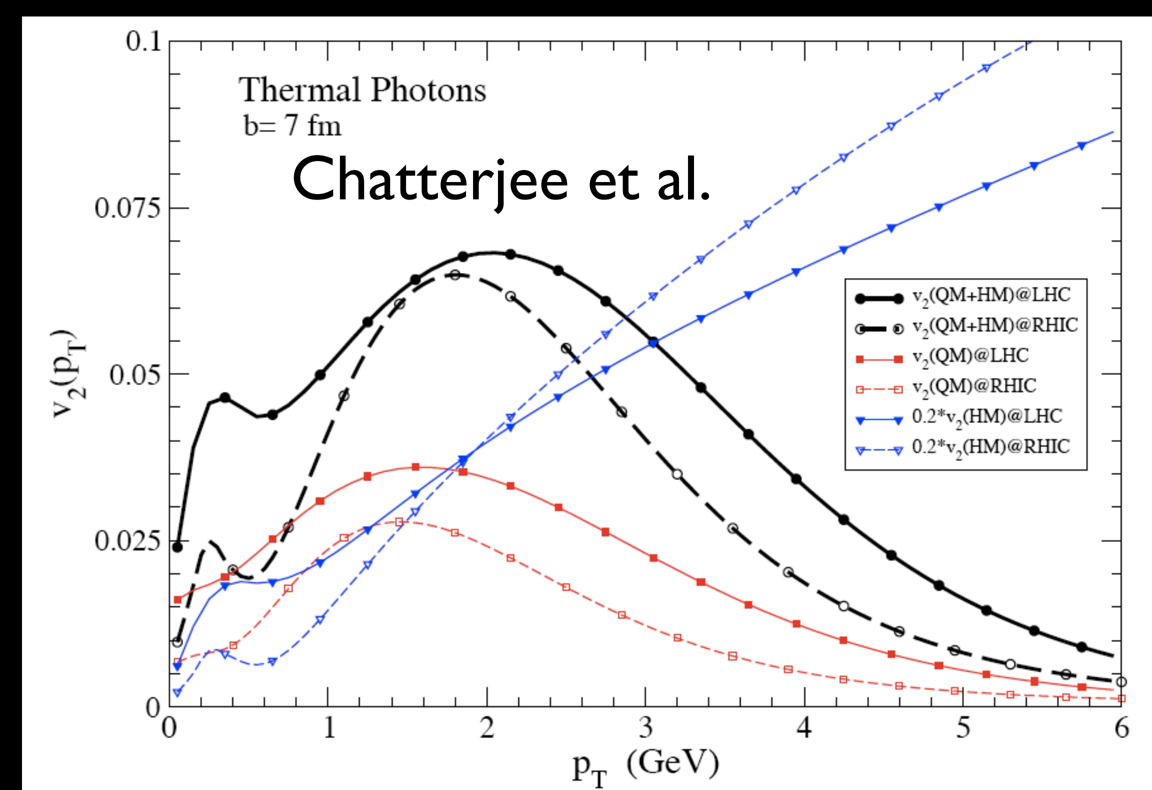


High p_T: quenching in fragmentation (also Arleo).

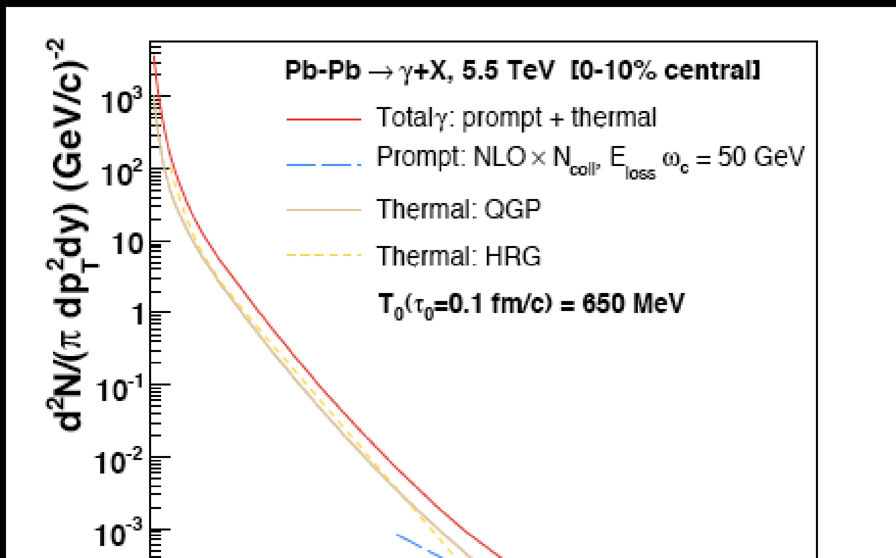
Low p_T: new effects e.g. conversions, thermal,... expected (also Rezaeian et al.).





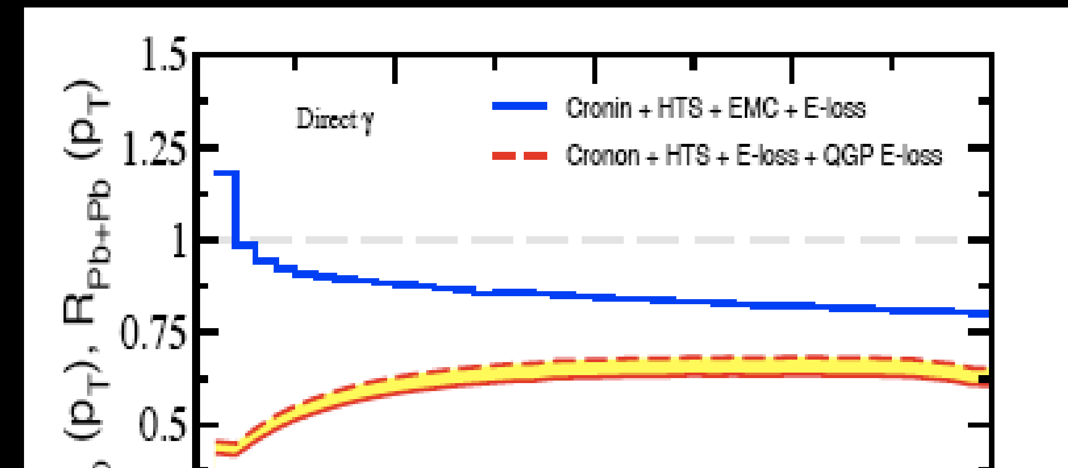


B.3. Leptonic probes and photons: photons



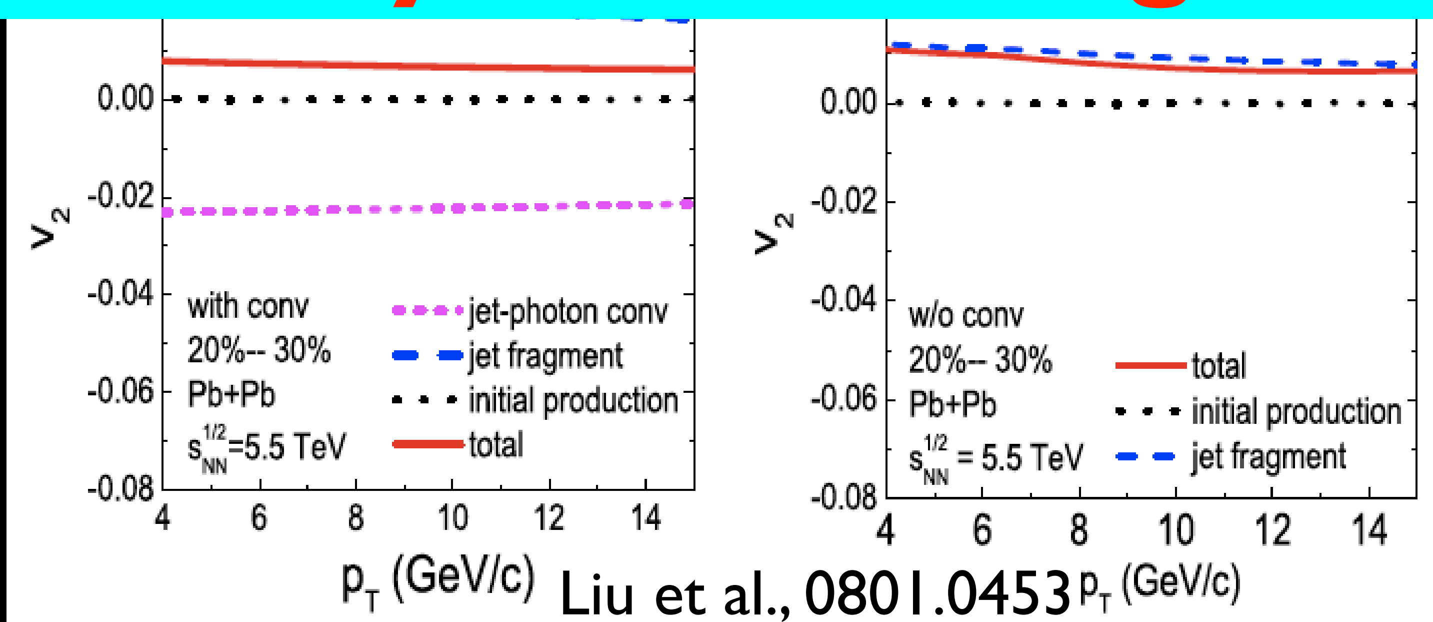
High p_T: quenching in fragmentation (also Arleo).

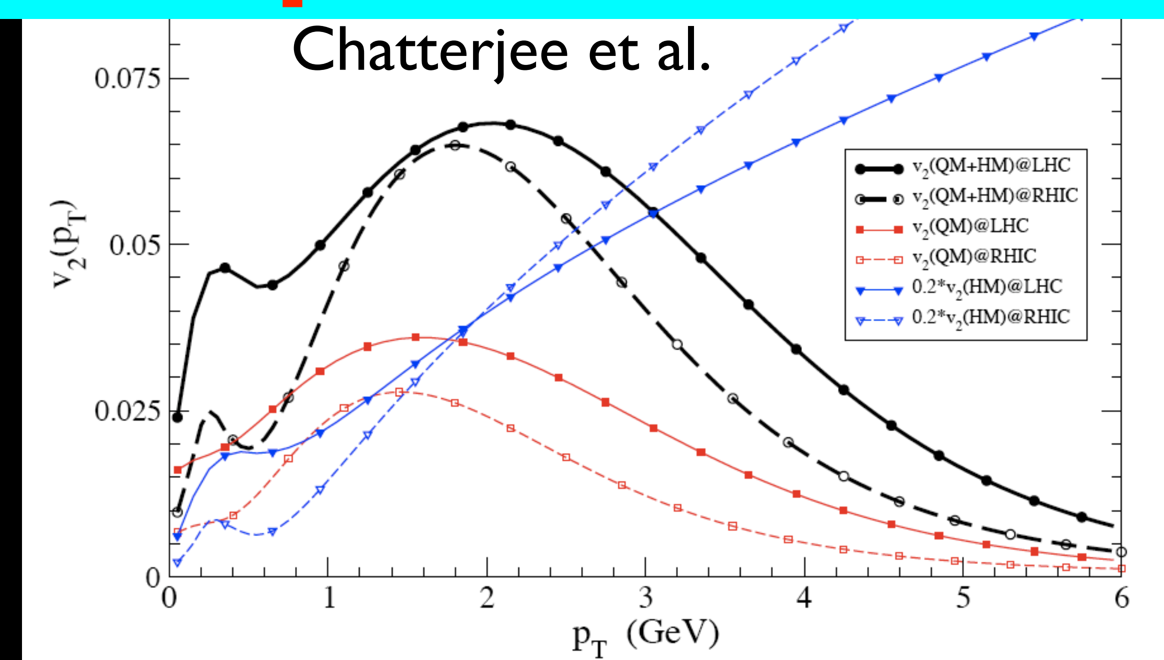
Low p_T: new effects e.g.



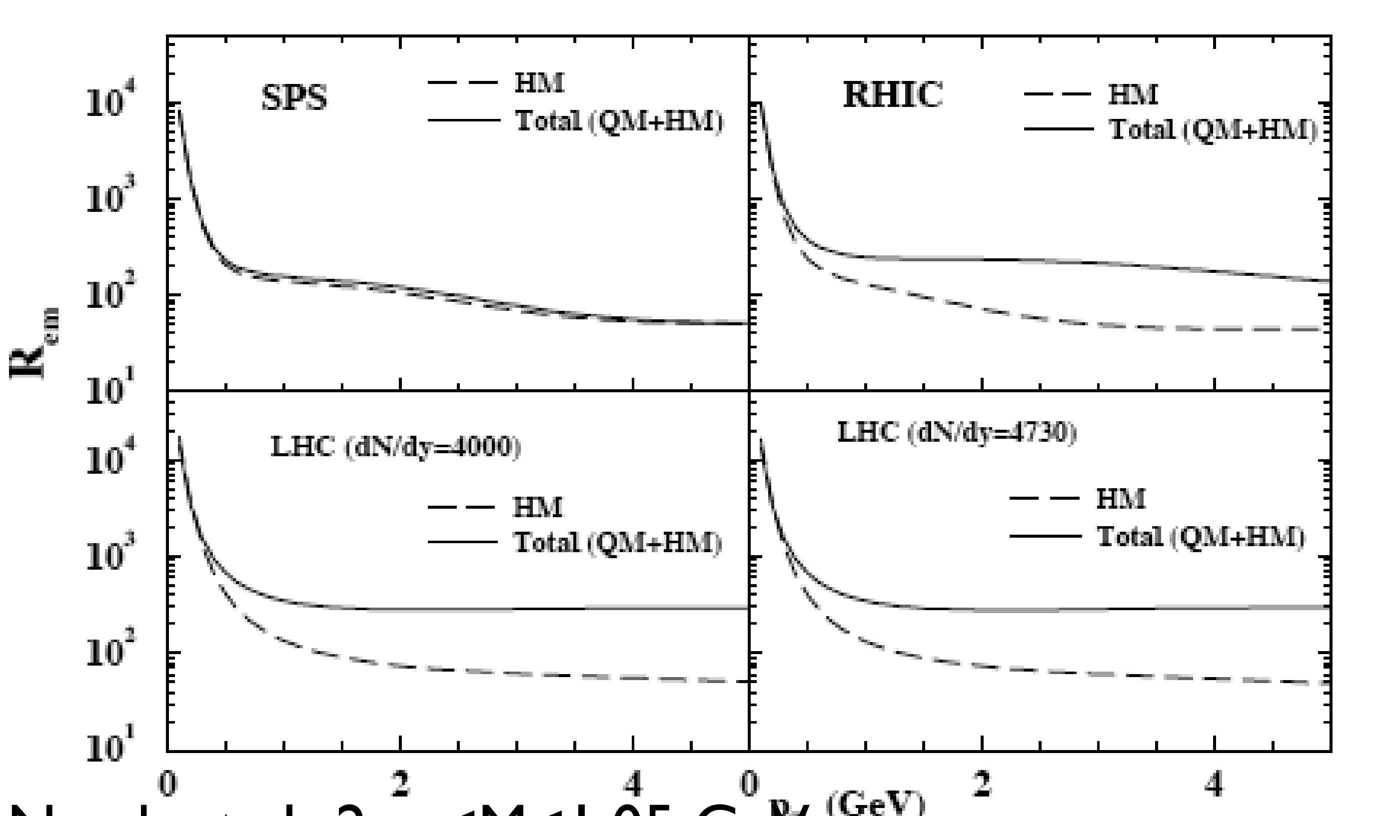
⇨ At the LHC, all the regions up to very high p_T can be studied.

⇨ Control of the benchmark, from pp to PbPb, key to disentangle thermal production.





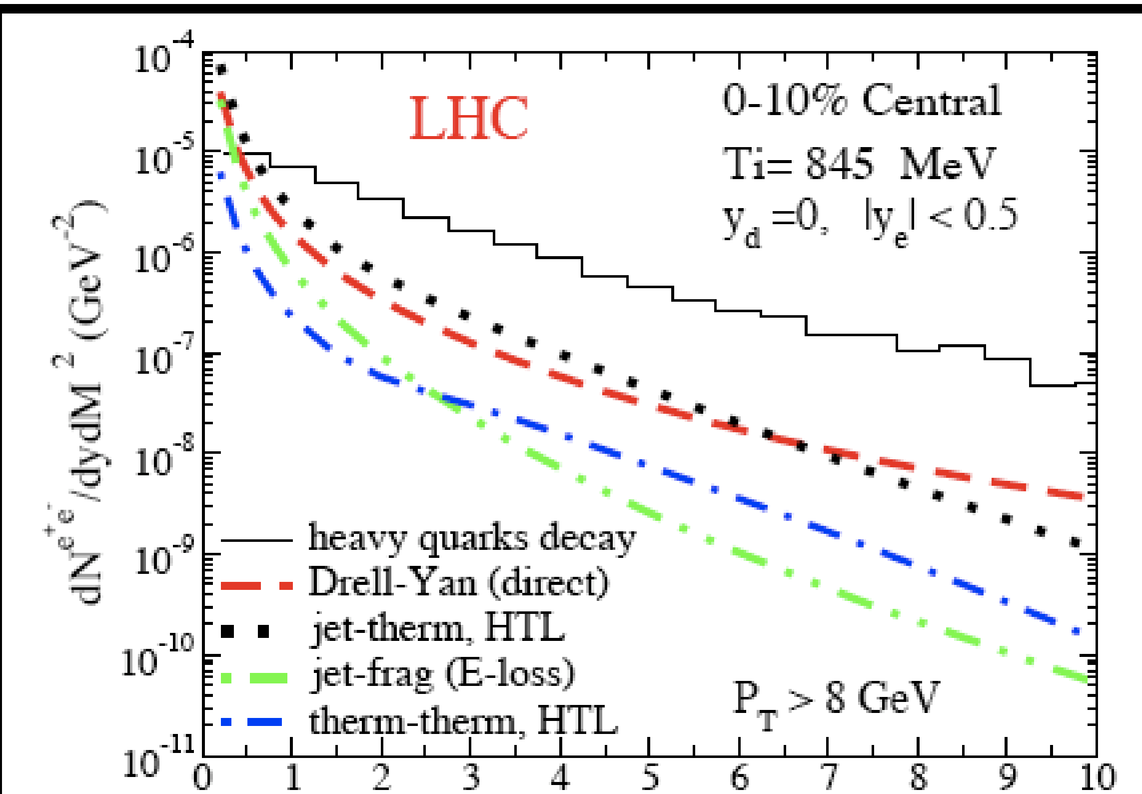
B.3. Leptonic probes and photons: dileptons



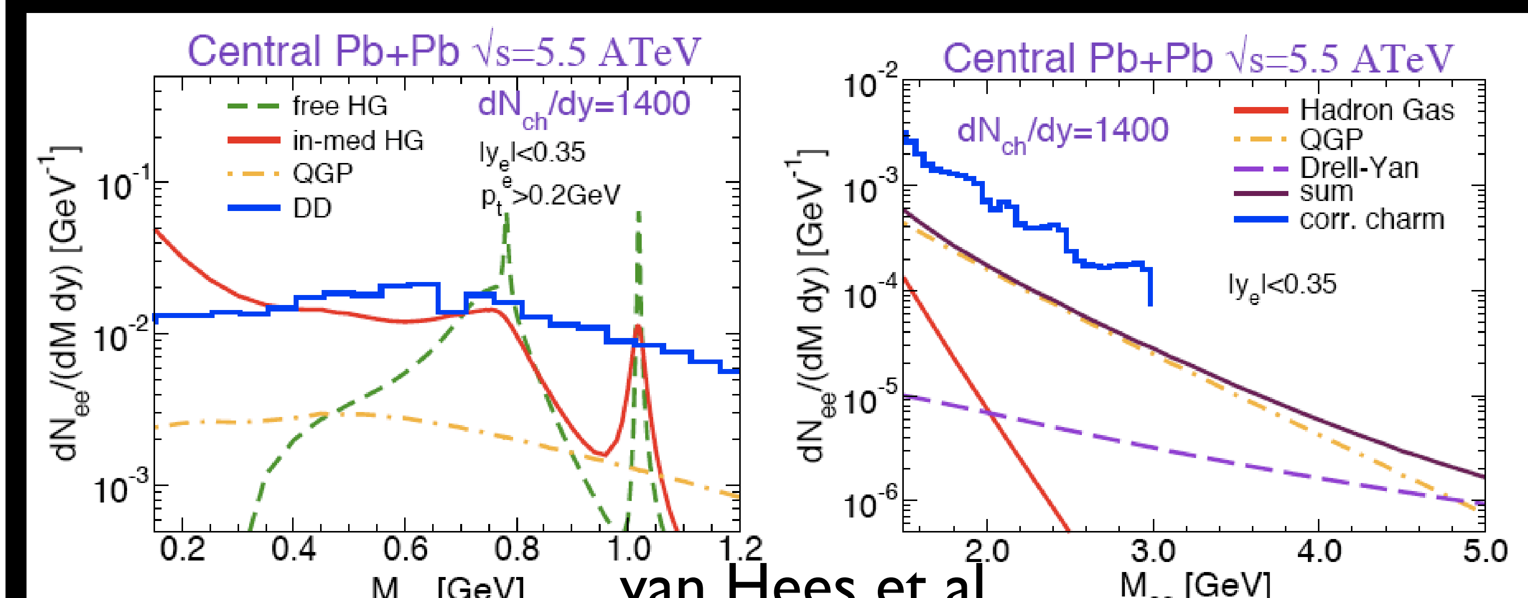
Nayak et al., $2m_\pi < M < 1.05$ GeV

Ratio γ/γ^* shows a plateau at large p_T of thermal origin, independently of details of expansion, EOS,...

Dremin: Cherenkov radiation as the origin of the 'broadening' of the ρ.

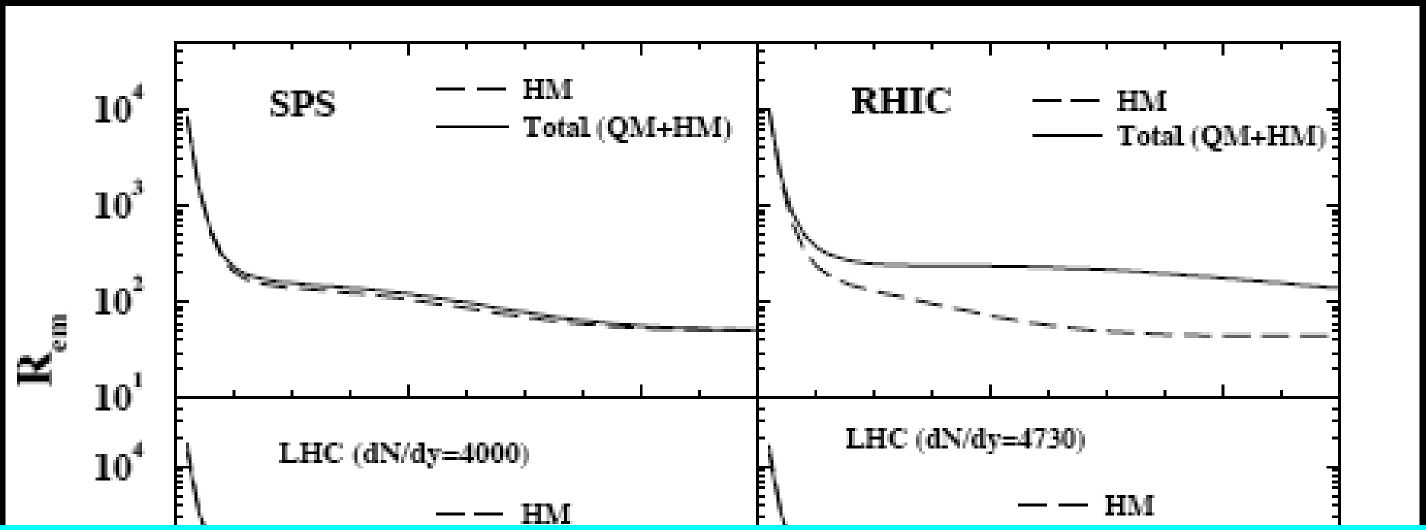


dN/dy=5625 Fries et al.



van Hees et al.

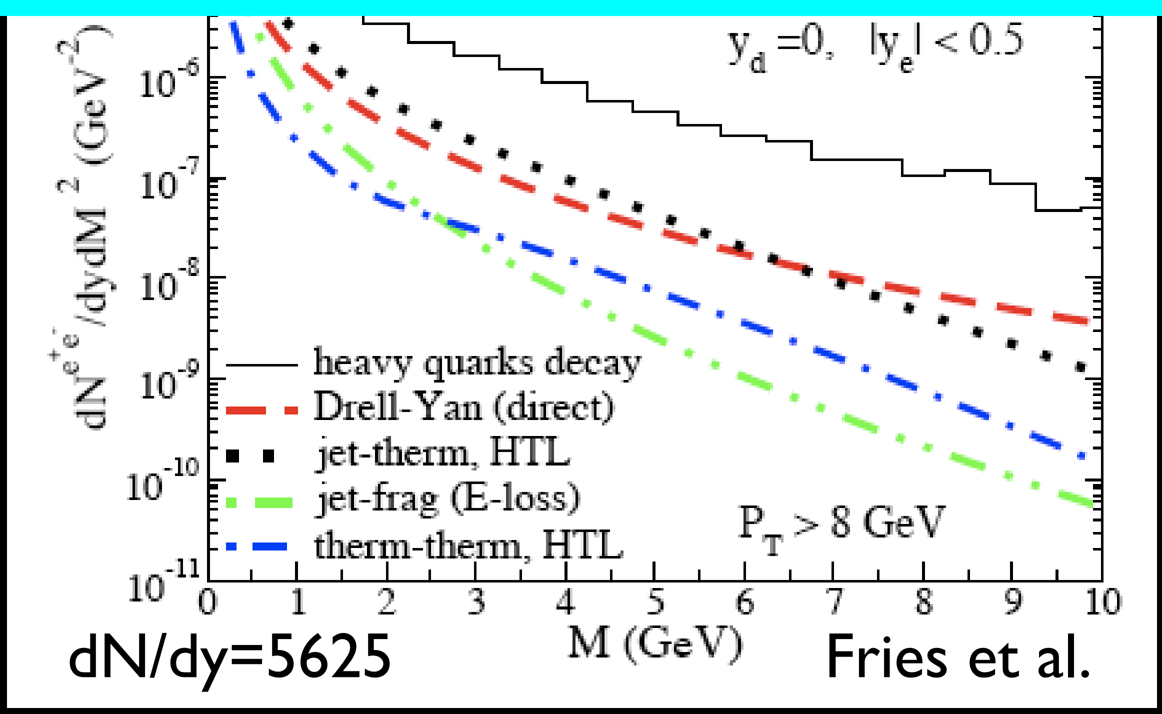
B.3. Leptonic probes and photons: dileptons

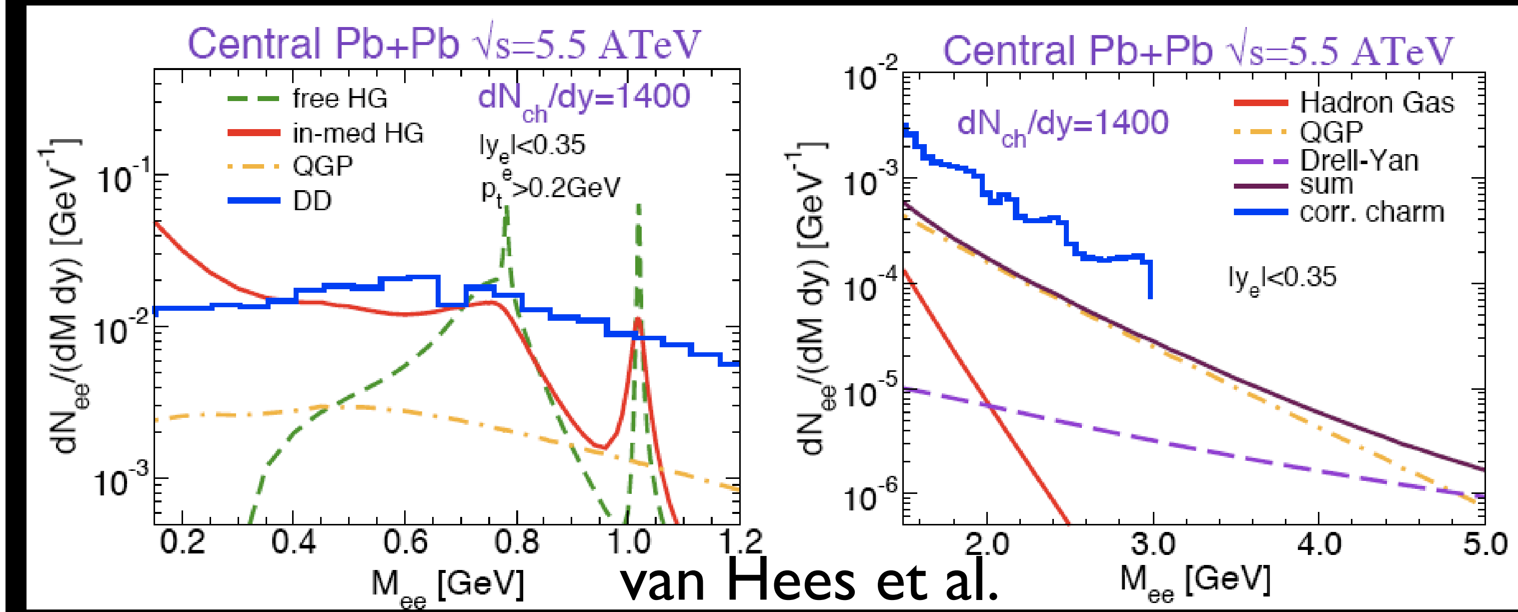


Ratio γ/γ* shows a plateau at large p_T of thermal origin, independently of details of expansion, EOS,...

➪ **Both low and high M and p_T required to disentangle different mechanisms.**

➪ **But the huge HQ contribution looks really challenging.**





RHIC-tested models face the LHC era

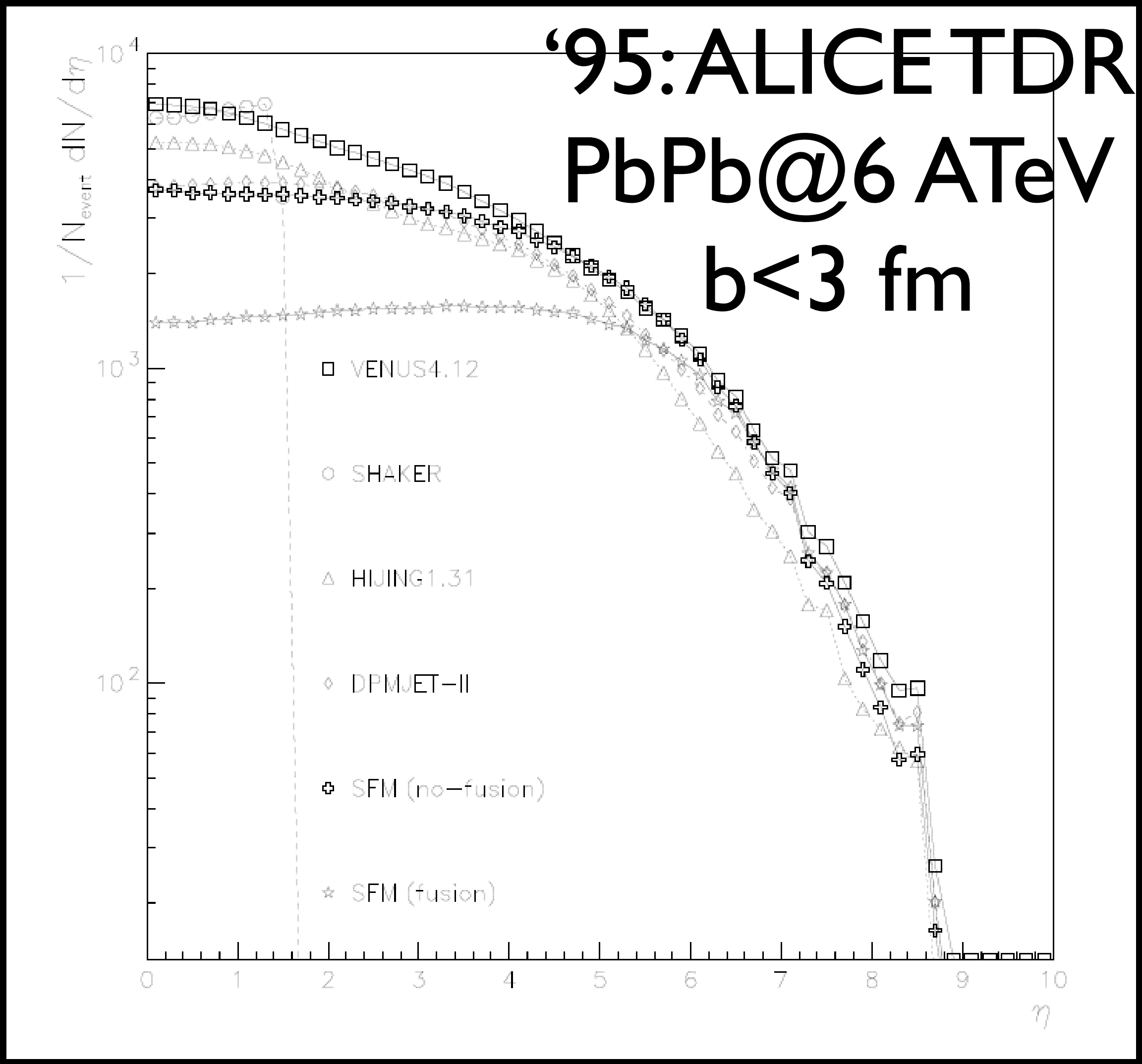
Observable at RHIC	Standard interpretation	Prediction for the LHC
Low multiplicity	Strong coherence in particle production	$dN_{ch}/d\eta\|_{\eta=0}<2000$ for central collisions
v_2 in agreement with ideal hydro	Almost ideal fluid	Similar or smaller $v_2(p_T)$
Strong jet quenching	Opaque medium	R_{AA}(20 GeV)~0.1-0.2 for π^0

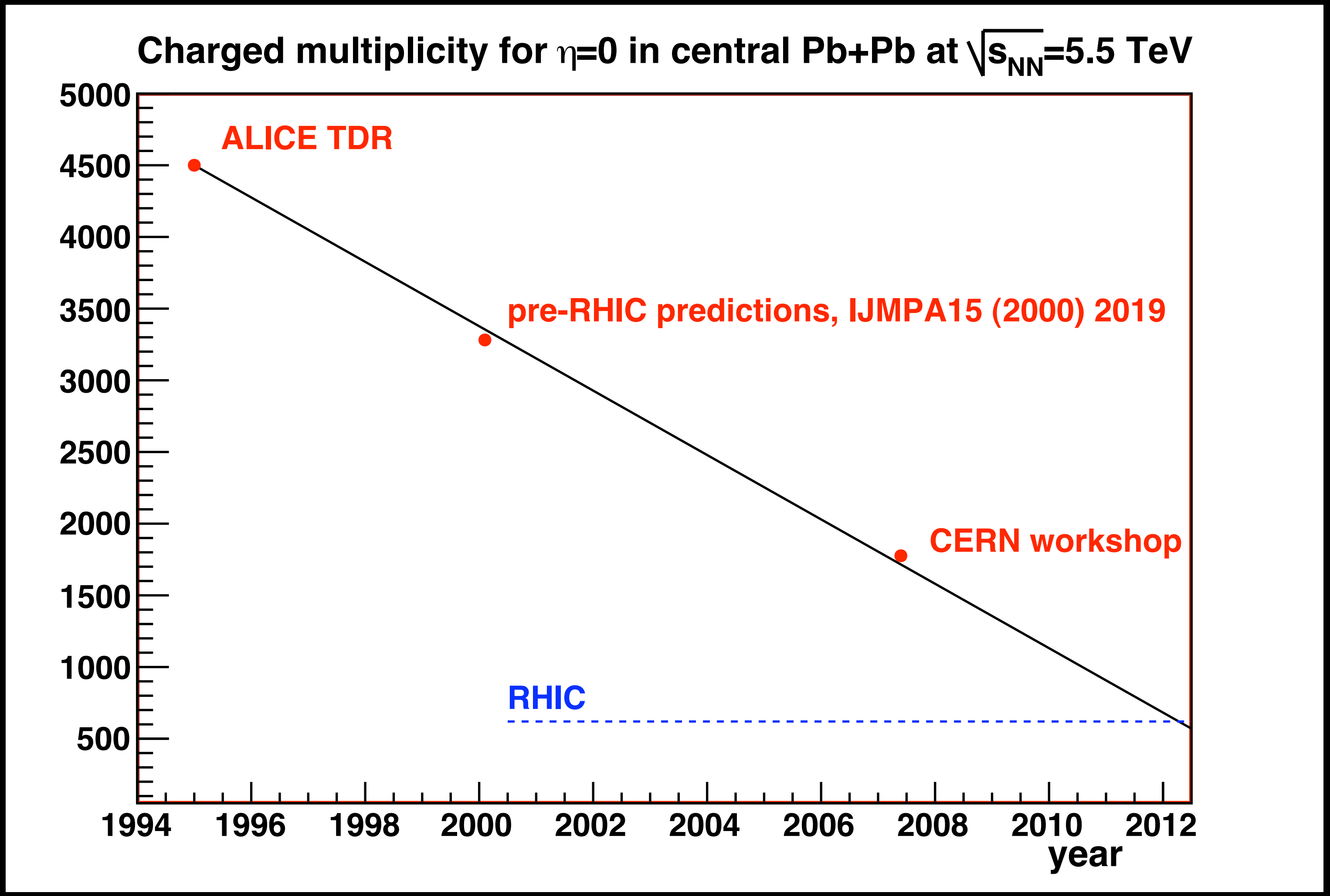
* This picture has motivated new theoretical developments: application of AdS/CFT, early thermalization, viscous hydro, CGC,...

* Major deviations from expectations will enlarge our understanding of Ultra-Relativistic Heavy-Ion Collisions: naive extrapolations tend to disagree with those from successful models at RHIC.

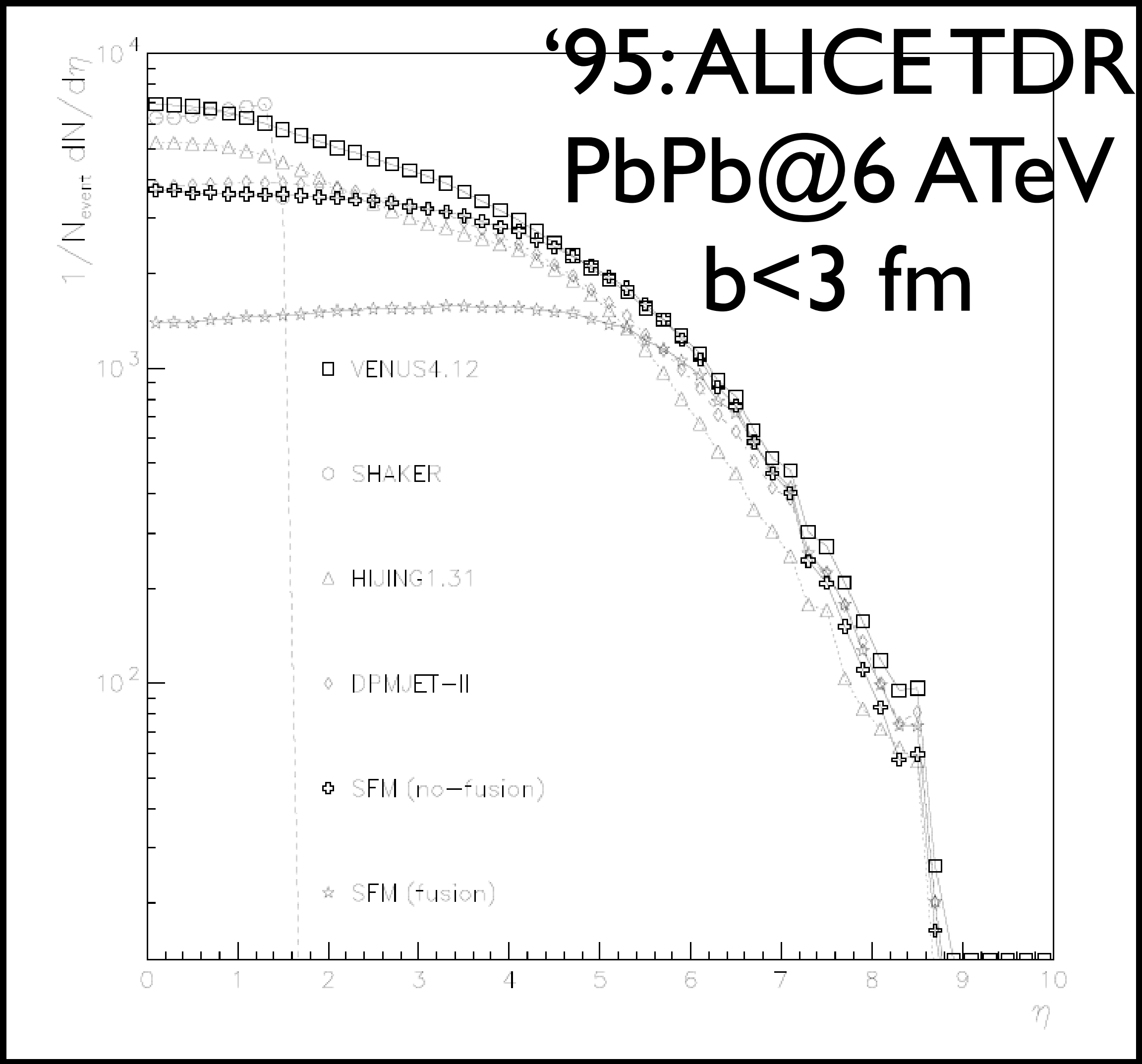
* New experimental observables at LHC: higher p_T, jets, higher quarkonium states,... demand new theoretical tools.

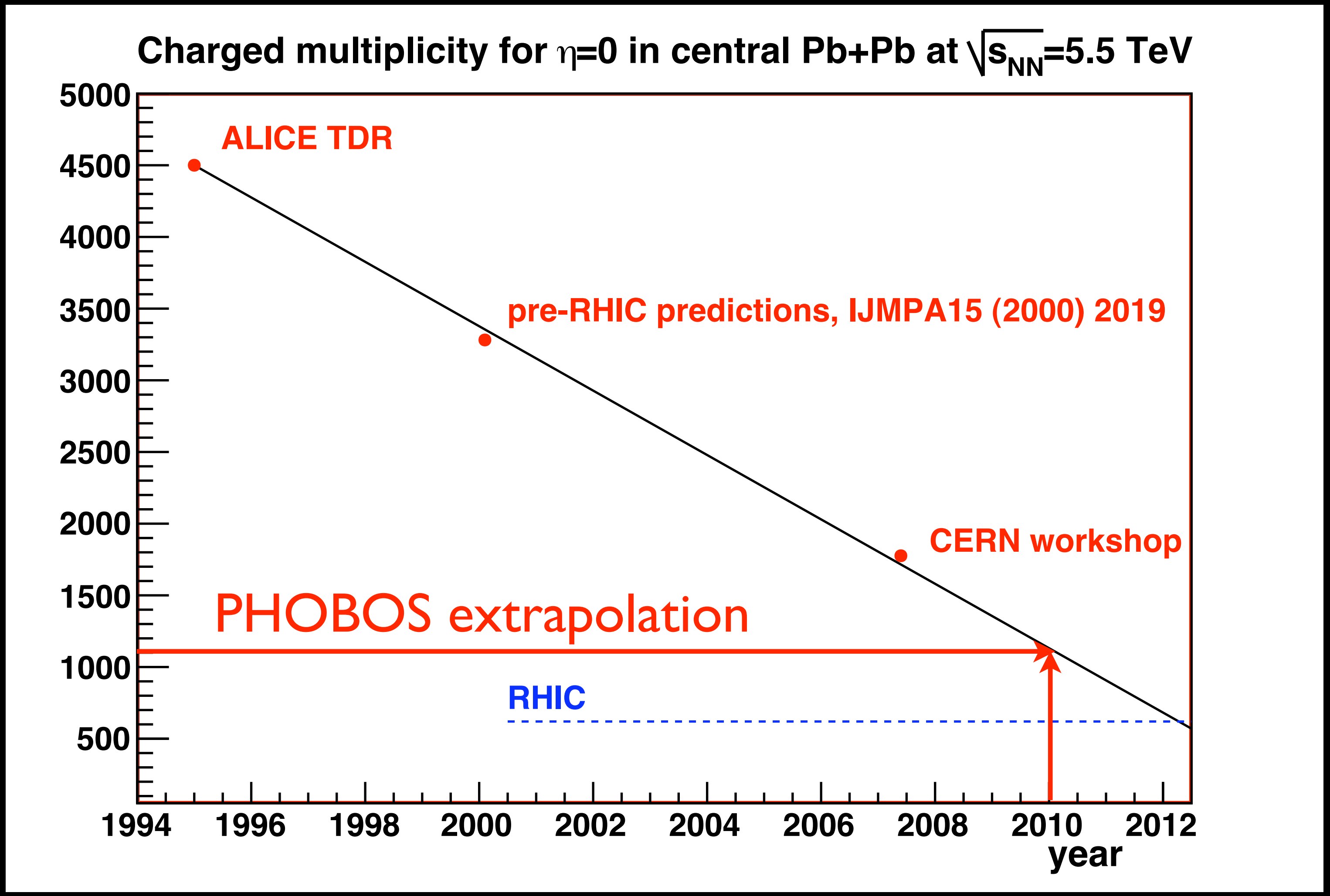
To conclude: a little bit of history



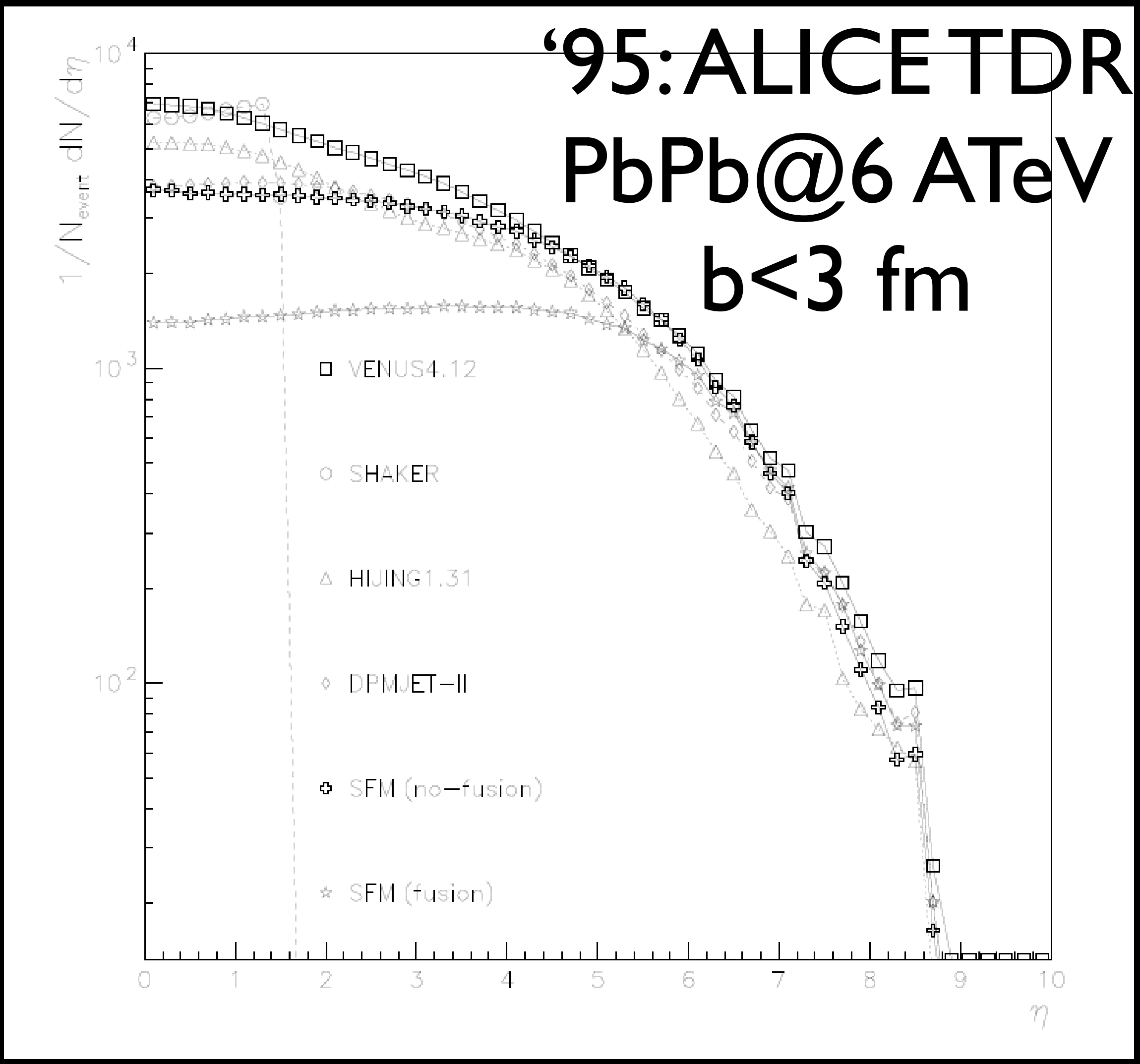


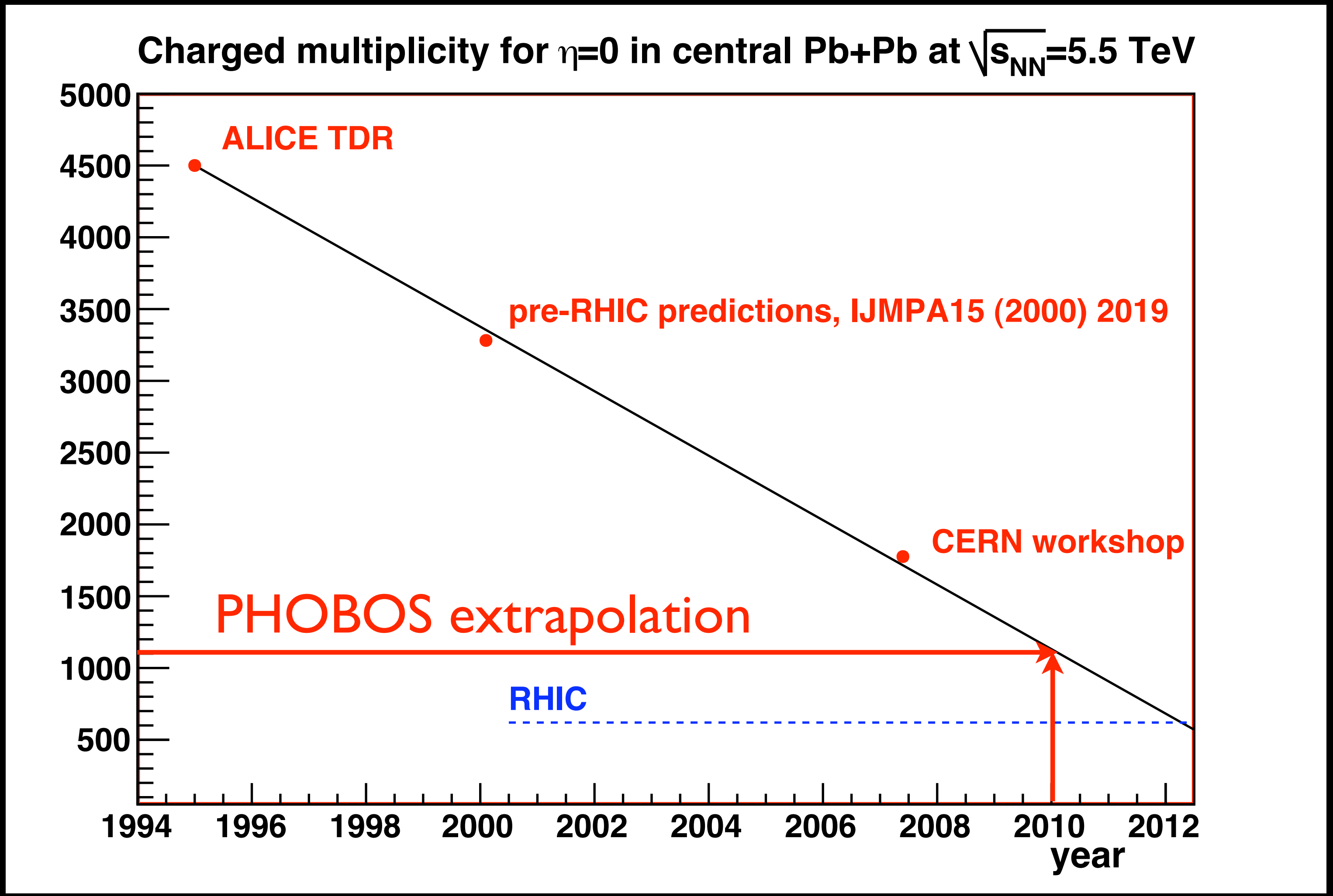
To conclude: a little bit of history





To conclude: a little bit of history

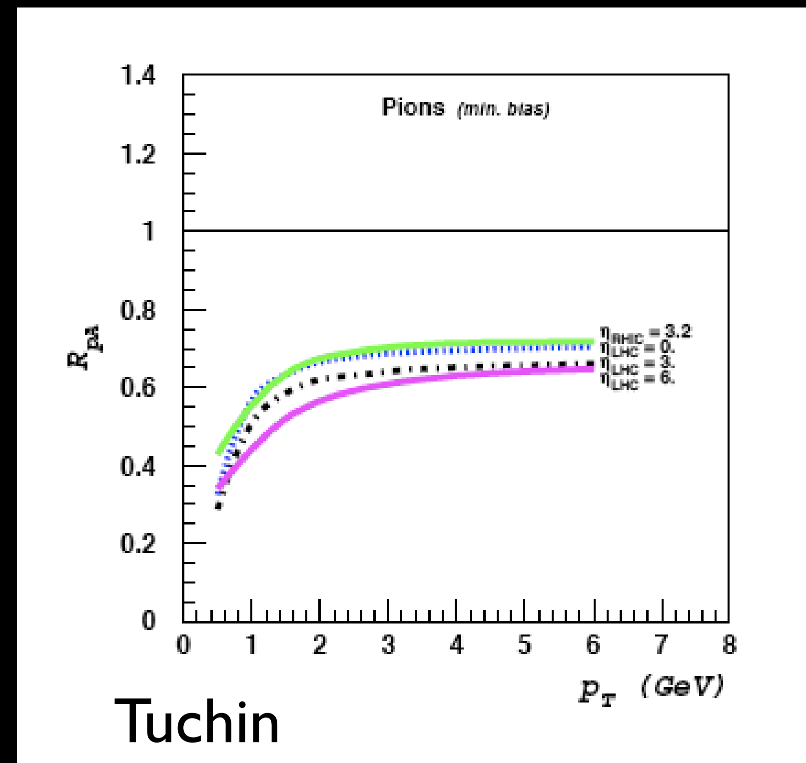


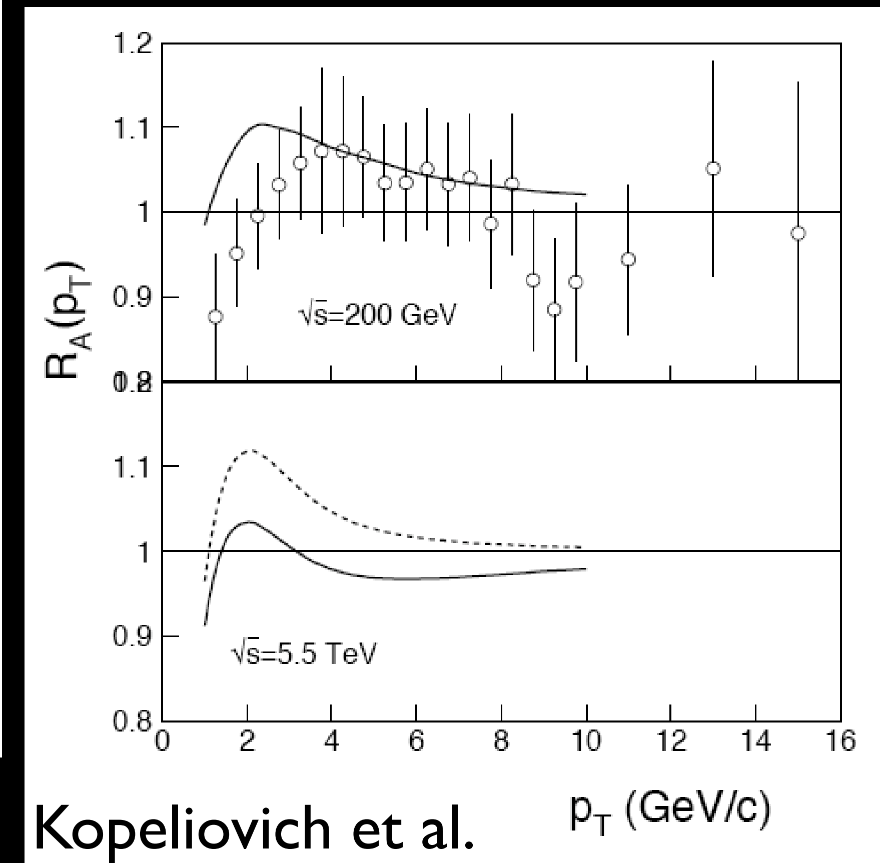


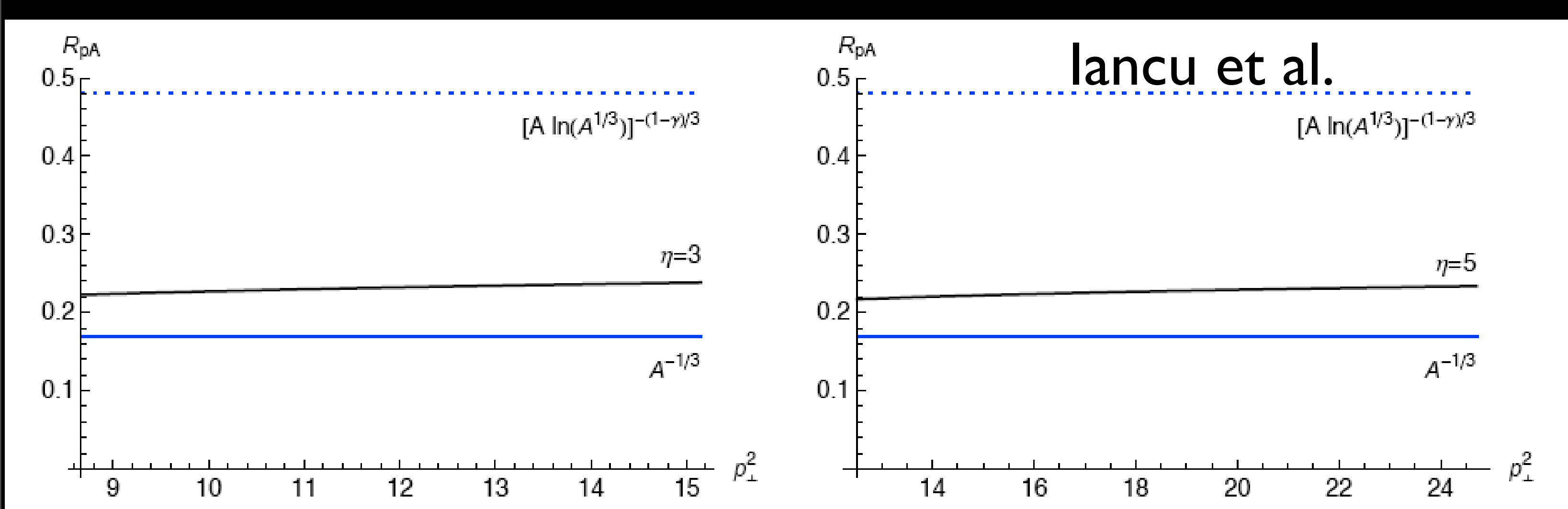
Thanks to J. Albacete, F. Bopp, W. Busza, L. Cunqueiro, A. Dainese, A. El, K. Eskola, U. Heinz, C.-M. Ko, I. Lokhtin, G. Milhano, C. Pajares, V. Pantuev, T. Renk, V. Topor Pop, R. Venugopalan, I. Vitev, X. N. Wang, K. Werner and G. Wolschin for feedback on their predictions, and to J. Albacete, J. Casalderrey-Solana, K. Eskola, E. Ferreiro, U. Heinz, P. Jacobs, C. Salgado, X. N. Wang and U. Wiedemann for discussions on the talk.

Backup I: pA

Forward $R_{pA}(p_T)$ as a probe of high density dynamics: saturation for light (Armesto et al., Boer et al.) and heavy (Fujii et al., Tuchin), or absence of saturation (Arsene et al.); Λ polarization (Boer et al.).

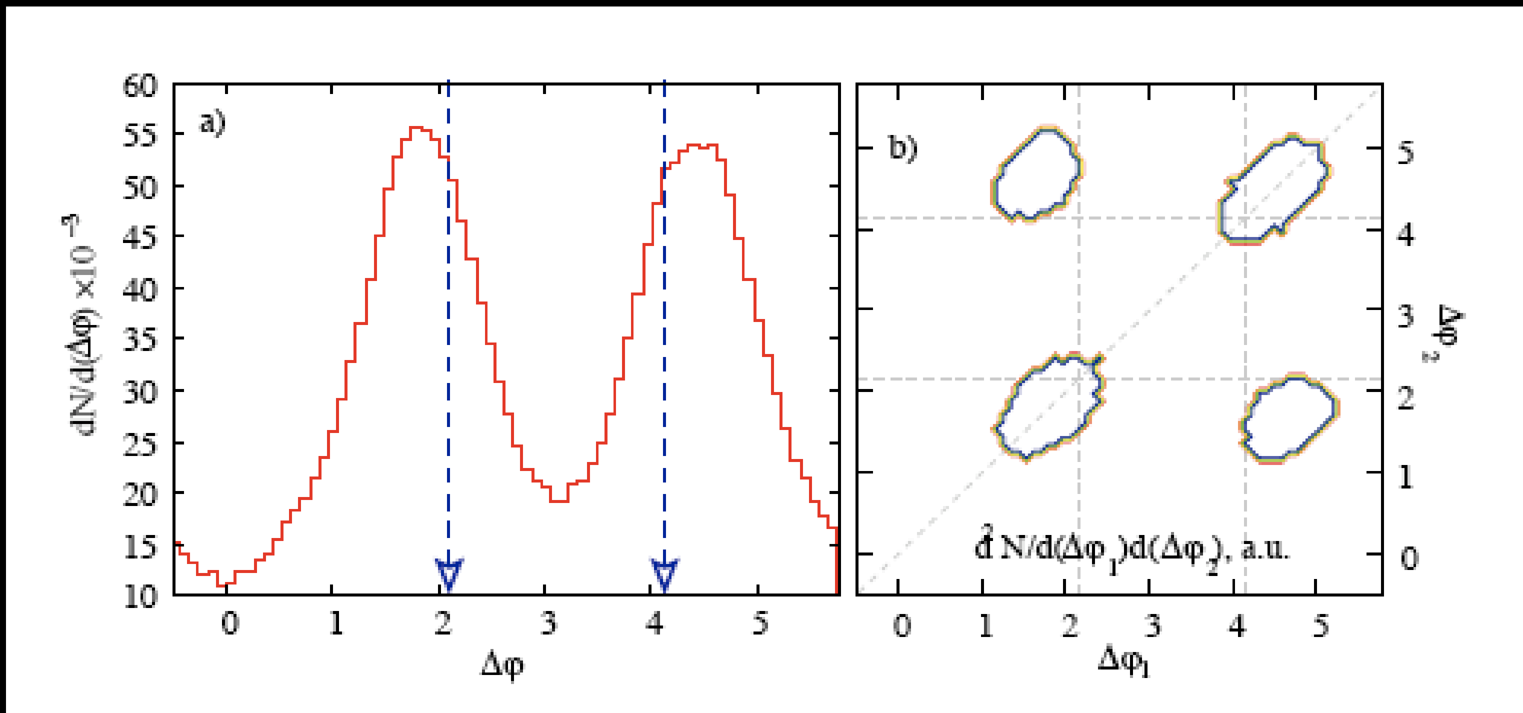




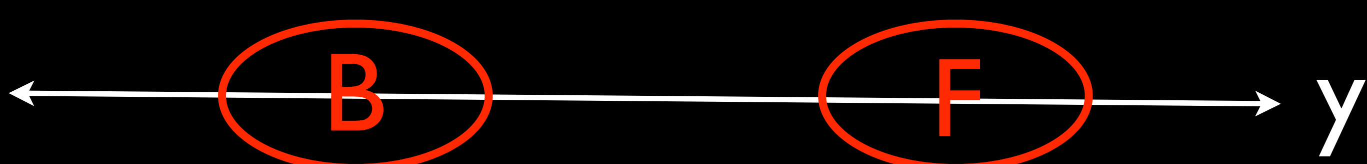


Within CGC, total shadowing due to fluctuations (Kozlov et al.) or running coupling effects.

A.4. Correlations at low p_T (II):



Bauchle et al., Mach cones in hydro, peak displaced from naive expectation; Betz et al., gradual energy deposition required. Other mechanism possible: Cherenkov (Dremin), and instabilities (Mannarelli et al.) - unstable modes for jets with speed larger than c_s, which peak at larger angles for larger speed.



$$\langle n_B \rangle_F = a + b n_F \,, \quad b \equiv D^2_{FB}/D^2_{FF} \,,$$

$$b = \frac{\langle n_B \rangle / \langle n_F \rangle}{1 + K/\langle n_F \rangle}$$

$$1/K = D^2_{FB}/\langle n_F \rangle \langle n_B \rangle$$

Dias de Deus et al.: FB correlations may help to establish the dynamics of particle production.

Backup II: fluctuations

$$\Psi^{N_1}_{N_1/N_2} = \frac{dN_1}{dy} \nu^{dyn}_{N_1/N_2}$$

$$\nu^{dyn}_{N_1/N_2} = (\sigma^{dyn}_{N_1/N_2})^2 = \sigma^2_{N_1/N_2} - (\sigma^{Poisson}_{N_1/N_2})^2 =$$

$$= \frac{\langle N_1(N_1-1)\rangle}{\langle N_1\rangle^2} + \frac{\langle N_2(N_2-1)\rangle}{\langle N_2\rangle^2} - 2\frac{\langle N_1 N_2\rangle}{\langle N_1\rangle\langle N_2\rangle}$$

Torrieri: fluctuations in particle ratios as a tool to verify the statistical model and decide which ensemble or non-eq. situation holds.

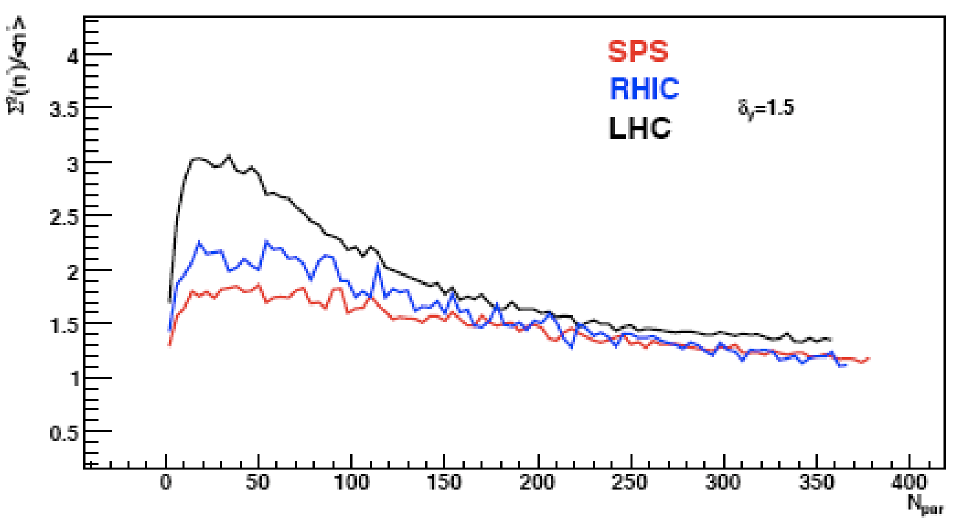
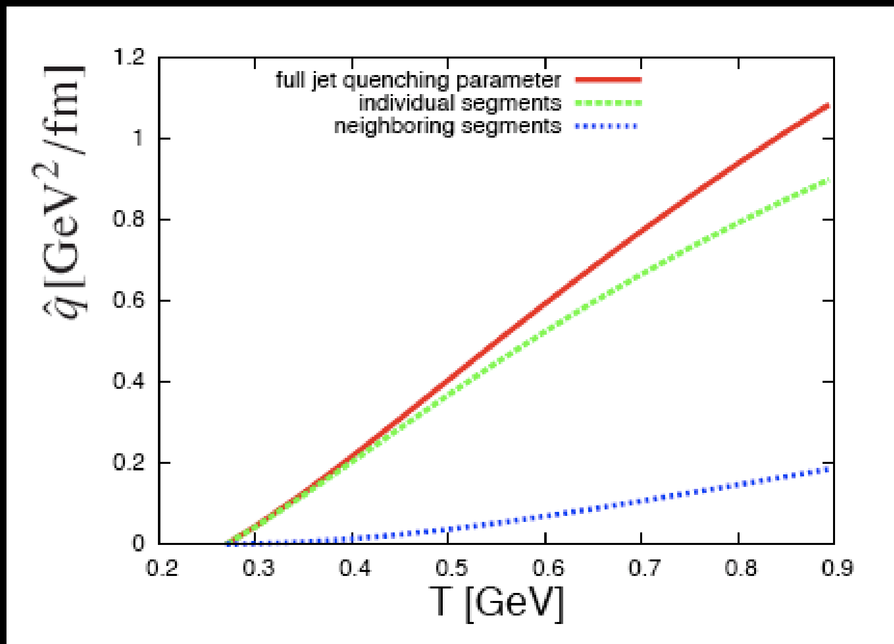


Figure 71: Scaled variance on negatively charged particles at, from up to down, LHC, RHIC and SPS.

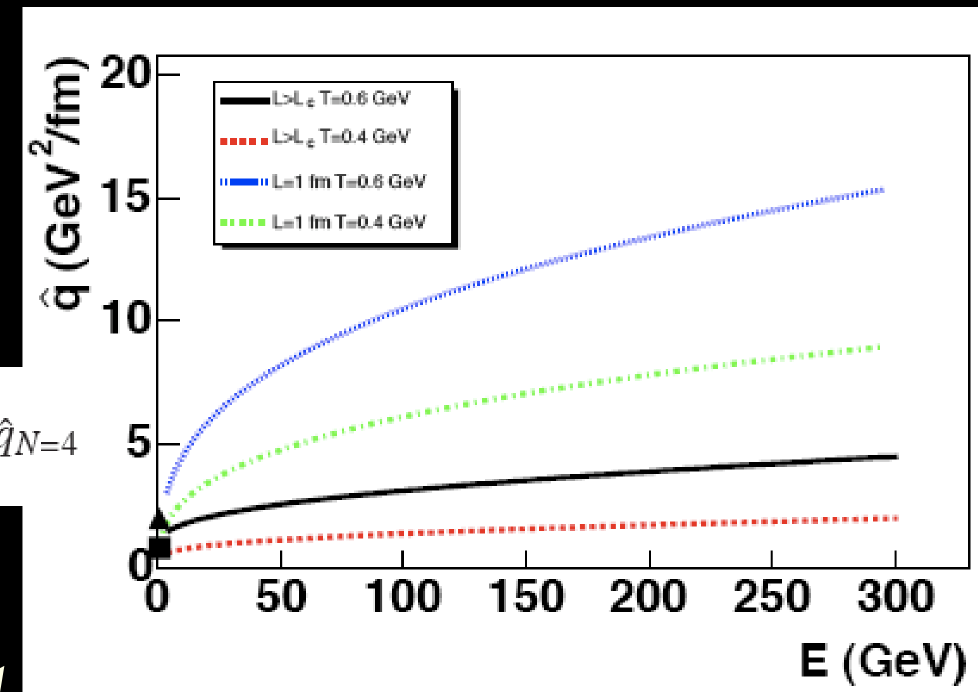
Cunqueiro et al.: multiplicity fluctuations determined by the number of coherent particle sources, possibility to verify phase transition scenarios.

B.1. High-pT observ.: theory



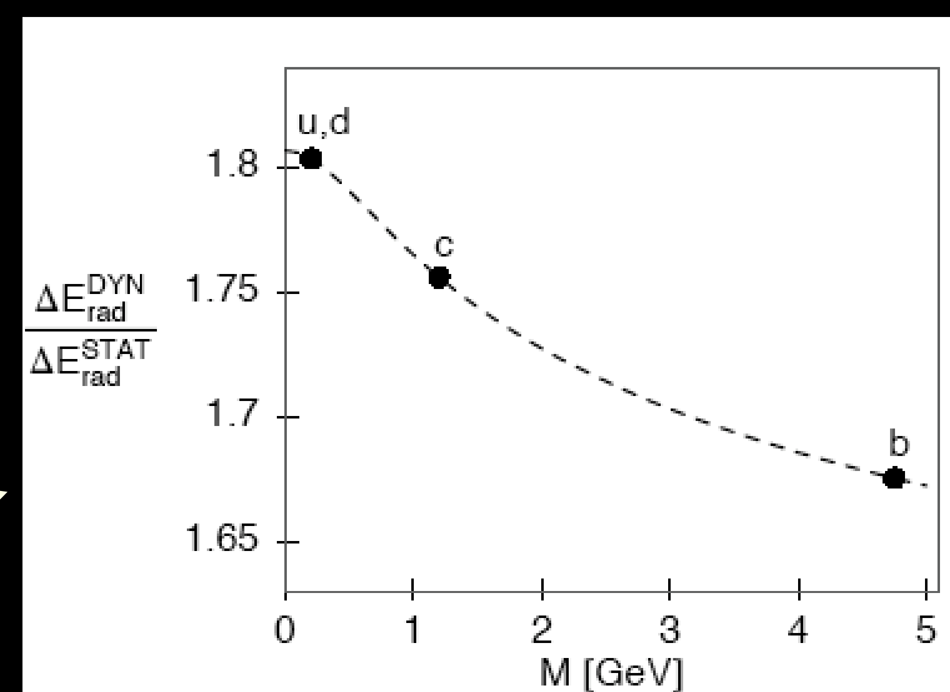
$$\hat{q}_{SYM} = \frac{\pi^{3/2}\Gamma(3/4)}{\Gamma(5/4)}\sqrt{\lambda}T^3$$

$$\hat{q}_{QCD} = \sqrt{\frac{s_{QCD}}{s_{N=4}}}\hat{q}_{N=4} = \sqrt{\frac{47.5}{120}}\hat{q}_{N=4} \simeq 0.63\,\hat{q}_{N=4}$$

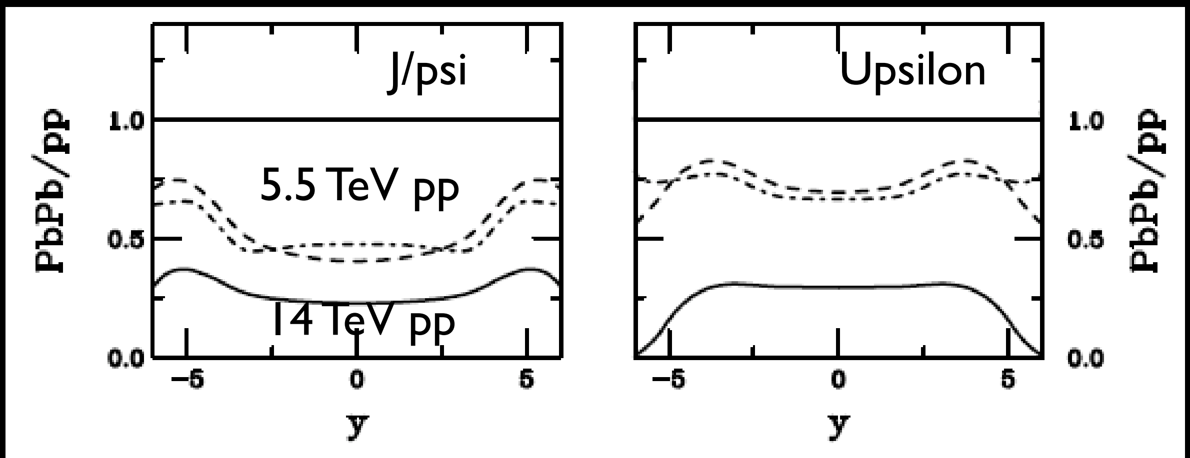


First-principle calculations of qhat in the vaccum correlator model (Antonov et al.), in N=4 SYM (H. Liu et al.) and in ThFT with coherence effects (Casalderrey et al.).

Inclusion of elastic eloss in DGLAP-like evolution (Pirner et al.) and consideration of a dynamical medium in GLV eloss (Djordjevic et al.).

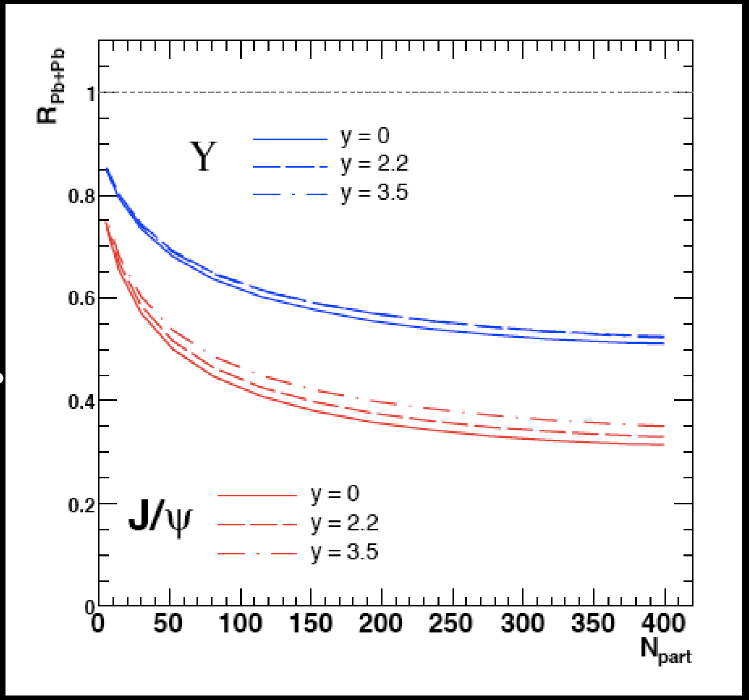


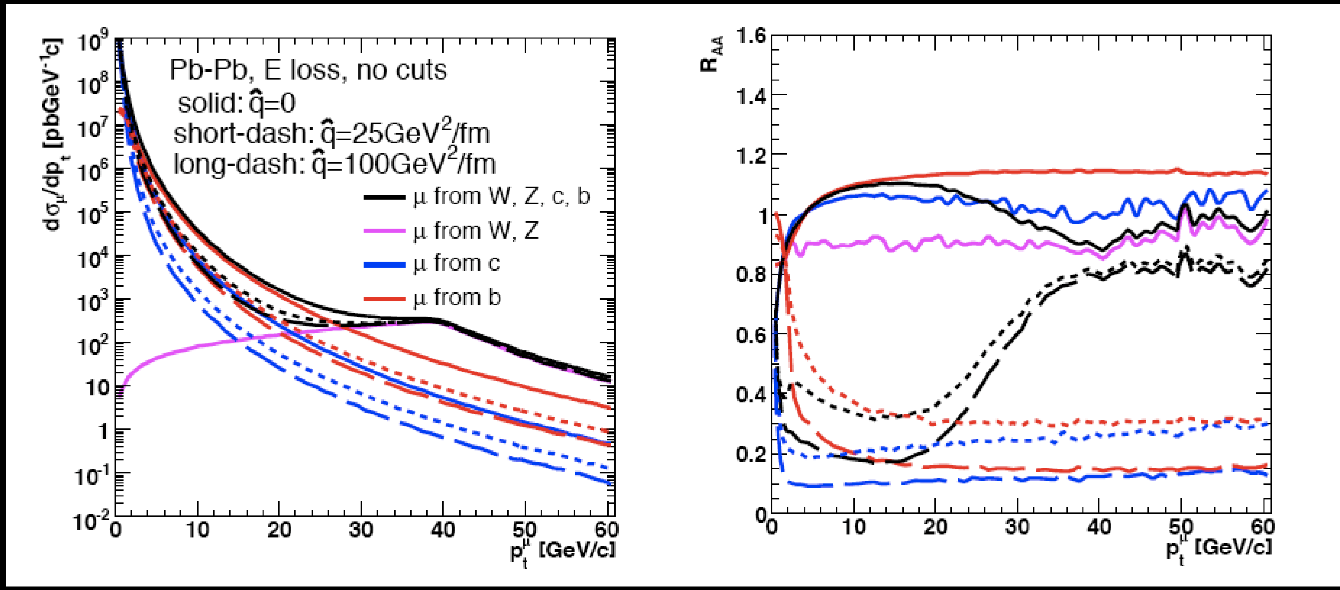
B.2. HQ and quarkonium: reference



Vogt, effect of npdf's (LT: EKS and nDSg): results very similar to other approaches.

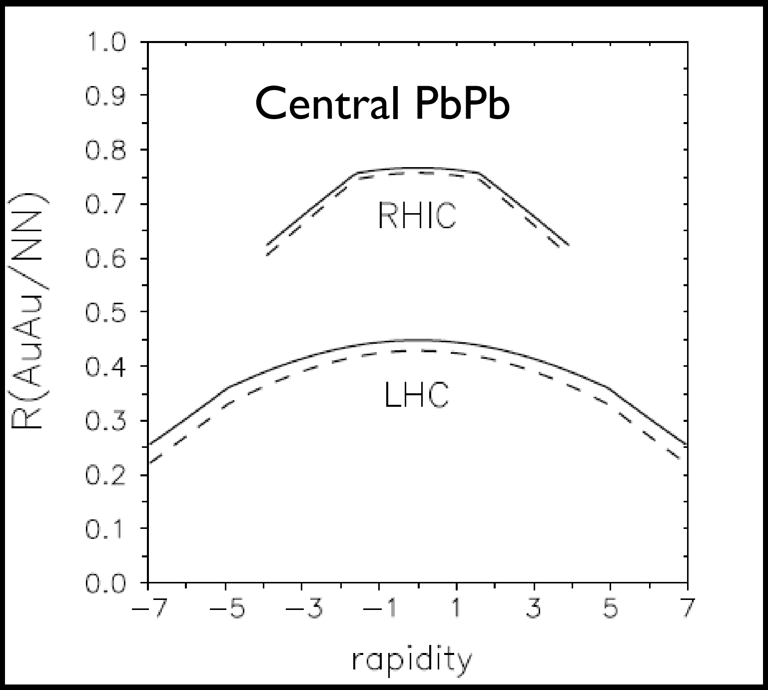
Arsene et al., Gribov shadowing (HT).



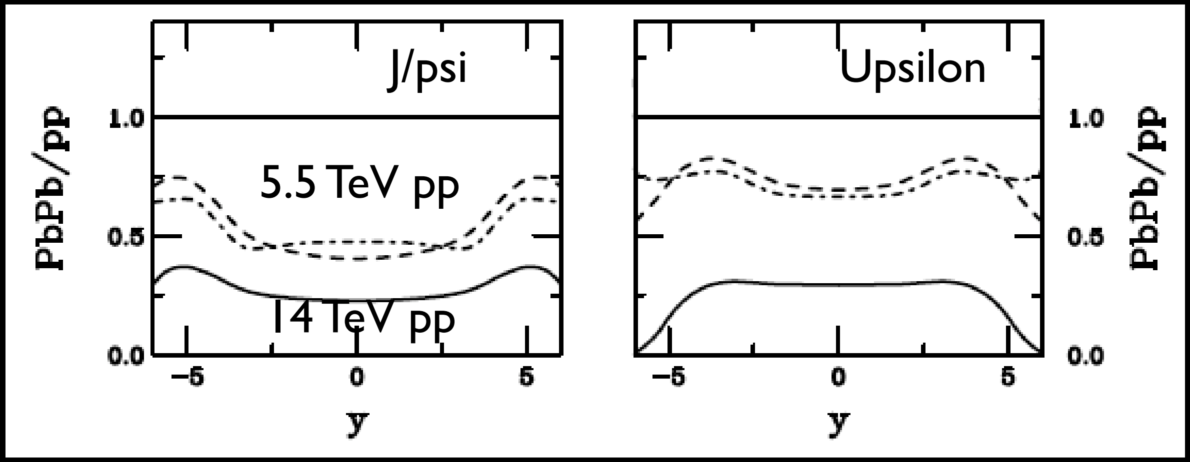


Conesa del Valle et al.: muons from W,Z as a reference for R_{AA}.

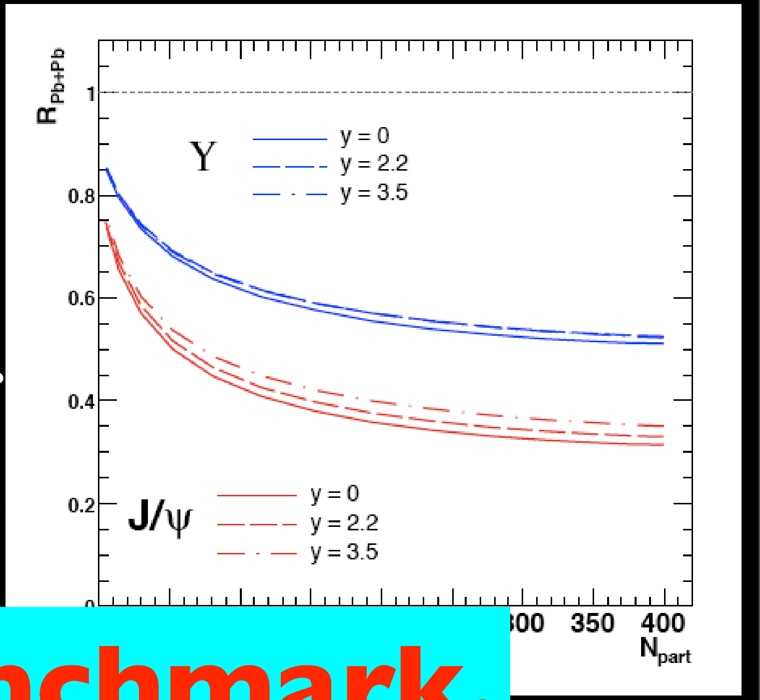
Kopeliovich et al., LT+HT process-dependent shadowing.



B.2. HQ and quarkonium: reference

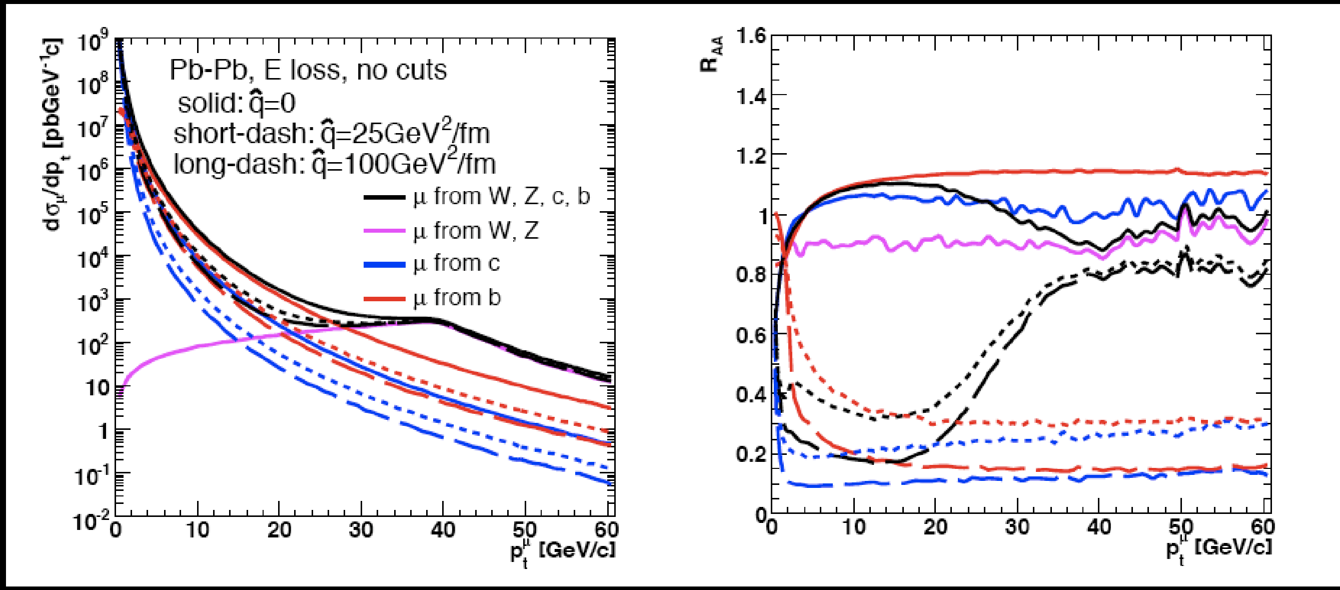


Vogt, effect of npdf's (LT: EKS and nD

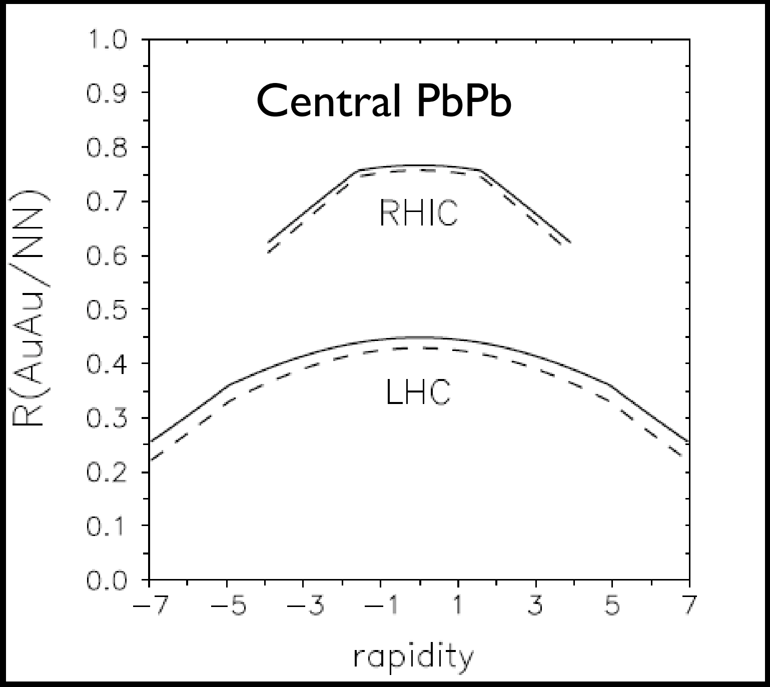


Arsene et al., Gribov shadowing (HT).

pPb most welcome for the benchmark.



Conesa del Valle et al.: muons from W,Z as a reference for R_{AA}.



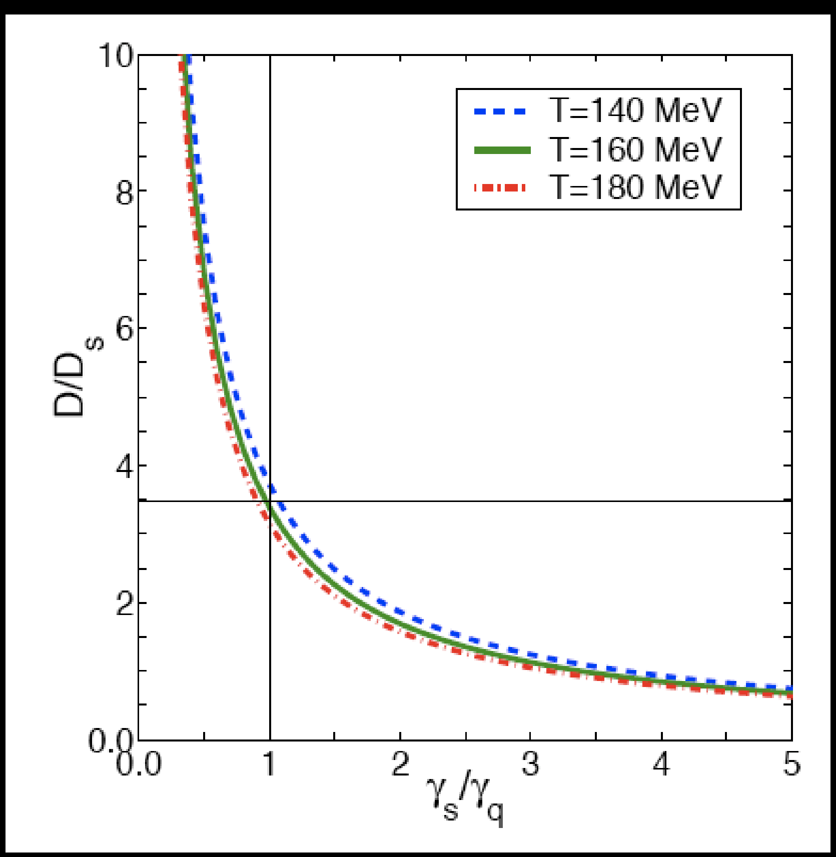
Kopeliovich et al., LT+HT process-dependent shadowing.

B.2. HQ and quarkonium: ratios

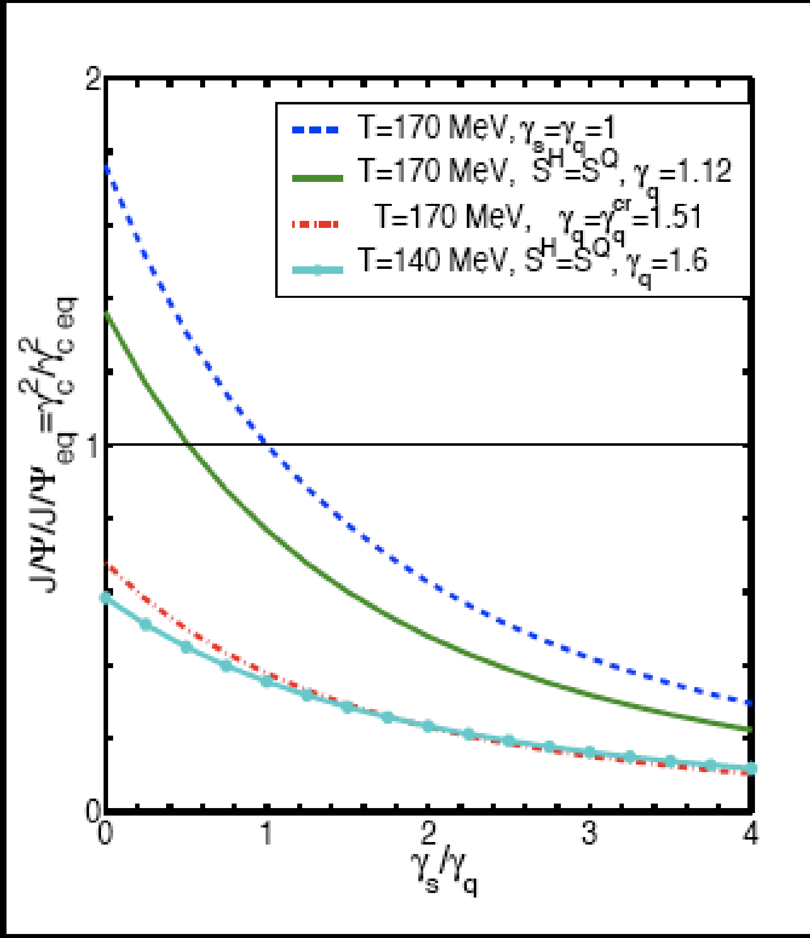
D^-/D^+	$\bar{D}_0/D_0$	D^{*-}/D^{*+}	D_s^-/D_s^+	$\bar{\Lambda}_c/\Lambda_c$	D^+/D_0	D^{*+}/D_0
1.00(0)	1.01(0)	1.01(0)	1.00(1)	1.00(1)	0.425(18)	0.387(15)

D_s^+/D_0	Λ_c/D_0	ψ'/ψ	η_c/ψ	χ_{c1}/ψ	χ_{c2}/ψ
0.349(14)	0.163(16)	0.031(3)	0.617(14)	0.086(5)	0.110(8)

Andronic et al.: ratios at equilibrium in the statistical model.



Kuznetsova et al.: strangeness over-saturation may lead to modifications in the ratios and to a suppression in the production of ccbar states.



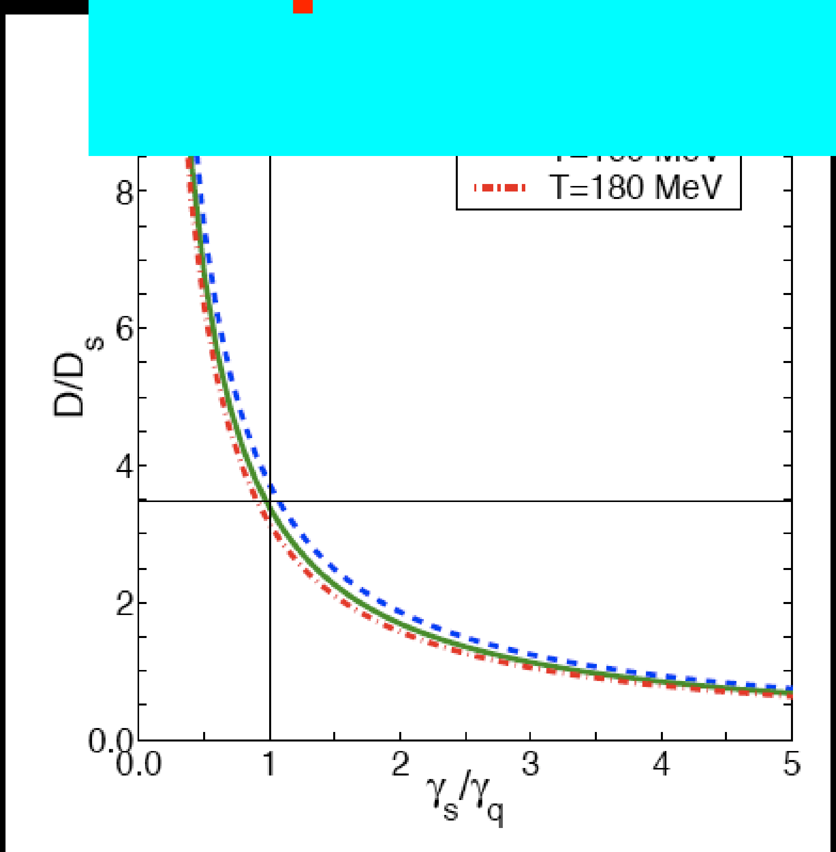
B.2. HQ and quarkonium: ratios

D^-/D^+	$\bar{D}_0/D_0$	D^{*-}/D^{*+}	D_s^-/D_s^+	$\bar{\Lambda}_c/\Lambda_c$	D^+/D_0	D^{*+}/D_0
1.00(0)	1.01(0)	1.01(0)	1.00(1)	1.00(1)	0.425(18)	0.387(15)

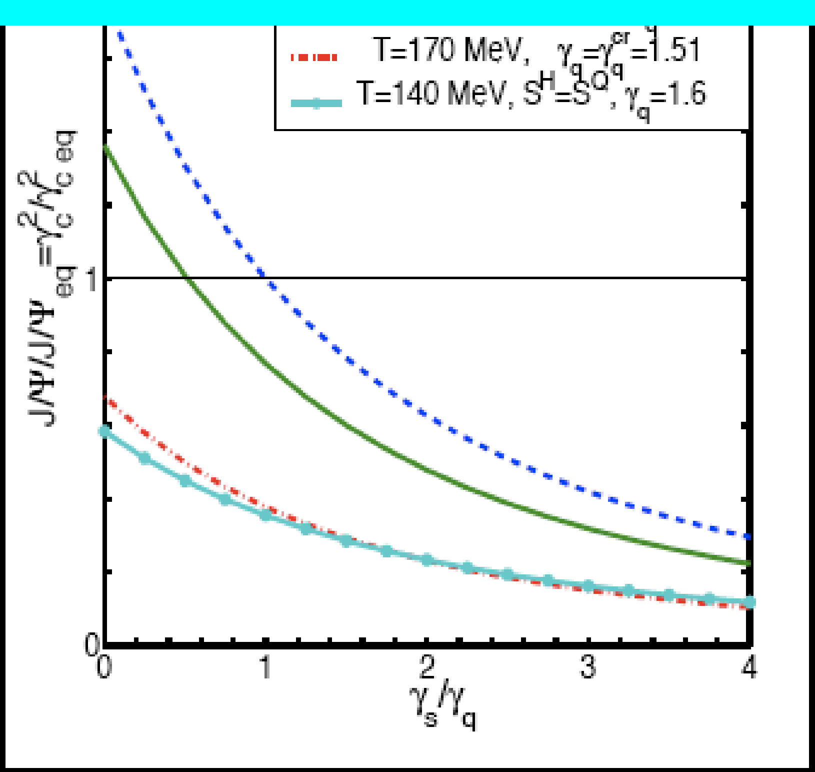
D_s^+/D_0	Λ_c/D_0	ψ'/ψ	η_c/ψ	χ_{c1}/ψ	χ_{c2}/ψ
0.349(14)	0.163(16)	0.031(3)	0.617(14)	0.086(5)	0.110(8)

Andronic et al.: ratios at equilibrium in the statistical model.

Chemical composition studies will have implications on recombination models for quarkonium.



strangeness over-saturation may lead to modifications in the ratios and to a suppression in the production of ccbar states.



B.2. HQ and quarkonium: others

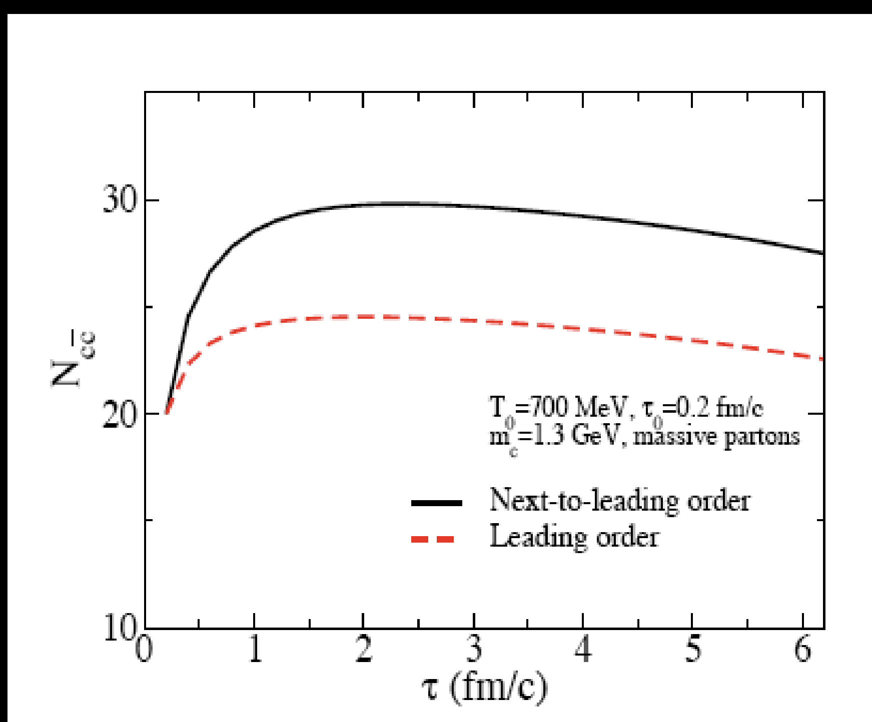
Table 7: Upper bound on quarkonium dissociation temperatures.

state	χ_c	ψ'	J/ψ	Υ'	χ_b	Υ
$T_{\rm dis}$	$\leq T_c$	$\leq T_c$	$1.2T_c$	$1.2T_c$	$1.3T_c$	$2T_c$

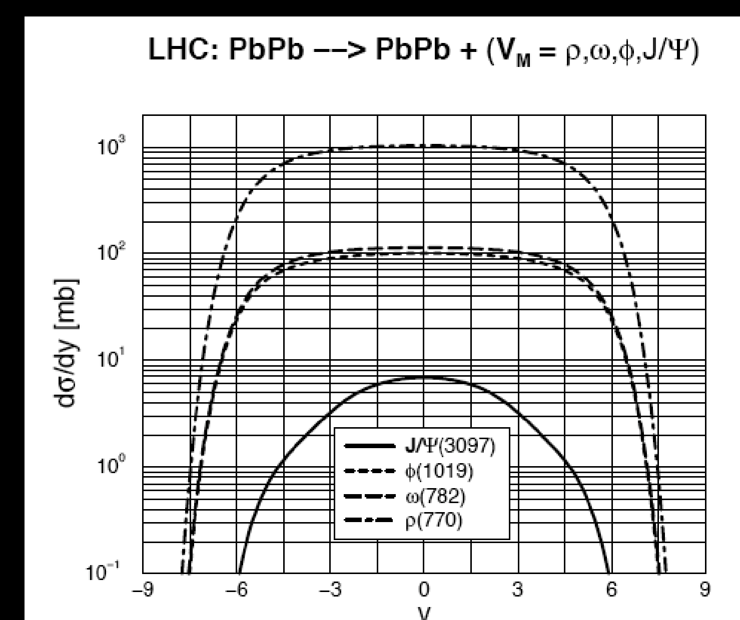
Mocsy et al., dissociation T in potential models.

$$L_s(v,T) \simeq L_s(0,T)/\sqrt{\gamma} \longrightarrow T_{\rm diss}(v) \simeq T_{\rm diss}(0)/\sqrt{\gamma}$$

H. Liu et al., screening lengths through the medium, new suppression at larger p_T if produced inside the medium



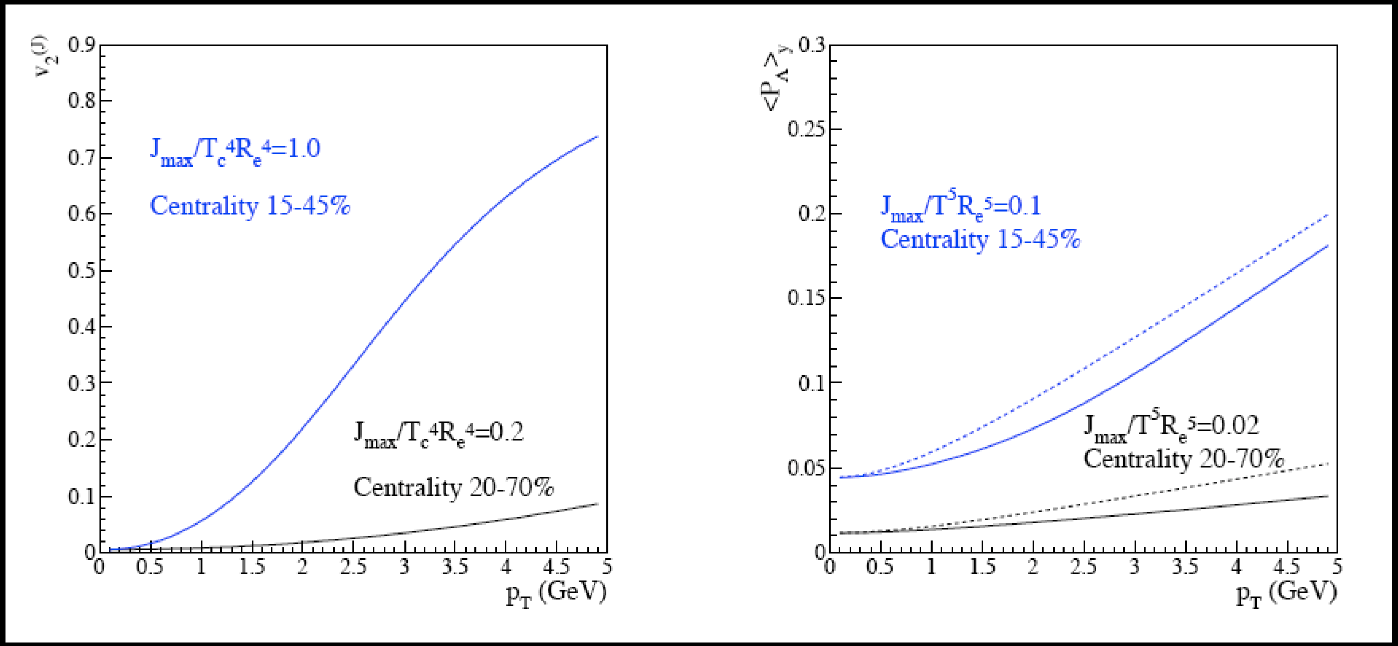
Zhang et al., thermal charm at NLO.



Gonçalves et al., charm in UPC, test of production and npdf's.

Backup III: others

Becattini et al.: in peripheral collisions, a highly spinning QGP may be formed → decreasing μ_b, larger v_2, polarization.



Stocker et al.: creation of black holes in HIC due to low-scale extra dimensions: suppression of dijets, remmants.

Lee et al.: coalescence formation of charmed exotic, multiquark hadrons, test of particle production mechanism.

Lokhtin et al.: exotic phenomena in HE CR, like alignment of tracks, may become visible at the LHC.