High p_T hadron suppression in A+A collisions: from SPS to RHIC

HARD PROBES'04

Ericeira, Portugal - Nov 7th, 2004

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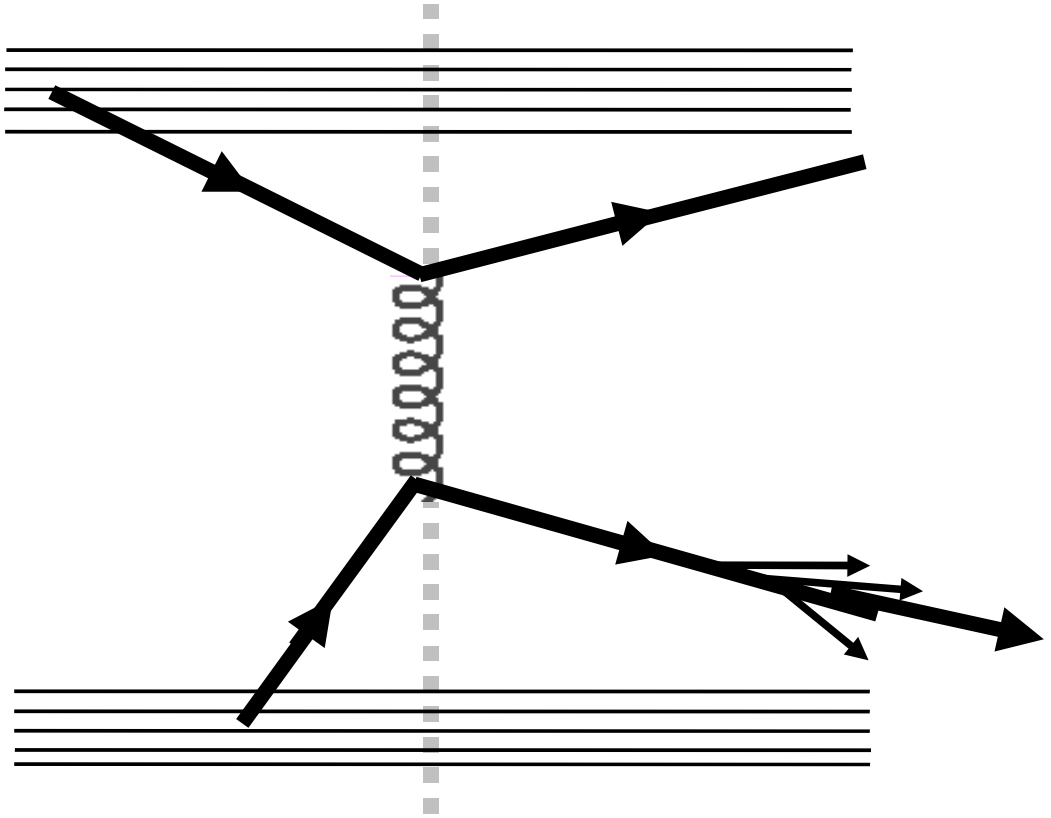
Nevis Labs, Columbia University, NY

Overview

- Motivation: High p_T in A+A collisions as a probe of the properties of QCD media (QGP, CGC) via p+p $\leftrightarrow$ p,d+A $\leftrightarrow$ A+A comparison
- High p_T A+A hadroproduction from $\sqrt{s_{NN}}$ = 20 to 200 GeV:
  - SPS $\sqrt{s_{NN}} \approx 20$ GeV results revisited:
    p+p reference, indications of suppression, comparison to E_{loss} models
  - RHIC results at $\sqrt{s_{NN}}$ = 62.4 GeV:
    p+p references, preliminary R_{AA}, comparison to E_{loss} models
  - A few new RHIC results at $\sqrt{s_{NN}}$ = 200 GeV:
    very high p_T π, η suppression, data vs. E_{loss} models
- Excitation function of high p_T suppression.
- Summary. 3 lessons learnt.

Hard scattering in A+A collisions



[Experimental handle: p+p]

Hard scattering in A+A collisions

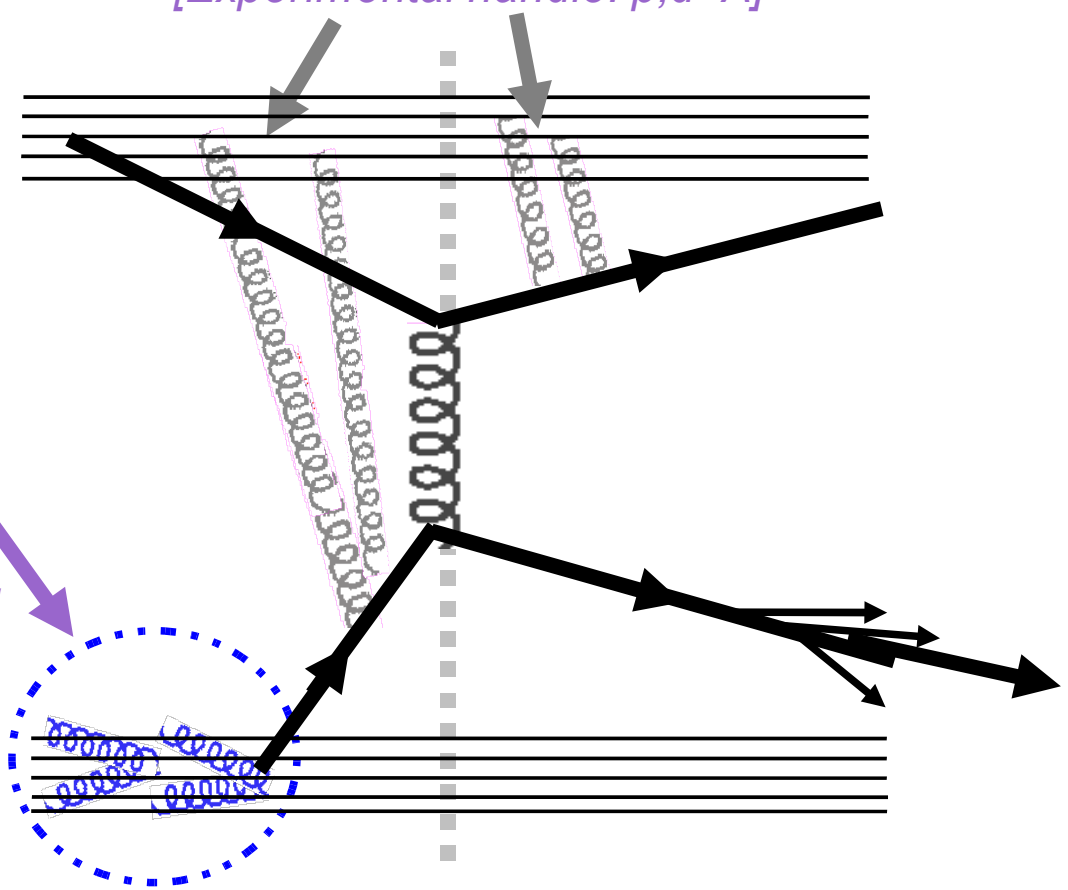
p_T broadening
(Cronin enhancement)

[Experimental handle: p,d+A]

Initial-state effects

Leading-twist shadowing
or
Gluon saturation (**CGC**)

[Experim. handle: e+A, p,d+A]



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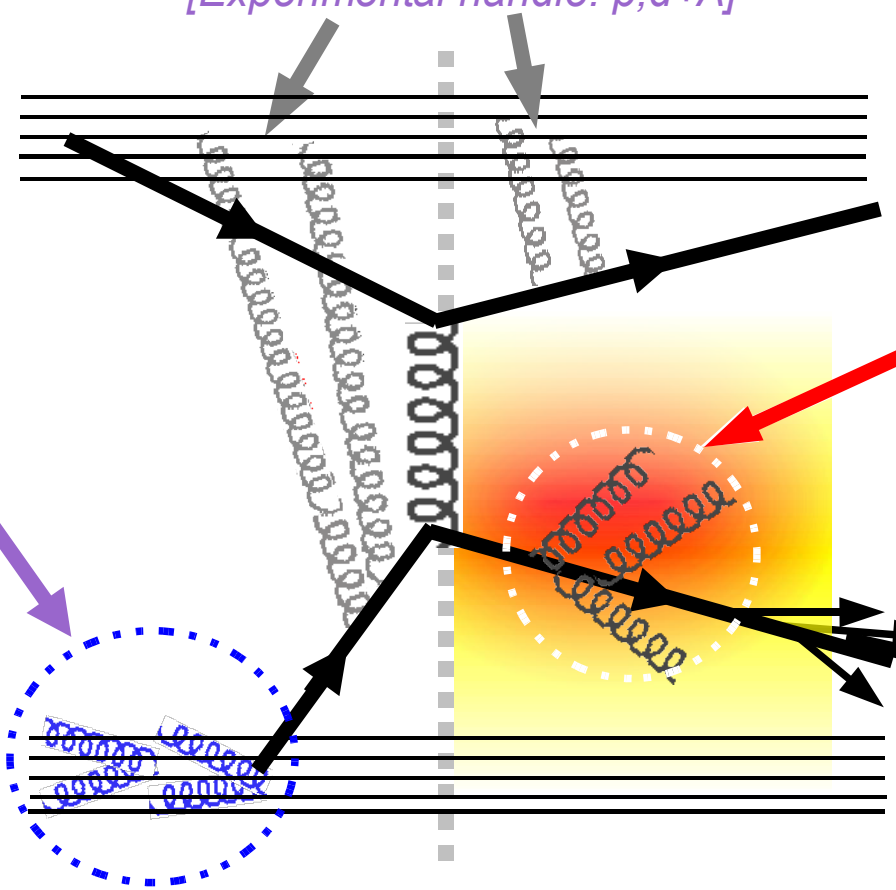
medium-induced
parton energy loss:
"jet quenching" in **QGP**

possible
hadronic
rescattering

[Experimental handle: A+A]



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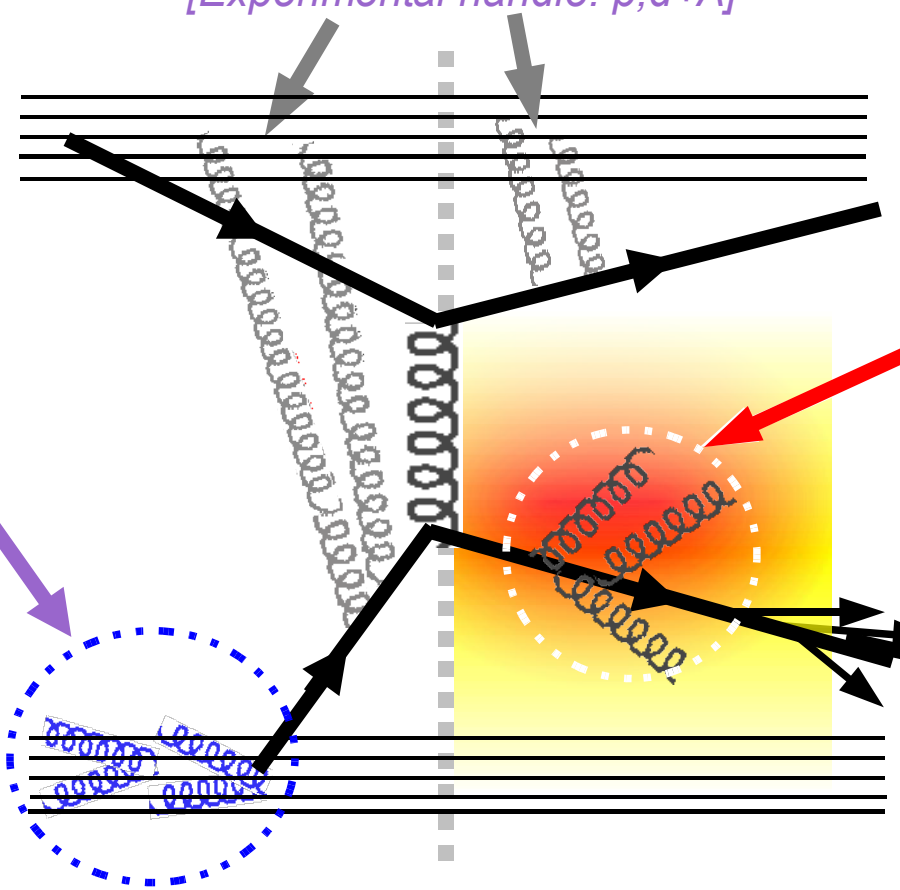


[Experimental handle: A+A]

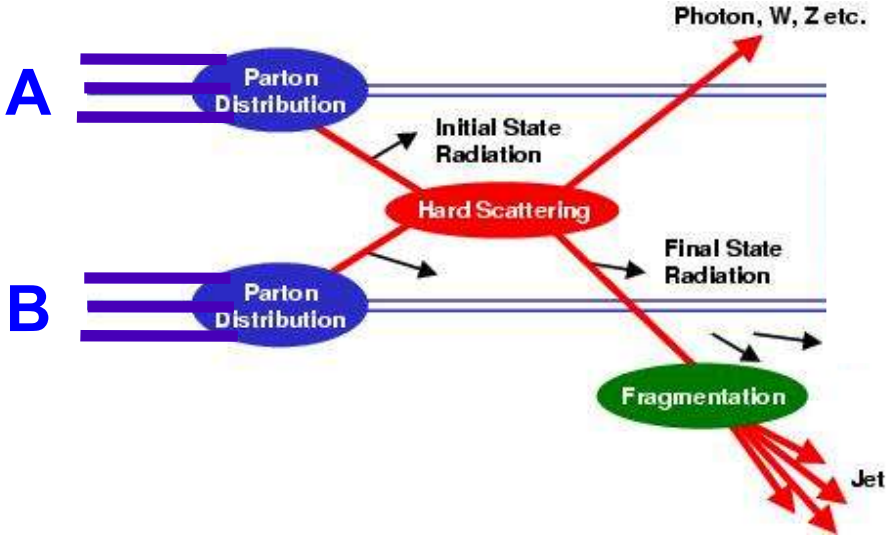
- Approach: Study modifications (dN/dp_T, particle composition, $dN_{pair}/d\varphi$) of high p_T in A+A with respect to p+p, p+A to learn about the properties of QCD media:
  - "Quark Gluon Plasma" (final-state A+A) and/or
  - "Color Glass Condensate" (initial-state A).

Expected hard scattering yields in A+A

- Production yields calculable theoretically via perturbative QCD:

"Factorization theorem":

$$d\sigma_{AB\to hX} = A\cdot B\cdot f_{a/A}(x_a,Q^2_a)\otimes f_{b/B}(x_b,Q^2_b)\otimes d\sigma_{a\,b\to cd}\otimes D_{h/c}(z_c,Q^2_c)$$



Independent scattering of "free" partons:

$$f_{a/A}(x,Q^2) = A\, f_{a/p}(x,Q^2)$$

A+B = "simple superposition of p+p collisions"

$$d\sigma_{AB\to hard} = A\cdot B\cdot d\sigma_{pp\to hard}$$

At impact parameter b:

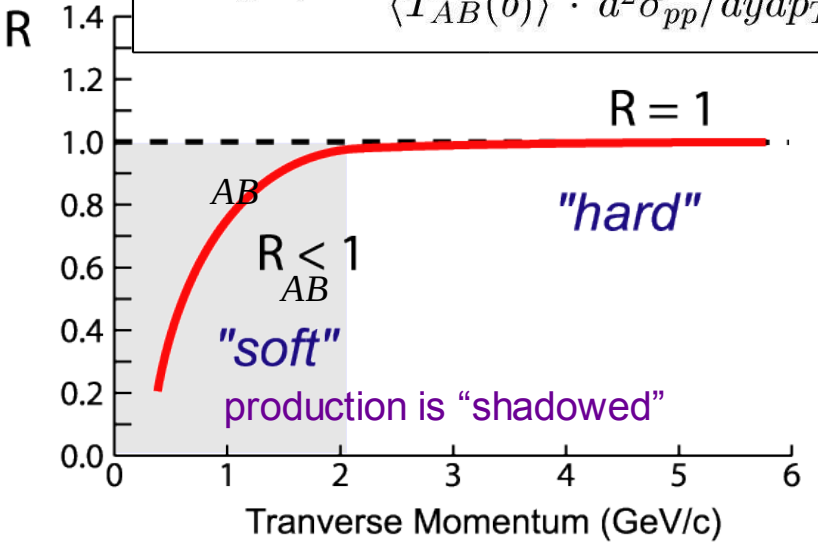
$$dN_{AB\to hard}(b) = T_{AB}(b)\cdot d\sigma_{pp\to hard}$$

geom. nuclear overlap at b

T_{AB} ~ # NN collisions ("N_{coll} scaling")

Nuclear Modification Factor:

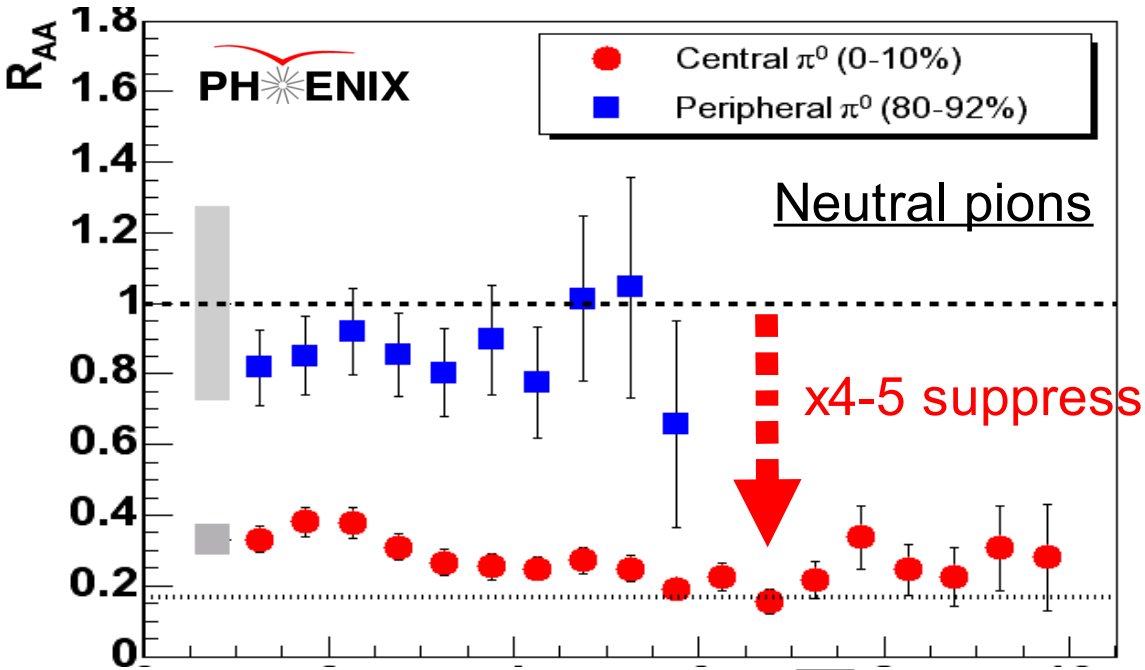
$$R_{AB}(p_T) = \frac{d^2N_{AB}/dydp_T}{\langle T_{AB}(b)\rangle \cdot d^2\sigma_{pp}/dydp_T}$$

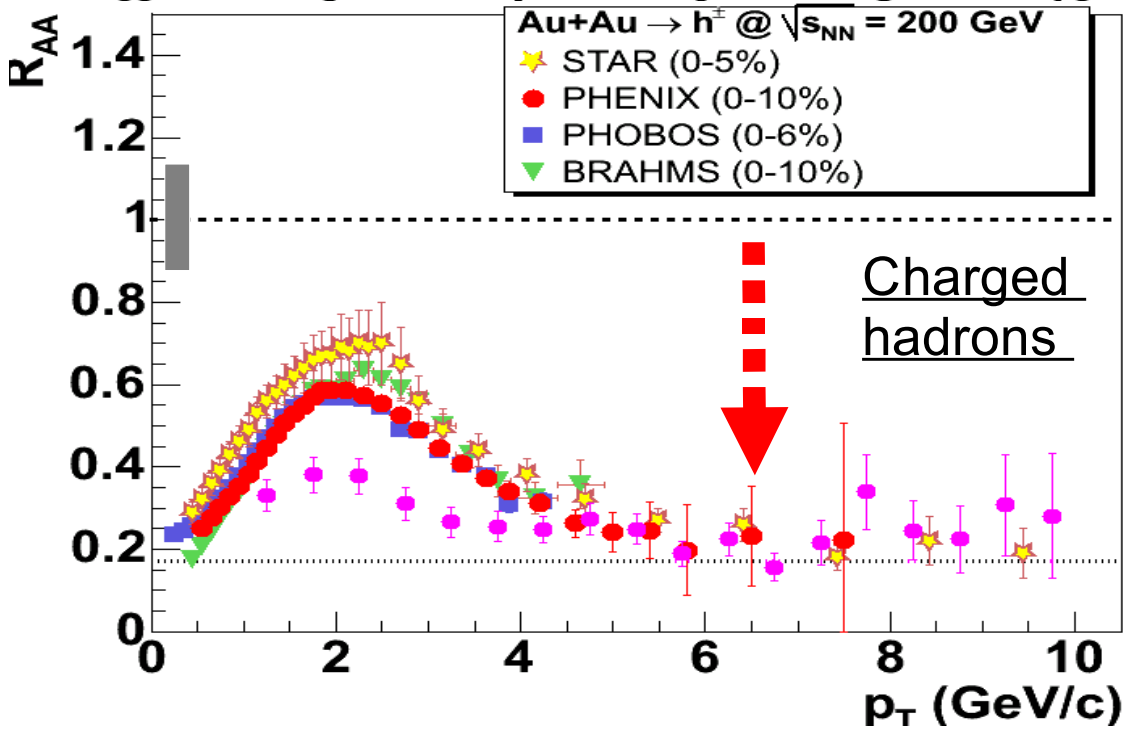


RHIC A+A "breakthroughs"(*) in the high p_T sector

(*) as given by PRL covers

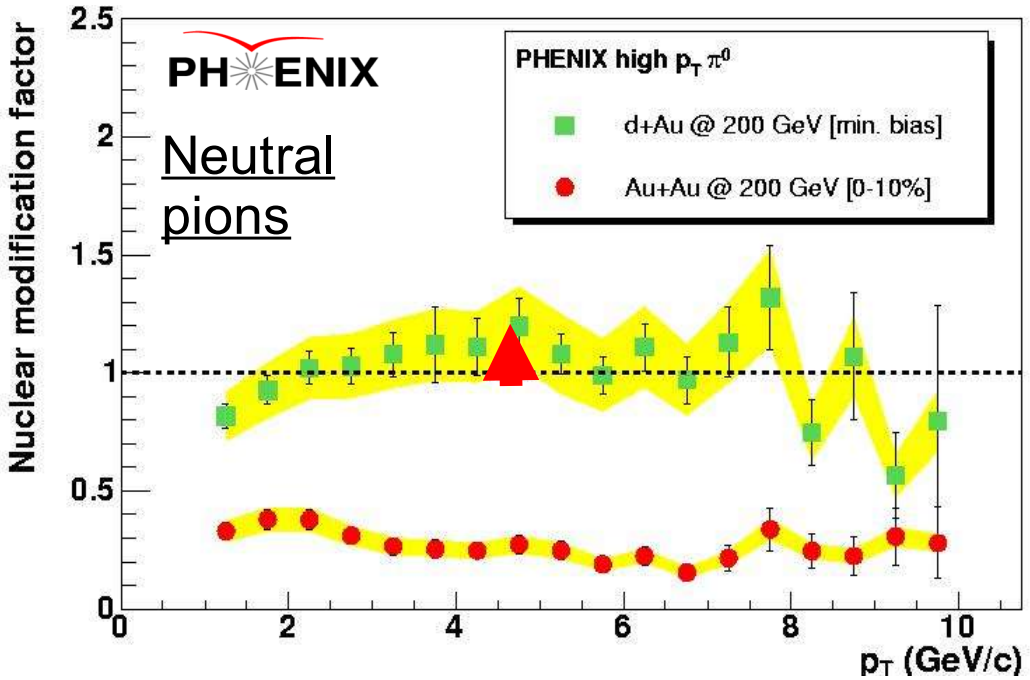
(1) High p_T suppression in central Au+Au @ 200 GeV

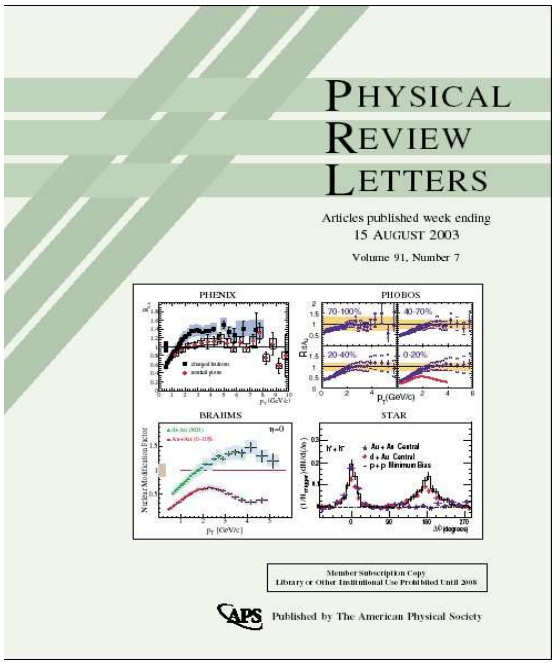


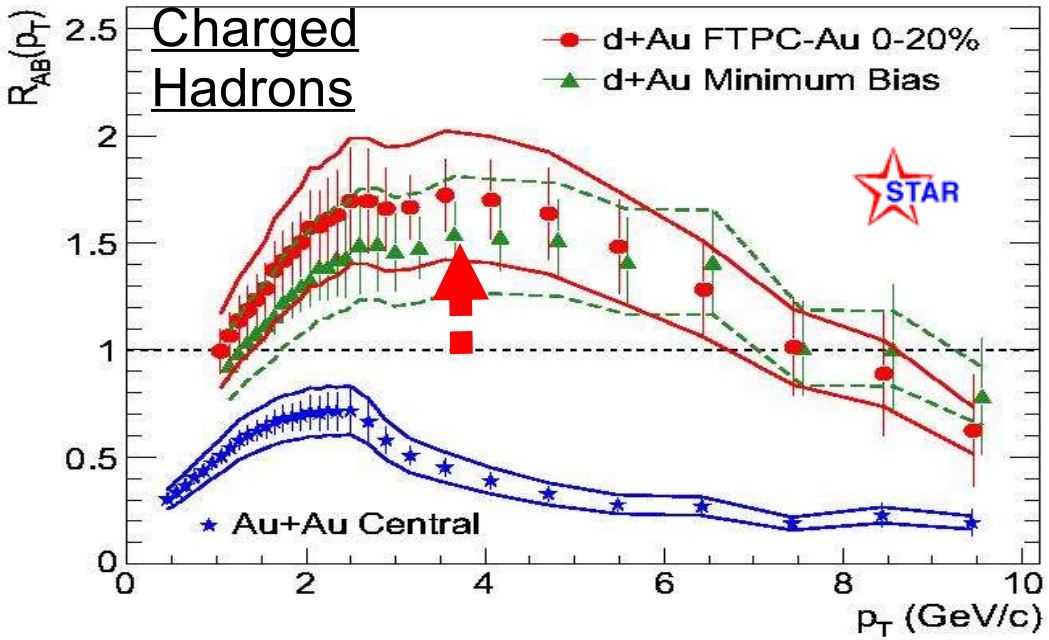


- R_{AA} << 1: well below pQCD (collinear factoriz.) expectations for hard cross-sections
- Consistent with "jet quenching" expectations for leading hadrons

(2) High p_T enhancement in d+Au @ 200 GeV



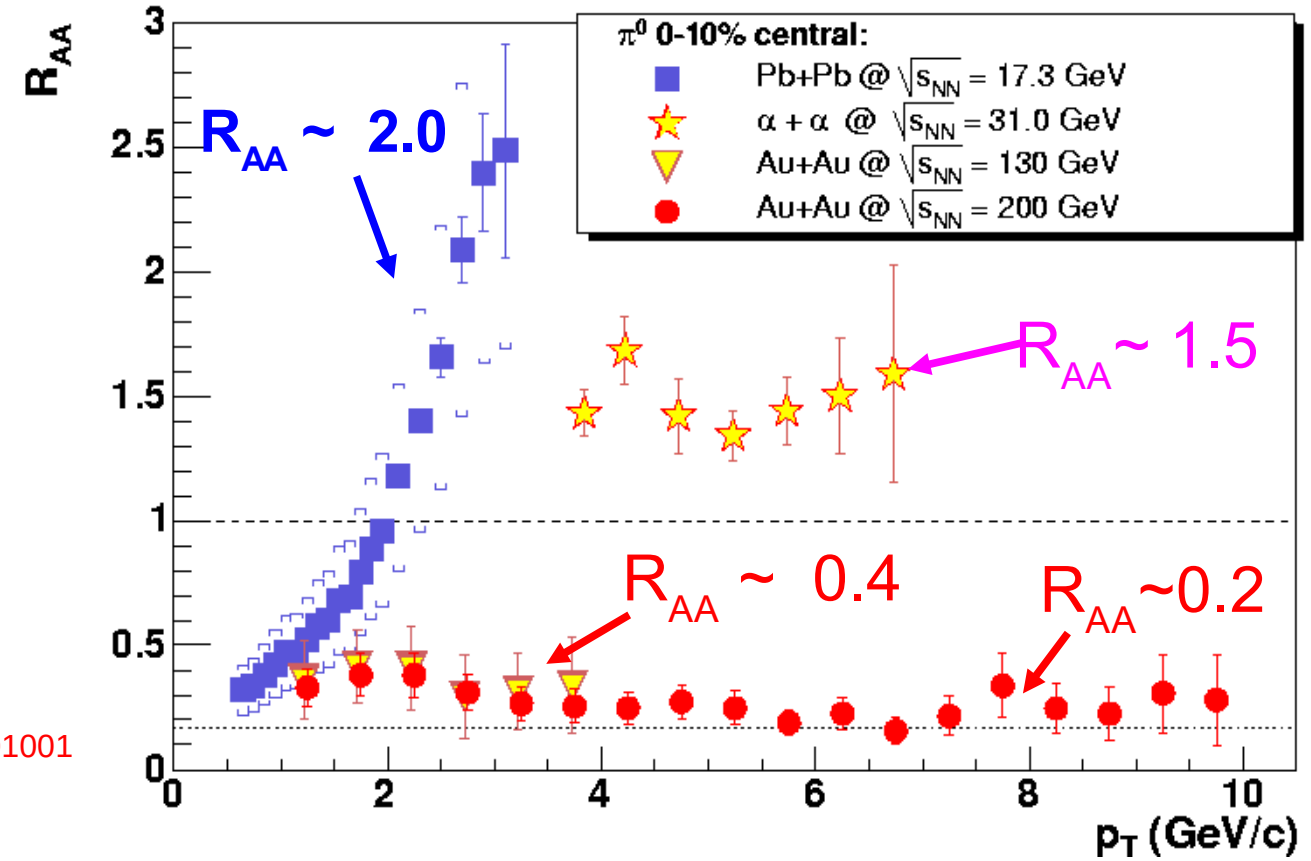




- d+Au @ RHIC shows "Cronin" p_T broadening as seen at lower $\sqrt{s}$ p+A
- Suppression in central Au+Au due to final-state effects

much of the excitement lies in the √s dependence ...

R_{AA} (π^0) in central A+A collisions (as of ~1 year ago):



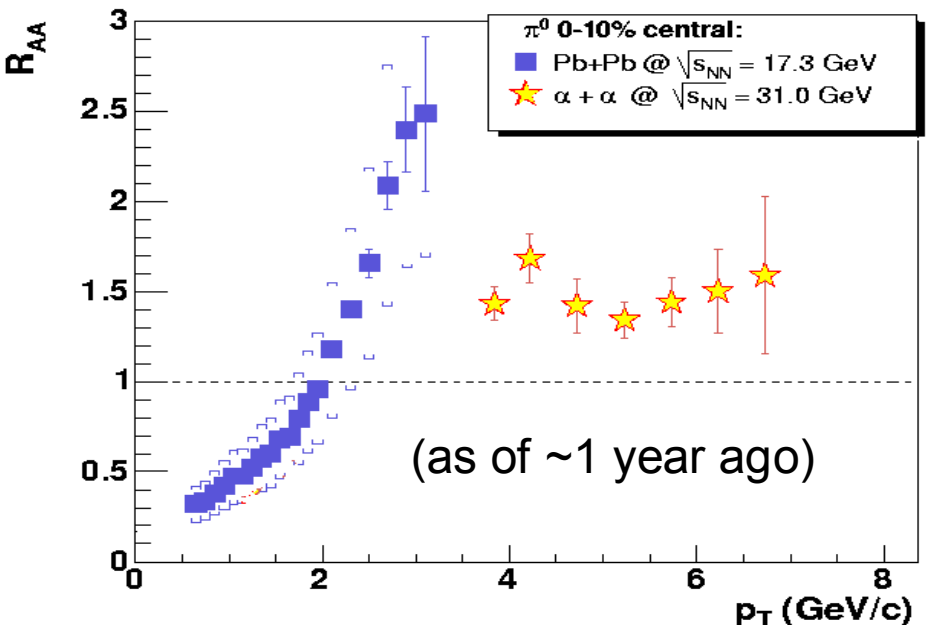
A.L.S.Angelis, PLB 185, 213 (1987)
WA98, EPJ C 23, 225 (2002)
PHENIX, PRL 88 022301 (2002)
PHENIX, PRL 91, 072303 (2003)

D.d'E
nucl-ex/0401001

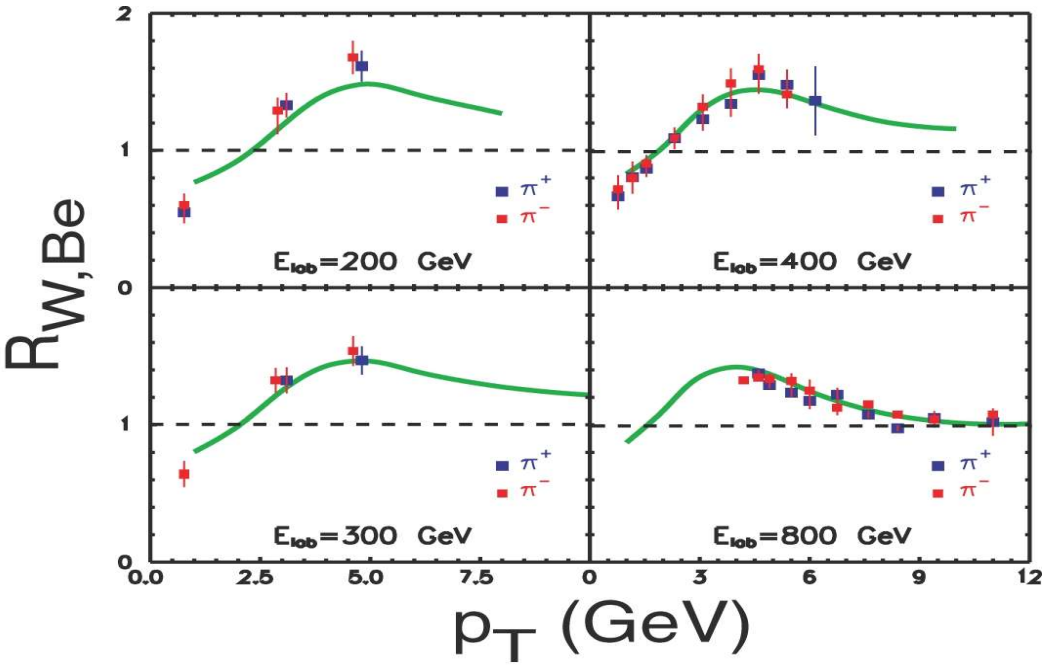
- CERN-SPS: Pb+Pb central ($\sqrt{s_{NN}}$ = 17.3 GeV): strong Cronin enhancement
- CERN-ISR: α+α ($\sqrt{s_{NN}}$ = 31 GeV): Cronin enhancement (small system)
- RHIC: Au+Au ($\sqrt{s_{NN}}$ = 130, 200 GeV): x 4-5 suppression !

A+A at SPS, ISR ≅ fixed-target p+A at Fermilab ...

A+ A @ $\sqrt{s_{NN}}$ = 17.3, 31 GeV



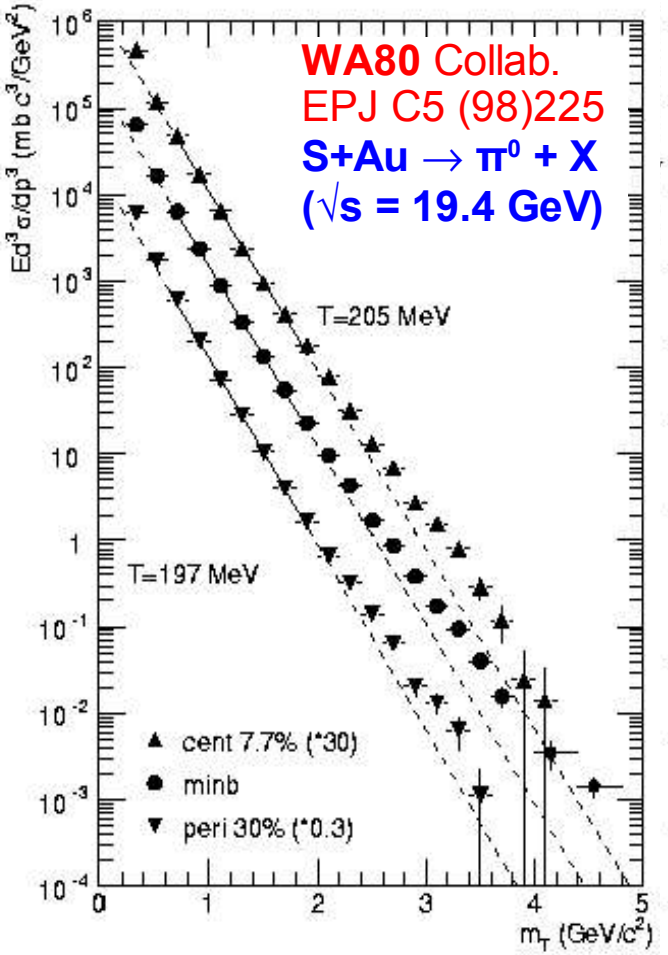
p+A @ $\sqrt{s_{NN}}$ = 20 - 40 GeV

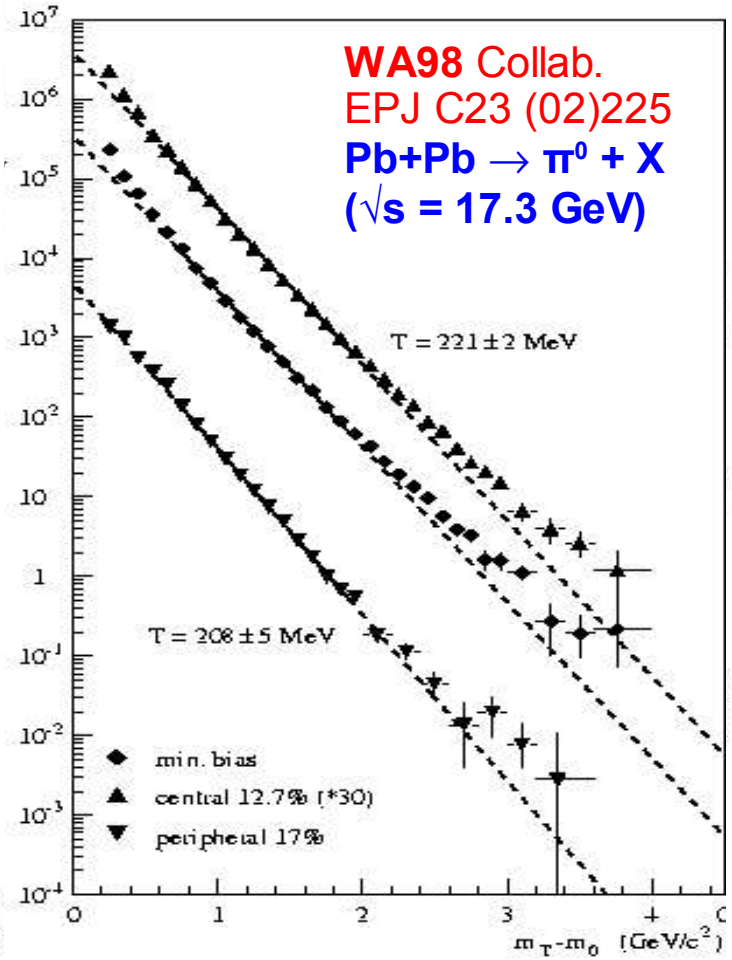


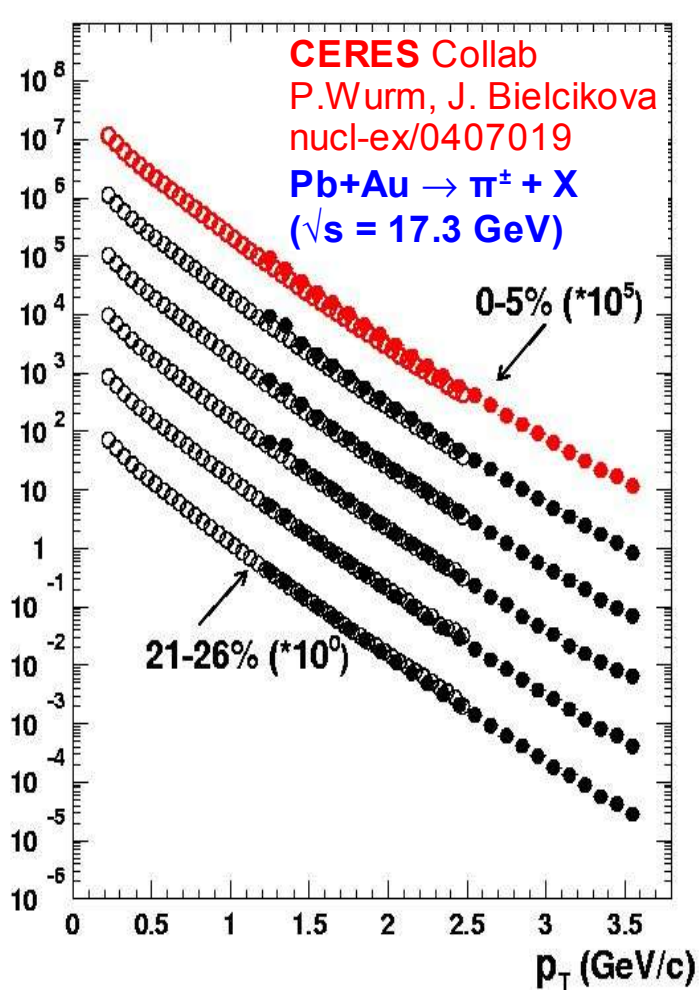
- Std. argument: "Initial-state effects dominate hard hadro-production in A+A at SPS energies. Final-state effects do not play a significant role."
- How can it be, however, that: $\varepsilon_{Bj}^{SPS} \approx 3$ GeV/fm^3 ($\Rightarrow dN^{q+g}/dy \approx 2\cdot\varepsilon^{3/4}\cdot\tau_0\cdot A_T \approx 600$) and yet there is no high p_T suppression at SPS !? (whereas there is a factor x5 suppression at RHIC w/ $\varepsilon_{Bj}^{RHIC} \approx 5$ GeV/fm^3)

High p_T in A+A at SPS ($\sqrt{s_{NN}} \approx 20$ GeV): Cronin or suppression ?

High p_T A+A spectra @ CERN-SPS



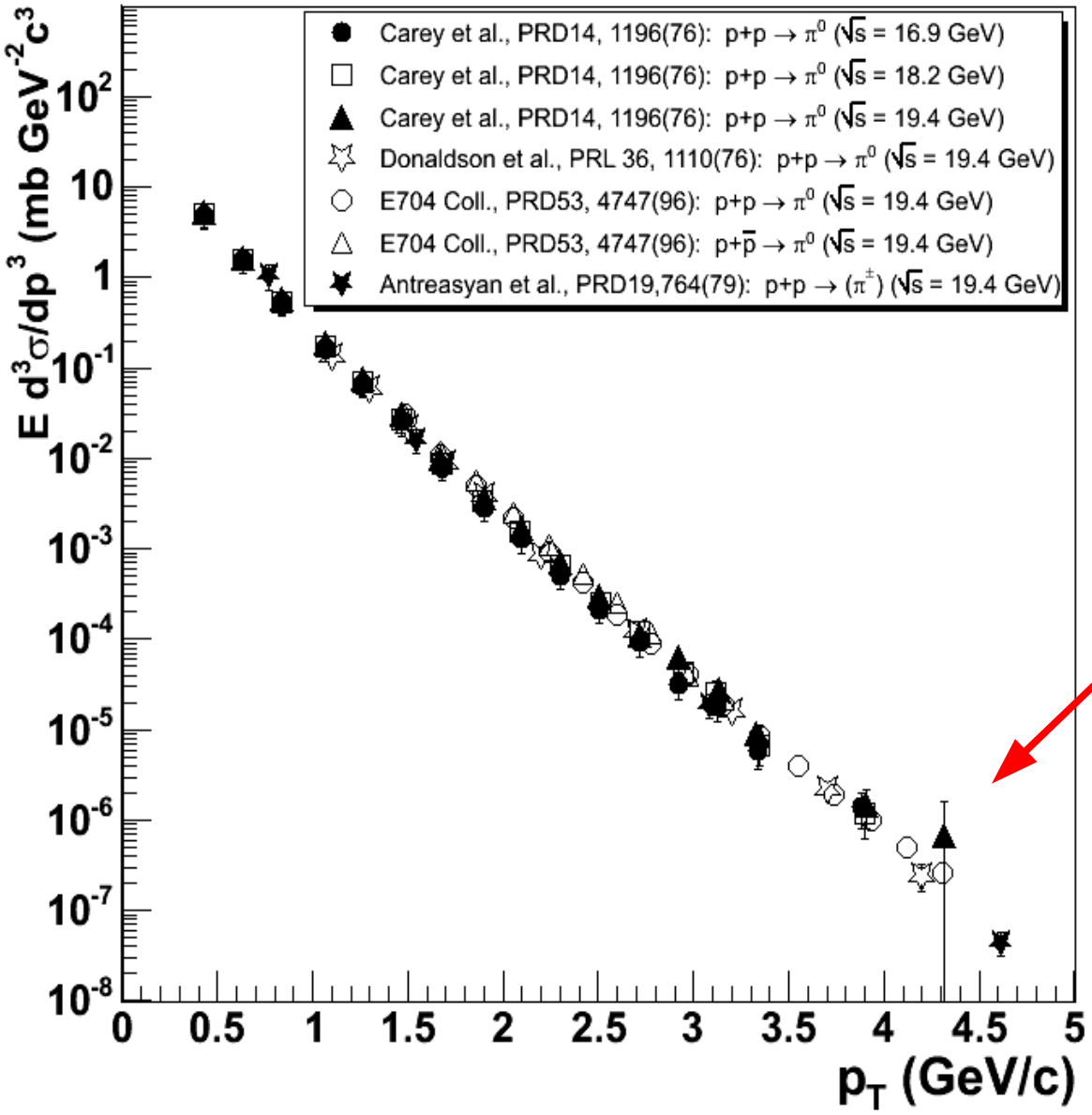




- Spectra go up to p_T~3.5-4 GeV/c (large stat. uncertainties in higher p_T bins).
- Evidence of hard scattering processes: power-law deviation from "soft" (exponential) behaviour observed above p_T~2 GeV/c.

High p_T baseline p+p spectra @ CERN-SPS ?

NO p+p → π +*X* reference measurement at SPS Pb+Pb energy (√s = 17.3 GeV)



Closest existing π p+p data for:

√s = 16.9 GeV
√s = 18.2 GeV
√s = 19.4 GeV

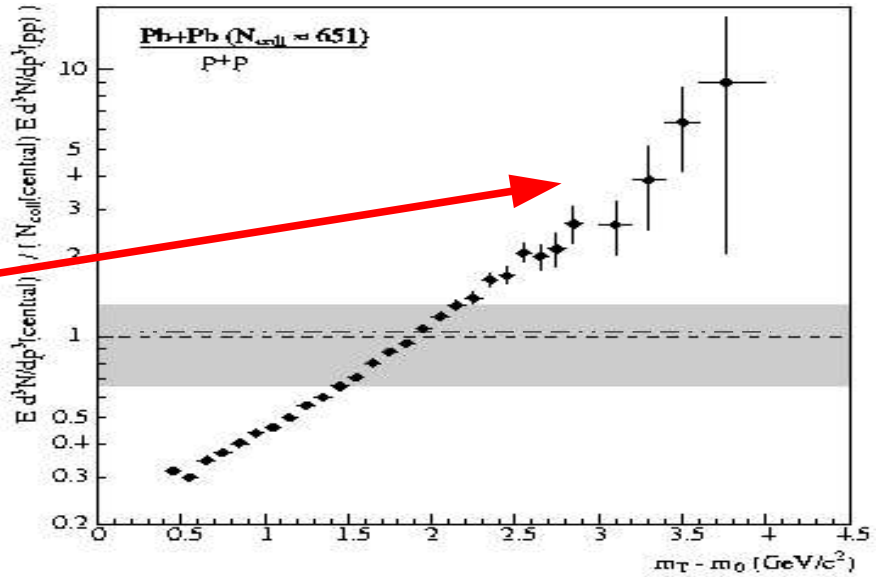
(not completely consistent among each other at high p_T)

Enhanced high p_T production @ CERN-SPS ?

- R_{AA} for central Pb+Pb constructed using 2 different p+p parametrizations:

WA98 Collab.
EPJ C23 (02)225

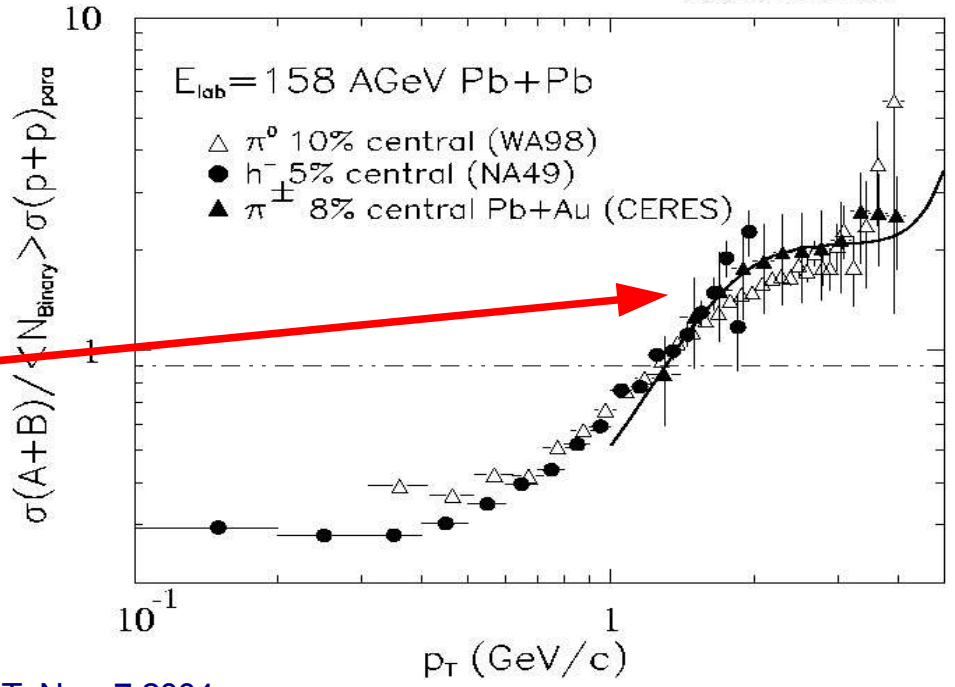
Huge Cronin enhancement above p_T~2 GeV/c



p+p ref. constructed from higher energy ISR π^0 data + x_T scaling

Wang&Wang
PRC 64 (01) 034901

Moderate Cronin enhancement above p_T~1 GeV/c



p+p ref. constructed from ISR $\pi^\pm$ data + pQCD-based $\sqrt{s}$ scaling

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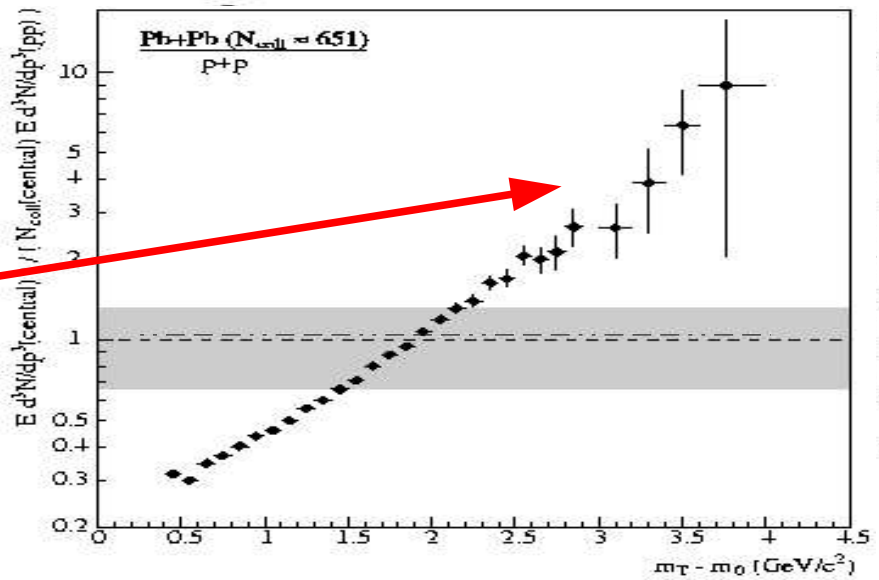

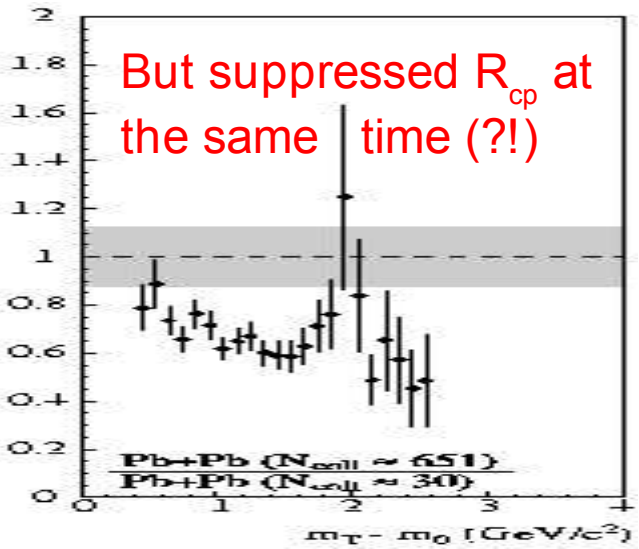

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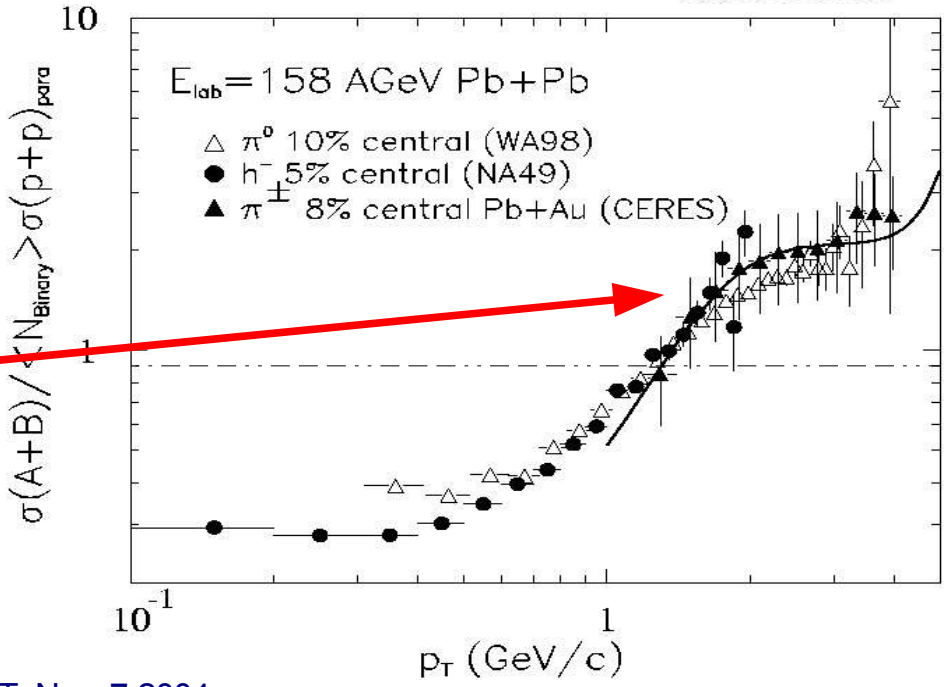
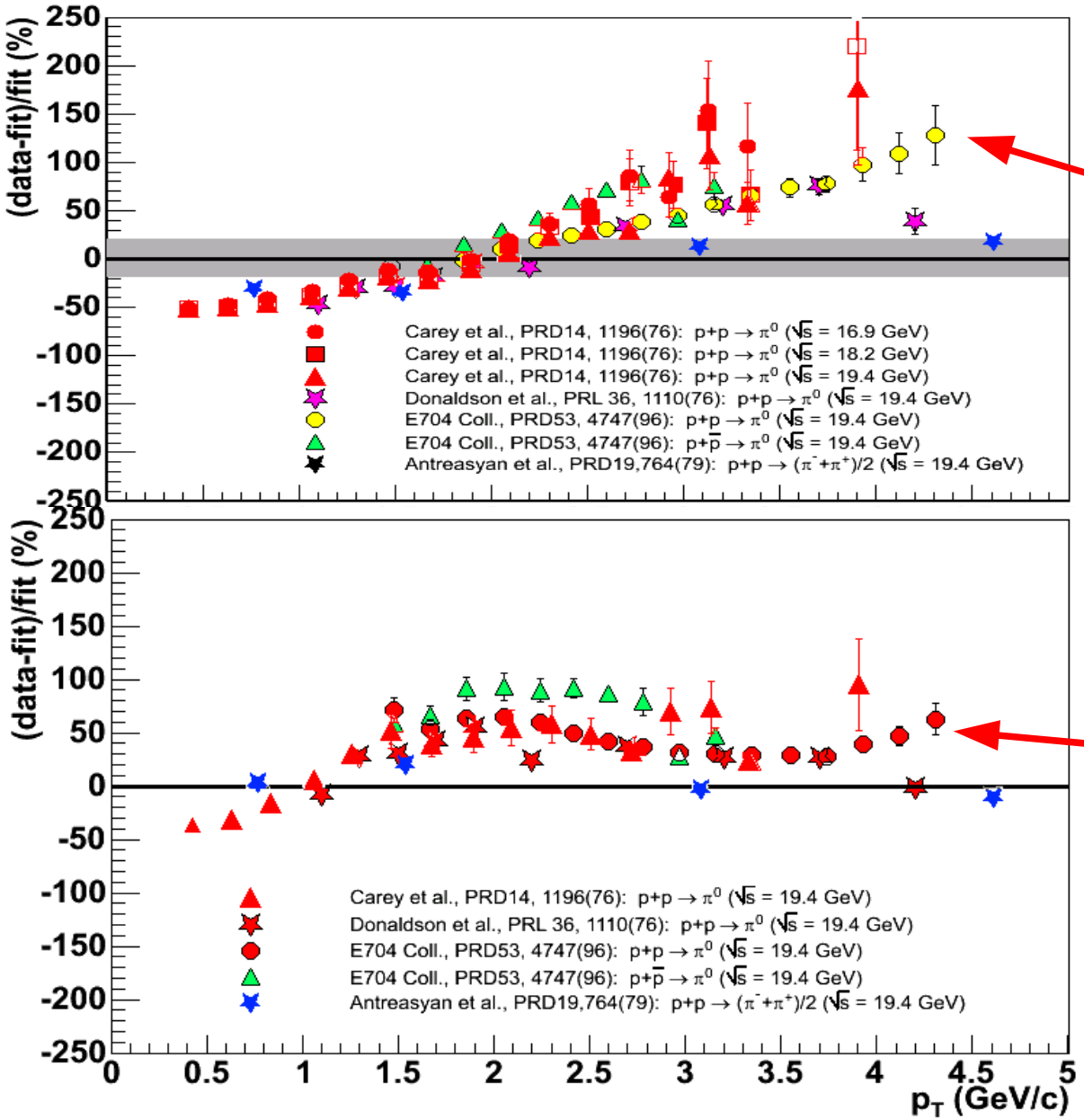


p+p → π+X @ √s ≈ 20 GeV : data vs. references

- WA98, Wang&Wang p+p parametrizations confronted to π data (√s = 16 – 20 GeV):



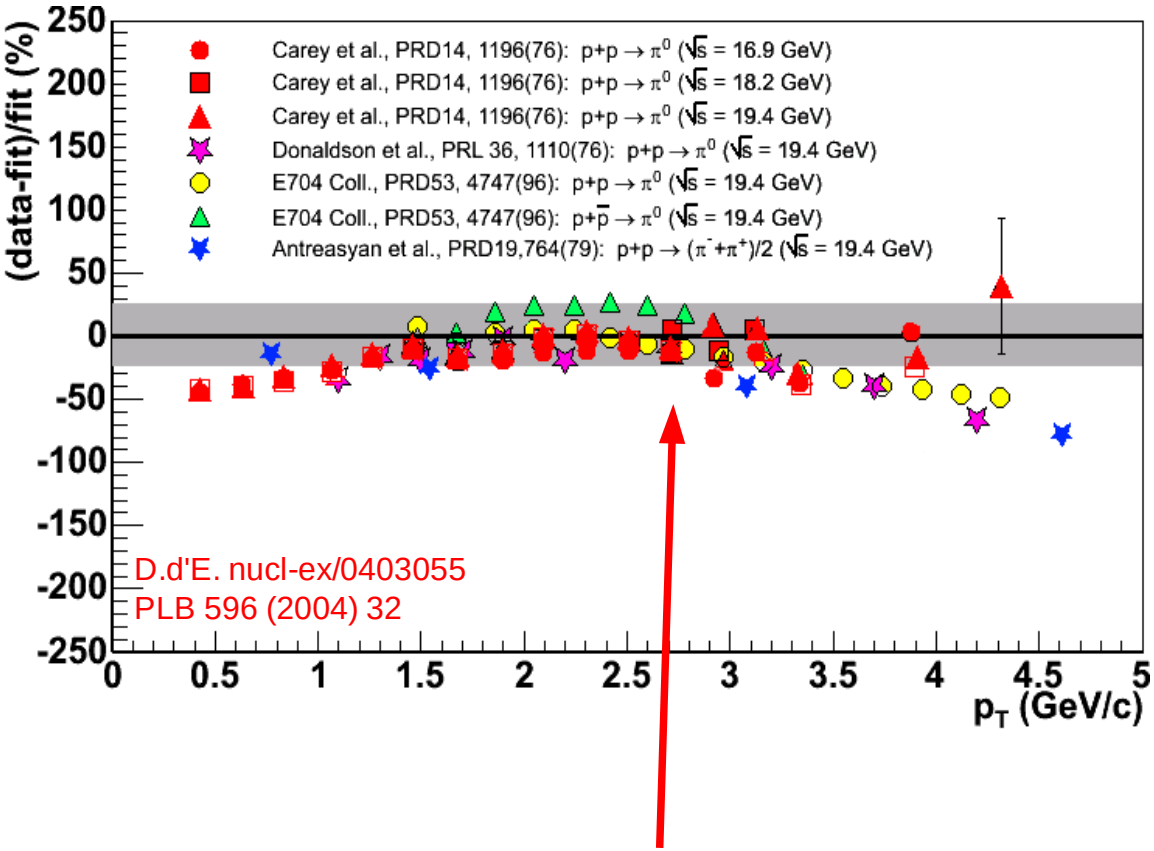
WA98 parametrization undershoots the data by up to a factor of ~3

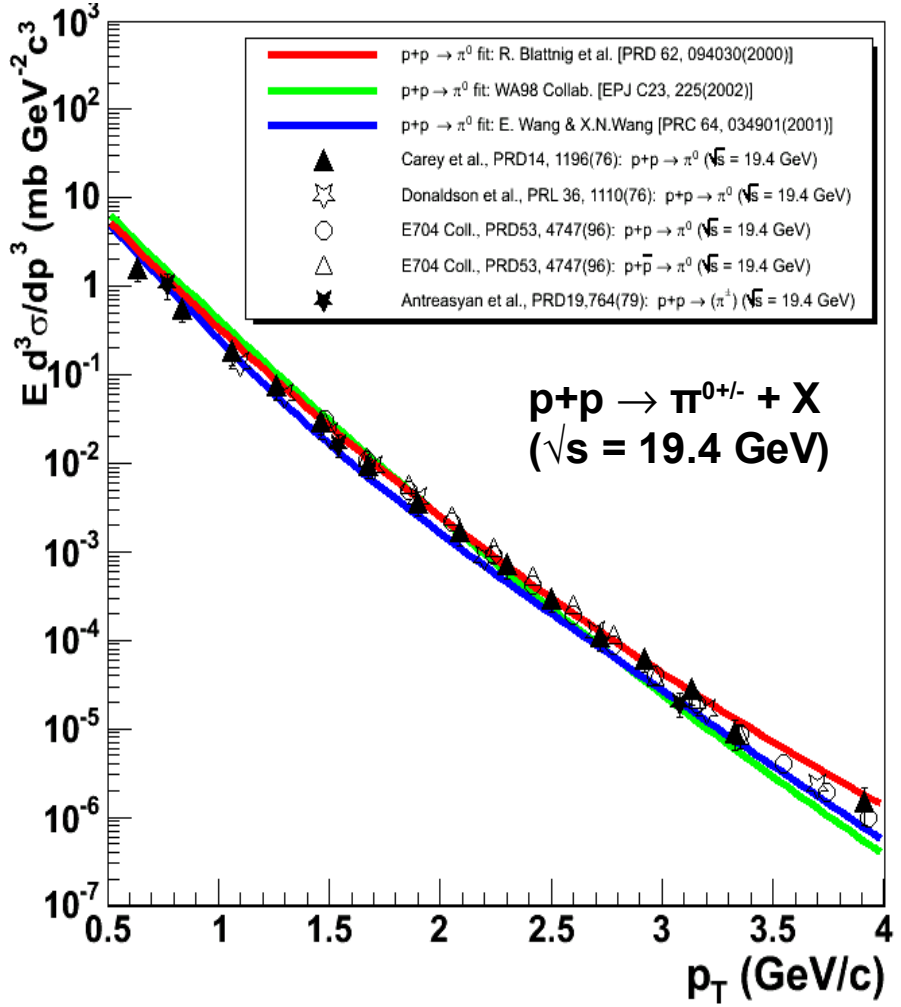
D.d'E. nucl-ex/0403055
PLB 596 (2004) 32

Wang&Wang parametriz. undershoots the data by up to a factor of ~2

New p+p → π+*X* reference @ √s ≈ 20 GeV

- New parametrization [Blattnig et al. PRD62 (2000) 094030] versus p+p data √s = 16 – 20 GeV:



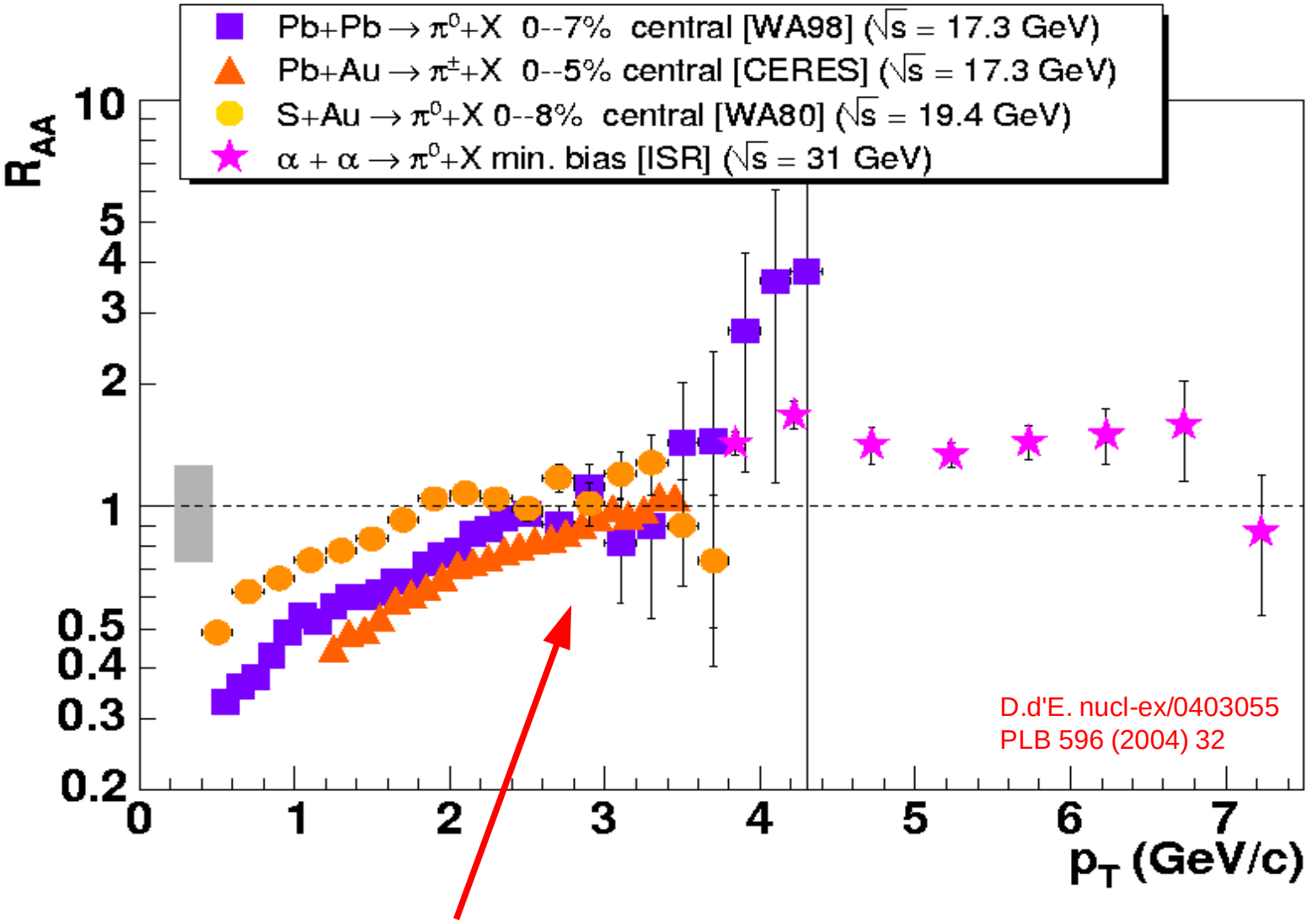


- Better agreement in shape & magnitude (within large exp. uncertainties).

- sqrt(s) dependence (√s = 16 – 20 GeV) of yields correctly reproduced.

"New" nuclear modification factors at SPS

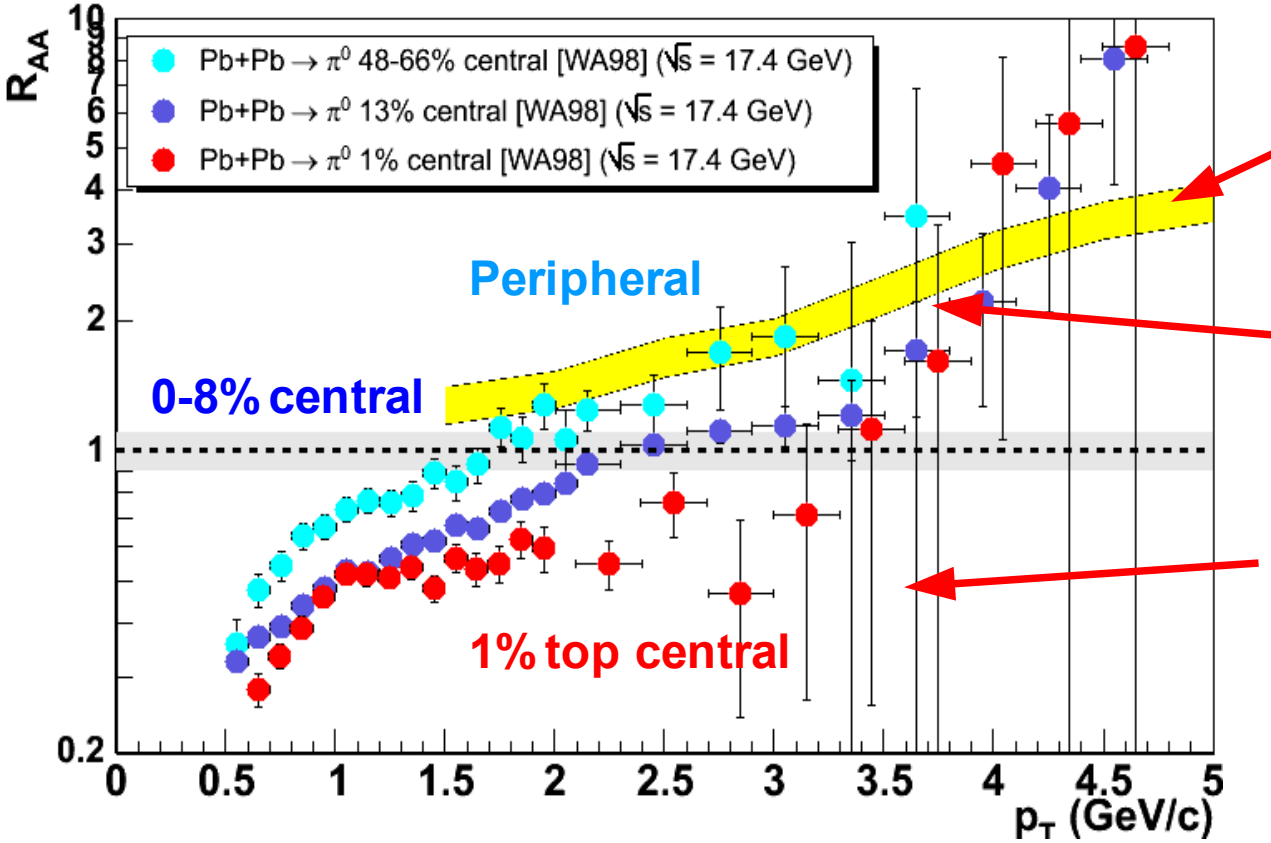
- High p_T π^0 production in ~0 –10% central A+A at SPS and ISR energies:



... not enhanced but consistent with "collision scaling" (R_{AA} ~ 1) above p_T~2 GeV/c

Indications of high p_T suppression @ SPS

- Centrality evolution of high p_T π^0 production (WA98 Pb+Pb $\sqrt{s}$ = 17.3 GeV):



R_{AA} GLV prediction at SPS: w/o energy loss (just Cronin)

[See A. Accardi talk also]

- "Cronin" enhancement in peripheral Pb+Pb
- Suppression in 1% (!?) most central Pb+Pb

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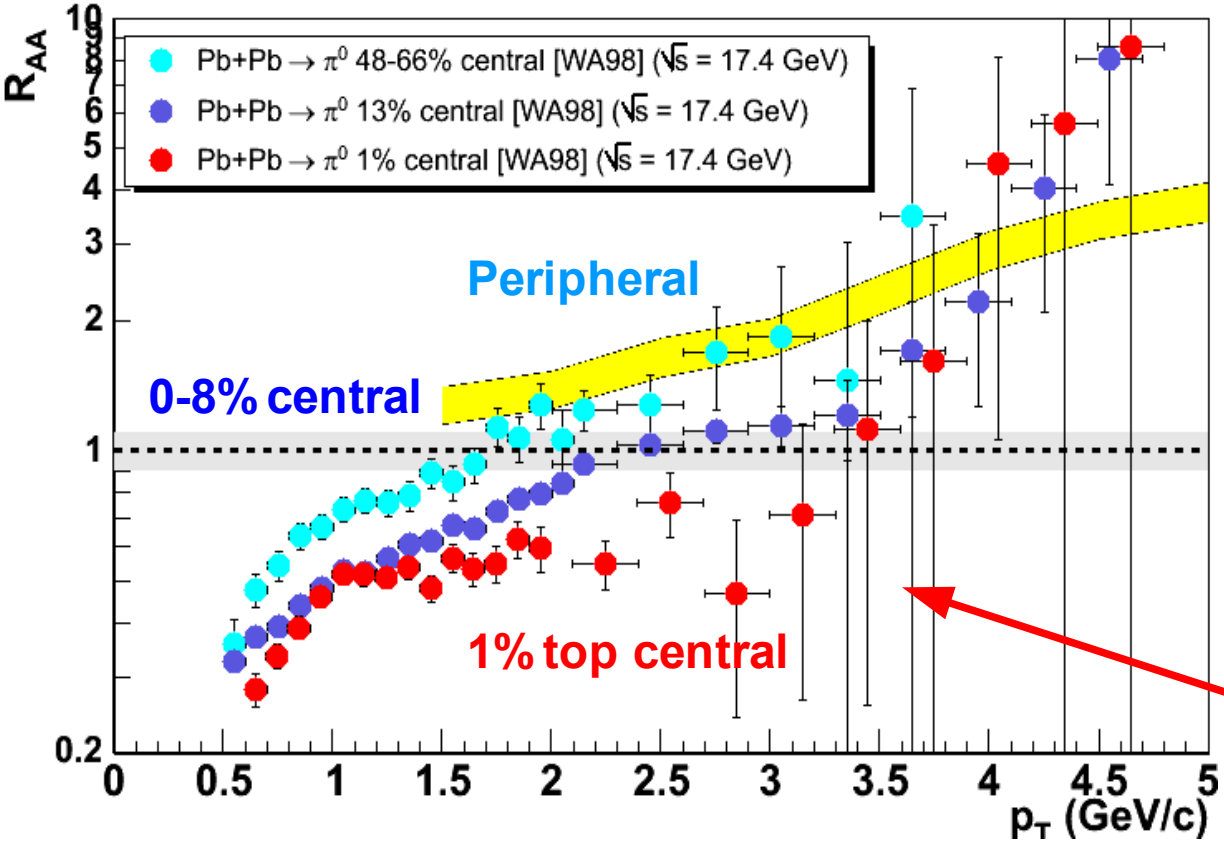
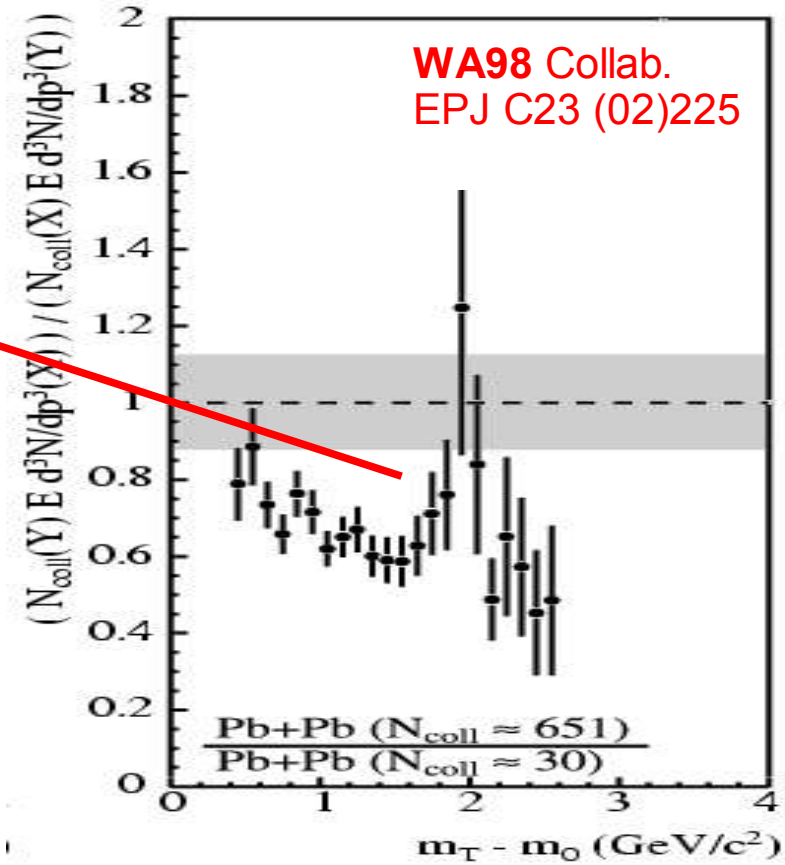
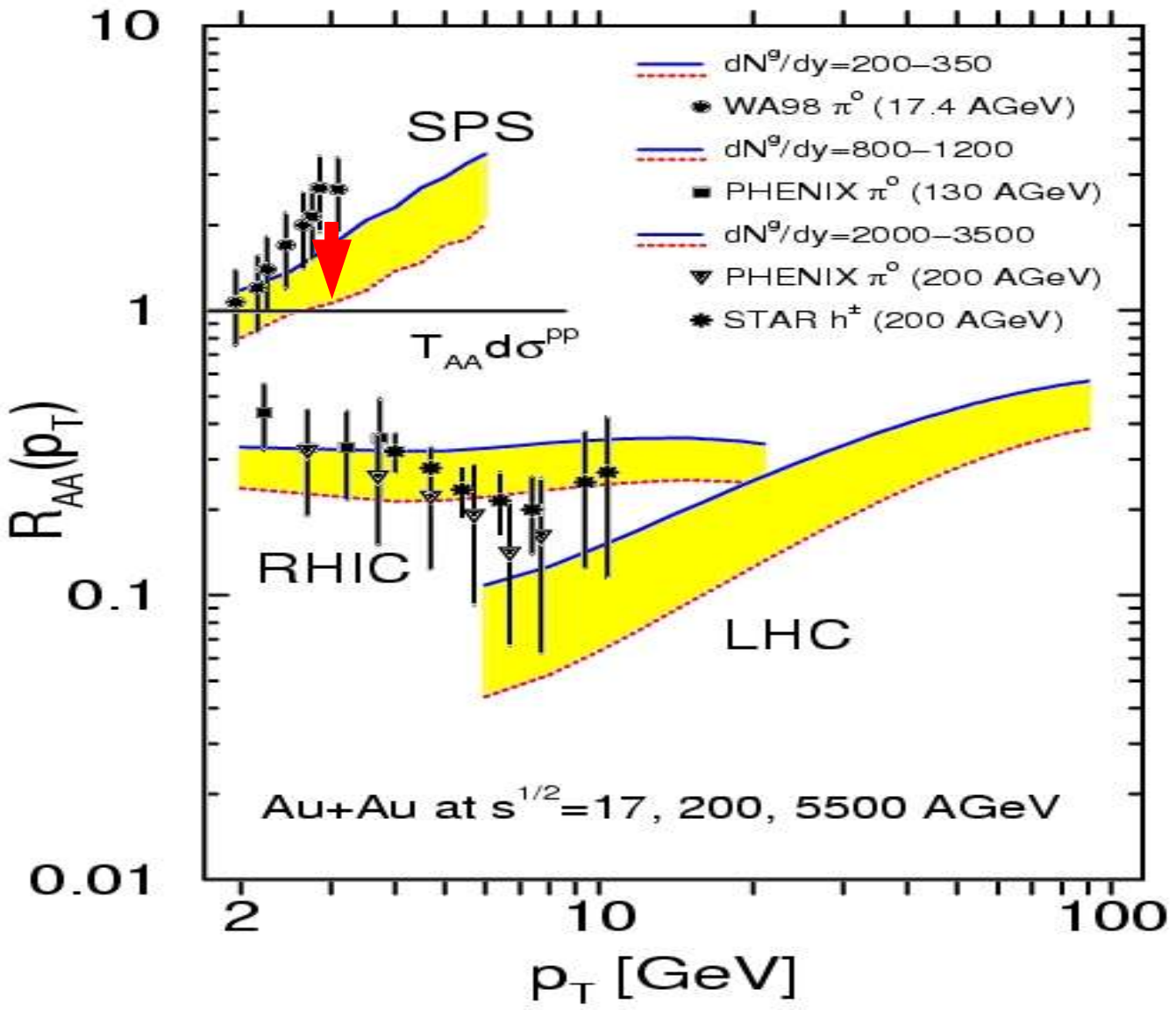




- New R_{AA} is now consistent with originally published WA98 suppressed R_{cp}

High p_T @ SPS: data vs. theory

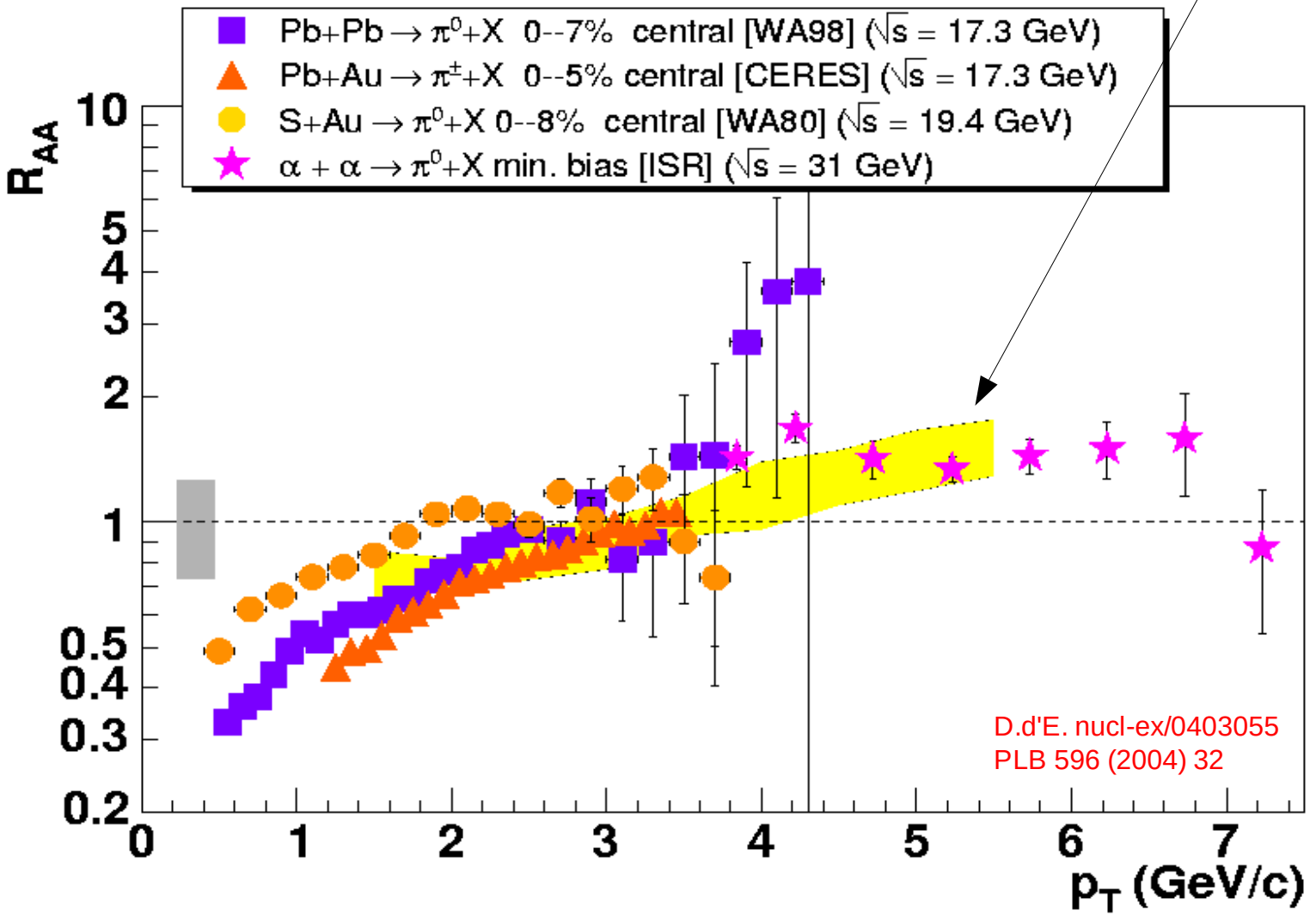
- New R_{AA} at SPS agree better with SPS parton energy loss predictions:



Vitev, Gyulassy
PRL 89 (2002) 252301

High p_T @ SPS: data vs. theory

- New R_{AA} at SPS agree with parton energy loss calculations [I.Vitev nucl-th/0404052] in moderately dense system: $dN^g/dy \sim 400\text{-}600$ (more consistent with estimated $\varepsilon_{Bj} \sim 3$ GeV/fm^3).



Measuring a high p_T p+p reference @ $\sqrt{s} \approx 20$ GeV ?

- Option (1):

SPS-NA49 ?

Concerning NA49 high-pt: With the existing data you could not do very much. The statistics in p+p is sufficient for h- up to pt=2-2.5 GeV/c, as it looks. But in the context of the NA49 future an extension of these measurements is proposed
However, an effort in this direction would require an upgrade of the NA49 DAQ, since you would need to collect like 100M p+p events to make a difference. So, it is feasible but difficult,

Christoph Blume
University of Frankfurt/Main, IKF

SPS- NA57 / WA97 ?

NA57 has data for Pb-Pb and p-Be (almost pp) at 160A GeV/c and at 40A GeV/c;
WA97, which is basically the same experiment has also p-Pb at 160A GeV/c.
The best thing would be to get R_AA = Pb-Pb/p-Be and R_pA = p-Pb/p-Be.
Of course the pt reach in p-Be might be quite limited...
At the moment we are trying to concentrate on Rcp for Pb-Pb at 160A GeV/c.

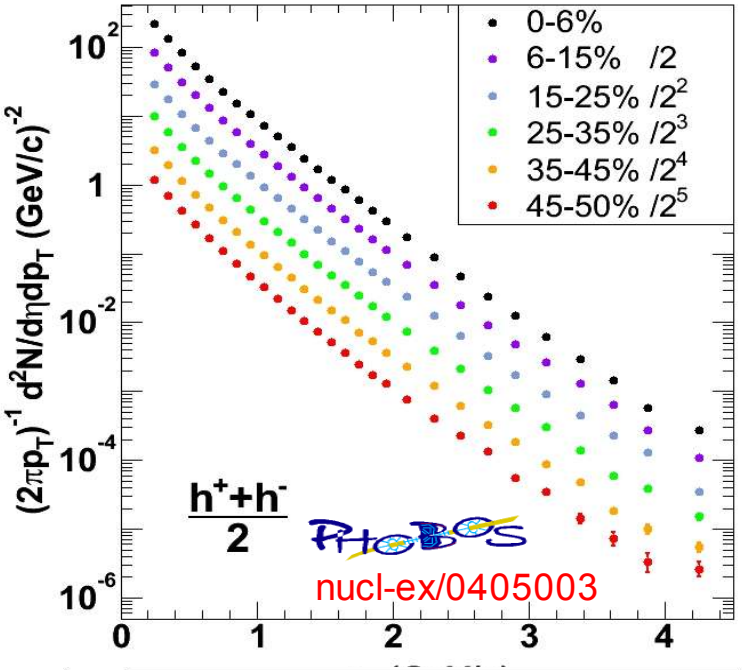
we will try to do it separately for h^-, K^0 and Lambda(+LambdaBar).
Concerning the pt reach, we still didn't finish to include the whole statistics we have, but it will be something on the ballpark of the WA98 pi^0 data.

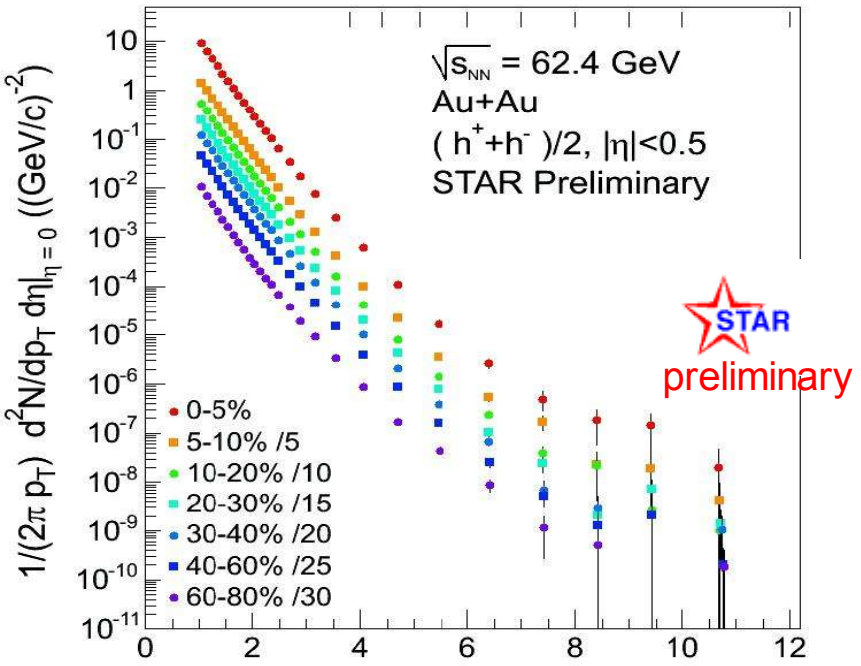
Andrea Dainese - ALICE Collaboration -
-
Universita' degli Studi di Padova
tel. +39 049 827 7106

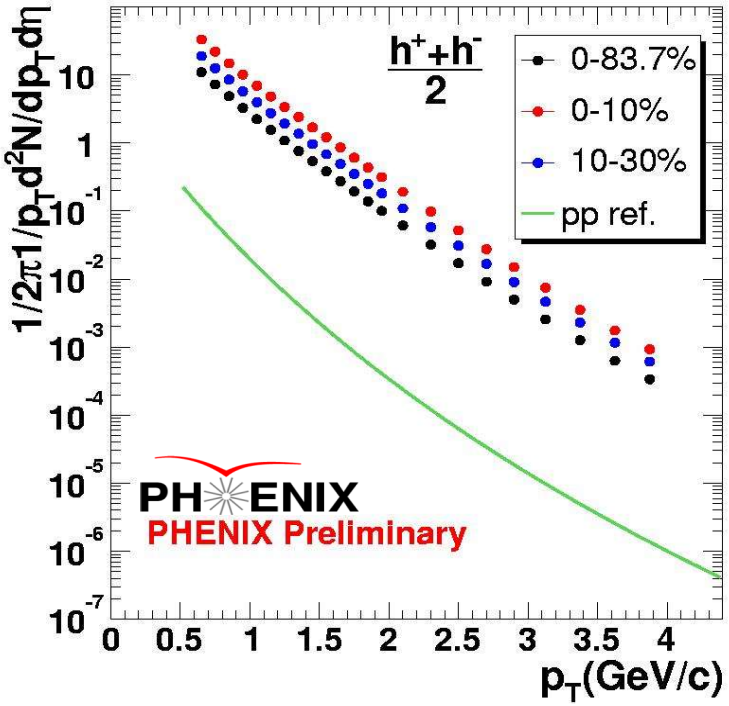
- Option (2): RHIC Au+Au, p+p run at $\sqrt{s} \approx 20$ GeV (feasible, though would need more support from RHIC community, long runs required to collect stat !)

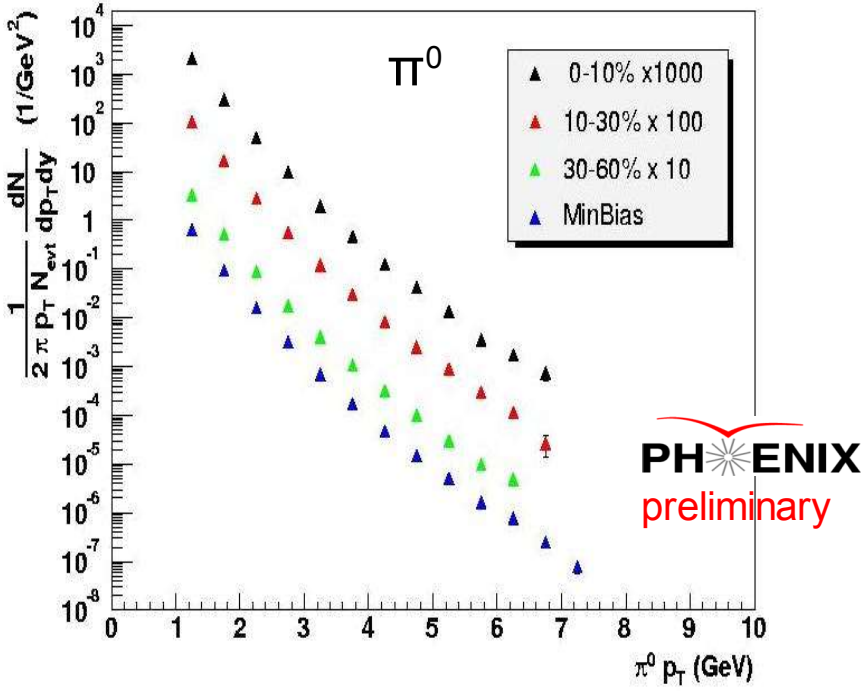
Au+Au @ RHIC:
High p_T suppression at $\sqrt{s_{NN}}$ = 62.4 GeV

High p_T Au+Au spectra @ RHIC 62.4 GeV



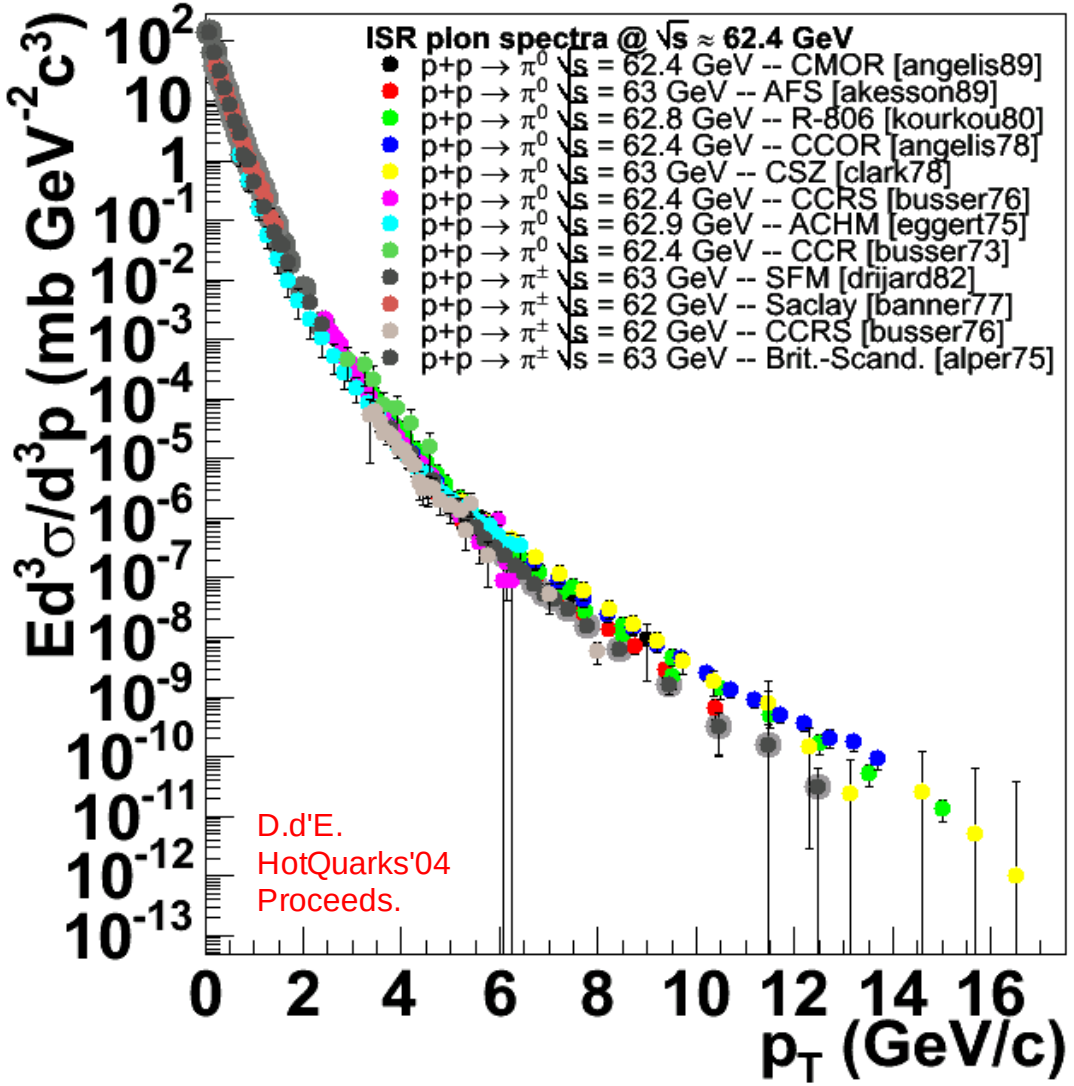


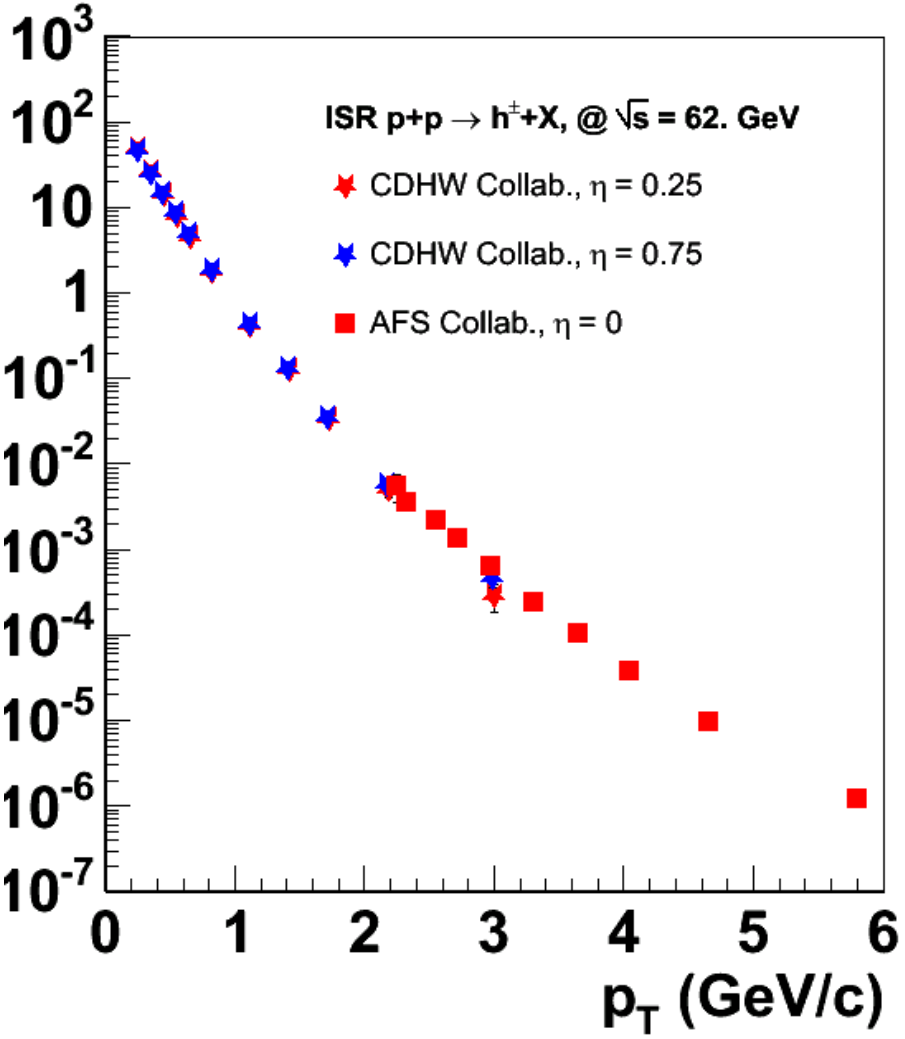




High p_T baseline p+p spectra @ 62.4 GeV ?

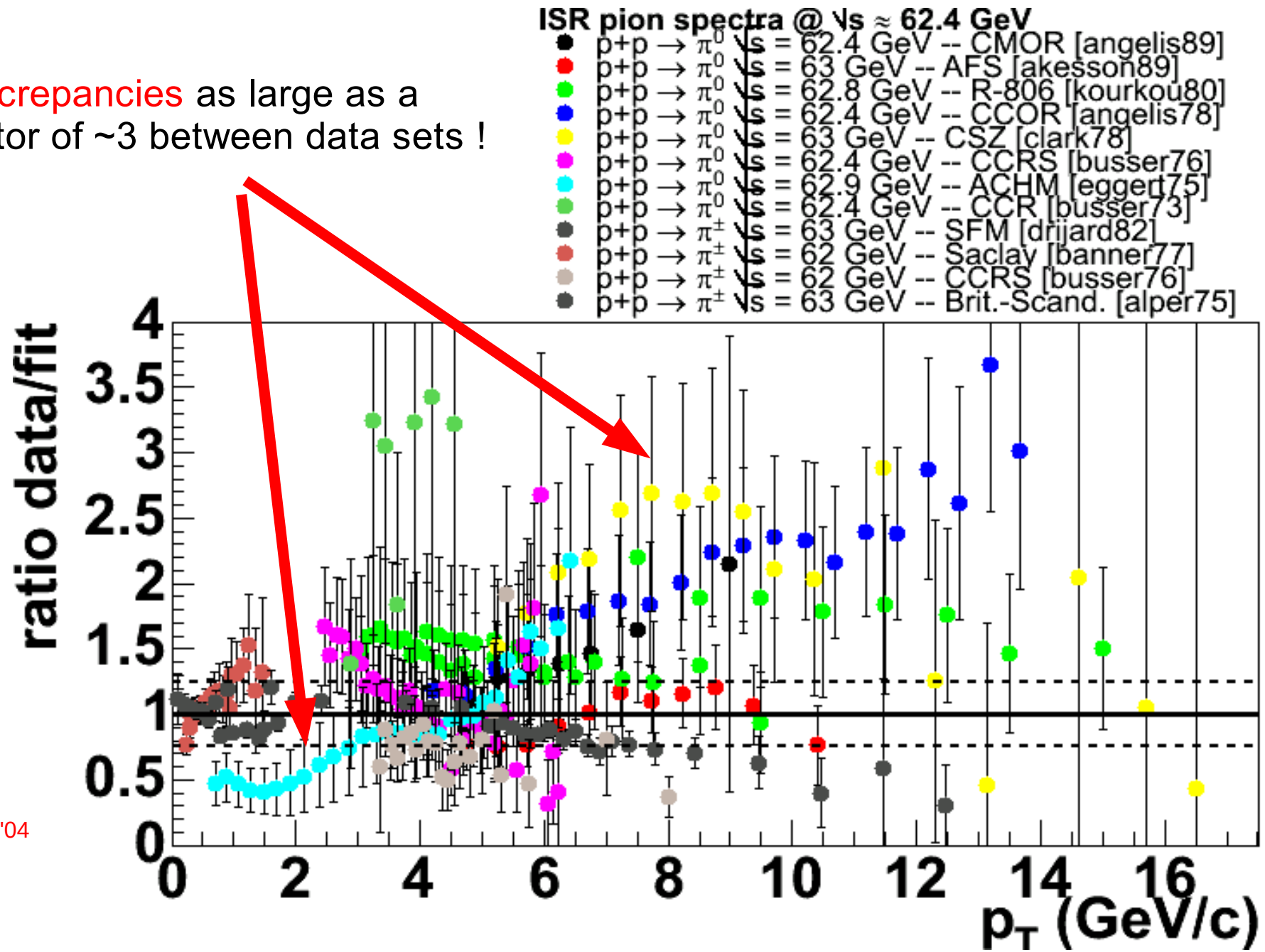
- No concurrent p+p @ 62.4 GeV measured at RHIC in Run-4 ...
- p+p @ 62–63 GeV measured at ISR: π^0 (8), $\pi^{\pm}$ (4), charged hadrons (2)





p+p → π+X spectra @ 62.4 GeV are not consistent

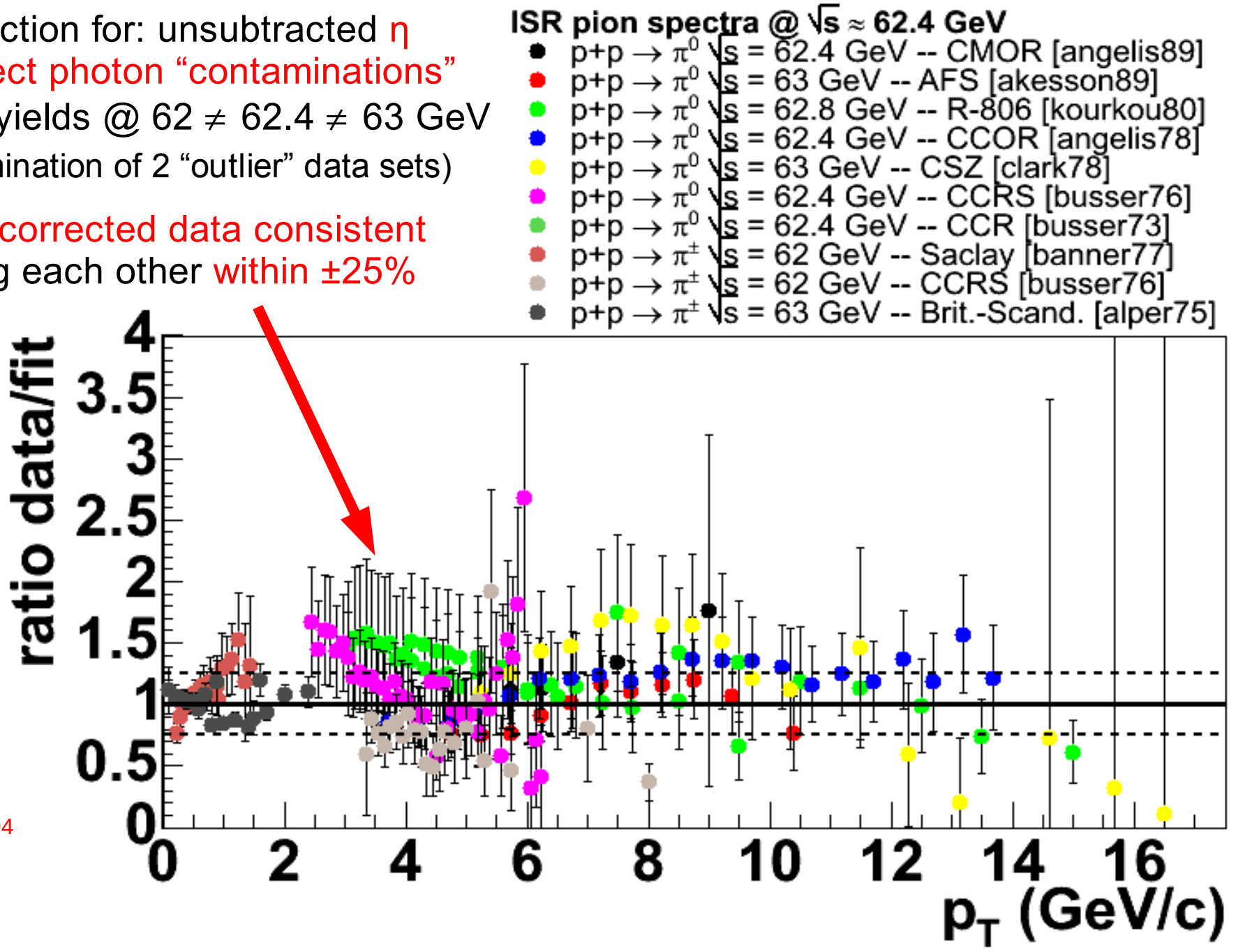
- Discrepancies as large as a factor of ~3 between data sets !



D.d'E. HotQuarks'04 Proceeds.

Final corrected p+p→ π+X spectra @ 62.4 GeV

- Correction for: unsubtracted η & direct photon "contaminations" hi-p_T yields @ 62 ≠ 62.4 ≠ 63 GeV
  (+ elimination of 2 "outlier" data sets)
- Final corrected data consistent among each other within ±25%

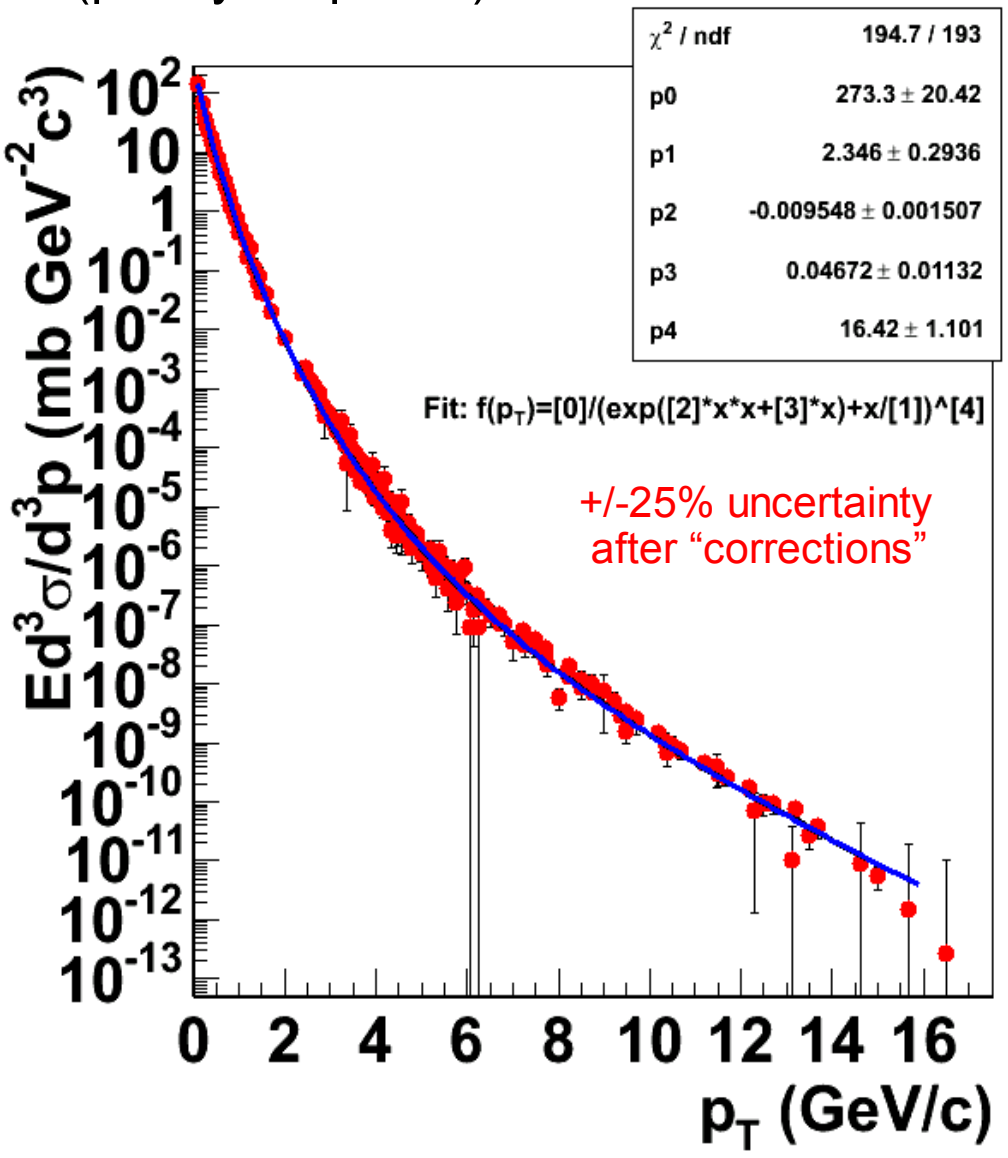


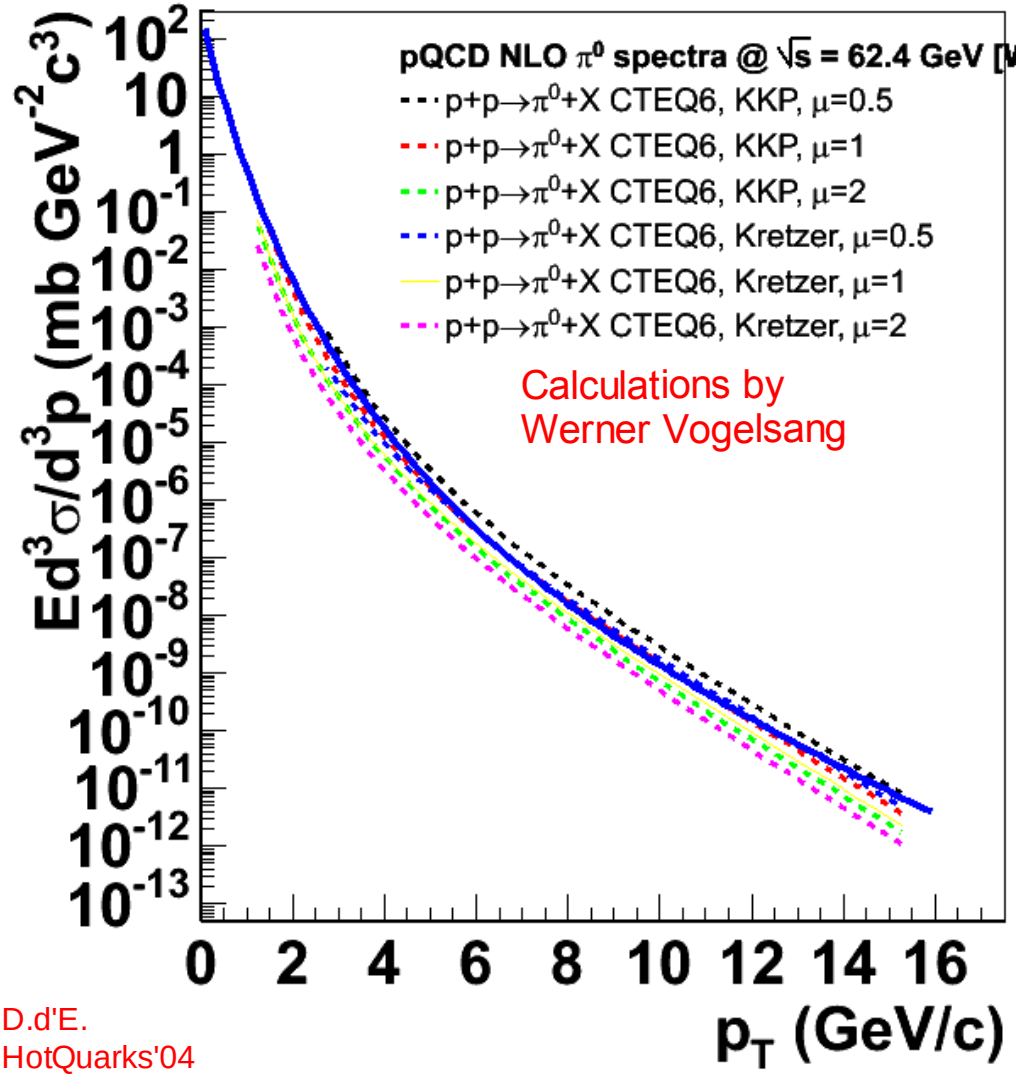
D.d'E. HotQuarks'04 Proceeds.

Parametrized p+p → π+X reference @ √s = 62.4 GeV

Parametrization: $f(p_T) = A/(e^{a\cdot x^2+b\cdot x} + x/p_0)^n$
(purely empirical)

Good agreement with NLO:

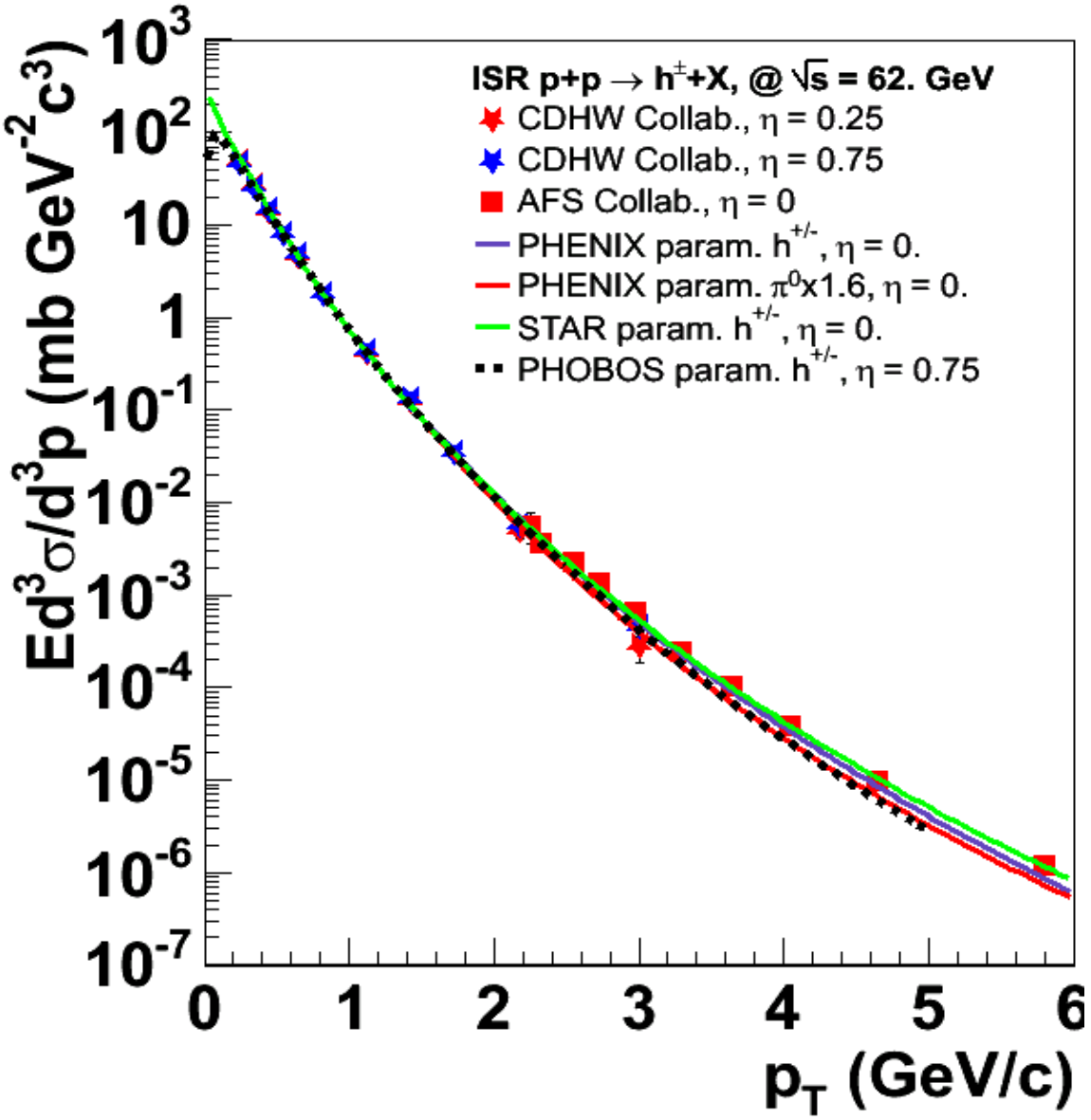




D.d'E. HotQuarks'04 Proceeds.

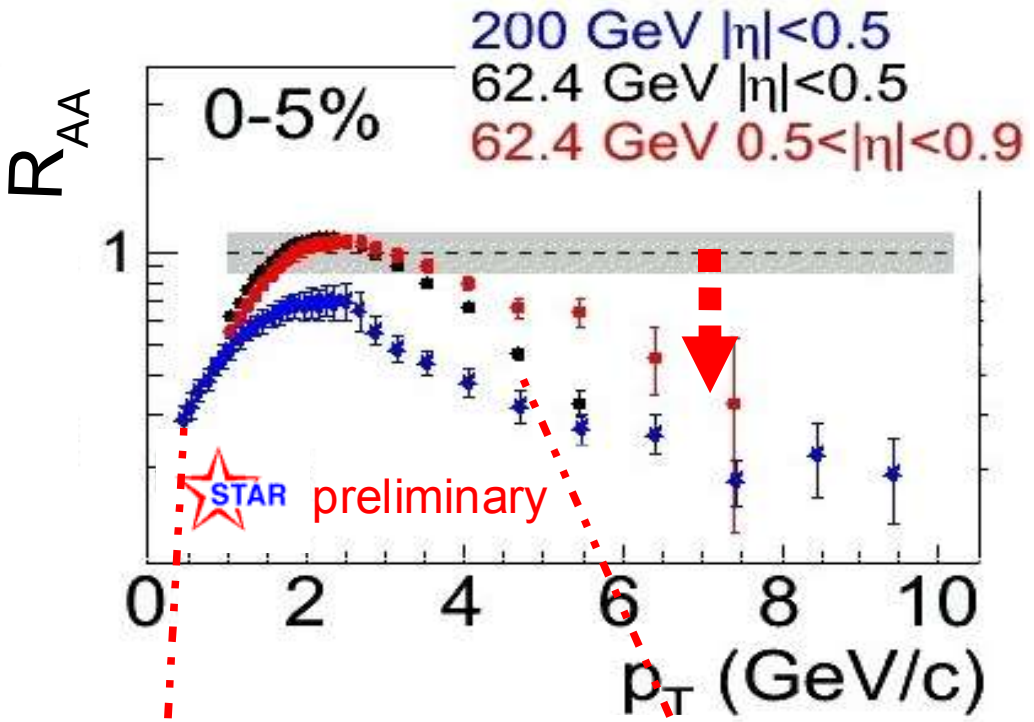
Parametrized p+p → $h^{\pm}$ +*X* reference @ $\sqrt{s}$ = 62.4 GeV

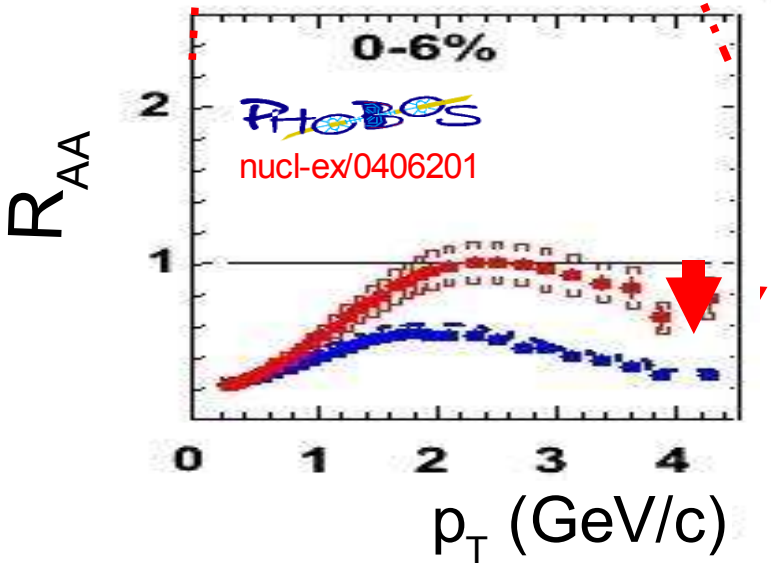
- Reasonable agreement (within ~30% norm. uncertainties) of PHOBOS/STAR/PHENIX $h^{+/-}$ parametrizations and existing data



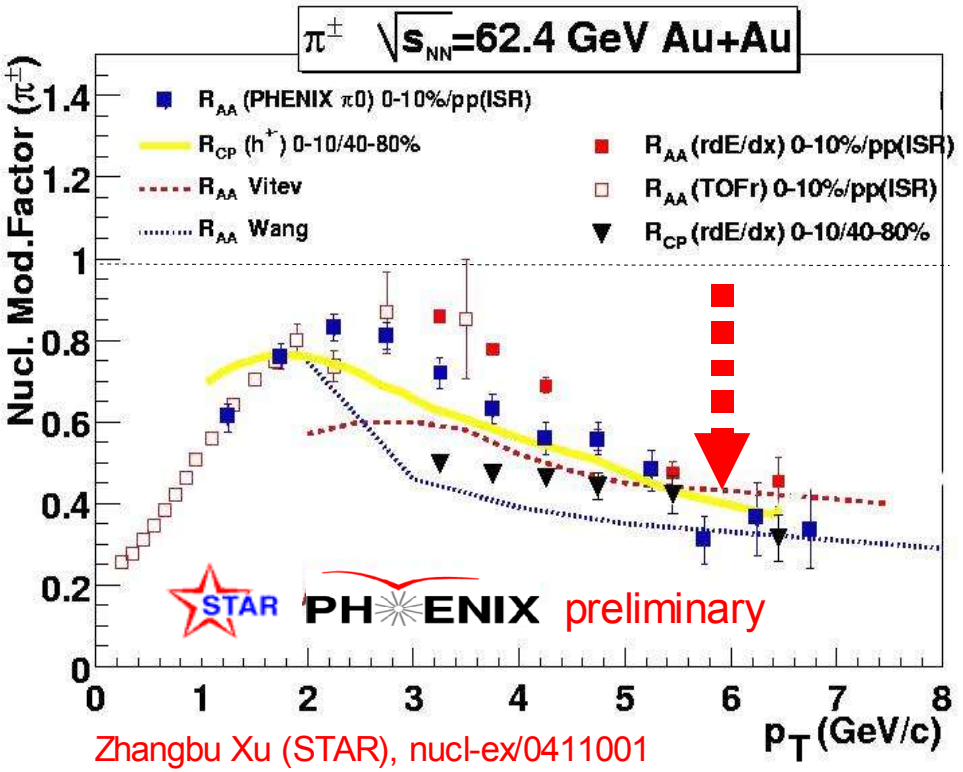
High p_T suppression in central Au+Au @ 62.4 GeV

Charged hadrons





Neutral & charged pions

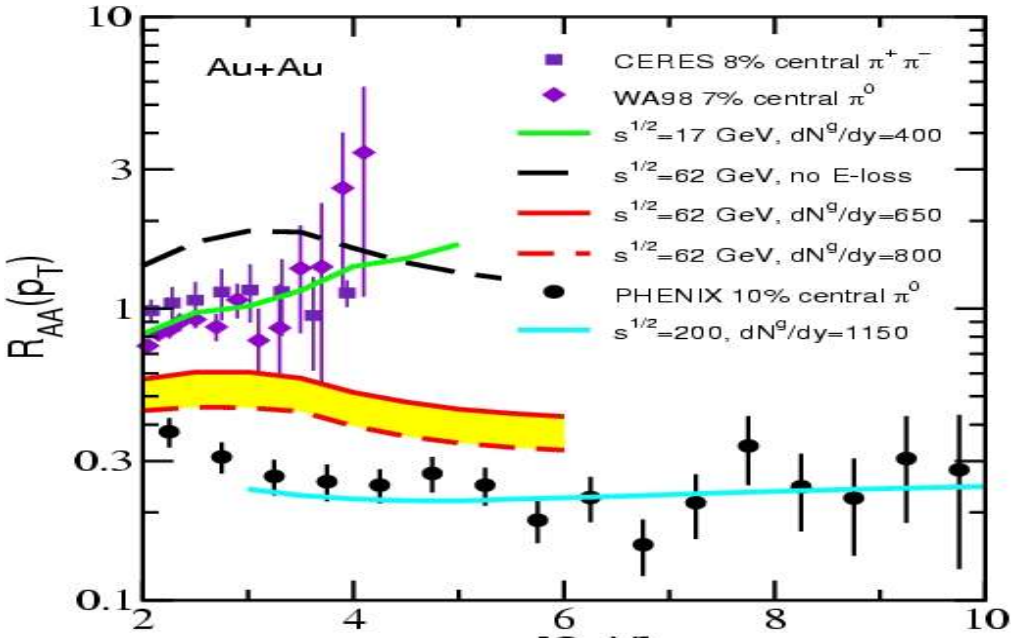


Zhangbu Xu (STAR), nucl-ex/0411001

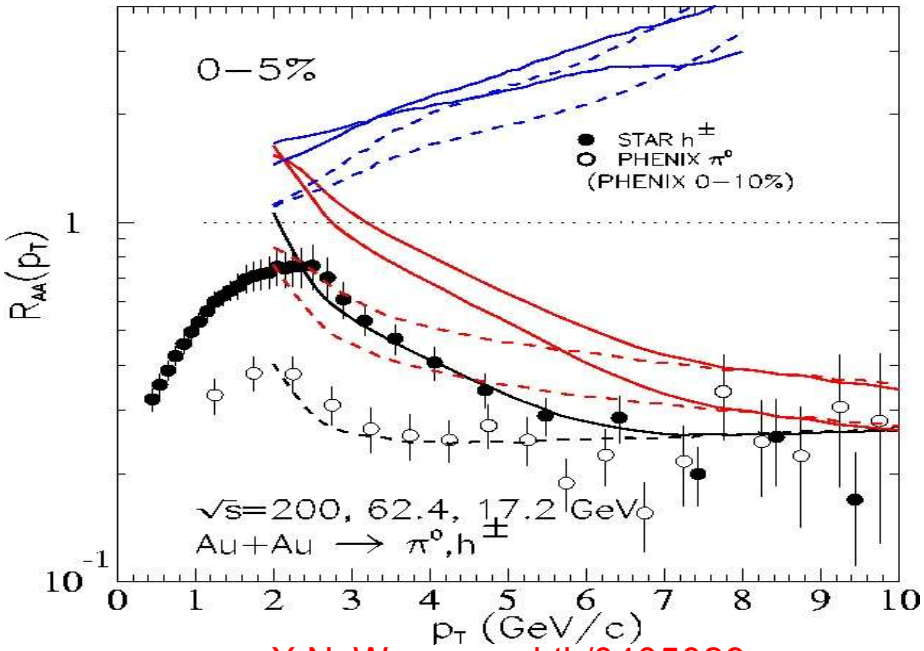
R_{AA} ~ 1 at p_T~2-3 GeV/c ($h^{\pm}$)
R_{AA} ~ 0.8 at p_T~2-3 GeV/c ($\pi^{0,\pm}$)
R_{AA} ~ 0.3 for p_T > 6 GeV/c ($h^{\pm}$,$\pi^{0,\pm}$)

- $h^{\pm}$ less suppressed than $\pi^{0,\pm}$ at intermediate p_T's ("baryon enhancement") [See talks by B.Jacak, R.Hwa, J.Velkovska]

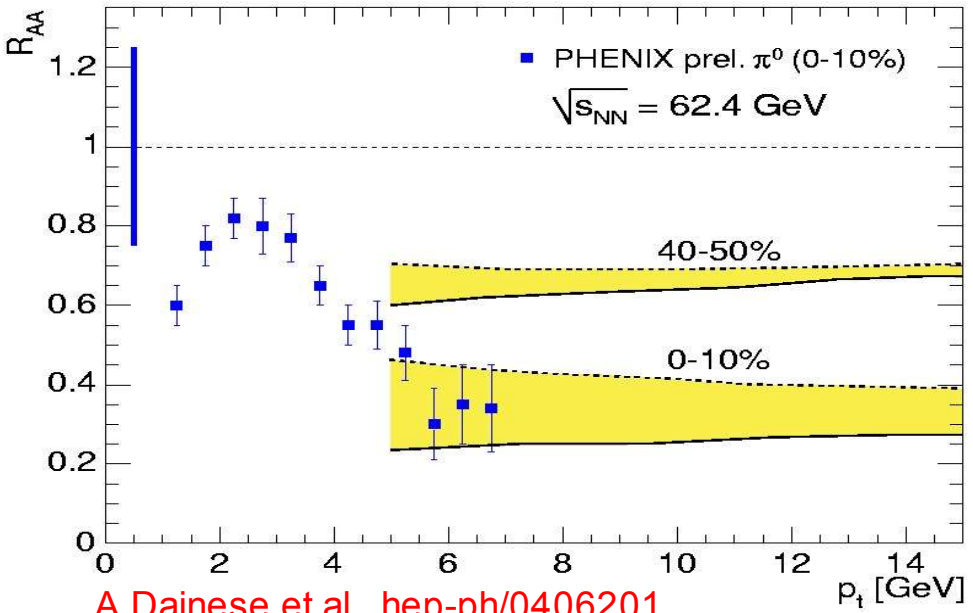
High p_T Au+Au @ 62.4 GeV : data vs theory



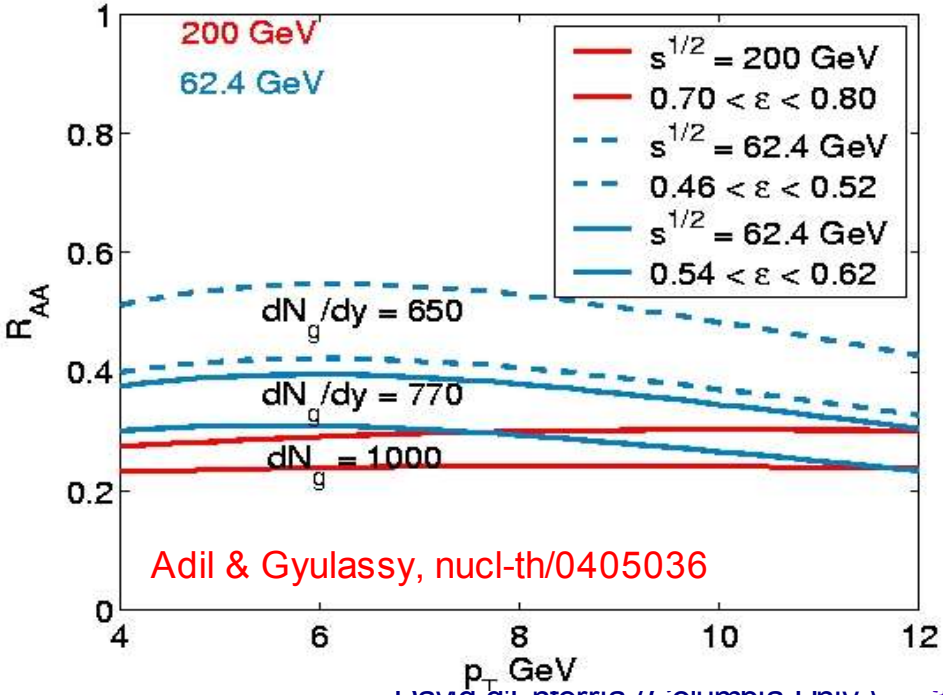
I. Vitev, nucl-th/0404052



X.N. Wang, nucl-th/0405029

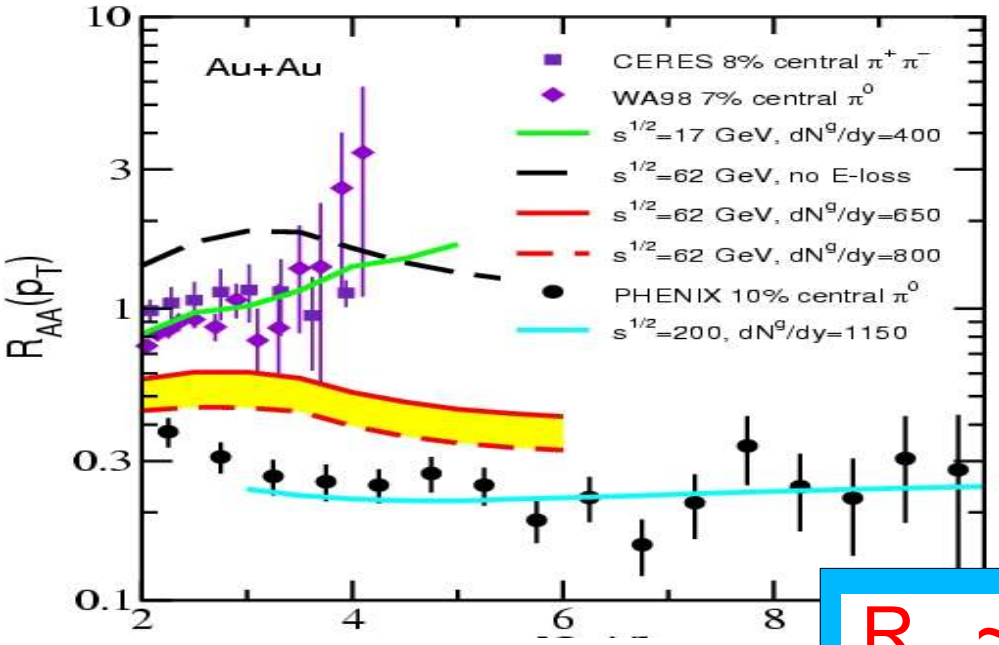


A.Dainese et al., hep-ph/0406201

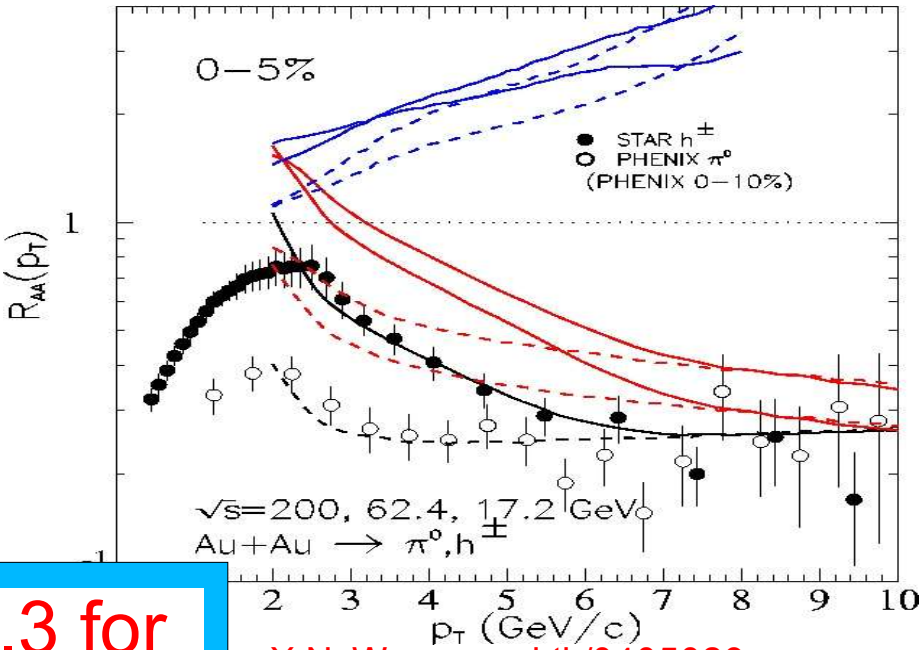


Adil & Gyulassy, nucl-th/0405036

High p_T Au+Au @ 62.4 GeV : data vs theory

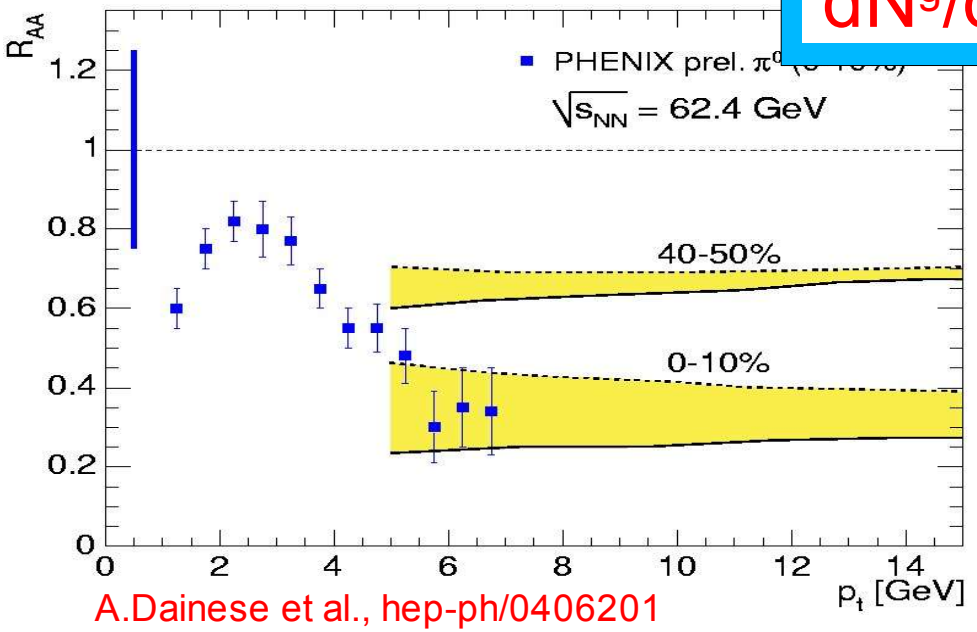


I. Vitev, nucl-th/0404052

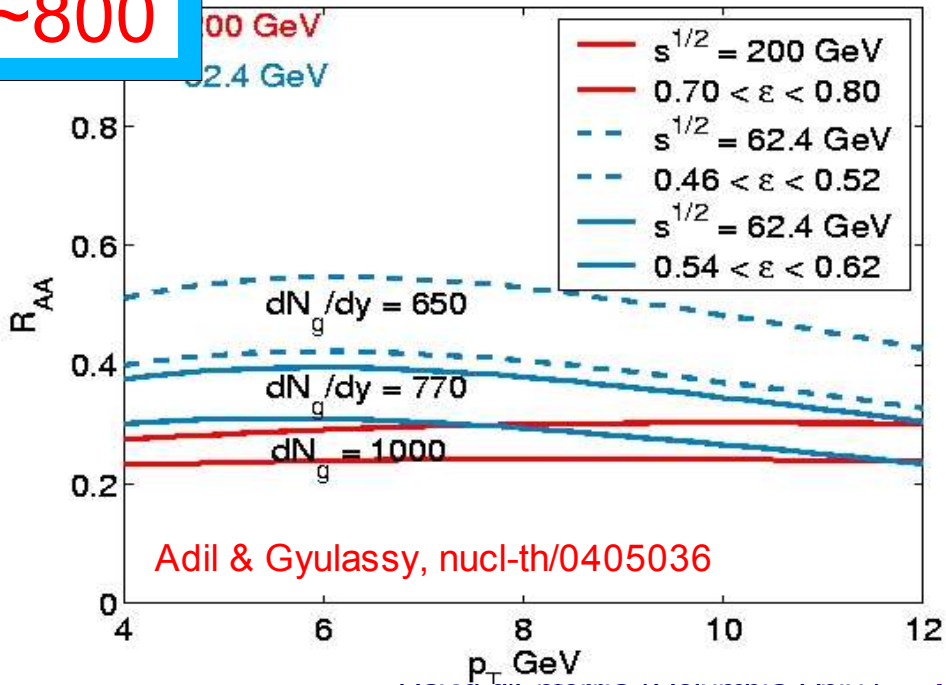


X.N. Wang, nucl-th/0405029

R_{AA}~0.3 for dN^g/dy~800



A.Dainese et al., hep-ph/0406201



Adil & Gyulassy, nucl-th/0405036

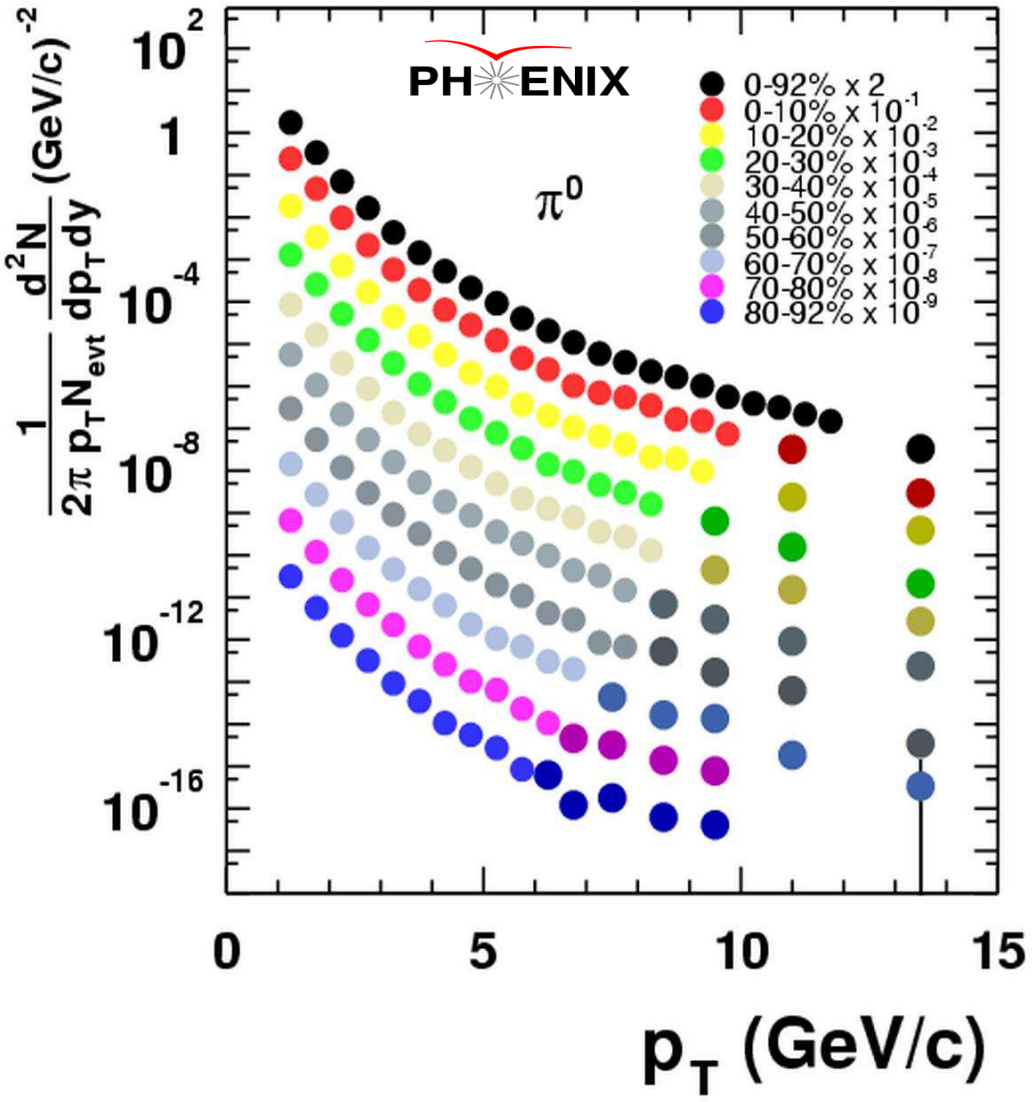
Au+Au @ RHIC:
High p_T suppression at $\sqrt{s_{NN}}$ = 200 GeV

some more recent stuff(*) ...

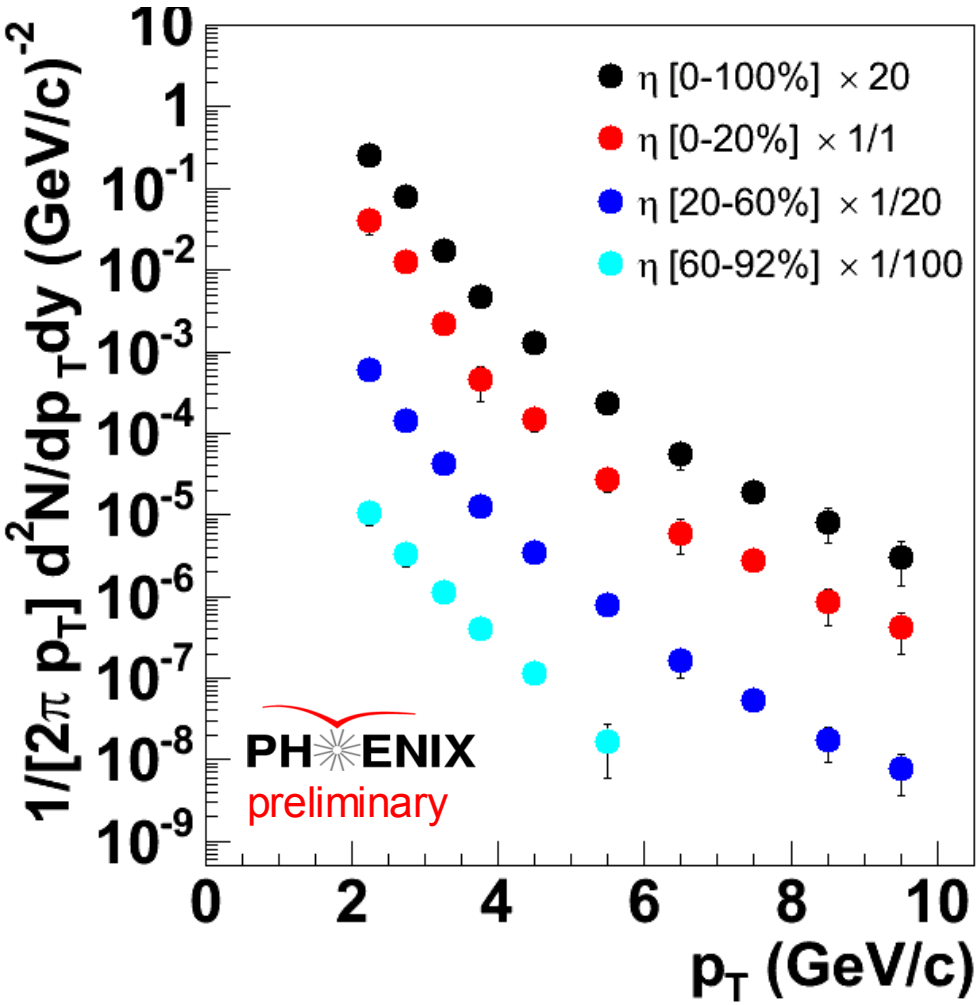
[(*) More details in Henner Buesching's talk tomorrow]

Latest high p_T Au+Au spectra @ RHIC 200 GeV

Au+Au → π^0 +X



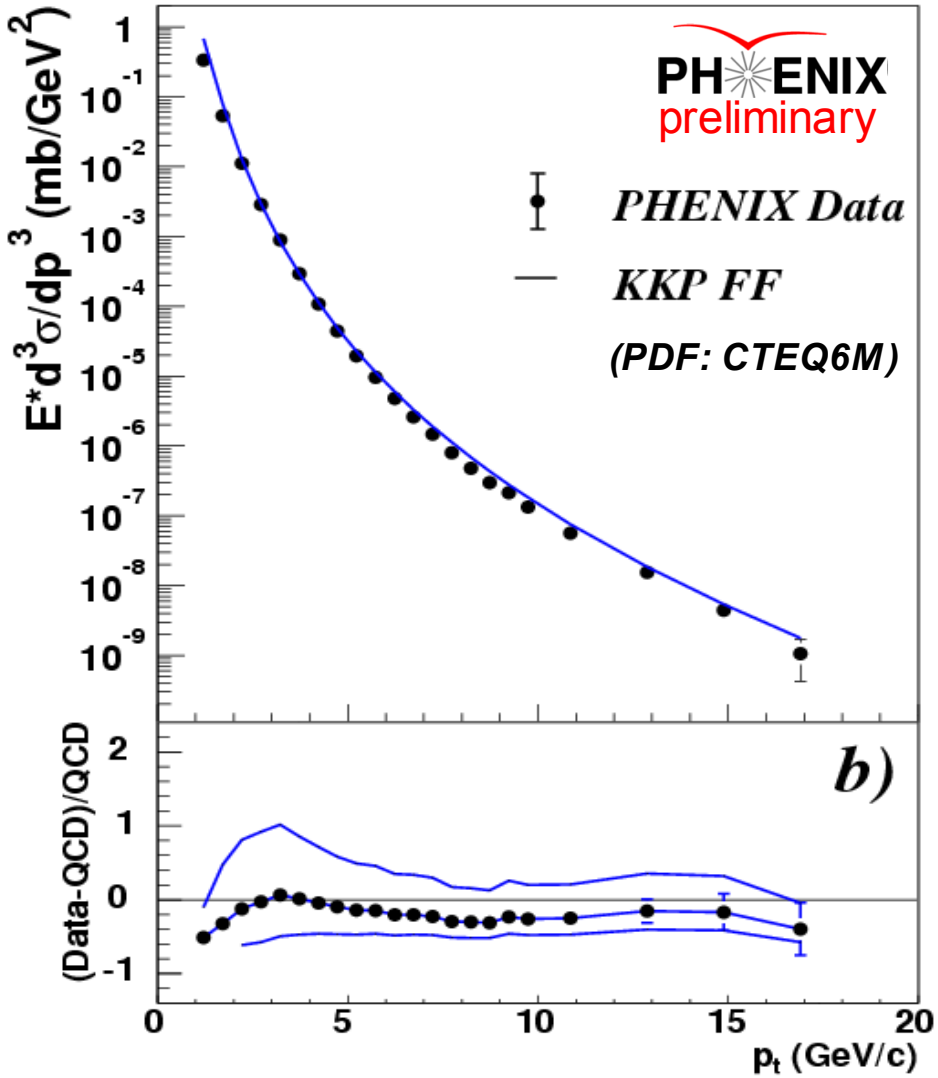
Au+Au → η+X



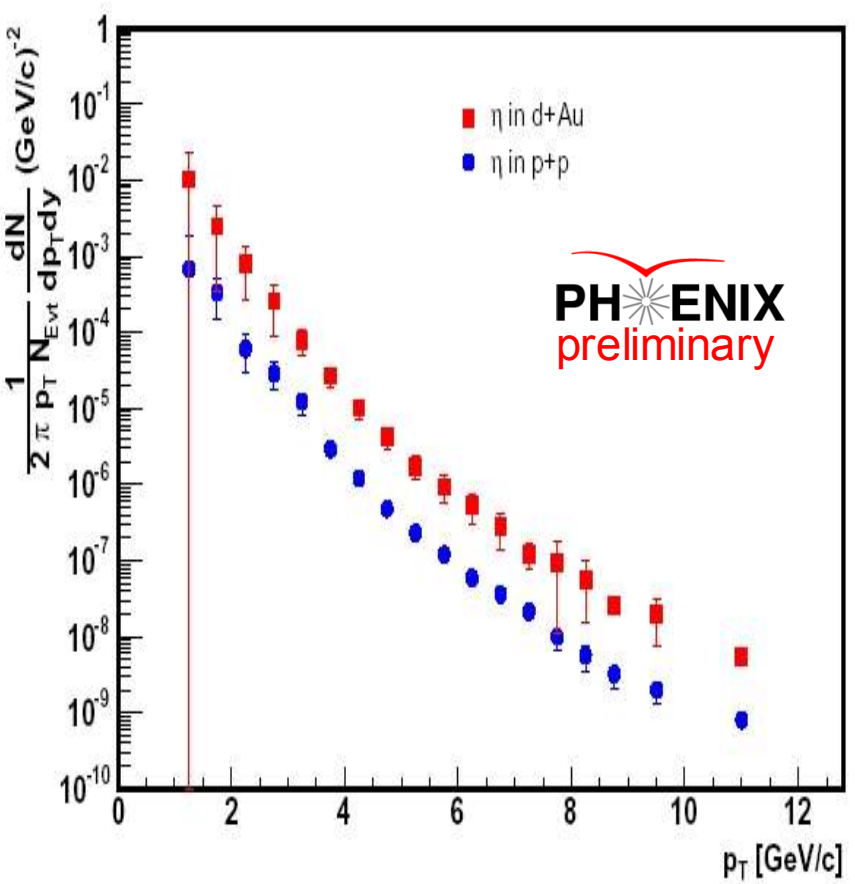
- Measured spectra well in the perturbative domain: p_T^{max} ~ 15 (10) GeV/c

Latest high p_T baseline p+p spectra @ 200 GeV

$p+p \rightarrow \pi^0 + X$



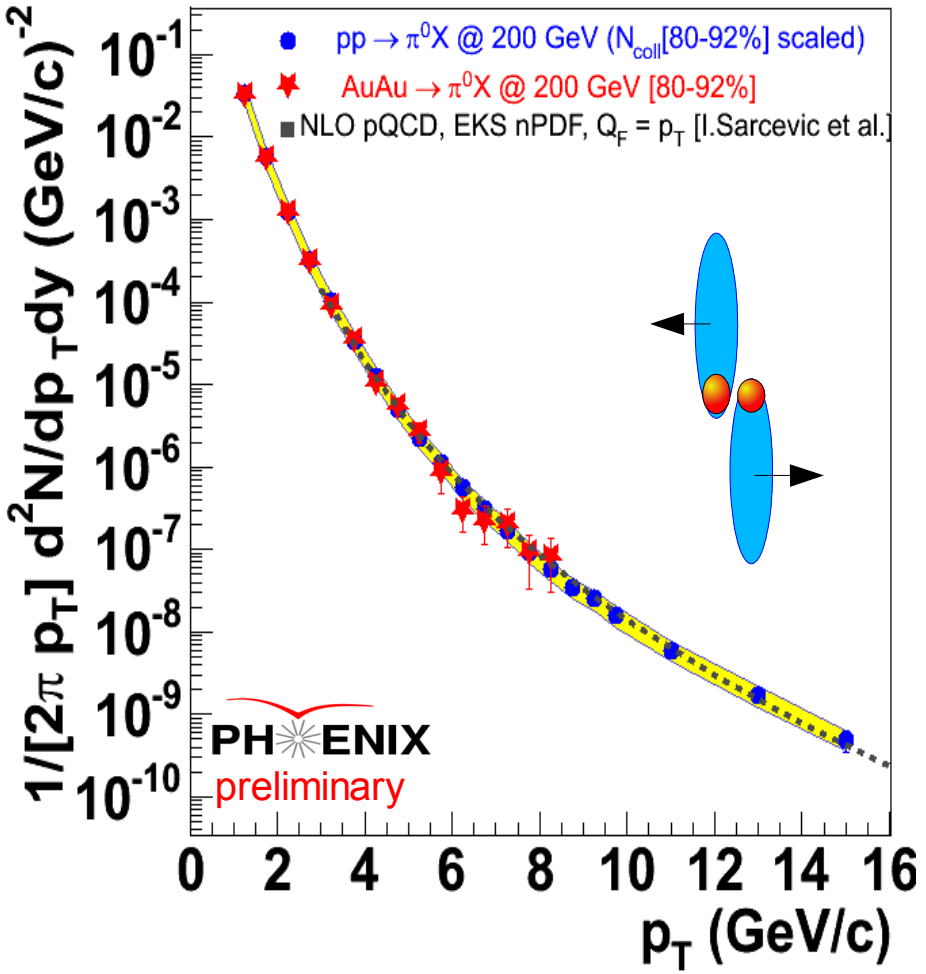
$p+p \rightarrow \eta + X$



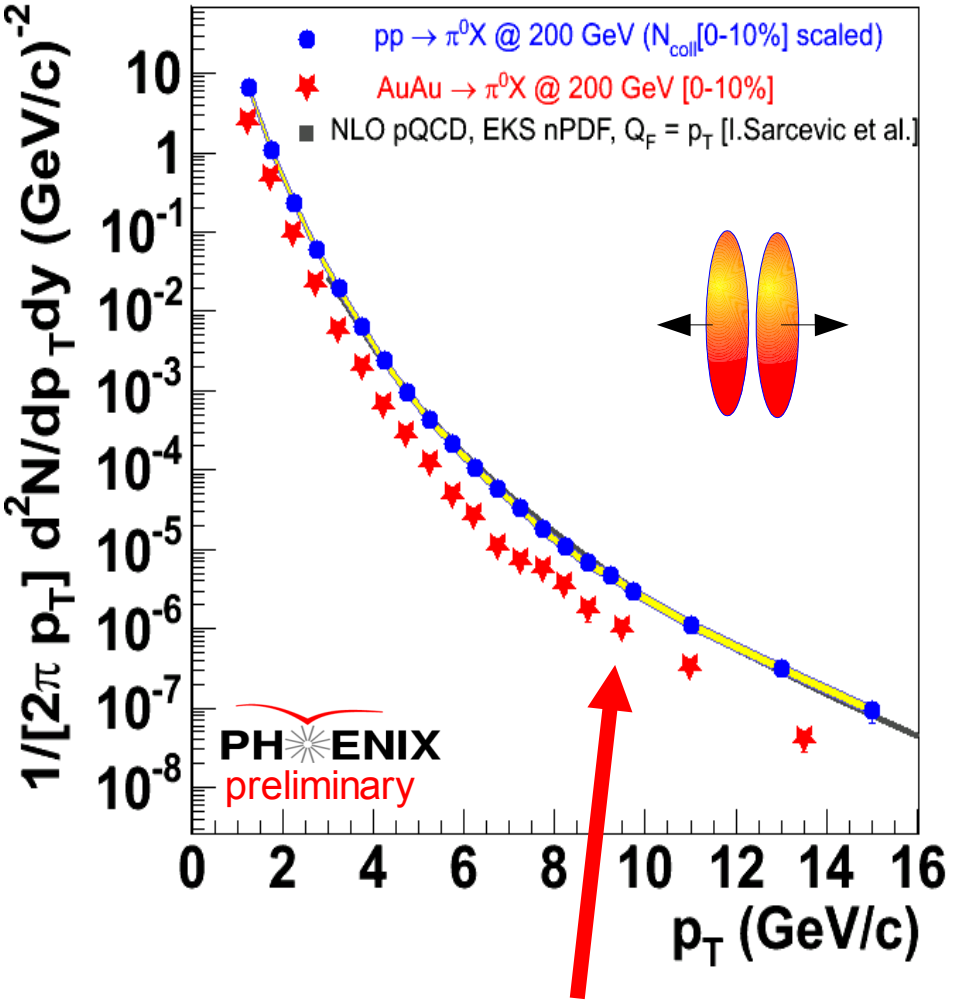
- Truly perturbative spectra (p_T^{max} = 17 GeV/c) well described by NLO pQCD

Au+Au *vs.* p+p @ 200 GeV (π^0)

Au+Au→ π^0 *X* (peripheral)



Au+Au→ π^0 *X* (central)

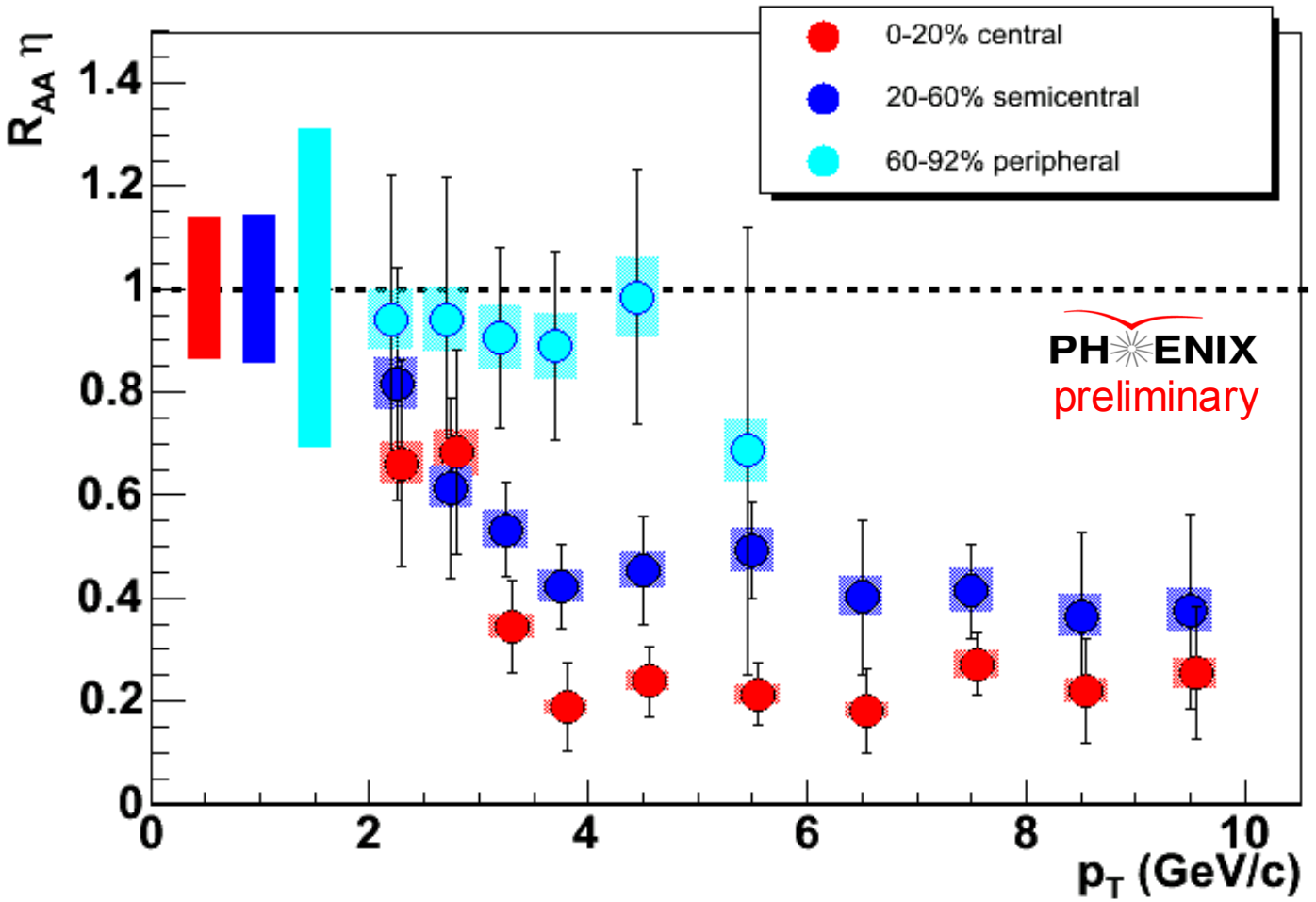


Peripheral data agree well with p+p (data&pQCD) plus N_{coll} scaling

Strong suppression in central Au+Au collisions

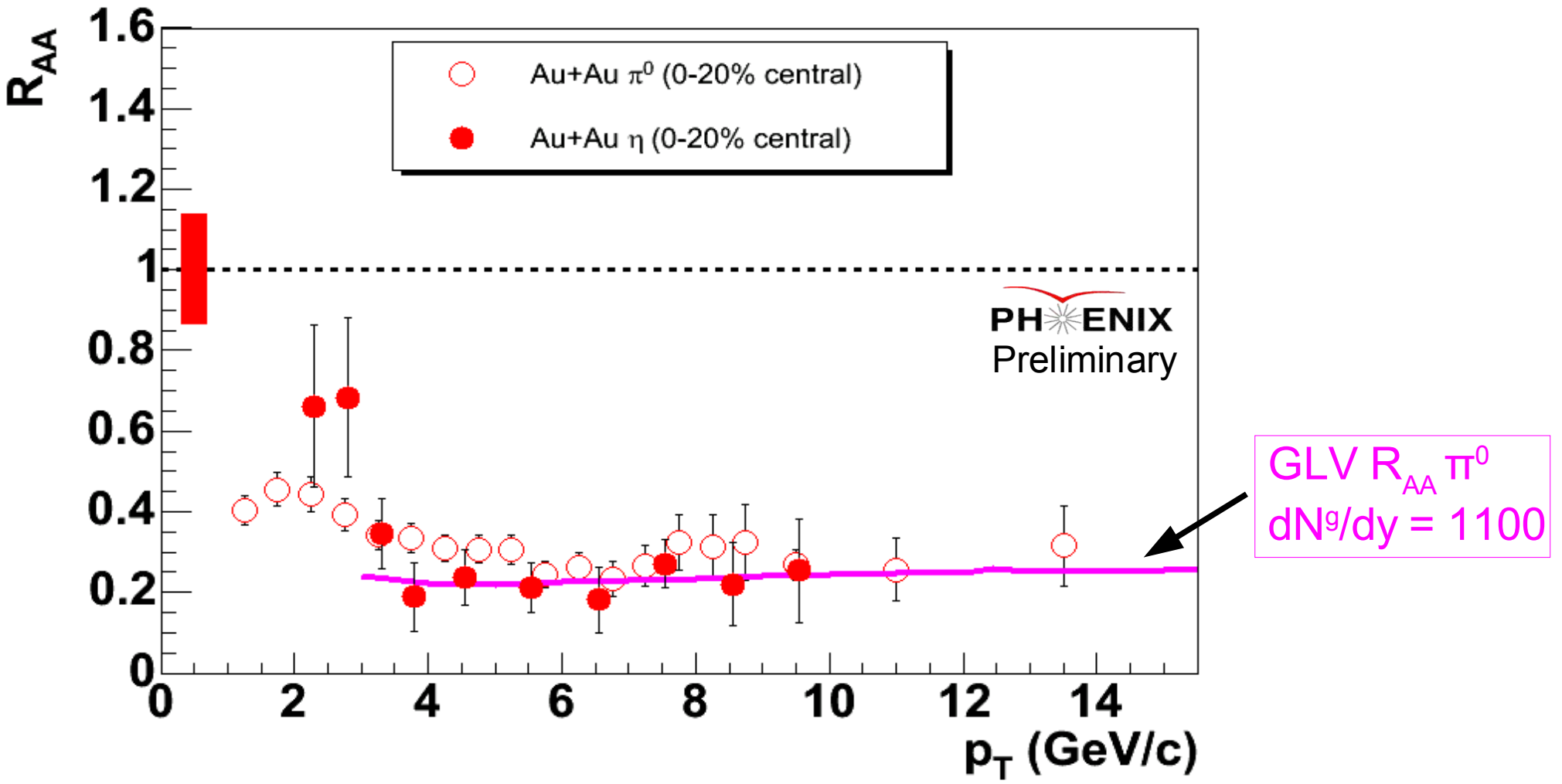
Latest R_{AA} in Au+Au @ 200 GeV

Au+Au→ η+*X* @ $\sqrt{s_{NN}}$ = 200 GeV



- Au+Au central: Strong suppression (R_{AA}~0.2)
- Au+Au semi-central: Suppression (R_{AA}~0.4)
- Au+Au peripheral: consistent w/ N_{coll} scaling (R_{AA}~0.9)

Latest R_{AA} @ 200 GeV

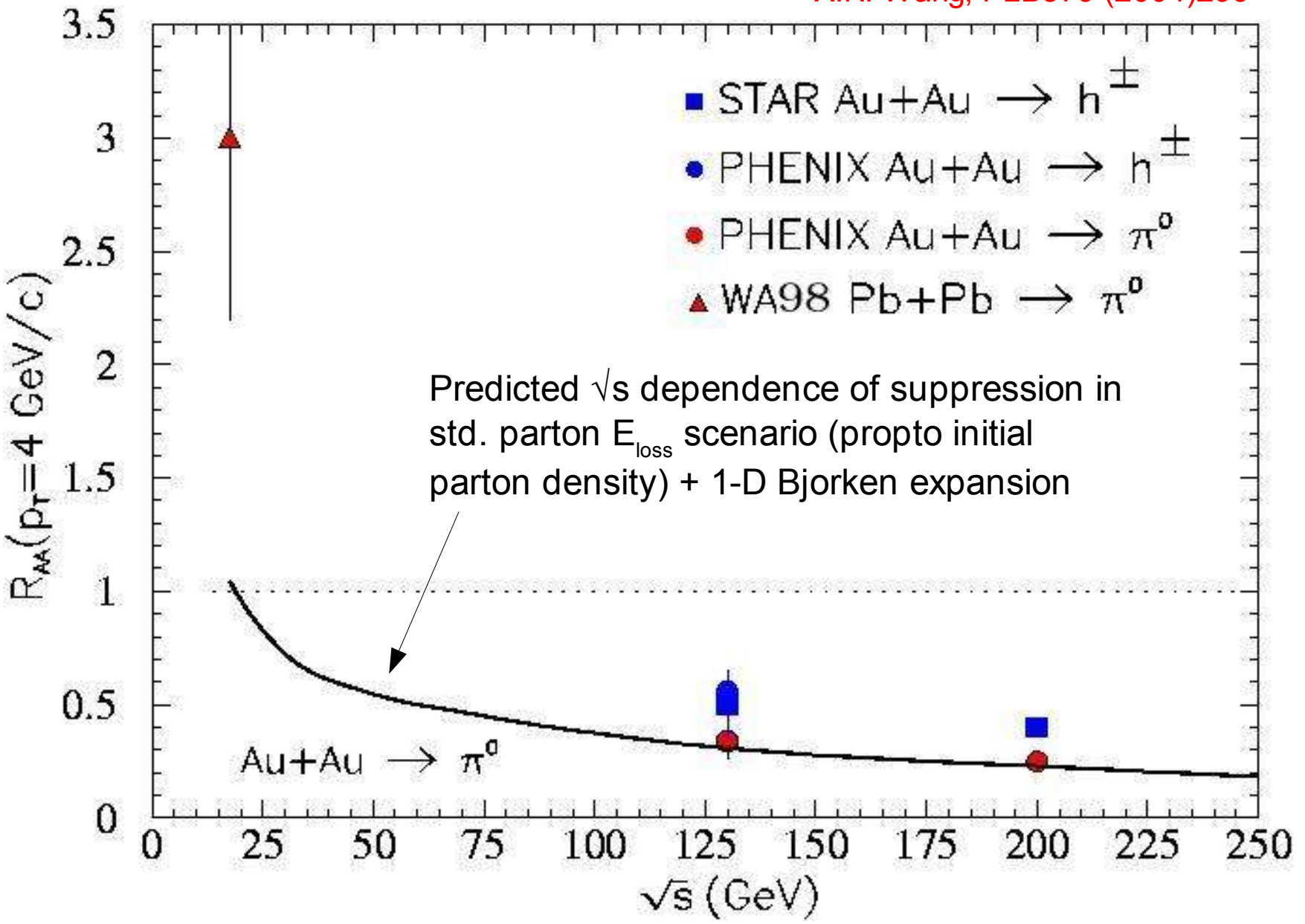


- Coincident suppression pattern for π^0 and η: magnitude, p_T dependence
- Agreement with parton energy loss (GLV) predictions in dense medium (flat behaviour up to the highest p_T values measured so far)

Excitation function of high p_T suppression from SPS to RHIC

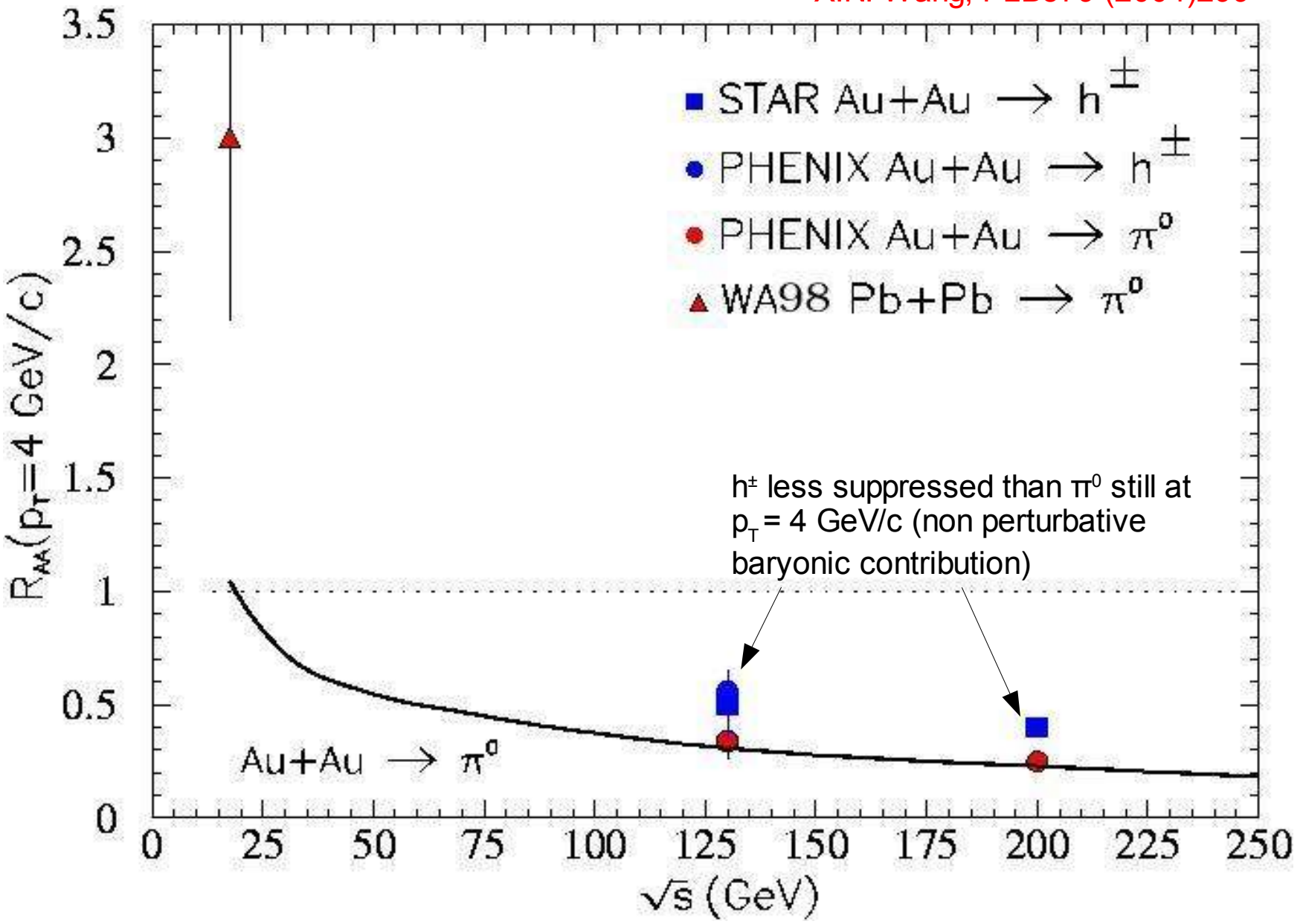
Excitation function of high p_T suppression

X.N. Wang, PLB579 (2004)299



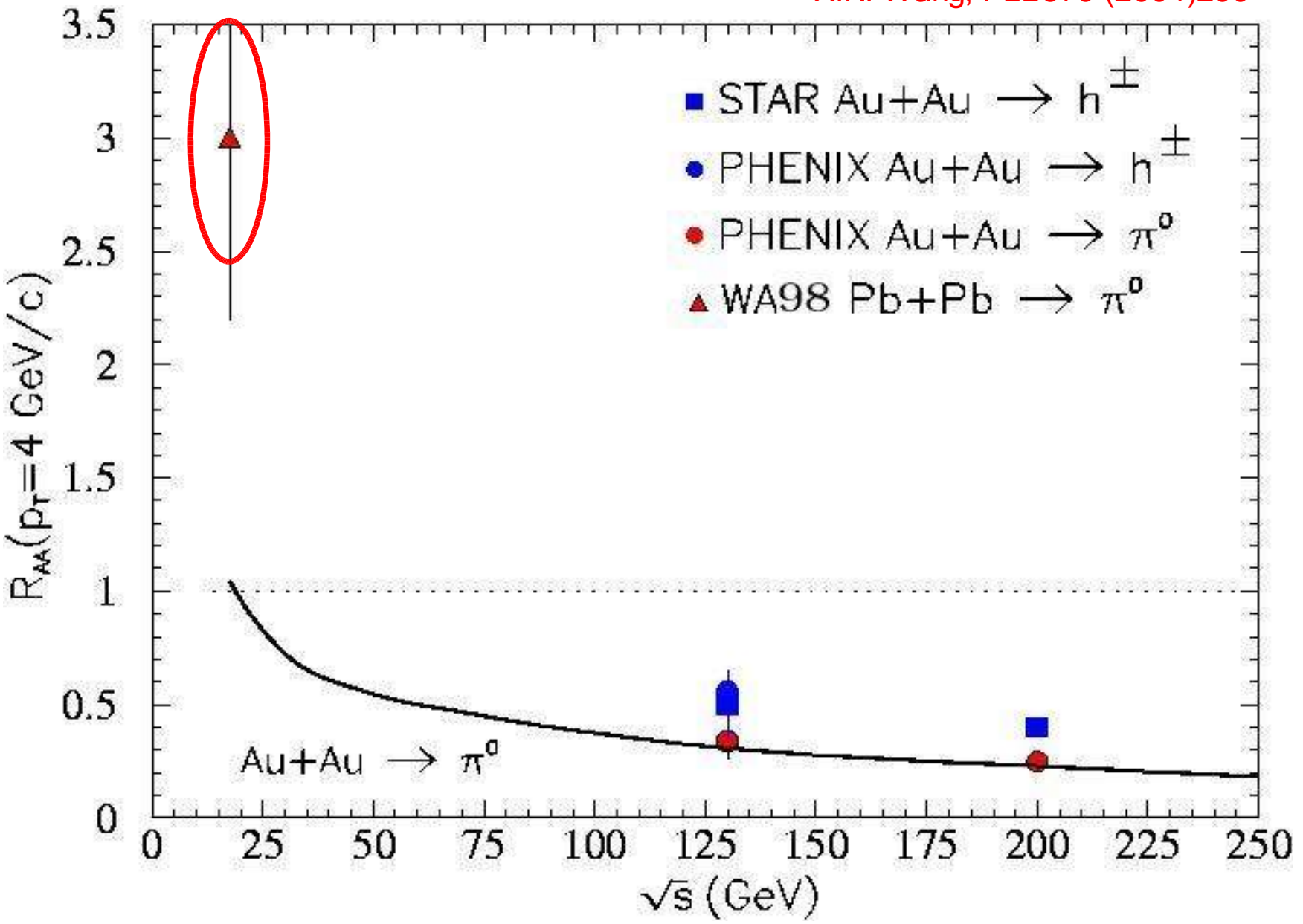
Excitation function of high p_T suppression

X.N. Wang, PLB579 (2004)299

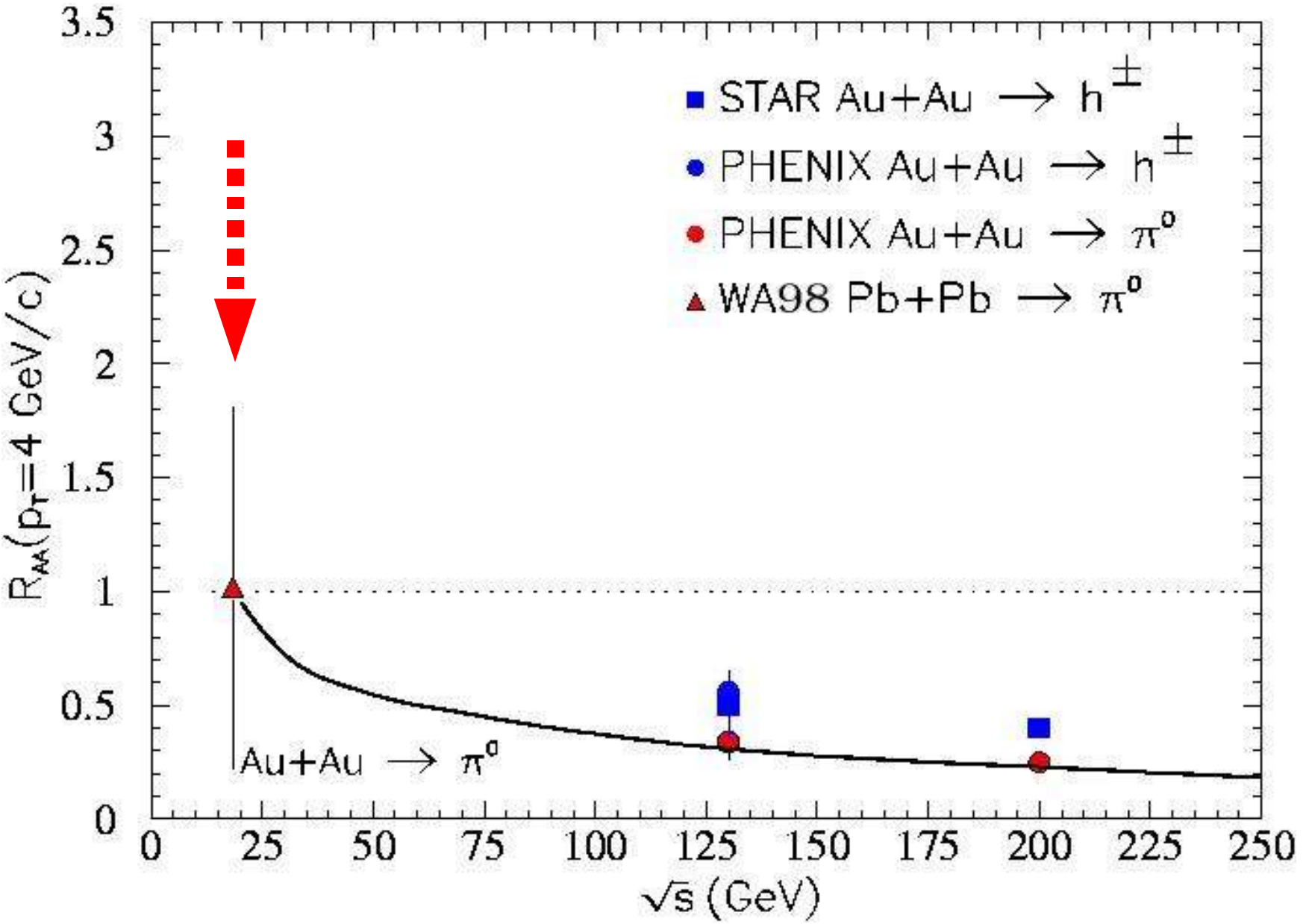


Excitation function of high p_T suppression

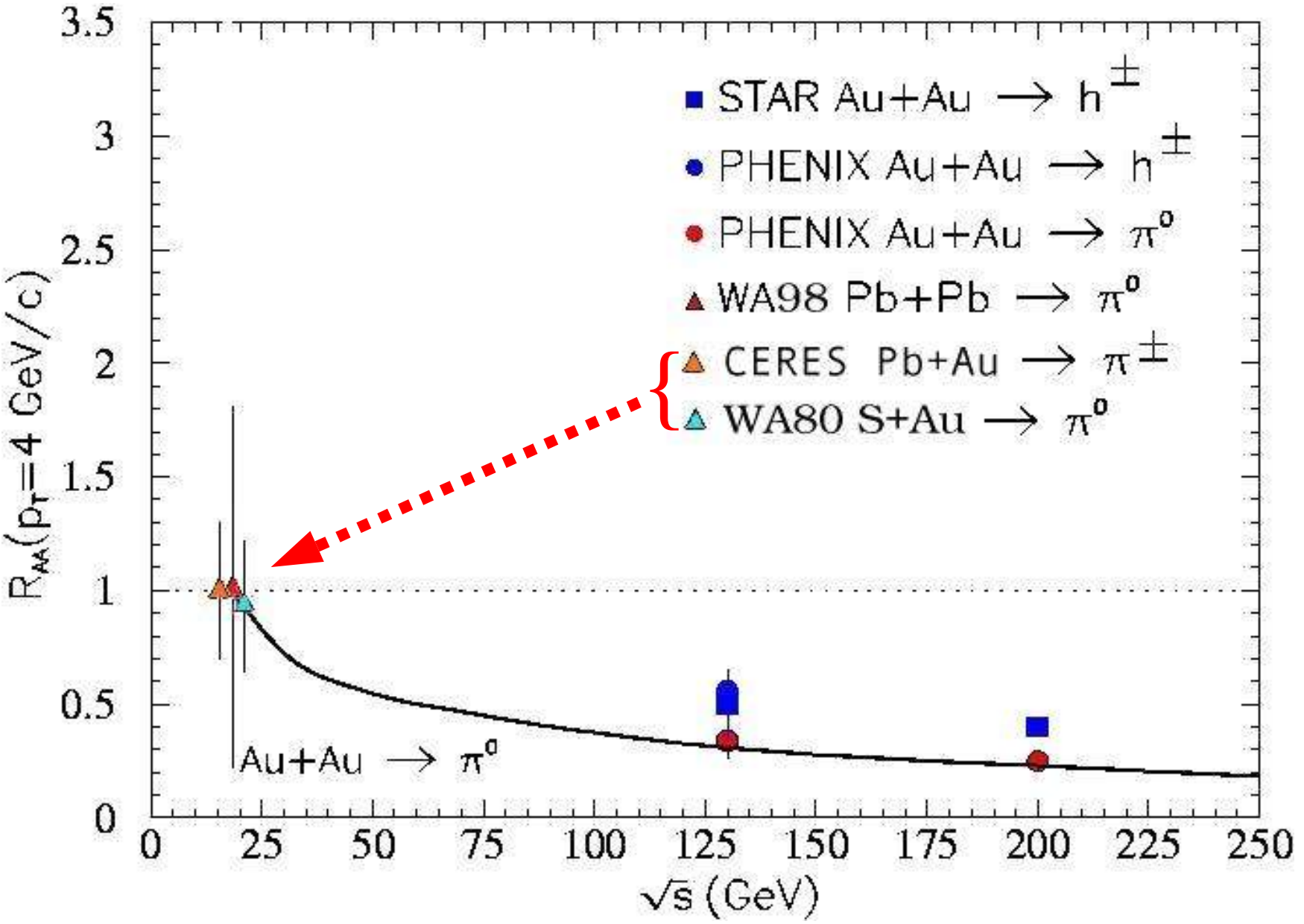
X.N. Wang, PLB579 (2004)299



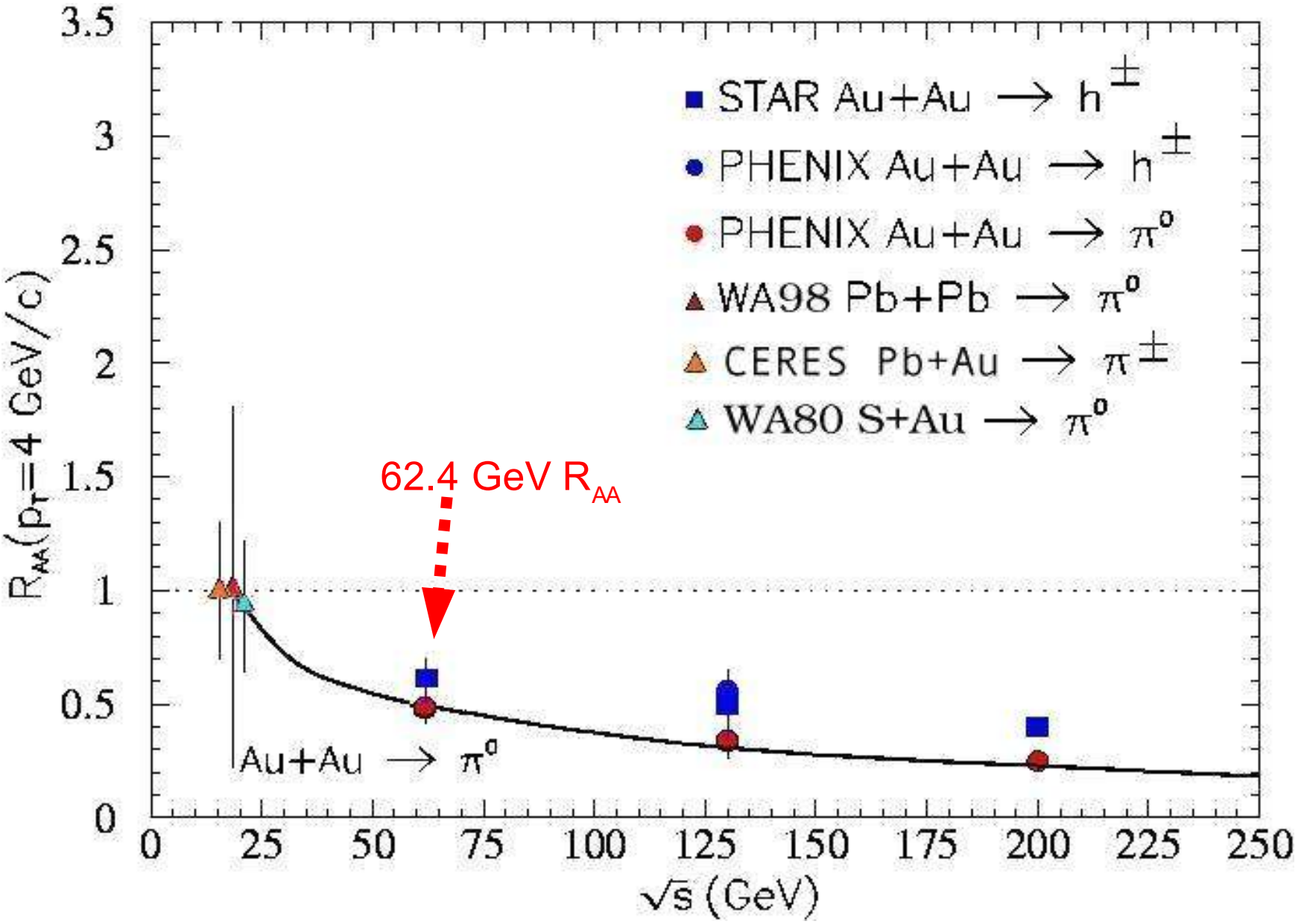
Excitation function of high p_T suppression



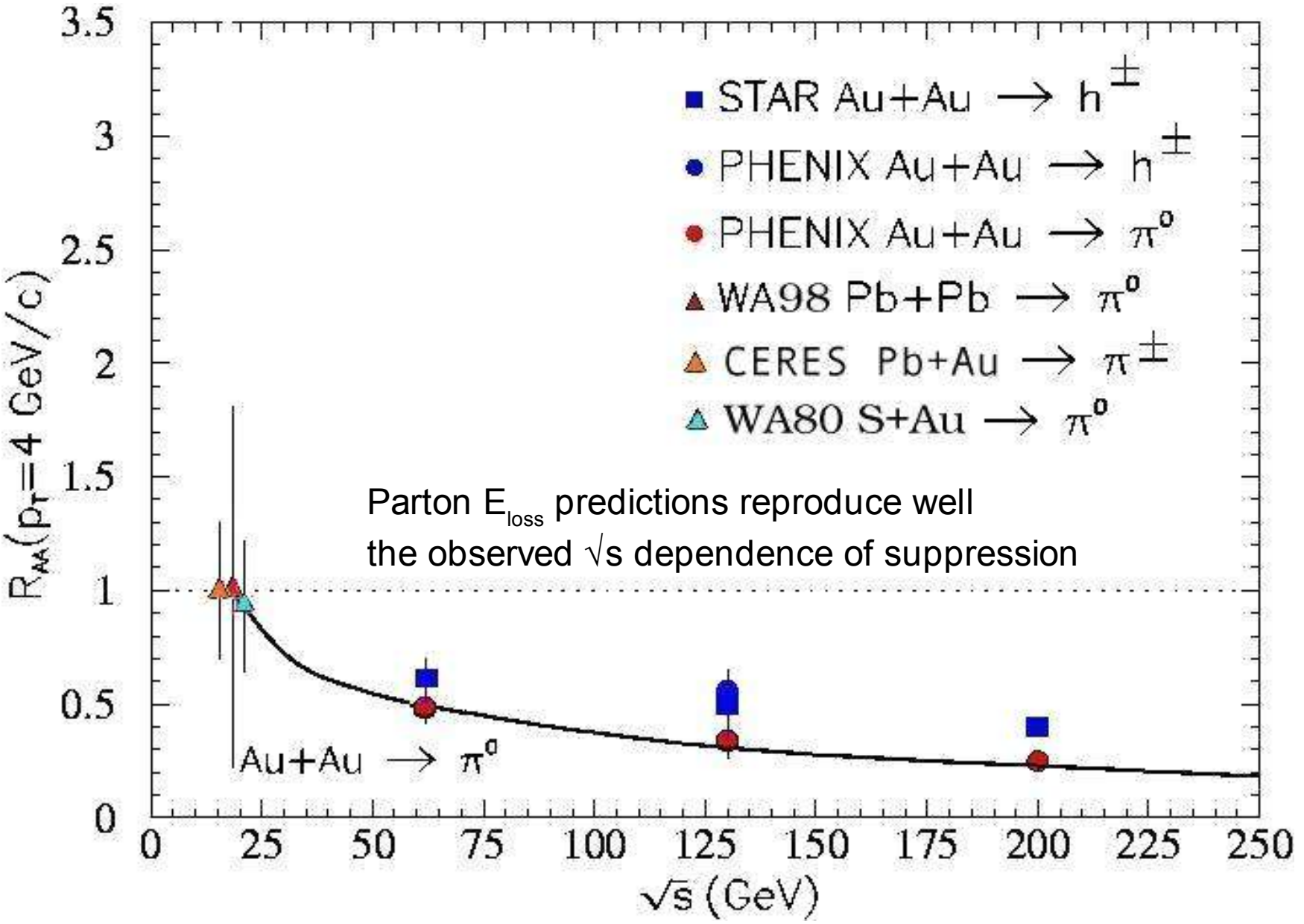
Excitation function of high p_T suppression



Excitation function of high p_T suppression



Excitation function of high p_T suppression



Summary

- R_{AA} for high p_T hadroproduction at CERN-SPS energies revisited using a new p+p reference:

  (1) R_{AA}(cent) ≈ 1. No Cronin. R_{AA}(cent) < R_{AA}(periph) consistent w/ factor ~1.6 suppress.
  (2) (new) R_{AA} consistent w/ (old) R_{cp}
  (3) R_{AA}(cent) in agreement w/ parton E_{loss} calculations in dense system:
  $dN^g/dy \approx 500$ (consistent with estimated $\varepsilon_{Bj} \approx 3$ GeV/fm^3).
  (4) (Re)measurement of A+A, p+p at $\sqrt{s_{NN}} \approx 20$ GeV desirable (look for onset of suppr.)

- R_{AA} at high p_T in Au+Au $\sqrt{s} = 62.4$ GeV

  (1) Current ISR-averaged p+p refs. have uncertainties of order ~30%.
  (2) R_{AA}(cent) in agreement w/ parton E_{loss} in dense system: $dN^g/dy \approx 800$
  (3) More quantitative study of high p_T suppression requires actual measurement of p+p at at $\sqrt{s}$ = 62.4 GeV (RHIC Run-5 ?).

- Latest R_{AA} at high p_T in Au+Au $\sqrt{s} = 200$ GeV

  (1) Universal suppression for all hadrons (π^0, η, $h^\pm$) above p_T~5 GeV/c.
  (2) Very high p_T suppression (p_T>10 GeV/c) in agreement w/ parton E_{loss} predictions

- Excitation function of suppression described by parton E_{loss} models

Corollary

3 lessons learnt:

(1) At CERN SPS energies one is likely creating the same (less dense) strongly interacting matter as at RHIC. Indications of high p_T suppression (need actual exp. confirmation !) are now more consistent w/ previous observations: J/ψ suppression, ε_{Bj}, ...

(2) If we want to constraint / challenge parton energy loss models (and we want to, in order to learn more about the properties of the dense QCD medium produced), we need more differential observables than (ratios of) spectra [R_{AA} vs. azimuthal angle, ...].

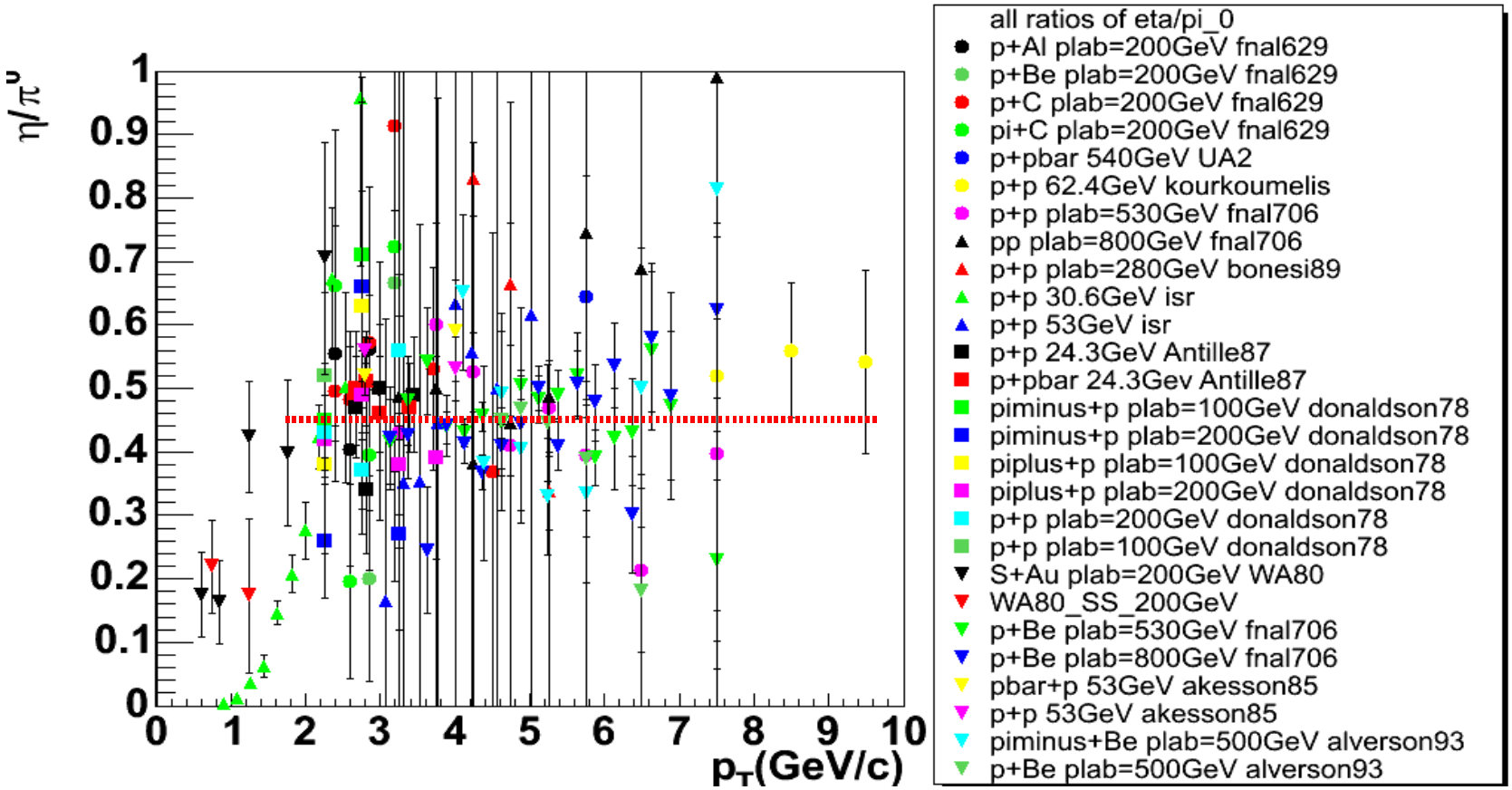
(3) If we want to characterize quantitatively the properties of the produced media in A+A collisions (QGP,CGC), we need a concurrent measurement of the p+p baseline at the same sqrt(s) !
[This applies for RHIC 62.4 GeV, but also for 5.5 TeV at CERN-LHC where we need to convince the "Higgs – beyond SM – SUSY..." community to run at ~1/3 of the nominal (maximal) p+p collision energy].

backup slides ...

Unsubstracted π^0 "contaminations" at ISR (1)

All but one measurement at ISR didn't substract the η and direct-γ

"World average" η/π^0 ~0.45 ratio at high p_T in hadronic colls.



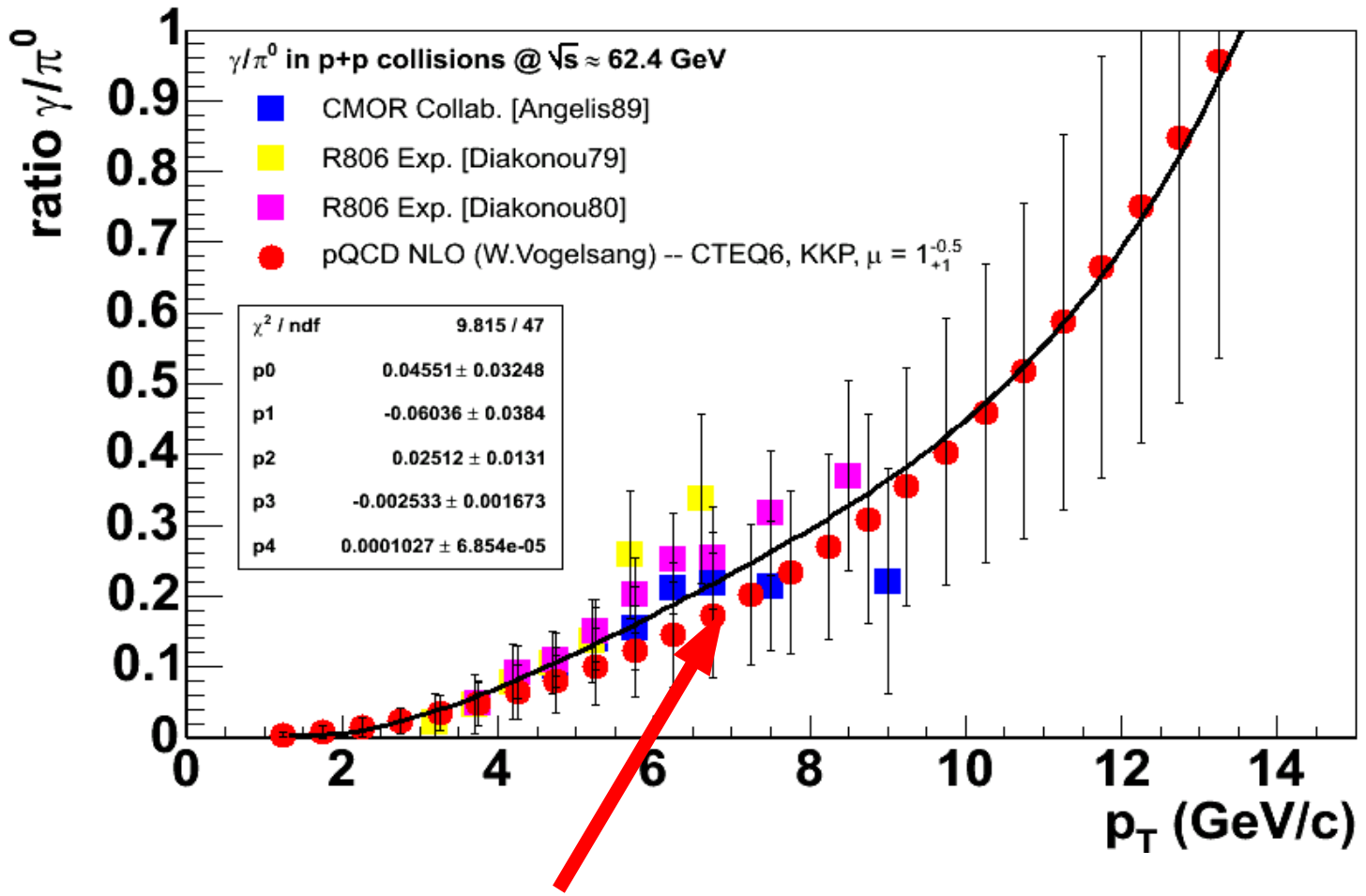
$$BR_{\eta \to \gamma\gamma} \cdot R_{\eta/\pi 0} = 0.39 \cdot 0.45 \approx 0.18$$

18% η contribution needs to be substracted from "unresolved" π^0 spectra.

Unsubstracted π^0 "contaminations" at ISR (2)

All but one measurement at ISR didn't substract the η and direct-γ

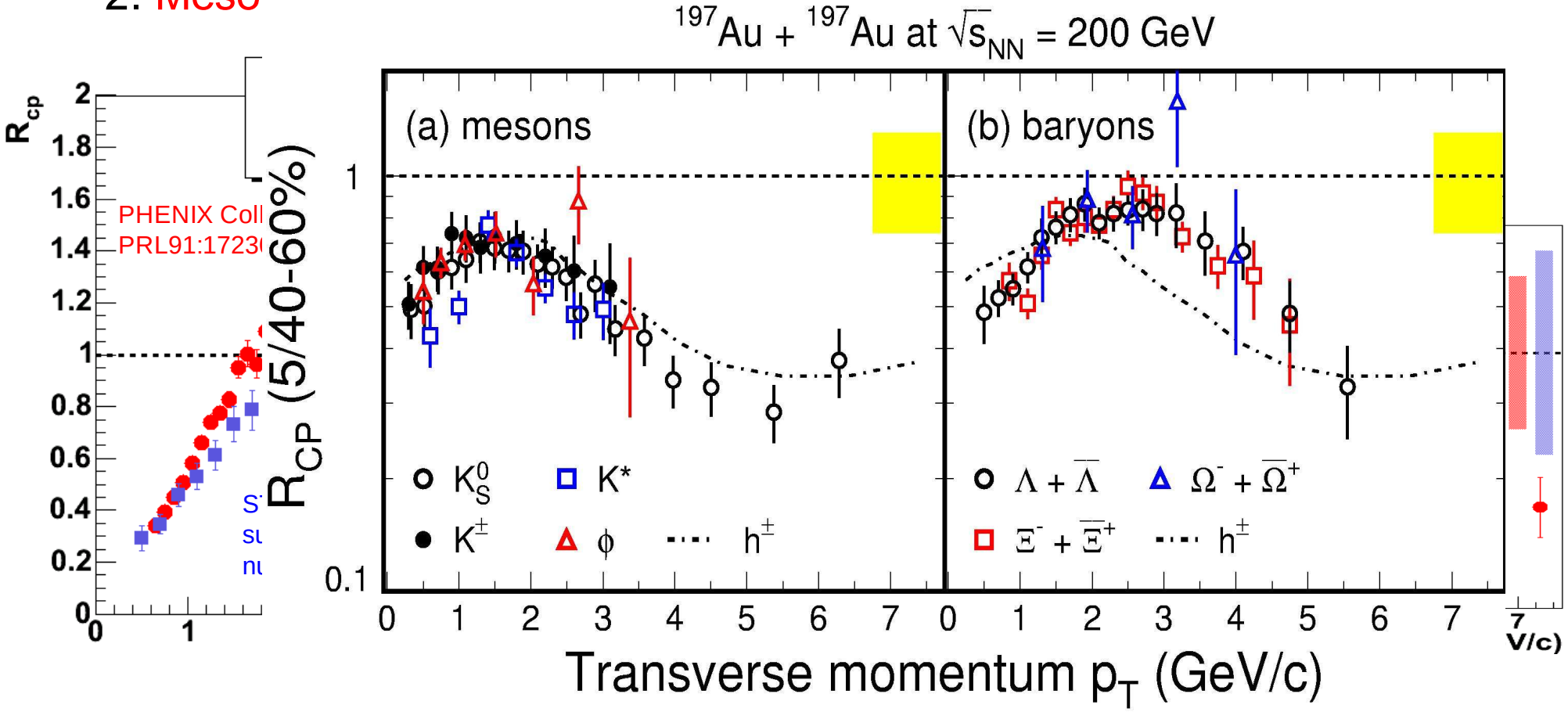
γ/π^0 ratio at high p_T in p+p at 62 GeV (data compared to NLO pQCD):



Prompt γ are a significant source of e.m. clusters above p_T~6 GeV/c that needs to be substracted too

High p_T suppression - baryons vs. mesons

- R_{cp} (ratio central/peripheral) at intermediate p_T = 2 – 4 GeV/c:
  1. Baryons: p, $\bar{p}$, Λ, $\bar{\Lambda}$ **NOT** (or much less) suppressed in central Au+Au.
  2. Meso



- Particle composition inconsistent with known fragmentation functions.
- Additional production mechanism for baryons in the intermediate p_T range (quark recombination ?).