Models of high-p_T parton energy loss in a colored medium

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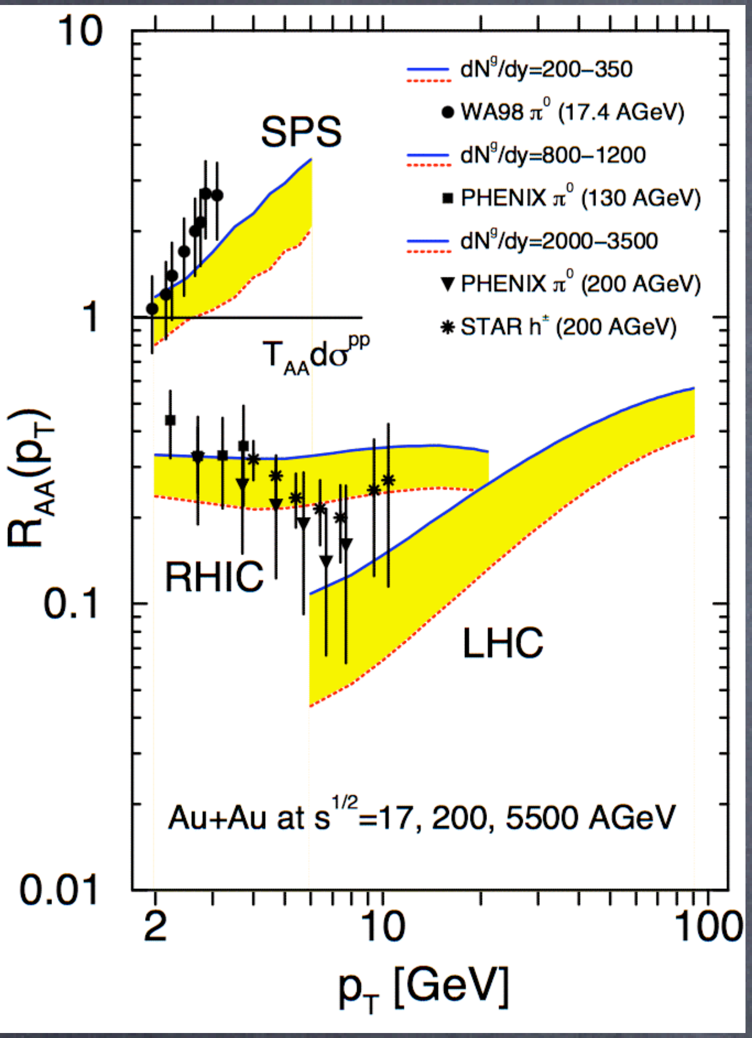

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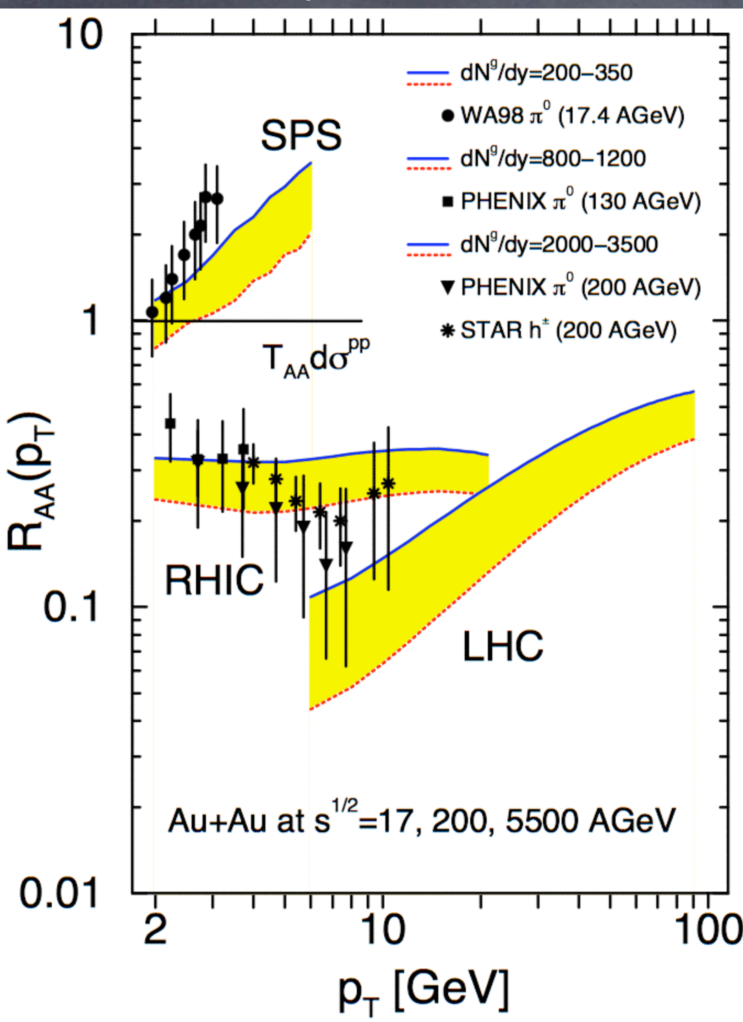

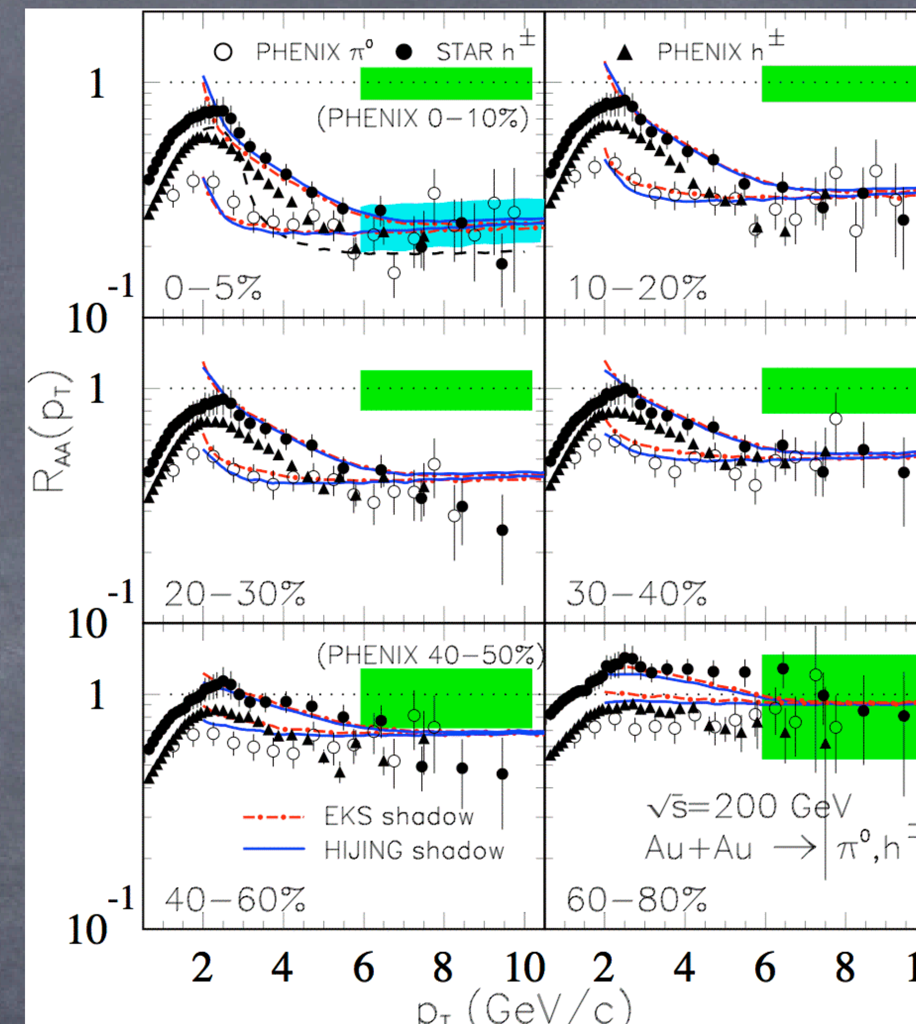

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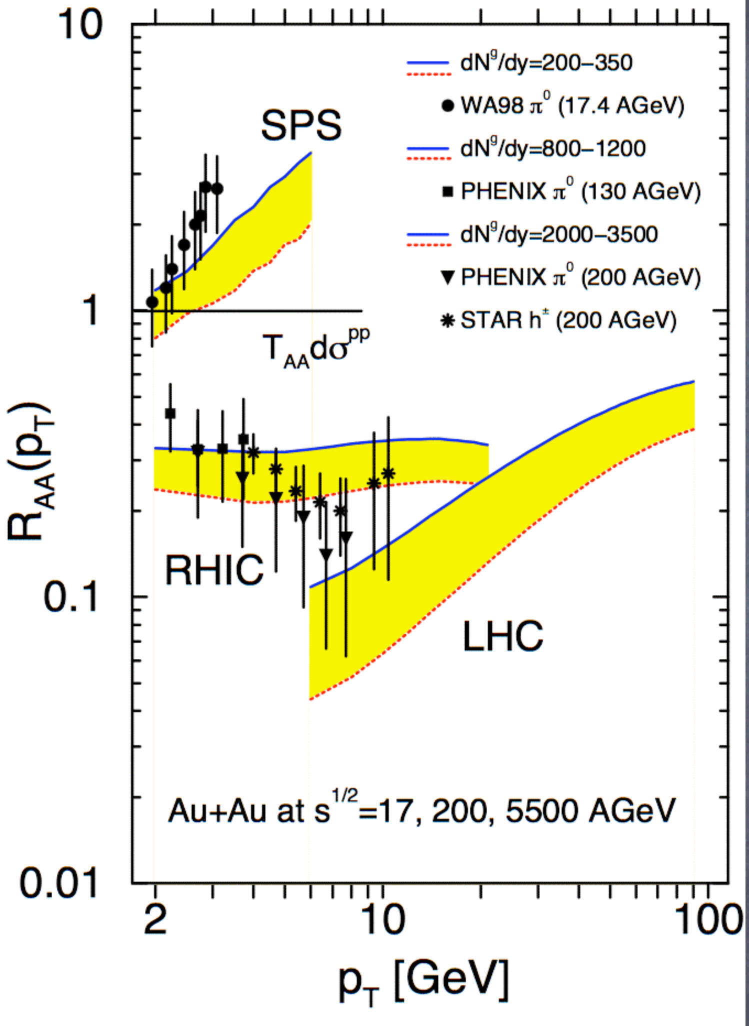

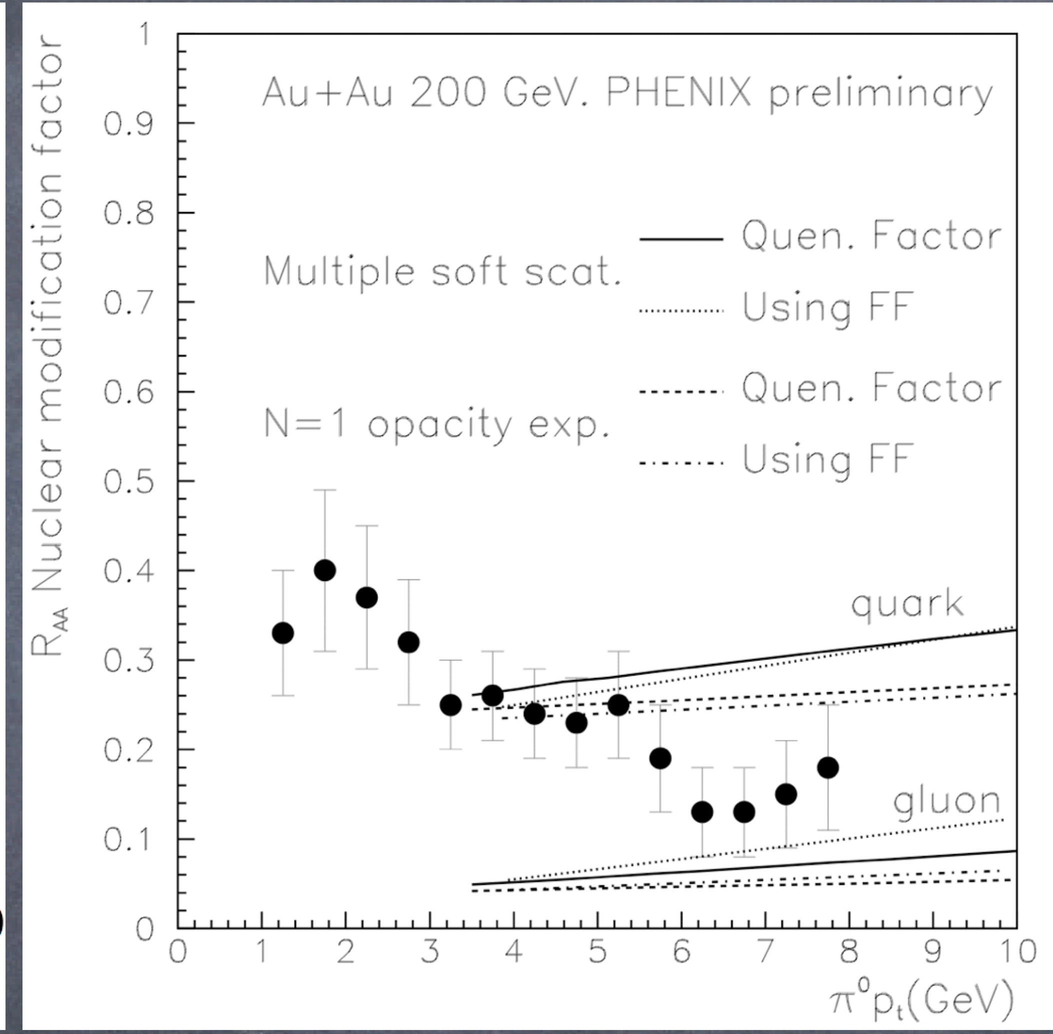

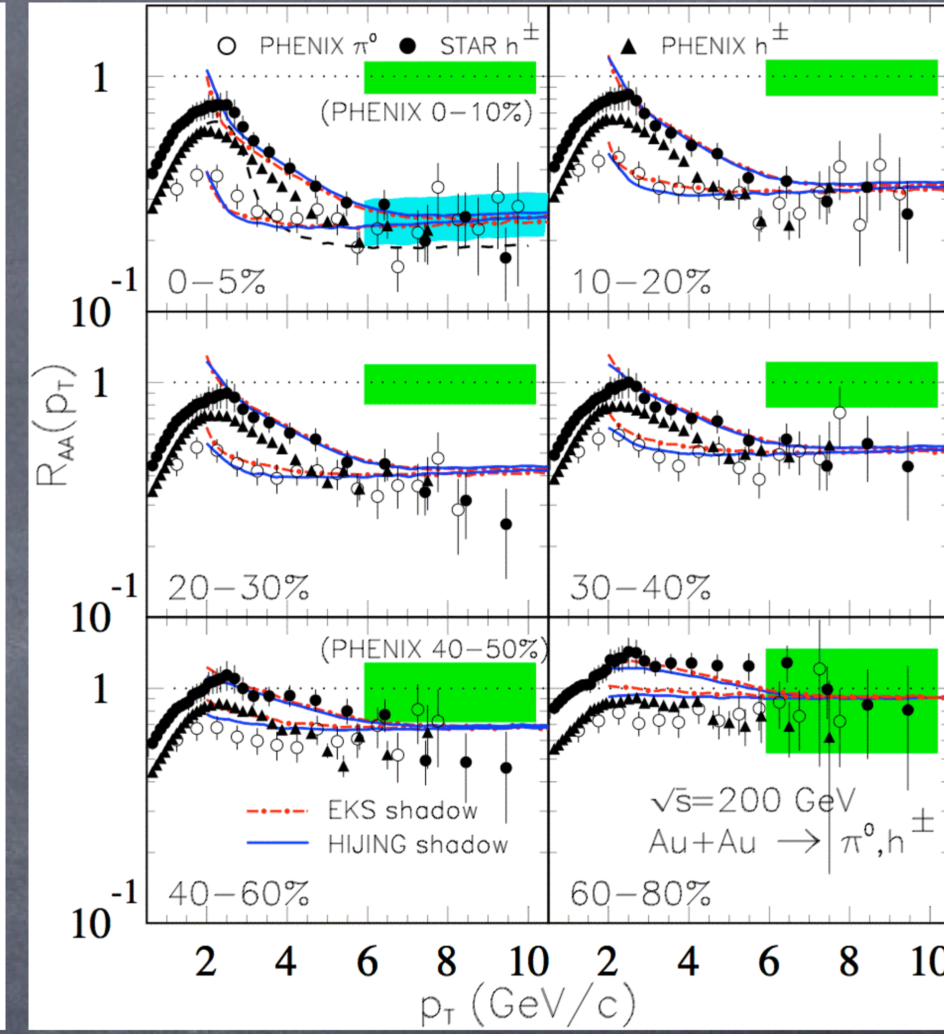

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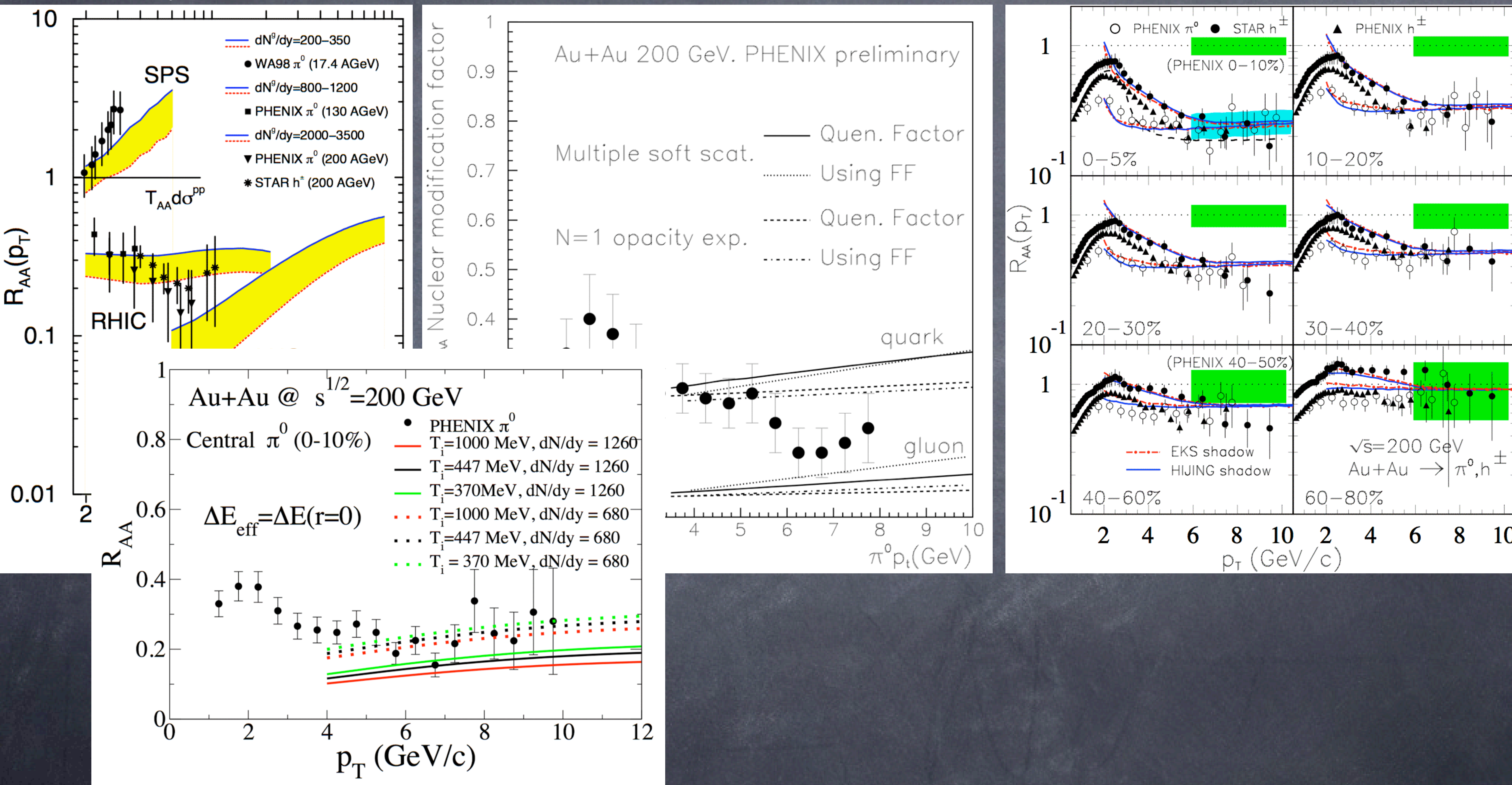

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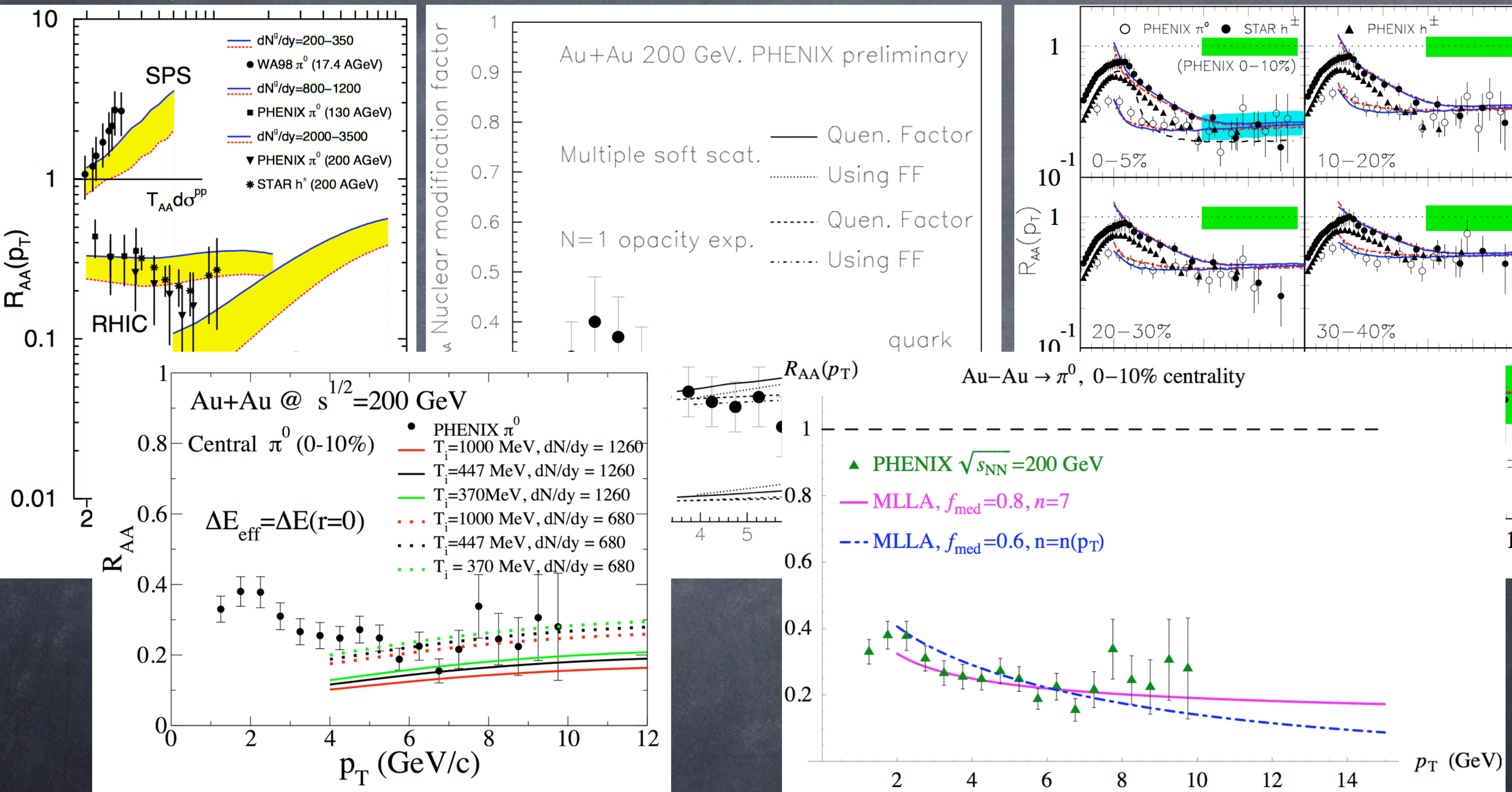

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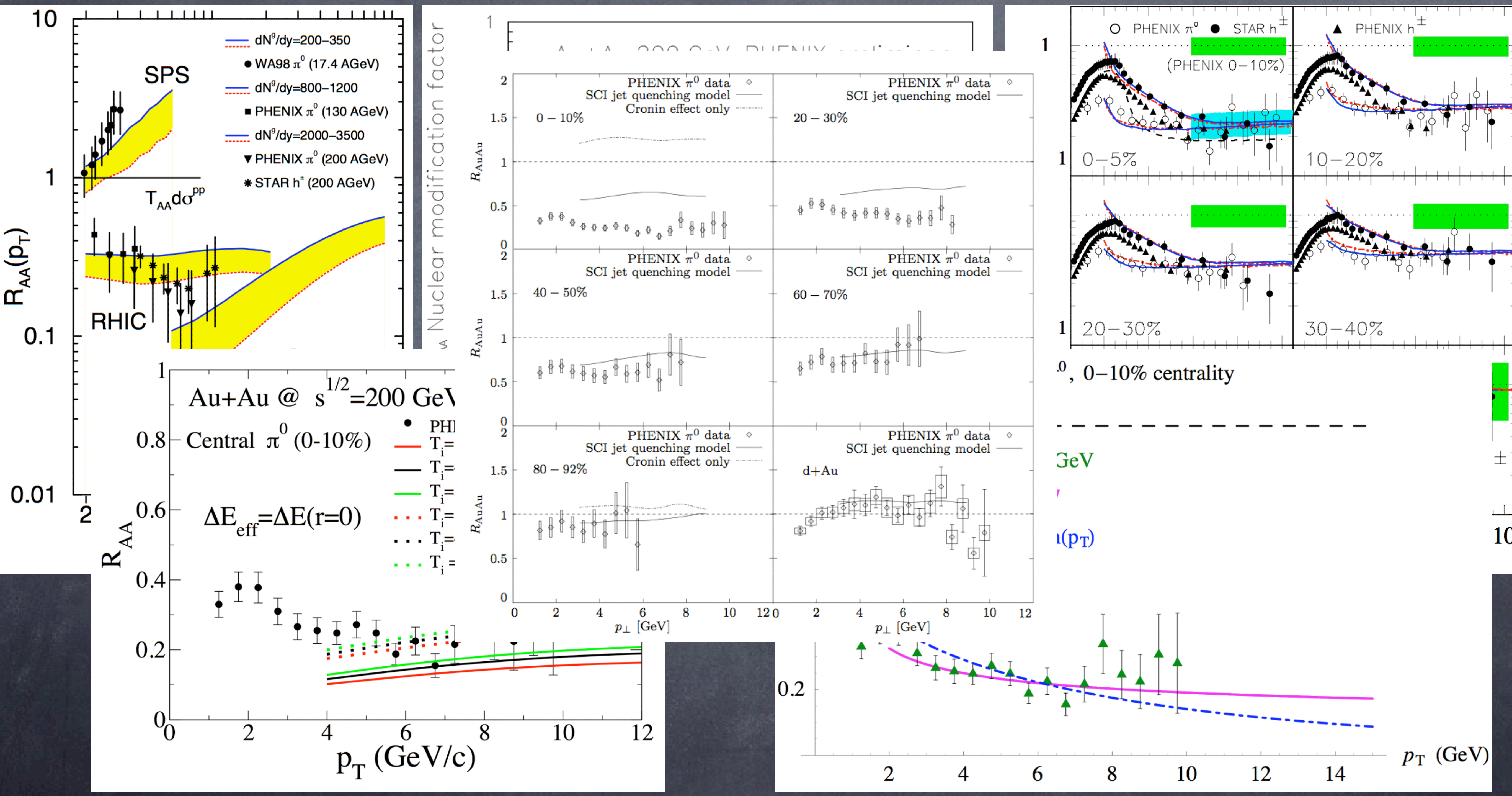


Models of high-p_T parton energy loss

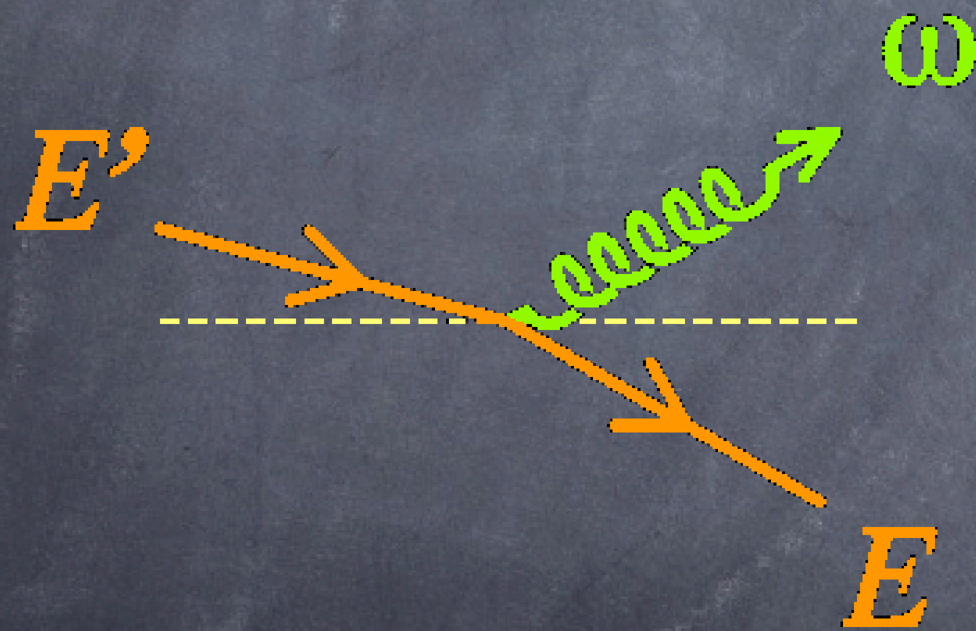
Welcome to the realm of acronyms!

- Radiative vs. collisional energy loss
- Theories and models of radiative energy loss
  - LPM-effect based approaches: BDMPS-Z & AMY
  - opacity expansion: GLV; (AS)W
  - medium-enhanced higher-twist effects
  - medium-modified MLLA
- Theories and models of collisional energy loss

Models of high-p_T parton energy loss

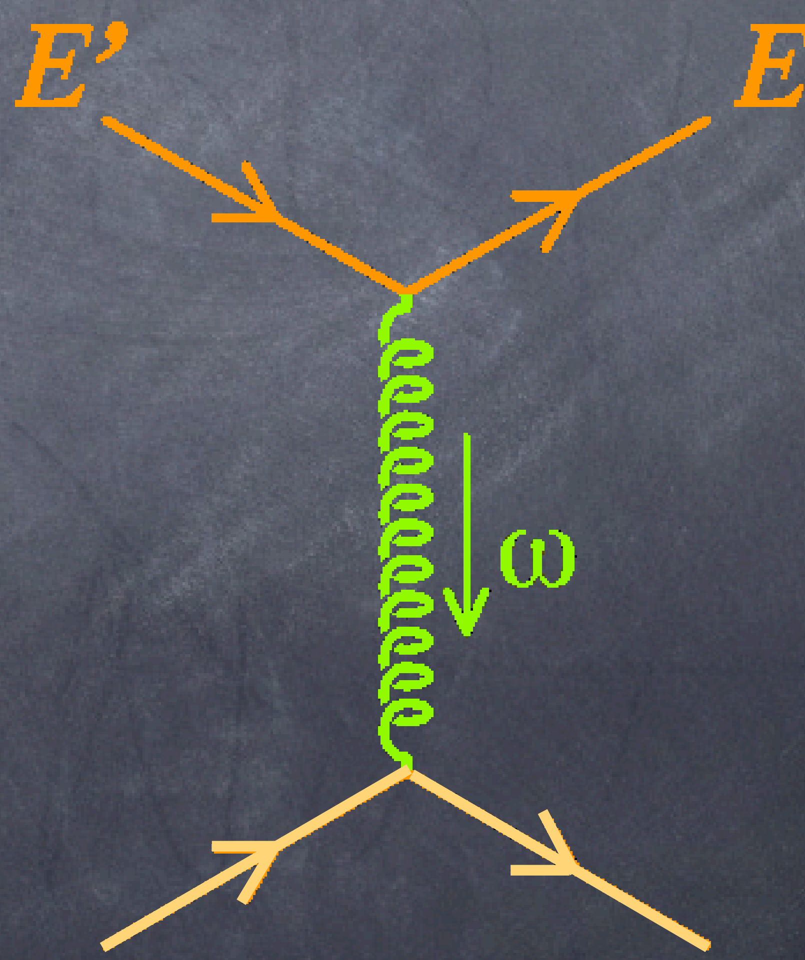
Two different "categories" of models of parton energy loss, depending on the basic underlying process:

"radiative" process (Bremsstrahlung)



also "in vacuum", but controlled by the presence of a medium

"collisional" process

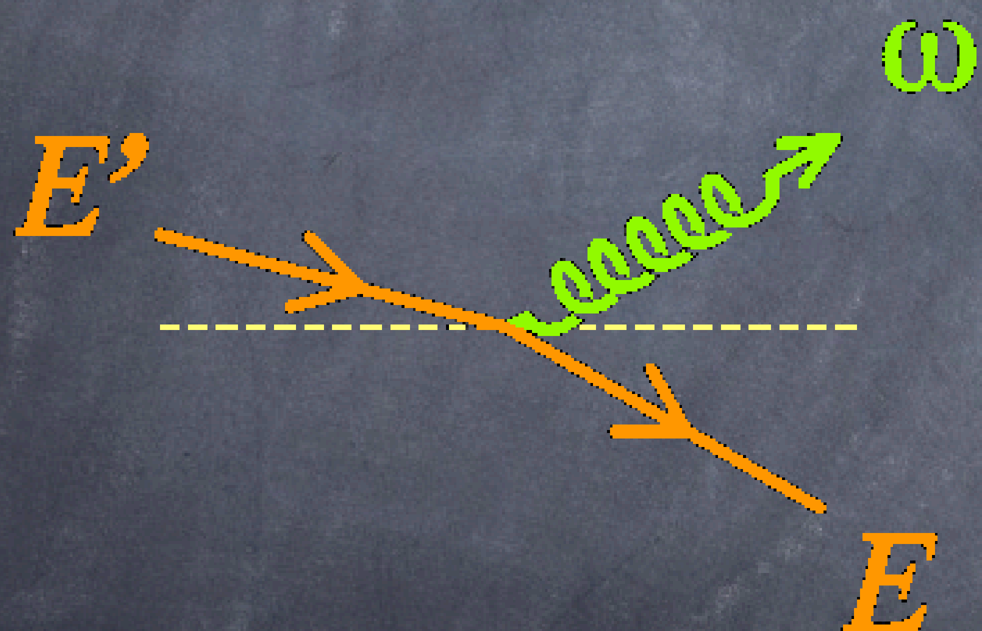


Models of high-p_T parton energy loss

Two different "categories" of models of parton energy loss, depending on the basic underlying process:

inelastic

"~~radiative~~" process (Bremsstrahlung)

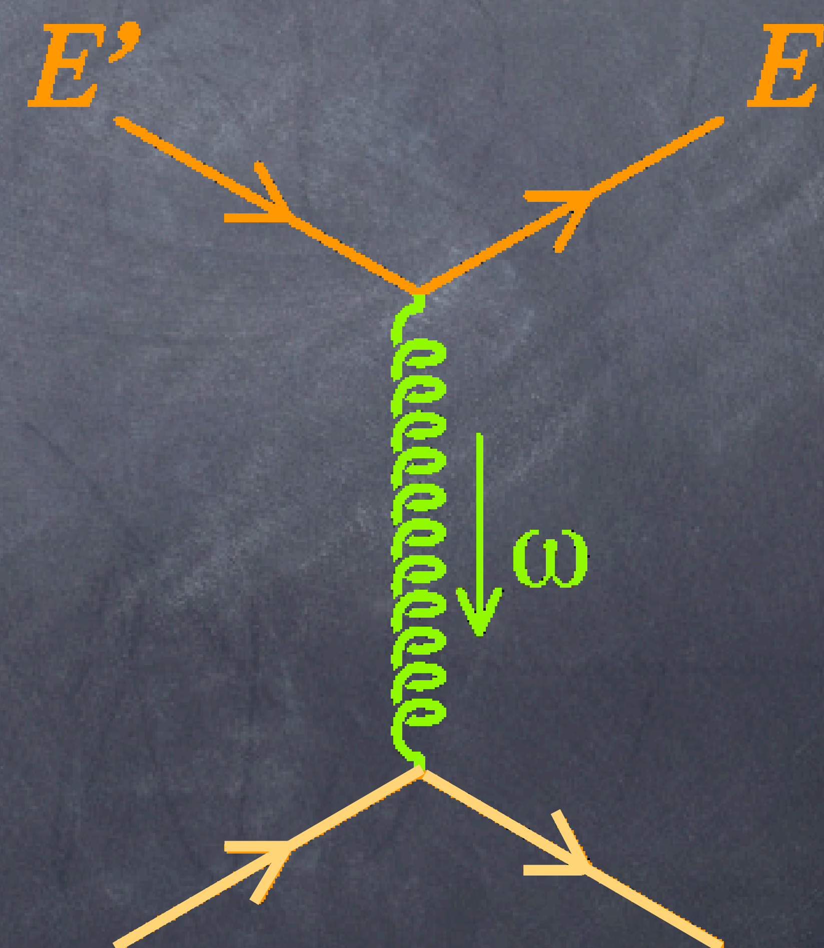


also "in vacuum", but controlled by the presence of a medium

→ collisions!

elastic

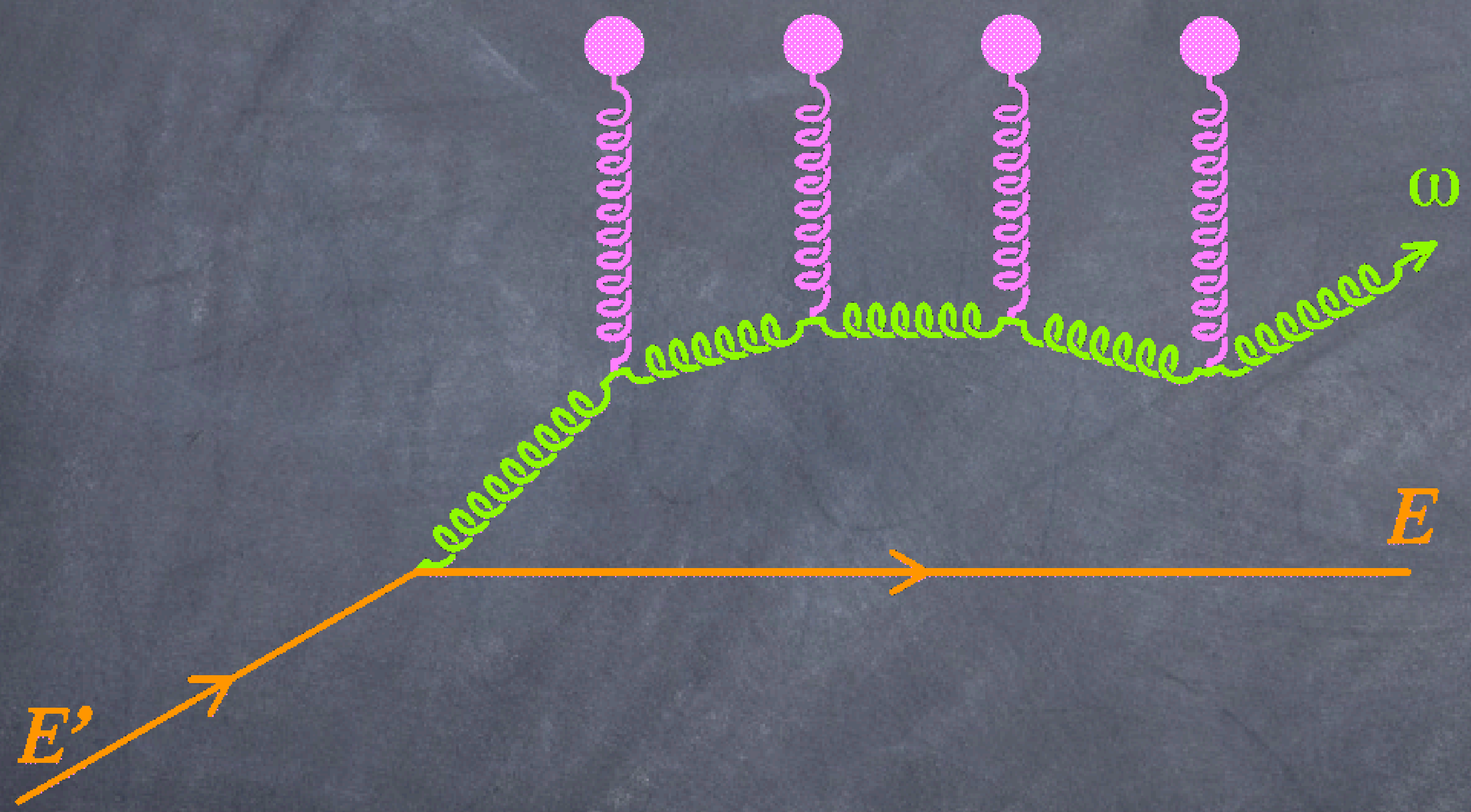
"~~collisional~~" process



Inelastic energy loss

Models based on the Landau-Pomeranchuk-Migdal effect [1/4]

The propagating high-p_T parton traverses a **thick target**.



It radiates soft gluons, which scatter **coherently** on independent color charges in the medium, resulting in a medium-modified gluon energy spectrum.

Multiple soft scattering limit

Inelastic energy loss

Models based on the Landau-Pomeranchuk-Migdal effect [2/4]

Independent scattering centers: $\lambda \gg 1/\mu$

mean free path (λ) — screening mass (μ)

Note the assumption, which actually underlies all models of in-medium partonic energy loss

Coherent scatterings: $\ell_{\rm coh} \sim \frac{2\omega}{k_\perp^2} \leq L$ (medium length)

coherence length ($\ell_{\rm coh}$) of the emitted gluon

$k_\perp^2 \simeq N_{\rm coh}\mu^2 \Rightarrow \ell_{\rm coh} = \sqrt{\frac{2\omega\lambda}{\mu^2}}$

Baier, Dokshitzer, Mueller, Peigné, Schiff (BDMPS); Zakharov

Inelastic energy loss

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Independent scattering centers: $\underbrace{\lambda}_{\text{mean free path}} \gg 1/\underbrace{\mu}_{\text{screening mass}}$

mean free path ← λ; μ → screening mass

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$\ell_{\rm coh}$ → coherence length of the emitted gluon

$k_\perp^2 \simeq N_{\rm coh}\,\mu^2 \quad \Rightarrow \quad \ell_{\rm coh} = \sqrt{\frac{2\omega\lambda}{\mu^2}}$

LPM only affects gluons with $\omega \lesssim \omega_c \equiv \frac{1}{2}\hat{q}L^2$

Medium characterized by the transport coefficient $\hat{q} \equiv \frac{\mu^2}{\lambda}$

Baier, Dokshitzer, Mueller, Peigné, Schiff (BDMPS); Zakharov

Inelastic energy loss

Models based on the Landau-Pomeranchuk-Migdal effect [3/4]

Gluon coherence length $\ell_{\rm coh} = \sqrt{\frac{2\omega\lambda}{\mu^2}}$

⇒ gluon energy spectrum per unit path length $\omega\frac{{\rm d}I}{{\rm d}\omega{\rm d}z} \simeq \frac{\alpha_s}{\ell_{\rm coh}} \simeq \alpha_s\sqrt{\frac{\hat{q}}{\omega}}$

For a path length L: $\omega\frac{{\rm d}I}{{\rm d}\omega} \simeq \alpha_s\sqrt{\frac{\hat{q}L^2}{\omega}}$

Average medium-induced energy loss: $\Delta E = \int^{\omega_c}\omega\frac{{\rm d}I}{{\rm d}\omega}\,{\rm d}\omega \simeq \alpha_s\omega_c \propto \alpha_s\hat{q}L^2$

☞ BDMPS-Z, only two parameters: $\hat{q}$ & L

Inelastic energy loss

Models based on the Landau-Pomeranchuk-Migdal effect [4/4]

What about the infrared ($\omega \to 0$) behaviour?

- BDMPS-Z: coherent regime requires

$$N_{\rm coh} > 1 \;\Leftrightarrow\; \ell_{\rm coh} > \lambda \;\Leftrightarrow\; \omega > E_{\rm LPM} \equiv \lambda\mu^2 = \mathcal{O}(1\text{ GeV})$$

- AMY (Arnold, Moore, Yaffe; Jeon, Gale, Turbide):

  interaction of the fast parton with a thermal bath

  ✓ LPM energy loss for $\lambda \sim 1/g_s^2 T$, $\mu \sim g_s T \;\Rightarrow\; \ell_{\rm coh} > \lambda \;\Leftrightarrow\; \omega \gtrsim T$

  ✓ and for $0 < \omega < E_{\rm LPM} \simeq 1$ GeV, Bethe-Heitler regime

  Energy loss per unit length proportional to the incoming energy

  In addition, they allow possible gains in the parton energy

  ☞ AMY approach, three parameters: T , L & α_s

Inelastic energy loss

Models based on an opacity expansion [1/2]

The high-p_T parton interacts with a thin target:

the energy loss results from an incoherent superposition of very few $\chi \equiv L/\lambda$ single hard scattering processes along the path length L.

χ ⟶ "opacity" (= number of collisions)

⇒ gluon energy spectrum per unit path length

$$\omega \frac{\mathrm{d}I}{\mathrm{d}\omega\,\mathrm{d}z} \simeq \left(\frac{L}{\lambda}\right) \frac{\alpha_s}{\ell_{\mathrm{coh}}} \simeq \left(\frac{L}{\lambda}\right) \alpha_s \frac{\mu^2}{\omega} \qquad \neq \alpha_s \sqrt{\frac{\hat{q}}{\omega}} \text{ within LPM}$$

leads to an average energy loss $\Delta E \propto L^2$ (for a static medium)

Gyulassy, Lévai, Vitev (GLV); Wiedemann

☞ three parameters: $\left(\frac{L}{\lambda}\right)$, μ & L

$\left(\frac{L}{\lambda}\right)$ ⟶ ⇔ the (linear) density of scattering centers

Inelastic energy loss

Models based on an opacity expansion [2/2]

- Within GLV, radiated gluons restricted to $\omega > \mu = \mathcal{O}$(500 MeV), "common value" of the screening mass and the plasmon excitation

- Energy loss actually dominated by energetic gluons $\omega \gtrsim \bar{\omega}_c \equiv \frac{1}{2}\mu^2 L$ (≠ LPM, where soft gluons with $\omega < \omega_c$ mainly contribute)

- Only very few (≈3) gluons are radiated by the fast parton

Inelastic energy loss

Approach based on a twist expansion

In QCD, a cross-section can actually be expanded in powers of $\frac{1}{q^2}$, where q is the exchanged (hard) momentum:

"twist expansion"

In vacuum, higher-twist terms are power suppressed (!).
But in a medium, these terms may become enhanced: $A^{1/3}\,/q^2$

⇒ allow systematic computation of energy loss

formulated in terms of "medium-modified fragmentation functions" (which can be evolved with DGLAP...)

Guo, Wang & Wang

Parameters (?): μ, T

Inelastic energy loss

A model based on modified parton splitting functions

Effect of the medium modeled by a (phenomenological) modification of the Altarelli-Parisi parton splitting functions, considering e.g.

$$P_{qq}(z) = C_F\left(\frac{2(1+f_{\rm med})}{1-z} - (1+z)\right)$$

where $f_{\rm med} = 0$ in the absence of a medium ($f_{\rm med}$ only parameter)

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Modified Leading Logarithmic Approximation (of QCD)

Inelastic energy loss

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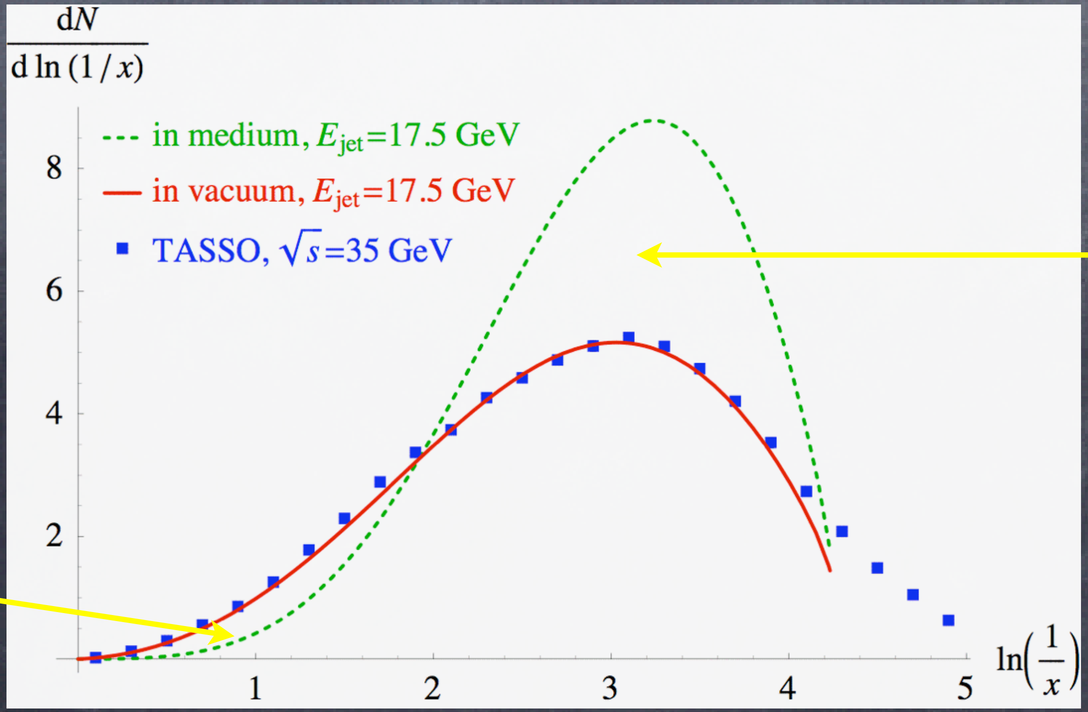

enhancement at small x

depletion at large x

Inelastic energy loss

A few model-independent remarks [1/2]

actually also valid for models of elastic energy loss

- All partons do not lose the same amount of energy, even when they traverse the same in-medium path length L
  ⇒ nuclear modification factor R_{AA} mostly reflects the few partons which have lost little energy
  - ☞ use of "quenching weights" (= probability to lose a given energy)

- The medium traversed by the parton is not static, but in expansion!
  - ☞ model-builders introduce dynamics (most often, à la Bjorken), which may lead to a redefinition ($\hat{q} \to \hat{q}_{\mathrm{eff}}$) of the parameters, to the introduction of new ones (τ_0 , T_0), or to a change in scaling properties ($\Delta E_{\mathrm{GLV}} \propto L$ instead of L^2)

Inelastic energy loss

A few model-independent remarks [2/2]

- A model of partonic energy loss has to be supplemented by several other elements to allow comparison with the data:
  - parton distribution functions inside the nuclei (shadowing, Cronin effect…)
  - production cross-sections

⇒ seemingly similar conclusions of different models may actually differ

- Turbide et al. (AMY approach), PRC **72** (2005) 014906: reproduce R_{AA} for pions assuming $T_i = 370$ MeV, $\tau_i = 0.26$ fm$/c$, $\frac{\mathrm{d}N}{\mathrm{d}y} = 1260$ & $\alpha_s = 0.3$.
  No need for initial state effects as shadowing & the Cronin effect
- GLV, PRL **89** (2002) 252301: $\frac{\mathrm{d}N^g}{\mathrm{d}y} = 1100$
  invoke competition between shadowing, Cronin effect and partonic energy loss to obtain a flat R_{AA}.

Elastic energy loss

The elder (Bjorken, 1984), yet still in its infancy...

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Conclusion... all this is very premature (and too "politics-driven"?)

Inelastic energy loss

a teaser slide...

Could one compute the transport coefficient $\hat{q}$ ab initio, even in the non-perturbative case?

Idea: use Maldacena's conjecture of a correspondence between QCD and its dual weakly coupled theory of gravity living in a 5-dimensional anti-de Sitter space-time.

More practically, since the dual of QCD is unknown, replace it by some supersymmetric Yang-Mills theory ("SYM N=4").

$$\hat{q}_{\mathrm{SYM}} = \frac{\pi^2\sqrt{2}\,\Gamma(\frac{3}{4})}{\Gamma(\frac{5}{4})}\sqrt{\alpha_{\mathrm{SYM}} N_c}\,T^3$$

Liu, Rajagopal, Wiedemann

$\hat{q}_{\mathrm{SYM}} \propto \sqrt{N_c}$ ≠ number of degrees of freedom is proportional to N_c^2

⟶ ⇔ entropy density

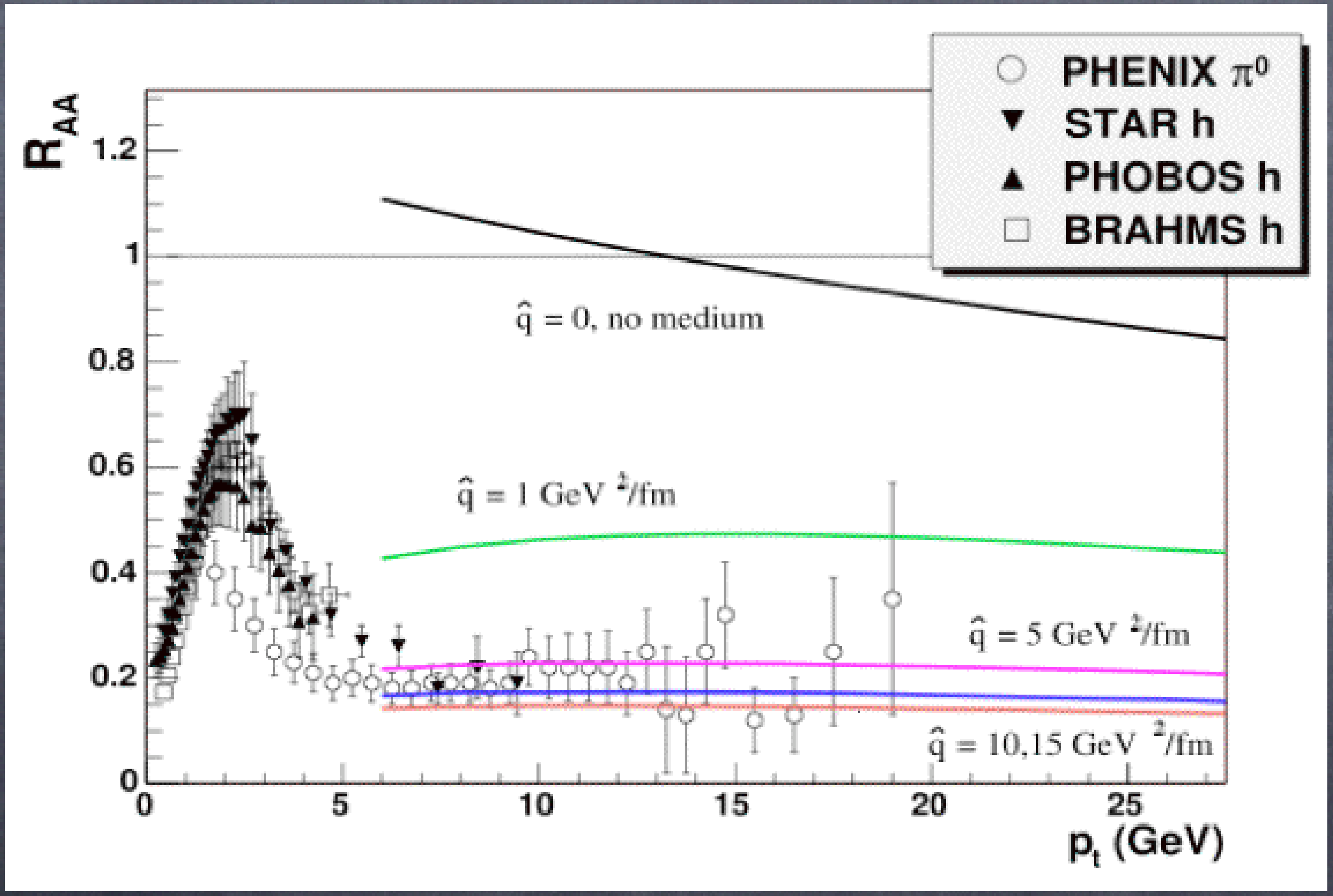
But... the result is not "universal" (may not hold for QCD)

Inelastic energy loss

Additional model-dependent remarks [1/2]

Drawing conclusions from fits to the data may not be easy!

"R_{AA} is fragile" (Eskola, Honkanen, Salgado, Wiedemann)



Data cannot allow to distinguish between $\hat{q} = 5$ or 15 GeV^2/fm

Inelastic energy loss

Additional model-dependent remarks [2/2]

Let me be even more pessimistic / skeptical...

- Eskola, Honkanen, Salgado, Wiedemann, NPA **747** (2005) 511:

  $\hat{q} = 5 - 15$ GeV^2/fm, with $\langle L \rangle \simeq 2$ fm

  which leads to strong (& questionable?) conclusions

- Arleo, hep-ph/0601075:

  $\hat{q} = 0.3 - 0.4$ GeV^2/fm, with $\langle L \rangle \simeq 5$ fm

  ...but François 1. fixed the latter value a priori & 2. assumed that all partons lose energy

- Baier & Schiff, hep-ph/0605183:

  $\hat{q} = 1 - 3$ GeV^2/fm, with $\langle L \rangle \simeq 3$ fm

  restricting the region of validity of the LPM effect