

An aerial photograph of a coastal landscape featuring prominent white cliffs and a sea stack. The cliffs are layered and show signs of erosion. A sandy beach runs along the base of the cliffs, and the sea is visible in the foreground. The sky is clear and blue.

A 25 minutes
overview of

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

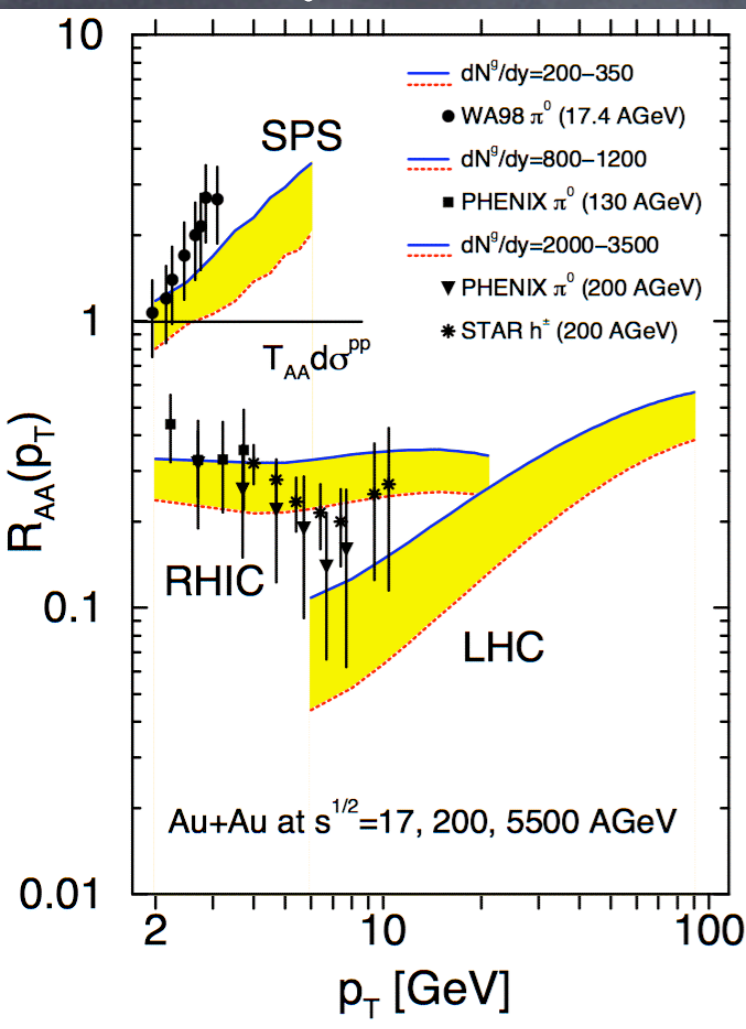
Nicolas BORGHINI

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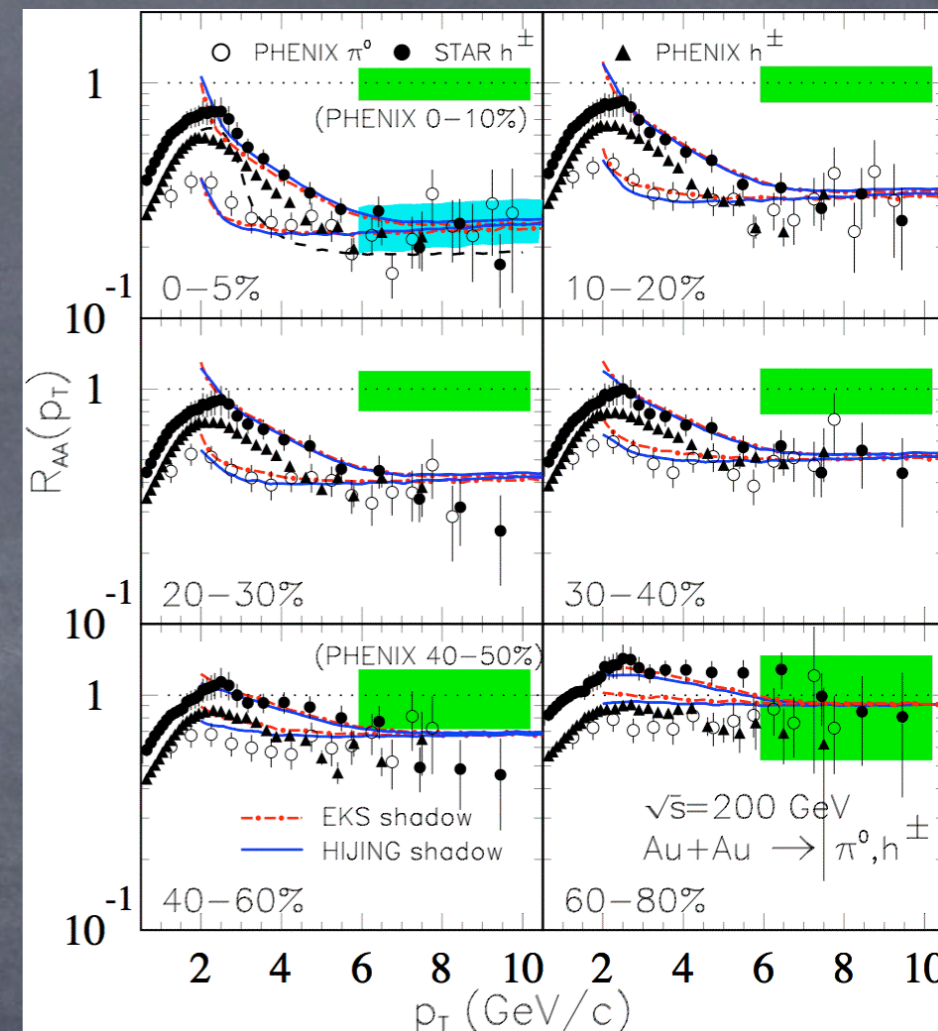
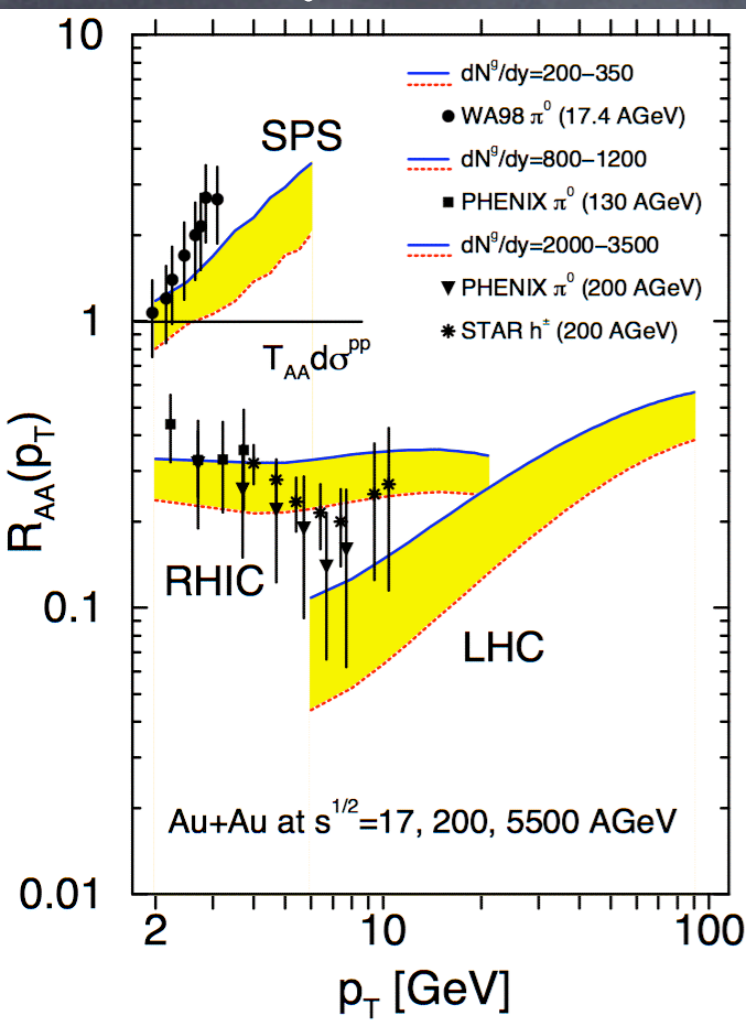
Models of high- p_T parton energy loss
reproduce the data remarkably well



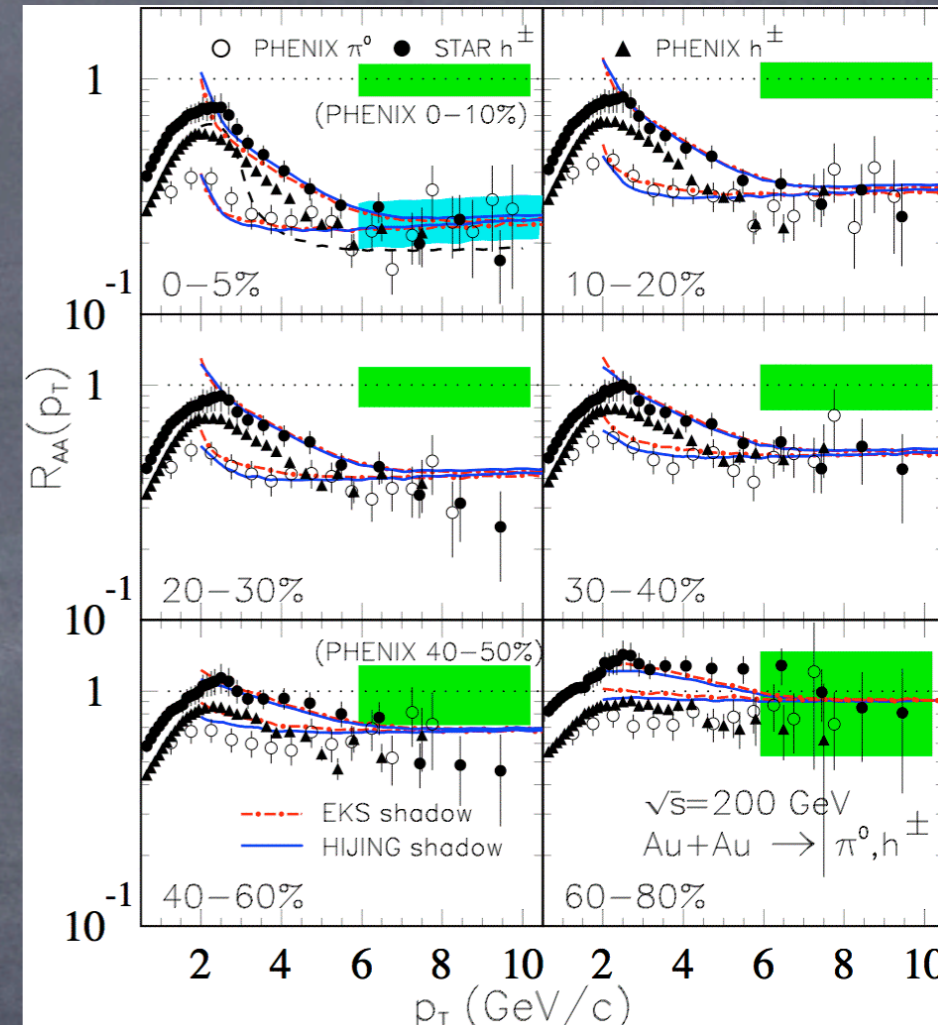
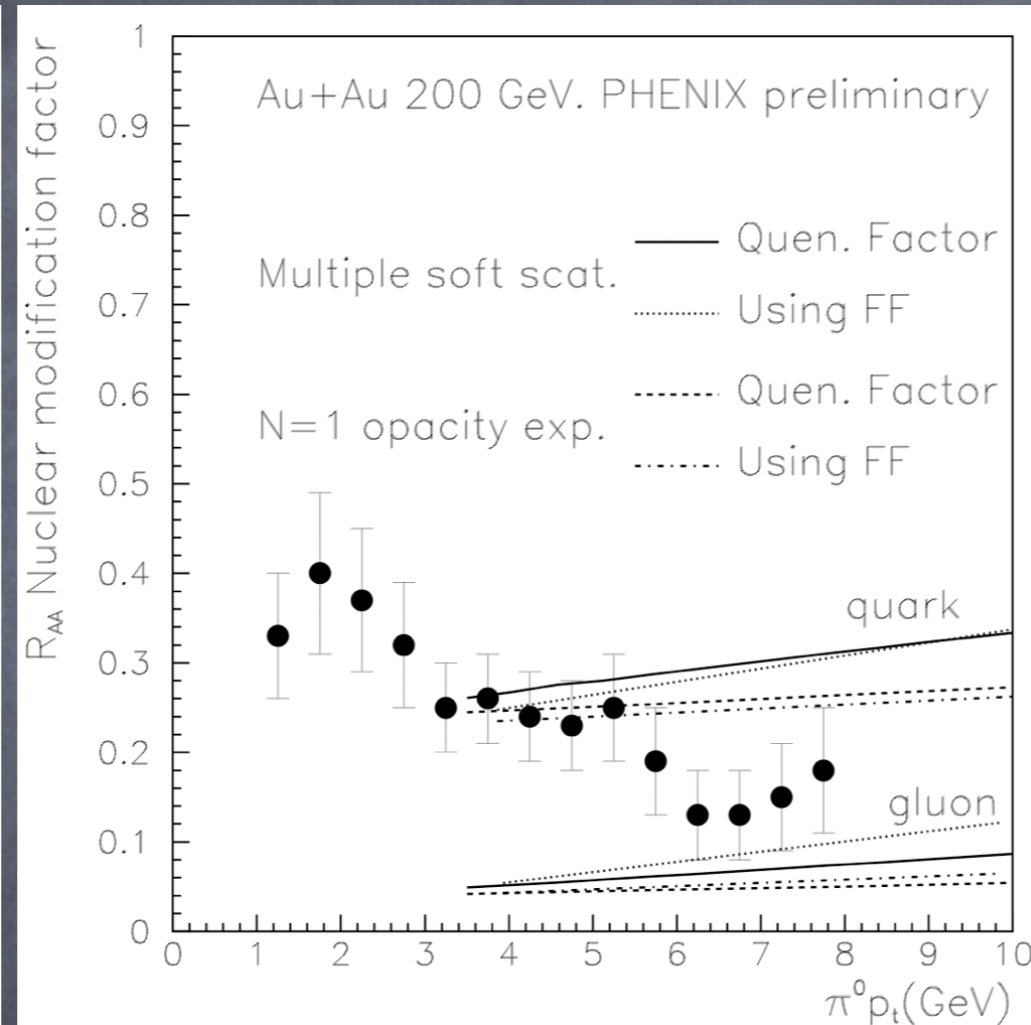
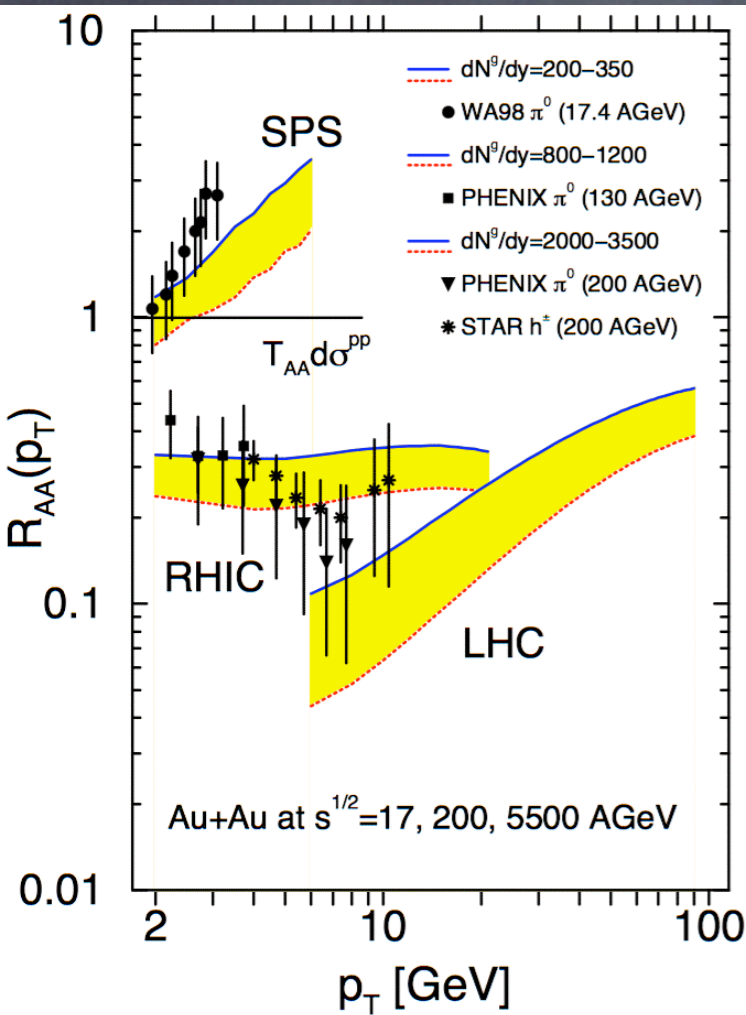
Models of high- p_T parton energy loss reproduce the data remarkably well



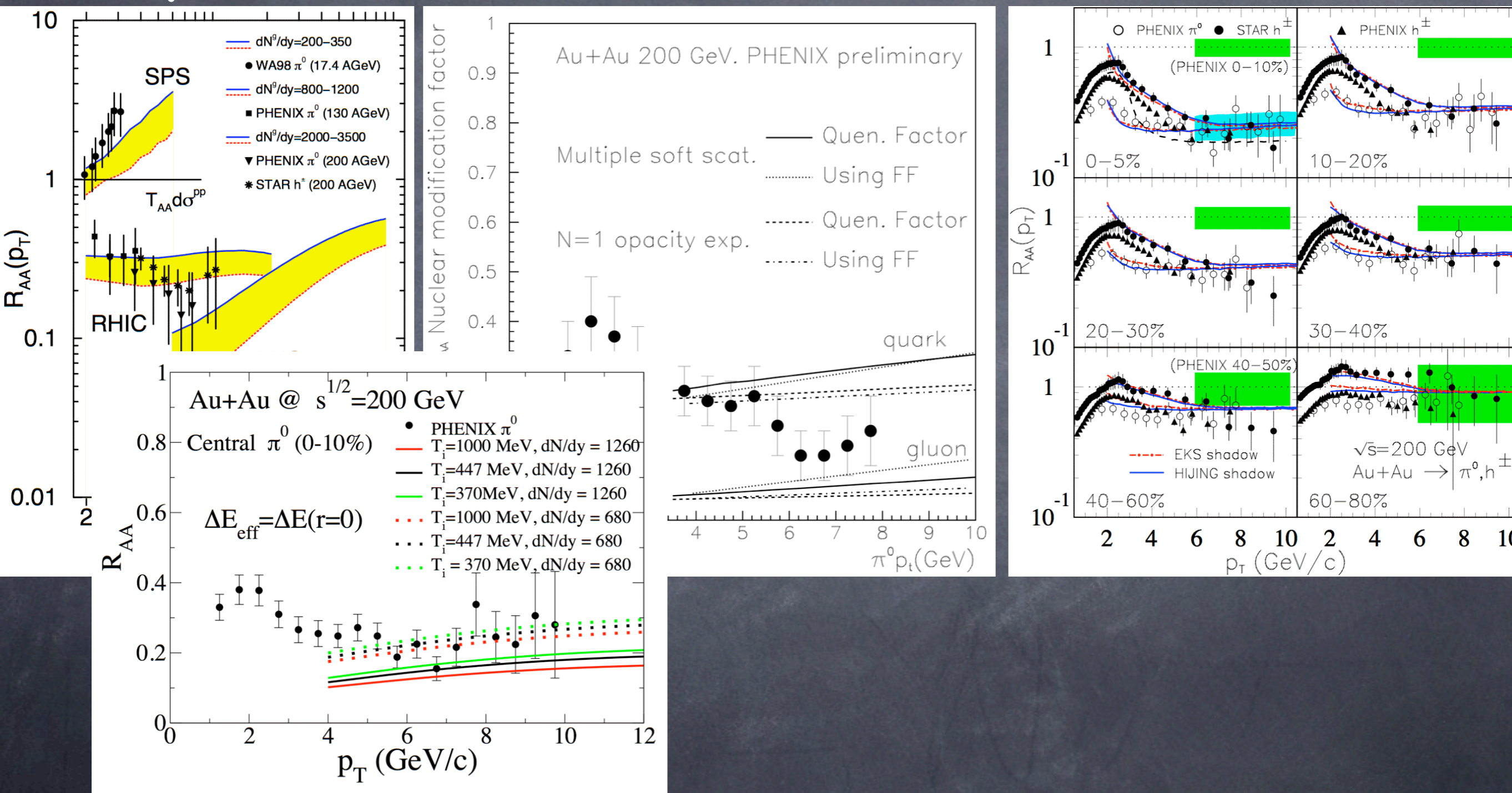
Models of high- p_T parton energy loss reproduce the data remarkably well



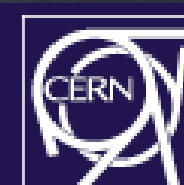
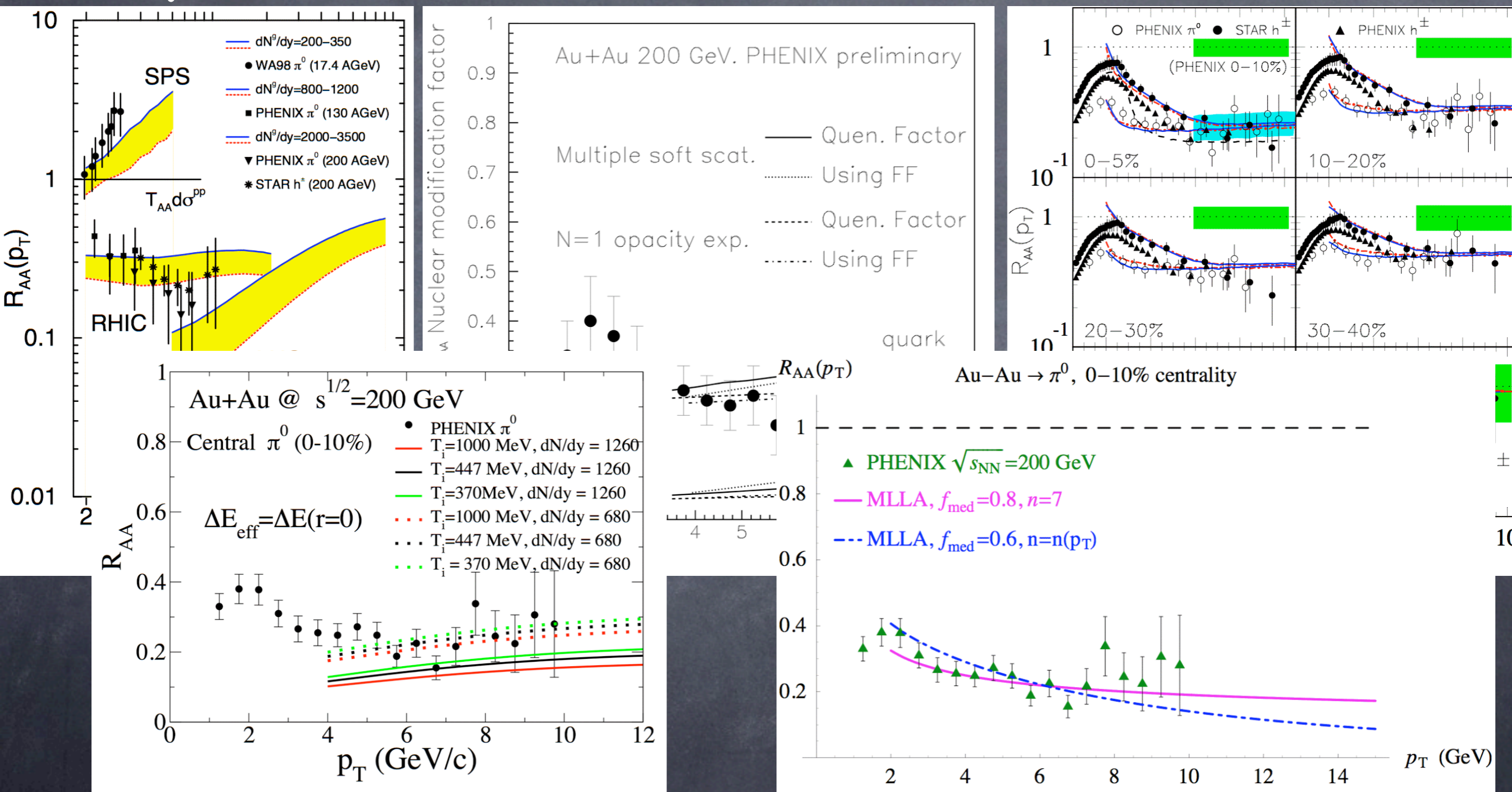
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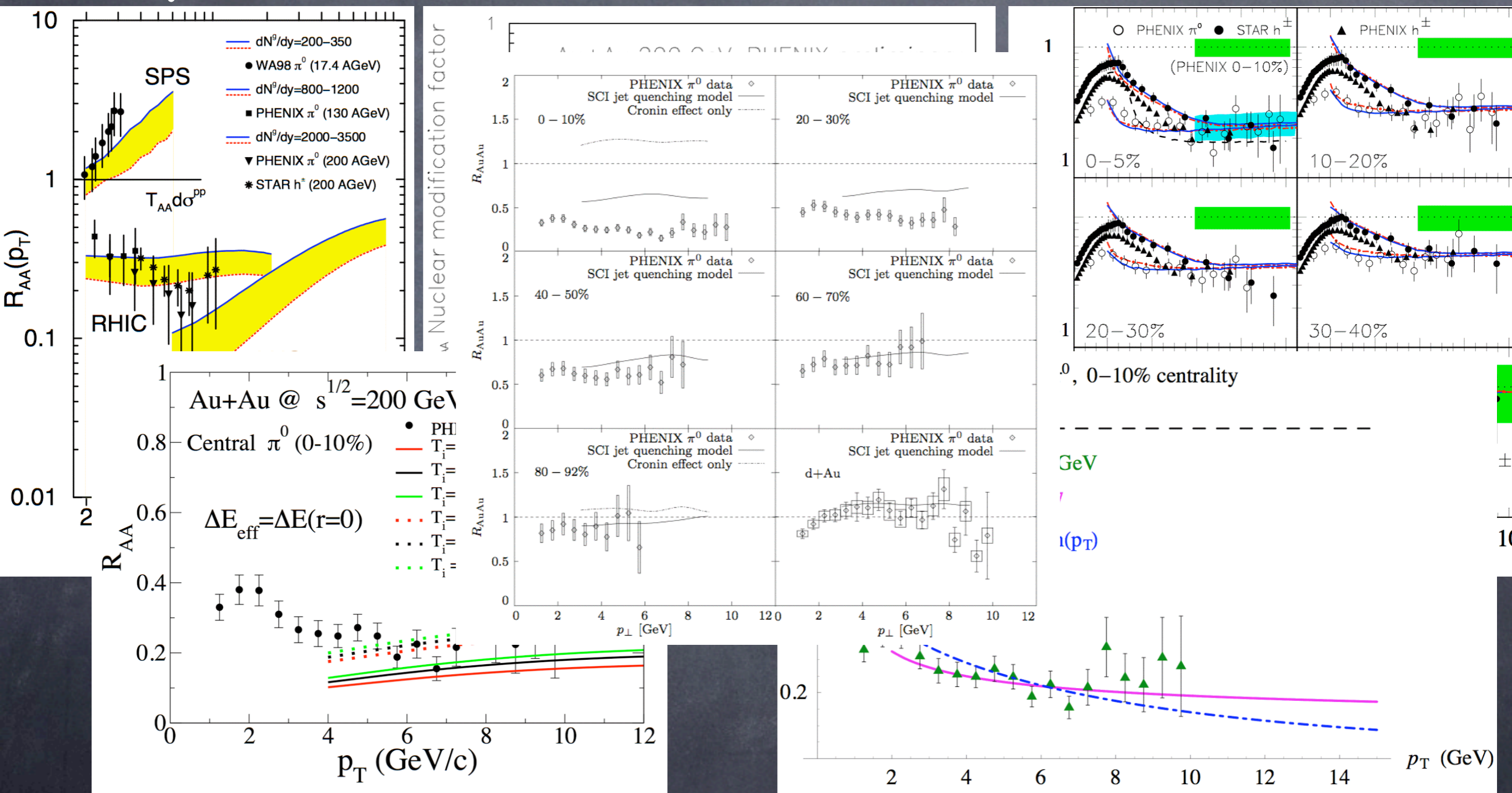
Models of high- p_T parton energy loss reproduce the data remarkably well



Models of high- p_T parton energy loss reproduce the data remarkably well



Models of high- p_T parton energy loss reproduce the data remarkably well



Models of high- p_T parton energy loss

Welcome to the realm of acronyms!

- ① Radiative vs. collisional **energy loss**
- ① 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**
- ① Theories and models of **collisional energy loss**

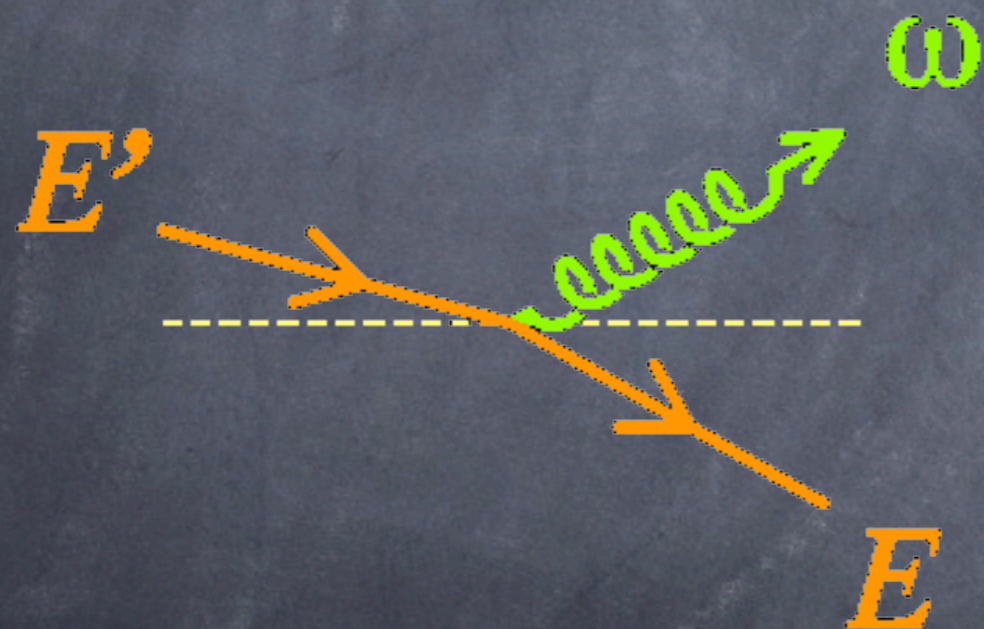


Models of high- p_T parton energy loss

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

inelastic

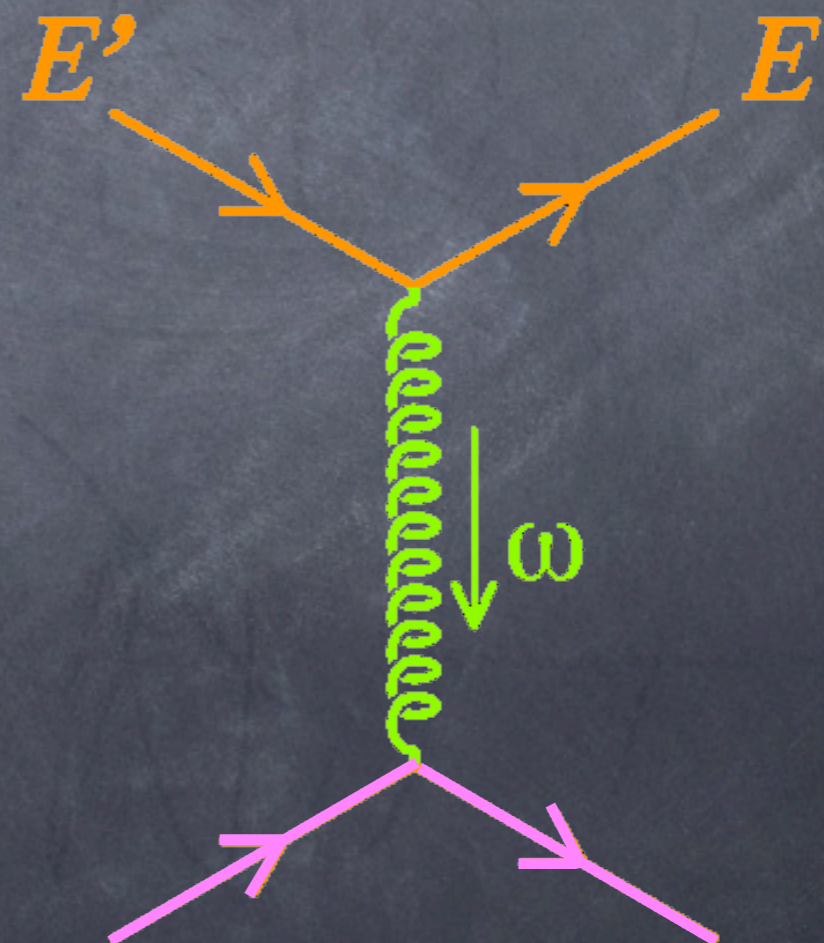
"radiative" process (Bremsstrahlung)



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

elastic

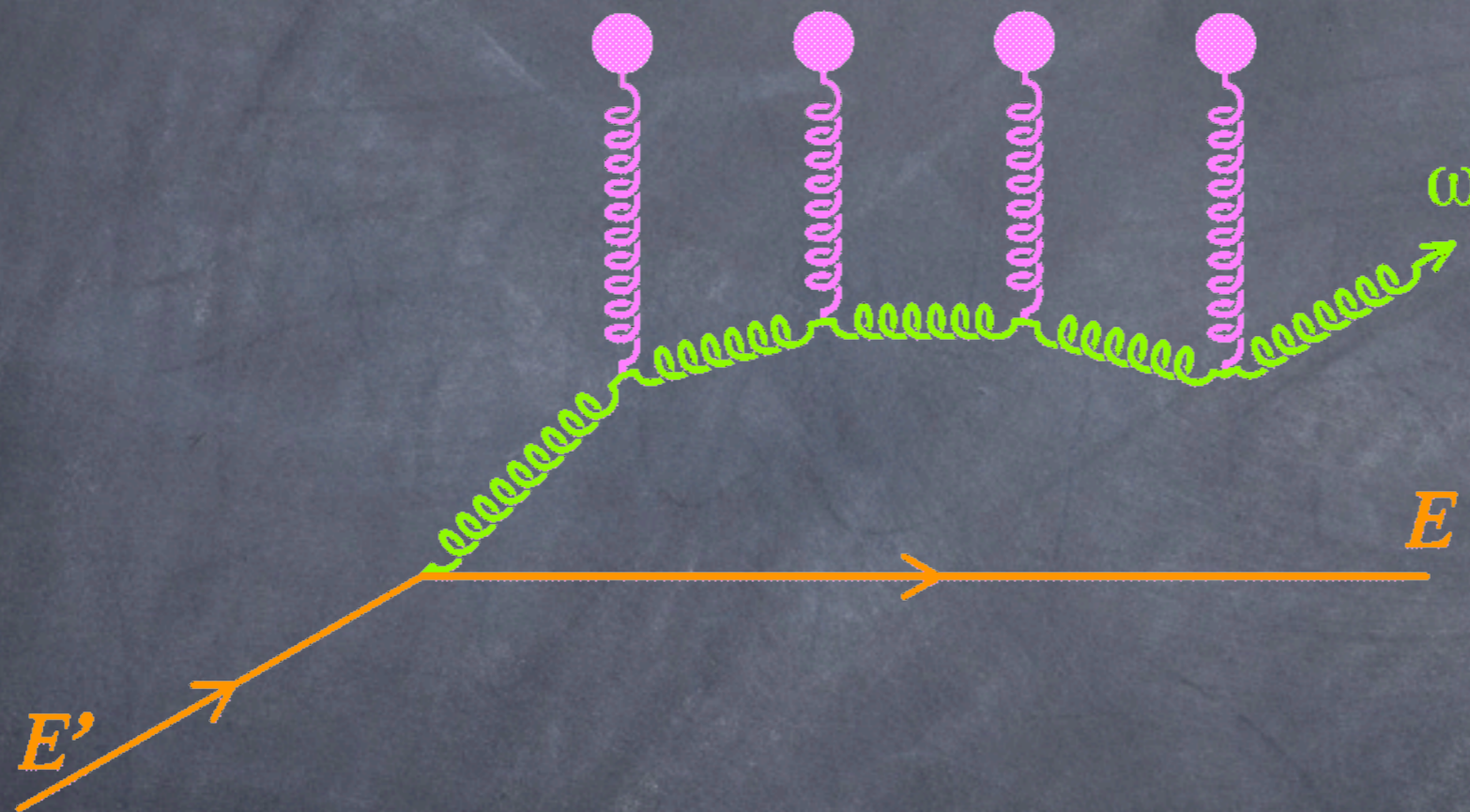
"collisional" process



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 \leftarrow λ \gg $1/\mu$ \rightarrow screening mass



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



Coherent scatterings: $\frac{l_{\text{coh}}}{k_{\perp}^2} \sim \frac{2\omega}{k_{\perp}^2} \leq L$ (medium length)
 coherence length \leftarrow $\frac{l_{\text{coh}}}{k_{\perp}^2}$ $\simeq N_{\text{coh}} \mu^2 \Rightarrow l_{\text{coh}} = \sqrt{\frac{2\omega\lambda}{\mu^2}}$
 of the emitted gluon

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

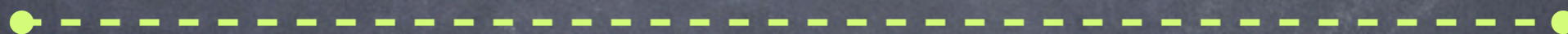
Models based on the Landau-Pomeranchuk-Migdal effect [3/4]

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

\Rightarrow gluon energy spectrum per unit path length $\omega \frac{dI}{d\omega dz} \simeq \frac{\alpha_s}{l_{\text{coh}}} \simeq \alpha_s \sqrt{\frac{\hat{q}}{\omega}}$

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

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



 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 ($\omega \rightarrow 0$) behaviour?

👁 BDMPS-Z: **coherent regime** requires

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

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

interaction of the **fast parton** with a **thermal bath**

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

✓ and for $0 < \omega < E_{\text{LPM}} \simeq 1 \text{ GeV}$, 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 .
↳ "opacity" (= number of collisions)

⇒ **gluon energy spectrum** per **unit path length**

$$\omega \frac{dI}{d\omega dz} \simeq \left(\frac{L}{\lambda}\right) \frac{\alpha_s}{l_{\text{coh}}} \simeq \left(\frac{L}{\lambda}\right) \alpha_s \frac{\mu^2}{\omega} \neq \alpha_s \sqrt{\frac{\hat{q}}{\omega}} \text{ within LPM}$$

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

Gyulassy, Lévai, Vitev (GLV); Wiedemann

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

↳ ⇔ the (linear) **density of scattering centers**



Inelastic energy loss

Models based on an **opacity** expansion [2/2]

- Within **GLV**, **radiated gluons** restricted to $\omega > \mu = \mathcal{O}(500 \text{ MeV})$, “common value” of the **screening mass** and the **plasmon excitation**
- **Energy loss** actually dominated by **energetic gluons** $\omega \gtrsim \bar{\omega}_c \equiv \frac{1}{2} \mu^2 L$ (\neq **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.

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

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



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⇒ modification of the “hump-backed plateau” of longitudinal particle distributions within a jet computed using MLLA

NB, Wiedemann



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Modified Leading Logarithmic Approximation (of QCD)



Inelastic energy loss

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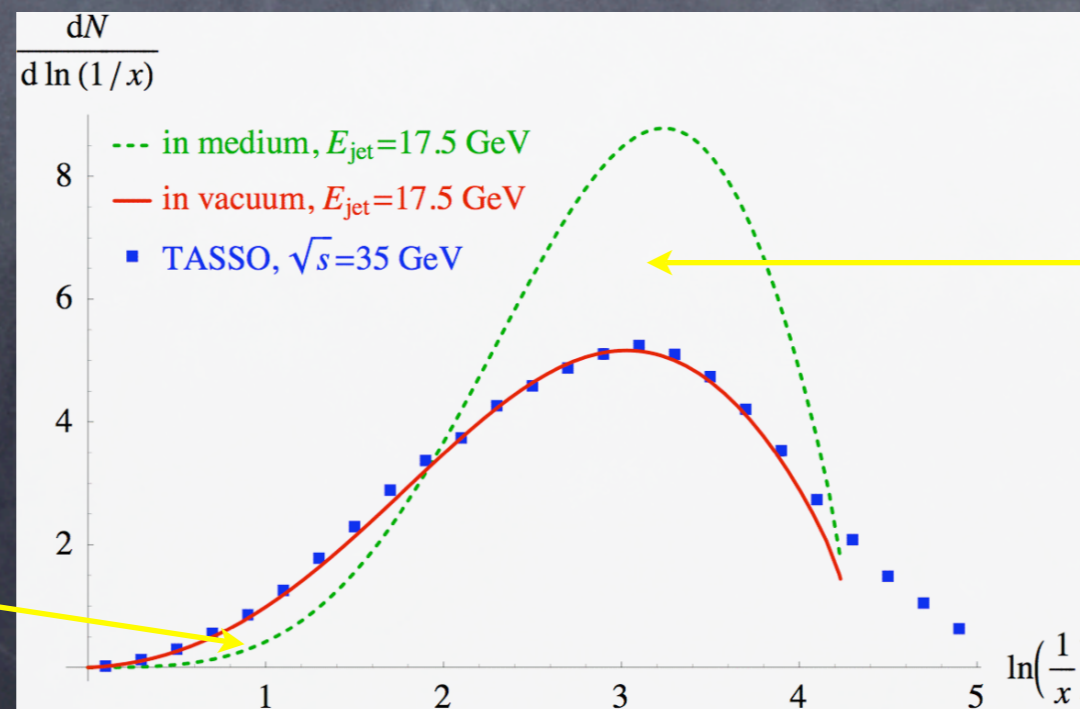
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⇒ modification of the “**hump-backed plateau**” of longitudinal particle distributions within a **jet** computed using **MLLA**

NB, Wiedemann

depletion
at large x



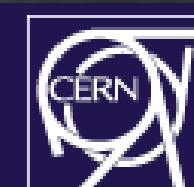
enhancement
at small x

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 ($\hat{q} \rightarrow \hat{q}_{\text{eff}}$) of the parameters, to the introduction of new ones (τ_0, T_0), or to a change in scaling properties ($\Delta E_{\text{GLV}} \propto L$ 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 $T_i = 370 \text{ MeV}$, $\tau_i = 0.26 \text{ fm}/c$,
 $\frac{dN}{dy} = 1260$ & $\alpha_s = 0.3$.
No need for **initial state effects** as **shadowing** & the **Cronin effect**
 - **GLV**, PRL 89 (2002) 252301: $\frac{dN^g}{dy} = 1100$
invoke competition between **shadowing**, **Cronin effect** and **partonic energy loss** to obtain a flat R_{AA} .

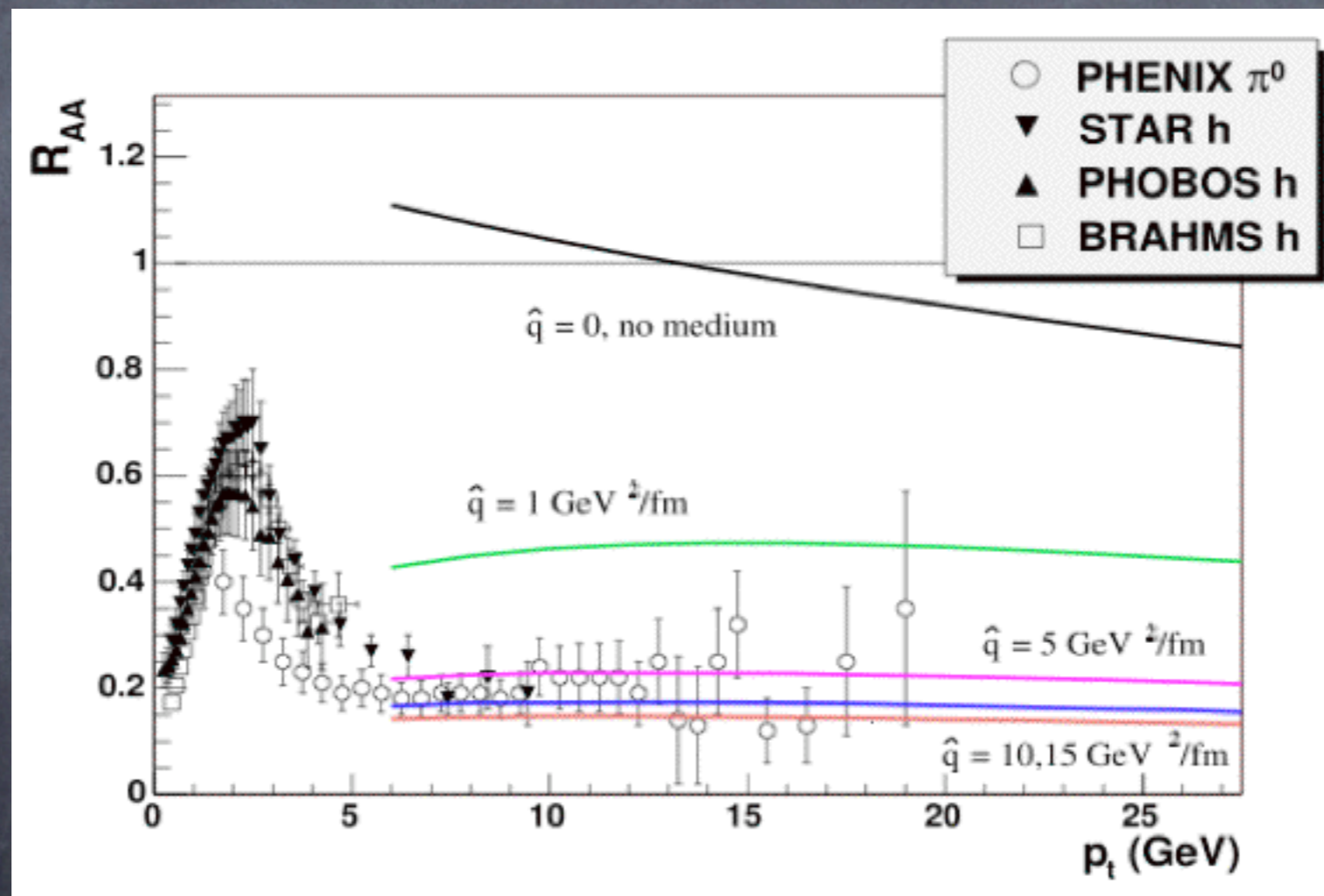


Inelastic energy loss

Further **model**-dependent remarks [1/3]

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 $15 \text{ GeV}^2/\text{fm}$

Inelastic energy loss

Further **model**-dependent remarks [2/3]

Let me be even more pessimistic / skeptical...

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

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

which leads to strong (& questionable?) conclusions

👁 Arleo, hep-ph/0601075:

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

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

👁 Baier & Schiff, hep-ph/0605183:

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

restricting the region of validity of the **LPM effect**



Inelastic energy loss

Further **model**-dependent remarks [3/3]

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").

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

Liu, Rajagopal, Wiedemann

$\hat{q}_{\text{SYM}} \propto \sqrt{N_c} \neq$ number of degrees of freedom is proportional to N_c^2
↔ entropy density

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



Elastic energy loss

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

Bjorken (1984), Thoma & Gyulassy (1991), Braaten & Thoma (1991), Wang, Gyulassy & Plumer (1995), Mustafa et al. (1998), Lin, Vogt & Wang (1998): $dE_{el.}/dz \approx 0.3 - 0.5 \text{ GeV/fm}$: negligible!

Then, all of a sudden...

Mustafa & Thoma (2003), Dutt-Majumder et al. (2004), Wicks, Horowitz, Djordjevic & Gyulassy (2006), Peshier (2006): it is sizable! (either for heavy quarks only, for c only, for light quarks as well...)

Yet, at the same time...

Peigné, Gossiaux, Gousset (2005): yes, elastic energy loss is negligible, because the parton is formed inside the medium, not at infinity.

Conclusion... { ask Pol-Bernard and/or Thierry for further detail
we'll know more at the time of the Deuxièmes Journées

