Status of Jet Quenching Theory

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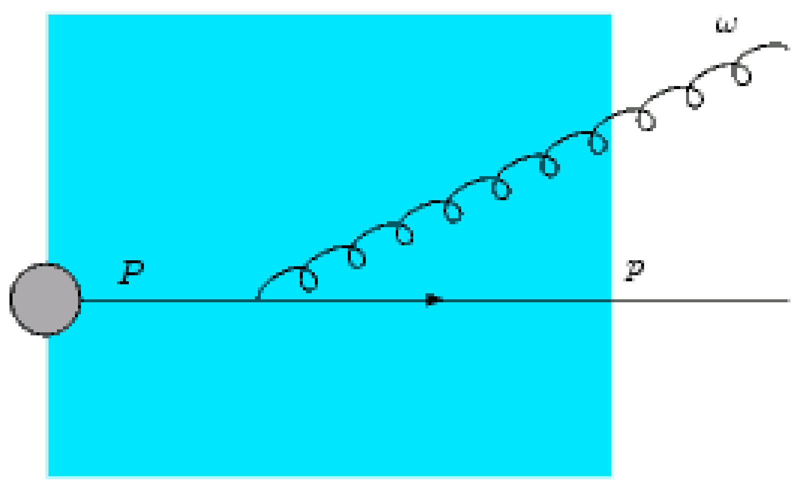
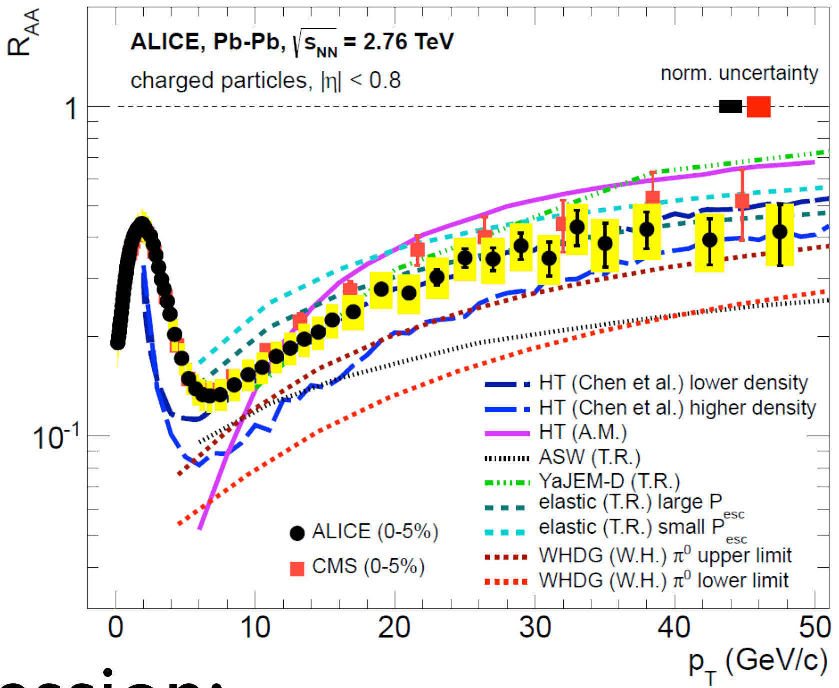
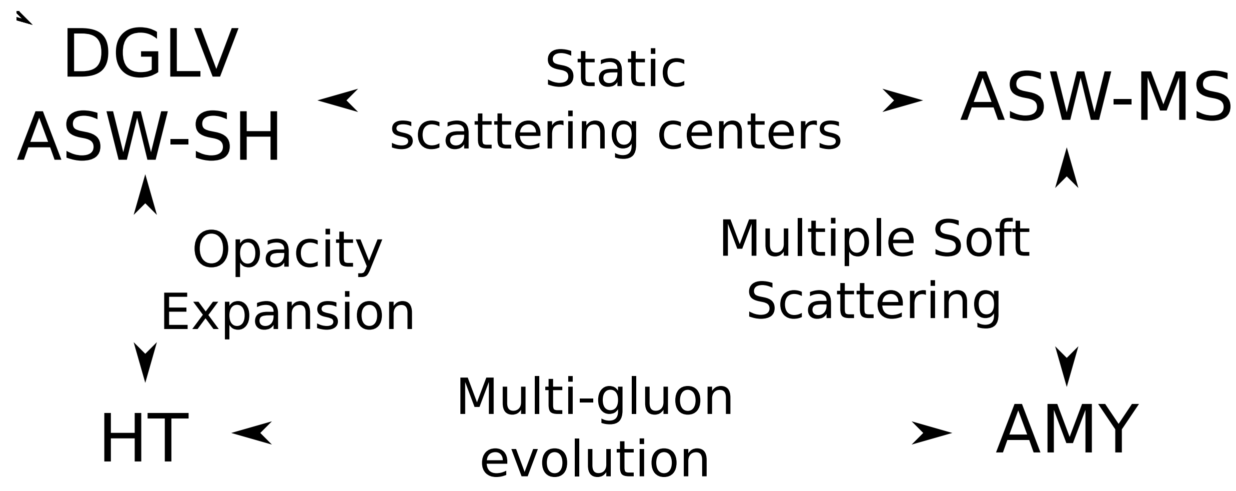
High-PT Particle Suppression





- Description of high-pt suppression:
  - E-loss from a single parton
  - Includes radiative and collisional losses
  - Fate of the radiated gluon is not followed
  - Mostly sensitive to longitudinal degradation
- The single gluon emission rate is under theoretical control (at least in certain limits)
  - Multi-gluon emissions described by iteration
  - Sensitive to non-perturbative FF.

Comparison Between Formalisms

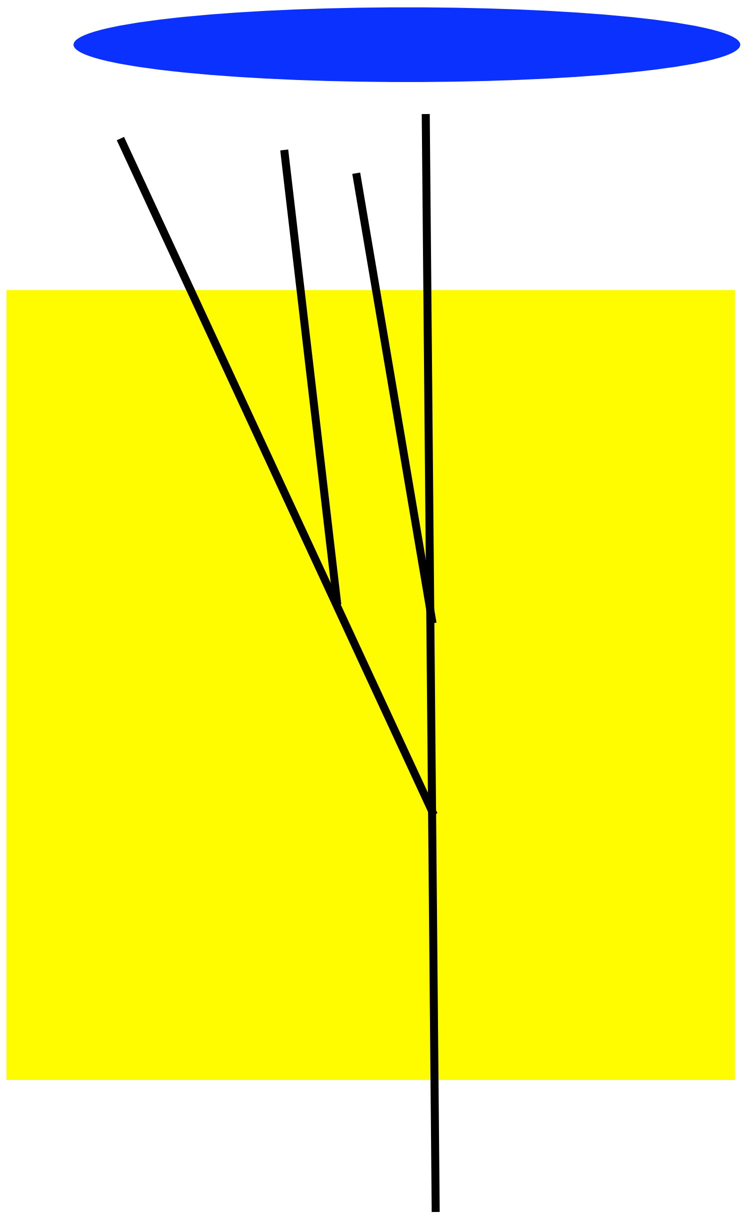


- A variety of formalisms all based on the same processes (diagrams)
- TECHQM: differences among formalisms arise from:
  - Different approximations to the emission dynamics
  - Treatment of the regions beyond theoretical control
  - Assumptions made on the medium proved

    Perturbative in most cases

    Difficult to separate from the formalism

From Single Parton To Jets



Medium induced gluon radiation: effective mechanism suppressing leading hadrons

Jets collect many partons:

Degradation of leading parton does not imply jet energy loss!

Parton shower leads to more sources

How and when do they loose energy?

Processes which take energy out of cone: Broadening effects, multiple scattering, elastic loss, large angle radiation...

Multi-particle problem which calls for a MC implementation

Monte Carlo Generators

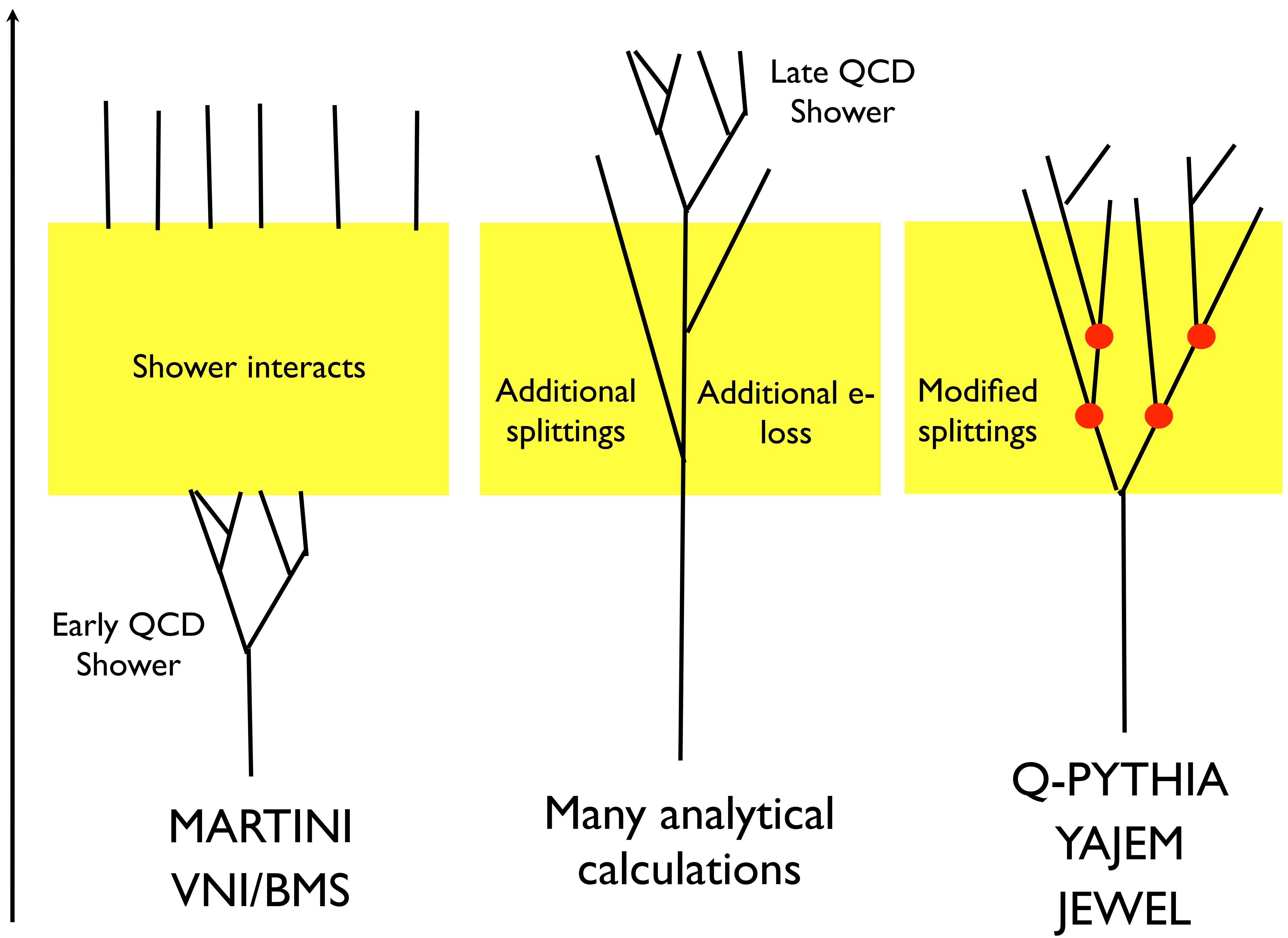
MARTINI VNI/BMS	YAJEM-X
Q-PYTHIA (MATTER++)	JEWEL

- Based on radiative-loss calculations. Many include elastic losses
- Very different implementation:
  - Different treatment of the vacuum showers
  - Different recipes for MC generation of medium induced rad.
  - Some include modifications of hadronization

The MC procedure is not grounded in well controlled calculations

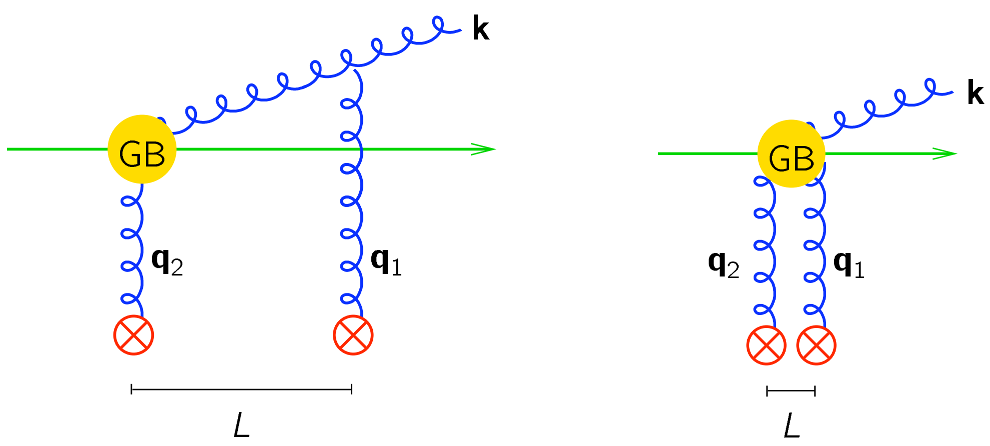
- A direct comparison is not obvious

Time Structure of the Shower



Formation Time and Vacuum Showers

- Induced radiation is dominated by formation time $\tau_f = 2\,\omega / k_\perp^2$



A MC implementation based on this time scale reproduces the main features of LPM

(Zapp, Stachel & Wiedemann 08)

- No equivalent calculation for the vacuum shower
- Standard approach: parametric estimate by uncertainty principle

$$\tau_f = \mathcal{C}\,\frac{E}{Q^2}$$

(unknown) constant of order one

- The distribution of time scales is unknown.

$$D(\tau) = \frac{1}{\tau_f} e^{-\tau/\tau_f}$$

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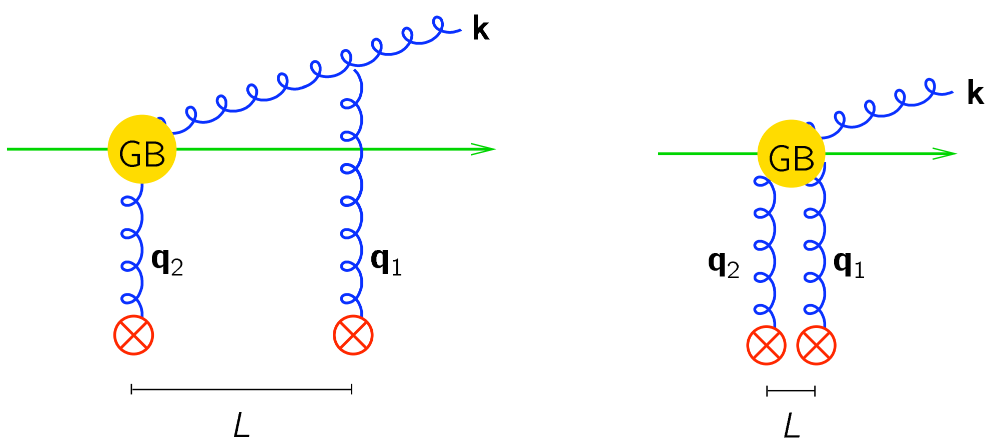

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$$\tau_f = \mathcal{C}\frac{E}{Q^2}$$

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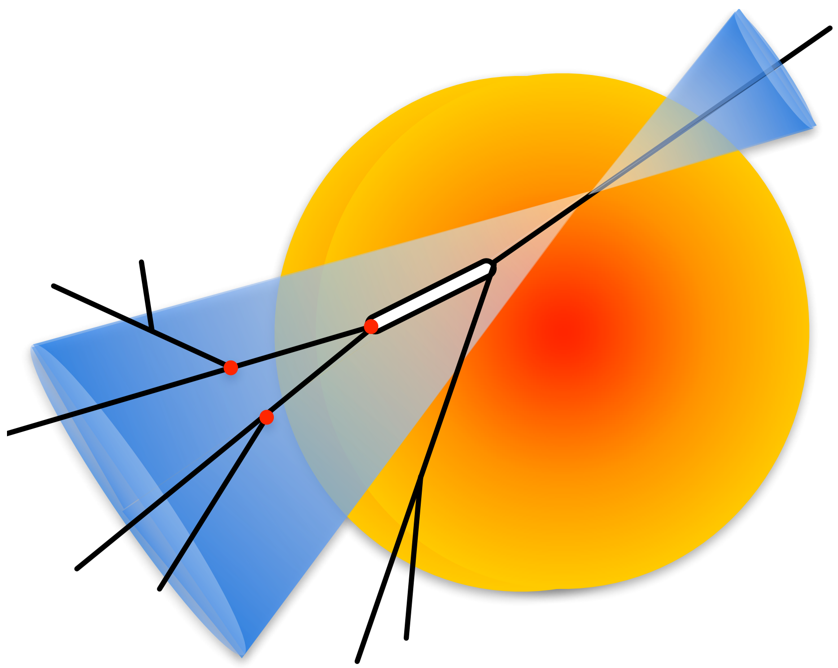
$$\tau_f = \mathcal{C} E_f \left(\frac{1}{Q_f^2} - \frac{1}{Q_d^2} \right)$$

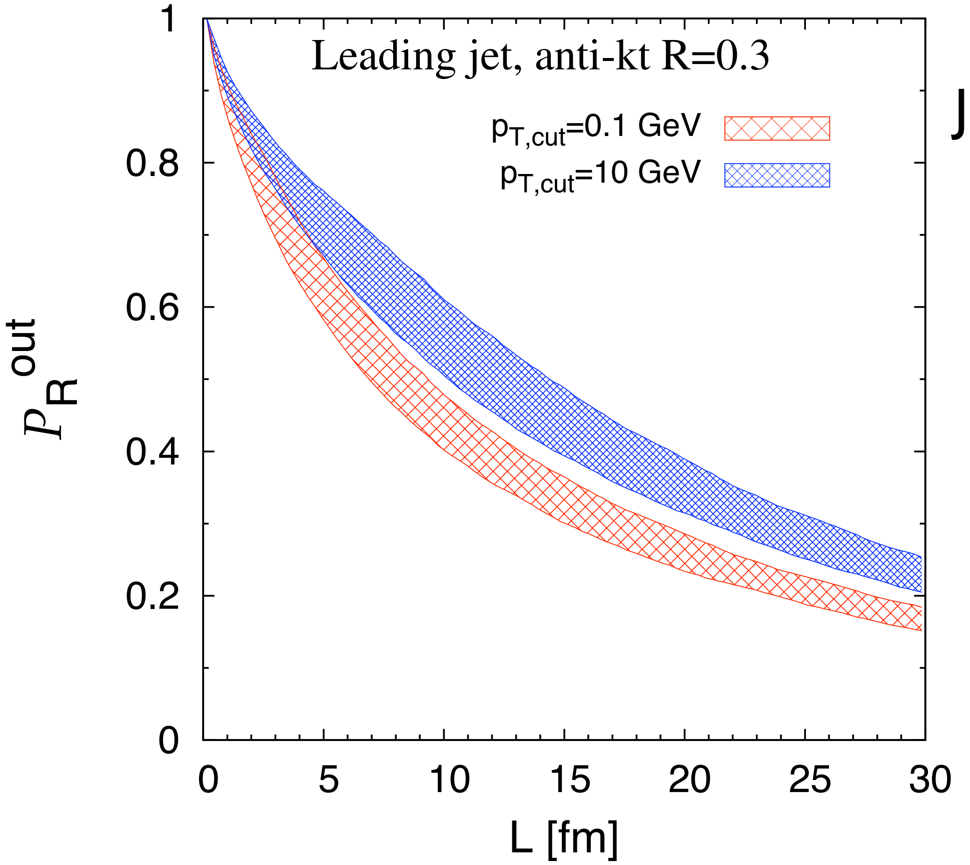
YAJEM

- The distribution of time scales is unknown.

$$D(\tau) = \frac{1}{\tau_f} e^{-\tau/\tau_f}$$

Long formation times





JCS, Quiroga, Milhano
11

- Typical formation time is comparable to medium size
- Sizable uncertainties due to the distribution function
- All jet path length dependence analysis are dependent on this estimate

MC In-medium Showers

- Martini:

  Rate equation based on AMY

  Short formation times and no interference with vac. radiation

  Incorporates broadening of fragments by multiple scattering

- QPYTHIA (MATTER++)

  In-Medium modification of Sudakov

  Resummation of single inclusive spectrum is assumed

  All energy and momentum shared into shower partons

- JEWEL , YAJEM

  Momentum transfers increase the virtuality of the QCD shower

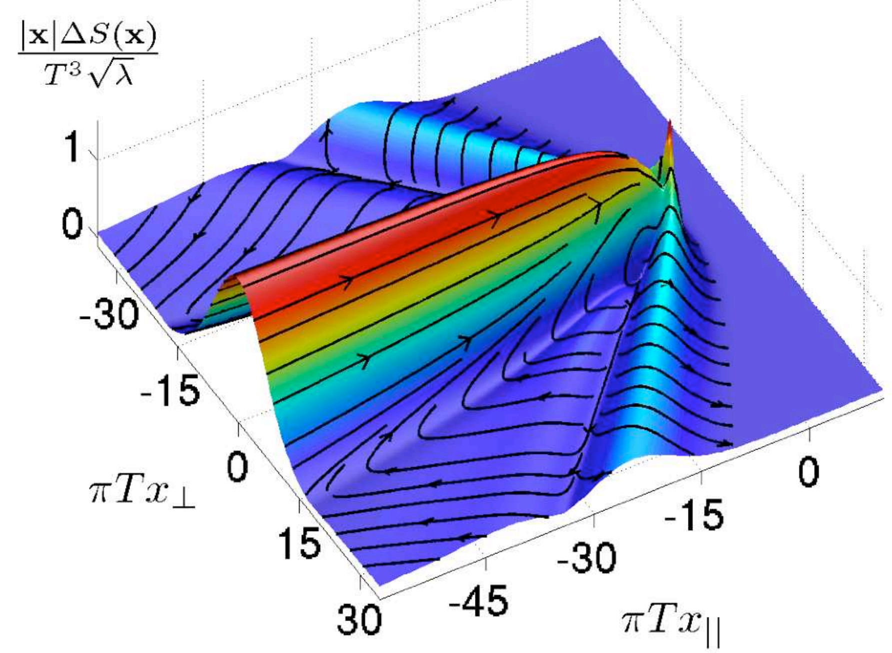
  JEWEL: Initial radiation prior to scattering introduced

  JEWEL: Well tested algorithm to include LPM interference

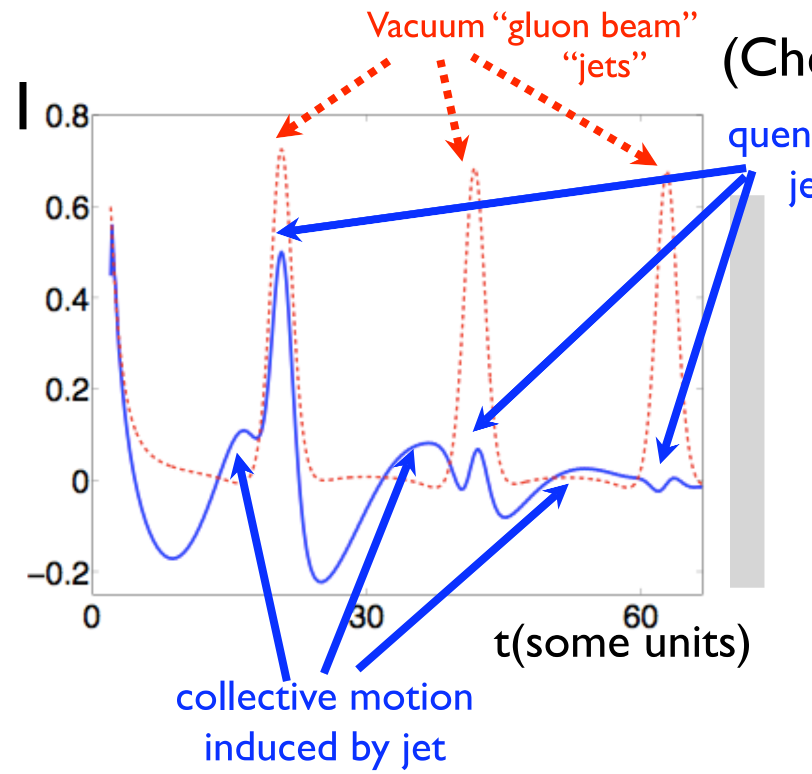
All these recipes are only partially supported by explicit calculations

Medium Back-Reaction

(Cherler and Yaffe 08)



(Cherler, Ho, Rajagopal 12)



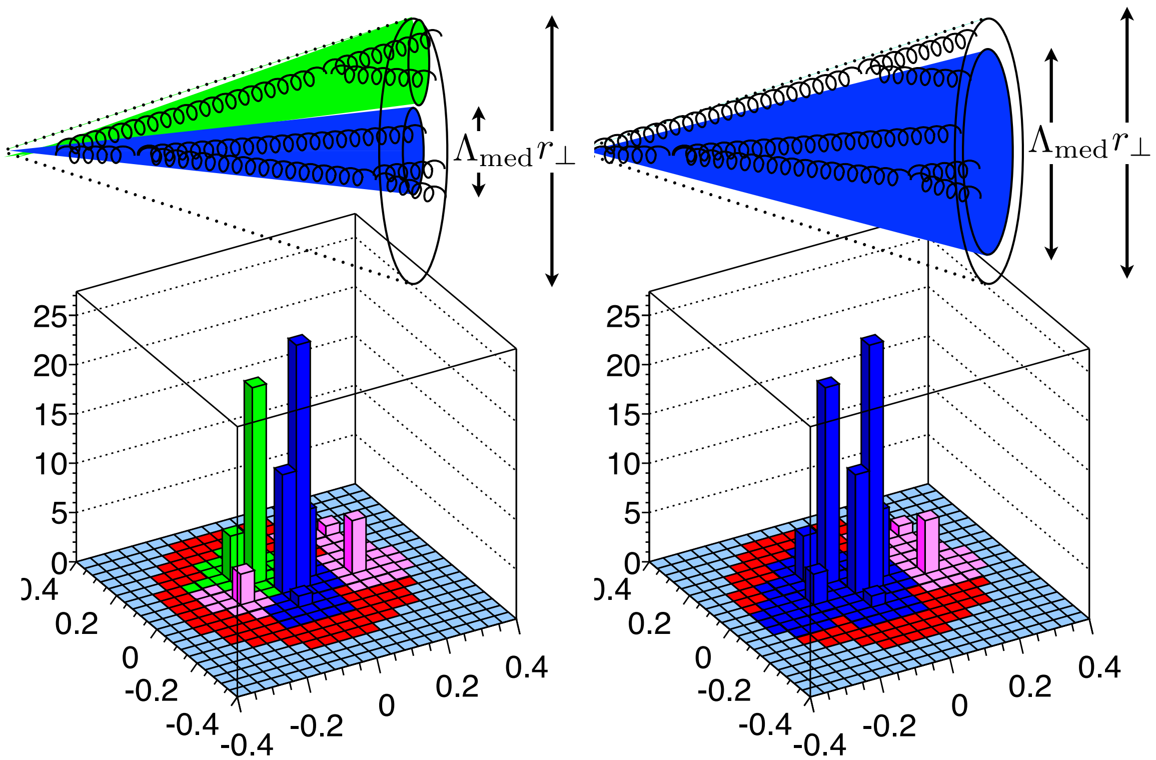
- Dynamics of the medium is not described in most models
- Expectation: medium particles correlated to the jet direction

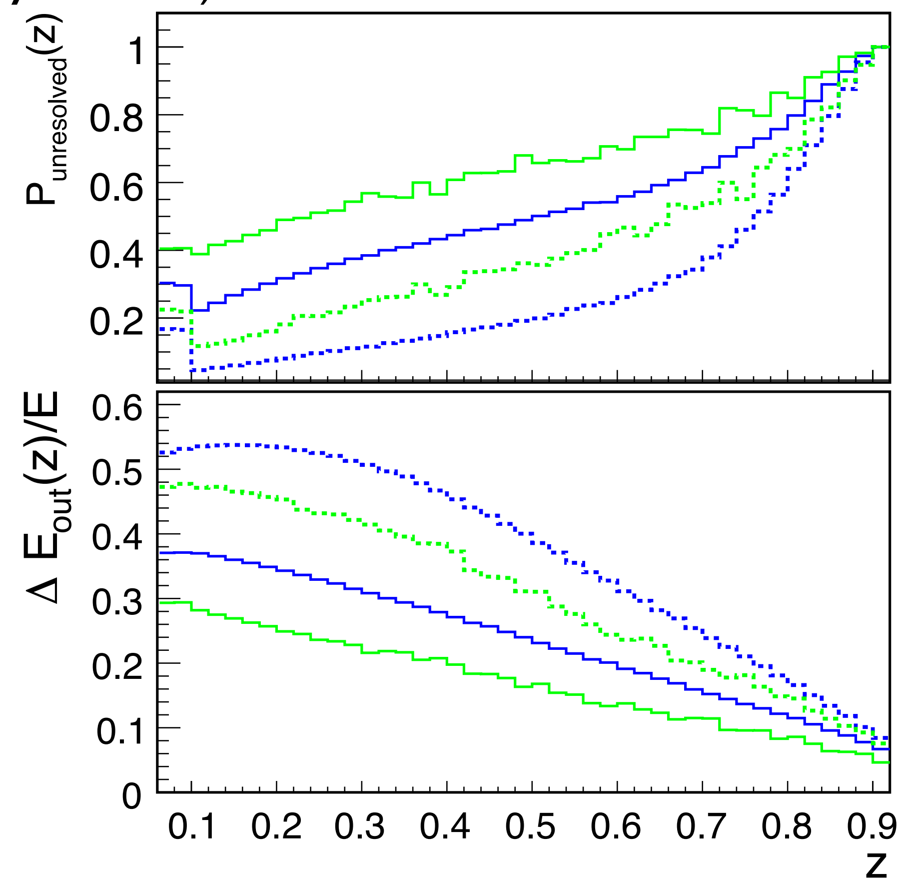
  Observed both at strong and weak coupling
- These soft particles enter in the jet finding. Not a background
- Fragments of few GeV get affected by this effect

  Enhancement of soft particles picked up from the medium
- Can we find a jet definition with little sensitivity to those?

Medium-Resolution

(JCS, Mehtar-Tani, Salgado Tywoniuk)





- Analysis of the QCD antenna:

  Non-trivial interference pattern between multiple sources

  (JCS, Mehtar-Tani, Salgado Tywoniuk)

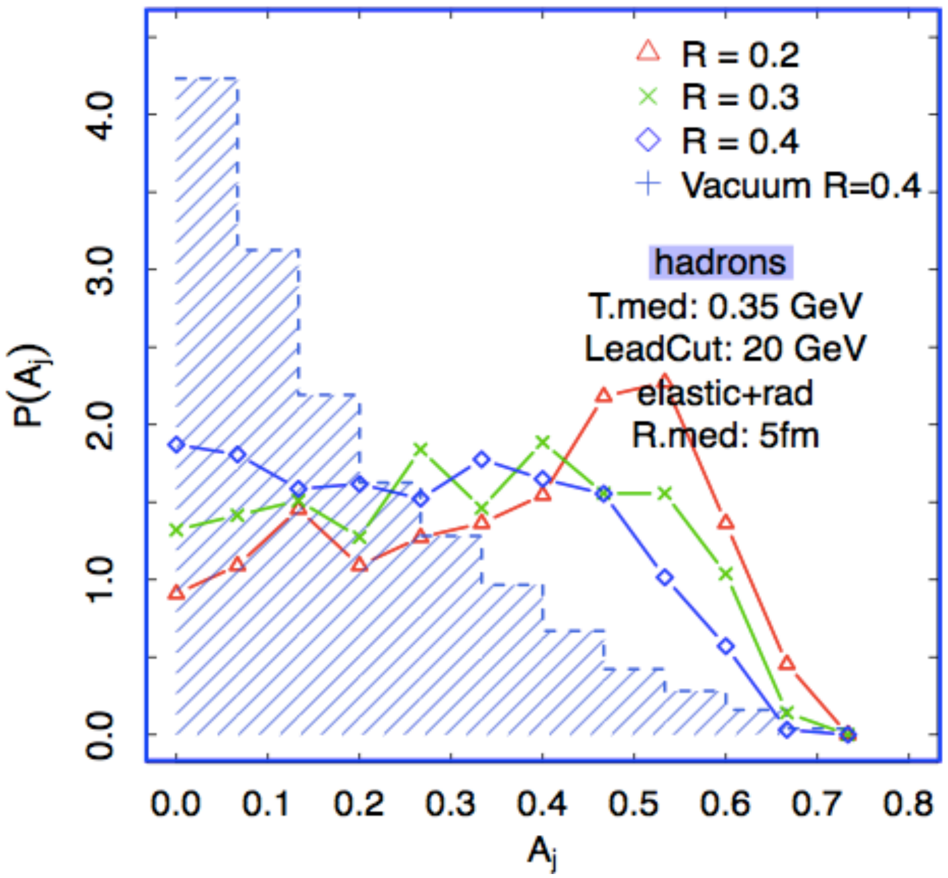
- A simple recipe to incorporate in

  Fragments with $r_\perp < \Lambda_{med}$ fragments radiate a single object

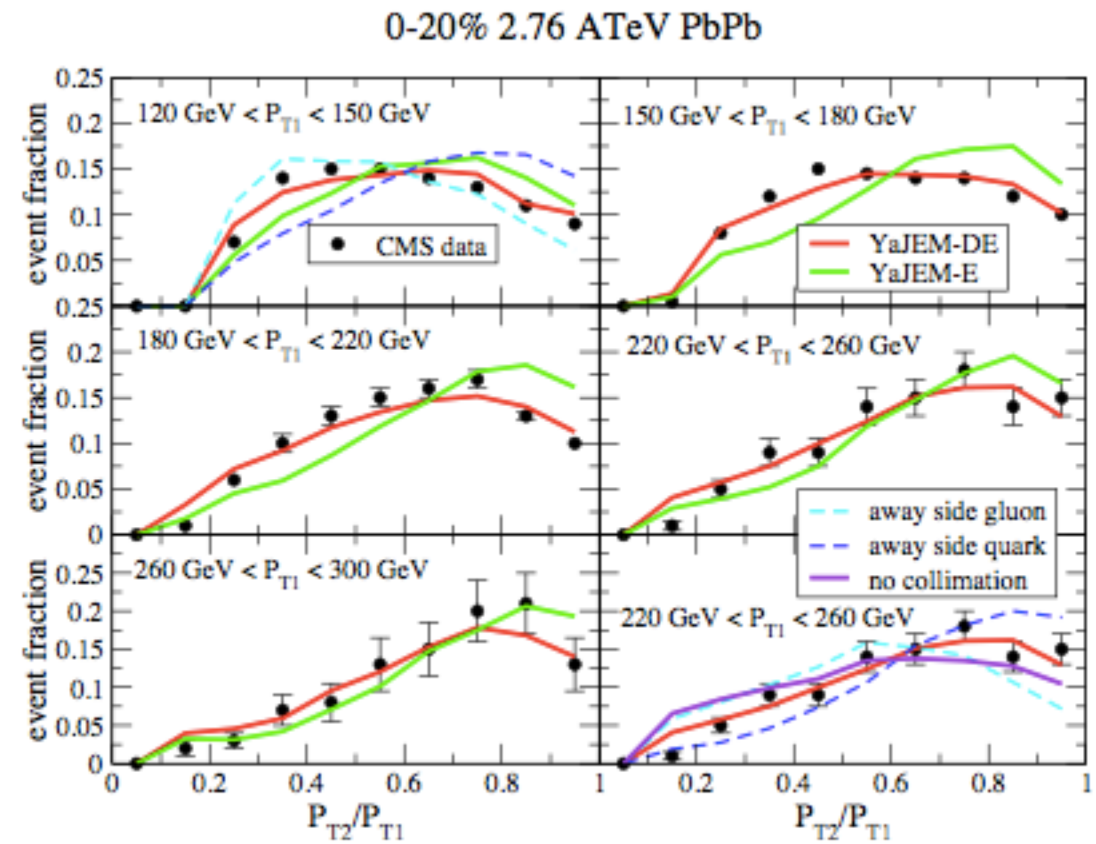
  (independent on when fragments are radiated)

- Narrow high energy jets behave mostly like one single emmiter

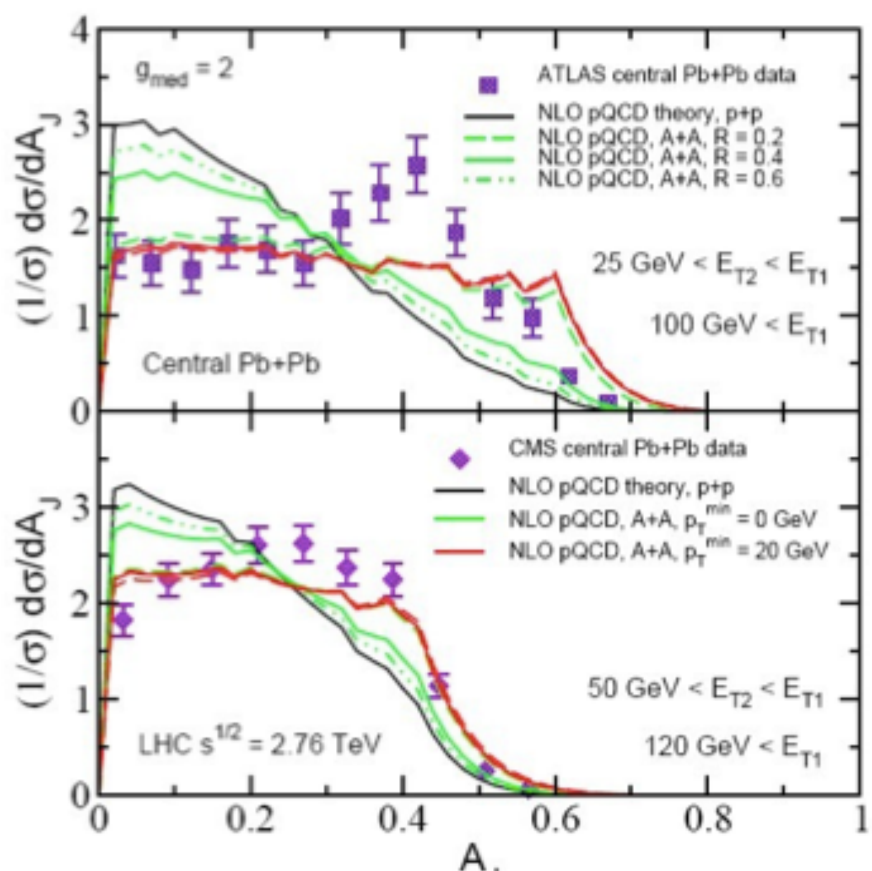
MC vs data



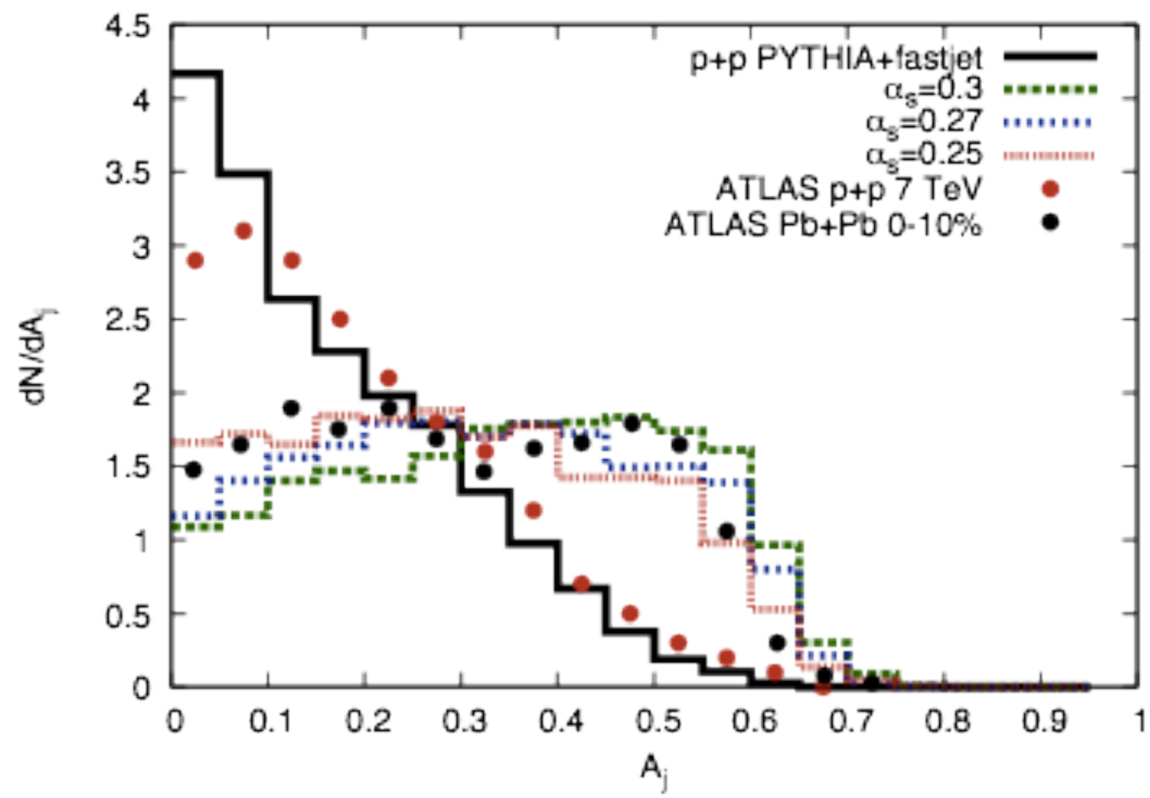
R = 0.2
R = 0.3
R = 0.4
Vacuum R=0.4
hadrons
T.med: 0.35 GeV
LeadCut: 20 GeV
elastic+rad
R.med: 5fm
P(A_j)
A_j
0.0 1.0 2.0 3.0 4.0
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8



0-20% 2.76 ATeV PbPb
120 GeV < P_T1 < 150 GeV
150 GeV < P_T1 < 180 GeV
180 GeV < P_T1 < 220 GeV
220 GeV < P_T1 < 260 GeV
260 GeV < P_T1 < 300 GeV
220 GeV < P_T1 < 260 GeV
CMS data
YaJEM-DE
YaJEM-E
away side gluon
away side quark
no collimation
event fraction
P_T2/P_T1



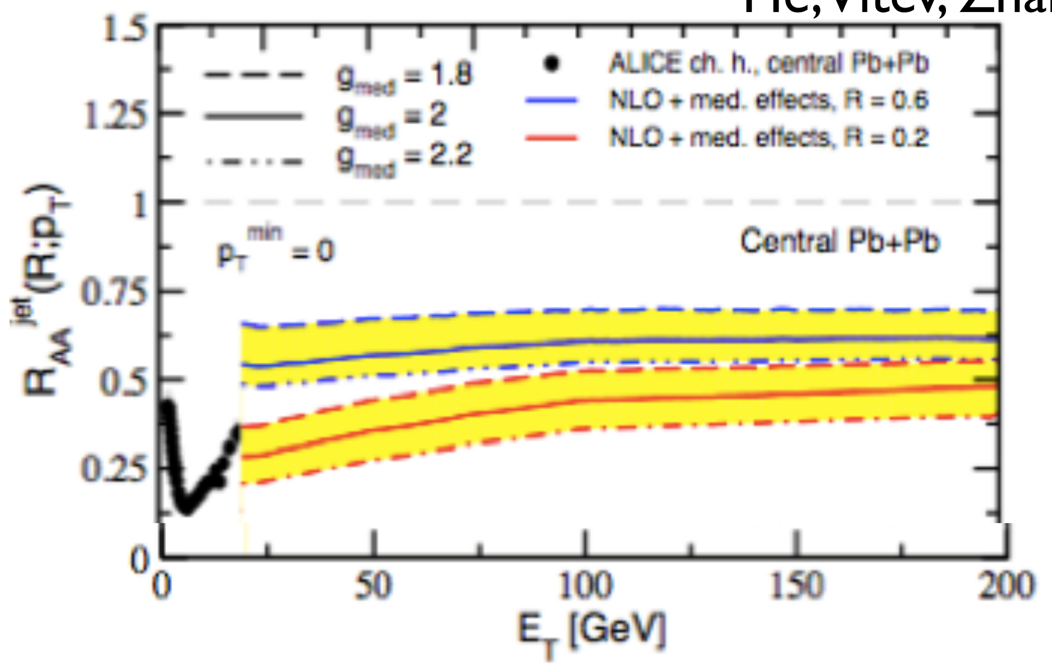
g_med = 2
ATLAS central Pb+Pb data
NLO pQCD theory, p+p
NLO pQCD, A+A, R = 0.2
NLO pQCD, A+A, R = 0.4
NLO pQCD, A+A, R = 0.6
25 GeV < E_T2 < E_T1
100 GeV < E_T1
Central Pb+Pb
CMS central Pb+Pb data
NLO pQCD theory, p+p
NLO pQCD, A+A, p_T^min = 0 GeV
NLO pQCD, A+A, p_T^min = 20 GeV
50 GeV < E_T2 < E_T1
120 GeV < E_T1
LHC s^1/2 = 2.76 TeV
(1/σ) dσ/dA_J
A_J

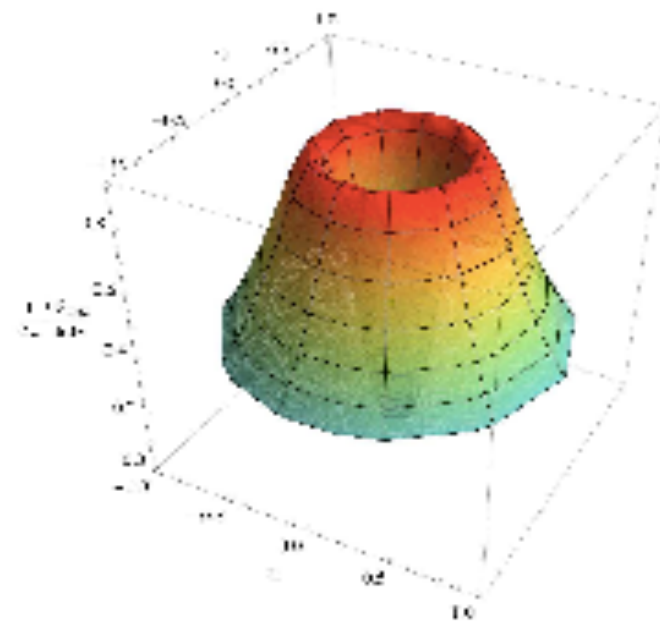


p+p PYTHIA+fastjet
α_s=0.3
α_s=0.27
α_s=0.25
ATLAS p+p 7 TeV
ATLAS Pb+Pb 0-10%
dN/dA_j
A_j

R-Dependence of E-loss

He, Vitev, Zhang 11





- From radiative losses R dependence of RAA was expected

  Well defined angular distribution of emitted gluons

  Collisional loss reduce this dependence

- Interaction of the emitted gluons was not considered

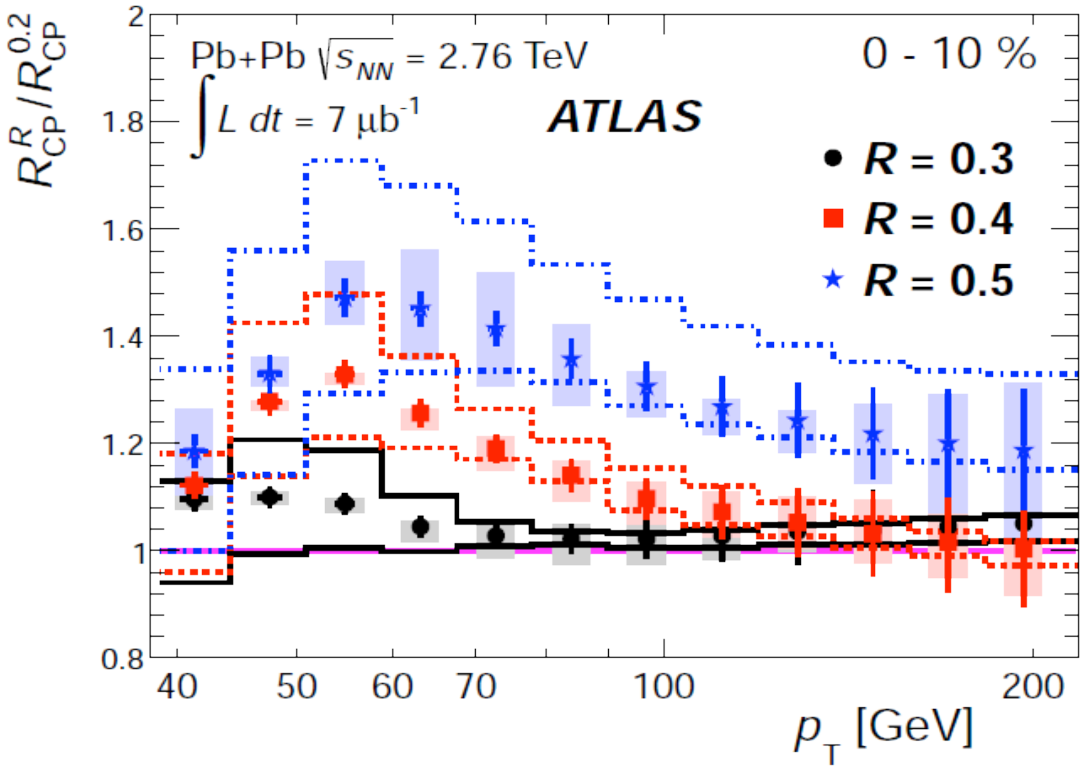
  Very fast degradation of soft emitted gluons (Blaizot, Mehtar-Tani, Iancu)

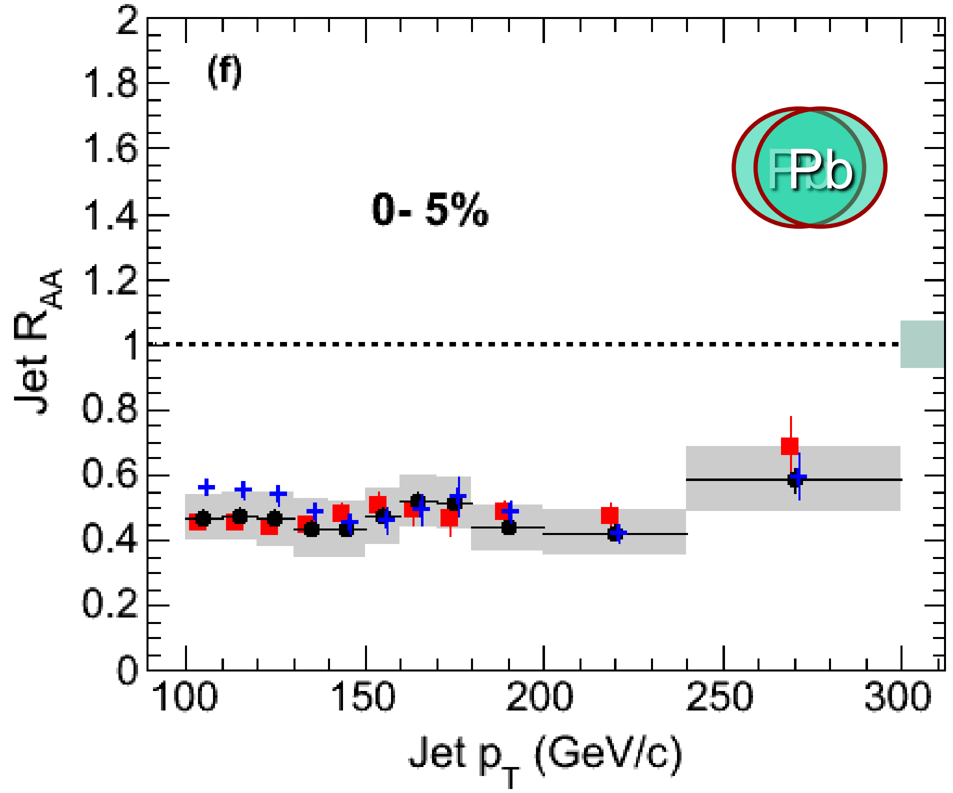
  “Collimation” or transport out of the cone (JCS, Milhano, Wiedemann)

- These effects are incorporated into MC codes

  Larger suppression at larger R?

R-Dependence of E-loss





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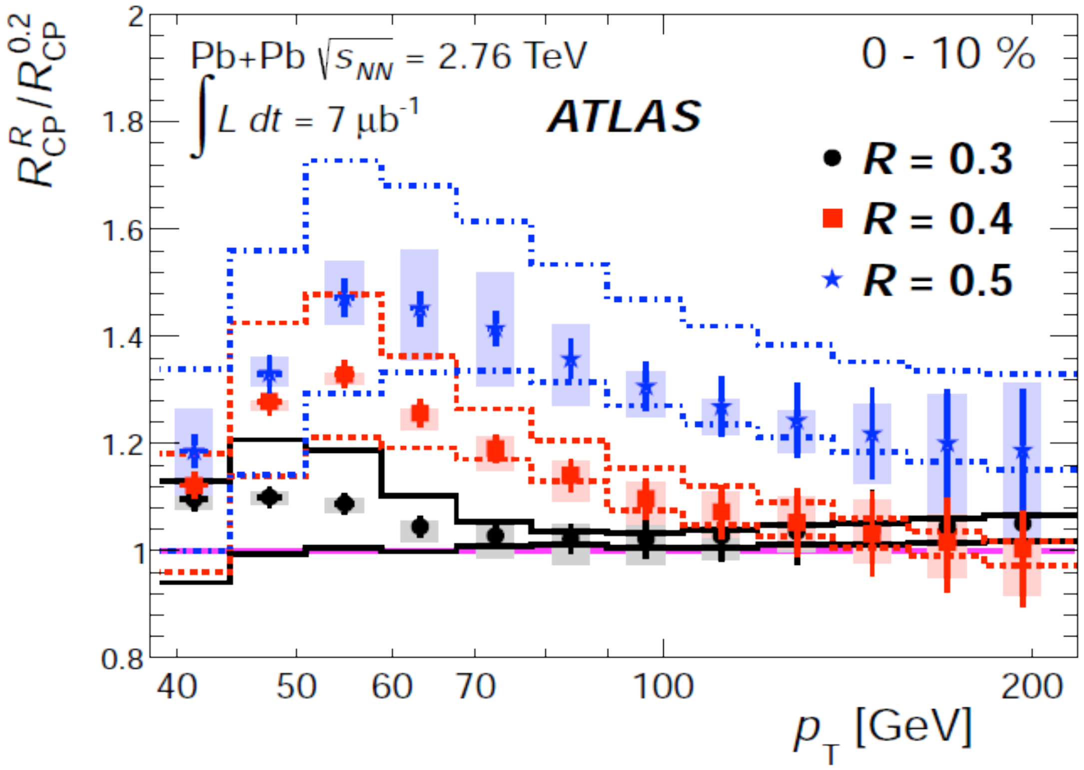

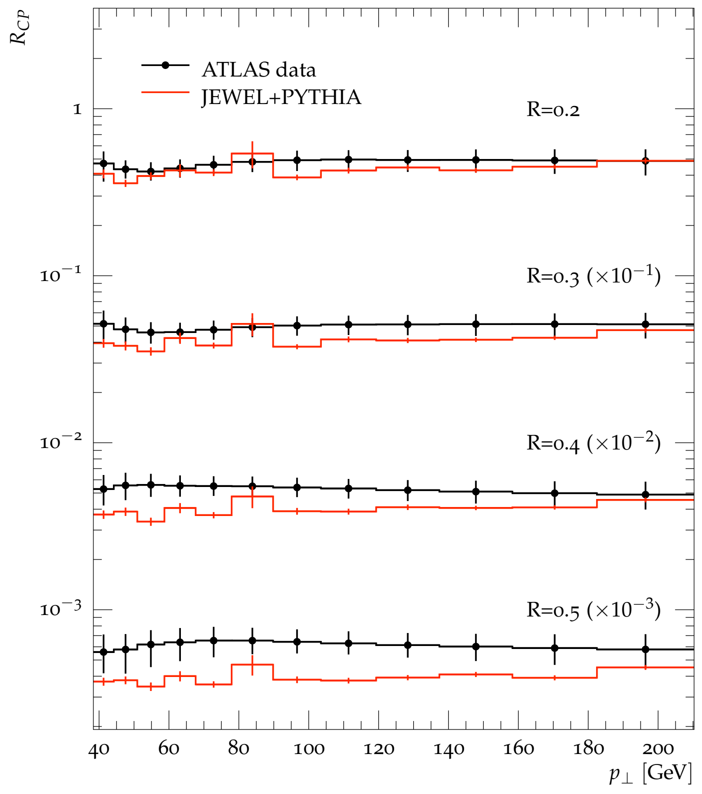

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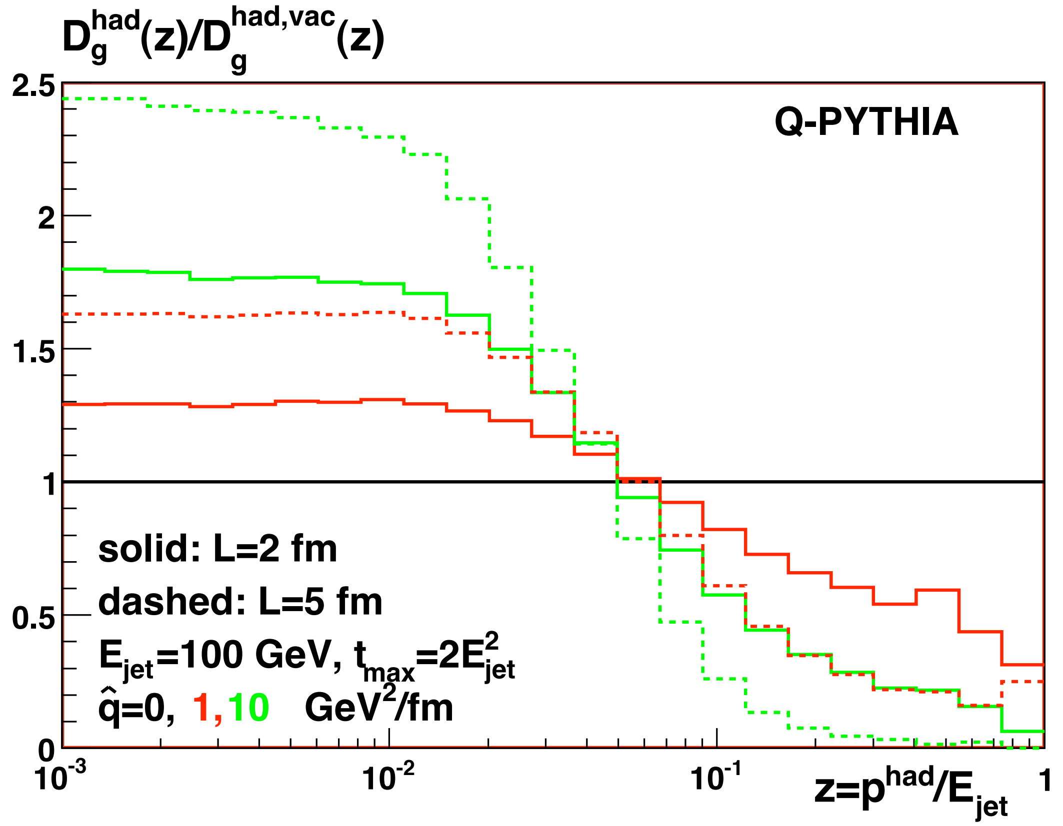
Fragmentation Functions



- General expectations:
  Suppression of high z. Energy loss
  Soft enhancement due to longitudinal degradation
- Measurements referred to the full jet energy:
  - Enhancement of soft fragments
    Softening or medium push?
  - Large-z fragments remain the same
    Removing soft fragments leads to high z enhacement
    Are soft particle emitted late/regenerated

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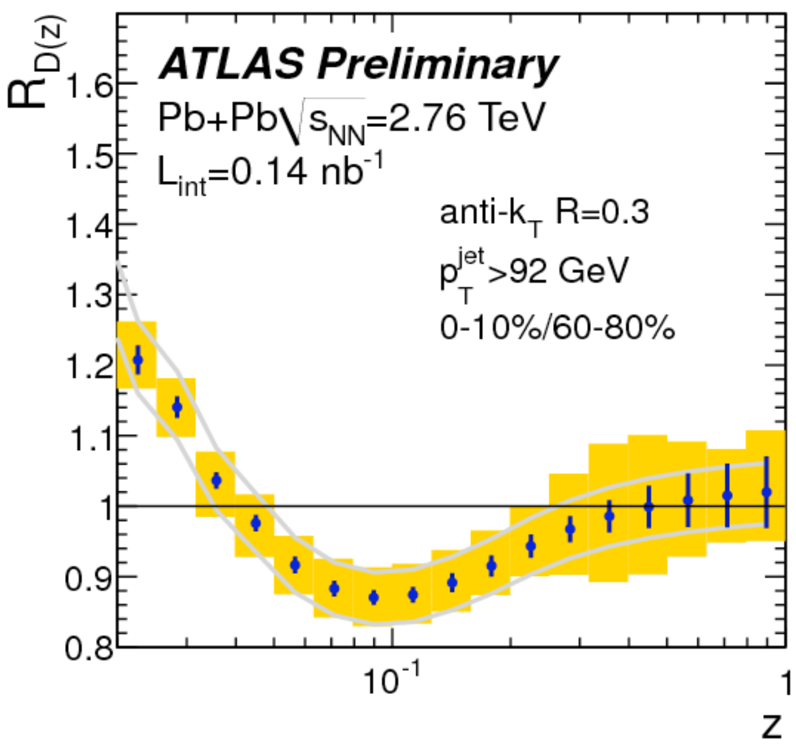

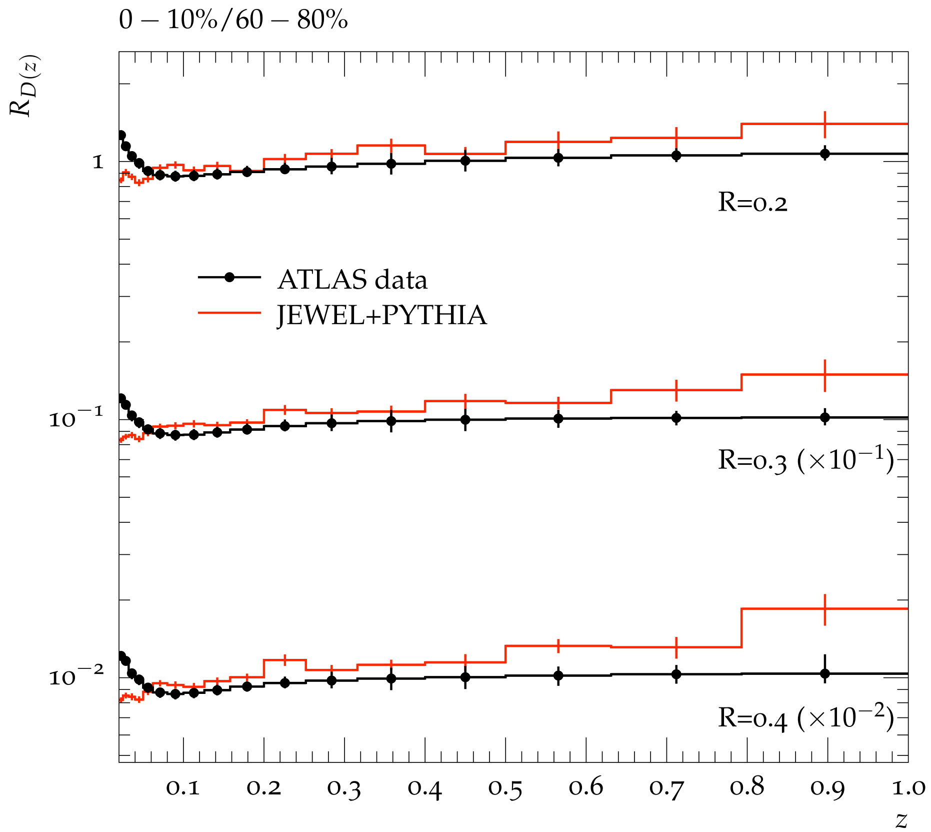

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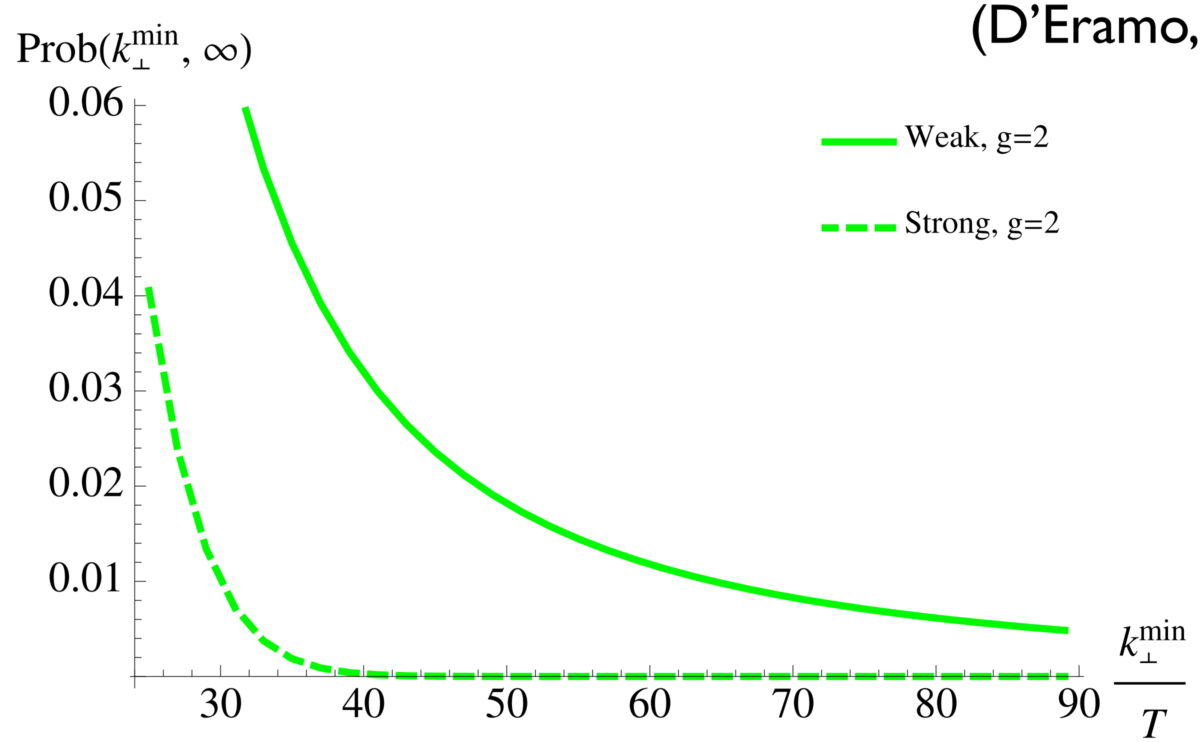
What Can We Extract?

(D'Eramo, Lekaveckas, Liu Rajagopal 12)



- Different implementations depend on different parameters

$$\alpha_s \quad \frac{dN_g}{dy} \quad \lambda_g \quad \mu_D \quad \hat{q} \quad \hat{e}_1 \quad \hat{e}_2 \quad \ldots$$

the models have intrinsically a (perturbative) picture of the medium

- Can we find a formalism which makes the least assumptions on the medium? Are the formalism valid if the medium is strongly coupled?
- Can we observed the constituents in some limit?

  (Rare) large angle deflected jet?

  Can they be deconvoluted from initial state rad?

Conclusions

- Monte Carlo models are essential for describing HI jet data
- Current Progress in current MC methods still faces difficulties
  - Interface with vacuum shower
    - Time structure
    - Interplay between vacuum and medium
  - Medium back-reaction (soft particles)
  - Inclusion of coherence effects.
  - The assumptions on the medium are intrinsic to the modeling of jet modifications