What can we learn from modified jets in Heavy Ion collisions?

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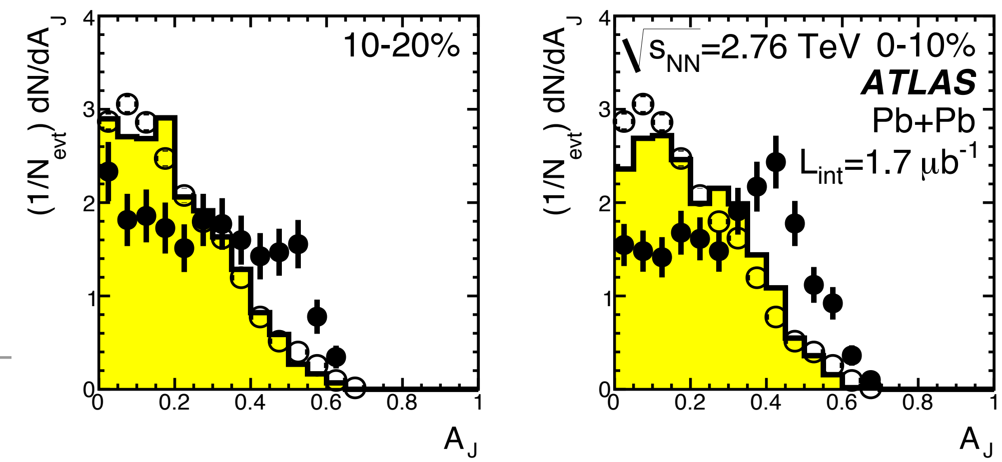
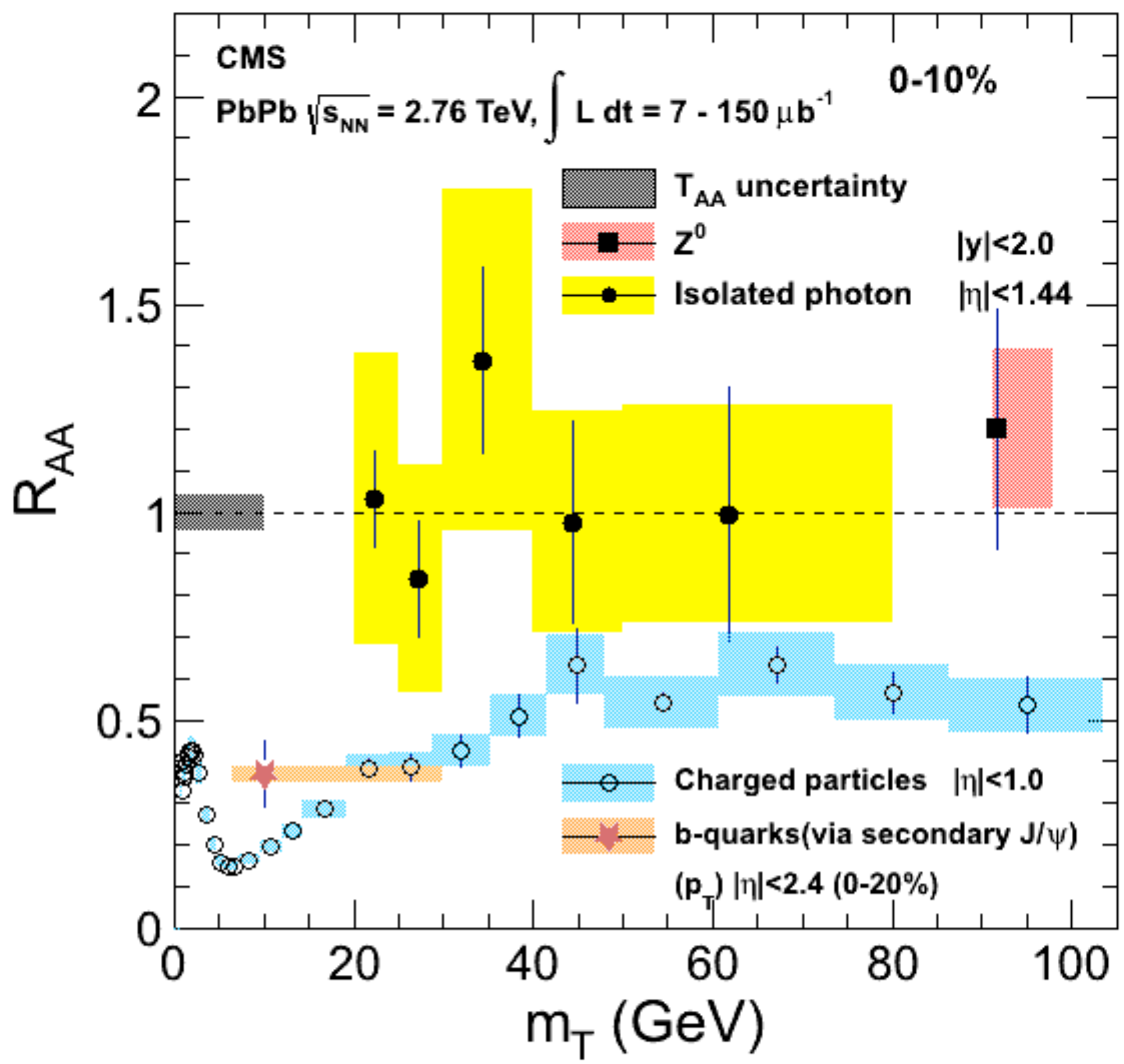
Introduction



- Jets & Hadrons are suppressed at RHIC and the LHC
- Jets gain lose energy and gain (some) transverse momentum from the medium
- Jet interactions are split into elastic and radiative, the strength of each is quantified by a transport coefficient: e-hat and q-hat.
- Measuring or calculating these is a major goal of heavy-ion jet physics
- What does the current zoo of jet observables actually tell us about the physics of quenching?



VNI/BMS Jet Simulation Methodology

VNI/BMS - 2.0, a simple JET transport model

- Partonic transport via the Boltzmann equation. Treats medium and jet on an equal footing.

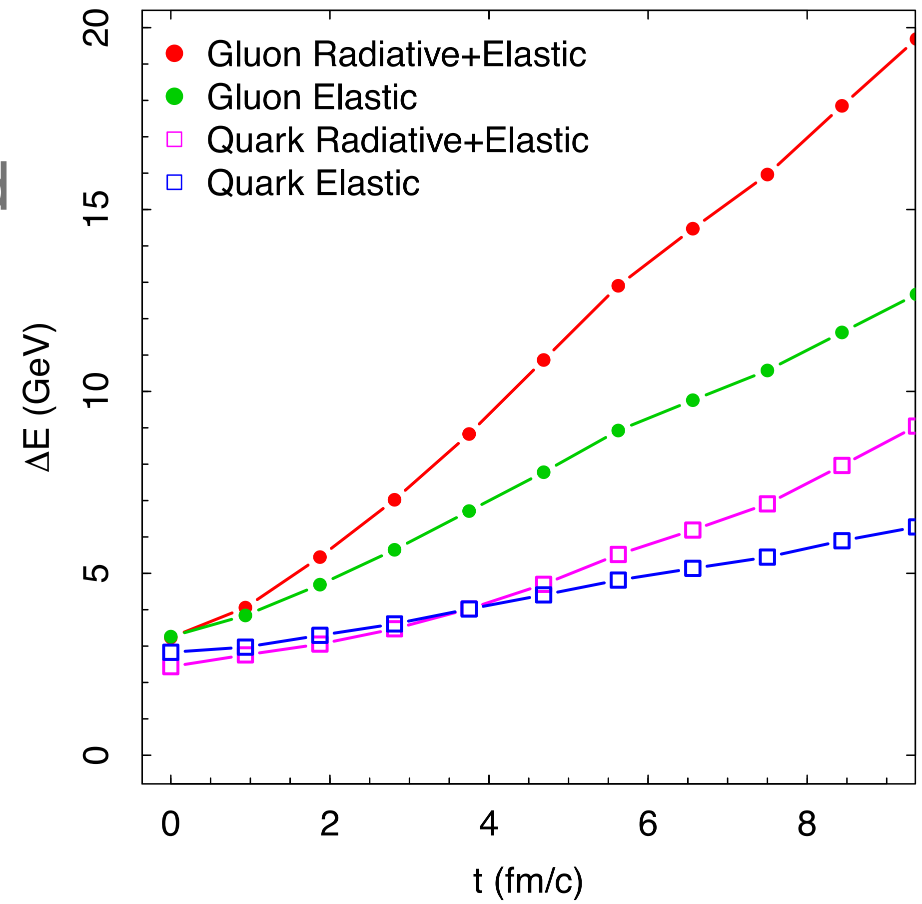
- Interactions are tree level 2->2 scatterings and final-state radiation. Radiation includes leading order (BDMPS-Z) LPM effect.

- Medium is a box of thermal partonic QGP at a fixed temperature. No expansion!

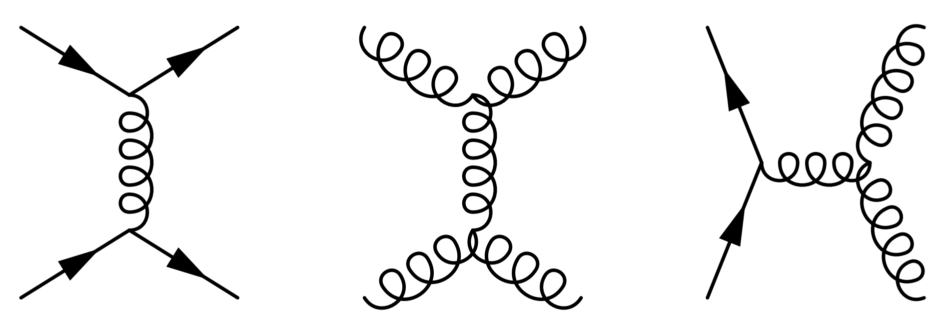
- Cross sections are screened by Debye mass, computed using the box temperature

- A generated jet is injected, cascade of interacting partons are tracked. Evolution of entire jet is recorded.

$$p^\mu \frac{\partial}{\partial x^\mu} F_k(x, \mathbf{p}) = \sum_{processes} \mathcal{C}_i F.$$

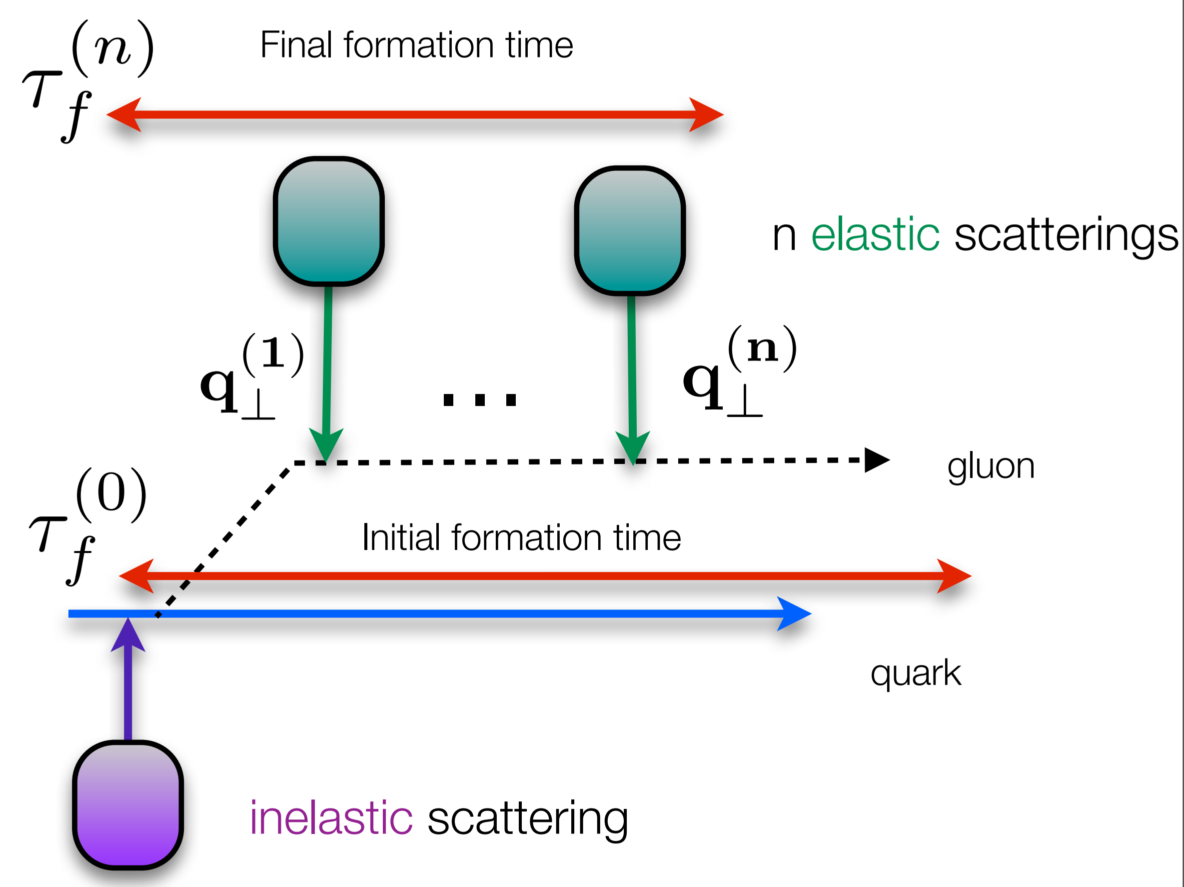


$$-\Delta E_{\mathrm{BDMPS}} = \frac{\alpha_s C_R}{8} \frac{\mu^2}{\lambda_g} L^2 \log \frac{L}{\lambda_g}.$$



Zapp and Wiedemann, LPM Algorithm

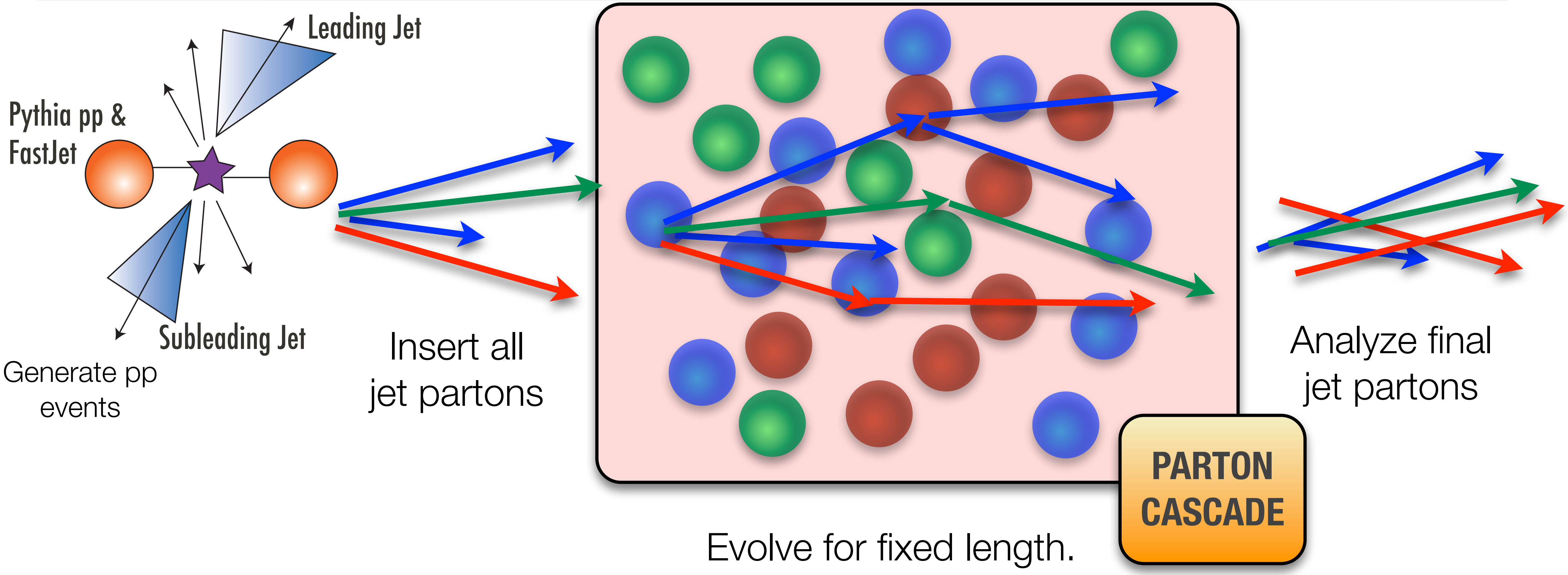
- Probabilistic local implementation of coherence, gives rise to an L^2 energy loss.
- Post Inelastic scattering, compute formation time of emitted gluon
  - Emitting parton does not interact during this time
  - Radiated gluon rescatters elastically off the medium, recompute modified formation time
  - Repeat until formation time expires
  - Quark and gluon propagate freely
- Simulates coherent emission from multiple centers



$$\tau_f^{(n)} = \frac{2\omega}{\left(\mathbf{k}_\perp + \sum_{i=0}^{n} \mathbf{q}_\perp{}^{(i)}\right)^2}$$

Zapp K, Wiedemann U. *Phys Rev Lett,* 103 (2009) JEWEL
CCS, S.A.Bass, D.K.Srivastava, *hep-ph/1101.4895*

Jet Simulation Method: Box Mode



- Insert all partons from each jet into parton cascade box and evolve for a fixed path length.
- Medium is partonic and static, temperature can be fixed for the entire evolution.
- Medium and jet interact on an equal footing, track all resulting partons

A fully controllable brick of QCD matter

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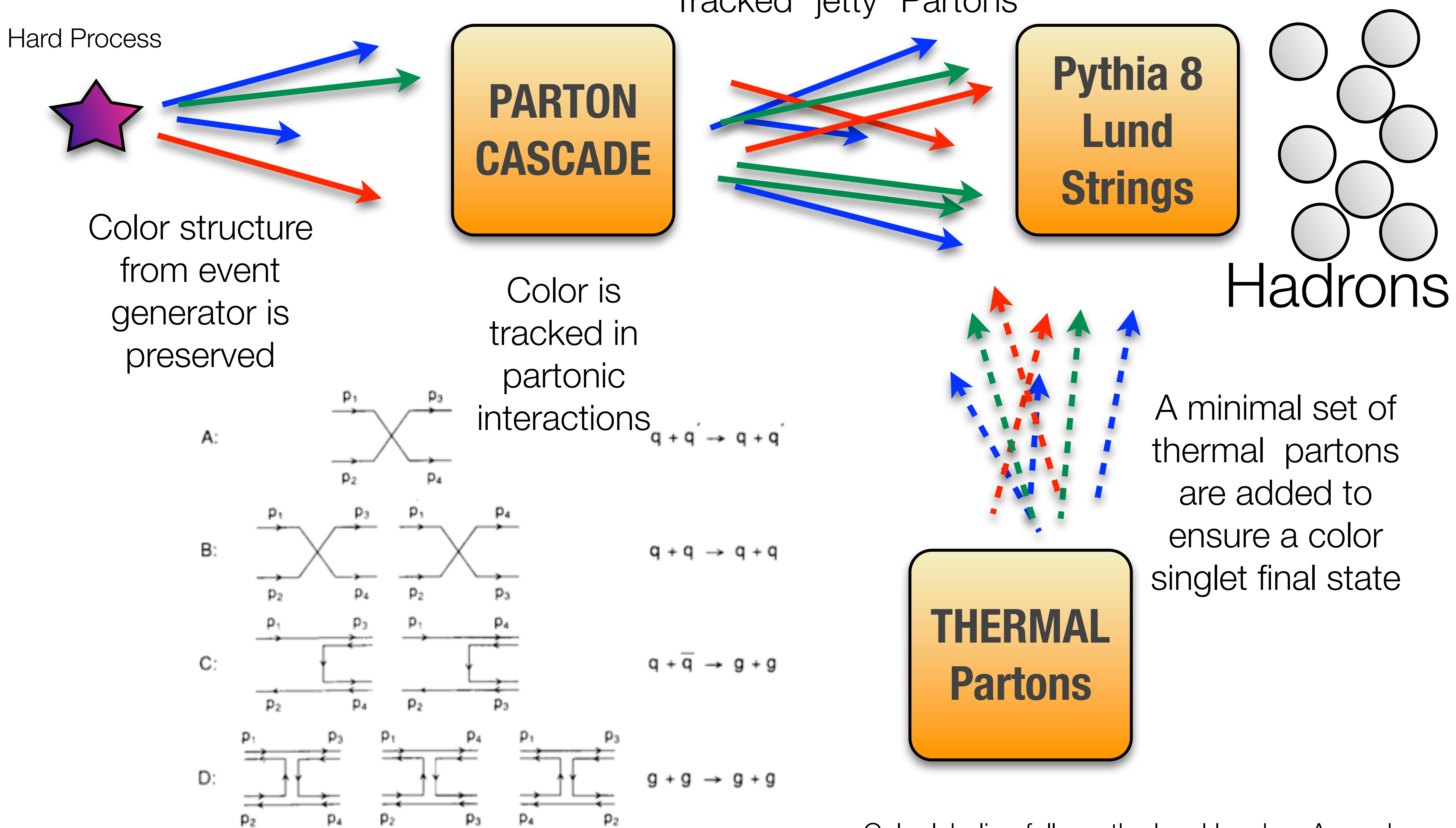
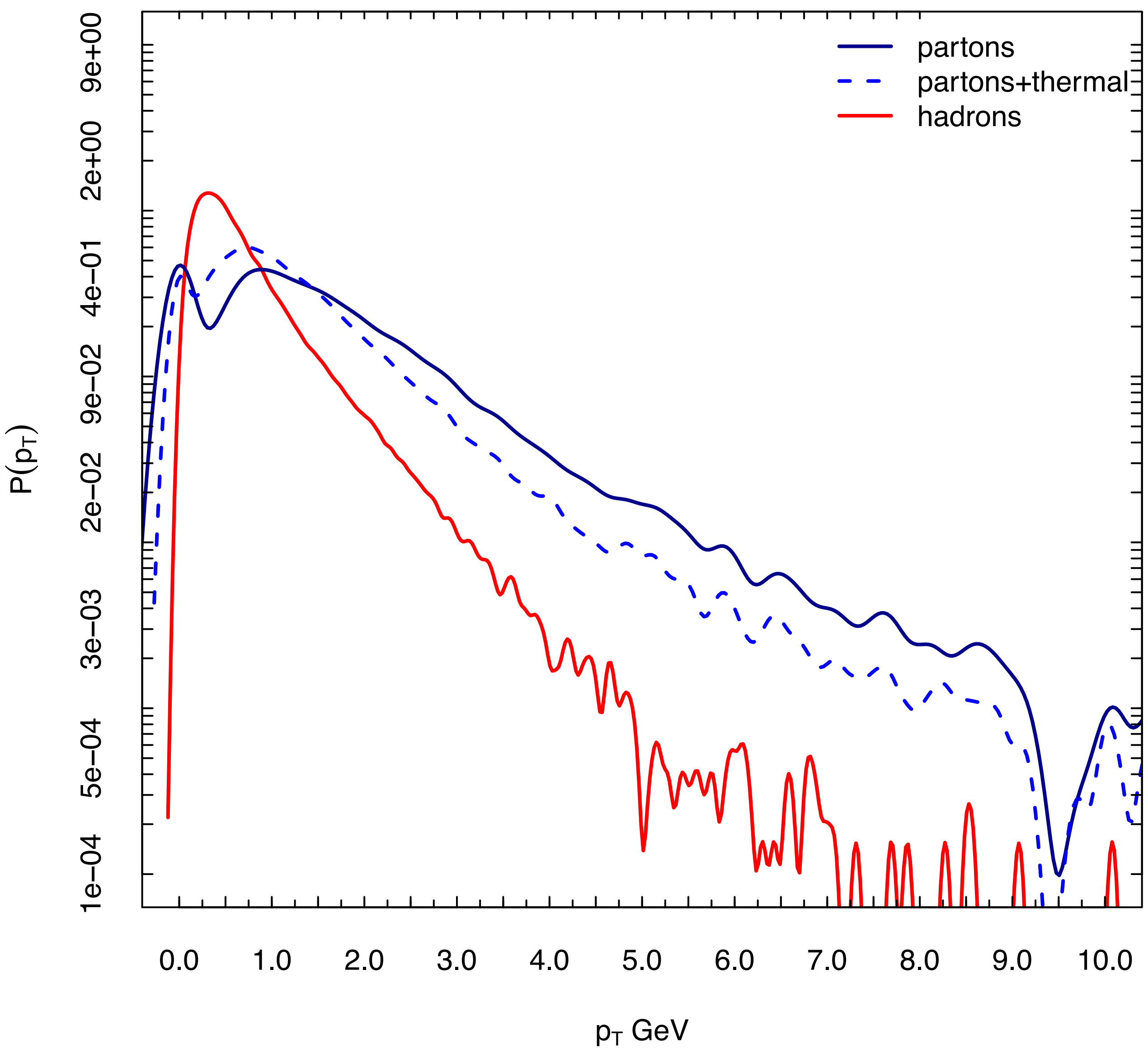
Hadronization In VNI/BMS - 2.0



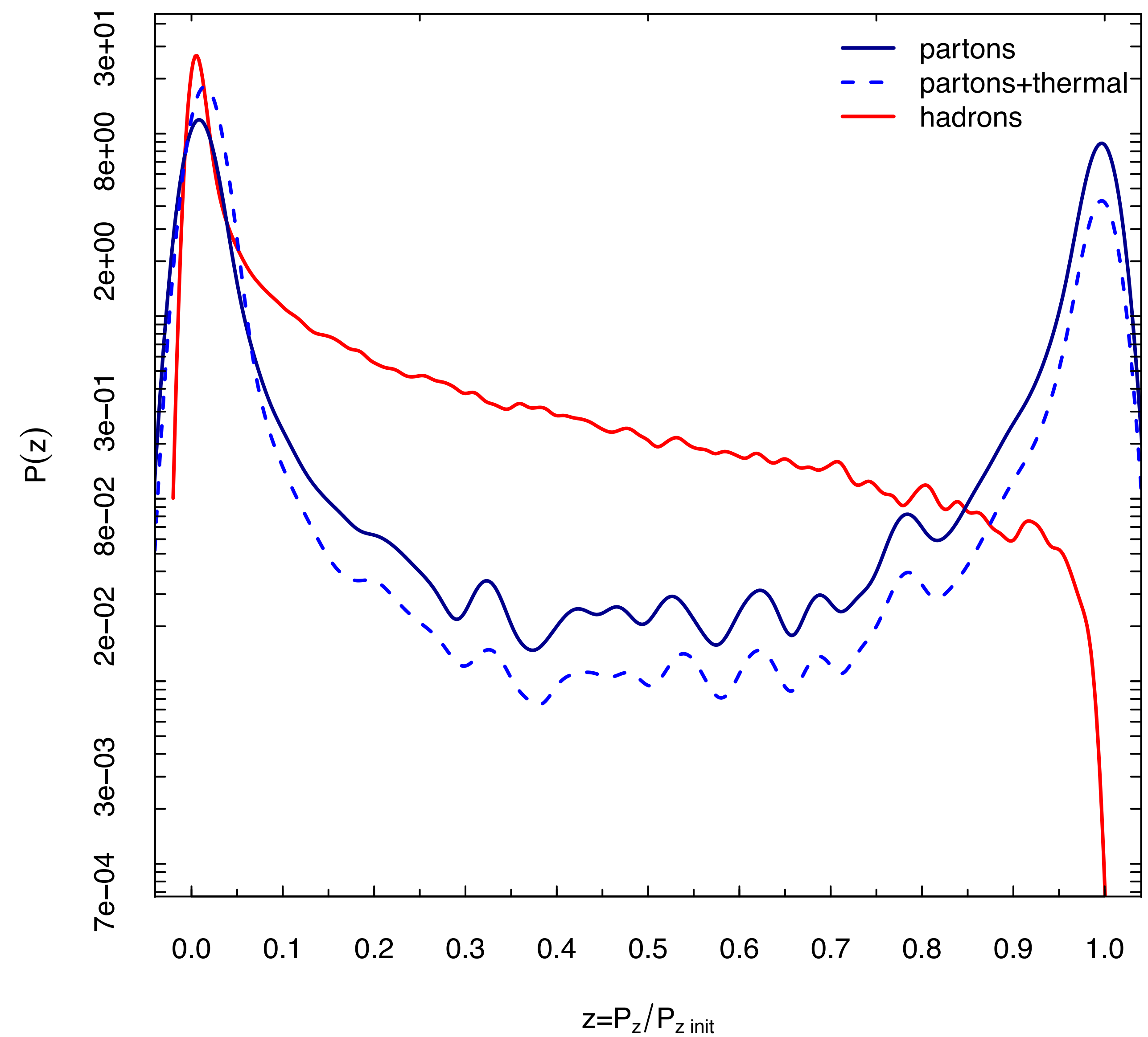
Color labeling follows the Les Houches Accord

Hadronization In VNI/BMS

100 GeV quark evolved for 4fm in a box at T=350 MeV



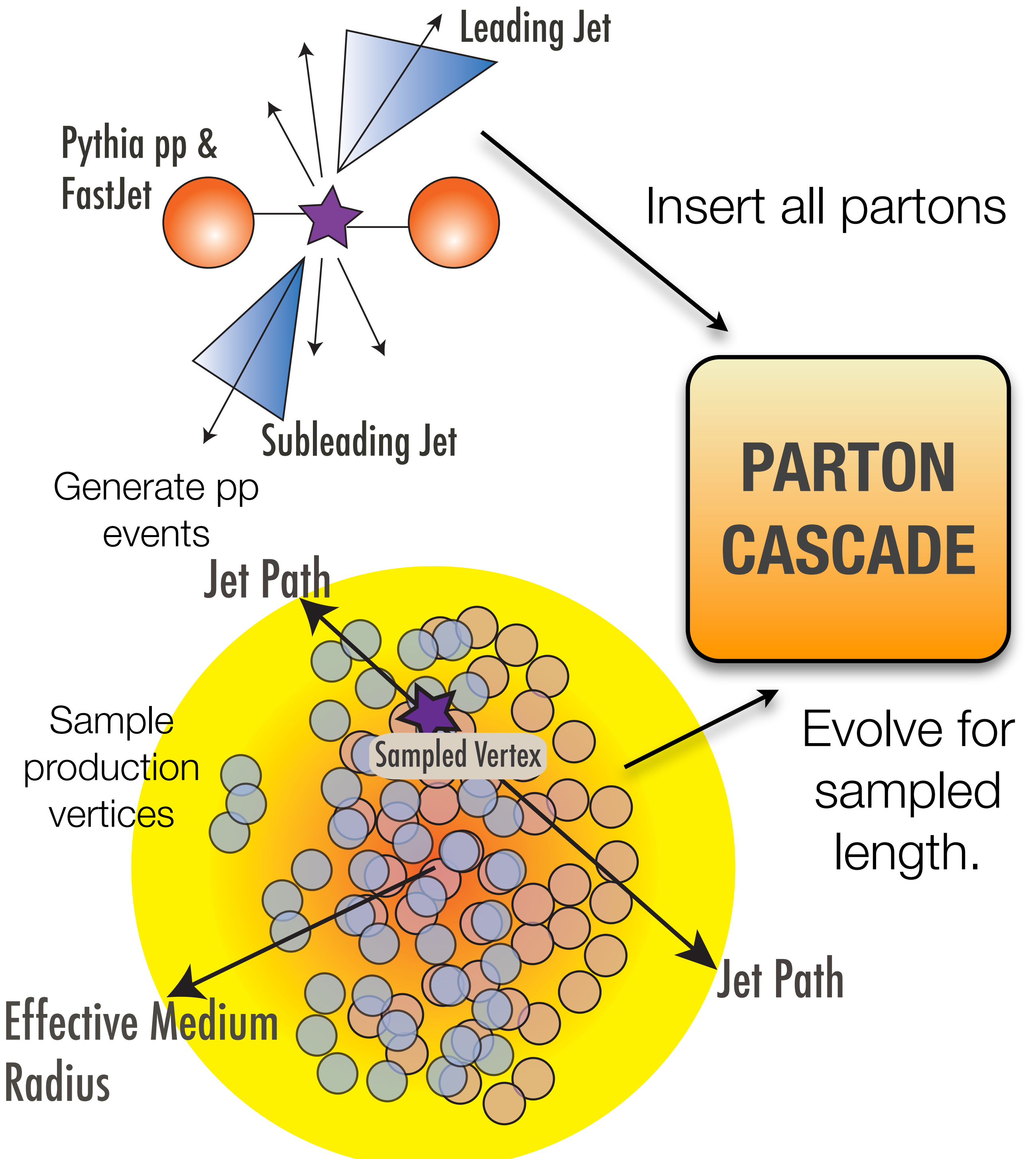
Hadronization contracts the transverse momentum distribution



Hadronization smooths the longitudinal distribution, peak at Z=1 is redistributed

Jet Observables - VNI/BMS - Box Mode

Dijet Simulation Method: Circle Mode

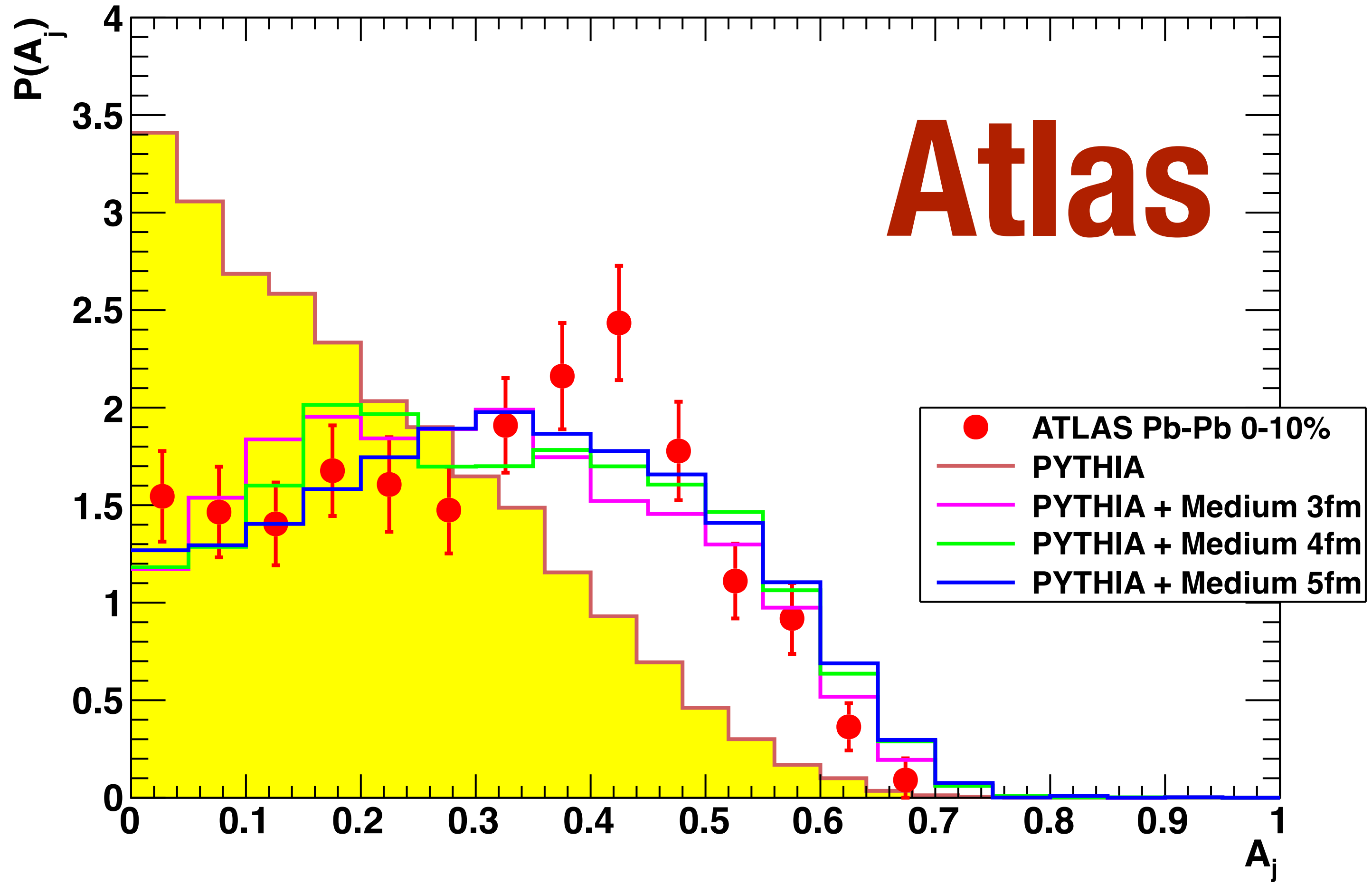


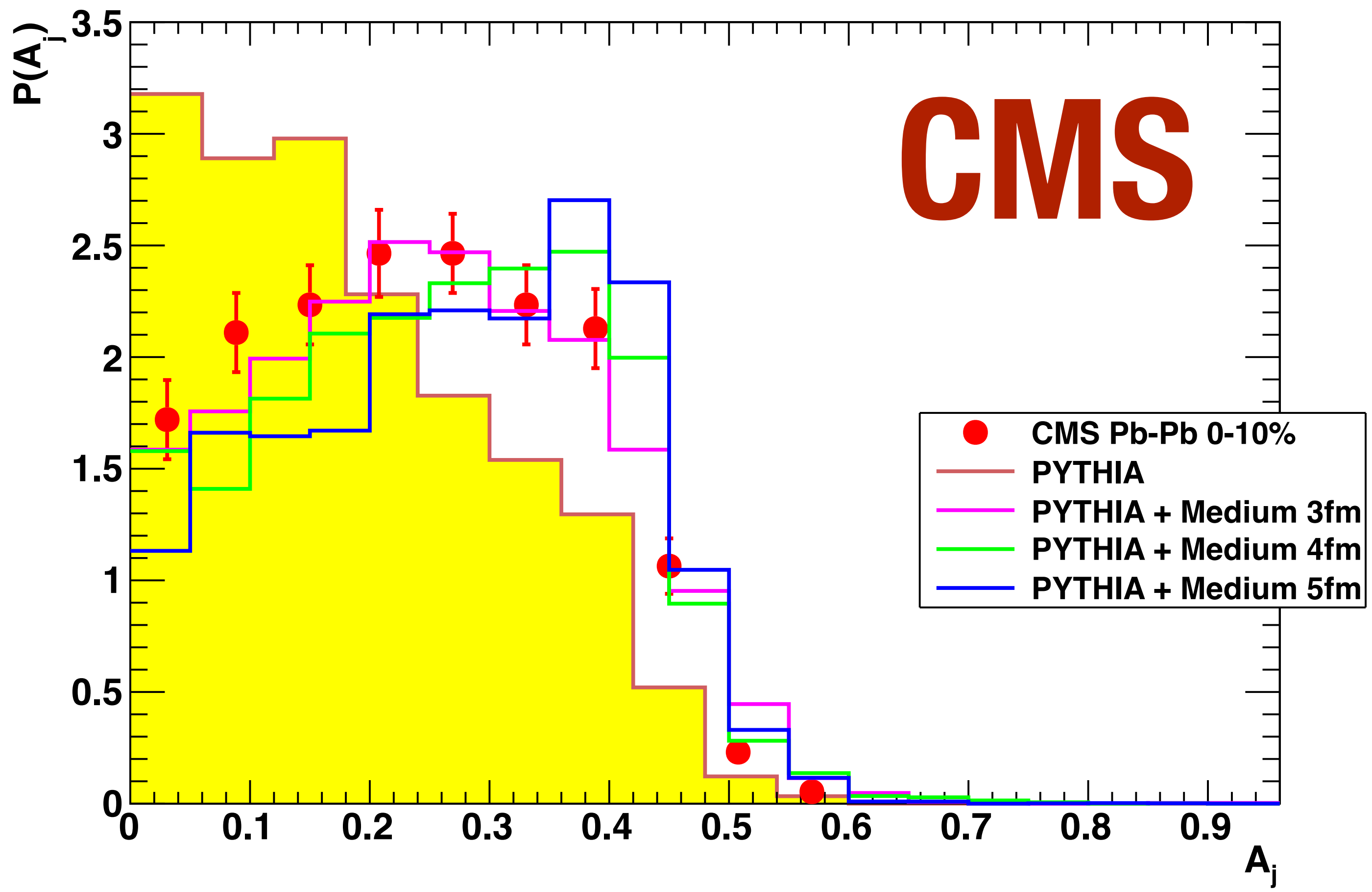
- Vacuum shower evolution takes place in Pythia.
- Sample production vertices uniformly within a circular medium of some radius R. Sample jet paths as length of random chord generated from vertices to edge of medium.
- Insert all partons from each jet into parton cascade box and evolve for sampled path length.
- Medium is partonic and static, temperature is fixed for duration of the evolution.

LHC Dijet Results

Circle Mode + Glauber Vertices can reproduce LHC data reasonably well.

Central collisions (0-10%)



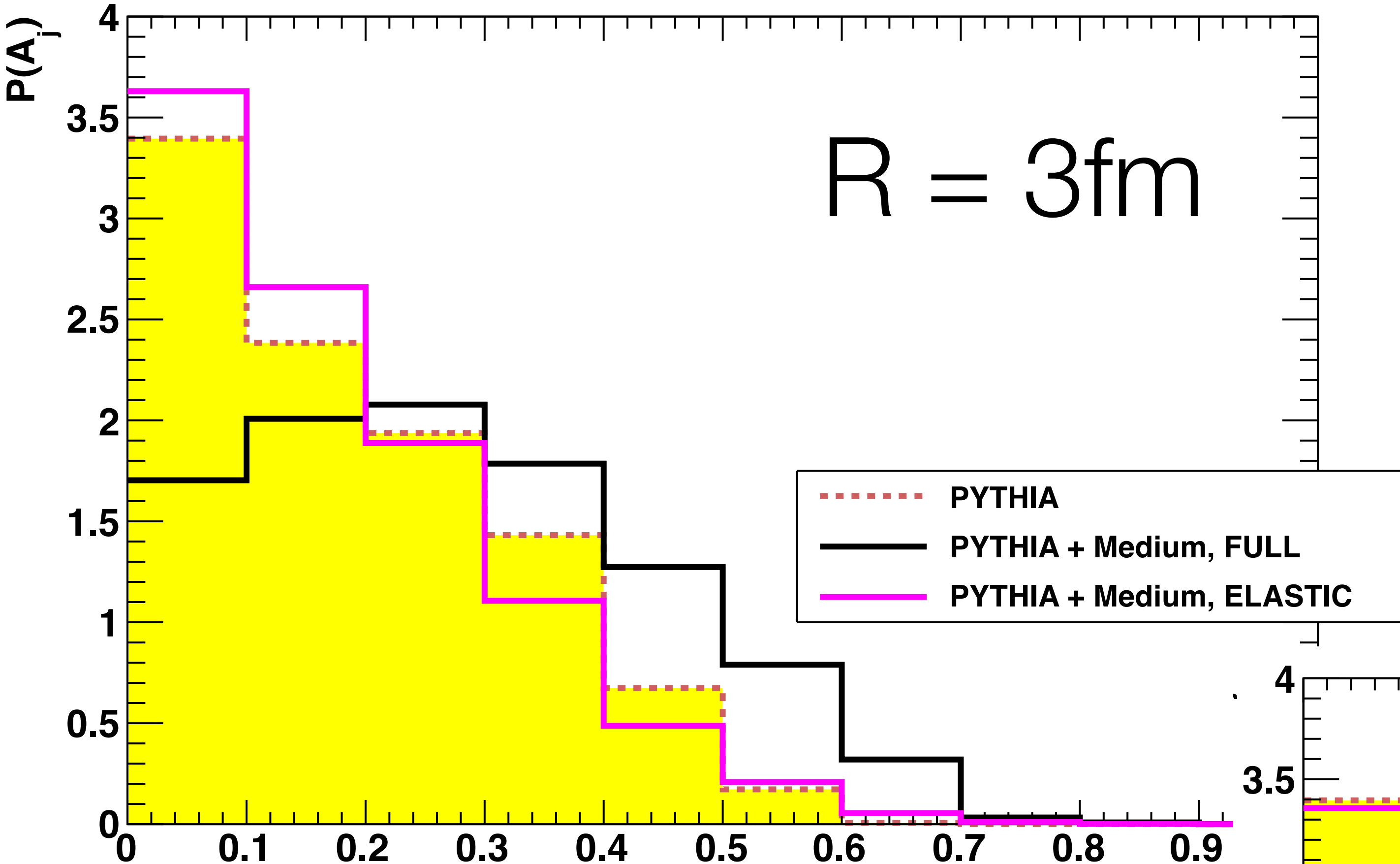


Both results include detector smearing effect

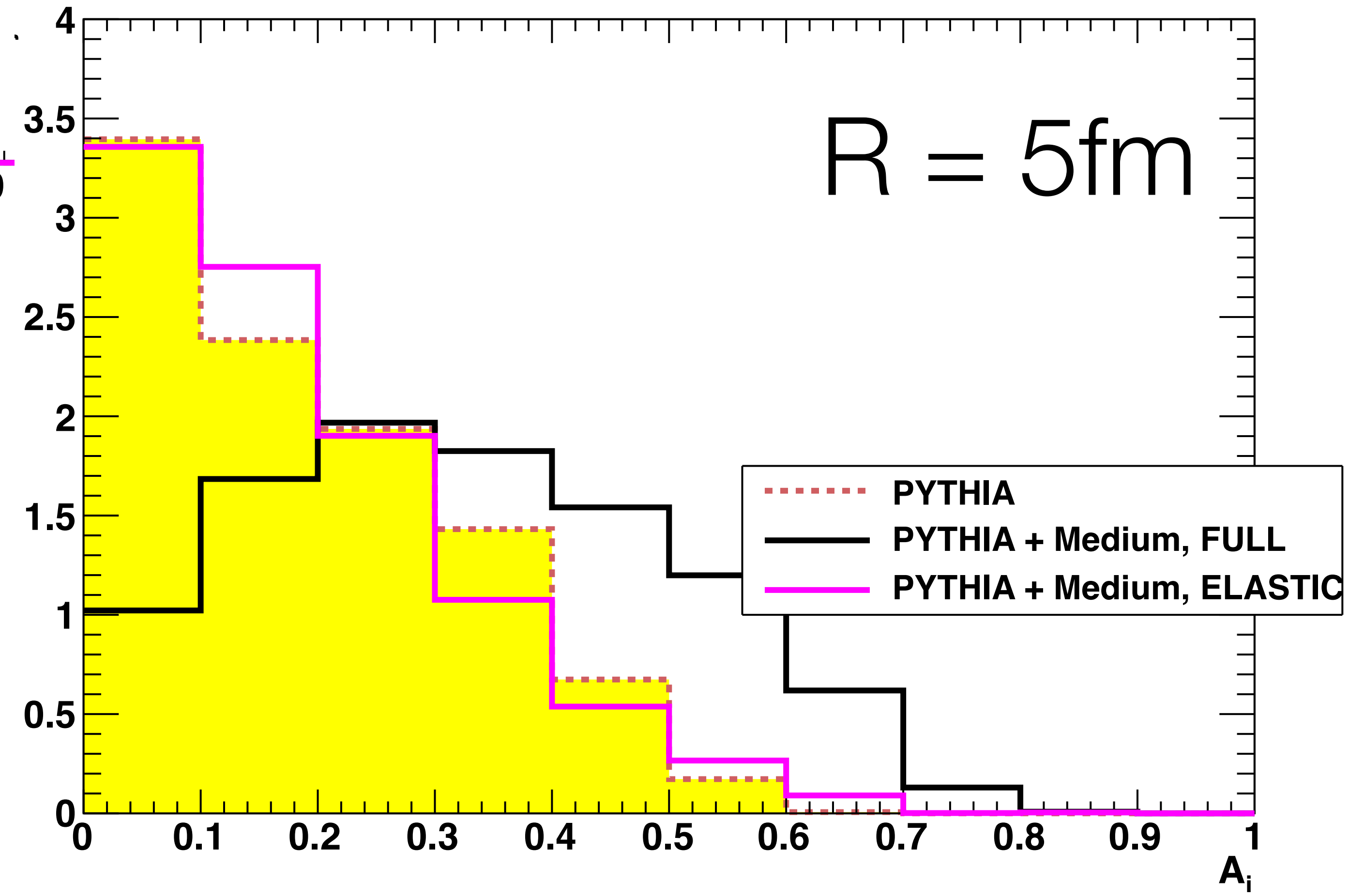
$$E_t^\star \sim N(E_t, \alpha\sqrt{E_t}), \quad \alpha \simeq 1.2$$

Presented at QM 2011

Process Dependence



- T = 0.35 GeV
- Elastic only, distribution shifts to the left. Medium reduces the asymmetry
- Jet "picks up" medium particles by forward scattering



$$E_{T1} > 100\text{GeV} \quad E_{T2} > 25\text{GeV}$$

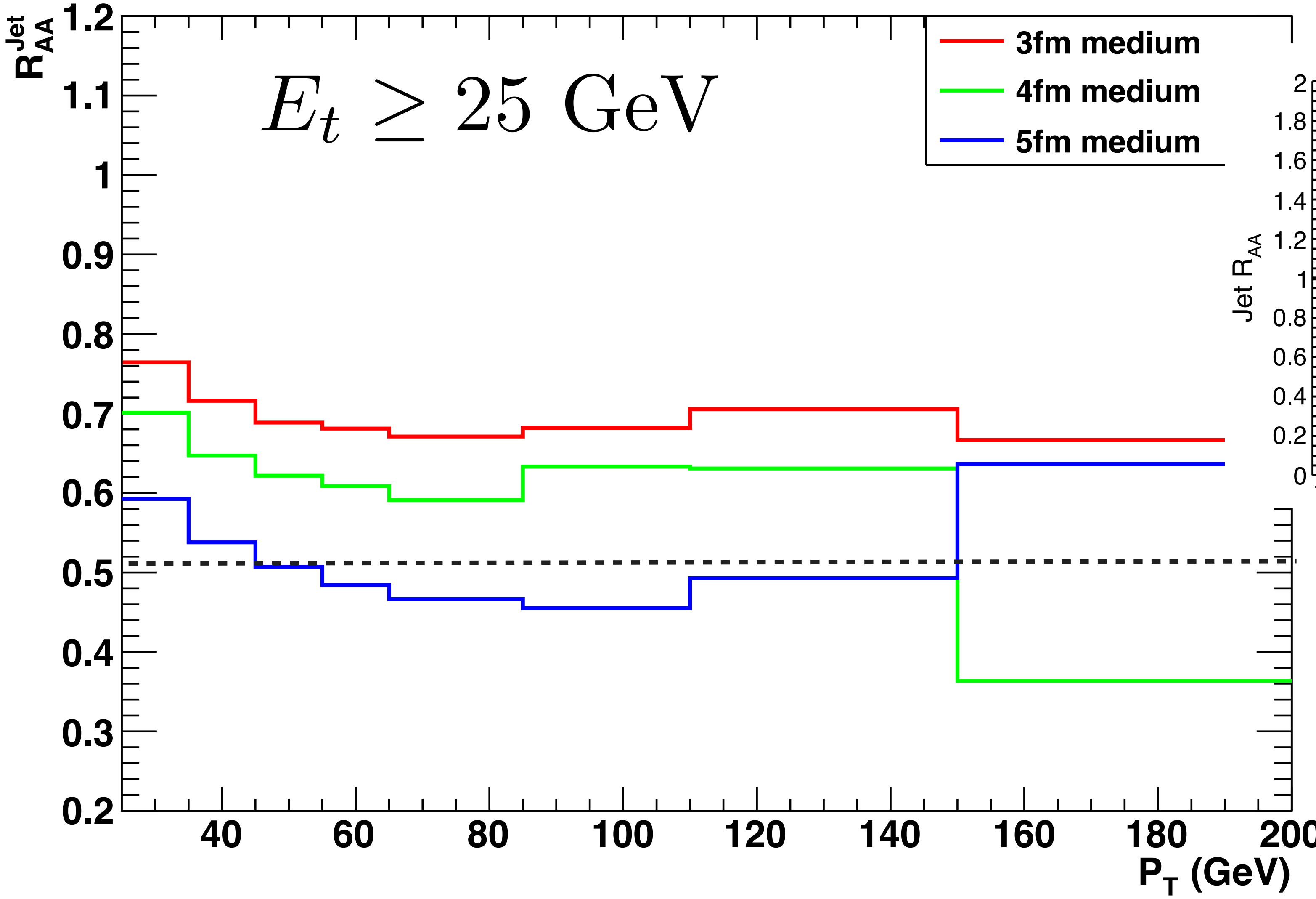
Radiation plus elastic gives increased asymmetry.

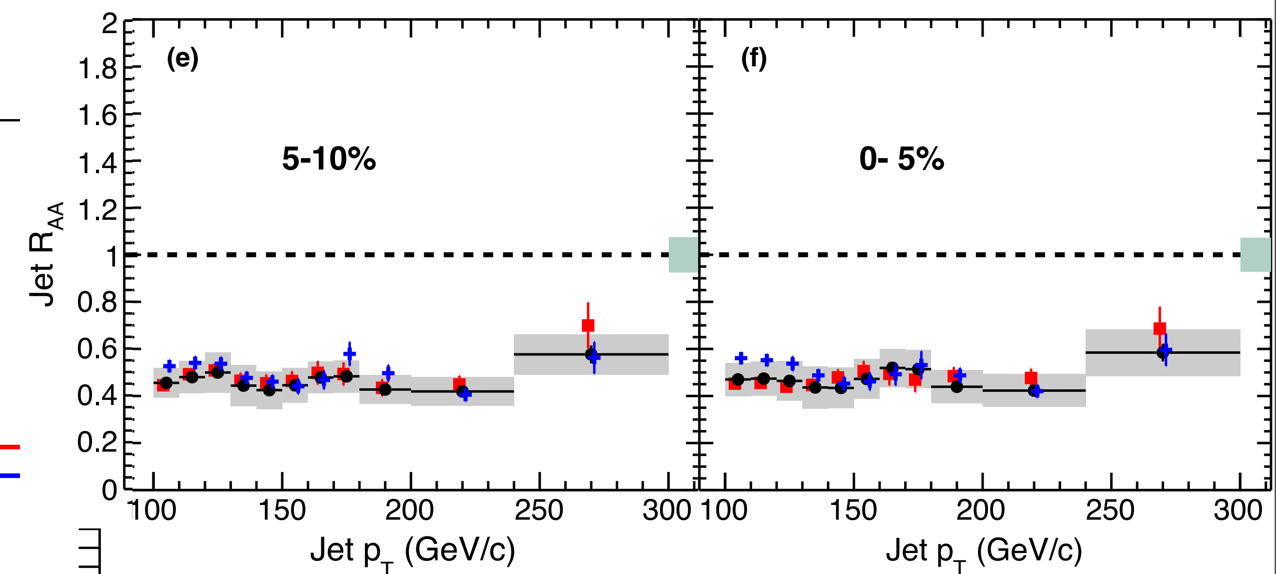
Soft radiated gluons can be elastically scattered out of the jet cone

Partonic Jet R_AA

$$R_{AA}^{Jet} = \frac{\frac{dN_{AA}^{Jet}}{dp_t}}{\frac{dN_{pp}^{Jet}}{dp_t}}$$

- Fixed T = 0.35 MeV, 0-10% central





CMS Preliminary

CMS data favors 5fm medium

Asymmetry favors 3fm

$R_{\rm cone} = 0.4$

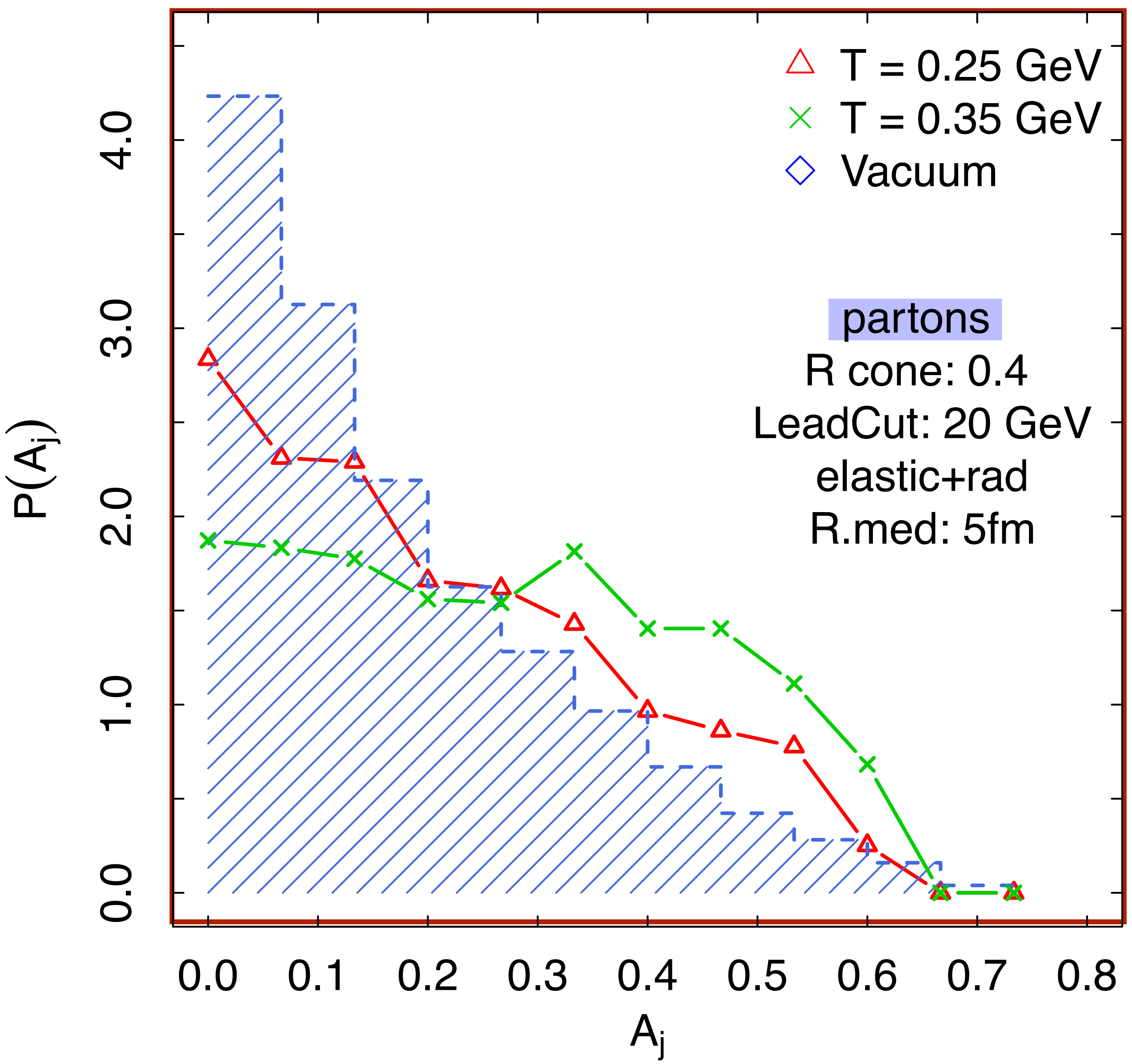
Di-jet Asymmetry at RHIC

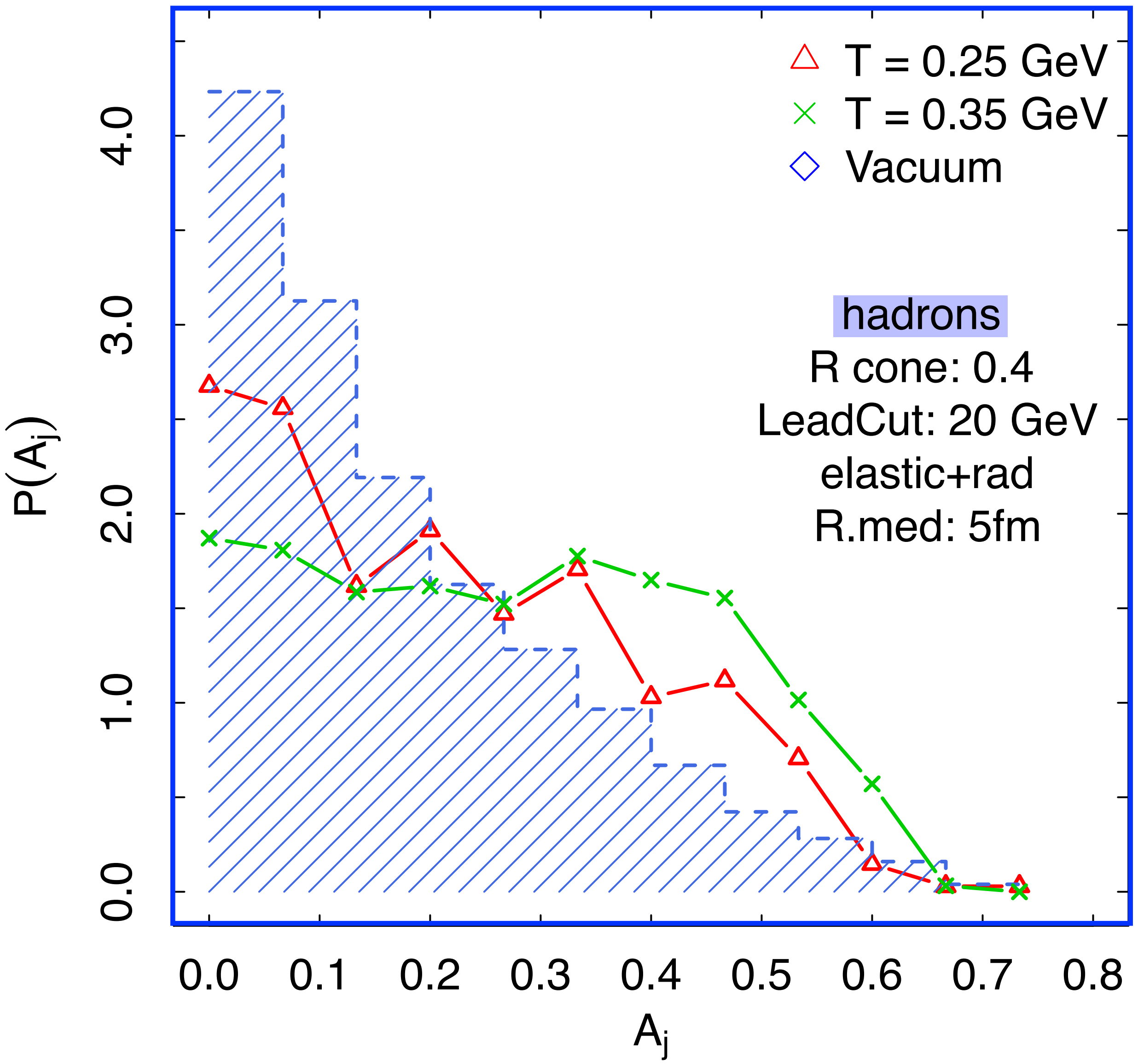
- Use VNI/BMS to try and understand dependence of Aj on:
  - Qhat, determined by the medium temperature: T = 250, 350 MeV
  - Distance travelled by the both jets
  - Cuts on leading jet energy and cone-radius:
    Elead > 20, 35, 50 GeV, R = {0.2, 0.3, 0.4}
  - Interaction mechanism, elastic or elastic+rad
- Setup:
  - Di-jets generated by p+p at 200GeV, with cuts / jet definition applied
  - Cuts and jet definition are applied in post-processing

C.C-S, B.Müller, "What can we learn from Dijet suppression at RHIC", Phys.Rev.C 86 (2012)

Dijet Asymmetry - Varying Medium Temperature

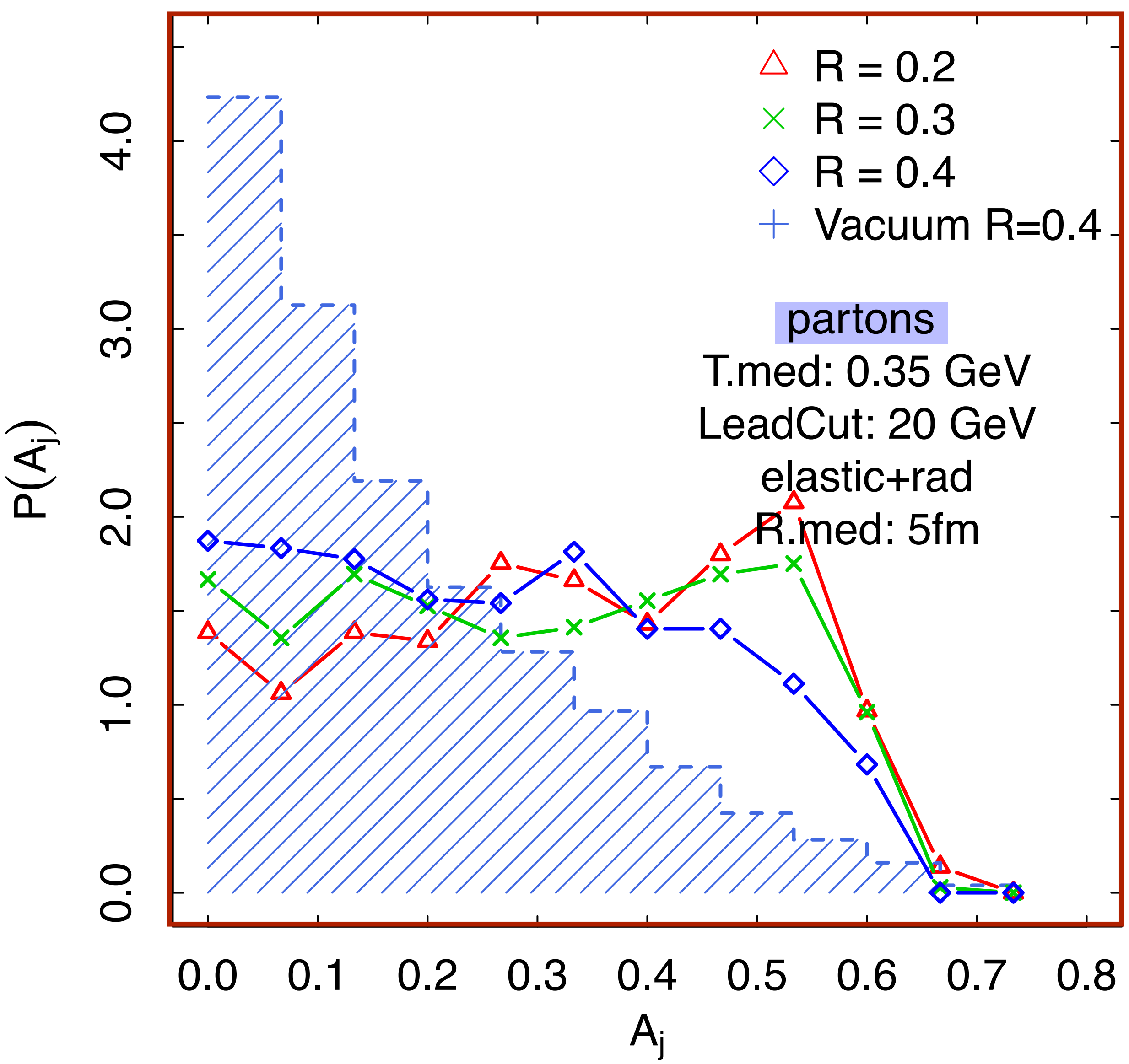
Increasing medium temperature increases asymmetry.

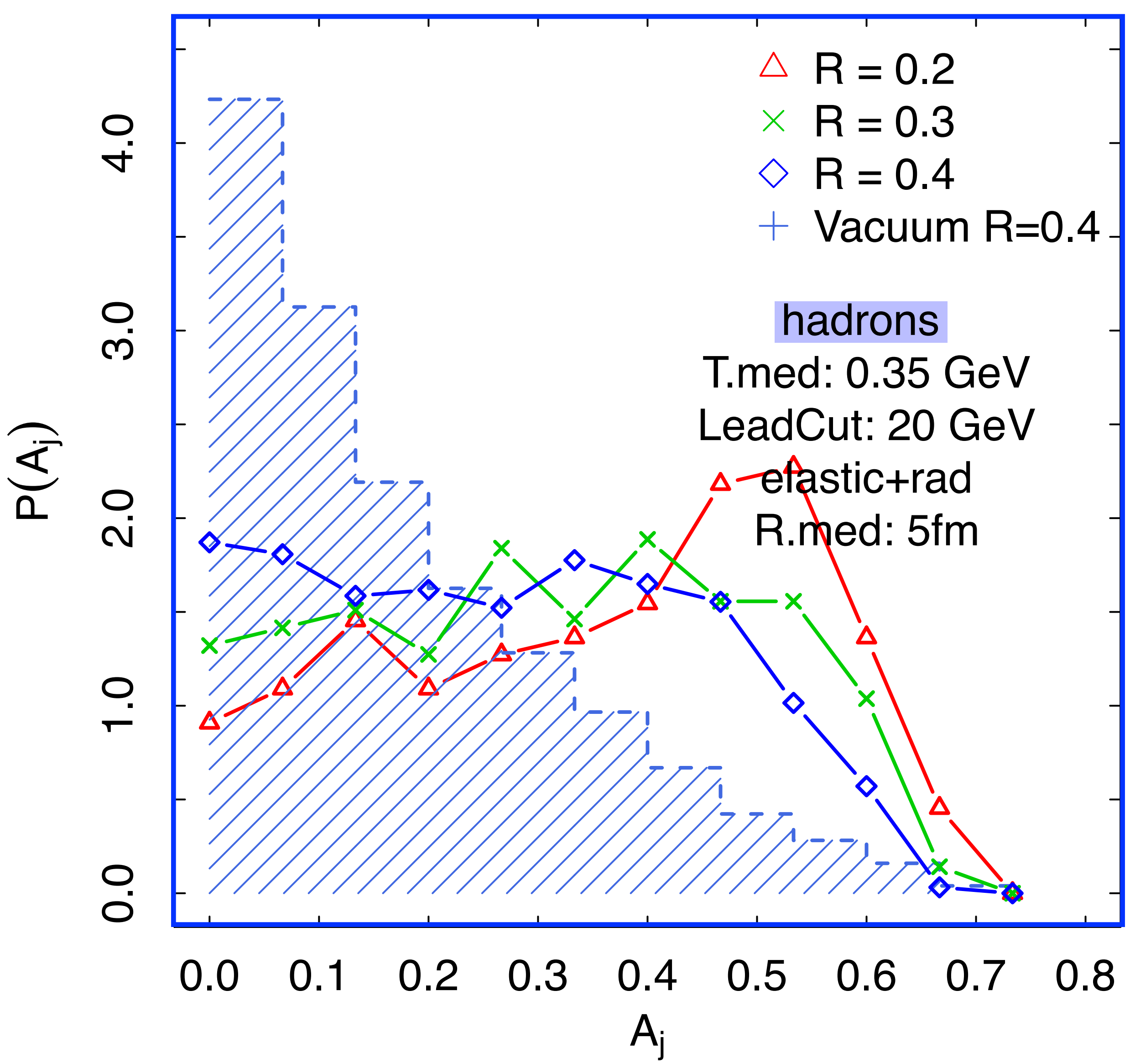




Dijet Asymmetry is similar for partonic and hadronic jets

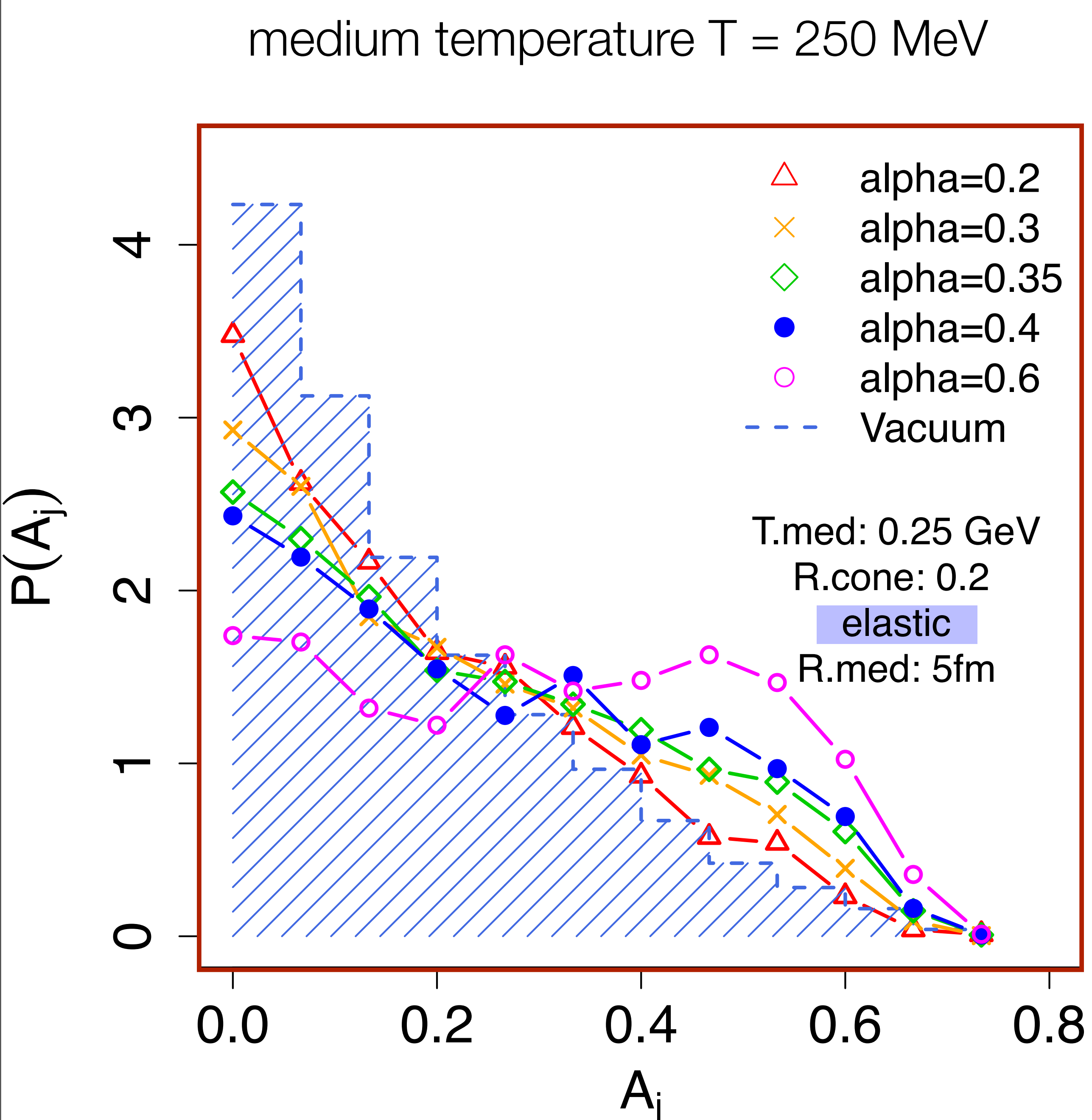
Dijet Asymmetry - Varying Jet Cone Radius

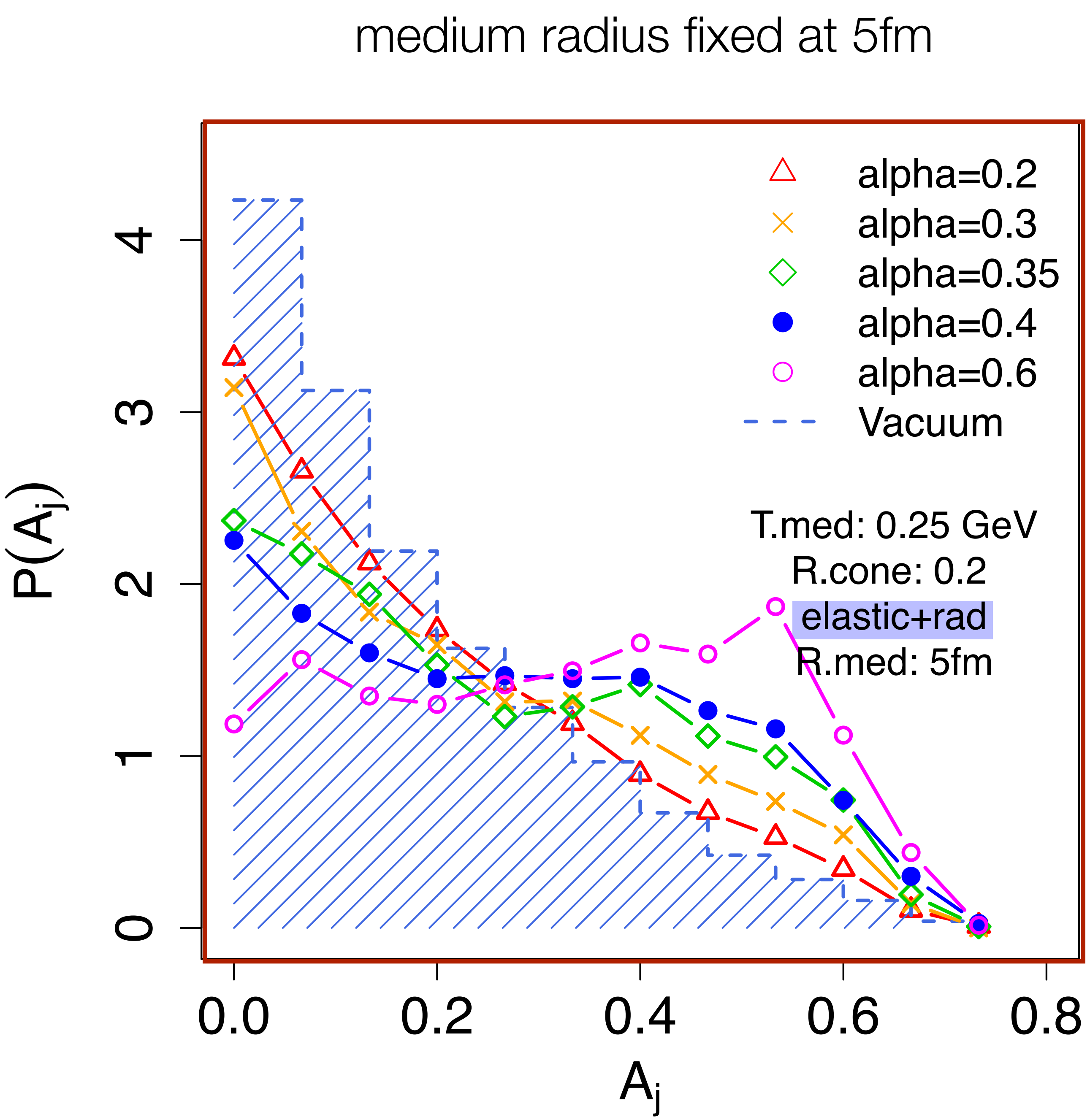




Increased Cone Radius reduces asymmetry,
captures more of the modified jet

RHIC Dijet Asymmetry - Varying Strong Coupling



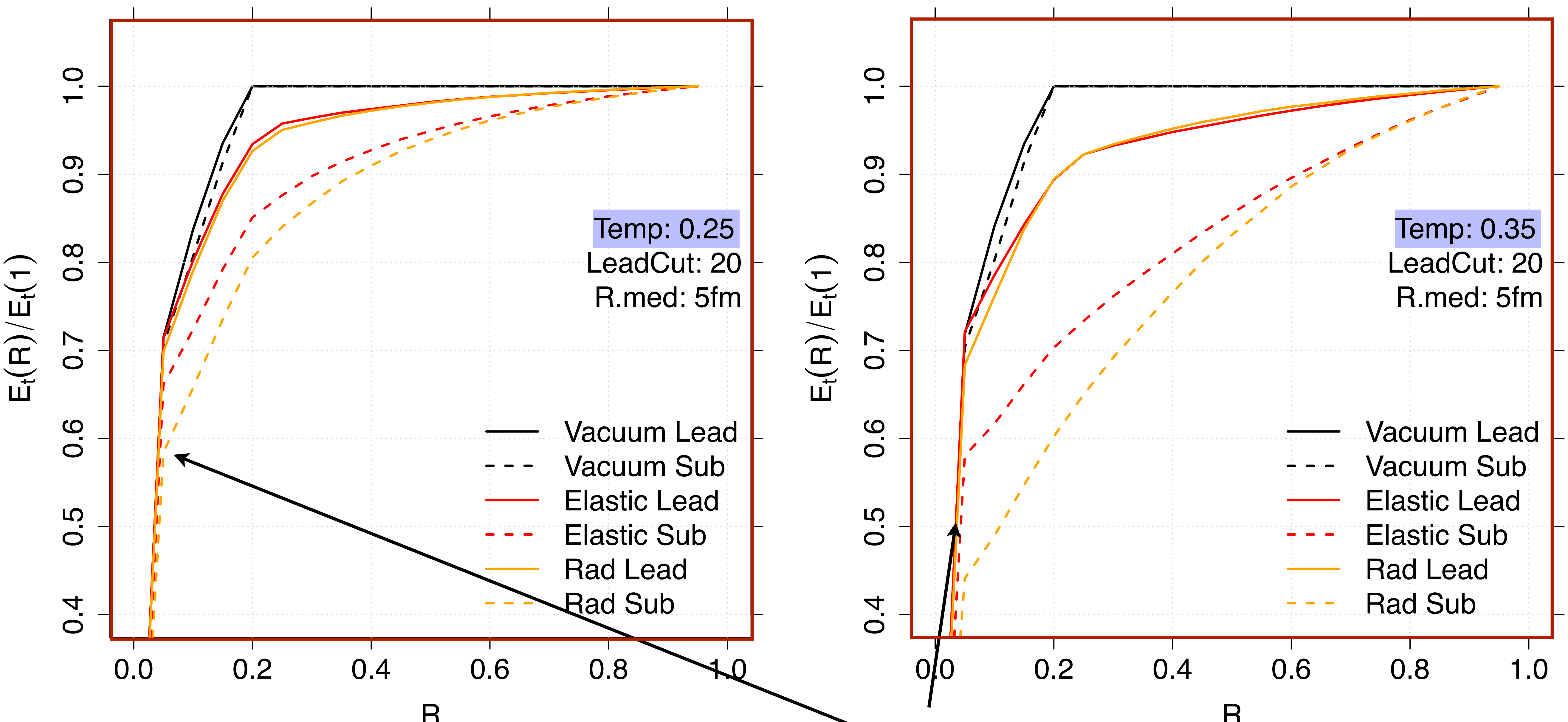


Increasing Strong Coupling increases asymmetry

C.C-S, B.Müller, “What can we learn from Dijet suppression at RHIC”, Phys.Rev.C 86 (2012)

RHIC - Jet Shape

Reconstruct jets with Anti-Kt at successively larger cone radii

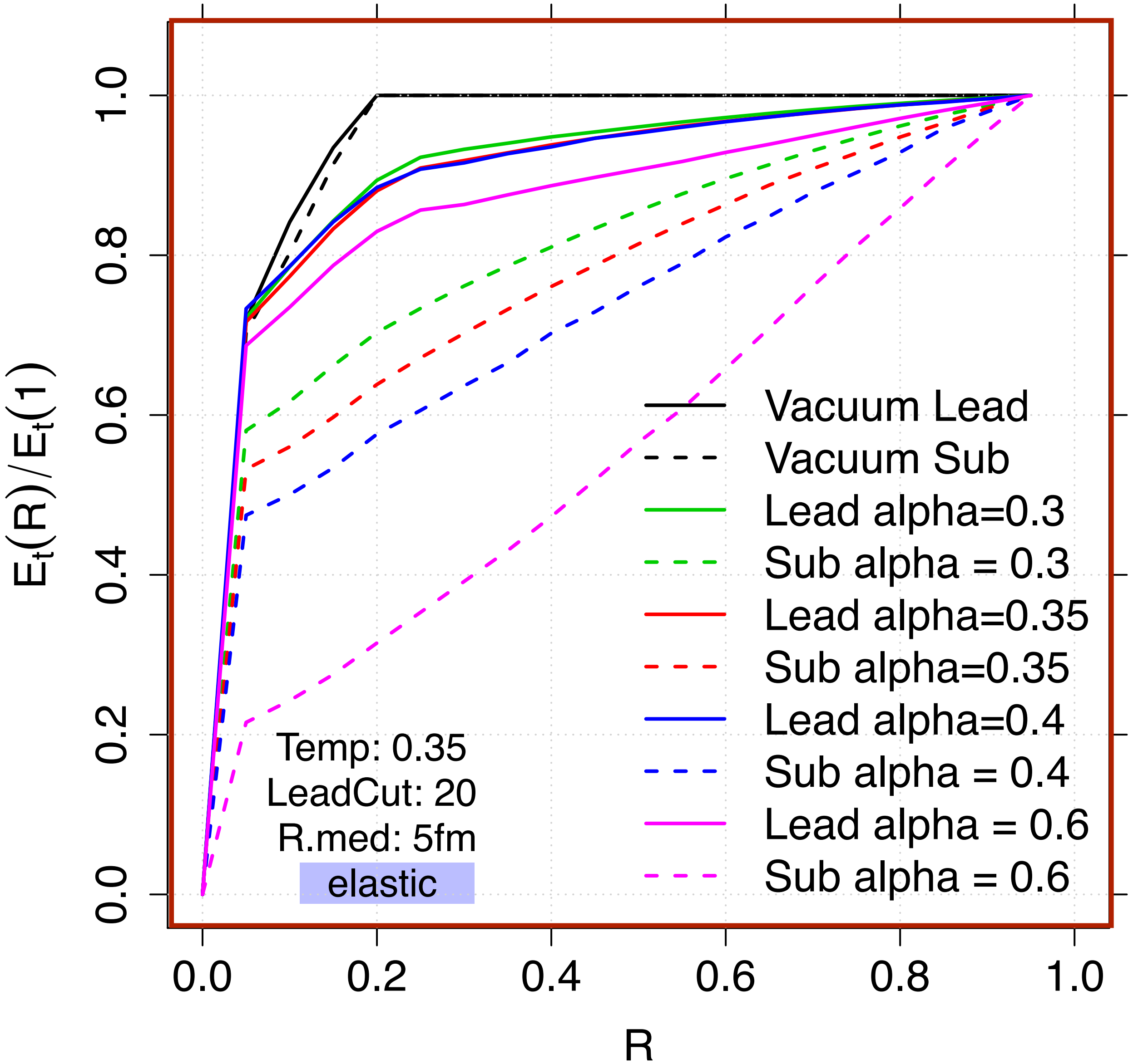


Difference between medium temperatures is very strong, note values as R->0

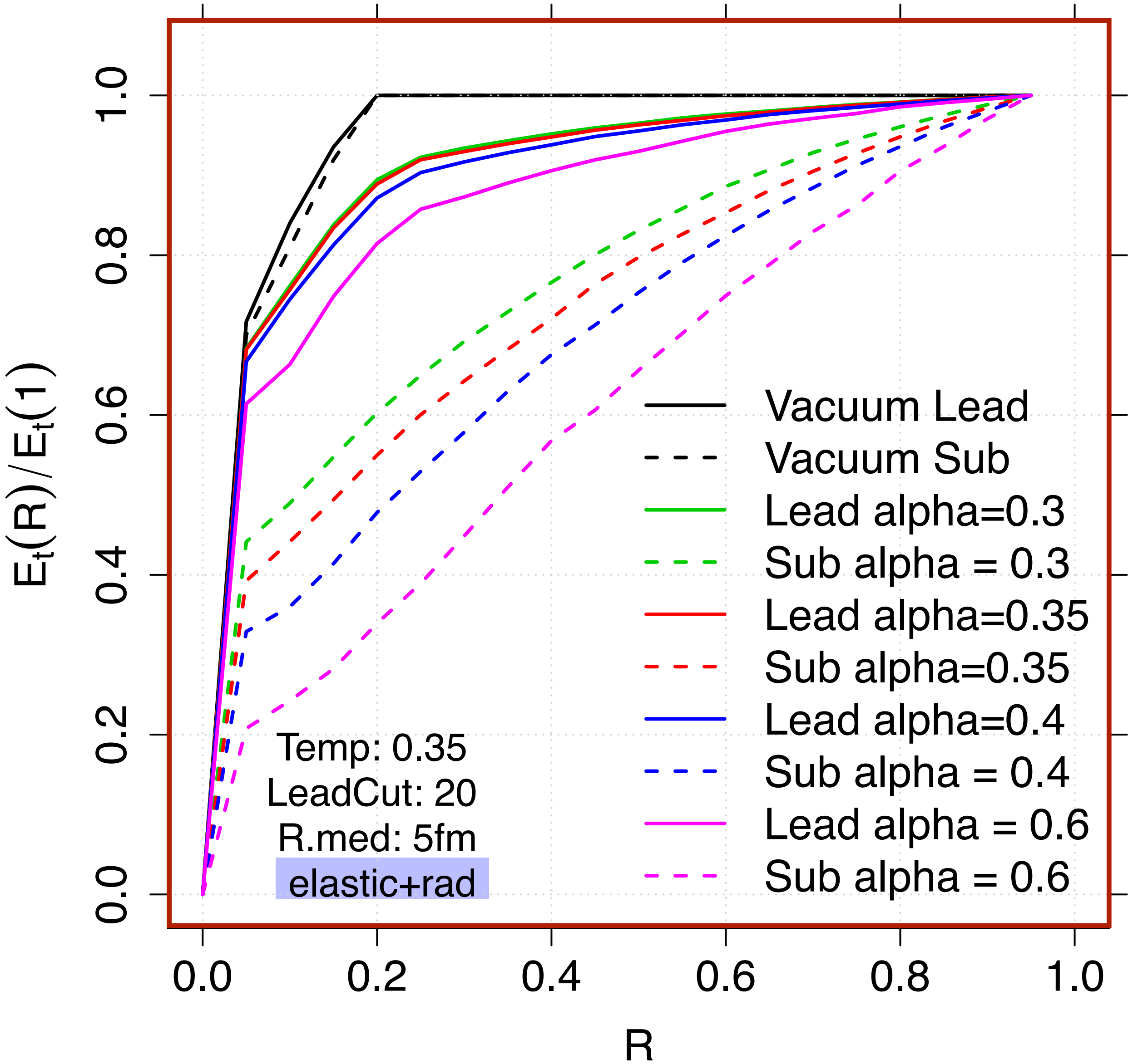
Clear separation between elastic (red) and radiative (orange) modes

C.C-S, B.Müller, "What can we learn from Dijet suppression at RHIC", Phys.Rev.C 86 (2012)

Jet Shape - 2, varying strong coupling



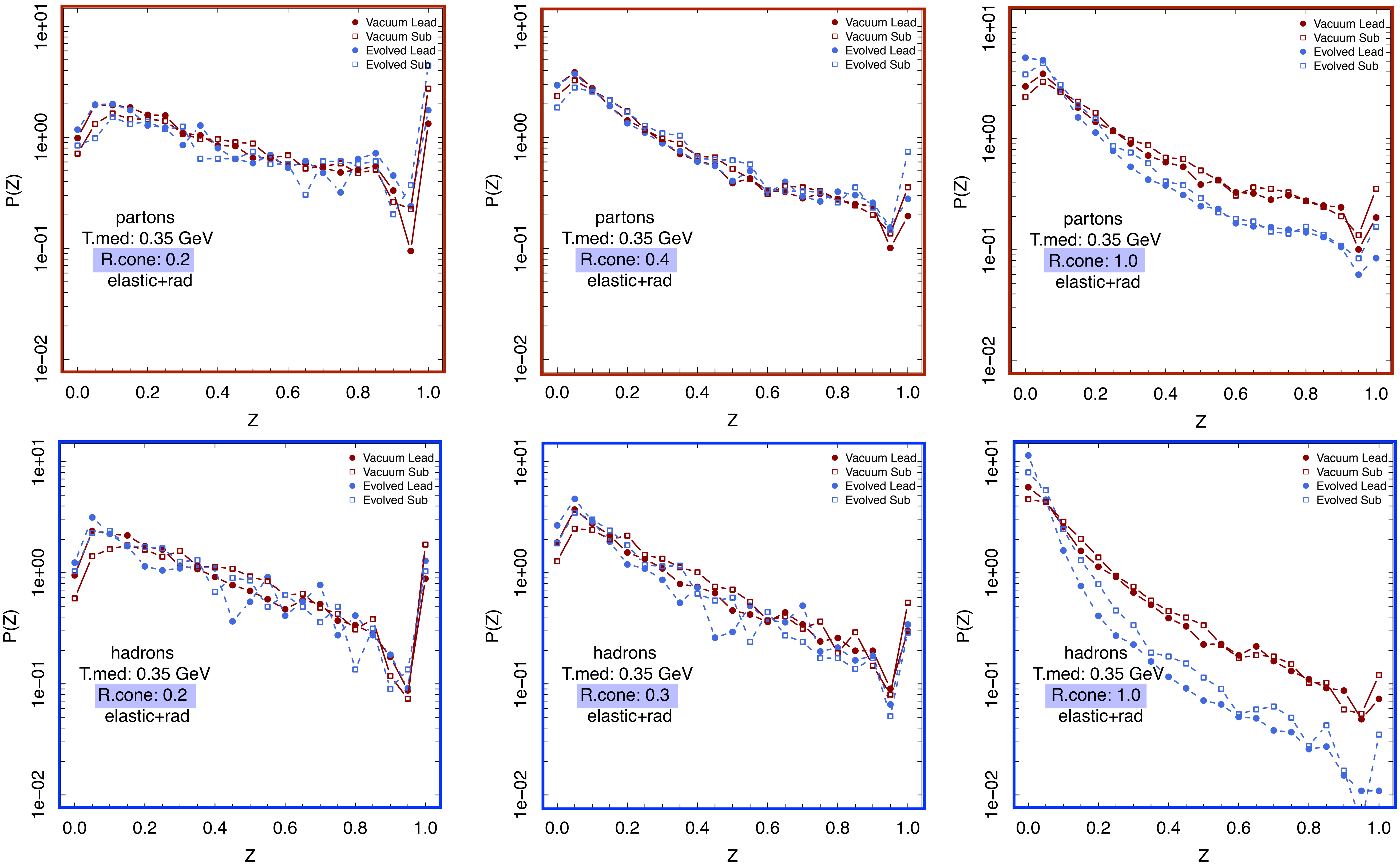
elastic interactions only



elastic+radiative

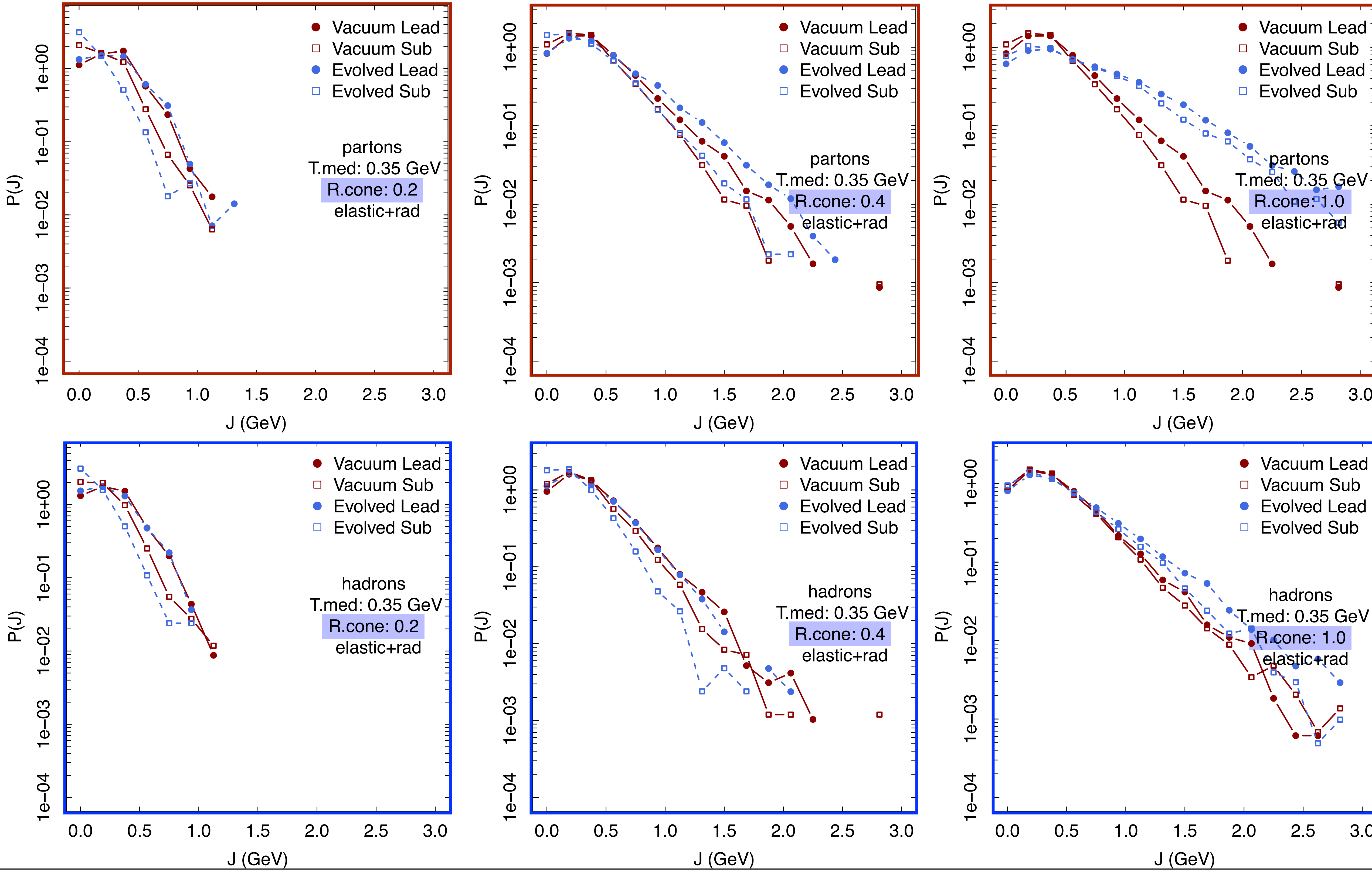
Elastic and Radiative modes show strong response to variation in alpha, profile shapes are qualitatively different

RHIC-Fragmentation - Longitudinal $z = E_T / E_{T,Jet} \cos \Delta R$



Jet Fragmentation - Transverse

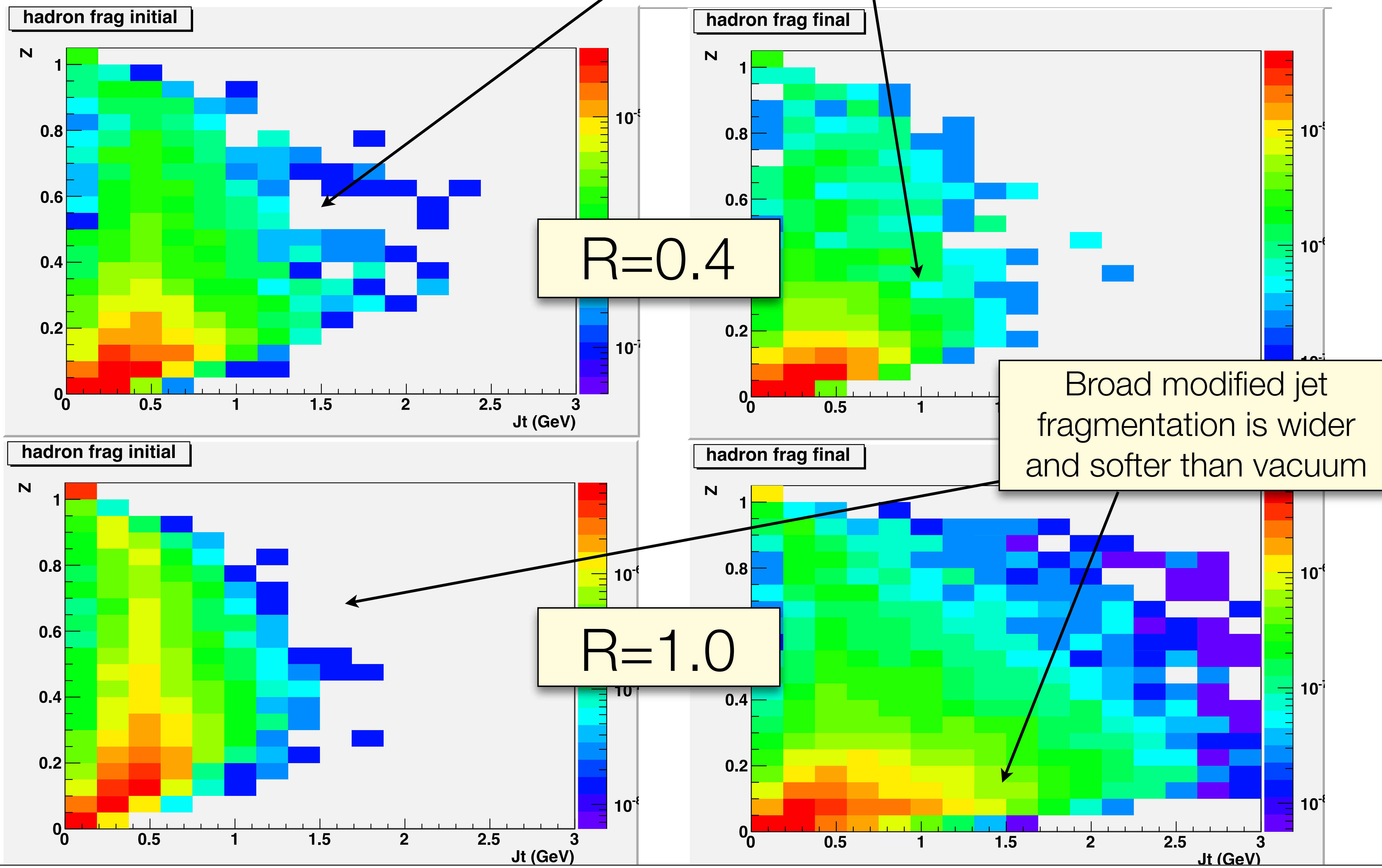
$$J_T = E_T \sin \Delta R$$



$$z = E_T / E_{T,Jet} \cos \Delta R$$
$$J_T = E_T \sin \Delta R$$

2d Fragmentation

Narrow modified jet fragmentation similar to vacuum



What do jet transport coefficients tell us about QGP?

- Jet transport coefficients encode medium density, and kinematic information

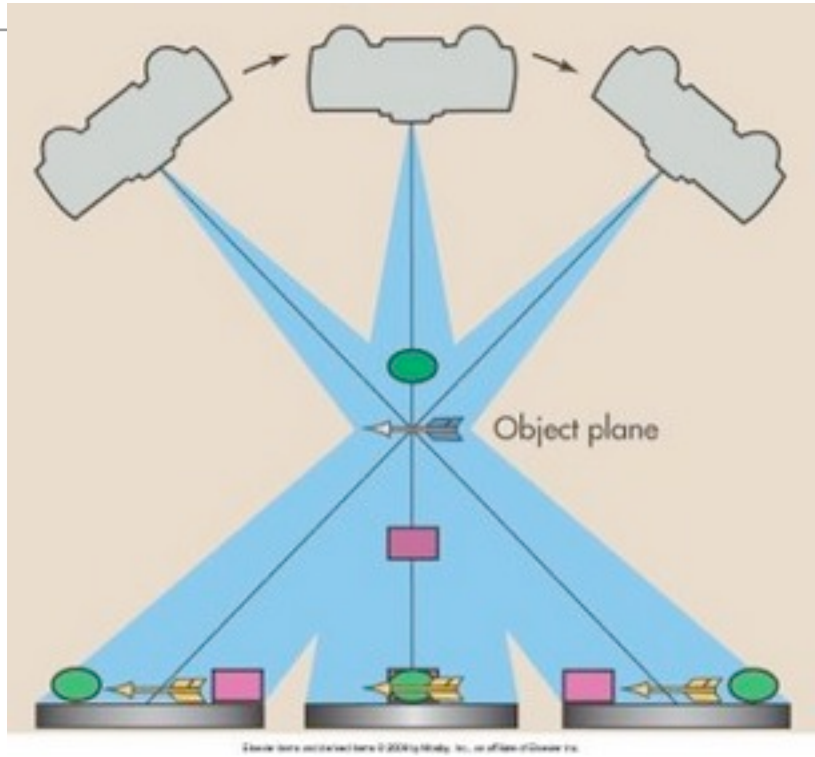
- Knowing q-hat and e-hat would allow for true jet **tomography**, given a set of observed jets from an event one could reconstruct the density profile.

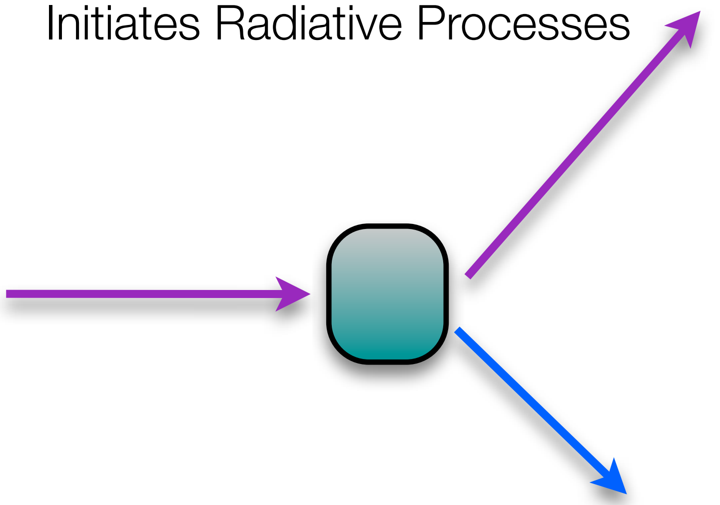
- q-hat measures transverse momentum transfer, e-hat measures longitudinal energy loss

- In the infinite probe momentum limit, radiation off static charges (q-hat) dominates energy loss

- In the low probe momentum limit, recoil of medium from elastic scattering (e-hat) dominates energy loss

- The ratio of the two coefficients is proportional to the mass of the medium constituents seen by the jet.





Thermal Masses for medium partons

- Previous results from VNI/BMS derived from a medium of massless partons

- Interaction cross-sections are always screened by the Debye mass $$m_D^2 = \frac{1}{6}(2N_c + N_f)g^2T^2$$

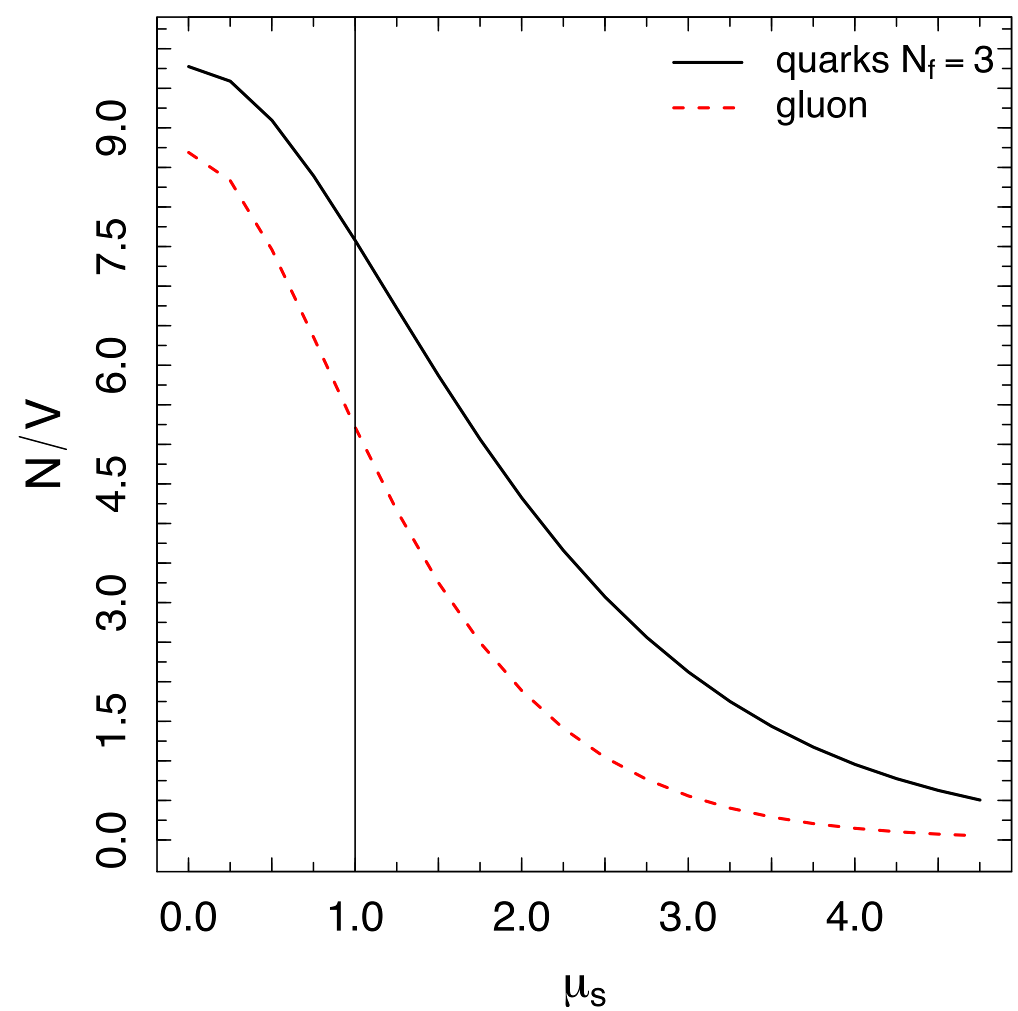
- Introduce asymptotic HTL masses for medium partons

$$m^2 = kg^2T^2, \quad k = \begin{cases} \frac{1}{6}N_c + \frac{1}{12}N_f & \text{gluon} \\ \frac{1}{4}C_F & \text{quark} \end{cases}$$

- Introduce a dimensionless scaling parameter μs to 'dial' medium masses

$$m^2 = k\mu_s^2 g^2 T^2.$$

- NB: Medium number density now scales with masses



$$\frac{N}{V} = \frac{gTm^2}{2\pi^2}K_2\left(\frac{m}{T}\right)$$

C.C-S, B.Müller, "Constituent Mass Dependence of transport coefficients in a quark gluon plasma", hep-ph/1209.3328

Measuring Transport Coefficients in VNI/BMS

- Fix medium temperature T=350 MeV, run code without radiation or hadronization.

- Run events with quark probes at fixed energies

- Extract q-hat and e-hat from transverse momentum and energy loss accumulated by the probe

$$\hat{q} = \frac{1}{L} \sum_{i=1}^{N_{\mathrm{coll}}} \Delta p_{T,i}^2. \qquad \hat{e} = \frac{1}{L} \sum_{i=1}^{N_{\mathrm{coll}}} \Delta E_i,$$

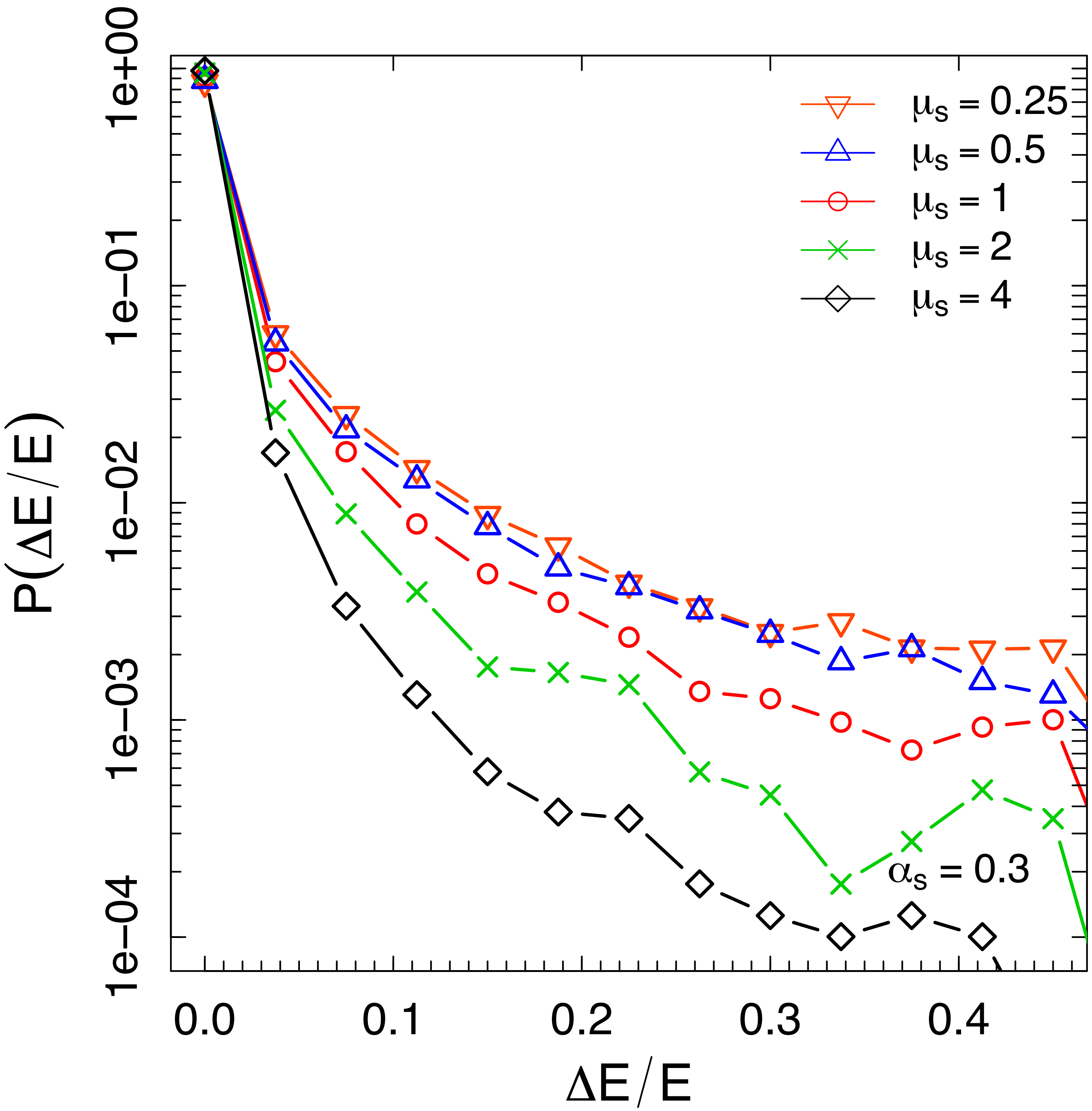
- For light probes in a massless medium we expect from pQCD calculations

$$\hat{q}(T) = 4\pi C_R \alpha_s^2 \mathcal{N}(T) \ln\left(\frac{q_{\mathrm{max}}^2}{m_D^2} + 1\right),$$

$$\mathcal{N}(T) = \frac{\zeta(3)}{\pi^2}\left(2N_c + \frac{3}{2}N_f\right) T^3,$$

$$\hat{e}(T) = \frac{4\pi\alpha^2 T^2}{3}\left(1 + \frac{N_f}{6}\right) \ln\left(\frac{ET}{m_D^2}\right)$$

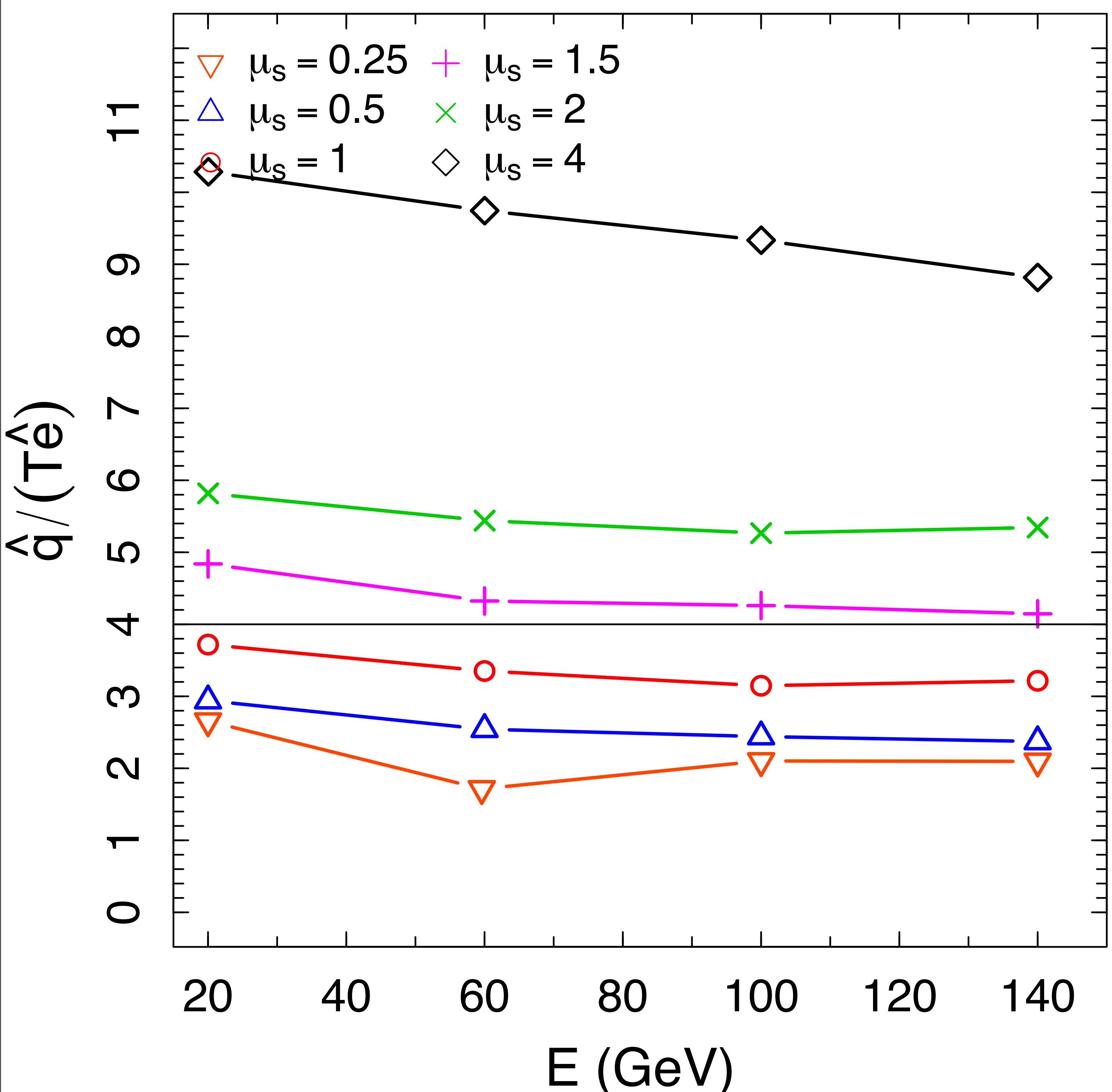
Elastic Energy Loss



Confirms kinematic intuition, higher medium constituent masses recoil less resulting in a lower energy loss

T=350 MeV, Alpha = 0.3

Q-hat / E-hat Ratio

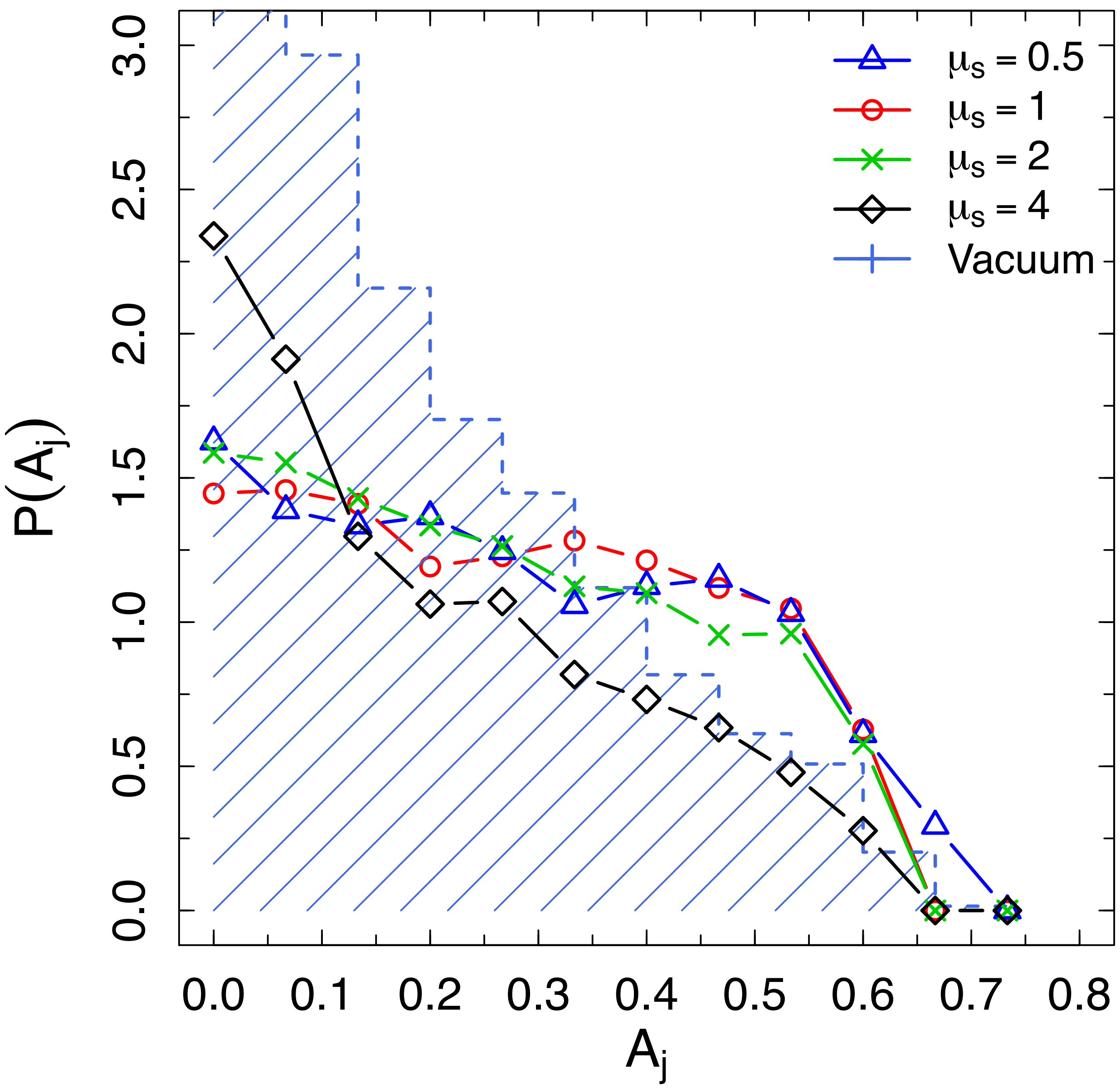


- Ratio scales linearly with the medium mass scale μs.
- Experimental measurements of q-hat and e-hat could provide insight into the nature of the QGP as seen by jets.
- Measurements made at different jet scales may reveal structure in quasi-particle mass spectrum.
- A possible precision measurement of hard probes and the QGP

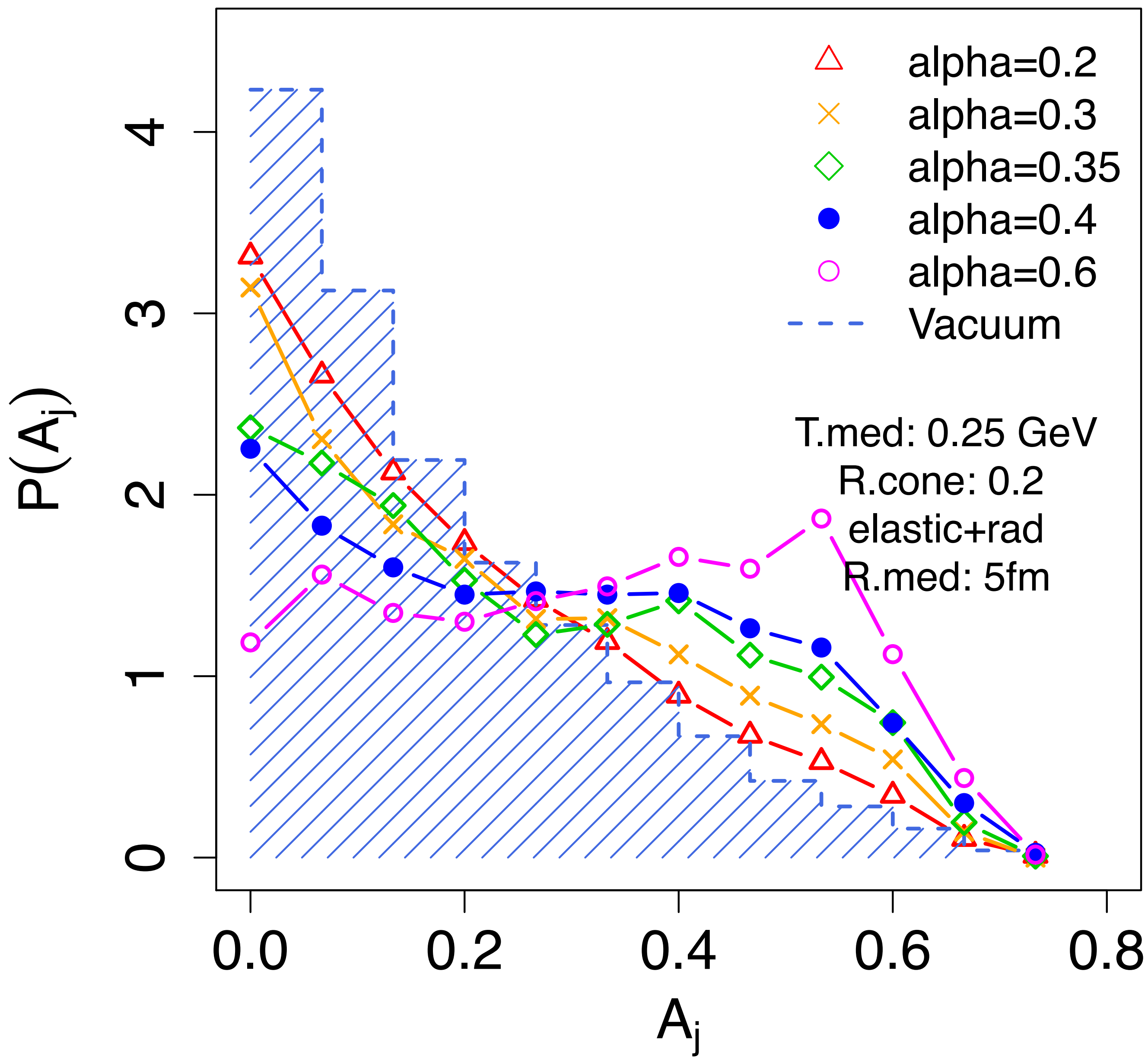
Dijet Response at RHIC - Aj

T=350 MeV, Et > 20GeV

Varying mu-s

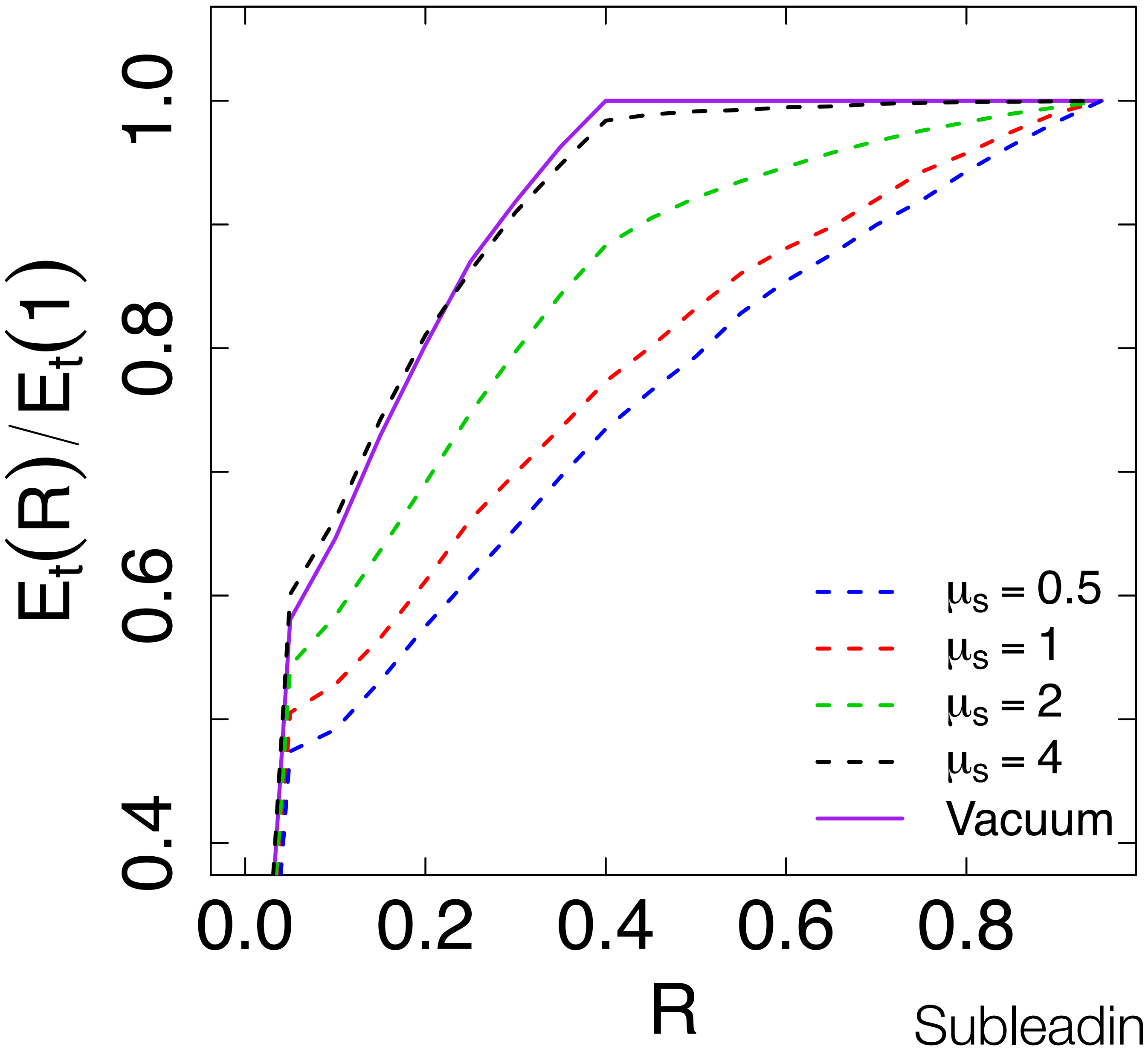


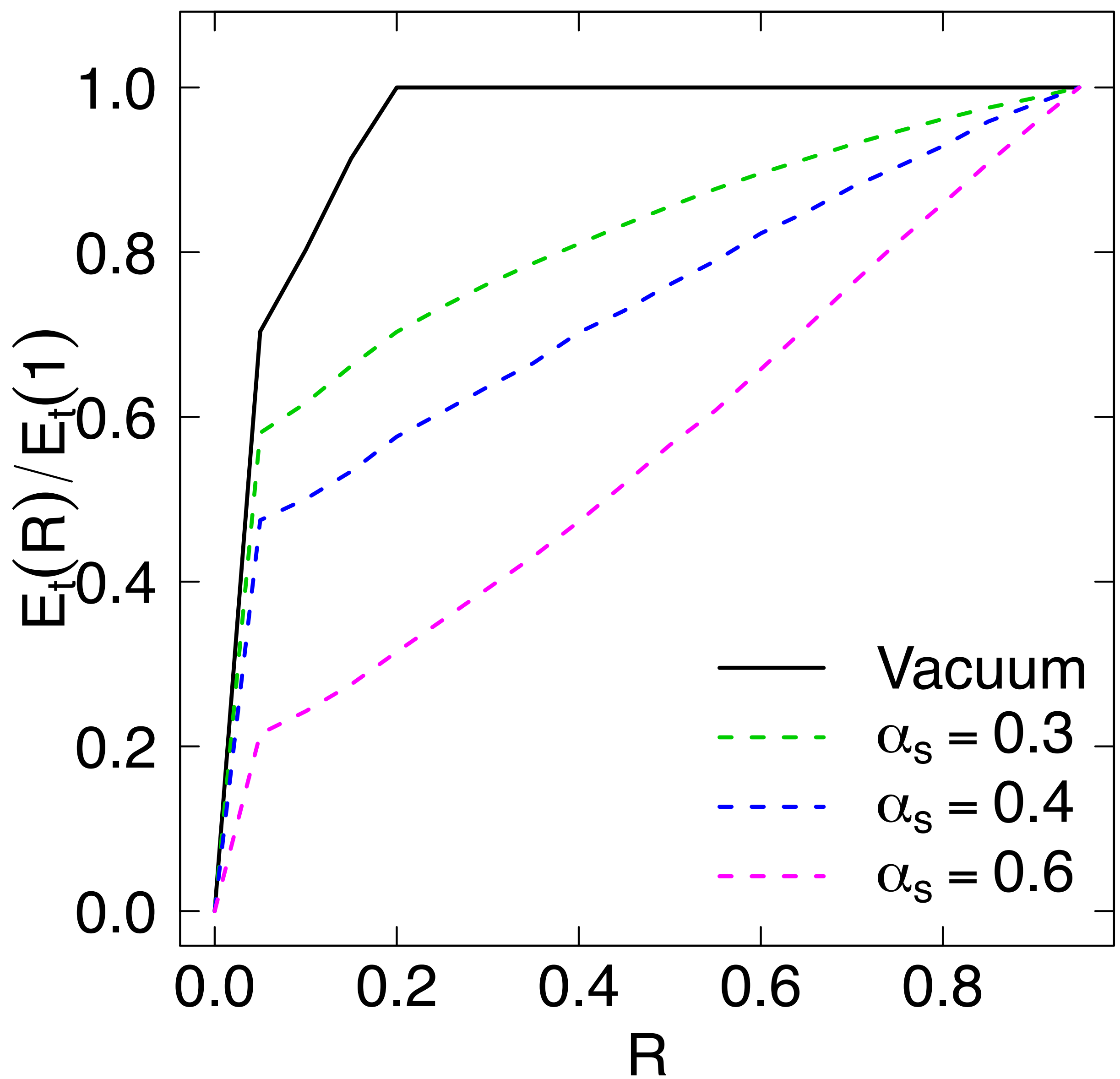
Varying alpha-s



Elastic Interactions Only

Dijet Response at RHIC - Subleading Jet Shape





Subleading Jet Shape

Jet shape is sensitive to elastic energy loss

Conclusions

- RHIC Dijet Asymmetry is sensitive to: strong coupling, medium radius, medium temperature and cone radius. Sometimes this is subtle.
- Modified jets have a softened radial profile (jet shape), partons are scattered transverse to the jet axis, transverse fragmentation profile softened.
- Fragmentation distributions look similar to vacuum for narrow jets, these jets are still strongly modified. Fragmentation of broad jets shows strong modifications over vacuum
- Modified jets retain a hard core that looks like a vacuum jet, surrounded by a soft cloud of radiated and liberated particles.
- Measurements of qhat/ehat ratio could provide insight into the nature of the medium as seen by jets.

How can we use what we know?

Unknown - modification process

Initial state - pQCD (pythia)

$$P(E^f, p_t^f) = \int P(E^f, p_t^f | E^I, p_t^I, Q^2, \rho, L, \ldots) P(\rho, L|b) P(L|b) P(b) P(E^I, p_t^I, Q^2) d\ldots$$

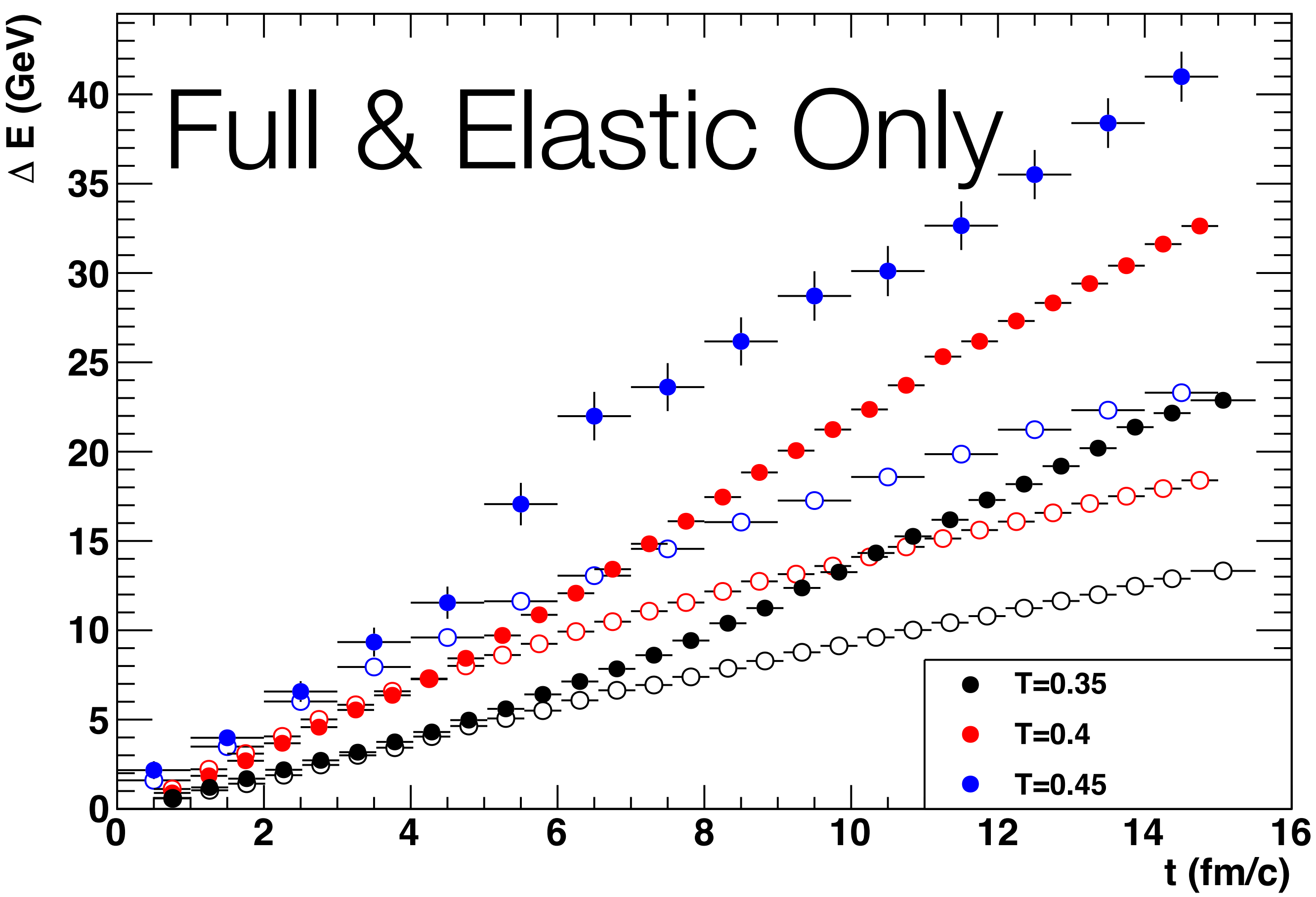
Hydro - path length and density encountered

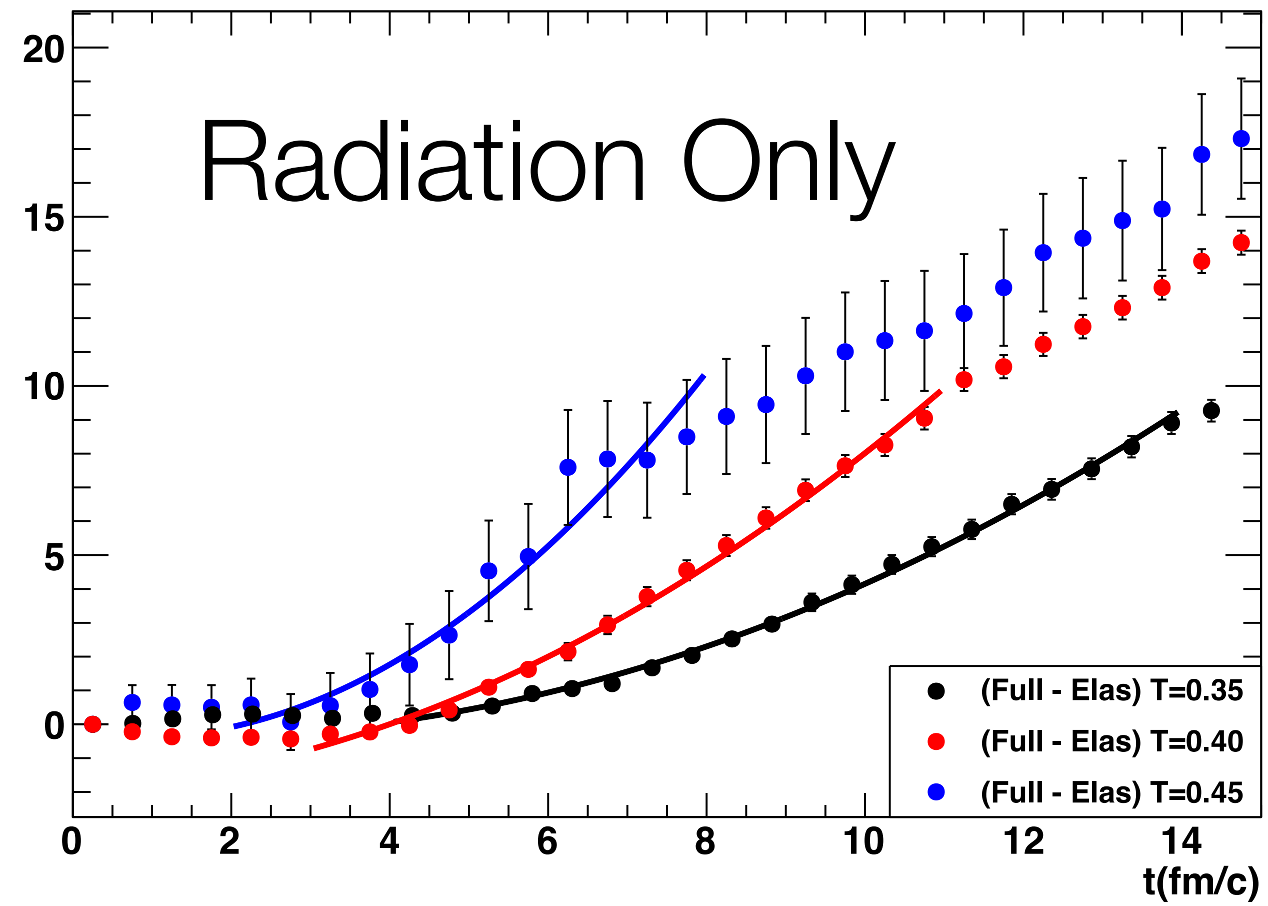
'measured' distributions of modified jets

- Experimental data gives a window into the after effects of the modification process
- How can we extract the maximum information about the modification process from the data?
- Typically people propose a form for the kernel and then attempt to reproduce observables
- Instead propose the most general meta-model for the modification kernel and then restrict the allowed form by requiring consistency with successively more difficult observables. A non-parametric model selection problem

Extras

Leading Parton Energy Loss





Radiation reproduces BDMPS-Z coefficient to 20%.

$$-\Delta E_{\mathrm{BDMPS}} = \frac{\alpha_s C_R}{8}\frac{\mu^2}{\lambda_g}L^2 \log\frac{L}{\lambda_g}.$$

Elastic (open circles) well described by pQCD results. $\Delta E_{elas} \propto T^2 L$

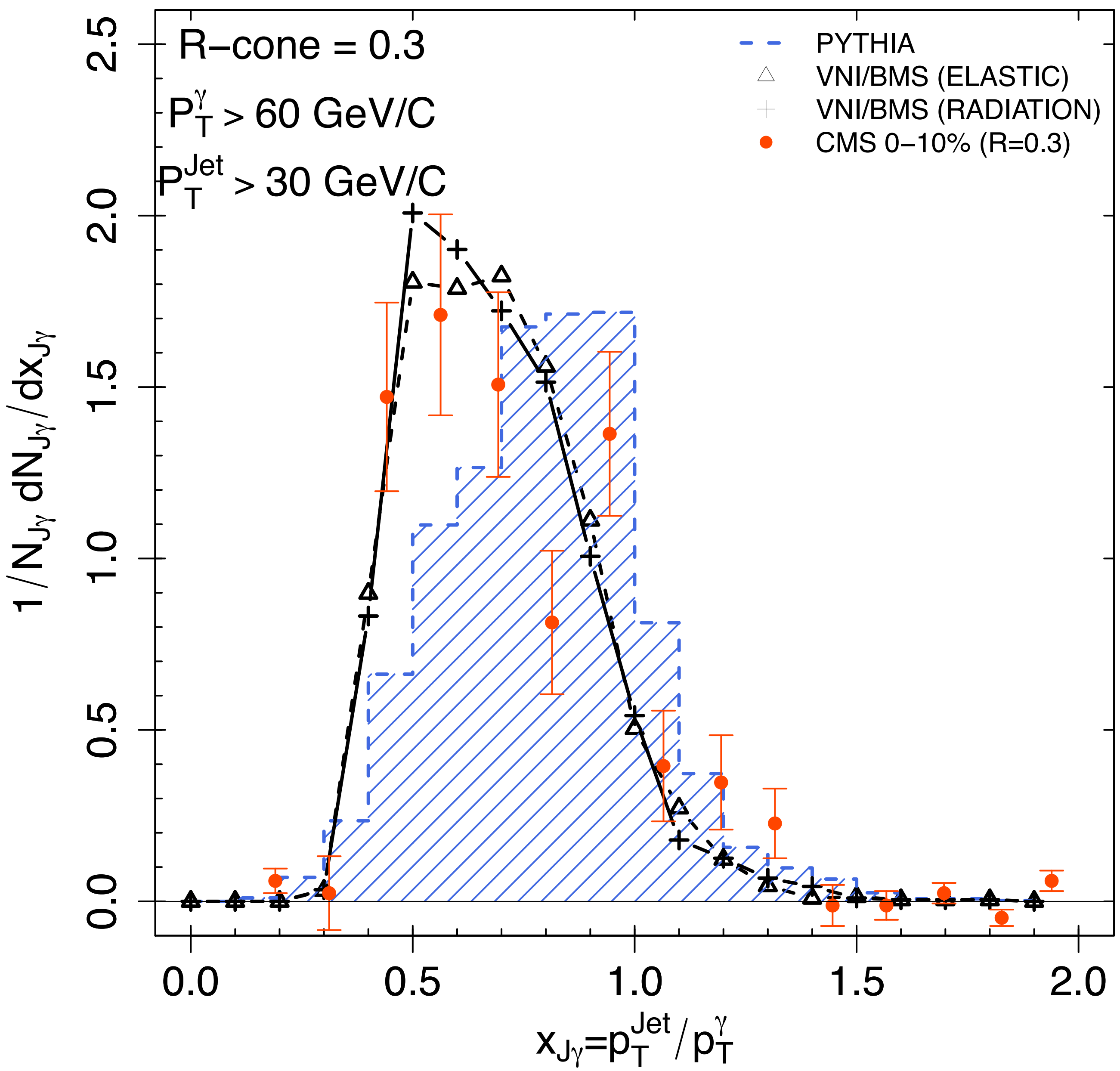
$$\hat{q} = \frac{1}{L}\sum_{i=1}^{N_{coll}} (\Delta p_{\perp,i})^2 = 2.2\ (\mathrm{GeV}^2/\mathrm{fm})$$

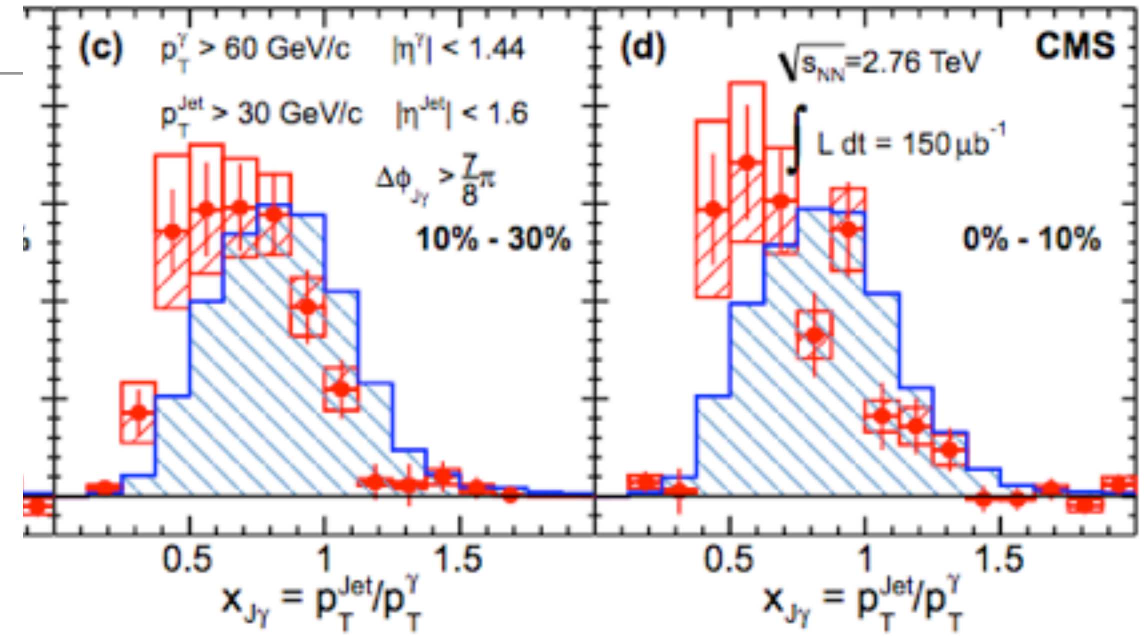
T=0.35 GeV

Calibration of PCM elastic processes: Bass.S.A et al *J.Phys.G37105112* (2010)
Baier et al (BDMPS) *Nucl Phys.B478* (1996), B.Zakharov, *JETP Lett.63* (1996),

CMS Photon - Jet Correlation

CMS hep-ex/1205.0206

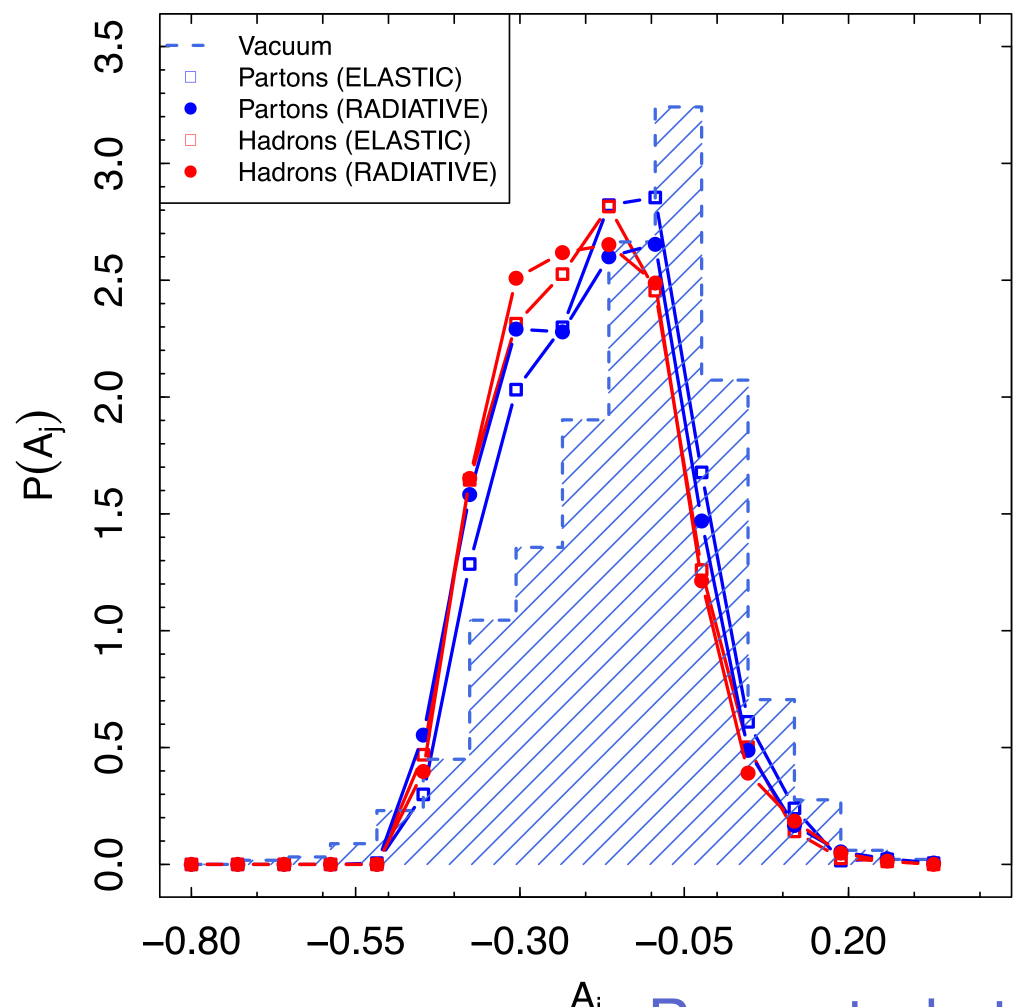




$$E_{T,\gamma} > 60\text{GeV}$$

$$E_{T,\text{Jet}} > 30\text{GeV}$$

$$A_j = \frac{E_{T,jet} - E_{T,\gamma}}{E_{T,jet} + E_{T,\gamma}}$$

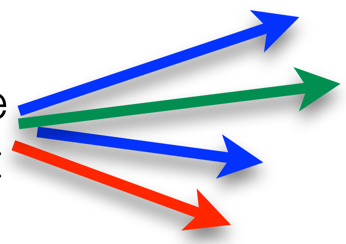


Presented at QM 2012

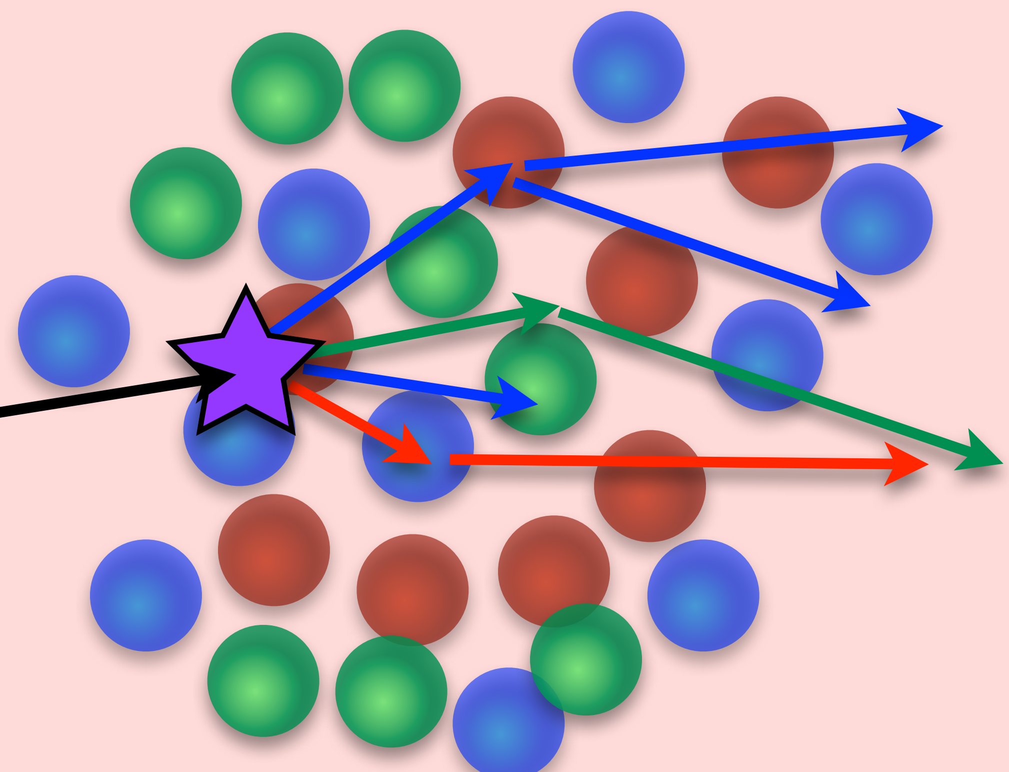
VNI/BMS - 2.0 + Hydro

Keep jetty partons at each time step. Discard 'old' medium partons

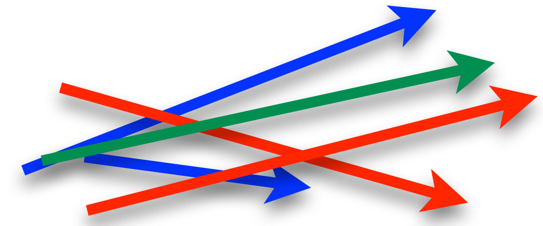
Generate pp event



Insert jet partons at binary scattering vertex



Use local temperature (from hydro) to regulate PCM cross-sections



Analyze final jetty partons

Hydro Evolution

Compute Hydro Event Profile

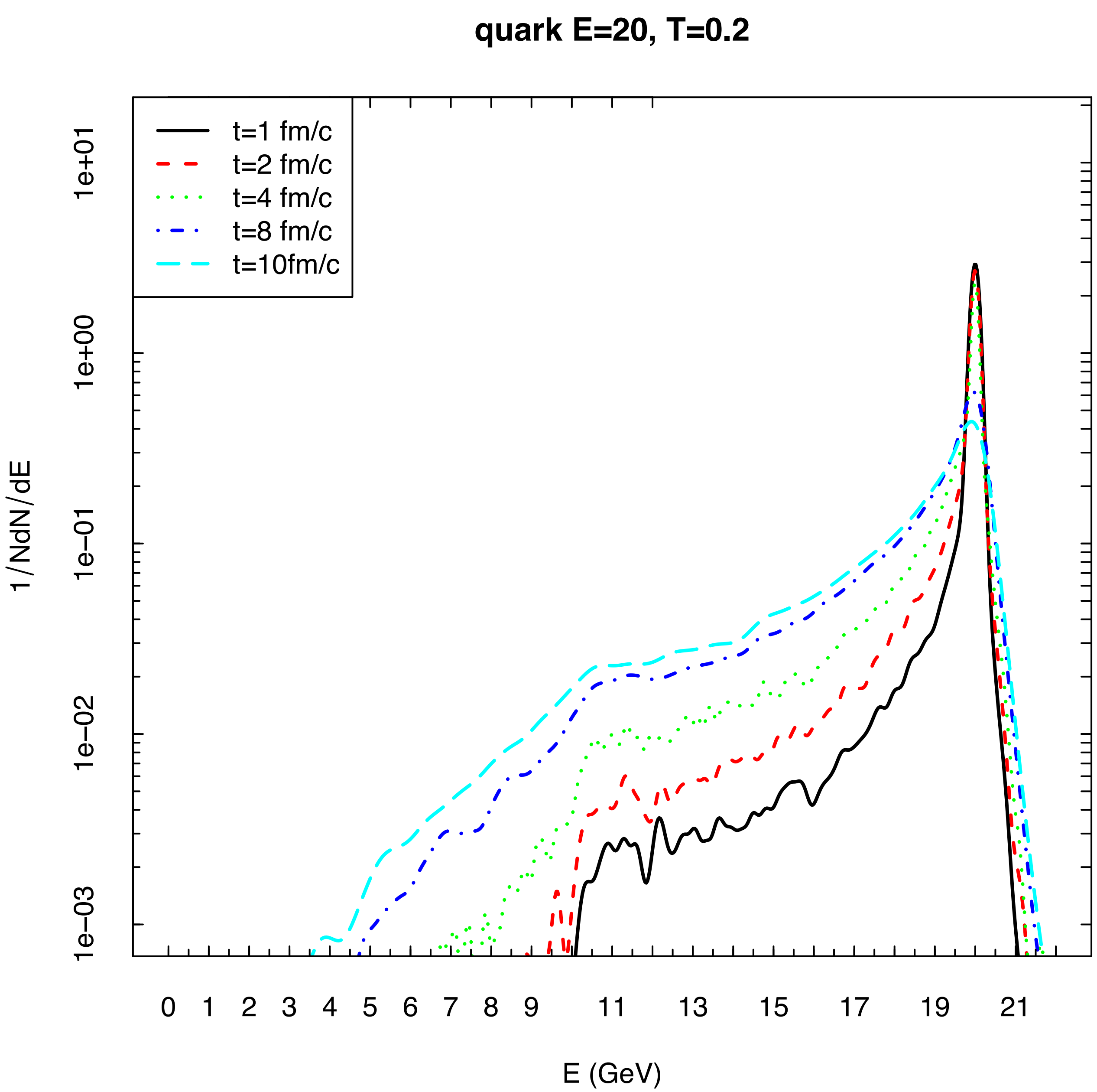
Sample Medium Partons from Hydro Profile at **each time step**

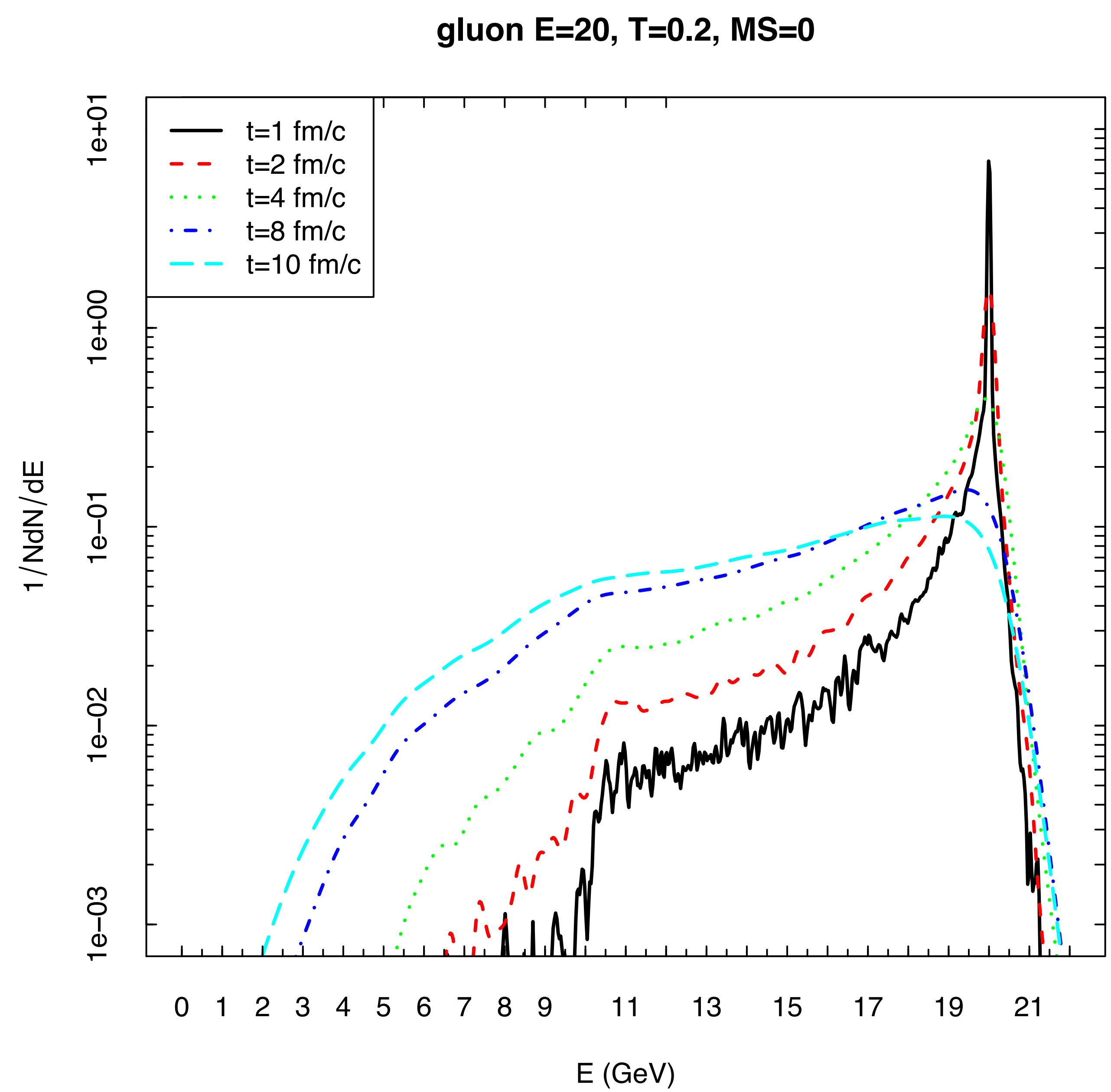
PARTON CASCADE

VNI/BMS - 2.0 Current + Future Features

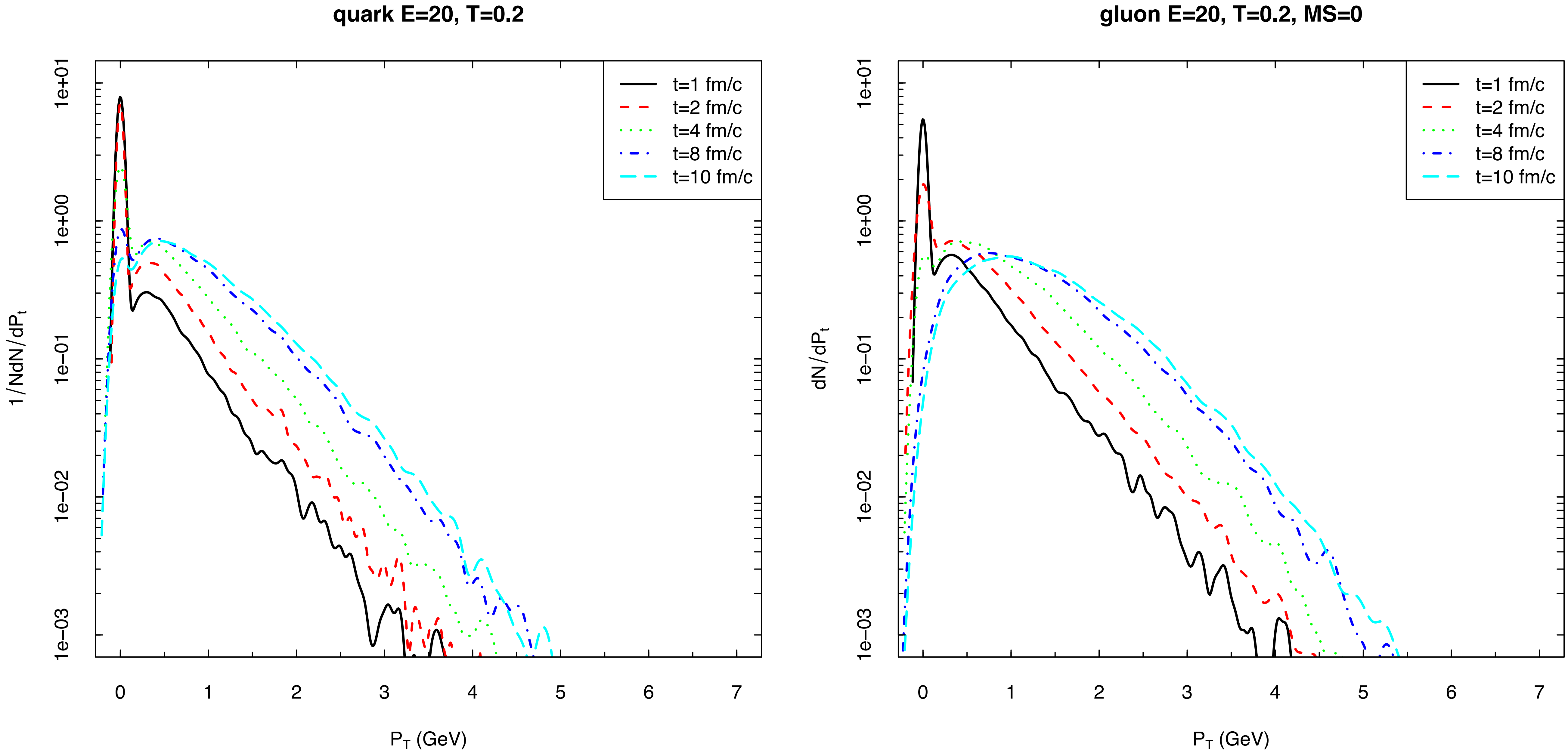
- Elastic and Radiative energy loss models, with BDMPS-Z LPM effect
- Lund Stringy Hadronization with full color tracking from the initial generator.
- Fixed medium temperature in simple box mode.
- Event by event hydro background.
- Variable medium constituent masses give control of qhat/ehat ratio.
- Integration with Pythia for hard process generation
- Jet level data analysis built in (and single hard probe)
- Relatively simple user-options
- Modern build system (CMAKE)

Leading Parton Energy Distribution, E=20 GeV





Leading Parton Pt Distribution, E=20 GeV



VNI/BMS Cross-Sections

g g → g g	$\frac{9}{2}\left(3-\frac{tu}{s^2}-\frac{su}{t^2}-\frac{st}{u^2}\right)$	q q′ → q q′	$\frac{4}{9}\frac{s^2+u^2}{t^2}$
q g→ q g	$-\frac{4}{9}\left(\frac{s}{u}+\frac{u}{s}\right)+\frac{s^2+u^2}{t^2}$	q qbar→ q′ qbar′	$\frac{4}{9}\frac{t^2+u^2}{s^2}$
g g → q qbar	$\frac{1}{6}\left(\frac{t}{u}+\frac{u}{t}\right)-\frac{3}{8}\frac{t^2+u^2}{s^2}$	q g →q γ	$-\frac{e_q^2}{3}\left(\frac{u}{s}+\frac{s}{u}\right)$
q q → q q	$\frac{4}{9}\left(\frac{s^2+u^2}{t^2}+\frac{s^2+t^2}{u^2}\right)-\frac{8}{27}\frac{s^2}{tu}$	q qbar → g γ	$\frac{8}{9}e_q^2\left(\frac{u}{t}+\frac{t}{u}\right)$
q qbar → q qbar	$\frac{4}{9}\left(\frac{s^2+u^2}{t^2}+\frac{u^2+t^2}{s^2}\right)-\frac{8}{27}\frac{u^2}{st}$	q qbar → γ γ	$\frac{2}{3}e_q^4\left(\frac{u}{t}+\frac{t}{u}\right)$
q qbar → g g	$\frac{32}{27}\left(\frac{t}{u}+\frac{u}{t}\right)-\frac{8}{3}\frac{t^2+u^2}{s^2}$		

- Dominant elastic interactions including screening mass

$$\mu_D = \sqrt{(2N_c+N_f)/6}gT$$

$$\frac{d\sigma^{gg\to gg}}{dq_\perp^2} = 2\pi\alpha_s^2\frac{9}{4}\frac{1}{(q_\perp^2+\mu_D^2)^2},$$

$$\frac{d\sigma^{gq\to gq}}{dq_\perp^2} = 2\pi\alpha_s^2\frac{1}{(q_\perp^2+\mu_D^2)^2},$$

$$\frac{d\sigma^{qq\to qq}}{dq_\perp^2} = 2\pi\alpha_s^2\frac{4}{9}\frac{1}{(q_\perp^2+\mu_D^2)^2},$$