Jets as QCD Matter Probes

Summary: Theory

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Jet Modification Workshop

Wayne State University

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Hard Probes

- High-p_T partons & jets
- Heavy quarks / open flavor hadrons
- Quarkonia (J/ψ, Υ)
- Electroweak probes (l^+l^-, γ, Z)

- Production rates are calculable in SM
  - Caveats: quarkonia, nuclear PDFs, etc.
- Final-state interactions can be factorized from production
- A+A results can be normalized to p+p and/or p(d)+A
- Final state interactions are negligible for EW probes

HP Methodology

- Formulate production in A+A as hard QCD process with factorizable final state interactions (FSI)
- Formulate FSI in terms of medium properties (e.g. transport coefficients) that can be calculated for any medium model
- Identify observables that are sensitive to certain aspects of the structure of the medium, e.g.:
    - Weakly vs. strongly coupled plasma
    - Scale separating weak from strong coupling
    - Quasiparticle structure
- Calculate medium properties relevant to FSI on the lattice

Hot QCD matter properties

Which **properties of hot QCD matter** can we hope to determine with the help of hard probes ?

Easy for LQCD

$$m_D = -\lim_{|x|\to\infty}\frac{1}{|x|}\ln\left\langle E^a(x)E^a(0)\right\rangle$$

Color screening: Quarkonium states

Hard for LQCD

$$\Pi^{\mu\nu}_{\mathrm{em}}(k) = \int d^4x\, e^{ikx}\left\langle j^\mu(x)j^\nu(0)\right\rangle$$

QGP Radiance: Lepton pairs, photons

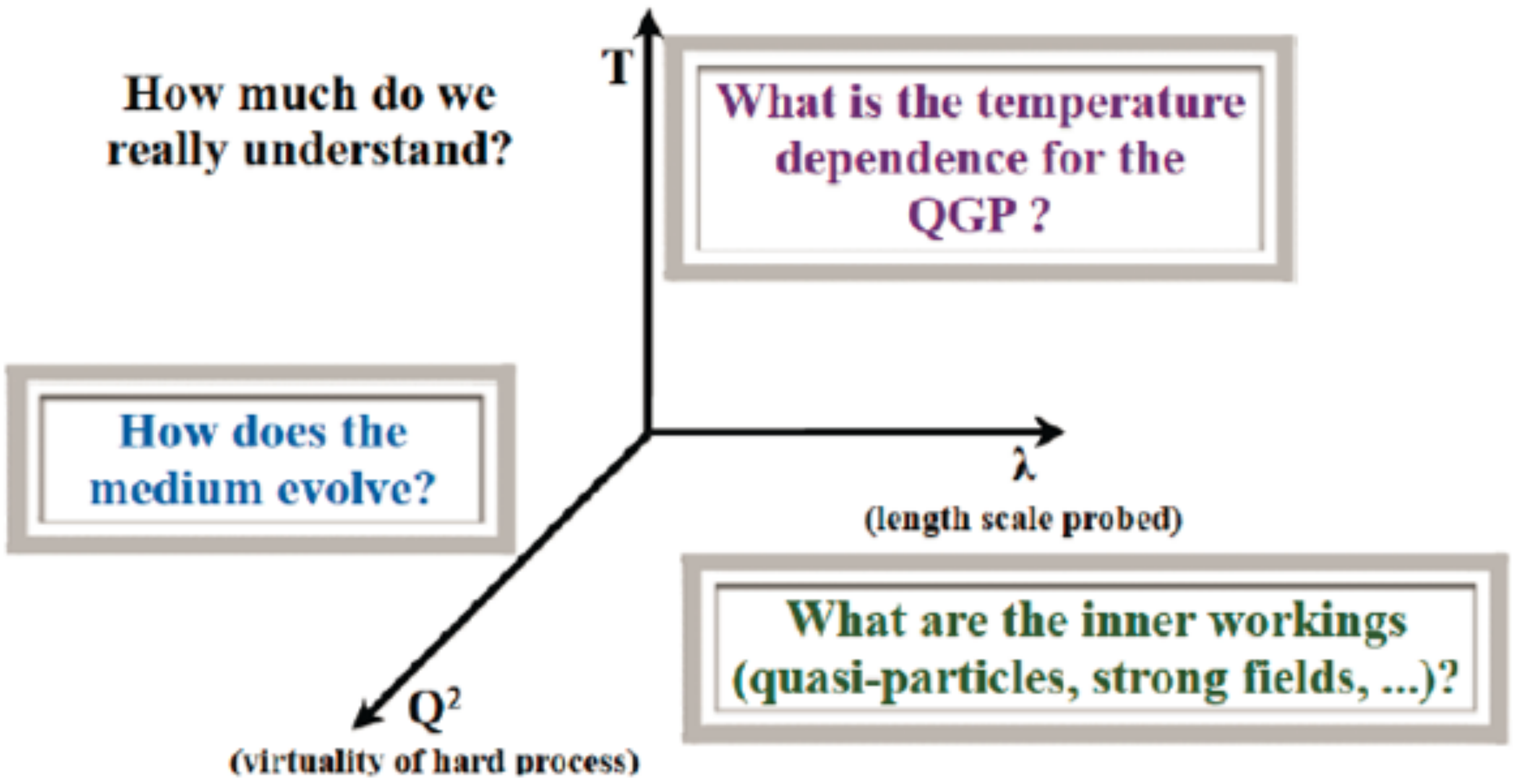
Very Hard for LQCD

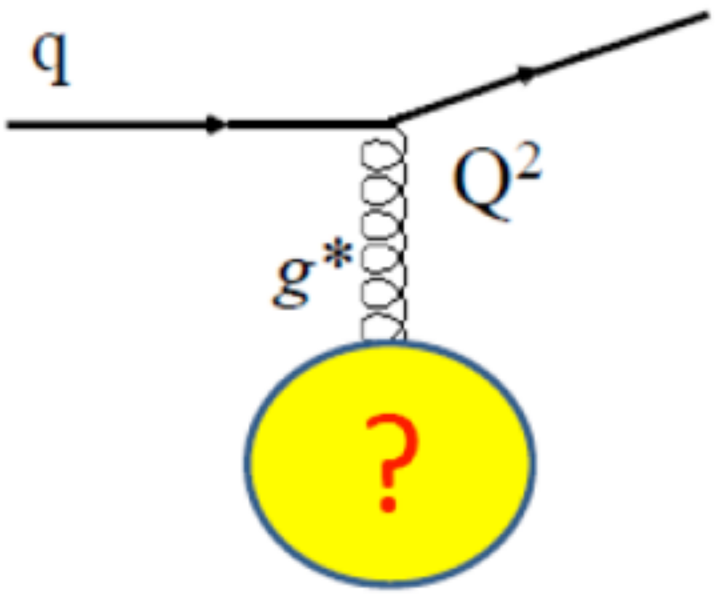
$$\left.\begin{aligned}
\hat{q} &= \frac{4\pi^2\alpha_s C_R}{N_c^2-1}\int dy^-\left\langle F^{a+i}(y^-)F_i^{a+}(0)\right\rangle \\
\hat{e} &= \frac{4\pi^2\alpha_s C_R}{N_c^2-1}\int dy^-\left\langle i\partial^- A^{a+}(y^-)A^{a+}(0)\right\rangle \\
\hat{e}_2 &= \frac{4\pi^2\alpha_s C_R}{N_c^2-1}\int dy^-\left\langle F^{a+-}(y^-)F^{a+-}(0)\right\rangle
\end{aligned}\right\}$$

Momentum diffusion:
parton energy loss, jet quenching

What we hope to learn

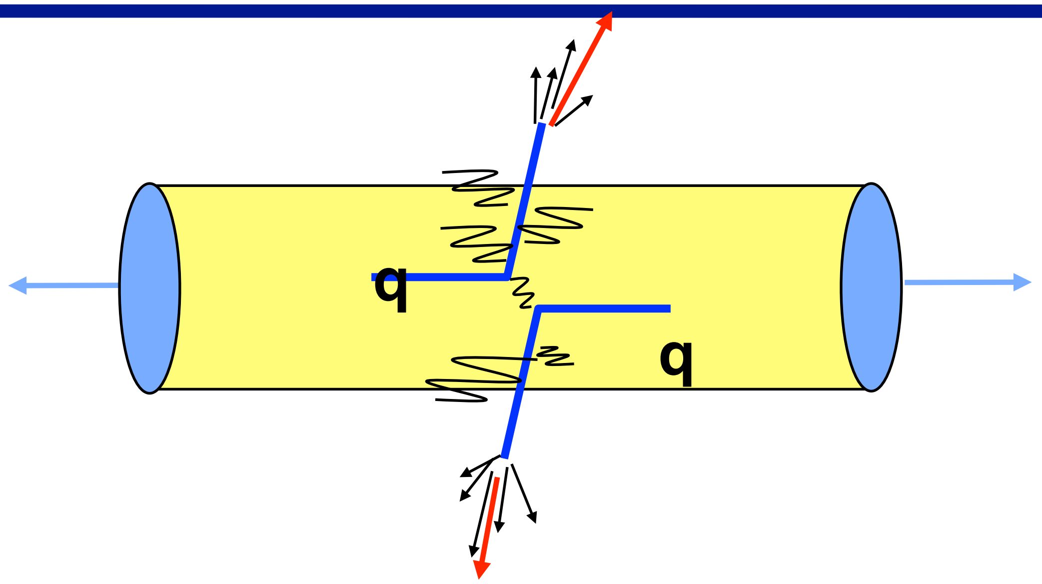
Apart from $\Pi^{\mu\nu}$ all medium properties are expressed as correlators of color gauge fields. They reflect the gluonic structure of the QGP.





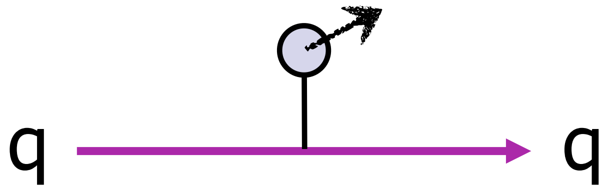
At high Q^2 and/or high T, the QGP is weakly coupled and has a quasiparticulate structure. At which Q^2 (T) does it become strongly coupled? Does it still contain quasiparticles? Can we use hard partons to locate the transition? Which quantities tell us where the transition occurs?

Parton energy loss

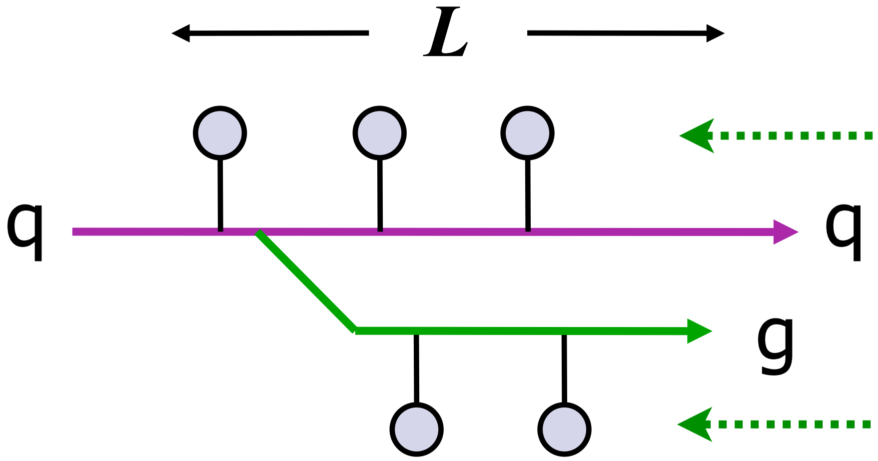


Elastic energy loss:

$$\frac{dE}{dx} = -C_2\,\hat{e}$$



Radiative energy loss:



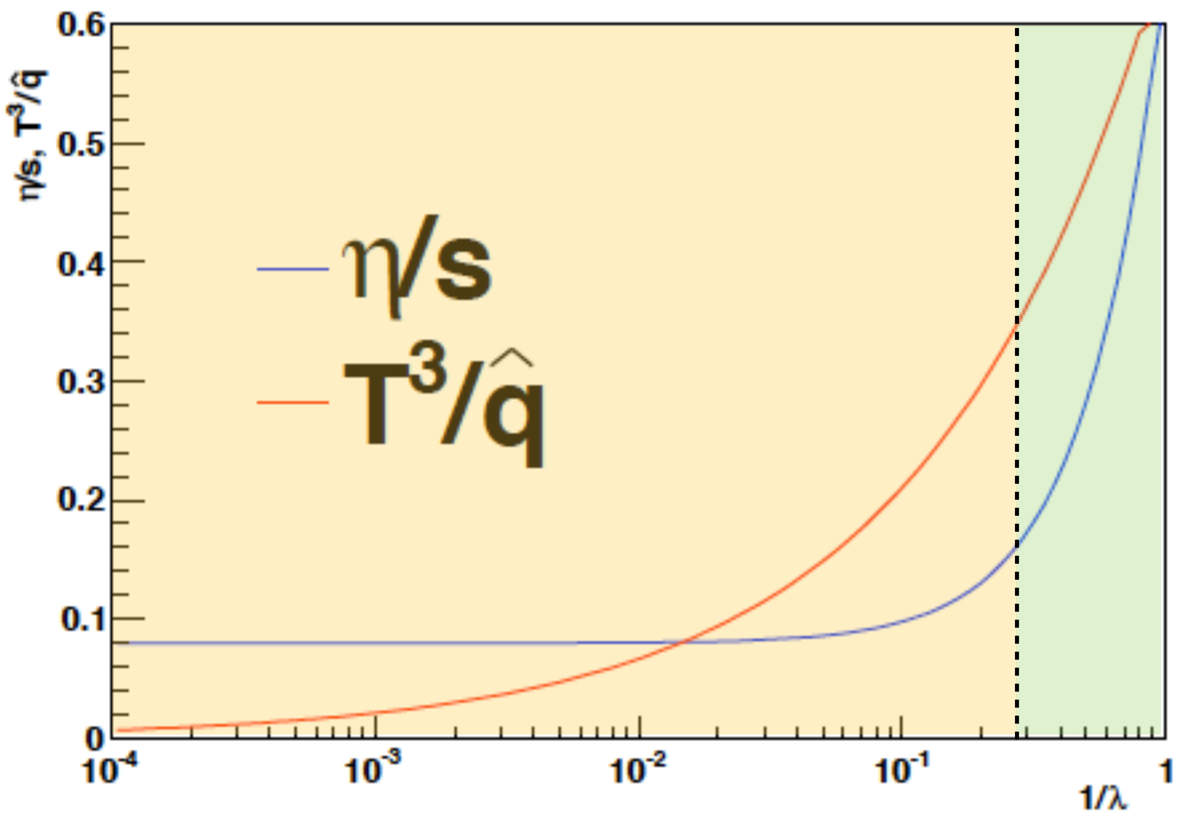
Scattering centers

⇔ color charges

$$\frac{dE}{dx} = -C_2\,\hat{q}\,L$$

$$\hat{q} = \rho \int q^2\, dq^2 \frac{d\sigma}{dq^2} = \int dx^- \left\langle F_i^{+}(x^-) F^{+i}(0) \right\rangle$$

Why q-hat is important

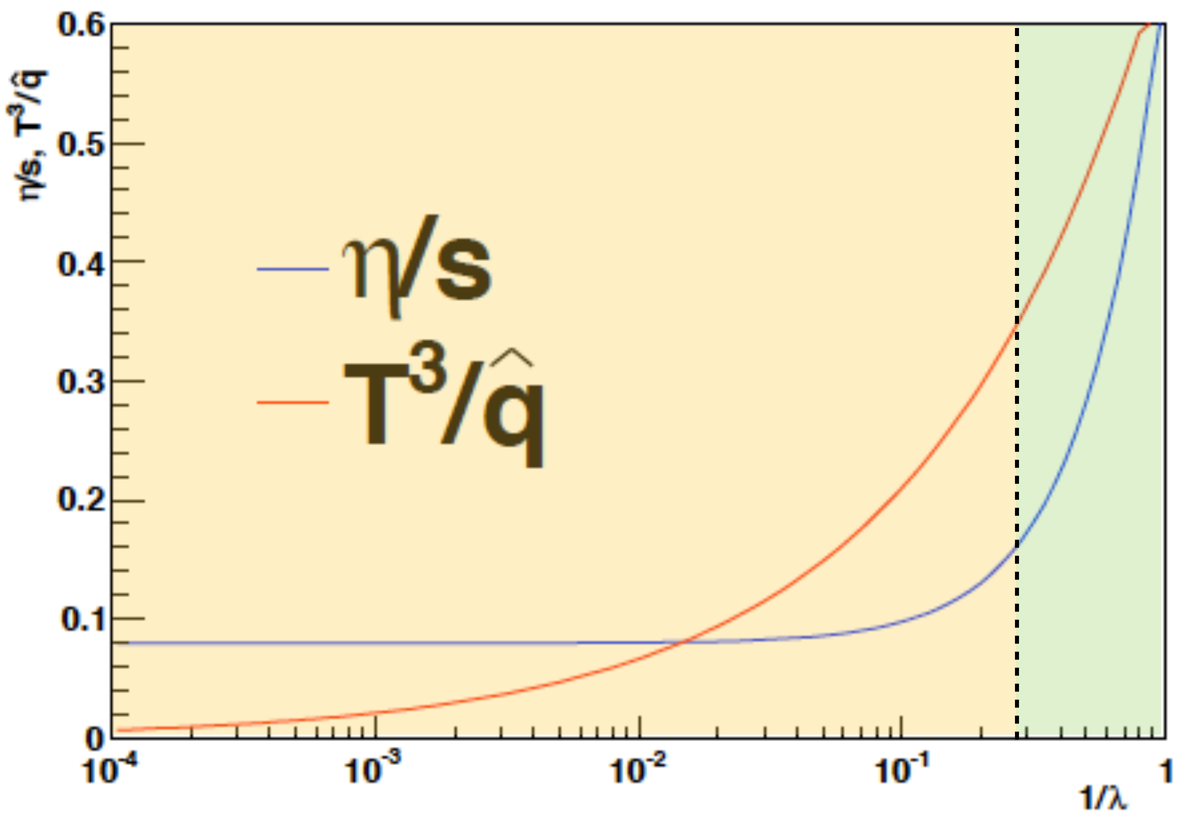


Majumder, BM, Wang argued that η/s and q̂ are related at weak coupling in gauge theories [PRL 99, 192301 (2007)]:

$$\eta / s = \mathrm{const} \times \mathrm{T}^3 / \hat{q}$$

At strong coupling, η/s saturates at 1/4π, but q̂ increases without limit. Unambiguous criterion for weak vs. strong coupling?

Why q-hat is important



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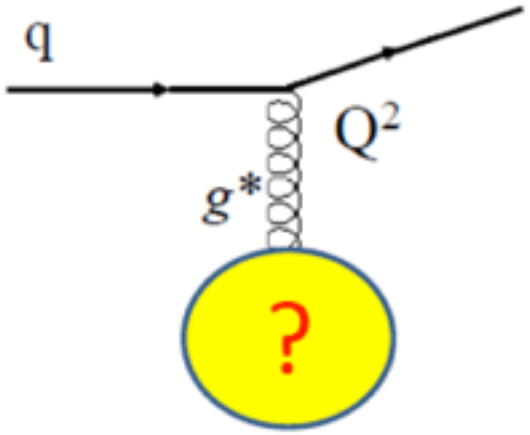
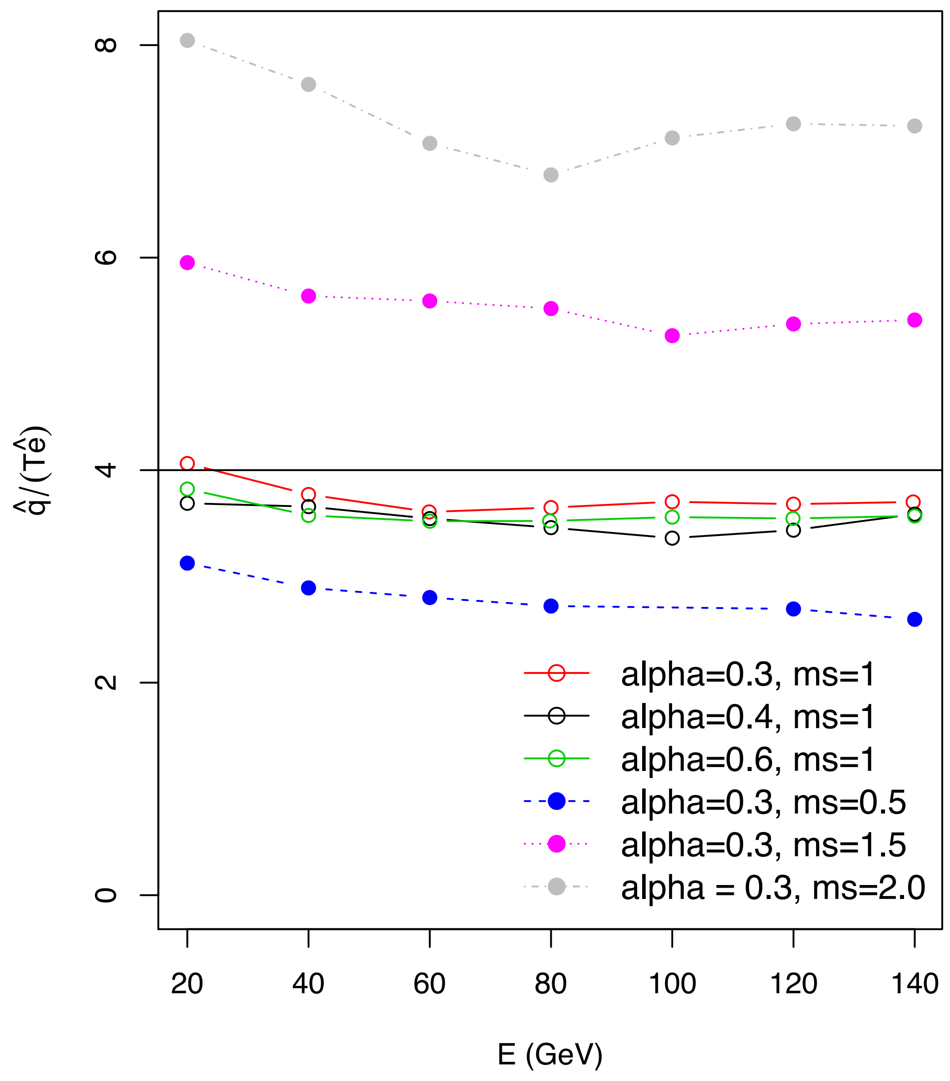
Collisional energy loss parameter ê is sensitive to mass *m* of scatterers, goes to zero in *m* →∞ limit, unless scatterings centers have a dense spectrum of excited states (*think*: atoms). Thus ê is a probe of medium structure at color screening scale.

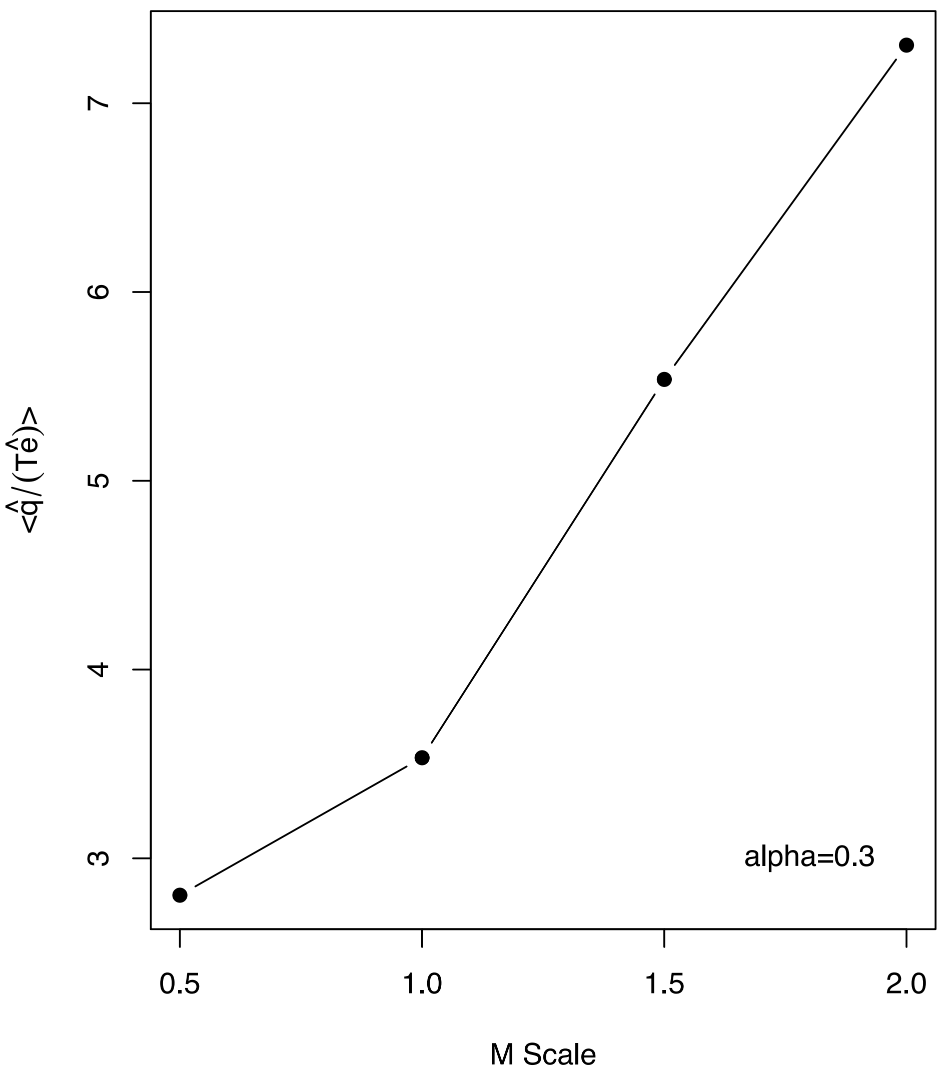


$\hat{q}/(T\hat{e})$ measures mass of constituents

VNI/BMS reproduces the perturbative (HTL) value for q-hat and e-hat with $\hat{q}/(T\hat{e}) \approx 4$

Assume that effective mass of partons in the medium is $M_{\text{eff}} = m_s \times M_{\text{HTL}}$



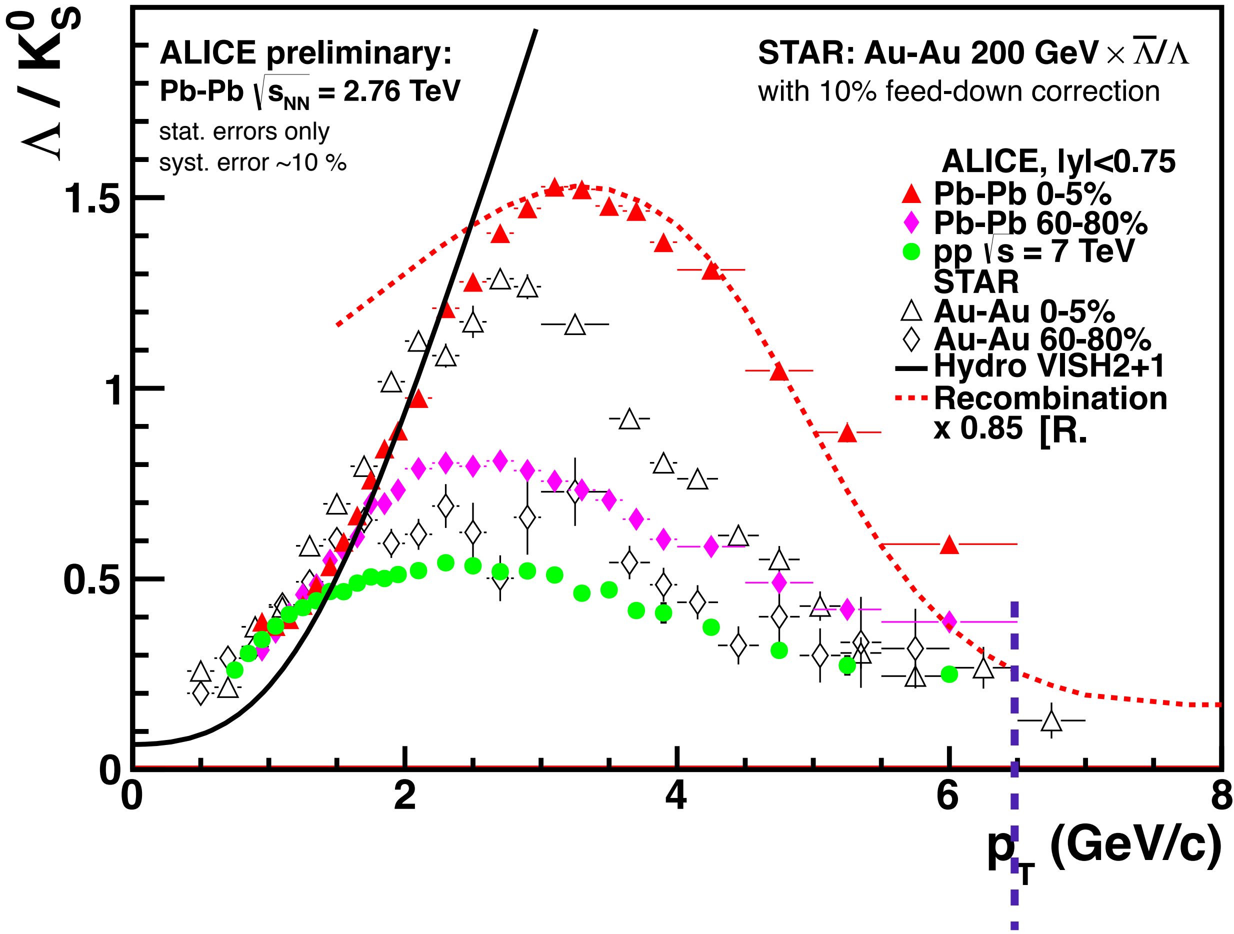


Core questions

- What is the mechanism of energy loss ?
  - ☐ “radiative” = into non-thermal gluon modes
  - ☐ “collisional” = directly into thermal plasma modes
- How are radiative and collisional energy loss affected by the structure of the medium (quasiparticles or not)?
  - ☐ e.g.: Bluhm et al, 1204.2469; Kolevatov & Wiedemann, 0812.0270
  - ☐ AdS/CFT inspired models with weak-strong coupling transition?
- What happens to the lost energy and momentum ?
  - ☐ If “radiative”, how quickly does it thermalize = what is its longitudinal momentum (z) distribution ?
  - ☐ What is its angular distribution (the jet “shape”) = how much is found in a cone of angular size R ?
- How do the answers depend on the parton flavor ?

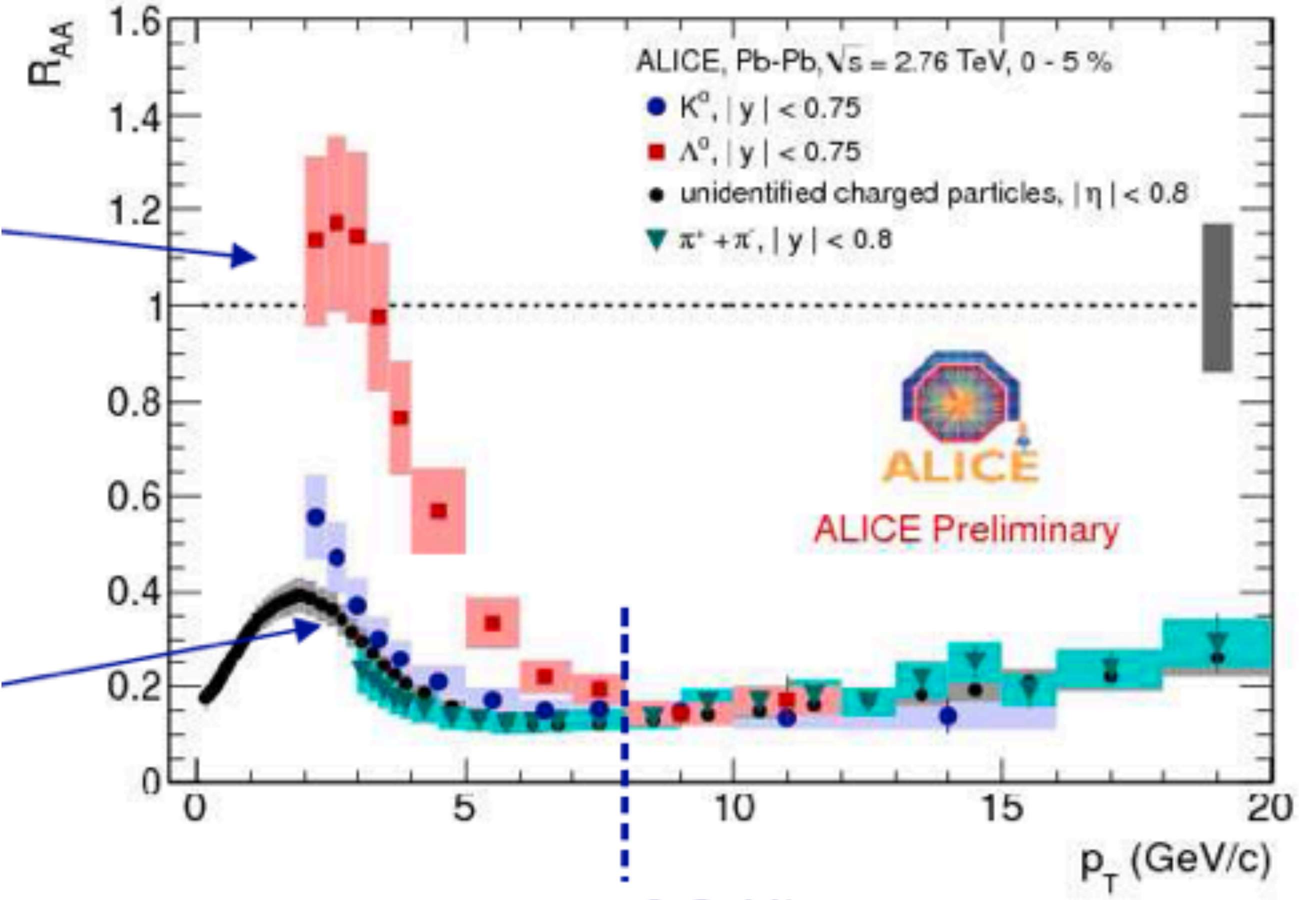
Where does jet physics start?

Baryon/meson



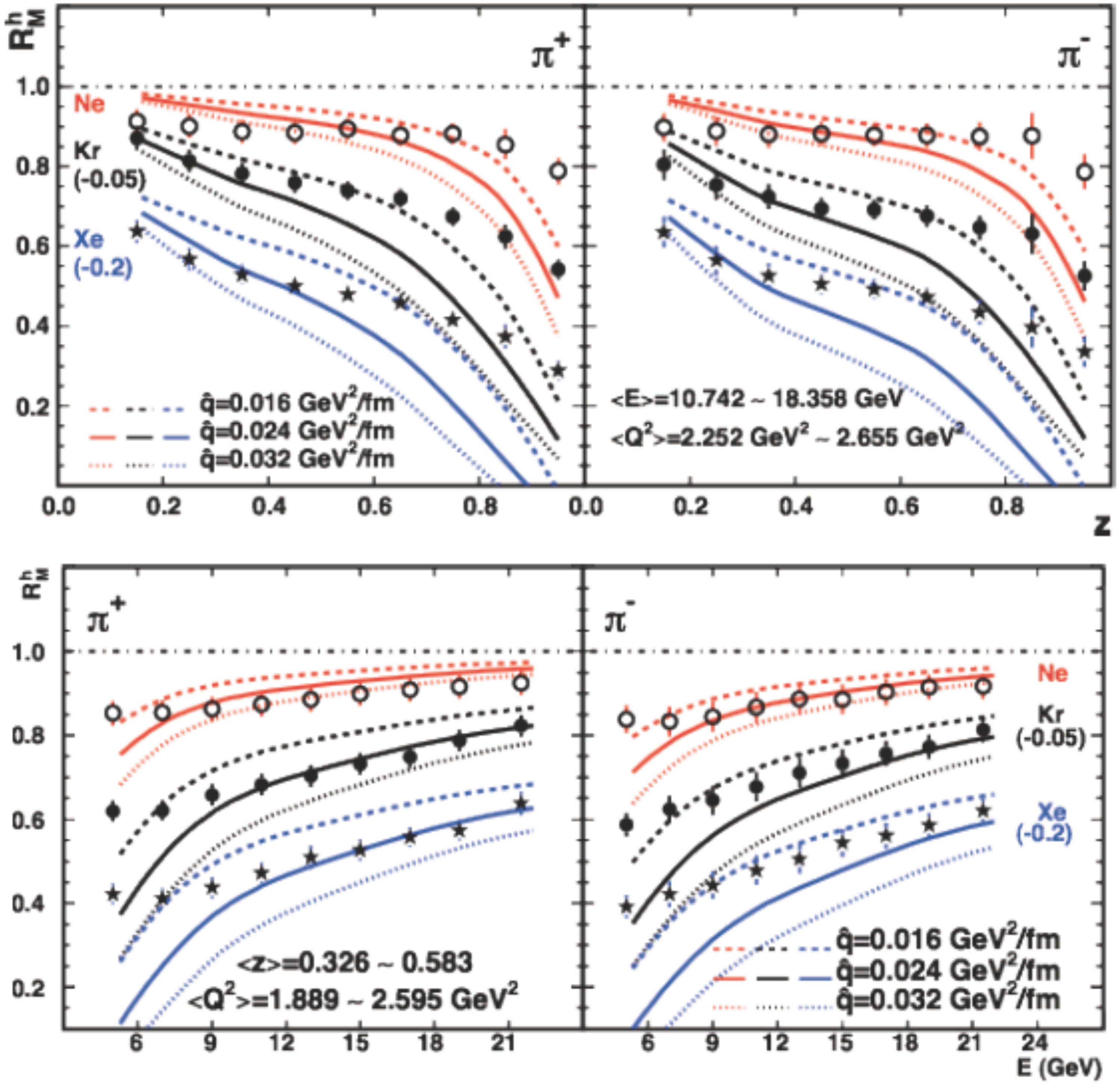
p_T > ~6.5 GeV/c:
All hadrons similar

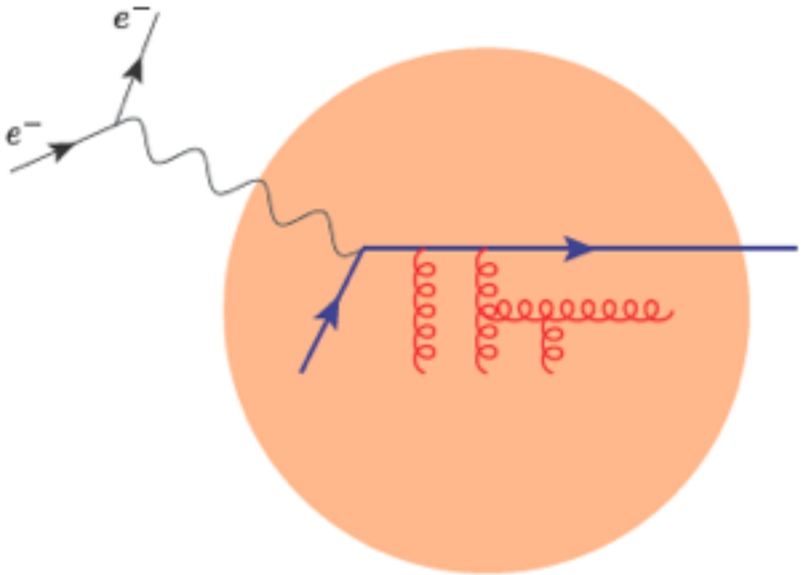
R_{AA}



$p_T \geq$ ~8 GeV/c:
All hadrons similar

The e-A baseline



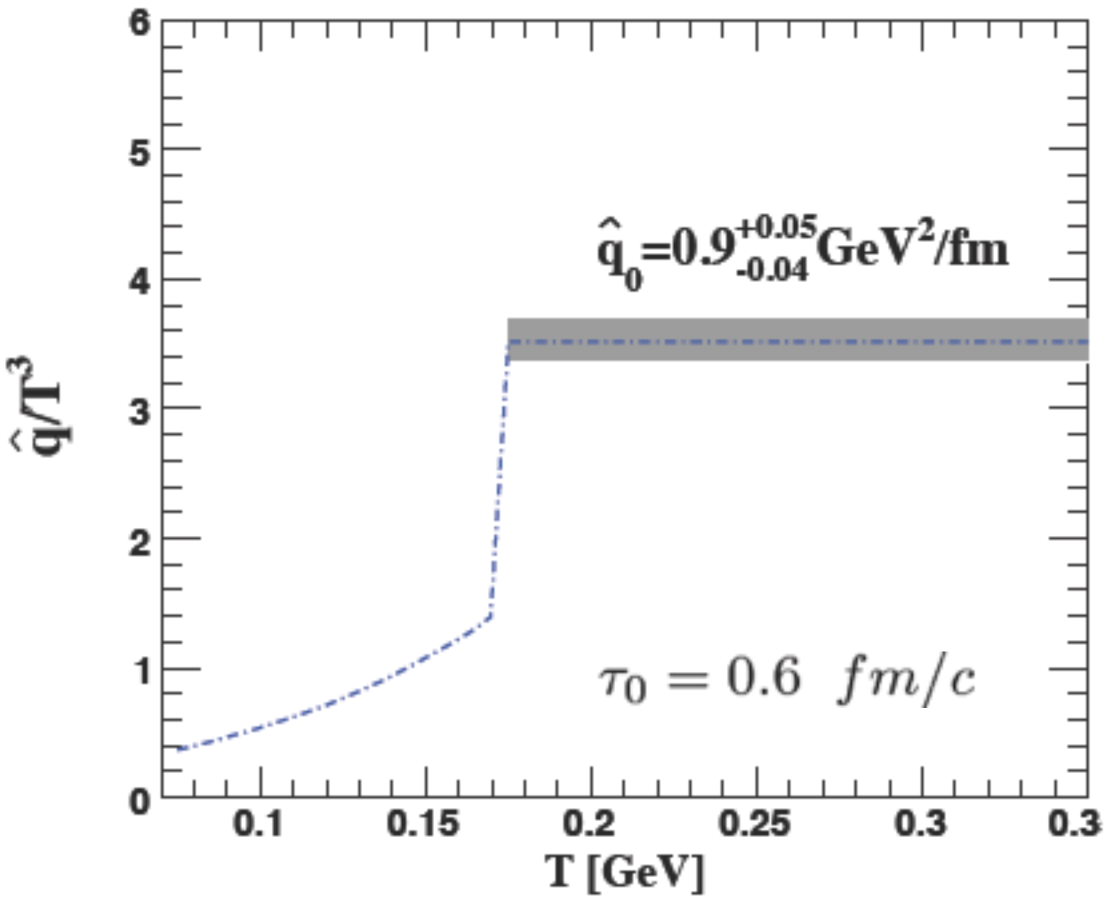


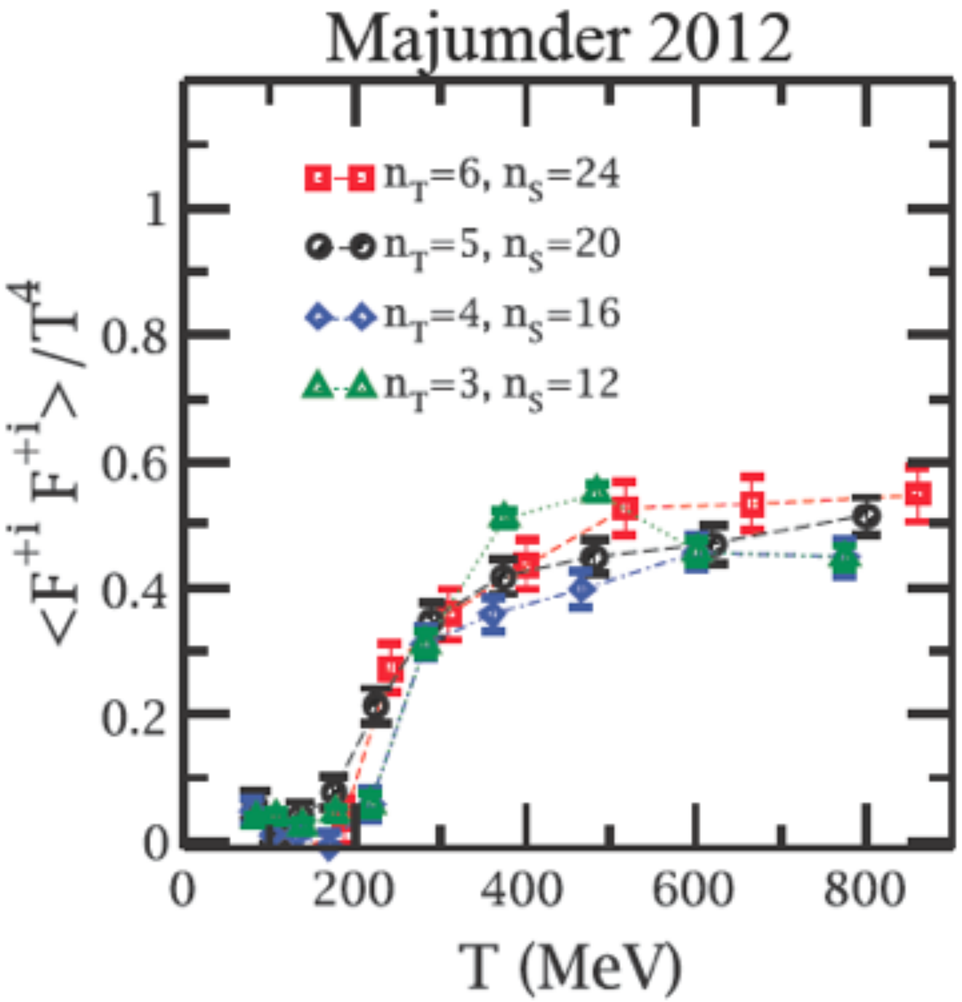
Deng & XNW (2010)

$$\hat{q}_N \approx 0.02\ \mathrm{GeV}^2/\mathrm{fm}$$

q-hat

Chen, Greiner, Wang, XNW, Xu （2010）

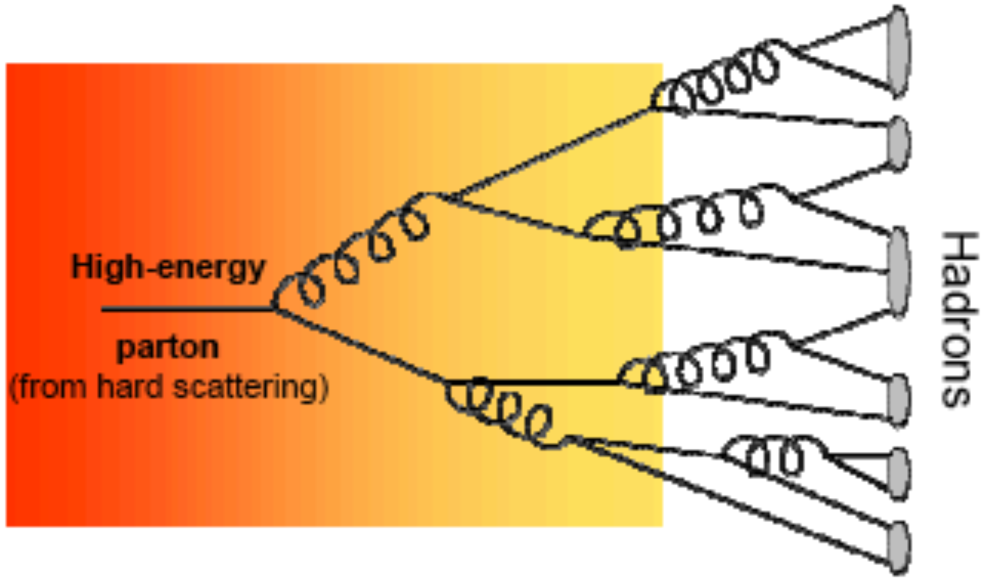



Majumder 2012

30% quenching from
hadronic phase

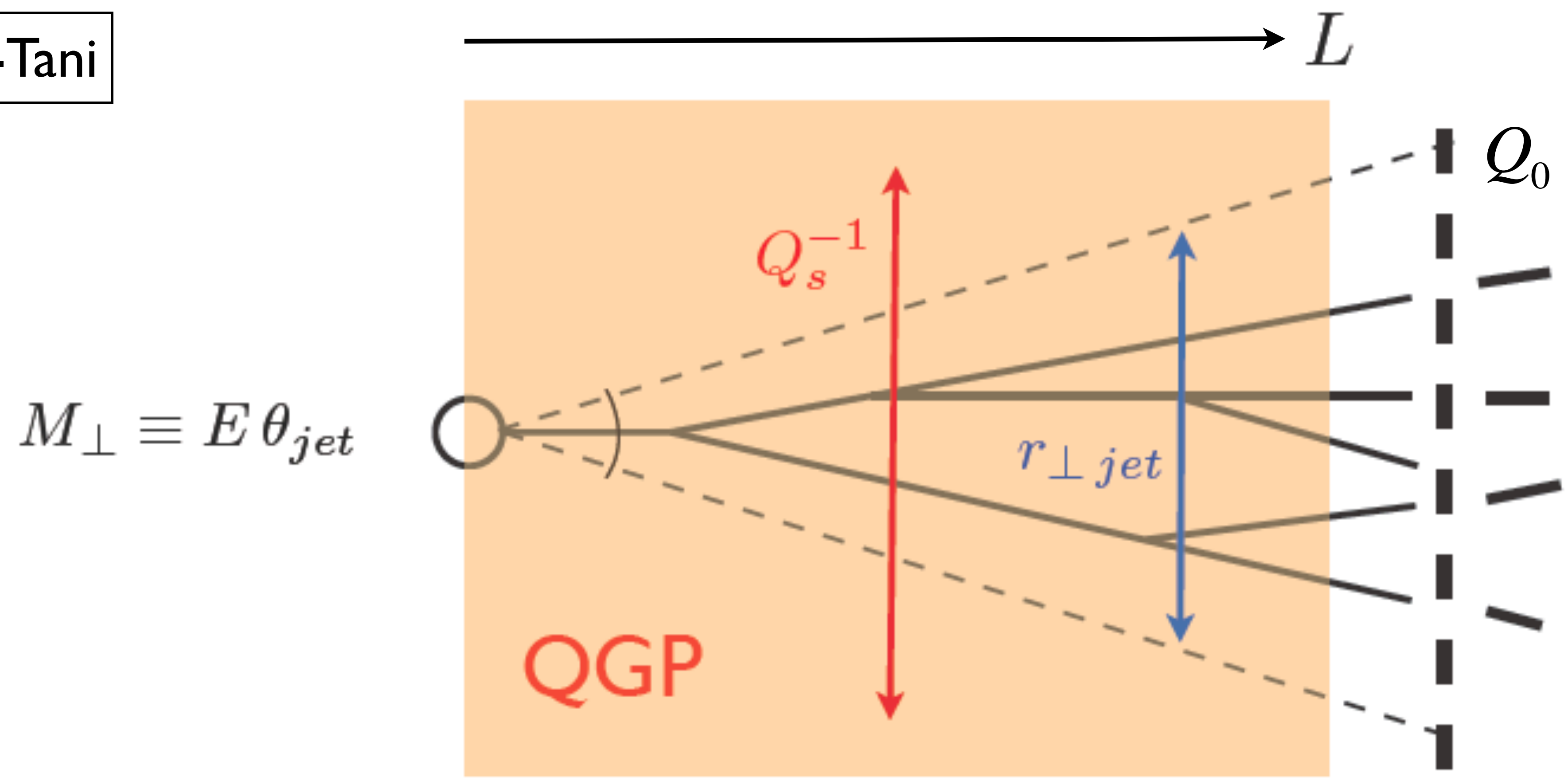
$$\hat{q} = \int dx^- \left\langle F_i^{+}(x^-)F^{+i}(0) \right\rangle$$

- **Understand production rates**
- **Understand parton energy loss process**
  - Energy loss as a function of density
  - Path length dependence
    - Elastic, radiative, synchrotron?
  - Interplay between vacuum and medium radiation
  - Broadening of shower:
    - Out-of-cone radiation
  - Leading hadron vs softening of FF
- **Use as a probe to determine medium density (and other properties)**



Jets in the medium

Mehtar-Tani

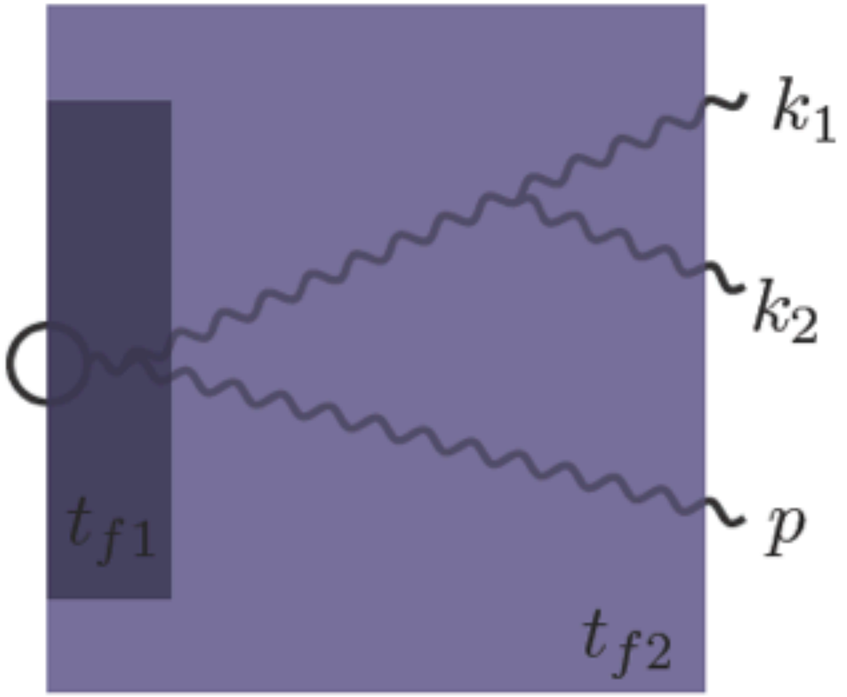


Momentum scale of medium $Q_s = \sqrt{qL} \approx m_D\sqrt{N_{\text{scatt}}}$

Transverse size of jet $r_{\perp\text{jet}} = \theta_{\text{jet}} L$

Leading log branching

FACTORIZATION OF BRANCHINGS IN VACUUM



$$\omega_2 \ll \omega_1 \ll E$$

$$\frac{E}{(p+k_1+k_2)^2} \sim \frac{E}{2p\cdot k_1} \sim \frac{\omega_1}{k_{1\perp}^2}$$

$$\frac{\omega}{(k_1+k_2)^2} \sim \frac{\omega_1}{2k_1\cdot k_2} \sim \frac{\omega_2}{k_{2\perp}^2}$$

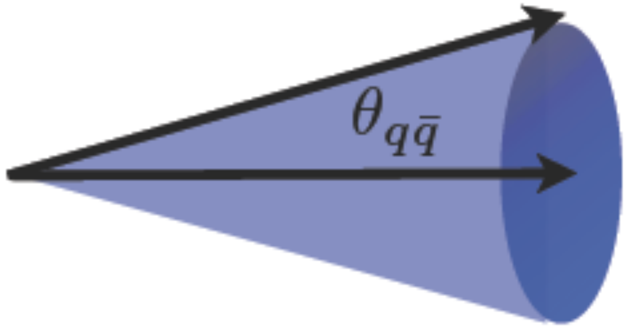
Logarithmic regions $t_{f2} \gg t_{f1}$

The softest gluon sees its parent as if they were produced at t=0

$$P_{12} = \left(\frac{\alpha_s C_A}{\pi}\right)^2 \int^E \frac{d\omega_1}{\omega_1} \int^{\omega_1} \frac{d\omega_2}{\omega_2} \int^{M_\perp} \frac{d^2k_{\perp 1}}{k_{\perp 1}^2} \int^{k_{\perp 1}} \frac{d^2k_{\perp 2}}{k_{\perp 2}^2}$$

Coherence

$$dN^{\mathrm{vac}}_{q,\gamma^*} = \frac{\alpha_s C_F}{\pi}\,\frac{d\omega}{\omega}\,\frac{\sin\theta\; d\theta}{1-\cos\theta}\,\Theta(\cos\theta - \cos\theta_{q\bar{q}}),$$



Angular ordering in vacuum: $\lambda_\perp \sim \frac{1}{k_\perp} < r_\perp \sim \tau_f \theta_{q\bar{q}} \sim \frac{\omega}{k_\perp^2}\theta_{q\bar{q}} \quad \Rightarrow \quad \theta < \theta_{q\bar{q}}$

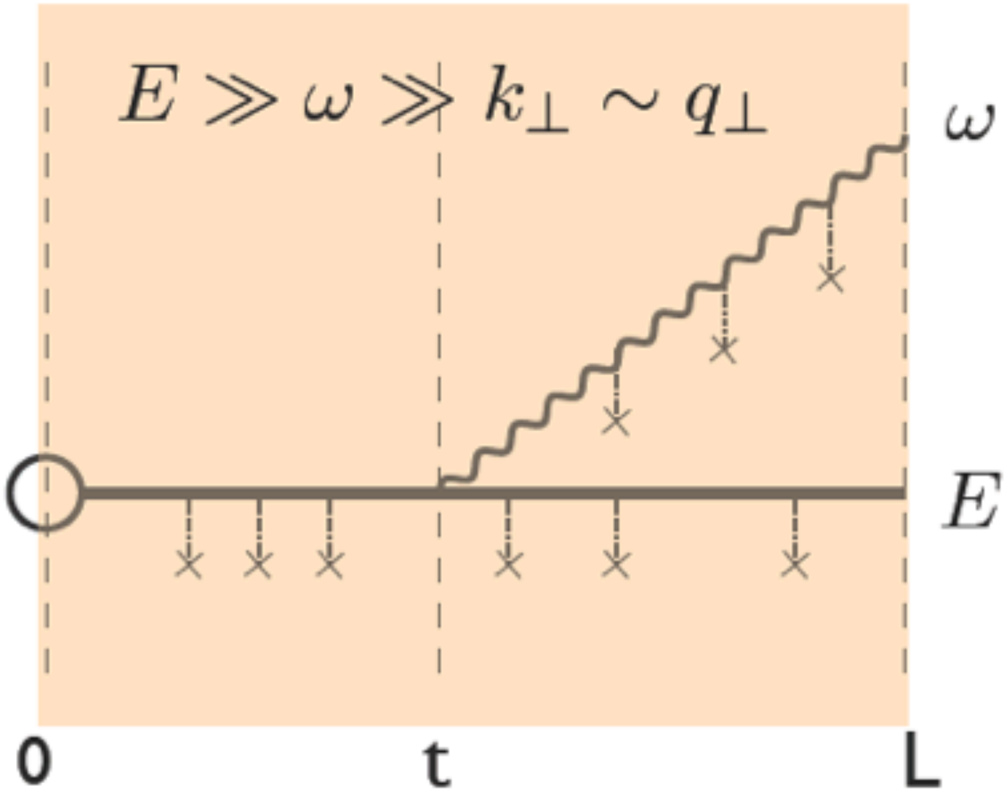
Recall DGLAP (no-angular ordering)

$$\frac{d}{d\ln M_\perp} D_A^B(x, M_\perp) = \frac{\alpha_s}{2\pi}\int_x^1 \frac{dz}{z} P_A^C(z)\, D_C^B(x/z, {\color{red} M_\perp})$$

MLLA (angular ordering)

$$\frac{d}{d\ln M_\perp} D_A^B(x, M_\perp) = \frac{\alpha_s}{2\pi}\int_x^1 \frac{dz}{z} P_A^C(z)\, D_C^B(x/z, {\color{red} z\, M_\perp})$$

In-medium radiative energy loss of hard partons



quark eikonal trajectory

$$U(0_\perp, t) = \mathcal{P}\exp\left[ig\int_0^t d\xi\, A^-(\xi, 0_\perp)\right]$$

Gluon prop. : Brownian motion in transverse plane

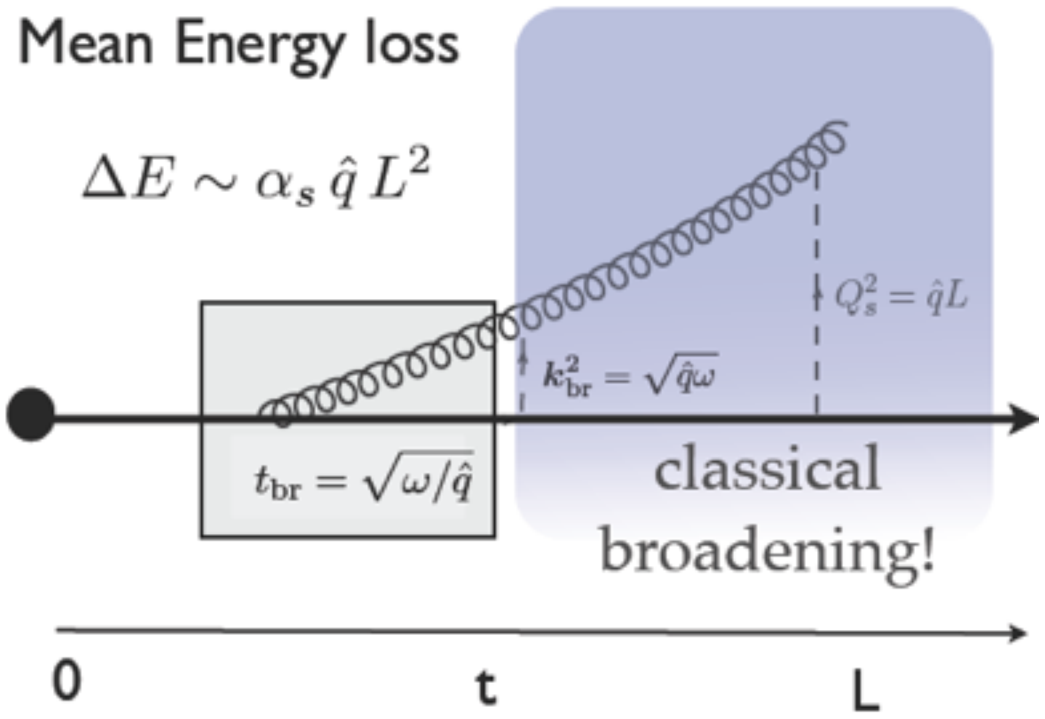
$$\mathcal{G}\left(x^+, \boldsymbol{x}; y^+, \boldsymbol{y}|k^+\right) = \int \mathcal{D}[\boldsymbol{r}]\, \exp\left[i\frac{k^+}{2}\int_{y^+}^{x^+} d\xi\, \dot{\boldsymbol{r}}^2(\xi)\right] U(x^+, y^+; [\boldsymbol{r}])$$

BDMPS-Z: Single emission

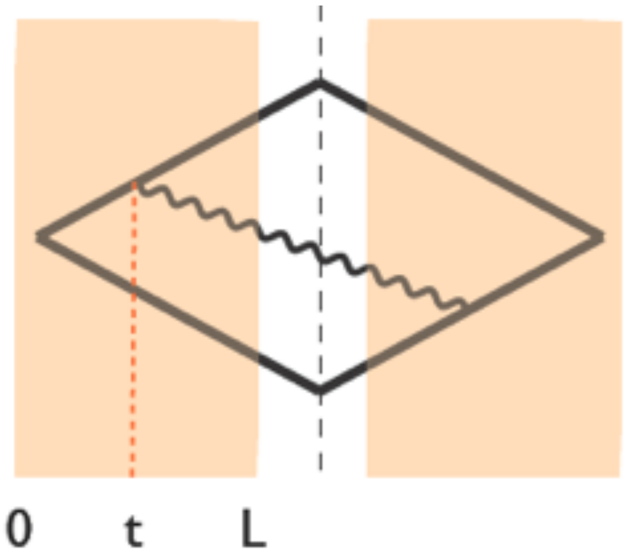
$$\omega \frac{dN}{d\omega} = \frac{C_F \alpha_s}{\pi} \sqrt{\frac{\hat{q} L^2}{\omega}} \propto \alpha_s \frac{L}{t_{\rm br}}$$

Mean Energy loss

$$\Delta E \sim \alpha_s \, \hat{q} \, L^2$$



Color coherence



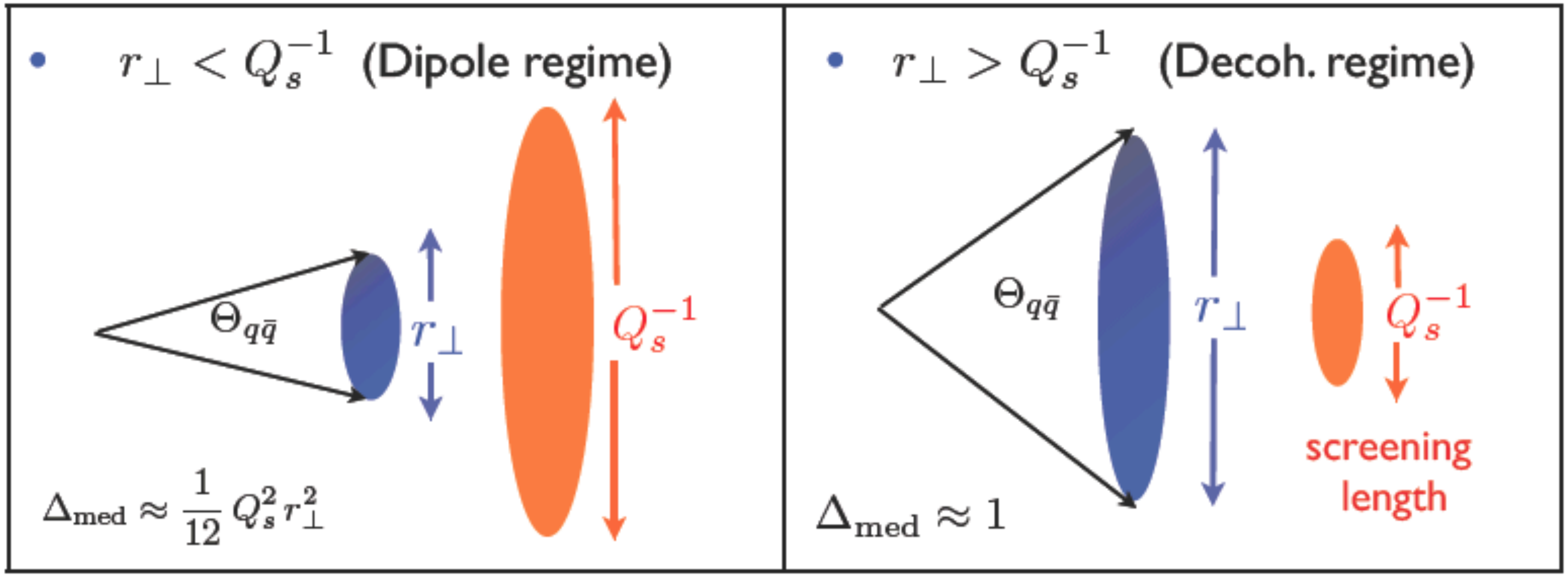
Decoherence parameter

$$\Delta_{\rm med} \approx 1 - \exp[-\frac{1}{12} Q_s^2 \, r_\perp^2]$$

$\Delta_{\rm med} \rightarrow 0$ Coherence

$\Delta_{\rm med} \rightarrow 1$ Decoherence

$Q_s^2 = \hat{q}\, L$ $\quad r_\perp = \theta_{q\bar{q}}\, L$ - a two scale problem!



- $r_\perp < Q_s^{-1}$ (Dipole regime)

$\Delta_{\rm med} \approx \frac{1}{12} Q_s^2 r_\perp^2$

- $r_\perp > Q_s^{-1}$ (Decoh. regime)

$\Delta_{\rm med} \approx 1$

Color transparency for $r_\perp < Q_s^{-1}$ or $\theta_{jet} < \theta_c \sim \dfrac{1}{\sqrt{\hat{q} L^3}}$

Decoherence $r_\perp > Q_s^{-1}$

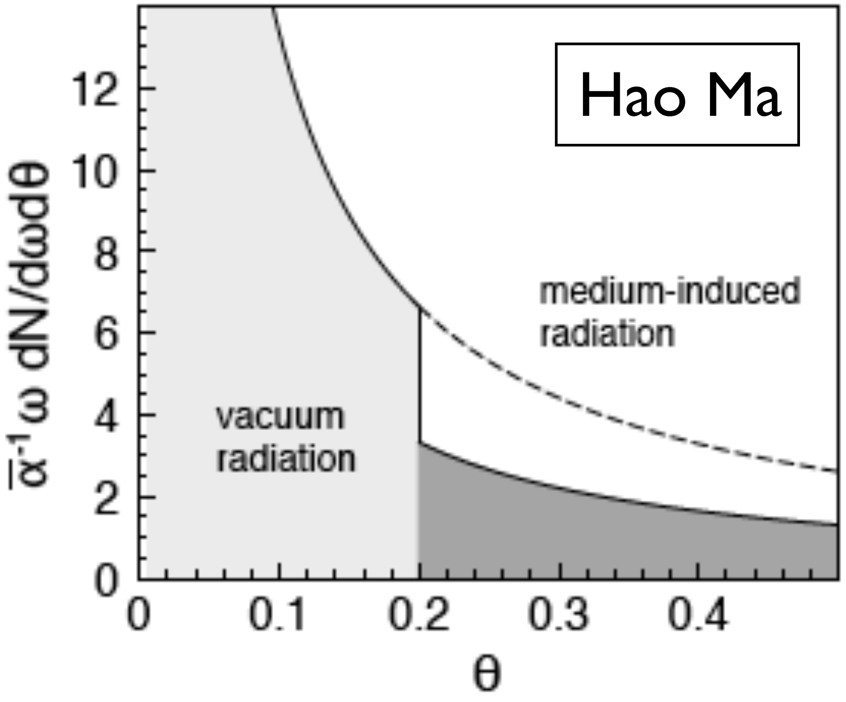
- The total spectrum in the soft gluon emission limit:

$$\omega\frac{dN^{\rm vac}}{d^3\vec{k}}+\omega\frac{dN^{\rm med}}{d^3\vec{k}}$$
$$=\frac{4\,\alpha_s\,C_F}{(2\,\pi)^2}\left[(1-\Delta)\left(\frac{1}{\boldsymbol{\kappa}^2}-\frac{\boldsymbol{\kappa}\cdot\bar{\boldsymbol{\kappa}}}{\boldsymbol{\kappa}^2\,\bar{\boldsymbol{\kappa}}^2}\right)+\frac{1}{\bar{\boldsymbol{\kappa}}^2}-(1-\Delta)\,\frac{\boldsymbol{\kappa}\cdot\bar{\boldsymbol{\kappa}}}{\boldsymbol{\kappa}^2\,\bar{\boldsymbol{\kappa}}^2}\right]$$

- In the opaque medium limit: $\Delta\to 1$

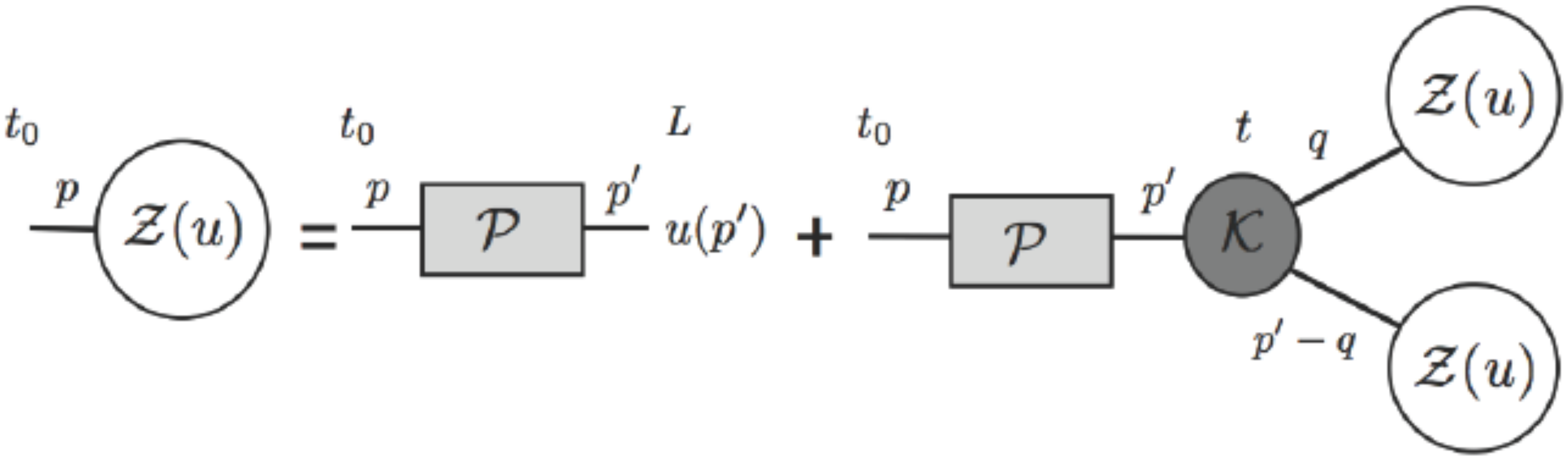
1. Saturation for incoming quark
2. Total decoherence for outgoing quark:

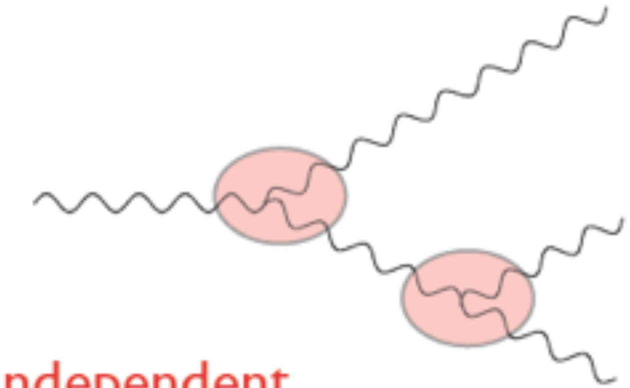
$$\omega\frac{dN^{\rm vac}}{d^3\vec{k}}+\omega\frac{dN^{\rm med}}{d^3\vec{k}}=\frac{4\,\alpha_s\,C_F}{(2\,\pi)^2}\,\frac{1}{\bar{\boldsymbol{\kappa}}^2}$$



Multiple radiation

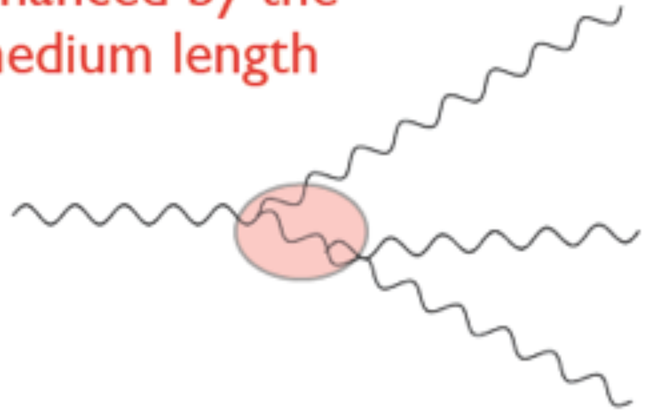
F. Dominguez





$$\sim \left(\alpha_s \frac{L}{t_f}\right)^2$$

Independent emissions are enhanced by the medium length



$$\sim \alpha_s^2 \frac{L}{t_f}$$

- Two-gluon production factorizes in the limit of short formation times
- Interferences are unimportant for soft emissions
- Full medium-induced branching process can be set in a suitable way for MC implementation (generating functional)

Scale matters

Virtuality Q^2 of the parton in the medium controls physics of radiative energy loss:

$$Q^2(L) \approx \max\left(\hat{q}\,L, \frac{E}{L}\right)$$

medium

vacuum

Weak coupling scenario

RHIC: 20 GeV parton, *L* = 3 fm

$$\hat{q}\,L \approx 1.5\,\mathrm{GeV}^2 \quad \approx \quad \frac{E}{L} \approx 1.5\,\mathrm{GeV}^2$$

Virtuality of primary parton is medium influenced and small enough to “experience” the strongly coupled medium

LHC: 200 GeV parton, *L* = 3 fm

$$\hat{q}\,L \approx 3.5\,\mathrm{GeV}^2 \quad < \quad \frac{E}{L} \approx 13\,\mathrm{GeV}^2$$

Virtuality of primary parton is vacuum dominated and only its gluon cloud “experiences” the strongly coupled medium

Three scales

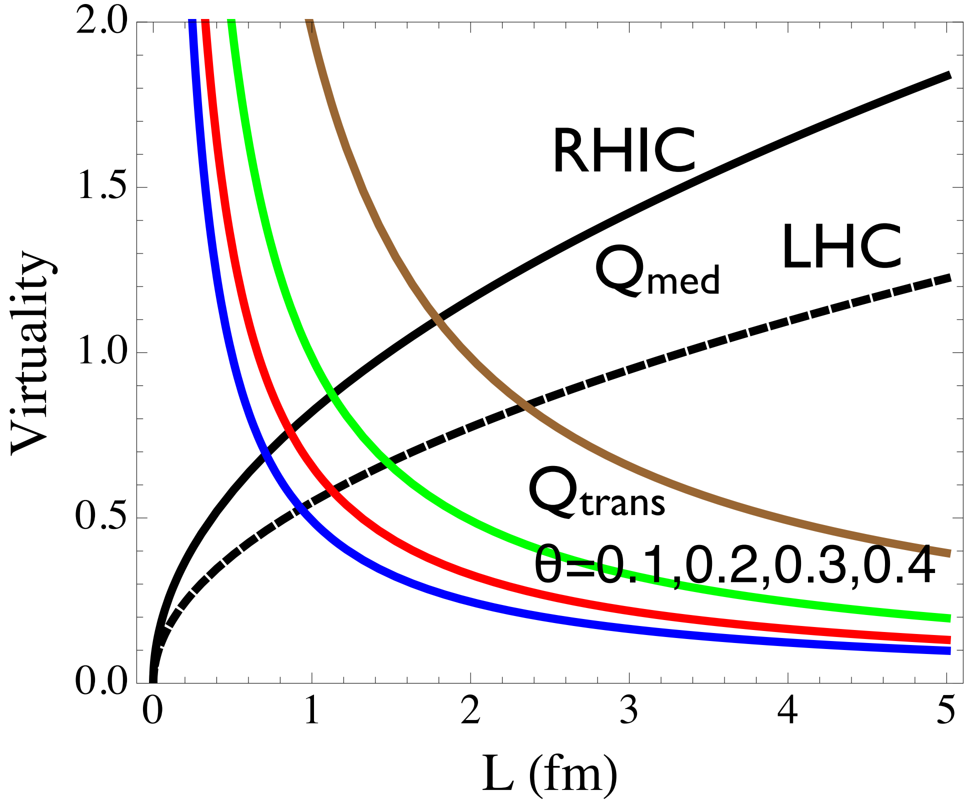
Intrinsic virtuality (uncertainty relation): $Q_{\text{int}} = \sqrt{\frac{z(1-z)E}{L}}$

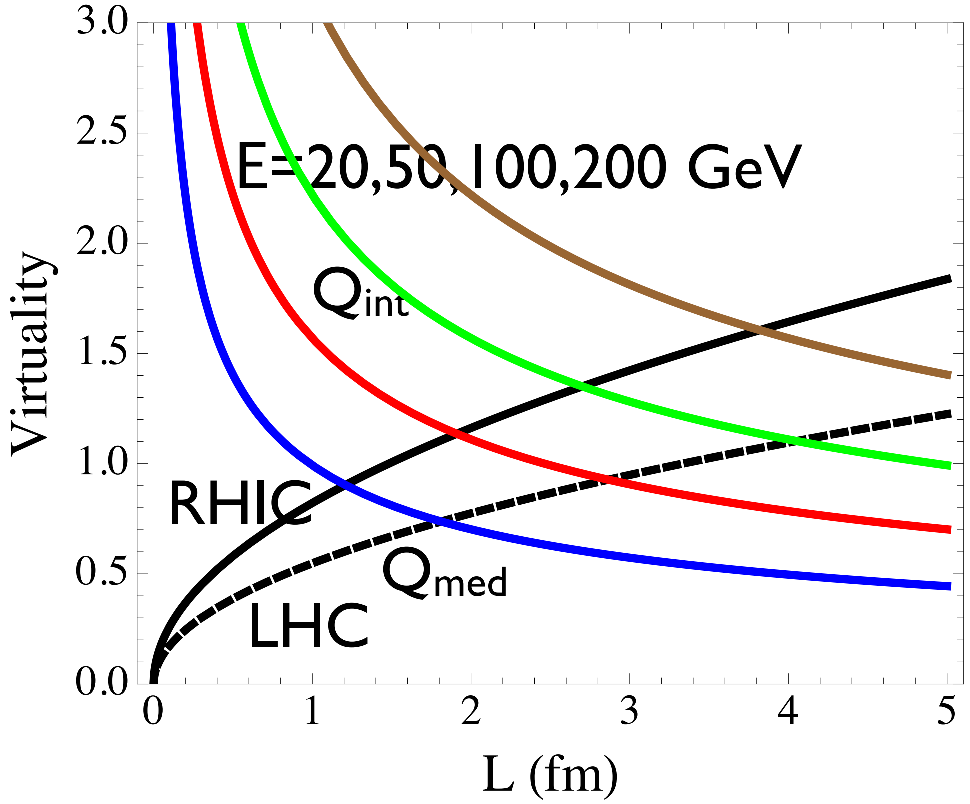
Virtuality of the medium: $Q_{\text{med}} = \sqrt{\hat{q}L}$

$\hat{q}_{\text{RHIC}} = 0.5 \text{ GeV/c}$

Scale of transverse jet size: $Q_{\text{trans}} = \frac{1}{\theta L}$

$\hat{q}_{\text{LHC}} = 2.3\hat{q}_{\text{RHIC}}$





HT formalism

$$\frac{\partial \tilde{D}_q^h(z_h,\mu^2)}{\partial \ln \mu^2} = \frac{\alpha_s(\mu^2)}{2\pi}\int_{z_h}^1 \frac{dz}{z}\left[\tilde{\gamma}_{q\to qg}(z,\mu^2)\tilde{D}_q^h(\frac{z_h}{z},\mu^2) + \tilde{\gamma}_{q\to gq}(z,\mu^2)\tilde{D}_g^h(\frac{z_h}{z},\mu^2)\right]$$

$$\frac{\partial \tilde{D}_g^h(z_h,\mu^2)}{\partial \ln \mu^2} = \frac{\alpha_s(\mu^2)}{2\pi}\int_{z_h}^1 \frac{dz}{z}\left[\sum_{q=1}^{2n_f}\tilde{\gamma}_{g\to q\bar{q}}(z,\mu^2)\tilde{D}_q^h(\frac{z_h}{z},\mu^2) + \tilde{\gamma}_{g\to gg}(z,\mu^2)\tilde{D}_g^h(\frac{z_h}{z},\mu^2)\right]$$

Modified splitting functions

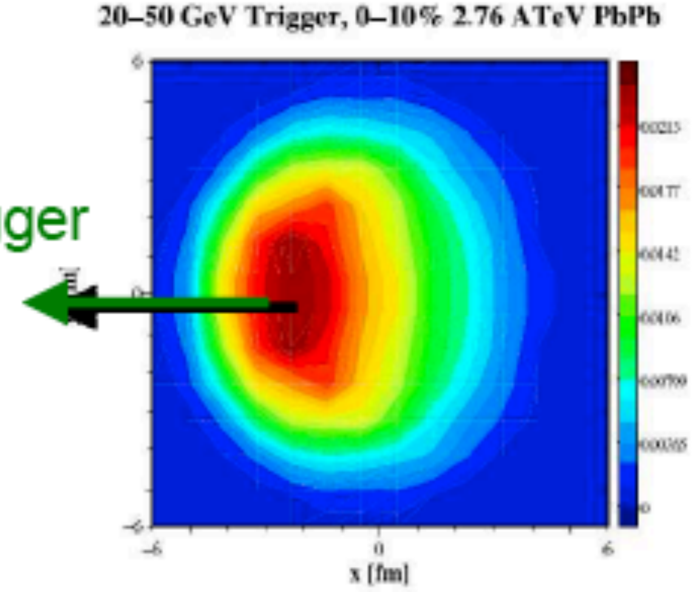
$$\tilde{\gamma}_{a\to bc}(z,l_T^2) = \gamma_{a\to bc}(z) + \Delta\gamma_{a\to bc}(z,l_T^2)$$

Less trigger bias

Hadron trigger: strong “surface bias”

maximizes recoil path length

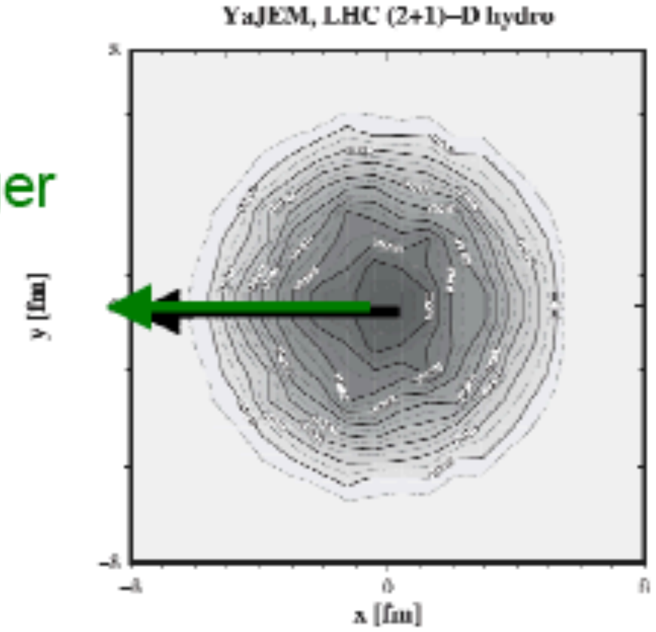
(T.Renk, private com.)



Hadron trigger

Full jet trigger: no geom. bias

partially cancelled by bkg fluctuations



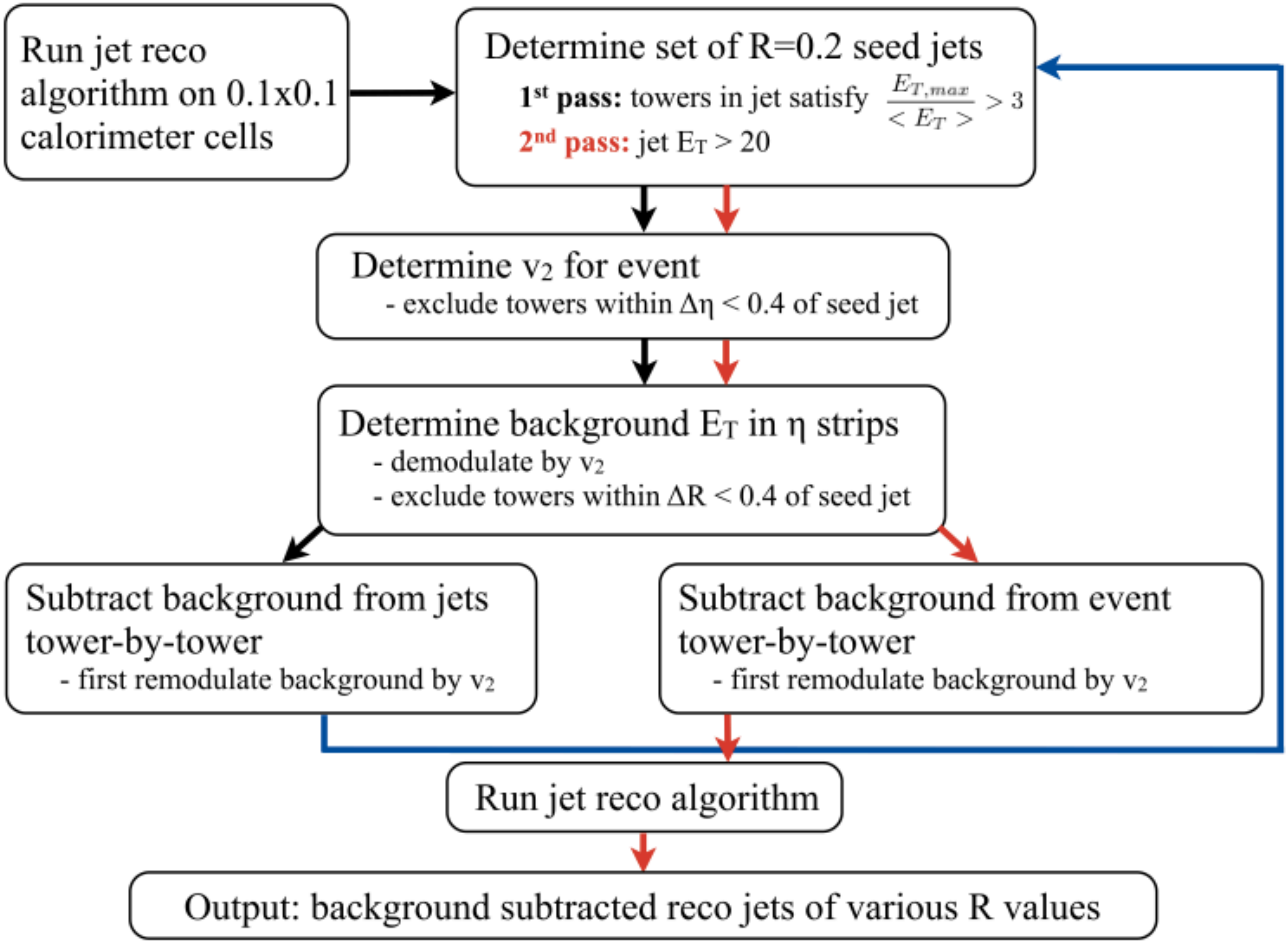
Jet trigger

T.Renk, PRC85 064908

Centrality and reaction plane biases:

- finite, but only weak trigger p_T dependence for high p_T^{trig}

UE subtraction (ATLAS)



Run jet reco algorithm on 0.1x0.1 calorimeter cells

Determine set of R=0.2 seed jets

1st pass: towers in jet satisfy $\frac{E_{T,max}}{< E_T >} > 3$

2nd pass: jet $E_T > 20$

Determine v_2 for event

- exclude towers within $\Delta\eta < 0.4$ of seed jet

Determine background E_T in η strips

- demodulate by v_2
- exclude towers within $\Delta R < 0.4$ of seed jet

Subtract background from jets tower-by-tower

- first remodulate background by v_2

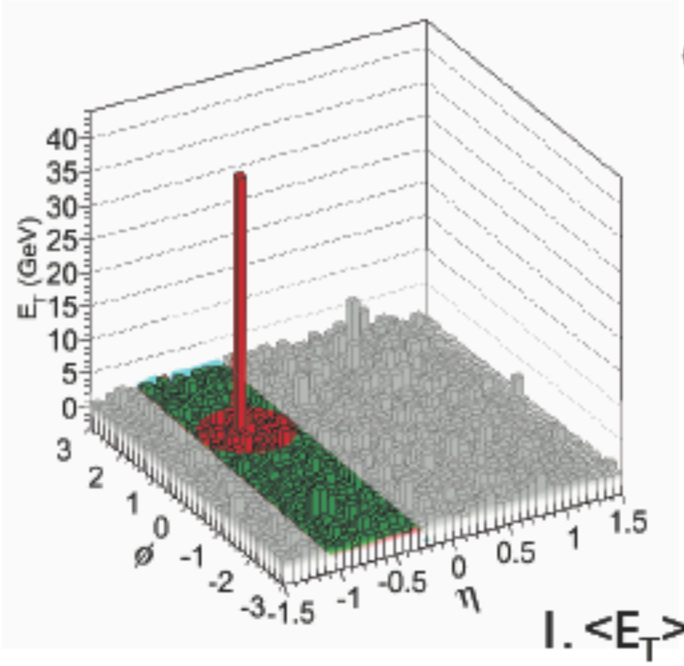
Subtract background from event tower-by-tower

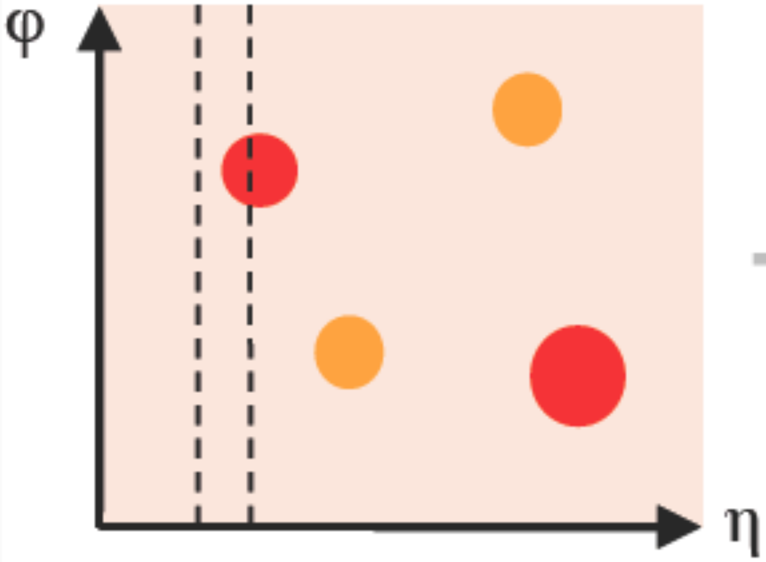
- first remodulate background by v_2

Run jet reco algorithm

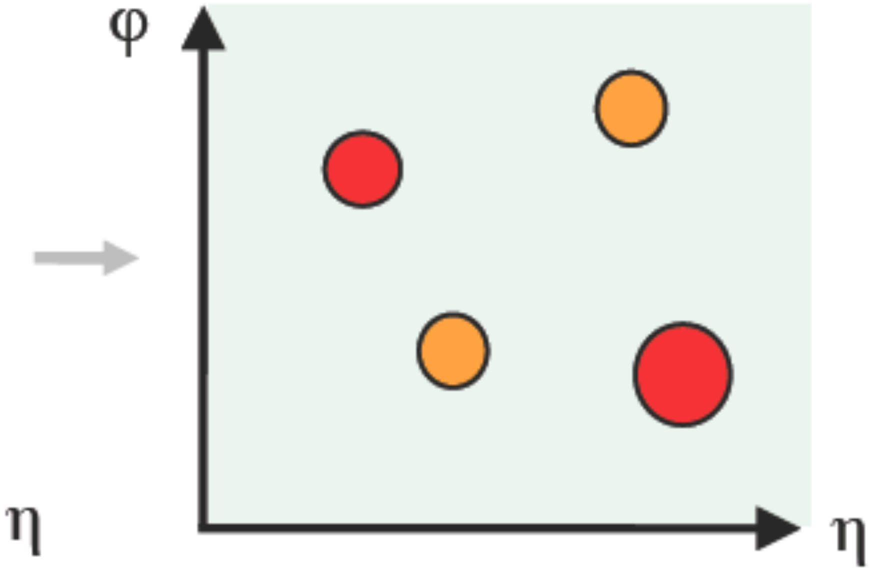
Output: background subtracted reco jets of various R values

UE subtraction (CMS)

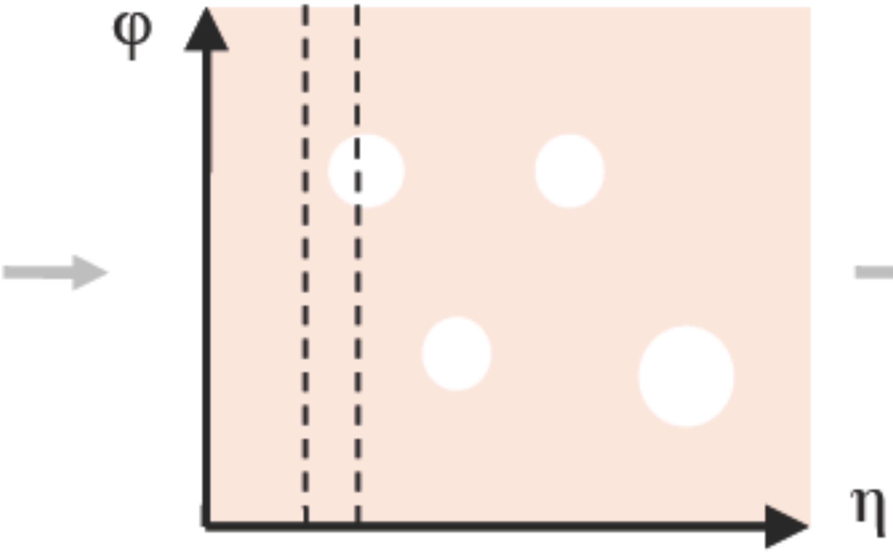




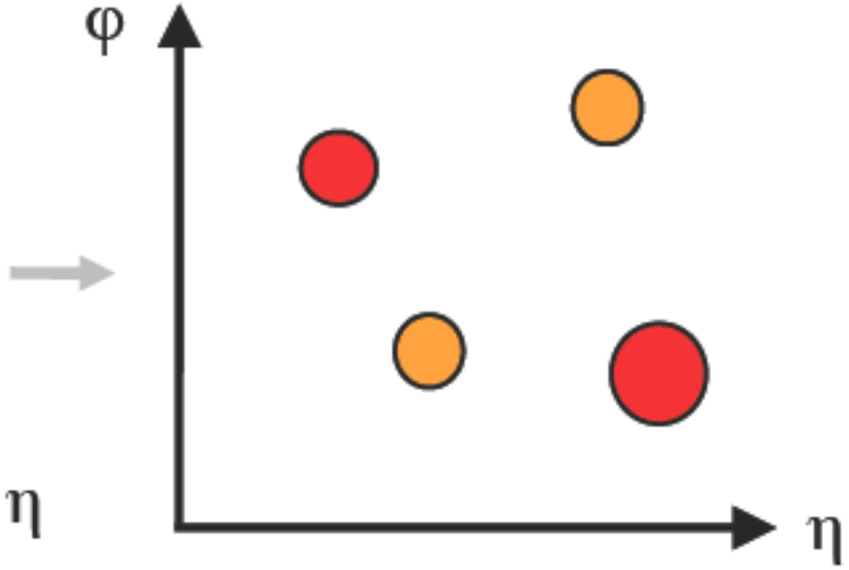
1. $\langle E_T \rangle$ calculated in strips of η. Subtract $\langle E_T \rangle + \sigma$



2. Run anti-k_T algorithm on background-subtracted towers



3. Exclude reconstructed jets and re-estimate background



4. Re-run anti-k_T algorithm to get final jets

For details see:
- CMS, arXiv:1102.1957
- Kodolova et al., EPJC 50 (2007) 117

Jet reconstruction

- Background (and fluctuations) subtraction techniques have become highly refined, but are also difficult to compare and evaluate. Would it be possible to move towards an at least partial standardisation?
- As an example, we propose a new moments-based approach to jet fragmentation functions that makes use of the same background subtraction technique one can use for inclusive jets, plus an observable-specific correction for fluctuations

$$M_N = \frac{1}{N_{jet}} \int_0^1 z^N \frac{dN_h}{dz}\, dz = \frac{1}{N_{jet}} \int_0^\infty e^{-N\xi} \frac{dN_h}{d\xi}\, d\xi$$

Cacciari

In practice, $M_N^{jet} = \frac{\sum_{i \in jet} p_{t,i}^N}{p_t^N}$ and averaging over many jets

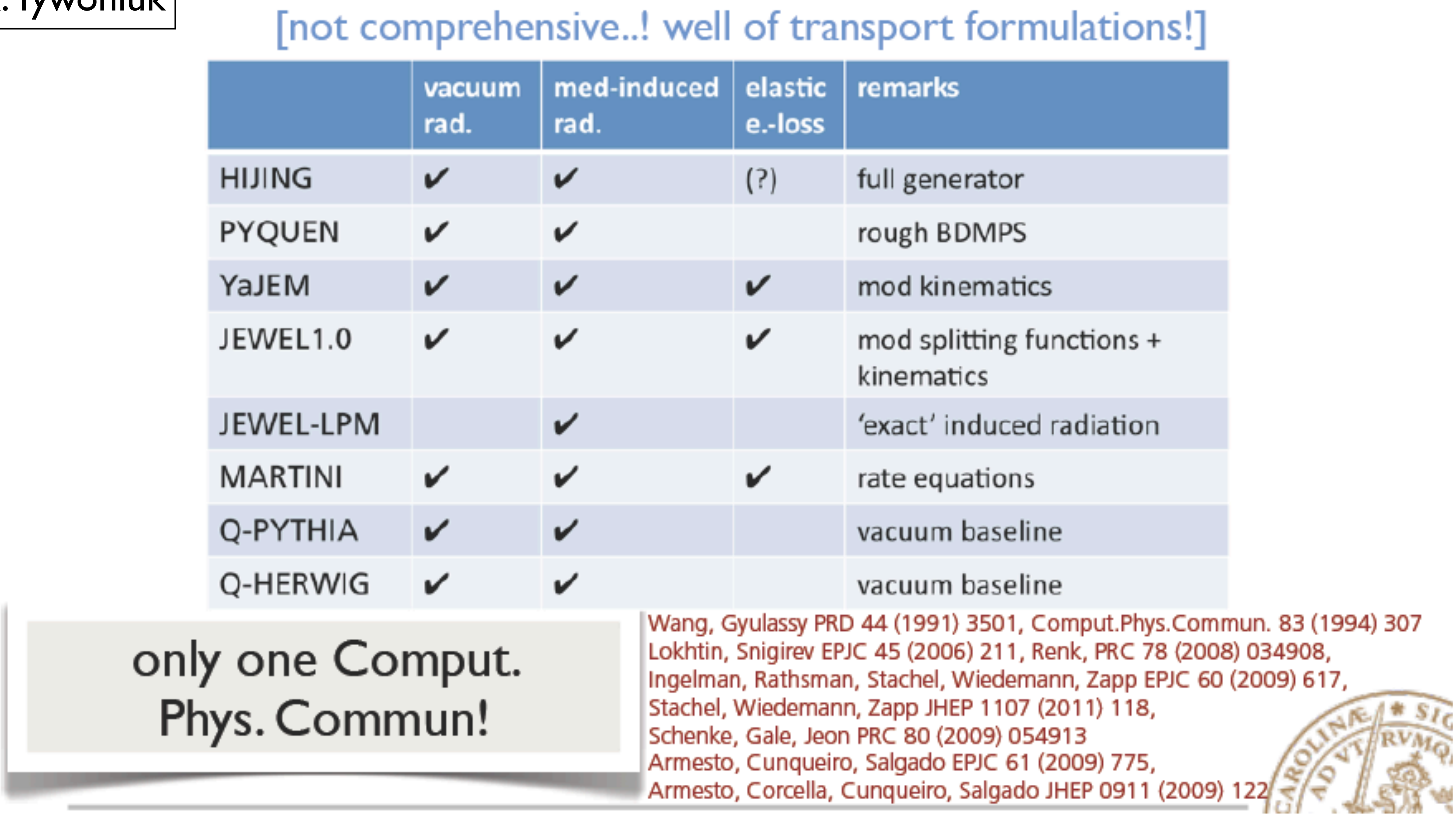
Potential role for JET Collaboration to develop “standard approach” ?

Jet observables proliferate

- Jet R_{AA} , R_{CP}
  - ☐ versus p_T, centrality, in-plane, out-of-plane
- Di-jet asymmetry
  - ☐ A_J, p_{T2}/p_{T1}
- γ-jet, Z-jet coincidences
- Jet “fragmentation” function $D(z \cdot p_{T,jet})$
  - ☐ Near side, away side
- γ-jet fragmentation function $D(z \cdot p_{T,\gamma})$
- Jet shape $E_T(\theta)$
- Jet chemistry
- Anything not yet thought of.....

Jet MC models

K. Tywoniuk

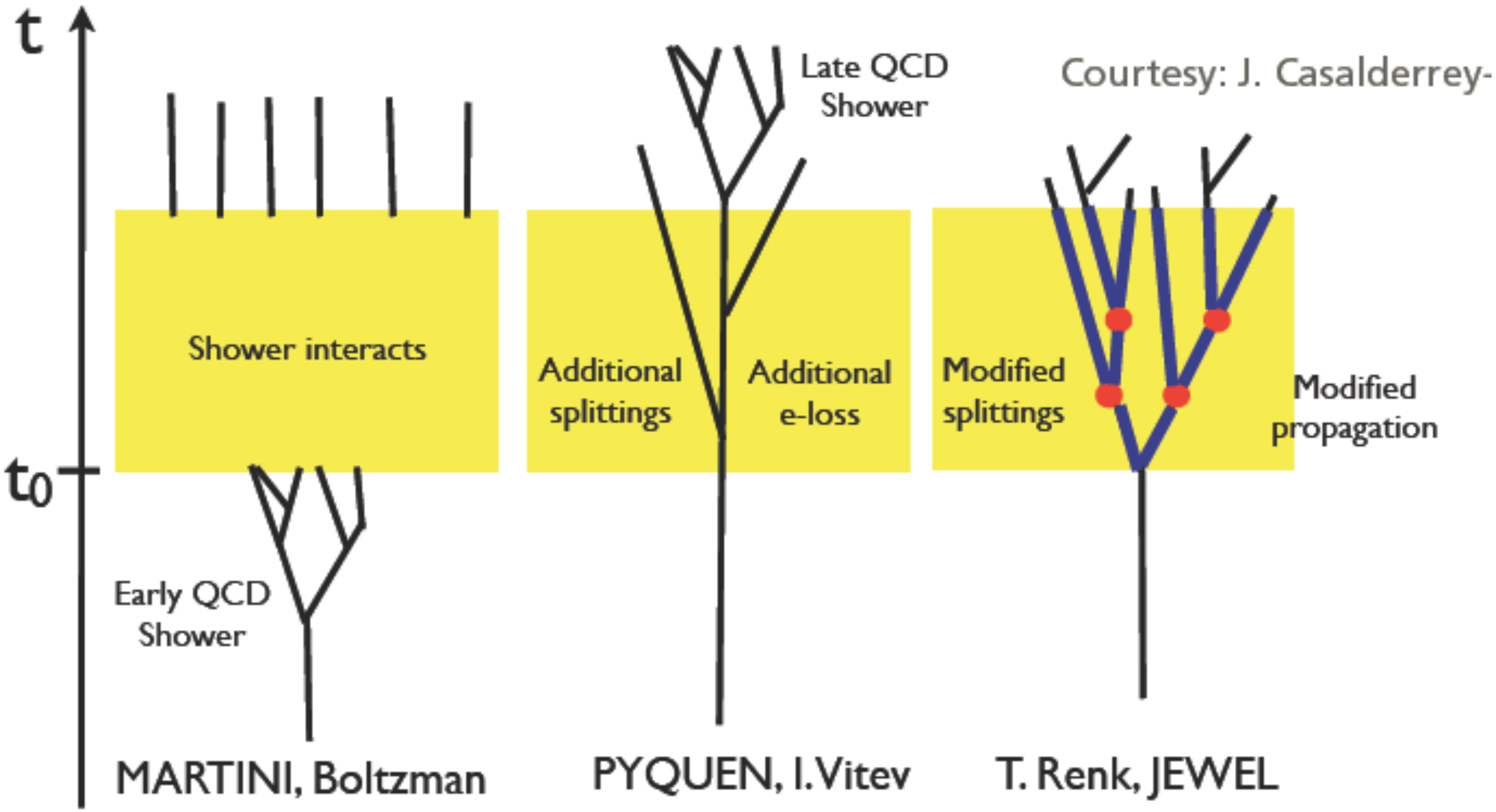


[not comprehensive..! well of transport formulations!]

	vacuum rad.	med-induced rad.	elastic e.-loss	remarks
HIJING	✔	✔	(?)	full generator
PYQUEN	✔	✔		rough BDMPS
YaJEM	✔	✔	✔	mod kinematics
JEWEL1.0	✔	✔	✔	mod splitting functions + kinematics
JEWEL-LPM		✔		'exact' induced radiation
MARTINI	✔	✔	✔	rate equations
Q-PYTHIA	✔	✔		vacuum baseline
Q-HERWIG	✔	✔		vacuum baseline

only one Comput. Phys. Commun!

Wang, Gyulassy PRD 44 (1991) 3501, Comput.Phys.Commun. 83 (1994) 307
Lokhtin, Snigirev EPJC 45 (2006) 211, Renk, PRC 78 (2008) 034908,
Ingelman, Rathsman, Stachel, Wiedemann, Zapp EPJC 60 (2009) 617,
Stachel, Wiedemann, Zapp JHEP 1107 (2011) 118,
Schenke, Gale, Jeon PRC 80 (2009) 054913
Armesto, Cunqueiro, Salgado EPJC 61 (2009) 775,
Armesto, Corcella, Cunqueiro, Salgado JHEP 0911 (2009) 122



t

t_0

Courtesy: J. Casalderrey-

Shower interacts

Early QCD Shower

Additional splittings

Additional e-loss

Late QCD Shower

Modified splittings

Modified propagation

MARTINI, Boltzman

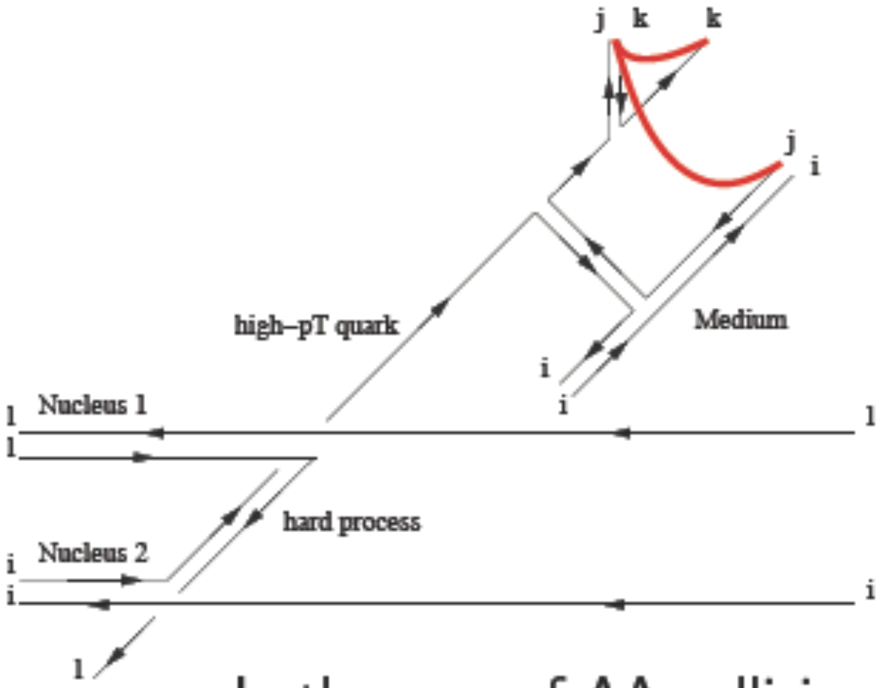
PYQUEN, I.Vitev

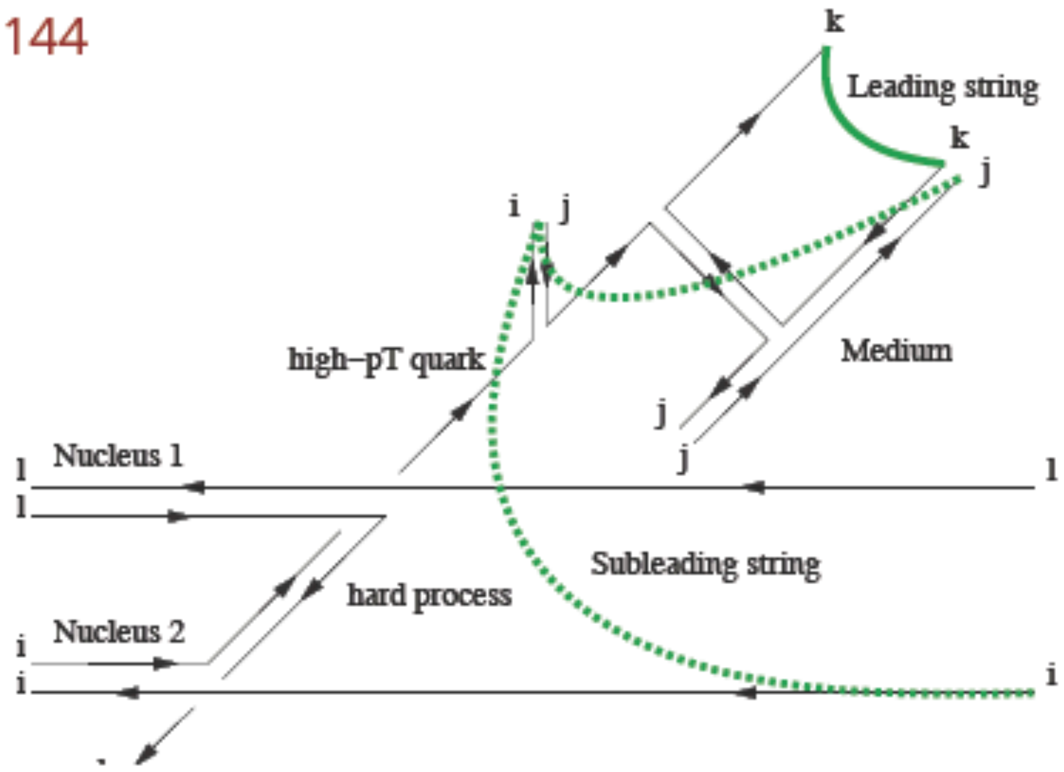
T. Renk, JEWEL

Is it reasonable to assume a separation of these processes?

Hadronization

Beraudo, Milhano, Wiedemann JHEP 1207 (2012) 144





In the case of AA collisions a naive convolution

$$\text{Parton Energy loss} \otimes \text{Vacuum Fragmentation}$$

without accounting for the modified color-flow would result into a too hard hadron spectrum: fitting the experimental amount of quenching would require an overestimate of the energy loss at the partonic level;

Andrea Beraudo, Hard Probes 2012

- The following theoretical problem appears at present to have *unsolved* status:

S. Caron-Huot

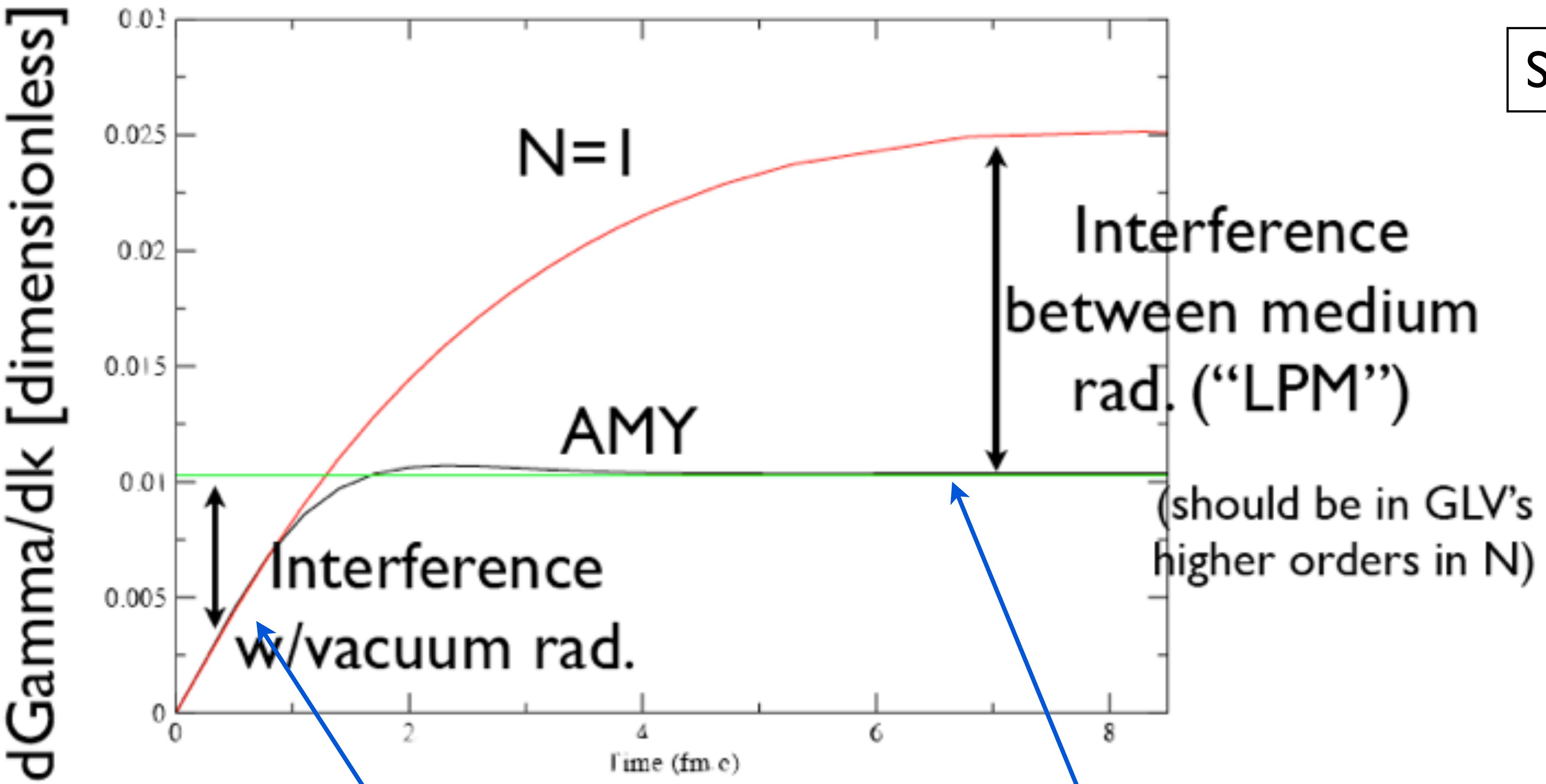
"Find a modification of vacuum jet shower, such that all:

-collinear logarithms $\alpha_s \log Q^2$ (DGLAP `71)
-soft logarithms $\alpha_s \log z$ (angle-ordered parton showers, 80's)
-length-enhanced effects $\alpha_s L/\ell_{\rm mfp}$
are resummed."

- I would argue it's a well-defined problem, thus having a unique and well-defined solution.

Interference

S. Caron-Huot



Interference between medium rad. ("LPM")

(should be in GLV's higher orders in N)

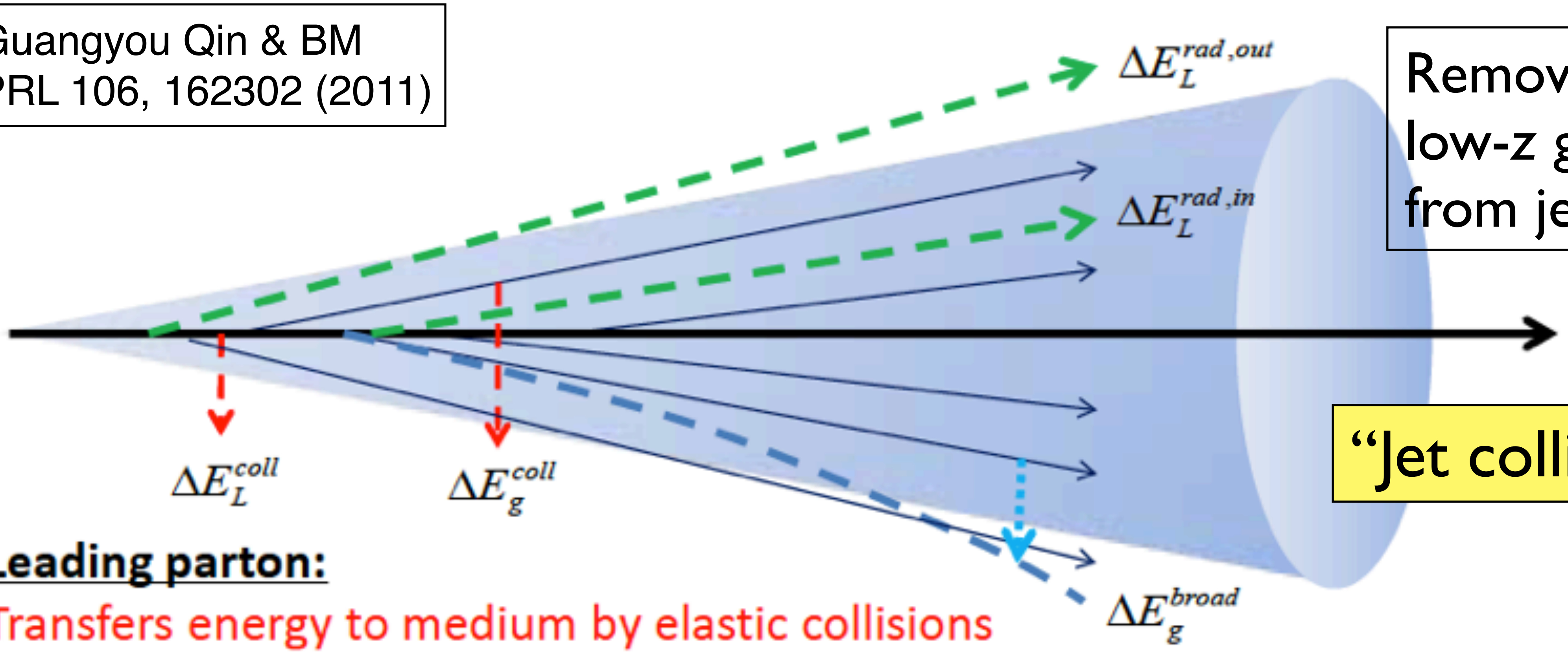
Interference w/vacuum rad.

Need two transport coefficients!

$$v(x_\perp) \quad \sim \quad C_1 x_\perp^2 \log(\mu_0^2 x_\perp^2) + \frac{1}{4} x_\perp^2 \hat{q}(\mu_0) + O(x_\perp^4)$$

Parton shower in matter

Guangyou Qin & BM
PRL 106, 162302 (2011)



Removes mostly low-z gluons from jet cone

“Jet collimation”

Leading parton:

Transfers energy to medium by elastic collisions

Radiates gluons scattering in the medium (*inside* and *outside* jet cone)

$$E_L(t) = E_L(t_i) - \int \hat{e}_L dt - \int \omega d\omega dk_\perp^2 dt \frac{dN_g^{med}}{d\omega dk_\perp^2 dt}$$

Radiated gluons (*vacuum* & *medium-induced*):

Transfer energy to medium by elastic collisions

Be kicked out of the jet cone by multiple scatterings after emission

$$\frac{df_g(\omega, k_\perp^2, t)}{dt} = \hat{e}\frac{\partial f_g}{\partial \omega} + \frac{1}{4}\hat{q}\nabla_{k_\perp}^2 f_g + \frac{dN_g^{med}}{d\omega dk_\perp^2 dt}$$

Boltzmann transport

LPM modified gluon radiation:

$$\frac{dN_g}{dz d\ell_\perp^2 dL} = \frac{C_A \alpha_s}{\pi} P(z) \frac{1}{\ell_\perp^4} \hat{q}(L)(1 - \cos(L/\tau_f))$$

Linearized Boltzmann transport (XN Wang et al.)

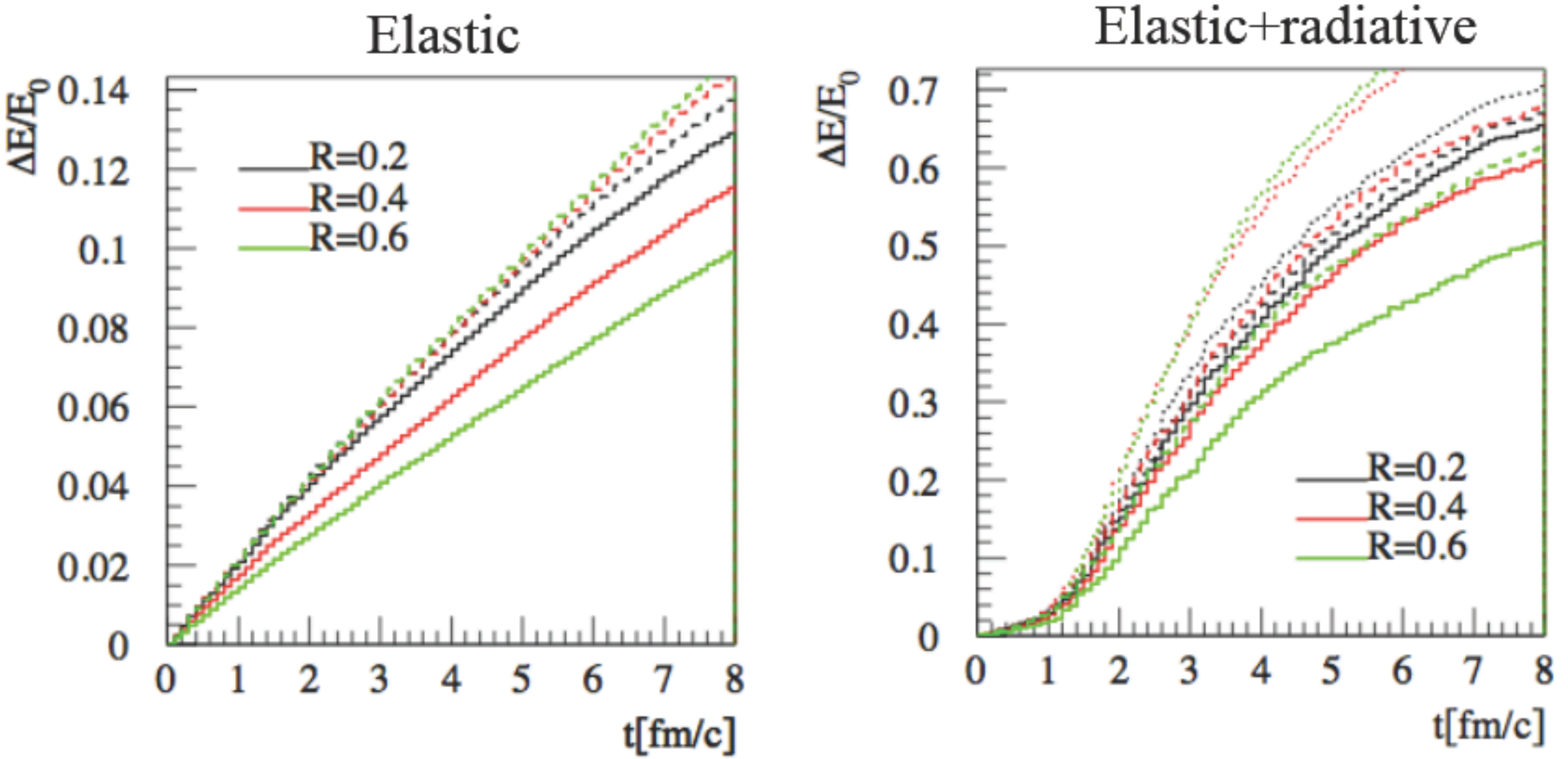
Nonlinear Boltzmann transport using VNI/BMS parton cascade (C. Coleman-Smith)

Allows for simulations of time-dependent energy deposition accounting for both, collisional (elastic) and radiative (inelastic) energy loss.

It would be useful to compare the predictions of the two codes in detail for standardized cases. Do they agree?

Energy loss

Gamma-jet: E_γ=60 GeV in uniform medium at T=300 MeV



Solid: jet+medium
Dashed: jet

Solid: jet+radiatied+medium
Dashed: jet+radiated
Dotted: jet

AMY formalism

C. Young

The evolution of partons in-medium is determined by an *integral* equation:

$$\frac{dP(E)}{dt} = \int d\omega \left[P(E+\omega)\frac{d\Gamma(E+\omega,E)}{d\omega} - P(E)\frac{d\Gamma(E,E+\omega)}{d\omega} \right]$$

MARTINI (Schenke et al. 2009) solves for the inclusive

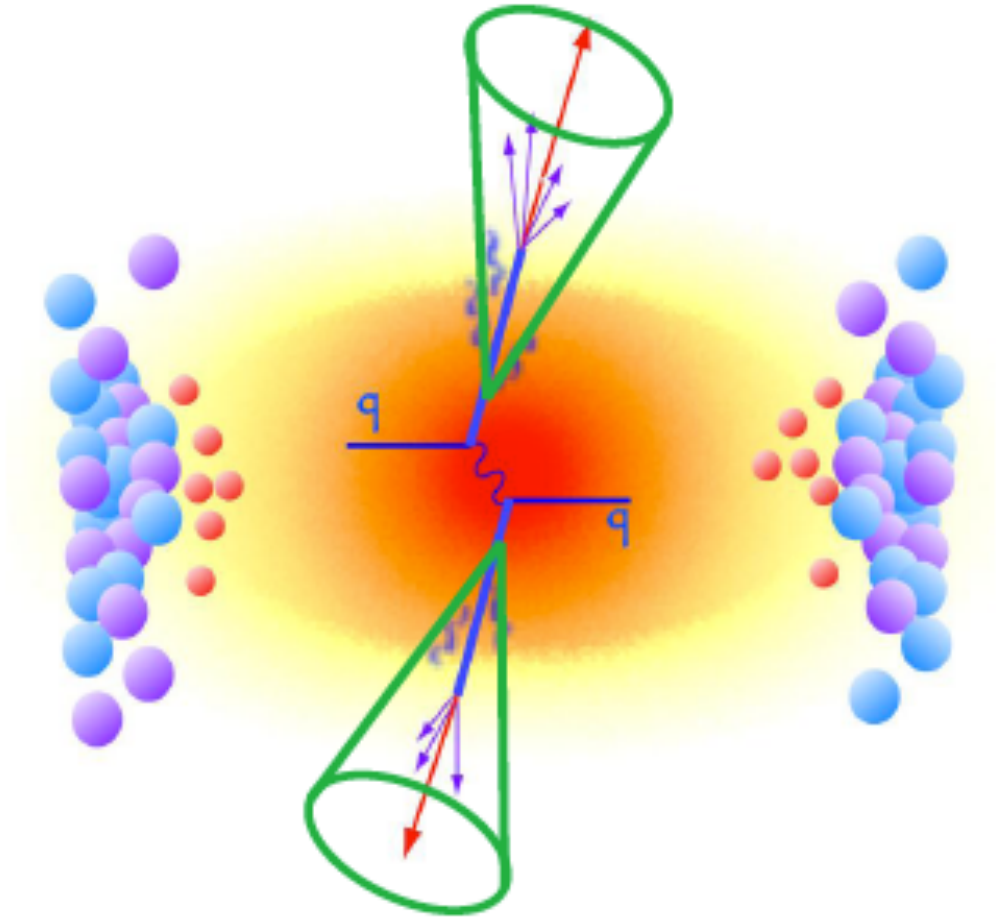
$$\begin{aligned} d\sigma_{AA\to h} &= \sum_{i,j}\int d\mathbf{b}\; dx_1\; dx_2\; f^i_{A_1}(x_1,Q^2) f^j_{A_2}(x_2,Q^2) d\sigma_{ij\to kl} \\ &\quad \times P(k,l|m,n;u^\mu,T) D_m D_n \end{aligned}$$

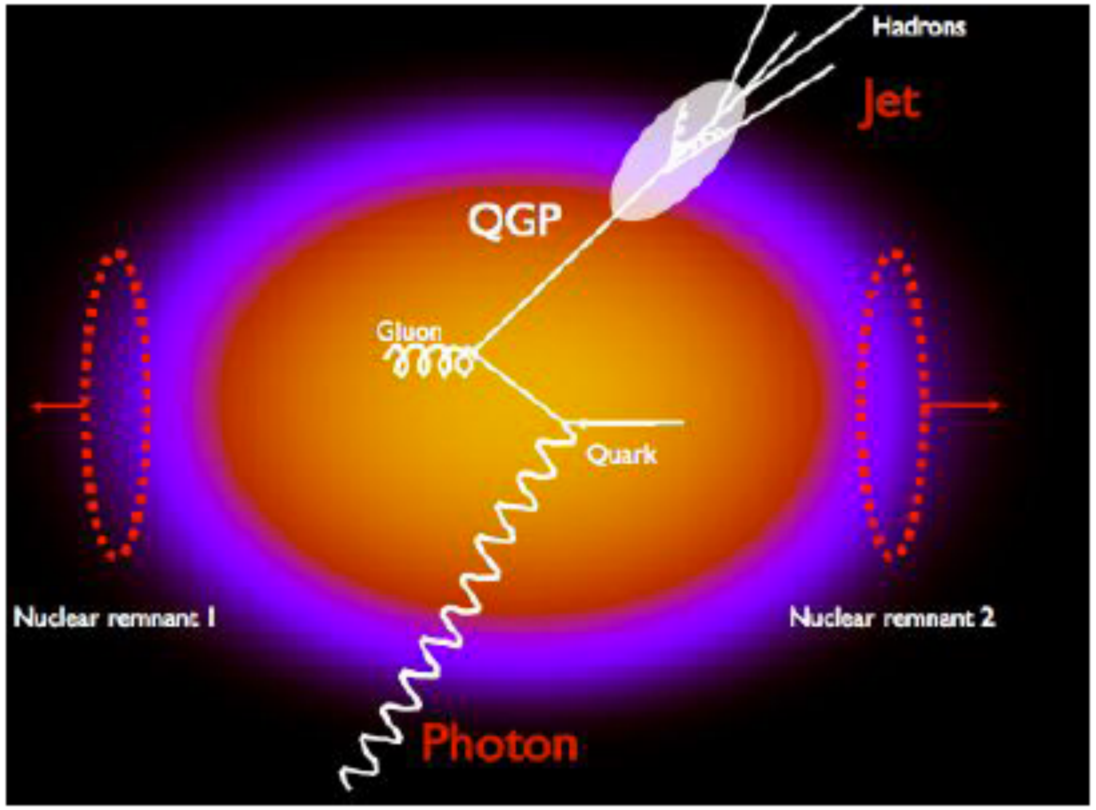
using event generation and Monte Carlo:

- Shadowing and anti-shadowing of pdf's, averaging over isospin
- PYTHIA8 for multiple final states via parton showering
- Monte Carlo for solving the elastic and inelastic rate equations, informed by the 3+1-dimensional hydrodynamical evolution calculated by MUSIC (Schenke et al. 2009)
- Hadronization via the Lund string model, *including* color flow in splittings
- Jet reconstruction via FASTJET, an anti-k_T algorithm

Fragmentation functions

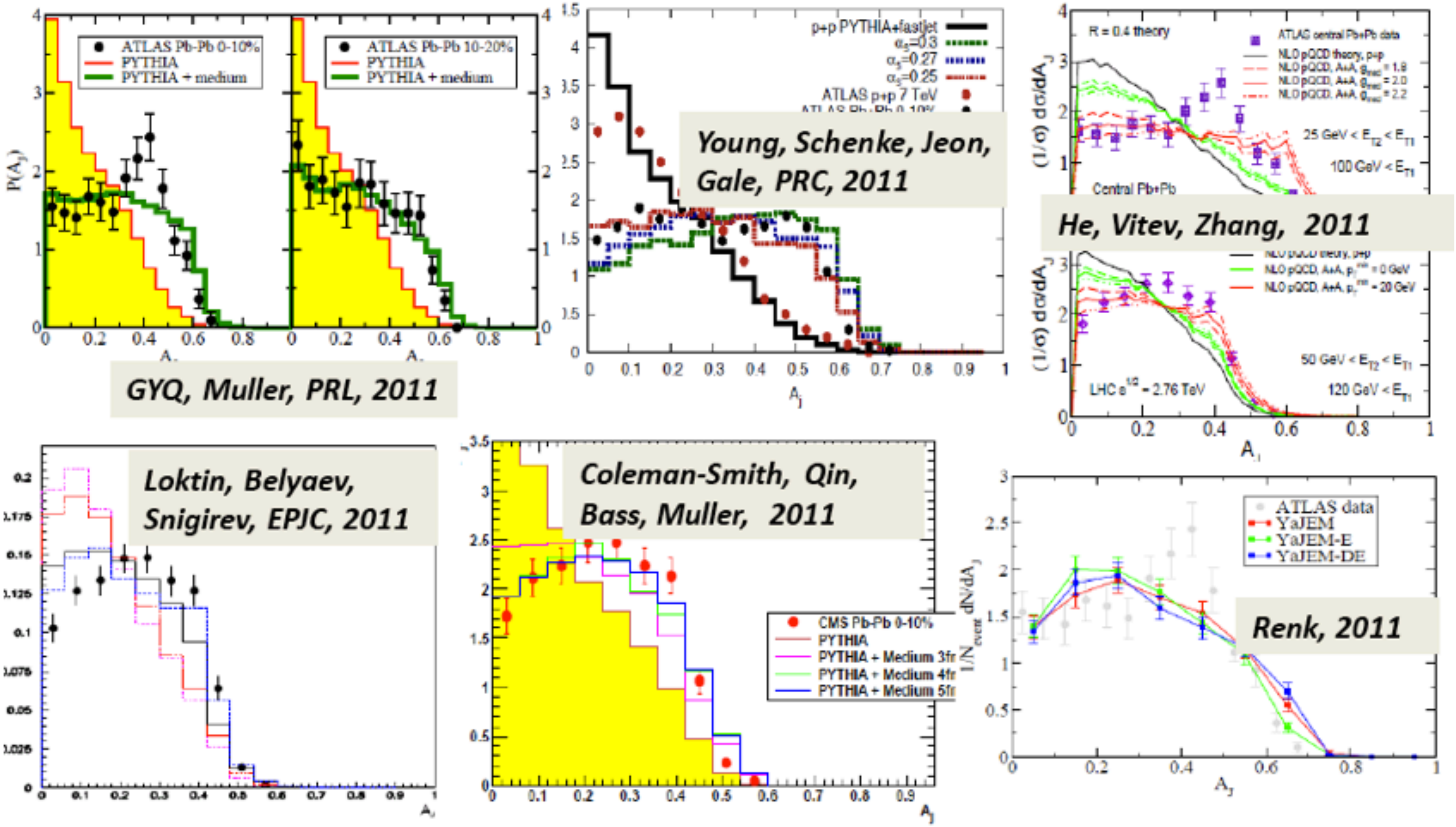
Di-jets versus Photon (Z) triggered jets





A_J is “easy”

Theory postdictions for dijet asymmetry



GYQ, Muller, PRL, 2011

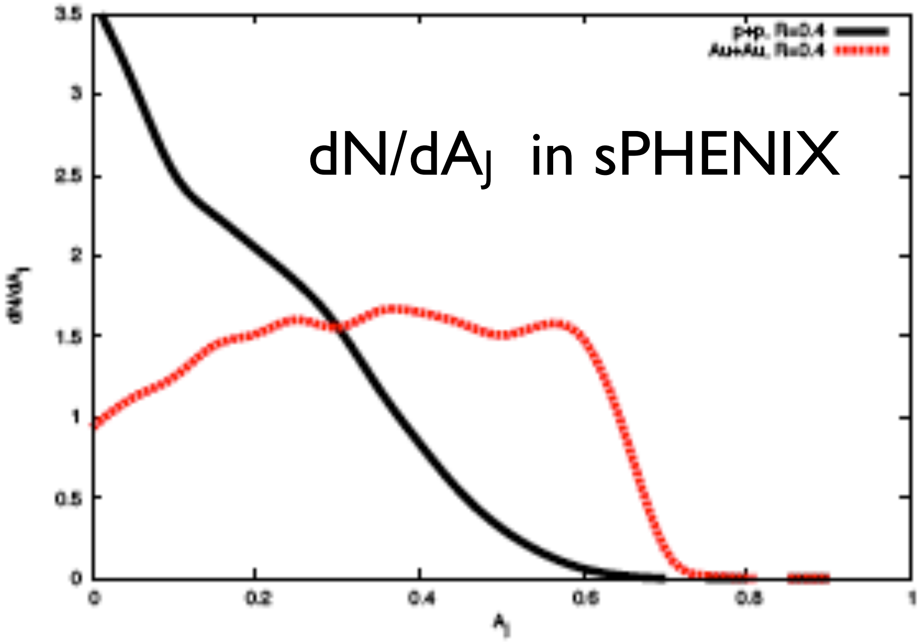
Young, Schenke, Jeon, Gale, PRC, 2011

He, Vitev, Zhang, 2011

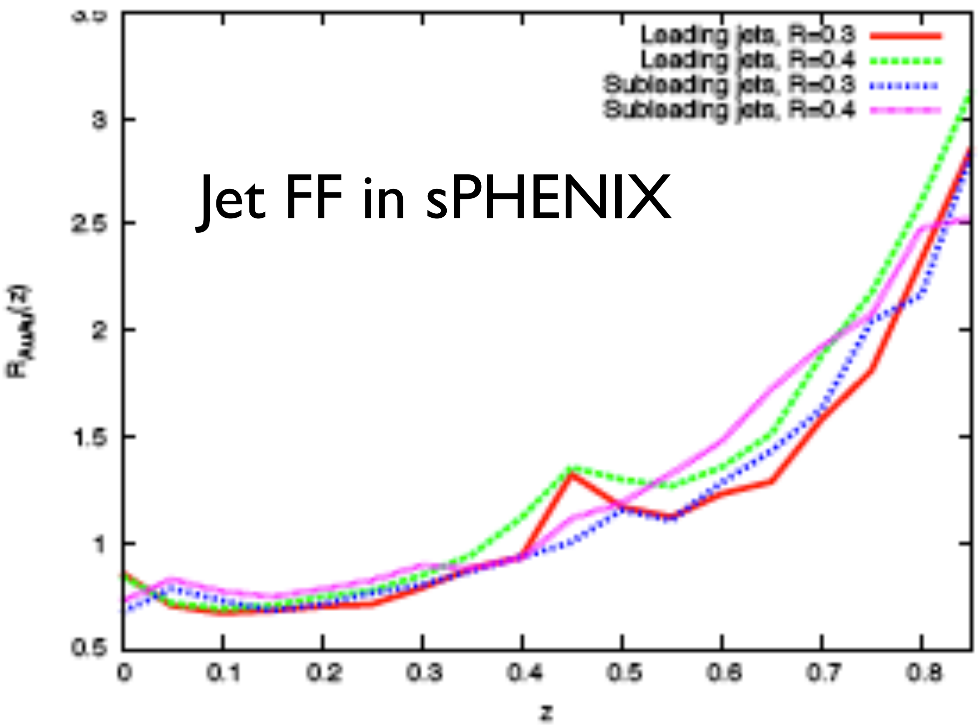
Loktin, Belyaev, Snigirev, EPJC, 2011

Coleman-Smith, Qin, Bass, Muller, 2011

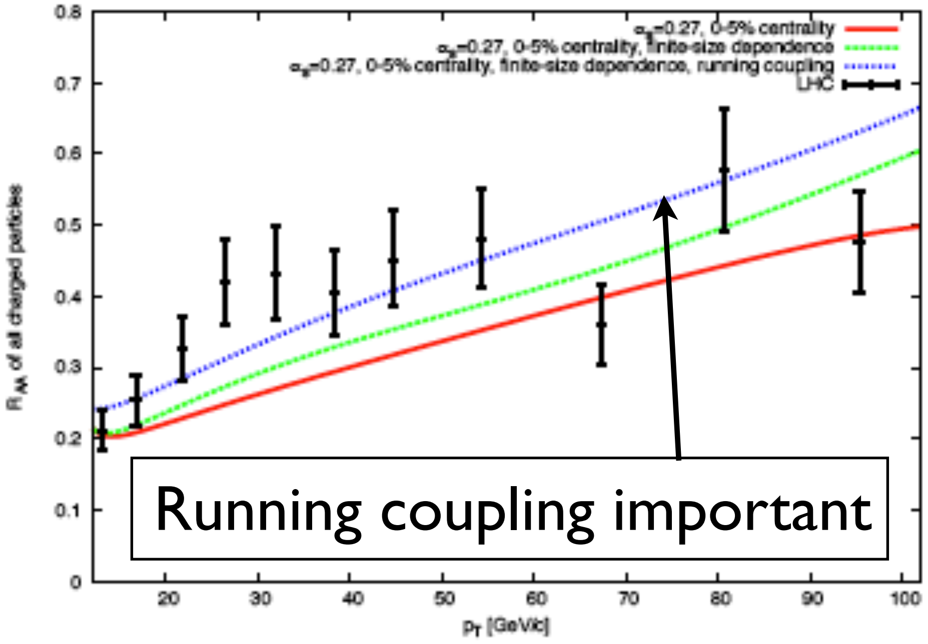
Renk, 2011



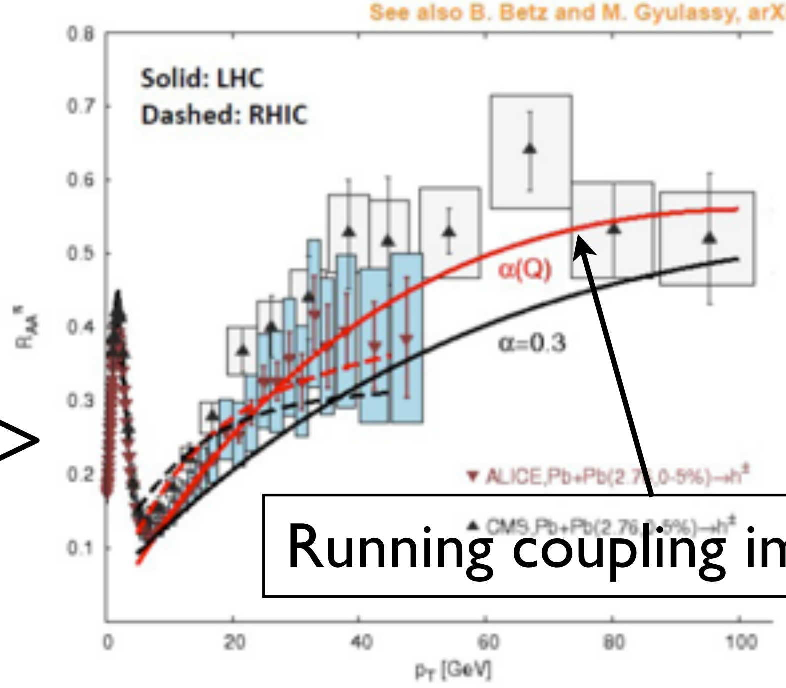
dN/dA$_J$ in sPHENIX



Jet FF in sPHENIX



Running coupling important

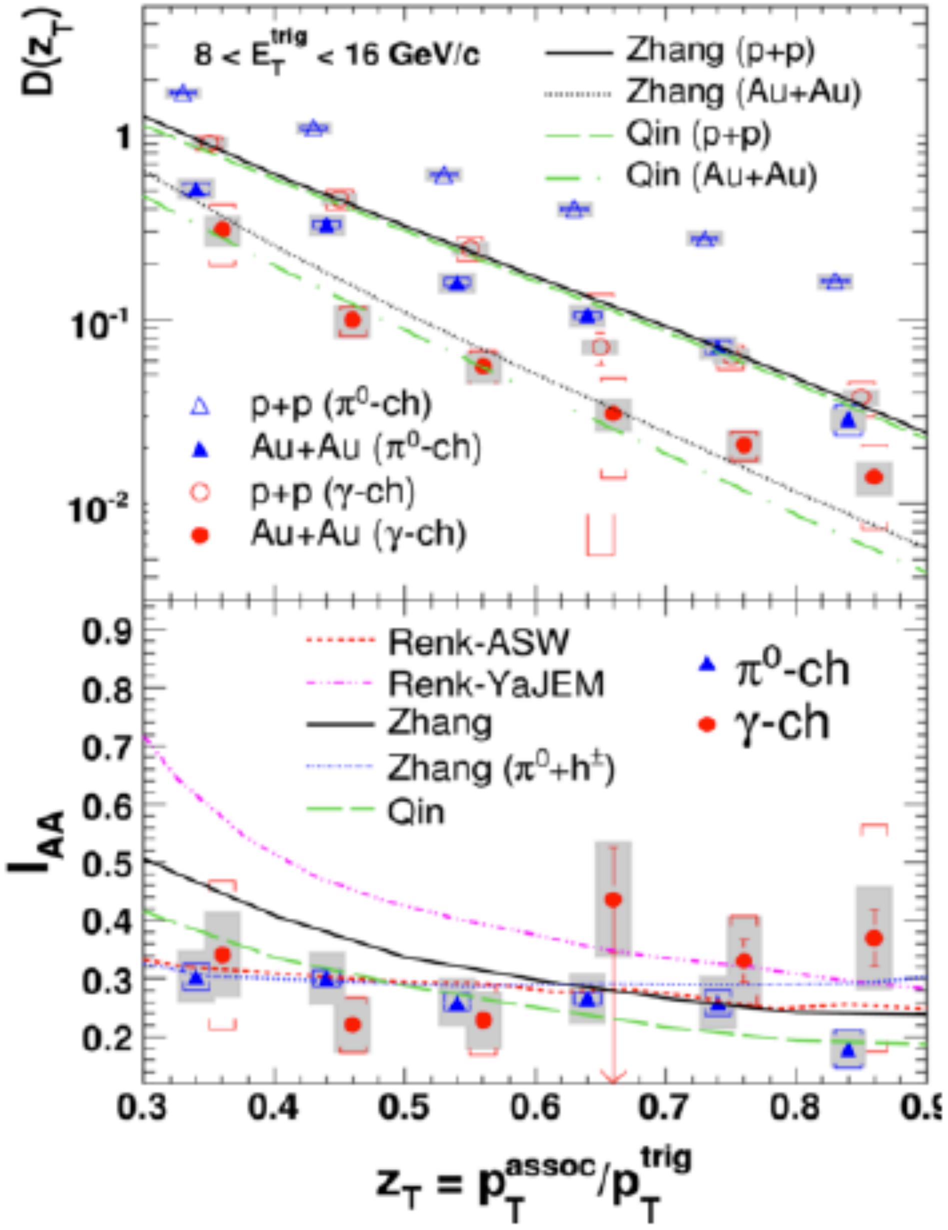


Buzatti

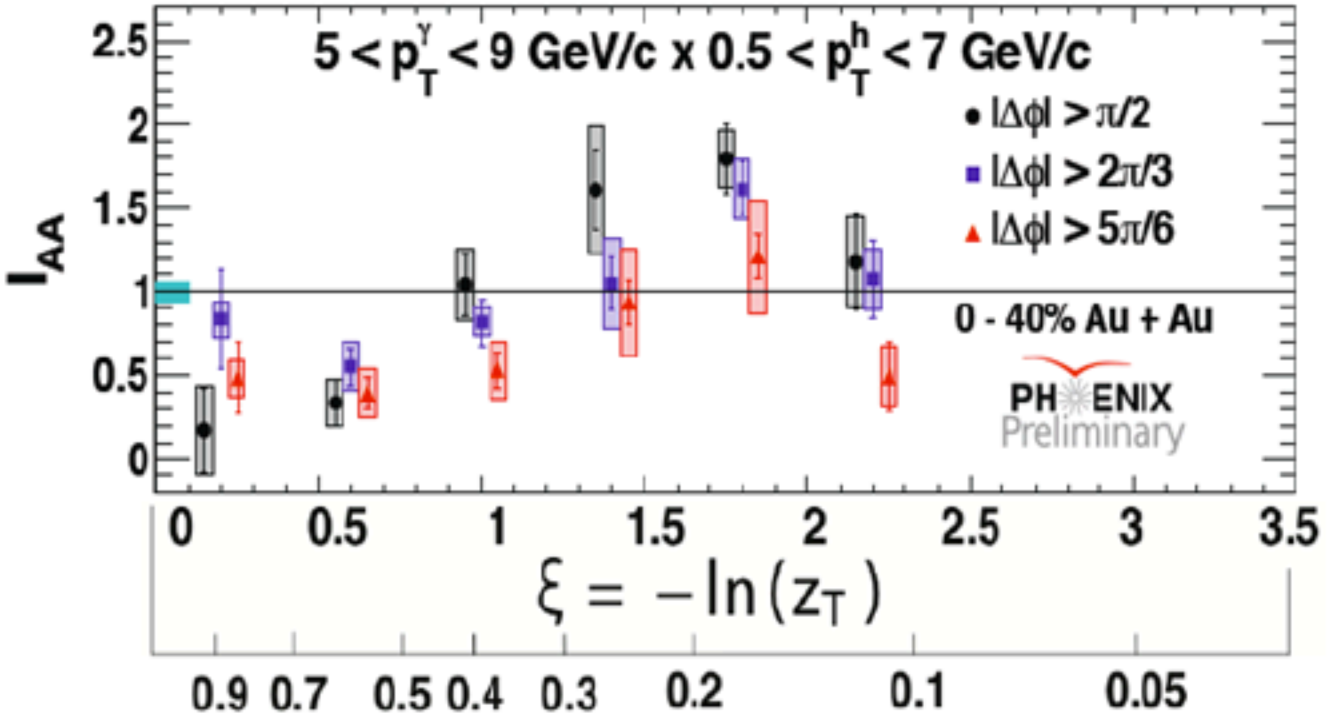
Running coupling important

G. Qin

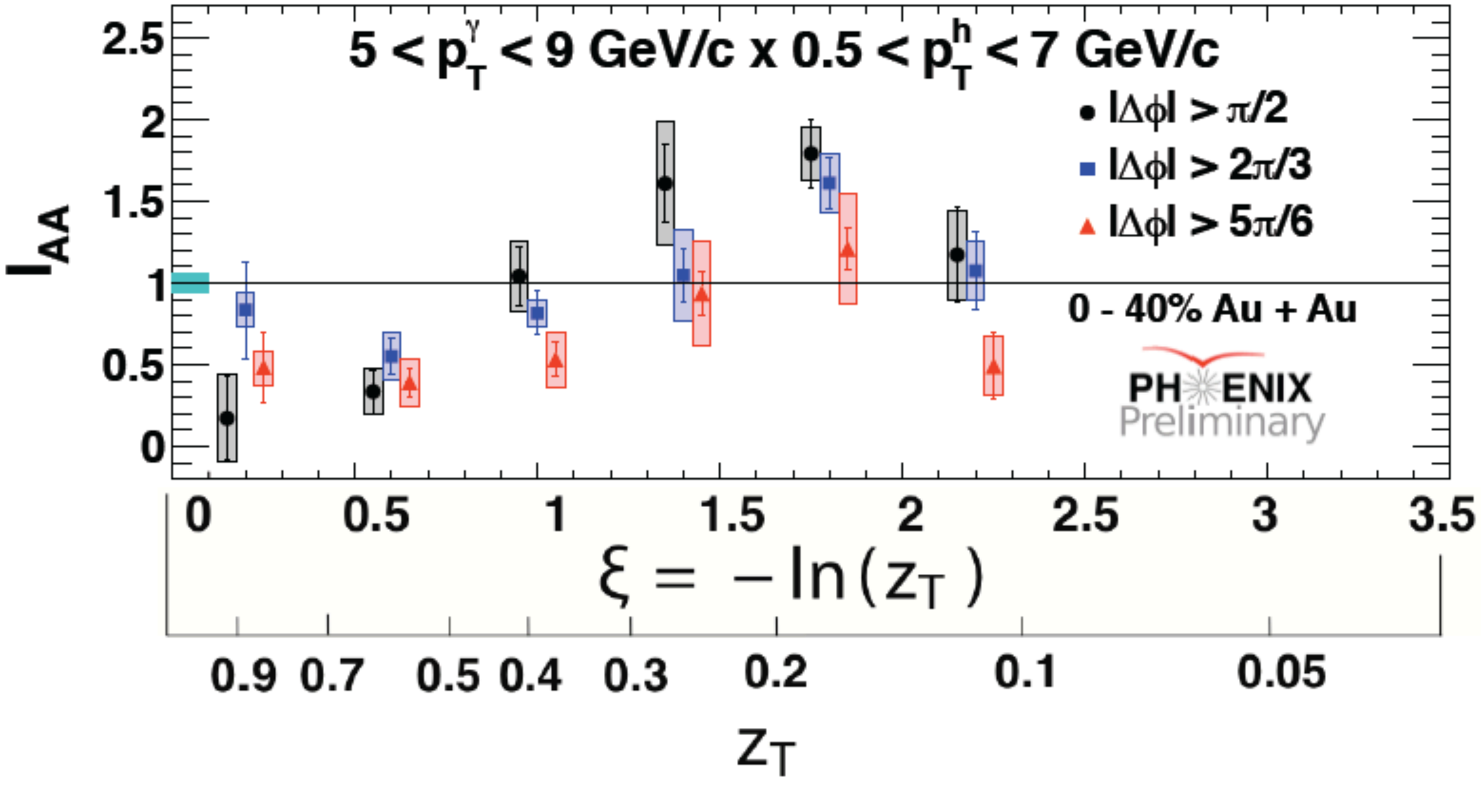
Photon-triggered FF



- *Good approximation of medium-modified fragmentation function*
- *Suppression at high z_T and enhancement at low z_T*
- *Consistent with the picture of jet energy loss and redistribution of lost energy from jet*



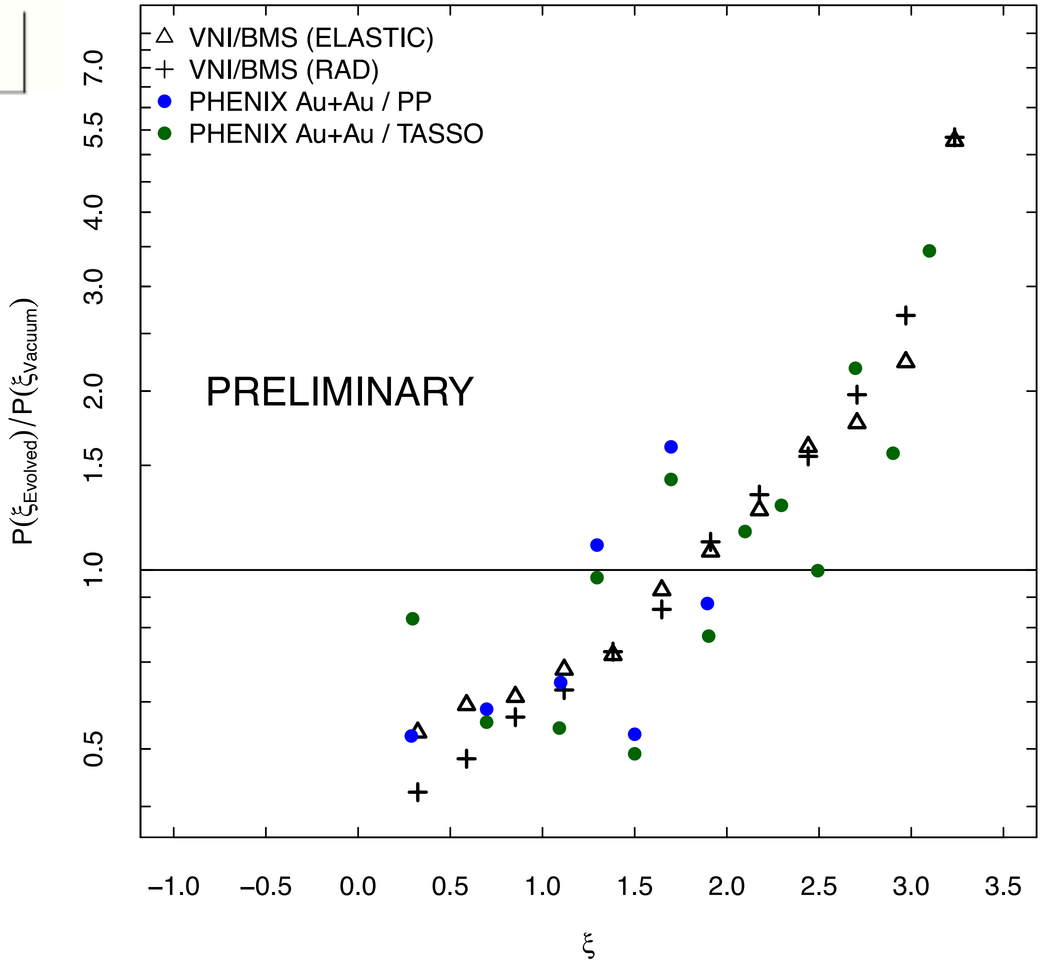
γ-hadron I_{AA}



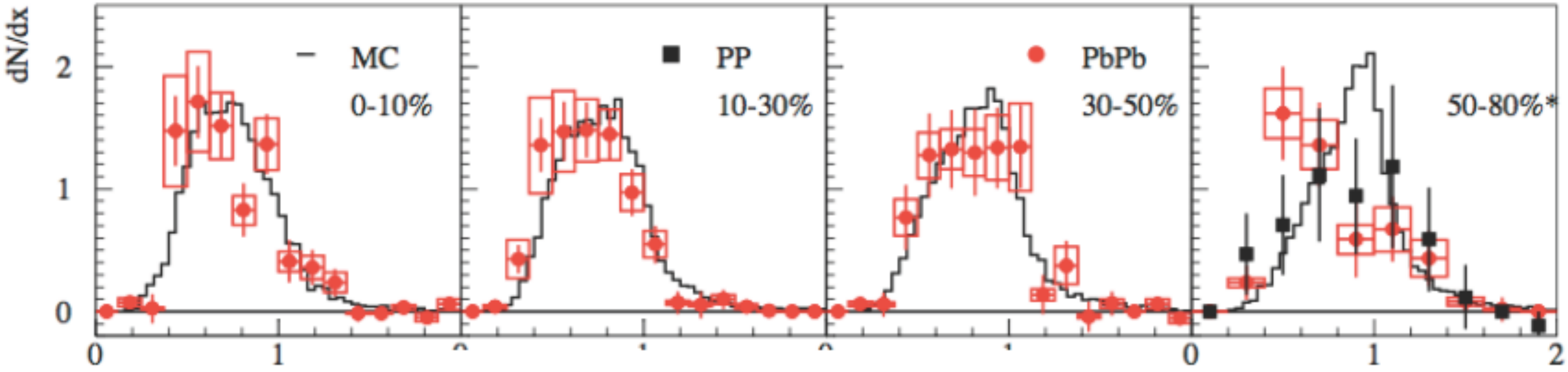
C. Coleman-Smith (preliminary)

correct shape, quantitative agreement needs to be checked for PHENIX specific kinematic cuts

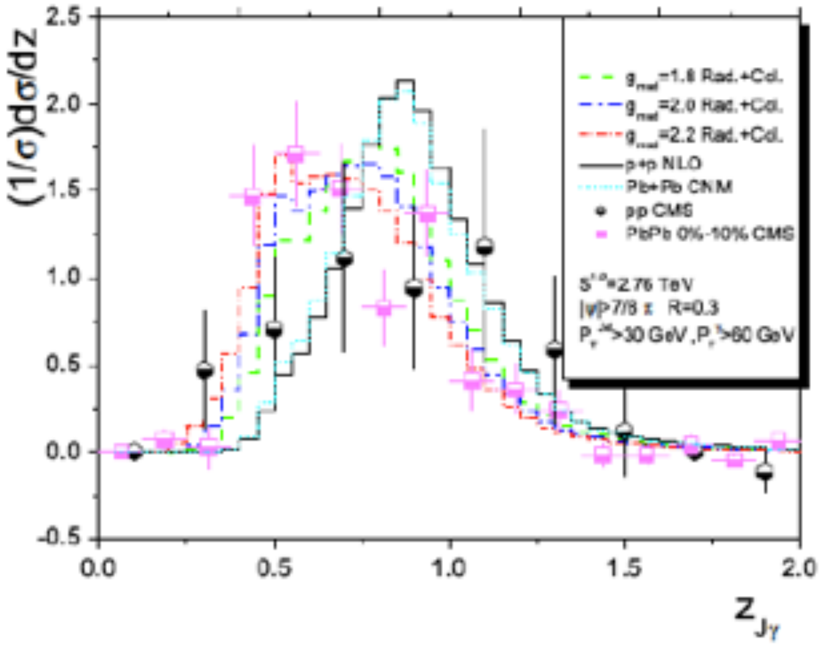
WARNING: Enhancements in medium modified FF's are seen for $p_T < 4$ GeV/c, in a p_T range, were hadron production is complex mixture of fragmentation, recombination, statistical production!



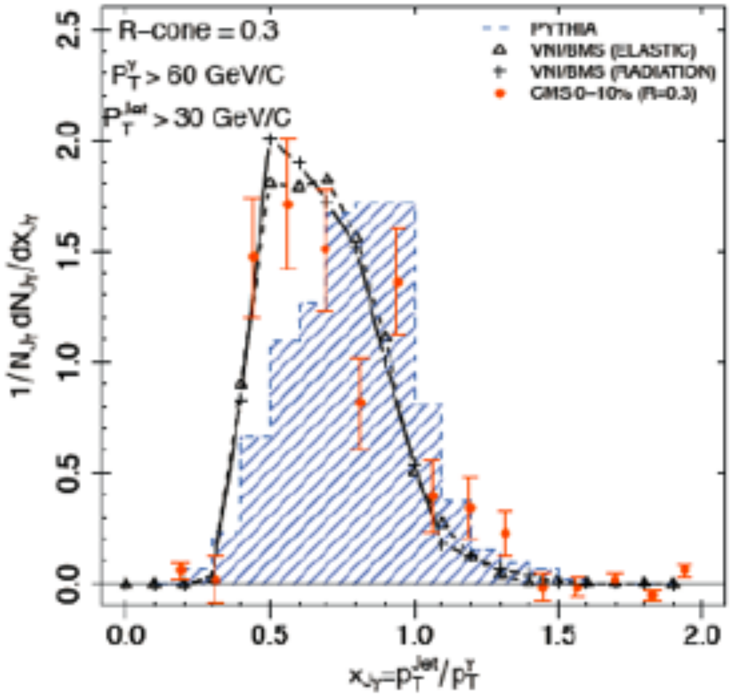
γ-jet coincidences



XN Wang et al.



Dai, Vitev, Zhang (2012)



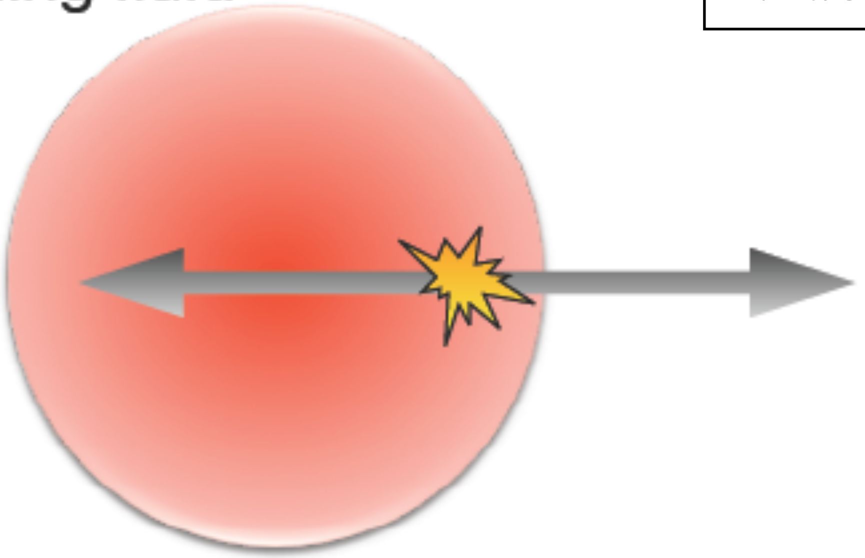
Coleman-Smith, QM 2012

Medium response

Y. Tachibana

- A pair of jets traveling through an expanding fluid

Flow induced by jets
+
Radially expanding background



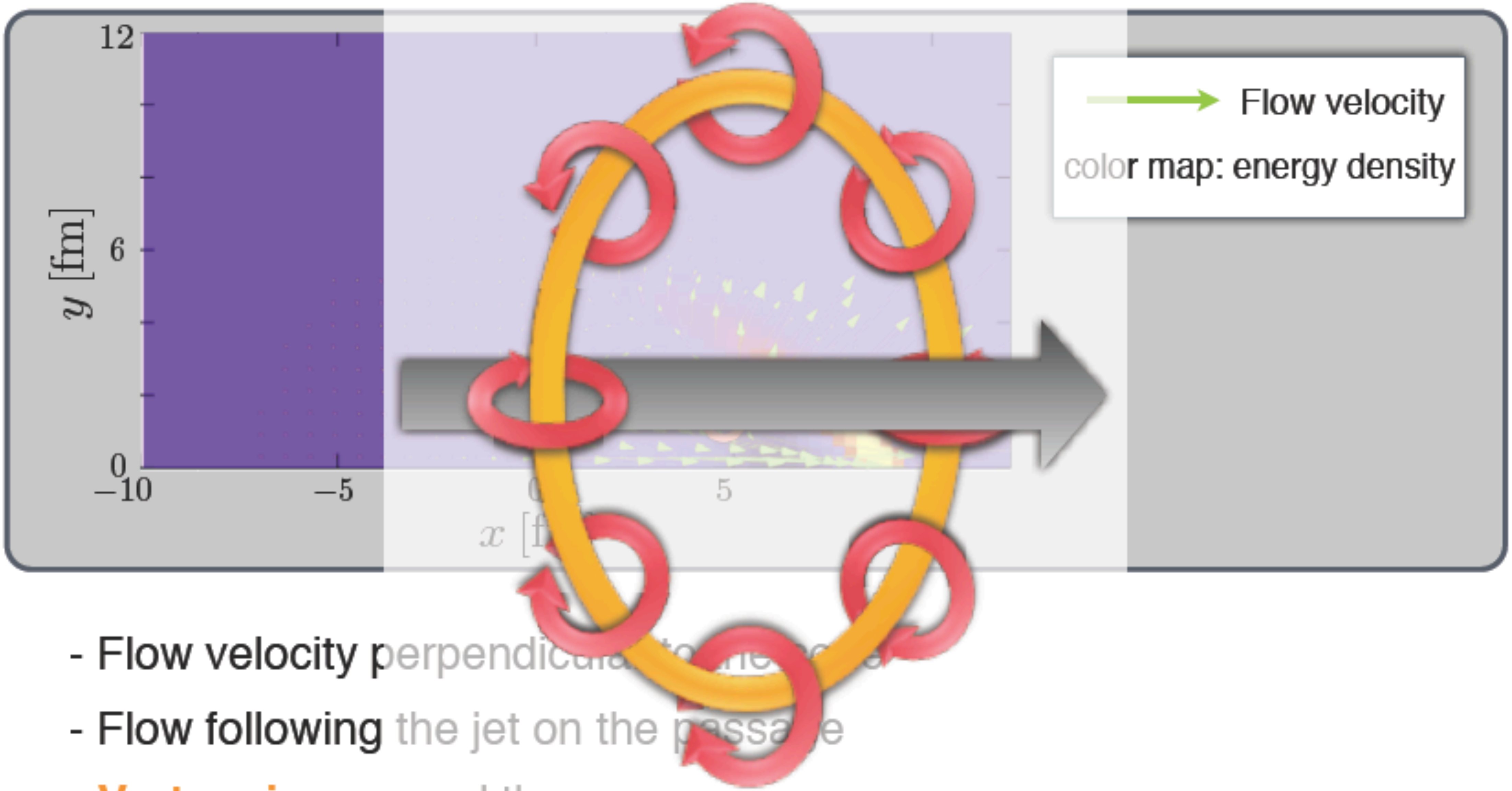
- Hydrodynamic equation with deposited energy and momentum

$$\boxed{\partial_\mu T^{\mu\nu} = J^\nu}$$

J^ν: **source term** (Energy and momentum deposited by jets)

Solve this nonlinear equation numerically without linearization

Describe the dynamics of jets and the QGP fluid simultaneously



- Flow velocity perpendicular to the core
- Flow following the jet on the passage
- **Vortex ring** around the passage

Concluding thoughts

- Parton transport in QCD medium and jet modification by a QCD medium are complicated processes.
- Why do we need to understand them?
- What do we expect to learn in the end that's worth the great theoretical (and experimental) effort?
- Are we aiming for qualitative or quantitative insights?
- What are the quantities that can be "measured"?
  - qhat, ehat, what else?
  - What physics do we learn from them?
- Which precision can we hope to aim for?

Considerations

- How do we ascertain the correctness of complex codes?
- How do we check that we calculate what the experiments measure?
- How do we match perturbative and nonperturbative physics?
- Which observables are most sensitive to the quantities we are interested in, and least sensitive to physics we do not have under good control?