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Theoretical uncertainties in high p_T heavy flavor production and modification

EMMI HF workshop, December 2016

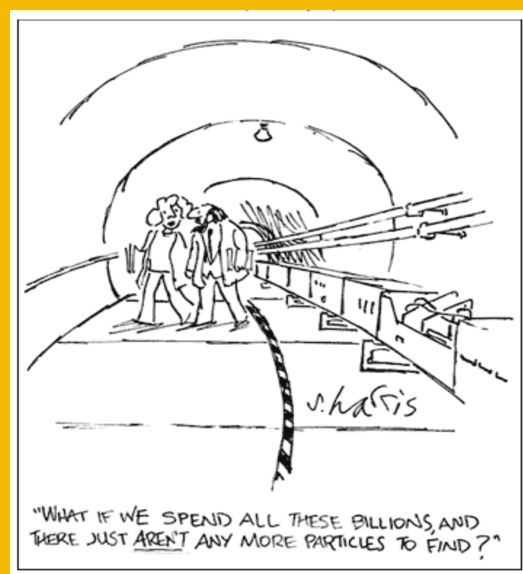
GSI, Darmstadt, Germany

Plan for the talk

Thanks to the organizer for the opportunity to talk remotely

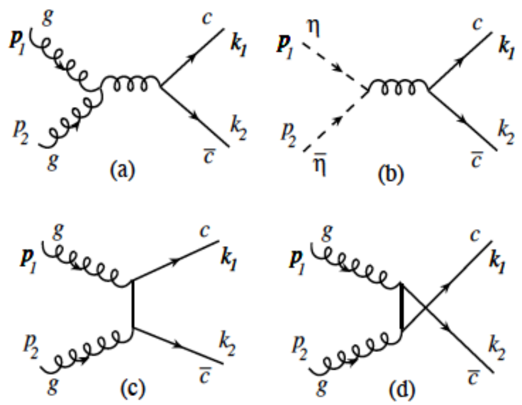
- Production mechanisms for heavy flavor
- Energy loss vs full parton showers
- Sensitivity to medium properties
- Sensitivity to models of the medium
- Uncertainties in quoting q-hat
- Non-locality of non-Abelian in-medium parton splitting
- Conclusions

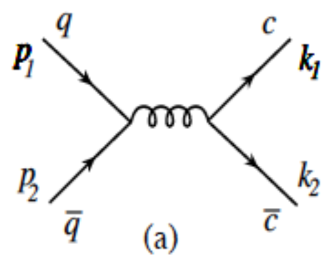
I. Heavy flavor production mechanisms

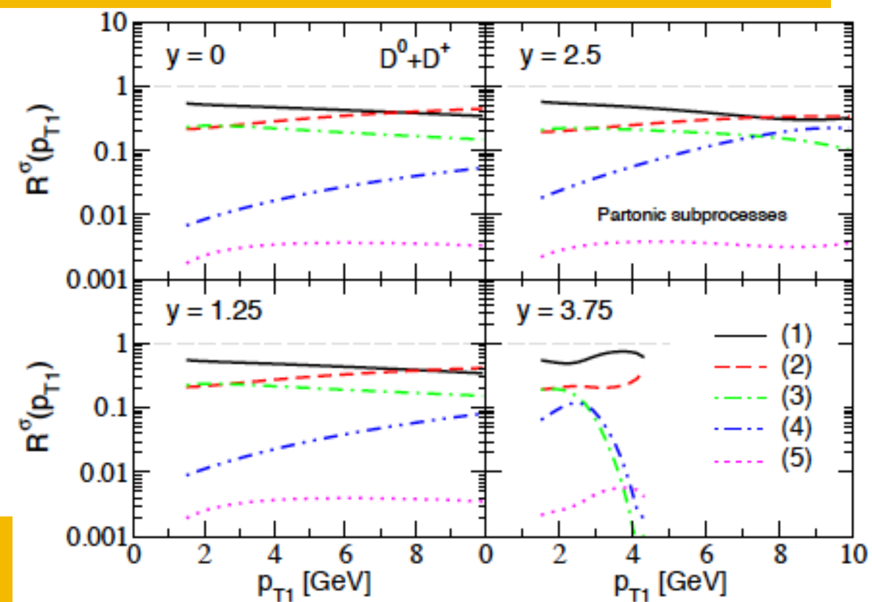


Fixed flavor number scheme

- FFNS at LO very large K factors (4-5)





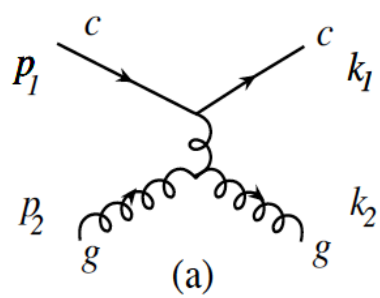


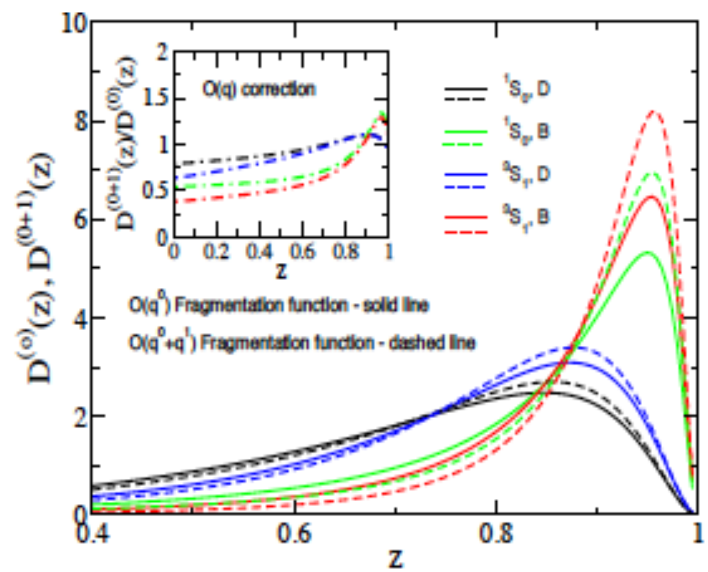
Vitev et al . (2007)

- FONLL – combines NLO with next-to-leading log resummation

Tries to capture the splitting to heavy quarks purely perturbatively

- VFNS at LO reduces or eliminates eliminates the K factors



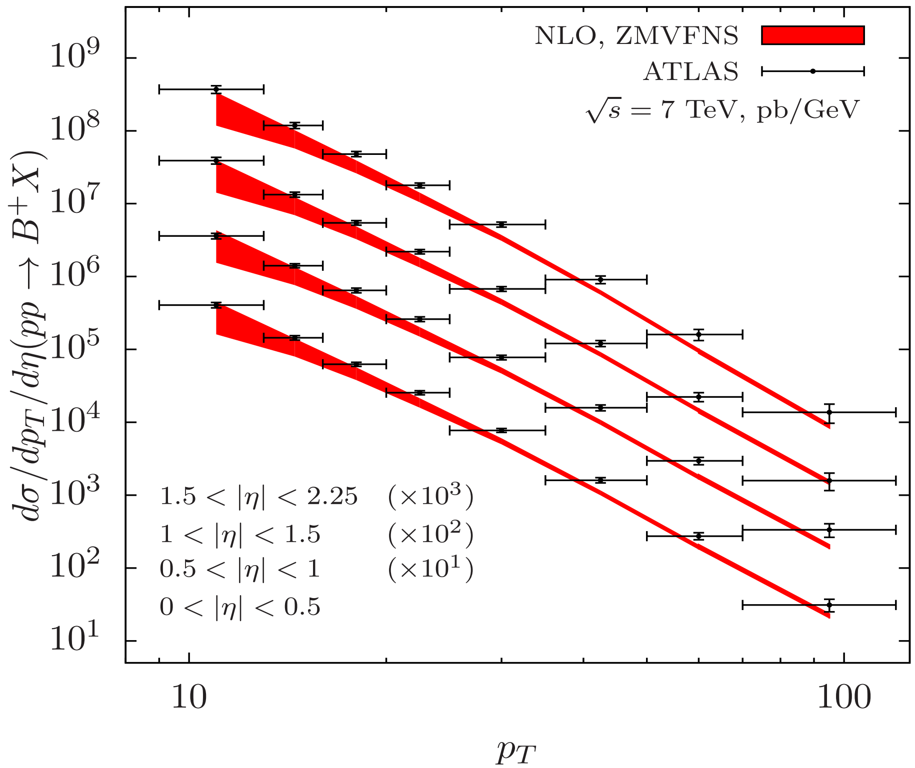


ZMVFS open heavy flavor at NLO

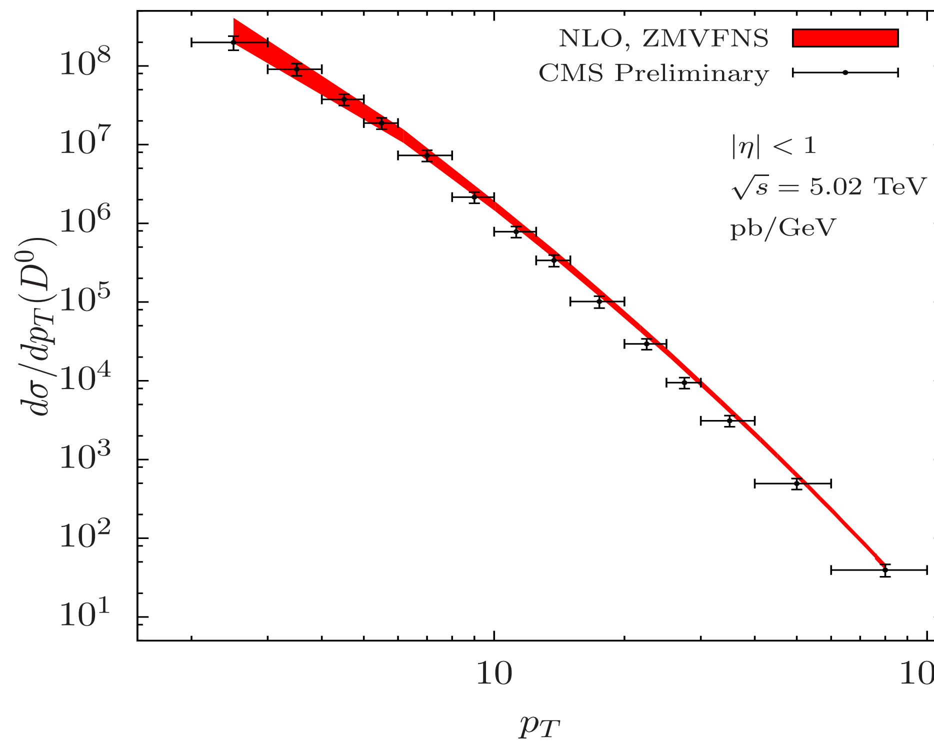
- Perform an NLO calculation

F. Ringer et al . (2016)

$$\frac{d\sigma_{pp}^{H}}{dp_T d\eta} = \frac{2p_T}{s}\sum_{a,b,c}\int_{x_a^{\min}}^{1}\frac{dx_a}{x_a}f_a(x_a,\mu)\int_{x_b^{\min}}^{1}\frac{dx_b}{x_b}f_b(x_b,\mu) \times \int_{z_c^{\min}}^{1}\frac{dz_c}{z_c^2}\frac{d\hat{\sigma}_{ab}^{c}(\hat{s},\hat{p}_T,\hat{\eta},\mu)}{dvdz}D_c^H(z_c,\mu),$$



Kneesch et al . (2008)

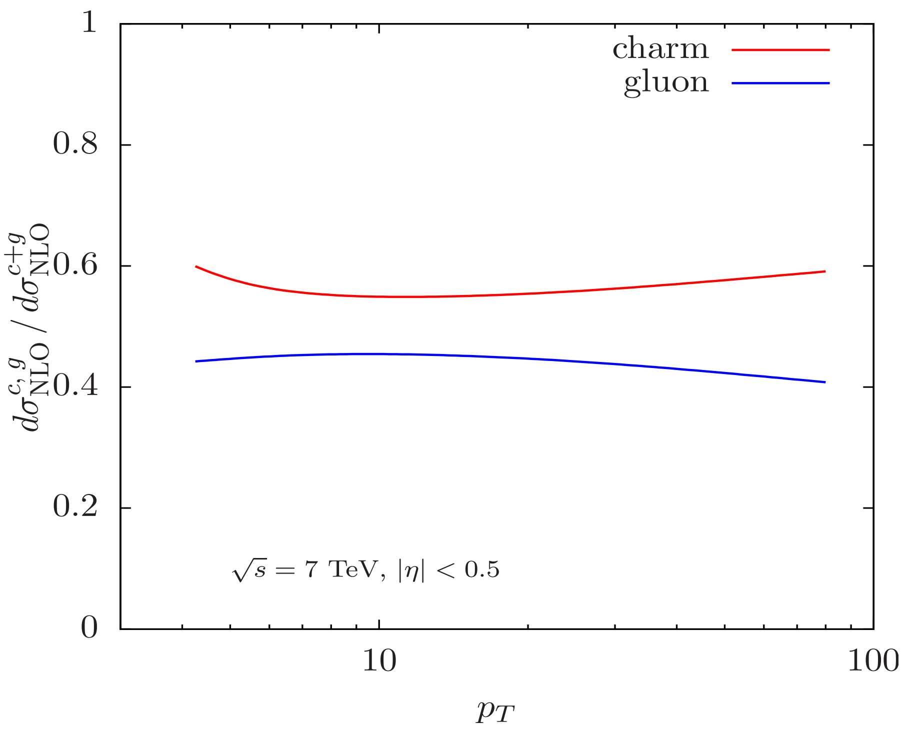


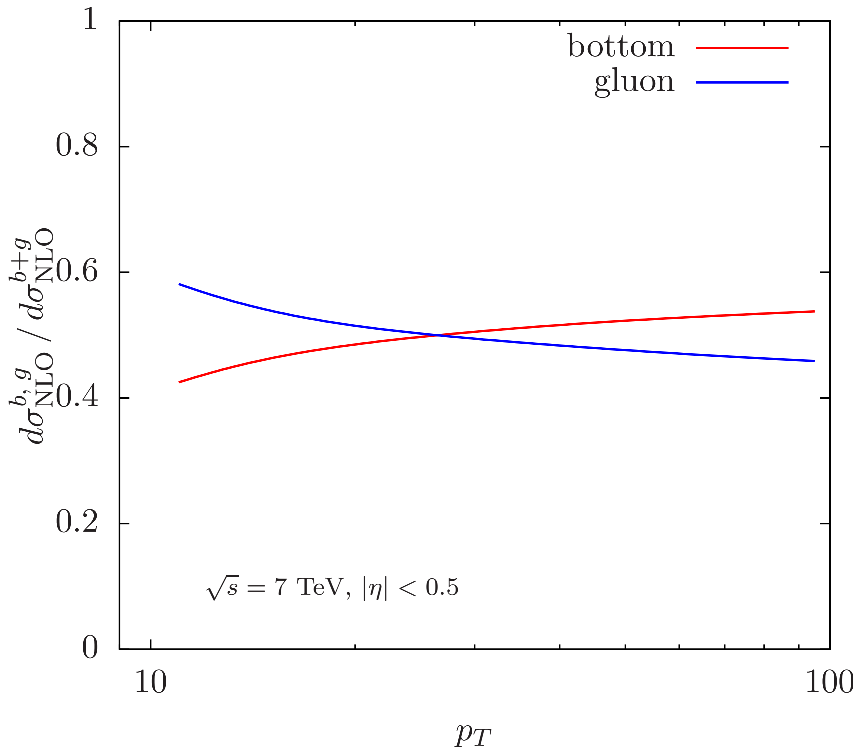
Kniehl et al . (2008)

When $p_T > m_c, m_b$ **Consistent with factorization, non-perturbative physics is long distance**

Implications for heavy flavor modification

- A very large contribution of gluon FF to heavy flavor



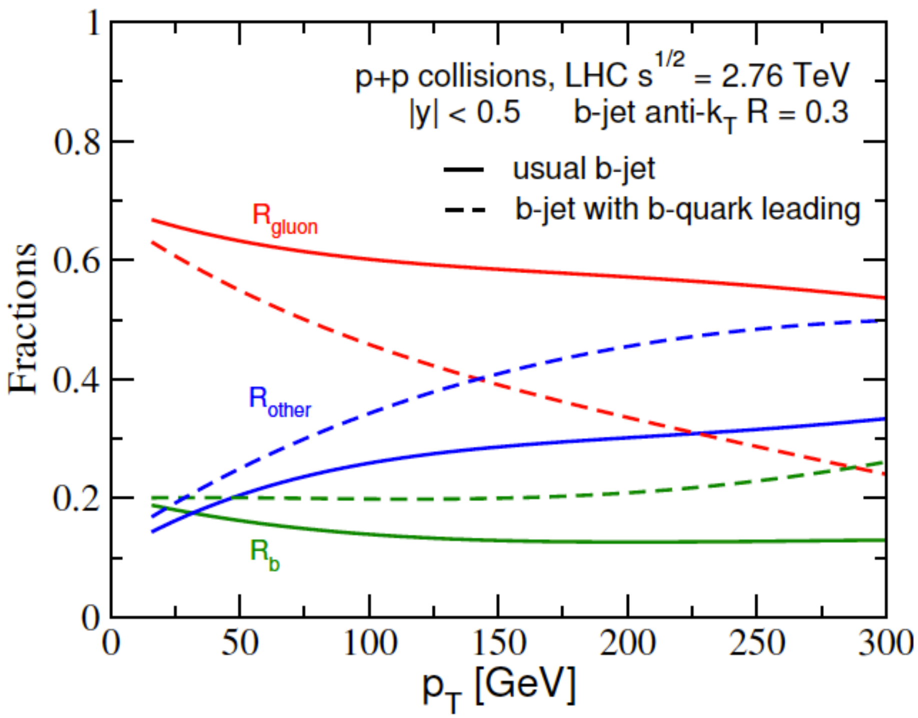


The important implication of this will affect the nuclear modification factor

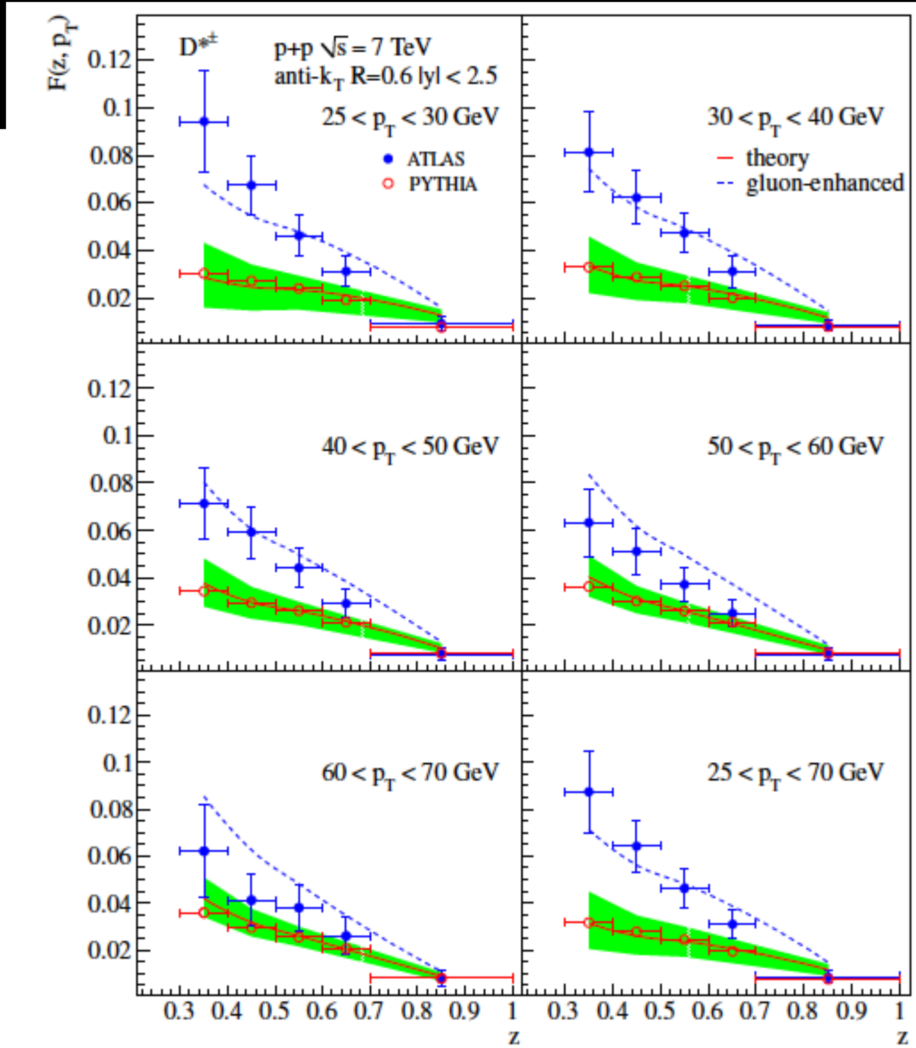
F. Ringer et al . (2016)

The same is true, of course, for b jets, JFF

- Slightly different approach. PYTHIA 8 simulations



Inclusive jets



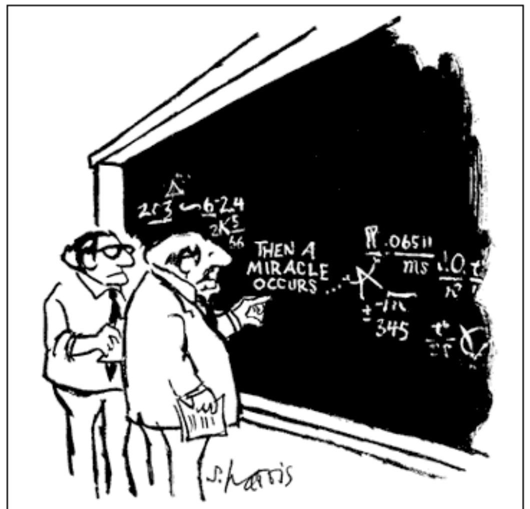
Jet fragmentation functions

- The reason for which b-jets are as suppressed as light jets at high p_T

J. Huang et al . (2013)

Y.T. Chien et al . (2015)

II. Uncertainties related to the in-medium modification application

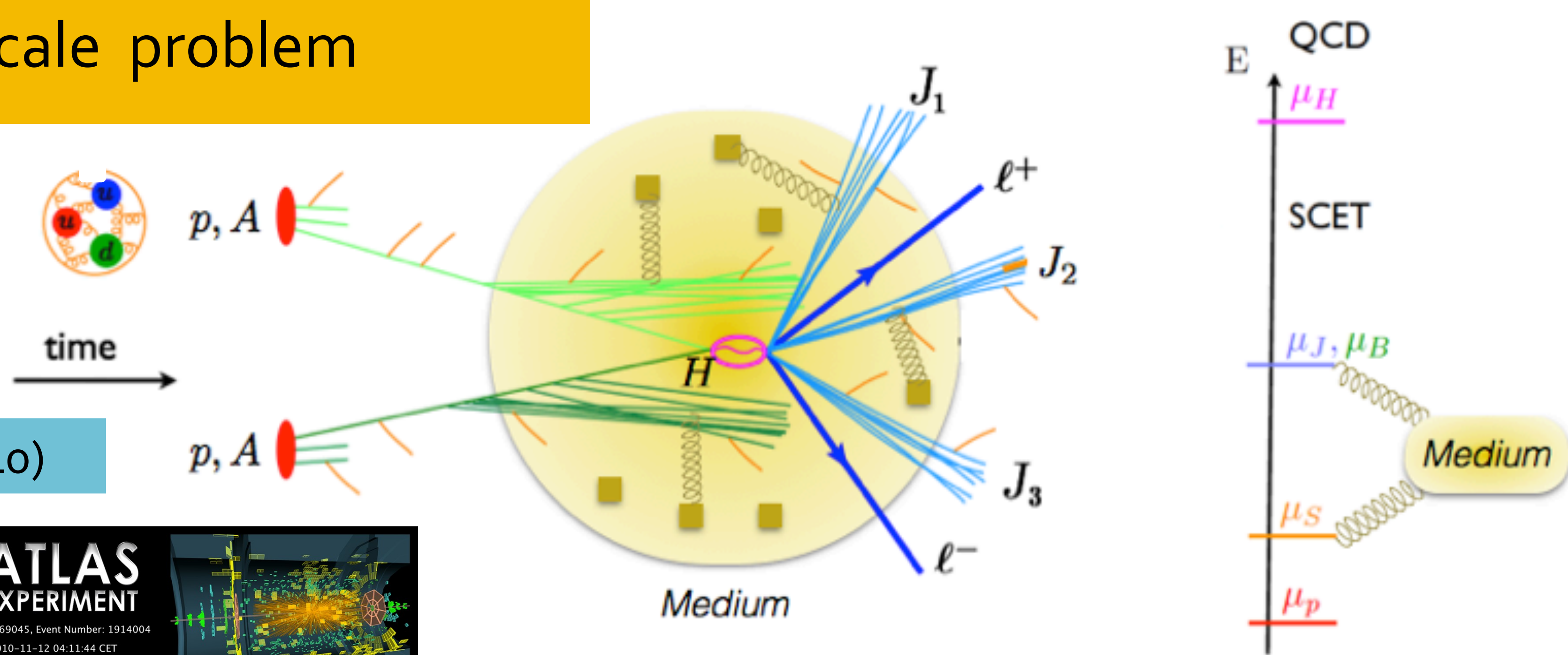


"I think you should be more explicit here in step two."

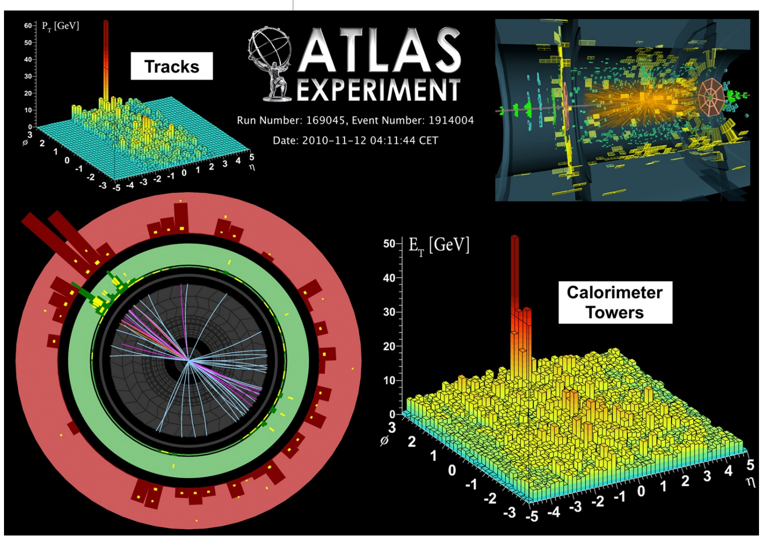
The big picture (you have seen it before)

- QCD in the medium remains a multiscale problem

Ovanesyan et al. (2011)



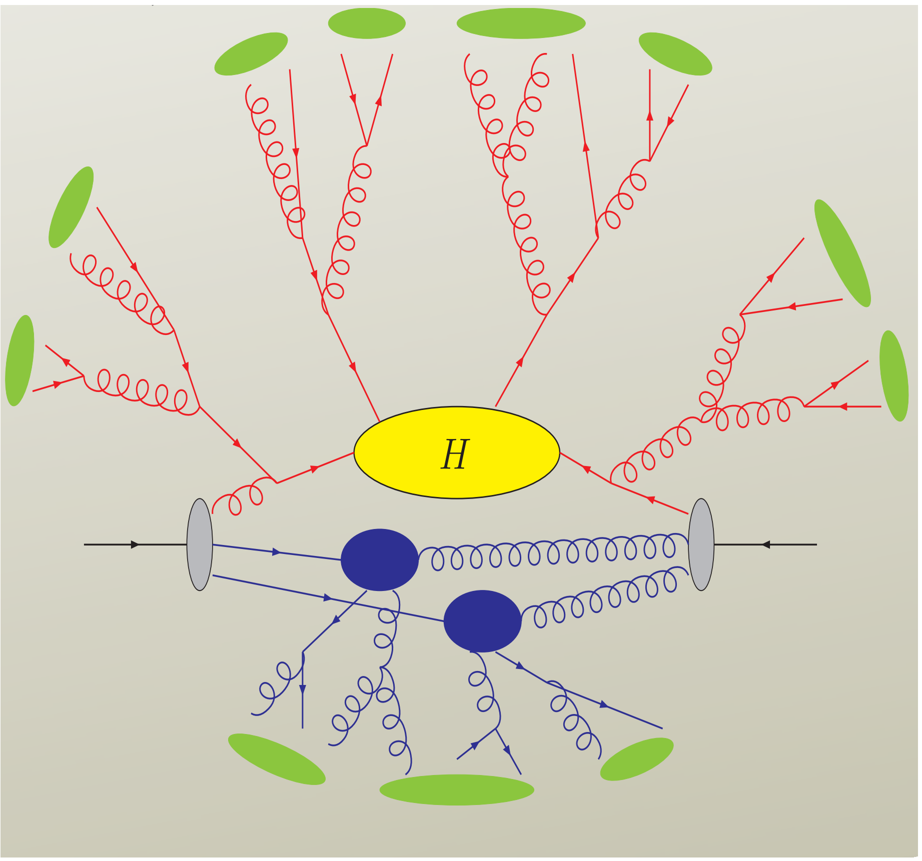
Aad et al. (2010)



- Factorization, with modified J (jet), B (beam), S (soft) functions

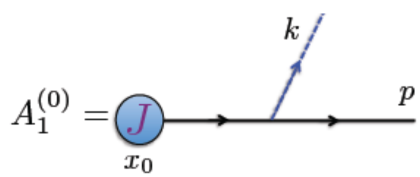
$$\sigma = \mathrm{Tr}(HS) \otimes \prod_{i=1}^{n_B} B_i \otimes \prod_{j=1}^{N} J_j + \text{power corrections}$$

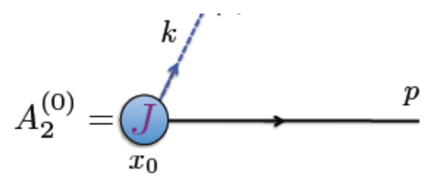
The splitting kernels



- Splitting functions are related to beam (B) and jet (J) functions in SCET

$$
\begin{aligned}
A_{q\to qg} &= \langle J|\, T\, \bar{\chi}_n(x_0)\, \mathrm{e}^{iS}\, |q(\boldsymbol{p})g(\boldsymbol{k})\rangle \\
A_{g\to q\bar{q}} &= \langle J|\, T\, \mathcal{B}^{\lambda c}(x_0)\, \mathrm{e}^{iS}\, |q(\boldsymbol{p})\bar{q}(\boldsymbol{k})\rangle \\
A_{g\to gg} &= \langle J|\, T\, \mathcal{B}^{\lambda c}(x_0)\, \mathrm{e}^{iS}\, |g(\boldsymbol{p})g(\boldsymbol{k})\rangle
\end{aligned}
$$





$$\Gamma_W^{\alpha,a}(k) = g T_r^a \frac{\bar{n}^\alpha}{k^+ + i\epsilon}$$

Gribov et al. (1972)

G. Altarelli et al. (1977)

Y. Dokshitzer (1977)

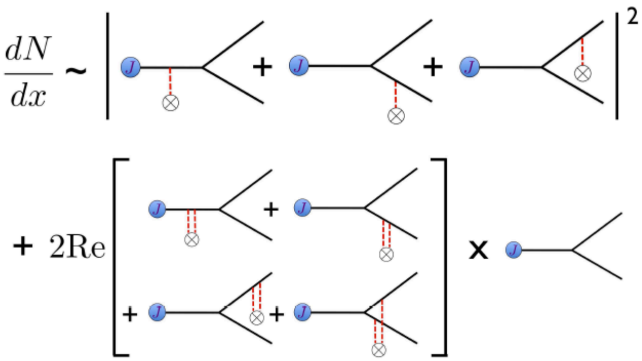
- In the vacuum we have the DGLAP splitting kernels that factorize from the hard scattering cross section and are process independent

Heavy quarks in the medium

Kinematic variables

$$A_\perp = k_\perp,\ B_\perp = k_\perp + x q_\perp,\ C_\perp = k_\perp - (1-x) q_\perp,\ D_\perp = k_\perp - q_\perp$$

$$\frac{dN}{dx} \sim$$



$$\Omega_1 - \Omega_2 = \frac{B_\perp^2 + \nu^2}{p_0^+ x(1-x)},\ \Omega_1 - \Omega_3 = \frac{C_\perp^2 + \nu^2}{p_0^+ x(1-x)},\ \Omega_4 = \frac{A_\perp^2 + \nu^2}{p_0^+ x(1-x)},$$

$$\begin{aligned} \nu &= m && (g \to Q\bar{Q}), \\ \nu &= x\, m && (Q \to Qg), \\ \nu &= (1-x)\, m && (Q \to gQ), \end{aligned}$$

F. Ringer et al . (2016)

$$\left(\frac{dN^{\rm med}}{dx d^2 k_\perp}\right)_{Q\to Qg} = \frac{\alpha_s}{2\pi^2} C_F \int \frac{d\Delta z}{\lambda_g(z)} \int d^2 q_\perp \frac{1}{\sigma_{el}} \frac{d\sigma_{el}^{\rm med}}{d^2 q_\perp} \left\{ \left(\frac{1+(1-x)^2}{x}\right) \left[\frac{B_\perp}{B_\perp^2+\nu^2} \right.\right.$$
$$\times \left(\frac{B_\perp}{B_\perp^2+\nu^2} - \frac{C_\perp}{C_\perp^2+\nu^2}\right)(1-\cos[(\Omega_1-\Omega_2)\Delta z]) + \frac{C_\perp}{C_\perp^2+\nu^2}\cdot\left(2\frac{C_\perp}{C_\perp^2+\nu^2} - \frac{A_\perp}{A_\perp^2+\nu^2}\right.$$
$$\left. - \frac{B_\perp}{B_\perp^2+\nu^2}\right)(1-\cos[(\Omega_1-\Omega_3)\Delta z]) + \frac{B_\perp}{B_\perp^2+\nu^2}\cdot\frac{C_\perp}{C_\perp^2+\nu^2}(1-\cos[(\Omega_2-\Omega_3)\Delta z])$$
$$+ \frac{A_\perp}{A_\perp^2+\nu^2}\cdot\left(\frac{D_\perp}{D_\perp^2+\nu^2} - \frac{A_\perp}{A_\perp^2+\nu^2}\right)(1-\cos[\Omega_4\Delta z]) - \frac{A_\perp}{A_\perp^2+\nu^2}\cdot\frac{D_\perp}{D_\perp^2+\nu^2}(1-\cos[\Omega_5\Delta z])$$
$$\left. + \frac{1}{N_c^2}\frac{B_\perp}{B_\perp^2+\nu^2}\cdot\left(\frac{A_\perp}{A_\perp^2+\nu^2} - \frac{B_\perp}{B_\perp^2+\nu^2}\right)(1-\cos[(\Omega_1-\Omega_2)\Delta z])\right]$$
$$\left. + x^3 m^2 \left[\frac{1}{B_\perp^2+\nu^2}\cdot\left(\frac{1}{B_\perp^2+\nu^2} - \frac{1}{C_\perp^2+\nu^2}\right)(1-\cos[(\Omega_1-\Omega_2)\Delta z]) + \ldots\right]\right\}$$

- Full massive in-medium splitting functions now available
- Can be evaluated numerically

The energy loss limit

3 splitting functions (g to gg is the same)

Dokshitzer et al . (2001)

$$x\left(\frac{dN^{\rm SGA}}{dx d^2\boldsymbol{k}_\perp}\right)_{Q\to Qg} = \frac{\alpha_s}{\pi^2} C_F \int d\Delta z \frac{1}{\lambda_g(z)} \int d^2\boldsymbol{q}_\perp \frac{1}{\sigma_{el}} \frac{d\sigma_{el}^{\rm med}}{d^2\boldsymbol{q}_\perp} \times \frac{2\boldsymbol{k}_\perp\cdot\boldsymbol{q}_\perp}{[\boldsymbol{k}_\perp^2+x^2m^2][(\boldsymbol{k}_\perp-\boldsymbol{q}_\perp)^2+x^2m^2]}\left[1-\cos\frac{(\boldsymbol{k}_\perp-\boldsymbol{q}_\perp)^2+x^2m^2}{xp_0^+}\Delta z\right]$$

A bit of an ambiguity in the diagonal splitting of how to treat x suppressed terms in the numerator

$$x\left(\frac{dN^{\rm SGA}}{dx d^2\boldsymbol{k}_\perp}\right)_{Q\to gQ} = \frac{\alpha_s}{\pi^2} C_F \left(\frac{x}{2}\right) \int d\Delta z \frac{1}{\lambda_q(z)} \int d^2\boldsymbol{q}_\perp \frac{1}{\sigma_{el}} \frac{d\sigma_{el}^{\rm med}}{d^2\boldsymbol{q}_\perp} \times \frac{2\boldsymbol{k}_\perp\cdot\boldsymbol{q}_\perp}{[\boldsymbol{k}_\perp^2+m^2][(\boldsymbol{k}_\perp-\boldsymbol{q}_\perp)^2+m^2]}\left[1-\cos\frac{(\boldsymbol{k}_\perp-\boldsymbol{q}_\perp)^2+m^2}{xp_0^+}\Delta z\right]$$

The ambiguity is removed by the off-diagonal splittings. Bottom line: x m corrections in the poles and interference phases but dropped in numerator

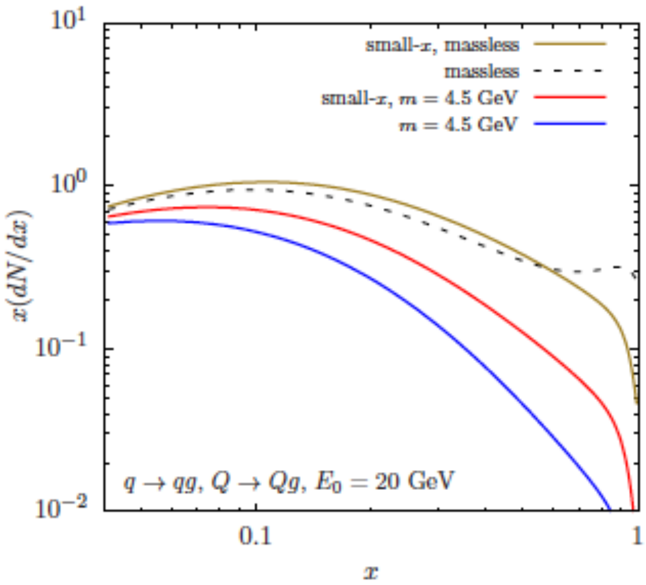
F. Ringer et al . (2016)

Numerical comparison

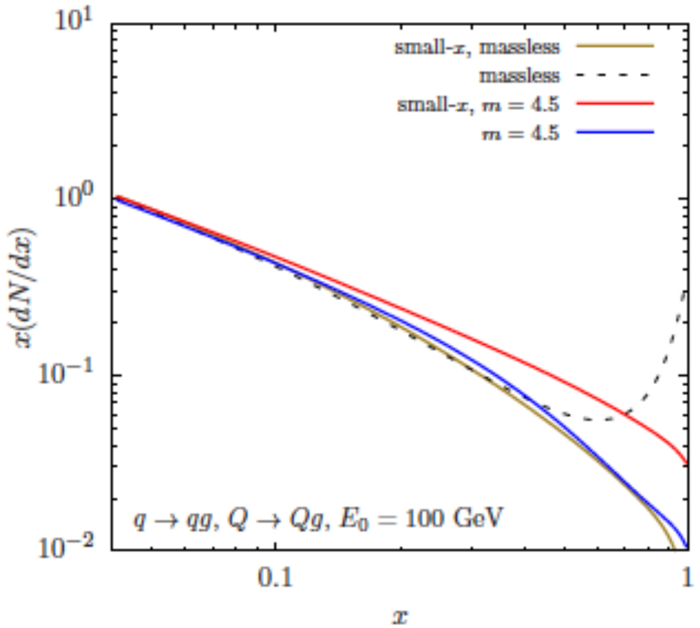
For pT 10-20 GeV even at "small-x" there is a difference

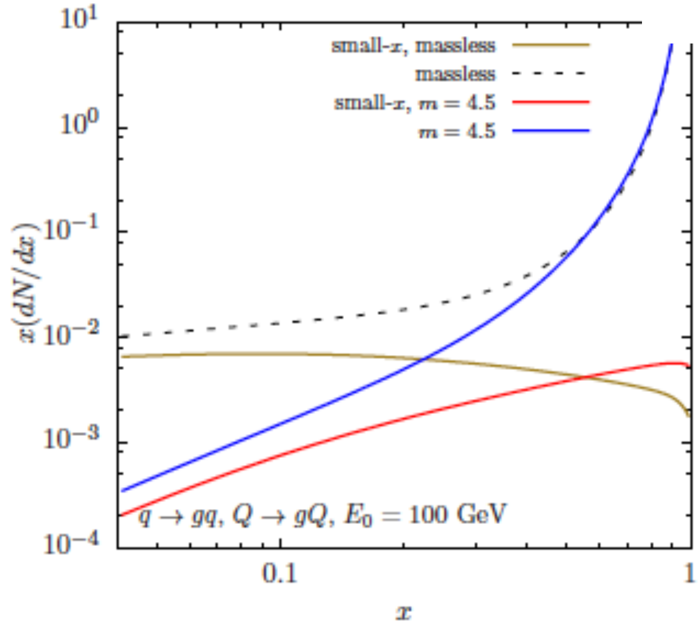
The –off-diagonal splittings are not small

F. Ringer et al . (2016)



Cannot be interpreted as energy loss: NLO implementation, evolution





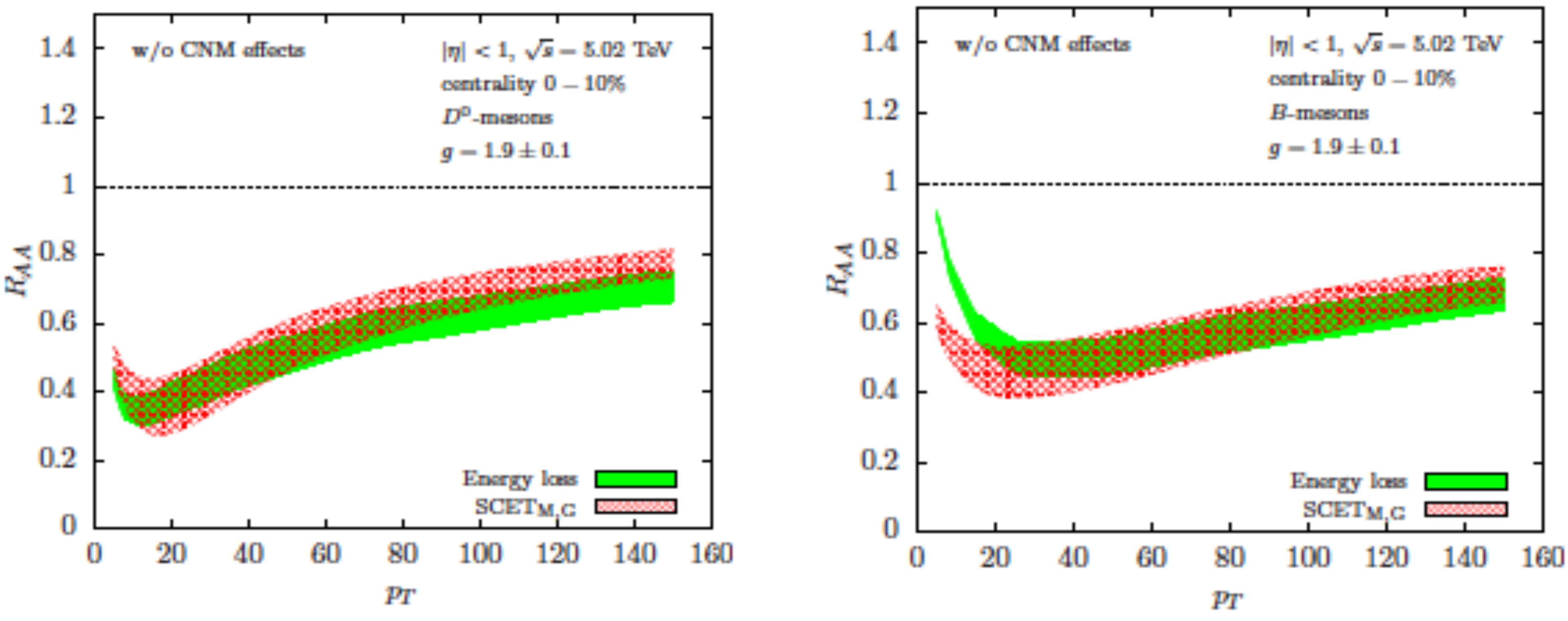
Qualitatively the same behavior of RAA / from light

Different g ~ 5%
Different qhat ~ 20%

Expect at least the same Uncertainty at least

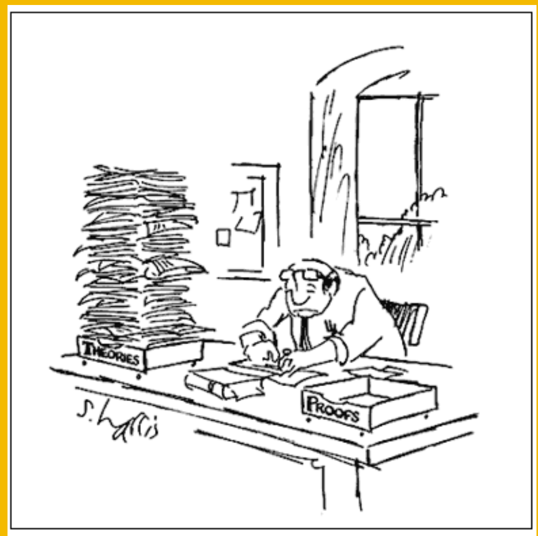
Combined uncertainty

Includes both production mechanism and e-loss vs parton shower



At high pT there is at least 20% combined uncertainty. Did not increase much since gluon fragmenatation in H is softer and offsets the difference between quark-gluon enegry loss. At low PT th eucertainties can grow to 30% D and 50 + % B. Does it further affect collisional interactions?

III. Differences between models



Generally 4 energy loss approaches

- The scattering lengths and momentum transfers are largely independent, providing a 2D parameter space. Such scenario would require expensive multi-parameter fits to data and has not been explored so far in the literature.
- Assuming local thermal equilibrium, density and temperature can be related at any space time point. The range of the interaction and parton scattering cross section can be estimated and depend on the typical coupling between the jet and the medium g. The scattering length is then obtained form the QGP density and the scattering cross section
- One can relate in thermal field theory all relevant medium parameters to the temperature T. In spirit, this is similar to the situation described above but in this case the scattering cross sections and densities are not explicitly evaluated.

Generally 4 energy loss approaches

- An approach to energy loss set in the limit of infinite energies and infinite number of scatterings assumes that at any scale the transverse momentum broadening of any scale is given purely by 2D Gaussian random. By discarding the detailed kinematic information that pertains to parton scattering one can relate the radiative intensity spectra to the transport parameter qhat
- In deep inelastic scattering the radiative spectrum can be related to higher twist matrix elements of field operators. The scattering length can be thought of as the inter-nucleon distance. The application to the QGP case is by analogy.

Improvements have been made in e-loss models. Papers have been written how model A=C, B=D. When it comes to application there are differences

General agreement on the form of the mass correction on the diagonal energy loss piece

Dokshitzer et al. (2001)

Djordjevic et al. (2003)

IV. The story of q-hat

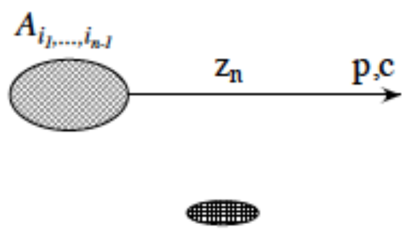
"I'm firmly convinced that behind every great man is a great computer."

Transverse momentum broadening of partons

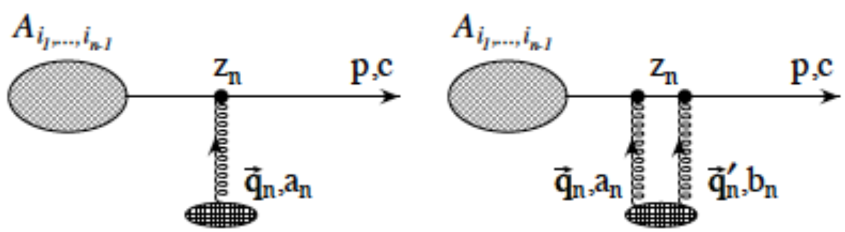
The transport parameter q-hat is discussed in the context of transverse momentum broadening.

Baier et al . (1997)

M. Gyulassy et al . (2002)



Calculate diagrams of this type
Use the reaction operator approach to sum the interactions in impact parameter space



Note that these are equivalent representations

$$dN(\mathbf{p}) = e^{-\sigma_{el}T(\mathbf{b}_0)} \int d^2\mathbf{b}\; e^{i\mathbf{p}\cdot\mathbf{b}}\, e^{\tilde{\sigma}_{el}(\mathbf{b})T(\mathbf{b}_0)} dN^{(0)}(\mathbf{b})$$

$$= \sum_{n=0}^{\infty} e^{-\chi}\frac{\chi^n}{n!}\int \prod_{i=1}^{n} d^2\mathbf{q}_i \frac{1}{\sigma_{el}}\frac{d\sigma_{el}}{d^2\mathbf{q}_i}\, dN^{(0)}(\mathbf{p}-\mathbf{q}_1-\cdots-\mathbf{q}_n)$$

Pure random walk approximation

The approximation arises as follows

M. Gyulassy et al . (2002)

$$\frac{d\tilde{\sigma}_{el}}{d^2\mathbf{q}}(\mathbf{b}) = \int \frac{d^2\mathbf{q}}{(2\pi)^2}\, e^{-i\mathbf{q}\cdot\mathbf{b}} \frac{1}{\pi} \frac{\mu^2}{(\mathbf{q}^2+\mu^2)^2} = \frac{\mu\, b}{4\pi^2} K_1(\mu b) \approx \frac{1}{4\pi^2}\left(1 - \frac{\xi\,\mu^2\, b^2}{2} + \mathcal{O}(b^3)\right)$$

$$\xi = 2\ln(1.08/\mu\; b)$$

Not only are sub-leading powers of energy neglected but also the leading logarythmic dependence must be neglected.

One must neglect the energy dependence

$$dN(\mathbf{p}) = \int d^2\mathbf{b}\, e^{i\mathbf{p}\cdot\mathbf{b}} \frac{1}{(2\pi)^2} \frac{e^{-\frac{\chi\mu_D^2\xi b^2}{2}}}{\chi\,\mu_D^2\,\xi} = \frac{1}{2\pi}\frac{e^{-\frac{\mathbf{p}^2}{2\chi\mu_D^2\xi}}}{\chi\,\mu_D^2\,\xi}$$

$$\langle \mathbf{p}^2\rangle = 2\chi\,\mu_D^2\,\xi, \qquad \xi \sim O(1)$$

The transport parameter q-hat

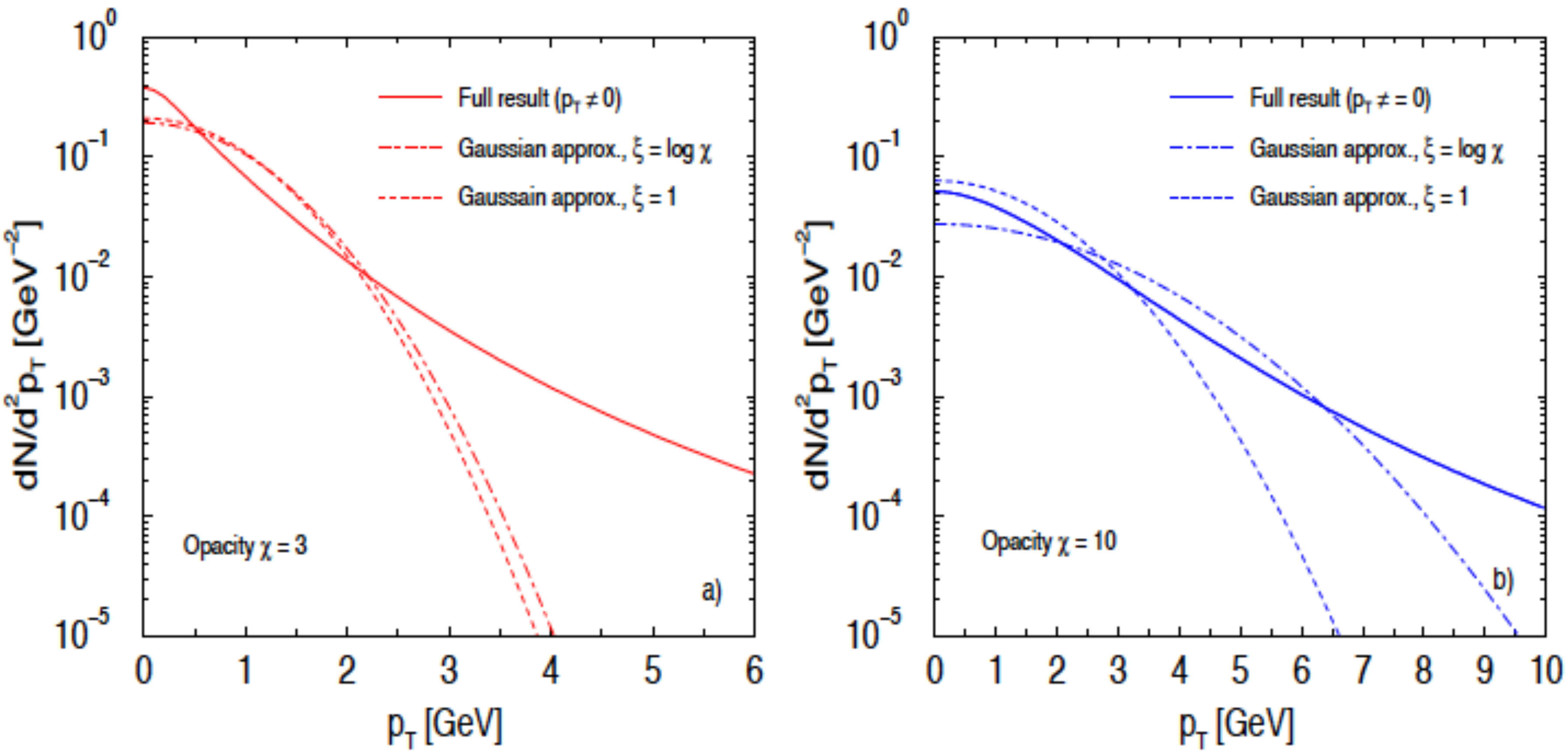
$$\langle \mathbf{p}^2\rangle = \int \hat{q}(z)\, d\Delta z\,, \qquad \hat{q}(z) = 2\frac{\mu_D^2(z)}{\lambda_g(z)}$$

Only in this original definition q-hat is related to the (transport) properties of the medium

Does it really describe parton broadening

No it doesn't

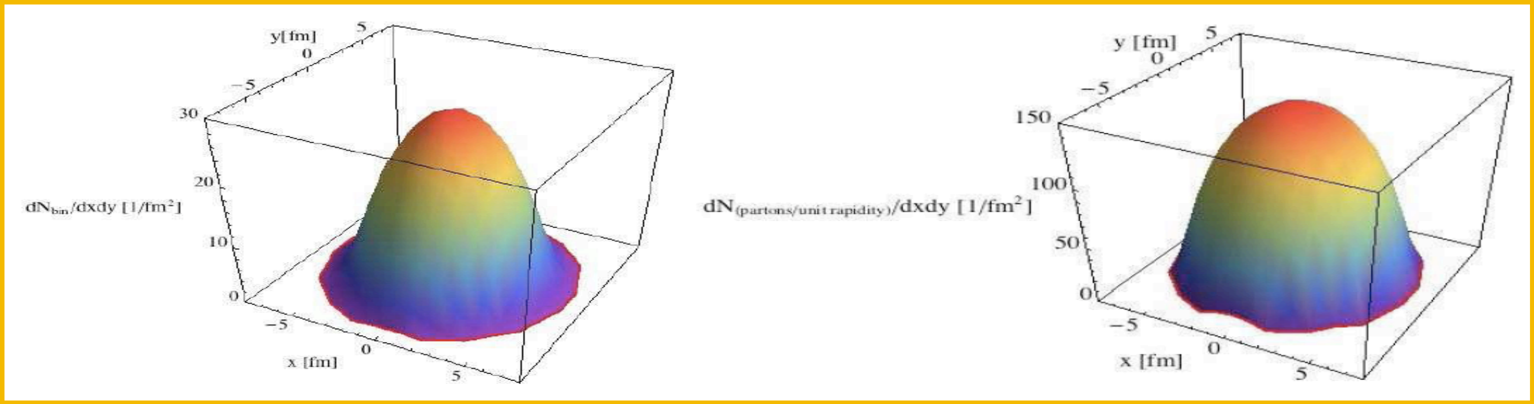
M. Gyulassy et al . (2002)



Certainly does not capture the tails of the distributions. But also does not work all that great for realistic opacities even at small p_T

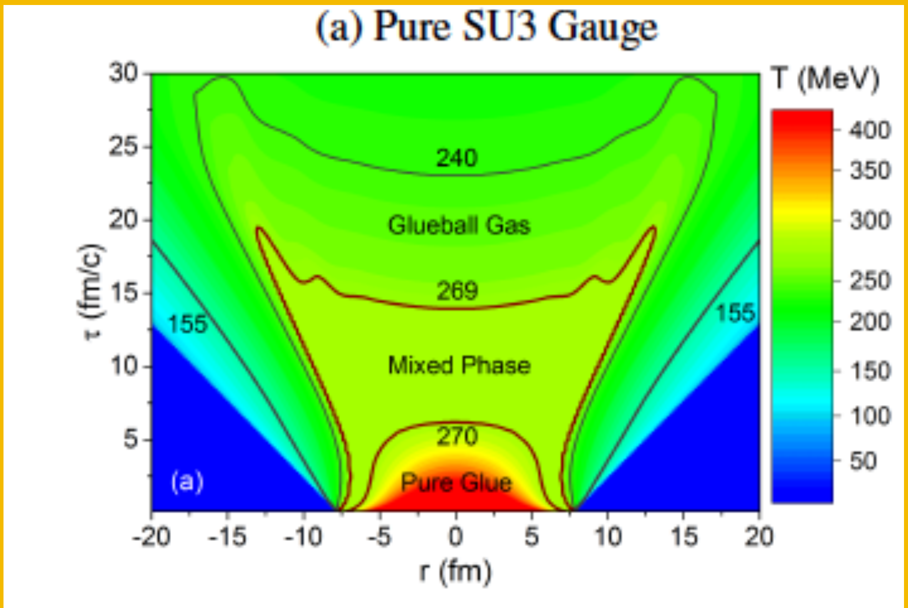
Uncertainties in quoting q-hat

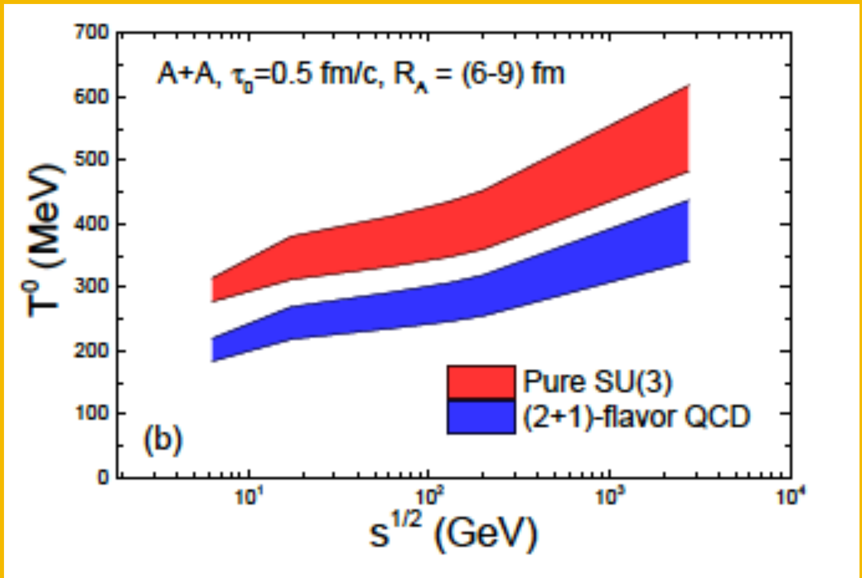
- Most theoretical energy loss models do not have q-hat as input. The prescription of how to wither implement it or quote it is a systematic uncertainty not possible to quantify, at least 100%
- Energy dependence should be removed by either quoting the Gaussian part or using working prescriptions how to cancel the leading logarythmic energy dependence. (some models do include energy dependence, this is not useful as characterization of the medium)
- Q-hat (or any other parameter, T, Debye screening, scattering length, energy density) depends on the space-time point.



Uncertainties in quoting q-hat

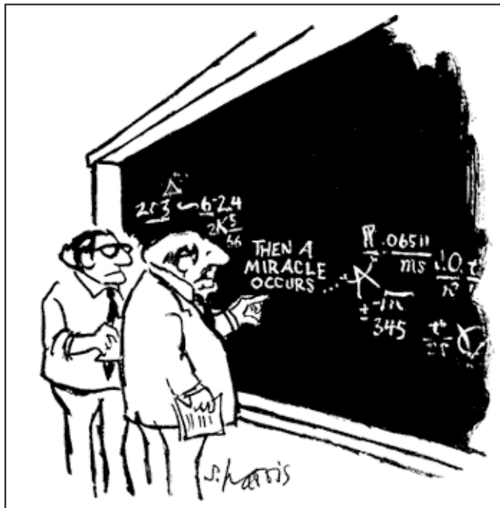
- If an average is quoted it should be specified, how are the different space-time points weighted
- Also may depend on the tupe of hydrodynamic medium, gluon dominated, quark-gluon, how many degrees of freedom





V. Vovchenko et al . (2002)

V. Non-locality of in-medium parton splittings / radiative energy loss



“I think you should be more explicit here in step two.”

Conclusions

- Uncertainties in heavy flavor tomography. Production mechanism of heavy flavor, energy loss vs parton showers. At high pT these are quantifiable uncertainties. ~ 20-30% uncertainty in the extraction of q-hat. At smaller pT differences can be 50-100% because of gluon fragmentation
- Uncertainties due to theoretical models. They take different approximations. When compared at face value they were 400% different. Even of improvements made – 100% difference
- Most models don't use q-hat. Different prescriptions are used for different models. This is hard to quantify. 100% uncertainty. The values of q-hat depend of the space-time point or average, what average, etc. Are logs of energy eliminated or not. 100%
- Within a specific model realistically one can quote transport parameters with 20% accuracy (if everything is specified)
- Between models I don see how better than 100% uncertainty can be achieved. Anything smaller would appear to be "optimistic"

2017 Jets and heavy flavor workshop

- Second in a series of workshops to bring the NP and HEP communities working on jets and heavy flavor, with emphasis on QCD and SCET