Ivan Vitev

A complete set of splitting functions in nuclear matter to any order in opacity

Initial Stages 2019, June 24 - 28, 2019

Columbia University, NYC, NY

Outline

A lot of credit for this work goes to my collaborators Matt Sievert and Boram Yoon

M. Sievert et al. (2018)

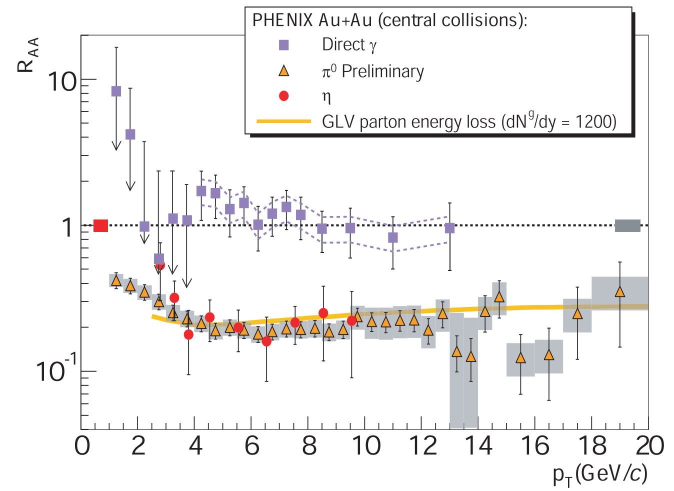
M. Sievert et al. (2019)

- Introduction and motivation
- Calculation of gluon emission off quarks beyond the soft approximation and to any order in opacity
- Calculation of all in-medium splitting functions / numerical evaluation
- Conclusions

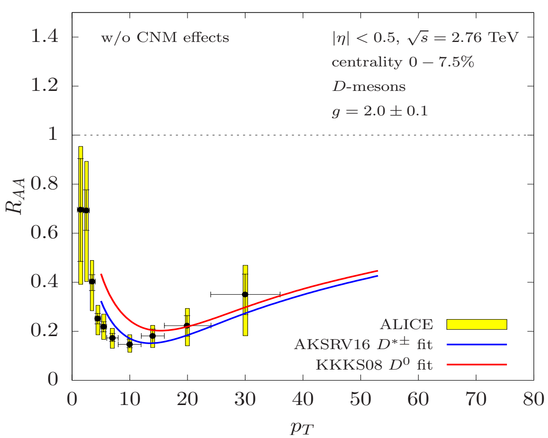
Introduction & Motivation

- In heavy ion collisions medium-induced energy loss and more generally in-medium parton showers are the cornerstone of high-p_T physics
- The associated phenomena were dubbed jet quenching and established in a myriad of observables

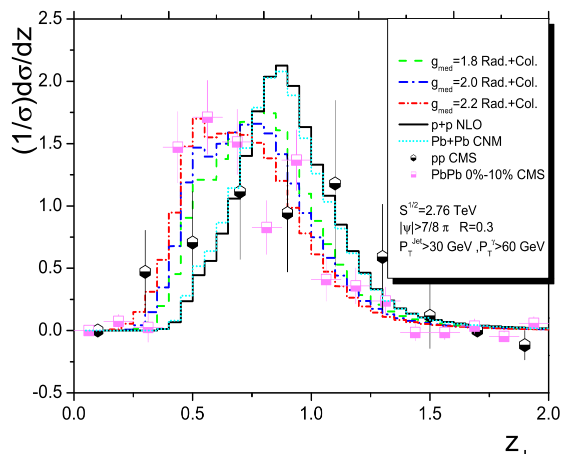
M. Gyulassy et al . (1992)



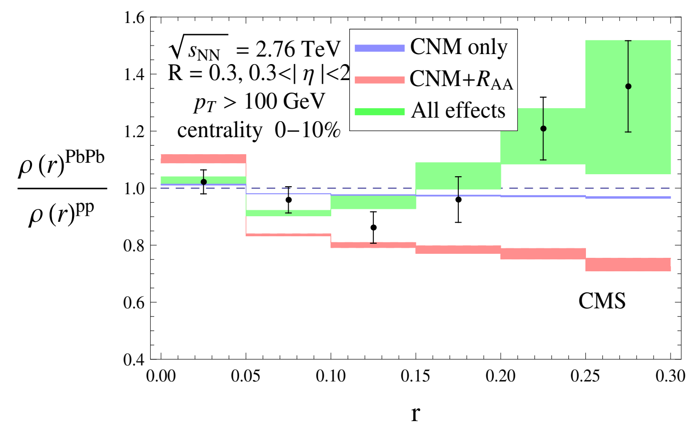
Inclusive hadron suppression, hadron correlations



Heavy flavor suppression, b jets,di-b jets



Jet suppression, enhanced dijet asymmetries, γ,Z⁰-tagged jets



Jet substructure modification, shapes, frag. Functions, splitting functions

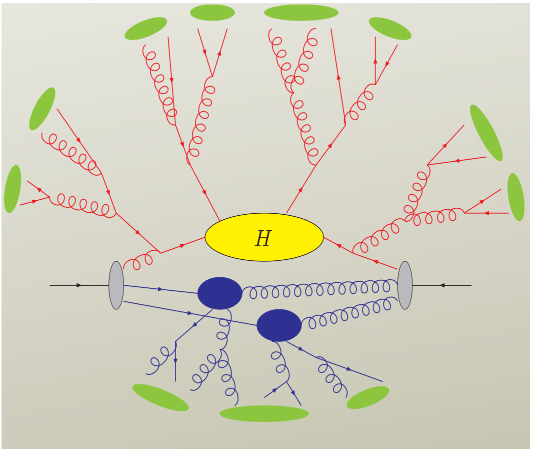
Full in medium splitting

- Full massless and massive in-medium splitting functions now available to first order in opacity

G. Ovanesyan et al . (2011)

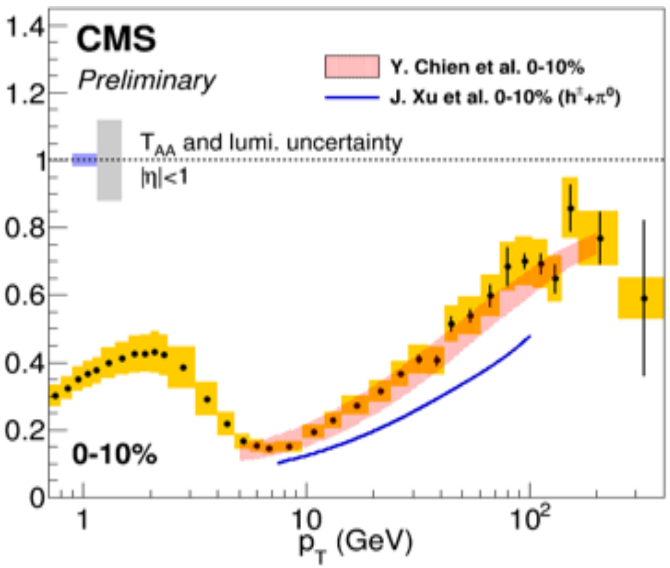
- SCET-based effective theories created to solve this problem

F. Ringer et al . (2016)



Representative example

$$
\begin{aligned}
\left(\frac{dN^{\rm med}}{dx\,d^2\boldsymbol{k}_\perp}\right)_{Q\to Qg} = {} & \frac{\alpha_s}{2\pi^2}C_F \int \frac{d\Delta z}{\lambda_g(z)}\int d^2\boldsymbol{q}_\perp \frac{1}{\sigma_{el}}\frac{d\sigma_{el}^{\rm med}}{d^2\boldsymbol{q}_\perp}\left\{\left(\frac{1+(1-x)^2}{x}\right)\left[\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2}\right.\right.\\
& \times\left(\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2}-\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2}\right)(1-\cos[(\Omega_1-\Omega_2)\Delta z]) + \frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2}\cdot\left(2\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2}-\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2}\right.\\
& \left.-\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2}\right)(1-\cos[(\Omega_1-\Omega_3)\Delta z]) + \frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2}\cdot\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2}(1-\cos[(\Omega_2-\Omega_3)\Delta z])\\
& +\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2}\cdot\left(\frac{\boldsymbol{D}_\perp}{\boldsymbol{D}_\perp^2+\nu^2}-\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2}\right)(1-\cos[\Omega_4\Delta z]) - \frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2}\cdot\frac{\boldsymbol{D}_\perp}{\boldsymbol{D}_\perp^2+\nu^2}(1-\cos[\Omega_5\Delta z])\\
& \left.+\frac{1}{N_c^2}\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2}\cdot\left(\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2}-\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2}\right)(1-\cos[(\Omega_1-\Omega_2)\Delta z])\right]\\
& \left.+x^3m^2\left[\frac{1}{\boldsymbol{B}_\perp^2+\nu^2}\cdot\left(\frac{1}{\boldsymbol{B}_\perp^2+\nu^2}-\frac{1}{\boldsymbol{C}_\perp^2+\nu^2}\right)(1-\cos[(\Omega_1-\Omega_2)\Delta z])+\ldots\right]\right\}
\end{aligned}
$$



Z. Kang et al . (2015)

- For the first time we were able to do is higher order and resummed calculations

Higher order opacity corrections

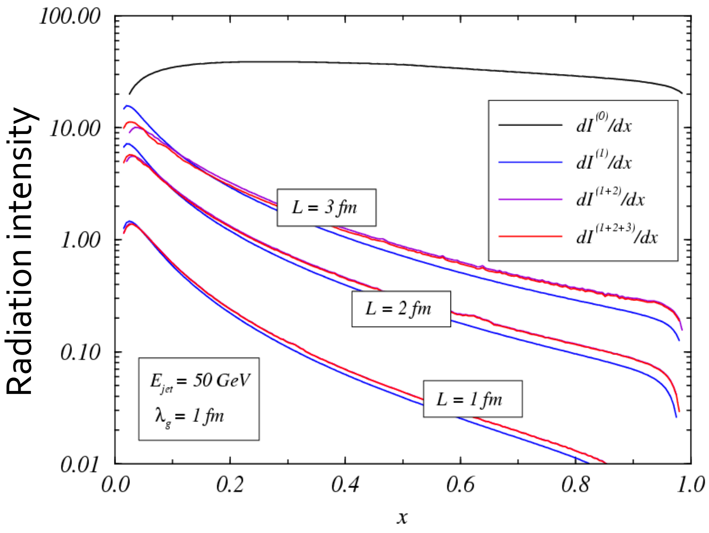
- The very thick medium approaches – they simplify the problem to resum the interactions

R. Baier et al . (1996)

- Finite opacity approaches – builds expansion in the correlation between the scattering centers

M. Gyulassy et al . (2000)

Clearly the next logical steps are
- Derive all in-medium splittings to any order in opacity with no approximations other than eikonal
- Perform numerical evaluation to find the first correction to jet and heavy flavor observables



It was also done to higher orders in opacity (~9) in the soft gluon emission limit

M. Gyulassy et al . (2000)

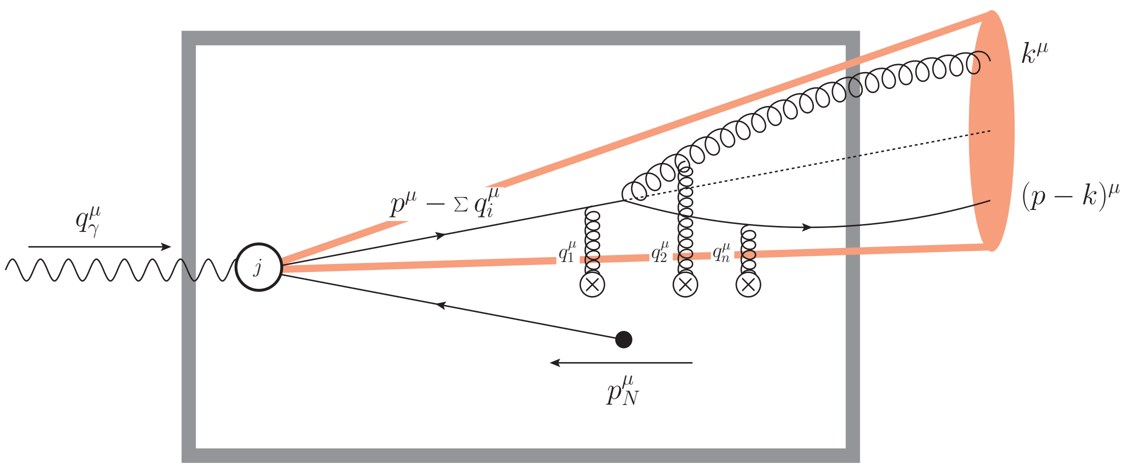
S. Wicks (2009)

Theoretical framework

- The theoretical framework is completely general – it is applicable for both cold nuclear matter and the QGP.
- This is achieved by isolating the medium in transport parameters and universal gluon-mediated interactions

$$\mathcal{L}_{opac.} = \mathcal{L}_{QCD} + \mathcal{L}_{ext}^{qG} + \mathcal{L}_{ext}^{gG} + \mathcal{L}_{G.F.} + \cdots$$

$$v(q_T^2) \to \frac{-g_{eff}^2}{q_T^2 + \mu^2} \qquad \frac{d\sigma^{el}}{d^2q} = \frac{1}{(2\pi)^2}\frac{C_F}{2N_c}[v(q_T^2)]^2$$



In deep inelastic scattering (DIS) the lowest order processes involve prompt quark. Even at NLO the prompt gluon jet contribution is small

F. Ringer et al . (2018)

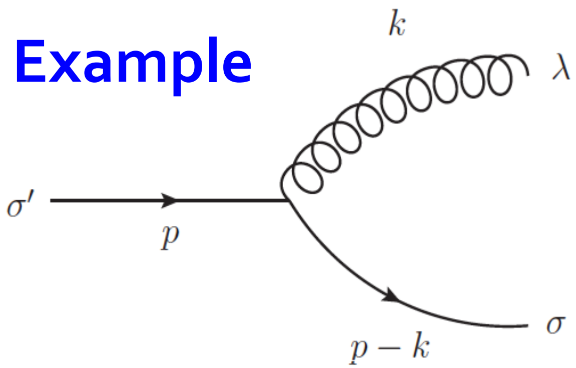
$$\frac{1}{p_N^-} \ll l_f^+ \sim \lambda^+ \sim L^+$$

$$\mathcal{O}\left(\frac{\perp^2}{Q^2}\right)$$

- The limit we are interested in
- We neglect collisional energy losses

Lightcone wave functions and parton branchings

Example



- The technique of lightcone wavefunctions

$$\psi(x, \underline{k-xp}) \equiv \frac{1}{2p^+}\frac{1}{p^- - (p-k)^- - k^-}\overline{U}_\sigma(p-k)\left[-g\not\epsilon^*_\lambda(k)\right]U_{\sigma'}(p)$$
$$= \frac{gx(1-x)}{(k-xp)_T^2 + x^2m^2}\left\{\frac{2-x}{x\sqrt{1-x}}\left(\epsilon^*_\lambda\cdot(\underline{k}-x\underline{p})\right)\left[\mathbb{1}\right]_{\sigma\sigma'} + \frac{\lambda}{\sqrt{1-x}}\left(\epsilon^*_\lambda\cdot(\underline{k}-x\underline{p})\right)\left[\tau_3\right]_{\sigma\sigma'} + \frac{im\,x}{\sqrt{1-x}}\epsilon^*_\lambda\times\left[\underline{\tau_\perp}\right]_{\sigma\sigma'}\right\}.$$

$$\langle\psi(x,\underline{\kappa})\,\psi^*(x,\underline{\kappa}')\rangle \equiv \sum_{\lambda=\pm1}\frac{1}{2}\mathrm{tr}\left[\psi(x,\underline{\kappa})\,\psi^*(x,\underline{\kappa}')\right]$$
$$= \frac{8\pi\alpha_s\,(1-x)}{\left[\kappa_T^2 + x^2m^2\right]\left[\kappa_T'^2 + x^2m^2\right]}\left[(\underline{\kappa}\cdot\underline{\kappa}')\;\left[1+(1-x)^2\right] + x^4m^2\right]$$

Useful to express in Pauli matrixes

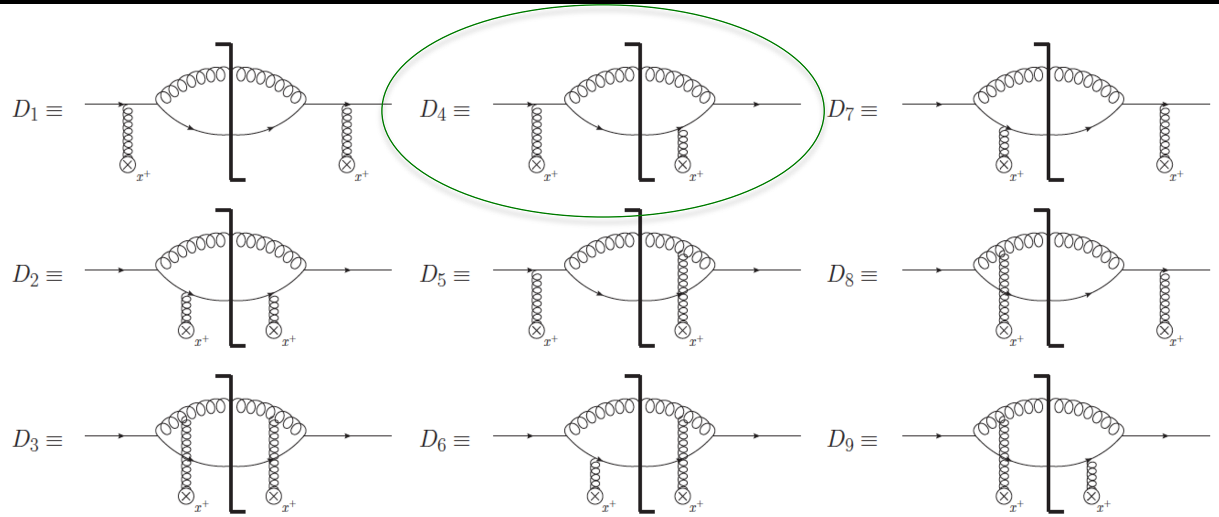
c.f. F. Ringer et al . (2016)

Branchings depending on the intrinsic momentum of the splitting $\underline{\kappa} = \underline{k - xp}.$

$$xp^+\frac{dN}{d^2k\,dx\,d^2p\,dp^+}\bigg|_{\mathcal{O}(\chi^0)} = \frac{\alpha_s\,C_F}{2\pi^2}\,\frac{(k-xp)_T^2\;\left[1+(1-x)^2\right] + x^4m^2}{\left[(k-xp)_T^2 + x^2m^2\right]^2}\times\left(p^+\frac{dN_0}{d^2p\,dp^+}\right)$$

- Certain advantages – can provide in “one shot” both massive and massless splitting functions
- Have checked that results agree for massless and massive DGLAP

Opacity expansion building blocks – direct terms



- Interaction in the amplitude and the conjugate amplitude (Direct or single Born diagrams)

Representative forward cut diagram

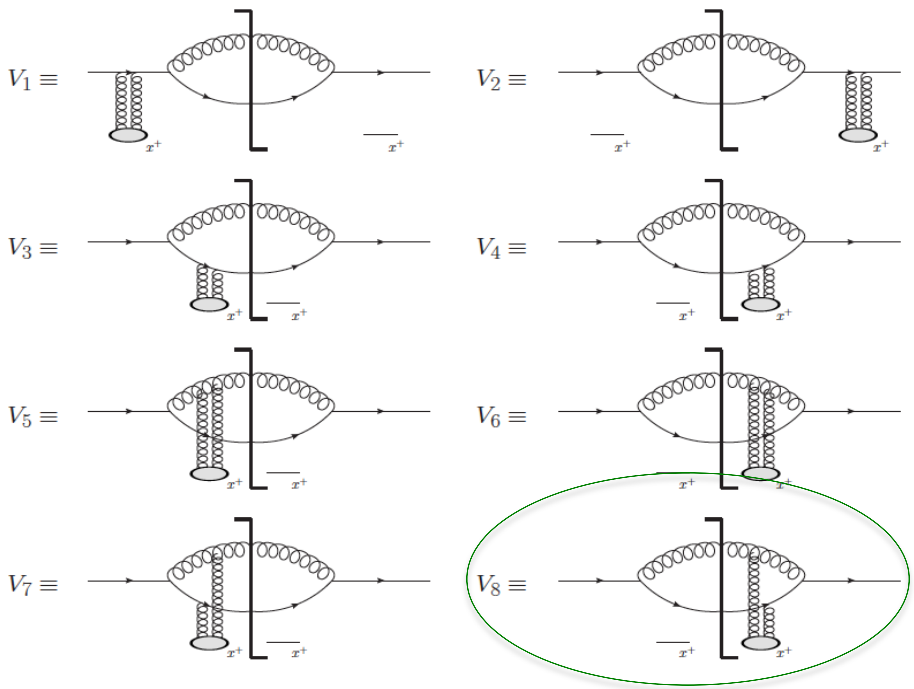
- Propagators hide in the wavefunctions

$$D_4 = \left[\frac{-1}{2N_c C_F} e^{+i[\Delta E^-(\underline{k}-x\underline{p})-\Delta E^-(\underline{k}-x\underline{p}+x\underline{q})]z^+} \right] \psi(x, \underline{k}-x\underline{p}) \left[0 - e^{-i\Delta E^-(\underline{k}-x\underline{p})z^+} \right]$$
$$\times \left[e^{+i\Delta E^-(\underline{k}-x\underline{p}+x\underline{q})z^+} - e^{+i\Delta E^-(\underline{k}-x\underline{p}+x\underline{q})x_0^+} \right] \psi^*(x, \underline{k}-x\underline{p}+x\underline{q}),$$

- Vitruallity changes enter the interference phases and are related to the propagators

$$p^- - k^- - (p-k)^- = \Delta E^-(\underline{k}-x\underline{p})$$

Opacity expansion building blocks –virtual terms



- Interaction in the amplitude or the conjugate amplitude (Virtual or double Born diagrams)

Agree with the full splitting functions of

G. Ovanesyan et al . (2011)

F. Ringer et al . (2016)

And energy loss of

M. Gyulassy et al . (2001)

- A more interesting diagram- Double born can contribute to virtuality changes

$$V_8 = \left[\frac{N_c}{2C_F} \, e^{i[\Delta E^-(\underline{k}-x\underline{p}) - \Delta E^-(\underline{k}-x\underline{p}-\underline{q})]z^+} \right] \psi(x, \underline{k} - x\underline{p}) \left[0 - e^{-i\Delta E^-(\underline{k}-x\underline{p})x_0^+} \right]$$
$$\times \left[e^{+i\Delta E^-(\underline{k}-x\underline{p}-\underline{q})z^+} - e^{+i\Delta E^-(\underline{k}-x\underline{p}-\underline{q})x_0^+} \right] \psi^*(x, \underline{k} - x\underline{p} - \underline{q}) \, .$$

Parton branching to any order in opacity

- Treating color (one complication in QCD).

M. Sievert et al . (2018)

$$\mathcal{C}_1 = \frac{1}{N_c C_F} \mathrm{tr}[t^b t^b\, t^a M^a] = \mathcal{C}_0\,,$$

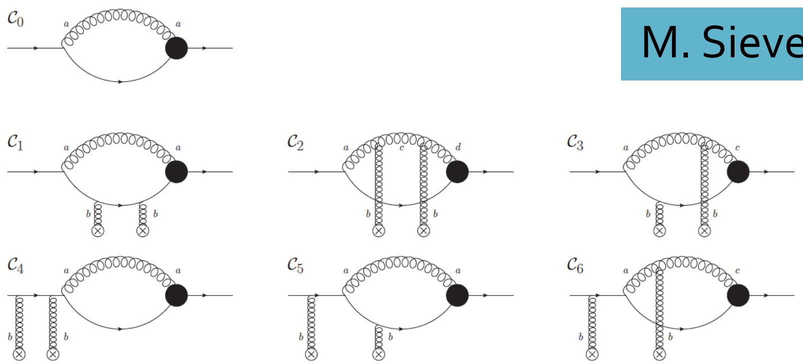
$$\mathcal{C}_2 = \frac{1}{N_c C_F} f^{acb} f^{cdb} \mathrm{tr}[t^a M^d] = -\frac{N_c}{C_F}\,\mathcal{C}_0\,,$$

$$\mathcal{C}_3 = \frac{1}{N_c C_F} f^{acb} \mathrm{tr}[t^b t^a M^c] = \frac{iN_c}{2C_F}\,\mathcal{C}_0\,,$$

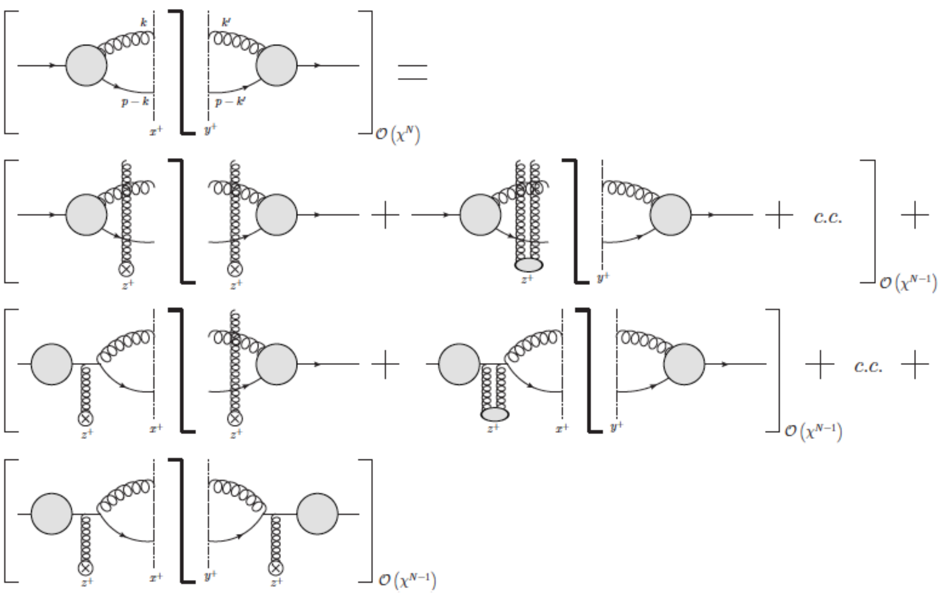
$$\mathcal{C}_4 = \frac{1}{N_c C_F} \mathrm{tr}[t^a\, t^b t^b M^a] = \mathcal{C}_0\,,$$

$$\mathcal{C}_5 = \frac{1}{N_c C_F} \mathrm{tr}[t^b t^a t^b M^a] = \frac{-1}{2N_c C_F}\,\mathcal{C}_0\,,$$

$$\mathcal{C}_6 = \frac{1}{N_c C_F} f^{acb} \mathrm{tr}[t^a t^b M^c] = \frac{-iN_c}{2C_F}\,\mathcal{C}_0\,.$$



- Color is not entangled, homogeneous structure and multiplicative factors that can be algebraically treated
- Finally, relative to the splitting vertex we classify the as
- Initial/Initial, Initial/Final, Final/Initial and Final/Final



Master equation – matrix form

- Upper triangular structure. Suggests specific strategy how to solve it. Calculated: initial conditions, kernels, and wrote a Mathematica code to solve it

$$\begin{bmatrix} f^{(N)}_{F/F}(\underline{k},\underline{k}',\underline{p};x^+,y^+) \\ f^{(N)}_{I/F}(\underline{k}',\underline{p};x^+,y^+) \\ f^{(N)}_{F/I}(\underline{k},\underline{p};x^+,y^+) \\ f^{(N)}_{I/I}(\underline{p};x^+,y^+) \end{bmatrix} = \int_{x_0^+}^{\min[x^+,y^+,R^+]} \frac{dz^+}{\lambda^+} \int \frac{d^2q}{\sigma_{el}} \frac{d\sigma^{el}}{d^2q} \begin{bmatrix} \mathcal{K}_1 & \mathcal{K}_2 & \mathcal{K}_3 & \mathcal{K}_4 \\ 0 & \mathcal{K}_5 & 0 & \mathcal{K}_6 \\ 0 & 0 & \mathcal{K}_7 & \mathcal{K}_8 \\ 0 & 0 & 0 & \mathcal{K}_9 \end{bmatrix} \begin{bmatrix} f^{(N-1)}_{F/F}(\underline{k},\underline{k}',\underline{p};x^+,y^+) \\ f^{(N-1)}_{I/F}(\underline{k}',\underline{p};x^+,y^+) \\ f^{(N-1)}_{F/I}(\underline{k},\underline{p};x^+,y^+) \\ f^{(N-1)}_{I/I}(\underline{p};x^+,y^+) \end{bmatrix}$$

Simplest kernel

$$\mathcal{K}_9 = \left[e^{-\underline{q}\cdot\underline{\nabla}_p}\, e^{+(z^+-x^+)\partial_{x^+}}\, e^{+(z^+-y^+)\partial_{y^+}} \right] + \left[-\frac{1}{2} \right] \left[e^{+(z^+-x^+)\partial_{x^+}} + e^{+(z^+-y^+)\partial_{y^+}} \right]$$

⋮

Most complicated kernel

$$\mathcal{K}_1 = \left[e^{i[\Delta E^-(\underline{k}-x\underline{p}+x\underline{q})-\Delta E^-(\underline{k}-x\underline{p})]z^+}\, e^{i[\Delta E^-(\underline{k}'-x\underline{p})-\Delta E^-(\underline{k}'-x\underline{p}+x\underline{q})]z^+} \right] \left[e^{-\underline{q}\cdot\underline{\nabla}_p}\, e^{+(z^+-x^+)\partial_{x^+}}\, e^{+(z^+-y^+)\partial_{y^+}} \right]$$
$$+ \left[\frac{N_c}{C_F} e^{i[\Delta E^-(\underline{k}-x\underline{p}-(1-x)\underline{q})-\Delta E^-(\underline{k}-x\underline{p})]z^+}\, e^{i[\Delta E^-(\underline{k}'-x\underline{p})-\Delta E^-(\underline{k}'-x\underline{p}-(1-x)\underline{q})]z^+} \right]$$
$$\times \left[e^{-\underline{q}\cdot\underline{\nabla}_k}\, e^{-\underline{q}\cdot\underline{\nabla}_{k'}}\, e^{-\underline{q}\cdot\underline{\nabla}_p}\, e^{+(z^+-x^+)\partial_{x^+}}\, e^{+(z^+-y^+)\partial_{y^+}} \right]$$

+ 8 more lines

Explicit solution to second order in opacity

- Present the first exact result to this order (including the ability to discuss broad or narrow sources)

$$x p^+ \frac{dN}{d^2k\, dx\, d^2p\, dp^+}\bigg|_{\mathcal{O}(\chi^2)} = \frac{C_F}{2(2\pi)^3(1-x)} \int_{x_0^+}^{R^+} \frac{dz_2^+}{\lambda^+} \int_{x_0^+}^{z_2^+} \frac{dz_1^+}{\lambda^+} \int \frac{d^2q_1}{\sigma_{el}} \frac{d^2q_2}{\sigma_{el}} \frac{d\sigma^{el}}{d^2q_1} \frac{d\sigma^{el}}{d^2q_2} \times \left\{ \left(p^+ \frac{dN_0}{d^2p\, dp^+} \right) \mathcal{N}_1 \right.$$

$$\left. + \left(p^+ \frac{dN_0}{d^2(p-q_1)\, dp^+} \right) \mathcal{N}_2 + \left(p^+ \frac{dN_0}{d^2(p-q_2)\, dp^+} \right) \mathcal{N}_3 + \left(p^+ \frac{dN_0}{d^2(p-q_1-q_2)\, dp^+} \right) \mathcal{N}_4 \right\}$$

$$\mathcal{N}_1 =$$

$$\left|\psi(\underline{k} - x\underline{p})\right|^2 \left[\frac{(C_F+N_c)^2}{C_F^2} - \frac{N_c(C_F+N_c)}{C_F^2} \cos(\delta z_1 \Delta E^-(\underline{k} - x\underline{p})) + \frac{N_c^2}{2C_F^2} \cos(\delta z_2 \Delta E^-(\underline{k} - x\underline{p})) \right.$$

$$\left. - \frac{N_c(2C_F+N_c)}{2C_F^2} \cos((\delta z_1 + \delta z_2) \Delta E^-(\underline{k} - x\underline{p})) \right]$$

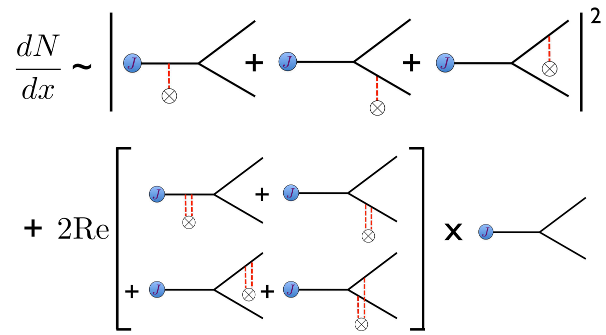
⋮

+ 9 more pages

- For broad sources and in the soft gluon limit we have checked that the result reduces to the GLV second order in opacity

Generalizing the result to all in-medium splittings (4)

- Note – all splittings have the same topology.
  Same - structure, interference phases, propagators
  Different - mass dependence, wavefunctions, color (which also affects transport coefficients)



$$\langle \psi(x,\underline{\kappa})\,\psi^*(x,\underline{\kappa}')\rangle = \frac{8\pi\alpha_s\, f(x)}{[\kappa_T^2+\nu^2 m^2]\,[\kappa_T'^2+\nu^2m^2]}\left[g(x)\,(\underline{\kappa}\cdot\underline{\kappa}')+\nu^4 m^2\right] \quad \Delta E^-(\underline{\kappa}) = -\frac{\kappa_T^2+\nu^2m^2}{2x(1-x)p^+}$$

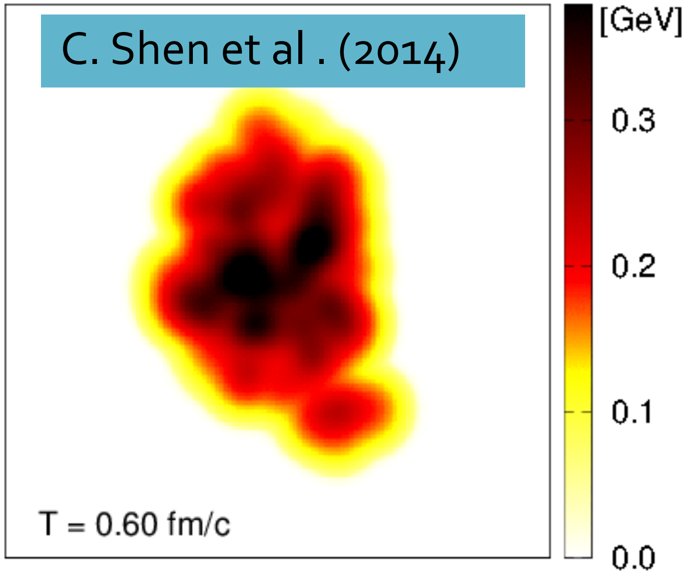
- Master table that gives all ingredients

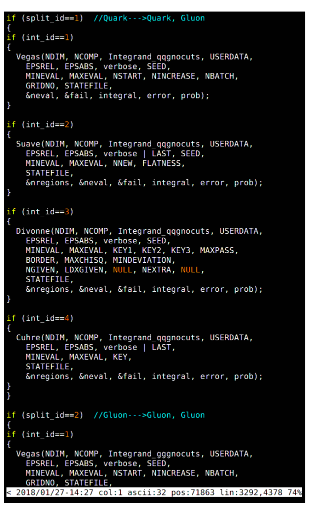
	d_1	d_2	d_3	d_4	d_5	d_6	v_1	v_2	v_3	v_4	λ_R^+	$\mathcal{C}_0$	ν	$f(x)$	$g(x)$
G/q	1	1	$\frac{N_c}{C_F}$	$\frac{-1}{2N_cC_F}$	$\frac{N_c}{2C_F}$	$\frac{-N_c}{2C_F}$	$-\frac{1}{2}$	$-\frac{1}{2}$	$\frac{-N_c}{2C_F}$	$\frac{N_c}{2C_F}$	λ_q^+	C_F	x	$1-x$	$1+(1-x)^2$
q/q	1	1	$\frac{N_c}{C_F}$	$\frac{-1}{2N_cC_F}$	$\frac{N_c}{2C_F}$	$\frac{-N_c}{2C_F}$	$-\frac{1}{2}$	$-\frac{1}{2}$	$\frac{-N_c}{2C_F}$	$\frac{N_c}{2C_F}$	λ_q^+	C_F	$1-x$	x	$1+x^2$
q/G	1	$\frac{C_F}{N_c}$	$\frac{C_F}{N_c}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2N_c^2}$	$-\frac{1}{2}$	$-\frac{C_F}{2N_c}$	$\frac{-N_c}{2C_F}$	$\frac{-1}{2N_c^2}$	λ_G^+	$\frac{1}{2}$	1	$x(1-x)$	$x^2+(1-x)^2$
G/G	1	1	1	$\frac{1}{2}$	$\frac{1}{2}$	$-\frac{1}{2}$	$-\frac{1}{2}$	$-\frac{1}{2}$	$-\frac{1}{2}$	$\frac{1}{2}$	λ_G^+	N_c	0	$1+x^4+(1-x)^4$	1

We have now solved the problem for all splitting functions

M. Sievert et al . (2019)

Improvements in physics & code





Refactoring

- Code is **restructured** (in C++) and shortened (**24K → 8K lines**). 20x speed improvement

Effective incorporation of simulated QGP medium

- Reduced overhead for calling QGP medium grid function. 2x speed improvement

Efficient on-node parallelization

- New parallelization shows much better scaling 10x speed improvement

Overall improvement:

18 days → 1 hour

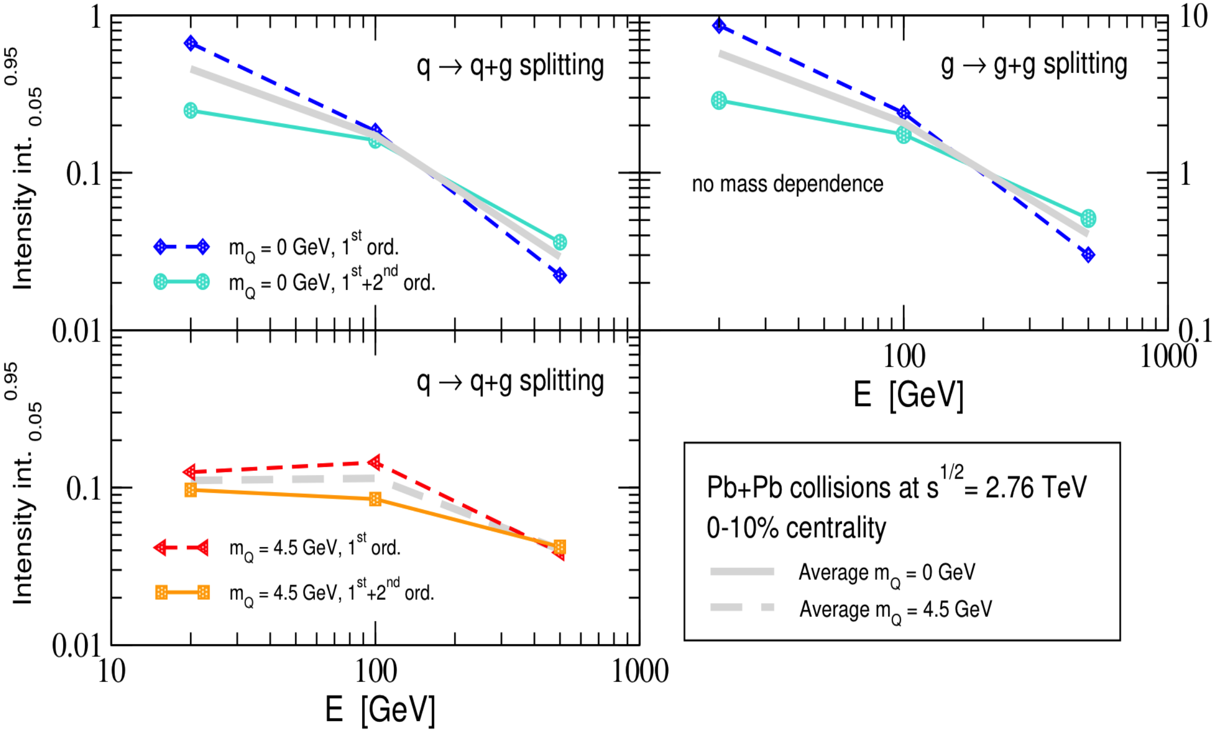
Medium-induced splitting intensity

Porting to code

- Results are directly exported from Mathematica to C++

Challenges

- Arise from larger number of evaluations

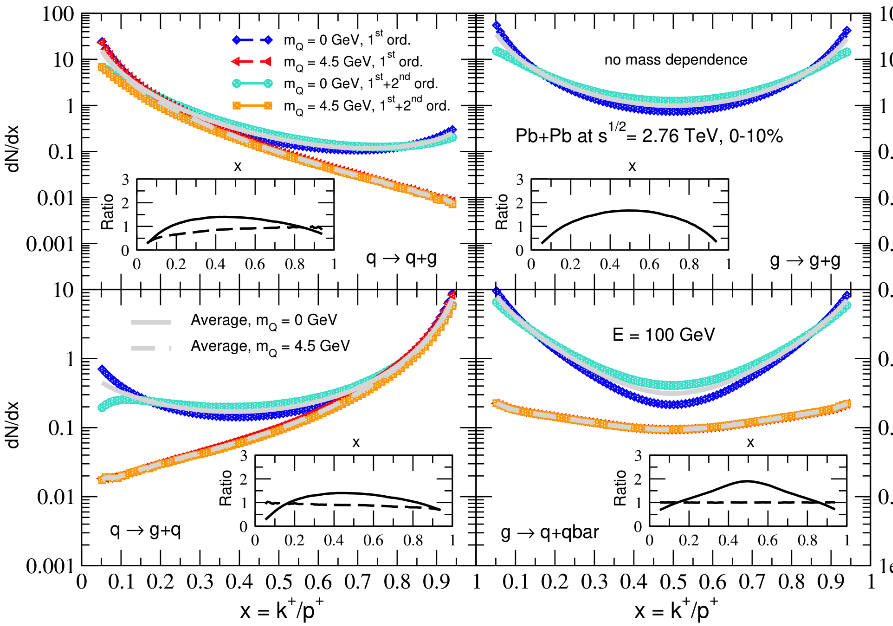


$$\mathcal{I}_{x_{\min}}^{x_{\max}} = \int_{x_{\min}}^{x_{\max}} dx \int d^2k \; x \frac{dN}{d^2k\, dx}$$

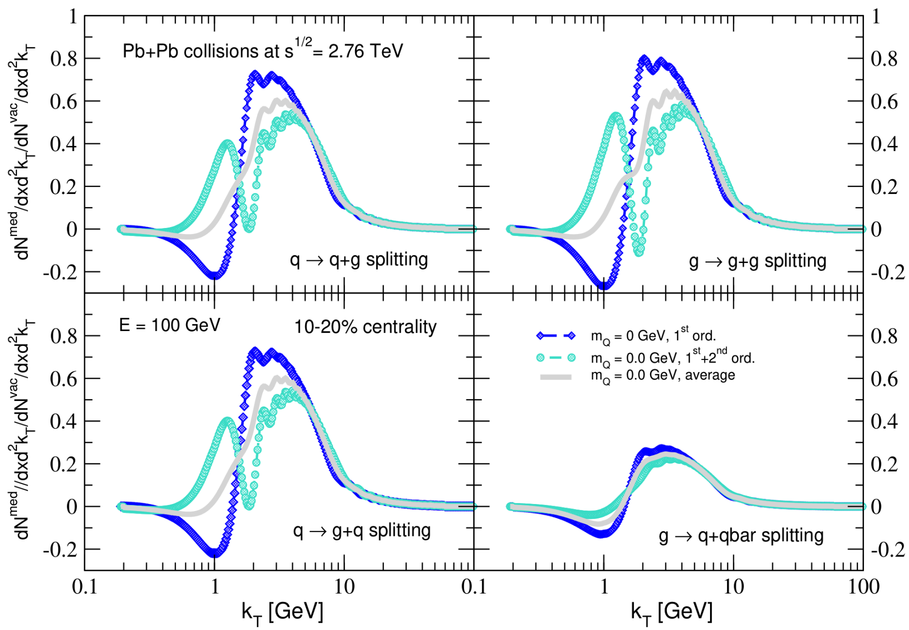
Energy loss – not a well defined concept for parton shower processes - define splitting intensity

- The main result is a change in the energy dependence of the splitting intensity – smother, or more slowly varying with E (understand jet modification with p_T)

Differential branching spectra

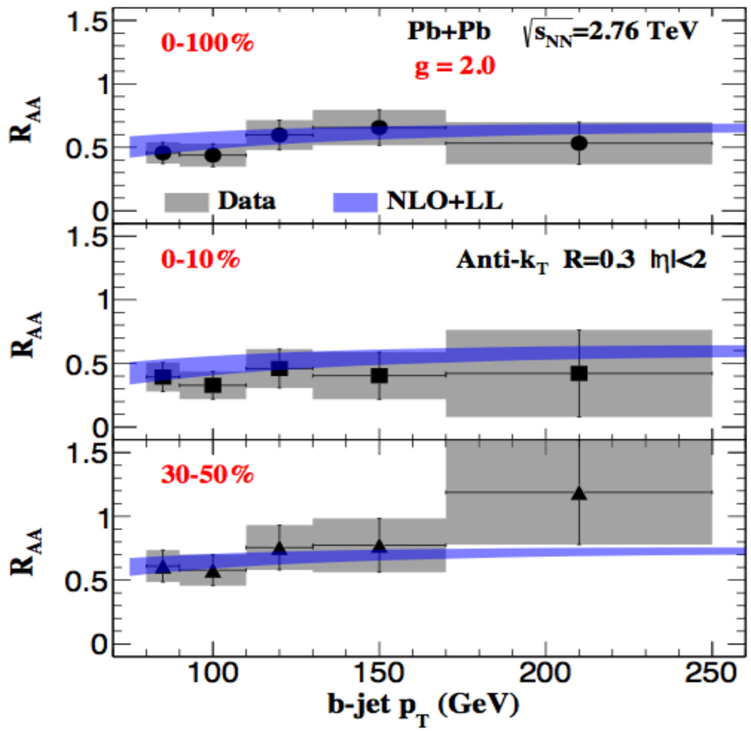


- Reduction of small-x and large-x probabilities (assymptotics modulated by thermal mass)
- Enhancement of democratic branching (x~0.5)

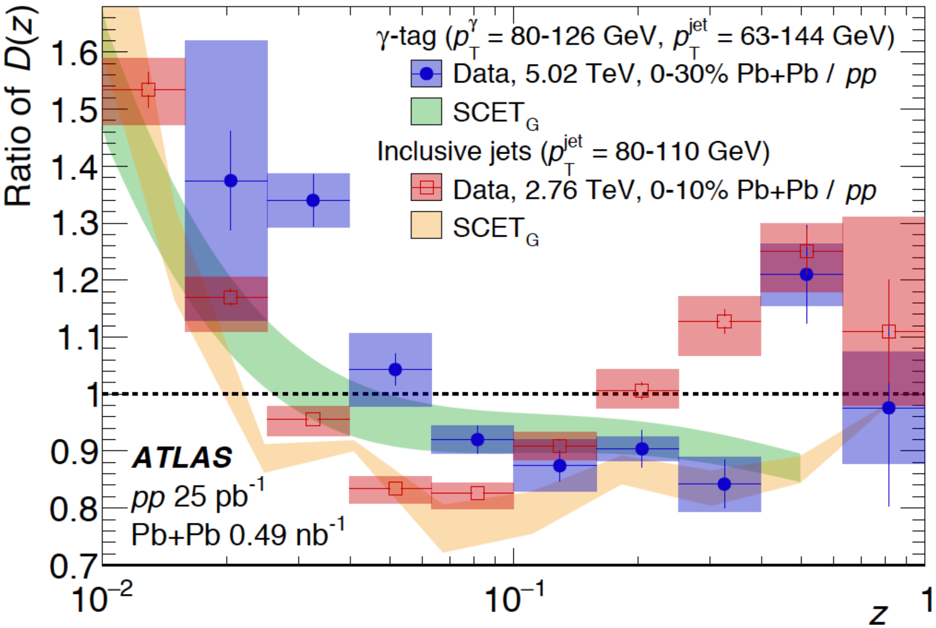


- Broder angular enhancement region
- Oscillating series – the average of 1st and 1^{st+}2nd order- candidate for pheno.

Application of the new formalism & code to jets



H. Li et al . (2018)



M. Aabound et al . (2019)

Note: new code but to 1st order in opacity

- First application to inclusive heavy flavor jets - using the technique of semi-inclusive jet functions
- Application to jet fragmentation – inclusive and photon tagged jets – captures the qualitative differences needs improvement (higher orders)

Conclusions

- Consistent progress over the past 2 decades, from energy loss to in medium parton showers to first order in opacity.
- For the first time consistent NLO and resummed calculations in the QGP environment - same language, techniques as in HEP
- Calculated the quark splitting function to any order in opacity and presented explicit results to 2^{nd} order. Cross checked the result against the known soft gluon emission limit
- We have now extended the derivation to all orders in opacity for all 4 splitting functions. Demonstrated numerical evaluation in realistic media
- Applications of new code/grids to jet physics problems, applications to second order in opacity in the near future

Motivation for numerical evaluation

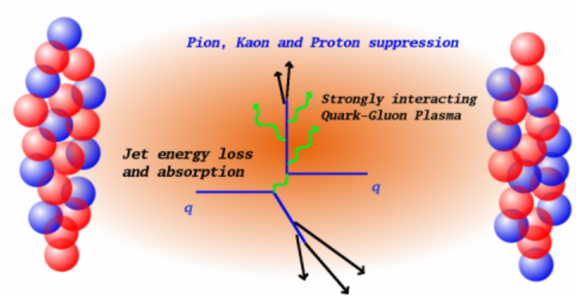
R. Baier et al . (1996)

- The very thick medium approaches – they simplify the problem to resum the interactions

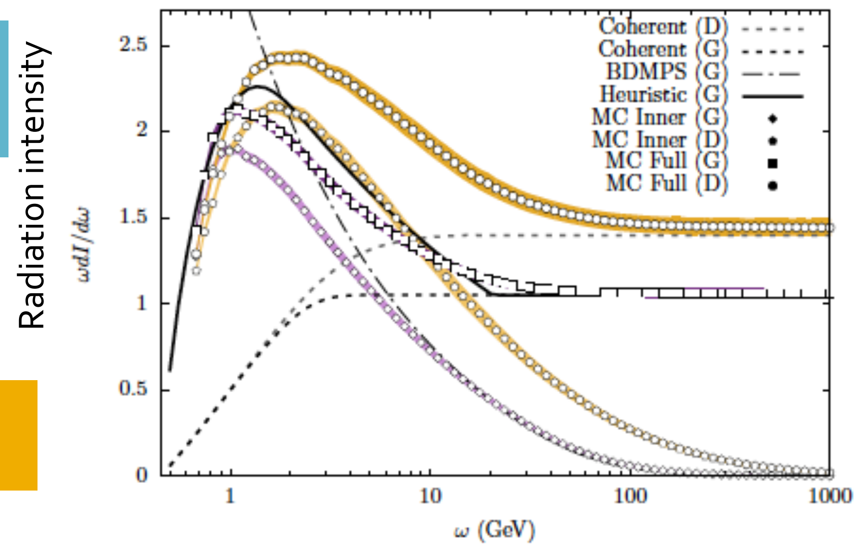
M. Gyulassy et al . (2000)

- Finite opacity approaches – builds expansion in the correlation between the scattering centers

Approaches to the theoretical problem



X. Feal et al . (2018)



Realistic QGP - q ~ 2.5 scatterings, g ~5 . Also problems with BDMPS not recovering known assymptotic limits

- Any order in opacity result

$$x\frac{dN^{(n)}}{dx\,d^2\mathbf{k}} = \frac{C_R\alpha_s}{\pi^2}\frac{1}{n!}\left(\frac{L}{\lambda_g(1)}\right)^n \int \prod_{i=1}^{n} \left\{ d\mathbf{q}_i \left(\frac{\lambda_g(1)}{\lambda_g(i)}\right)\left(\bar{v}_i^2(\mathbf{q}_i) - \delta^2(\mathbf{q}_i)\right)\right\}$$

Medium properties

$$\times \left[-2\,\mathbf{C}_{(1,\cdots,n)}\cdot\sum_{m=1}^{n} \mathbf{B}_{(m+1,\cdots,n)(m,\cdots,n)}\left(\cos\left(\sum_{k=2}^{m} \omega_{(k,\cdots,n)}\Delta z_k\right) - \cos\left(\sum_{k=1}^{m} \omega_{(k,\cdots,n)}\Delta z_k\right)\right)\right]$$

propagators

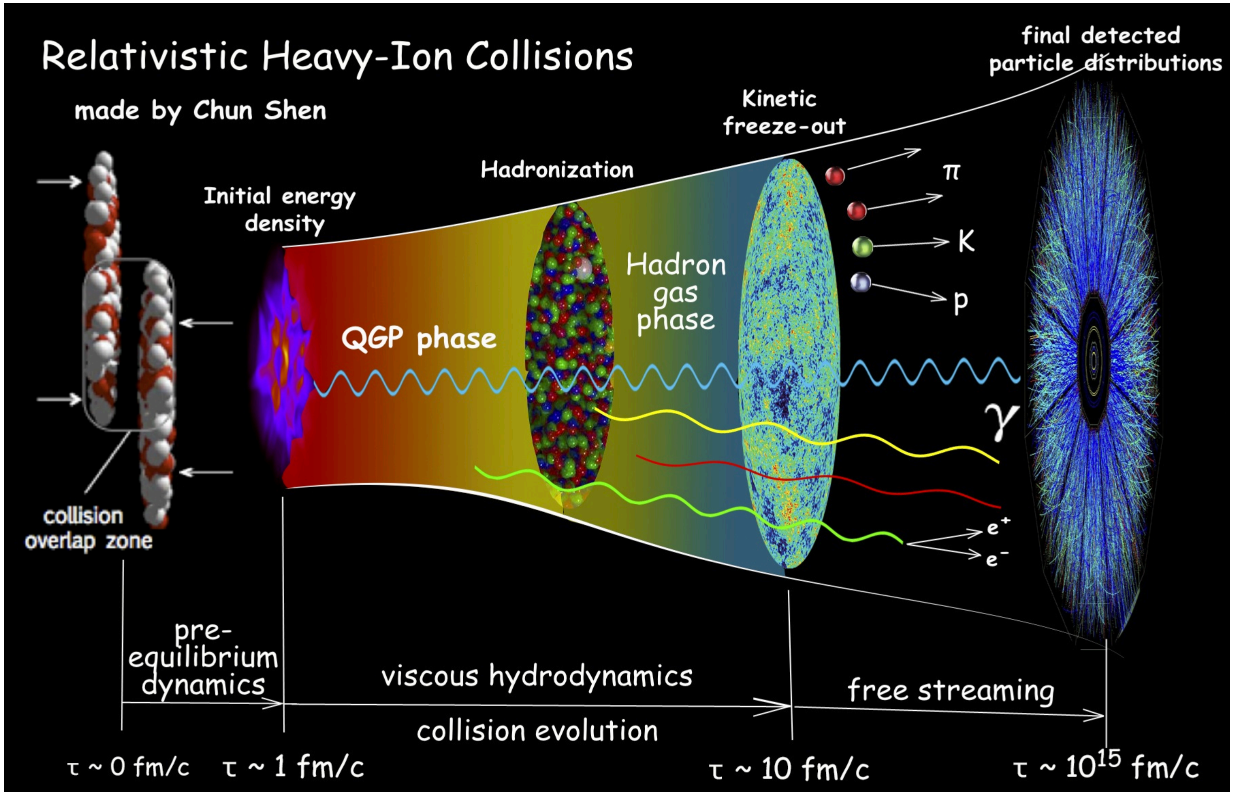
Interference phases

Numerical implementation

- Numerics can be challenging due to lengthy equations and mulit-dimensional integration
- Implementation for the case of QGP (simplified Bjorken expansion)

Lashoff-Regas et al . (2014)

- Still, code needed 3 days for a set of splittings



iEBE-VISHNU package

- Hydro + hadron cascade simulator for relativistic heavy-ion collisions
- Developed by Chun Shen and collaborators